Leveraging Silicon Carbide Defects to Build Quantum Information Hardware

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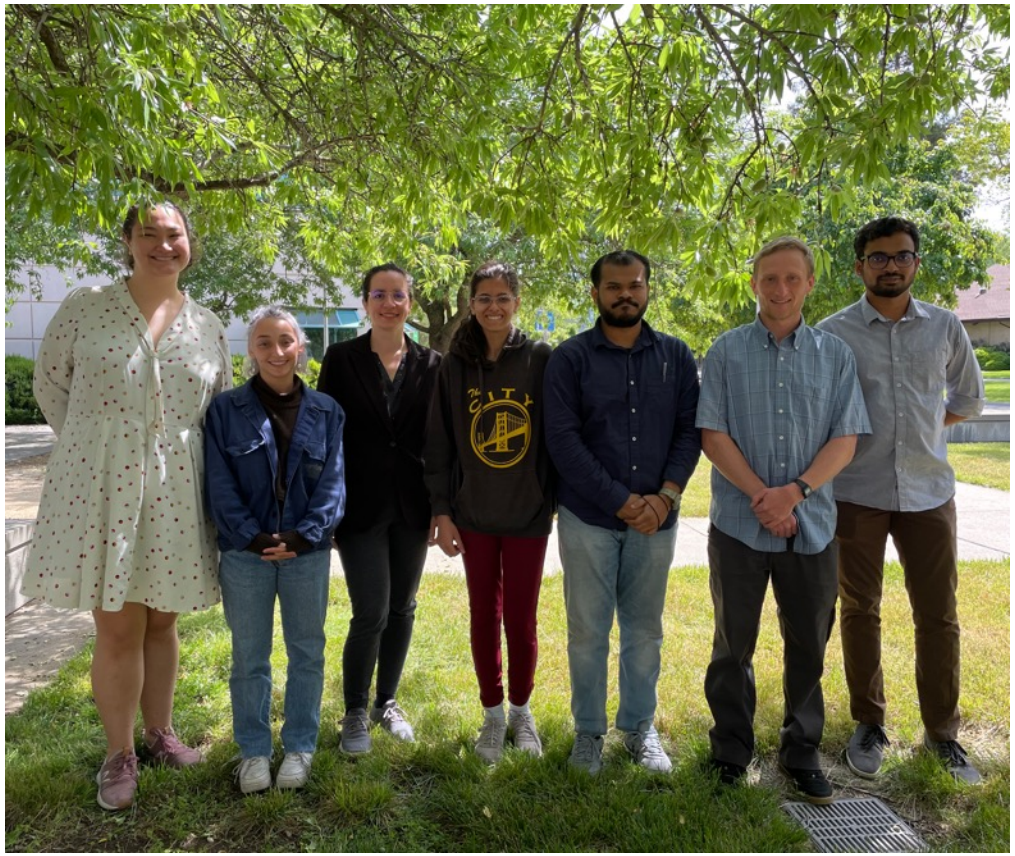


Victoria Norman, Eliana Mann, M.R., Brinda Puri, Pranta Saha, Tristan Adams, Sridhar Majety

Stanford University
Jelena Vuckovic

Stuttgart University
Jörg Wrachtrup
Florian Kaiser

Linkoping University
Nguyen Tien Son
Jawad Ul-Hassan

QST Japan
Takeshi Ohshima

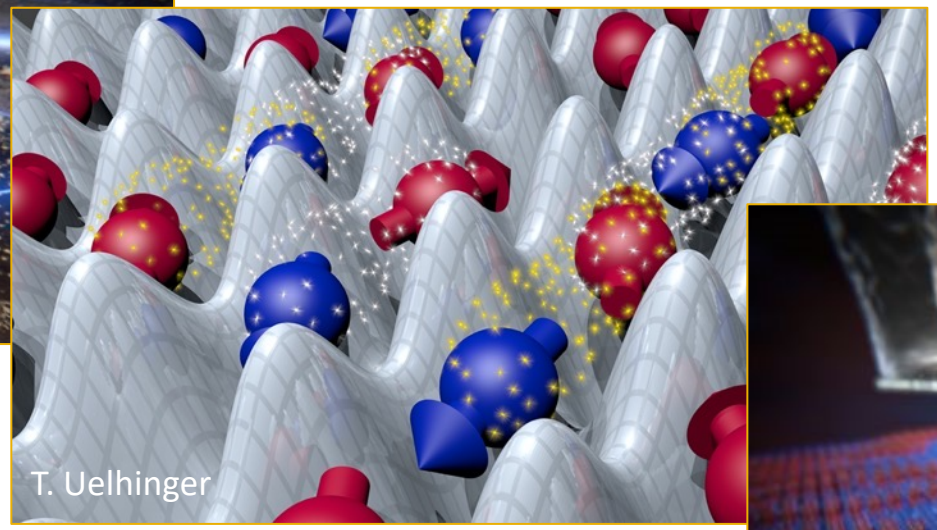
TU Munich
Kai Müller

UC Davis
Richard Scalettar

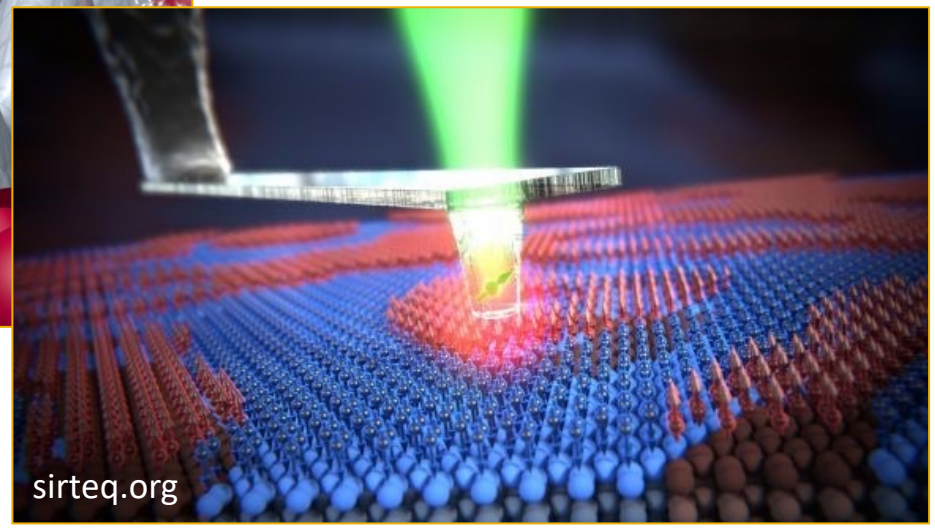
ETH Zurich
Marina Krstic Marinkovic

Quantum information technologies

Quantum Internet



Quantum Simulation & Computing



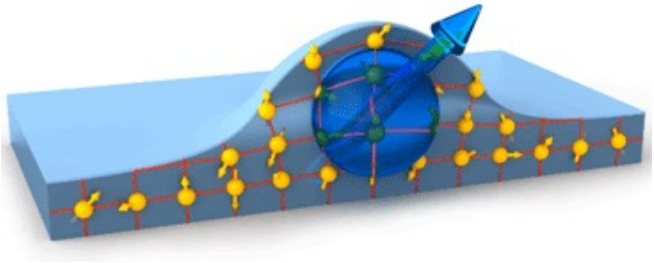
Quantum Sensing

J. H. Kimble, *Nature* 453.7198, 1023-1030 (2008)
V. A. Norman, S. Majety, Z. Wang, W. H. Casey, N. Curro, **M. R.**, *InfoMat*, 1- 24 (2020)

Solid state quantum emitters

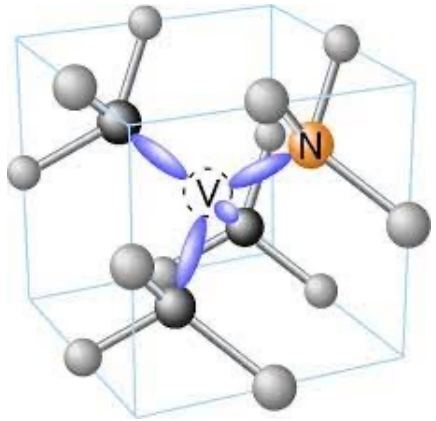
Quantum Dots

+ bright, strong cavity coupling
- inhomogeneous



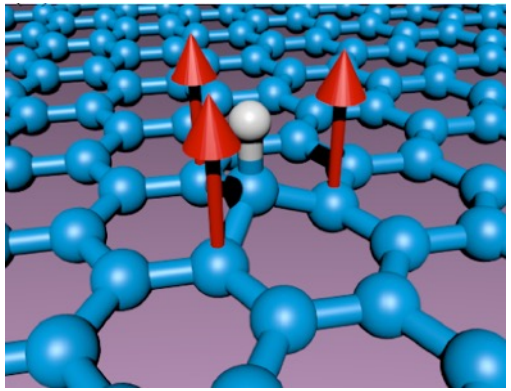
Color Centers in Bulk

+ homogeneous, long coherence
- weak cavity coupling



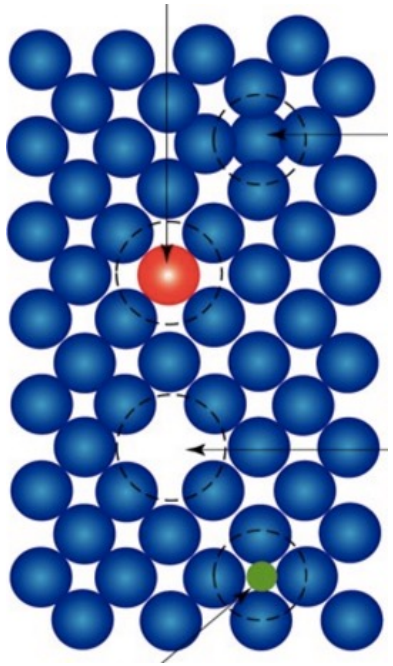
Emitters in 2D Materials

+ compact
- inhomogeneous, weak coupling

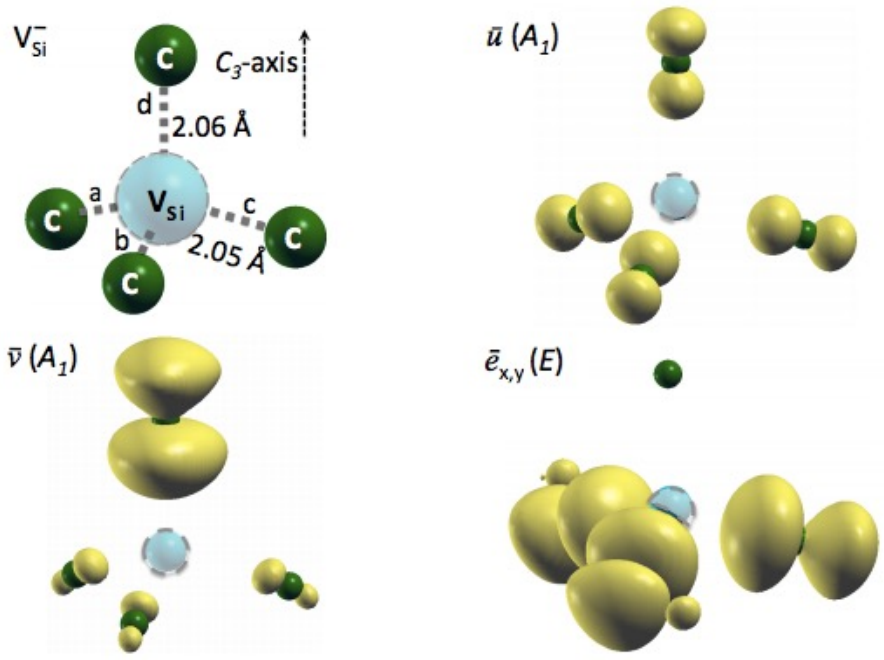


Color centers

Lattice point defects



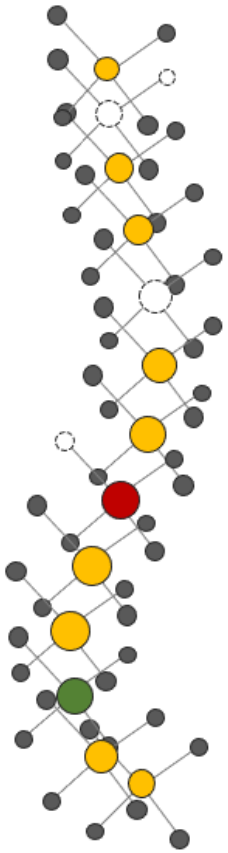
Localized electronic orbitals



V_{Si}^- in 4H-SiC

O.O. Soykal, et al., *Phys. Rev. B* **93**, 081207(R) (2016)

Quantum Technology Backbone



Quantum Internet

- Single-photon emission for QKD
- Indistinguishable photon emission for entanglement distribution
- Spin-photon entanglement and long spin coherence for quantum repeaters

Quantum Computing

- Cluster entangled state generation for the measurement-based quantum computing

Quantum Simulation

- Emitter-cavity systems simulating condensed matter physics

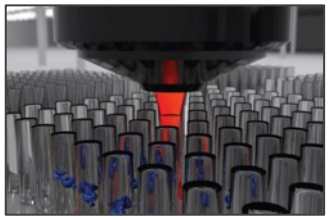
Quantum Sensing

- ODMR for magnetometry and thermometry

INTEGRATED PHOTONIC BOOST

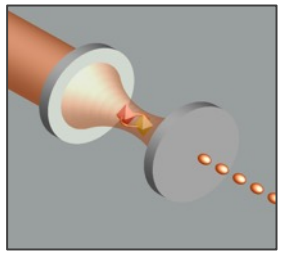
Passive photonics

- Nanopillars
- Waveguides



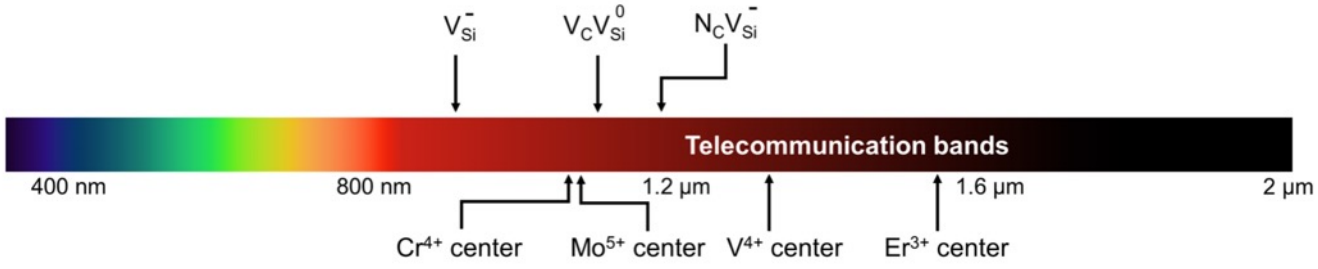
Active photonics

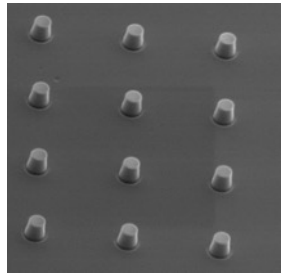
- Nanocavities
- Coupled cavity arrays



NIR emission

Majety *et al.,* arXiv:2111.00136

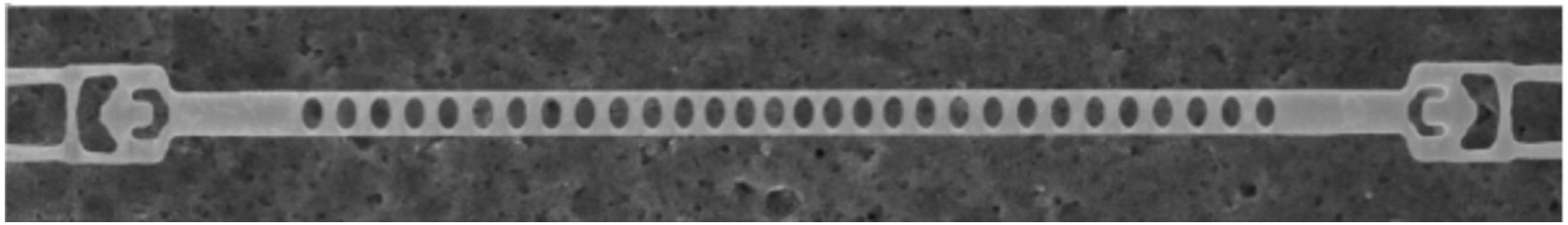




MOLECULAR FOUNDRY

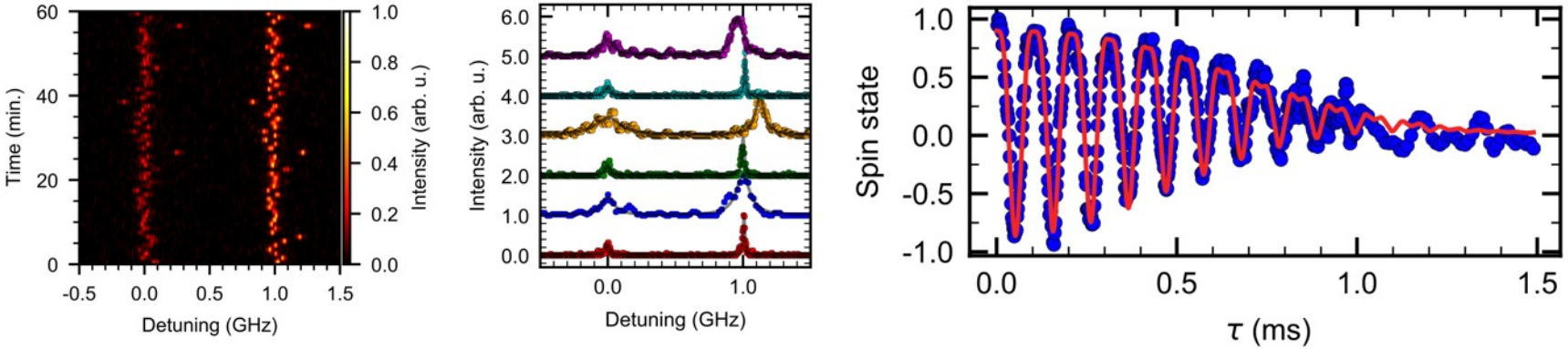
Inversely designed devices

Lukin *et al., Nature Photonics* (2020)



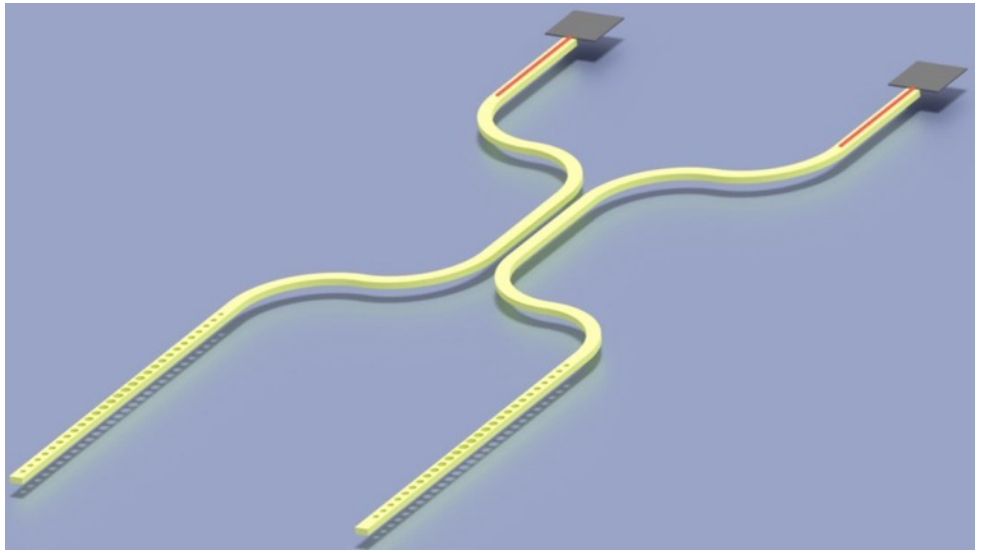
Integration preserves properties

Babin *et al. Nature Materials* (2022)

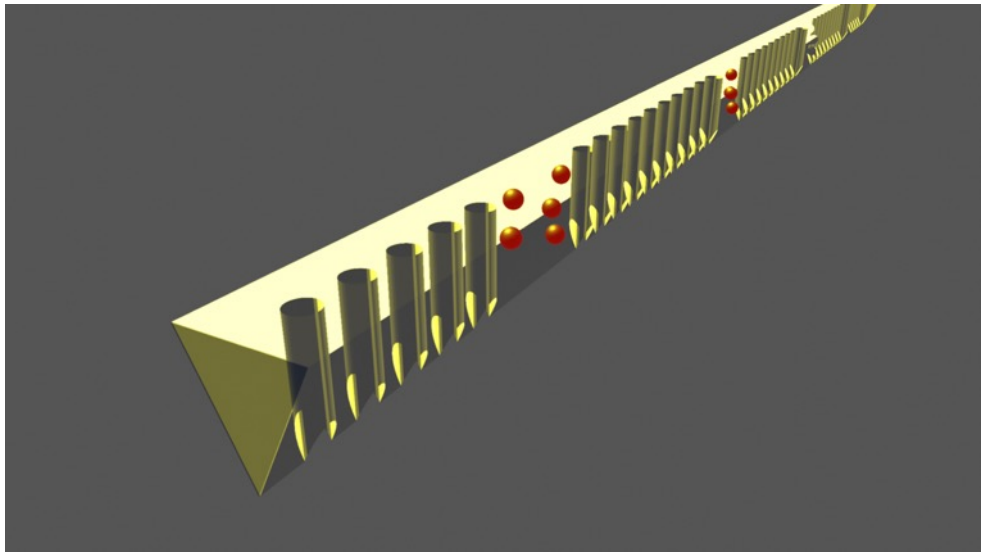


Integrated Quantum Photonics in Silicon Carbide

Hong-Ou-Mandel interferometer on chip



Coupled cavity arrays with color center ensembles



S. Majety, P. Saha, V. A. Norman, **M. R.**, *Journal of Applied Physics* **131**, 130901 (2022)

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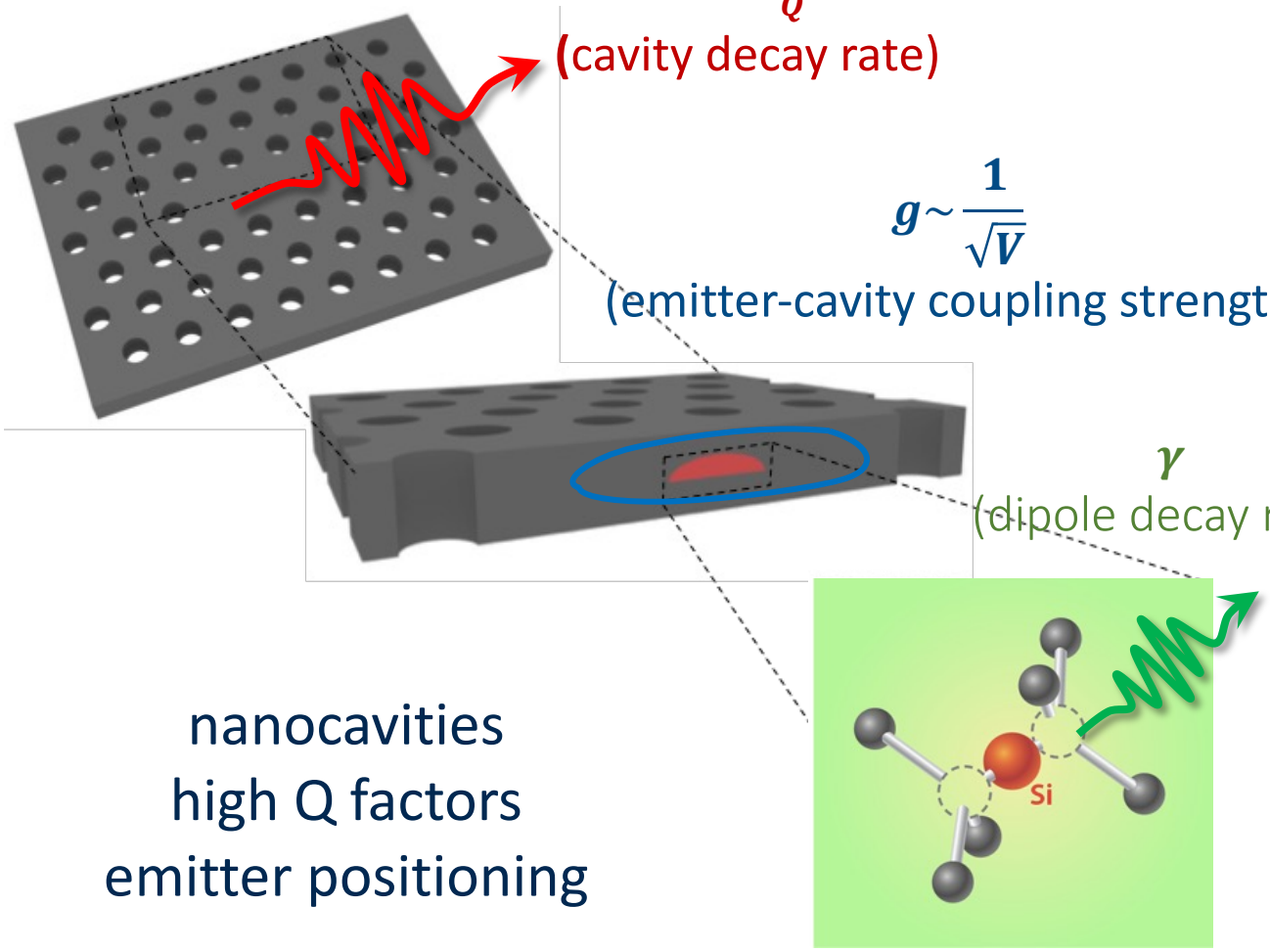
Emitter-cavity interaction

$\kappa = \frac{\omega}{Q}$

(cavity decay rate)



$g \sim \frac{1}{\sqrt{V}}$

(emitter-cavity coupling strength)

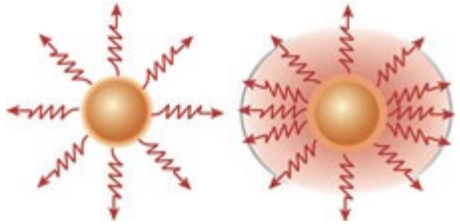
γ

(dipole decay rate)

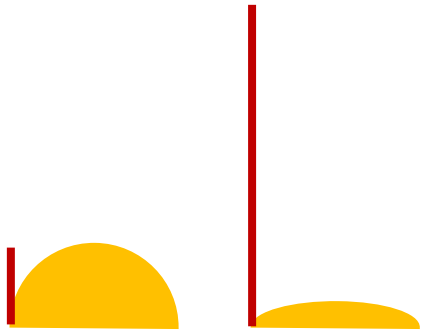
nanocavities
high Q factors
emitter positioning

Weak coupling regime: $g < \frac{\kappa}{2}$

Purcell enhancement of the emission rate



$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda_c}{n}\right)^3\left(\frac{Q}{V}\right)$$

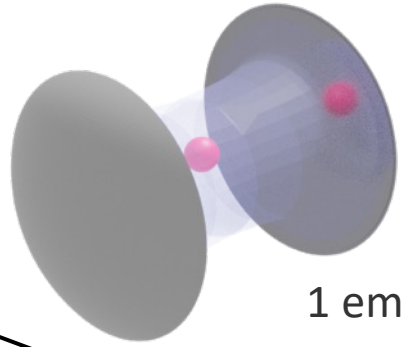


ZPL enhancement

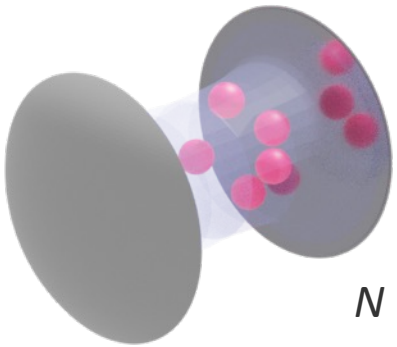
Strong coupling regime: $g > \frac{\kappa}{2}, \frac{\gamma}{2}$

Polariton – hybridized light-matter state

$$\frac{|\text{light}\rangle + e^{i\varphi}|\text{matter}\rangle}{\sqrt{2}}$$

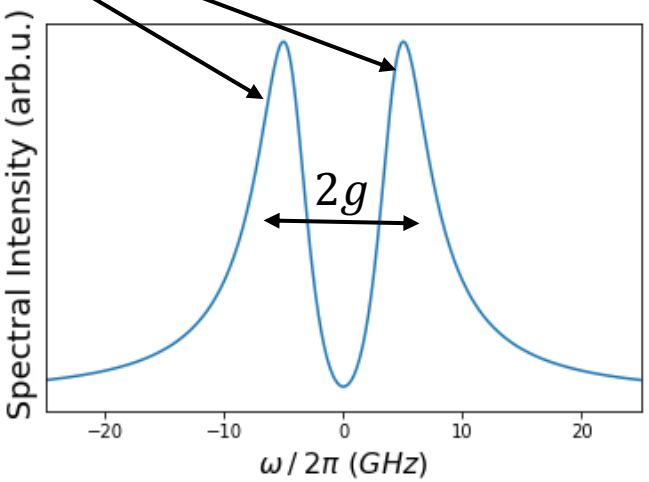


1 emitter

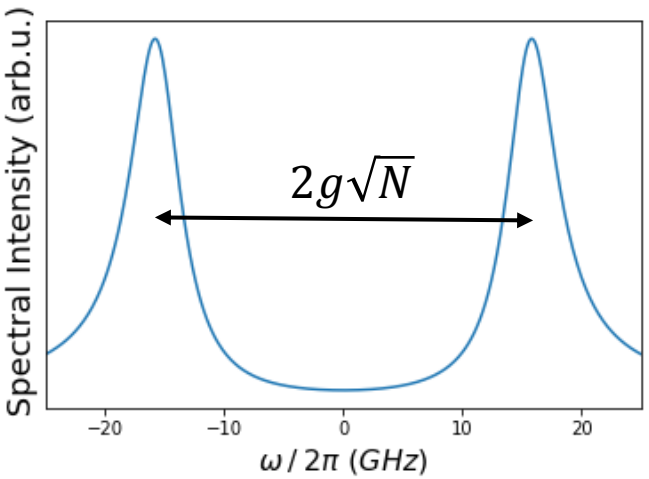


N emitters

$$g > \frac{\kappa}{2}, \frac{\gamma}{2}$$



Jaynes-Cummings model



Tavis-Cummings model

$$g\sqrt{N} > \frac{\kappa}{2}, \frac{\gamma}{2}$$

$$g\sqrt{N} \gtrsim \Delta$$

inhomogeneous broadening (mainly strain)

M.R., K. Fischer, J. Vuckovic, *AAMOP 66, 3* (2017), **M.R.** *et al.*, *PRA* 96, 011801(R) (2017)
R. Trivedi, **M. R.**, K. Fischer, J. Vuckovic, *PRL* 122, 243602 (2019)

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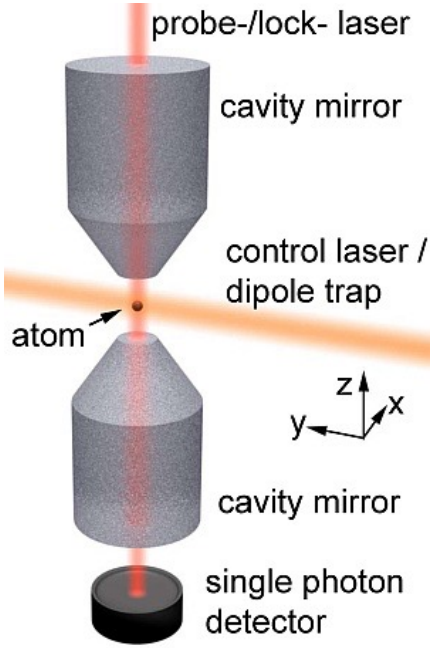
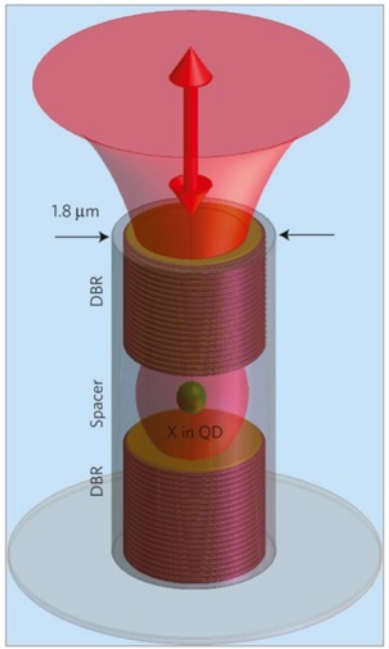
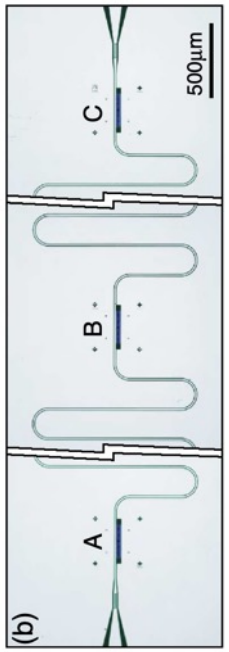
Jaynes-Cummings and Tavis-Cummings experiments

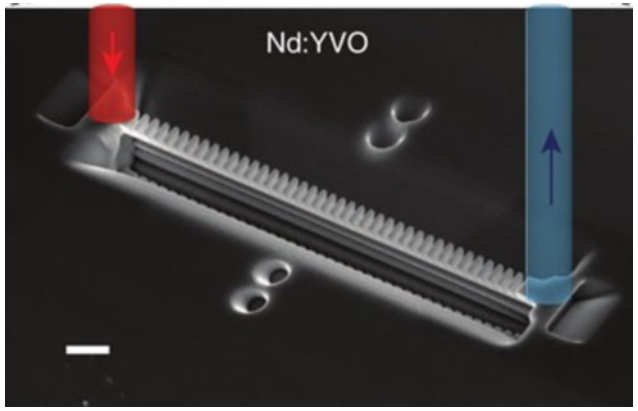
N = 1 emitter in cavity

N > 1 emitter in cavity









Single atom

Quantum dot

Superconducting circuit

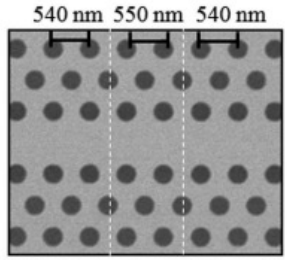
Rare-earth doped crystal

Image credit: http://quantum-technologies.iap.uni-bonn.de/, *Nature Materials* **9**, 304–308 (2010)
PRL **103**, 083601 (2009), *Nature Communications* **8**, 14107 (2017)

Active photonics in silicon carbide

6H-SiC, smart-cut

Noda

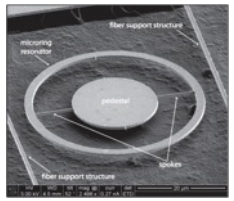


SiC photonic crystal cavity

Q ~ 10,000

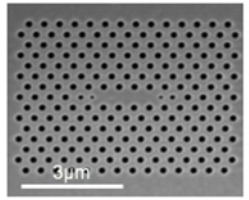
3C-SiC on Si

Lipson

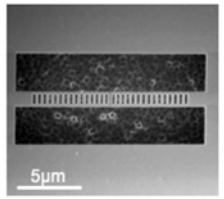


Q ~ 14,000

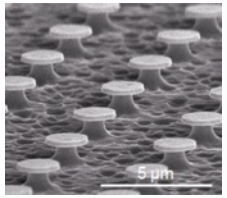
Vuckovic



Q ~ 800

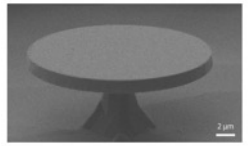


Q ~ 1,500



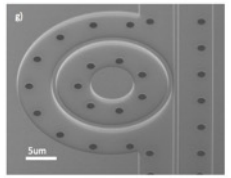
Q ~ 2,500

Lin



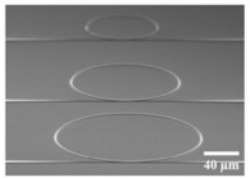
Q ~ 51,000

Politi



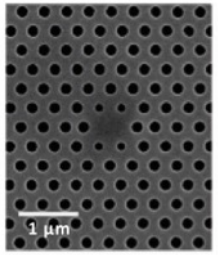
Q ~ 24,000

Adibi



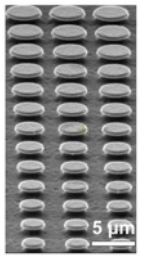
Q ~ 142,000

Awschalom



Q ~ 1,500

Johnson

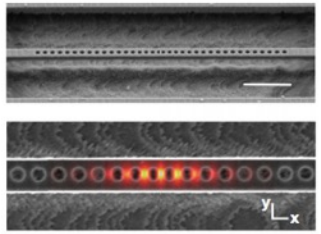


Q ~ 1,900

4H-SiC, variable approaches

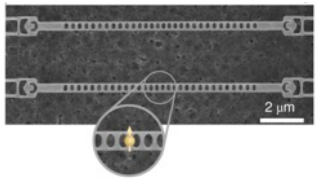
Hu

Q ~ 9,200

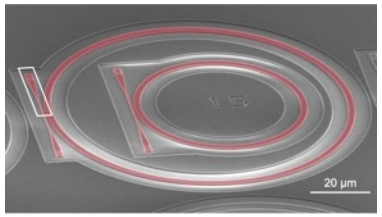


Q ~ 5,300

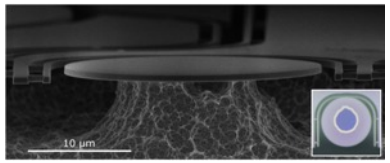
Vuckovic



Q ~ 19,300

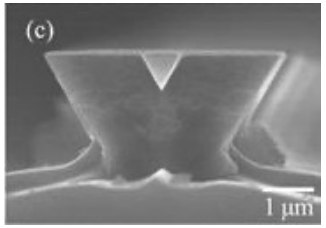


Q ~ 1,100,000



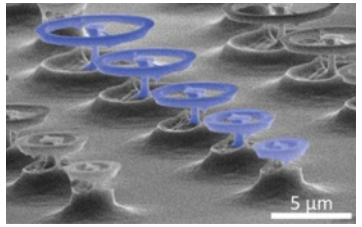
Q ~ 130,000

Noda



Q ~ 40,000

Aharonovich



Q ~ 3,500

***Photonic crystal cavities**

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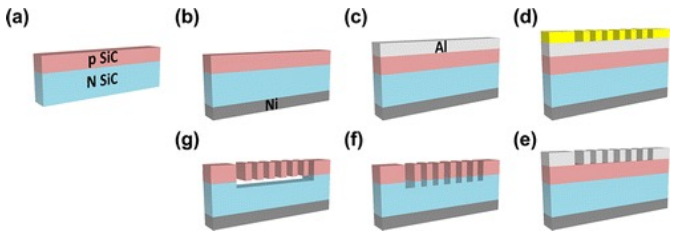
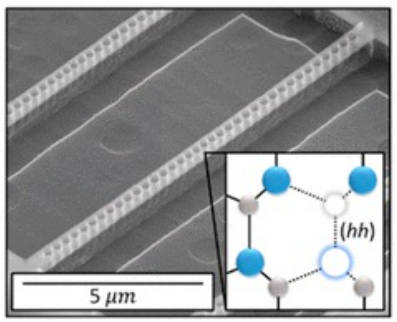
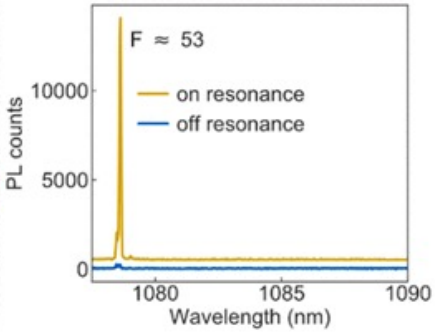
SiC cavity fabrication

Photo-electro-chemical etching

demonstrated coherent control

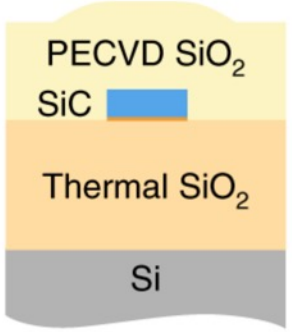


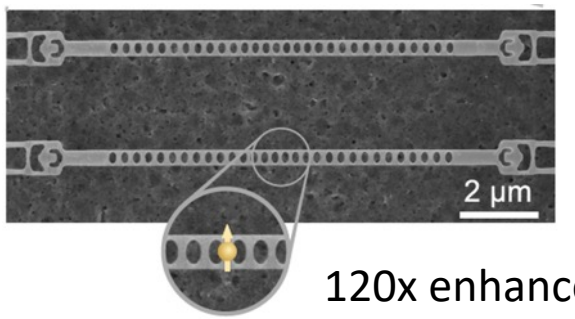




SiC on insulator

record Purcell enhancement

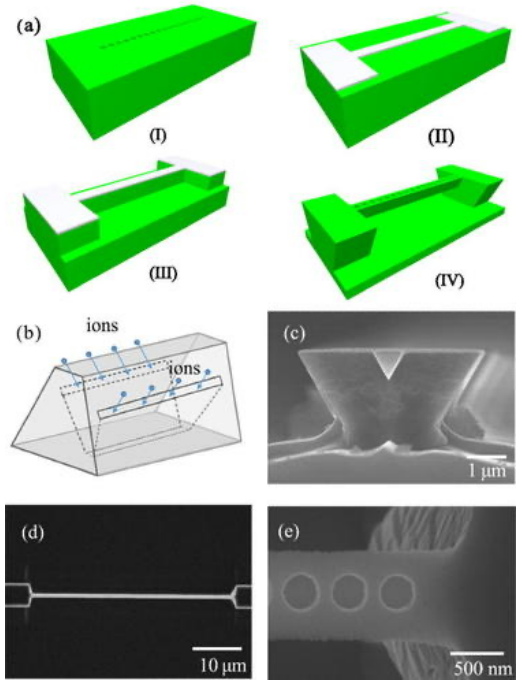




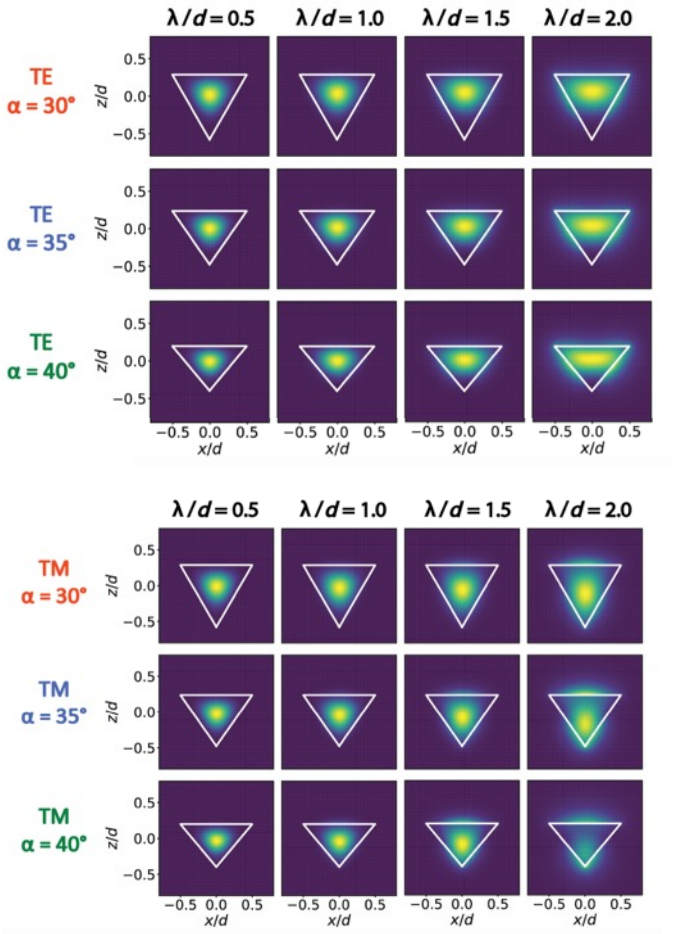
120x enhancement

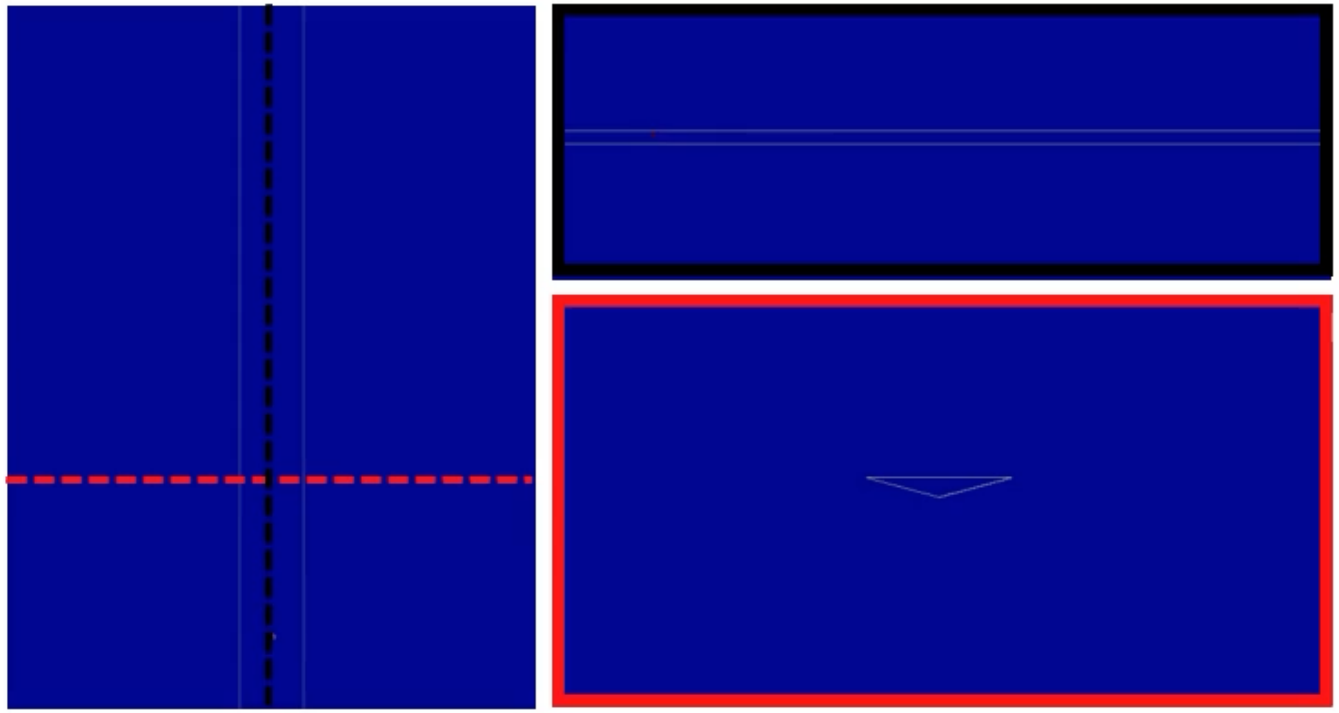
Faraday cage etching

arbitrary samples, scalable

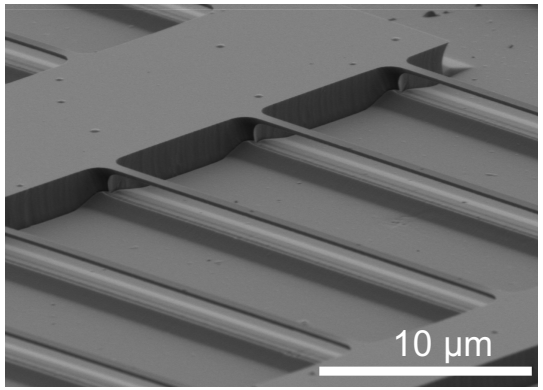


Triangular SiC waveguides



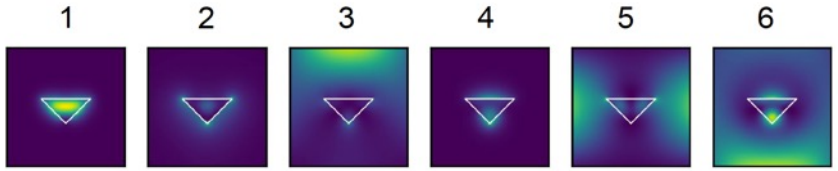


Color centers in SiC triangular photonics

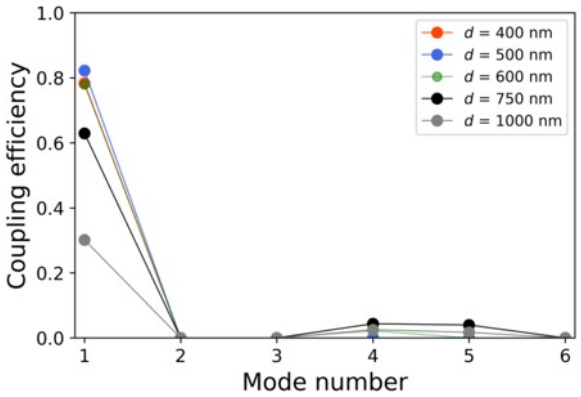


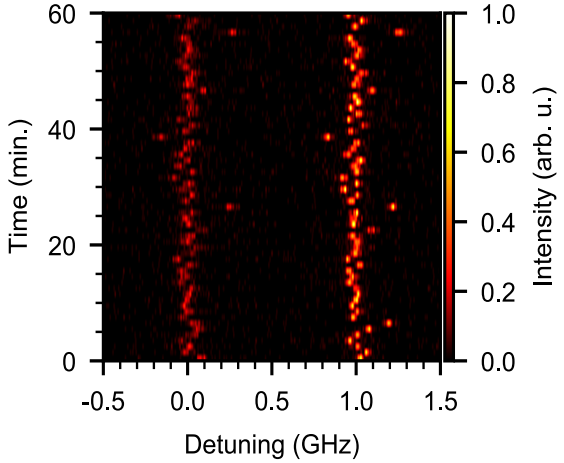
Stable optical emission and nearly-identical V2 emitters in triangular SiC waveguides

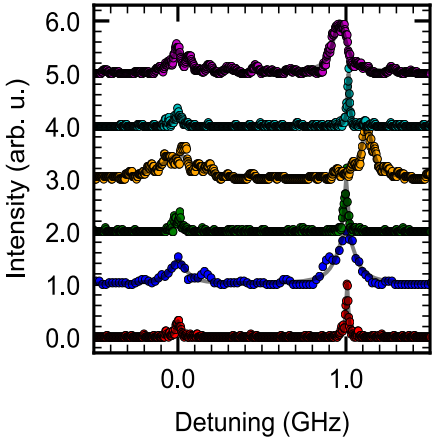
spin $T_2 = 0.84 \pm 0.01$ ms



Single-mode propagation







Collaboration with Astakhov, Son, Ul-Hassan, Kaiser, Wrachtrup groups

C. Babin, et al., *Nature Materials* **21**, 67–73 (2022)

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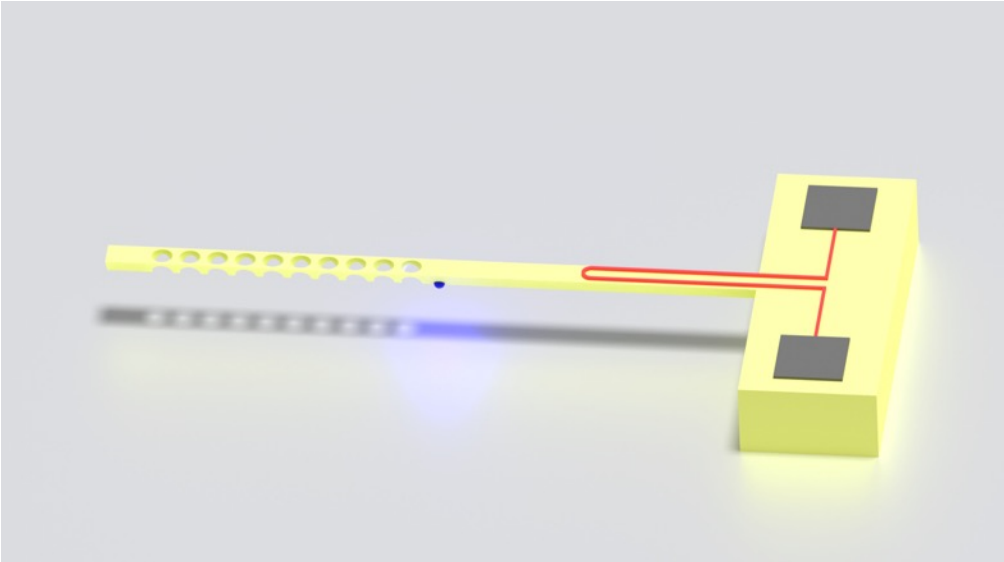
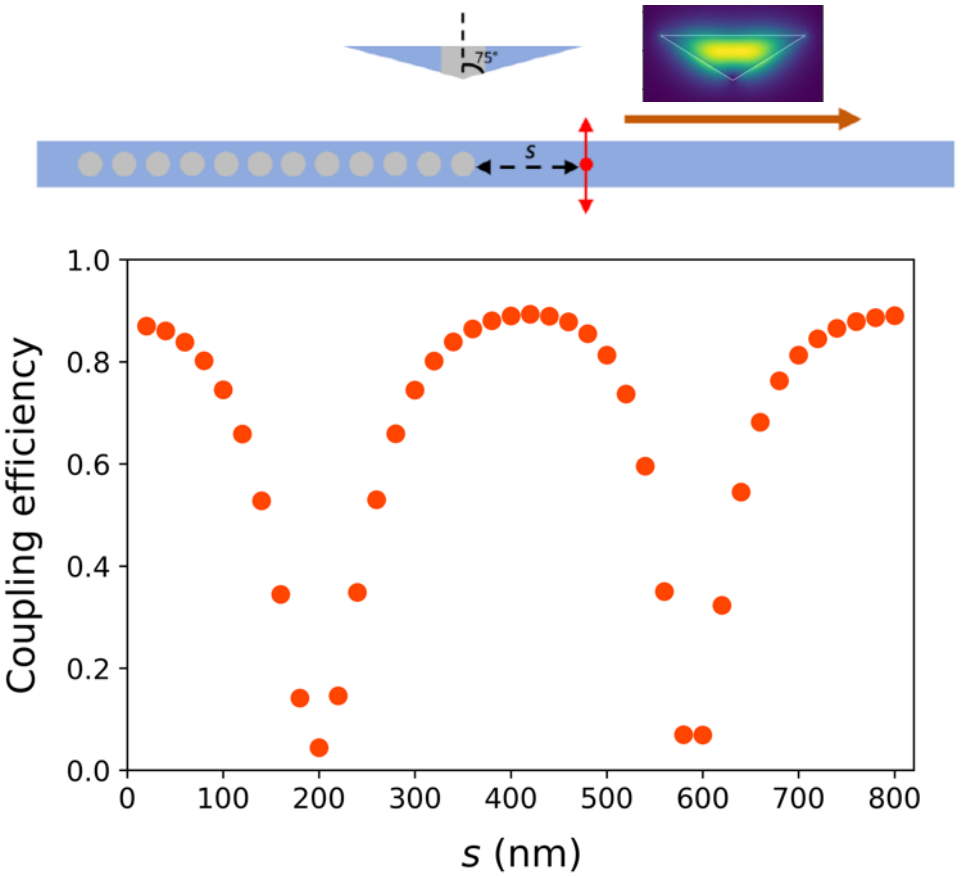
Efficient collection and detection of emission



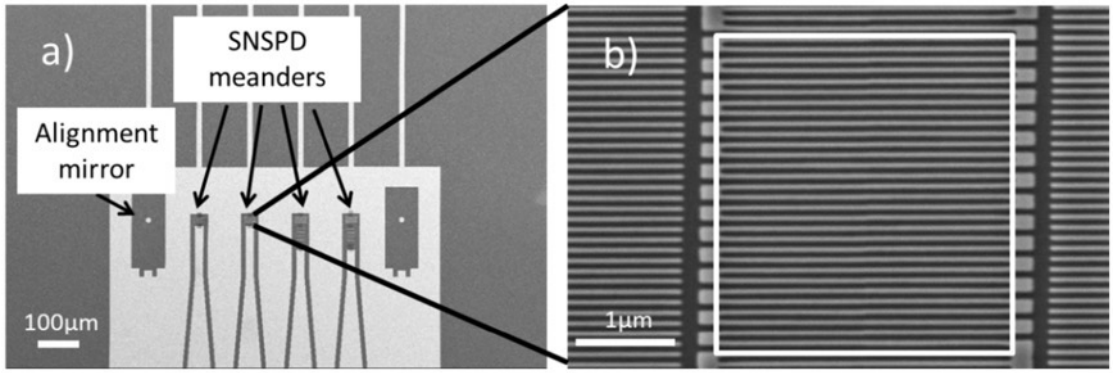
Photonic crystal mirror



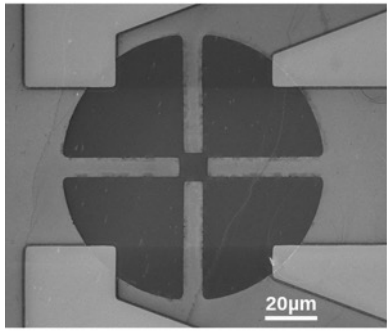
S. Majety, [**M.R.**] *et al.*, *arXiv:2208.05569*

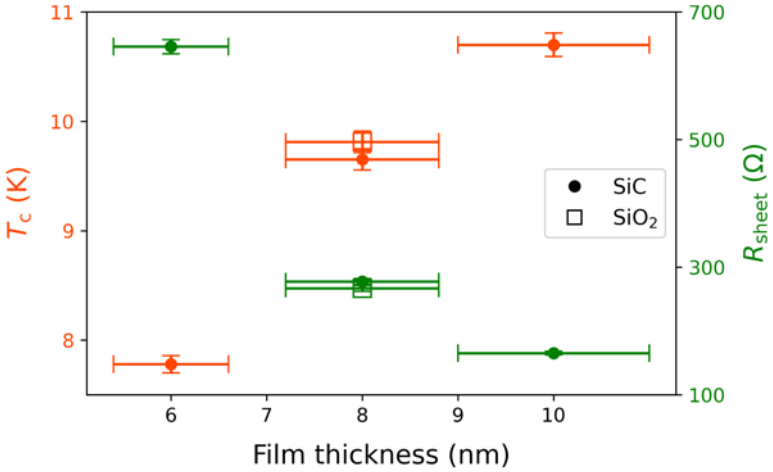
Superconducting detector integration

NbN SNSPD integration with 3C-SiC



NbTiN integration with 4H-SiC





Martini et al., *Opt. Express* 27, 29669-29675 (2019)
Collaboration with Mueller group, S. Majety, [**M.R.**] *et al.*, *arXiv:2208.05569*

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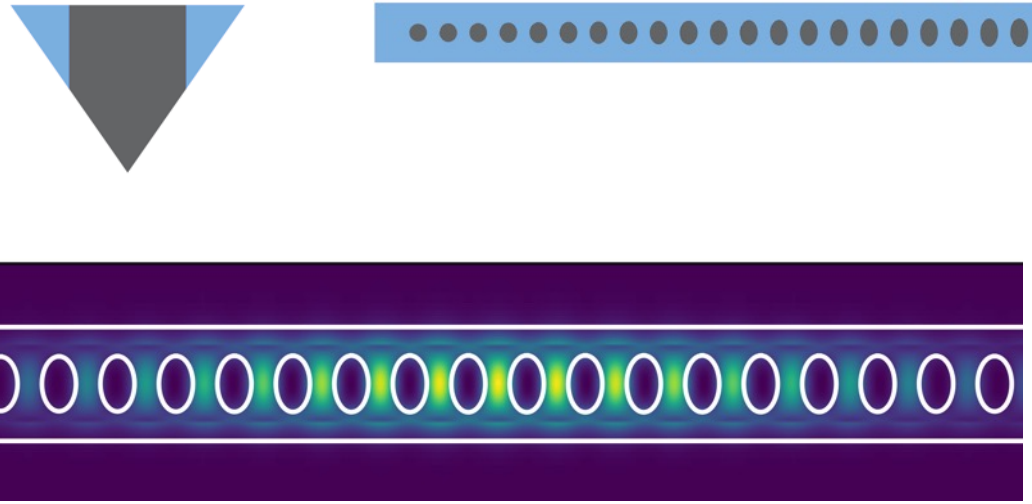
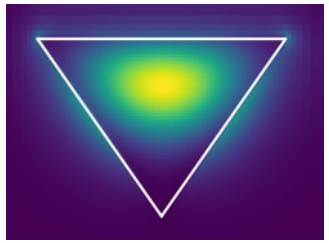
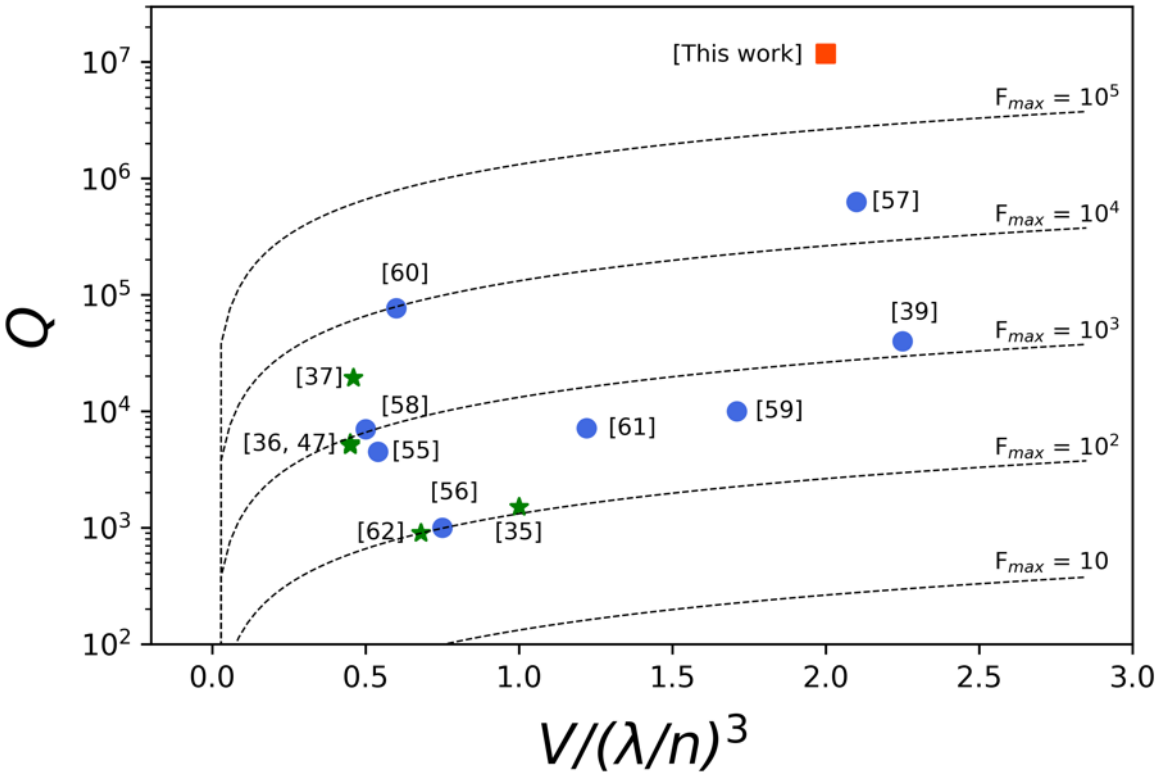
Triangular SiC nanobeam cavities





$$V \sim 2(\lambda/n)^3$$

$$Q \sim 10^7$$



S. Majety, V. A. Norman, L. Li, M. Bell, **M. R.**, *J. Phys. Photonics* **3**, 034008 (2021)

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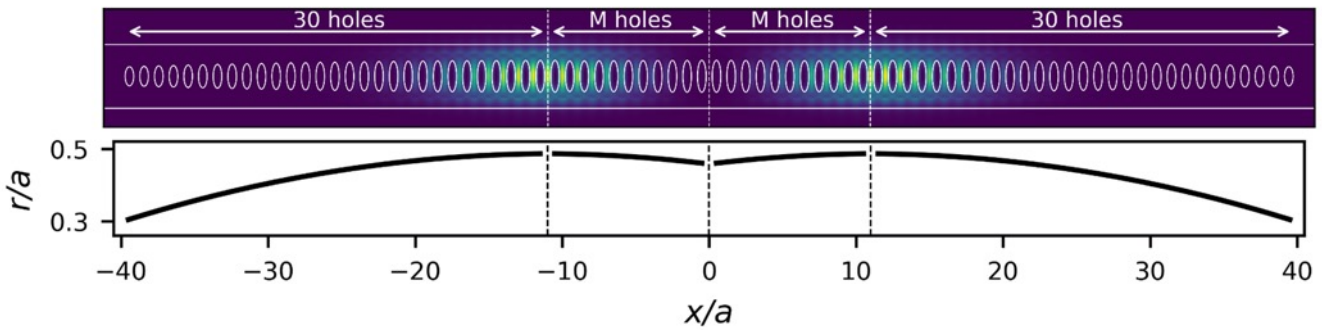
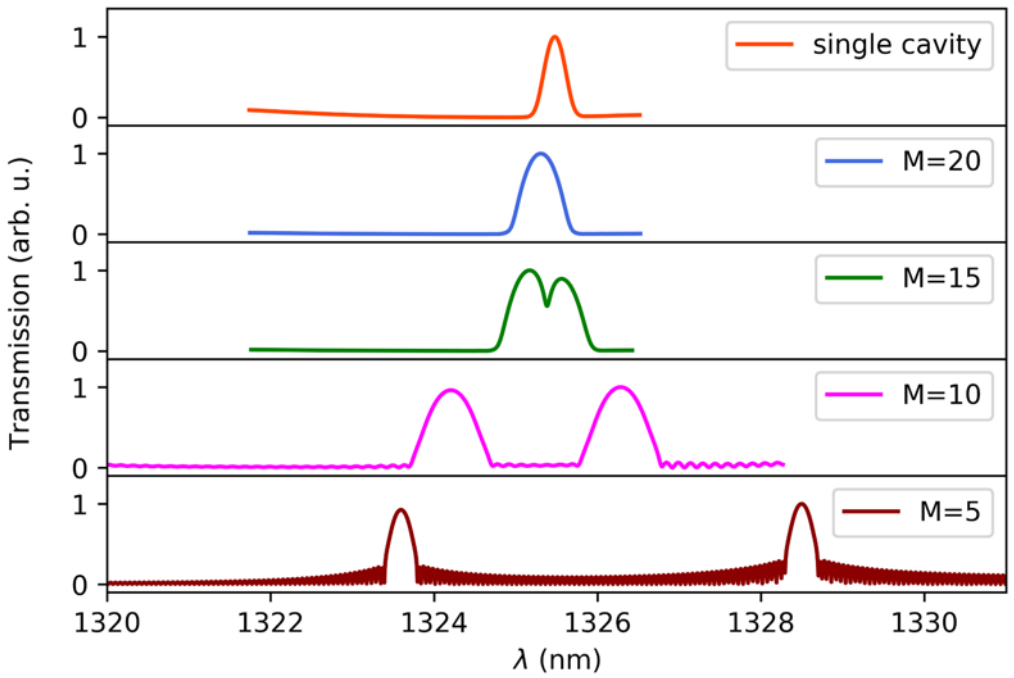
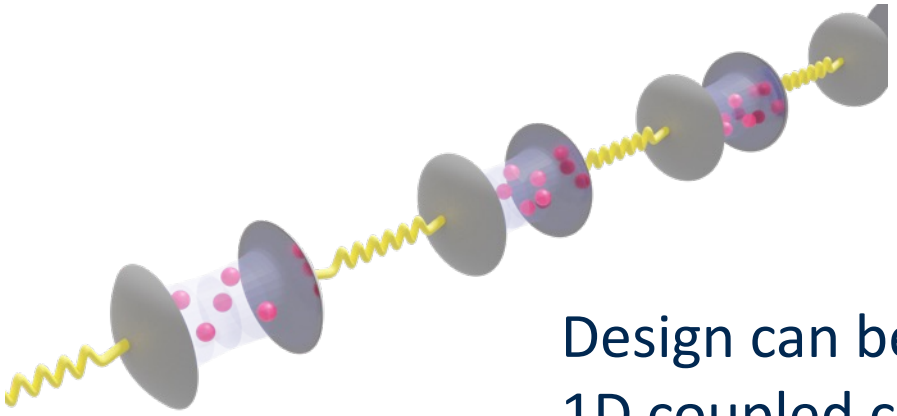
Dual SiC cavities – photonic molecule







Design can be expanded into a large
1D coupled cavity array (CCA) **with emitters**

S. Majety, V. A. Norman, L. Li, M. Bell, **M. R.**, *J. Phys. Photonics* **3**, 034008 (2021)

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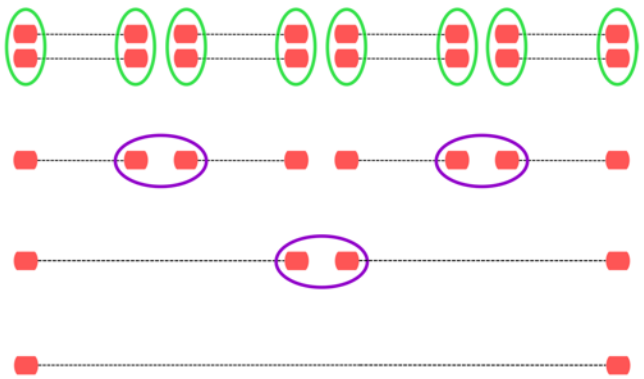
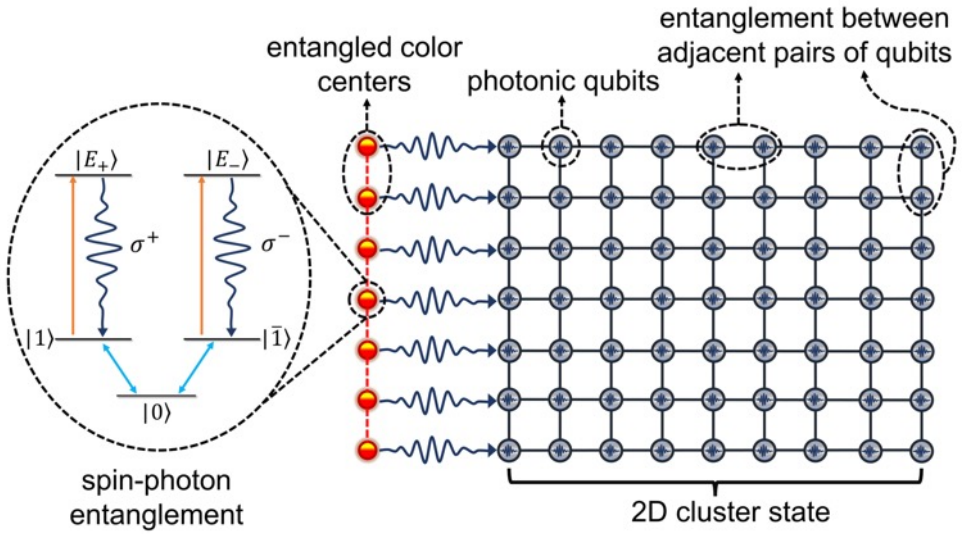
Applications of triangular SiC cavities

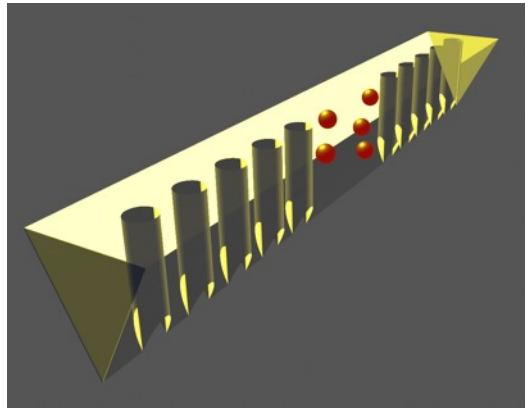
Quantum repeaters



Cluster entangled state generation



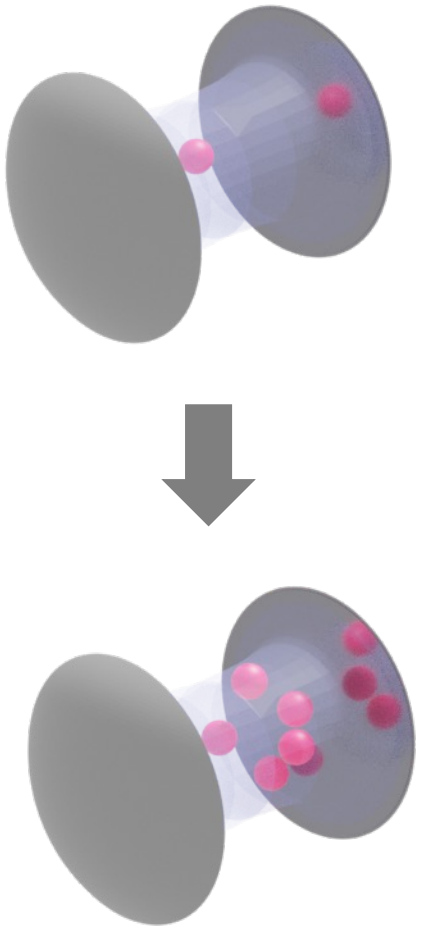
Quantum light generation



S. Majety, P. Saha, V. A. Norman, **M. R.**, arXiv:2111.00136 (2022)

N atoms in a cavity

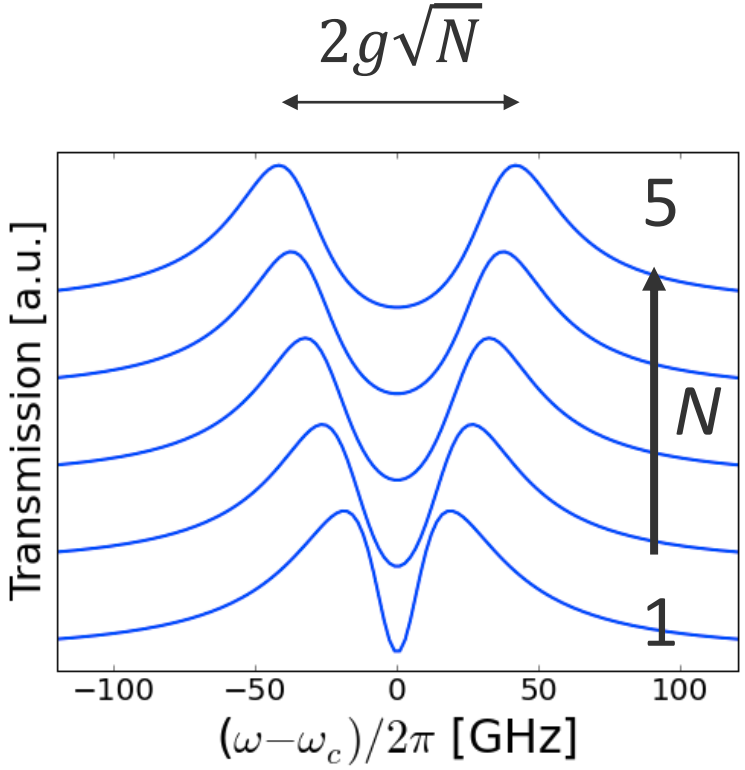
$$H_{TC} = \omega_c a^\dagger a + \sum_{n=1}^{N} \left[\omega_{e,n}\sigma_n^+\sigma_n^- + g_n(\sigma_n^+ a + a^\dagger \sigma_n^-)\right]$$



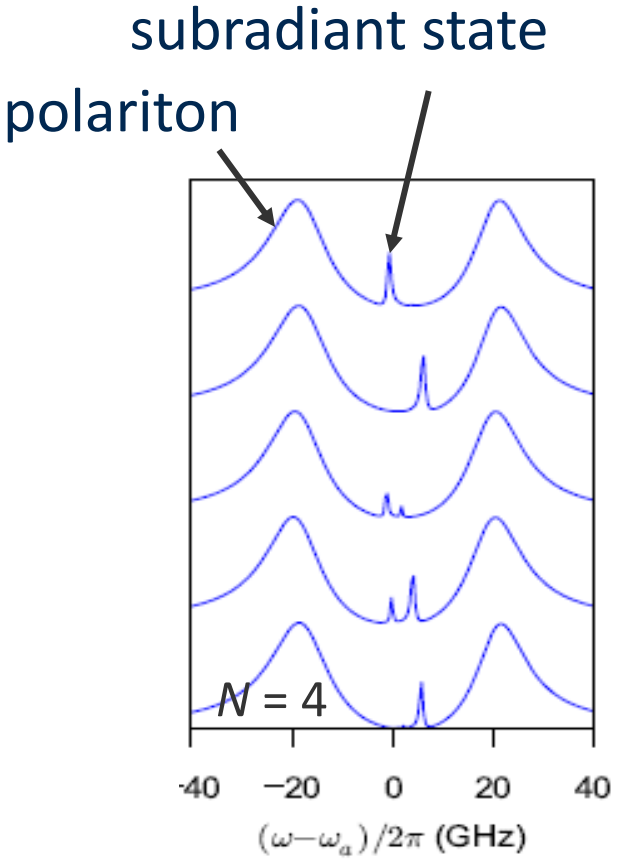
N atoms

$g_n = g$

$\boldsymbol{g_N = g\sqrt{N}}$

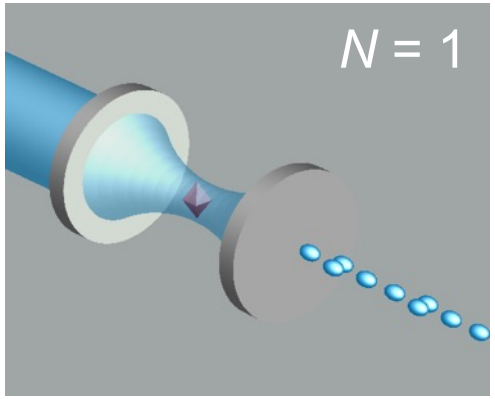


interaction strength increases with $\sqrt{\boldsymbol{N}}$

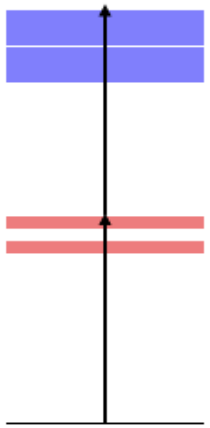


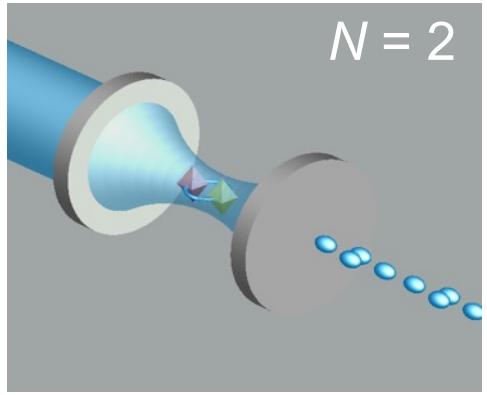
Tavis-Cummings model & inhomogeneous broadening

Photon Blockade (PB) in multi-emitter-cavity systems

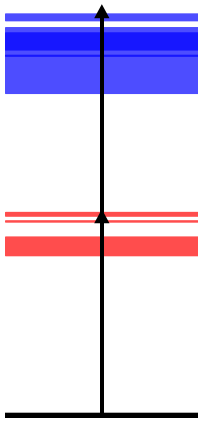


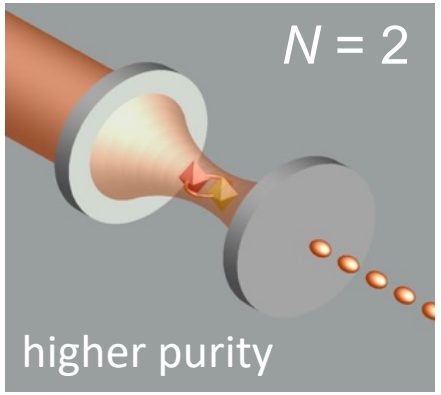
polaritonic PB



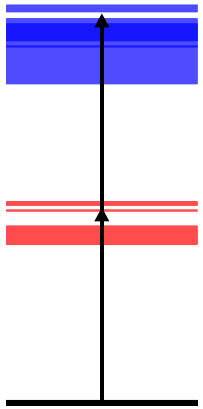


polaritonic PB





subradiant PB



M.R., K. Fischer, J.L. Zhang, K. Lagoudakis, J. Vuckovic, *Phys. Rev. A* 96, 011801(R) (2017)
R. Trivedi, **M. R.**, K. Fischer, J. Vuckovic, *Phys. Rev. Lett.* **122**, 243602 (2019)

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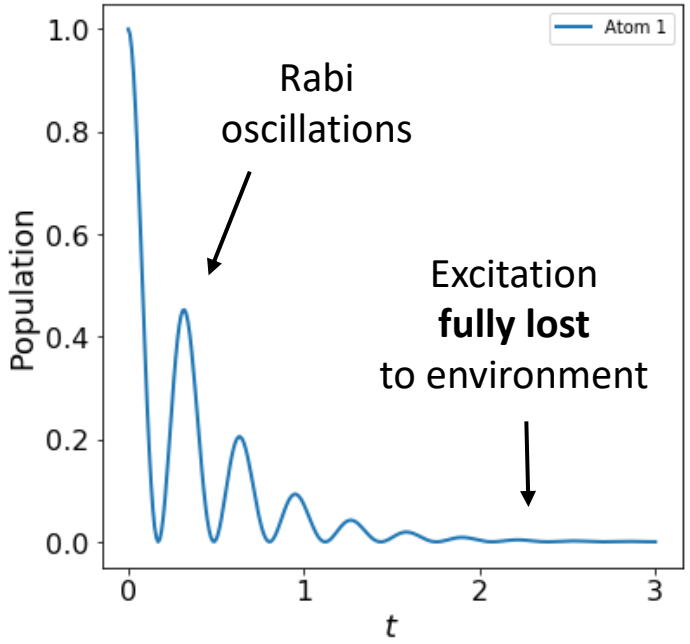
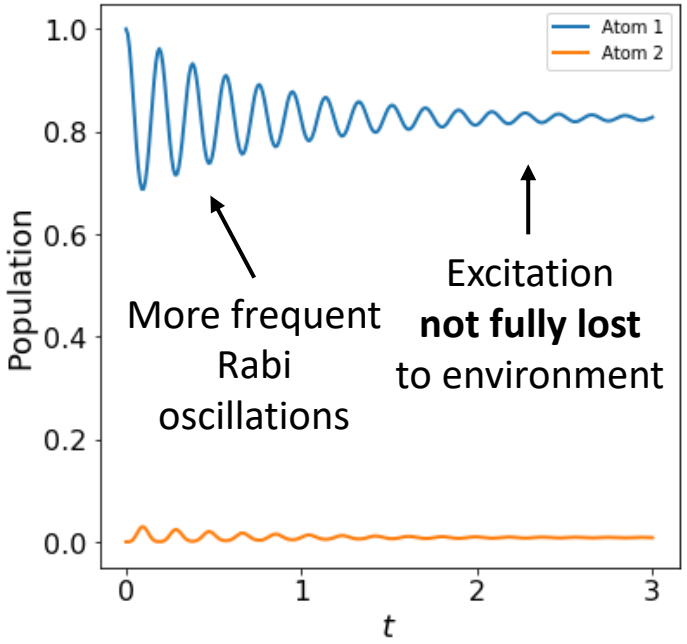
Excited atom time evolution in a lossy cavity

$N = 1$
Jaynes-Cummings model



$N = 11$
Tavis-Cummings model

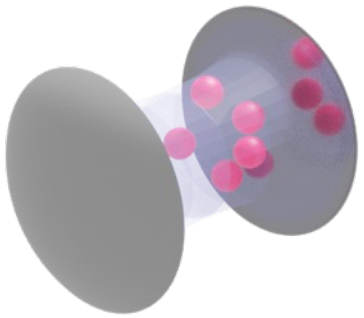


Open Quantum System Tavis-Cummings Dynamics

Exact approach

- Quantum Master Equation – **exponential** memory and runtime scaling

Atom / a two-level system / qubit

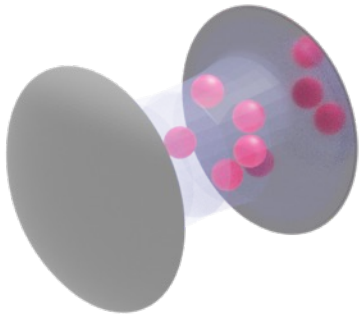


1 excitation

$$c_1|100\ldots0\rangle + c_2|010\ldots0\rangle + c_3|001\ldots0\rangle + \cdots + c_N|000\ldots1\rangle$$

How do the atomic amplitudes evolve in a lossy cavity?

Quantum mapping of the Tavis-Cummings dynamics

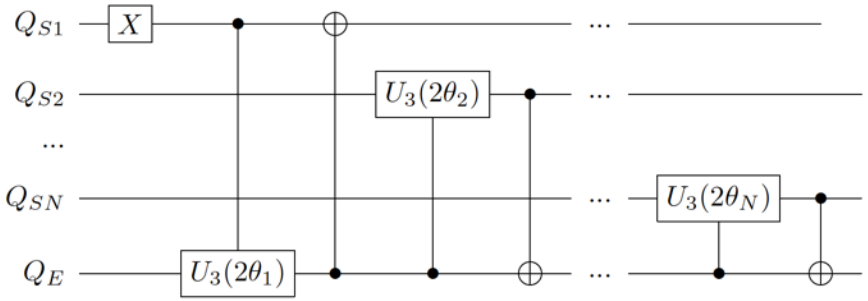


Hamiltonian + interaction picture

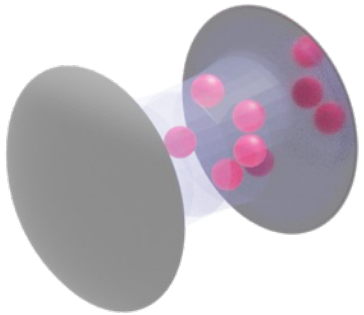
Schrödinger equation + single excitation

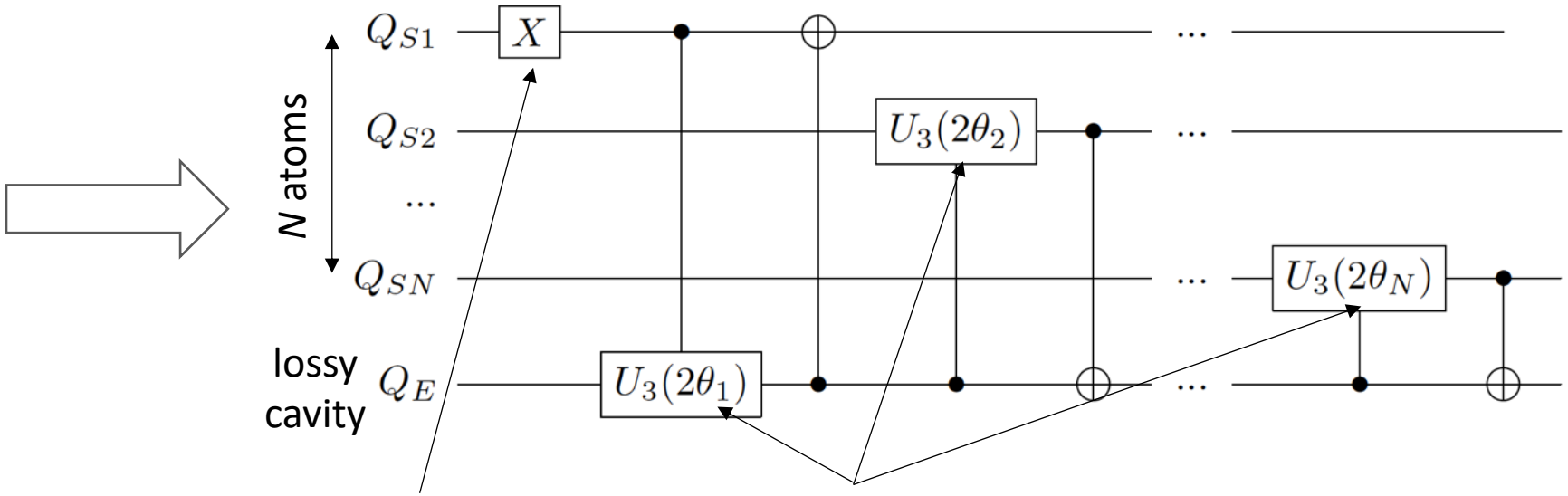
Trace out the environment + Laplace transform

System density matrix + quantum circuit mapping



Quantum Mapping Algorithm of Resonator Interaction with *N* Atoms (Q-MARINA)

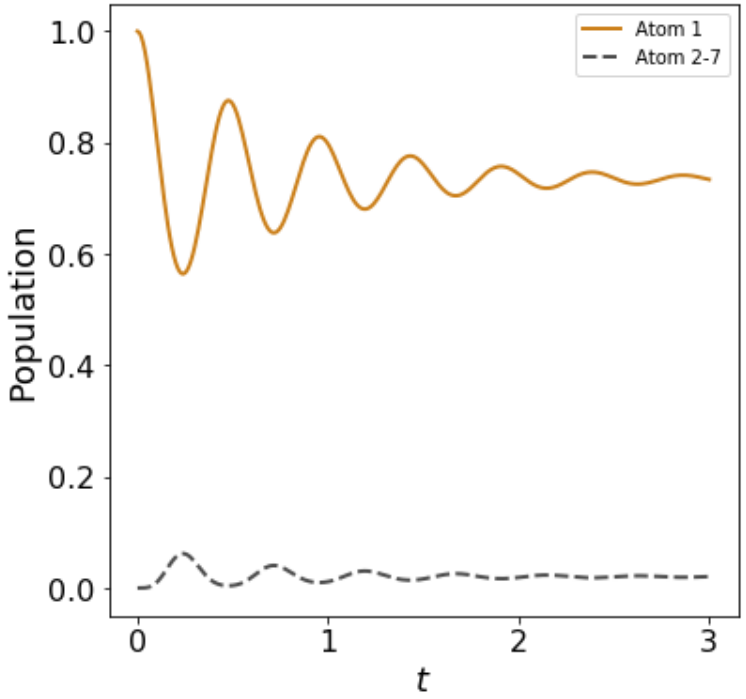




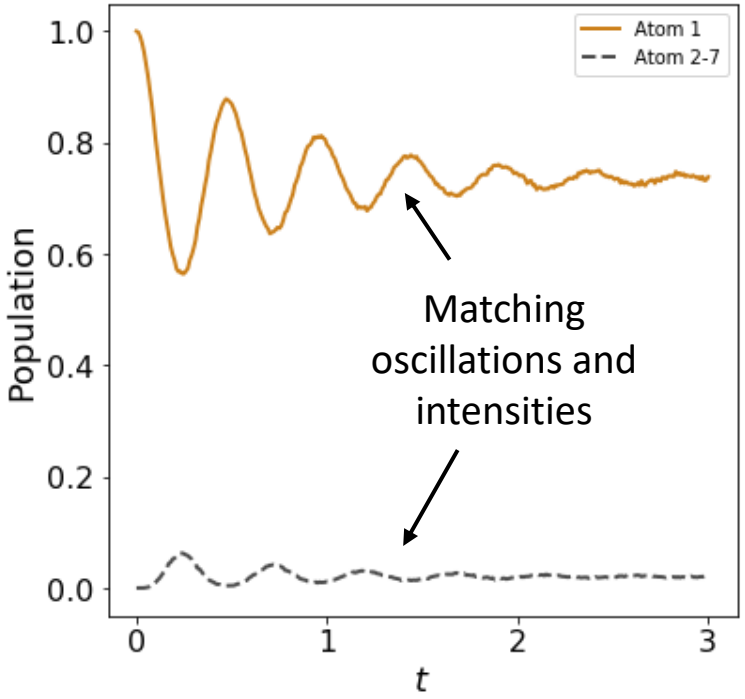
Digital quantum modeling of an analog quantum system – time and space complexity O(*N*)

Tavis-Cummings time evolution for $N = 7$

QuTiP
(exact QME solution)



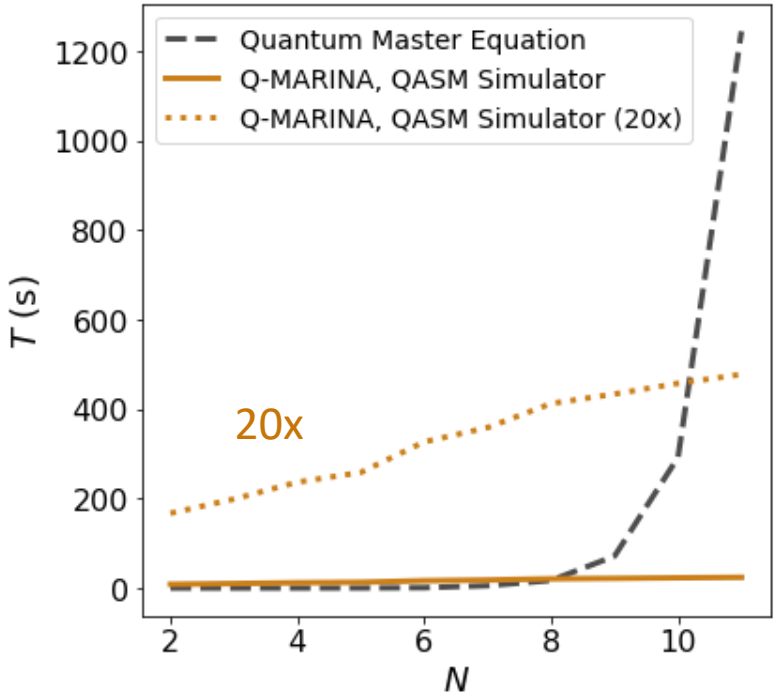
Q-MARINA Qiskit QASM
shots = 40,000



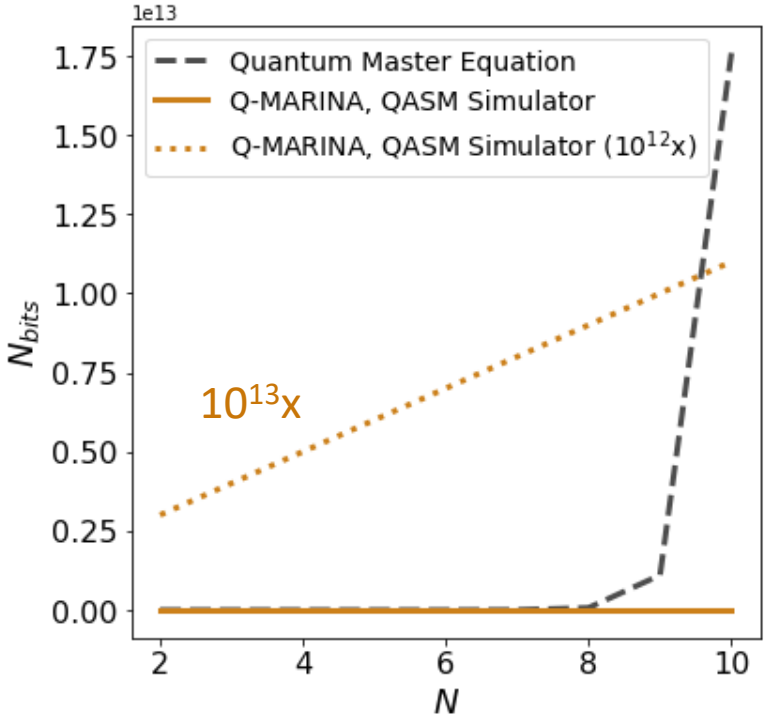
$\kappa = 5, g = 10$

Tavis-Cummings time evolution scaling

exponential QME runtime scaling
linear Q-MARINA runtime scaling



exponential QME memory scaling
linear Q-MARINA memory scaling



M. K. Marinkovic, **M. R.**, arXiv.2208.12029

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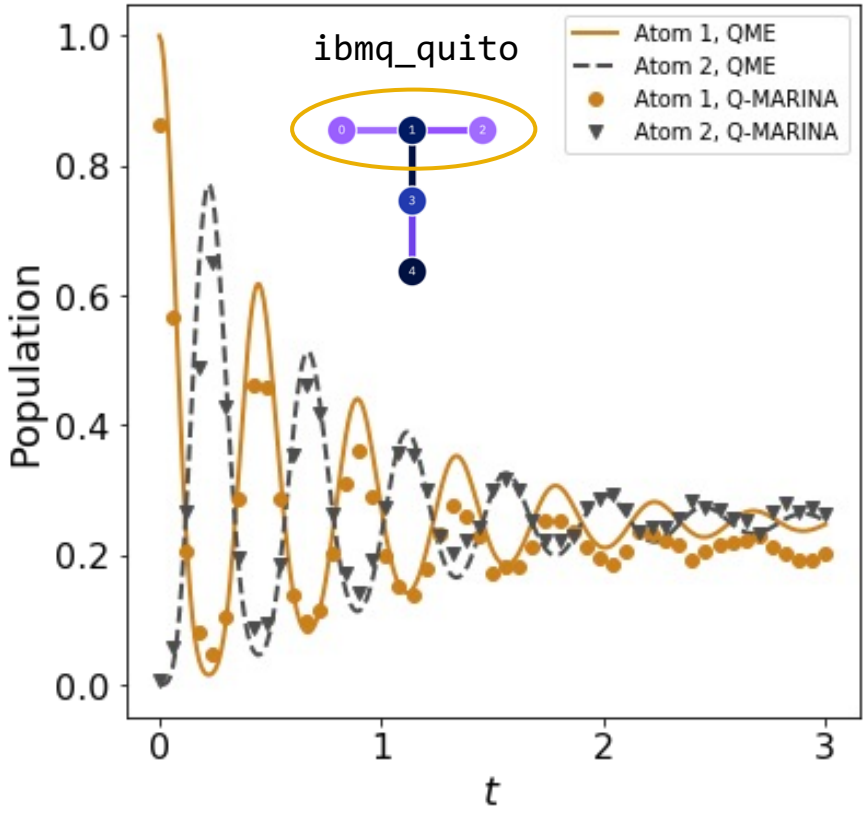
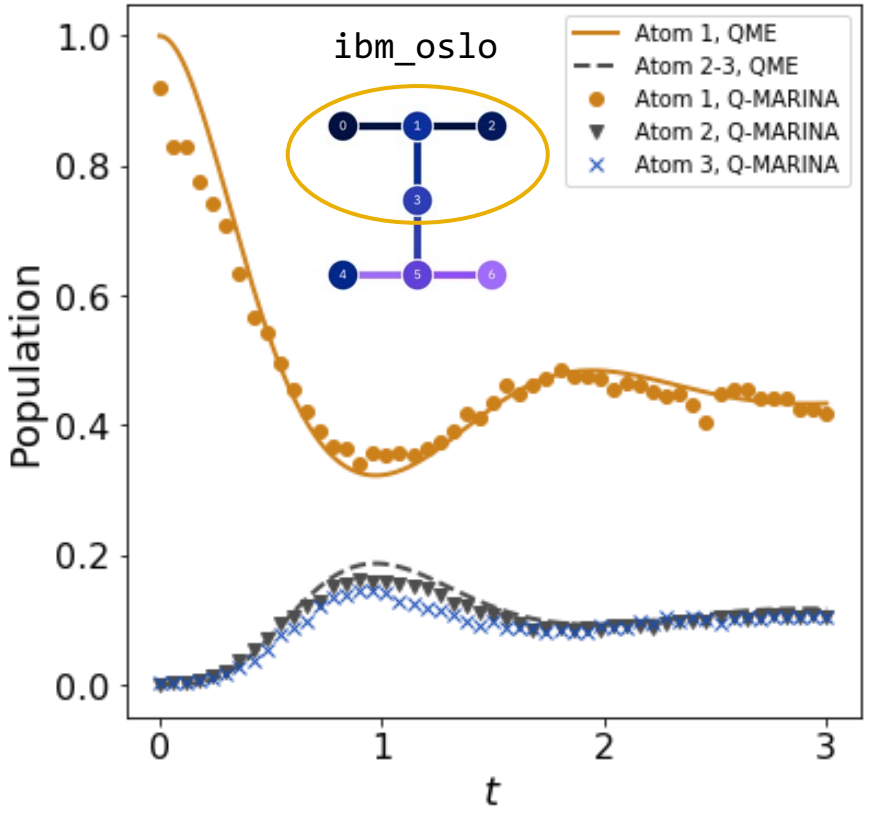
Q-MARINA tests on IBM Q hardware

$N = 2, \kappa = 5, g = 10$, shots = 10,000

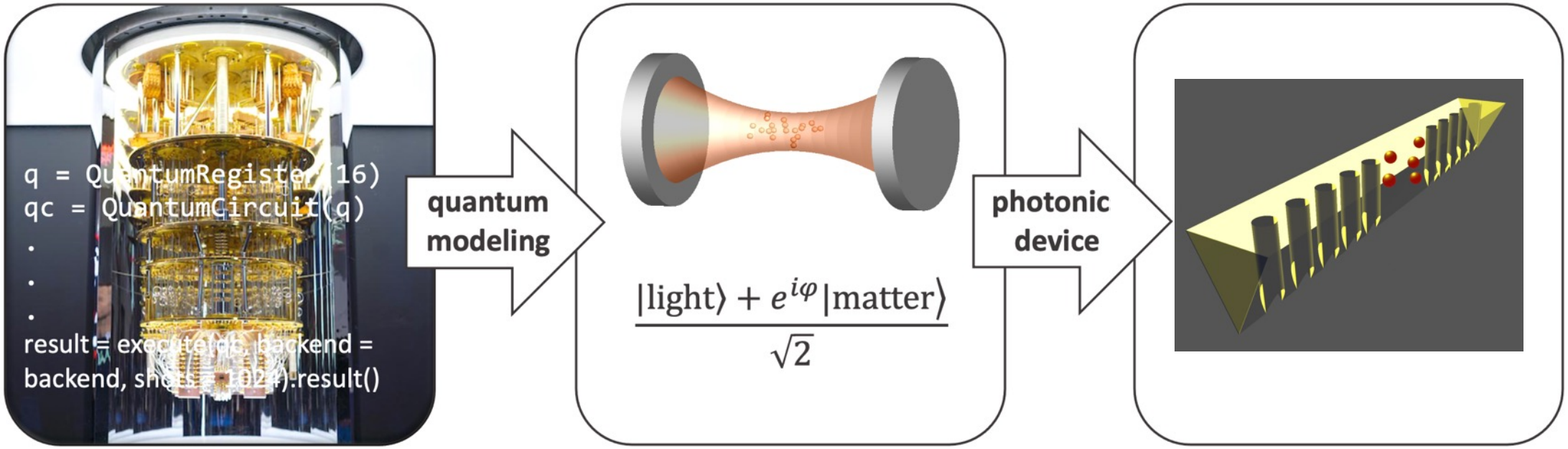


$N = 3, \kappa = 5, g = 2$, shots = 10,000

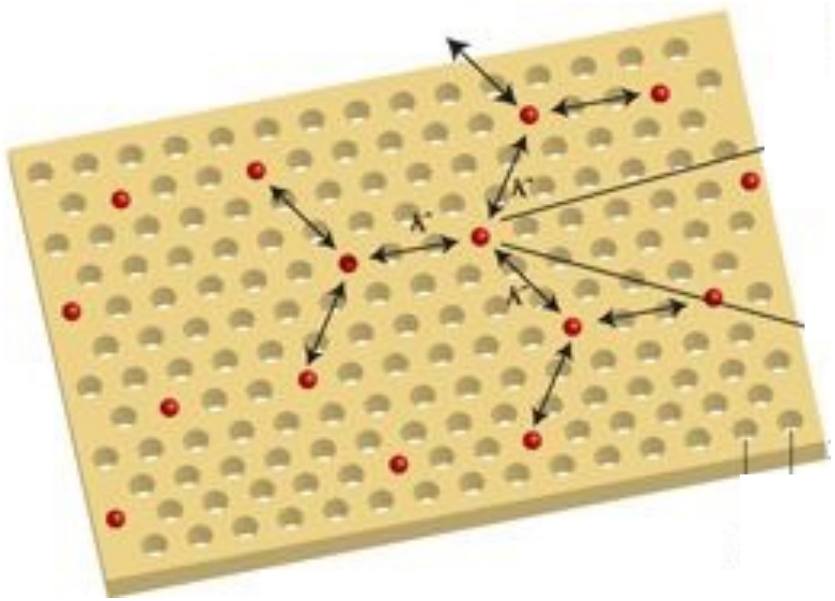


M. K. Marinkovic, **M. R.**, arXiv.2208.12029

NISQ-design of analog quantum photonic hardware



All-photonic quantum simulators



All-photonic quantum simulation

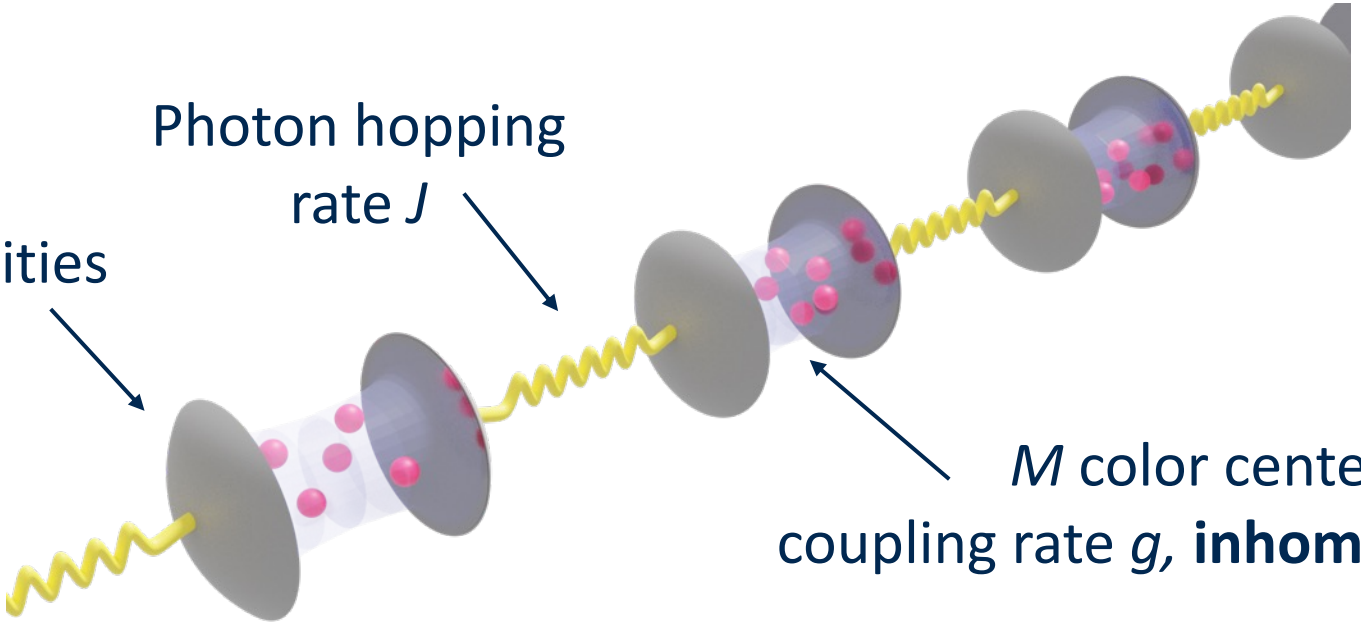
- Superfluid-Mott insulator transition
- Fractional Quantum Hall effect
- Localization effects

Localization vs. delocalization

Cavity-emitter interaction vs. cavity-cavity hopping

Hartmann, Brandao, Plenio, *PRL* **2**, 527 (2008)
Carusotto and Ciuti, *Rev. Mod. Phys.* **85**, 299 (2013)

Coupled cavity arrays with multiple emitters

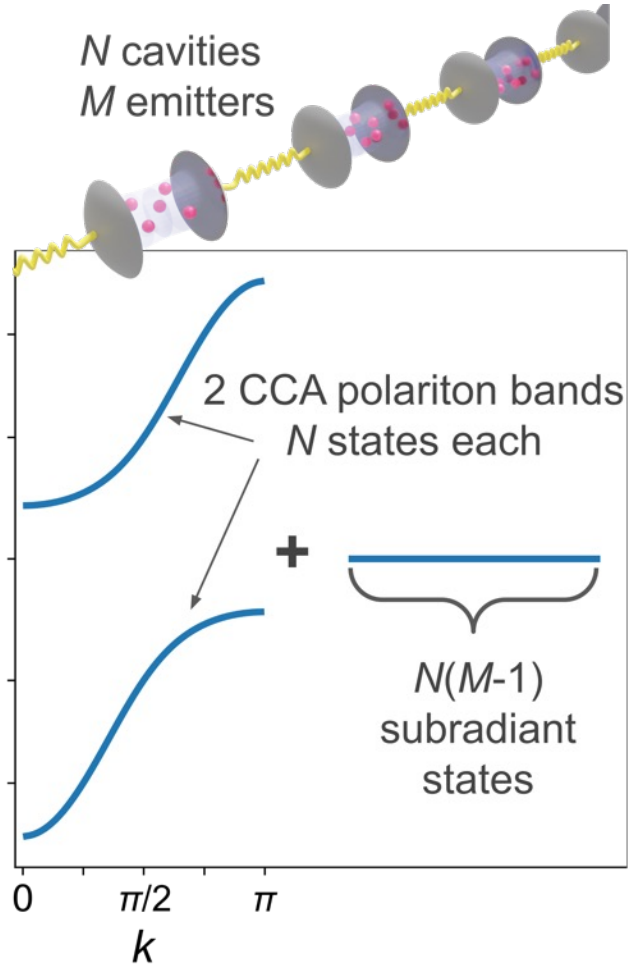


Modeled by the Tavis-Cummings-Hubbard Hamiltonian

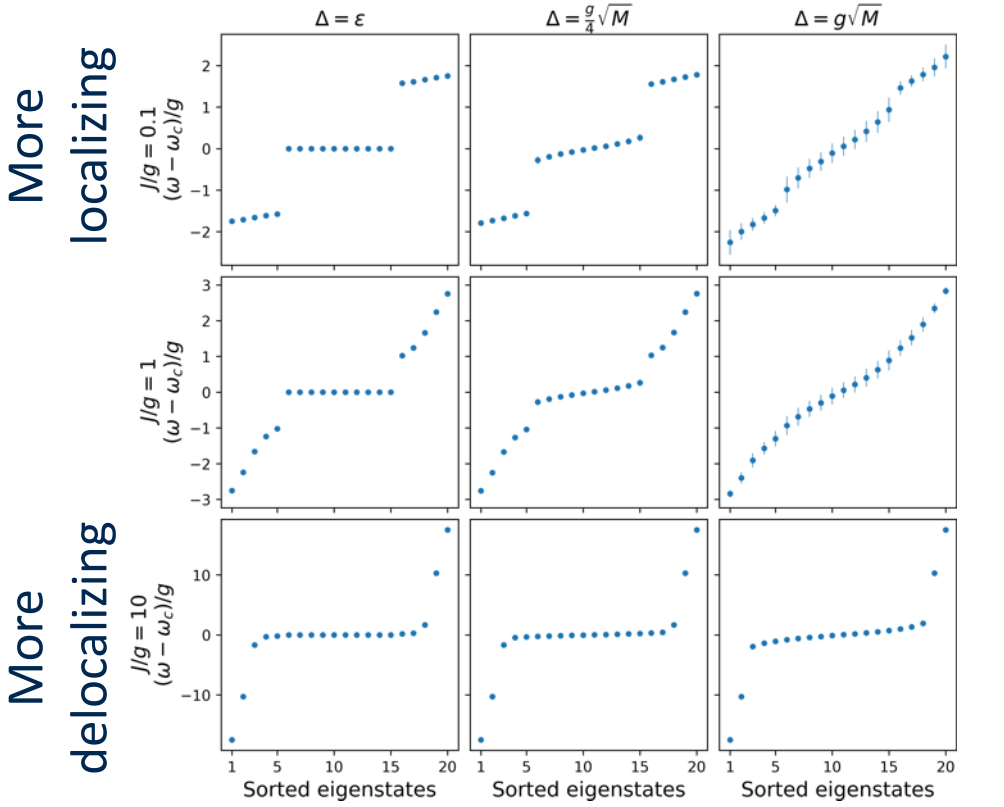
$$H_{TCH} = \sum_{i=1}^{n} \left\{ \Omega_i a_i^\dagger a_i + \sum_{j=1}^{N_i} \left[\omega_{i,j} \sigma_{i,j}^+ \sigma_{i,j}^- + g_{i,j} \left(a_i^\dagger \sigma_{i,j}^- + \sigma_{i,j}^+ a_i \right) \right] \right\} - \sum_{i=1}^{n-1} J_{i,i+1} \left(a_i^\dagger a_{i+1} + a_{i+1}^\dagger a_i \right)$$

Localizing terms **Delocalizing terms**

Spectrally disordered emitters in CCAs



Energy spectrum (N=5, M=3)



Collaboration with Scalettar group

J. Patton, V. A. Norman, R. Scalettar, **M.R.**, arXiv:2112.15469

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Participation ratio metrics for wavefunctions

Nodal Participation Ratio P_N

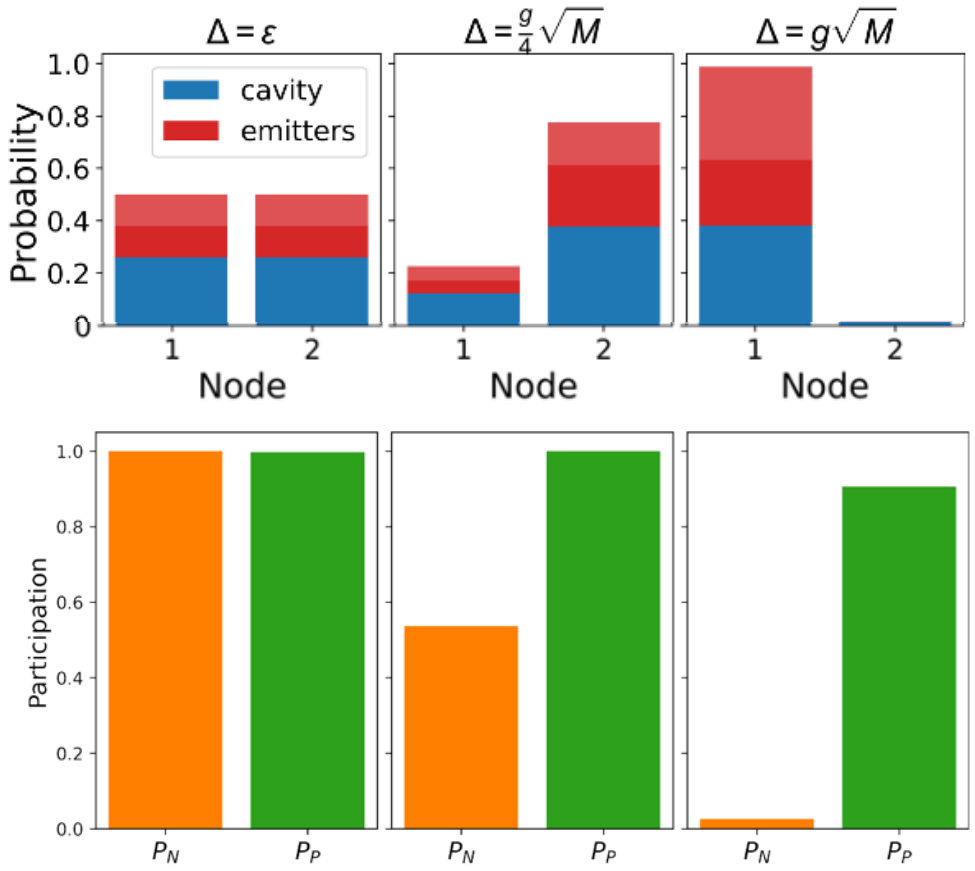
Is the wavefunction delocalized across all nodes?

$$P_N = \left[\sum_l^N \left(\langle \mathcal{N}_{ph,l} \rangle + \langle \mathcal{N}_{e,l} \rangle \right)^2 \right]^{-1}$$

Polaritonic Participation Ratio P_P

Is the wavefunction light-matter hybridized?

$$P_P = \left[\left(\sum_l^N \langle \mathcal{N}_{ph,l} \rangle \right)^2 + \left(\sum_l^N \langle \mathcal{N}_{e,l} \rangle \right)^2 \right]^{-1}$$



Collaboration with Scalettar group

J. Patton, V. A. Norman, R. Scalettar, **M.R.**, arXiv:2112.15469

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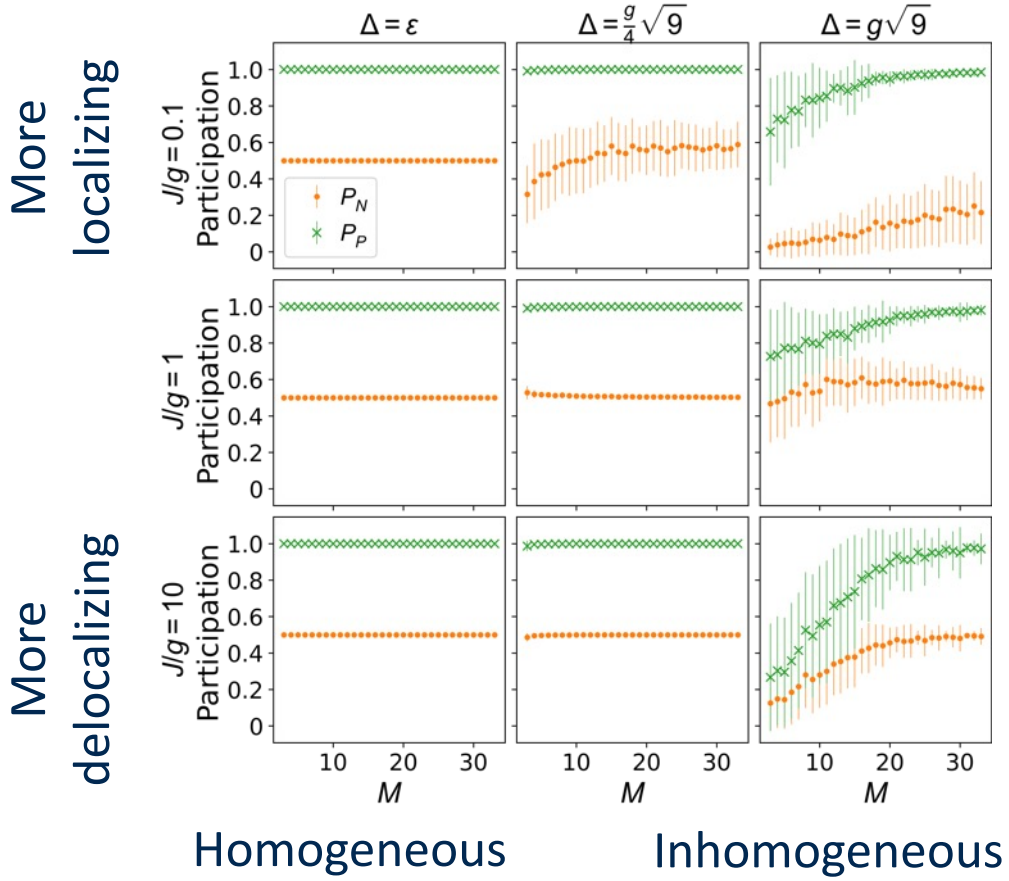
Multi-emitter coupling vs. inhomogeneity

Metrics for N=5, Δ=*const*



Light-matter interaction engineering

- Quantification of cavity QED effects
- Number of emitters needed to design a highly polaritonic state
- Parameters that optimize polaritonic character for a specific wavefunction
- Localizing vs. delocalizing configurations

Collaboration with Scalettar group

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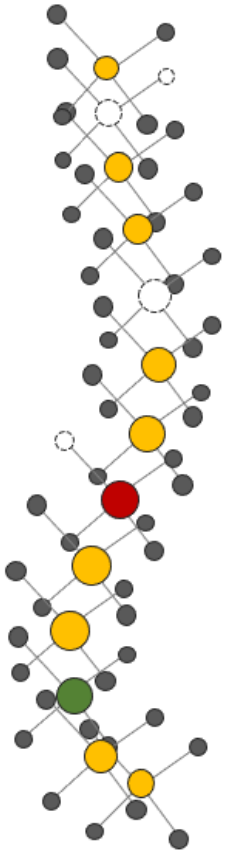
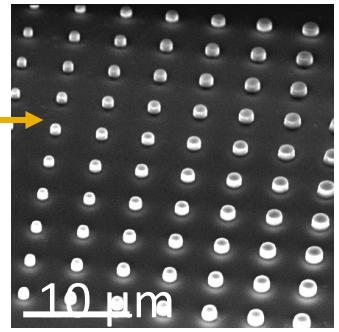
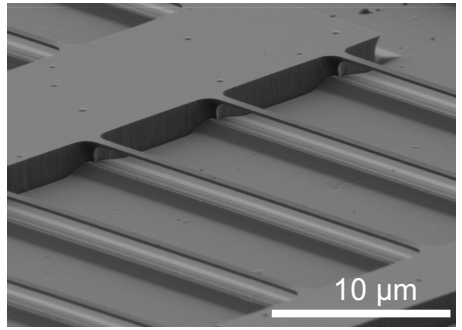
Summary: SiC Quantum Tech Backbone

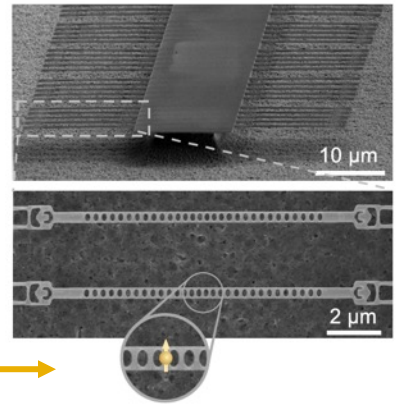


Quantum Sensing

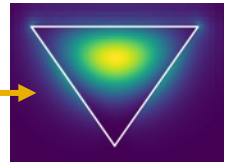


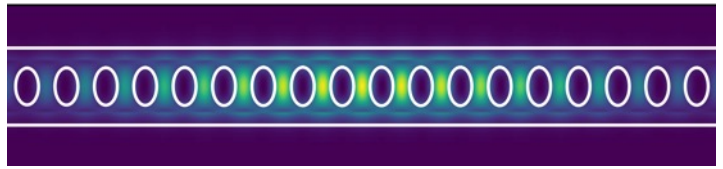


Quantum Internet

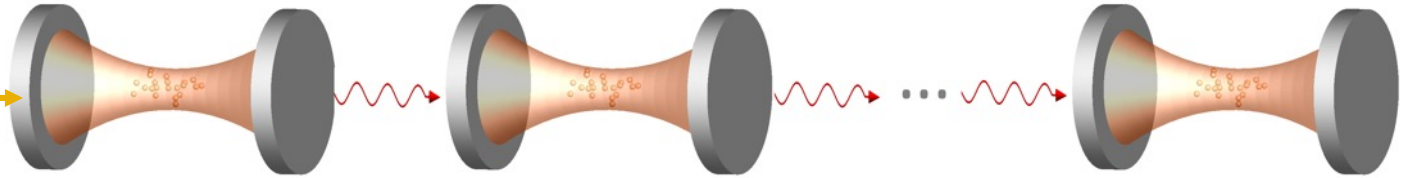


Quantum Computing

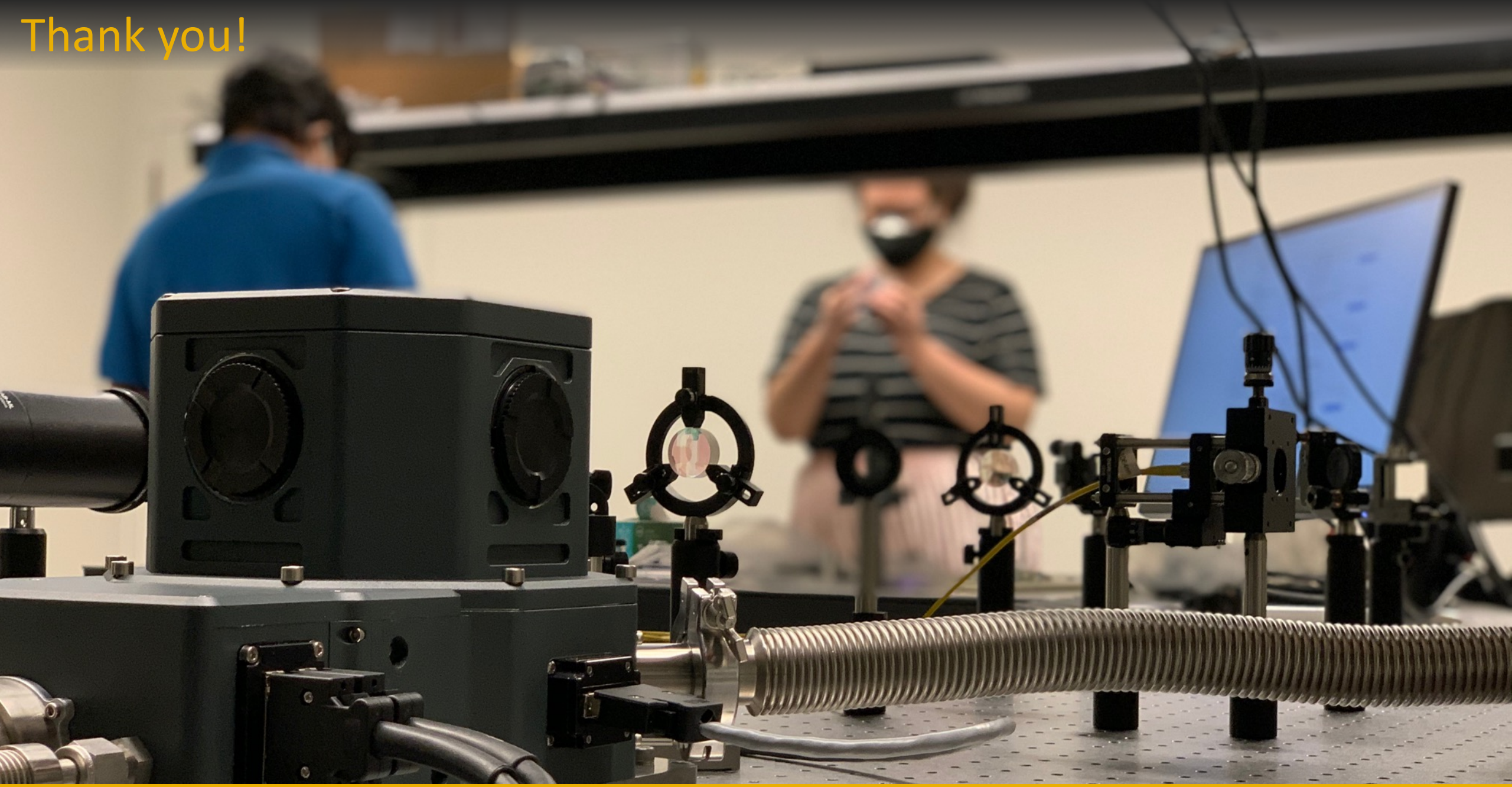




Quantum Simulation



Thank you!



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