Moonshot international symposium

***December 18,2019 @ Kyoto, Japan***

*Topic 3*

# Research Trend in Quantum Network


Hideo Kosaka

***Yokohama National University, Japan***

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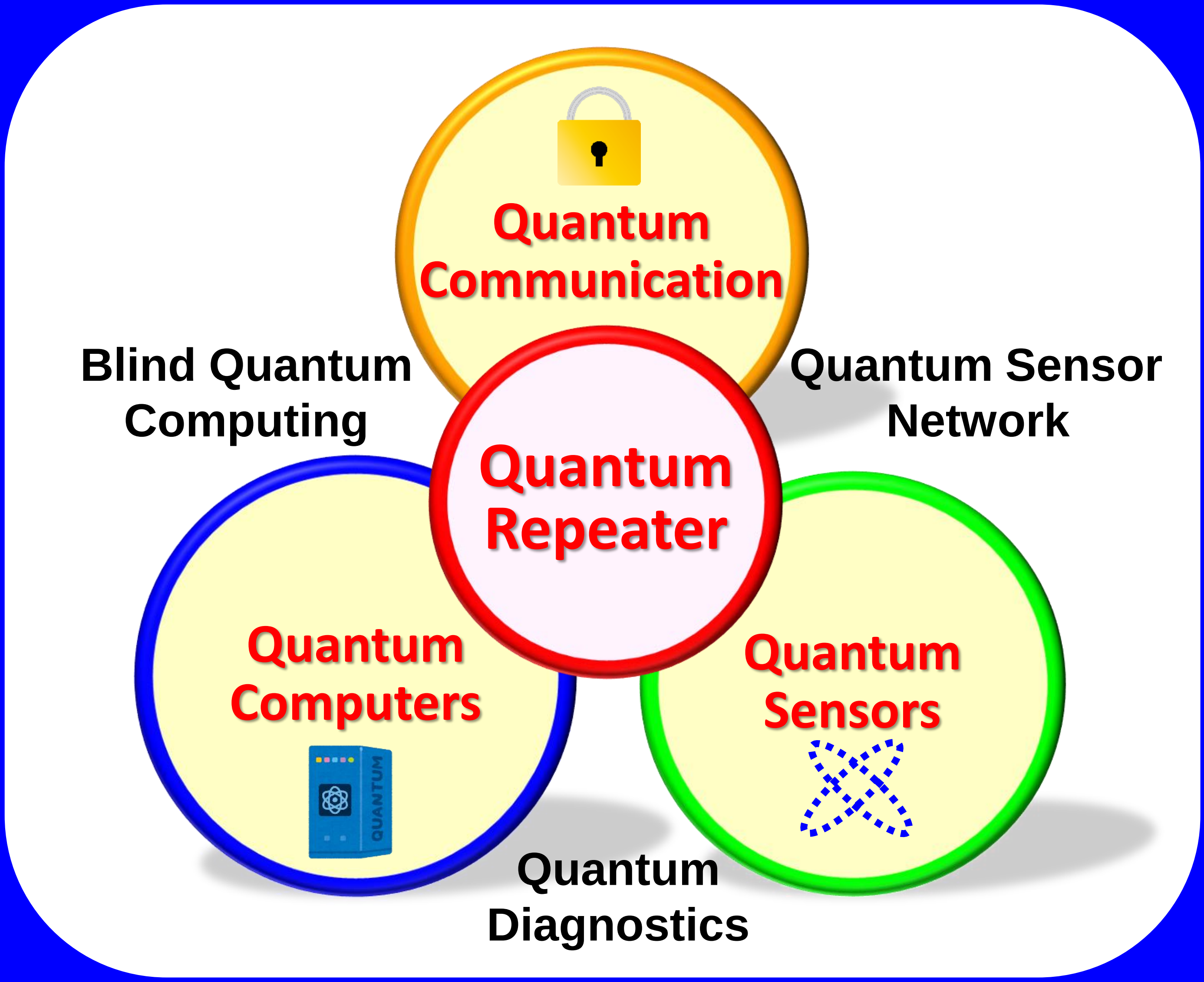
# Quantum Internet

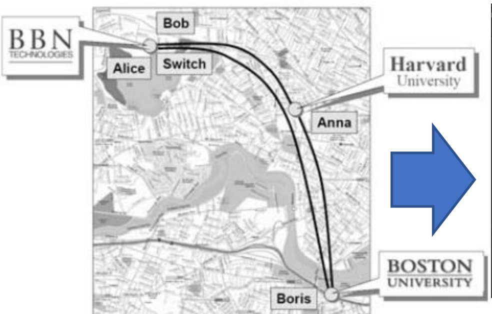
# Quantum Internet

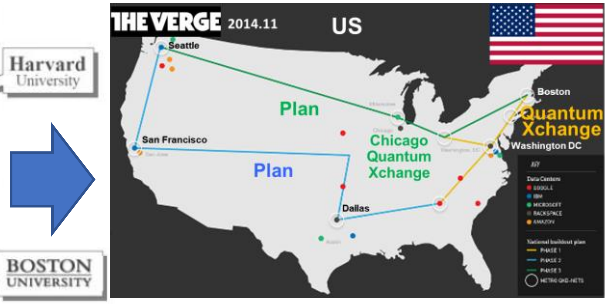


# Quantum Key Distribution (QKD) Network

*By Courtesy of NICT*

**USA** 2004 DARPA Quantum Network (Boston)




C. Elliot et al., arXiv:quant-ph/0503058

Figure 11: Logical Map of the Cambridge-Area Fiber Network.

**Europe** 2008 SECOQC Network (Vienna)

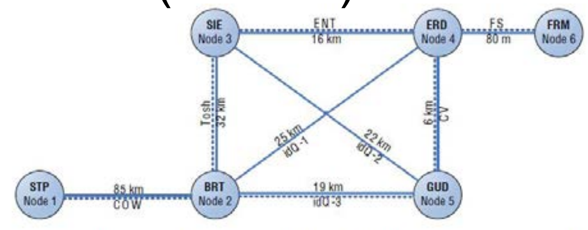
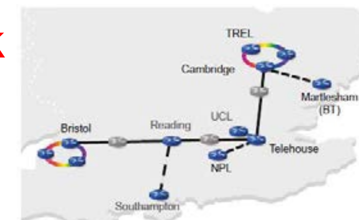



Figure 2. Network topology of the SECOQC QKD network prototype. Solid lines represent quantum communication channels, dotted lines denote classical communication channels.

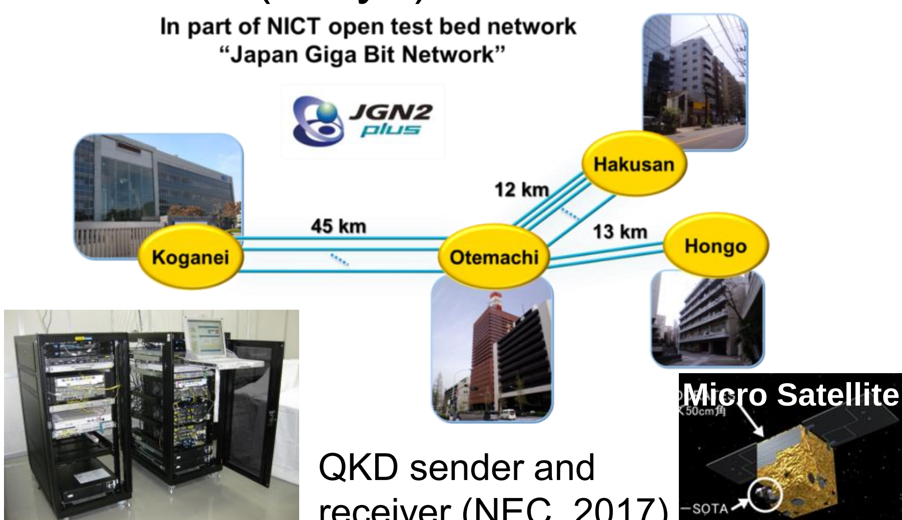
M. Peev et al., New J. Phys. 11, 075011 (2009)

UK quantum network (Cambridge-Bristol, under construction)



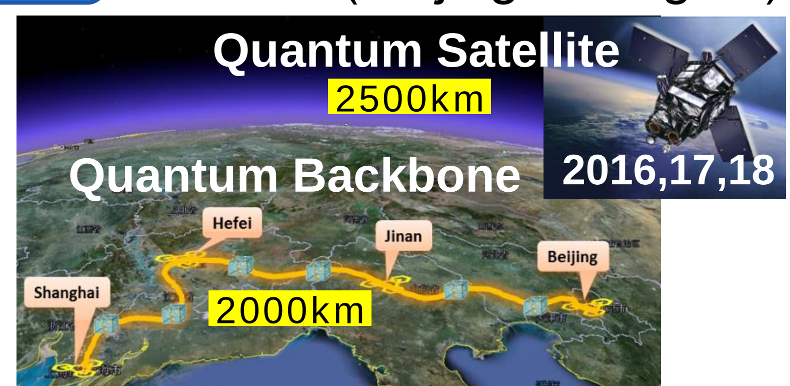

**Japan** 2010～ Tokyo QKD Network (Tokyo)

In part of NICT open test bed network "Japan Giga Bit Network"




QKD sender and receiver (NEC, 2017)

**China** 2017～ Quantum Backbone Network (Beijing-Shanghai)




**Quantum repeaters are not used yet!**

# QUANTUM INTERNET ALLIANCE

**with quantum repeaters**

*The long-term ambition of the European Quantum Internet Alliance is to build a Quantum Internet that enables quantum communication applications between any two points on Earth*

LEARN MORE | CONTACT

http://quantum-internet.team/

Leading actors from industry

CMS Crystalline Mirror Solutions · elementsix a De Beers Group Company · JPE Experts in Positioning Janssen Precision Engineering · μQuans · MyCryoFirm Cryodevices & Consulting · SAP · SURF SARA · Swabian Instruments · TNO innovation for life · Toptica Photonics · VeriQloud · ABN·AMRO · amsix · le cnam · i2cat · IDQ · kpn · QuantiCor · RIPE NCC · SURF NET · TOSHIBA Leading Innovation · TOYOTA

**AUSTRIAN ACADEMY OF SCIENCES – IQOQI**
The Institute for Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences dedicates its work to theoretical and experimental basic research in the areas of quantum optics …

**CNRS**
The National Center for Scientific Research, or CNRS, is a public organization under the responsibility of the French Ministry of Education and Research. People Eleni Diamanti Professor in Quantum …

**ICFO**
ICFO is a young research institution that aims to advance the very limits of knowledge in Photonics; the science and technology of harnessing Light.

**INSTITUTO DE TELECOMUNICAÇÕES**
Instituto de Telecomunicações (IT) is a national research institute in Portugal, rated Excellent in its international assessments. It promotes research & development, as well as advanced training, in all aspects of …

**MAX PLANCK INSTITUTE OF QUANTUM OPTICS**
En Route to the New Quantum World – Even one century after its discovery quantum physics still remains extremely fascinating. This is because the quantum world is so radically different …

**NIELS BOHR INSTITUTE – UNIVERSITY OF COPENHAGEN**
In nano-sized optical devices, light-matter interactions can be made so strong that quantum mechanical effects are decisive. The main focus of the Quantum Photonics Group is on techniques to control the quantum dynamics of quantum dots …

**QUTECH – TU DELFT**
QuTech is an advanced research center for quantum computing and quantum internet, a collaboration founded by Delft University of Technology and TNO.

**SORBONNE UNIVERSITY**
Sorbonne Université is a new university with a centuries-old tradition, through the merger of UPMC and Paris-Sorbonne on 1st January, 2018, bringing together Arts & Humanities, Medicine and Science & …

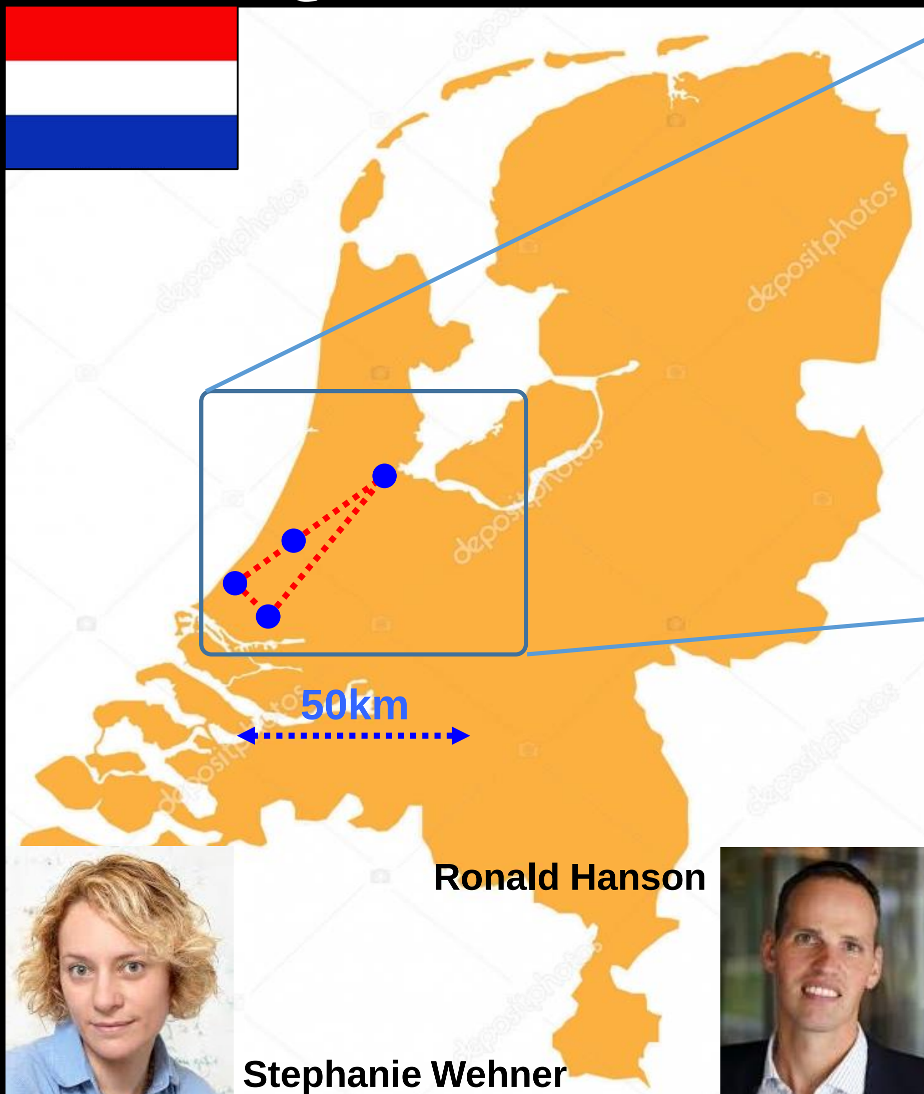
**UNIVERSITY OF BASEL**
Our research is focused on quantum optics, i.e. the application of quantum theory to phenomena involving light and its interaction with atomic and mechanical systems. The tools of quantum optics, …

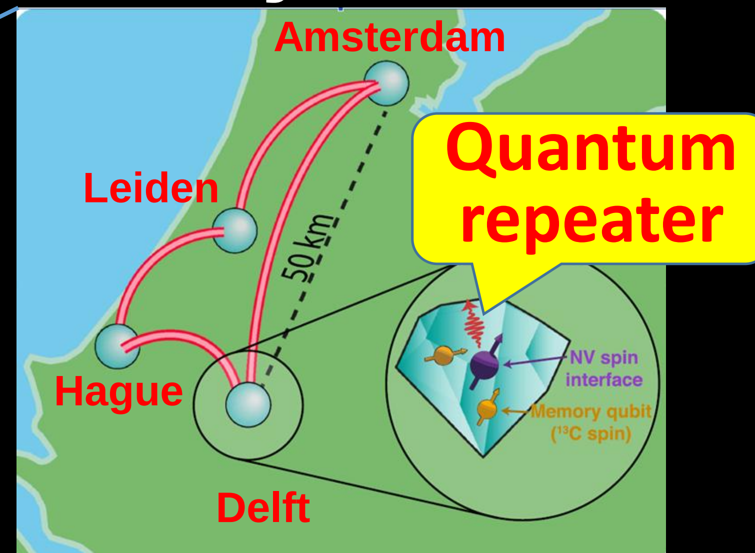
**UNIVERSITY OF GENEVA**
Quantum Memories are devices that can store the quantum state of a photon, without destroying the volatile quantum information. Quantum Memories will be key components in future quantum networks, such …

**UNIVERSITY OF INNSBRUCK**
The Innsbruck Physics Research Center is committed to carry out excellent, worldwide competitive research addressing a broad range of modern topics in physics.

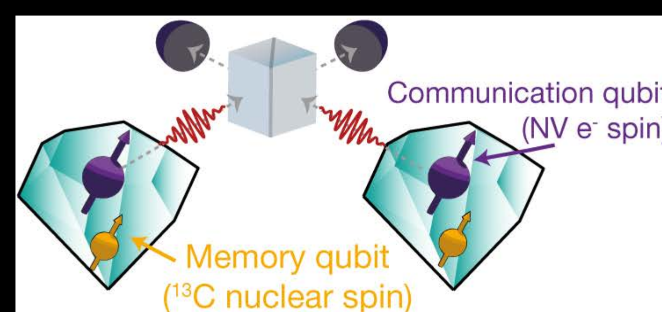
**UNIVERSITY OF STUTTGART**
Science at the institute comprises solid state quantum optics and spintronics with applications in modern microscopy and metrology. Common to all experimental approaches is the use of photons as central …

# Netherlands
# Quantum Internet Project




**Quantum loop connecting 4 cities**
**100km in total**




Quantum Sci. Technol. 2 (2017) 034002

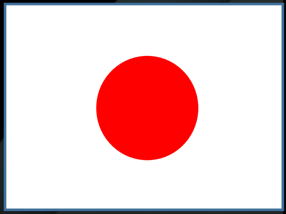
https://labs.ripe.net/Members/becha/introduction-to-the-quantum-internet

# Japan

# Quantum Internet Task Force

ITF
QUANTUM INTERNET
TASK FORCE

News Team Publications Contact

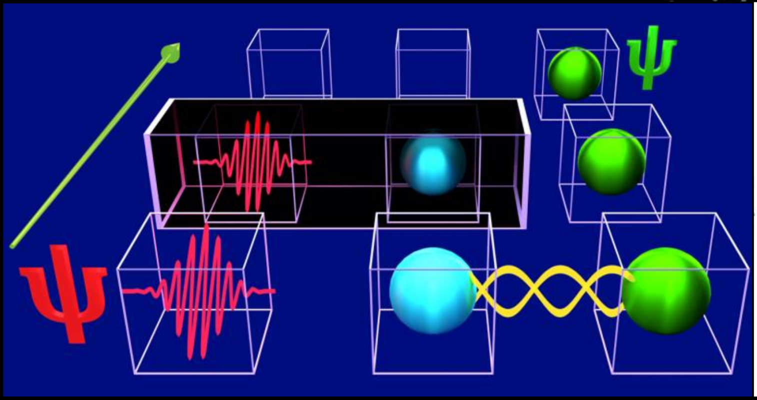


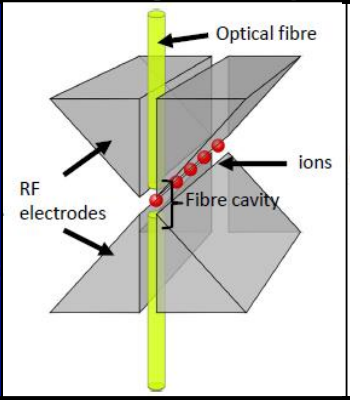
QUANTUM
INTERNET
TASK FORCE

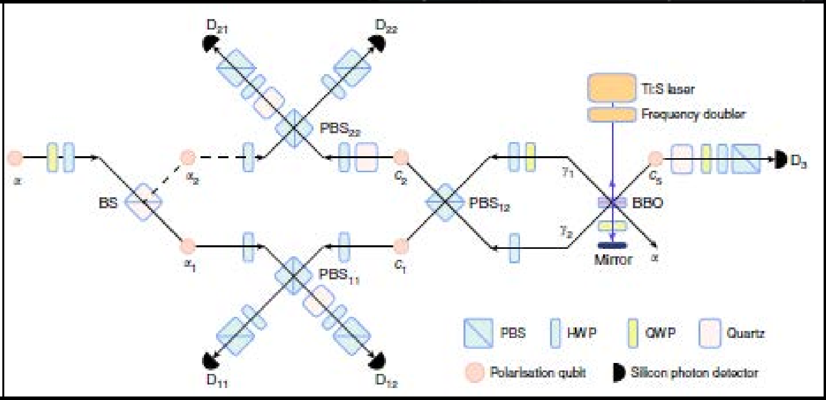
日本中の研究者・開発者を集め、新規参入者と共に、量子インターネットによる未来の情報社会を目指す。

SEE MORE →

## Quantum Repeater platforms






Diamond

Ion/Atom

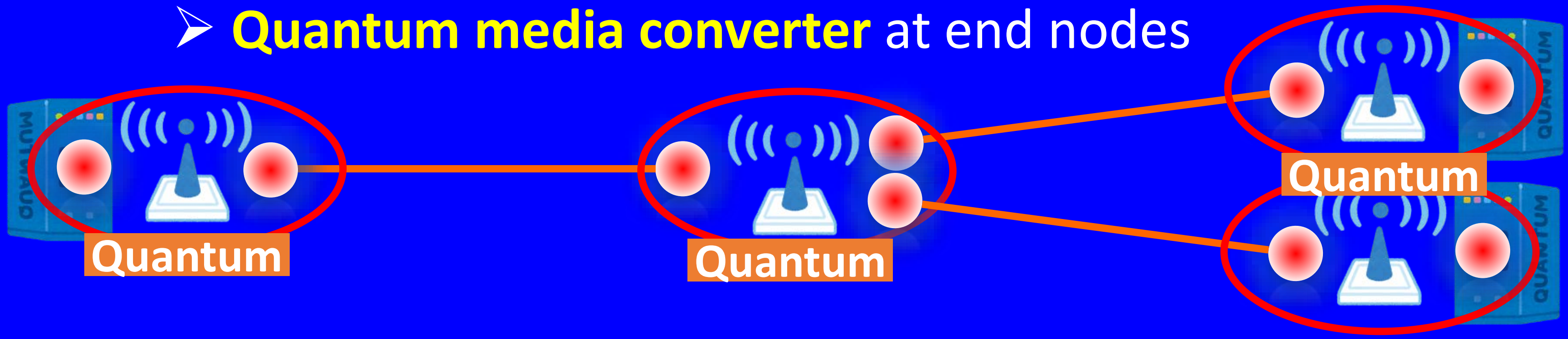
All-photon

# Development Steps for Quantum Internet

1. **Trusted node** QKD system
   - Quantum enhanced security but not absolutely secure


2. **Quantum repeater**–based QKD system
   - Absolutely secure quantum network
   - Long-distance & multiparty connections


3. **Quantum computer network**
   - **Quantum media converter** at end nodes

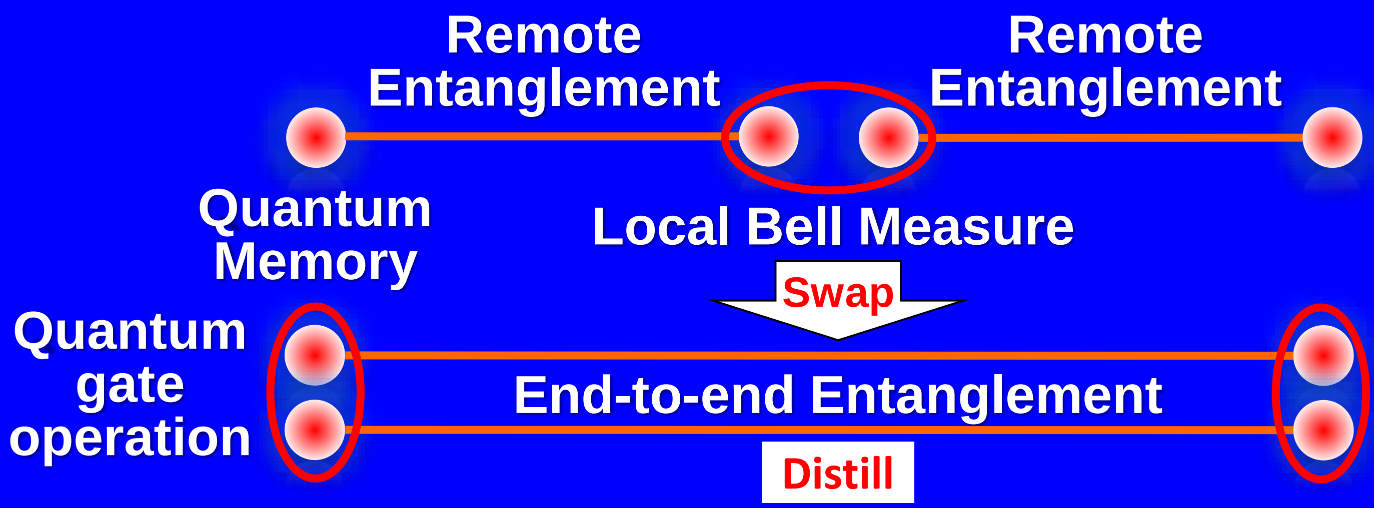


## Quantum Repeater

1. Required functions
2. Promising qubits
3. Diamond repeater
4. Current status and prospects

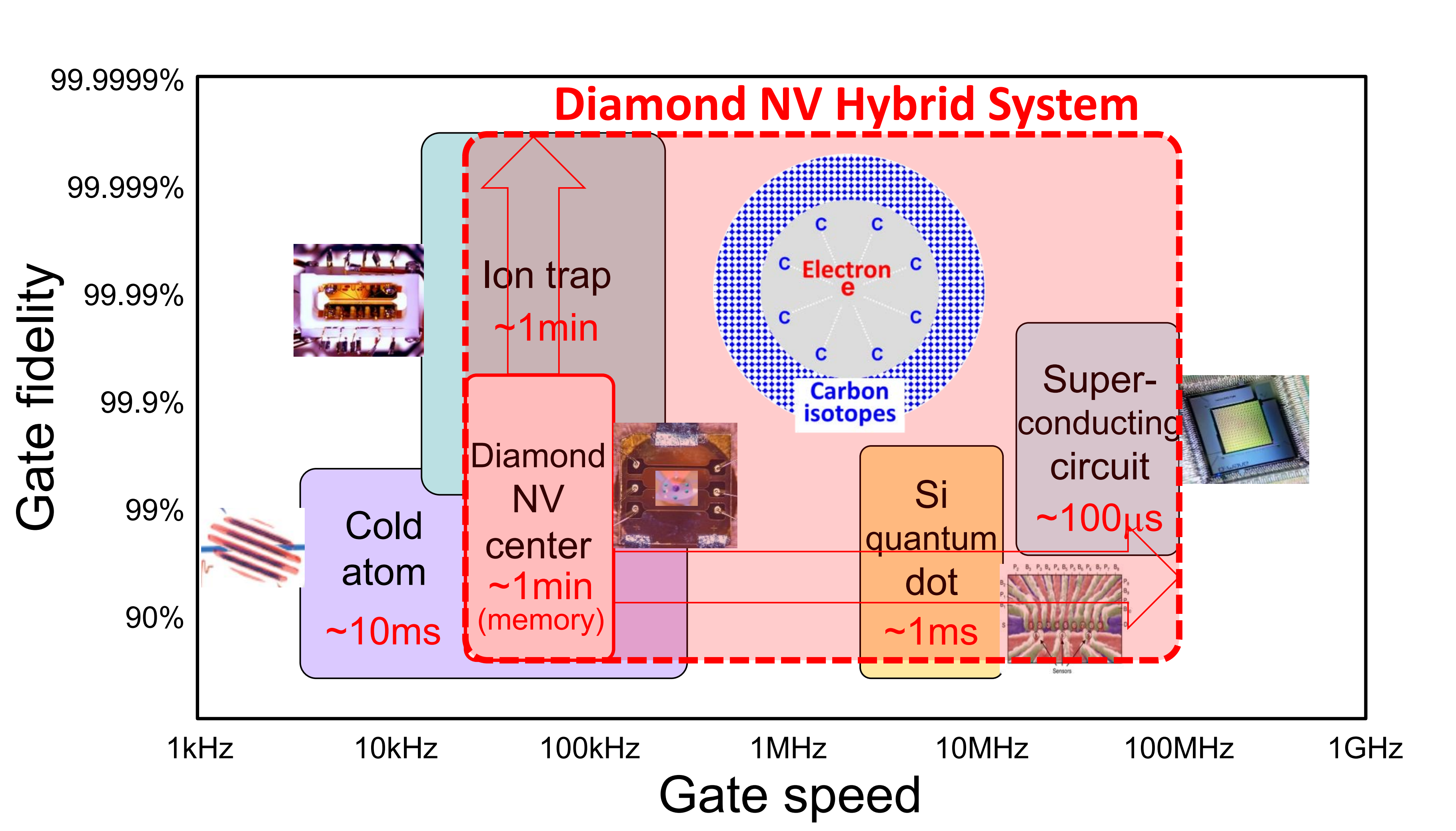
# Required functions

- **Remote Entanglement**
  - can be probabilistic but should be **heralded**
- **Local Bell Measurement**
  - should be **deterministic**
- **Quantum Gate operation**
  - allows not only **swapping** but also **distillation**
- **Quantum Memory**
  - allows **scalable** quantum network



# Promising Qubits

## Requirements: Gate speed, Gate fidelity, Memory time



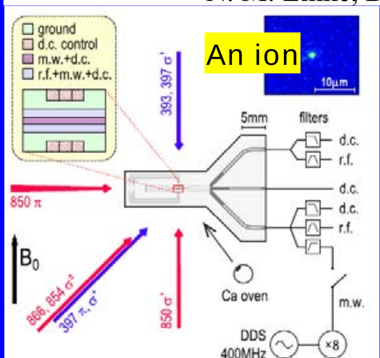

Based on JST-CRDS report 2019

# Ion/Atom

## UK 2014 (ion)

**High-Fidelity Preparation, Gates, Memory, and Readout of a Trapped-Ion Quantum Bit**

T. P. Harty, D. T. C. Allcock, C. J. Ballance, L. Guidoni, H. A. Janacek, N. M. Linke, D. N. Stacey, and D. M. Lucas

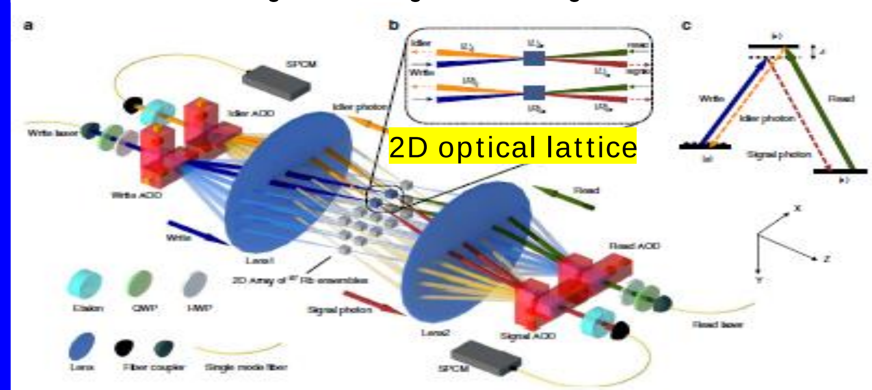



| Preparation&readout: 99.93% | Error |
|---|---|
| Stretched state $S_{1/2}^{4,+4}$ preparation | $< 1 \times 10^{-4}$ |
| Transfer to qubit (3 or 4 m.w. $\pi$ pulses) | $1.8 \times 10^{-4}$ |
| Transfer from qubit (4 m.w. $\pi$ pulses) | $1.8 \times 10^{-4}$ |
| Shelving transfer $S_{1/2}^{4,+4} \to D_{5/2}$ | $1.7 \times 10^{-4}$ |
| Time-resolved fluorescence detection | $1.5 \times 10^{-4}$ |
| **Single-qubit gate: 99.9999%** | **Mean EPG** |
| Microwave detuning offset (4.5 Hz) | $0.7 \times 10^{-6}$ |
| Microwave pulse area error ($5 \times 10^{-4}$) | $0.3 \times 10^{-6}$ |
| Off-resonant effects | $0.1 \times 10^{-6}$ |

## China 2017 (atom)

**Experimental realization of a multiplexed quantum memory with 225 individually accessible memory cells**

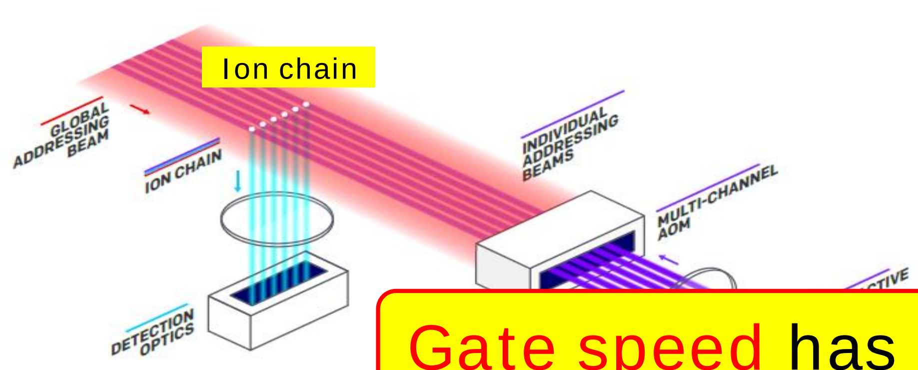
Y.-F. Pu, N. Jiang, W. Chang, H.-X. Yang, C. Li & L.-M. Duan




## US 2019 (ion)

**Benchmarking an 11-qubit quantum computer**

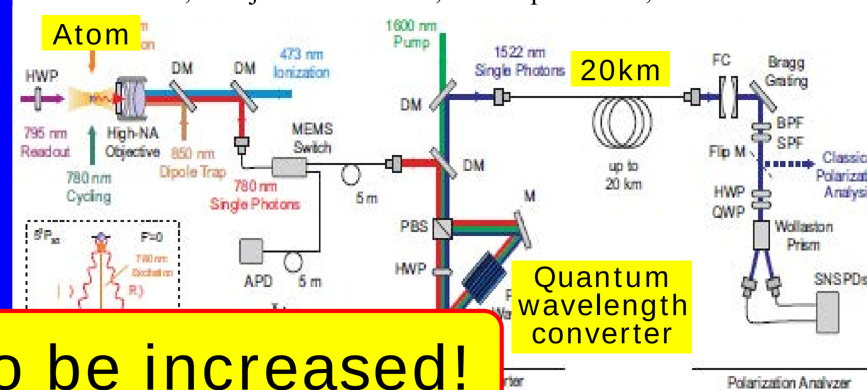
K. Wright, K. M. Beck, S. Debnath, J. M. Amini, Y. Nam, N. Grzesiak, J.-S. Chen, N. C. Pisenti, M. Chmielewski, C. CollinsK. M. Hudek, J. Mizrahi, J. D. Wong-Campos, S. Allen, J. Apisdorf, P. Solomon, M. Williams, A. M. Ducore, A. Blinov, S. M. Kreikemeier, V. Chaplin, M.Keesan, C. Monroe & J. Kim




## Germany 2019 (atom)

**Long-distance distribution of atom-photon entanglement at telecom wavelength**

Tim van Leent, Matthias Bock, Robert Garthoff, Kai Redeker, Wei Zhang, Tobias Bauer, Wenjamin Rosenfeld, Christoph Becher, Harald Weinfurter



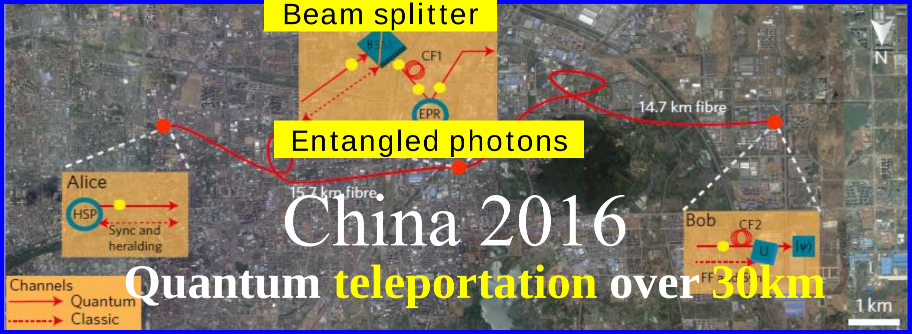

**Gate speed has to be increased!**

# All-Photon

No Memory!


## Canada 2016

**Quantum teleportation over 13km**




Beam splitter

Entangled photons

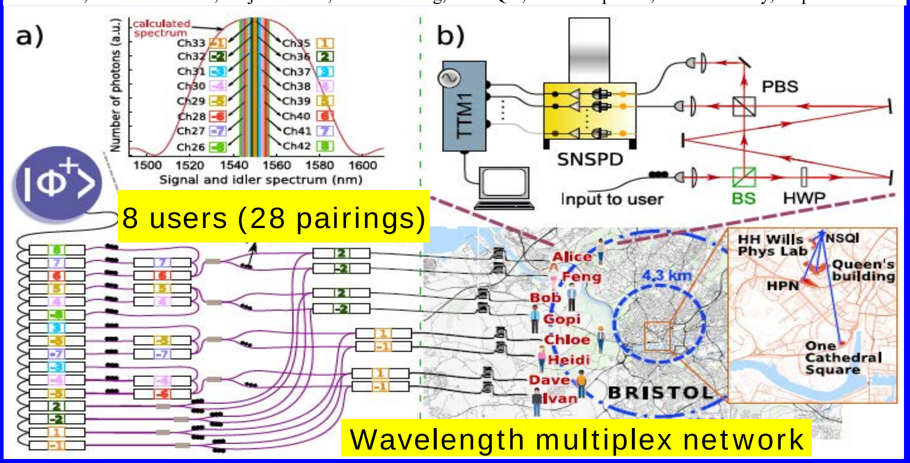
## China 2016

**Quantum teleportation over 30km**

## UK 2019

**A trusted-node-free eight-user metropolitan quantum communication network**

Siddarth Koduru Joshi, Djeylan Aktas, Sören Wengerowsky, Martin Lončarić, Sebastian Philipp Neumann, Bo Liu, Thomas Scheidl, Željko Samec, Laurent Kling, Alex Qiu, Mario Stipčević, John G. Rarity, Rupert Ursin




8 users (28 pairings)

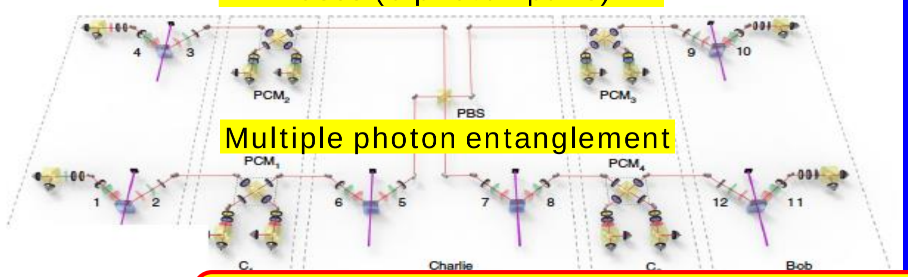
Wavelength multiplex network

## China 2019

**Experimental quantum repeater without quantum memory**

Zheng-Da Li, Rui Zhang, Xu-Fei Yin, Li-Zheng Liu, Yi Hu, Yu-Qiang Fang, Yue-Yang Fei, Xiao Jiang, Jun Zhang, Li Li, Nai-Le Liu, Feihu Xu, Yu-Ao Chen & Jian-Wei Pan

4 uses (6 photon pairs)



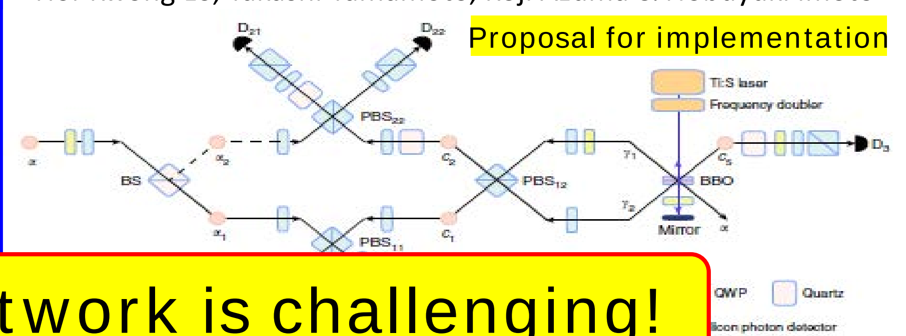

Multiple photon entanglement

## Japan 2019

**Experimental time-reversed adaptive Bell measurement towards all-photonic quantum repeaters**

Yasushi Hasegawa, Rikizo Ikuta, Nobuyuki Matsuda, Kiyoshi Tamaki, Hoi-Kwong Lo, Takashi Yamamoto, Koji Azuma & Nobuyuki Imoto

Proposal for implementation




**Scalable quantum network is challenging!**

# Diamond — All-Solid QR with memory

replace ion trap with electron trap in an vacancy in diamond

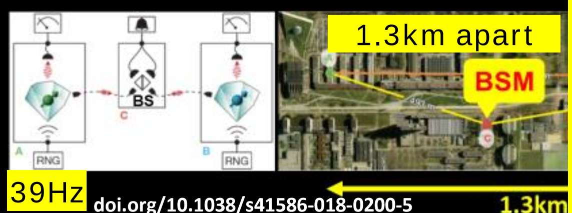
## Netherlands 2015

nature 2015

Entanglement distribution between diamonds 1.3km apart

**Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres**

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[1,2], A. Reiserer[1,2], N. Kalb[1,2], M. S. Blok[1,2], J. Ruitenberg[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], C. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

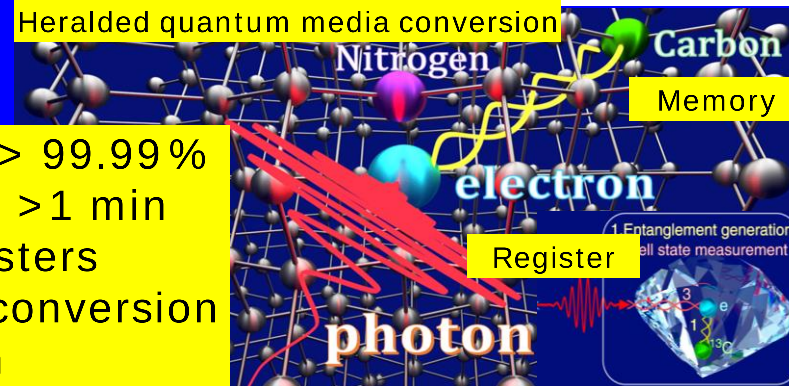



doi.org/10.1038/s41586-018-0200-5

## Japan 2019

**Quantum teleportation-based state transfer of photon polarization into a carbon spin in diamond**

Kazuya Tsurumoto, Ryota Kuroiwa, Hiroki Kano, Yuhei Sekiguchi & Hideo Kosaka

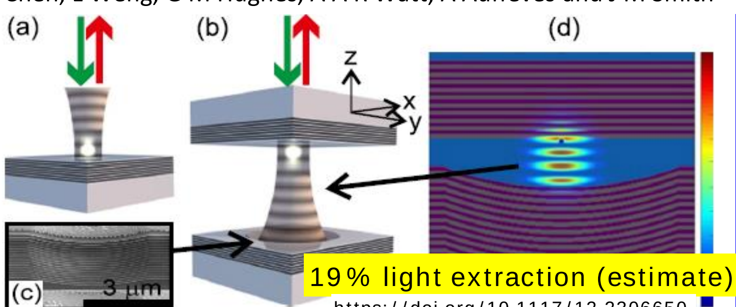



- Gate fidelity > 99.99%
- Memory time >1 min
- 10-qubit resisters
- Wavelength conversion
- Teleportation
- Error correction
- Distillation

## UK 2015

**Tunable cavity coupling of the zero phonon line of a nitrogen vacancy defect in diamond**

S Johnson, P R Dolan, T Grange, A A P Trichet, G Hornecker, Y C Chen, L Weng, G M Hughes, A A R Watt, A Auffèves and J M Smith

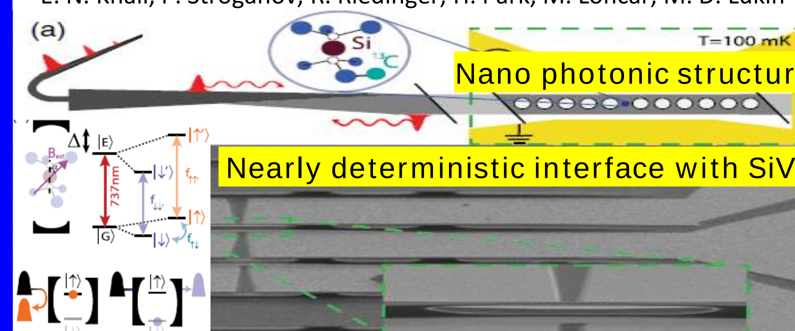



https://doi.org/10.1117/12.2306650

## US 2019

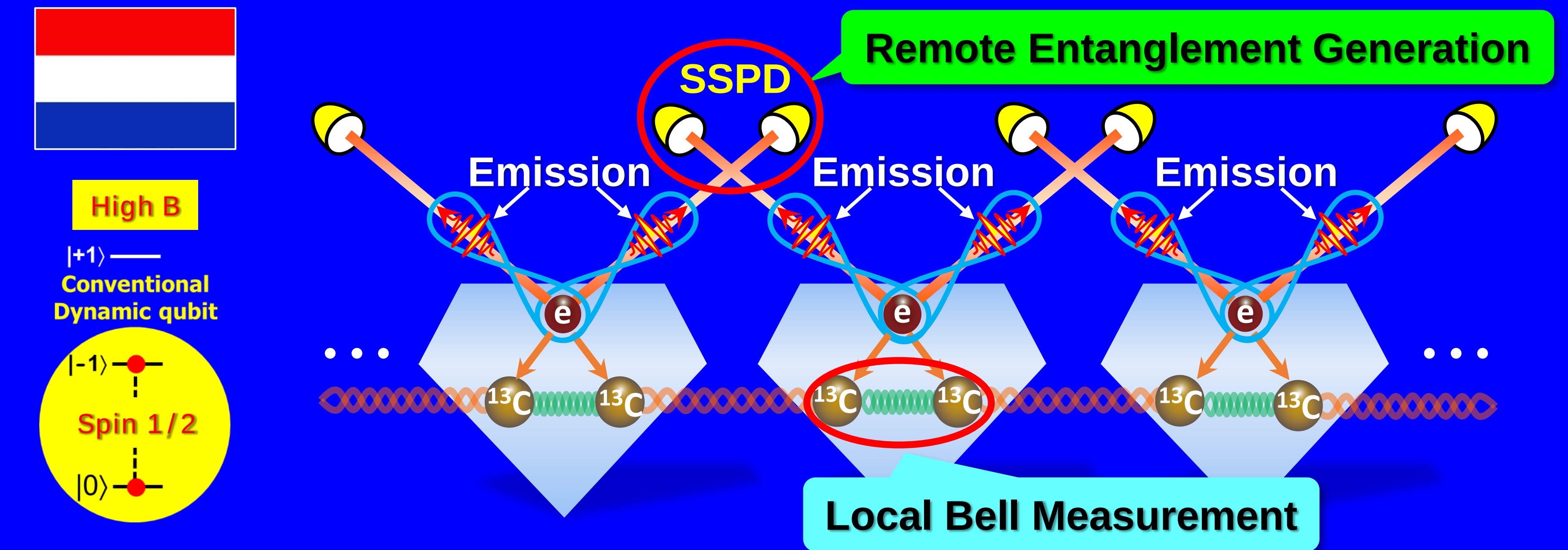
**Quantum network nodes based on diamond qubits with an efficient nanophotonic interface**

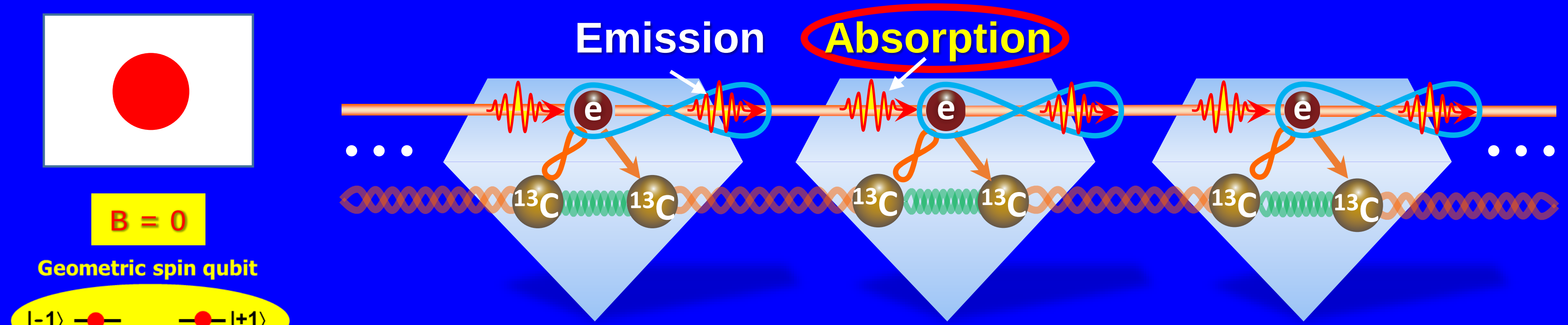
C. T. Nguyen, D. D. Sukachev, M. K. Bhaskar, B. Machielse, D. S. Levonian, E. N. Knall, P. Stroganov, R. Riedinger, H. Park, M. Lončar, M. D. Lukin

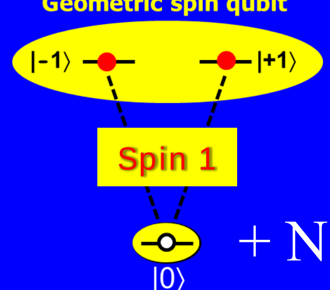



**All of these are still component level.**

# Diamond



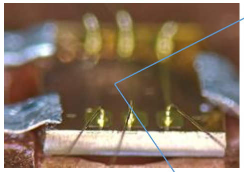

+ No need of **SSPD** in the middle of nodes

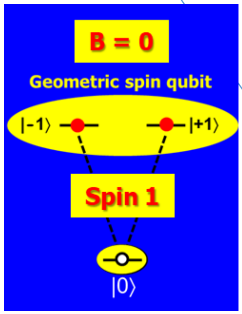
+ 30 times higher efficiency without high-Q cavity

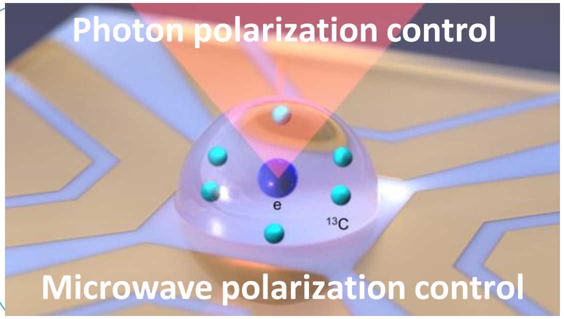
+ No need of **magnetic field** allows integration with **superconductor**

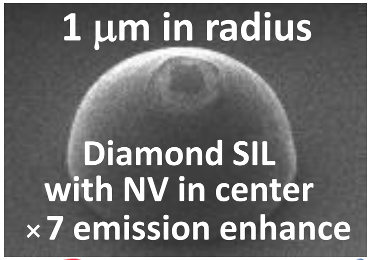
# Current Status & Prospects

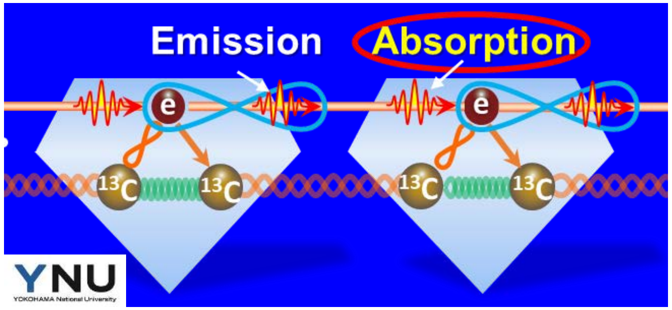
| Required functions for QR | Current | Short-term goal | Mid-term goal |
|---|---|---|---|
| Single-qubit gate operation fidelity (gate speed) | $\gtrsim$99.4% @3MHz | >99.99% @10MHz | >99.999% @100MHz |
| Preparation and readout fidelity | $\gtrsim$98% | >99.9% | >99.99% |
| Electron-photon entanglement generation | $\gtrsim$90% | >99% | >99.9% |
| Photon-to-memory heralded transfer | $\gtrsim$90% | >99% | >99.9% |
| Bell state measurement | $\gtrsim$90% | >99% | >99.9% |
| Quantum error correction (distillation) | $\gtrsim$74% | >90% | >99% |
| Individually accessible qubits | $\gtrsim$10 | >20 | >100 |





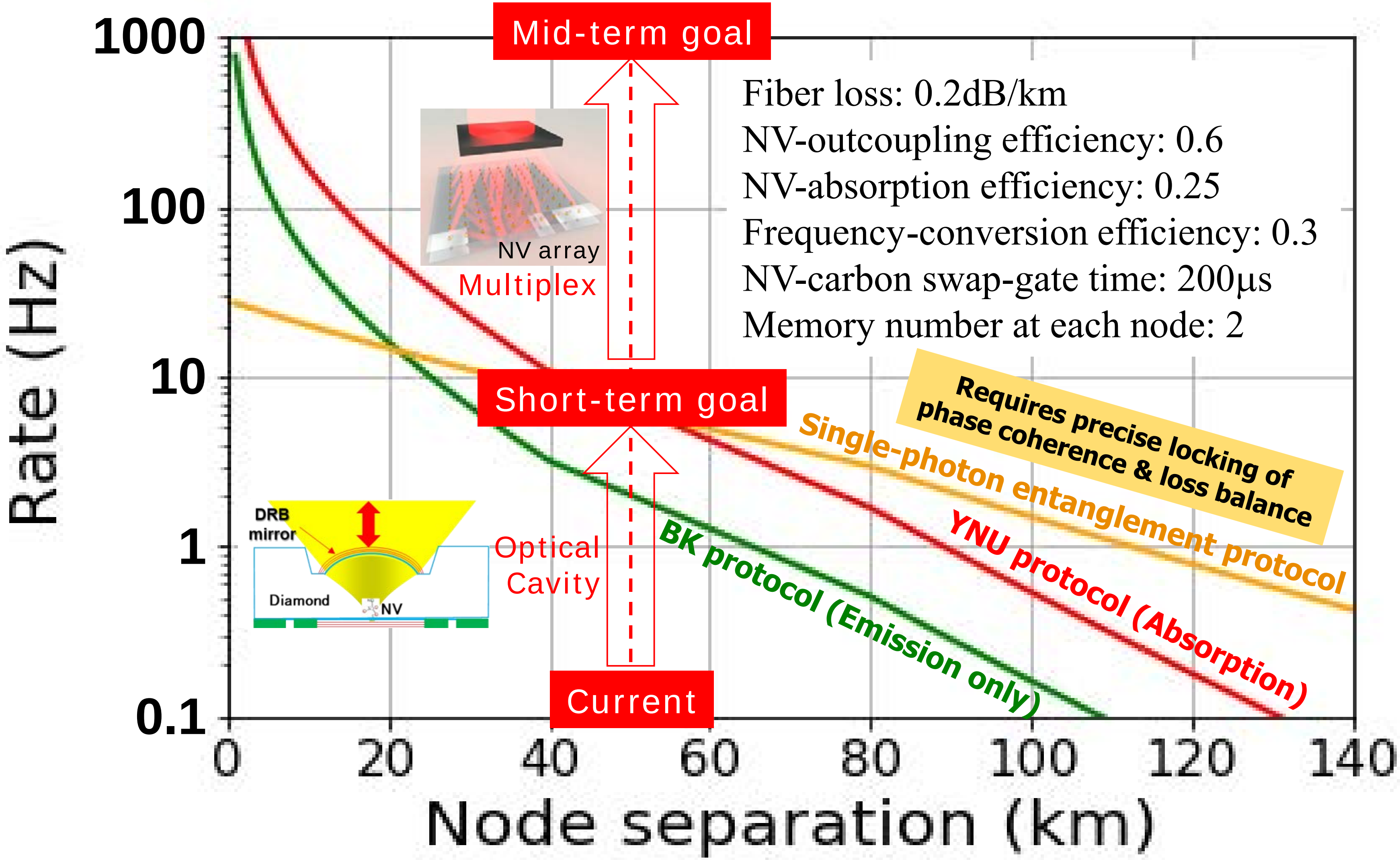




***Nature Photonics*, 10,507-511(2016)**
***Nature Communications*, 7, 11668 (2016)**
***Nature Photonics*, 11, 309-314 (2017)**
***Nature Communications*, 9, 3227 (2018)**
***Optics Letters*, 43, 2380-2383 (2018)**
***Communictions Physics*, 2, 74 (2019)**
***Physical Review Applied*, 12, 051001 (2019)**

# Modeled Entanglement Distribution Rate

**Independent of node number**

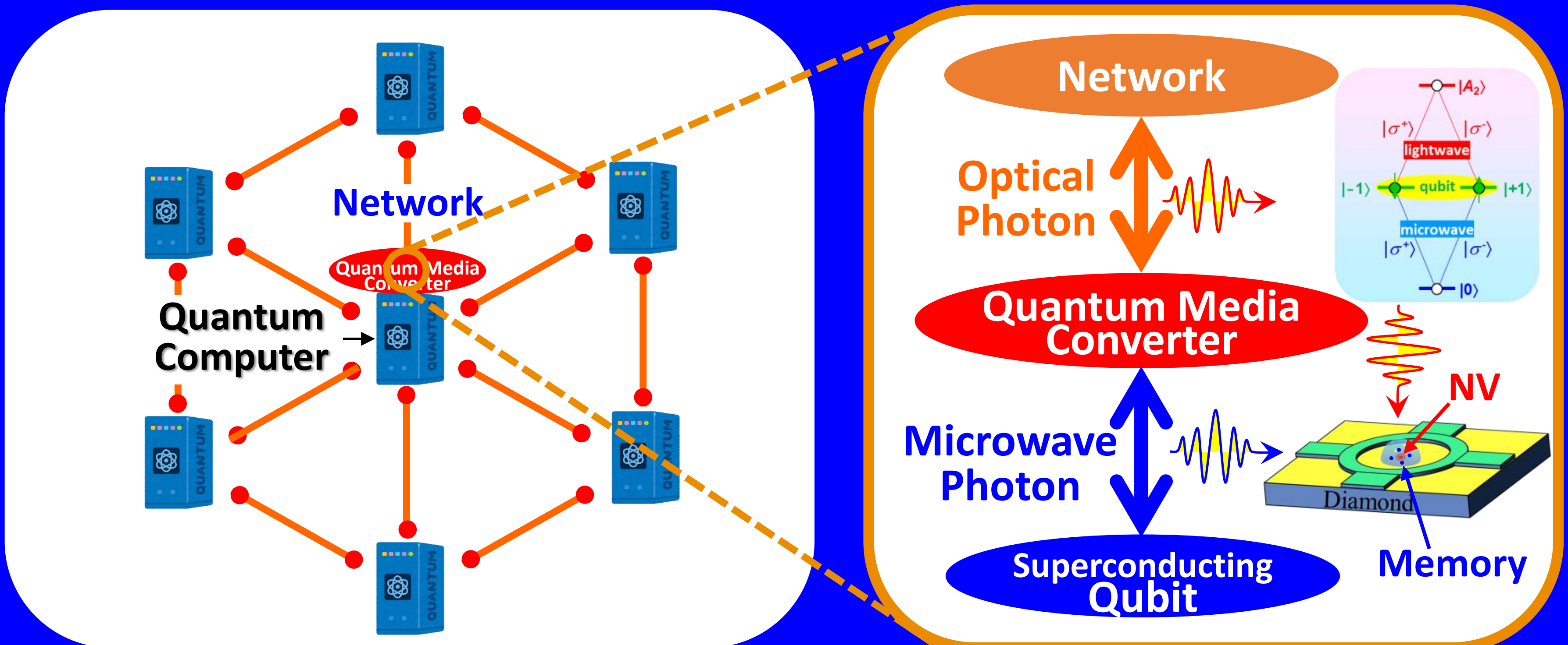



Based on Dam et al., Quantum Sci. Technol. (2017)

# Quantum Computer Network

# Quantum Computer Network

- **Quantum media converter**
  - **Interface** **Quantum Computer to Network**
  - **Distributed Quantum Computer** could be built
- **NV center in diamond** under a zero magnetic field
  - Interface **optical & microwave photons** with **memory**
  - Other candidates are magnon, surface acoustic wave …



# Roadmap

Present (2019) → In 5 years (2024) → In 10 years (2029) → In 20 years (2039)

## Quantum entanglement distribution

- Field demonstration of quantum repeater
- Entanglement distribution b/w 3 parties via a quantum repeater
- Remote entanglement generation b/w memories by emission & absorption
- Entanglement with communication-band photon
- Entanglement distribution > 500 km via quantum repeater
- Multi-party entanglement via quantum memories
- **Key rate > 1 kbps via entanglement distribution**

## Quantum memory

- · Single-qubit gate
  · Single-shot measurement
  · Quantum error correction
- Multiple memories ~10 memory time > 1 min
- Two-qubit gate fidelity > 99.9%
- Complete Bell state measurement on memories transferred from photons
- Individual access memories 100~1000 bits
- Fault-tolerant logical memory with quantum coding
- **Scalable reconfigurable quantum repeater**

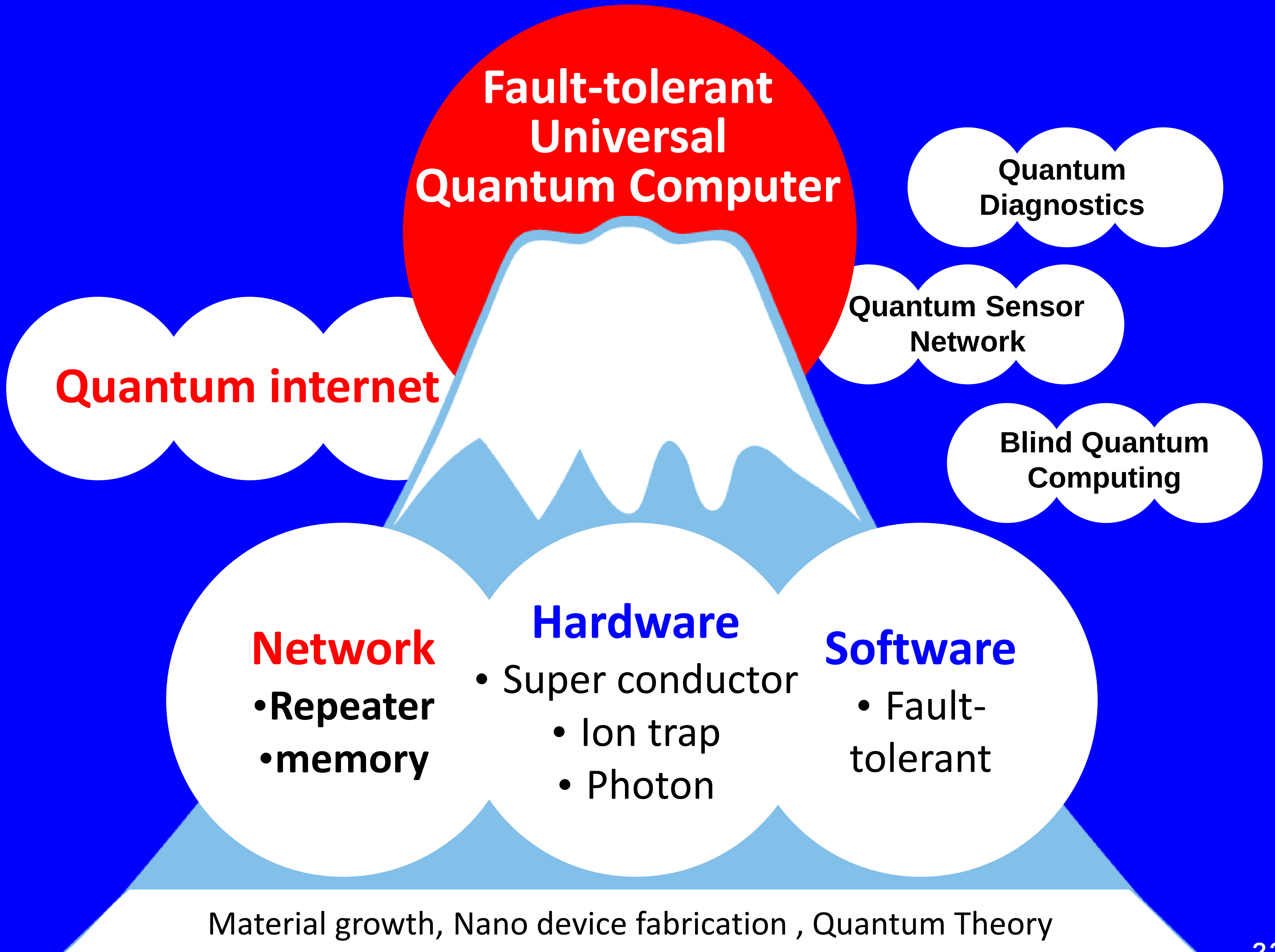
## Quantum interface

- Quantum media conversion b/w photon & quantum memory
- Quantum wavelength conversion
- Single photon fiber coupling
- Quantum media conversion b/w superconducting qubit & quantum memory
- Quantum wavelength conversion module
- Wavelength division multiplexing quantum communication
- **Distributed quantum computer and quantum sensor**

## Photon source

- Single photon source
  Entangled photon source
- All-photonic quantum repeater

Based on the draft final report of the "Quantum Technology and Innovation Strategy"


Fault-tolerant
Universal
Quantum Computer
Quantum
Diagnostics
Quantum Sensor
Network
Blind Quantum
Computing
Quantum internet
Network
•Repeater
•memory
Hardware
• Super conductor
• Ion trap
• Photon
Software
• Fault-
tolerant
Material growth, Nano device fabrication , Quantum Theory

# Advantages of Japanese QST

- Material growth (Diamond)
- Nano fabrication (Photonic circuit, SC circuit)
- Device fabrication (Optical nonlinear device)
- Single photon detector (SSPD)
- Quantum memory (NV, Optical Lattice)
- Quantum interface (Quantum media converter)
- Quantum security system (QKD)

# Summary: Development Targets

- **Quantum repeater**
  - Allow absolutely secure quantum network
  - For long-distance & multiparty connections
  - Entanglement generation rate is issue

- **Quantum memory**
  - NV center allows long time and high fidelity memory
  - Interface b/w photon and spin memory
  - Material growth, Nano device fabrication

- **Quantum media converter**
  - Interface b/w optical & microwave photons
  - For quantum computer network
  - Quantum internet, Blind computing, Sensor network