

Erbium dopants for quantum networks

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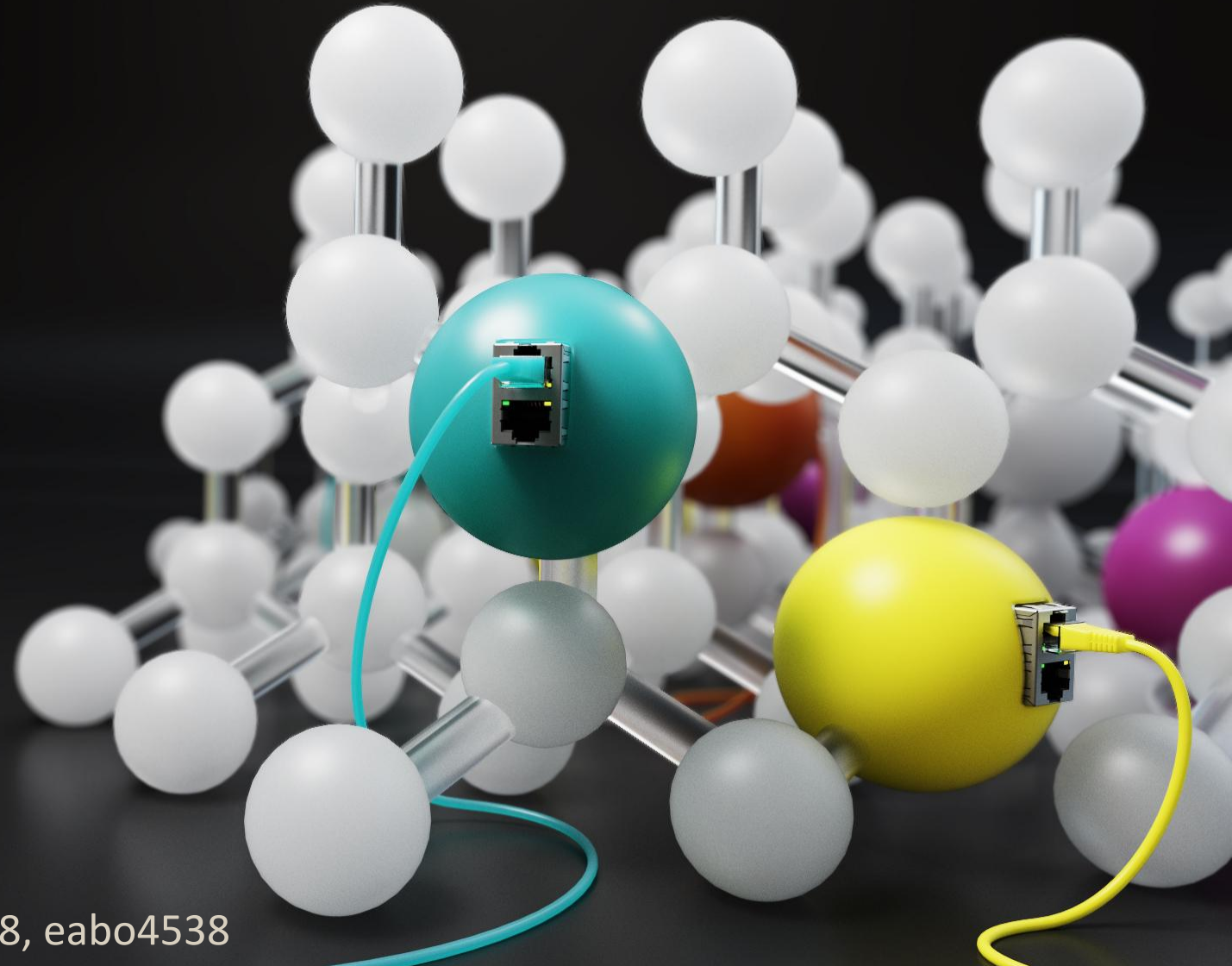
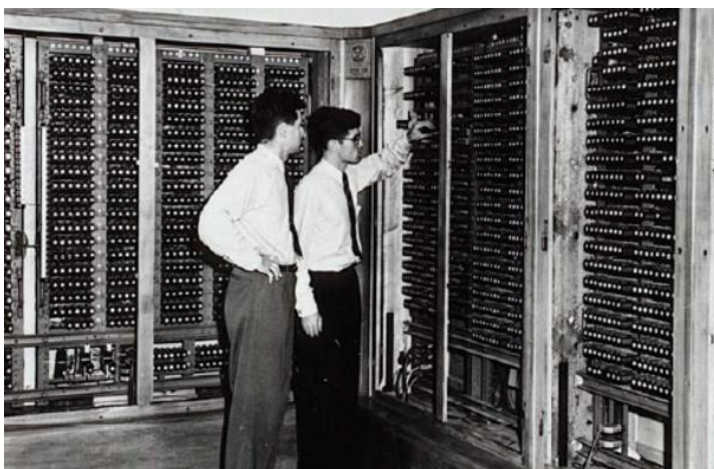


Image: Criss Hohmann, MCQST, Science Adv. 8, eabo4538

The digital revolution



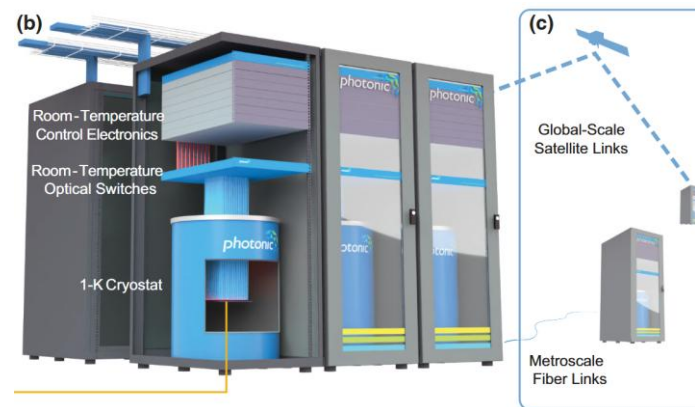
First computers



Networked computers



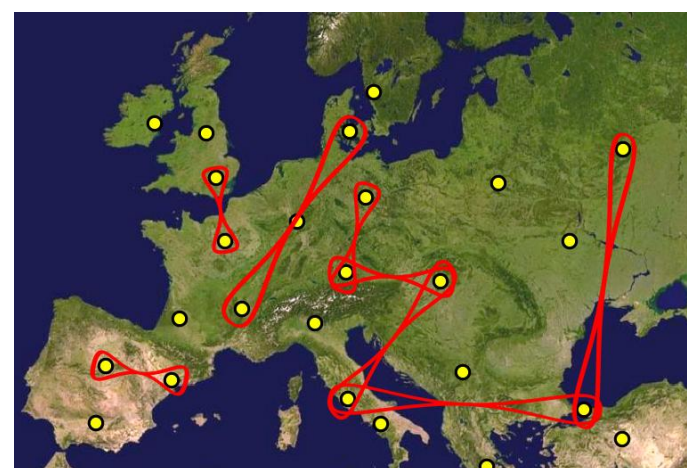
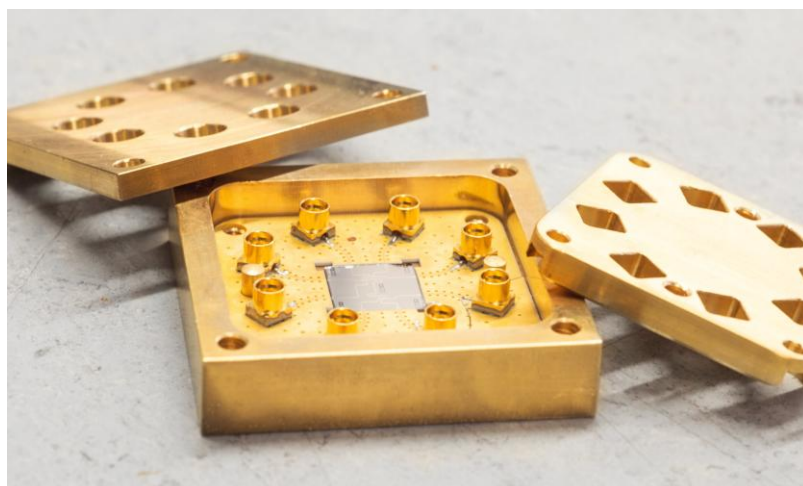
The (second) quantum revolution



Modular QC
Simmons, PRX
Quantum 5 (2024)

Blind QC
Fitzsimons et al., npj
Quant. Inf. 3 (2017)

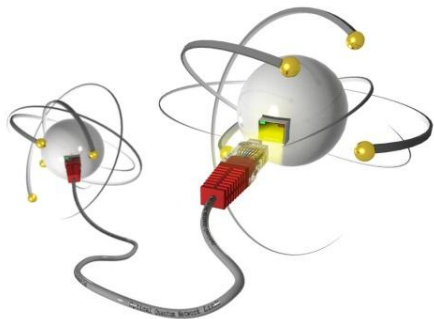
First quantum computers → Quantum networks



Provably secure communication

Distributed clocks and sensors

Wehner et al.
Science 362 (2018)

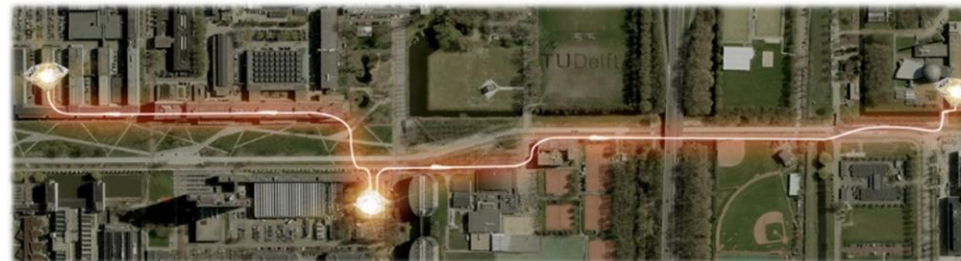


Atoms in vacuum

Distance: 21 m	40 km
Success rate: ~100 Hz	~ mHz
Fidelity: 85 %	~ 83 %

Ritter et al., Nature 484 (2012)

*van Leent et al.
Nature 607 (2022)*



Spins in diamond

Distance: 1.3 km	40 km
Success rate: mHz to Hz	~ mHz
Fidelity ~ 83 %	~ 69 %

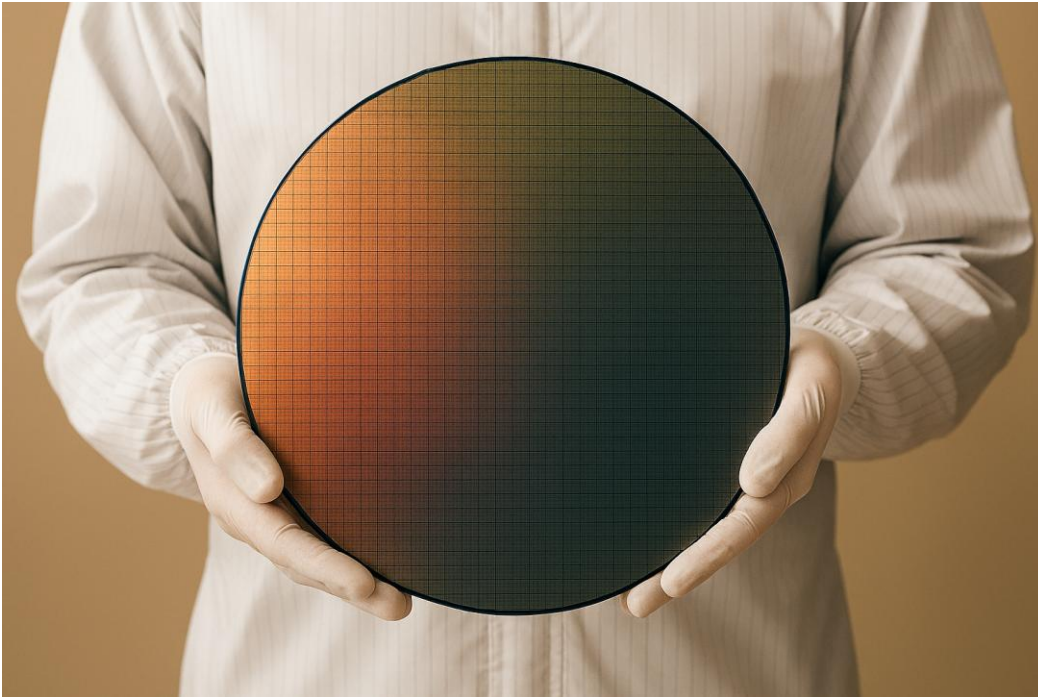
B. Hensen et al., Nature 526 (2015)

*Knaut et al.
Nature 629 (2024)*

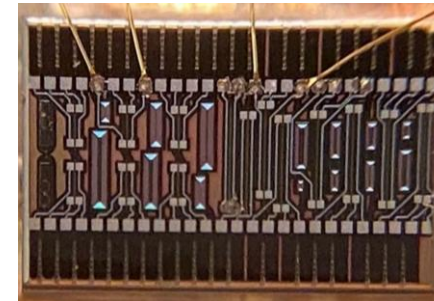
Moderate rate and fidelity prevents up-scaling. We need better hardware.
Our approach: Erbium-doped silicon

Why silicon?

- Established nanofabrication
- Photonic components readily available
- Spatial multiplexing!



Trillions of transistors

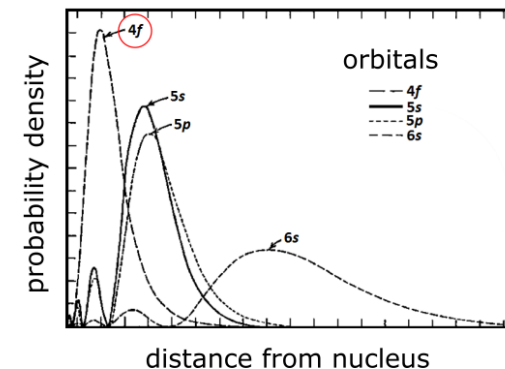
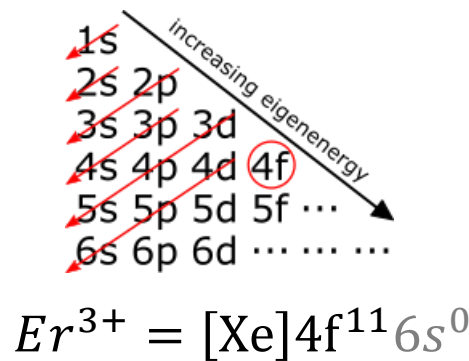
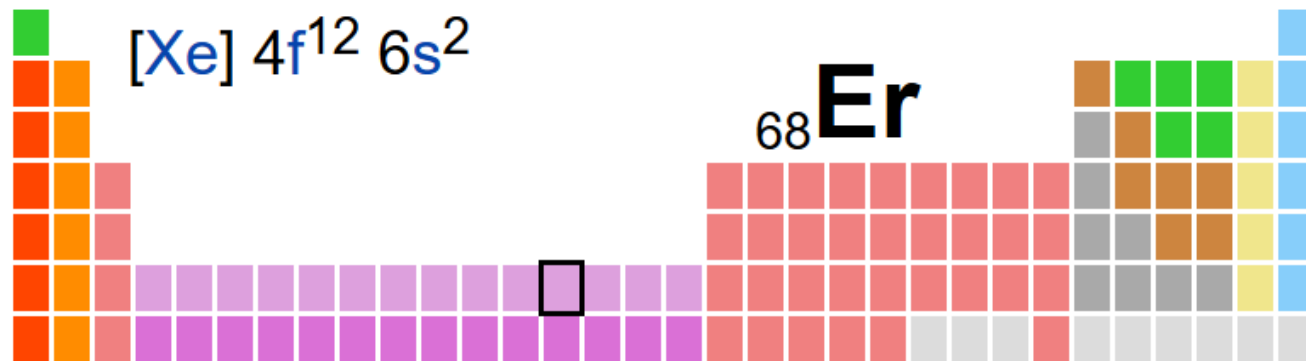


2x3 mm²

Rinner et al. Nanophotonics, 12 (2023)

- Good host of spin qubits!
 - Pure crystals
 - Magnetic vacuum in photonic SOI by isotopically purified MBE growth
- Liu et al., Journ. Cryst. Growth (2022)*

Why Erbium?




Nucleus

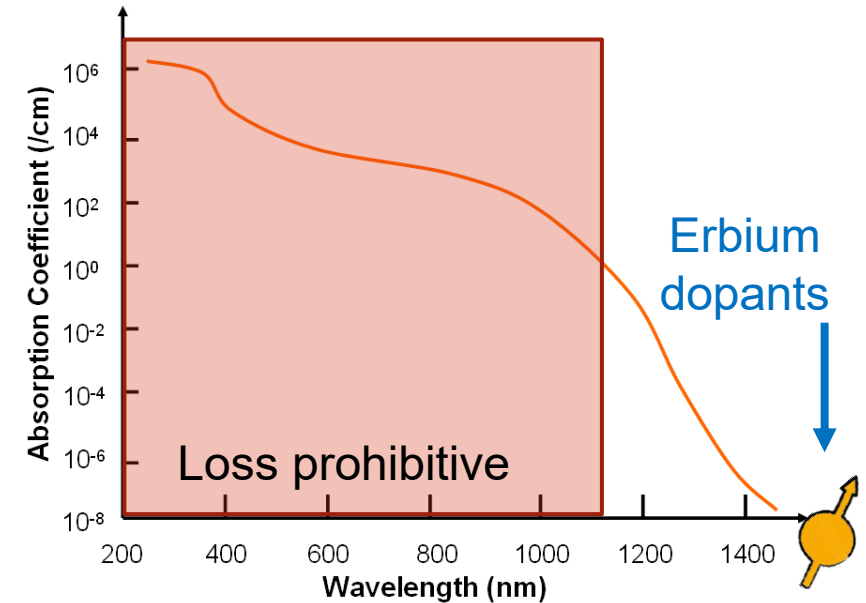
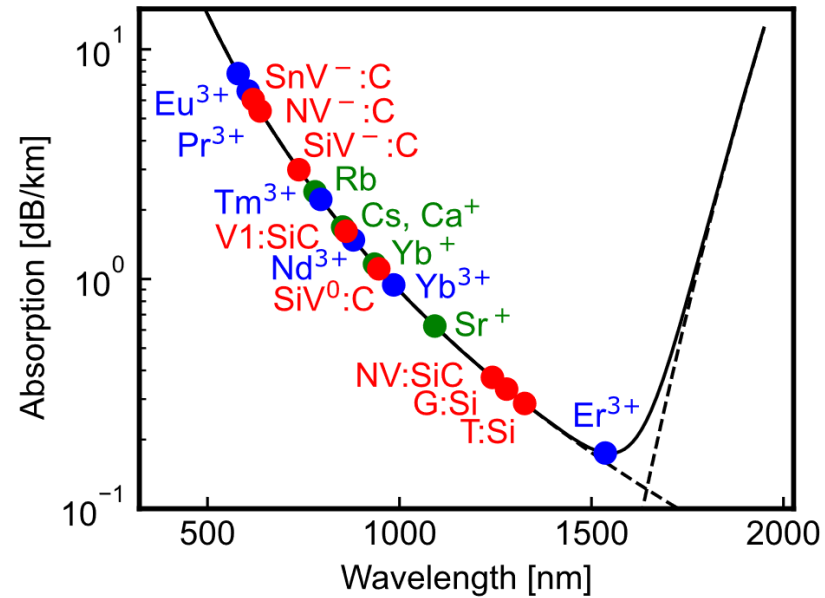
Filled inner shells

Filled 5s, 5p: shielding „Faraday cage“

4f electrons
Hyperfine T₂ up to **six hours**
Zhong et al. Nature 517 (2015)

Kandinsky: Squares with Concentric Circles (1913 – before Bohr!)

Why erbium dopants?



Photon transmission after 100 km fiber:

- NV centers (637 nm): $< 10^{-50}$; color-centers in silicon: 0.1%
- Erbium dopants (1536 nm): $\sim 1\%$
- Routing using robust room-temperature components

Reiserer, Rev. Mod. Phys. 94 (2022)

Holewa et al. Nanophotonics 14 (2025)

On-chip optical qubit control:

- Compact nanophotonic devices
- No cross-talk, low power driving (\sim nW)
- high bandwidth \rightarrow frequency multiplexing

González Tudela et al. Nat. Rev. Phys. 6 (2024)

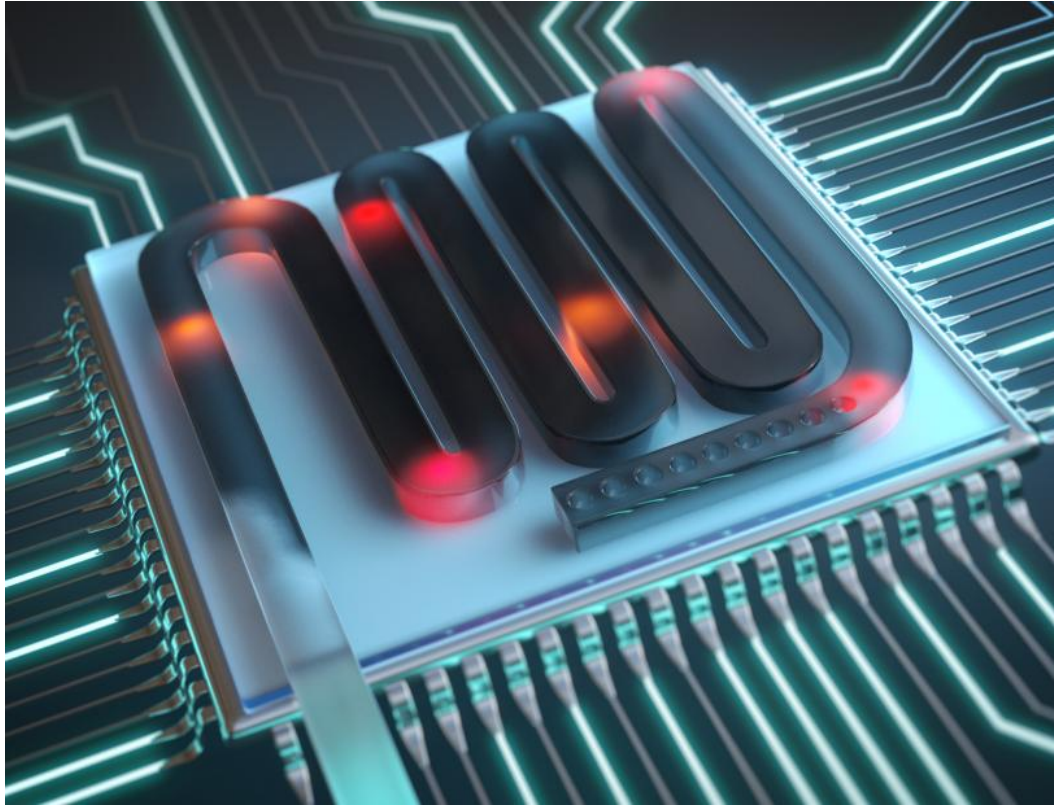
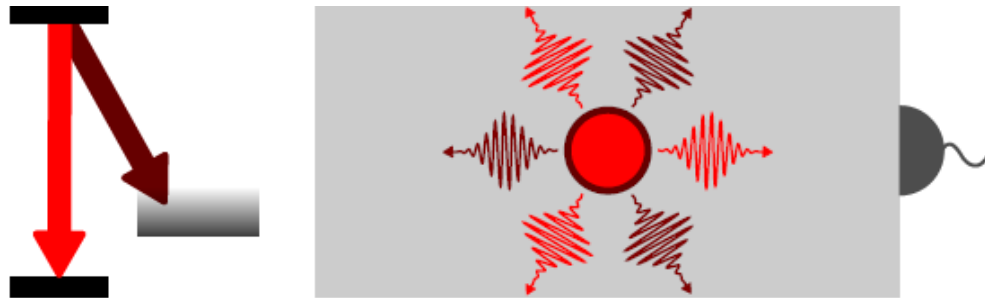


Image: Criss Hohmann, MCQST

Our group has pioneered this new hardware platform:

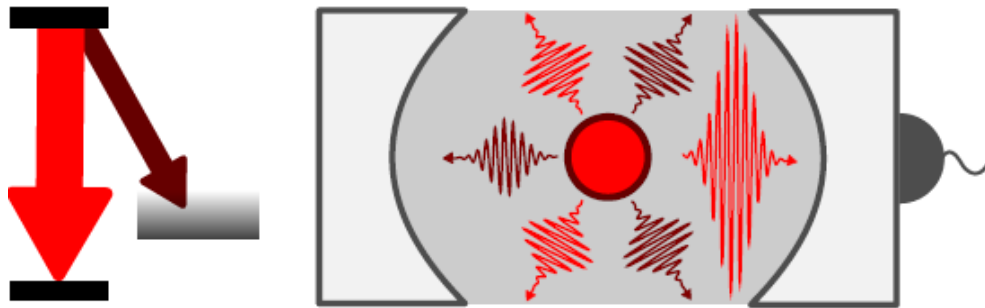
- Er can be reliably integrated in photonic Si *Optica 8 (2021)*
- **Exceptional optical coherence** *Phys. Rev. X 12 (2022)*
- Foundry-based fabrication *Nanophotonics, 12 (2023)*
- **Single emitters, single photon generation** *Optica 10 (2023)*
- Spin Hamiltonian & Symmetry *Adv. Quant. Techn. 8 (2024)*
- Nanoscale Thermometry *Nanophotonics 14 (2025)*
- **Spin qubit readout and control** *Nat. Commun. 16 (2025)*
- Lifetime-limited photon coherence *arXiv:2601.13666 (2026)*

Many setups for Er:Si experiments currently built by other groups.



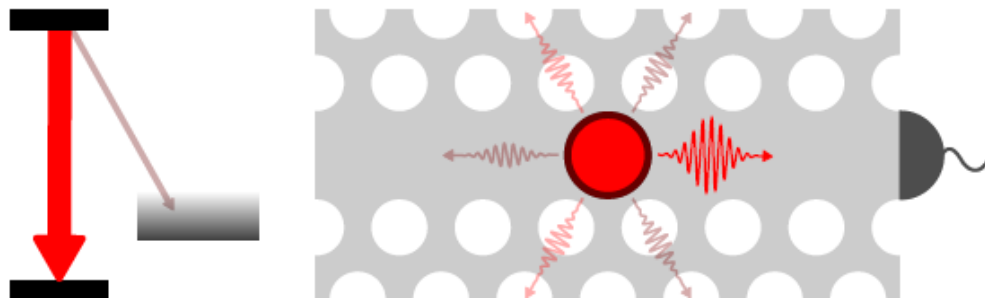
Common challenges for all single-photon emitters:

- Efficient collection of emitted light
- Unwanted transitions



Common solution: Optical resonators

- Purcell enhancement of a single mode: $P \propto Q/V$
Purcell, Phys. Rev. 69, 681 (1946).
- Very small V ? \rightarrow only few emitters
- Very high Q ? \rightarrow Narrowband; precise tuning required

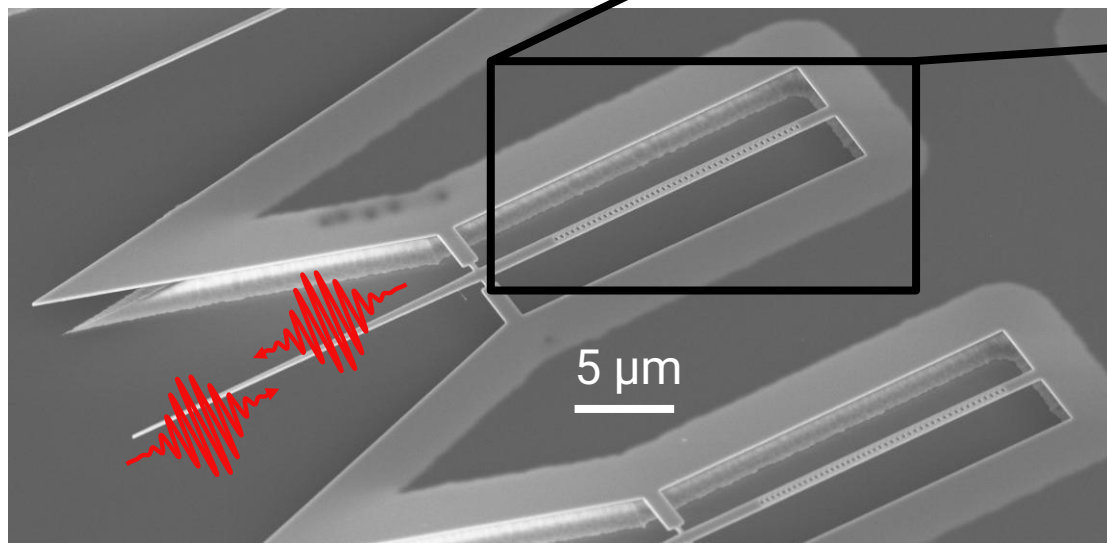
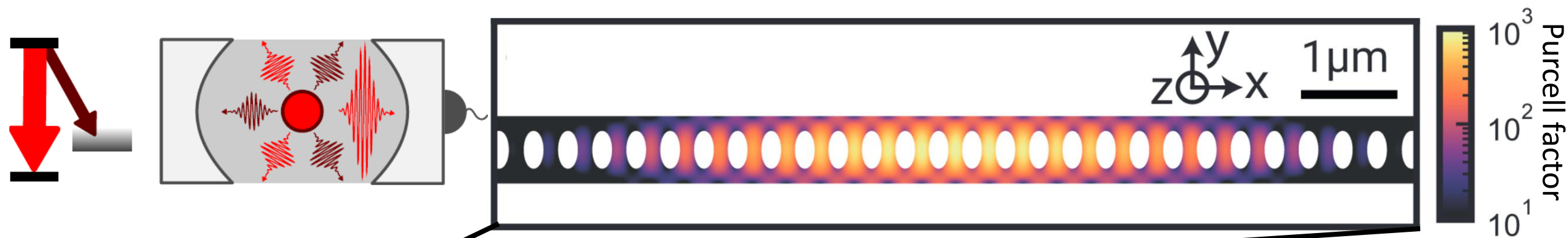


Alternative idea: Inhibited spontaneous emission

- Idea: Photonic bandgap suppresses all modes except one
- Broadband, robust, no tuning required!

Burger et al., arXiv:2511.23301 (2025)

Nanophotonic cavity

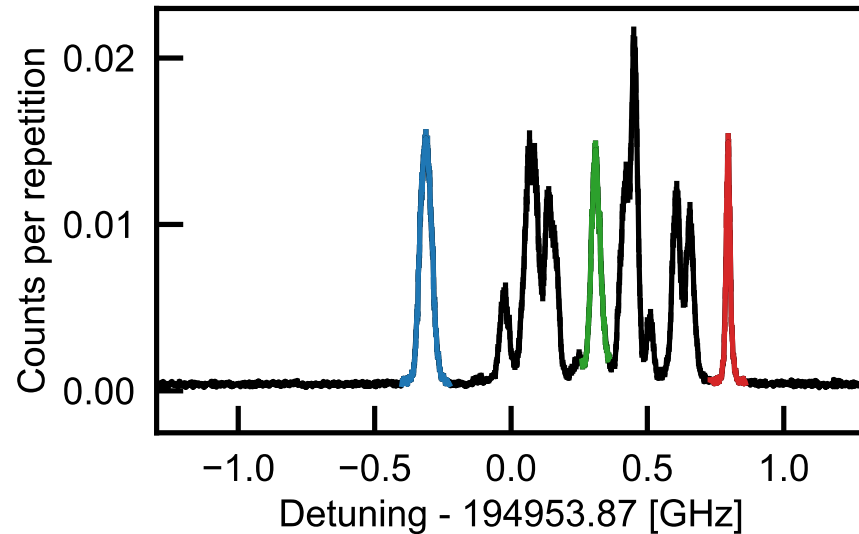


- Long optical lifetime (140 μs) favors a strong Purcell enhancement $P \propto Q/V$.
- Q-factor $\approx 80\,000$; Mode volume $V \approx 0.8 (\lambda/n)^3$
- Expected $P_{max} \sim 1600$ (so <100 ns decay)

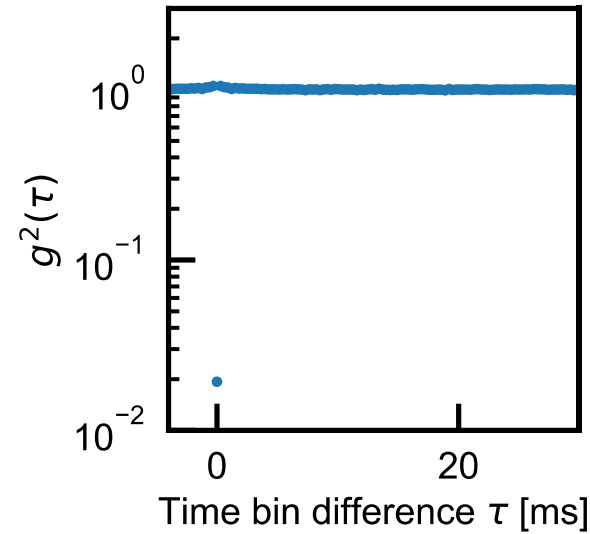
Gritsch, A. et al. Optica 10 (6): 783–89 (2023).

Tapered-fiber coupling and single-sided cavity \rightarrow more than 20% of the emitted photons are collected.

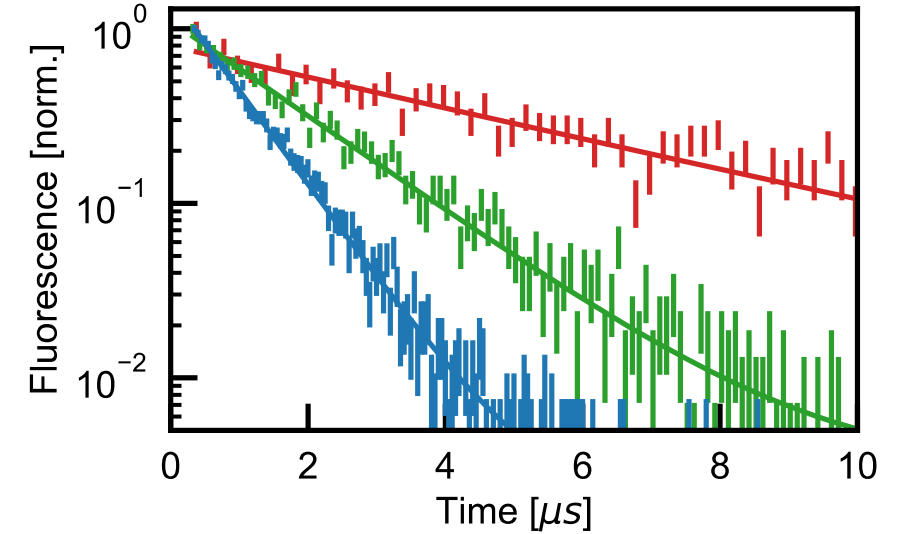
Spectral multiplexing of single dopants



Autocorrelation function $g^{(2)}(0) < 0.02$



Purcell enhancement up to $P = 177$

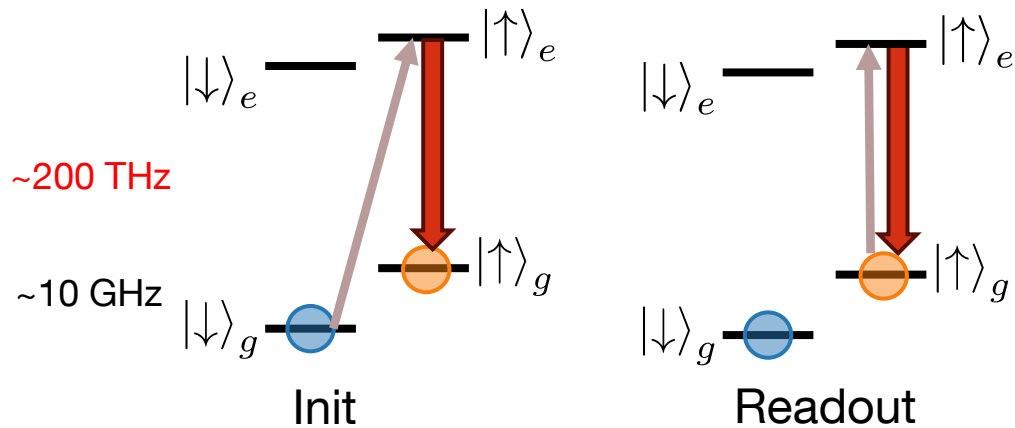


~9-fold less Purcell enhancement than expected.

Gritsch, Ulanowski, Reiserer: *Optica* **10** (6): 783–89 (2023).

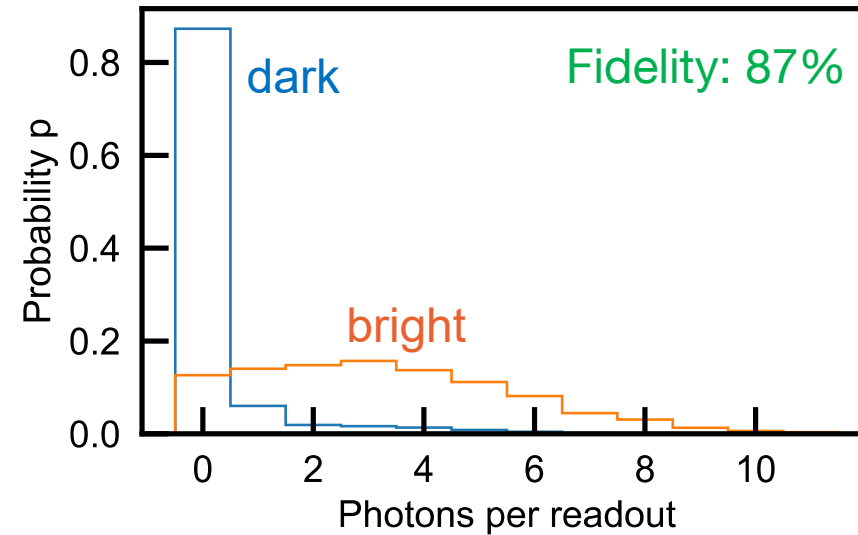
Gritsch, Ulanowski, Pforr, Reiserer, *Nature Communications* **16**, 64 (2025).

Selective enhancement of one transition

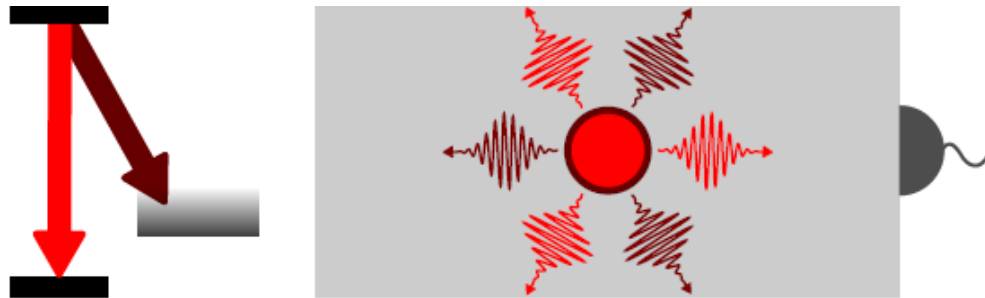


Spin qubit lifetime: ~ 0.5 s
 @ 0.3T and 3K; $\propto T/B^5$

Optical single-shot spin qubit readout in silicon

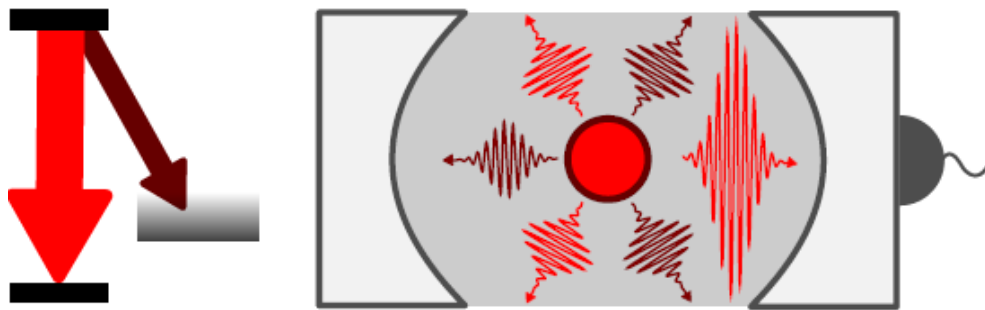


Coherent spin rotations: $T_2 = 48(2)$ μ s.
 Improvement: dynamical decoupling or ^{28}Si
Berkman et al. Npj Quantum Inf. 11 (2025)



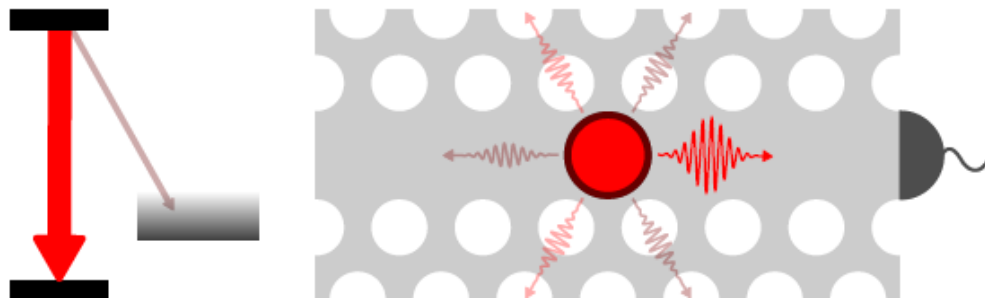
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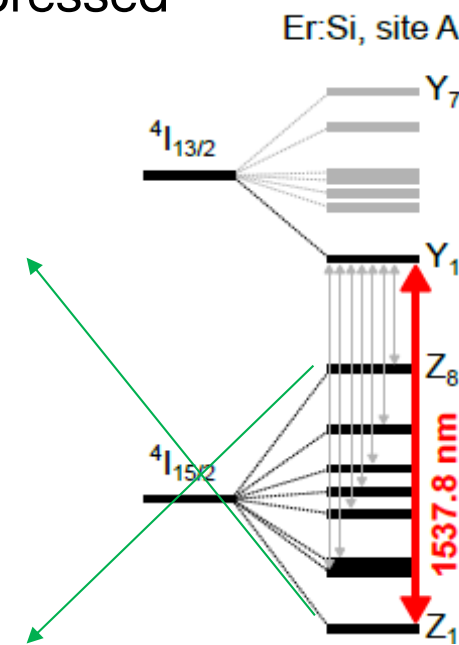
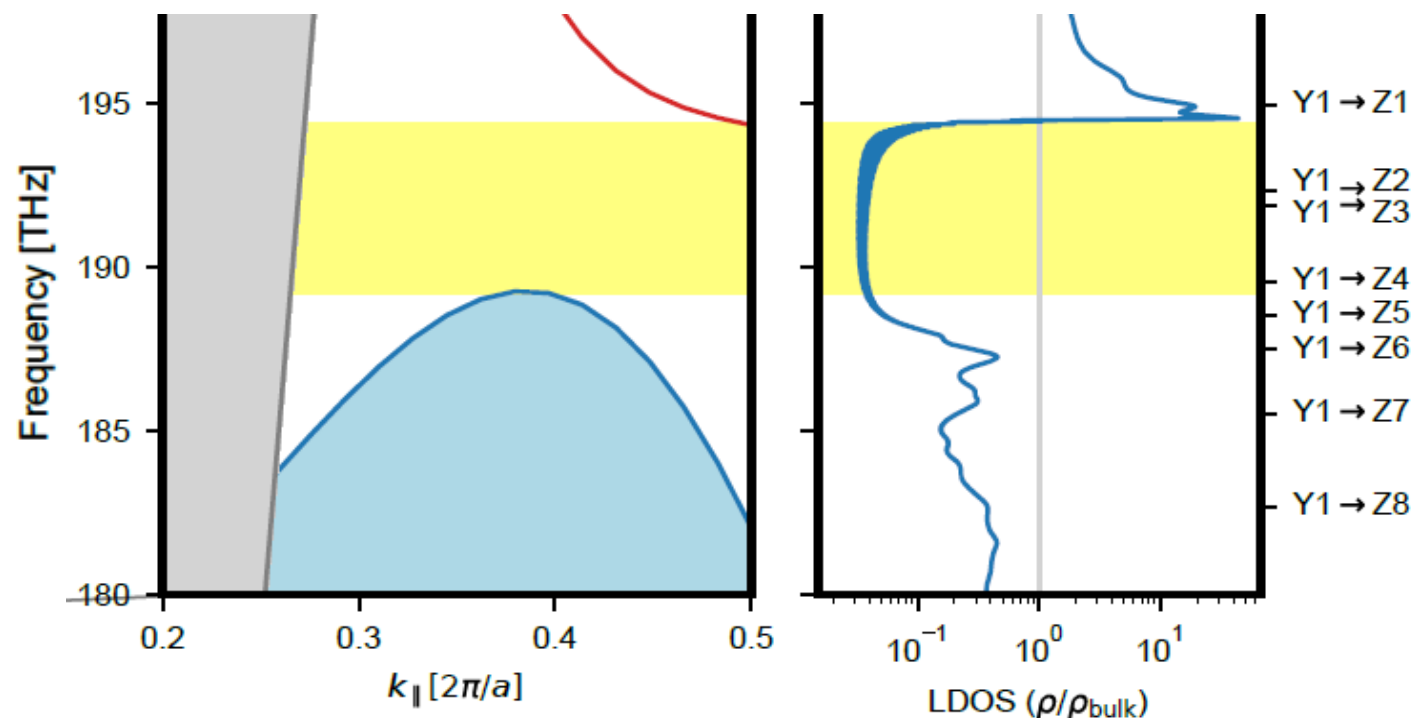
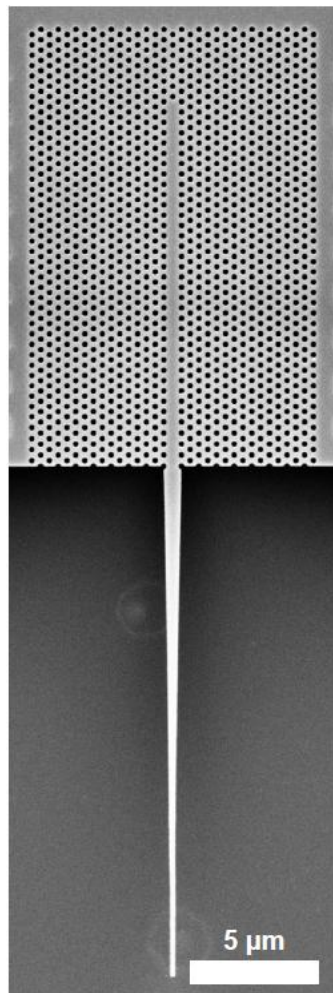
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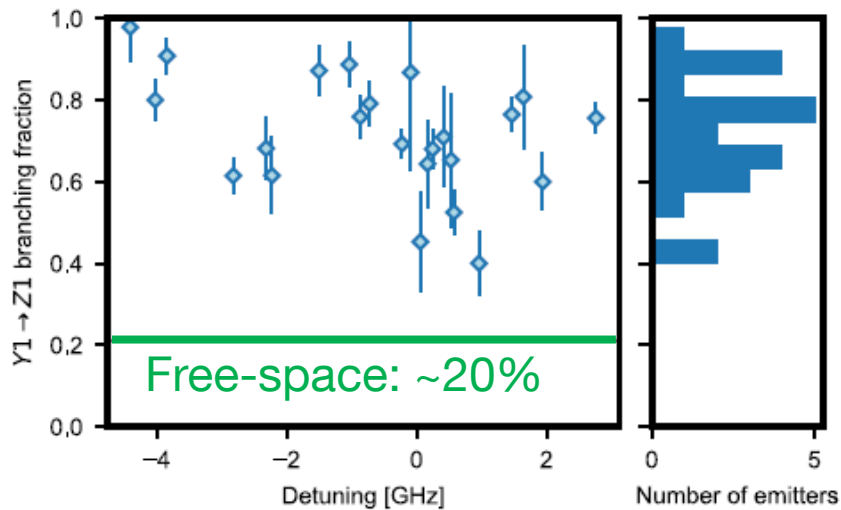
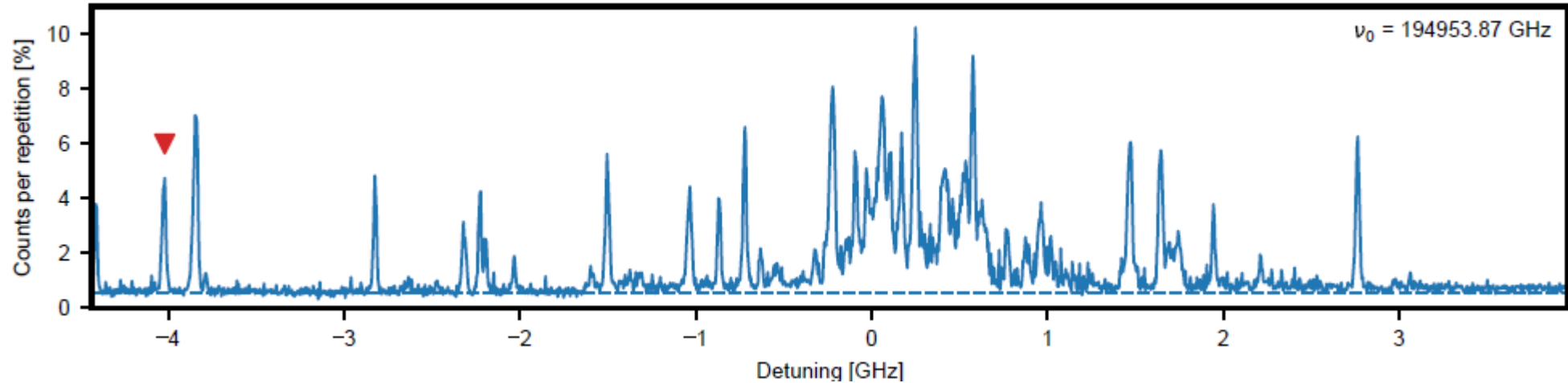
Kleppner, "Inhibited Spontaneous Emission," PRL 47 (1981).

- Idea: Photonic engineering suppresses all modes except one
- Broadband, robust, no tuning required!
- Better for spectroscopy!

Spin-photon interfaces

- Use photonic crystal waveguide with a broad bandgap
- $Y1 \rightarrow Z1$ transition in guided mode (red) slightly enhanced ($LDOS > 1$)
- All other transitions in the bandgap (yellow), so strongly suppressed





- Resonant excitation spectroscopy: Efficient photon collection from single emitters ($\sim 20\%$ fiber-coupled)
- Broadband: Spectral multiplexing of >20 dopants
- Most of the light emitted on the $Y1 \rightarrow Z1$ transition
- Radiative lifetime: Unchanged or even extended (up to ~ 3 -fold, depending on emitter position)
- Outlook: Collective coupling to the waveguide?

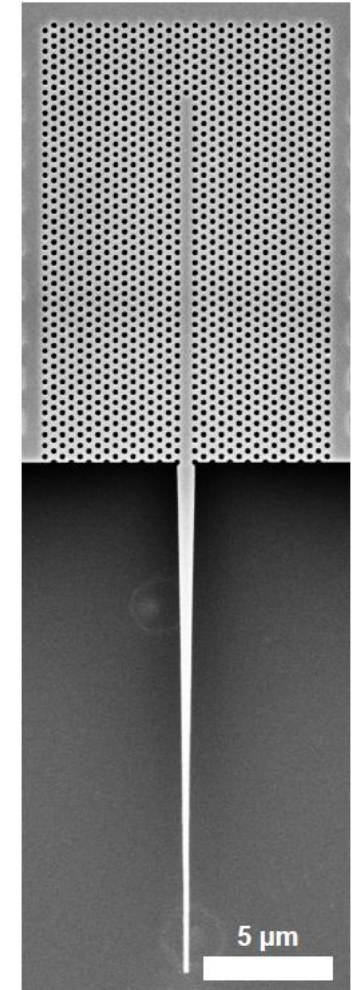
González-Tudela et al. Nat. Rev. Phys. (2024)

Burger et al. (arXiv:2511.23301). Previous work with QDs: Lodahl et al. Rev. Mod. Phys. 87 (2015).

- Erbium dopants promising for quantum networking: Second-long ground state coherence, lifetime-limited photon emission in the telecom C-band, frequency domain multiplexing
- Our current work: efficient spin-photon interfaces
- Two approaches:
 - Purcell enhancement
 - Inhibited spontaneous emission

Outlook:

- High-rate remote entanglement (\sim kHz over 50 km of optical fiber)
- Spatial and spectral multiplexing in nanophotonic chips ($>$ 1000 qubits)
- Foundry-made quantum memory for photonic QC
- Quantum networking demonstrator experiments
 - Connect quantum computers via microwave-to-telecom transduction
 - Build ultrastable lasers for networked optical atomic clocks



Thank you!

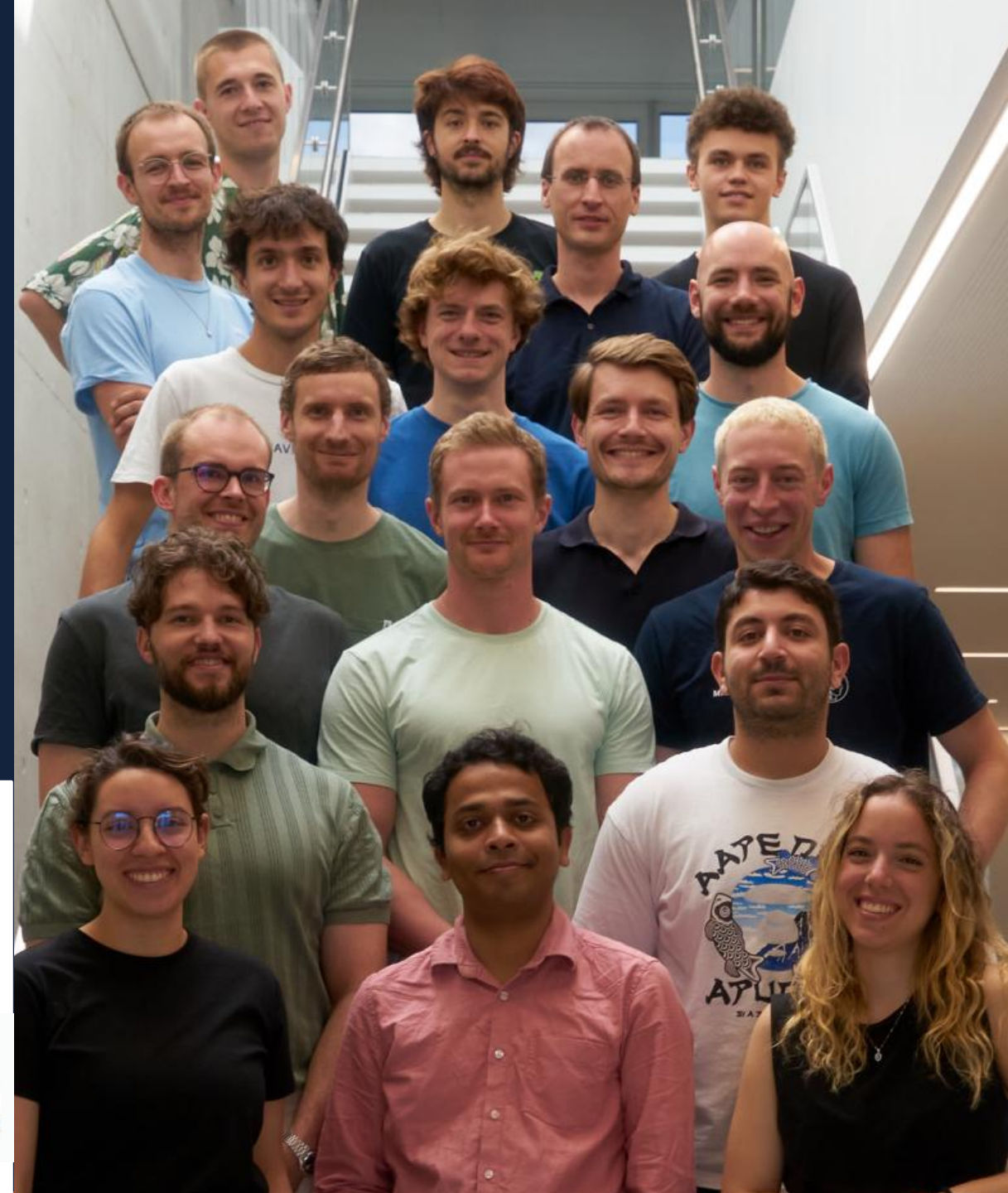
Fabry-Perot resonators: Alexander Ulanowski, Johannes Früh, Fabian Salamon, Noah Weinhold

Silicon nanophotonics: Andreas Gritsch, Florian Burger, Stephan Rinner, Jonas Schmitt, Jakob Pforr, Nilesh Goel, Benedikt Braumandl, Arantza Gonzalez Pineda, Francesca Molteni, Paul von Massow, Andrew Propper

Microwave-to-telecom conversion: Daniele Lopriore, Maysane Selmani, Devansh Bardwai

Laser stabilization: Aaron Schäpers, Kilian Sandholzer, Juan Baratech Soriano, Ginevra Fulco

Collaborators: T. Chaneliere (CNRS Grenoble), K. Gradwohl (IKZ Berlin), Bertet / Flurin (CEA Paris), P. Goldner (Chem. Paris T.)



QUANTUM
INTERNET
ALLIANCE



Bundesministerium
für Forschung, Technologie
und Raumfahrt

