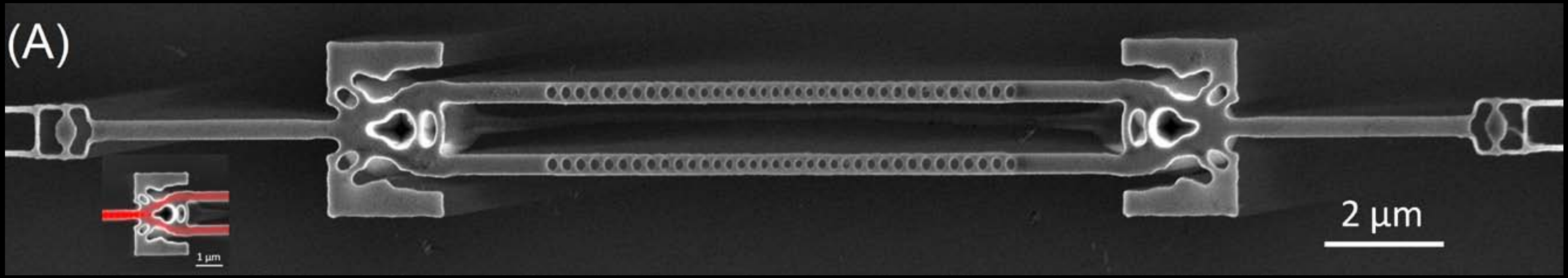
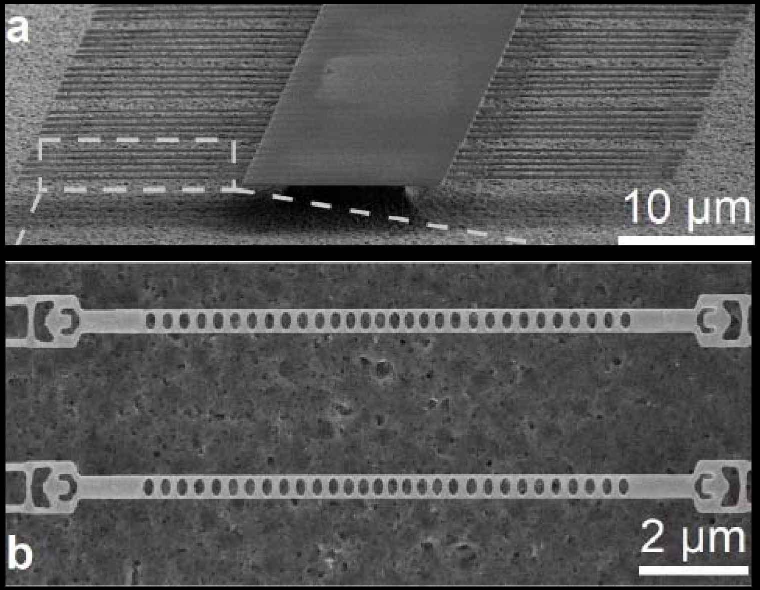
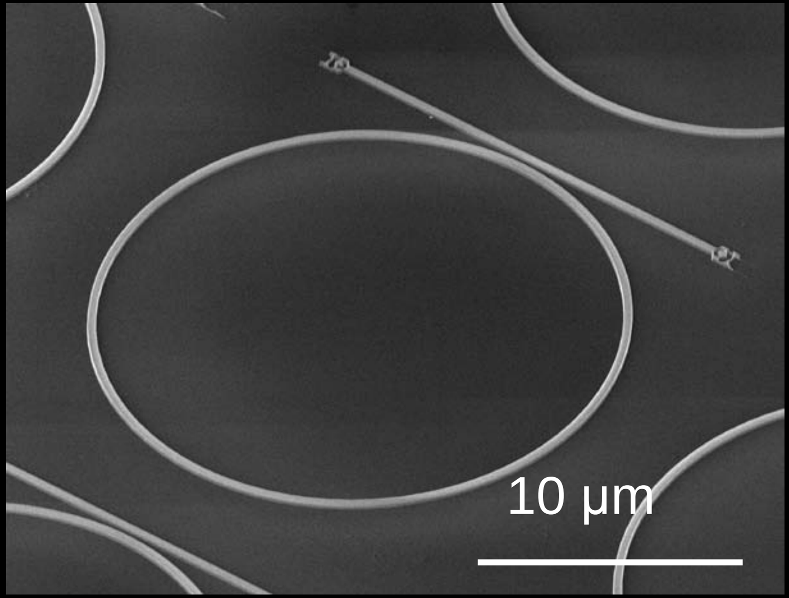
Connecting quantum systems through optimized photonics







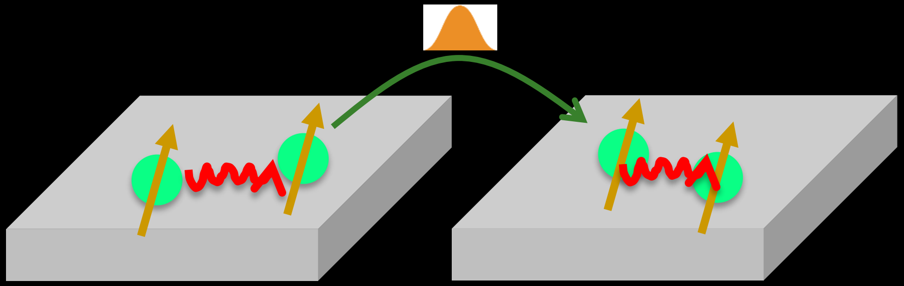
Jelena Vuckovic

Stanford University

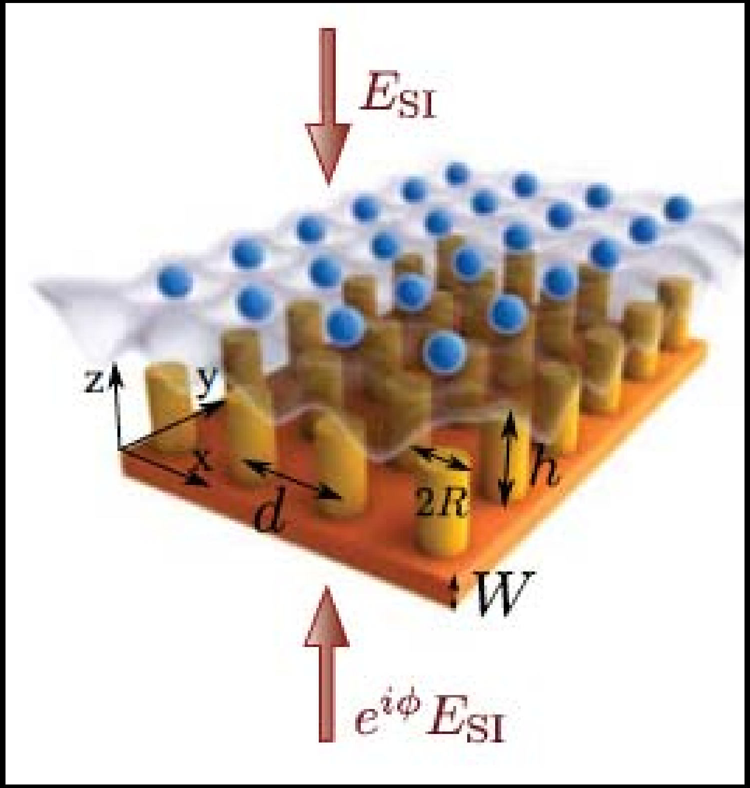
KITP, May 2019

Quantum technologies

Quantum repeaters and networks



Quantum simulators



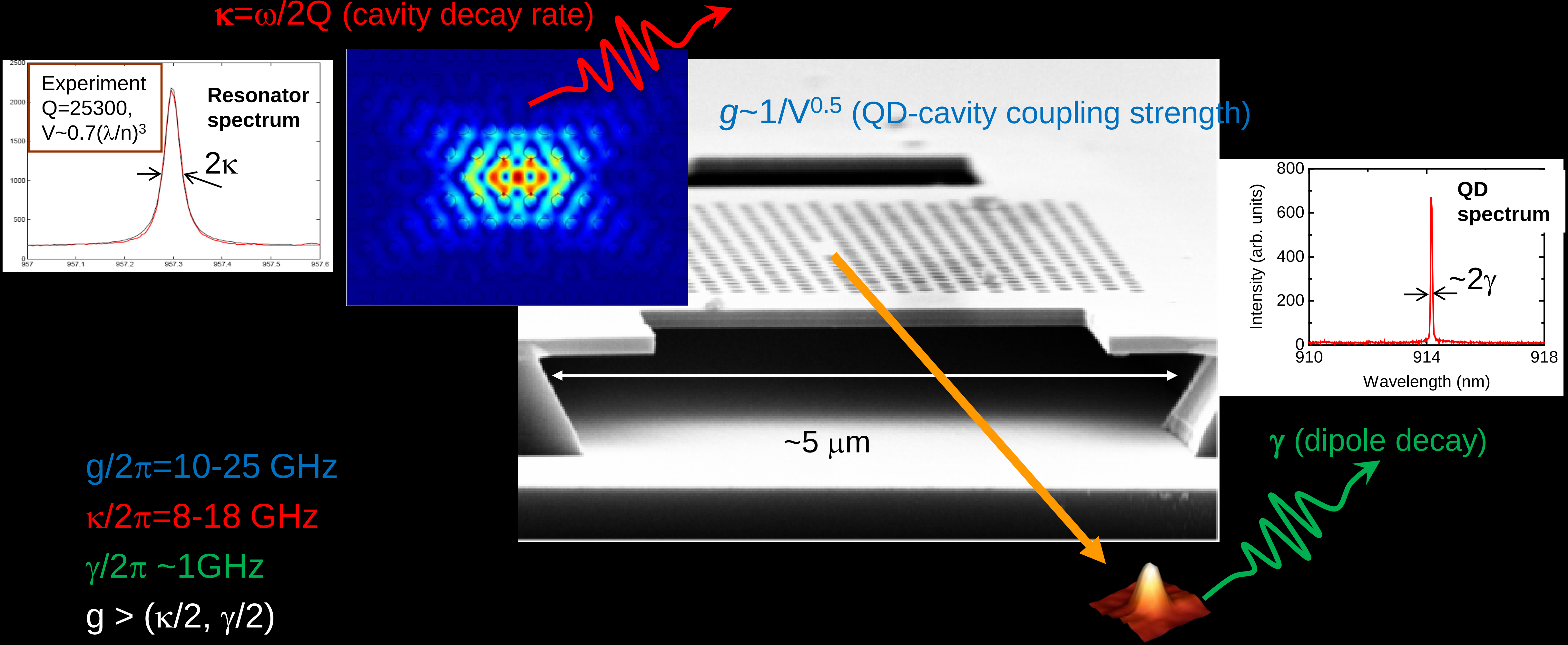
Gonzales-Tudela et al., *Nature Photonics* 9, 320-325 (2015).
Douglas et al., *Nature Photonics* 9, 326-331 (2015).

What do we need?

1) Homogeneous qubits with optical interfaces

2) Efficient optical interconnects

Quantum dot strongly coupled to a cavity (InAs/GaAs)



κ=ω/2Q (cavity decay rate)

Experiment
Q=25300,
V~0.7(λ/n)^3

Resonator spectrum

g~1/V$^{0.5}$ (QD-cavity coupling strength)

QD spectrum

γ (dipole decay)

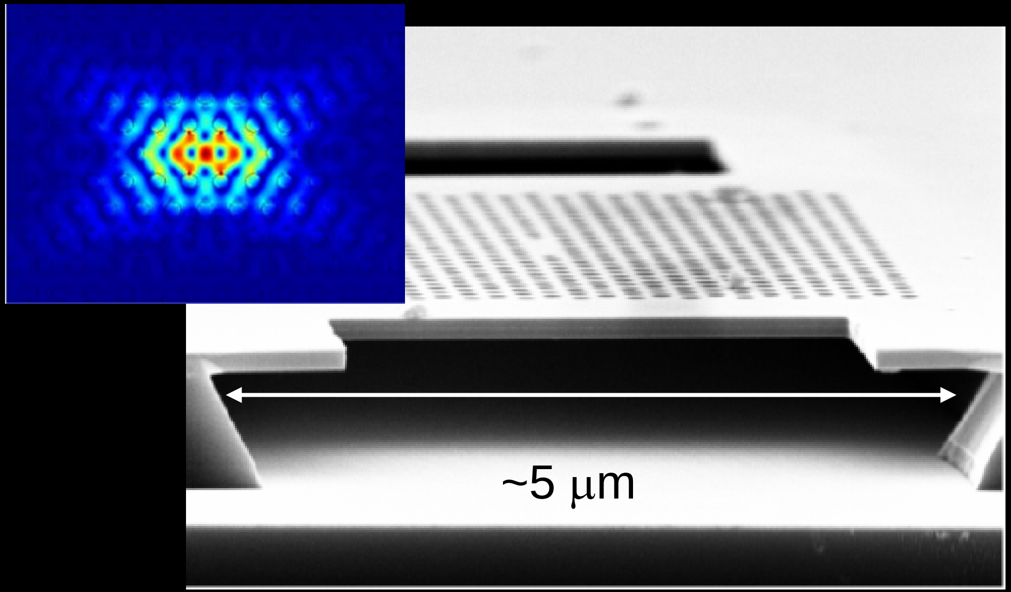
$g/2\pi$=10-25 GHz

$\kappa/2\pi$=8-18 GHz

$\gamma/2\pi$ ~1GHz

$g > (\kappa/2, \gamma/2)$

Strong coupling

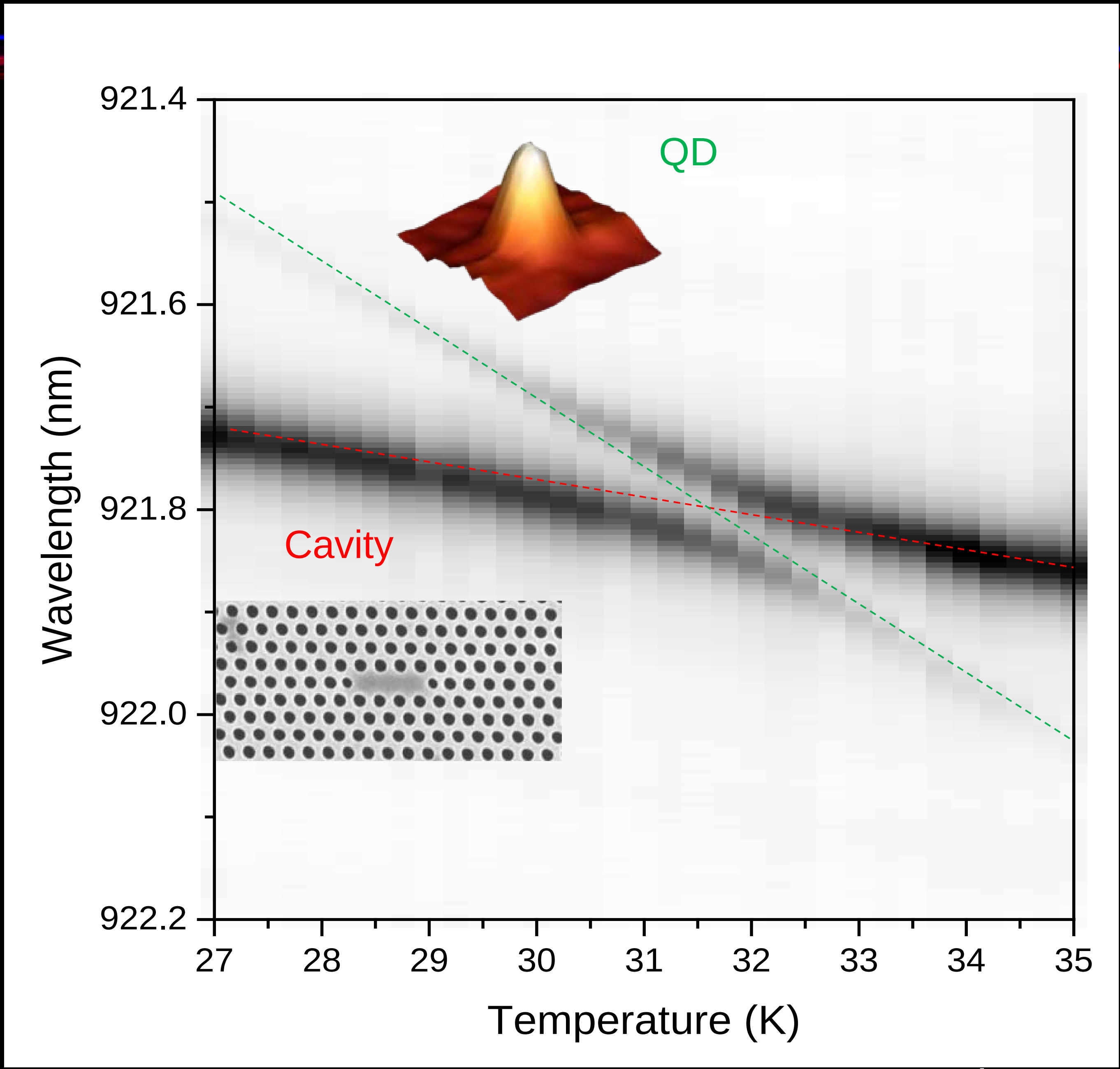


$g/2\pi$=10-25 GHz

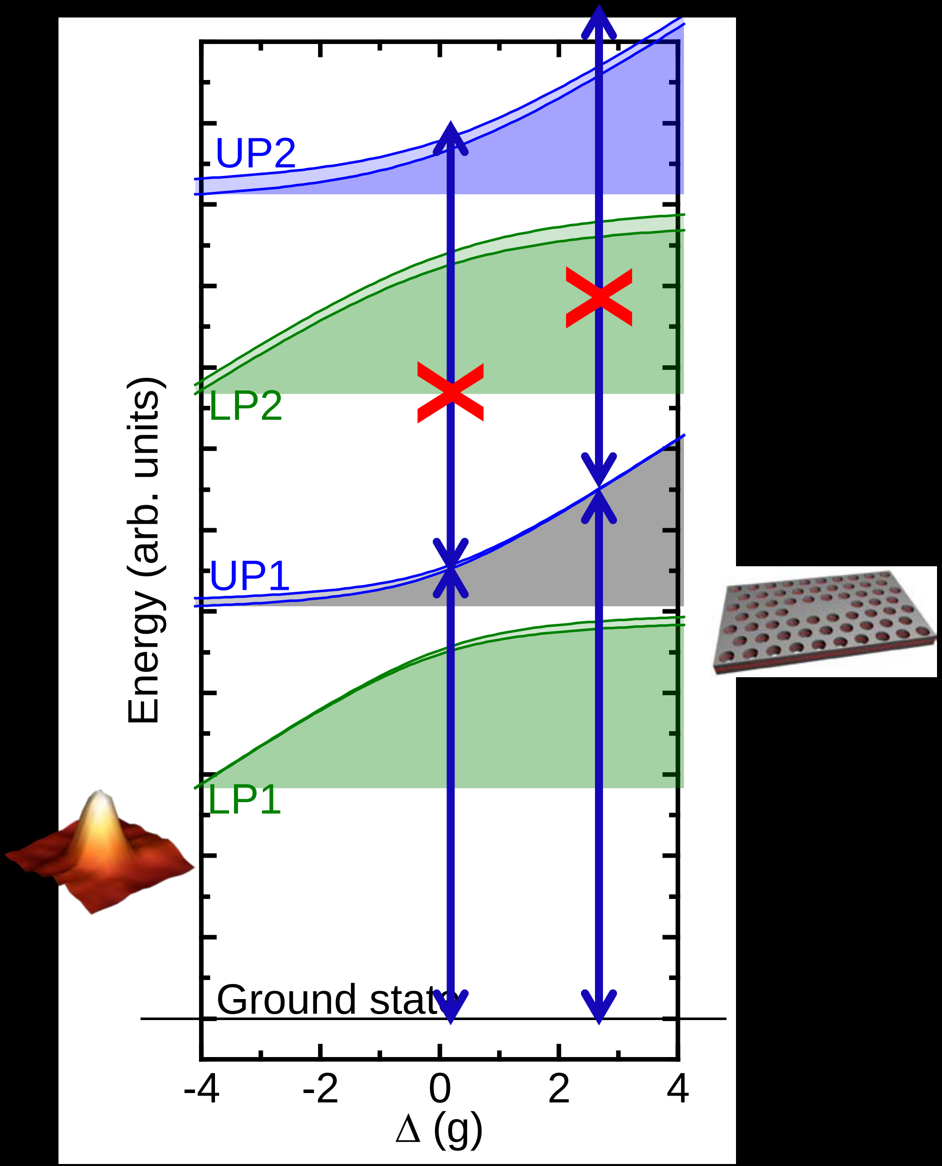
$\kappa/2\pi$=8-18 GHz

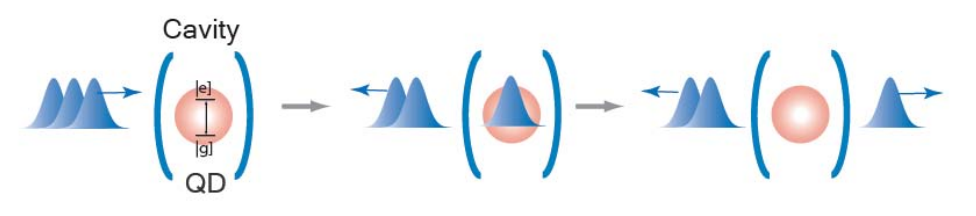
$\gamma/2\pi$ ~1GHz

Nature **450**, 857-861 (2007)
PRL **104**, 073904 (2010)

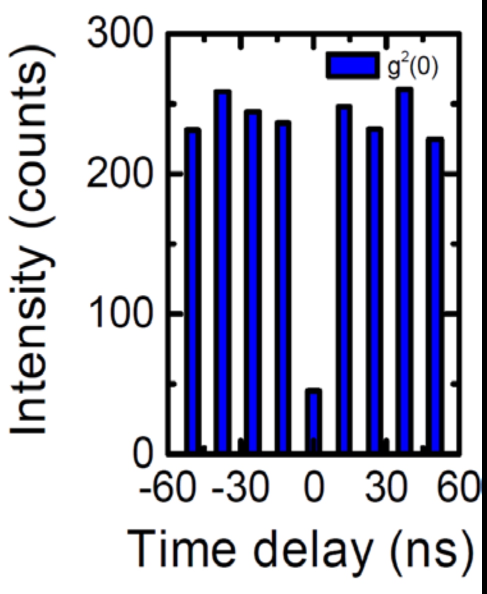


Photon-blockade

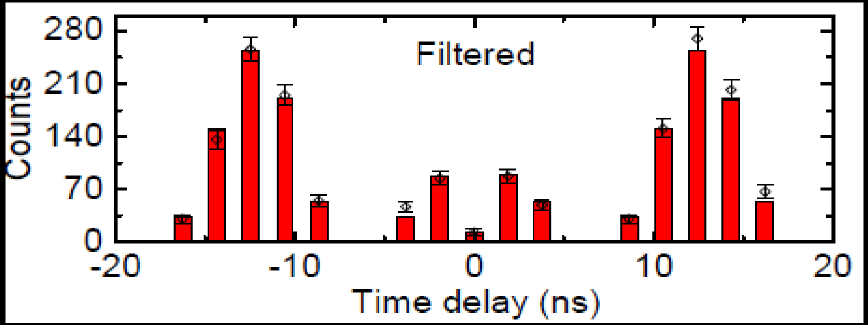




$g^2(0)$~0.1



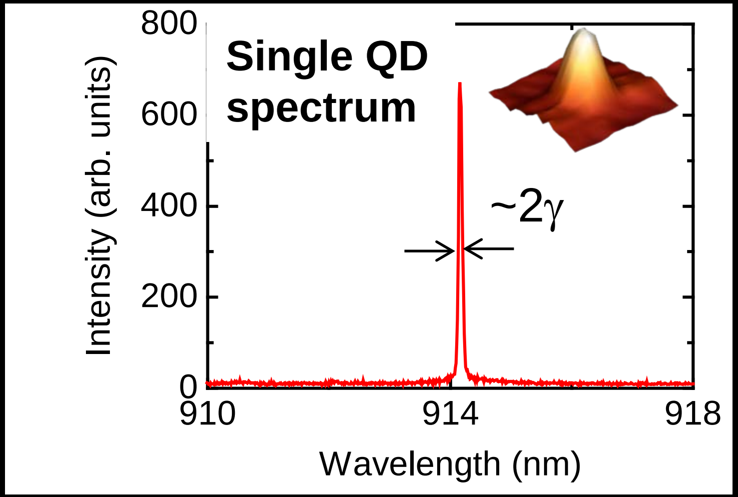
Photon indistinguishability ~96%

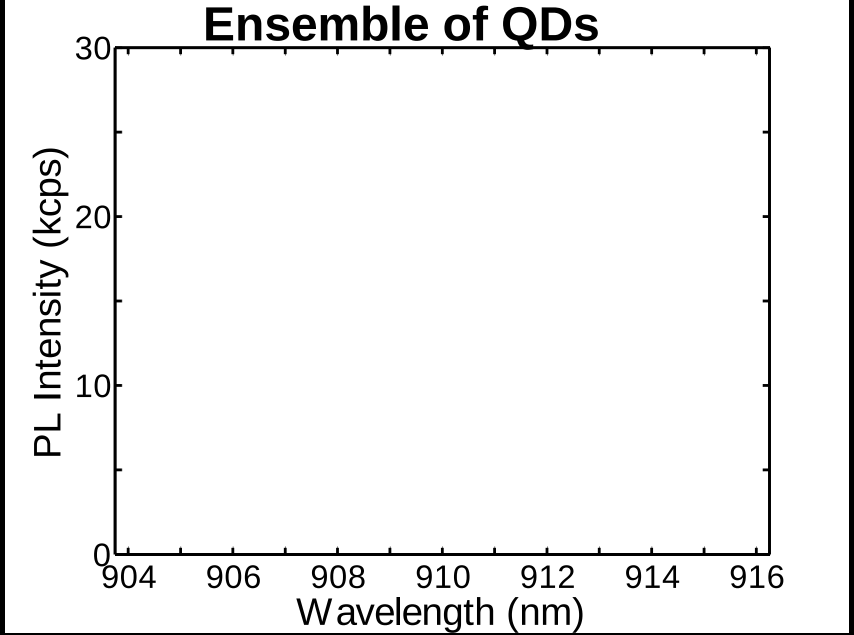


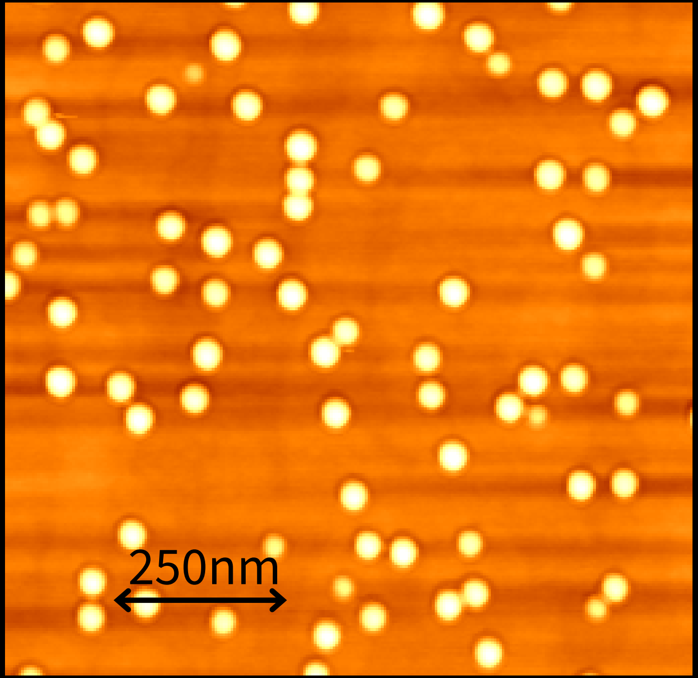
Nature Physics **4**, pp. 859-863 (2008)
Phys. Rev. Lett. **114**, *233601* (2015)
Nature Photonics **10**, 163-166 (2016)
Optica **3**, 931-936 (2016)

AMO: Birnbaum et al, Nature 436 (2005); Rempe: PRL 101, (2008) ; QD: Volz et al, Nat Phot 6, (2012); Circuit QED: Wallraff, PRL106, 243601 (2011)

Why are quantum dots hard to scale?





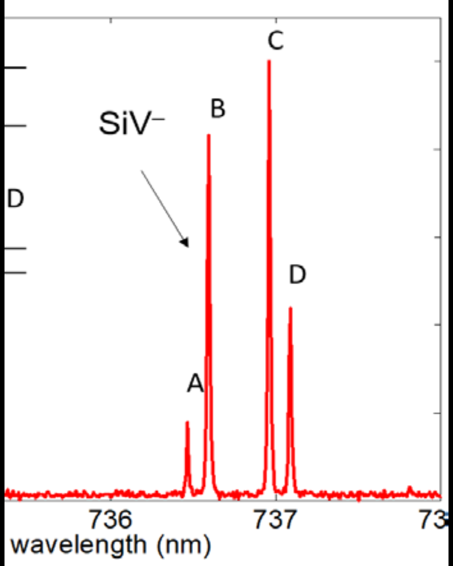


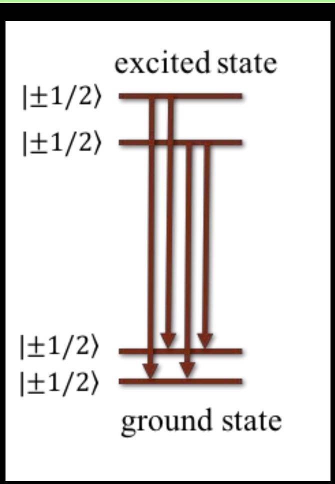
Color centers in diamond and SiC

collaboration with
Wrachtrup, Ohshima,
Lee, Bonato, Economou
groups

SiV^- (and SnV^-) in diamond

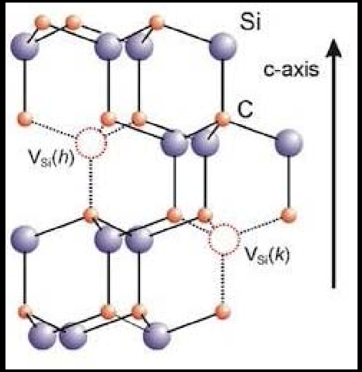
Collaboration with ZX Shen, N.Melosh,
S.Chu (Stanford)

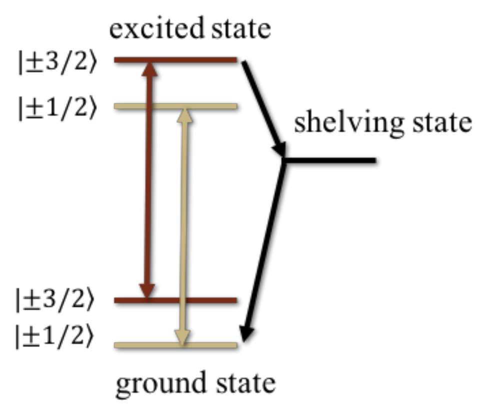


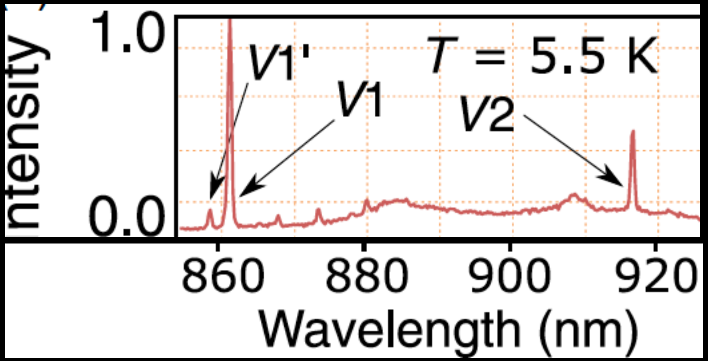


Nano Letters 16 (1), pp. 212-217 (2016)
Optica 4 (11), 1317-1321 (2017)

V_{Si}^- in 4H-SiC



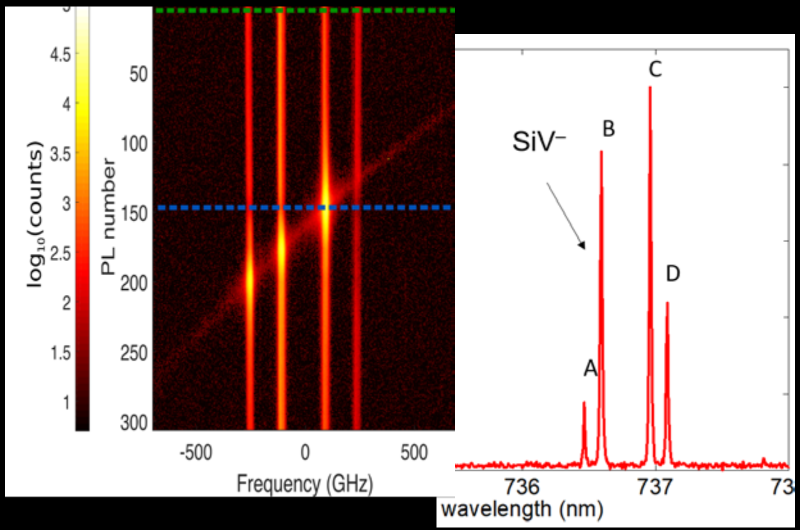




Nano Letters 17 (3), pp 1782–1786 (2017)
Physical Review Applied, **9**, 034022 (2018)

SiV color centers in diamond

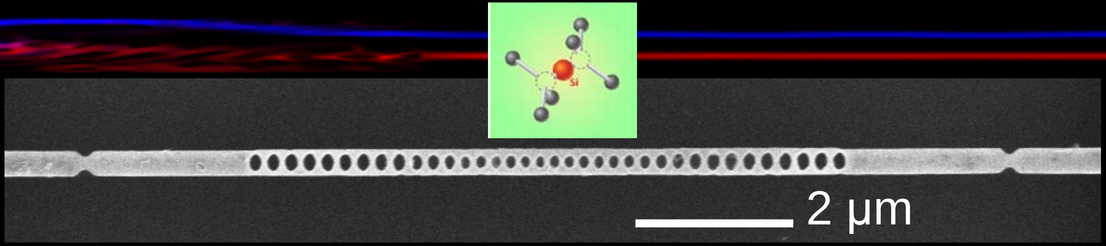
Collaborators: @Harvard: M. Loncar; @ Stanford:, N.Melosh, ZX Shen, S.Chu, A Safavi-Naeini (Stanford)

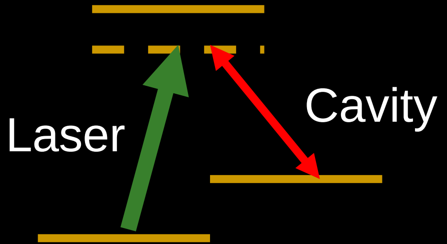


Excellent photonic interface

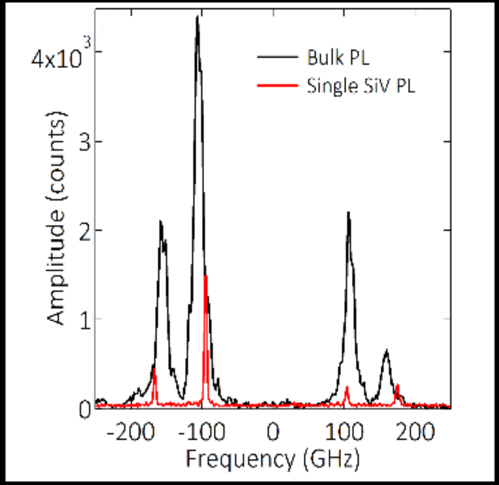
Nano Lett., *18* (2), pp 1360–1365 (2018)

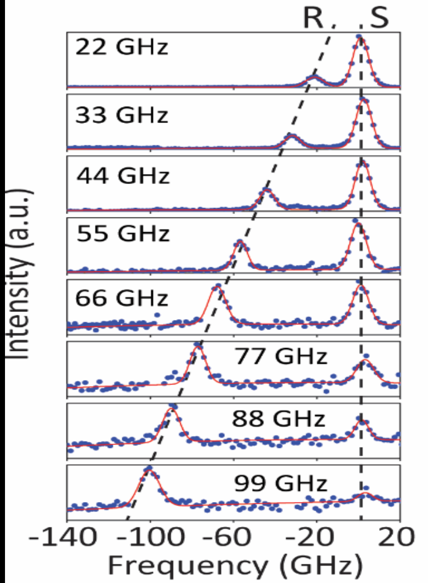
2 qubit interaction:
Lukin & Loncar Groups @ Harvard,
Science 362, 662-665 (2018)





Only up to 30GHz spectral broadening for SiVs on optical chip

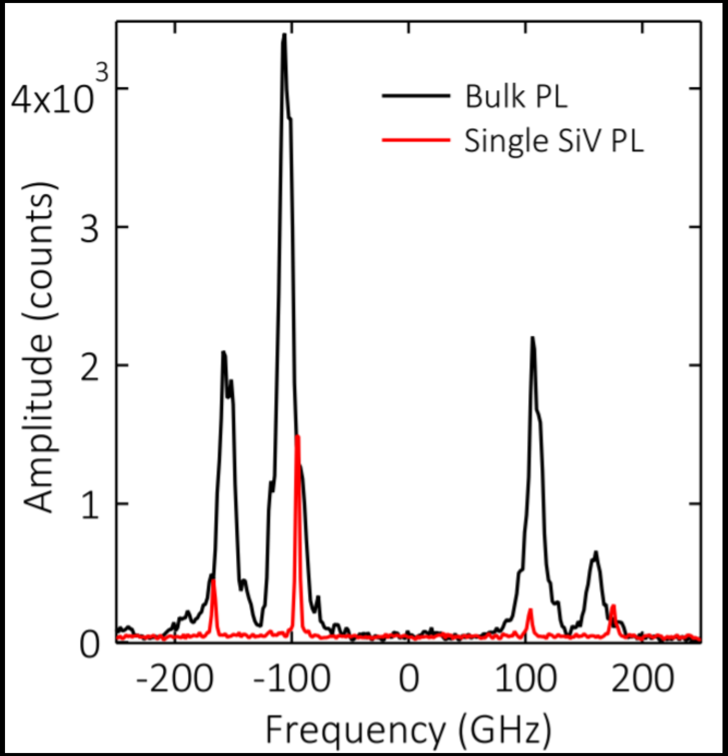




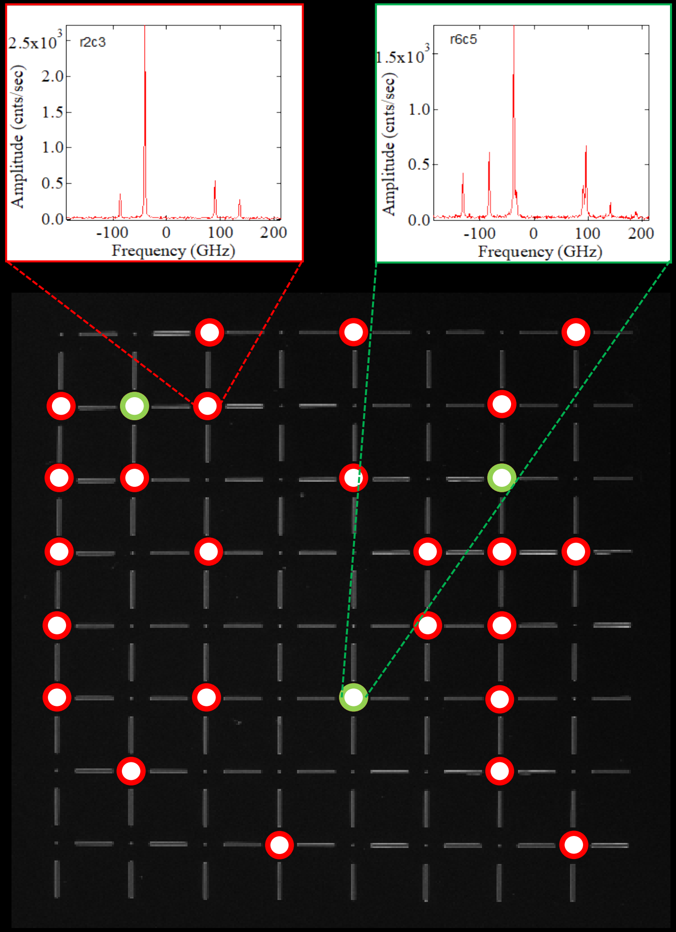
Can couple any SiVs on chip detuned by up to 100GHz by Raman scattering

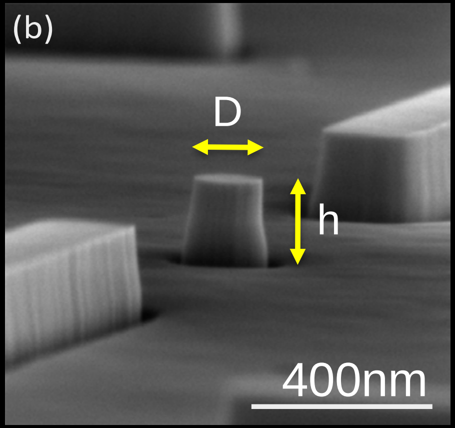
Phys. Rev. Letters 121, 083601 (2018)

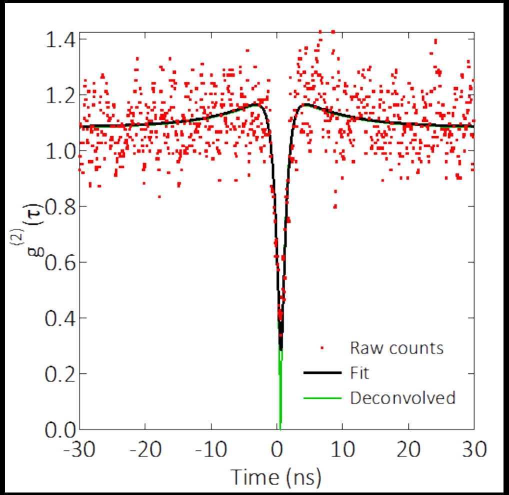
Scalable photonics with single emitters in diamond



~ 31% contain single
~ 6% contain 2+
emitters



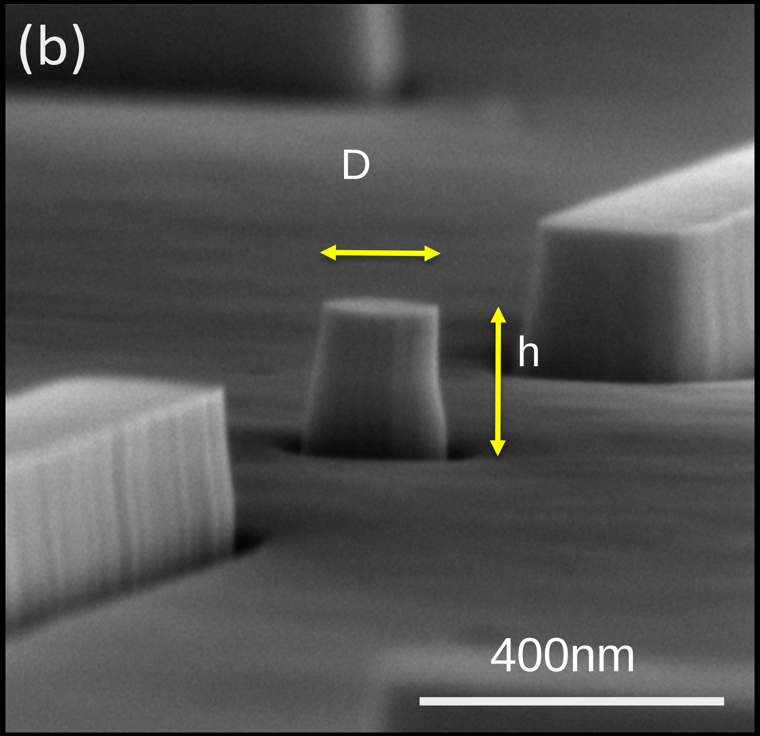




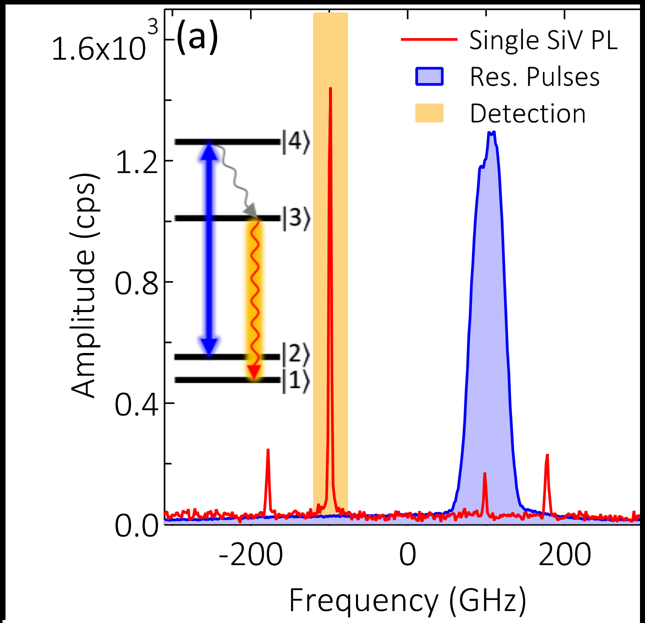
Only ~30GHz spectral broadening for SiVs on chip

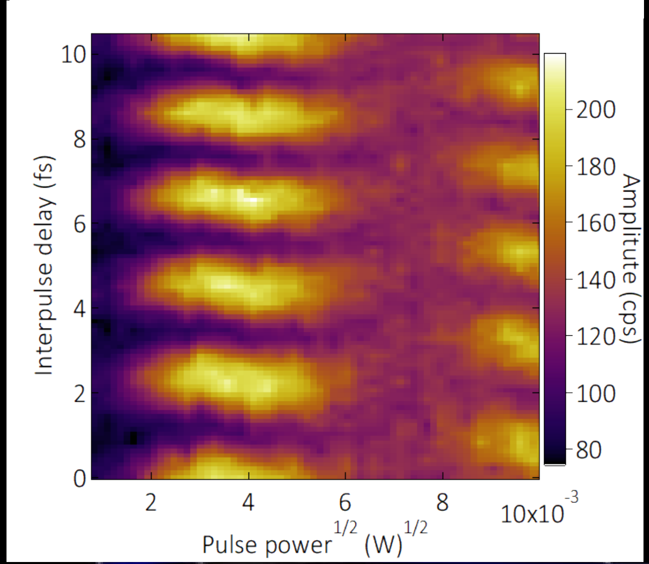
Zhang *et al.* Optica, 4, 1317-1321 (2017)

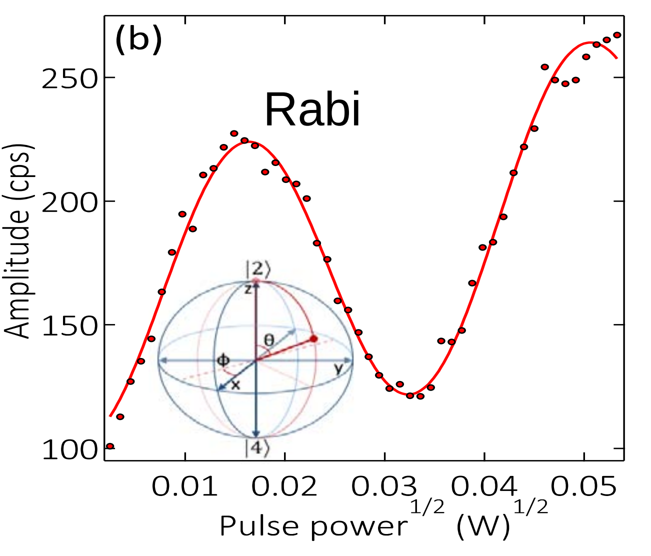
Ultrafast coherent control of individual SiV centers

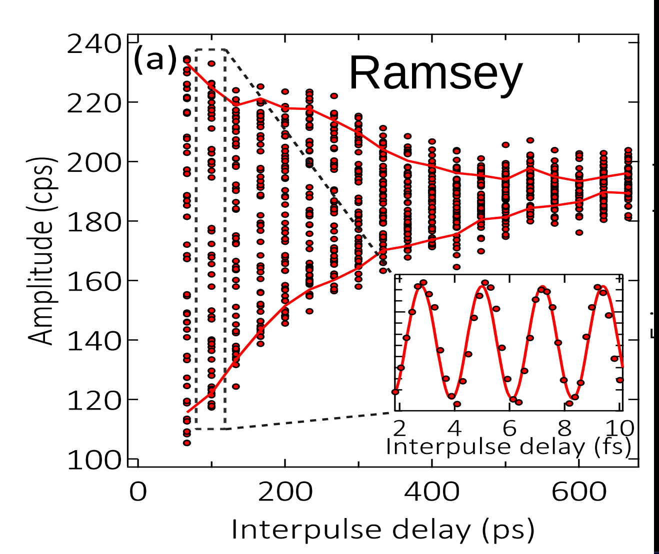


Zhang *et al.* Optica, 4, 1317-1321 (2017)



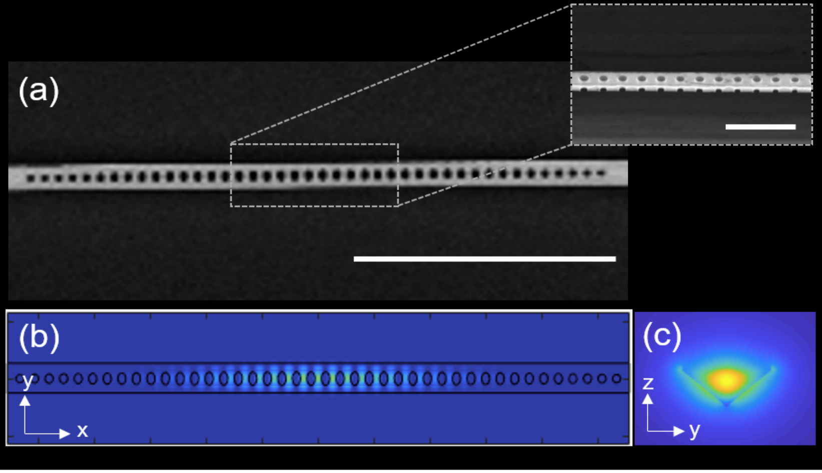


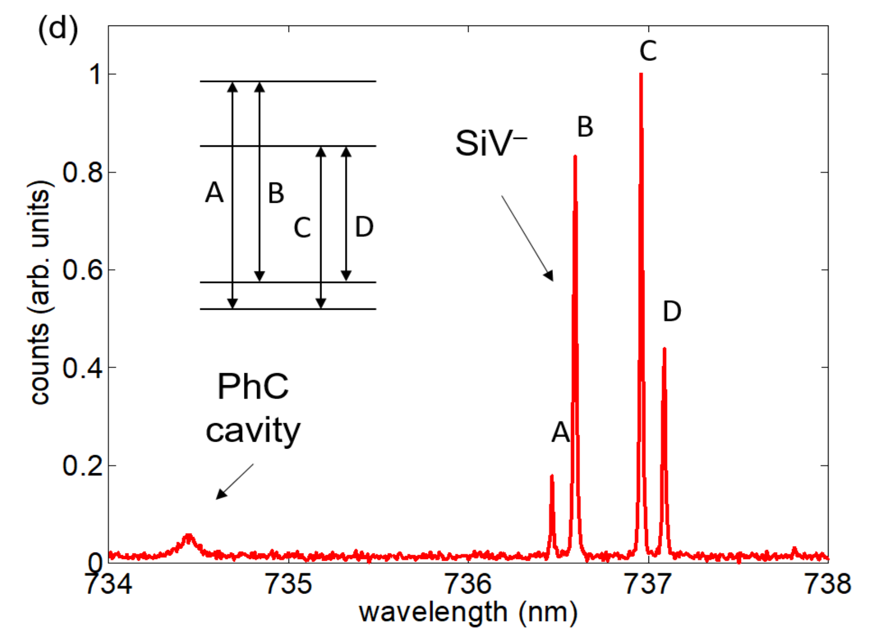


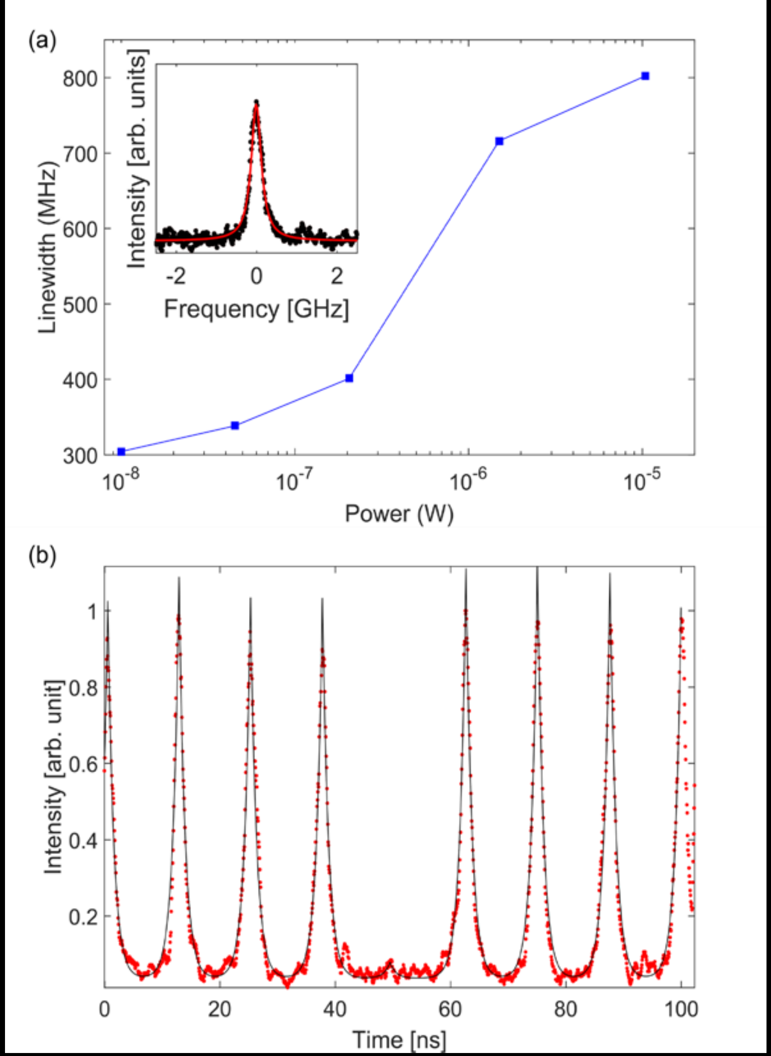


Photon interface for SiV in diamond

Diamond etching: Marko Loncar, Harvard



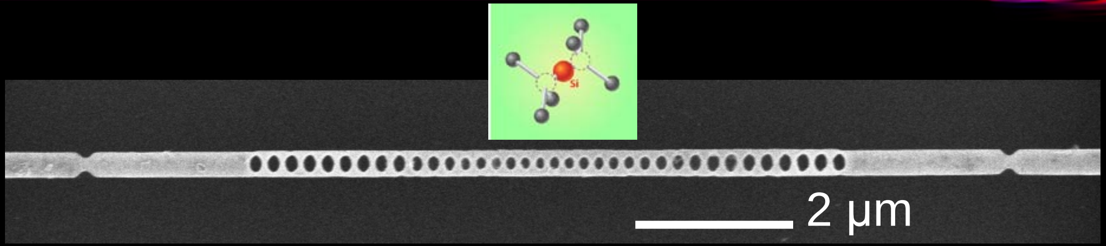




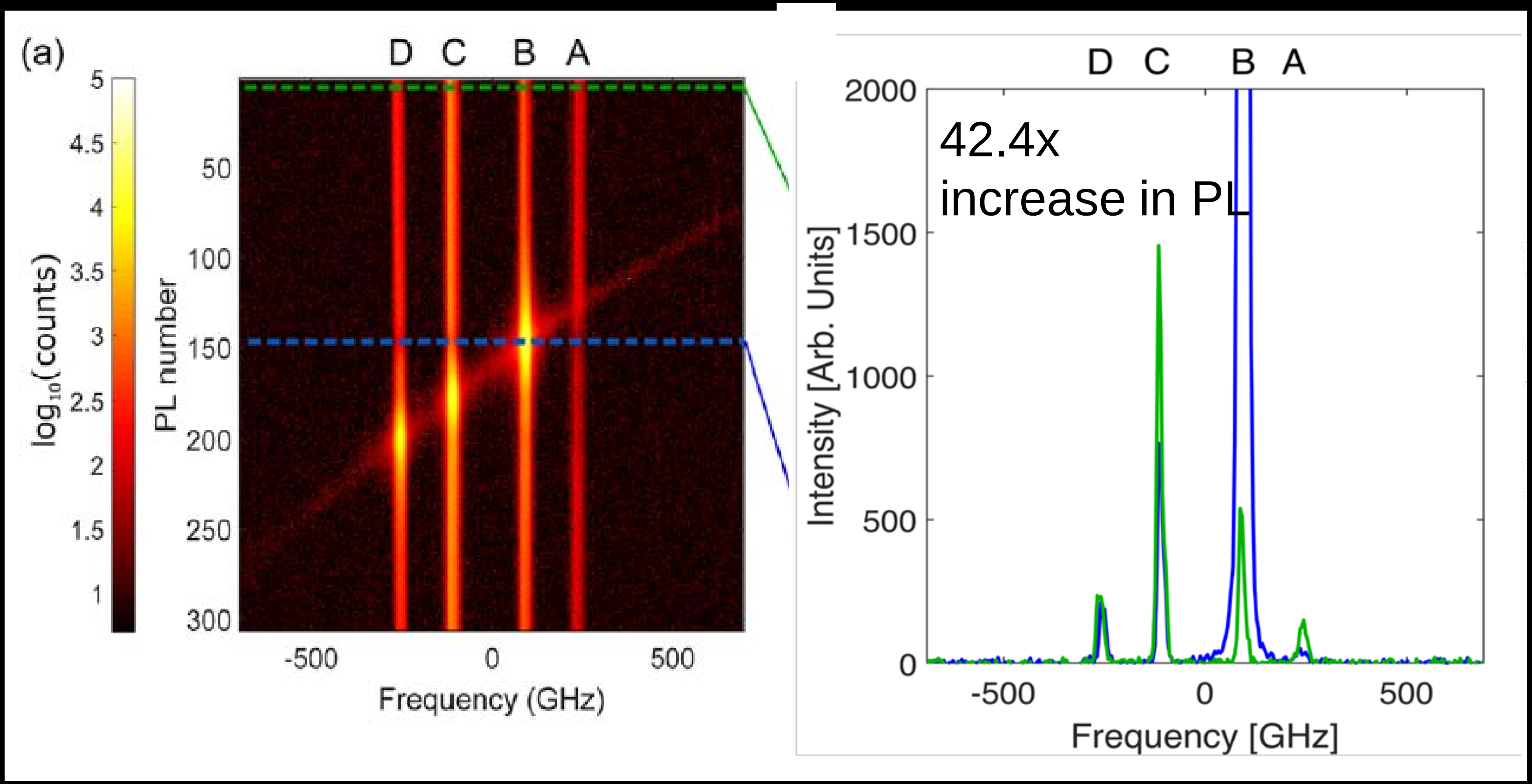
Jelena Vuckovic, Stanford

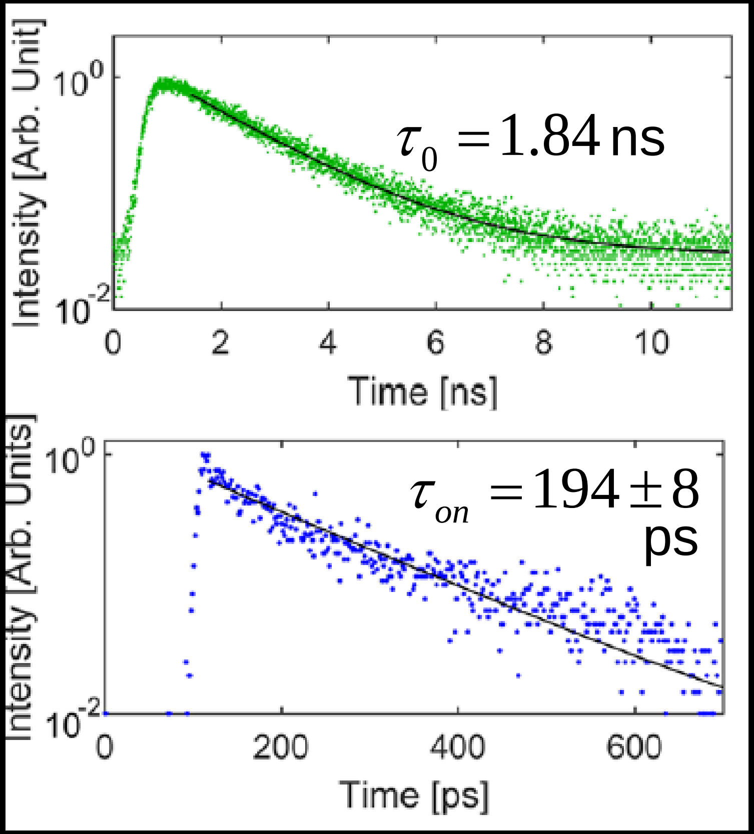
L. Zhang et al, *Nano Lett.*, *18* (2), pp 1360–1365 (2018)

Photon interface for SiV in diamond



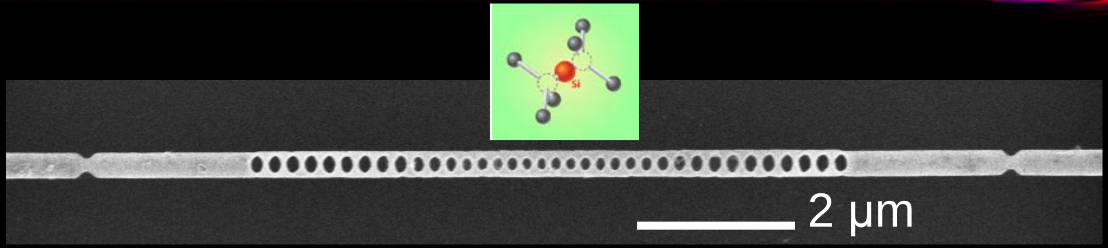
$g/2\pi$= 5 GHz, $\kappa/2\pi$=25GHz, $\gamma/2\pi$ ~1GHz





L. Zhang et al, *Nano Lett.*, *18* (2), pp 1360–1365 (2018)

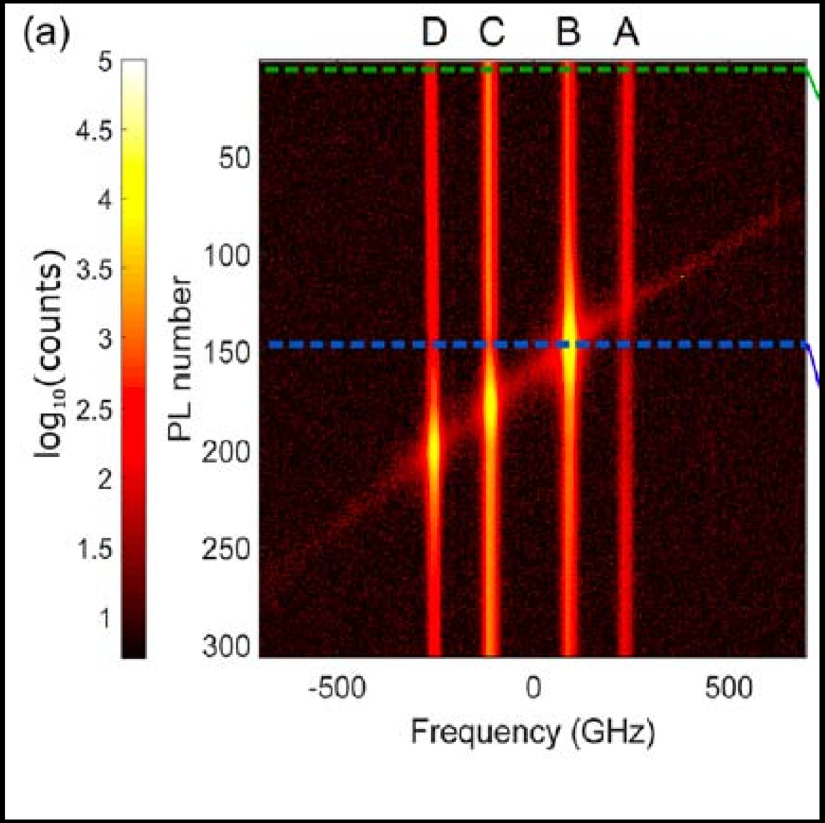
Photon interface for SiV in diamond

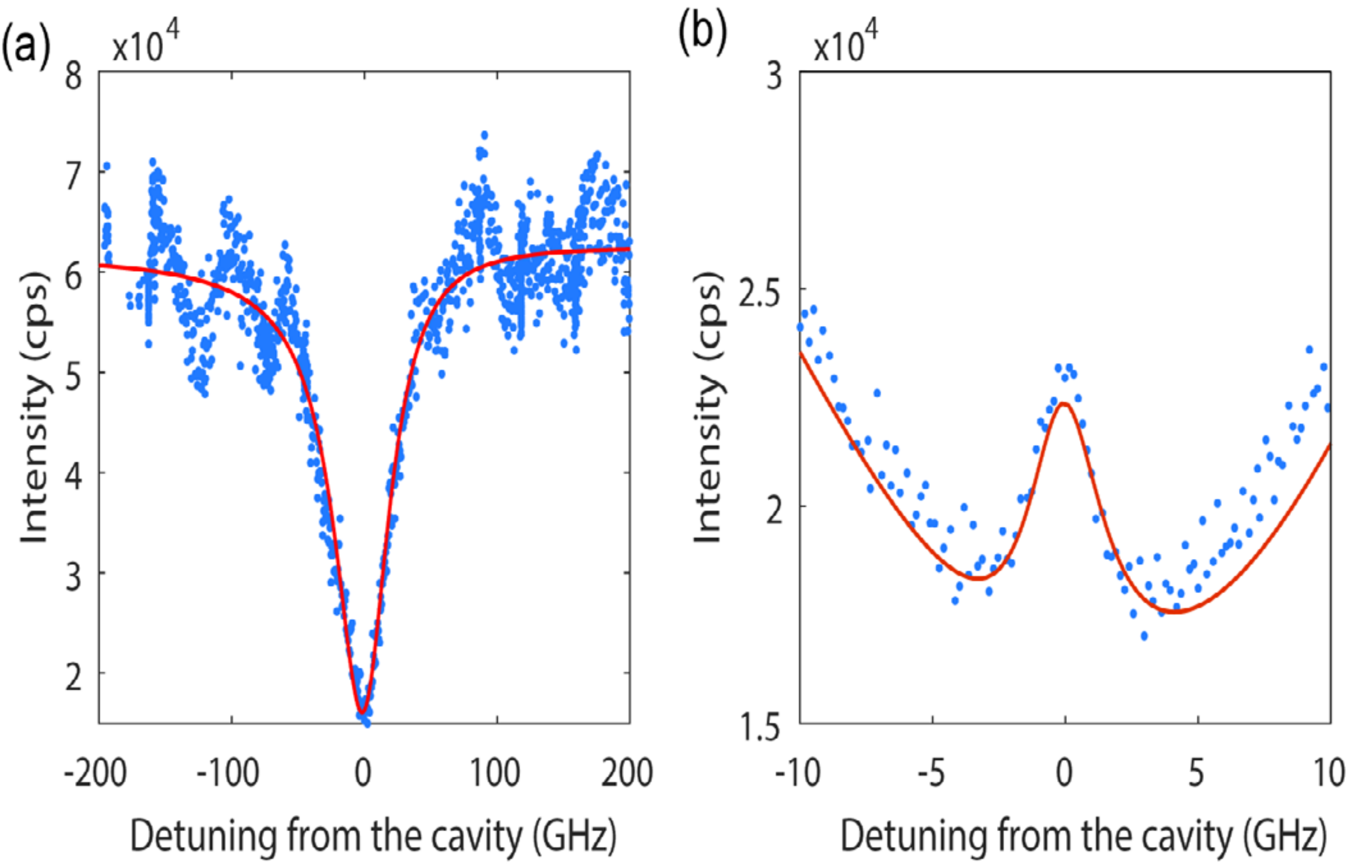


$g/2\pi$= 5 GHz, $\kappa/2\pi$=25GHz, $\gamma/2\pi$ ~1GHz

Cooperativity C=1.4

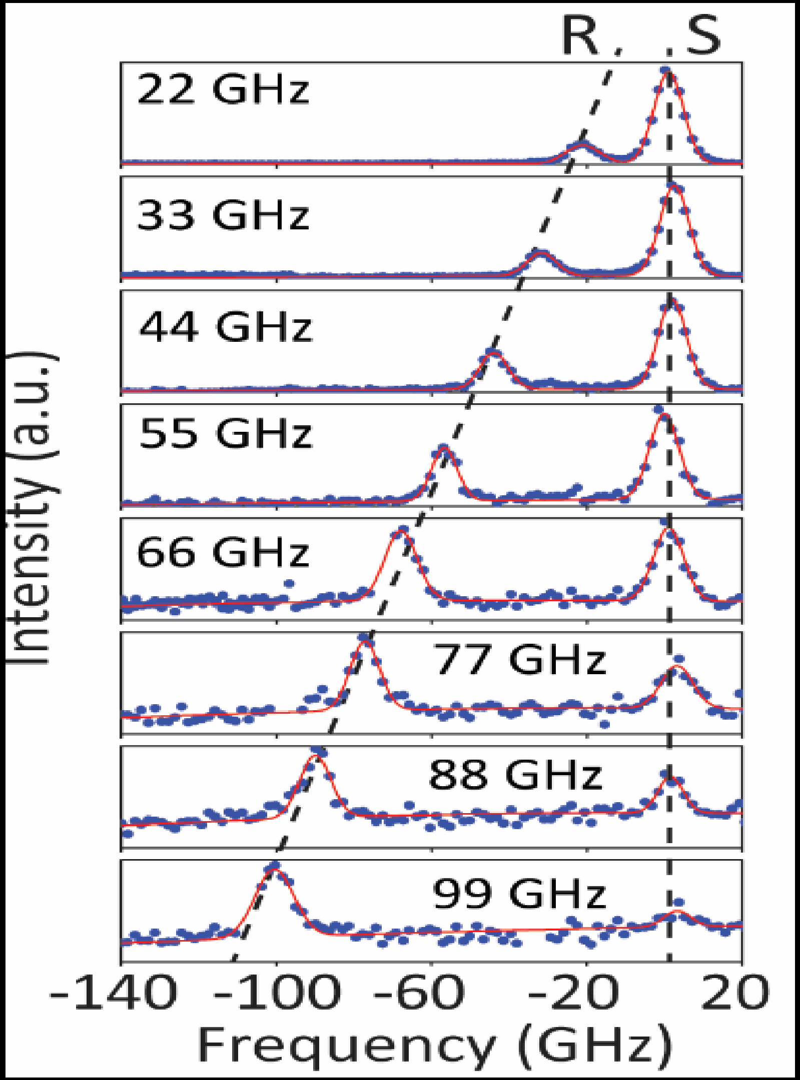
Recent work: C~20 at mK temperature
(R. Evans et al, *Science* 362, 662-665 (2018))

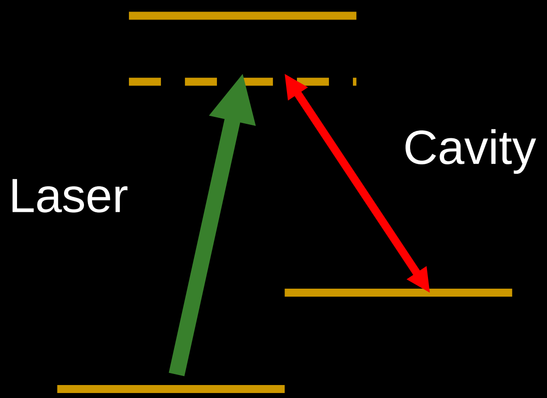




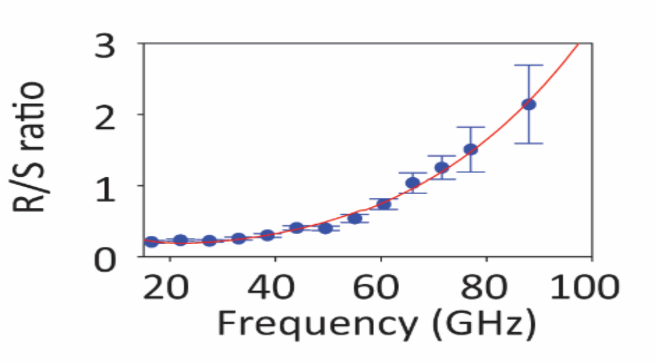
L. Zhang et al, *Nano Lett.*, *18* (2), pp 1360–1365 (2018)

Cavity enhanced Raman scattering from SiV



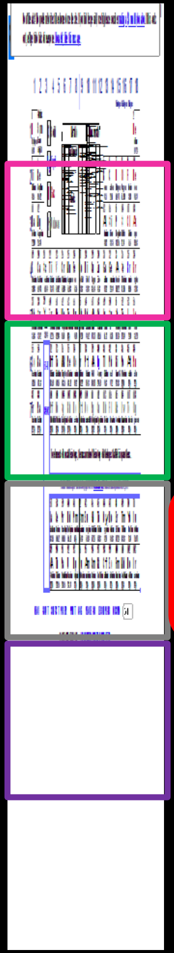


- 100 GHz **tuning** range
- previously 10GHz in waveguide @ Harvard – (Science 2016)

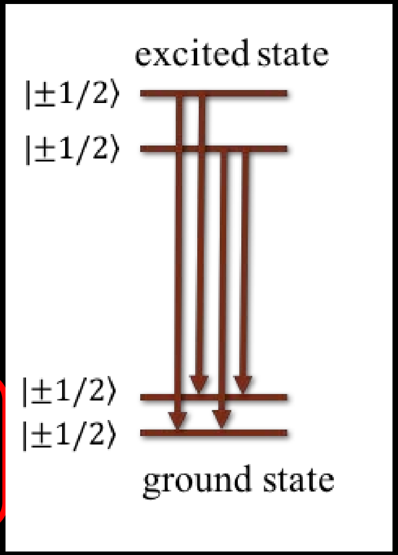


Shuo Sun et al, *Phys. Rev. Letters* 121, 083601 (2018)

New inversion symmetric color centers



	Ground state splitting	Debye–Waller factor	Quantum efficiency
SiV$^-$	50 GHz [1]	78% [6]	30% [8], 14% *[5]
GeV$^-$	152 GHz [2]	61% [7]	90% *[5]
SnV$^-$	850 GHz [3]	41% [3]	80% [3], 91% *[5]
PbV$^-$	2 THz [4] 4.4 THz *[5]	20% *[5]	unknown

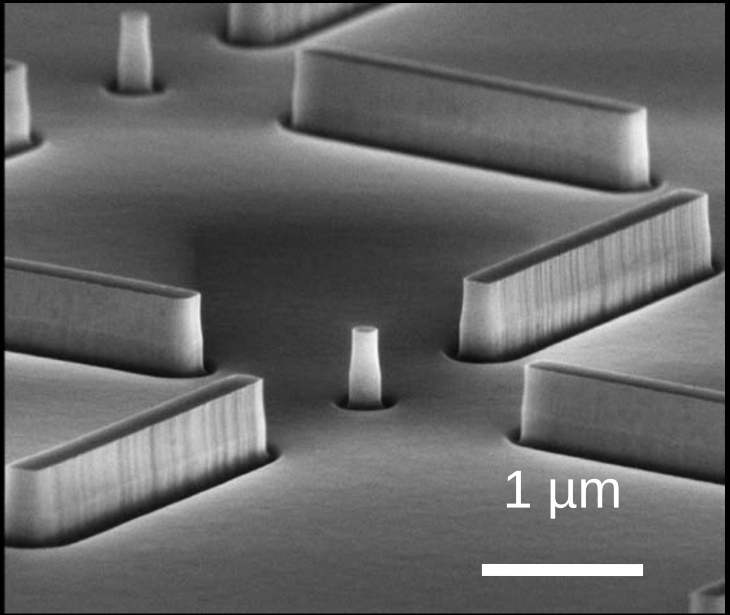


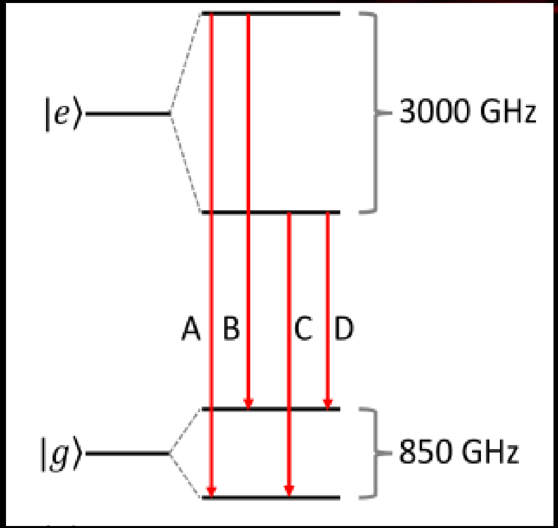
[1] Hepp et al., *Phys. Rev. Lett.* 112, 036405 (2014)
[2] Bhaskar et al., Phys. Rev. Lett. 118, 223603 (2017)
[3] Iwasaki et al., Phys. Rev. Lett. 119, 253601 (2017)
[4] Trusheim et al., arXiv:1805.12202
[5] Thiering and Gali, Phys. Rev. X 8, 021063 (2018)

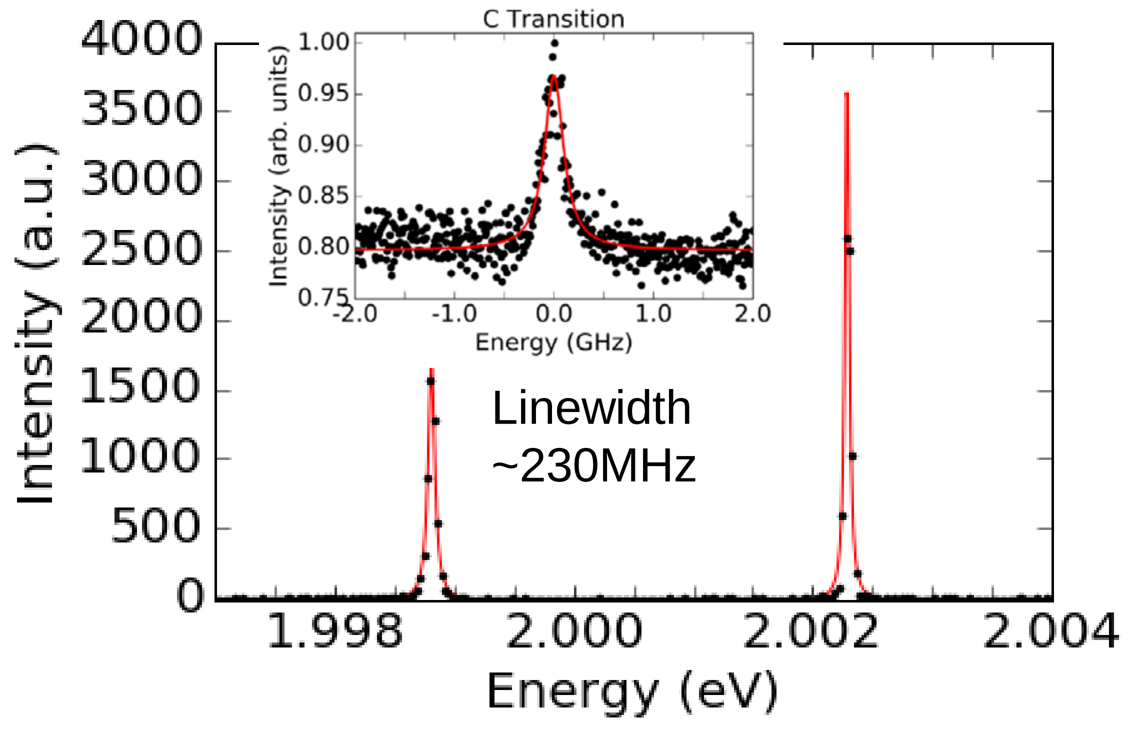
[6] Neu et al., *New J. Phys.* 13, 025012 (2011)
[7] Palyanov et al., *Sci. Rep.* 5, 14789 (2015)
[8] Becker and Becher, Phys. Status Solidi A 214, 1700586 (2017)

* Based on *ab initio* calculations

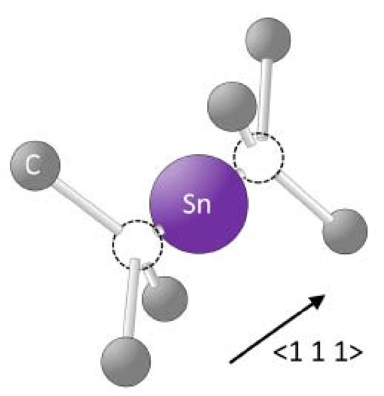
Characterization of single SnV's

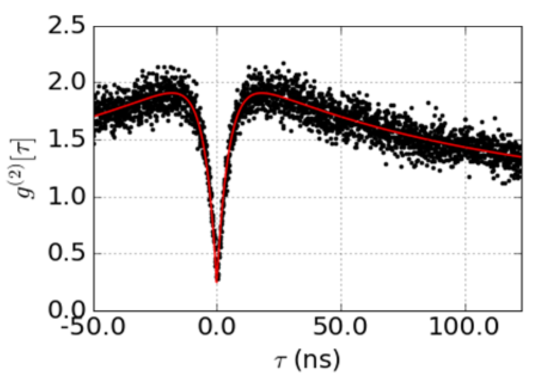


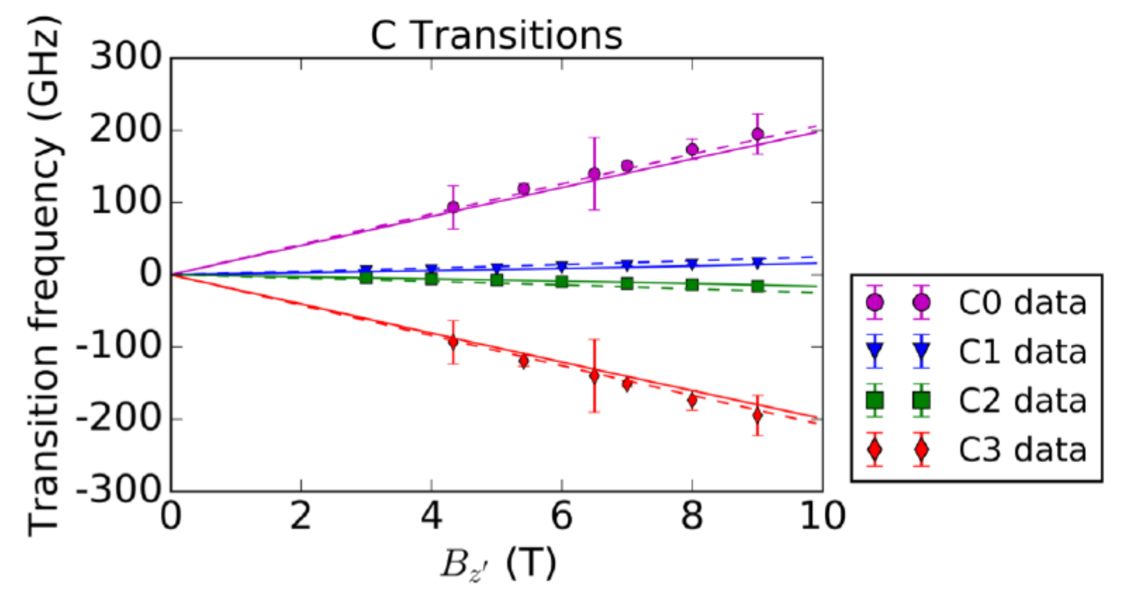




Linewidth ~230MHz



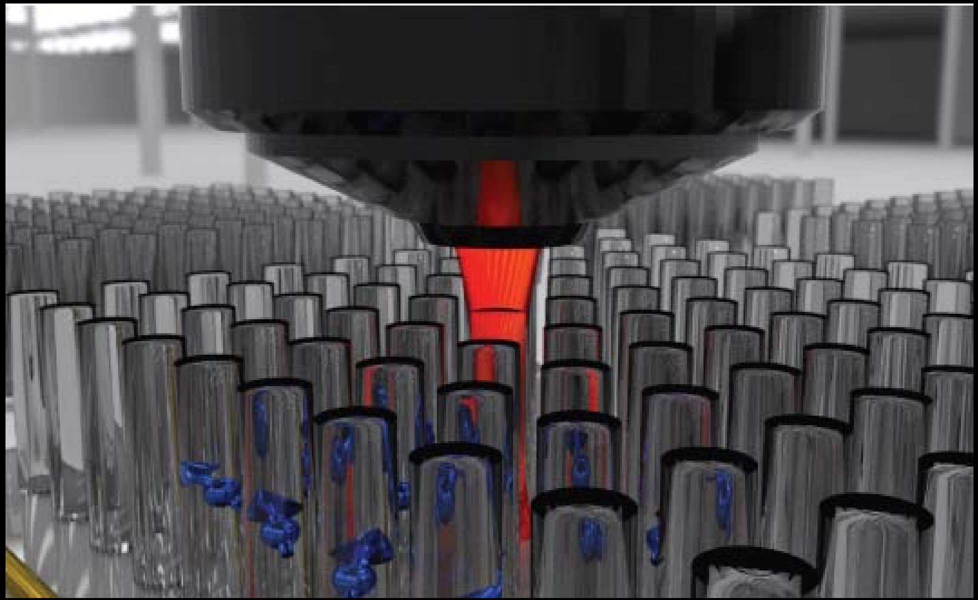


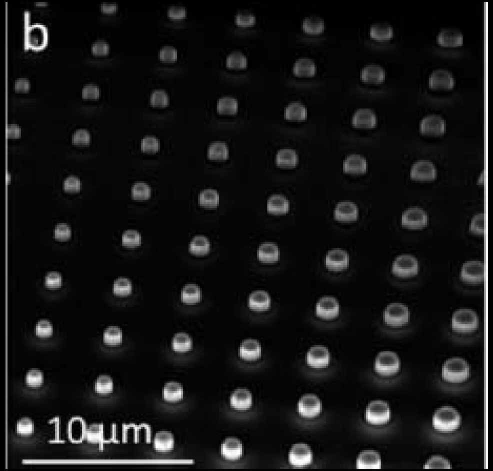


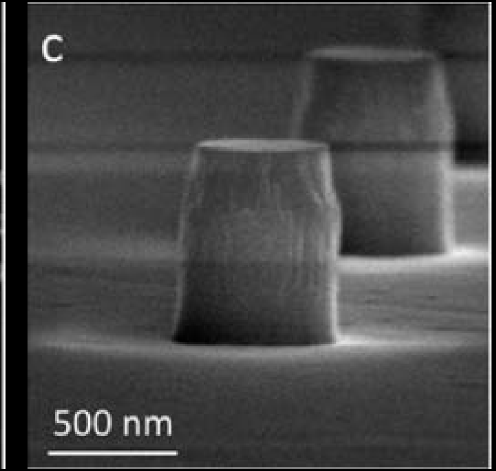
A. Rugar, et al., *Phys Rev B*, in press, arXiv:1811.09941

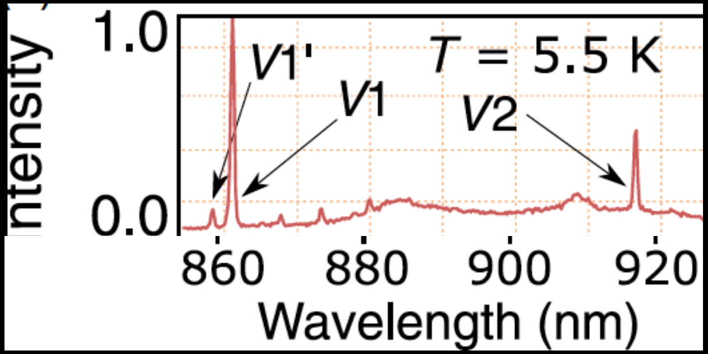
Similar work: Trusheim et al., arXiv:1811.07777

Single V_{Si} in 4H-SiC pillars





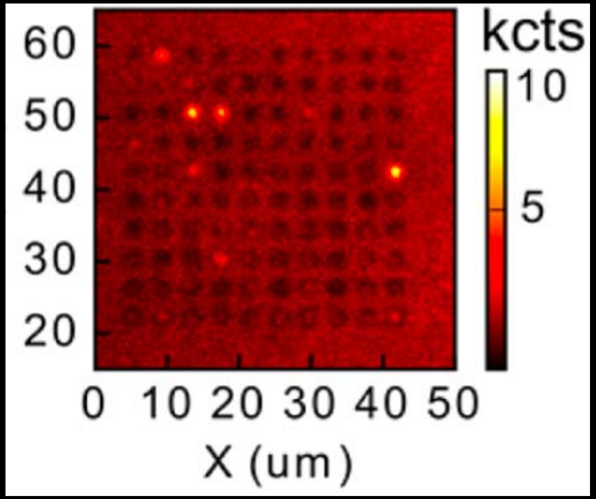


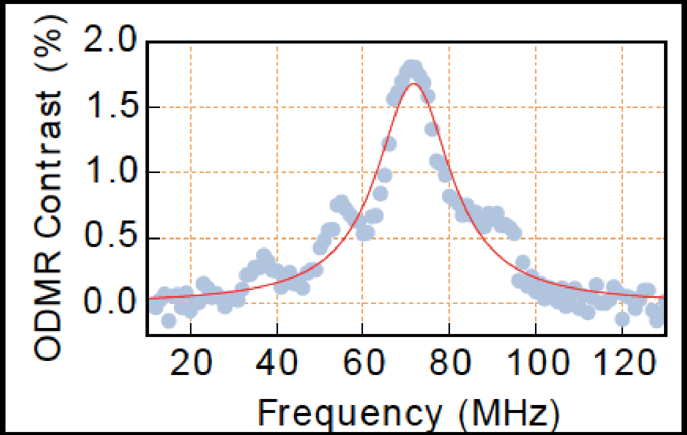


M. Radulaski, M. Widmann, et al., *Nano Letters* **17**, 3, 1782-1786 (2017)

R. Nagy, M. Widmann, et al., *Physical Review Applied*, **9**, 034022 (2018)

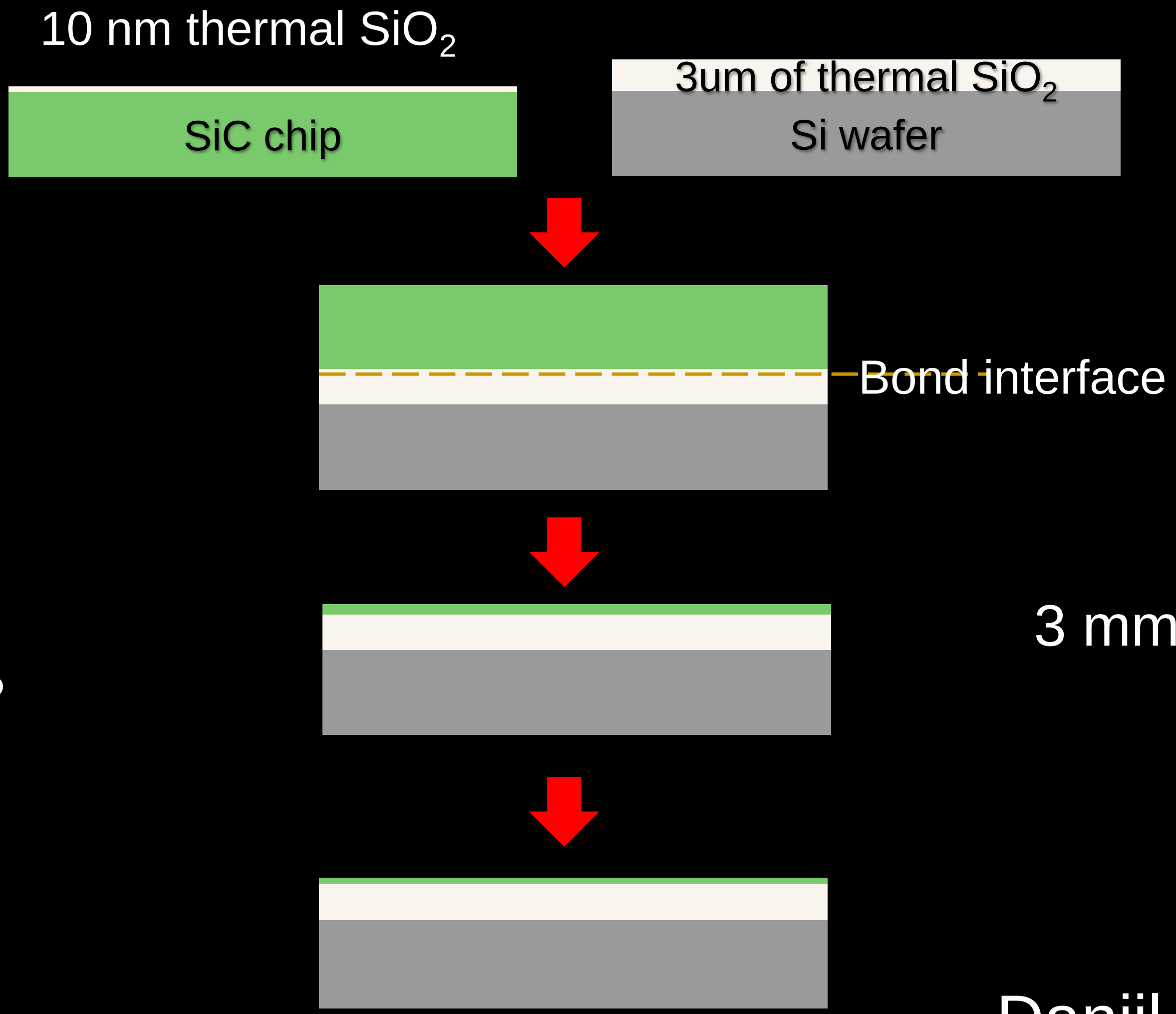
V_2 at T = 300 K





e-spin coherence time ~0.6ms

Fabrication of the SiCOI (SiC on Insulator)

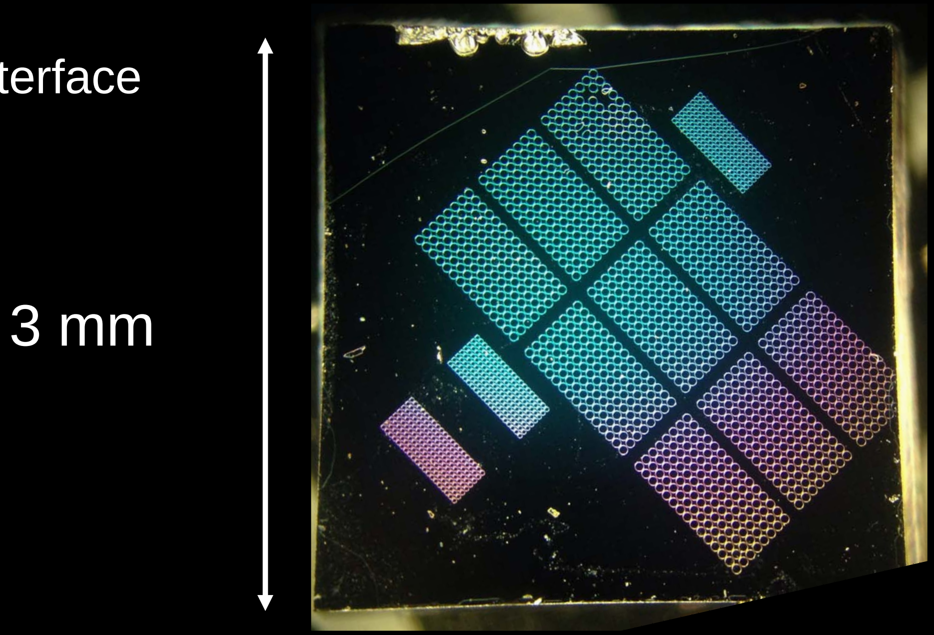


Preparation of the stack

Fusion bonding (900 °C)

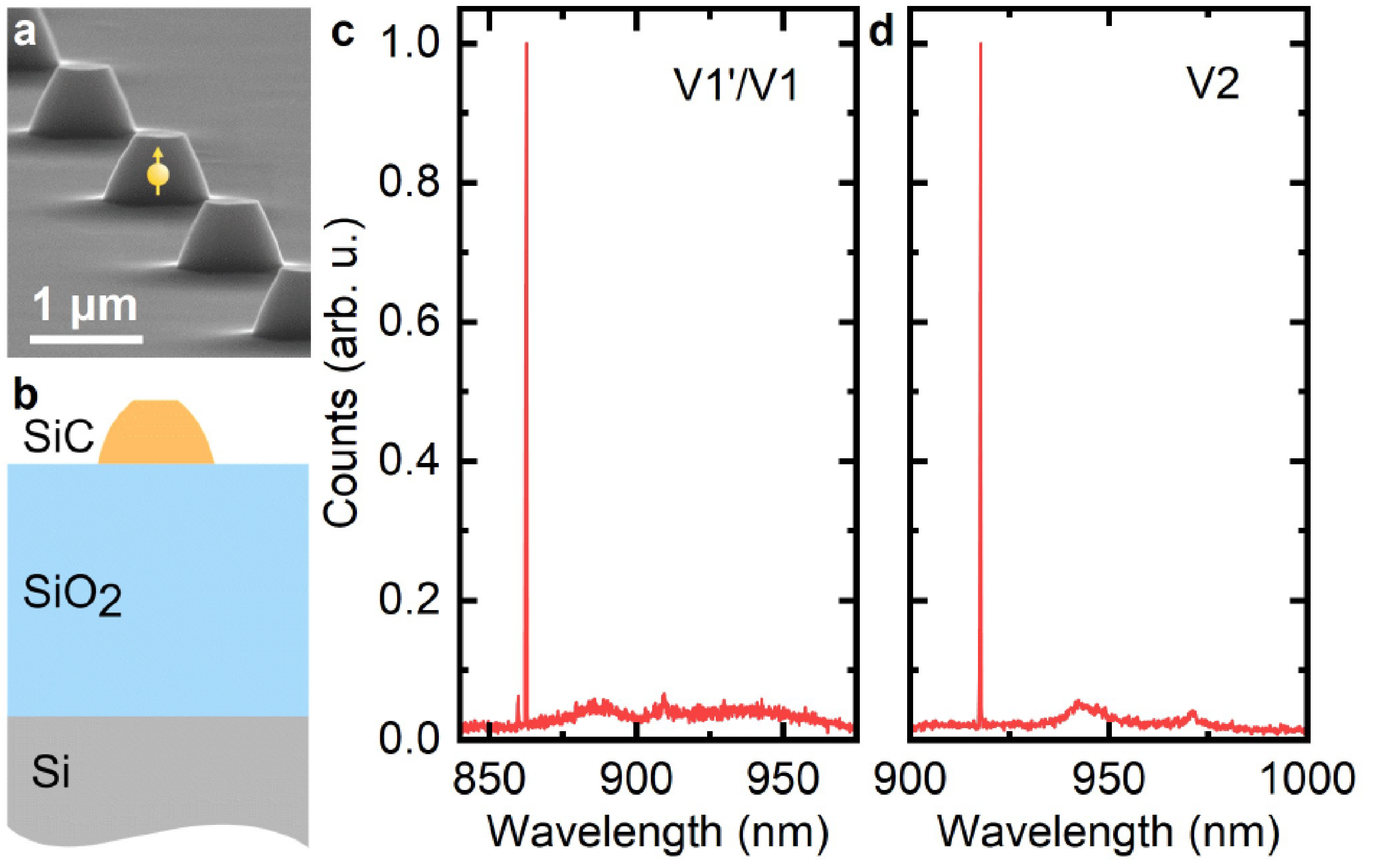
Grinding and CMP

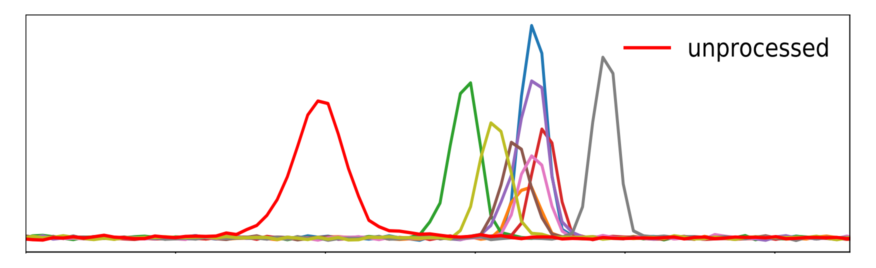
RIE thinning



Daniil Lukin, Constantin Dory

SiCOI Quantum Platform with Single V_{Si}



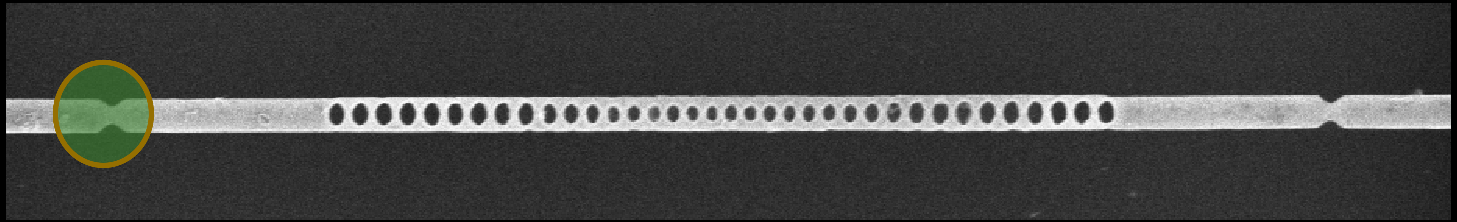


Emitter density <0.1/µm^3

Small spectral broadening

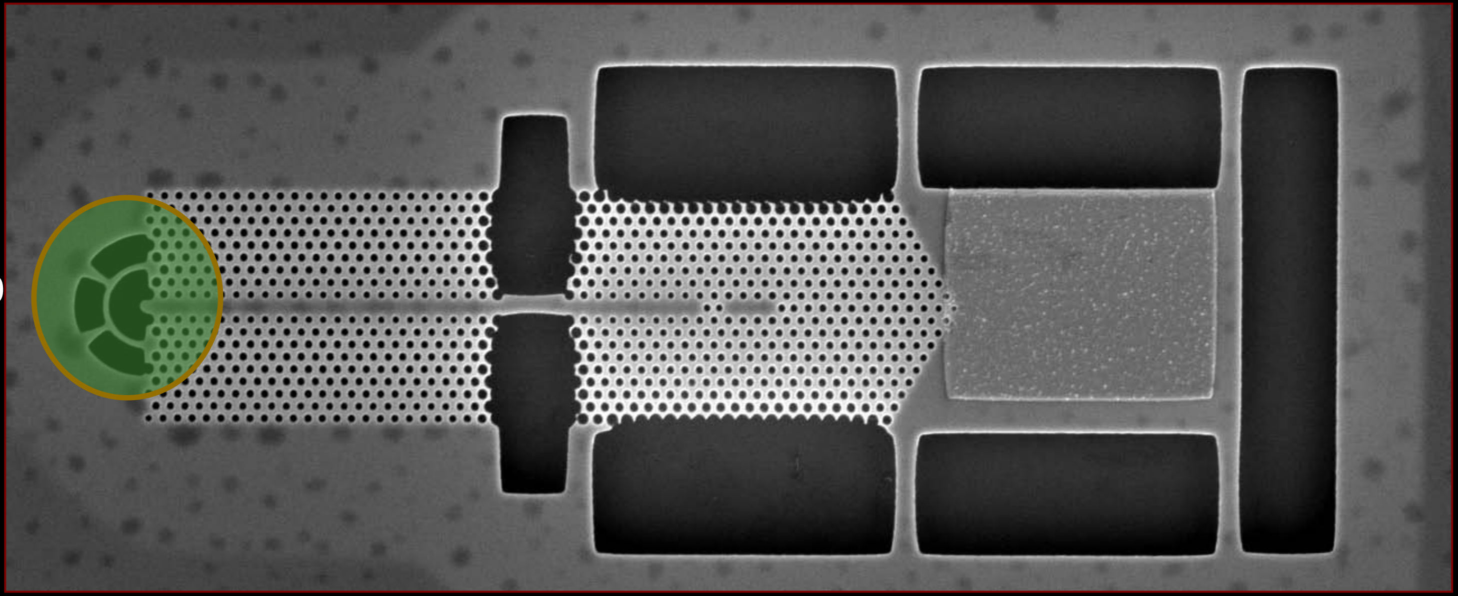
We also need to significantly improve the efficiency of the optical interconnects for system-level integration

1%



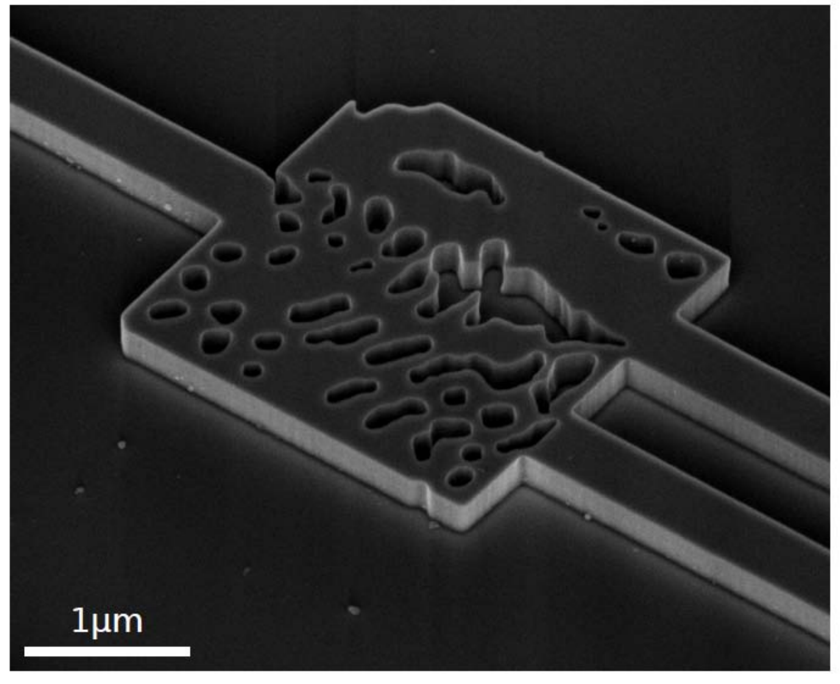
Zhang*, Sun* et al., *Nano Lett.* 18, 1360–1365 (2018)

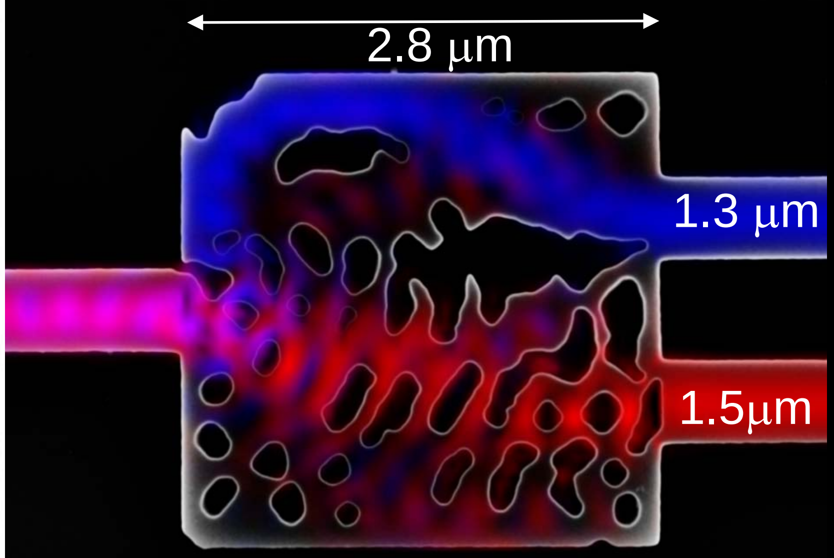
~5%



Faraon et al., *Optics Express* 16, 12154 (2008)

Could we design and make better photonics?





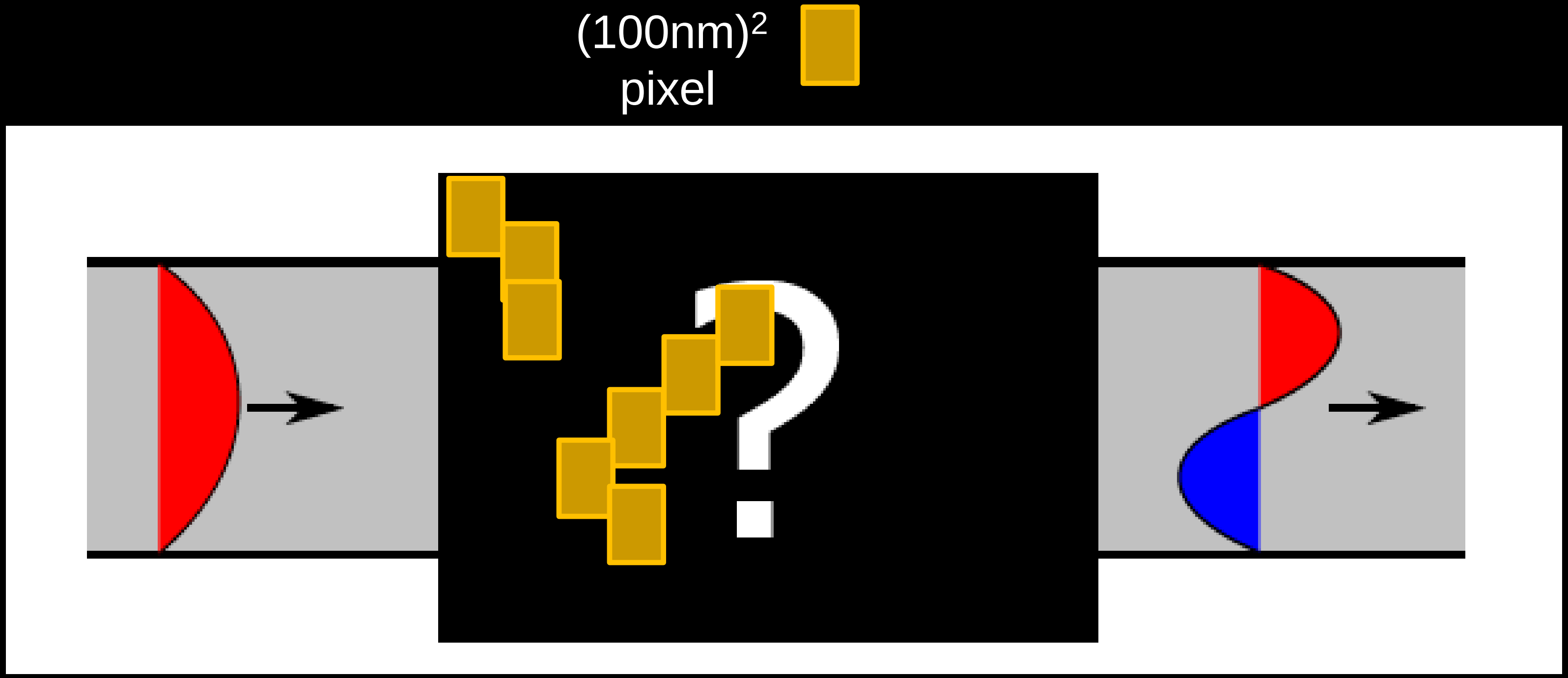
Fabricated device with superimposed E-fields

Developed a design method for *any* 3D nanophotonic device

J. Lu and J. Vuckovic, *Optics Express* Vol. 21, 11, pp. 13351-13367 (2013)

Inverse design in nanophotonics, Sean Molesky, Zin Lin, Alexander Y. Piggott, Weiliang Jin, Jelena Vučković, Alejandro W. Rodriguez, *Nature Photonics, vol.* 12, pp. 659–670 (2018)

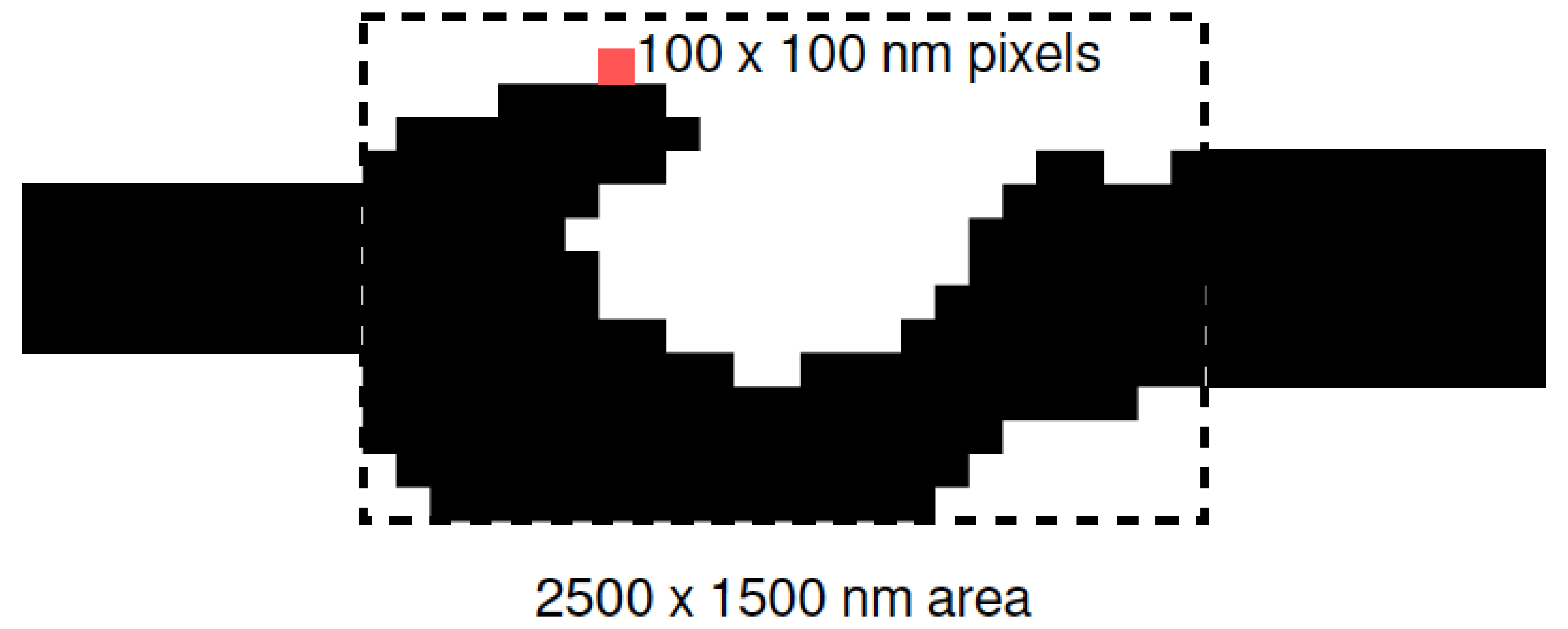
Inverse design example



2500nm x 1500nm footprint, >90% efficiency

(many orders of magnitude smaller than state of the art)

Full parameter design



Number of possible designs (include/exclude pixel): $2^{25x15}=2^{375}\sim10^{112}$

Brute force search not feasible!
Perform physics guided design – not blind search!

Physics guided optimization – stage 1

Full GPUs)

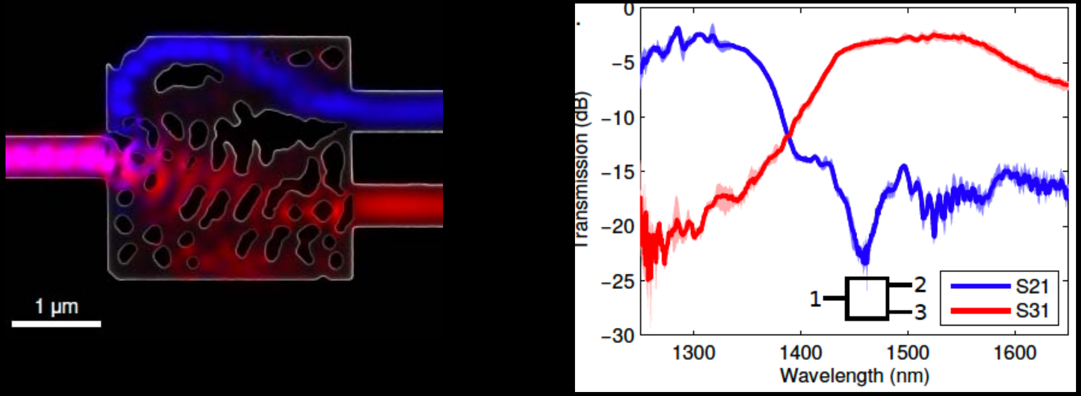
Working on spee le-X arXiv:1902.00090)

Physics guided optimization – stage 2

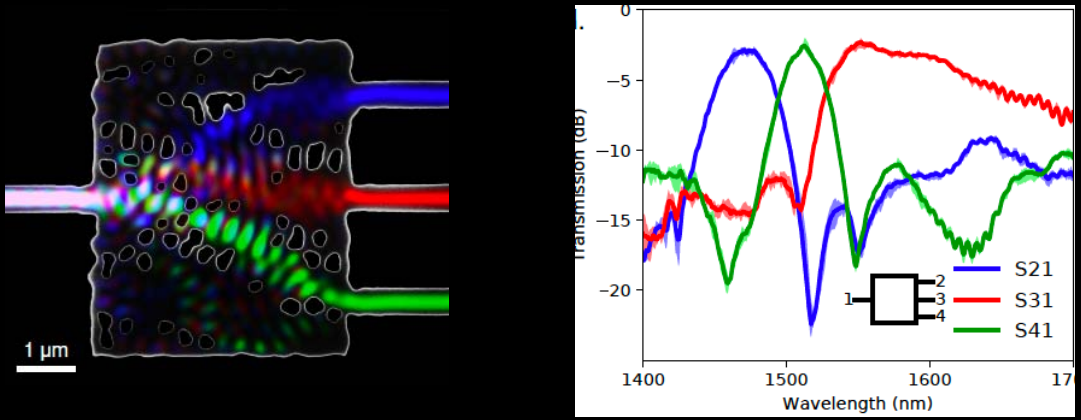
Fu Us)

Working on spe arXiv:1902.00090)

Photonics can be robust and insensitive to errors



A. Piggott et al, *Nature Photonics* (2015)



L. Su et al, *ACS Photonics*, 5 (2), pp 301–305 (2018)

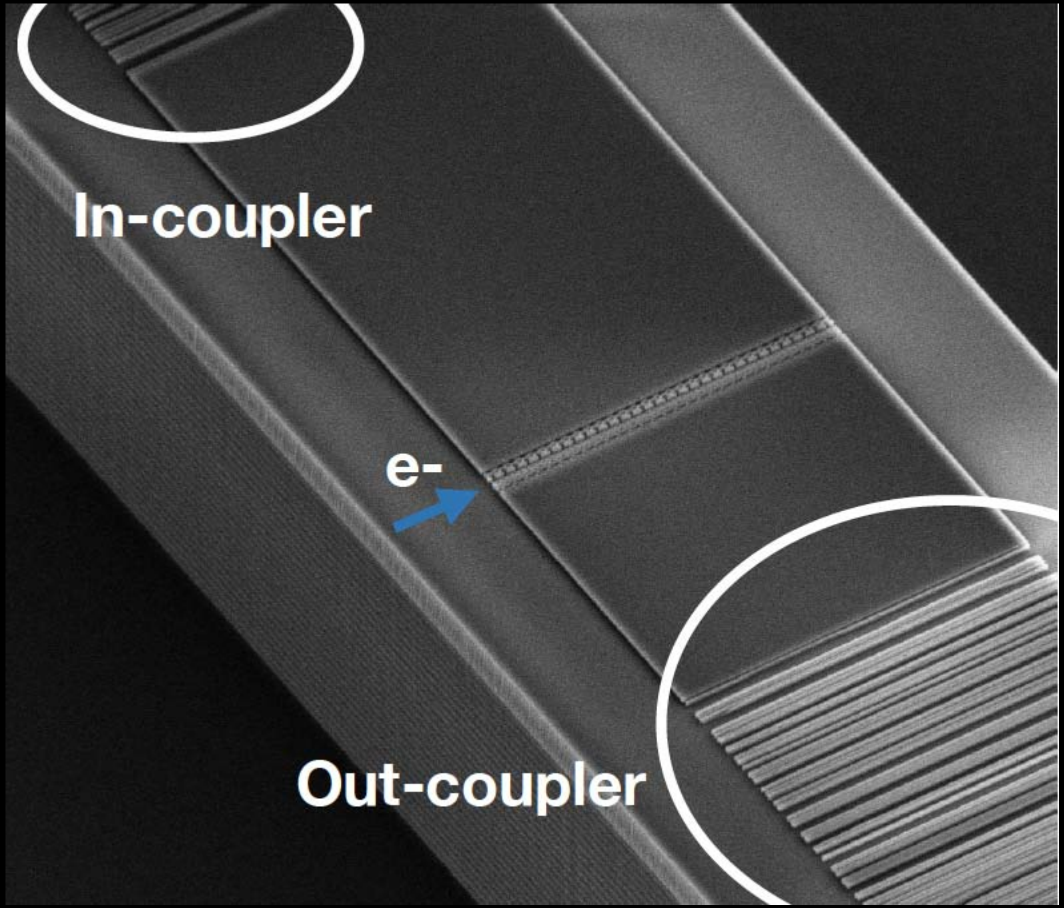
Stanford **P**hotonics **IN**verse design **S**oftware (**SPINS**)

Vuckovic Group - Stanford OTL Docket Number: S18-012

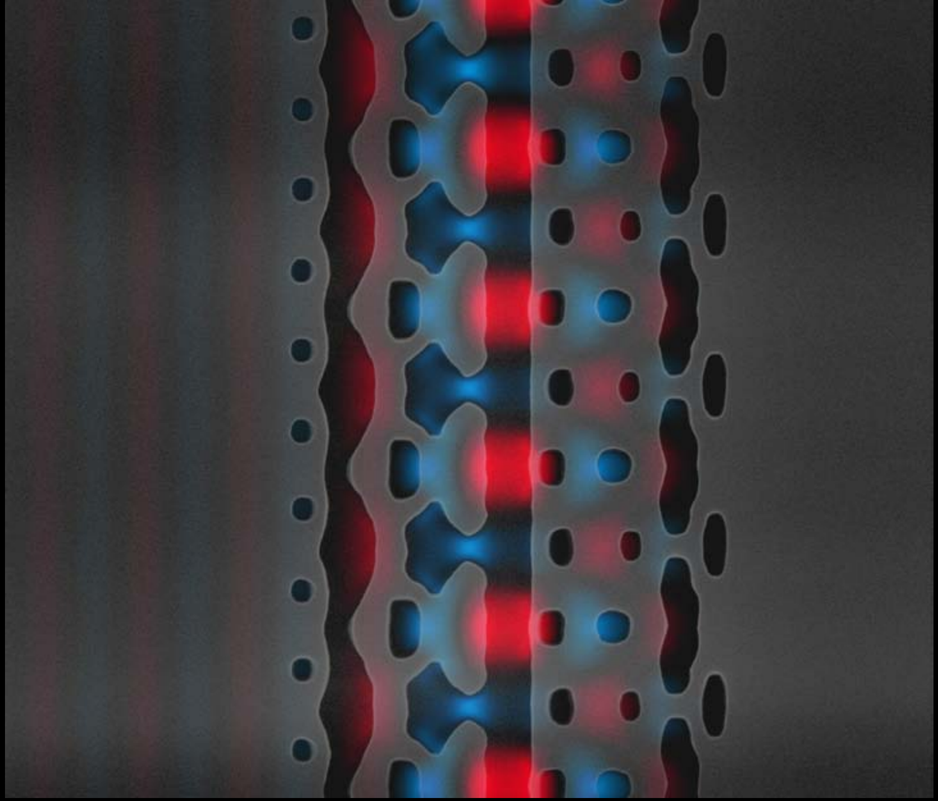
SPINS–B (open source) on Github

http://github.com/stanfordnqp/spins-b

On-chip laser driven particle accelerators (ACHIP)

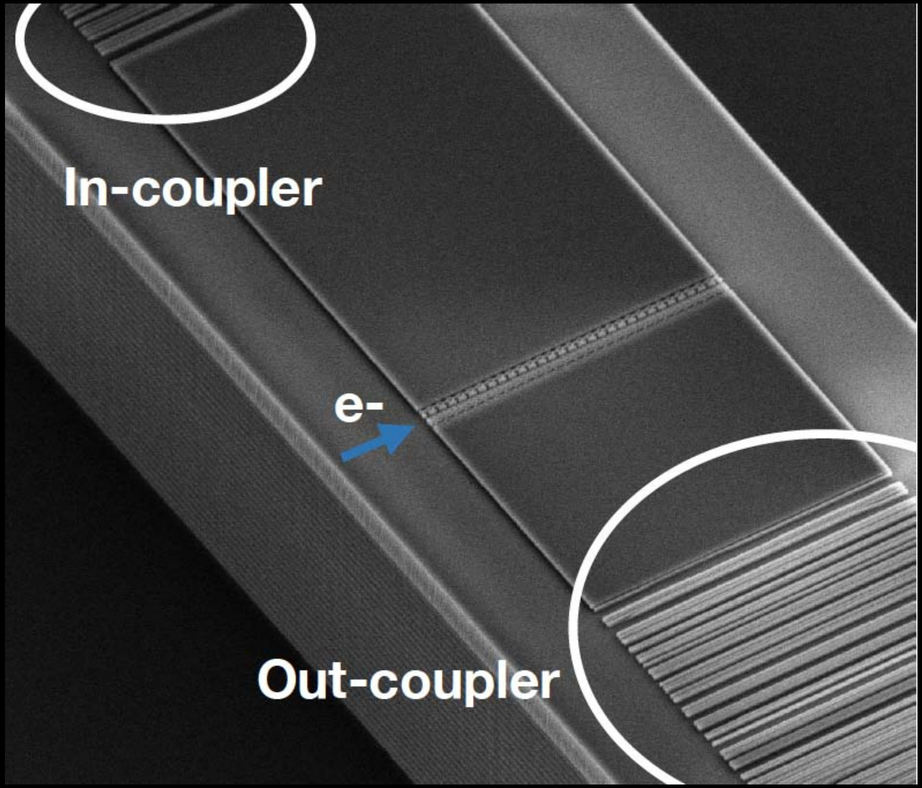


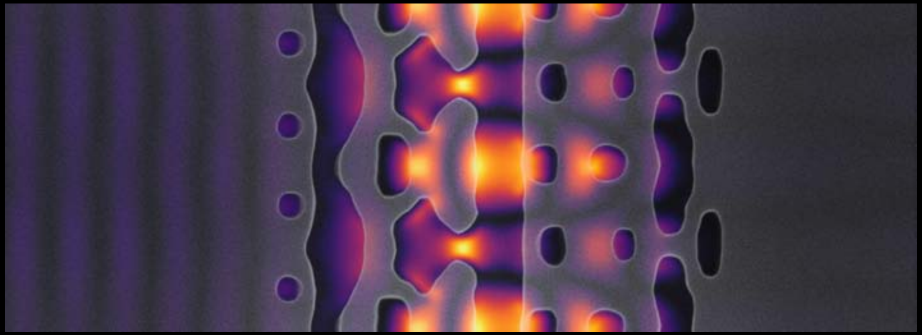
ACHIP project (B. Byer, P. Hommelhoff)

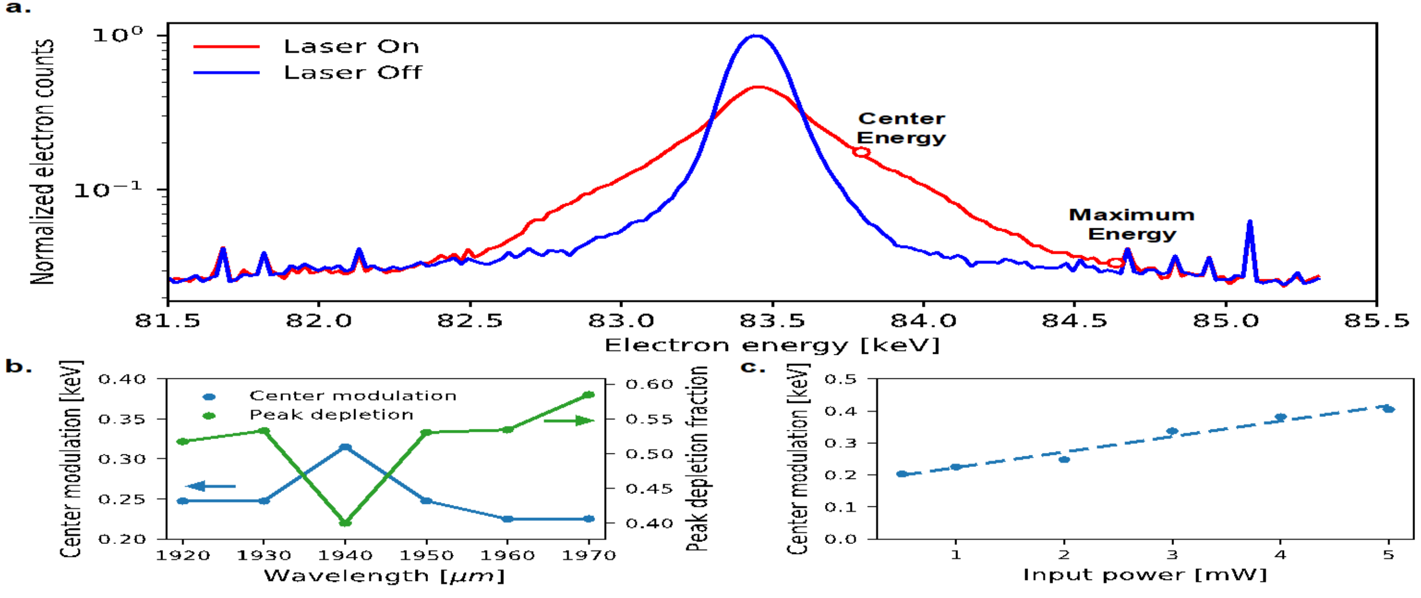


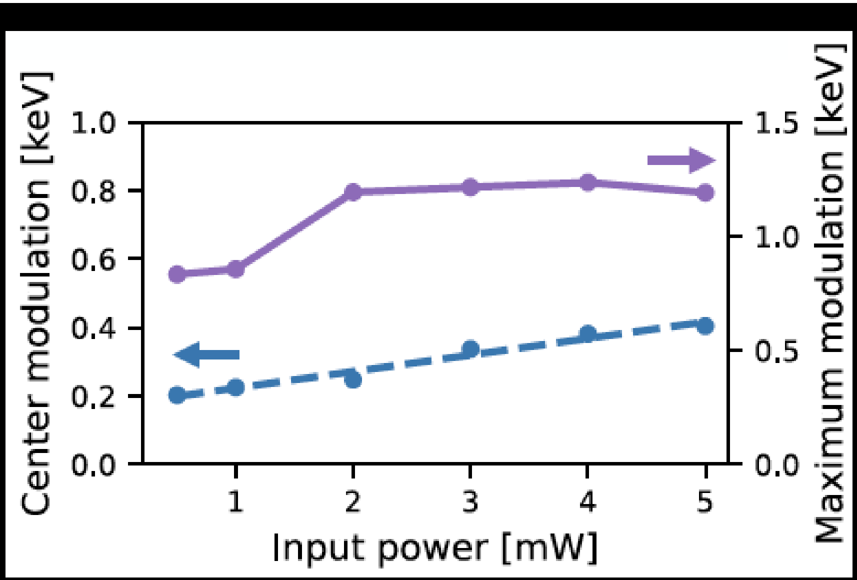
N. Sapra, K. Yang et al

ACHIP – accelerator on chip (experiment)



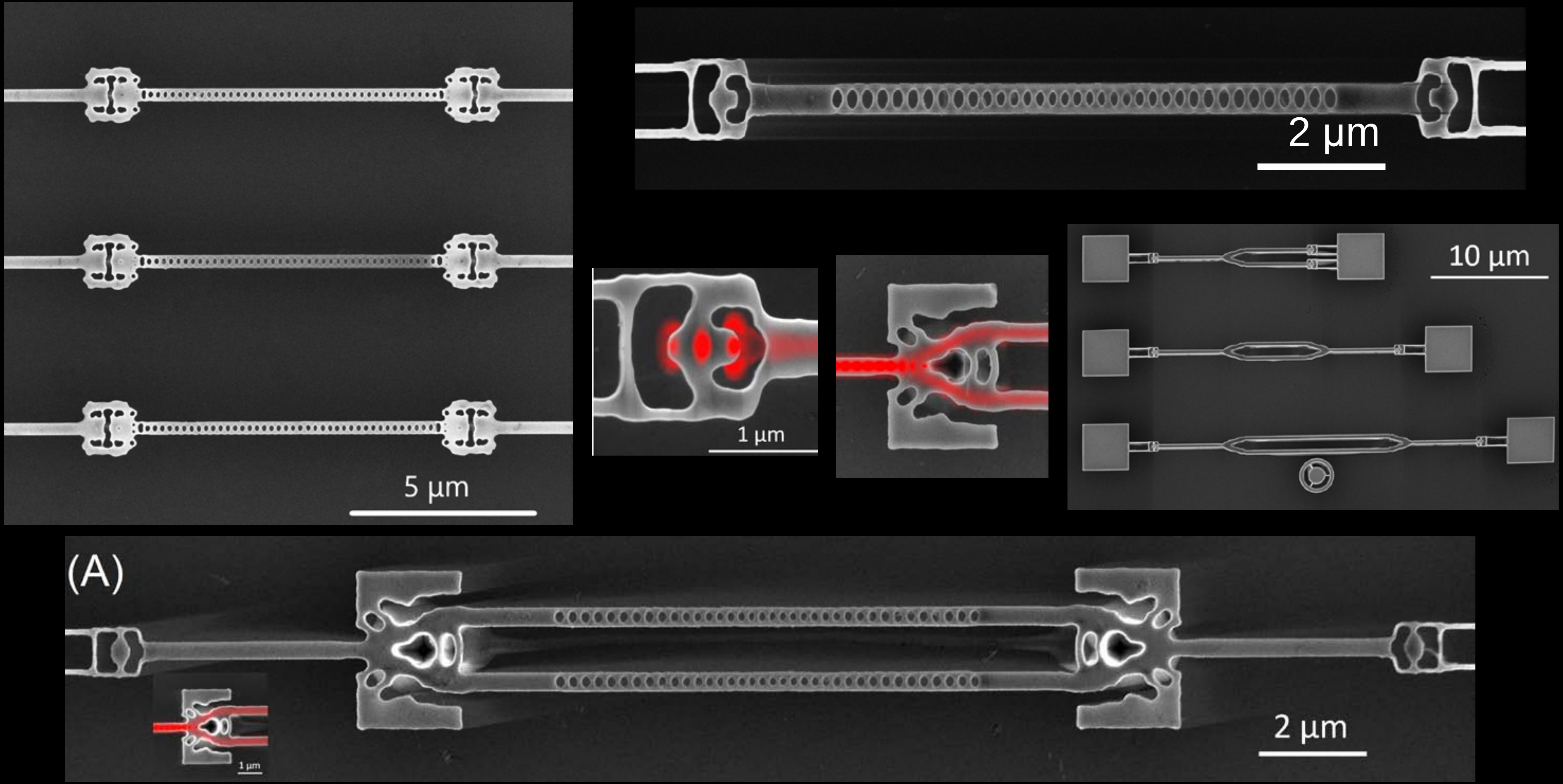






N. Sapra,
K. Yang et al

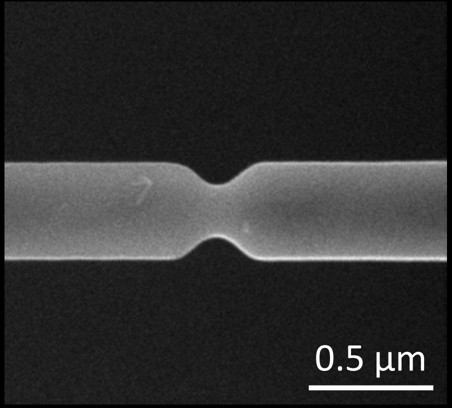
Optimized diamond quantum photonics

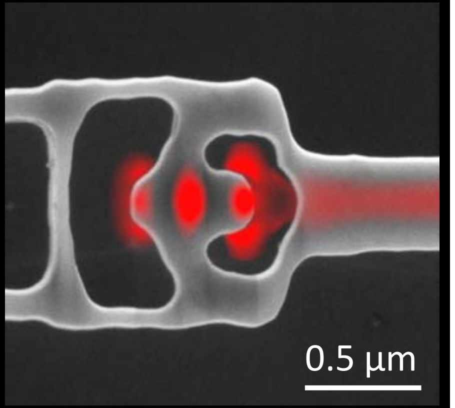


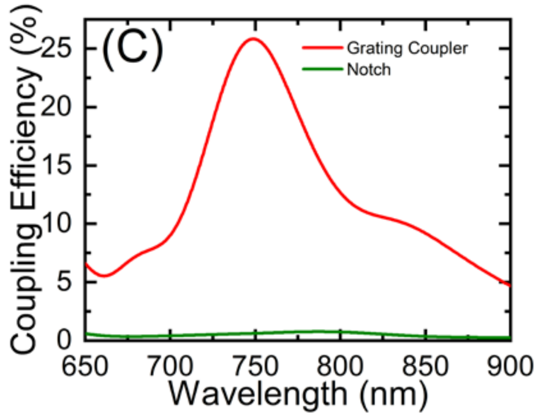
Fabrication method developed by Constantin Dory, Daniil Lukin
(inspired by work from Paul Barclay, Calgary; Dirk Englund, MIT)

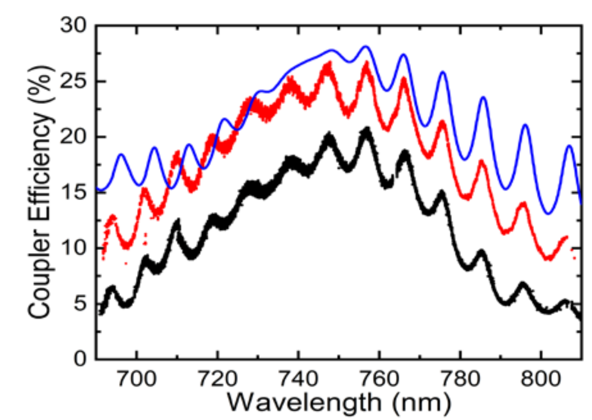
C. Dory, et al., arXiv:1812.02287

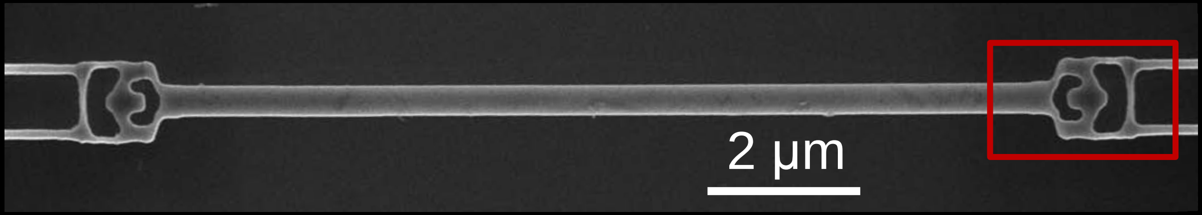
Inverse-designed vertical couplers in diamond

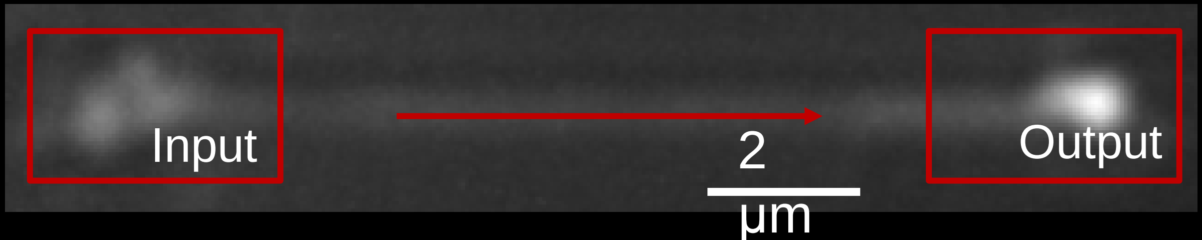


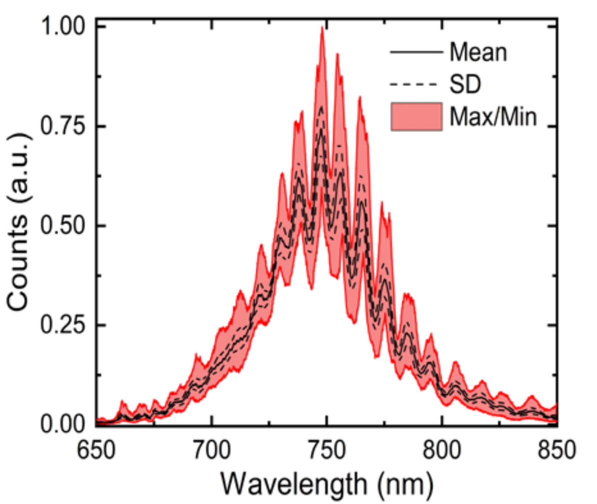








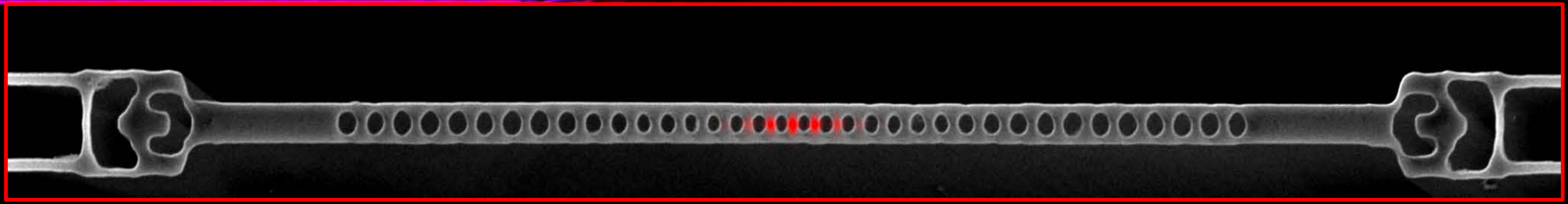


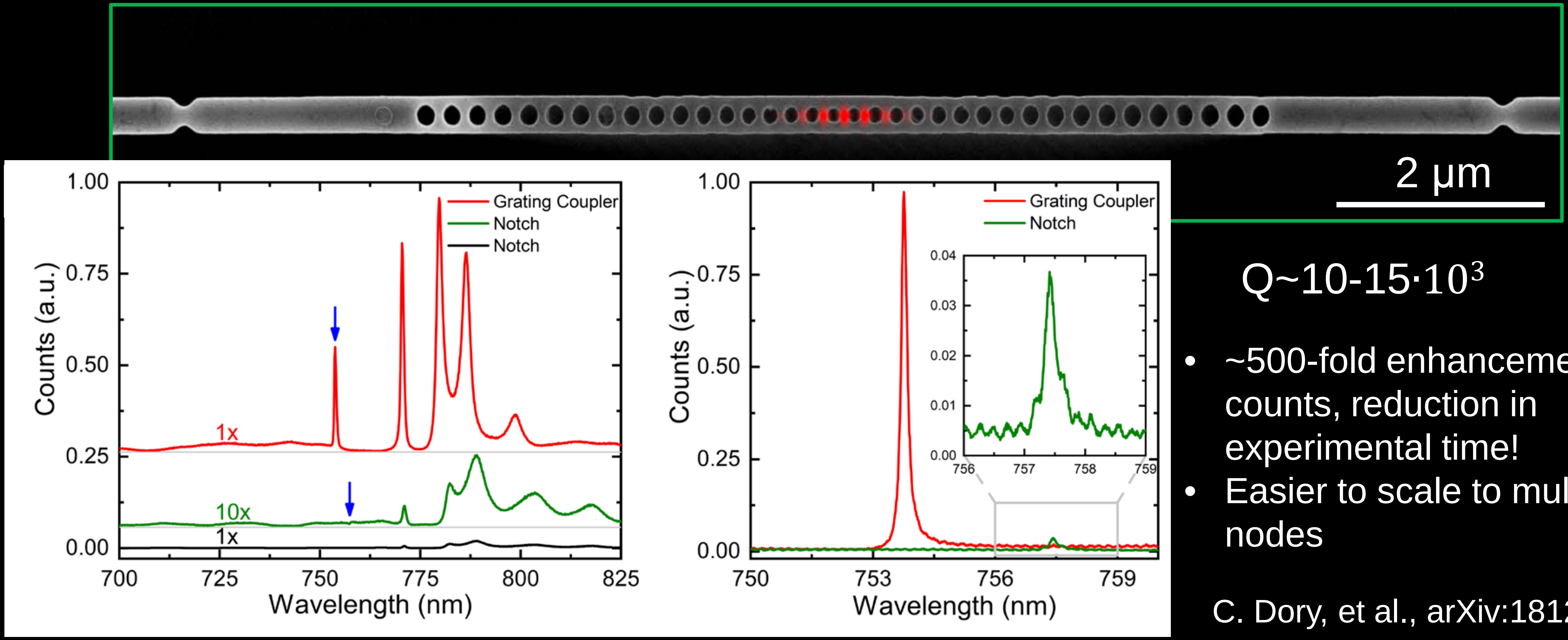


>27% per coupler (multimode fiber); >21% per coupler (single-mode fiber)

C. Dory, et al., arXiv:1812.02287

Optimized coupler-cavity integration



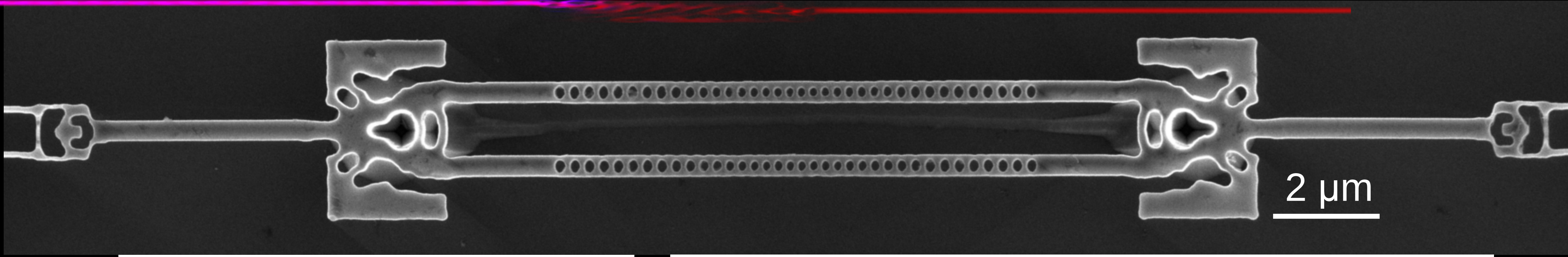


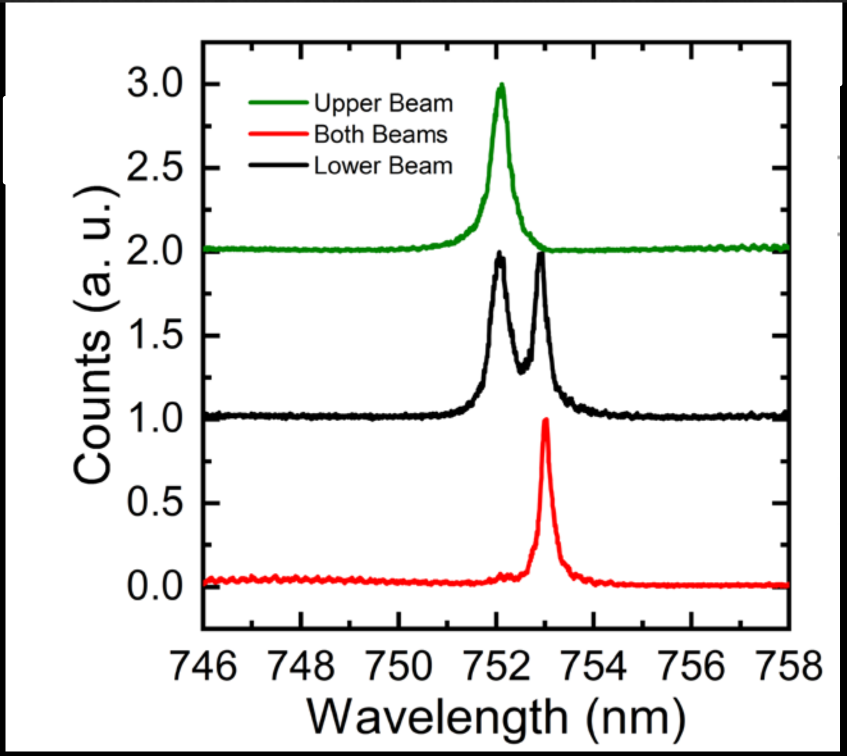
Q~10-15·10^3

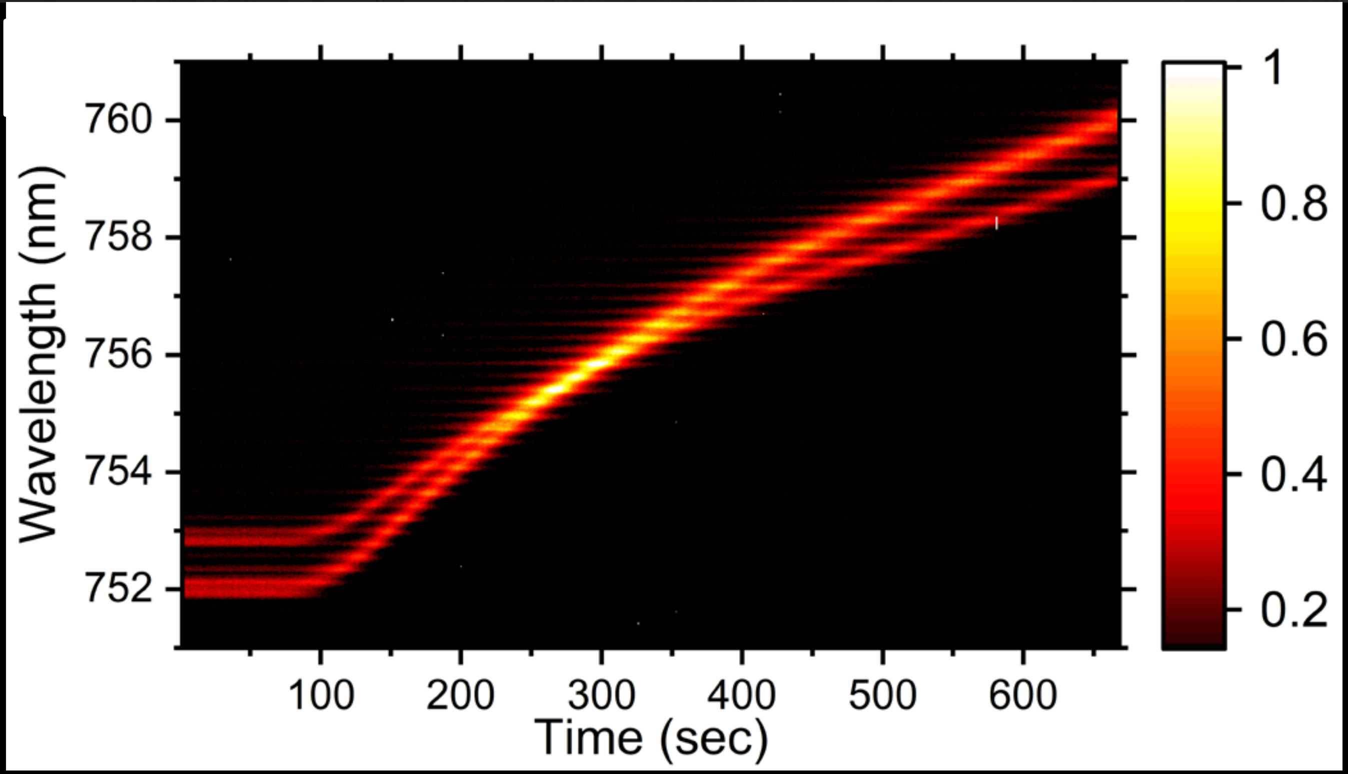
- ~500-fold enhancement in counts, reduction in experimental time!
- Easier to scale to multiple nodes

C. Dory, et al., arXiv:1812.02287

Diamond Photonic Circuits

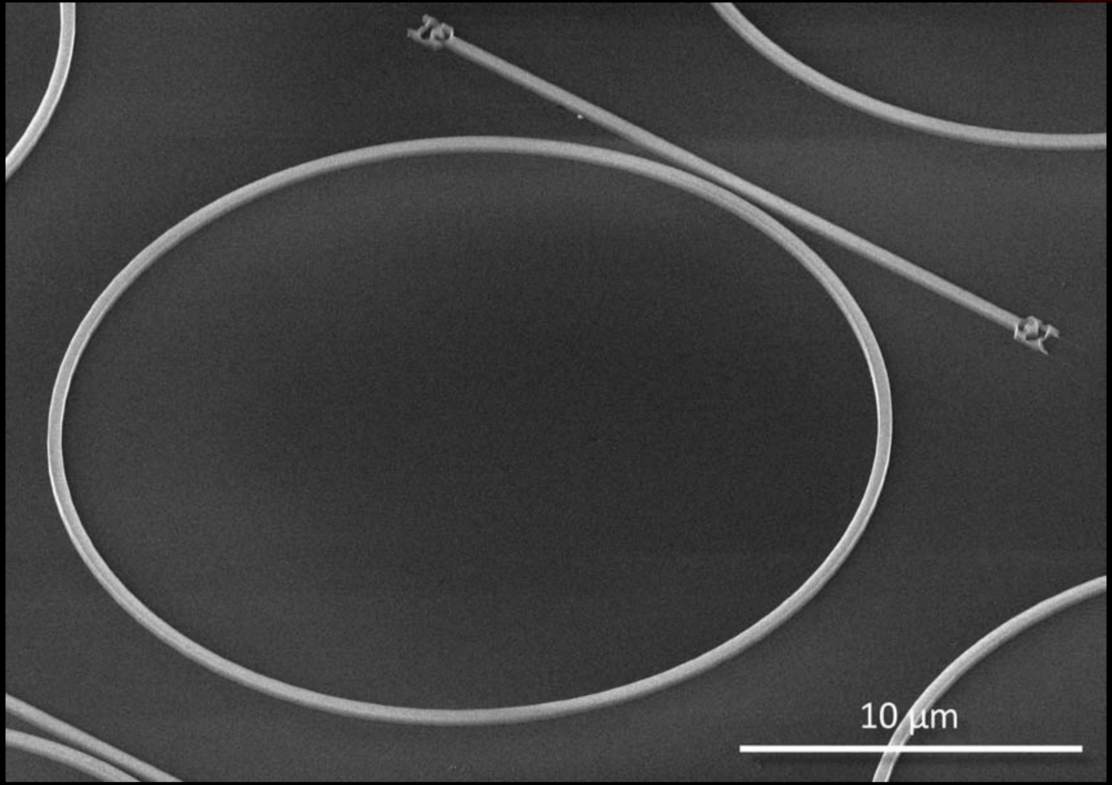


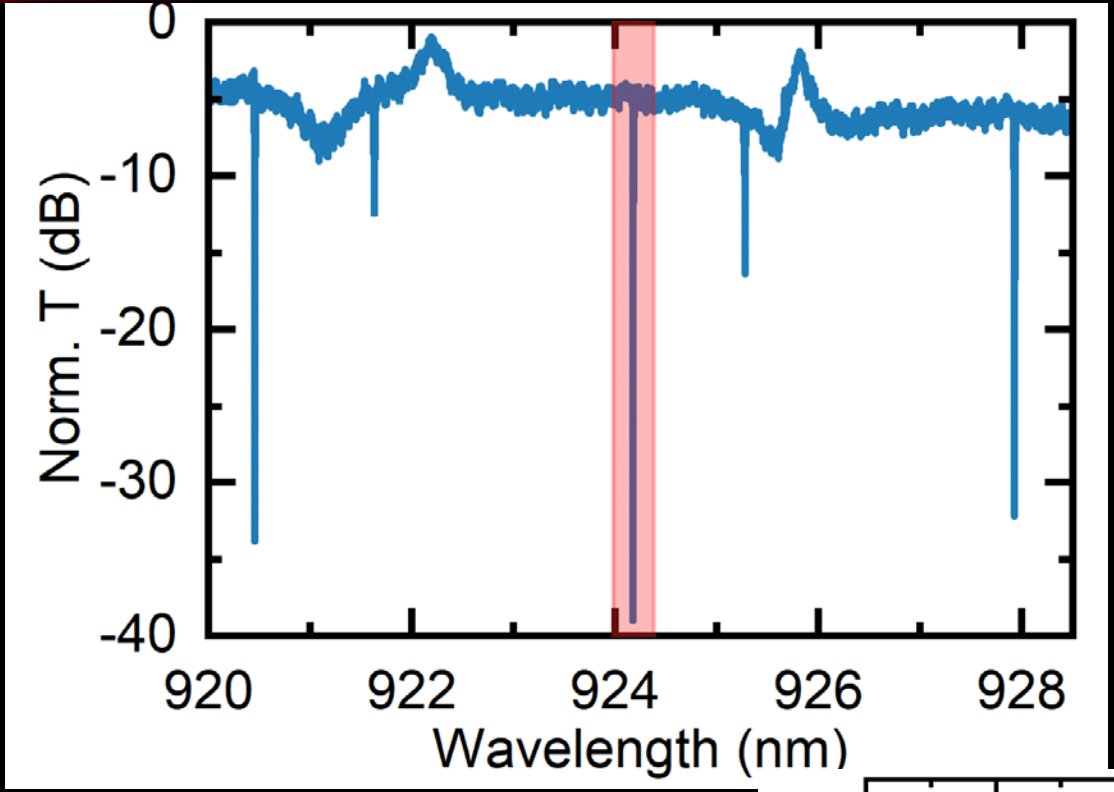


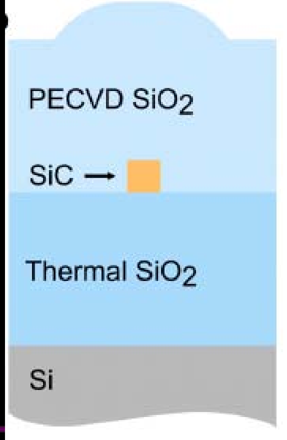


C. Dory, et al., arXiv:1812.02287

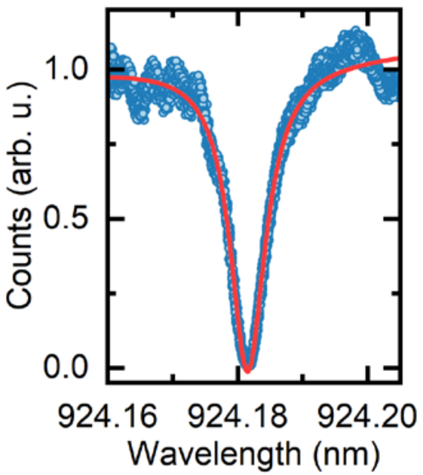
Inverse designed photonic devices in SiCOI



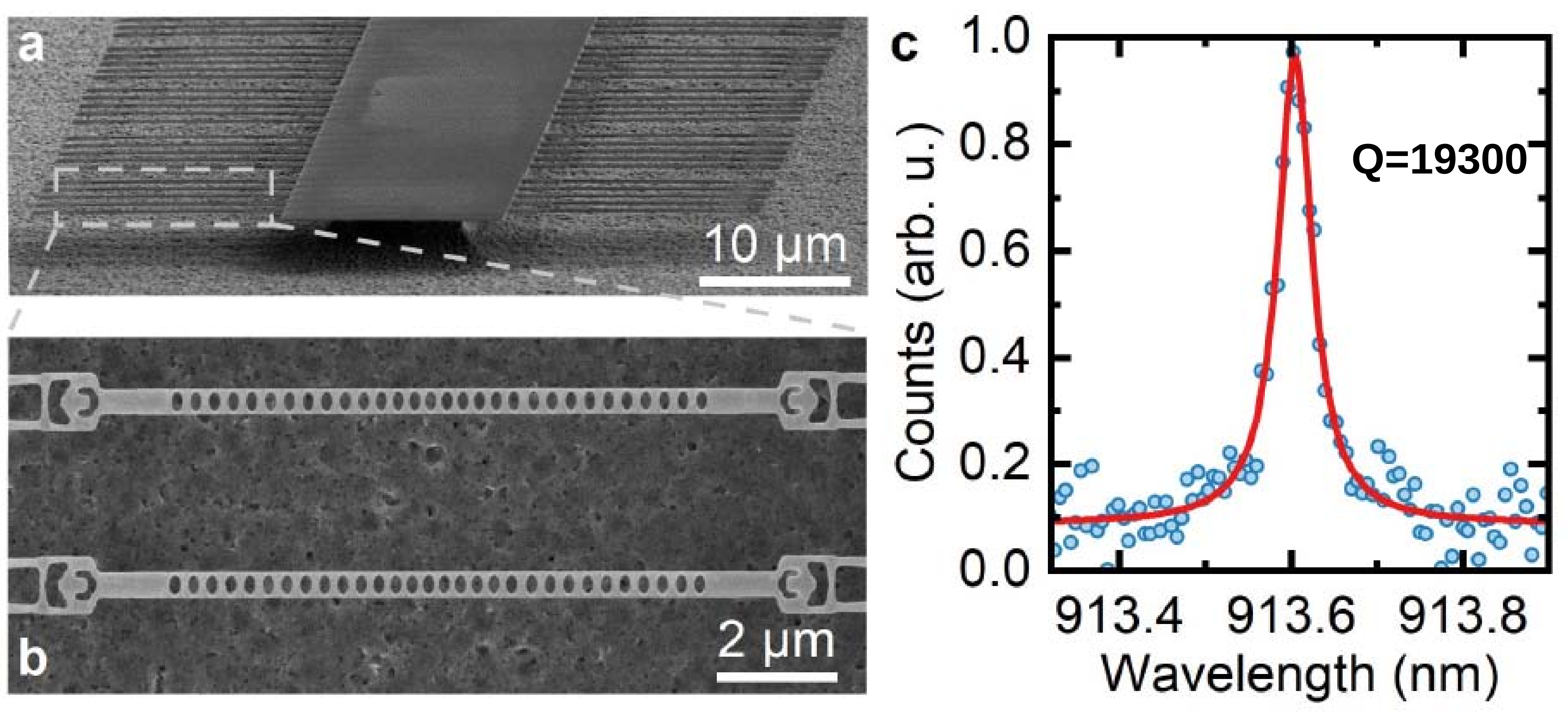




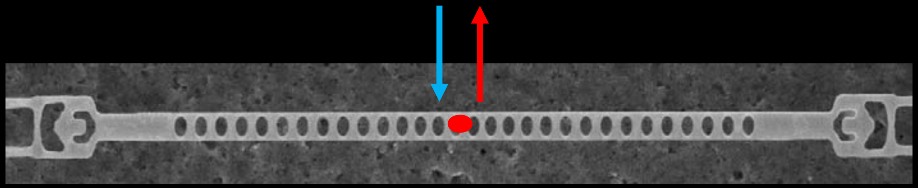
→ loaded Q=1.4·10^5
→ intrinsic Q=2.8·10^5

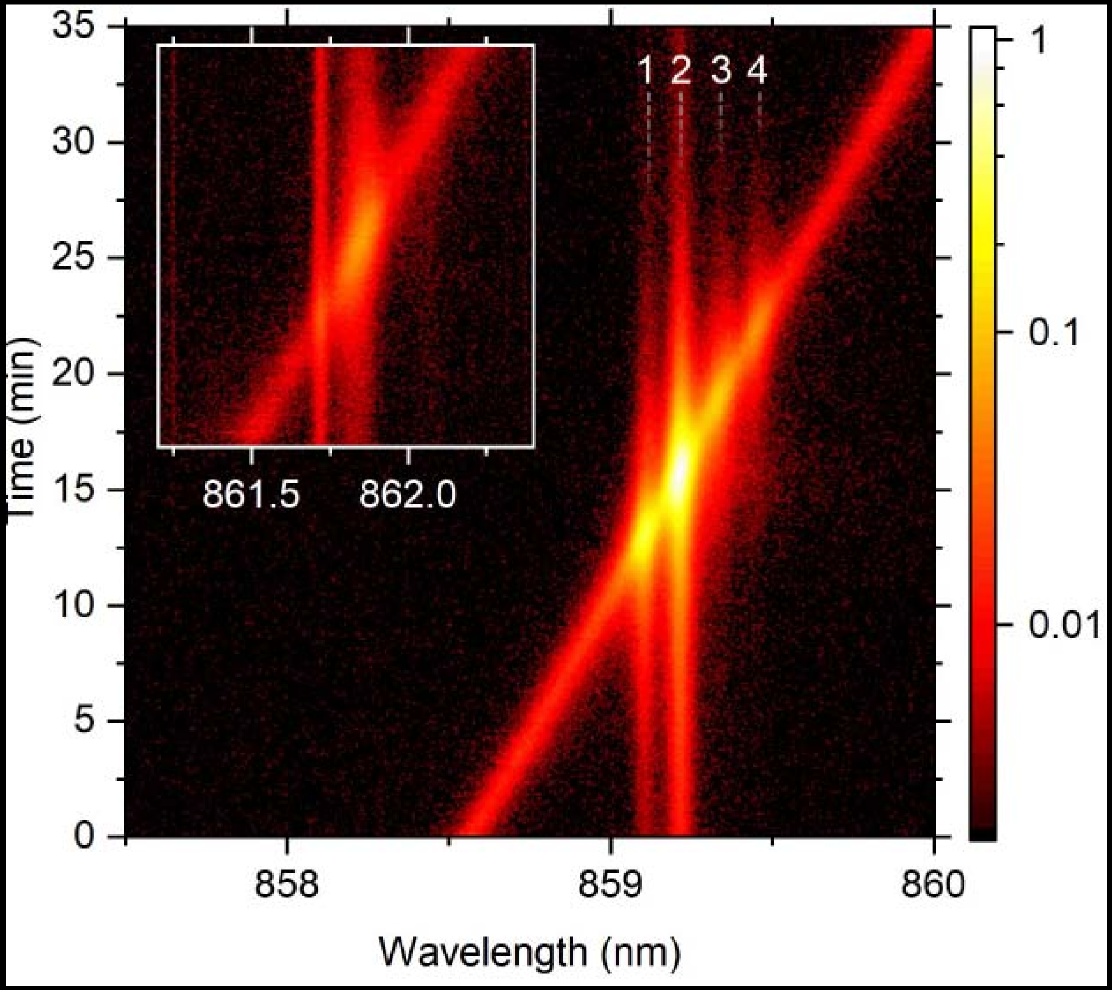


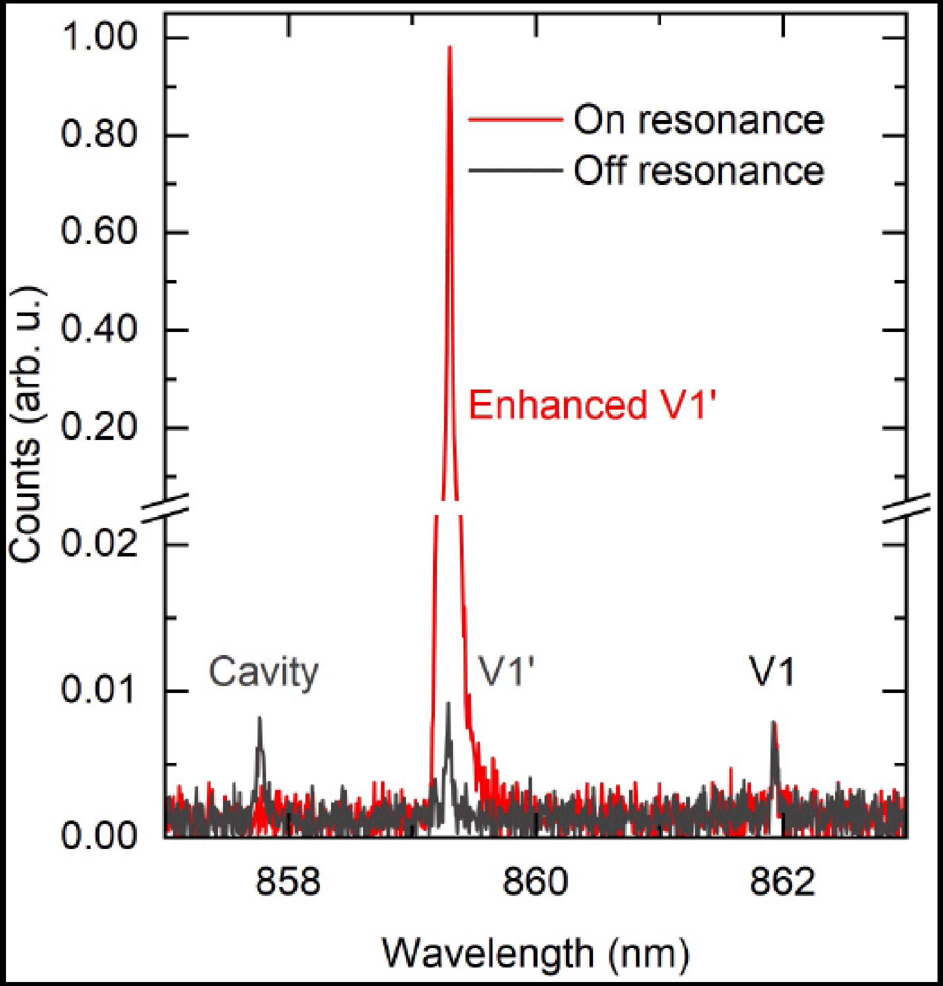
Photonic Crystal Nanobeam Cavities in SiCOI

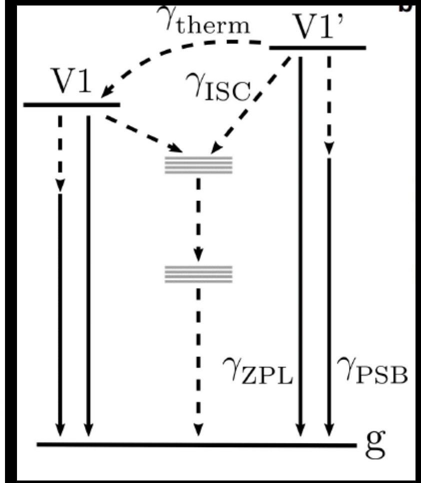


Intensity enhancement of V1’



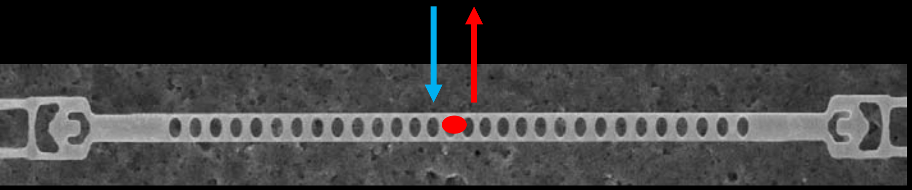






~100-fold enhancement on cavity resonance

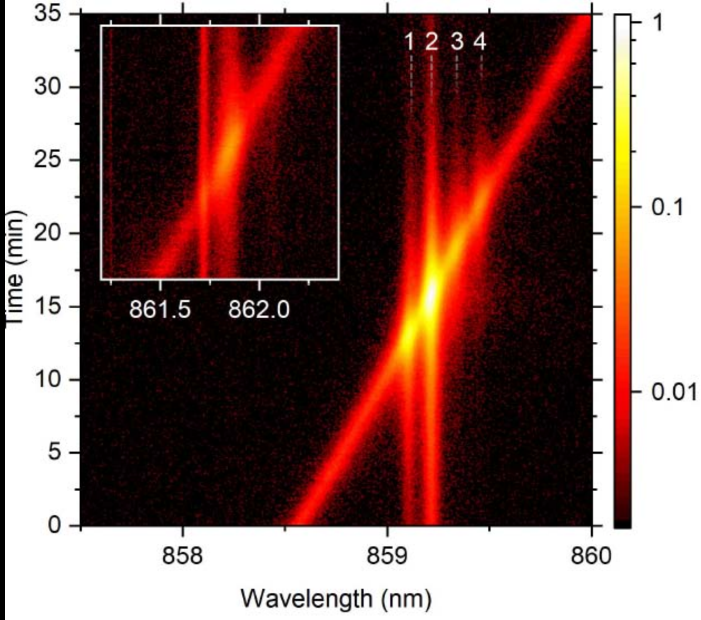
Purcell enhancement of V1’

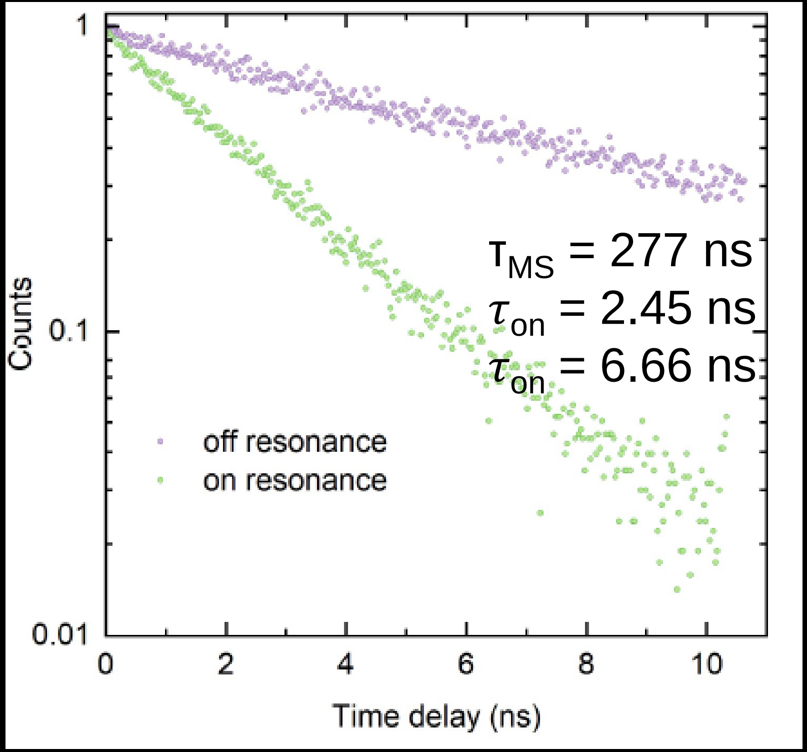


Purcell Enhancement Lower Bound: $F = \frac{\tau_{of}}{\tau_{or}}$

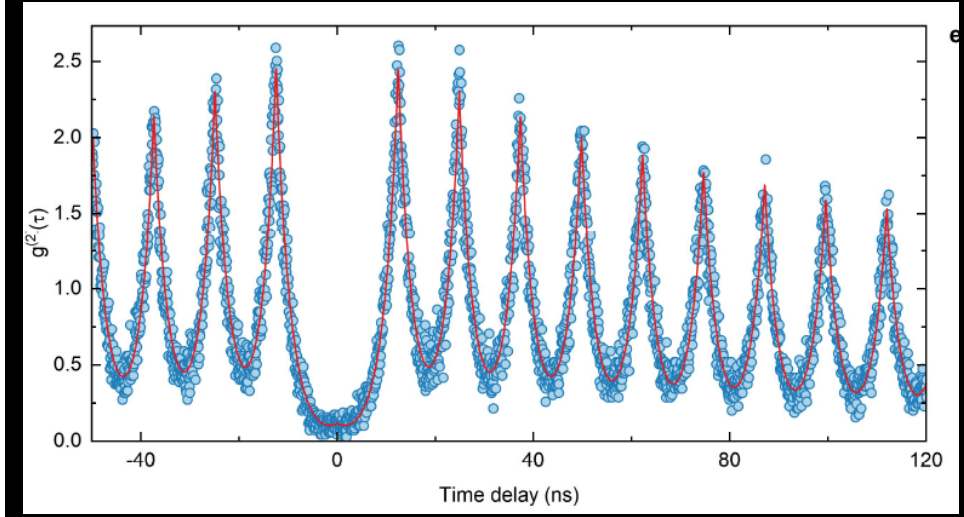
$\xi = 0.19$ Debye-Waller Factor (upper limi

F>>9

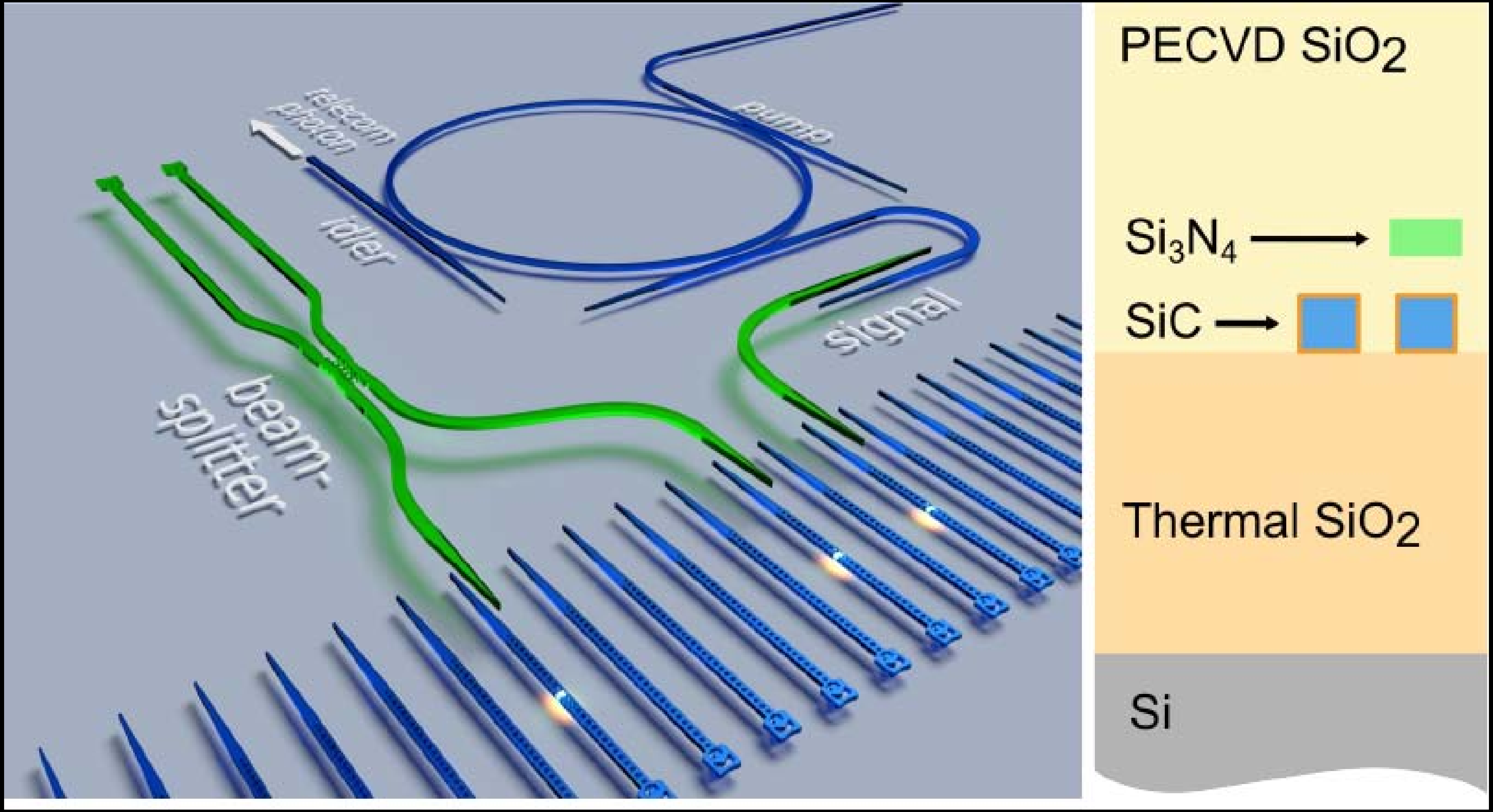




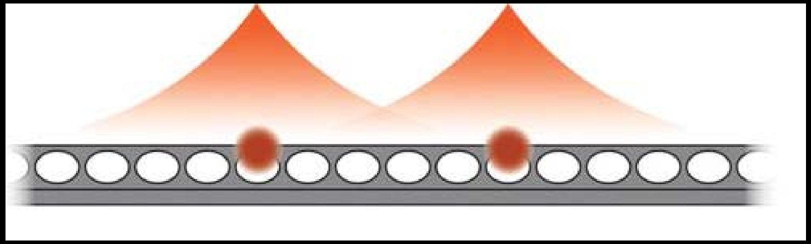
$\tau_{MS} = 277$ ns
$\tau_{on} = 2.45$ ns
$\tau_{on} = 6.66$ ns



Outlook – SiCOI chip-scale quantum networks

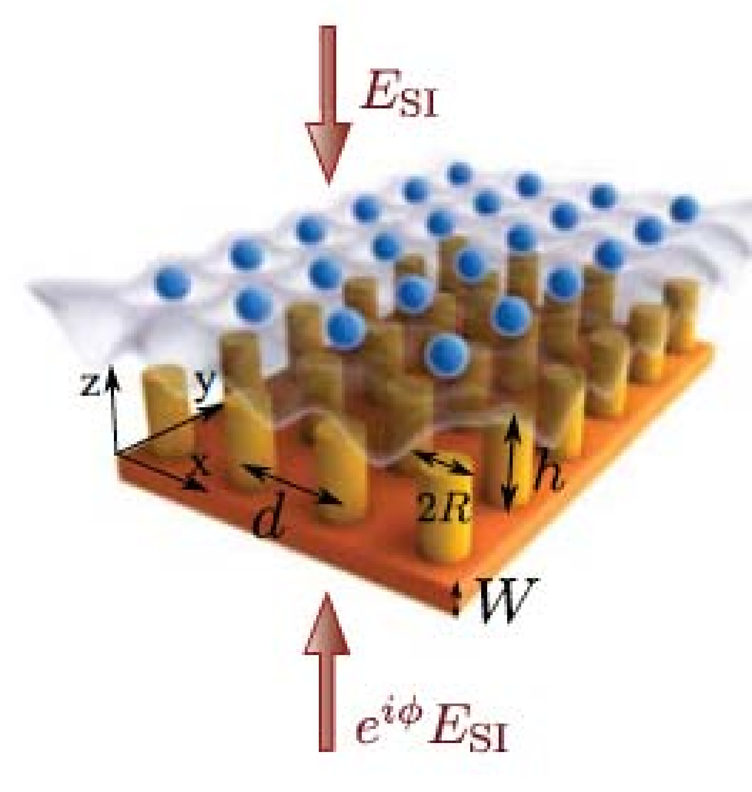


Outlook: applying inverse design for tailoring photon-mediated many-body interactions



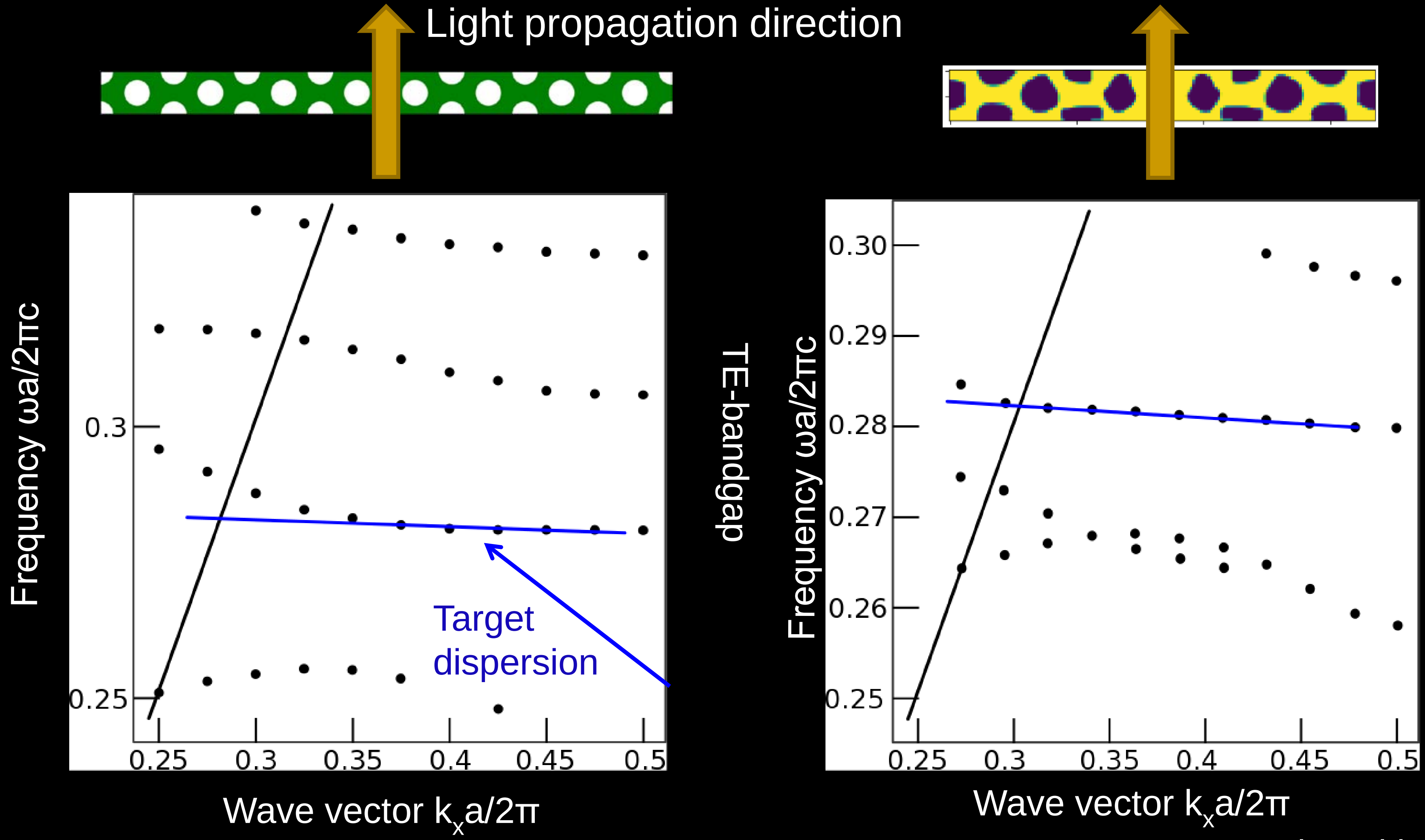
$$H_I \approx \frac{\hbar \bar{g}_c^2}{\bar{\Delta}_c}\sum_{j,l}^{N}\sigma_{eg}^{j}\sigma_{ge}^{l}\boxed{f(z_j, z_l)}$$

We can specify an interaction Hamiltonian by inverse engineering the photonic environment!



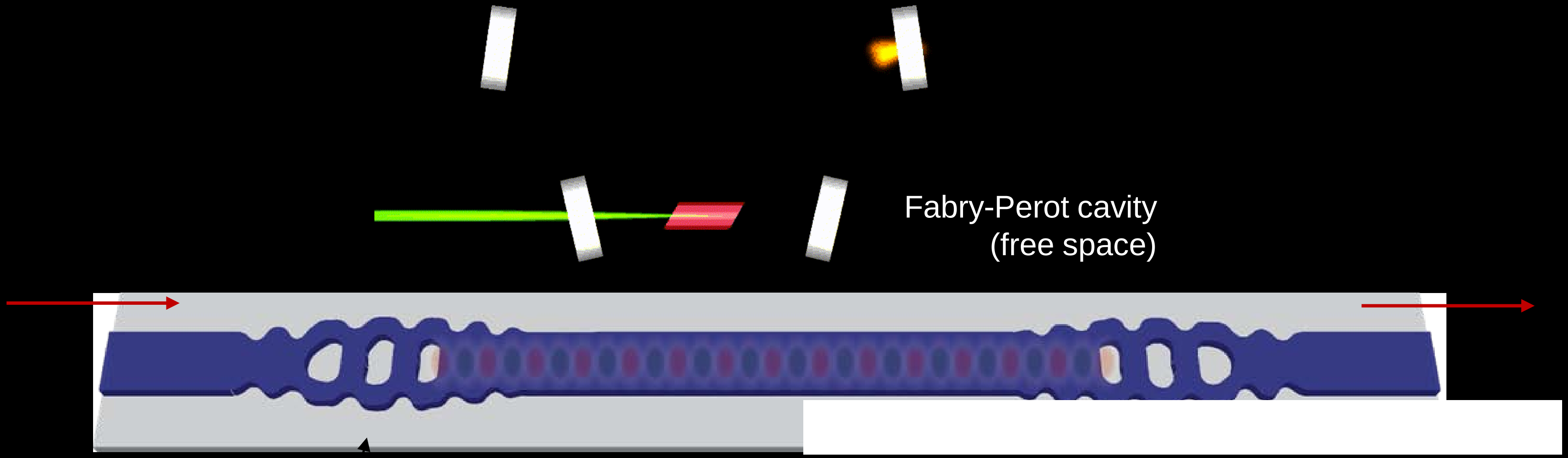
González-Tudela et al., *Nature Photonics* 9, 320–325 (2015).
Douglas et al., *Nature Photonics* 9, 326–331 (2015).

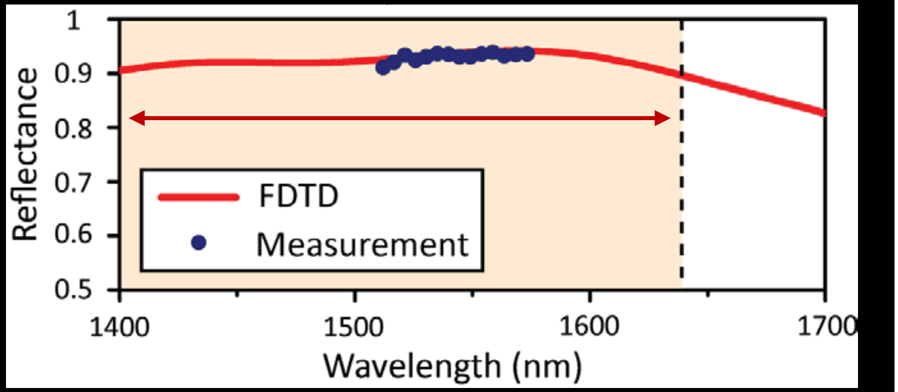
Example: slow-light engineering with silicon photonics

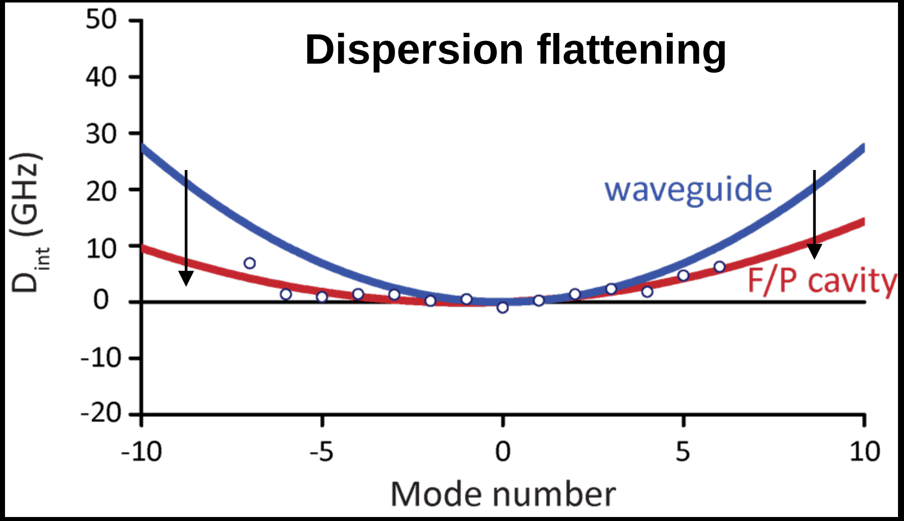


Designed by Dries Vercruysse

Inverse design for dispersion engineering





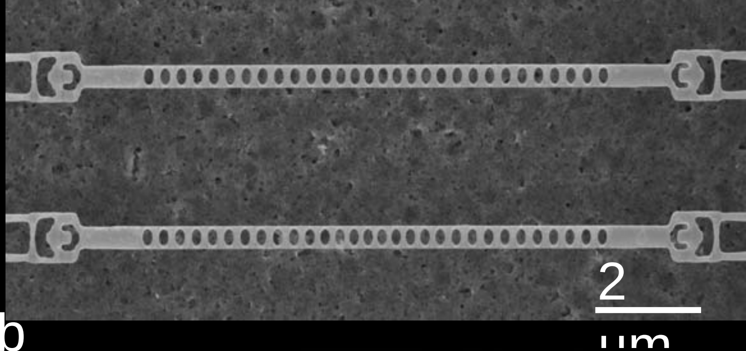


Inverse design can tailor group velocity dispersion of F/P cavity (reflector group delay).

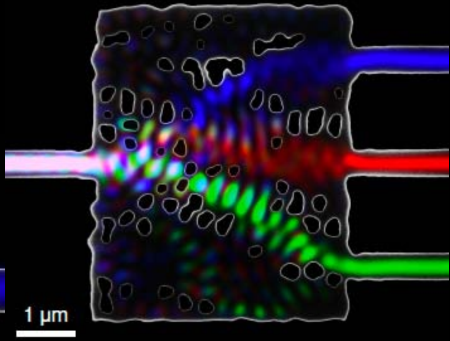
K. Yang, J. Skarda et al

- **Photonics optimization critical for implementation of scalable and practical systems**

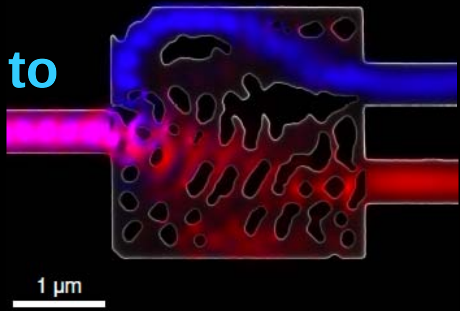
Stanford **P**hotonics **IN**verse design **S**oftware (**SPINS**)
Vuckovic Group - Stanford OTL Docket Number: S18-012
SPINS–B (open source) on Github http://github.com/stanfordnqp/spins-b



- **Demonstrated strong Purcell enhancement for SiV in a diamond cavity**
  L. Zhang et al, *Nano Lett.*, *18* (2), pp 1360–1365 (2018)



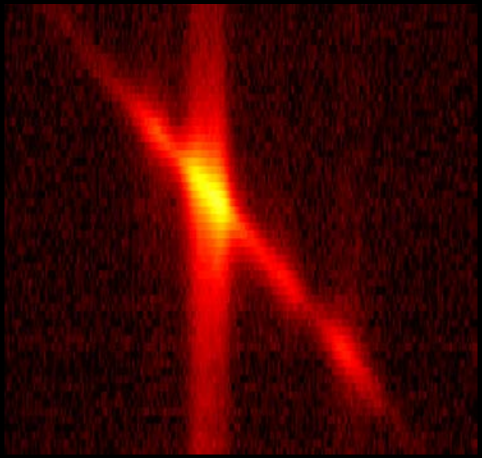
- **Demonstrated Raman scattering from a SiV in a cavity, for up to 100GHz detuning (>>30GHz spectral broadening)**
  Shuo Sun et al, *Phys. Rev. Letters* 121, 083601 (2018)

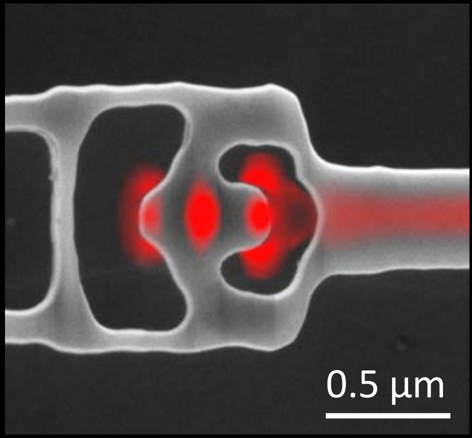


- **Demonstrated inverse design of diamond photonics**
  C. Dory et al, arXiv:1812.02287

- **Studies of SnV in diamond structures**
  A Rugar et al, arXiv:1811.09941

- **Developed 4H silicon Carbide Quantum Photonics for VSi**
  Purcell enhancement of 32 - D. Lukin, C. Dory et al





Open questions

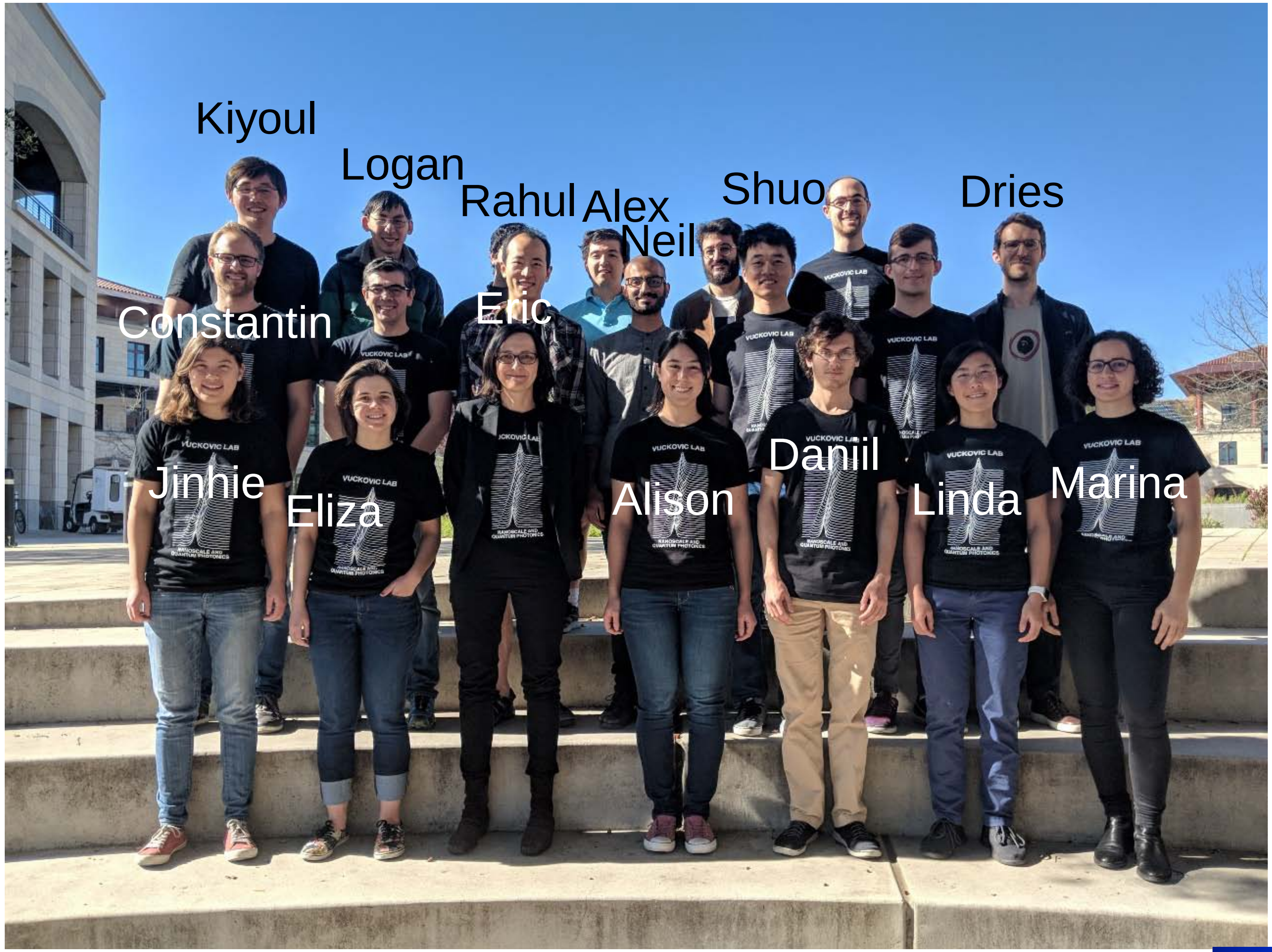
Is it possible to build quantum simulators using optically interfaced artificial atoms, such as color centers in photonic structures?

***Advantages*:**

- **Interaction beyond nearest neighbor (**González-Tudela et al., *Nature Photonics* 9, 320–325 (2015))
- **Artificial atoms at fixed positions, naturally trapped by crystal**
- **Engineering Hamiltonian by optimizing photonic structure**
- **If scaling is possible, then building a simulator with millions of artificial atoms in 2D lattice is not much more difficult than building 10 atom simulator in 1D lattice**

Main challenges:

- **overcoming inhomogeneous broadening and imperfections of artificial atoms (imperfect optical lattice)**
- **quantum microscope for solid state?**



& new members:
Melissa Guidry, Sattwik Mishra, Geun Ho Ahn

Collaborators:
Amir Safavi-Naeini, Zhi-Xun Shen, Nicholas A. Melosh and Steven Chu @Stanford

Marko Loncar @Harvard

Joerg Wrachtrup @Stuttgart

Andrea Alu @CUNY