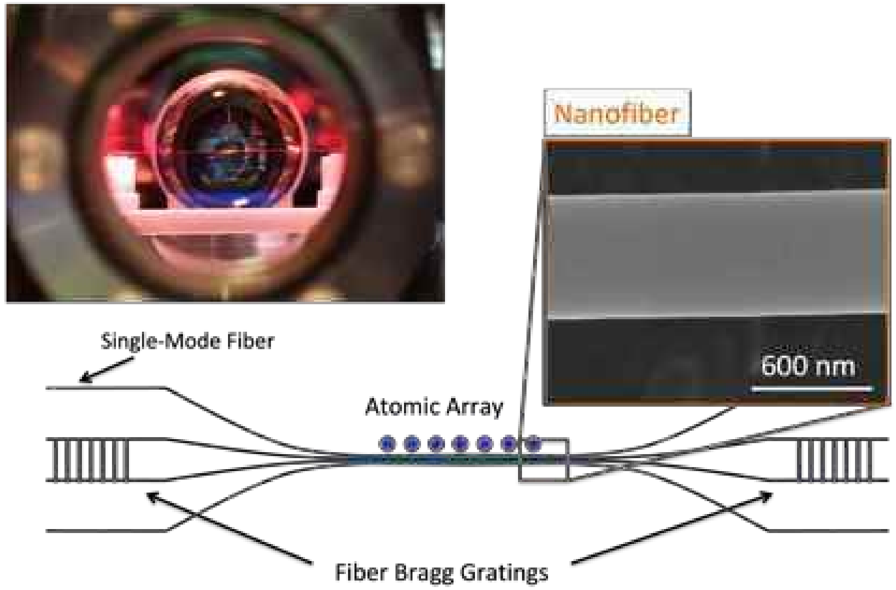


Quantum-Computing Hardware Based on Nanofiber-Cavity QED

Takao Aoki

Waseda University

JST Moonshot R&D Grant Number JPMJMS2268

PI's

Waseda Univ.

PoC

Scaling-Up/Distributed QC

PI: Takao Aoki

Social Implementation

Nanofiber Quantum Technologies (NanoQT)

PI: Akihisa Goban

Quantum Error Correction Theory

PI: Yuuki Tokunaga

Frequency-Stabilized
Light-Source System

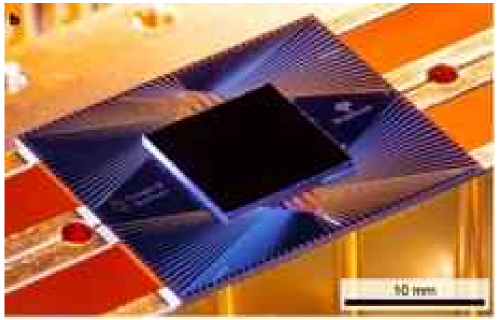
PI: Hajime Inaba

Strong collaboration in academia,
national lab, and industry

Toward Fault-Tolerant Universal Quantum Computing

Various Platforms for Quantum Computing

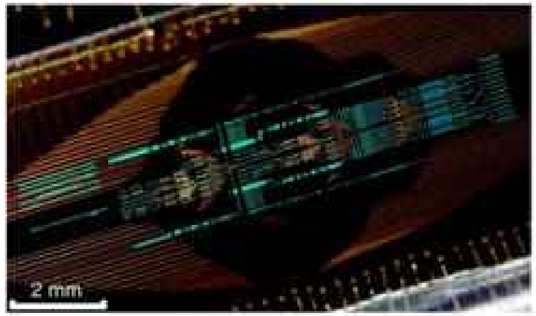
Superconducting Circuits



F. Arute *et al.*, Nature 574, 505 (20

Ion Traps

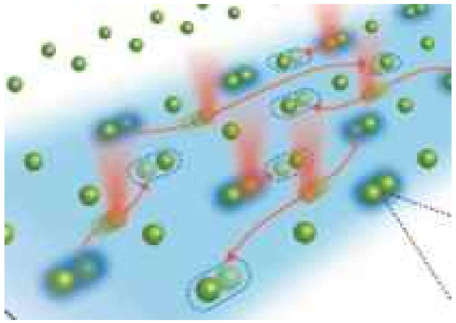
Photons



et al., Nat. Phys. 17, 1137 (2021)

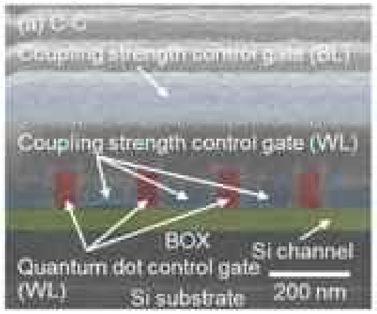
Technical challenges for increasing the number of qubits
by several orders of magnitude

Neutral Atoms



D. Bluvstein *et al.,* Nature 604, 451 (2022)

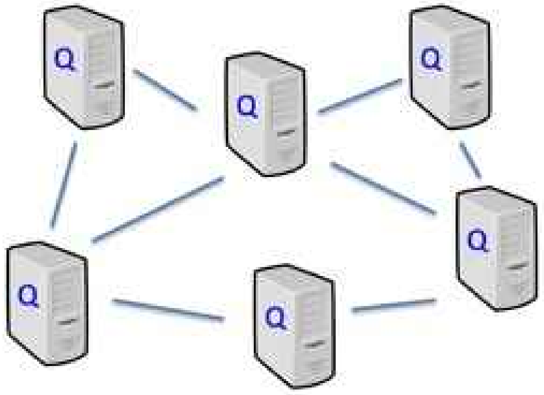
Silicon QDs



N. Lee *et al*, Appl. Phys. Lett. 116, 162106 (2020)

Promising Solution for Scaling Up

Distributed Quantum Computing



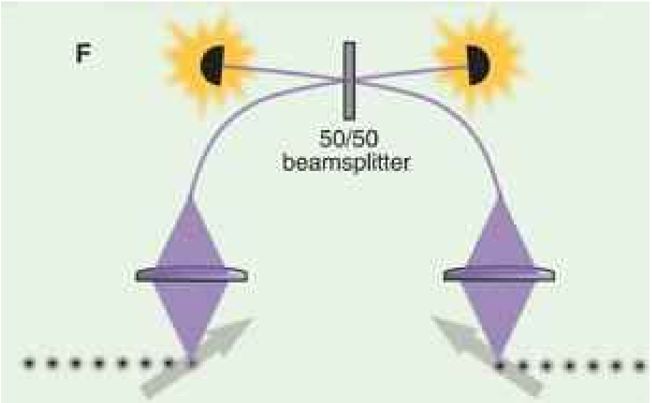
- Build a quantum network by connecting many small-scale QCs (QPUs)
- The whole network functions as a large-scale QC

Superconducting Circuits

https://www.eurekalert.org/news-releases/758461

- “Cryo” cables are needed for direct (microwave) connection

Ion Traps, Neutral Atoms

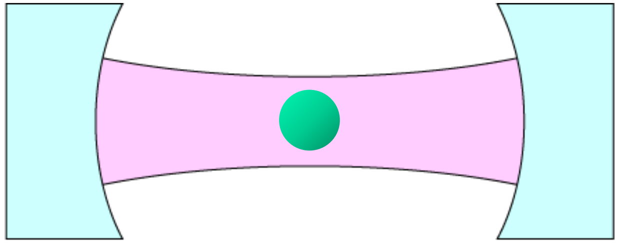


C. Monroe and J. Kim, Science 339, 1164 (2013)

- Directly interfaced with optical photon
- Technical challenges for high efficiency

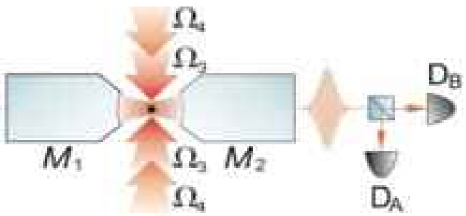
Cavity QED as a Quantum Computing Platform

Cavity QED



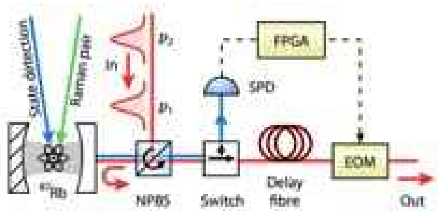
- Hybrid system with atom(s) and photons
- Ideal interface between atomic and photonic qubits
- Building blocks for QC based on cQED have been demonstrated with free-space cavities

Single-photon source



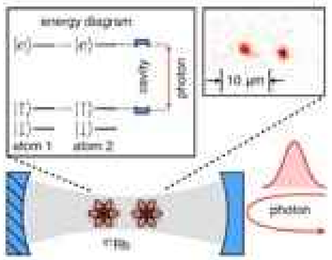
J. McKeever *et al.*, Science **303**, 1992 (2004)

Photon-photon gate



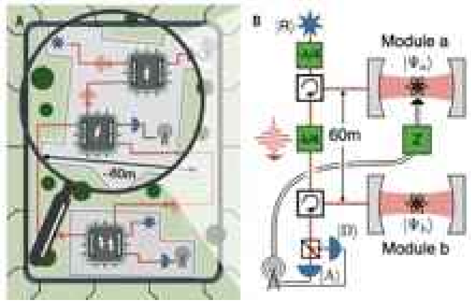
B. Hacker *et al.*, Nature **536**, 193 (2016)

Local atom-atom gate



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

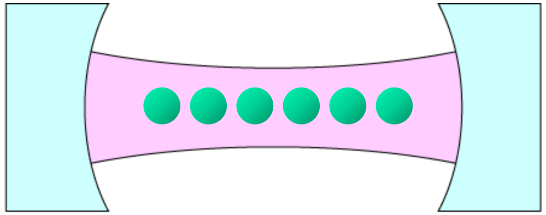
Remote atom-atom gate

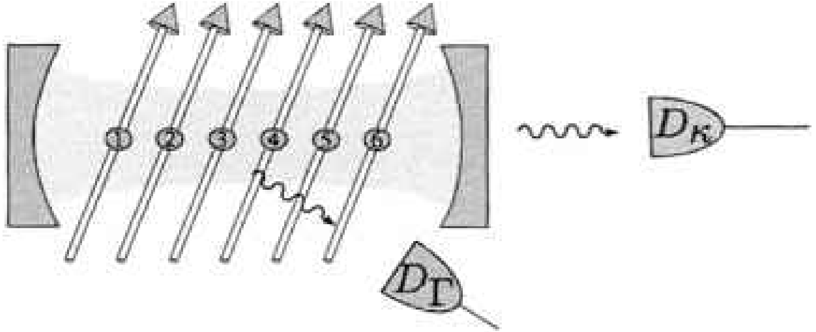


S. Daiss *et al.*, Science **371**, 614 (2021)

Cavity QED as a Quantum Computing Platform

Cavity QED

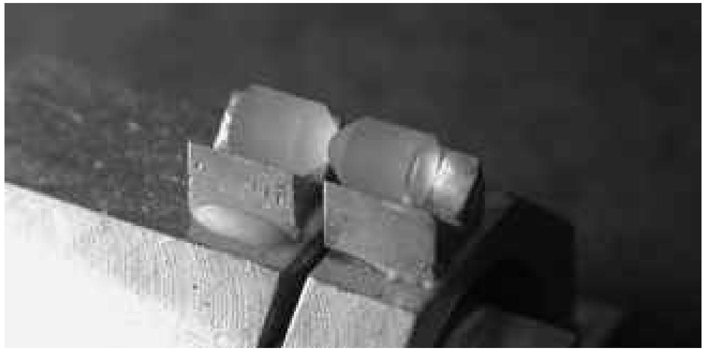




T. Pellizzari *et al.*, PRL 75, 3788 (1995)

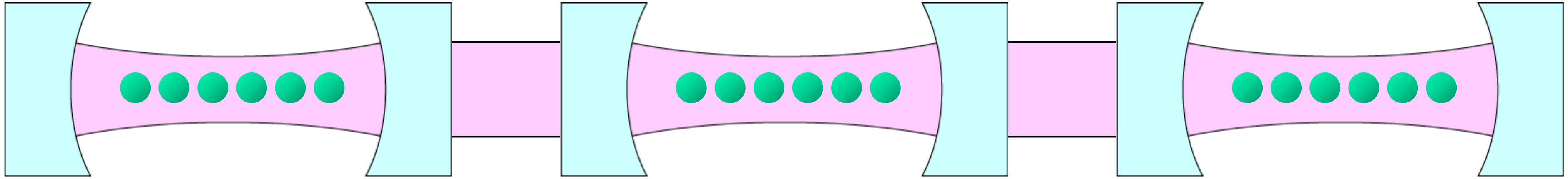
By placing many atoms in a cavity with each atom strongly coupled to the cavity, and by individually addressing each atom, the system can function as a quantum computer.

Difficult to achieve with conventional, free-space cavities



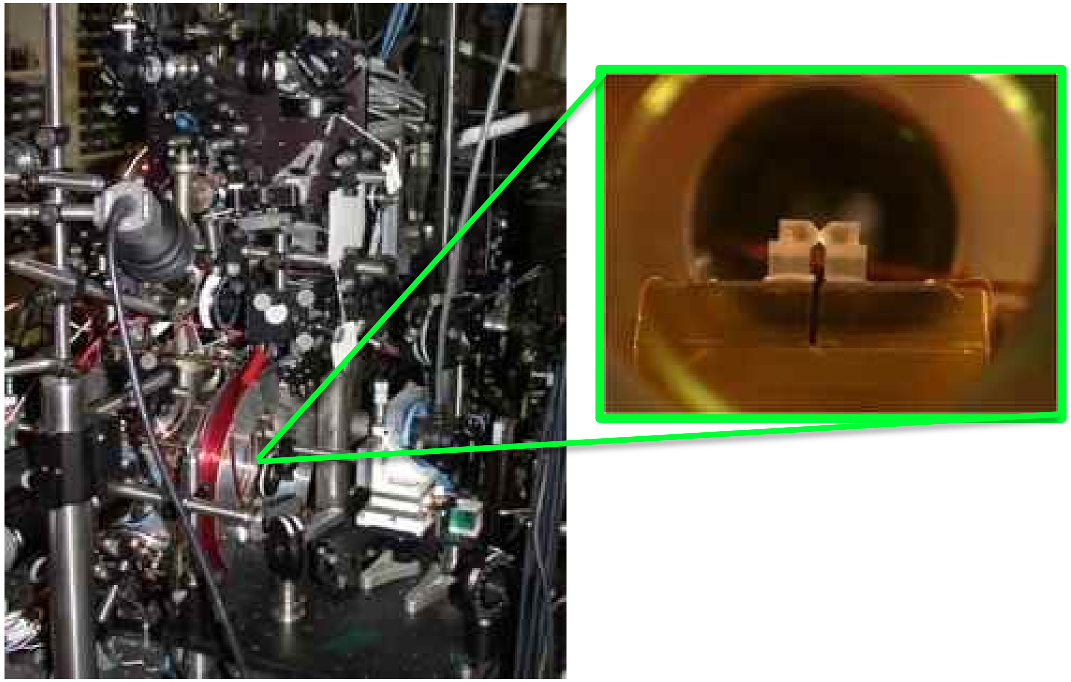
J. R. Buck, Ph.D. thesis, Caltech (2003)

Cavity QED as a Quantum Computing Platform



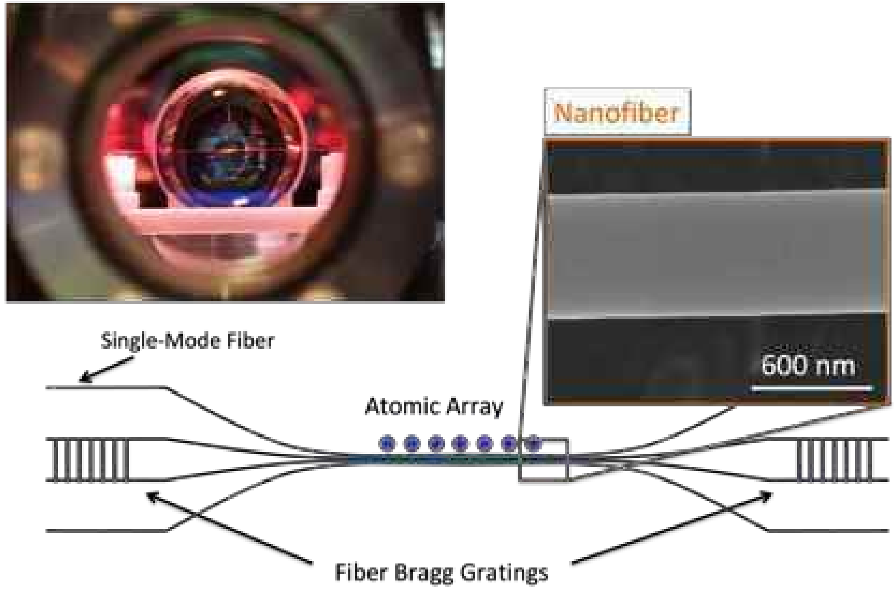
Furthermore, by connecting multiple cavities with low losses, distributed quantum computing can be realized.

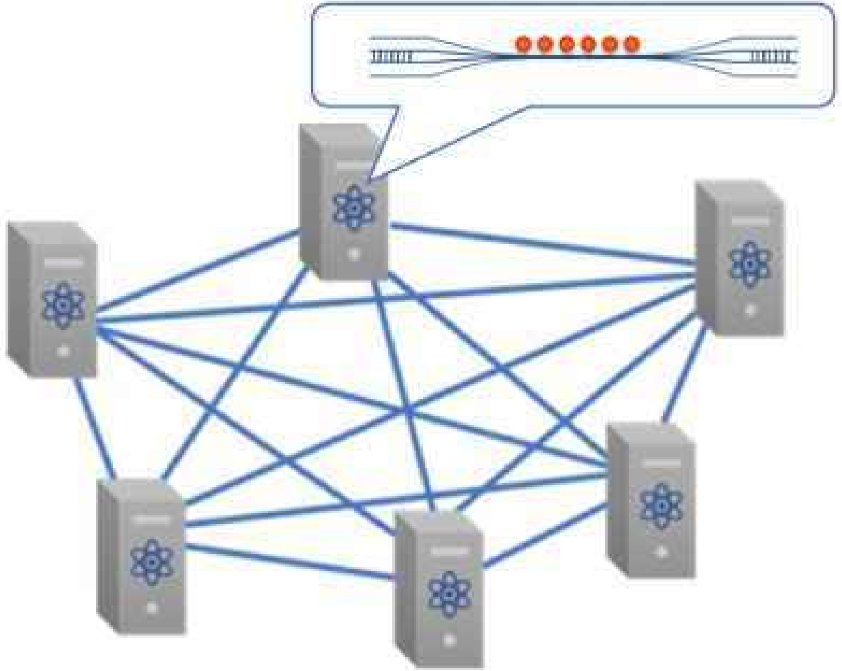
Difficult to achieve with conventional, free-space cavities



J. R. Buck, Ph.D. thesis, Caltech (2003)

This Project: Nanofiber Cavity QED



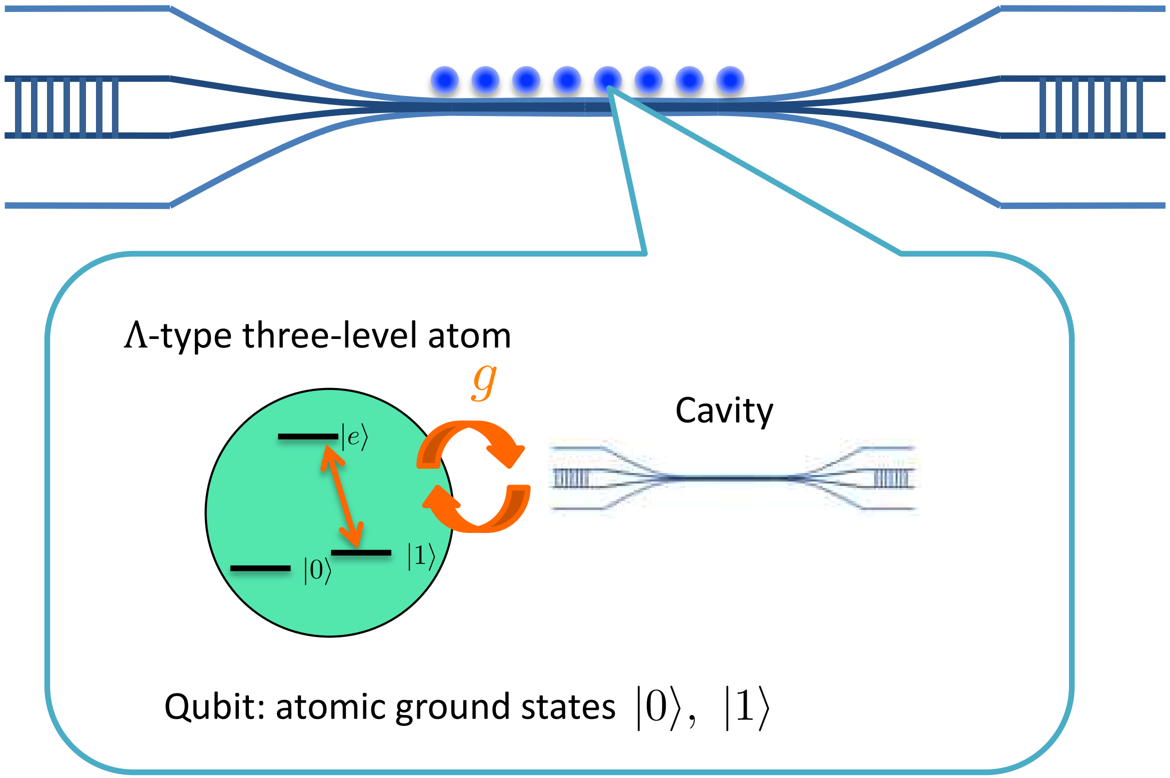


- All-fiber cavity QED system with many, individually addressable atoms

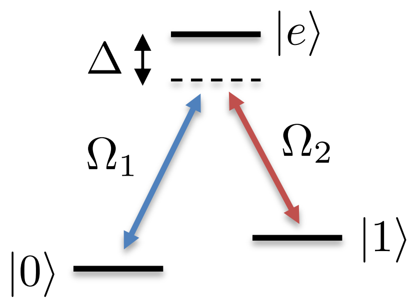
- Each unit is a middle-scale quantum computer (QPU)
- Many units are connected by optical fibers

Large-Scale Distributed Quantum Computing

QPU Based on Nanofiber CQED



- One-Qubit Gates

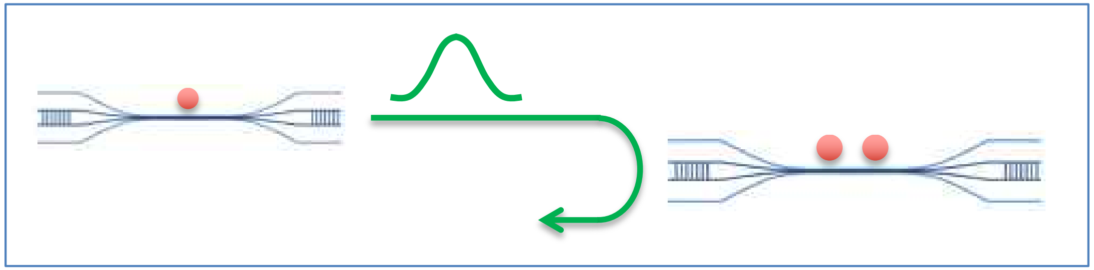


Two-photon Raman transition driven by Ω_1, Ω_2

QPU Based on Nanofiber CQED

- Two-Qubit Gates (and *N*-Qubit Gates)

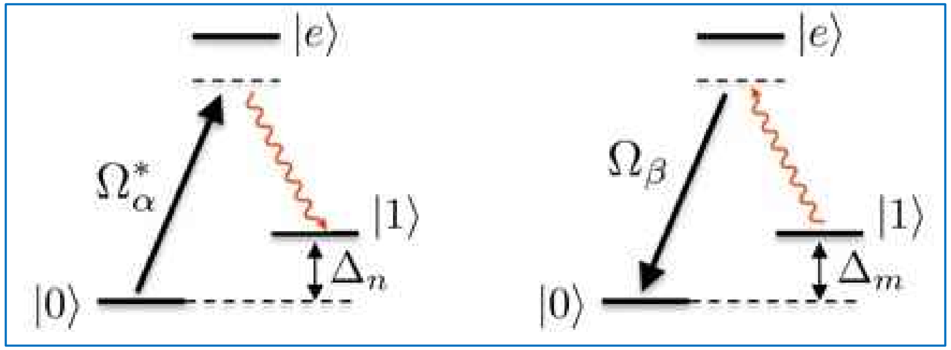
  - "Duan-Kimble" scheme



L. -M. Duan *et al.*, PRA **72**, 03233 (2005)
A. Reiserer *et al.*, Nature **508**, 237 (2014)
T. G. Tiecke *et al.*, Nature **508**, 241 (2014)
B. Hacker *et al.*, Nature **536**, 193 (2016)
S. Welte *et al.*, PRX **8**, 011018 (2018)
S. Daiss *et al.*, Science **371**, 614 (2021)

    - Phase flip conditioned on atomic state
    - Atom-photon, atom-atom (local/remote), photon-photon gates
    - High fidelities with photon detection

  - Dispersive scheme

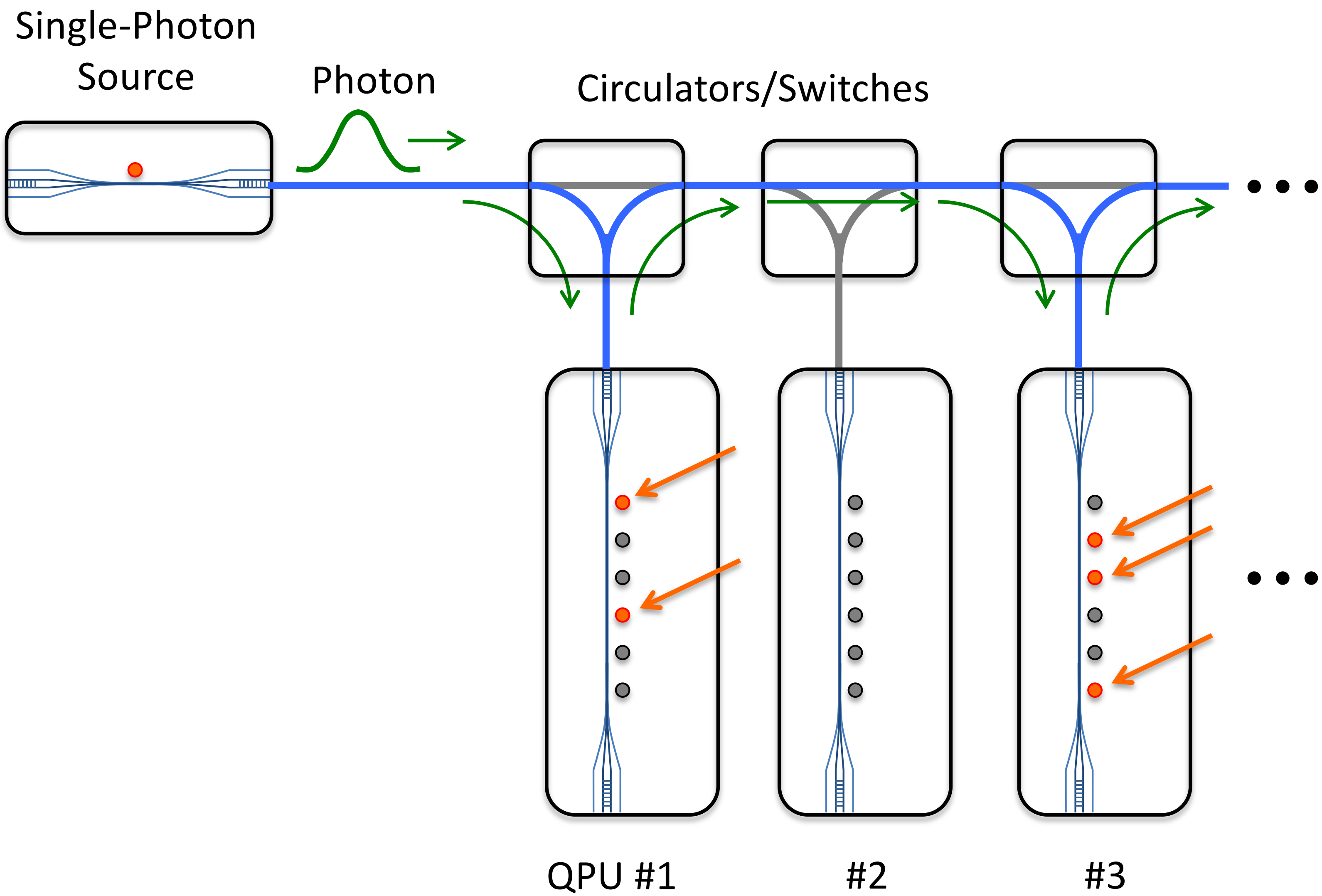


C. -L. Hung *et al.*, PNAS **113**, 4336 (2016)
A. Periwal *et al.*, Nature **600**, 630 (2021)

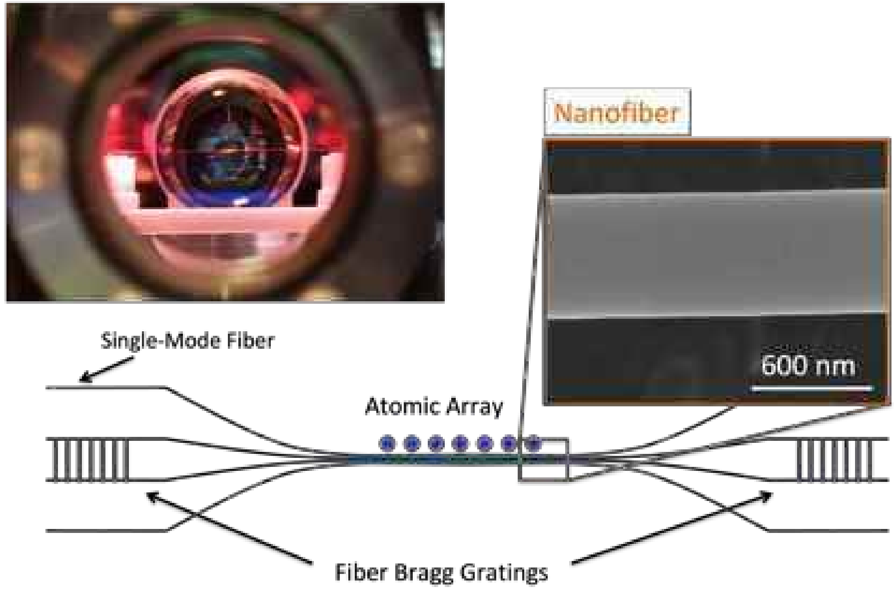
    - Atom-atom interaction via exchange of photon
    - Parallel operation with multi-color driving

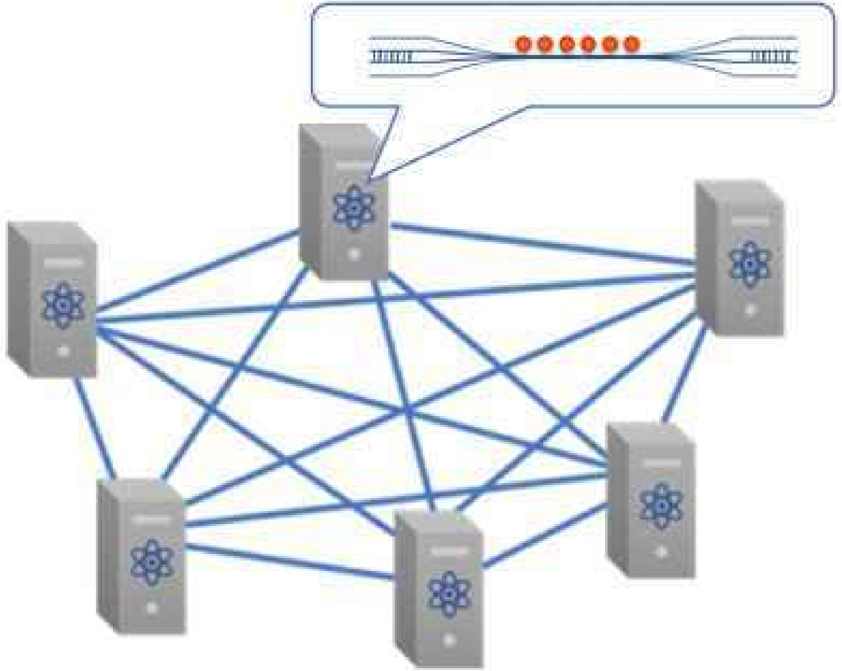
Distributed QC With Nanofiber CQED

PCT/JP2021/25783



This Project: Nanofiber Cavity QED





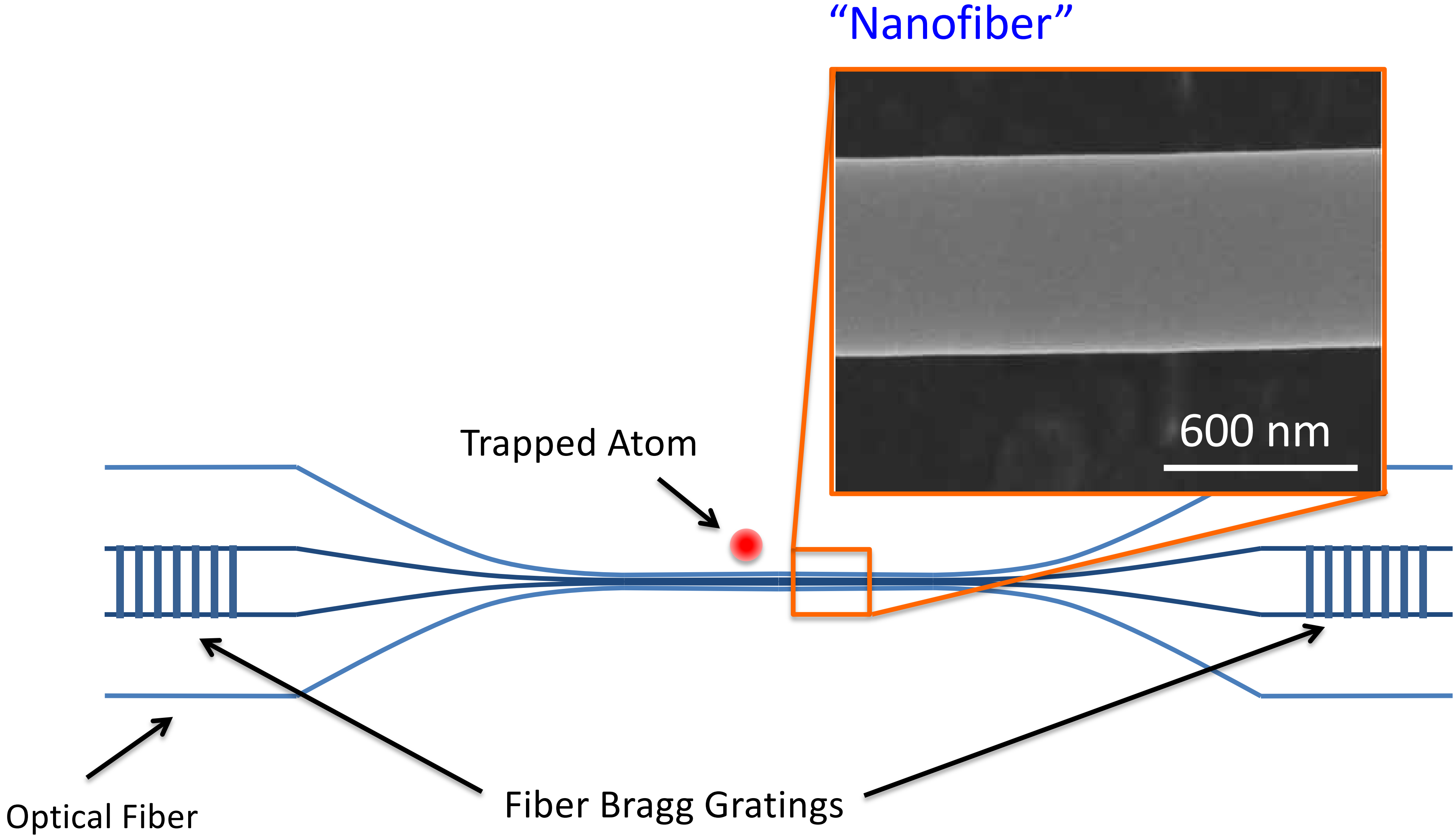
- All-fiber cavity QED system with many, individually addressable atoms

- Each unit is a middle-scale quantum computer (QPU)
- Many units are connected by optical fibers

Large-Scale Distributed Quantum Computing

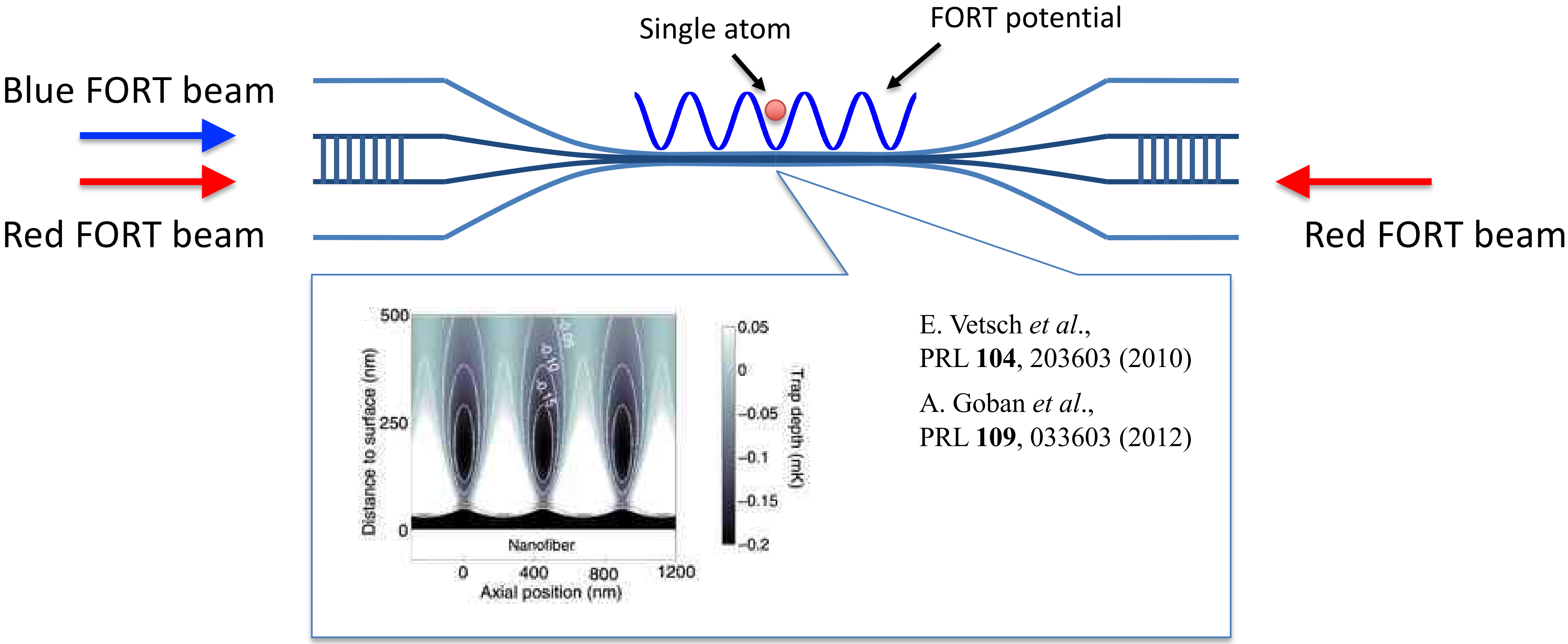
Our Technologies

Nanofiber Cavity QED System



Trapping an Atom

Far-Off-Resonance Optical Trapping (FORT) of single atom using evanescent field

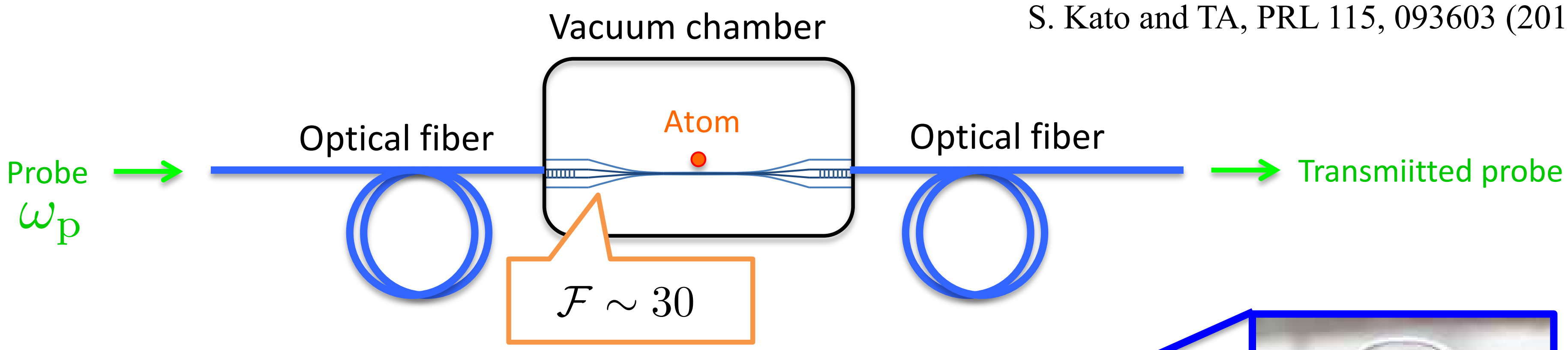


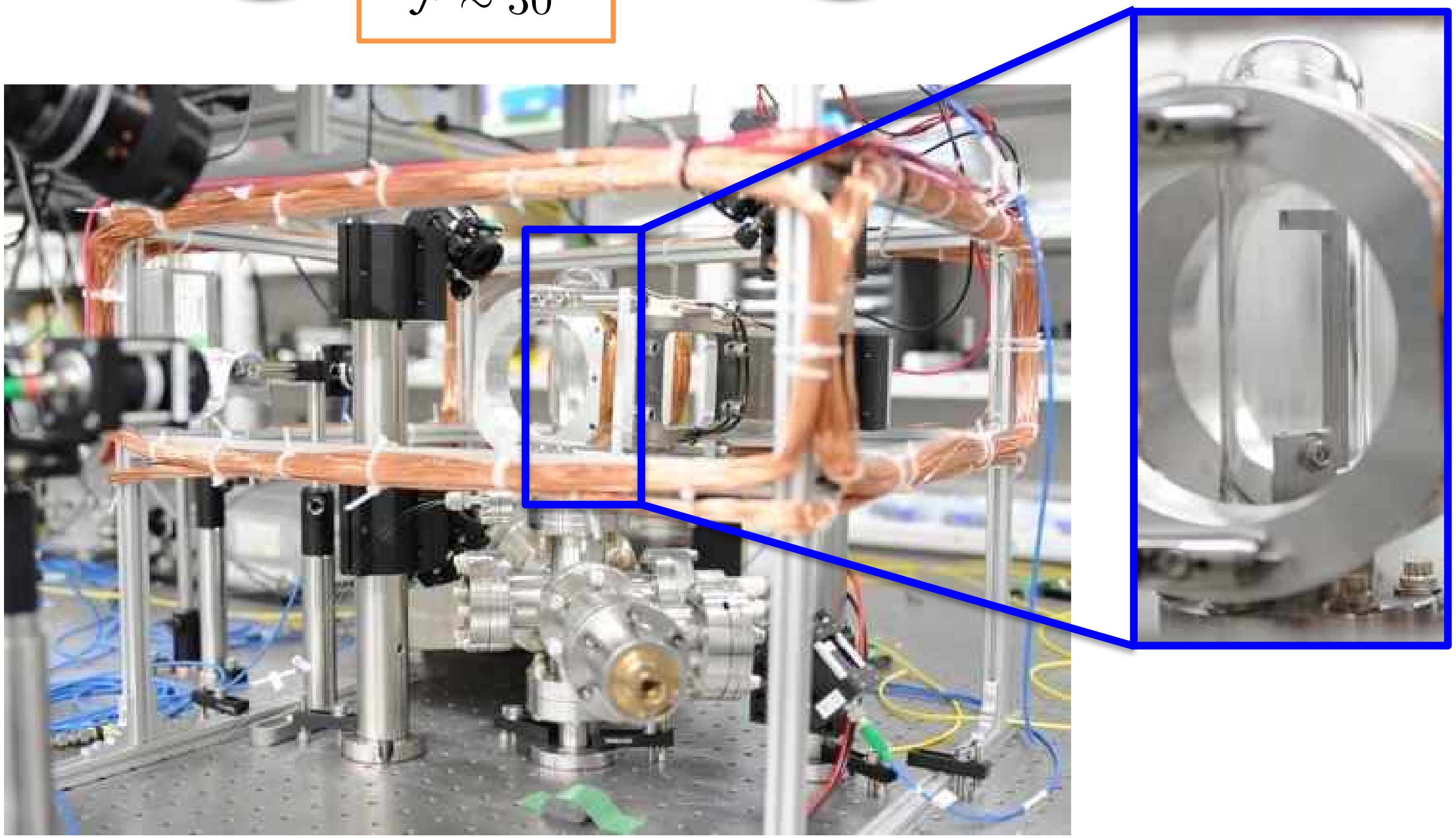
E. Vetsch *et al.*,
PRL **104**, 203603 (2010)

A. Goban *et al.*,
PRL **109**, 033603 (2012)

Nanofiber Cavity QED System

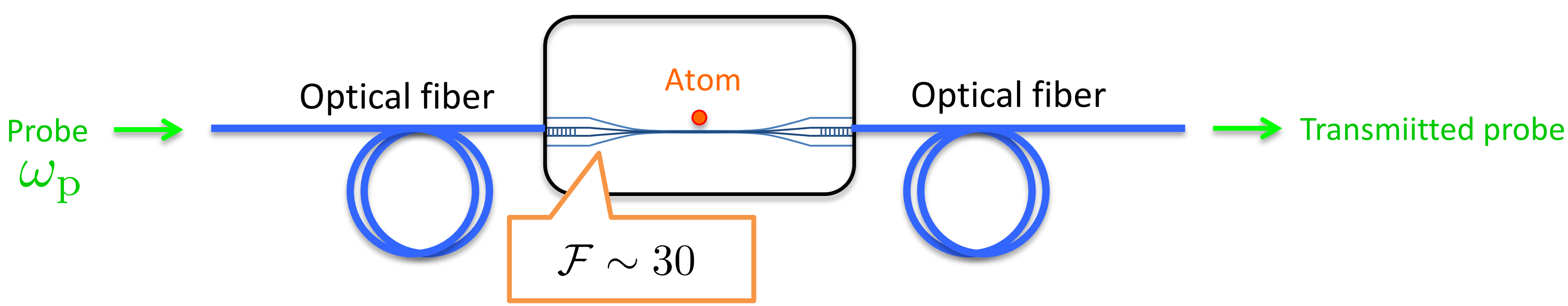
S. Kato and TA, PRL 115, 093603 (2015)

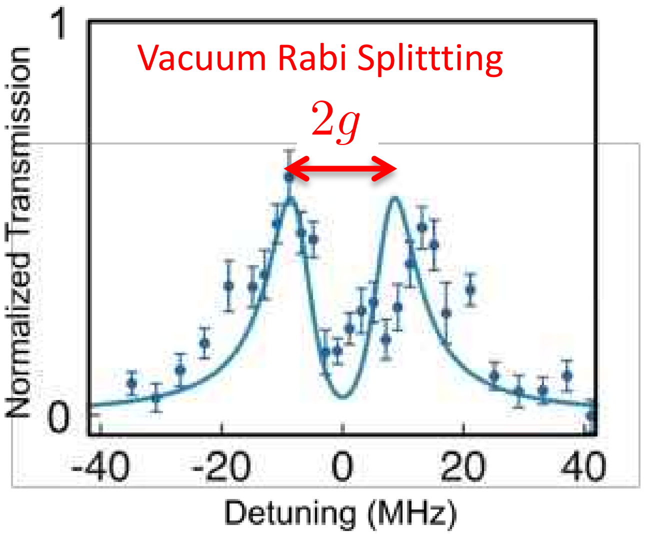


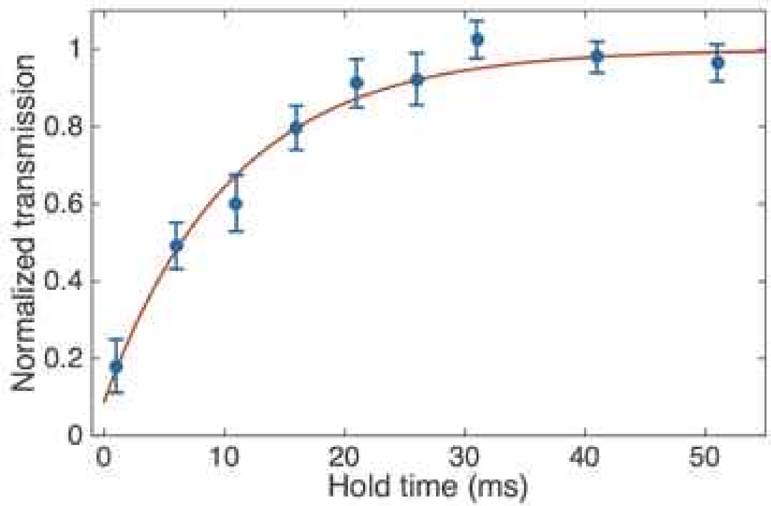


Nanofiber Cavity QED System

S. Kato and TA, PRL 115, 093603 (2015)







$$(g, \kappa, \gamma)/2\pi = (7.8, 6.4, 2.6)\ \mathrm{MHz}$$

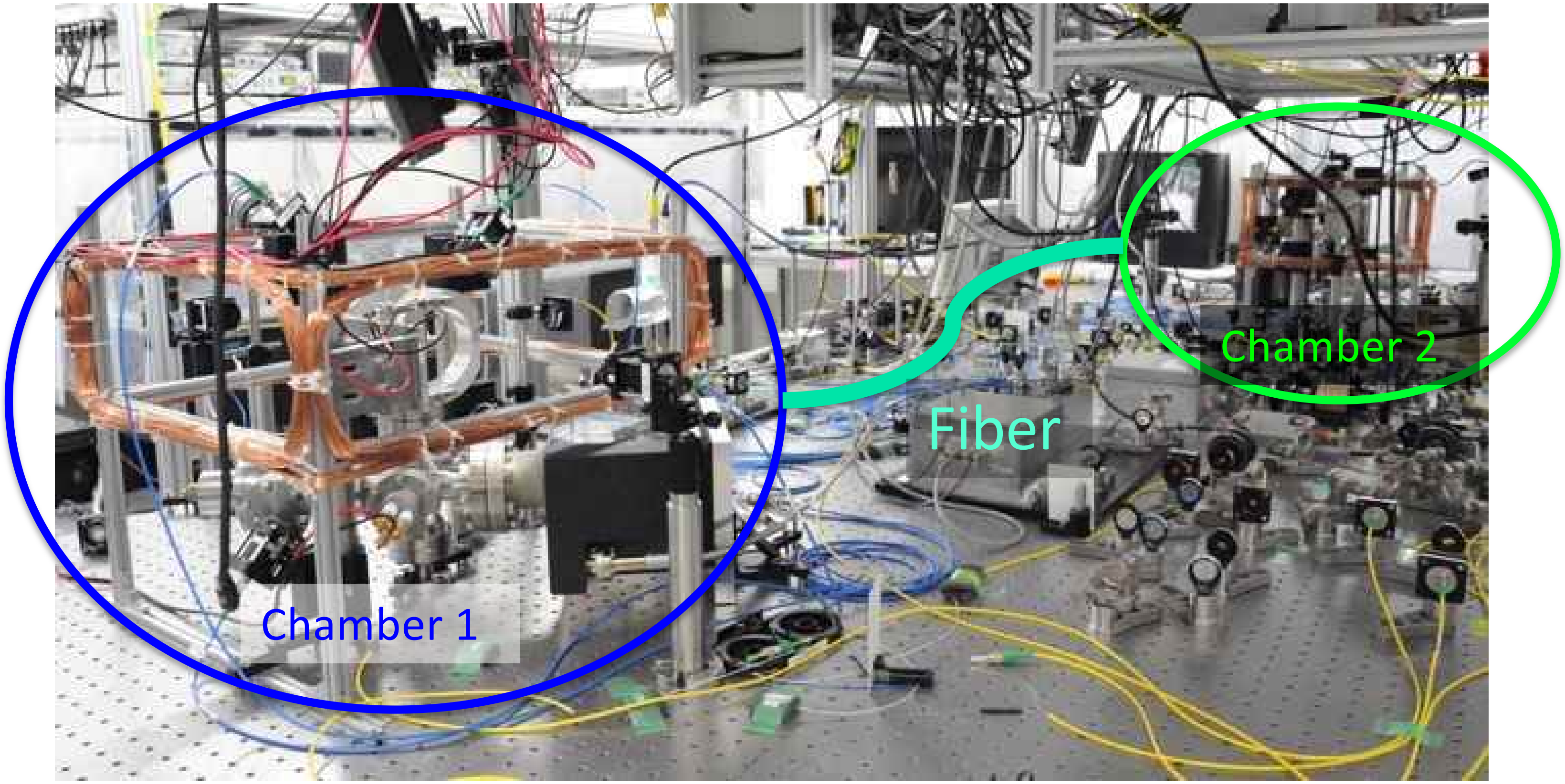
Trap lifetime = 11 ms

Strong coupling ($g > \gamma, \kappa$) is achieved.

Connecting Two Nanofiber CQED Systems

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

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

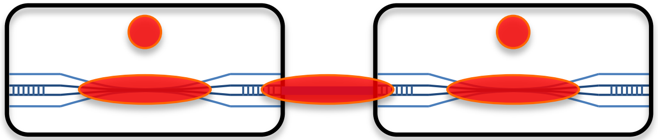


Eigenstates

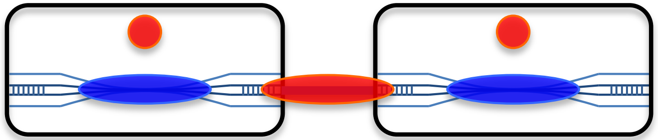
$$\zeta = \sqrt{g^2 + 2v^2}$$

Bright modes

$$|\mathrm{BS1}\rangle \propto g|\mathrm{A}_1\rangle + g|\mathrm{A}_2\rangle + \zeta|\mathrm{C}_1\rangle + \zeta|\mathrm{C}_2\rangle + 2v|\mathrm{F}\rangle$$

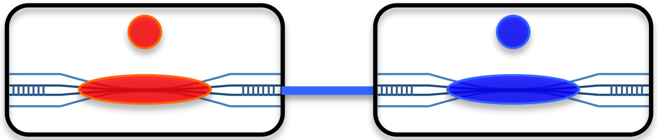


$$|\mathrm{BS2}\rangle \propto g|\mathrm{A}_1\rangle + g|\mathrm{A}_2\rangle - \zeta|\mathrm{C}_1\rangle - \zeta|\mathrm{C}_2\rangle + 2v|\mathrm{F}\rangle$$

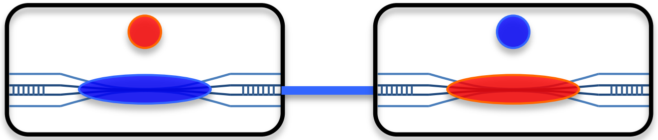


Fiber-dark modes

$$|\mathrm{FD1}\rangle \propto |\mathrm{A}_1\rangle - |\mathrm{A}_2\rangle + |\mathrm{C}_1\rangle - |\mathrm{C}_2\rangle$$

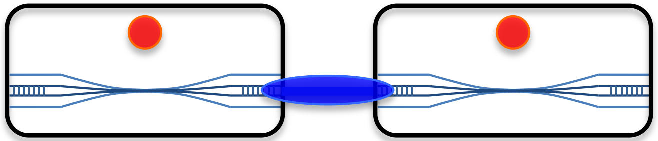


$$|\mathrm{FD1}\rangle \propto |\mathrm{A}_1\rangle - |\mathrm{A}_2\rangle - |\mathrm{C}_1\rangle + |\mathrm{C}_2\rangle$$



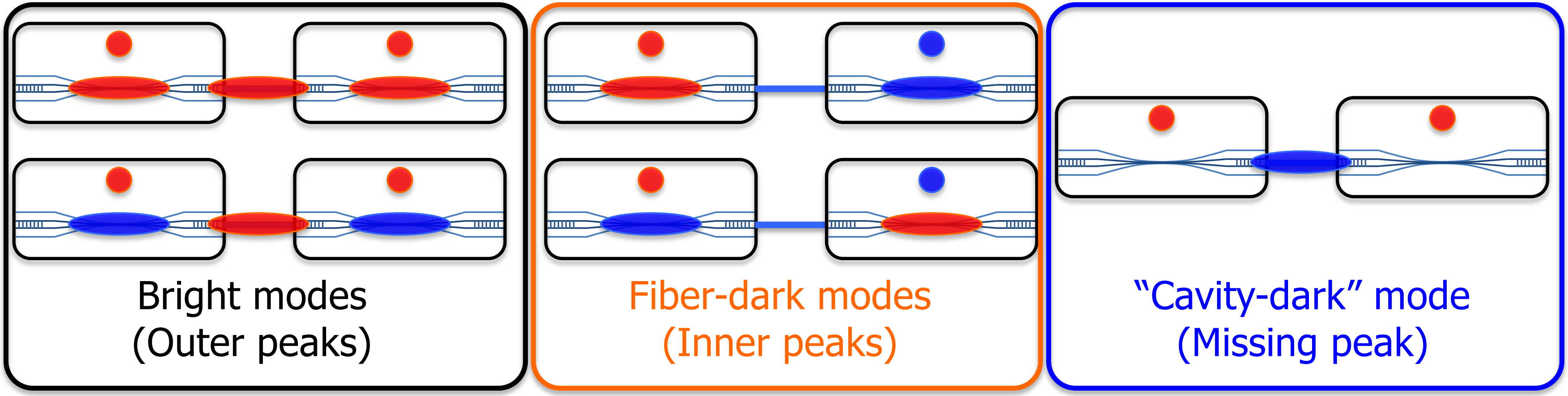
Cavity-dark mode

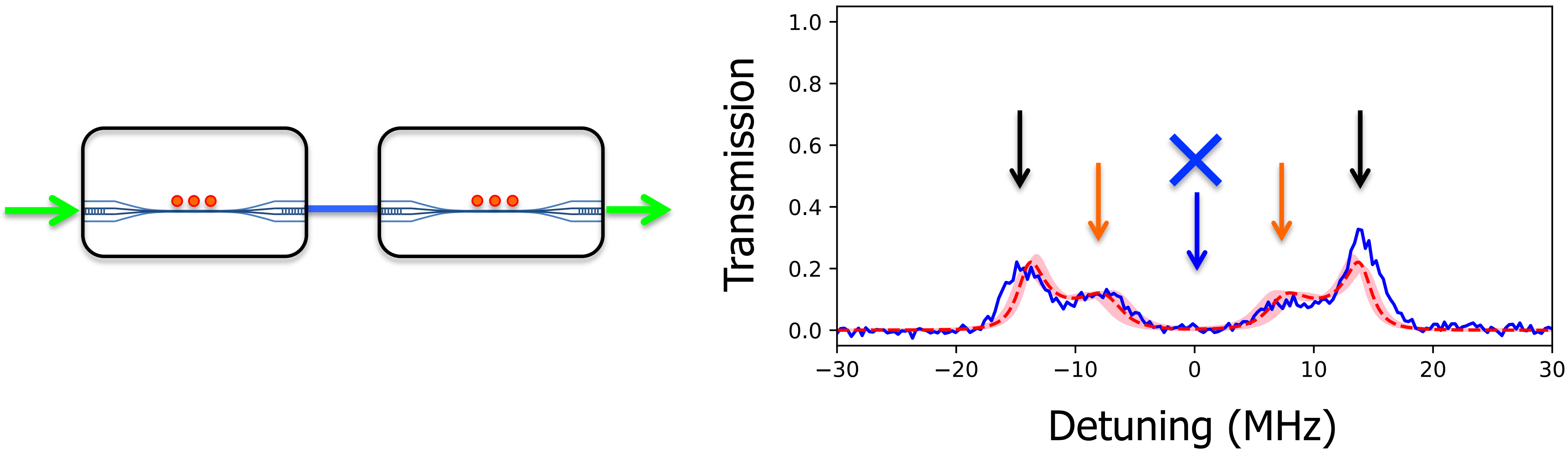
$$|\mathrm{CD}\rangle \propto v|\mathrm{A}_1\rangle + v|\mathrm{A}_2\rangle - g|\mathrm{F}\rangle$$



Observation of Normal Modes

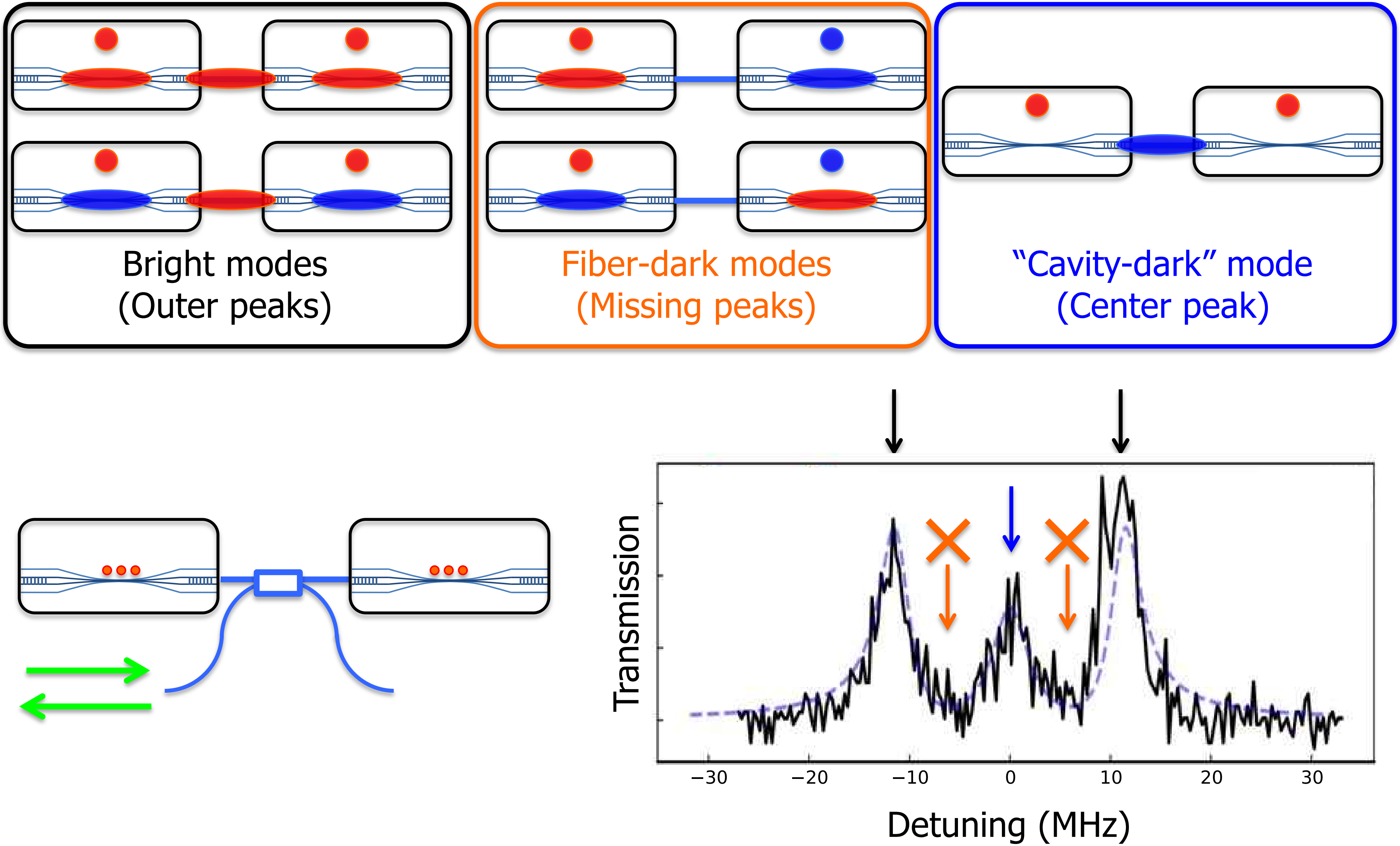
S. Kato *et al.*, Nature Commun. 10, 1160 (2019)





Observation of Normal Modes

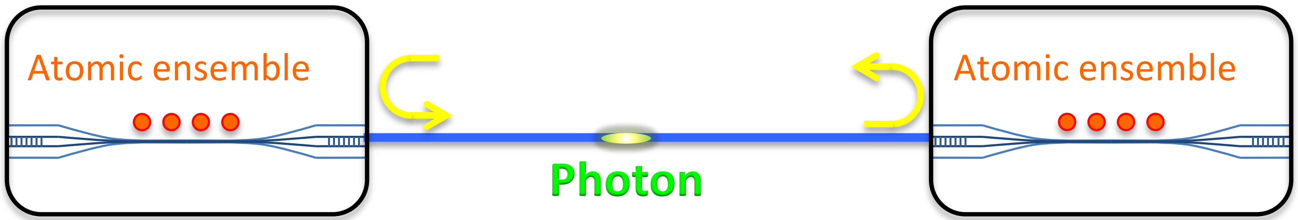
D. White *et al.*, PRL 122, 253603 (2019)

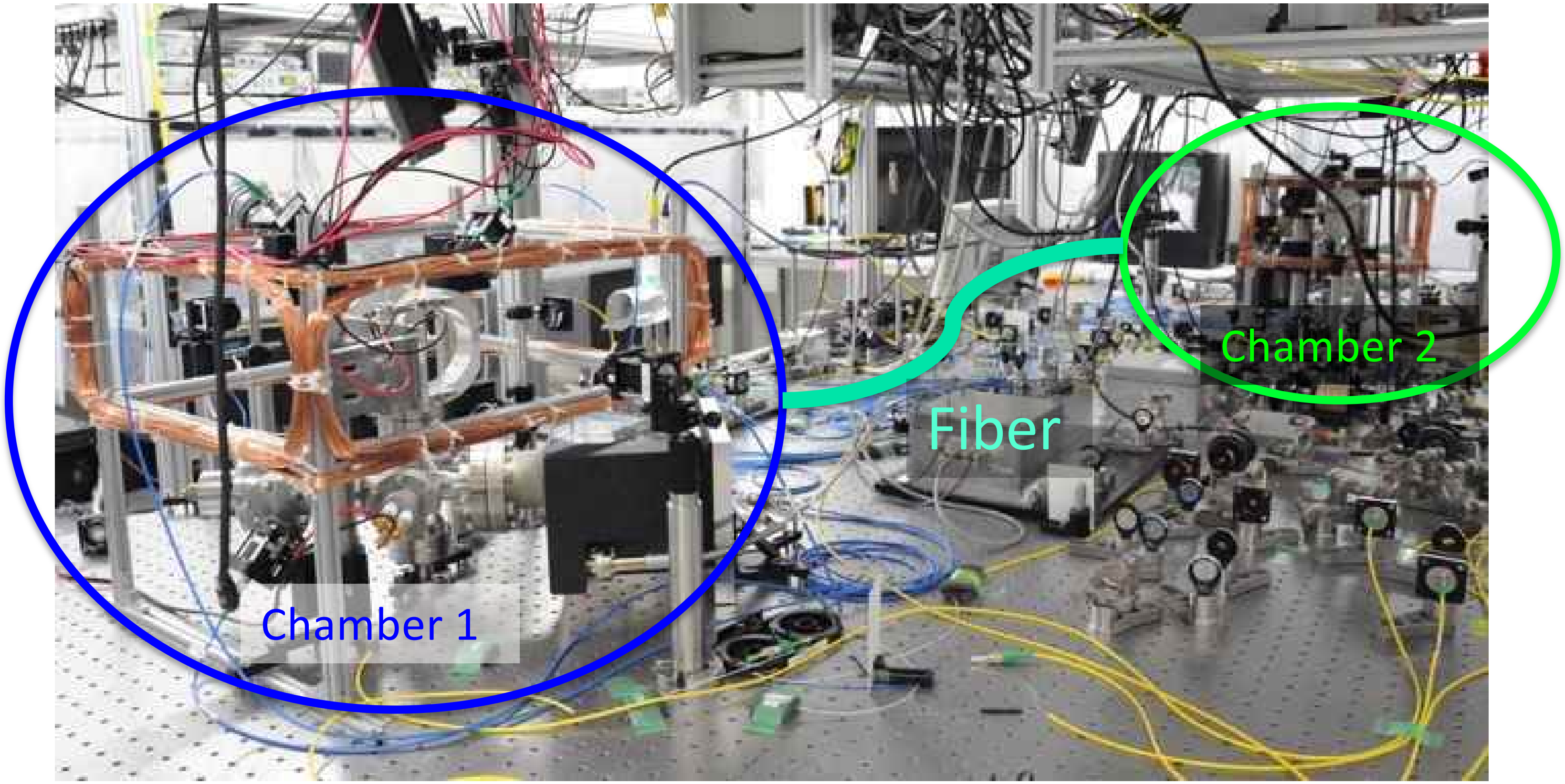


Connecting Two Nanofiber CQED Systems

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

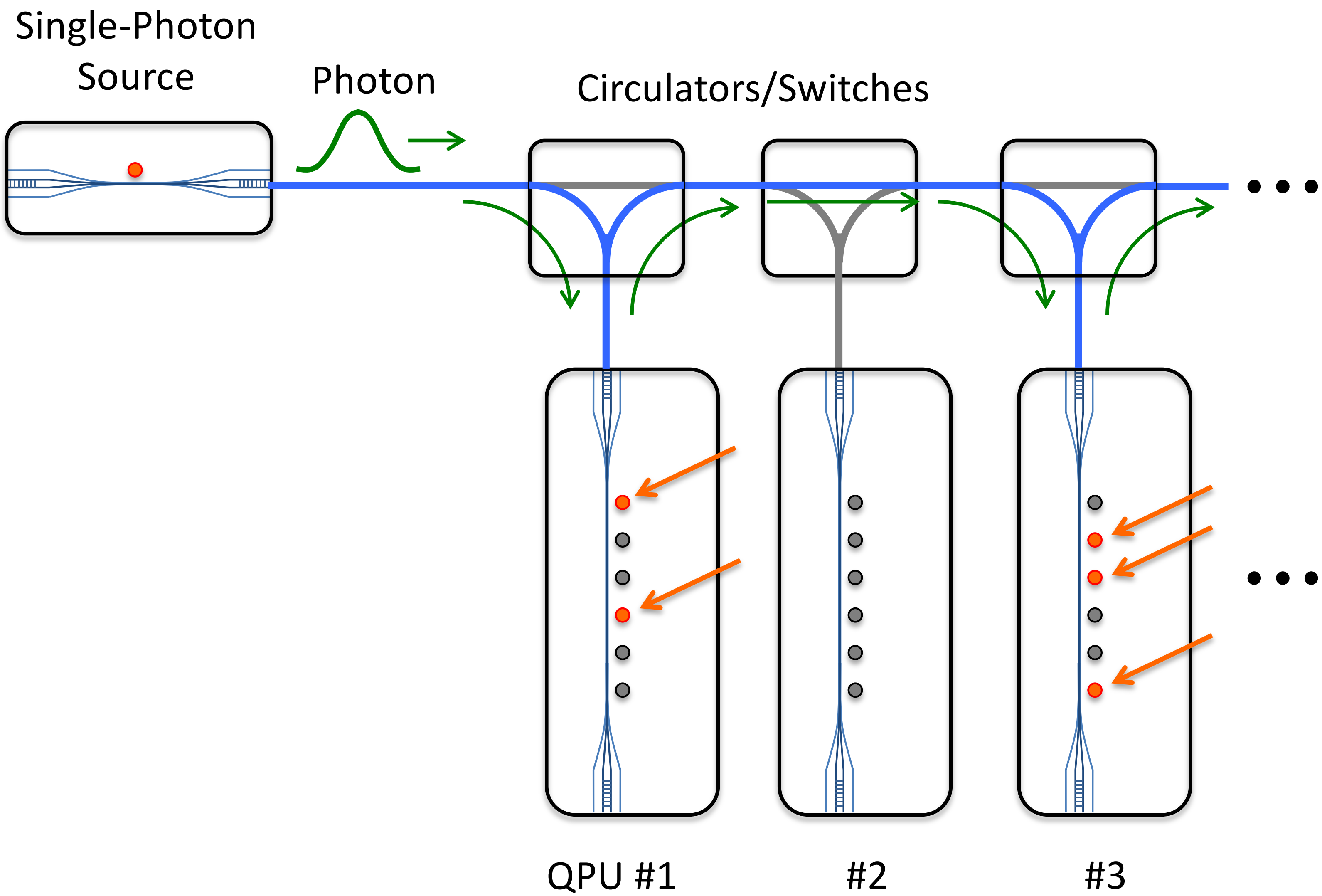
D. White *et al*., PRL 122, 253603 (2019)





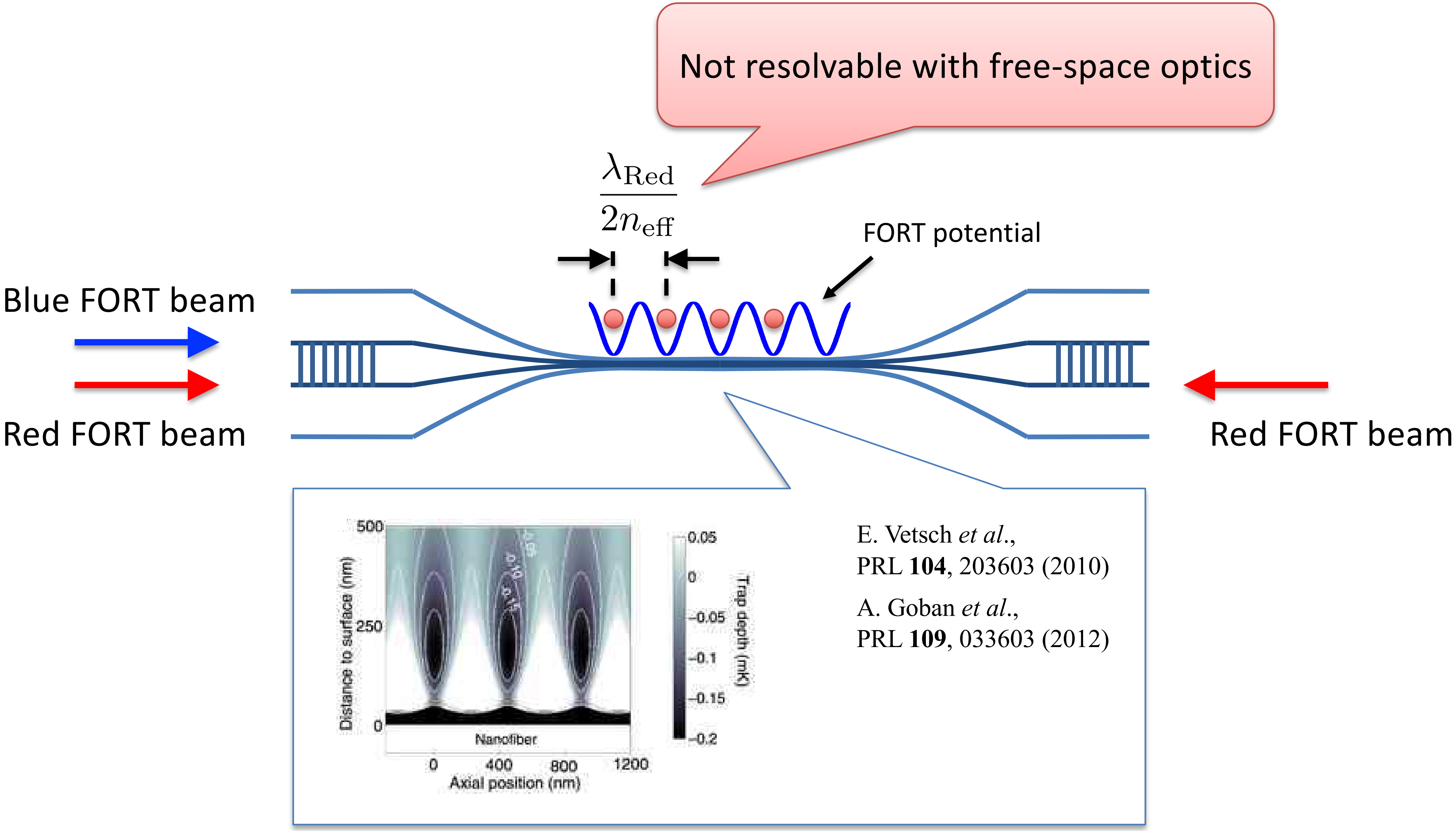
Distributed QC With Nanofiber CQED

PCT/JP2021/25783



Trapping Many "Individually Addressable" Atoms

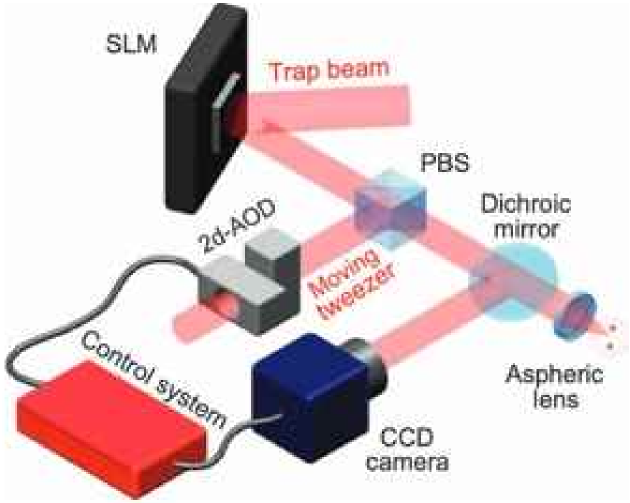
Far-Off-Resonance Optical Trapping (FORT) of single atoms using evanescent field

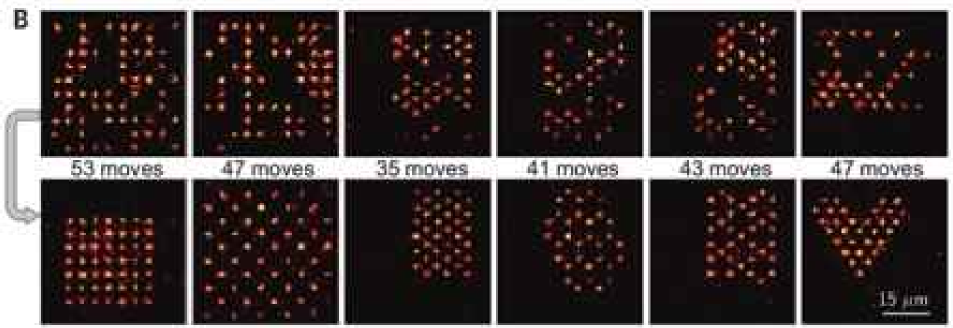


Trapping Many “Individually Addressable” Atoms

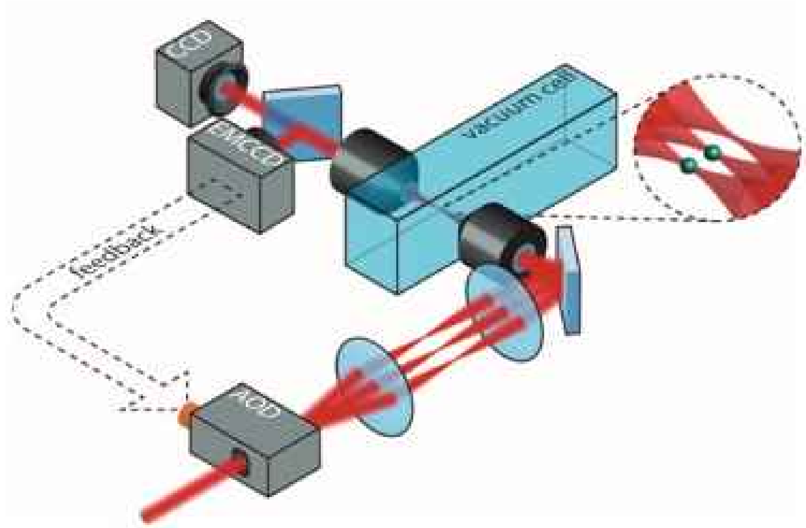
- Optical Tweezers

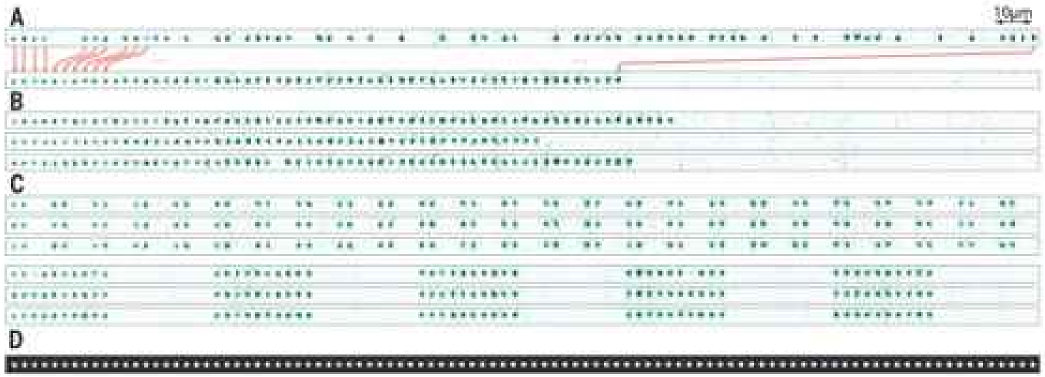
D. Barredo *et al*., Science 354, 1021 (2016)





M. Endres *et al*., Science 354, 1024 (2016)

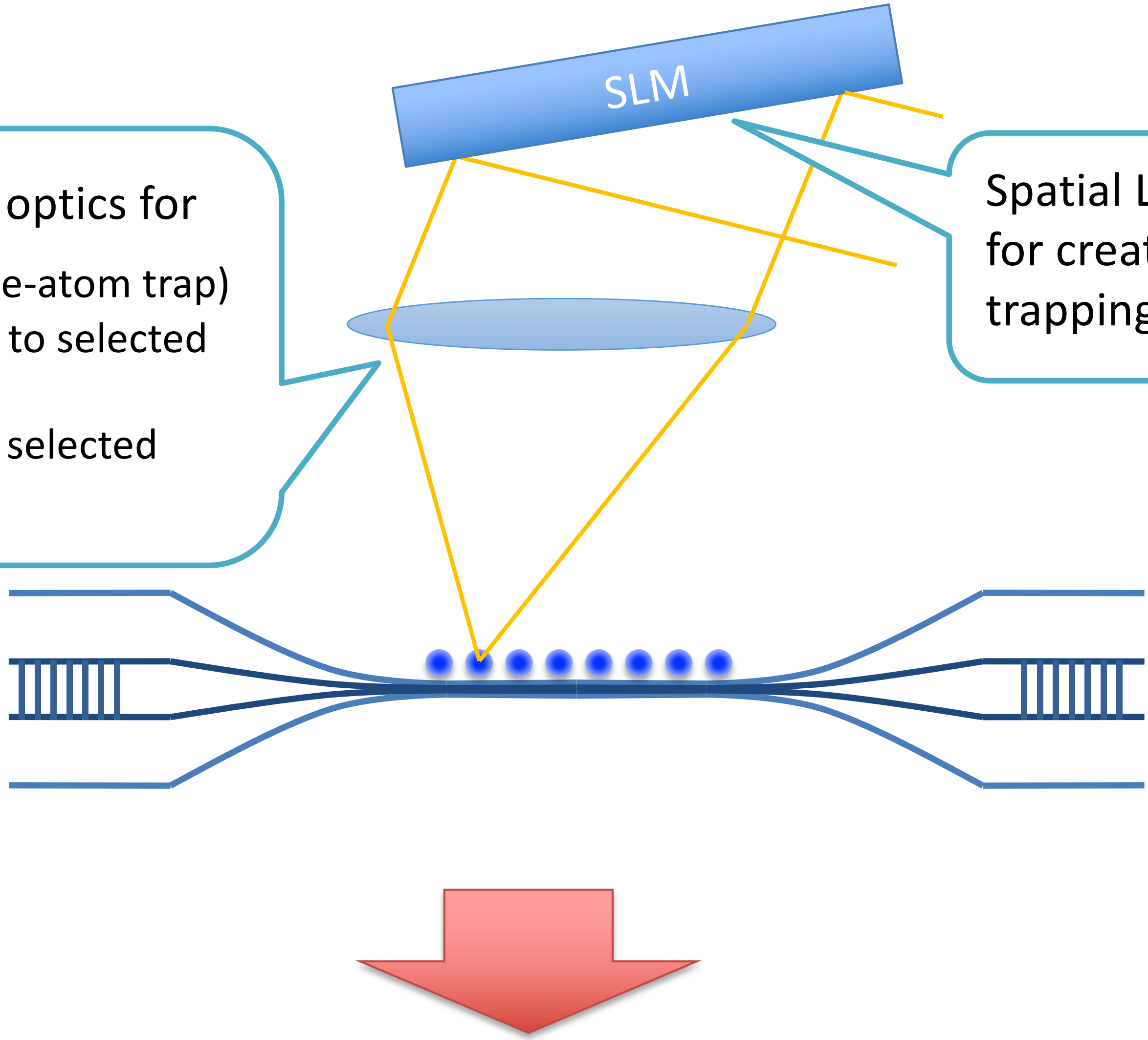




Trapping Many "Individually Addressable" Atoms

Site-resolved imaging optics for

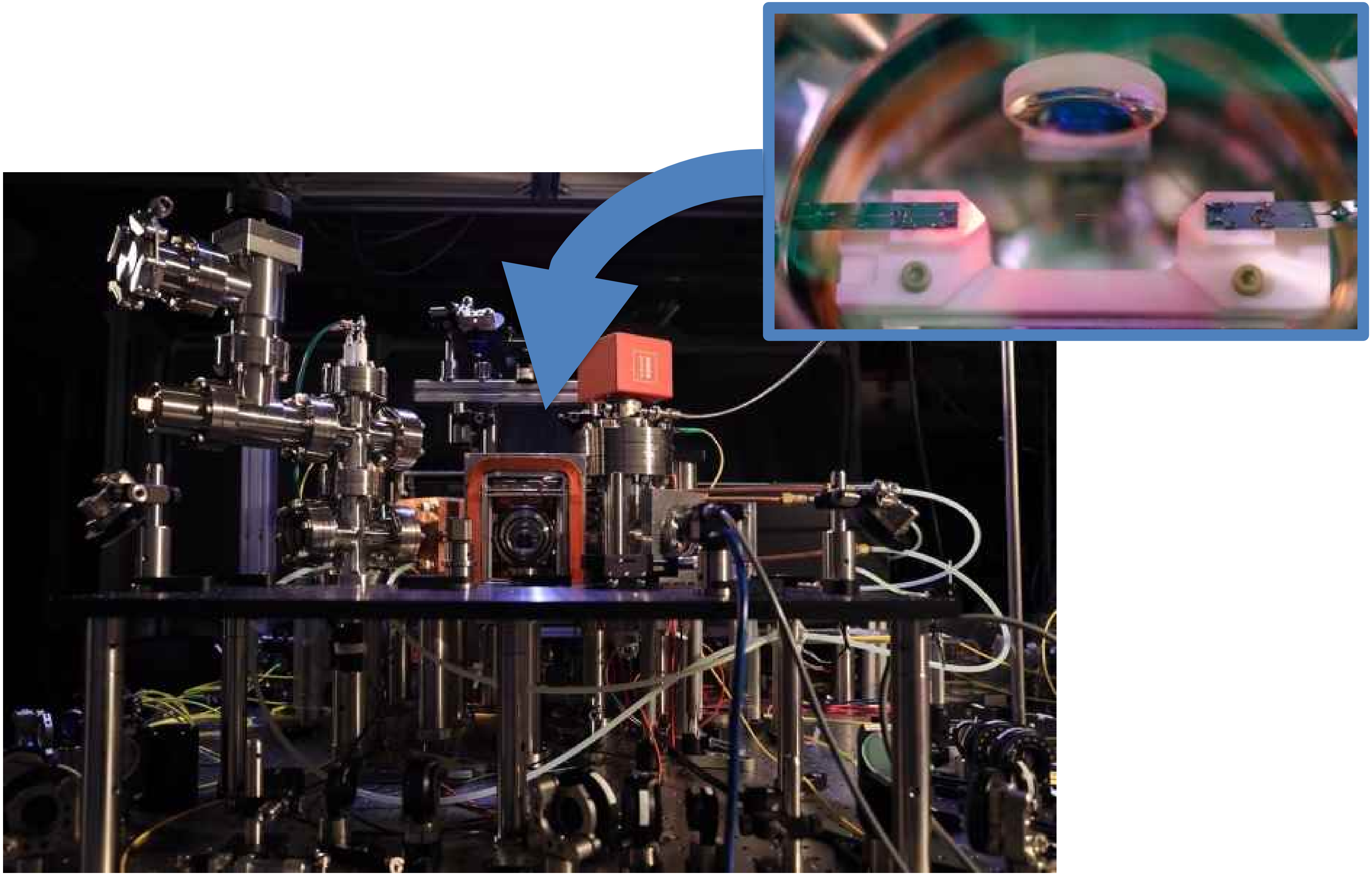
- Optical tweezer (single-atom trap)
- Applying control field to selected atom(s)
- Applying light shift to selected atom(s)



Spatial Light Modulator for creating 1d array of trapping potential

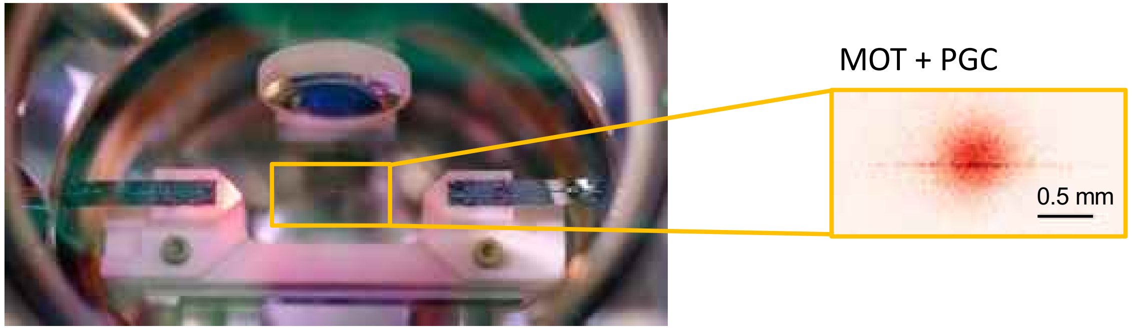
Quantum Processing Unit (QPU) based on nanofiber CQED

QPU Prototype Under Construction

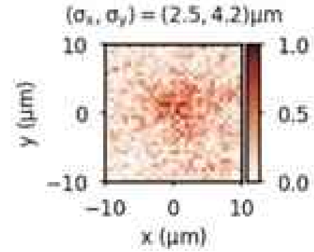


QPU Prototype Under Construction

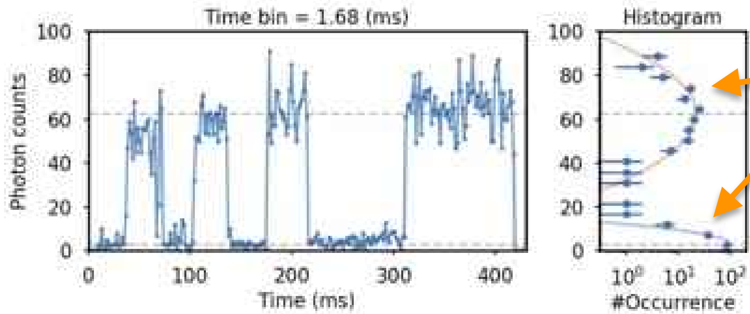
Single-atom trapping with optical tweezer



Fluorescence imaging of trapped single atom



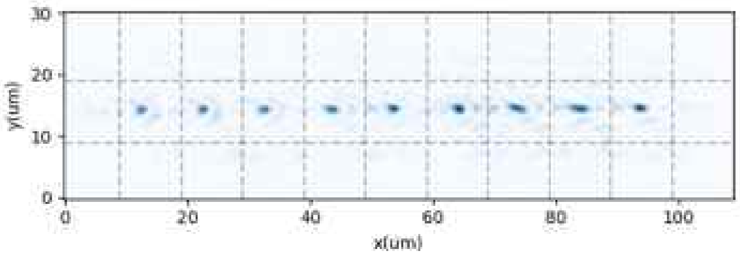
Observation of cavity-enhanced resonance fluorescence

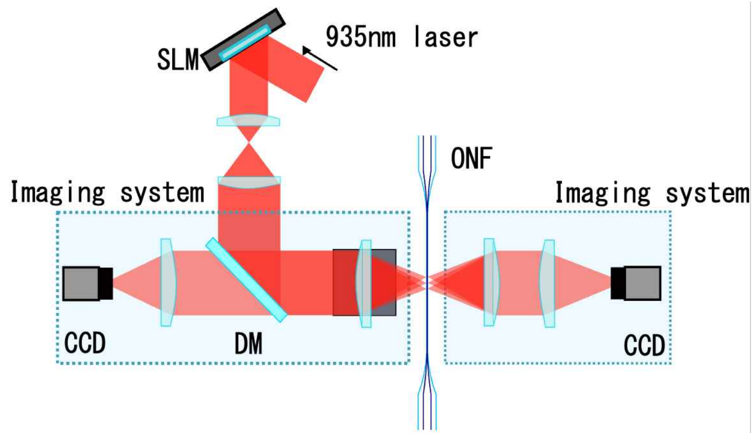


Bimodal distribution

(Single-atom trapping with collisional blockade)

Creation of optical tweezer array with SLM





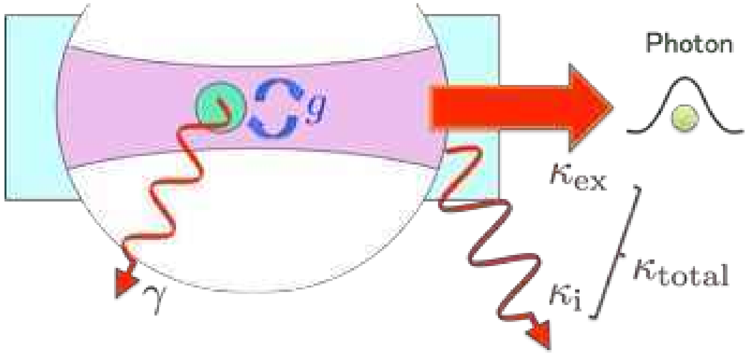
Theory for QC With Cavity QED

H. Goto *et al*., Phys. Rev. A **99**, 053843 (2019)
"*Figure of merit for single-photon generation based on cavity quantum electrodynamics*"

$$P_S^{\max}(\tau \to \infty) = \boxed{\frac{\kappa_{\text{ex}}}{\kappa_{\text{total}}}}\boxed{\frac{C}{1+C}}$$

Extraction efficiency
(Escape efficiency)

Internal efficiency



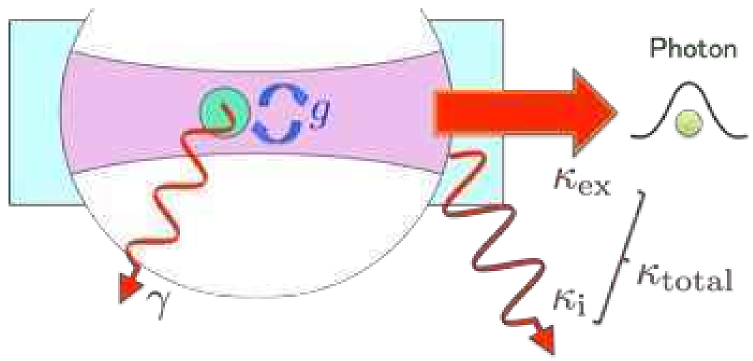
Theory for QC With Cavity QED

H. Goto *et al*., Phys. Rev. A **99**, 053843 (2019)
"*Figure of merit for single-photon generation based on cavity quantum electrodynamics*"

$$P_S^{\max}(\tau \to \infty) = \frac{\kappa_{\mathrm{ex}}}{\kappa_{\mathrm{total}}} \frac{C}{1+C}$$

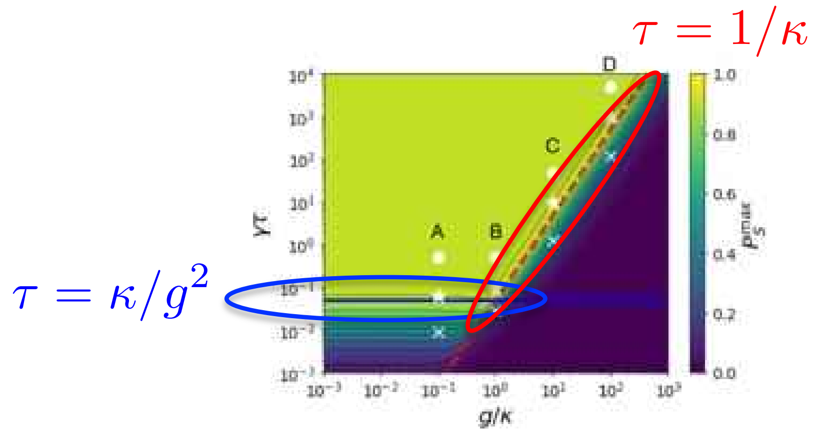
$$\leq 1 - \frac{2}{1+\sqrt{1+C_{\mathrm{i}}}}$$

(Equality holds for $\kappa_{\mathrm{ex}}^{\mathrm{opt}} = \kappa_{\mathrm{i}}\sqrt{1+C_{\mathrm{i}}}$)



"Internal cooperativity" $C_{\mathrm{i}} \equiv \dfrac{g^2}{2\kappa_{\mathrm{i}}\gamma}$

T. Utsugi *et al*., Phys. Rev. A **106**, 023712 (2022) "*Gaussian-wave-packet model for single-photon generation based on cavity quantum electrodynamics under adiabatic and nonadiabatic conditions*"



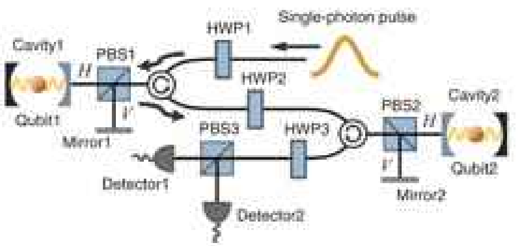
Theory for QC With Cavity QED

R. Asaoka *et al.*, CLEO-PR 2020, “*Suitable fault-tolerant schemes for cavity-QED based quantum computation*”

Threshold for FTQC with topological 3d cluster states

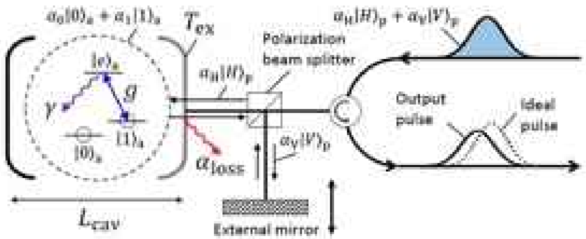
$$C_{\rm i} \sim \mathcal{O}(10)$$

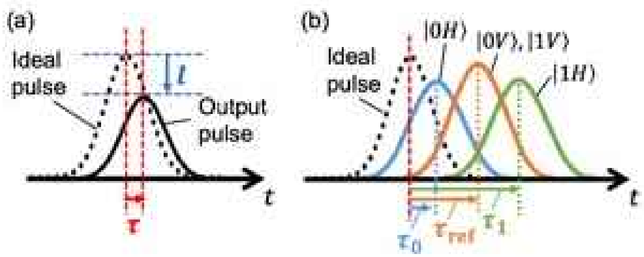
R. Asaoka *et al.*, Phys. Rev. A **104**, 043702 (2021) “*Requirements for fault-tolerant quantum computation with cavity-QED-based atom-atom gates mediated by a photon with a finite pulse length*”

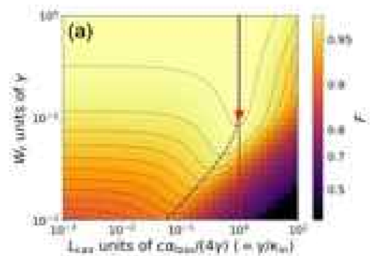


Parameter regime	Main condition for low pulse-distortion error probability
Bad-cavity regime	$g^2/\kappa \gg 1/W_t$
Strong-coupling regime	$\kappa \gg 1/W_t$

T. Utsugi *et al.*, arXiv:2211.04151, “*Optimal cavity design for minimizing errors in cavity-QED-based atom-photon entangling gates with finite temporal duration*”







Internal Cooperativity

"Internal cooperativity"

$$C_\mathrm{i} \equiv \frac{g^2}{2\kappa_\mathrm{i}\gamma}$$

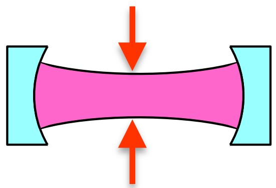
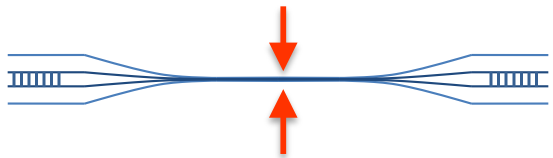
$$\propto \frac{1}{\alpha A} \quad \left(\propto \frac{\mathcal{F}}{A} \right)$$

$$g \propto \frac{1}{\sqrt{AL}}, \quad \kappa_\mathrm{i} \propto \frac{\alpha}{L}$$

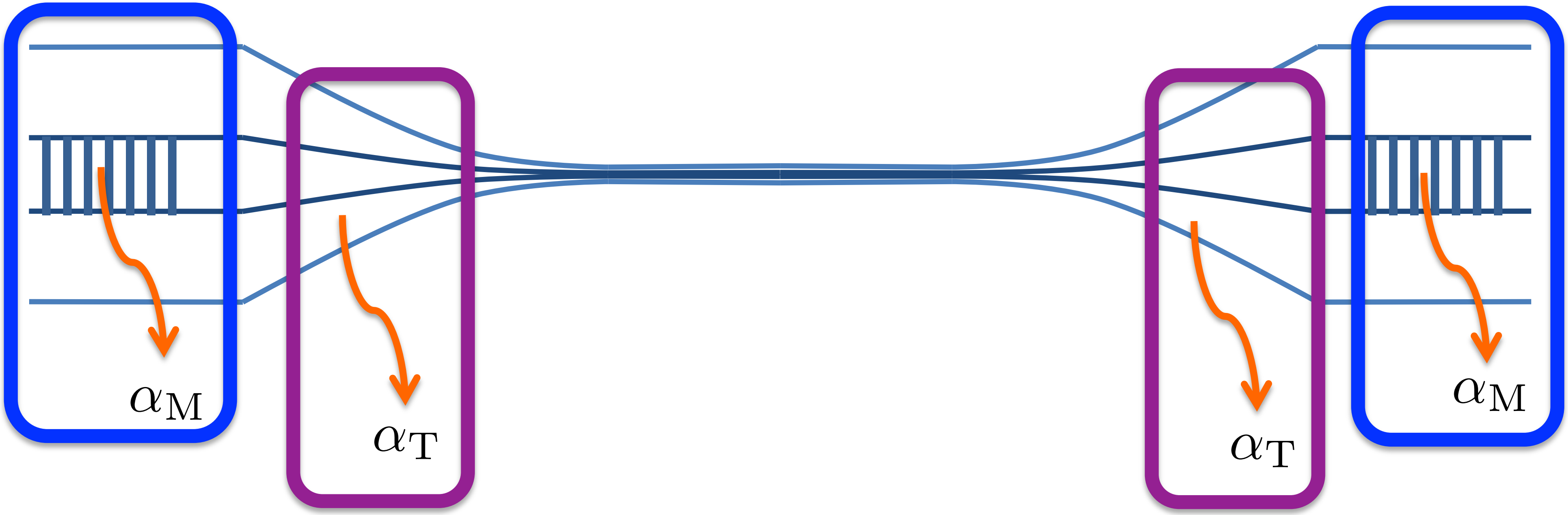
A : mode area

L : cavity length

α : intra-cavity loss

	Free-Space 	Nanofiber 
Mode area A	$\sim 1000\ \mu\mathrm{m}^2$	$\sim 1\ \mu\mathrm{m}^2$
Intra-cavity loss α	$\sim 10^{-6}$	$< 10^{-3}$ (projected)

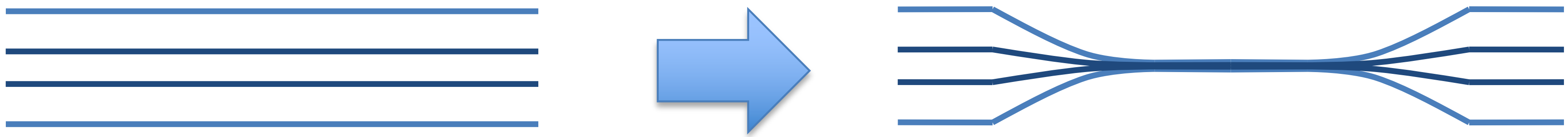
Losses in Nanofiber Cavity

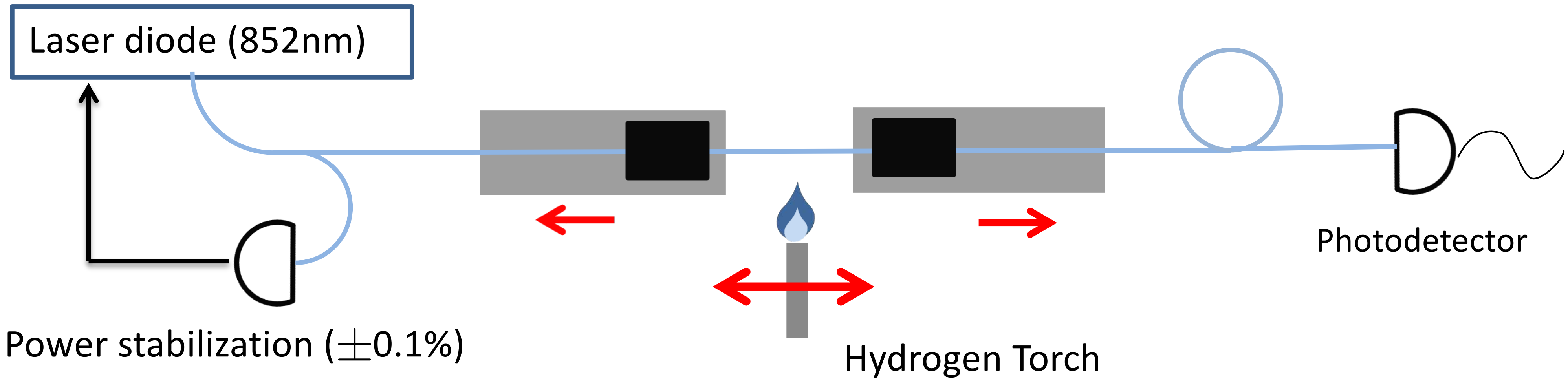


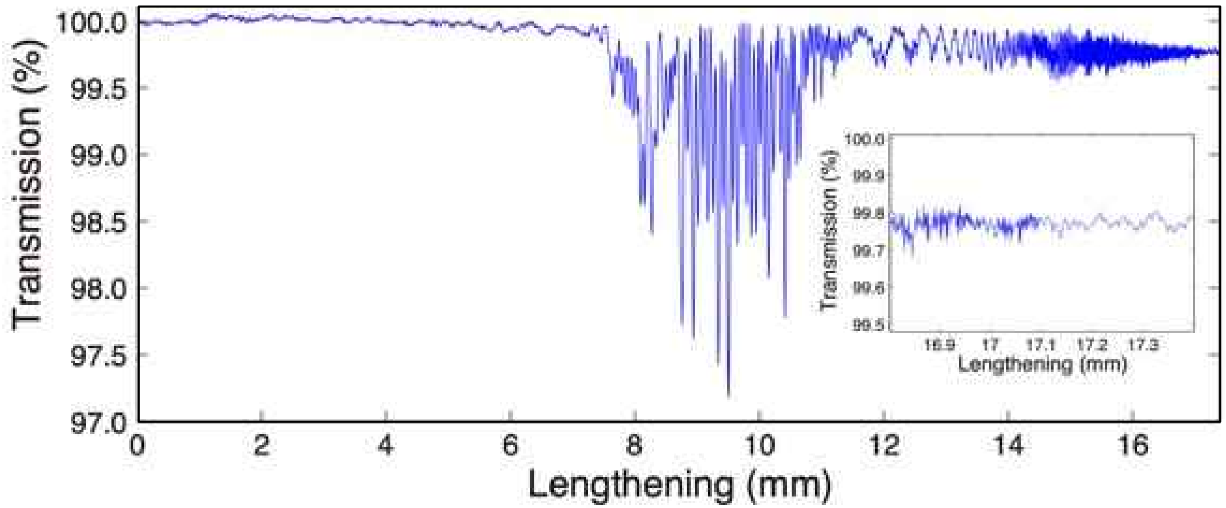
- Losses at tapered region
- Losses at FBGs

Fabrication of Low-Loss Tapers

R. Nagai and T. Aoki, Opt. Express 23, 28427 (2014)

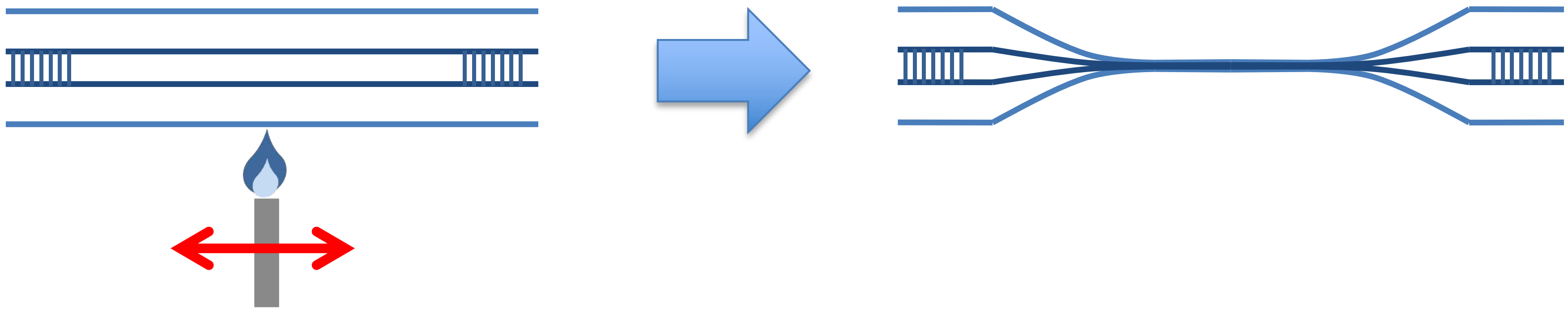




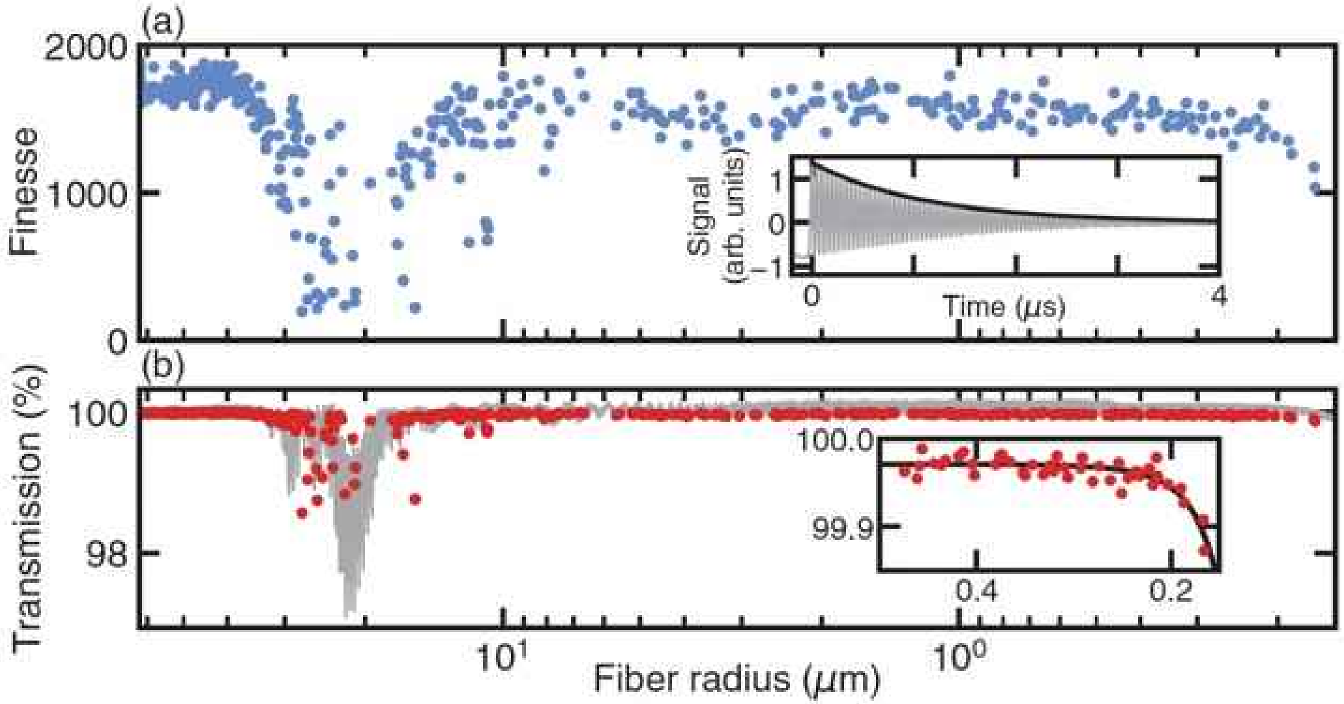


Fabrication of Low-Loss Tapers

S. K. Ruddell *et al.*, Opt. Lett. 45, 4875 (2020)

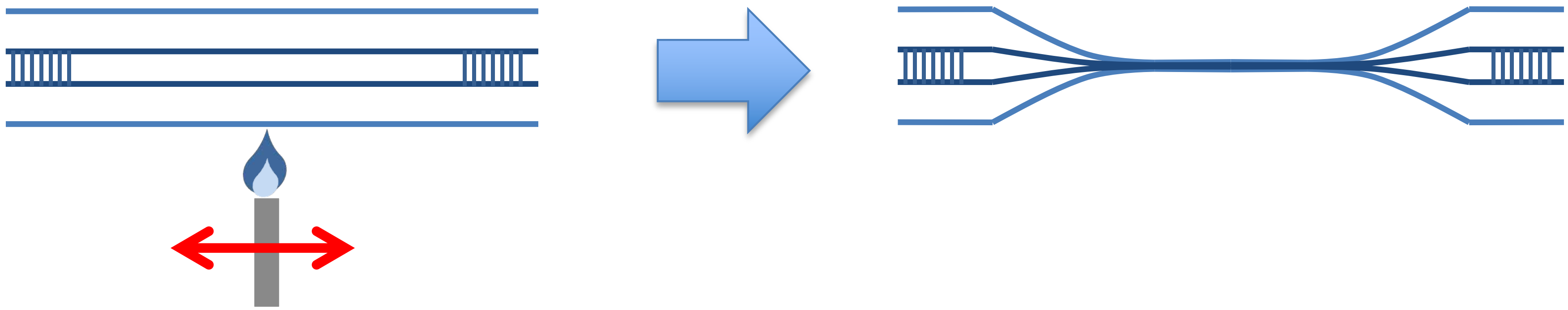


- Real-time monitoring of cavity finesse by means of repetitive ring-down measurement
- Real-time monitoring of nanofiber diameter by means of beat spectrogram measurement



Fabrication of Low-Loss Tapers

S. K. Ruddell *et al.*, Opt. Lett. 45, 4875 (2020)



- Real-time monitoring of cavity finesse by means of repetitive ring-down measurement
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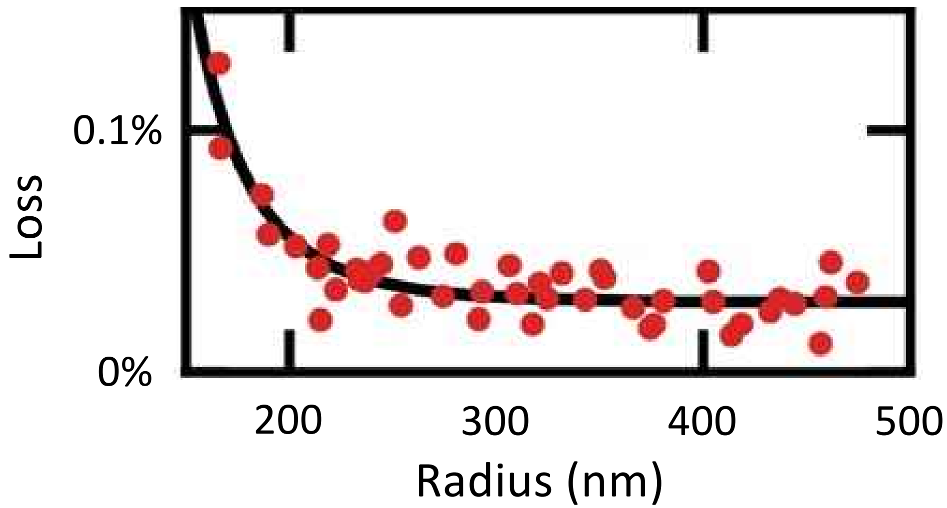


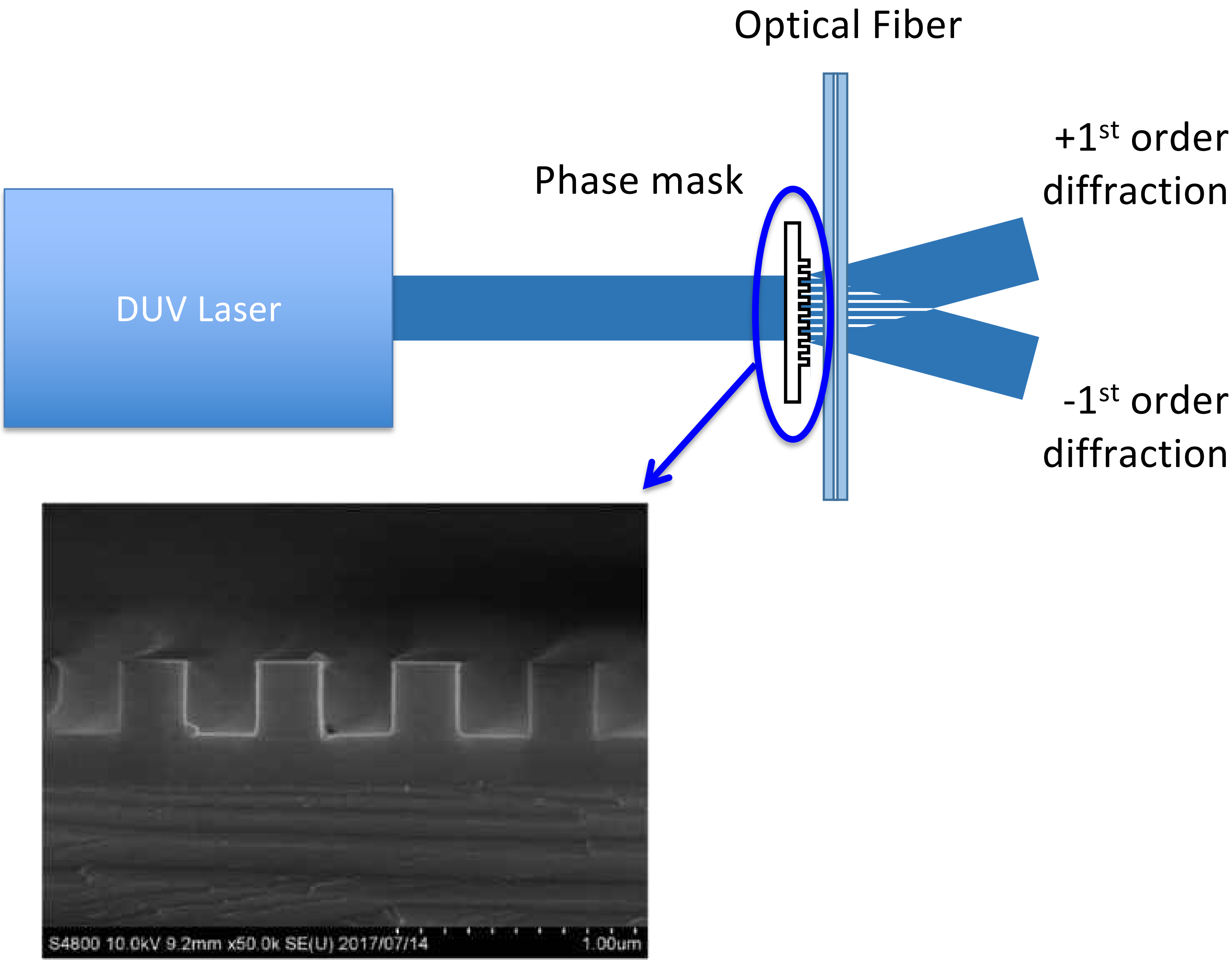
Taper losses at $r \lesssim 500\,\mathrm{nm}$ can be fitted with

$$\alpha(r) = \alpha_0 + \left(\frac{r_0}{r}\right)^{\tau}$$

$$\begin{cases} \alpha_0 = 0.028\% \\ r_0 = 49\,\mathrm{nm} \\ \tau = 5.8 \end{cases}$$

$\alpha \sim 0.03\%$ at $r \gtrsim 250\,\mathrm{nm}$

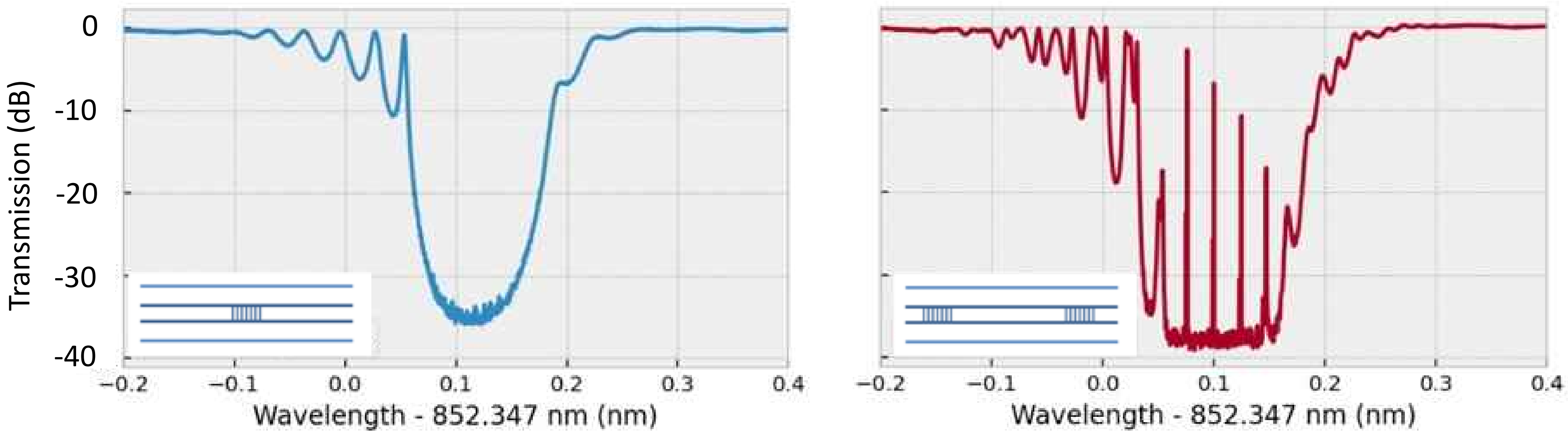
Fabrication of Low-Loss FBG's



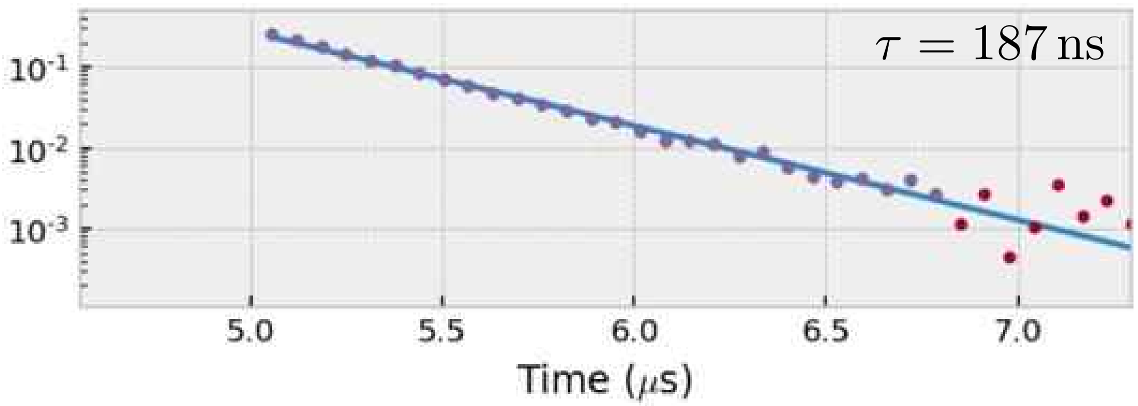
Fabrication of Low-Loss FBG's

S. Kato and T. Aoki, Opt. Lett. 47, 5000 (2022)

Transmission Spectra



Ringdown measurement



$\tau = 187\,\mathrm{ns}$

$\Delta_{\mathrm{FWHM}}/(2\pi) = 853.5\,\mathrm{kHz}$

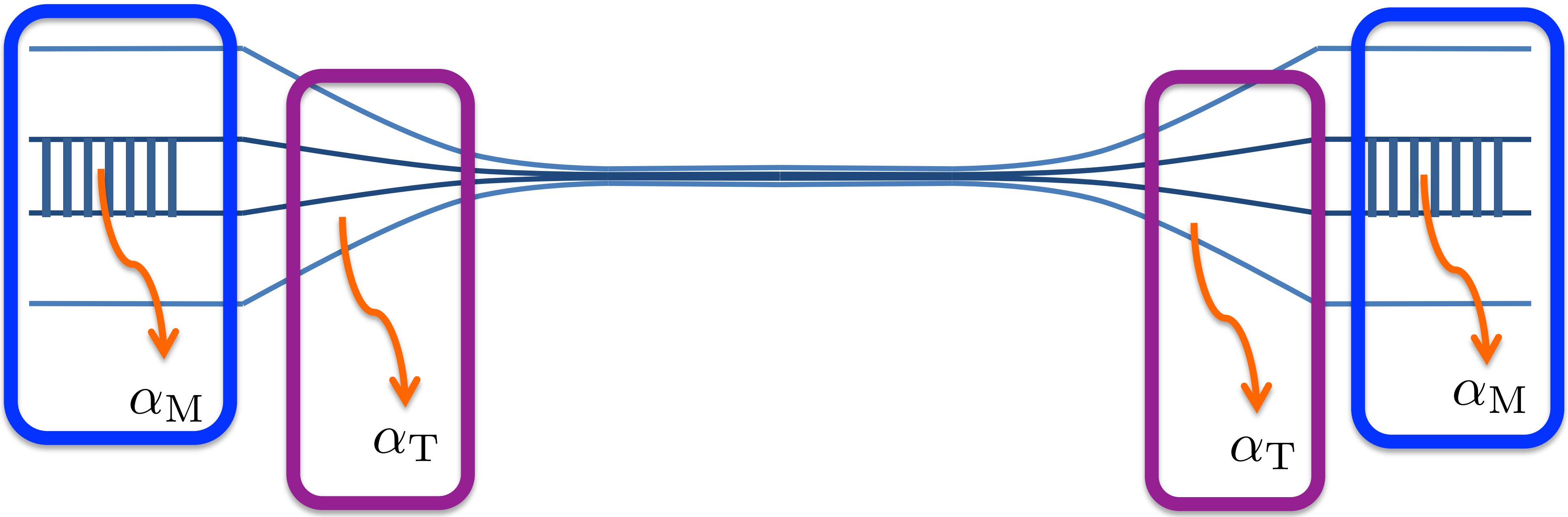
$L = 14.65\,\mathrm{mm}$

$\Delta_{\mathrm{FSR}}/(2\pi) = 10.242\,\mathrm{GHz}$

$\mathcal{F} = 12,000$

$(\alpha_{\mathrm{M}} < 0.026\%)$

Losses in Nanofiber Cavity



- Losses at tapered region $2\alpha_{\mathrm{T}} \lesssim 0.03\%$
- Losses at FBGs $\alpha_{\mathrm{M}} \lesssim 0.026\%$

Projected round-trip loss $\lesssim 0.1\%$

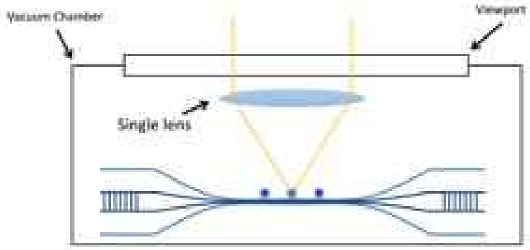
$(\mathcal{F} \gtrsim 6,000)$

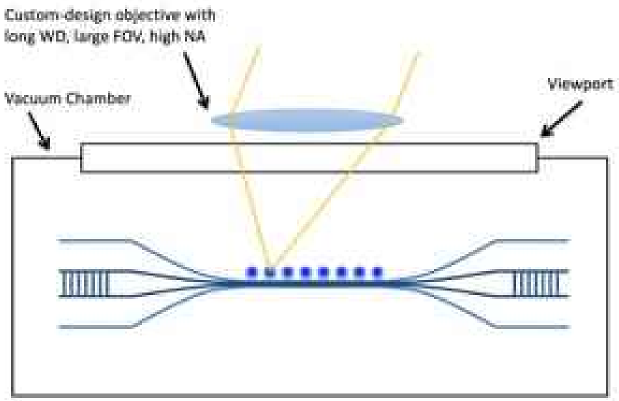
Projected cooperativity $C > 100$

Other Technologies Being Developed

- Scaling up

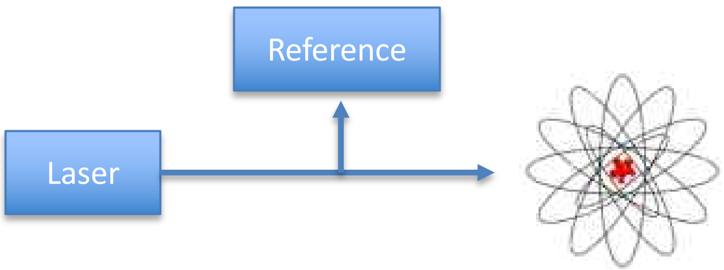
PoC Unit



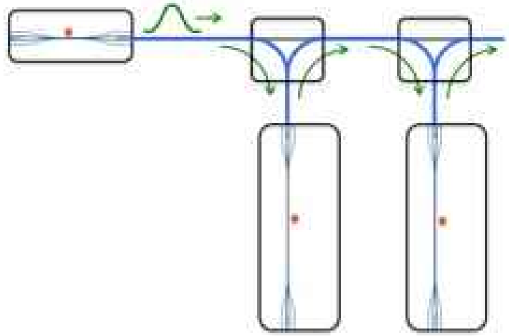


Large-Scale Unit

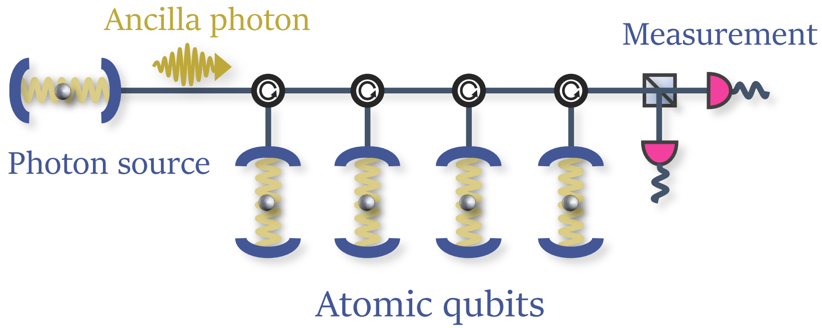
- Stable light source



- Distributed QC

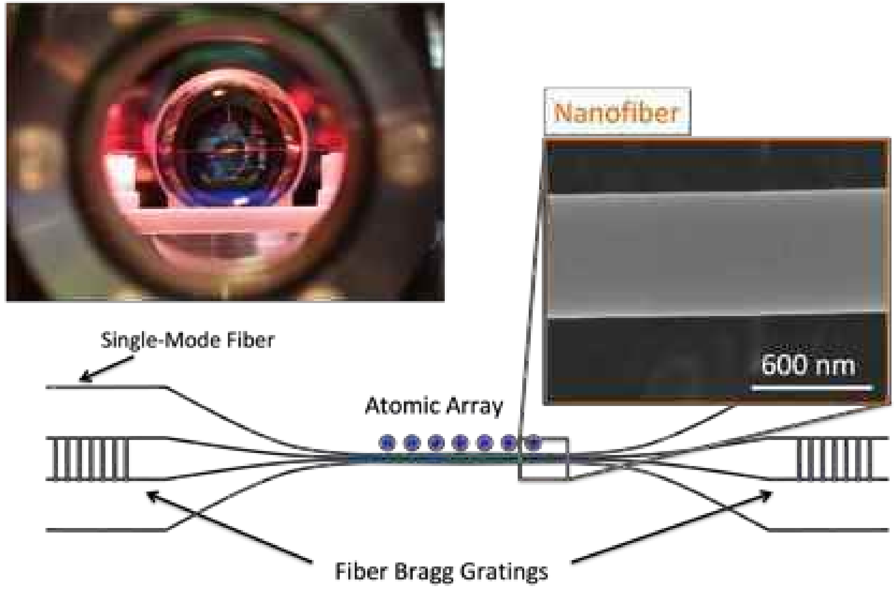


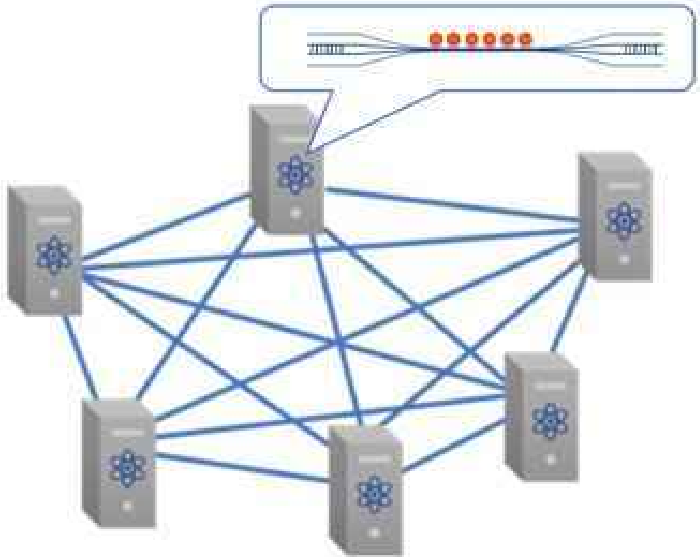
- Quantum error correction theory for cavity QED



- Social implementation

Summary





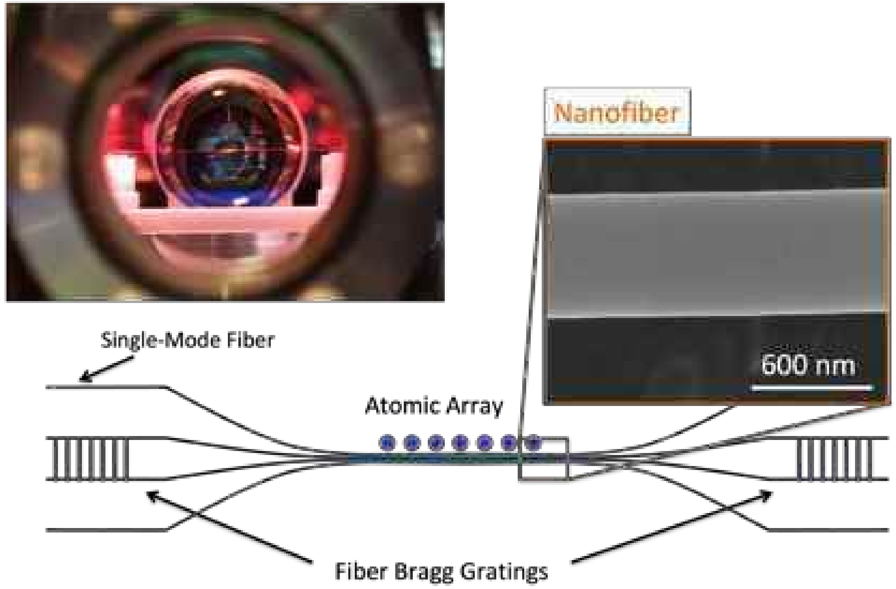
Cavity QED is a hybrid system with atoms and photons.

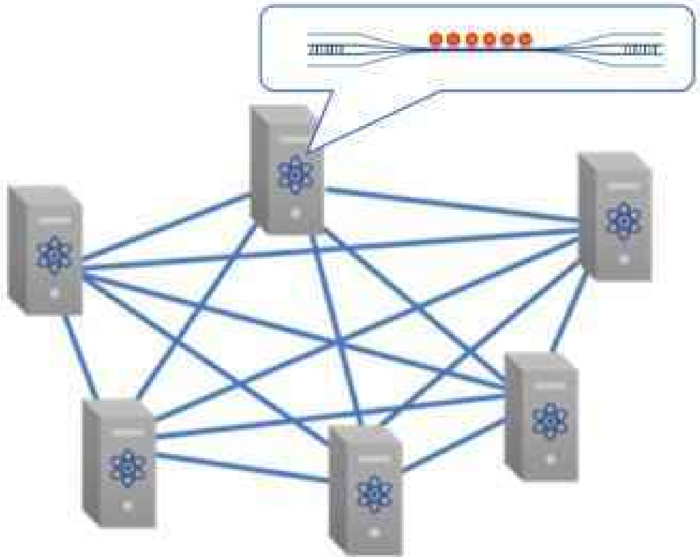
Nanofiber cavity QED is a promising platform for realizing distributed quantum computing.

We have developed technologies for fabricating ultra-low-loss nanofiber cavities and for constructing nanofiber cavity QED systems.

We have succeeded in coupling single atoms to the nanofiber cavity by using optical tweezers.

Prospects





We will demonstrate a proof-of-concept for a nanofiber cavity QED quantum computer hardware.

We will develop technologies for distributed quantum computing based on nanofiber cavity QED.

We will also develop scaling-up technologies, quantum error correction theory, and stable light source systems.

Furthermore, we will promote the social implementation of our technologies.