Quantum Information:

From Tests of Quantum Foundations to New Quantum Technologies

Quantum
Physics & Quantum Information

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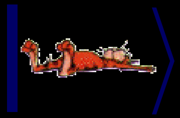
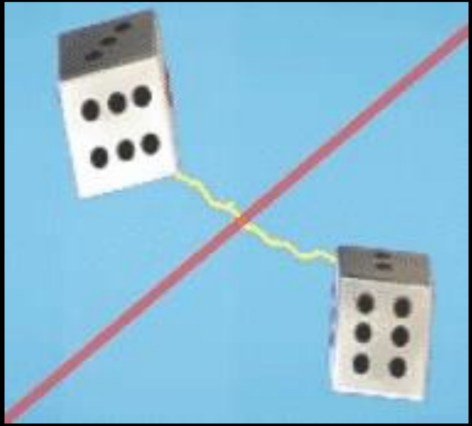
Quantum superposition and entanglement

Classical Physics: "bit"  or 

Quantum Physics: "qubit"  + 

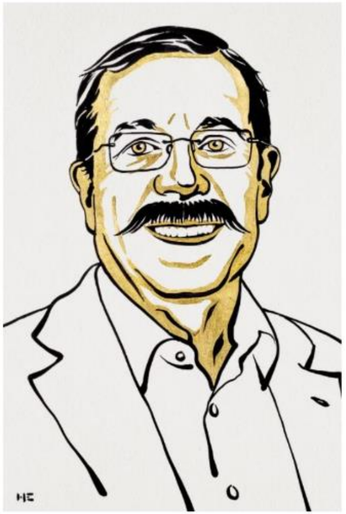
Quantum entanglement:

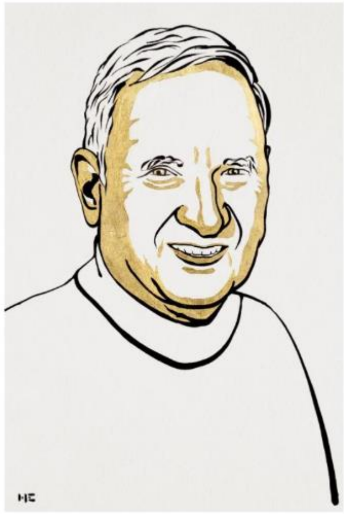
  +  

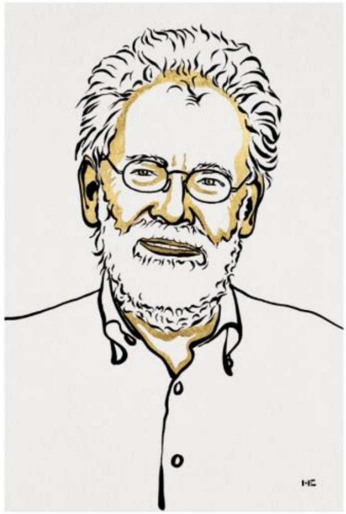


Albert Einstein: *Spooky action at a distance*

the Nobel Prize in physics 2022

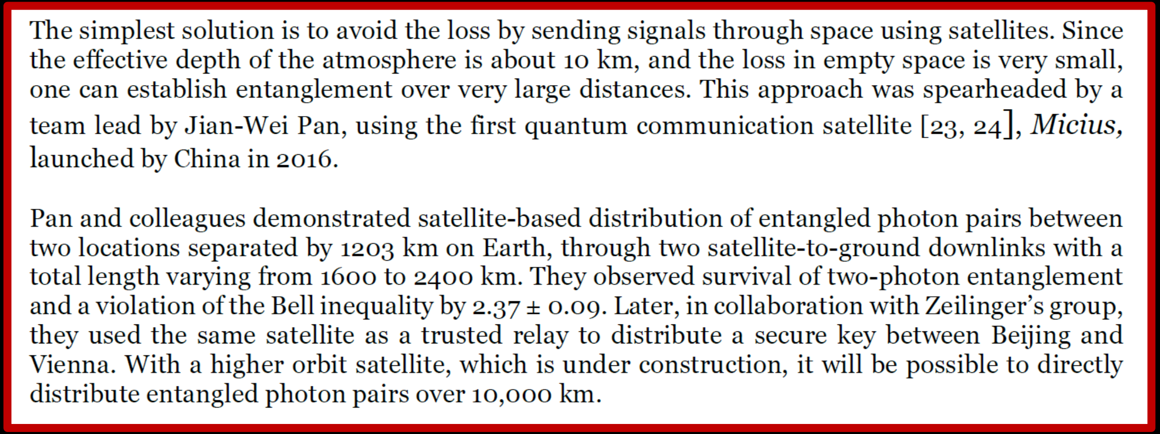

Alain Aspect


John Clauser


Anton Zeilinger

"For experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science "

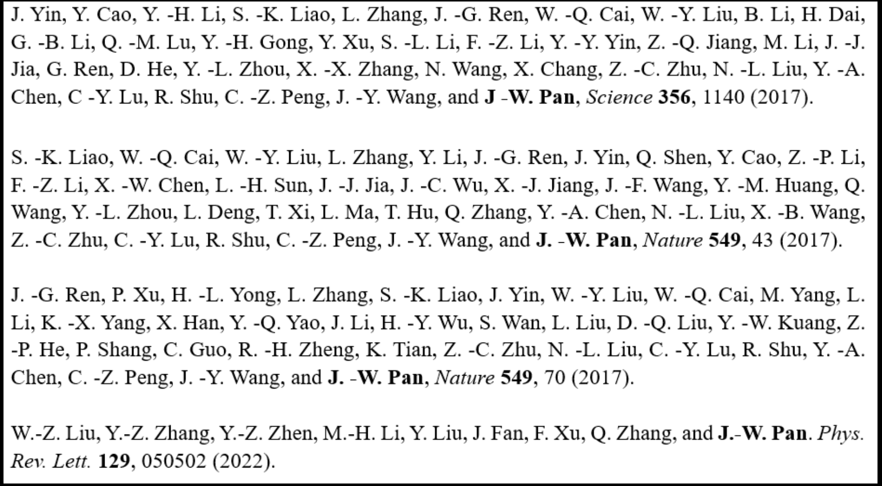
the Nobel Prize in physics 2022



The simplest solution is to avoid the loss by sending signals through space using satellites. Since the effective depth of the atmosphere is about 10 km, and the loss in empty space is very small, one can establish entanglement over very large distances. This approach was spearheaded by a team lead by Jian-Wei Pan, using the first quantum communication satellite [23, 24], *Micius*, launched by China in 2016.

Pan and colleagues demonstrated satellite-based distribution of entangled photon pairs between two locations separated by 1203 km on Earth, through two satellite-to-ground downlinks with a total length varying from 1600 to 2400 km. They observed survival of two-photon entanglement and a violation of the Bell inequality by 2.37 ± 0.09. Later, in collaboration with Zeilinger's group, they used the same satellite as a trusted relay to distribute a secure key between Beijing and Vienna. With a higher orbit satellite, which is under construction, it will be possible to directly distribute entangled photon pairs over 10,000 km.

- Satellite-based entanglement distribution
- Satellite-to-ground quantum key distribution
- Ground-to-satellite quantum teleportation
- Demonstration of device-independent quantum key distribution



J. Yin, Y. Cao, Y. -H. Li, S. -K. Liao, L. Zhang, J. -G. Ren, W. -Q. Cai, W. -Y. Liu, B. Li, H. Dai, G. -B. Li, Q. -M. Lu, Y. -H. Gong, Y. Xu, S. -L. Li, F. -Z. Li, Y. -Y. Yin, Z. -Q. Jiang, M. Li, J. -J. Jia, G. Ren, D. He, Y. -L. Zhou, X. -X. Zhang, N. Wang, X. Chang, Z. -C. Zhu, N. -L. Liu, Y. -A. Chen, C -Y. Lu, R. Shu, C. -Z. Peng, J. -Y. Wang, and **J -W. Pan**, *Science* **356**, 1140 (2017).

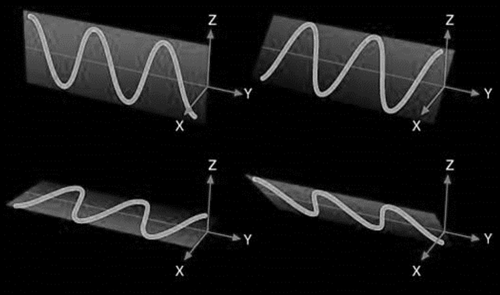
S. -K. Liao, W. -Q. Cai, W. -Y. Liu, L. Zhang, Y. Li, J. -G. Ren, J. Yin, Q. Shen, Y. Cao, Z. -P. Li, F. -Z. Li, X. -W. Chen, L. -H. Sun, J. -J. Jia, J. -C. Wu, X. -J. Jiang, J. -F. Wang, Y. -M. Huang, Q. Wang, Y. -L. Zhou, L. Deng, T. Xi, L. Ma, T. Hu, Q. Zhang, Y. -A. Chen, N. -L. Liu, X. -B. Wang, Z. -C. Zhu, C. -Y. Lu, R. Shu, C. -Z. Peng, J. -Y. Wang, and **J. -W. Pan**, *Nature* **549**, 43 (2017).

J. -G. Ren, P. Xu, H. -L. Yong, L. Zhang, S. -K. Liao, J. Yin, W. -Y. Liu, W. -Q. Cai, M. Yang, L. Li, K. -X. Yang, X. Han, Y. -Q. Yao, J. Li, H. -Y. Wu, S. Wan, L. Liu, D. -Q. Liu, Y. -W. Kuang, Z. -P. He, P. Shang, C. Guo, R. -H. Zheng, K. Tian, Z. -C. Zhu, N. -L. Liu, C. -Y. Lu, R. Shu, Y. -A. Chen, C. -Z. Peng, J. -Y. Wang, and **J. -W. Pan**, *Nature* **549**, 70 (2017).

W.-Z. Liu, Y.-Z. Zhang, Y.-Z. Zhen, M.-H. Li, Y. Liu, J. Fan, F. Xu, Q. Zhang, and **J.-W. Pan**. *Phys. Rev. Lett.* **129**, 050502 (2022).

Quantum Superposition & Quantum Entanglement

One bit of information per photon (encoded in polarization)



↔ ↕

$|H\rangle = |0\rangle$ $|V\rangle = |1\rangle$

Qubit: $|\psi\rangle = \alpha|H\rangle + \beta|V\rangle, |\alpha|^2 + |\beta|^2 = 1$

Bell states – maximally entangled states:

$$|\Phi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2)$$

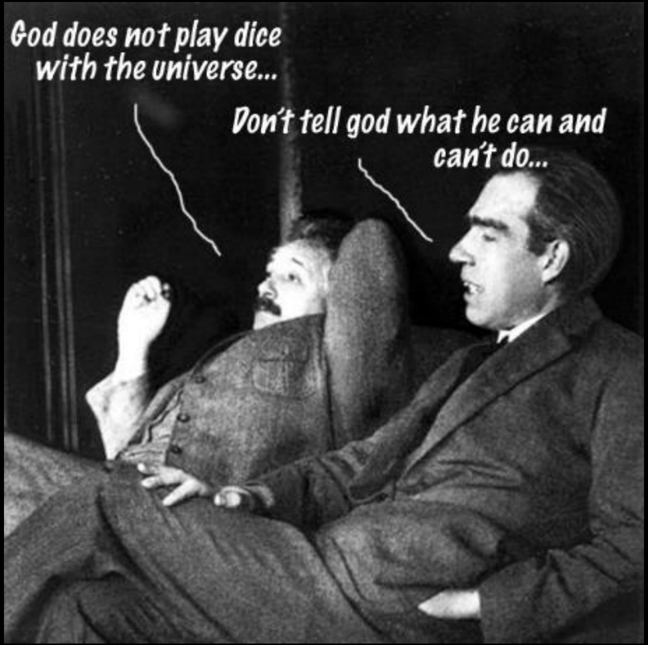
$$|\Psi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2)$$

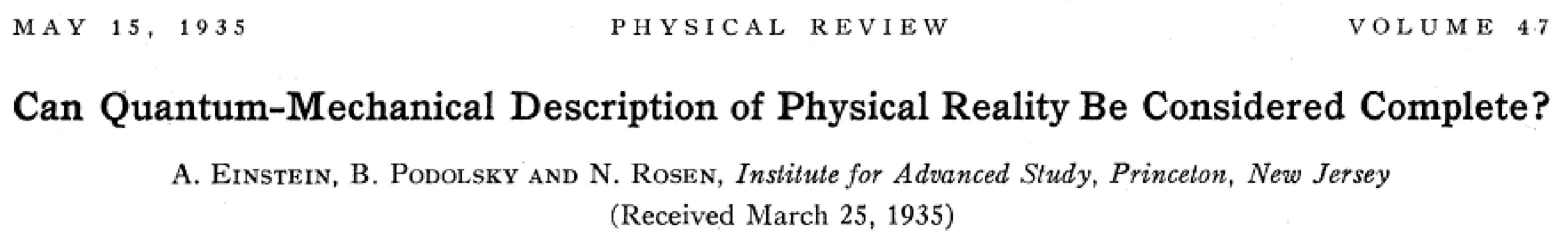
Quantum mechanical prediction

Quantum mechanics predicts:

- Initially, the individual states of two entangled particles are not identified
- The measurement outcome on particle A will not only determine its state, but also the state of particle B immediately!

Quantum nonlocality




MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

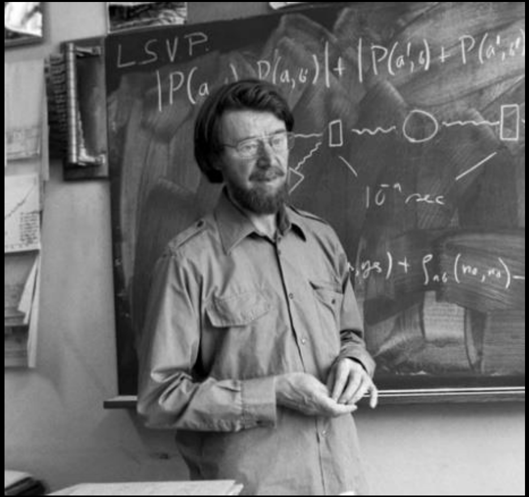
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

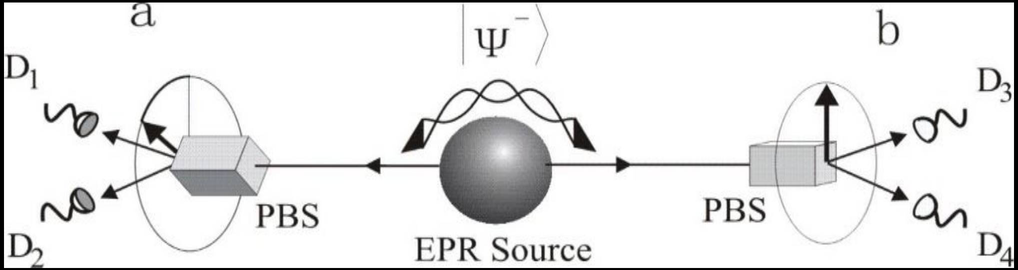
A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

Bell's inequality: testing the battle

Experimental testable inequality: Bell, Physics 1, 195 (1964)





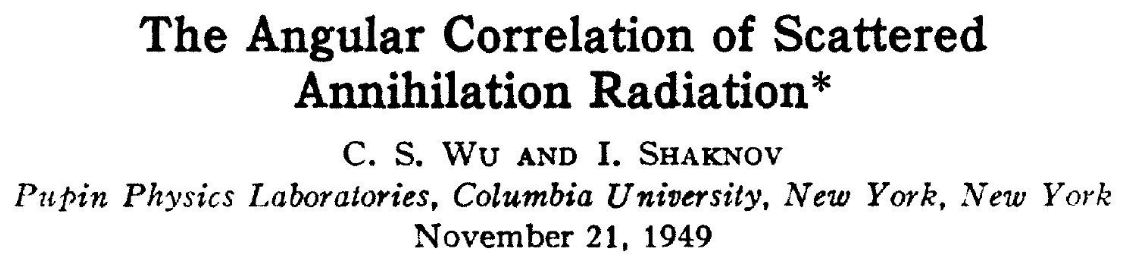
$$S = |E(\phi_A\phi_A) - E(\phi_A\phi'_B) + E(\phi'_A\phi_B) + E(\phi'_A\phi'_B)|$$

- Einstein's local realism: $S_{\max} \leq 2$
- Quantum mechanics: $S_{\max} = 2\sqrt{2}$

First observation of quantum entanglement

Chien-Shiung Wu

As pointed out by D. Bohm and Y. Aharonov [Phys. Rev. 108, 1070 (1957)]



The Angular Correlation of Scattered Annihilation Radiation*

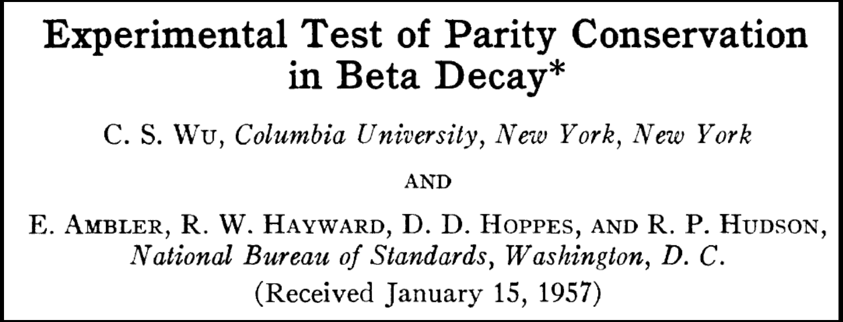
C. S. Wu and I. Shaknov

Pupin Physics Laboratories, Columbia University, New York, New York

November 21, 1949

Phys. Rev. 77, 136 (1950)

Verification of parity nonconservation predicted by Tsung-Dao Lee and Chen-Ning Yang (the Nobel Prize in Physics 1957)



Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

and

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,

National Bureau of Standards, Washington, D. C.

(Received January 15, 1957)

Bell's inequality: testing the battle

- Freedman & Clauser, PRL 28, 938 (1972)

First Bell experiment, two measurement sites are not space-like separated

- Aspect *et al.*, PRL 49, 1804 (1982)

Fast switch controlled by pre-set quasiperiodic signals

- Weihs *et al.*, PRL 81, 5039 (1998)

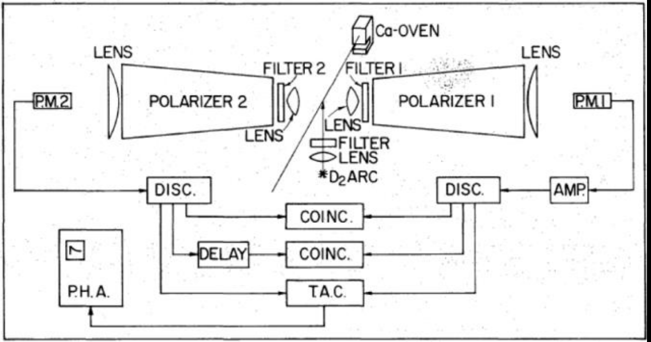
Fast switch controlled by random number generator, closed locality loophole

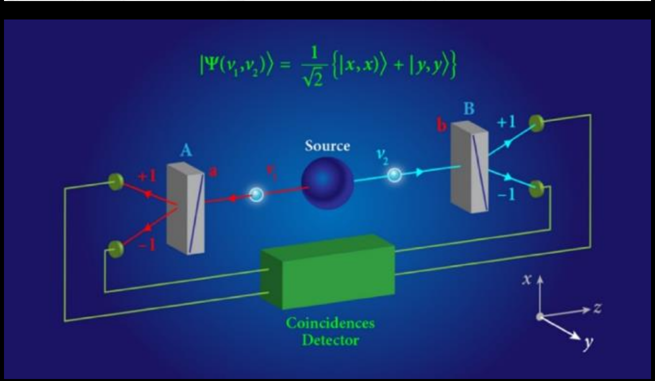
- Rowe *et al.*, Nature 409, 791 (2001)

Closed detection loophole

- Hensen *et al.*, Nature 526, 682 (2015)
- Giustina *et al.*, PRL 115, 250401 (2015)
- Shalm *et al.*, PRL 115, 250402 (2015)

Closed both detection and locality loopholes





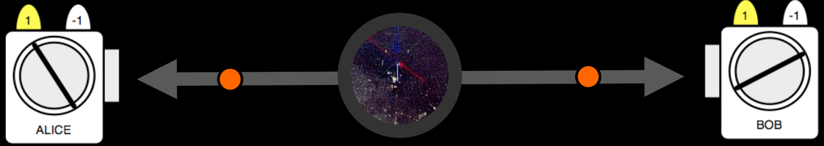
Quantum mechanics is right! But still with loopholes, such as freedom of choice loophole and collapse locality loophole, that need to be addressed further.

Violation of Bell inequality and intrinsic randomness

Violation of Bell inequality

God plays dices (intrinsic randomness) !

Immediately application: device-independent quantum random-number generation, true random number via violation of Bell inequality even with suspect devices!



- Bierhorst *et al.*, Nature 556, 223 (2018) by NIST
  Secure against classical adversary
- Liu *et al.*, Nature 562, 548 (2018) by USTC
  Secure against classical and quantum adversary

DI-QRG could find various applications in:

Numerical modelling

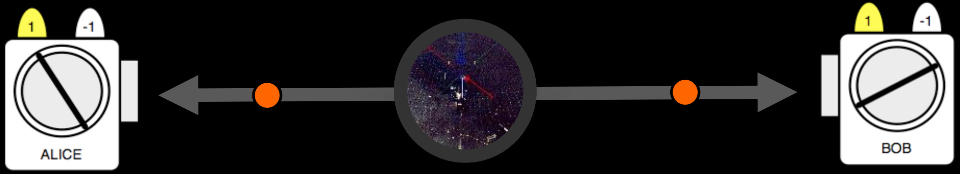
Artificial intelligence

Cryptography

……

Violation of Bell inequality and intrinsic randomness

Entanglement-assisted secure communication
Ekert, PRL 67, 661 (1991)



- Using perfect correlation of entanglement to share secret key between Alice and Bob
- Detecting eavesdropping and ensuring security of key by violation of Bell inequality
  - Without eavesdropping: entanglement will not be disturbed, $S_{\max} = 2\sqrt{2}$
  - With eavesdropping: unauthorized measurements leave states of photons identified, $S \leq 2$

- Demonstrations of device-independent quantum key distribution certified by Bell's theorem
  - Liu *et al.*, PRL 129, 050502 (2022) by USTC
  - Nadlinger *et al.*, Nature 607, 682 (2022) by Oxford
  - Zhang *et al.*, Nature 607, 687 (2022) by MPQ

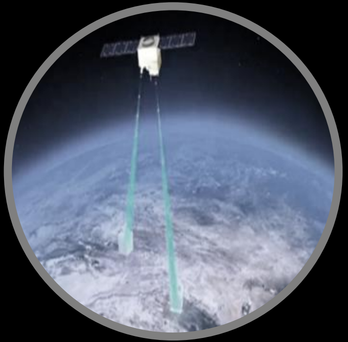
From quantum foundations to emerging quantum technologies

Test of quantum nonlocality

Coherent manipulation of quantum systems

Enabling encode and process information in quantum states, outperform classical information systems in terms of

Unconditional security

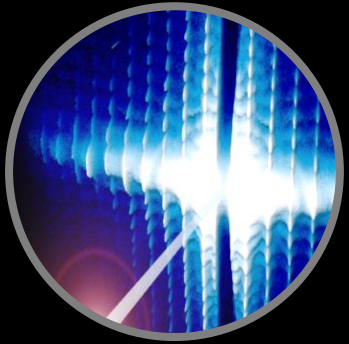


Quantum communication

Computational capacities

Quantum computation and simulation

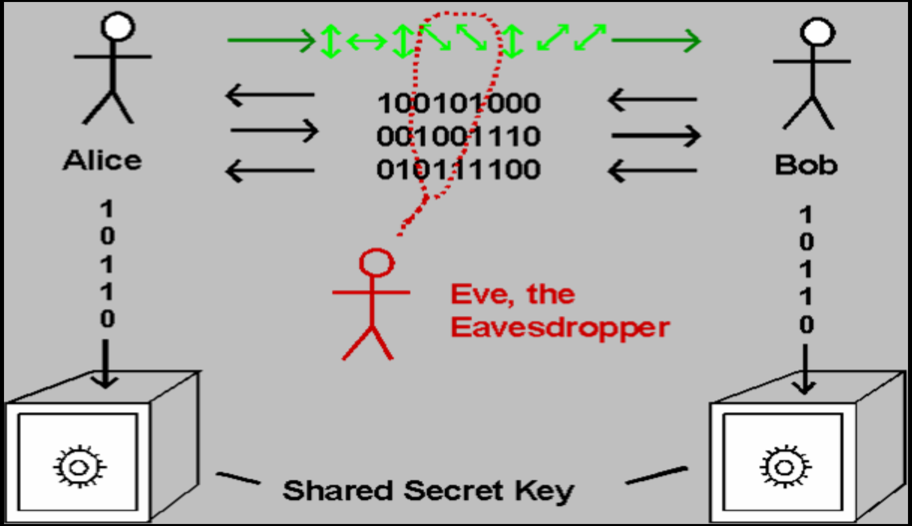
Super-resolution



Quantum metrology

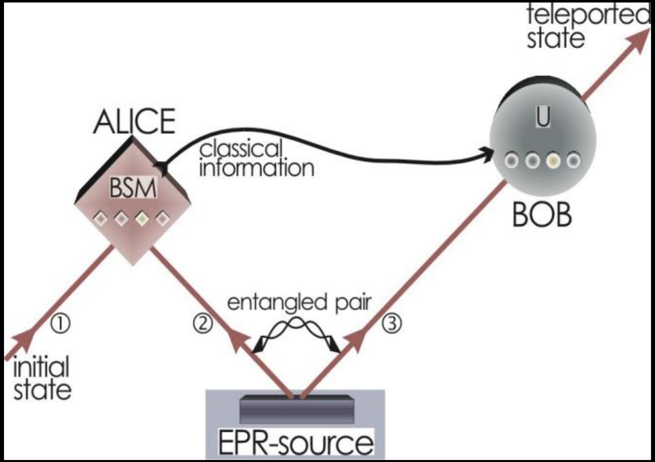
Quantum Key Distribution

- **Single Photon Scheme:**
  [Bennett & Brassard, BB84 protocol (1984)]



- **Entanglement-based QKD:** [Ekert, PRL 67, 661 (1991)]

Quantum Teleportation



Initial state

$$|\Phi\rangle_1 = \alpha|0\rangle_1 + \beta|1\rangle_1$$

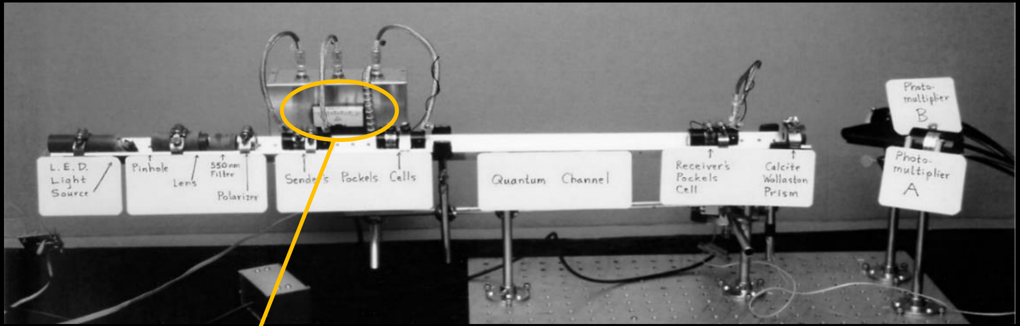
The shared entangled pair

$$|\Phi^+\rangle_{23}$$

$$\begin{aligned}|\Psi\rangle_{123} = {} & |\Phi^+\rangle_{12}\otimes(\alpha|0\rangle_3 + \beta|1\rangle_3) + \\ & |\Phi^-\rangle_{12}\otimes(\alpha|0\rangle_3 - \beta|1\rangle_3) + \\ & |\Psi^+\rangle_{12}\otimes(\alpha|1\rangle_3 + \beta|0\rangle_3) + \\ & |\Psi^-\rangle_{12}\otimes(\alpha|1\rangle_3 - \beta|0\rangle_3)\end{aligned}$$

Essential ingredient for distributed quantum network

Proof of Concept Demostrations of QKD



Proof-of-principle demonstration

Bennett *et al.*, J. Cryptol. 5, 3 (1992

☒ Very short distance: 32cm

☒ Security loopholes due to imperfection of realistic devices


Randomly choosing 0 or 1 ← Different voltages → Different **NOISE**

> "The experiment is unconditionally secure, unless you are a deaf"
>
> --Gilles Brassard

Challenges for Large-scale Secure Quantum Communication

Security ?

Long distance ?

Applications ?

- ☒ Absorption ➡ photon loss
- ☒ Decoherence ➡ degrading entanglement quality
- ☒ Probabilistic entangled photons and single photon source ➡ exponential resource cost

For 1000 km commercial fiber, even with a perfect 10 GHz single-photon source and ideal detectors, only 0.3 photon can be transmitted on average per century!

Quantum attacking with Realistic Devices

Attack	Source/Detection	Target component	Manner	Year
Photon-number-splitting (Brassard et al., 2000; Lütkenhaus, 2000)	Source	WCP (multi-photons)	Theory	2000
Detector fluorescence (Kurtsiefer et al., 2001)	Detection	Detector	Theory	2001
Faked-state (Makarov et al., 2006; Makarov and Hjelme, 2005)	Detection	Detector	Theory	2005
Trojan horse (Gisin et al., 2006; Vakhitov et al., 2001)	Source&Detection	Backflection light	Theory	2006
Time shift (Qi et al., 2007; Zhao et al., 2008)	Detection	Detector	Experiment	2007
Time side-channel (Lamas-Linares and Kurtsiefer, 2007)	Detection	Timing information	Experiment	2007
Phase remapping (Fung et al., 2007; Xu et al., 2010)	Source	Phase modulator	Experiment	2010
Detector blinding (Lydersen et al., 2010b; Makarov, 2009)	Detection	Detector	Experiment	2010
Detector blinding (Gerhardt et al., 2011a,b)	Detection	Detector	Experiment	2011
Detector blinding (Lydersen et al., 2011; Wiechers et al., 2011)	Detection	Detector	Experiments	2011
Faraday mirror (Sun et al., 2011)	Source	Faraday mirror	Theory	2011
Wavelength (Huang et al., 2013; Li et al., 2011)	Detection	Beam-splitter	Experiment	2011
Dead-time (Henning et al., 2011)	Detection	Detector	Experiment	2011
Channel calibration (Jain et al., 2011)	Detection	Detector	Experiment	2011
Intensity (Jiang et al., 2012; Sajeed et al., 2015b)	Source	Intensity modulator	Experiment	2012
Phase information (Sun et al., 2012, 2015; Tang et al., 2013)	Source	Phase randomization	Experiment	2012
Memory attacks (Barrett et al., 2013)	Detection	Classical memory	Theory	2013
Local oscillator (Jouguet et al., 2013; Ma et al., 2013)	Detection	Local oscillator	Experiment	2013
Trojan horse (Jain et al., 2014, 2015)	Source&Detection	Backflection light	Experiment	2014
Laser damage (Bugge et al., 2014; Makarov et al., 2016)	Detection	Detector	Experiment	2014
Detector saturation (Qin et al., 2016)	Detection	Homodyne detector	Experiment	2016
Pattern effect (Yoshino et al., 2018)	Source	Intensity modulator	Experiment	2018

F. Xu, X. Ma, Q. Zhang, H.-K. Lo, J.-W. Pan, Rev. Mod. Phys. 92, 025002 (2020)

Security of QKD with Realistic Devices

MDI-QKD

+

DIY light source (Do It Yourself)

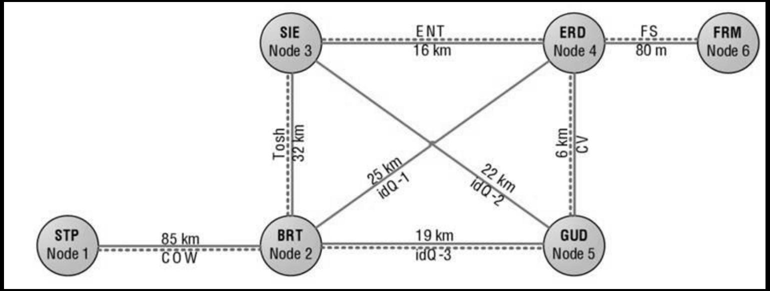
Information-theoretically secure QKD with realistic devices can be approached properly!

> In MDI-QKD……They need only trust themselves not to have inadvertently created a side channel to Eve through incompetent design of their do-it-yourself light sources
>
> -- Charles Bennett

Practical Metropolitan QKD Networks

First all-pass network (Hefei, China)

Chen *et al.*, Optics Express 17, 6540 (2009)



SECOQC Network (Europe)

Peev *et al.*, New J. Phys. 11, 075001 (2009)

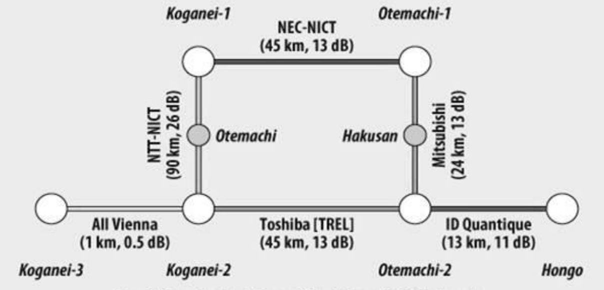
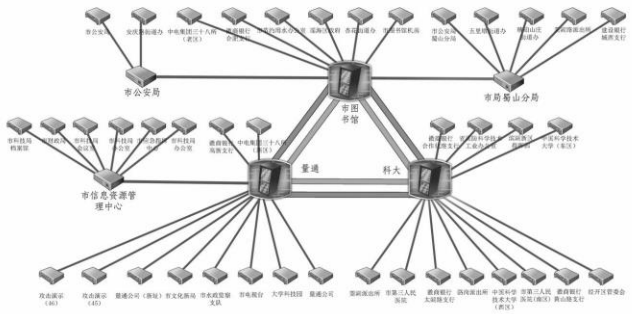


Fig. 3 Topological Map of the Tokyo QKD Network

Tokyo QKD Network (Japan)

M. Sasaki *et al.*, Opt. Express 19, 10387 (2011)

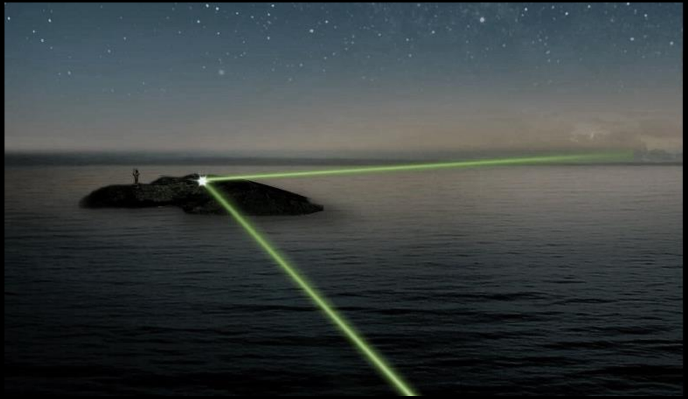


First scaled metropolitan network

Hefei intra-city QKD network (46 nodes, 2012)

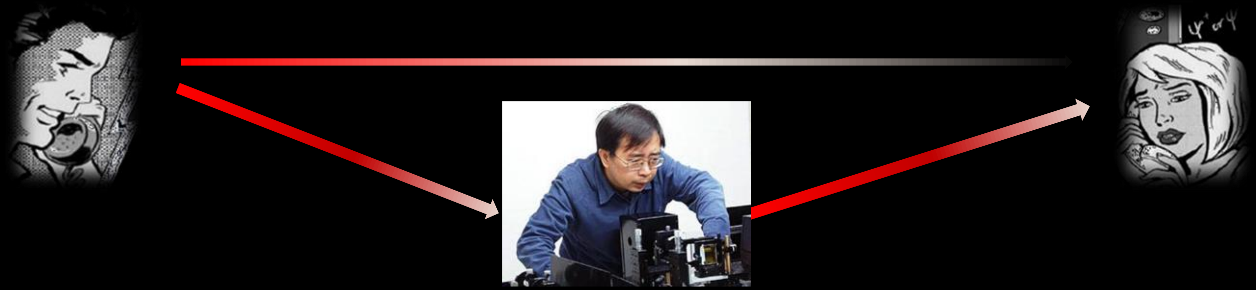
Challenge towards Scalable Quantum Communications

- Longest distance of point-to-point in fiber: ~500km (1000km with TF recently)
  - Yin *et al.*, PRL 117, 190501 (2016) MDI-QKD;
  - Boaron et al., Phys. Rev. Lett. 121, 190502 (2018) Decoy
- Longest distance of quantum teleportation in terrestrial free space: ~100km
  - *Yin et al., Nature 488, 185 (2012) by Chinese group*
  - *Ma et al., Nature 489, 269 (2012) by Austrian group*



How to extend the quantum communication distance further?

Long-term Solution: Quantum Repeater



Long-term Solution: Quantum Repeater

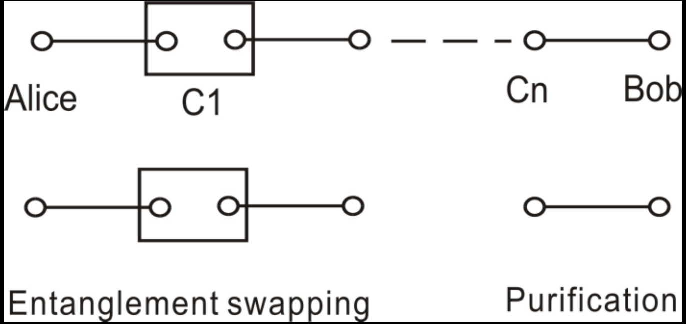
Solution to photon loss: Entanglement swapping

Zukowski *et al.*, PRL 71, 4287 (1993)

Solution to decoherence: Entanglement purification

Bennett *et al.*, PRL 76, 722 (1996)

Deutsch *et al.*, PRL 77, 2818 (1996)



Requirement:

- Entanglement swapping with high precision
- Entanglement purification with high precision
- Quantum memory with high performance

Briegel *et al.*, PRL 81, 5932 (1998)

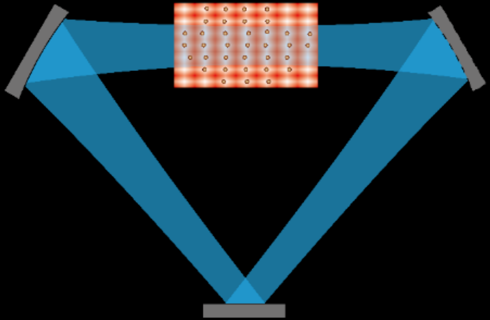
Duan *et al.*, Nature 414, 413 (2001)

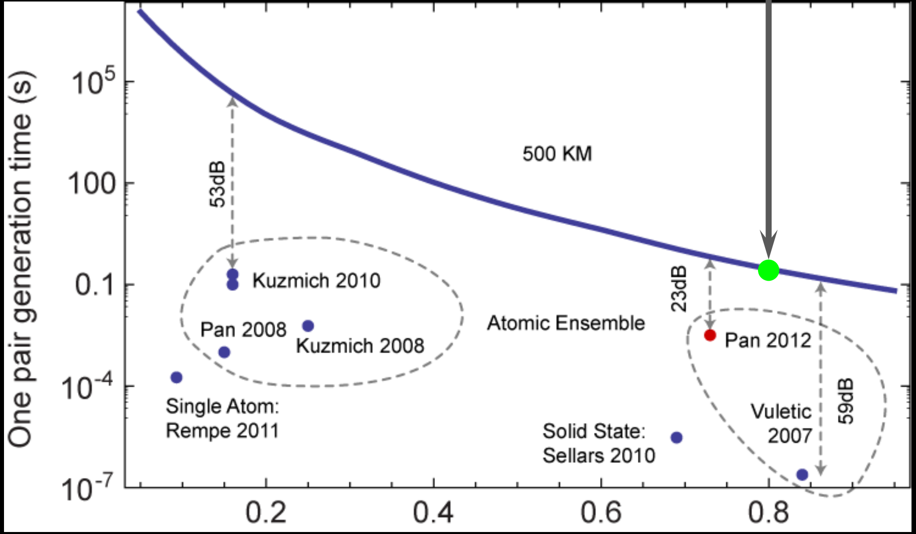
Practically Still Challenging

With ring cavity + optical lattice confinement:

Life time 220ms, retrieve efficiency 76%

Yang *et al.*, Nature Photonics 10, 381 (2016)





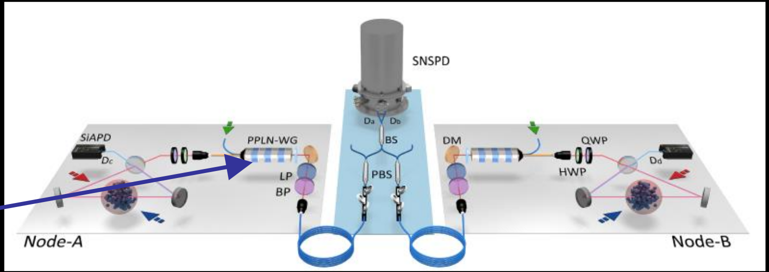
- ☑ Support quantum repeaters enabling quantum communication at a range of ~500km
- ☒ But the probability of generating photon-atom entanglement is still low

Long-distance entanglement of quantum memories

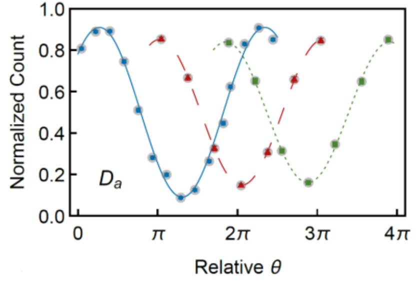
To connect quantum memory nodes with fiber, one needs to shift the atomic wavelength to telecom wavelength

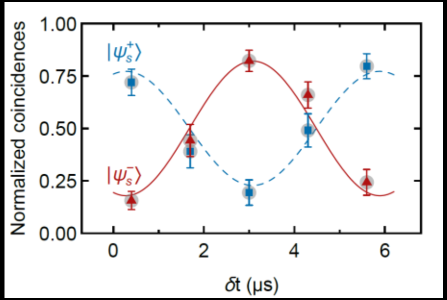
Frequency conversion:

atomic wavelength (795 nm) ➡ telecom wavelength (1342 nm)

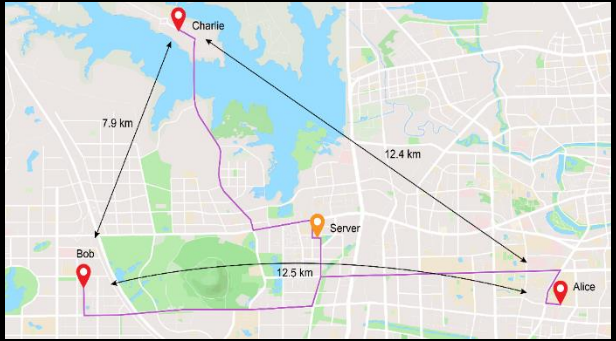


- Quantum entanglement between remote quantum memories over tens of kilometers
  Yu *et al.*, Nature 578, 240 (2020)





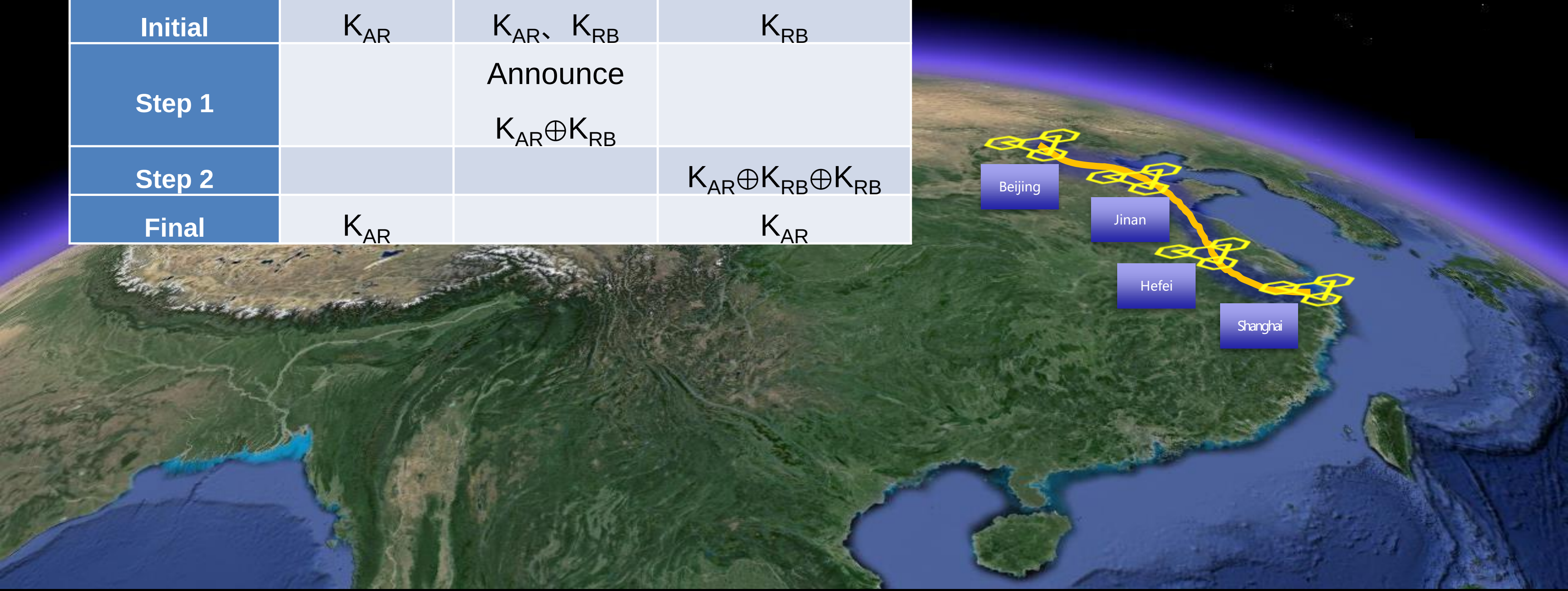
- First multi-node entanglement-based quantum network over a metropolitan area
  Liu *et al.*, Nature 629, 579 (2024)

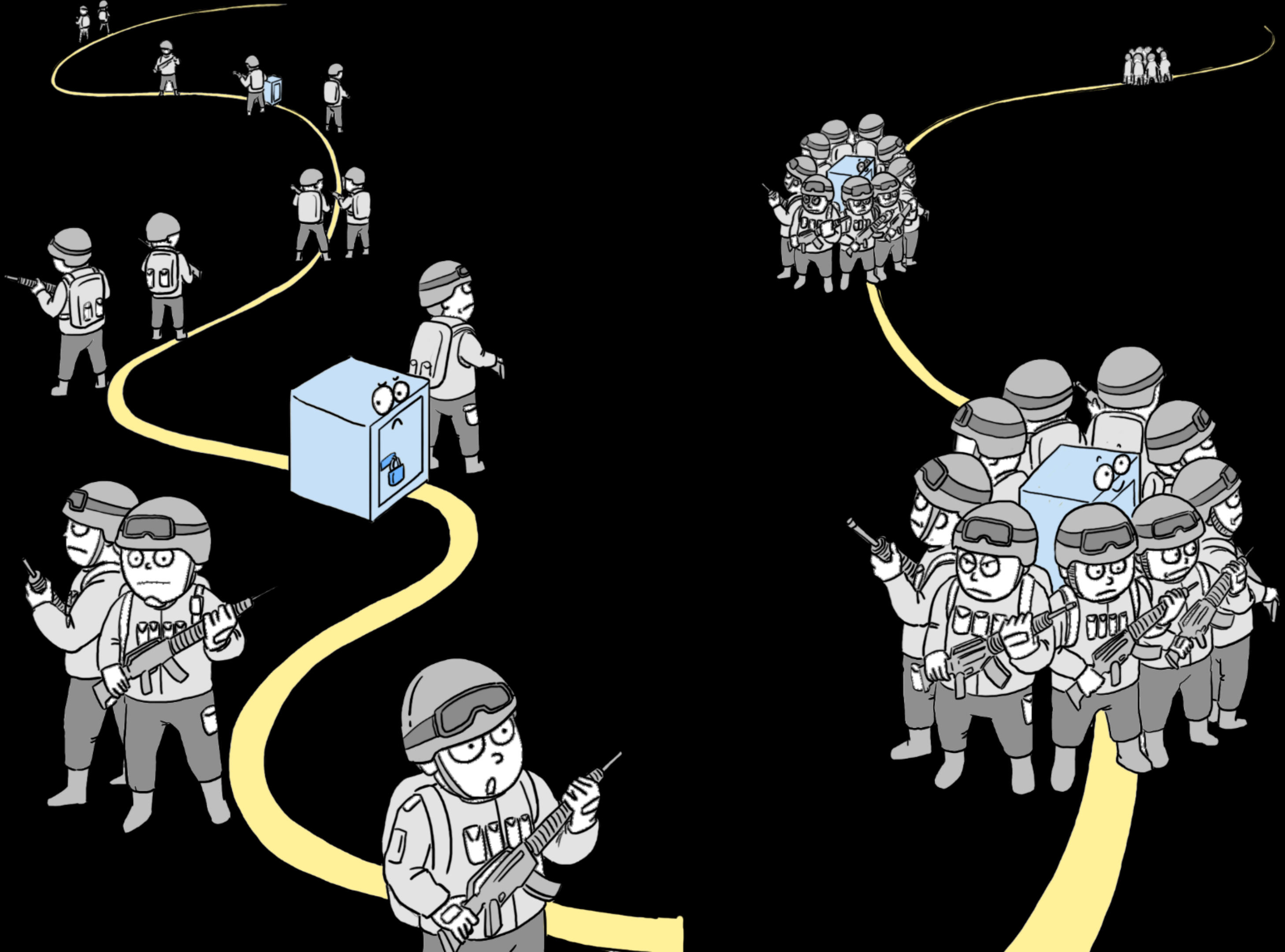


A practical quantum repeater at 1000km scale might still need 10 more years

Temporary Solution: Quantum Secure Backbone (Trustable Relay)

	A	Relay	B
Initial	K_{AR}	K_{AR}、 K_{RB}	K_{RB}
Step 1		Announce $K_{AR}\oplus K_{RB}$	
Step 2			$K_{AR}\oplus K_{RB}\oplus K_{RB}$
Final	K_{AR}		K_{AR}



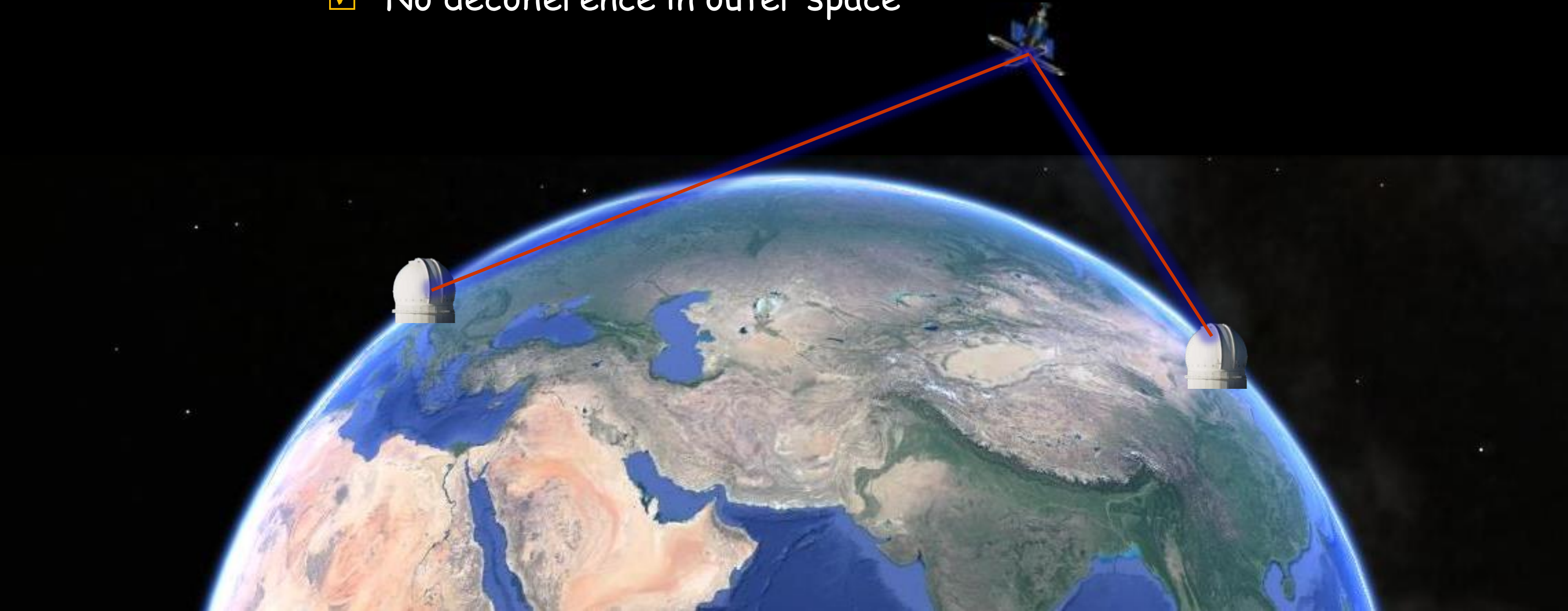


More effecient: Satellite-based Free Space Quantum Communication

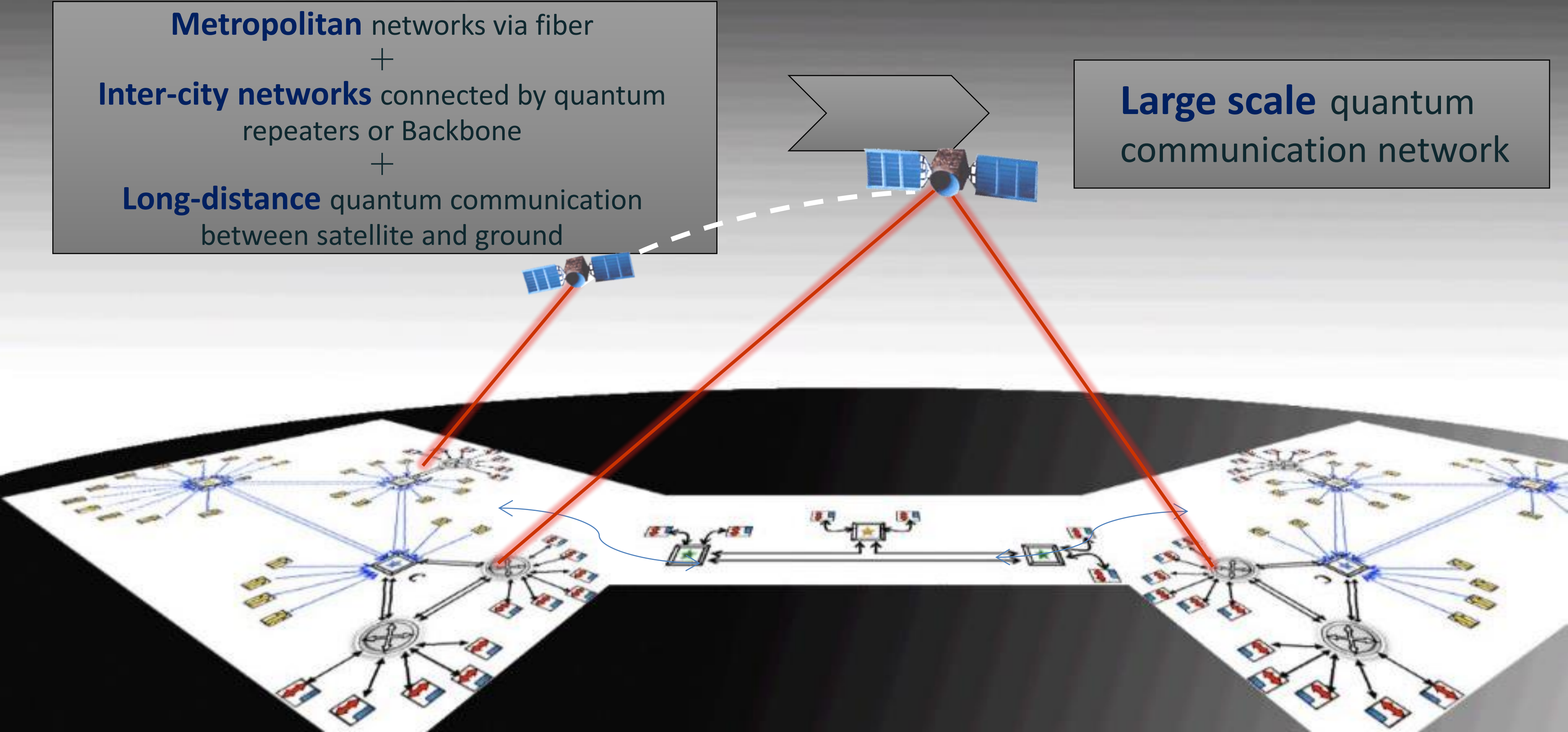
☑ Non-obstruction from terrestrial curve and barrier

☑ Effective thickness of atmosphere is only ~10km

☑ No decoherence in outer space



Roadmap: Large Scale Quantum Communication



Metropolitan networks via fiber
+
Inter-city networks connected by quantum repeaters or Backbone
+
Long-distance quantum communication between satellite and ground

Large scale quantum communication network

2006

- ■ Secure distance exceed 100km with Decoy BB84

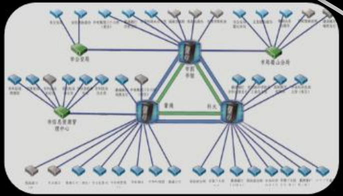
China creates quantum network

2008

- ■ Secure distance exceed 200 km for the first time
- ■ All pass network (Hefei 5 nodes)

■ First quantum telephone network (Hefei 3 nodes)

2009



2012

- ■ Metropolitan network (46 nodes)
- ■ Demonstration of application in financial information transmission

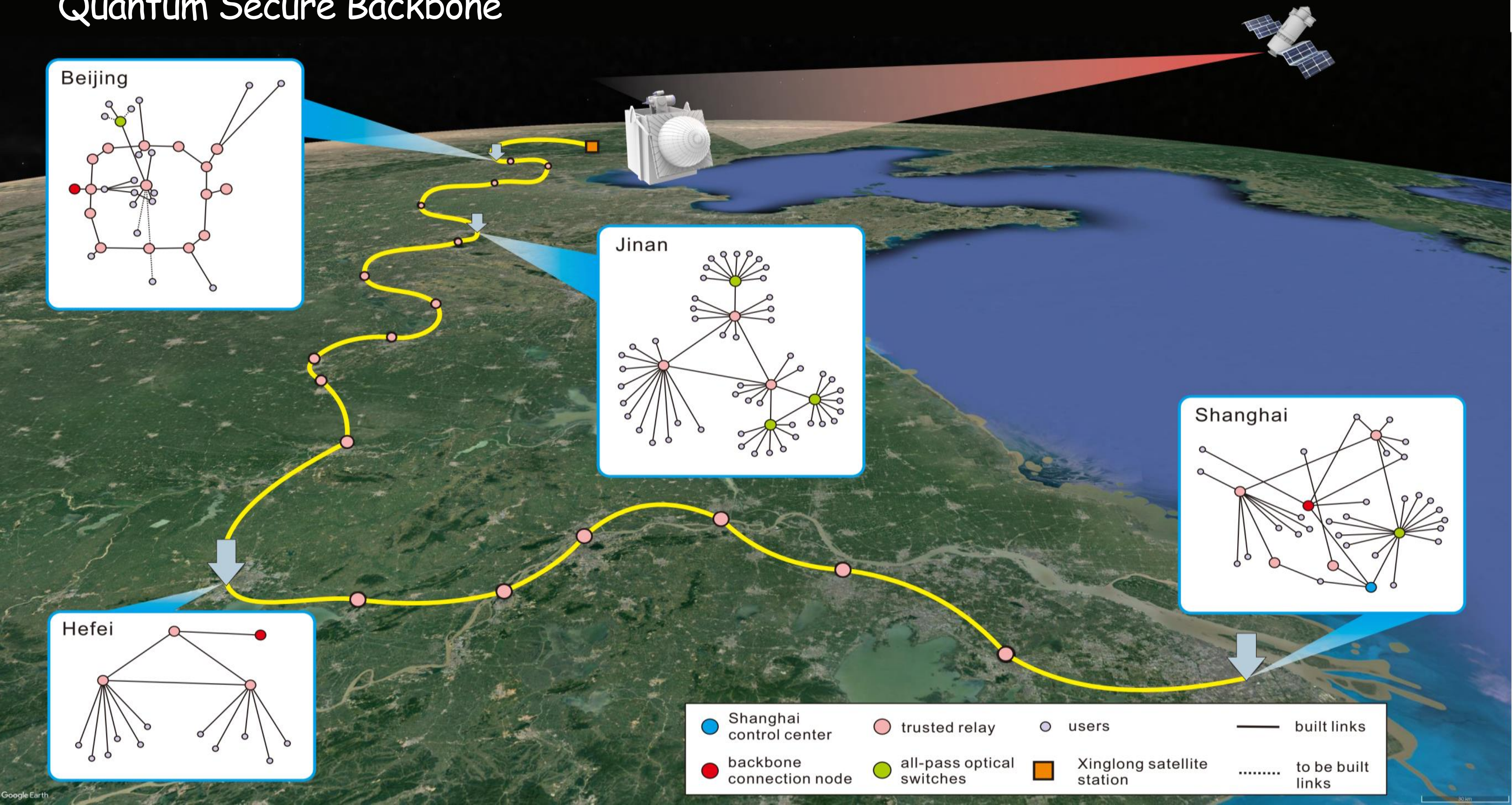
2013

■ Metropolitan network Jinan (56 nodes 95 users, 7×24 hours, running for more than 24 months)

2014

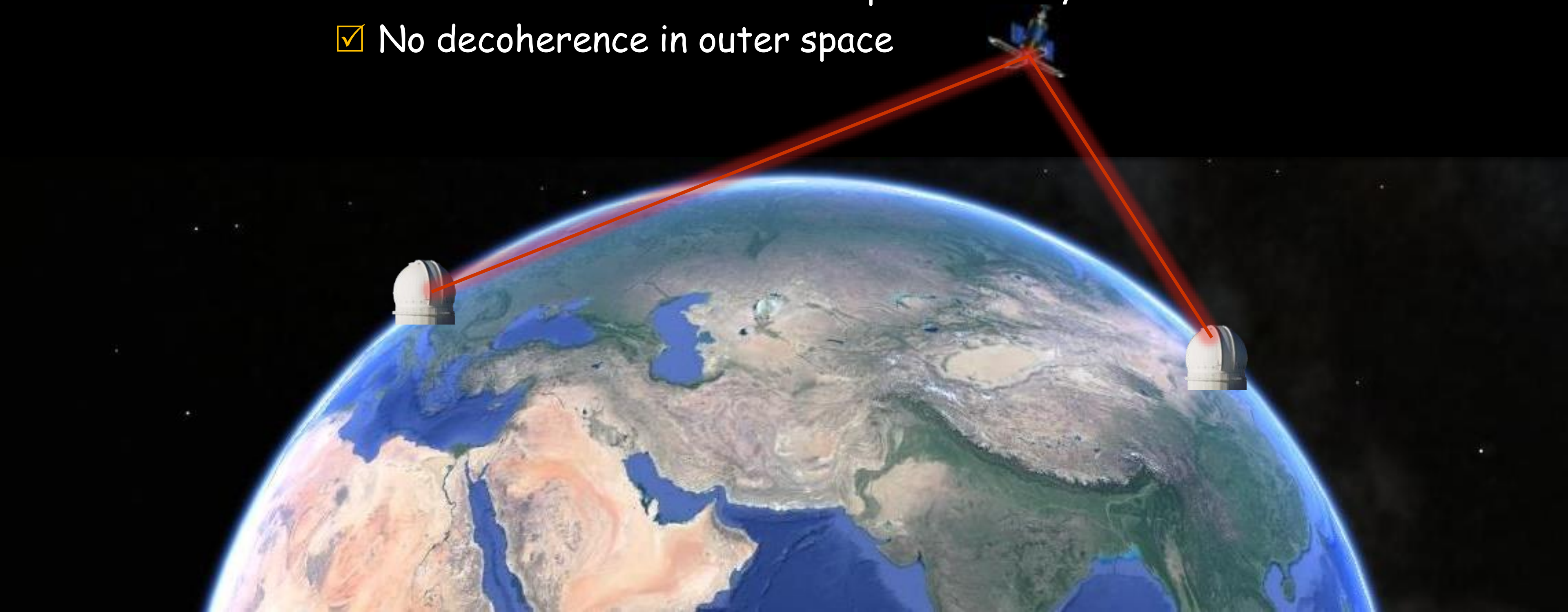
■ Quantum secure communication Beijing-Shanghai backbone

Quantum Secure Backbone



More efficient way: satellite-based quantum communication

- ☑ Non-obstruction from terrestrial curve and barrier
- ☑ Effective thickness of atmosphere is only ~10km
- ☑ No decoherence in outer space

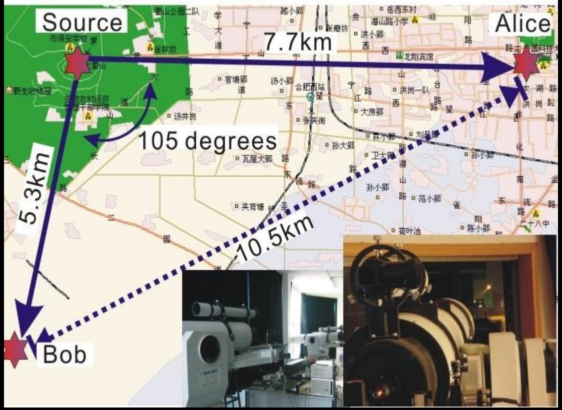


Quantum Science Satellite

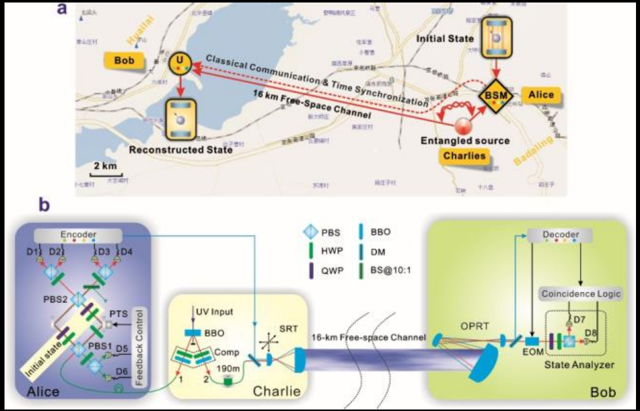
10-years journey of ground tests

Phase 1:

Test the possibility of single photon and entangled photons passing through atmosphere (supported by CAS since 2003)



Free-space quantum entanglement distribution ~13km
Peng *et al.*, Phys. Rev. Lett. 94, 150501 (2005)



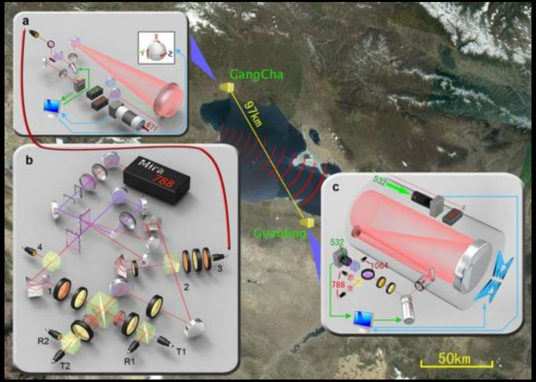
Free-space quantum teleportation (16km)
Jin *et al.*, Nature Photonics 4, 376 (2010)

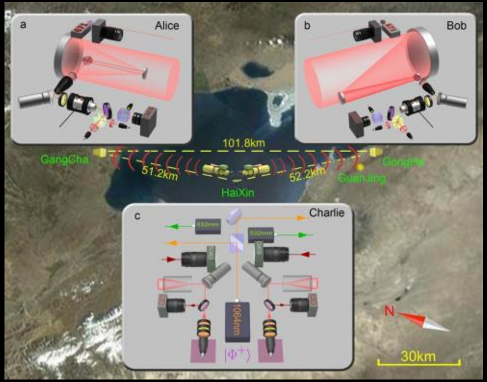
Well beyond the effective thickness of the aerosphere!

10-years journey of ground tests

Phase 2:

Test the feasibility of quantum communication via high-loss satellite-to-ground channel





Channel loss: 35-53dB

V. S.

Loss for an uplink of ground to satellite: 45dB

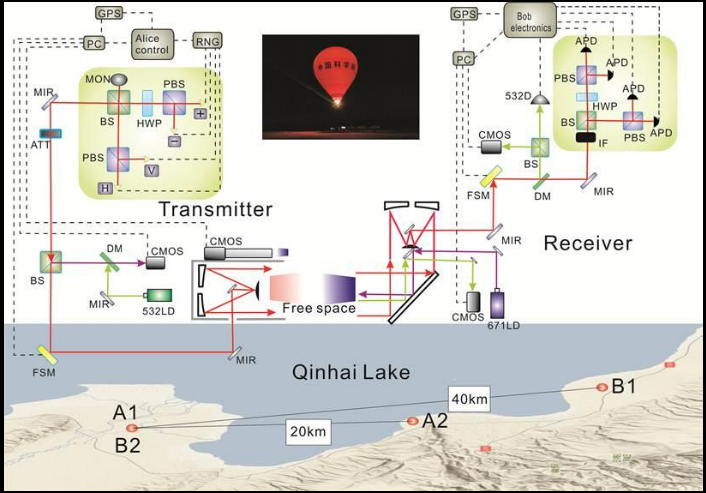
Channel loss: 66-85dB

V. S.

Loss for two-downlink between satellite and two ground stations: 75dB

10-years journey of ground tests

Phase 3: Direct and full-scale verifications towards satellite-to-ground quantum key distribution



☑ Mimicking the satellite’s angular motion
☑ Mimicking the satellite’s attitude change
☑ A huge loss channel (about 50 dB loss, 97 km)

Overcoming all the demanding conditions for ground-satellite QKD

Wang *et al.*, Nature Photonics 7, 387 (2013)

Quantum Science Satellite “Micius”

Launched on 16th Aug, 2016 in Jiuquan Satellite Launch Center

2011

The “Quantum Science Satellite” project was officially approved

2012

The first prototype satellite started

2014

The first prototype satellite was completed and the ground station in Xinglong was completed

2015

The flight model of the satellite was completed. The ground stations in Nanshan and Delingha were completed.

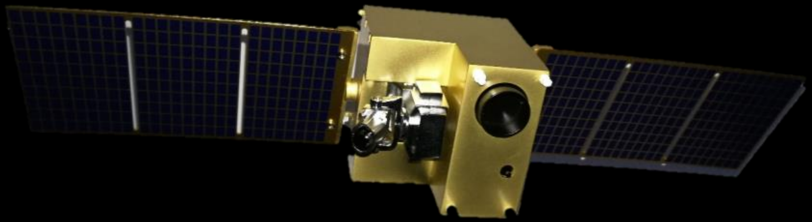
2016

Lijiang and Ali was complete.

The satellite was launched.

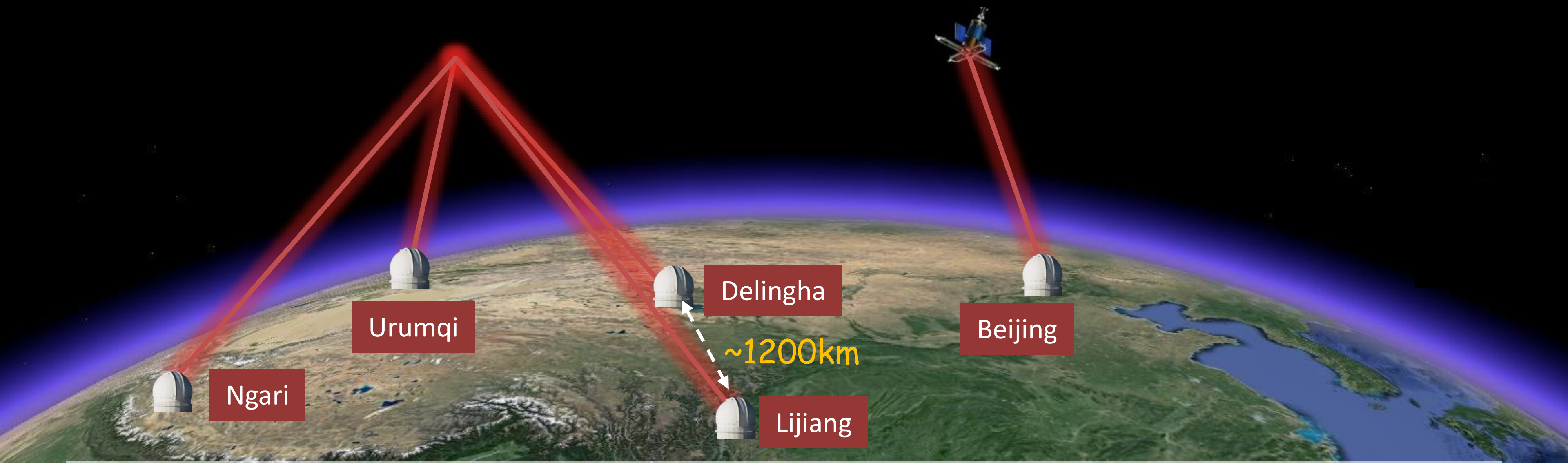
Quantum science satellite "Micius"

Launched on 16th Aug, 2016 in Jiuquan Satellite Launch Center



- Weight: ~640kg
- Power: 560W
- Sun-synchronous orbit, altitude 500km

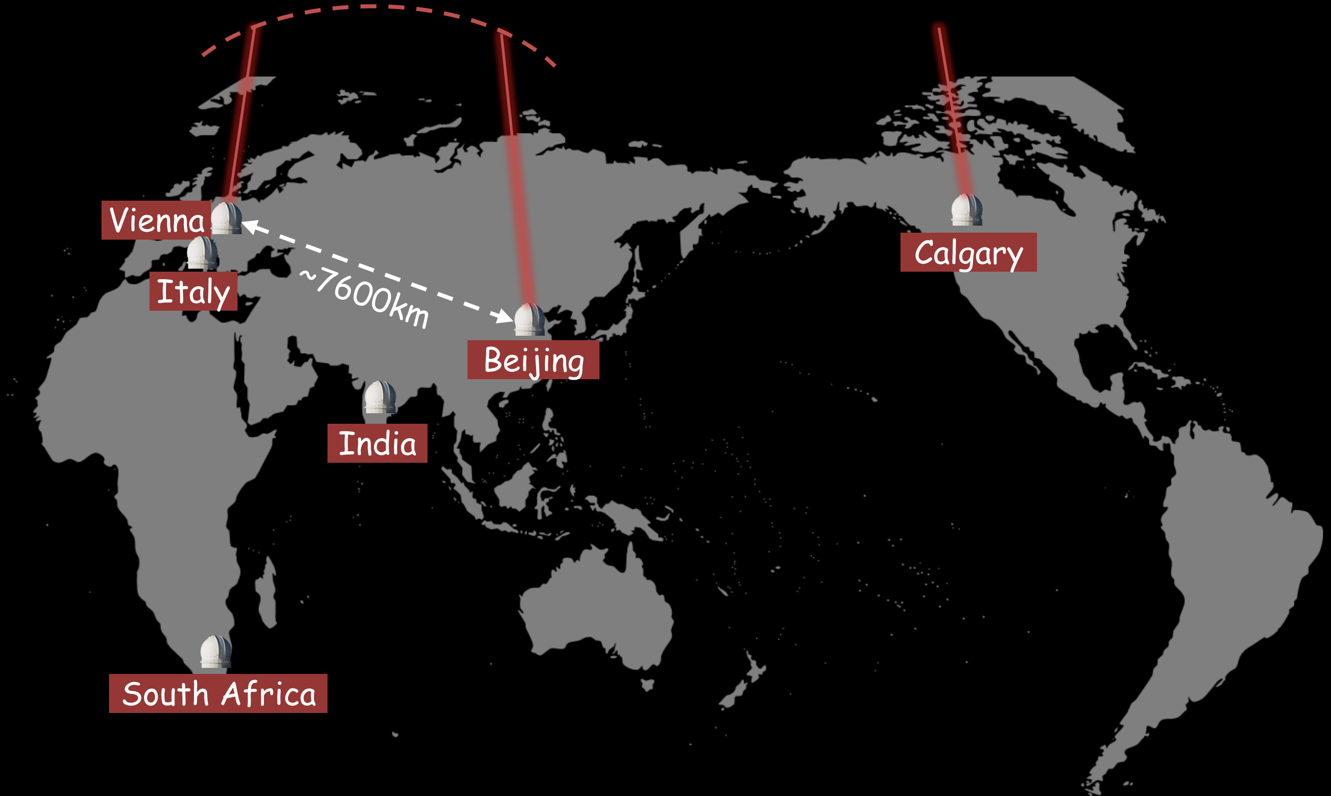
Micius' three missions



- QKD between satellite and ground, final key rate ~1kbps (recently ~100kbps) ➡ 20 orders of magnitudes higher than using fiber channel at 1200 km [Liao *et al.*, Nature 549, 43 (2017)]
- Quantum entanglement distribution from satellite, test of quantum nonlocality under strict Einstein's locality condition [Yin *et al.*, Science 356, 1140 (2017)]
- Quantum teleportation between ground and satellite [Ren *et al.*, Nature 549, 70 (2017)]

Intercontinental quantum key distribution

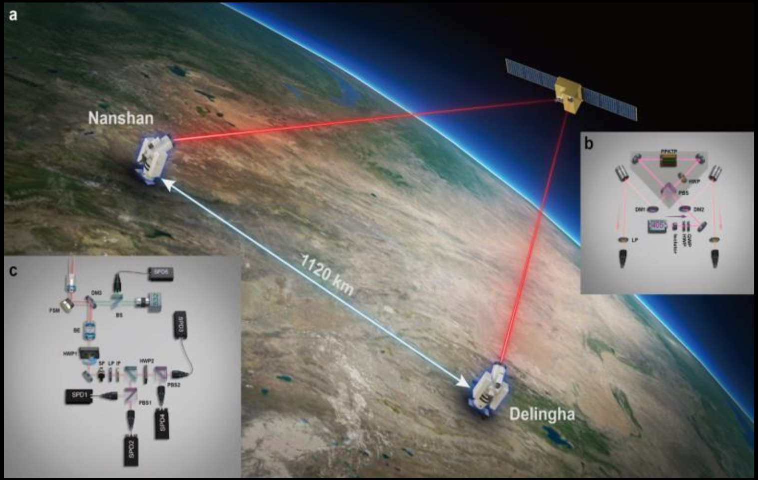
- Satellite as a trusted relay [Liao *et al.*, Phys. Rev. Lett. 120, 030501 (2018)]
- QKD between Micius and Calgary in Canada
- Collaborations with Italy, India and South Africa etc. are ongoing



Long-distance entanglement-based QKD

Even the satellite is controlled by your enemy, once entanglement is verified the security of QKD can still be ensured!

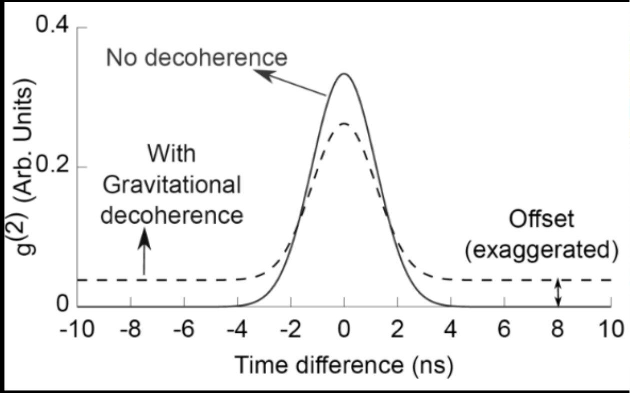
- **Scheme:** Ekert, Phys. Rev. Lett. 67, 661 (1991)
  Bennett *et al.*, Phys. Rev. Lett. 68, 557 (1992)
- **Experiment:** Entanglement-based QKD over 1120 km
  Yin *et al.*, Nature 582, 501 (2020)
  - Channel loss: 56~71dB, received 2 pairs/s
  - $S=2.56\pm0.07$
  - QBER: 4.51%±0.37%
  - Final key: 0.42bps
  - If load GHz entanglement source, up to 10kbits per orbit

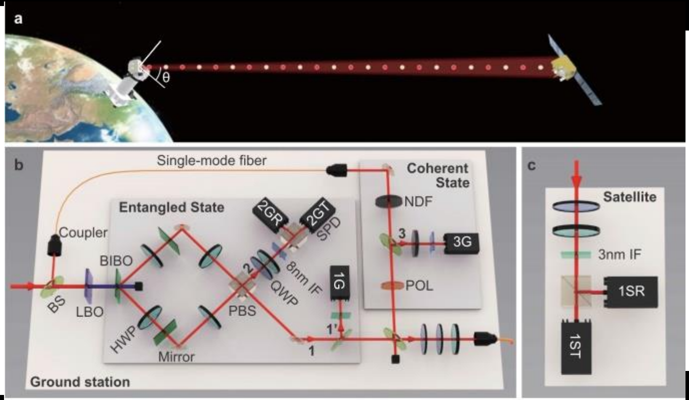


> *This would thus achieve the Holy Grail that all cryptographers have been dreaming of for thousands of years*
>
> --Gilles Brassard

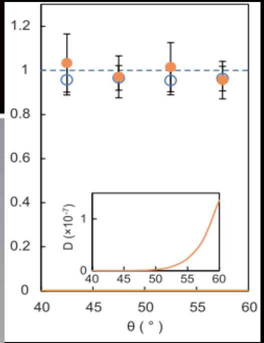
Investigation at the interface of quantum physics and gravity

Event Formalism model: gravitationally induced decorrelation of time-energy entanglement in exotic spacetime [Scheme: Ralph *et al.*, Phys. Rev. A 79, 022121 (2009)]





Experiment



Theory

The experiment excludes the prediction of a strong event formalism model

Xu *et al.*, Science 366, 132 (2019)

Quantum superposition and quantum computation

Quantum Parallelism

Bits		Qubits
0 or 1		0 + 1
00， 01， 10 or 11	V. S.	00 + 01 + 10 + 11
000， 001， 010……		000 + 001 + 010 + ……

Evaluating a function f(x) for many different values of x simultaneously

$$U\frac{1}{\sqrt{2^N}}\sum_{i=0}^{2^N-1}|i\rangle|0\rangle=\frac{1}{\sqrt{2^N}}\sum_{i=0}^{2^N-1}|i\rangle|f(i)\rangle$$

→ Exponentially speedup!

Quantum superposition and quantum computation

Shor Algorithm (1994):

E.g. factor a 300-digit number with

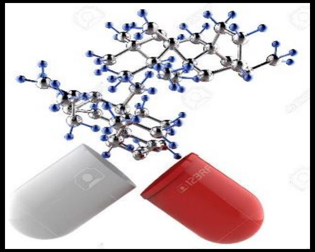
- Classical THz computer: 150,000 years
- Quantum THz computer: 1 second!

- Code-breaking can be done in minutes, not in millennia
- Public key encryption, based on factoring, will be vulnerable!

Code-breaking

Weather forecast

Financial analysis

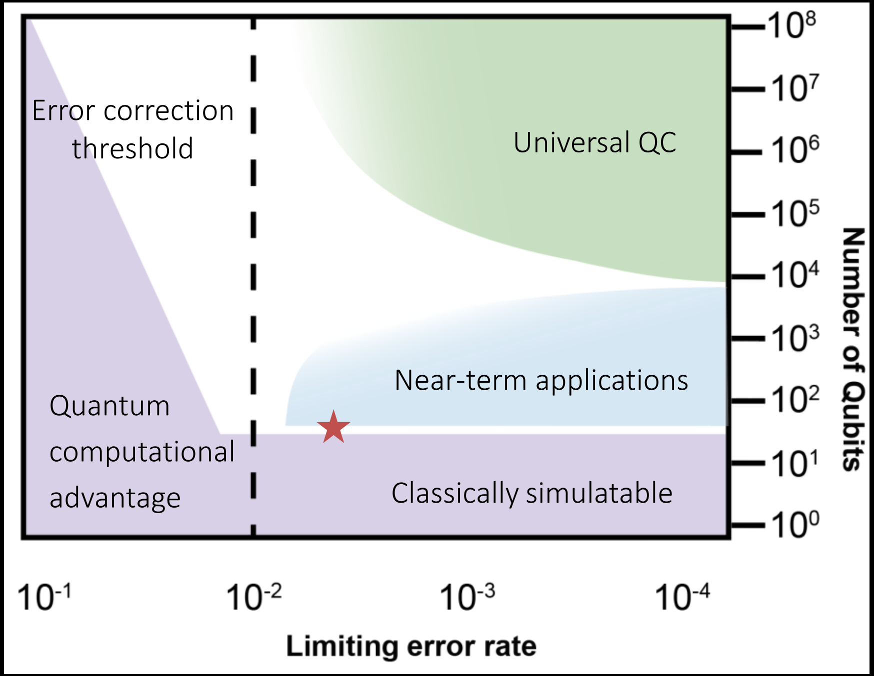


Drug design

Roadmap of quantum computing

- Milestone 1 (quantum computational advantage) : Beating classical supercomputer in specific tasks

  The speedup is so overwhelmingly huge that no classical computer can perform the same task in a reasonable amount of time and is unlikely overturned by classical algorithm or hardware improvements



- Milestone 2: quantum simulator to efficiently mimic the evolution of a complex quantum system (e. g., high temperature superconductivity, etc.)
- Milestone 3: Universal and programmable quantum computation with help of quantum error correction

Quantum computational advantage

An important milestone: quantum computational advantage, showing essential difference between classical and quantum physics

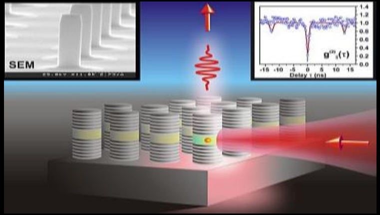
Bell's theorem

Nonlocal correlations and intrinsic randomness that cannot be simulated by any local hidden variable models ➡ Refutes Einstein' s local realism!

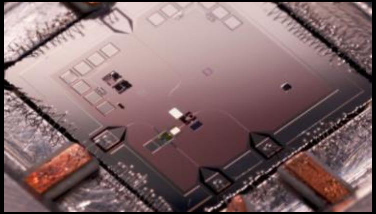
Quantum computational advantage

A complex quantum process cannot be efficiently simulated by classical computers
➡ Refutes the extended Church-Turing thesis (classical computers can simulate computational power of any physical process with polynomial overhead)

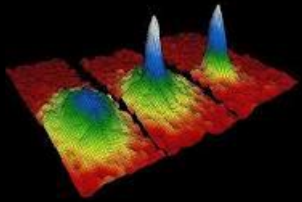
Candidates for quantum computation



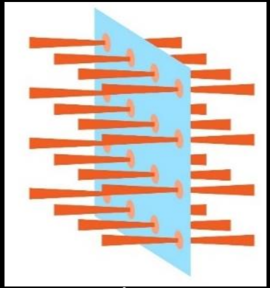
Photons



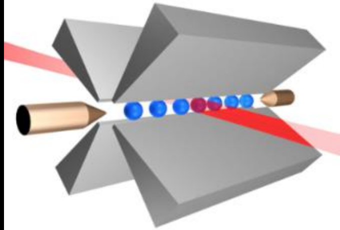
Super conductors



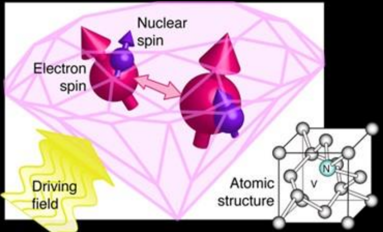
Ultra-cold atoms



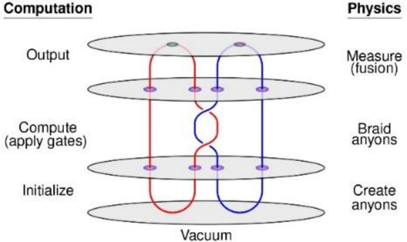
Atomic arrays



Trapped ions



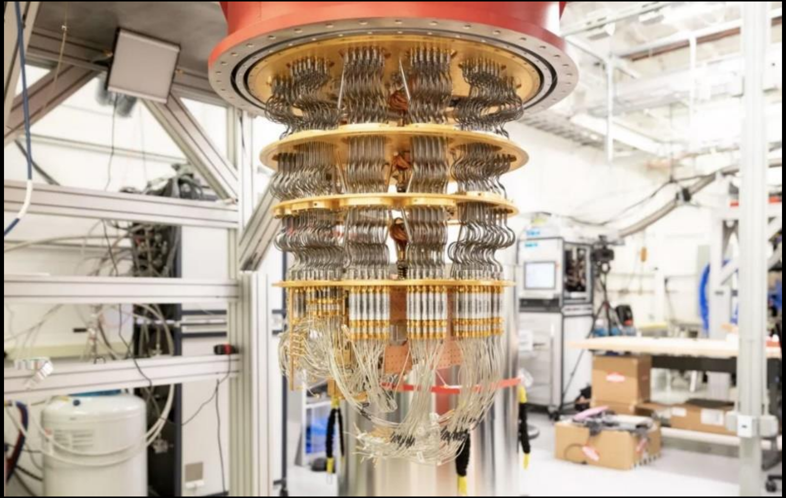
Solid states



Topological

Precise manipulations of quantum superposition and entanglement (e.g., high-performance quantum light sources, phase locking, mode matching, and photon detection techniques developed in experimental quantum communications) ➡ Quantum computational advantage is feasible!

Quantum computational advantage



- Google first announced quantum supremacy with a 53 superconducting qubits quantum processor "Sycamore"

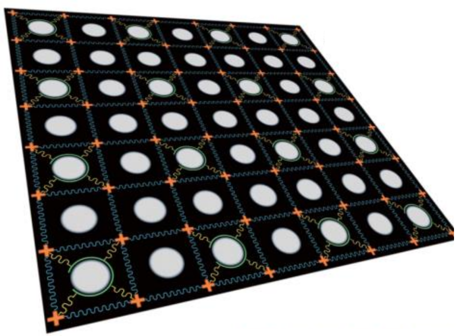
  Arute *et al.*, Nature 574, 505 (2019)

- Recent study has shown that 1 million uncorrelated samples with higher XBE score can be generated in a few tens seconds on classical supercomputer

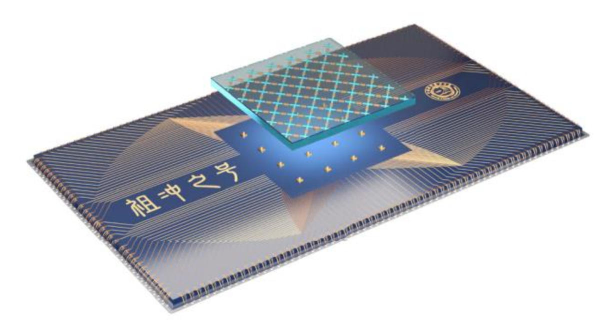
  Zhang & Pan, PRL 129, 050902 (2022)

Quantum computational advantage

Zuchongzhi（祖冲之号）



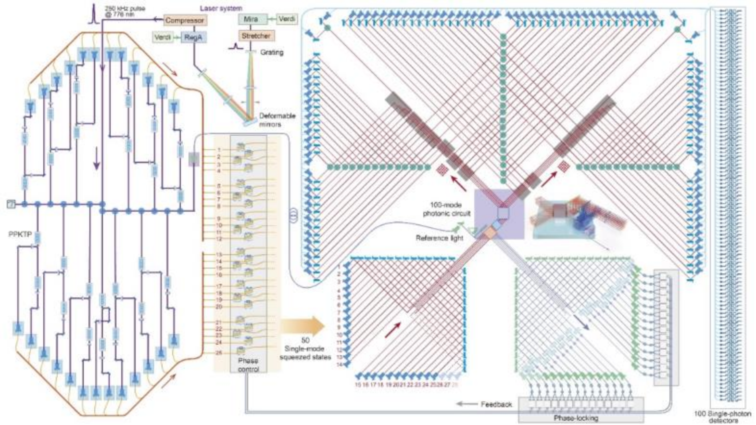
Zuchongzhi 2.0 & Zuchongzhi



	Sycamore	Zuchongzhi 2.0	Zuchongzhi 2.1
Number of qubits	54	66	66
Single-qubit gate error	0.16%	0.14%	0.16%
Two-qubit gate error	0.62%	0.59%	0.60%
Readout error	3.8%	4.5%	2.26%
T1	15.54 μs	30.8 μs	26.5μs

- Quantum walks on a programmable two-dimensional 62-qubit superconducting processor
  Science 372, 948 (2021)
- Strong quantum computational advantage using a 66-qubit superconducting quantum processor, achieved sampling task is about 6 orders of magnitude more difficult than that of Sycamore [PRL 127, 180501 (2021)]
- Genuine entanglement up to 51 superconducting qubits [Nature 619, 738 (2023)]

Quantum computational advantage

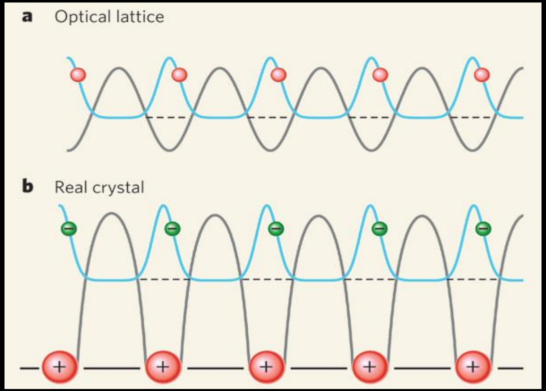


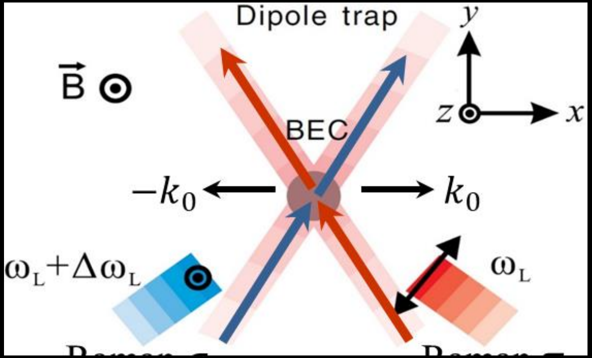
Strong quantum computational advantage using photons (Gaussian Boson sampling)

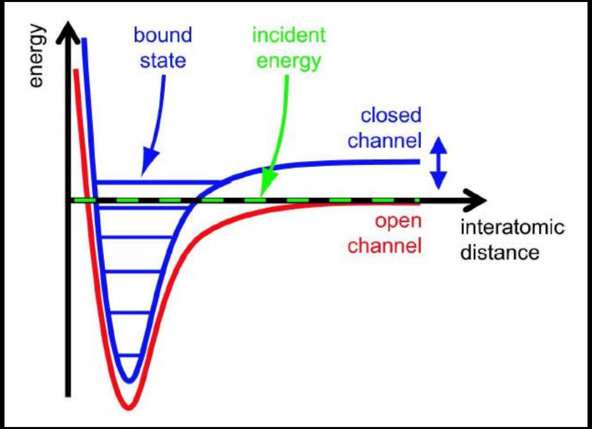
- "Jiuzhang": up to 76 detected photons, sampling rate ~10^5 times faster than classical supercomputer with optimal classical algorithm updated in 2022
  Science 370, 1460 (2020)
- "Jiuzhang 2.0": up to 113 detected photons, ~10^{10} times faster than classical supercomputer
  PRL 127, 180502 (2021)
- "Jiuzhang 3.0": up to 255 detected photons, ~10^{16} times faster than classical supercomputer
  PRL 131, 150601 (2023)

Quantum simulation with ultracold atoms

"Quantum engineering" of Hamiltonians







Optical lattices:

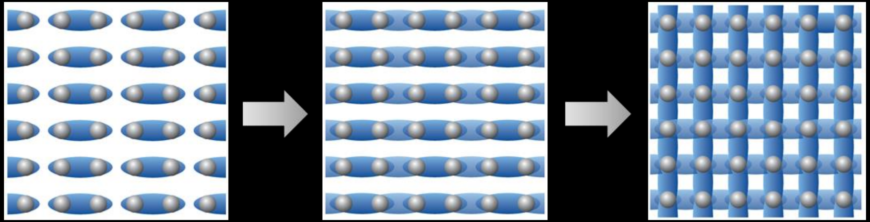
☑ To mimic crystal structures

☑ To entangle many atoms

☑ To synthesize artificial gauge potentials by Raman technique

☑ Tunable atom-atom interaction strength by Feshbach resonance

Quantum simulation with ultracold atoms



Atom-atom entanglement in optical lattices

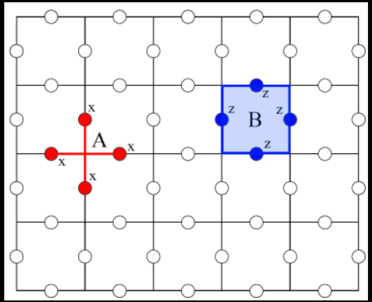
~600 pairs: Nature Physics 12, 783 (2016)

~1200 pairs with 99.3% fidelity:
Science 369, 550 (2020)

$$H_0 = -\sum_s A_s - \sum_p B_p$$

$$A_s = \prod_{j\in\mathrm{star}(s)} \sigma_j^x$$

$$B_p = \prod_{j\in\mathrm{boundary}(p)} \sigma_j^z$$



Demonstration of Toric-code Hamiltonian and the anyonic fractional statistics

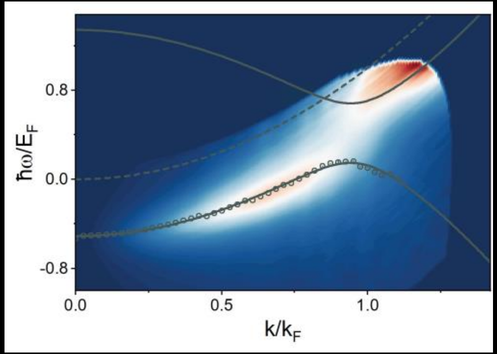
Nature Physics 13, 1195 (2017)

Quantum simulation with ultracold atoms

- Quantum simulation of Fermi-Hubbard model by “Tian Yuan” （天元）

Preparation of homogeneous Fermi gas with large Fermi energy

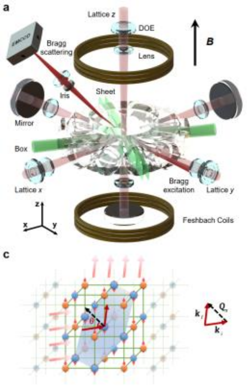
- With Bragg spectroscopy with low transferred momentum, observed second sound attenuation and critical divergence of thermal conductivity [Science 375, 528 (2022)]

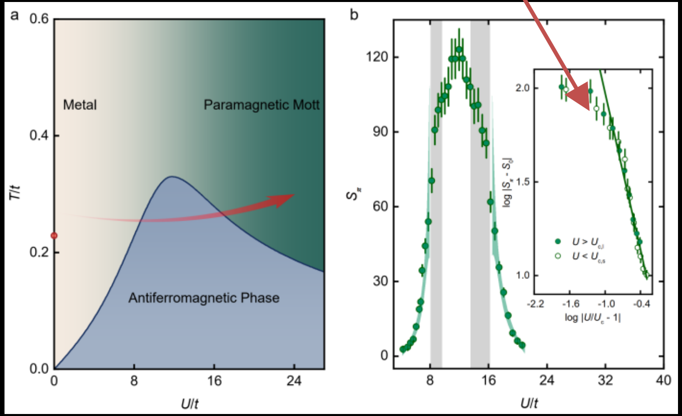


- With momentum-resolved microwave spectroscopy, observed pairing pseudogap supporting the role of preformed pairing as a precursor to superfluidity [Nature 626, 288 (2024)]

- Loading the Fermi gas into a 3D flat-top optical lattice
- Realization of a 3D homogeneous Fermionic Hubbard model with 800,000 atoms

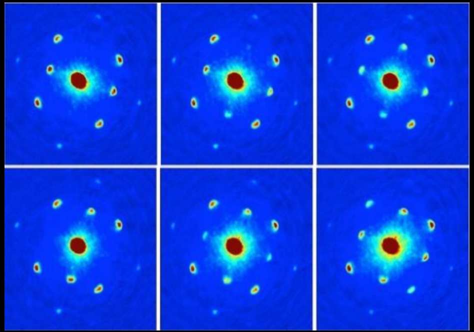
Observed critical divergence of spin structure factors



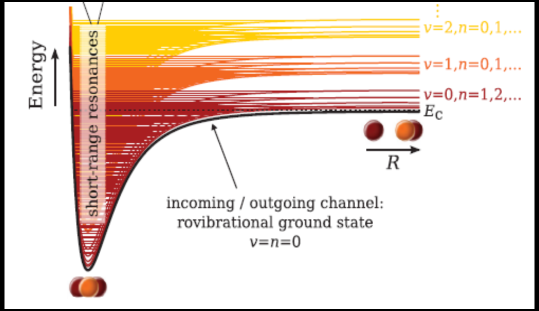


- Providing conclusive evidence of antiferromagnetic phase transition in a 3D fermionic Hubbard model [Nature 632, 267–272 (2024)]

Quantum simulation with ultracold atoms



- *Quantum simulation of Gauge potential with neutral atoms*
  - Phase diagram of 1D spin-orbit coupling [PRL 109, 115301 (2012)]
  - Realization of 2D SOC [Science 354, 83 (2016)]
  - Realization of ideal Weyl semimetal band with 3D SOC [Science 372, 271 (2021)]



- *Quantum simulation of ultracold chemistry with molecules*
- Obtaining information of potential energy of triatomic molecule containing 49 electrons *(cannot be obtained with classical numerical simulation)* [Science 363, 261 (2019)]
- Association of triatomic molecules in ultracold ^{23}Na^{40}K + ^{40}K mixtures [Nature 602, 229 (2022)]
- Creating ultracold gas of triatomic molecules from atom-diatomic molecule mixture [Science 378, 1009 (2022)]

Next step:

- Manipulating ~10000 atoms to study scalable multipartite entanglement and error correction
- Mimicking strongly correlated topological matter, phase diagram of Fermi-Hubbard model, dynamics of ultracold chemistry……

Future prospects

Towards global quantum communication network and quantum internet

Chen *et al.*, Nature 589, 214 (2021)

Fiber-based metropolitan QC network

☑ Mature and practical

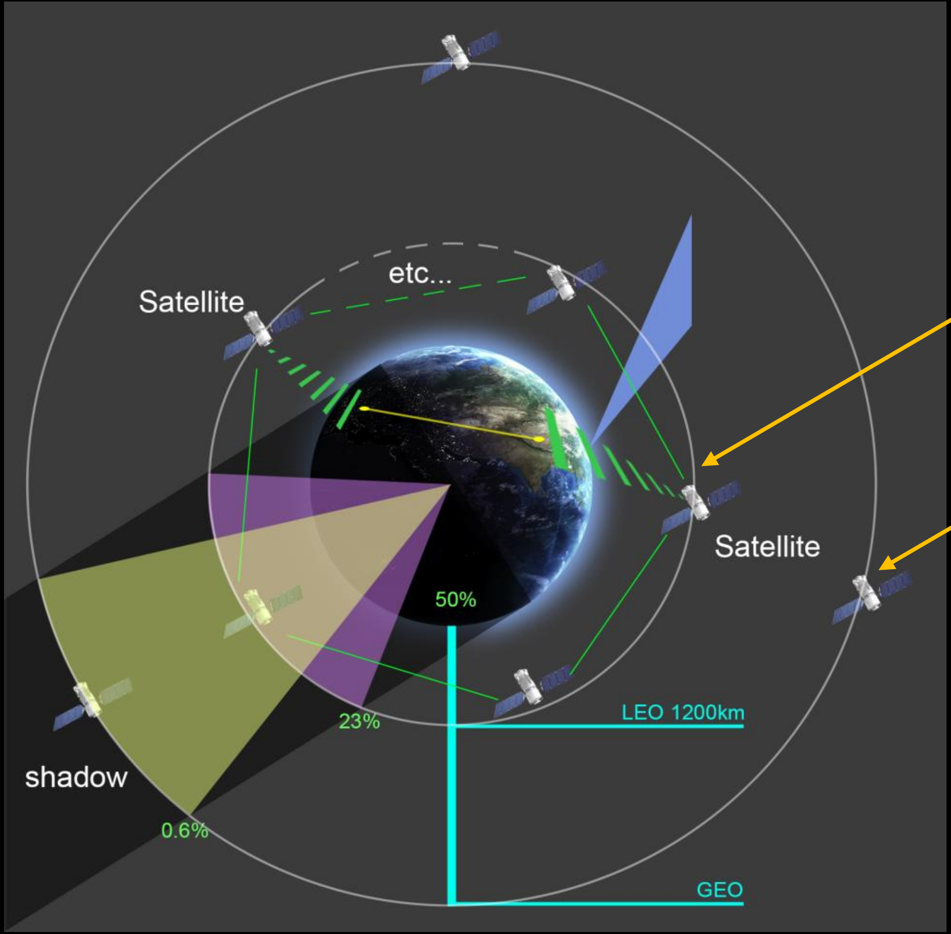
Inter-city QC connected by quantum repeaters

☑ Support QC at a distance of ~1000 km in about 10 years

Long-distance QC with quantum satellites

Challenge: single LEO satellite cannot cover the whole earth directly

Future prospects



Solution:

☑ Higher network efficiency: Quantum Constellation (satellites network)

☑ Distributing more keys: GEO Quantum Satellites with much longer mooring time

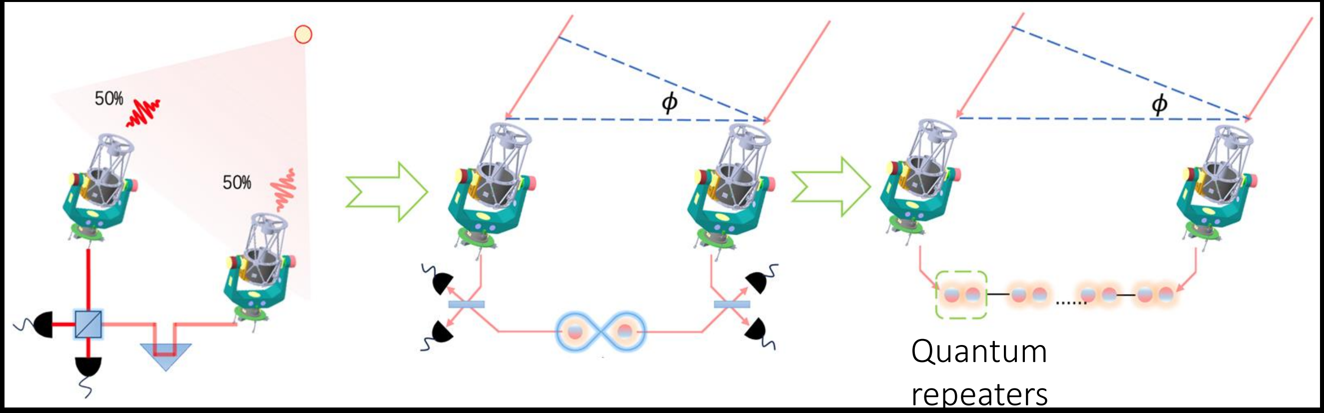
The first GEO satellite for QC is under development and scheduled to be launched around 2027

Future prospects

Large-scale quantum communication network also provides a new platform for the study of quantum metrology

Quantum-enhanced telescope array

- The interference of starlight can be equivalent to single photon interference
- Assisted by long-distance quantum teleportation, one can achieve interference without directly transmitting starlight thus the length of baseline can be greatly increased [Nature 535, 478 (2016)]



Direct single-photon interference

Baseline: ~ 100 m

Angular resolution: ~ 10 nrad

Assisted by quantum teleportation

Baseline: ~ 1 km – 10000 km

Angular resolution: ~ nrad – 0.1 prad

Future prospects

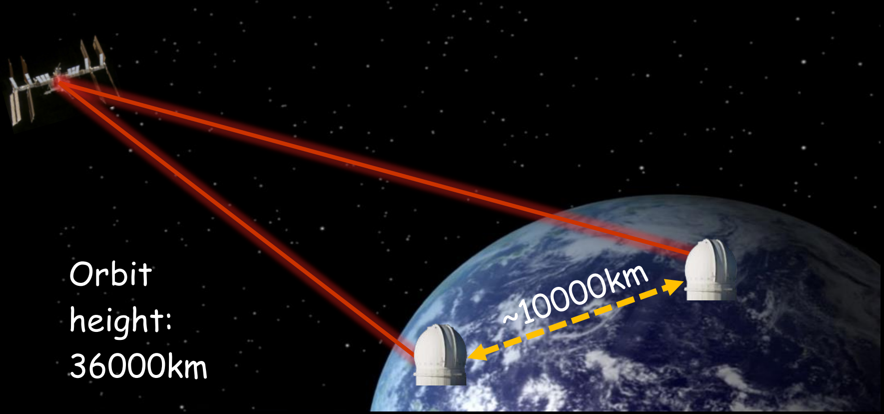
Large-scale quantum communication network also provides a new platform for the study of quantum metrology

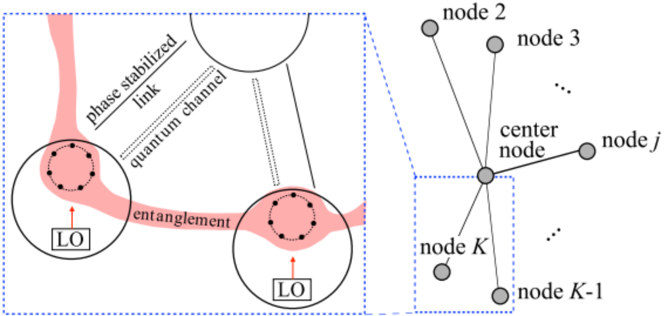
Entanglement distribution at ~10000km

Global entanglement distribution

Entangling N atoms in remote atom clocks, short term instability is $\sqrt{N}$ times better than classical method

Kómár *et al.*, Nat. Phys. 10, 582 (2014)

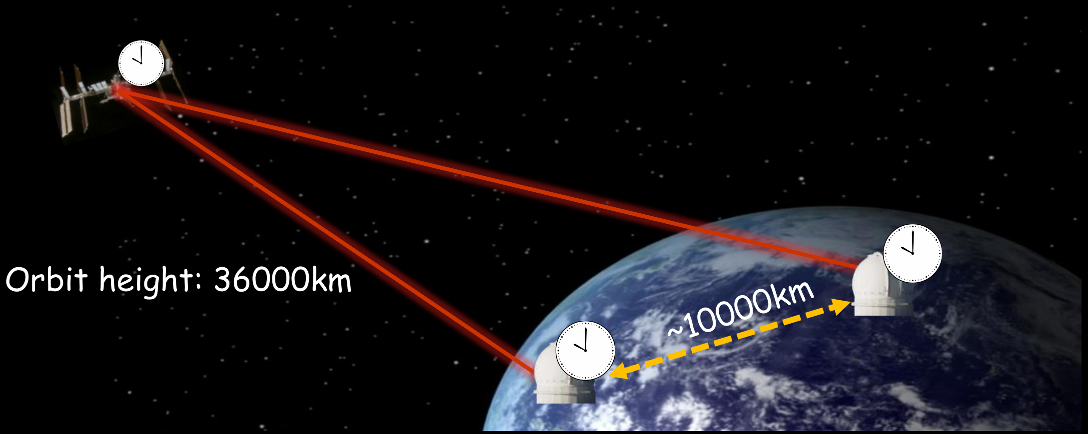




Future prospects

Global precise timing information sharing (new definition of "the second"):

- In GEO orbit, long mooring time, long comparison time
- Optical atomic clocks + Optical frequency transfer ➡ long time instability to 10^{-19} (4 orders of magnitude better than microwave time sharing)



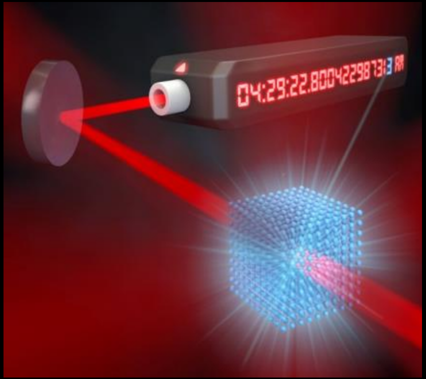
A preliminarily test: Shen *et al.*, Nature 610, 661 (2022)

Future prospects

In outer space:

- Ultra-precise optical clock (fractional instability ~10^{-21})
- Ultra-precise timing information sharing network
- Long baseline interferometer

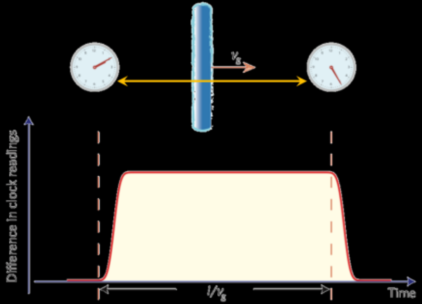
In next 5 years:

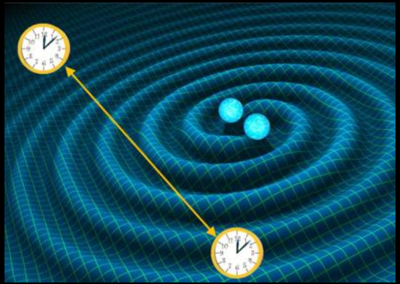


$\Delta E \cdot \Delta t \sim \hbar$

- Developing key techniques for fractional instability of 10^{-20}
- Exploring the feasibility in space with the GEO satellite

In next 10-15 years:

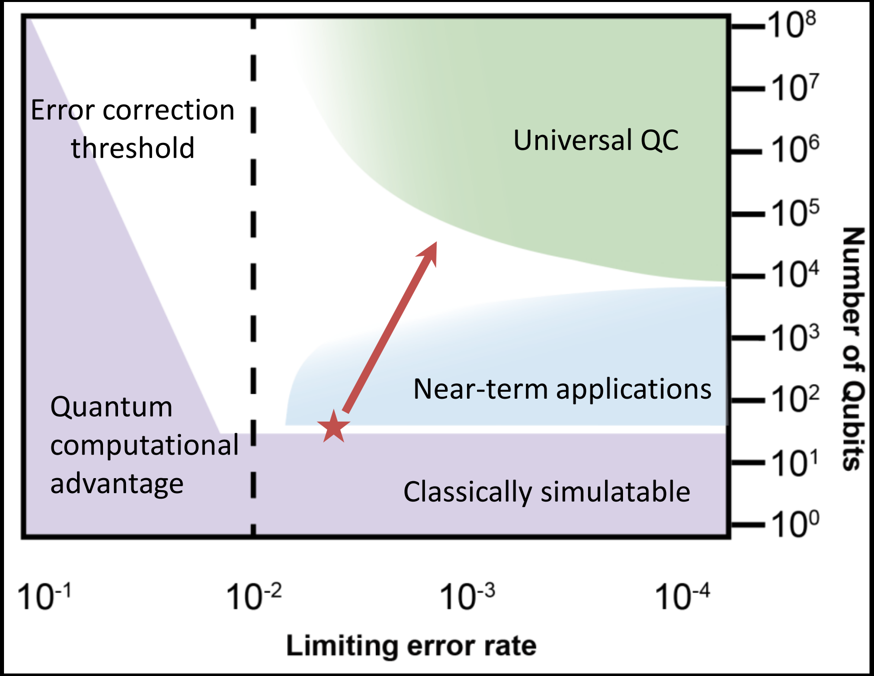




- Fractional instability reach ~ 10^{-21} in higher orbit than GEO
- Hunting for dark matter [Nat. Phys. 10, 933 (2014); Nat. Astron. 1, 9 (2016); PRD 104, 103025 (2021)]
- Detecting gravitational wave signal with lower frequency to 0.1Hz (LIGO: ~100Hz) [PRD 94, 124043 (2016); Class. Quantum Grav. 35, 085010 (2018); Eur. Phys. J. D 74, 94 ((2020)]

Aforementioned efforts of quantum communication, Micius quantum experiments in space and future plans can be found in our recent review:
Lu *et al.*, Rev. Mod. Phys. 94, 035001 (2022)

Future prospects



- In next 5 years: coherent manipulation of a few hundreds to thousands qubits ➡ study the mechanism of high-temperature superconducting, quantum hall effect and so on
- In next 10-15 years: coherent manipulation of millions of qubits ➡ Lay the foundation for universal quantum computation with help of quantum error correction

Thanks!

Quantum Physics & Quantum Information