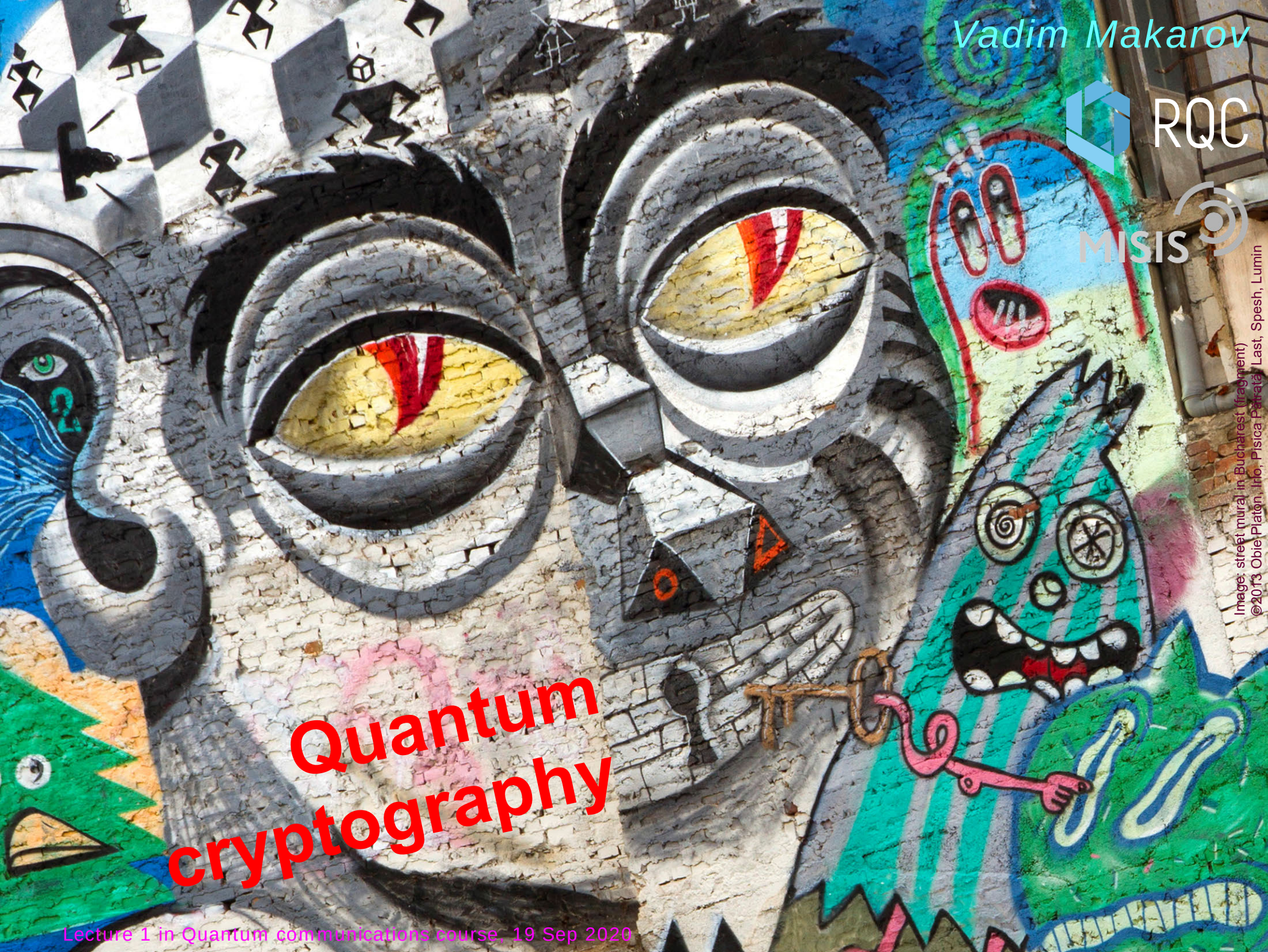

Quantum cryptography

Vadim Makarov

RQC

MISIS

Lecture 1 in Quantum communications course, 19 Sep 2020

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

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

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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Quantum cryptography	invented 1984, in development	**impossible***
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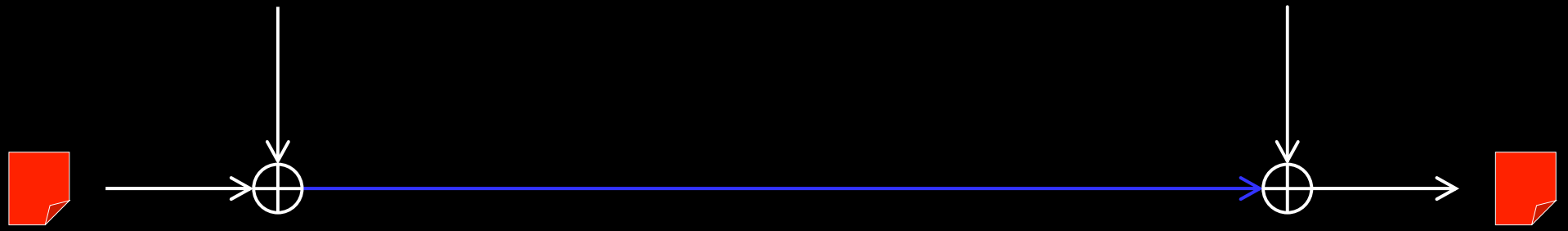
One-time pad

Alice

Bob

Random
secret key of same length as message

Random
secret key



Message

Message

α	β	α⊕β
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)

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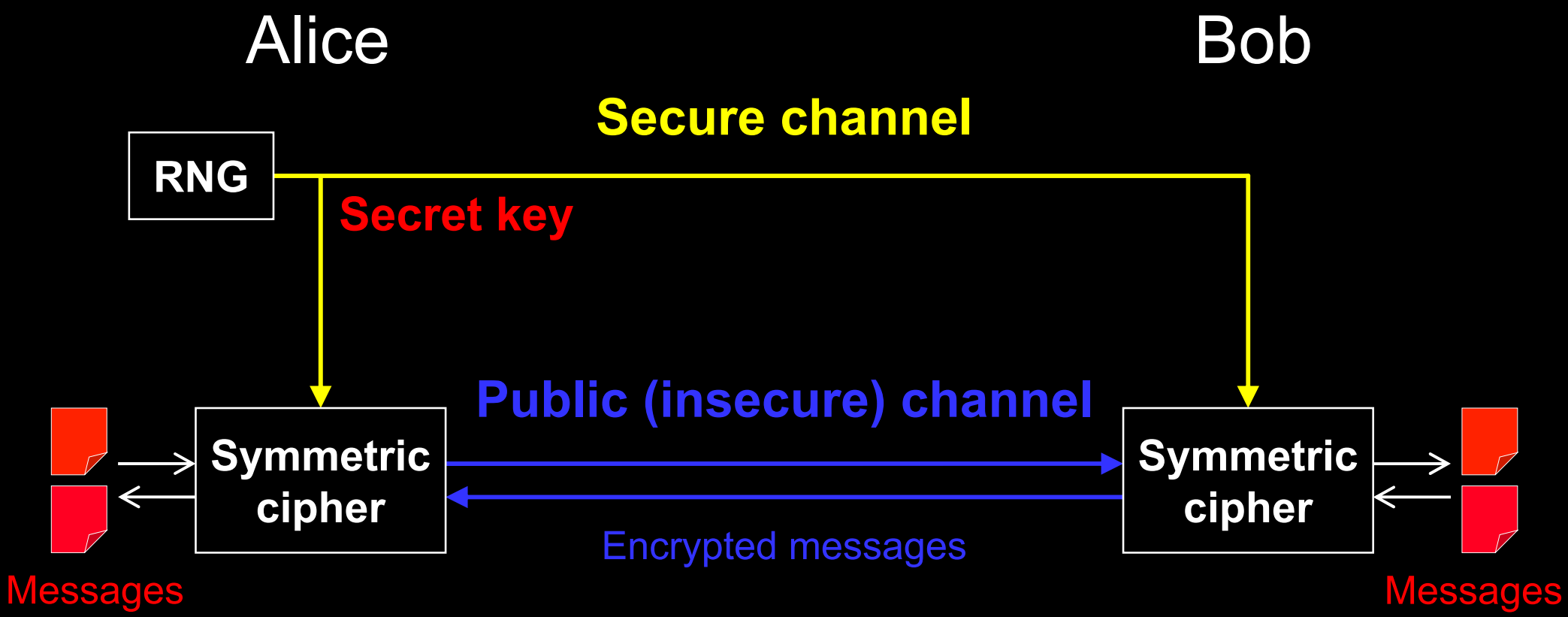
Quantum communication primitives	Advantages over classical primitives: Unconditionally secure?	Less resources?	Other quantum advantages?
Money	●		
Key distribution	●		
Secret sharing	●		
Digital signatures	●	●	
Superdense coding		●	
Fingerprinting		●	
Oblivious transfer	Impossible		●
Bit commitment	Impossible		●
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

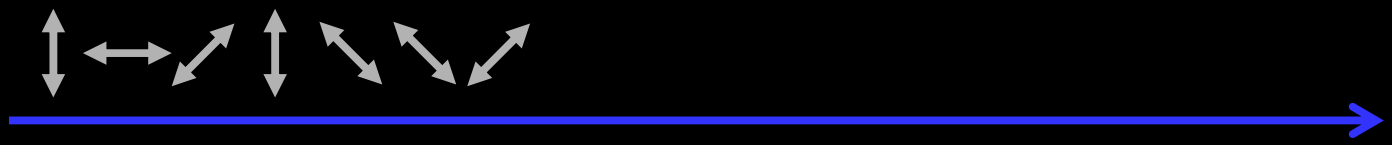


Quantum key distribution transmits secret key by sending quantum states over *open channel.*

Quantum key distribution (QKD)

Alice

Bob



Prepares photons

or ?

Measures photons

(0), (1)

(0), (1)

Eavesdropping introduces errors

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)

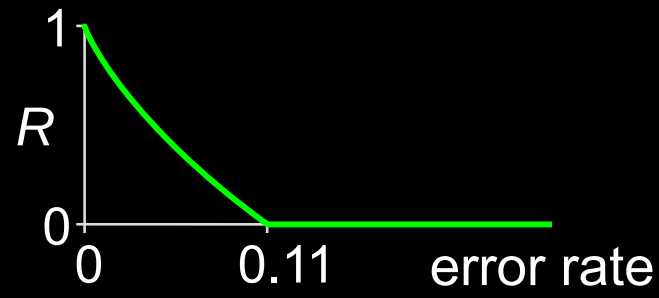
↓

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 → **Authentication Alice–Bob**

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)

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

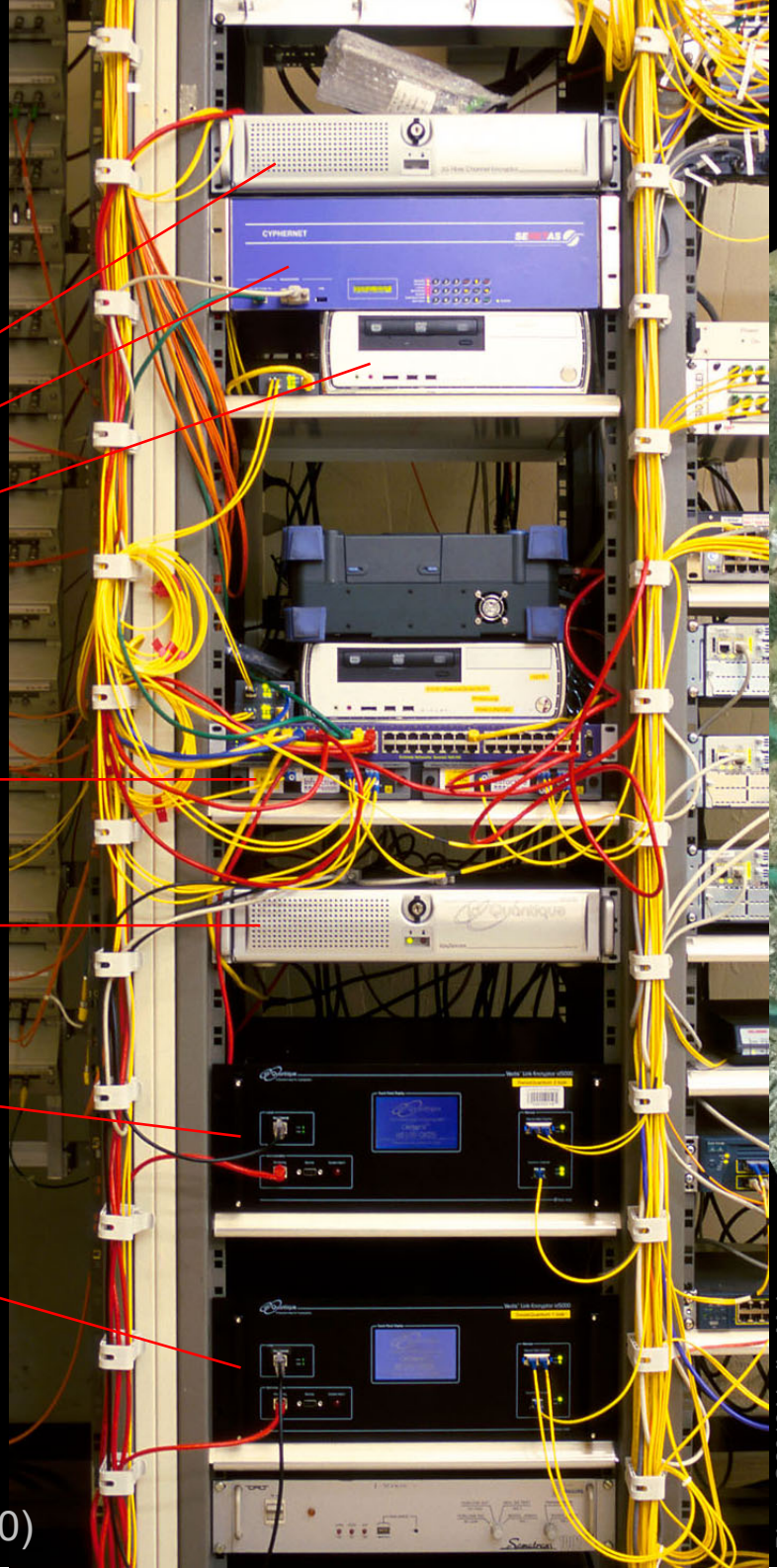
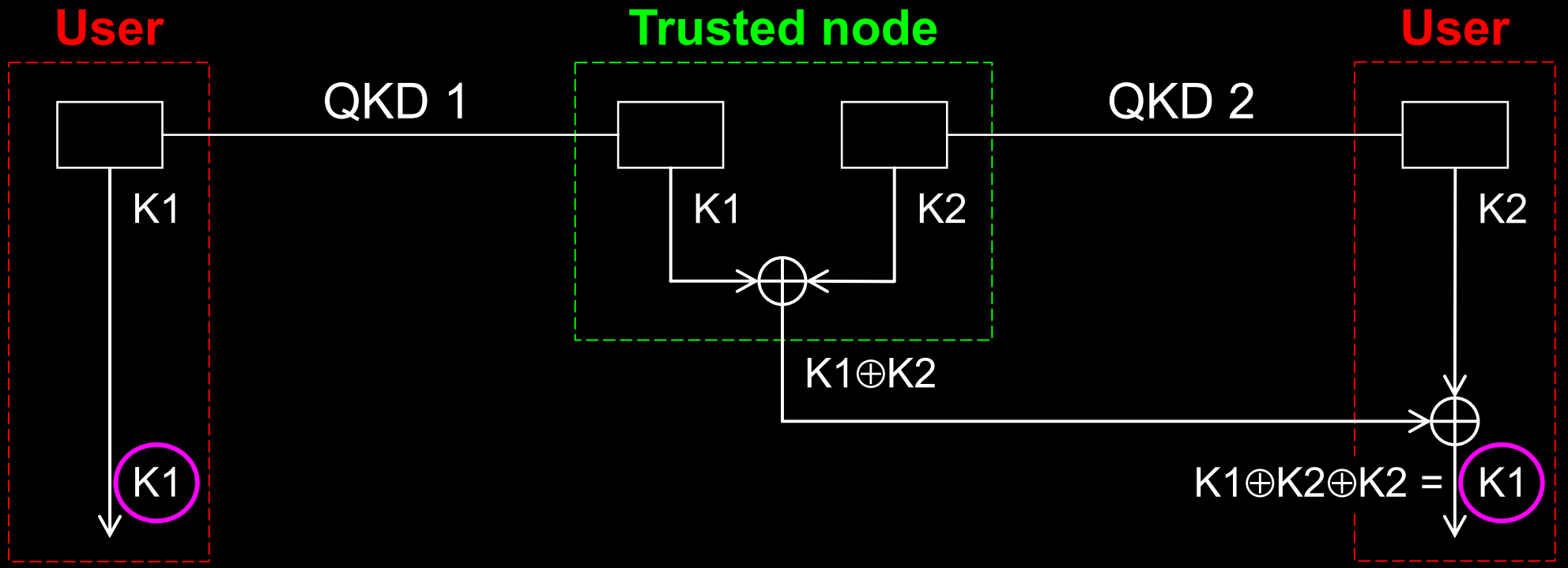
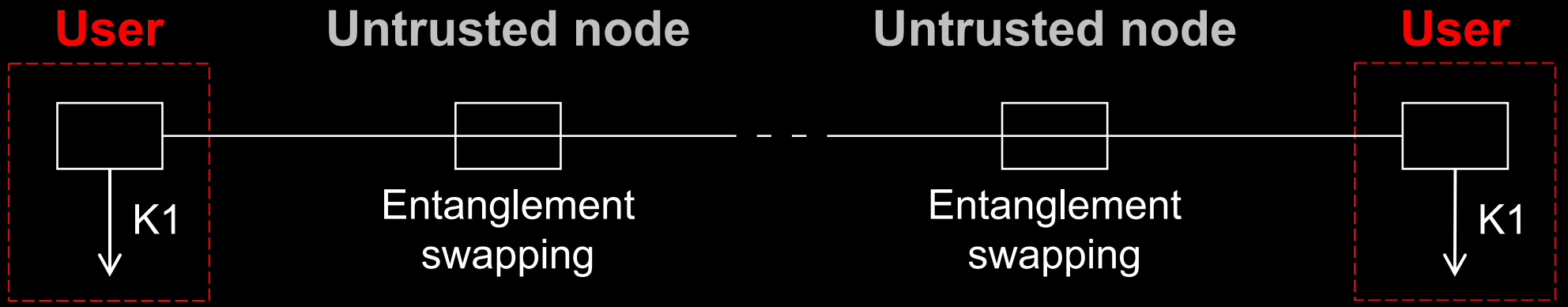


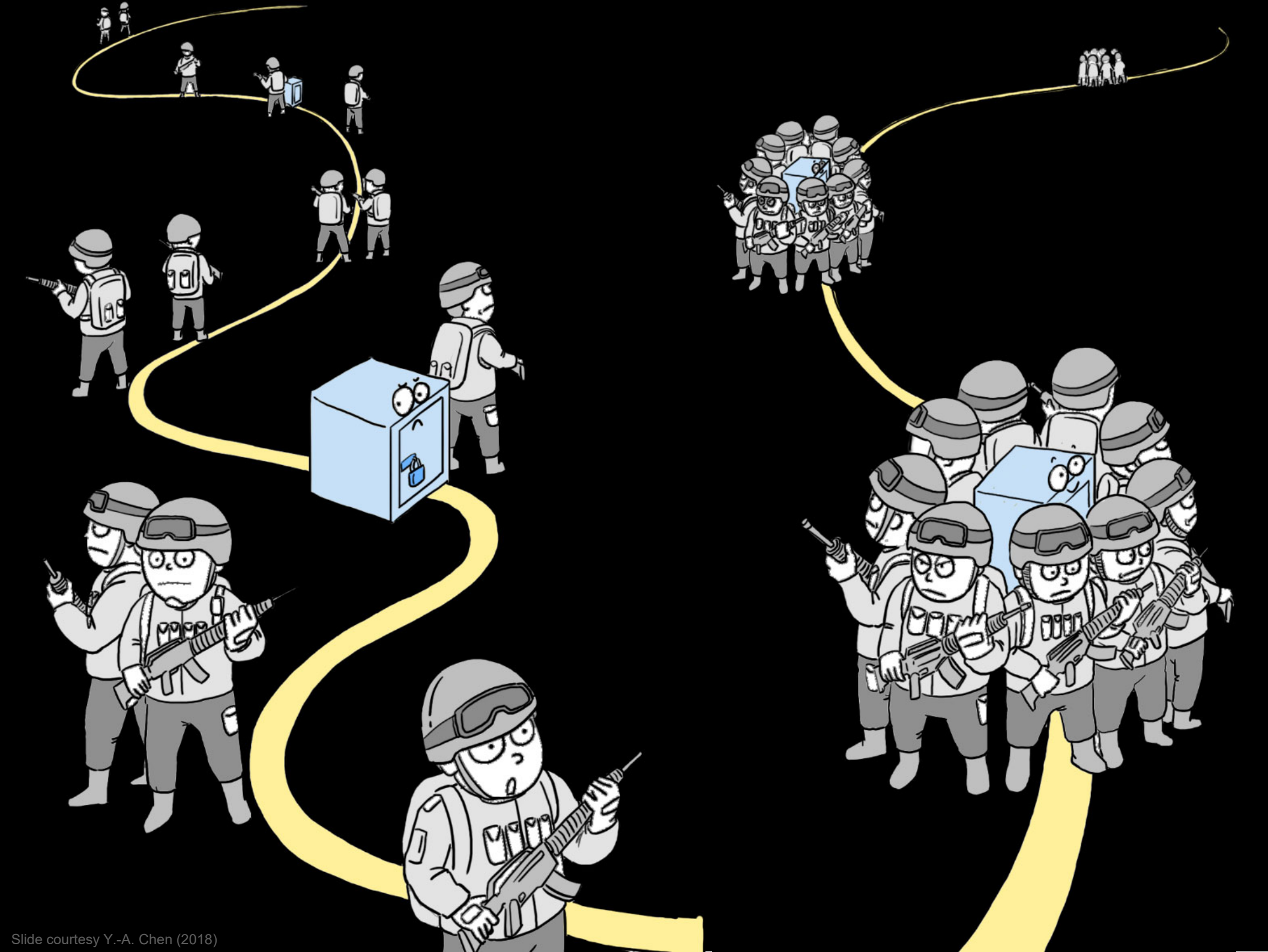
Photo ©2010 Vadim Makarov

Today: trusted-node repeater



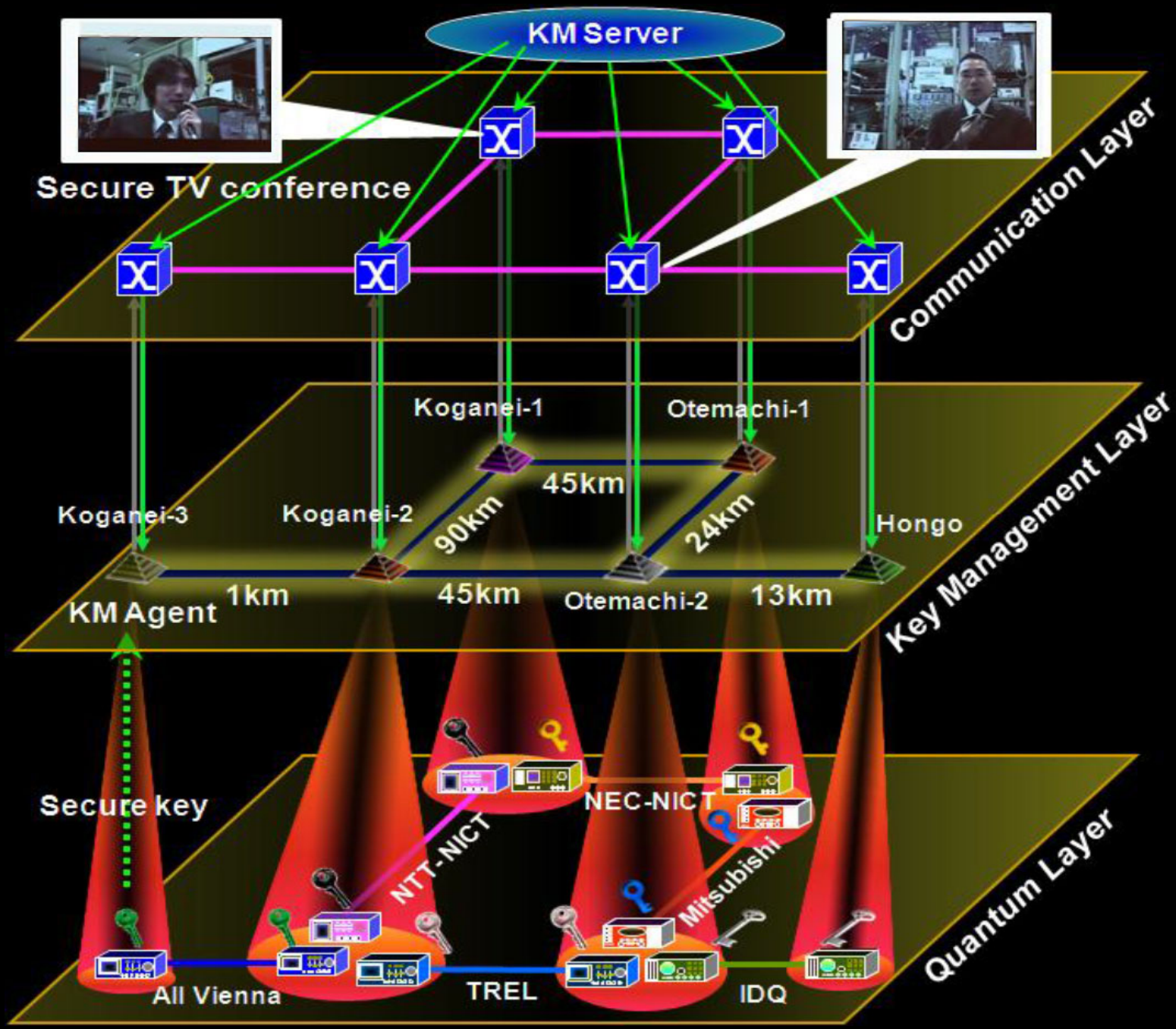
Future: quantum repeater





Slide courtesy Y.-A. Chen (2018)

Trusted-node network



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

Quantum Backbone

- Total Length 2000 km
- 2013.6-2016.12
- 32 trustable relay nodes

  31 fiber links
- Metropolitan networks

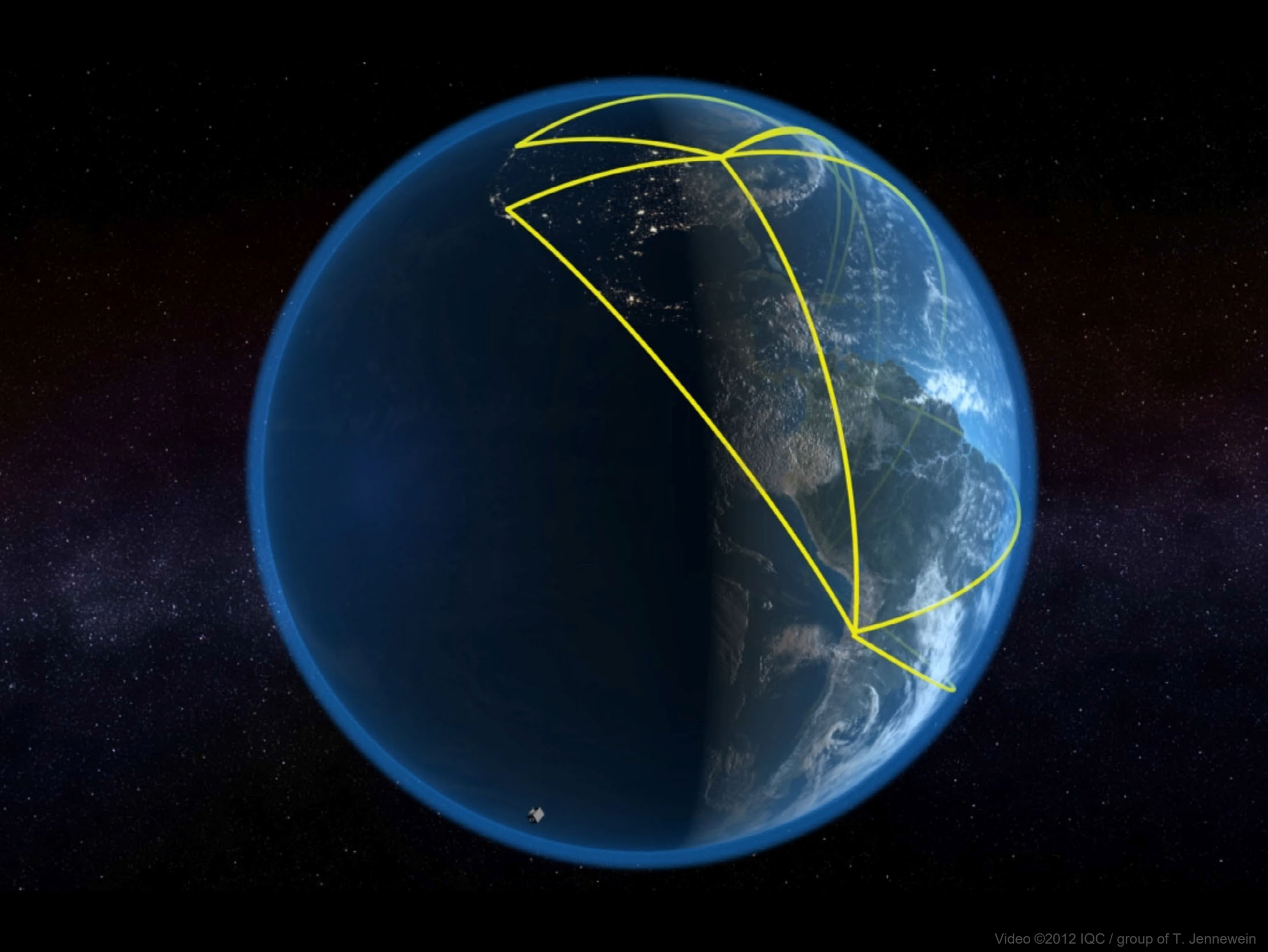
  Existing: Hefei, Jinan

  New: Beijing, Shanghai
- Customer: China Industrial & Commercial Bank; Xinhua News Agency; CBRC

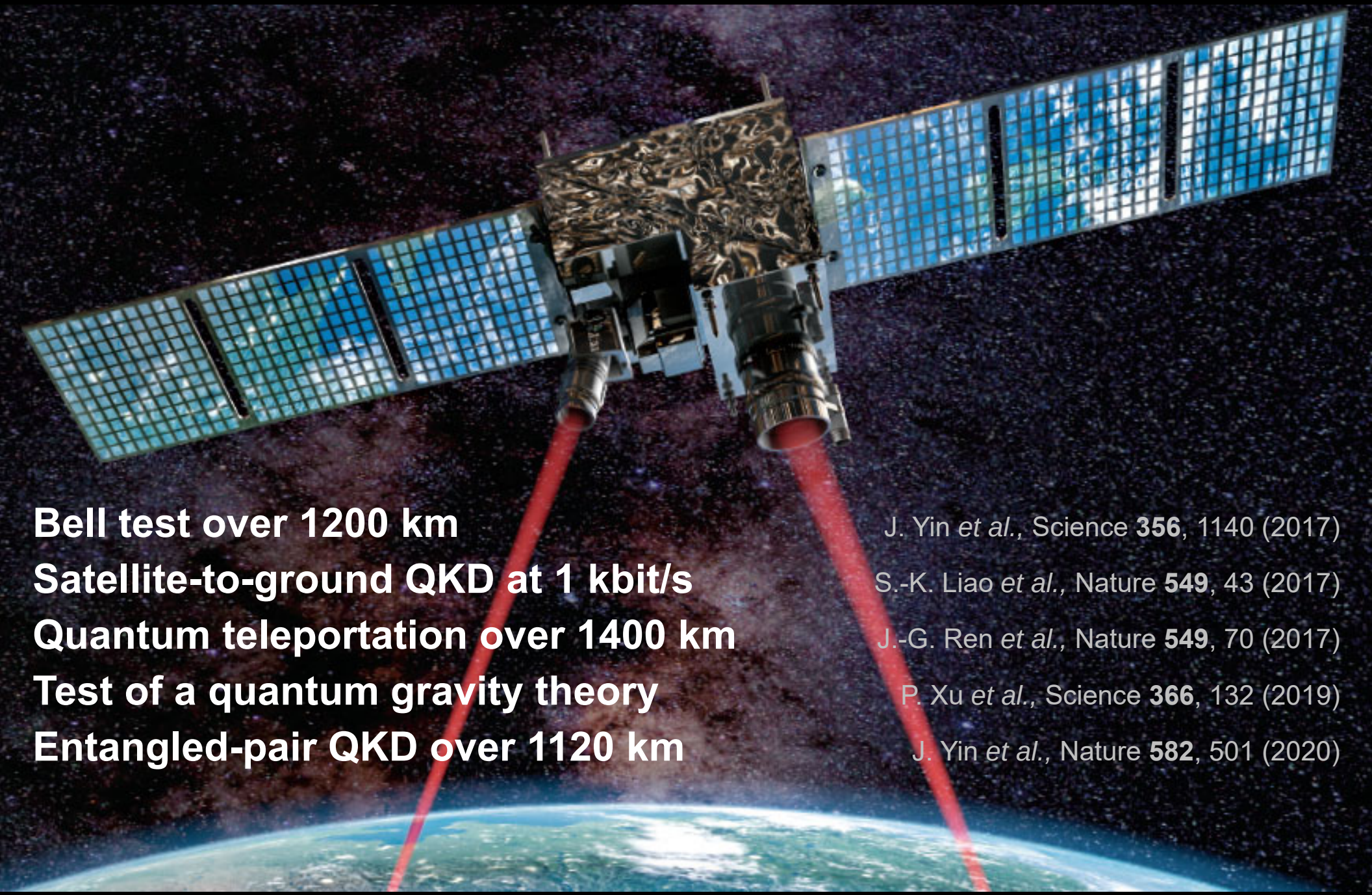
Q. Zhang, talk at QCrypt 2014

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


Global
quantum key distribution
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)

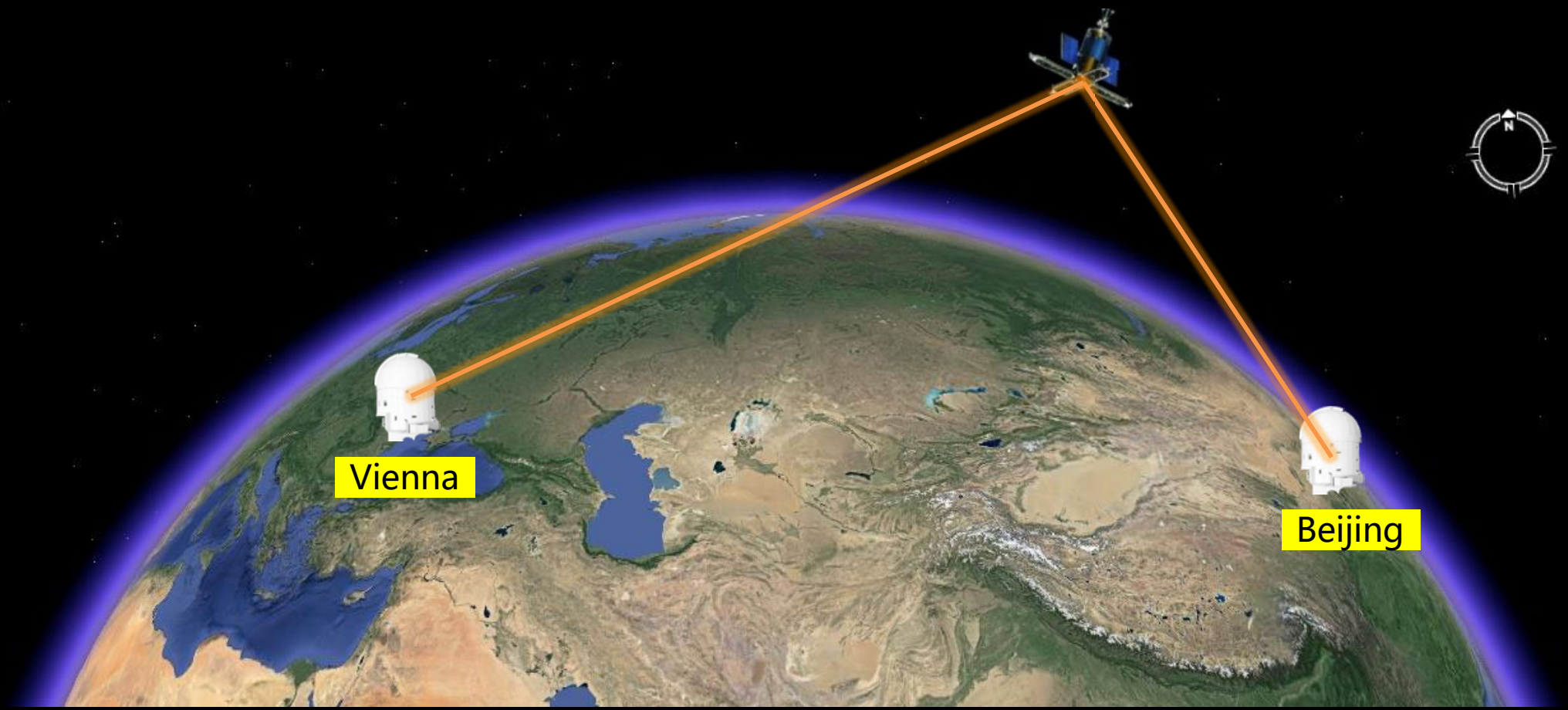
Quantum teleportation over 1400 km — J.-G. Ren *et al.*, Nature **549**, 70 (2017)

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)

CAS Strategic Priority Research Program: Quantum Satellite

- Intercontinental quantum key distribution



Yury Kurochkin (QRATE)

Denis Sych
(theory)

Vadim Makarov
(hacking)

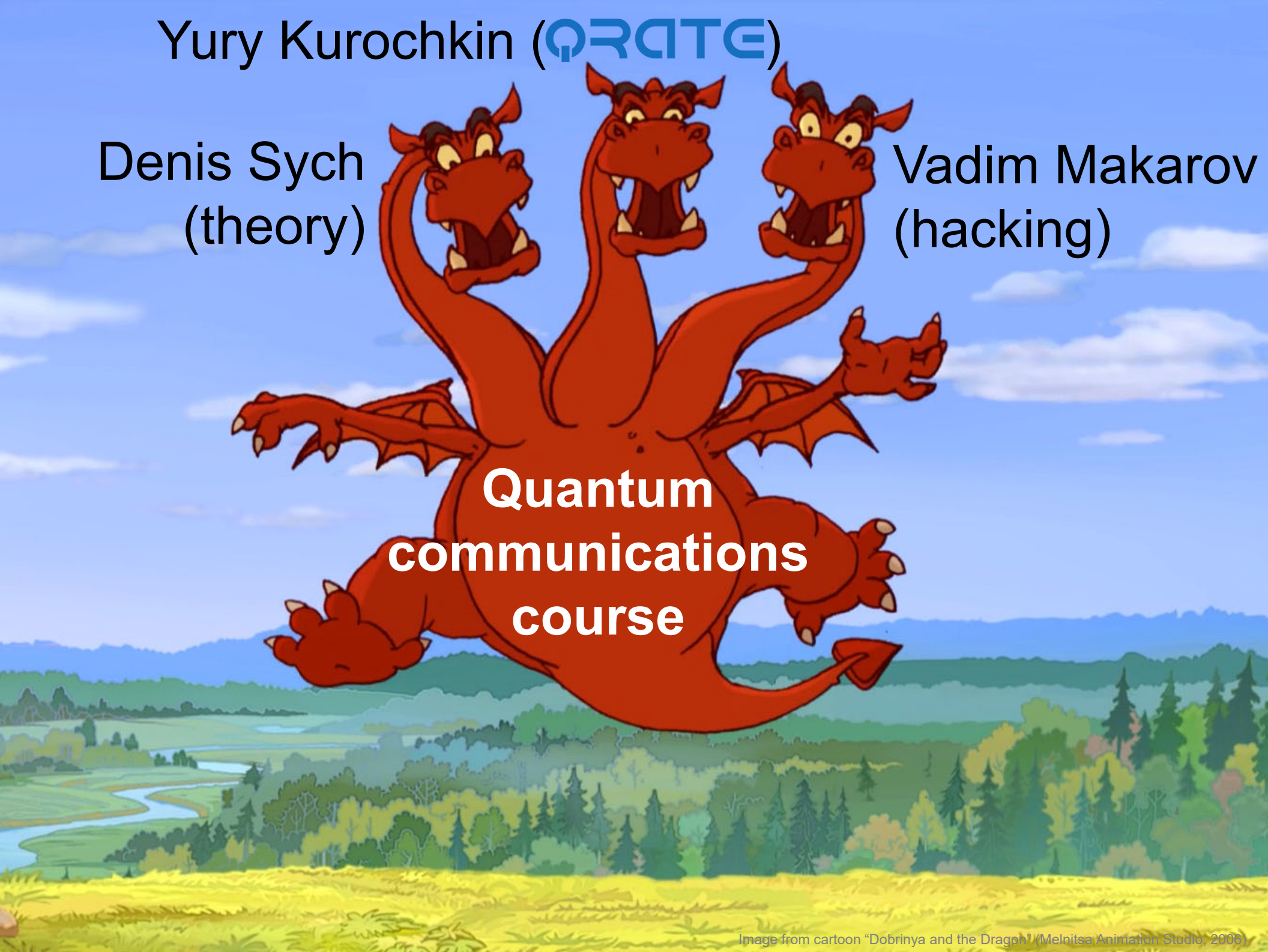
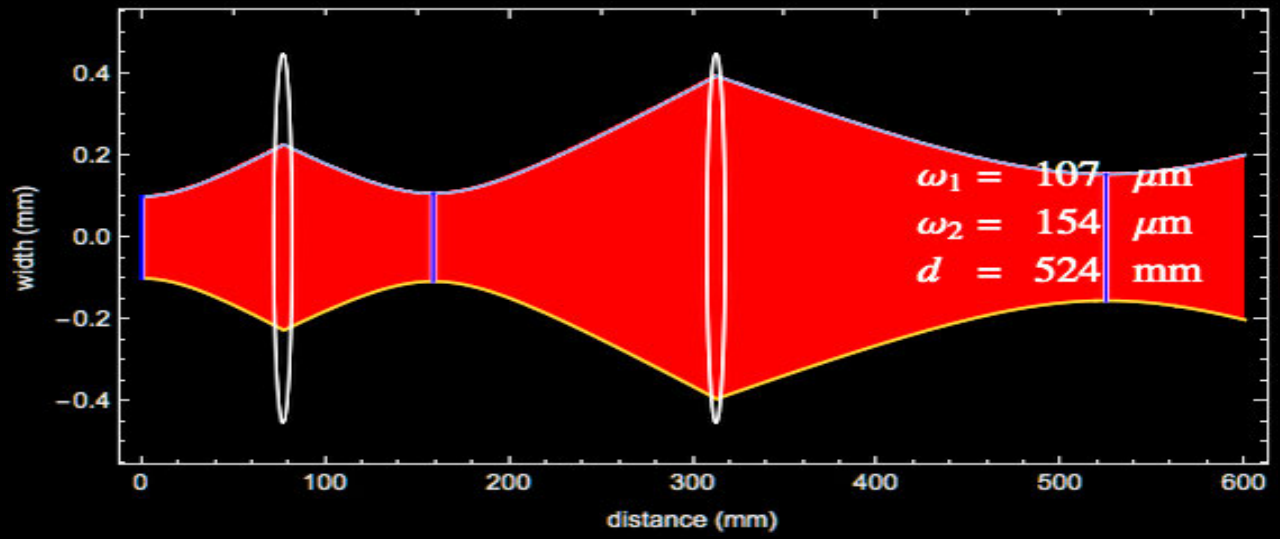


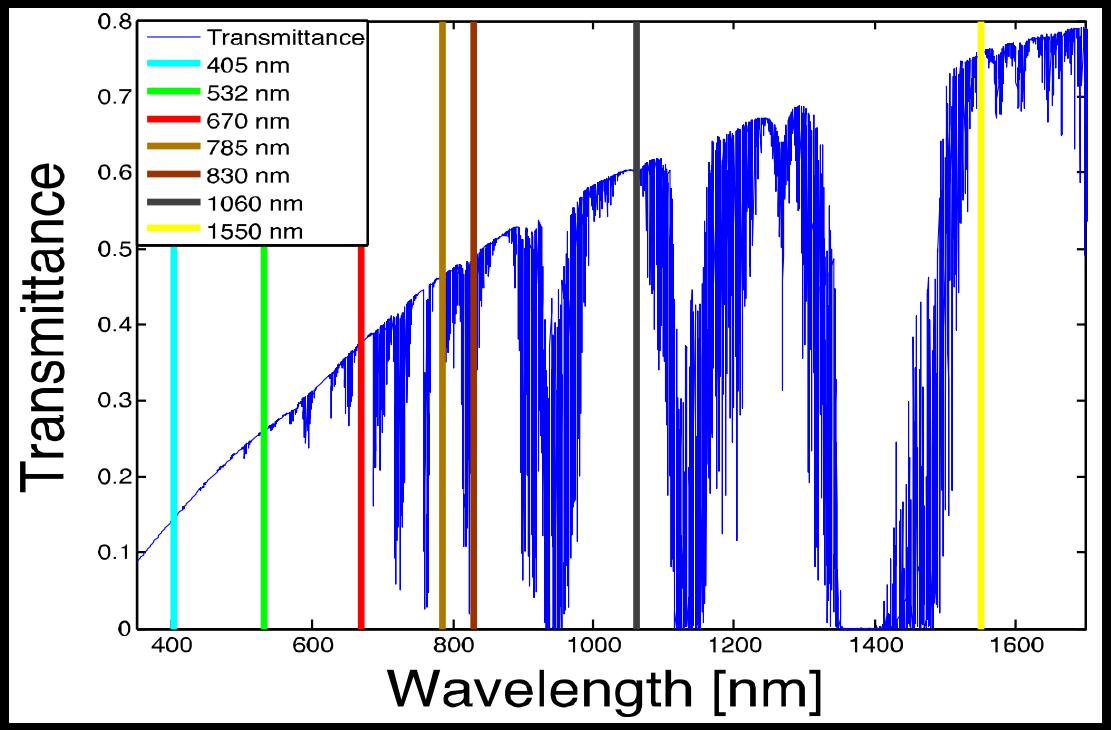
Image from cartoon “Dobrinya and the Dragon” (Melnitsa Animation Studio, 2006)

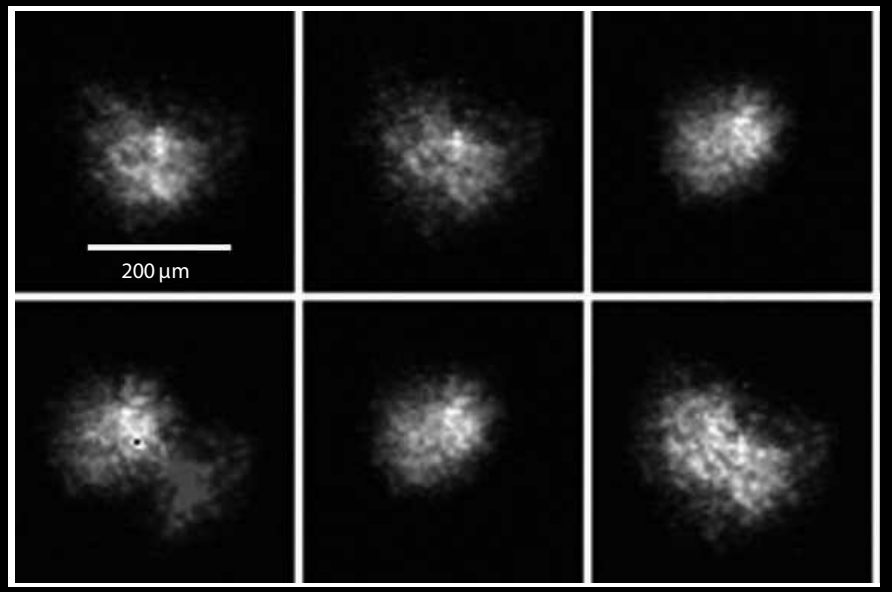
Transmission in free space

Vacuum: Gaussian optics



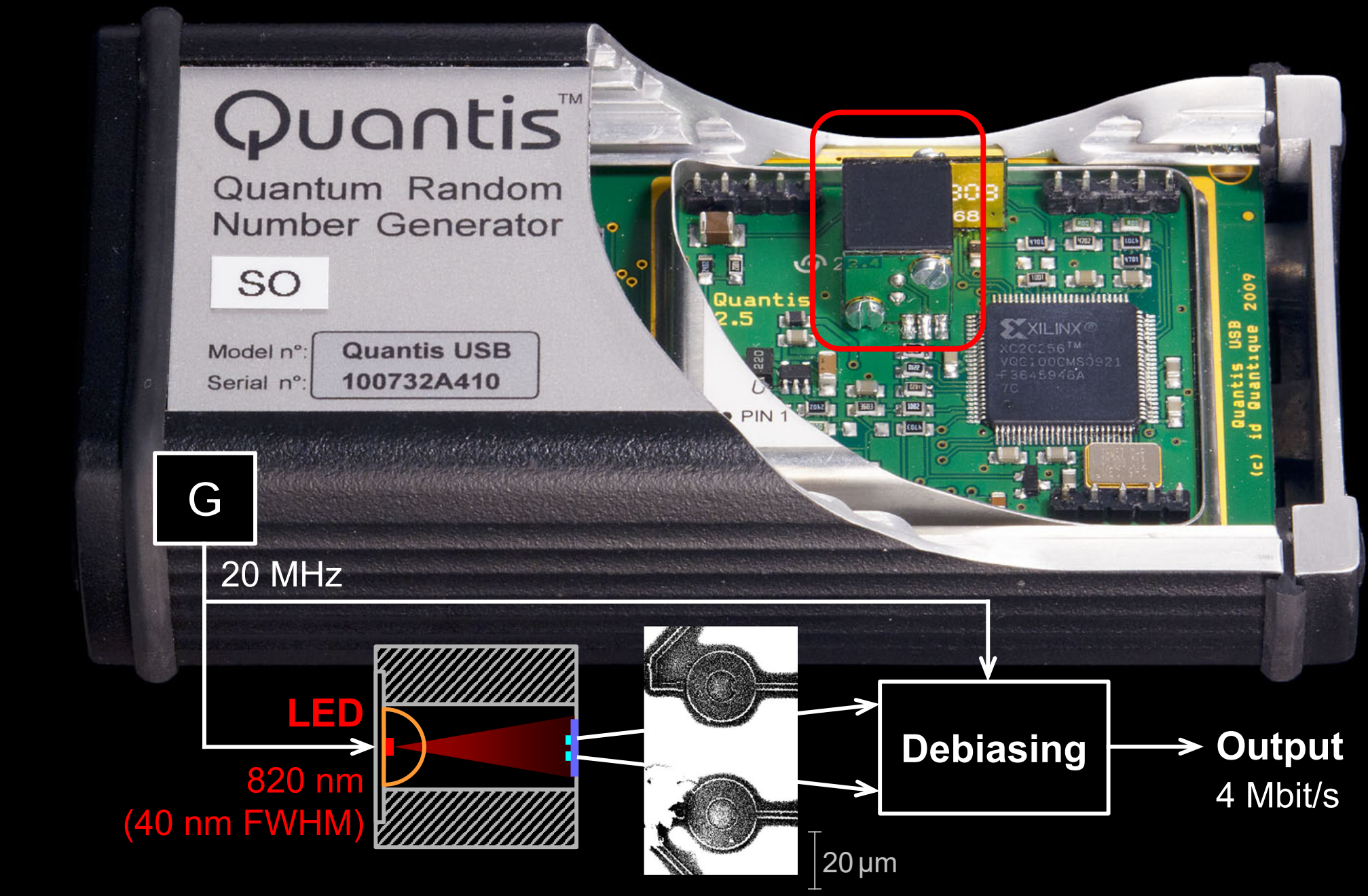
Atmosphere: loss, turbulence





Images reprinted from: https://demonstrations.wolfram.com/GaussianBeamPropagationThroughTwoLenses/; Wikipedia; J.-P. Bourgoin *et al.*, New J. Phys. **15**, 023006 (2013); R. Ursin *et al.*, Nat. Phys. **3**, 481 (2007)

Quantis RNG: what's inside?



G. Ribordy, O. Guinnard, US patent appl. US 2007/0127718 A1 (filed in 2006)
M. Petrov, I. Radchenko *et al.*, arXiv:2004.04996