

Quantum Innovation 2025

August 2, 2025@Osaka, Japan



JPMJMS2062

Moonshot goal 6: Fault-tolerant quantum computer

Development of Quantum Interfaces for Building Quantum Computer Networks

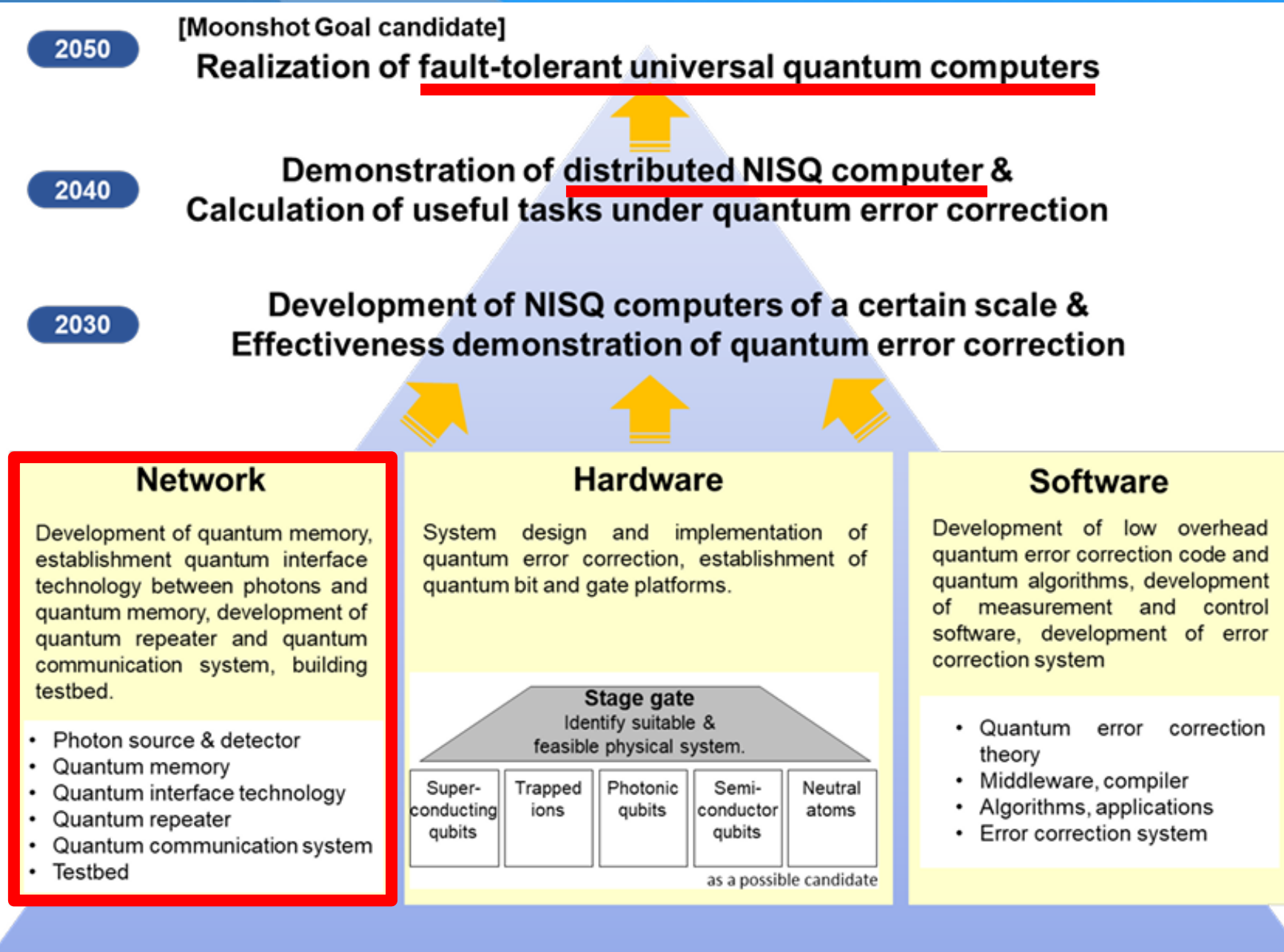
Project Manager **Hideo Kosaka**

Professor, **YOKOHAMA** National University

Director, Quantum Information Research **Center**

Research fellow, The University of **Tokyo**
Japan





Kosaka Pj



Quantum communications

KOSAKA
Hideo

YAMAMOTO
Takashi

NAGAYAMA
Shota

Fault-tolerance

KOASHI
Masato

KOBAYASHI
Kazutoshi

Quantum computer hardware

Super
conducting

YAMAMOTO
Tsuyoshi

Trapped
ion

TAKAHASHI
Hiroki

Photon

FURUSAWA
Akira

Semi
conductor

MIZUNO
Hiroyuki

Semi
conductor

TARUCHA
Seigo

Neutral
atom

OHMORI
Kenji

Neutral
atom

AOKI
Takao

Quantum interfaces, quantum memories and quantum communications
for distributed quantum computers

Quantum networking system for distributed quantum computers

Theory and software for fault-tolerant quantum computers

Development of quantum error correction system

Moonshot **Kosaka** Project – Quantum Interconnect



MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM
JPMJMS2062

9 PIs
107 members

Diamond

**Super-productive
nano-fabrication**



Satoshi Fujii



Toshiharu Makino



Hiromitsu Kato
13 members

Optics



Satoshi Iwamoto
17 members

Photonic crystal cavity



Masahiro Nomura
6 members

Phononic crystal cavity

3D Integration



Fumihiro Inoue



Katsuya Kikuchi

**Silicon
photonics**



Hodaka Kurokawa



Hirotaka Teraoka



Yoshihiro Shimazu

**Quantum
transducer**



Toshihiko Baba
6 members

**Microwave
circuit**



Nobuyuki Yoshikawa
3 members

**Quantum
memory**



Hideo Kosaka
32 members



Kazuki Koshino
1 member

Theory



Tokuyuki Teraji
2 members



Shinobu Onoda
27 members

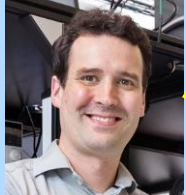


**Super-precision
ion implantation**



Kazumasa Narumi

**Super-pure
diamond**



Tim Taminiau



Yuhei Sekiguchi

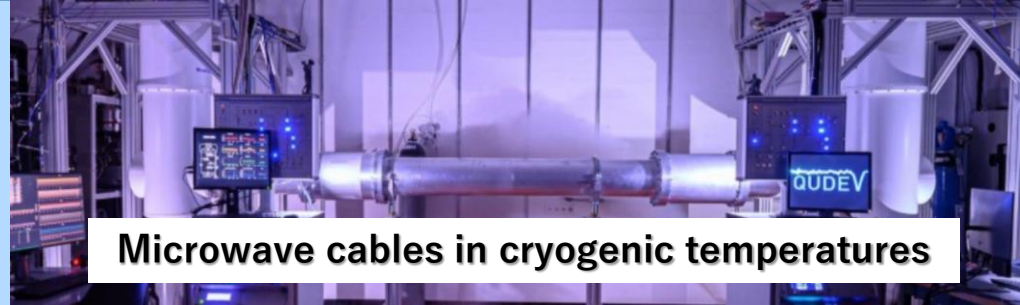
Motivation - Quantum Interconnect Solid qubits

(Distributed) Super Computer

Optical
connection

Fujitsu "Fugaku"

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



Microwave cables in cryogenic temperatures

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)

(Distributed) Quantum Supercomputer

100,000-qubit
quantum-centric
supercomputer
—
2033

Optical
connection

Modules

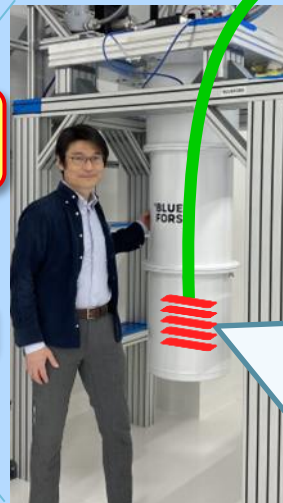
CHICAGO
QUANTUM
EXCHANGE

THE UNIVERSITY OF
CHICAGO

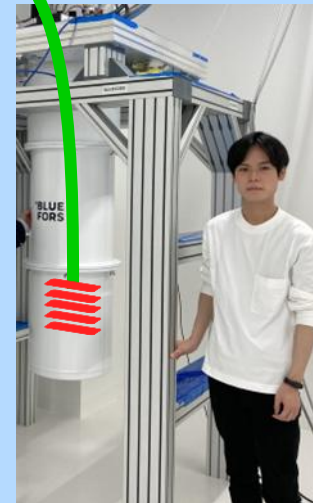
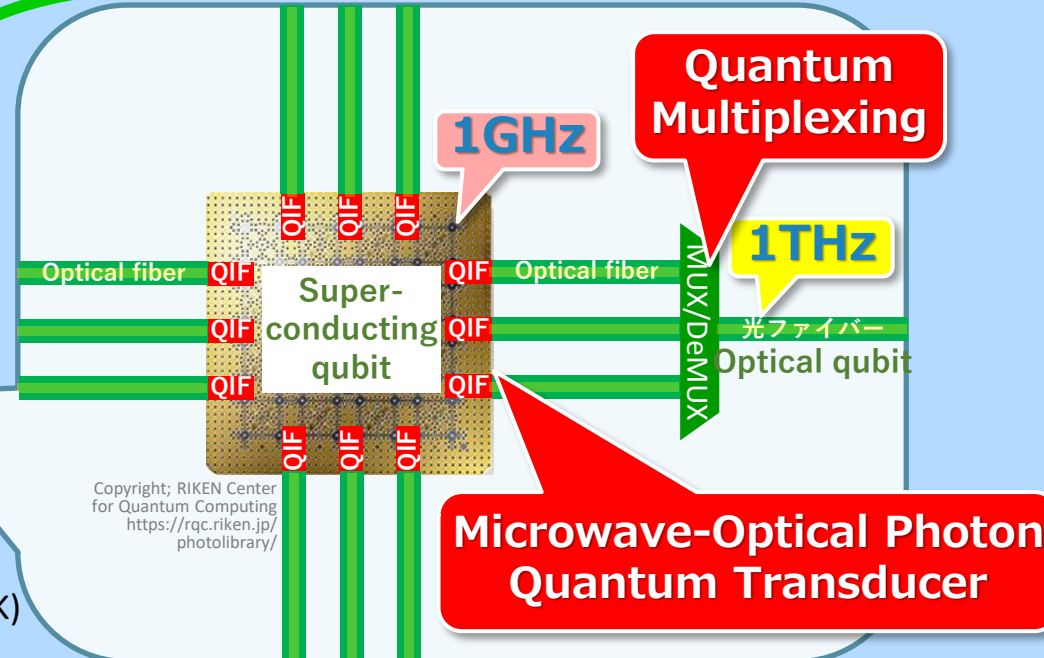
IBM

IBM Quantum

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

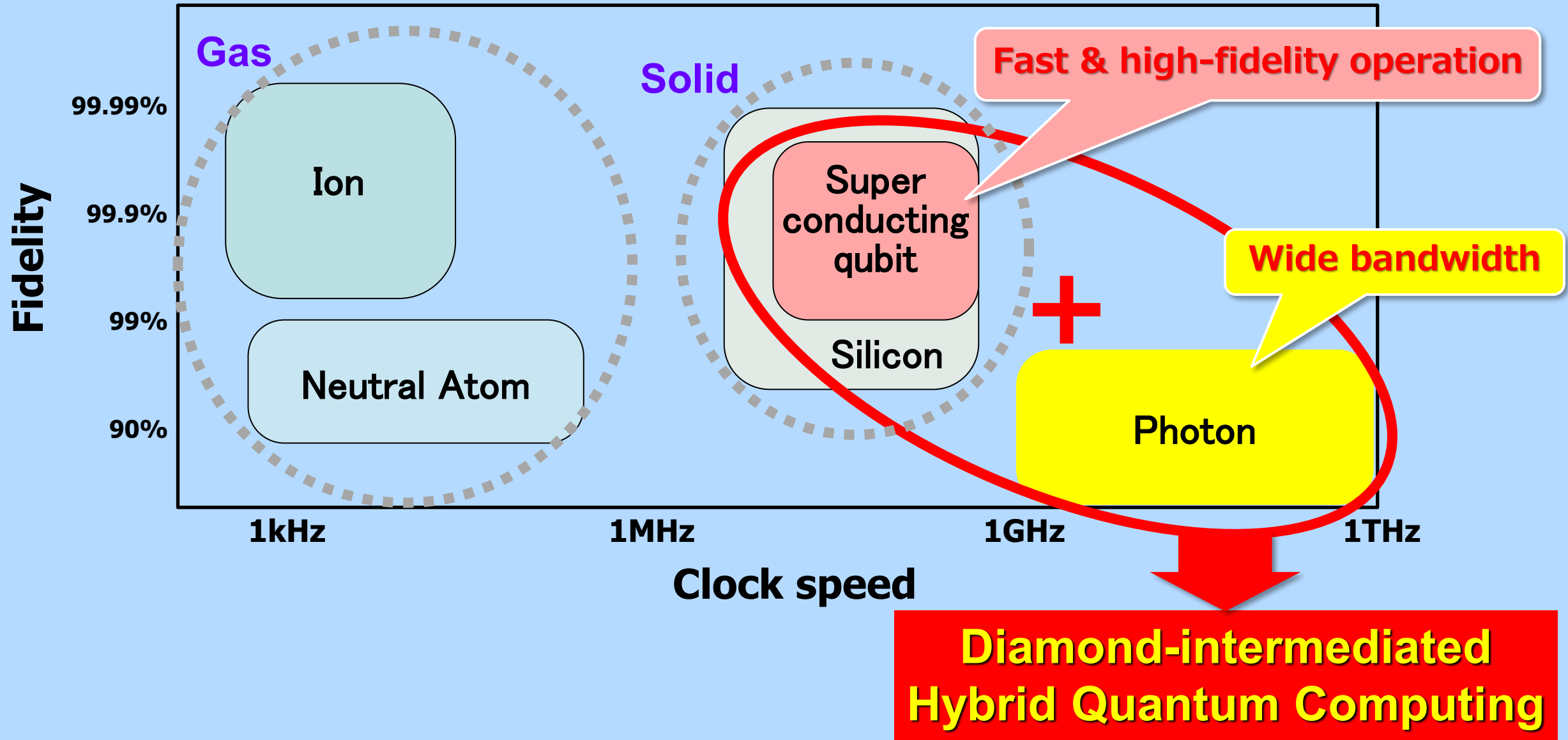


Dilution fridge (~10mK)

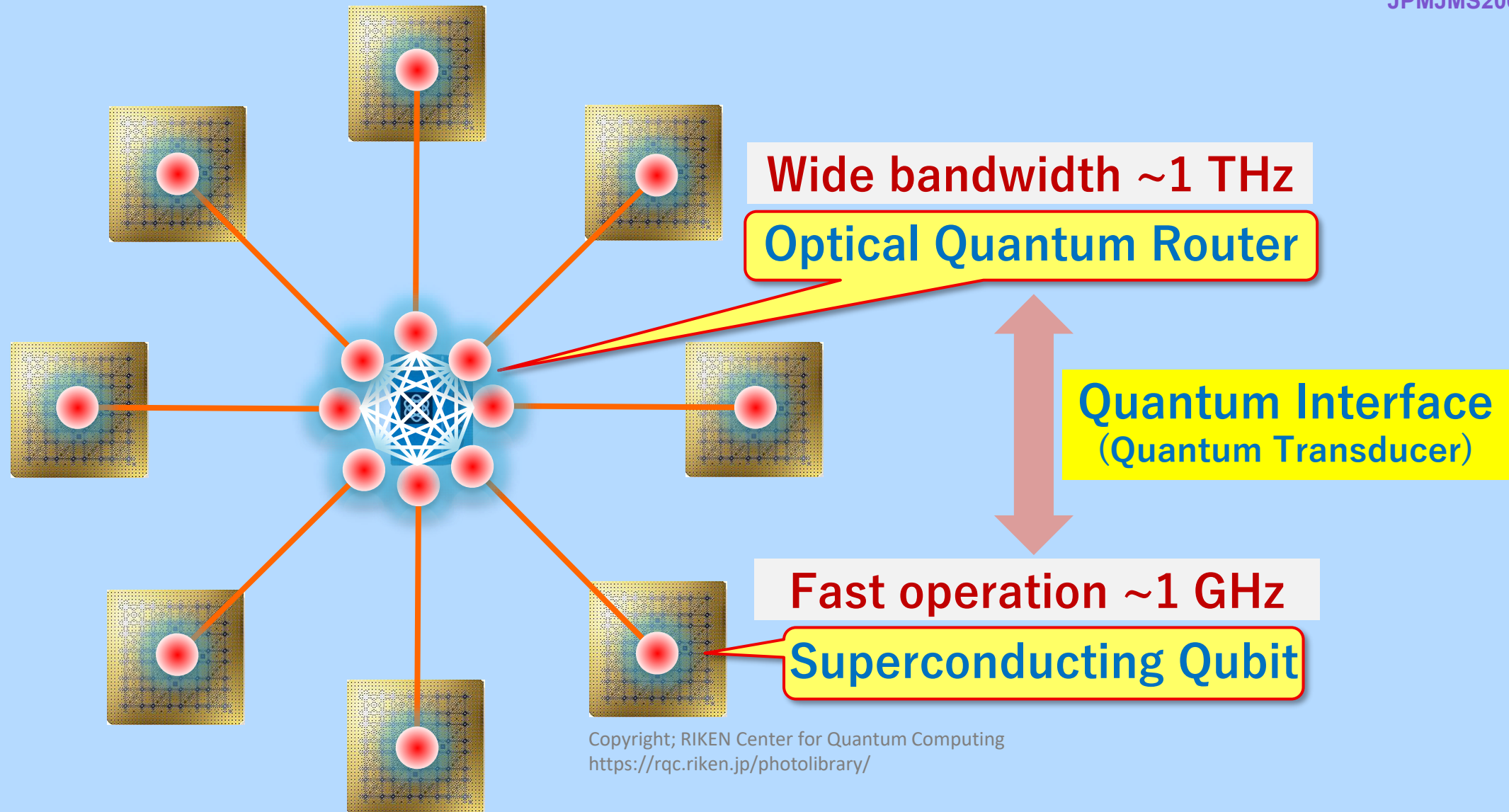


Dilution fridge (~10mK)

Diamond-mediated Hybrid Quantum Computing



Distributed Quantum Computing



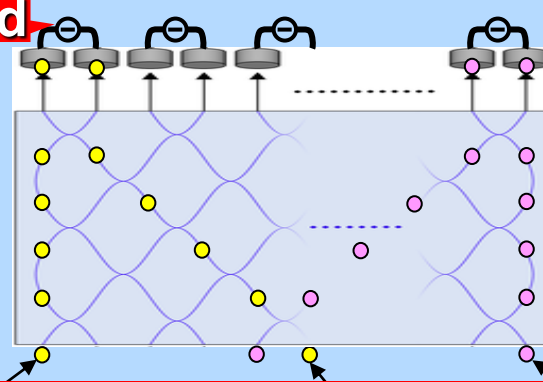
Distributed Quantum Computing with Quantum Interconnect



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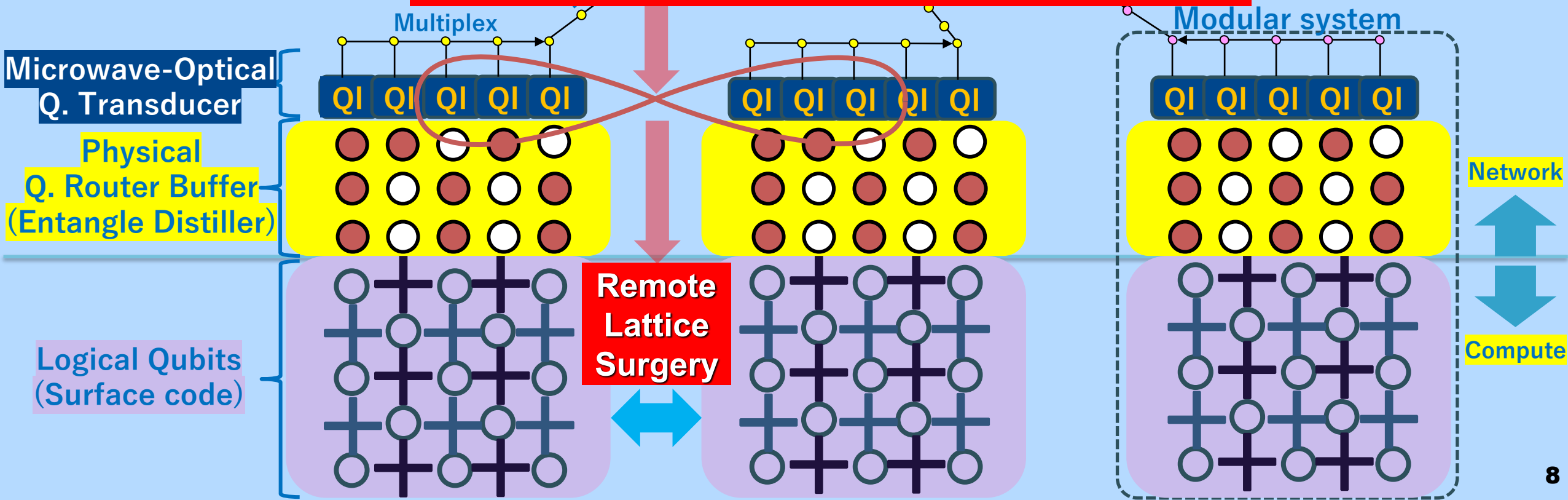
Heralded Bell pairs are injected into logical qubits for remote lattice surgery

Herald



Logical
Q. Router

All-to-all Quantum Interconnects



Quantum Transducer = Quantum Media Converter

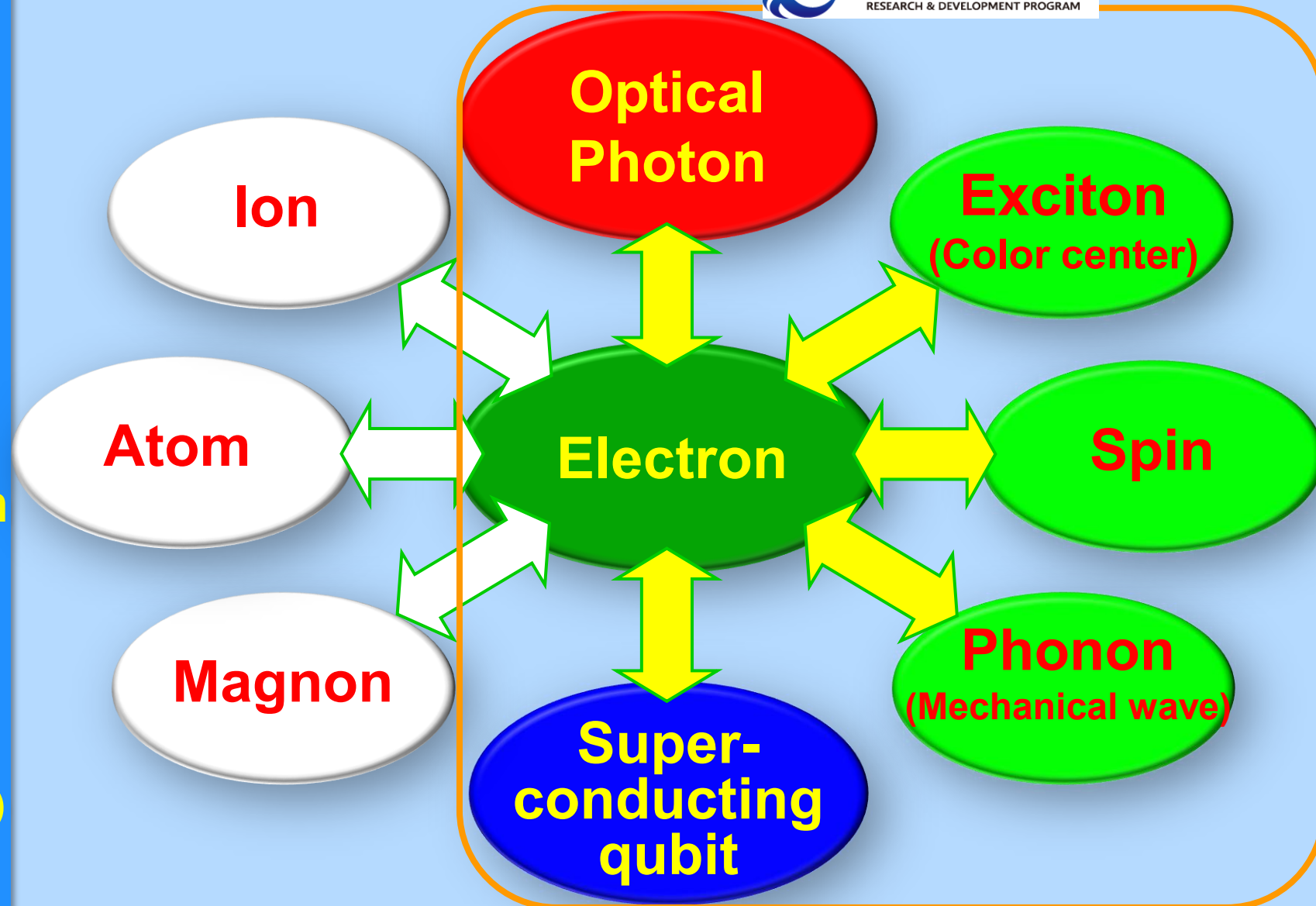
Quantum Transducers
convert excitation between
different quantum media

However

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



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

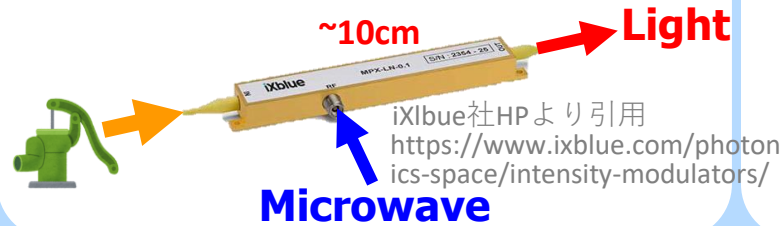


Power reduction of Quantum Transducer

Microwave Photon ($\sim 10\text{GHz}$) emitted from **Superconducting Qubit** is converted to **Optical Photon** ($\sim 500\text{THz}$)

Modulator
W-class pump light

EO modulator



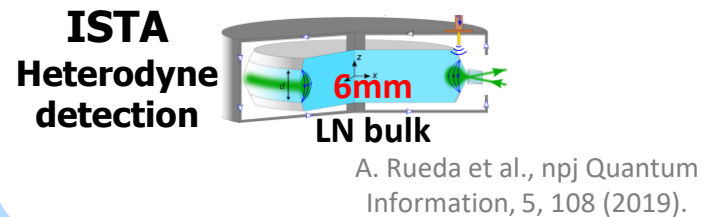
AO modulator



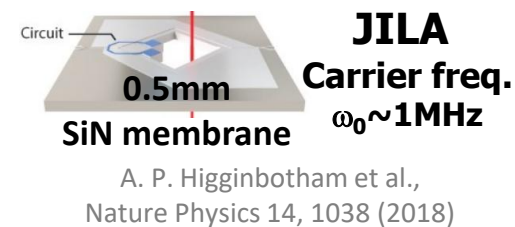
Resonator

mW-class pump light

EO resonator



AO resonator



OMC

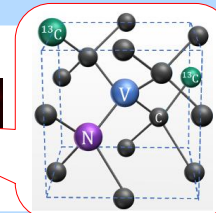
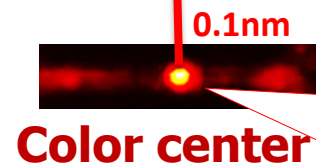
μW -class pump light

Opto-Mechanical Crystal (Photonic & Phononic crystal)

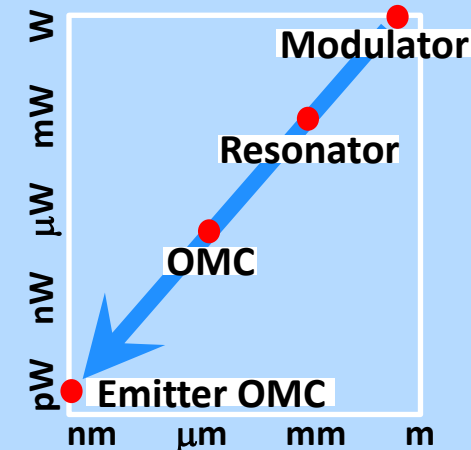


Emitter in OMC

pW-class pump light



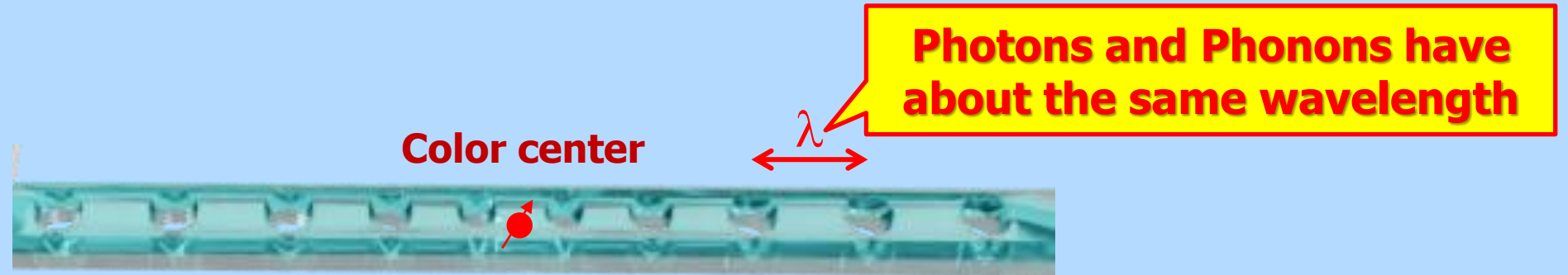
Pump power



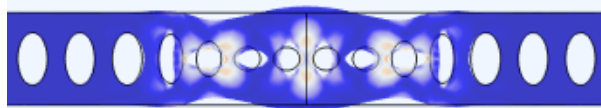
Chip size

Noise Reduction

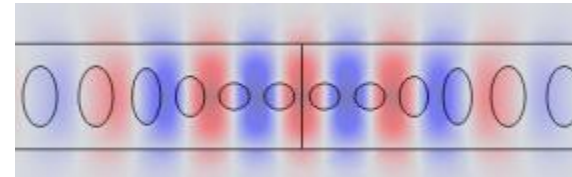
Opto-Mechanical Crystal



**Mechanical mode
(Phononic crystal)**



**Optical mode
(Photonic crystal)**



Conventional OMC Transducers

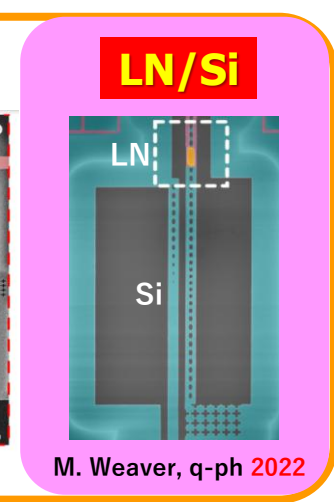
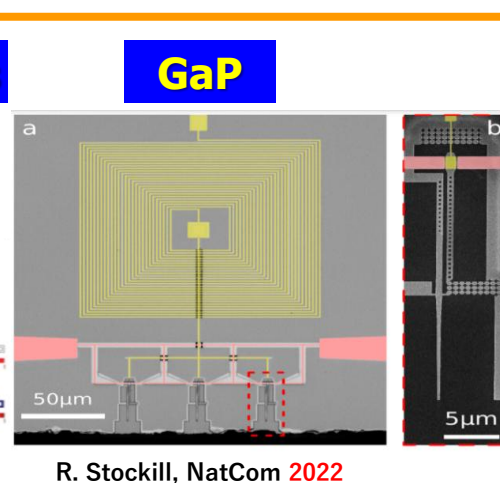
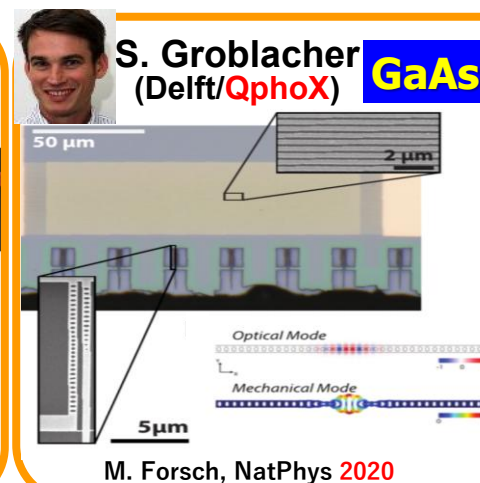
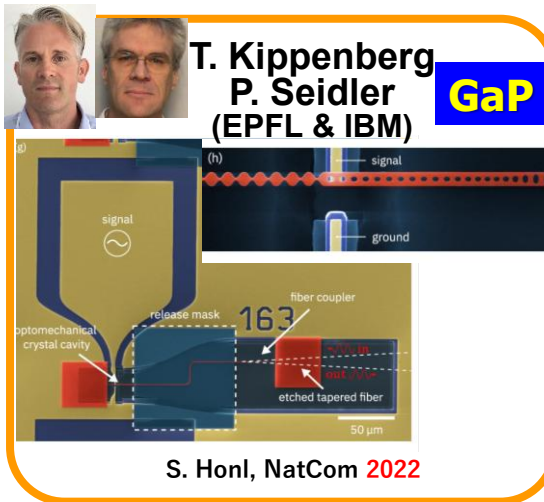
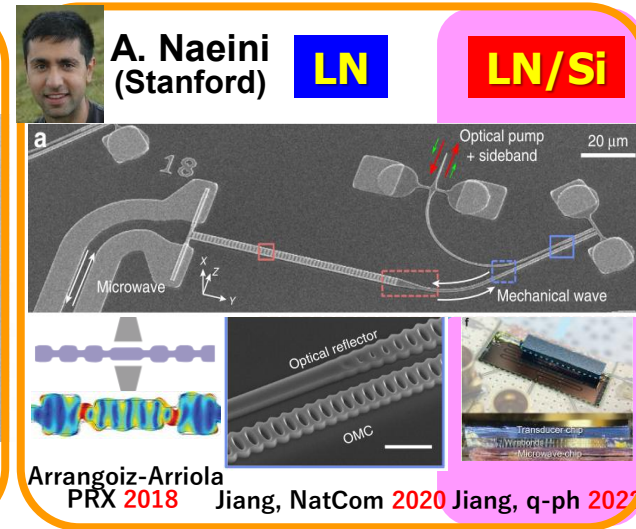
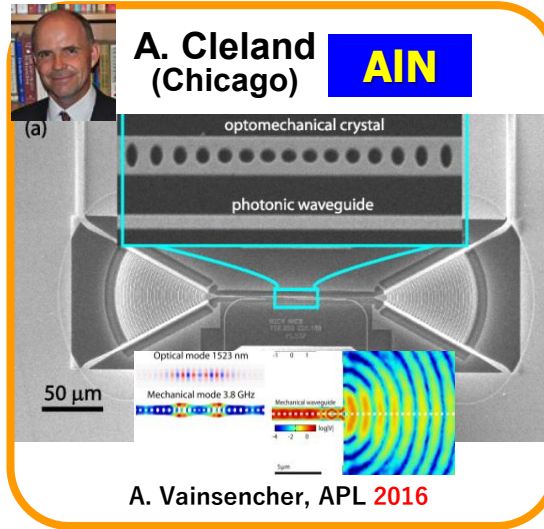
Piezo material
(AlN, LN, GaP)
or
Piezo on Silicon
(AlN/Si, LN/Si)



High pump power



Induce noise



Challenges for Diamond OMC with color centers

A **color center**
in Diamond
mediates conversion

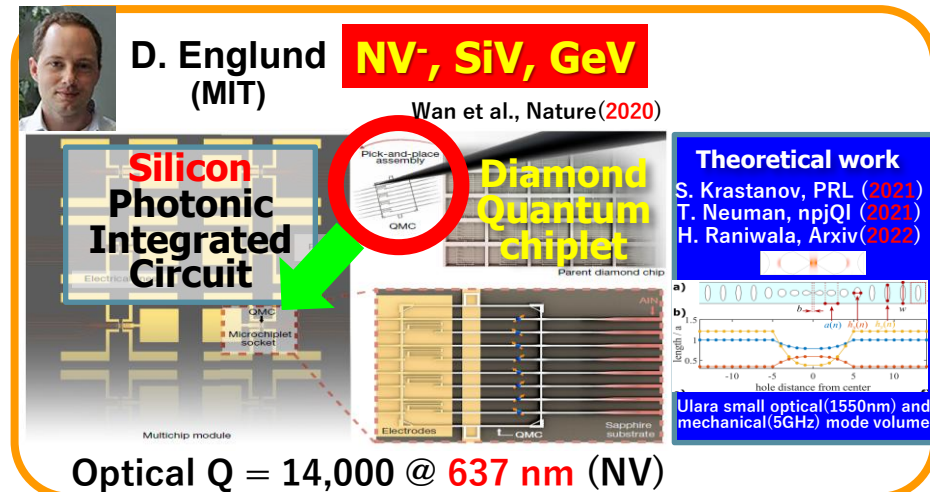
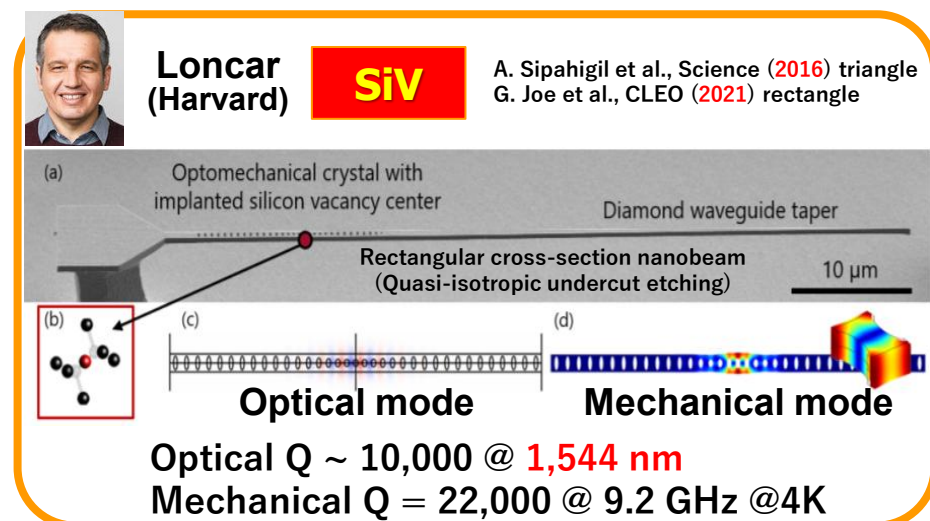
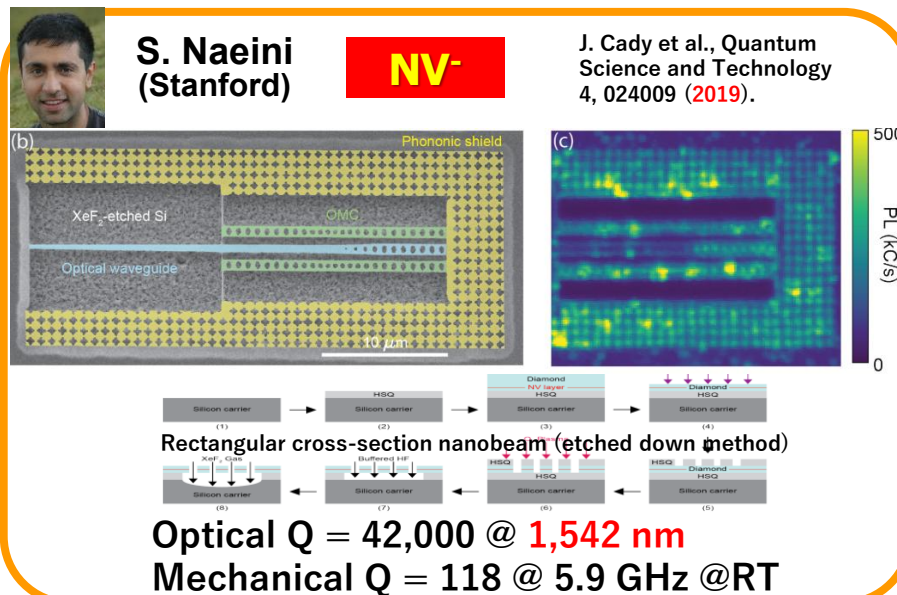
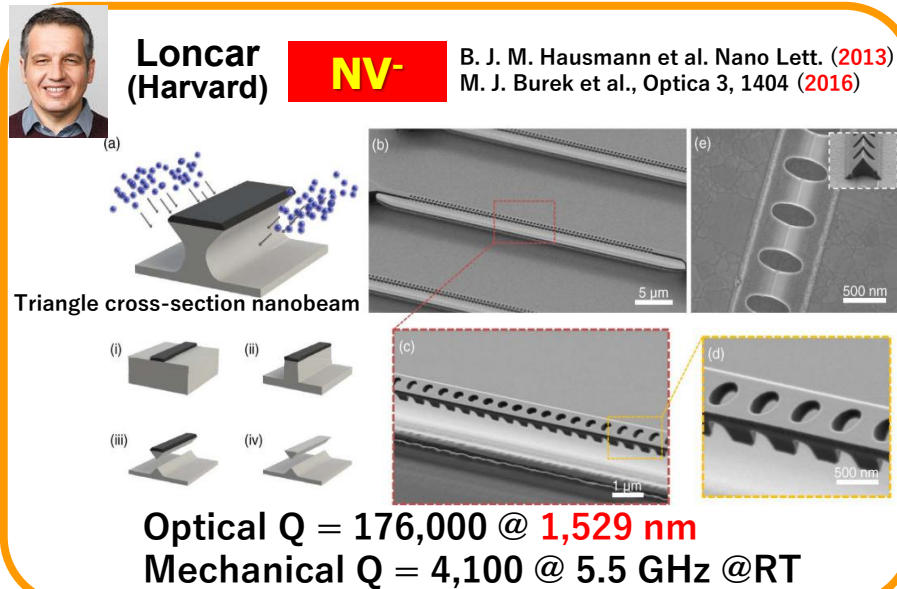


Low pump power

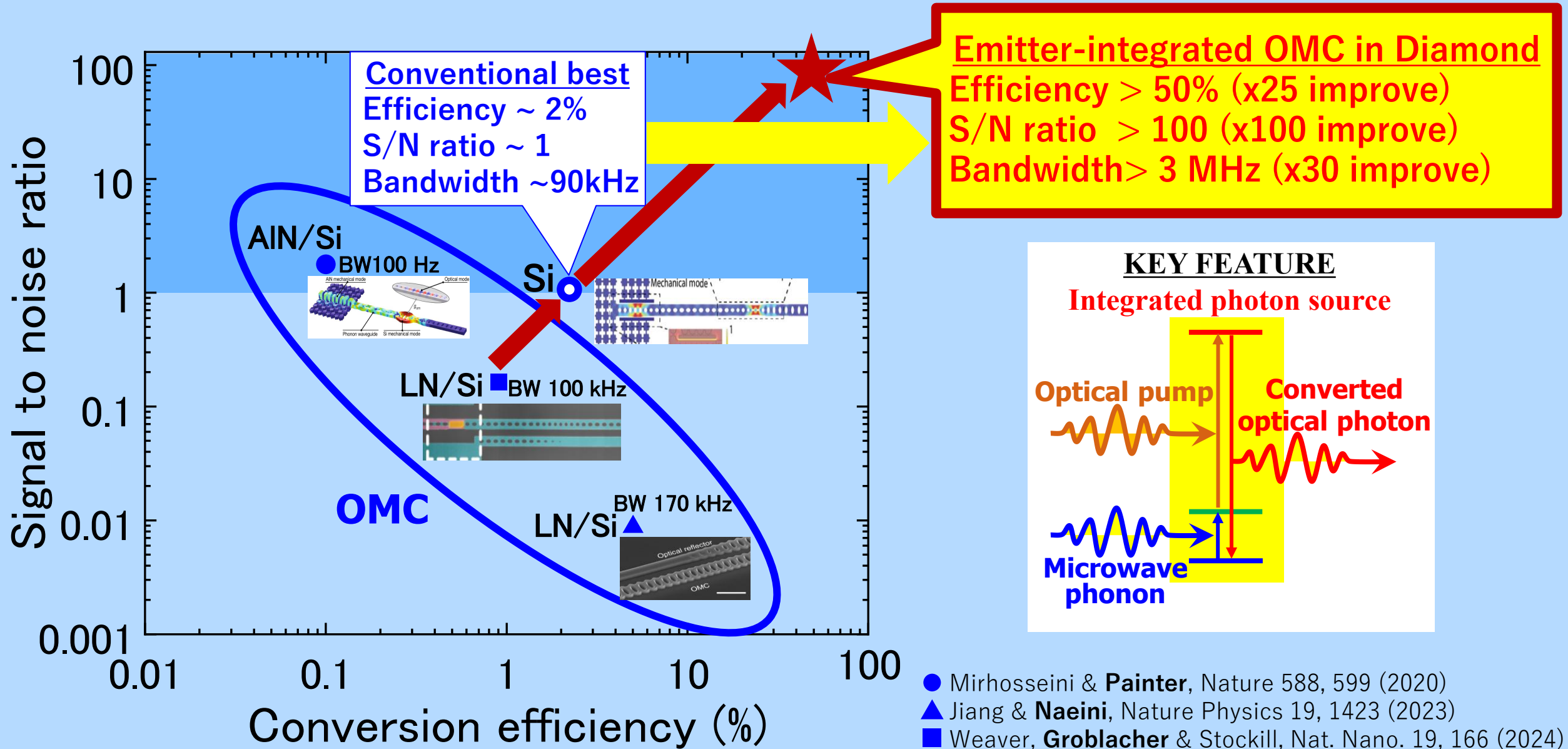


Noise reduction

No demonstration
of Q. transducer



Advances in OMC Transducers

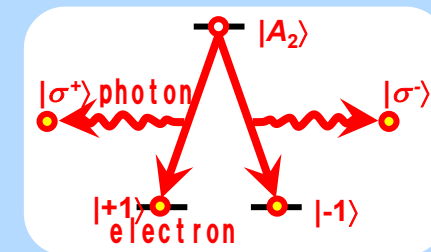
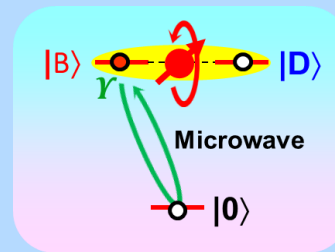
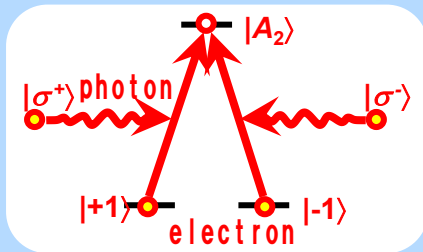


- Mirhosseini & Painter, Nature 588, 599 (2020)
- ▲ Jiang & Naeini, Nature Physics 19, 1423 (2023)
- Weaver, Groblacher & Stockill, Nat. Nano. 19, 166 (2024)
- Zhao & Mirhosseini, Nature Nano. 20, 602 (2025)

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)

Q. State Transfer

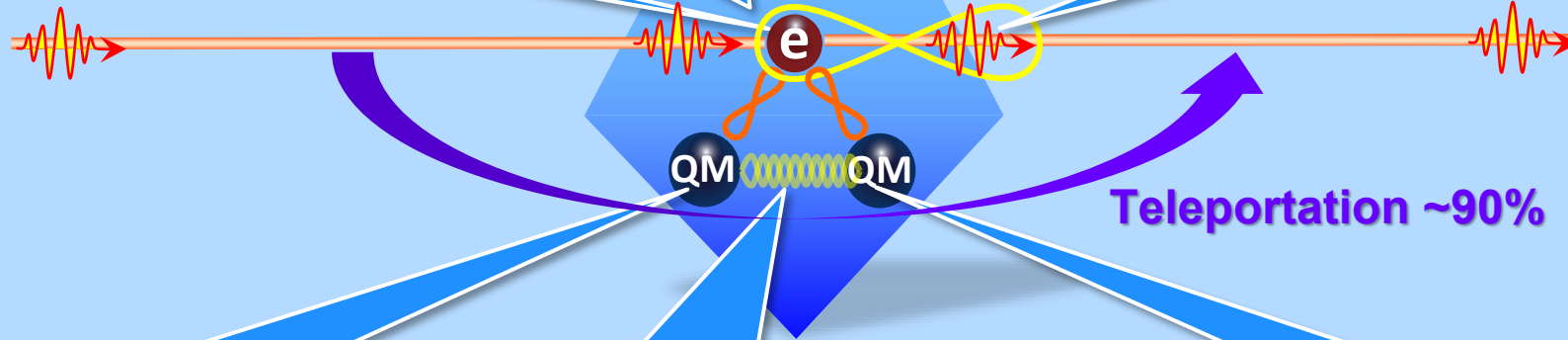
Fault-tolerant Q. Gate

Entangled Emission

98%

99.97%

98%



Initialization & Readout

Bell State Meas.

Q. Error Correction

99.7%

90%

86%

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

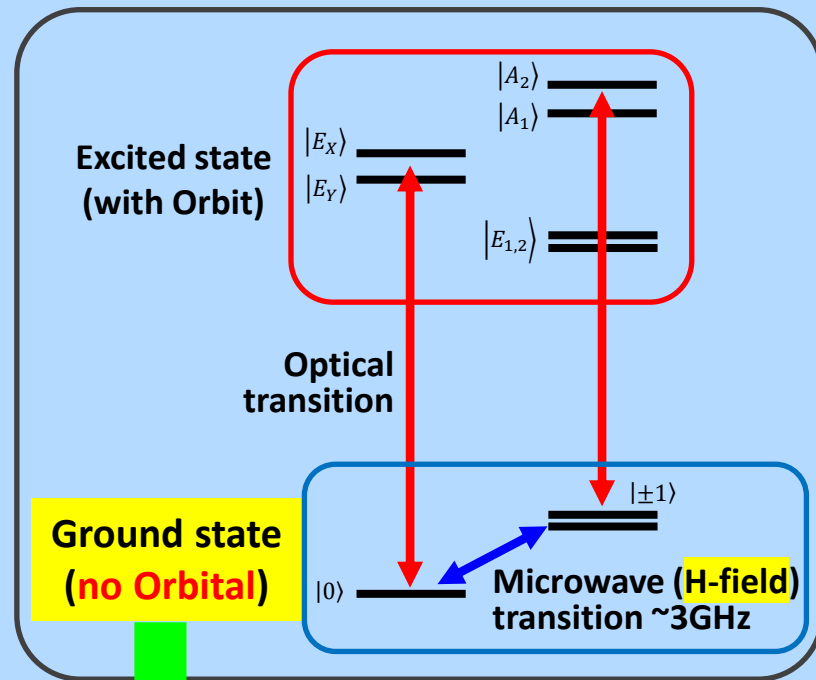


Neutral NV^0 center for Quantum Transducer



Hodaka Kurokawa
(YNU)

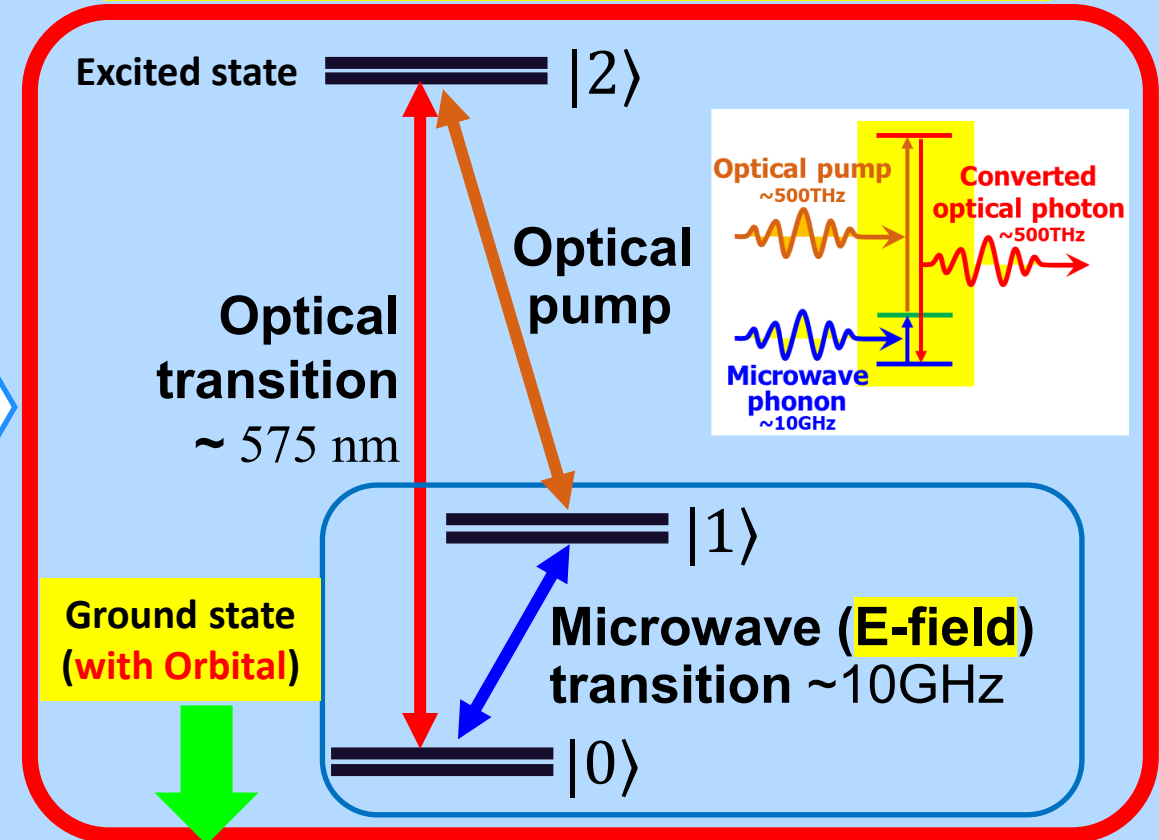
Energy level structure of NV^-



Insensitive to E-field

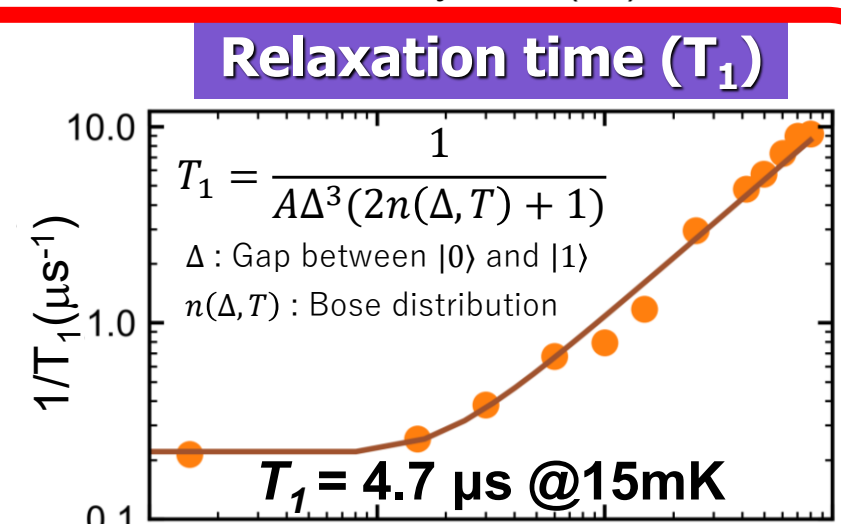
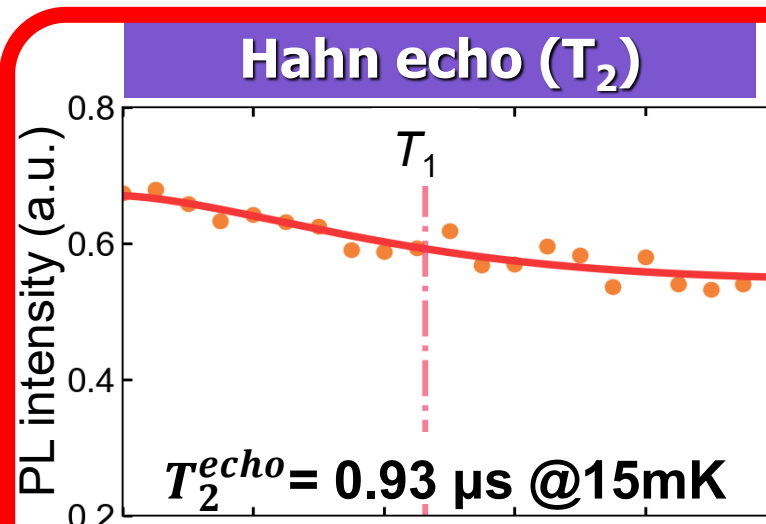
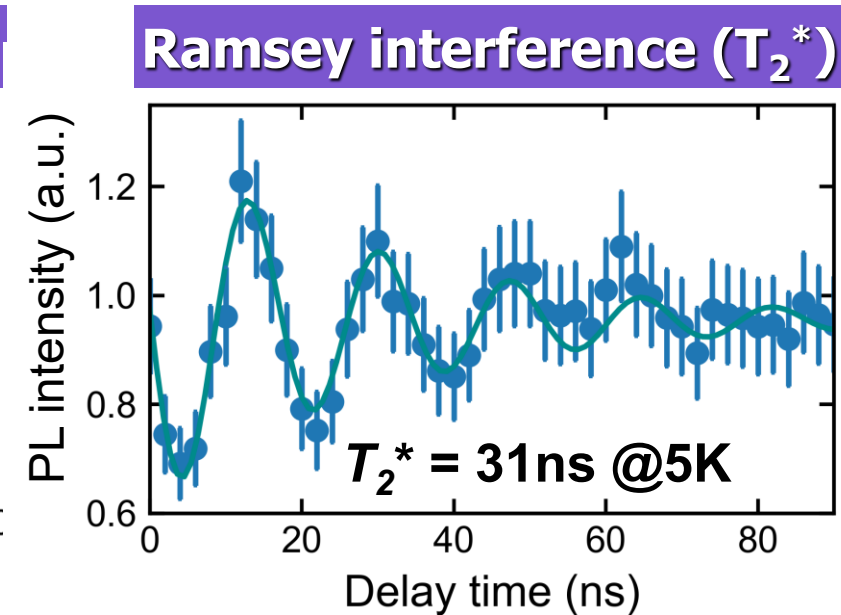
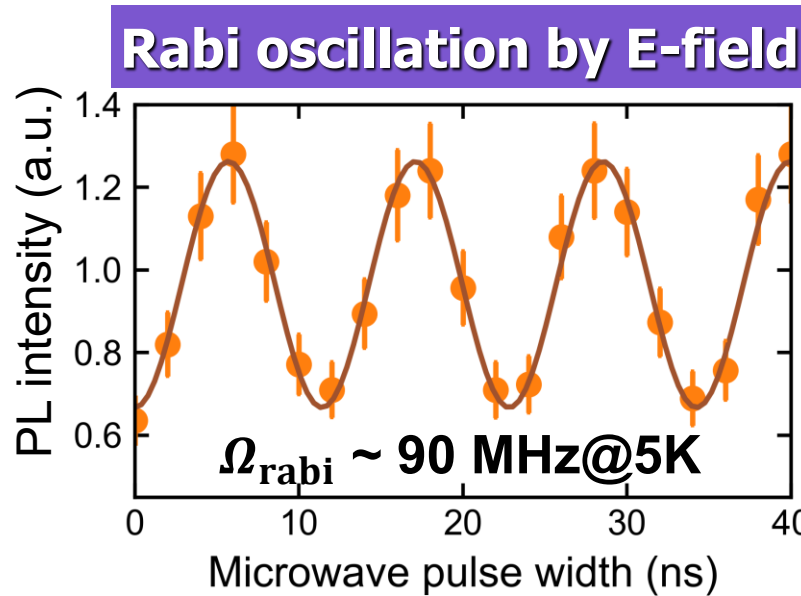
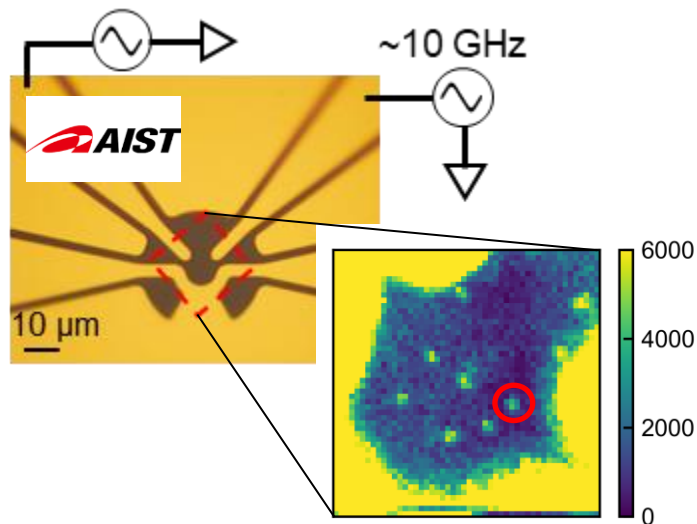
X 1000

Energy level structure of NV^0



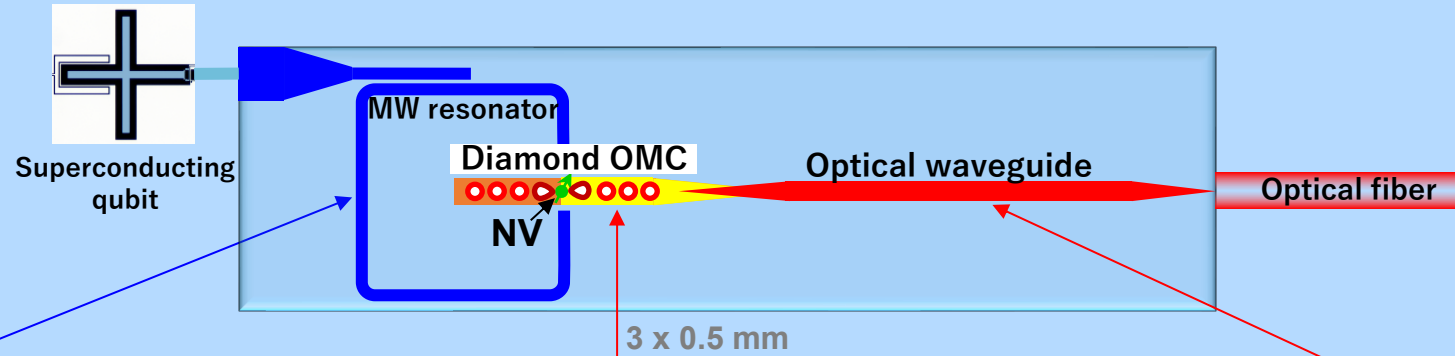
Sensitive to E-field at $B=0$
 $\sim 10\text{ GHz}$ ground state S-O splitting
Tunable by DC E-field

Coherent control of **Neutral NV⁰** center

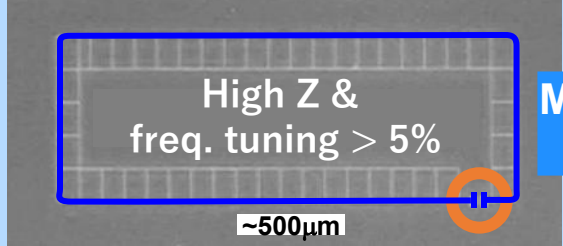


T_1 & T_2 are long enough for quantum transduction

Core elements of Quantum Transducer



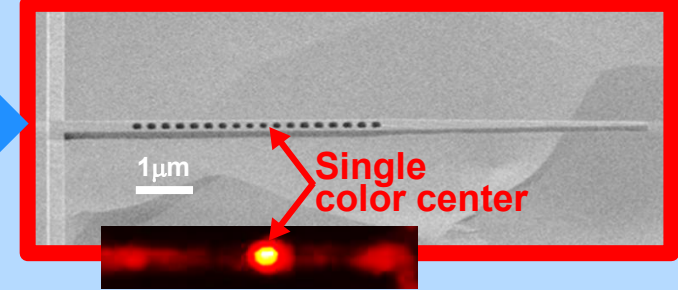
Superconducting Microwave Resonator



NbTiN Nanowire on Si

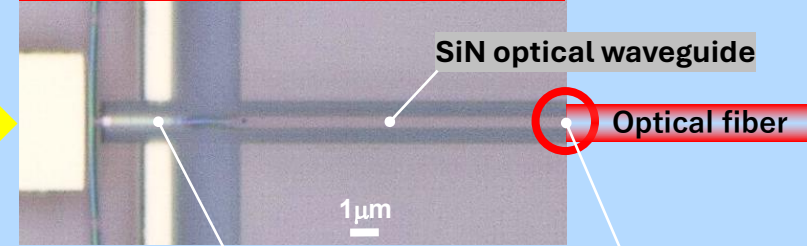
Microwave photon

Diamond Opto-Mechanical Crystal



Optical photon

Silicon Nitride Optical Circuit



Diamond color center nano cavity

Spot-size conversion



Hirotaka Terai



Satoshi Iwamoto



Masahiro Nomura



Shinobu Onoda



Toshihiko Baba



Toshihiko Baba

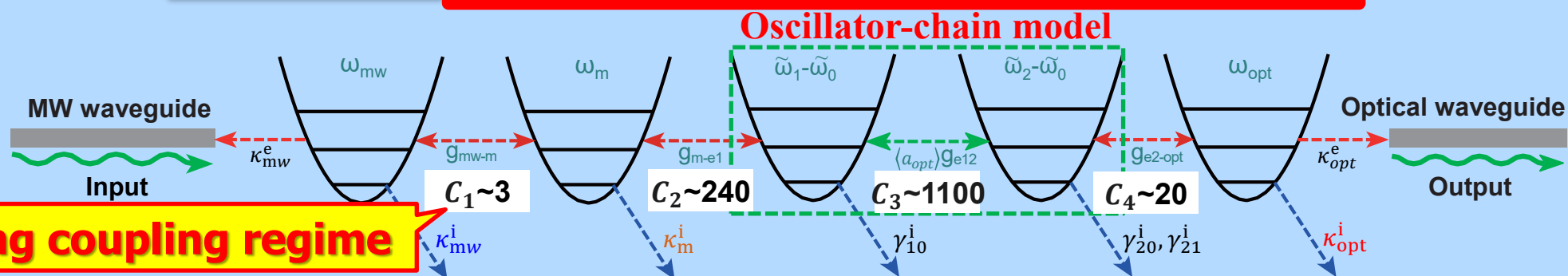
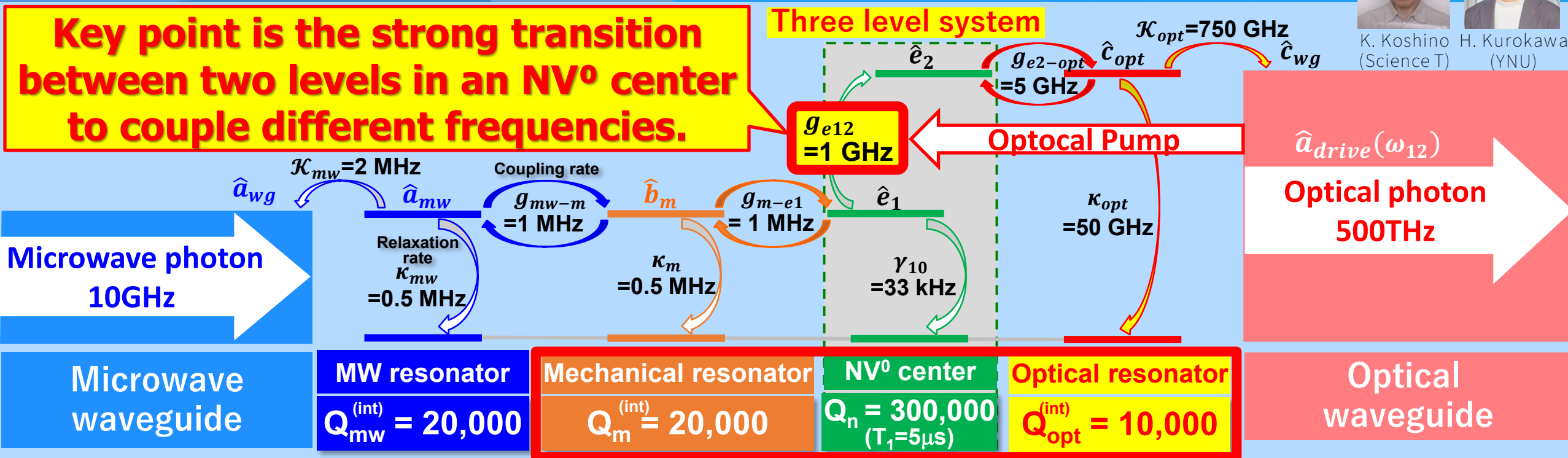
Core elements are ready for quantum transducer implementation.

Theoretical model and design



K. Koshino (Science T) H. Kurokawa (YNU)

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

$$\begin{aligned}
 H_0 &= \omega_{mw} a^\dagger a + \omega_m b^\dagger b + \omega_{e1} e_1^\dagger e_1 + \omega_{e2} e_2^\dagger e_2 + \omega_{opt} c^\dagger c \\
 H_{int} &= g_{mw-m} (a^\dagger b + b^\dagger a) + g_{m-e1} (b^\dagger e_1 + e_1^\dagger b) + g_{e2-opt} (e_2^\dagger c + c^\dagger e_2) + \langle a_{opt} \rangle g_{e12} (e_2^\dagger e_1 c + c^\dagger e_1^\dagger e_2) \\
 &\quad + \sqrt{\mathcal{K}_{mw}} (a^\dagger a_{wg} + a_{wg}^\dagger a) + \sqrt{\mathcal{K}_{opt}} (c^\dagger c_{wg} + c_{wg}^\dagger c)
 \end{aligned}$$

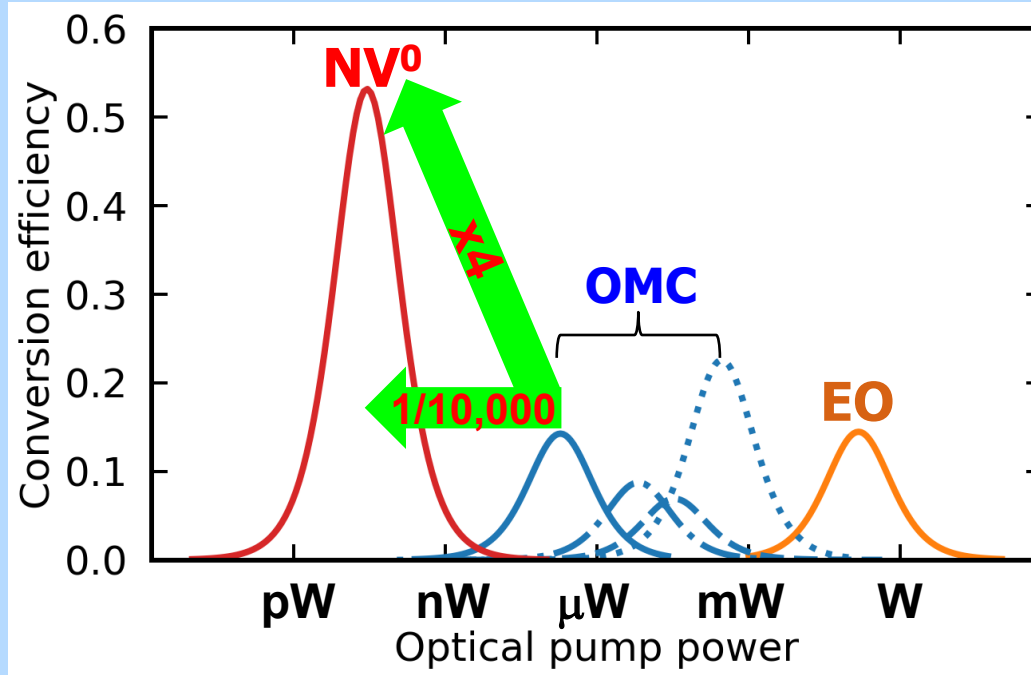
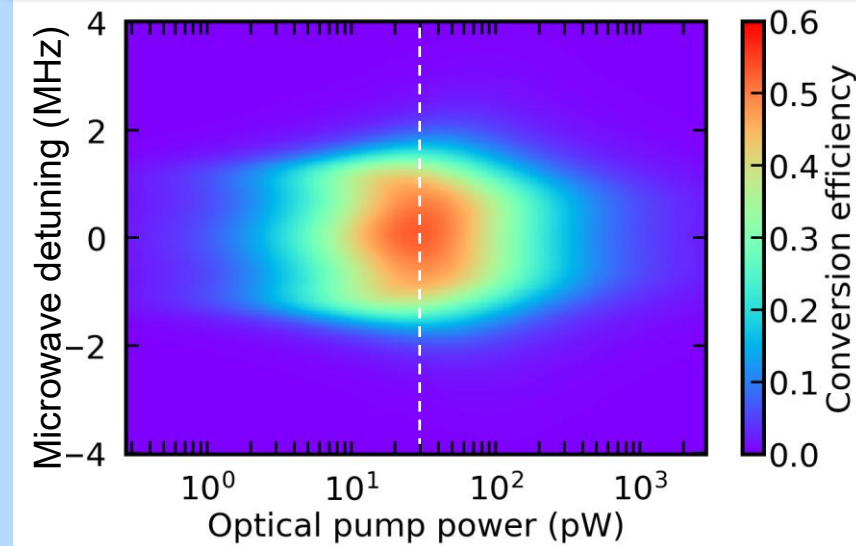
Estimation of Conversion Efficiency & Bandwidth



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

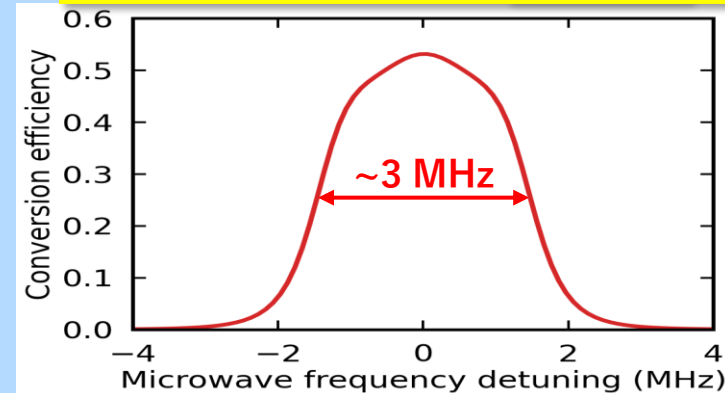
Poster PO-CP-022, QI2025

**Conversion Efficiency ~ 50%
at pump power ~ 30 pW**



EO: Electro-Optic resonator
OMC: Opto-Mechanical crystal

Bandwidth ~ 3 MHz



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

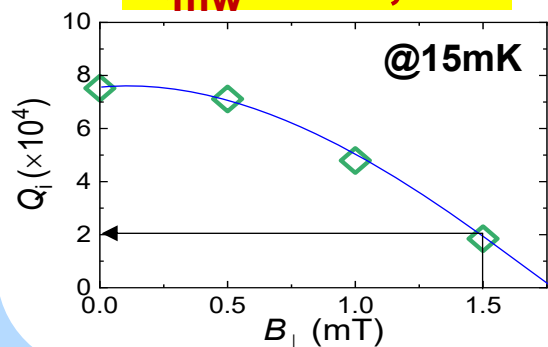
World record
(Simulation with realistic parameters)

Performance of Core Elements

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

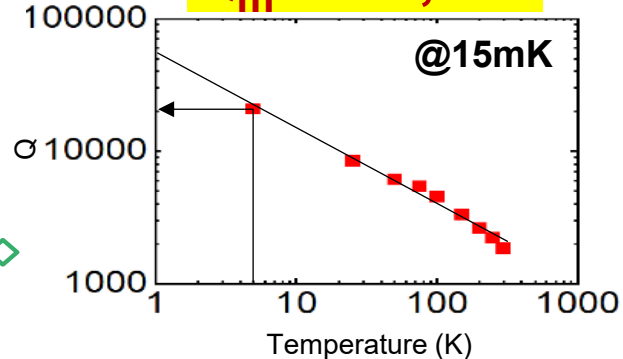
Microwave

$Q_{mw} > 20,000$



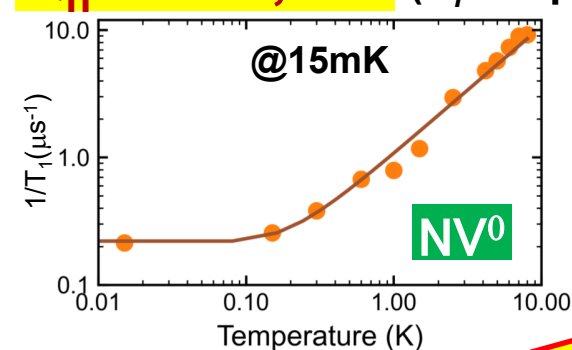
Mechanical

$Q_m > 20,000$



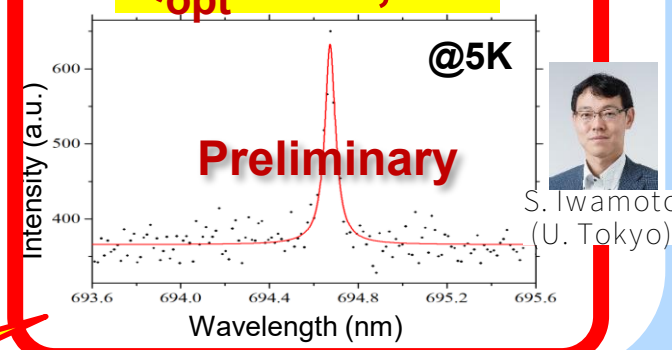
NV⁰

$Q_n \sim 300,000$ ($T_1 \sim 5 \mu s$)

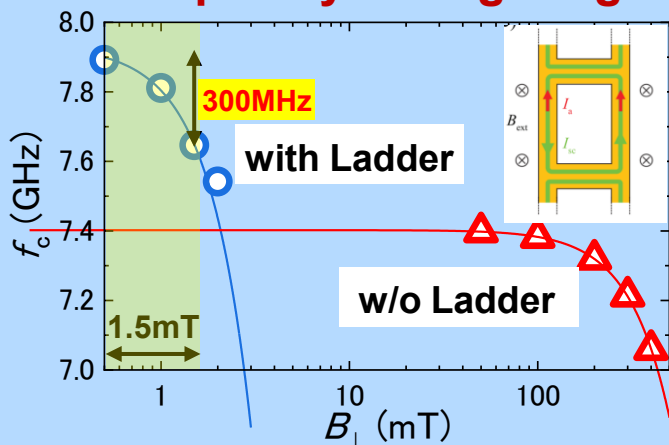


Optical

$Q_{opt} \sim 10,000$

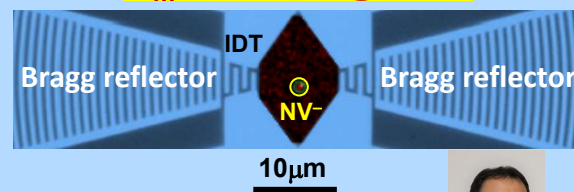


Frequency tuning range



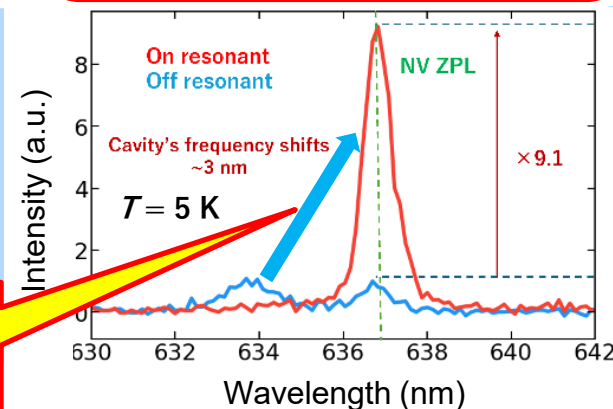
Diamond SAW

$Q_m > 20,000$ @5GHz



**World record
with Quasi-
isotropic etching**

**Purcel factor ~ 10
@ $Q=500$**



Diamond Phononic crystal



Diamond Photonic crystal

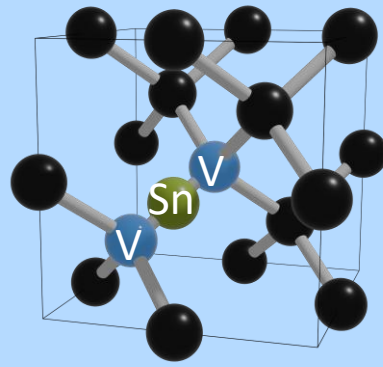


Compatible Structure

Demonstration of Quantum Transducer

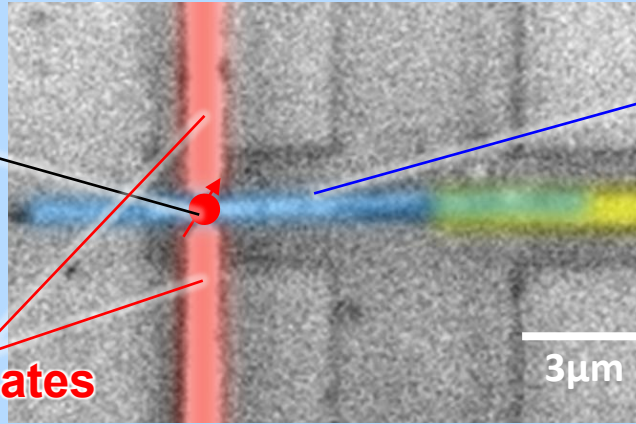


Y. Sekiguchi
(YNU)



SnV

Split gates



Diamond OMC with emitter

Optical waveguide

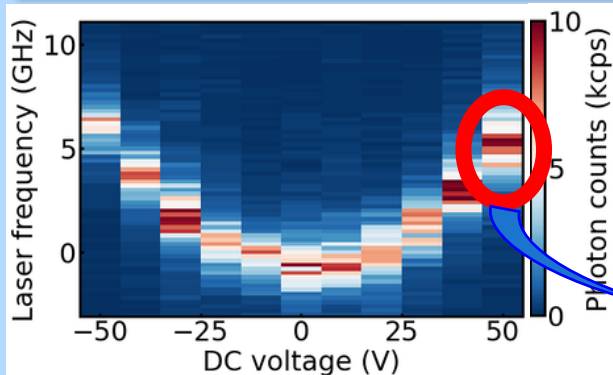


Satoshi Iwamoto
(U. Tokyo)

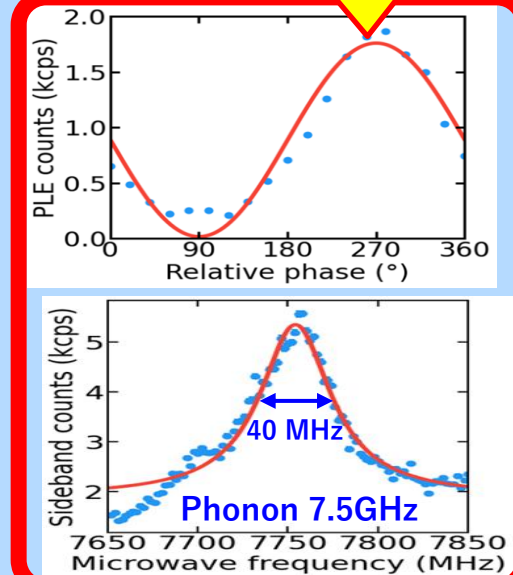
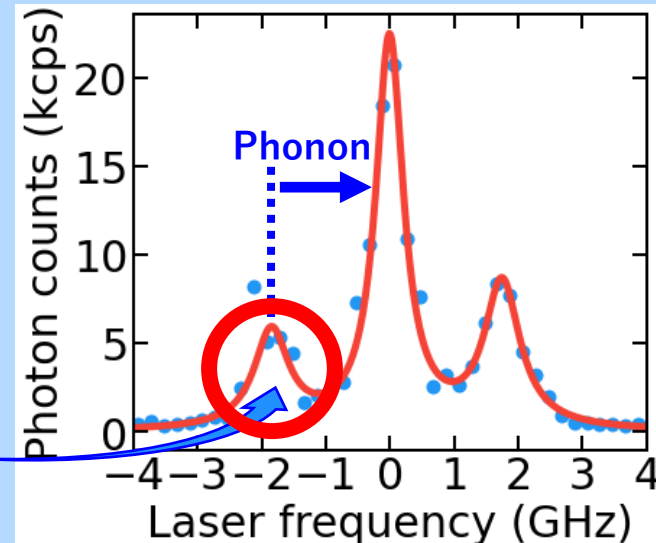
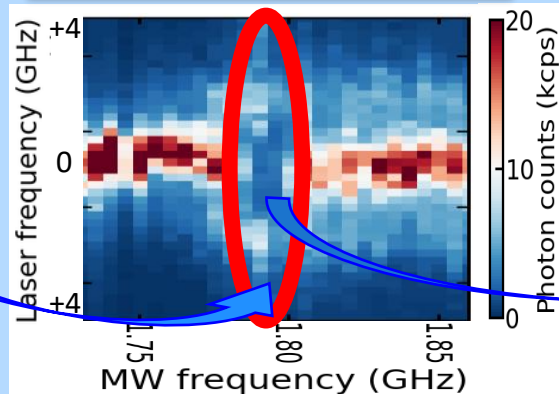
Phonon-mediated MW–optical photon conversion successfully demonstrated with emitter OMC.

Quantum Coherence

Optical transition frequency shifts with DC E-field



The frequency splits with DC + Microwave





Yuhei Sekiguchi
(YNU)

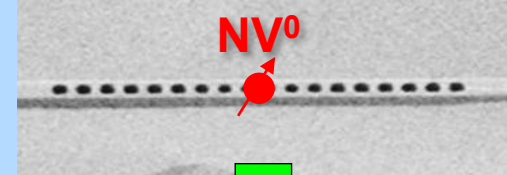
Reduction of **Charge Fluctuation** in Photonic Crystal

Conventionally
~5 GHz

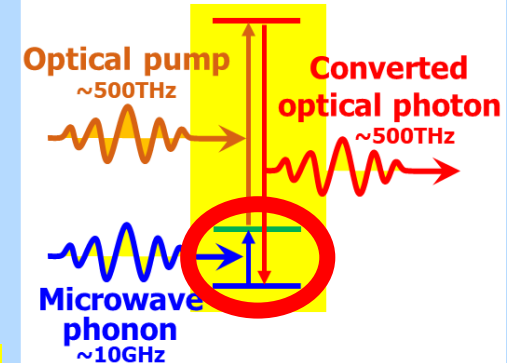
→ **FWHM = 230 MHz**
with **Charge & Resonance** check

FWHM ~ 270 MHz
with **Charge & Resonance** check

World record
for any color
center in PhC



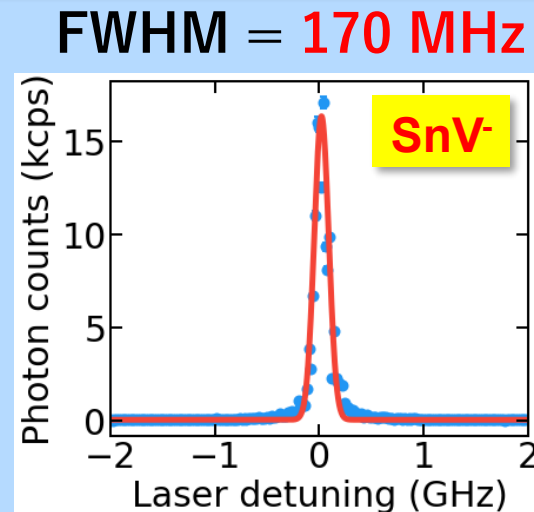
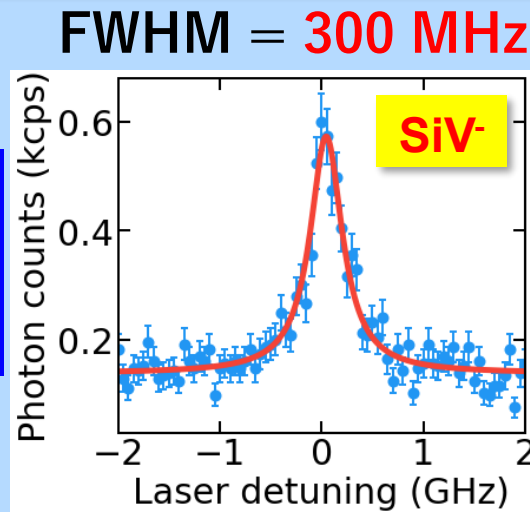
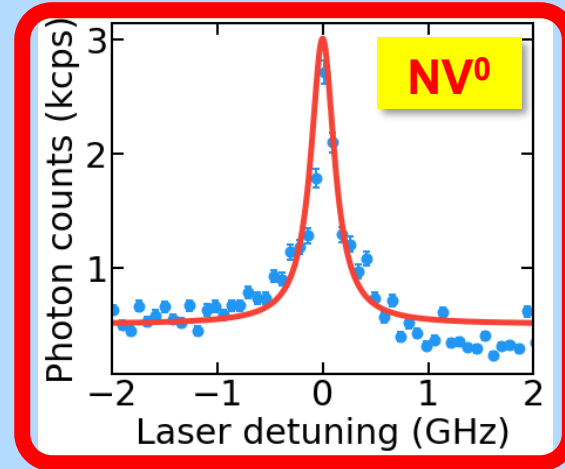
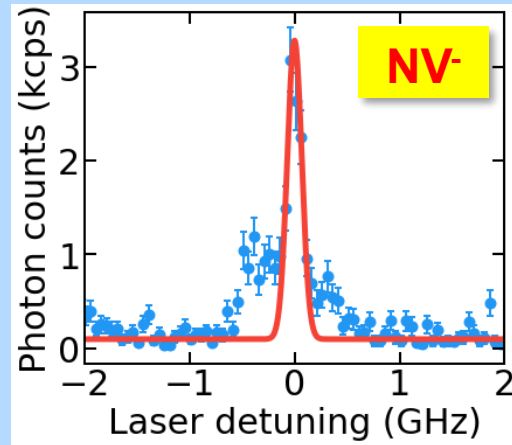
That of MW
transition should
be 5 ~ 50 MHz



	IV	V	
5	6	7	8
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

Group V
(Asymmetric)

Group IV
(Symmetric)



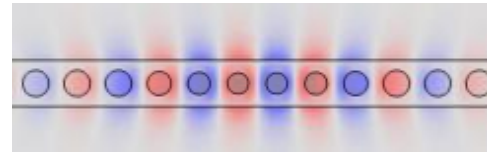
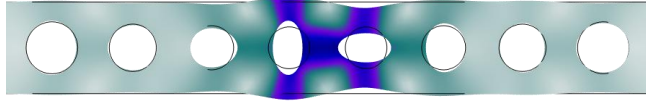
Charge fluctuation should not be a fatal obstacle.

Improvement of Diamond OMC

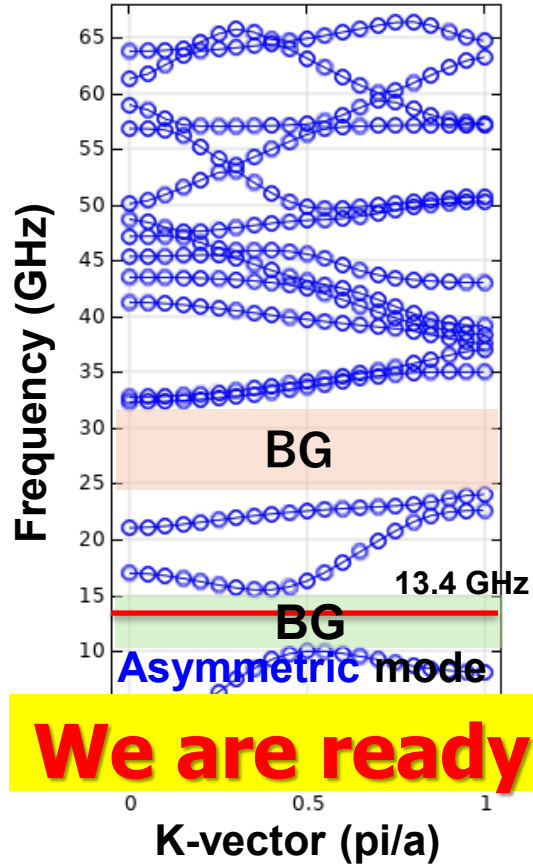


Masahiro Nomura
(U. Tokyo)

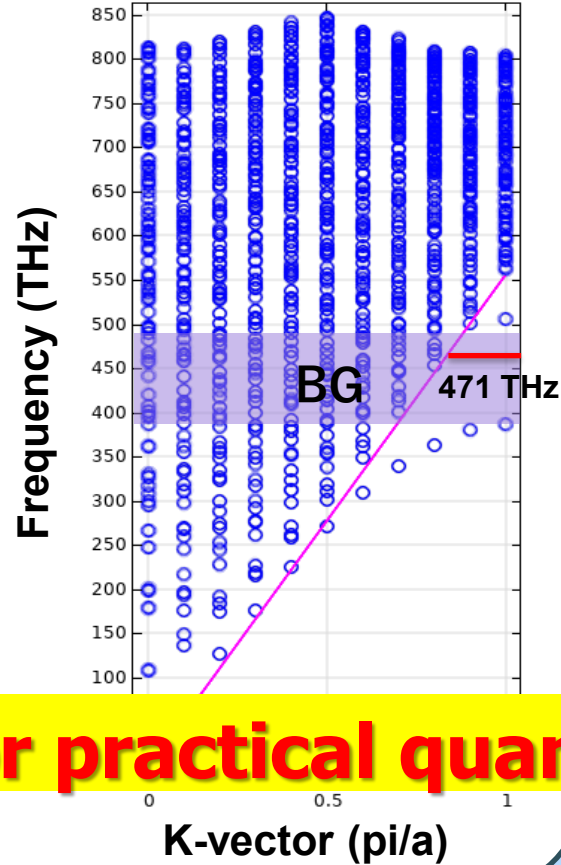
Current Design



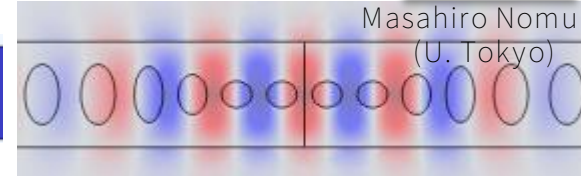
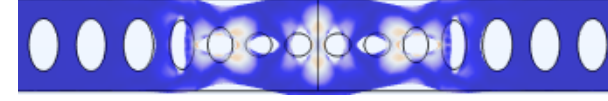
Mechanical mode
Q-factor: 30,000



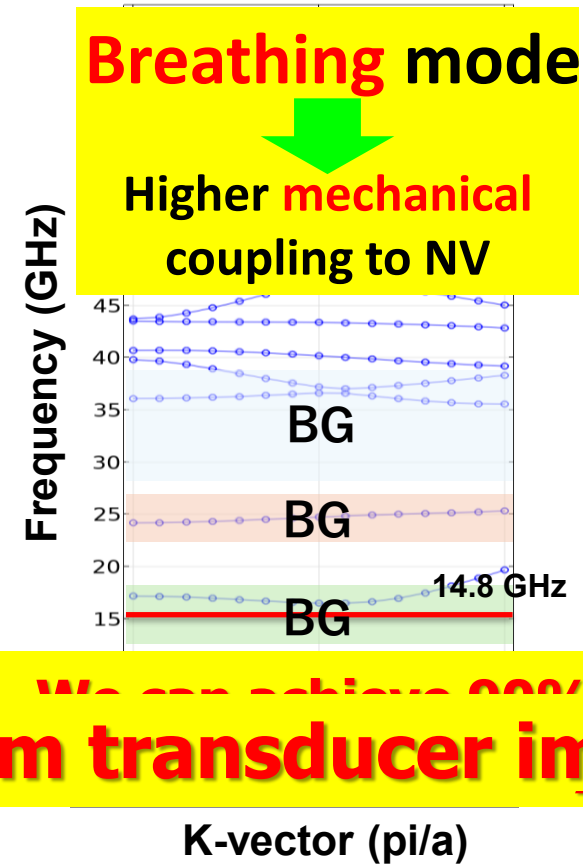
Optical mode (TE)
Q-factor: 6,200



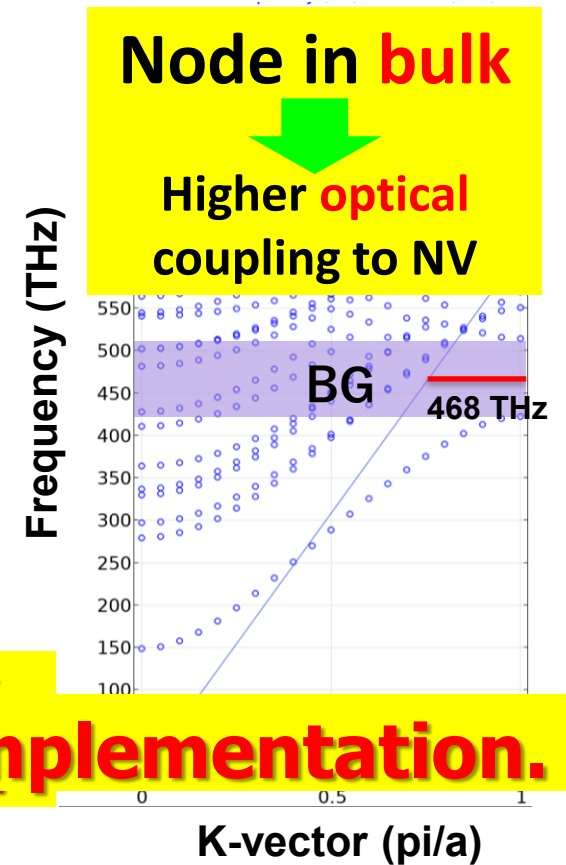
Improved Design



Mechanical mode
Q-factor: 8,000,000



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



Breathing mode

Higher mechanical coupling to NV

Node in bulk

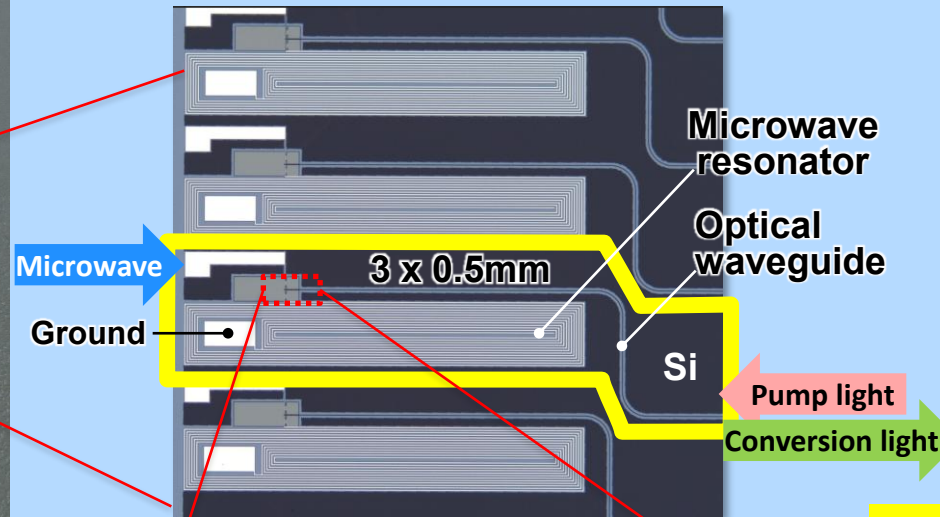
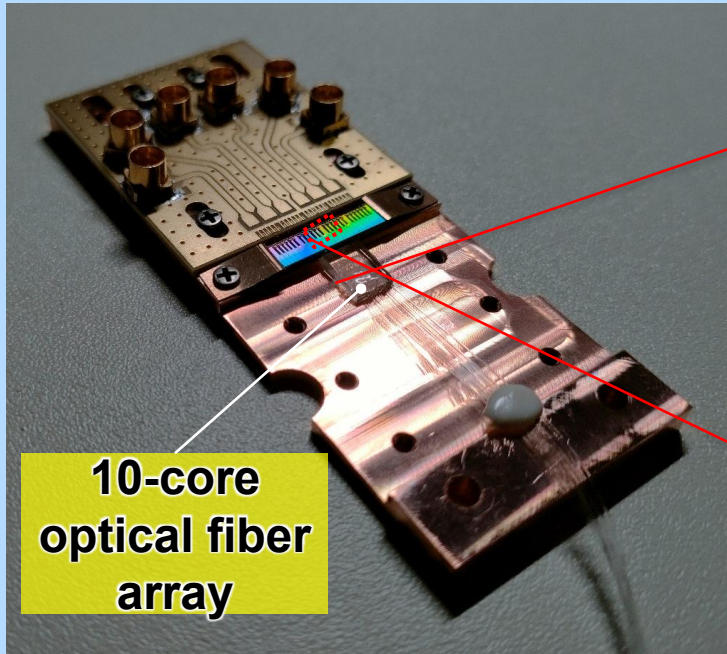
Higher optical coupling to NV

We are ready for practical quantum transducer implementation.

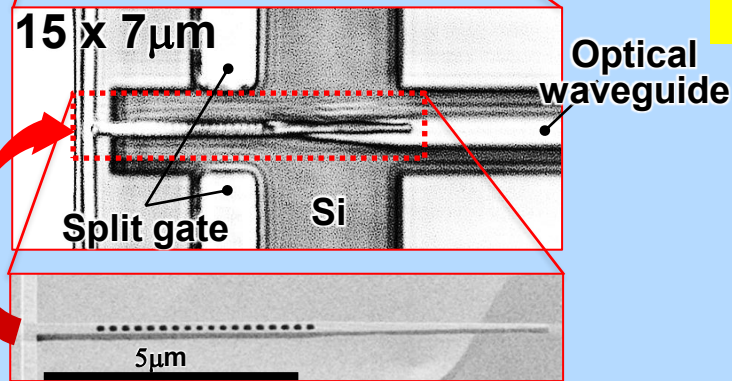
Quantum Chiplet Integration & Optical Fiber Coupling

We employ 3D packaging technologies.

MW resonator – OMC – Optical WG
Chip-let Integration



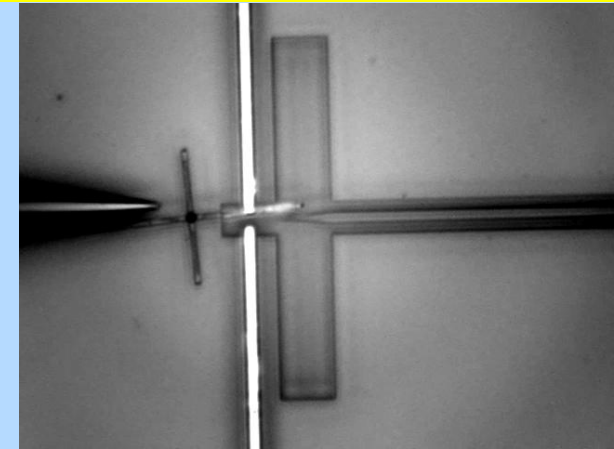
Transfer printing



Diamond opto-mechanical crystal resonator with a color center

Optical waveguide coupling

Optical resonator $\rightarrow$ Optical waveguide
Alignment accuracy <50 nm @95% (design)

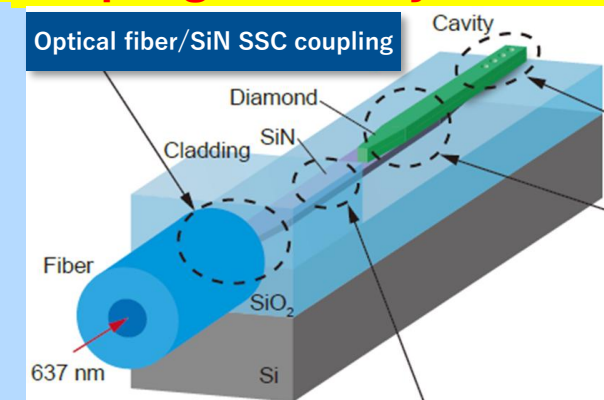


Satoshi Iwamoto
(U. Tokyo)

Yuhei Sekiguchi
(YNU)

Optical fiber coupling

Optical waveguide $\rightarrow$ Optical fiber
Coupling efficiency ~60% at RT



Toshihiko Baba
(YNU)

Frequency Tuning of Individual Elements



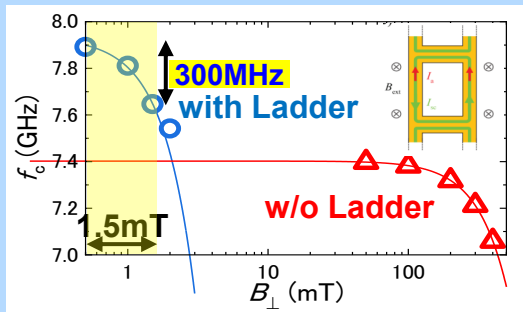
Hodaka Kurokawa
(YNU)

We can tune all the frequencies within the target accuracy.

Microwave

B field

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



Mechanical

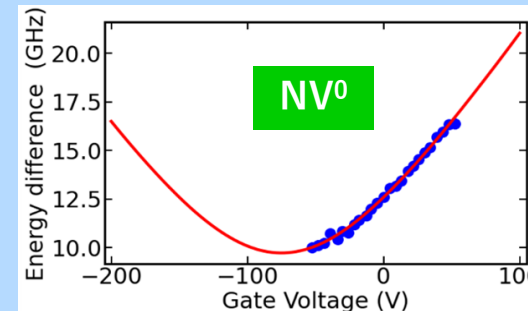
Fixed

No tunability
(synchronized with optical frequency)

NV⁰

E field

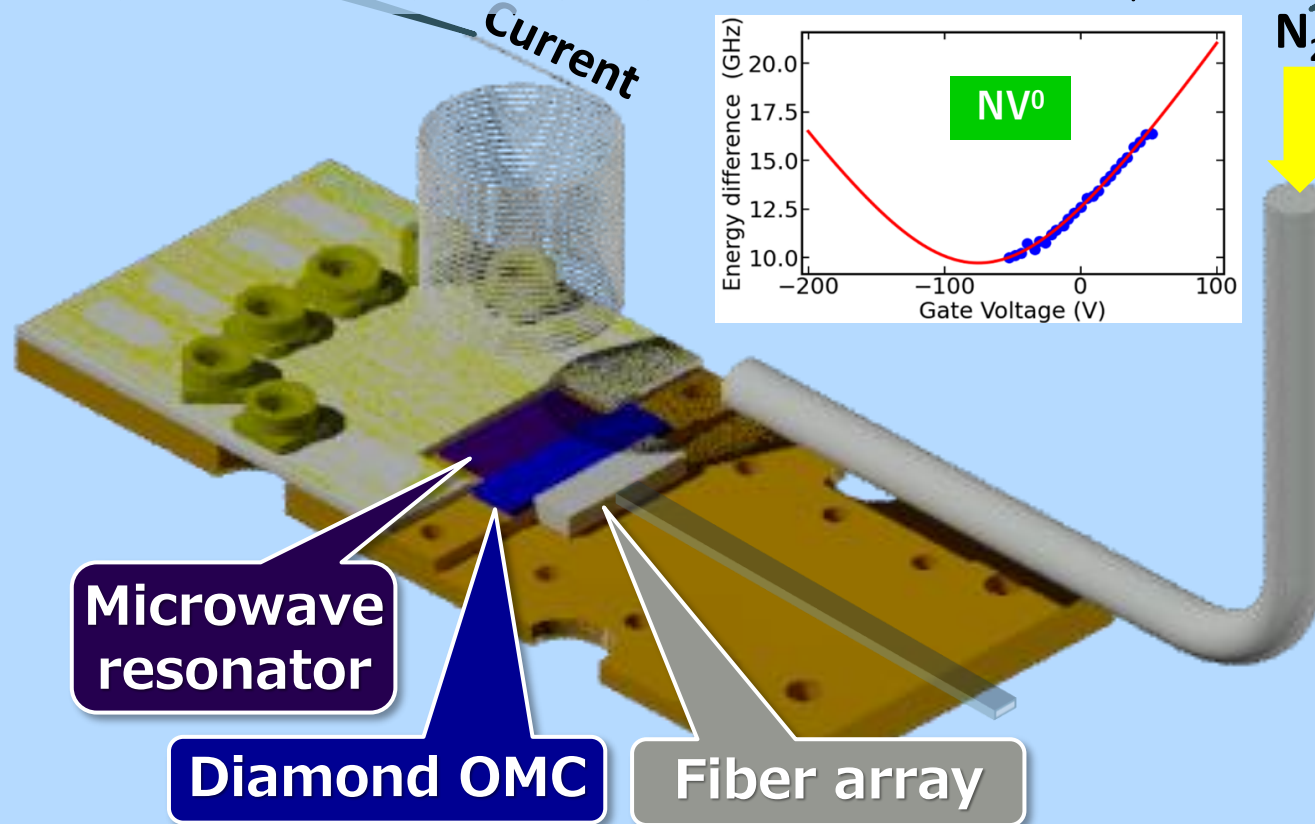
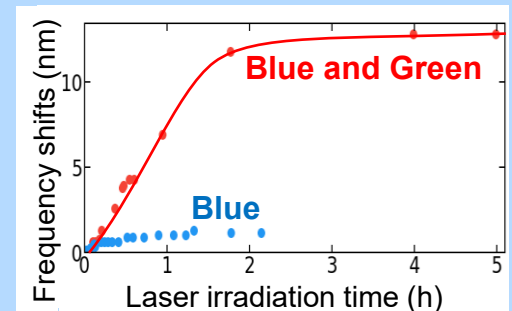
Range ~2 GHz
(Tolerance ~5 MHz@50 μ V)



Optical

Gas

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



Strategy for Frequency Tuning

Microwave

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

Mechanical

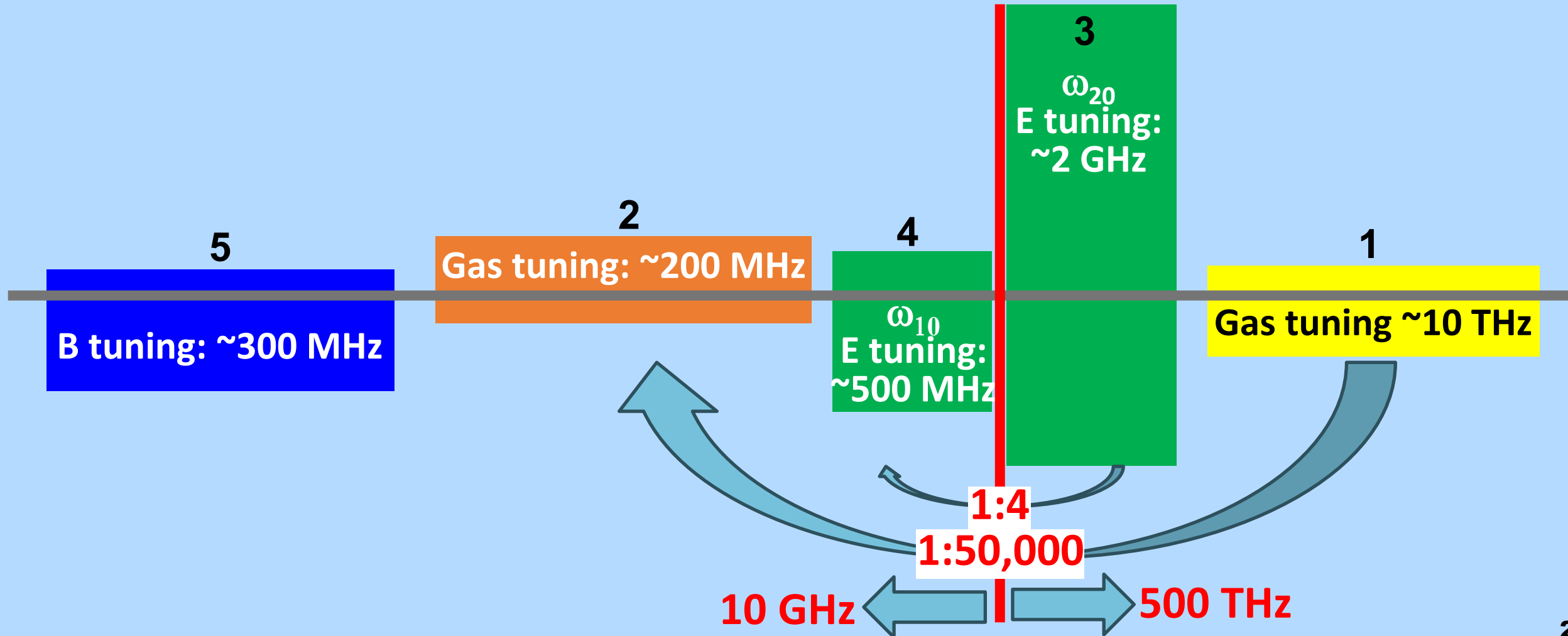
No tunability
(synchronized with optical frequency)

NV⁰

Range ~2 GHz
(Tolerance ~5 MHz@50 μ V)

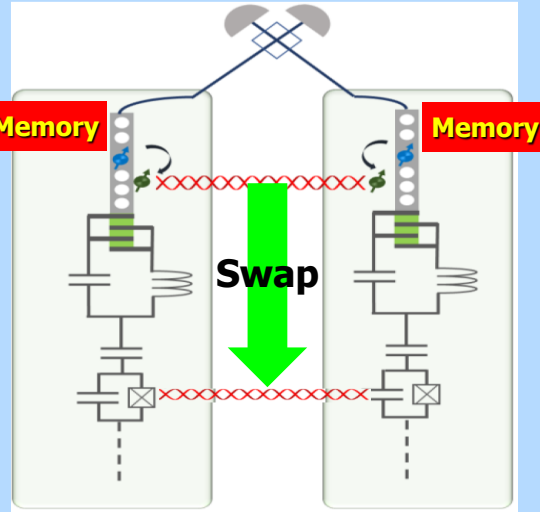
Optical

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

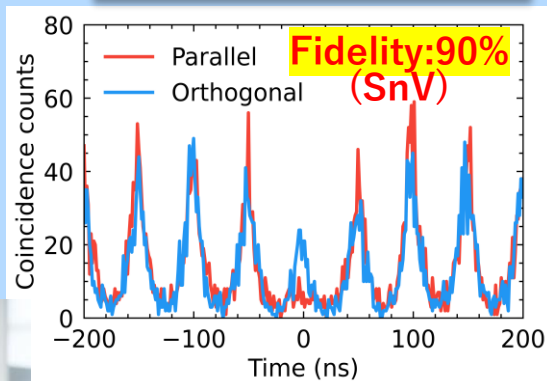


Estimation of Bell-pair Generation Rate between SC qubits

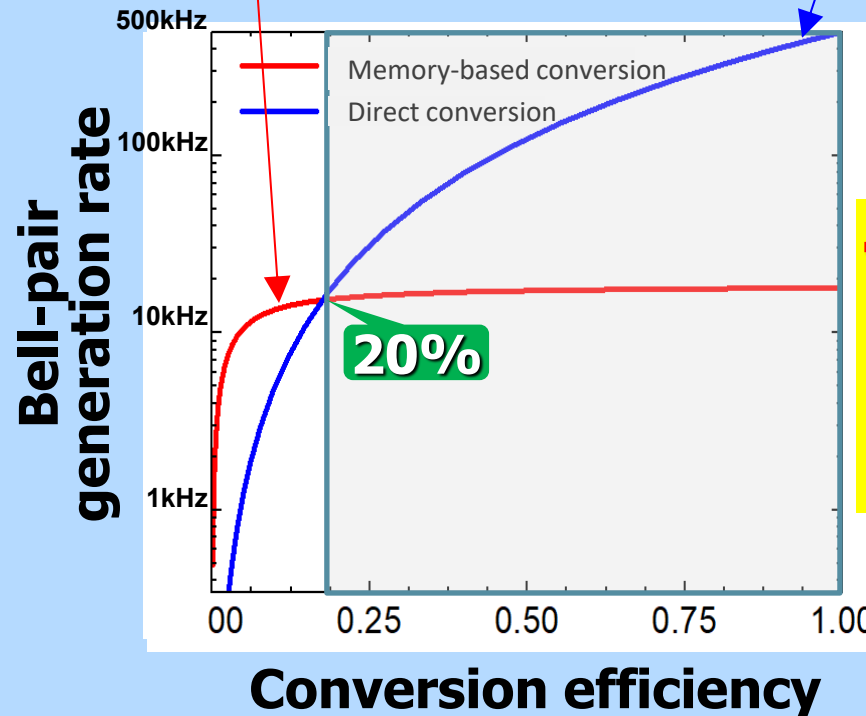
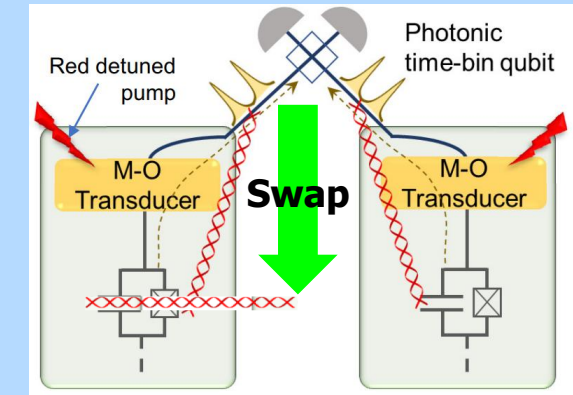
Memory-based conversion ~ 20 kHz



HOM Interference



Direct conversion ~ 0.5 MHz



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



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).

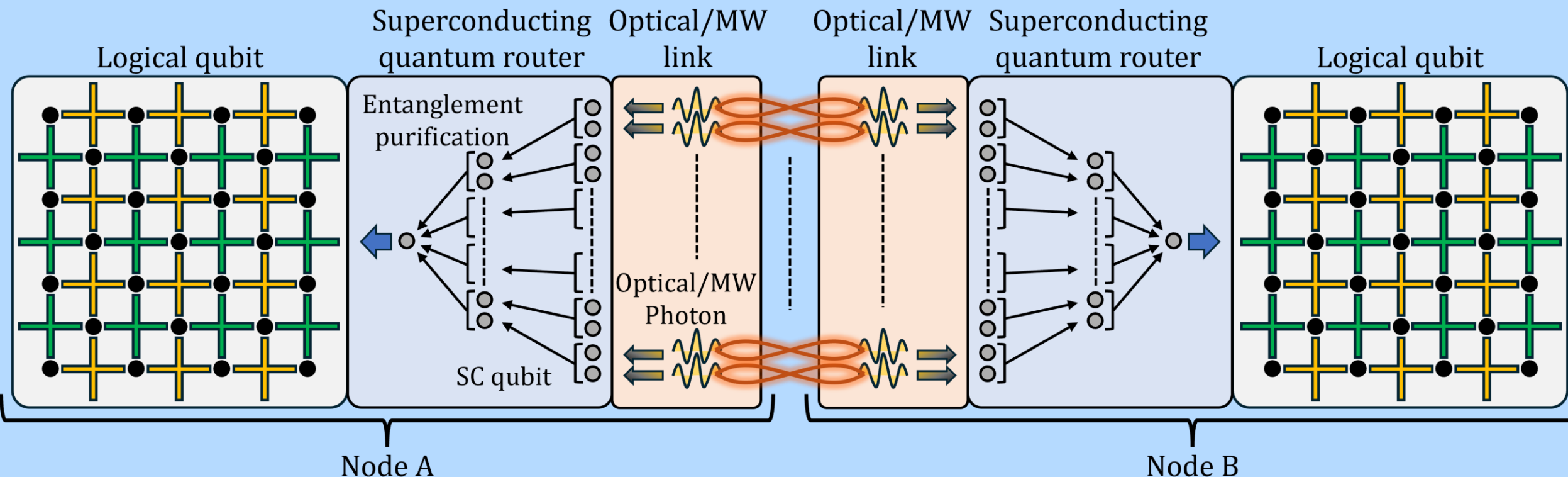
Purified Bell-pair Generation Rate



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

OTakumi 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

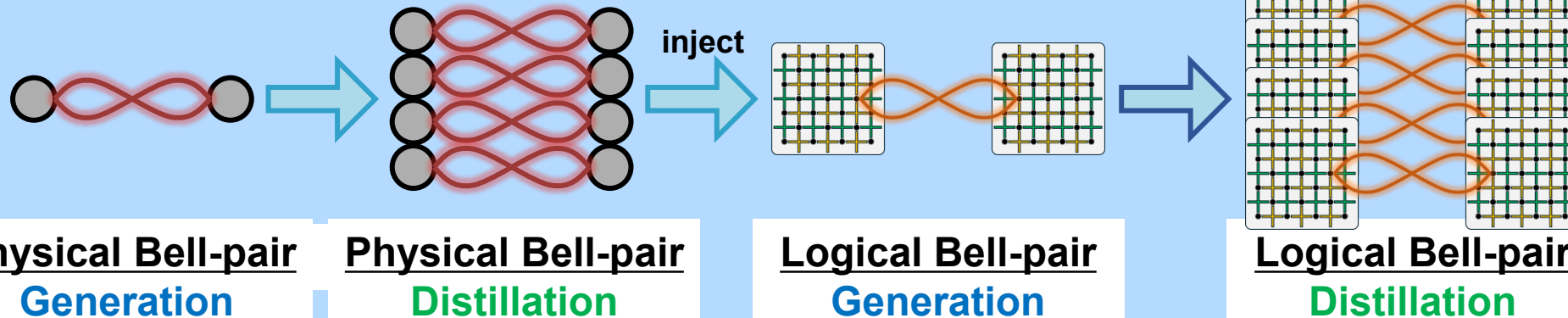
Purified Bell-pair Generation Rate



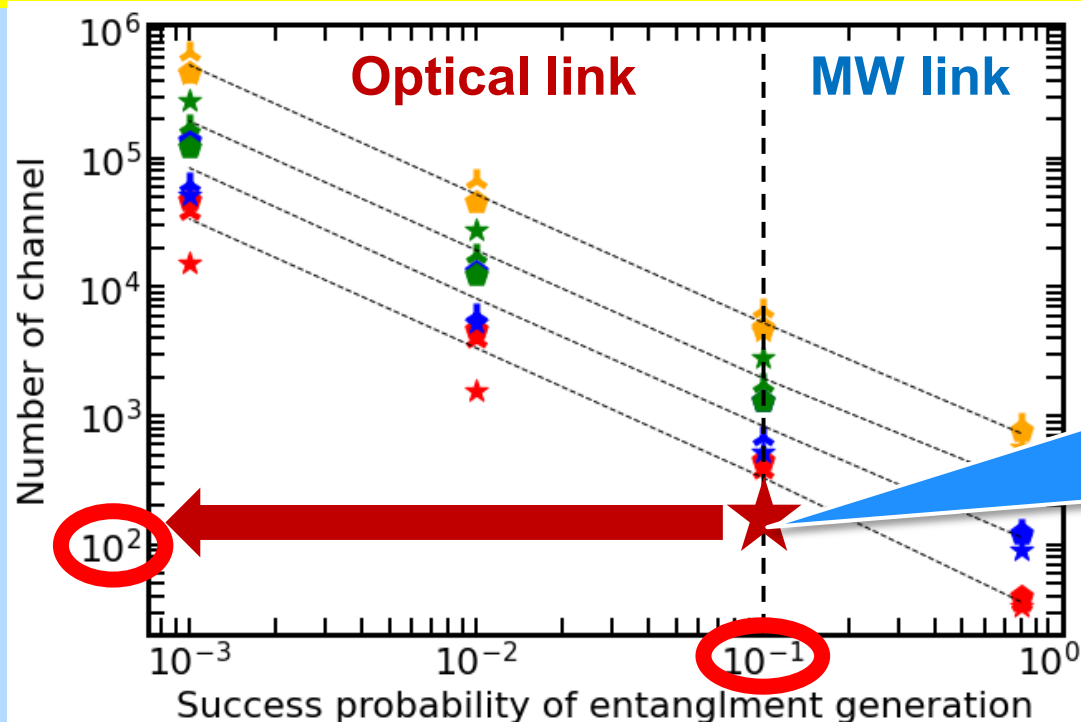
Takumi Kobayashi
(YNU)



Yasunari Suzuki
(RIKEN)
Koashi-Pj



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

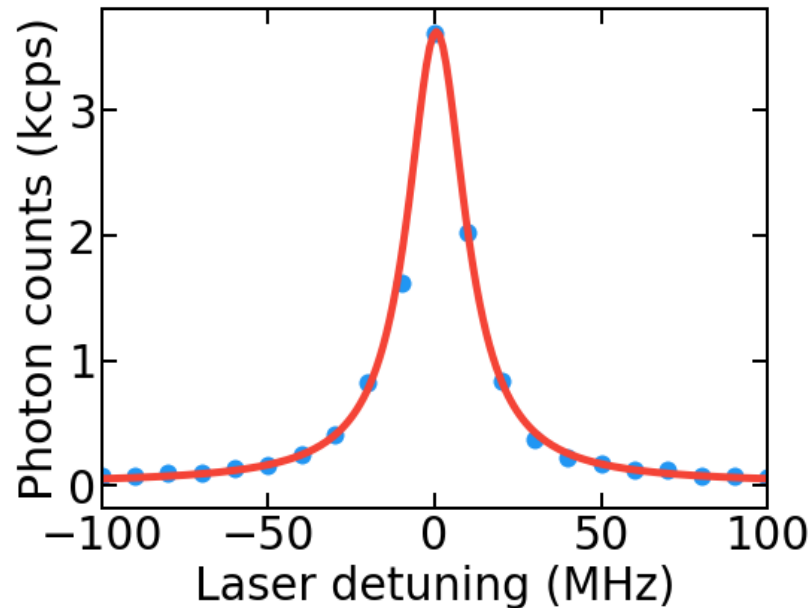


Tokuyuki Teraji
(NIMS)

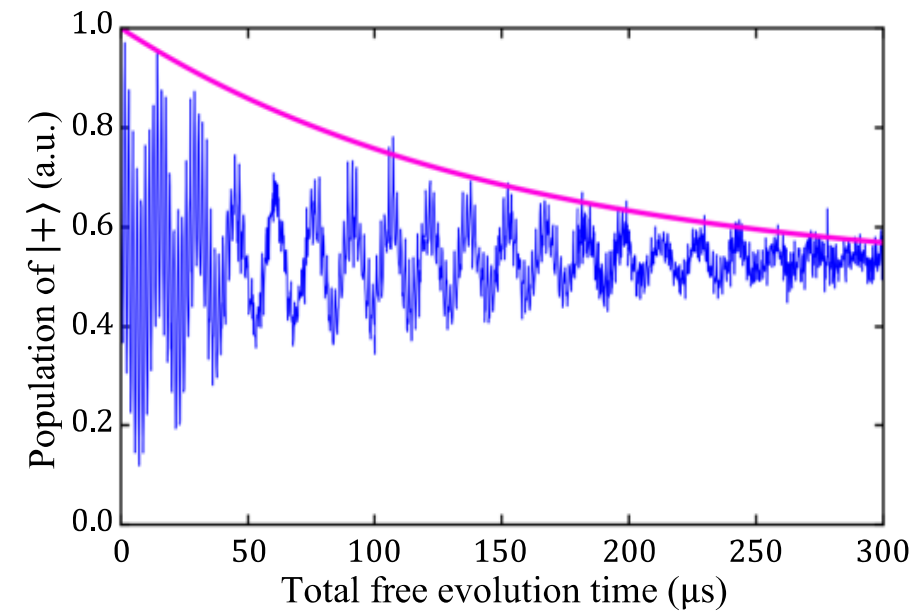
Nearly natural linewidth with
material purity of **99.99999999%**



Long coherence time with
isotropic purity of **99.998%**



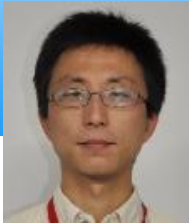
FWHM: 21 MHz



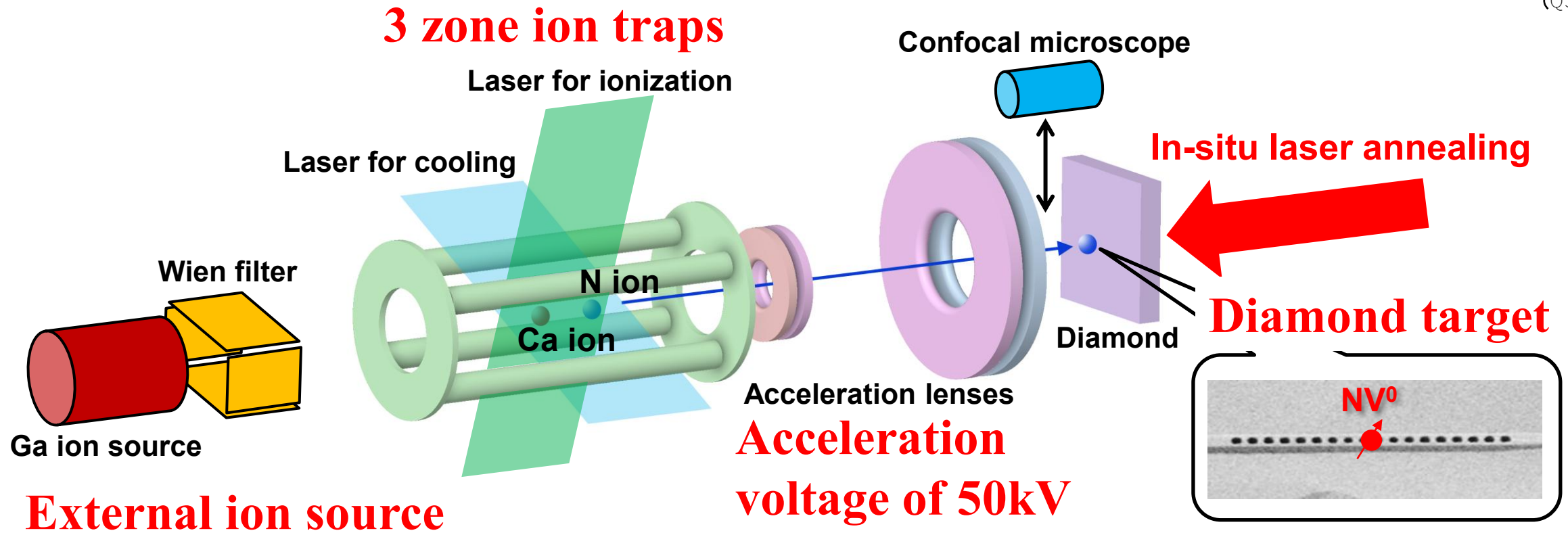
$T_2^* : 150 \mu\text{s}$, $T_2 : 1.5 \text{ ms}$

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

Professor



Toshihiko Baba

Professor



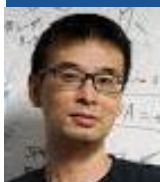
Nobuyuki
Yoshikawa

Professor



Tomoyuki
Horikiri

Professor



Daisuke
Akamatsu

Professor



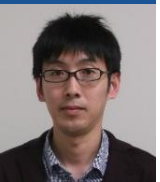
Akihiro
Minamino

**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

Japanese Universities

National Institutes

**Center
Vice Director**



Satoshi Iwamoto



**Visiting
Professor**



Masahiro Nomura



**Visiting
Associate
Professor**



Kazuki Koshino



**Visiting
Professor**



Toshiharu Makino



**Visiting
Professor**



Tokuvuki Teraji



**Visiting
Professor**



Hiromitsu Kato



**Visiting
Associate
Professor**



Shinobu Onoda



International

**Visiting
Professor**



Fedor Jelezko



**Visiting
Professor**



Jonathan Finley



**Visiting
Professor**



Christoph Becher



**Visiting
Professor**



Kai Mueller



Company

**Visiting
Professor**



Yu Mimura
**FURUKAWA
ELECTRIC**

**Visiting
Associate
Professor**



Mamiko Kujiraoka

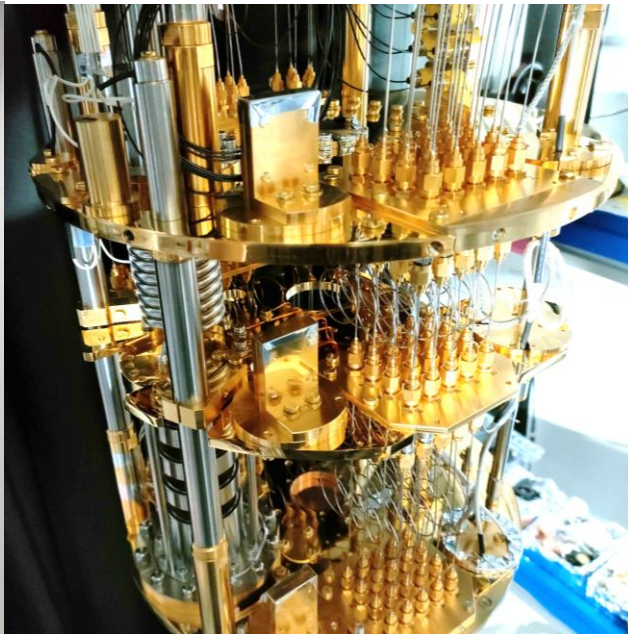
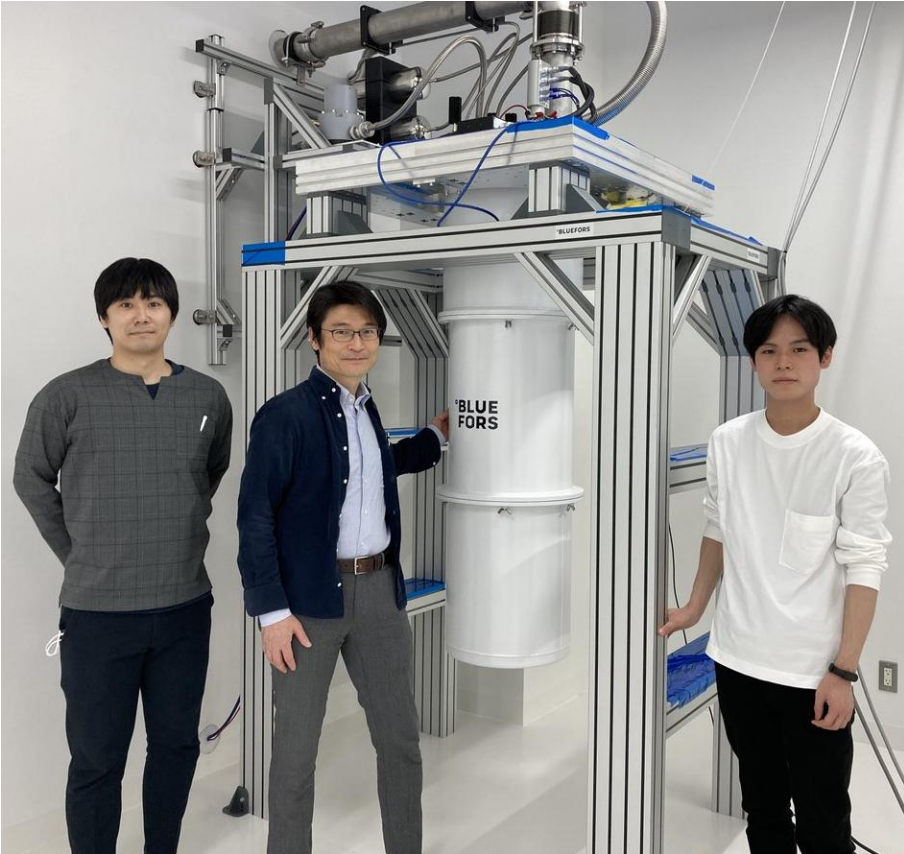


Partnership



Joint Research





<https://youtu.be/83ux1NhPbSw>

QIC Research Video Featured
at the APS Global Physics Summit 2025



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

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



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



Inside Japan's Quantum Future: Fostering Innovation & Connecting Minds at QIC



WebsEdge Science
チャンネル登録者数 2.33万人

チャンネル登録

👍 20



🔗 共有

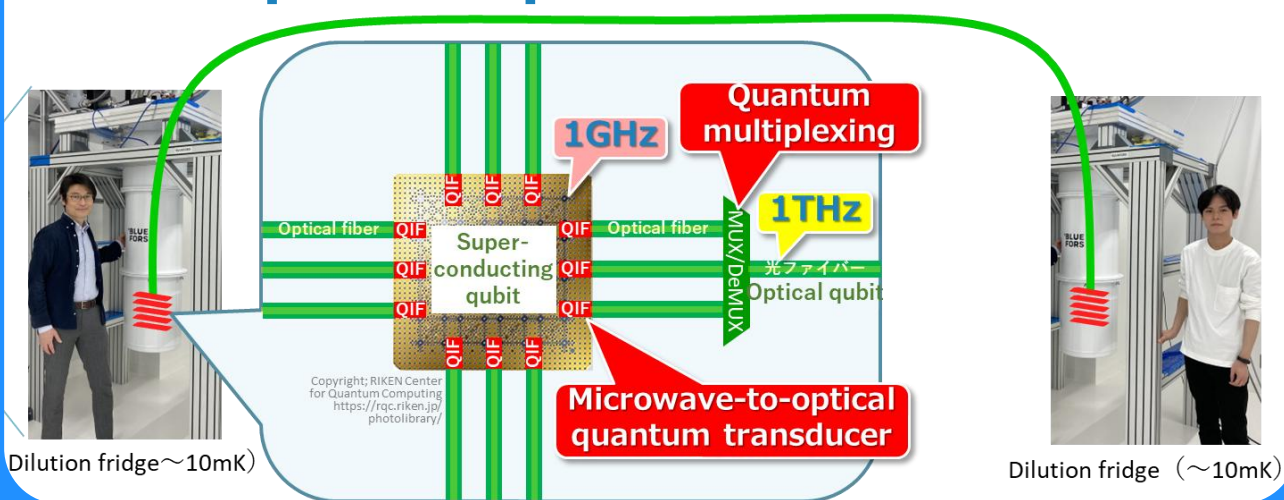
📄 オフライン



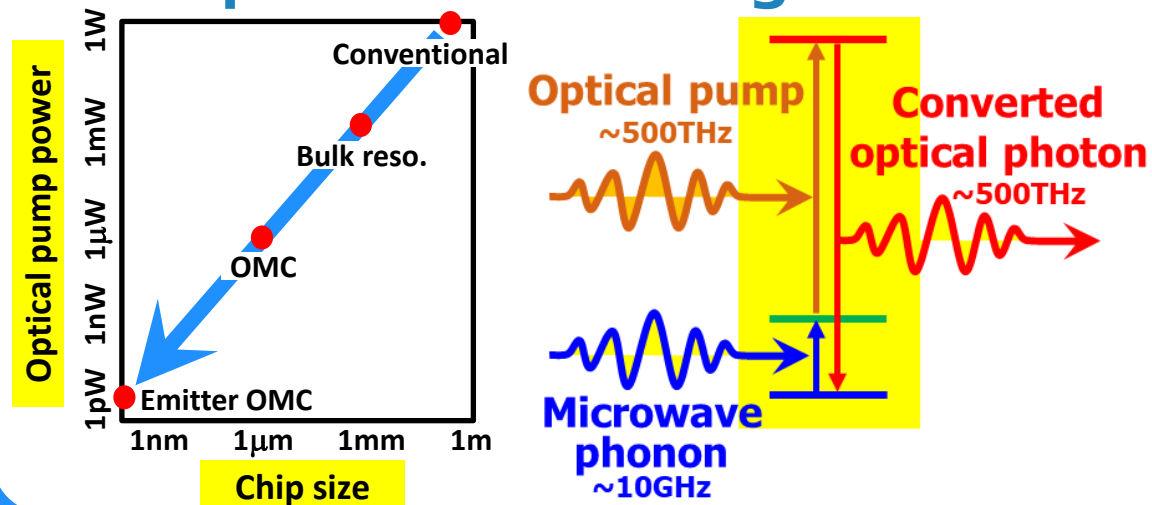
Summary



Purpose: Optical interconnect



Concept: Emitter-integrated OMC



Status: Core Elements are ready to build up

Microwave

Mechanical

NV⁰

Optical

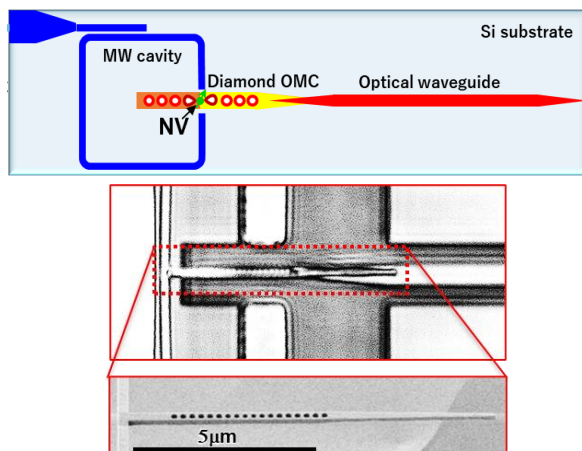
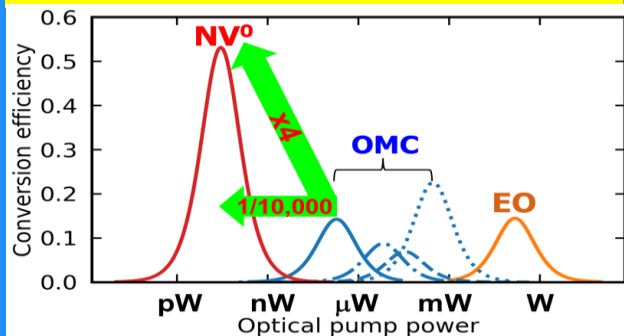
$Q_{mw} > 20,000$

$Q_m > 20,000$

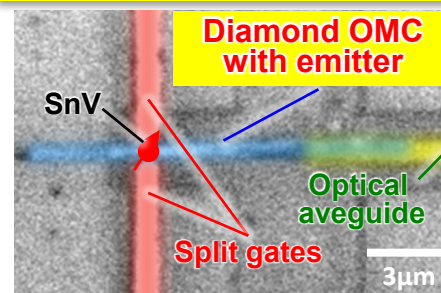
$Q_n \sim 300,000$

$Q_{opt} \sim 10,000$

Efficient and Broad BW with Low Pump Power



MW-optical photon coherent conversion



Towards Distributed Quantum Computing

