Harald Weinfurter

Experiments on Bell's theorem: past, present, and future

MCQST

Everyday Loophole-free

Florian Fertig
Pooja Malik
Chengfeng Xu
Yiru Zhou

Wei Zhang
Tim van Leent
Robert Garthof
Kai Redeker
Weniamin Rosenfeld

Daniel Burchardt
Sebastian Eppelt
Norbert Ortegel
Markus Rau
Mathias Seubert
Derya Taray

René Schwonnek
Valerio Scarani
Charles C.-W. Lim

NUS National University of Singapore

Jake Covey — U Illinois
Hannes Bernien — U Chicago

Funding by IMPRS, CSC, BMBF, DFG

- the early days
- Aspect
- SPDC: new tools and long distances
- towards closing loopholes

- new strategies and detectors

- loophole free

- future: more users – networks – closing more loopholes?

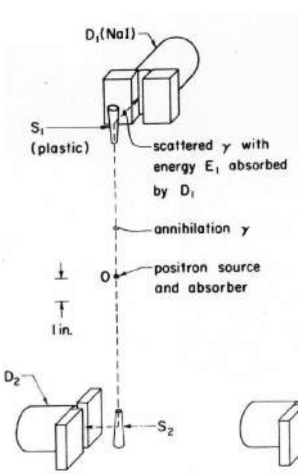
Chien-Shiung Wu

- Wu-Shaknov
  First observation of quantum correlations using electron-positron annihilation with parallel analyzers ('50)

- L. Kasday
  - angle dependent Compton scattering

violation of
Bell-inequality (70)

L. Kasday, Proc.
School Enrico Fermi IV (71)




EXPERIMENTAL TEST OF QUANTUM PREDICTIONS 207

quantum prediction and exceeded the upper limits derived from Bell's inequality and from the BA hypothesis.

The following conclusions were drawn:

1) We find no evidence for a breakdown in the quantum predictions for Compton scattering of annihilation protons. Our results, therefore, are consistent with the work of WU and SHAKNOV [1], who were the first to show good quantitative agreement between quantum theory and experiment; the work of BERTOLINI et al. [2]; and the excellent, thorough work of LANGHOFF [3]. [Also, H. MÜLLER [15] has verified the quantum predictions for circular polarization.]

2) Furthermore, if we make the assumption that it is possible in principle to construct an ideal linear polarization analyser and that quantum theory correctly relates results obtained with ideal and Compton analysers, then it follows that a local hidden-variable theory cannot describe the annihilation photons. We repeat that the assumptions could be false, and indeed the counter-examples described in Subsect. 2'1 above show that this experiment cannot rule out local hidden-variable theories.

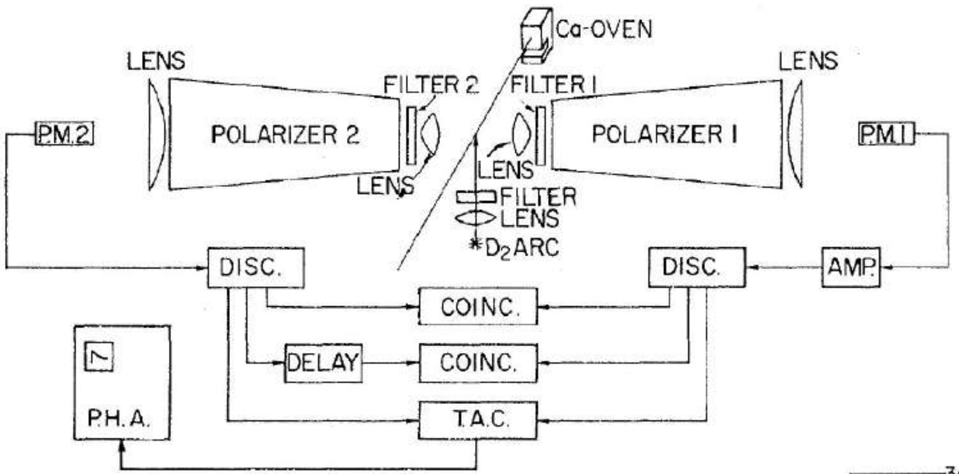
3) Finally, assuming that the quantum theory of Compton scattering is correct, we conclude that the Bohm-Aharonov hypothesis does not hold for this experimental arrangement. JAUCH has suggested, however, that the BA hypothesis may still be valid when the photons are separated by much more than twice the coherence length (*), when the flight paths of the photons are unequal, or when two different particles are involved.

Fig. 5. – Comparison between experimental (exp) results, quantum (QM) predictions, and the upper limits derived from Bell's inequality and the Bohm-Aharonov hypothesis. The error bars on the experimental points indicate statistical uncertainties. The other error bars indicate uncertainties in instrumental corrections of the various theoretical predictions. 1) Bell upper limit. 2) Bohm-Aharonov upper limit.

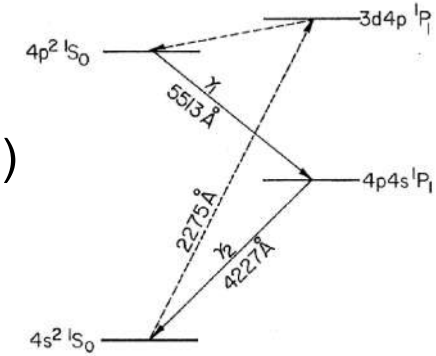
Photon Cascades

S.J. Freedman, J.F. Clauser, PRL **28**, 938 (1972)

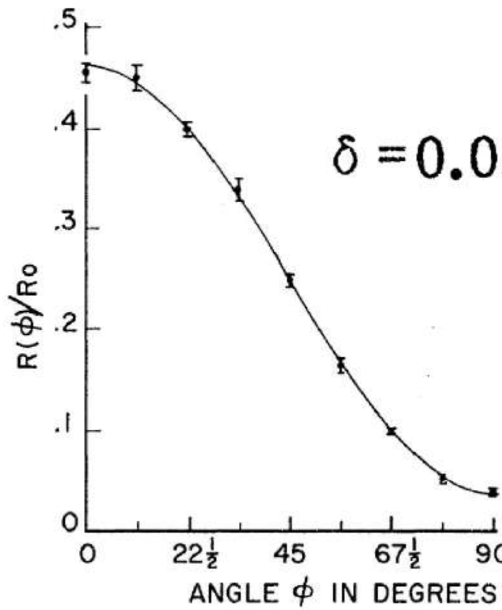
Freedman, Clauser 1972



- experimental design by Kocher Commins (|| orient.)
- Ca excited by D_2-lamp
- ~0.2 coincidence counts/s
- 200 h measurement time



$$\delta = |R(22\tfrac{1}{2}°)/R_0 - R(67\tfrac{1}{2}°)/R_0| - \tfrac{1}{4} \leq 0$$



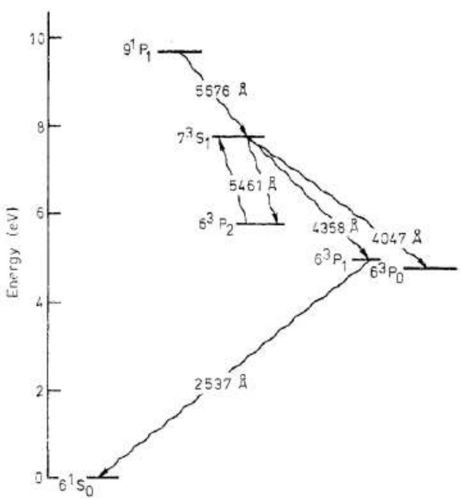
$\delta = 0.050 \pm 0.008$

> We consider these results to be strong evidence against local hidden-variable theories.

E.S. Fry, R.C. Thompson, PRL **37**, 465 (1976)

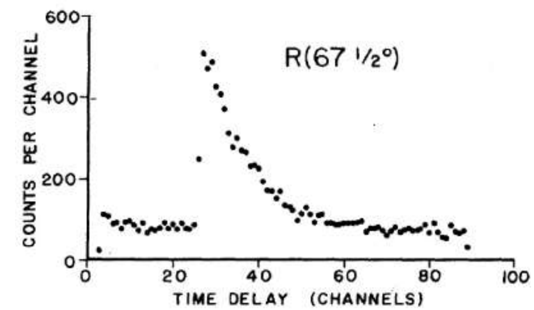
Holt, Pipkin (unpublished)

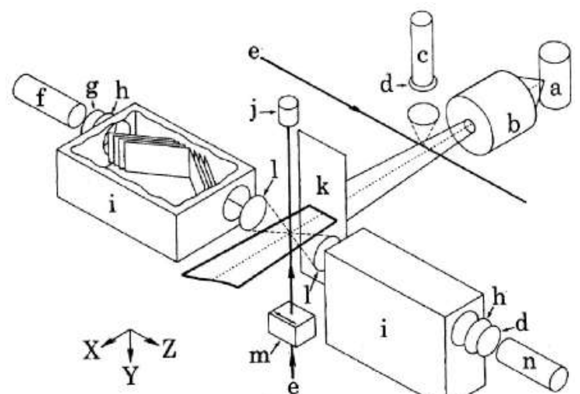
- cascade in Hg – 567.6 nm & 404.7 nm
- use $|R(\pi/8) - R(3\pi/8)|/R_0 \leq \frac{1}{4}$ but don't observe violation
- stress in bulb, in lens
- Clauser repeats experiment with violation



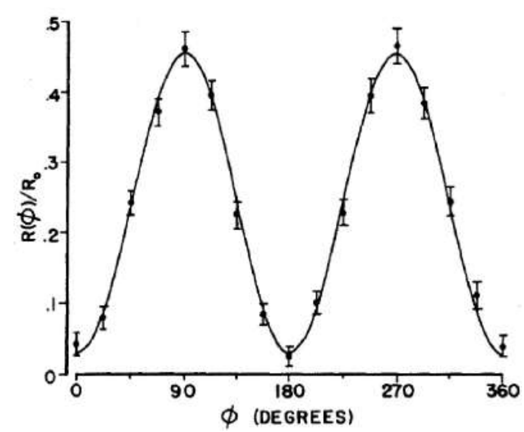
Fry, Thomson

- Hg – 435.8 nm and 253.7 nm
- e- + dye-laser, improved optics
- 80 min collection/point

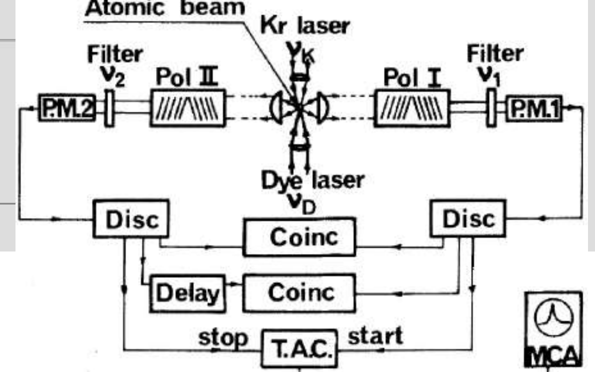




$$\delta_{exp} = 0.046 \pm 0.014$$

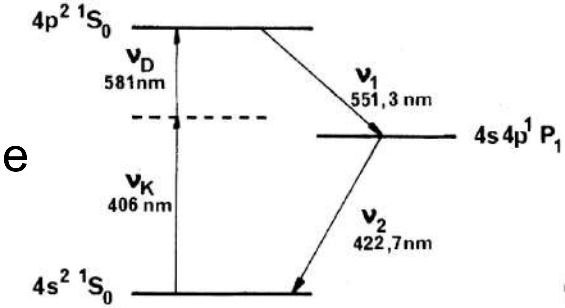


Aspect's (et al.) experiments

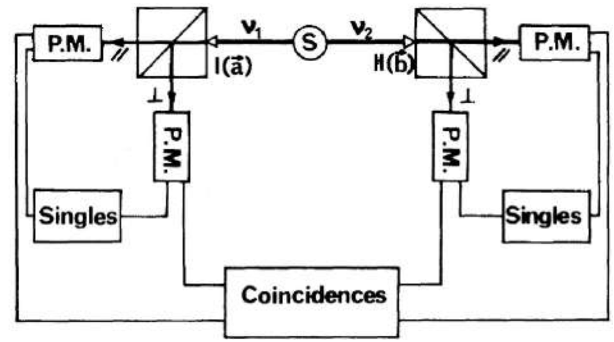


$$\delta_{exp} = 5.72 \times 10^{-2} \pm 0.43 \times 10^{-2}$$

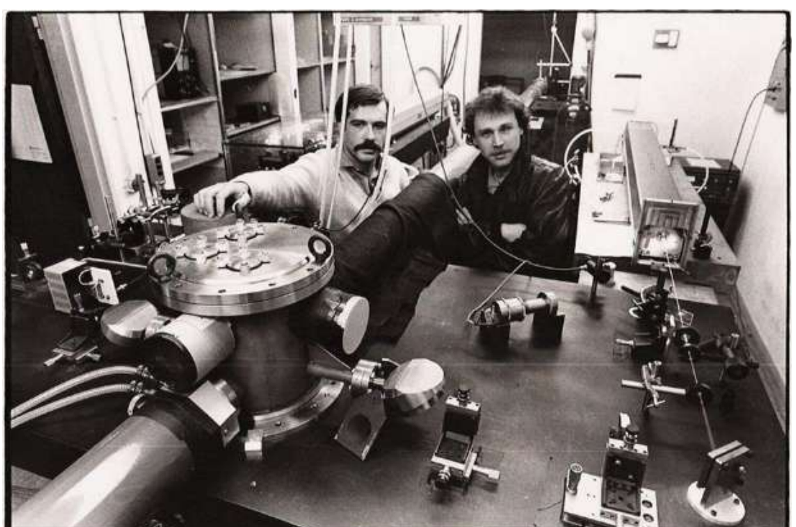
Alain Aspect



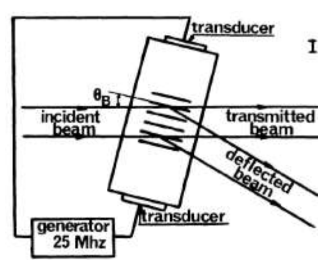
- pushed for improved experime
- together with P. Grangier, J. Dalibard, G. Roger
- Ca-cascade, resonant excitation by lasers
  small volume, high efficiency (singles 40000/s 120000/s, coinc 240/s, minus 90/s accidental)
- two-way polarizer
- time-dependent analyzers

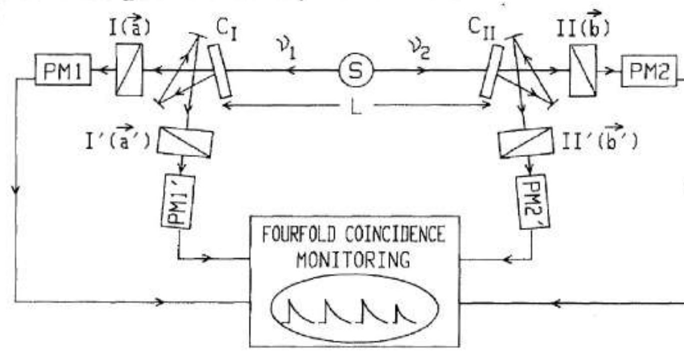


$$S_{expt} = 2.697 \pm 0.015$$



change the settings of the polarizers, at a rate greater than c/L.





A. Aspect, P. Grangier, G. Roger, PRL **47**, 460 (1981)
A. Aspect, P. Grangier, G. Roger, PRL **49**, 91 (1982)
A. Aspect, J. Dalibard, G. Roger, PRL **49**, 1804 (1982)

SPDC sources

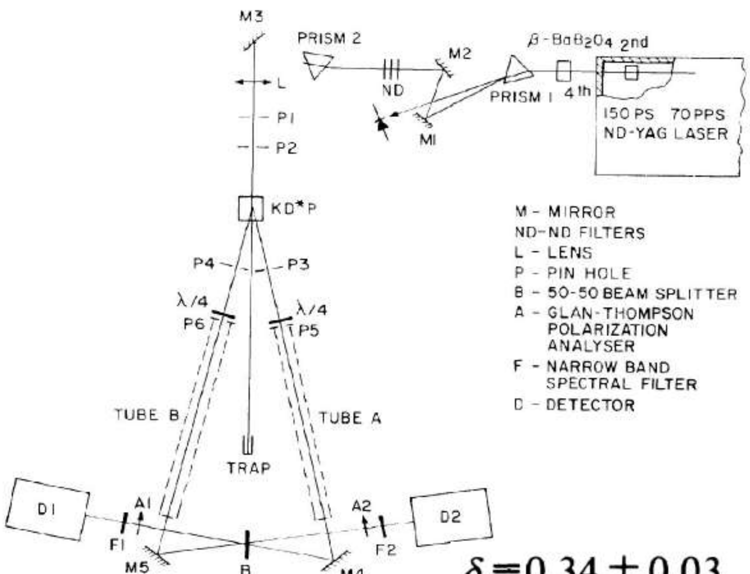
Y.H. Shih, C.O. Alley, PRL **61**, 2921 (1988)
Z.Y. Ou, L. Mandel, PRL **61**, 50 (1988)

spontaneous parametric downconversion

- directed emission
- different degrees of freedom

Shih, Alley

- L & R polarised photons overlapped at a beamsplitter
- selection for coincidences



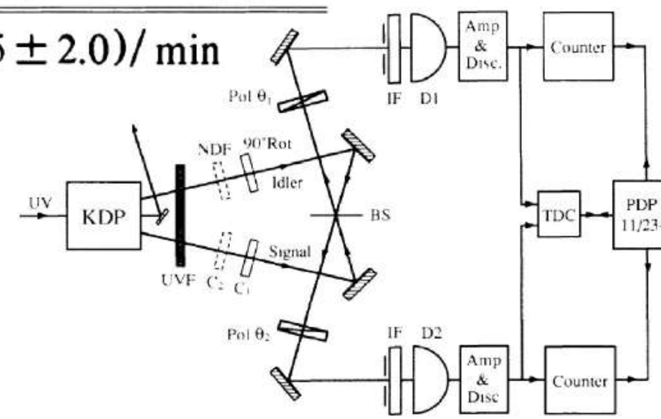
$$\delta = 0.34 \pm 0.03$$

Ou, Mandel

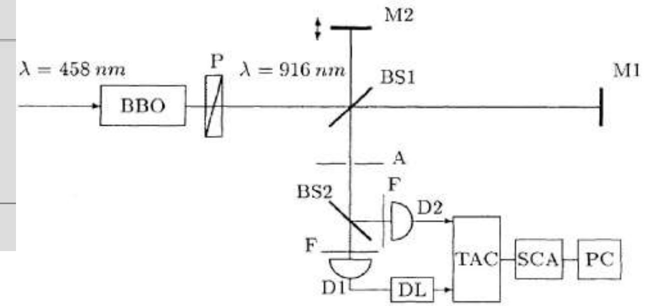
- orthogonal polarisation at a beamsplitter + selection
- CH-inequality (with conincidences)

θ_1	θ_2	Coincidence rate per minute $\mathcal{R}$
67.5°	45°	28.3 ± 0.8
22.5°	45°	29.8 ± 0.8
67.5°	0°	29.9 ± 0.8
22.5°	0°	5.6 ± 0.7
67.5°	No polarizer	34.7 ± 0.9
No polarizer	45°	36.2 ± 0.9

$$\tilde{S} = (11.5 \pm 2.0)/\,\text{min}$$

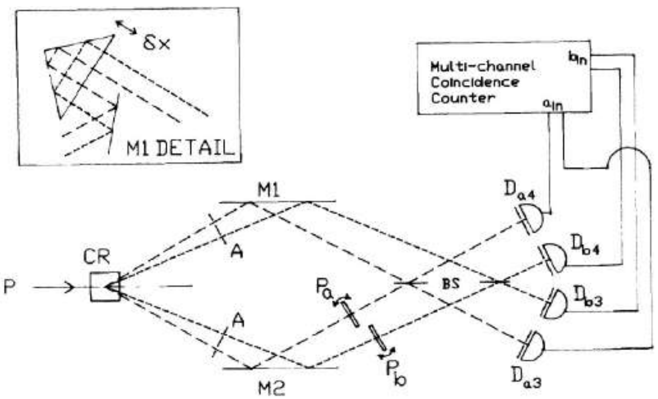


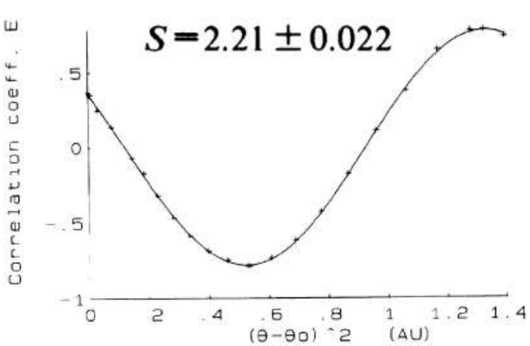
other degrees of freedom



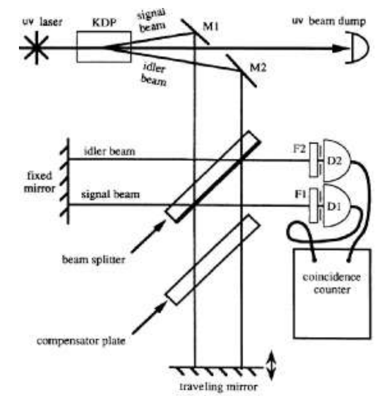
Rarity, Tapster

- entanglement in $\vec{k}$ - momentum of the photons
- dual Mach-Zehnder IFM



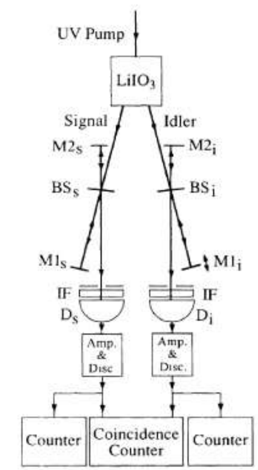


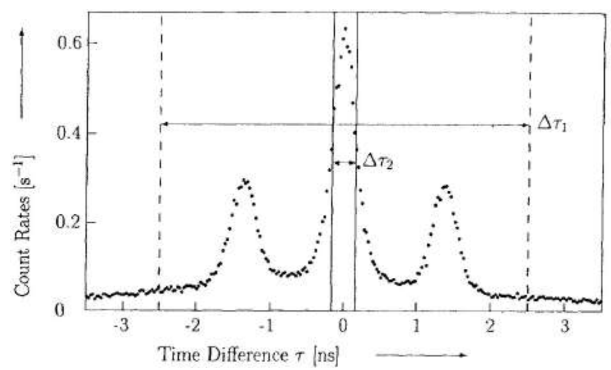
- entanglement in ω
- dual Michelson-IFM



Kwiat et al. (Chiao)
Ou et al. (Mandel)
Brendel et al. (Martienssen)

- Bell test possible in principle
- separation in time or modes would be necessary



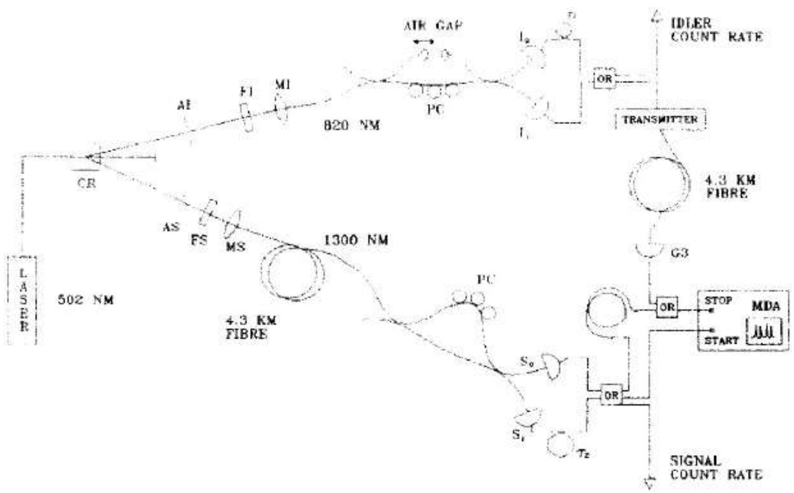


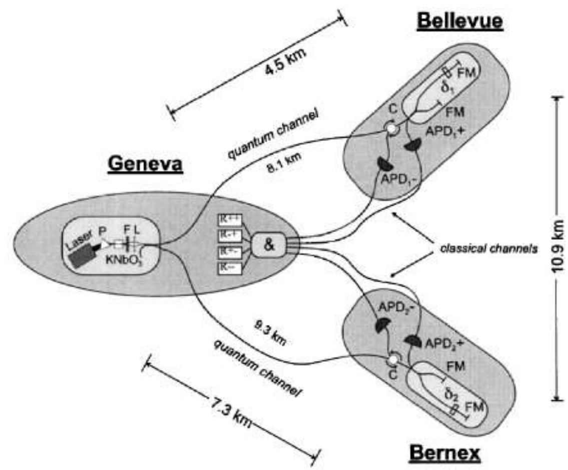
J.G. Rarity, P.R. Tapster PRL **64**, 2495 (1990)
Z.Y. Ou et al., PRL **65**, 321 (1990)
P.G. Kwiat et al., PRA **41**, 2910 (1990)
J. Brendel et al., PRL **66**, 1142 (1991)

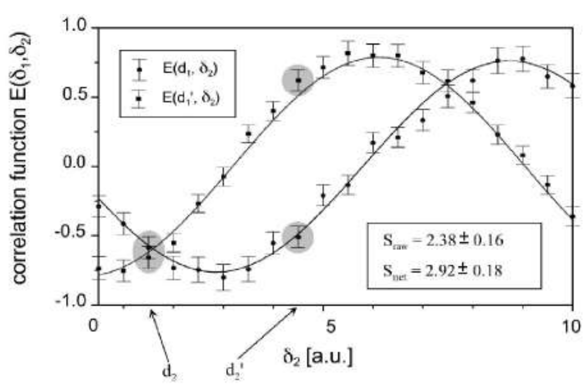
long distances

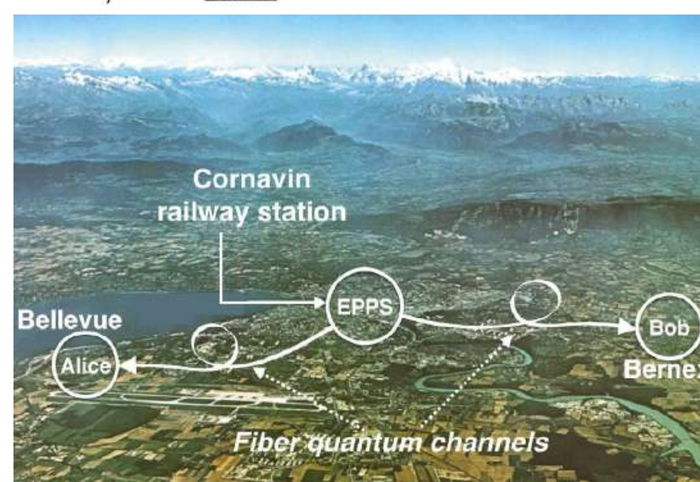
Tapster, Rarity, Owen
- dual wavelength
- 4.3 km in 1300 nm arm

Tittel, Brendel, Gisin, Zbinden
- deployed fibers, both photons 1310 nm
- 10.9 km between observers



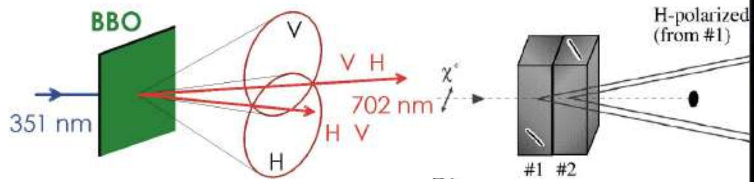


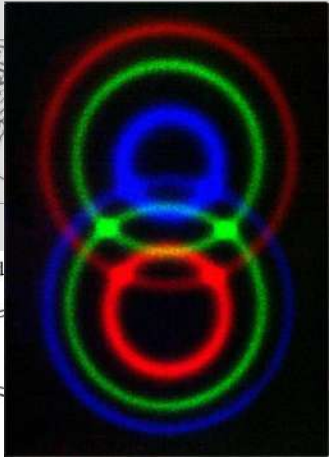




P.R. Tapster et al., PRL **73**, 1932 (1994)
W. Tittel et al., PRL **81**, 3563 (1997)

closing (some) loopholes



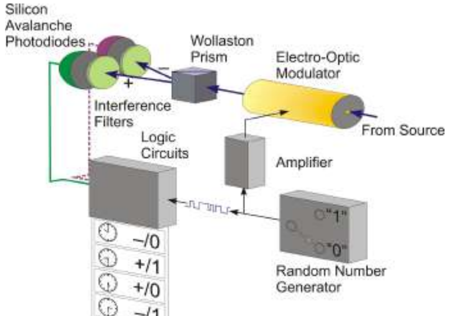


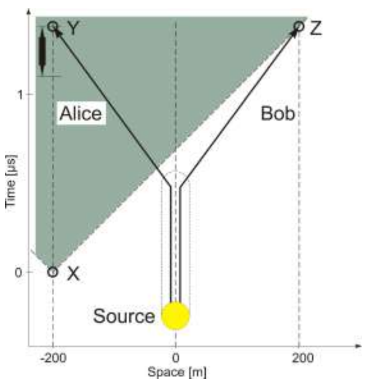
new methods:

- polarization entanglement (Kwiat)
- quantum logic gates

Weihs (Innsbruck):
locality loophole

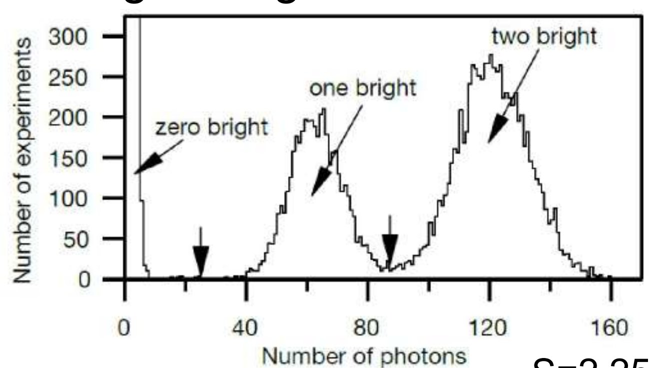
- quantum random numbers
- fast electro-optic switches
- independent data recording
- 400 m line-of-sight
- ~5% of pairs detected





Rowe (Boulder):
detection loophole

- entangled ions (!)
  using quantum logic gates
- unit detection efficiency
- ions are detected without
  distinguishing them

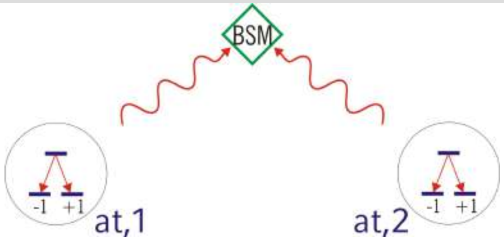


S=2.25±0.03

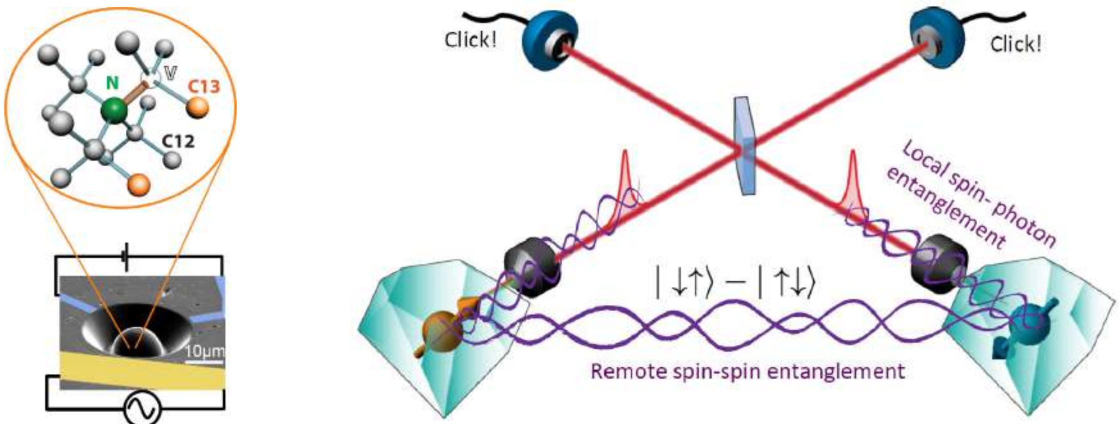
G. Weihs et al., PRL **81**, 5039 (1998)
M.A. Rowe et al., Nature **409**, 791 (2001)

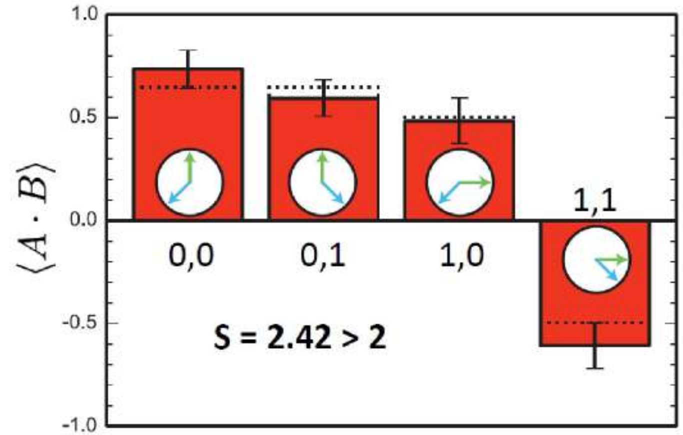
closing detection and locality loopholes

new methods:
- matter-light entanglement + entanglement swapping
- superconducting single-photon detectors



Hensen (Delft)
- NV-centers in diamond
- efficient preparation and readout





B. Hensen et al., Nature **526**, 682 (2015)

closing detection and locality loopholes

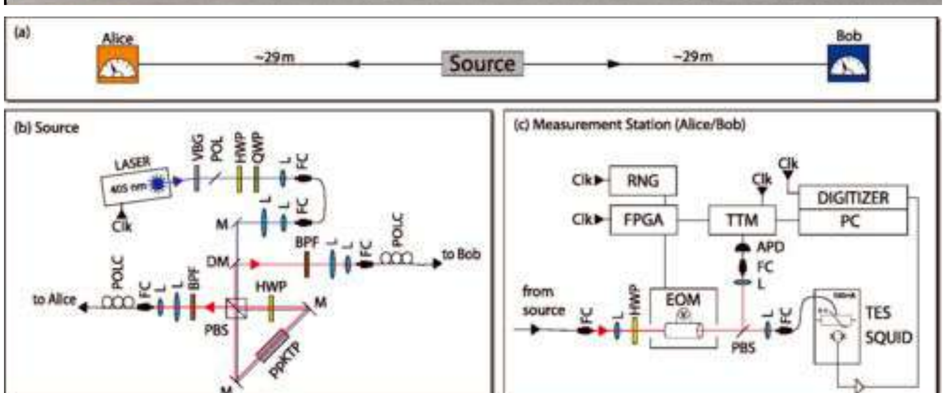
Eberhard inequality

- lower detection efficiency of 2/3 required for asymmetric entanglement

$$|\Psi\rangle = \frac{1}{\sqrt{1+r^2}}\left(|V\rangle_A |H\rangle_B + r\,|H\rangle_A |V\rangle_B\right)$$

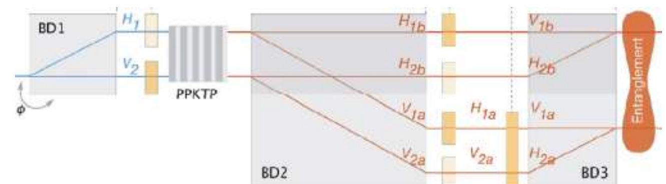
Giustina (Vienna)

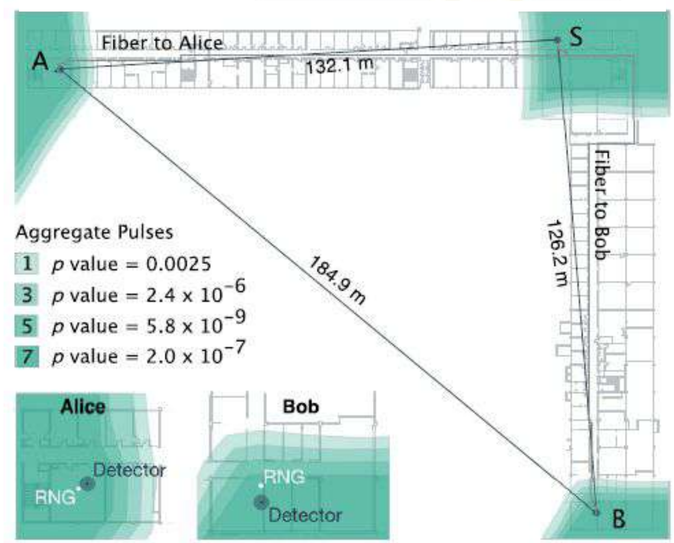
- 60 m in the basement of the Hofburg



Shalm (Boulder)

- high fidelity source design



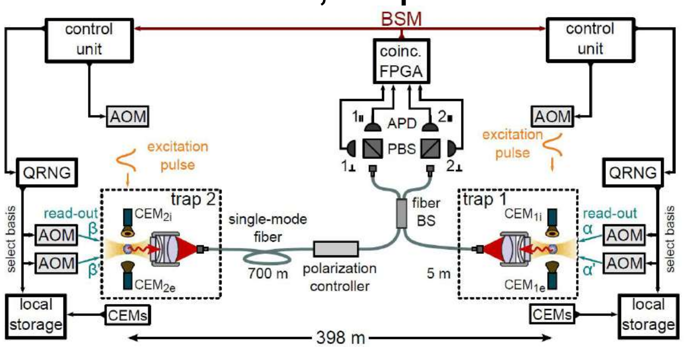


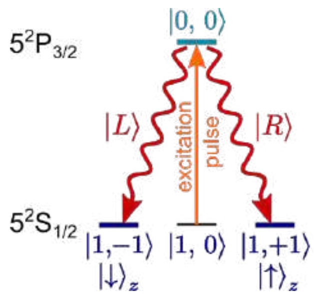
M. Giustina et al., PRL **115**, 250401 (2015)
L.K. Shalm et al., PRL **115**, 250402 (2015)

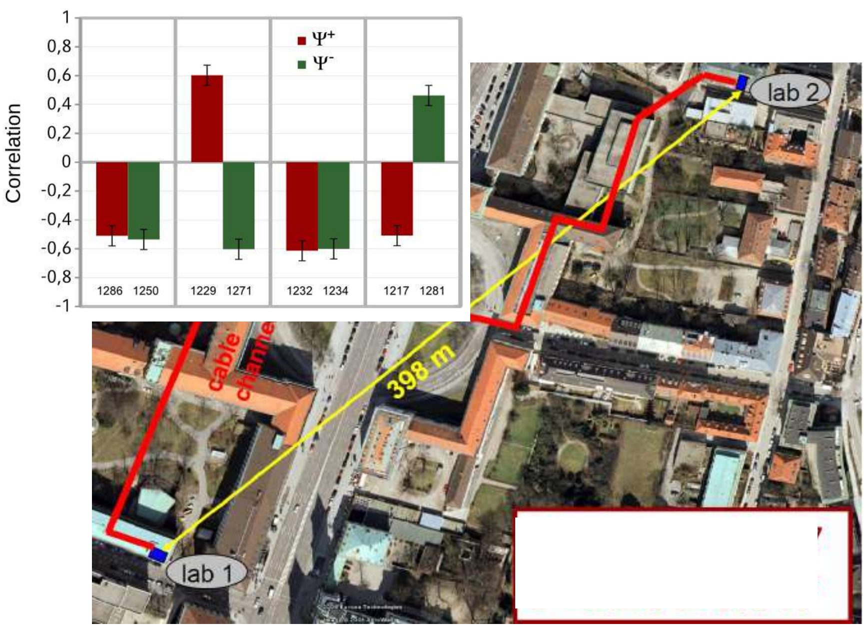
closing detection and locality loopholes

Rosenfeld (Munich)

- atom-atom entanglement over 400 m, ~1µs for measurement

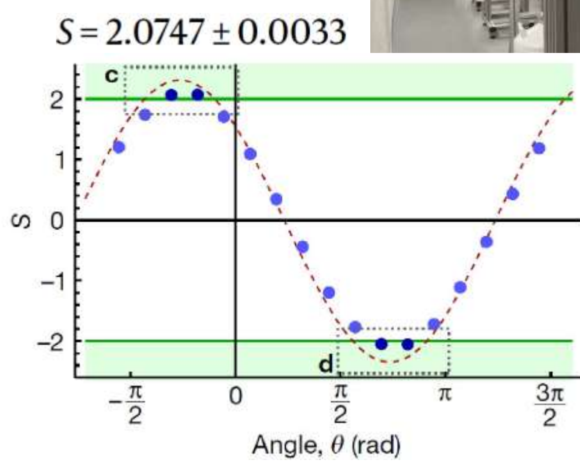






Storz (Zürich)

- superconducting qubits, 30 m
- entanglement via absorption of µ-wave photon entangled with first qubit

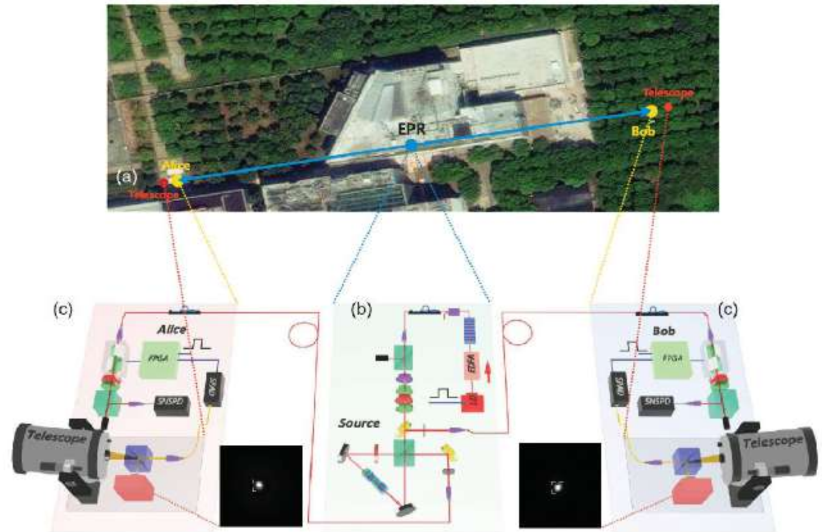


W. Rosenfeld et al., ., PRL **119**, 010402 (2017)
S. Storz et al., Nature **617**, 215 (2023)

freedom-of-choice

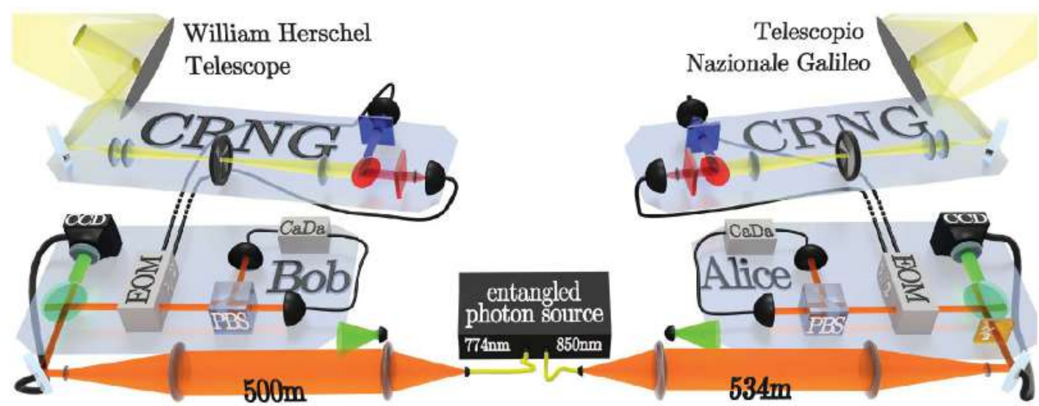
Li (Shanghai)

- 2-photon experiment closing detection and locality loophole
- random numbers according to detection of photons from stars
- $\tau_{AB} \gtrsim 100$ y



Rauch (Vienna)

- random numbers according to colours of photons emitted from distant quasars
- 12.2 Gyr & 7.8 Gyr
- locality loophole closed



M-H Li et al., ., PRL **121**, 080404 (2018)
D. Rauch et al., **121**, 080403 (2018)

Future ?

Student labs
- SPDC + single photon detectors comerzialized

alternative tests
- continous variables
- All versus Nothing – tests GHZ, Hardy,…

network tests
- multi-party
- topology
- signaling

…

S-R Zhao et al., PRL **133**, 060201 (2024)
D. Dehlinger, M. Mitchell, Am. J. Phys. **70**, 898 (2002)

•

From Foundations to Quantum Networks

Wei Zhang
Tim van Leent
Florian Fertig
Robert Garthof

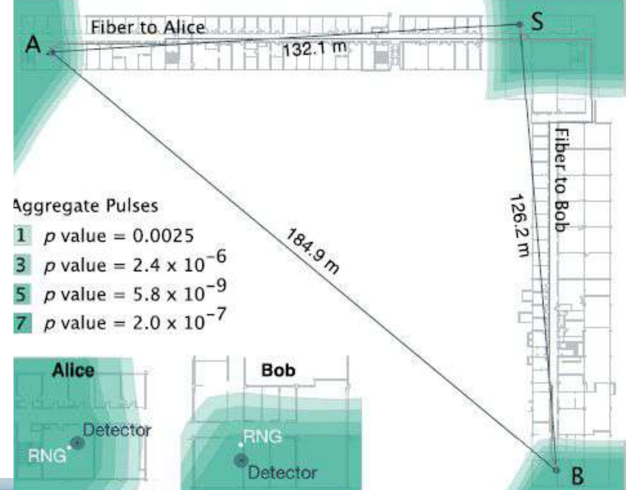
Yiru Zhou
Pooja Malik
Anastasia Reinl
Kai Redeker

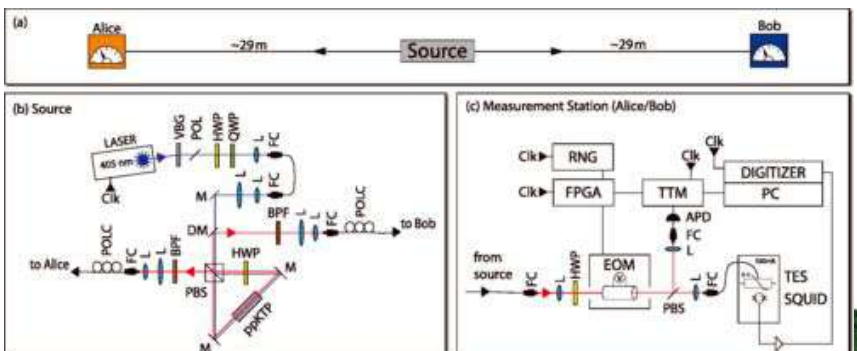
Daniel Burchardt
Sebastian Eppelt
Norbert Ortegel
Markus Rau
Mathias Seubert
Derya Taray

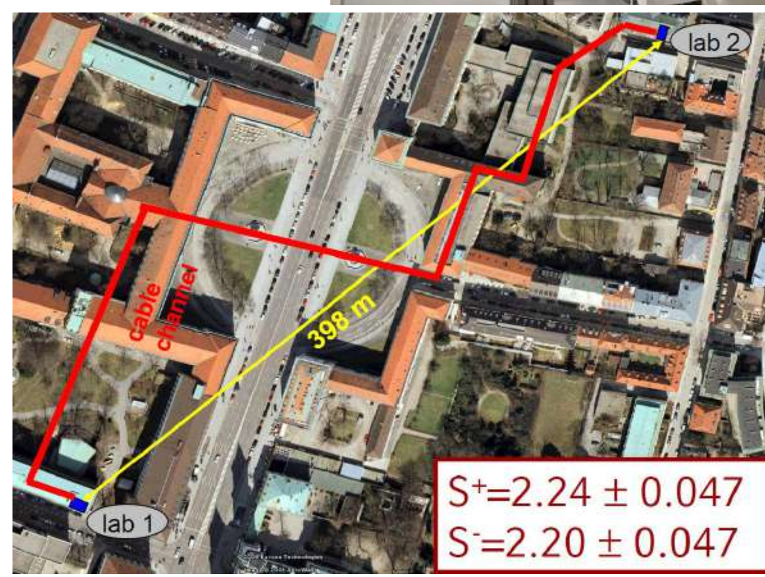
René Schwonnek
Valerio Scarani
Charles C.-W. Lim

her

NV-center
B. Hensen et al., Nature, **526**, 682 (2015))
Photons
M. Giustina et al., PRL **115**, 250401 (2015)
K. Shalm et al., PRL **115**, 250402 (2015)
M-H Li et al., PRL **121**, 080404 (2018)
sc-qubits
S. Storz et al., Nature volume **617**, 265 (2023)
Rb-atoms
W. Rosenfeld et al., PRL **119**, 010402 (2017)







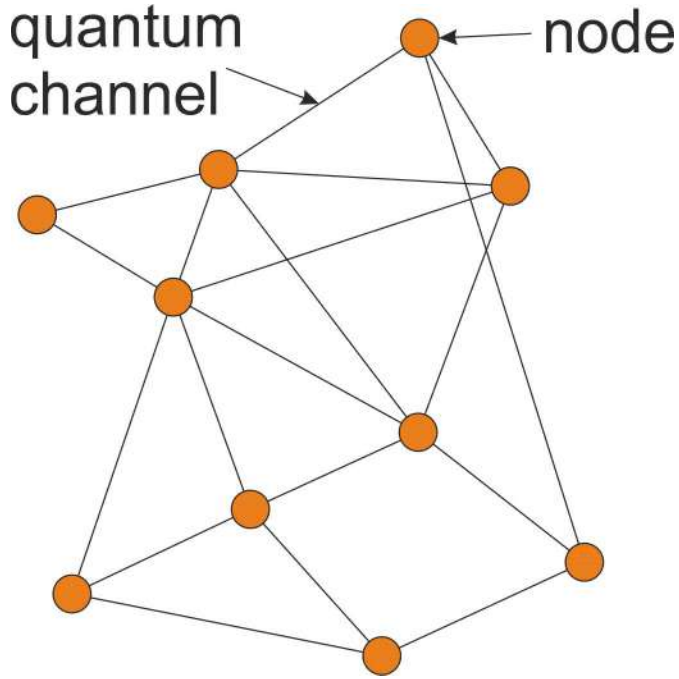
quantum networks ?

Bell-experiment

long distance

high fidelity

device independence

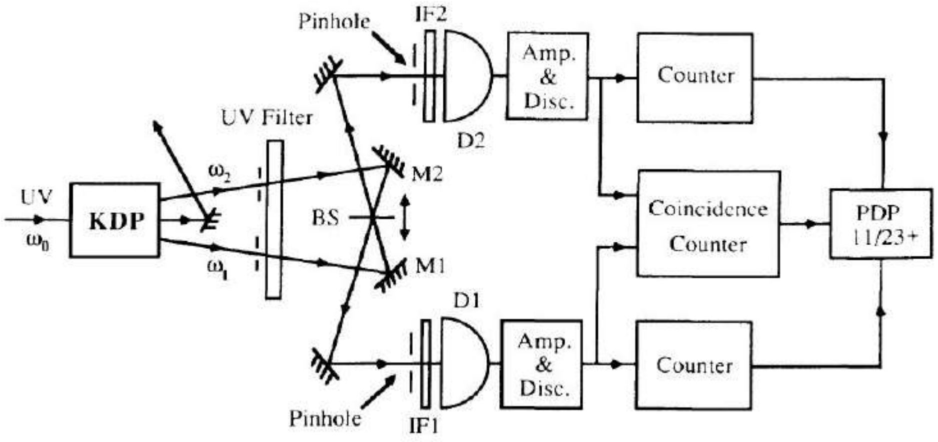


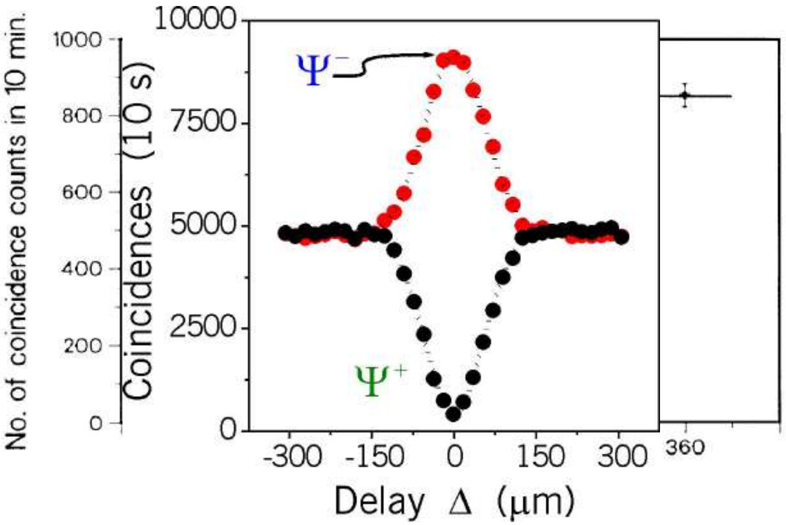
VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 10 July 1987)

A fourth-order interference technique has been used to measure the time intervals between two photons, and by implication the length of the photon wave packet, produced in the process of parametric down-conversion. The width of the time-interval distribution, which is largely determined by an interference filter, is found to be about 100 fs, with an accuracy that could, in principle, be less than 1 fs.





K. Mattle, et. al, Phys. Rev. Lett. **76**, 4656 (1996)

□ distinguish Bell states

EPR

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*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Bell's theorem

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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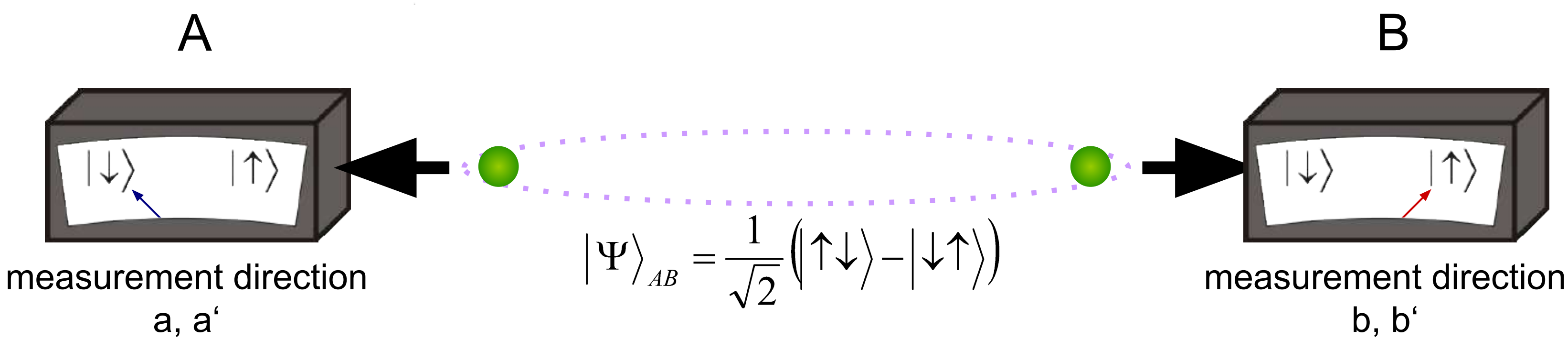

$$|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

Physics Vol. 1, No. 3, pp. 195–200, 1964

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

local realistic theories: $|\langle S\rangle| \leq 2$

QM: $S = 2\sqrt{2}$

Bell‘s theorem

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*

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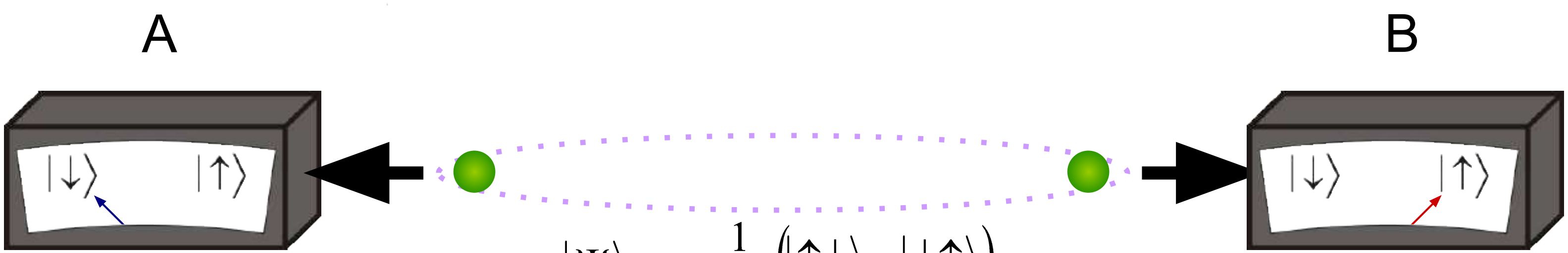

$$|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

Physics Vol. 1, No. 3, pp. 195–200, 1964

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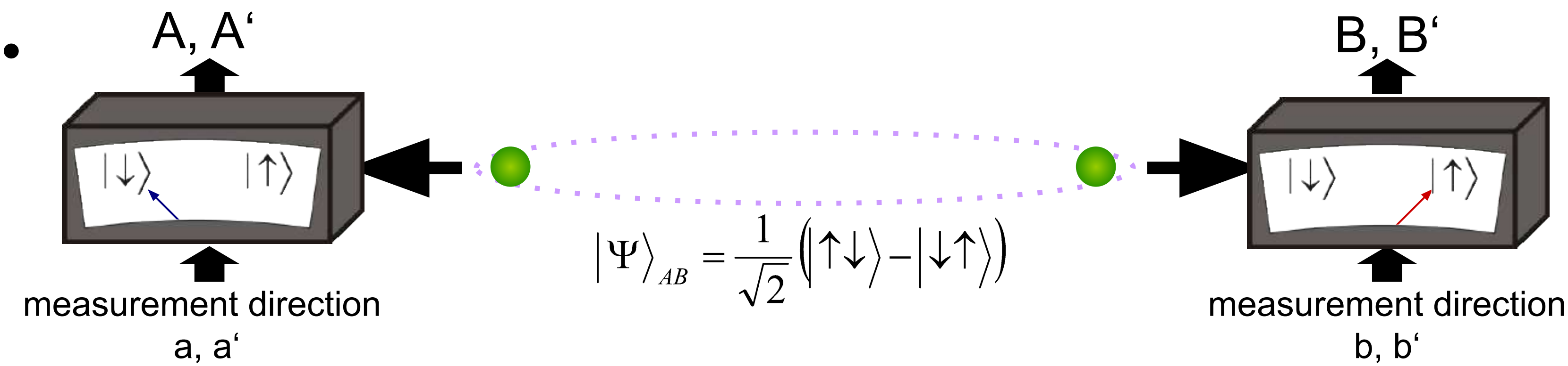
LHV: $S \leq 2$ QM: $S = 2\sqrt{2}$

a game

- 

- Results A, A', B, B' $= +1$ or -1

→ evaluate expression

$$S = A * (B - B') + A' * (B + B')$$

gives in a single run: $S = \pm 2$

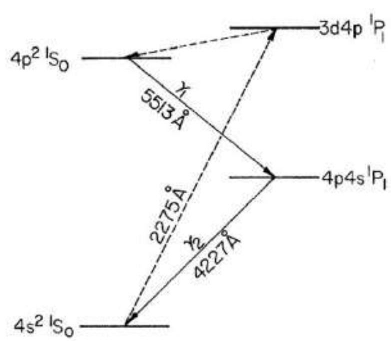
→ average over many runs: $-2 \leq \langle S \rangle \leq +2$

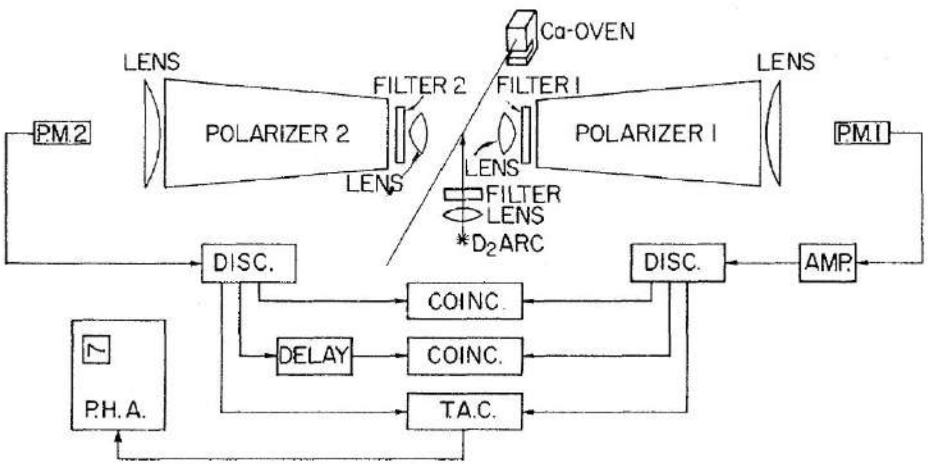
fullfilled by all local realistic theories

QM: $S = 2\sqrt{2}$

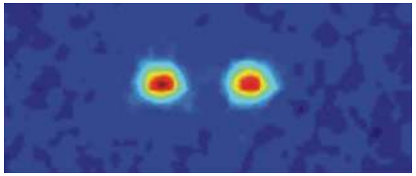
Bell tests: the starting point

- Freedman, Clauser 1972



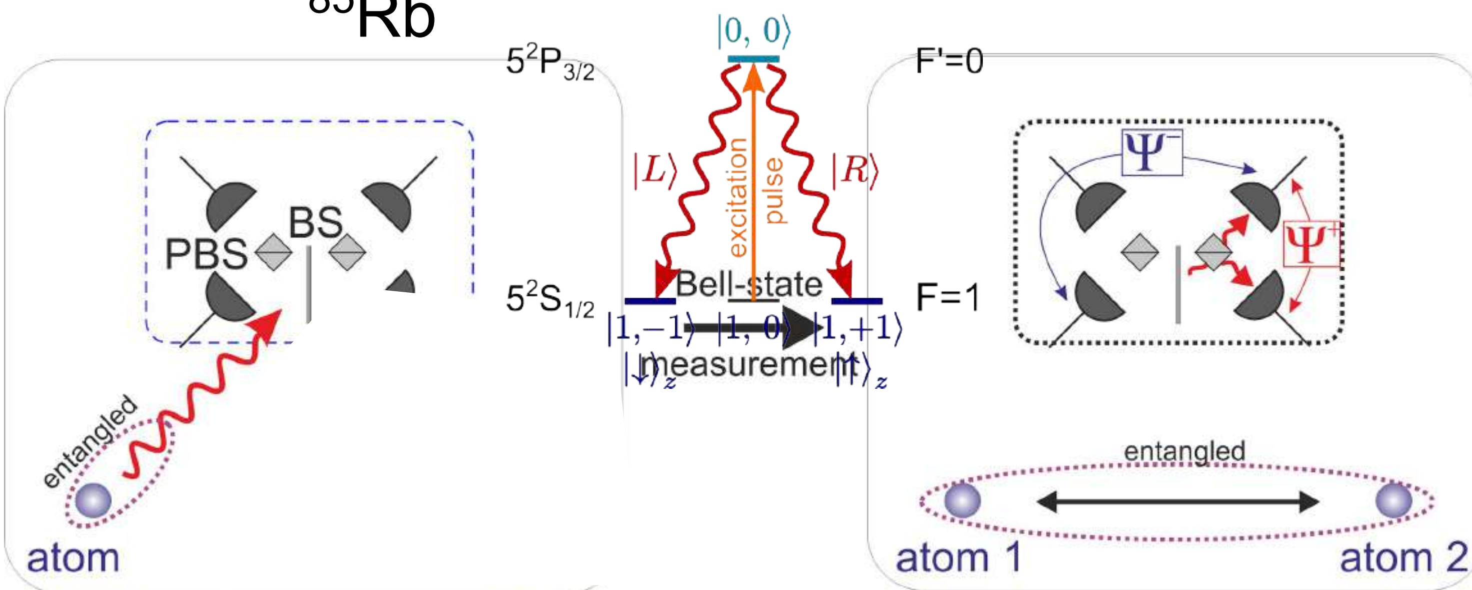


- loopholes: detection, locality
  - Weihs et al. 1998: independent observers
  - Rowe et al. 2000 (Ch. Roos et al. 2004): efficient detection of 2 entangled ions



starting point

^{85}Rb



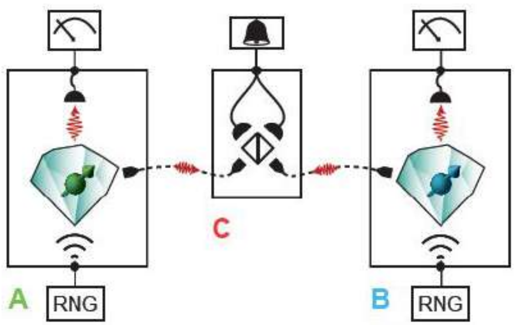
$$\left|\Psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|-1\right\rangle_{at}\left|L\right\rangle_{ph} + \left|+1\right\rangle_{at}\left|R\right\rangle_{ph}\right)$$

- entanglement between separated atoms
- heralded entanglement
- “event ready“ Bell test
- quantum networks

M. Zukowski, A. Zeilinger, M.A. Horne, A. K. Ekert, Phys. Rev. Lett. 71, 4287 (1993)

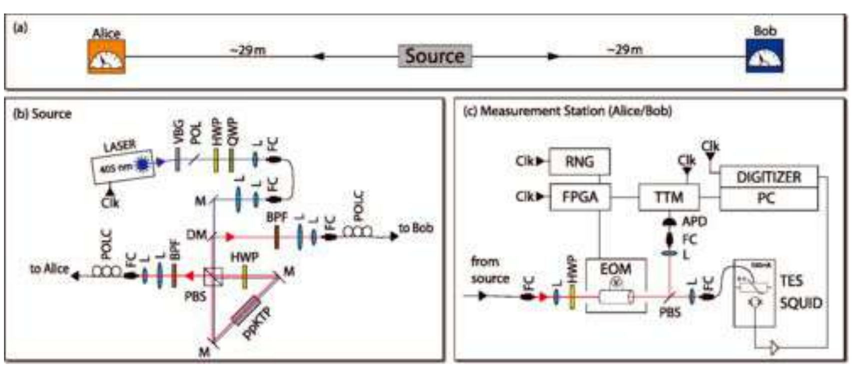
other experiments

- **NV-center** (Delft, B. Hensen et al., Nature, **526**, 682 (2015))

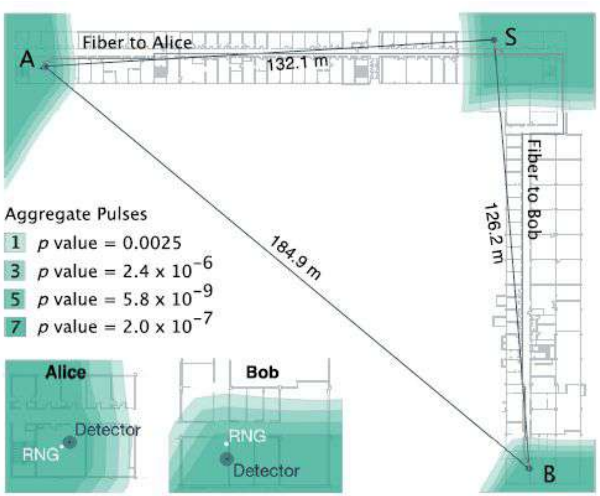


- **Photons**

Vienna, M. Giustina et al., PRL **115**, 250401 (2015)



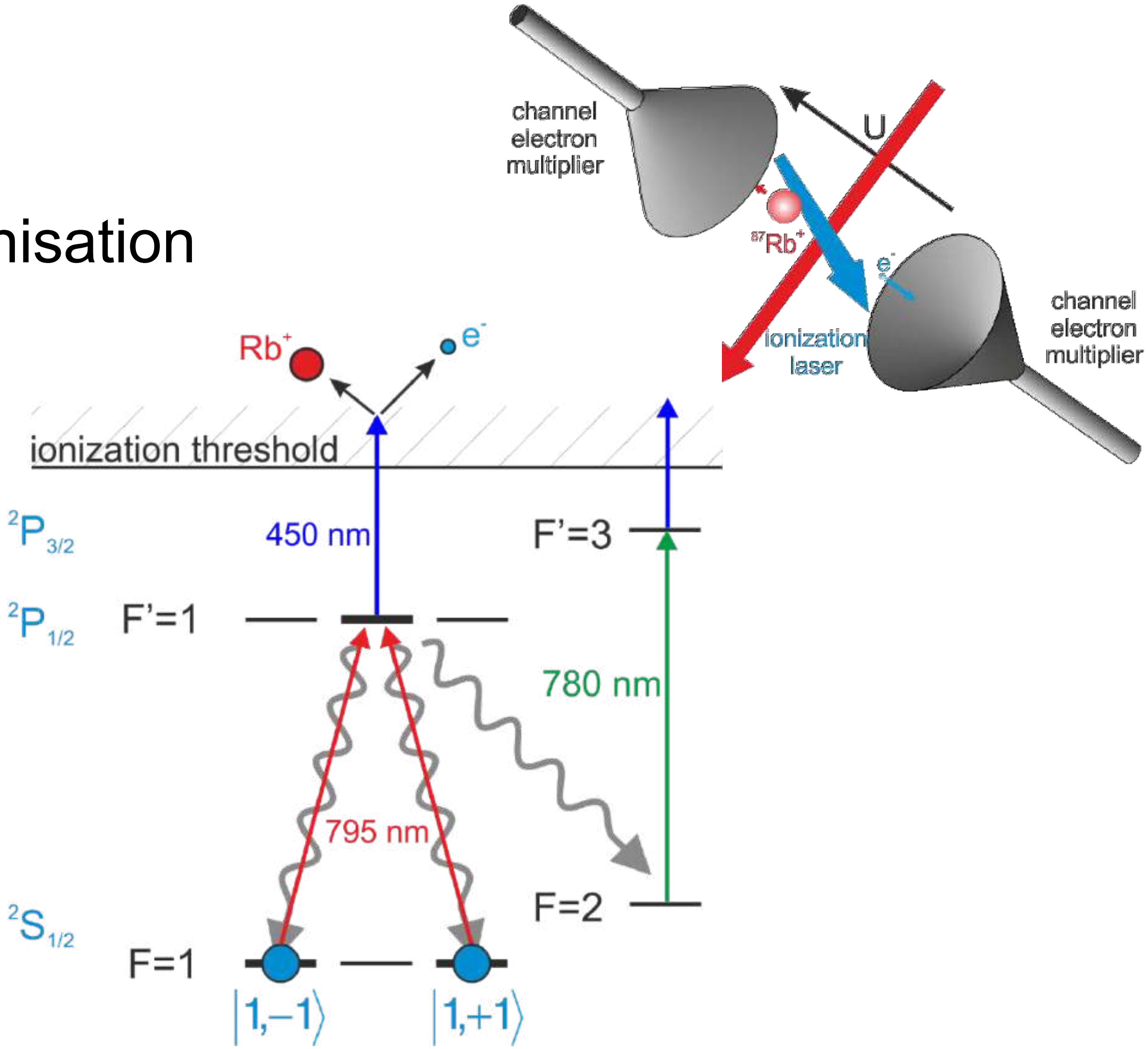
Boulder, K. Shalm et al., PRL **115**, 250402 (2015)



Hefei 2018   ETHZ (sc-qubits) 2023

fast atomic state analysis

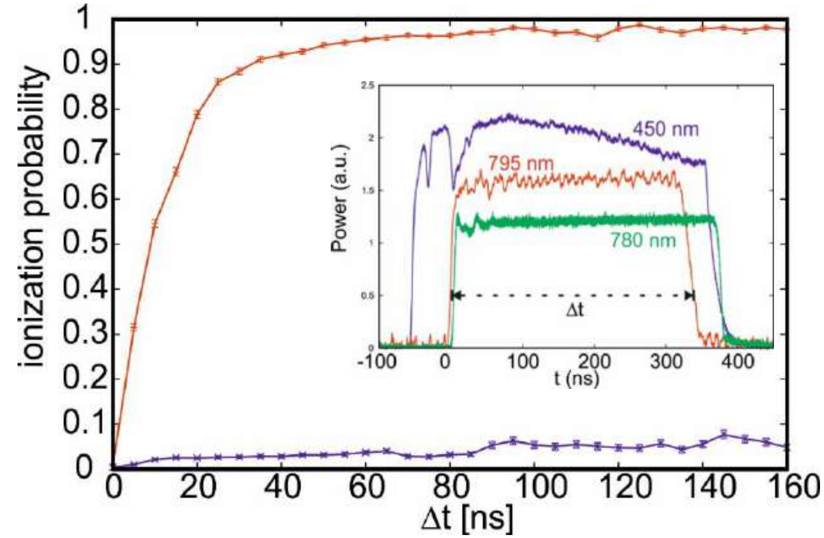
- state selective ionisation

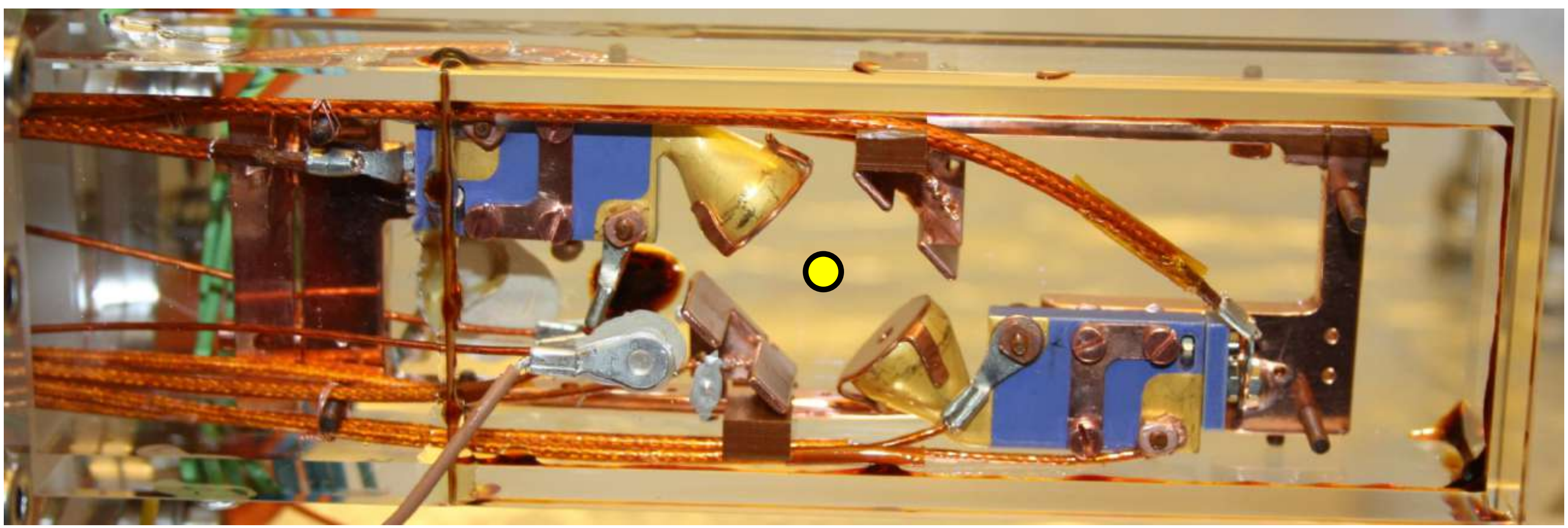


bright / dark state
depending on polarization

fast atomic state analysis

- ionisation
  - t = ~130 ns
  - F = 0.965





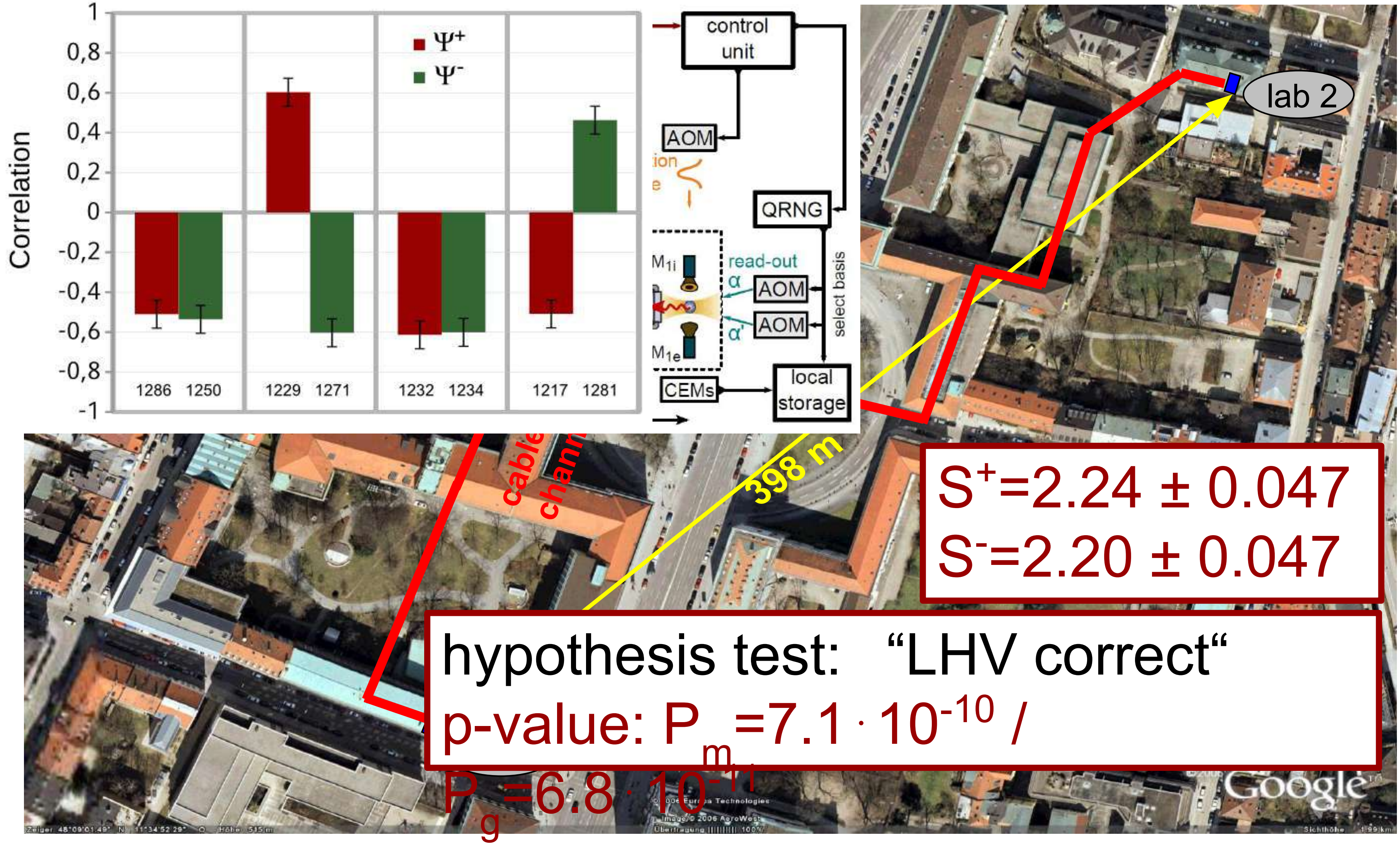
time budget

- random number via photon count
- trigger from Bell state measurement

- selection of meas with fast AOMs
- state selective io
- time of flight of ic fragments to det
- buildup of avalar electron multiplie
- detection logic o

t < 1 μs

atom – atom entanglement



$S^{+}=2.24 \pm 0.047$

$S^{-}=2.20 \pm 0.047$

hypothesis test: "LHV correct"

p-value: $P_m=7.1 \cdot 10^{-10}$ / $P_g=6.8 \cdot 10^{-11}$

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

what is it good for?

Physics Vol. 1, No. 3, pp. 195–200, 1964

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

test, whether Nature can be described by
a local, realistic theory

⇔

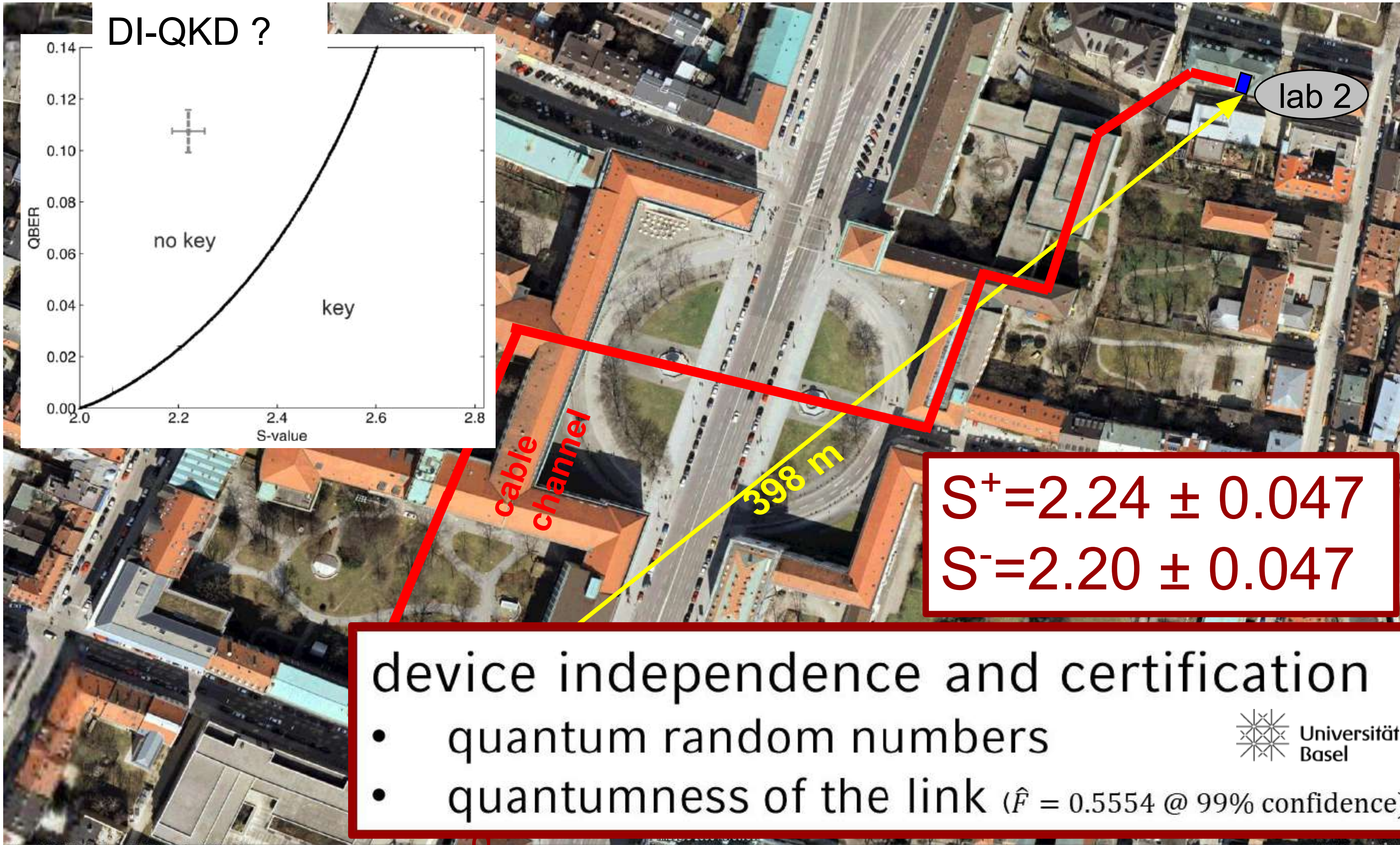
test, whether knowledge about measurement results is
available locally

- entanglement based QKD
- quantum origin, fewer security assumptions
- NO trust or knowledge about the devices required

A. Ekert, Phys. Rev. Lett. **67**, 661 (1991)

D. Mayers and A. Yao, Proc. 39th FOCS, p. 503 (1998)
A. Acin, et al., Phys. Rev. Lett. **98,** 230501 (2007)

atom – atom entanglement



$S^{+}=2.24 \pm 0.047$
$S^{-}=2.20 \pm 0.047$

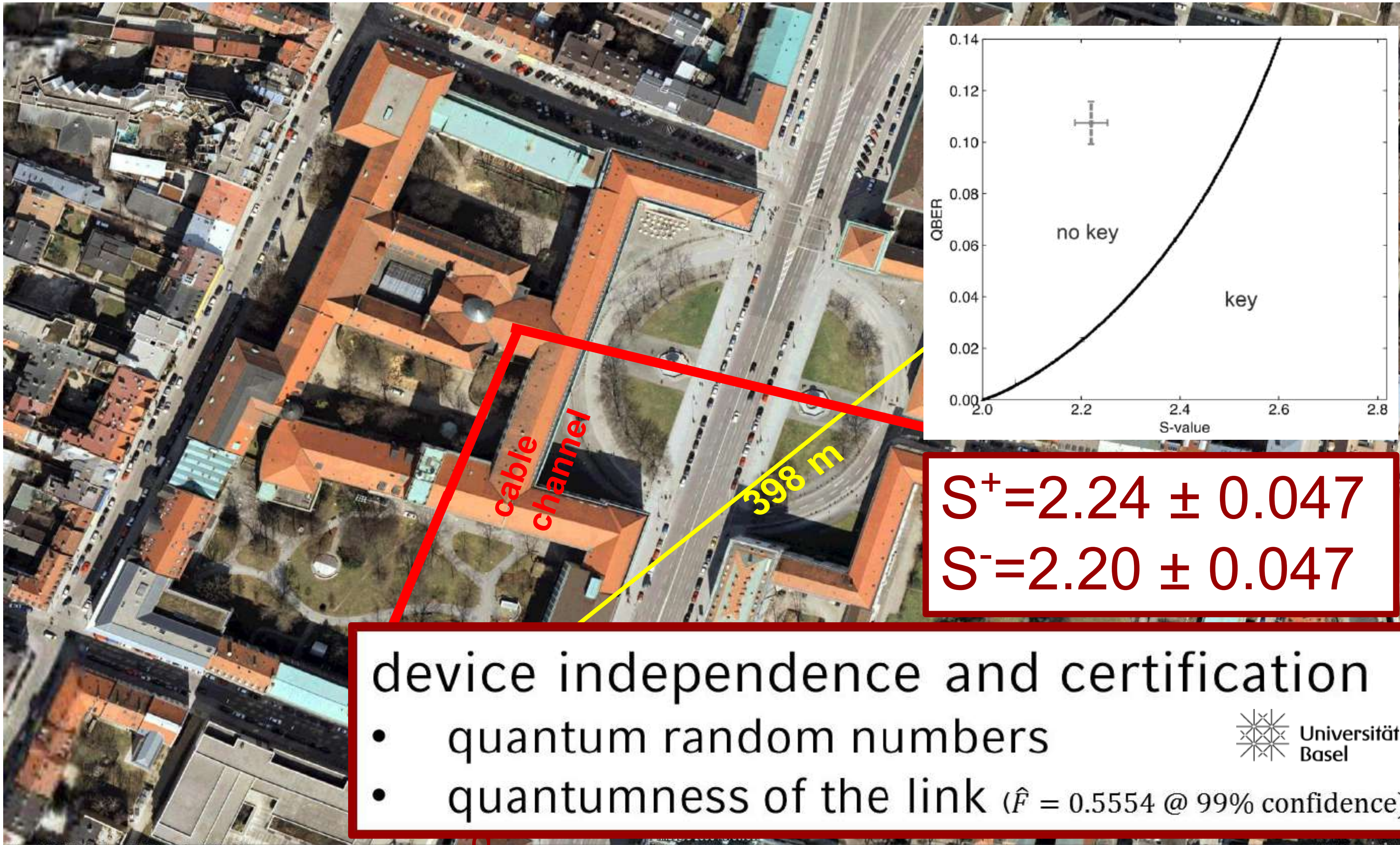
device independence and certification

- quantum random numbers
- quantumness of the link ($\hat{F} = 0.5554$ @ 99% confidence)

Universität Basel

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

atom – atom entanglement



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device independence and certification

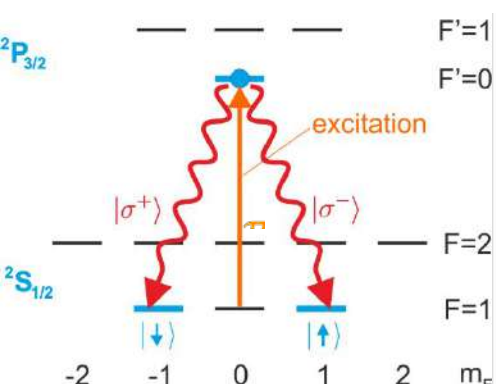
- quantum random numbers
- quantumness of the link ($\hat{F} = 0.5554$ @ 99% confidence)

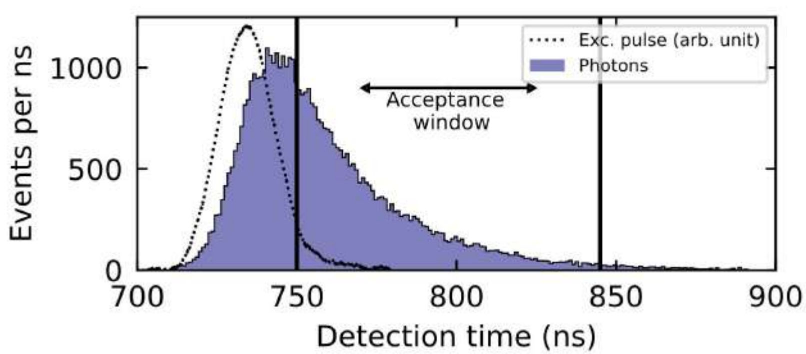
Universität Basel

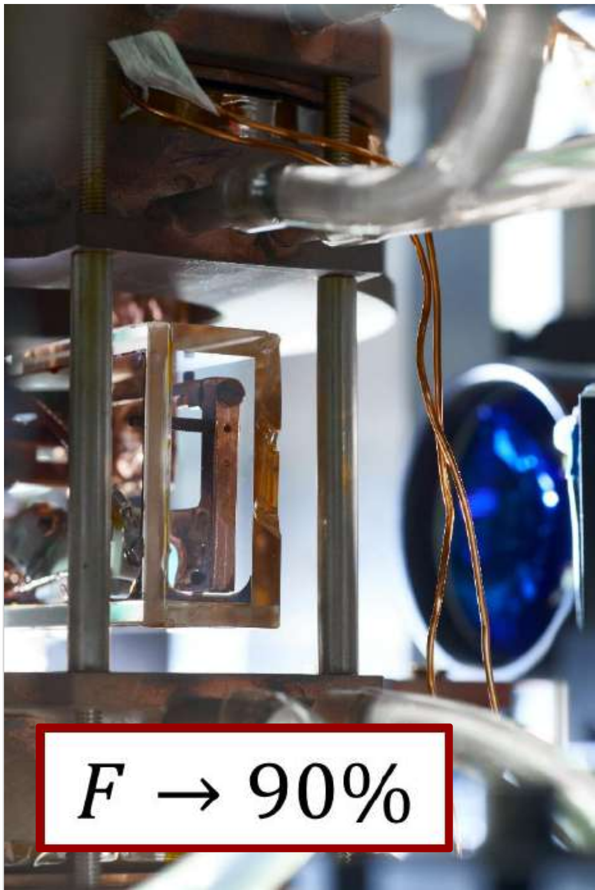
W. Rosenfeld et al., PRL **119**, 010402 (2017)

improvements

- experiment:
  - new high-NA objectives:
    - better beam definition: less heating when atoms move
    - higher collection efficiency: higher rate
  - magnetic fields
    - guiding field
    - lower trapping potential
  - time selection
    - improve visibility of BSM



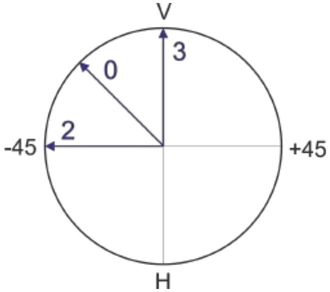




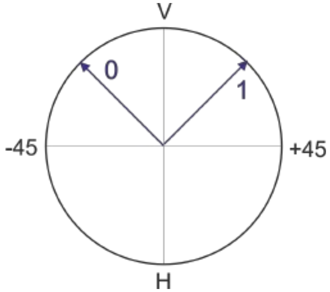
improvements

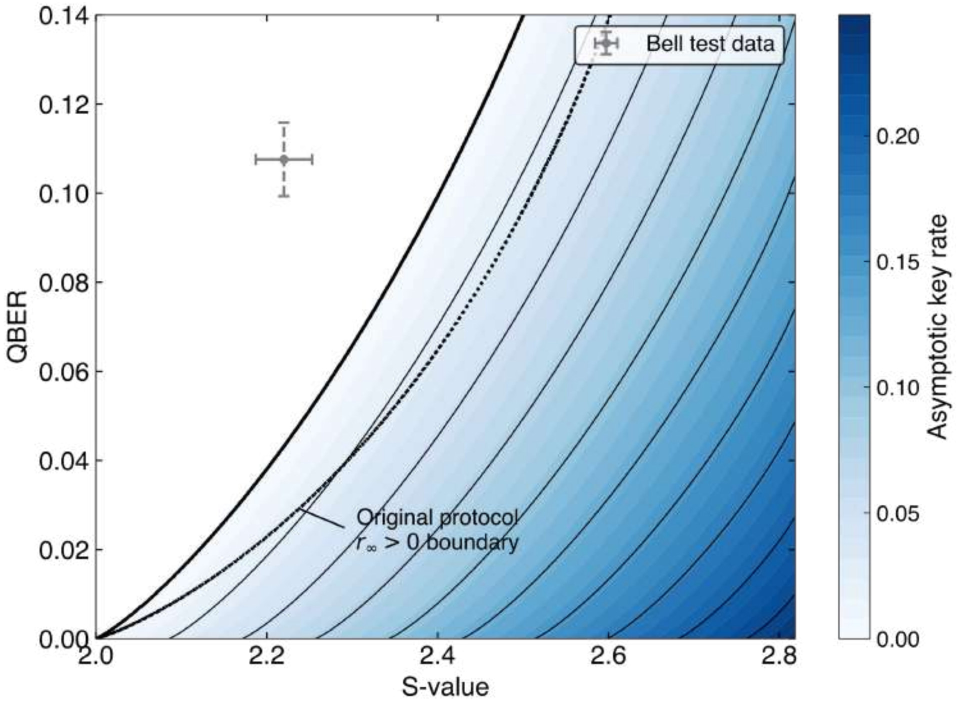
- noise tolerant protocol
  - two bases for key generation and QBER determination
  - Bell test:
    - Alice X={2, 3} & Bob Y={0, 1}
  - Key exchange (Q):
    - Alice X={0, 1} & Bob Y={0, 1}

Settings Alice (X)

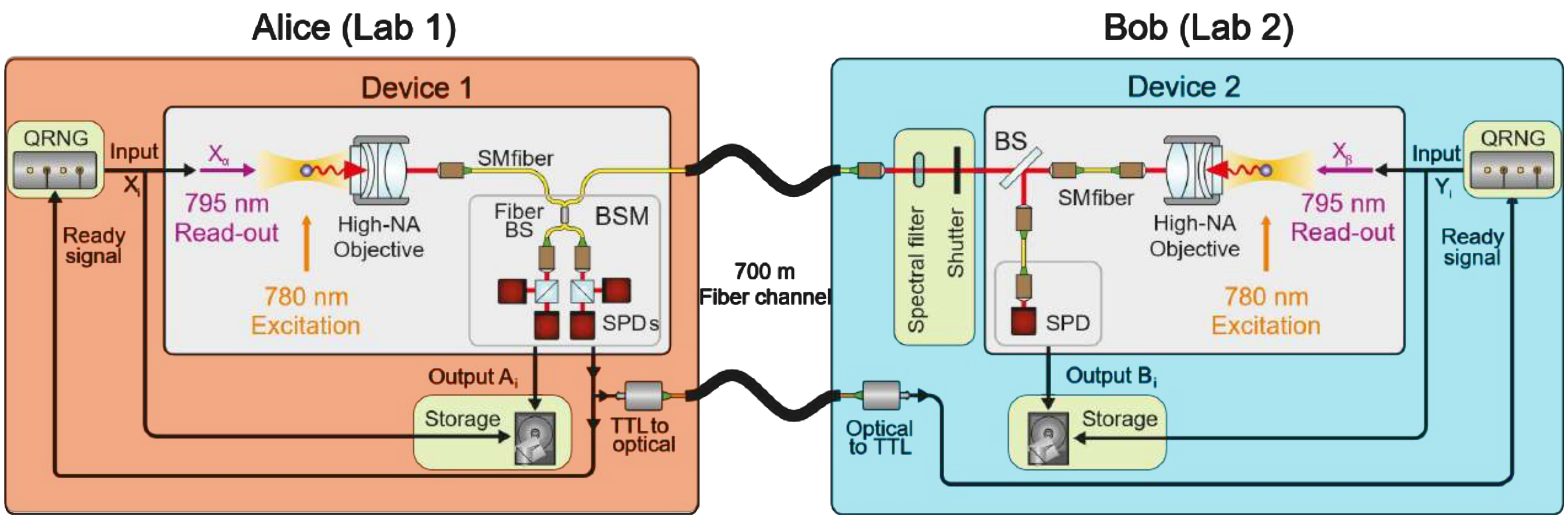


Settings Bob (Y)





R. Schwonnek, et al., Nat Commun **12,** 2880 (2021)



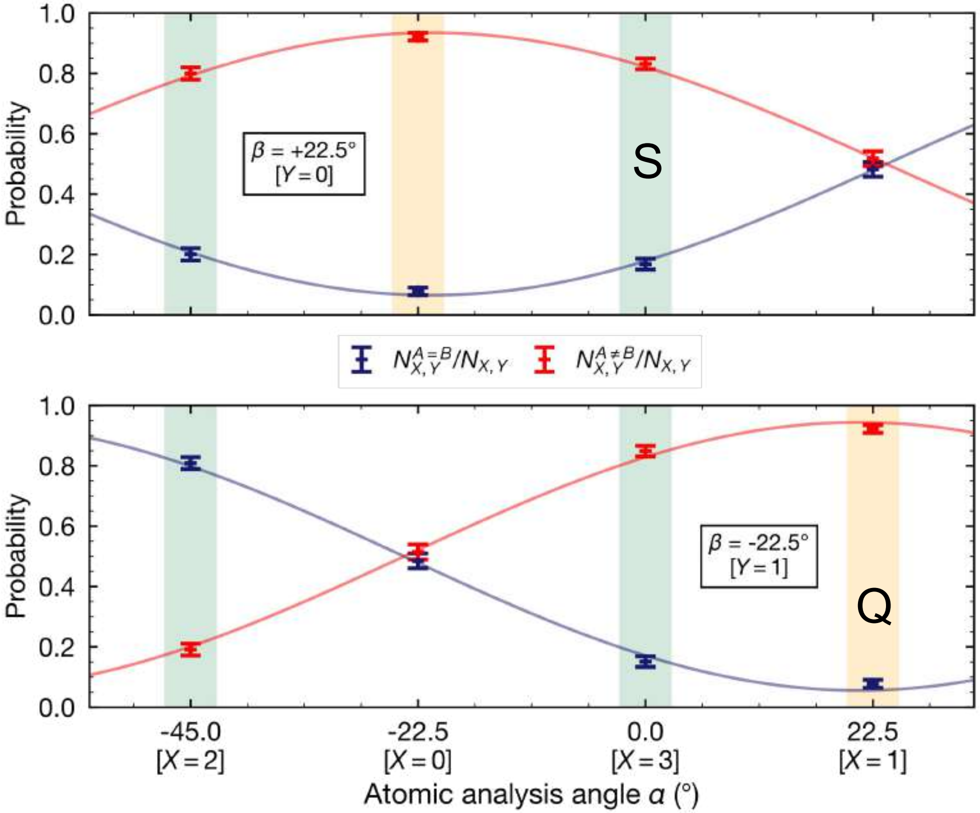
Alice's and Bob's equipment:

1. Single-atom trap
2. Bell-state measurement
3. QRNG
4. Trusted storage

- For Alice:
  - BSM detectors used for fluorescence detection
- For Bob:
  - Extra SPD installed for fluo. Detection
  - Spectral filter and shutter to shield readout result and setting

measurement

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



Number of rounds:
- N=3342 in 75 hours

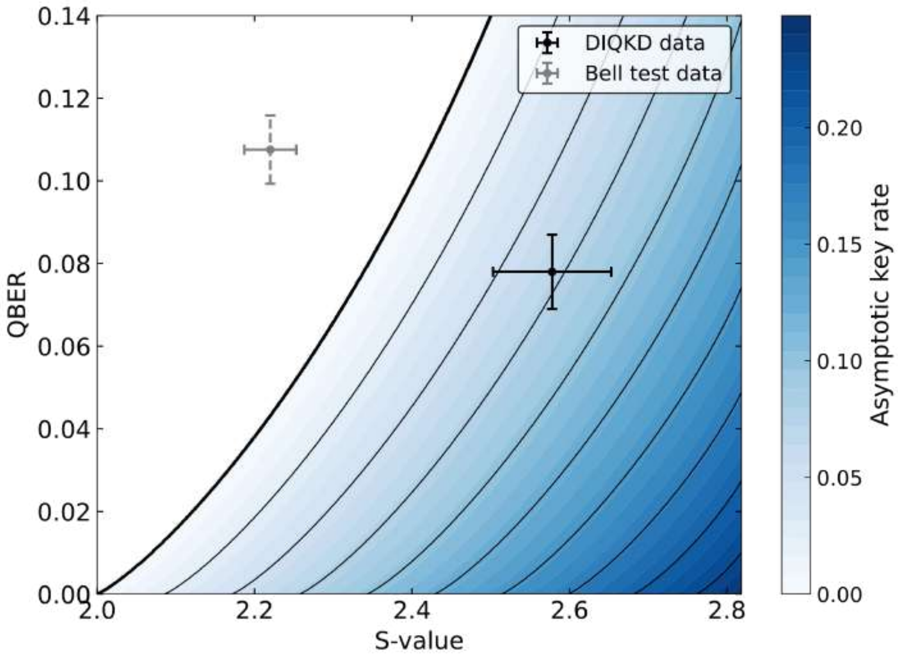
Visibility fits:
- 0.869(25) & 0.888(45)

Fidelity:
- ≥0.892(12)

W. Zhang, et al., Nature **607,** 687 (2022)

performance

- asymptotic limit



Measurement outcome:

- S = 2.578(75)
- Q_1 = 0.078(13)
- Q_2 = 0.078(13)

Asymptotic key rate:

- R=0.07
  per entanglement event

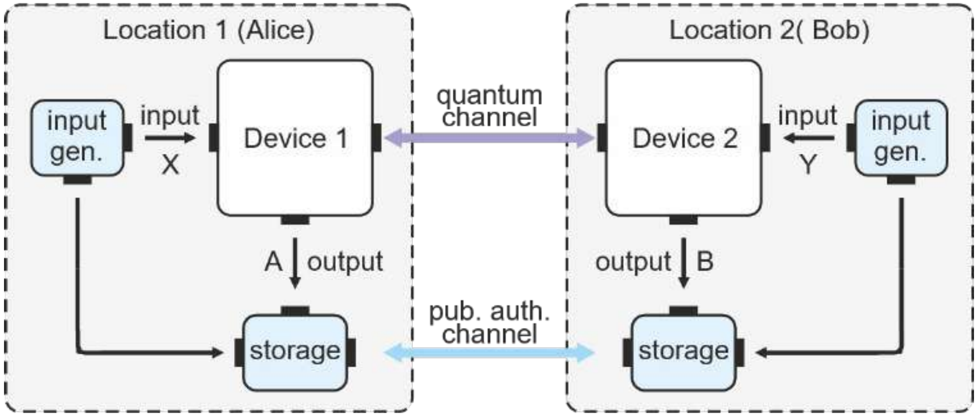
- R>0 with >99% confidence
  (assuming Beta distributed errors)

also at University of Oxford and USTC Hefei

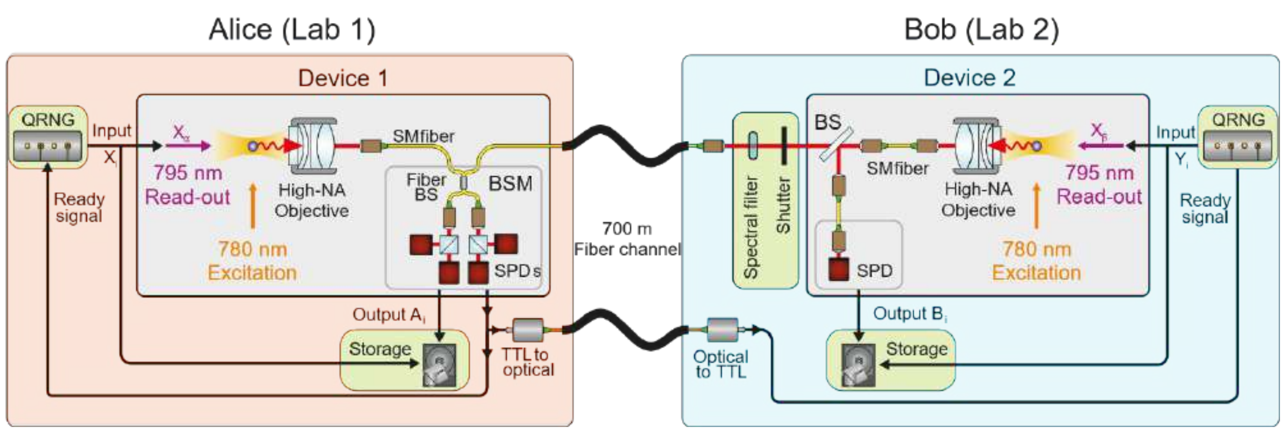
W. Zhang, et al., Nature **607,** 687 (2022)

DI-QKD

- device-independent
- QKD systems could be
  - uncharacterized
  - manipulated by producer

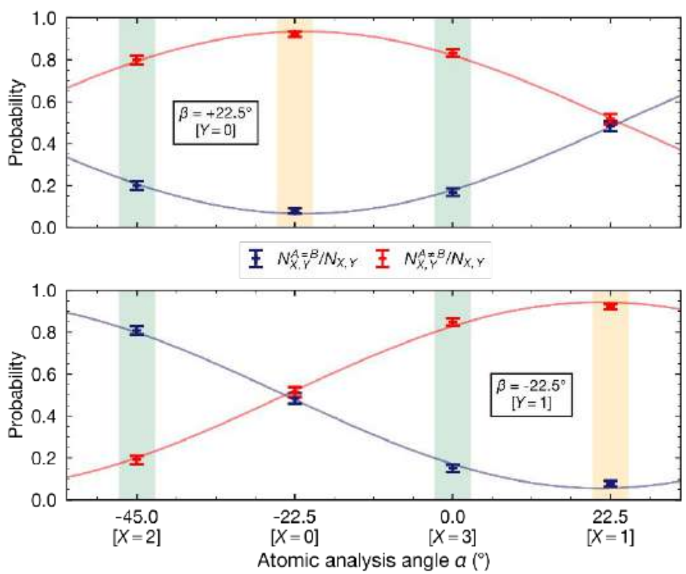


- Bell test: violation □ secrecy
  - efficient detection, no unauthorized communication

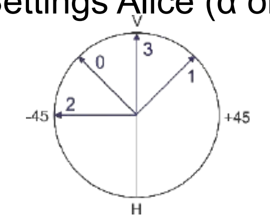


- More robust against noise with BB84 like settings

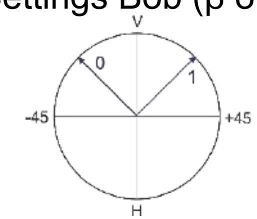
Schwonnek, et al., Nat Commun **12,** 2880 (2021)

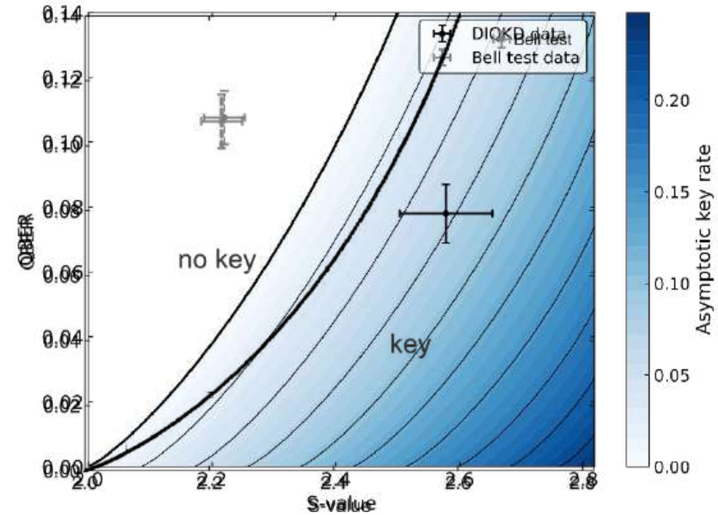


Settings Alice (α or X)



Settings Bob (β or Y)





Number of rounds:
- N=3342 in 75 hours

Visibility:
>0.869(25)

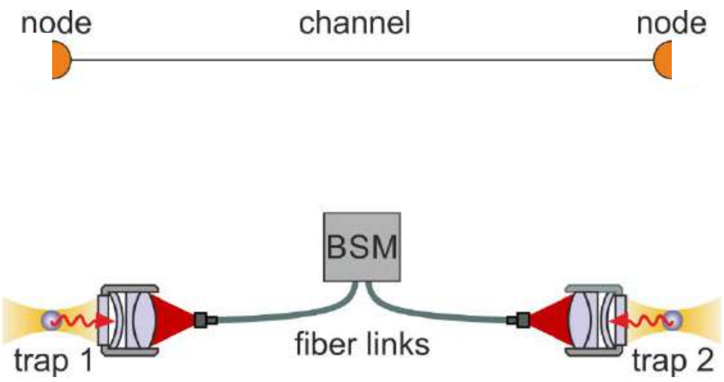
key (asymptotic limit):
0.07 / 0.25 per event

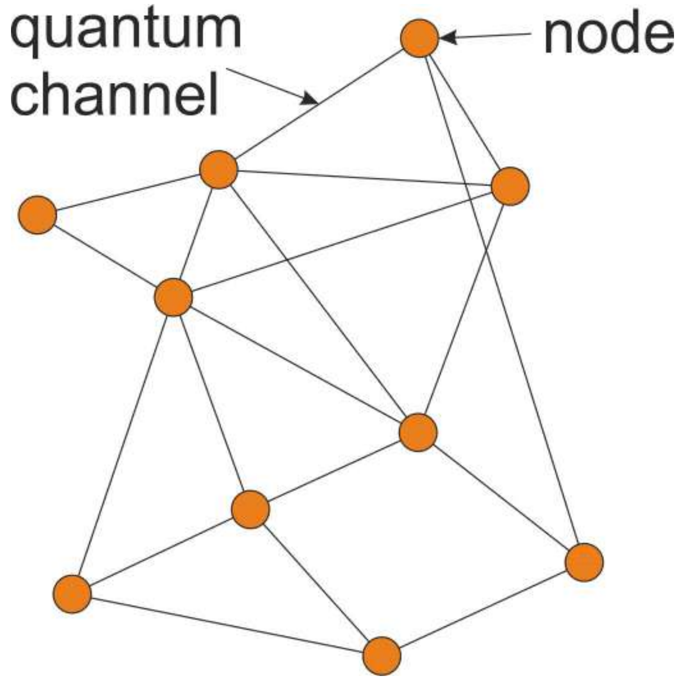
also at University of Oxford and USTC Hefei

W. Zhang, et al., Nature **607,** 687 (2022)

towards quantum networks

▪ a quantum link

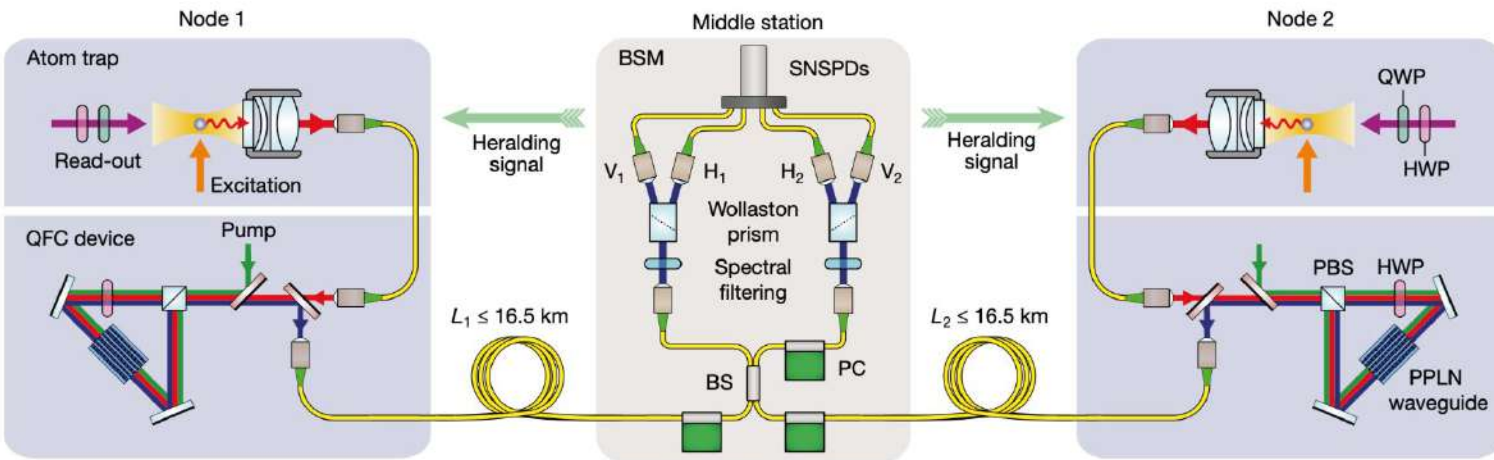




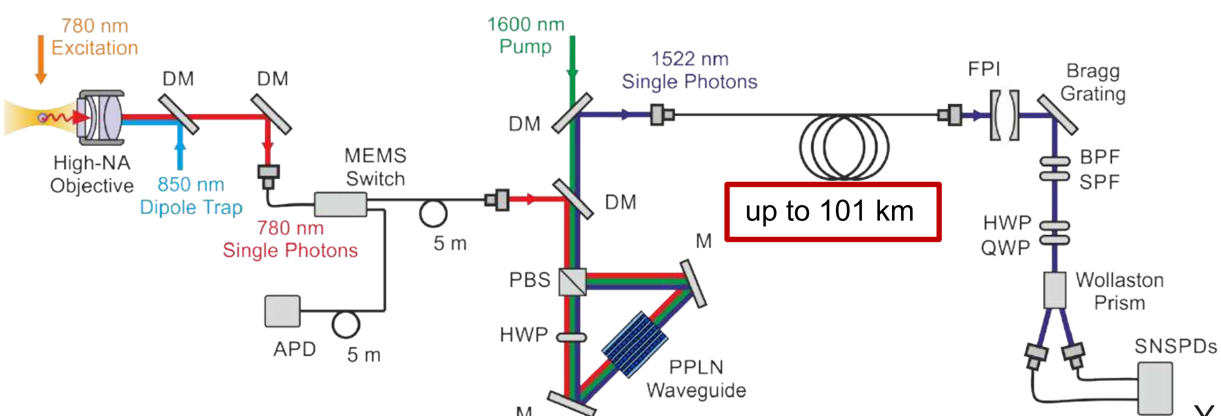
- local quantum system + photonic interface
- NV-centers
- quantum dots
- ensembles of colour centers or atoms …
- Rb-Atoms

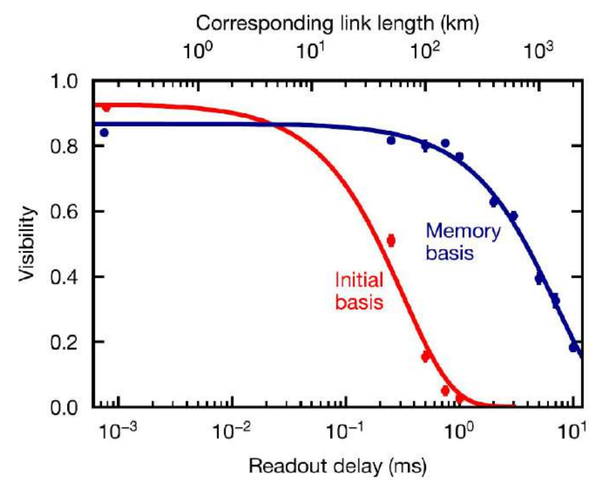
long-distance entanglement distribution

33 km glas fiber between nodes



101 km atom-photon entanglement

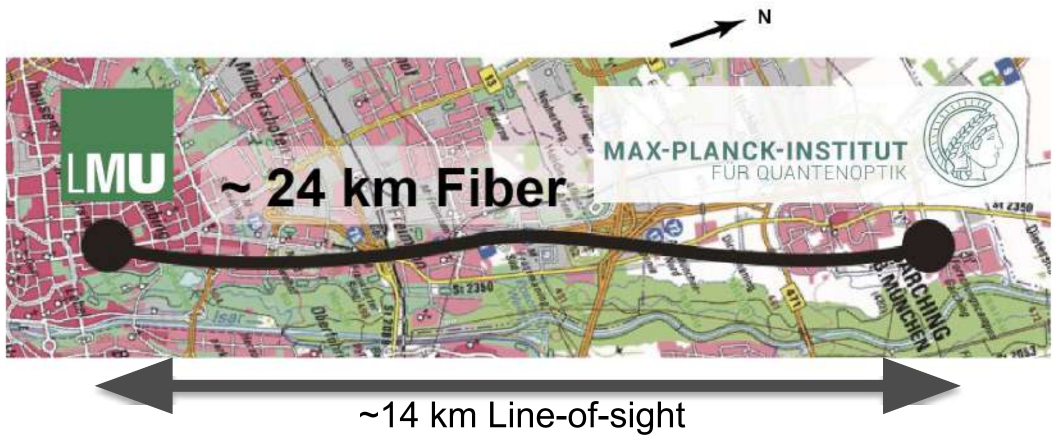


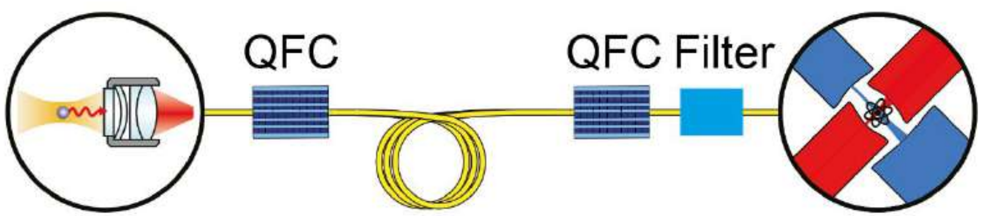


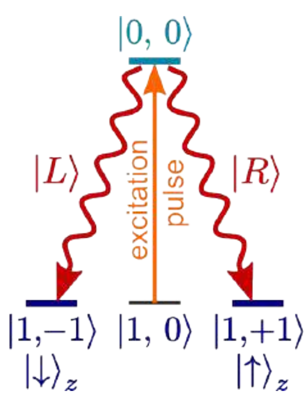
T. van Leent, et al., Nature **607,** 69 (2022)
Y. Zhou, et al., PRX Quantum **5**, 020307 (2024)

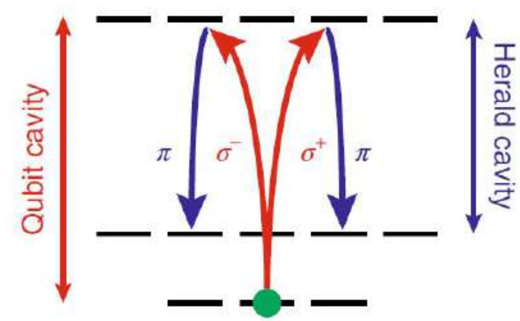
LMU-MPQ entanglement distribution

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK
Tobias Frank
Gianvito Chiarella
Maya Büki
Marvin Scholz
Pau Farrera
Gerhard Rempe





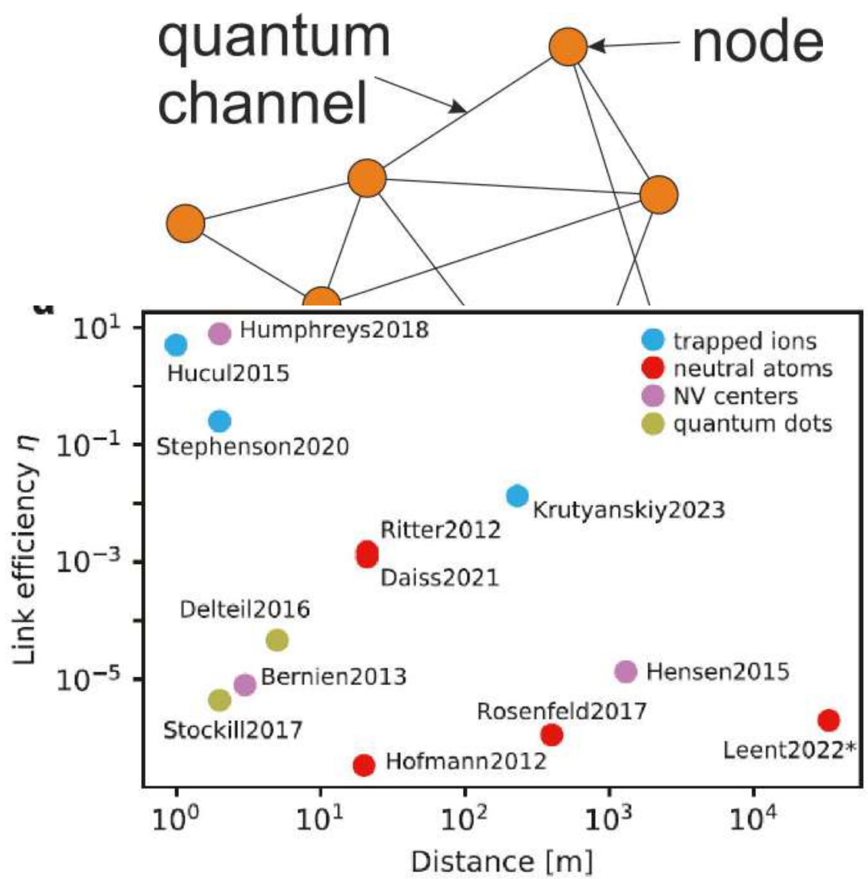




M. Brekenfeld et al., Nature Physics 16, 647-651 (2020)

quantum networks?

- quantum channel:
  efficient distribution quantum repeater functionality
  - quantum memory
  - quantum logic operation
    for entanglement purification
    and Bell-state measurement



- quantum node:
  - **provide entanglement at all times**
  - one link:
    link efficiency

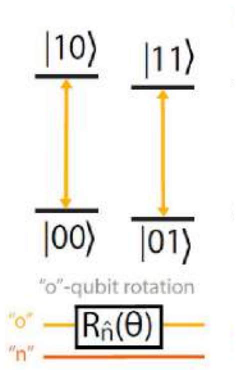
$$\eta = \gamma_{ent} / \gamma_{dec} > 1$$

Jake Covey, HW, Hannes Bernien, npj Quantum Information **9**, 90 (2023)

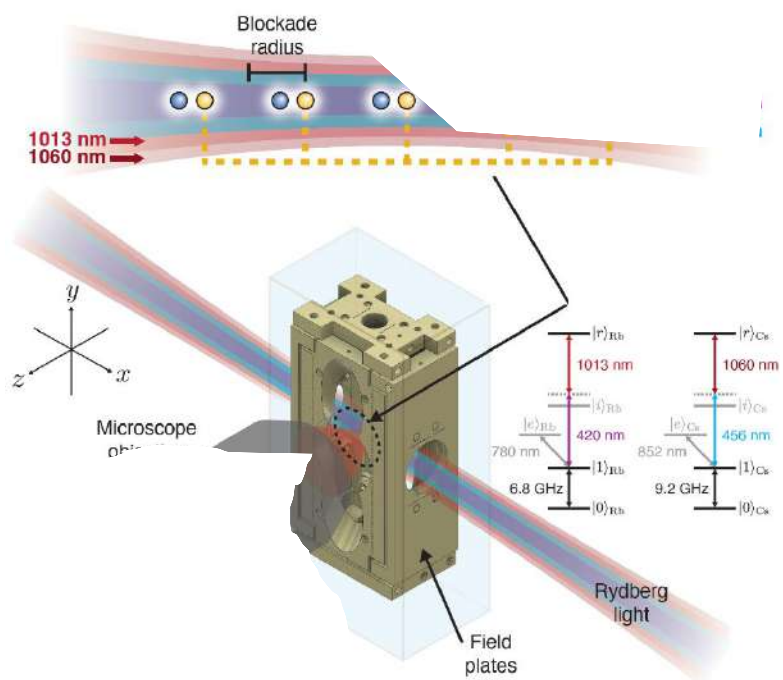
quantum networks?

$$\eta = {\gamma_{ent}}/{\gamma_{dec}} > 1$$

- quantum memories
  - □ quantum error correction
- neutral atom implementations:

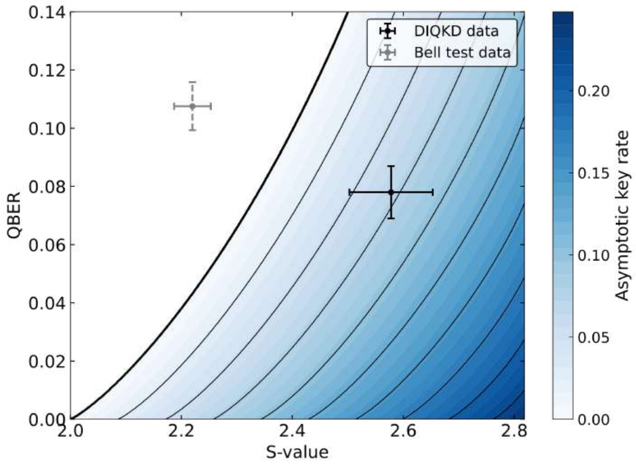


Yb ququart



Z. Jia et al., arXiv:2402.13134
S. Anand et al., arXiv:2401.10325
S.G. Menon et al., Nature Comm. **15**, 6156 (2024)
D. Bluvstein et al., Nature **626**, 58 (2024)

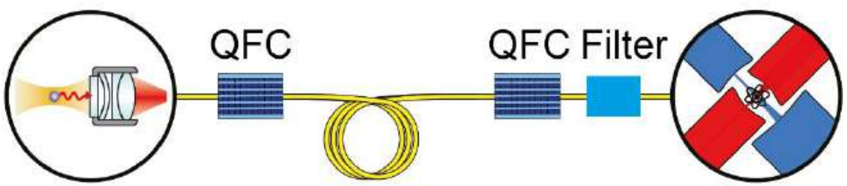
Summary

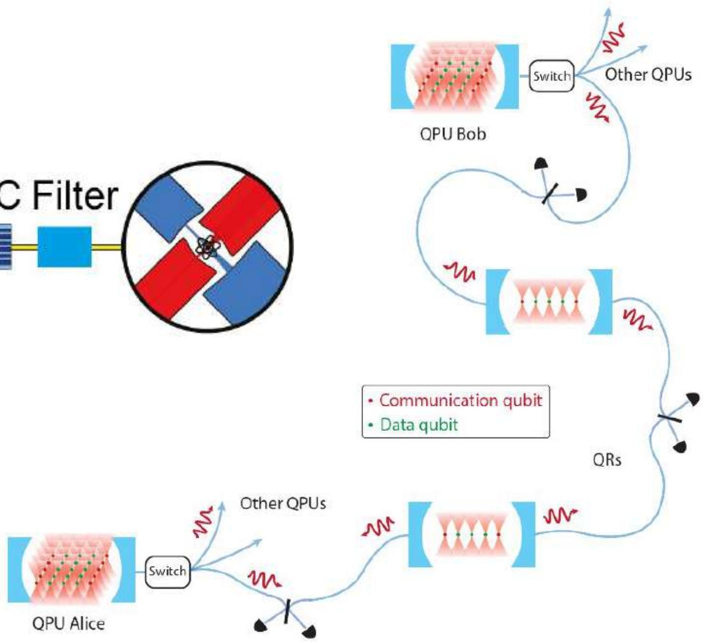


- Atom-Atom-Entanglement
  - atom-photon entanglement
    + entanglement swapping

□ loophole free Bell-test

- DIQKD between distant users
- longer distances
- LMU-MPQ link





- quantum networks:

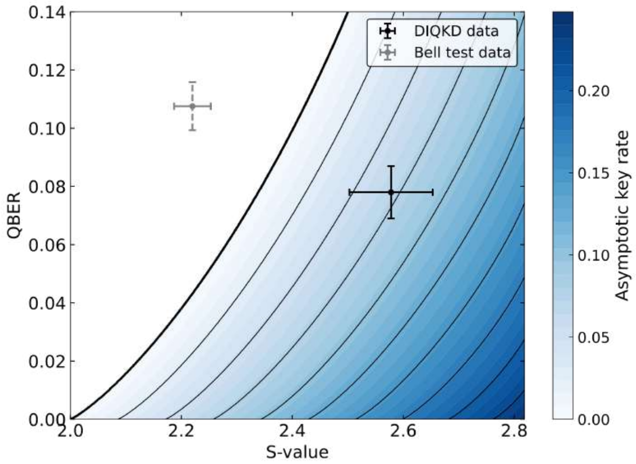
  □ memory, local nodes, rates

xqp

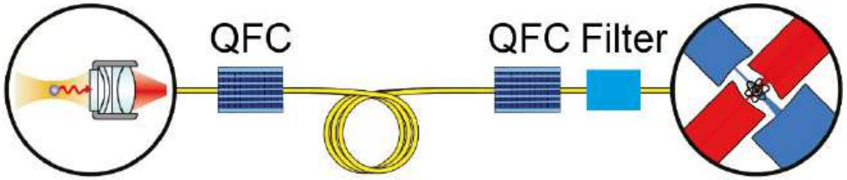
Summary

- Atom-Atom-Entanglement
  - atom-photon entanglement + entanglement swapping

□ loophole free Bell-test

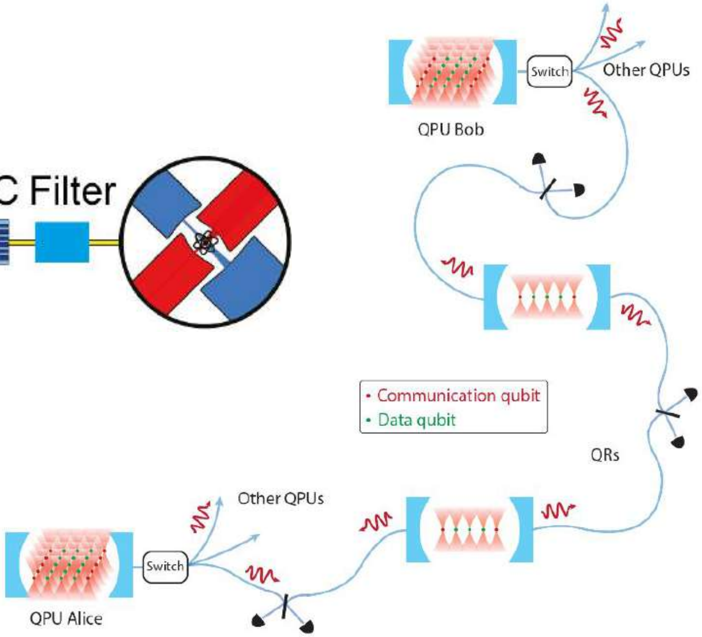


- DIQKD between distant users
- longer distances
- LMU-MPQ link

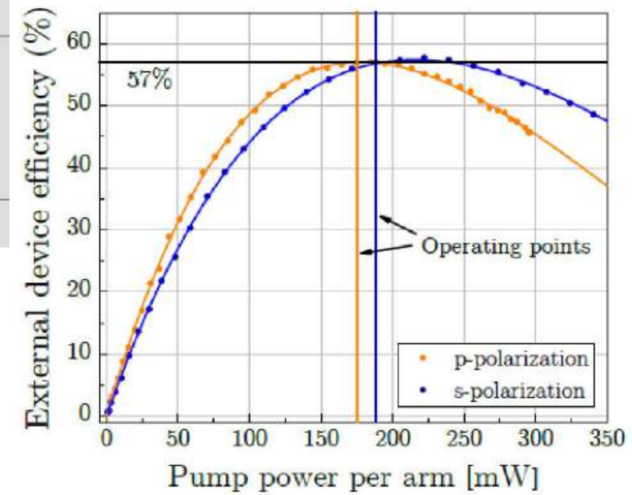


- quantum networks:

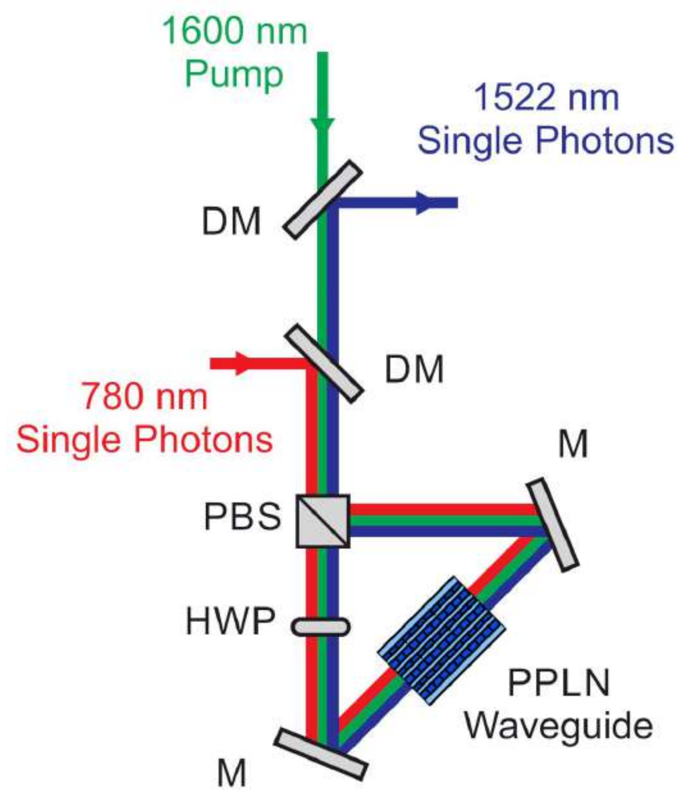
  □ memory, local nodes, rates

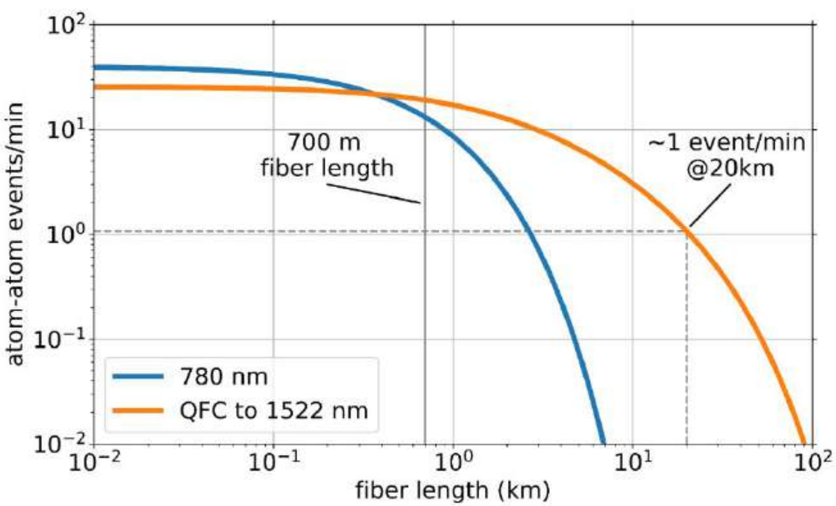


long distances



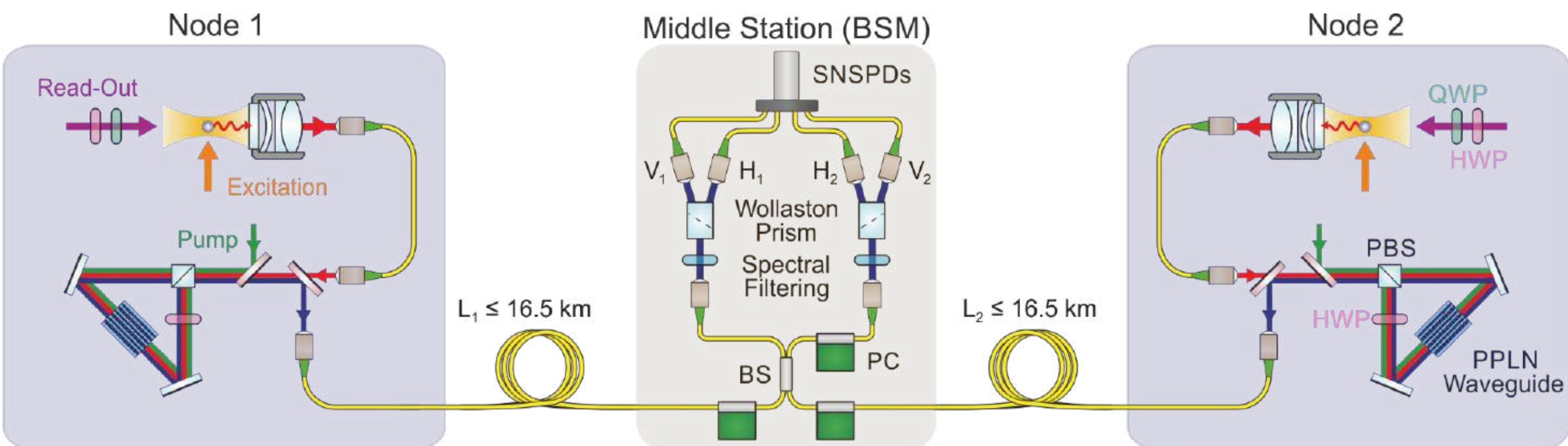
- efficient optical coupling
- long coherence times
  vector light shift → lower temp, standing wave
  magnetic field → new encoding
- absorption in fiber
  → quantum frequency conversion





Tim van Leent, Matthias Bock et al., Phys. Rev. Lett. **124**, 010510 (2020)

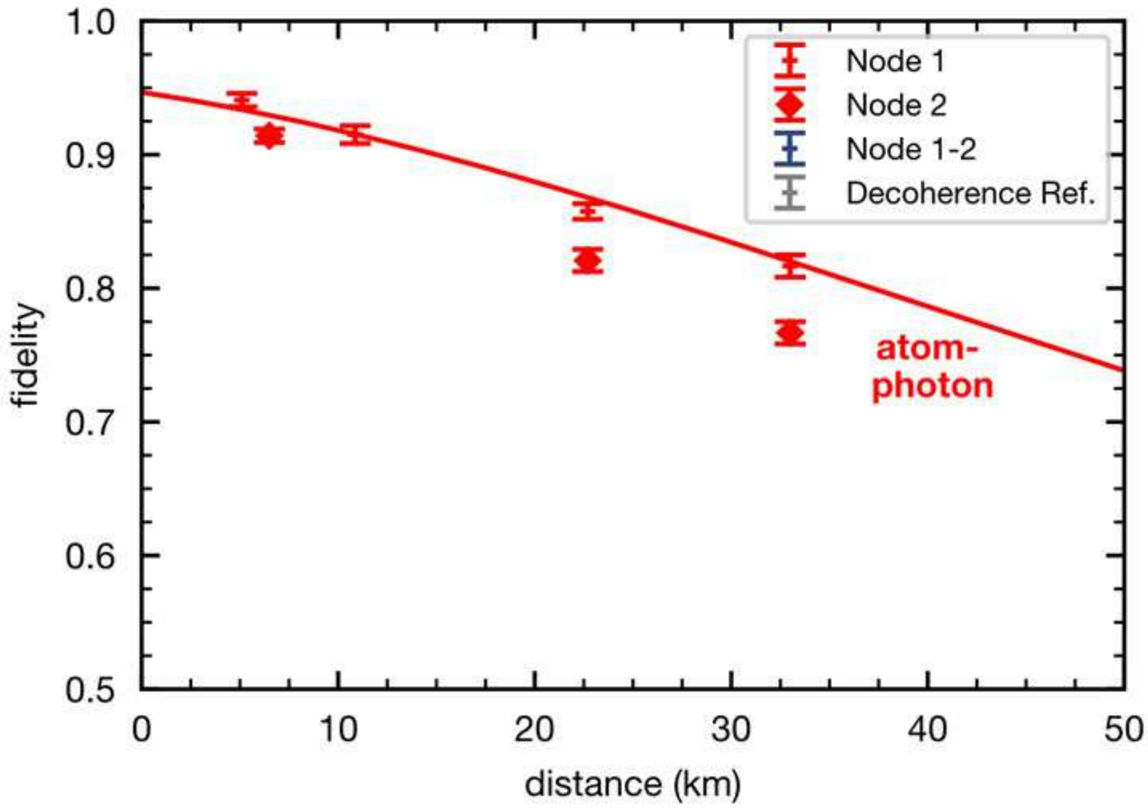
• two conversion units + BSM at telecom wavelengths



- Physical separation between nodes equals 400 m
- Different symmetric fiber configurations: L = 6, 11, 23, and 33 km
- Implement delay for communication of the heralding signal

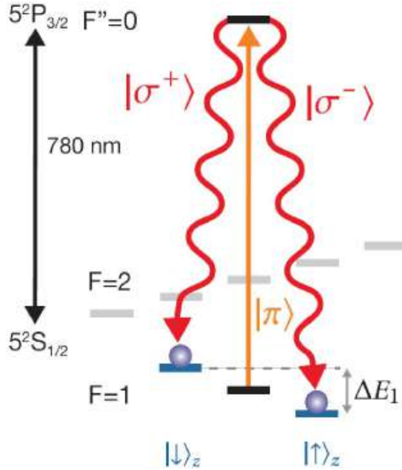
□ decoherence for long times + Raman noise from converter

- atom-atom entanglement over up to 30 km

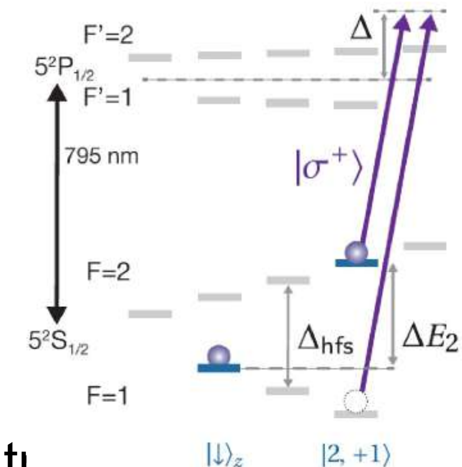


decoherence ? dephasing !

magnetic fields: subway,…, strongly focused light

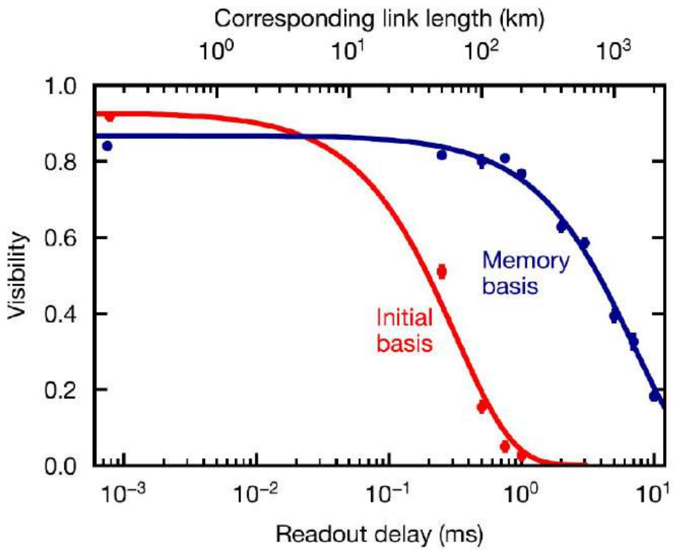


$\Rightarrow$

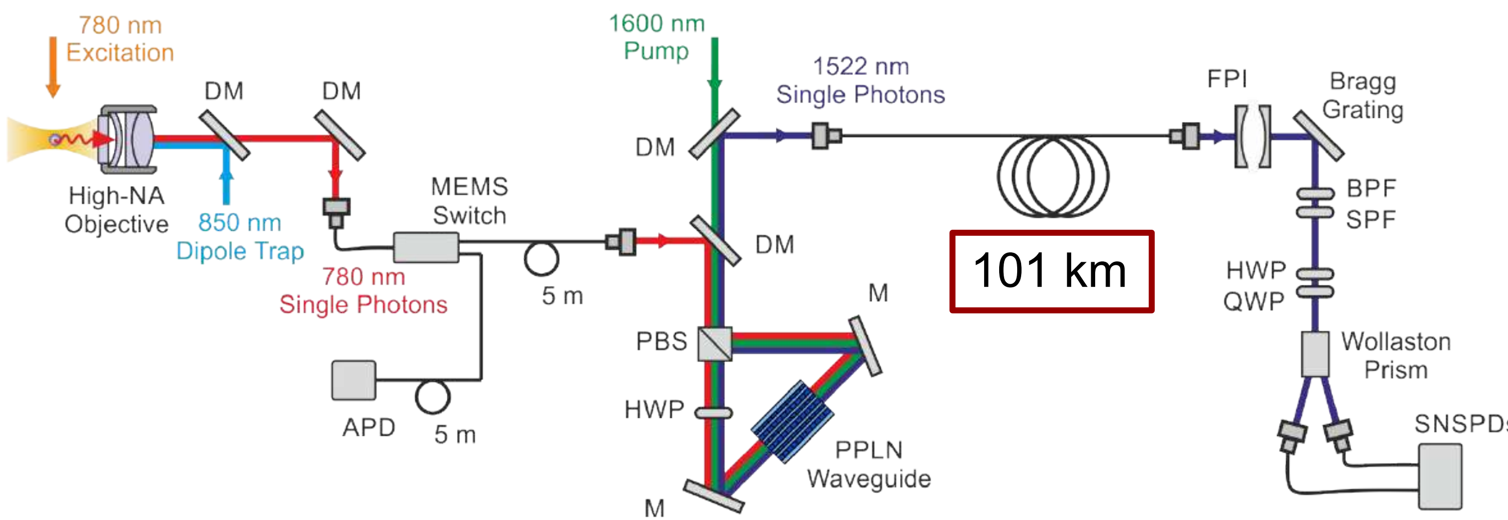


shielding, uiding fields

$\Rightarrow$ state t

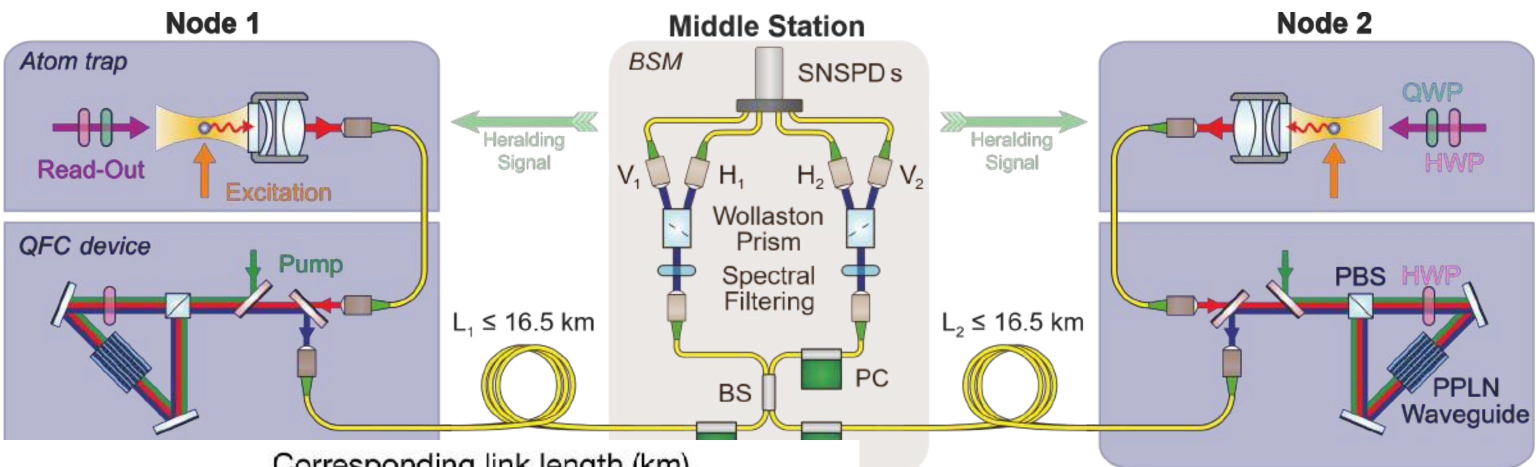


distance	fidelity
50 km	84.8 ± 1.1 %
101 km	70.8 ± 2.4 %

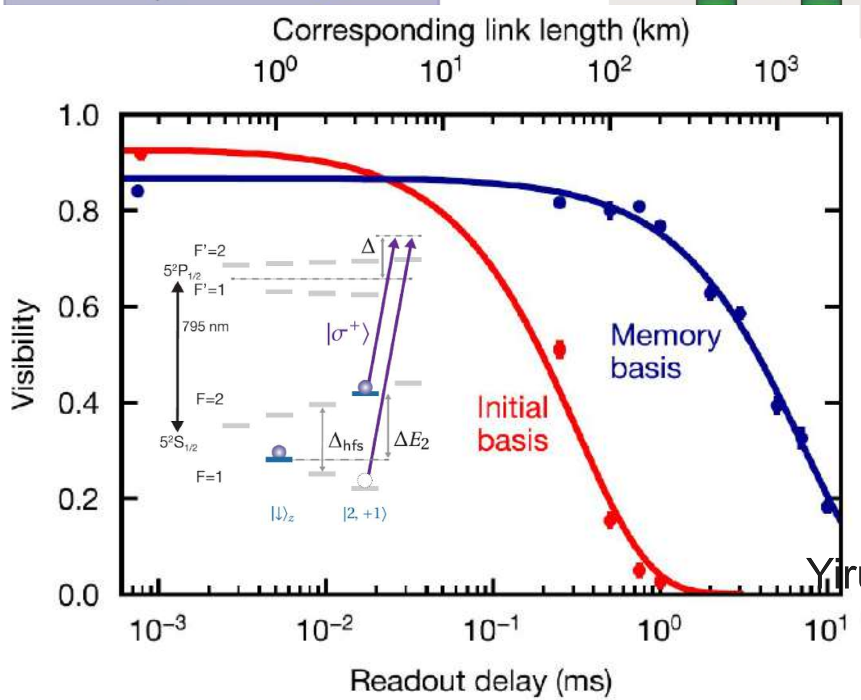


Yiru Zhou, et al., arXiv:2308.08892

long(er) distances



- … 3 km
- … om



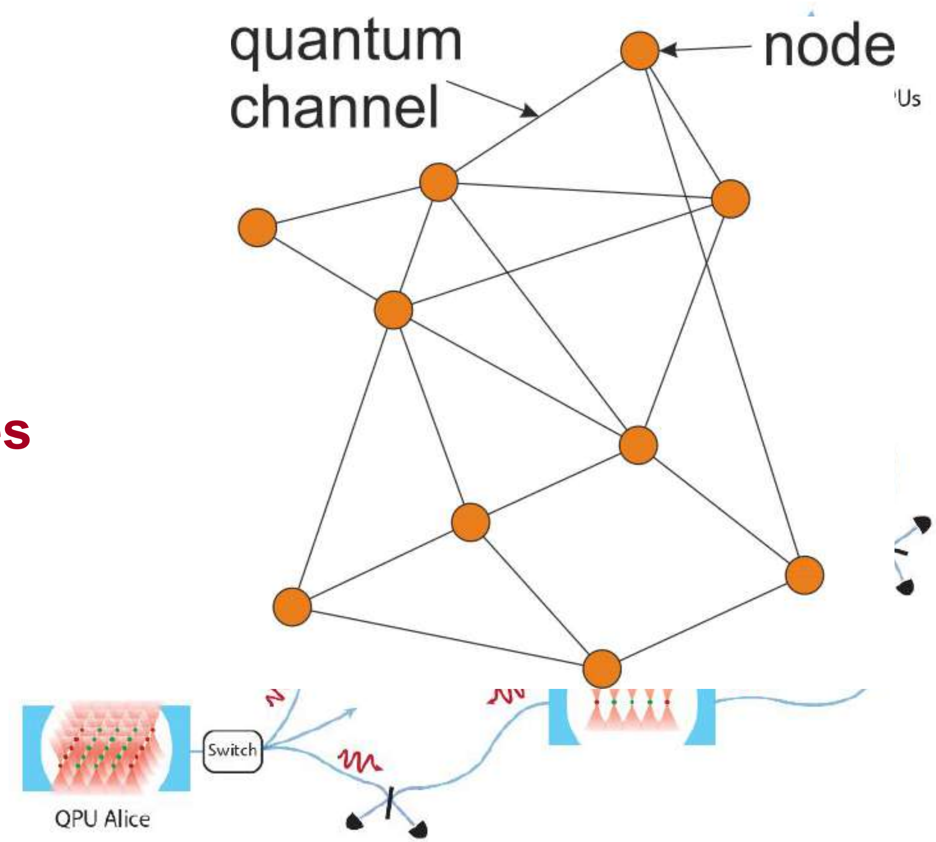
detector dark counts

Yiru Zhou, et al., PRX Quantum **5**, 020307 (2024)

T. van Leent, et al., Nature **607**, 69 (2022)

quantum networks?

- quantum channel:
  efficient □ quantum repeater functionality
  - quantum memory
  - quantum logic operation
    for entanglement purification
    and Bell-state measurement



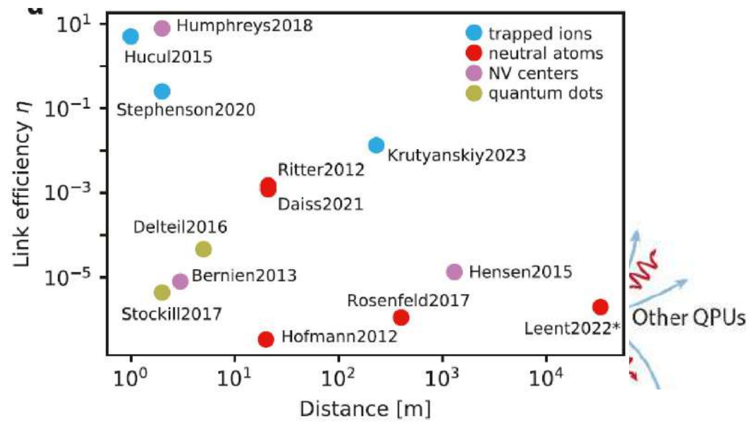
- quantum node:
  - **provide entanglement at all times**
  - one link:
    link efficiency

$$\eta = \gamma_{ent} / \gamma_{dec} > 1$$

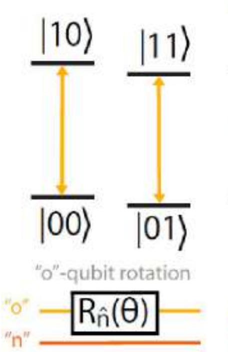
Jake Covey, HW, Hannes Bernien, npj Quantum Information **9**, 90 (2023)

quantum networks?

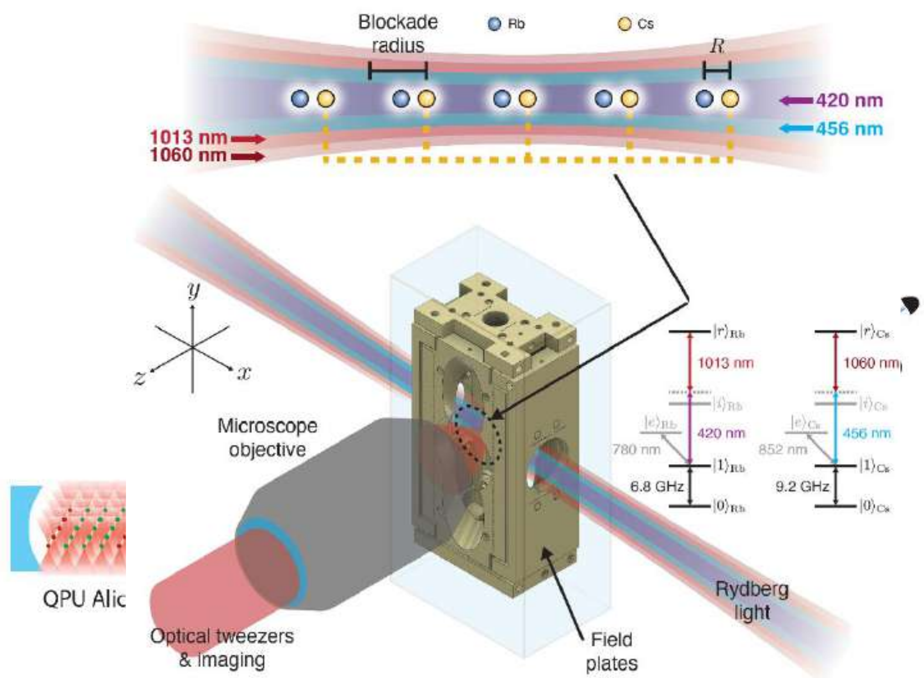
$$\eta = \gamma_{ent} / \gamma_{dec} > 1$$



- quantum memories
  - □ quantum error correction
- neutral atom implementations:



Yb ququart

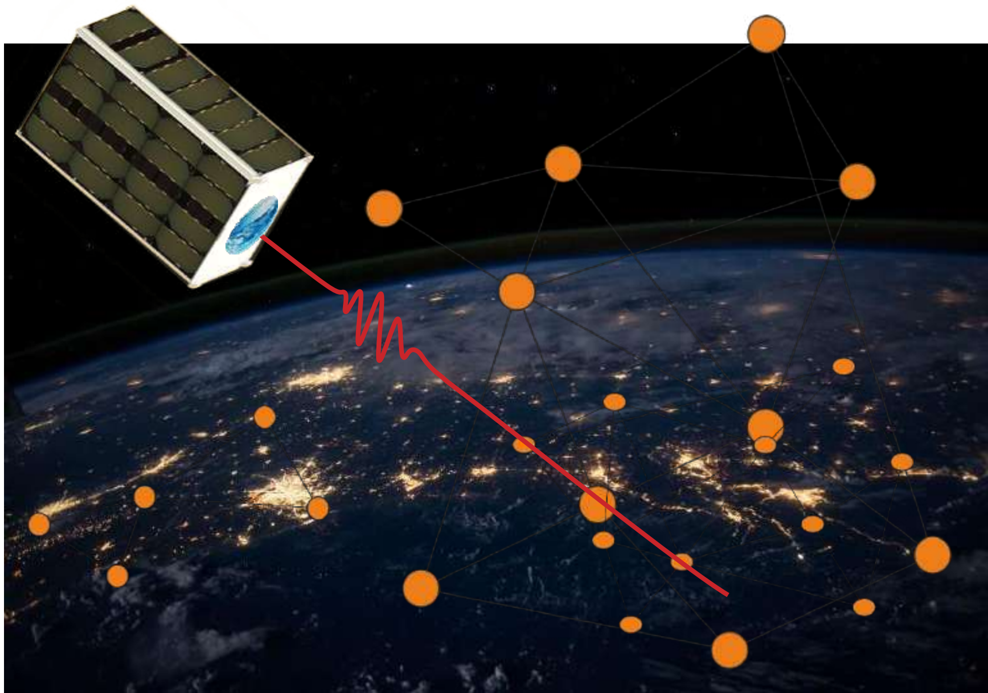


Z. Jia et al., arXiv:2402.13134
S. Anand et al., arXiv:2401.10325
S.G. Menon et al., Nature Comm. **15**, 6156 (2024)
D. Bluvstein et al., Nature **626**, 58 (2024)

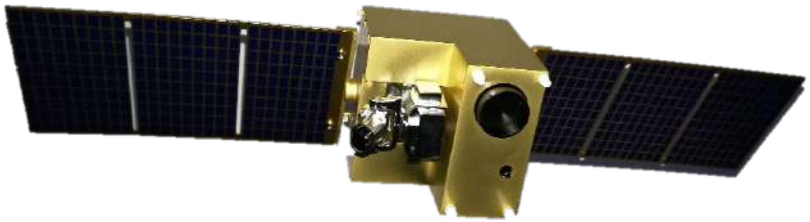
Overview

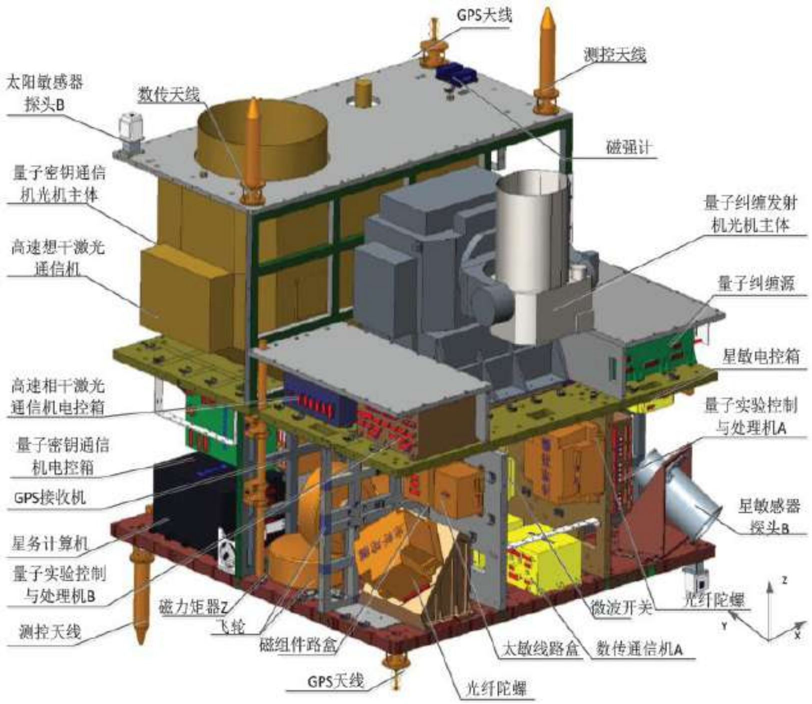
- Fundamental elements of Quantum Physics
- secure communication
- towards quantum networks

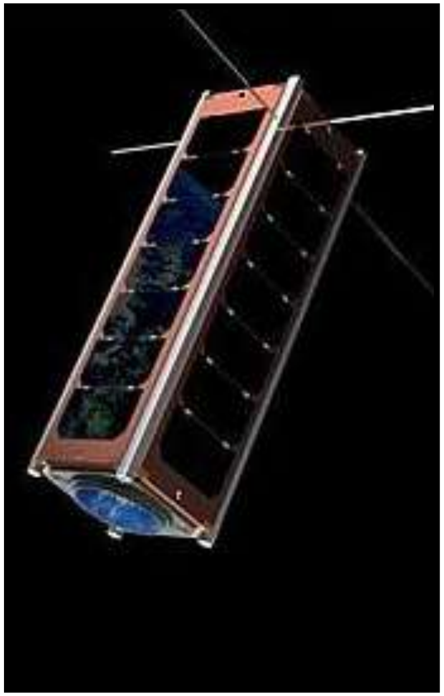
Loophole-free Bell test
DI-QKD



MICIUS □ CUBE satellite ?





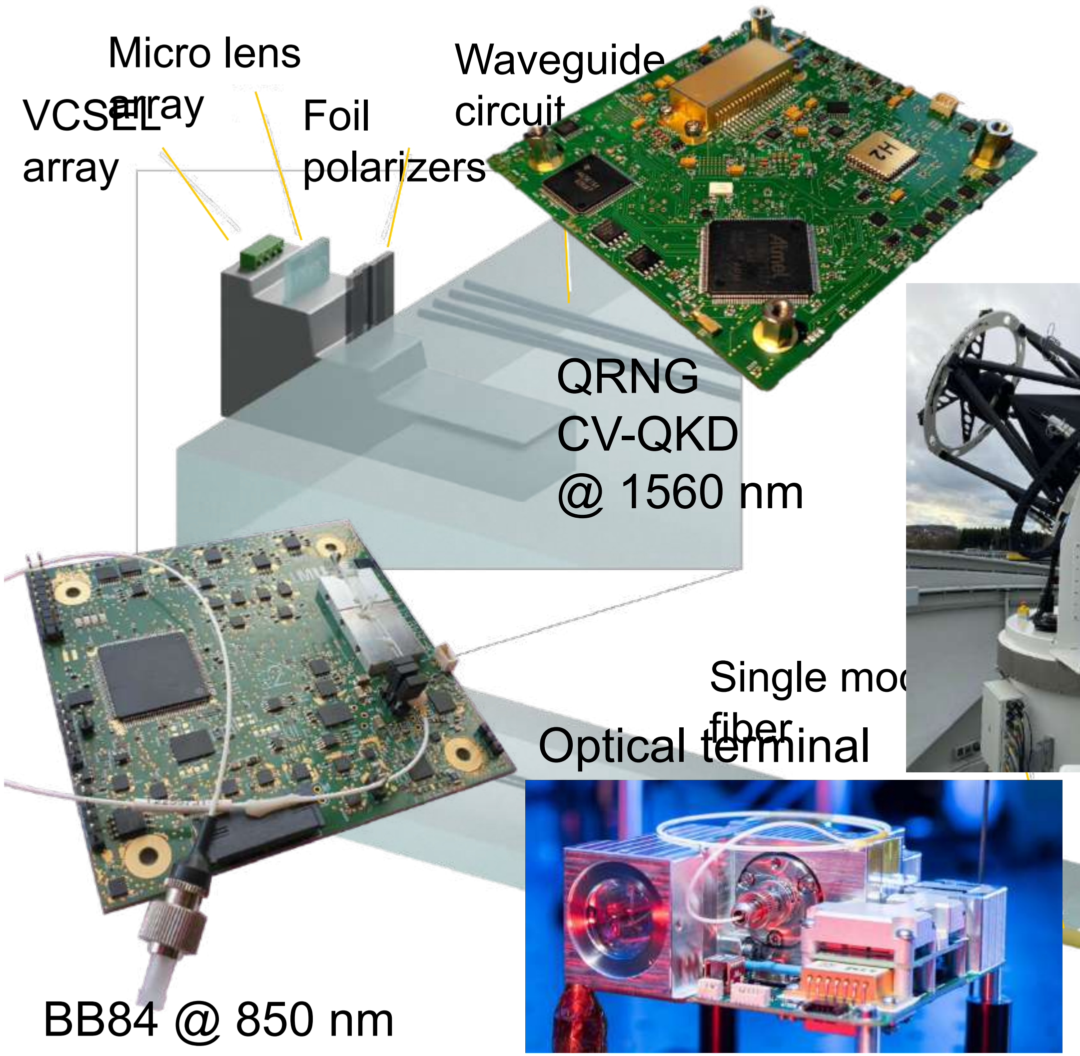


SWaP : size, weight, and power

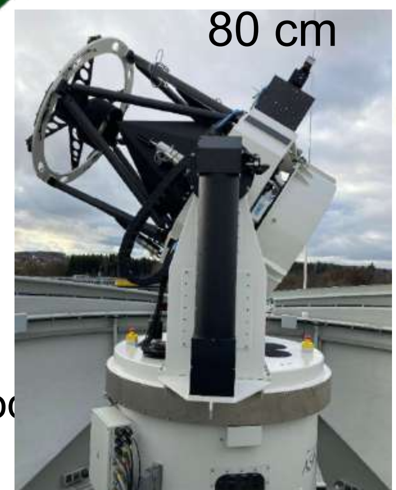
QKD on cubesats?

QUBE

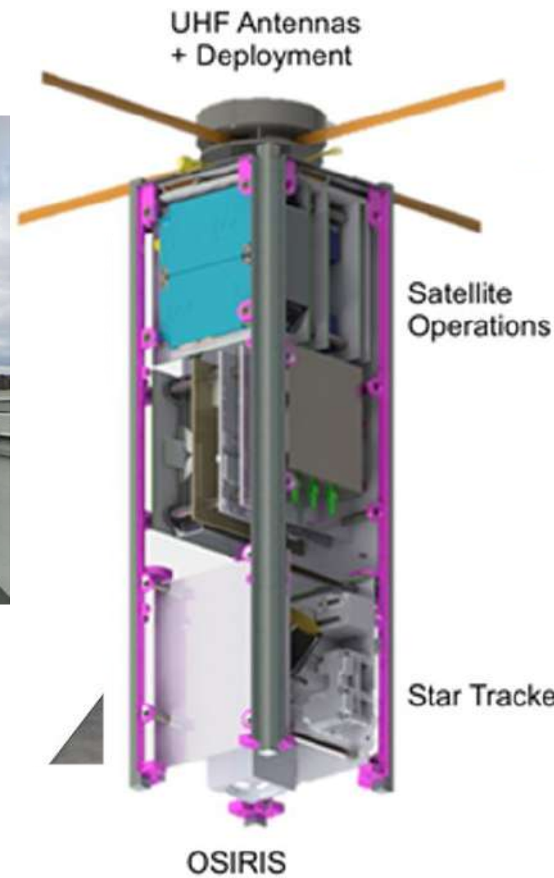
2017 – 2021



ground station
80 cm



Optical terminal



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QUBE August 16th, 2024