NanoQT
Nanofiber Quantum Technologies

Atom-Photon Interface using Nanofiber Cavities with Neutral Atoms

FoPM 2nd International Symposium
Feb. 19, 2025

Akihisa Goban, CTO

Company overview

NanoQT
Nanofiber Quantum Technologies

Core technology:

Ultra-low loss nanofiber cavity devices for cavity-QED atom-photon interface

Collaborators and Accelerators

- 🇨🇦 University of Calgary
- 🇺🇸 University of Maryland
- 🇺🇸 Quantum Startup Foundry
- 🇺🇸 MIT Center for Quantum Engineering
- 🇨🇦 Creative Destruction Lab
- 🇺🇸 Berkeley SkyDeck
- 🇨🇦 Xanadu
- 🇺🇸 |QuEra> Computing Inc.

Support (VC, government funding)

- 🇯🇵 WUV
- 🇯🇵 JAFCO
- 🇯🇵 SPARX
- 🇯🇵 KII
- 🇺🇸 Phoenix Venture Partners
- 🇯🇵 NEDO
- 🇺🇸 Maryland Department of Commerce

2022
Founded as the 1st quantum computing hardware startup in Japan

22
Patents filed in US

12
Ph.D. scientists/engineers from MIT, Caltech, Oxford, U of Tokyo, etc

+13.5 M USD
Raised capitals from VCs & Government grant from JP and USA

USA/Japan
Global location: Tokyo (Hardware), Maryland (Theory) and CA (HQ)

Global locations and operations

🔴 Collaborator & Partner location

🔵 Office location

Collaboration with
C. Simon @**Calgary**
(Quantum repeater)

Research visitors/interns
from **Harvard/MIT**
(Bosonic code, AMO physics)

Palo Alto, CA
Headquarter
Co-working member at
Japan Innovation Campus

College Park, MD
Theory Research
Research visitors/interns
from **UMD/JQI**
(qLDPC code, Bosonic code)

Oxford, UK
Theory research operation
(Oxford University)

Research visitors/interns
from **EPFL** (Experiment)

Nagano, Japan
Fiber production
(Deltafiber,Inc.)

Other collab. in Japan
- **Takahashi group** (Kyoto University)
- **NTT**, etc

Tokyo, Japan
Hardware development
(Waseda University)

Team

Management and corporate


Masashi Hirose, Ph.D.

Co-founder & CEO
McKinsey and Company
Ph.D. MIT


Akihisa Goban, Ph.D.

Co-founder & CTO
Postdoc at Waseda University and JILA
Ph.D., Caltech


Prof. Takao Aoki

Co-founder & CSO
Professor at Waseda University
Ph.D., University of Tokyo


Dai Tsukada

Head of Global Operation


Rieko Shinohara

HR/Office manager

Advisor


Richard Ogawa, Esq.

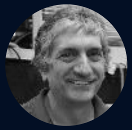
General counsel and intellectual property advisor


Vicky Xiao, CPA

Finance and accounting advisor


Prof. Vladan Vuletić

Cavity QED advisor
Professor of Physics, MIT


Prof. John Martinis

System Engineering advisor
Professor of Physics, UCSB

R&D

Hardware


Ryotaro Inoue, Ph.D.
VP, Quantum System
Ph.D. Tokyo Institute of Technologies


Hideki Konishi, Ph.D.
VP, Photonic Integration
Ph.D. Kyoto University


Shinya Kato, Ph.D.
Principal Research Scientist
Ph.D. Kyoto Univ.


Nicola Komagata, Ph.D.
Research Scientist
Ph.D. University of Neuchatel


Hideki Ozawa, Ph.D.
Research Scientist
Ph.D. Kyoto University


Masafumi Shimasaki, Ph.D.
Device Engineer
Ph.D. Kyoto University


Yusuke Hisai, Ph.D.
Research Scientist
Ph.D. Yokohama National University

Theory


Hayata Yamazaki, Ph.D.
Principal Research Scientist (Architecture/Theory)
Ph.D. University of Tokyo


Shinichi Sunami, Ph.D.
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Ph.D. Oxford University

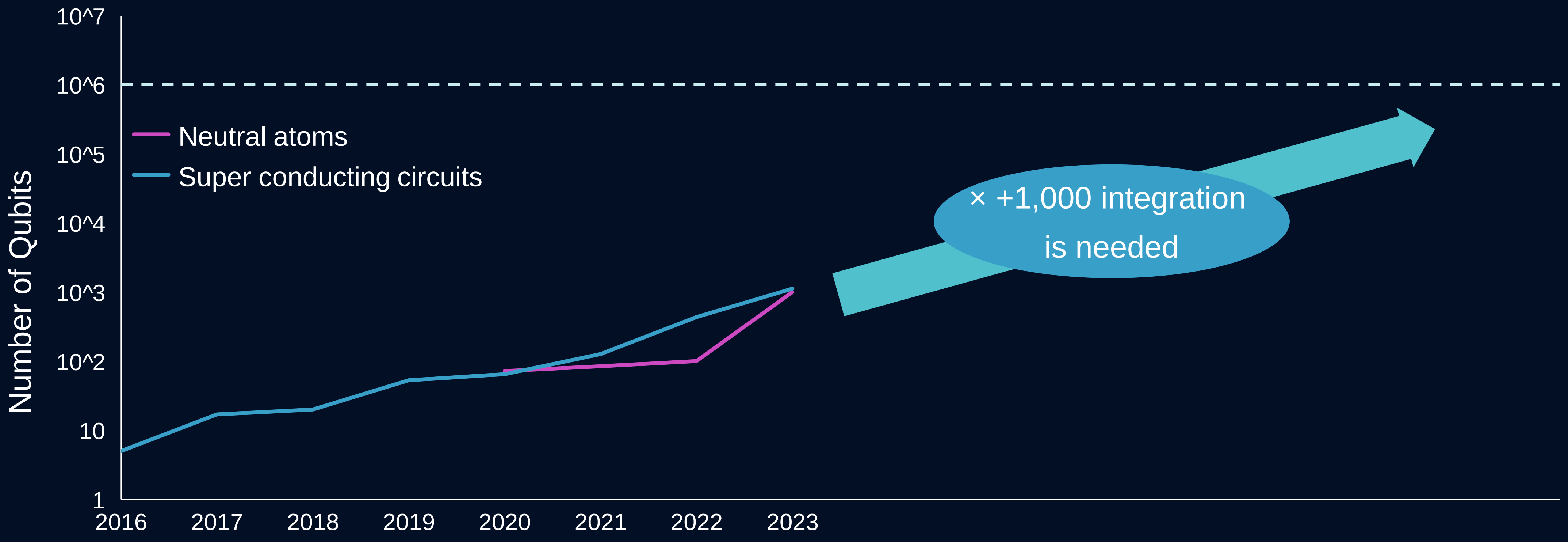

Shiro Tamiya, Ph.D.
Research Scientist (Theory)
Ph.D. University of Tokyo


Seigo Kikura, M.S.
Research Staff (Theory)
M.S. University of Tokyo

Quantum computing is limited by scalability of hardware

- 1–2 trillion USD value at stake: Chemicals, Pharmaceuticals, Materials, etc.
- However, its performance is limited by the computational resources (qubits)

Progress of Quantum Computing Hardware



× +1,000 integration is needed

Source: McKinsey and Company, Web search

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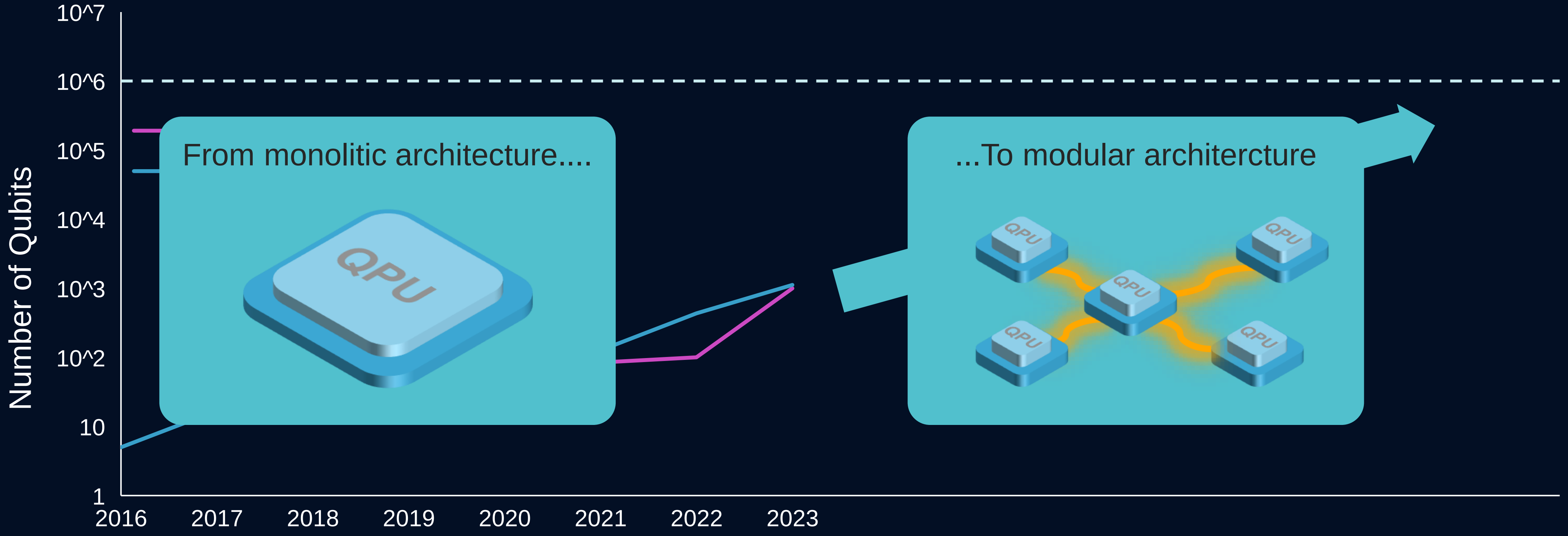
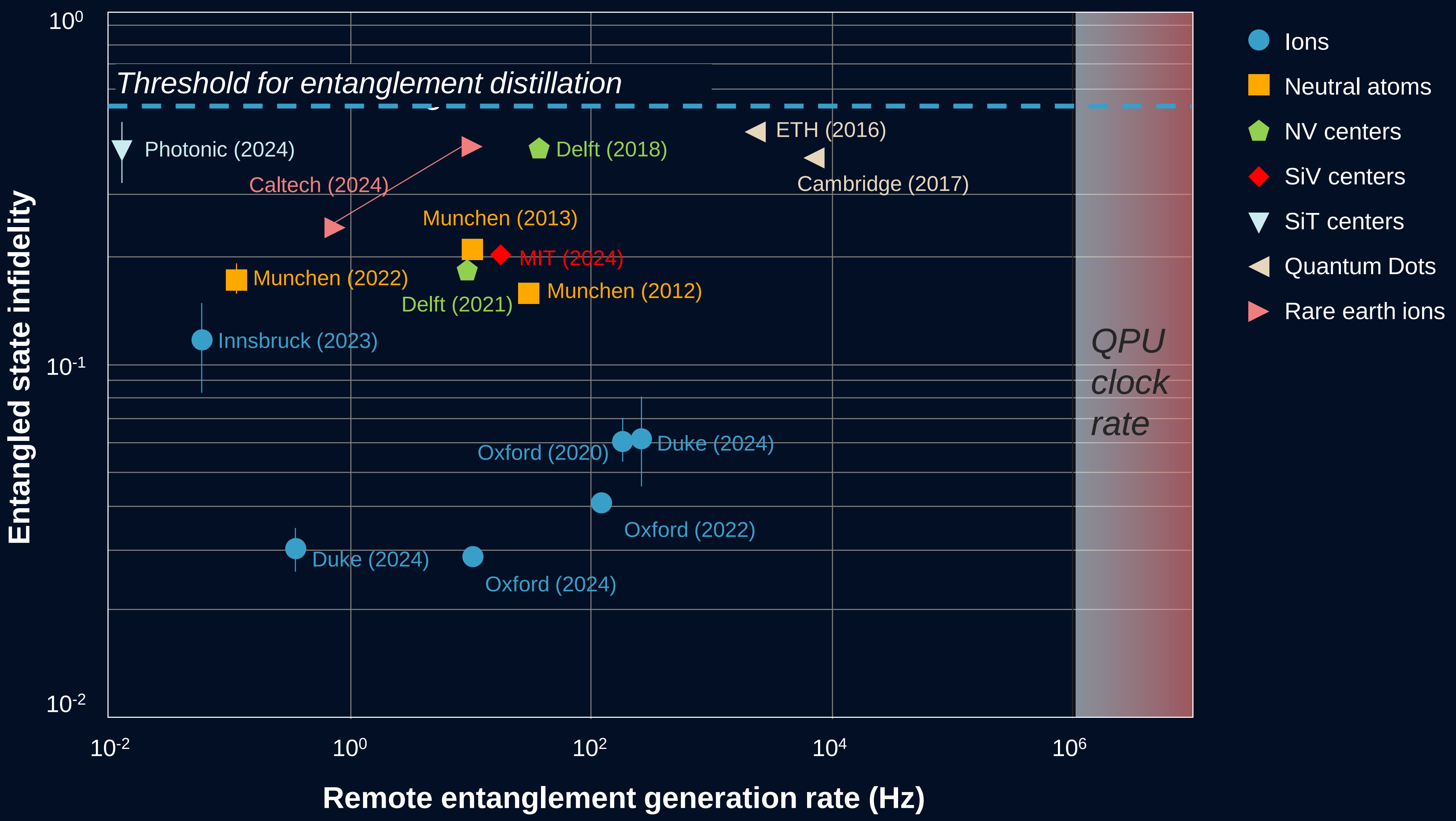


Source: McKinsey and Company, Web search

Current quantum platforms are limited by slow entanglement rates, restricting their practical scalability



Reference: Prof. D. Lucas's talk on ICAP2024

Solution: nanofiber cavity QED platform

1

Low-loss nanofiber cavity QED @ nanoQT

- Projected large cooperativity $C > 100$, based on
  - FBG loss < 0.02 % [Opt. Lett. **47**, 5000 (2022)]
  - Nanofiber loss < 0.03% [Opt. Lett. **45**, 4875 (2020)]
- Waveguide with negligible propagation loss
  - Long cavity; couple many atoms at once

2

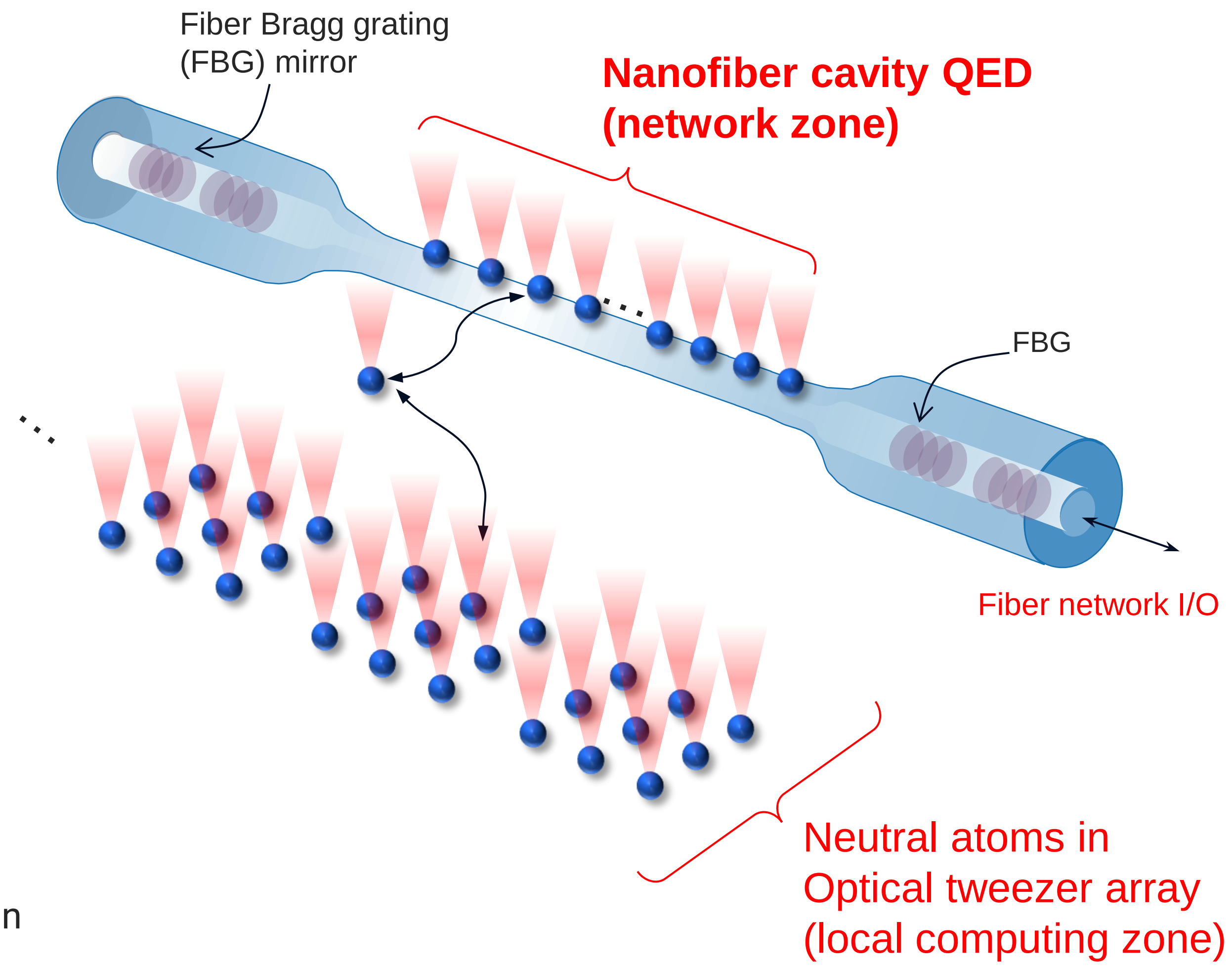
Combining nanofiber cQED & free-space atom array

- Optical tweezer array to couple atoms to cavity
- Move the optical tweezer to interface the two zones
- Low profile: significant channel multiplexing

3

Telecom operation, direct fiber networking

- Neutral Ytterbium atoms:
  - High-fidelity local 1Q and 2Q gates, long coherence time
  - Telecom-band transitions for long-distance communication



Solution: nanofiber cavity QED platform

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Low-loss nanofiber cavity QED @ nanoQT

- Projected large cooperativity C > 100, based on
  - FBG loss < 0.02 % [Opt. Lett. **47**, 5000 (2022)]
- Wave

2

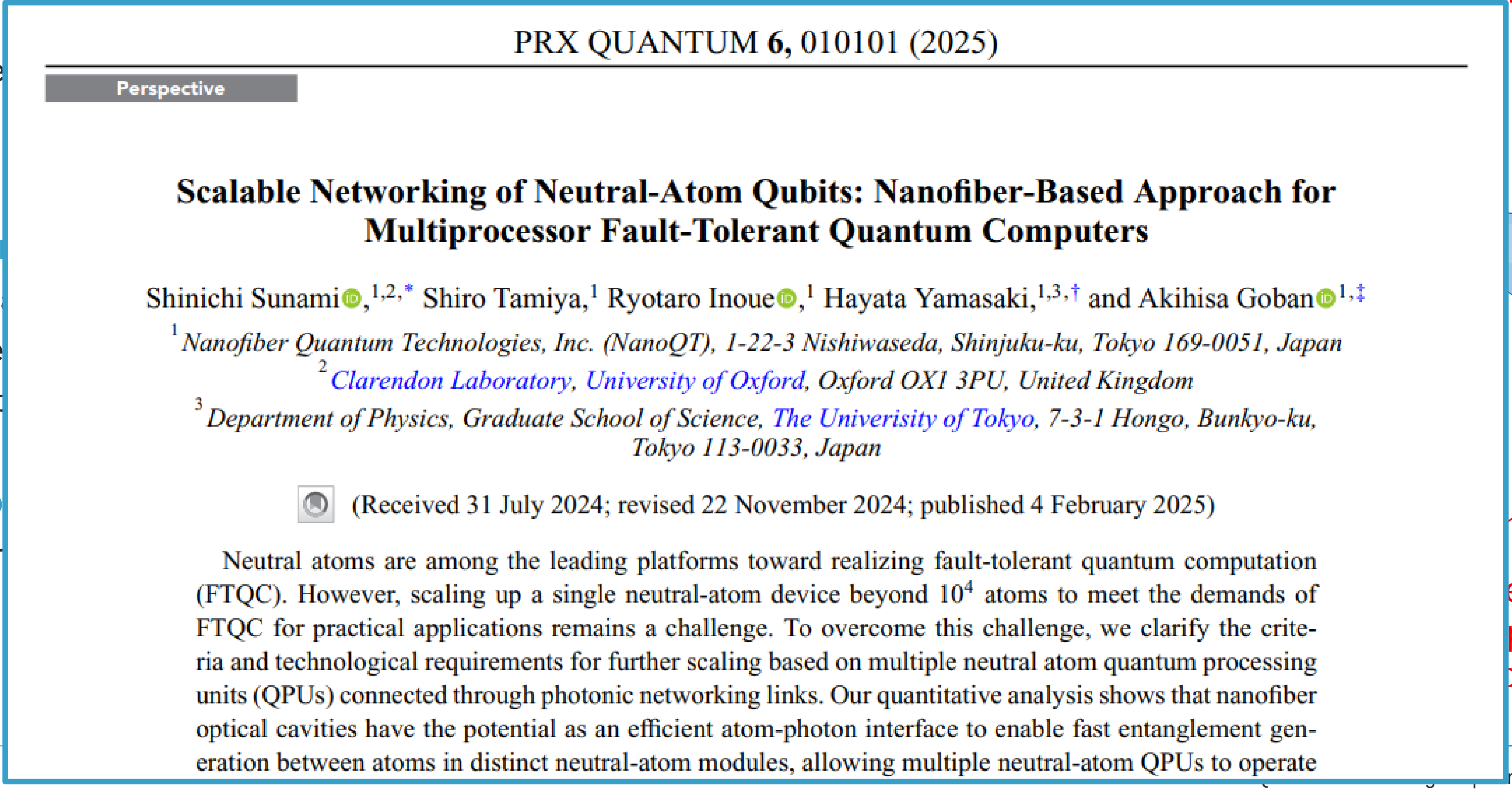
Combi

- Optic
- Move
- Low p

3

Teleco

- Neutr



PRX QUANTUM **6,** 010101 (2025)

Perspective

Scalable Networking of Neutral-Atom Qubits: Nanofiber-Based Approach for Multiprocessor Fault-Tolerant Quantum Computers

Shinichi Sunami,[1,2,*] Shiro Tamiya,[1] Ryotaro Inoue,[1] Hayata Yamasaki,[1,3,†] and Akihisa Goban[1,‡]

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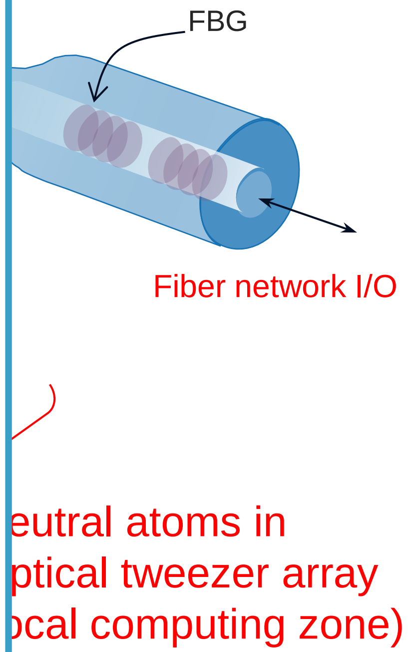
Neutral atoms are among the leading platforms toward realizing fault-tolerant quantum computation (FTQC). However, scaling up a single neutral-atom device beyond 10^4 atoms to meet the demands of FTQC for practical applications remains a challenge. To overcome this challenge, we clarify the criteria and technological requirements for further scaling based on multiple neutral atom quantum processing units (QPUs) connected through photonic networking links. Our quantitative analysis shows that nanofiber optical cavities have the potential as an efficient atom-photon interface to enable fast entanglement generation between atoms in distinct neutral-atom modules, allowing multiple neutral-atom QPUs to operate

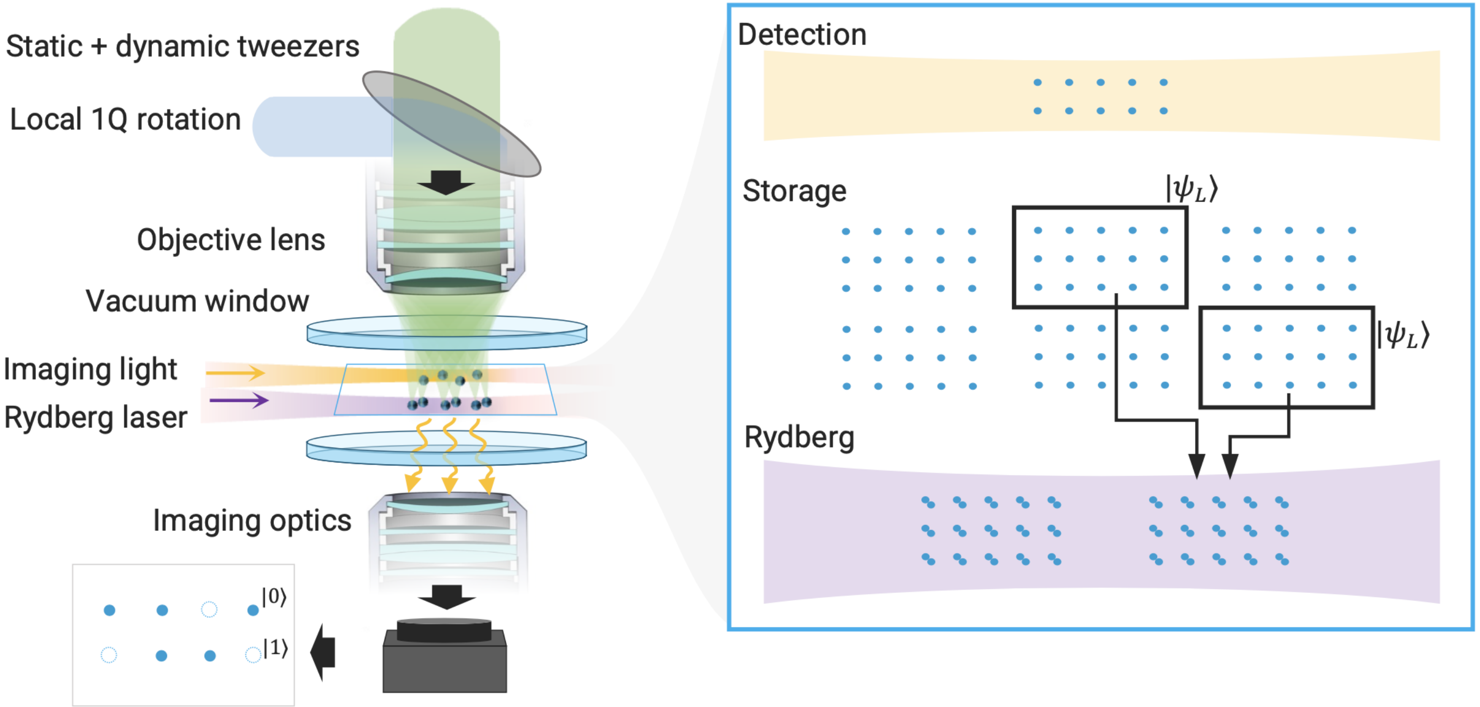


1

Section

Multiprocessor QPU with atoms

Tweezer array of atoms for quantum computation



Storage zone

Rydberg zone

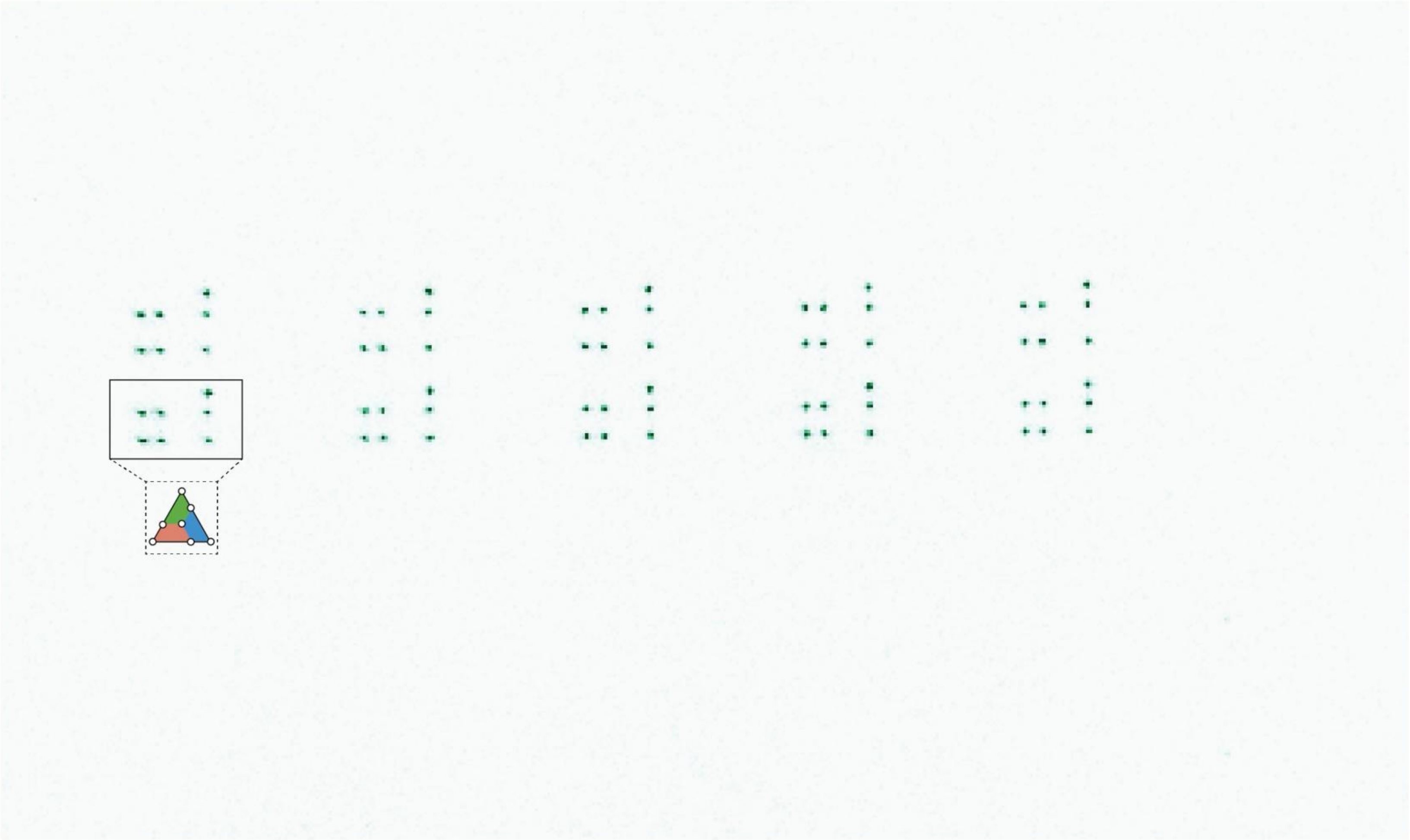
Imaging zone

State-of-the-art (Harvard, Caltech, Princeton..)

- Lots of progress in 2023-24.
- >99% 2Q gate fidelity, 99.9% expected with laser stability/power improvements
- 1000s of atoms in a single module, 10^4 expected

Rearranging single-atom arrays

QuEra computing

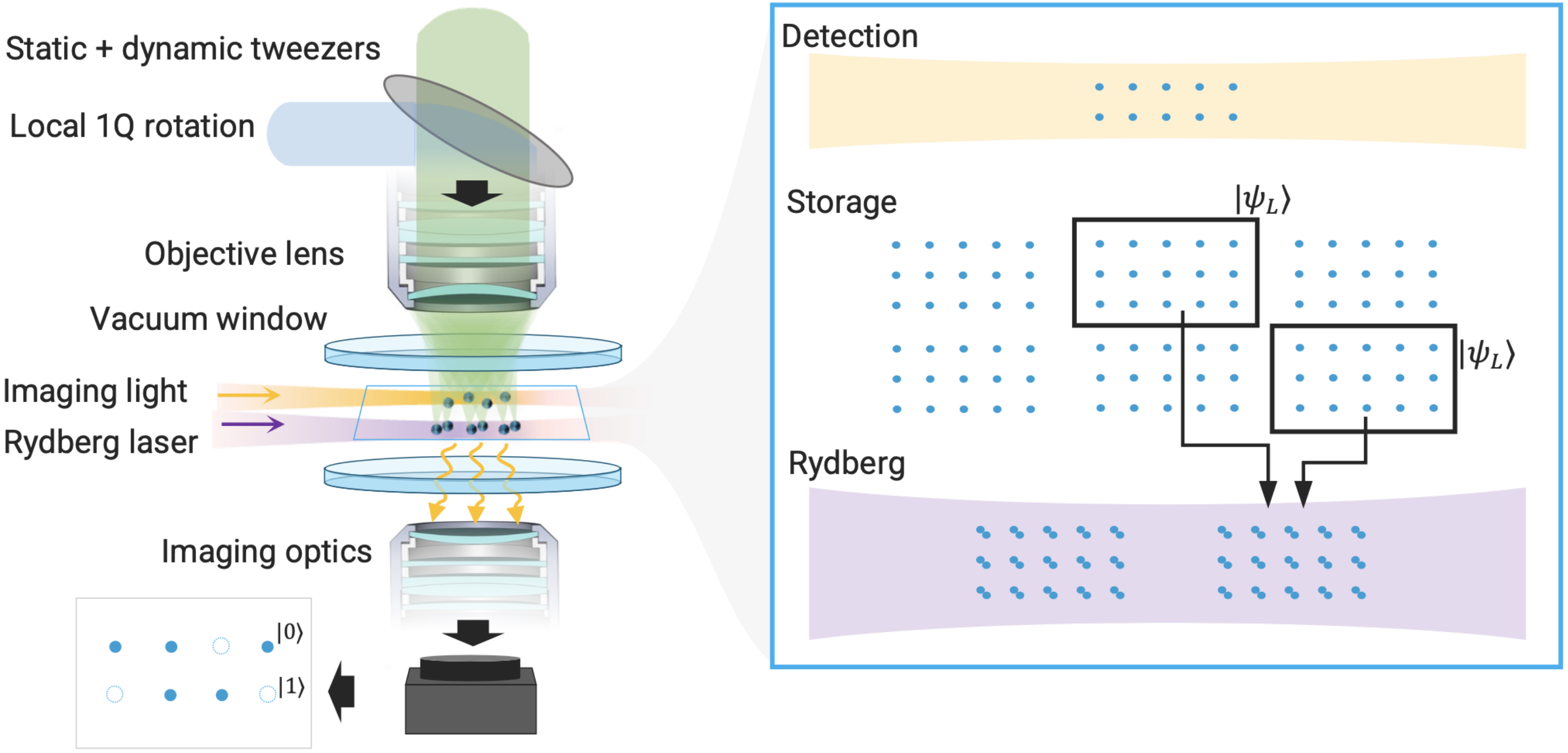


D. Bluvstein *et al.*, Nature **626**, 58 (2024)

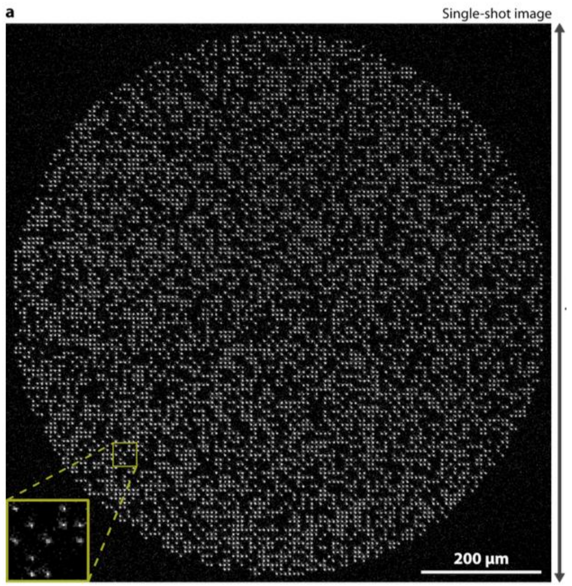
Neutral-atom QPU startups:

- **QuEra (US)**
- **Atom Computing (US)**
- Infleqtion (US)
- Planqc (Germany)
- Pasqal (France)
- etc

3. Designing architecture



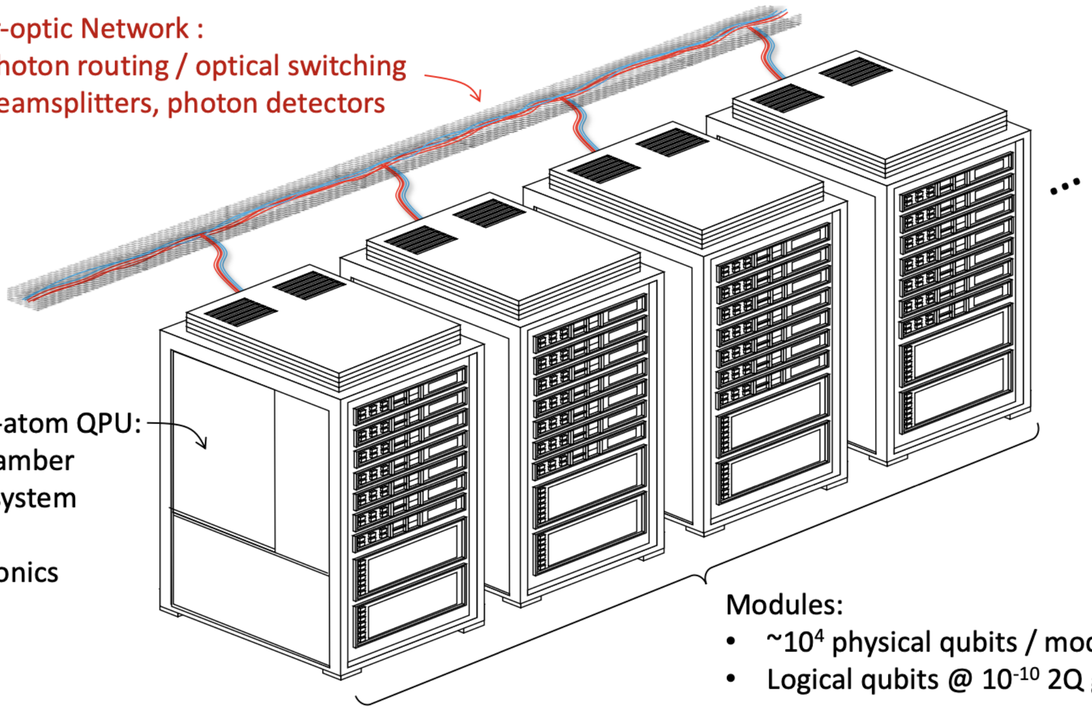
~ 6000 qubits



c.f. expt image @ Caltech

- Hardware operations: atom transport + zones **+ nanofiber**
- Define *microinstructions* (how to move atoms / when to shine lasers) for each commands in machine language (QECC specific, next page)

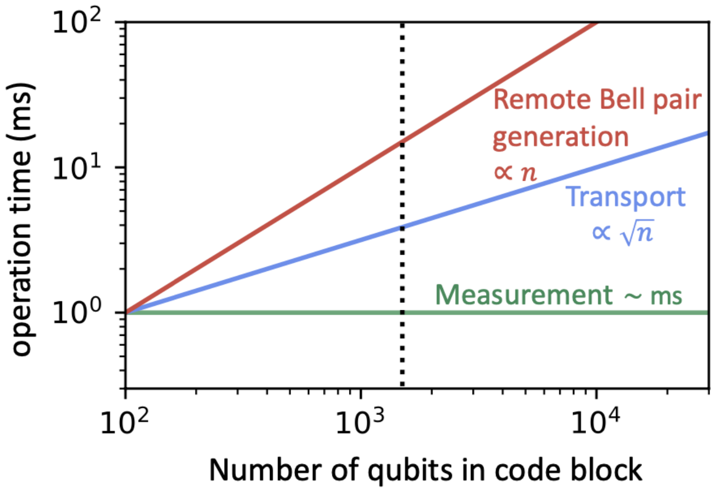
Toward multiprocessor neutral-atom FTQC



Fiber-optic Network :
- Photon routing / optical switching
- Beamsplitters, photon detectors

Neutral-atom QPU:
UHV chamber
+ laser system
+ optics
+ electronics

Modules:
- ~10^4 physical qubits / module @ 10^{-3} 2Q gate error
- Logical qubits @ 10^{-10} 2Q gate error



- **Inherently sequential & probabilistic** operation means network module **is slow**
- Fidelity of photon-assisted remote operations are typically **limited**
- Even for slow neutral-atom QPUs, ~MHz rate needed to keep up with local ops.

2

Section

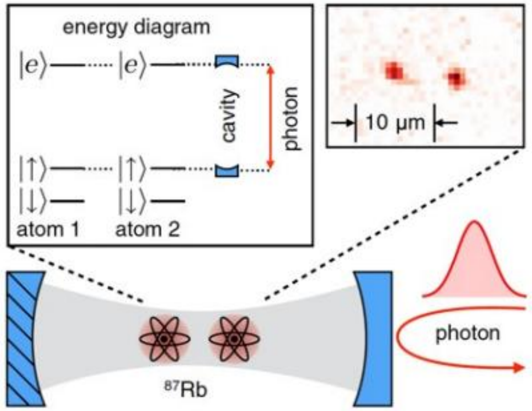
Technology overview

Background: Free-space cQED systems

Proof-of-concept of optical quantum computing and networking

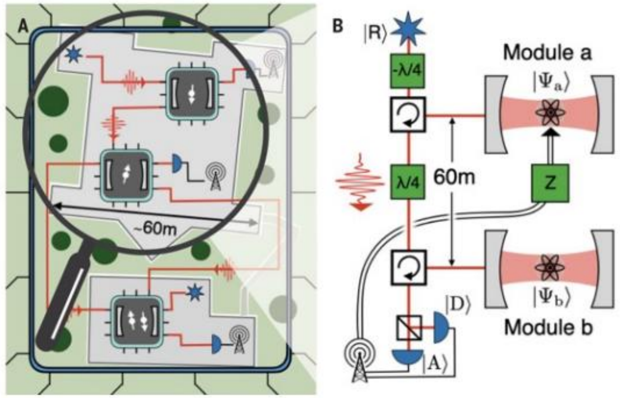
Local CNOT gate

S. Welte *et al.*, PRX **8**, 011018 (2018).



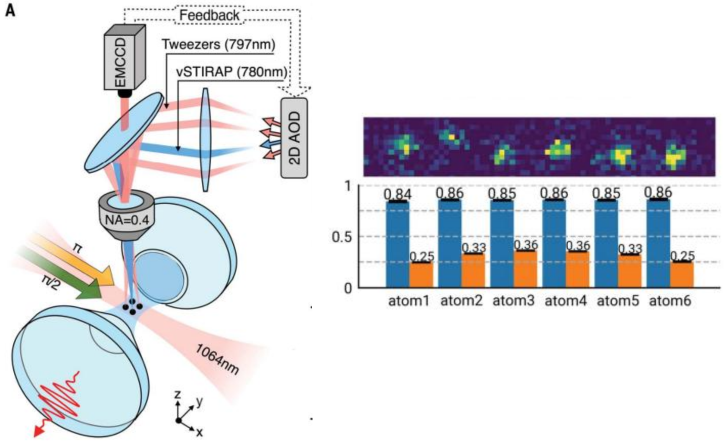
Remote CNOT gate

S. Daiss *et al.*, Science **371**, 614 (2021).



Scalability

L. Hartung *et al.*, Science **385** 179 (2024).



Challenges: Scalability per unit and efficient integration to fiber network

Challenges: Scalability of free-space cQED platforms

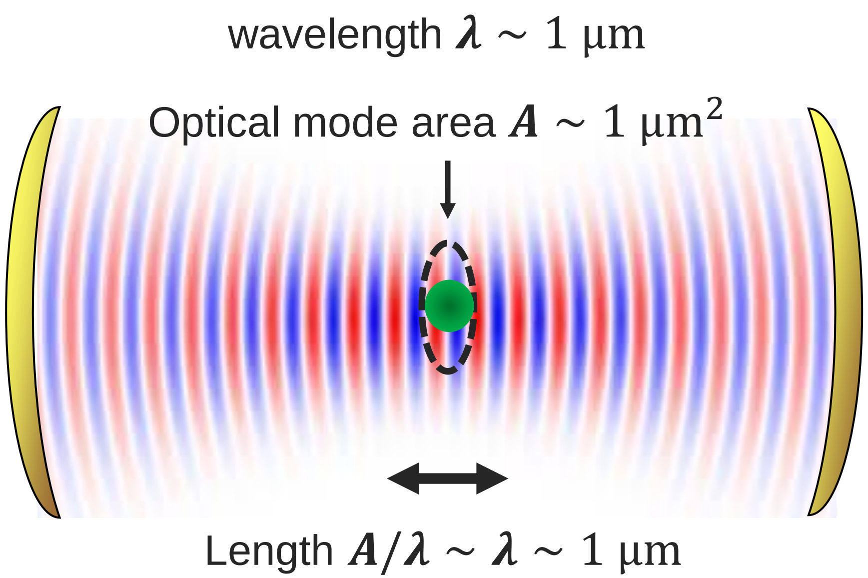
Fundamental limit of light in free space

Diffraction limit in a free-space cavity

Trade-off between interaction strength and scalability

1. Maximize interaction: **Match the size of atom and photon**
    - Area of atom (optical): $\boldsymbol{\sigma_0} \sim \boldsymbol{\lambda^2} \sim 1\ \mu\text{m}^2$
    - Area of photon: $\boldsymbol{A} \sim \boldsymbol{\lambda^2} \sim 1\ \mu\text{m}^2$ ← ***diffraction limit***
2. Maximize scalability: **Longer is better**
    - Length of photon: $\boldsymbol{A}/\boldsymbol{\lambda} \sim \boldsymbol{\lambda} \sim 1\ \mu\text{m}$ ← ***diffraction limit***

→ **one-atom capacity**



Need diffraction-free light propagation for strong interaction and scalability

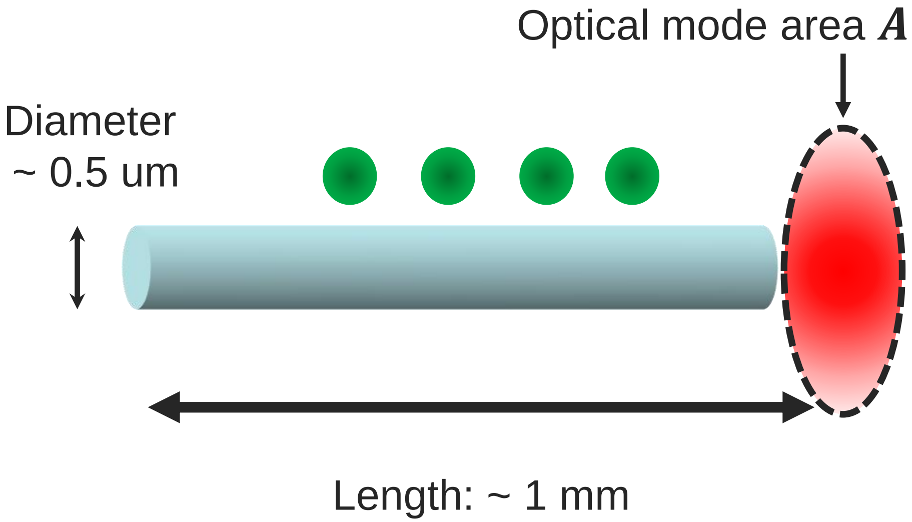
Solution: Scalability of nanofiber cQED platforms

Diffraction free by nanofiber waveguide

Compatibility of strong interaction and scalability

1. Maximize interaction: **Match the size of atom and photon**
   - Area of atom (optical): $\sim \boldsymbol{\lambda}^2 \sim 1\ \mu\text{m}^2$
   - Area of photon: $\boldsymbol{A} \sim \boldsymbol{\lambda}^2 \sim 1\ \mu\text{m}^2$ ← smallest by waveguide
2. Maximize scalability: **Longer is better**
   - Length of photon: **No fundamental limit,**

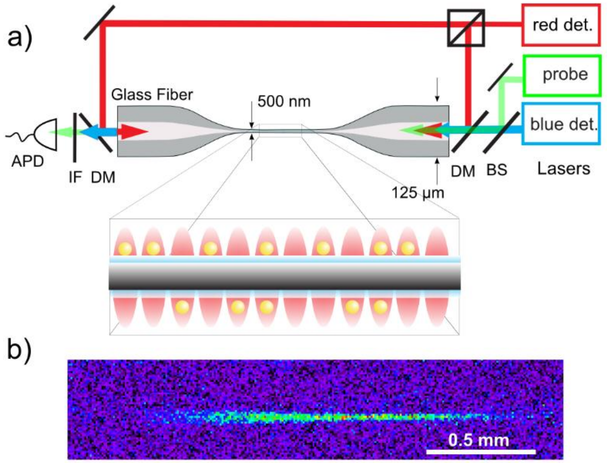
     current. 1 mm → ~ 200-atom capacity



Waveguide mitigates the trade off between coupling strength and scalability

Novel approaches with nanofibers

Evanescent trap



Vetsch *et al. PRL* **104**, 203603 (2010). [Rauschbeutel]

AG *et al. PRL* **109**, 033603 (2012).[Kimble]

Polzik, Orozco/Rolston, Barreiro, Hakuta etc.

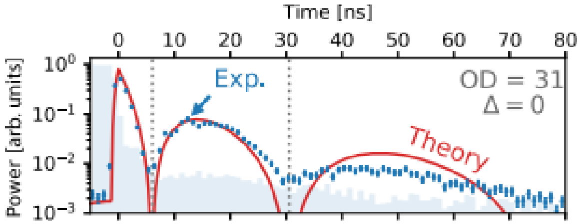
> 1000 atoms trapped and probed via nanofiber guided light

Demonstration of Novel quantum optical phenomena

Collective emission: Super/subradiance

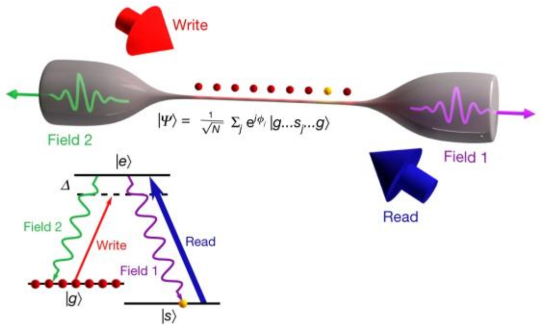
Solano *et al.*, Nature commun. **8**, 1857 (2017).

Liedl *et al.*, PRX **14**, 011020 (2024)



Single-photon generation via DLCZ

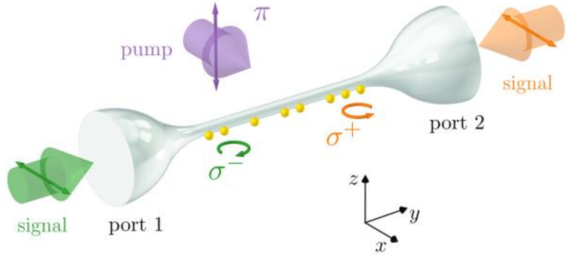
Corzo *et al.*, Nature **566**, 359 (2019)



Chiral photon transport

Mitsch *et al.,* Nature Commun. **5**, 5713 (2014).

Pucher *et al.,* Nature Photon. **16**, 380 (2022)



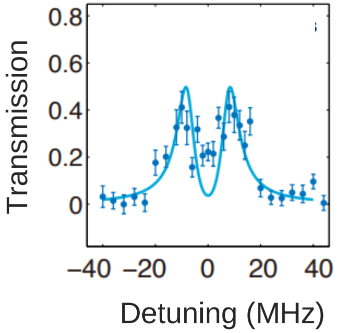
Quantum memory via EIT

Sayrin *et al.*, Optica **2**, 353 (2015).

Gouraud *et al.*, PRL **114**, 180503 (2015)

Nanofiber + cavity: our past experiments

Strong coupling w/ nanofiber cavity

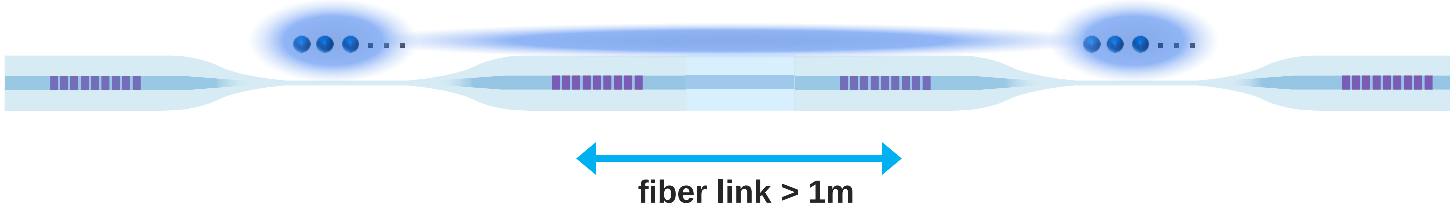


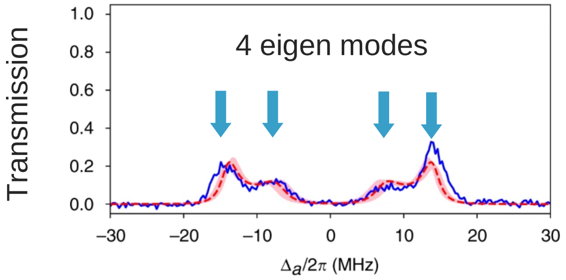
- Combined with fiber-Bragg grating (FBG) mirrors
- Strong coupling with cooperativity ~3 using **moderate finesse ~ 40 → now we have 4000**

Kato and Aoki *et al. PRL* **104**, 203603 (2015).

c.f. Photonic crystal cavity [Thompson *et al.,* Science ’13, Tiecke *et al*, Nature ’14, Dordevic *et al.*, Sciecne ’21, etc]

Coupled distant atom-cavity systems





- Delocalized photonic mode across fiber link due to low-loss connection to the fiber
- Potential application to remote entanglement generation

Kato *et al.,* Nature Commun **10**, 1160 (2019).

White *et al.*, PRL **122**, 253603 (2019).

Nanofiber cavity fabrication: visible and near-infrared wavelength

In-house FBG and nanofiber fabrication

FBG mirrors

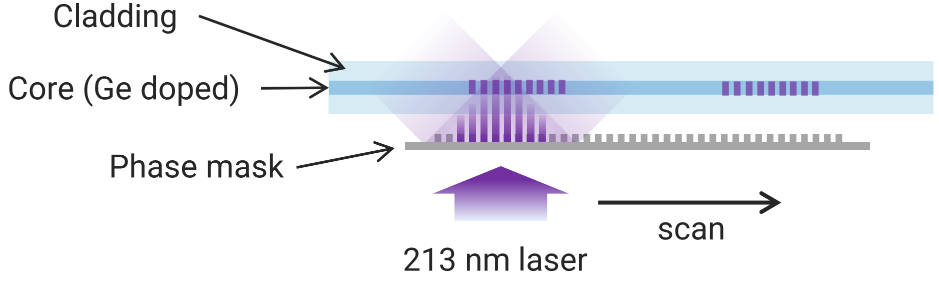
- ✓ High-finesse FBG cavity: ***F* >10000** [Kato *et al.* Opt.Lett.‘22]
- ✓ Narrowband FBG mirror: Bandwidth: **~ 100 GHz**
- ✓ Reproducibility: Accuracy **~ 10 GHz**
- Strong birefringence: **> 100 MHz** polarization-mode splitting

Nanofiber

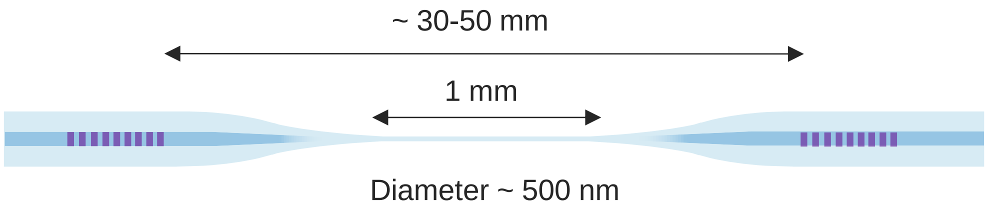
- ✓ Low-loss nanofiber cavity at near-infrared and telecom bands: **Finesse > 4000**

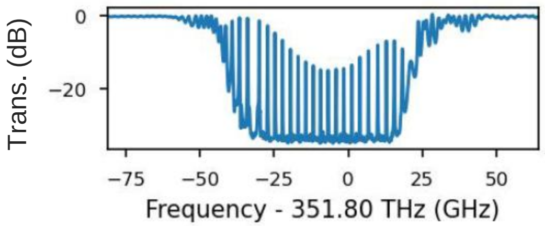
  [Ruddel *et al.*, Opt. Lett. ’20, Horikawa *et al.*, *in preparation*]

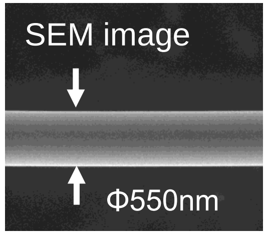
1. Create small refractive index modulation by scanning DUV laser



2. Heat and pull the central region



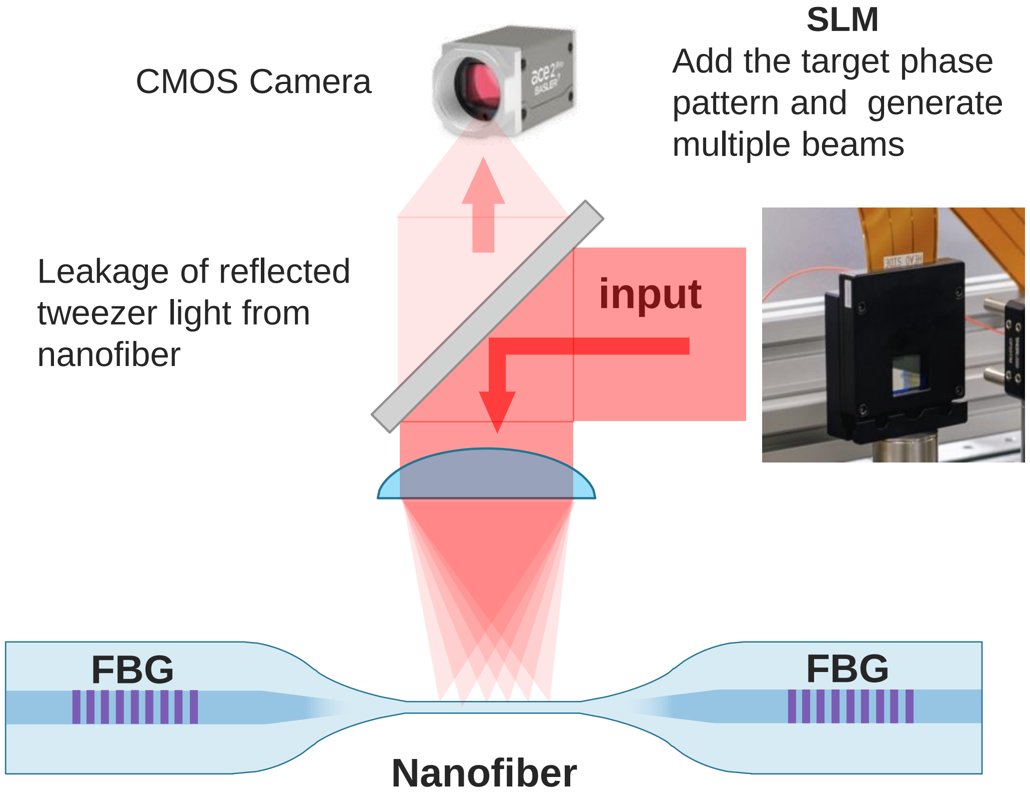




Optical tweezer array + nanofiber

***In-situ* beam profiling a tweezer spot**

Generate multiple spots with SLM



CMOS Camera

SLM
Add the target phase pattern and generate multiple beams

Leakage of reflected tweezer light from nanofiber

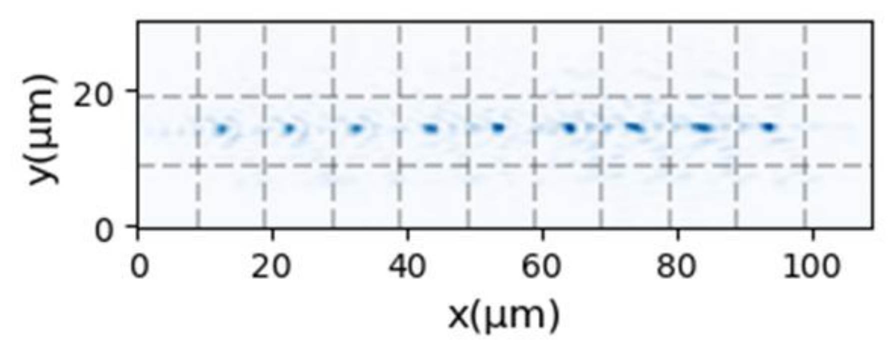
Nanofiber

Reflection of multiple tweezer beams

Measured tweezer spots by a CMOS camera

- Current system: max # of spots ~20 w/ 5 um separation
- New system (design phase): max # ~200

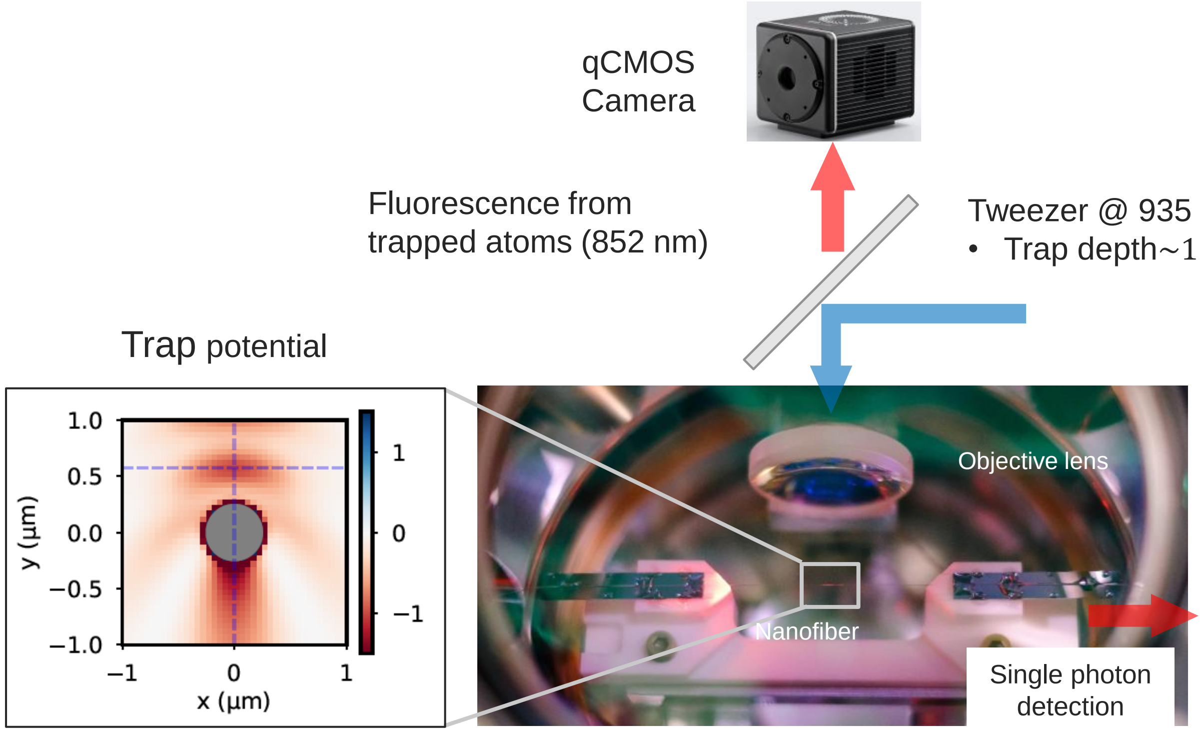
Example image of reflected tweezer beams



Our current PoC experiment with Cs atoms

Single-atom detection

Imaging single atom while cooling



qCMOS
Camera

Fluorescence from
trapped atoms (852 nm)

Tweezer @ 935 nm
- Trap depth~ 1 mK

Trap potential

Objective lens

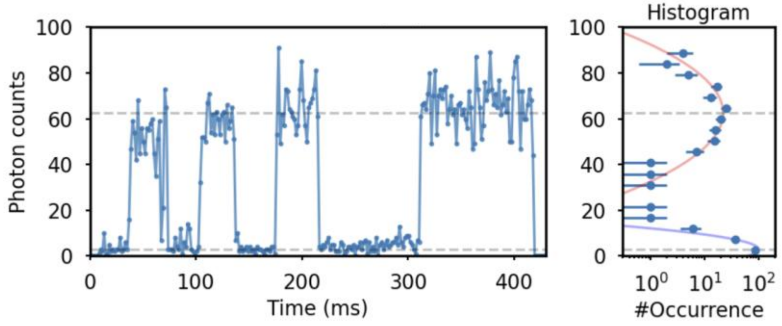
Nanofiber

Single photon
detection

Close-up view of the nanofiber cavity in the vacuum

Multiple atoms near the nanofiber

Detection of a single atom via cavity

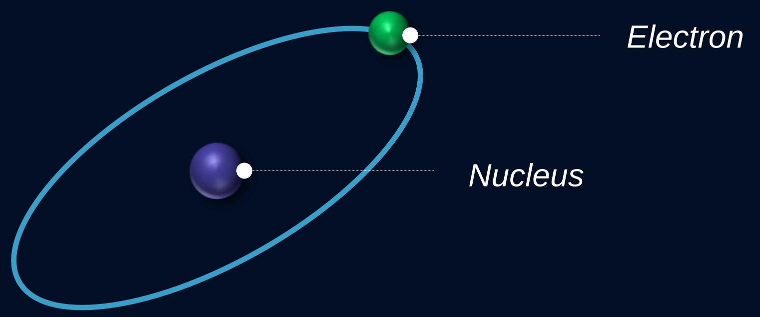


On-going: Generation of atom-photon entanglement

Pursuit of ideal netural atom qubits

Incumbent system: Rb, Cs

QuEra, Pasqal, Infleqtion etc

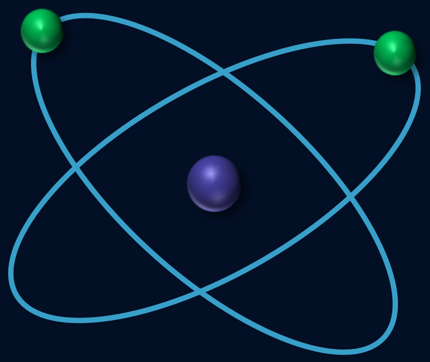


- **Electron-spin qubits:**

  Challenge: sensitive to noise, i.e. magentic field

New system: Yb, Sr

Atom computing, Planqc



- **Nuclear-spin qubits:**

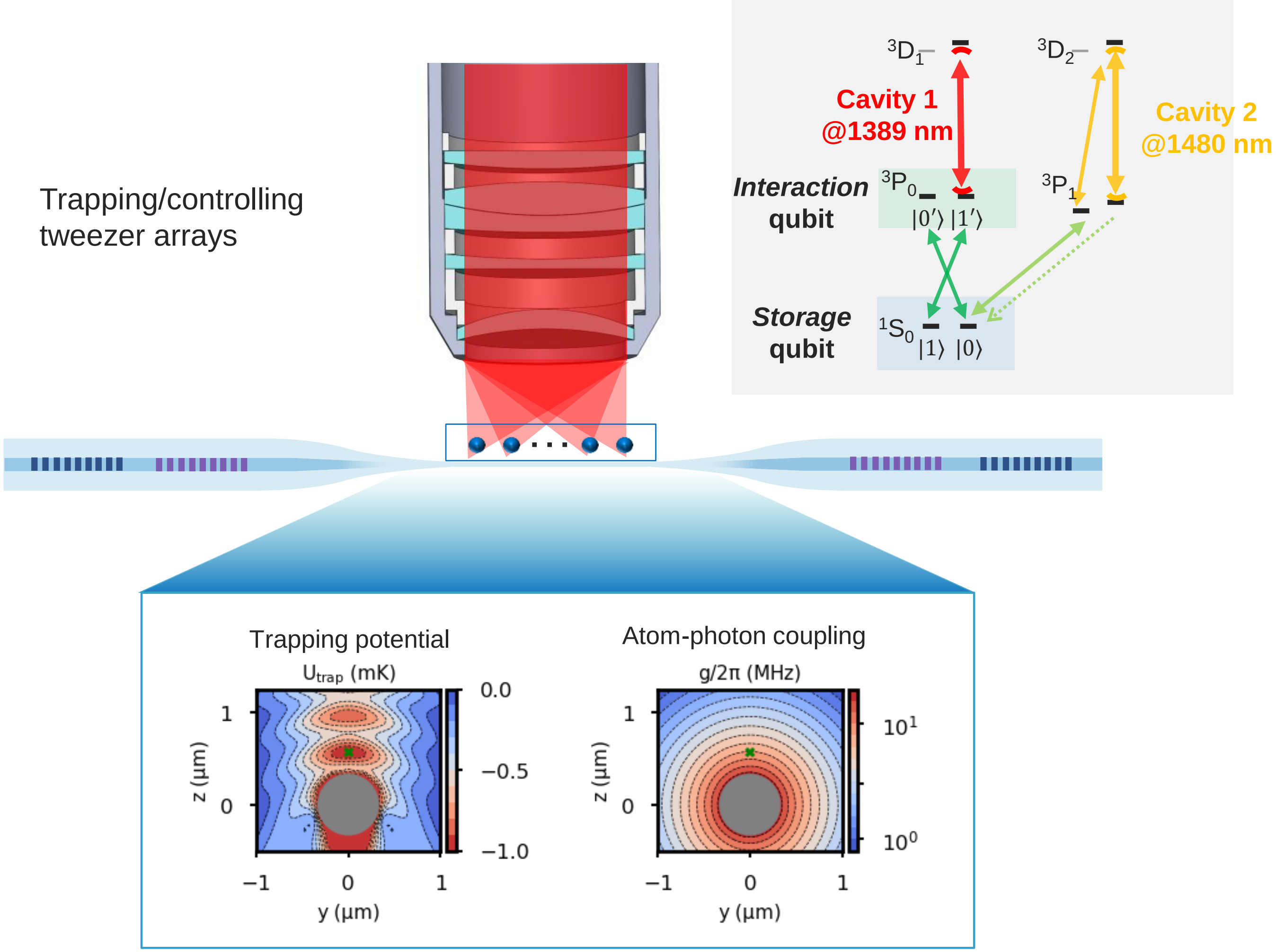
  Advantage: ~ 1000 times less sensitive to noise

- **Telecomband photon generation:**

  Compatible w/ optical fiber network

Coupling Yb atom qubits to telecom-band cavity

Interfacing Yb atoms with a nanofiber cavity



Optical-metastable-ground state architecture enables

- Coherently connect storage and interaction qubit states
- Selective atom-cavity coupling

Multiple telecom transitions:

- 1389 nm, 1480 nm and 1539 nm available for ^3P_x-^3D_y lines [Cov *et al*, ’19, etc]

Other fundamental and technical challenges are mediated by:

- Nuclear spin ½:
  - Ideal qubit system: >99.9 % Singe qubit control
  - Long coherence time > 10 sec
- No cross talk between storage and interaction states:
  - > 99.9% fidelity SPAM

Ref:

- Yb numbers : Thompson, Kaufman group, Atom computing

On-going development of Yb system

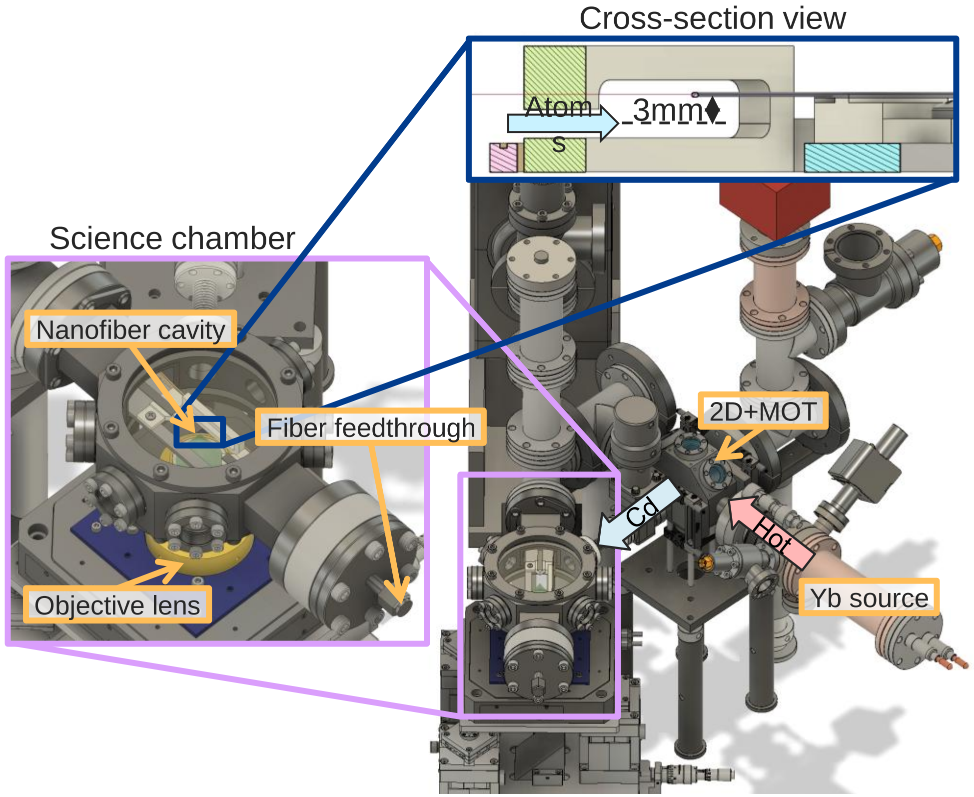
Design overview of cold atoms preparation

Cooling / trapping / imaging

- 2D+MOT cold atom source
- Narrow-line MOT below the nanofiber
- Out-vacuum objective with NA=0.5
- Magic wavelength (759 nm) tweezers
- Background-free imaging at 399 nm with 556 nm cooling

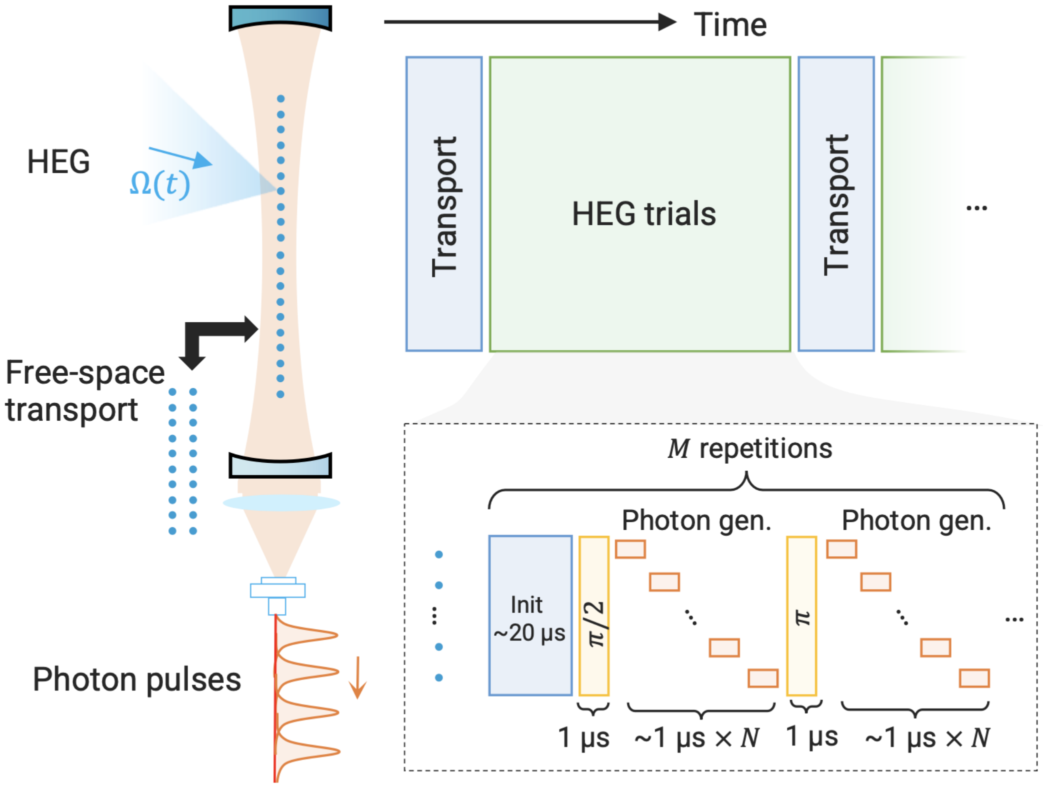
Clock laser + Frequency chain

- Frequency stabilization via an optical frequency comb
- Collaboration with Yasuda/Inaba group @ AIST

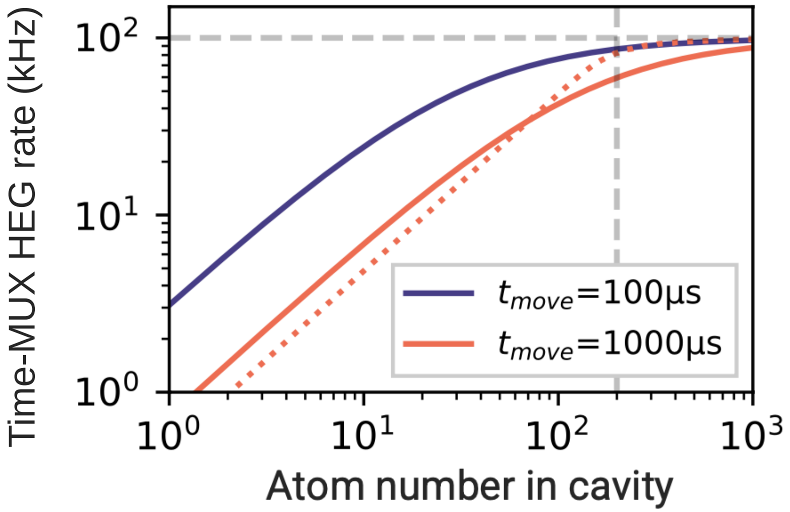


Tweezer array in free space → Telecomband single-photon generation

1. Making the network module scalable



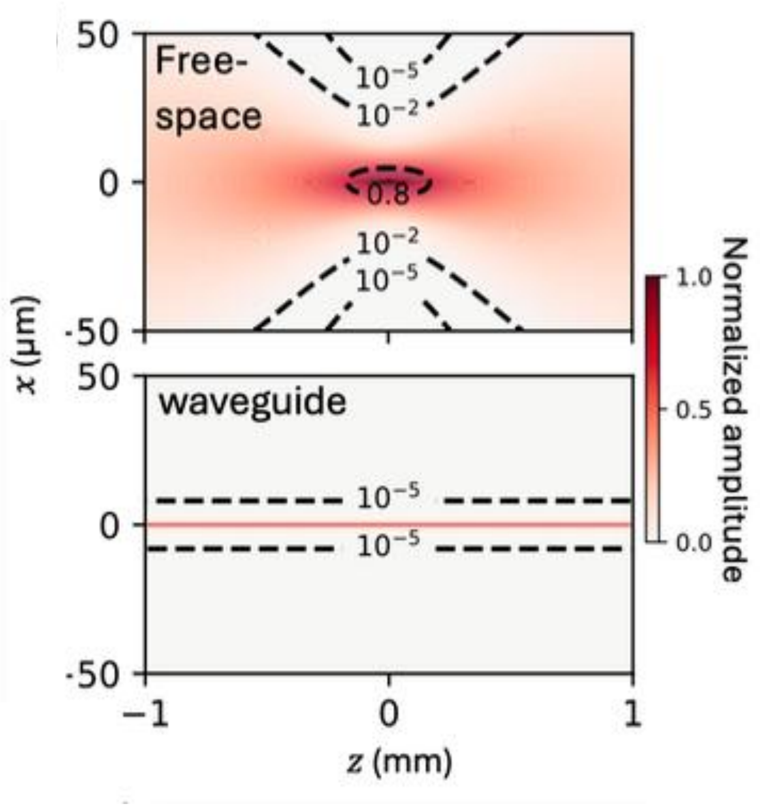
S. Sunami *et al.*, PRX Quantum 6, 010101 (2025).

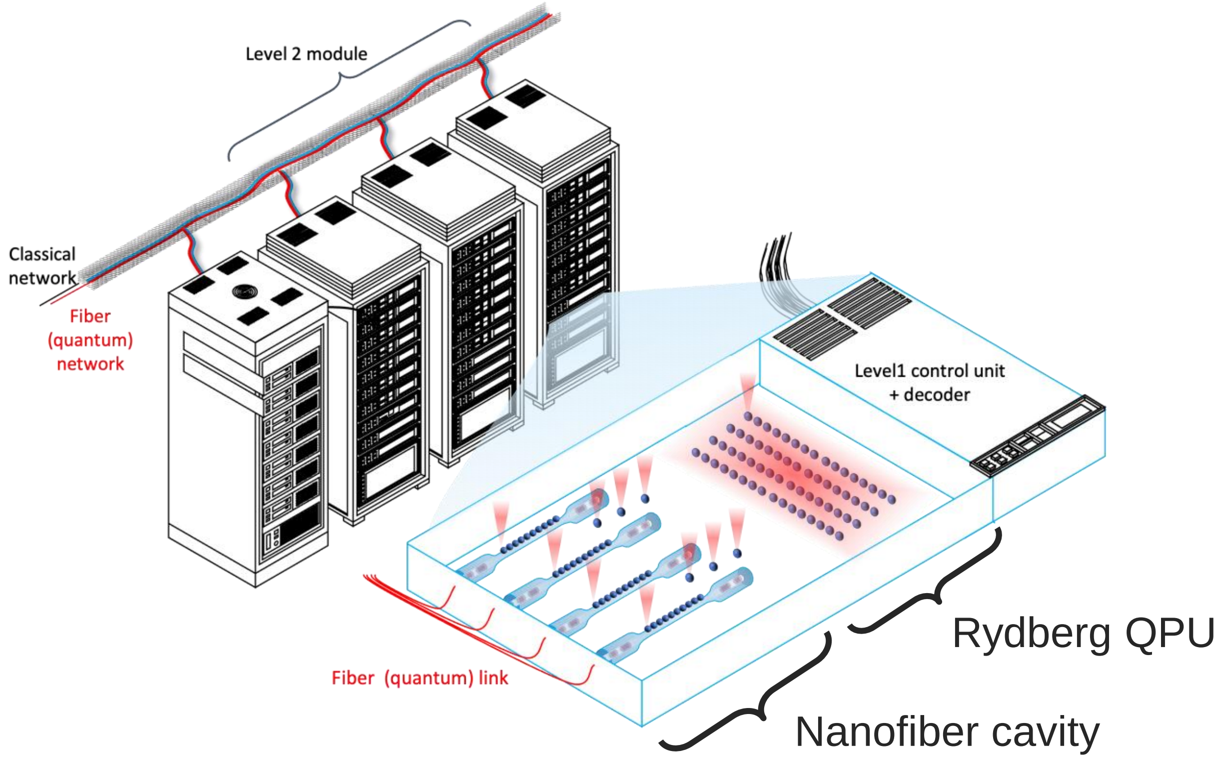


- **Time multiplexing**; parallelizing as much as possible with 100s of atoms
- Needed to achieve rate bounded by cavity speed, reaching 100 kHz (100s of pairs / EC cycle)

Sunami et al., arXiv:2407.11111

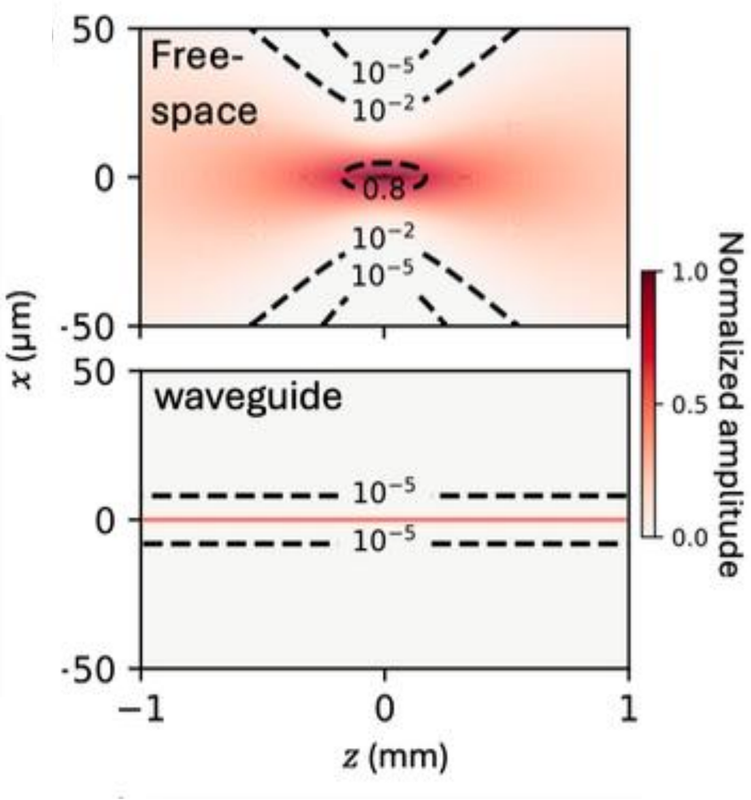
1. Making the network module scalable

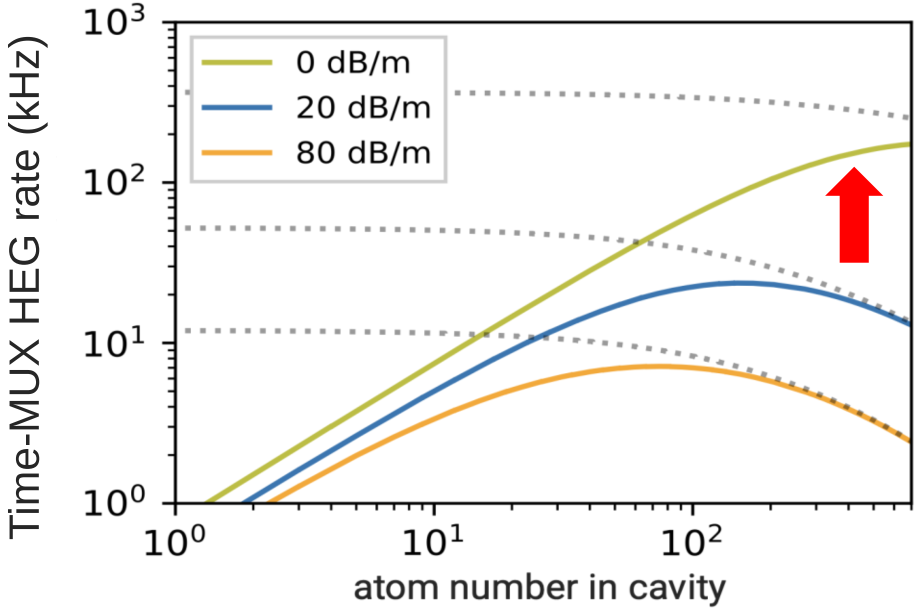




- **Channel multiplexing** with small-footprint nanophotonic cavity
- Unique feature of nanofiber: negligible waveguide loss

1. Making the network module scalable



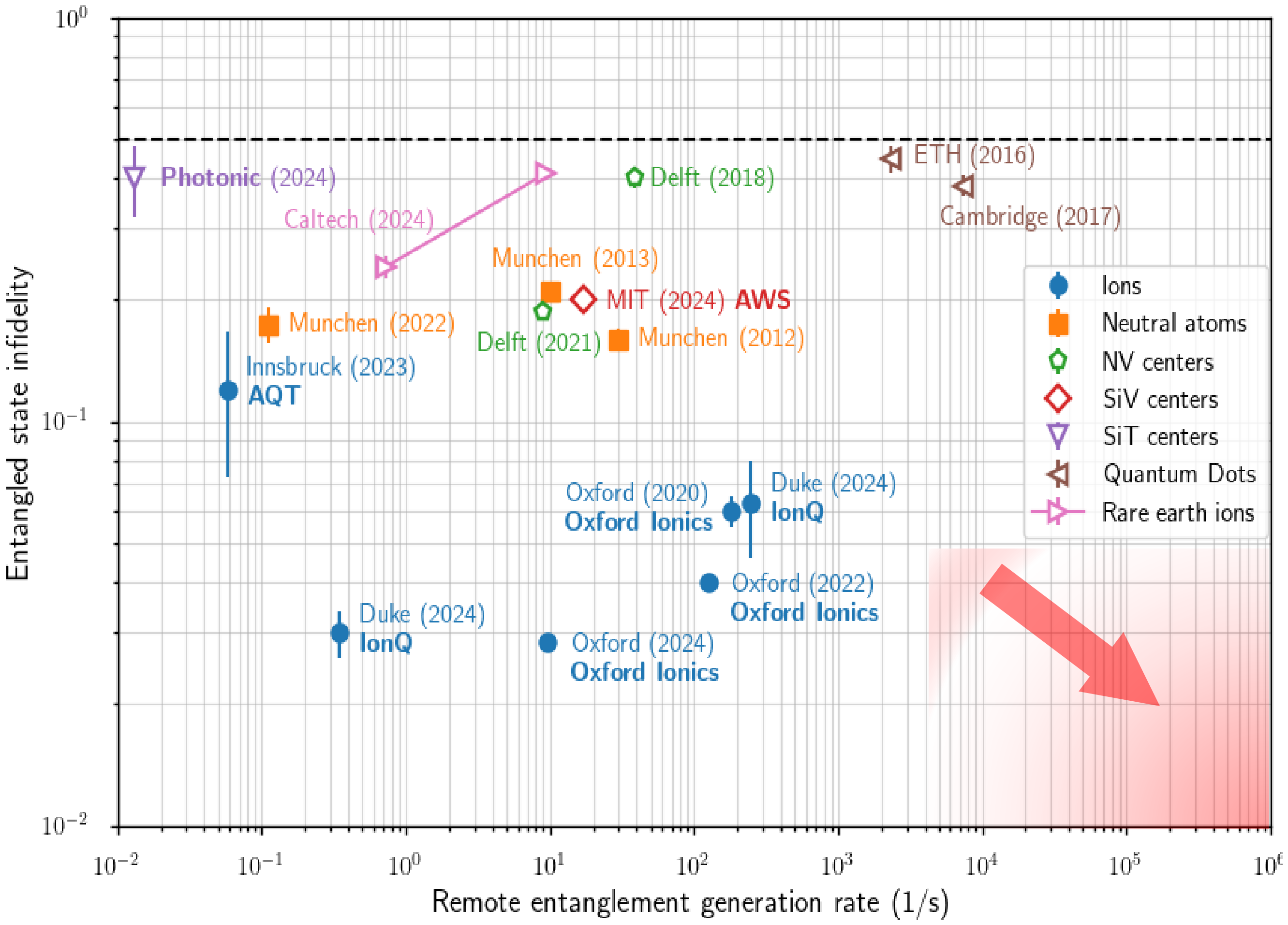


Nanofiber
< 1 dB/m

PCC, photonic chip,
etc..
>10 dB/m

- **Channel multiplexing** with small-footprint nanophotonic cavity
- Unique feature of nanofiber: negligible waveguide loss

2. Fidelity of generated Bell pairs



Ref. Prof. D. Lucas's talk on ICAP2024

State-of-the-art:

- **Record: >97% by Oxford** ion trapper
  @ limited success rate (<kHz)
- Not clear when/whether >99% achieved
- Even with 99%, teleported CNOT will be worse.

Architecture needs to have room to accommodate **few % error** in Bell pair

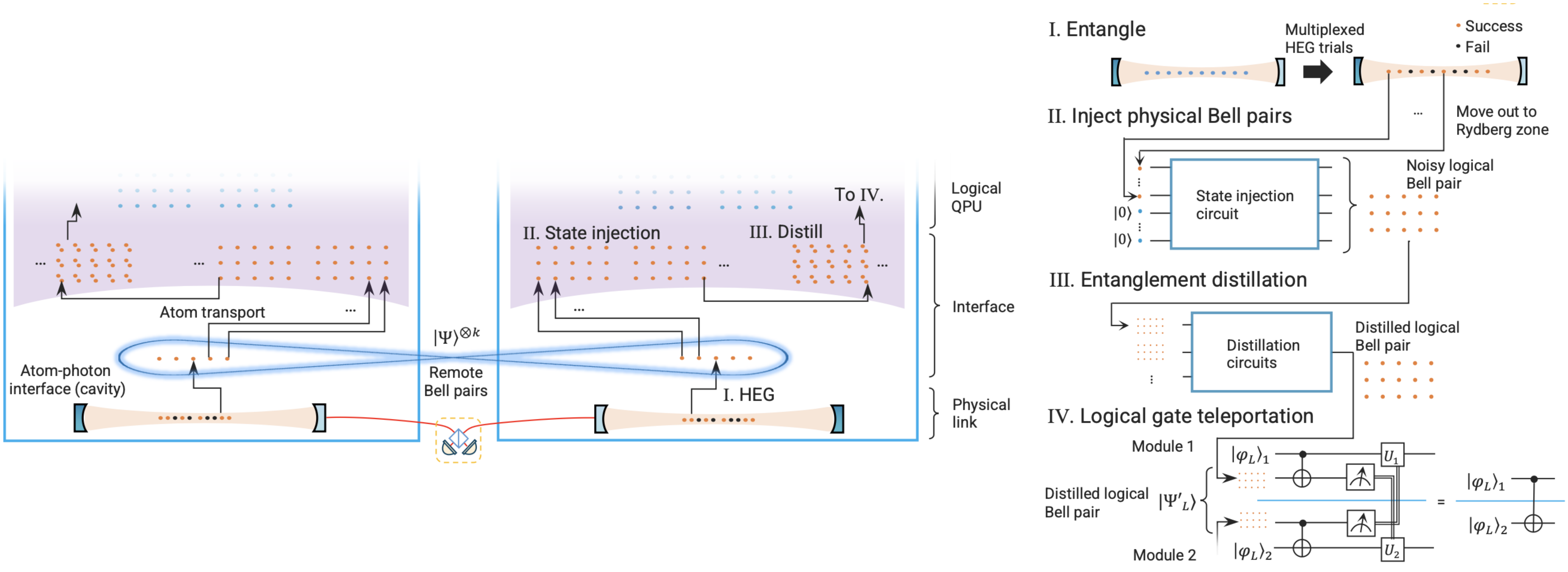
Target spec for scalable interconnect

- Infidelity ~ 1%
- Rate > 10^5 s^{-1}
- Small footprint

Nanofiber with:

- Time MUX
- Channel MUX

2. Working around low fidelity with distillation



- Network cost: k physical Bell pair × # states needed for distillation (10s)
- Allowed initial infidelity % order expected
- **Ongoing**: state injection and distillation protocol development

Sunami et al., arXiv:2407.11111

3

Section

Theory and Architecture design

Theory team & Collaborators

Hayata Yamazaki, Ph.D.
Principal Research Scientist (Architecture/Theory)
Ph.D. University of Tokyo

Shinichi Sunami, Ph.D.
VP, Theory and Architecture
Ph.D. Oxford University

Shiro Tamiya, Ph.D.
Research Scientist (Theory)
Ph.D. University of Tokyo

Yosuke Ueno, Ph.D.
Visiting Research Scientist (Theory)
Ph.D. University of Tokyo

Seigo Kikura, M.S.
Research Staff (Theory)
M.S. University of Tokyo

Quantum information / FTQC

- Computer system architecture design and evaluation
- High-rate QEC (qLDPC, Concat. codes)
- Quantum algorithms, quantum machine learning

AMO / microarchitecture

- Design FTQC implementation with atom array + cavity
- High-speed, high-fidelity atom-photon protocol devevelopment

Collaborators

Quantum repeater design

- C. Simon (Calgary)

Bosonic code

- V. Albert (UMD)

Cavity-assisted atom-photon gate

- O. Rubies-Bigorda (MIT, Yelin group)

TN simulation/decoding of surface code

- A. Darmawan (Kyoto)

Multiprocessor FTQC architecture

- NTT quantum group

etc..

Big picture: computer architecture

Sorting with computer architecture layers:

Application
Economic/social impact

Algorithm
Provable advantage

Assembly Language
Subroutines and their compilation

Machine Code
Quantum circuit compilation

Instruction-set architecture
Selection of FT gadgets

Theory/Software
(programmers)

Micro architecture
Atom transport scheduling etc

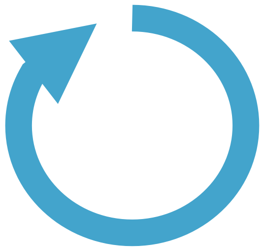
Gates/Registers
Qubit control protocol / hardware

Physical operations
Cavity QED, Rydberg gates

Hardware
(manufacturers)

Motivation:

- Understand requirements for the atom-photon interface
- Mid- and long-term R&D direction for both hardware and theory, by finding bottleneck



System-wide evaluation

Bottleneck search

System (processor) design

resource allocation, network rate / fidelity, …

Ref: T. Tanimoto’s talk @ AQIS ‘24

Summary & outlook

Overview of Atom-photon interface

- Technology of nanofiber cavity
- Development outline (FY~25): PoC of Yb atom-photon entanglement at telecom-band

Rate fidelity estimation:

- Optimized cavity parameter for high-rate entanglement generation
- Infidelity due to photon recoil

Modular QPU architecture

- High-rate concatenated code for modular computation

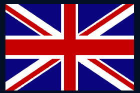
We are global team

Our team members come from various institutions around the world:

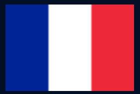
University of Tokyo
Kyoto University
Tokyo Institute of Technologies
Waseda University
University of Electro-Communications
Yokohama National University

MIT
Caltech
University of Maryland
UC Berkeley

University of Waterloo
University of Calgary



Oxford University



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Delft University of Technologies

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Current Openings

- Research Scientist (Hardware)
- Research Scientist (Theory, FTQC/Quantum Information)
- Research Scientist (Theory, AMO Physics)
- Research Staff (Hardware)
- Research Intern (Hardware)
- Research Intern (Theory)