Quantum Innovation 2025
August 2, 2025@Osaka, Japan
MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM
JPMJMS2062
Moonshot goal 6: Fault-tolerant quantum computer
Development of Quantum Interfaces for Building Quantum Computer Networks
Project Manager Hideo Kosaka
Professor, YOKOHAMA National University
Director, Quantum Information Research Center
Research fellow, The University of Tokyo
Japan
YNU
YOKOHAMA National University
QIC
UTokyo
JST
Japan Science and Technology Agency

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Moonshot Program 6

JPMJMS2062

2050 [Moonshot Goal candidate]

Realization of fault-tolerant universal quantum computers

2040 **Demonstration of distributed NISQ computer & Calculation of useful tasks under quantum error correction**

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
- 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 qubits	Trapped ions	Photonic qubits	Semi-conductor qubits	Neutral atoms

as a possible candidate

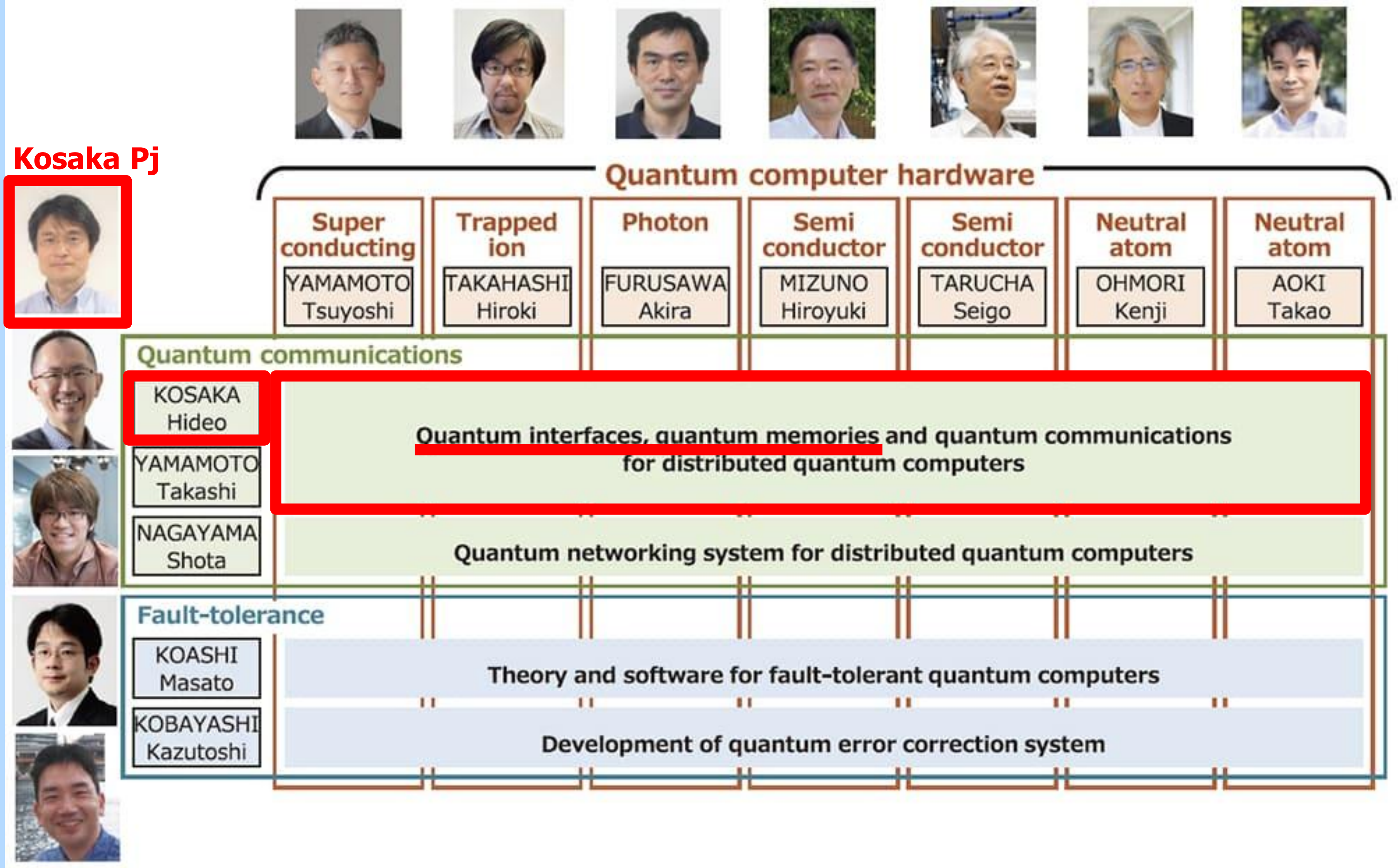
Software

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

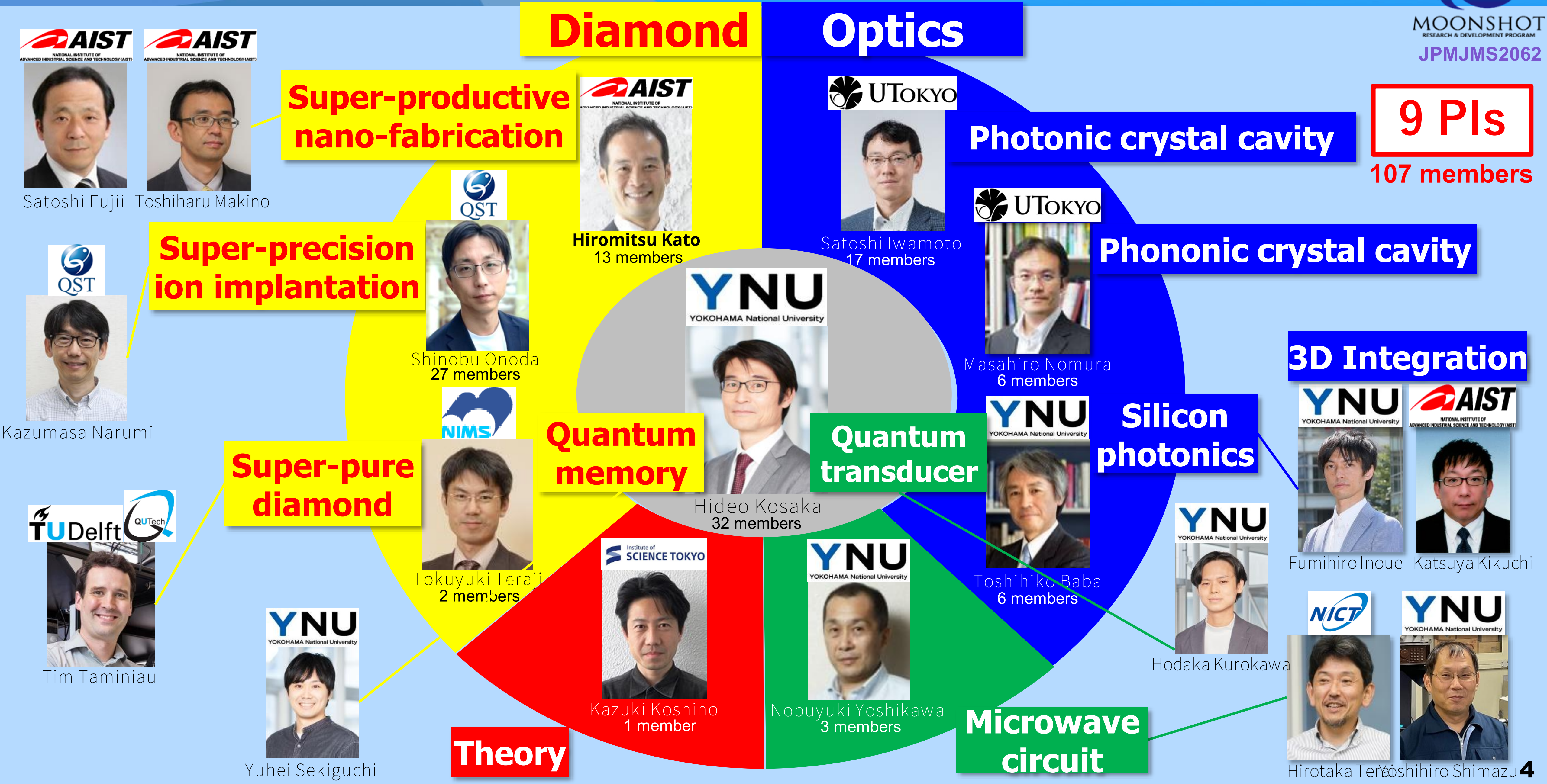
- Quantum error correction theory
- Middleware, compiler
- Algorithms, applications
- Error correction system

Moonshot Program 6

JPMJMS2062



Moonshot Kosaka Project – Quantum Interconnect



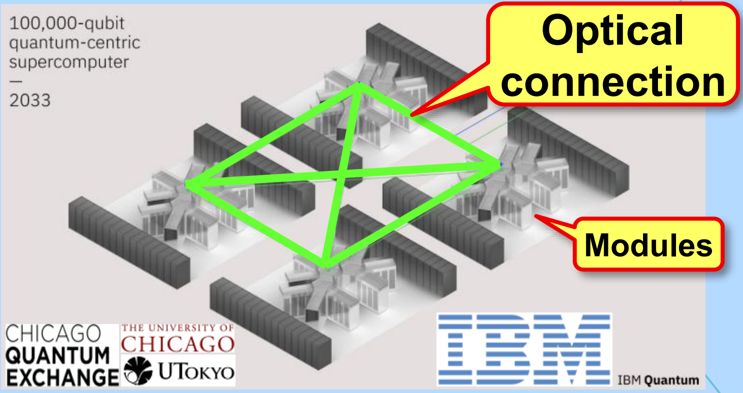
Motivation - Quantum Interconnect Solid qubits

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM
JPMJMS2062

(Distributed) Super Computer

理研HP: www.riken.jp/pr/news/2021/20210309_2/index.html

(Distributed) Quantum Supercomputer



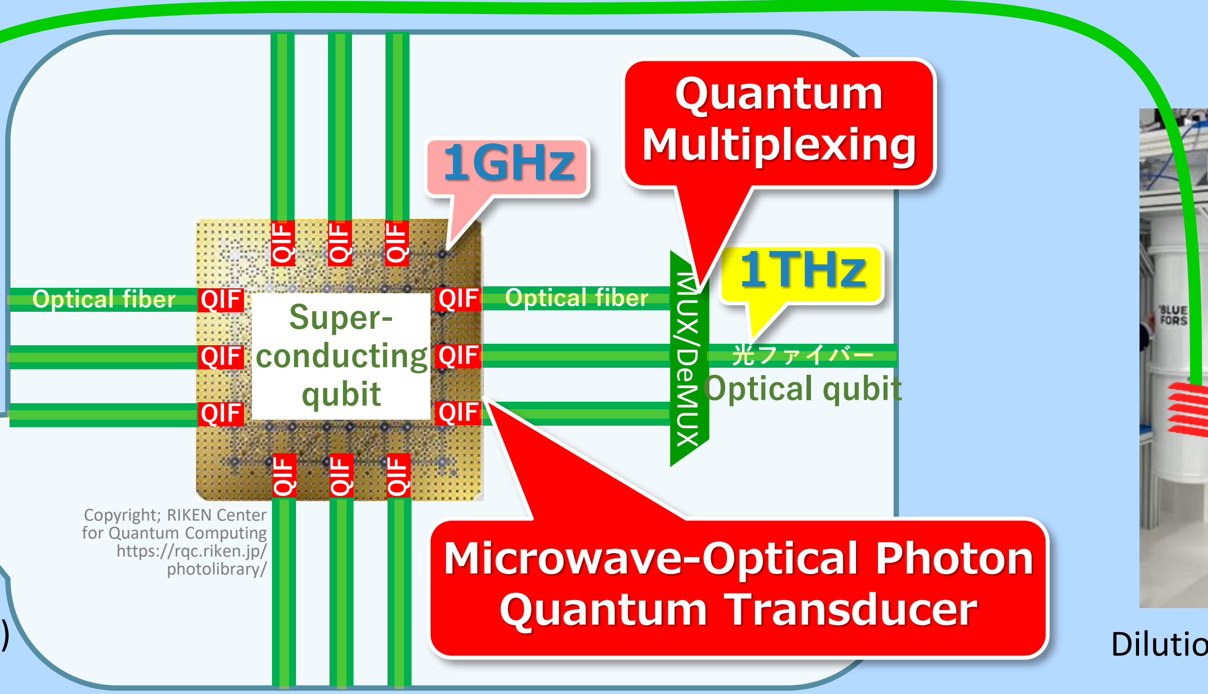
IBM社HP: newsroom.ibm.com/2023-05-21-IBM-Launches-100-Million-Partnership-with-Global-Universities-to-Develop-Novel-Technologies-Towards-a-100,000-Qubit-Quantum-Centric-Supercomputer

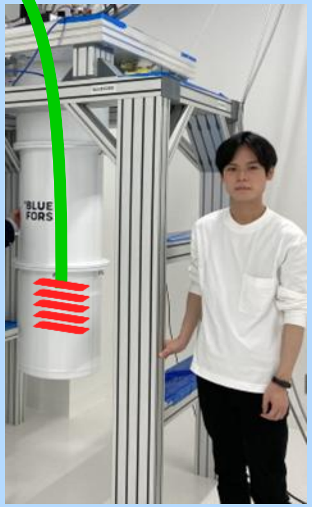
Wallraff ETH
P. Magnard et al., Phys. Rev. Lett. 125, 260502 (2020).

Replaced by optical fibers at room temperature

Reconfigurable Optical Interconnects
(also enable blind quantum computation)

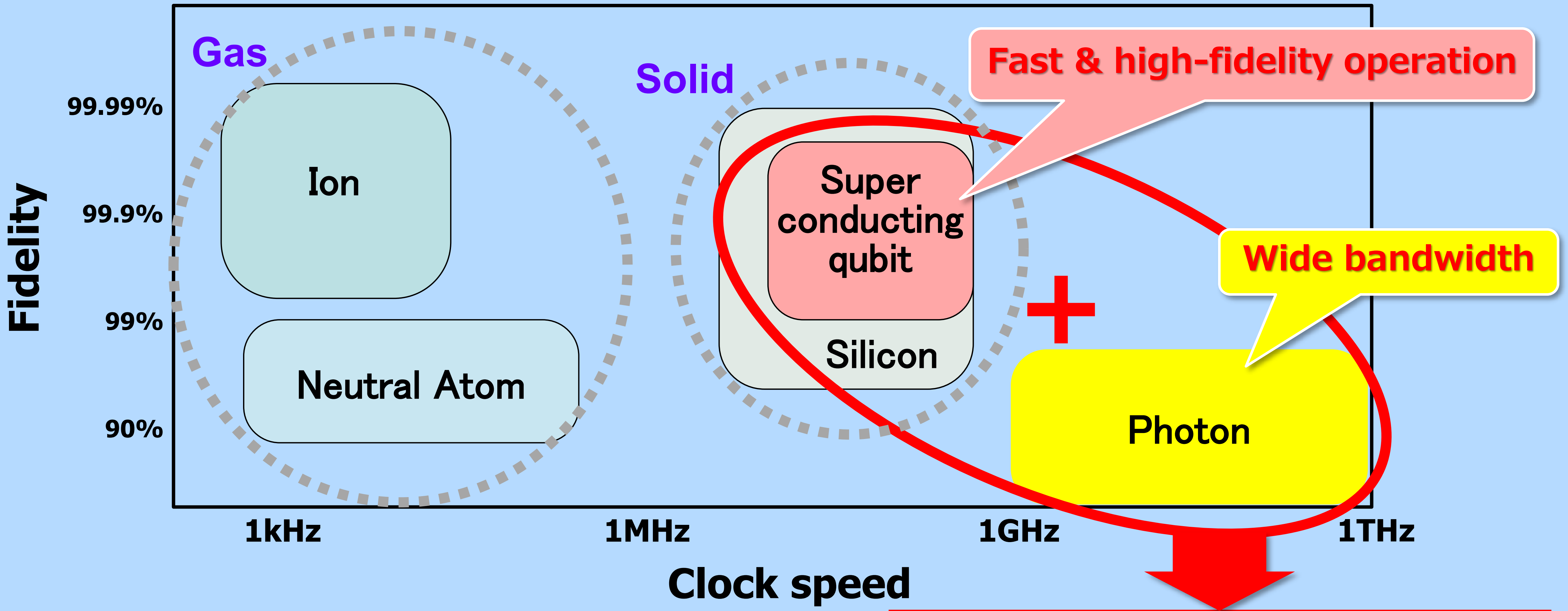
Dilution fridge (~10mK)





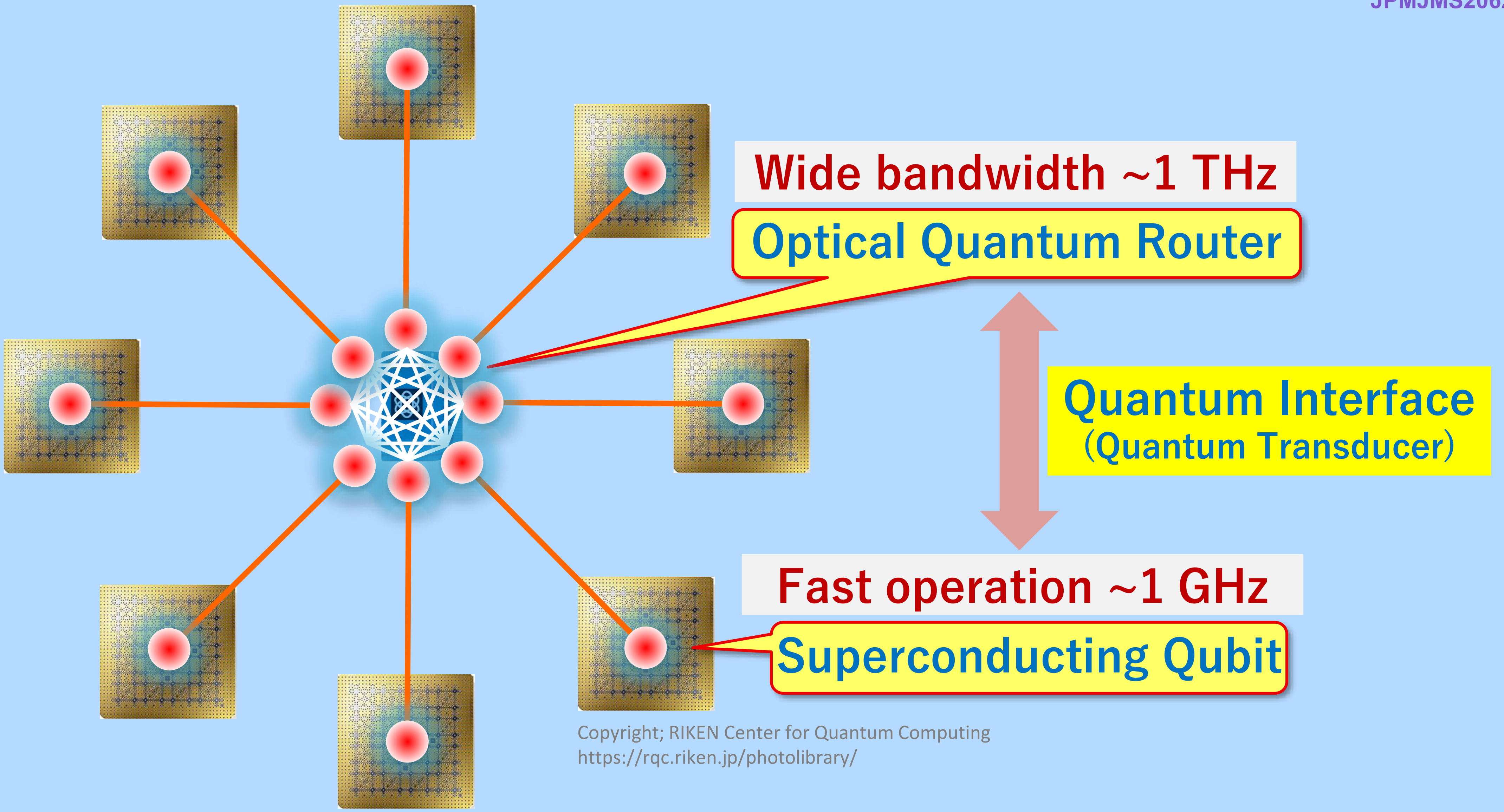
Dilution fridge (~10mK)

Diamond-mediated Hybrid Quantum Computing



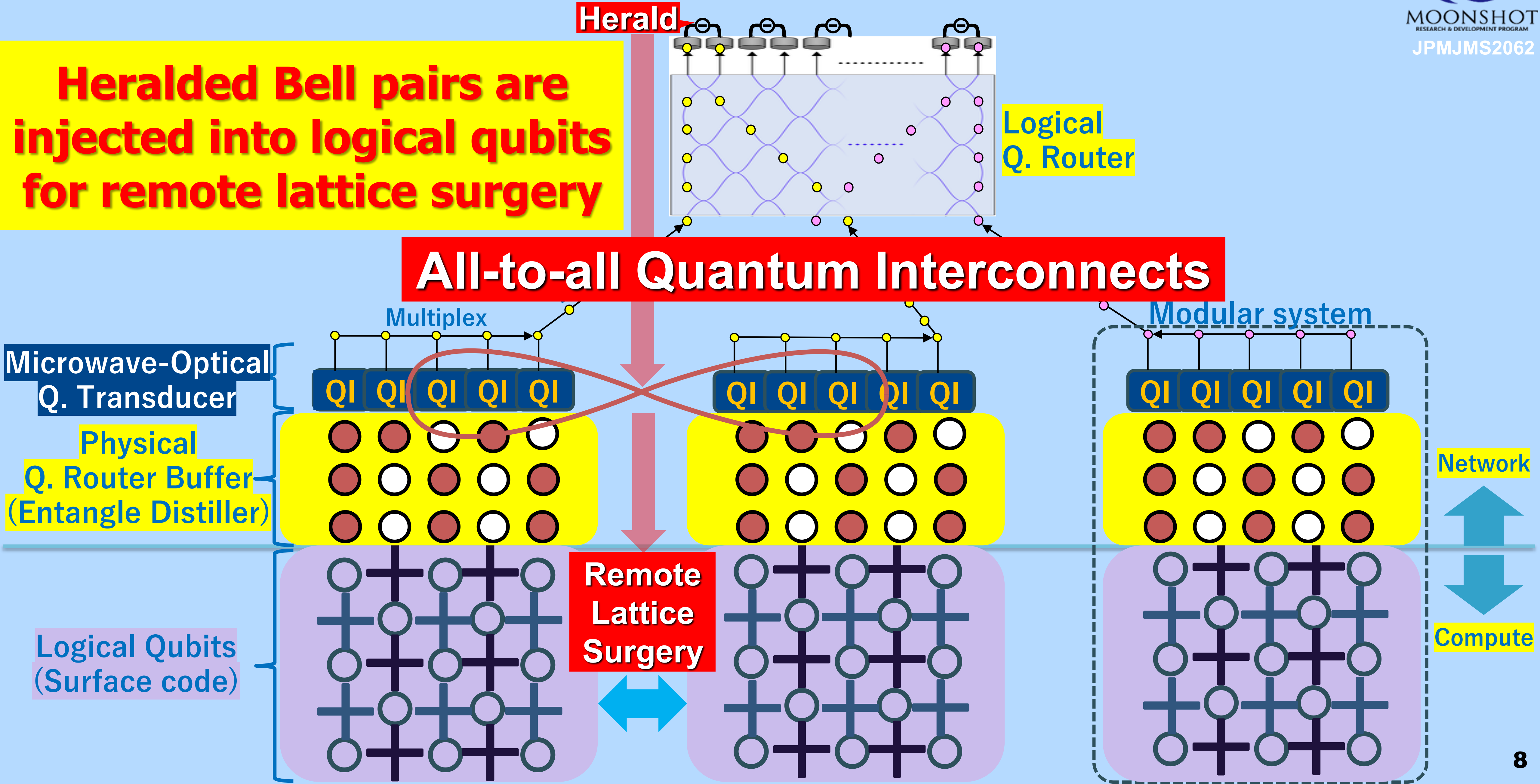
Diamond-intermediated Hybrid Quantum Computing

Distributed Quantum Computing



Distributed Quantum Computing with Quantum Interconnect

Heralded Bell pairs are injected into logical qubits for remote lattice surgery



MOONSHOT RESEARCH & DEVELOPMENT PROGRAM
JPMJMS2062

Quantum Transducer = Quantum Media Converter

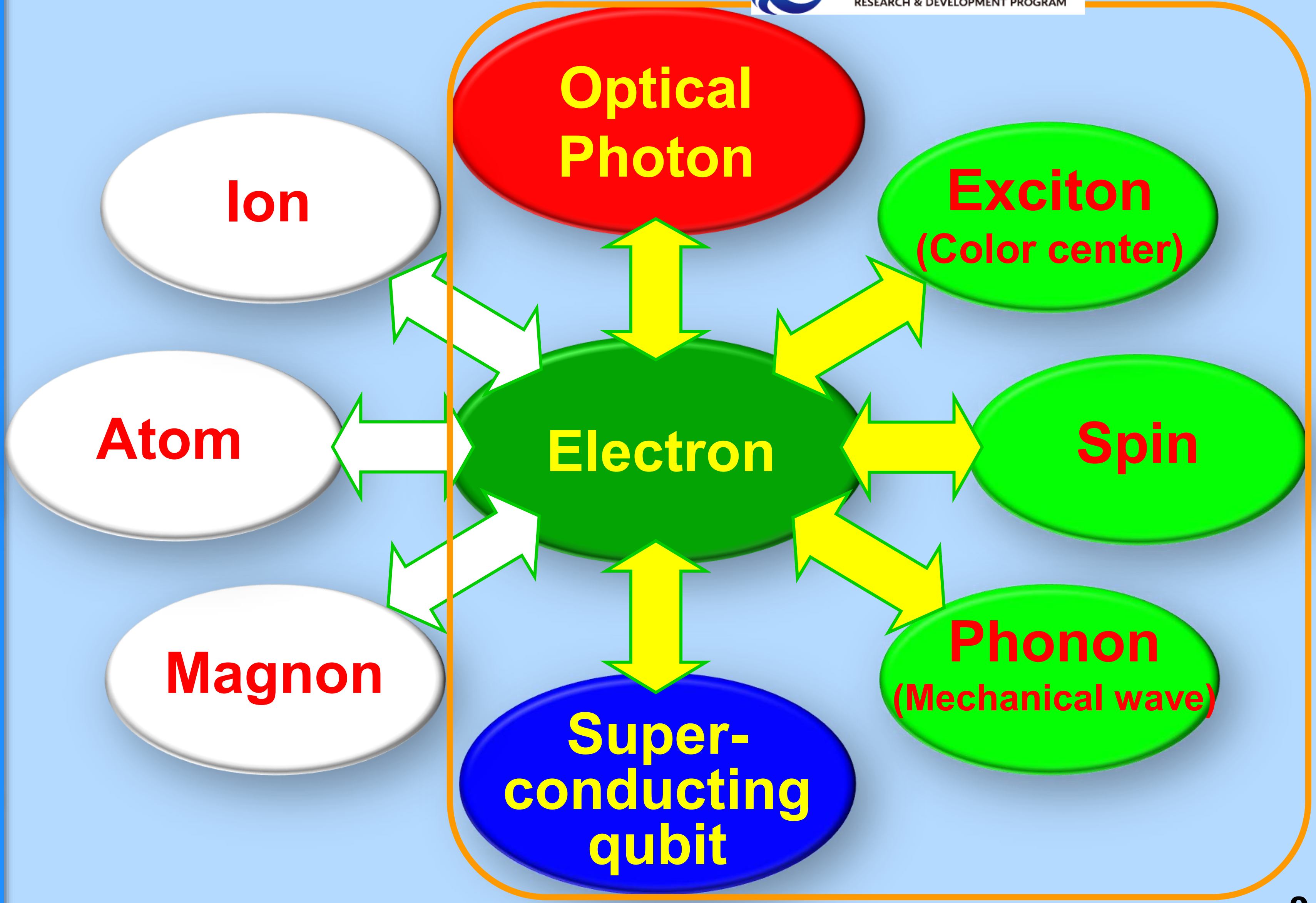
Quantum Transducers convert excitation between different quantum media

However

Superconducting Qubit cannot be converted directly to **Optical Photon**

⬇

Exciton (color center), **Spin** & **Phonon** (mechanical wave) mediate the conversion



Power reduction of Quantum Transducer

Microwave Photon (~10GHz) emitted from Superconducting Qubit is converted to Optical Photon (~500THz)

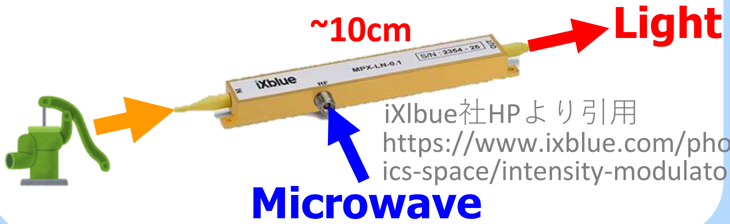
Modulator
W−class pump light

Resonator
mW−class pump light

OMC
μW−class pump light

Emitter in OMC
pW−class pump light

EO modulator



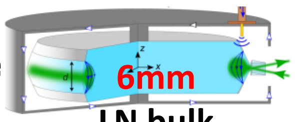
iXlbue社HPより引用
https://www.ixblue.com/photonics-space/intensity-modulators/

AO modulator

Gooch&Housego社HPより引用
https://gandh.com/products/acoustooptics/modulators

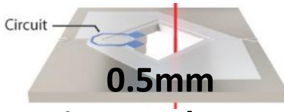
EO resonator

ISTA
Heterodyne detection



A. Rueda et al., npj Quantum Information, 5, 108 (2019).

AO resonator



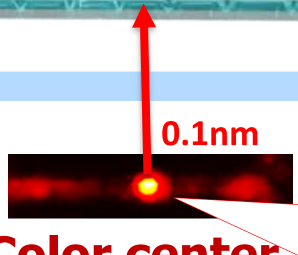
JILA
Carrier freq.
ω_0~1MHz

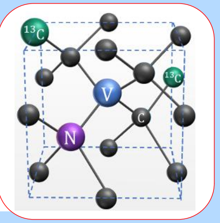
A. P. Higginbotham et al., Nature Physics 14, 1038 (2018).

Opto-Mechanical Crystal
(Photonic & Phononic crystal)

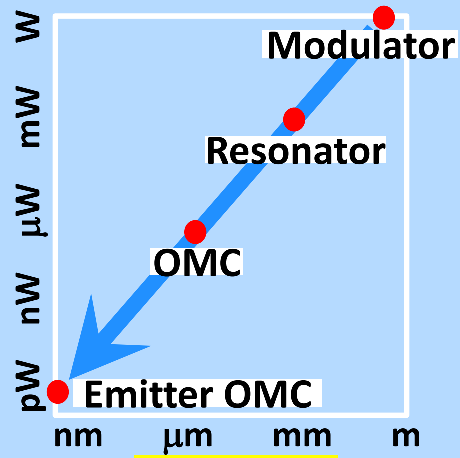
Microwave photon

Optical photon





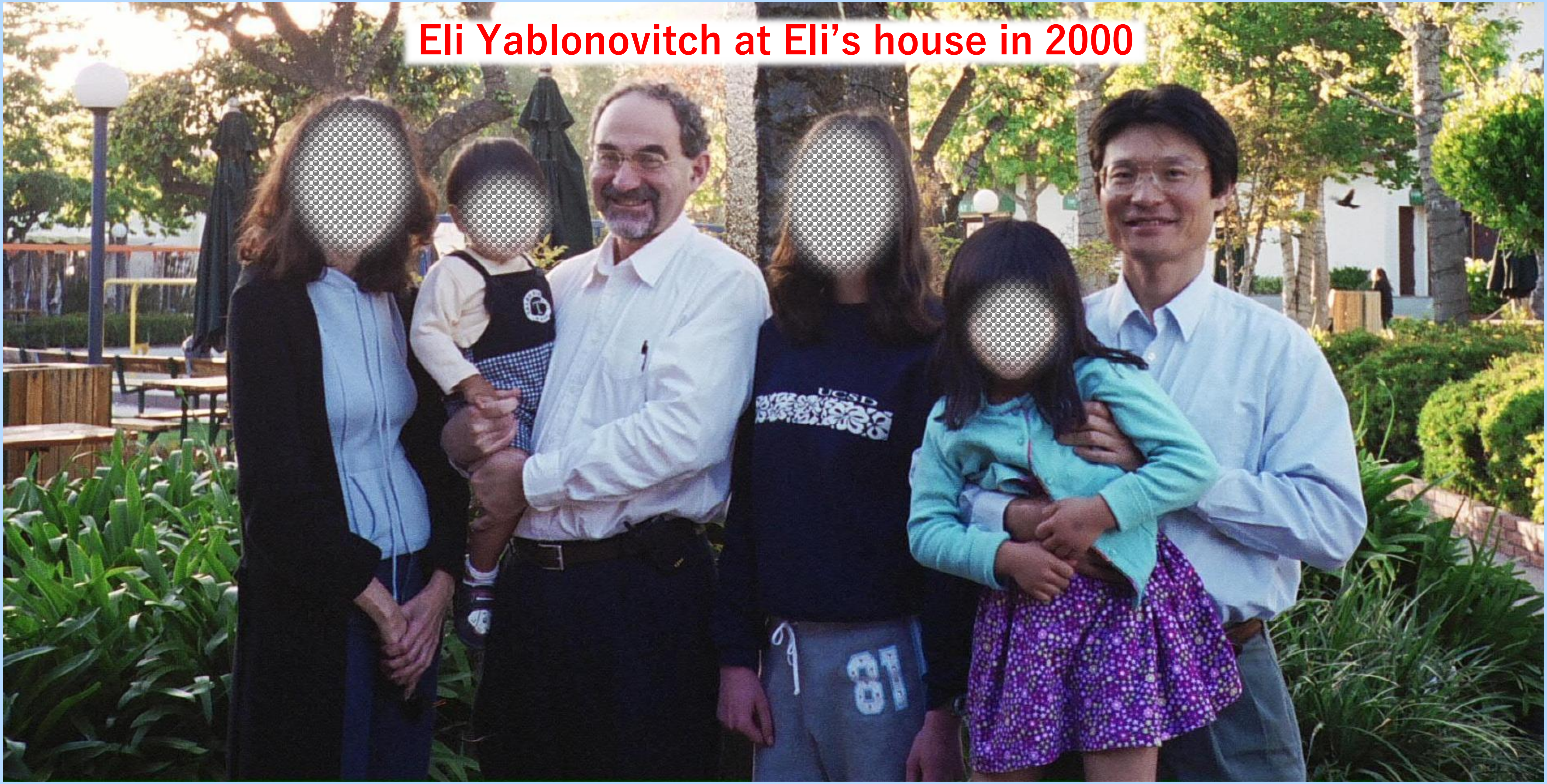
Pump power



Chip size

Noise Reduction

Photonic Crystal

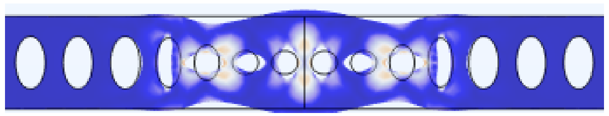


Eli Yablonovitch at Eli's house in 2000

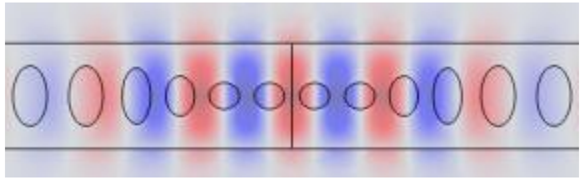
Opto-Mechanical Crystal

Photons and Phonons have about the same wavelength

Mechanical mode (Pho<u>n</u>onic crystal)



Optical mode (Pho<u>t</u>onic crystal)



Conventional OMC Transducers

Piezo material
(AlN, LN, GaP)
or
Piezo on Silicon
(AlN/Si, LN/Si)

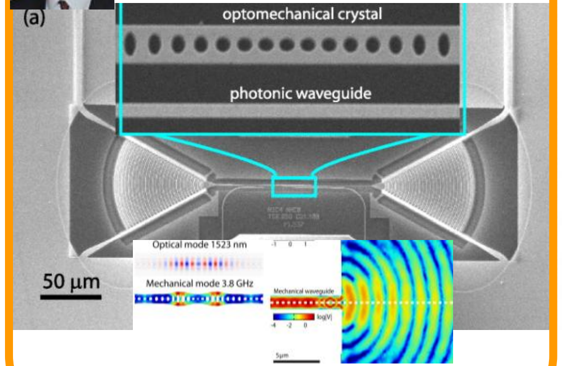
⬇

High pump power

⬇

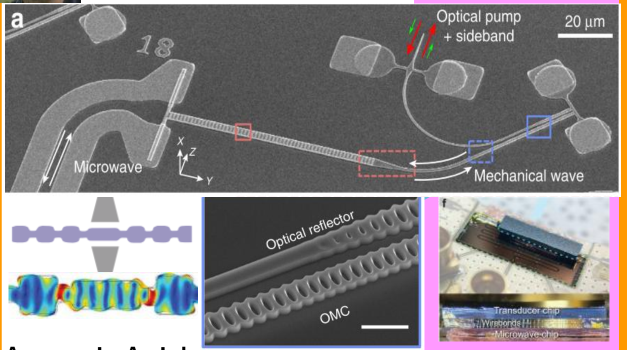
Induce noise

A. Cleland (Chicago) **AlN**



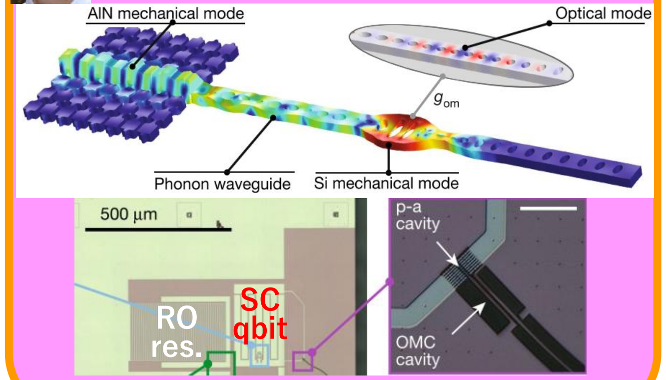
A. Vainsencher, APL 2016

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



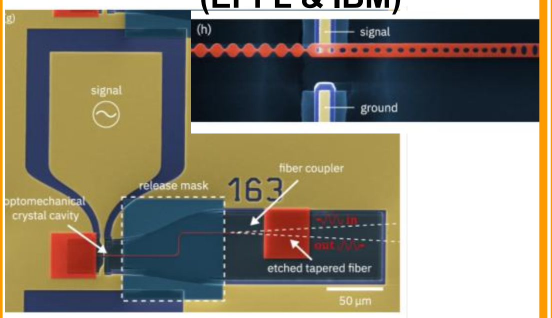
Arrangoiz-Arriola PRX 2018 | Jiang, NatCom 2020 | Jiang, q-ph 2022

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



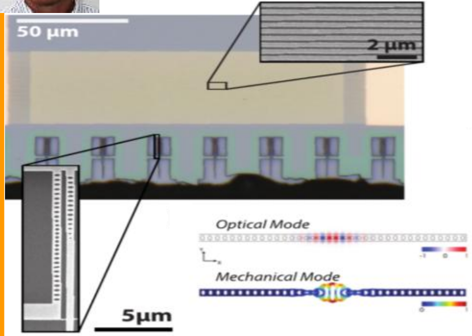
M. Mirhosseini, Nature 2020

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

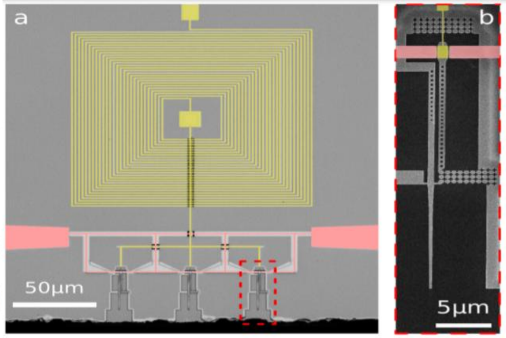


S. Honl, NatCom 2022

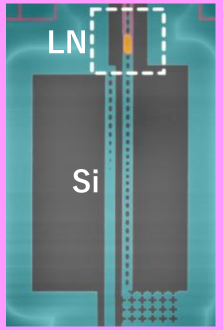
S. Groblacher (Delft/QphoX) **GaAs** **GaP** **LN/Si**



M. Forsch, NatPhys 2020



R. Stockill, NatCom 2022



M. Weaver, q-ph 2022

Challenges for Diamond OMC with color centers

A **color center** in Diamond mediates conversion

↓

Low pump power

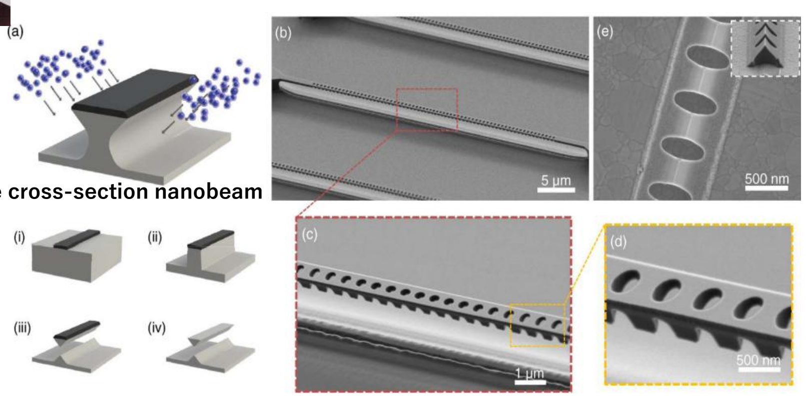
↓

Noise reduction

No demonstration of Q. transducer

Loncar (Harvard) **NV⁻**

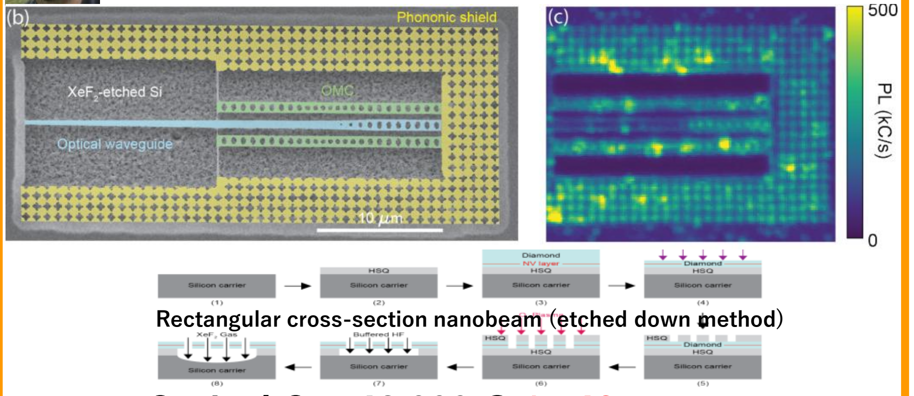
B. J. M. Hausmann et al. Nano Lett. (2013)
M. J. Burek et al., Optica 3, 1404 (2016)



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).

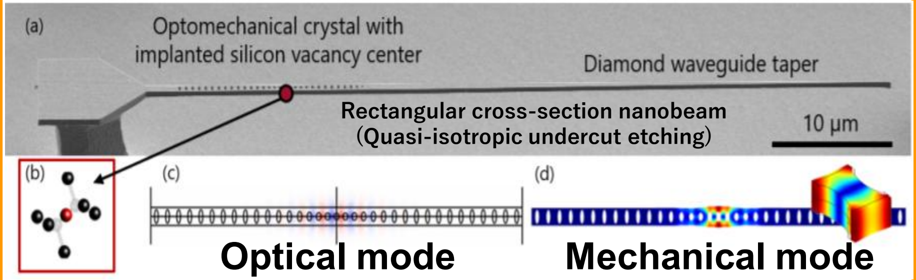


Rectangular cross-section nanobeam (etched down method)

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

Loncar (Harvard) **SiV**

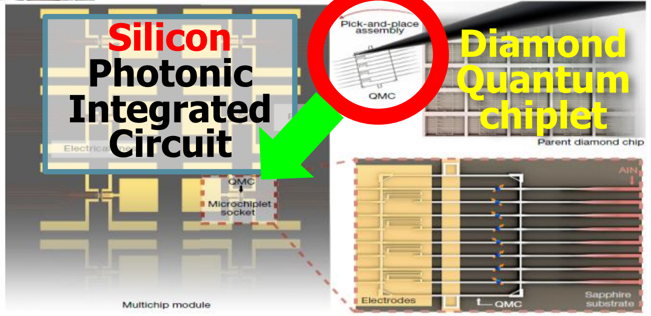
A. Sipahigil et al., Science (2016) triangle
G. Joe et al., CLEO (2021) rectangle



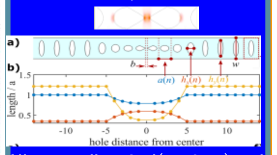
Optical Q ~ 10,000 @ 1,544 nm
Mechanical Q = 22,000 @ 9.2 GHz @4K

D. Englund (MIT) **NV⁻, SiV, GeV**

Wan et al., Nature(2020)



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



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

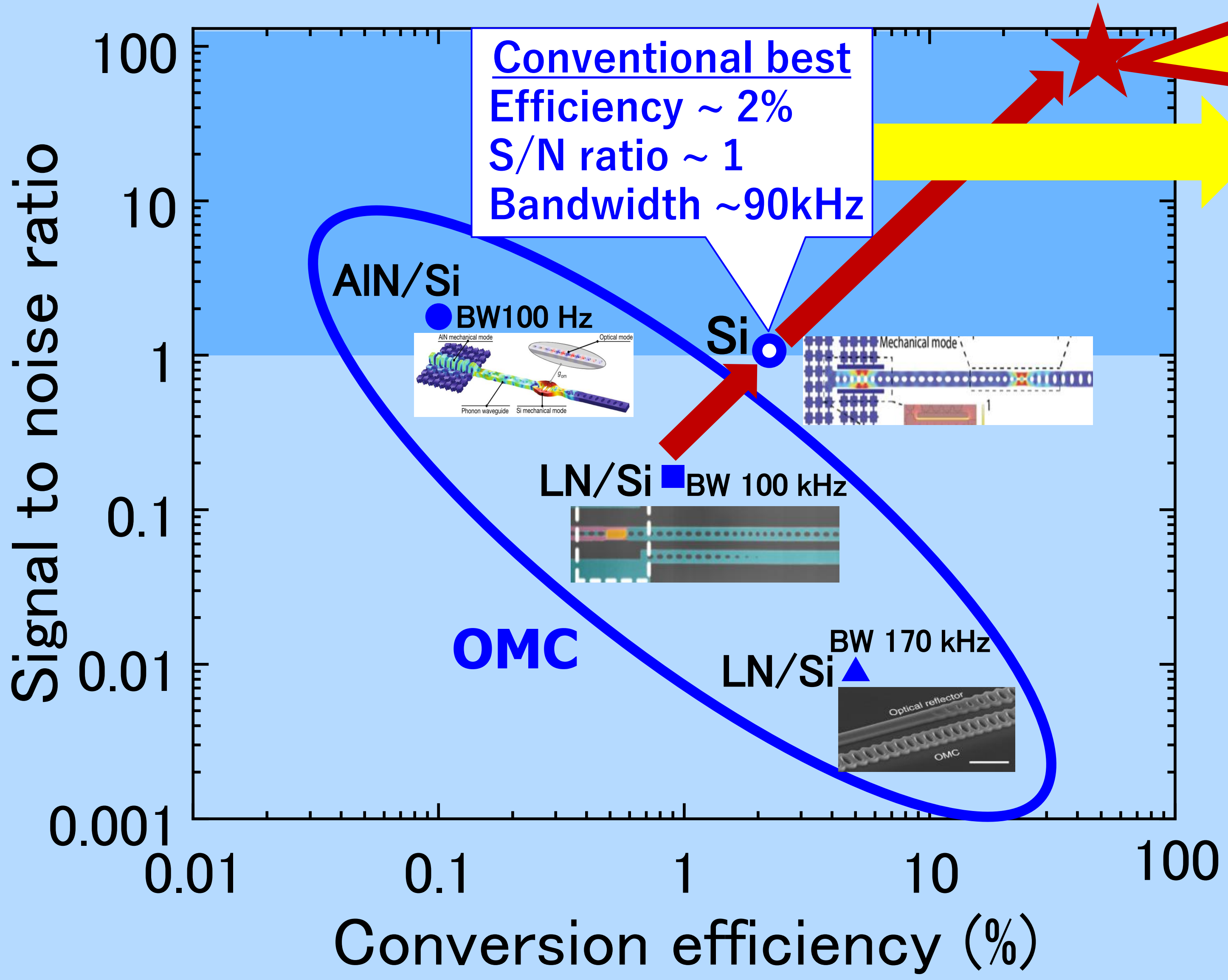
Optical Q = 14,000 @ 637 nm (NV)

Hanson/Groblacher (QuTech/QphoX)

APS meeting (2023)

SnV 737 nm

Advances in OMC Transducers

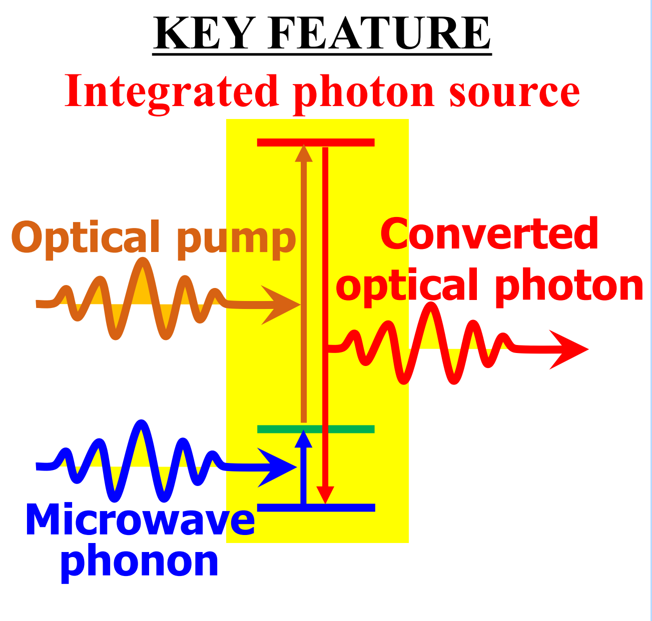


Emitter-integrated OMC in Diamond

Efficiency > 50% (x25 improve)

S/N ratio > 100 (x100 improve)

Bandwidth> 3 MHz (x30 improve)

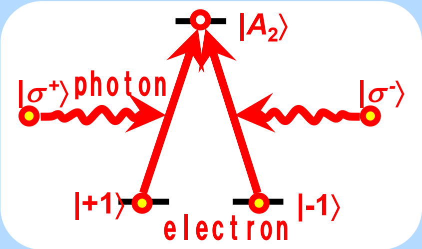


- ● Mirhosseini & **Painter**, Nature 588, 599 (2020)
- ▲ Jiang & **Naeini**, Nature Physics 19, 1423 (2023)
- ■ Weaver, **Groblacher** & Stockill, Nat. Nano. 19, 166 (2024)
- ○ Zhao & **Mirhosseini**, Nature Nano. 20, 602 (2025)

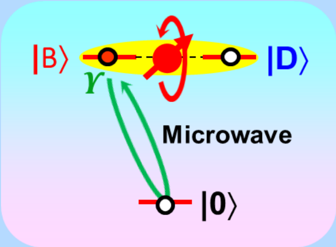
Negatively-charged NV^- center for Quantum Network

Long coherence time>0.1s, fast operation>400MHz→high fidelity>99.97%

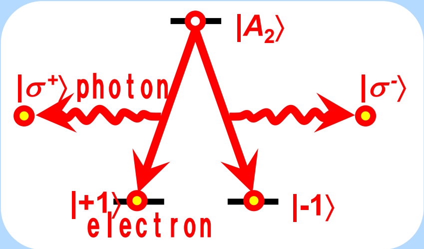
Under zero magnetic field at relatively high temperature (10K)



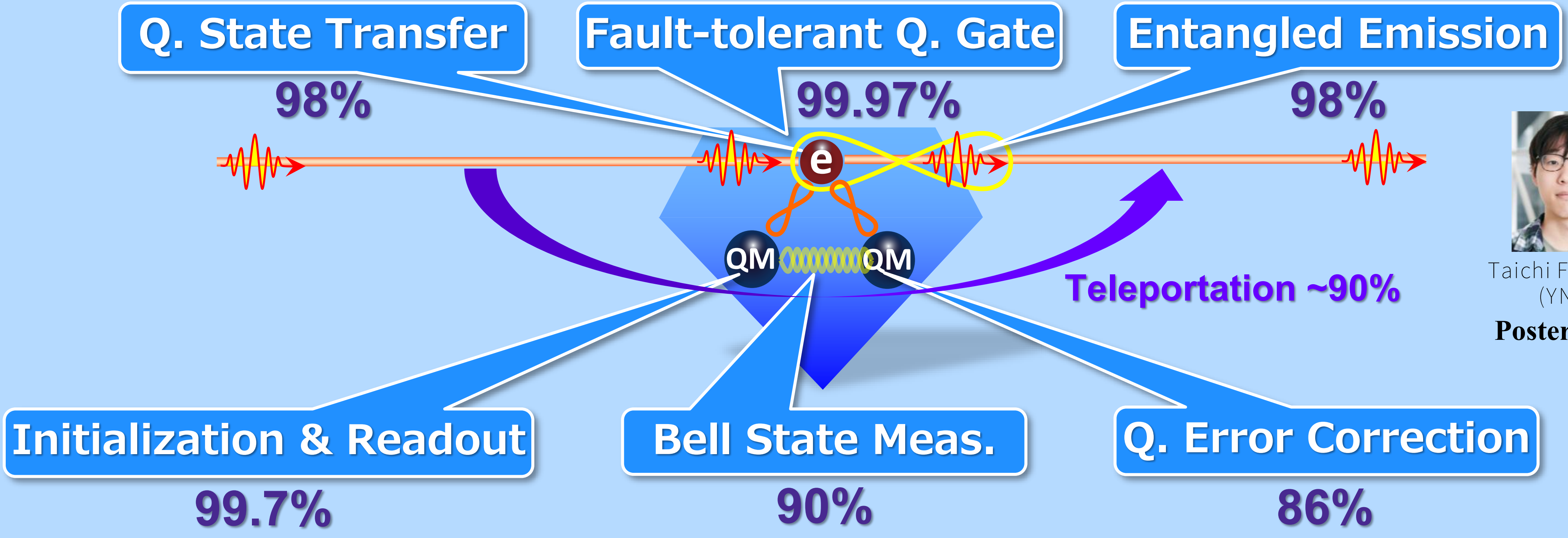
Physical Review Letters, 114, 053603 (2015)



Nature Communications, 7, 11668 (2016)



Communications Physics, 4, 264 (2021)



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

Appl. Phys. Lett. 120, 194002 (2022)
npj Quantum Information 9, 101 (2023)

Communications Physics 5, 102 (2022)

Taichi Fujiwara (YNU)

Yuhei Sekiguchi (YNU)

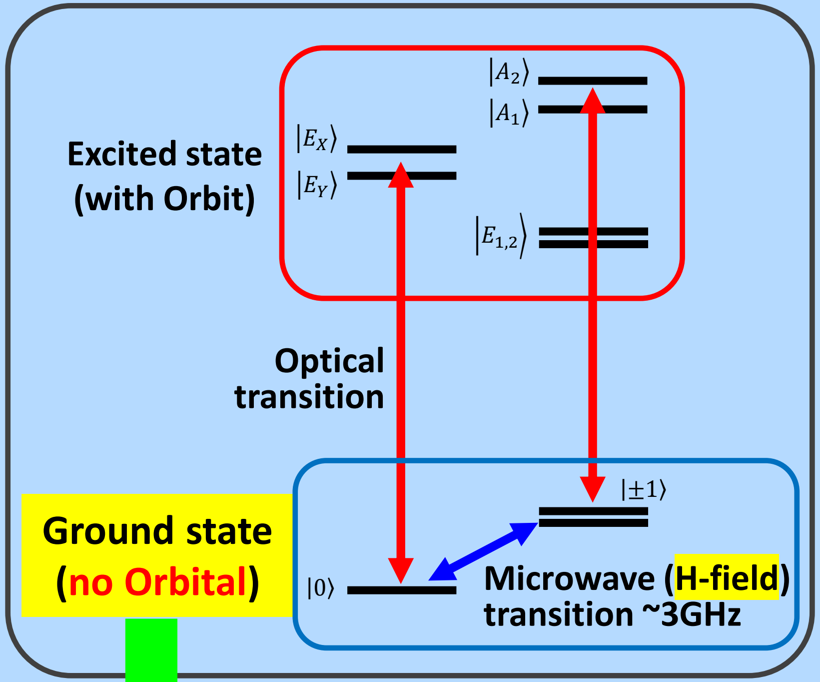
Poster PO-CP-033, QI2025

Partially supported
MIC
JPMI00316

Neutral NV^0 center for Quantum Transducer

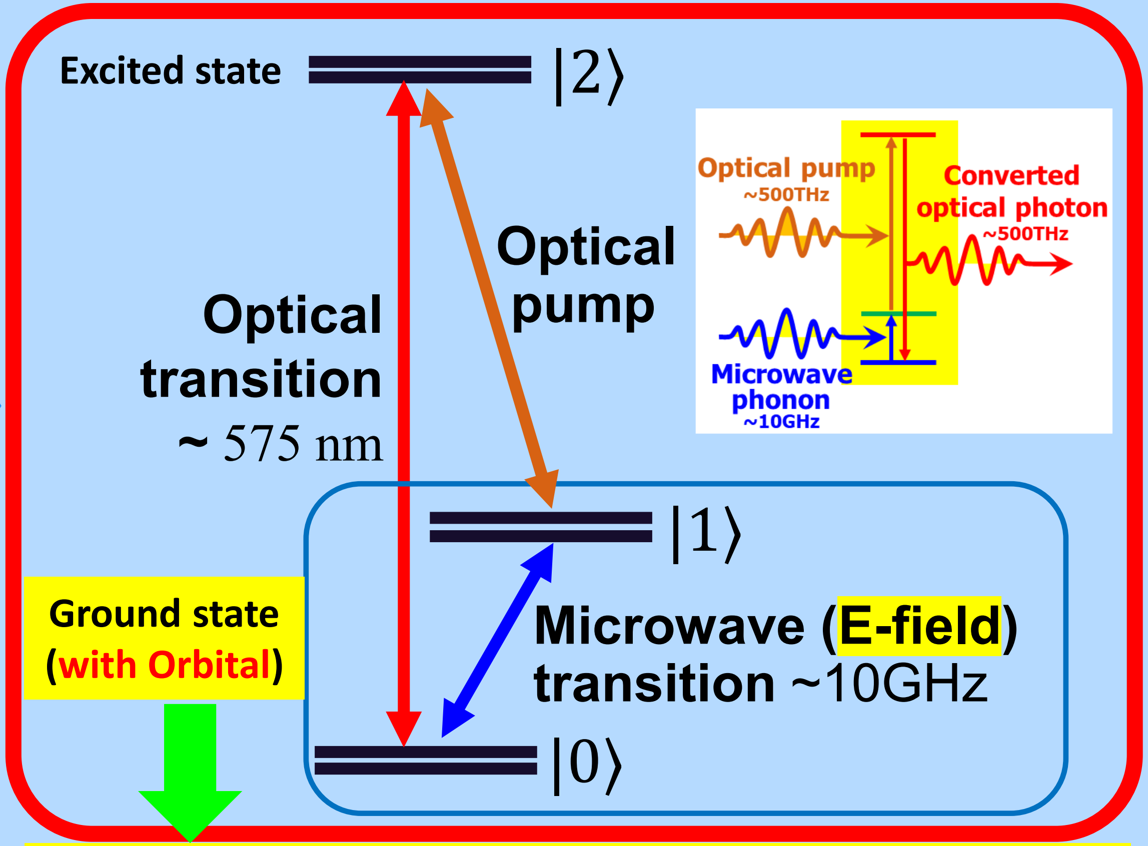
Hodaka Kurokawa (YNU)

Energy level structure of NV^-



New NV

Energy level structure of NV^0

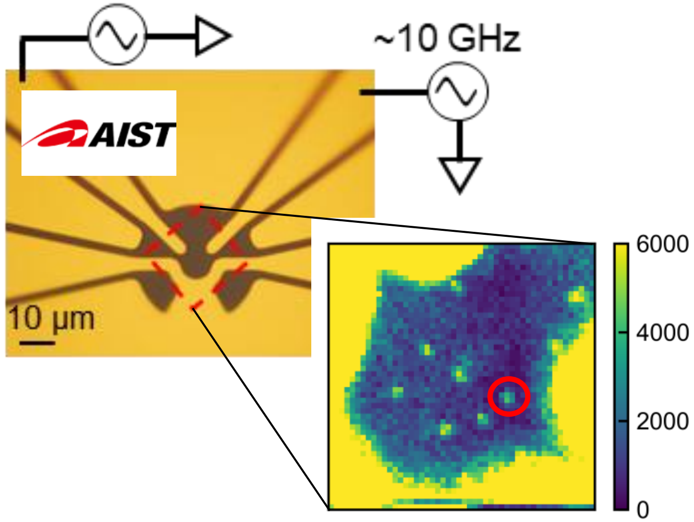


Insensitive to E-field

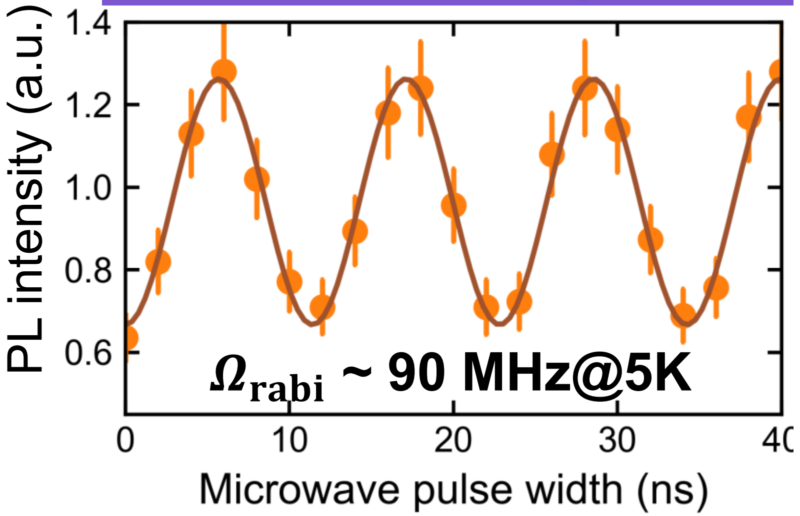
X 1000

Sensitive to E-field at B=0
~10 GHz ground state S-O splitting
Tunable by DC E-field

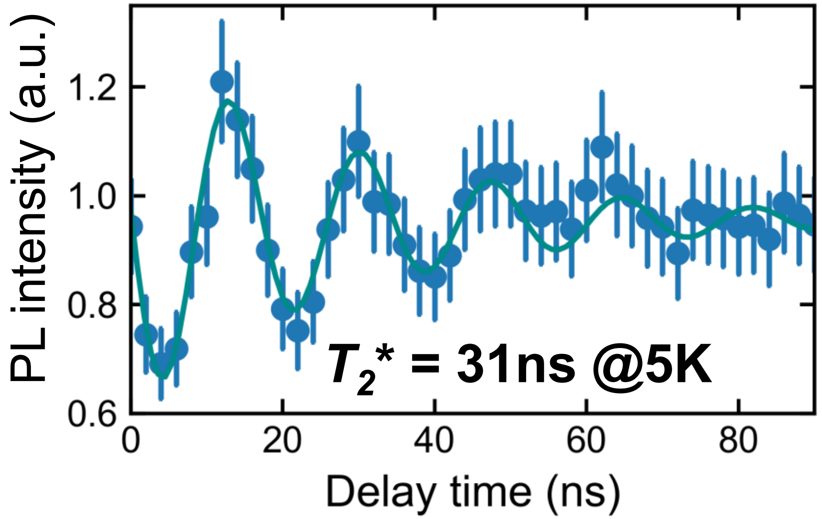
Coherent control of Neutral NV^0 center



Rabi oscillation by E-field

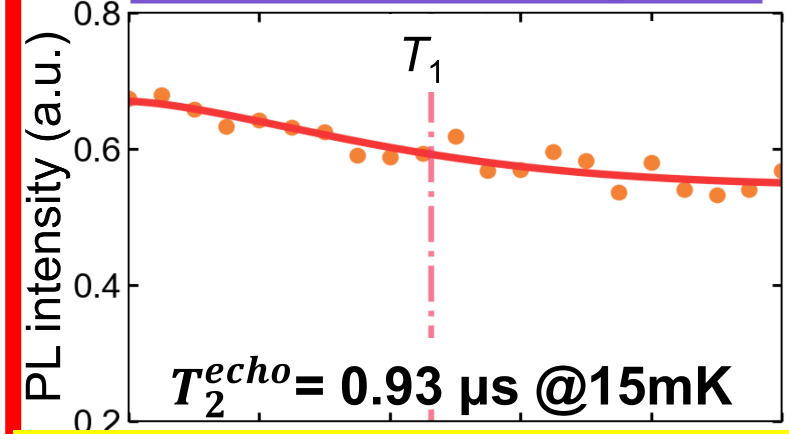


Ramsey interference (T_2^*)

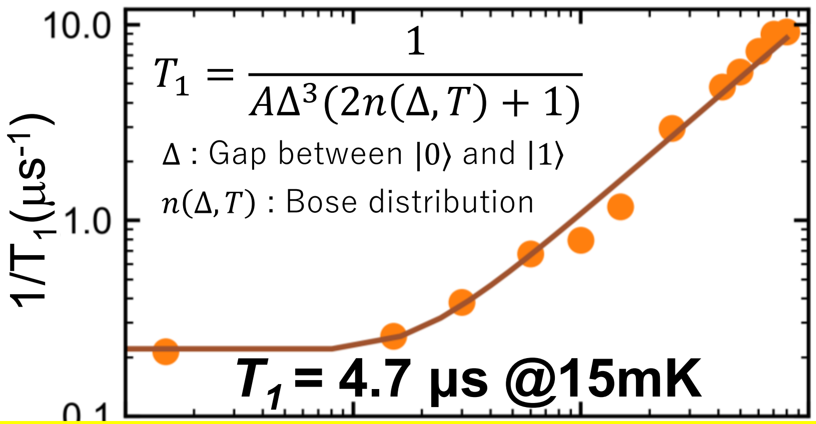


- ✓**E-field** control of orbital
  → **10^{-3}** power of H-field
- ✓T_2 ~1 μs
  → **30× longer** than T_2^*
- ✓T_1~5 μs

Hahn echo (T_2)



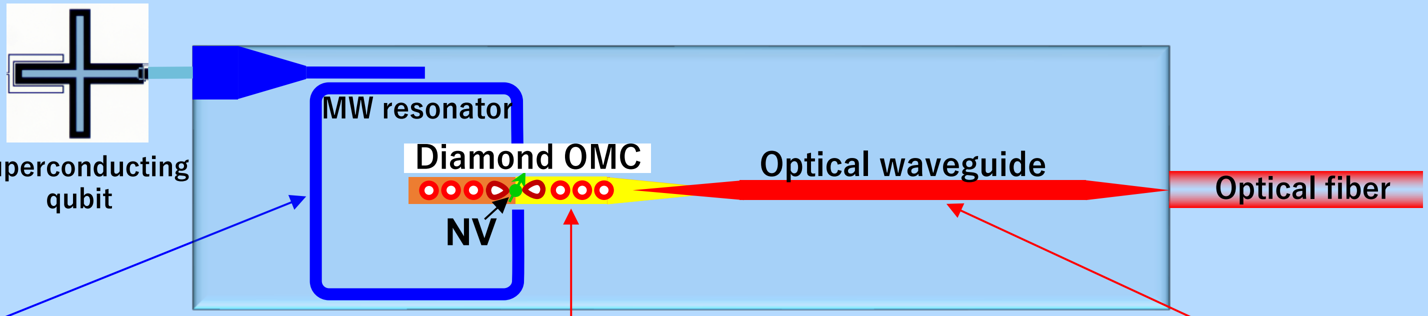
Relaxation time (T_1)



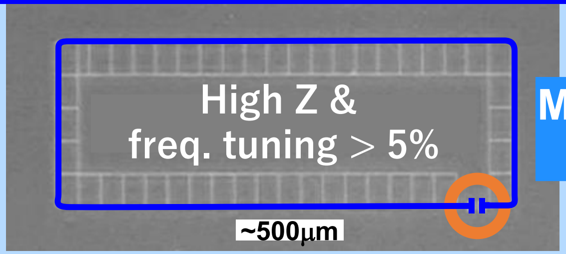
T_1 & T_2 are long enough for quantum transduction

Kurokawa&HK, Nature Communications 15, 4039 (2024) Kurokawa&HK, Phys. Rev. Lett. 135, 016902 (2025)

Core elements of Quantum Transducer



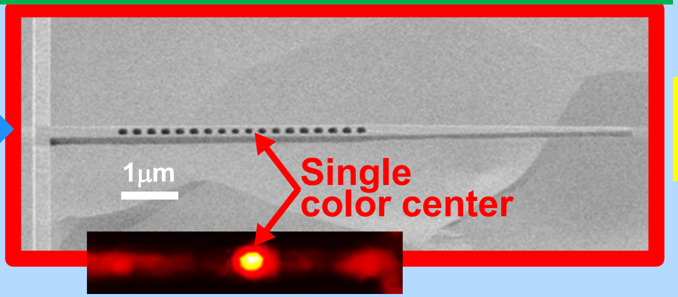
Superconducting Microwave Resonator



NbTiN Nanowire on Si

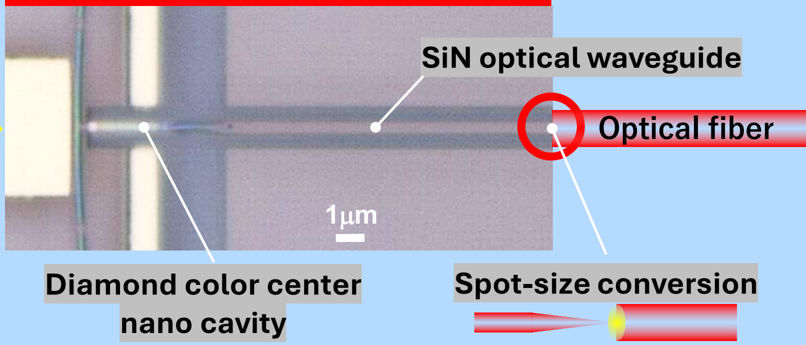
Microwave photon

Diamond Opto-Mechanical Crystal

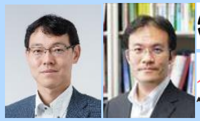


Optical photon

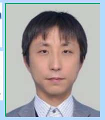
Silicon Nitride Optical Circuit



Hirotaka Terai



Satoshi Iwamoto Masahiro Nomura



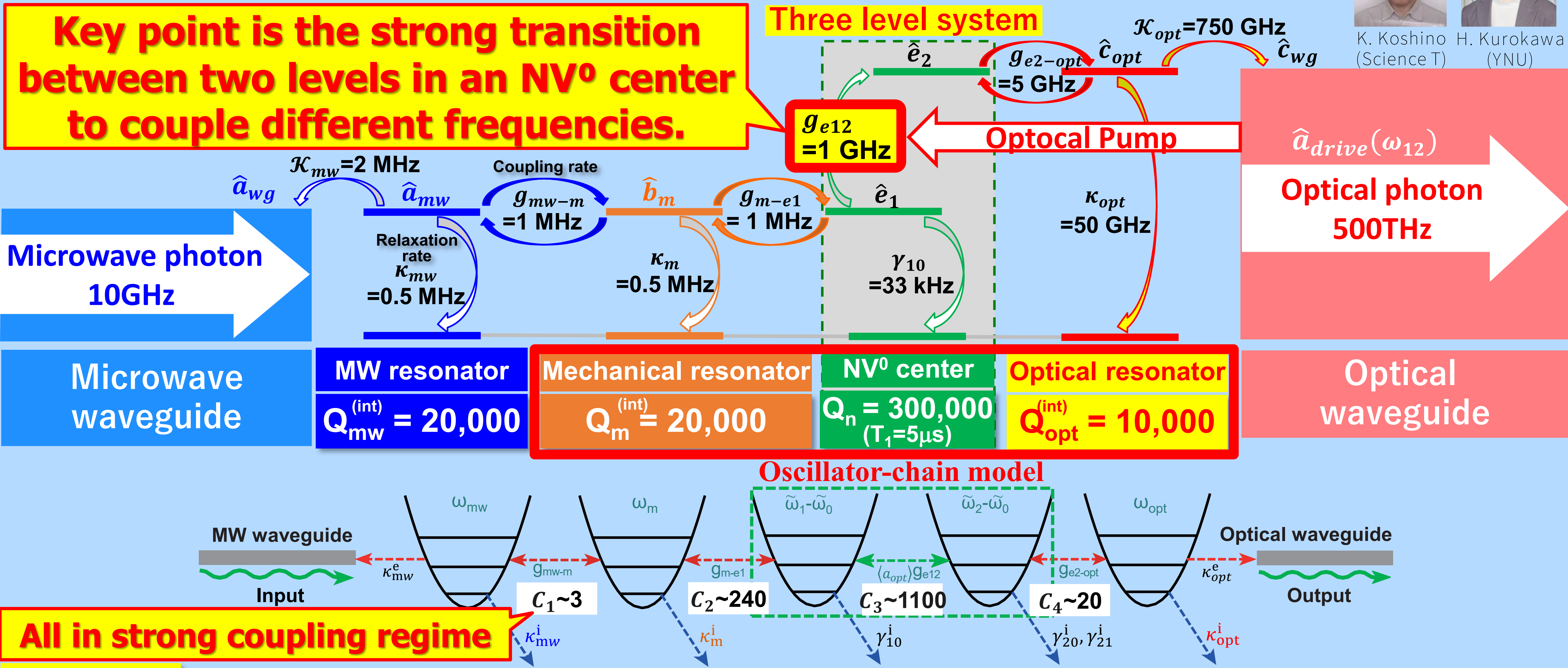
Shinobu Onoda

Toshihiko Baba

Core elements are ready for quantum transducer implementation.

Theoretical model and design

Key point is the strong transition between two levels in an NV⁰ center to couple different frequencies.



All in strong coupling regime

JC Model + Input-Output Theory

$$H_0 = \omega_{mw} a^\dagger a + \omega_m b^\dagger b + \omega_{e1} e_1{}^\dagger e_1 + \omega_{e2} e_2{}^\dagger e_2 + \omega_{opt} c^\dagger c$$

$$H_{int} = g_{mw-m}(a^\dagger b + b^\dagger a) + g_{m-e1}(b^\dagger e_1 + e_1{}^\dagger b) + g_{e2-opt}(e_2{}^\dagger c + c^\dagger e_2) + \langle a_{opt}\rangle g_{e12}(e_2{}^\dagger e_1 c + c^\dagger e_1{}^\dagger e_2) + \sqrt{\mathcal{K}_{mw}}(a^\dagger a_{wg} + a_{wg}{}^\dagger a) + \sqrt{\mathcal{K}_{opt}}(c^\dagger c_{wg} + c_{wg}{}^\dagger c)$$

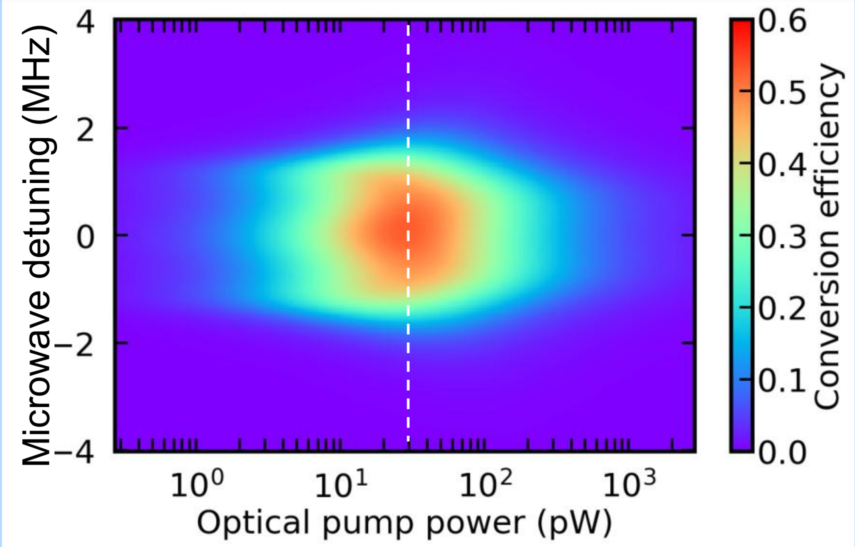
Estimation of Conversion Efficiency & Bandwidth

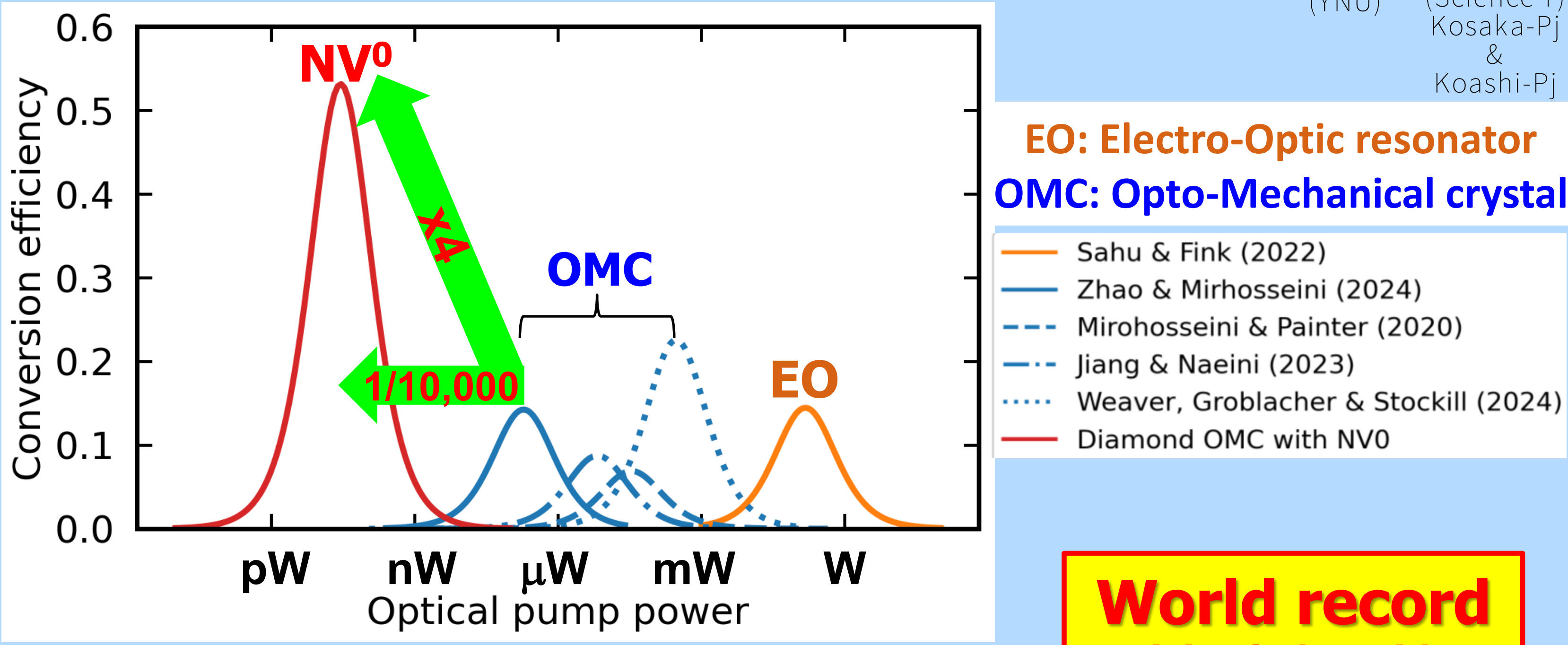

Poster PO-CP-022, QI2025

K. Goto (YNU)

K. Koshino (Science T) Kosaka-Pj & Koashi-Pj

Conversion Efficiency ~ 50% at pump power ~ 30 pW

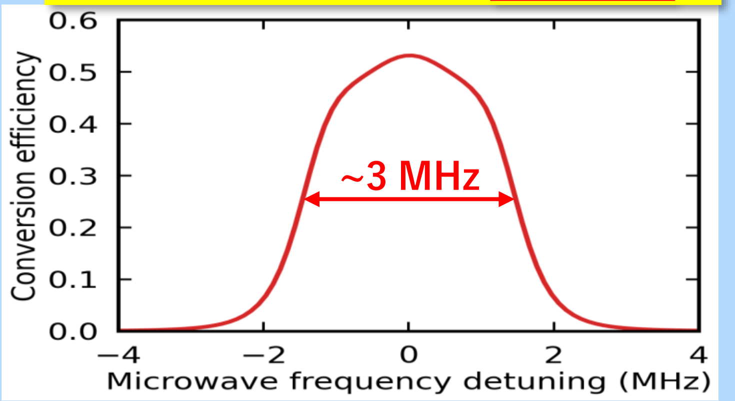




EO: Electro-Optic resonator

OMC: Opto-Mechanical crystal

Bandwidth ~ 3 MHz



World record
(Simulation with realistic parameters)

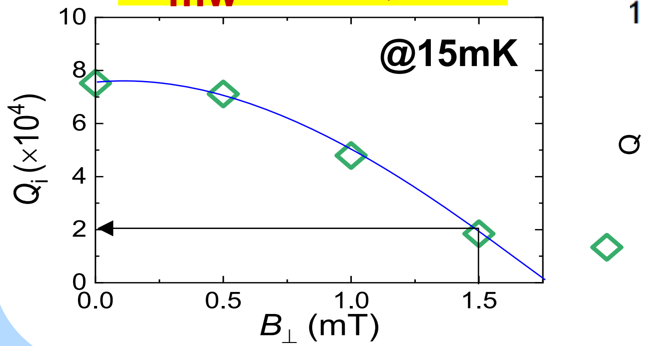
4× efficiency and 30× bandwidth with 1/10,000 pump power than the best OMC transducer

Performance of Core Elements

We successfully achieved the parameters used in the simulation through experiment.

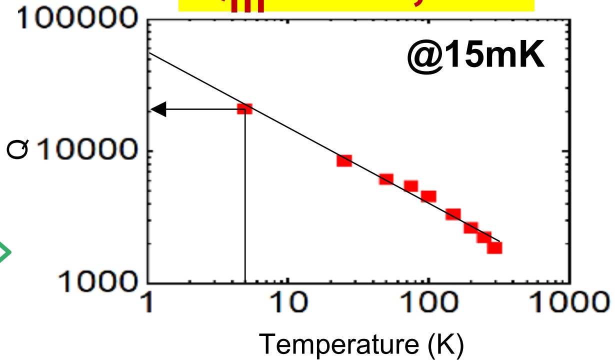
Microwave

Q_{mw} > 20,000



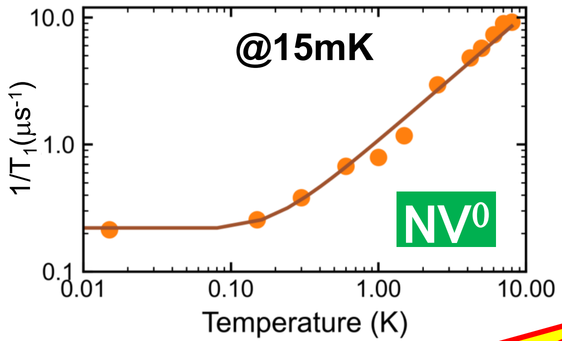
Mechanical

Q_m > 20,000



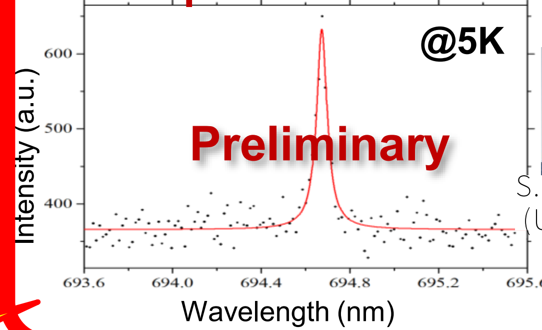
NV[0]

Q_n ~ 300,000 (T_1 ~ 5 μs)



Optical

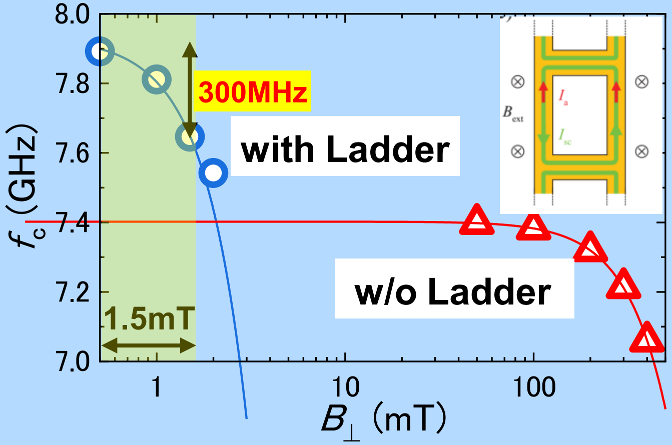
Q_{opt} ~ 10,000



S. Iwamoto (U. Tokyo)

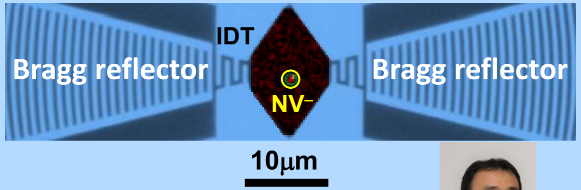
World record with Quasi-isotropic etching

Frequency tuning range

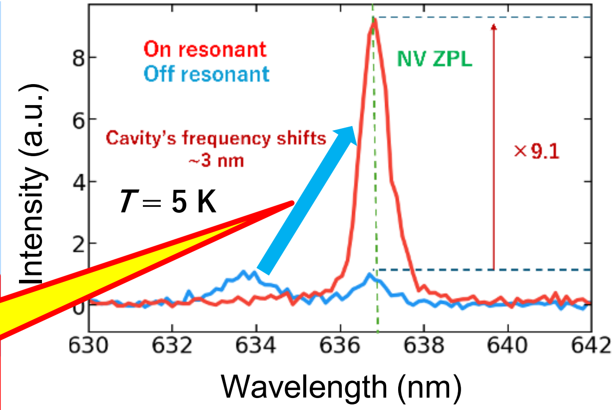


Diamond SAW

Q_m > 20,000 @5GHz



T. Makino (AIST)

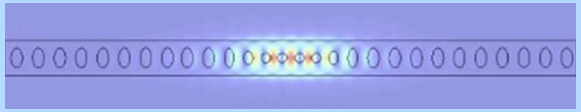


Purcel factor ~ 10 @Q=500

Diamond Phononic crystal

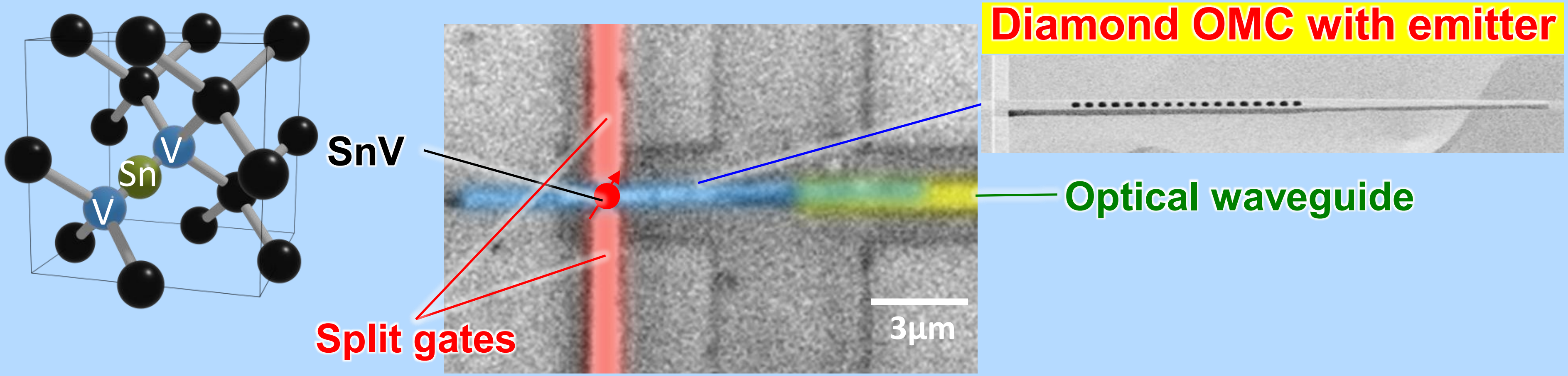
Compatible Structure

Diamond Photonic crystal



Demonstration of Quantum Transducer


Y. Sekiguchi (YNU)

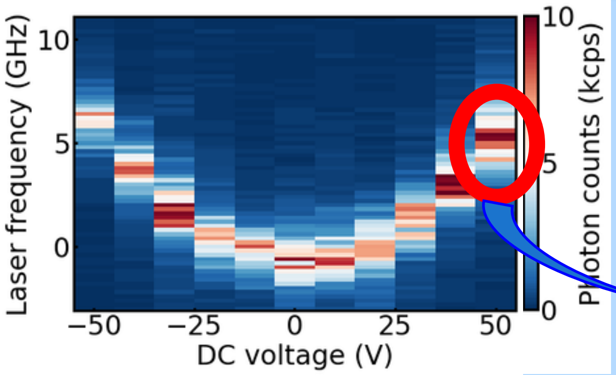



Satoshi Iwamoto (U. Tokyo)

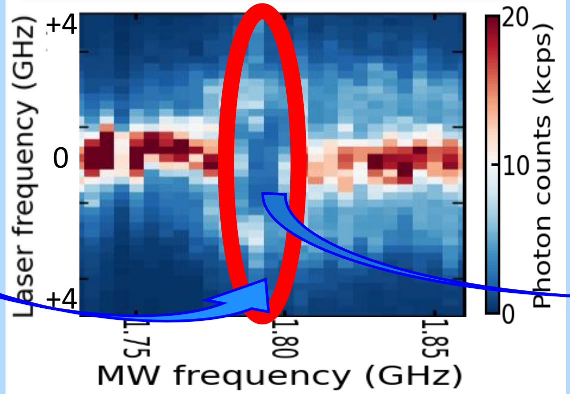
Phonon-mediated MW–optical photon conversion successfully demonstrated with emitter OMC.

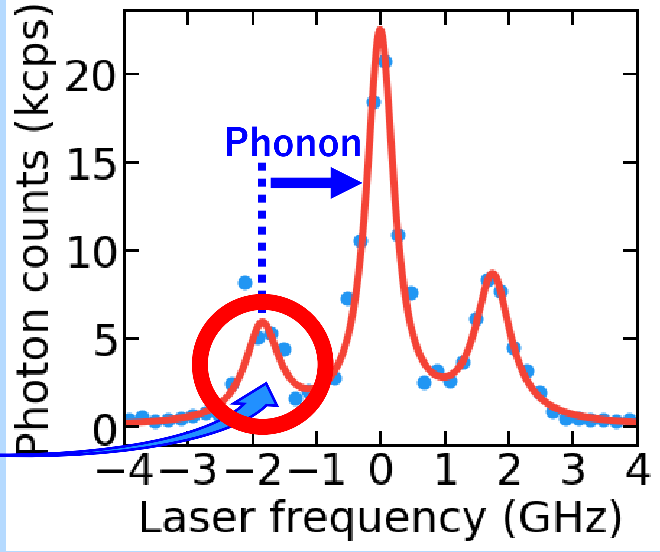
Quantum Coherence

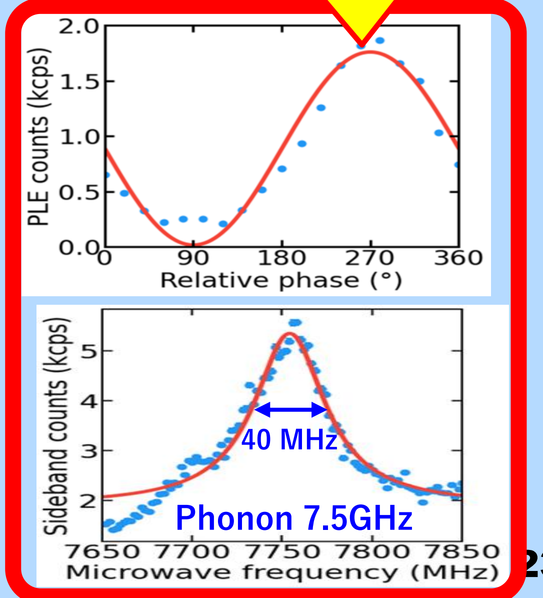
Optical transition frequency shifts with DC E-field



The frequency splits with DC + Microwave







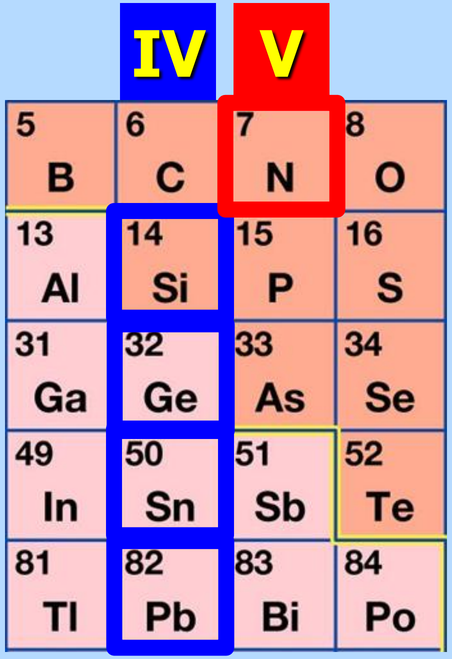
Reduction of Charge Fluctuation in Photonic Crystal

Yuhei Sekiguchi
(YNU)

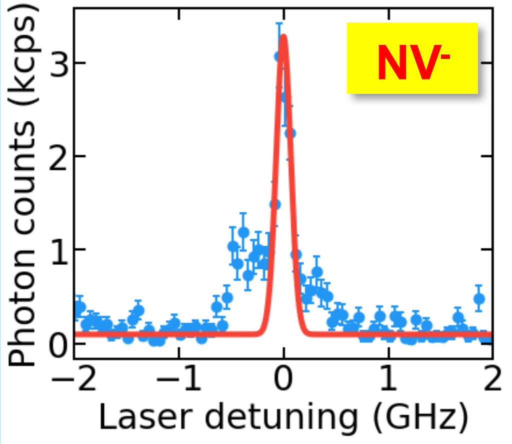
Conventionally
~5 GHz

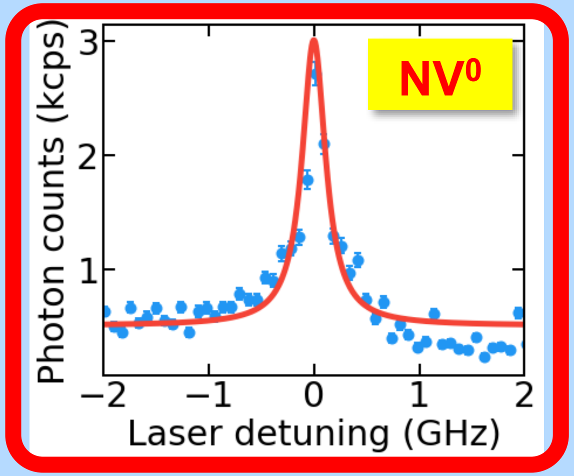
→ FWHM = 230 MHz
with Charge & Resonance check

FWHM ~ 270 MHz
with Charge & Resonance check

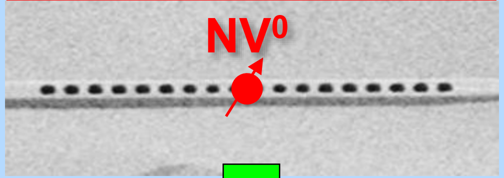


Group
V
(Asymmetric)





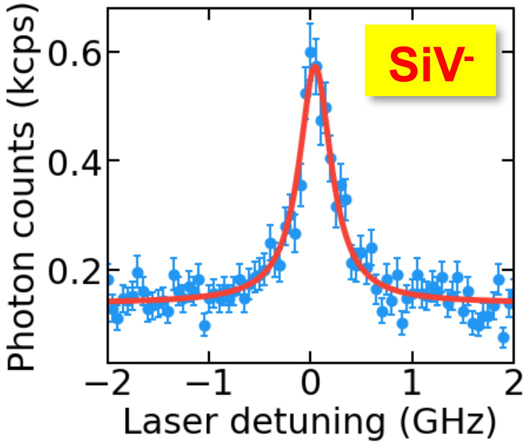
World record
for any color
center in PhC



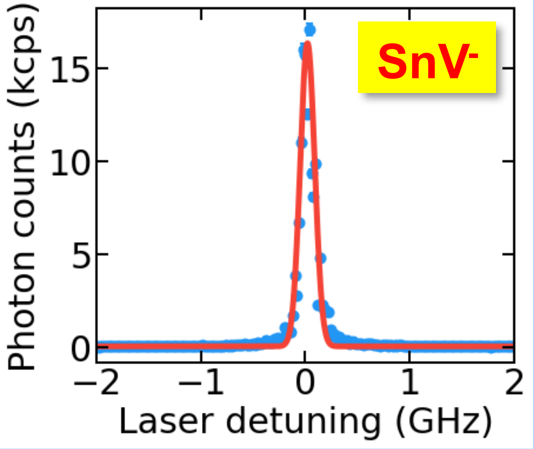
That of MW
transition should
be 5 ~ 50 MHz

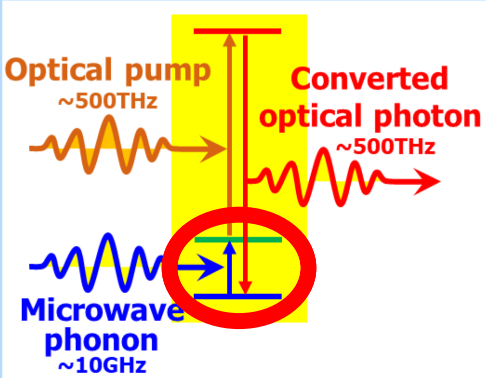
Group
IV
(Symmetric)

FWHM = 300 MHz



FWHM = 170 MHz





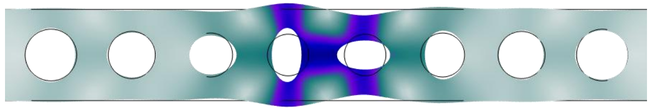
Charge fluctuation should not be a fatal obstacle.

Improvement of Diamond OMC

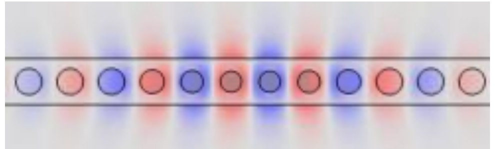
Masahiro Nomura (U. Tokyo)

Current Design → Improved Design

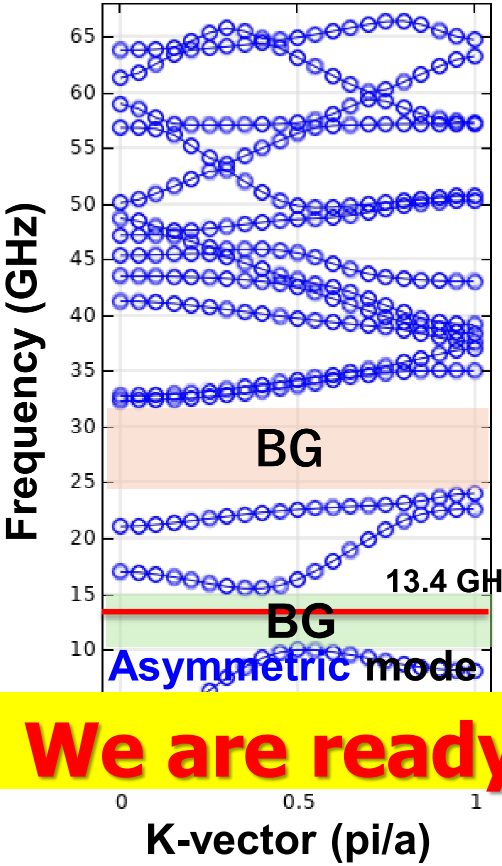
Current Design

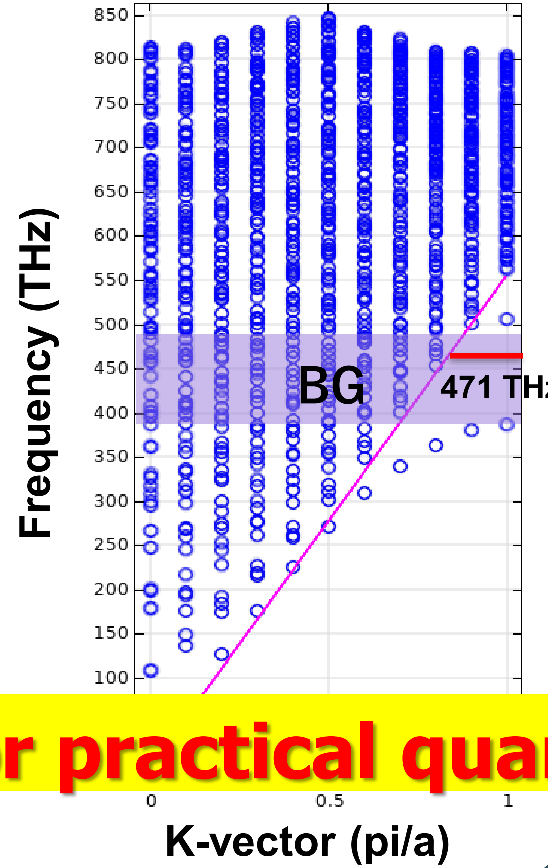


Mechanical mode
Q-factor: 30,000

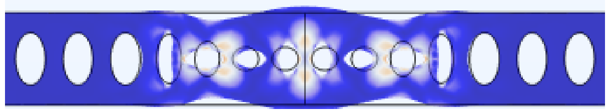


Optical mode (TE)
Q-factor: 6,200

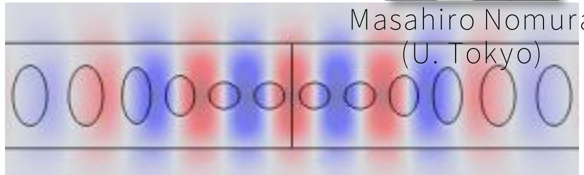




Improved Design



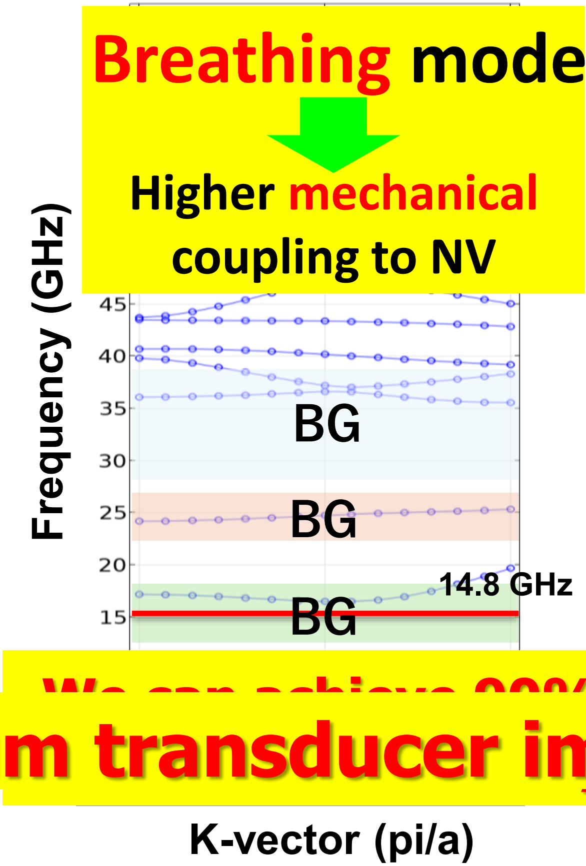
Mechanical mode
Q-factor: 8,000,000

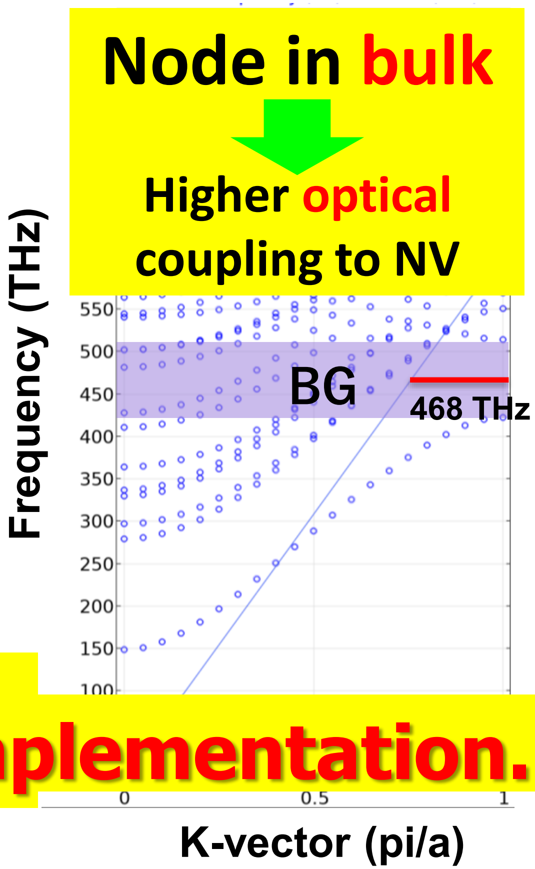


Optical mode (TE)
Q-factor: 10,000

Breathing mode
→ Higher mechanical coupling to NV

Node in bulk
→ Higher optical coupling to NV



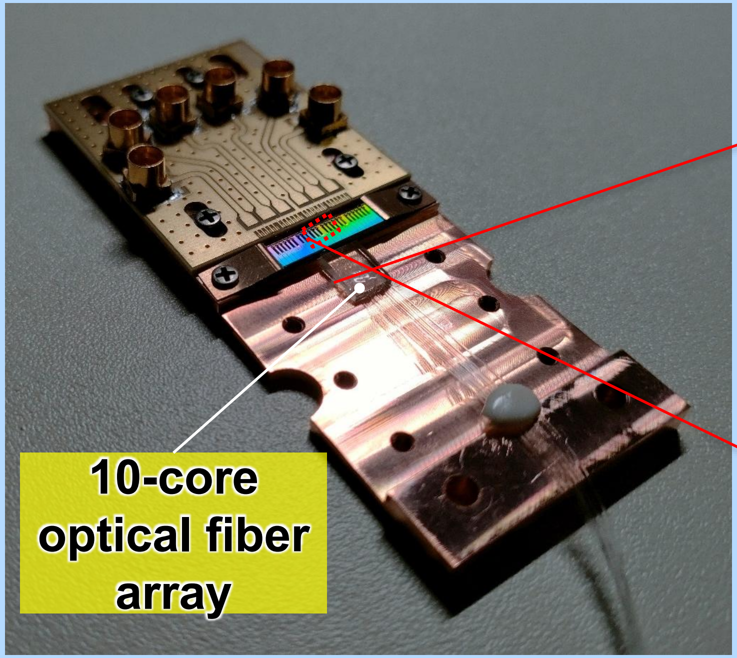


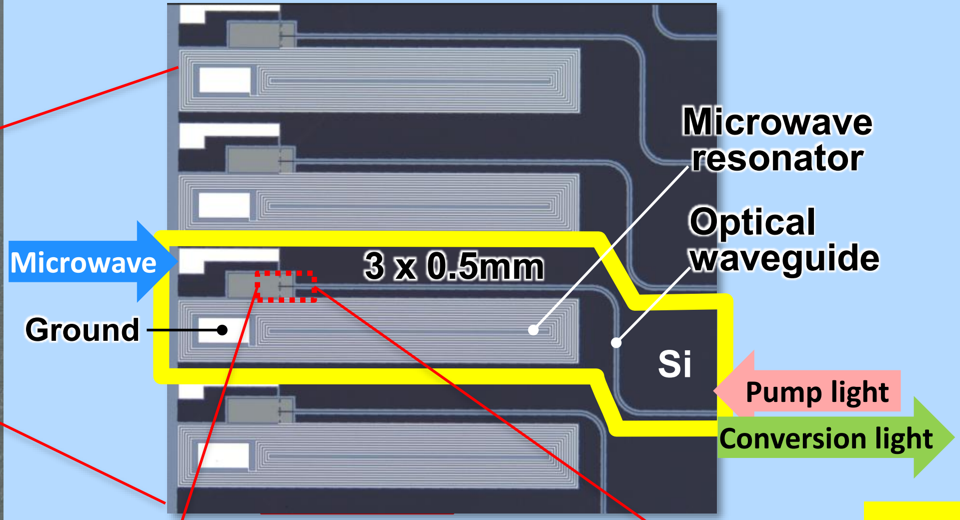
We are ready for practical quantum transducer implementation.

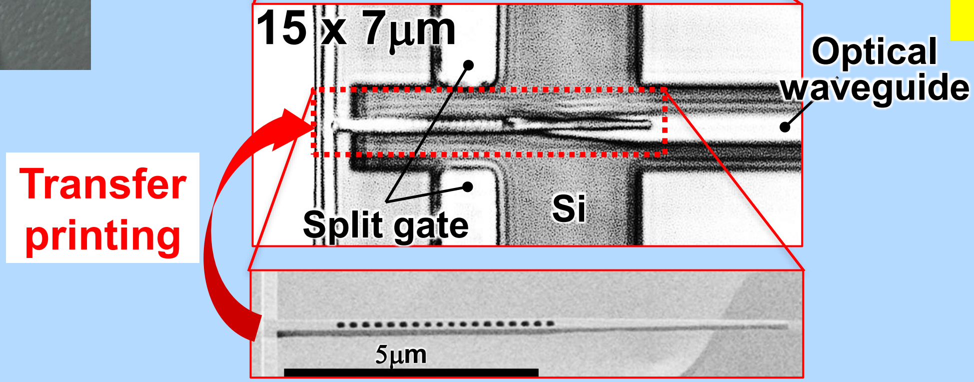
Quantum Chiplet Integration & Optical Fiber Coupling

We employ 3D packaging technologies.

MW resonator – OMC – Optical WG
Chip-let Integration



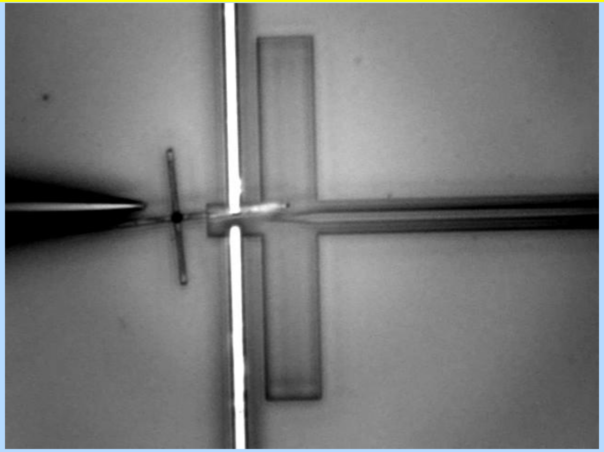




Diamond opto-mechanical crystal resonator with a color center

Optical waveguide coupling

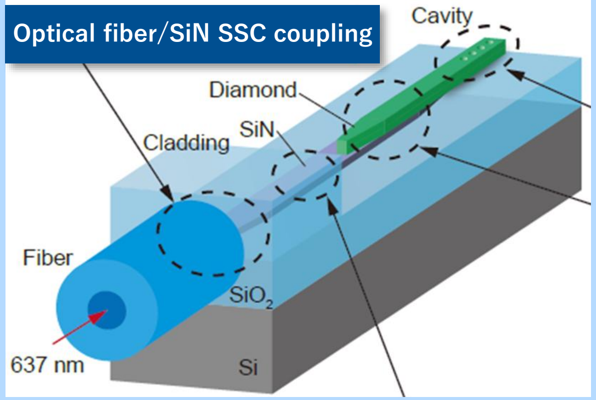
Optical resonator → Optical waveguide
Alignment accuracy <50 nm @95% (design)



Yuhei Sekiguchi (YNU)

Optical fiber coupling

Optical waveguide → Optical fiber
Coupling efficiency ~60% at RT



Toshihiko Baba (YNU)

Frequency Tuning of Individual Elements

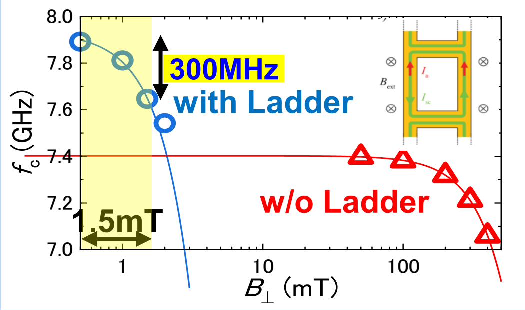
Hodaka Kurokawa
(YNU)

We can tune all the frequencies within the target accuracy.

Microwave — Mechanical — NV^0 — Optical

B field

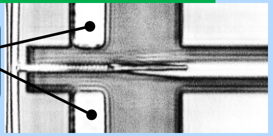
Tuning range: ~300 MHz
(Tuning tolerance ~5 MHz@25μT)



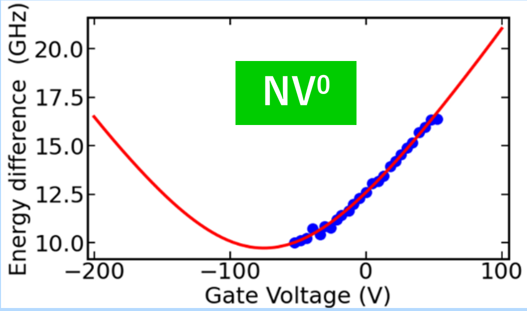
Fixed

No tunability
(synchronized with optical frequency)

E field

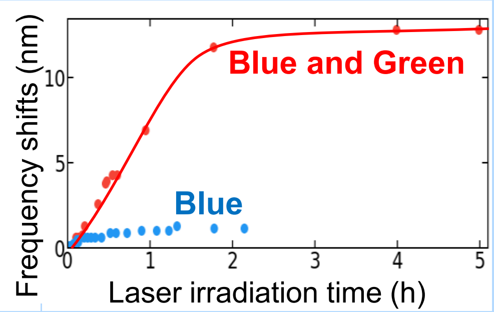


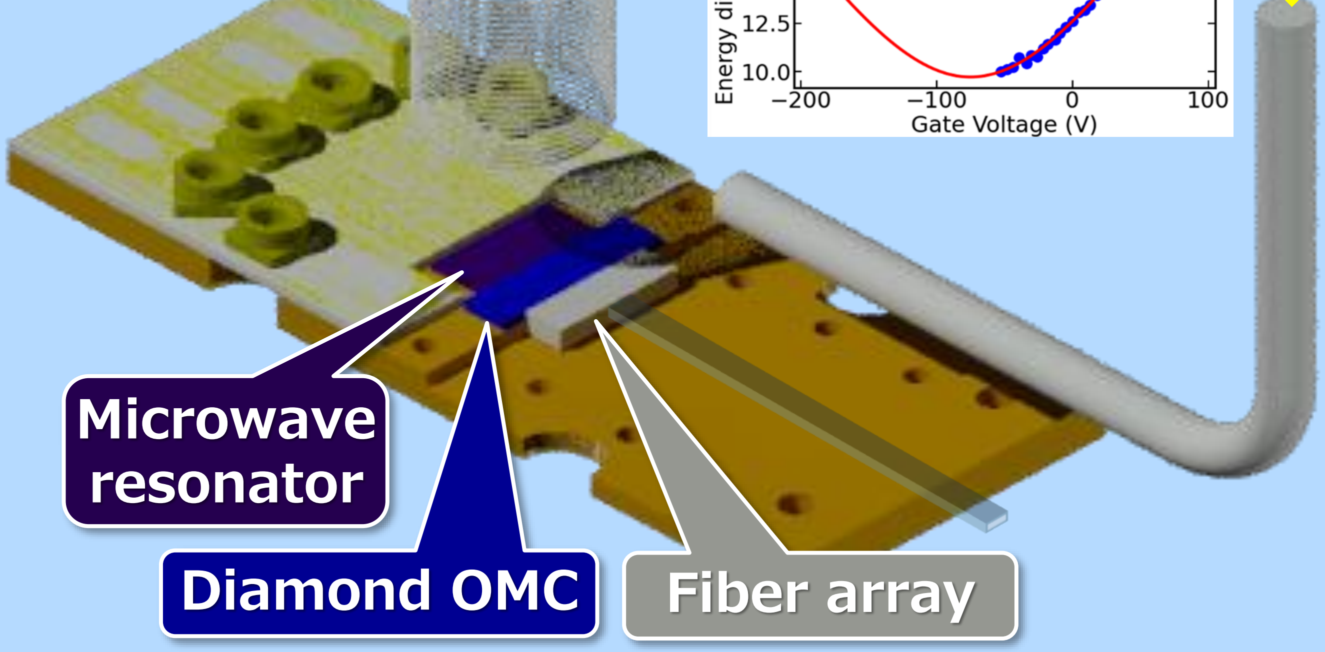
Range ~2 GHz
(Tolerance ~5 MHz@50μV)



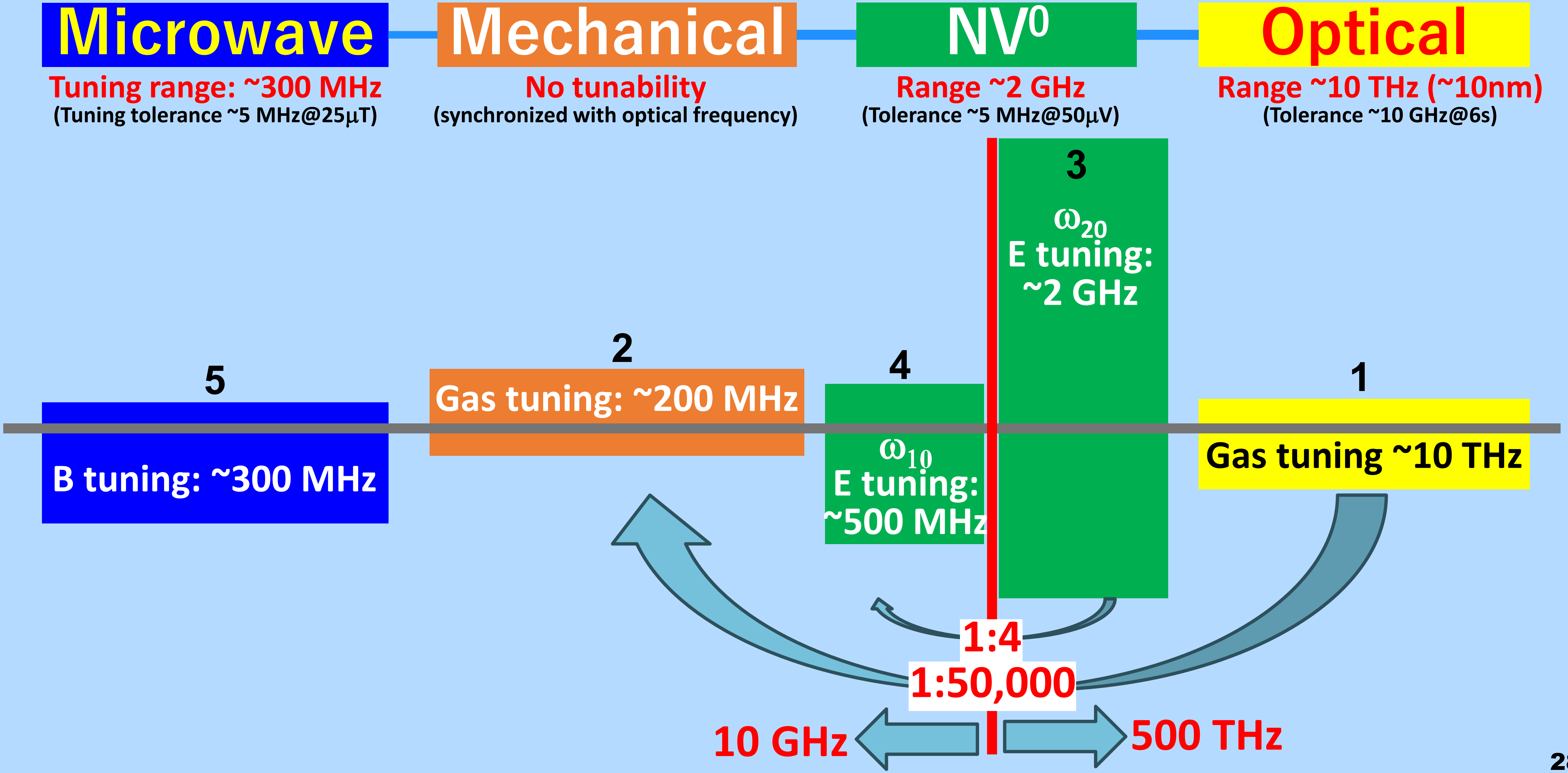
Gas

Range ~10 THz (~10nm)
(Tolerance ~10 GHz@6s)





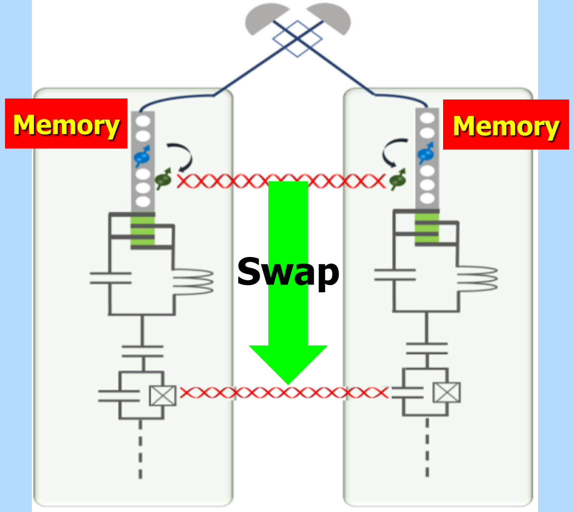
Strategy for Frequency Tuning

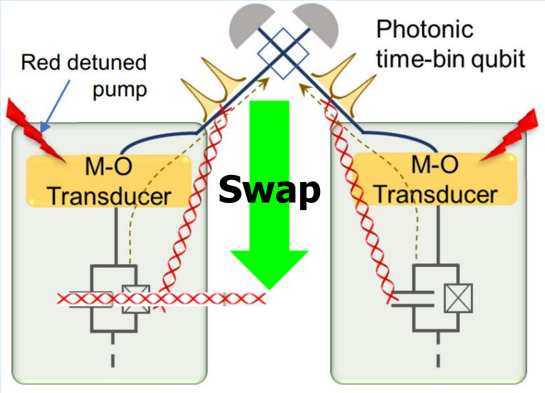


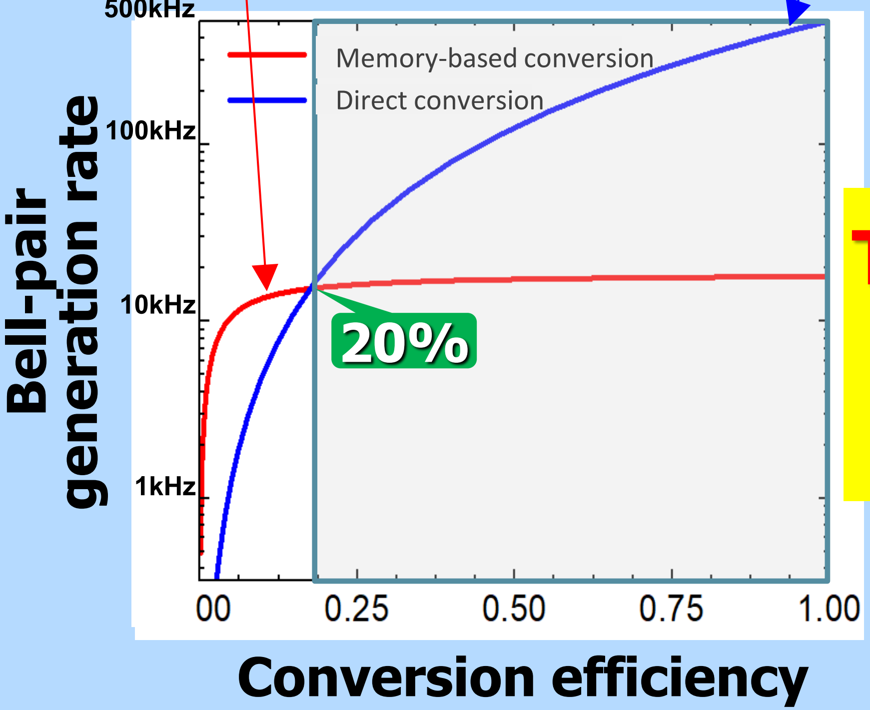
Estimation of Bell-pair Generation Rate between SC qubits

Memory-based conversion ~ 20 kHz

Direct conversion ~ 0.5 MHz

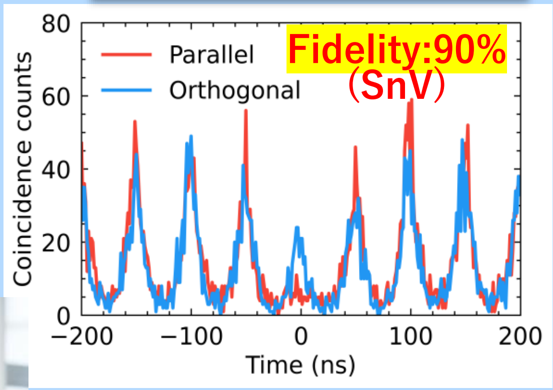






The Bell-pair generation rate can reach 3 MHz with Multiplexing.

HOM Interference



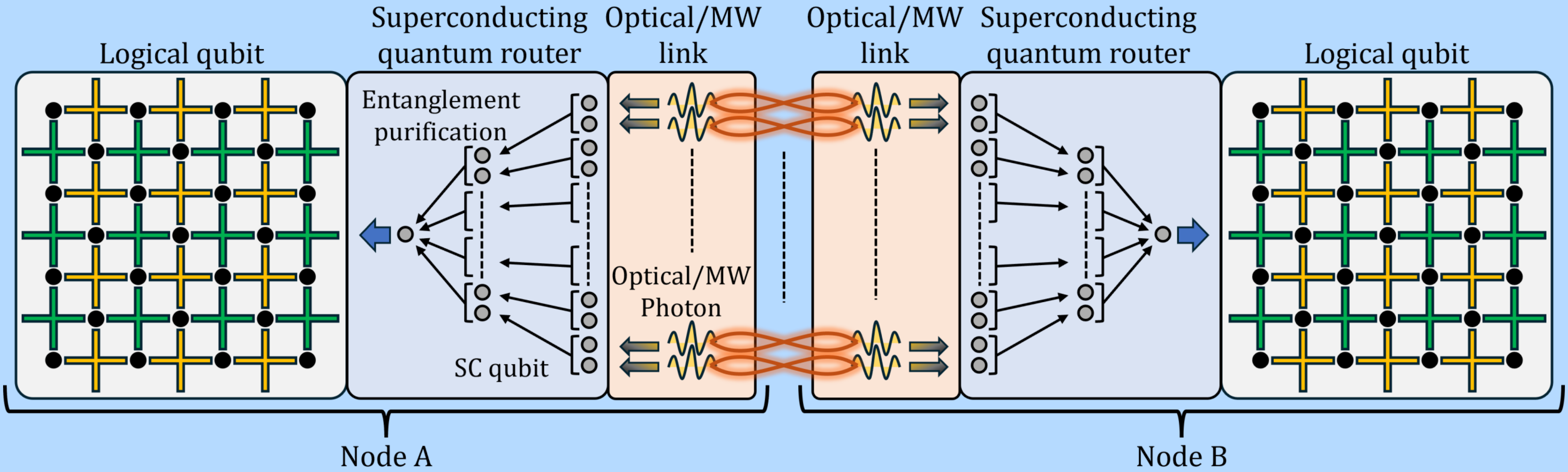
Yuhei Sekiguchi (YNU)

H. Kurokawa, M. Yamamoto, Y. Sekiguchi, and H. Kosaka, Phys. Rev. Applied 18, 064039 (2022).
B. Kim, H. Kurokawa, H. Kosaka, and M. Nomura, Phys. Rev. Applied 20, 044037 (2023).

Purified Bell-pair Generation Rate

Takumi Kobayashi
(YNU)

Yasunari Suzuki
(RIKEN)
Koashi-Pj



Poster PO-CP-034, QI2025

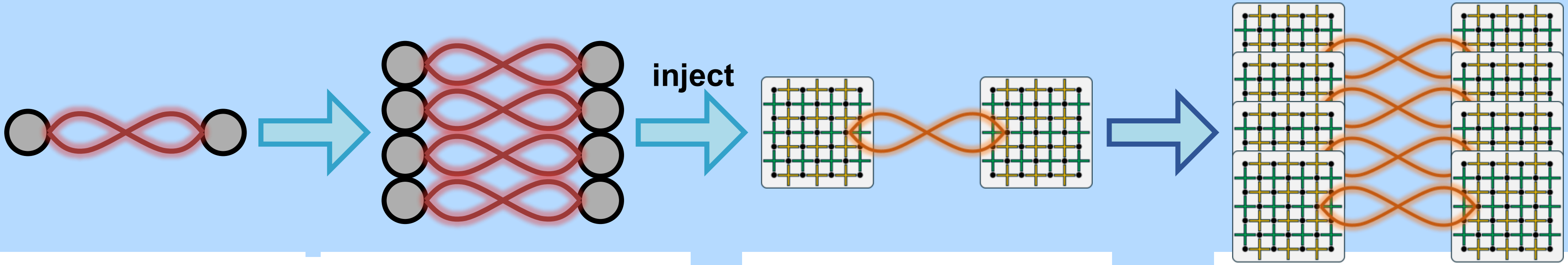
Estimates of entanglement generation rate and error rate in entanglement purification using superconducting quantum routers

○Takumi Kobayashi[A], Hodaka Kurokawa[B], Yasunari Suzuki[C], Hideo Kosaka[A,B]
Department of Physics, Graduate School of Engineering Science, Yokohama National University [A],
Quantum Information Research Center, Institute of Advanced Sciences, Yokohama National University [B],
RIKEN Center for Quantum Computing [C]

Purified Bell-pair Generation Rate

Takumi Kobayashi (YNU)

Yasunari Suzuki (RIKEN) Koashi-Pj



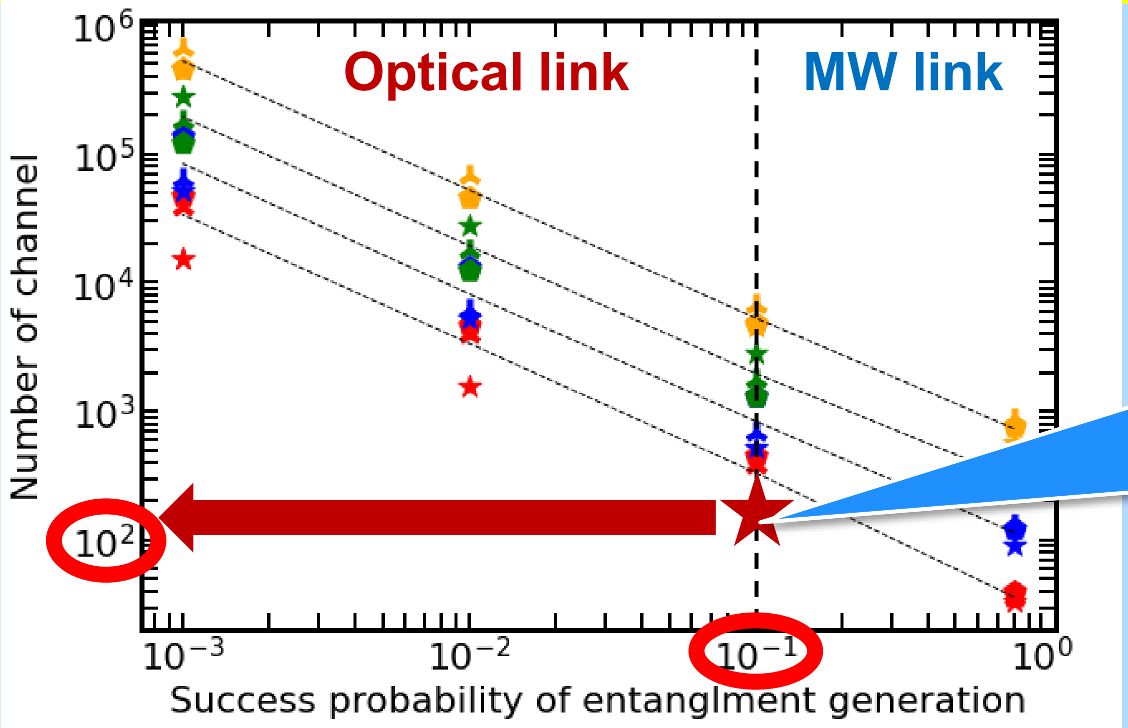
Physical Bell-pair Generation

Physical Bell-pair Distillation

Logical Bell-pair Generation

Logical Bell-pair Distillation

Number of channels required to achieve a purified Bell-pair generation rate of 1 MHz with >99% fidelity.



100 buffers are required for Bell-pair distillation

Assumptions

Trial rate of physical Bell-pair generation: 1 MHz

Probability of physical Bell-pair generation: 10%

Fidelities of
- physical Bell-pair: 95%
- two-qubit gate: 99.99%
- measurement: 100%
- single-qubit gate: 100%

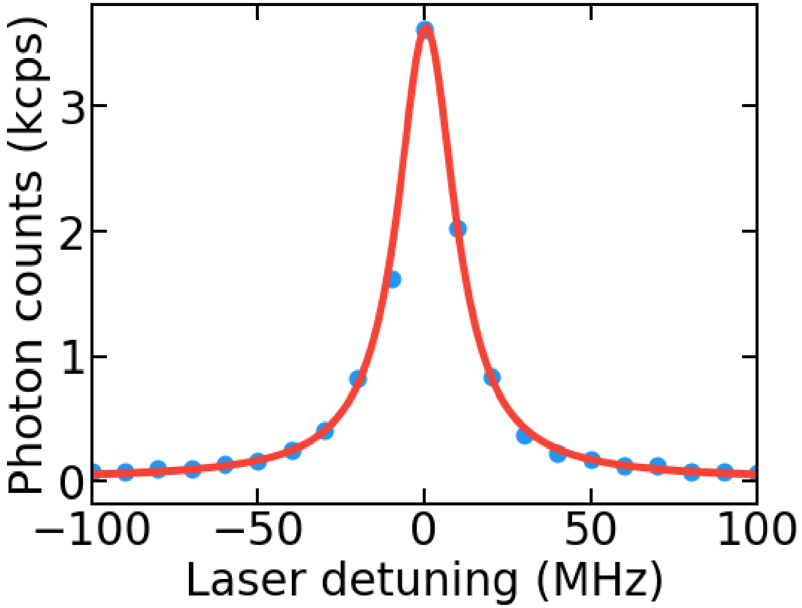
Super-pure Diamond Growth

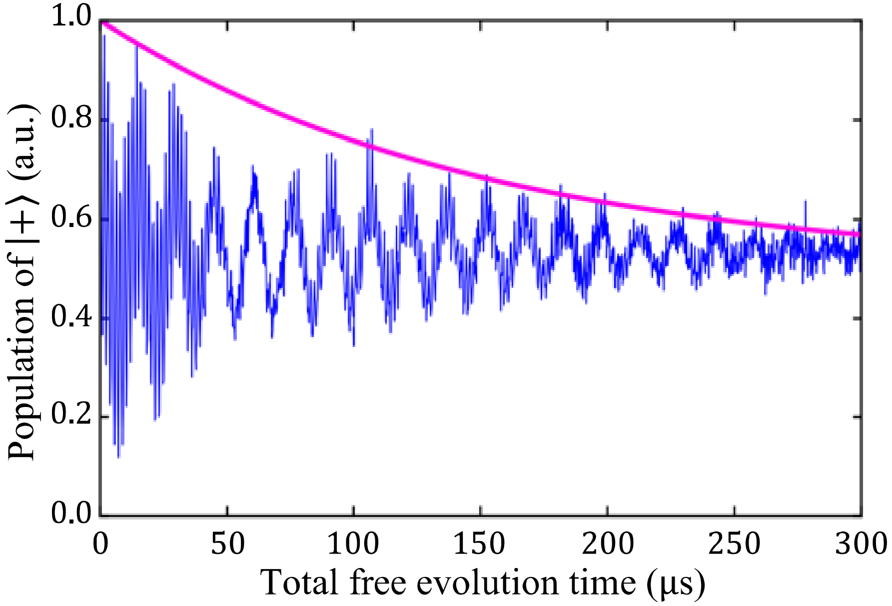
Tokuyuki Teraji (NIMS)

Nearly natural linewidth with material purity of 99.99999999%

\+

Long coherence time with isotropic purity of 99.998%





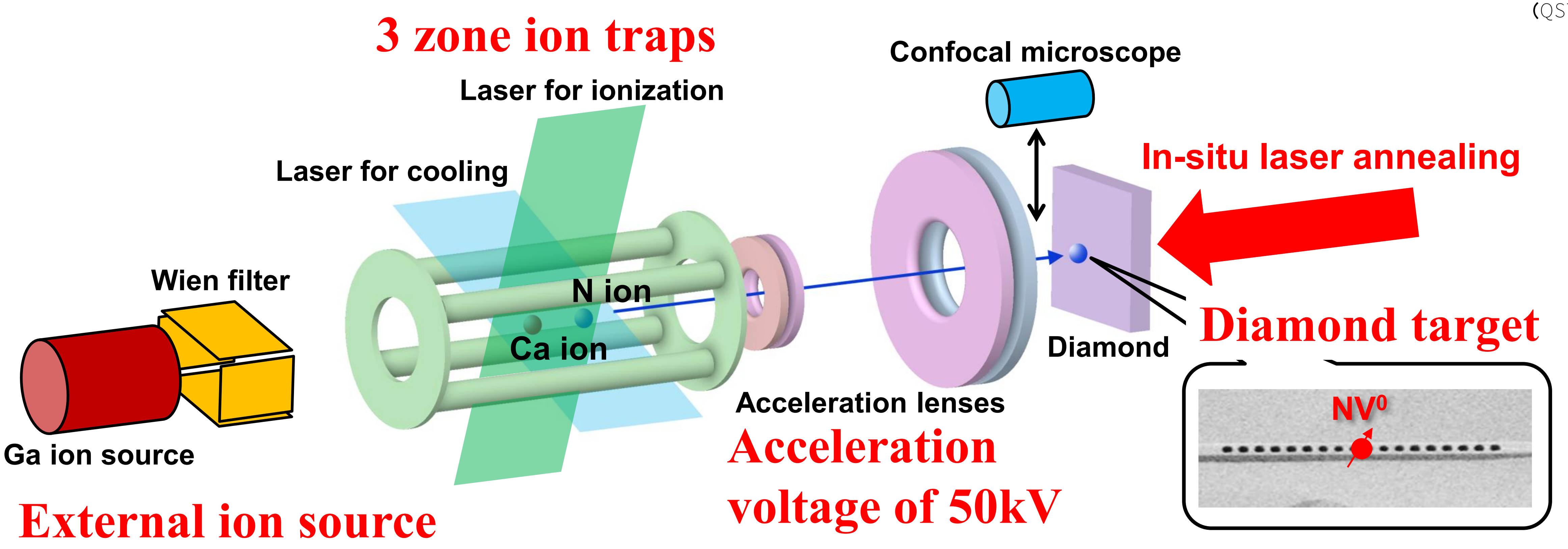
FWHM: 21 MHz

T_2^* : 150 μs、 T_2 : 1.5 ms

Sufficient purity of diamond growth for quantum transducers.

Super-resolution Ion implantation with Laser Cooling

Shinobu Onoda
(QST)



Sufficient accuracy of NV creation for quantum transducers.

Quantum Information Center (QIC)

Management

PM
Center Director
Hideo Kosaka

International collaboration
Assistant Professor
Anton Myalitsin

International PR
Adjunct Teaching Staff
Annelies Volders

IP Strategy
Intellectual Property Producer
Kinya Kumazawa

Management
Assistant Professor
Teruyuki Kinno

Japanese Universities

Professor
Toshihiko Baba

Professor
Nobuyuki Yoshikawa

Professor
Tomoyuki Horikiri

Professor
Daisuke Akamatsu

Professor
Akihiro Minamino

Associate Professor
Yoshiaki Nishijima

Associate Professor
Yuki Yamanashi

Associate Professor
Akira Ozawa

Associate Professor
Fumihiro Inoue

Associate Professor
Yoshihiro Shimazu

Assistant Professor
Yuhei Sekiguchi

Assistant Professor
Hodaka Kurokawa

Assistant Professor
Akira Kamimaki

Assistant Professor
Abdul Nasir Kuzhiyan Thadathil

Assistant Professor
Jowesh Avisheik Goundar

YNU YOKOHAMA National University

Center Vice Director
Satoshi Iwamoto
UTokyo

Visiting Professor
Masahiro Nomura
UTokyo

Visiting Associate Professor
Kazuki Koshino
Institute of SCIENCE TOKYO

National Institutes

Visiting Professor
Toshiharu Makino
AIST

Visiting Professor
Hiromitsu Kato
AIST

Visiting Professor
Tokuyuki Teraji
NIMS

Visiting Associate Professor
Shinobu Onoda
QST

Visiting Professor
Hirotaka Terai
NICT

Visiting Professor
Shigehito Miki
NICT

International

Visiting Professor
Fedor Jelezko
universität ulm

Visiting Professor
Christoph Becher
SAARLAND UNIVERSITY

Visiting Professor
Jonathan Finley
TUM

Visiting Professor
Kai Mueller
TUM

Company

Visiting Professor
Yu Mimura
FURUKAWA ELECTRIC

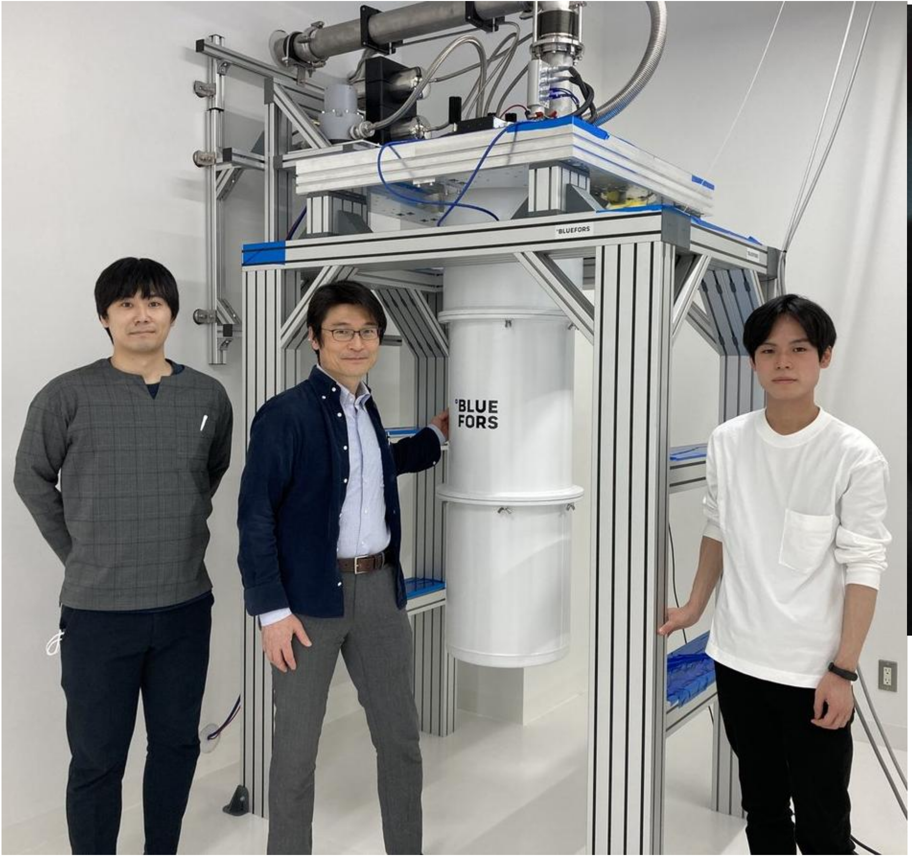
Visiting Associate Professor
Mamiko Kujiraoka
TOSHIBA

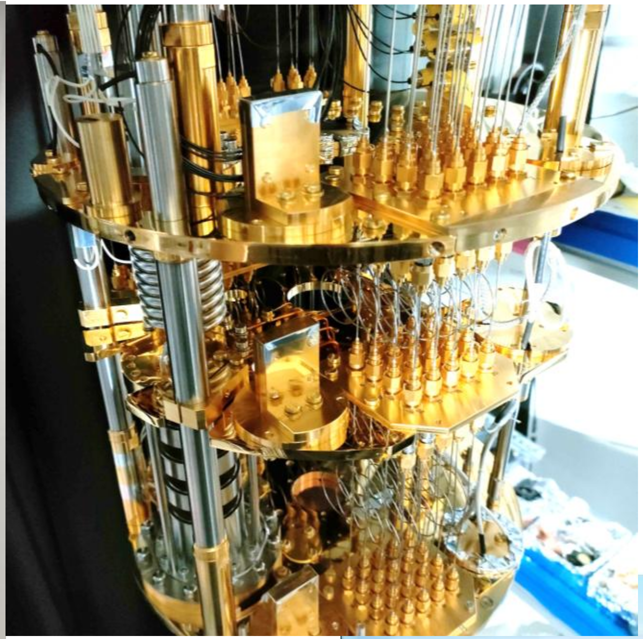
Partnership

UTokyo-IIS
RIKEN
QST
universität ulm
University of Stuttgart
Germany

Joint Research

NICT
FURUKAWA ELECTRIC
QuTech





https://youtu.be/83ux1NhPbSw

QIC Research Video Featured
at the APS Global Physics Summit 2025

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

https://moonshot.ynu.ac.jp/en/index.html

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

QiC
量子情報研究センター
Quantum Information Research Center

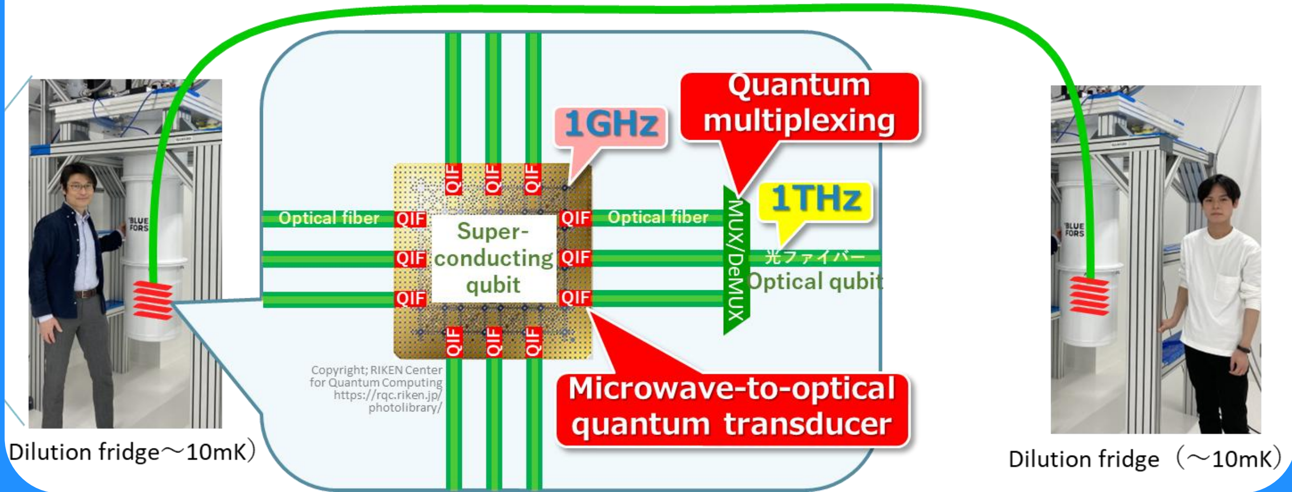
kosaka laboratory

https://kosaka-lab.ynu.ac.jp/publications/papers/

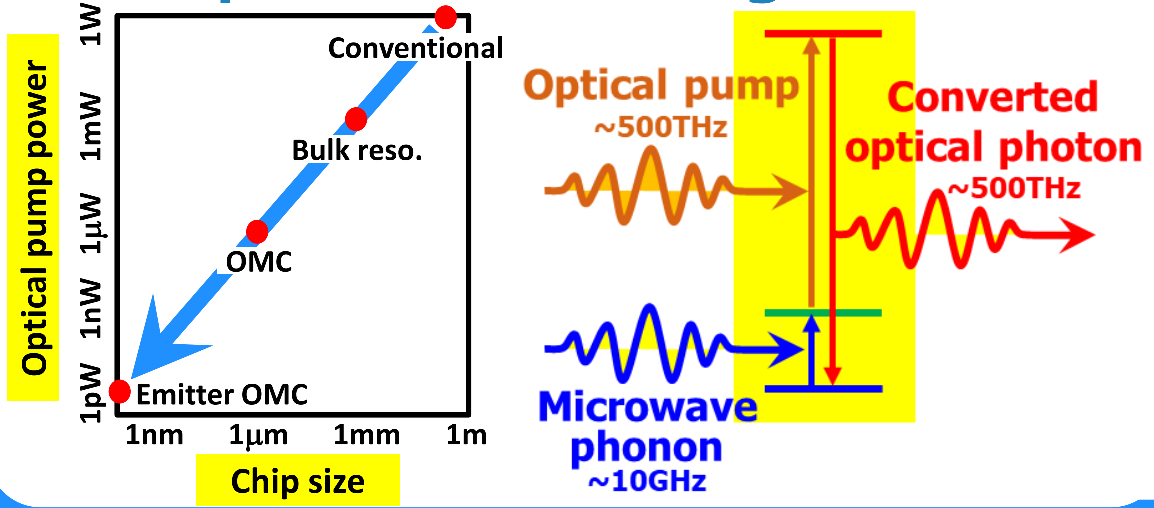
https://twitter.com/kosaka_lab_YNU

Summary

Purpose: Optical interconnect



Concept: Emitter-integrated OMC

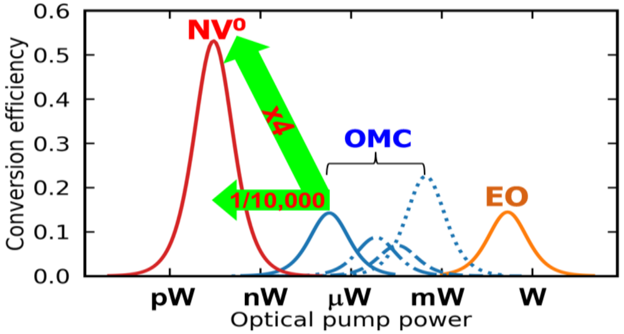


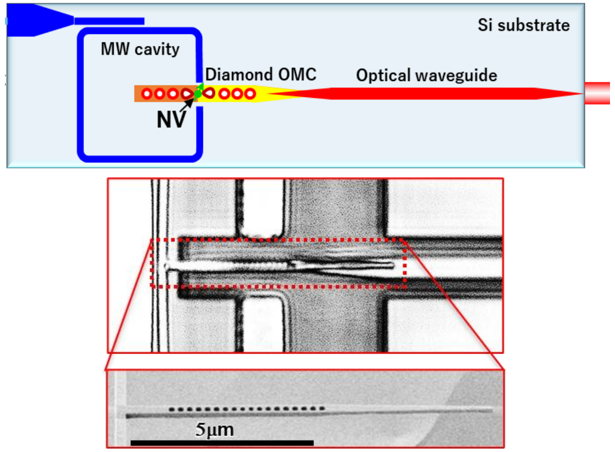
Status: Core Elements are ready to build up

Microwave — Mechanical — NV^0 — Optical

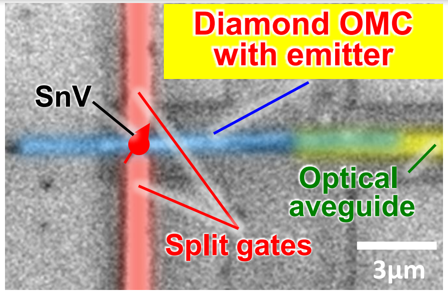
$Q_{mw} > 20,000$ | $Q_m > 20,000$ | $Q_n \sim 300,000$ | $Q_{opt} \sim 10,000$

Efficient and Broad BW with Low Pump Power





MW-optical photon coherent conversion



Towards Distributed Quantum Computing