Advances in entanglement-based QKD for space applications

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Sebastian Ecker

21/06/2022

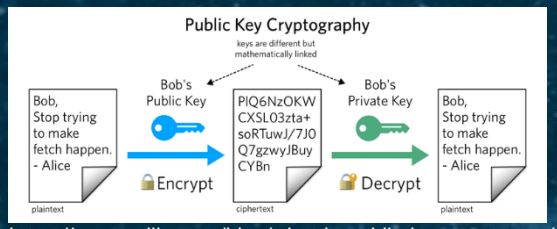
Outline

- Fundamentals of quantum key distribution (QKD)
  - Why QKD instead of classical cryptography?
  - QKD protocols
  - Sources of entangled photon pairs
  - Distribution of photons over long distances

- Advances in entanglement-based QKD
  - High-performance entangled photon pair sources
  - Integrated photonic entanglement sources
  - Wavelength division multiplexing
  - High-dimensional QKD
  - Adaptive optics for quantum receivers
  - Space-based quantum repeater

Quantum Key Distribution (QKD) – Why?

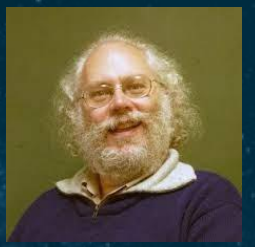
Secure communication relies on asymmetric cryptography (e.g. RSA)
Messages encrypted with public key, decrypted with private key.



https://www.twilio.com/blog/what-is-public-key-cryptography

Public key cryptography

Peter Shor



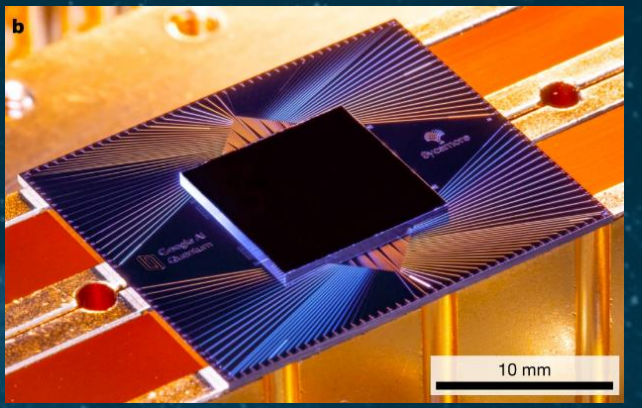
Security based on computational hardness **assumption**

Shor‘s (quantum) algorithm: Massive speedup – breaks cryptosystems!

Until 10-20 years ago this threat was theoretical
2019/2020: first demonstrations of quantum advantage

Programmable quantum computer „around the corner“ (20,30,40 years?)
IBM, Google, Microsoft, Honeywell, Rigetti, Zapata,...

Han-Sen Zhong et al. Science 370, 6523 (2020)



Frank Arute et al. Nature **574**, 7779 (2019)

Peter Shor, IEEE Comput. Soc. Press (1994)

QKD Protocols

→ Symmetric cryptography

→ Assumption-free

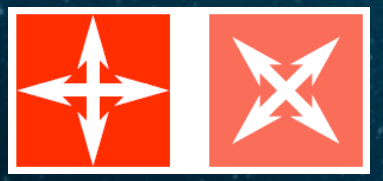
→ Security guaranteed by the laws of physics (Information-theoretic security)

<u>QKD relies on one fundamental quantum mechanical principle:</u>

- Outcome of measurement is not predetermined (quantum indeterminacy)
- Copying of quantum states is impossible (no-cloning theorem)
- Preparation in one “basis” makes information in another “basis” inaccessible

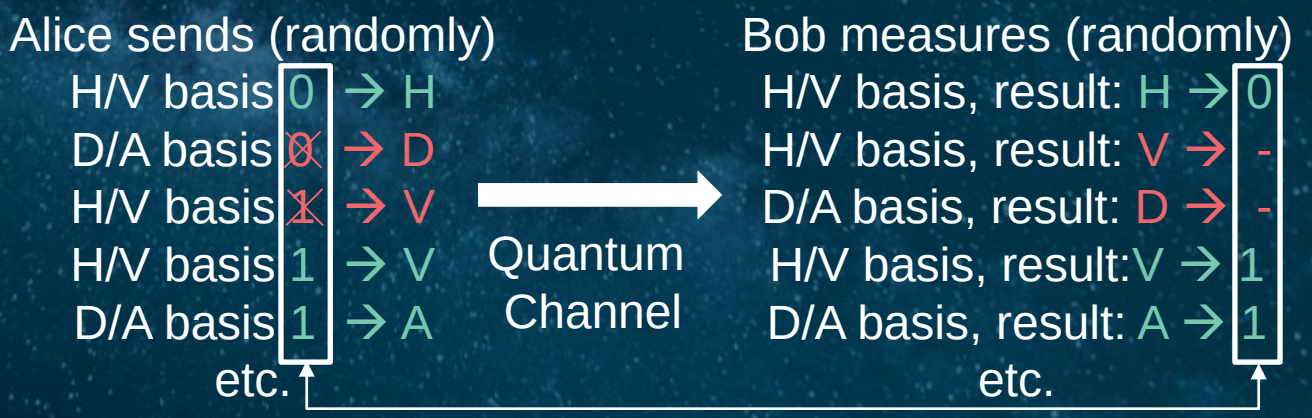
Polarization of (single) photons

H/V and D/A basis mutually exclusive



H/V basis D/A basis

H and V orthogonal
D and A orthogonal



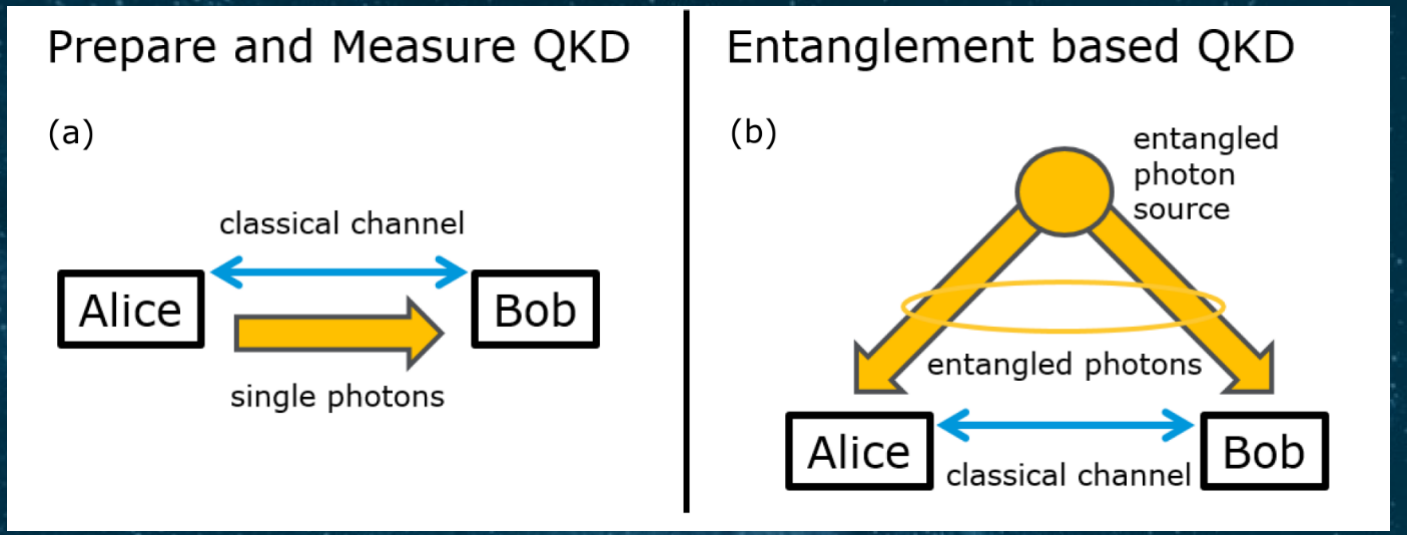
Secret key (for symmetric encryption), e.g. OTP

C. H. Bennett and G. Brassard, Theoretical Computer Science **560** (2014)

QKD Protocols

BB84-type protocols

BBM92-type protocols



Why focus on entanglement-based potocols?

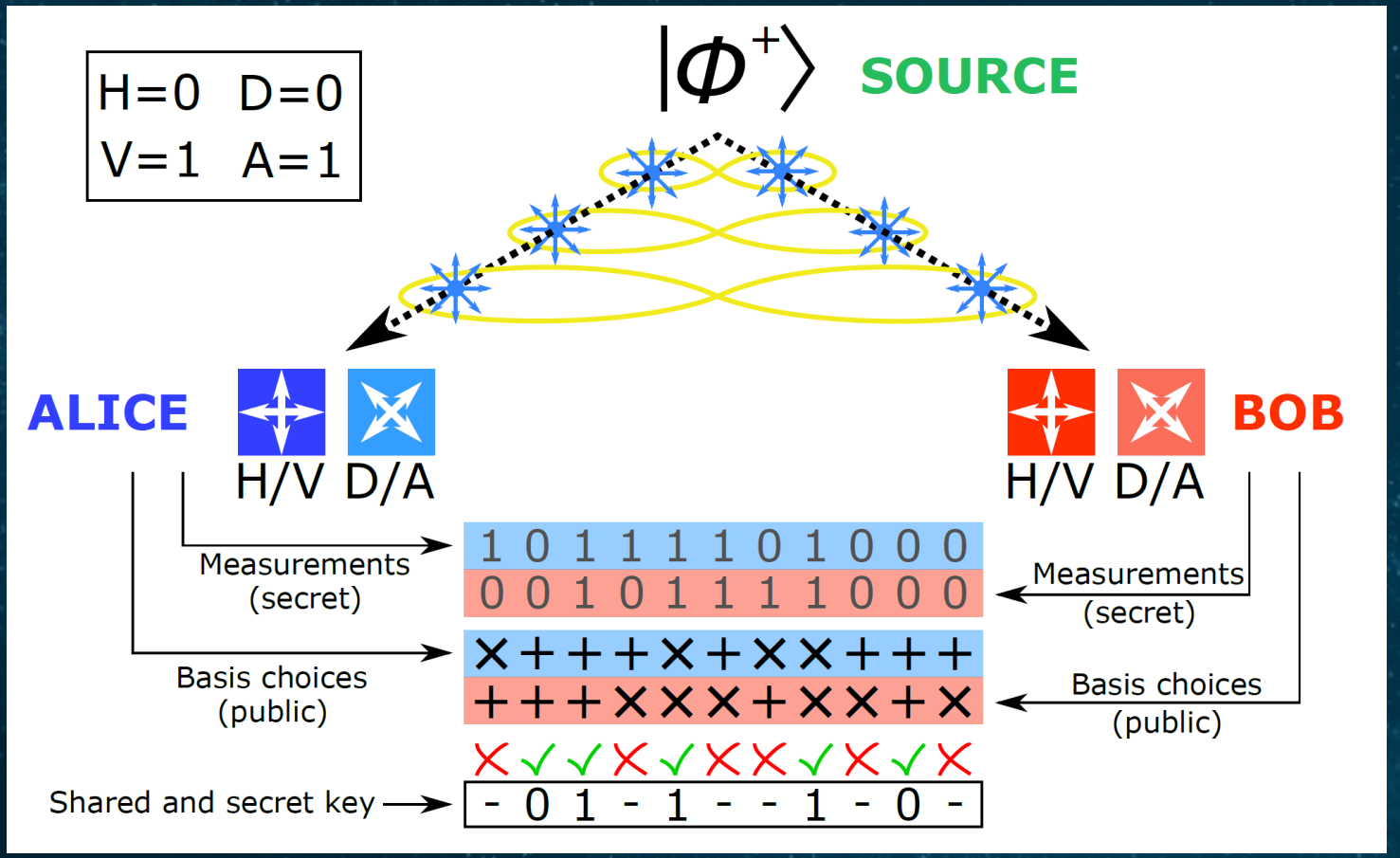
- Party owning the entangled photon source can be malicious (untrusted) – Satellites!
- Distribution of entanglement important for many quantum technological applications

E. Wille *et al.*, *Free-Space Laser Communications* ***XXXII***, p. 21. (2020)
C. Bennett, G. Brassard, and N. Mermin, Physical review letters **68**, 5 (1992)

QKD Protocols

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$$
$$= \frac{1}{\sqrt{2}}(|DD\rangle + |AA\rangle)$$

BBM92-protocol



C. Bennett, G. Brassard, and N. Mermin, *Physical review letters* **68**, 5 (1992)

Sources of entangled photon pairs

SPDC (second-order nonlinear process)

Pump laser
CW / pulsed

Photon pair properties:

- (Non-classical) two-photon state
- Spontaneous emission, probabil.
- Highly correlated in time (ps)
- Half the frequency of pump
- 1-100 nm bandwidth

Single-photon detection

SPAD

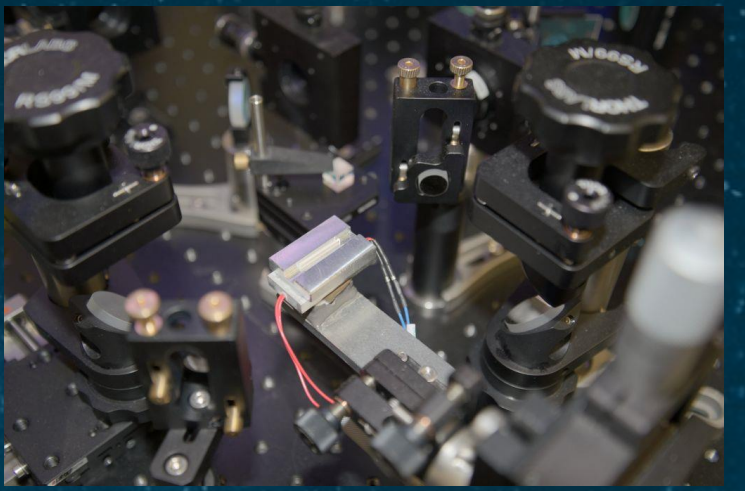
- medium timing jitter
- medium efficiency
- medium dead time
- low cost

SNSPD

- low timing jitter
- high efficiency
- low dead time
- high cost / complexity

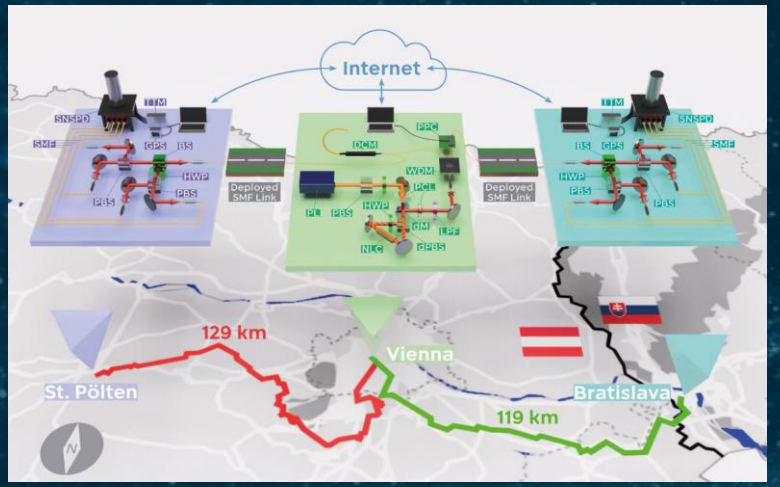
Engineering of photon pair sources:

- SPDC process (spectrum,collinear,polarization,..)
- Focal parameters (fiber coupling, pair rate)
- Overlap of several processes (Polarization entanglement!)
- Entanglement in different DoF



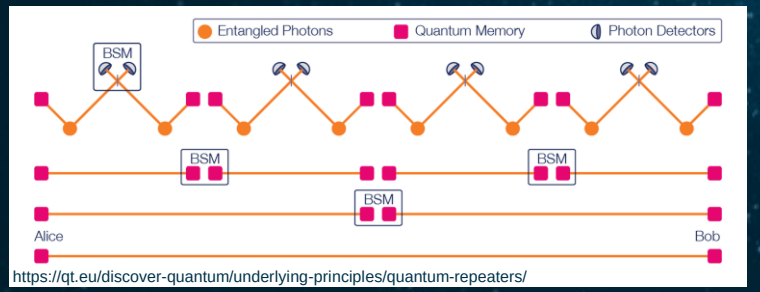
Distribution of photons over long distances

Optical fiber distribution (~0.2 dB/km)



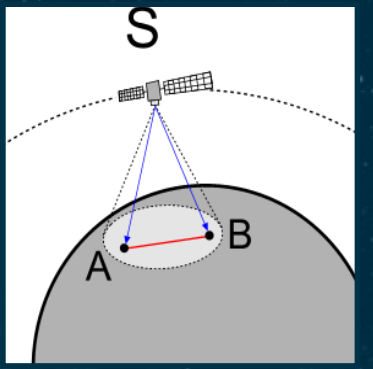
Exponential scaling of loss – absorption limited
→ Maximal distances of a few hundred km

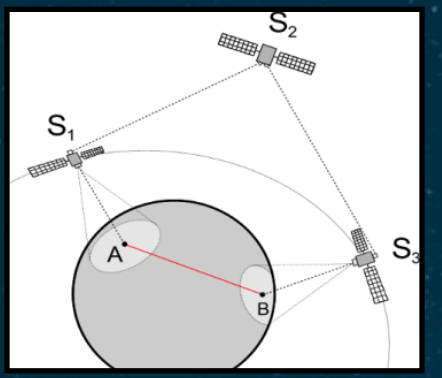
Quantum repeater (first lab demonstrations)

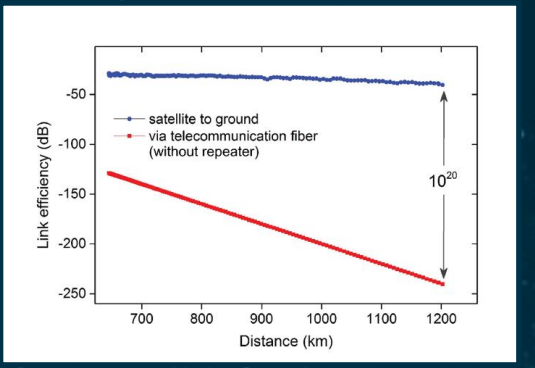


https://qt.eu/discover-quantum/underlying-principles/quantum-repeaters/

Satellite-based distribution

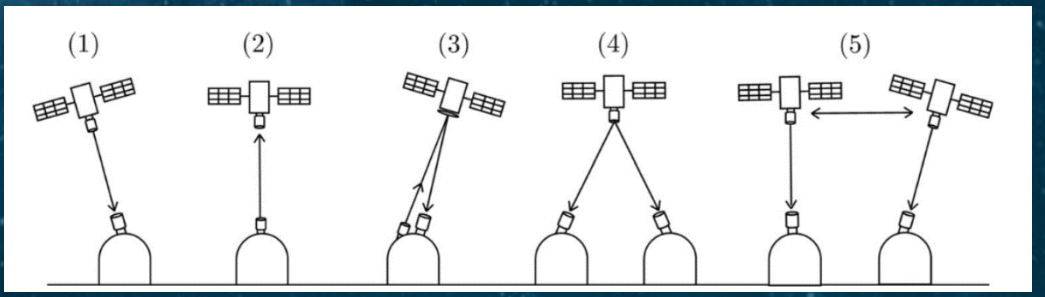






Quadratic scaling of loss – diffraction limited
→ Global coverage

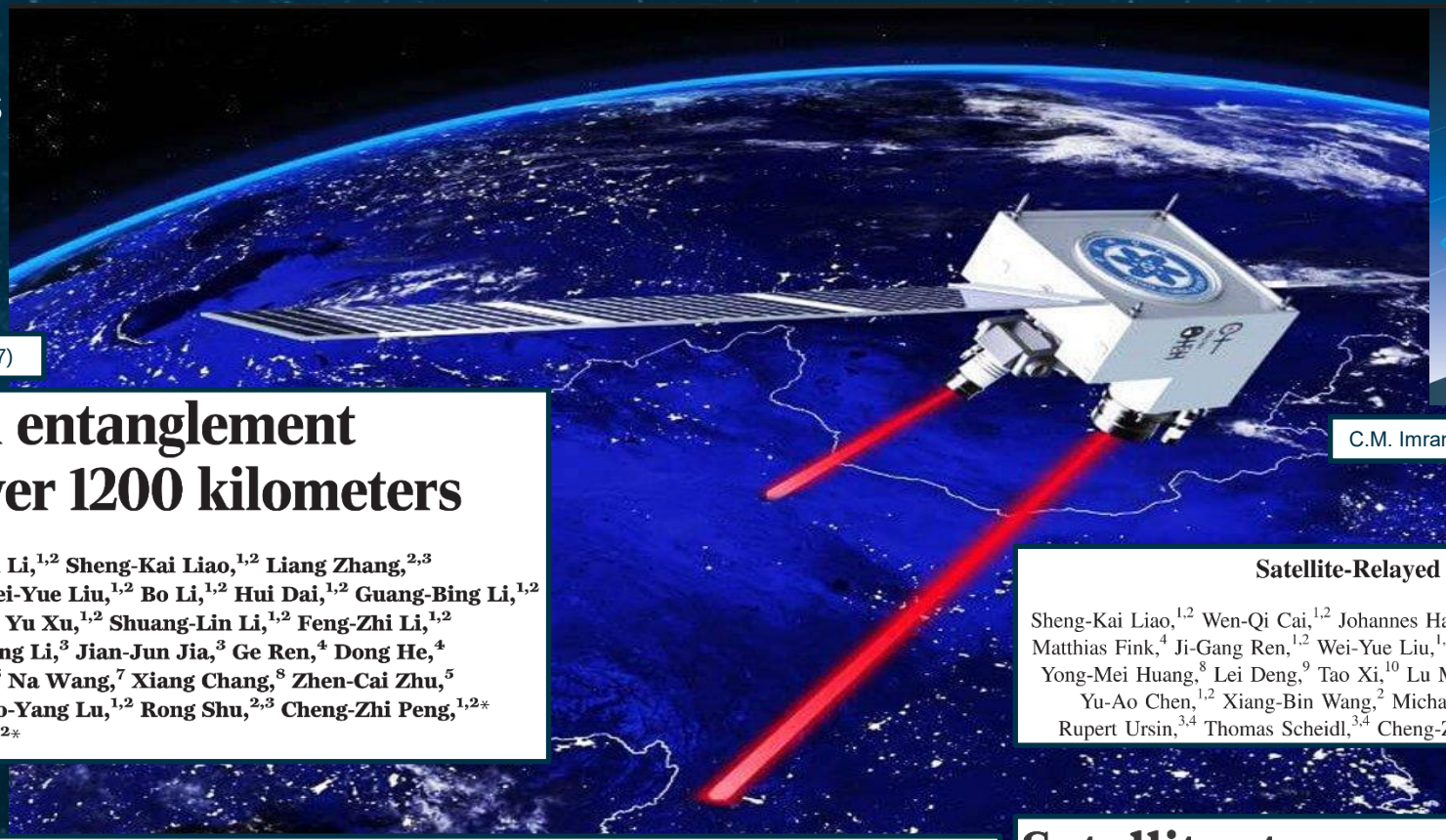
Possible link configurations

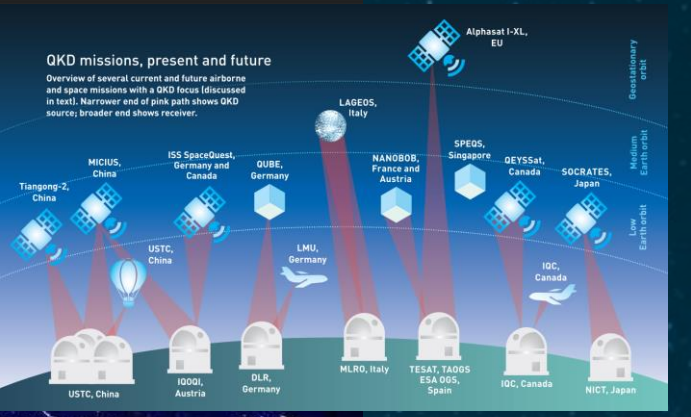


Yin, J., et al., Science, **356**, 6343 (2017)
S.P. Neumann, arXiv:2203.12417 (2022)
O. Lee, T. Vergoossen, and A. Ling, arXiv:1909.13061 (2019)

Micius satellite (QUESS mission)

Launch: 2016
Sun-synchronous
488-584 km
630 kg
97.4° inclination





C.M. Imran et al., "Satellite-Based QKD," Opt. Photonics News – OSA (2018)

Science, *356*(6343), 1140–1144 (2017)

Satellite-based entanglement distribution over 1200 kilometers

Juan Yin,[1,2] Yuan Cao,[1,2] Yu-Huai Li,[1,2] Sheng-Kai Liao,[1,2] Liang Zhang,[2,3] Ji-Gang Ren,[1,2] Wen-Qi Cai,[1,2] Wei-Yue Liu,[1,2] Bo Li,[1,2] Hui Dai,[1,2] Guang-Bing Li,[1,2] Qi-Ming Lu,[1,2] Yun-Hong Gong,[1,2] Yu Xu,[1,2] Shuang-Lin Li,[1,2] Feng-Zhi Li,[1,2] Ya-Yun Yin,[1,2] Zi-Qing Jiang,[3] Ming Li,[3] Jian-Jun Jia,[3] Ge Ren,[4] Dong He,[4] Yi-Lin Zhou,[5] Xiao-Xiang Zhang,[6] Na Wang,[7] Xiang Chang,[8] Zhen-Cai Zhu,[5] Nai-Le Liu,[1,2] Yu-Ao Chen,[1,2] Chao-Yang Lu,[1,2] Rong Shu,[2,3] Cheng-Zhi Peng,[1,2]* Jian-Yu Wang,[2,3]* Jian-Wei Pan[1,2]*

Physical Review Letters, 120(3), 30501 (2018)

Satellite-Relayed Intercontinental Quantum Network

Sheng-Kai Liao,[1,2] Wen-Qi Cai,[1,2] Johannes Handsteiner,[3,4] Bo Liu,[4,5] Juan Yin,[1,2] Liang Zhang,[2,6] Dominik Rauch,[3,4] Matthias Fink,[4] Ji-Gang Ren,[1,2] Wei-Yue Liu,[1,2] Yang Li,[1,2] Qi Shen,[1,2] Yuan Cao,[1,2] Feng-Zhi Li,[1,2] Jian-Feng Wang,[7] Yong-Mei Huang,[8] Lei Deng,[9] Tao Xi,[10] Lu Ma,[11] Tai Hu,[12] Li Li,[1,2] Nai-Le Liu,[1,2] Franz Koidl,[13] Peiyuan Wang,[13] Yu-Ao Chen,[1,2] Xiang-Bin Wang,[2] Michael Steindorfer,[13] Georg Kirchner,[13] Chao-Yang Lu,[1,2] Rong Shu,[2,6] Rupert Ursin,[3,4] Thomas Scheidl,[3,4] Cheng-Zhi Peng,[1,2] Jian-Yu Wang,[2,6] Anton Zeilinger,[3,4] and Jian-Wei Pan[1,2]

Nature, *549*(7670), 70–73 (2017)

Nature, *549*(7670), 43–47 (2017)

Ground-to-satellite quantum teleportation

Ji-Gang Ren[1,2], Ping Xu[1,2], Hai-Lin Yong[1,2], Liang Zhang[2,3], Sheng-Kai Liao[1,2], Juan Yin[1,2], Wei-Yue Liu[1,2], Wen-Qi Cai[1,2], Meng Yang[1,2], Li Li[1,2], Kui-Xing Yang[1,2], Xuan Han[1,2], Yong-Qiang Yao[4], Ji Li[5], Hai-Yan Wu[5], Song Wan[6], Lei Liu[6], Ding-Quan Liu[3], Yao-Wu Kuang[3], Zhi-Ping He[3], Peng Shang[1,2], Cheng Guo[1,2], Ru-Hua Zheng[7], Kai Tian[8], Zhen-Cai Zhu[6], Nai-Le Liu[1,2], Chao-Yang Lu[1,2], Rong Shu[2,3], Yu-Ao Chen[1,2], Cheng-Zhi Peng[1,2], Jian-Yu Wang[2,3] & Jian-Wei Pan[1,2]

Satellite-to-ground quantum key distribution

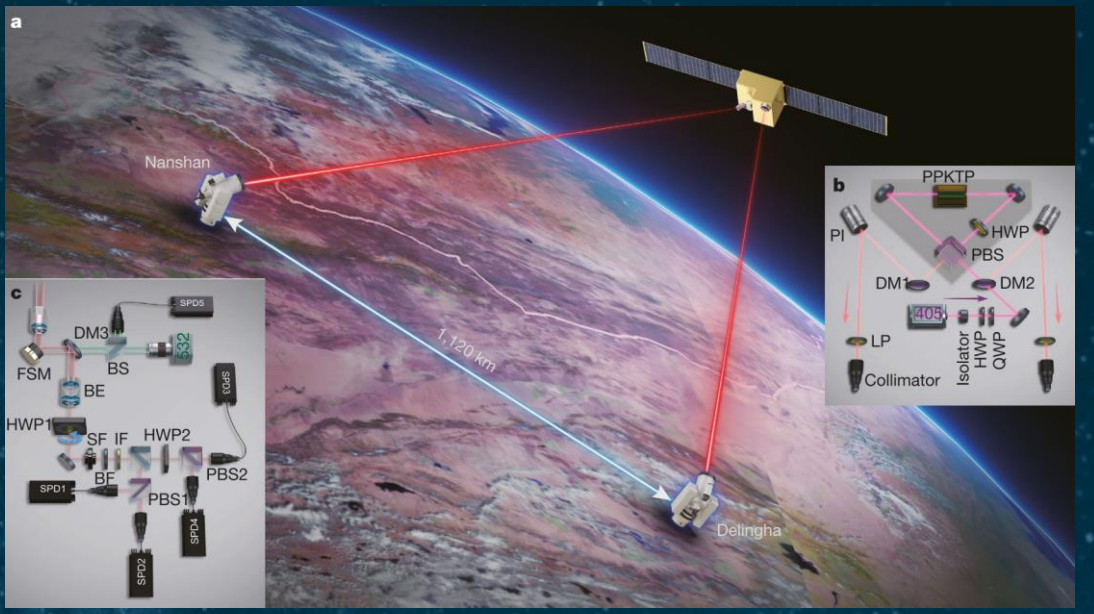
Sheng-Kai Liao[1,2], Wen-Qi Cai[1,2], Wei-Yue Liu[1,2], Liang Zhang[2,3], Yang Li[1,2], Ji-Gang Ren[1,2], Juan Yin[1,2], Qi Shen[1,2], Yuan Cao[1,2], Zheng-Ping Li[1,2], Feng-Zhi Li[1,2], Xia-Wei Chen[1,2], Li-Hua Sun[1,2], Jian-Jun Jia[3], Jin-Cai Wu[3], Xiao-Jun Jiang[4], Jian-Feng Wang[4], Yong-Mei Huang[5], Qiang Wang[5], Yi-Lin Zhou[6], Lei Deng[6], Tao Xi[7], Lu Ma[8], Tai Hu[9], Qiang Zhang[1,2], Yu-Ao Chen[1,2], Nai-Le Liu[1,2], Xiang-Bin Wang[2], Zhen-Cai Zhu[6], Chao-Yang Lu[1,2], Rong Shu[2,3], Cheng-Zhi Peng[1,2], Jian-Yu Wang[2,3] & Jian-Wei Pan[1,2]

Advances in entanglement-based QKD

Secret-key rate of Micius: 0.12 bits/s over 1120 km ground distance (entanglement-based protocol)

Operation at maximal capacity – little room for optimization

→ Fundamentally new techniques/methods are required for commercial success!



Yin et al., *Nature* 582, 501–505 (2020)

Advances should:

- Increase the secure key rate
- Reduce SWaP and complexity of quantum payloads
- Decrease the costs per secret bit

TRL of presented advances: Lab demonstrations and/or terrestrial free-space links

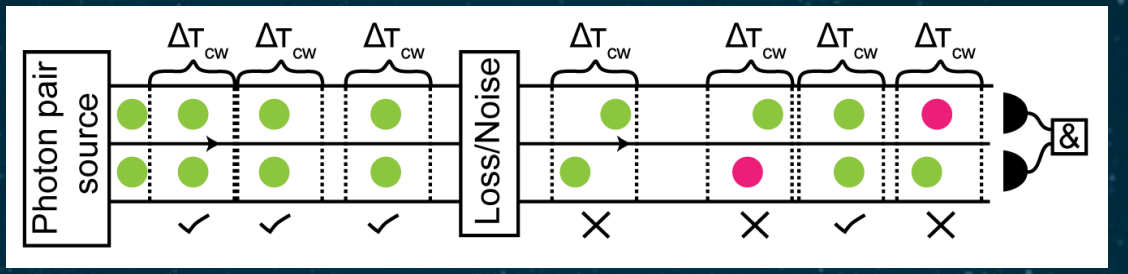
High-performance entangled photon pair sources

Performance parameters of entangled sources for QKD:

- **Fidelity** (>99%) – no potential
- **Heralding efficiency** (>50%) – no potential
- **Brightness** (>10^7 pairs/s/mW of pump power) – potential?

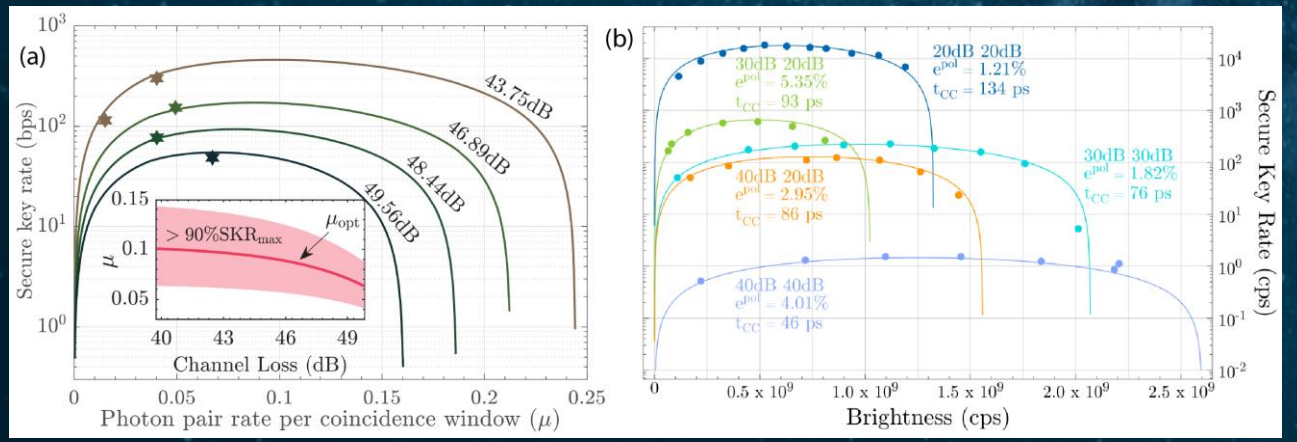
Higher brightness ≠ Higher key rate !

Accidental coincidences



Terrestrial free-space link

Lab experiment with SNSPDs



Brightness of state-of-the art photon pair sources sufficient!

Increased brightness required for:

- Lower timing jitter with SNSPDs (<10 ps)
- Multiplexed QKD

S. P. Neumann *et al.*, *Phys. Rev. A*, **104**, 2 (2021)
S. Ecker et al., *npj Quantum Information*, **7**, 5 (2021)

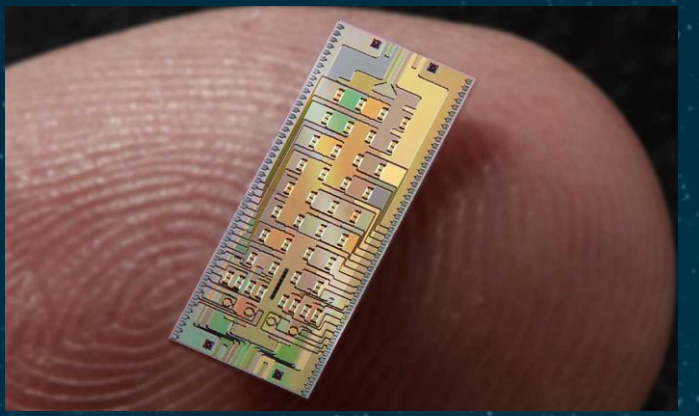
Integrated photonic entanglement sources

Photonic integrated circuits (PIC):

- Miniaturisation of table-top bulk optical setups
- Opto-electronic integration
- Primarily used in telecom, biomed and photonic quantum information processing

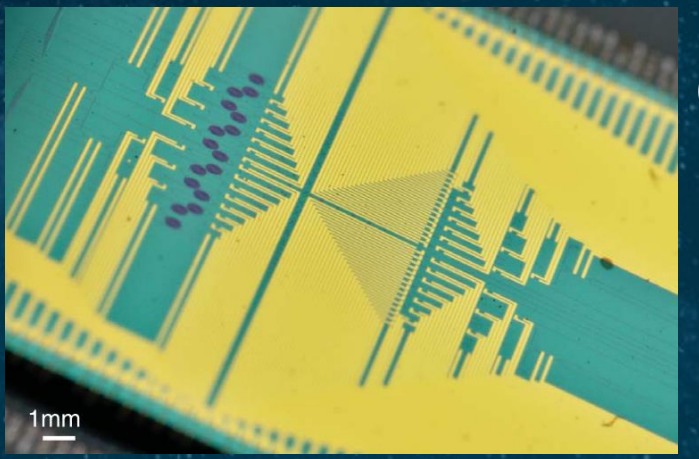
Integrated sources for space applications:

- Reduce SWaP
- Non-linearity inherent to the materials
- Robustness and phase-stability (misalignment of bulk optical setups)
- Scalability and existing fabs - costs (same as for CMOS fabrication)
- Multiple sources on a satellite (no single point of failure / parallelization)



https://www.swissphotonics.net/home?event_id=4065

PIC for telecom



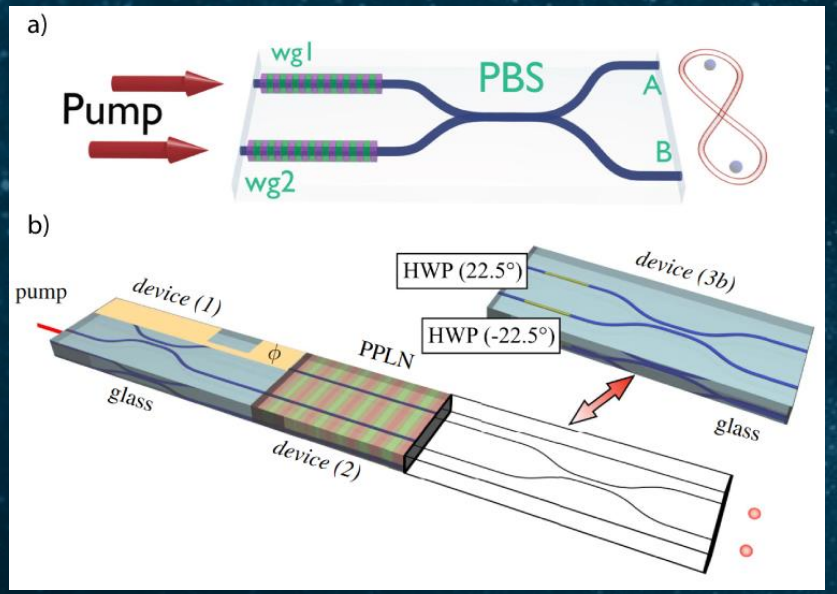
J. Wang *et al.*, *Science* **360**, 6386 (2018)

PIC for photonic quantum computing

Integrated photonic entanglement sources

Two candidate platforms meeting the requirements for QKD (brightness + integration level):

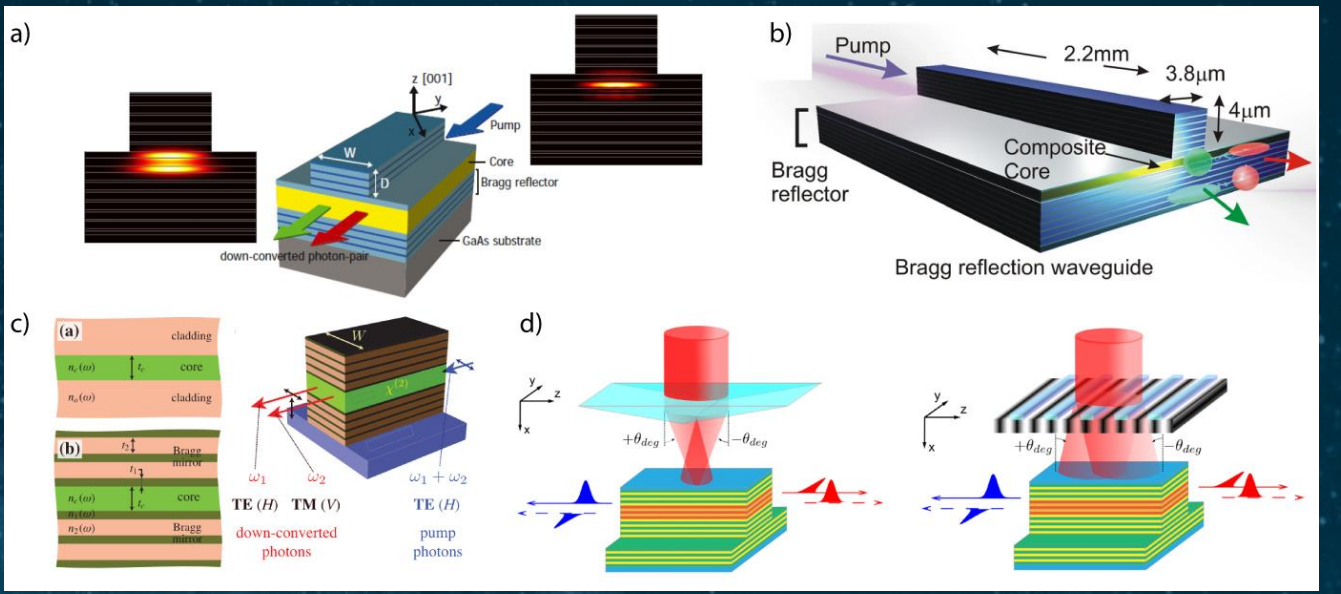
Integrated periodically-poled waveguide sources



L. Sansoni *et al.*, *npj Quantum Inf.*, **3**, 1 (2017)
S. Atzeni *et al.*, *Optica*, **5**,3 (2018)

- SPDC in a ppLN waveguide
- Hypbrid material assembly
- Brightness ~ 5e6 pairs/(s·nm·mW)
- Dimension: few cm

Monolithic III-V semiconductor sources



G. Boucher *et al.*, *Phys. Rev. A*, **89**, 3 (2014)
S. V. Zhukovsky et al., Phys. Rev. A, **85**, 1 (2012)
A.Vallés *et al.*, *Opt. Express*, **21**, 9 (2013)
R. T. Horn *et al.*, *Sci. Rep.*, **3** (2013)

- SPDC in GaAs structures
- Bragg reflection waveguides
- Brightness ~ 1e6 pairs/(s·nm·mW)
- Dimension: 1.2 mm

Integrated photonic entanglement sources

Considerations for space deployment:

- Electrical injection for full integration
- Efficient coupling into SM fibers (mode clean-up / guiding)
- Temperature-stability on 0.1° level must be guaranteed
- Packaging and assembly (launch conditions)

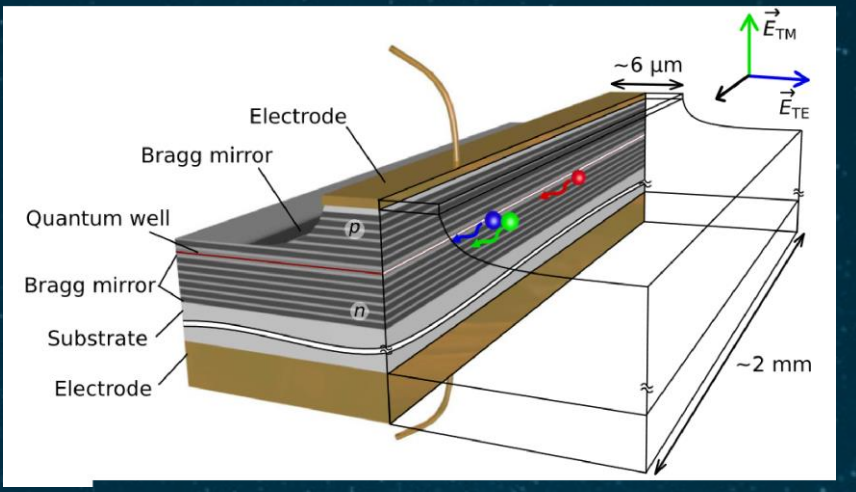
Obvious contender for replacing bulk optical components in space (except for Tx/Rx optics)

Interest in integrated optics for space applications is increasing:

- Integrated photonic source on ISS (SEAQUE) by NASA
- Photonic integrated circuits part of ESAs building missions

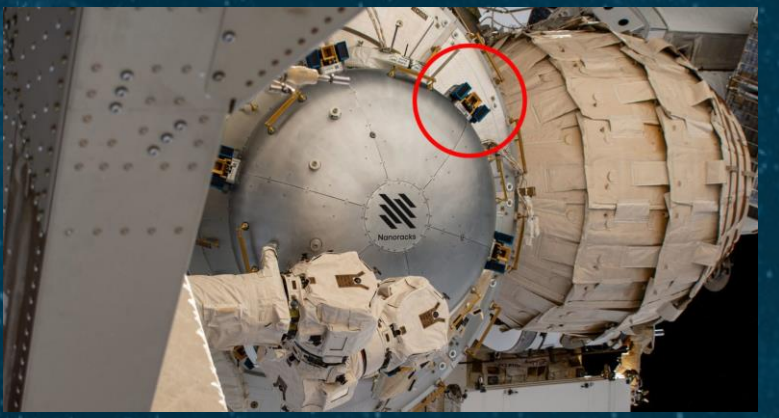
https://www.jpl.nasa.gov/news/space-station-to-host-self-healing-quantum-communications-tech-demo
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Space_Optoelectronics/Photonics

Electrically injected pair source

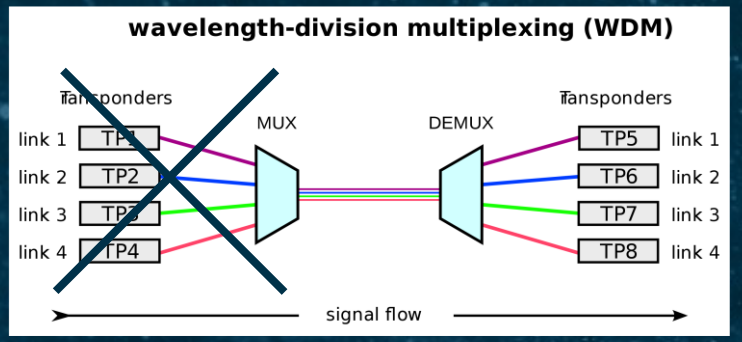


F. Boitier *et al.*, *Phys. Rev. Lett.*, 112, 18 (2014)

SEAQUE on ISS (launch 2022)



Wavelength-division multiplexing



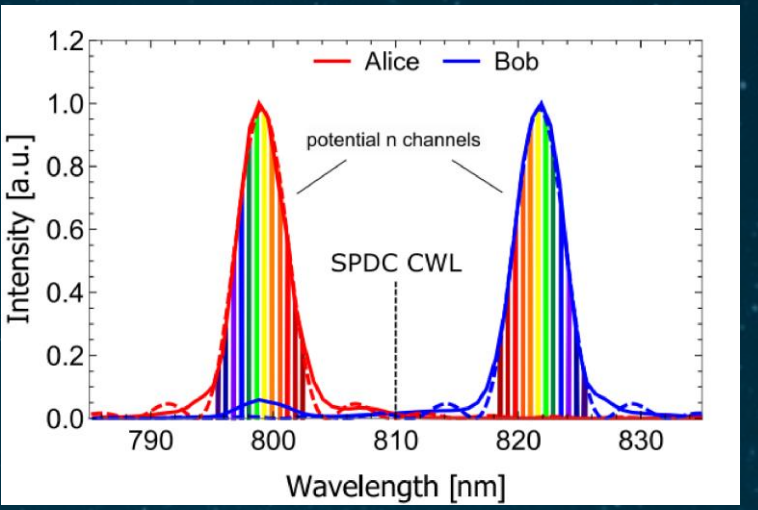
Xens, CC BY-SA 3.0 via Wikimedia Commons

Energy conservation in SPDC:

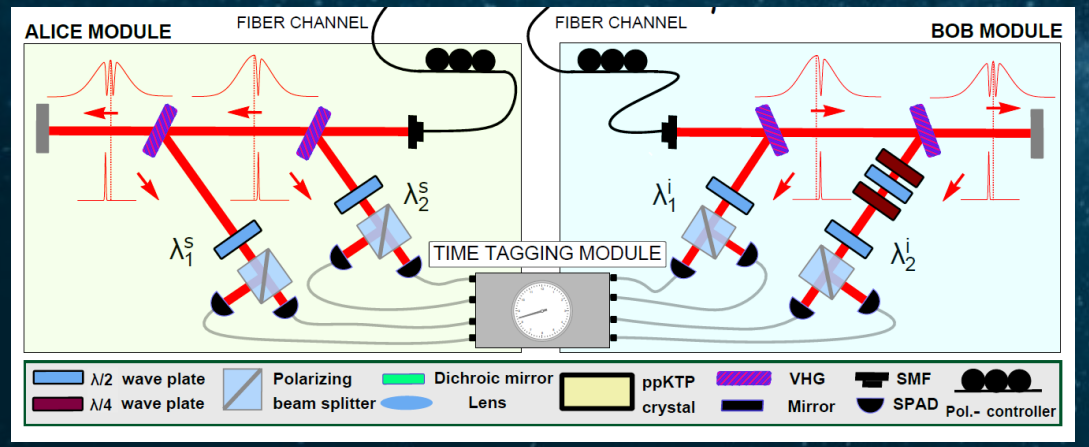
$\omega_{Alice} + \omega_{Bob} = \omega_{pump}$

Frequency correlations!

→ no active multiplexing necessary



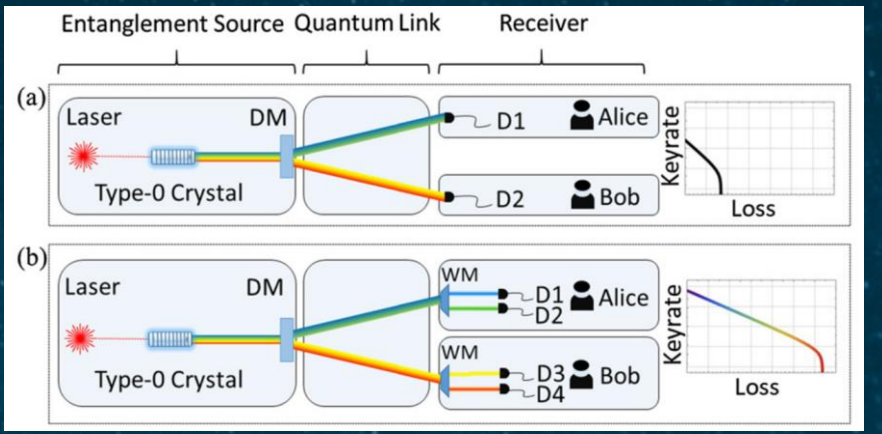
Realization with VHGs (volume holographic gratings)



J. Pseiner, L. Achatz, L. Bulla, M. Bohmann, and R. Ursin, *Quantum Sci. Technology* **6**,3 (2021)

Detection:
Frequency unresolved

Detection:
Frequency resolved

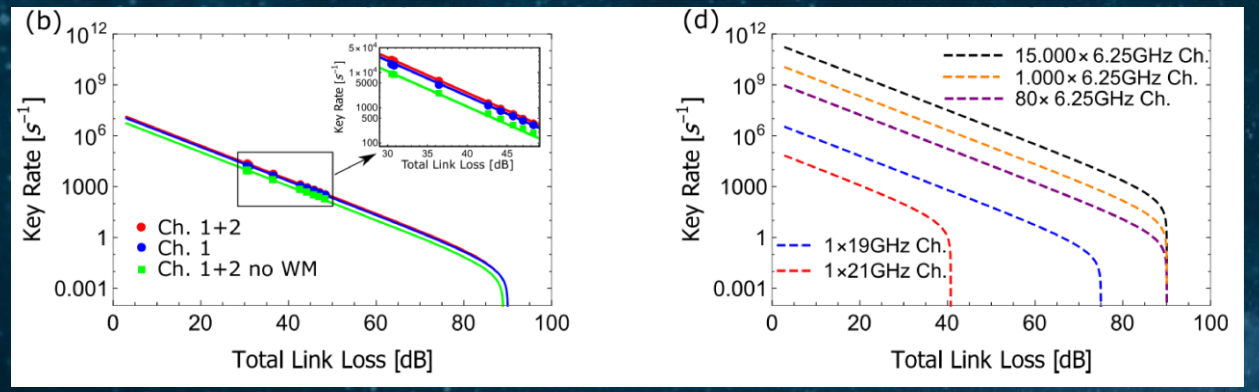


Wavelength-division multiplexing

WDM for telecom: each additional wavelength channel increases the total data rate

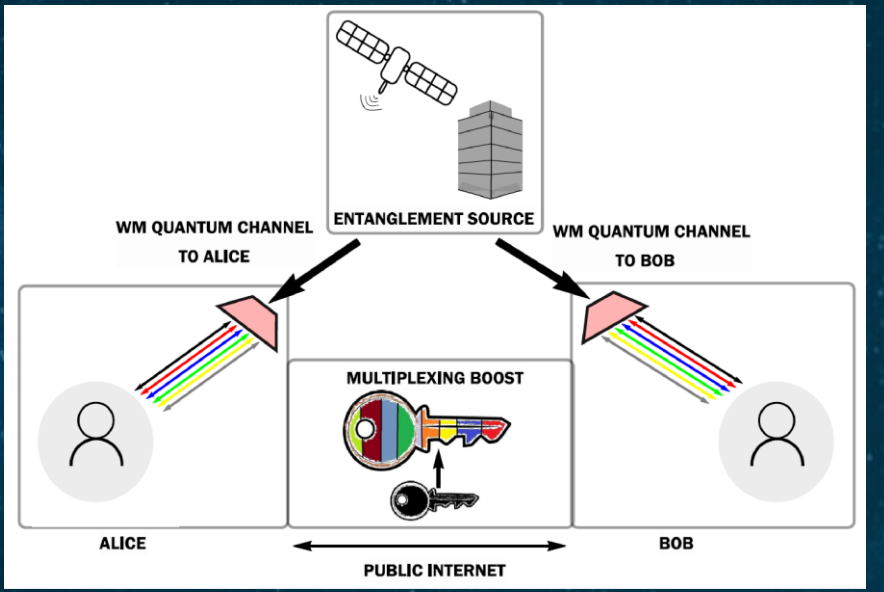
WDM for QKD: all frequencies were detected before, so where is the benefit?
rate/ freq. channel lower → less accidental coincidences
→ source brightness increased to optimum
→ ~ n-fold increase of secure key rate!
(n…number of wavelength channels)

Experimental results and scaling



J. Pseiner, L. Achatz, L. Bulla, M. Bohmann, and R. Ursin, *Quantum Sci. Technology* **6**,3 (2021)

Satellite implementation

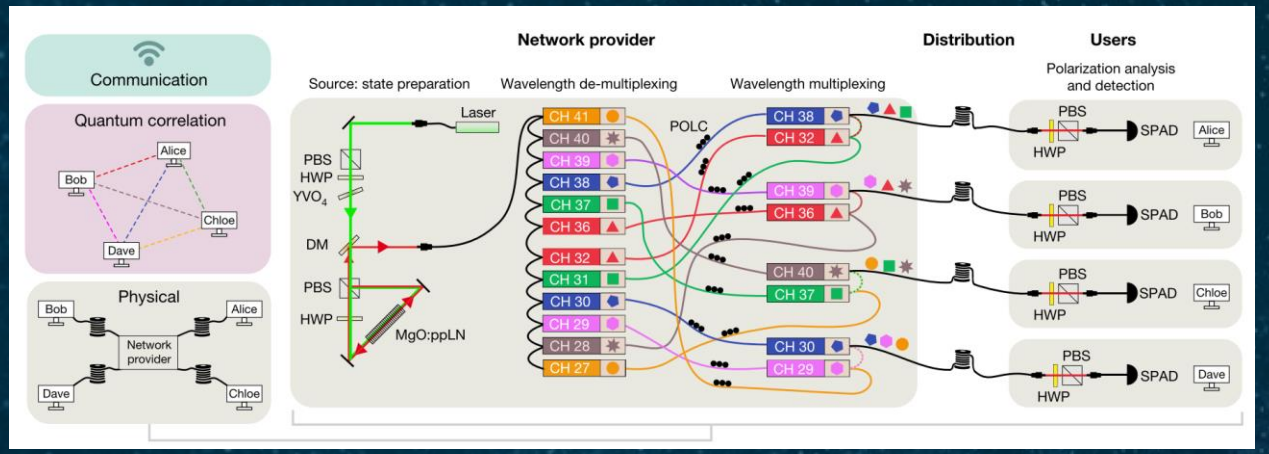


Considerations for satellite implementation:

- No increase in complexity for quantum payloads (only prerequisite: broad SPDC spectrum)
- Quantum receivers can be easily upgraded
- Angle-of-arrival fluctuations in receivers problematic

Wavelength-division multiplexing

Fully-connected 4 user-network via wavelength de-multiplexing and selective multiplexing of ITU channels

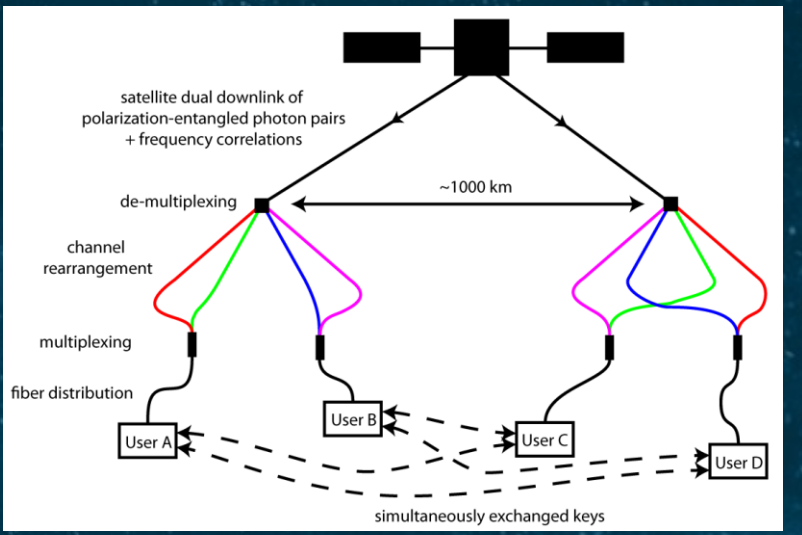


S. Wengerowsky, S. K. Joshi, F. Steinlechner, H. Hübel, and R. Ursin, **564**, 225–228 (2018)

<u>Realization for space-based scenarios:</u>

1. n-user network multiplexed on satellite (as above)
   n simultaneous downlinks – all ground receivers are fully connected

2. De-multiplexing and selective multiplexing on ground (right figure)
   all users between two remote cities are simultaneously connected



High-dimensional QKD

2-dim: $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ e.g. $\frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$

d-dim: $\frac{1}{\sqrt{d}}\sum_{i=1}^{d}|i\rangle$ e.g. $\frac{1}{\sqrt{3}}(|\omega_1\rangle + |\omega_2\rangle + |\omega_3\rangle)$

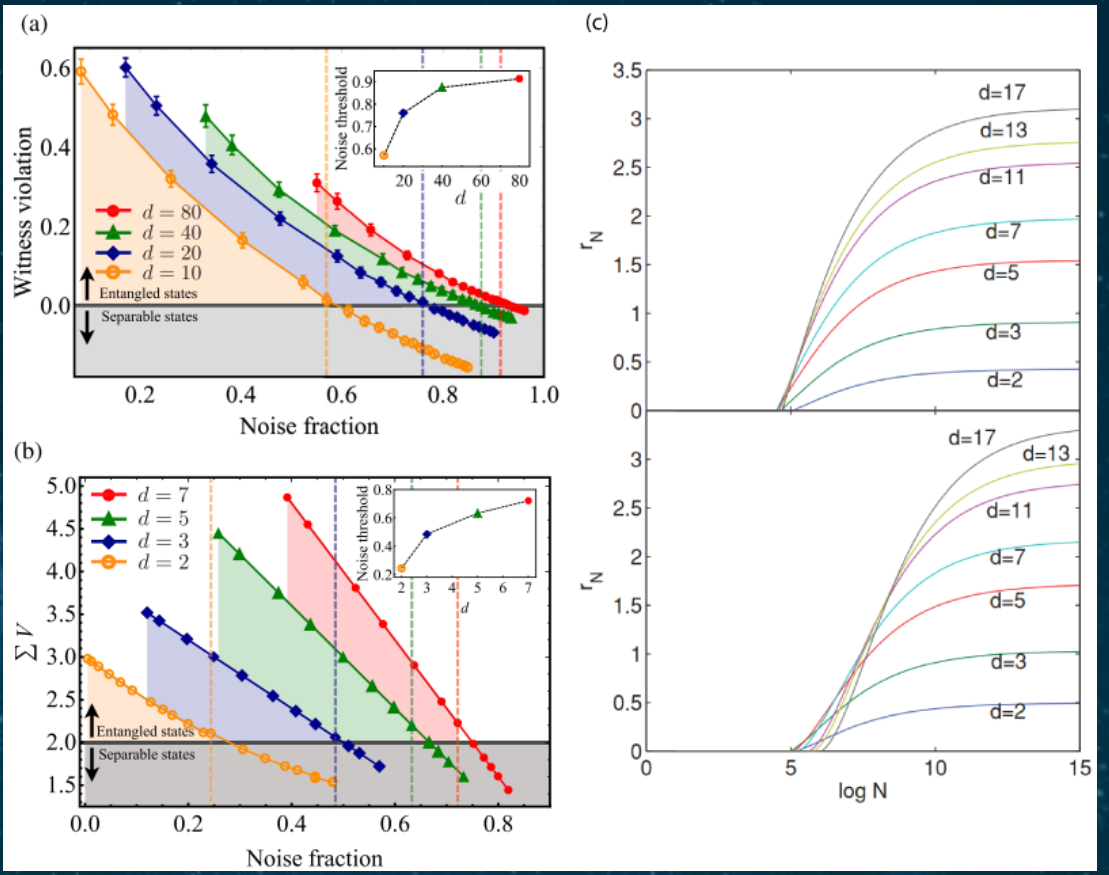
<u>High-dimensional QKD protocols offer:</u>

- **Noise resilience**: higher noise levels are tolerated (sun, light sources, detector dark counts, errors,…)
- **Increased key rate**: $\log_2(d)$ bits/photon important in photon-starved scenarios

Many different high-dim QKD protocols are known

Noise resilience

Increased key rate



S. Ecker *et al.*, *Phys. Rev. X*, **9**, 4 (2019)
L. Sheridan and V. Scarani, *Phys. Rev. A*, **82**,3 (2010)

High-dimensional QKD

High-dimensional entanglement in spatio-temporal properties comes “for free” in SPDC:

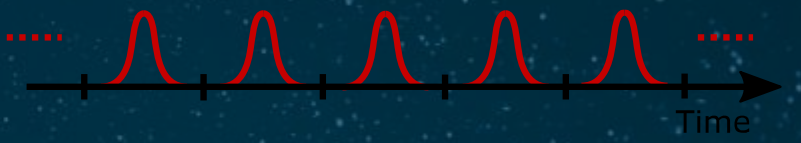
Energy conservation
→ Energy (time) entanglement

Momentum conservation
→ Momentum (spatial) entanglement

Path Entanglement

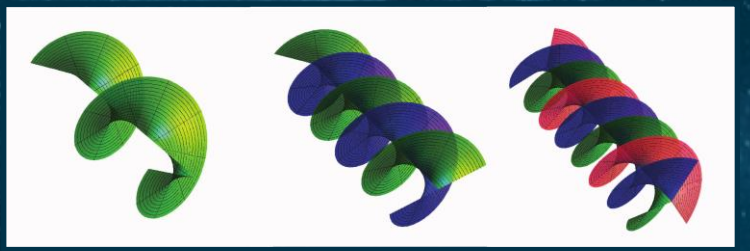
$$\sum_{n=1}^{d} c_n |a_n\rangle_A |b_n\rangle_B$$

Time-bin Entanglement



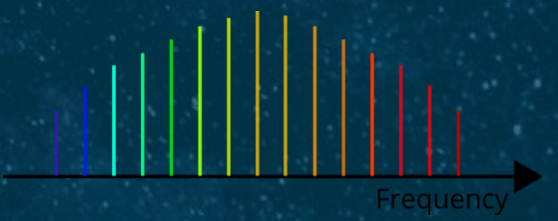
$$\sum_{n=1}^{d} c_n |t + n\Delta T\rangle_A |t + n\Delta T\rangle_B$$

Spatial mode Entanglement



$$\sum_{l=1}^{d} c_l (|l\rangle_A |-l\rangle_B + |-l\rangle_A |l\rangle_B)$$

Frequency Entanglement

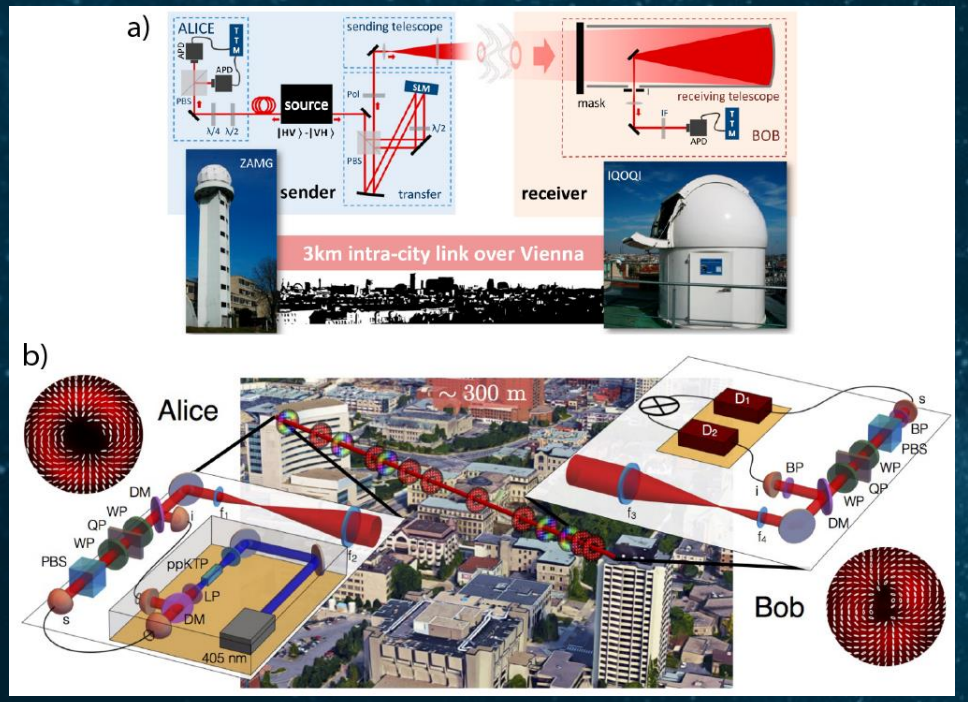


$$\sum_{n=1}^{d} c_n |\omega_0 - n\Delta\omega\rangle_A |\omega_0 + n\Delta\omega\rangle_B$$

High-dimensional QKD

Free-space transmission of spatiotemporal properties

Spatial mode (OAM) transmission

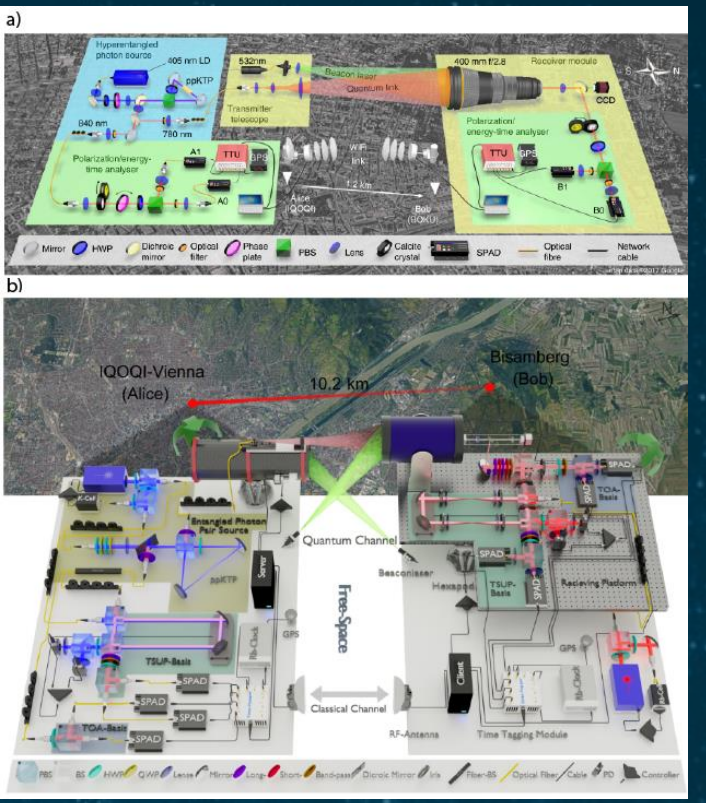


M. Krenn, et al., *Proc. Natl. Acad. Sci.*, **112**, 46 (2015)
A. Sit *et al.*, Optica **4**, 1006-1010 (2017)

Not robust
Decoherence due to atmospheric turbulence

Robust
Energy and temporal encodings can be used for satellite links

Temporal mode transmission



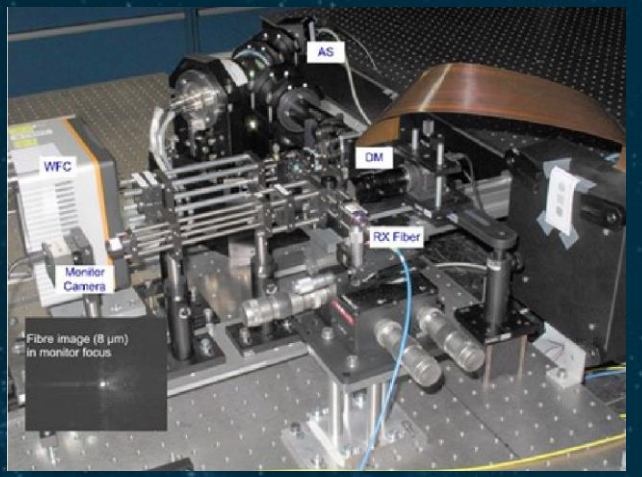
F. Steinlechner *et al.*, *Nat. Commun.*, **8**, 15971 (2017)
L. Bulla *et al.*, arXiv: 2204.07536 (2022)

Adaptive optics for quantum receivers

AO systems long history in astronomy

Increasing relevance for optical comms

→ loss mitigation + single-mode operation



E.Fischer et al., 017 IEEE International Conference on Space Optical Systems and Applications, ICSOS (2017)

https://www.eso.org

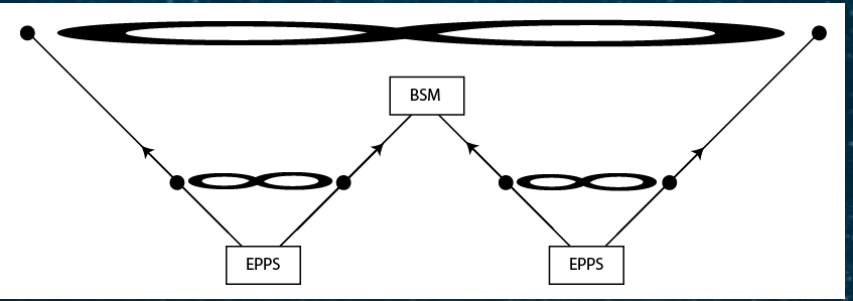
Benefits for space-based QKD:

- Loss reduction in up-or downlinks (geometrical loss)
- Multi-mode free-space beam converted into single spatial mode beam (compatibility with fiber networks)
- Avoidance of transverse spatial decoherence (for encoding in transverse spatial modes)

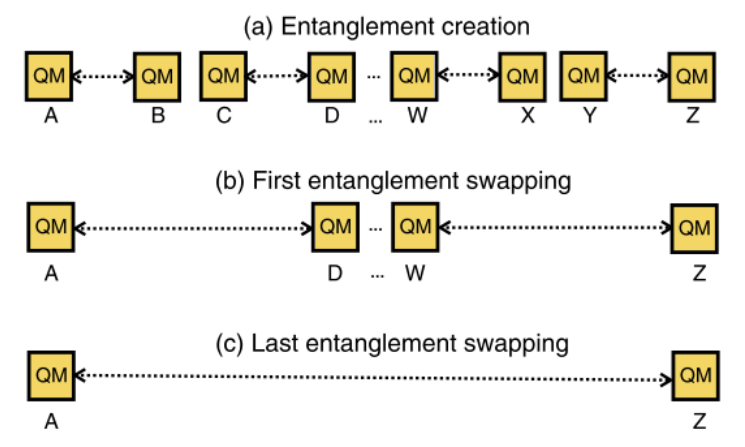
Space-based quantum repeater

Quantum repeater – only way to overcome direct transmission limit in optical fiber
(**polynomial** instead of **exponential** scaling)

Entanglement swapping



Nested entanglement swapping



H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, *Phys. Rev. Lett.*, **81**, 48 (1998)

<u>The quantum repeater scheme:</u>

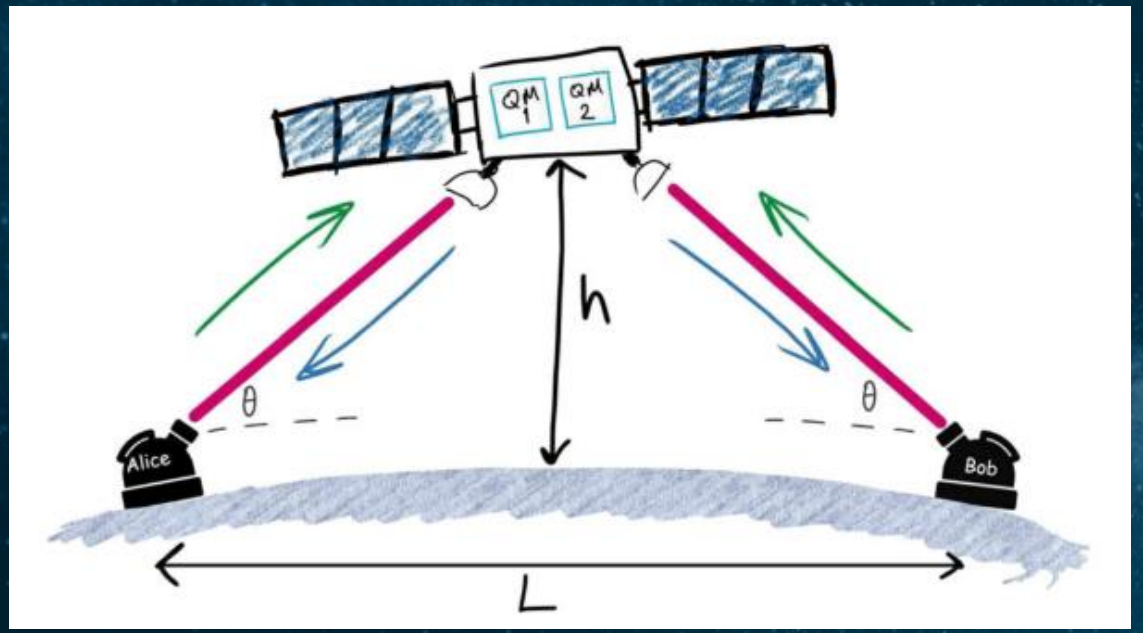
- Division of long-distance links into elementary links
- Entanglement distribution between elementary links
- Storage of photons in quantum memories (QM)
- Nested entanglement swapping through all levels

Even for most optimistic estimates, fiber-based quantum repeater limited by a few thousand km

→ Truly global quantum networks require space-based quantum repeater!

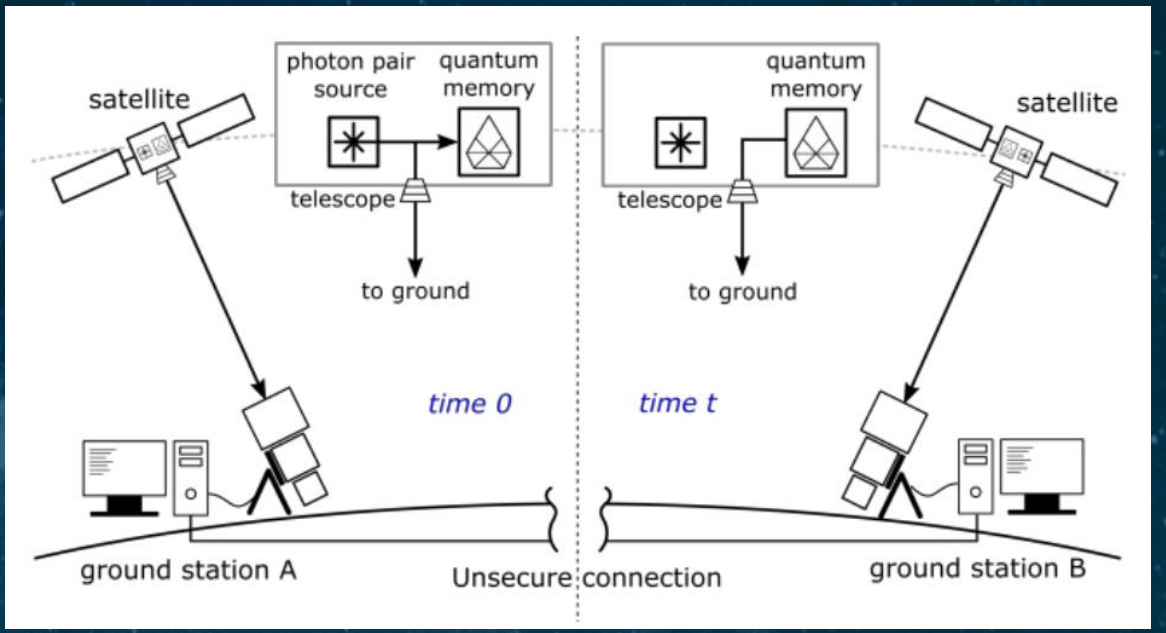
Space-based quantum repeater

Single-node quantum repeater



M. Gündoğan *et al.*, *npj Quantum Inf.*, **7**,1 (2021)

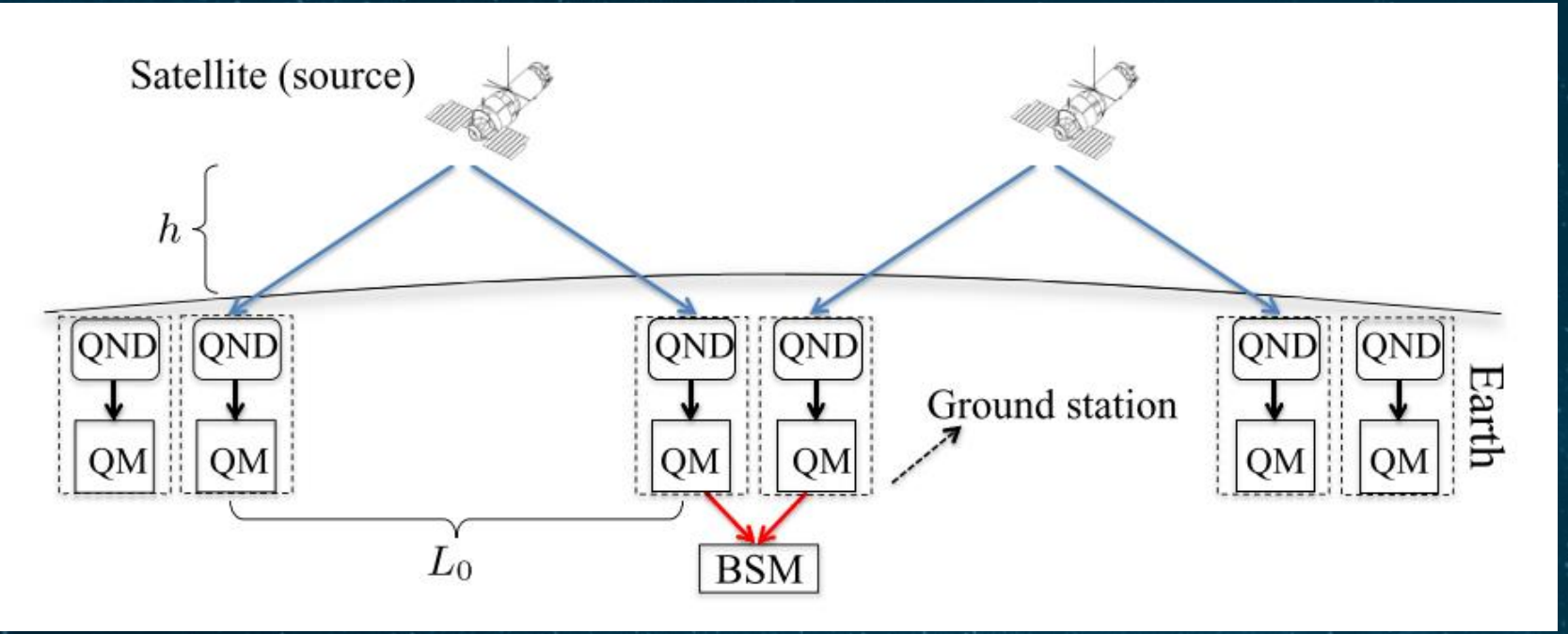
Single satellite global quantum key distribution



S. E. Wittig et al., *Proc. Int. Astronaut. Congr. IAC*, **8**, September (2017)

Space-based quantum repeater

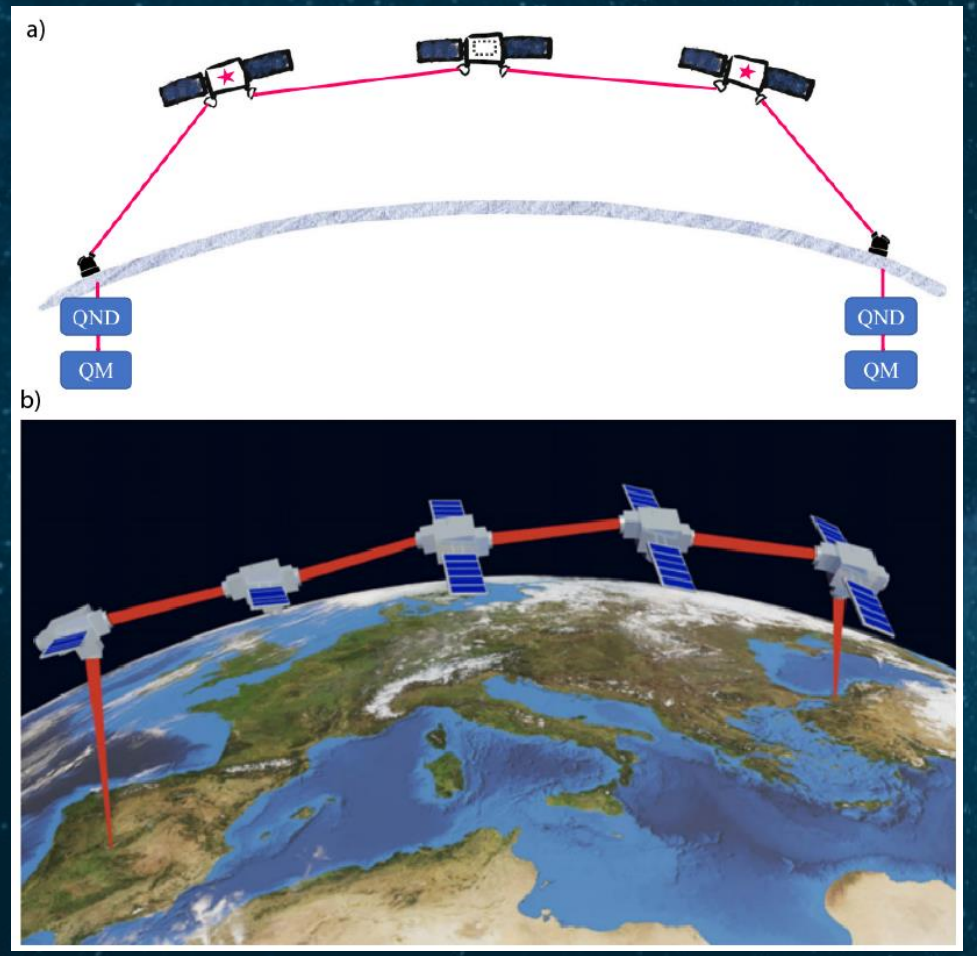
Hybrid space-based quantum repeater



K. Boone et al., *Phys. Rev. A*, **91**, 5 (2015)

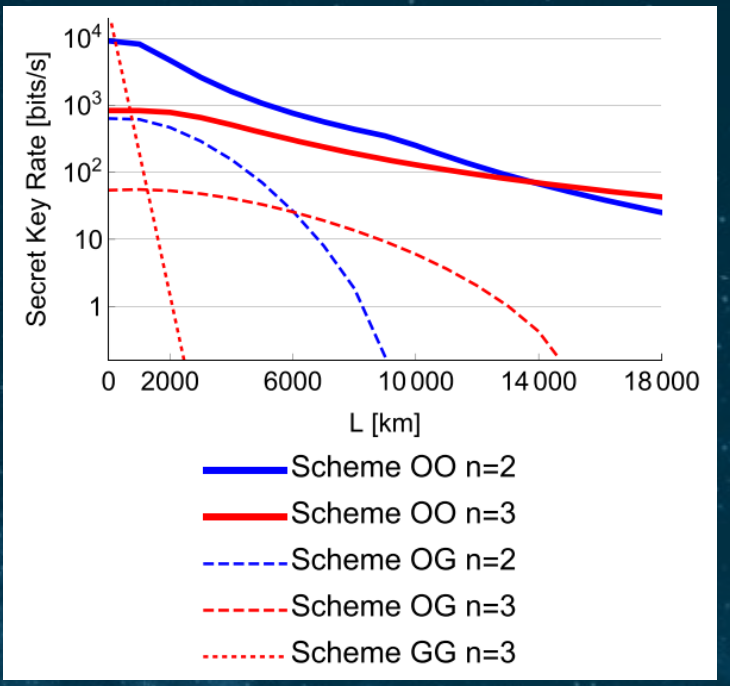
Space-based quantum repeater

Fully space-based quatum repeater



C. Liorni, H. Kampermann, and D. Bruß, *New J. Phys.*, **23**, 5 (2021)

Comparison of QR schemes



GG…ground based scheme
OG…hybrid scheme
OO…fully space-based scheme

Overview of advances and implications

High-performance entangled photon pair sources

- Increasing the secure key rate
- Only necessary for low timing jitter or multiplexing

Integrated photonic entanglement sources

- Reducing SWaP requirements
- Robustness, Scalability, Full integration

Wavelength division multiplexing

- Increasing the secure key rate substantially
- Enabling complex network topologies

High-dimensional QKD

- Increasing the secure key rate
- Resilience to noise

Adaptive optics for quantum receivers

- Increasing the secure key rate (geom. loss)
- Compatibility to fiber networks
- Wavefront distortions mitigated

Space-based quantum repeater

- Essential for global quantum communication

→ Final report

Thanks for your attention!

Questions?

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