WE ARE ON

OSA Quantum Optical Science and Technology Technical Group

Engineering Solutions to Scale Quantum Information Processing

Sara Mouradian, University of California, Berkeley

Technical Group Leadership 2020

Chair: Dr. Graciana Puentes
University of Buenos Aires, AR

Vice-Chair: Dr. Lee Bassett
University of Pennsylvania, US

Webinars Officer: Dr. Pablo Bianucci
Concordia University, CA

Events Officer: Dr. Sara Mouradian
UC Berkeley, US

Liason with Industry: Dr. Mo Soltani
Raytheon BBN Technologies, US

Our Technical Group at a Glance

- Experiment, theory, and technologies relevant for quantum measurements and quantum information within the purview of quantum optical science
- Nearly 3000 members worldwide
- Webpage https://www.osa.org/oq
- Webinars, technical events, networking events, campfire sessions etc.
- Suggestions, ideas for events, email us at OSA TGActivities/gpuentes@df.uba.ar
- Interested in becoming our Social Media Officer? Please reach out!

Welcome to the Quantum Optical Science and Technology Technical Group Webinar!

Engineering Scalable Quantum Systems

Sara Mouradian
Ion Trap Group, UC Berkeley
IC Postdoctoral Fellow

OSA Quantum Optical Science and Technology Technical Group
Oct 15, 2020

Outline

1. Overview of Quantum Technologies

- Connectivity, Control, Coherence

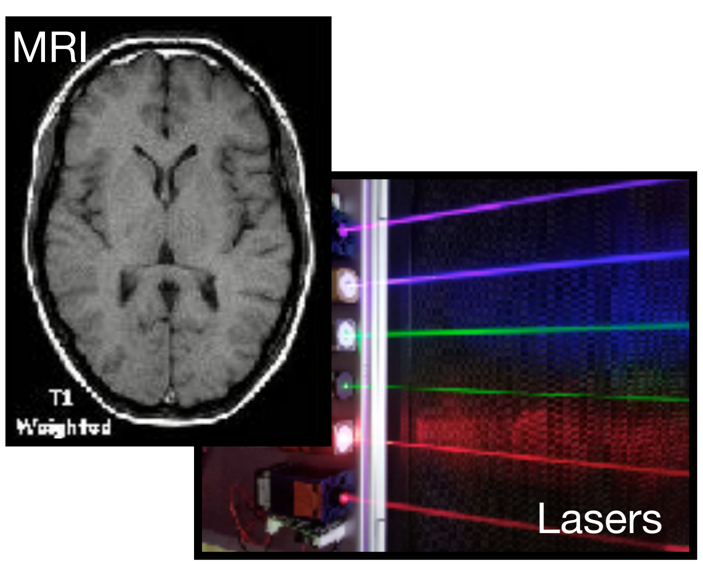
2. Increasing connectivity - Solid State Defects

3. Increasing control - Trapped Ions

Timeline of Quantum Technologies

1920s — Quantum Theory

1960s — 1st Wave of Quantum Technologies



1990s — Quantum Computing Theory

Control Over Small Quantum Systems

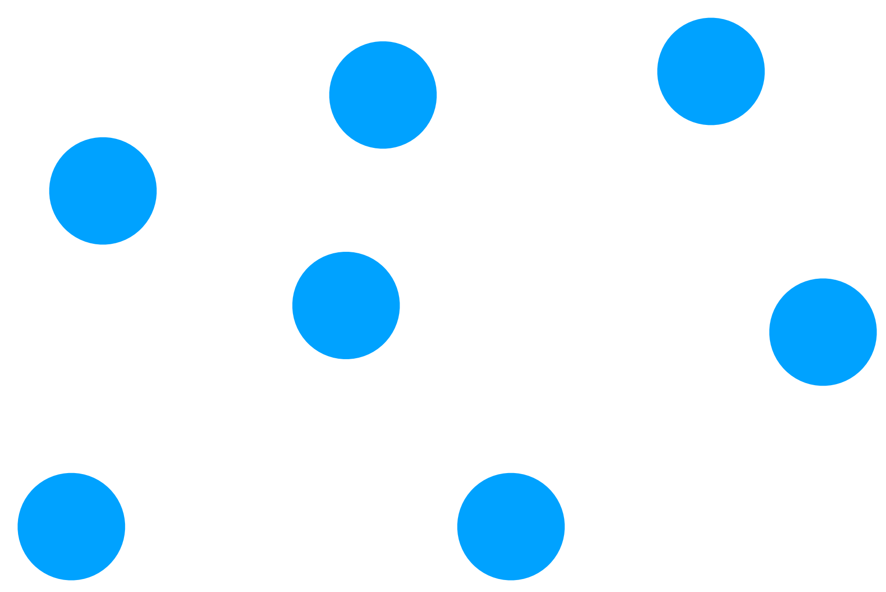
... ? — Large Engineered Quantum Systems

???

Engineered Quantum Systems

Need to increase **Connectivity** and **Control**

Without reducing **Coherence**



Engineered Quantum Systems

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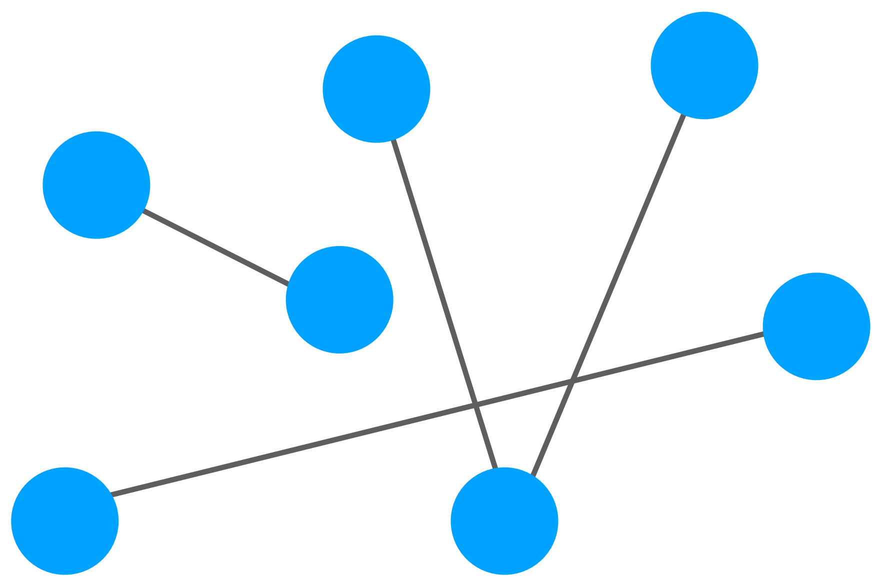

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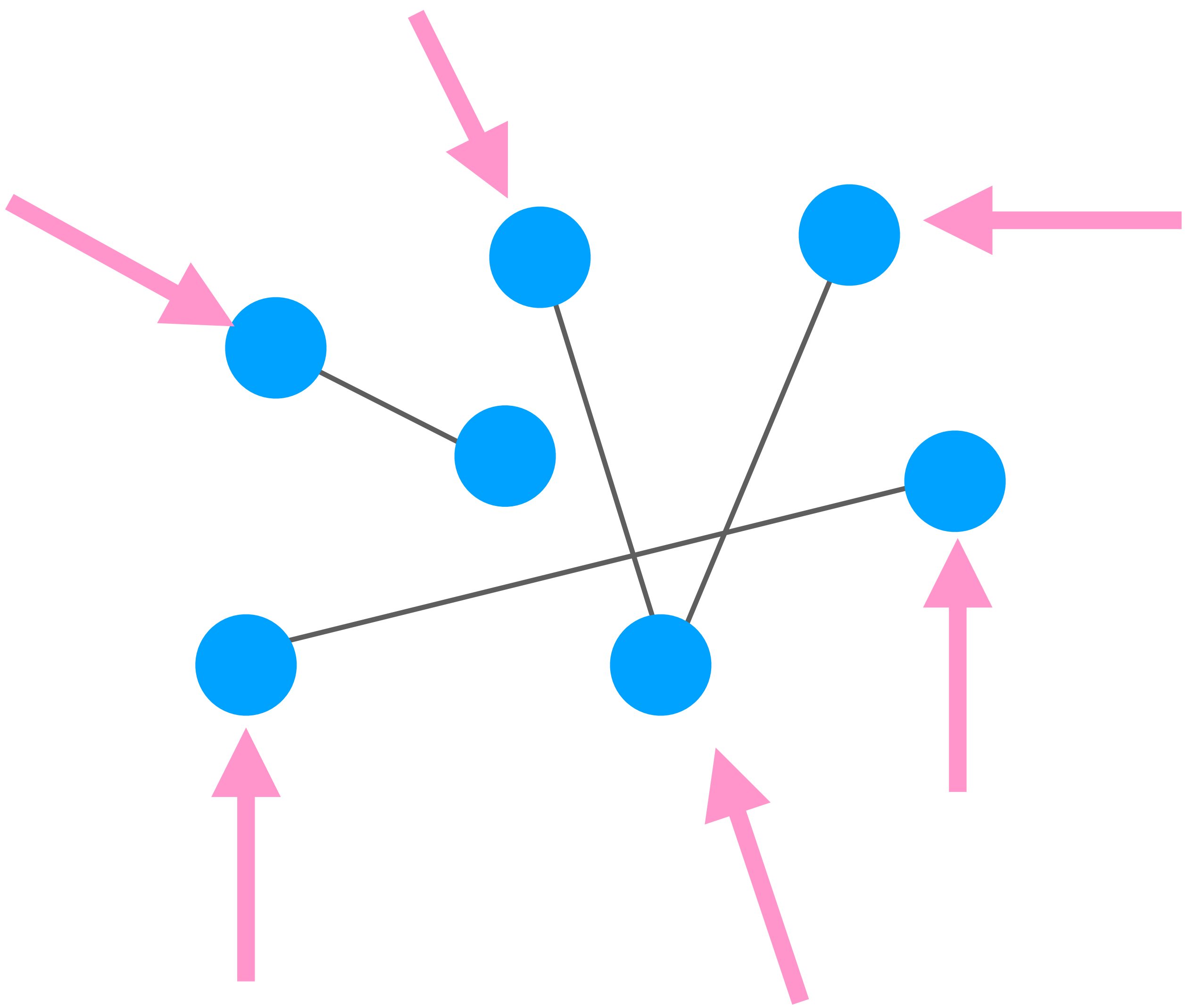

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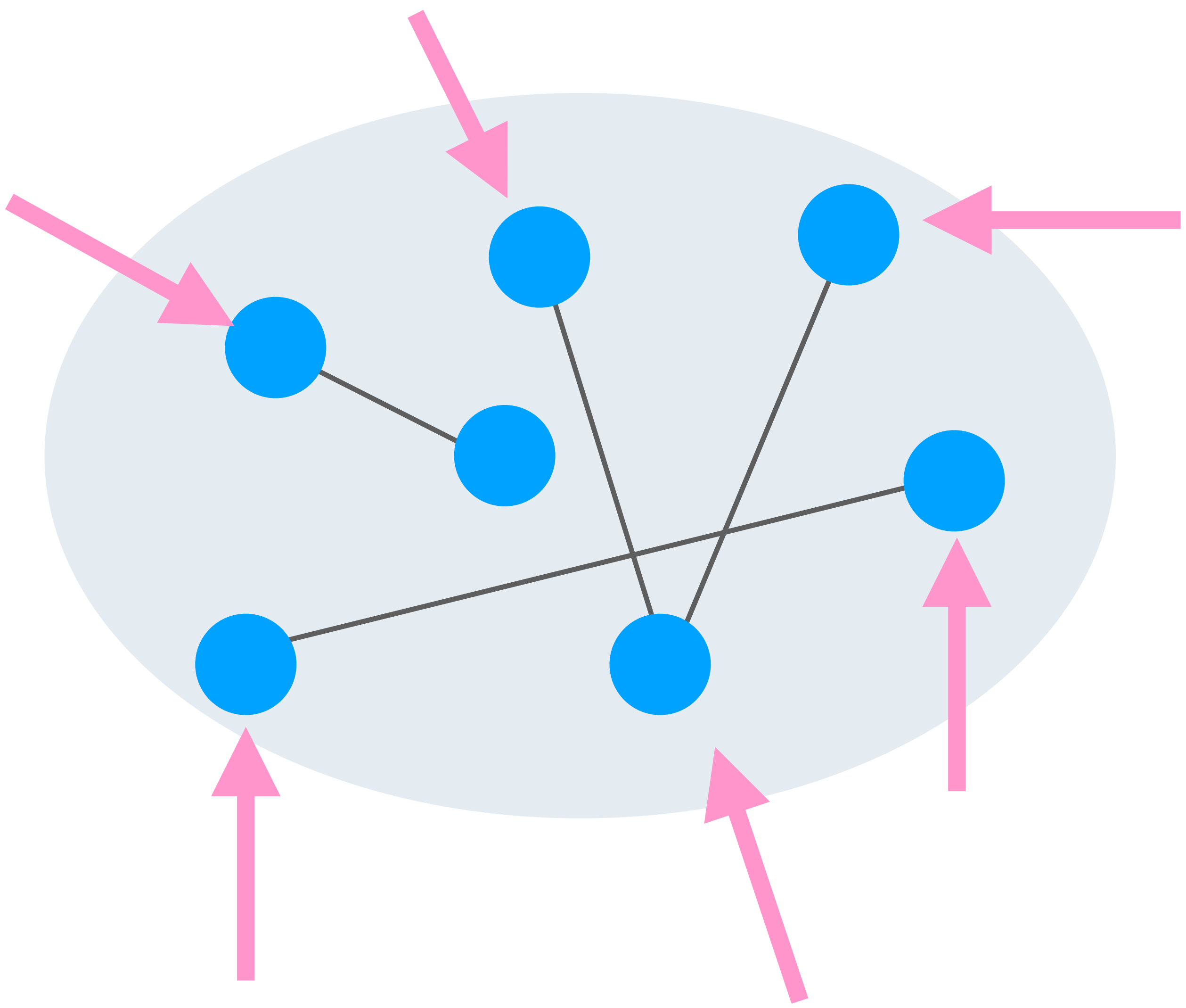


Modular Architecture

Need to increase **Connectivity** and **Control**

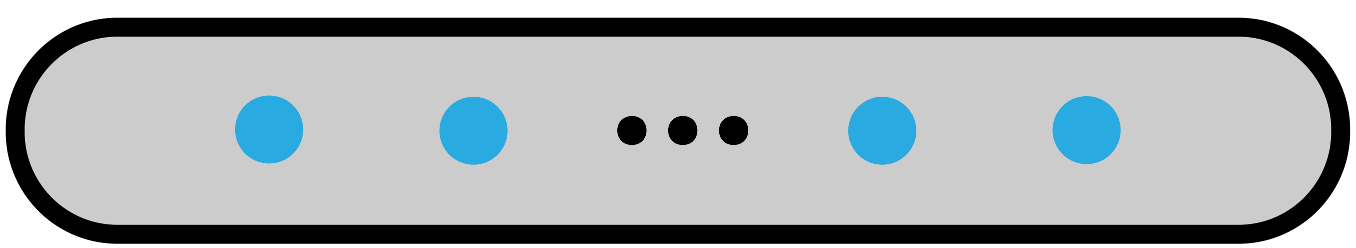
Without reducing **Coherence**

Modular Architecture

Need to increase **Connectivity** and **Control**

Without reducing **Coherence**

Each Module has high fidelity:



Construction

Modular Architecture

Need to increase **Connectivity** and **Control**

Without reducing **Coherence**

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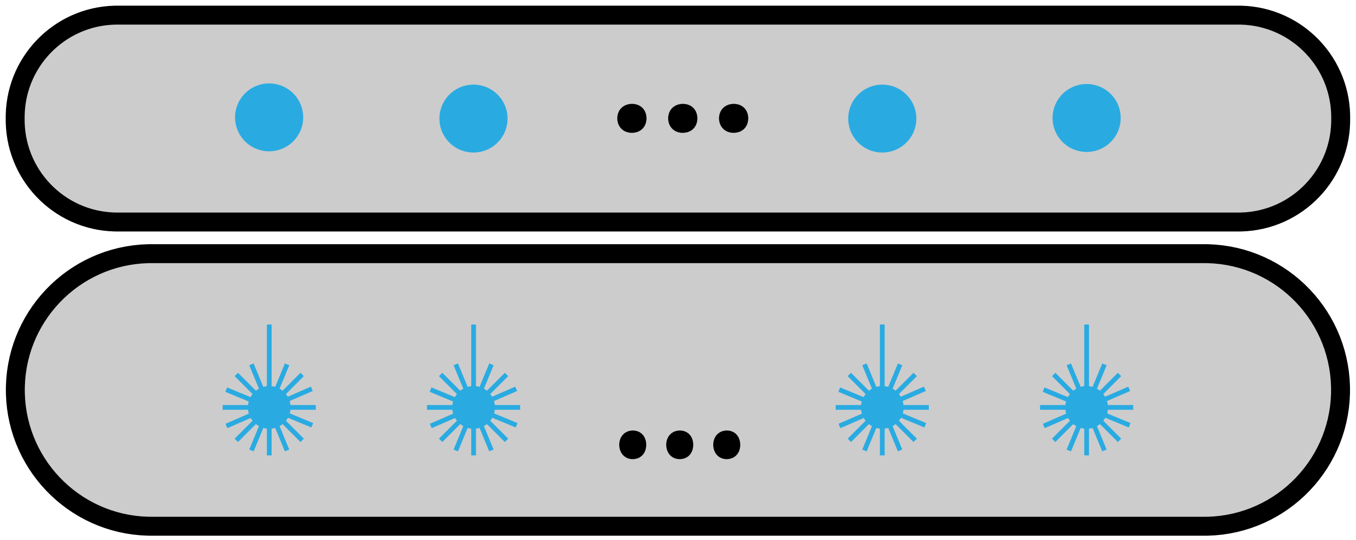

Construction

Control

Modular Architecture

Need to increase **Connectivity** and **Control**

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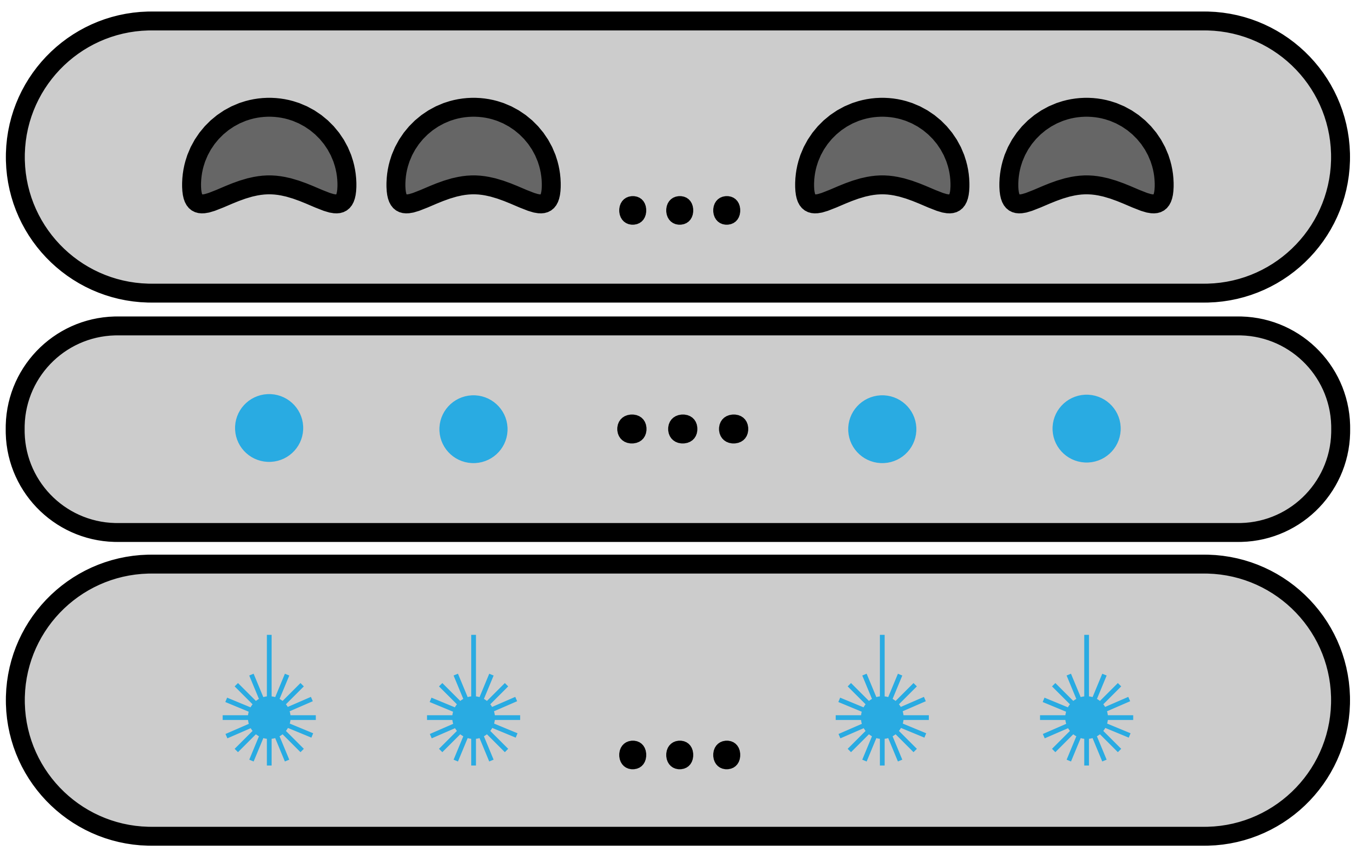


Detection

Construction

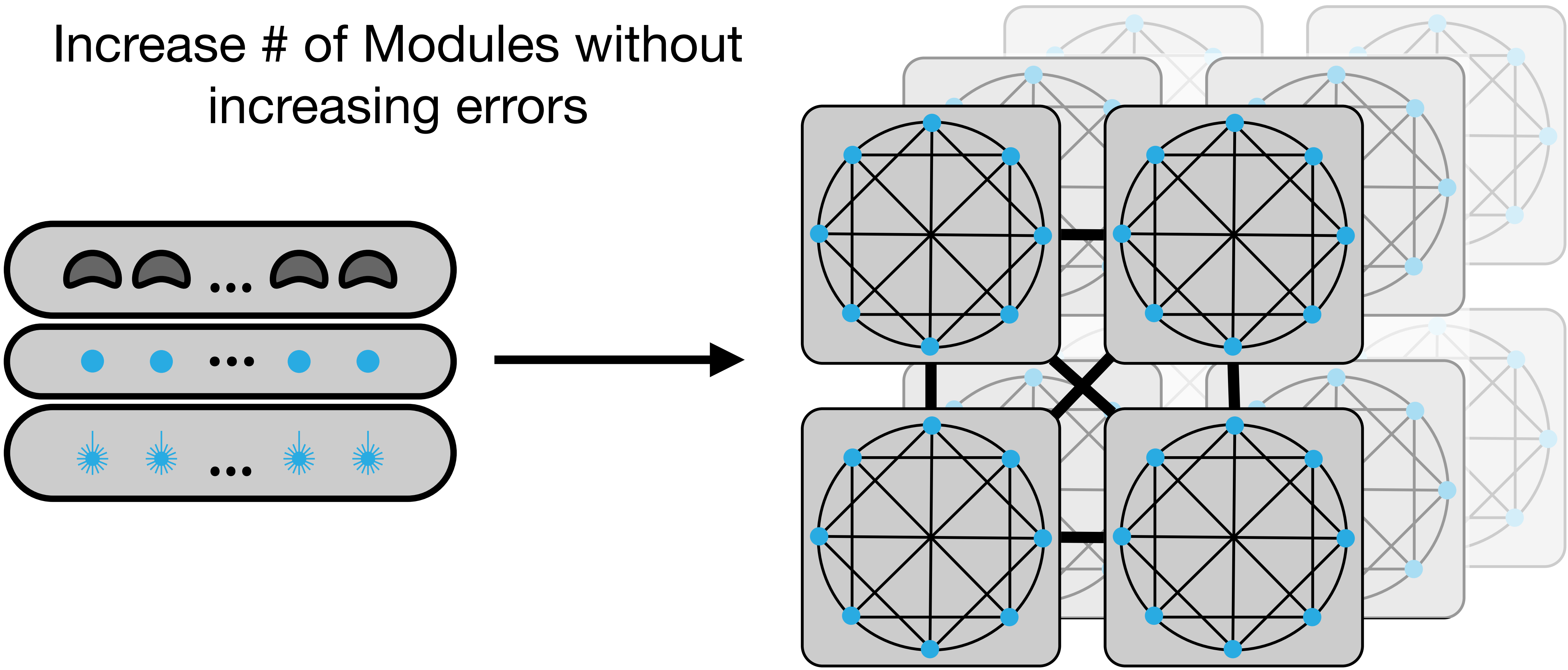
Control

Modular Architecture

Need to increase **Connectivity** and **Control**

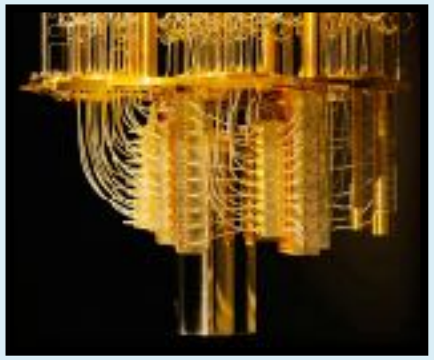
Without reducing **Coherence**

Increase # of Modules without increasing errors



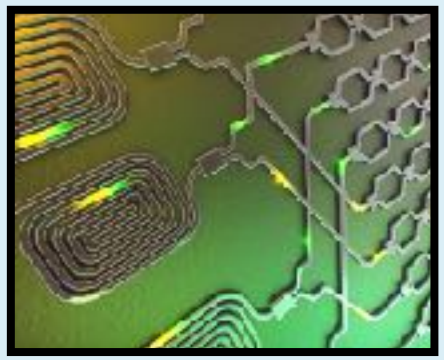
Quantum Technologies

Superconducting



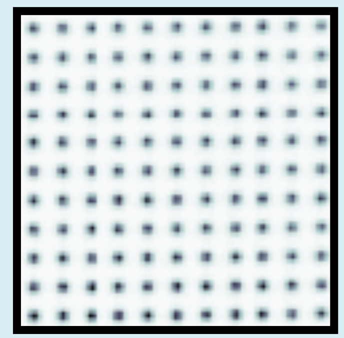
Schoelkopf (Yale)
Oliver (MIT/LL)
Siddiqi (Berkeley)
… and more …

Photonic



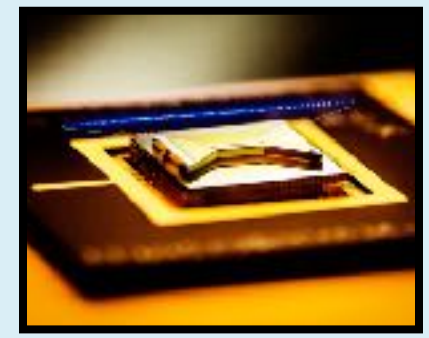
Englund (MIT)
Rudolph (ICL)
Guha (Arizona)
… and more …

Neutral Atoms



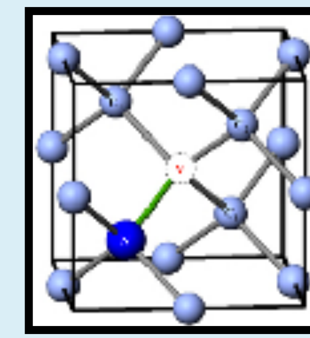
Lukin (Harvard)
Endres (Caltech)
… and more …

Ions



Haeffner (Berkeley)
Blatt (Innsbruck)
Chuang (MIT)
Monroe/Kim/Brown (Duke)
Lincoln Labs
… and more …

Solid State



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Quantum Technologies

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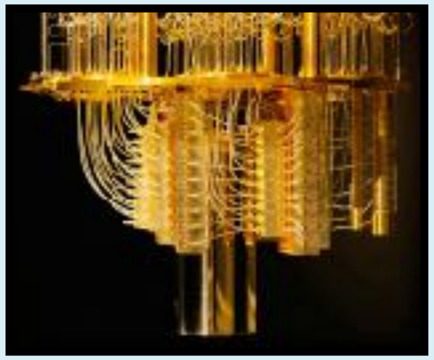

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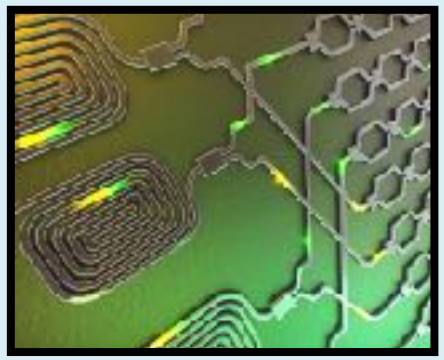

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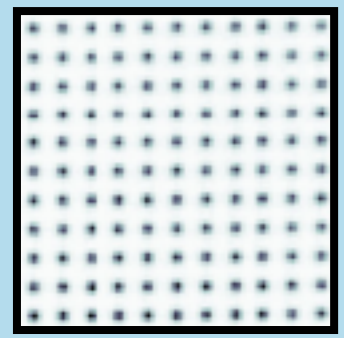

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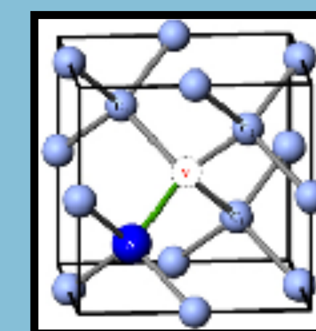

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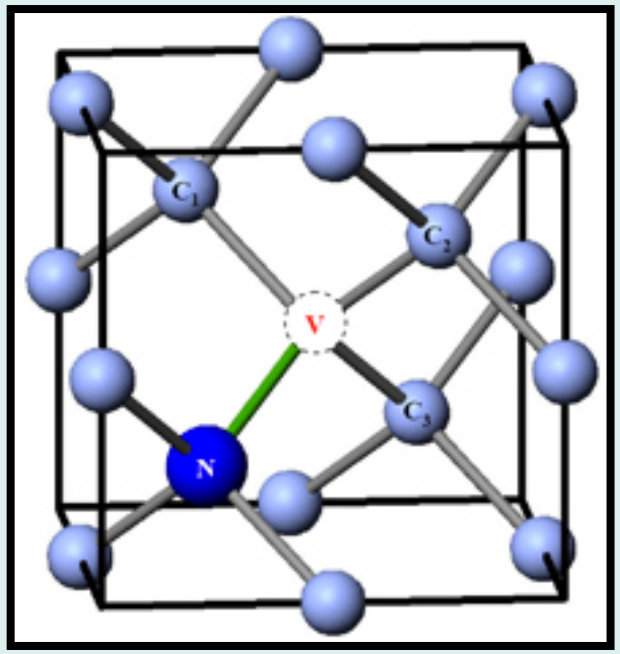
2. Increasing connectivity — Solid State Defects

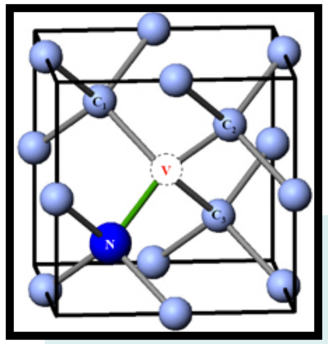
- Photonic devices for improving entanglement rate

3. Increasing control - Trapped Ions

The Nitrogen Vacancy Center in Diamond



Naturally trapped atom.



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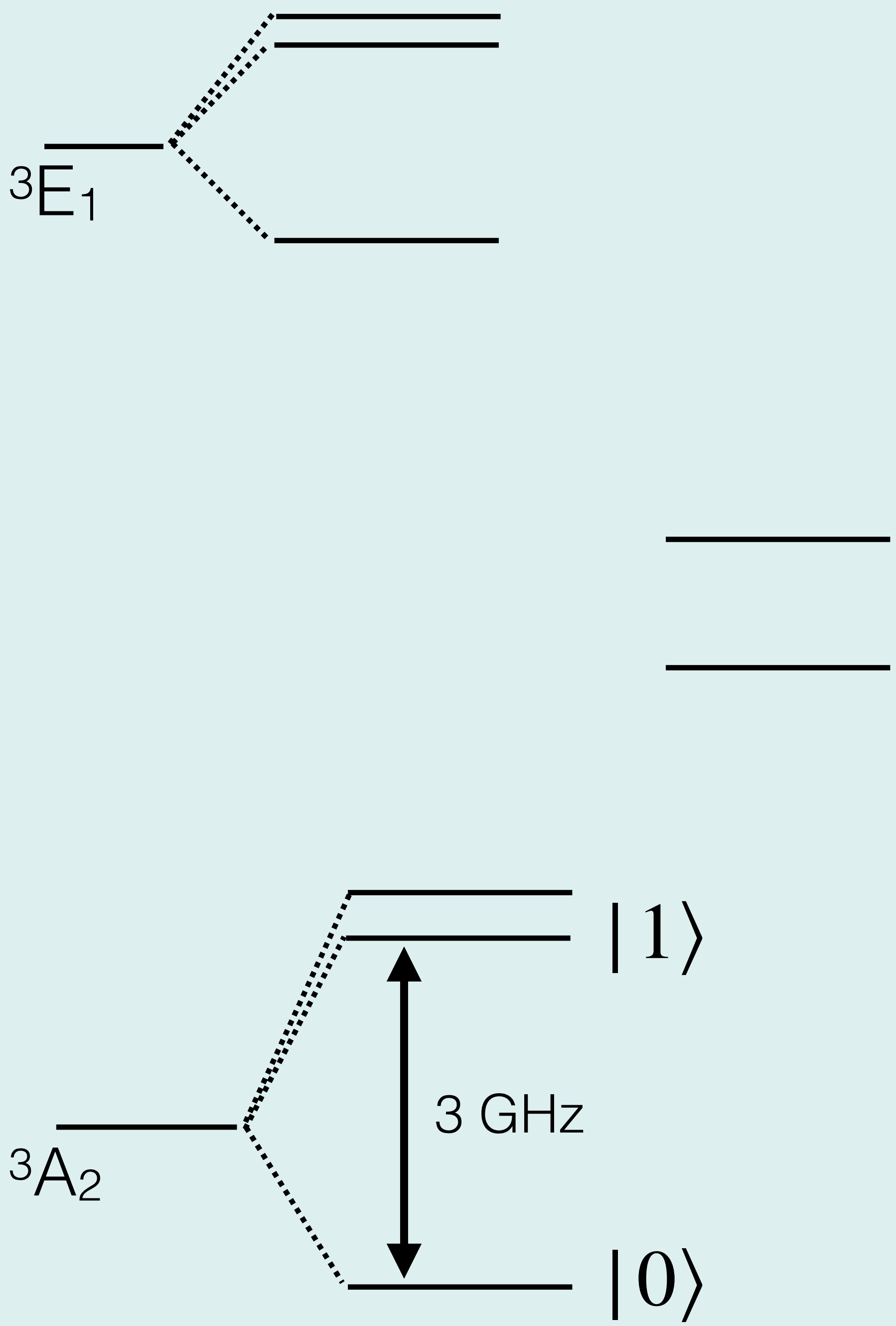

Electron spin
coherence time > 1ms.

Nuclear spin
coherence time > 1s
(N and nearby C^{13}).

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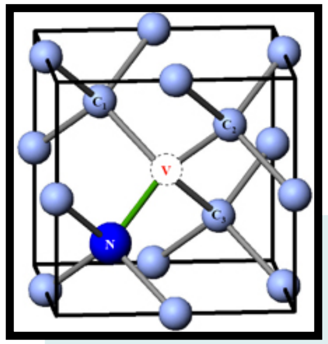

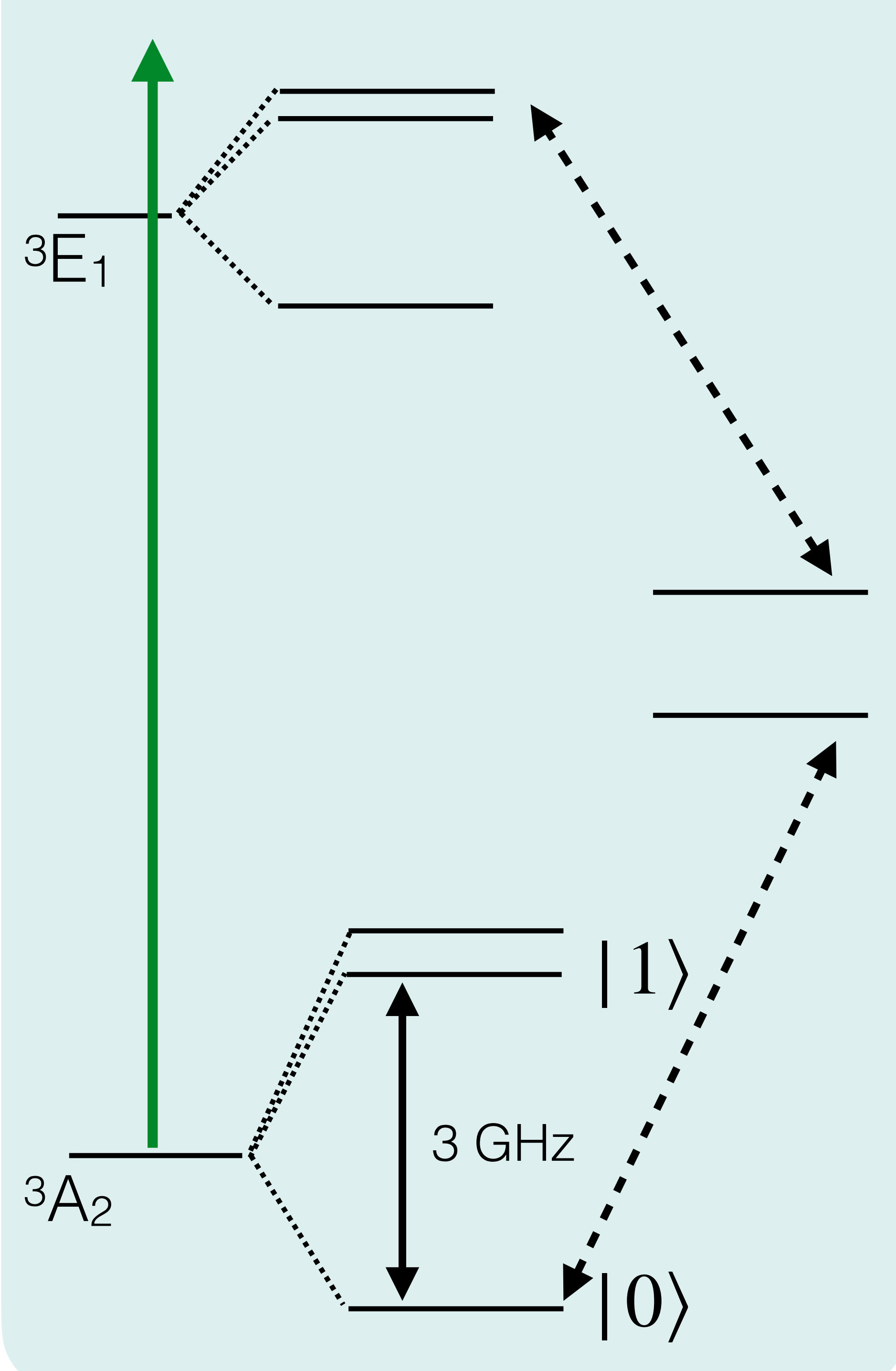

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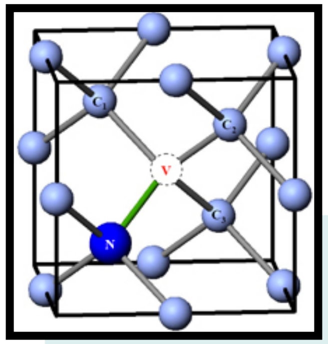
Optical pumping into the $m_s = 0$
> 99.9% initialization fidelity.



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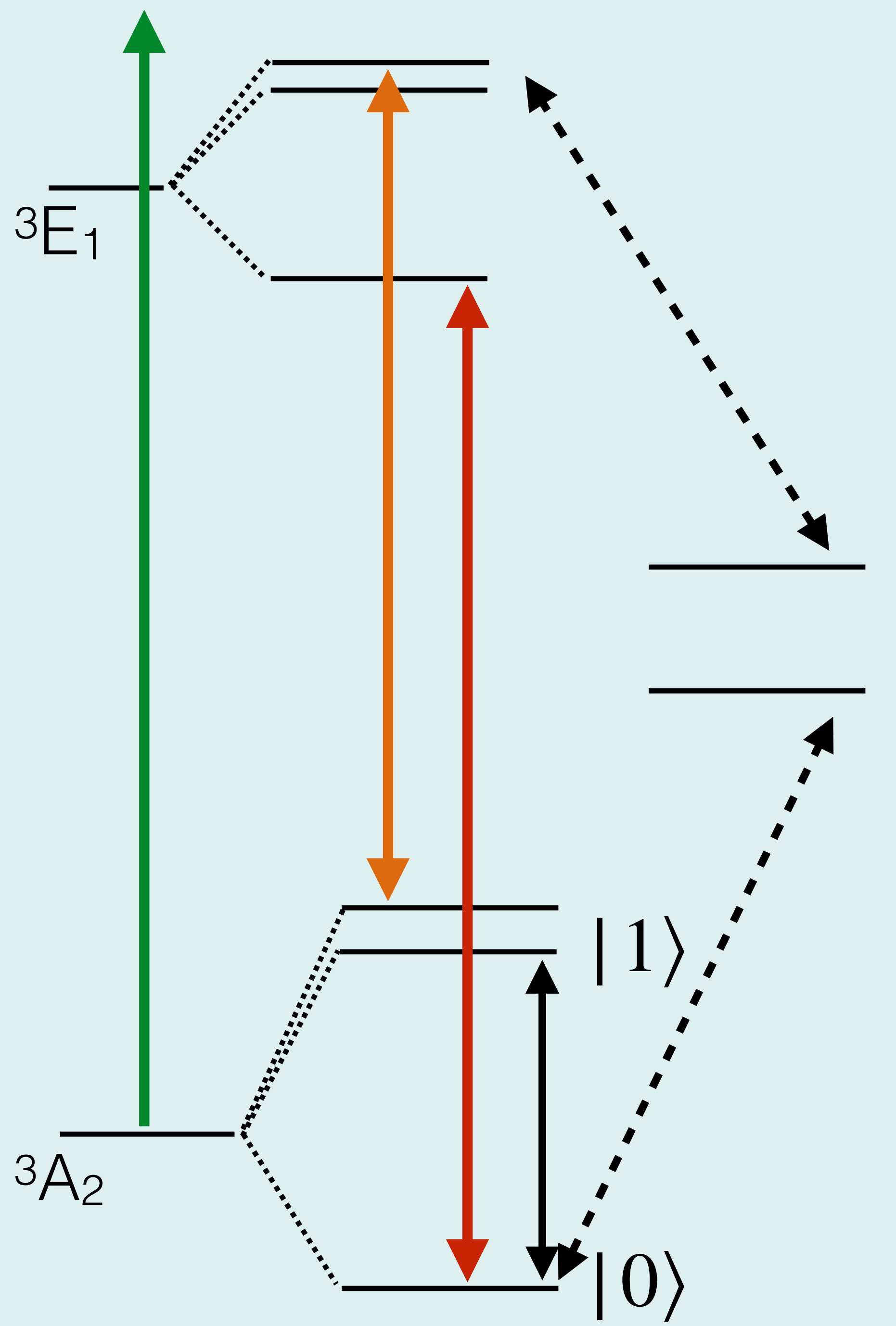

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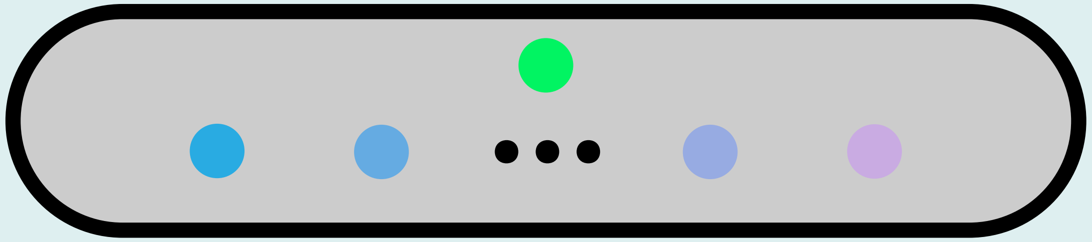
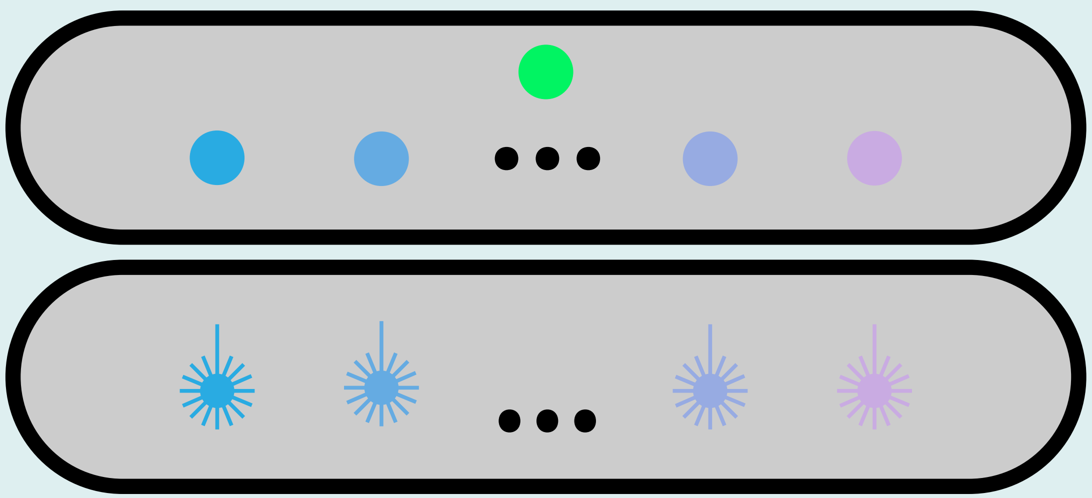
Spin can be entangled
with the photon state.

Modular Architecture



Construction
Ensemble of C + N spins.

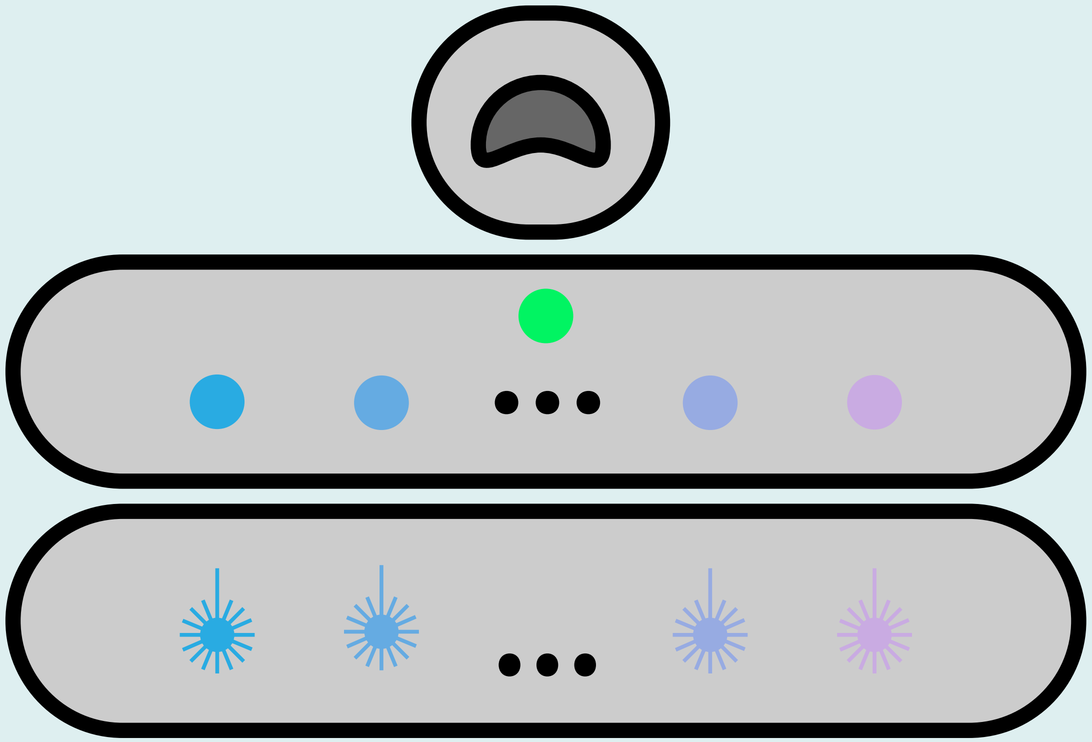
Modular Architecture



Construction
Ensemble of C + N spins.

Control
Via MW control.

Modular Architecture

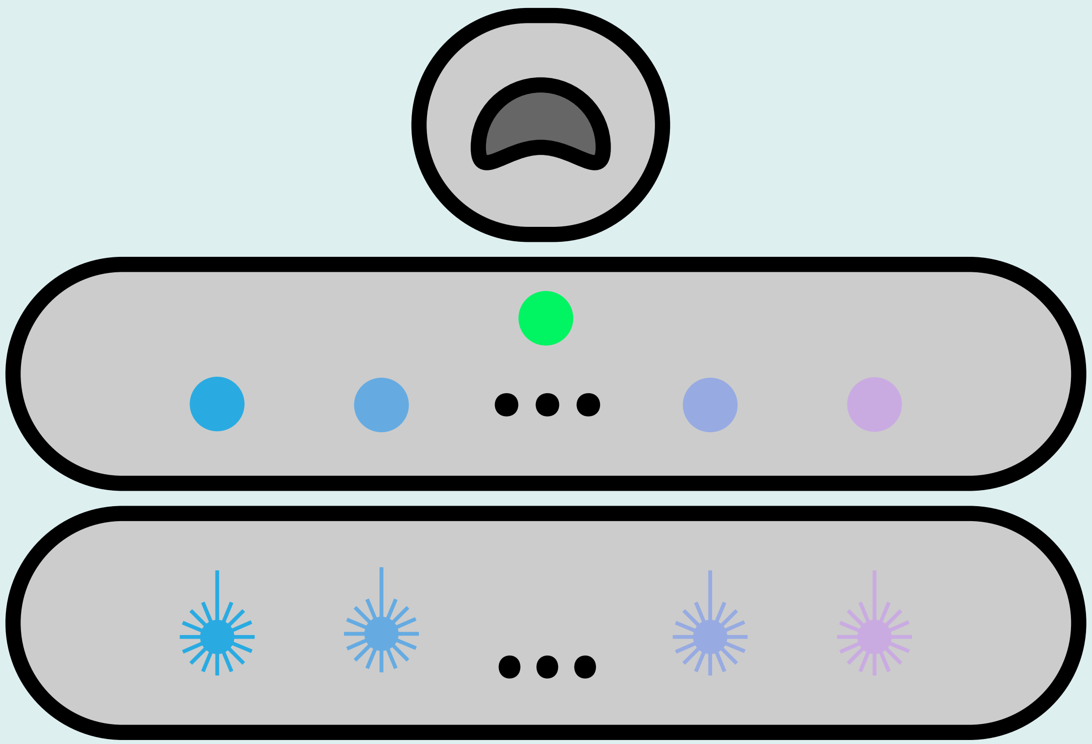


Detection
Through coupling to
and readout of the NV center.

Construction
Ensemble of C + N spins.

Control
Via MW control.

Modular Architecture



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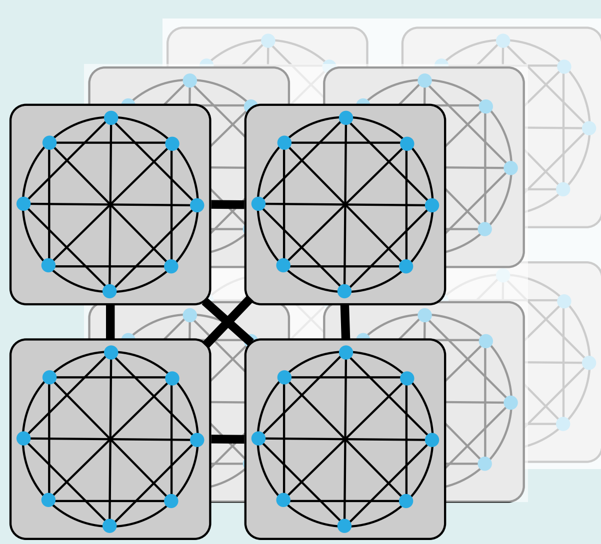
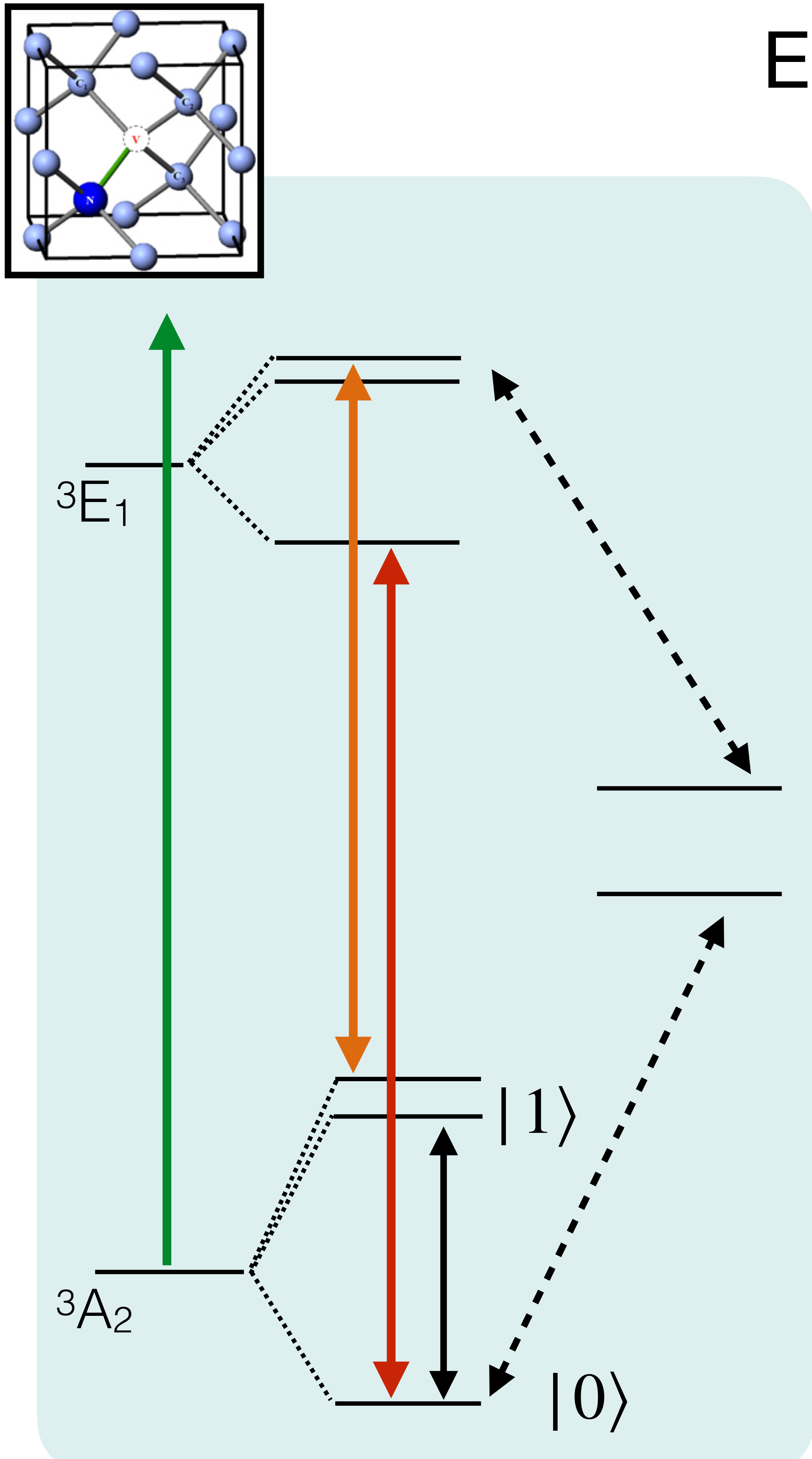
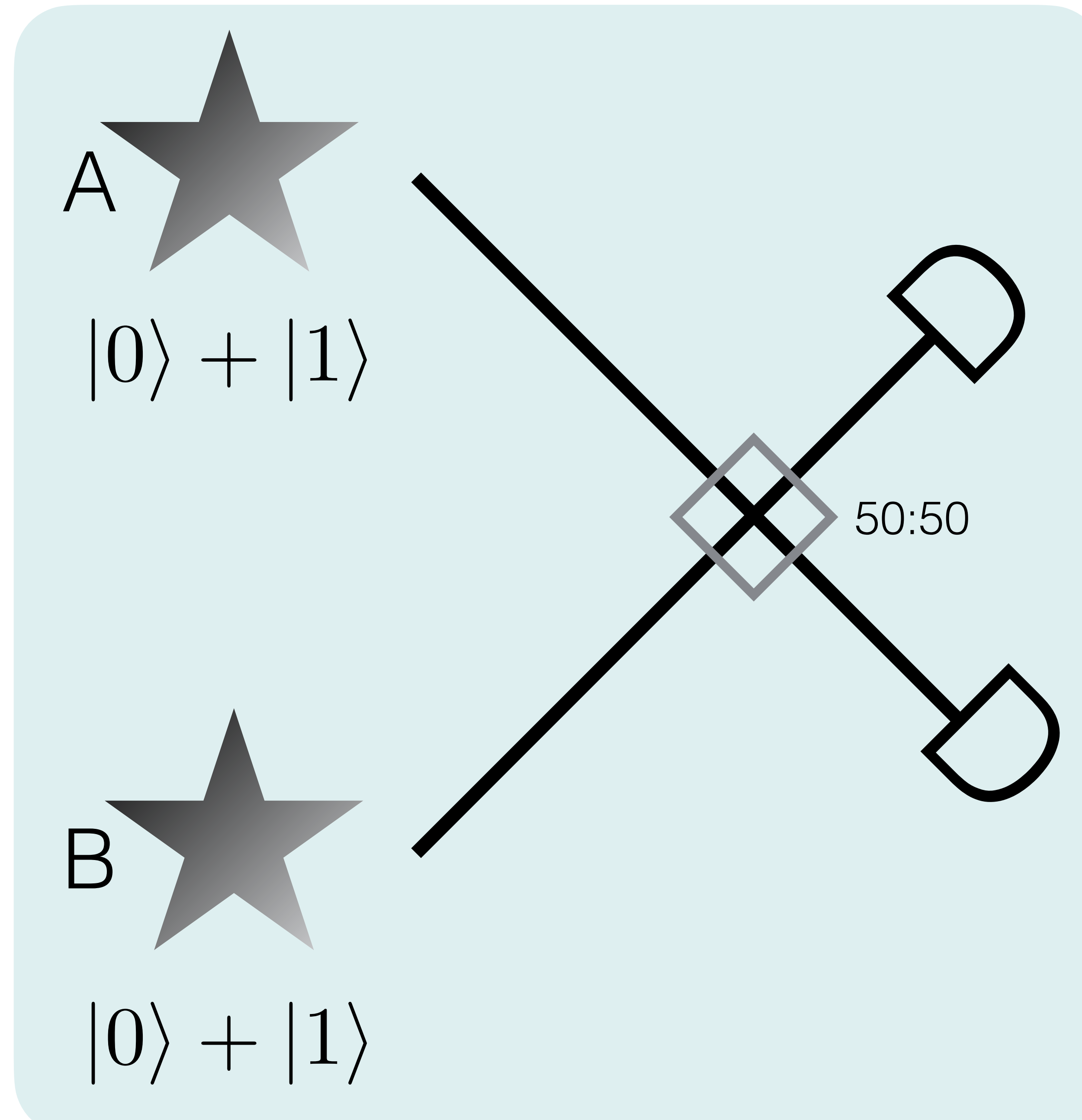


Connection
Photonic links mediated by
NV optical transitions

Entangling 2 NVs





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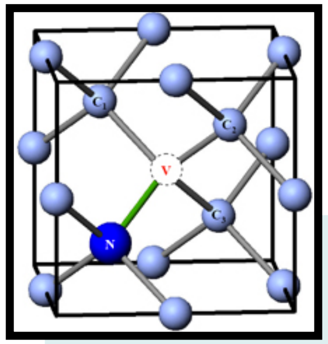

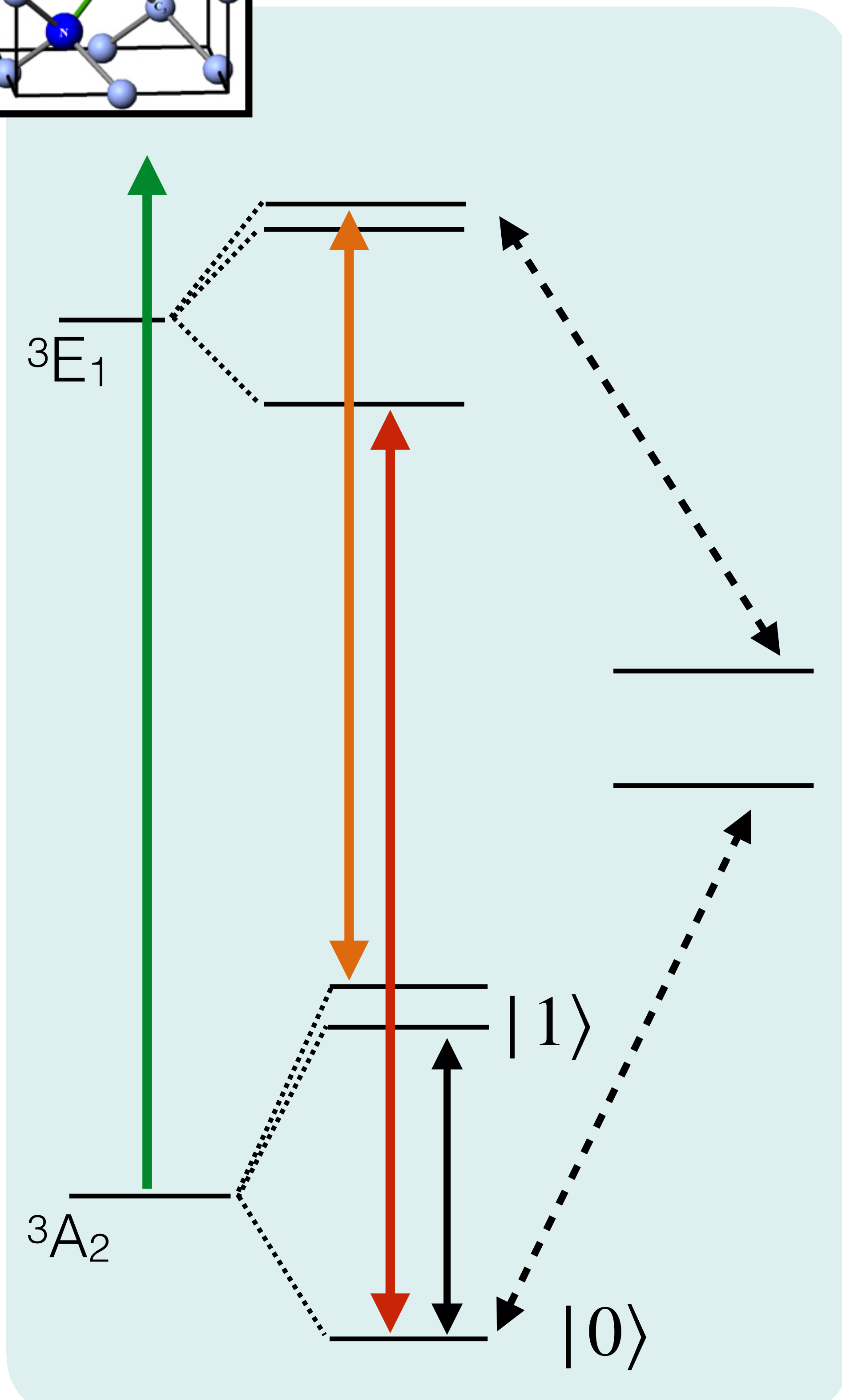

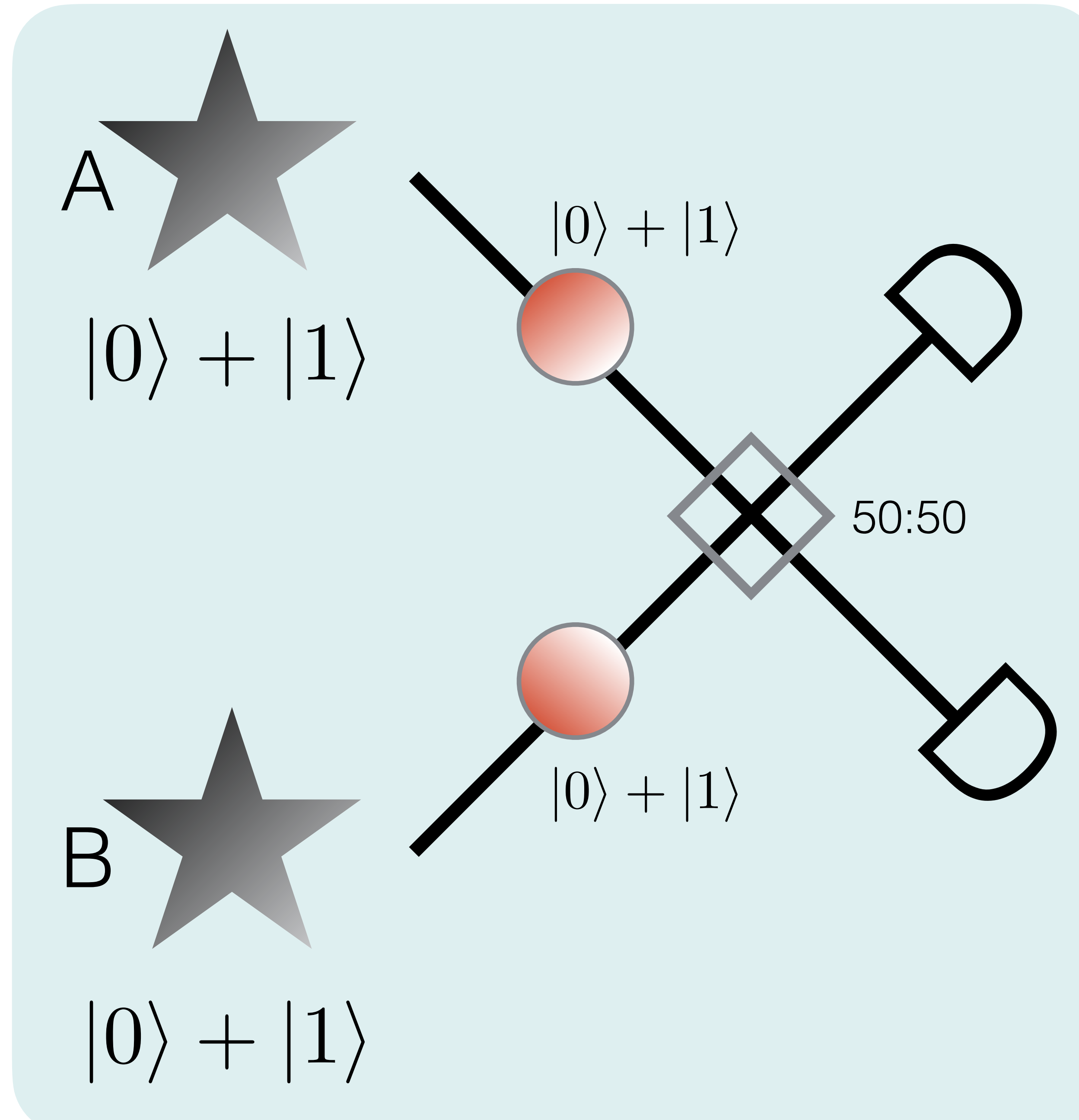

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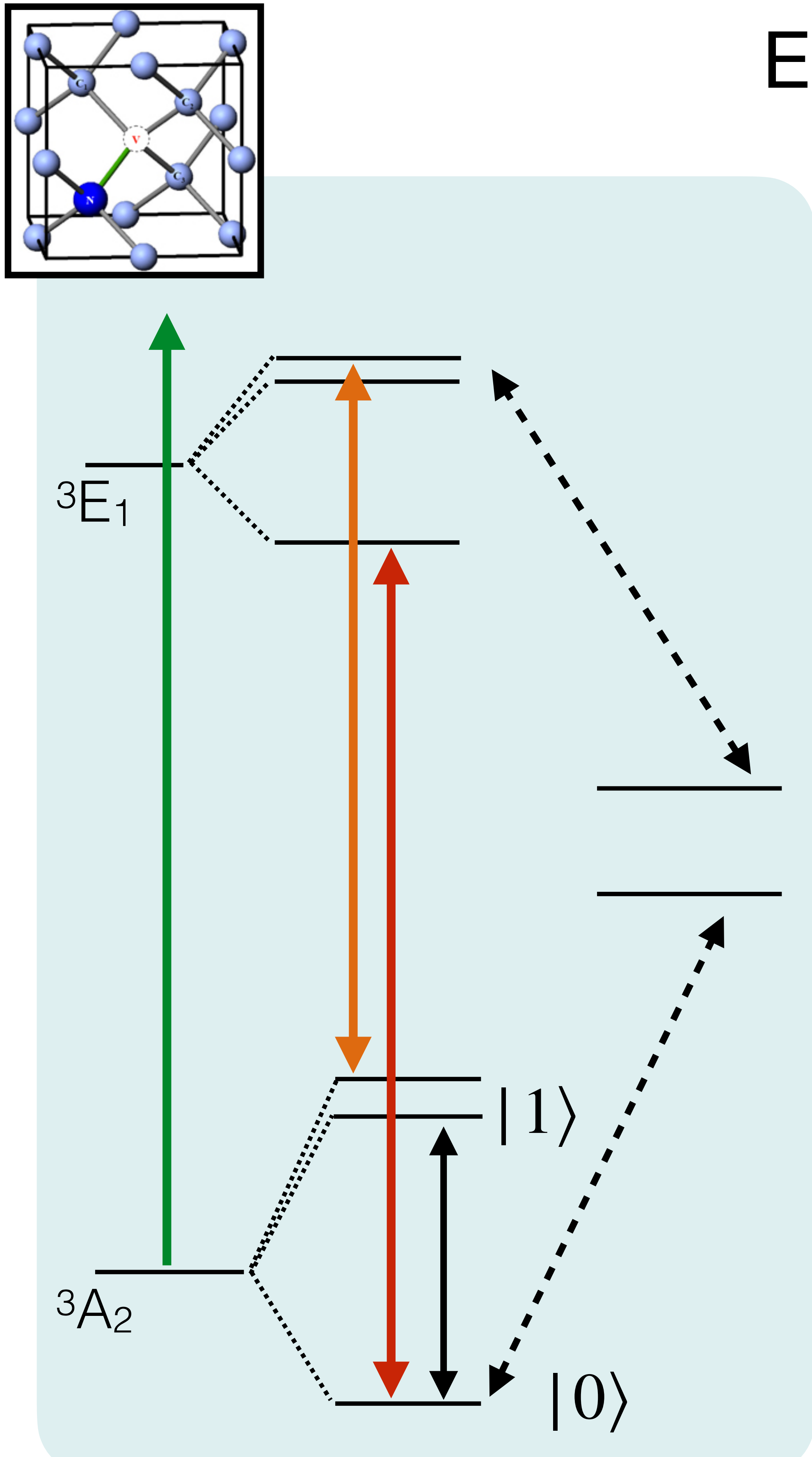
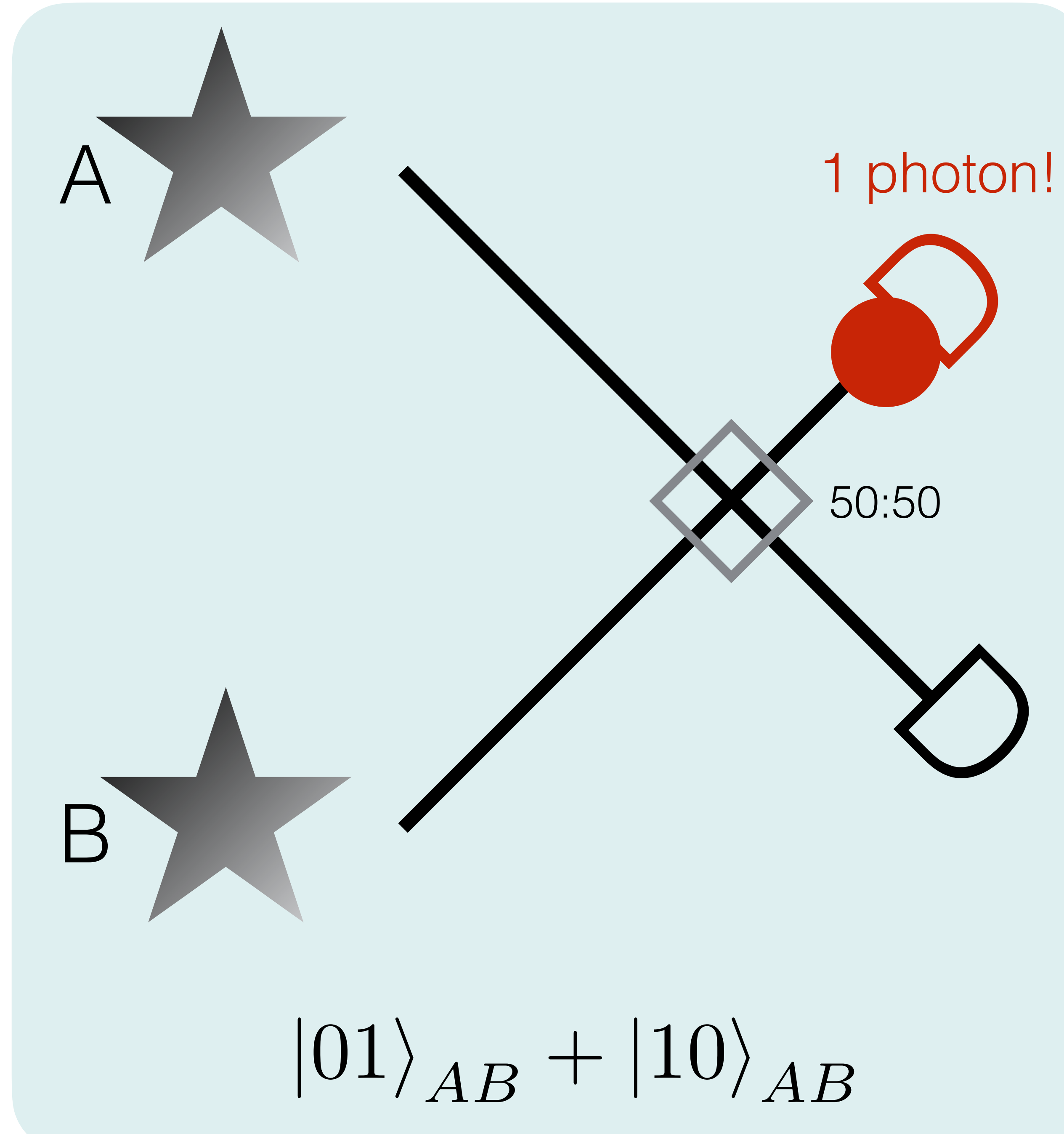
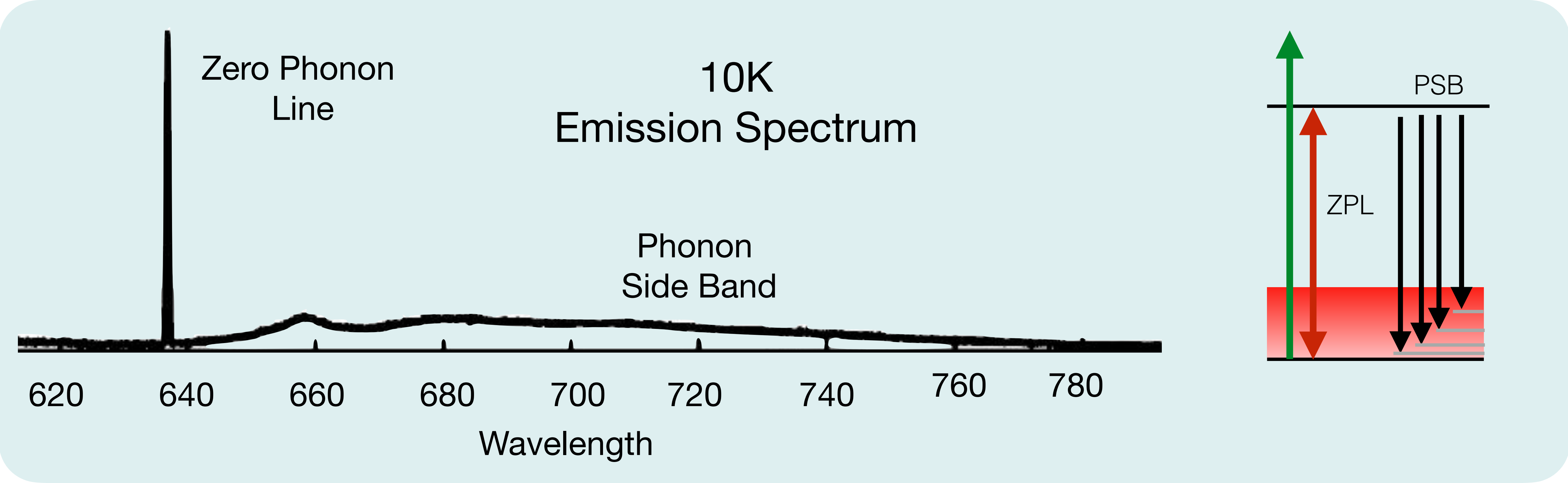




Optical Properties of NV Centers



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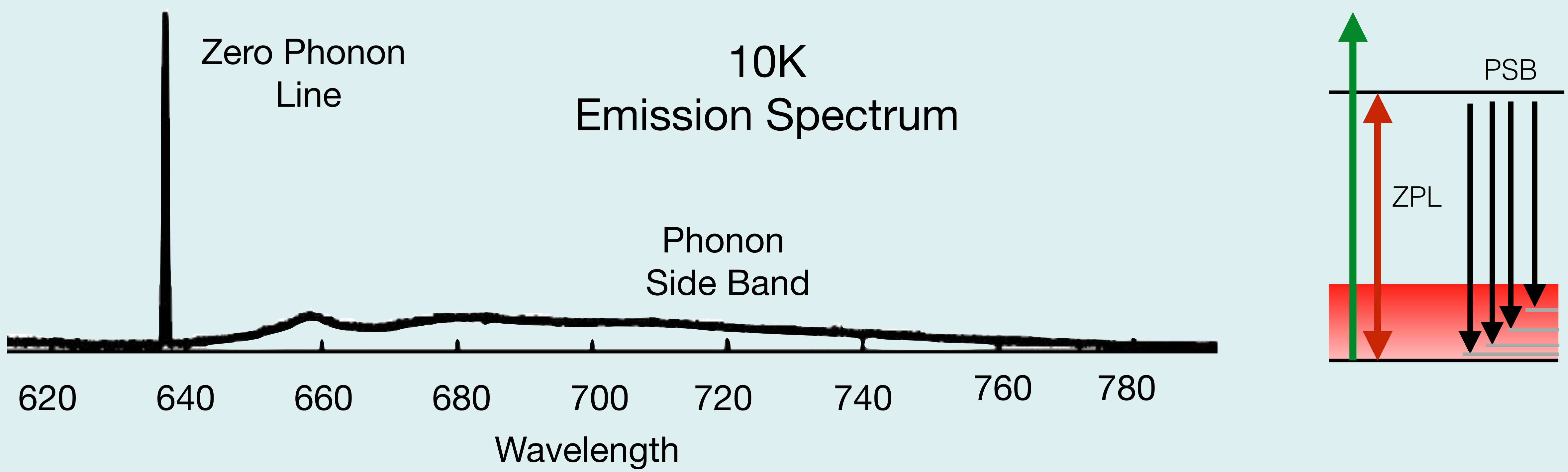


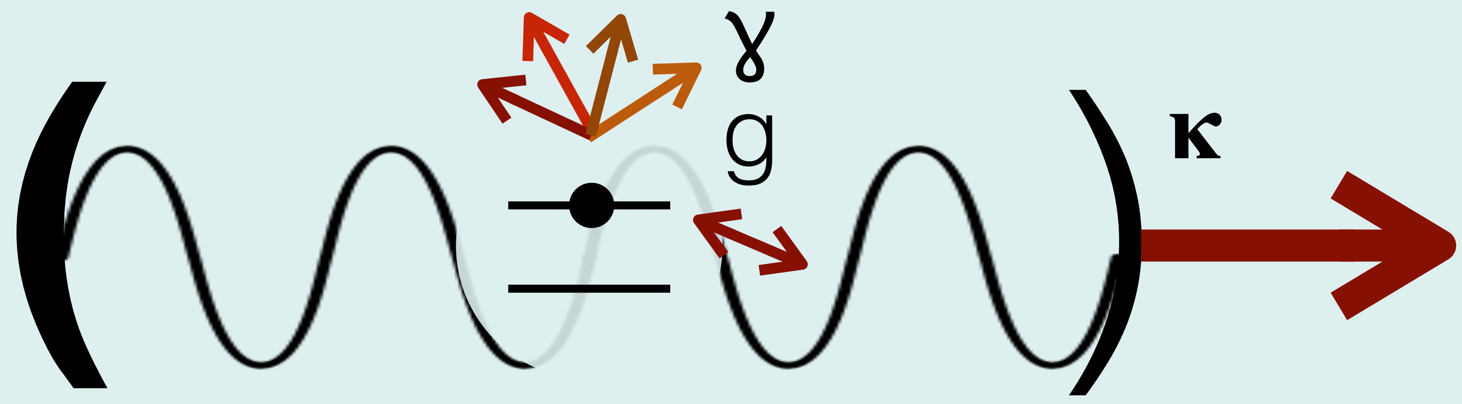
Only 3% of emission coherent with spin state

Dipole emission is difficult to collect

Spectral diffusion limits indistinguishability

Need to improve for high fidelity, high rate connections between nodes

Cavity Enhancement

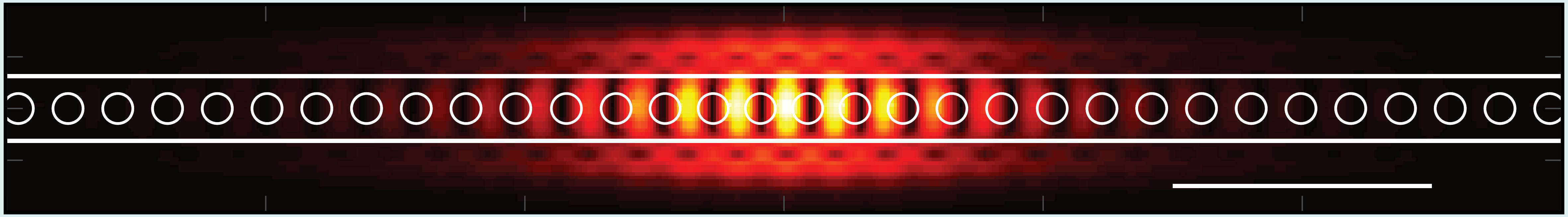


(1) Increased emission at transition coherent with spin state (Q / V)

(2) Engineered collection into a single (useful) mode

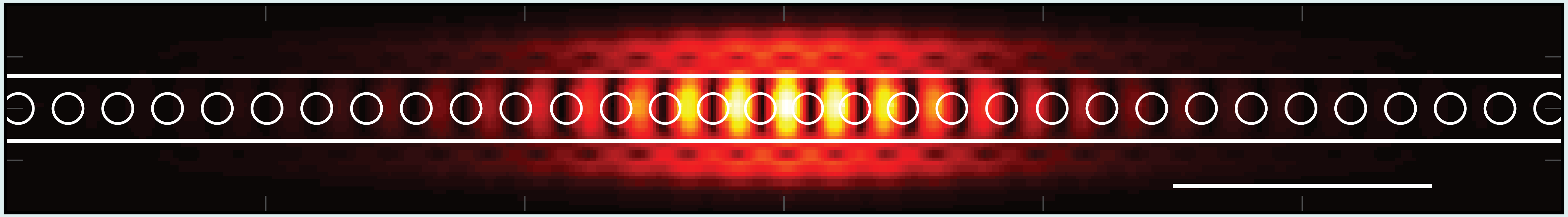
Increased Rate of Entanglement

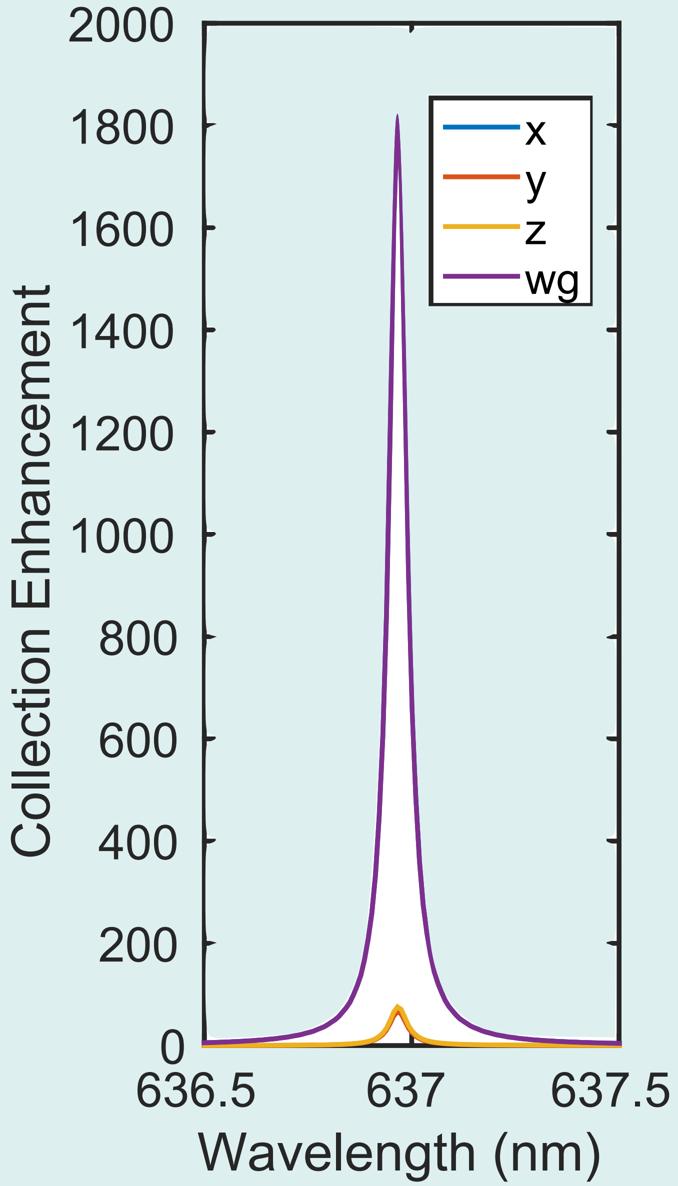
Cavity Enhancement



$Q > 10^6$, $V \sim (\lambda/n)^3$ from FDTD simulations.

Cavity Enhancement



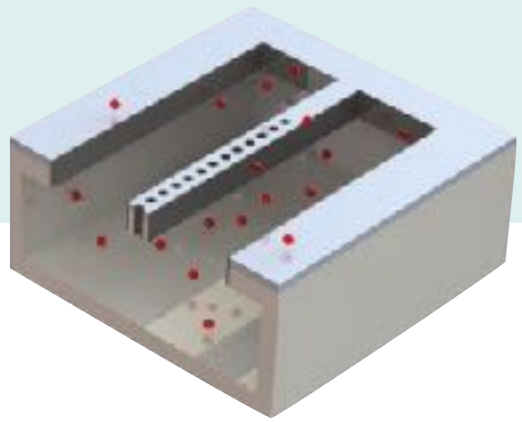


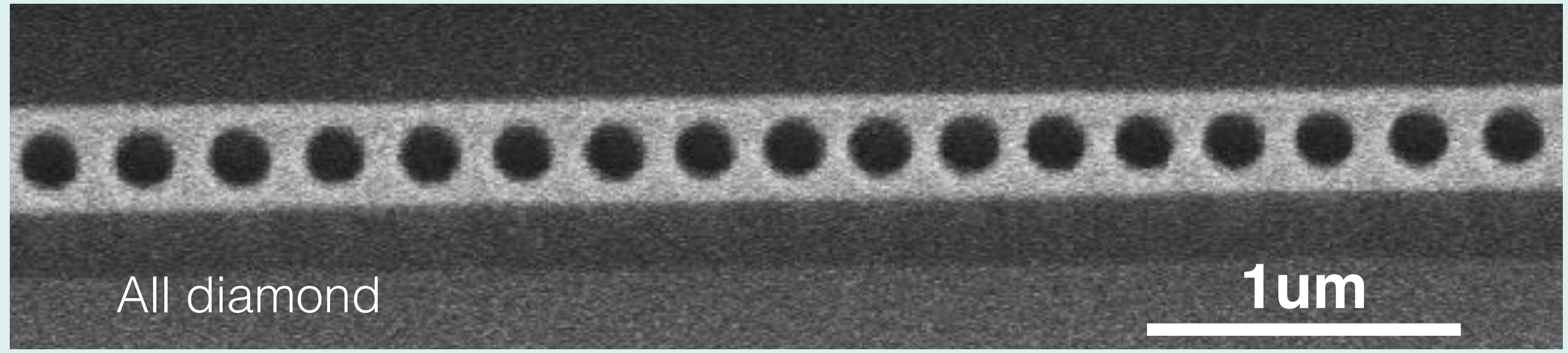
$Q > 10^6$, $V \sim (\lambda/n)^3$ from FDTD simulations.

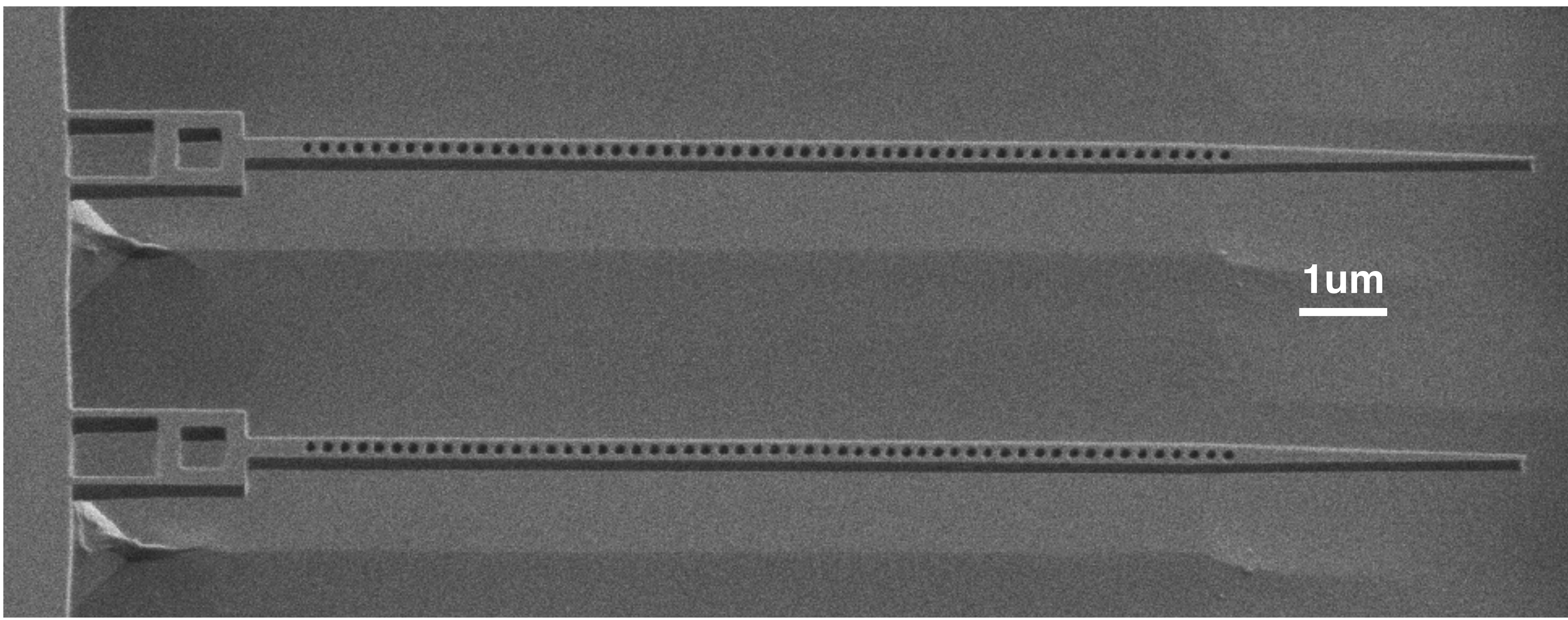
Holes can be removed from one side to increase collection into the waveguide mode.

Nanofabrication in Diamond

Isotropic O_2 Etch
(No Bias, High Power)

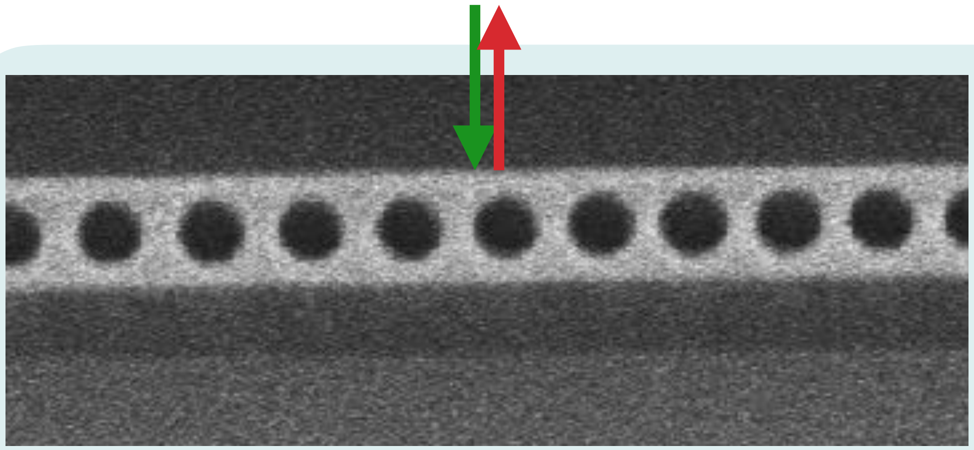






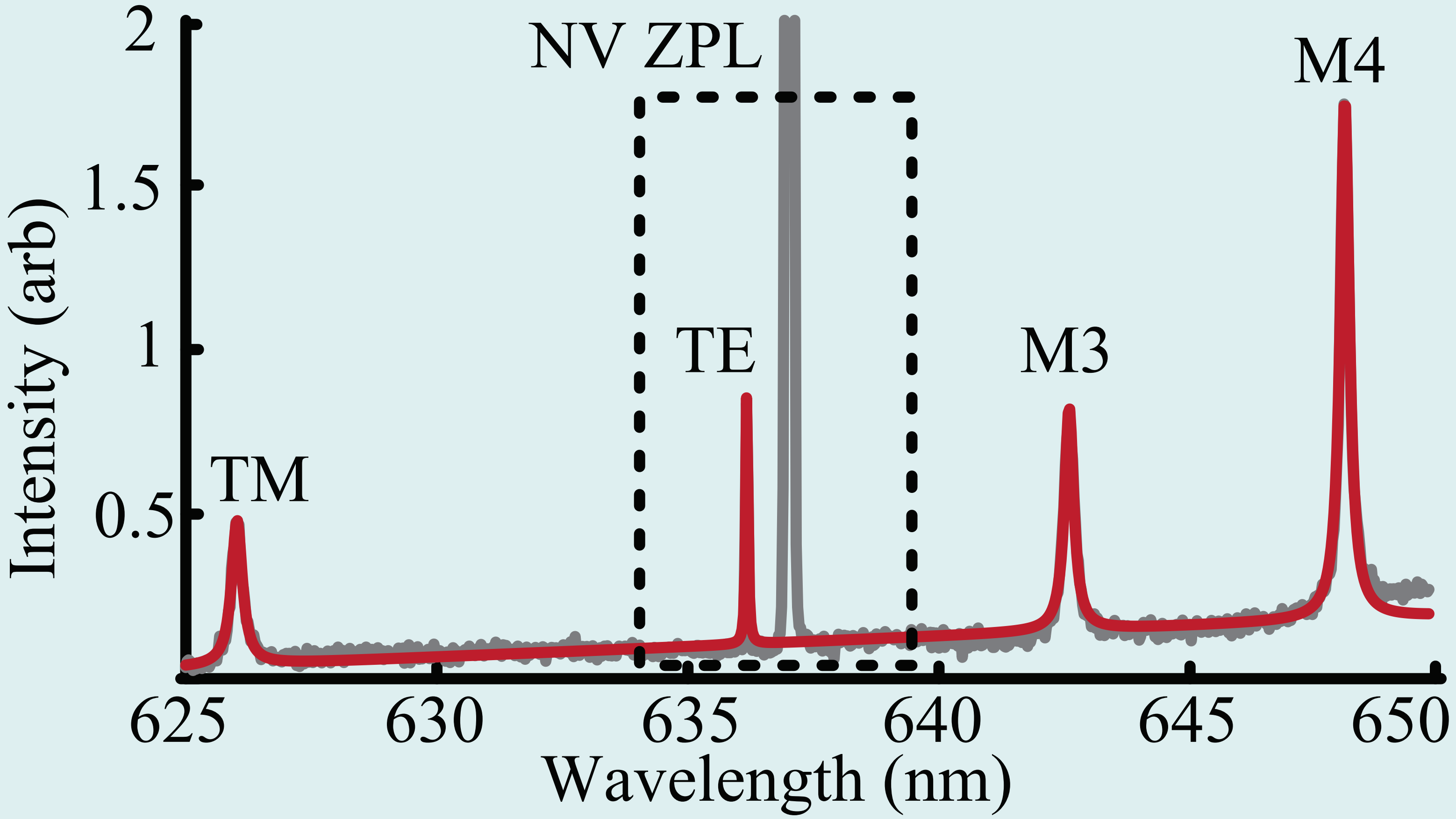
Mouradian, Wan et al APL 021103, 2017
Wan, Mouradian et al APL 141102, 2018

Diamond Cavities



532 nm excitation of NVs.

Collection of NV-fed cavity emission.

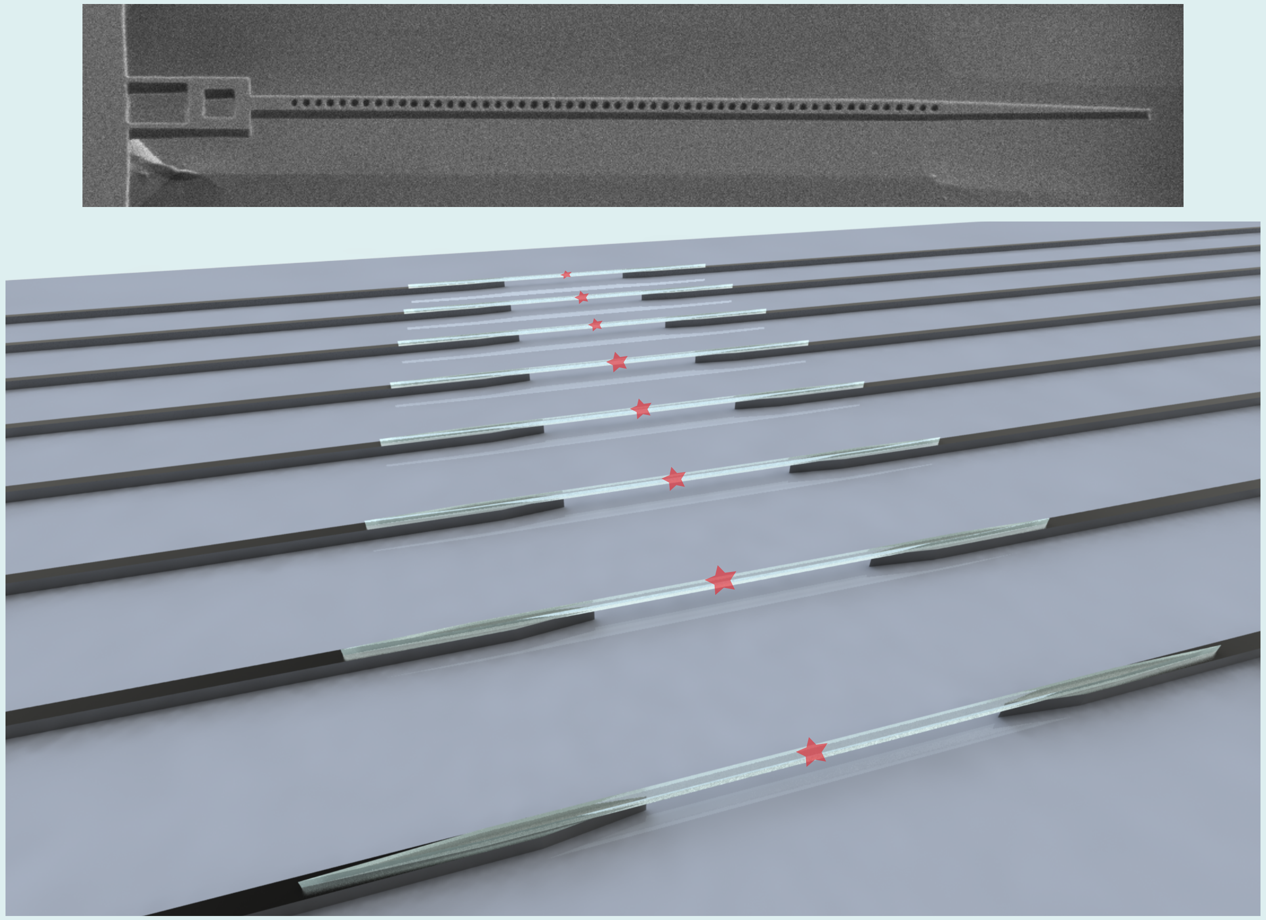


Q > 14,000

Consistent fabrication across the chip

Mouradian, Wan et al APL 021103, 2017
Wan, Mouradian et al APL 141102, 2018

On-Chip Integration



Compact

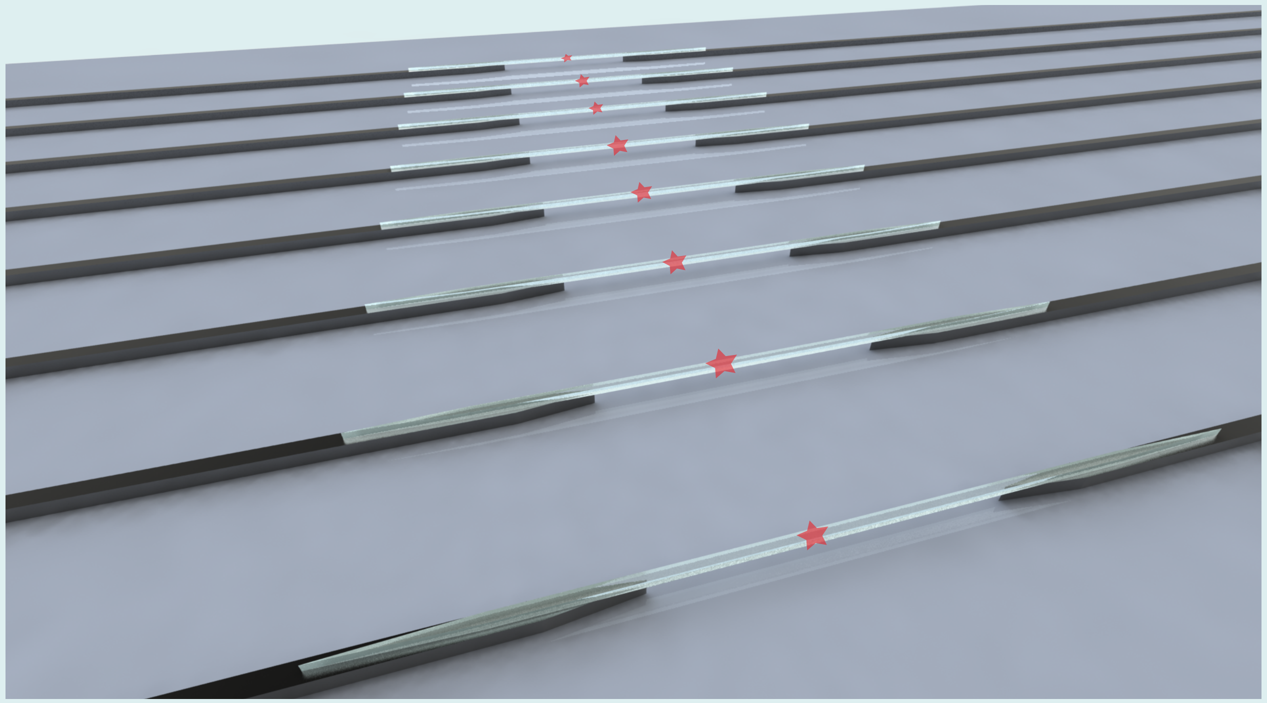
Phase stable

Low loss

	SiN	$LiNbO_3$	AlN
Ease of Fabrication	O	X	O
Low Fluorescence	X	O	O
Low Loss	O	O	O
Active	X	31pm/V	0.6pm/V

Bayn, Mouradian et al APL 211101, 2014
Mouradian et al PRX 031009, 2015

On-Chip Integration



Hybrid Architecture:

Components fabricated separately.

Only best are integrated

Compact

Phase stable

Low loss

Bayn, Mouradian et al APL 211101, 2014
Mouradian et al PRX 031009, 2015

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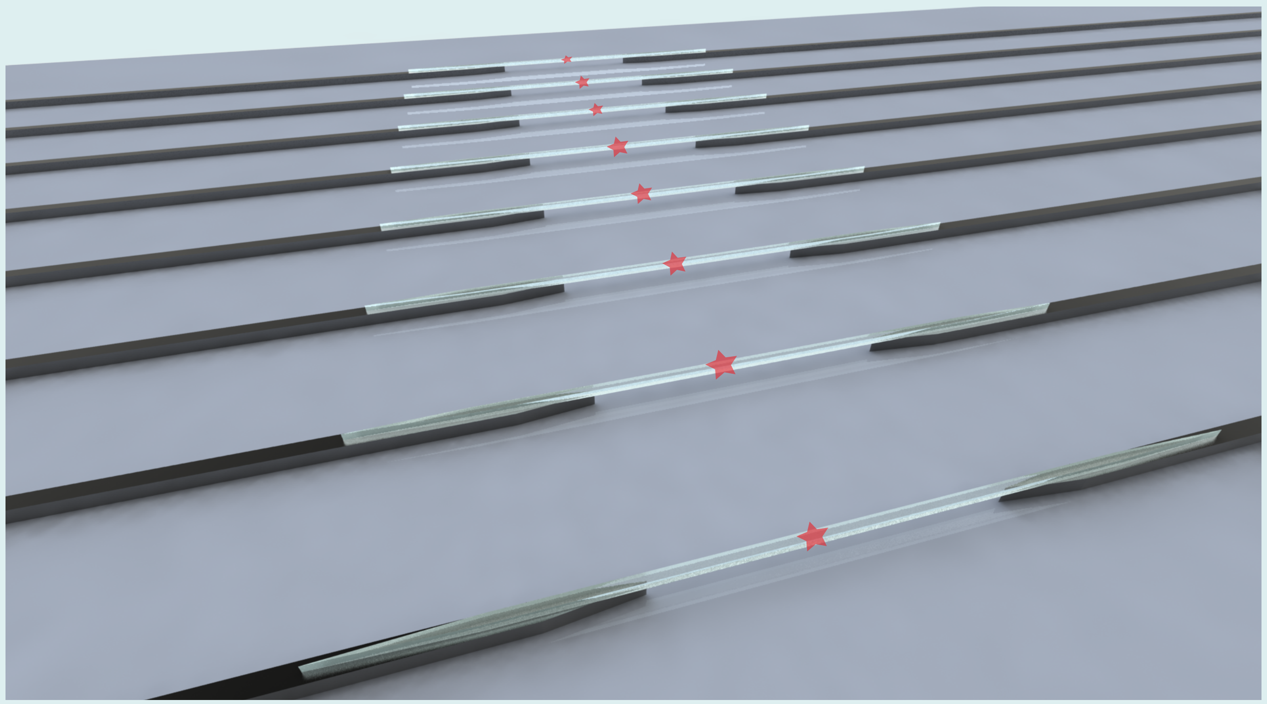

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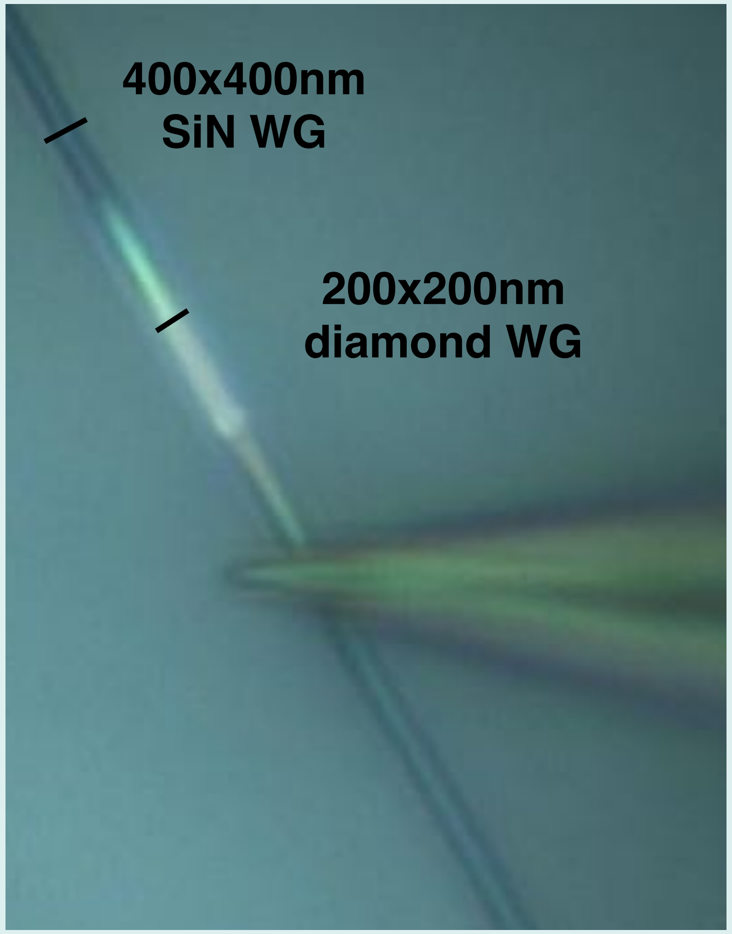
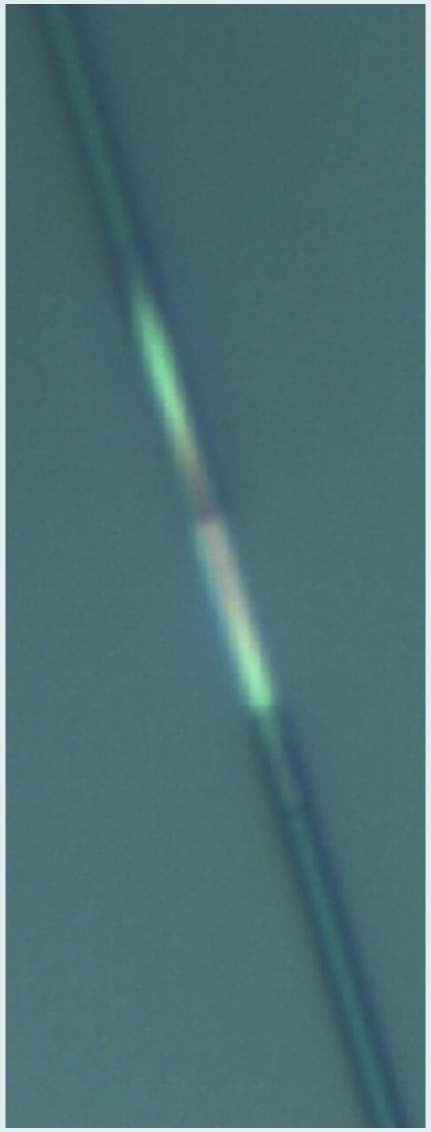
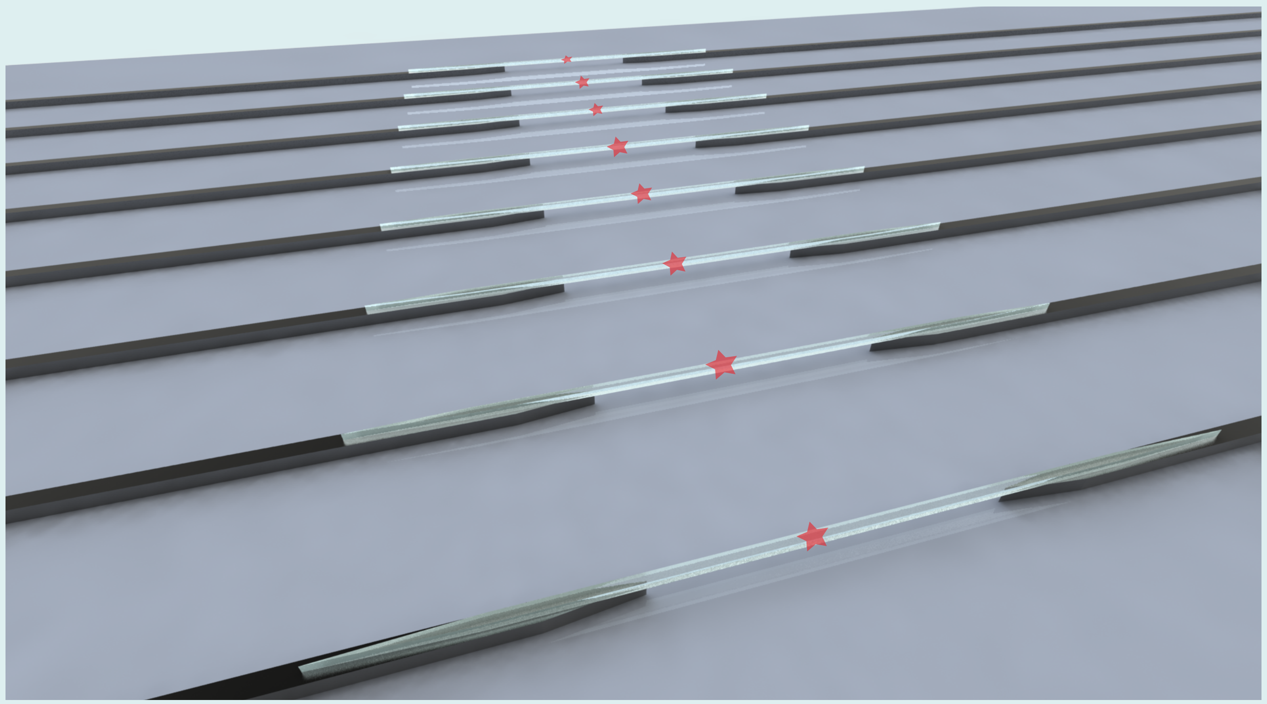




Mouradian et al PRX 031009, 2015

On-Chip Integration



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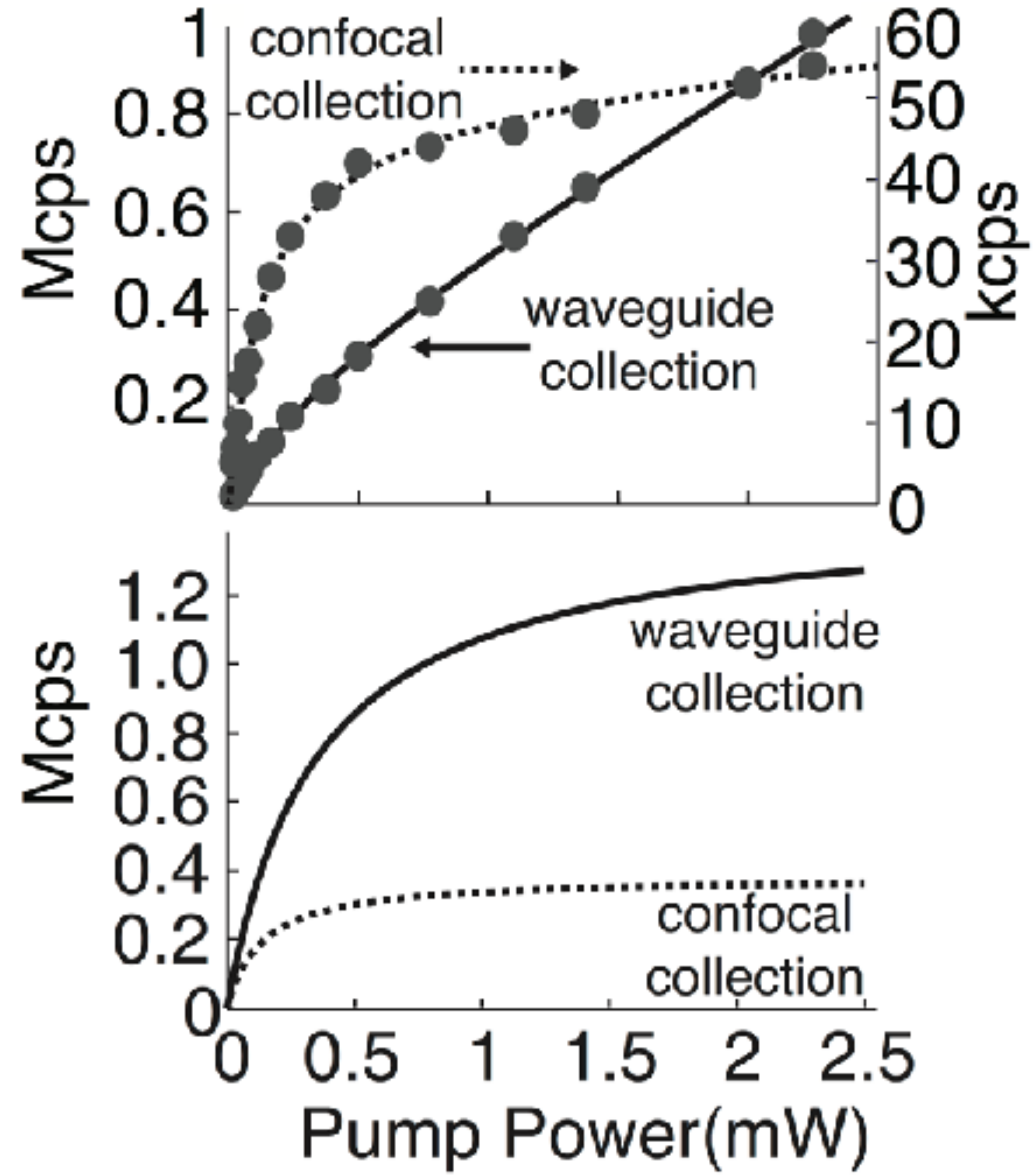
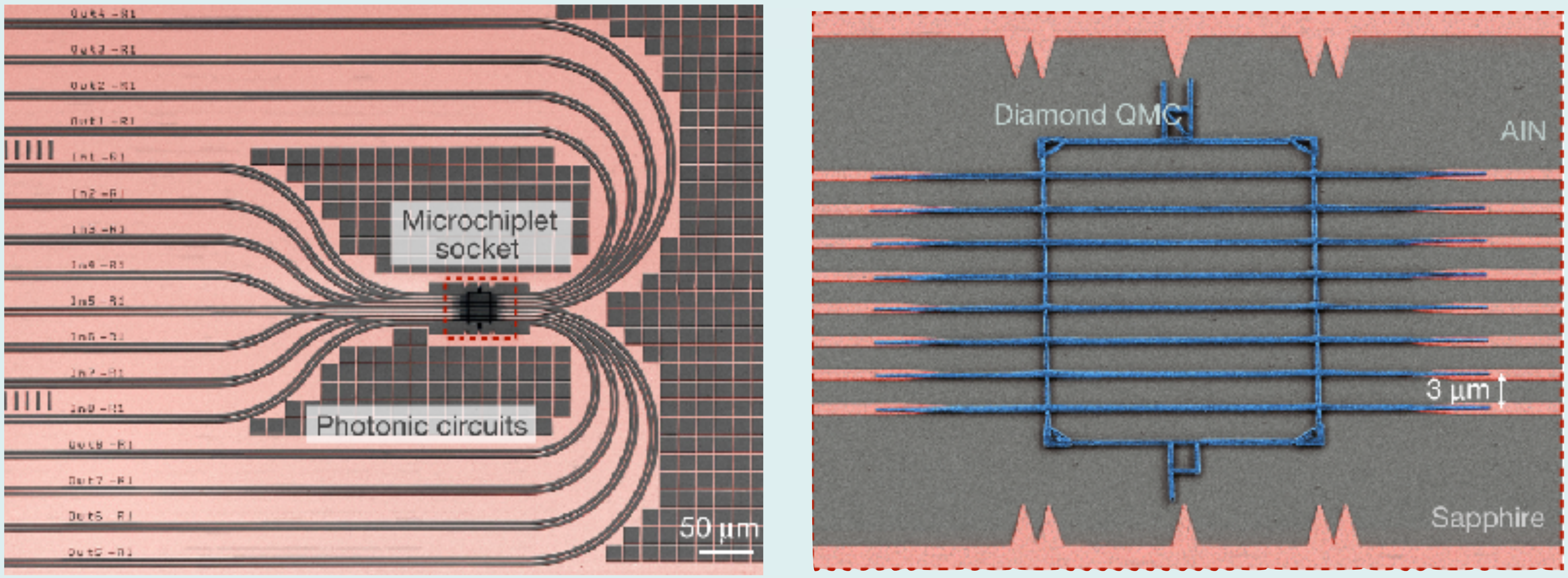


Mouradian et al PRX 031009, 2015

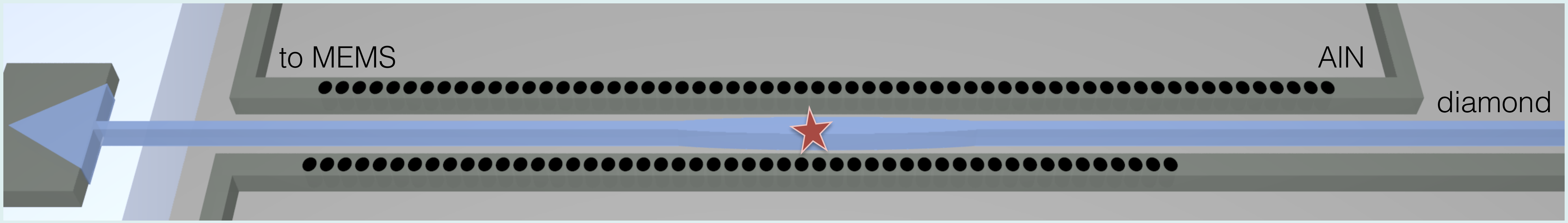
On-Chip Integration - Advancements

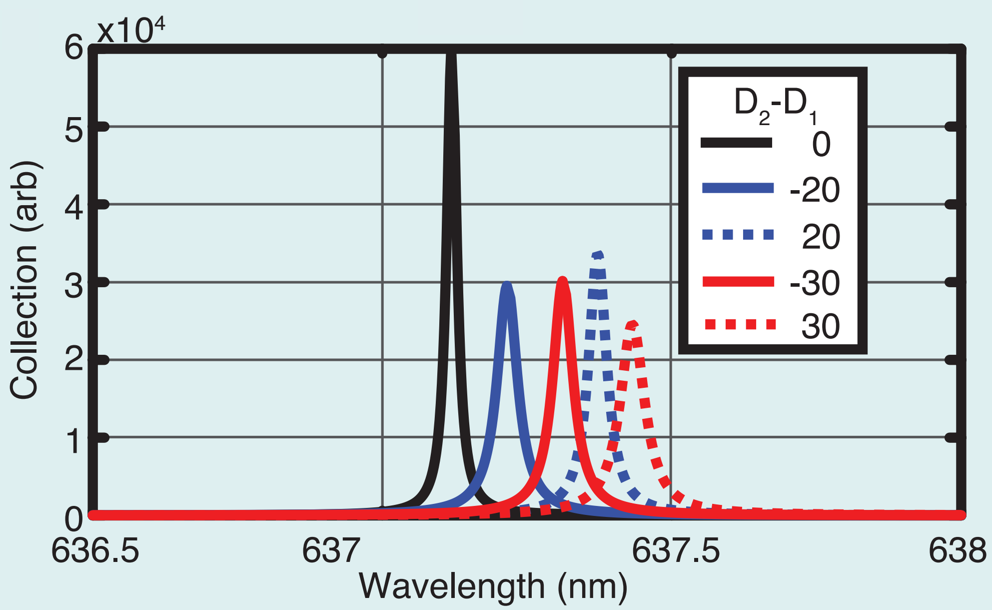


Large-scale integration with Aluminum Nitride

Wan, Lu et al Nature 582, 2020

On-Chip Integration - Advancements





Hybrid structure limits diamond patterning

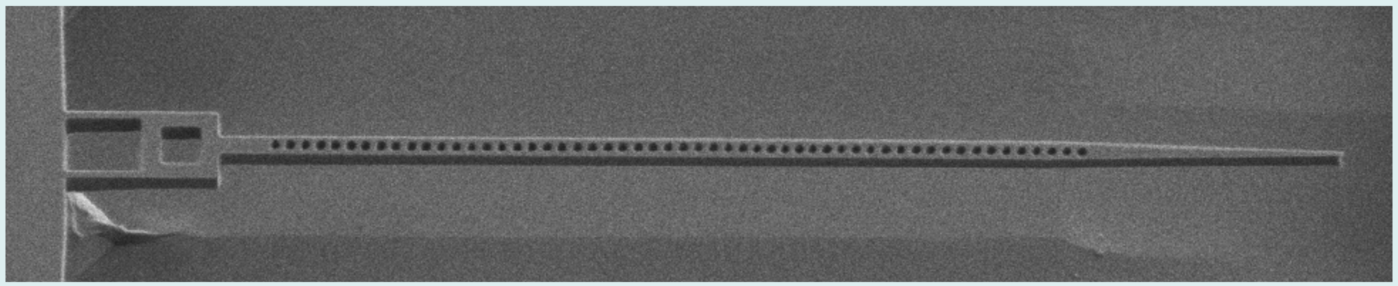
Unloaded Q > 10^6

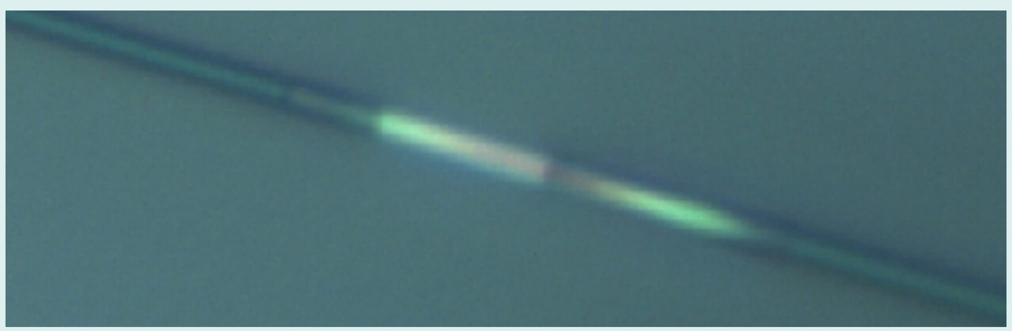
Loaded Q =55,000, 75% coupled into AlN

MEMS tuning

Mouradian, Englund APL Photonics 2, 2016

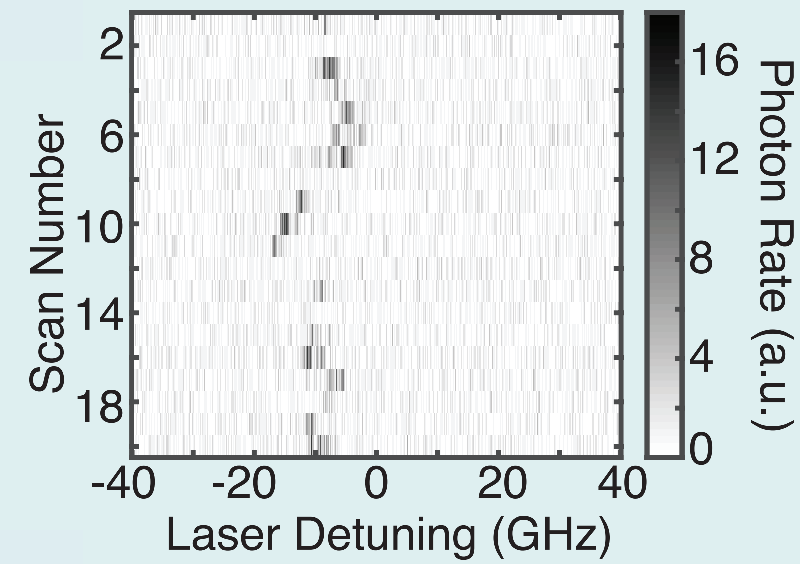
NV Centers - Review



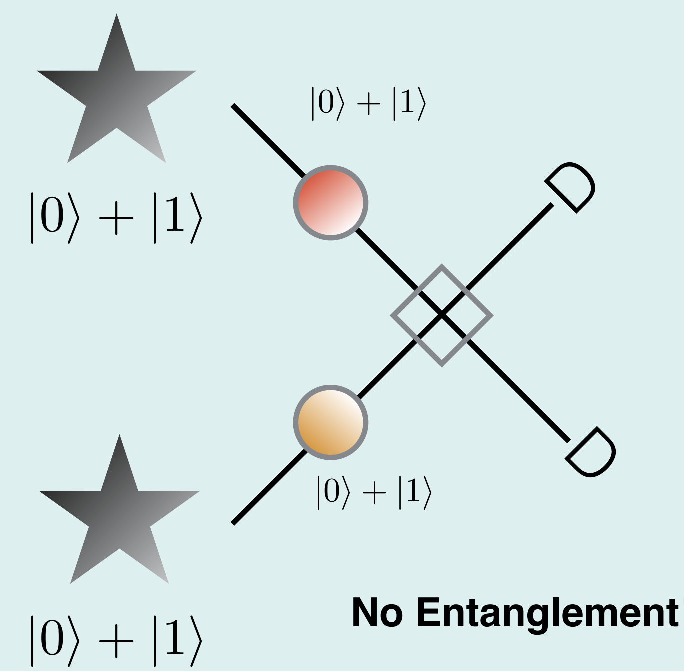


Nanophotonics and Integrated Systems can improve connectivity.

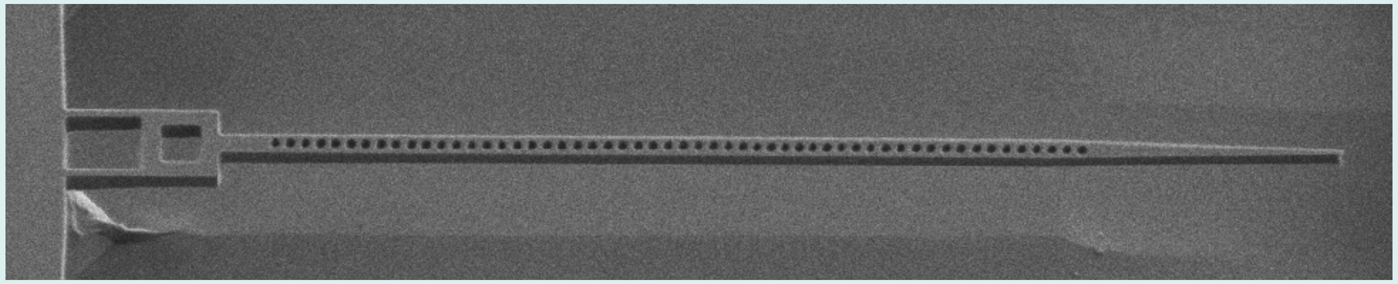
Van Dam, Walsh et al PRB 161203, 2019

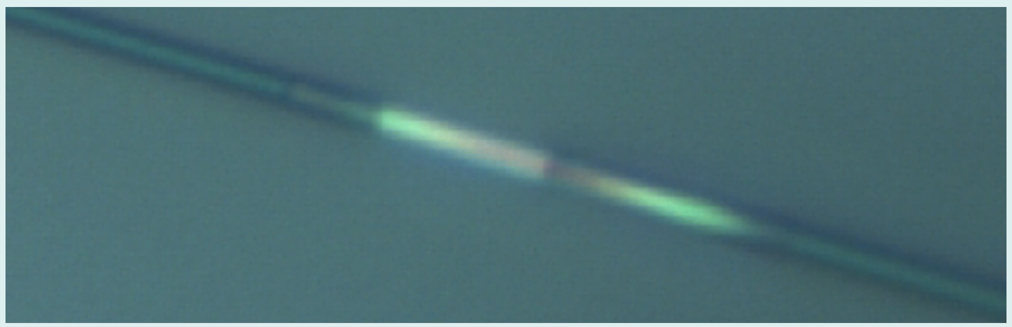


Surface and lattice defects cause spectral wandering



NV Centers - Review

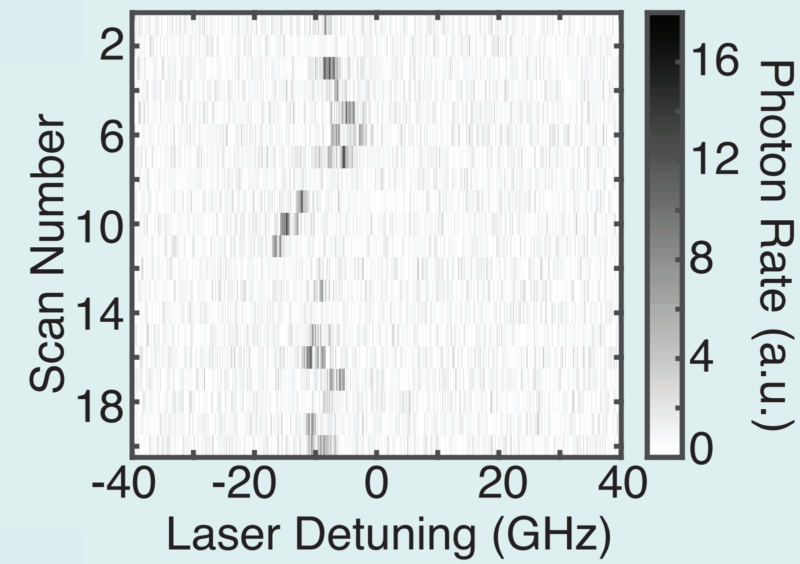




Nanophotonics and Integrated Systems
can improve connectivity.

If only we had a better qubit…..

Van Dam, Walsh et al PRB 161203, 2019



Surface and lattice defects
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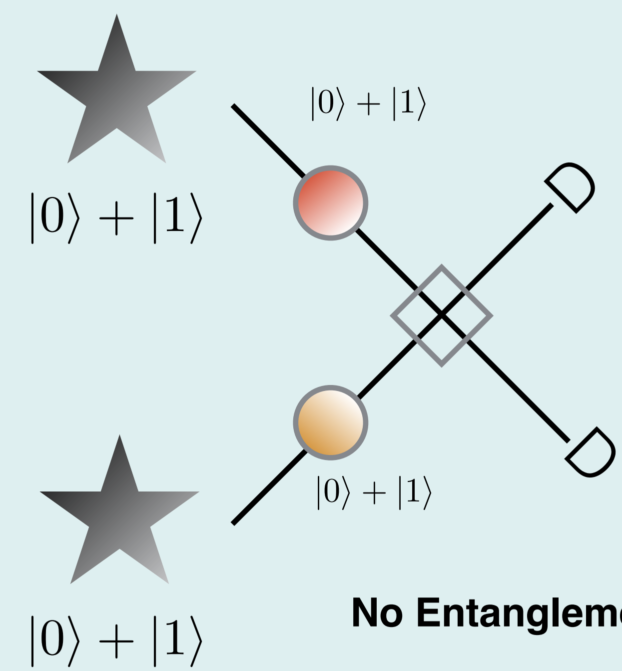


No Entanglement!

Outline

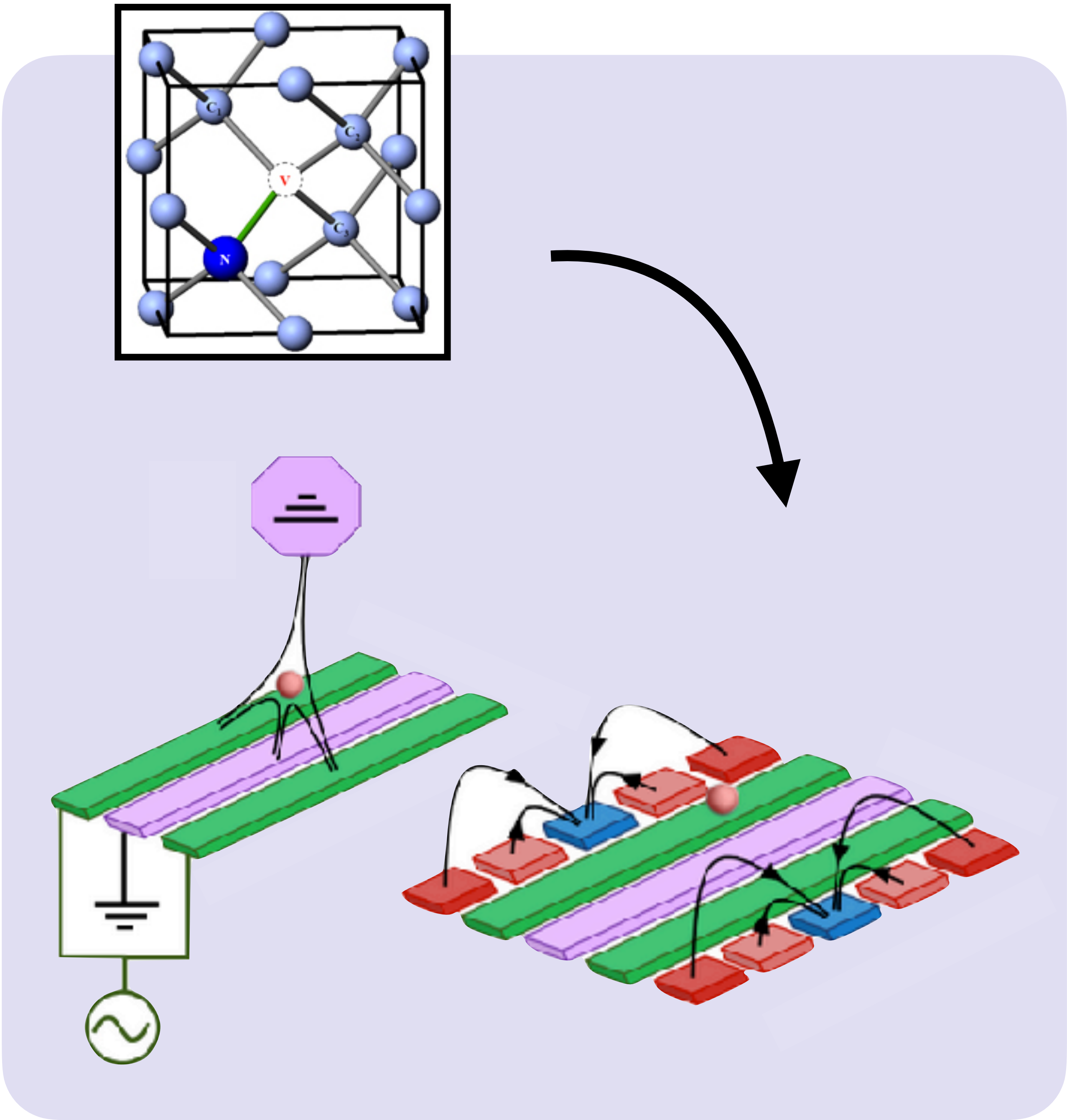
1. Overview of Quantum Technologies

2. Increasing connectivity — Solid State Defects

3. Increasing control - Trapped Ions

- Integrated photonics for scalable control

Trapped Ions - Background

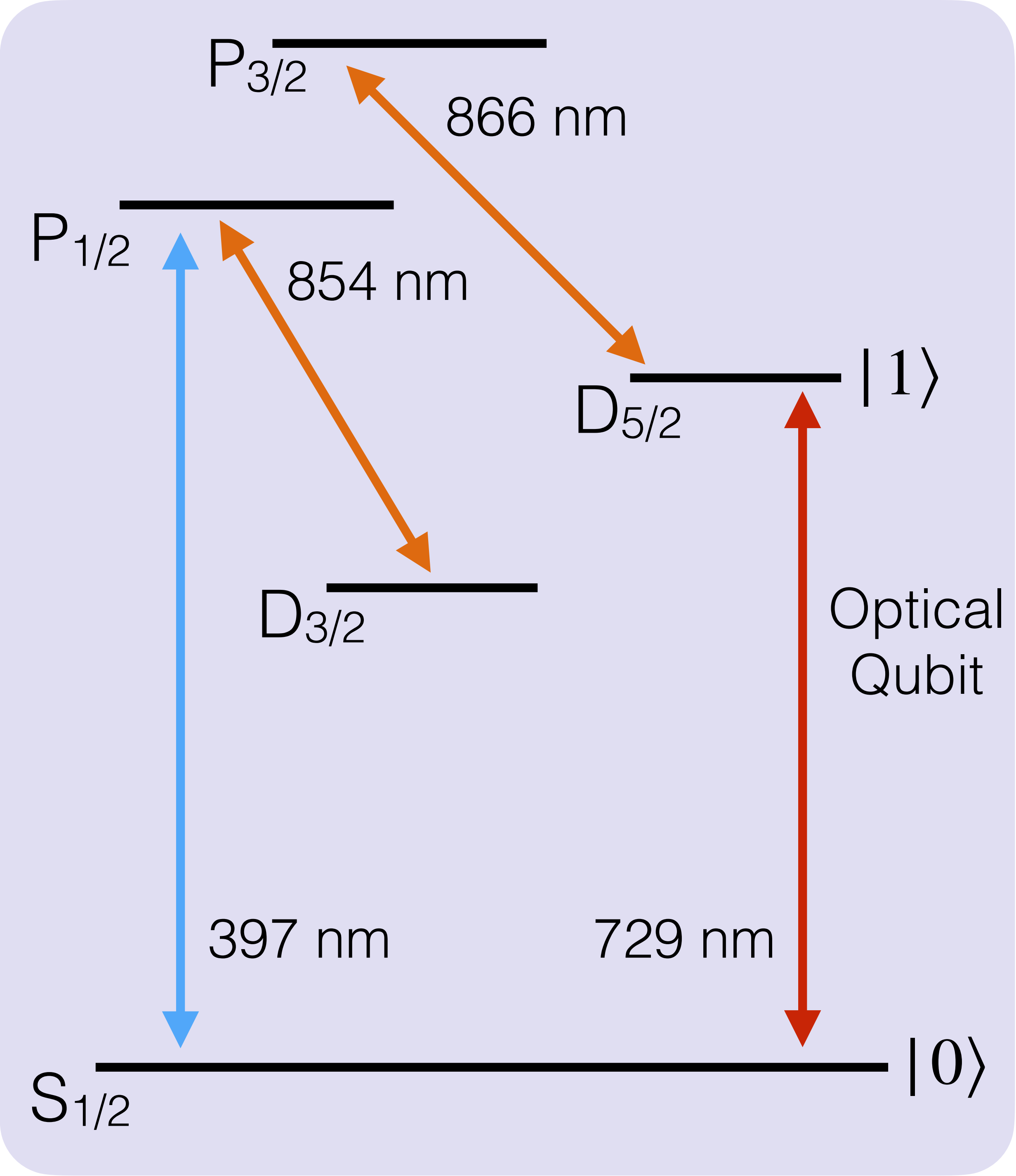


High vacuum - 10^{-11} mbar

DC & RF fields

2 ionization lasers
2 cooling lasers
1 repump laser
1 qubit laser

Trapped Ions - Background



Optical qubit:
T_2 ~200ms

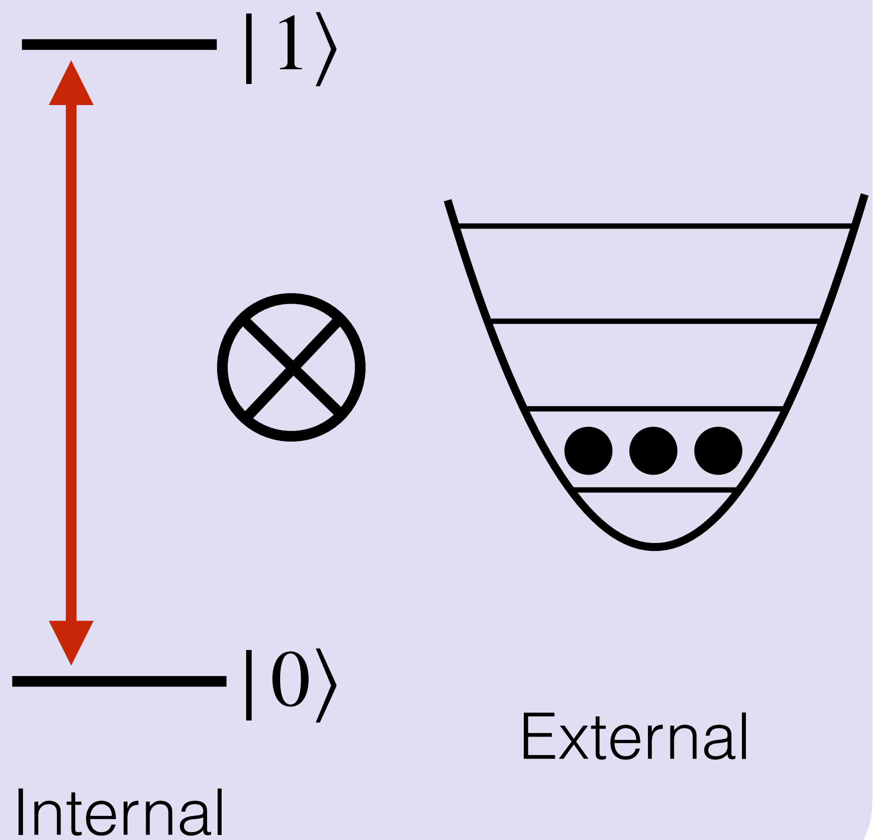
1 qubit gate:
~1 us, 99.995% fidelity

2 qubit gate:
10-100 us, 99.6% fidelity

SPAM errors:
$2x10^{-4}$

Trapped Ions - Background

Motional Modes



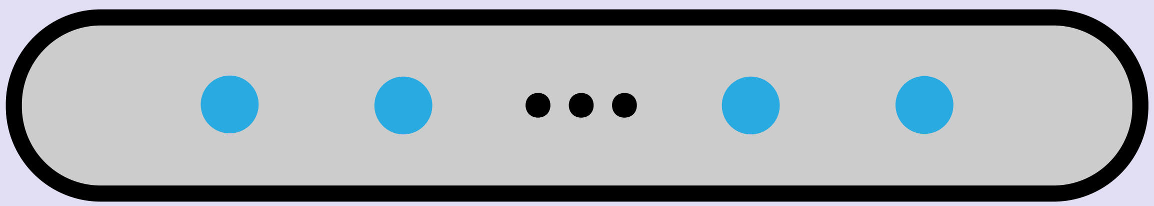
can be cooled to ground state

occupation can be engineered

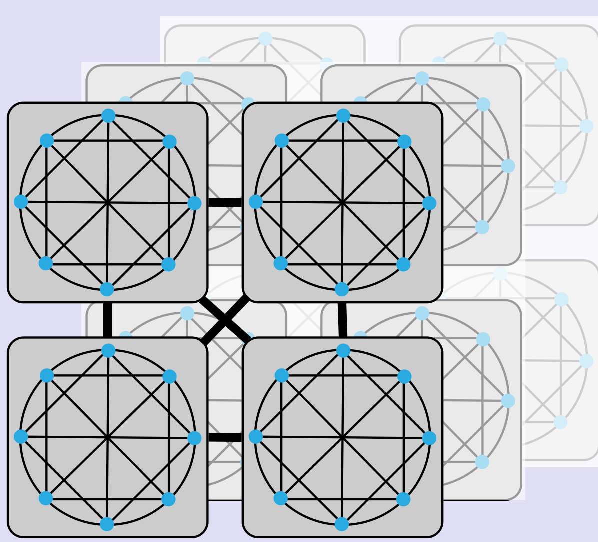
Entanglement is natural between ions in the same trap

Any-to-any connectivity is possible (with correct control fields)

Modular Architecture

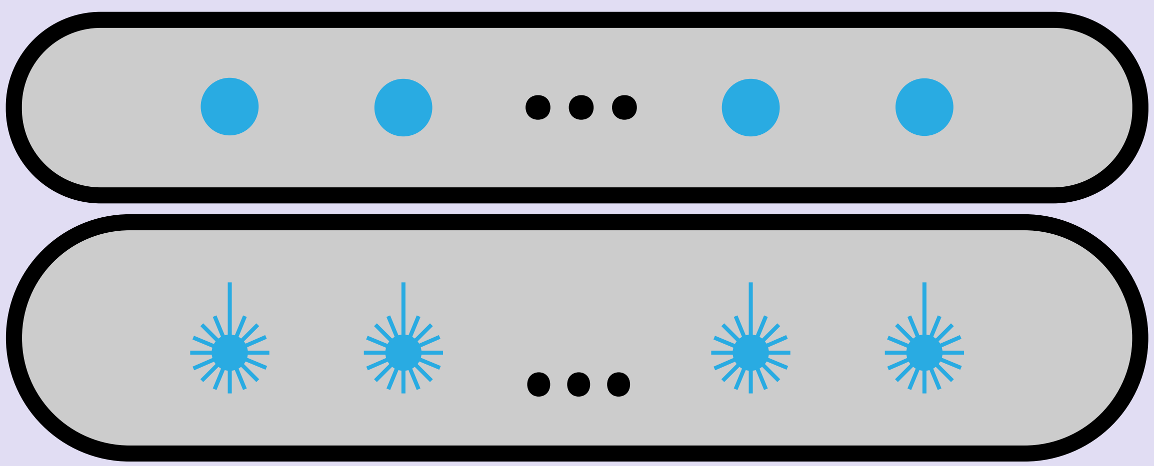


Construction
Linear chains co-trapped.



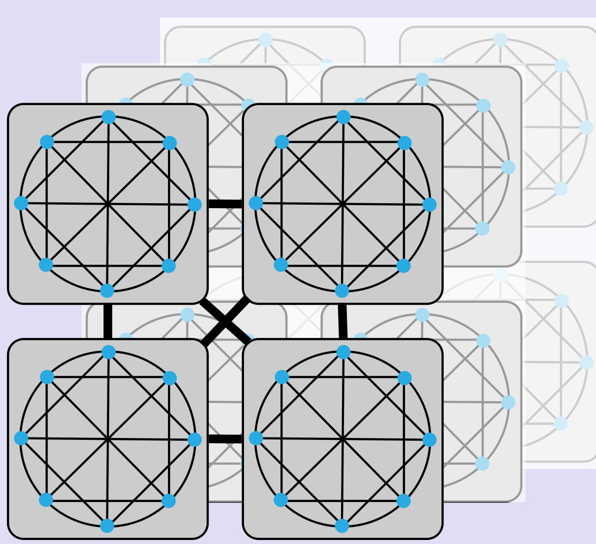
Connection
Photonic links or
physical links via shuttling

Modular Architecture



Construction
Linear chains co-trapped.

Control
Optical control on each ion.



Connection
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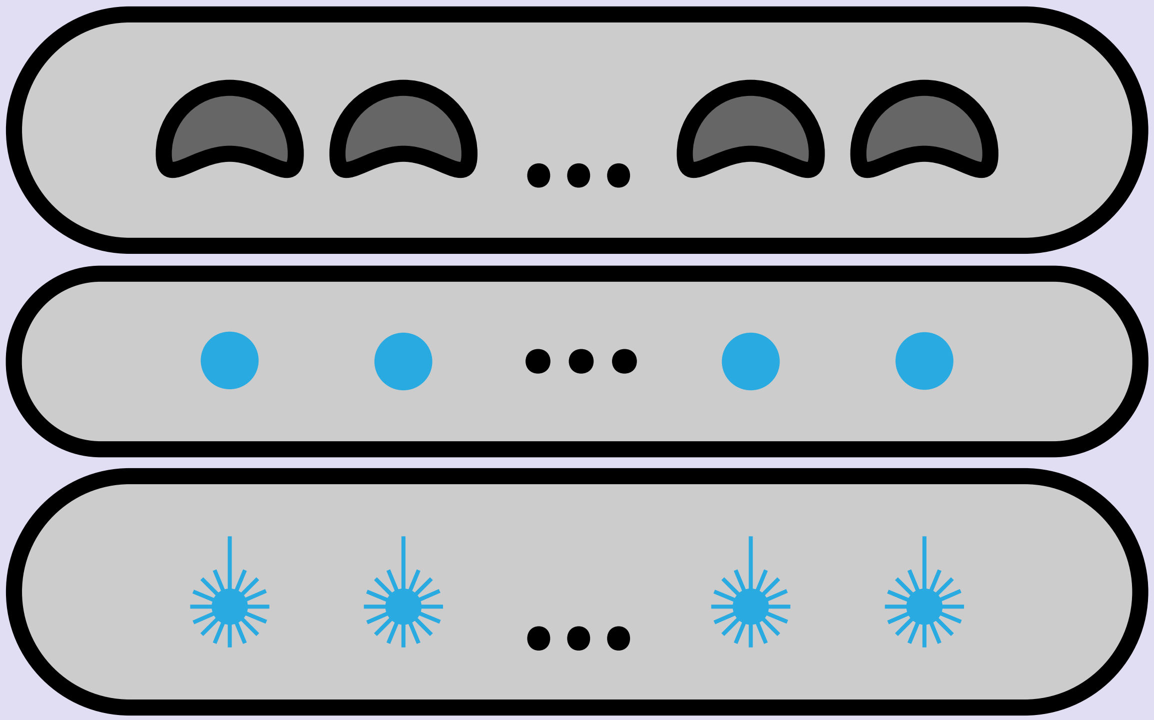
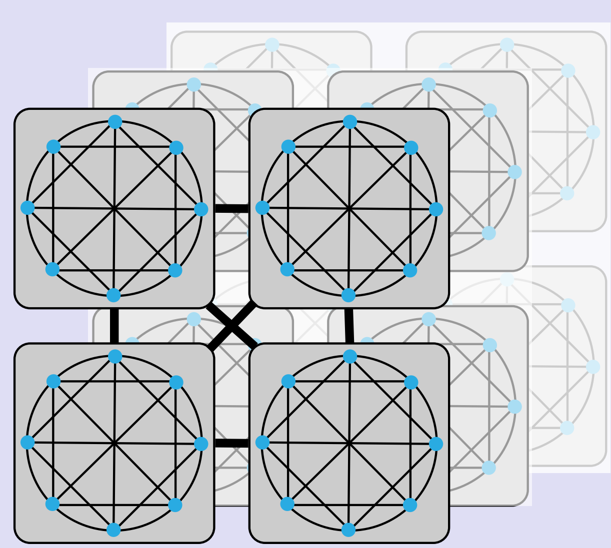
Modular Architecture



Detection
Scattering off a cycling,
State-dependent transition

Construction
Linear chains co-trapped.

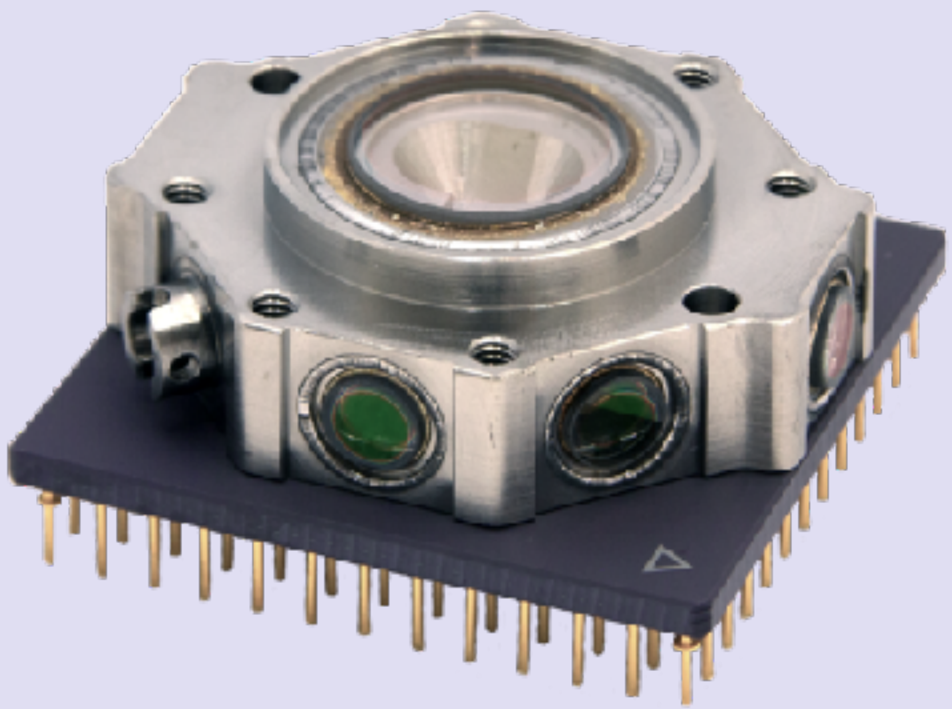
Control
Optical control on each ion.



Connection
Photonic links or
physical links via shuttling

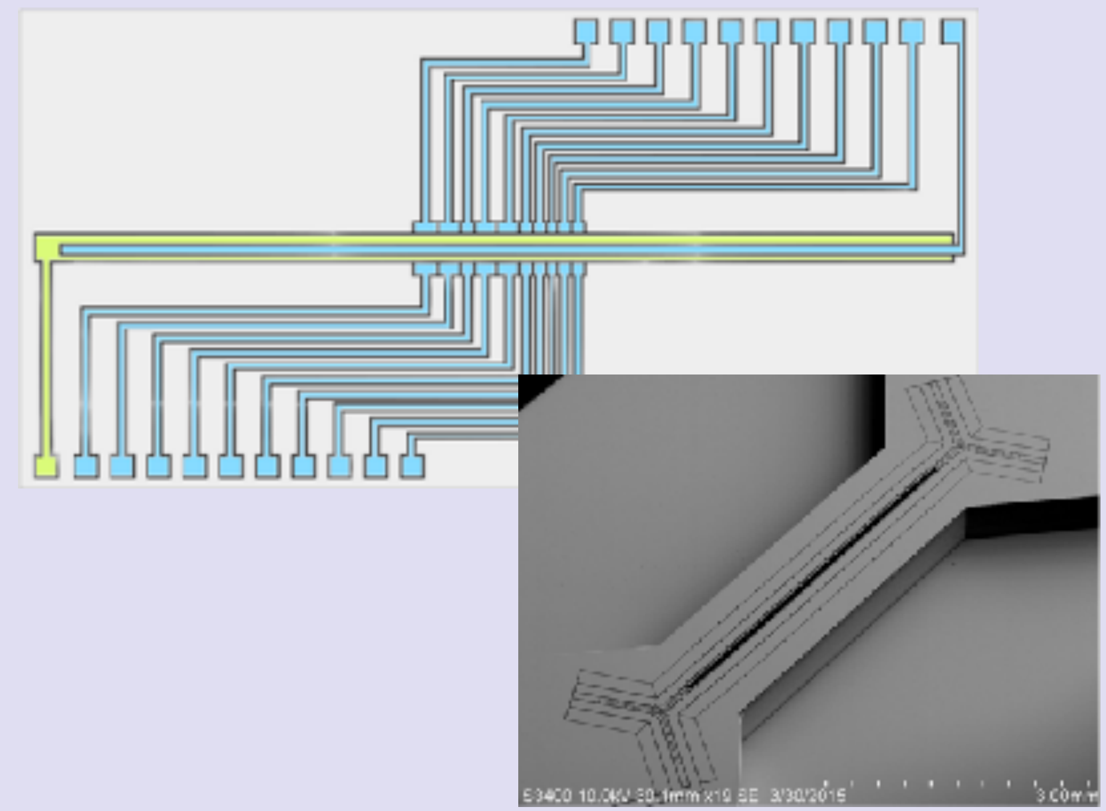
Trapped Ions -Scalability

(1) Ultra High Vacuum



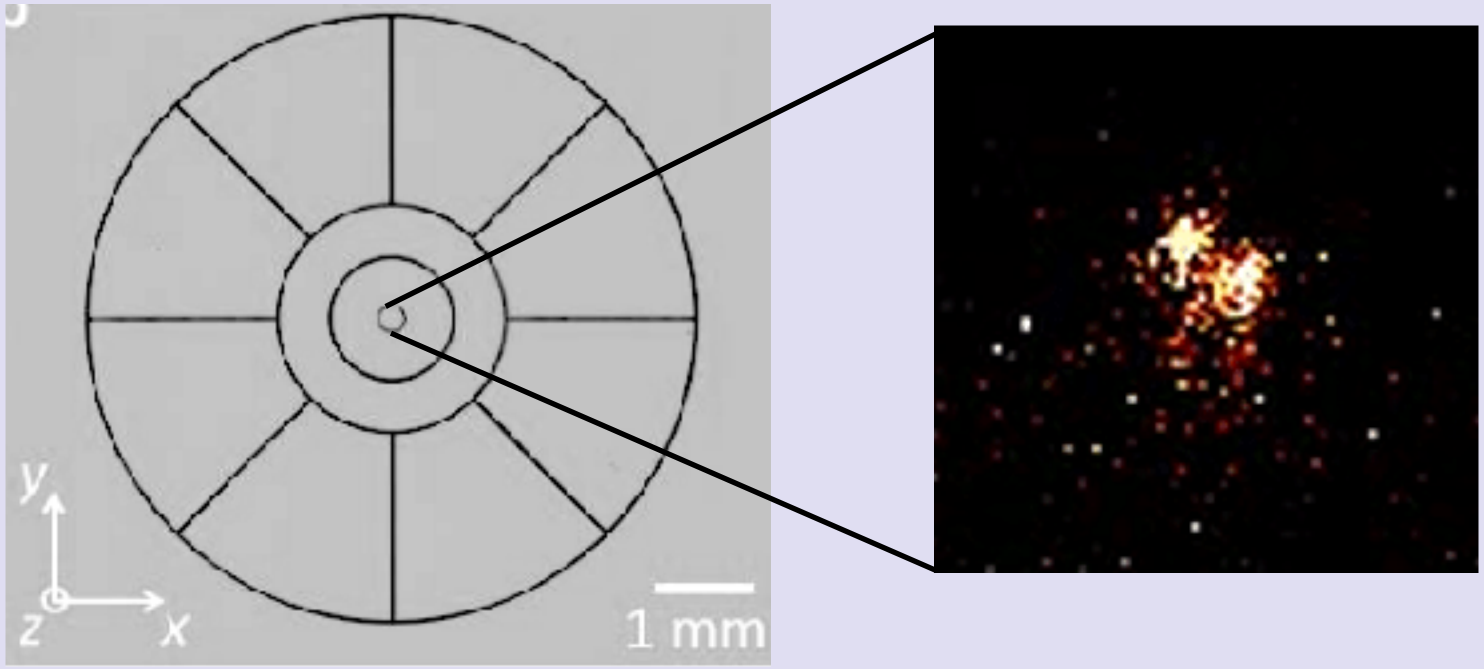
Commercial, packaged, cryogenic systems by Cold Quanta

(2) Trapping Electrodes



Microfabricated surface traps using standard techniques

Rotational Interlude

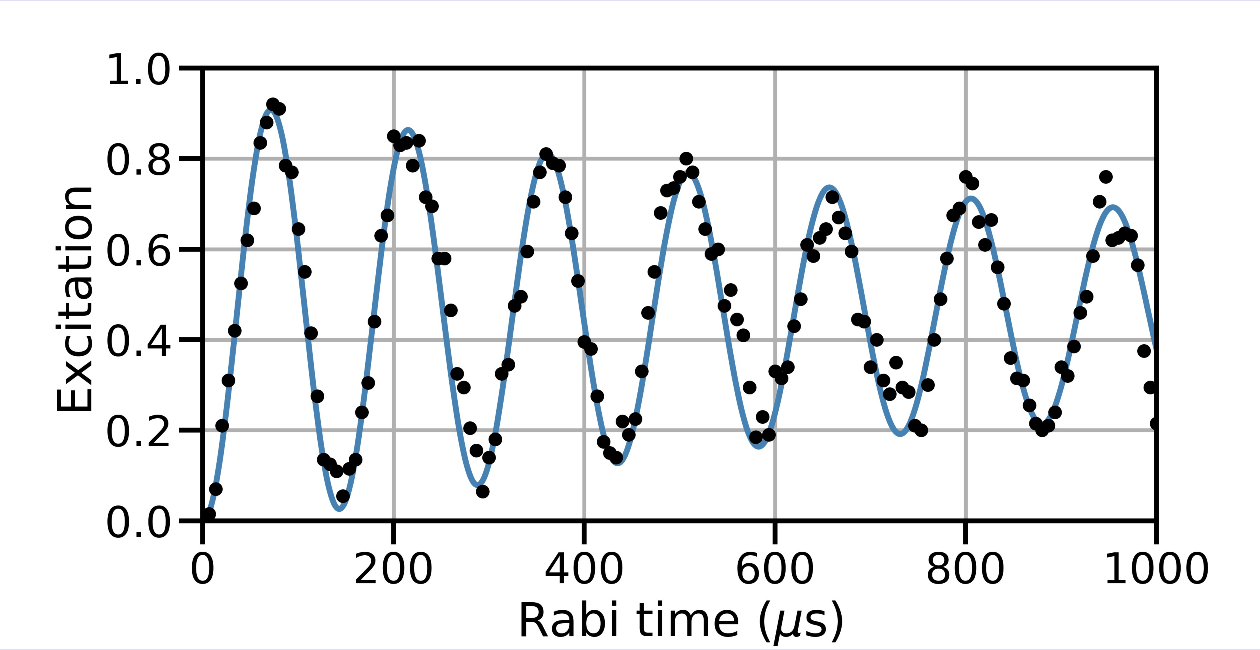


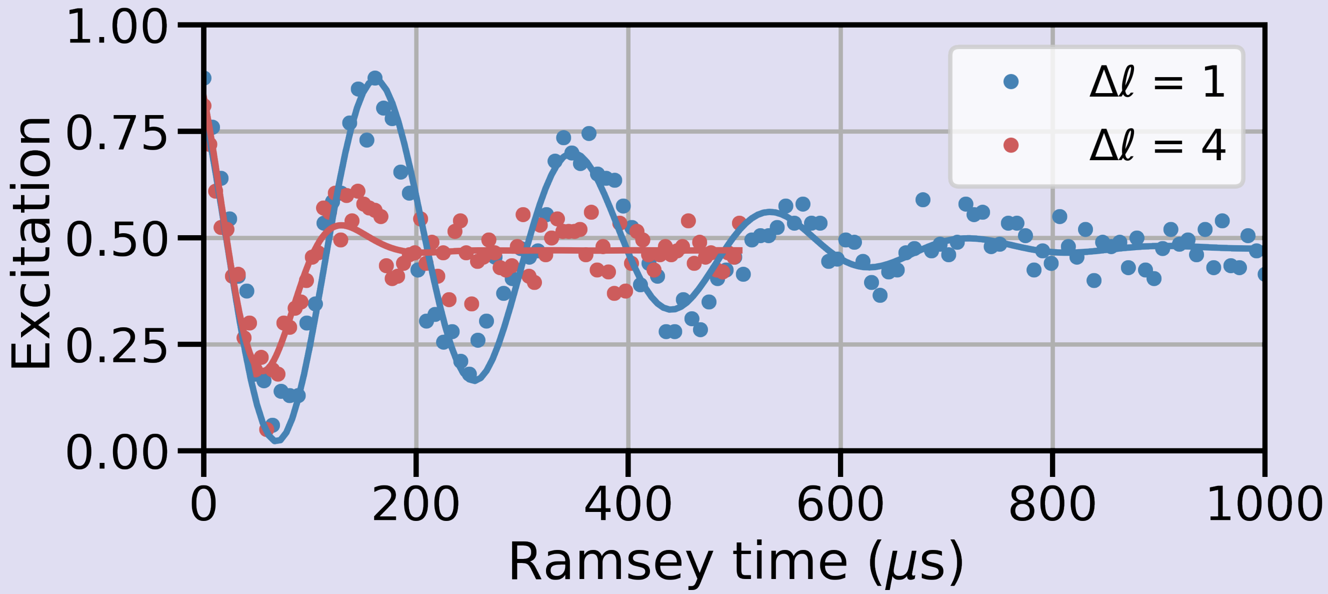
Silicon micro fabrication allows for control of the rotational modes of a symmetric ion crystal

Li, Urban, et al PRL 053001, 2017

Urban, Glikin, Mouradian, Krimmel, Hemmerling, Haeffner, PRL 133202, 2019

Rotational Interlude





First demonstration of quantum control of rotational degrees of freedom.

Can be used for:

Fundamental tests of indistinguishability.

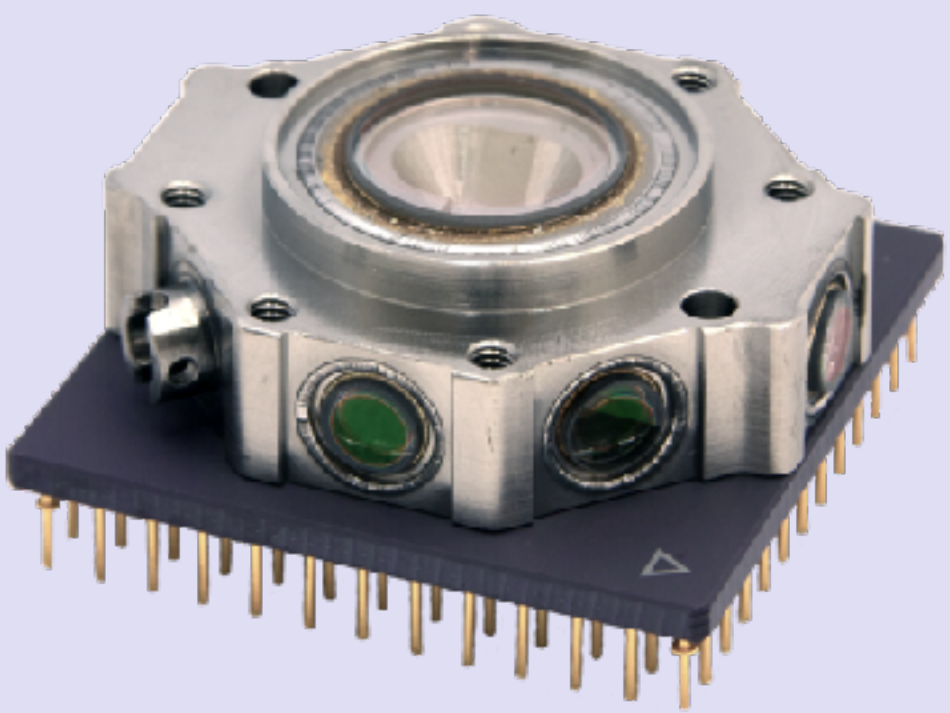
Detection of OAM modes.

Information storage in noise-insensitive rotational states

Urban, Glikin, Mouradian, Krimmel, Hemmerling, Haeffner, PRL 133202, 2019

Trapped Ions -Scalability

(1) Ultra High Vacuum



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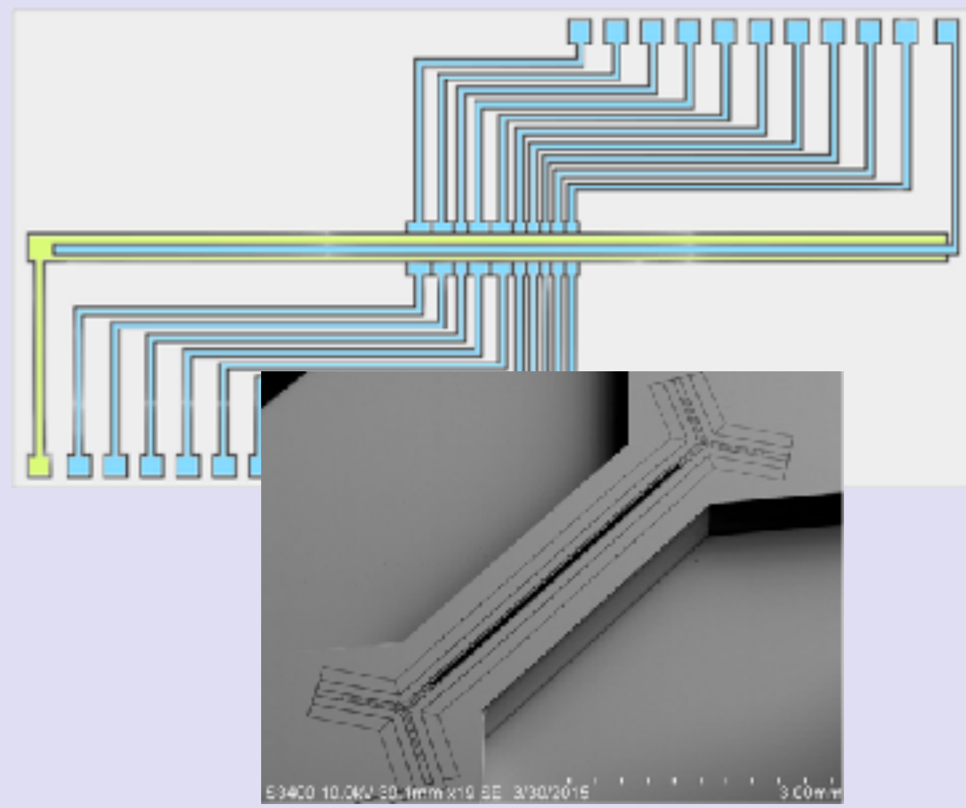
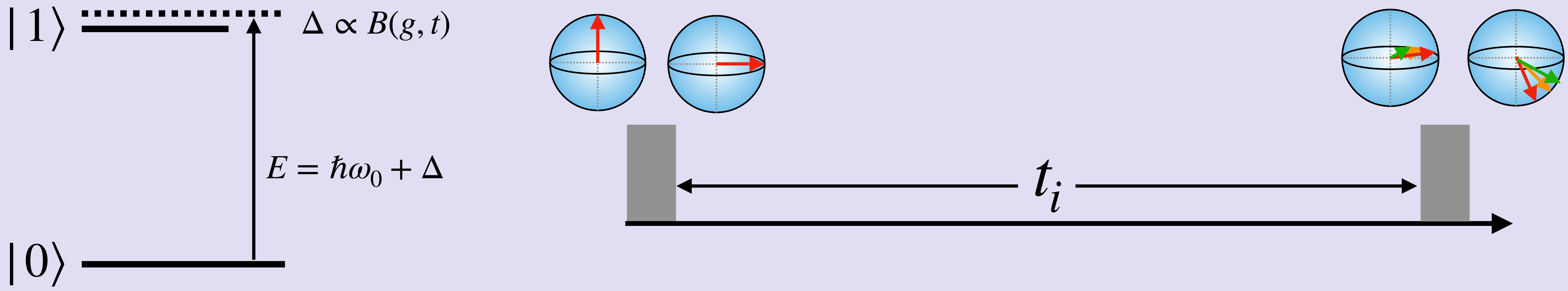


Microfabricated surface traps using standard techniques

(3) Optical Control

??

Enhanced Sensing



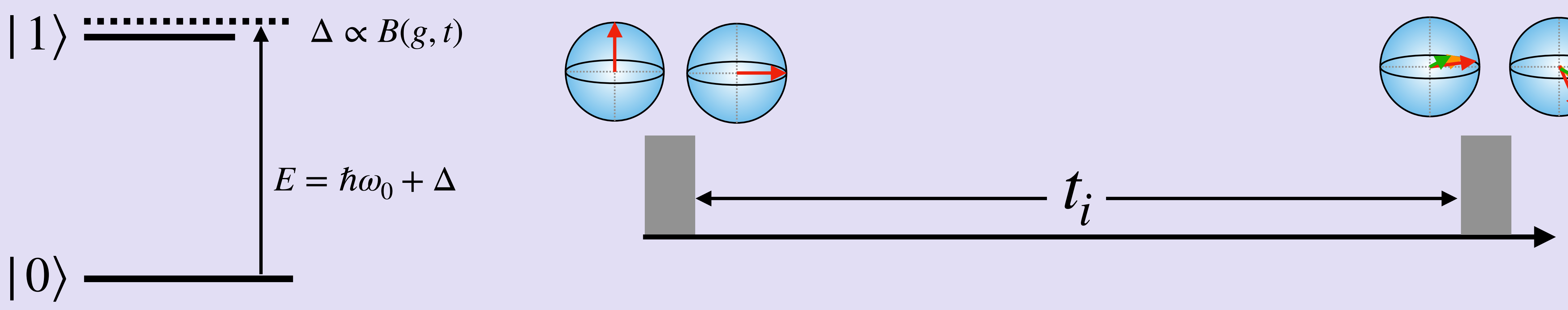
How do you build a good sensor?

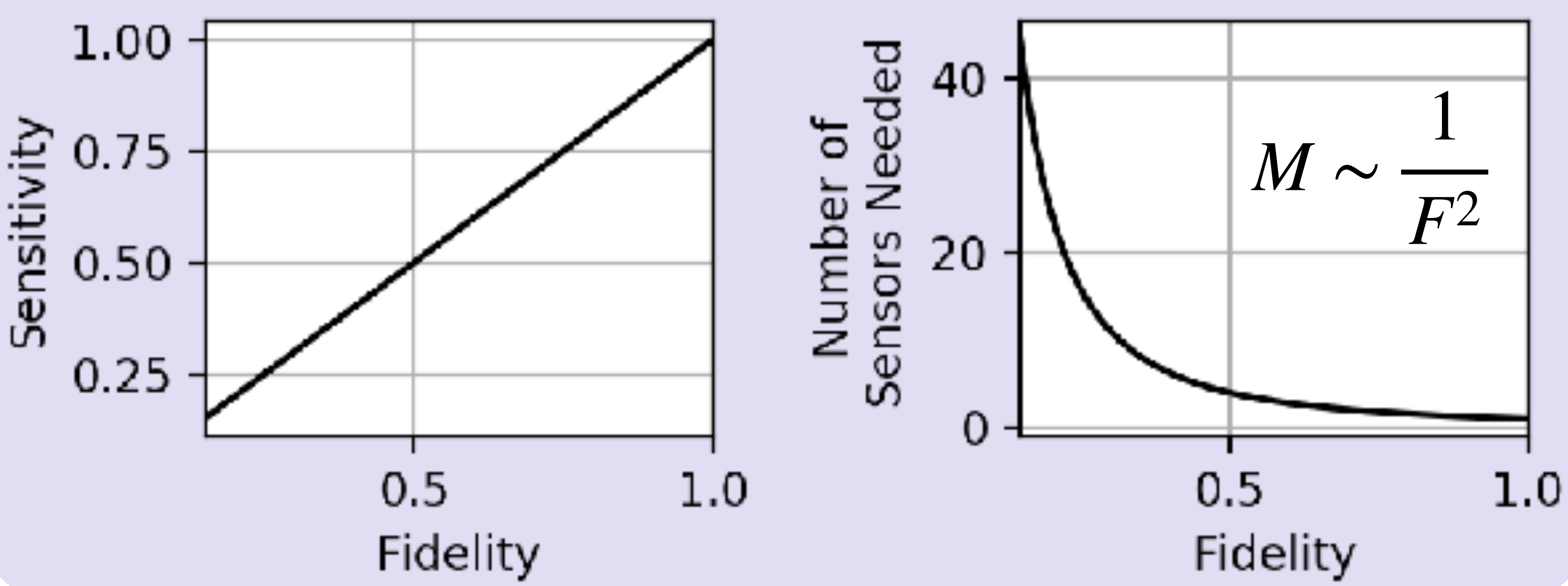
Trade-off between:

(1) number of sensors and
(2) control fidelity

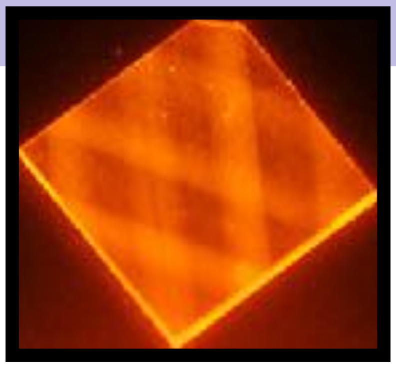
Mouradian, et al, ArXiV 2020

Enhanced Sensing



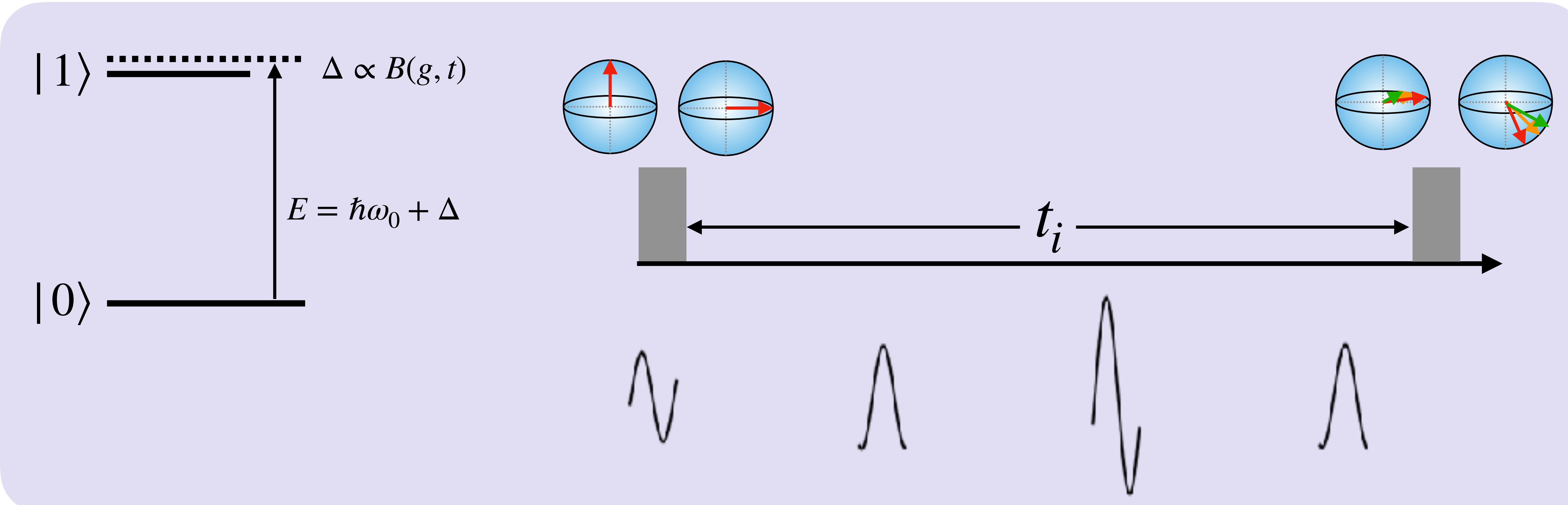


Can get away with sacrificing fidelity for number of sensors



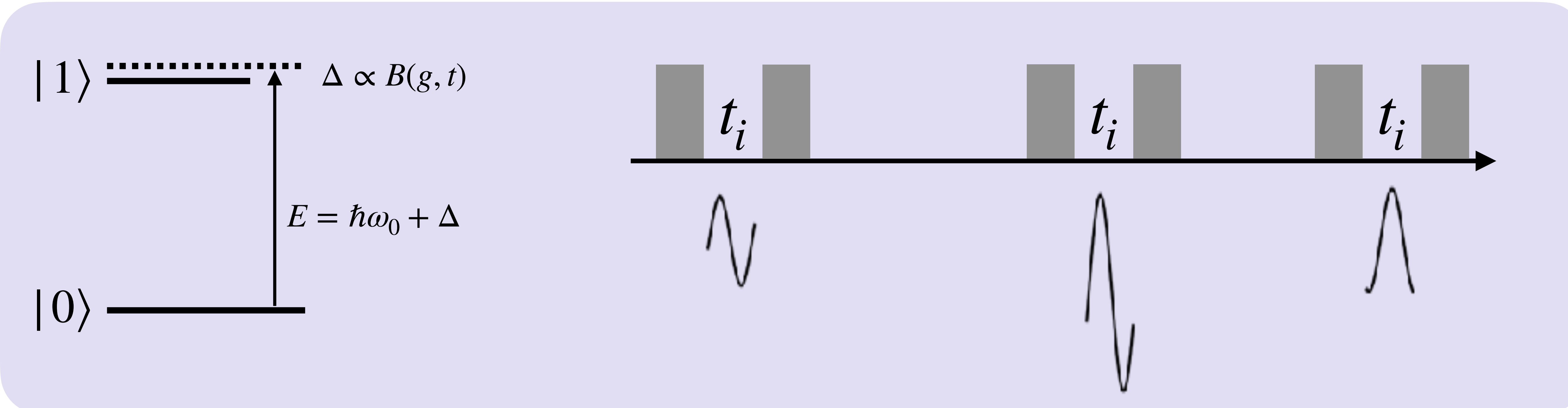
Mouradian, et al, ArXiV 2020

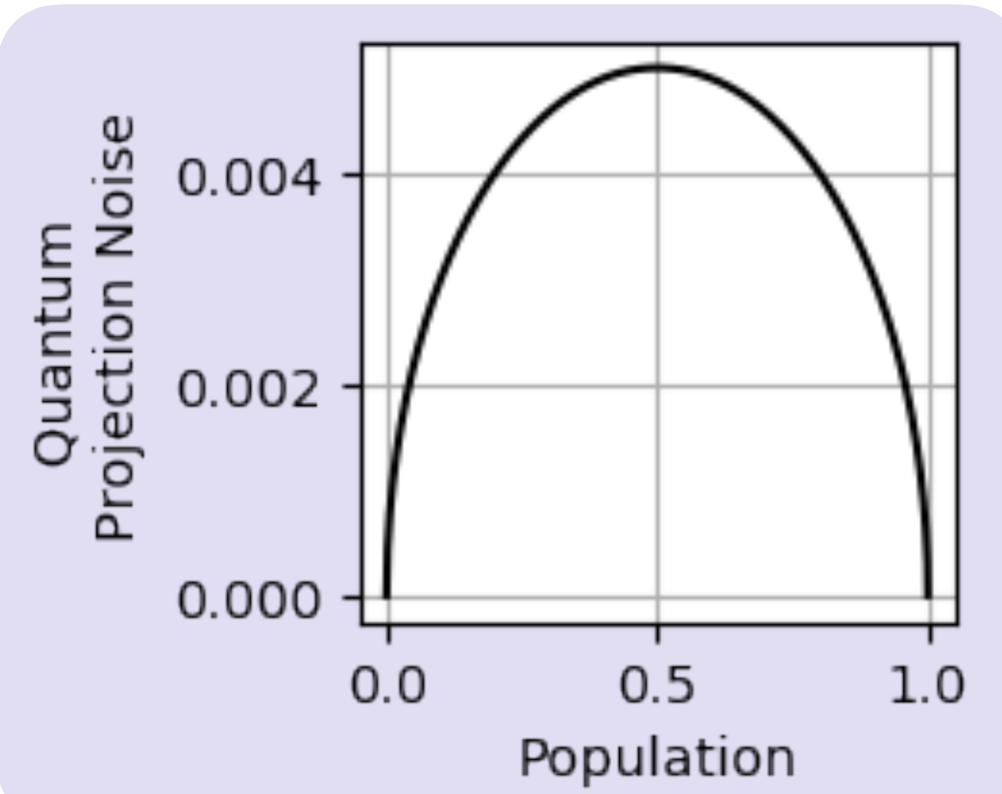
Enhanced Sensing - Intermittent Signal



Mouradian, et al, ArXiV 2020

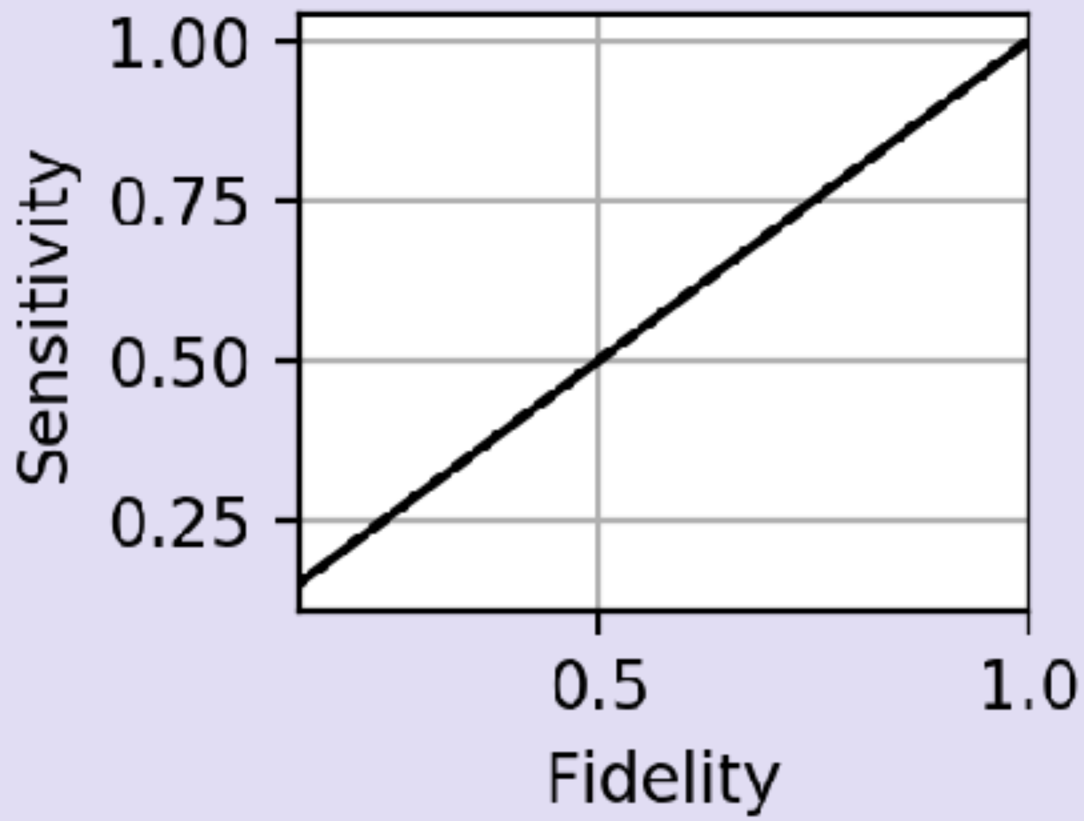
Enhanced Sensing - Intermittent Signal

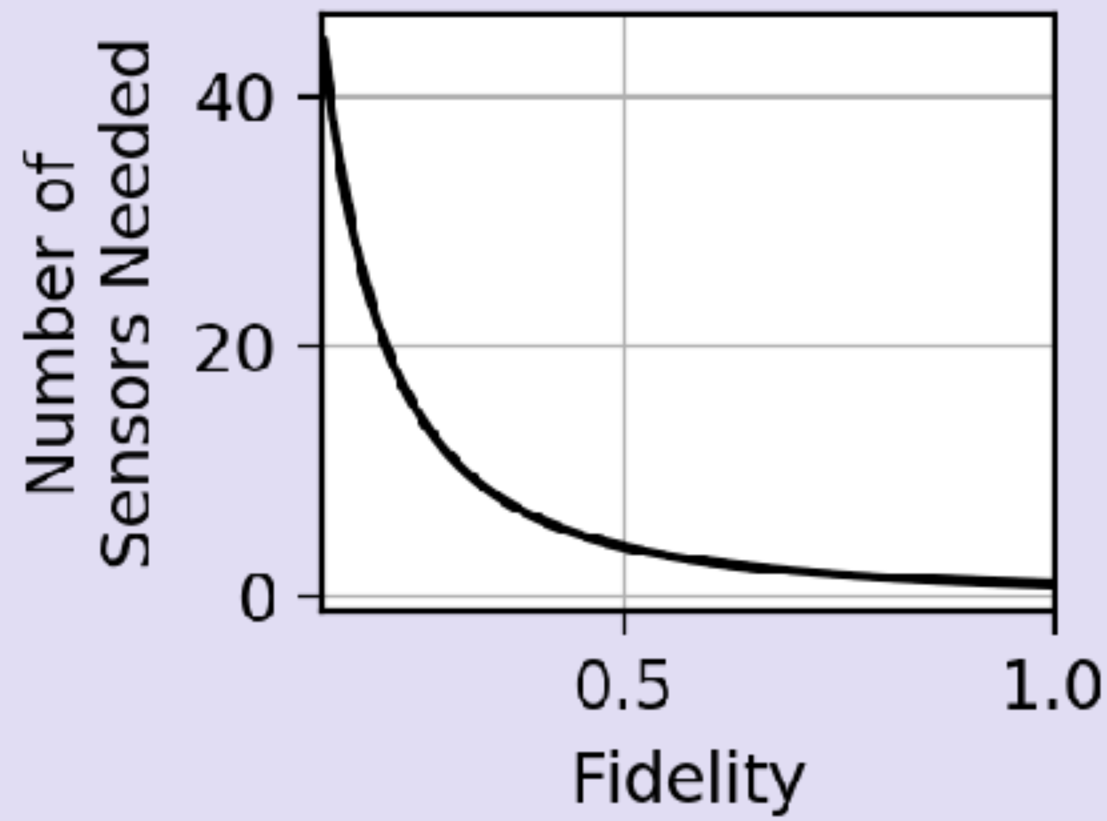




Mouradian, et al, ArXiV 2020

Enhanced Sensing

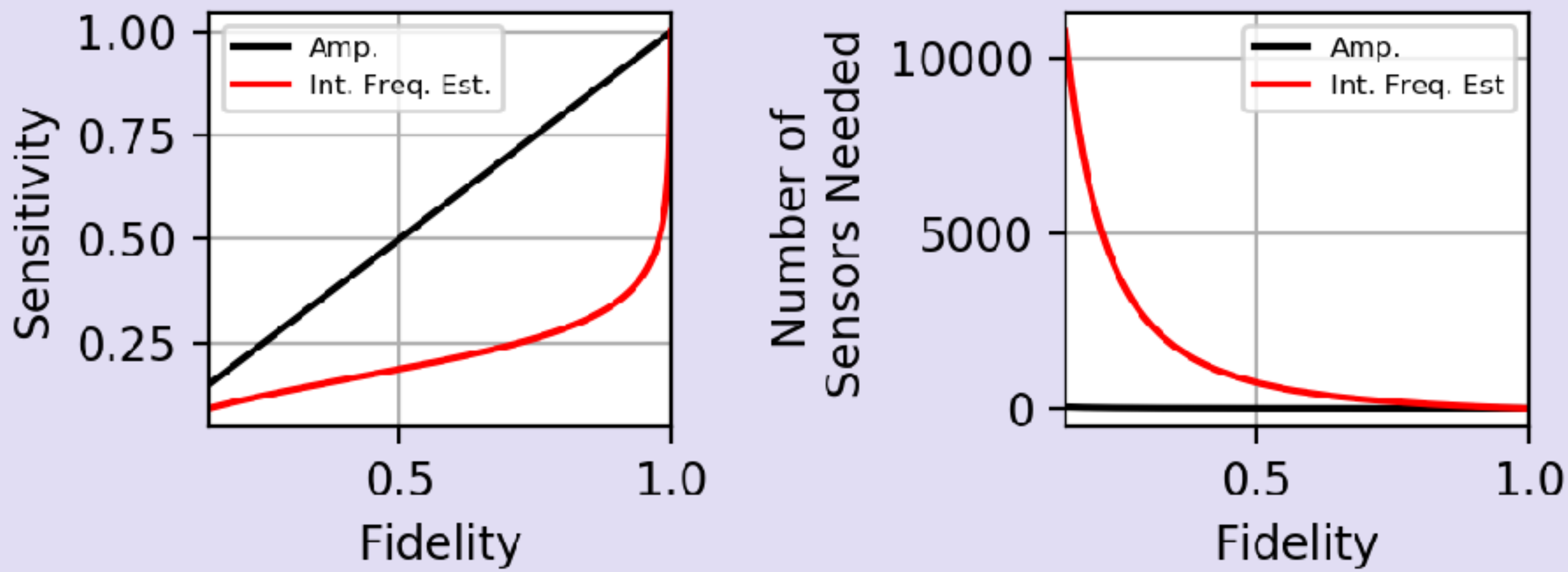




Maintaining fidelity while increasing the # of sensors is especially important for intermittent signals.

Mouradian, et al, ArXiV 2020

Enhanced Sensing



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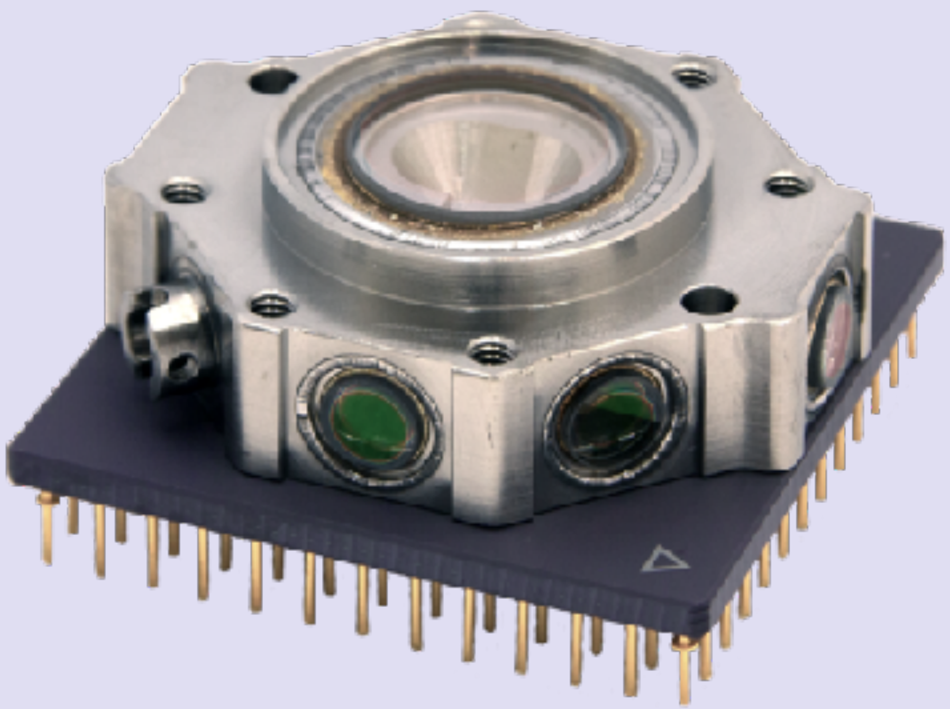
Mouradian, et al, ArXiV 2020

Trapped Ions -Scalability

(1) Ultra High Vacuum



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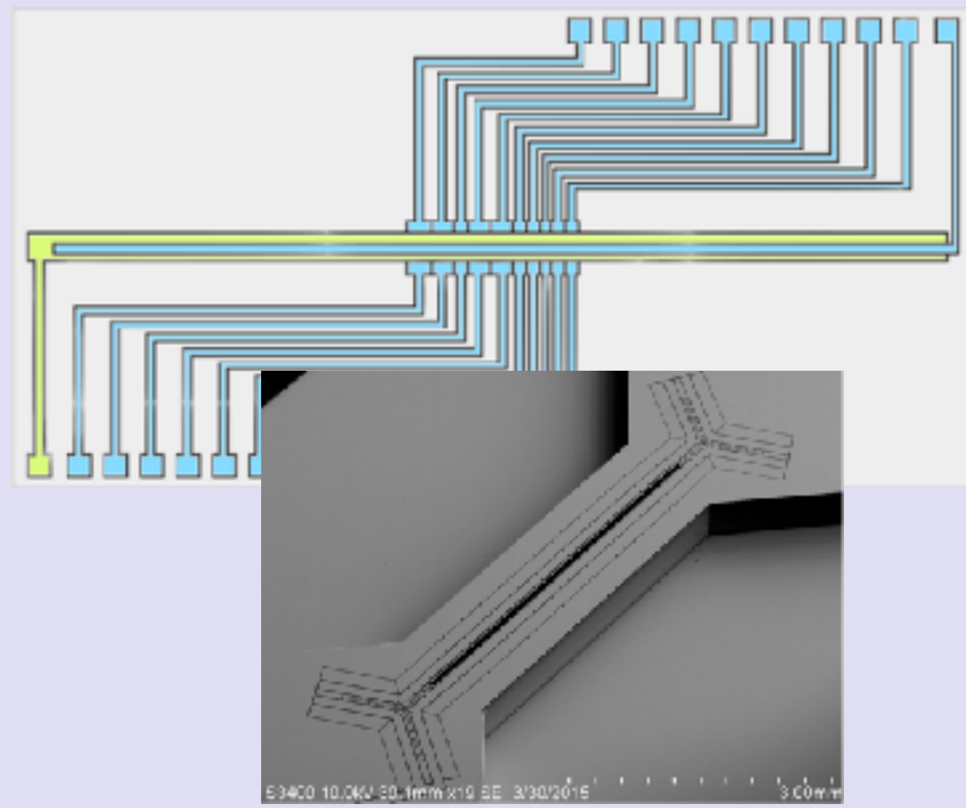
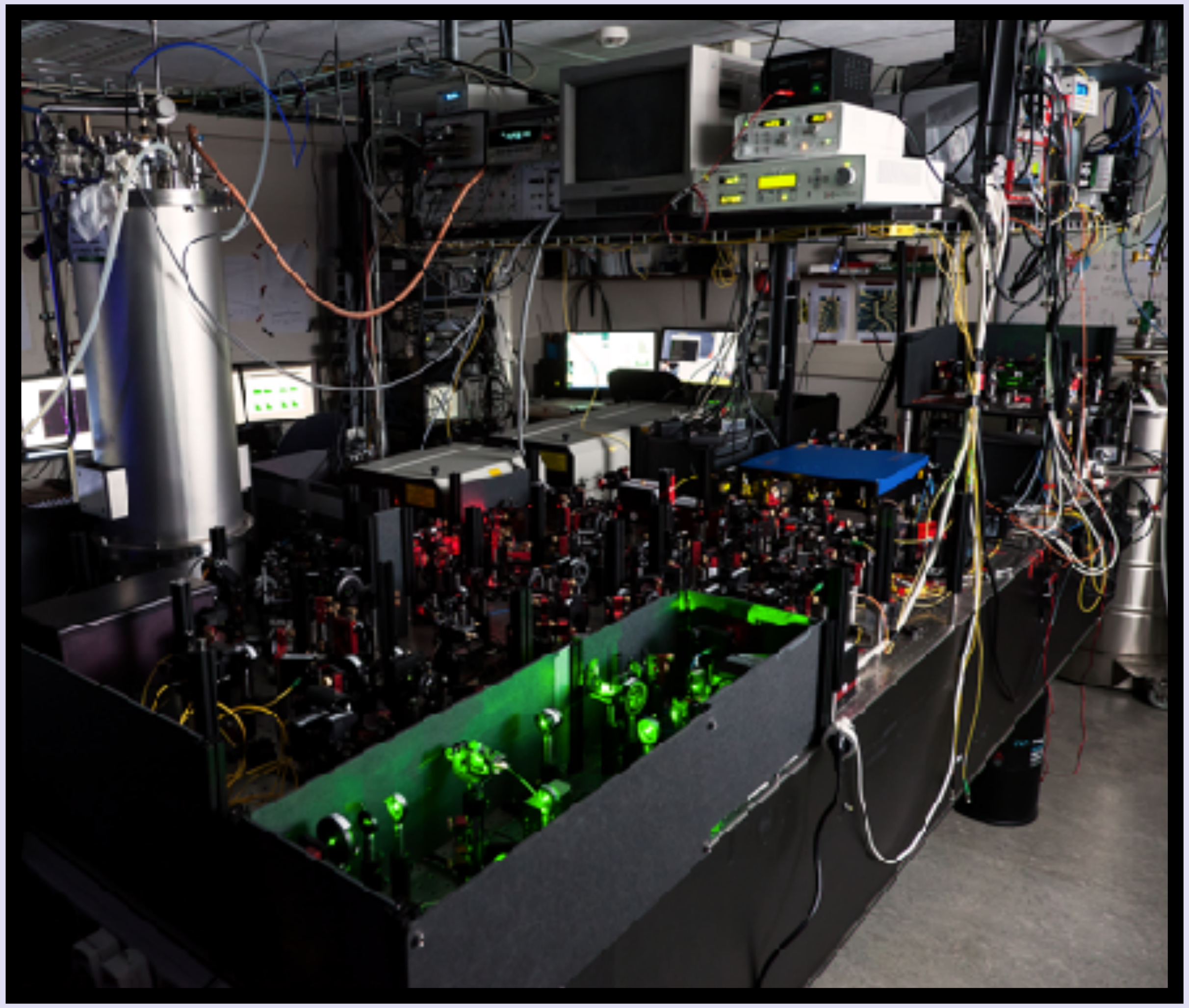


Microfabricated surface traps using standard techniques

(3) Optical Control

??

Current Control Systems - Bulk Optics



Easy to Implement

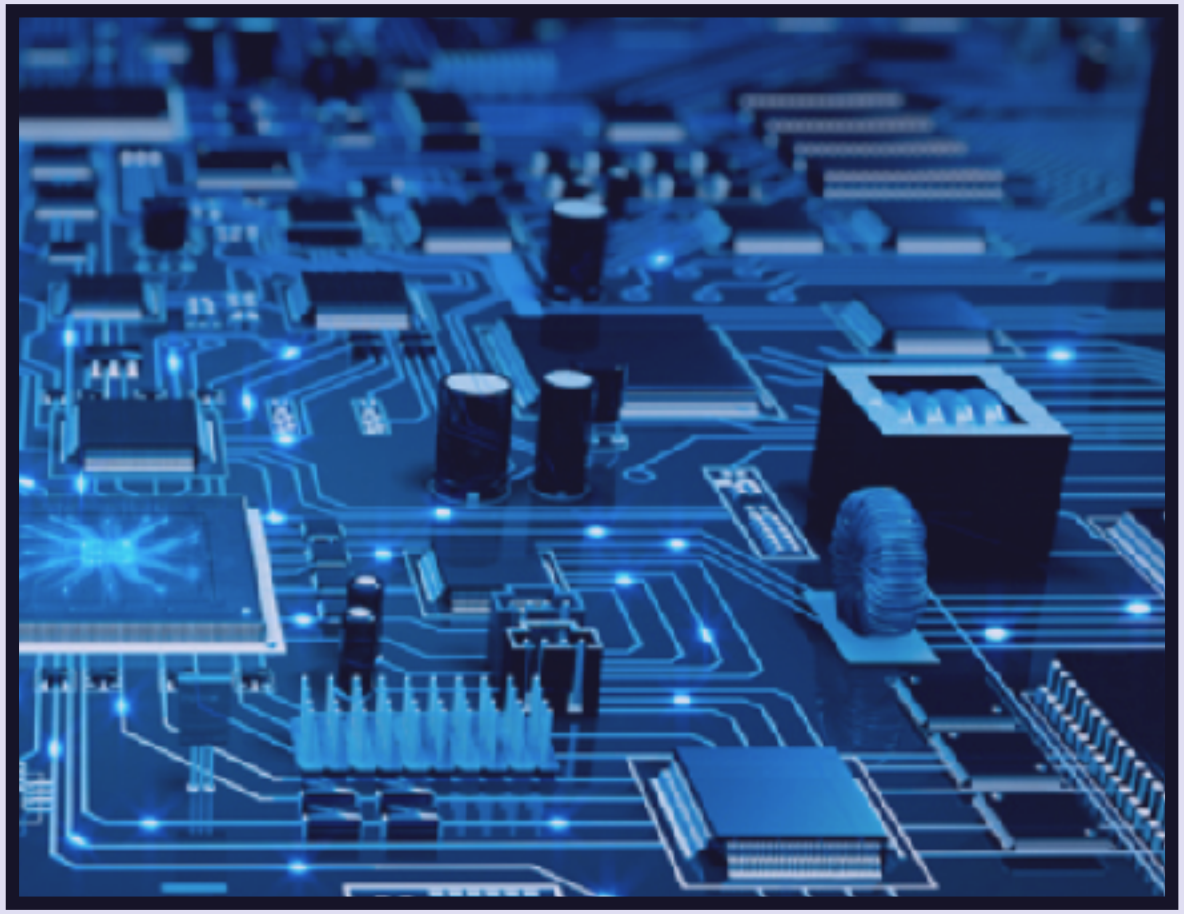
Well Understood

Bulky

Heavy

Unstable

Next Gen. Control Systems - Integrated Optics



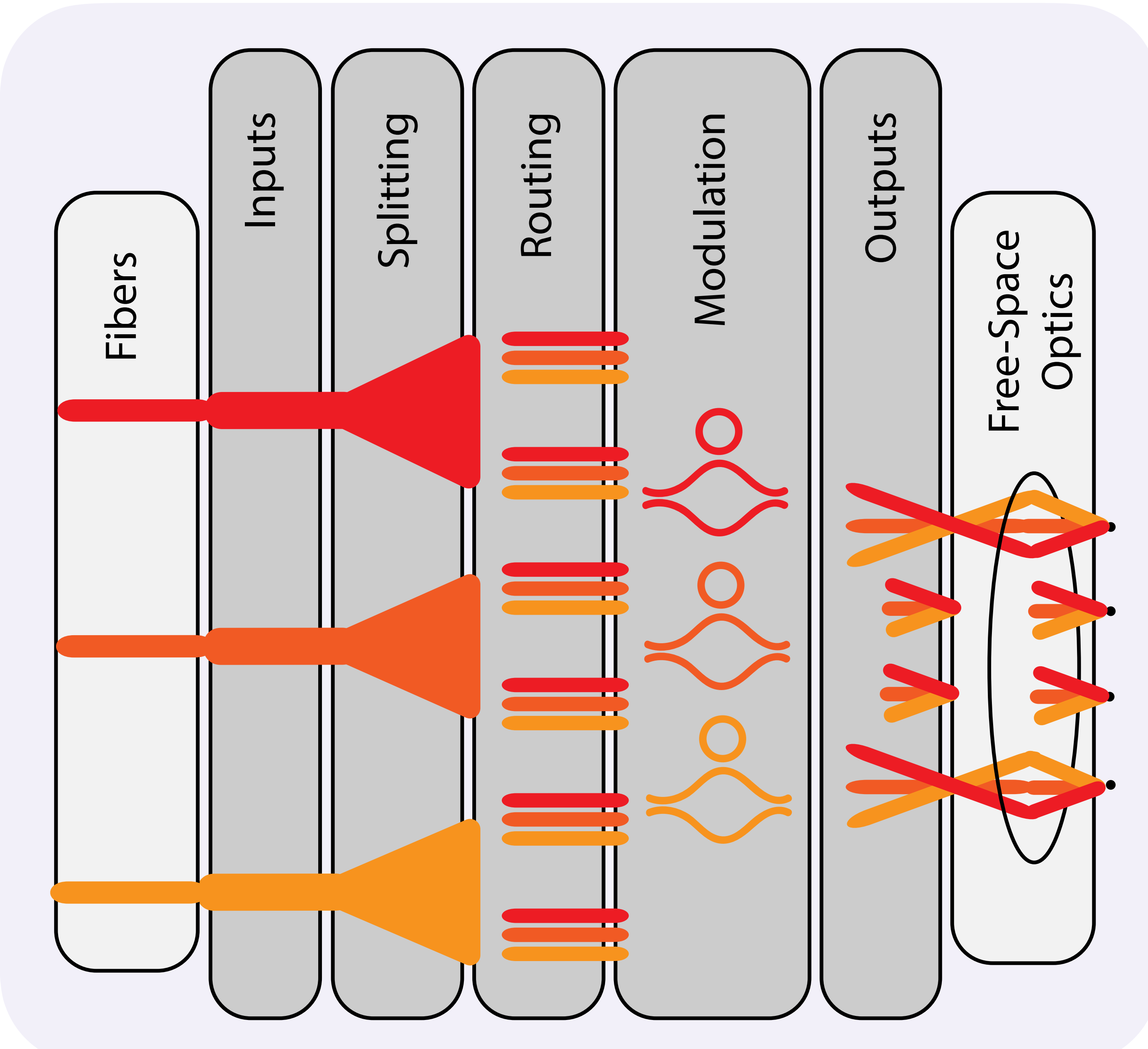
Large Engineering Challenge

Compact

Stable

Scalable

Trapped Ions -Scalability



Components

Low-loss Input

Splitting to *M* channels

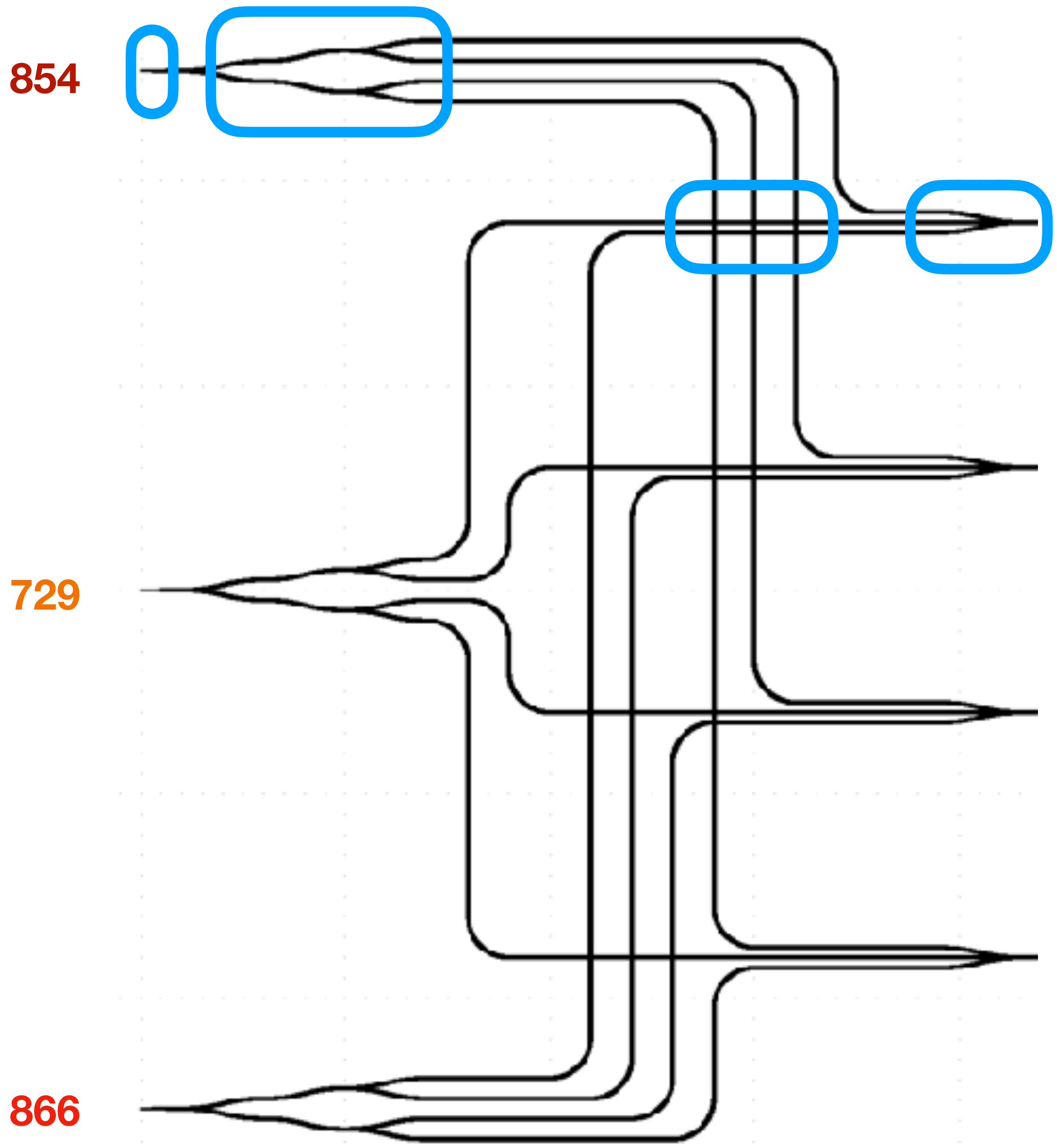
Active Amplitude, Phase, and Frequency Control

Waveguide Crossings

Multi-Wavelength Merging

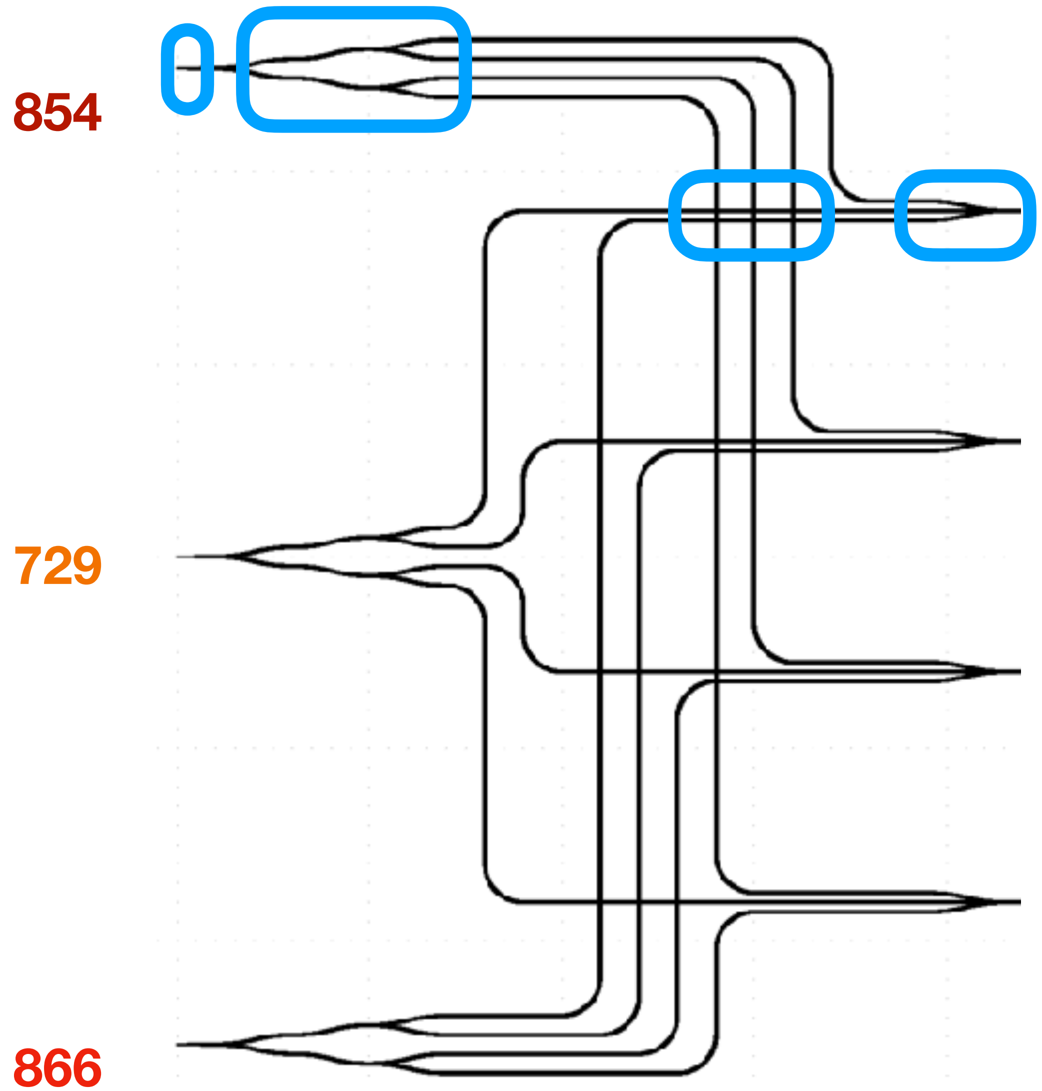
Output Imaging

Integrated Large-Scale Trapped Ion Sensor



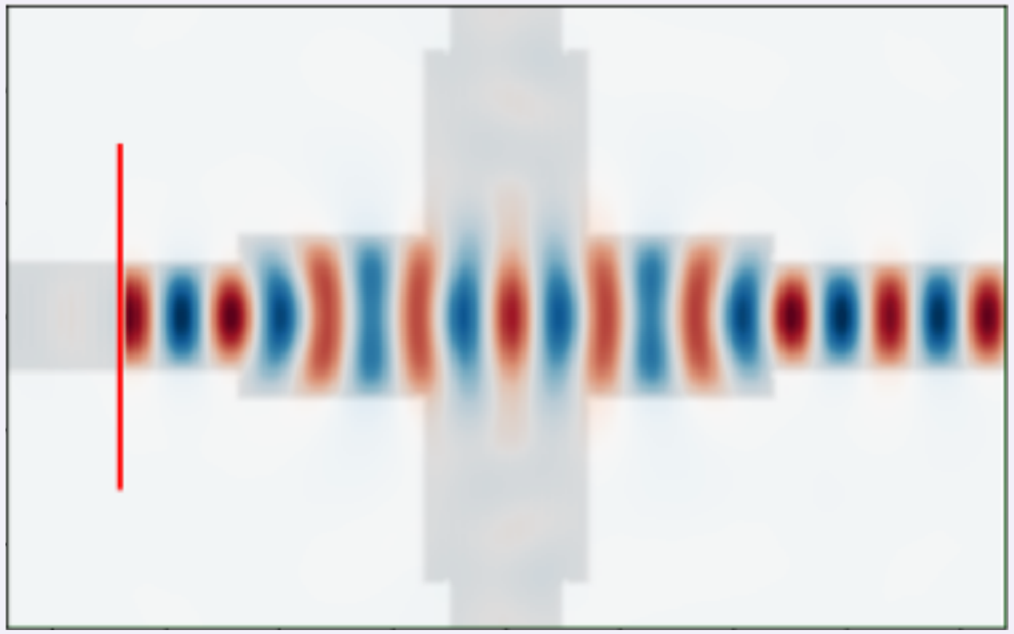
All sensors controlled in parallel, so don't need on-chip active control.

Integrated Large-Scale Trapped Ion Sensor



All components must be optimized:

e.g. Waveguide Crossings

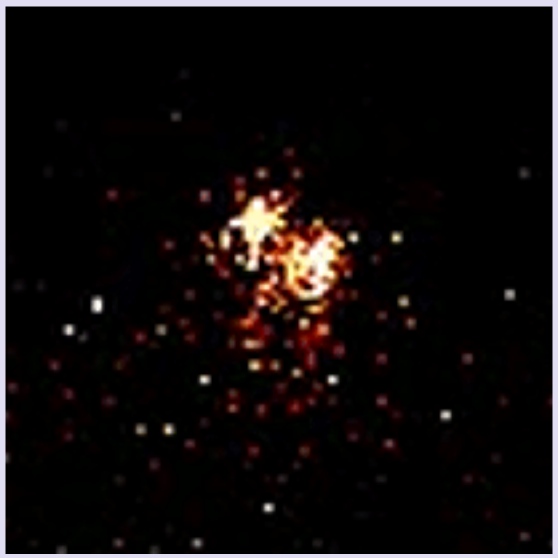


e.g. waveguide crossings

96.8% efficiency
0.3% cross-talk

Trapped Ions - Review

A great qubit allowing for state-of-the-art coherent control



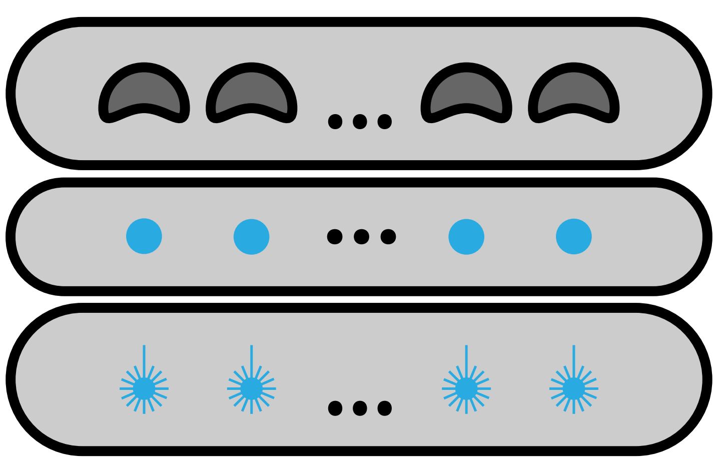
Next Steps:

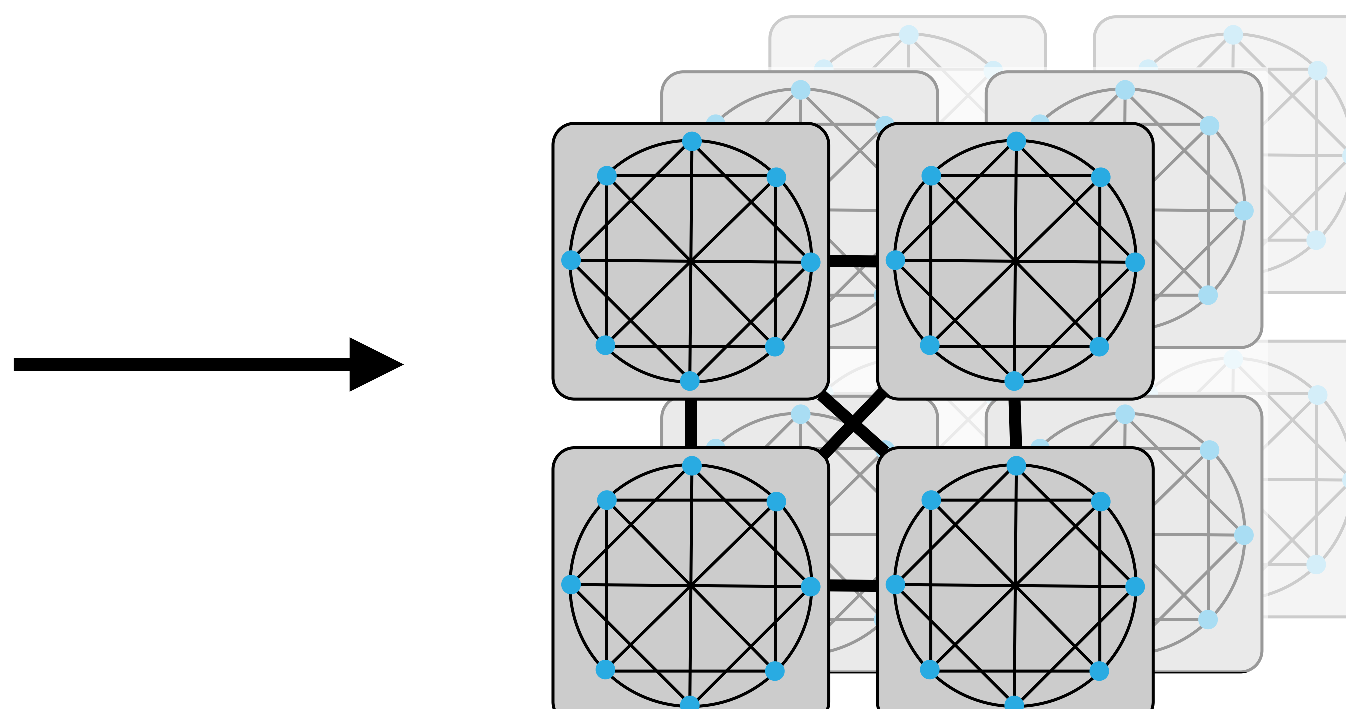
Passive integrated photonics for a large-scale sensor

Integrated Amplitude + Phase control

Integrated Frequency control

Improved detection





Thank you!

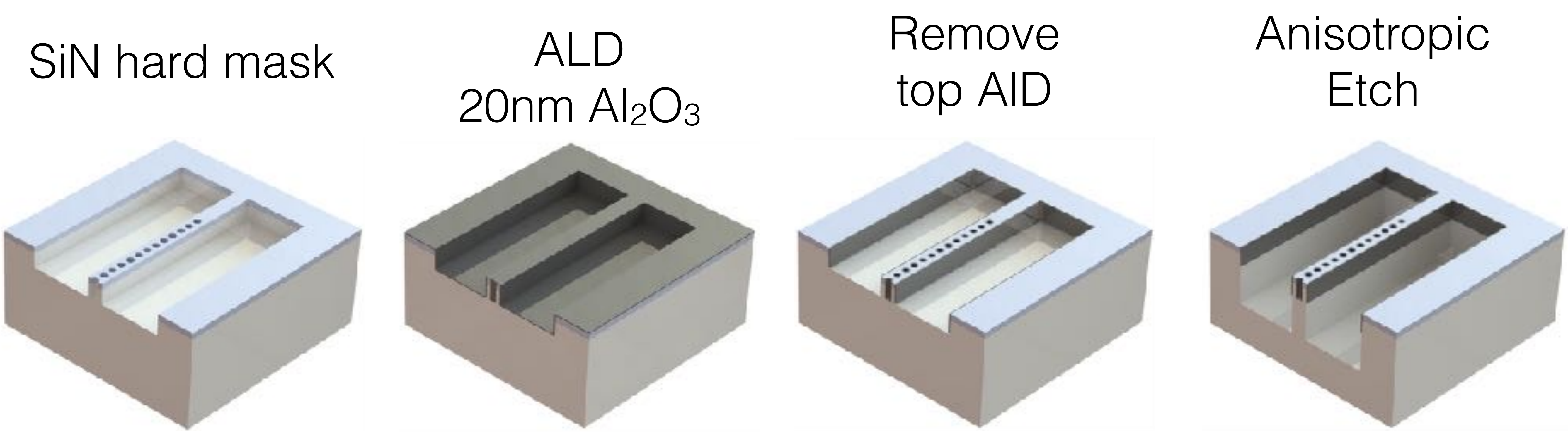
Ion Collaborators
Prof. Hartmut Haeffner
Prof. Alex Retzker
Neil Glikin
Dr. Eli Megidish
Kai-Isaak Ellers

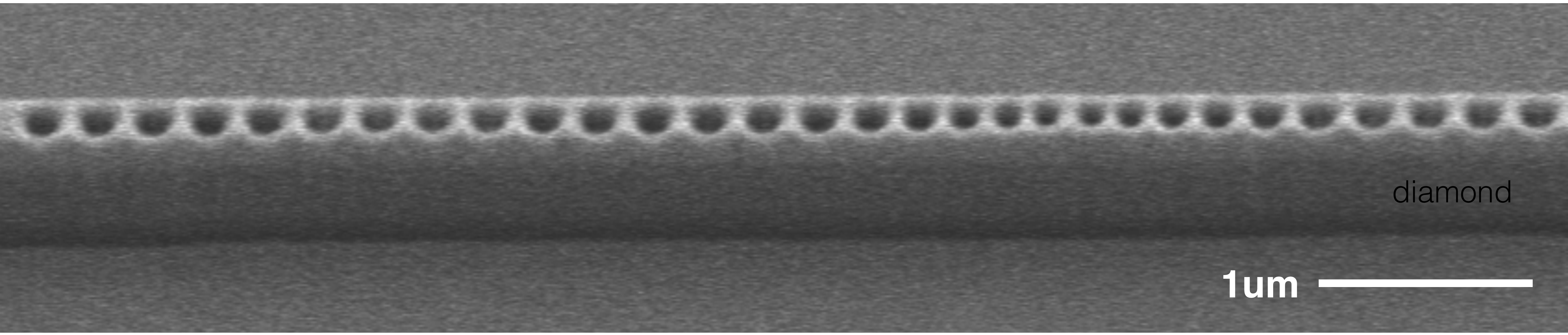
NV Collaborators
Prof. Dirk Englund
Prof. Tim Schroeder
Dr. Noel Wan
Dr. Michael Walsh
Eric Bersin

Funding
IC Postdoctoral Fellowship

This research was supported by an appointment to the Intelligence Community Postdoctoral Research Fellowship Program at UC Berkeley, administered by Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the Office of the Director of National Intelligence.

Fabrication in Diamond





Mouradian et al. APL vol 111 (2017)