Overview of International Quantum Networking Efforts

Liang Jiang
University of Chicago

The Quantum Internet Blueprint Workshop
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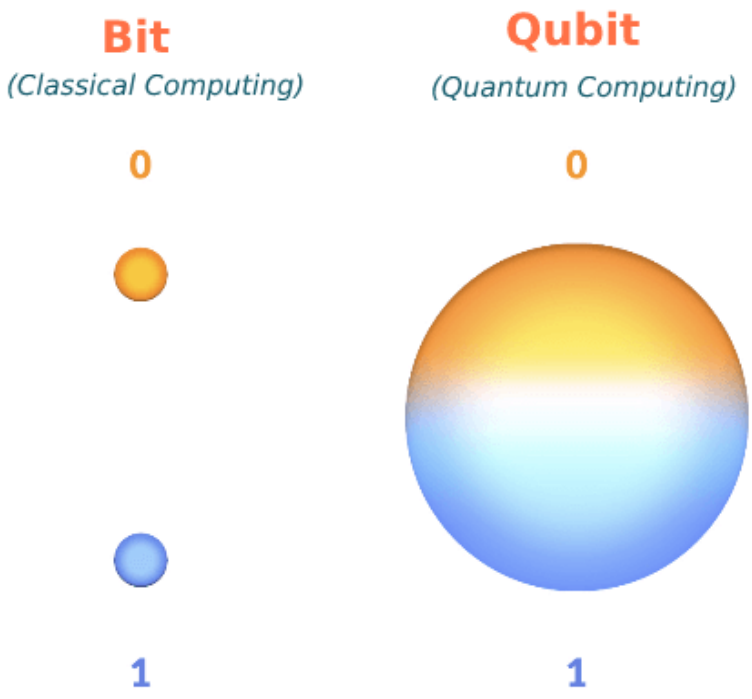
PRITZKER SCHOOL OF
MOLECULAR ENGINEERING

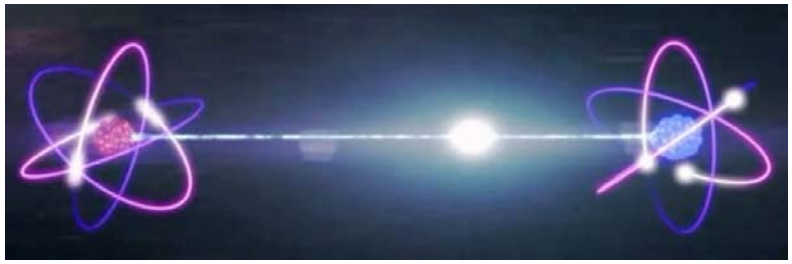
Two Key Ingredients in Quantum Information Processing

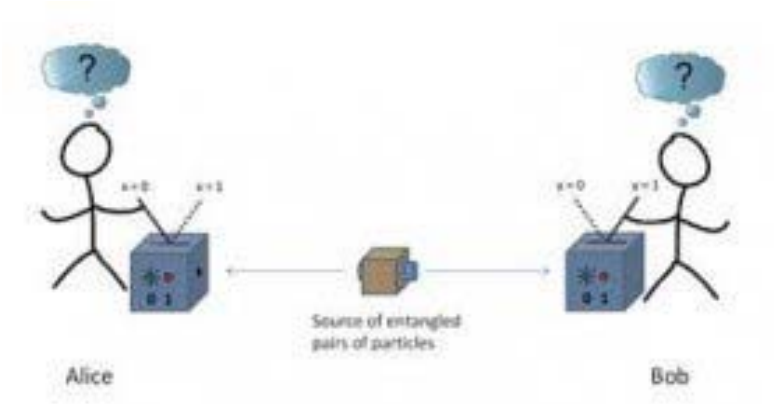
Superposition



Speed up computation, simulation, sensing …

Entanglement





Enable communication security, teleportation

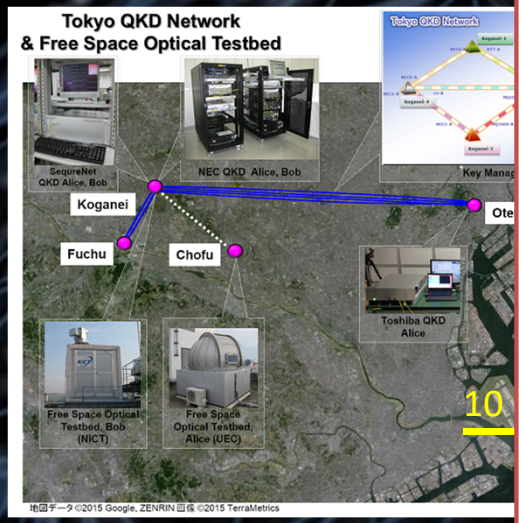
Quantum Networks

Key Ingredient: Entanglement

- Secure communication
- Secure quantum computing in the cloud
- Clock synchronization & quantum sensors
- Quantum games, …

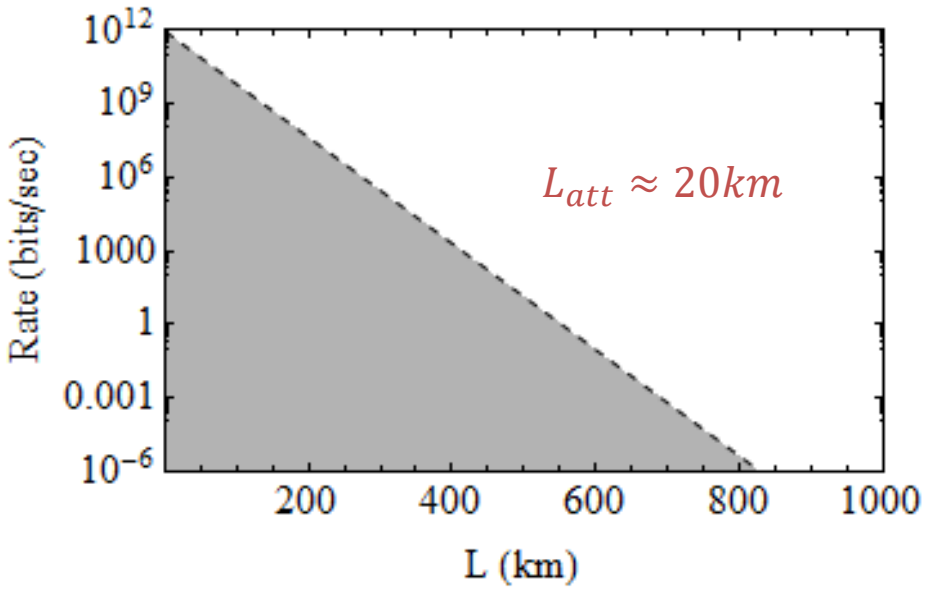
Quantum Networks

Tokyo QKD Network (20

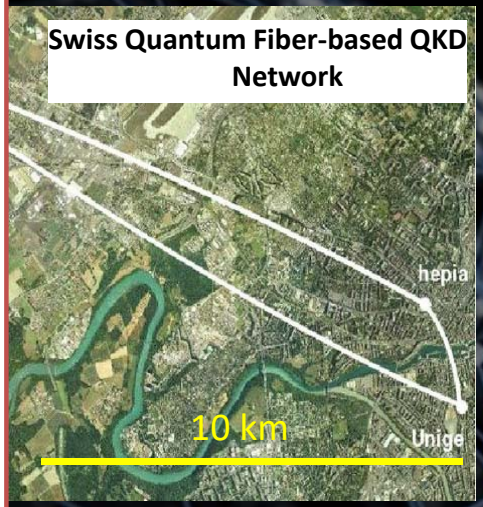


Major Challenge:

Attenuation in Quantum Communication Channel



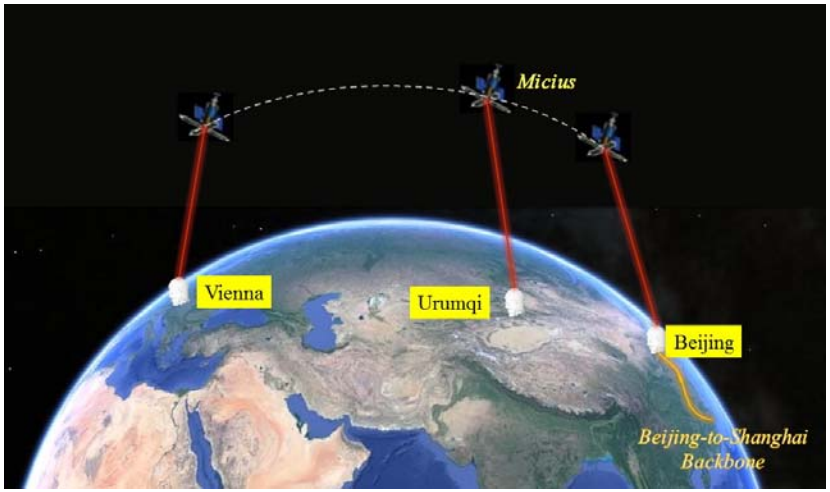
-based QKD Network (2011)



Takeoka, Guha & Wilde, Nature Commun. (2014). Pirandola, Laurenza, Ottaviani, & Banchi, Nature Commun. (2015)

Different Approaches to Overcome Attenuation

Solution 1: Satellite based Quantum Links



Recently launched quantum satellite.

- *Advantage: Long distance*
- *Challenges: limited bandwidth, weather dependent, expensive to launch, …*

Liao, et al., Nature 549, 43 (2017)

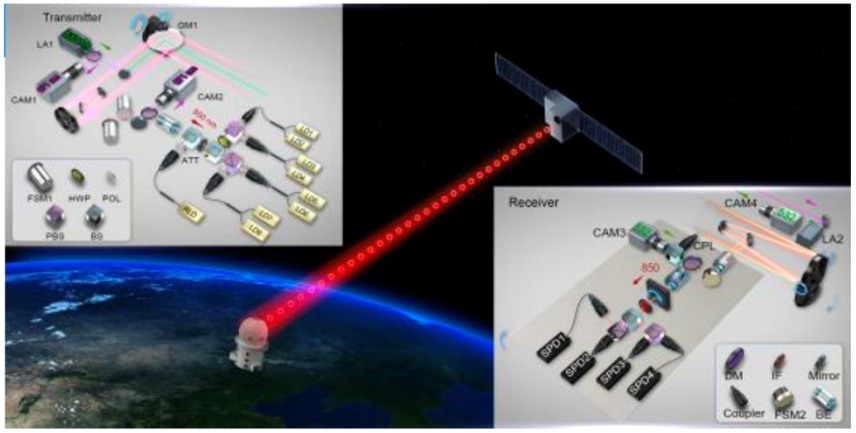
Solution 2: Ground based Quantum Links

Quantum reapters not demonstrated yet …

- *Advantages: Compatible with fiber network, more reliable, high bandwidth, …*
- *Challenges: Need quantum memory, entanglement swapping, …*

Wehner, et al., Science 362, eaam9288 (2018)

China's Quantum Satellite (2016)



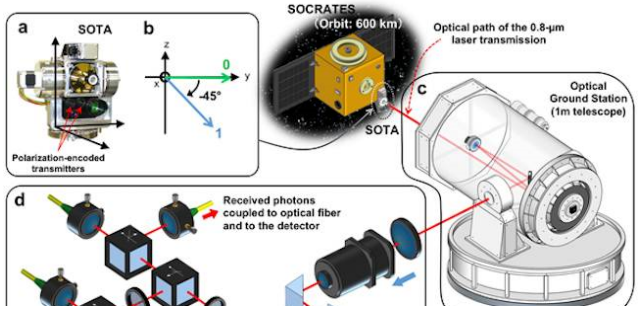
- Satellite: Entanglement source (10 MHz count rate, 600 kg)
- Satellite-Ground (500 ~1200 km): Quantum key distribution (few kHz rate; 35 dB loss)
- Ground-Satellite-Ground (1200 km): Entanglement generation (Hz rate; 70 dB loss)

Nature 549, 43 (2017); Science 356, 1140 (2017)

Worldwide Quantum Satellite Efforts

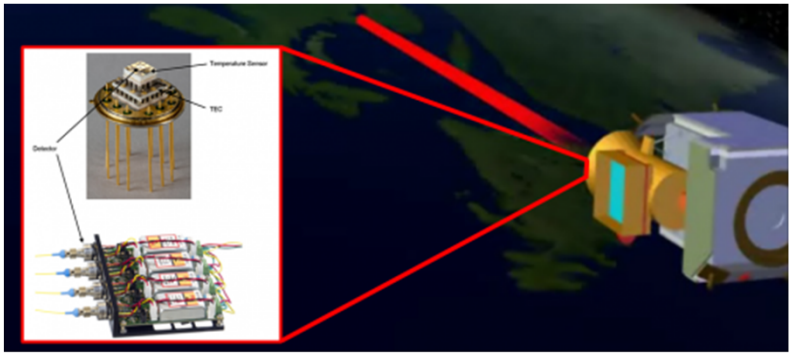
China: Micius Quantum Satellite (launched in 2016)

Japan: SOCRATES satellite (launched 2014, QKD test 2017)
[satellite quantum crypto-technology (planning?)]



Singapore-UK: "QKD Qubesat" Satellite (~2021)

Canada: Quantum Encryption & Science Satellite (~2022)



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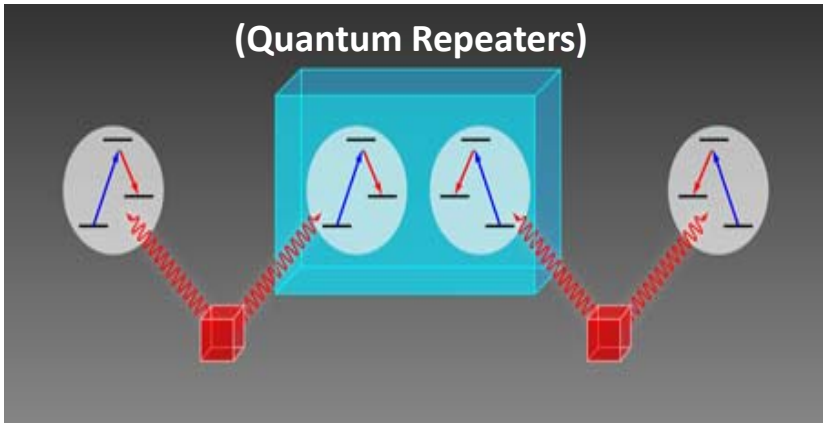


Quantum reapters not demonstrated yet …

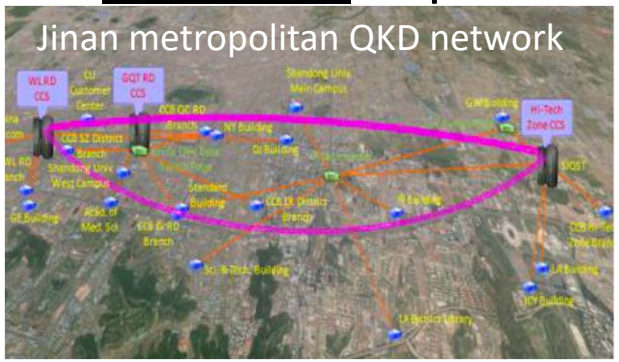
- *Advantages: Compatible with fiber network, more reliable, high bandwidth, …*
- *Challenges: Entanglement swapping, quantum memory, operation errors, …*

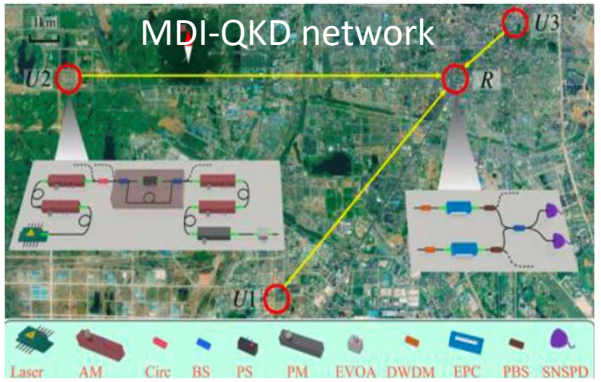
Liao, et al., Nature 549, 43 (2017)

Wehner, et al., Science 362, eaam9288 (2018)

China: Beijing-Shanghai Trunk Line (2000 km, 2017)

- 2000 km over Beijing-Jinan-Heifei-Shanghai
- 32 Trusted Nodes
- Bandwidth 20 kbits/sec
- Additional trunk lines (e.g,. Wuhan-Hefei 300 km & Shanghai-Hangzhou 260 km in 2018)
- Long-term Goal: Quantum Networks with *Untrusted* Repeater Nodes

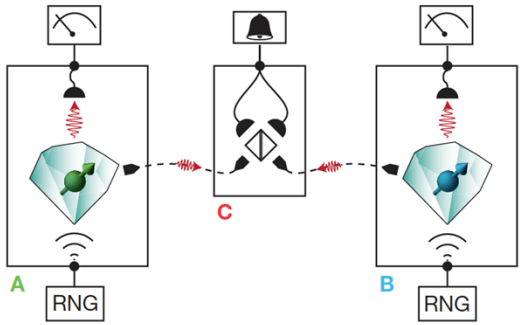




Qiu, et al., Nature 508, 441 (2014)

Europe: Delft Quantum Network

Loophole free Bell Test (1.3 km, 2015)



Delft (4-node) quantum network

Theory: Quantum Network Simulators & Quantum Link Layer Protocol

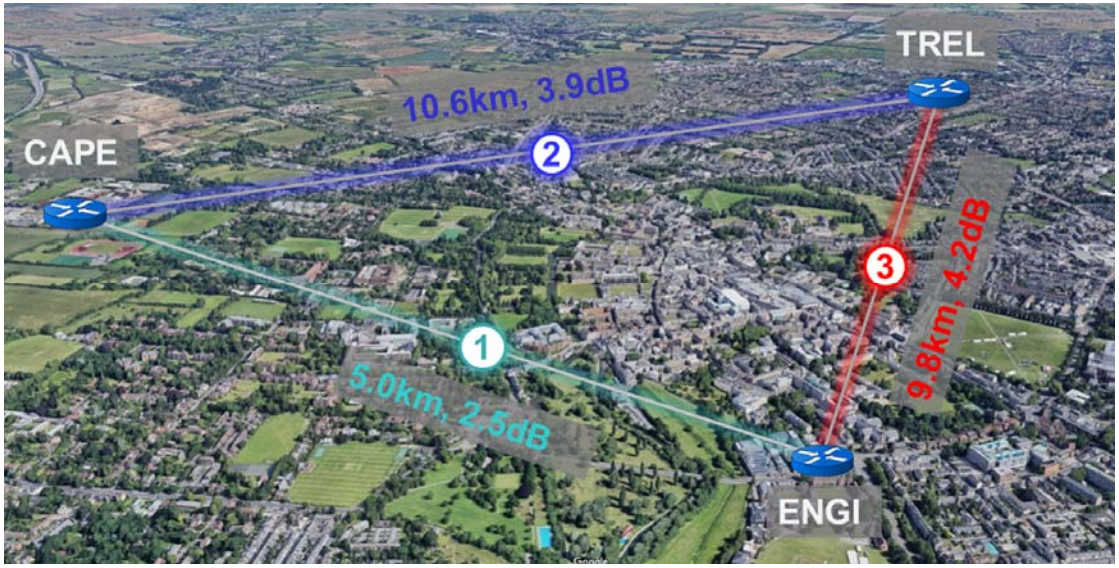
Application	
Transport	Qubit transmission
Network	Long distance entanglement
Link	Robust entanglement generation
Physical	Attempt entanglement generation

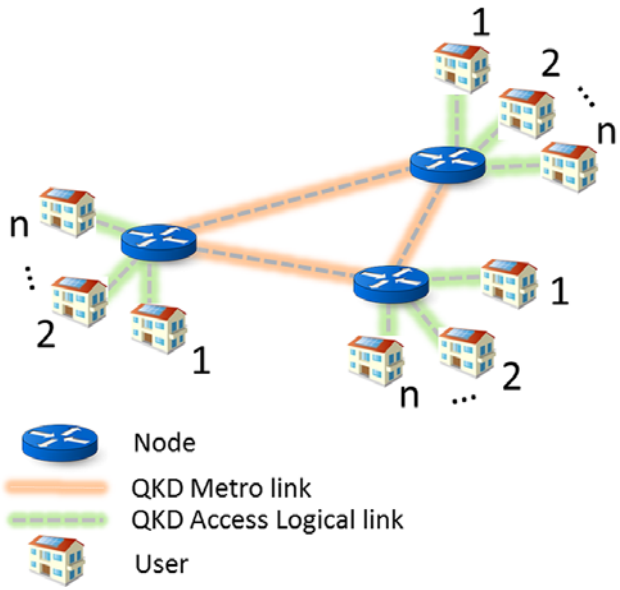
Hensen, et al., Nature 526, 682 (2017); Dahlberg, et al., ACM (2019)

Europe: UK Quantum Communication Hub

- 8 UK universities + private sector (e.g., Toshiba) funded by EPSRC

Cambridge Quantum Network





Comparison of Different Ground based QKD Networks

	Tokyo QKD network	Geneva QKD network	Hefei-Chaohu-Wuhu QKD network	Zhucheng–Huangshang QKD link	Cambridge quantum network
Number of nodes	**6**	**3**	**9**	**2**	**3**
Fibre type	Installed field fibre	Installed field fibre	Installed field fibre	Installed field fibre	Installed field fibre
Longest point-to-point fibre link (loss)	**45 km (14.5 dB)**	**14.4 km (5.6 dB)**	**85.1 km (18.4 dB)**	**66 km (13 dB)**	**10.6 km (3.9 dB)**
Secure bit rate (highest)	300 kbps				2580 kbps
Total secure key material (best link)	0.026 Tb			Tb	120 Tb
Operation period	~1 day				~580 days
Key delivery /key management interface	Yes	Yes		No	Yes
Data multiplexing	No	No	No	Yes	Yes
Data launch powers	N/A	N/A	N/A	Up to 20 dBm	Up to –7 dBm
Multiplexed data bandwidth	N/A	N/A	N/A	3.6 Tbps	200 Gbps

No Demonstration of Quantum Repeater yet!

Dynes, et al, npj Quantum Info 5, 101 (2019)

Challenges for Ground based Quantum (Repeater) Networks

- **Quantum No-Cloning Theorem**
  - Unknown quantum states cannot be perfectly cloned
- **Realistic Imperfections & Challenges:**
  - *Loss errors* (Fiber loss L_{att}≈20km, coupling & detector inefficiency)
  - *Operation errors* (Channel decoherence, memory errors, local gate/measurement errors)

Different Generations of Quantum Repeaters

Challenges	Approaches	1G-QR	2G-QR	3G-QR
Loss Error	Quantum Error Detection [two-way signaling]	✓	✓	
	Quantum Error Correction [one-way signaling]			✓
Operation Error	Quantum Error Detection [two-way signaling]	✓		
	Quantum Error Correction [one-way signaling]		✓	✓
	Rate:	$\sim \frac{c}{L_{tot}}$	$\sim \frac{c}{\eta^2 L_0}$	$\sim \frac{1}{\tau_{opr}}$

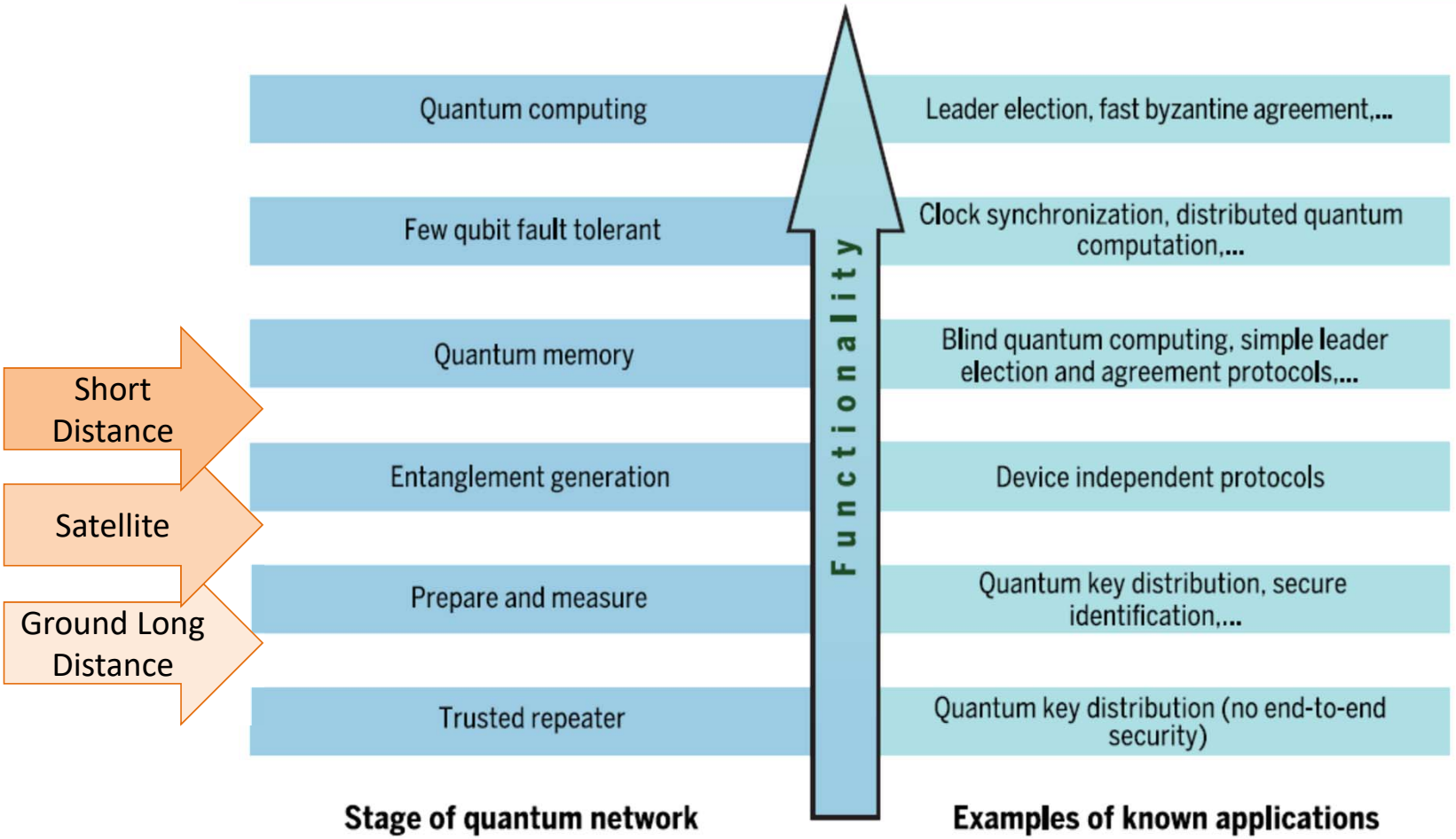
Scientific Reports 6, 20463 (2016)

Worldwide Quantum Network Development

	Country	Project
Satellite-based	China	Micius Quantum Satellite (launched in 2016)
	Japan	SOCRATES satellite (launched 2014, QKD test 2017) Satellite Quantum Crypto-technology (planning?)
	Canada	QEYSSat Quantum Satellite (started in 2017, expected launch 2022)
	Singapore-UK	QKD Qubesat Satellite (started in 2018, expected launch 2021)
Ground-based	Japan	Tokyo free-space QKD Network (45 km, 2011)
	Switzerland	Geneva QKD Network (14 km, 2011)
	China	Beijing-Shanghai Trunk Line (2000 km, 2017)
	UK	Cambridge Quantum Network (Universities + Toshiba) (11 km, 2017)
	Netherland	Delft Quantum Network (100 km, ...)

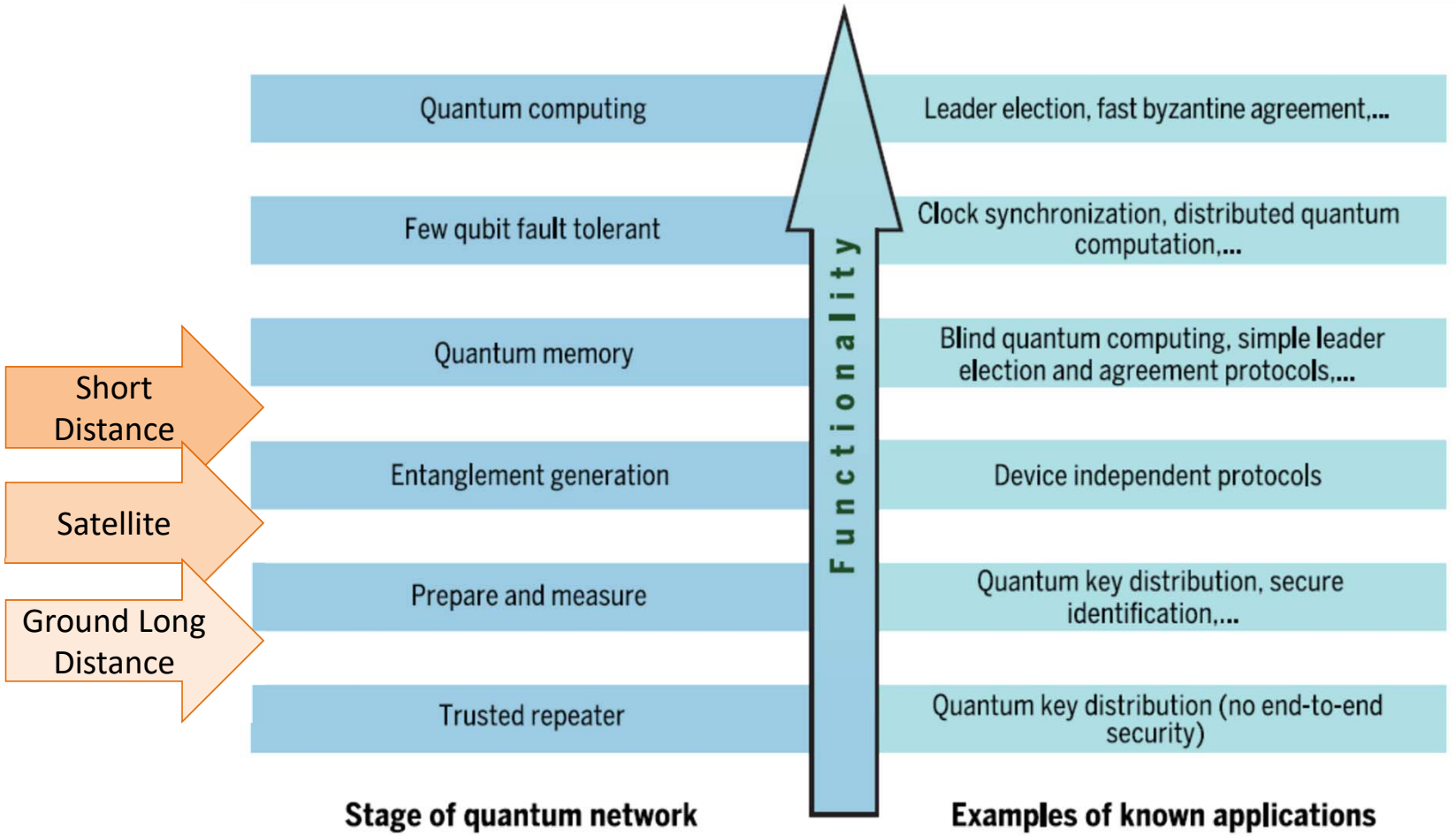
*Potentially collaboration with Canada, Europe, Japan, …

Stages of Quantum Network Development



Wehner, Elkouss, Hanson, *Science* **362**, 6412:9288 (2018).

Stages of Quantum Network Development



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Shared Wish List among Quantum Network Community

- Quantum Sources
  - Single photons, Entangled photons, …
- Efficient Low-noise Detector
  - SNSPD, Number resolving detectors, …
- Quantum Memory (with optical interface) [e.g., Geneva, ICFO, …]
  - Atomic ensembles, REIs, cavity QED, color defect centers, …
- Quantum Nodes with Processing Power
  - Routing signals, Entanglemeng swapping & purification, …
- Quantum Transduction (high efficiency, low noise)
  - Optical-optical conversion
  - Microwave-optical conversion
- Simulation & Control Layer

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