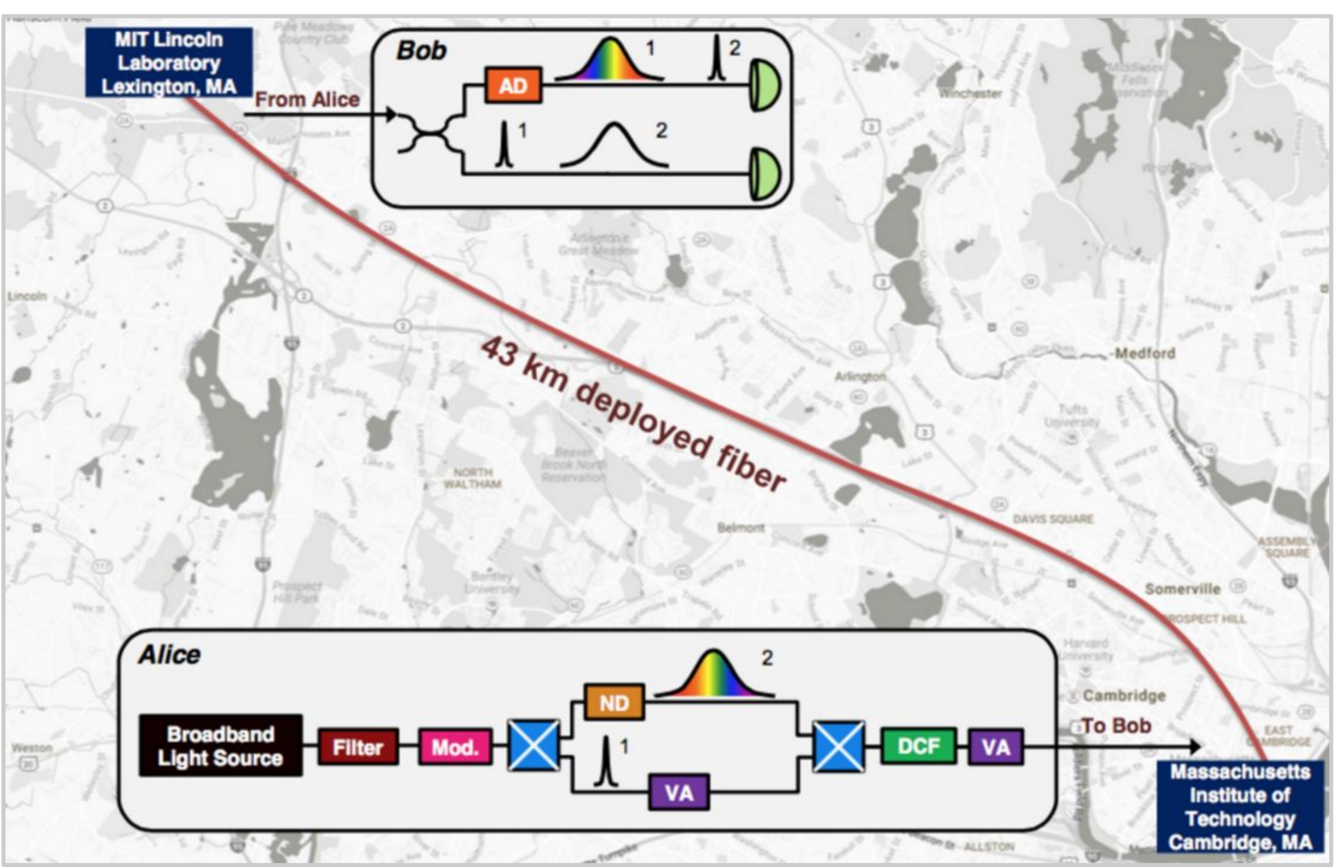
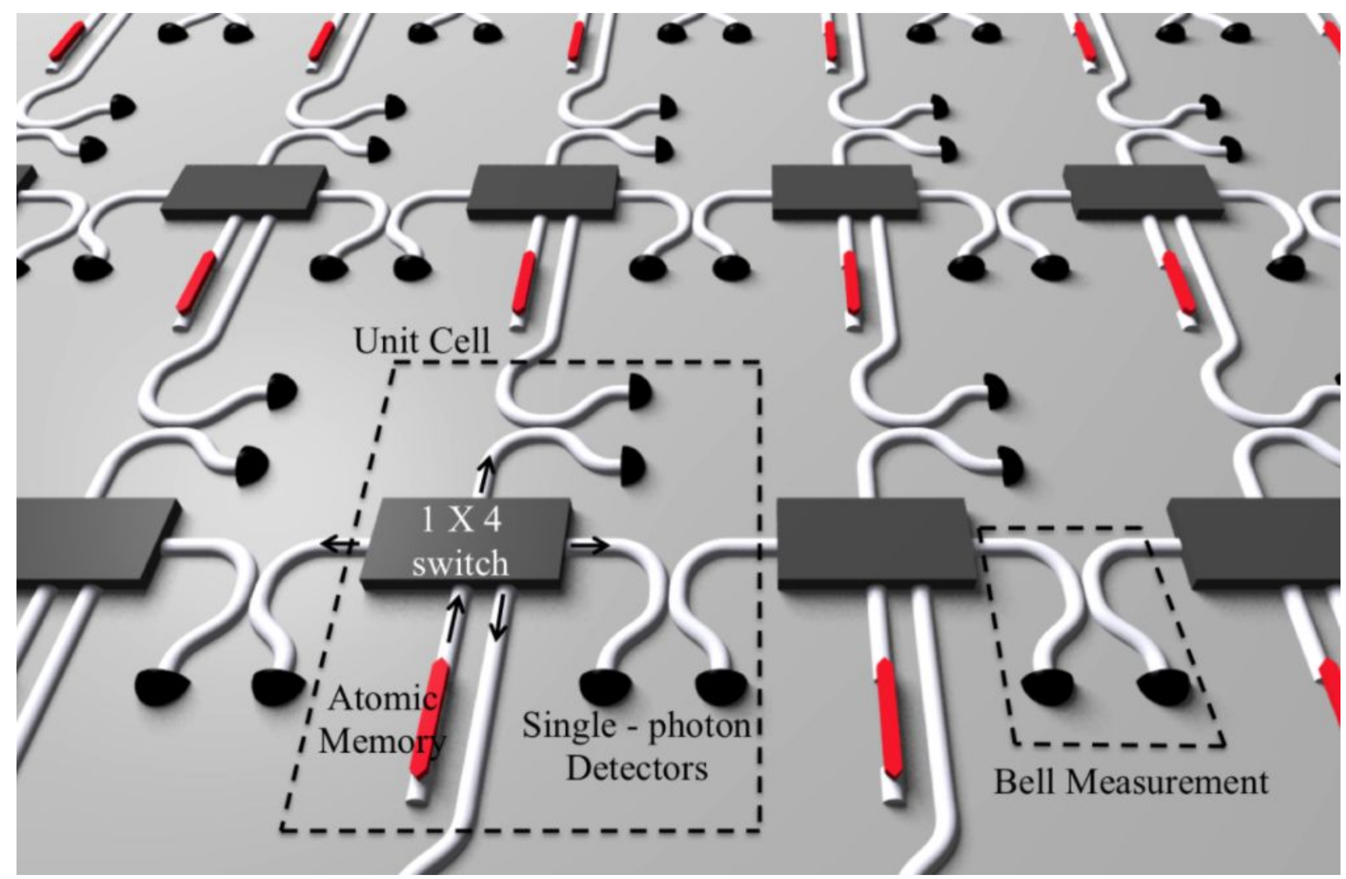
Semiconductor Quantum Technologies for Communications and Computing

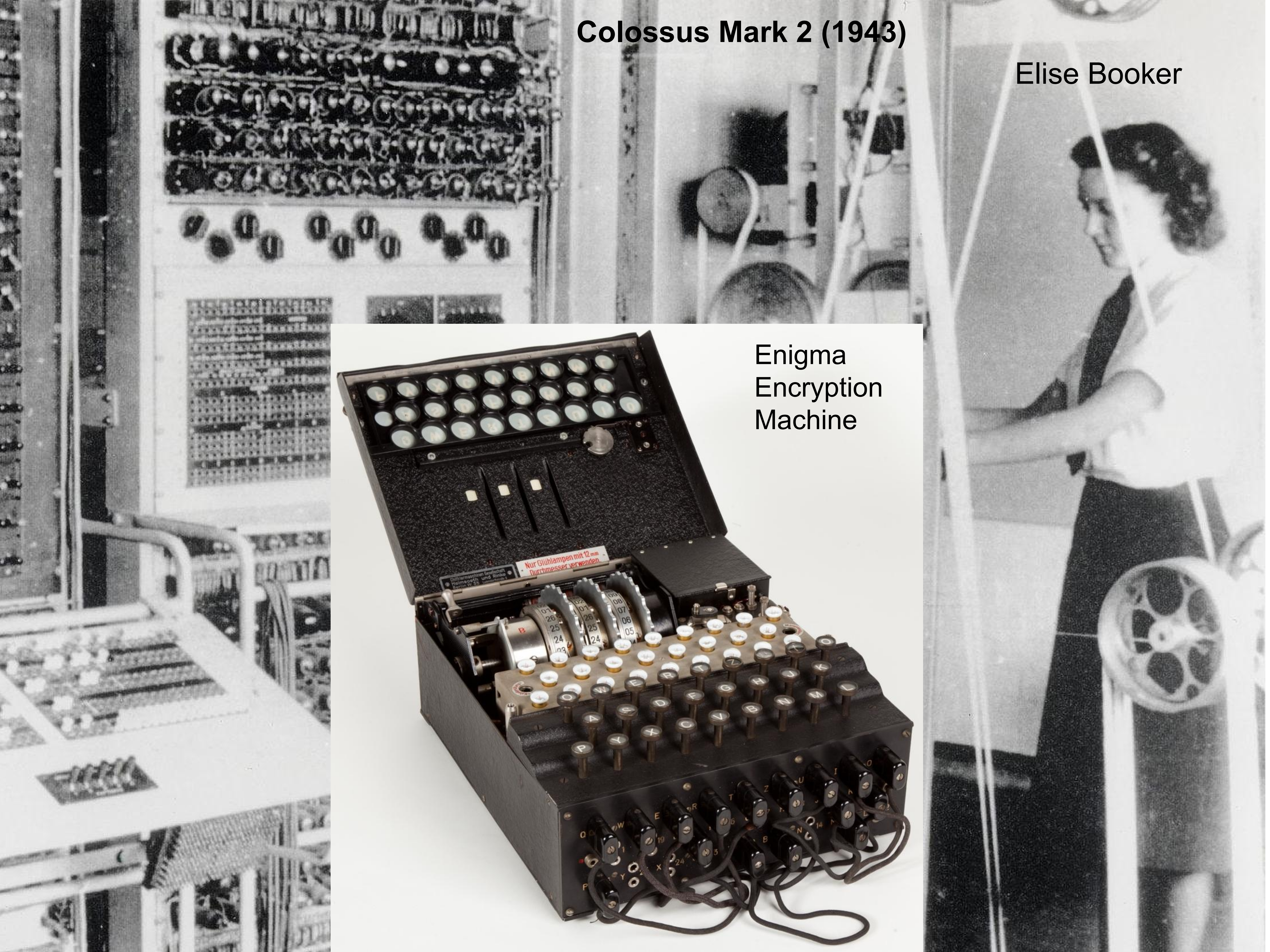
Dirk Englund
MIT EECS Department | RLE and MTL

2017 MIT Research and Development Conference
November 15, 2017

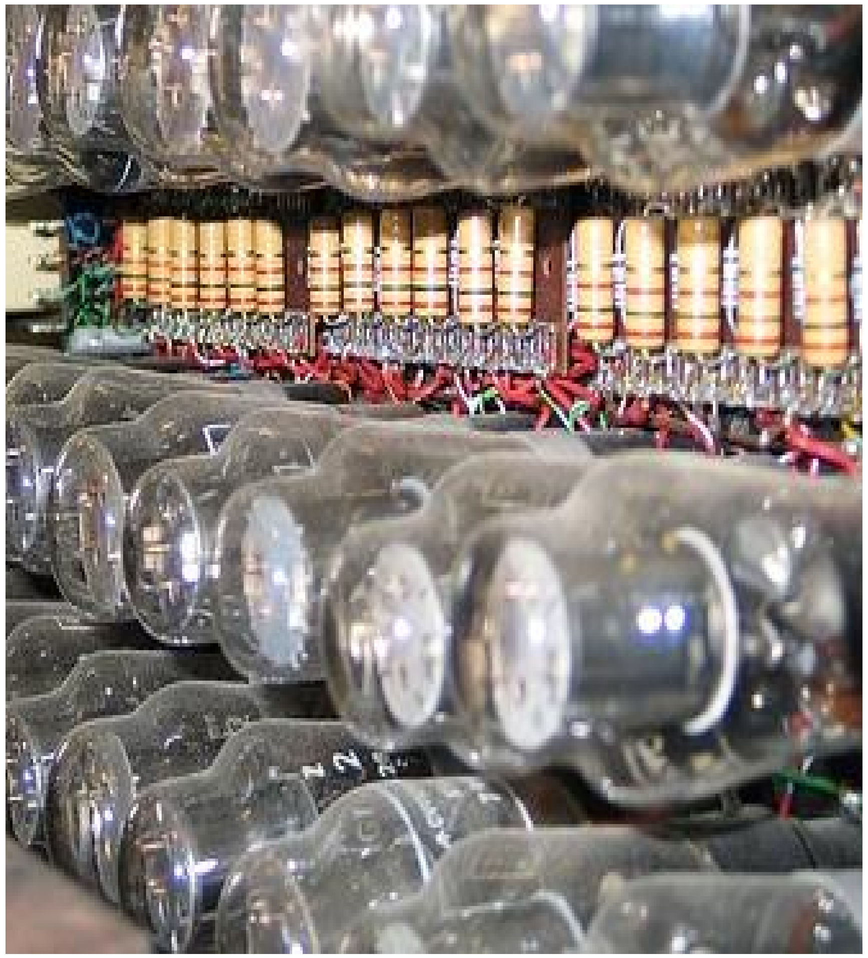




Colossus Mark 2 (1943)

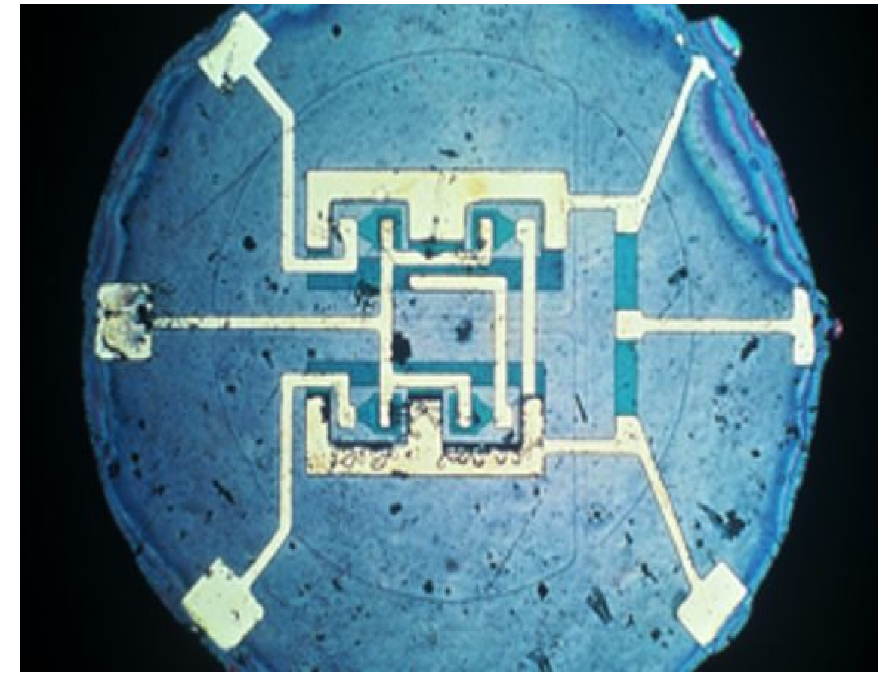


Miniaturizing the Colossus

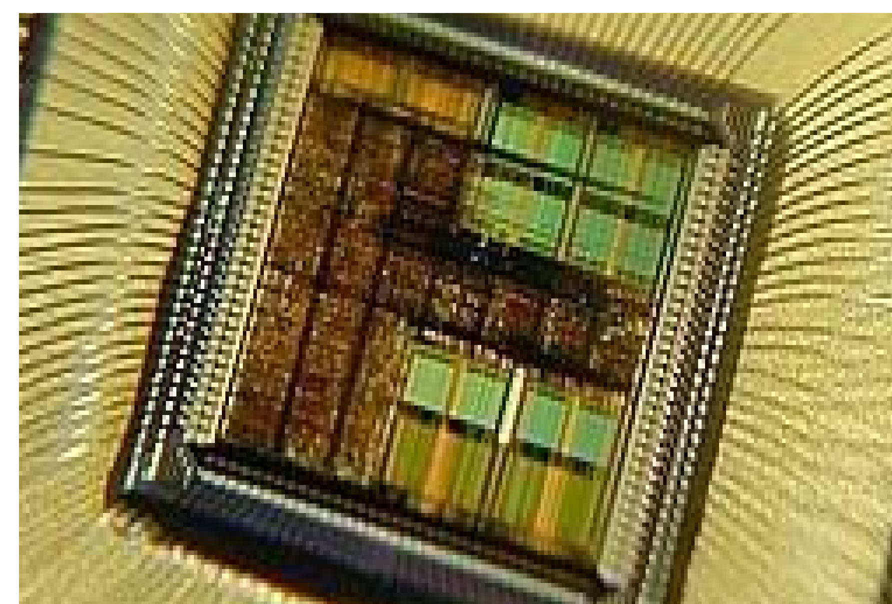


Thermionic vacuum tubes in Colossus Mark 2 (1940s) (Bletchley Park Museum)

First Transistor: 1947
1950s First Si transistor (TI)

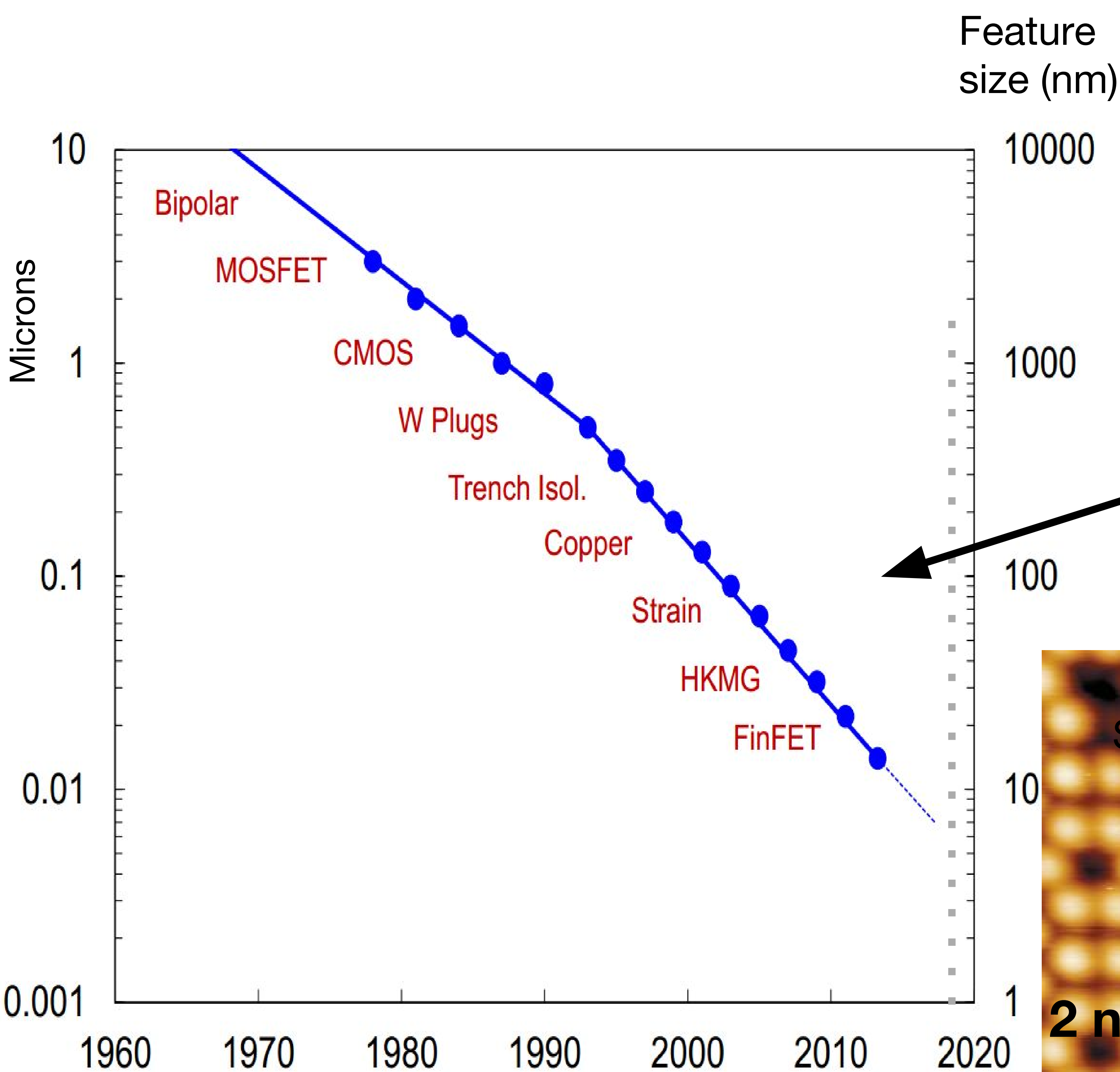


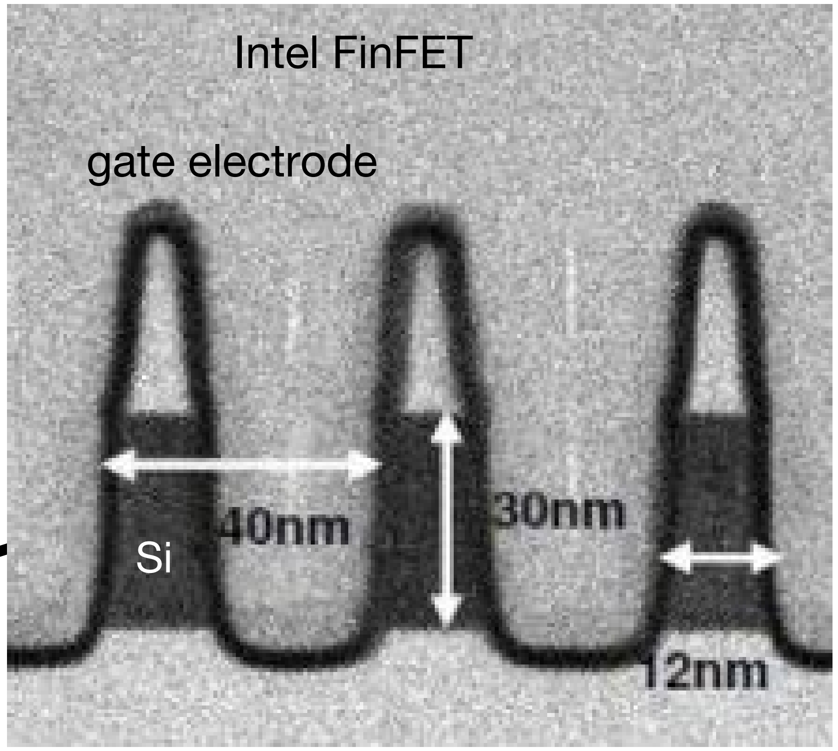
First IC - 1958 - J. Kilby, TI. See also Robert Noyce - Fairchild S.C.

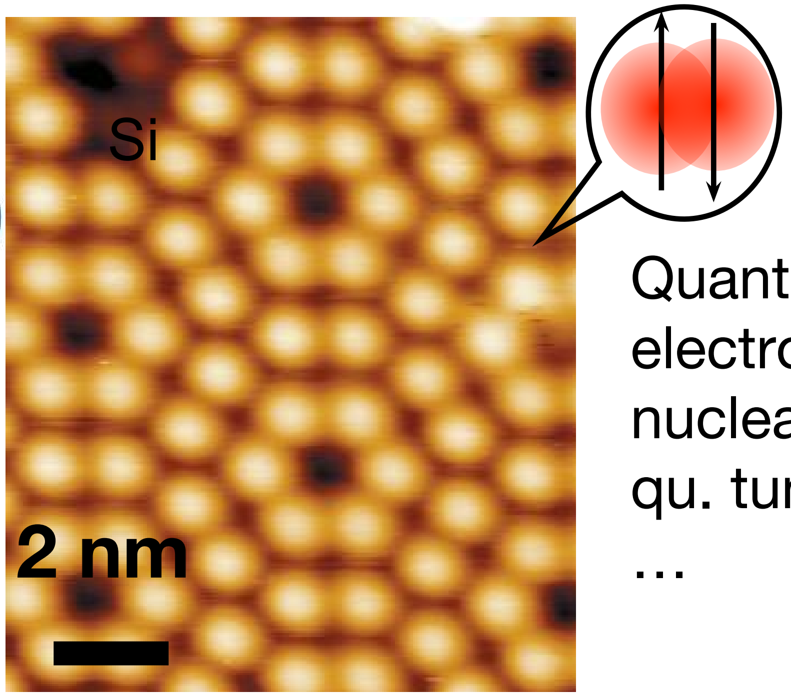


Today: Intel Phi with ~ 5 Billion transistors

Moore’s law meets the atomic scale



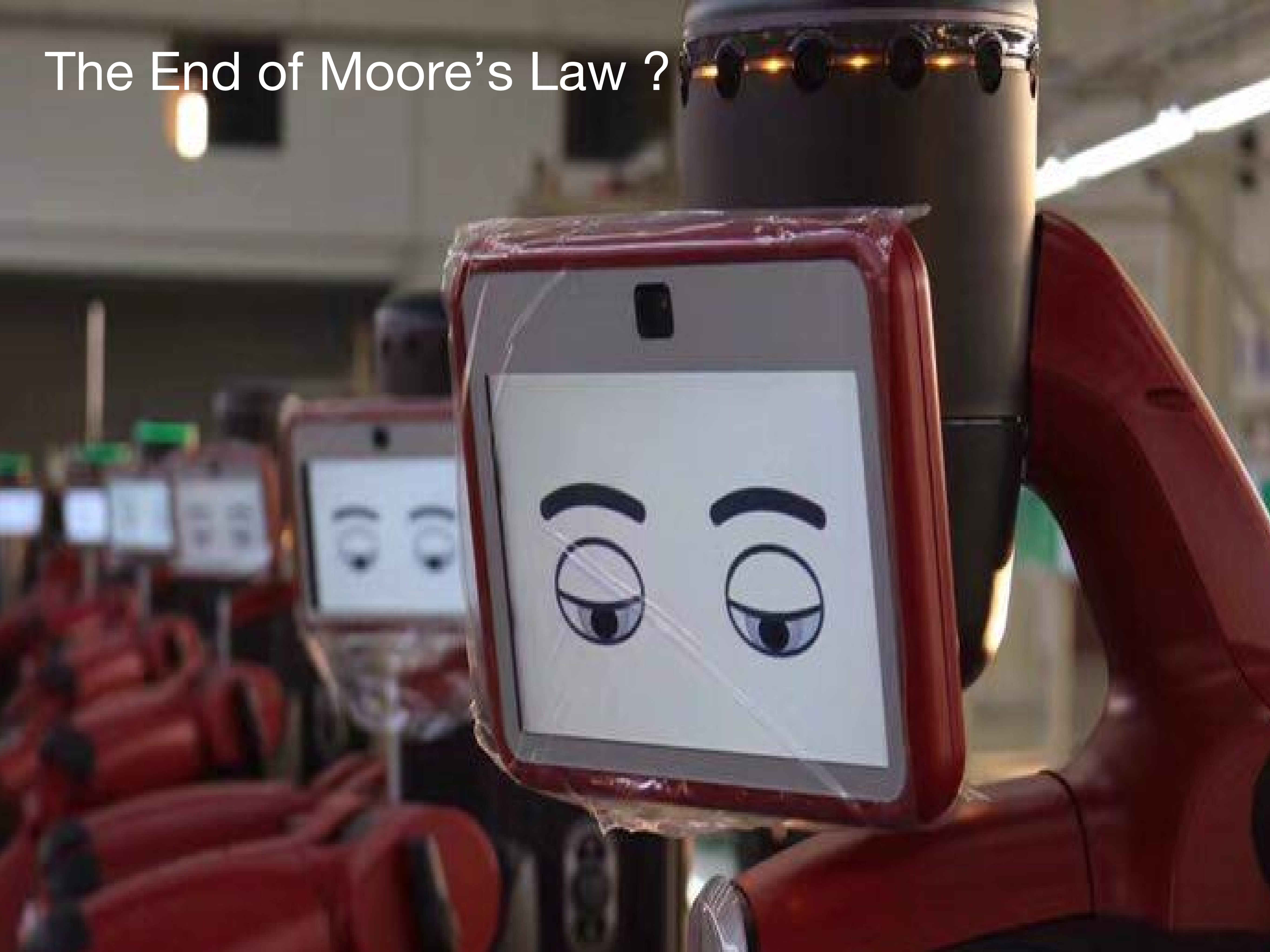




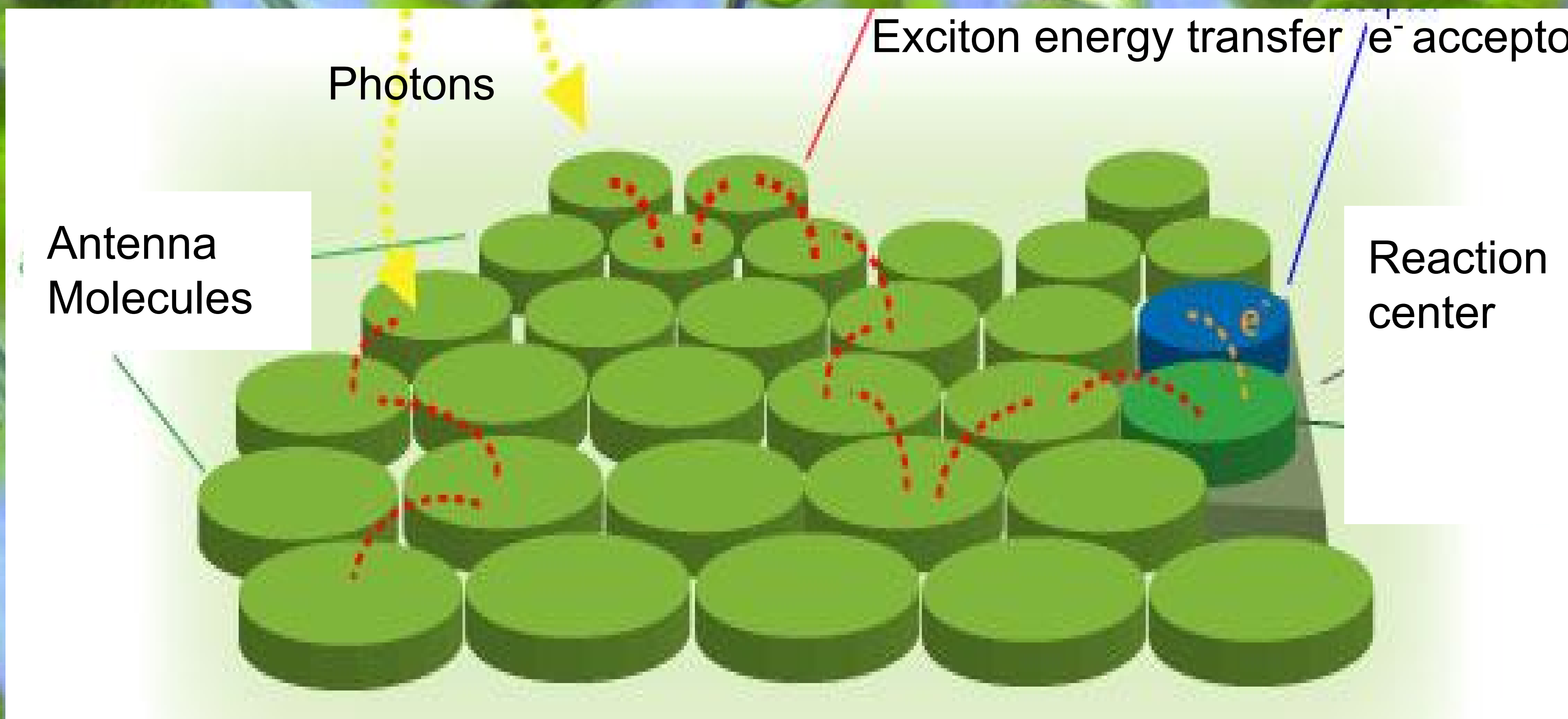
Quantum effects:
electron spins
nuclear spins
qu. tunneling
…

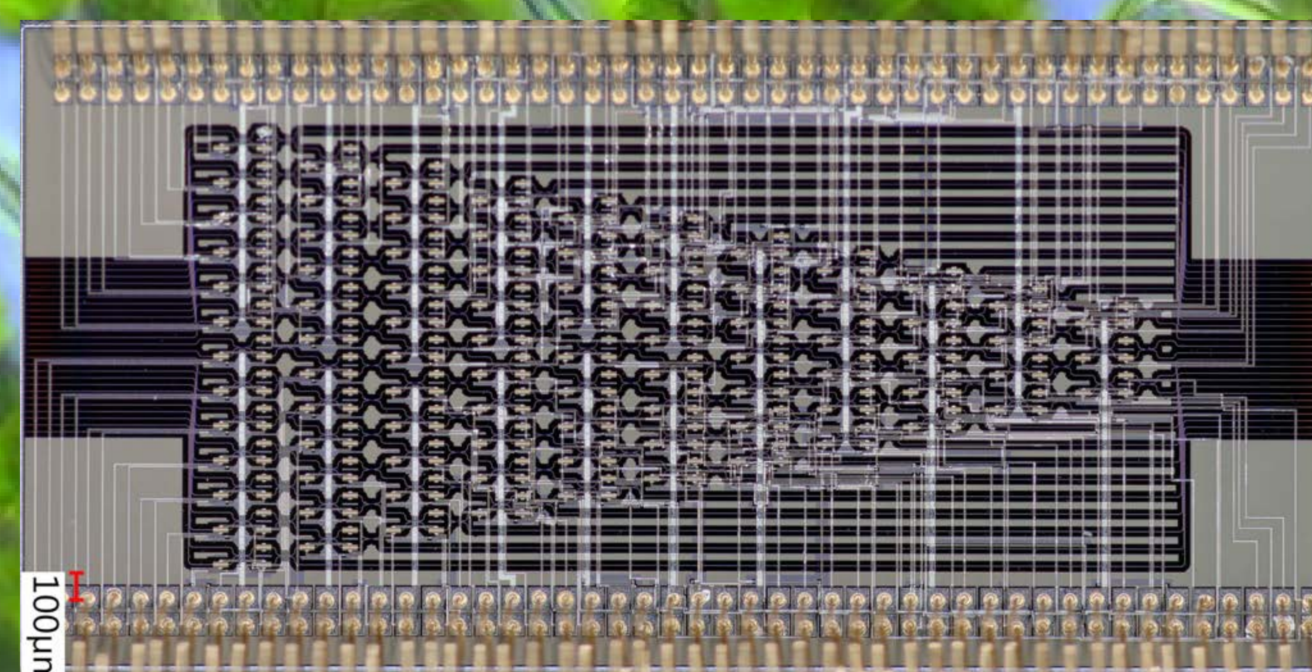
Source:
Intel

The End of Moore's Law ?



Nature “computes” using quantum mechanics

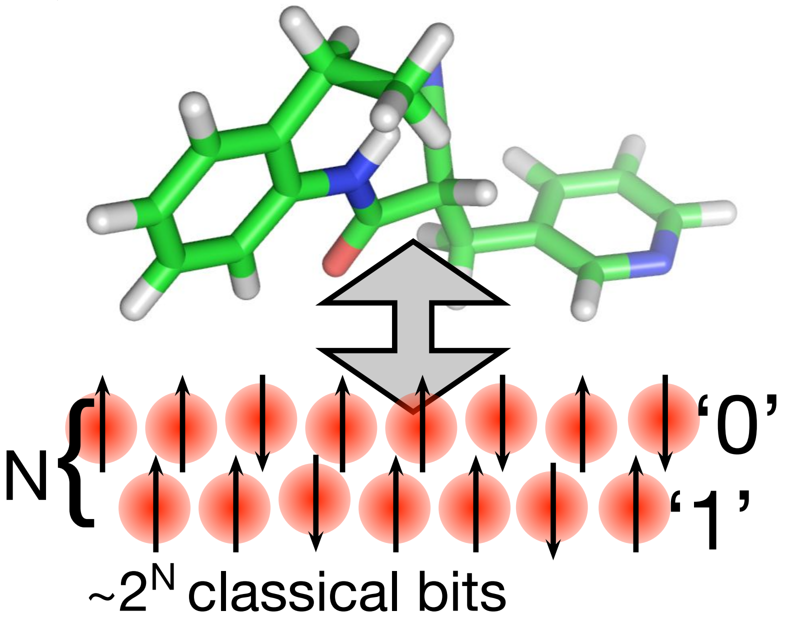




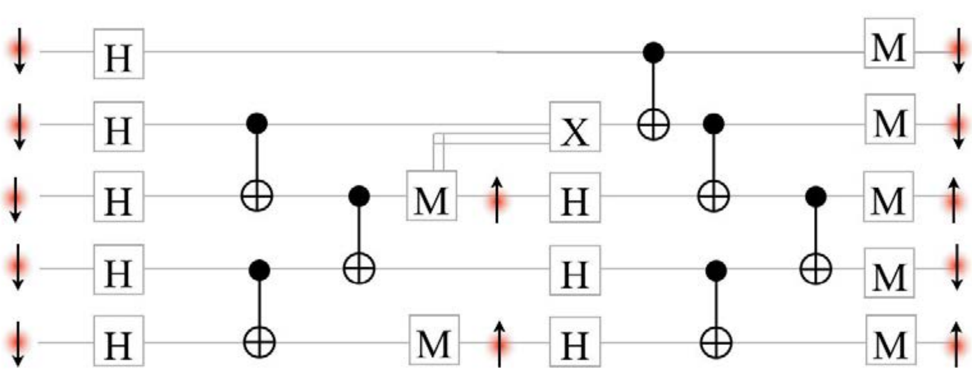
N. Harris et al., Nature Photonics 11 (2017)

Quantum Technologies

Quantum Simulation



Quantum Computing



Code-breaking, search big data, ..

1. Superposition principle

01 → 00 01 10 11

Bell State: 00+11

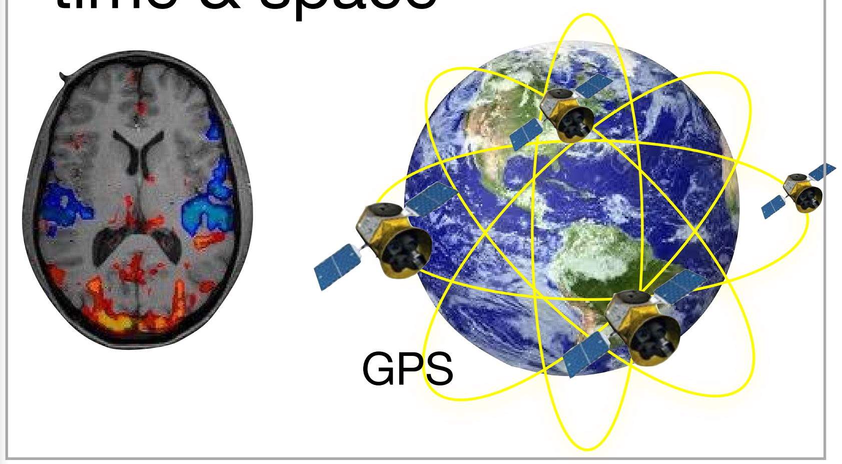
2. No Cloning Theorem

$$|\Psi\rangle \nrightarrow |\Psi\rangle\ |\Psi\rangle$$

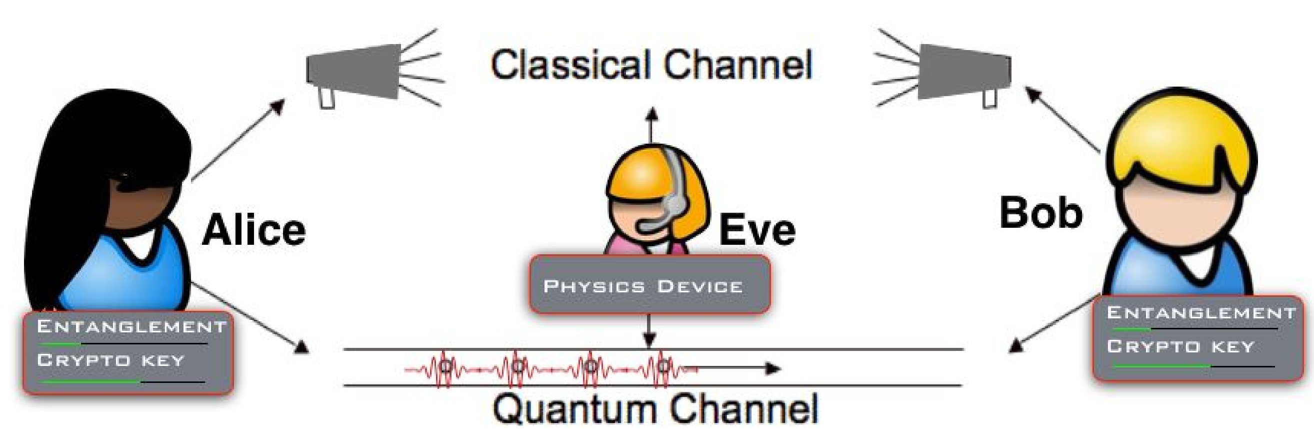
Precision Measurements

-forces & fields

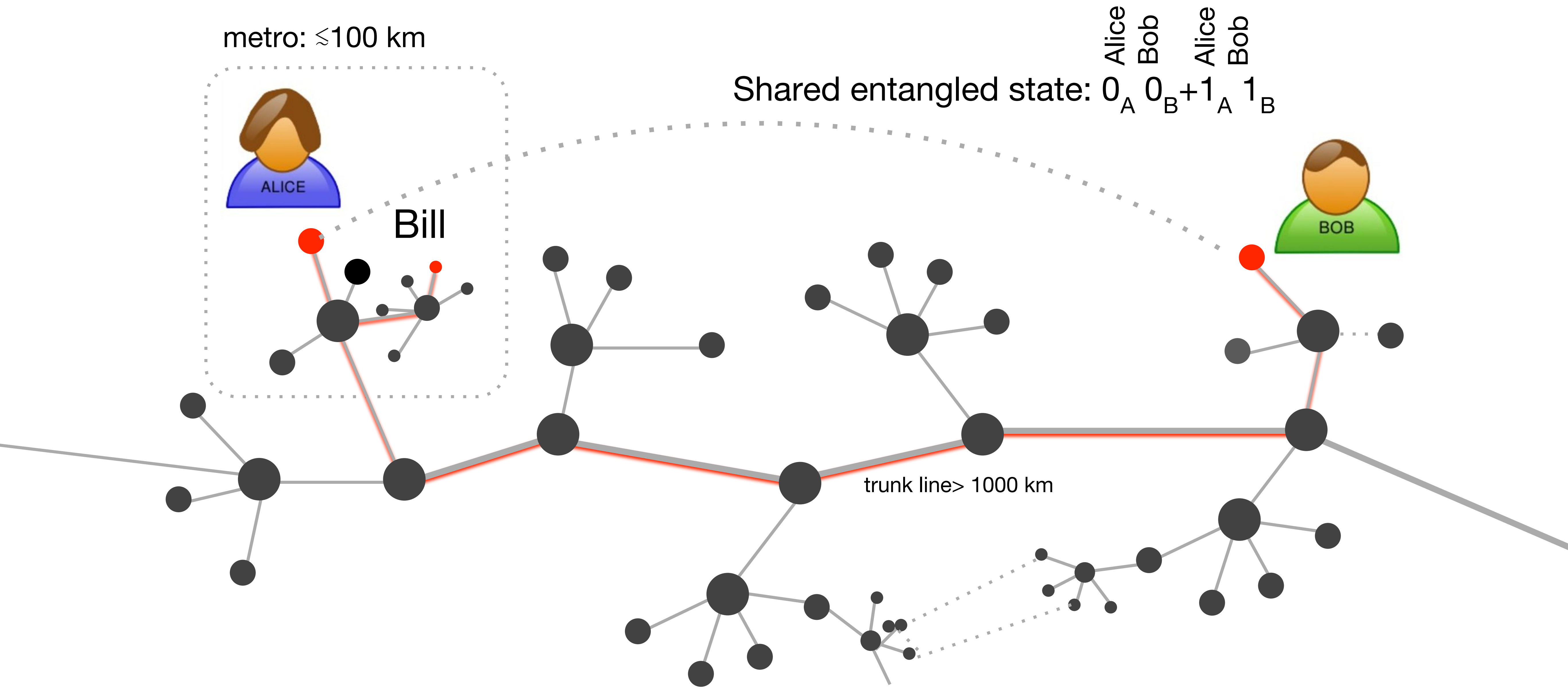
-time & space



Quantum Secure Communication

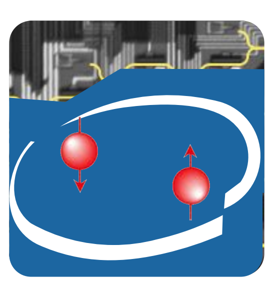


Quantum Networks

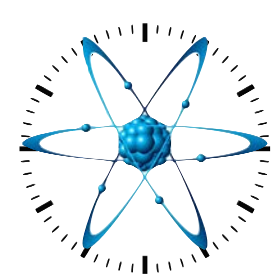


Quantum Network Applications

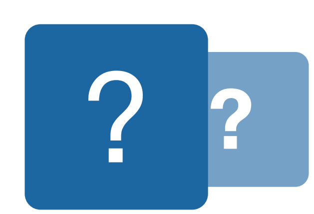
Secure Comm, Quantum foundations



Networked quantum comp., blind QC



Sensing, Timing, GPS, ..



Undis-covered app's

Repeater-less QKD growing up

id Quantique

QuantumCTek

SeQureNet
A Quantum Key to Network Security

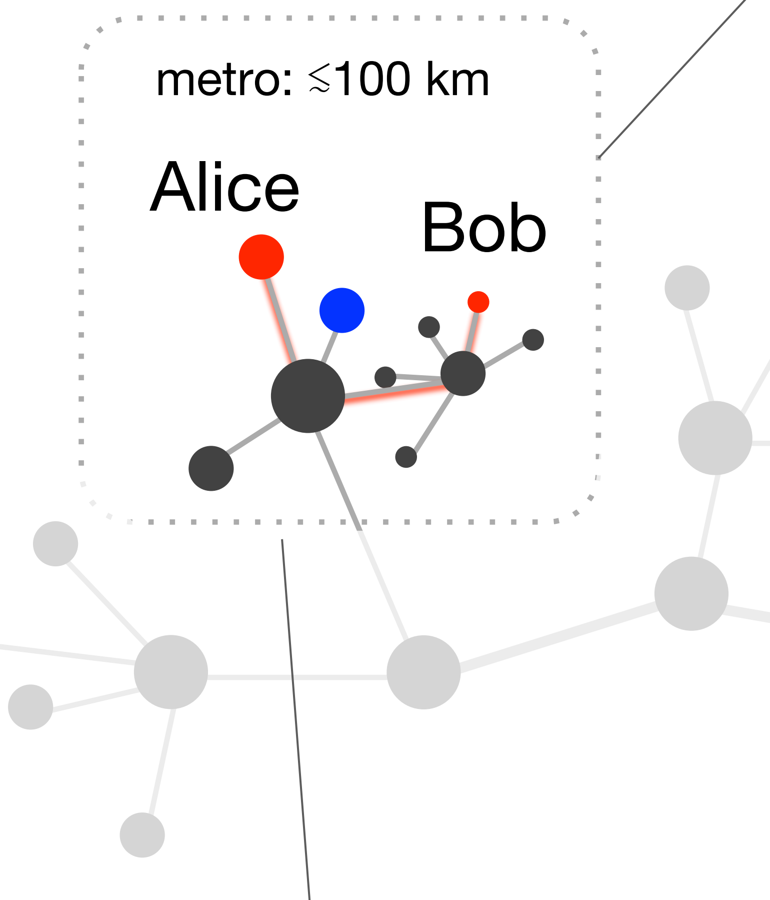
Quintessence labs
Quantum Cyber Defense™

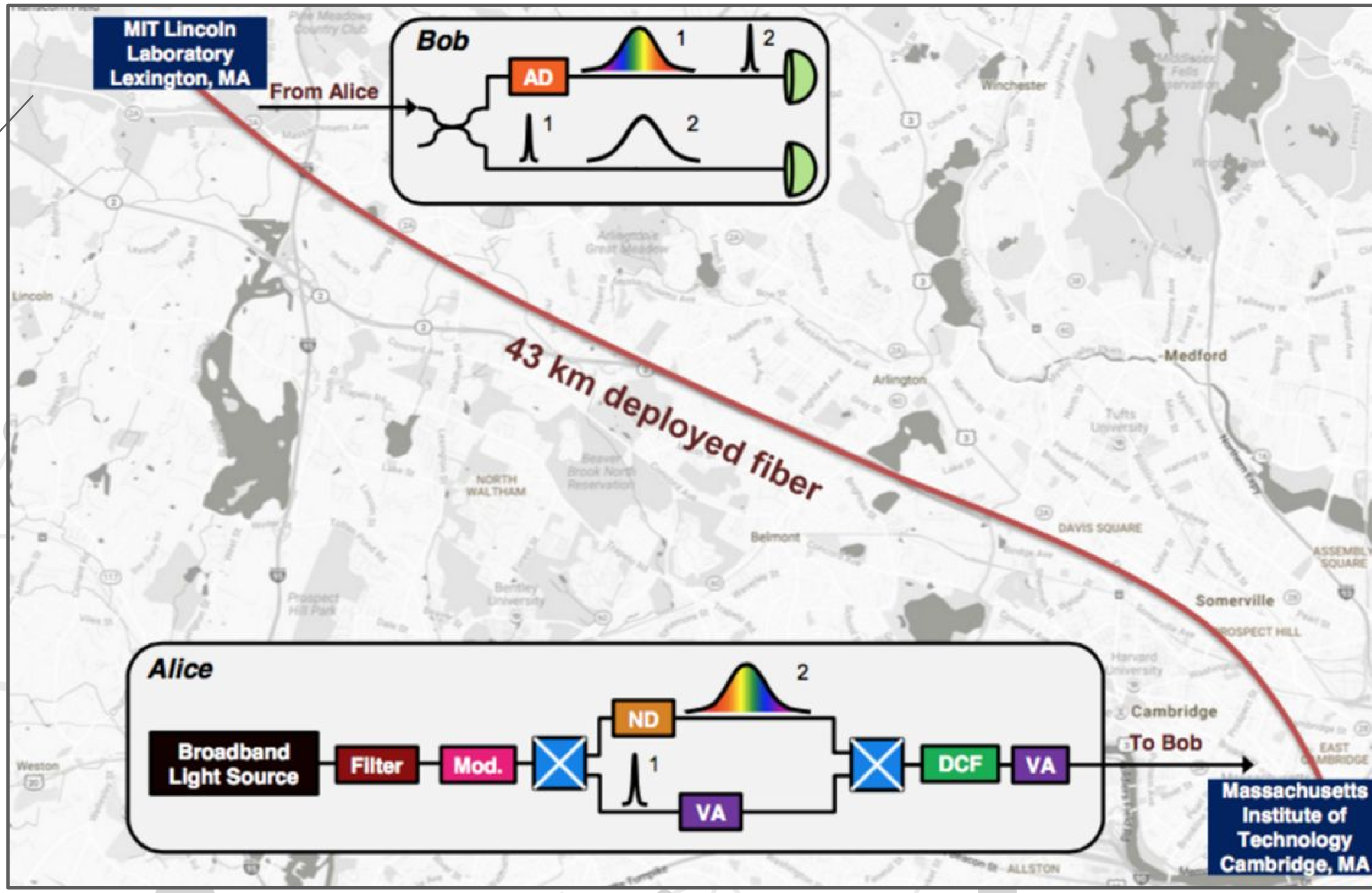
research only IBM
NTT TOSHIBA

Satellite-based photon entanglement distributed over 1,200 kilometers
J. Yin et al (J-W Pan group, USTC), Science (2017)

High-dimensional QKD field trial in Boston area

Use alphabet size d up to 1024 to maximize secret key capacity



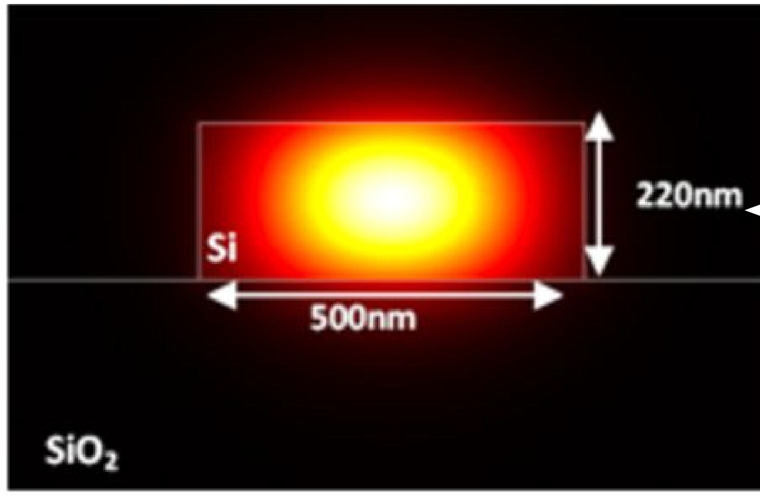


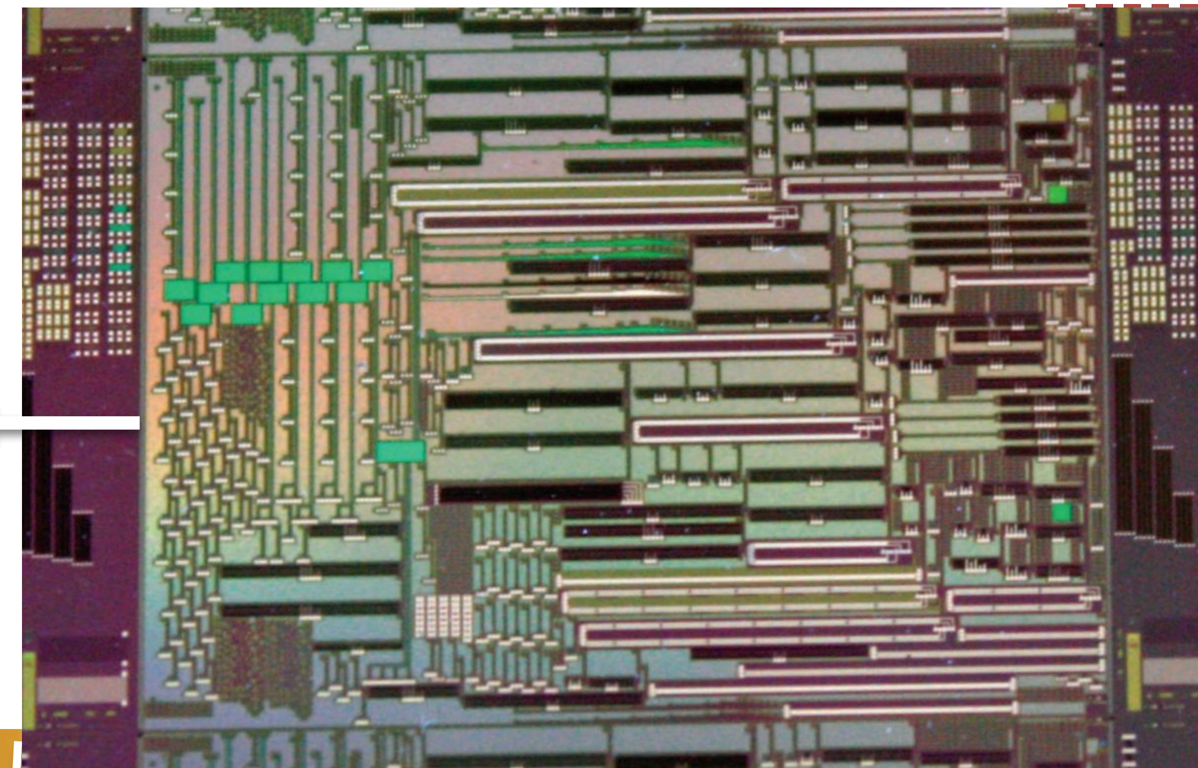
MIT-Lincoln Labs 43-km field test: > 1 Mbit/sec; > 20 Mbit/s for low loss

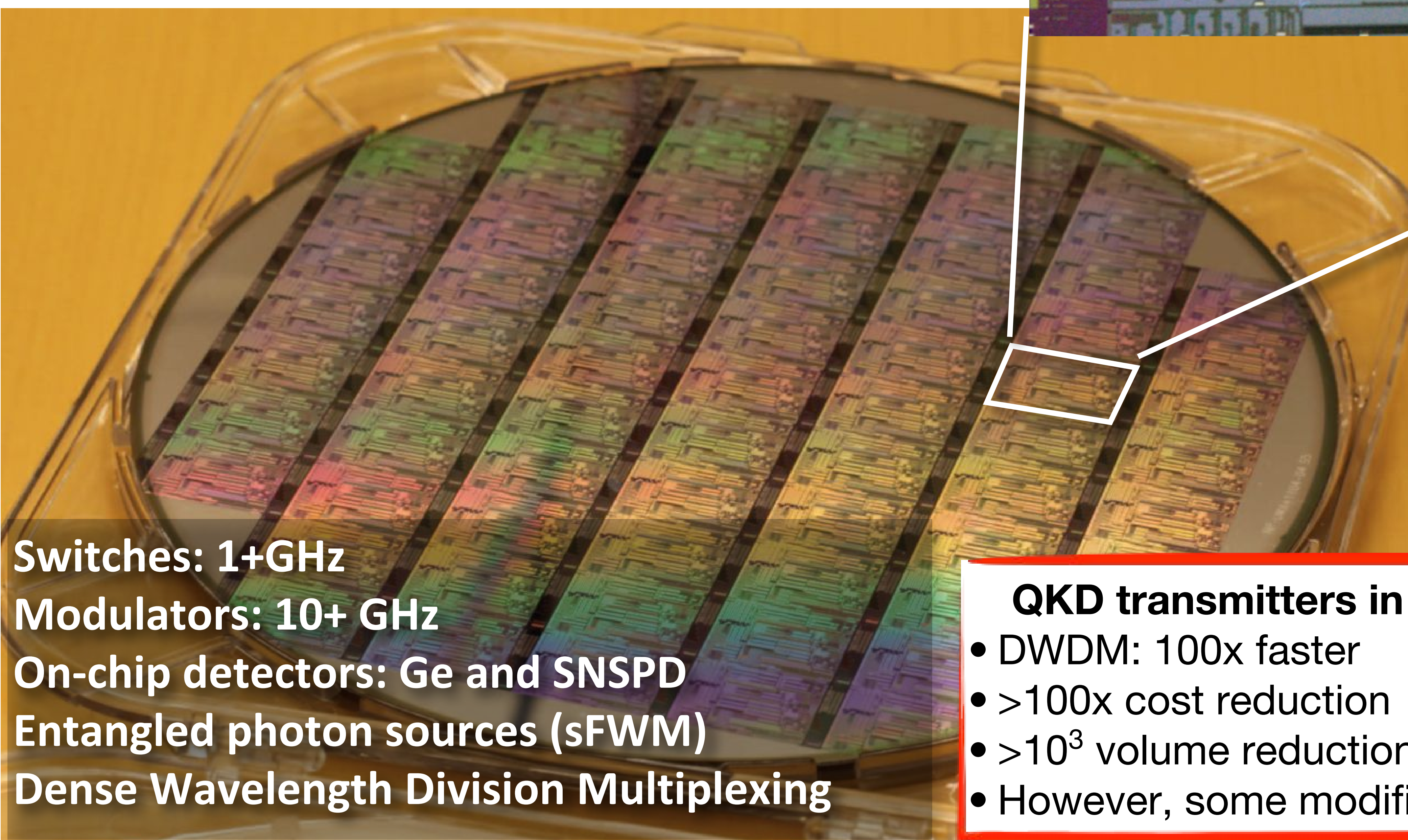
Catherine Lee et al, arXiv:1611.01139 (2016) [under review]

Security Proofs: J. Mower et al, PRA 87 (2013); Z. Zhang et al], PRL **112** (2014)
.. with finite-key correction: C. Lee et al], Qu. Inf. Proc **14** (2015)
.. with decoy state protection against photon splitting side channel attack: D. Bunandar et al, PRA 91 (2015)
Lab Demo: C. Lee et al, PRA **90**, 062331 (2014)

Silicon Photonics for QKD







Switches: 1+GHz
Modulators: 10+ GHz
On-chip detectors: Ge and SNSPD
Entangled photon sources (sFWM)
Dense Wavelength Division Multiplexing

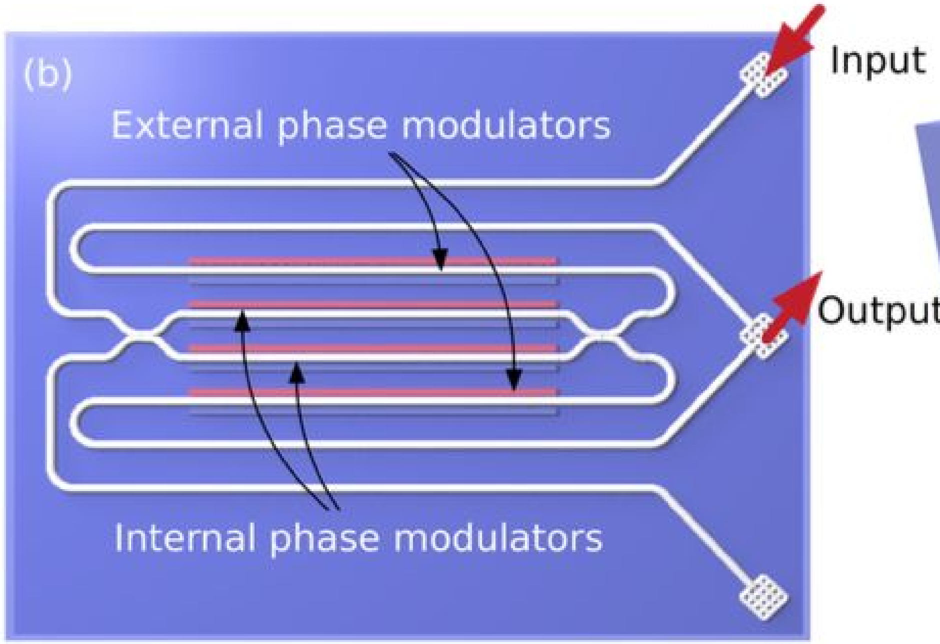
QKD transmitters in Silicon Photonics:

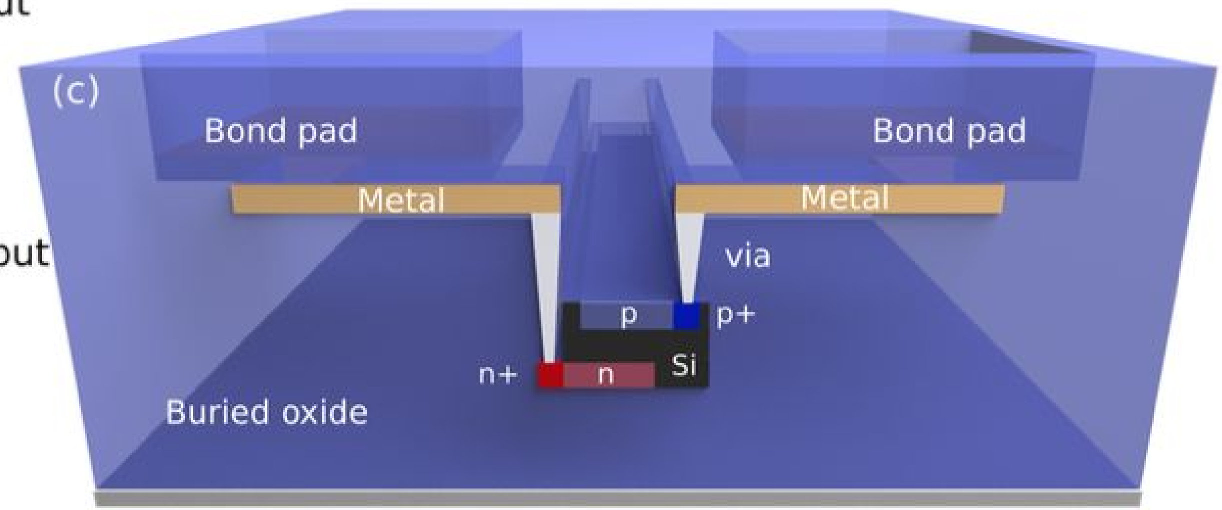
- DWDM: 100x faster
- >100x cost reduction
- >10^3 volume reduction
- However, some modification needed

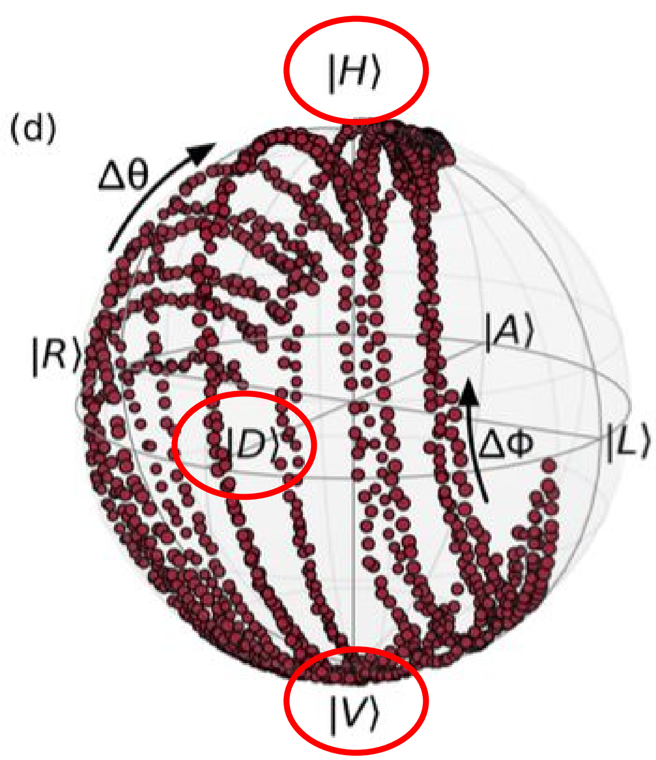
PIC for Polarization-Based QKD

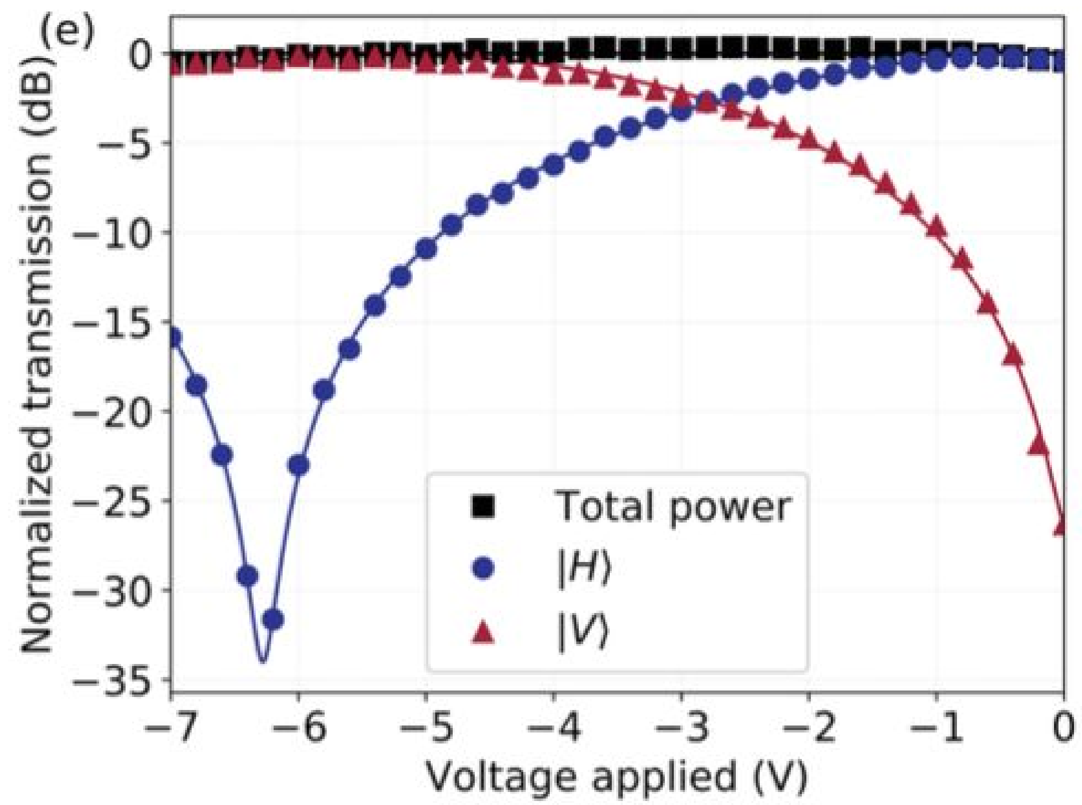
Darius Bunandar

PIC: Sandia National Laboratory





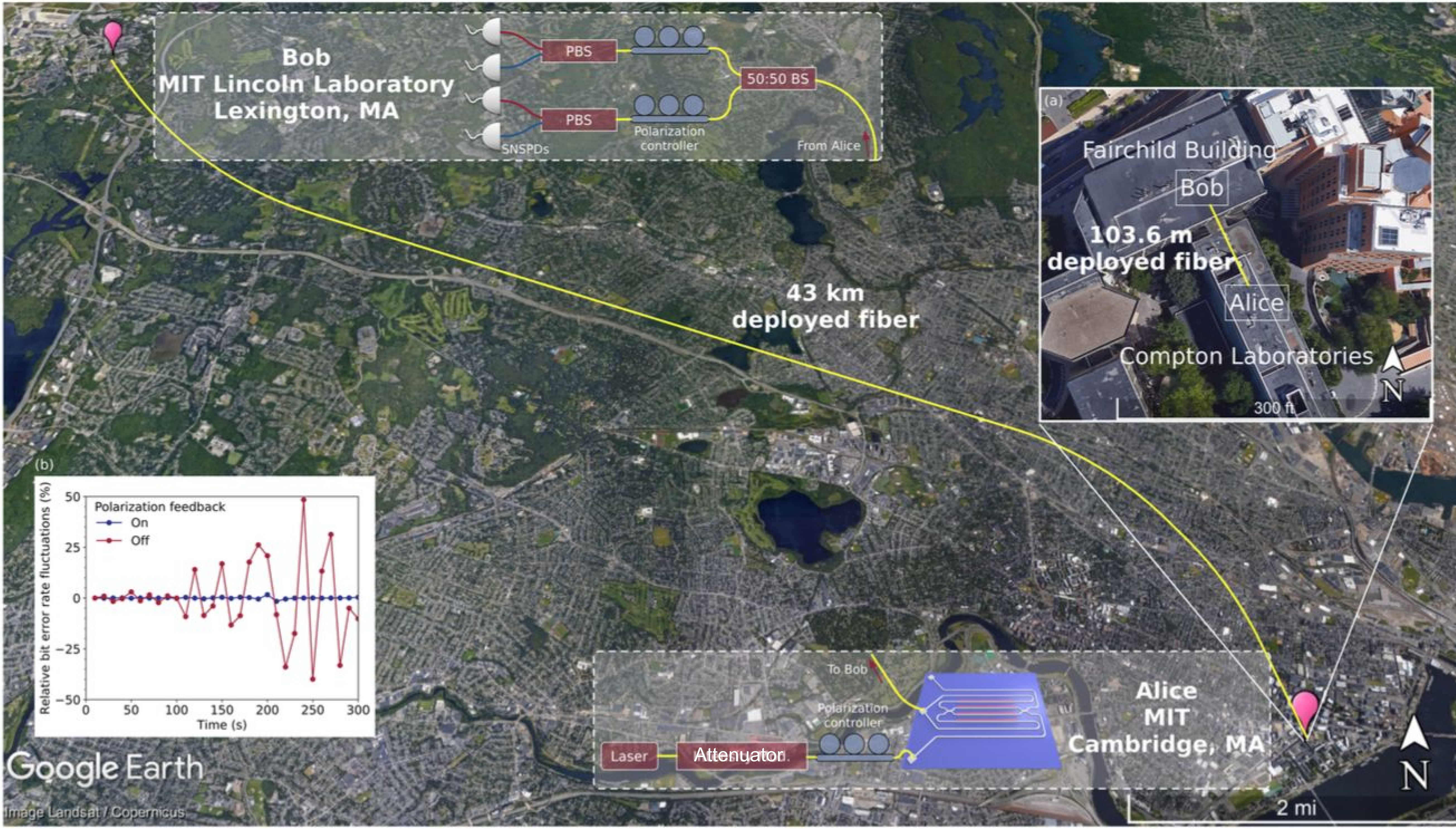




See also:
P. Sibson et al (O'Brien and Thompson groups, Bristol), Optica **4** 2 (2017)
C. Ma al (J. Poon group), Optica **3** 11 (2016)
Y. Ding et al (Oxenloewe group, DTU), npj Quantum Information (2017)

D Bunandar, Anthony Lentine, C Lee, H Cai, C Long, N Boynton, N Martinez, C DeRose, C Chen, M Grein, D Trotter, A Starbuck, A Pomerene, S Hamilton, F N. C. Wong, R Camacho, P Davids, J Urayama, and D Englund, ArXiv:708.00434 [quant-ph]; under review (2017)

Field Test with Polarization Feedback



Transmission: 1_Z, 0_Z, 1_X; detection on all 4 states (X and Z)

D Bunandar, Anthony Lentine, C Lee, H Cai, C Long, N Boynton, N Martinez, C DeRose, C Chen, M Grein, D Trotter, A Starbuck, A Pomerene, S Hamilton, F N. C. Wong, R Camacho, P Davids, J Urayama, and D Englund, ArXiv:708.00434 [quant-ph]; under review (2017)

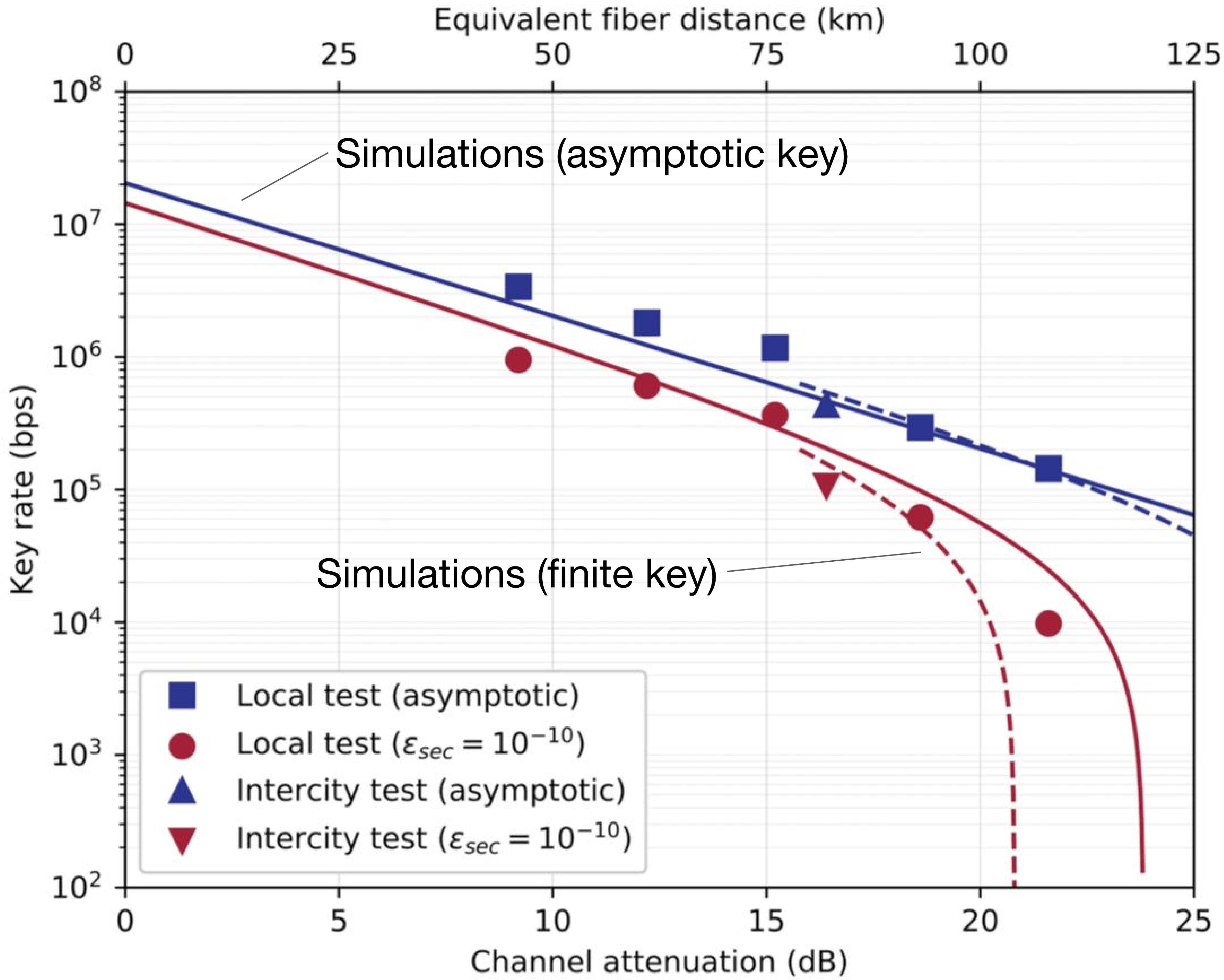
Results

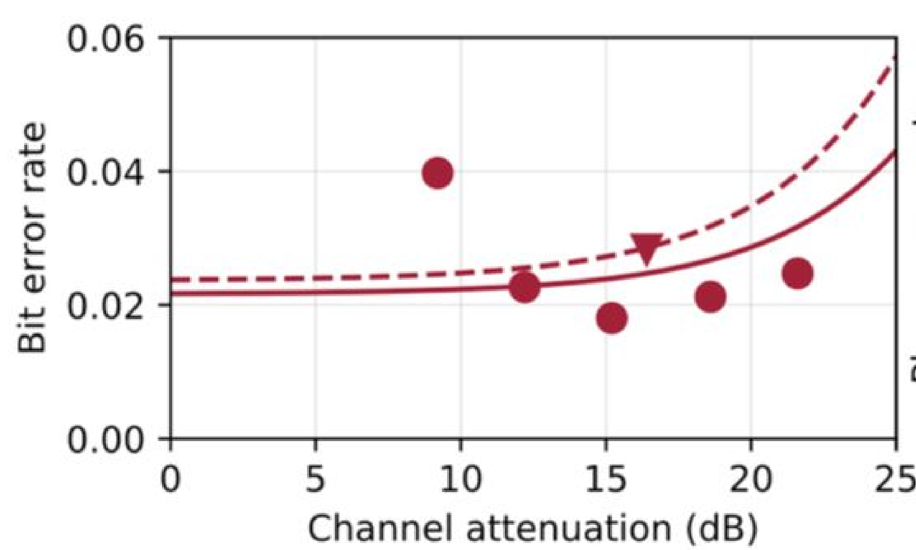
Laser decoy protocol: $\mu, \mu_{DC1}, \mu_{DC2}$=0.12, 0.012, 0.003

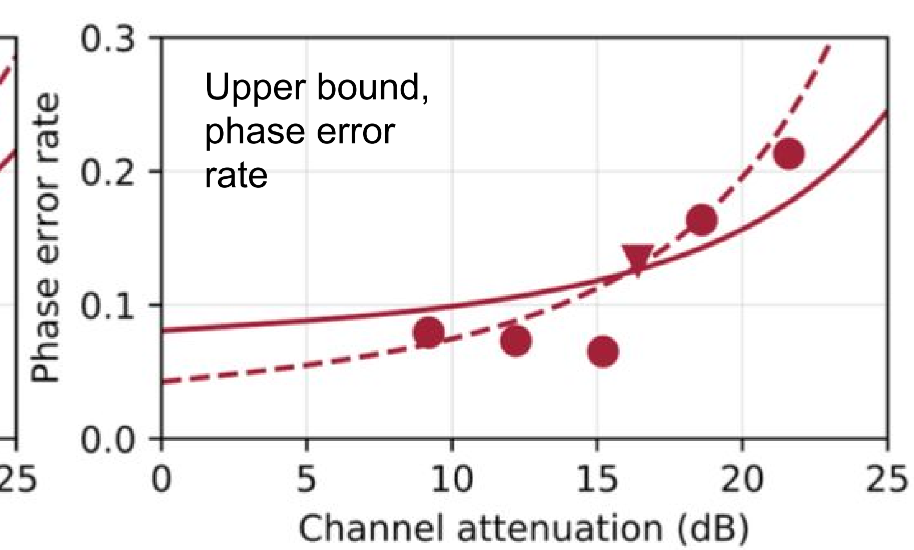
Clock @ 650 MHz

Uses only 3 state transmission w/ finite-key analysis*

Composable security: tight security parameter of ε_{sec} =10^{-10}





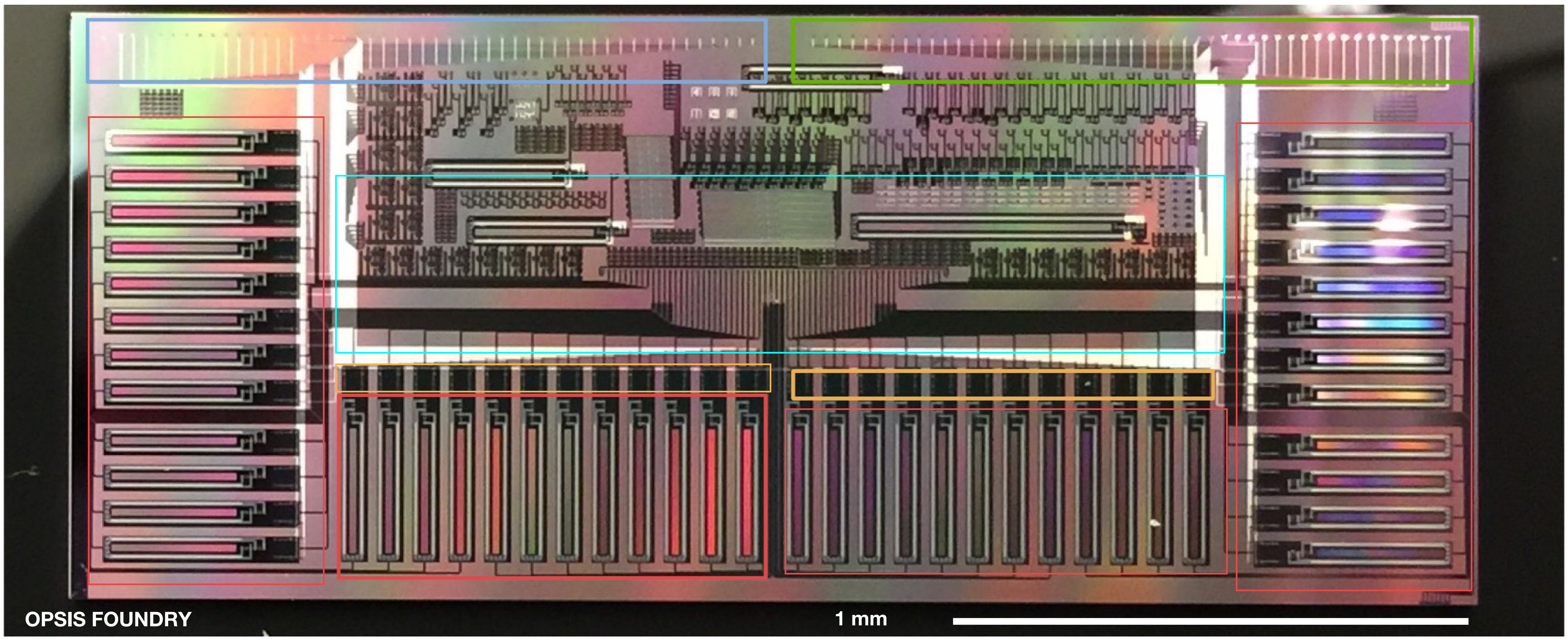


*A. Mizutani et al, New J. of Phys. **17** (2015)
D. Bunandar et al, ArXiv:708.00434

48-channel transmitter for time-bin encoded QKD

Next: wavelength-division multiplexing

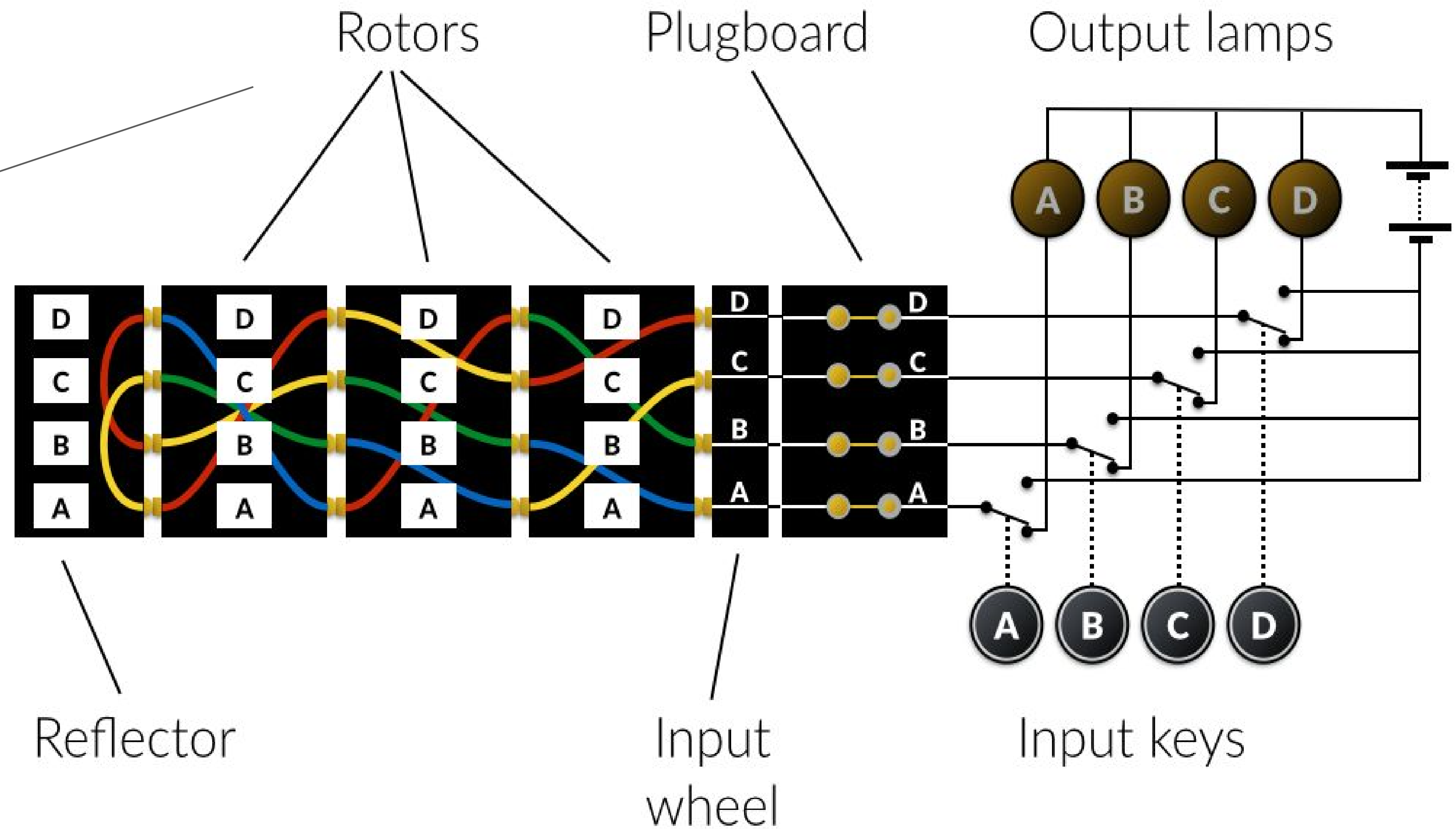
Adapted from OPSIS foundry



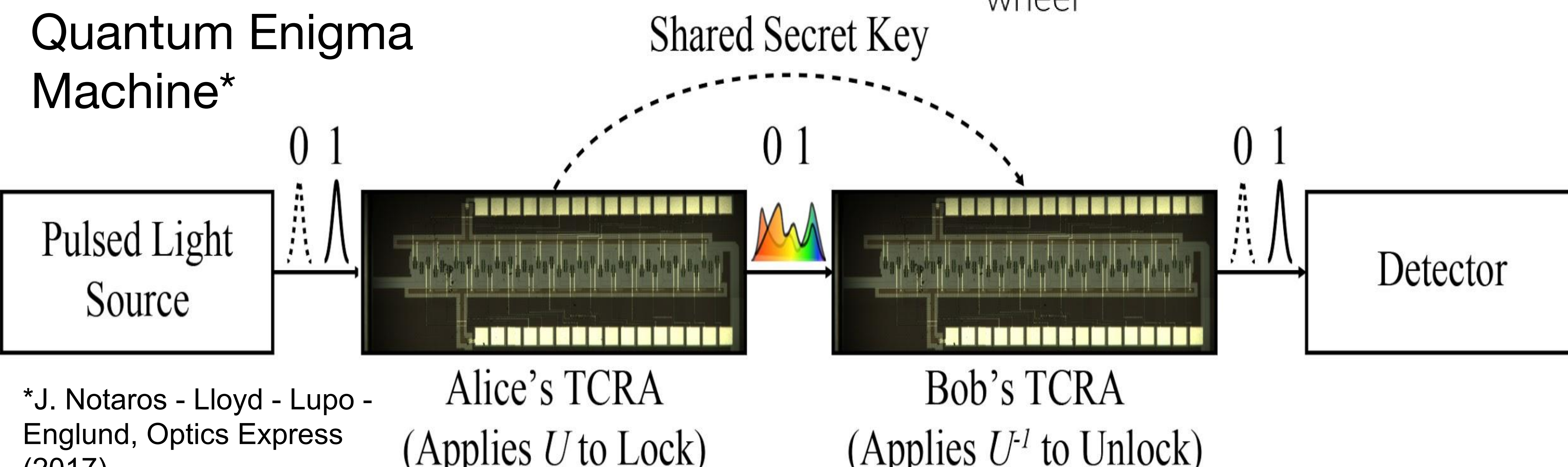
48 Traveling Wave Modulators	Input Grating Couplers	Output Grating Couplers	Phase Modulators	Multiplexing

Collaboration with Michael Hochberg and Tom Baer Jones

Enigma Machine Revisited

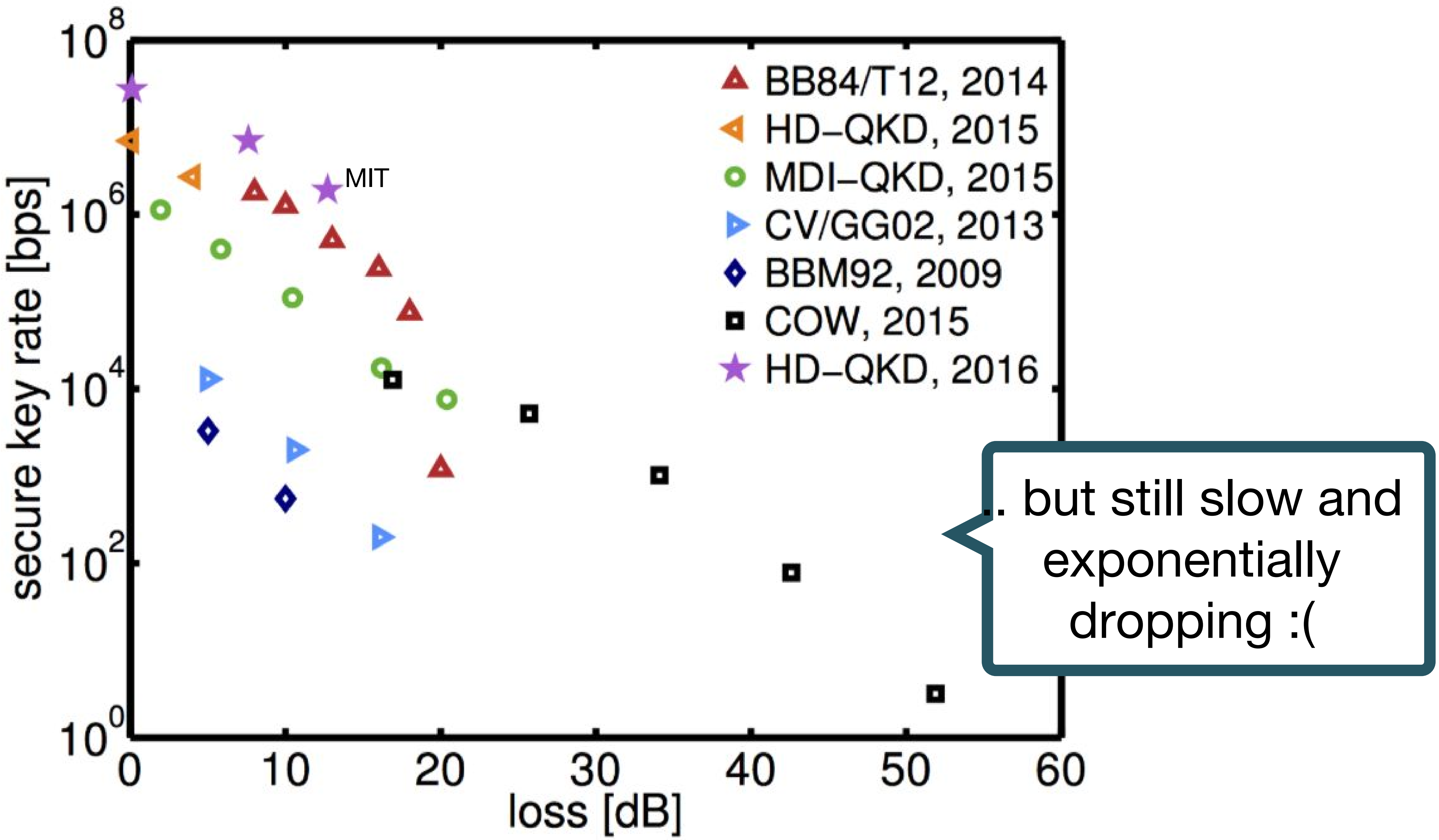


Quantum Enigma Machine*



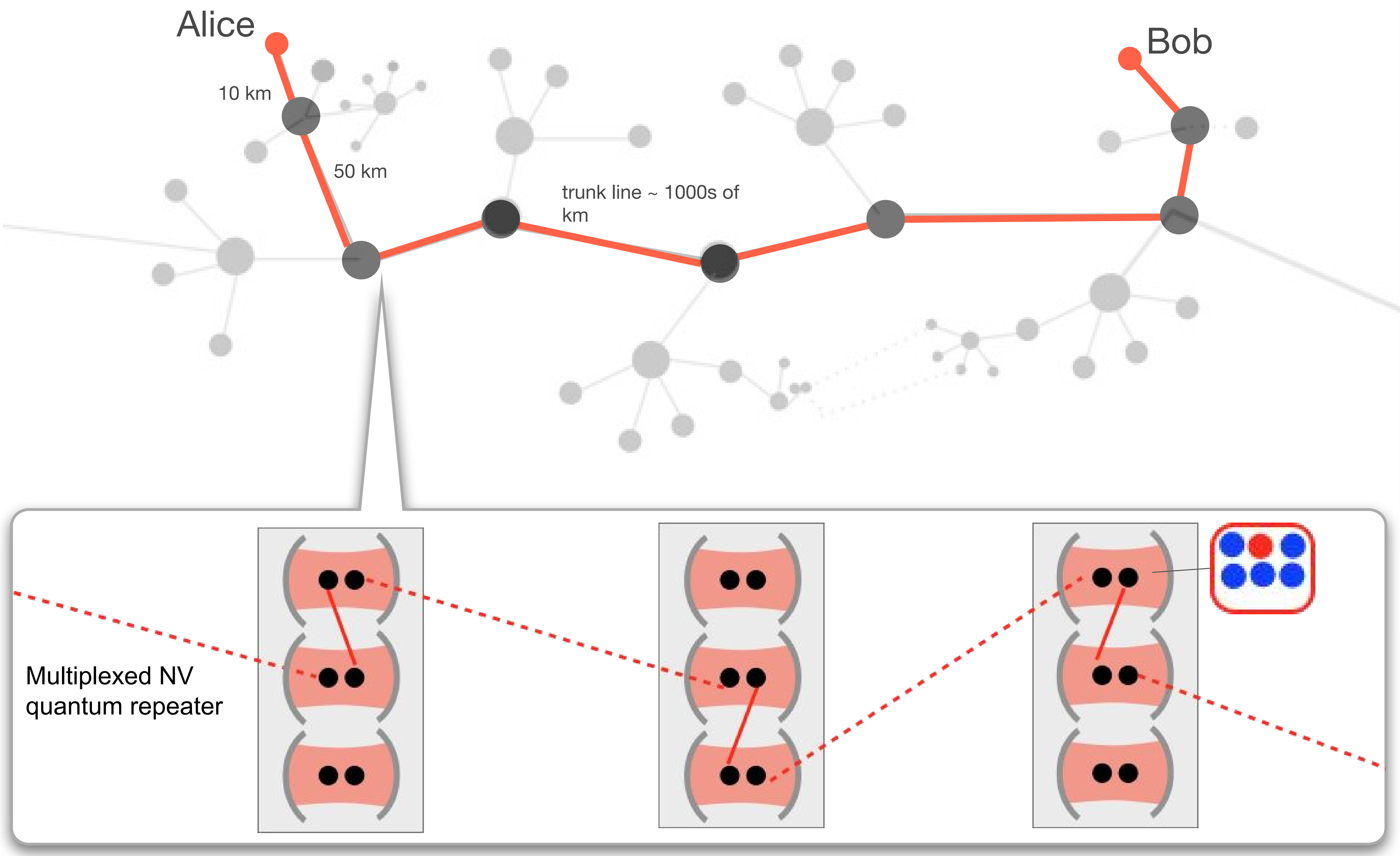
*J. Notaros - Lloyd - Lupo - Englund, Optics Express (2017)

QKD records..



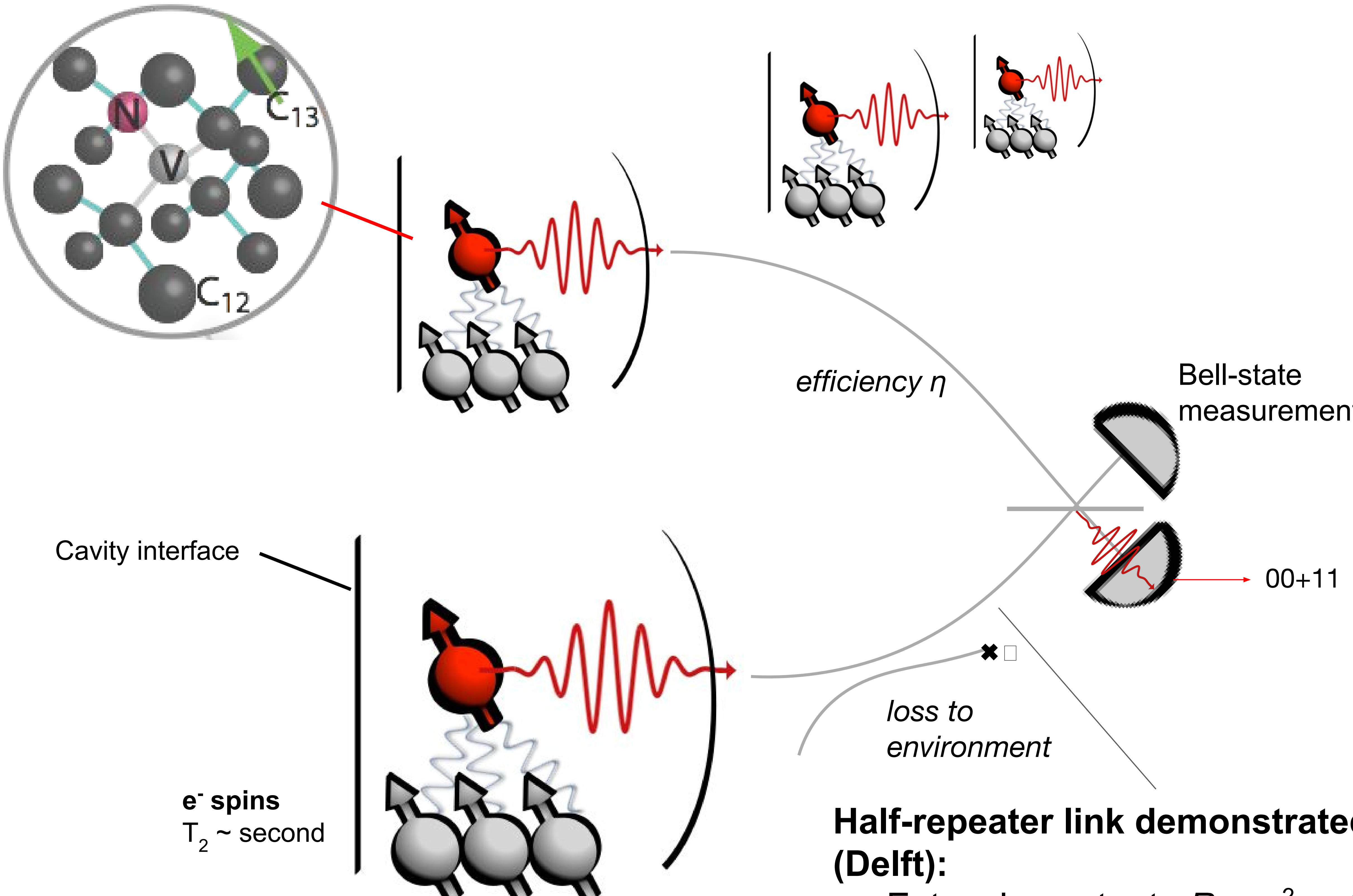
Recent record secure key generation rates (in bits per second), plotted against the experimental quantum channel loss (in dB), of the different QKD protocols: prepare-and-measure BB84 QKD (Comandar et al., 2014), high-dimensional QKD (HD-QKD) (Zhong et al., 2015), measurement-device-independent QKD (MDI-QKD) (Comandar et al., 2016), continuous variable (CV)/GG02 QKD (Jouguet et al., 2013), six-state BBM92 QKD (Treiber et al., 2009), coherent-one-way (COW) QKD (Korzh et al., 2014). The record highest secret key generation rate (HD-QKD, 2016) is our most recent experimental result (Lee et al., 2016).

Quantum repeater networks



H. Briegel et al, PRL 81 (1998)

Quantum networks with diamond NV centers



Nuclear spins
T_2 ~ second

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

Half-repeater link demonstrated (Delft):

- Entanglement rate $R \propto \eta^2$, ~1/10 sec
- W. Pfaff et al (Delft), Science 345, 2014; N. Kalb et al, (Deflt) arXiv:1703.03244v1

Long-Range Entanglement with Solid State Qubits

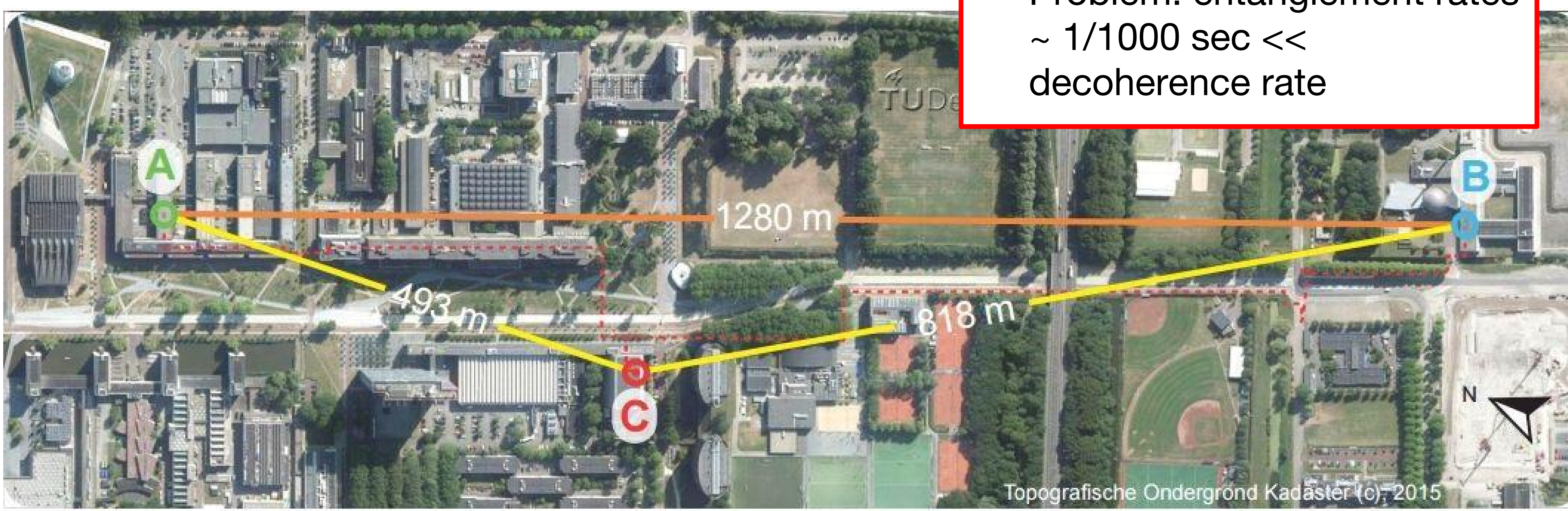
Sorry, Einstein. Quantum Study Suggests 'Spooky Action' Is Real.

By JOHN MARKOFF OCT. 21, 2015

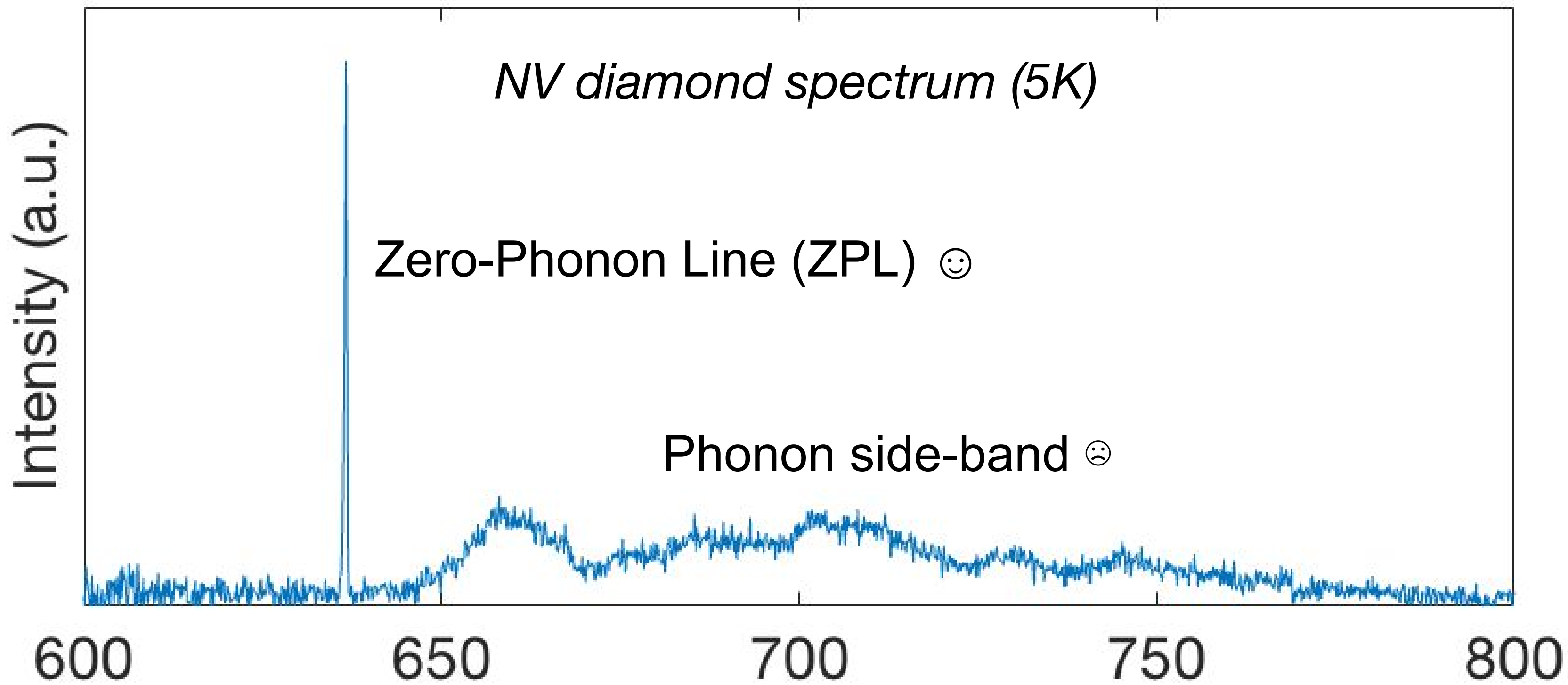
New York Times

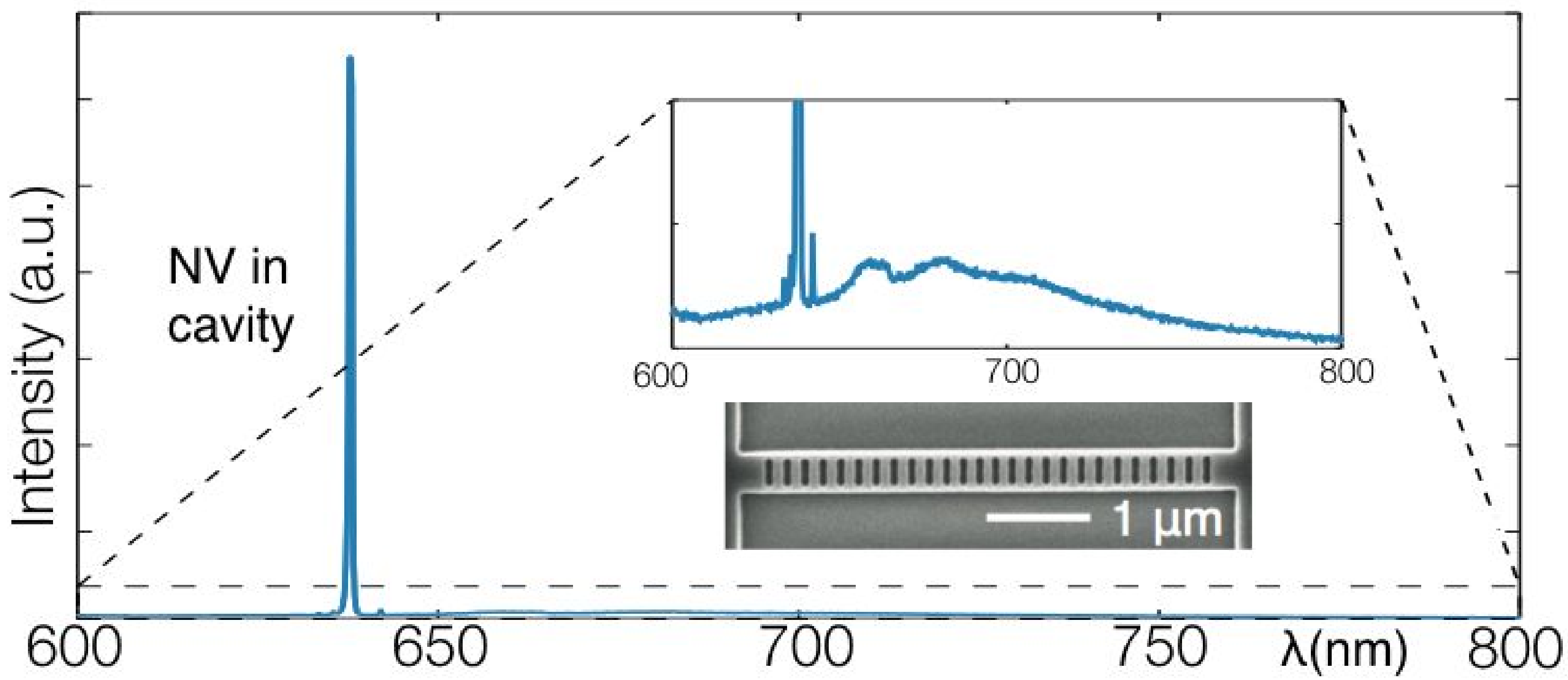
- Remote spin entanglement demonstrated for 2 Nitrogen Vacancy (NV) centers in diamond at 1.3 km:
  - B. Hensen et al, Nature 526, 682-686 (2015)

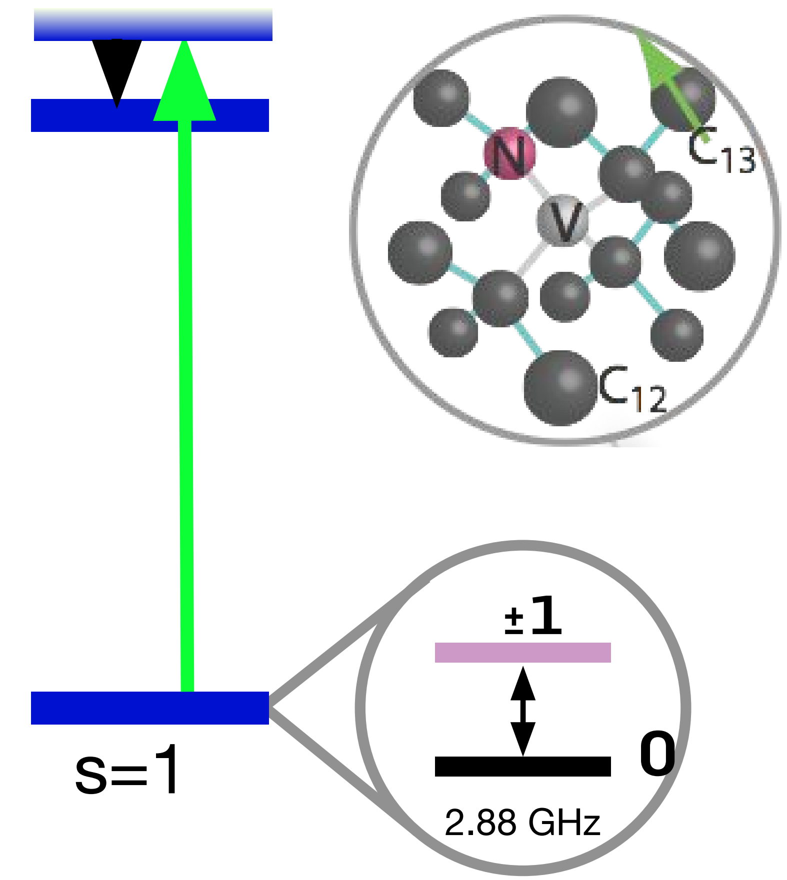
Problem: entanglement rates ~ 1/1000 sec << decoherence rate



"Fixing" the NV







Outstanding challenges:

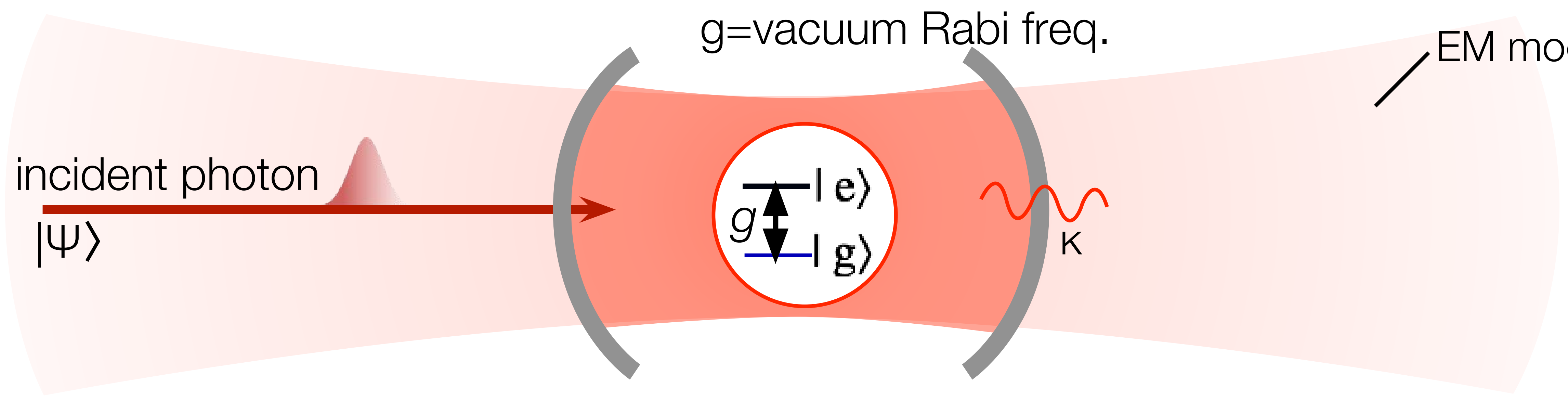
- Spectral stability
- Photon interfaces
- Device yield

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

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

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

Cavity increases spin-photon scattering

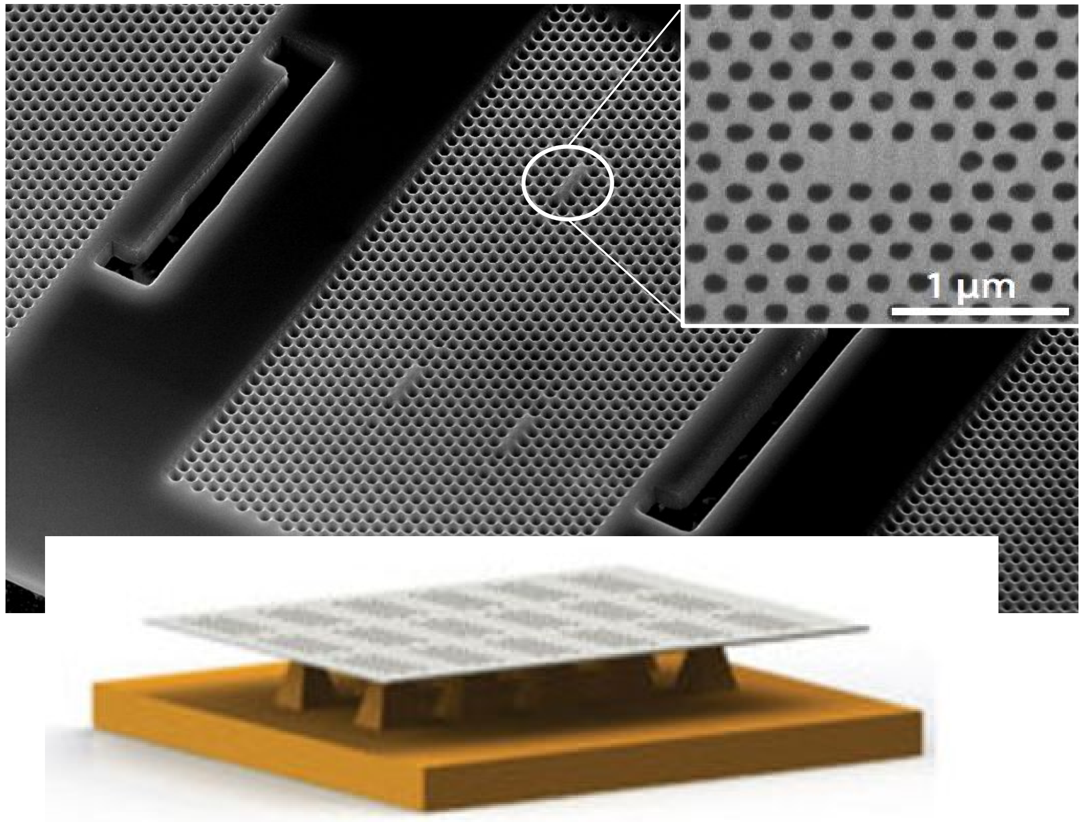


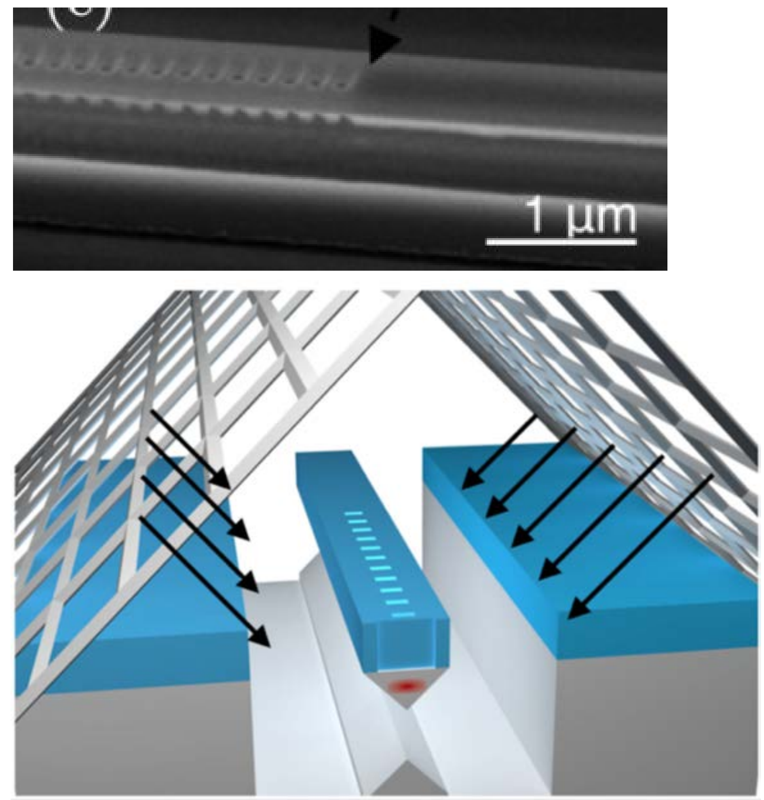
Scattering rate increases with $F_P \propto Q/V_{mode}$

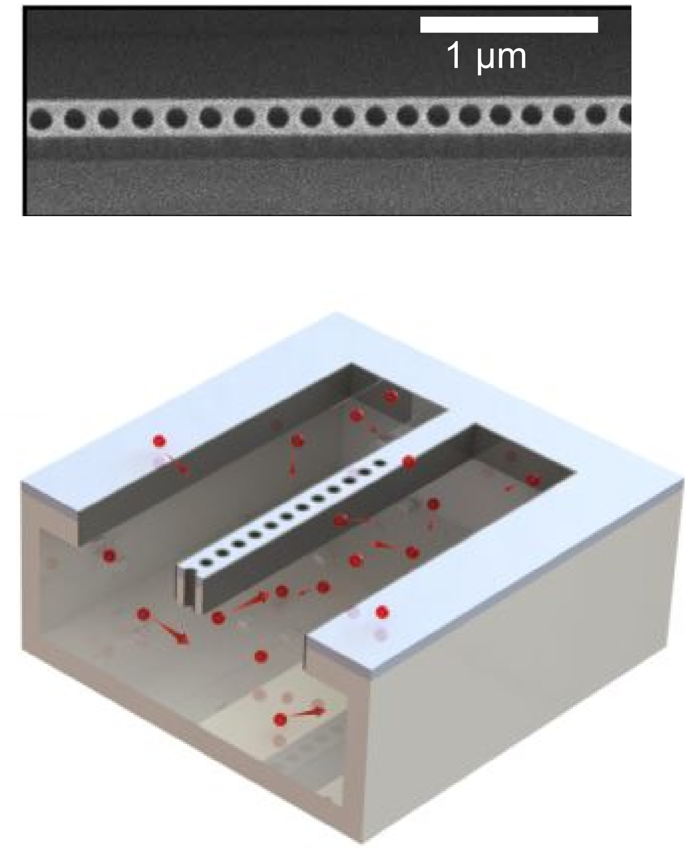
[1] E. M. Purcell, Phys. Rev. 69, 681 (1946)

Weak-coupling regime, $g < \kappa, \gamma$

Diamond PhC Patterning







Q < 10,000
NV: λ_{ZPL} ~ 10s GHz

Aligned emitters✔
Chip Size: 100x100 µm✘
yielding cavities>10^2

L. Li et al Sci Rep 5 (2015)

Q > 8,000
NV: λ_{ZPL} < 5 GHz

Aligned emitters✔
Chip Size: 4x4 mm✔
yielding cavities>10^3

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

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

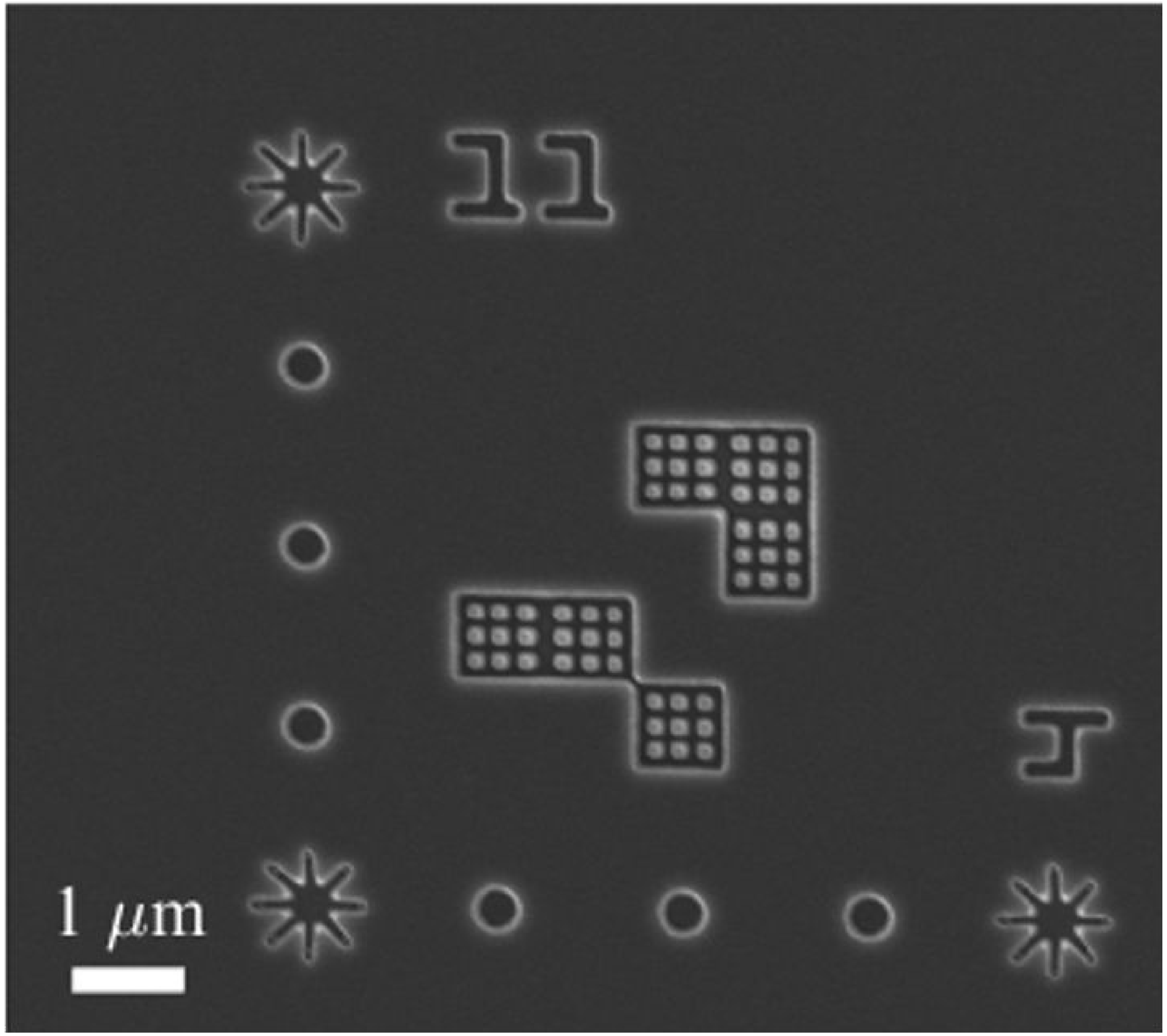
I. Bayn et al, Applied Physics Letters 105, 21 (2014)

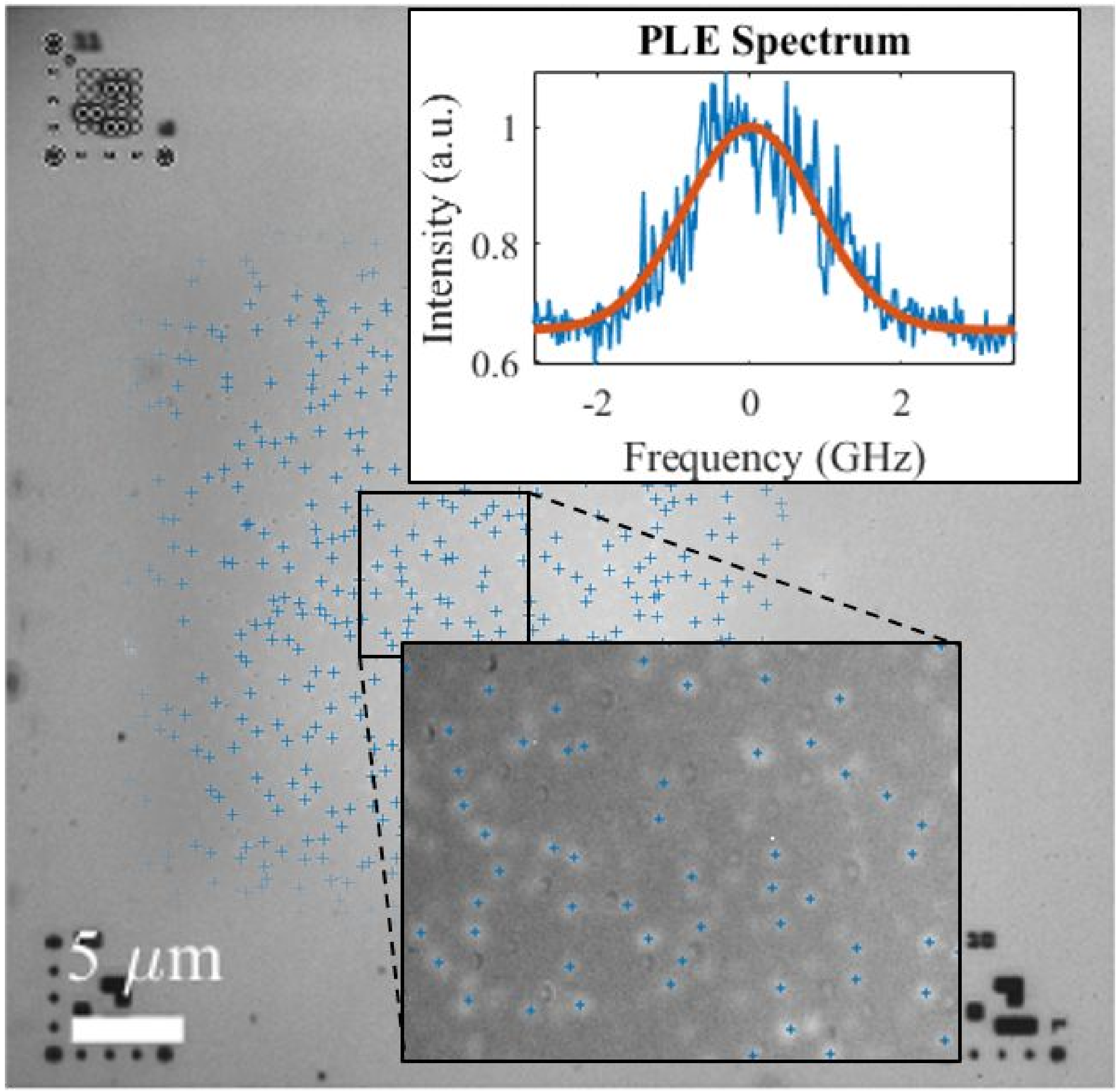
Q > 14,000
NV: λ_{ZPL} < 1 GHz

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

S. Mouradian, N. Wan et al, APL **111** (2017)

Increasing the device yield



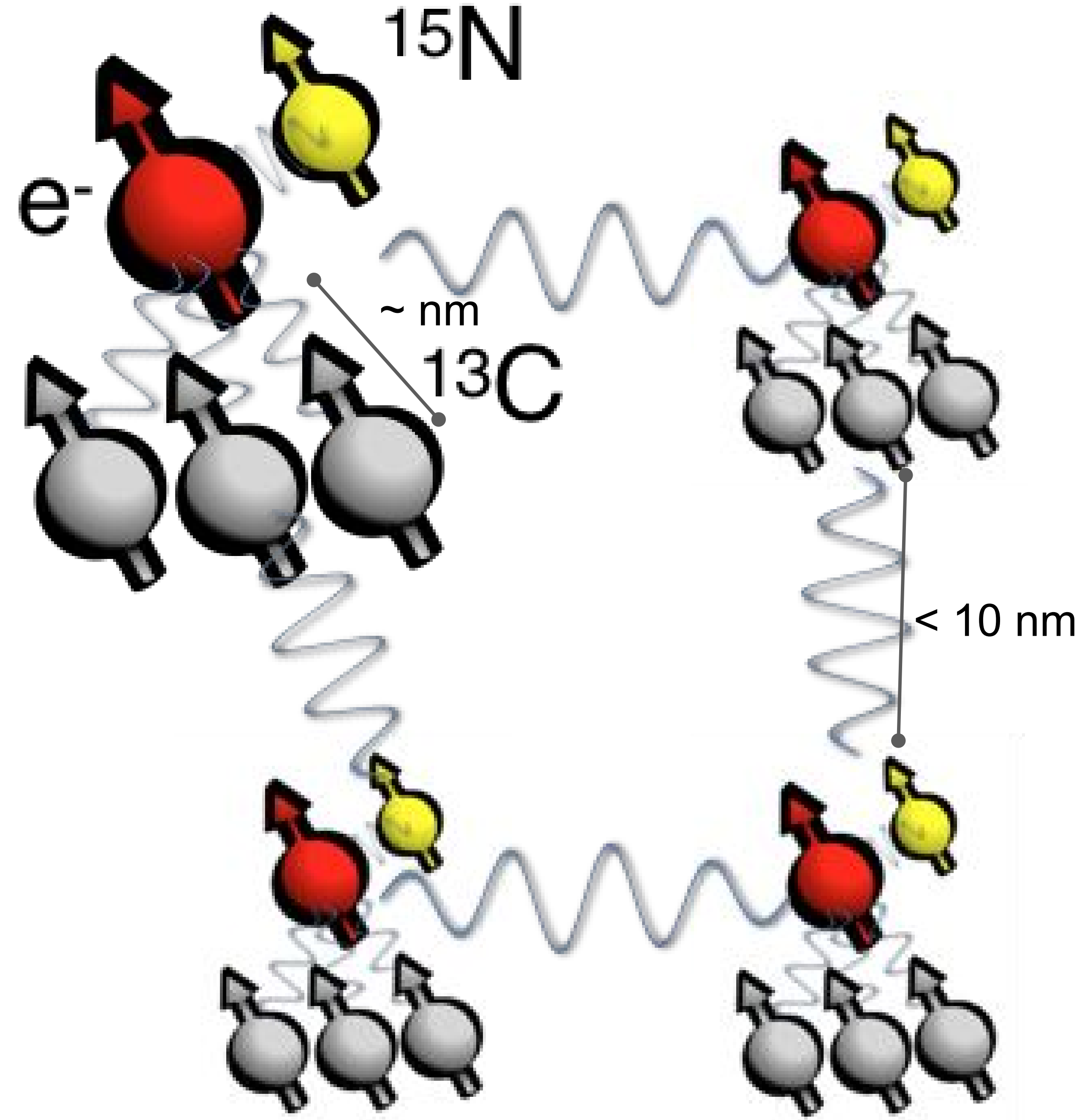


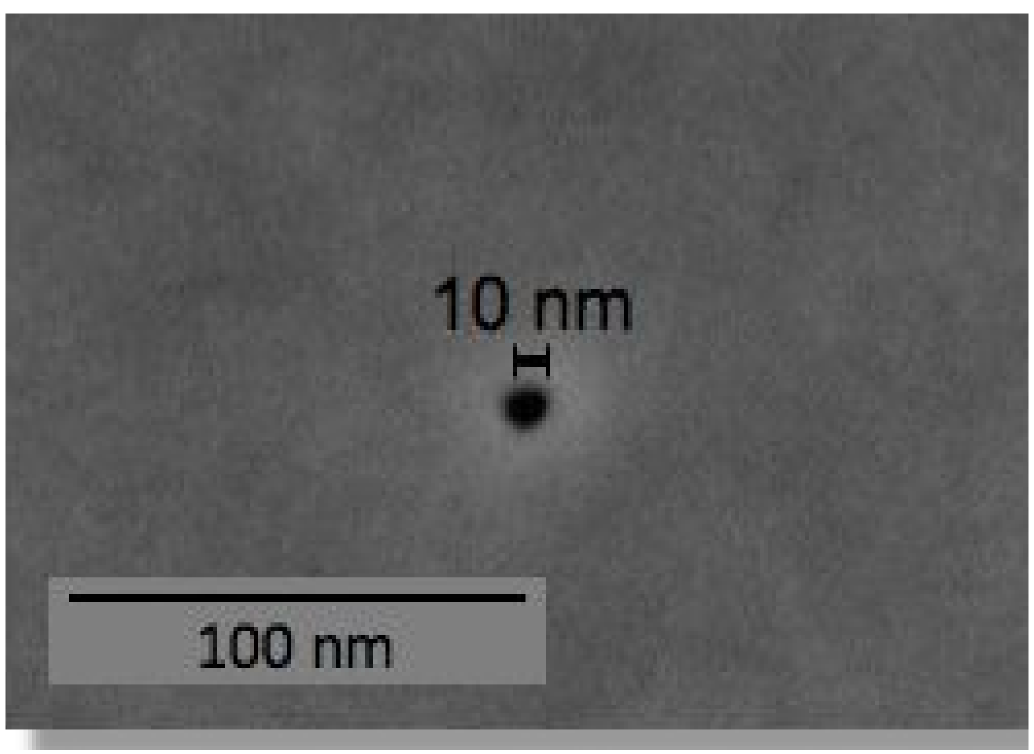
Aligned NV-cavity systems with near-perfect yield.

Multi-NV sites for error correction

E.C. necessary for scalable networks or computing.

E.C. demonstrated with 3 data qubits[1], but General EC requires at least 9 qubits
⇒ Need NV arrays → implantation[2]

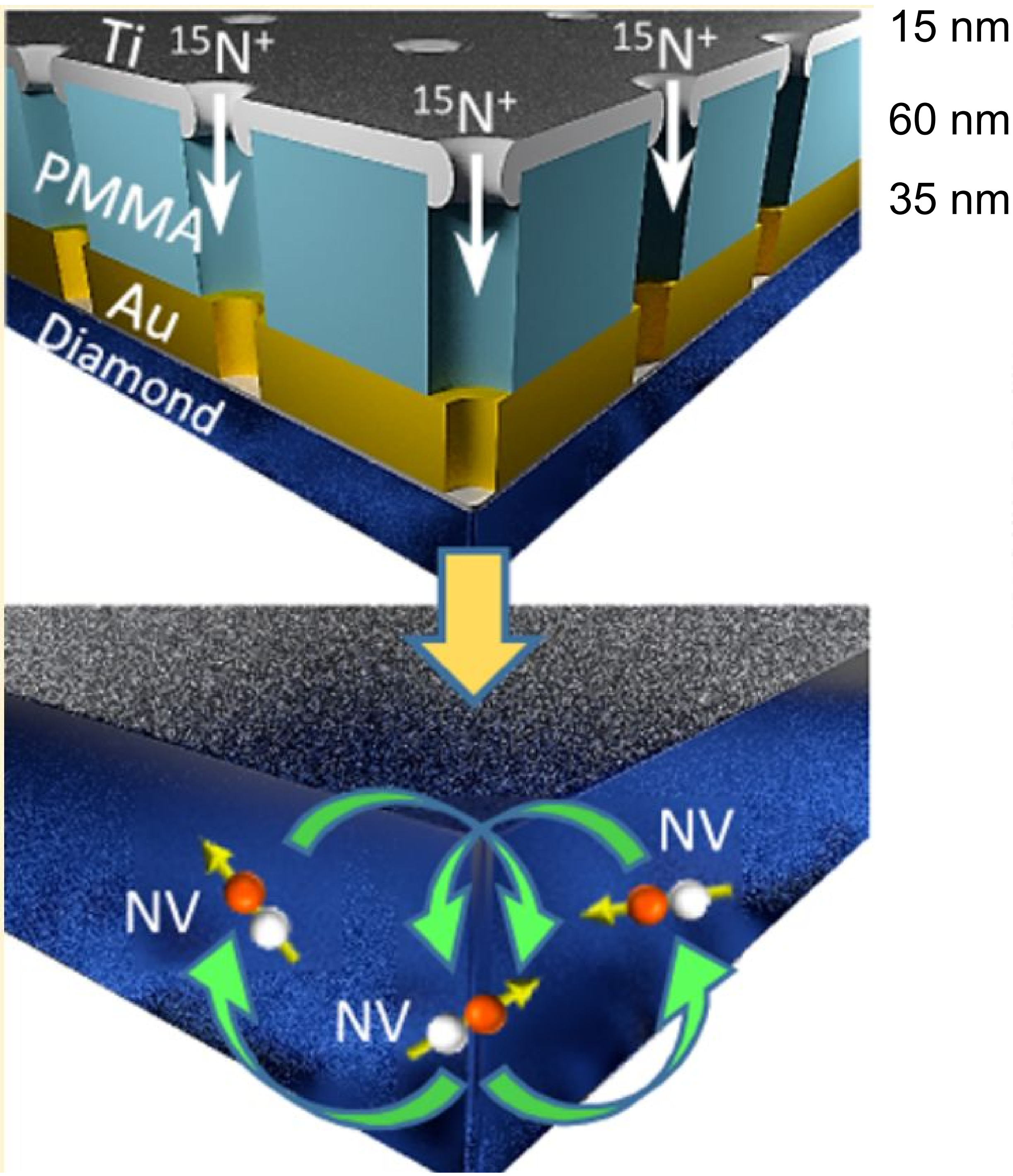


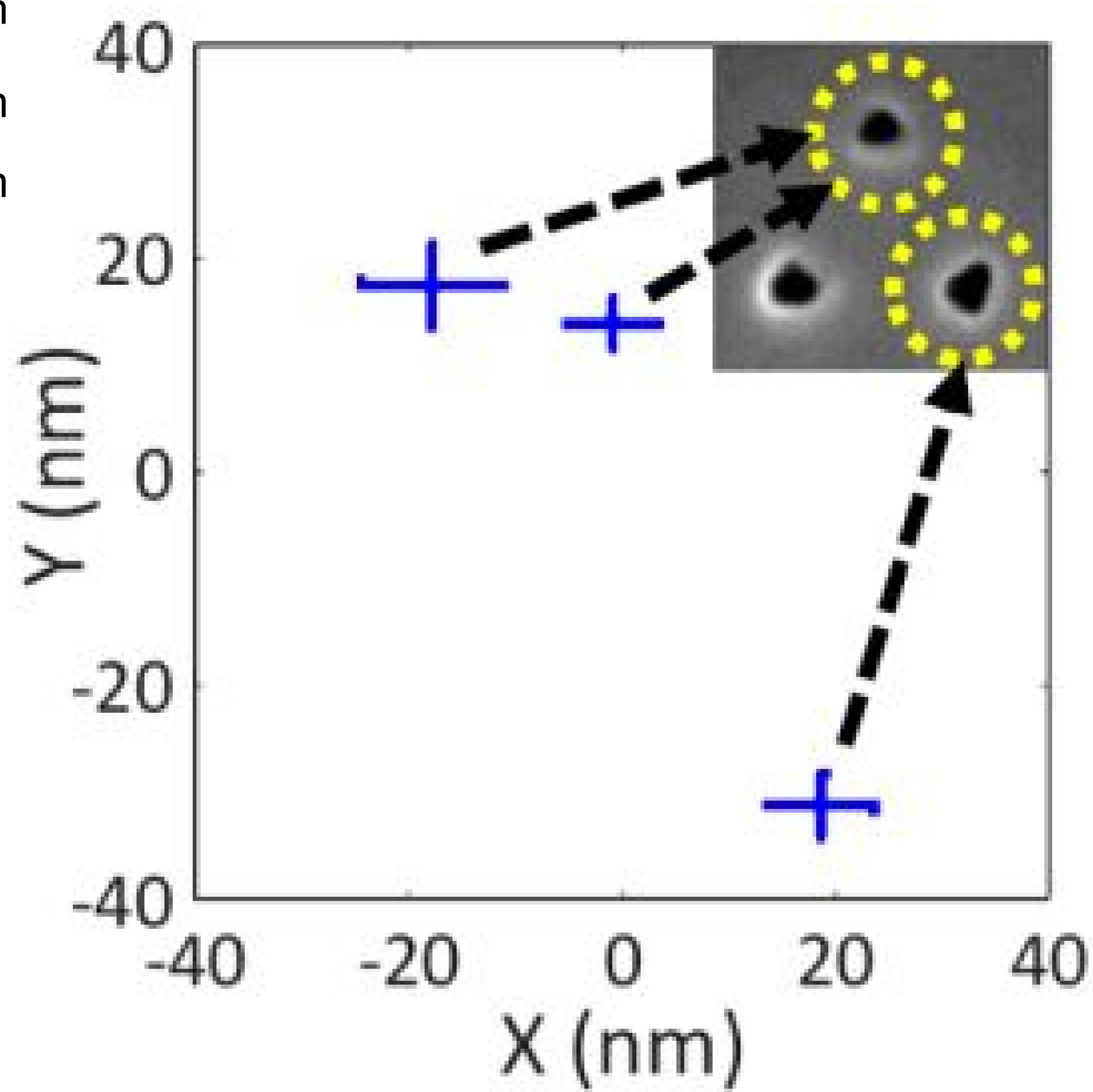


[1] J.Cramer et al, NCOMM 7 (2016)
[2] D Scarabelli, M. Trusheim, et al, Nano Letters 16 (2016); I. Bayn et al, Nano Letters **15**, 3 (2015)

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Implanting a few NVs at the nanometer scale





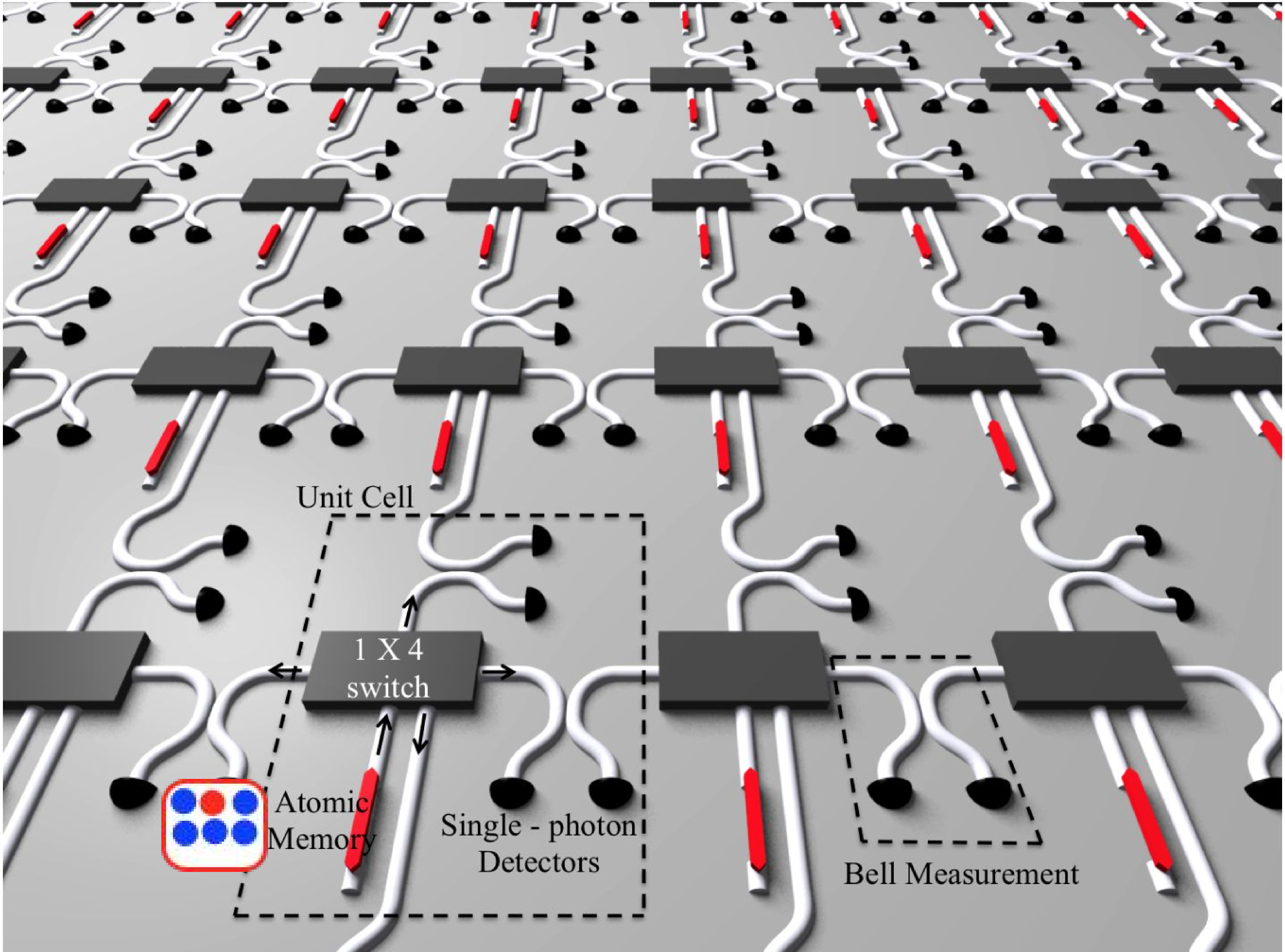
D Scarabelli, M. Trusheim, et al (Wind), Nano Letters 16 (2016); see also I. Bayn et al, Nano Letters **15** (2015)

Sub-diffraction limited imaging technique: E. H. Chen et al, Nano Letters 13, 2073 (2013)

See also Wrachtrup group/U. Stuttgart: 2 coupled nearby NVs

Collaboration with Shalom Wind, Columbia U.

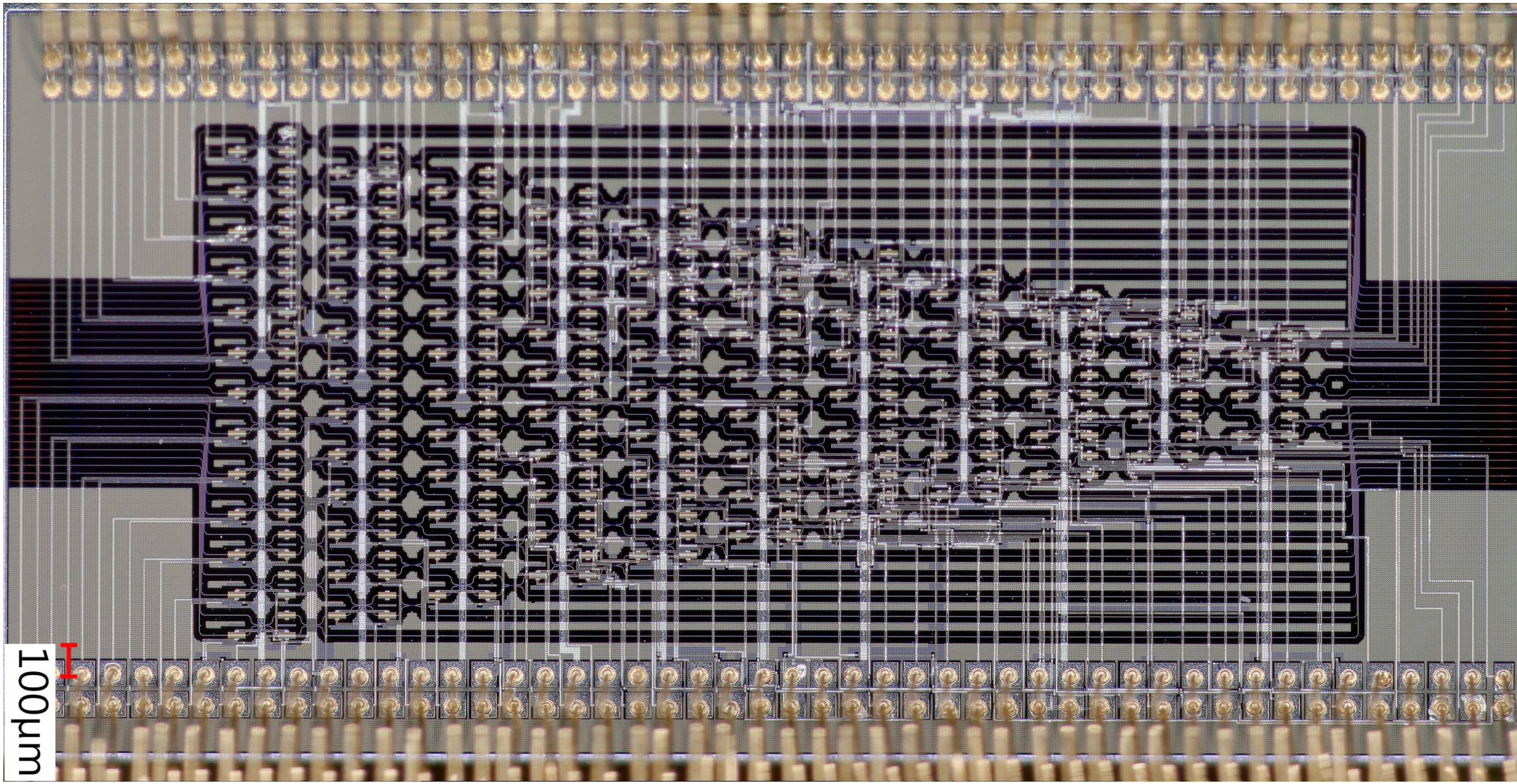
Quantum Repeater / Mod. Quantum Computer Architecture



M. Pant et al, arXiv:1704.07292 (2017)

Programmable circuits in silicon photonics

Programmable PIC



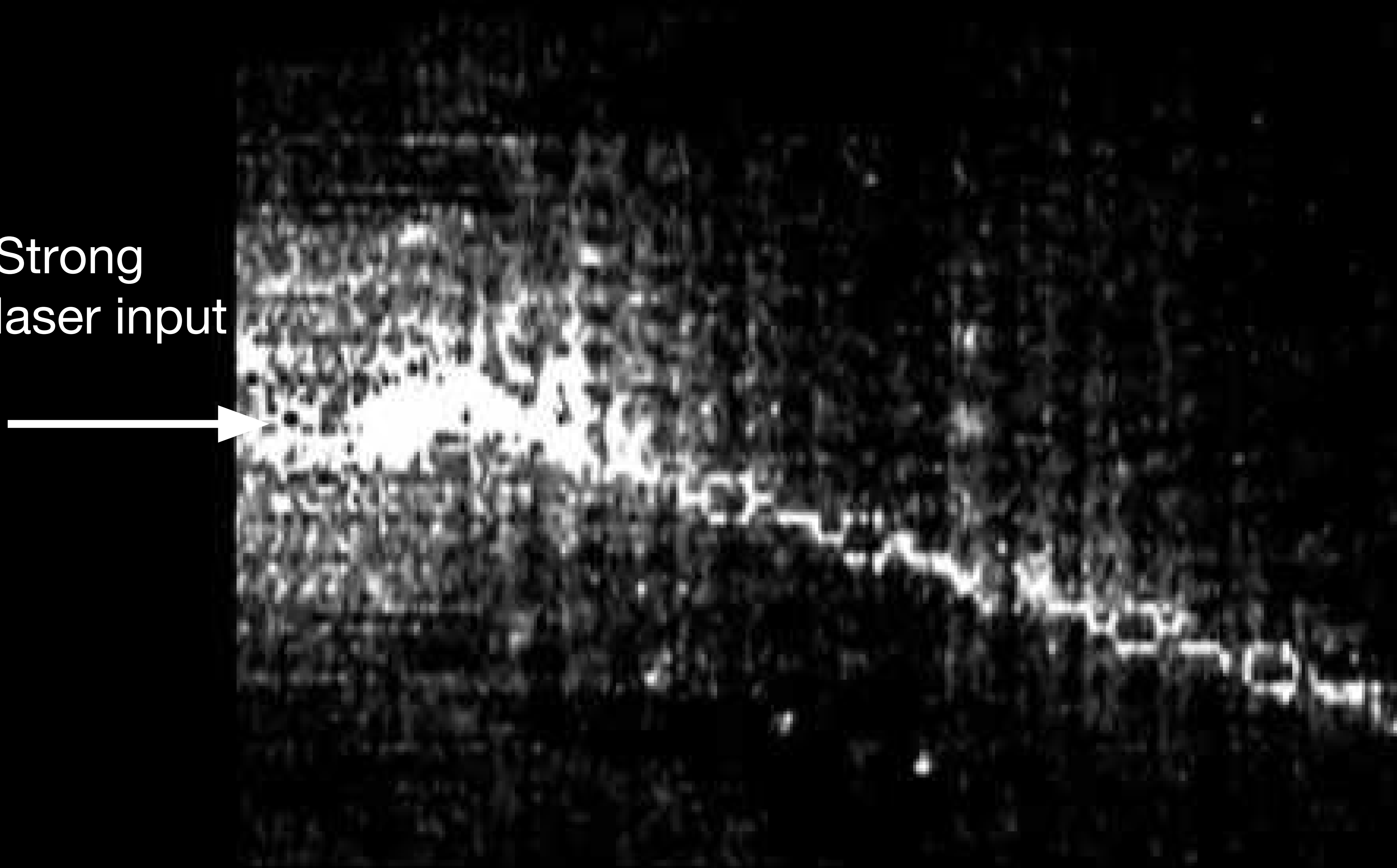
88 MZIs, 26 input modes, 26 output modes, 176 phase shifters

References:

- N. Harris et al, Nature Photonics **11** (2017)
- Y. Shen*, N. C. Harris*, et al, Nature Photonics **11** (2017)
- N. Harris et al, Nanophotonics **5** (3) (2016)

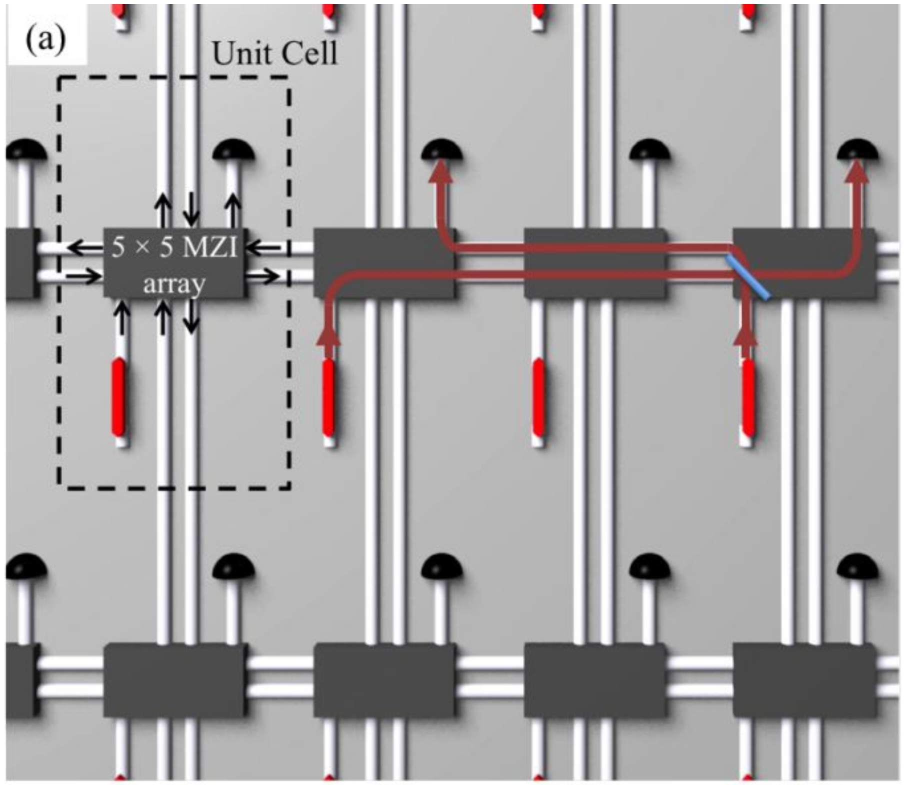
See also D.A.B.M Miller, "Sorting out Light" , Science **347** (2017)

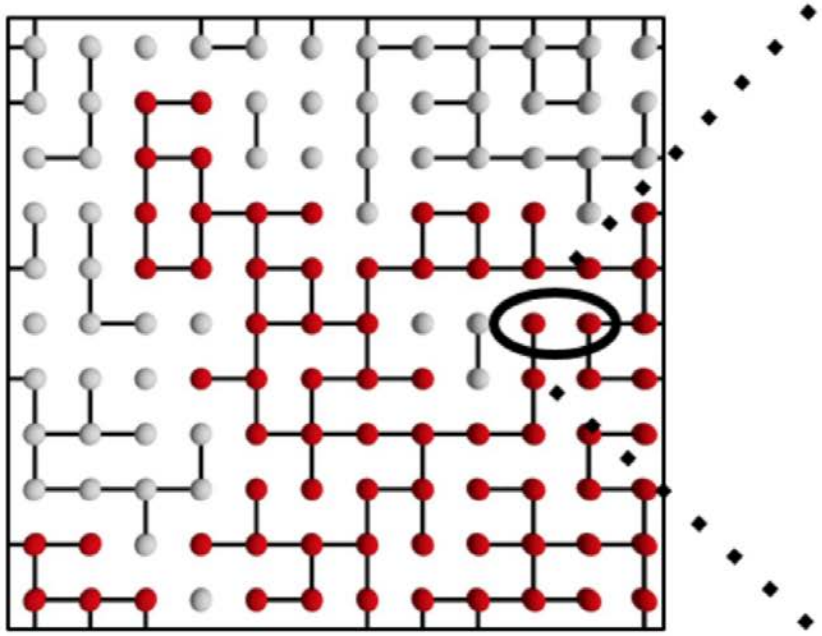
Switch array in action

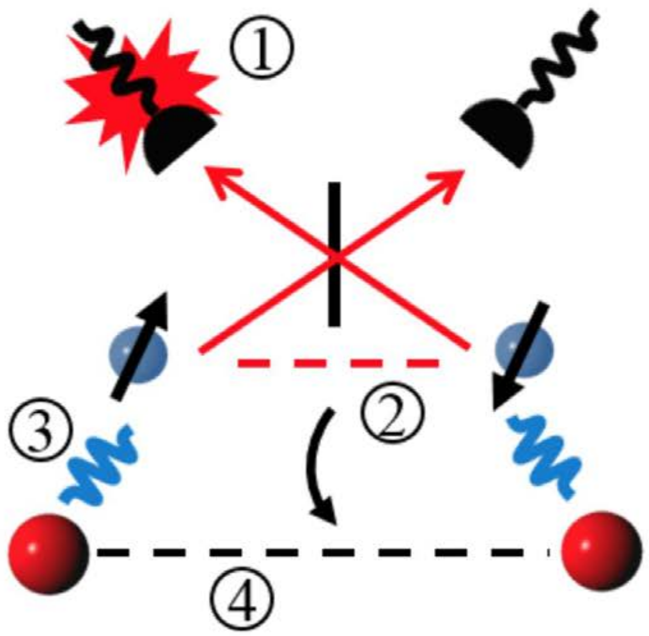


Perspective

General-purpose quantum computers will require lots of qubits; scheme for generation large NV cluster states in perhaps <1 ms by percolation:







M. Pant et al, arXiv:1704.07292 (2017)

Photonic cluster states for computing and repeaters?

w/ Saikat Guha, BBN: Mihir Pant et al, arXiv:1701.03775v1 (2017); M. Pant et al, PRA 95 (2017);

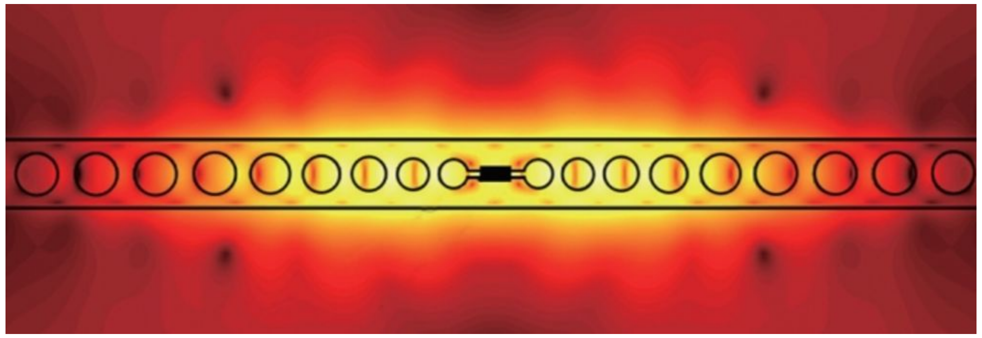
Entanglement distribution network protocol:

Mihir Pant et al, arXiv:1701.03775v1 (2017)

Graphene single-photon detectors?

Evan D. Walsh et al, [K.C. Fong, BBN], ArXiv:1703.09736 (2017)

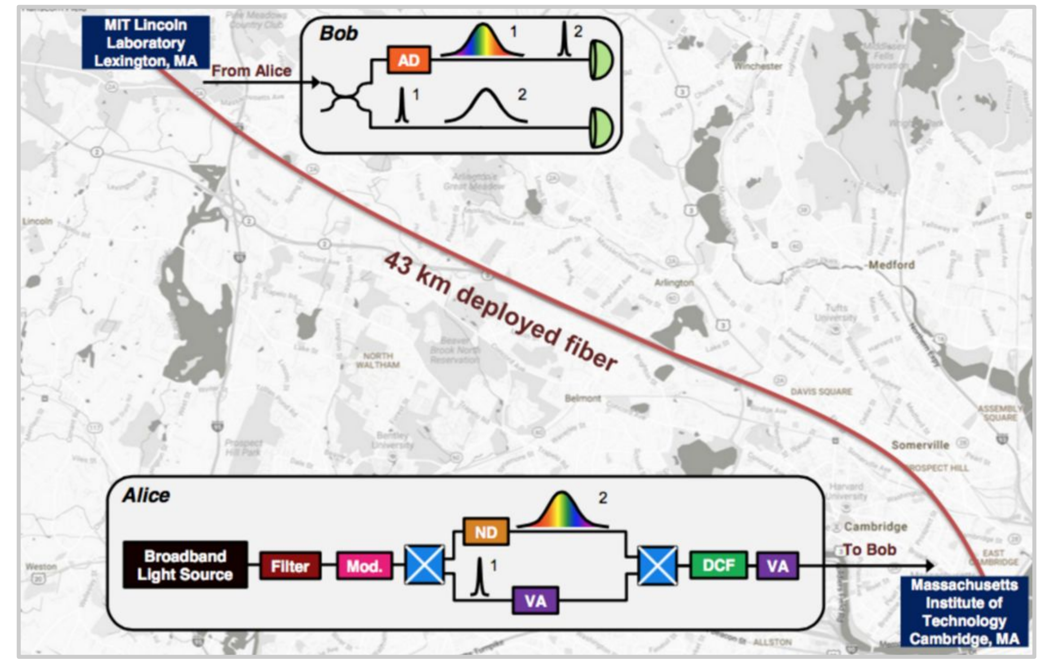
Ultra-strong cavity-QED coupling:



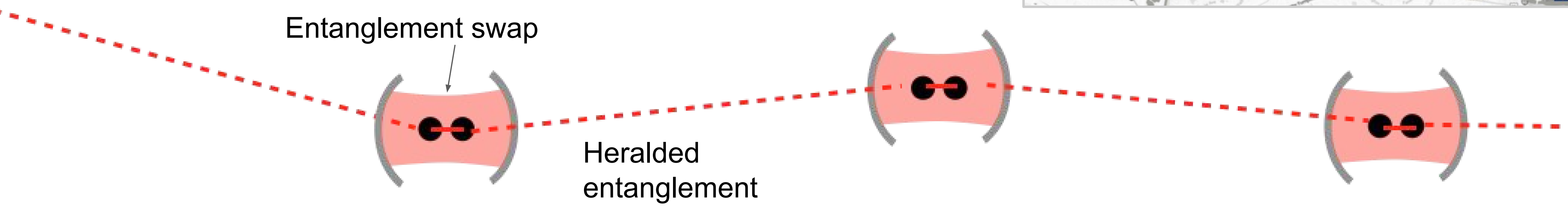
H. Choi et al, PRL 118 (2017) [see also S. Hu and S. Weiss, ACS Photonics (2016)]

Summary

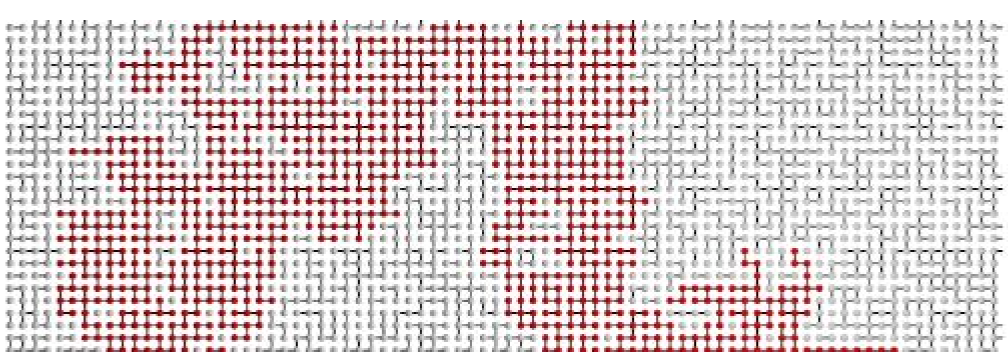
1. Repeaterless quantum key distribution: high-speed HD-QKD & photonic integrated circuits

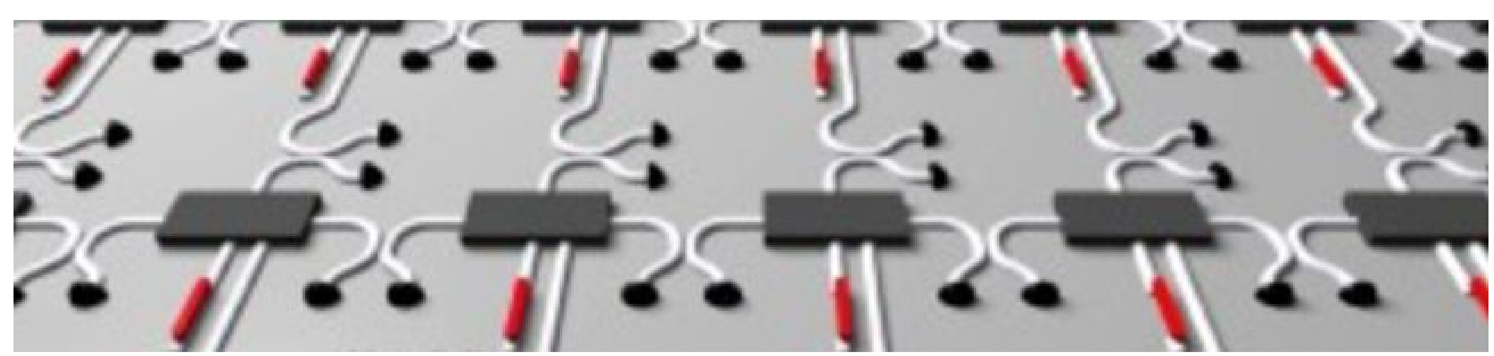


2. Towards quantum repeaters w/ diamond spins



3. Outlook: blueprint for modular quantum computers





Acknowledgements

- **MIT Quantum Photonics Group :**
- *Graduate Students*: Catherine Lee, Nick Harris, Darius Bunandar, Mihir Pant, Matt Trusheim, Sara Mouradian, Noel Wan, Michael Walsh, Hyongrak Choi
- *Postdocs*: Tim Schroeder (-> Niels Bohr Institute, Copenhagen)

- **Collaborators:**
- **MIT**: Prof. Jeffrey Shapiro, Dr. Franco Wong, Dr. Z. Zhang; Prof. Karl Berggren, Prof. Seth Lloyd
- **Harvard:** Prof. Mikhail Lukin, Prof. Marko Loncar
- **Raytheon BBN:** Dr Saikat Gua, Dr. Hari Krovi, K.C. Fong
- **U. Delaware**: M. Hochberg, T. Baehr-Jones
- **Rome Air Force Laboratory:** Dr. Paul Alsing, Michael Fanto
- **Lincoln Laboratory**: Scott Hamilton, Danielle Braje, Ben Dixon, Matt Grein, Ryan Murphy
- **Sandia National Laboratory:** J Urayama, N Boynton, N Martinez, C DeRose, A Lentine, P Davids, R Camacho, E. Edward S. Bielejec

Funding