Apr. 23 2021
Moonshot International Symposium for Goal6

Fault-tolerant Quantum Computing with Photonically Interconnected Ion Traps

Okinawa Institute of Science and Technology
Graduate University

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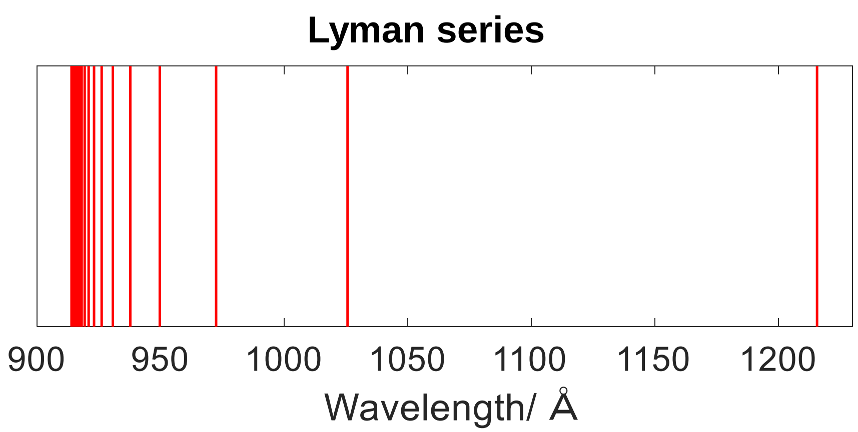
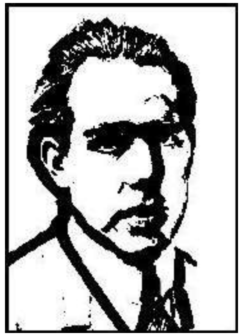
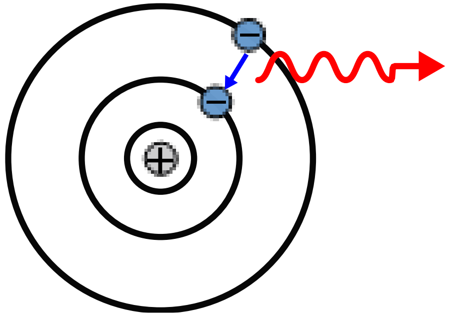
Quantum Mechanics and Atoms



Quantum Mechanics started with studies of simple atoms (e.g. Hydrogen).

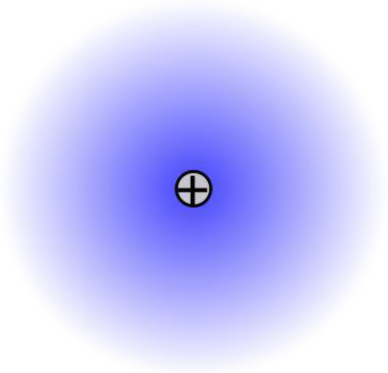


N.Bohr



Bohr model

E. Schrödinger



Wave function

$\Psi(x)$

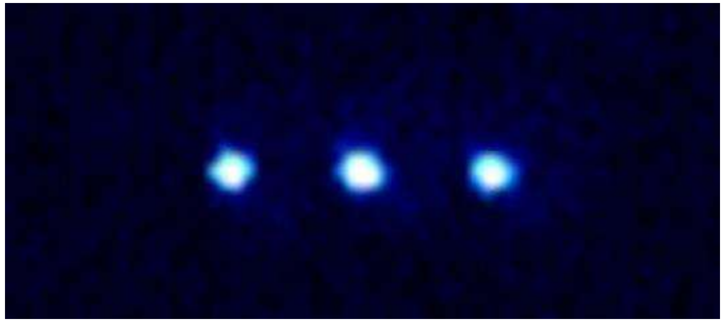
- Physics of isolated atoms **well understood** and in domain of **precision science**.
- Quantum effects manifested in **isolated atoms**.

A way to make a quantum computer？

- **What if we could line up individual atoms one by one？**

Each atom works as a qubit!

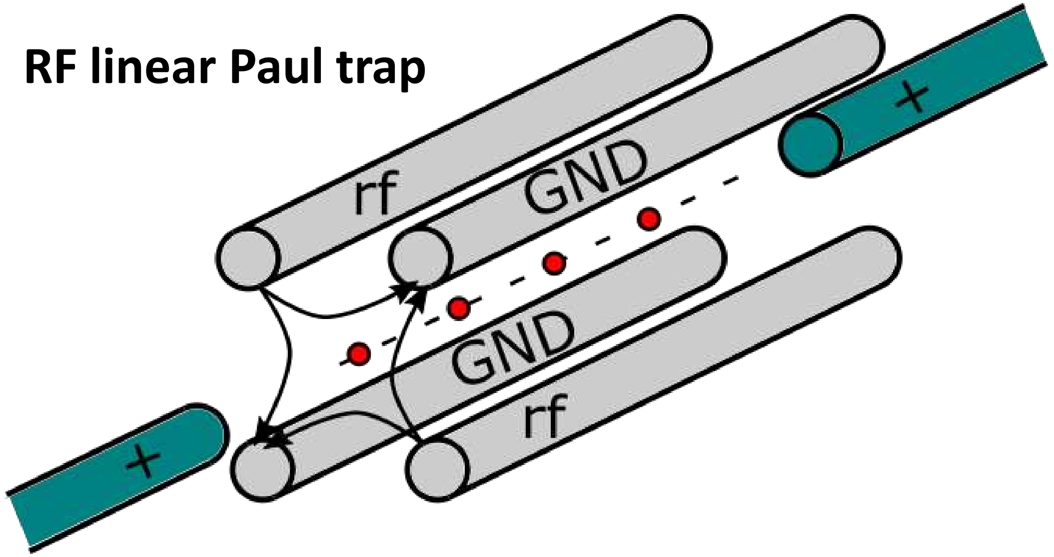
- **Ion trapping just does that ！**



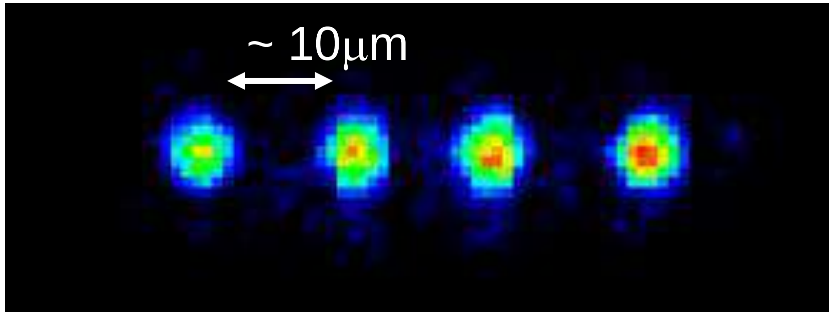
What's ion trap?

- **Ions →** Charged atomic particles.
- **Why ions? →** Motion can be controlled electrically.
- **Trapped in vacuum →** Isolated from environment.
- **Laser cooling→** Cooled down to μK $\sim$ mK.

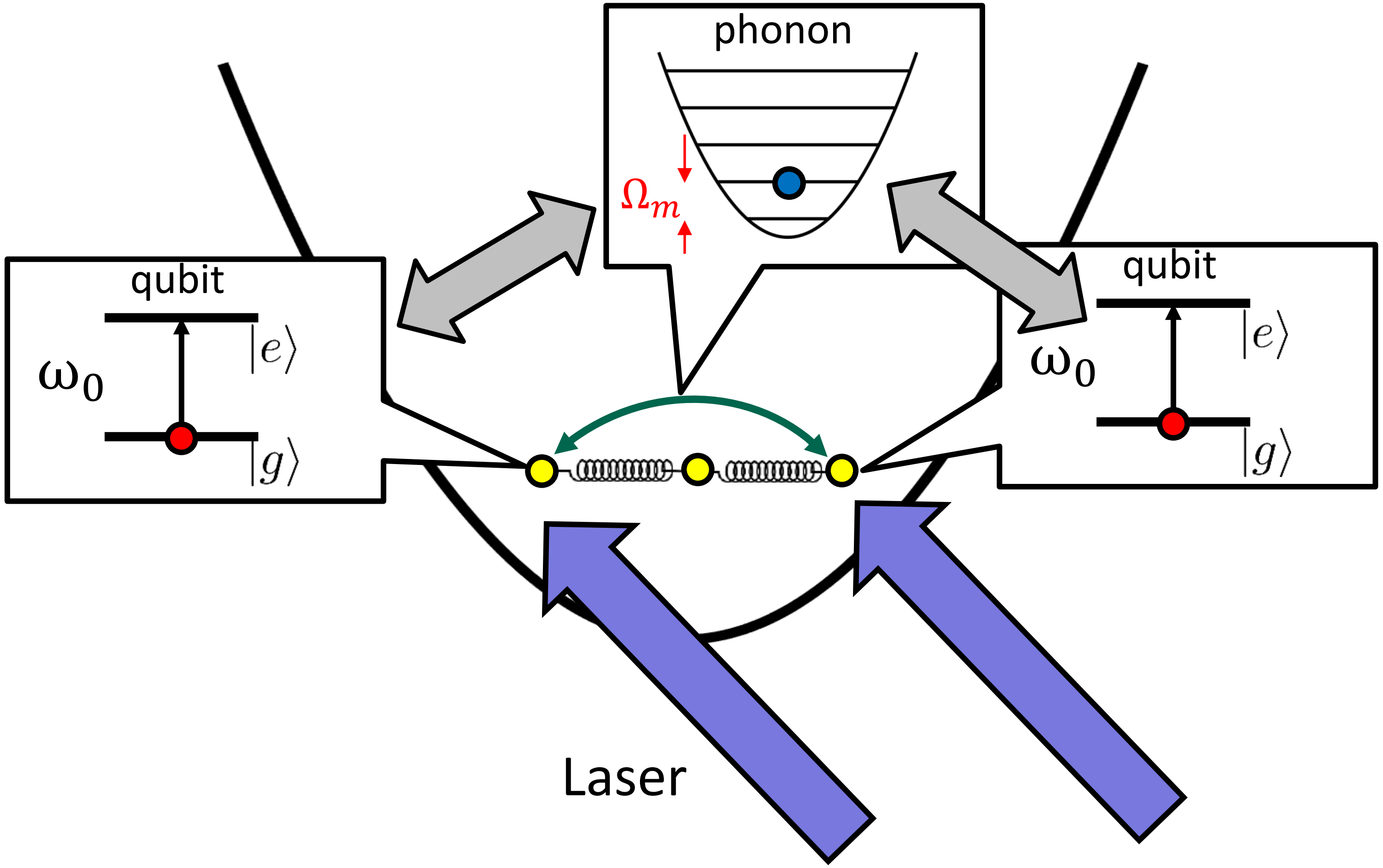
RF linear Paul trap



Applying **voltages to electrodes**, multiple ions are trapped and **linearly aligned** with almost **no residual motion**.



Principles of ion trap QIP



- Qubit-qubit interaction via **collective phonons**.
- Two-qubit entangling gate:
  - Cirac-Zoller gate
  - **Mølmer–Sørensen gate**
- Entanglement between an arbitrary pair. → **All-to-all connection.**

State of the art

- **Basic elements demonstrated with high fidelities:**
  - Single qubit gate ･･ F=99.9999 %
  - Two qubit gate ･･ F= 99.9 %
  - SPAM ･･ F> 99.9 %
- **Long coherence times:**
  - T_2 > 1hr (Nat Commun. 12, 233 (2021)).

https://physicsworld.com/a/ion-based-commercial-quantum-computer-is-a-first/

Image credit: IonQ

- **Cloud-based services provided by IonQ and Honeywell.**
- **Current issue ： How to increase # of qubits.**
  - 13 ions (arXiv: 2009.11482(2020)), 20 ions (PRX 8, 021012(2018)).
  - What's the bottleneck?

Can we scale up as it is?

http://iontrap.umd.edu/wp-content/uploads/2017/06/cropped-50ionsblur-3.jpg

TIQI Group, University of Maryland

Q. Can we increase the number of ions in a ***single trap*** *indefinitely?*

A. No. There's a practical limit. 50-100 ions?

<u>Issues with increasing number of ions</u>:

1. **Trap becomes shallower.**
   → Decreasing trap freq.:
   $\omega \approx 0.73\, N^{-0.87}$
   → Slow gates, motional heating, trap instability.
2. **Number of sidbands (=3*N*) increases. Crowding in freq. space.**
   → Erroneous cross talks between sidebands.

Challenges

- Increasing ions in a single trap does not work in a long run.
- A technology to **connect multiple ion traps** is necessary.

Quantum CCD
(By shuttling)

Figure 1
in
Kielpinski et al.
Nature **417** 709
(2002).

Kielpinskii, Monroe&Winland (2002)

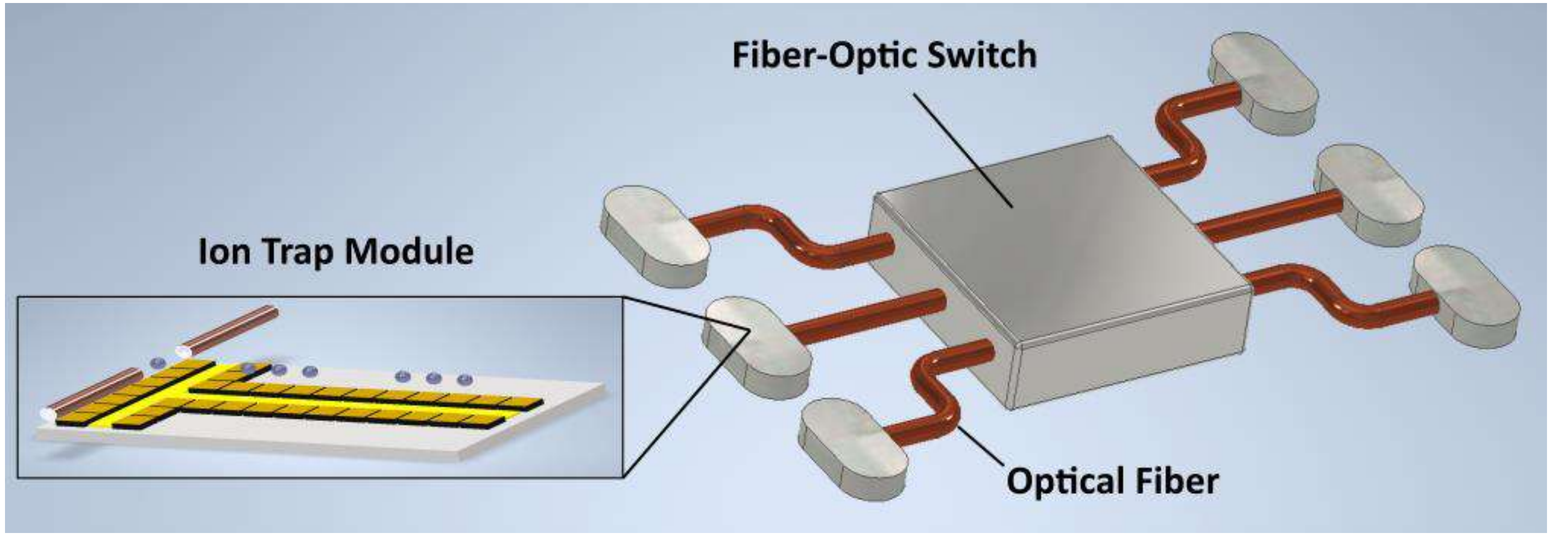
Photonic interconnects
(By photons)

Figure 4
In
Monroe & Kim
Science **339,** 1164 (2013).

Monroe & Kim, *Science* **339,** 1164 (2013).

Design concept

Photonically interconnected ion trap modules



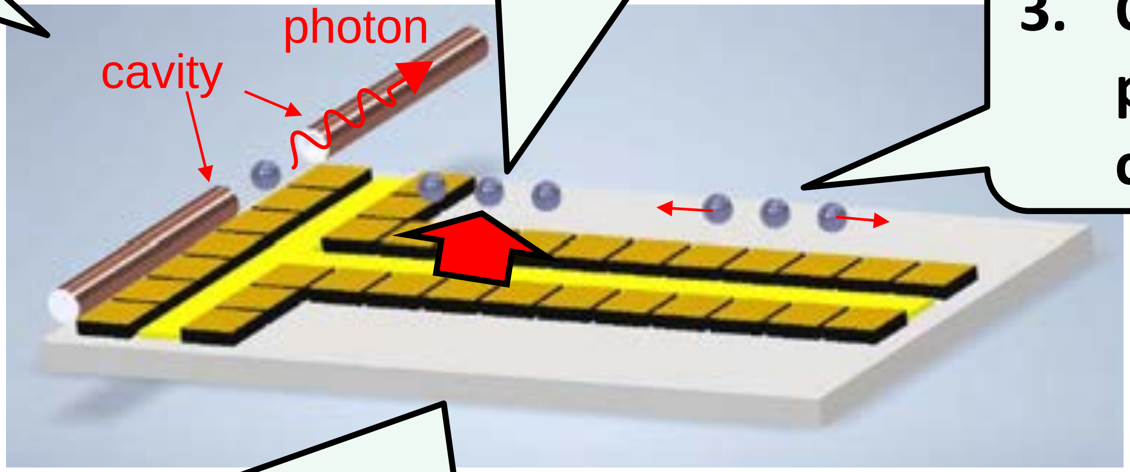
1. Interconnecting **ion trap modules** with photons.
   → Scalability **beyond a single trap**.
2. Ion trap modules with **novel functionalities**.
   → Exploiting **optical, MW, phononic** DoF of ions.

Development of the ion trap module

1. Efficient ion-photon quantum interface

2. High fidelity fast quantum logic

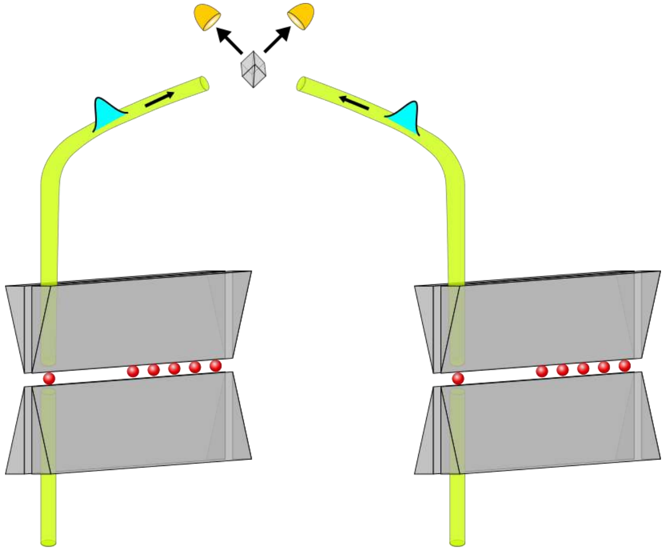
3. Quantum control of phonons towards error correction

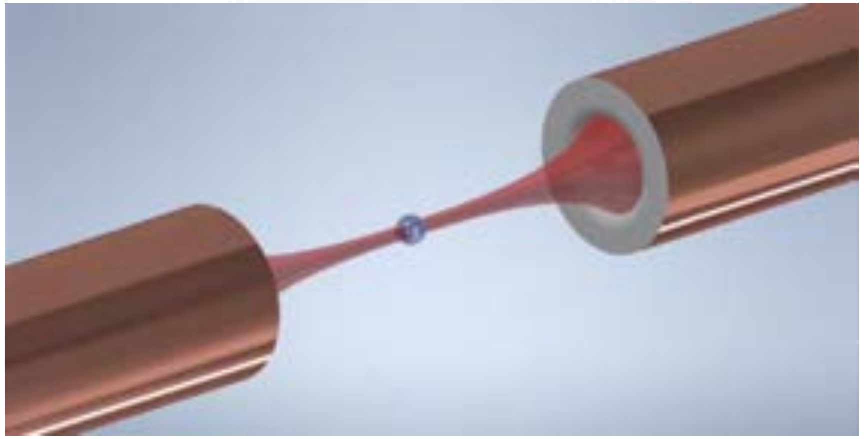


4-1. Fabrication & characterization of high-performance ion traps
4-2. R&D for cloud quantum computing

1: Photonic interconnects of ion traps

Hiroki Takahashi
(OIST)

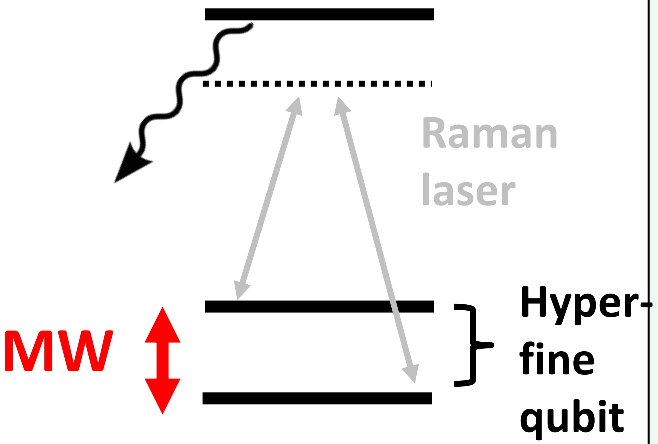


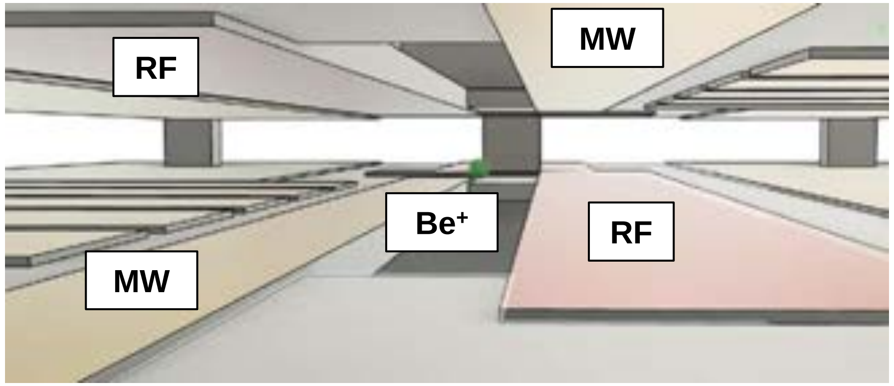


- Improve the efficiency of photonic interconnects via **cavity QED**.
- **Strong coupling** between an ion and a photon (PRL 124 013602).
- Integrating **micro-optical cavities in a linear trap.**
- Remote entanglement rate >10kHz (2 orders of mag. improvement)

2: Ion traps using superconducting MW circuits

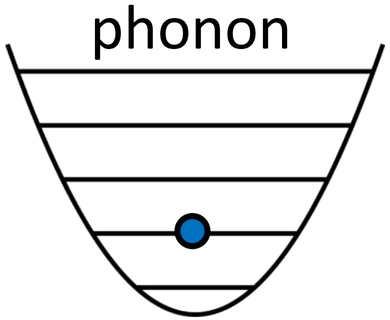
Atsushi Noguchi
(U. Tokyo)



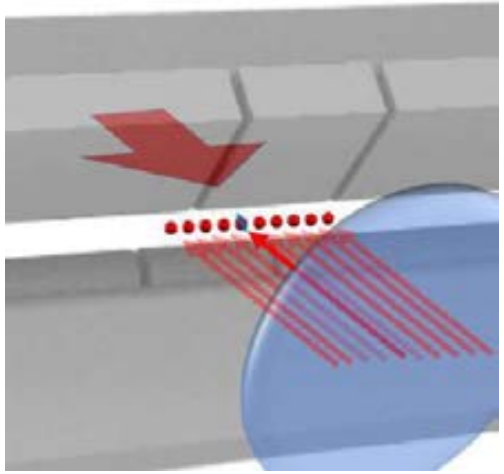


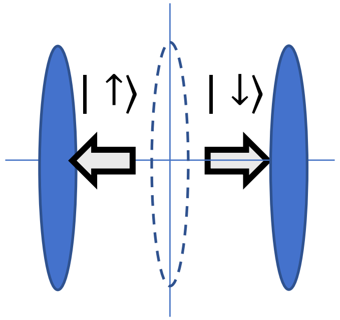
- Direct MW drive of hyperfine qubits, **eliminating spontaneous emissions**.
- **Superconducting MW resonators** generates strong fields with low input.
  → **High-fidelity fast quantum logic**
  10 times faster w/ 1/1000 input power.
- **High frequency phonons**
  → Speed up cooling and shuttling
- **Ultra-low vibration cryostat**.
- High freq. + Cryo → **Low heating rate**

3: Quantum error correction using the phononic DoF



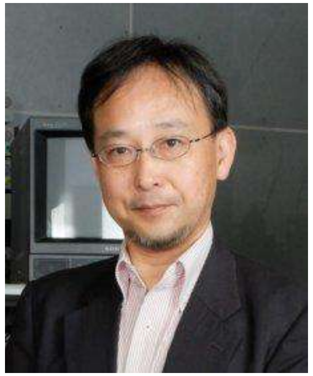
Kenji Toyoda
(Osaka U.)





- Utilizing continuous variables in harmonic oscillators for error correction.
  → **Bosonic encoding**
- **Quantum control of multiple collective phonon modes**
  - **Beam splitter interaction** between the modes.
  - **Nonlinearity** by two-level system.
  - **Squeezed states** + BS → **cluster states.**
  - **Superposition of squeezed states → GKP states.**

4-1: Fabrication & characterization of high-performance ion traps



Kazuhiro Hayasaka
（NICT）

- Fabrication, testing and supply of high-performance ion traps .

- **Planar as well as 3D ion traps** by microfabrication.

- Supplying ion traps specific for each sub-projects:
  - Ion traps for photonic interconnects (OIST)
  - Superconducting ion traps (U. Tokyo)
  - Ion traps for phonon engineering (Osaka U.)
- **Supplying ion traps to the community**.

- International collaboration:
  - Planar traps: C. Ospelkaus (Hannover)
  - 3D traps: T. Mehlstaeubler (PTB)

4-2: R&D for cloud quantum computing

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Kenji Toyoda
(Osaka U.)

Specs for ion trap cloud computing prototype

- $^{171}Yb^{+}$
- Hyperfine qubits (infinite T_1)
- Long coherence times w/ Zeeman insensitive qubits
- 4-10 ions
- micro- 3D trap by NICT
- Middleware/Software (Fast optimal pulse modulation, cloud connection)
- Fidelity target: 0.99 – 0.995

Aims

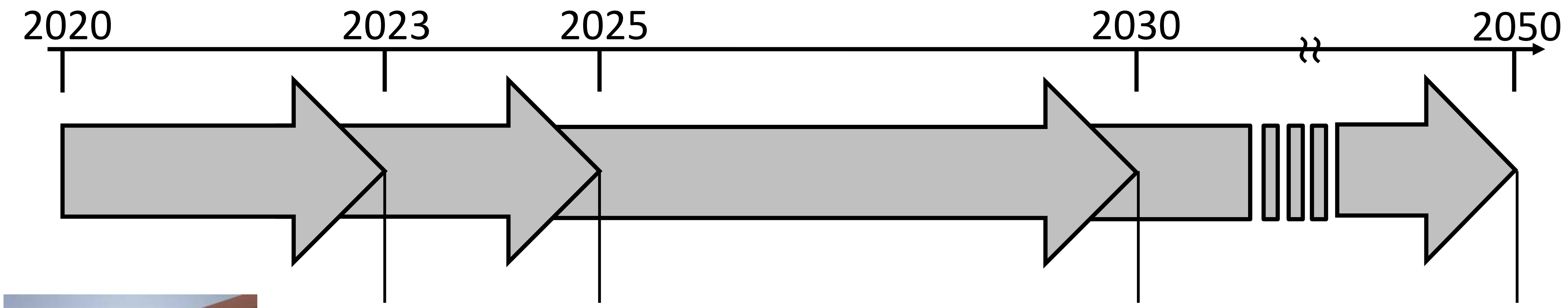
- Preparation for the future social/commercial implementation.
- Education use: "**Remote lab**"

Underlying technologies @Osaka

Ca+ 4-qubit collective gate F=0.96 [1]
Ca+ 2-qubit individual access, analog sim.[2]
Ca+ 4-qubit individual access, analog sim.[3]
Ca+ 10-qubit trapping [unpublished]

[1] A. Noguchi, S. Haze, K. Toyoda and S. Urabe, *Phys. Rev. Lett.* **108**, 060503 (2012).
[2] K. Toyoda, R. Hiji, A. Noguchi and S. Urabe, *Nature* **527**, 74 (2015).
[3] M. Tamura, T. Mukaiyama and K. Toyoda, *Phys. Rev. Lett.* **124**, 200501 (2020).

Timeline

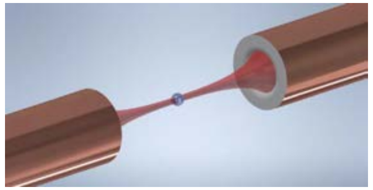


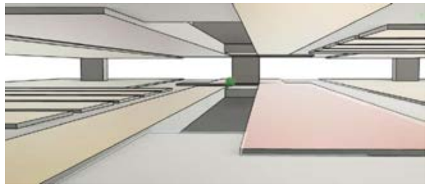
Establishing underlying technologies

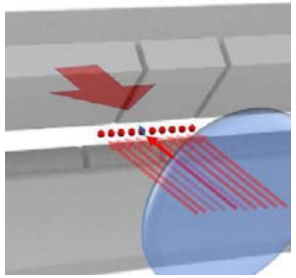
Demonstration of essential functions for the ion trap module

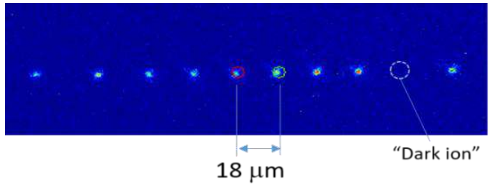
QC w/ photonically interconnected ion trap modules

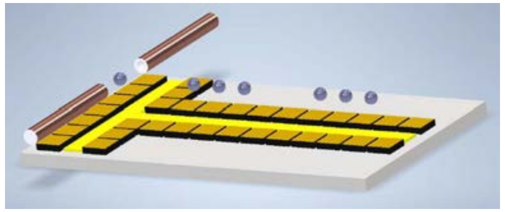
Fault-tolerance

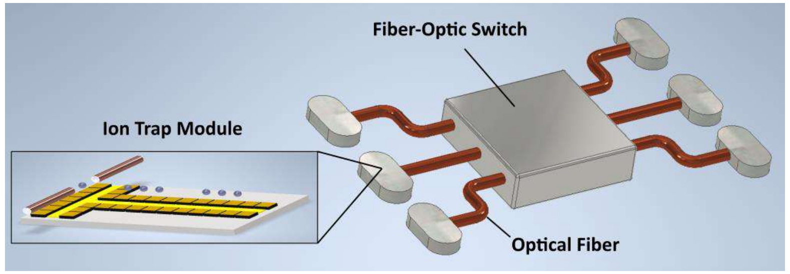












Thank you!