MOONSHOT RESEARCH & DEVELOPMENT PROGRAM
Goal 6: International Symposium 2023
Jul. 19, 2023 @Akasaka Intercity Conference

Kosaka Project: QuINT Quantum INTerfaces
"Development of Quantum Interfaces for Building Quantum Computer Networks"

Hideo Kosaka
Project Manager
Professor, Yokohama National University
Director, Quantum Information Research Center
Research fellow, The University of Tokyo
Japan

YNU YOKOHAMA National University
QIC
UTokyo

CONTENTS

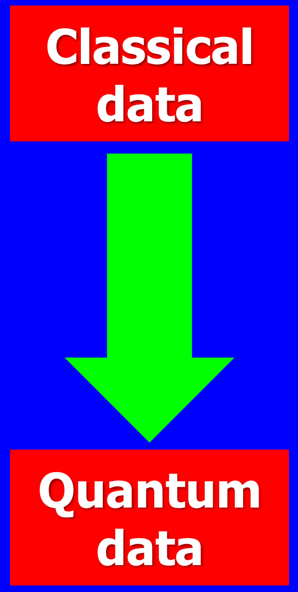
Development Steps toward Quantum Networks

1. Trusted-node Quantum Key Distribution(QKD) network

- Quantum enhanced security but not absolutely secure

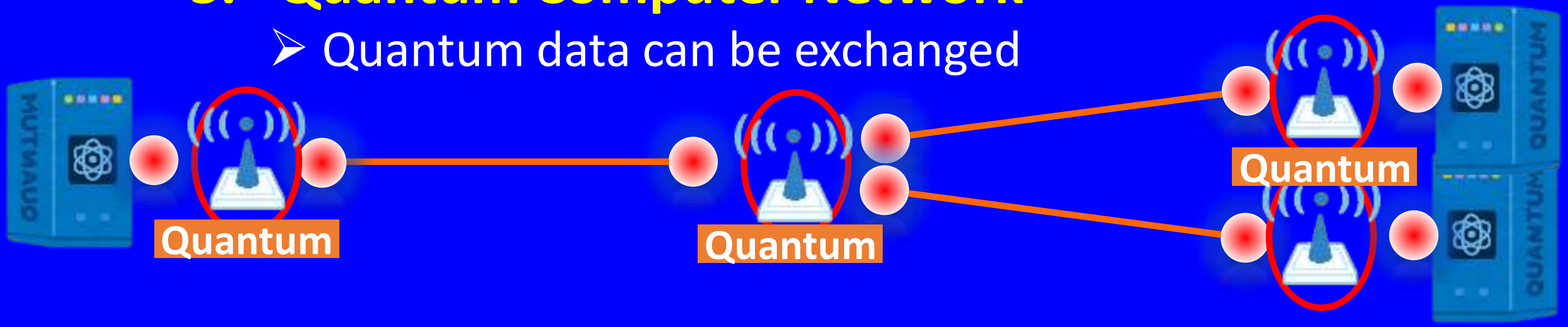
2. Quantum Repeater Network

- Absolutely secure QKD network with multiparty connections



3. Quantum Computer Network

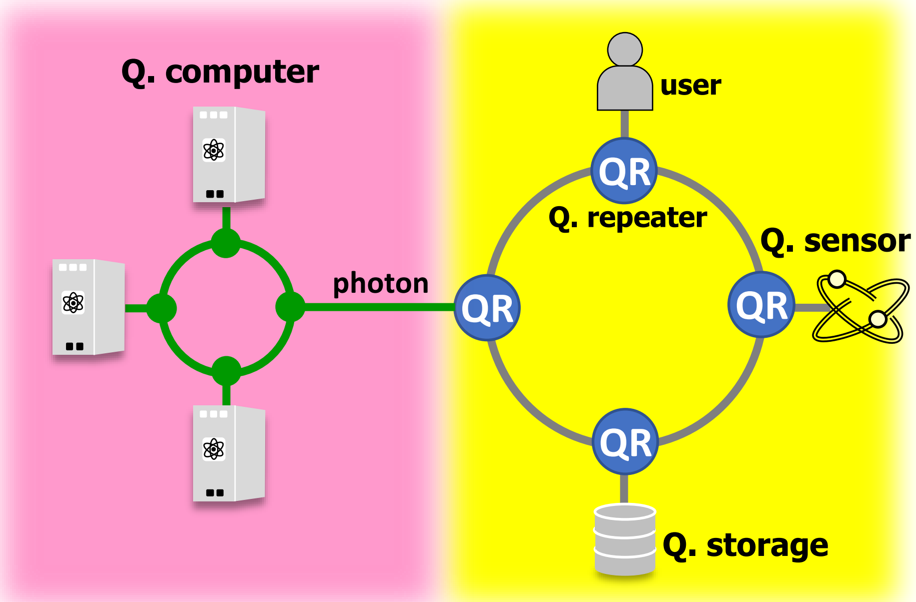
- Quantum data can be exchanged



National Projects toward Quantum Networks

QC&QC

Quantum Computer Networks ＋ Quantum Communication Networks



Short distance

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

Long distance

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

Nanotech phase	Device phase	System phase	Protocol phase	Service phase

10～30 year

Basic research → Applied research

Quantum Communication Networks

Project

QuREP
QUANTUM REPEATER TECHNOLOGY

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

Program

GlobalQKD

Agency

MIC

JPMI00316

Global QKD Network Program

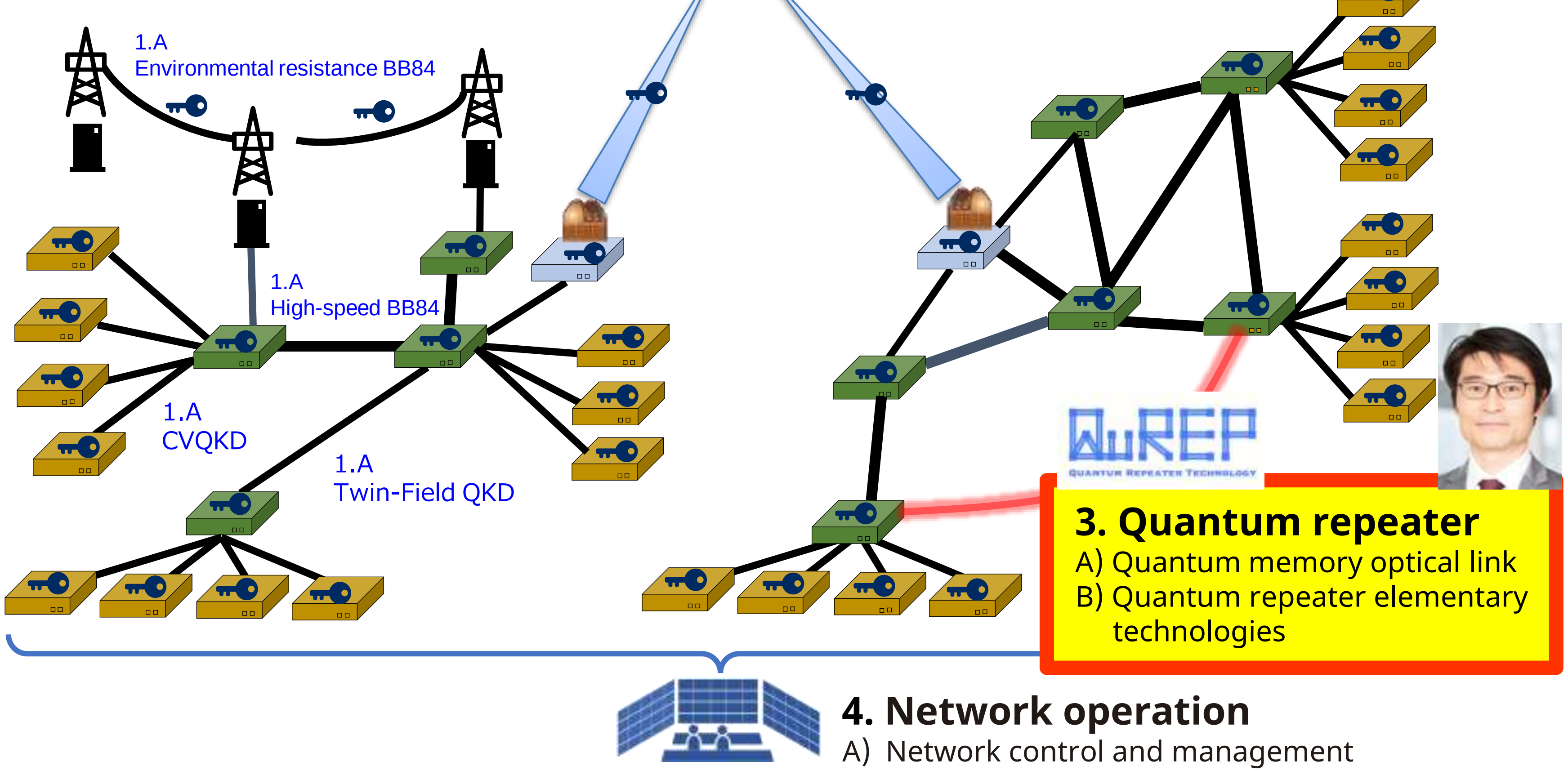
JPMI00316

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



3. Quantum repeater

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

4. Network operation

A) Network control and management

4 Companies

TOSHIBA, FURUKAWA ELECTRIC, NEC, HAMAMATSU

3 National Institutes

NICT, AIST (NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)), NIMS

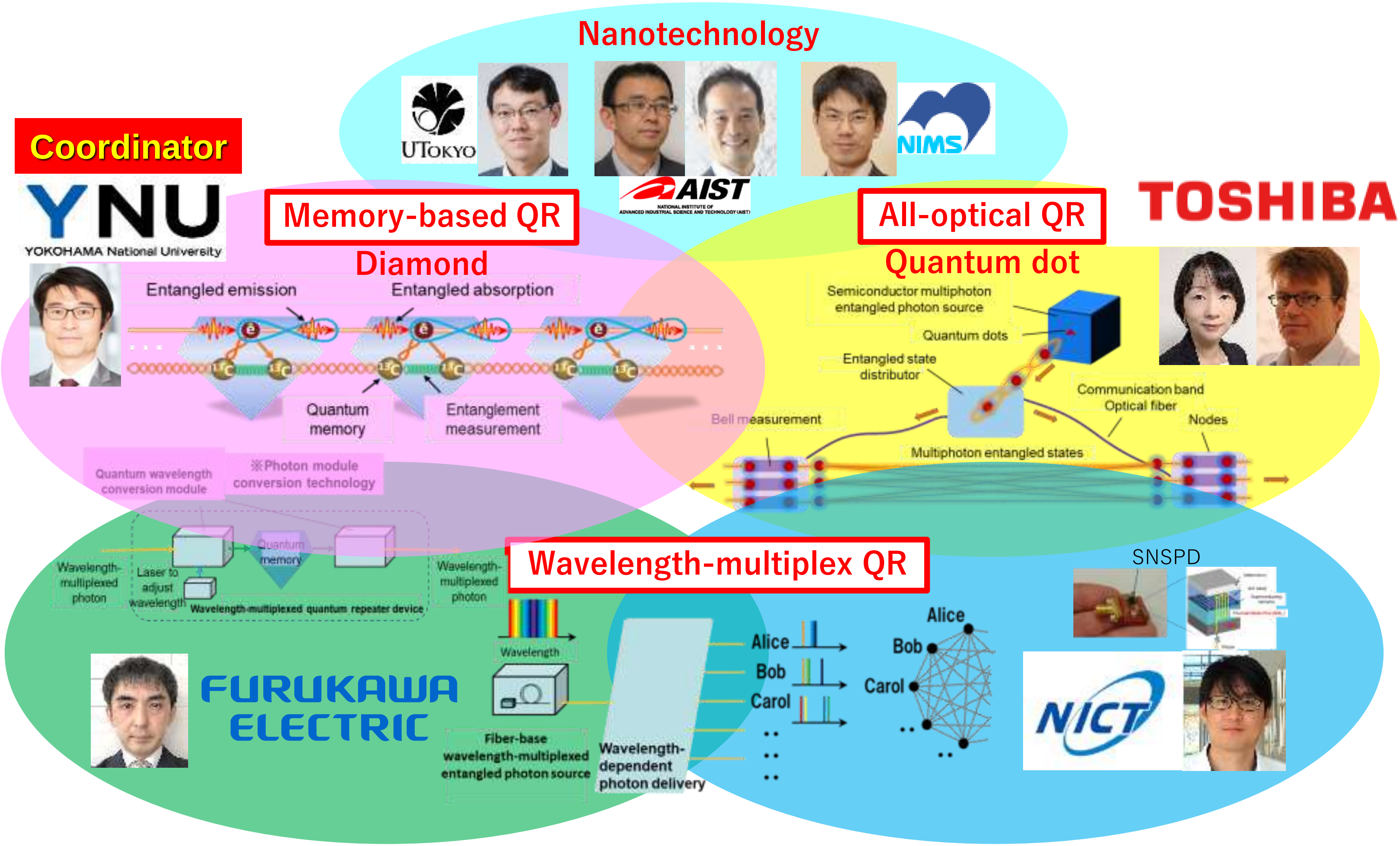
4 Universities

YNU (YOKOHAMA National University), UTokyo, HOKKAIDO UNIVERSITY, GAKUSHUIN UNIVERSITY

Quantum Repeater Project

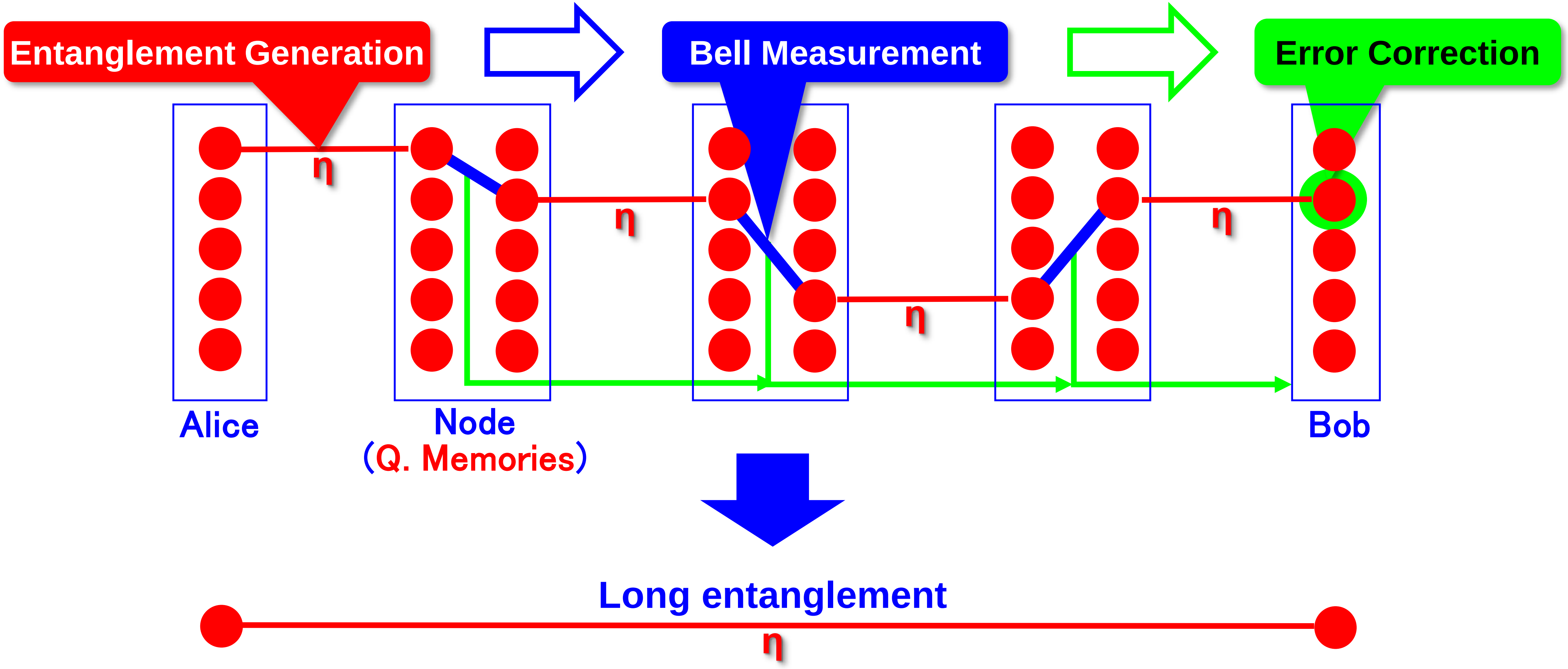
https://qurep.ynu.ac.jp/

JPMI00316



Principle of Quantum Repeaters

QR ＝ Quantum Error Correction System



Three schemes for Quantum Repeaters

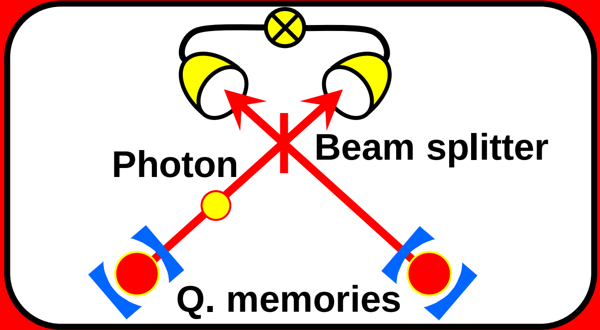
DLCZ

QuTech

YNU

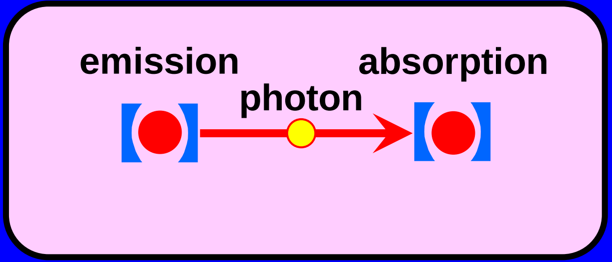
Entanglement

Single-photon interference



Sensitive to phase, frequency, loss

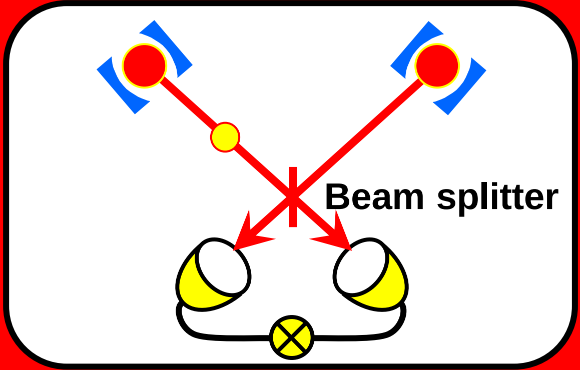
Emission-absorption



Insensitive to phase, frequency, loss

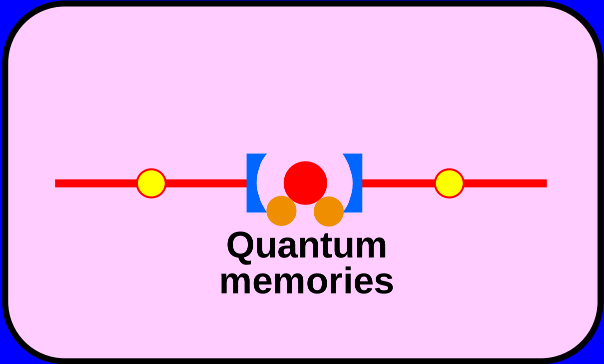
Bell measurement

Single-photon interference



Probablistic

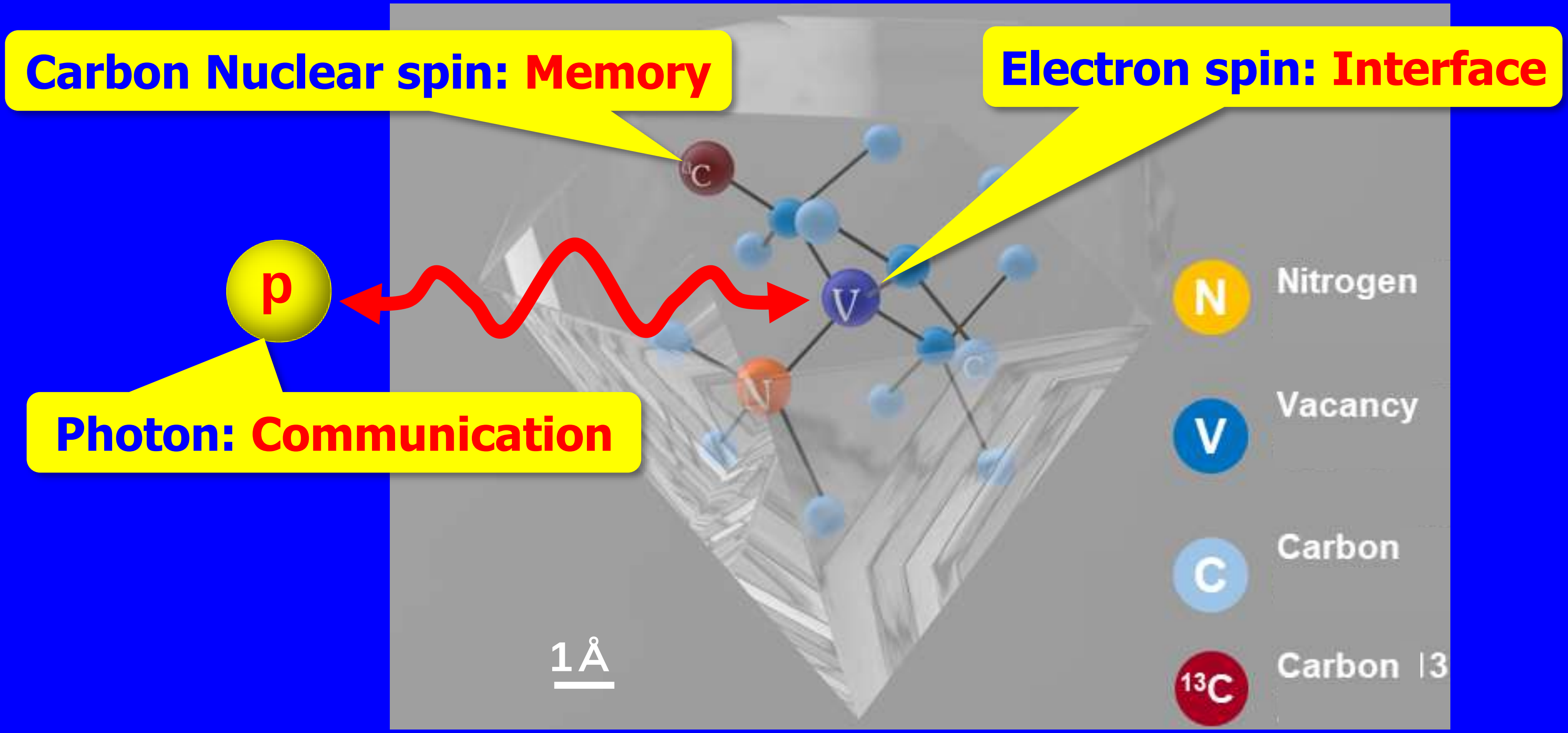
Complete Bell state measurement



Deterministic to be scalable

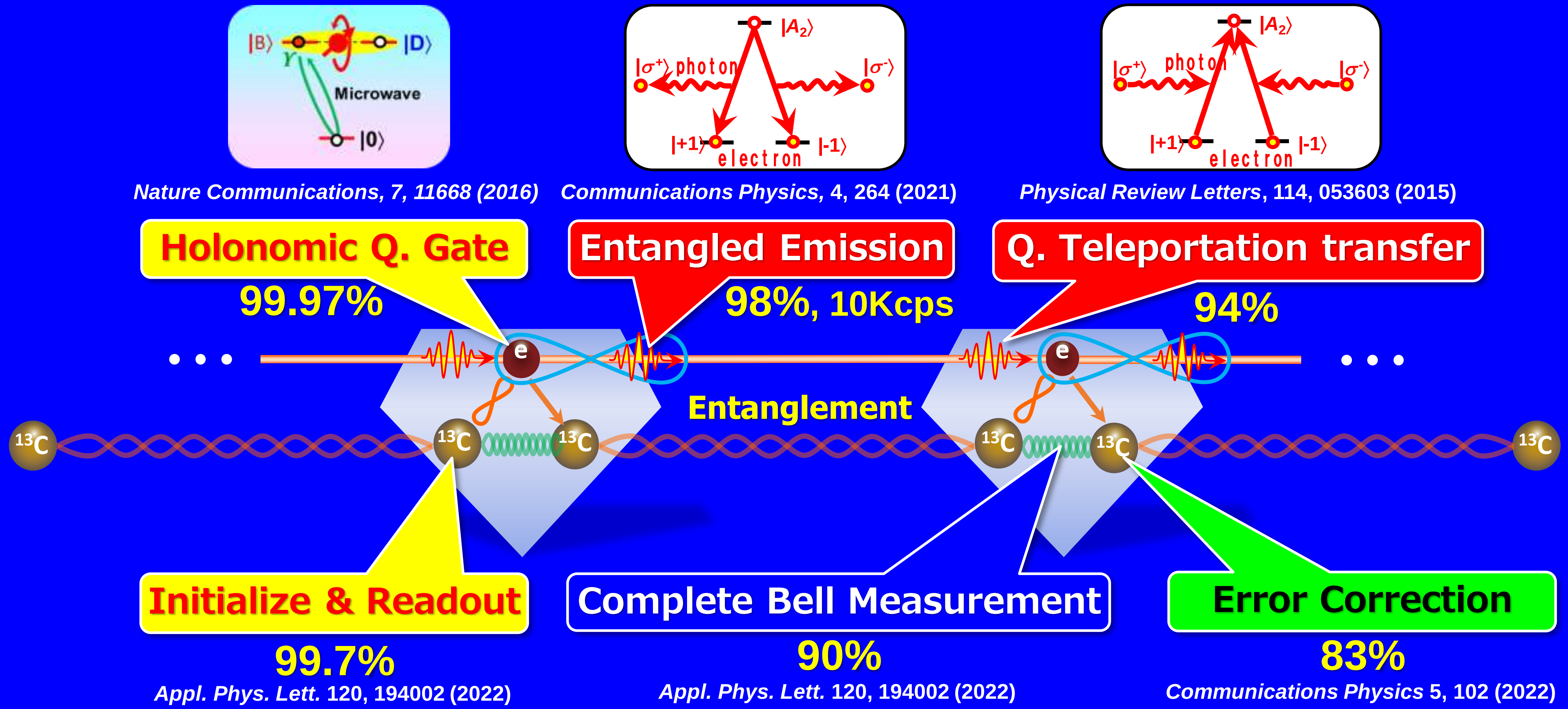
A Color Center in Diamond

NV Center

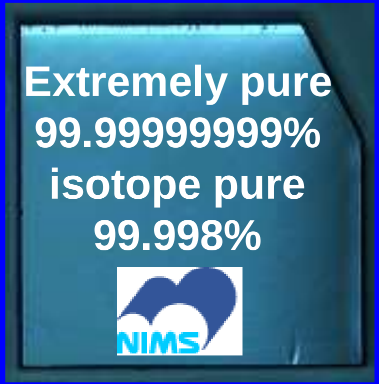


Performance of Diamond chip in YNU scheme

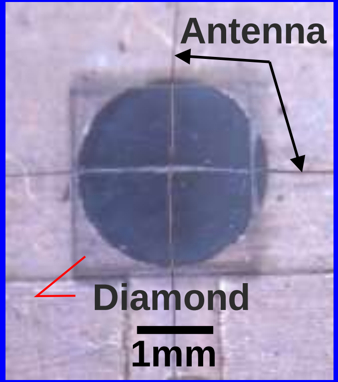
Emission & absorption ⇒ Insensitive to phase, freq. & loss balance
Geometric qubit under a zero magnetic field ⇒ Robust to noise



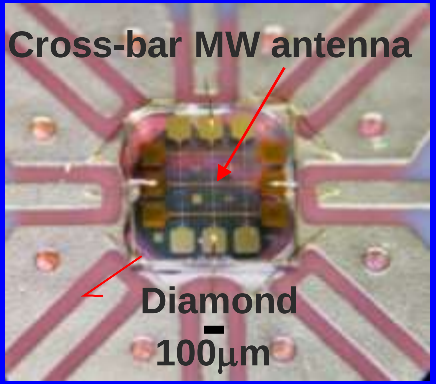
Challenges for Enhanced Photon Emission



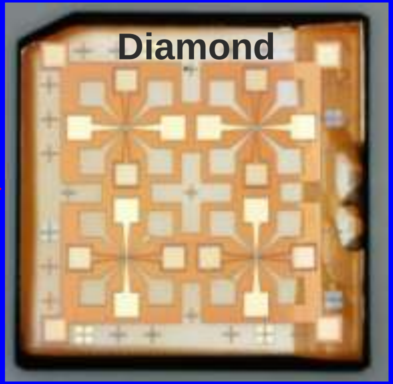
0G (1mm)

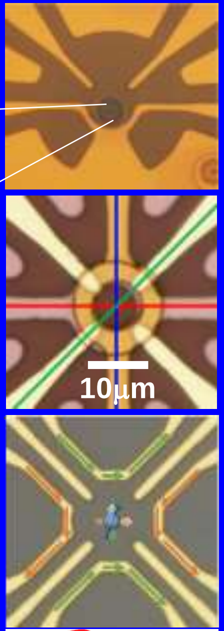


1G (100μm)



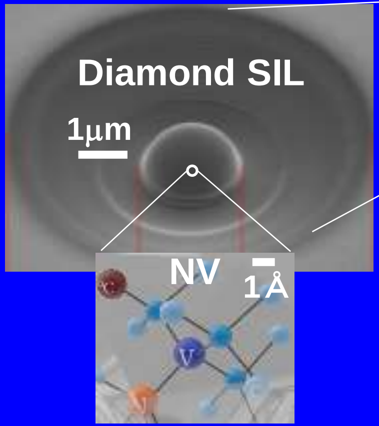
2G (10μm)



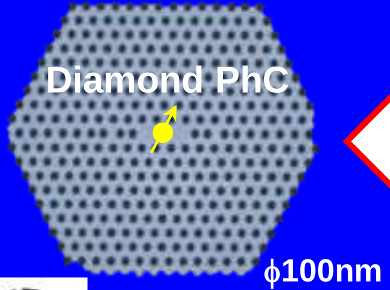


Antenna for arbitrary microwave polarization

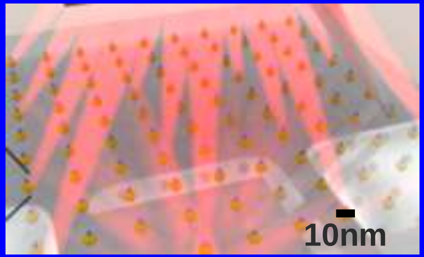
3G (1μm)



4G (100nm)



5G (10nm)

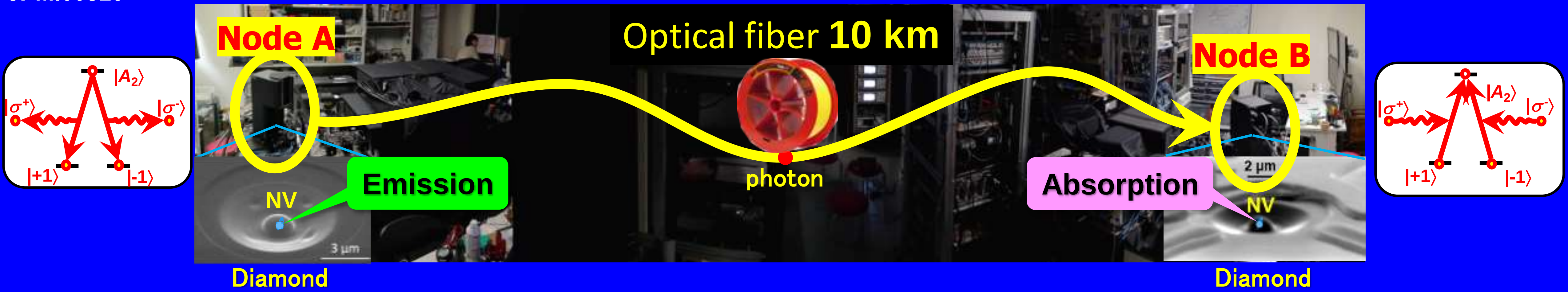


5G	4G	3G
Nanobeam Ion Implantation & Laser Annealing	Diamond Photonic Crystal	Diamond Solid Immersion Lens
Photon-bus coupled Integrated Q. Memory	Emission Enhance x 1000	Emission Increase x 50

MIC

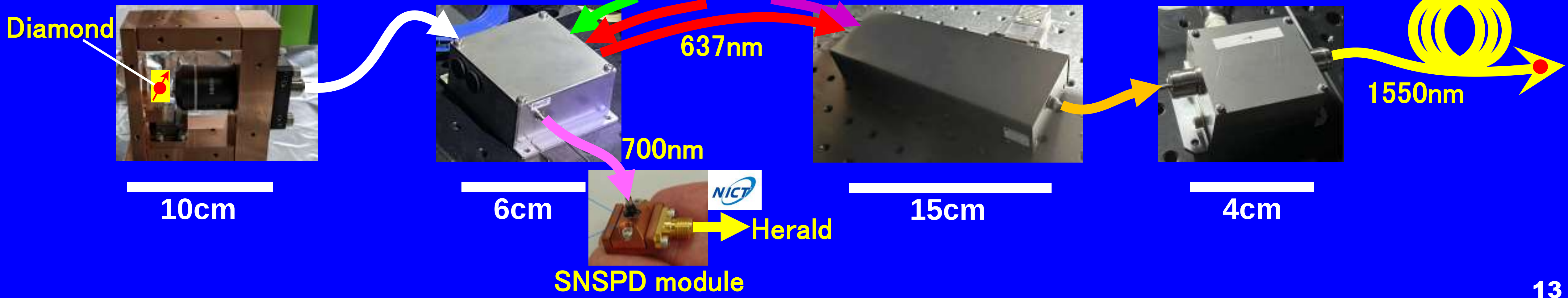
Challenges for Remote Entanglement

JPMI00316



We succeeded in transmitting a photon entangled with an NV over 10 km

Objective module — Trichroic module — Wavelength conversion module — Filter module



Quantum Computer Networks

Project

QuINT
Quantum INTerfaces

https://moonshot.ynu.ac.jp

Program

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

JPMJMS2062

Agency

Cabinet Office

MEXT

Moonshot Goal 6

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

QuINT Quantum INTerfaces

JPMJMS2062

【Network Project】

Photon Source & Detector

+

Quantum Memory

↓

Quantum Interface

↓

Quantum Network

[Moonshot Goal candidate]

2050 — Realization of fault-tolerant universal quantum computers — FTQC

2040 — Demonstration of distributed NISQ computer & Calculation of useful tasks under quantum error correction — Net QC

2030 — Development of NISQ computers of a certain scale & Effectiveness demonstration of quantum error correction

Network

Development of quantum memory, establishment quantum interface technology between photons and quantum memory, development of quantum repeater and quantum communication system, building testbed.

- Photon source & detector
- Quantum memory
- Quantum interface technology
- Quantum repeater (short distance)
- Quantum communication system
- Testbed

Hardware

System design and implementation of quantum error correction, establishment of quantum bit and gate platforms.

Stage gate
Identify suitable & feasible physical system.

Super-conducting qubit	Trapped ions	Photonic qubits	Semi-conductor qubits	Neutral atoms

as a possible candidate

Software

Development of low overhead quantum error correction code and quantum algorithms, development of measurement and control software, development of error correction system

- Quantum error correction theory
- Middleware, compiler
- Algorithms, applications
- Error correction system

Quantum Network Project

Project Manager Hideo Kosaka
(Director of Quantum Information Research Center)

10 PIs: All-Japan Nanotechnology Researchers from 4 Universities and 5 National Institutes

Diamond Q. Memory

- Hideo Kosaka (YNU)
- Hiromitsu Kato, Toshiharu Makino (AIST)
- Tokuyuki Teraji (NIMS)
- Shinobu Onoda (QST)
- Satoshi Fujii

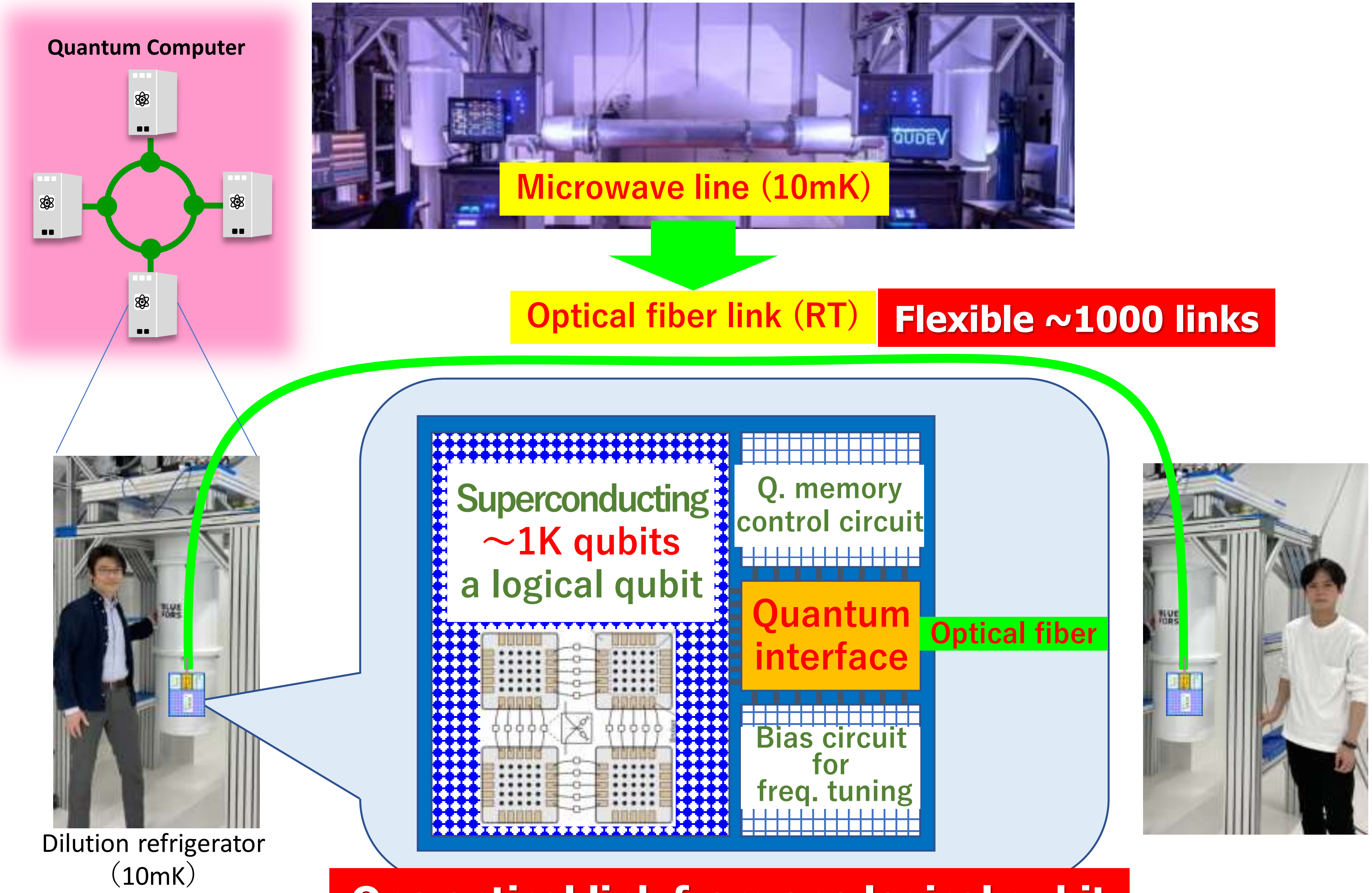
Opto-Mech. Resonator

- Satoshi Iwamoto (UTokyo)
- Toshihiko Baba (YNU)
- Masahiro Nomura (UTokyo)

Piezo-MW Resonator

- Hideo Kosaka (YNU)
- Nobuyuki Yoshikawa (YNU)
- Kazuki Koshino (TMDU)
- Fumihiro Inoue (YNU)
- Yoshihiro Shimazu (YNU)
- Hirotaka Terai (NICT)
- Kunihiro Inomata (AIST)
- Ryo Sasaki (RIKEN)

Why we need Quantum Interface?



One optical link from one logical qubit

What is Quantum Interface?

Quantum frequency converter between microwaves (~10 GHz) & lightwaves (~500 THz)

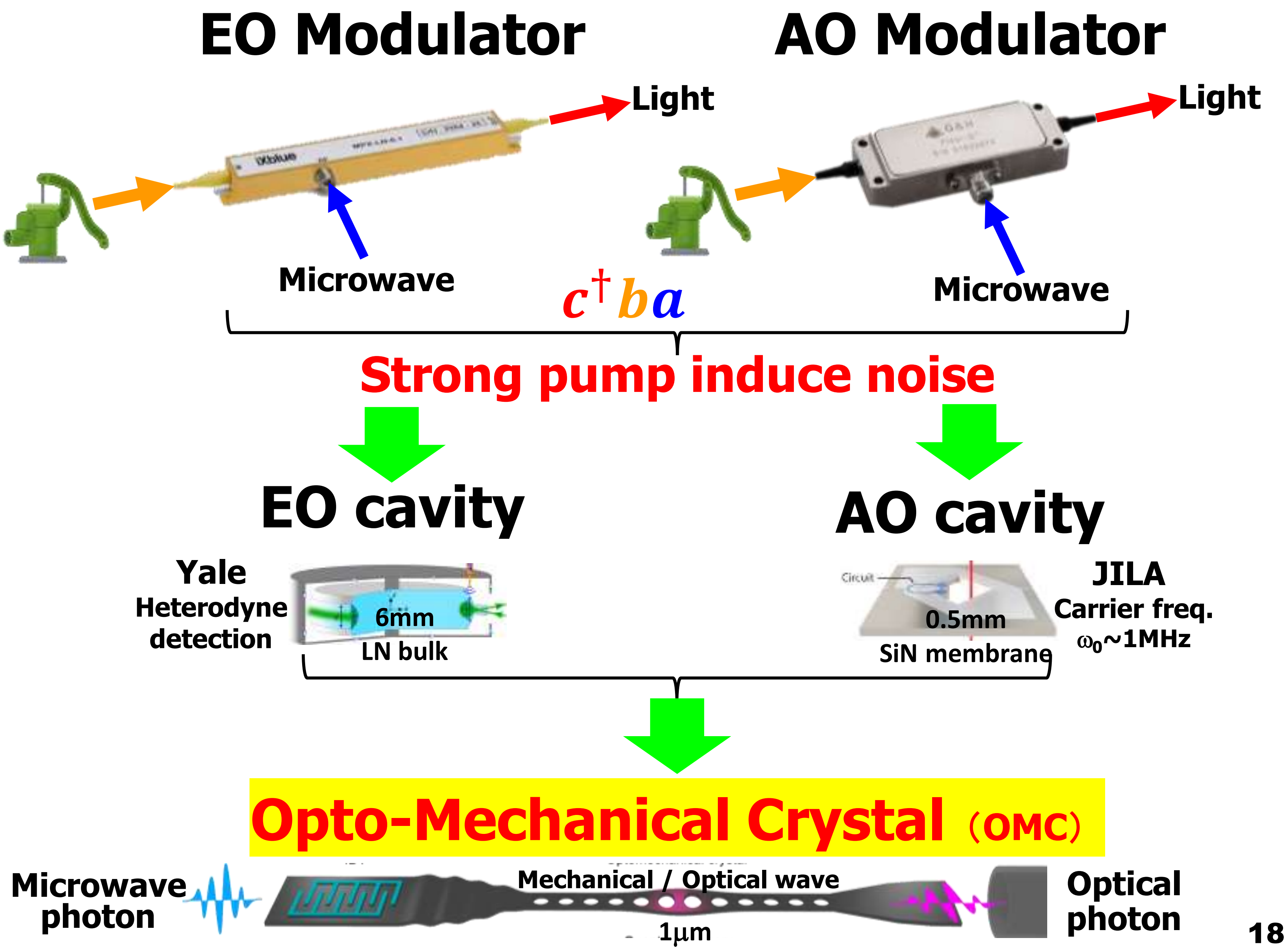
Conventional EOM/AOM require strong pump induce noise

⇩

High-Q EO/AO cavities to reduce pump

⇩

Opto-Mechanical Crystal in nano-structure to further reduce pump



Conventional Opto-Mechanical Crystal

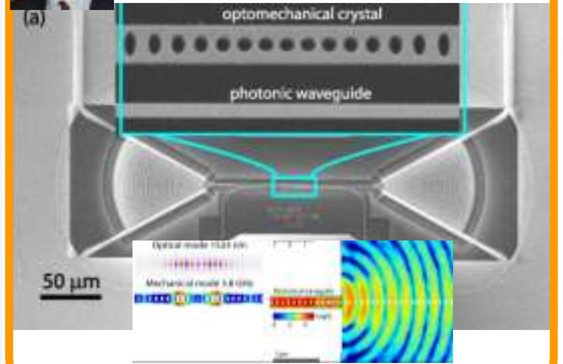
Homo-structure (AlN, LN, GaP) to hetero-structure (Si)

Issues are …

Low efficiency <10^{-4} with pump noise

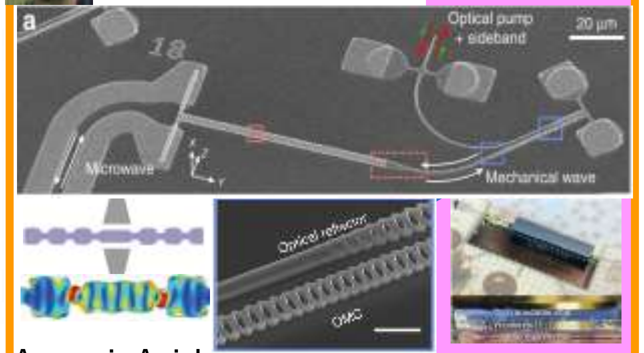
Low carrier freq. < 5GHz
⇒ thermal noise

A. Cleland (Chicago) **AlN**



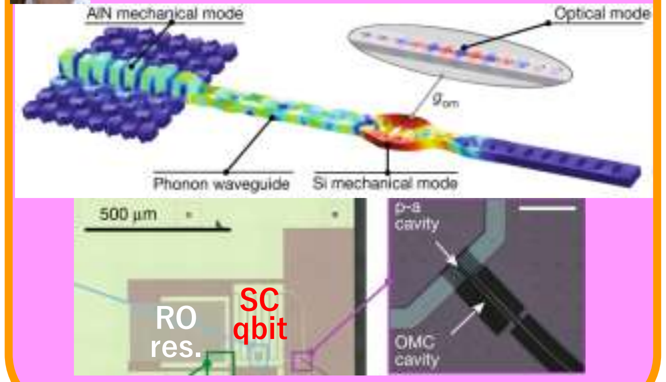
A. Vainsencher, APL 2016

A. Naeini (Stanford) **LN** → **LN/Si**



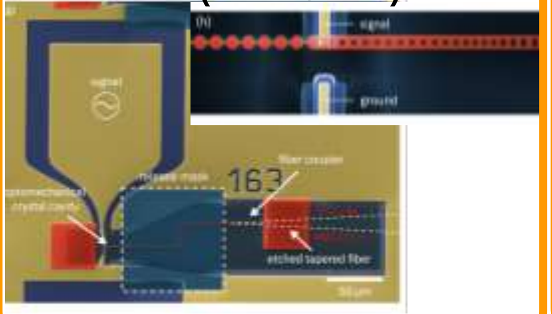
Arrangoiz-Arriola PRX 2018 | Jiang, NatCom 2020 | Jiang, q-ph 2022

O. Painter (Caltech/AWS) **AlN/Si**



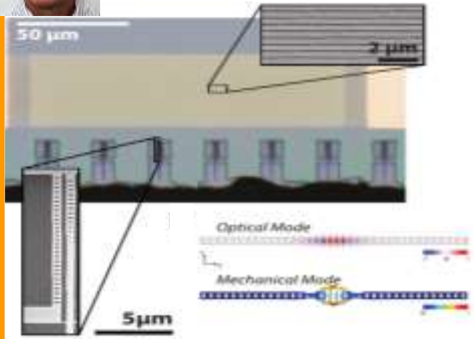
M. Mirhosseini, Nature 2020

T. Kippenberg
P. Seidler
(EPFL & IBM) **GaP**

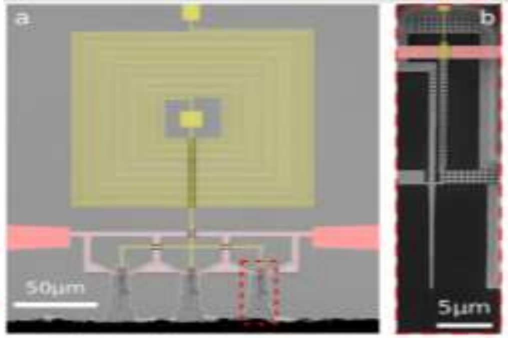


S. Honl, NatCom 2022

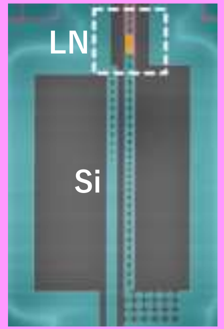
S. Groblacher (Delft/QphoX) **GaAs** → **GaP** → **LN/Si**



M. Forsch, NatPhys 2020



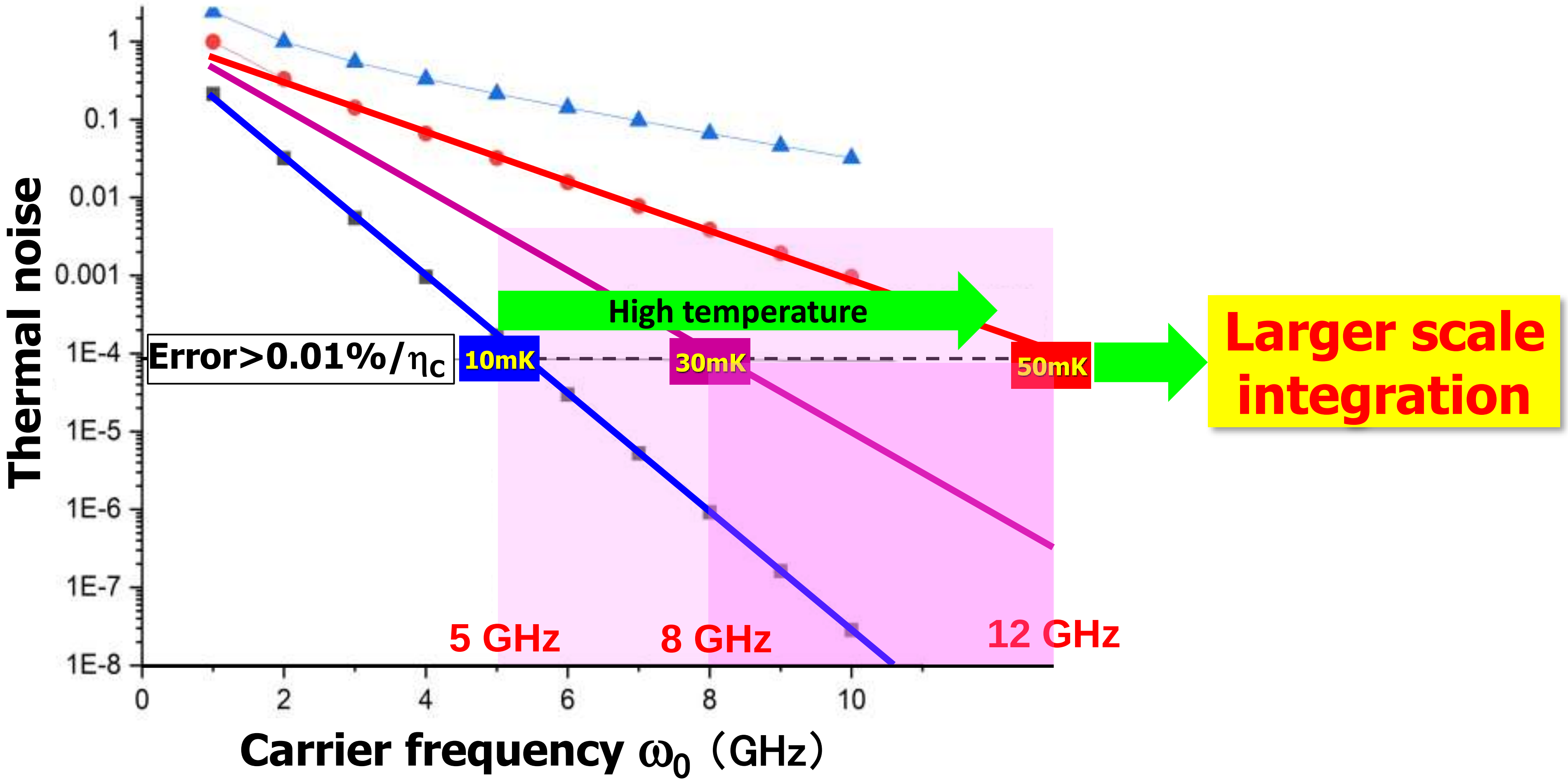
R. Stockill, NatCom 2022



M. Weaver, q-ph 2022

Advantage of high carrier frequncy

High frequency >5GHz is highly preferred for achieving low thermal noise



Diamond Opto-Mechanical Crystal

Advantages are …

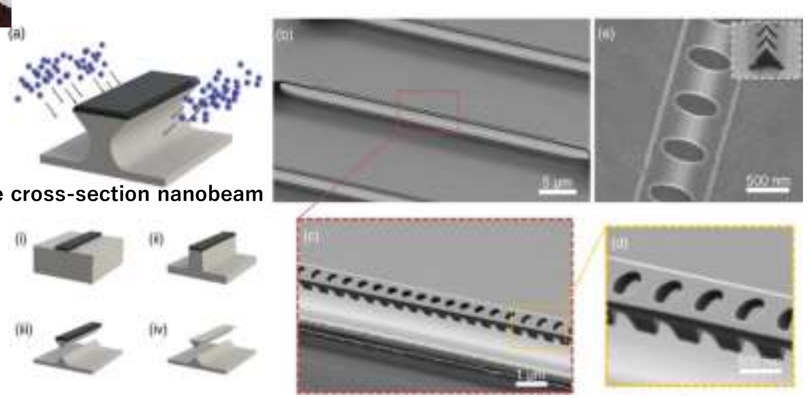
High freq. >5GHz
⇒ Low thermal noise

A color center mediate conversion
⇒ High efficiency w/o pump noise

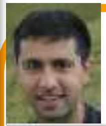
In addition …
High sound velocity
High thermal conduc
Low thermal elasticity
Low dielectric loss

Loncar (Harvard) — **NV^-**

B. J. M. Hausmann et al. Nano Lett. (2013)
M. J. Burek et al., Optica 3, 1404 (2016)

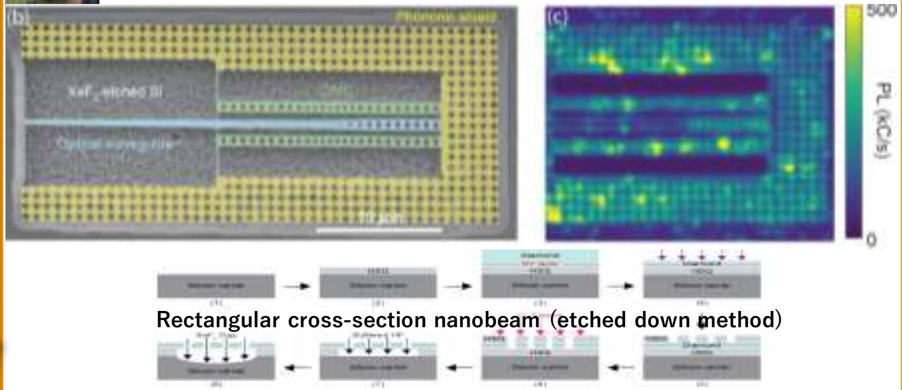


Optical Q = 176,000 @ 1,529 nm
Mechanical Q = 4,100 @ 5.5 GHz @RT



S. Naeini (Stanford) — **NV^-**

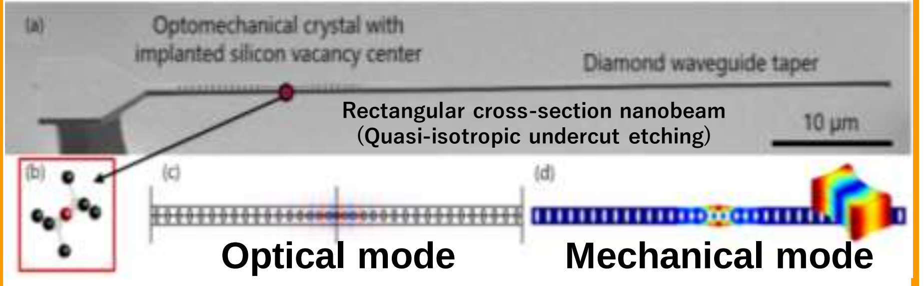
J. Cady et al., Quantum Science and Technology 4, 024009 (2019).



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

Loncar (Harvard) — **SiV**

A. Sipahigil et al., Science (2016) triangle
G. Joe et al., CLEO (2021) rectangle

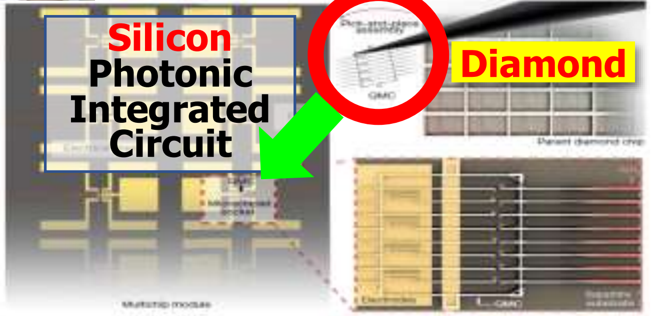


Optical Q ~ 10,000 @ 1,544 nm
Mechanical Q = 22,000 @ 9.2 GHz @4K

D. Englund (MIT) — **NV^-, SiV, GeV**

S. Mouradian et al., APL, 111, 021103 (2017)

Wan et al., Nature(2020)



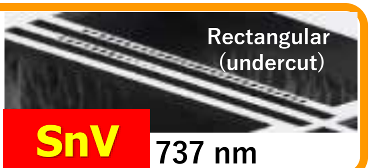
Theoretical
S. Krastanov, PRL (2021)
T. Neuman, npjQI (2021)
H. Raniwala, Arxiv(2022)

Ulara small optical(1550nm) and mechanical(5GHz) mode volume

Optical Q = 14,000 @ 637 nm (NV)

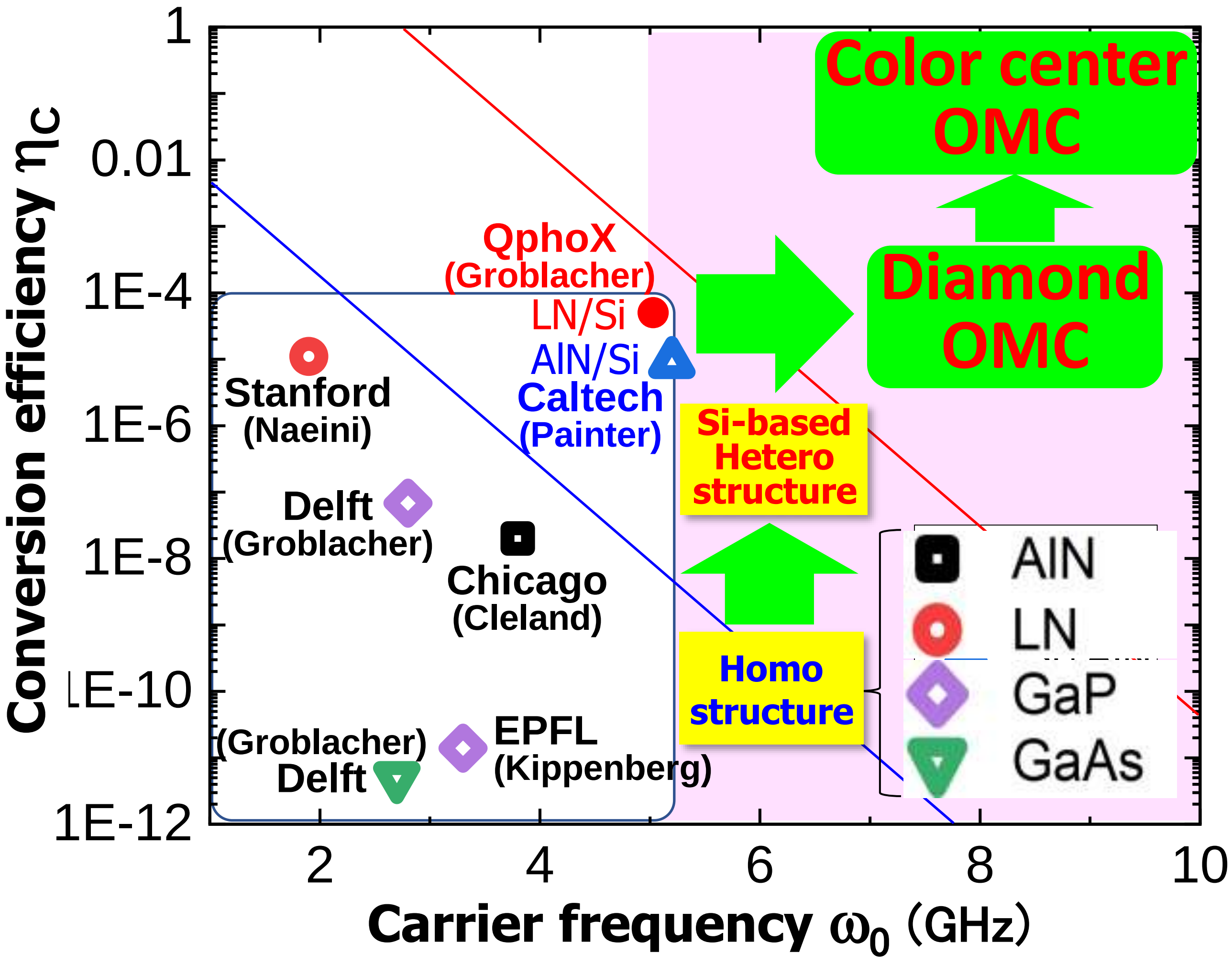
Hanson/Groblacher (QuTech/QphoX)

APS meeting (2023)



SnV 737 nm

Diamond OMC with a Color Center



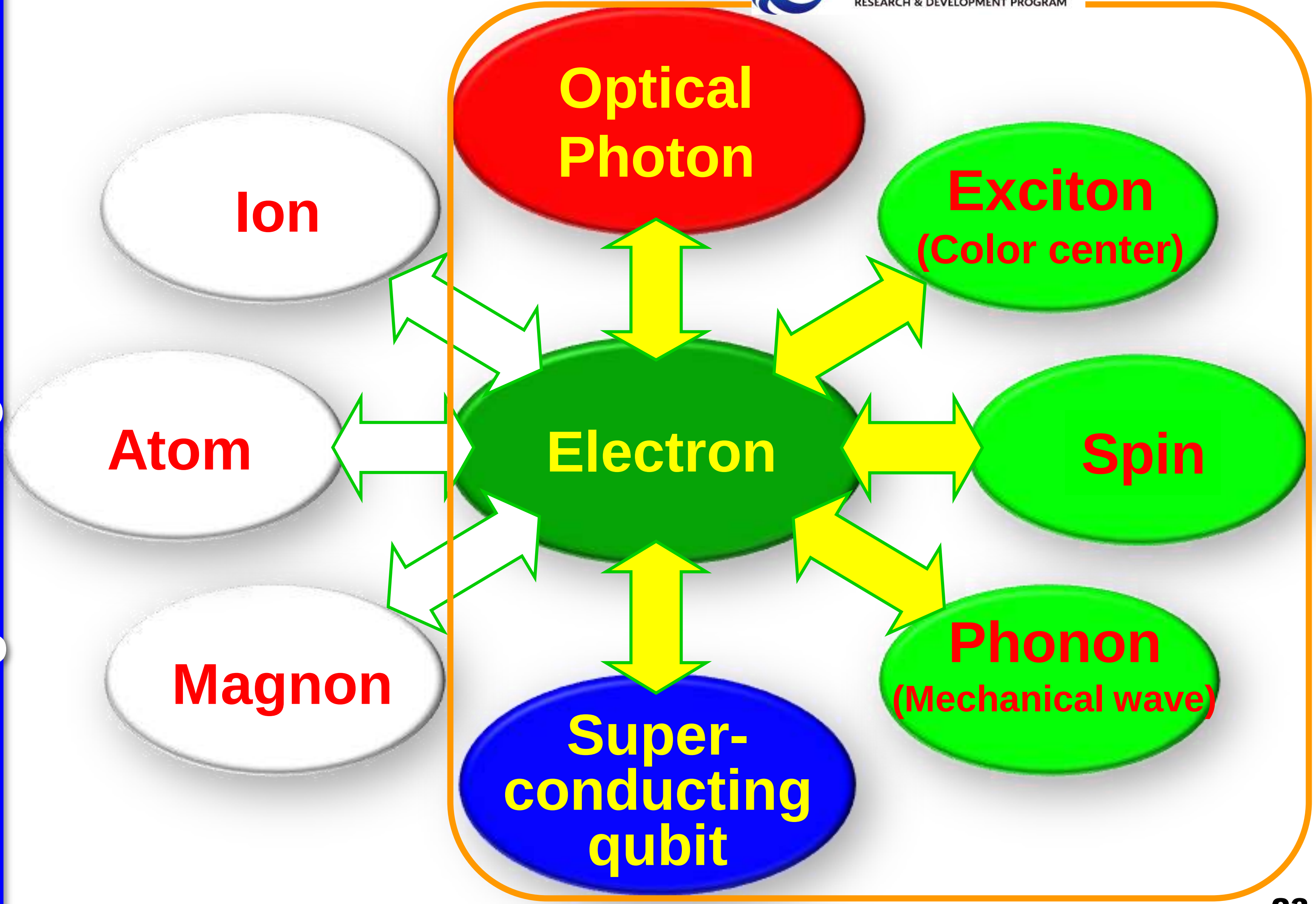
Quantum Interface = Quantum Media Converter

Quantum interface converts excitation between quantum media

Optical photon cannot be be directly converted into superconducting qubit

⬇

Not only electron but also exciton(color center), spin and phonon(mecha wave) have to be used

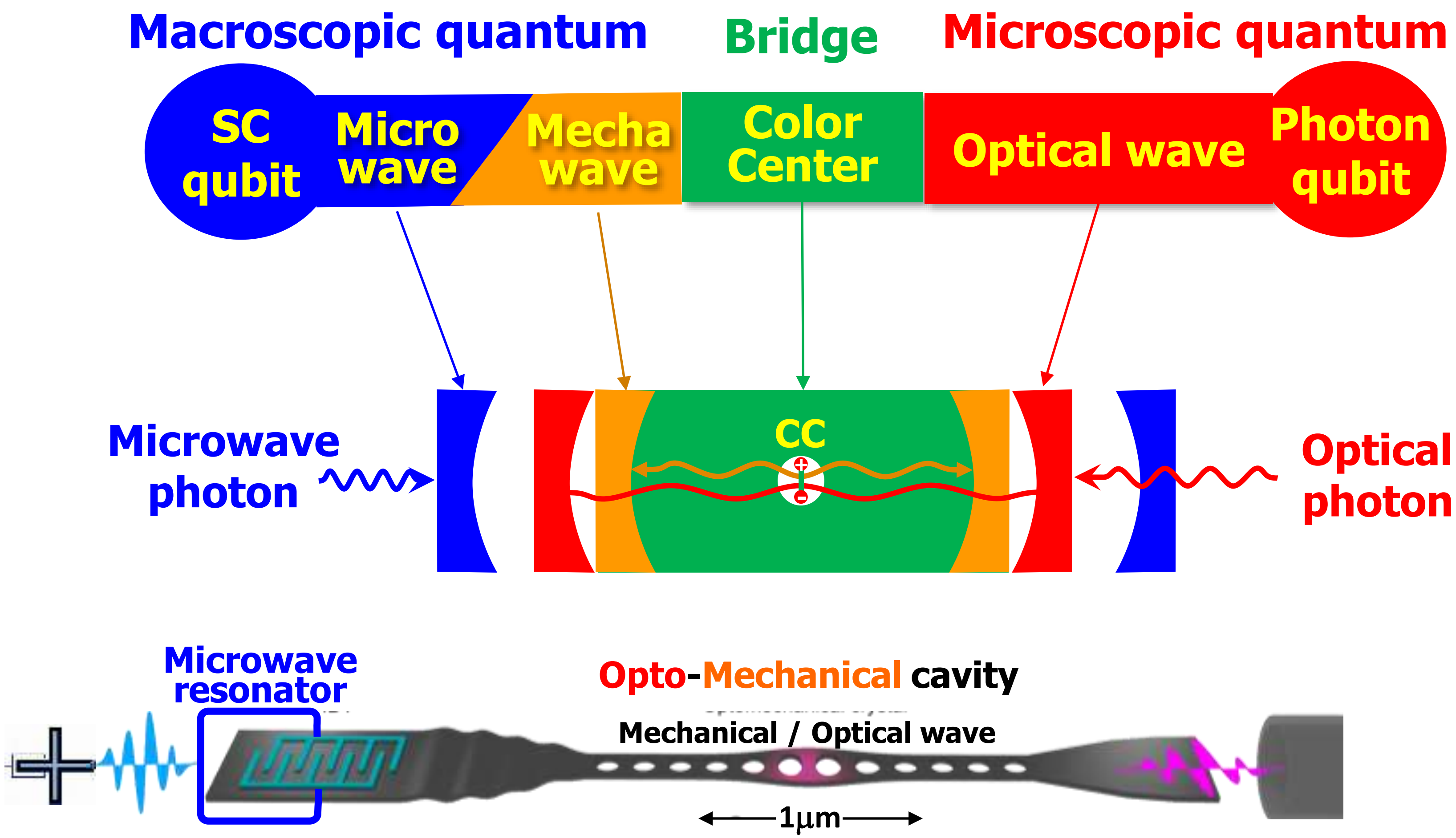


Diamond OMC with a Color Center

A Color Center bridges Macro & Micro Quanta

Microwave + Mechanical + Optical Resonators

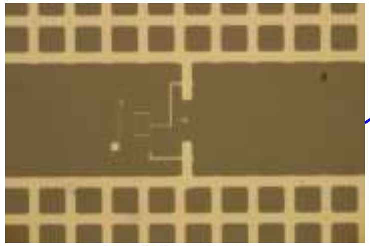
Enhancement of conversion efficiency



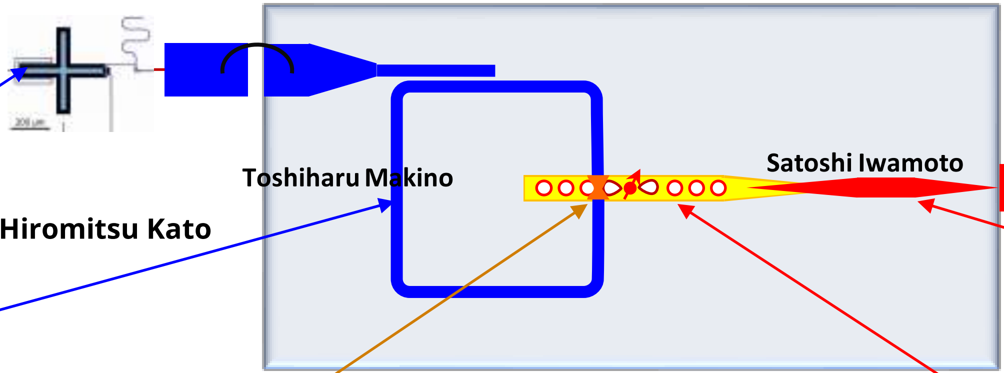
Performance of Element Components

Supercon. qubit | Micro wave | Mecha wave | Color Center | Optical wave | Photon qubit

Transmon Qubit



YNU



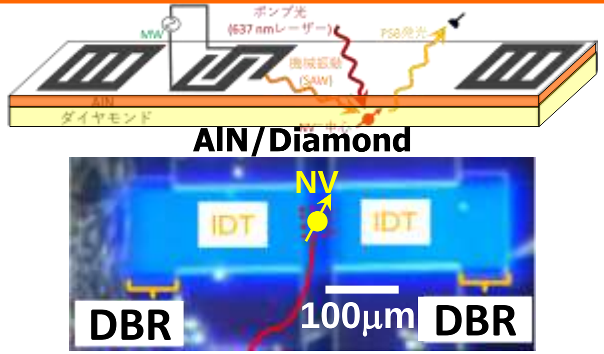
Microwave Resonator

NbTiN/Si 100nm nano wire

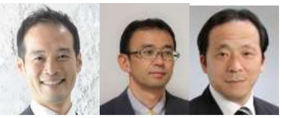
Q = 8,000 @ 5GHz,15 mK
(Measured)

NICT AIST

Diamond Mecha Resonator

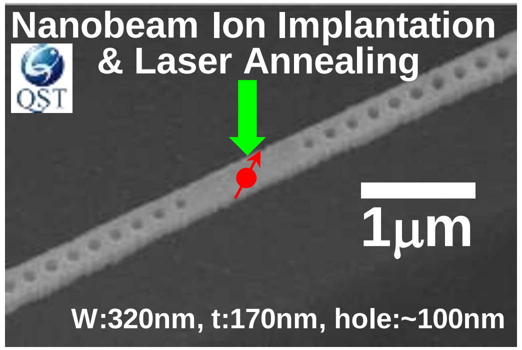


Q = 20,000 @ 5GHz,5 K
(Measured)



AIST YNU

Diamond Optical Resonator

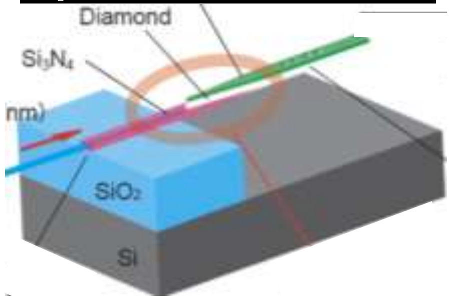


Q_{opt}=10,000 (F_P ~ 4,000), Q_{mech}=1M
(Designed)

UTokyo AIST

Optical Waveguide

Spot-size converter



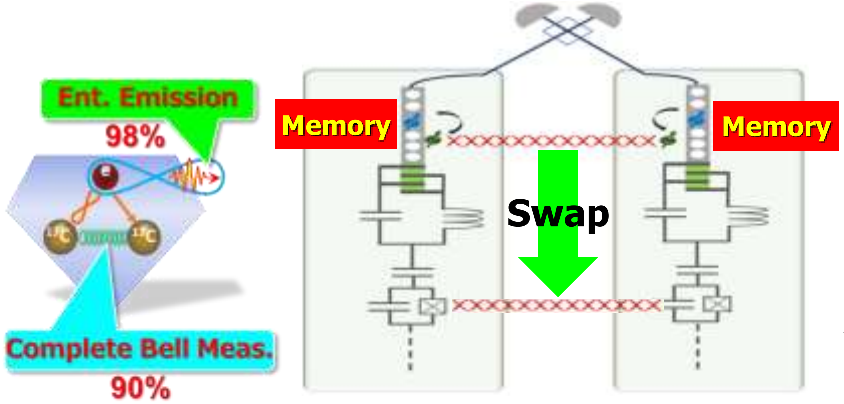
Coupling Loss < 1dB
(Designed)

YNU AIST

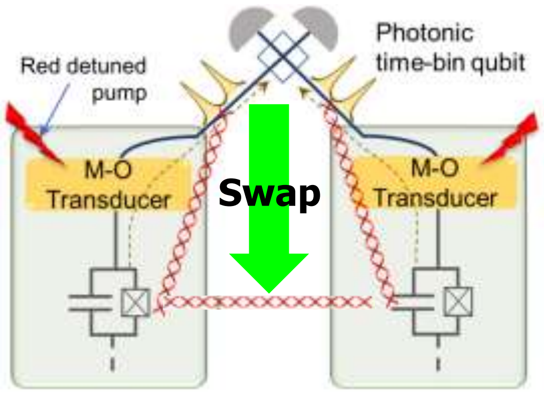
M. Yamamoto et. al, arXiv.2307.10271 (2023) Ishida et. al., 15p-A501-2, Oubutsu 2023S

Estimation of Entanglement Rate

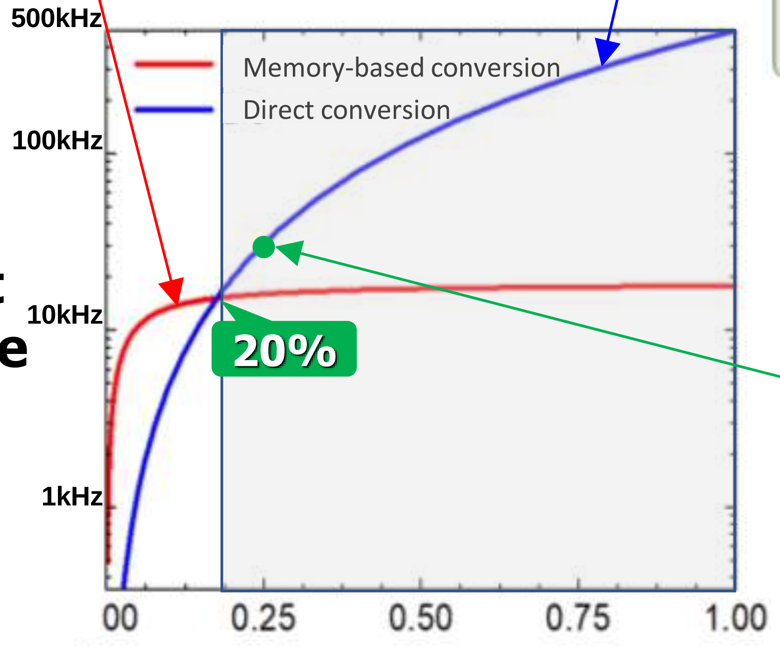
Memory-based conv. ~ 20kHz



Direct conversion ~ 0.5MHz

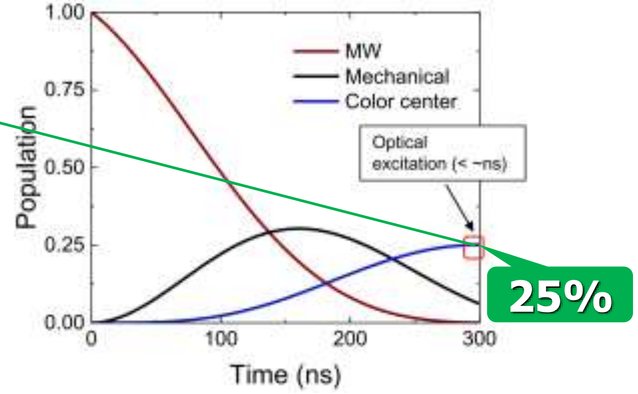


Entanglement Generation rate between SC qubits



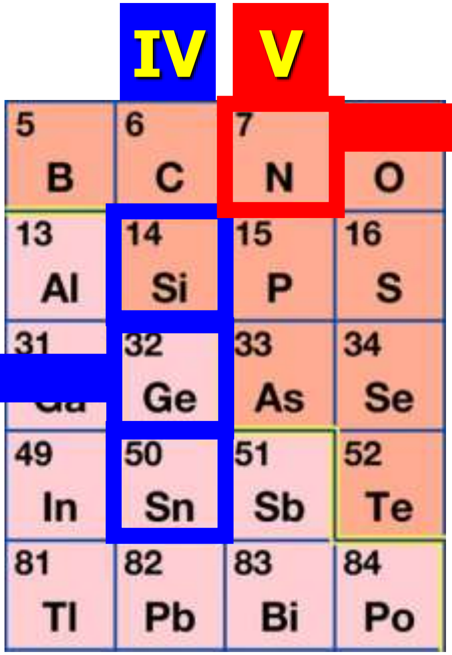
Conversion Efficiency

Simulation of conversion efficiency for NV^0



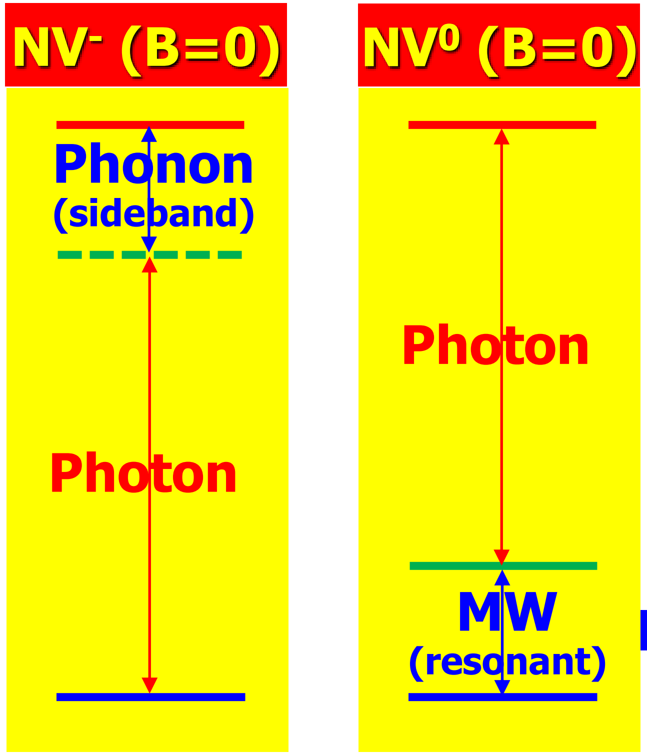
H. Kurokawa, M. Yamamoto, Y. Sekiguchi, and H. Kosaka, Phys. Rev. Applied 18, 064039 (2022).
B. Kim, H. Kurokawa, H. Kosaka, and M. Nomura, arXiv:2305.08306 (2023).

Coherent Orbital Control of a Color Center

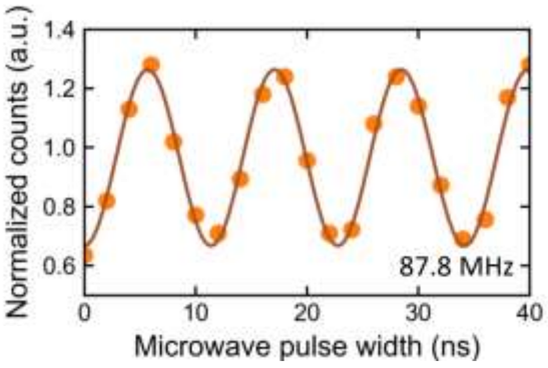


High B field
High strain
required

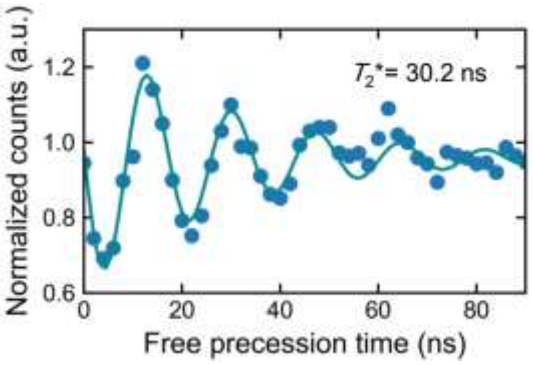
Two charge states



Rabi oscillation



Ramsey interference

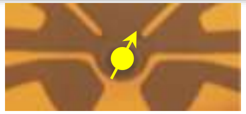


@5.5K

We have succeeded in coherent orbital control by

Mechanical wave

E fields of Microwave



Require 3 orders of magnitude smaller power than spin control by B fields

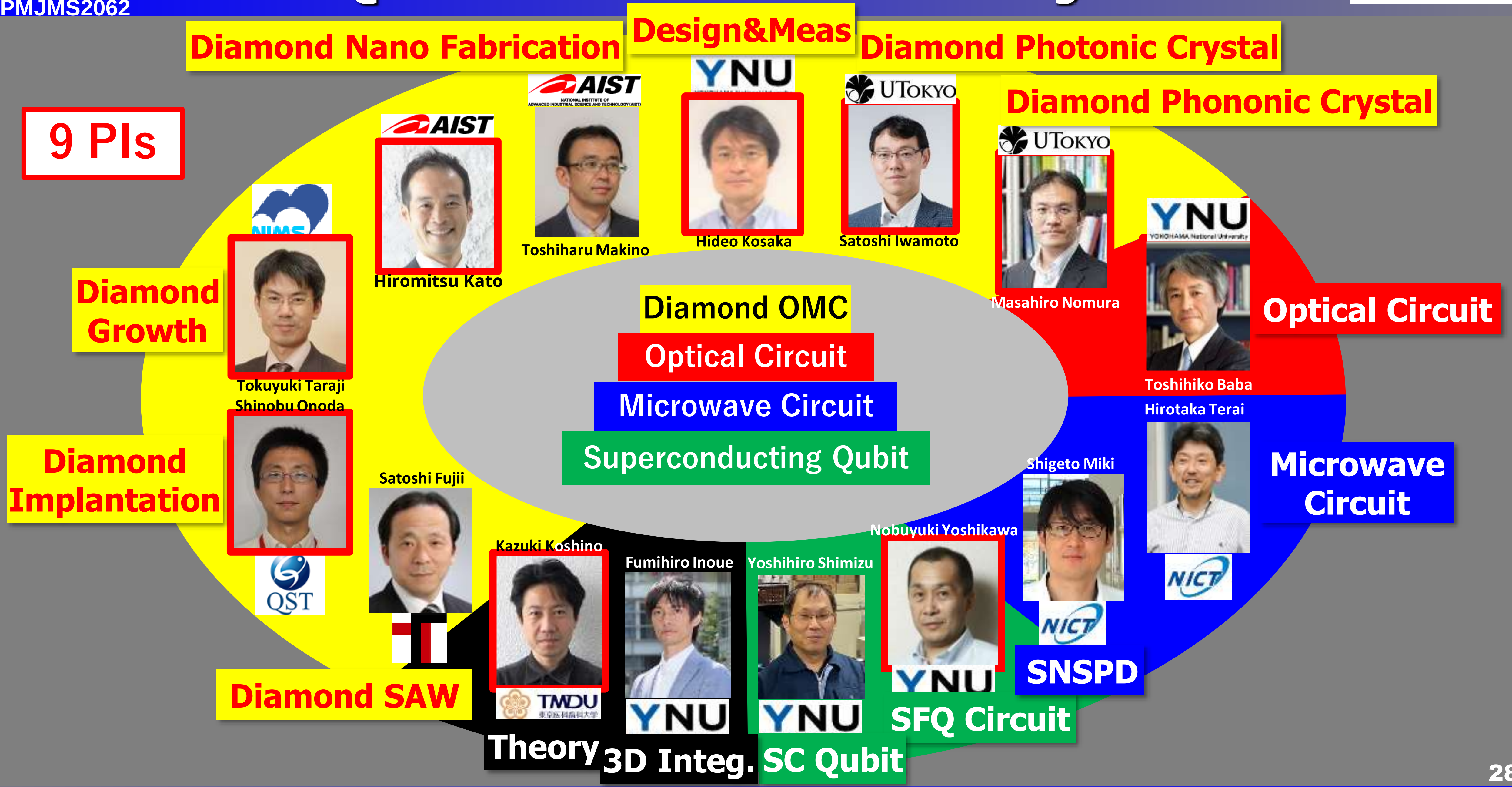
M. Yamamoto, H. Kurokawa, S. Fujii, T. Makino, H. Kato, and H. Kosaka, , arXiv.2307.10271 (2023).
H. Kurokawa, K. Wakamatsu, S. Nakazato, T. Makino, H. Kato, Y. Sekiguchi, and H. Kosaka, arXiv:2307.07198 (2023).

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

JPMJMS2062

Quantum Network Project

QuINT Quantum INTerfaces



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Tokuyuki Teraji

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Hirotaka Terai

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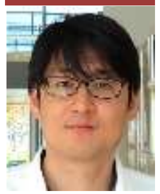

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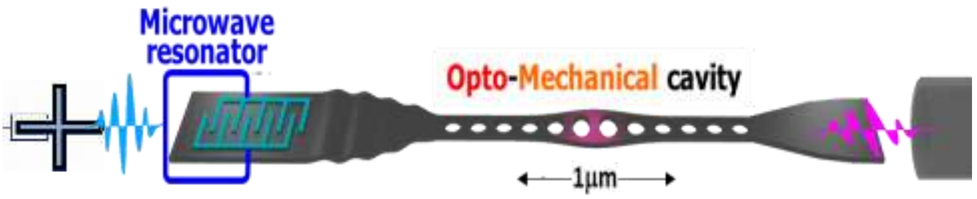
Summary

We are developing diamond-based

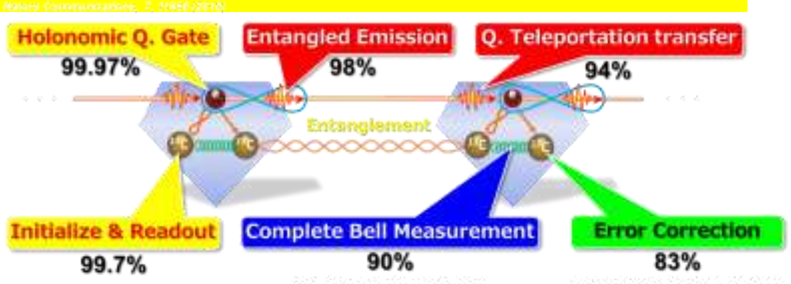
Quantum Interface for Quantum Computer Networks

Quantum Repeater for Quantum Communication Networks



toward Quantum Networking

QC&QC

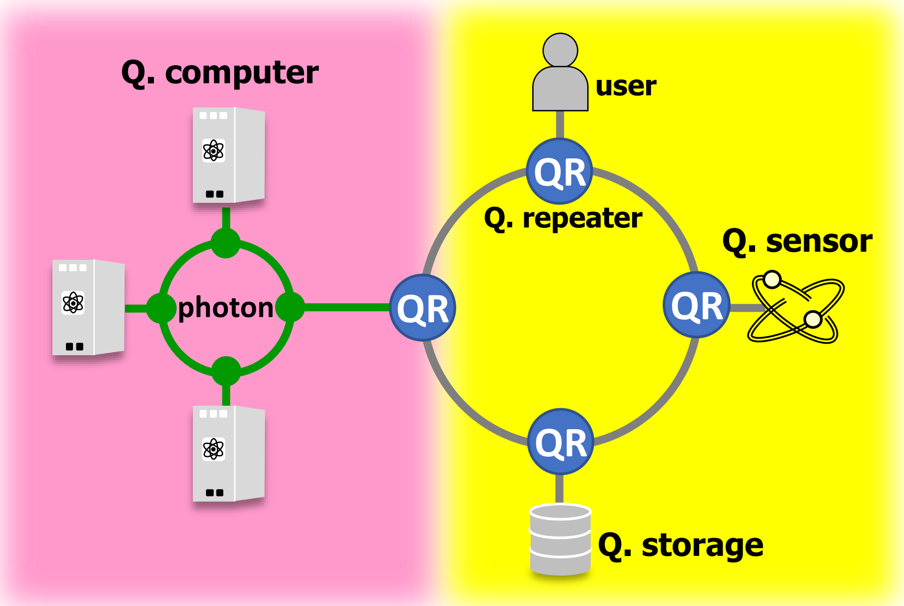


Project
QuINT
Quantum INTerfaces
https://moonshot.ynu.ac.jp

Program
MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Agency
Cabinet Office

Short distance



Project
QuREP
QUANTUM REPEATER TECHNOLOGY
https://qurep.ynu.ac.jp

Program
GlobalQKD

Agency
MIC

Long distance