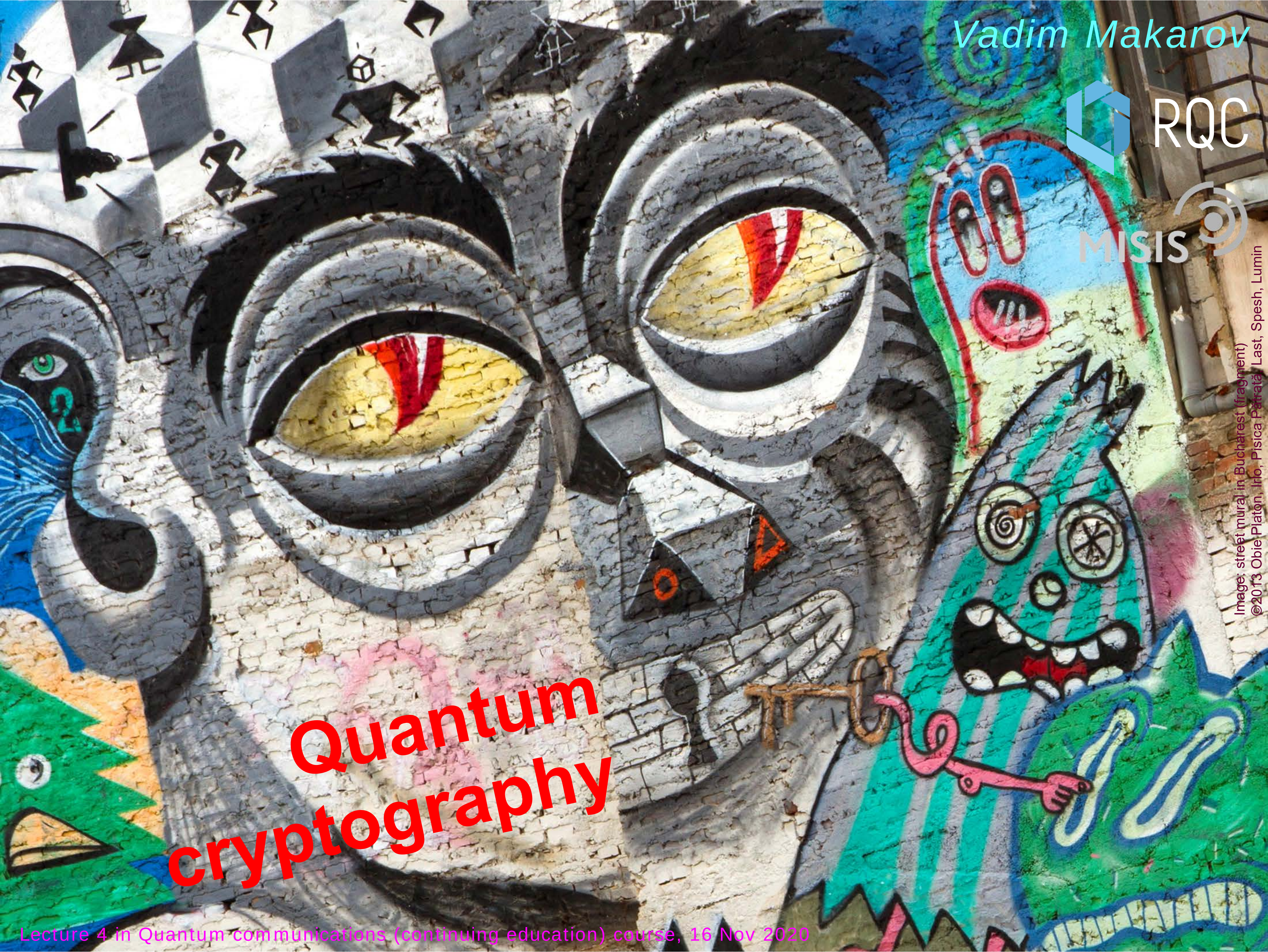


Vadim Makarov

RQC

MISIS

Quantum cryptography

Lecture 4 in Quantum communications (continuing education) course, 16 Nov 2020

Image: street mural in Bucharest (fragment)
©2013 Obie Platon, Irlo, Pisica Pătrată, Last, Spesh, Lumin

Communication security you enjoy daily

Paying by credit card in a supermarket

Cell phone conversations, SMS

Email, chat, online calls

Secure browsing, shopping online, content delivery

Cloud storage and communication between your devices

Software updates on your computer, phone, tablet

Online banking

Off-line banking: the *bank* needs to communicate internally

Electricity, water: the *utility* needs to communicate internally

Car keys, electronic door keys, access control

Government services (online or off-line)

Medical records at your doctor, hospital

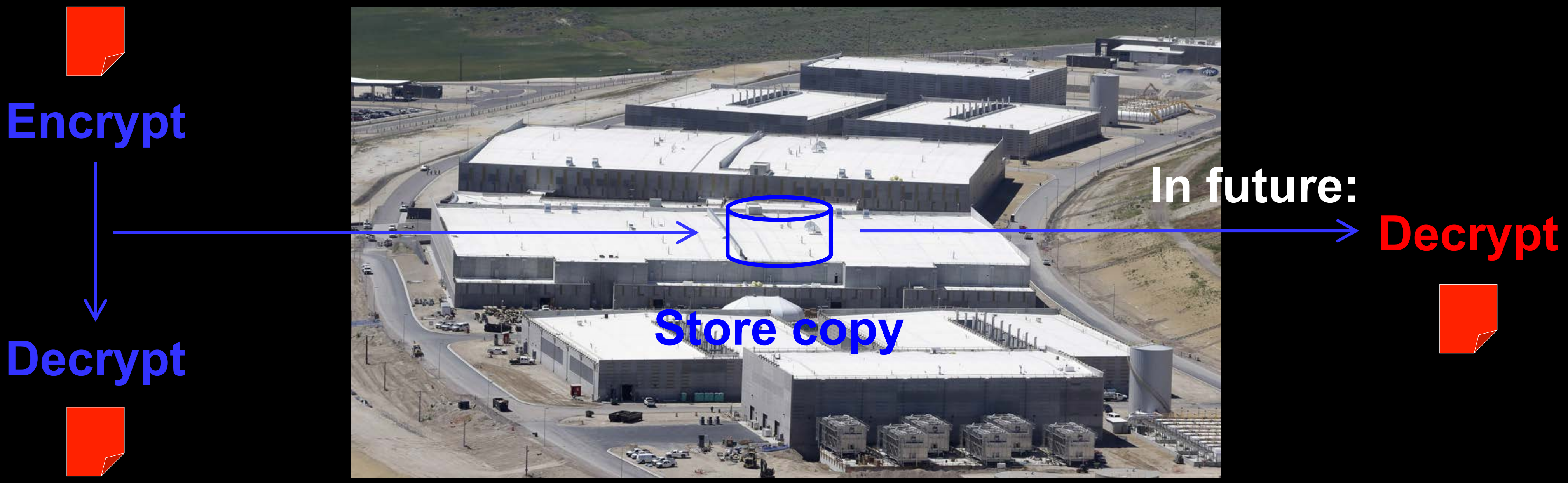
Bypassing government surveillance and censorship

CCTV, industrial automation, military, spies...

A (very) brief history of cryptography

		Broken?
Monoalphabetic cipher	invented ~50 BC (J. Caesar)	~850 (Al-Kindi)
Nomenclators (code books)	~1400 – ~1800	✓
Polyalphabetic (Vigenère)	1553 – ~1900	1863 (F. W. Kasiski)
…		
Polyalphabetic electromechanical (Enigma, Purple, etc.)	1920s – 1970s	✓
…		
DES	1977 – 2005	1998: 56 h (EFF)
Public-key crypto (RSA, elliptic-curve)	1977 –	will be once we have q. computer (P. Shor 1994)
AES	2001 –	?
Public-key crypto ('quantum-safe')	in development	?

Breaking cryptography retroactively



Encrypt

Decrypt

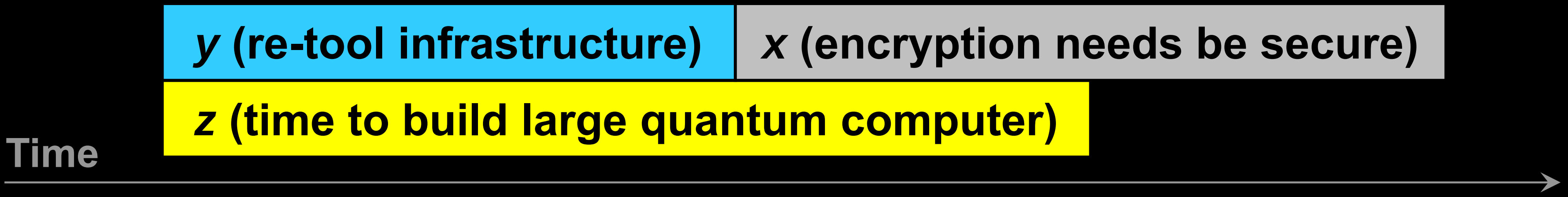
Store copy

In future:

Decrypt

Photo ©2013 AP / Rick Bowmer

Mosca theorem



y (re-tool infrastructure)

x (encryption needs be secure)

z (time to build large quantum computer)

Time

If $x + y > z$, then worry.

M. Mosca, http://eprint.iacr.org/2015/1075

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One-time pad	invented 1918 (G. Vernam)	**impossible** (C. Shannon 1949)
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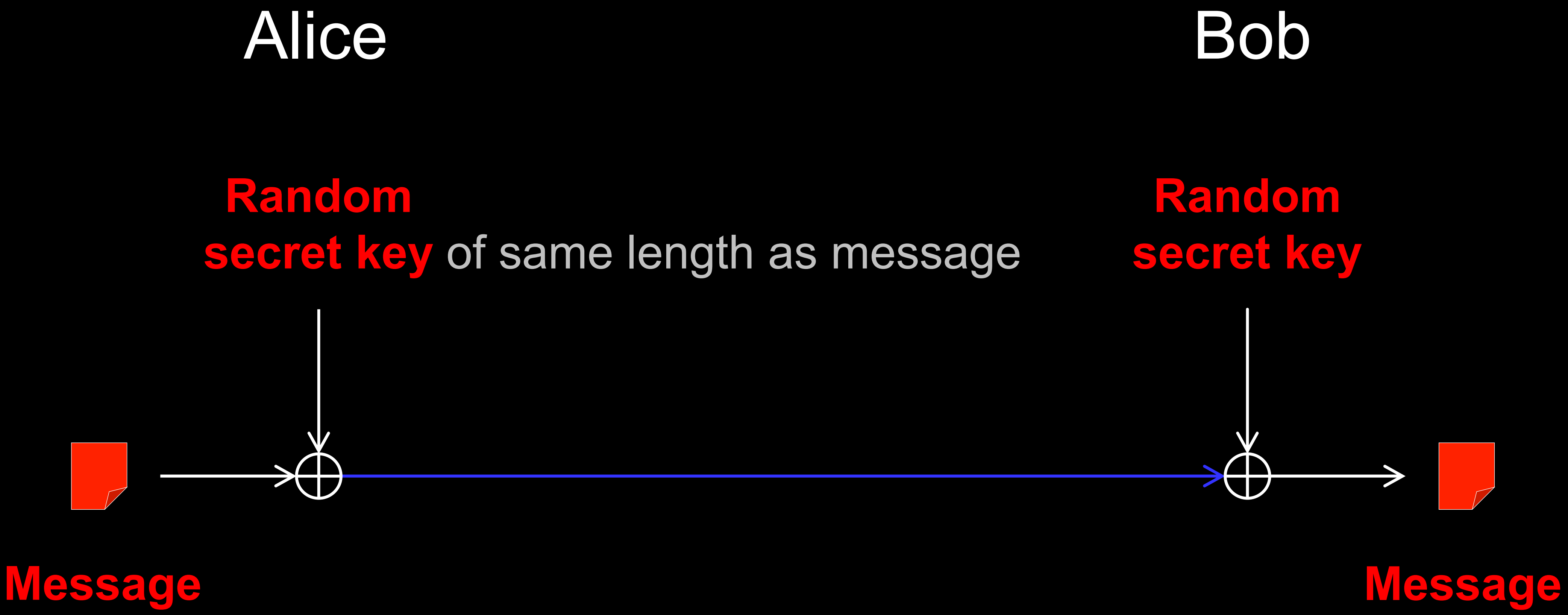
Quantum cryptography	invented 1984, in development	**impossible***
Public-key crypto (‘quantum-safe’)	in development	?

One-time pad



Alice

Bob

Random secret key of same length as message

Random secret key

Message

Message

α	β	$\alpha \oplus \beta$
0	0	0
0	1	1
1	0	1
1	1	0

G. Vernam, U.S. patent 1310719 (filed in 1918, granted 1919)
C. E. Shannon, Bell Syst. Tech. J. **28**, 656 (1949)

A (very) brief history of cryptography

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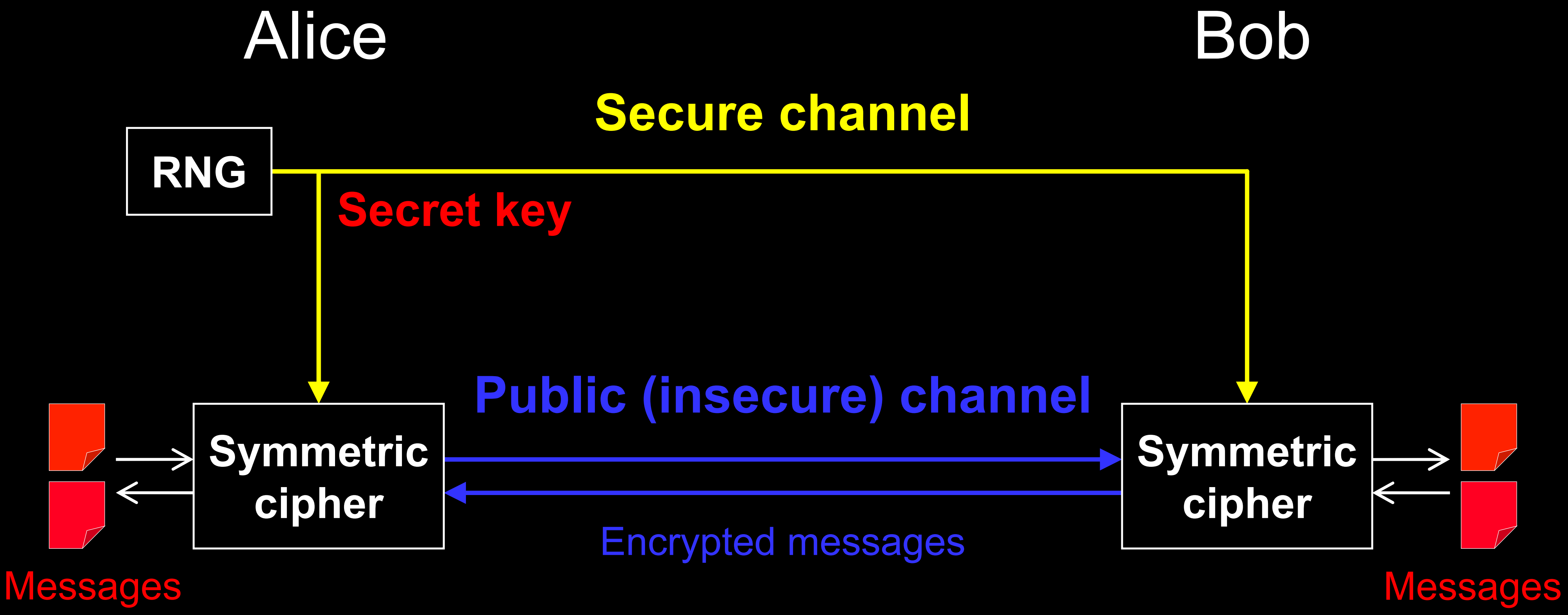
Public-key crypto (‘quantum-safe’)	in development	**?**

Quantum communication primitives	Advantages over classical primitives:		
	Unconditionally secure?	Less resources?	Other quantum advantages?
Money	●		
Key distribution	●		
Secret sharing	●		
Digital signatures	●	●	
Superdense coding		●	
Fingerprinting		●	
Oblivious transfer	Impossible		●
Bit commitment	Impossible		●
Coin-tossing	●		
Cloud computing	●		
Bitcoin		●	
Bell inequality testing	(no classical equivalent)		
Teleportation			
Entanglement swapping			
Interaction-free measurement			
Random number generators	●		

Quantum communication primitives

Money	S. Wiesner, unpublished circa 1970, Sigact News **15**, 78 (1983); S. Aaronson, P. Christiano, Proc. STOC'12, 41 (2012)
Key distribution	idquantique.com, quantum-info.com, qasky.com, goqrate.com
Secret sharing	W. P. Grice *et al.*, Opt. Express **23**, 7300 (2015).
Digital signatures	R. Collins *et al.*, Phys. Rev. Lett. **113**, 040502 (2014)
Superdense coding	C. H. Bennett, S. J. Wiesner, Phys. Rev. Lett. **69**, 2881 (1992)
Fingerprinting	J.-Y. Guan *et al.*, Phys. Rev. Lett. **116**, 240502 (2016)
Oblivious transfer	C. Erven *et al.*, Nat. Commun. **5**, 3418 (2014)
Bit commitment	T. Lunghi *et al.*, Phys. Rev. Lett. **111**, 180504 (2013)
Coin-tossing	A. Pappa *et al.*, Nat. Commun. **5**, 3717 (2014)
Cloud computing	S. Barz *et al.*, Science **335**, 303 (2012)
Bitcoin	J. Jogenfors, arXiv:1604.01383
Bell inequality testing	B. Hensen *et al.*, Nature **526**, 682 (2015)
Teleportation	X.-S. Ma *et al.*, Nature **489**, 269 (2012)
Entanglement swapping	M. Żukowski *et al.*, Phys. Rev. Lett. **71**, 4287 (1993)
Interaction-free measurement	A. C. Elitzur, L. Vaidman, Found. Phys. **23**, 987 (1993)
Random number generators	idquantique.com, picoquant.com

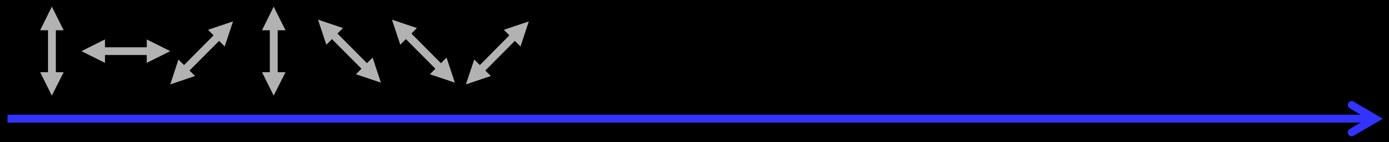
Key distribution for encryption



Quantum key distribution transmits secret key by sending quantum states over *open channel.*

Quantum key distribution (QKD)

Alice



Bob

Prepares photons

↔ (0), ↕ (1)

↘ (0), ↗ (1)

✚ or ✕ ?

Eavesdropping introduces errors

Measures photons

✚

✕

C. H. Bennett, G. Brassard (1984)

Post-processing in QKD

Alice ⟷ **Classical channel** (e.g., internet) ⟷ Bob

Raw photon detection data

↓

Sifting (discard bits Bob failed to detect or detected in incompatible basis)

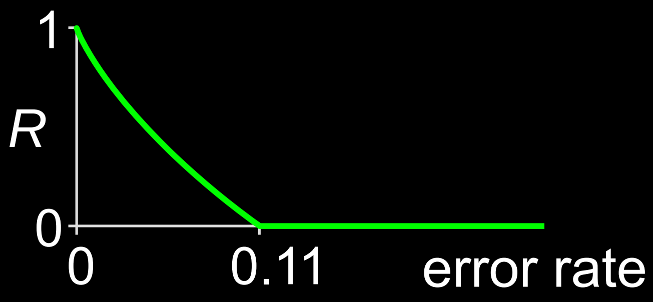
↓

Error correction

↓ error rate

Secret key rate estimation

↓ R



Privacy amplification (compress key using a hash function)

↓

Authentication Alice–Bob ← 1st time: initial short key, or public-key infrastructure

↓

Secret key small fraction

C. H. Bennett *et al.*, J. Cryptology **5**, 3 (1992); N. Lütkenhaus, Phys. Rev. A **59**, 3301 (1999)

Commercial QKD

Classical encryptors:

L2, 2 Gbit/s

L2, 10 Gbit/s

L3 VPN, 100 Mbit/s

WDMs

Key manager

QKD to another node (4 km)

QKD to another node (14 km)

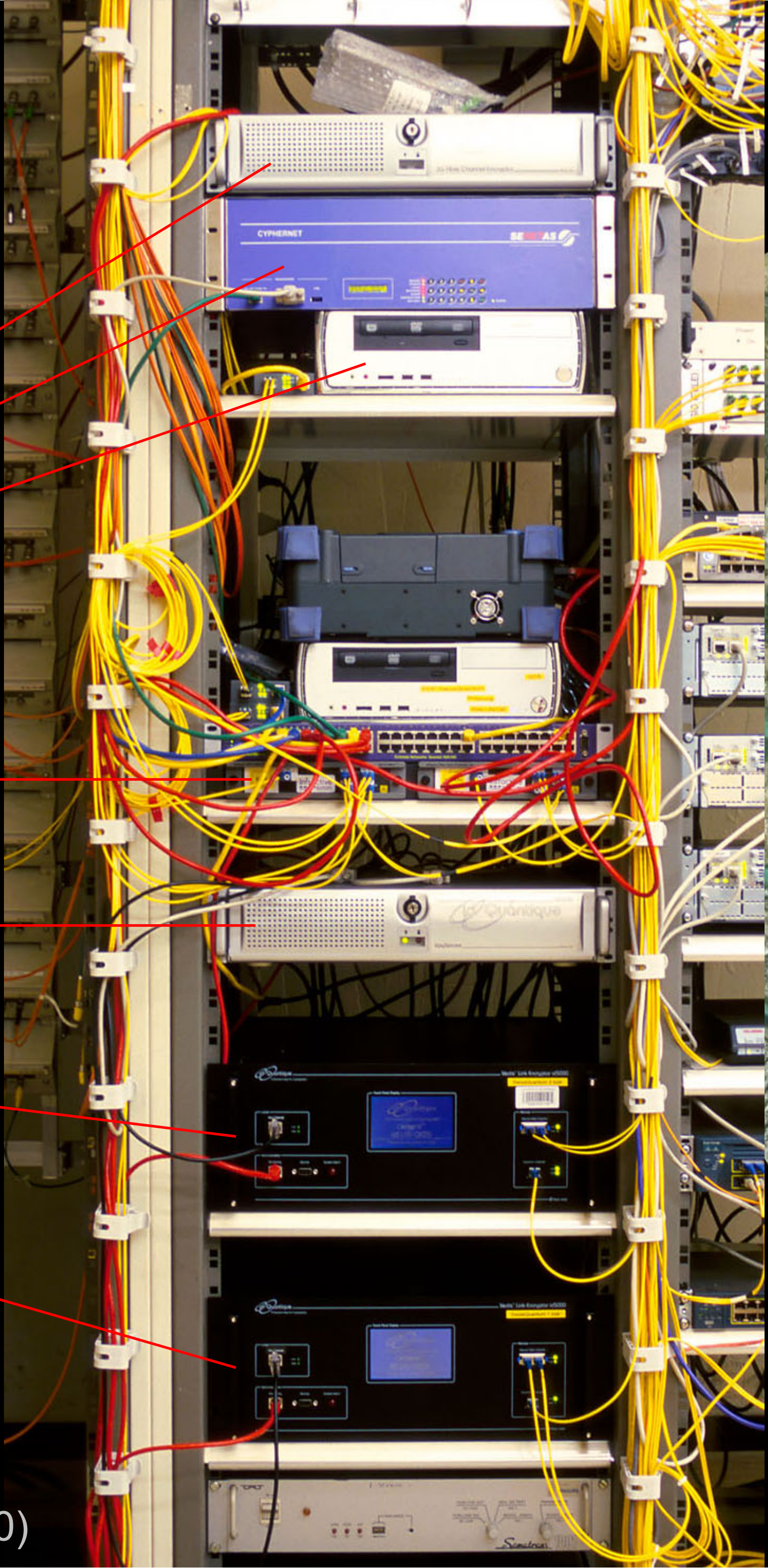
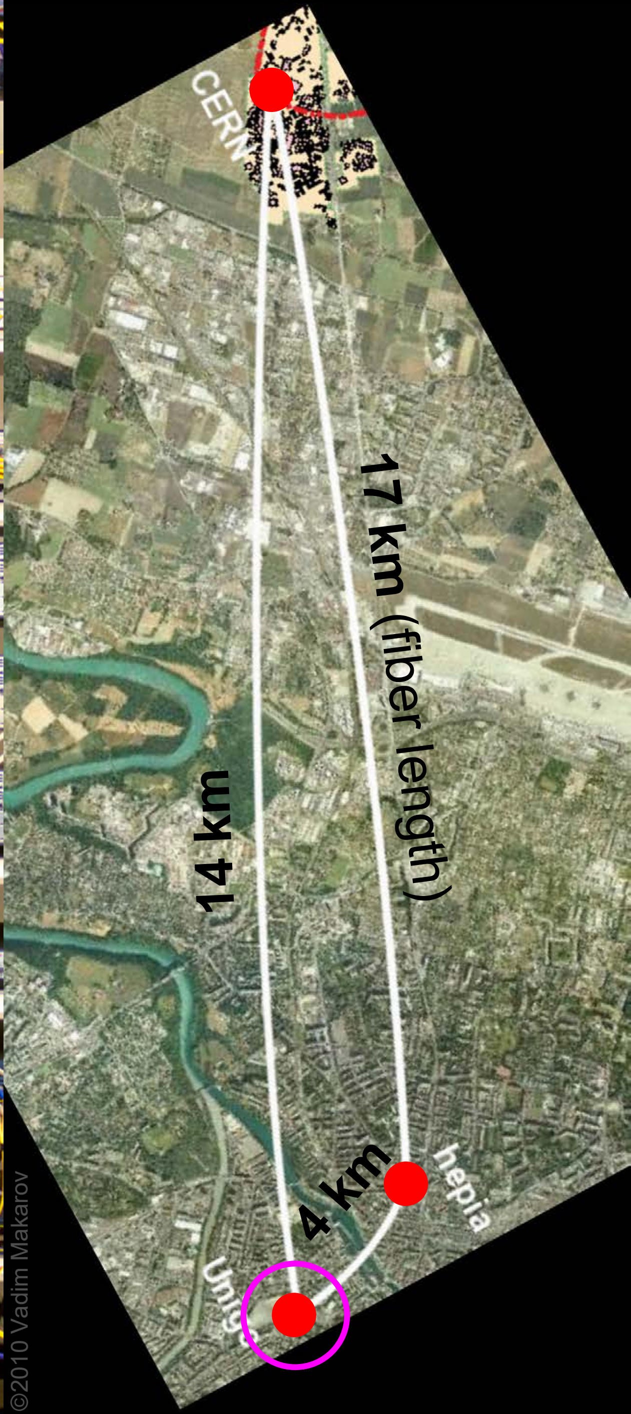
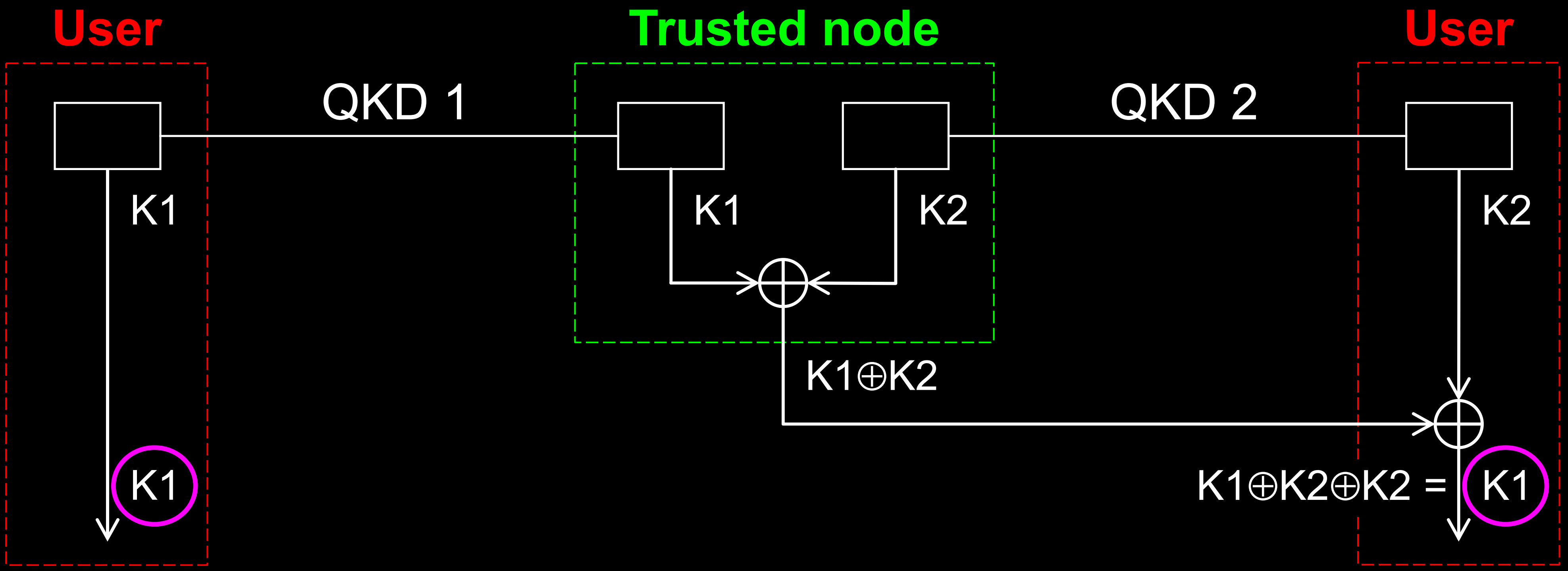


Photo ©2010 Vadim Makarov



www.swissquantum.com
ID Quantique *Cerberis* system (2010)

Today: trusted-node repeater



User

Trusted node

User

QKD 1

QKD 2

K1

K1

K2

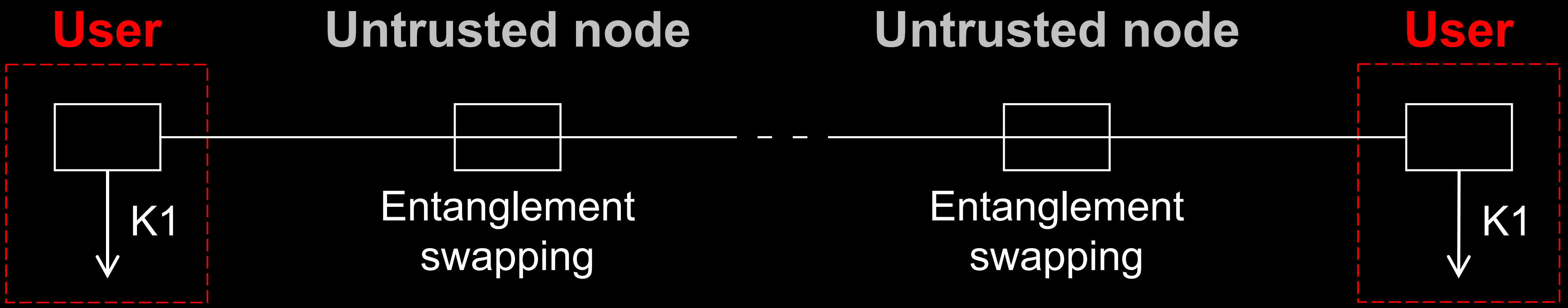
K2

$K1 \oplus K2$

K1

$K1 \oplus K2 \oplus K2 =$ K1

Future: quantum repeater



User

Untrusted node

Untrusted node

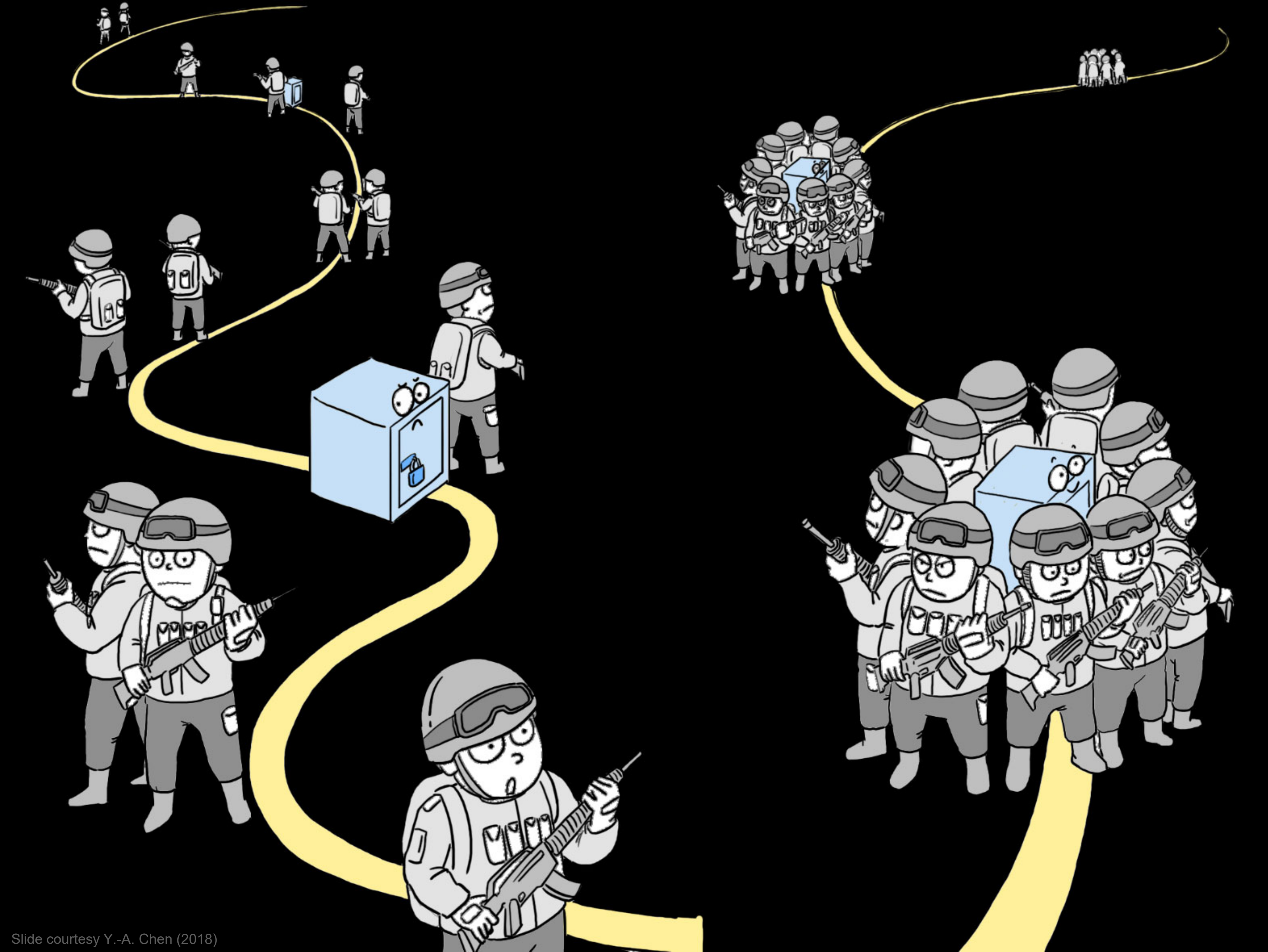
User

K1

Entanglement swapping

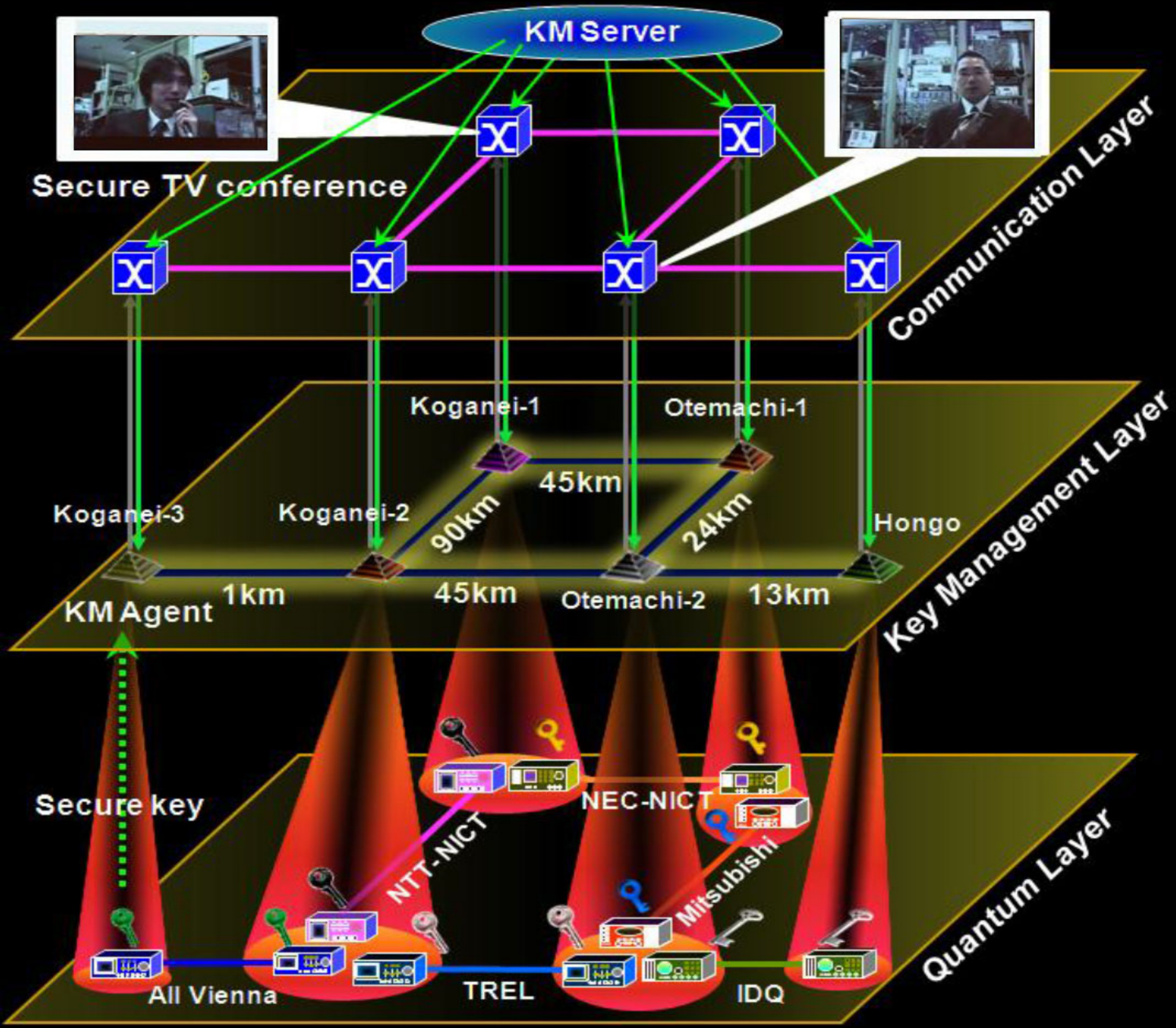
Entanglement swapping

K1



Slide courtesy Y.-A. Chen (2018)

Trusted-node network



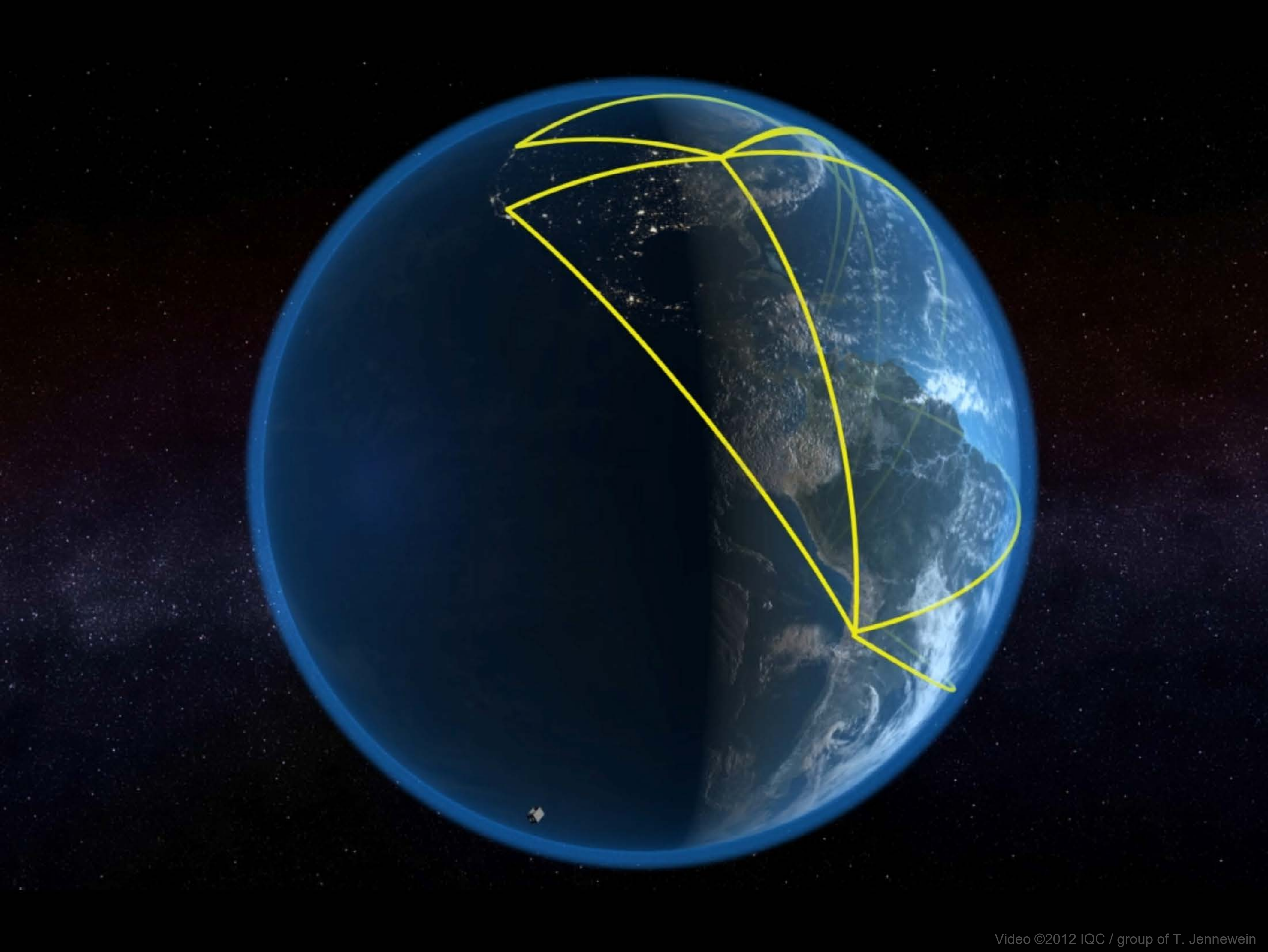
M. Sasaki *et al.*, Opt. Express **19**, 10387 (2011)

Photo ©2016 Vadim Makarov

Shanghai control center of the Chinese quantum key distribution network and satellite

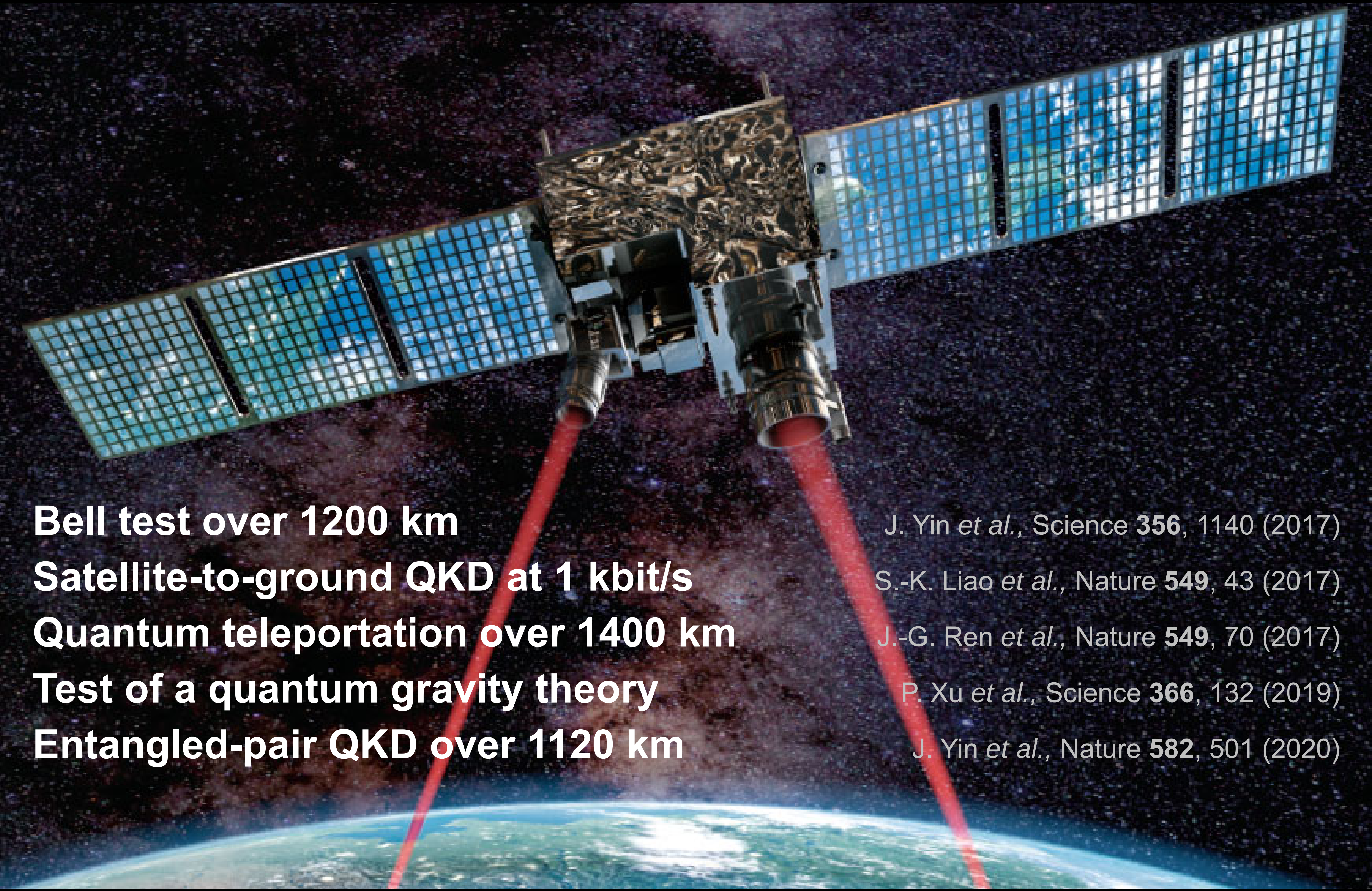
Global quantum key distribution

Video ©2012 IQC / group of T. Jennewein



Video ©2012 IQC / group of T. Jennewein

Chinese quantum satellite Micius (launched 2016)

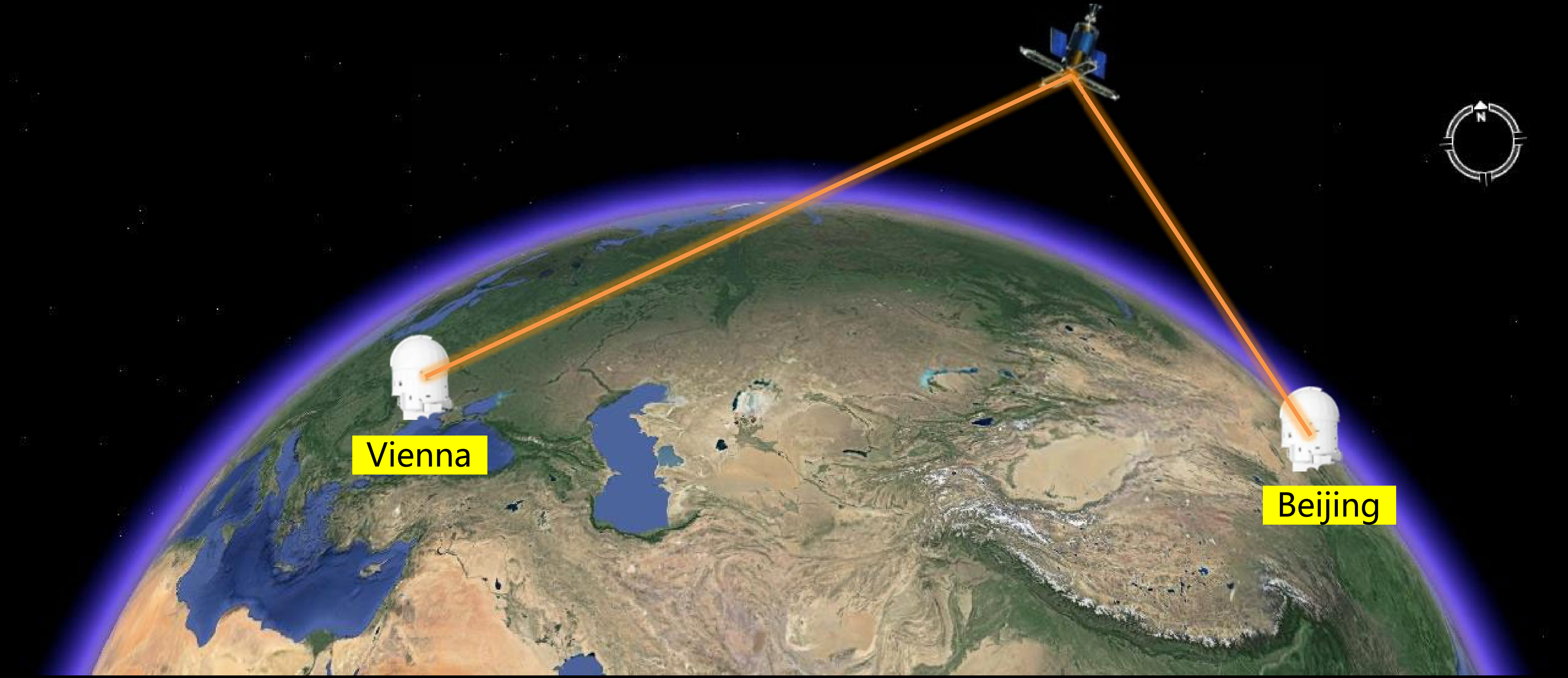


Bell test over 1200 km	J. Yin *et al.*, Science **356**, 1140 (2017)
Satellite-to-ground QKD at 1 kbit/s	S.-K. Liao *et al.*, Nature **549**, 43 (2017)
Quantum teleportation over 1400 km	J.-G. Ren *et al.*, Nature **549**, 70 (2017)
Test of a quantum gravity theory	P. Xu *et al.*, Science **366**, 132 (2019)
Entangled-pair QKD over 1120 km	J. Yin *et al.*, Nature **582**, 501 (2020)

Graphics ©2017 C. Bickel / Science

CAS Strategic Priority Research Program: Quantum Satellite

- Intercontinental quantum key distribution



Presentation by Jian-Wei Pan at TyQI conference, Shanghai, June 27–30, 2016