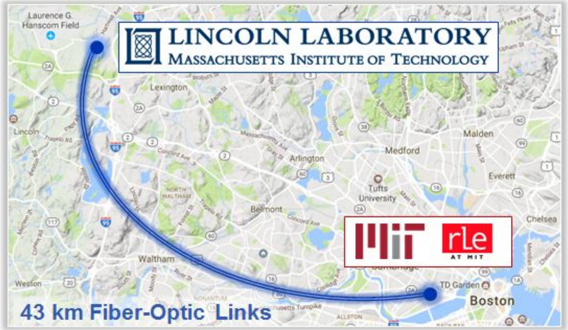
Large-Scale Quantum Photonics for Computing and Communications

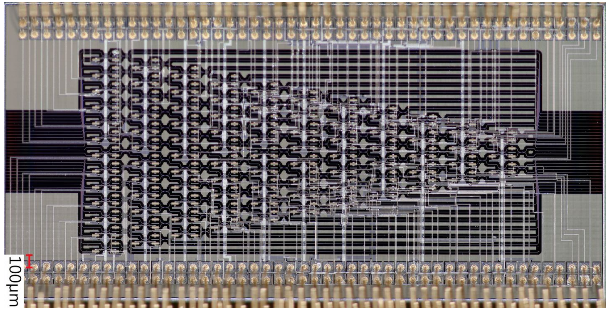
Dirk Englund | Electrical Engineering and Computer Science, MIT

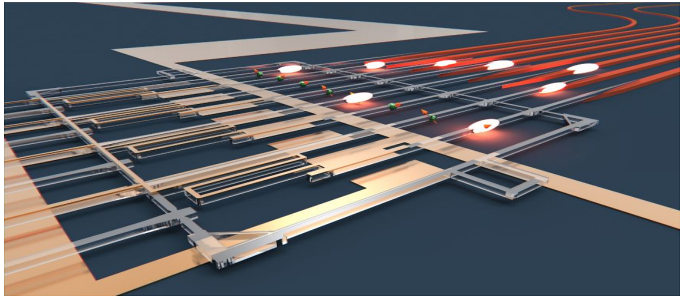
Photonics for Quantum | 7/17/2020

Postdoc positions available in **theory** and **experiment**

See qplab.mit.edu



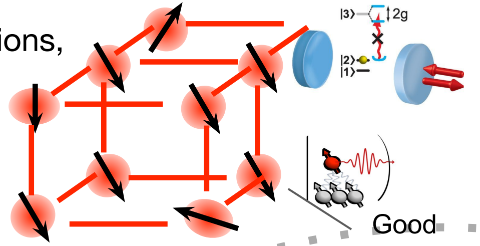




The need for scalable photonic control

Quantum networks: Atomic qubits, assisted by lossy photonic qubits

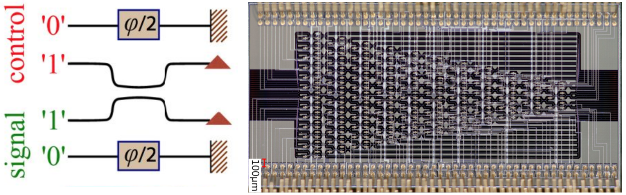
→ communications, computing



Good atomic memories

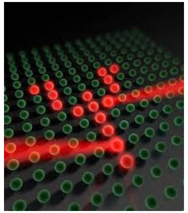
Photonic qubits (lossy)

Photonic qubits, assisted by atoms or bulk nonlinearities

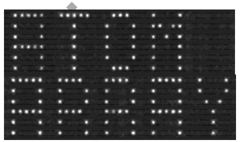


Matter-assisted 2-photon gates

Rydberg gates controlled by semiclassical light fields



I. Bloch, MPQ



Lukin, Vuletic, Greiner

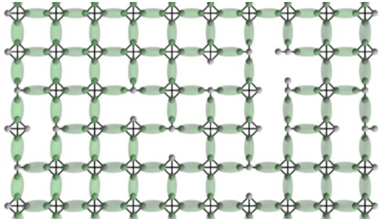
Cold atom lattices

Algorithms

Photonic control

Photonic circuits + electronics control

Measurement-based gates



All-photonic

Acknowledgements

MIT Quantum Photonics Group :

PhD: Noel Wan, Michael Walsh, Eric Bersin, Tsung-Ju Lu, Donggyu Kim (--> QuEra), Saumil Bandyopadhyay, Chris Foy, Mohammad Ibrahim, Kevin Chen, Ian Christen, Isaac Harris, Nick Harris (--> LightMatter), Darius Bunandar (--> LightMatter), Mihika Prabhu, Uttara Chakraborty

Postdocs: Tim Schroeder (->Humboldt-Universität Berlin), Matt Trusheim, Lorenzo De Santis, Jacques Carolan, Mikkel Heuck

Collaborators:

MIT: Karl Berggren, Ruonan Han

Harvard: Mikhail Lukin, Marko Loncar, Prineha Narang

Delft QuTech: R. Hanson, T. Taminiau

Cambridge U: Mete Atature

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MIT Lincoln Laboratory: Danielle Braje, Scott Hamilton, Ben Dixon, Matt Grein, Ryan Murphy

U. of Arizona: Saikat Guha

Stanford: David A.B. Miller

Rochester Institute of Technology: Stefan Preble

Oak Ridge NL: Stephen Jesse

Sandia NL: M Eichenfield

Funding

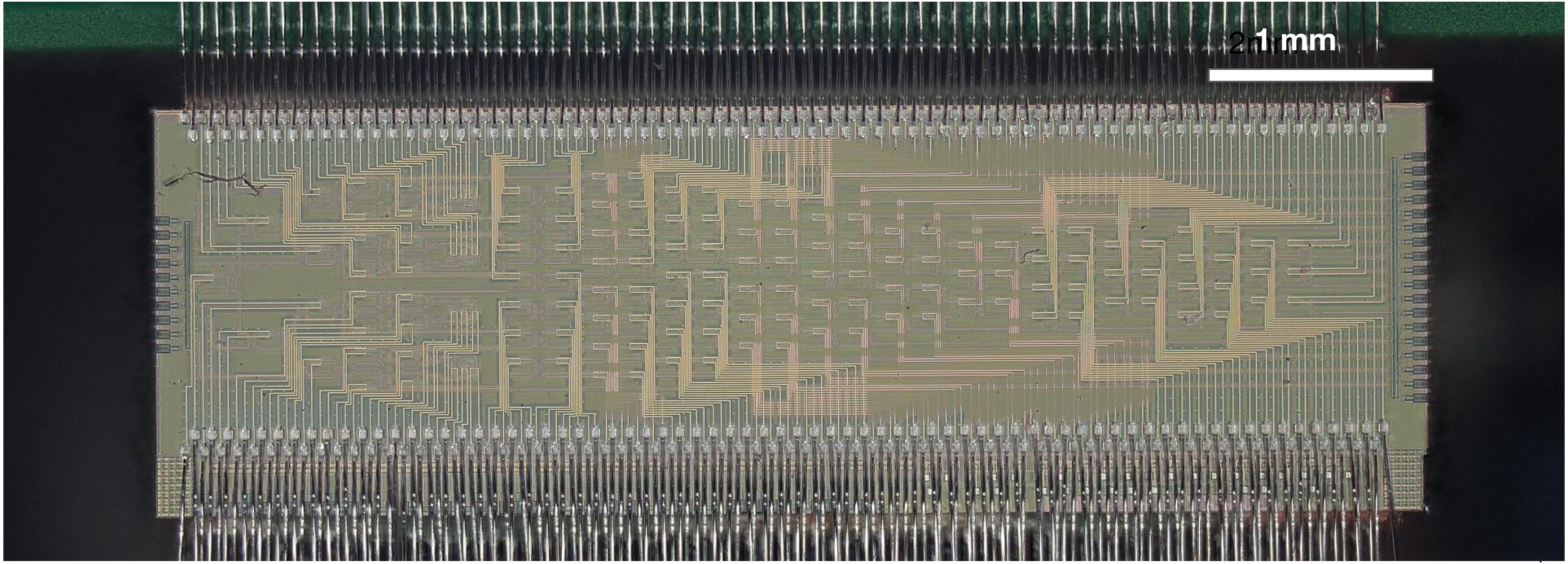
Outline

QUANTUM PHOTONICS

Photonic Integrated Circuits

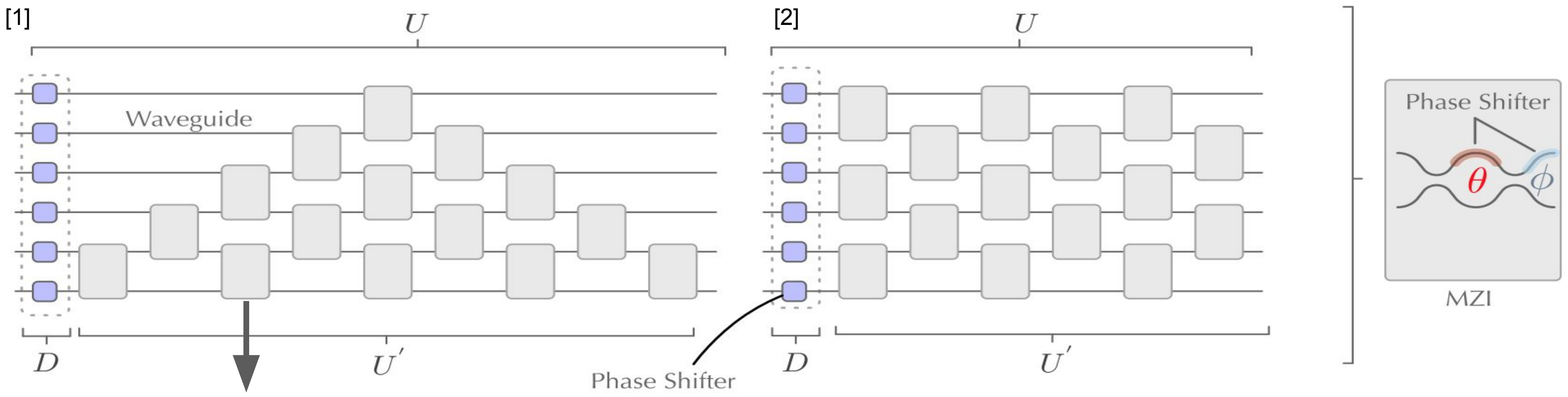
+ Atomic quantum memories

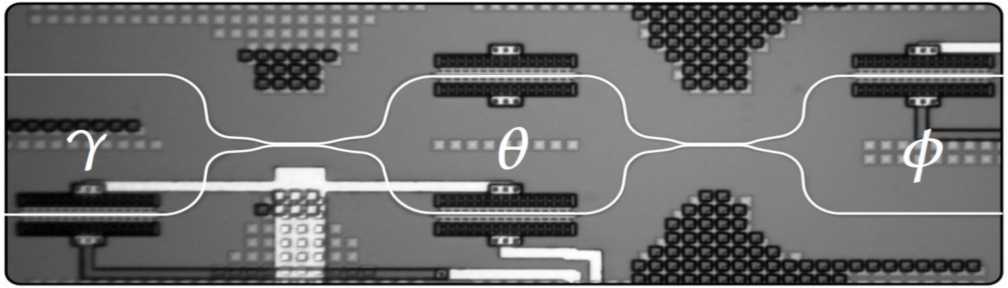
⇒ Scaling Quantum Systems



Programmable Linear Optics

Any linear-optics unitary transformation between input and output modes by SU(2) MZI transformations [1-4]

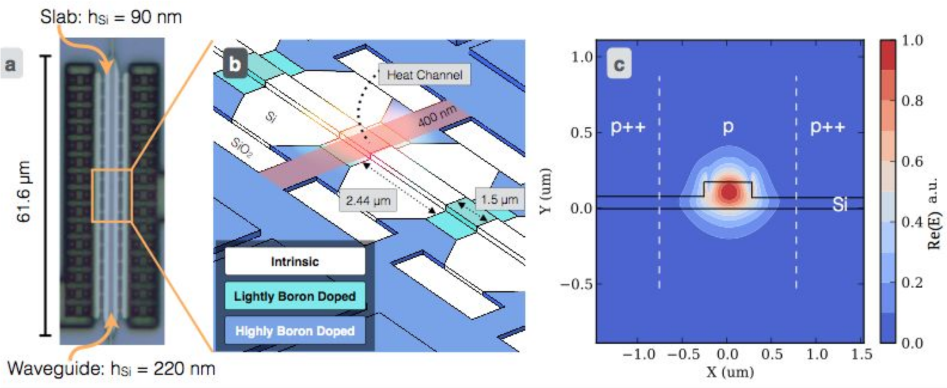


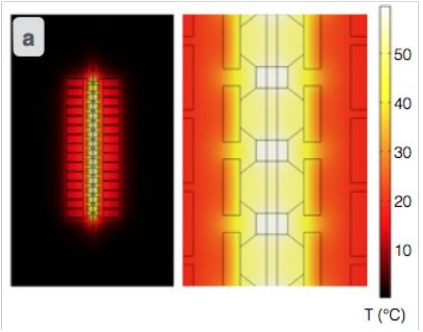


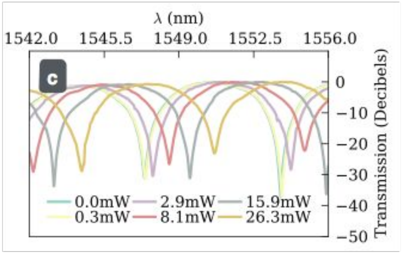
[1] M. Reck et al, PRL 73 (1994). [2] D.A.B. Miller, Opt.Express 5 (2013); D. A. B. Miller, “Applied Optics: Sorting out Light.” Science 347 (2015)
[3] W. Clemens et al, Optica **3** (2016)
[4] J. Mower, G. Steinbrecher, N. Harris et al, Phys. Rev. A 92, 032322 (2015)

Modulators

Thermal



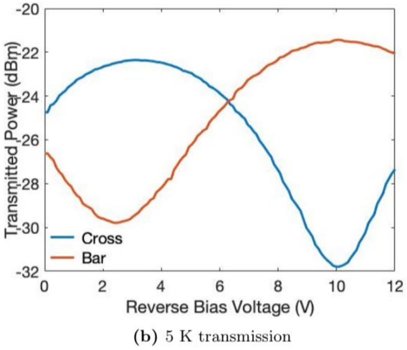




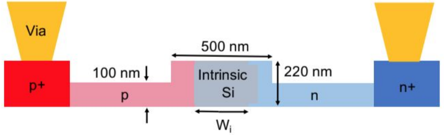
insertion loss as low as ~0.1 dB

Nicholas C. Harris et al, Optics Express, **22**, 9 (2014)

5K EO modulation in silicon

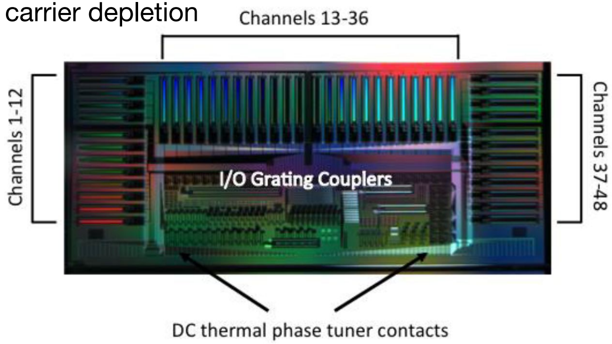


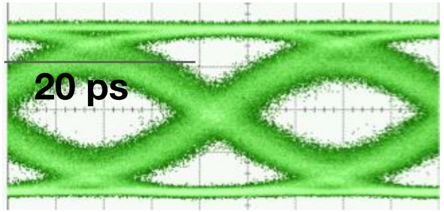
E-field induced pockels



U. Chakraborty et al, to be submitted (2020)

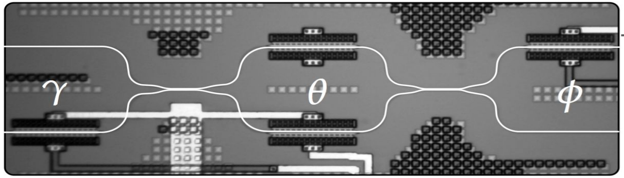
Free carrier depletion

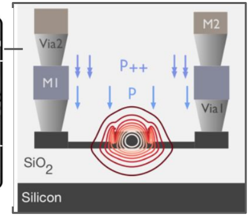


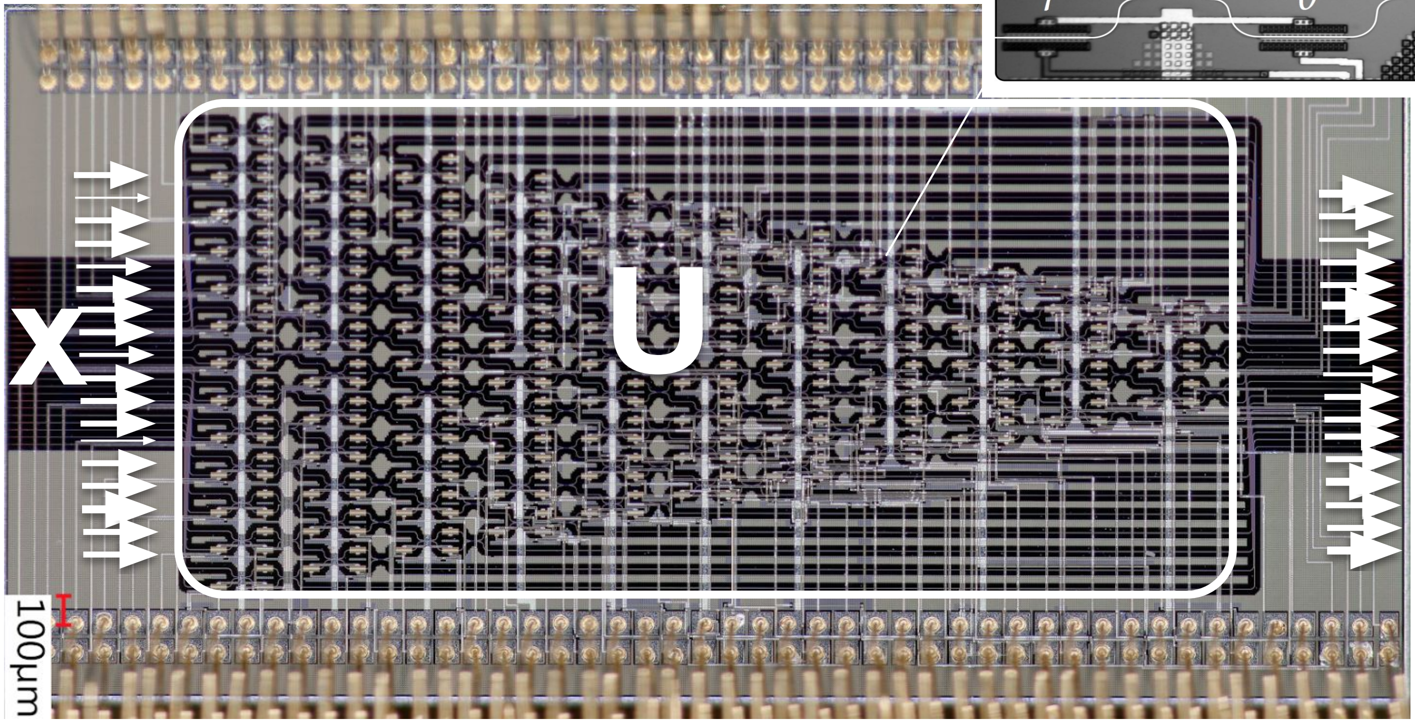


R. Davis et al, in preparation

Programmable Linear Optics







88 MZIs, 26 input modes, 26 output modes, 176 phase shifters

1. Quantum transport simulations: N. Harris et al, Nature Photonics **11** (2017)
2. Y. Shen*, N. C. Harris*, et al [with M Soljacic, MIT], Nature Photon **11** (2017). * equal authors
   a. See also D.A.B.M Miller, “Sorting out Light” , Science **347** (2017)
3. Review: Nicholas Harris et al, Optica **5** (2018)

OPSIS Foundry

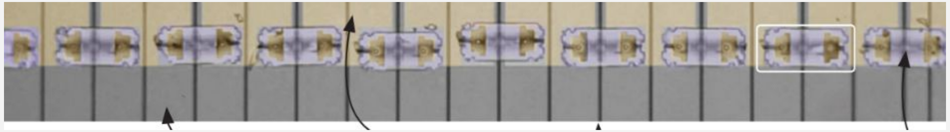
Collaborators: Michael Hochberg, Michael Fanto, Paul Alsing (AFRL), Stefan Preble (RIT), Philip Walther (U. Vienna)

Very Large System Integration PICs

Hardware

Experimental:

- Programmable PICs: modulators, detectors, passives..
- Atomic memories
- Superconducting single photon det. (w/ K. Berggren)[F] Najafi, J Mower, et al, Nature Comm **6** (2015), D. Zhu, et al, Nat. Nano., **13**, (2018)



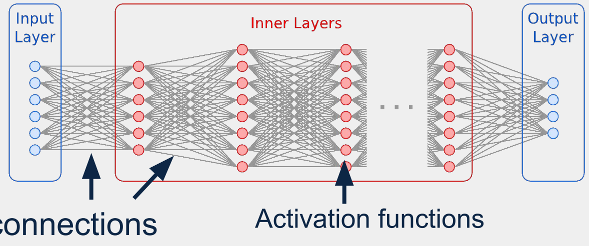
- $\chi^{(3)}$ - entangled pair sources w/ integrated filters J. Carolan et al, Optica **3** (2019)
- Single microwave (<50 GHz) detection G. H. Lee … D.E., K.C. Fong, Arxiv:1909.05413 (2019) - to appear in Nature (2020)

Proposals:

- Photon-photon logic by $\chi^{(3)}$ M. Heuck, K. Jacobs, D.E. PRL **124** (2020)
- High-fidelity on-demand single photon sources: M. Heuck, M Pant, D.E., NJP **20** (2018)
- Photonic logic qubit & gate S. Krastanov et al - ArXiv 2002.07193 (2020)
- Room-temp single photon detection C. Panuski et al, PRB 99

Applications

Machine learning accelerators



Proof of concept Y. Shen*, N. C. Harris*, et al [w/ M Soljacic, MIT], Nature Photon **11** (2017)

Neural network computing below the thermodynamic limit R Hamerly, A Sludds, L Bernstein, M Soljacic, and D Englund, PRX 9 (2019)

Quantum optical neural networks G. Steinbrecher et al, NPJ Quantum Information Processing 5 (2019)

Quantum optical neural networks G. Steinbrecher et al, NPJ Quantum Information Processing 5 (2019)

Learning quantum circuits J. Carolan et al., Nature Physics **16** (2020)

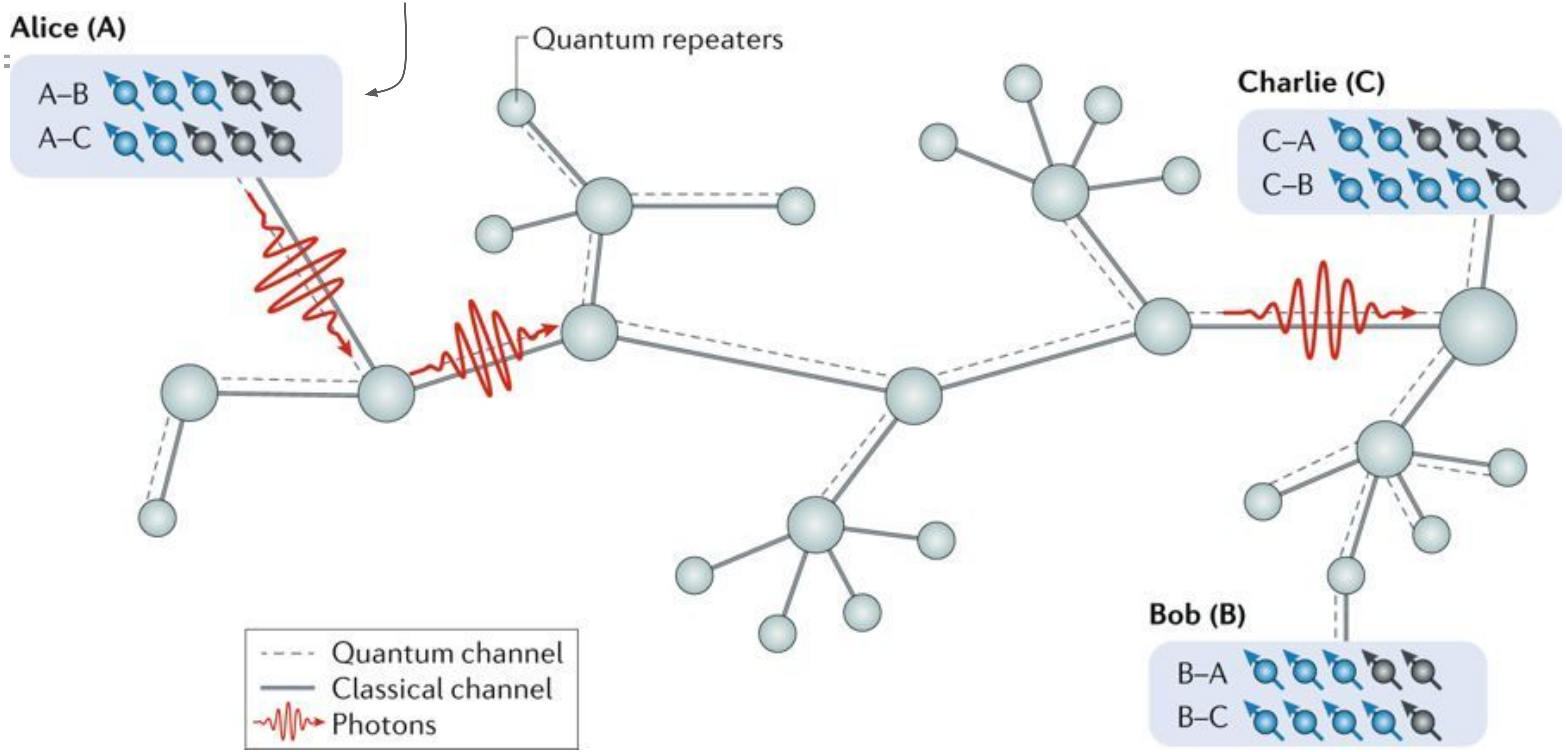
Quantum networks & quantum computing

Outline

Photonic Integrated Circuits

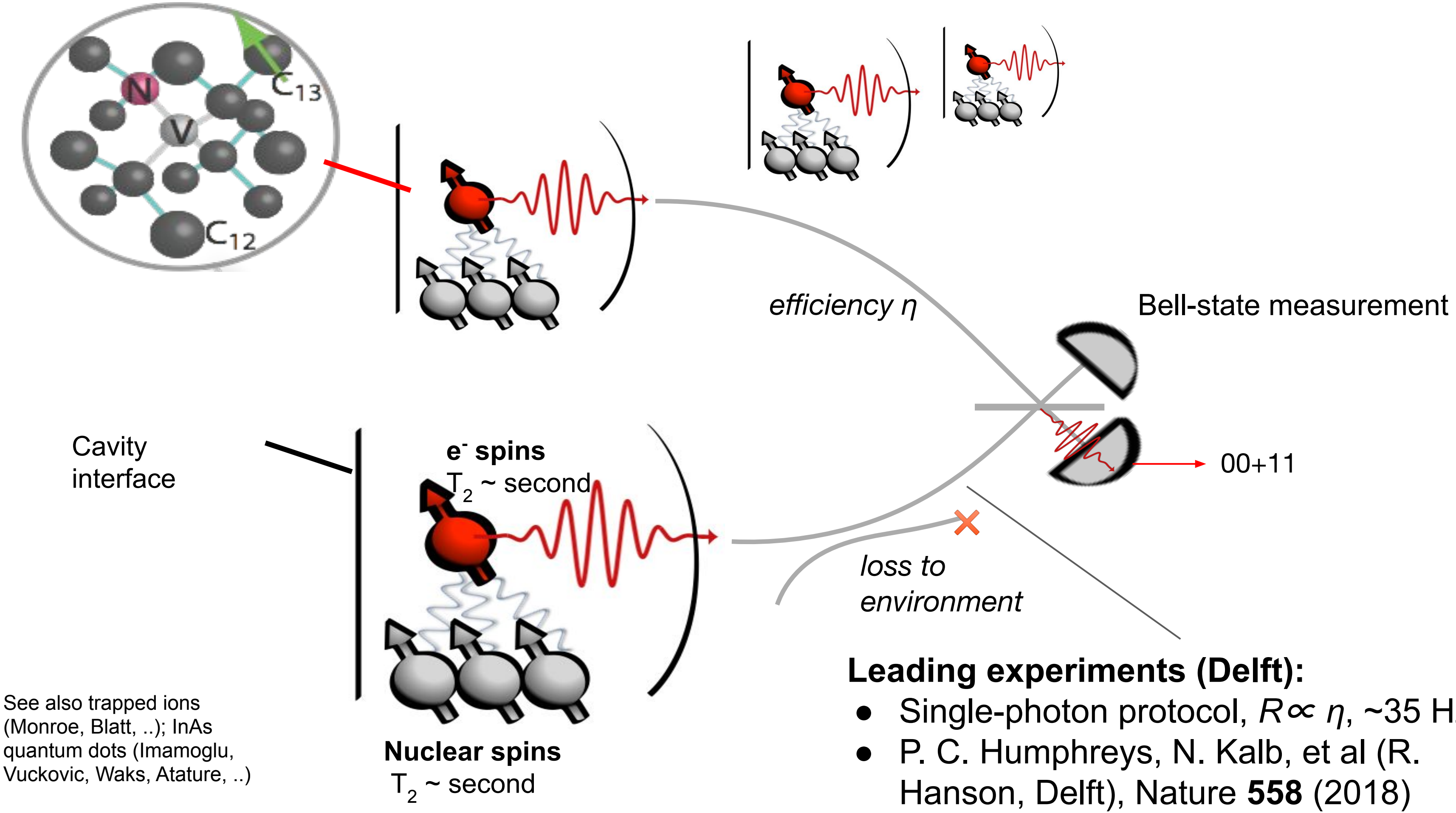
Repeaters being developed using solid state spins[Delft, MIT, Harvard, Caltech, Stanford, Cambridge, Stuttgart, ..], neutral atoms[MQP, Harvard, ..], trapped ions[Innsbruck, UMD,..], ..

\+ Atomic quantum memories



Atatüre, Englund, Vamivakas, Lee, Wrachtrup: Nature Reviews Materials (2018); See also S Wehner, D Elkouss, R Hanson, Science (2018)

Quantum networks with diamond NV centers

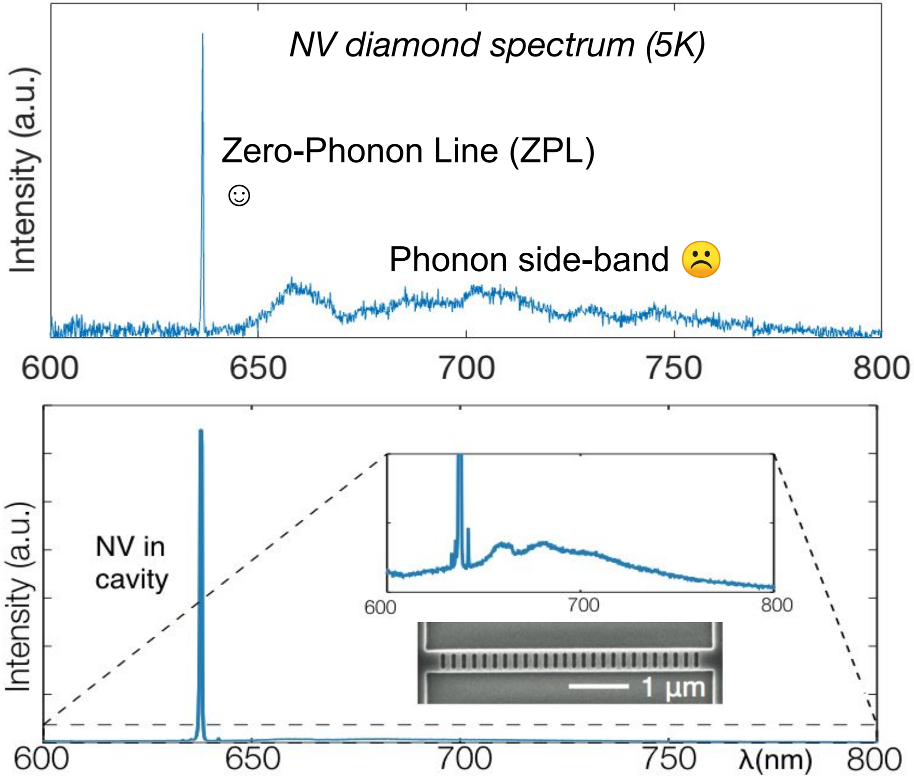


See also trapped ions (Monroe, Blatt, ..); InAs quantum dots (Imamoglu, Vuckovic, Waks, Atature, ..)

Leading experiments (Delft):

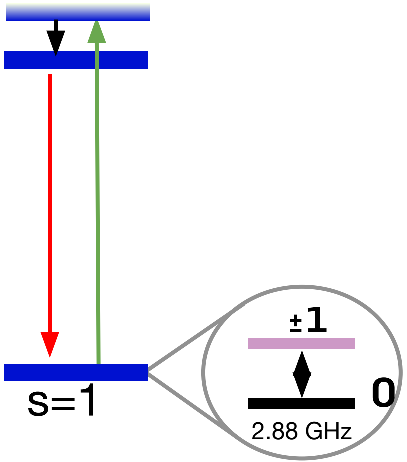
- Single-photon protocol, $R \propto \eta$, ~35 Hz
- P. C. Humphreys, N. Kalb, et al (R. Hanson, Delft), Nature **558** (2018)

"Fixing" the NV



L. Li, T. Schroeder, E. Chen, et al, NCOMM **6**, 6173 (2015)

See also: Harvard, Vienna, Saarland, Delft, HP, Basel

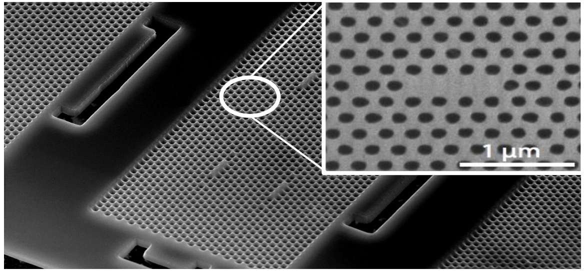


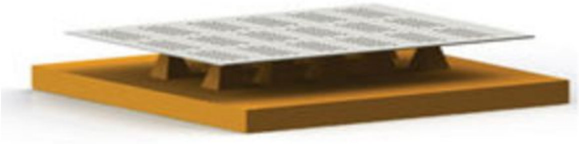
Outstanding challenges:

- Spectral stability
- Photon interfaces
- Device yield

Early NV work: Wrachtrup(U. Stuttgart), Jelezko (Ulm) , Lukin (Harvard), Awschalom (UCSB), Manson (ANU), ..

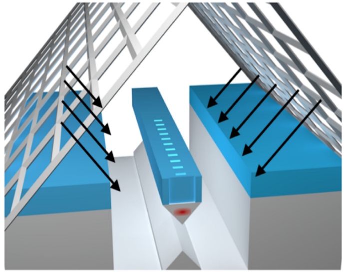
Diamond PhC Patterning





Q < 10,000
NV: λ_{ZPL} ~ 10s GHz

L. Li, T. Schroeder, E. Chen, et al, NCOMM 6, 6173 (2015)



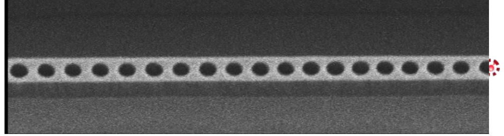
Angular etch (pioneered by Loncar, Harvard)

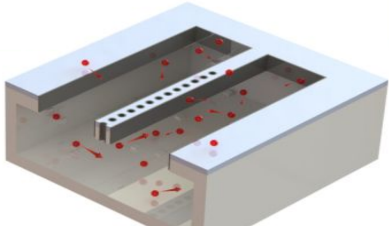
Aligned emitters✔
yielding cavities>10^3

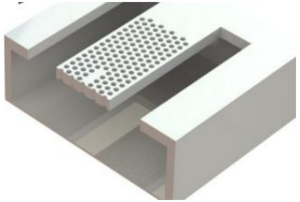
M. Schukraft et al, APL Photonics 1, 020801 (2016)

T. Schroeder et al, Material Optics Express 7, 5 (2017)

I. Bayn et al, Applied Physics Letters 105, 21 (2014)





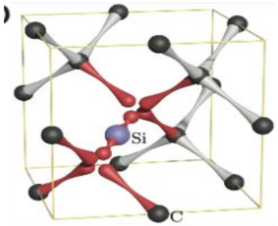


Aligned emitters✔
Chip Size: 4x4 mm✔
yielding cavities>10^4

1D : S. Mouradian, N. Wan et al, APL **111** (2017)
2D: Noel Wan et al, APL **112** (2018)
See early work by P. Barclay

Frequency-stable artificial atoms in diamond

Silicon Vacancy (SiV^-)



Group IV-V centers don't have permanent electric dipole moment →
Stable, narrow ZPL, DWF~0.8. IQE ~ 10 %

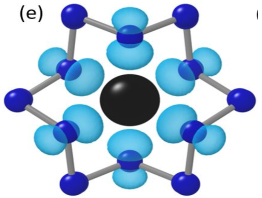
Low temperature (~100 mK): T_2 ~10-ms (Lukin), Becher (Saarbrücken)

Strain can extend coherence time (Loncar, Harvard)

Neutral SiV^0 promising (Nathalie deLeon, Princeton)

SiV in diamond: Saarbrucken (Becher), Ulm (Jelezko), U. Cambridge (Atature), Harvard (Loncar, Lukin), MIT (DE)

GeV^-, SnV^-, PbV^-



PbV center[111]

Stable, narrow ZPL, DWF~0.8. IQE > 50%

Large orbital splitting → possibility of decoupling from phonons

GeV: Nonlinear optics : M. K. Bhaskar et al (Harvard), PRL 118 (2017)

SnV: T. Iwasaki et al, Phys. Rev. Lett. 119, 253601 (2017)

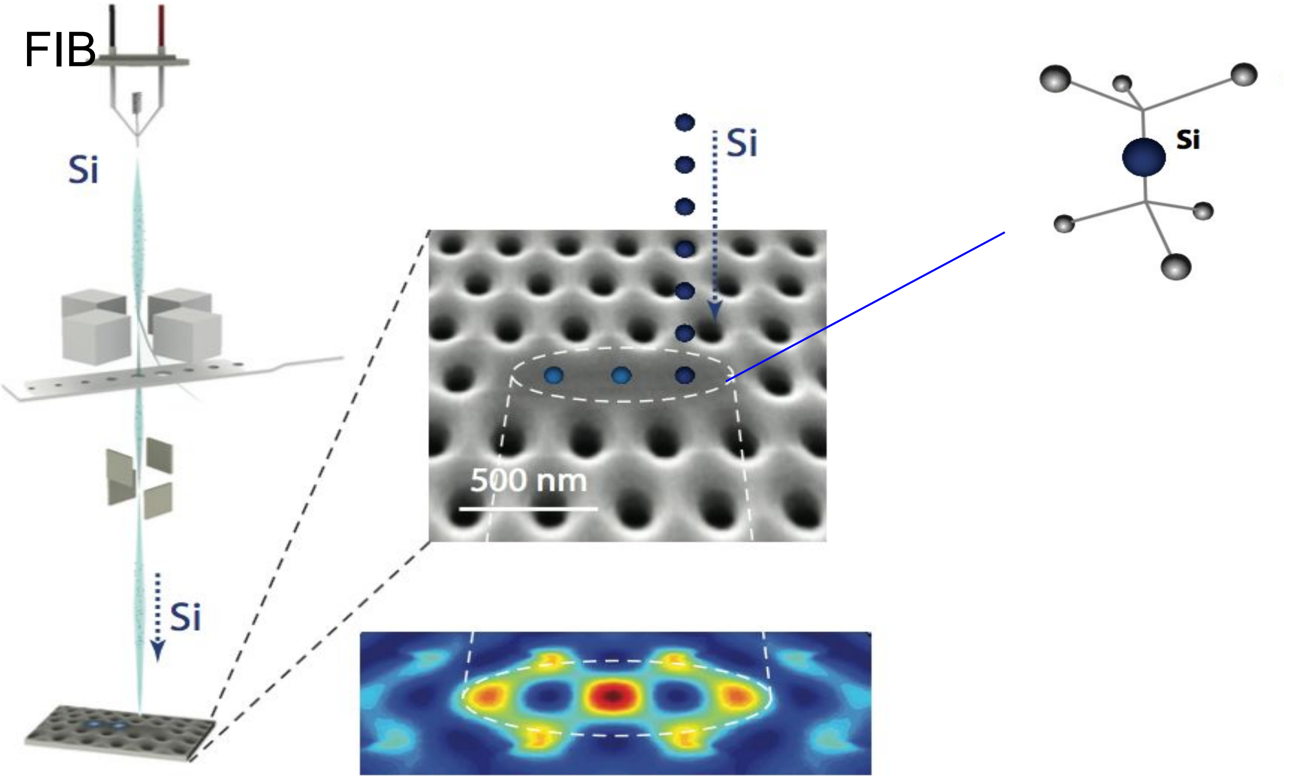
SnV: Observed T_1 > 10 ms at 4 K: "Transform-limited photons from a tin-vacancy spin in diamond," Phys. Rev. Lett.:124, 023602 (2020); A. Rugal et al (Vuckovic), PRB 99 (2019)

PbV: M Trusheim et al [Narang-Englund grps], PRB 99 (2019); D Tchernij et al, ACS Photonics (2019)

III-V centers: electronic spin-1, symmetry-protected optics

* I Harris, C J. Ciccarino, J Flick, DE, & P Narang, arXiv:1907.12548 (2019)

Emitters by ion implantation

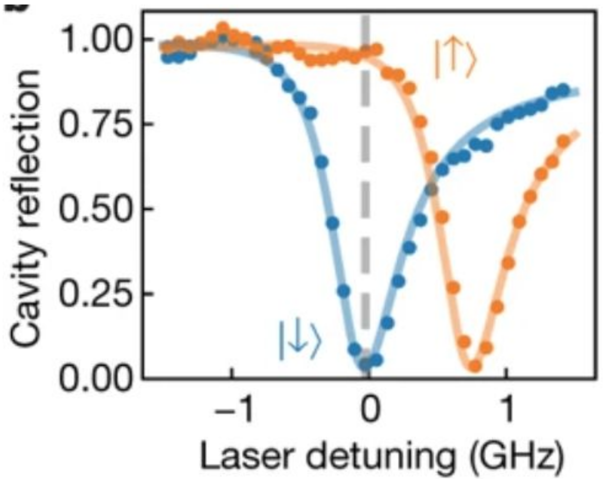


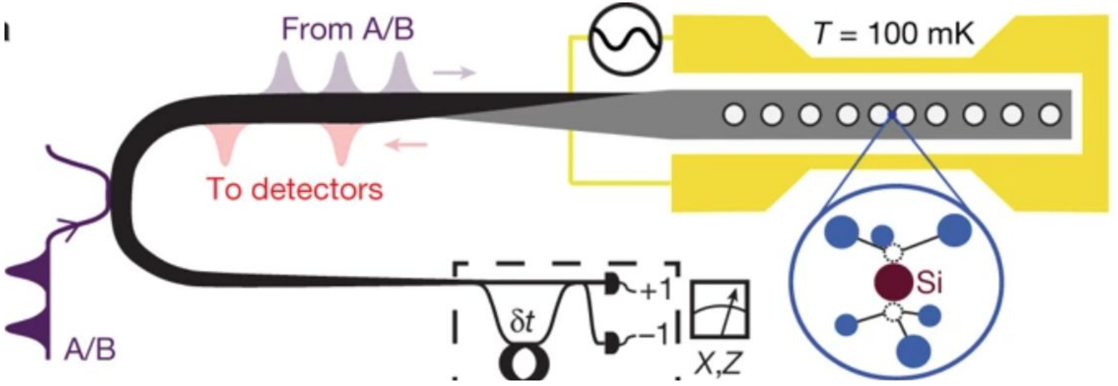
T. Schroeder et al, Nature Communications 8, 15376 (2017)

See also A Sipahigil, Science 354 (2016)

Collaboration with Lukin group (Harvard) and Sandia Nat'l Laboratory

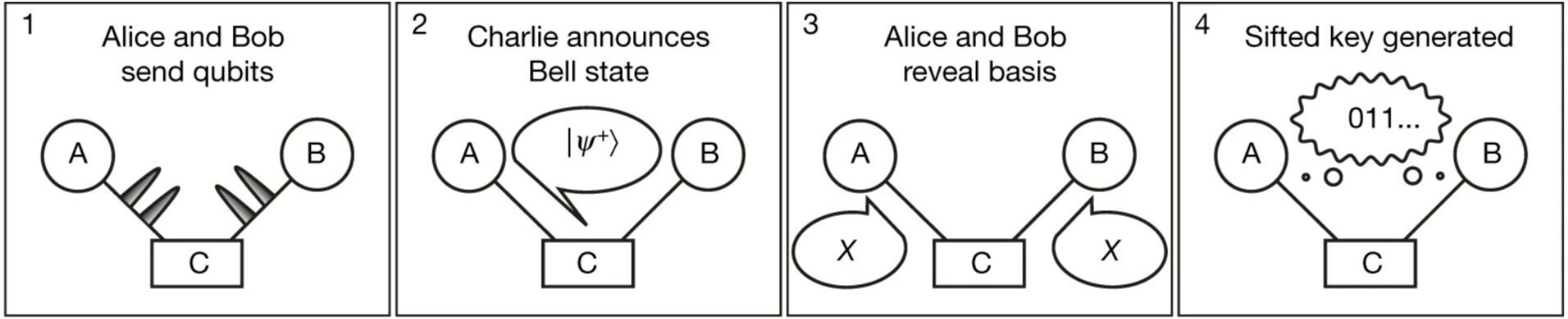
SiV spin-dependent reflection





Spin-photon entanglement by L.-M. Duan & H. J. Kimble, PRL ***92*** *(2004)*

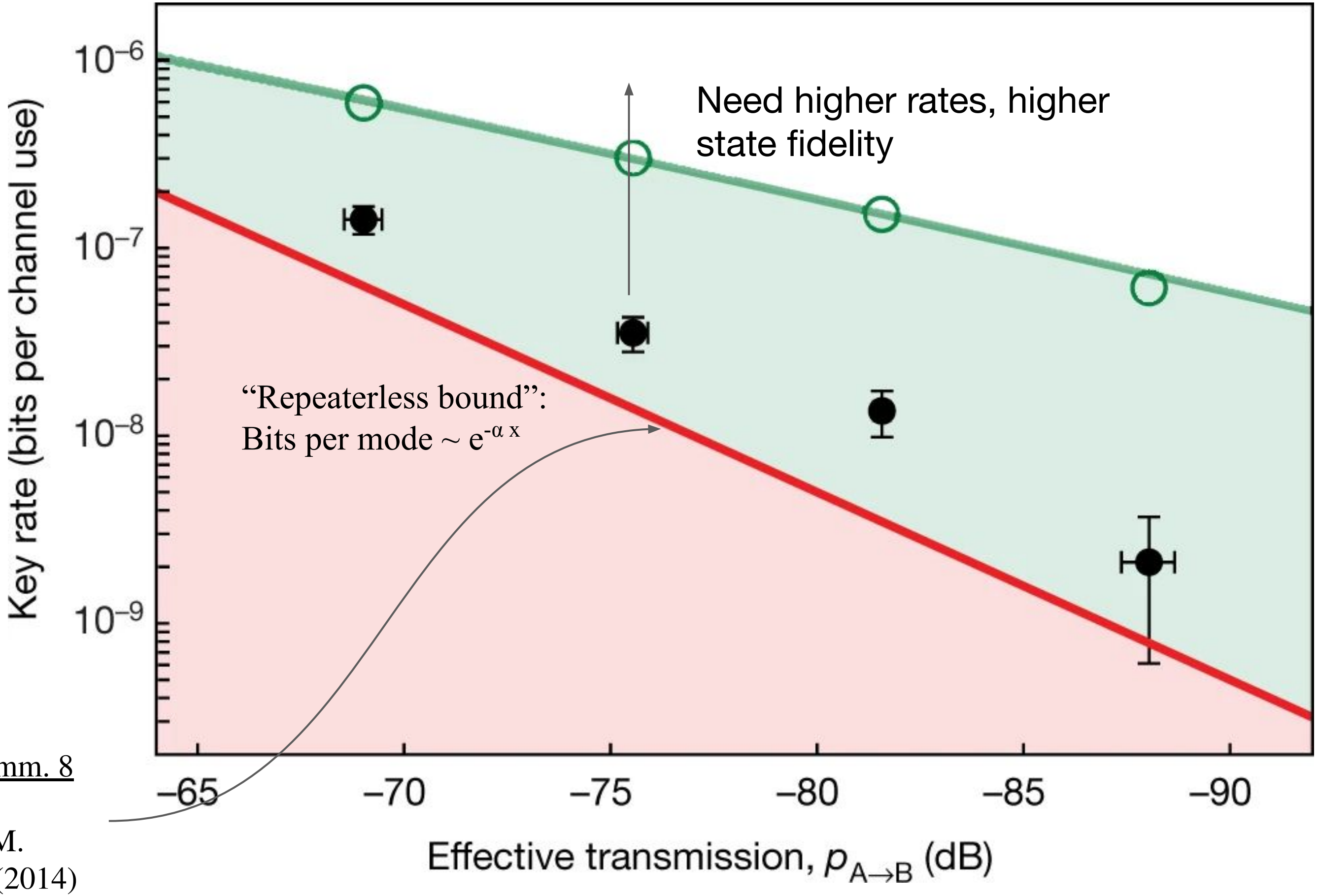
Memory-enhanced measurement-device-independent QKD:



M. Bhaskar, R. Riedinger, et al (Englund, Loncar, M. Lukin), Nature **580**, (2019).

First memory-enhanced quantum communication

QUANTUM PHOTONICS



Stefano Pirandola et al, Nature Comm. 8 (2017)
See also: M. Takeoka, S. Guha & M. Wilde, Nature Communications **5** (2014)

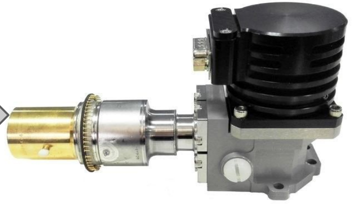
But how do we go from dil fridge to fieldable systems?

$600k, ~ 50 mK

$200k, 800 mK

Packaging & systems
(MIT - Harvard)

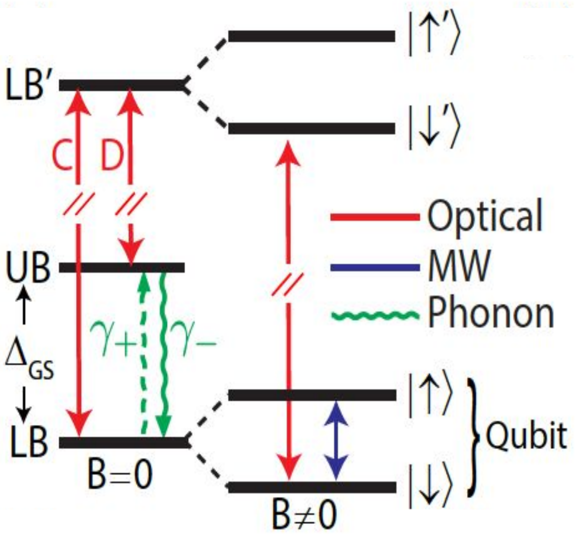
$10k? 10 K



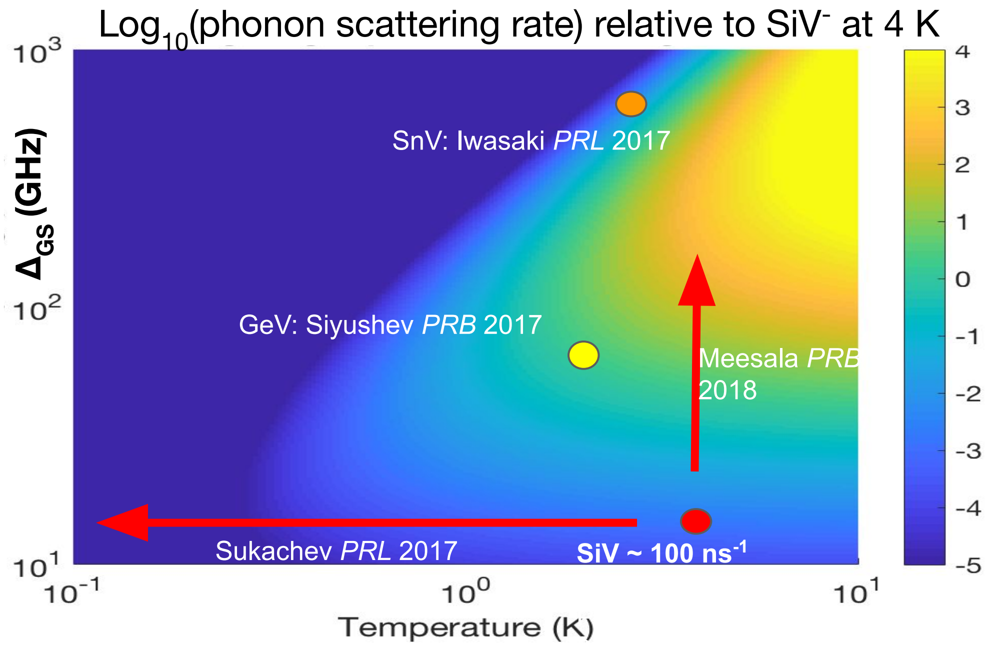
Phonon scattering limits spin coherence

$$\gamma_+ = 2\pi\chi\rho\Delta_{gs}^3 n(\Delta_{gs}, T)$$

- density of states coeff. (ρ)
- Spin-orbit splitting (Δ_{gs})
- Phonon mode occupation (n)
- Acoustic phonon interaction (χ)

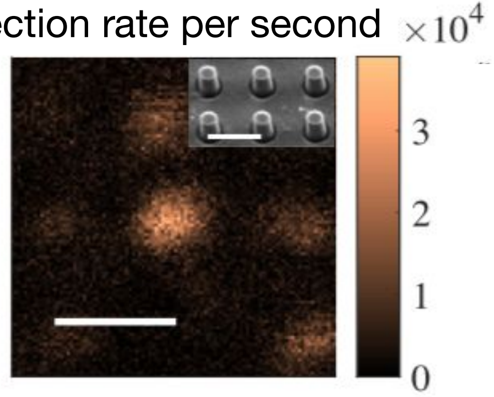


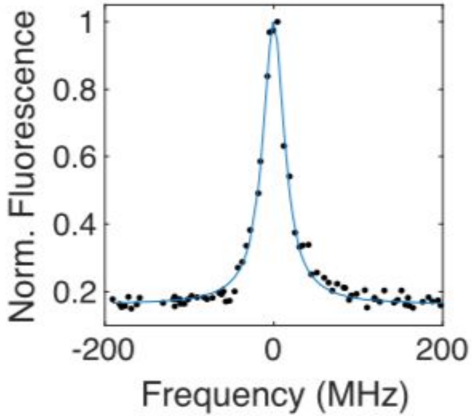
Sukachev *PRL* 2017, Jahnke *NJP* 2014



Tin-vacancy center

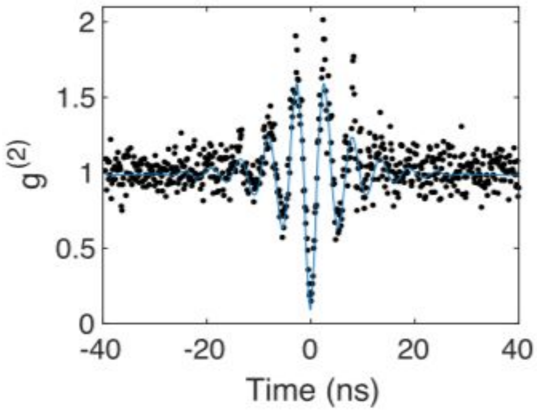
Photon collection rate per second

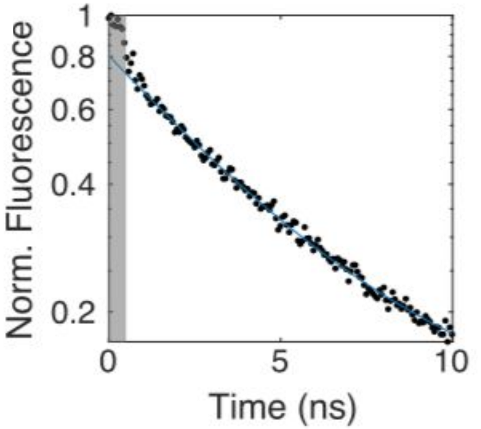




υ_{FHWM} =

30±2 MHz





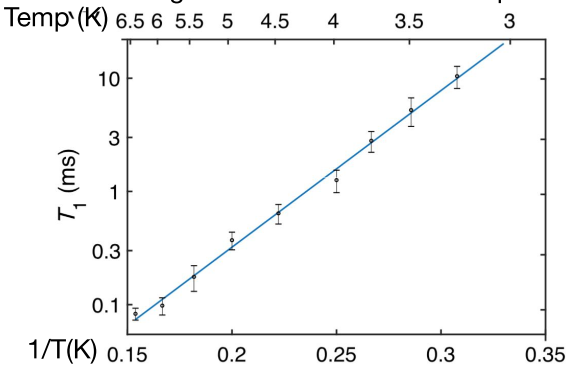
τ = 5.9 ± 0.3 ns

$1/(2\pi\ \tau) = 26.5 \pm 1.5$ MHz

M E. Trusheim, et al (Walmsley - Atature - Englund grps), Transform-limited photons from a tin-vacancy spin in diamond, PRL **124** (2020)
See also A. Rugal et al (Vuckovic), PRB 99 (2019)

SnV center: same group theory model as for SiV^{-*} & more stable spin

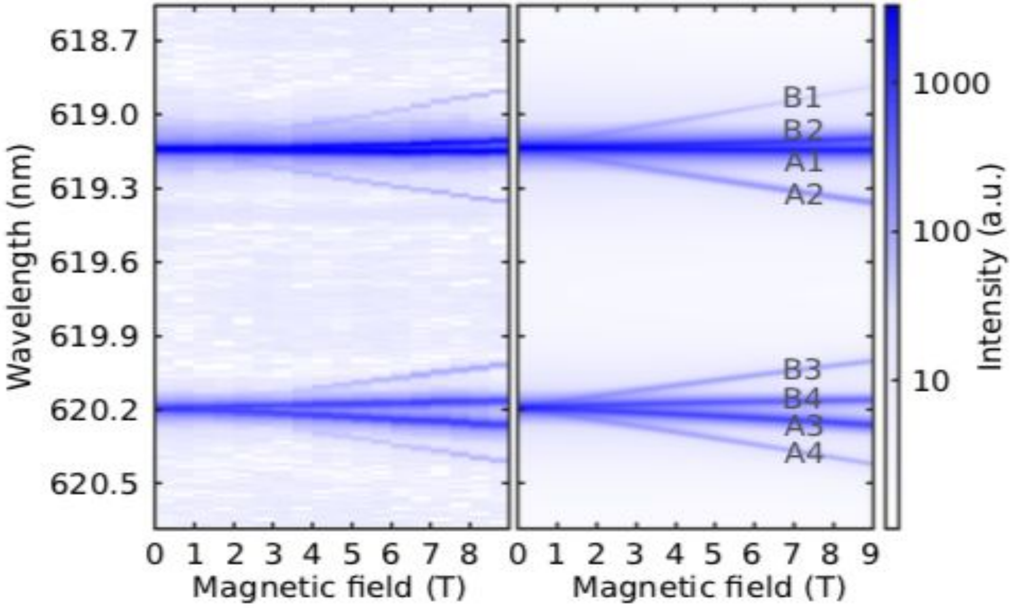
Long coherence at modest temp

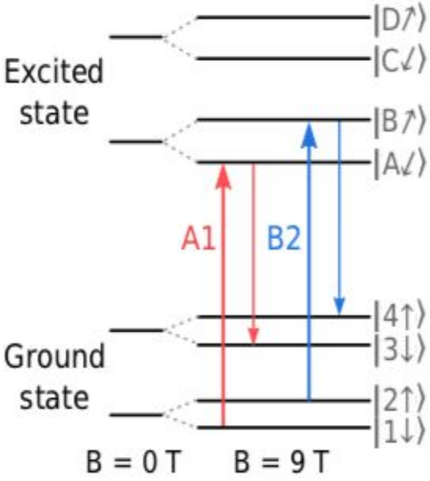


Rate equation model

Experiment

Simulation



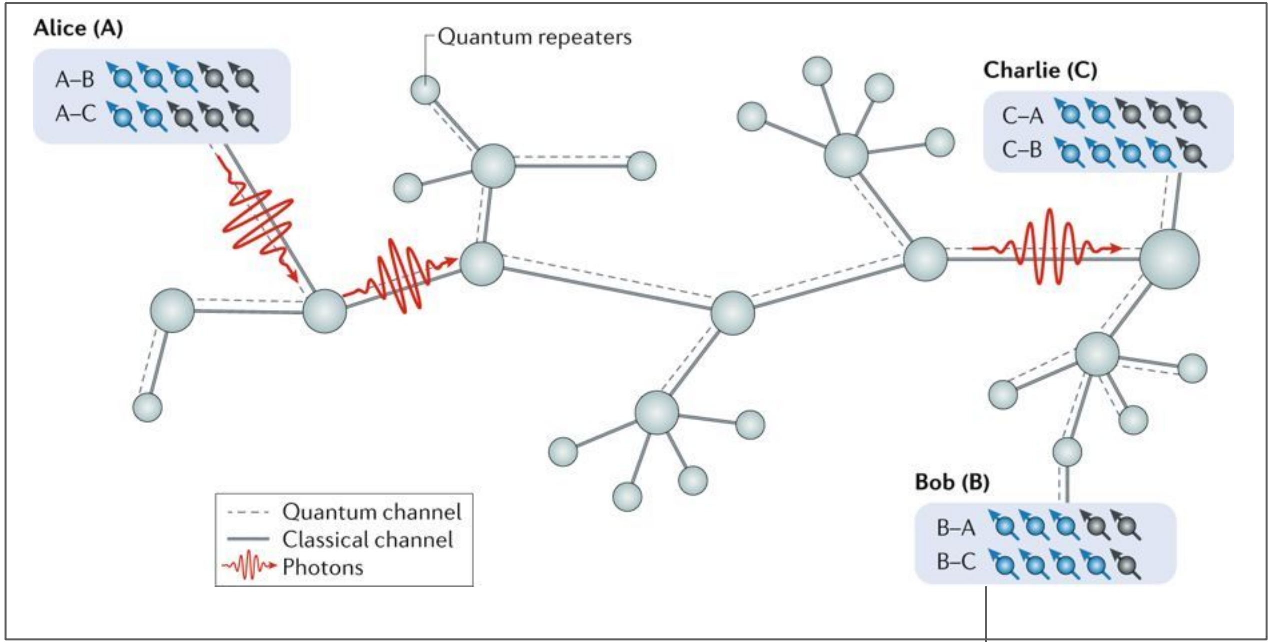


*Jahnke NJP 2014 *T2 measurements in progress

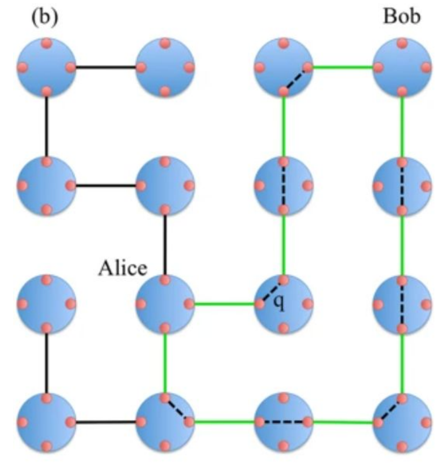
Matthew E. Trusheim*, Benjamin Pingault*, et al (with I. Walmsley & M. Atature), PRL **124** (2020)

Co-Design of quantum network protocols & hardware

Network



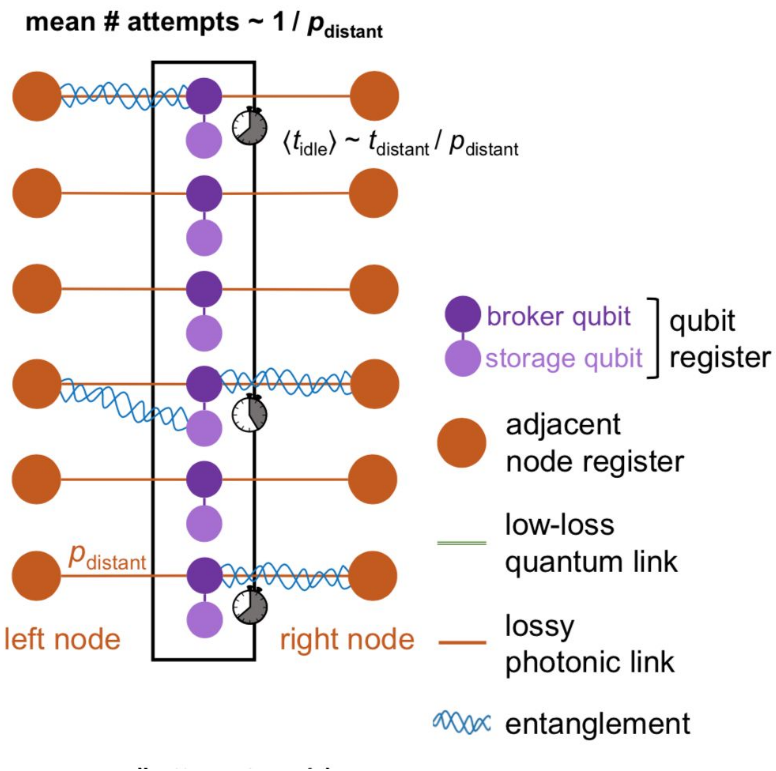
Network management protocols



M Pant, H Krovi, D Towsley, L Tassiulas, L Jiang, P Basu, D Englund, S Guha, NPJ Quantum Information **5** (2019)

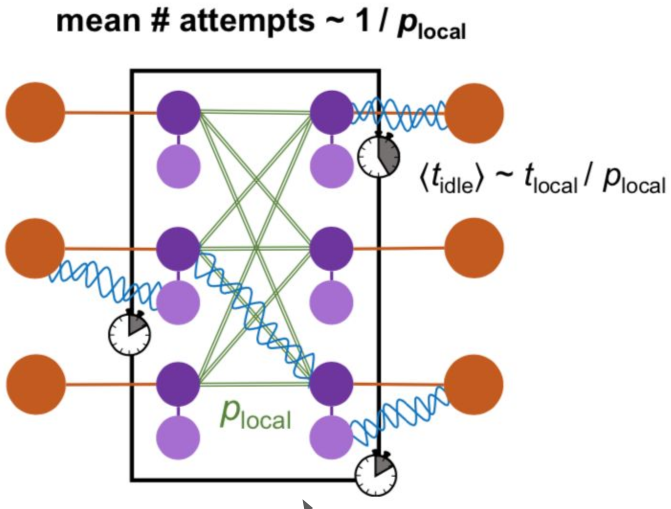
?

Repeater designs



Standard

Same number of qubits, but much less wait time per qubit!

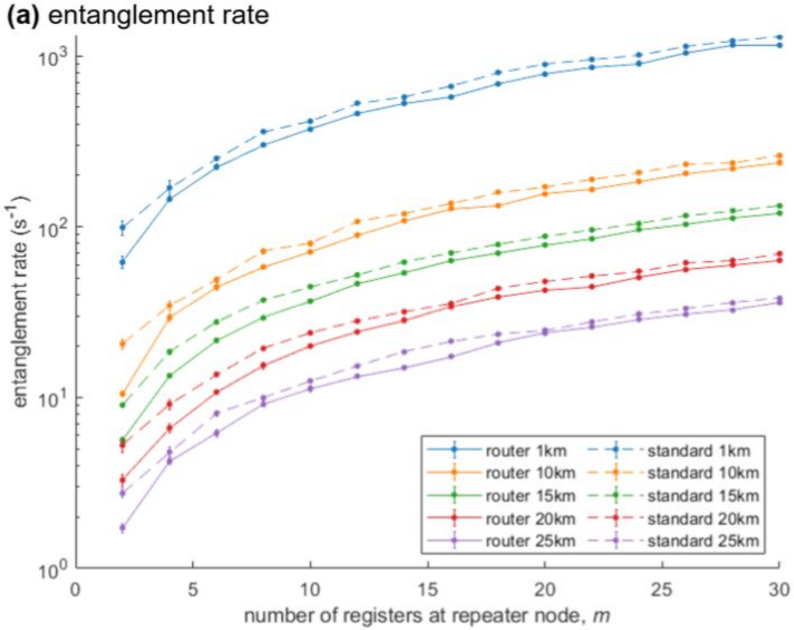


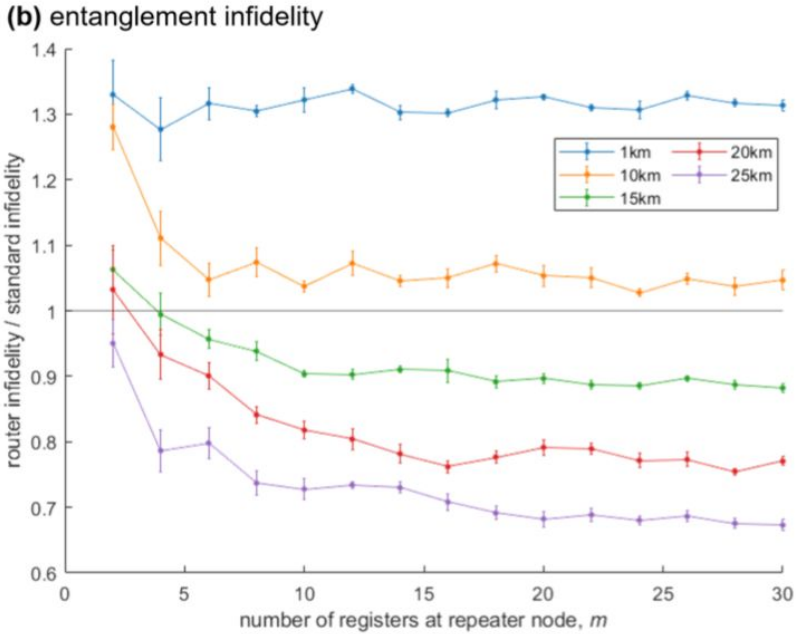
Router design with photonic switchboard

Y Lee, E Bersin, A Dahlberg, S Wehner, D Englund, "A Quantum Router Architecture for High-Fidelity Entanglement Flows in Multi-User Quantum Networks", ArXiv (2020)

Benefits of quantum router

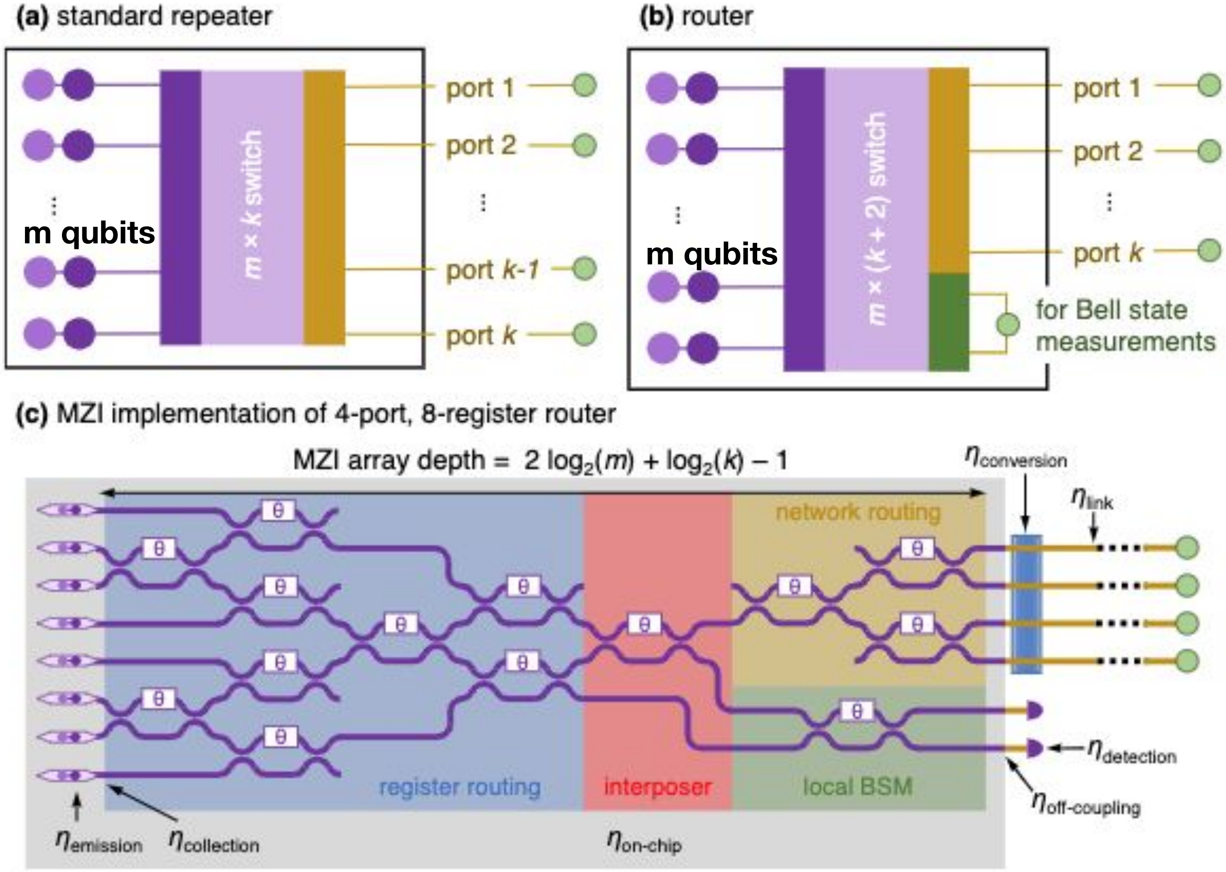
Simulations for a 3-node network, using NetSquid event-based simulator (Delft, Wehner grp)





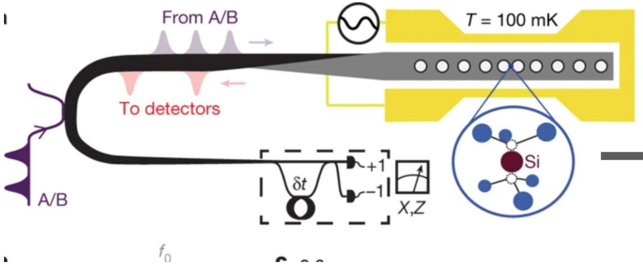
Y Lee, E Bersin, A Dahlberg, S Wehner, D Englund, "A Quantum Router Architecture for High-Fidelity Entanglement Flows in Multi-User Quantum Networks", ArXiv (2020)

Standard repeater and router require roughly same hardware

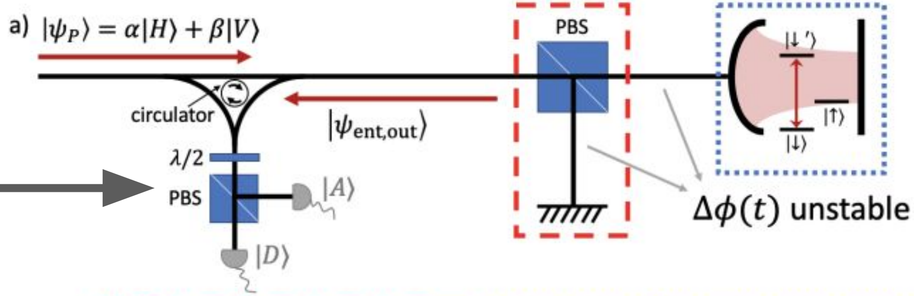


Y Lee, E Bersin, A Dahlberg, S Wehner, D Englund, “A Quantum Router Architecture for High-Fidelity Entanglement Flows in Multi-User Quantum Networks”, ArXiv (2020)

Temporal encoding requires long path delay -- difficult to multiplex!

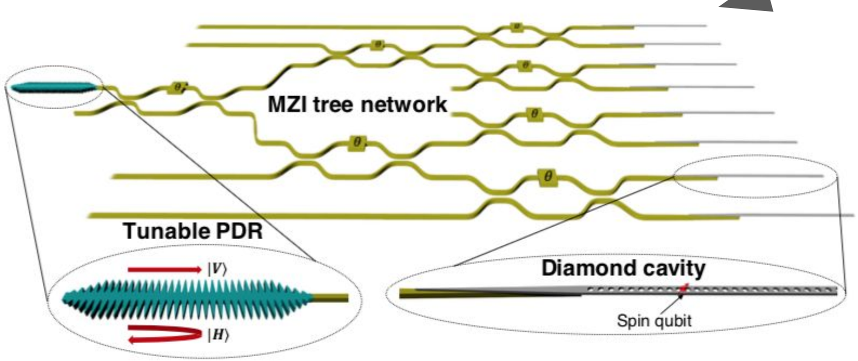


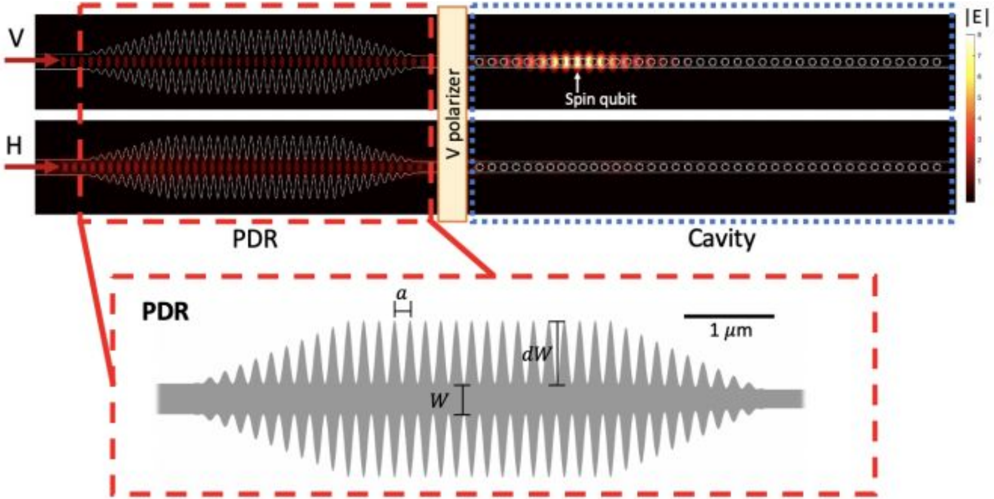
Polarization encoding a la Duan and Kimble (2002)



→ PIC design avoids Michelson interferometer delay

PIC multiplexing

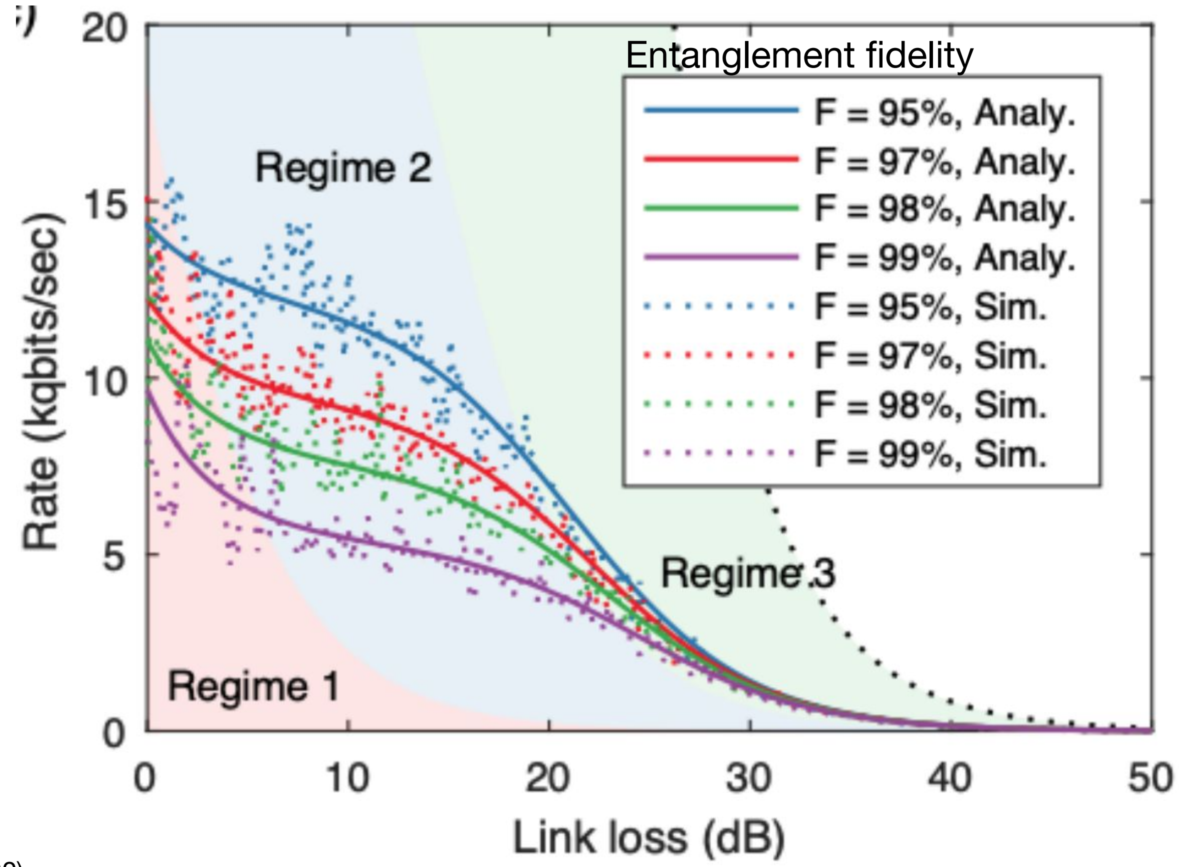




K Chen, E Bersin, DE, ArXiv 2004.02381 (2020)

Performance estimate: Memory-enhanced MDI-QKD per qubit

Simulations assume SiV center parameters from M. Bhaskar, R. Riedinger, et al (Englund, Loncar, M. Lukin), Nature 580, (2019).



K Chen, E Bersin, DE, ArXiv 2004.02381 (2020)

Outline

Photonic Integrated Circuits

\+ Atomic quantum memories

⇒ Scaling Quantum Systems

Article

Large-scale integration of artificial atoms in hybrid photonic circuits

Noel H. Wan[1,4]✉, Tsung-Ju Lu[1,4]✉, Kevin C. Chen[1], Michael P. Walsh[1], Matthew E. Trusheim[1], Lorenzo De Santis[1], Eric A. Bersin[1], Isaac B. Harris[1], Sara L. Mouradian[1,3], Ian R. Christen[1], Edward S. Bielejec[2] & Dirk Englund[1]✉

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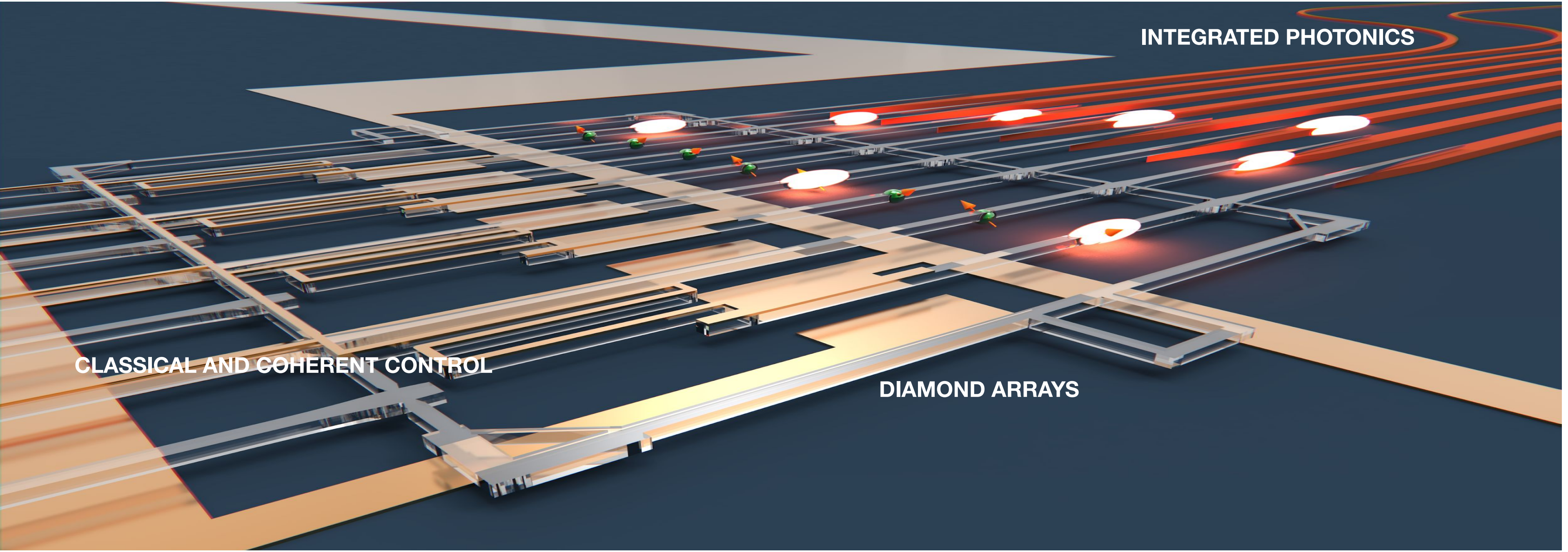
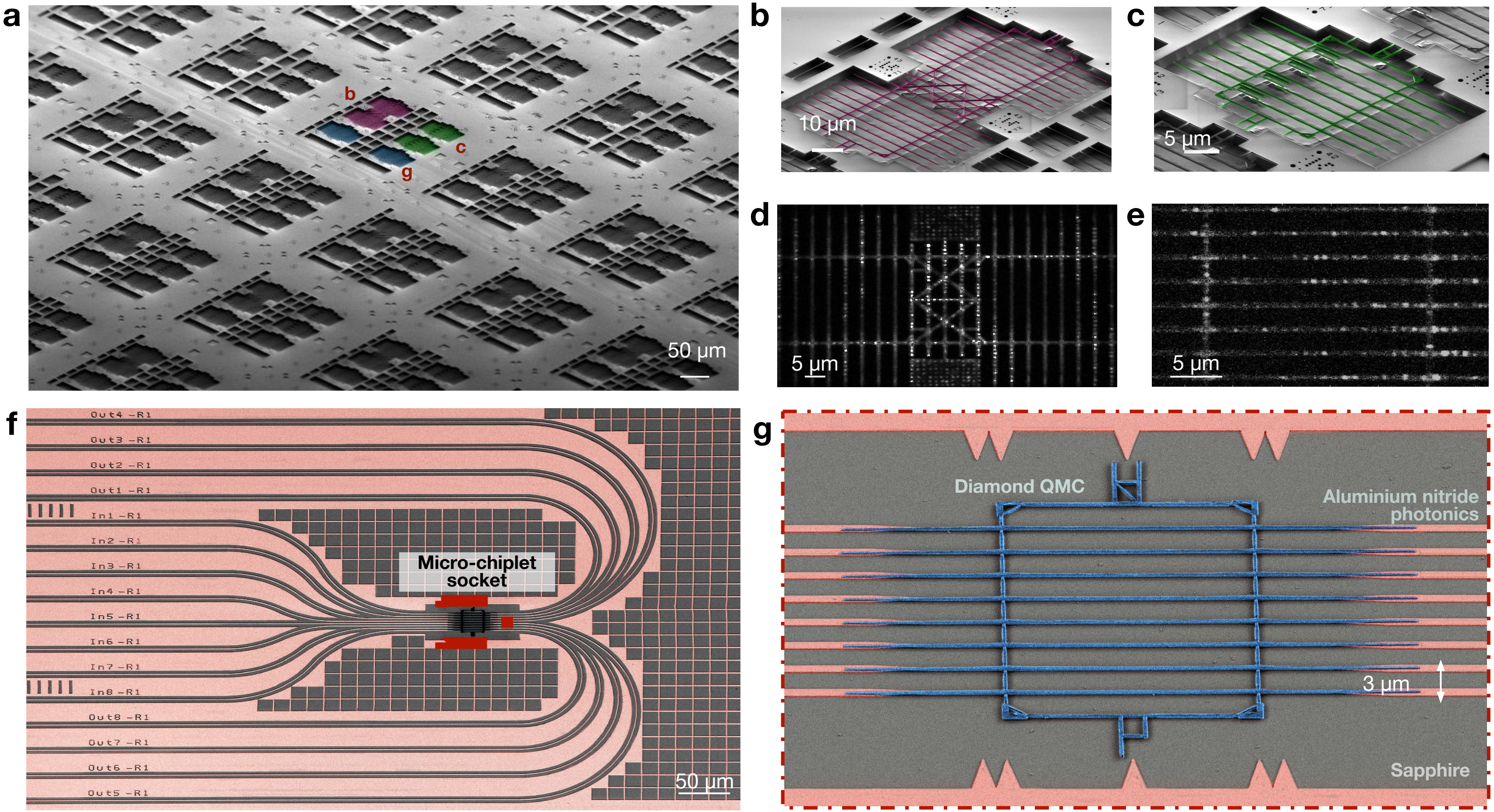
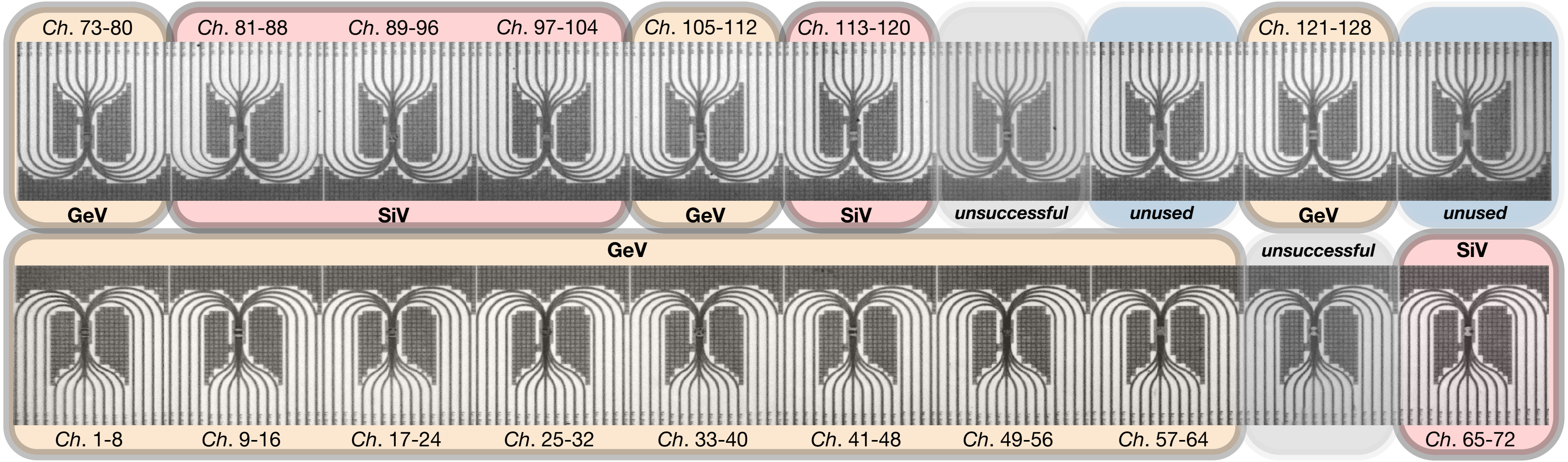


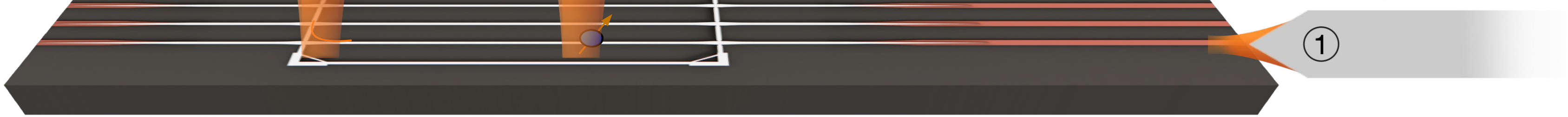
Fabrication & assembly

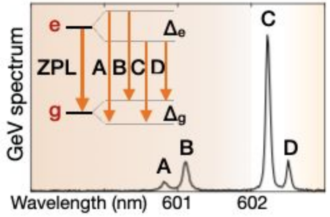


Noel H. Wan*, Tsung-Ju Lu*, Dirk Englund *et al*. **Nature 583 (2020)**

Characterizing a 128-channel quantum PIC

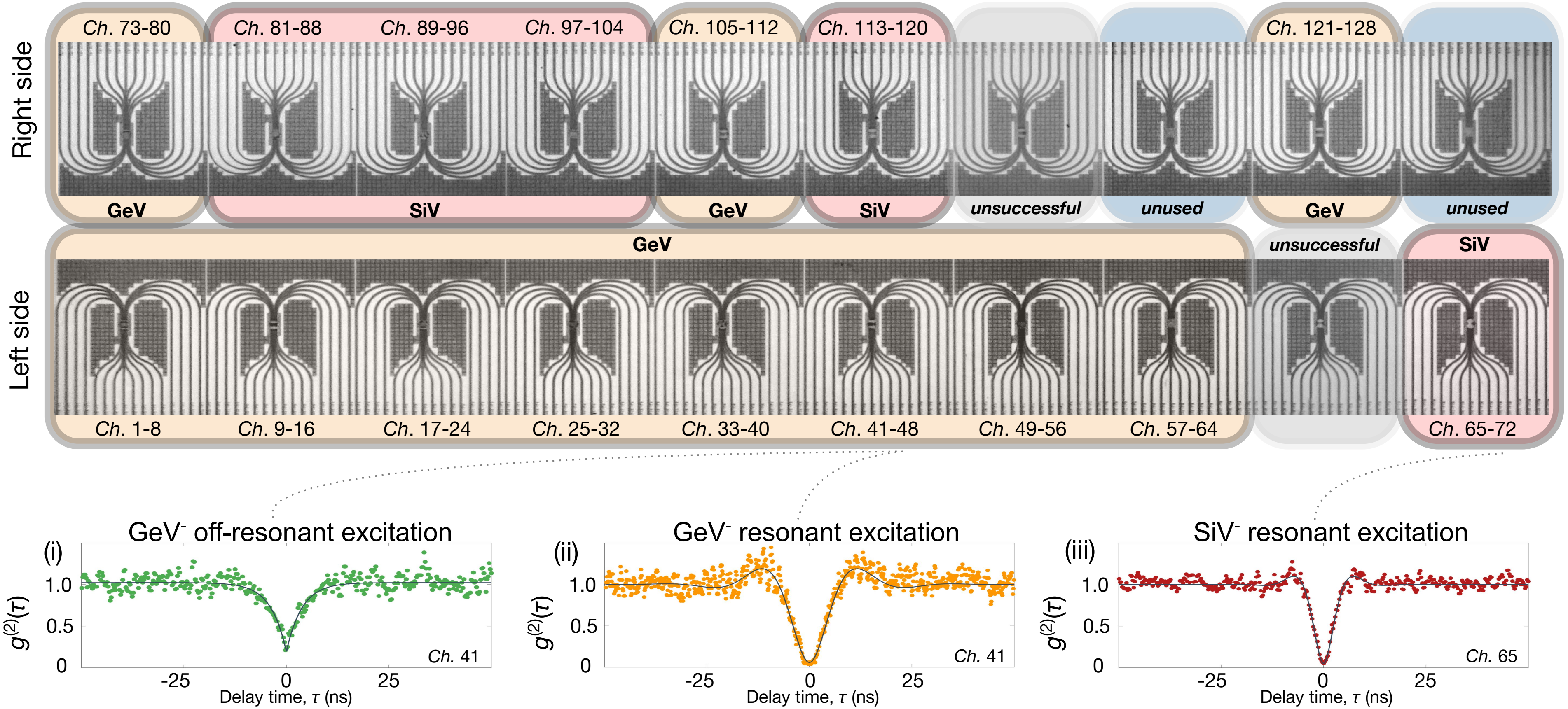






Noel H. Wan*, Tsung-Ju Lu*, Dirk Englund *et al*. **Nature 583 (2020)**

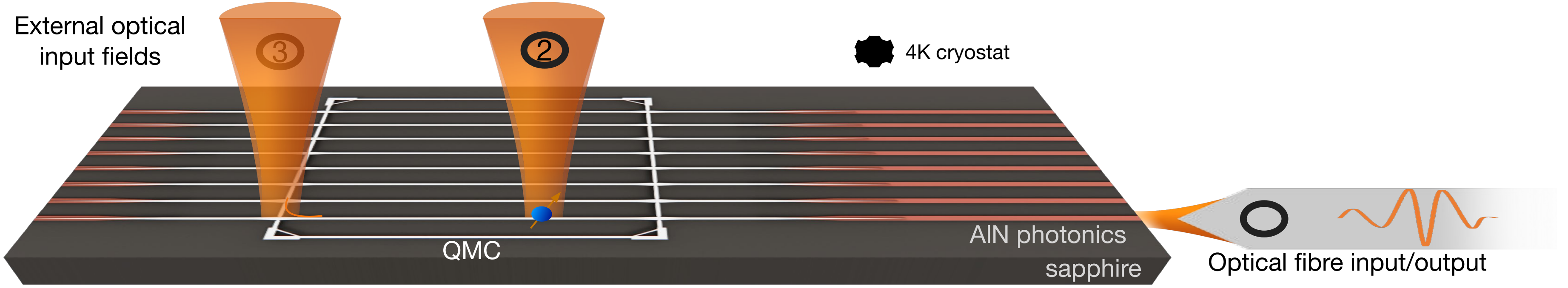
Anti-bunched photons routed on chip and coupled to fiber



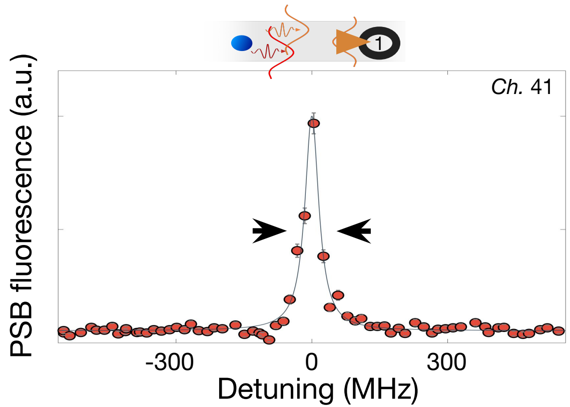
Noel H. Wan*, Tsung-Ju Lu*, Dirk Englund *et al*. **Nature 583 (2020)**

Stable color centers

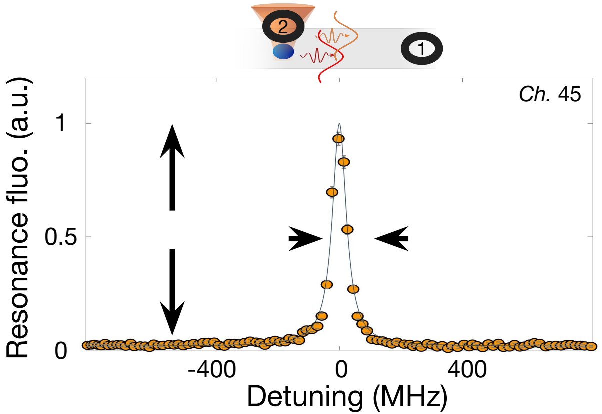
QUANTUM PHOTONICS



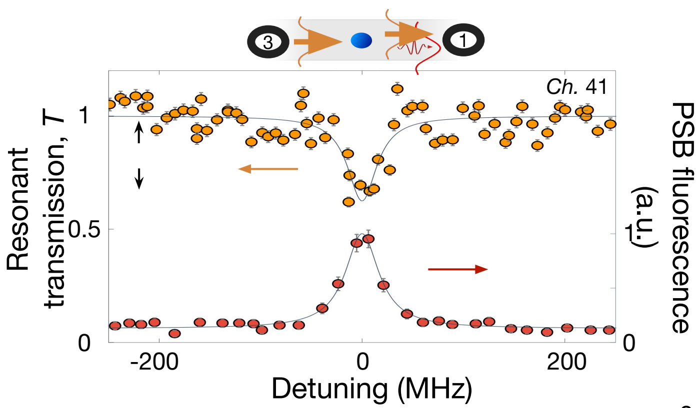
Microscope-free spectroscopy



Resonance fluorescence detection



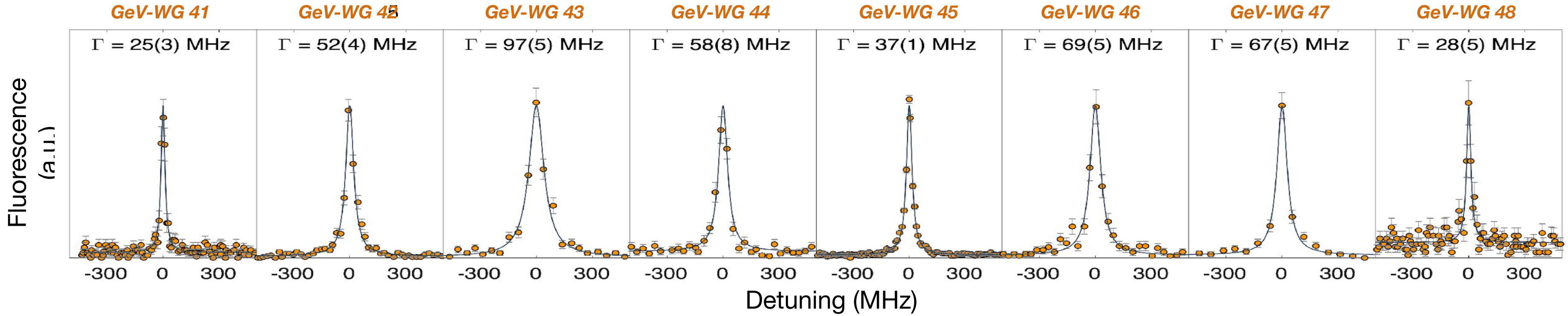
Extinction of light by a single GeV center



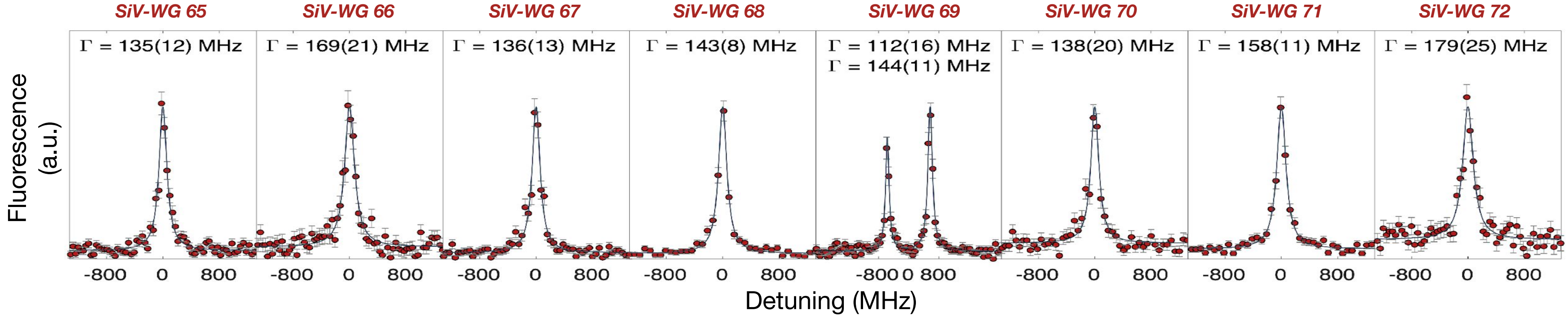
Noel H. Wan*, Tsung-Ju Lu*, Dirk Englund *et al*. **Nature 583 (2020)**

Defect-free arrays of optically coherent emitters

Germanium-Vacancy Fourier-limited linewidth: Δv ≃ 26 MHz

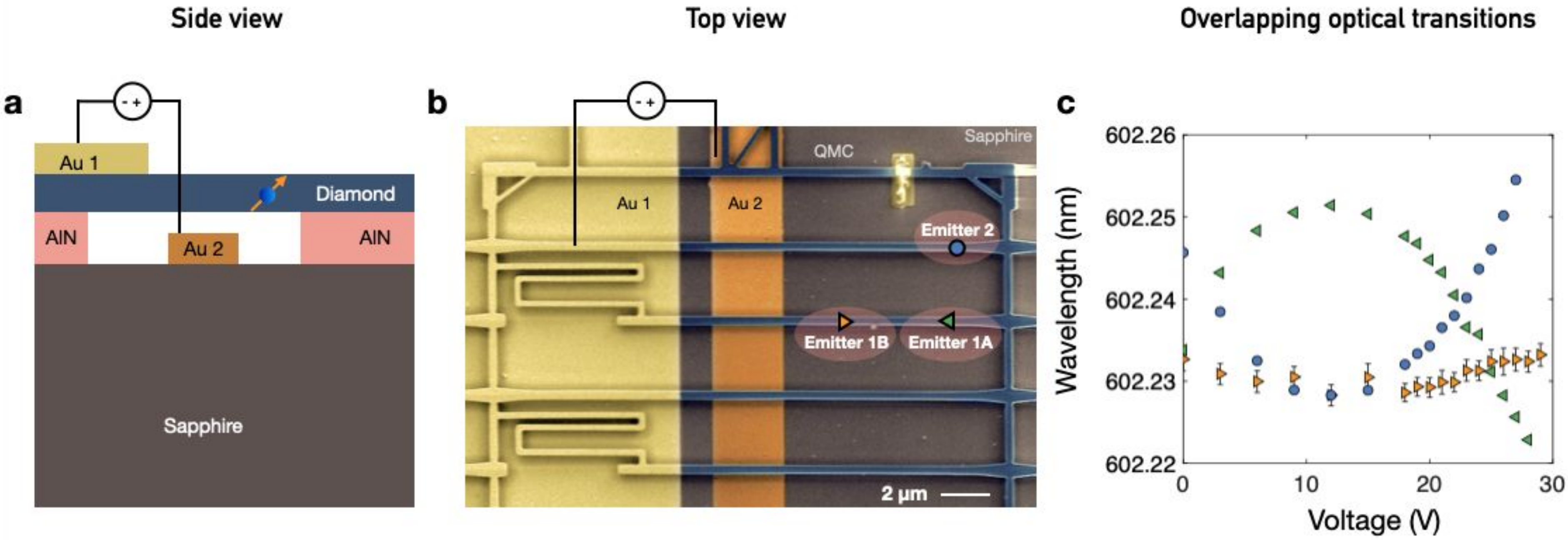


Silicon-Vacancy Fourier-limited linewidth: Δv ≃ 95 MHz



Noel H. Wan*, Tsung-Ju Lu*, Dirk Englund *et al*. **Nature 583 (2020)**

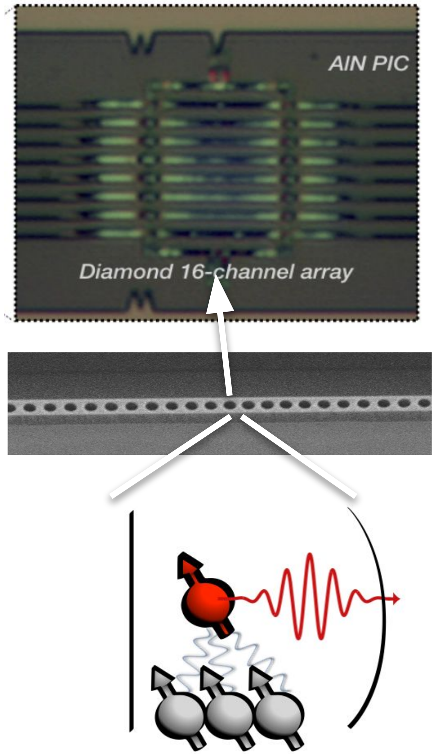
Tuning optical transitions using strain



Noel H. Wan*, Tsung-Ju Lu*, Dirk Englund *et al*. **Nature 583 (2020)**

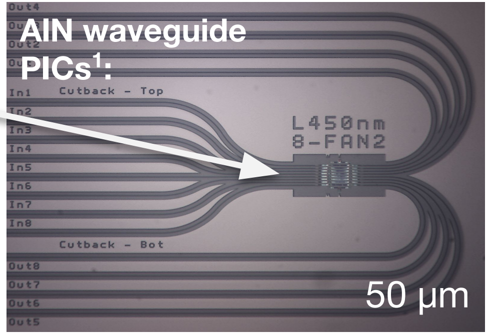
Large-scale modular quantum architectures

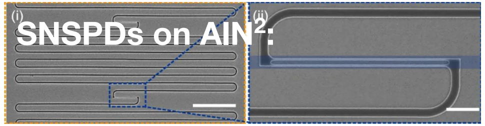
Spins coupled to photons



+

Photonic circuits



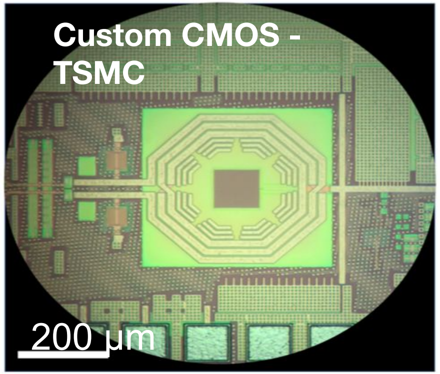


1) TJ Lu*, Michael Fanto*, et al, Opt. Express (2018). Review: N. Harris et al, Optica **5**, 12 (2018)

2) Di Zhu et al (DE, K Berggren), Nature Nanotechnology **13** (2018). Collaboration with Berggren group, MIT

+

Spin control



D Kim, M Ibrahim, C. Foy, R Han, & D.E., Nature Electronics (2019)

M I. Ibrahimet al, ISSCC (2018)

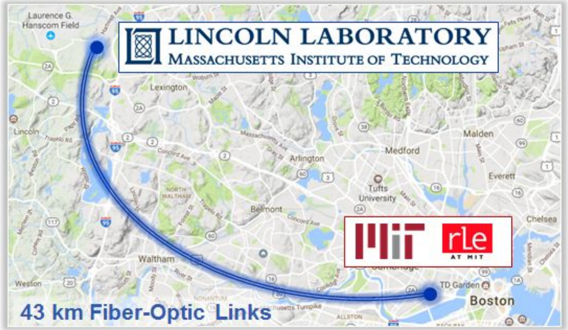
IEEE VLSI Circuits Symposium (2018)

Boston-Area Quantum Network Testbed

High-dimensional QKD with temporal encoding

~1 Mbit/sec @16 dB loss (43 km MIT ←→ Lincoln Lab).
> 20 Mbit/second locally.

C. Lee et al, Optics Express Vol. 27, Issue 13, pp. 17539-17549 (2019);
Security Proofs [J. Mower et al, PRA 87 (2013)] .. with finite-key correction [C. Lee et al, Qu. Inf. Proc 14 (2015)] and decoy state protection [D. Bunandar et al, PRA 91 (2015)]

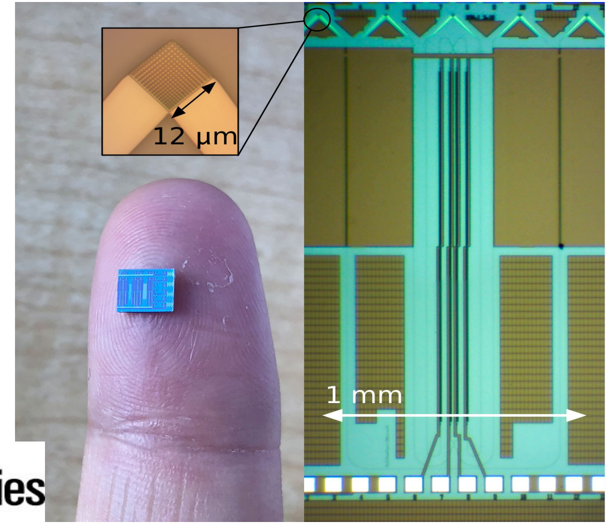


Silicon Photonics: Polarization-based QKD

106 kbps over 43 km (16.4 dB loss) MIT ←→ Lincoln Lab, including polarization stabilization

D Bunandar et al, Phys. Rev. X (2018)

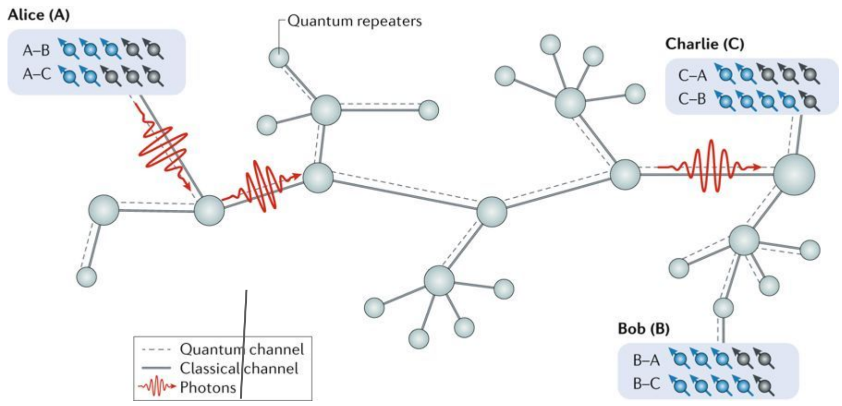
[partial support from Samsung Advanced Institute of Technology Global Research Outreach]



Sandia National Laboratories

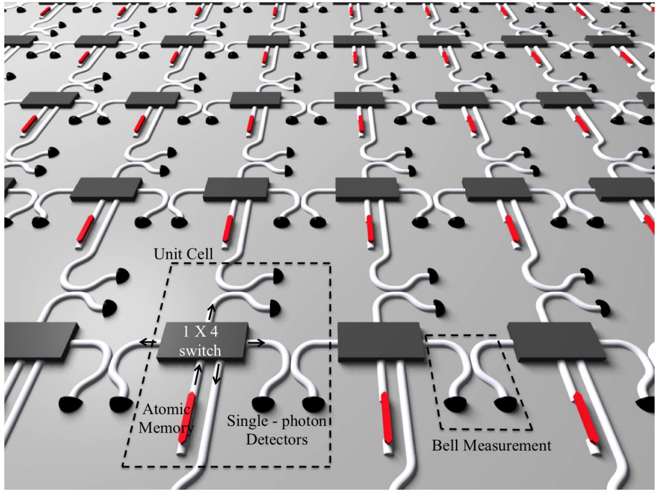
Outlook for memory-integrated PNPs

Quantum repeater networks becoming possible now



Atatüre, Englund, Vamivakas, Lee, Wrachtrup: Nature Reviews Materials (2018)

Gate-based modular quantum computing with large numbers (millions) of near-identical artificial atoms and error correction.



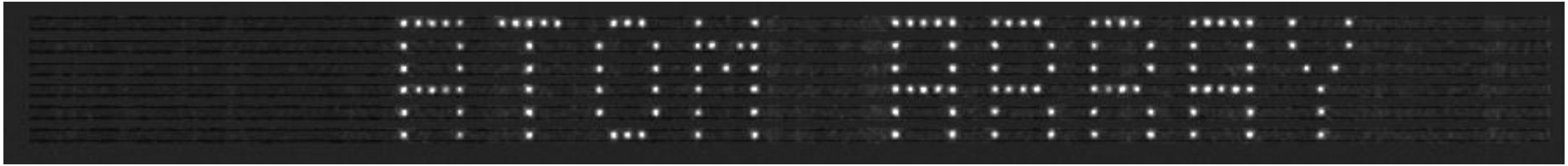
M. Pant et al, arXiv:1704.07292 - in review (2019); for cavities see H. Choi et al, PRL **118** (2017); PRL **122**, 183602 (2019).

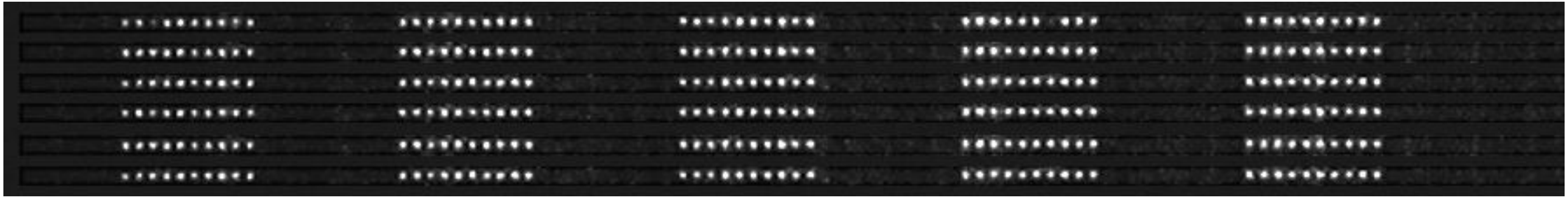
Outline

Photonic Integrated Circuits

+ Atomic quantum memories

⇒ Scaling Quantum Systems : Precision Control of Rydberg atom arrays





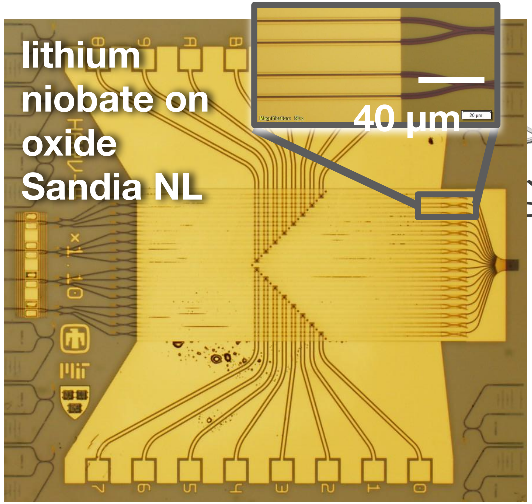
Mikhail Lukin group, Harvard
Markus Greiner group, Harvard
Vladan Vuletic group, MIT

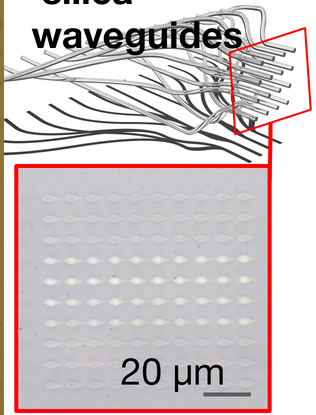
Photonics for cold atom computing

Postdoc positions available in **theory** and **experiment**: See qplab.mit.edu

UV-VIS photonics for cold atoms and trapped ion control

- Collaboration with Sandia NL: Matt Eichenfield - LN, SiN-on-oxide
- AlN-on-sapphire: Jeff Lu, Michael Fanto, et al, Optics Express **26** (2018)

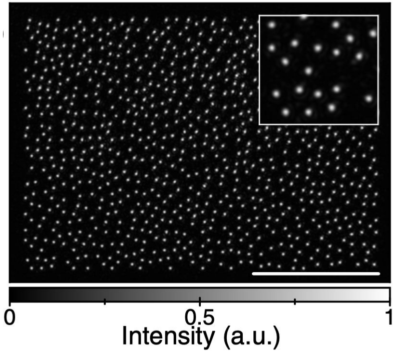


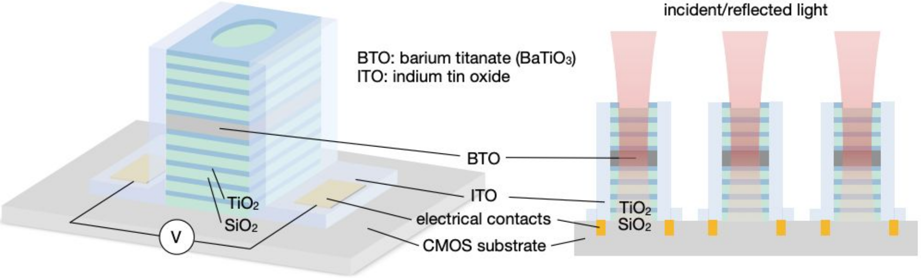


With J. Booth, Oxford U.

C Peng, R Hamerly, M Soltani, D Englund, Optics Express **27**, Issue 21, pp. 30669-30680 (2019)

D. Kim et al, Optics Letters Vol. 44, Issue 12, pp. 3178-3181 (2019)





Summary & outlook

Hardware

Experimental:

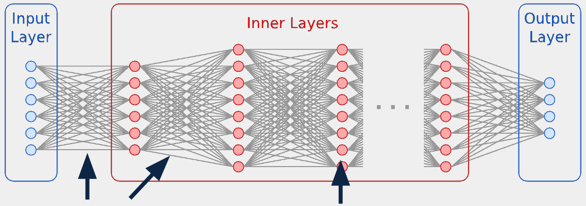
- Programmable PICs: modulators, detectors, passives..
- Atomic memories
- Superconducting single photon det. (w/ K. Berggren)[F] Najafi, J Mower, et al, Nature Comm **6** (2015), D. Zhu, et al, Nat. Nano., **13**, (2018)
- $\chi^{(3)}$ - entangled pair sources w/ integrated filters J. Carolan et al, Optica **3** (2019)
- Single microwave (<50 GHz) detection G. H. Lee … D.E., K.C. Fong, Arxiv:1909.05413 (2019) - to appear in Nature (2020)

Proposals:

- Photon-photon logic by $\chi^{(3)}$ M. Heuck, K. Jacobs, D.E. PRL **124** (2020)
- High-fidelity on-demand single photon sources: M. Heuck, M Pant, D.E., NJP **20** (2018)
- Photonic logic qubit & gate S. Krastanov et al - ArXiv 2002.07193 (2020)
- Room-temp single photon detection C. Panuski et al, PRB 99

Applications

Machine learning accelerators



Synaptic connections

Activation functions

Proof of concept Y. Shen*, N. C. Harris*, et al [w/ M Soljacic, MIT], Nature Photon **11** (2017)

Neural network computing below the thermodynamic limit R Hamerly, A Sludds, L Bernstein, M Soljacic, and D Englund, PRX 9 (2019)

Quantum optical neural networks G. Steinbrecher et al, NPJ Quantum Information Processing 5 (2019)

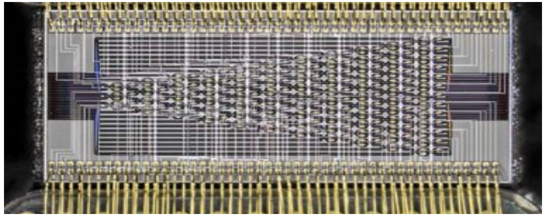
Quantum optical neural networks G. Steinbrecher et al, NPJ Quantum Information Processing 5 (2019)

Learning quantum circuits J. Carolan et al., Nature Physics **16** (2020)

Quantum networks & quantum computing

Summary & Outlook

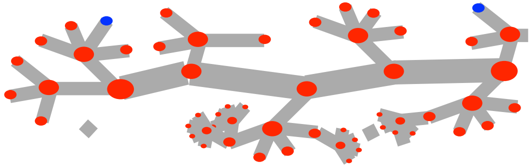
Postdoc positions available in **theory** and **experiment**: See qplab.mit.edu



1. **Programmable Nanophotonic Processor (PNP)**
   a. Programmable high-fidelity unitary mode transformations
      i. Two-photon logic gates: arXiv:1905.02134 (2019)
2. **Optical Accelerators for Deep Neural Networks**
   a. PNPs perform matrix-vector multiply on the fly
   b. Time-encoded neurons, optical fan-out, and photoelectric multiplication: Compute < Landauer limit of digital-equivalent DNN?
      i. R. Hamerly et al, Phys. Rev. X 9, 021032 (2019)

Quantum Optical Neural Networks: G. Steinbrecher et al, NPJ Quantum Information (2019); Y. Lahini et al, npj Quantum Information, 4 (2018)

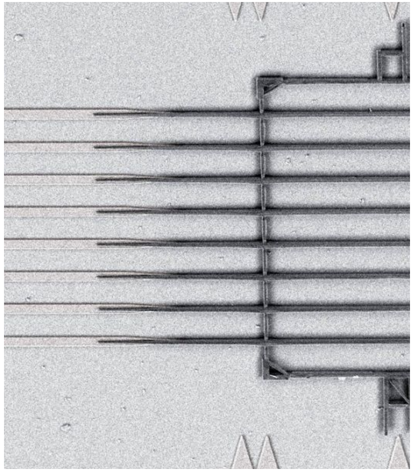
   c. Possibility of self-training quantum information processors! J Carolan et al, Nature Physics (2020)



arxiv:1909.05413 (2019)

PICs for quantum repeaters and computers

Quantum memory-integrated PICs



Quantum emitters getting close to "repeatable and good":

- Stable emitters: SiV, GeV, PbV, SnV; diamond III-vacancy centers? I. Harris, C. Ciccarino, et al, [DE, Prineha Narang], arXiv:1907.12548 (2019).
- Strain-tunable emission wavelength: see Loncar
- Large-scale integration: 128 near-ideal emitters on a PIC [N Wan, TJ Lu, 2019]

Spin control by CMOS:

- D Kim, M Ibrahim, C. Foy, R Han, & D.E., Nature Electronics (2019)

VIS-UV PICs:

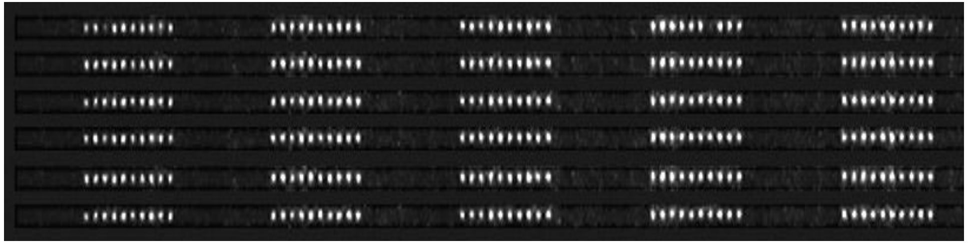
- AlN-sapphire: with Michael Fanto & Stefan Preble - AFRL, RIT
- LN, SiN, Al_2O_3,... (MITRE Quantum Moonshot, with M Eichenfield / Sandia NL)

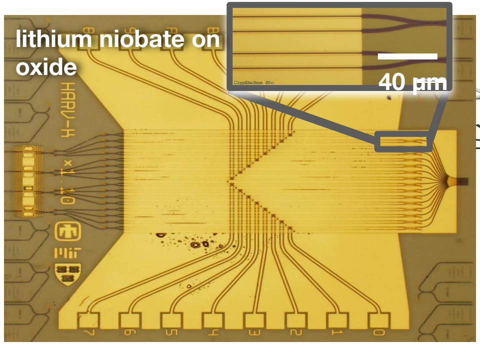
Postdoc positions available in **theory** and **experiment**: See qplab.mit.edu

DUST IDENTITY

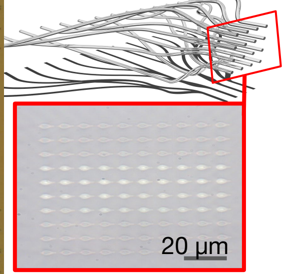
|QuEra⟩ COMPUTING INC.

Large-scale PICs → large-scale quantum computing





silica waveguides



Acknowledgements

Postdoc positions available in **theory** and **experiment**: See qplab.mit.edu

MIT Quantum Photonics Group :

PhD: Noel Wan, Michael Walsh, Eric Bersin, Tsung-Ju Lu, Donggyu Kim (--> QuEra), Saumil Bandyopadhyay, Chris Foy, Mohammad Ibrahim, Kevin Chen, Ian Christen, Isaac Harris, Nick Harris (--> LightMatter), Darius Bunandar (--> LightMatter), Mihika Prabhu, Uttara Chakraborty

Postdocs: Tim Schroeder (->Humboldt-Universität Berlin), Matt Trusheim, Lorenzo De Santis, Jacques Carolan, Mikkel Heuck

Collaborators:

MIT: Karl Berggren, Ruonan Han

MIT Lincoln Laboratory: Danielle Braje, Scott Hamilton, Ben Dixon, Matt Grein, Ryan Murphy

Harvard: Mikhail Lukin, Marko Loncar, Prineha Narang

U. of Arizona: Saikat Guha

Delft QuTech: R. Hanson, T. Taminiau

Stanford: David A.B. Miller

Cambridge U: Mete Atature

Rochester Institute of Technology: Stefan Preble

Air Force Research Laboratory: Michael Fanto, Paul Alsing

Oak Ridge NL: Stephen Jesse

MITRE Corp: Gerry Gilbert, Mark Dong, Gen Clark

Sandia NL: M Eichenfield

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AFOSR

NSF

ARL

Army Research Office

MITRE