

Kosaka Project:

“Development of Quantum Interfaces for Building Quantum Computer Networks”

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Director, Quantum Information Research Center

Research fellow, The University of Tokyo

Japan



CONTENTS

1. Quantum Networks = QC&QC
2. Quantum Communication Networks
3. Quantum Computer Networks

Development Steps toward Quantum Networks

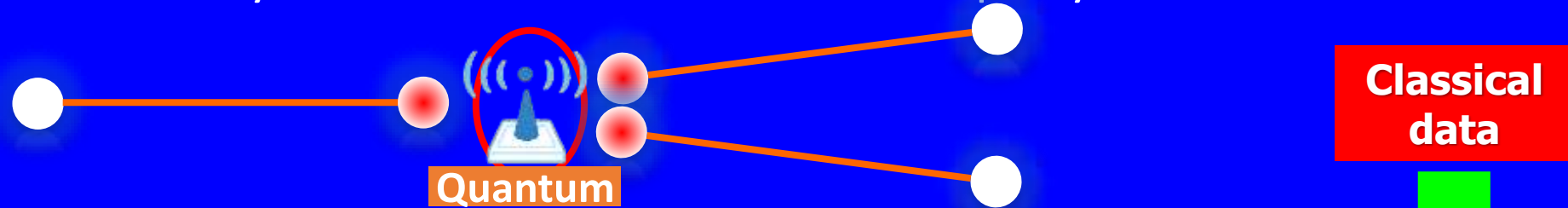
1. Trusted-node Quantum Key Distribution(QKD) network

- Quantum enhanced security but not absolutely secure



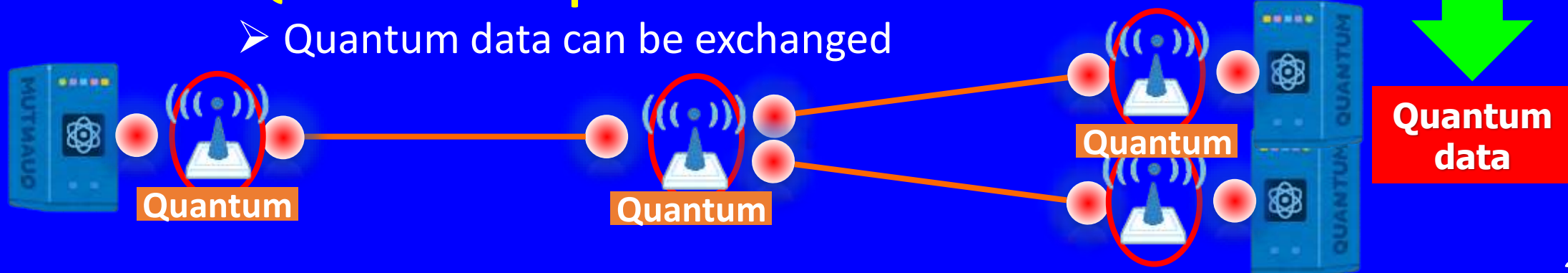
2. Quantum Repeater Network

- Absolutely secure QKD network with multiparty connections



3. Quantum Computer Network

- Quantum data can be exchanged



National Projects toward Quantum Networks

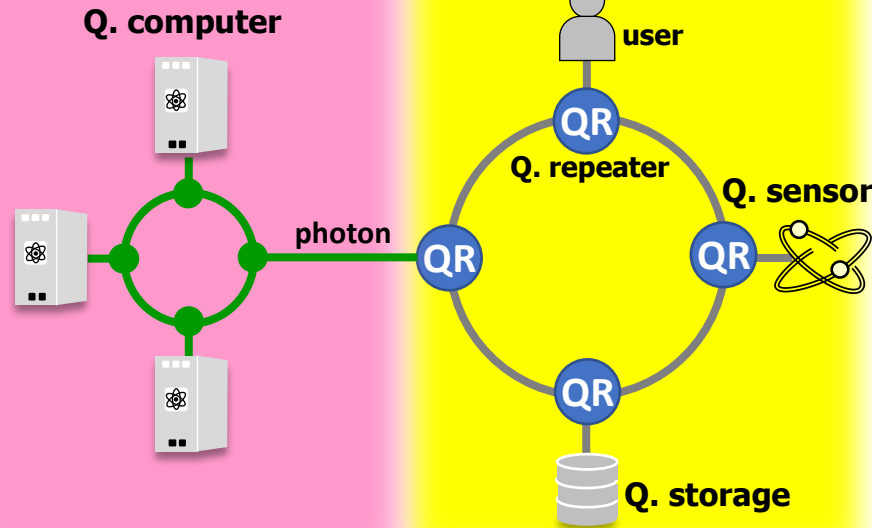


QC&QC

Quantum Computer Networks + Quantum Communication Networks

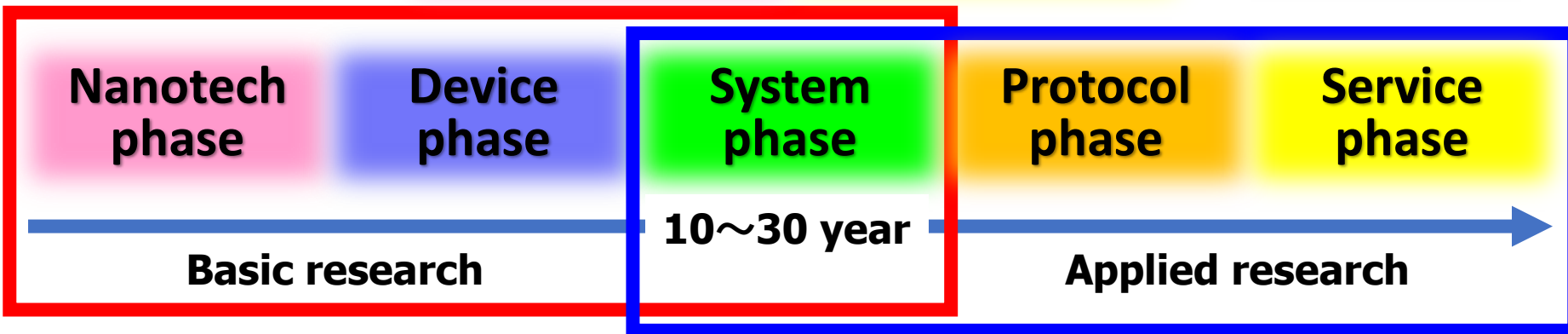
Project
QuINT
Quantum INterfaces
<https://moonshot.ynu.ac.jp>
Program
MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM
Agency
MEXT
Cabinet Office

Short distance



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

Long distance



Quantum Communication Networks

Project



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

Program

GlobalQKD

Agency

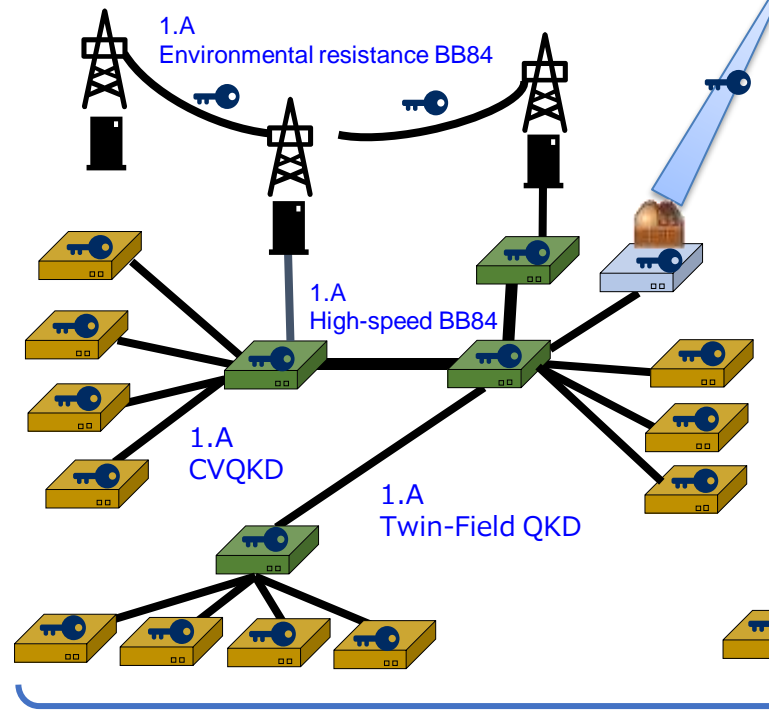


JPMI00316

JPMI00316

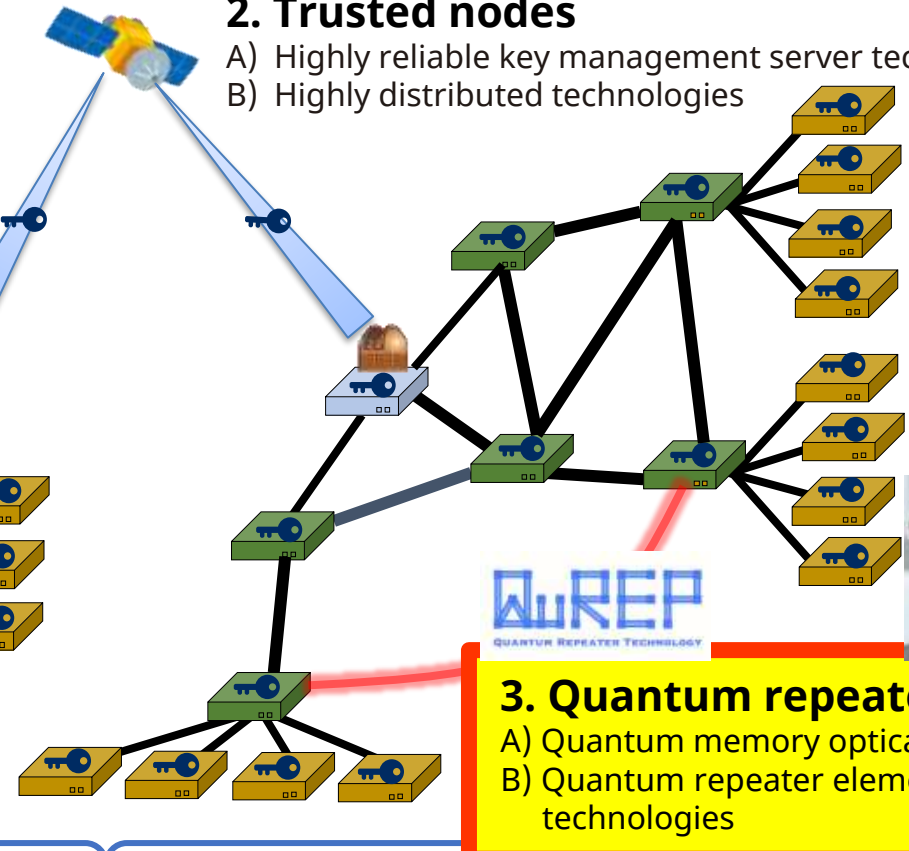
1. Quantum crypto link

- 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

3 National Institutes

4 Universities

Nanotechnology



Coordinator

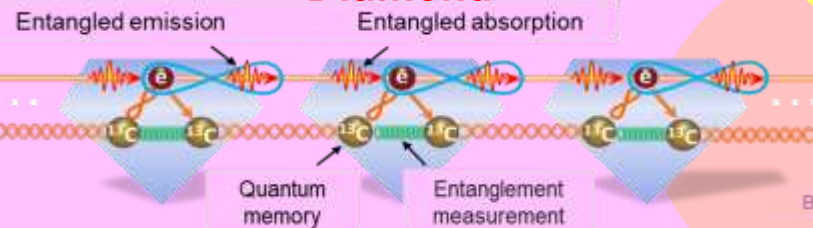


Memory-based QR



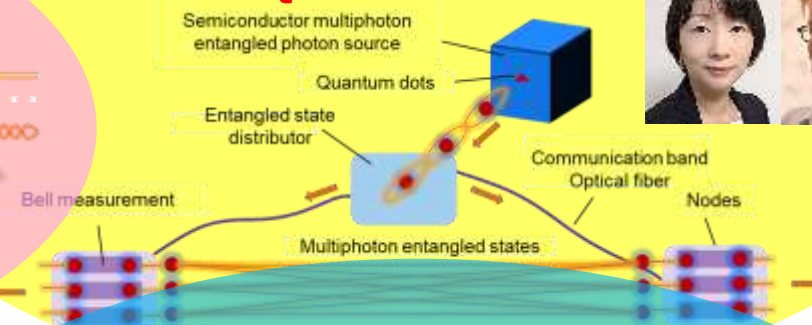
All-optical QR

TOSHIBA



Quantum wavelength conversion module
* Photon module conversion technology

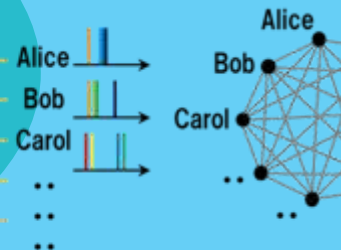
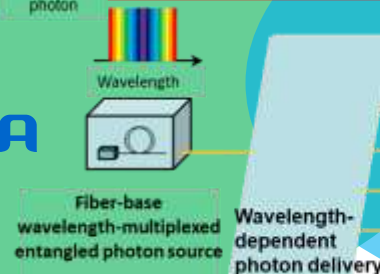
Quantum dot



Wavelength-multiplex QR

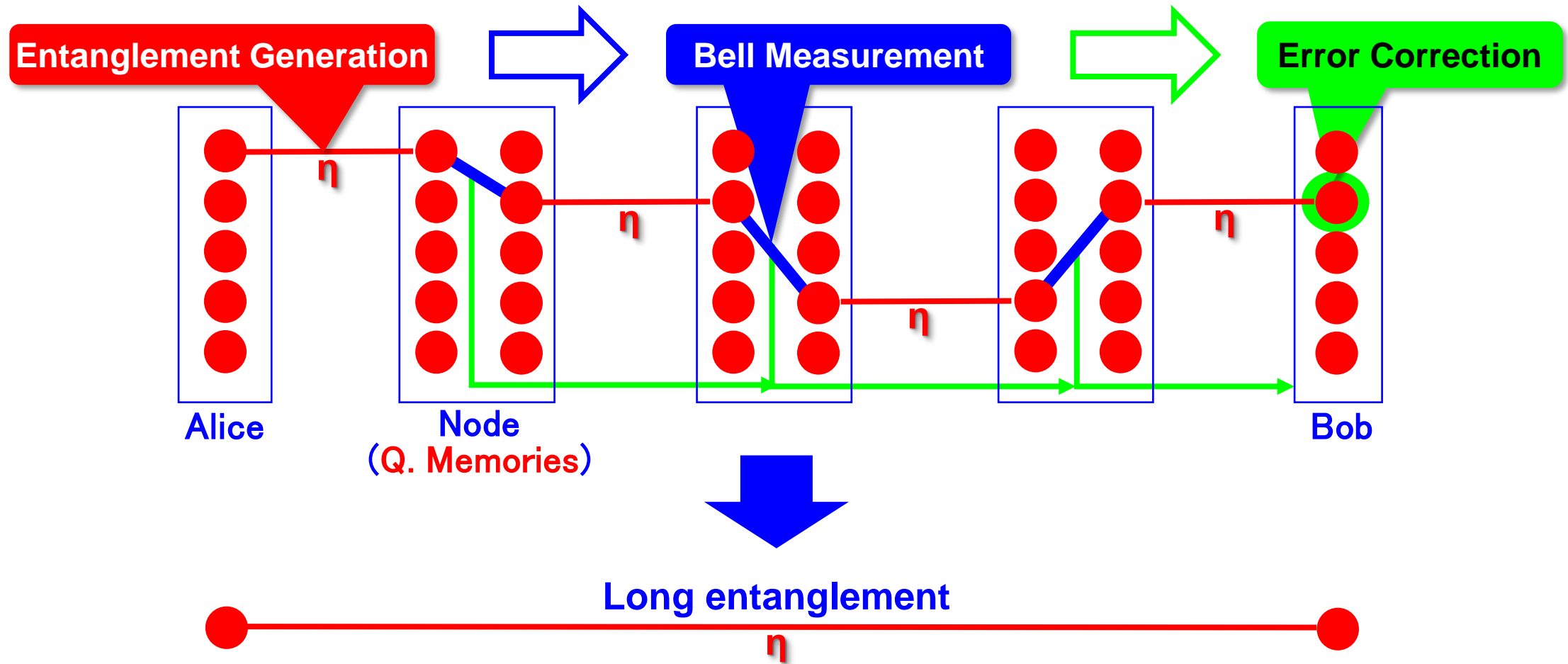


FURUKAWA ELECTRIC



Principle of Quantum Repeaters

QR = Quantum Error Correction System



Three schemes for Quantum Repeaters

DLCZ



QuTech

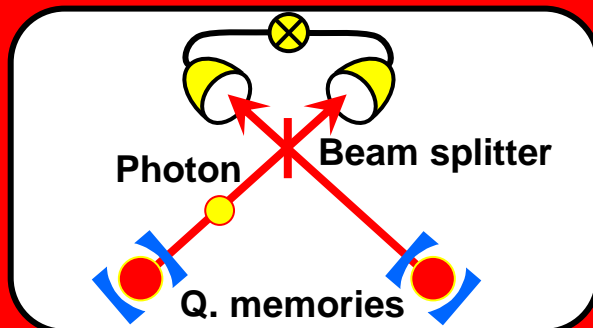


YNU



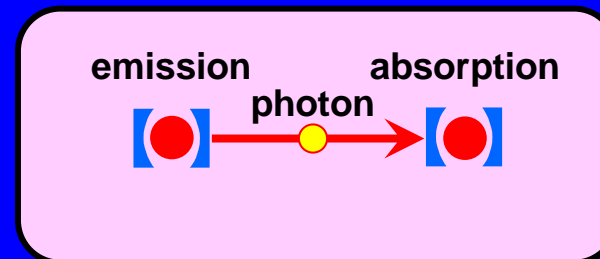
Entanglement

Single-photon interference



Sensitive to phase, frequency, loss

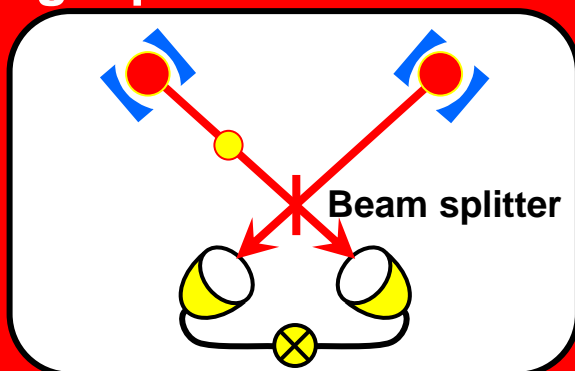
Emission-absorption



Insensitive to phase, frequency, loss

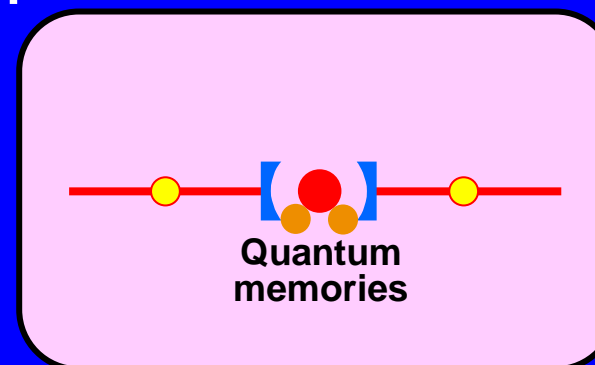
Bell measurement

Single-photon interference



Probabilistic

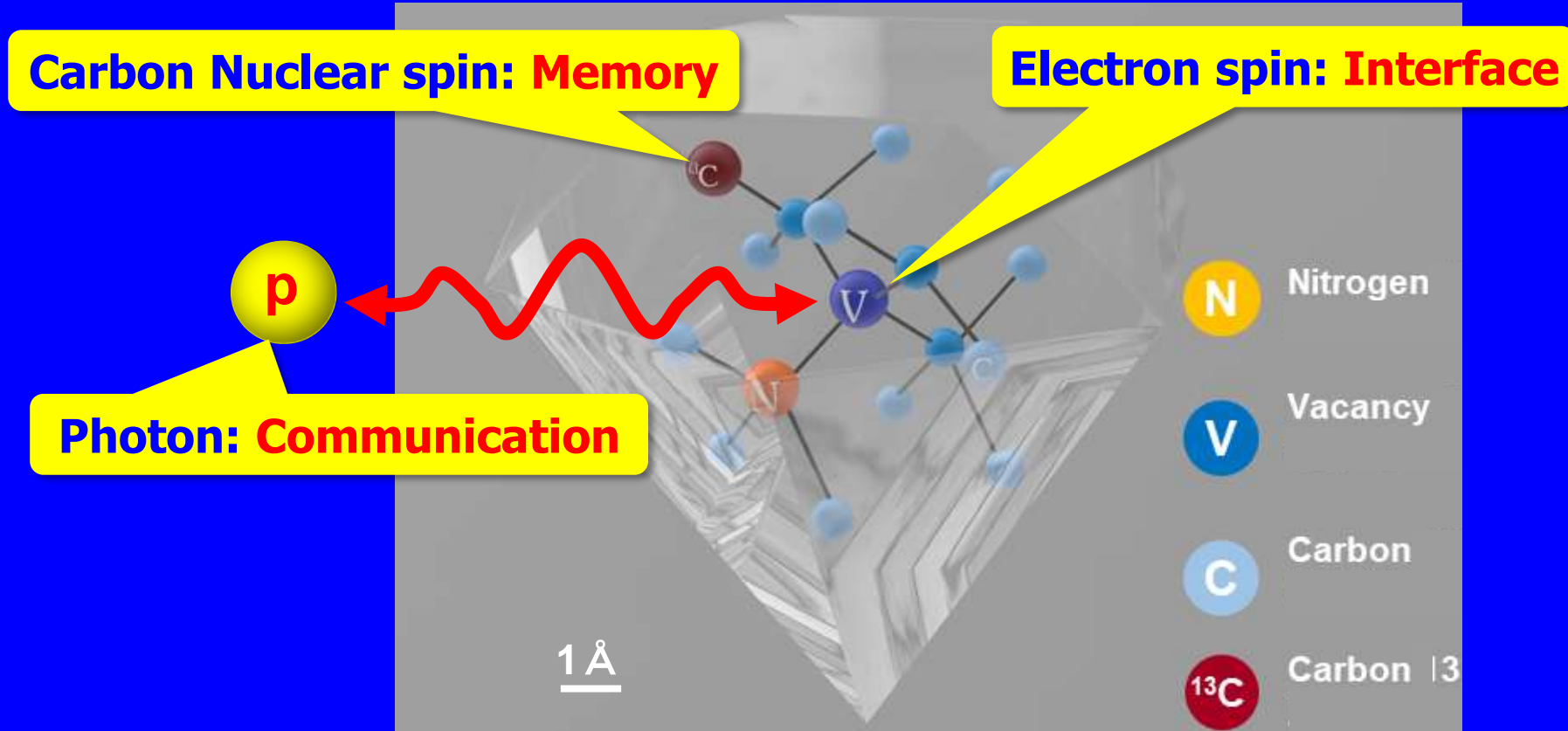
Complete Bell state measurement



Deterministic to be scalable

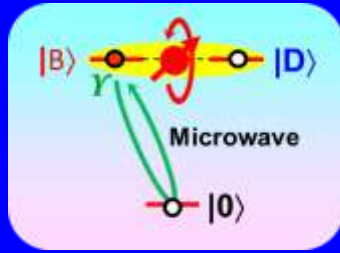
A Color Center in Diamond

NV Center

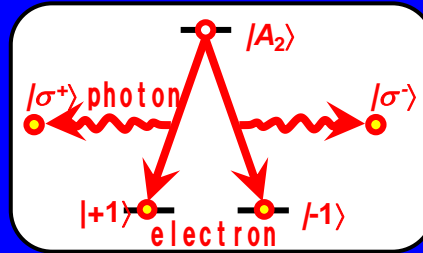


Performance of Diamond chip in YNU scheme

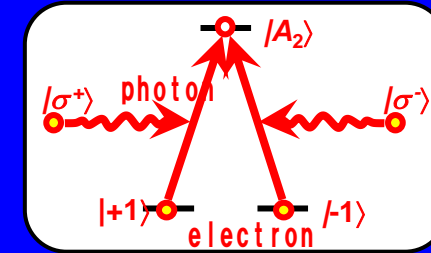
Emission & absorption \Rightarrow Insensitive to phase, freq. & loss balance
Geometric qubit under a zero magnetic field \Rightarrow Robust to noise



Nature Communications, 7, 11668 (2016)



Communications Physics, 4, 264 (2021)

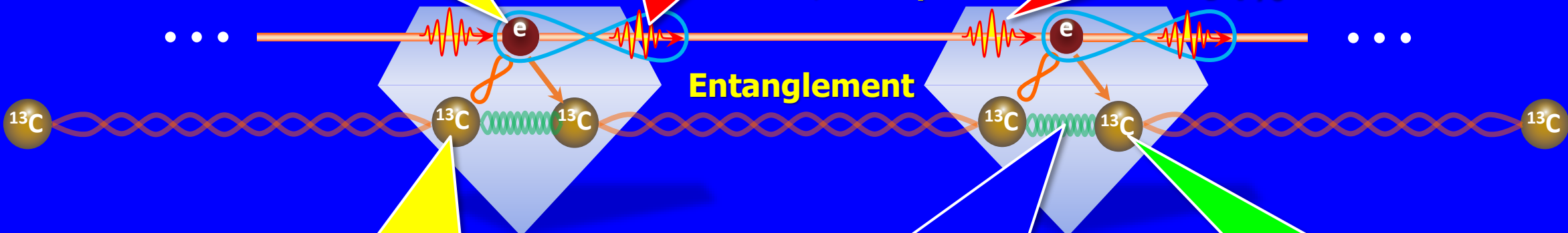


Physical Review Letters, 114, 053603 (2015)

Holonomic Q. Gate
99.97%

Entangled Emission
98%, 10Kcps

Q. Teleportation transfer
94%



Initialize & Readout
99.7%

Complete Bell Measurement
90%

Error Correction
83%


Appl. Phys. Lett. 120, 194002 (2022)

Appl. Phys. Lett. 120, 194002 (2022)

Communications Physics 5, 102 (2022)

Challenges for Enhanced Photon Emission

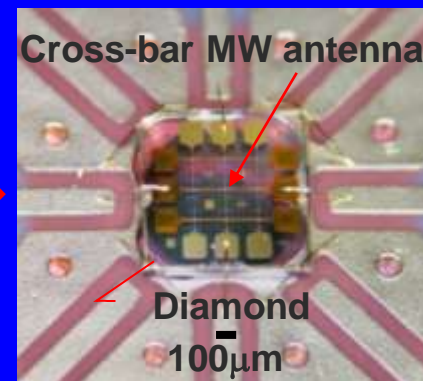
Extremely pure
99.99999999%
isotope pure
99.998%



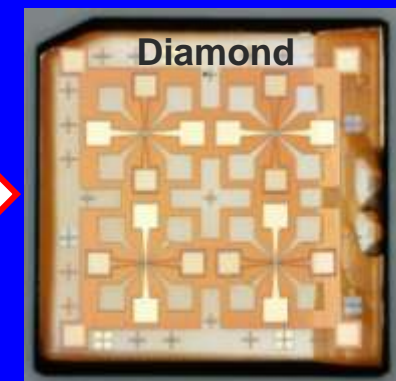
0G (1mm)



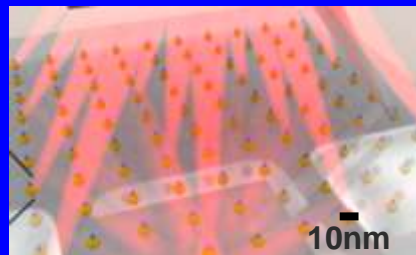
1G (100μm)



2G (10μm)



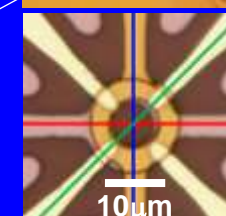
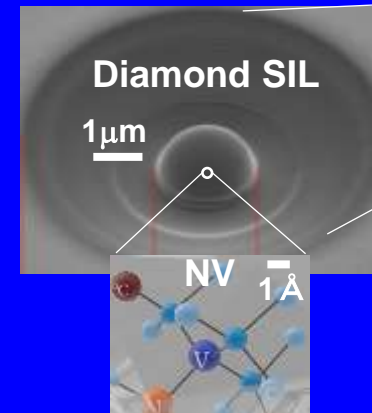
5G (10nm)



4G (100nm)



3G (1μm)



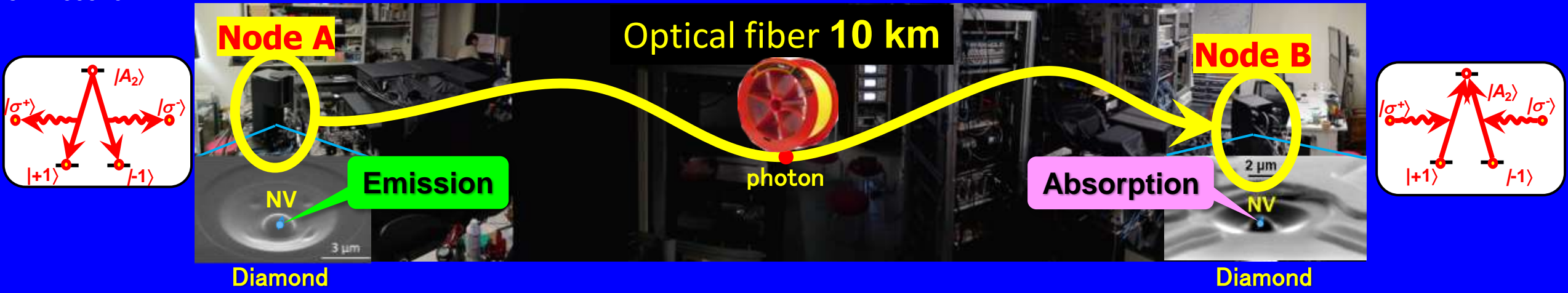
Antenna for arbitrary microwave polarization

Nanobeam Ion Implantation & Laser Annealing
Photon-bus coupled Integrated Q. Memory

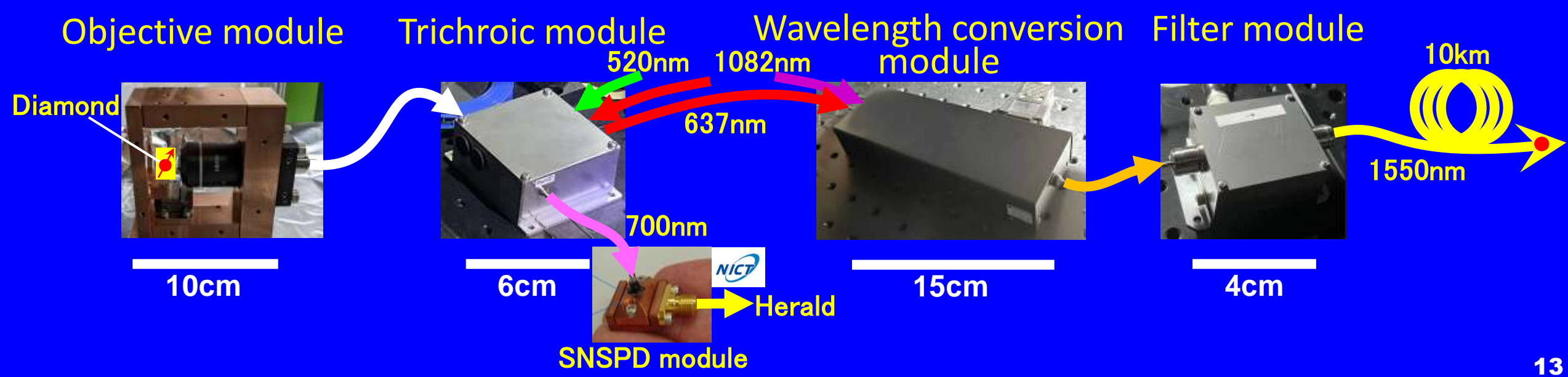
Diamond Photonic Crystal Emission Enhance x 1000

Diamond Solid Immersion Lens Emission Increase x 50

JPMI00316

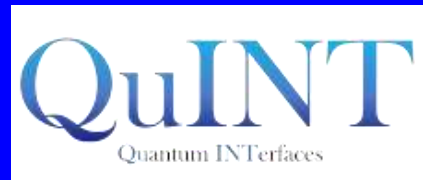


We succeeded in transmitting a photon entangled with an NV over 10 km



Quantum Computer Networks

Project



<https://moonshot.ynu.ac.jp>

Program



JPMJMS2062

Agency

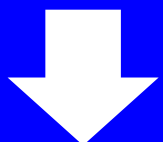


【Network Project】

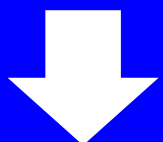
Photon Source & Detector



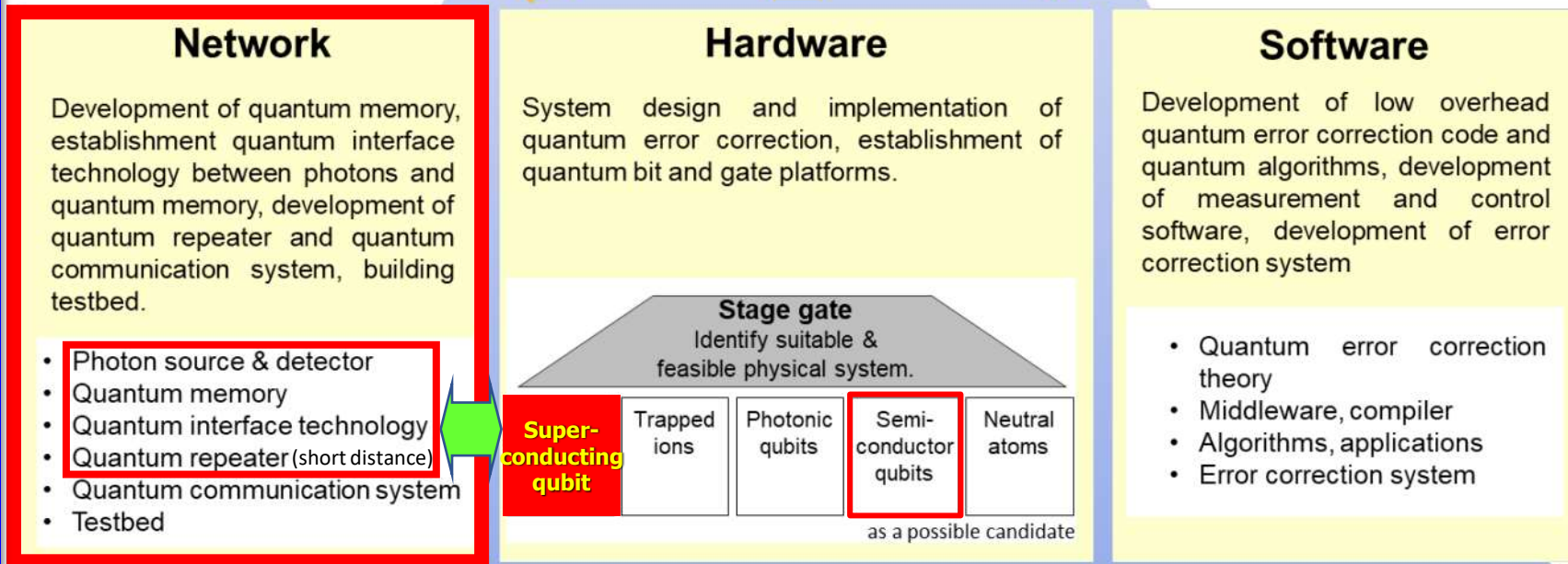
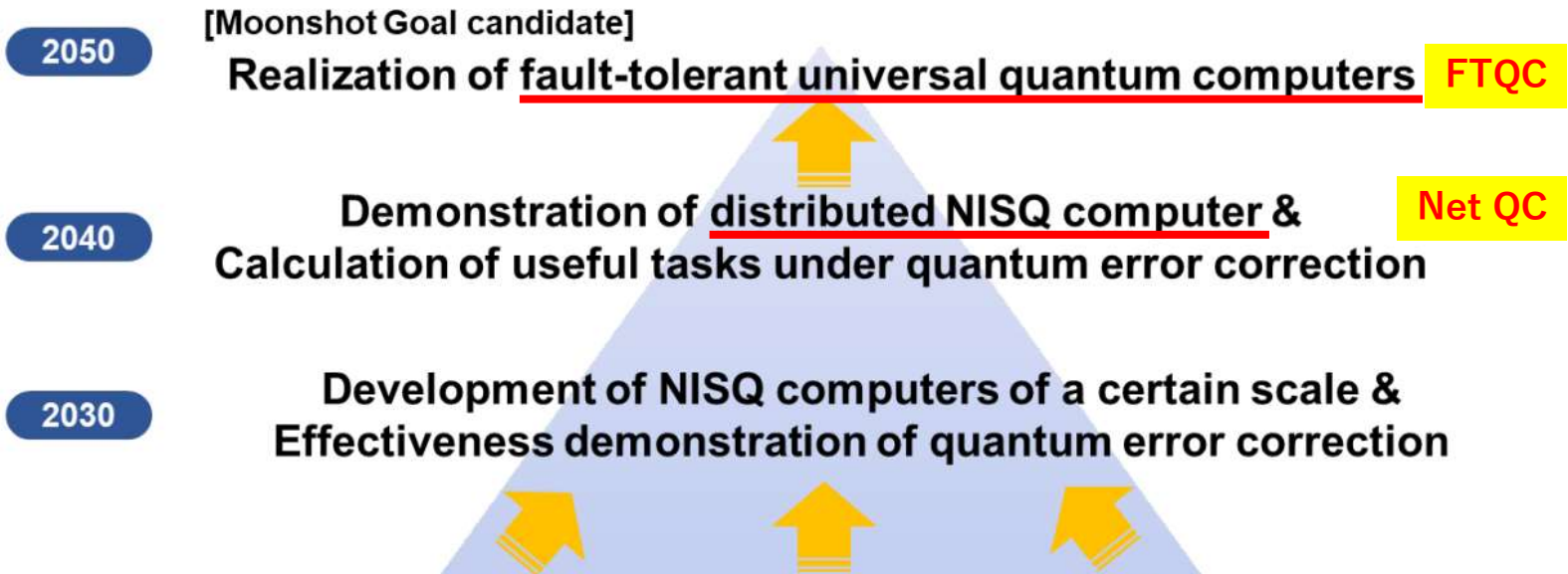
Quantum Memory



Quantum Interface



Quantum Network





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



➤ Hiromitsu Kato



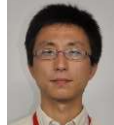
Toshiharu Makino



➤ 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

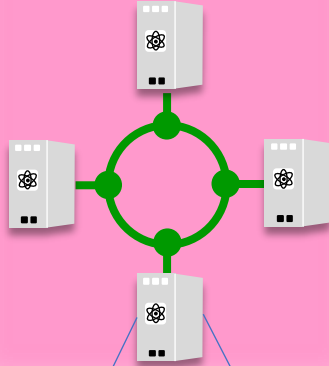


➤ Ryo Sasaki



Why we need Quantum Interface?

Quantum Computer

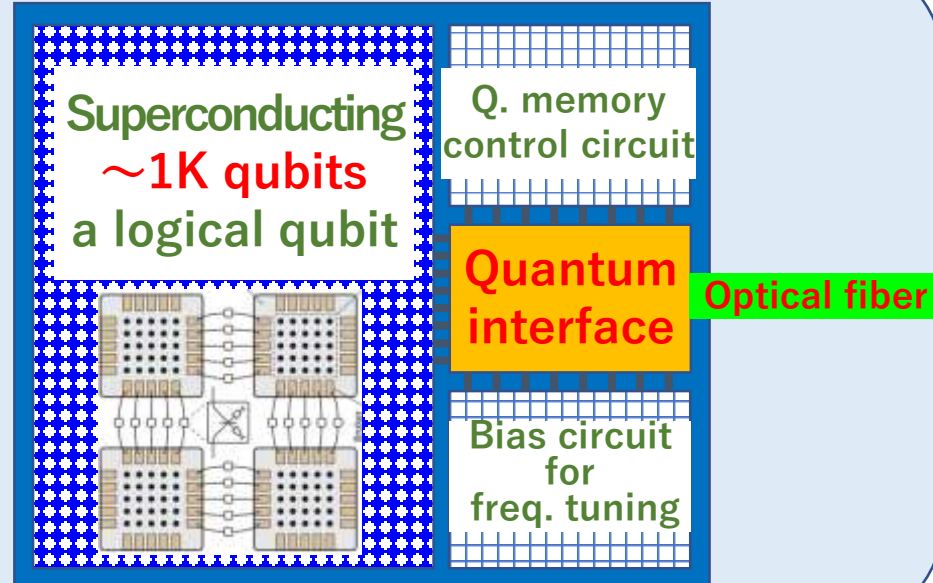


Microwave line (10mK)

Optical fiber link (RT) Flexible ~1000 links



Dilution refrigerator (10mK)



One optical link from one logical qubit

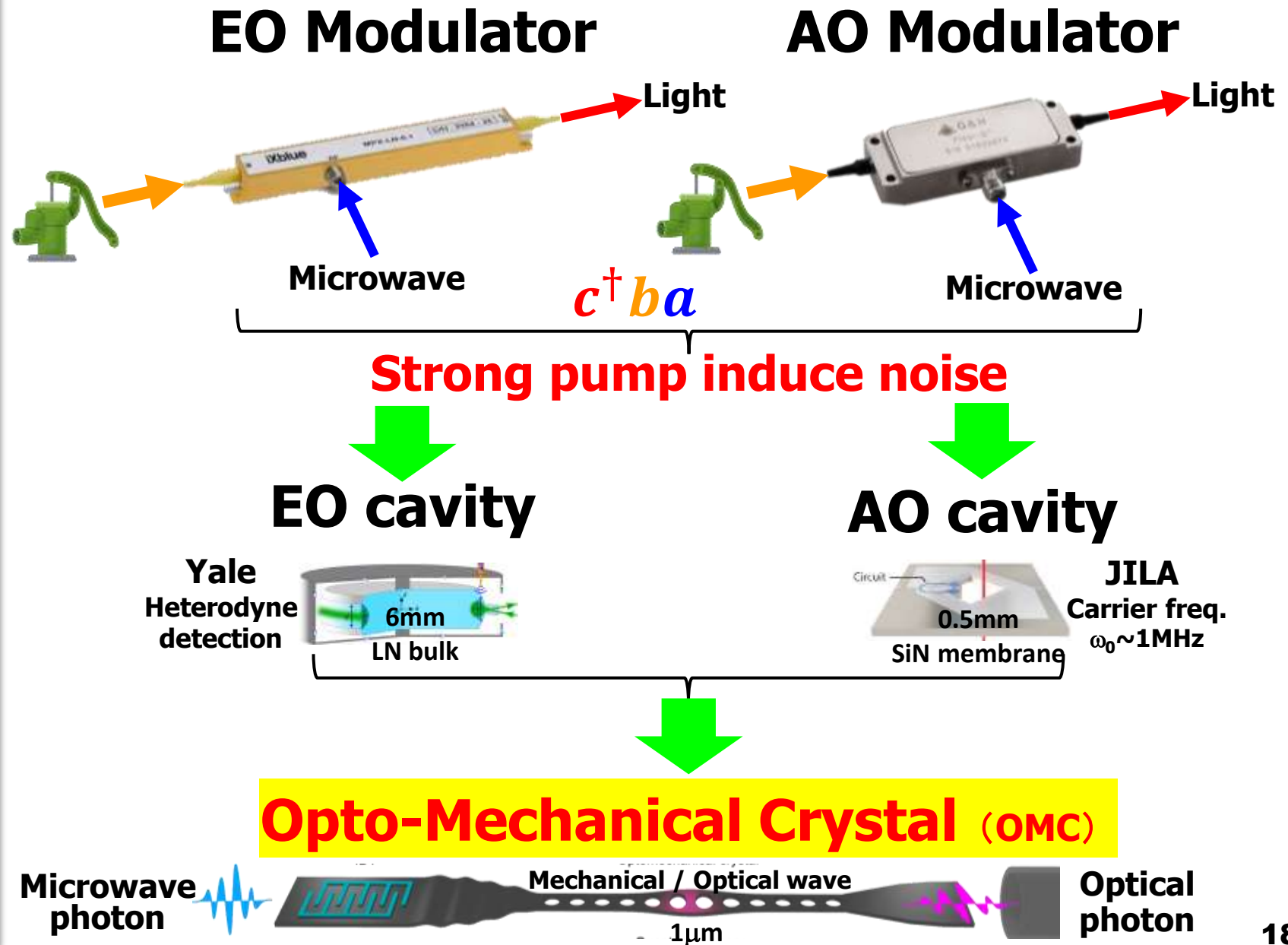
What is Quantum Interface?

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.
 $< 5\text{GHz}$
 \Rightarrow thermal noise

A. Cleland (Chicago) **AlN**

(a) optomechanical crystal
photonic waveguide

50 μm

A. Vainsencher, APL 2016

A. Naeini (Stanford) **LN** \rightarrow **LN/Si**

(a) 20 μm
Optical pump + sideband
Mechanical wave
Microwave

Optical resonator
OMC

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

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

AlN mechanical mode
Optical mode
Phonon waveguide
Si mechanical mode

500 μm
RO res.
SC qbit
p-a cavity
OMC cavity

M. Mirhosseini, Nature 2020

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

(a) 50 μm
signal
ground
fiber resonator
163
etched tapered fiber

S. Honl, NatCom 2022

S. Groblacher (Delft/QphoX) **GaAs** \rightarrow **GaP**

(a) 5 μm
Optical Mode
Mechanical Mode

M. Forsch, NatPhys 2020

(b) 5 μm

R. Stockill, NatCom 2022

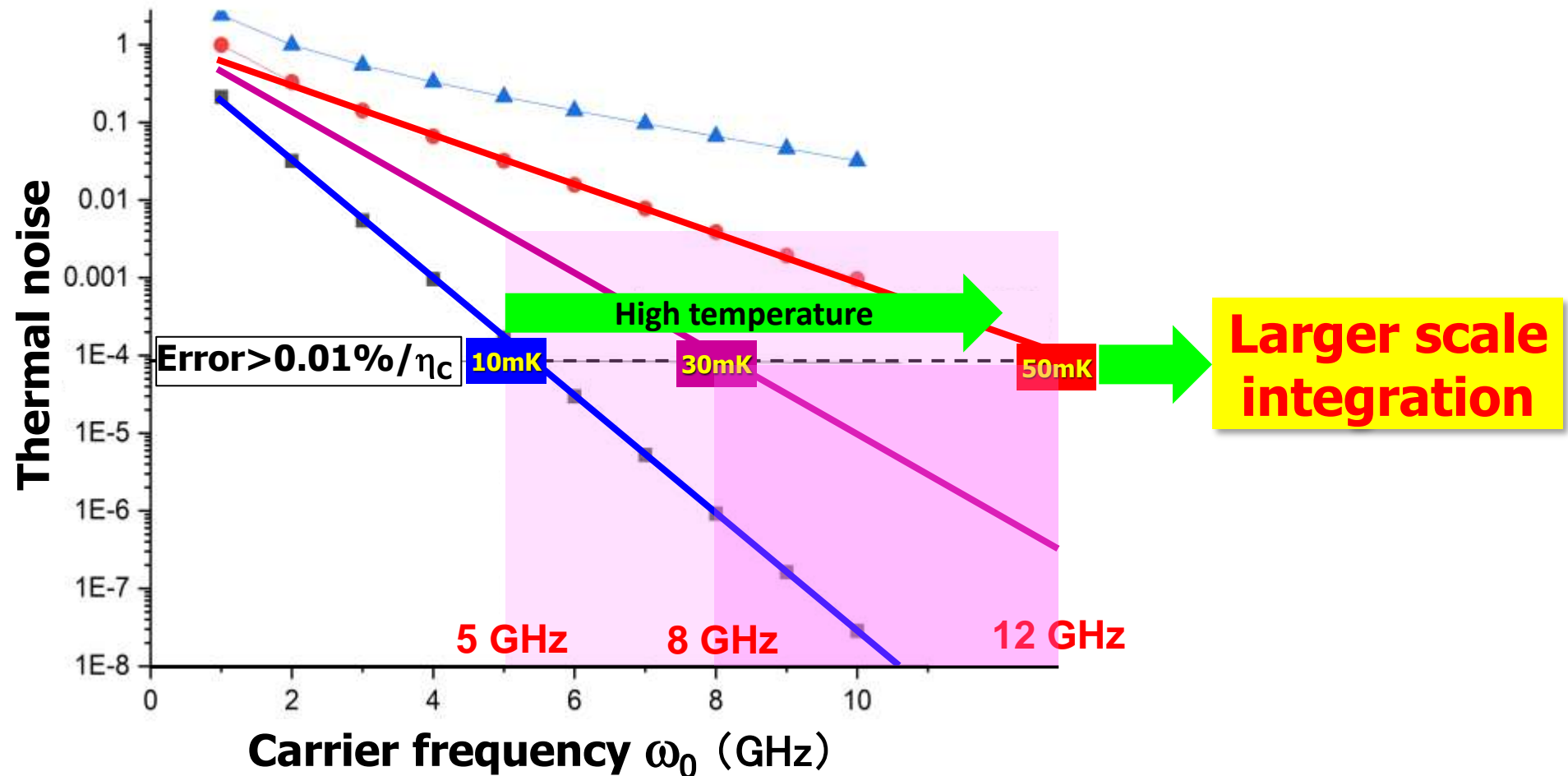
LN/Si

LN
Si

M. Weaver, q-ph 2022

Advantage of high carrier frequency

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)

Triangle cross-section nanobeam

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).

Rectangular cross-section nanobeam (etched down method)

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

Optomechanical crystal with implanted silicon vacancy center
 Diamond waveguide taper
 Rectangular cross-section nanobeam (Quasi-isotropic undercut etching)

Optical mode Mechanical mode

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)

Silicon Photonic Integrated Circuit
 Diamond

Rectangular (undercut)

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

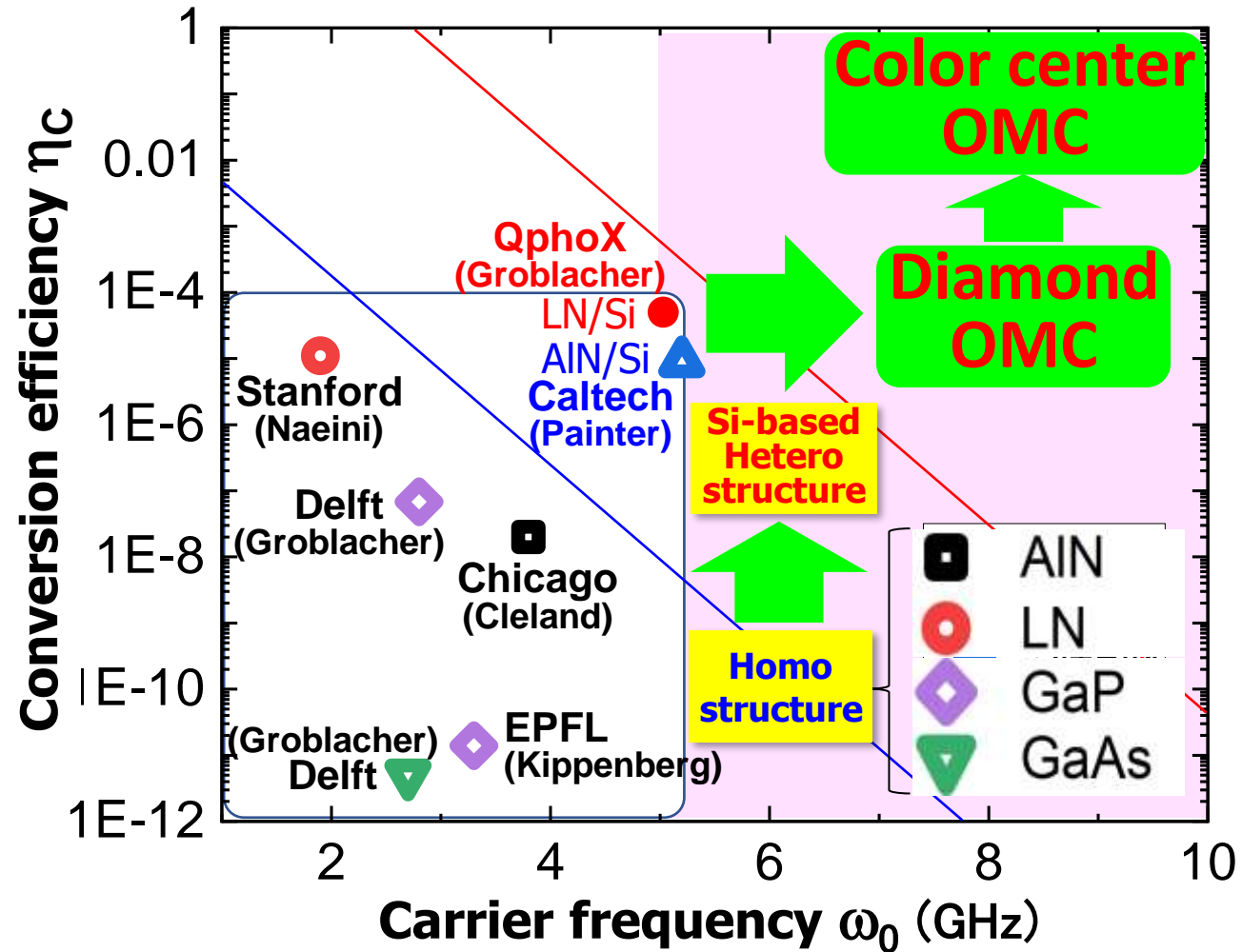
Optical Q = 14,000 @ 637 nm (NV)

Hanson/Groblacher (QuTech/QphoX) APS meeting (2023)

Rectangular (undercut)

SnV 737 nm

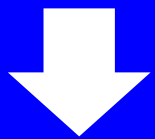
Diamond OMC with a Color Center



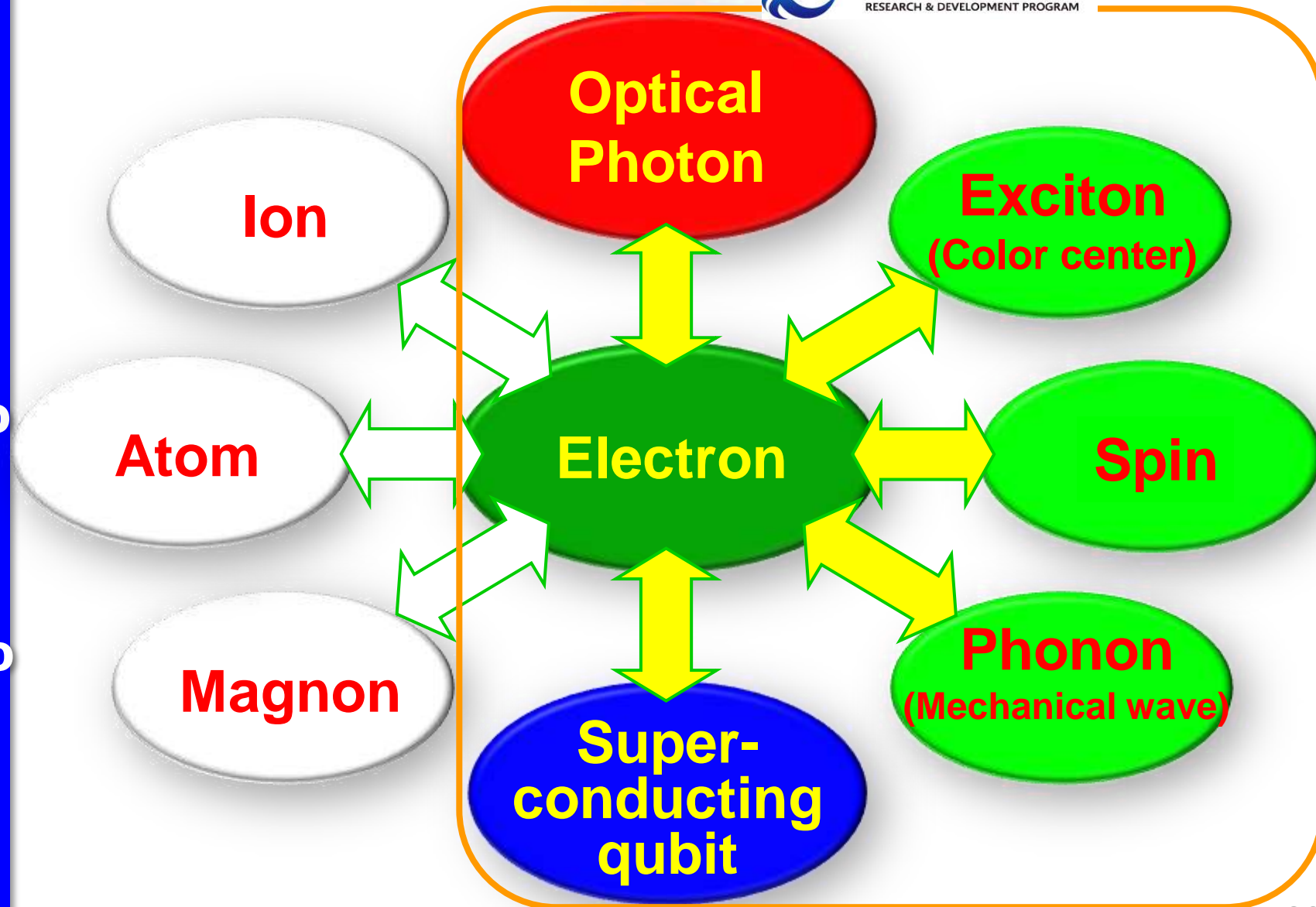
Quantum Interface = Quantum Media Converter

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



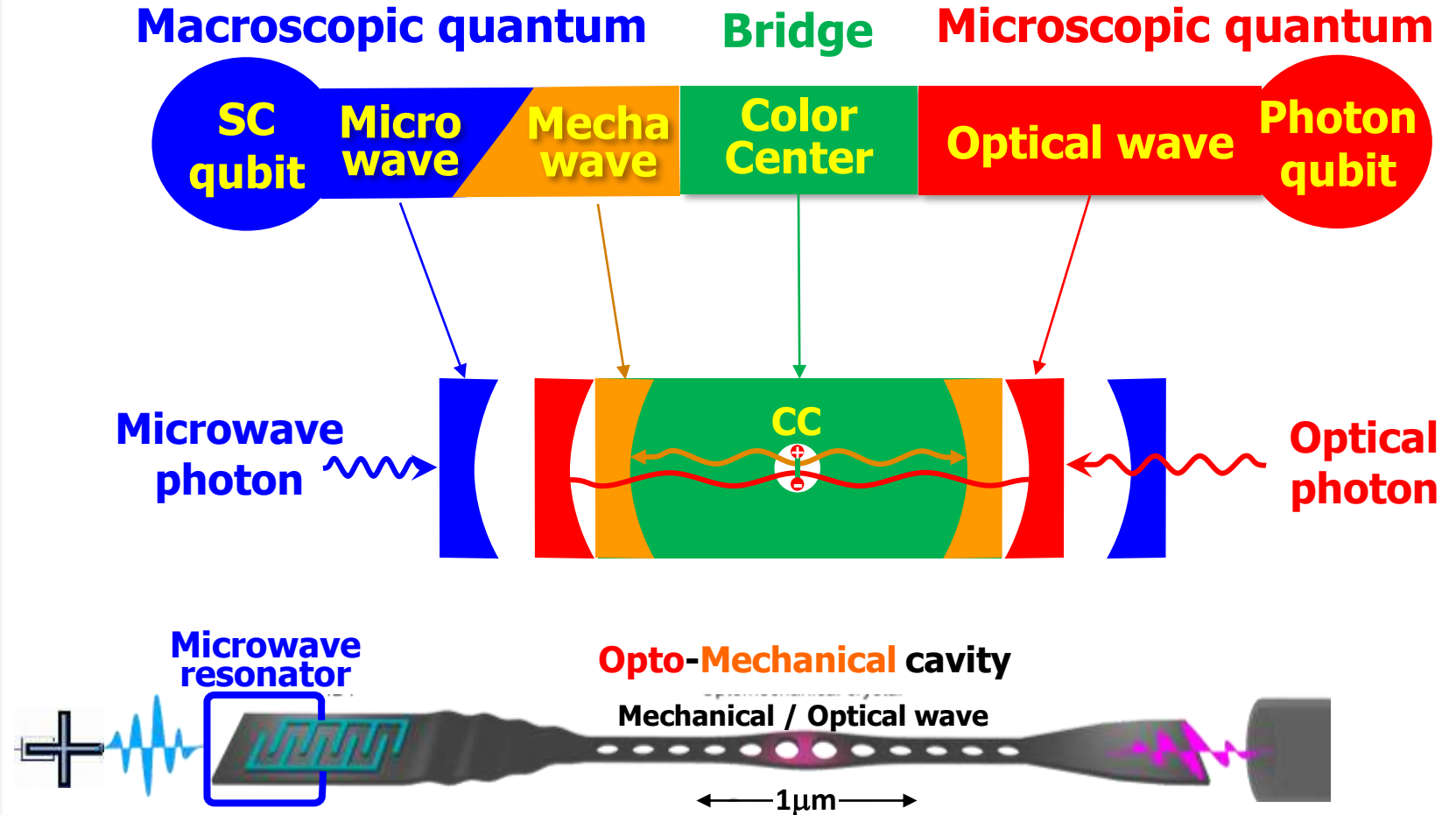
Diamond OMC with a Color Center

A Color Center bridges
Macro & Micro Quanta

Microwave + Mechanical
+ Optical Resonators



Enhancement of
conversion efficiency



Performance of Element Components

Supercon. Micro qubit wave

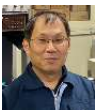
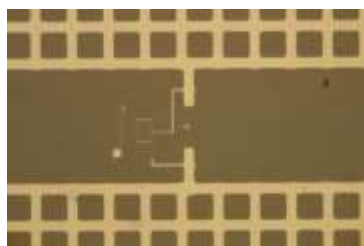
Mecha wave

Color Center

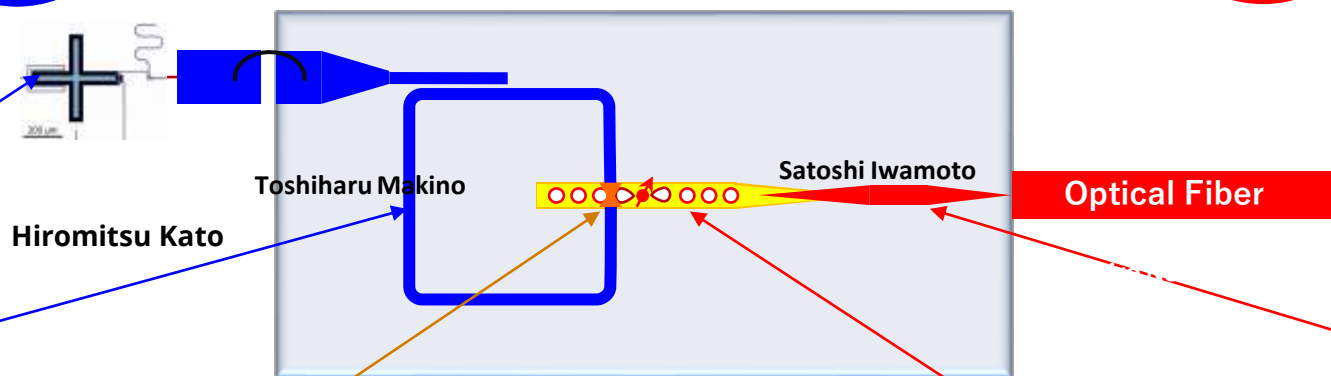
Optical wave

Photon qubit

Transmon Qubit



YNU
YOKOHAMA National University

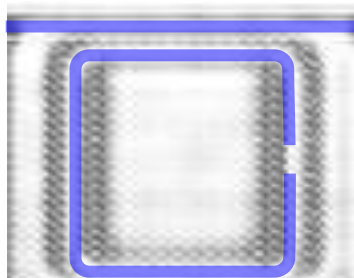


Microwave Resonator

Diamond Mecha Resonator

Diamond Optical Resonator

Optical Waveguide

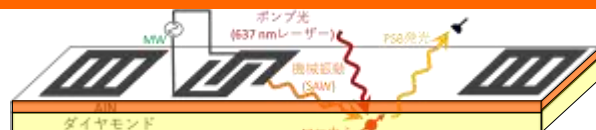


500µm
NbTiN/Si 100nm nano wire

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



M. Yamamoto et. al, arXiv.2307.10271 (2023)



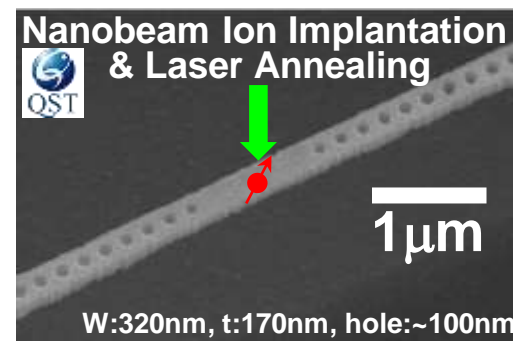
AIN/Diamond



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



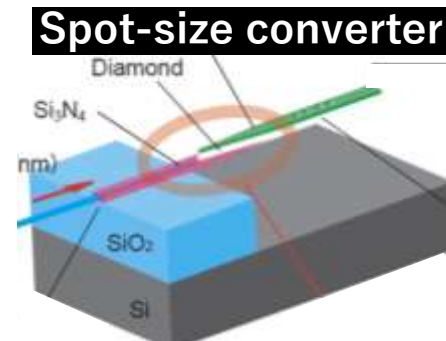
Ishida et. al., 15p-A501-2, Oubutsu 2023S



Nanobeam Ion Implantation & Laser Annealing

W:320nm, t:170nm, hole:~100nm

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



Spot-size converter

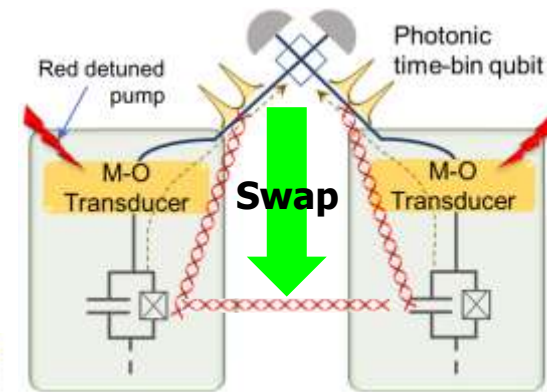
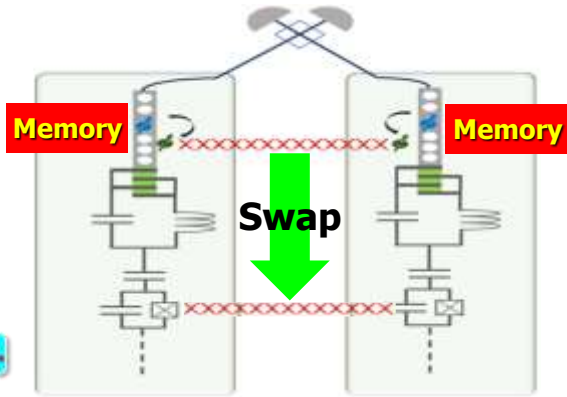
Coupling Loss < 1dB
(Designed)



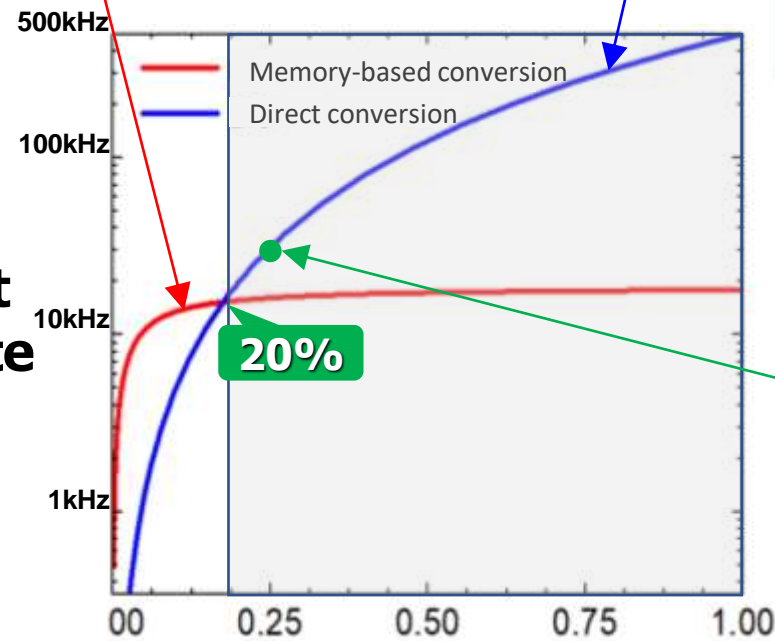
Estimation of Entanglement Rate

Memory-based conv. $\sim 20\text{kHz}$

Direct conversion $\sim 0.5\text{MHz}$

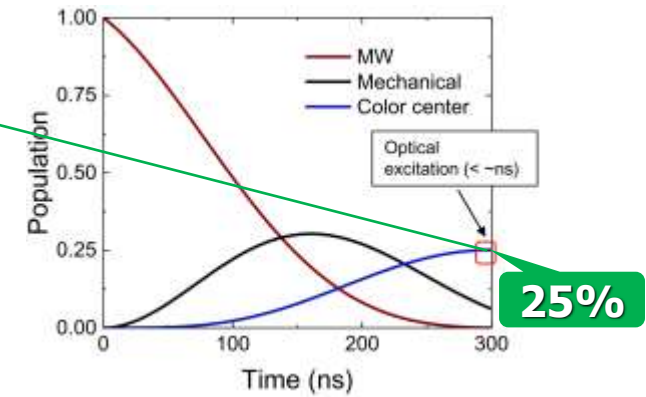


**Entanglement
Generation rate
between
SC qubits**



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

	IV	V	
5	6	7	
B	C	N	O
13	14	15	16
Al	Si	P	S
31	32	33	34
Ga	Ge	As	Se
49	50	51	52
In	Sn	Sb	Te
81	82	83	84
Tl	Pb	Bi	Po

Two charge states

NV⁻ (B=0)

NV⁰ (B=0)

Phonon
(sideband)

Photon

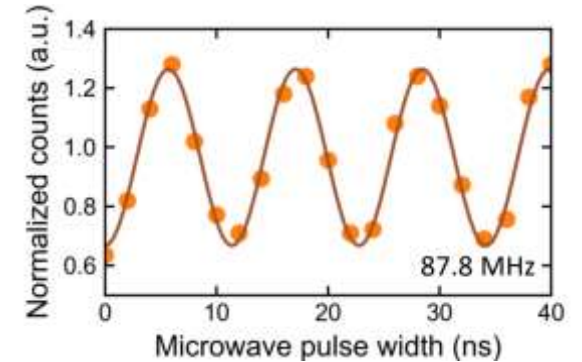
Photon

MW
(resonant)

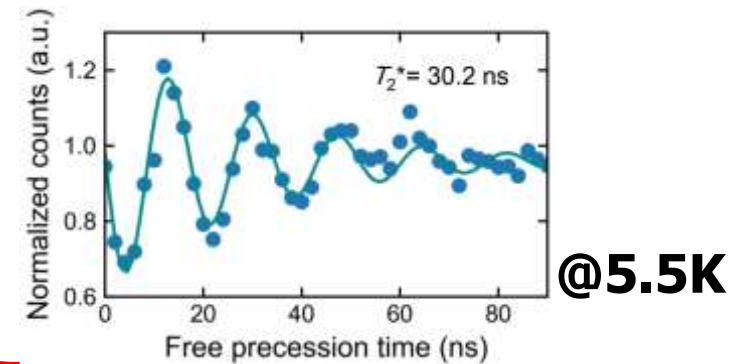
Mechanical
wave

E fields of
Microwave

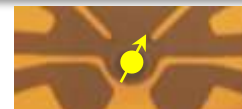
Rabi oscillation



Ramsey interference



We have succeeded in
coherent orbital control by



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).

Diamond Nano Fabrication

Design&Meas

Diamond Photonic Crystal

Diamond Phononic Crystal

9 PIs

Diamond Growth

Diamond Implantation

Diamond SAW

Theory 3D Integ. SC Qubit

Diamond OMC

Optical Circuit

Microwave Circuit

Superconducting Qubit

SNSPD

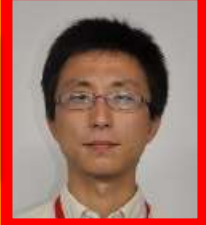
SFQ Circuit

Optical Circuit

Microwave Circuit



Tokuyuki Taraji
Shinobu Onoda



Hiromitsu Kato



Satoshi Fujii



Toshiharu Makino



Kazuki Koshino



Hideo Kosaka



Fumihiro Inoue



Satoshi Iwamoto



Yoshihiro Shimizu



Masahiro Nomura



Shigeto Miki



SNSPD



Toshihiko Baba



Hirota Terai



Quantum Information Research Center



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PM
Center Director



Hideo Kosaka

Associate PM

Associate Professor



Shinichiro Fujii

PR International

Adjunct Teaching Staff



Annelies Volders

IP Strategy
Intellectual Property
Producer



Kinya Kumazawa

PR Industry-Academy-Government

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Toshihiko Baba

Professor



Nobuyuki Yoshikawa

Associate Professor



Yuki Yamanashi

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Fumihiro Inoue

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Yoshihiro Shimazu

Associate Professor



Christopher Ayala

Assistant Professor



Yuhei Sekiguchi

Assistant Professor



Hodaka Kurokawa

Assistant Professor



Akira Kamimaki

Visiting Professor



Satoshi Iwamoto

Visiting Professor



Masahiro Nomura

Visiting Associate Professor



Kazuki Koshino

Visiting Associate Professor



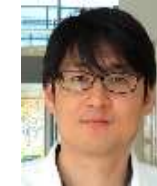
Katsuaki Tanabe

Visiting Professor



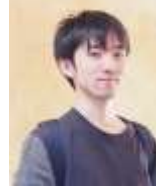
Hiroataka Terai

Visiting Professor



Shigehito Miki

Visiting Researcher



Ryo Sasaki

National Institutes

Visiting Professor



Toshiharu Makino

Visiting Professor



Hiromitsu Kato

Visiting Professor



Tokuyuki Teraji

Visiting Associate Professor



Shinobu Onoda

Company

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Mamiko Kujiraoka

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SAARLAND UNIVERSITY

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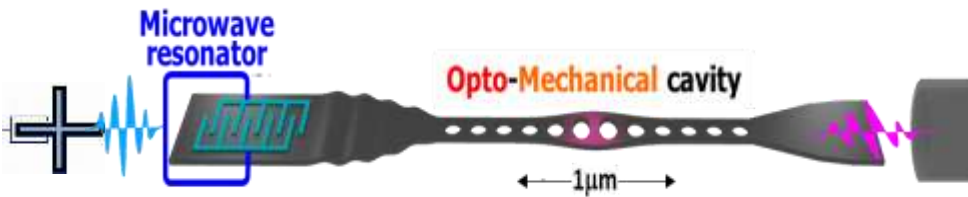
**Worldwide Nanotech
Researchers from 6 Univs
& 5 National Institutes**

Summary

We are developing diamond-based

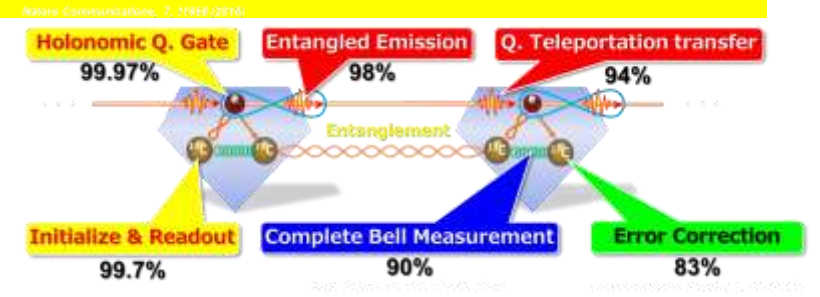
Quantum Interface
for
Quantum Computer Networks

Quantum Repeater
for
Quantum Communication Networks



toward
Quantum Networking

QC & QC



Project
QuINT
Quantum INterfaces

<https://moonshot.ynu.ac.jp>

Program

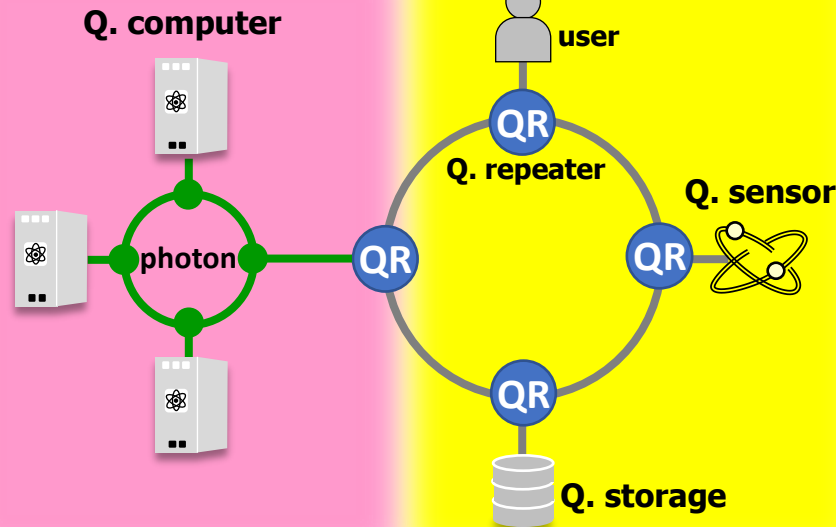


Agency



Cabinet Office

**Short
distance**



Project
QuREP
QUANTUM REPEATER TECHNOLOGY

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

Program



Agency



**Long
distance**