Quantum Innovation 2022

Nov. 29, 2022 Online

From Quantum Repeater Networks to the Quantum Internet

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Professor, Yokohama National University

Director, Quantum Information Research Center

Research fellow, The University of Tokyo

Japan

YNU YOKOHAMA National University

QiC

UTokyo

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

QuINT Quantum INTerfaces

CREST

MIC Ministry of Internal Affairs and Communications

QuREP Quantum Repeater Technology

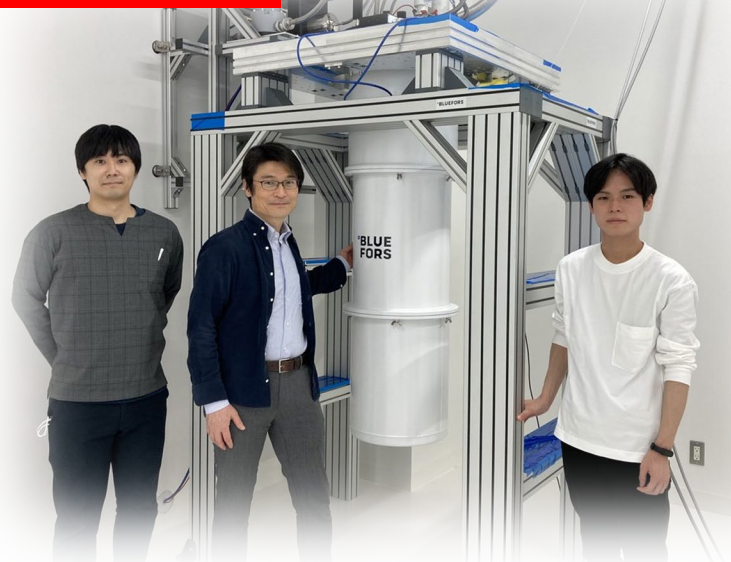
Q. Information Research Center

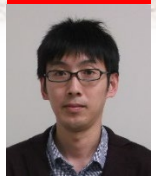
https://moonshot.ynu.ac.jp

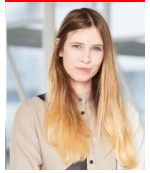
https://qic.ynu.ac.jp/

https://qurep.ynu.ac.jp

~50 members



Center Director	Professor	Professor	Associate Professor	Associate Professor	Associate Professor	Associate Professor	Assistant Professor	Assistant Professor	Assistant Professor	Associate Professor
										
Hideo Kosaka	Toshihiko Baba	Nobuyuki Yoshikawa	Yuki Yamanashi	Christopher Ayala	Fumihiro Inoue	Yoshihiro Shimazu	Yuhei Sekiguchi	Hodaka Kurokawa	Akira Kamimaki	Shinichiro Fujii

Visiting Professor	Visiting Professor	Visiting Professor	Visiting Professor	Visiting Associate Professor	Visiting Associate Professor	Visiting Professor	Visiting Associate Professor	Visiting Researcher	Intellectual Property Producer	Adjunct Teaching Staff
										
Satoshi Iwamoto	Masahiro Nomura	Toshiharu Makino	Tokuyuki Teraji	Shinobu Onoda	Kazuki Koshino	Hirotaka Terai	Katsuaki Tanabe	Ryo Sasaki	Kinya Kumazawa	Annelies Volders
UTokyo	UTokyo	AIST	NIMS	QST	TMDU	NICT	Kyoto University	RIKEN		

CONTENTS

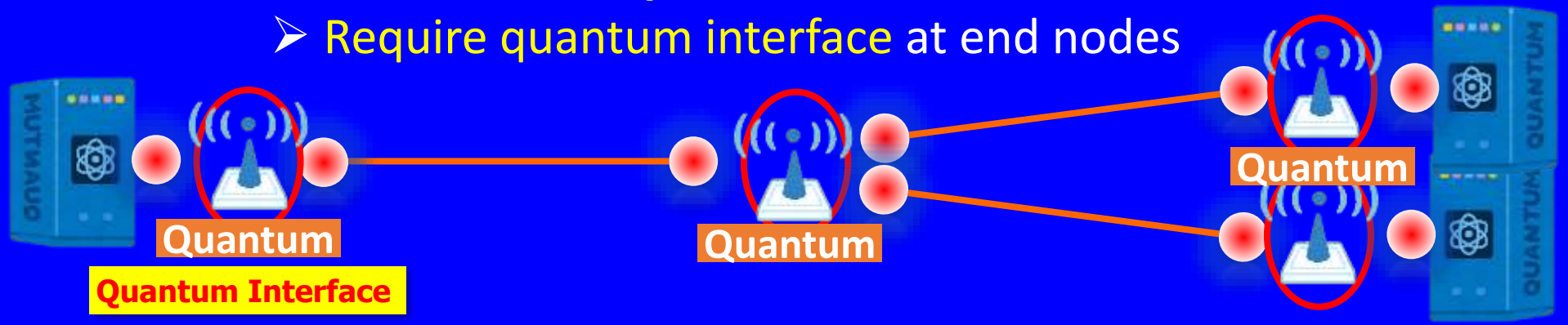
1. Quantum Internet
2. Quantum Computer Networks
3. Quantum Repeater Networks

Development steps toward 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**
   - Require quantum interface at end nodes



Classical data

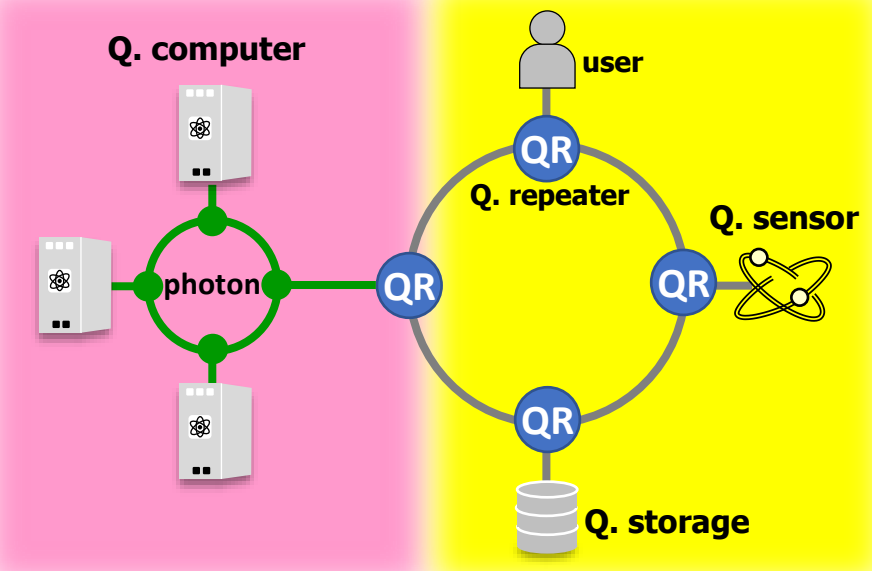
Quantum data

Quantum Internet

Quantum Computer Networks + Quantum Repeater Networks

Project QuINT (Quantum INTerfaces)
https://moonshot.ynu.ac.jp
Program MOONSHOT RESEARCH & DEVELOPMENT PROGRAM
Agency MEXT, Cabinet Office

Short distance



Project QuREP (Quantum Repeater Technology)
https://qurep.ynu.ac.jp
Program GQuNET
Agency MIC

Long distance

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Nanotech phase | Device phase | System phase | Protocol phase | Service phase

10~30 year

Basic research → Applied research

GQuNET

Quantum Computer Networks

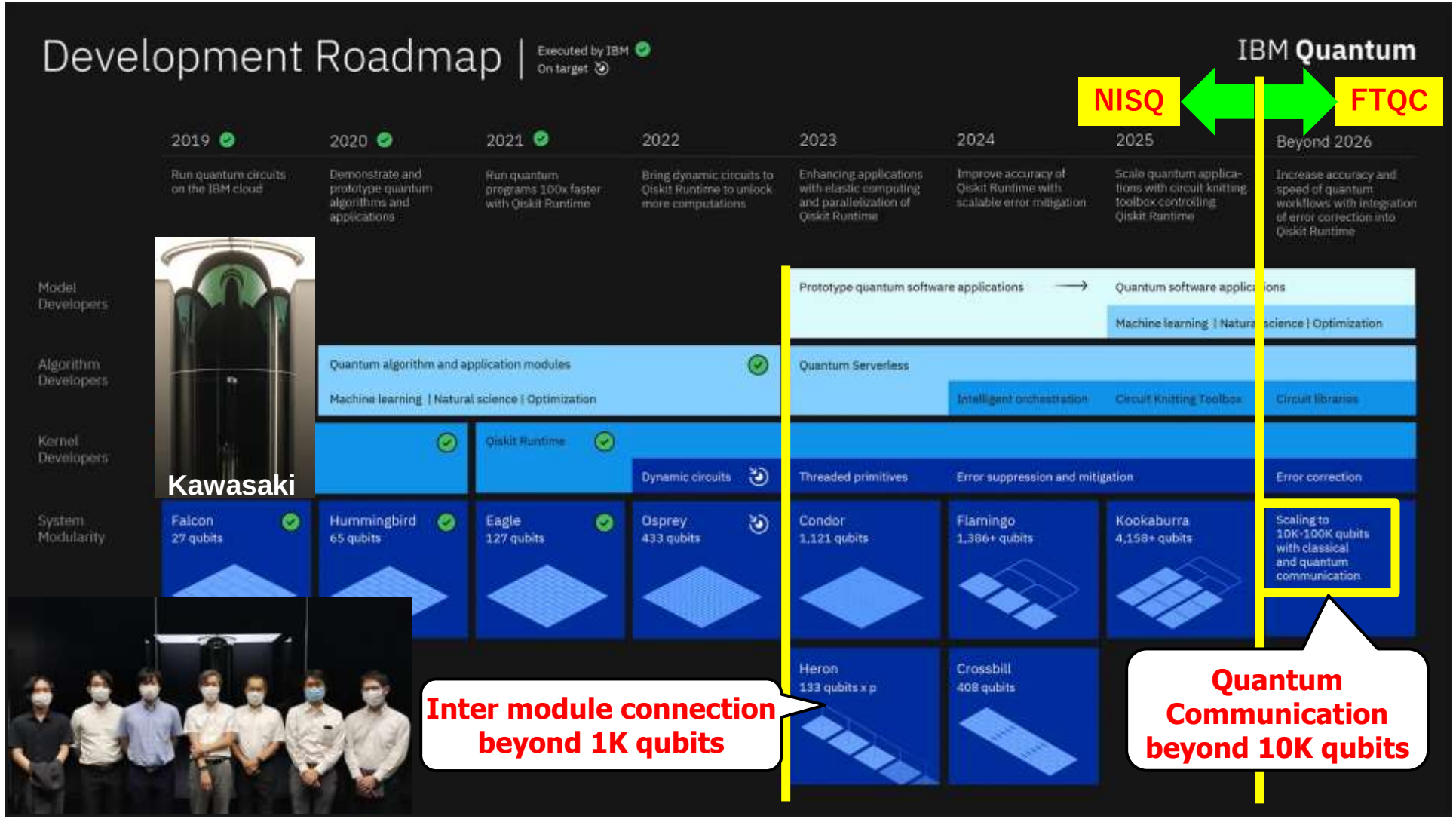
Project 

https://moonshot.ynu.ac.jp

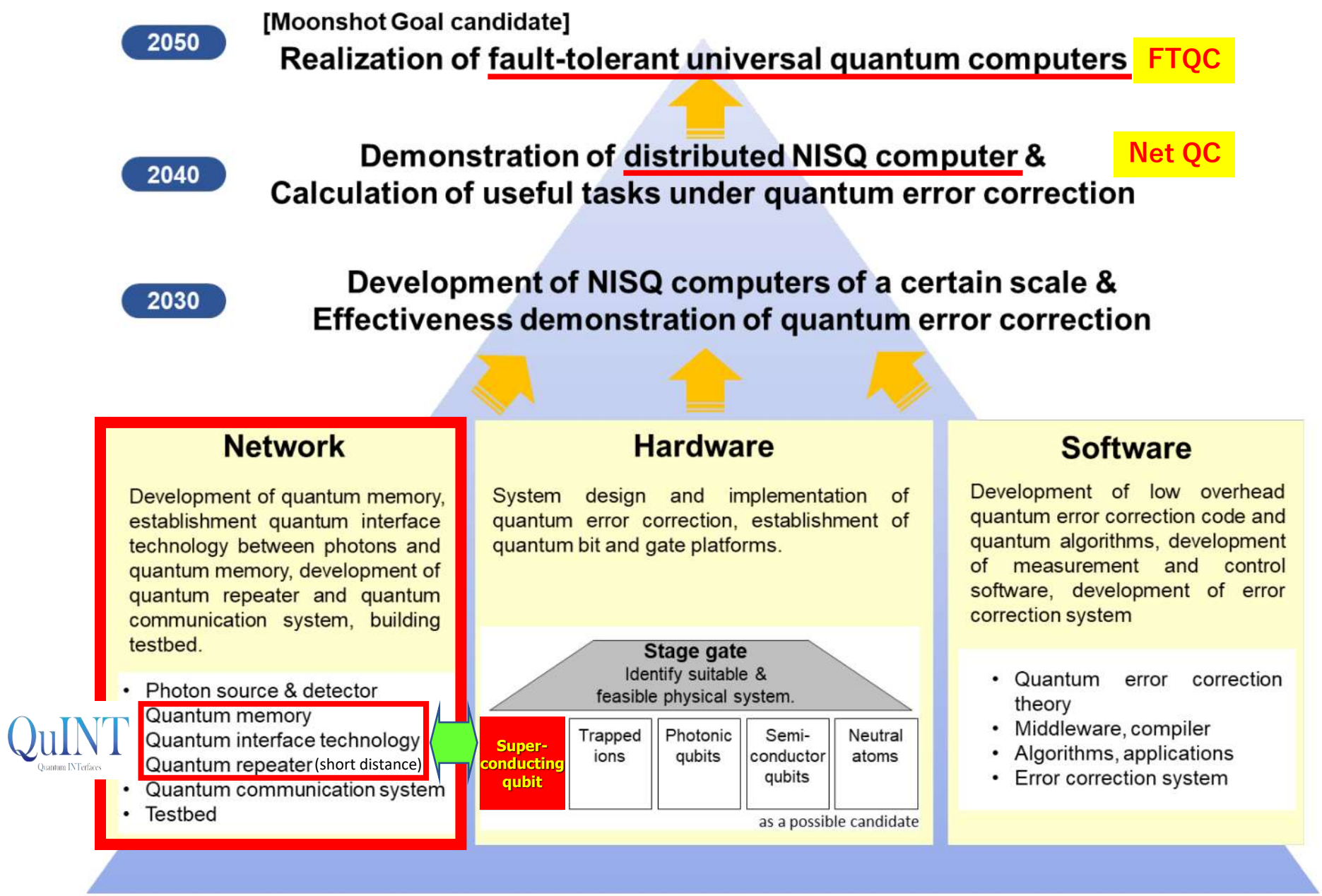
Program 

Agency 

Development Roadmap for Superconductor Quantum Computer



Moonshot Quantum Computer Program



Quantum Interface Project

https://moonshot.ynu.ac.jp

PM Hideo Kosaka
(Director of Quantum Information Research Center)

World-wide Nanotechnology Researchers in 8 universities and 5 national institutes

Diamond Q. Memory

- Hideo Kosaka 
- Hiromitsu Kato 
  Toshiharu Makino 
- Tokuyuki Teraji 
- Shinobu Onoda 
- Satoshi Fujii

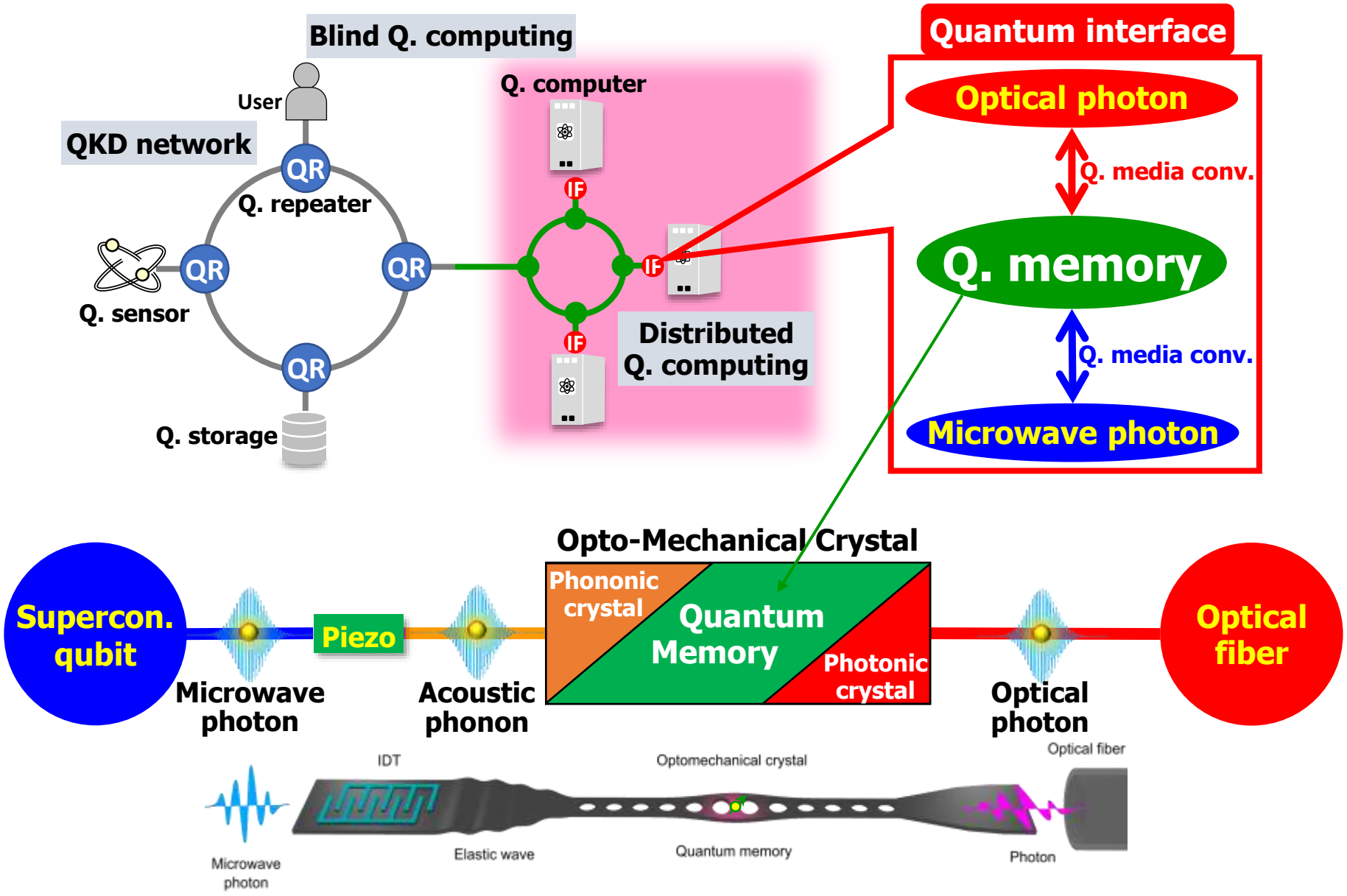
Opto-Mech. Resonator

- Satoshi Iwamoto 
- Toshihiko Baba 
- Masahiro Nomura 

Piezo-MW Resonator

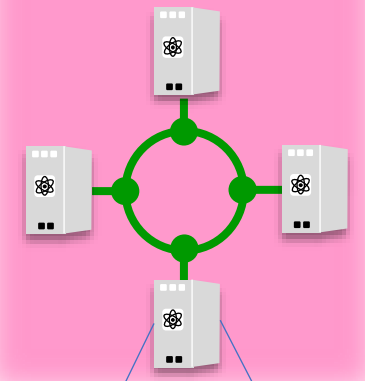
- Hideo Kosaka 
- Nobuyuki Yoshikawa 
- Kazuki Koshino 
- Fumihiro Inoue
- Yoshihiro Shimazu
- Hirotaka Terai
- Kunihiro Inomata
- Ryo Sasaki
- Katsuaki Tanabe

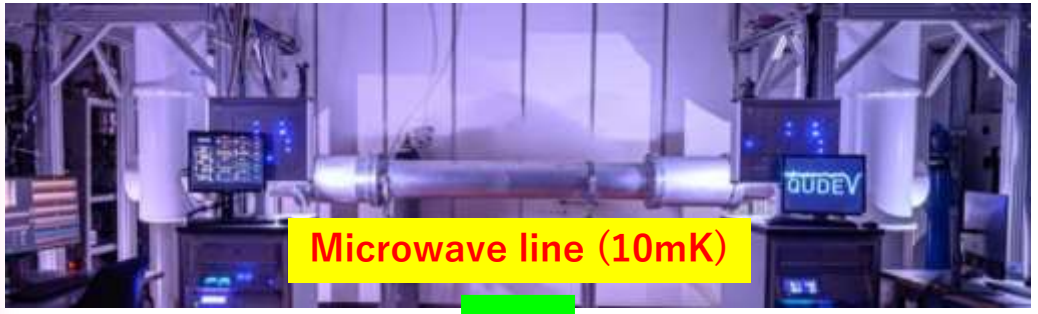
Quantum Interface Project



Optically connected QCs

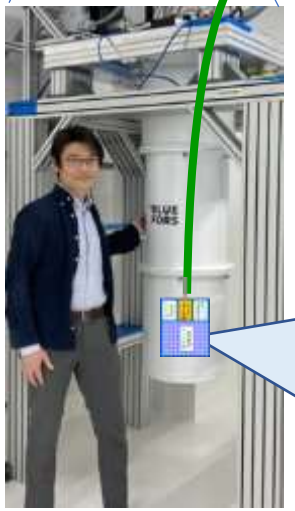
Quantum Computer



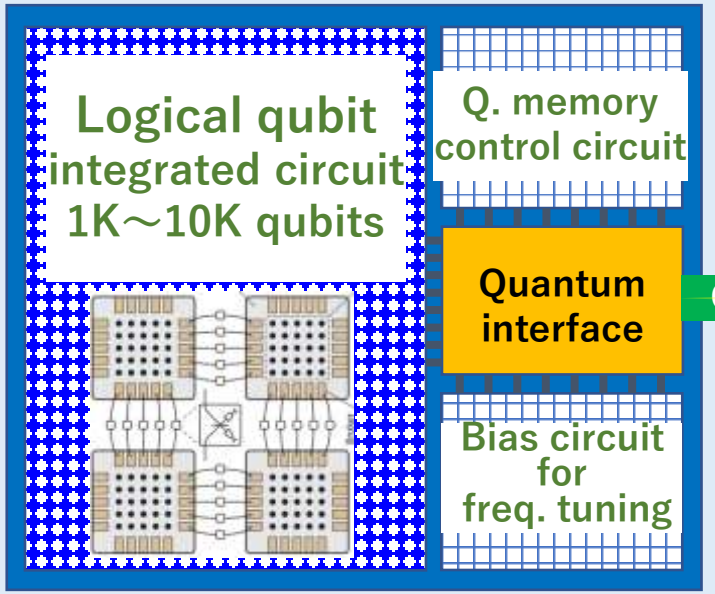


Optical fiber (RT)

Scalable!



Dilution refrigerator
(10mK)



One link from one logical qubit could be enough

Opto-Mechanical Crystal QI

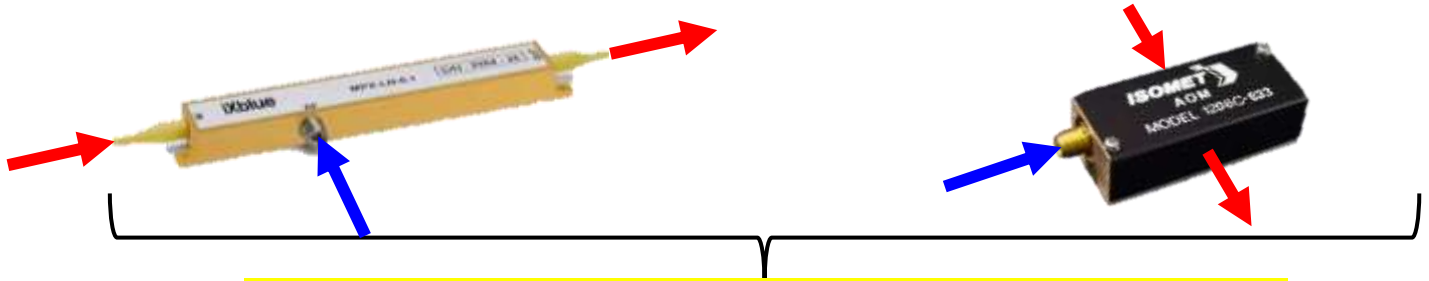
Conversion between EM field (μwave) - EM field (Optical)
~5 GHz ~500 THz
with 5-orders different Frequency & Spatial-mode

EO modulator

Electro-Optic modulator
Fast but low extinction ratio

AO modulator

Acousto-Optic modulator
High extinction ratio but slow



High power optical pumps are needed

Heterodyne detection (Yale)

LN bulk

EO or AO resonator

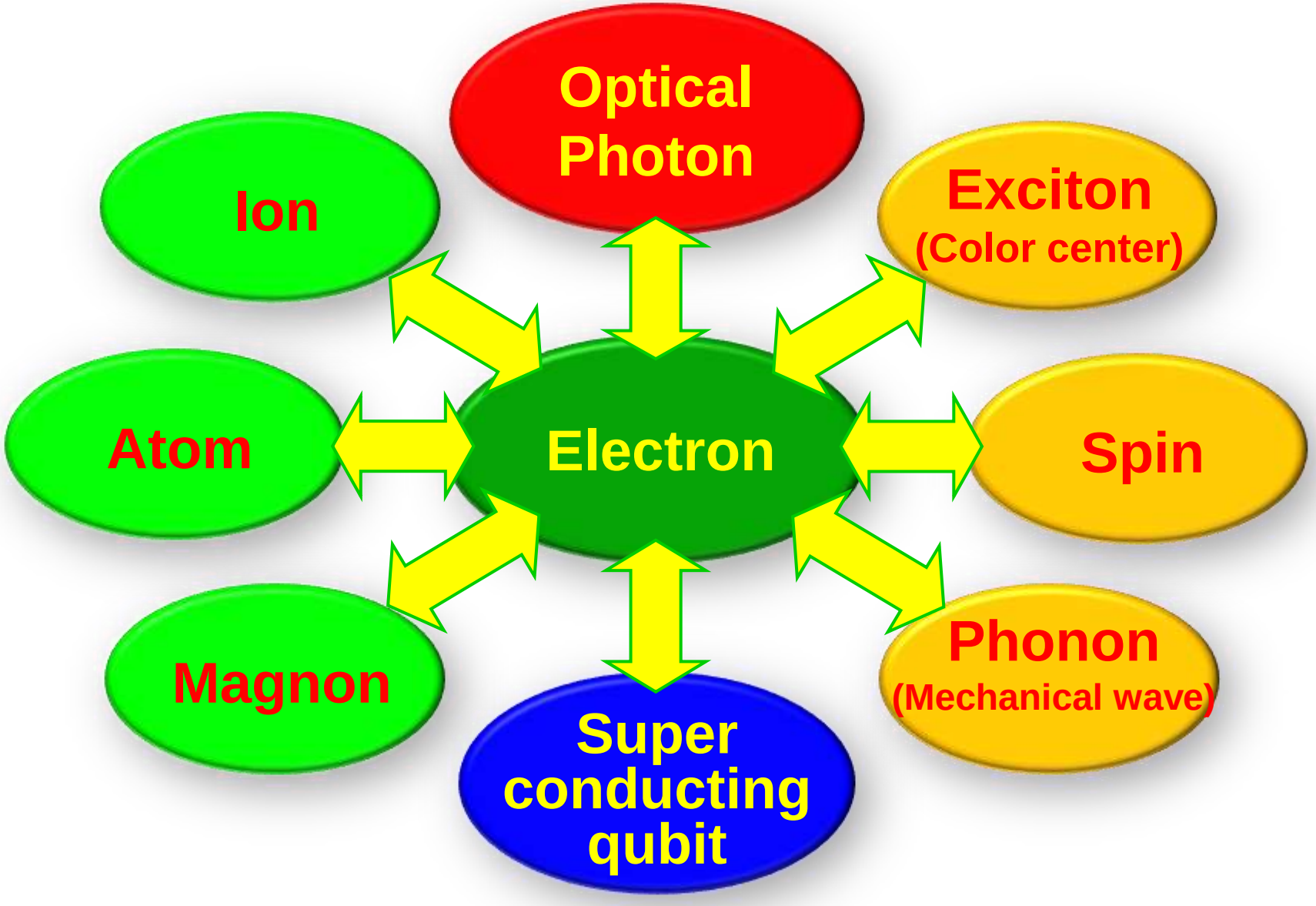
SiN membrane

Carrier frequency ω_0~1MHz (JILA)

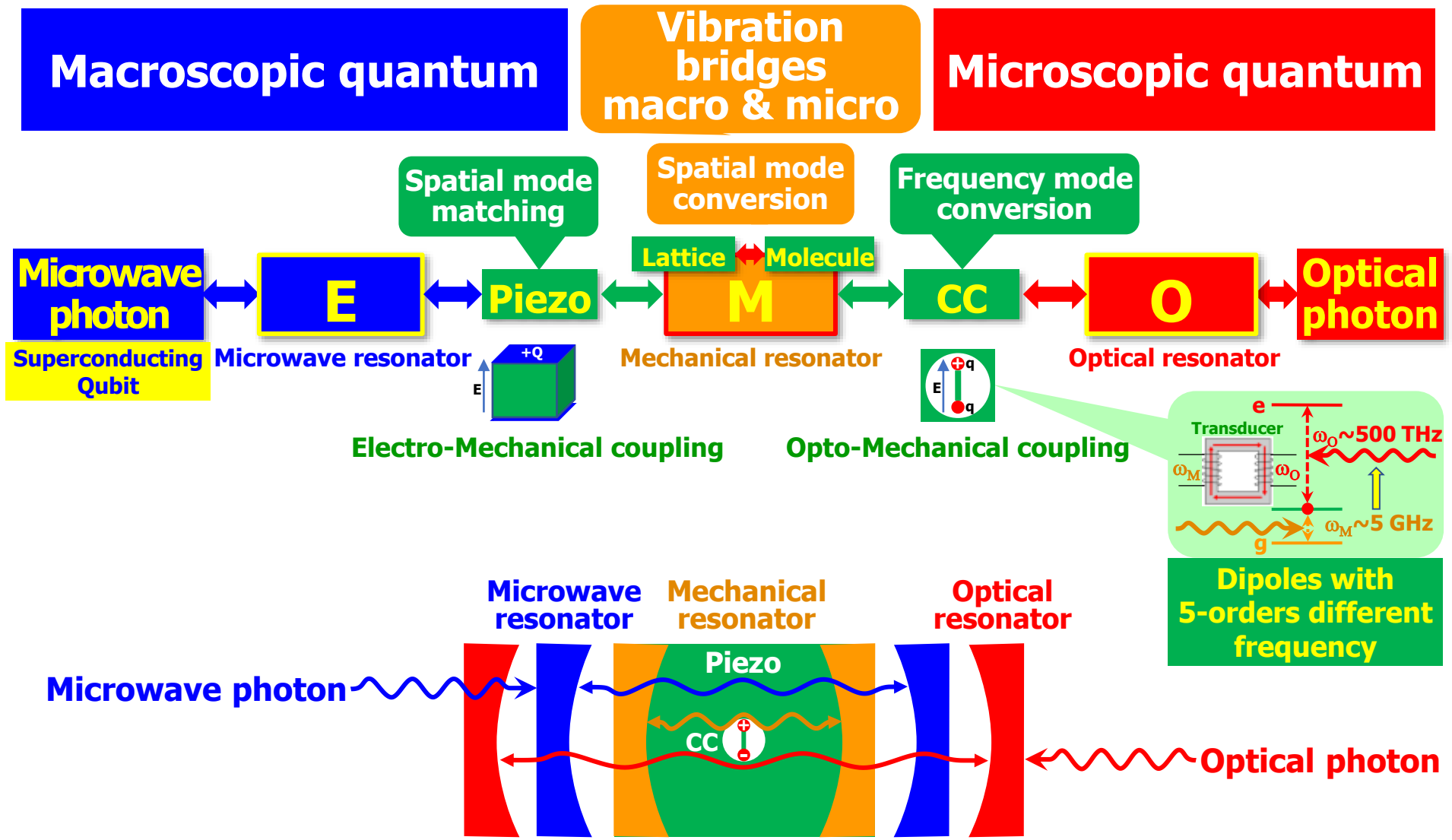
Opto-Mechanical Crystal (OMC) + Color Center (CC)

High-efficiency, High-bandwidth, High-repetition, High-fidelity & On-demand

Principle = Quantum Media Conversion



Mechanism of OMC-QI with CC

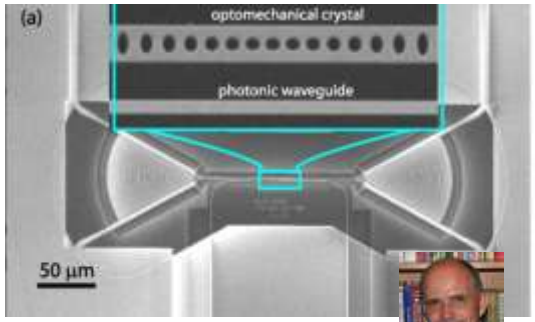


H. Kurokawa, M. Yamamoto, Y. Sekiguchi & H. Kosaka, arXiv:2202.07888, Phys. Rev. Appl. in press (2022).

Conventional OMC-QI

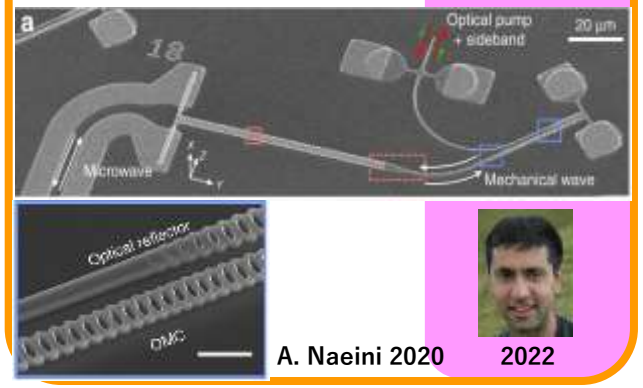
Homogeneous structure ⇒ Heterogeneous structure

Chicago (Cleland) AlN



A. N. Cleland 2016

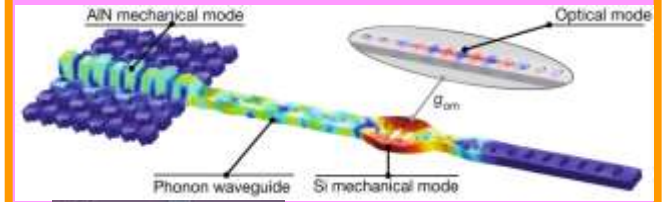
Stanford (Naeini) $LiNbO_3$ → LN/Si

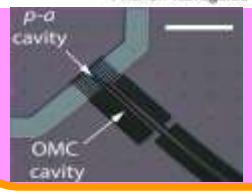


A. Naeini 2020

2022

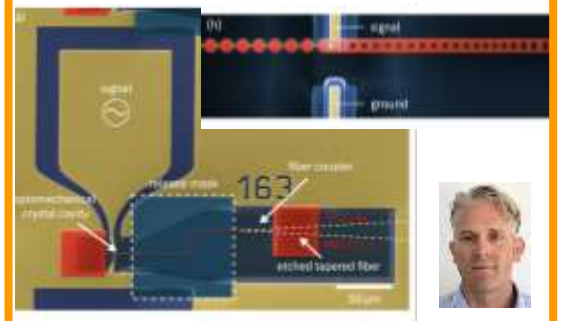
Caltech (Painter) AlN/Si





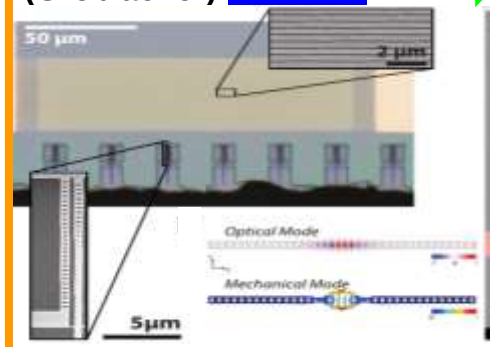
O. Painter 2020

EPFL & IBM (Kippenberg & P. Seidler) GaP

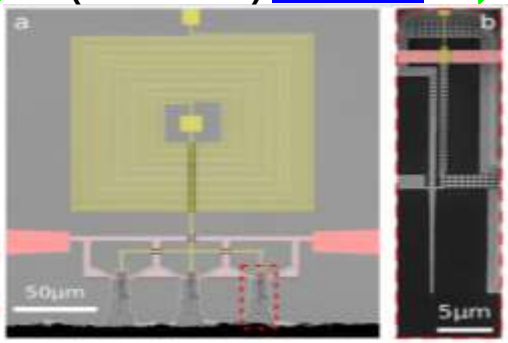


T. J. Kippenberg & P. Seidler 2022

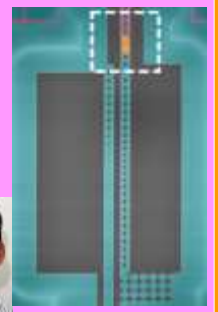
Delft (Groblacher) GaAs → Delft (Groblacher) GaP → QphoX LN/Si



S. Groblacher 2020



S. Groblacher 2021



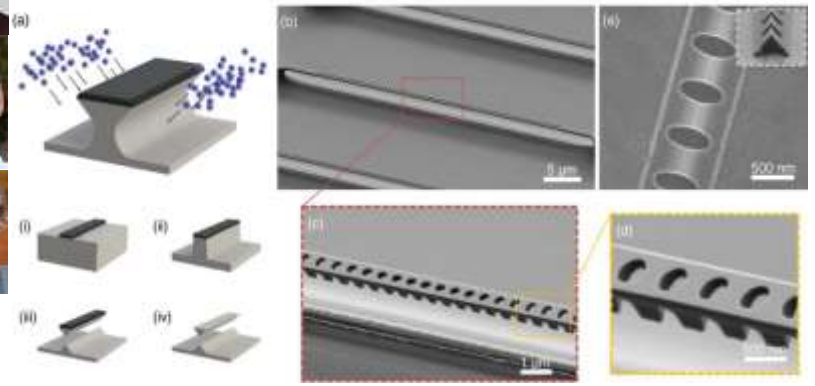
S. Groblacher 2022

Diamond Opto-Mechanical Crystal

Heterogeneous structure with Piezo is required for QI

Harvard, Caltech (Loncar, Painter, Lukin)

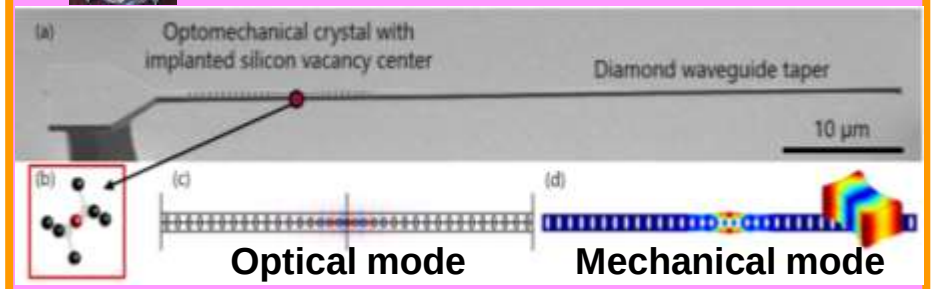
M. J. Burek et al., Optica 3, 1404 (2016).



Optical Q = 176,000 @ 1,529 nm
Mechanical Q = 4,100 @ 5.5 GHz @RT

Harvard (Loncar) — SiV

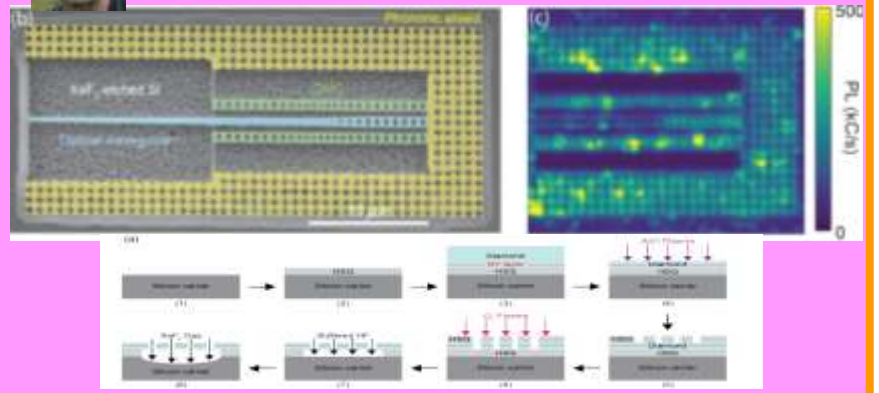
G. Joe et al., CLEO (2021)



Optical Q ~ 10,000 @ 1,544 nm
Mechanical Q = 22,000 @ 9.2 GHz @4K

Stanford (Naeini) — NV

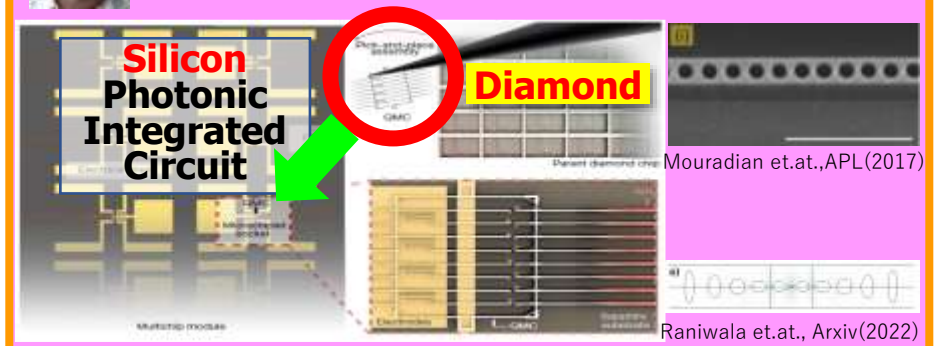
J. Cady et al., Quantum Science and Technology 4, 024009 (2019).



Optical Q = 42,000 @ 1,542 nm
Mechanical Q = 118 @ 5.9 GHz @RT

MIT (Englund) — SiV, GeV

Wan et.al., Nature(2020)



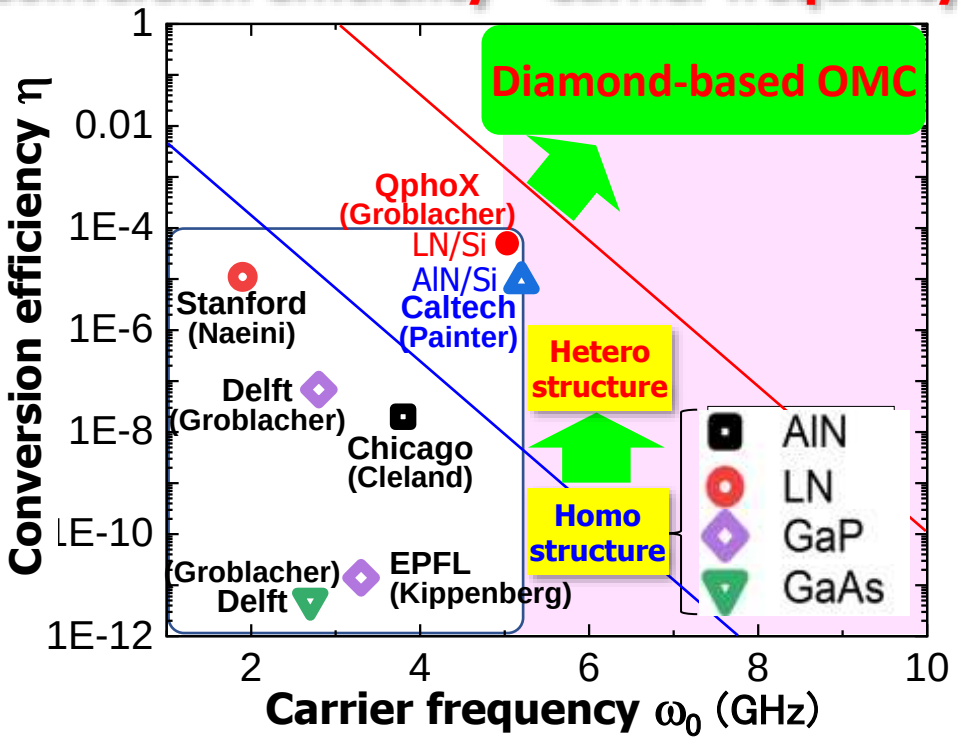
Mouradian et.at.,APL(2017)

Raniwala et.at., Arxiv(2022)

Optical Q = 14,000 @ 637 nm

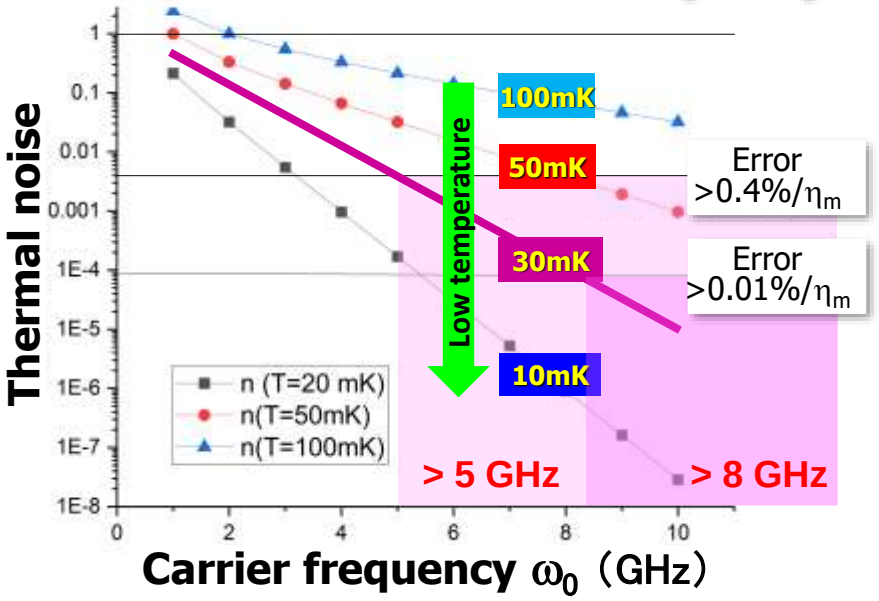
Advantage of diamond OMC-QI

Conversion efficiency - Carrier frequency

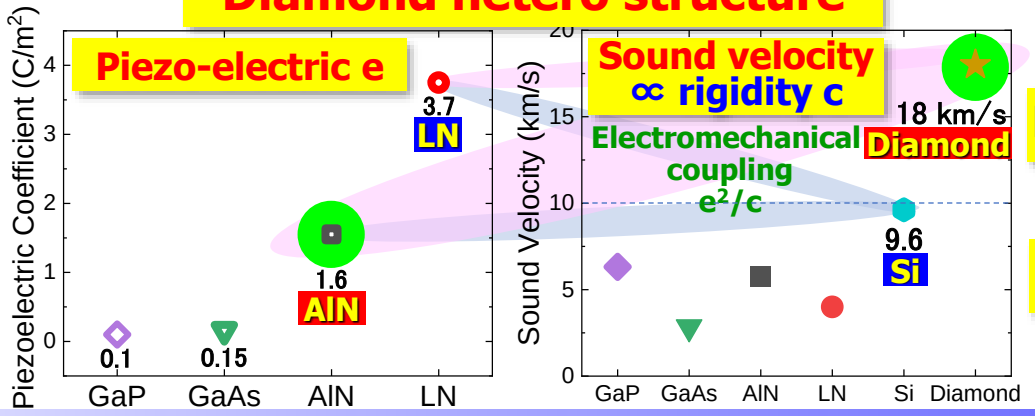


High frequency >5GHz is needed for low thermal noise

Thermal noise - Carrier frequency



Diamond hetero structure

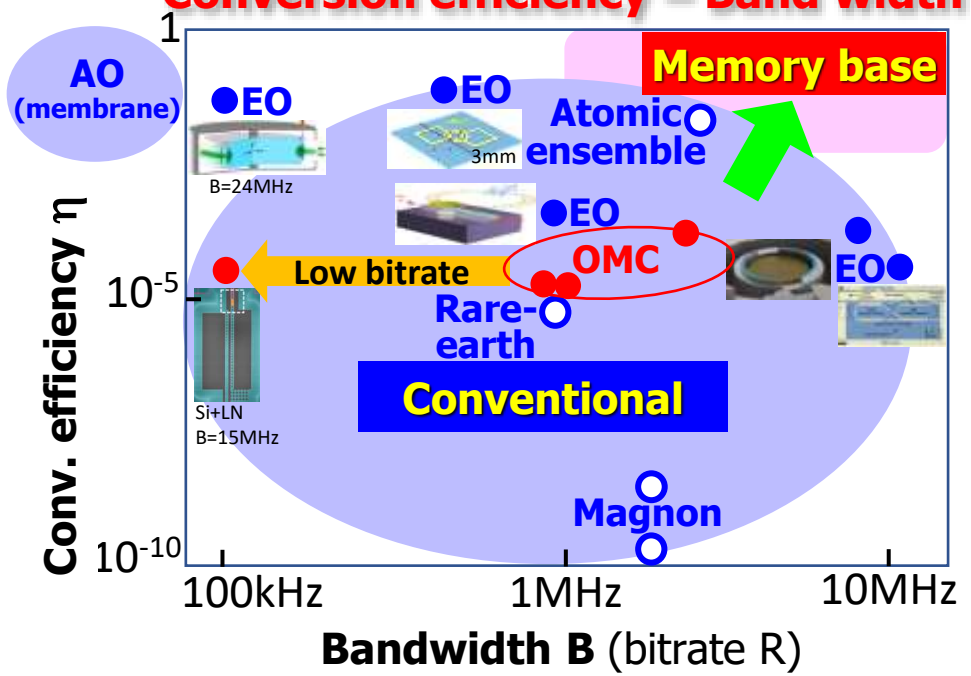


High modulus → **Low dissipation at high frequency**

Fast velocity → **Wavelength match photon - phonon**

Advantage of memory-based QI

Conversion efficiency – Band width

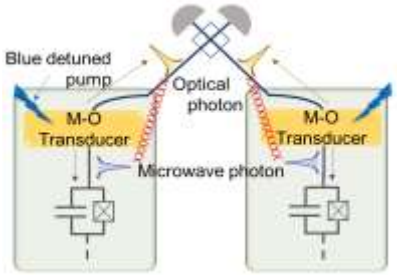


Conventional QI — High optical pump → **High photon noise, High thermal noise**

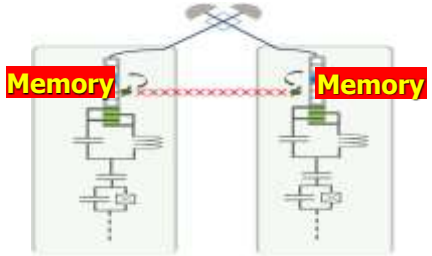
Memory-based QI — Photon scattering → **No photon noise, No thermal noise**

High fidelity + High rep. rate = High bitrate

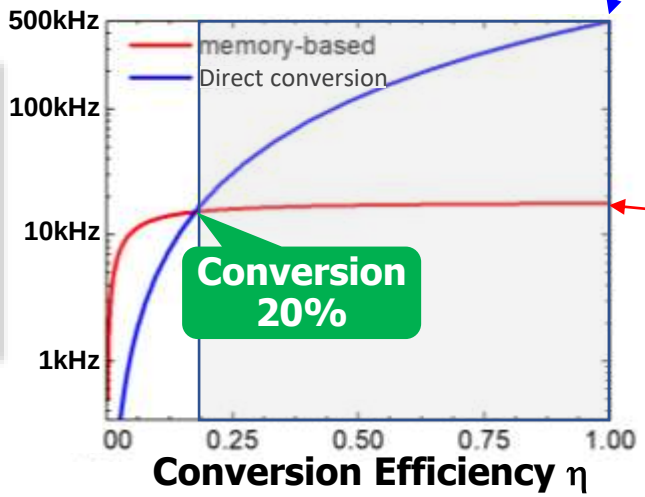
Direct conversion ~ 0.5MHz



Memory-based conv. ~ 20kHz

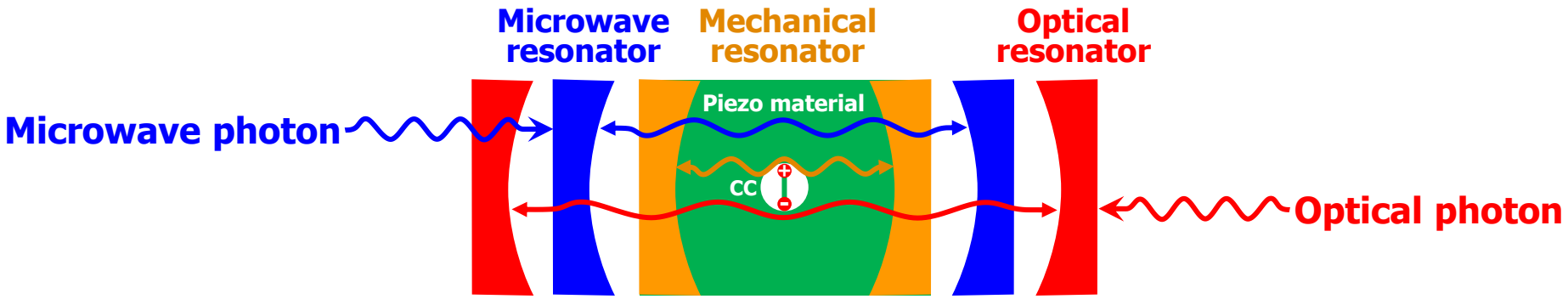


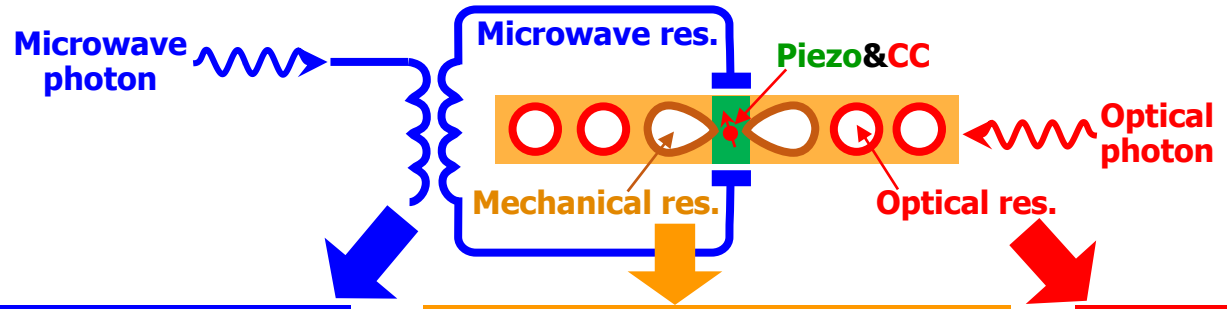
Entanglement generation rate between SC qubits



H. Kurokawa, M. Yamamoto, Y. Sekiguchi & H. Kosaka, arXiv:2202.07888, Phys. Rev. Appl. in press (2022).

Fabrication challenge for Diamond OMC

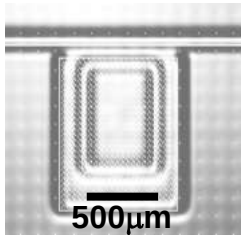


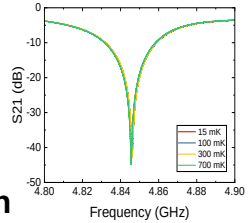


Superconducting microwave resonator

NbTiN/Si

Q = 8,000 @ 5GHz,15 mK





100nm line width

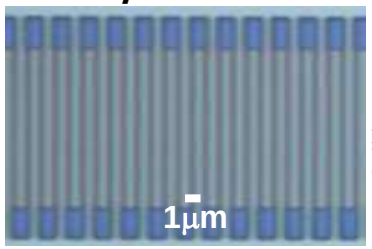
H. Terai

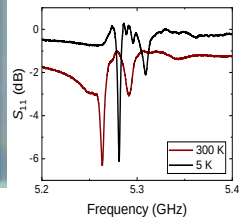
T. Makino, H. Kato

Diamond piezo-electric mechanical resonator

AlN/Diamond

Q = 10,000 @ 5GHz,5 K





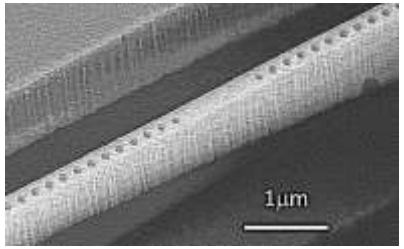
1μm pitch

S. Fujii

T. Makino, H. Kato

Diamond photonic crystal optical resonator

Diamond nanobeam



250nm pitch, 260nm width, 500nm high

S. Iwamoto

T. Makino, H. Kato

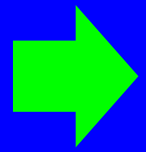
Quantum Repeater Networks

Project

https://qurep.ynu.ac.jp/

Program

Agency



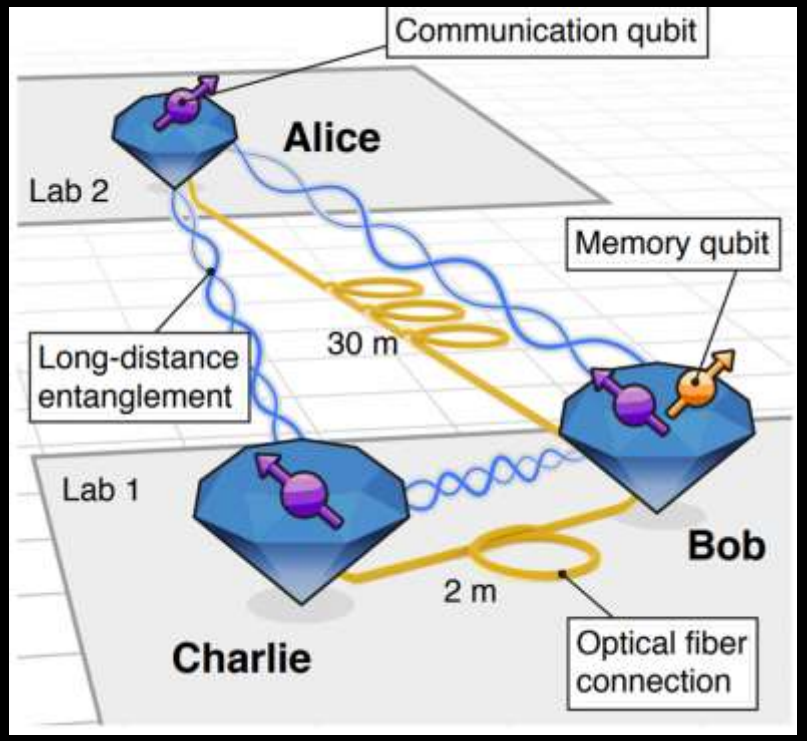
Program

Agency

QuTech / TU Delft

Science 2021

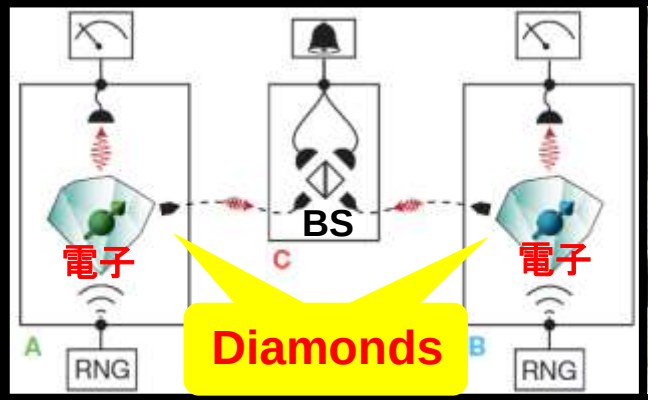
Multiparty Quantum Repeater Network



First demonstration of diamond-based Quantum Internet?

M. Pompili et.al. , Science 372, 259–264 (2021)

nature 2015



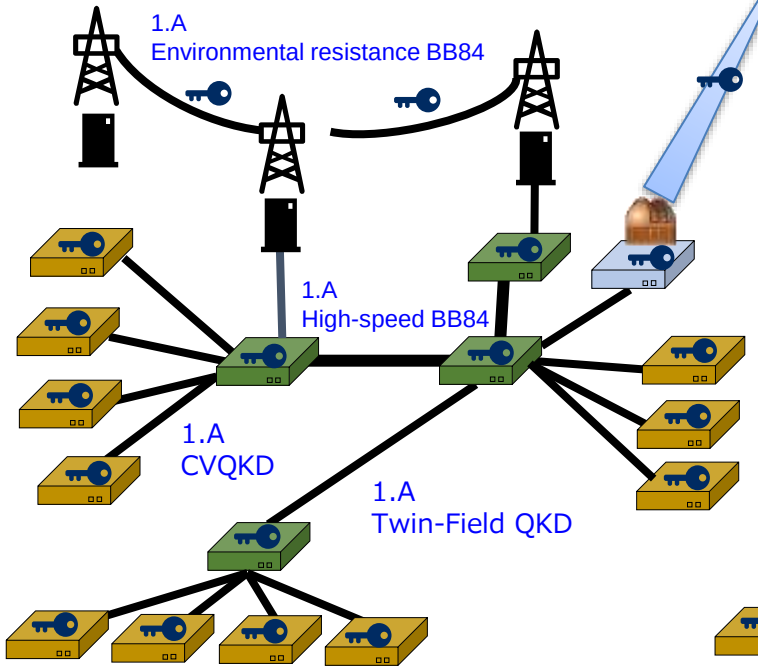
B.Hensen et.al., Nature 526, 682 (2015)

Global Quantum Network Program

GQuNET

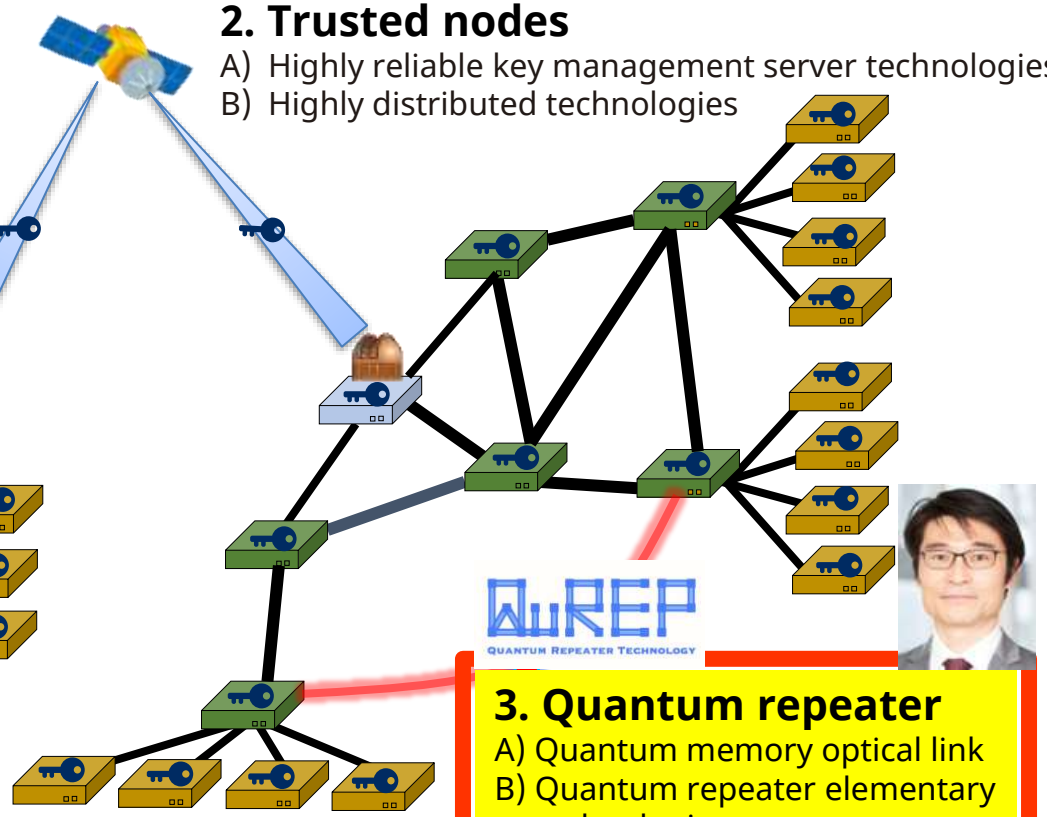
1. Quantum crypto link

A) High-performance quantum cryptography
B) Photon detection



2. Trusted nodes

A) Highly reliable key management server technologies
B) Highly distributed technologies



QuREP
Quantum Repeater Technology

3. Quantum repeater

A) Quantum memory optical link
B) Quantum repeater elementary technologies

4. Network operation

A) Network control and management

YNU YOKOHAMA National University
UTokyo
TOSHIBA
MITSUBISHI ELECTRIC
FURUKAWA ELECTRIC
AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)
NIMS
NICT
HOKKAIDO UNIVERSITY
GAKUSHUIN UNIVERSITY
NEC
HAMAMATSU

Quantum Repeater Project

https://qurep.ynu.ac.jp/

YNU YOKOHAMA National University

Coordinator

AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

NIMS

東京大学 THE UNIVERSITY OF TOKYO

TOSHIBA

Memory- based quantum repeater

Quantum memory in diamonds

Entangled emission

Entangled absorption

Quantum memory

Entanglement measurement

Quantum repeater module

Quantum wavelength conversion module

※Photon module conversion technology

Wavelength-multiplexed photon

Laser to adjust wavelength

Quantum memory

Wavelength-multiplexed quantum repeater device

FURUKAWA ELECTRIC

Diamond microfabrication

High-performance - micro resonator

All-optical quantum repeater

Semiconductor multiphoton entangled photon source

Quantum dots

Entangled state distributor

Communication band Optical fiber

Nodes

Bell measurement

Multiphoton entangled states

Wavelength-multiplex quantum repeater

Superconducting single photon detector

Wavelength-multiplexed photon

Wavelength

Fiber-base wavelength-multiplexed entangled photon source

Wavelength-dependent photon delivery

Alice

Bob

Carol

Alice

Bob

Carol

NICT

Memory-based Quantum Repeater

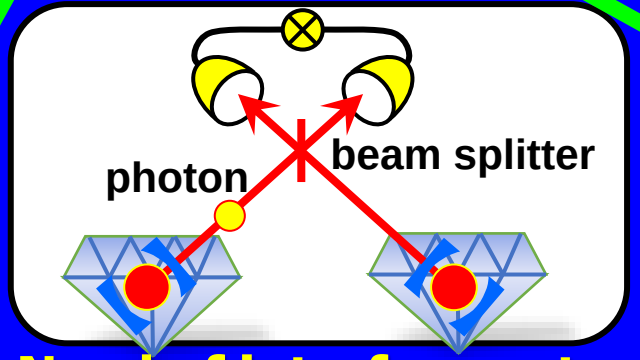
DLCZ

YNU

Remote ent generation

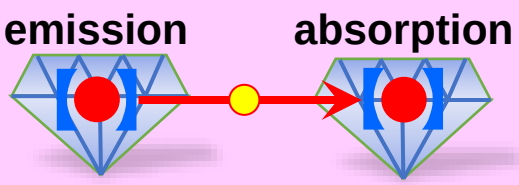
Local ent measurement

Emission-emission

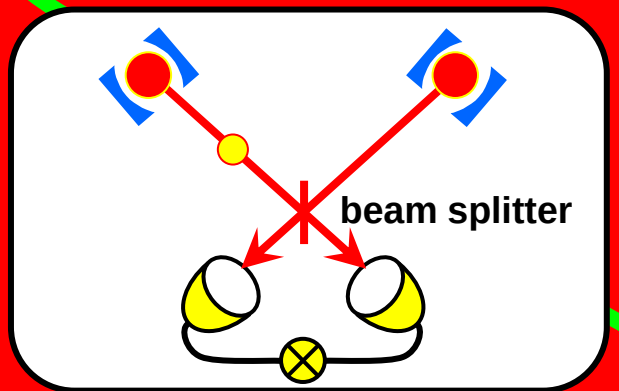


Need of interferometer

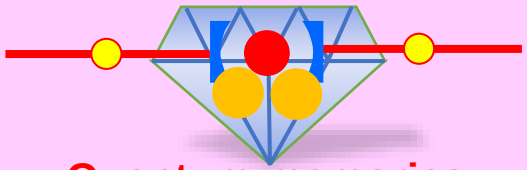
Emission-absorption



No need of interferometer



Probabilistic



Quantum memories
(enable Complete BSM)

Deterministic

QuTech

× No scalability

○ Scalable

On-demand

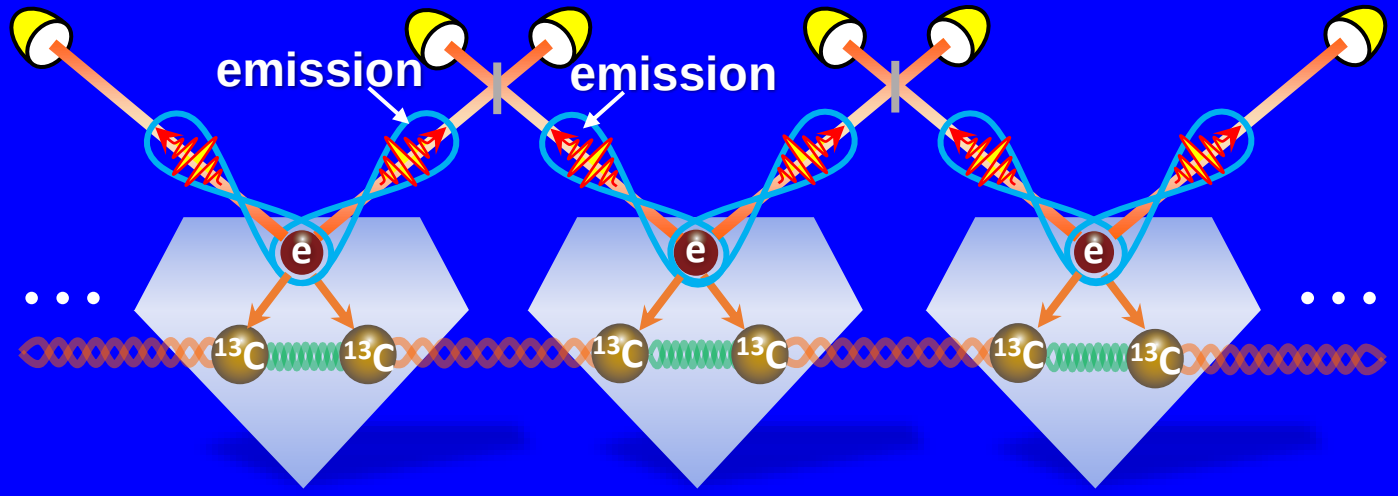
Comparison of diamond QR schemes

QuTech

High B-field

Single-photon interference

subjects to photon loss of only a half path

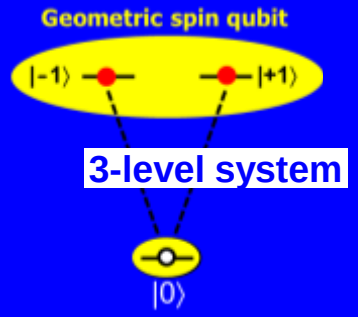


High **bitrate** with extreme loss

YNU

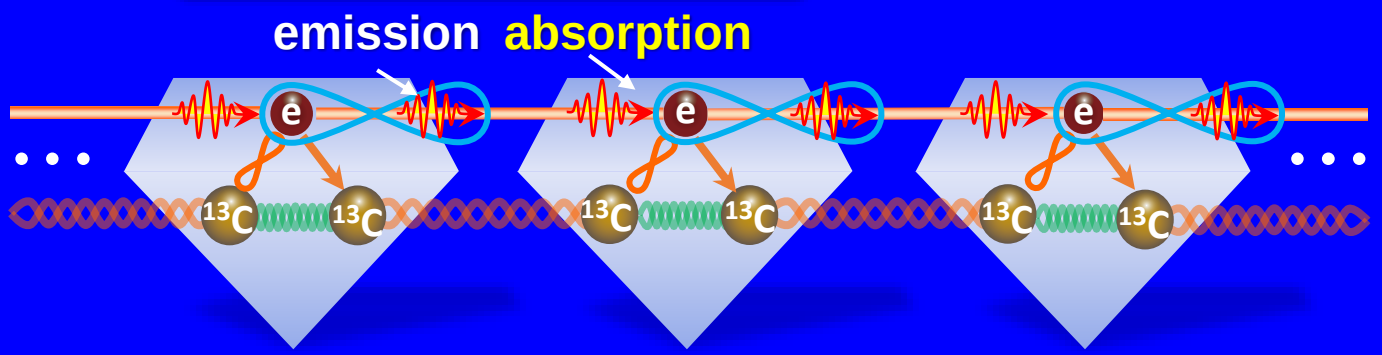
B = 0

Integration with SC qubit



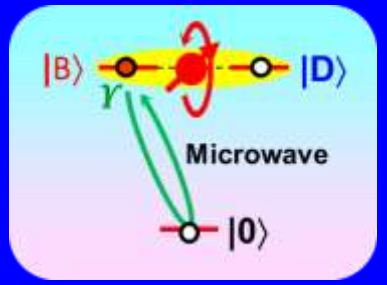
Single-photon absorption

does not rely on extreme loss



High **fidelity** without loss limit

Required functions for YNU QR scheme



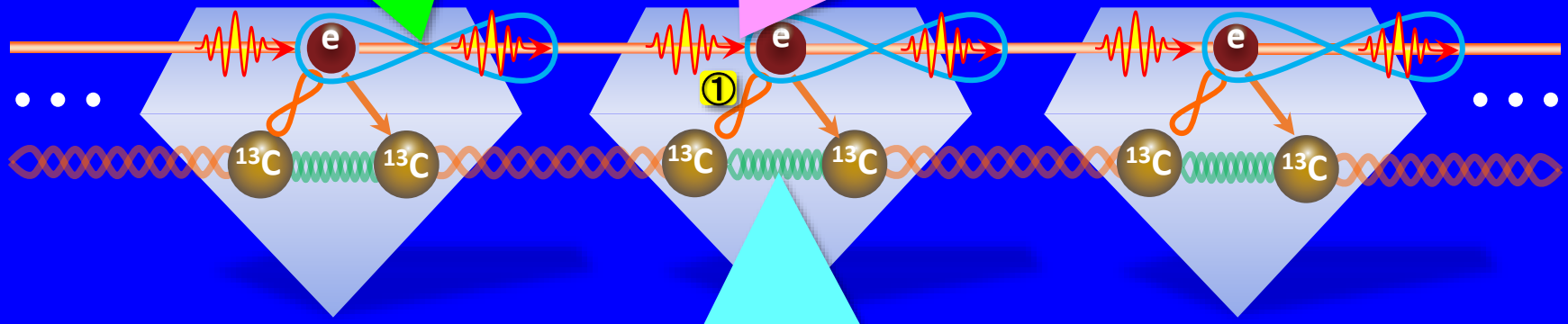
Manipulate degenerate qubit
with holonomic quantum gate

B = 0

1. Universal quantum gates

2. Entangled emission

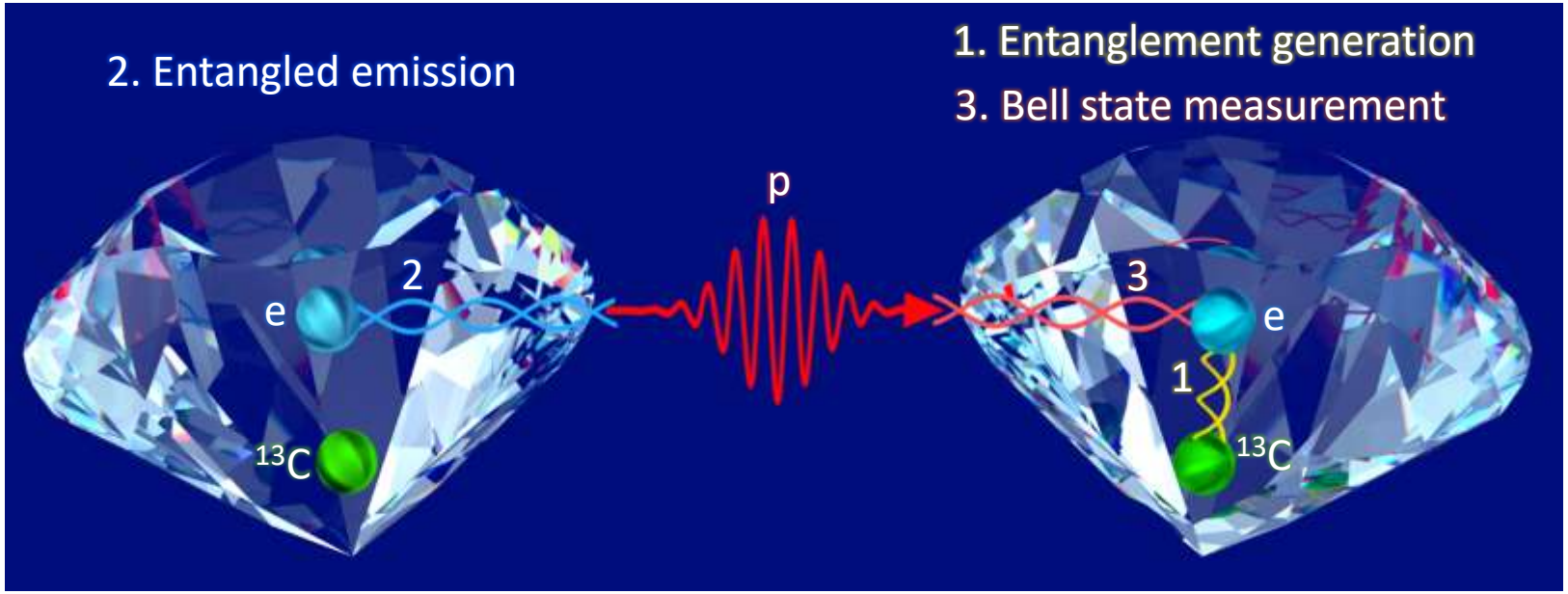
3. Quantum teleportation trasfer



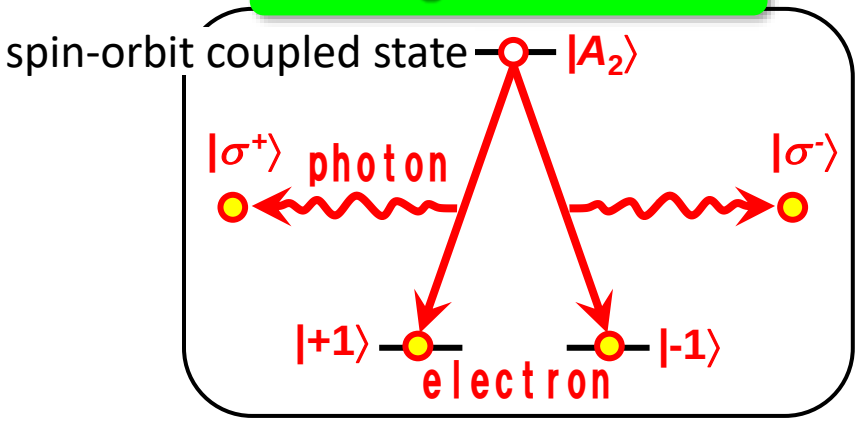
4. Complete Bell measurement + **5. Quantum error correction**

★*Nature Photonics*, 10,507-511(2016)
★*Nature Photonics*, 11, 309-314 (2017)
★*Nature Photonics*, 16, 662-666 (2022)
★*Nature Communications*, 7, 11668 (2016)
★*Nature Communications*, 9, 3227 (2018)
★*Communications Physics*, 2, 74 (2019)
★*Communications Physics*, 4, 264 (2021)
★*Communications Physics*, 5, 102 (2022)
Physical Review Letters, 114, 053603 (2015)
Physical Review Applied, 12, 051001 (2019)

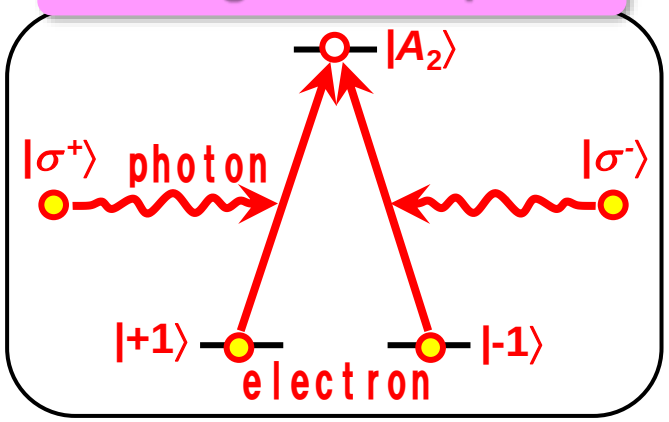
Entangled emission & absorption



Entangled emission



Entangled absorption

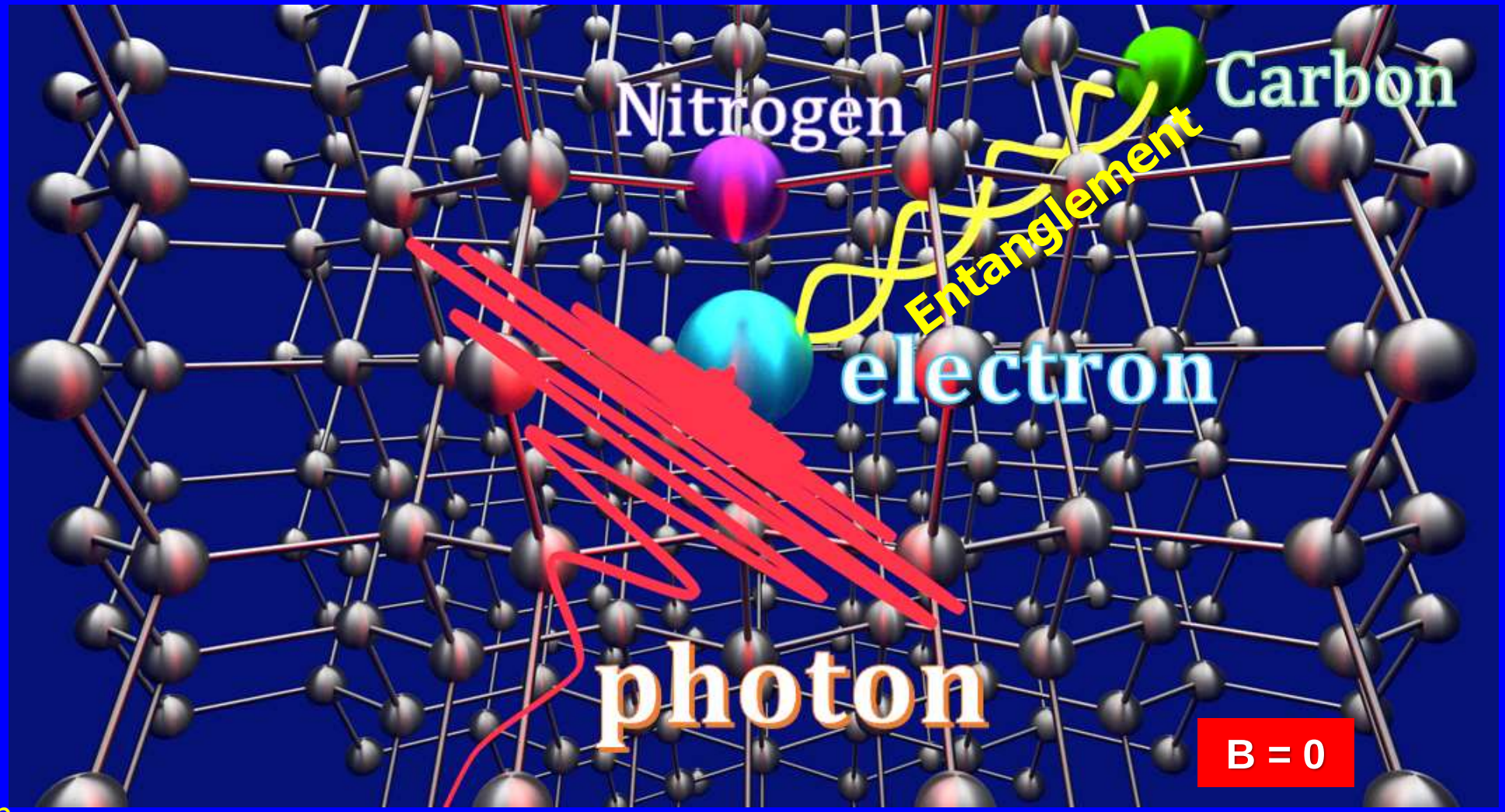


Quantum teleportation into carbon

Fidelity ~ 100%

Quantum Teleportation into a Memory

We have succeeded to exclusive transfer and store a quantum state from an optical photon to a selected carbon quantum memory

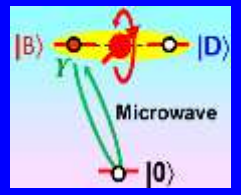
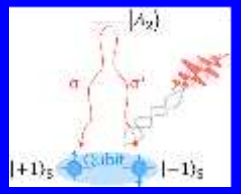
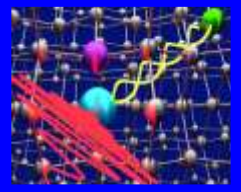
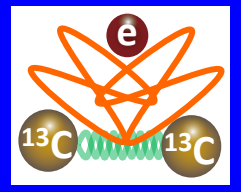
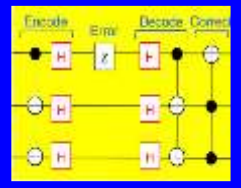


Collaboration

Joerg Wrachtrup
(U. Stuttgart) → Nature Photonics, 10, 507(2016) Communications Physics 2, 74 (2019)

Performances of YNU QR device

(Single NV⁻ @ 5K, B=0)

	Functions	Status
	① Universal quantum gate fidelity (e)	99.97%
	Gate speed (e)	180 MHz
	② Entangled emission fidelity (e & p)	98%
	Photon generation rate (ZPL)	10 Kcps
	③ Quantum teleportation fidelity (p→C)	94%
	Memory time (e / C)	0.1s / 1s
	④ Complete Bell measurement fidelity (2C)	90%
	Single-shot readout fidelity (C)	99.7%
	⑤ Quantum error correction fidelity (N+2C)	83%
	Controllable memory number (e+N+8C)	10

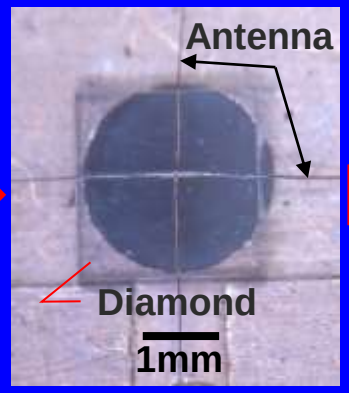
We succeeded to achieve all the functions required for on-demand QR

Challenge for higher efficiency & multimode

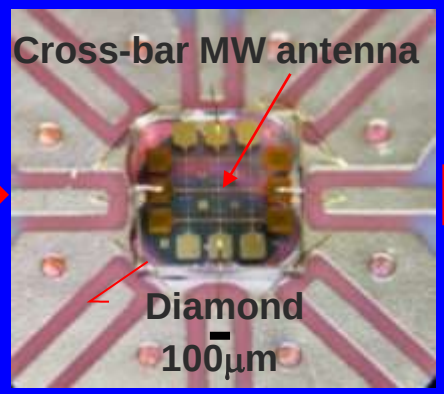
High-purity diamond

NIMS

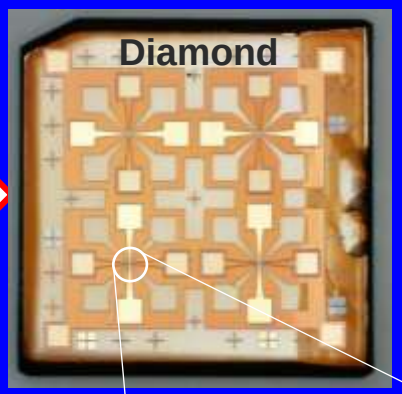
0G (1mm)



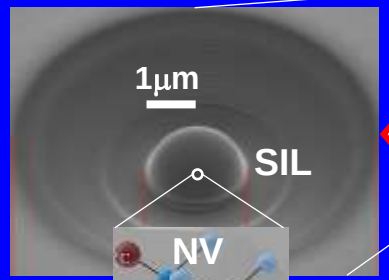
1G (100μm)



2G (10μm)



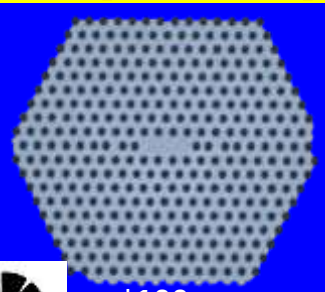
3G (1μm)



Diamond micro lens (SIL)

Emit/abs increase x 50

4G (100nm)



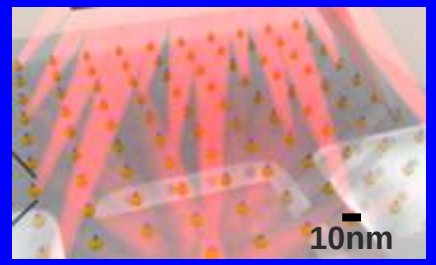
UTokyo

AIST
NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

Diamond photonic crystal

Emit/abs enhance x 1000

5G (10nm)



NIMS

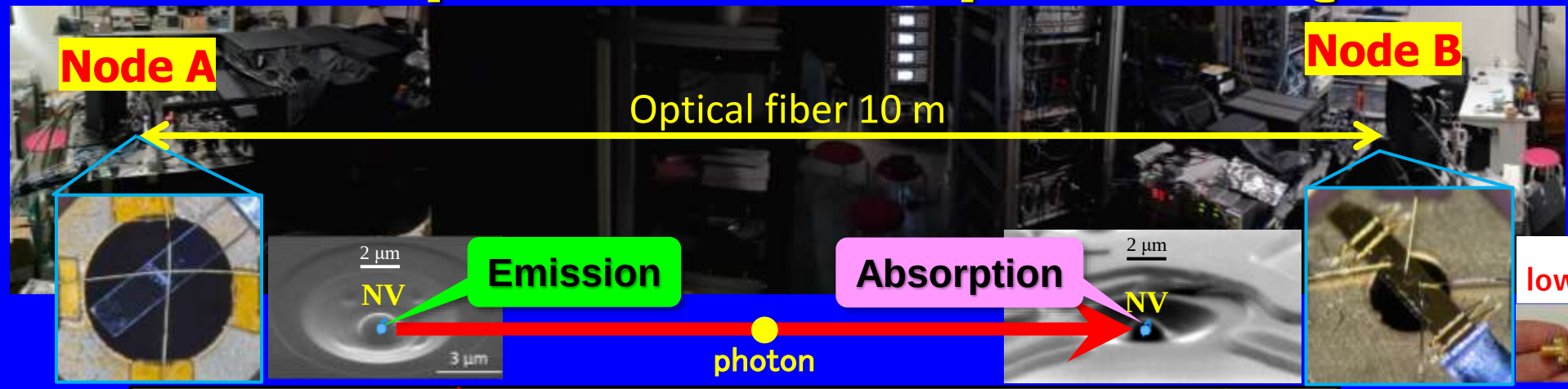
QST

Nanobeam single ion implantation

Multimode~1Kbits Optical QRAM

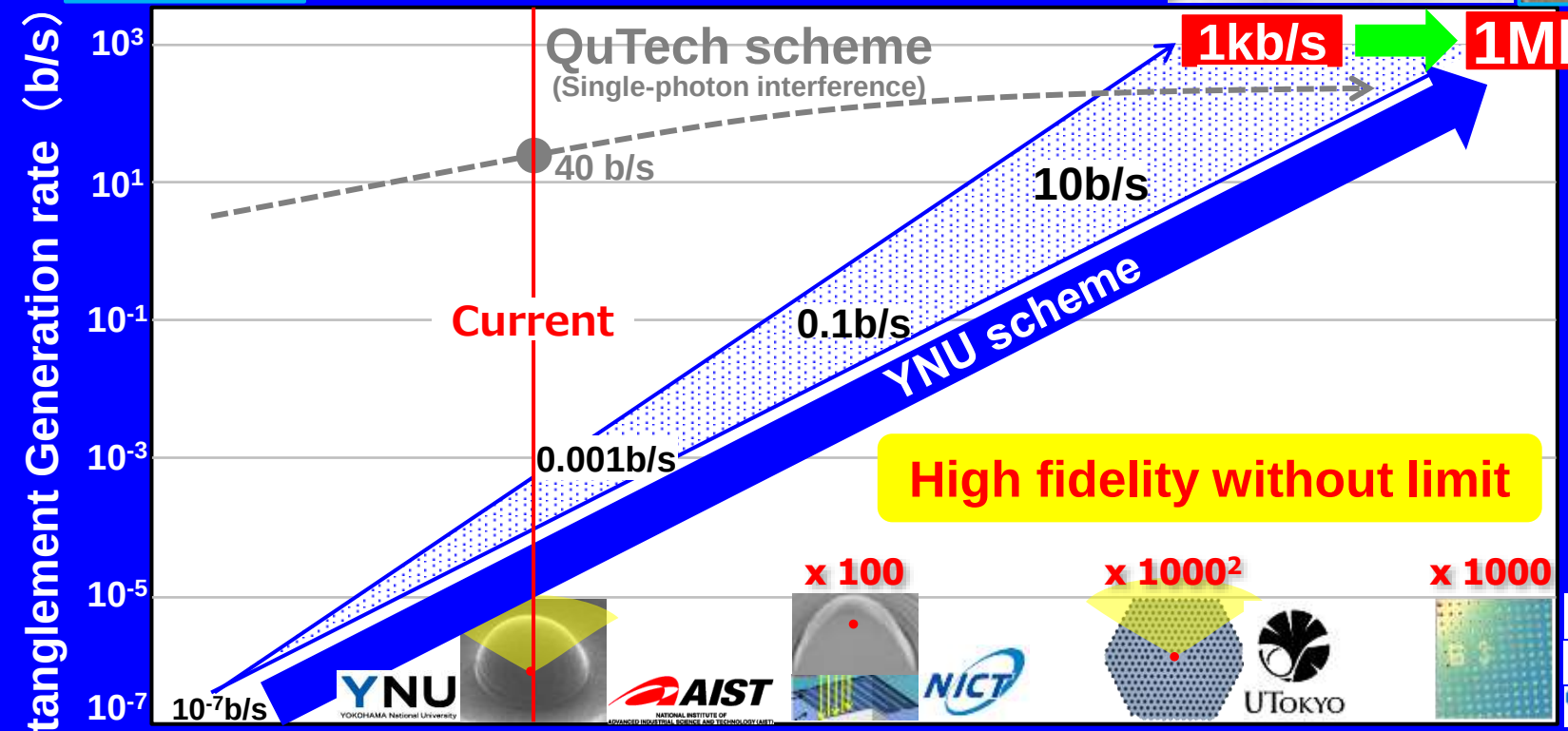
Nature Photonics, 16, 662-666 (2022)

Development Roadmap of YNU QR



Heralded by low-noise SNSPD

Shigehito Miki



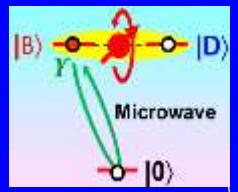
QST TOSHIBA FURUKAWA ELECTRIC

Space
Time
Frequency

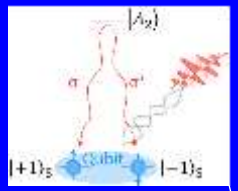
Publications on YNU QR scheme

★: Nature Journals

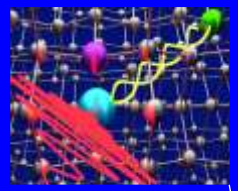
① Universal quantum gate



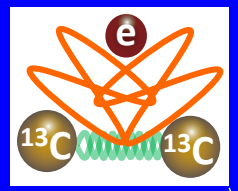
② Entangled emission



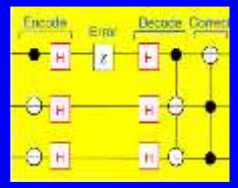
③ Quantum teleportation transfer



④ Complete Bell measurement



⑤ Quantum error correction



All under B=0

★ **Nature Communication 2016**
Nature Communications, 7, 11668 (2016)

★ **Nature Photonics 2017**
Nature Photonics, 11, 309-314 (2017)

★ **Nature Communications 2018**
Nature Communications, 9, 3227 (2018)

Optics Letters 2018
Optics Letters, 43, 2380-2383 (2018)

Physical Review Applied 2019
Physical Review Applied, 12, 051001 (2019)

★ **Nature Photonics 2022**
Nature Photonics, 16, 662-666 (2022)

★ **Communications Physics 2021**
Communications Physics, 4, 264 (2021)

Phys. Rev. Lett. 2015
Physical Review Letters, 114, 053603 (2015)

★ **Nature Photonics 2016**
Nature Photonics, 10, 507-511 (2016)

★ **Communications Physics 2019**
Communictions Physics, 2, 74 (2019)

Applied Physics Letters 2022
Appl. Phys. Lett. 120, 194002 (2022)

★ **Communications Physics 2022**
Communications Physics 5, 102 (2022)

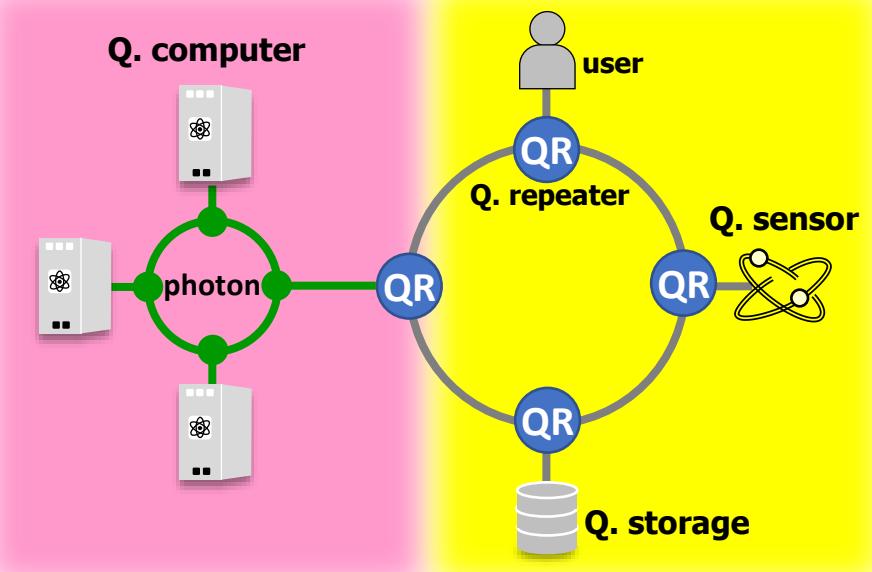
Summary

We are developing diamond-based
Quantum Interface device for Quantum Computer Networks
and
Quantum Repeater device for Quantum Repeater Networks
toward Quantum Internet.

Project
QuINT
Quantum INTerfaces
https://moonshot.ynu.ac.jp
Program
MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM
Agency
Cabinet Office

Short distance

Quantum Computer Networks + **Quantum Repeater Networks**



Project
QuREP
QUANTUM REPEATER TECHNOLOGY
https://qurep.ynu.ac.jp
Program
GQuNET
Agency
MIC

Long distance