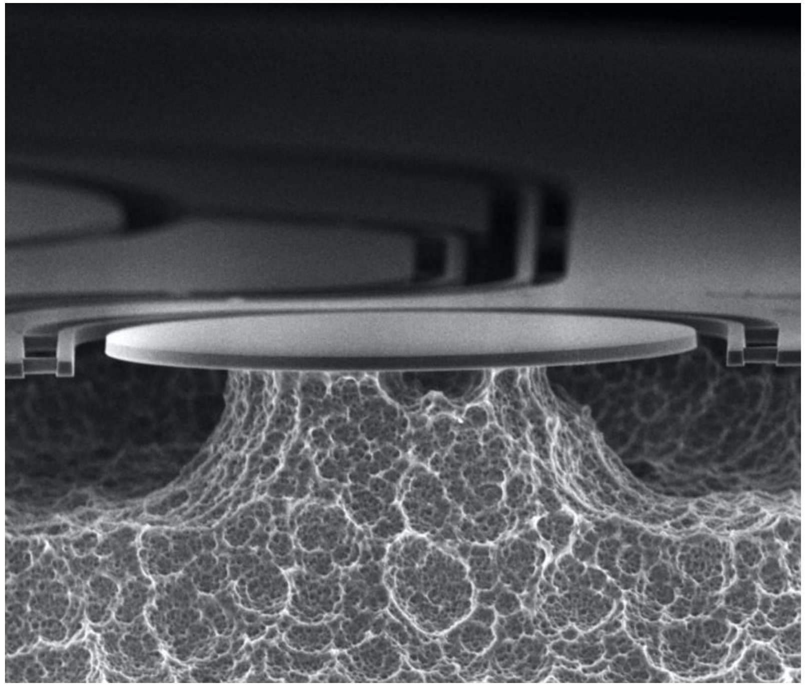
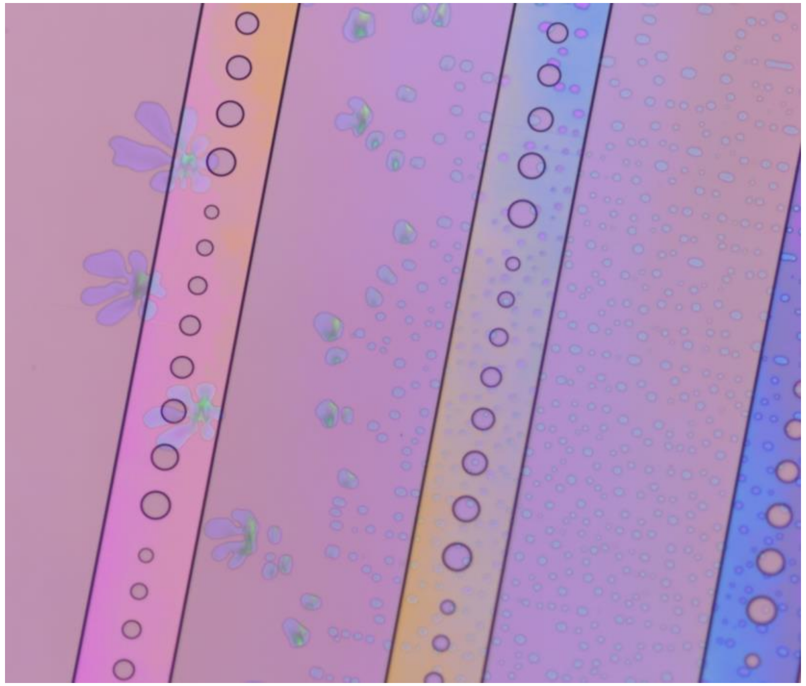




# Quantum & Nonlinear Photonics in Silicon Carbide


Daniil Lukin

Nanoscale and Quantum Photonics Lab, Prof. Jelena Vučković, Stanford University


NNCI Etch Symposium

April 22, 2022

Stanford University

# Silicon Carbide

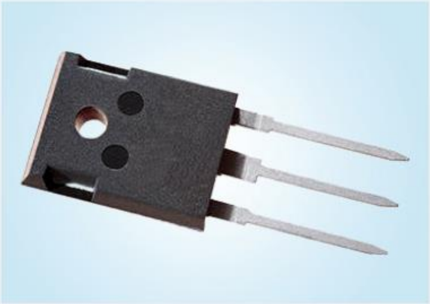
Primary applications of Silicon Carbide

Heteroepitaxy substrate

Abrasives

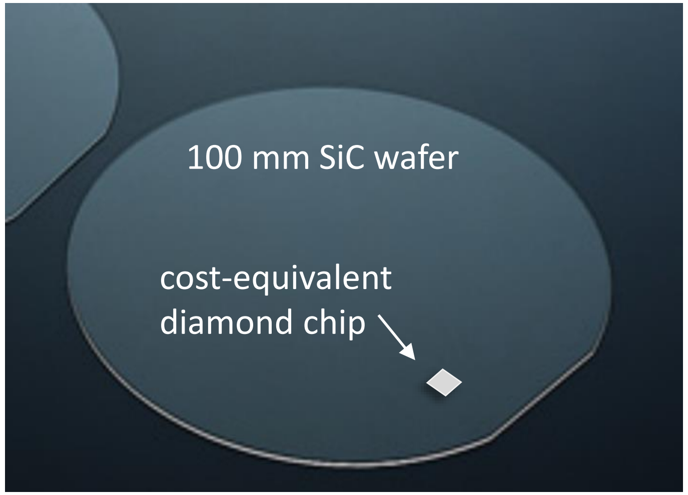
Fake diamonds

Heating elements

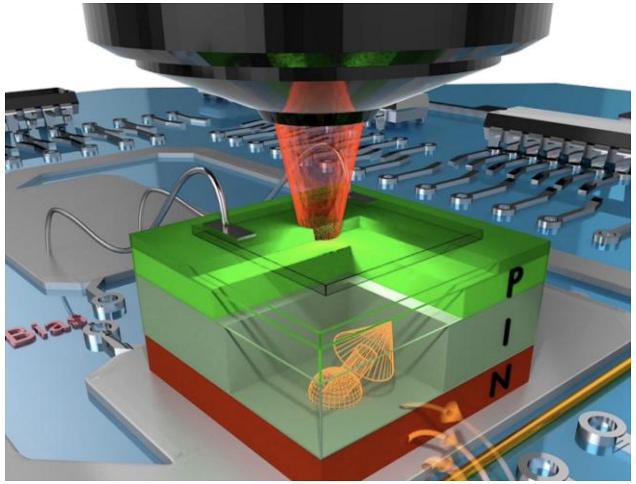


Power electronics

- Available on a wafer scale

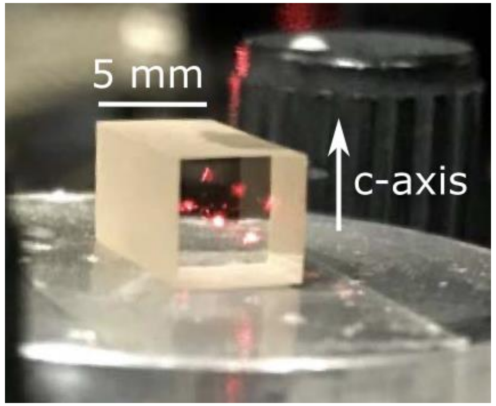



- Advanced semiconductor processing technology



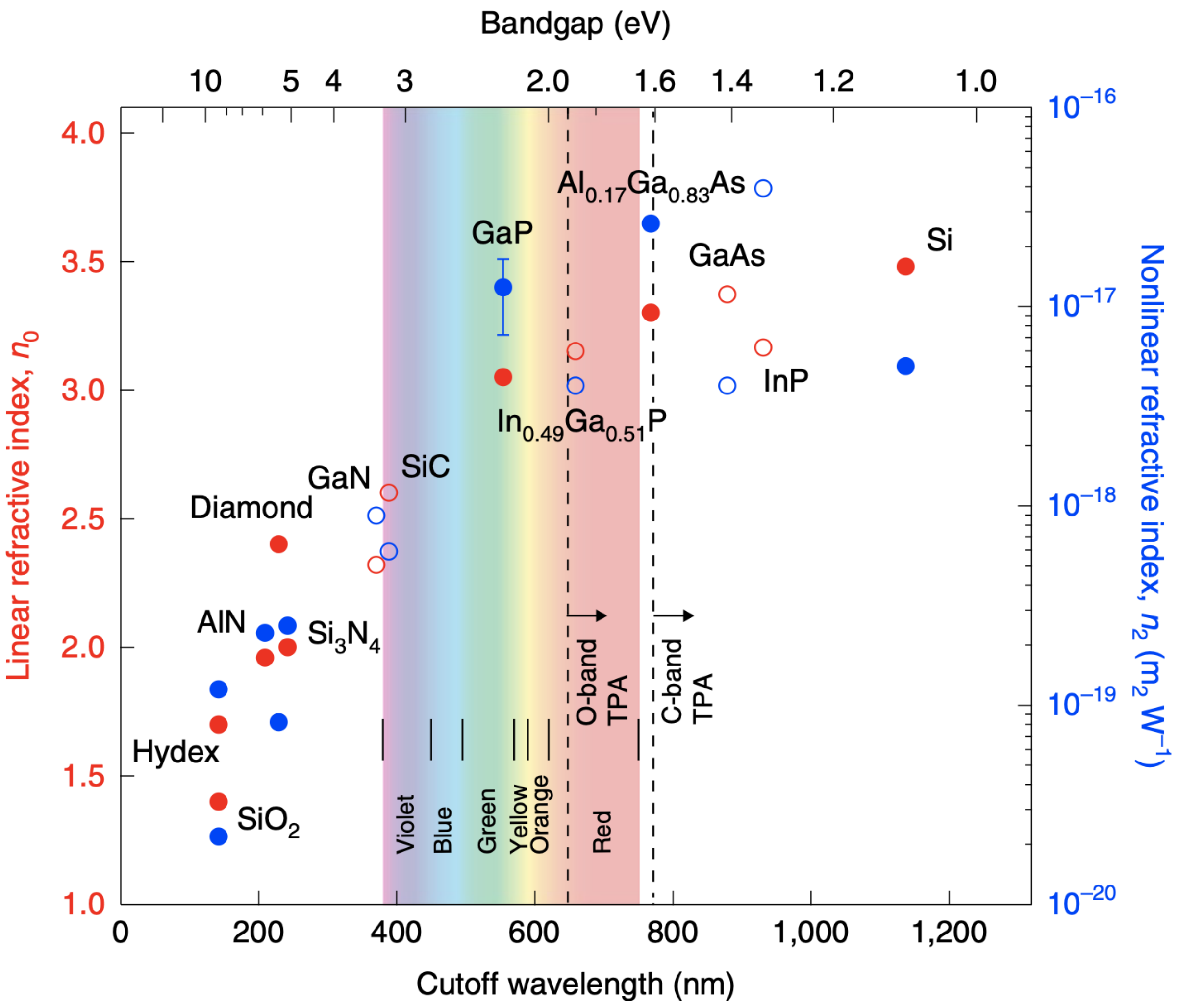

Widmann et al., Nano Letters (2019)

- Excellent linear and nonlinear optical properties




Guidry et al., Optica (2020)

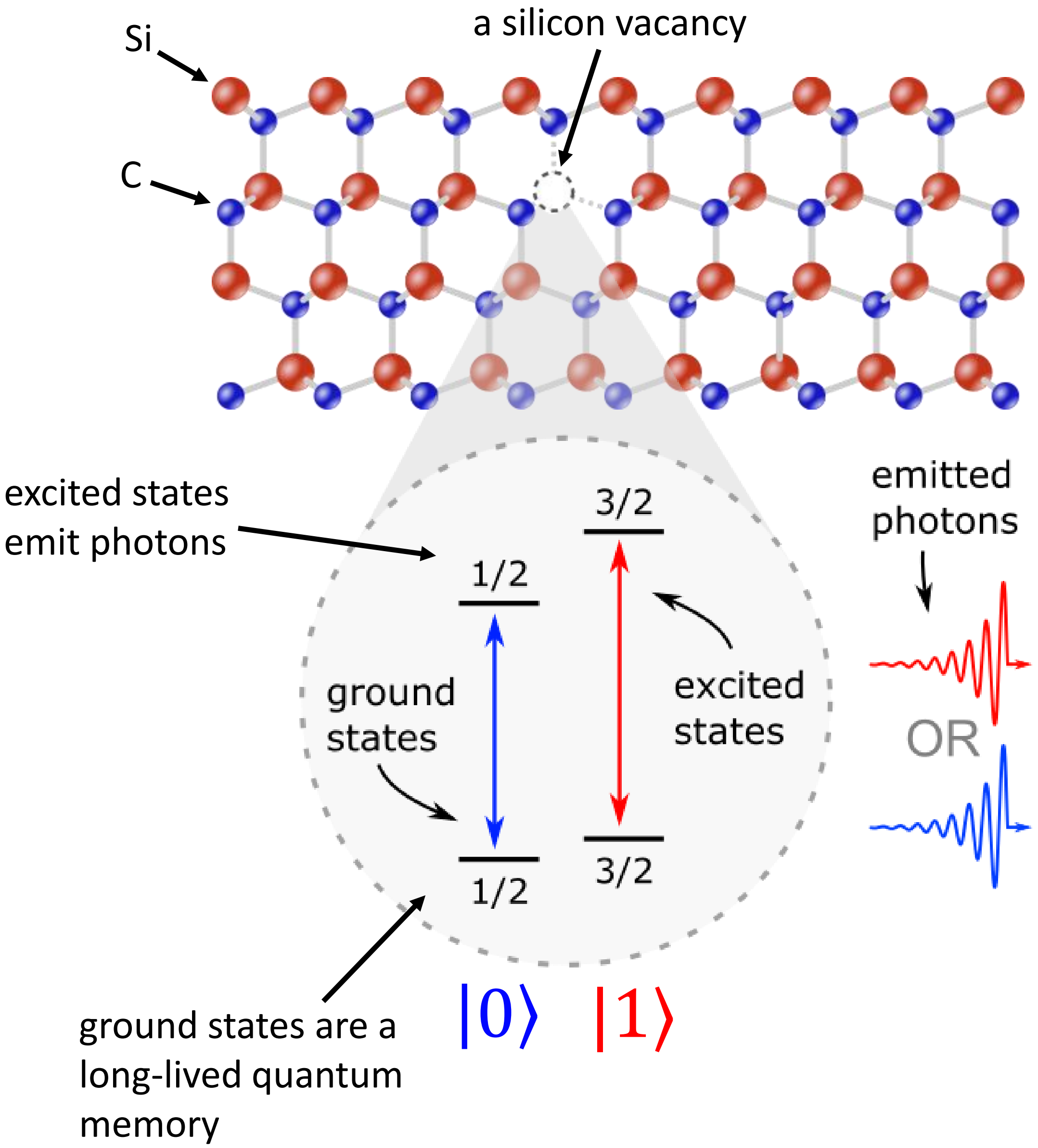
# Optical properties of silicon carbide



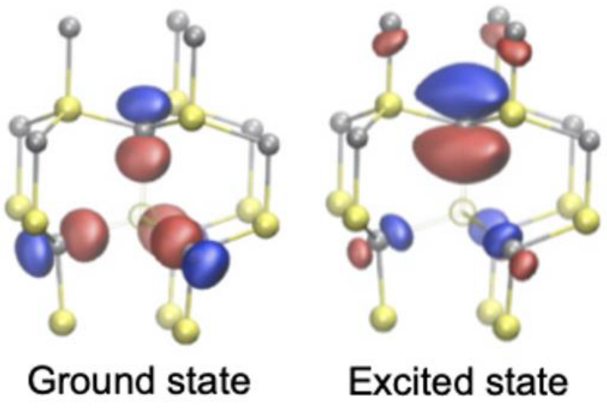

Wilson et al., Nat. Photon. (2020)

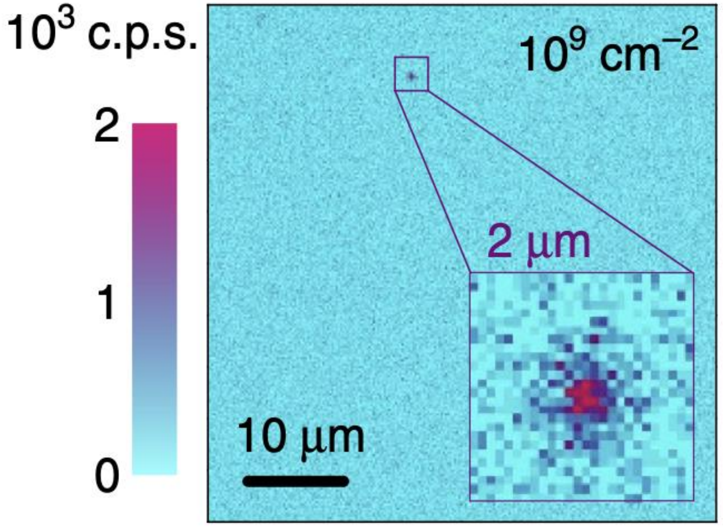
- High refractive index
- Wide bandgap suitable for visible photonics
- Large second- and third-order nonlinearity
- CMOS compatible

# Color centers in silicon carbide for quantum photonics



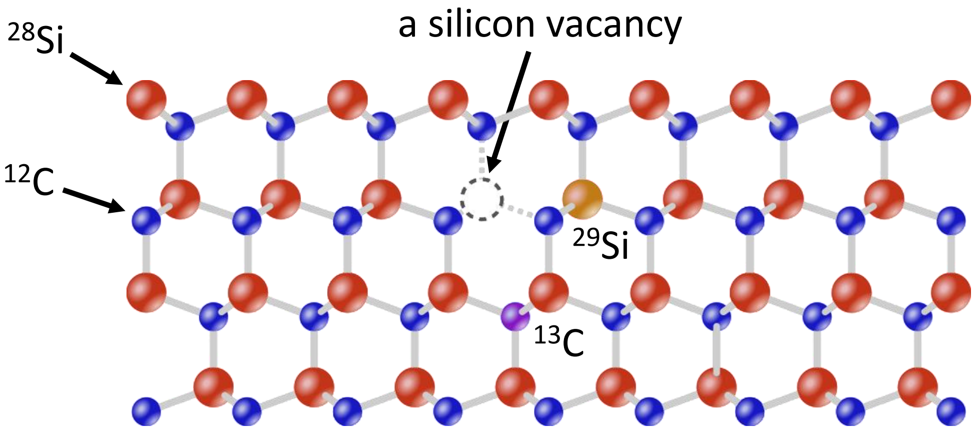

a color center has localized electronic states:
It is ”an atom in semiconductor vacuum”

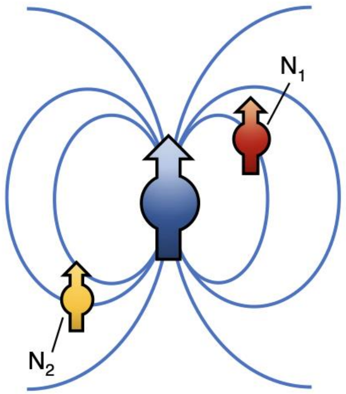


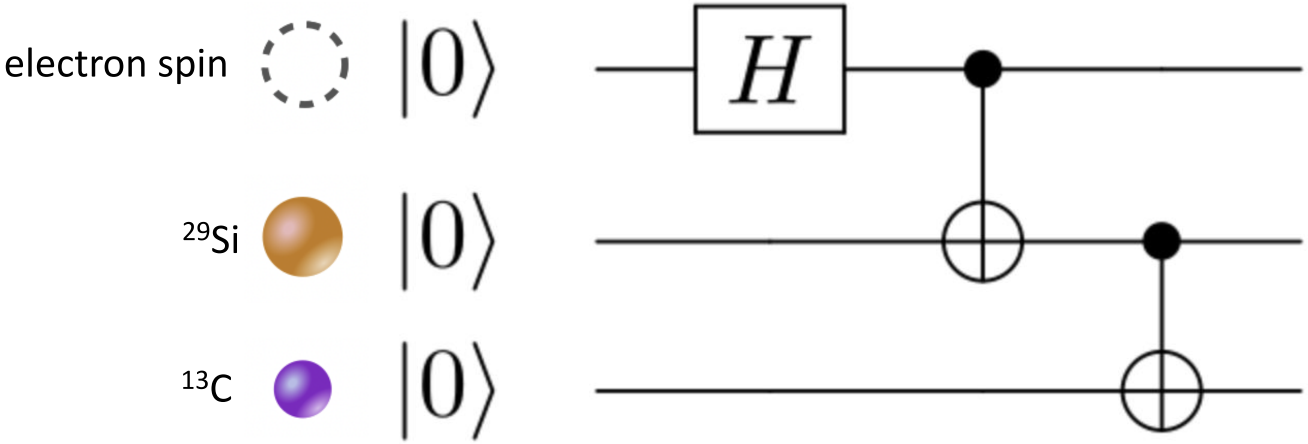

single color centers can be isolated
(Fuchs et al, *Nat. Comm.*, 2015)

# One color center comprises multiple qubits, aka a quantum register

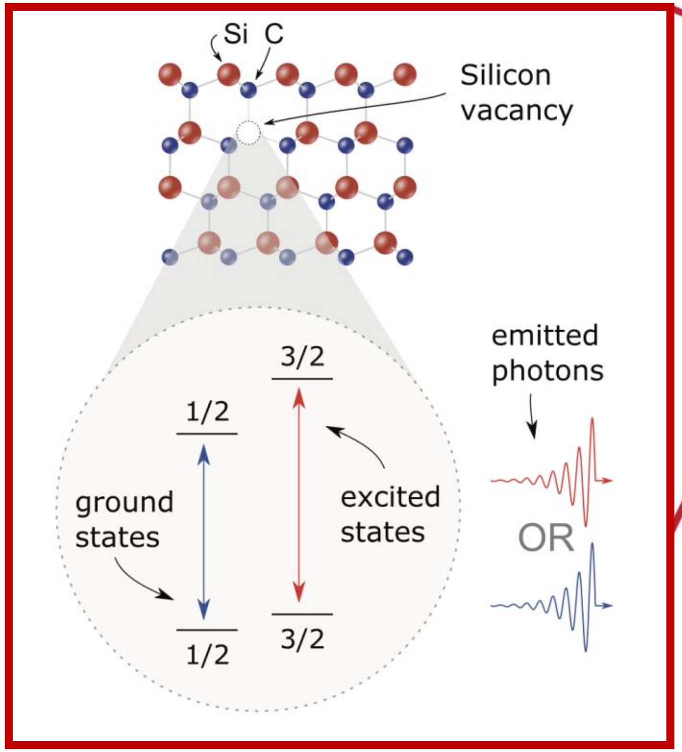


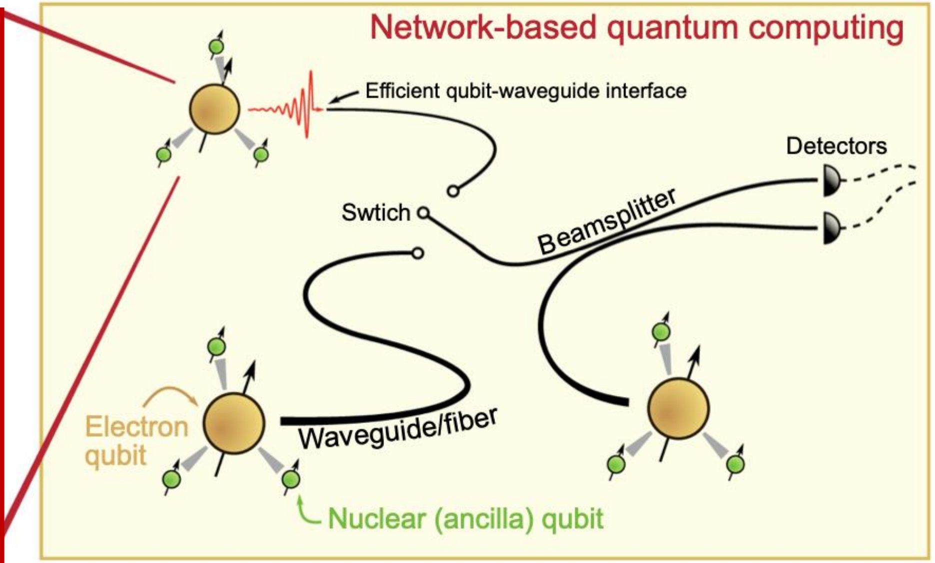




$^{12}C$ and $^{28}$Silicon don't have a nuclear spin
$^{13}C$ and $^{29}$Silicon are spin 1/2



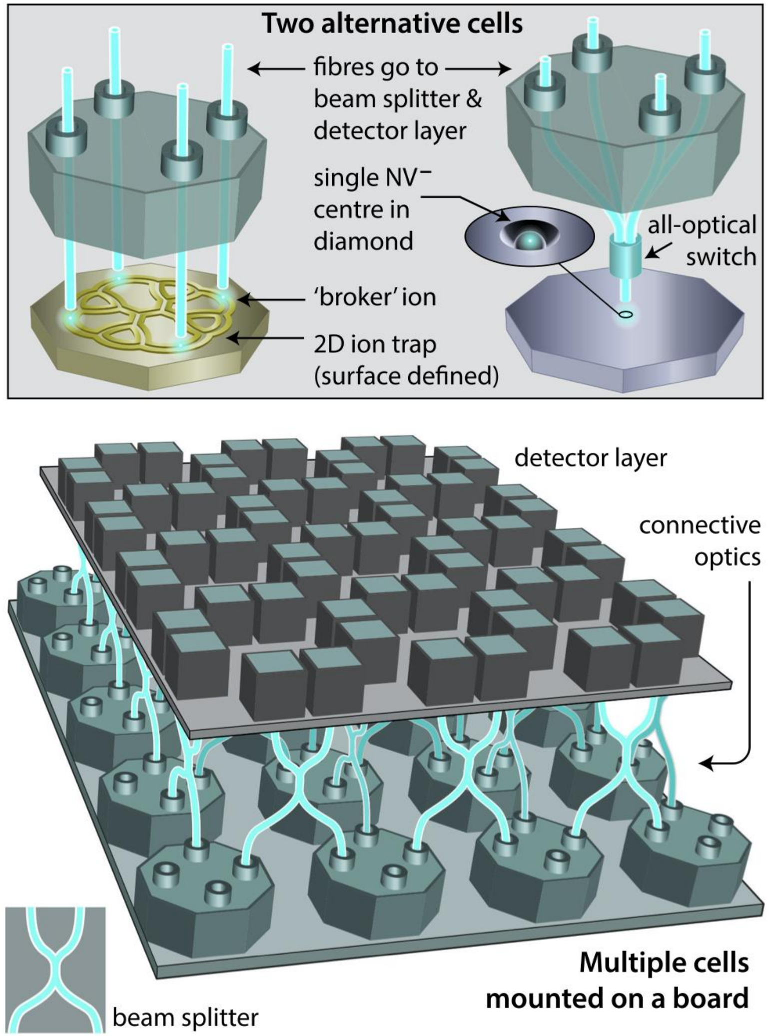
# Network-based quantum computing architecture




Lukin et al., PRX Quantum (2020)

Nickerson et al, *Phys. Rev. X* 2014

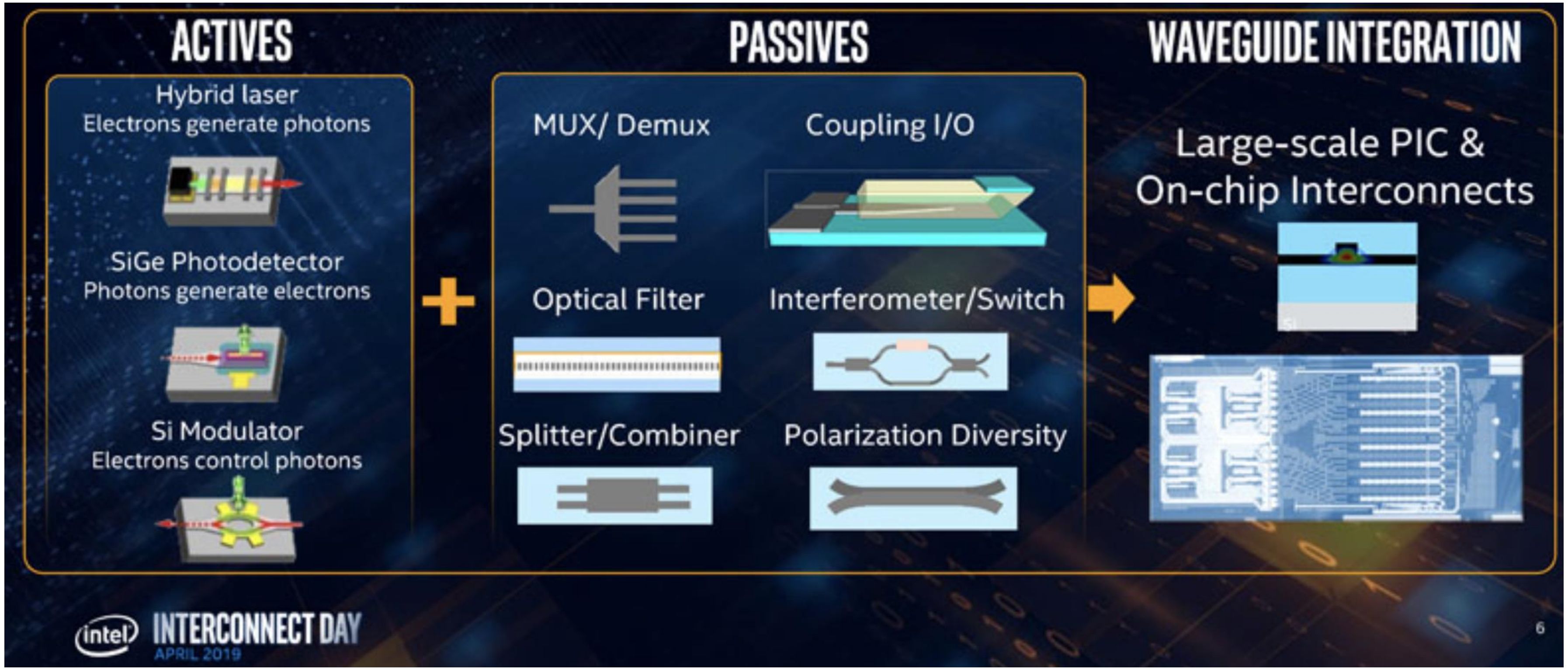



**Low-loss photonic interconnects are critical for fault tolerance.**

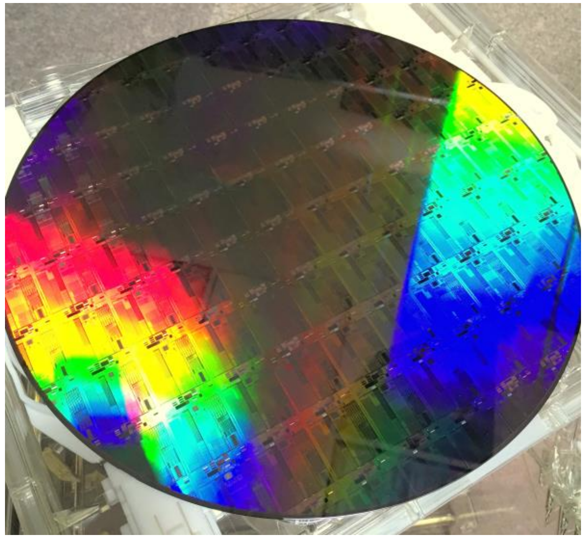
# What are the photonic circuit requirements?

- Photonic resonators
- Low-loss passive and active components: waveguides, switches, beamsplitters
- Efficient detectors
- Tunable of elements for homogenous operation
- Scalability to thousands of nodes

**Silicon photonics have proved the required level of performance is possible for classical devices.**




*Hong Hou Intel Silicon Photonics Integration*

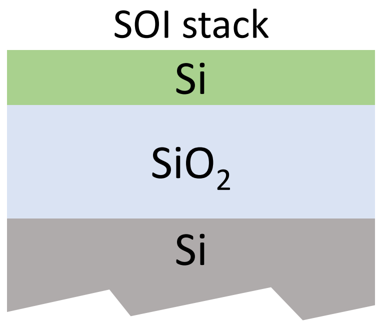


12 inch silicon photonics wafer

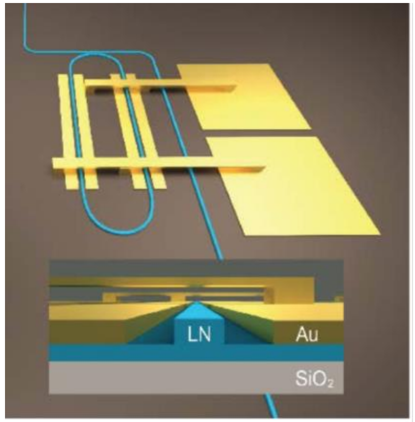
**Can silicon carbide enable the same capabilities for quantum photonics?**

# A pattern in integrated photonics revolutions

1960's: Silicon (Si) wafers commercialized.
2000's: Silicon-on-Insulator (SOI) commercialized.
→ **Silicon nanophotonics enters golden age:**
scalable high density photonic circuits

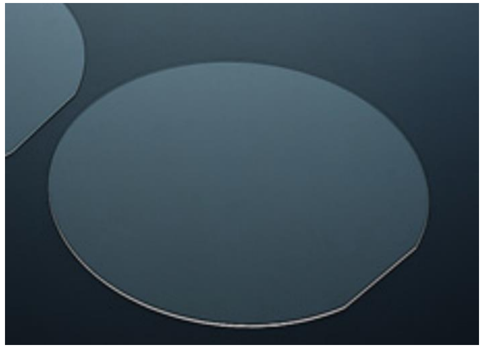



1990's: Lithium Niobate ($LiNbO_3$) wafers commercialized.
2010's: $LiNbO_3$-on-Insulator is commercialized.
→ **$LiNbO_3$ nanophotonics enters golden age**
ultra-efficient second-order nonlinear photonics

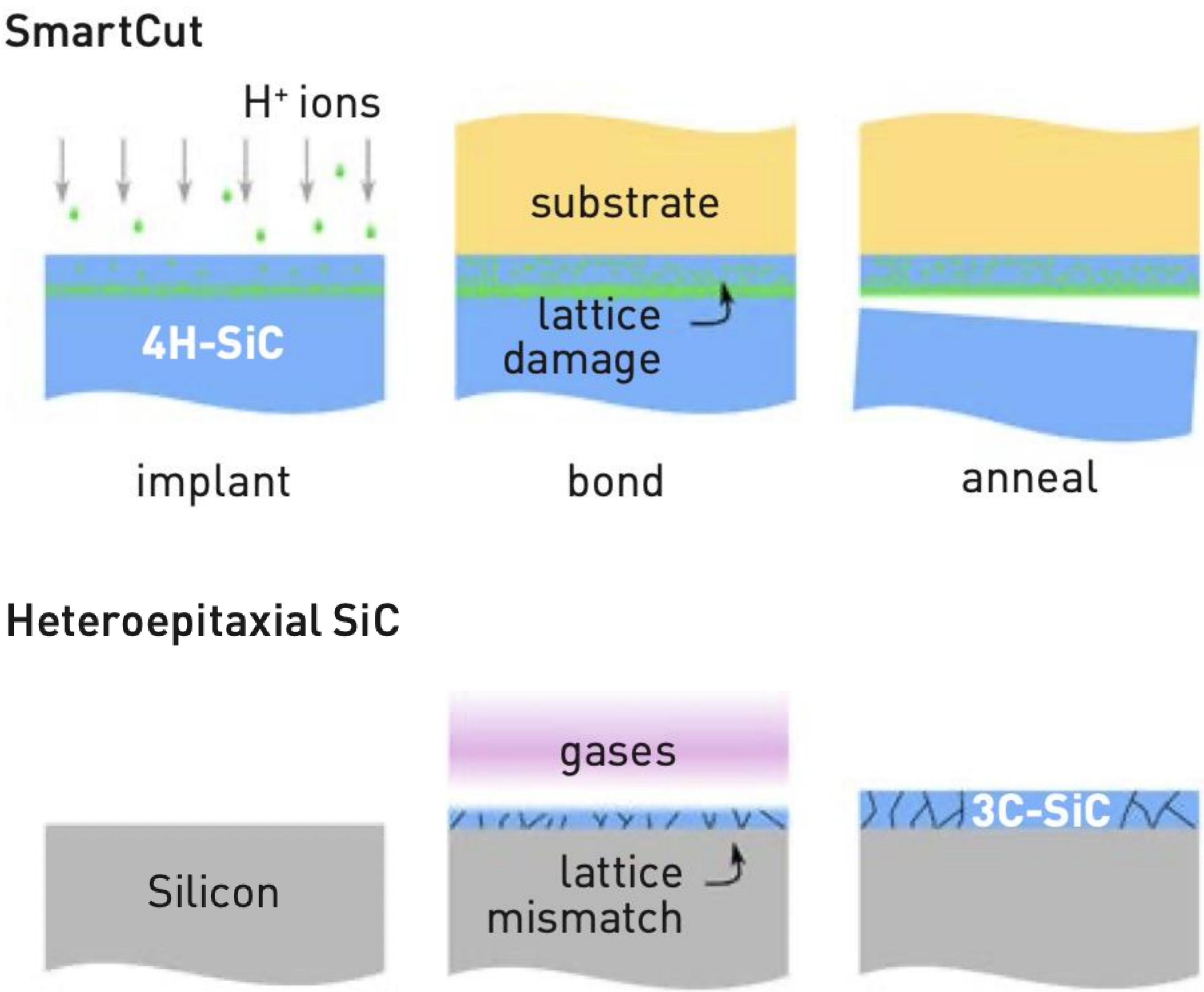


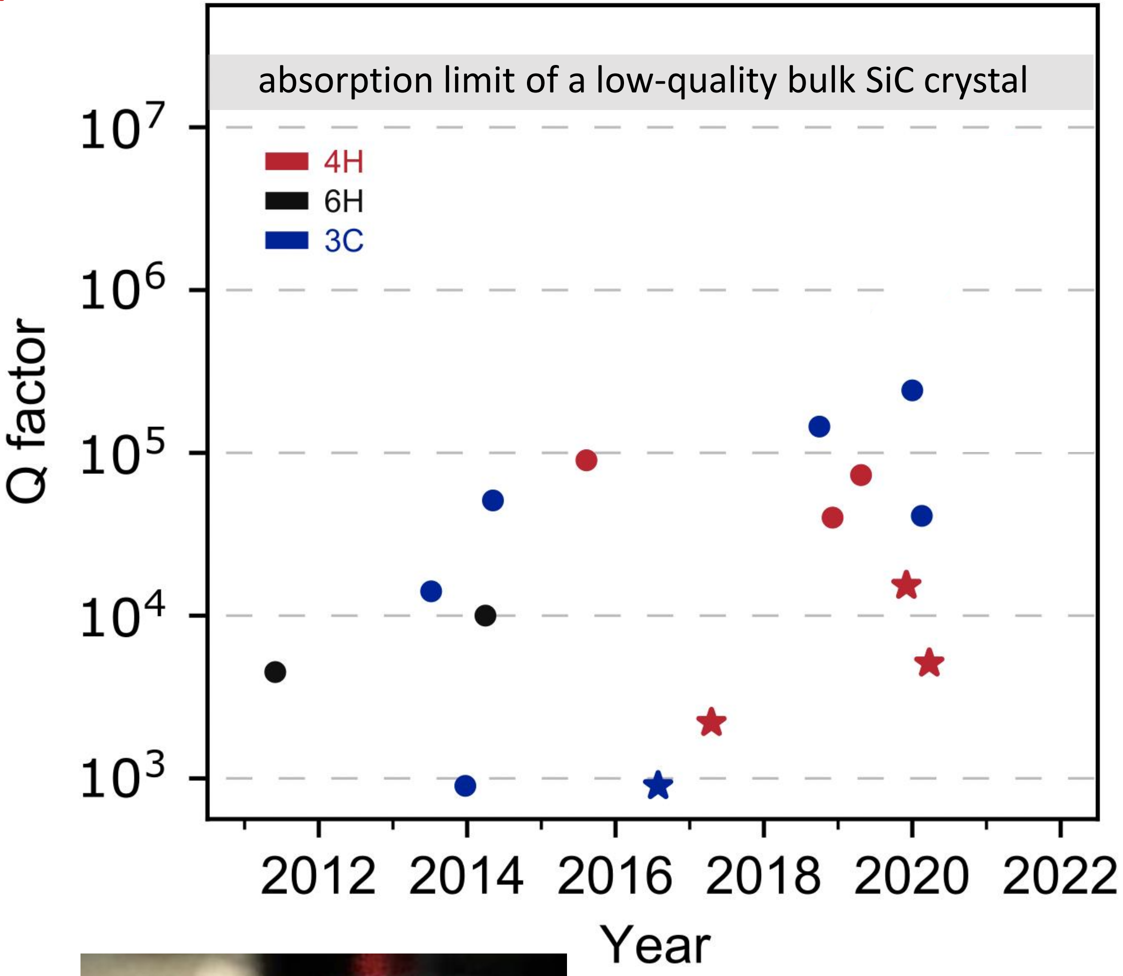

C. Wang, Opt. Express 26, 2018

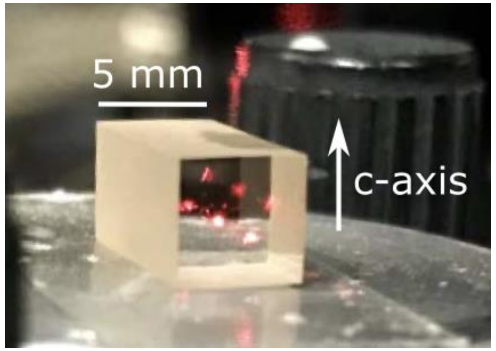
1990's: SiC wafers commercialized
…



# Silicon Carbide on insulator: previous approaches

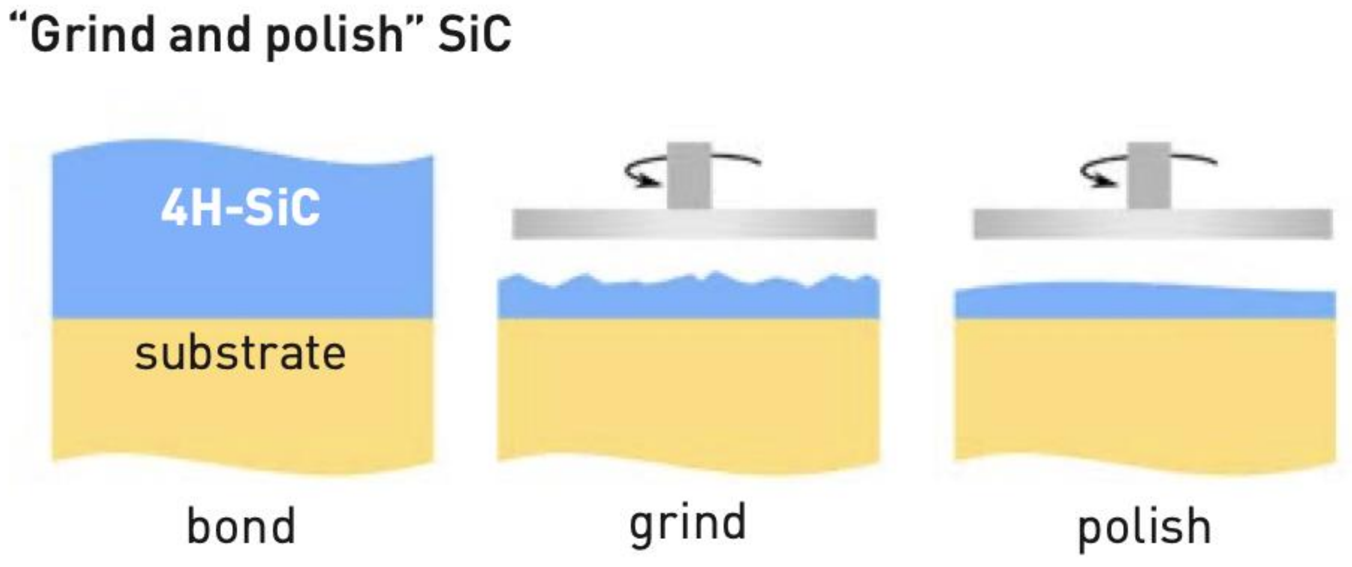


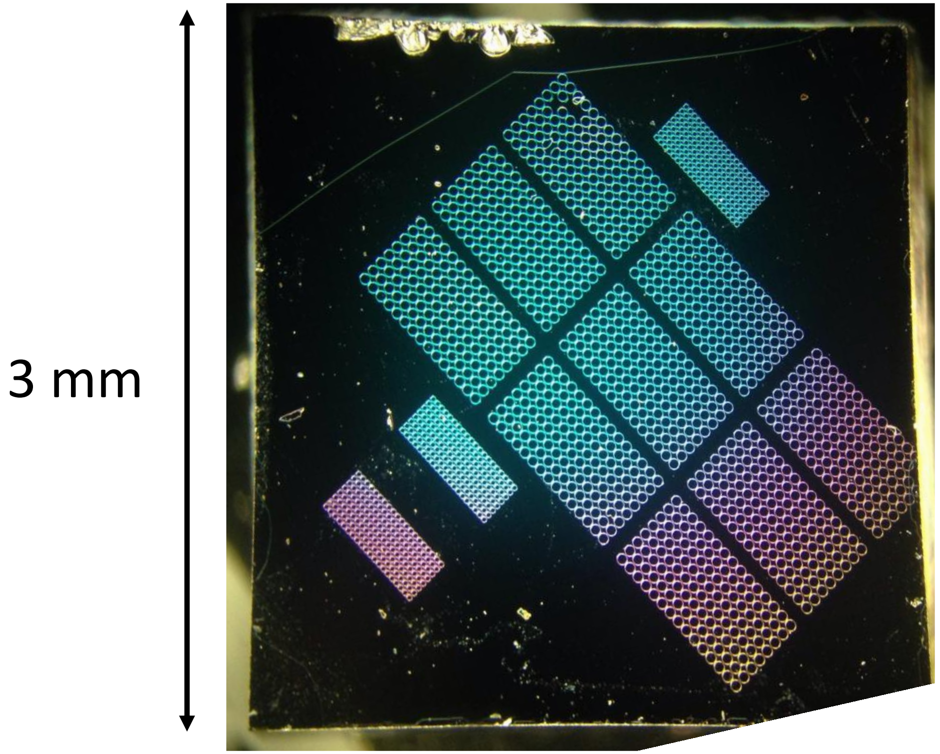




Guidry et al., Optica (2020)

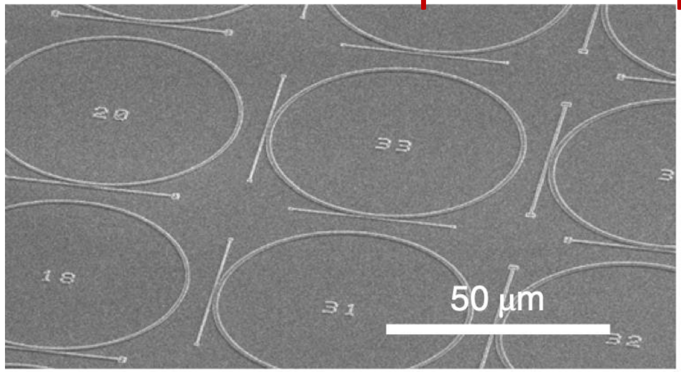
# SiC-on-insulator with pristine crystal quality



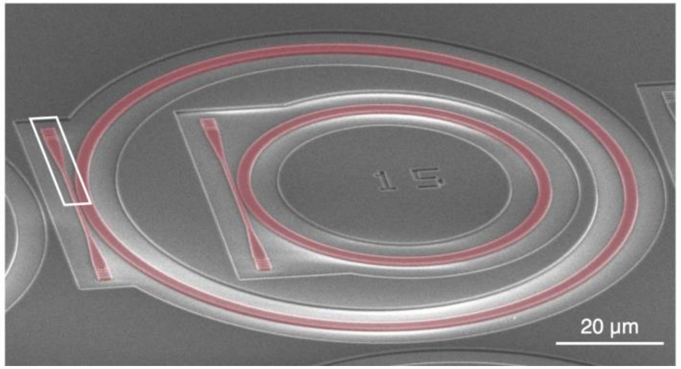
# Developing ultra-low-loss photonics in SiC

# CMOS compatible processing



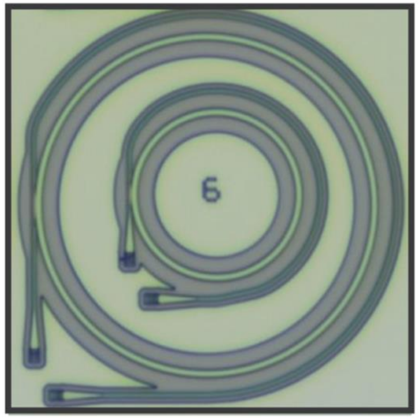

Q = 7.8 x $10^5$

Lukin et al., Nature Photonics (2020)




Q = 1.1 x $10^6$

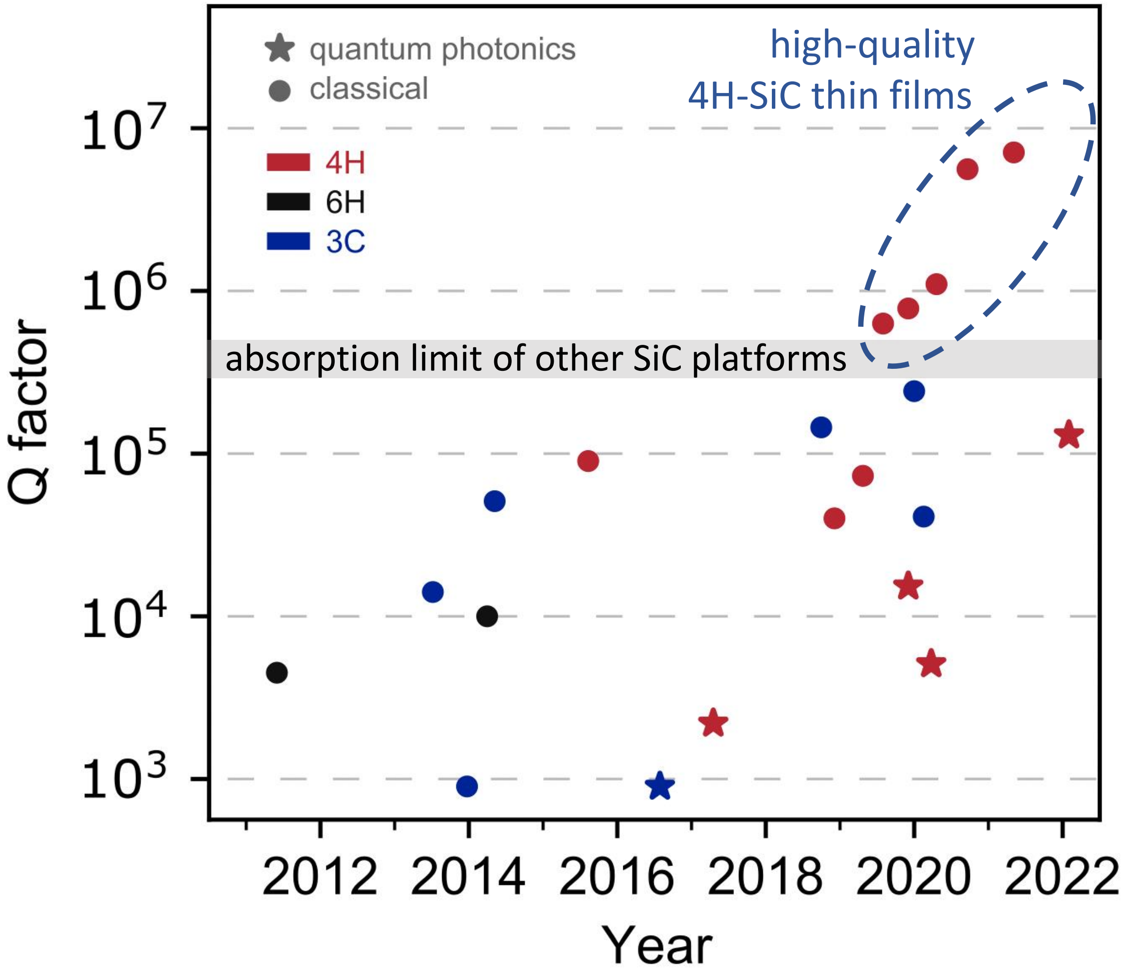
Guidry et al., Optica (2020)



Q = 5.6 x $10^6$

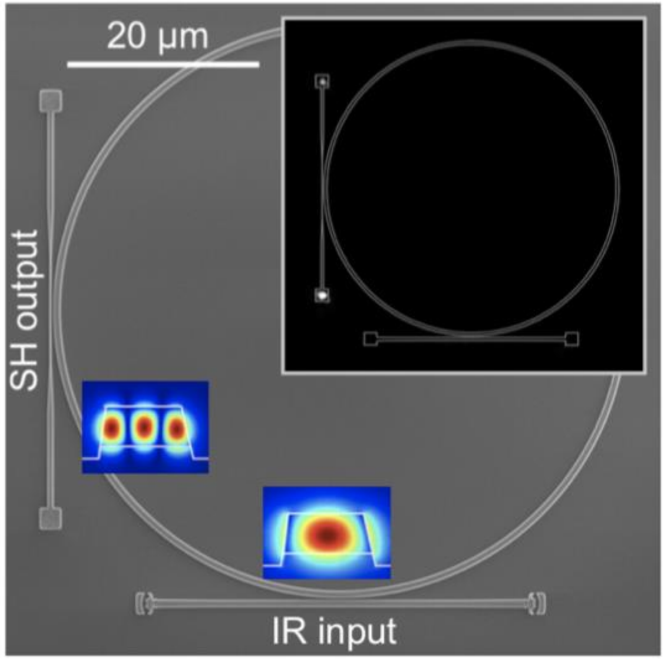
0.08 dB/cm loss

Guidry et al., Nature Photonics (2022)

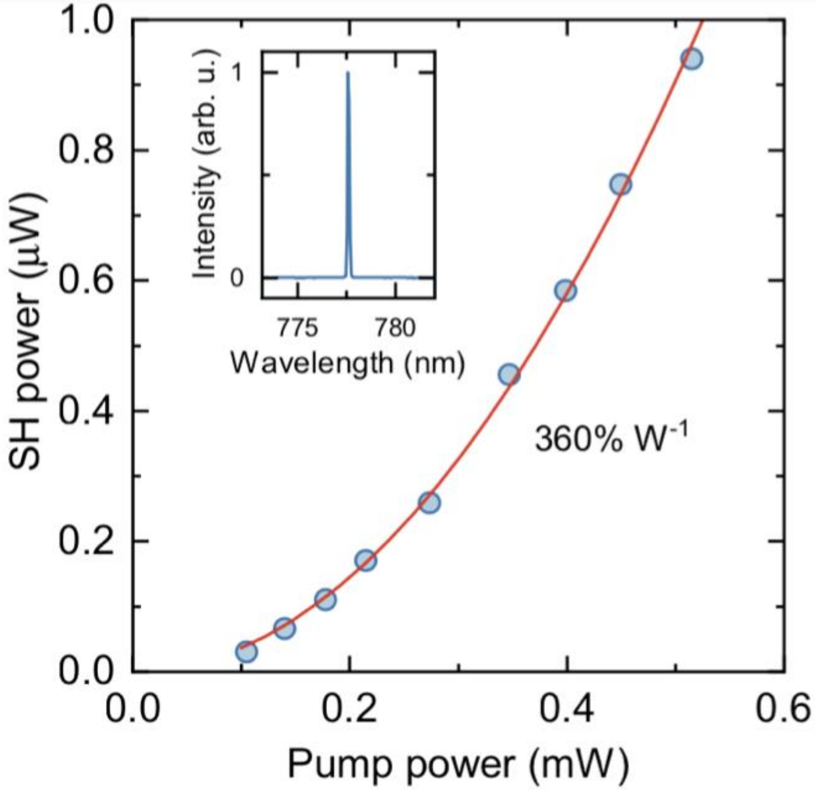



**CMOS- compatible processing**

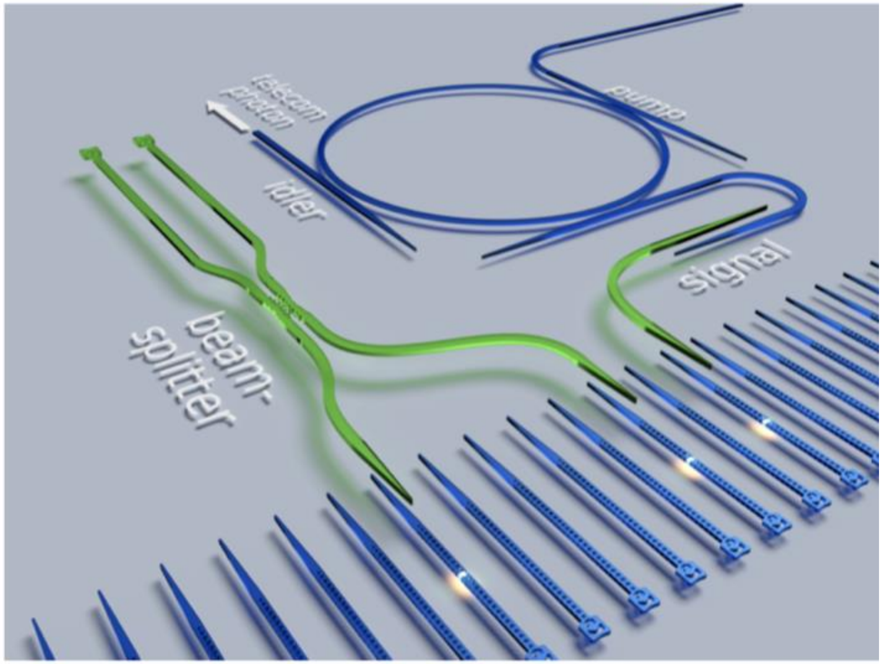
# Nonlinear optics in SiC – Second Harmonic Generation




Ring resonator optimized for second harmonic generation




Demonstration of efficient SHG in SiC resonators



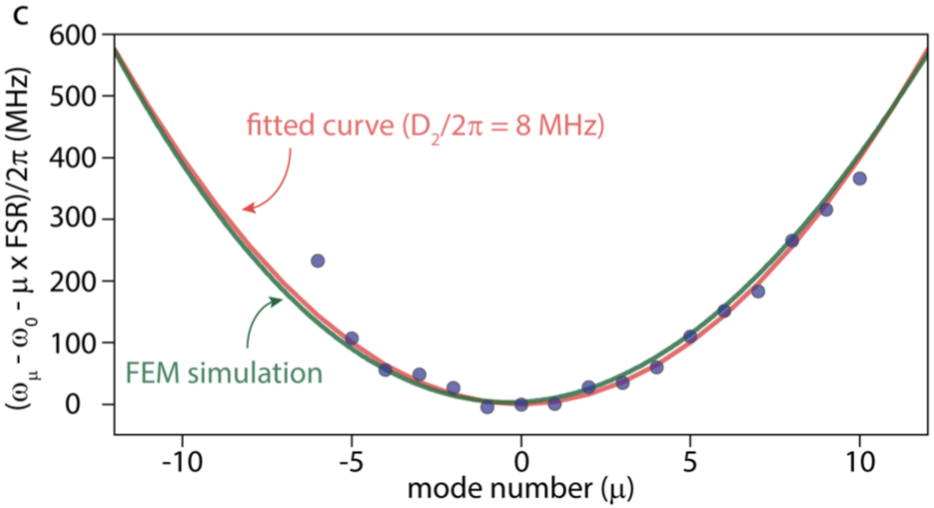

Concept figure of integrating quantum emitters with on chip frequency conversion

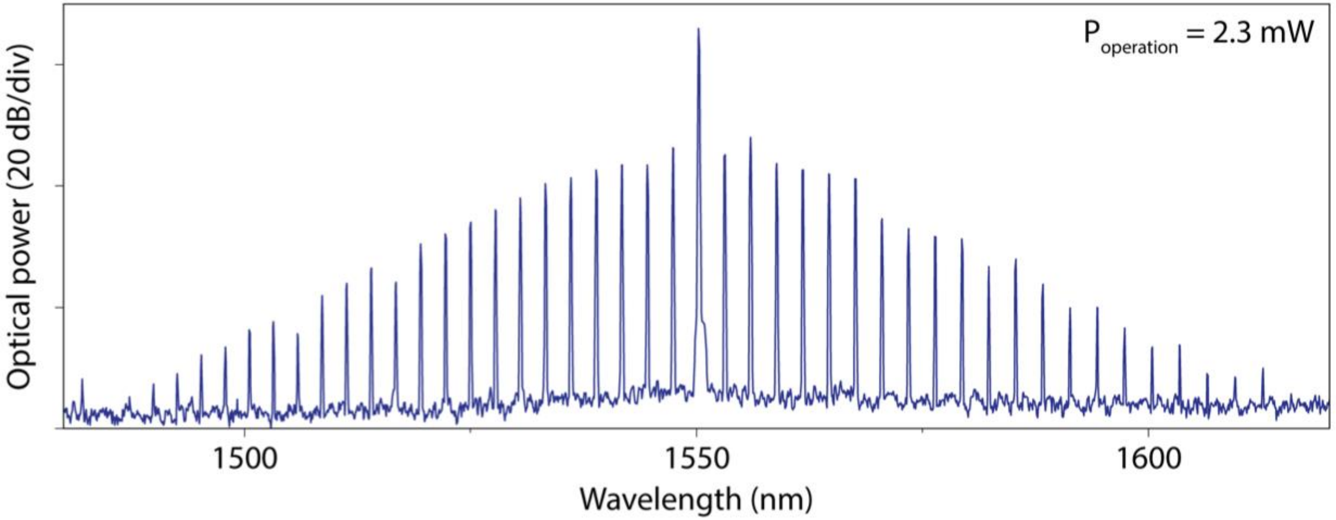
Lukin et al., Nature Photonics (2020)

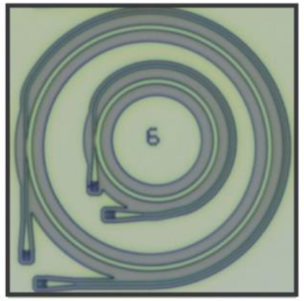
# Nonlinear optics in SiC – Soliton generation


Melissa Guidry


Kiyoul Yang



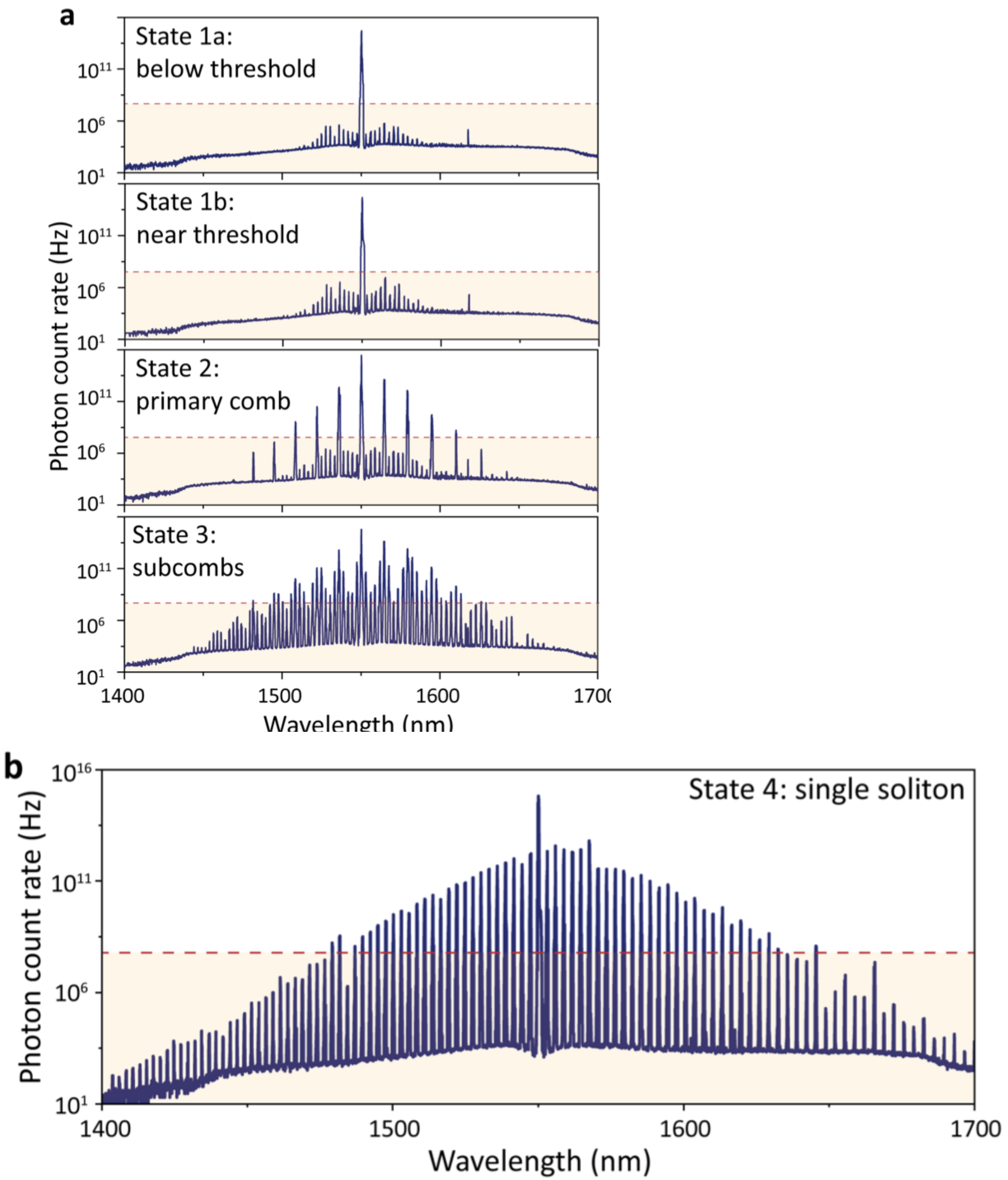



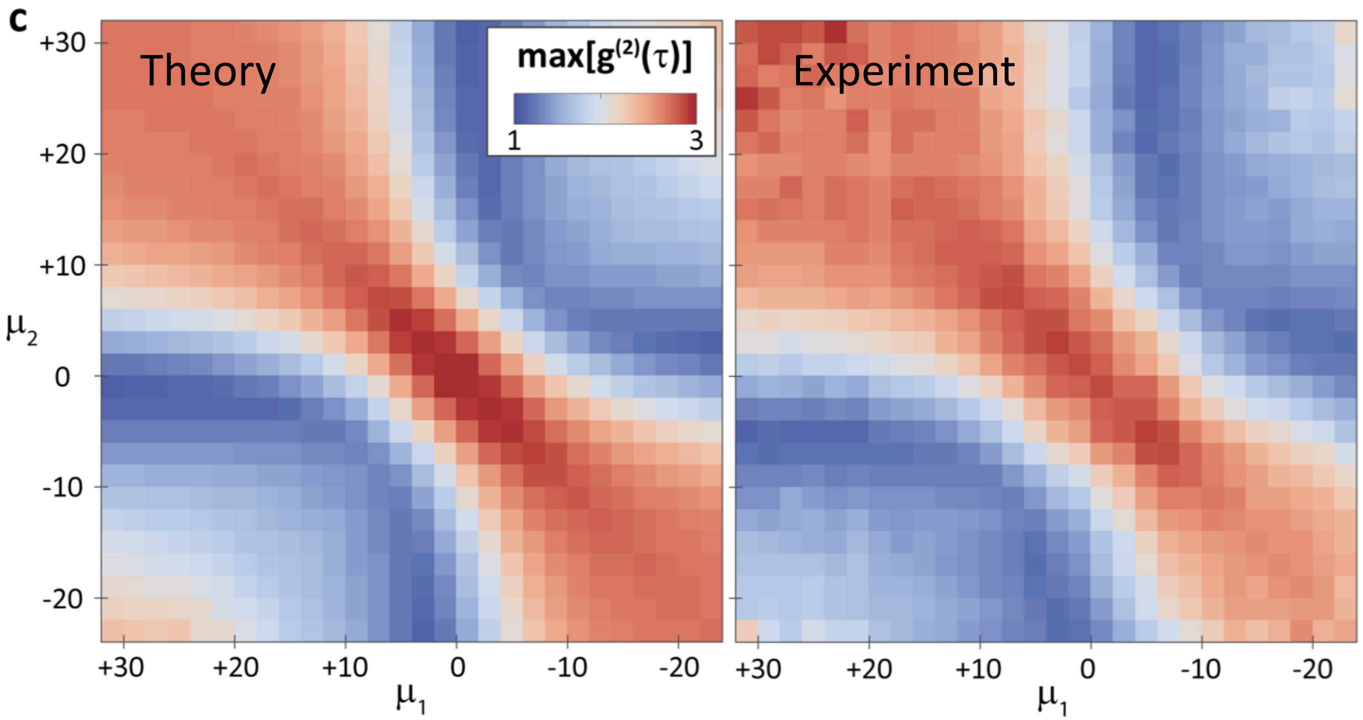
| Material | $Q_0$ (M) | FSR (GHz) | Soliton operation power (OPO threshold) (mW) | Reference |
|---|---|---|---|---|
| $Si_3N_4$ | 260 | 5 | ~ 20 | Bowers (UCSB) |
| $Si_3N_4$ | 8 | 194 | 1.3 (1.1) | Lipson (Columbia) |
| $Si_3N_4$ | 15 | 99 | 6.2 (1.7) | Kippenberg (EPFL) |
| $SiO_2/Si_3N_4$ | 120 | 15 | 28 (5) | Vahala (Caltech) |
| $LiNbO_3$ | 2.4 | 199.7 | 5.2 | Lin (Rochester) |
| AlGaAs | 1.5 | 450 | 1.77 (0.07) | Bowers (UCSB) |
| SiC | 5.6 | 350 | → 2.3 (0.51) ← | Vuckovic (Stanford) |

Guidry et al., Nature Photonics (2022)

# Nonlinear optics in SiC – Quantum study of solitons






Observation and theoretical modeling of quantum properties of soliton microcombs

Guidry et al., Quantum Optics of Soliton Microcombs, Nature Photonics (2022)

# Photonic inverse design

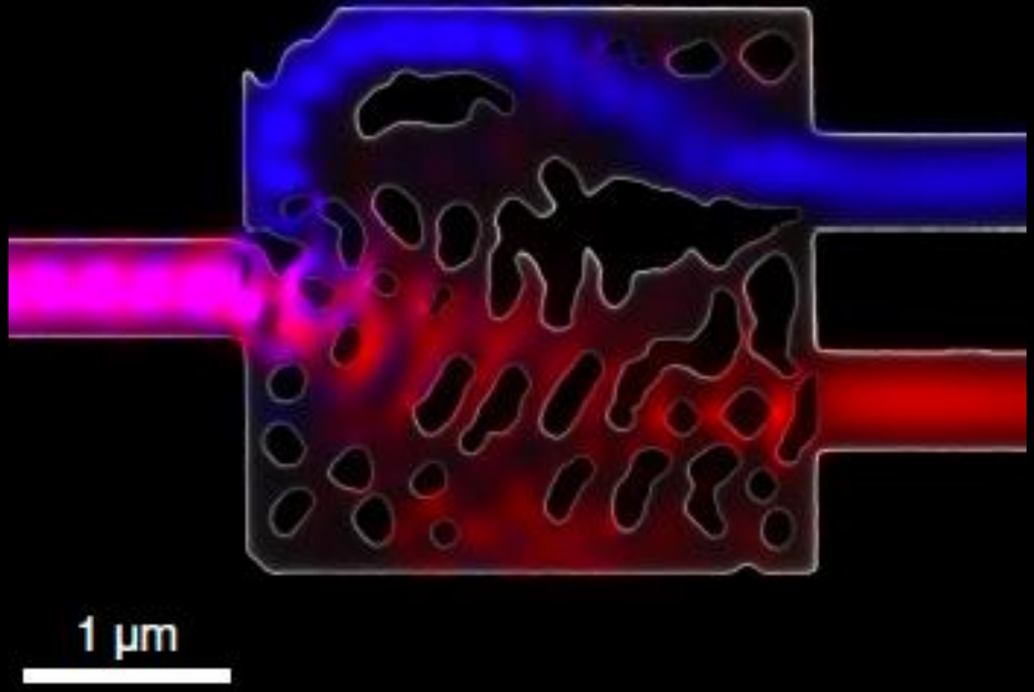
- **Photonics optimization critical for implementation of scalable and practical systems**

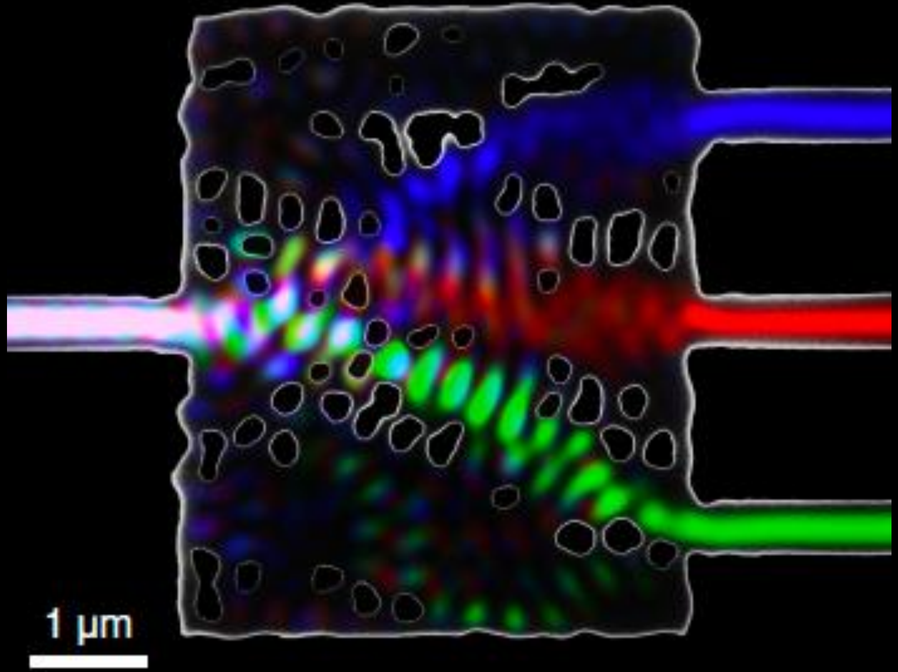
**S**tanford **P**hotonics **IN**verse design **S**oftware (**SPINS**)

Vuckovic Group - Stanford OTL Docket Number: S18-012

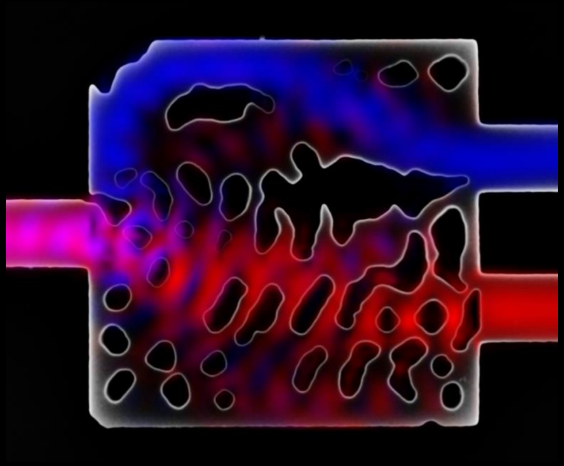
**SPINS–B** (open source) on Github http://github.com/stanfordnqp/spins-b

L. Su et al, *Applied Physics Reviews*, Vol.7, Issue 1, DOI: 10.1063/1.5131263 (2020)

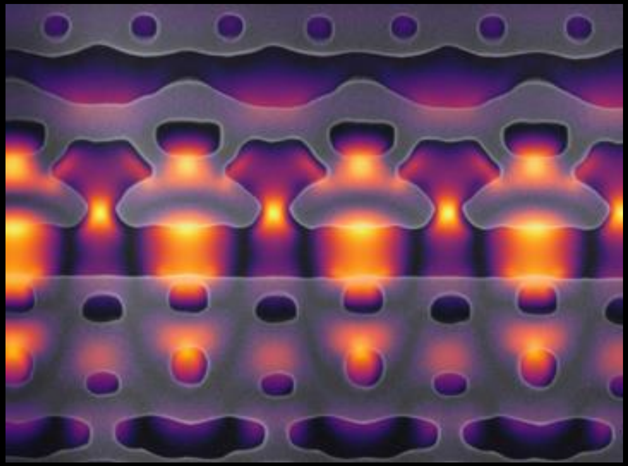


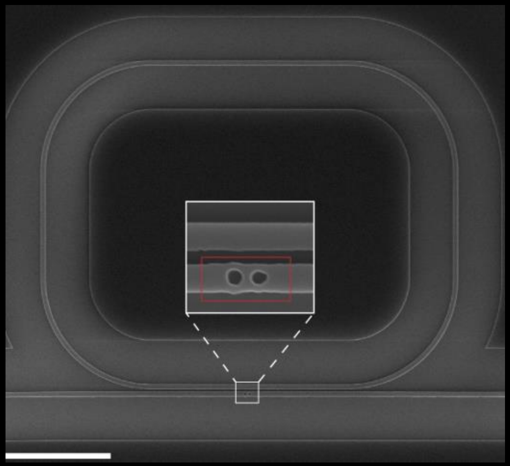
# Photonic inverse design



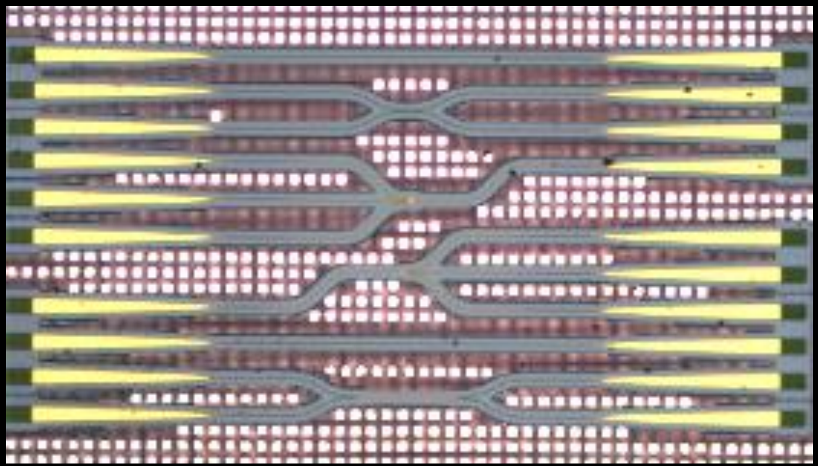
Wavelength demultiplexer
Nat. Photon. 9, 374 – 377 (2015).



Particle accelerator
Science 367, 79 – 83 (2020)



Non-reciprocal pulse router
Nat. Photon. 14, 369 – 374 (2020).



Inverse designs for foundries
ACS Photonics 7, 569 – 575 (2020).

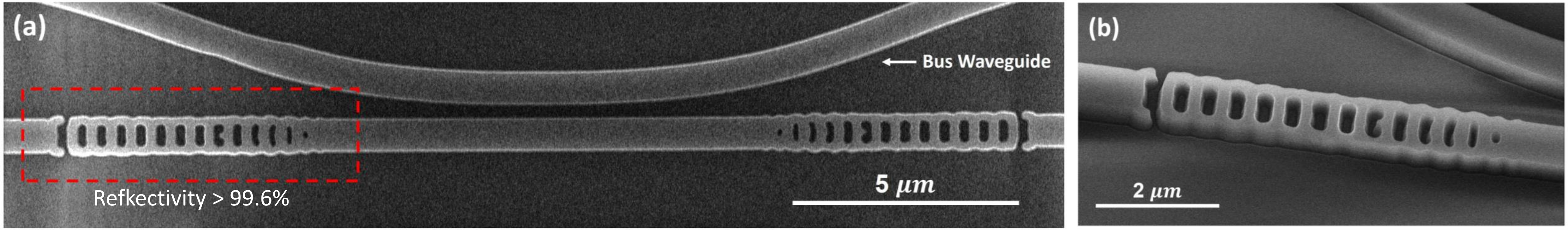
- Photonic circuits require very high efficiencies and often novel functionalities
- Rely on sophisticated optimization techniques, but also take into account fabrication constraints

Logan Su et al, *Appl. Phys. Rev.* 7, 011407 (2020)

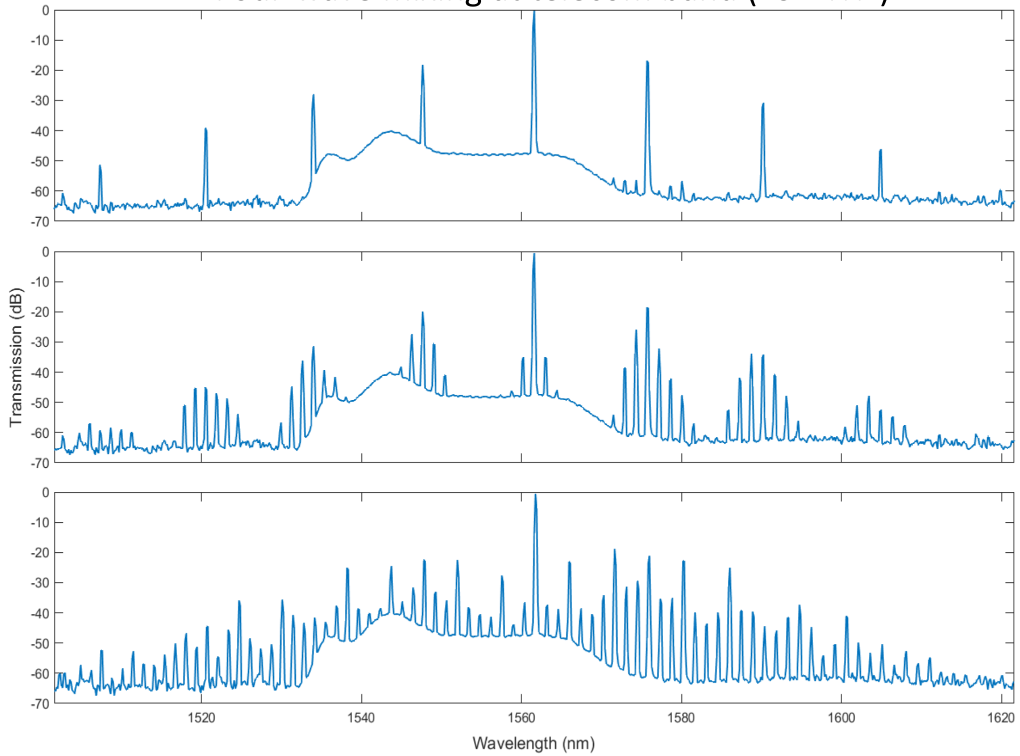
**S**tanford **P**hotonics **IN**verse design **S**oftware (**SPINS**)
Vuckovic Group - Stanford OTL Docket Number: S18-012

**SPINS–B** (open source, 3D) on Github
http://github.com/stanfordnqp/spins-b

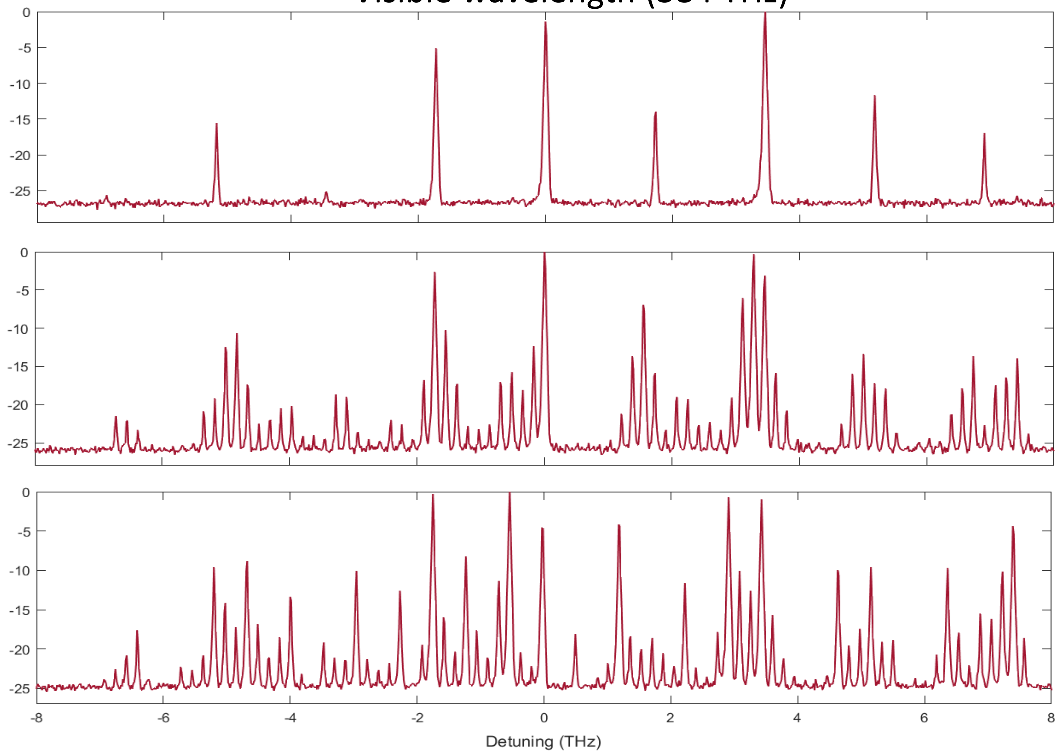
# Inverse design + SiC enables numerically-optimized nonlinear photonics




Four-wave mixing at telecom band (192 THz)



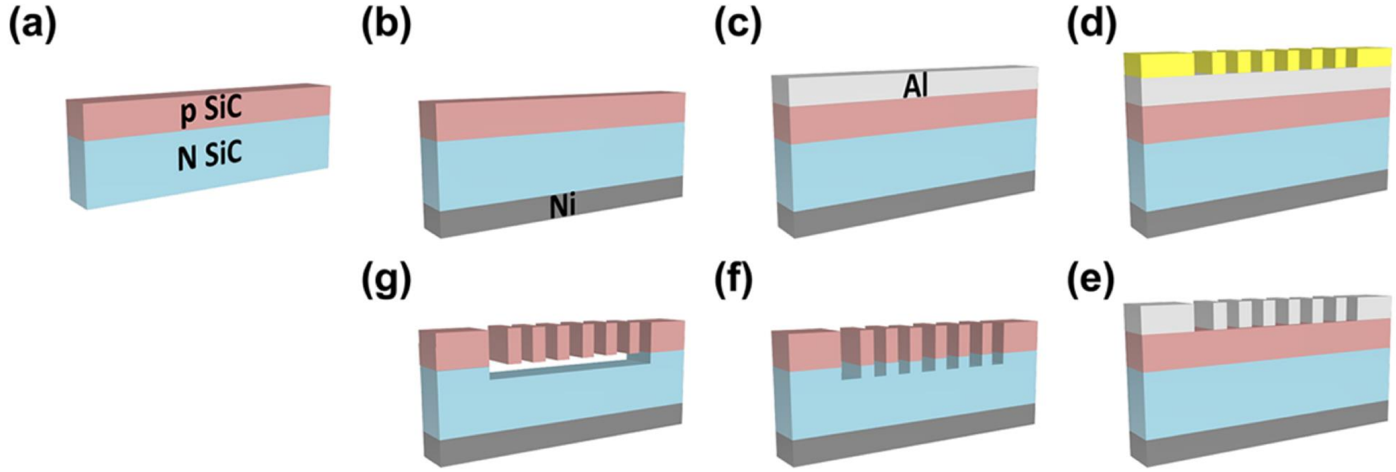

Visible wavelength (384 THz)



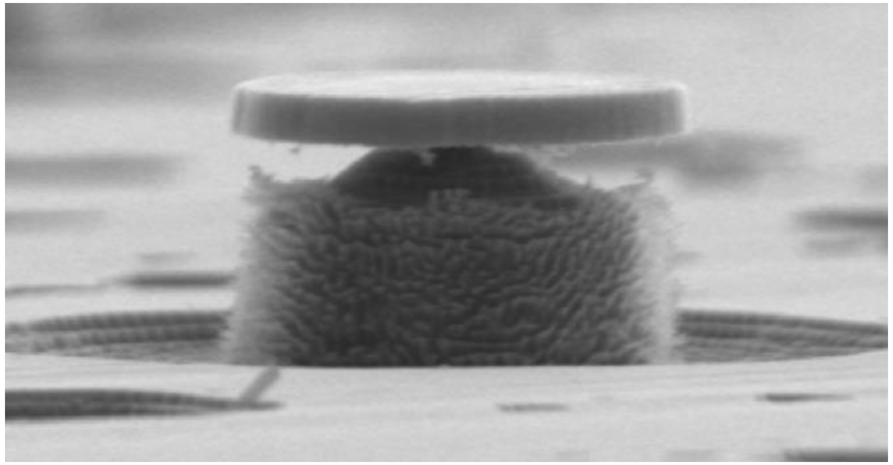

Joshua Yang

Kiyoul Yang

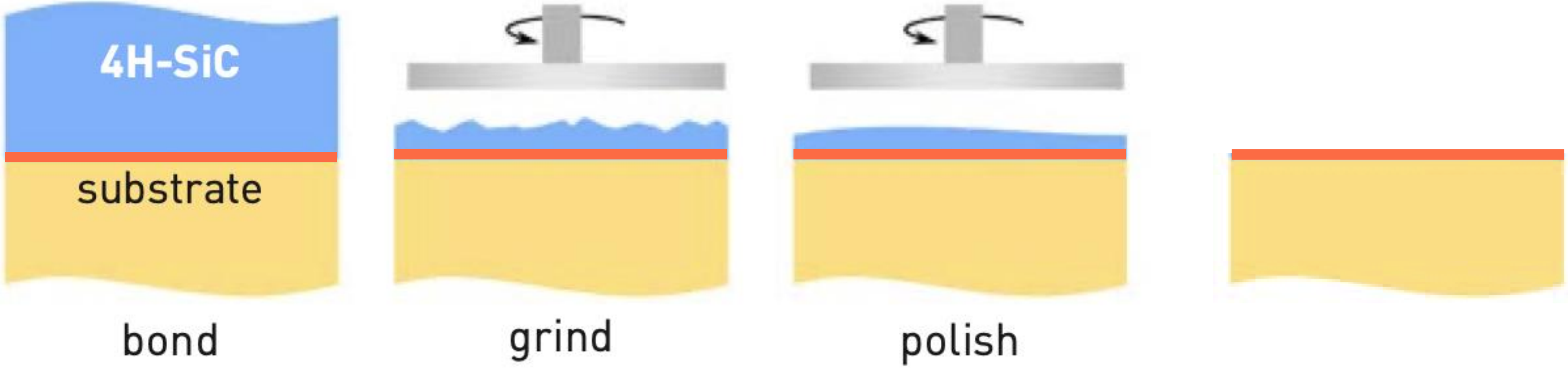
# Towards commercial waferscale SiC on insulator: photoelectrochemically



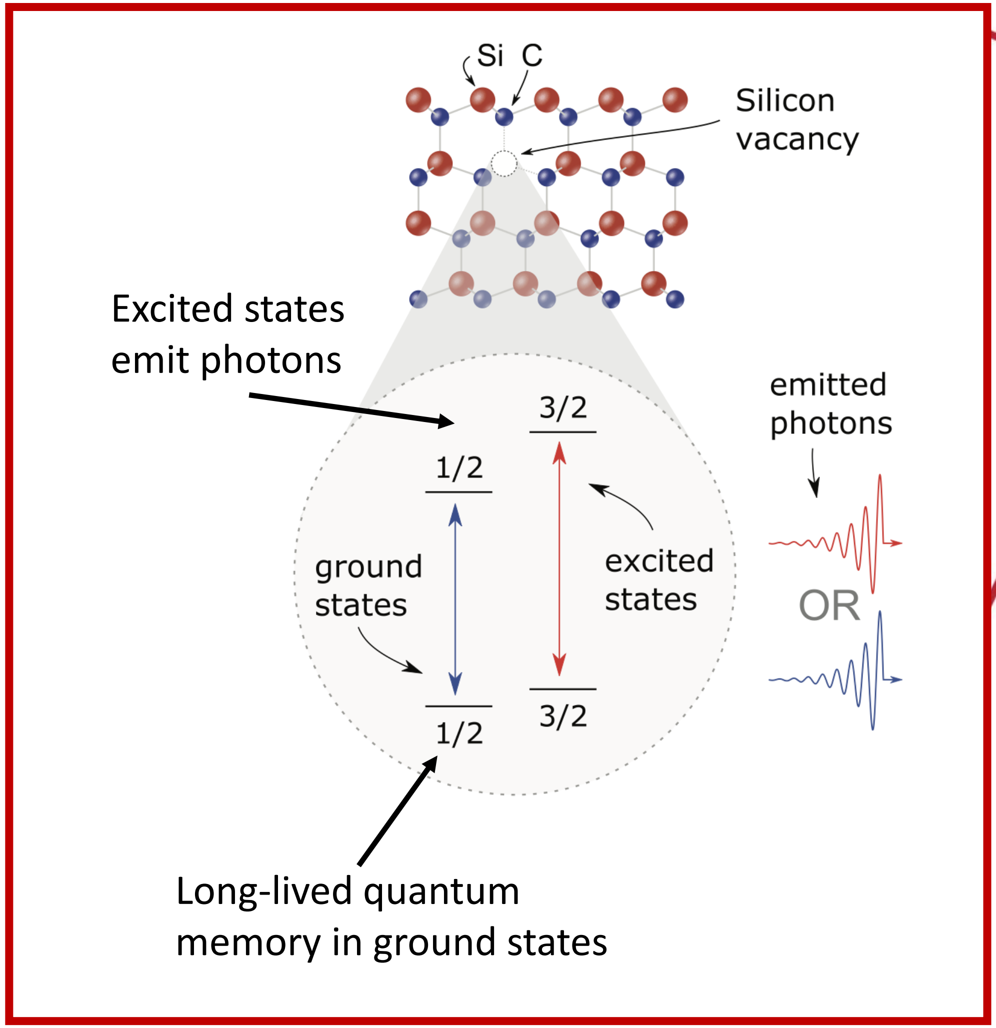

Bracher and Hu et al, APL, 2015



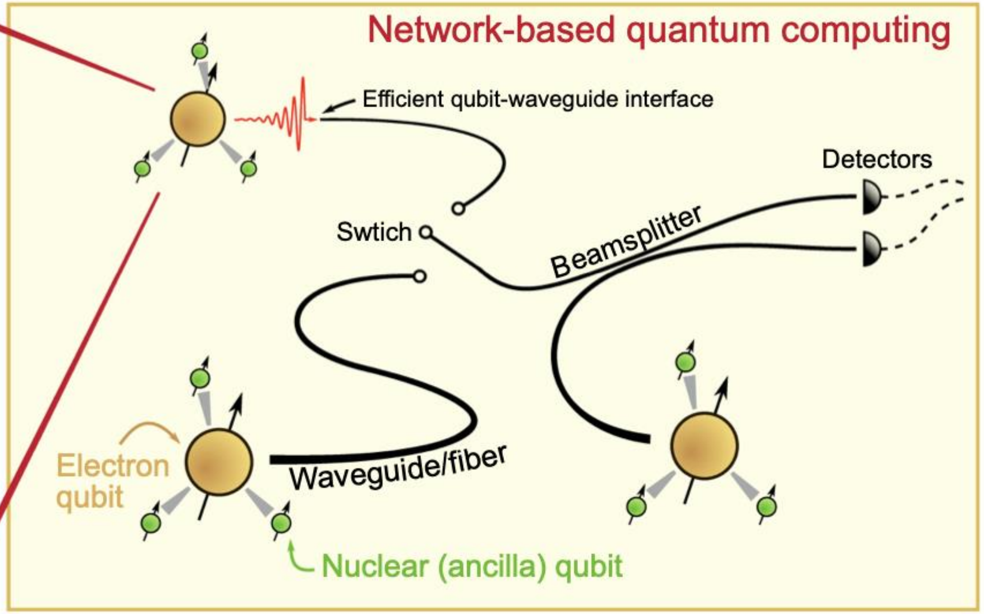
Magyar et al, APL, 2014

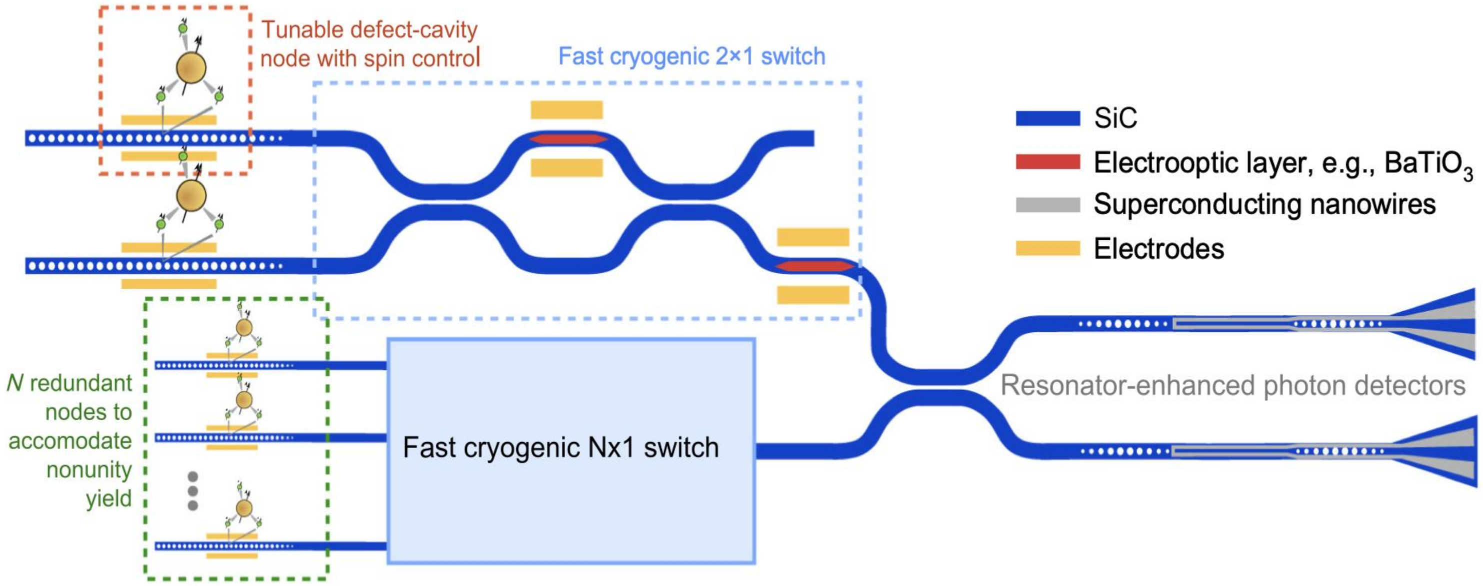


# Goal: Monolithic realization of integrated quantum network in SiC

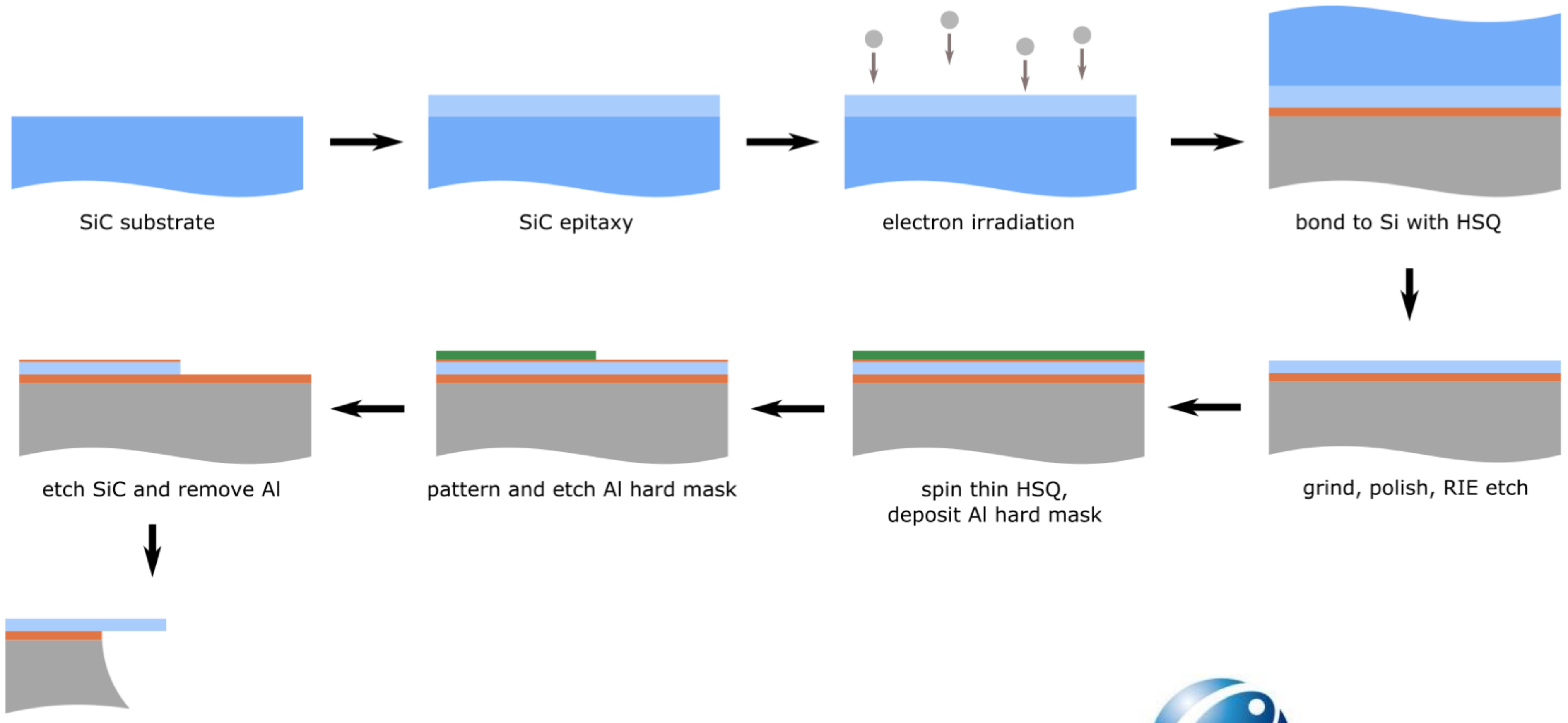



Lukin et al., PRX Quantum (2020)



# SiCOI devices in high-quality SiC epitaxy

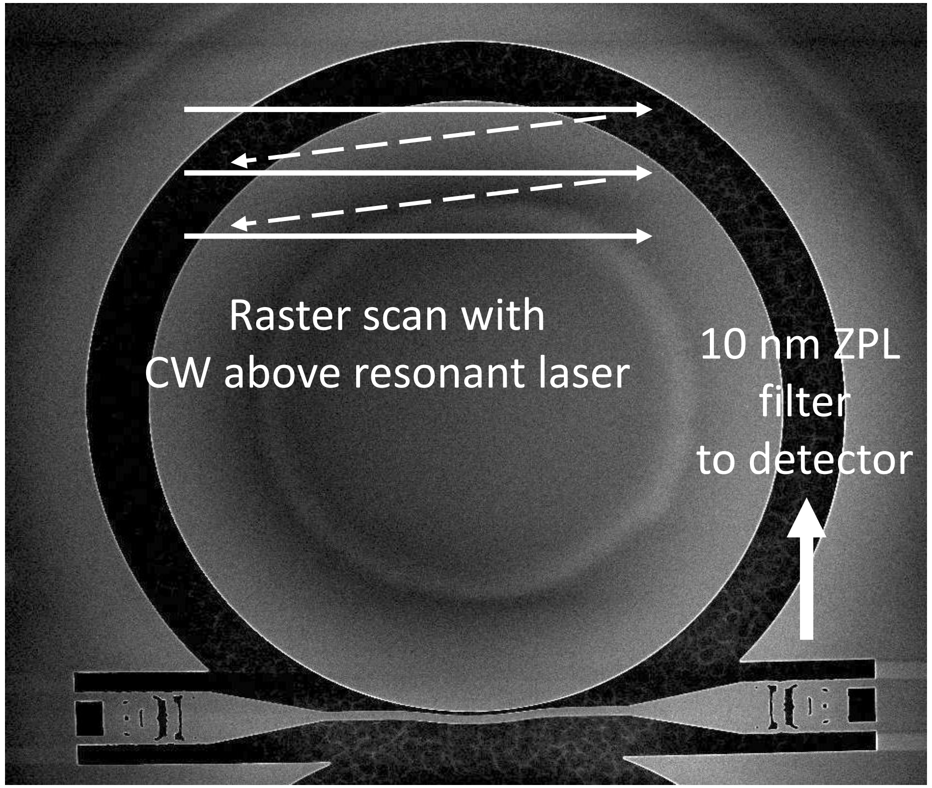


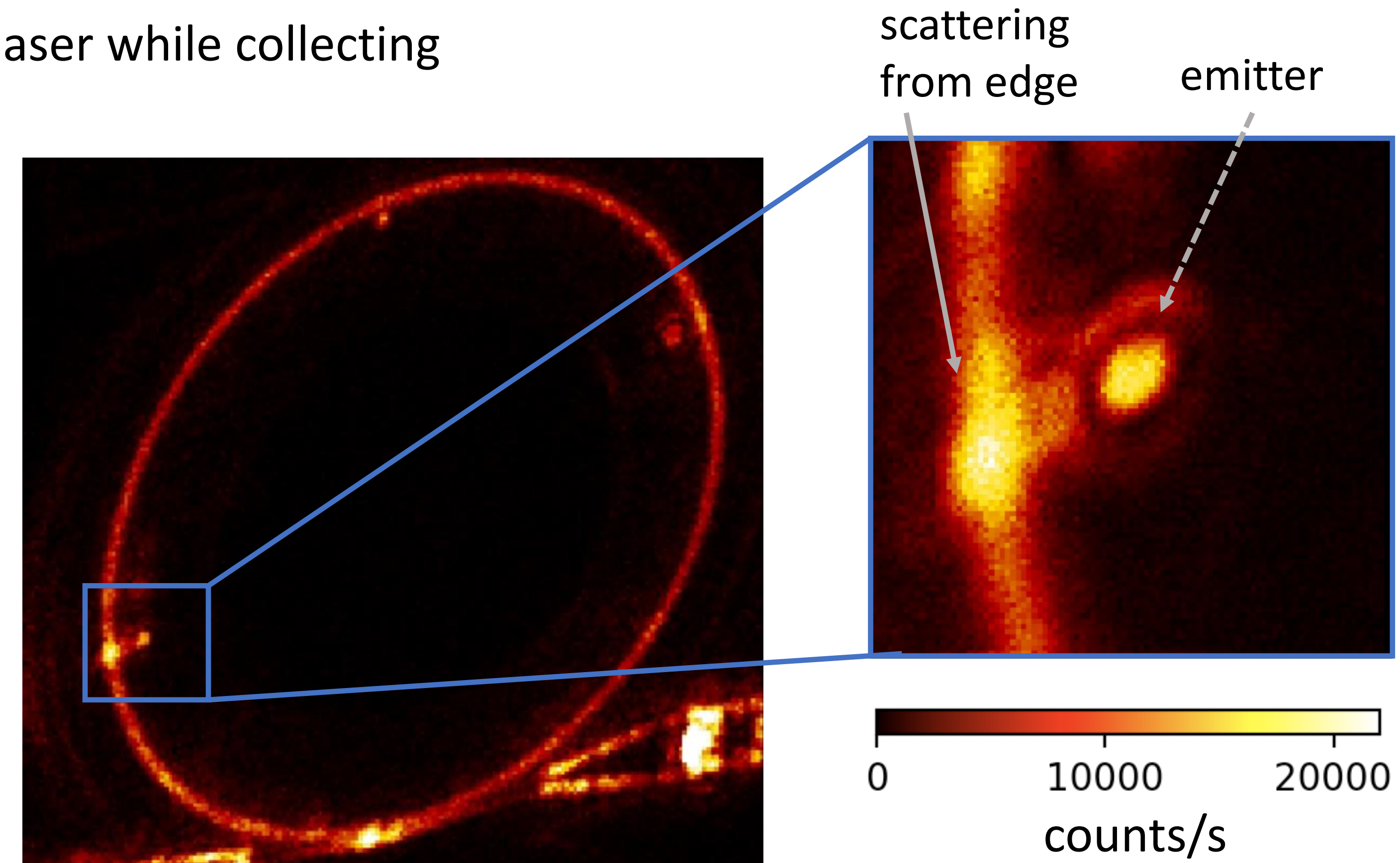

Takeshi Ohshima

Jawad Ul-Hassan

# Locating single defects in microdisk resonators

Once on resonance, scan a CW above resonant laser while collecting emission from the coupler.



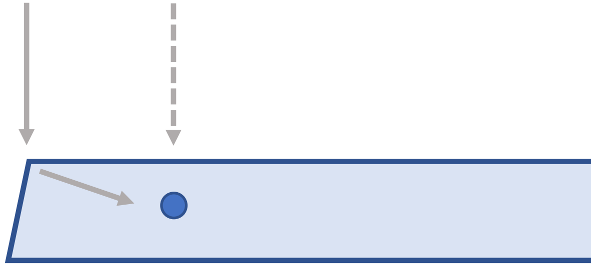
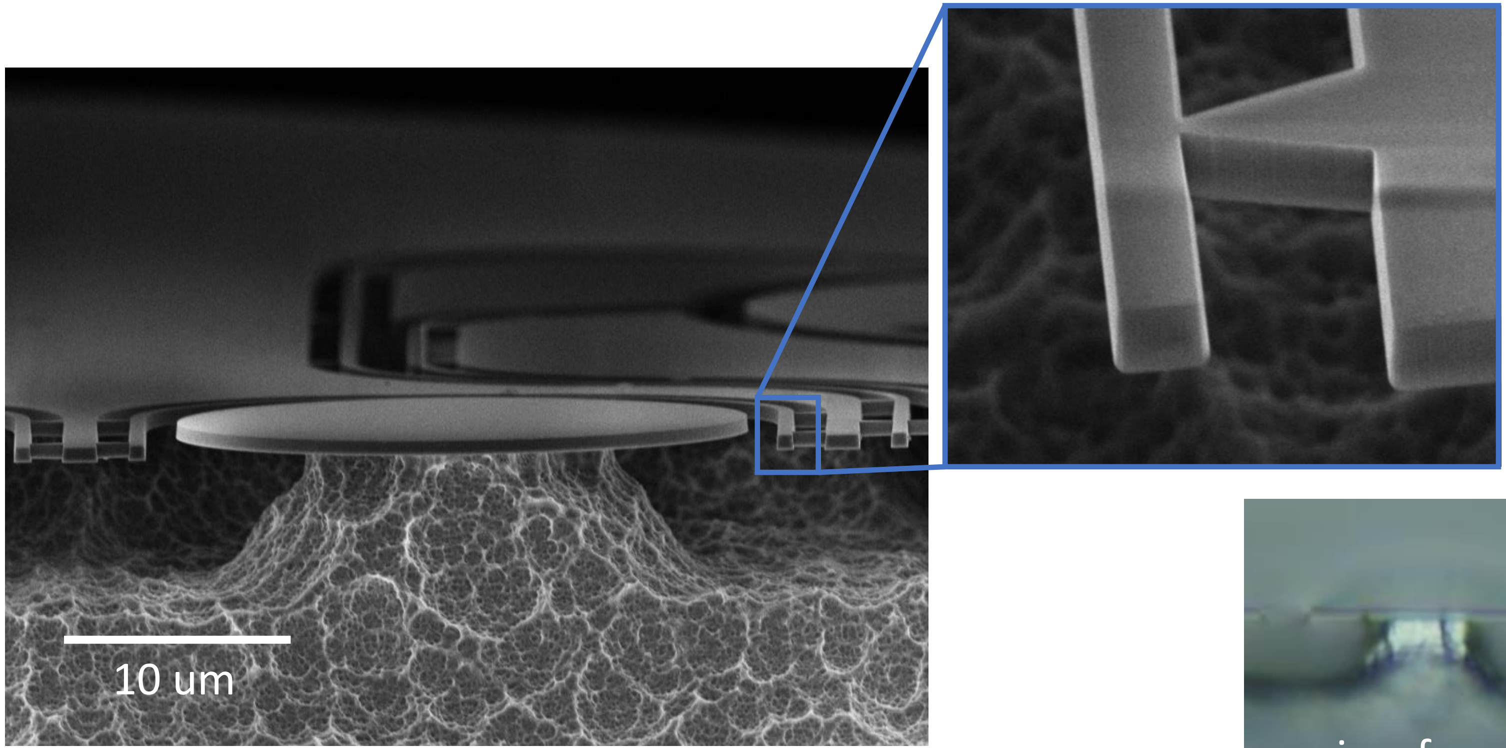
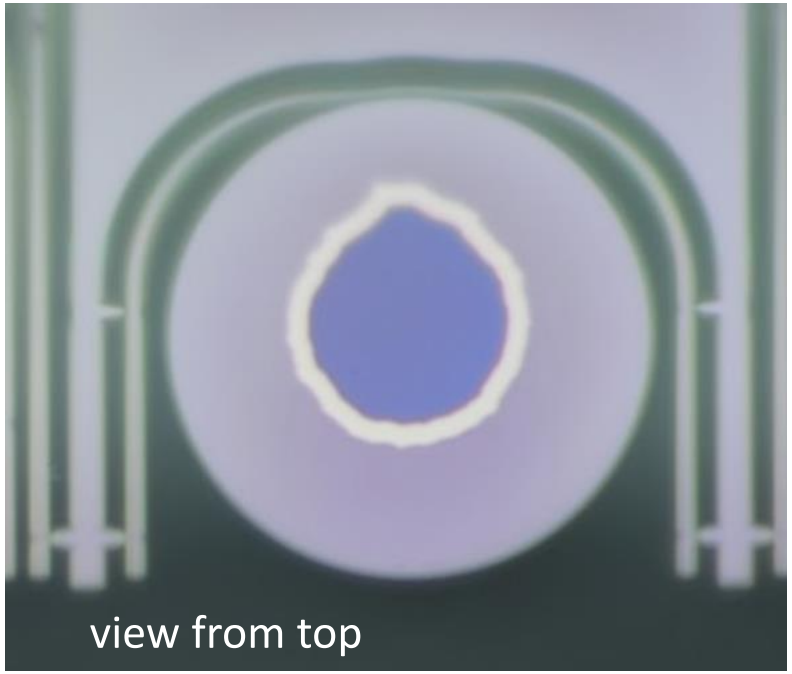



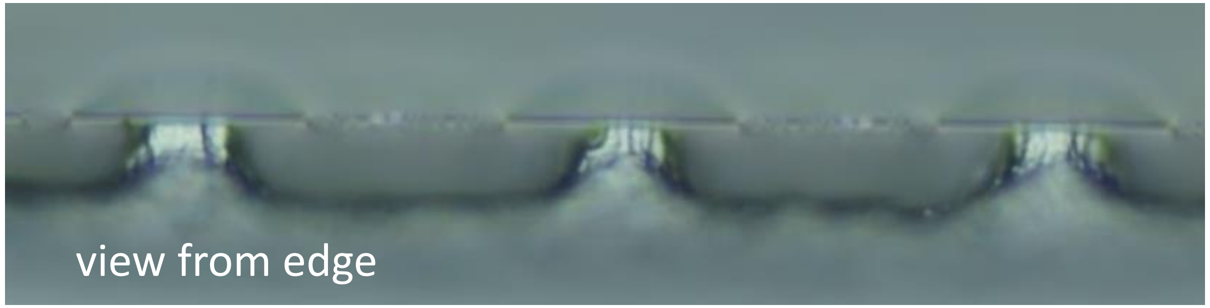
diagram of the edge scattering

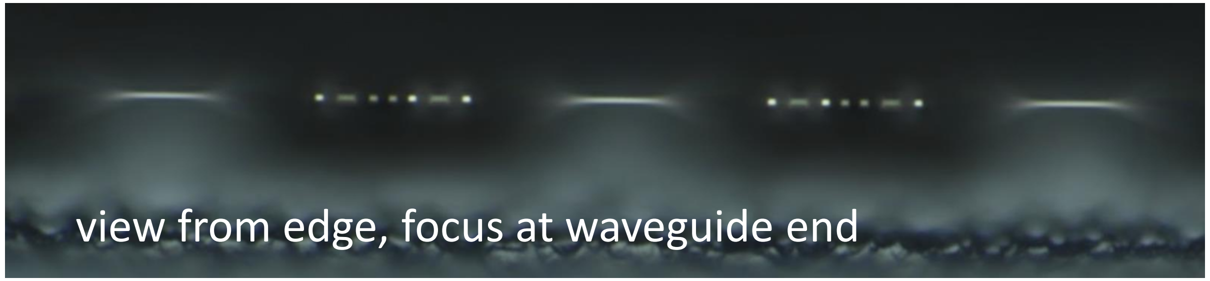
# Edge-coupled disk resonators

scattering loss from support
< 1% in simulation



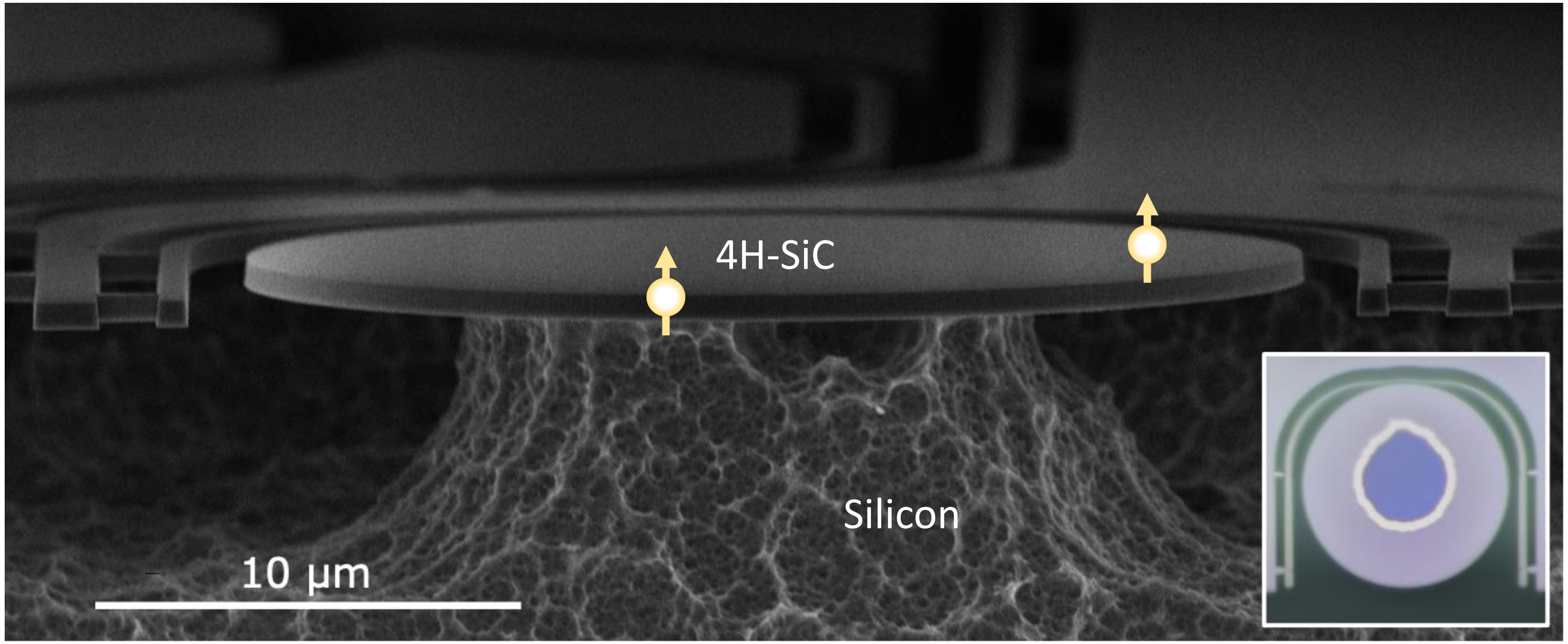



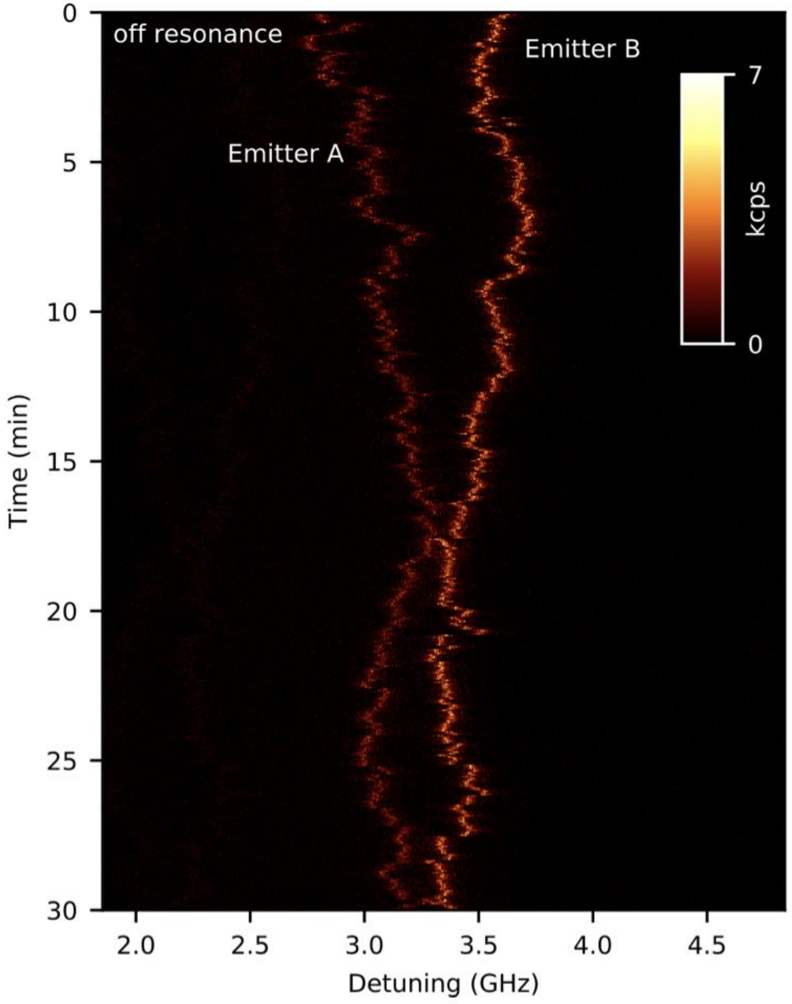




Total coupling efficiency into single-mode fiber up to 24%

# Stable color centers in SiCOI nanophotonics

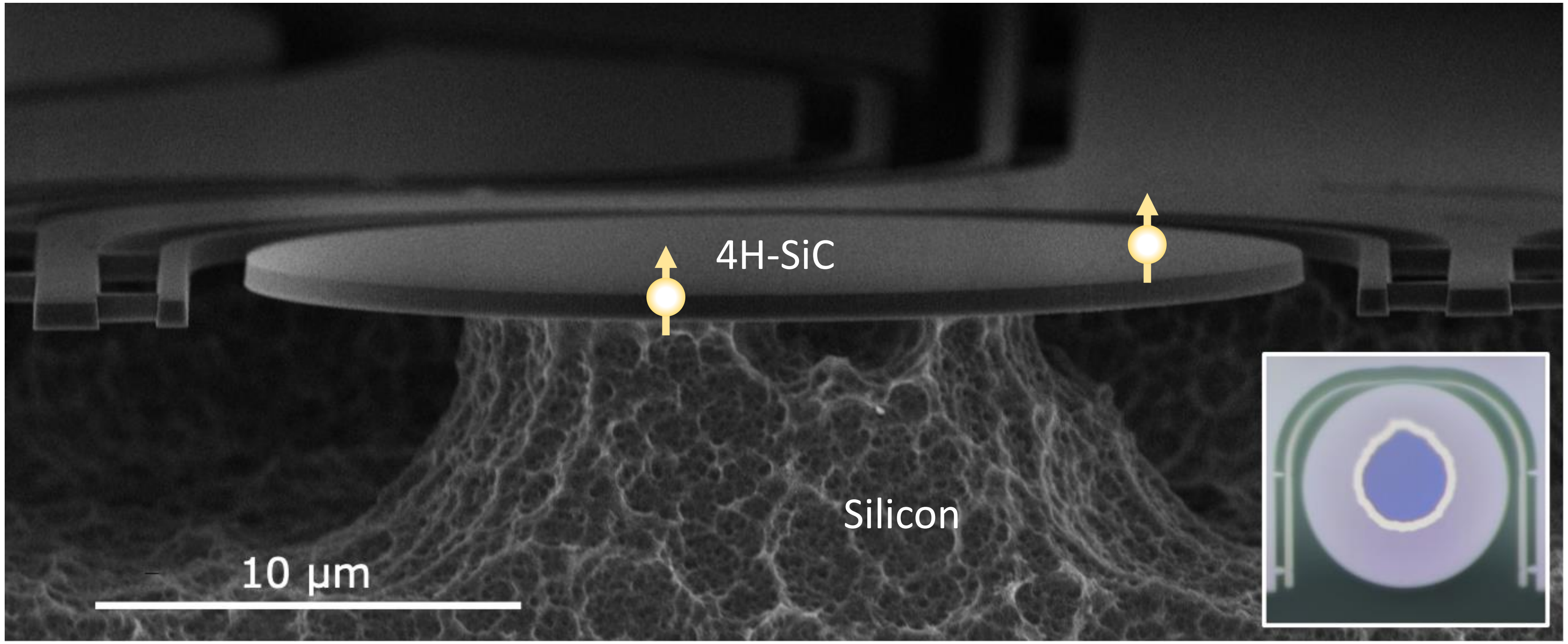
Lukin, Guidry et al, arXiv:2202.04845 (2022)

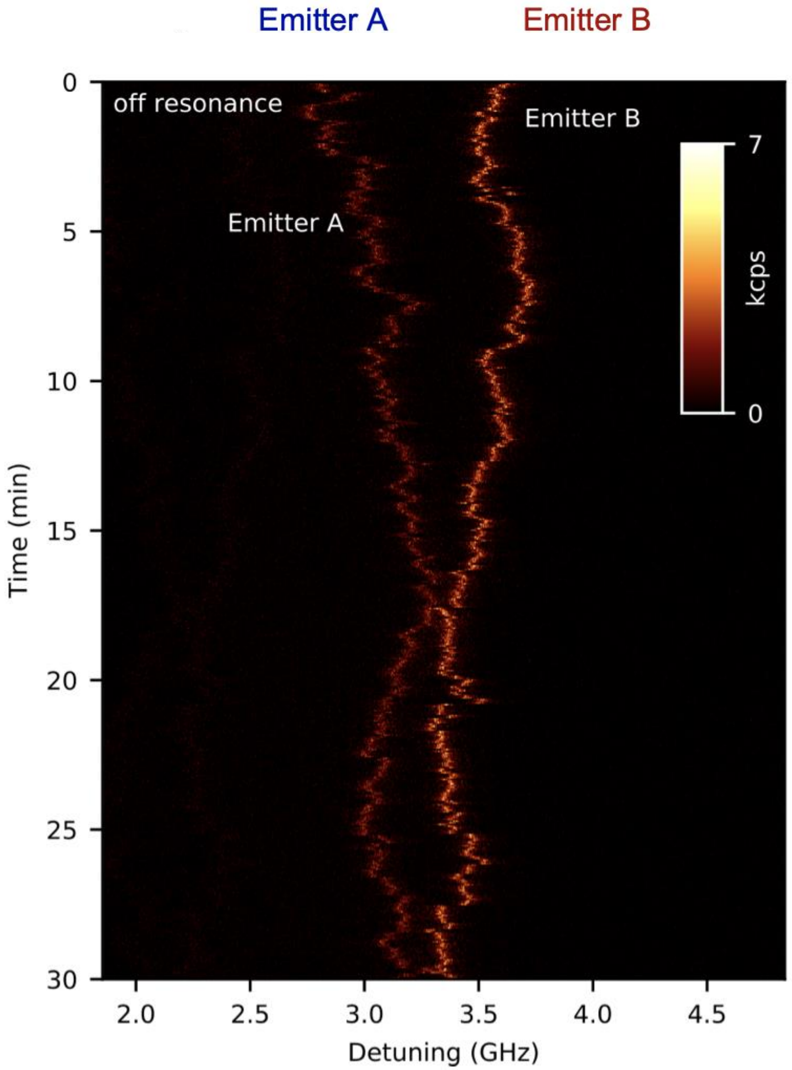


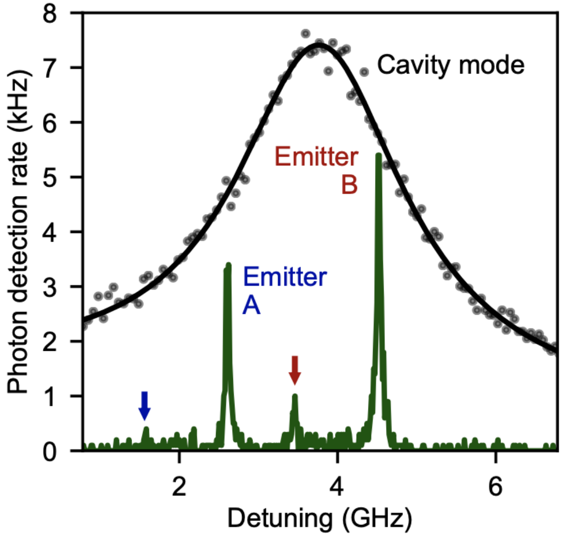



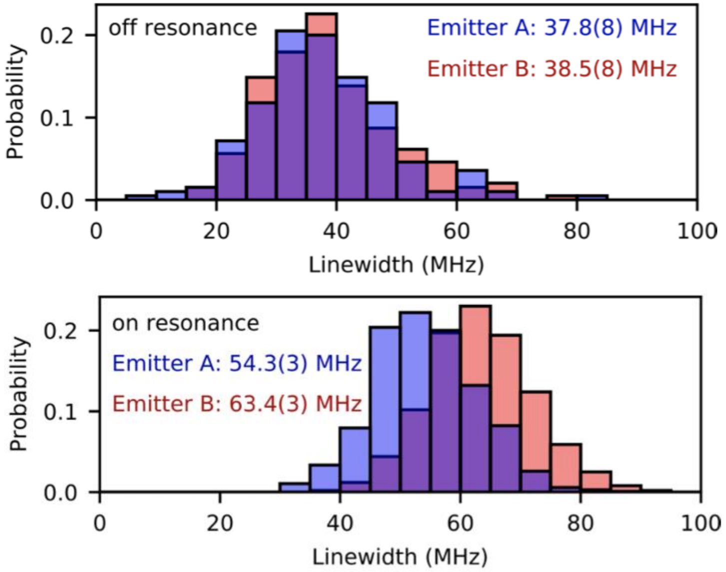
# Purcell enhancement

Lukin, Guidry et al, arXiv:2202.04845 (2022)



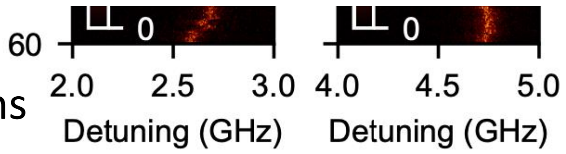




$$C = \frac{4g^2}{\kappa\gamma} \equiv$$

C = 0.6 emitt

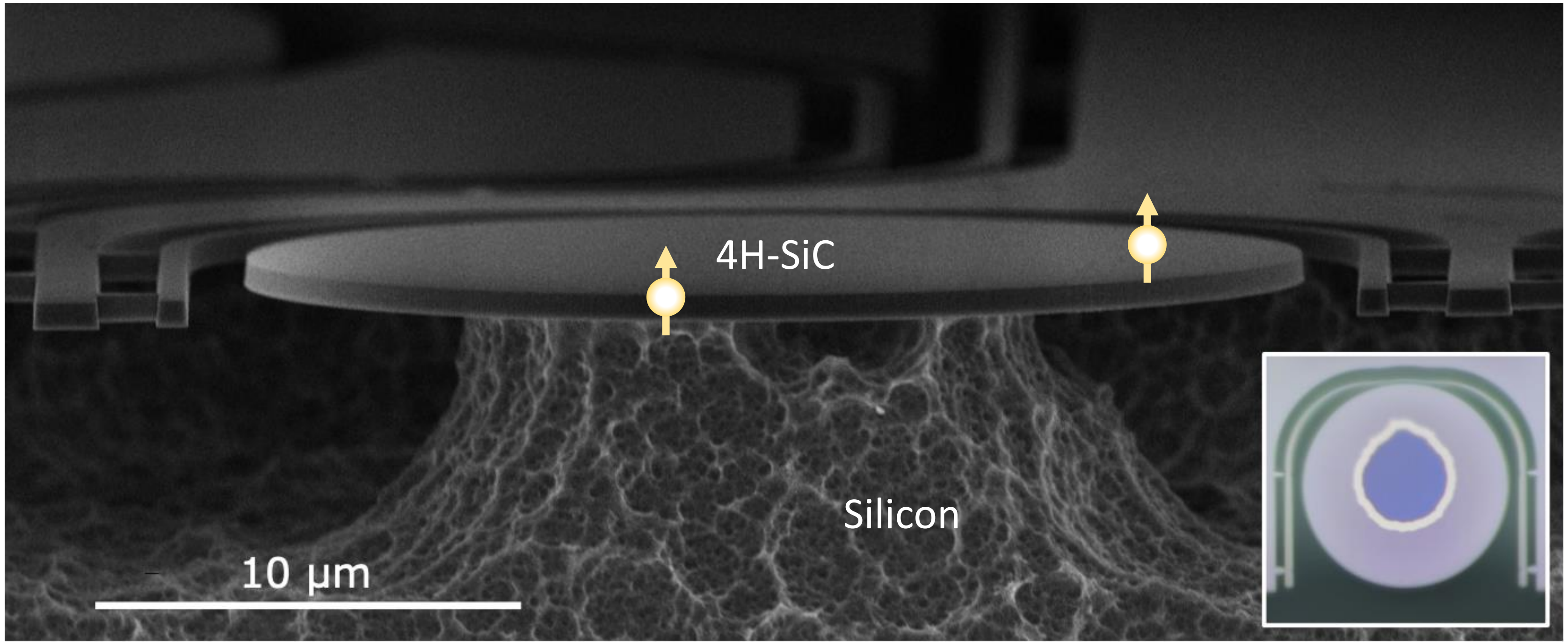
C = 0.8 emitt

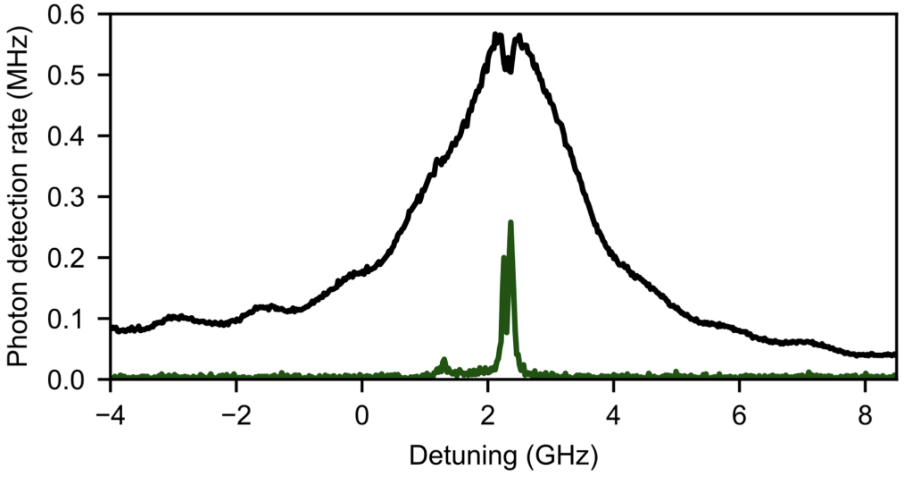
Approaching deterministic emitter-photon interactions

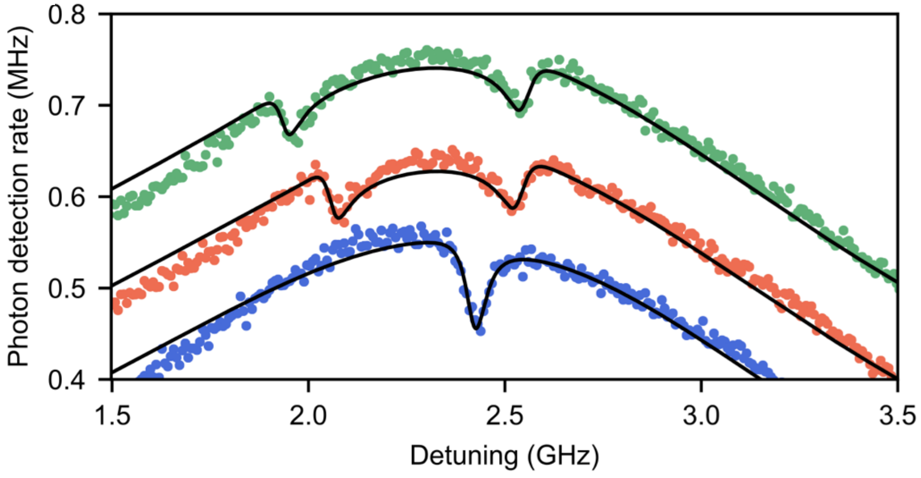


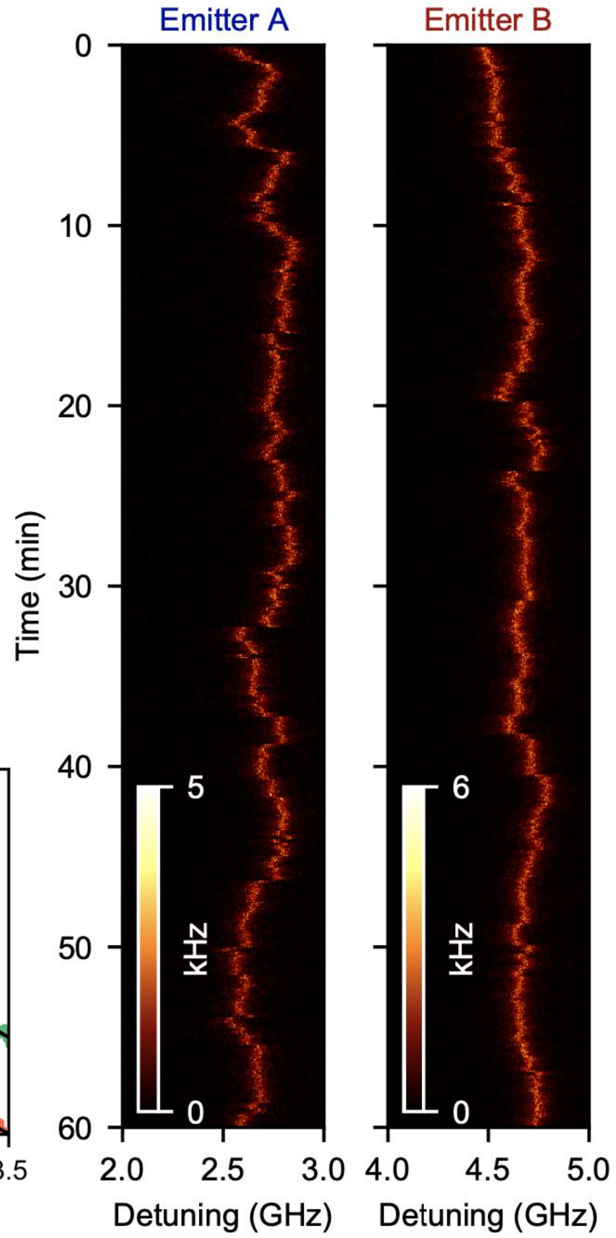
# Dipole induced transparency

Lukin, Guidry et al, arXiv:2202.04845 (2022)

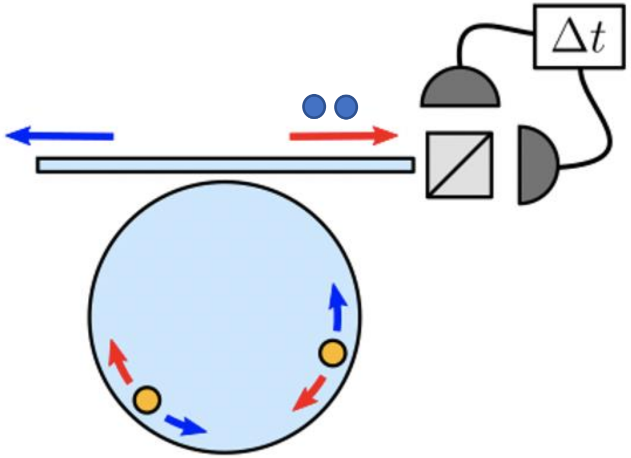


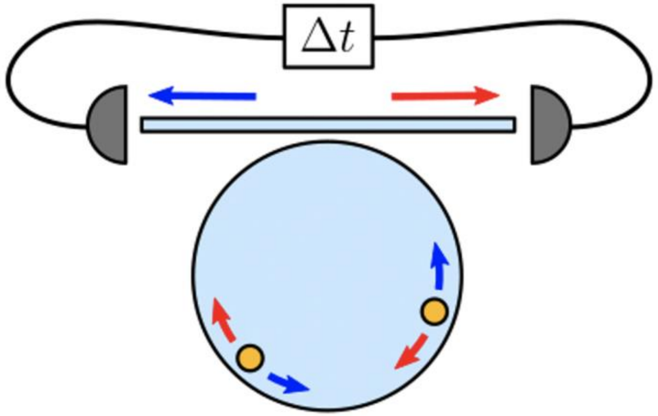



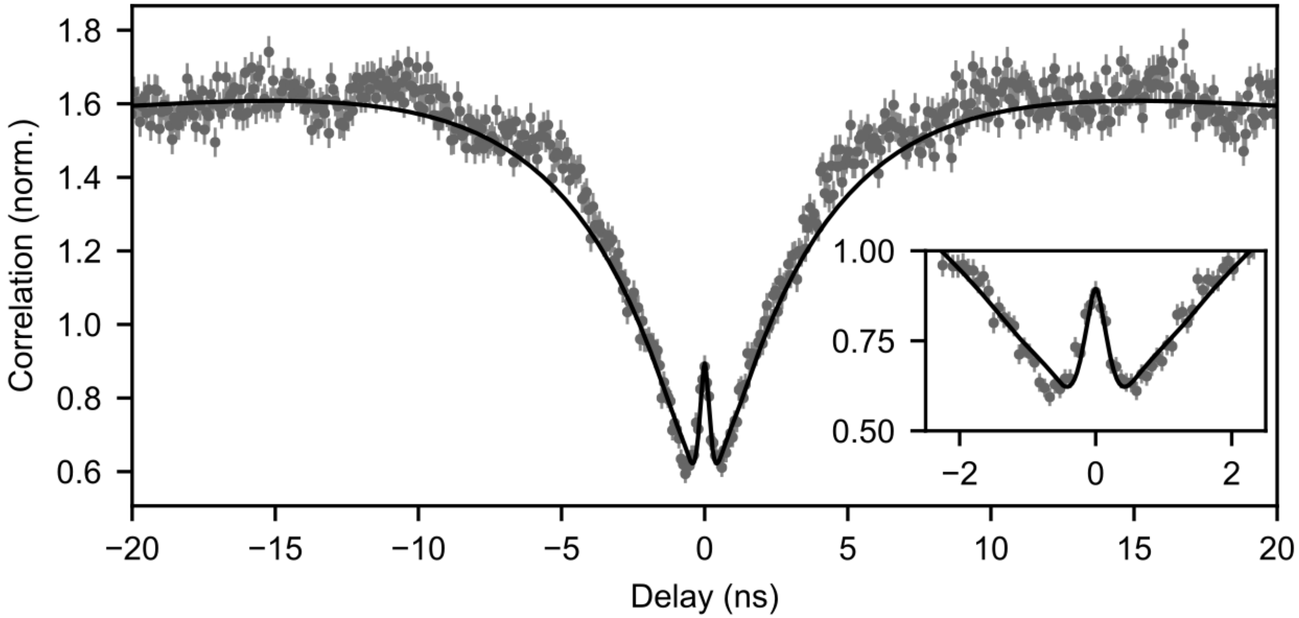



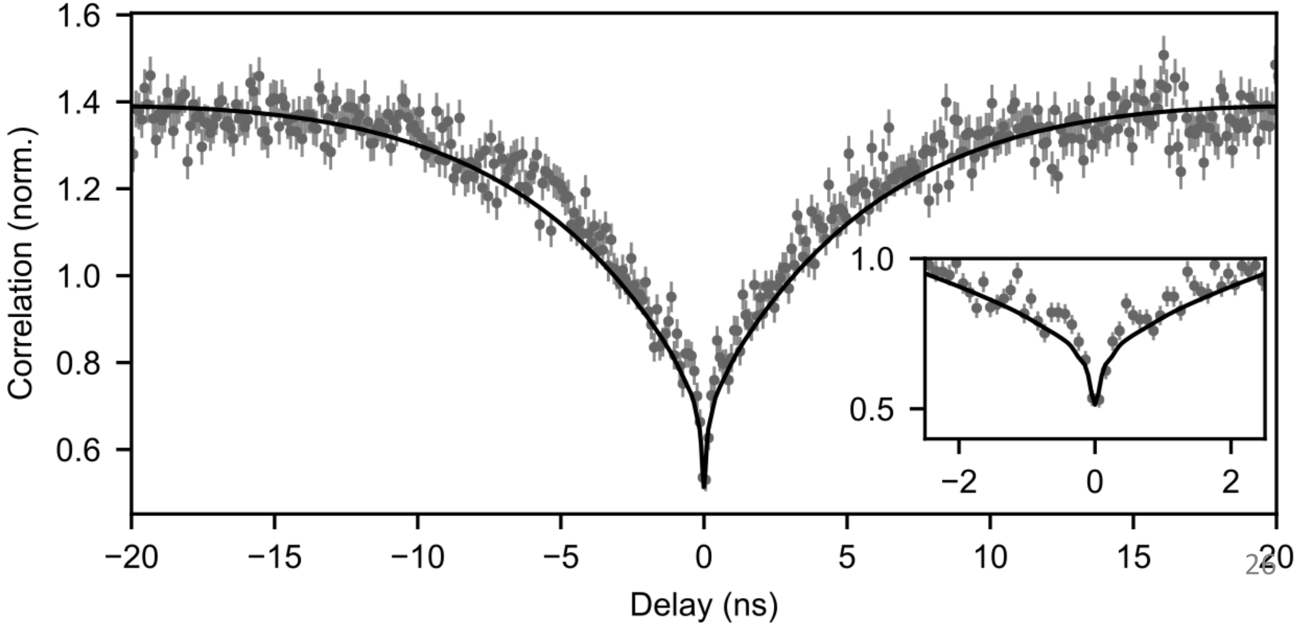
# Two-photon interference between two SiC color centers



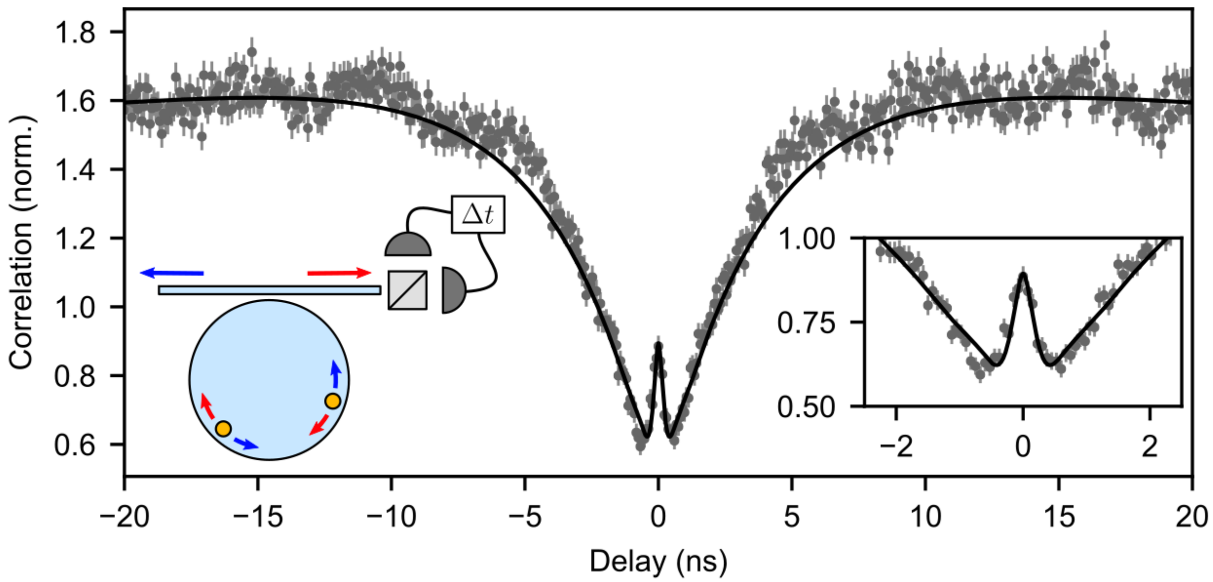

red: clockwise mode
blue: counterclockwise mode

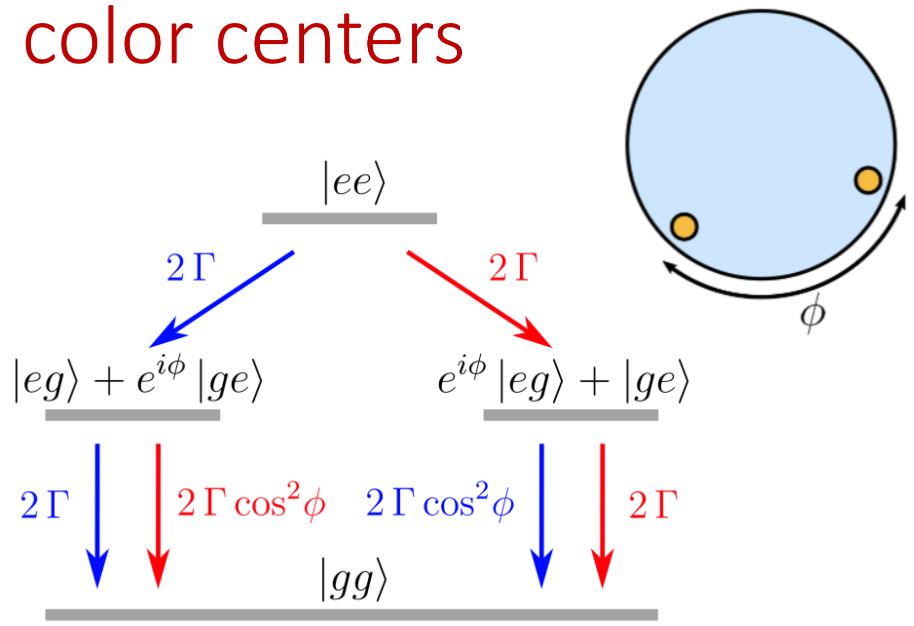


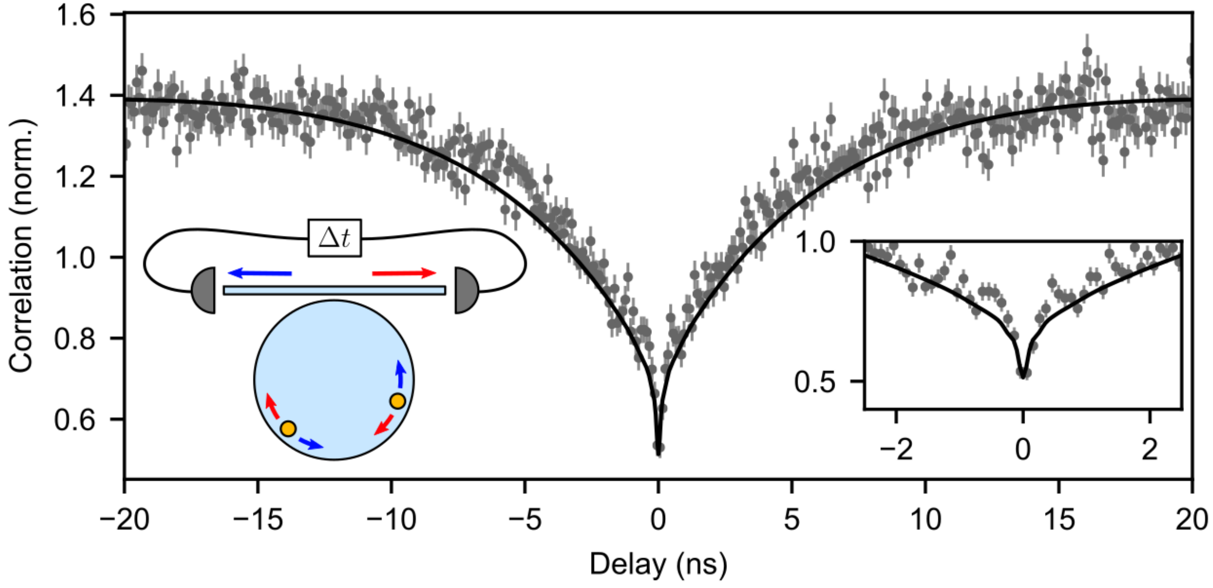



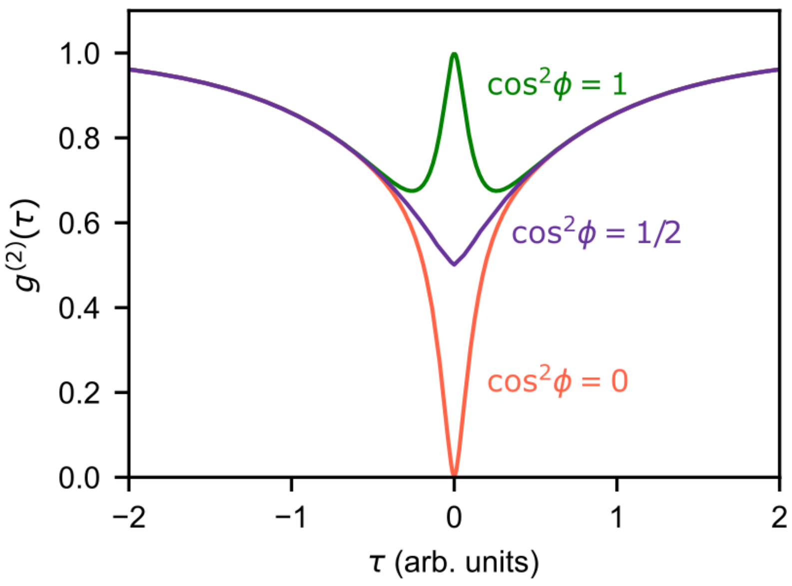



# Two-photon interference between two SiC color centers



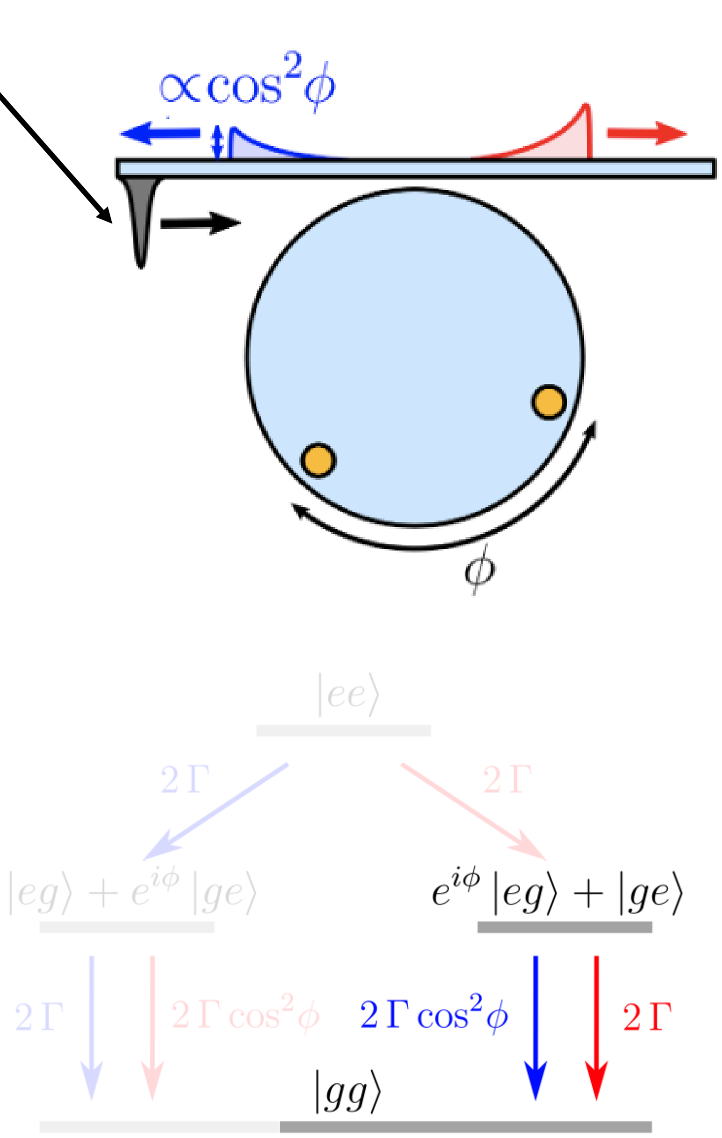



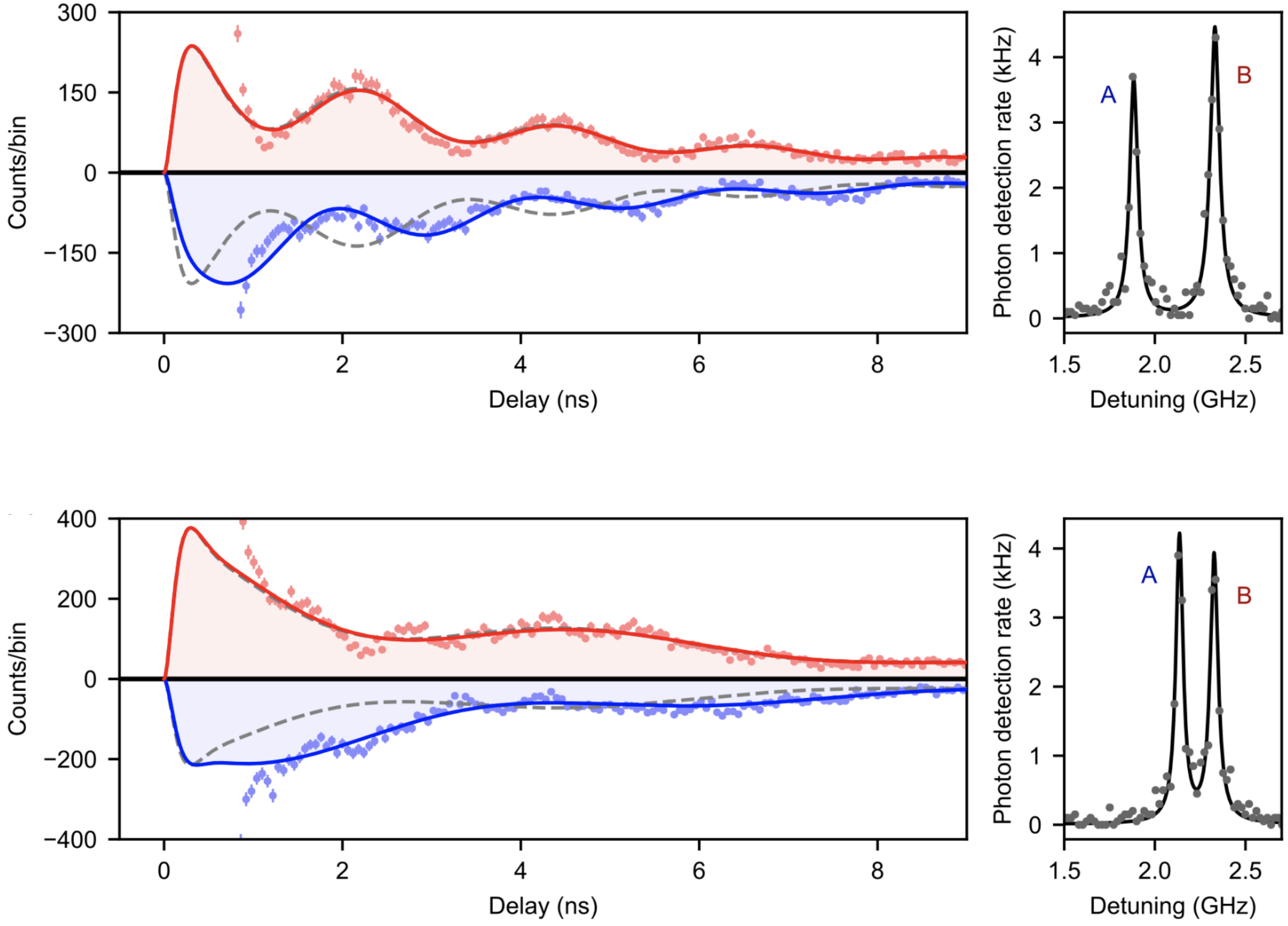



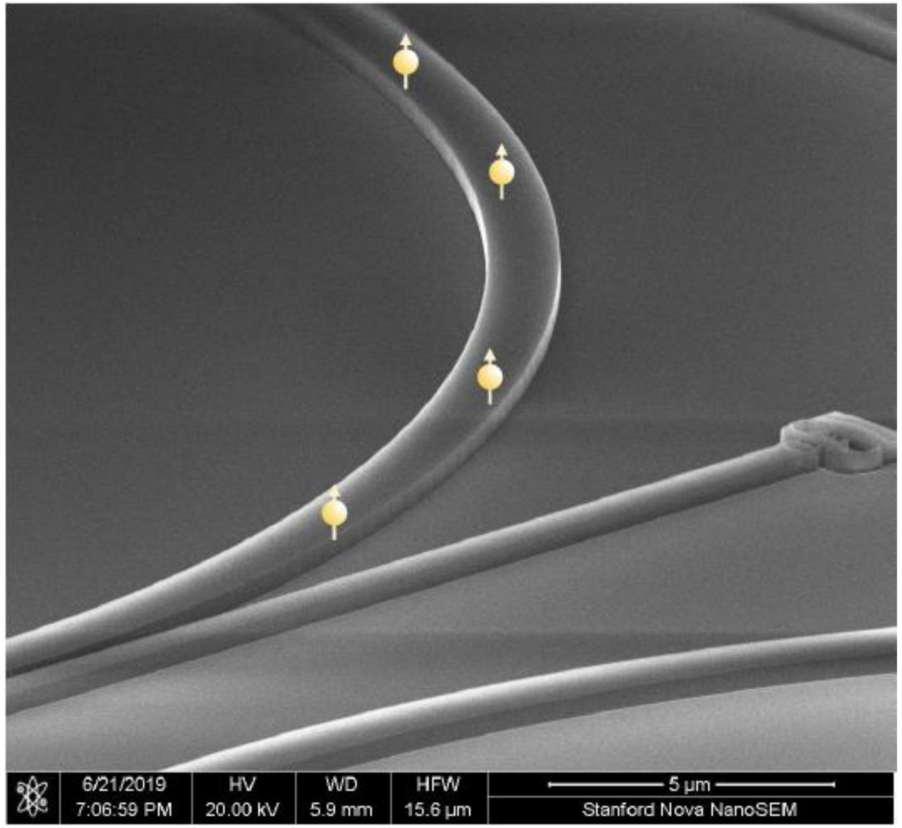
# Single-photon interference between two emitters in a resonator

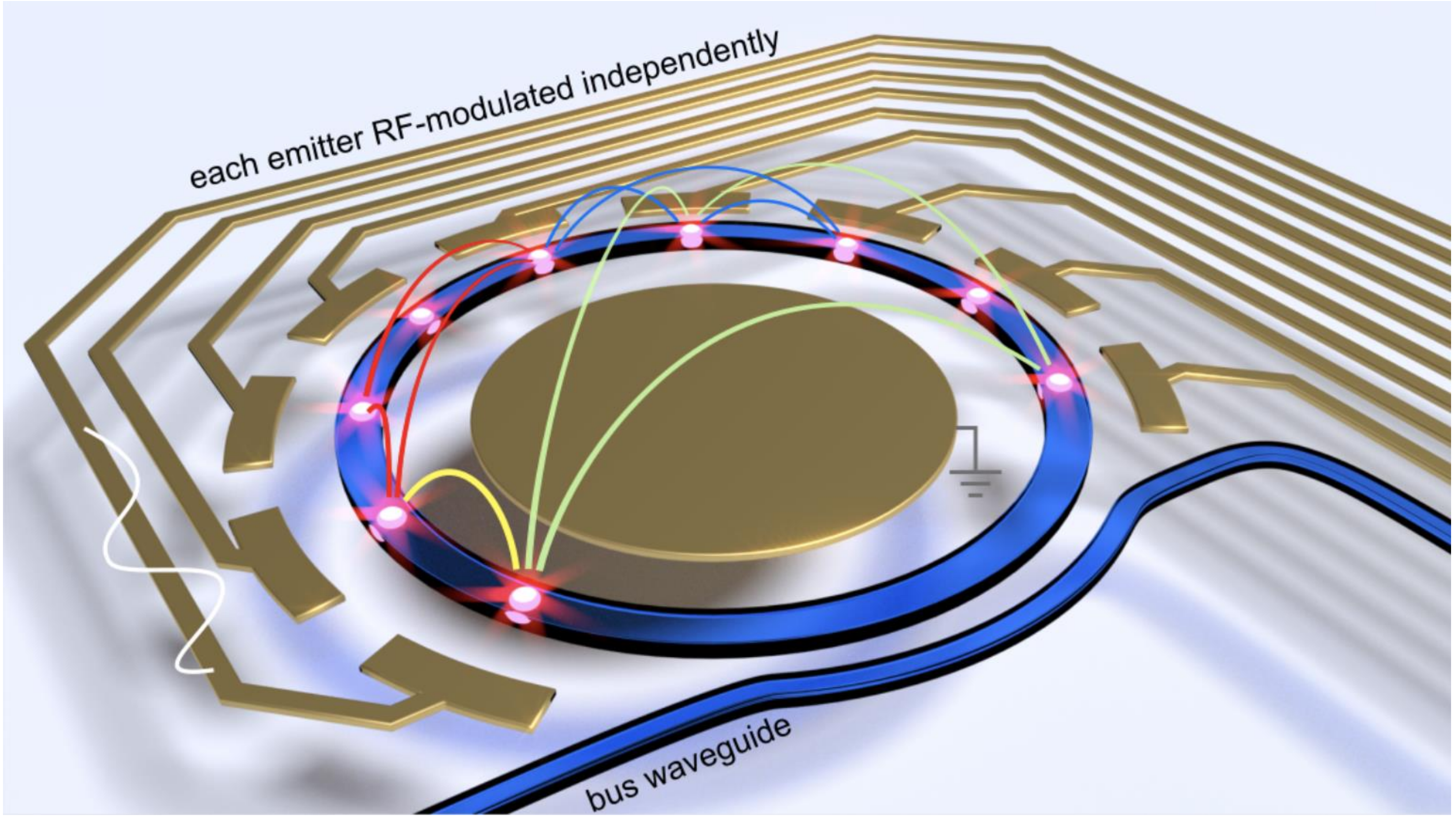
excitation with a weak coherent resonant pulse



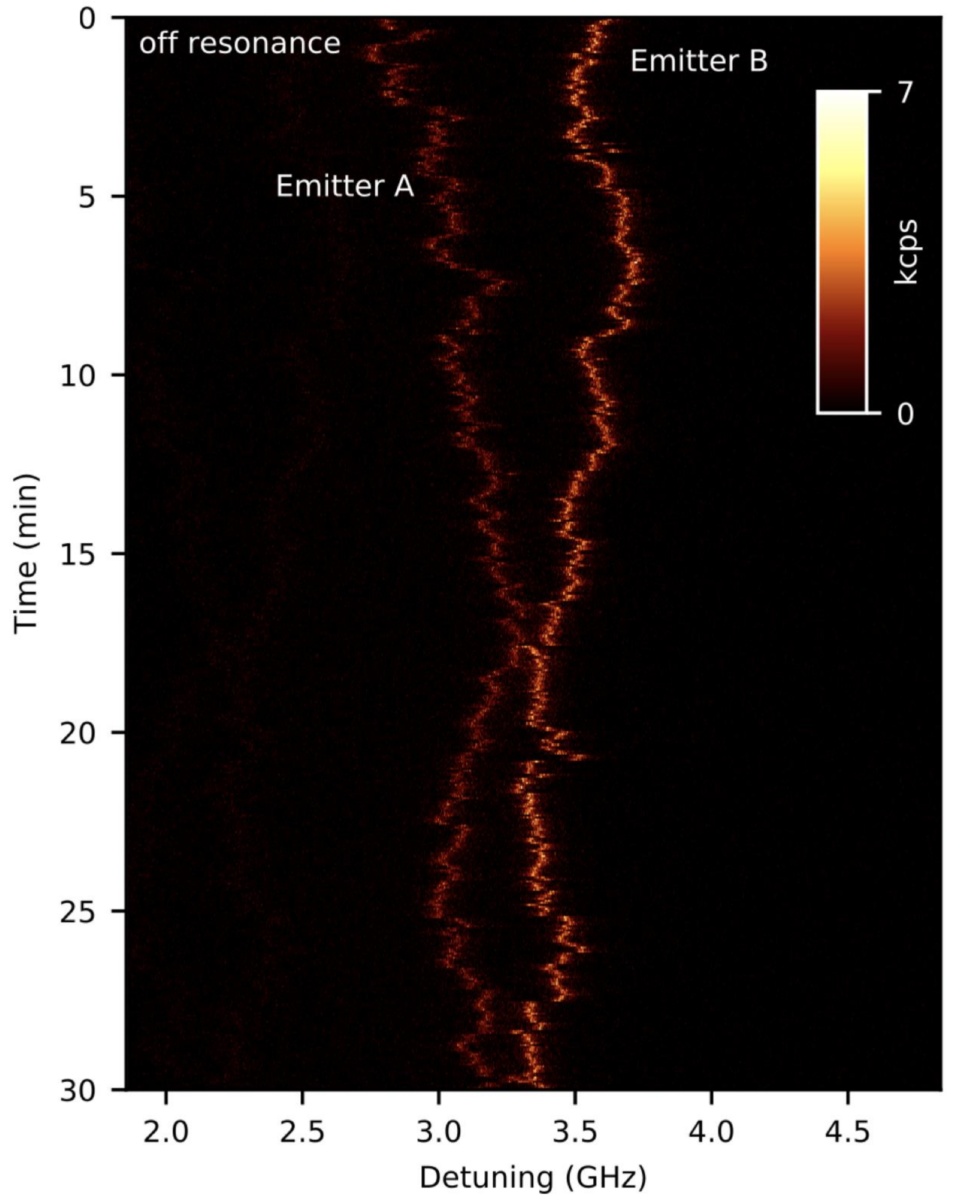



# Toward many-emitter systems via spectral control

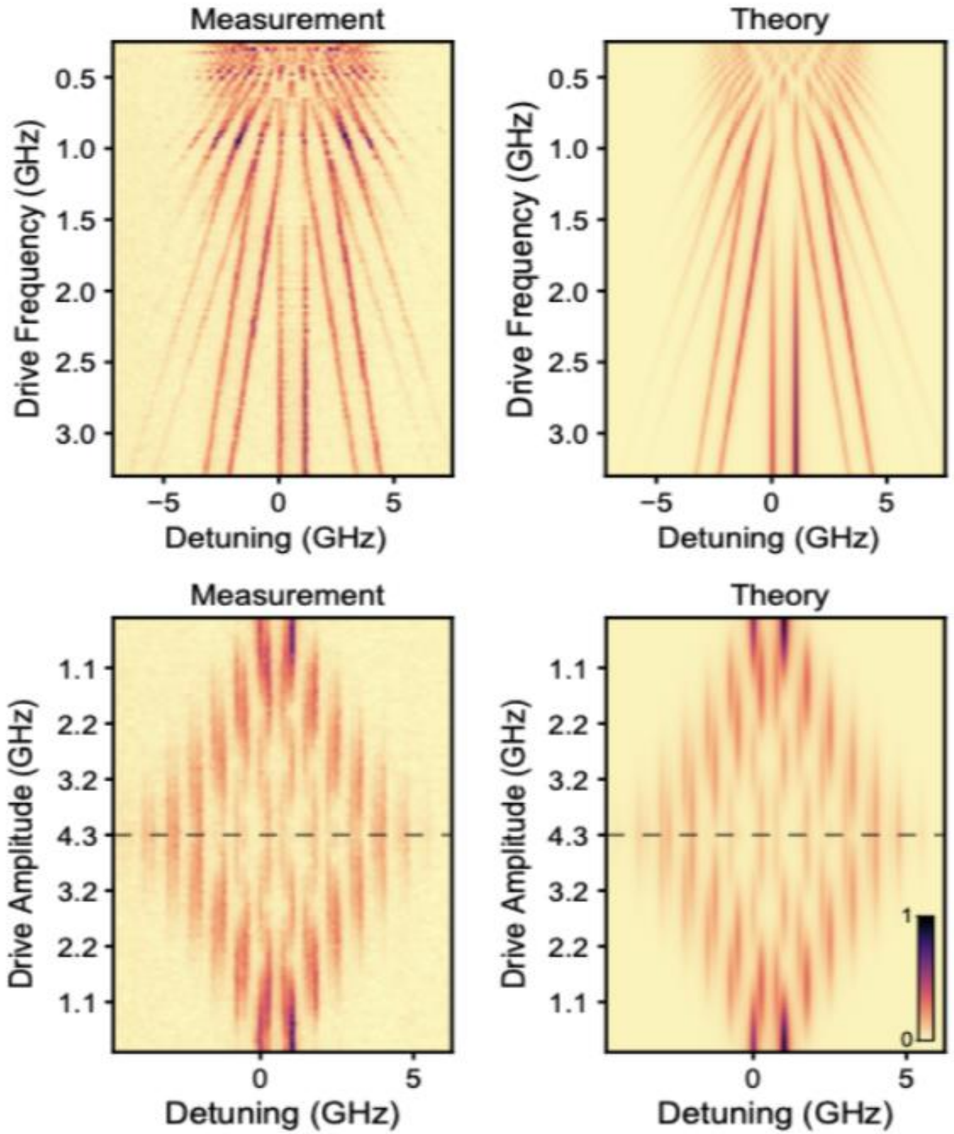


# Frequency control of color centers



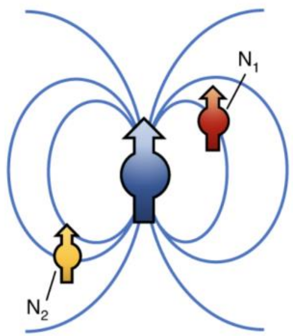

Floquet states



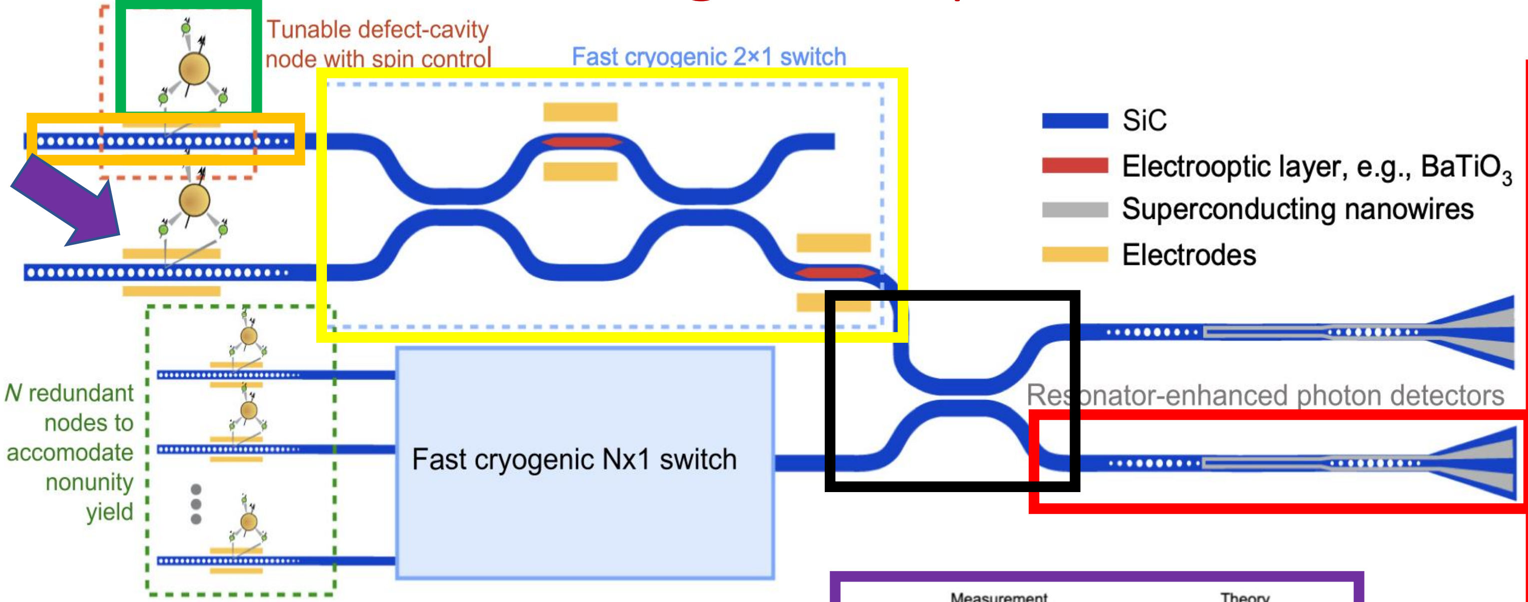

Lukin, White et al, npj Quantum Info (2020)

# Goal: Monolithic realization of integrated quantum network in SiC

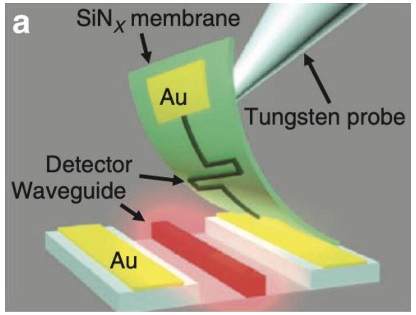
Babin et al, Nat. Mater. (2021)
Bourassa et al, Nat. Mater. (2020)



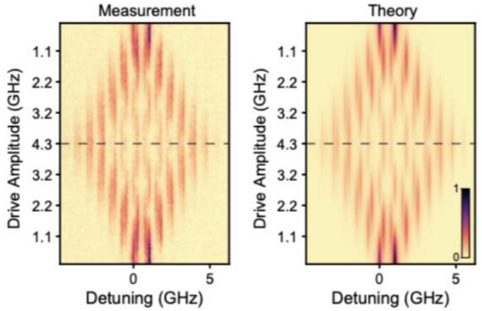

SiC color centers with nuclear spin qubits




Najafi et al, Nat. Commun. (2015)

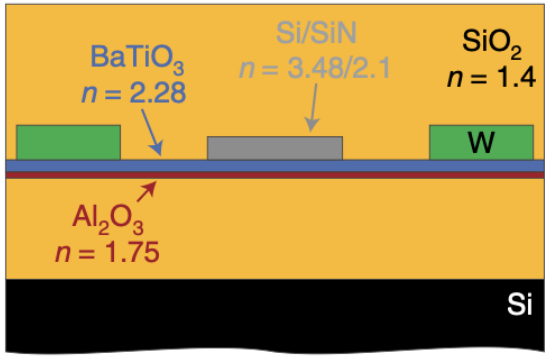



On chip waveguide-integrated detectors

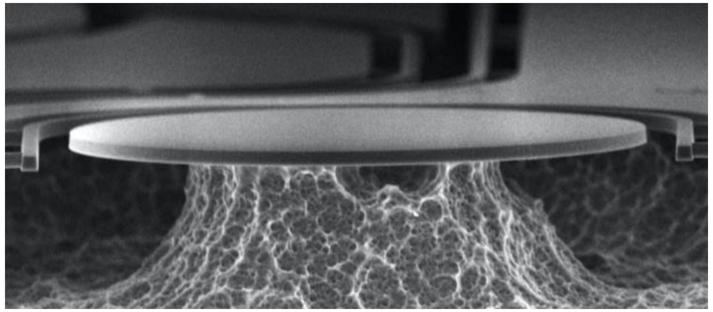



Spectral control

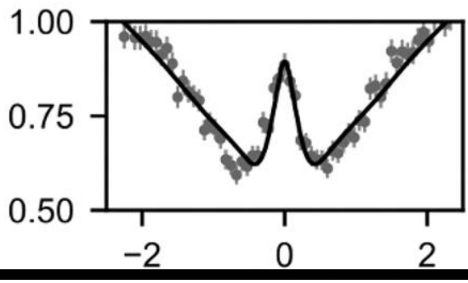
Eltes et al, Nat. Mater. (2020)




Cryogenic electro-optic reconfigurable circuits



Coherent cavity-integrated color centers




chip-integrated photon interference

# Acknowledgements



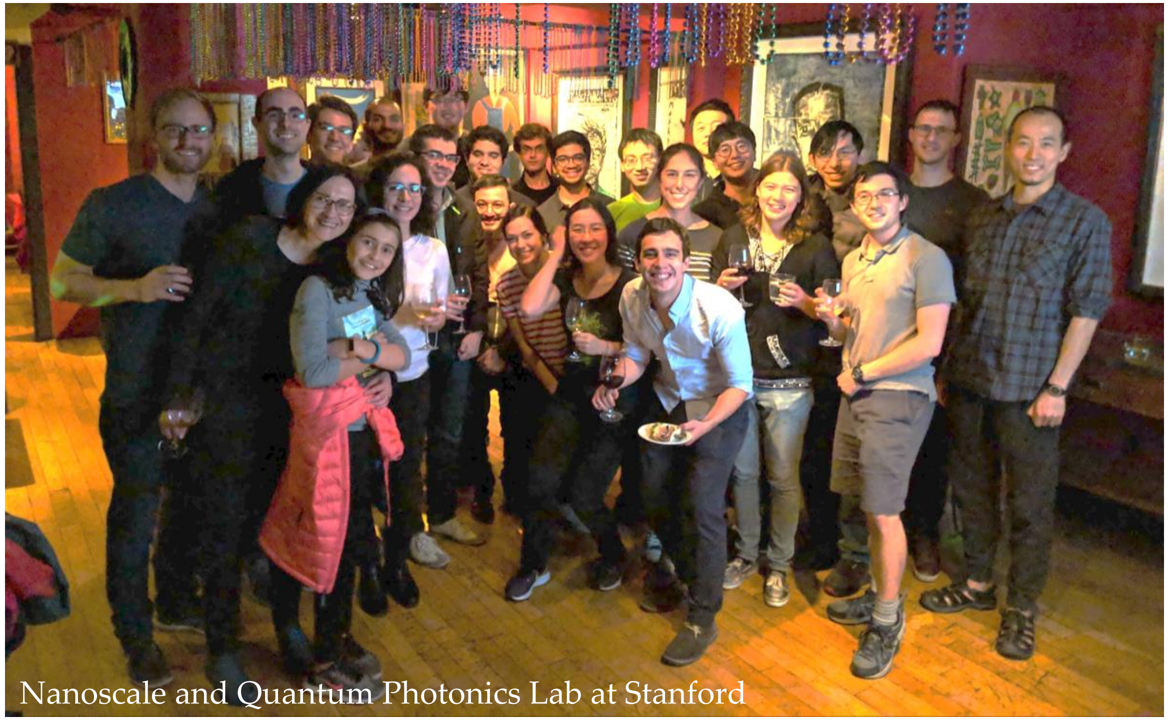
Jelena Vučković


Melissa Guidry


Joshua Yang


Kiyoul Yang


Sattwik Deb Mishra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Stanford University

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