

High-efficiency microwave-optical transduction for quantum sensing and computing

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Abstract

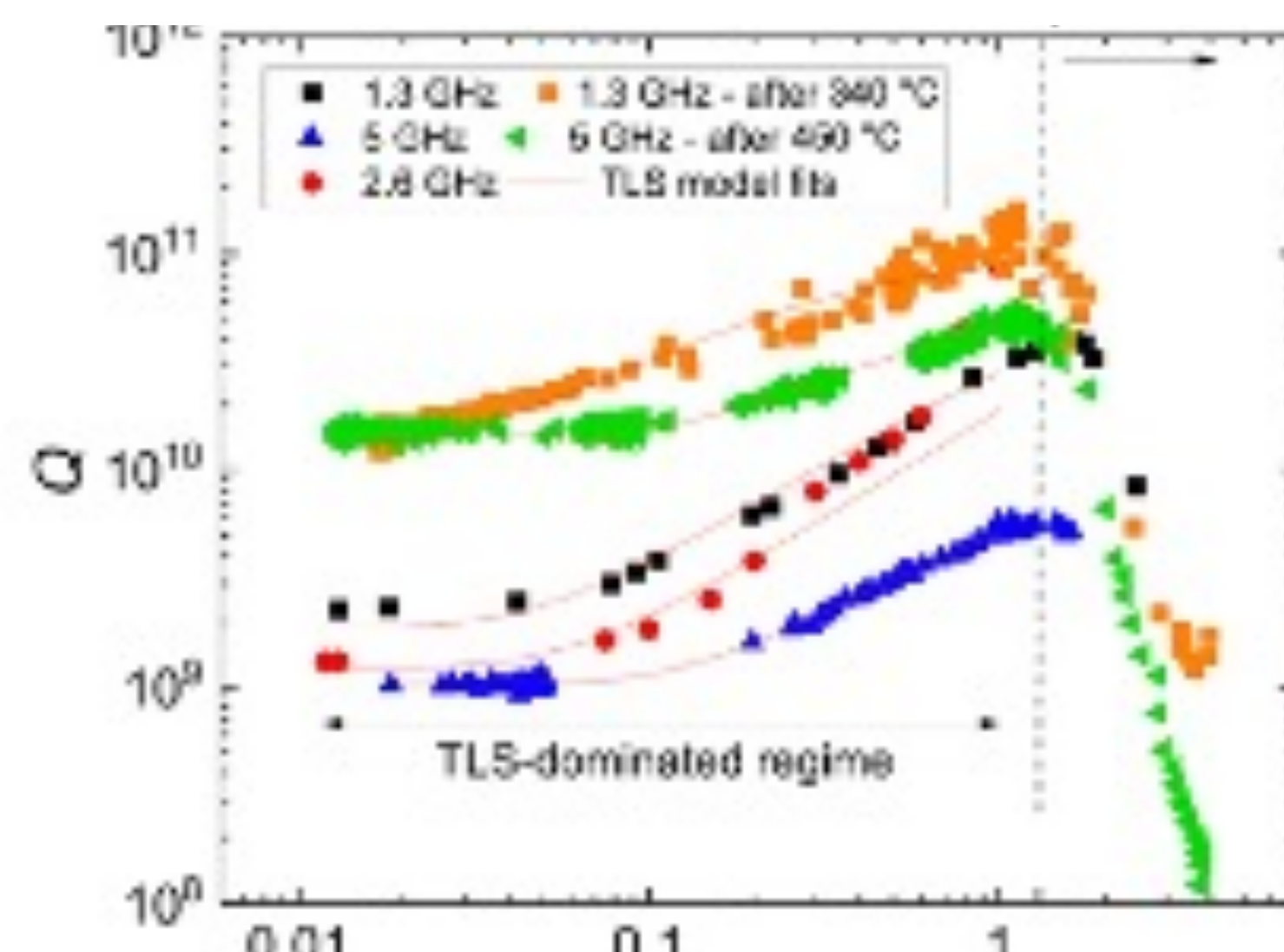
Superconducting radio-frequency (SRF) cavities play a crucial role in quantum computing and various quantum applications. These cavities also provide powerful tools to probe fundamental physics.

At Fermilab, we are exploring ways to use hybridized SRF cavities as quantum transducers to convert microwave-optical quantum signals with high fidelity and high efficiency.

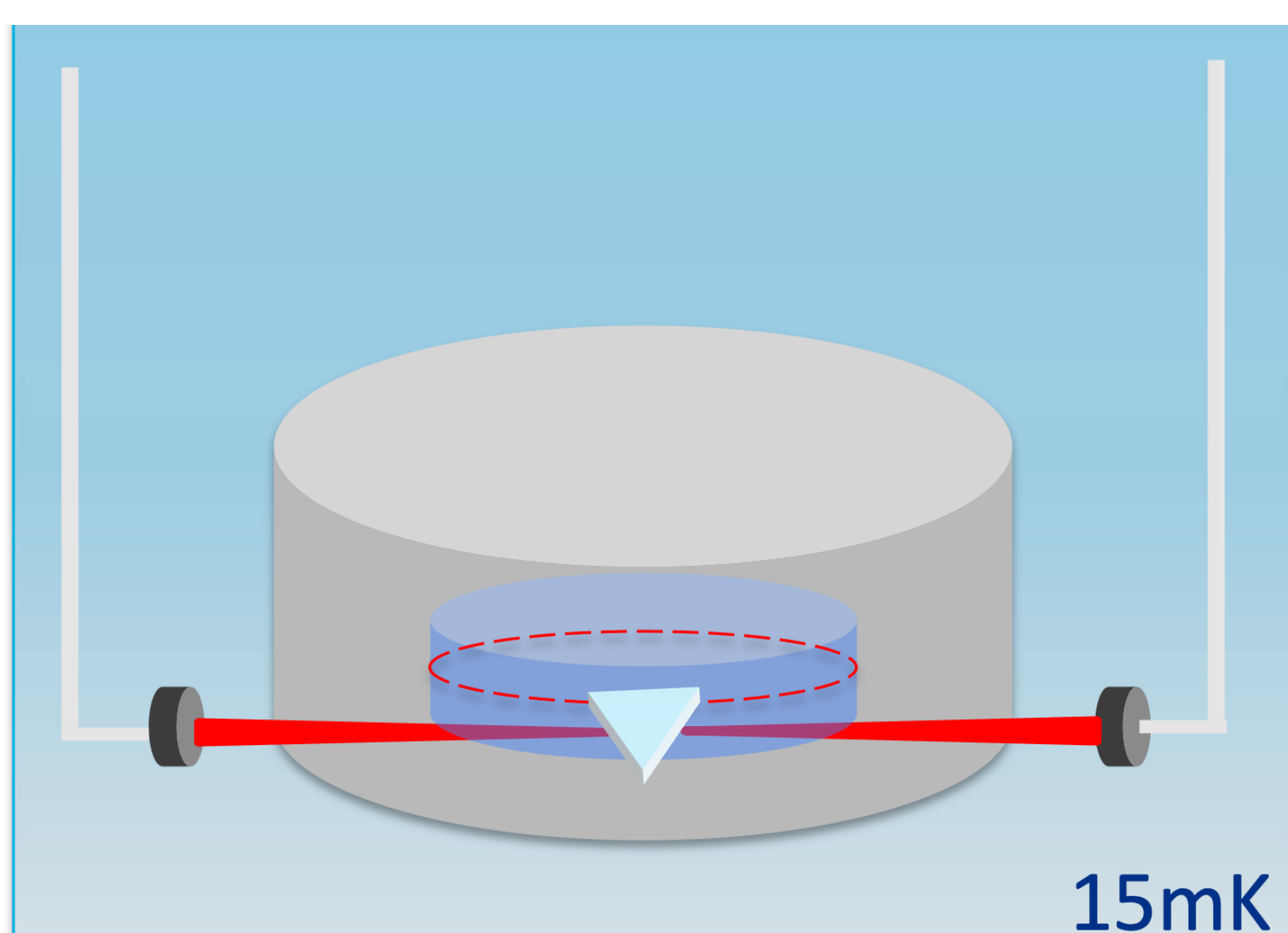
Current quantum transduction demonstrations are **limited in conversion efficiency**, with most schemes operating in the **high-pump regime**, therefore with large noise. With 3D superconducting devices, we can achieve high efficiency at the quantum threshold.

Device and system design

At Fermilab, we have developed bulk Nb superconducting radio-frequency (SRF) cavities with record-high 2 second photon lifetime, which represents a significant improvement compared to previous efforts in this field.



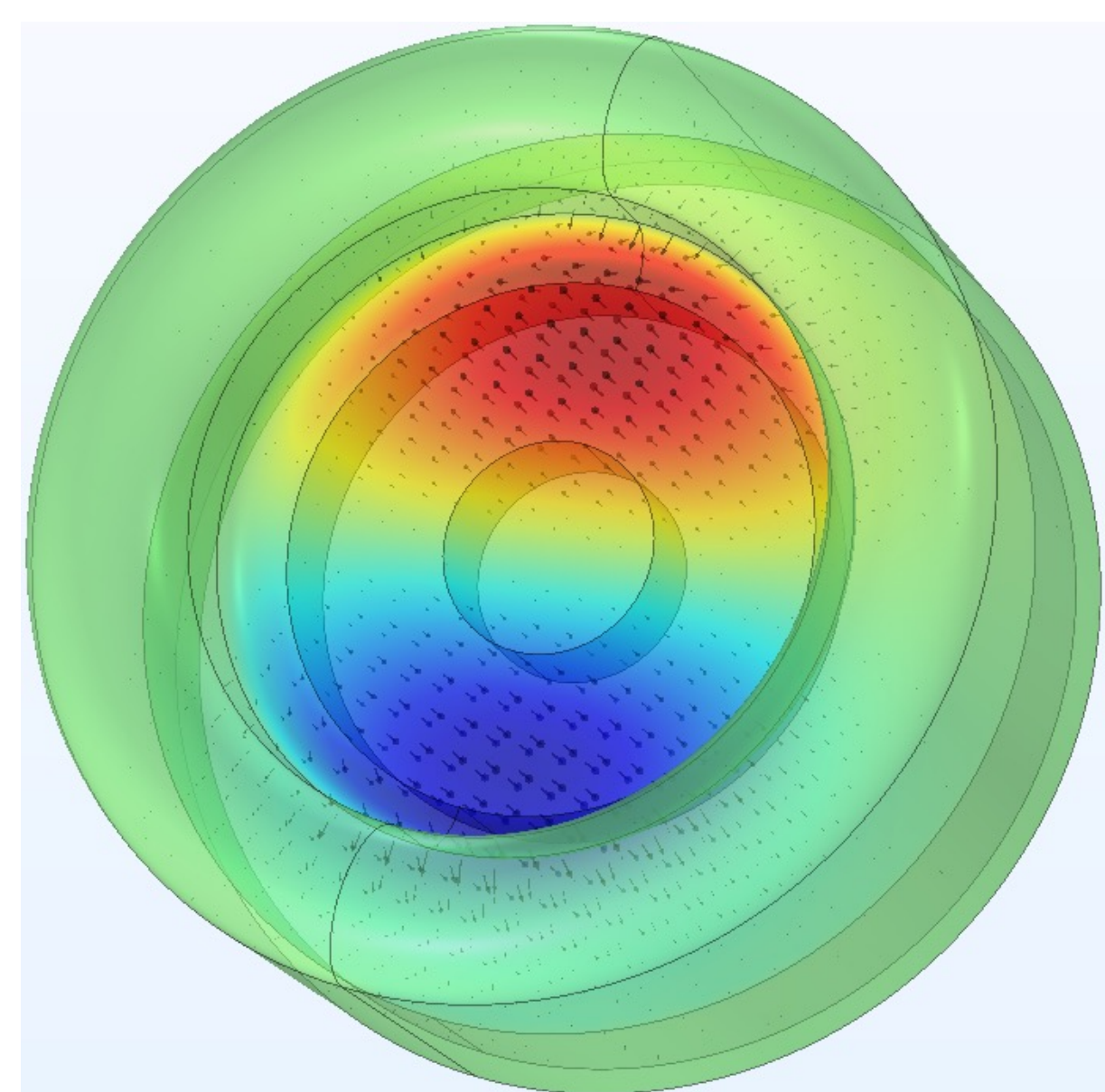
Romanenko, A., Pilipenko, R., Zorzetti, S., Frolov, D., Awida, M., Belomestnykh, S., Posen, S. & Grassellino, A. (2020). *Physical Review Applied*, 13(3), 034032.



The 3D hybrid quantum system consists of a bulk Nb SRF cavity embedded with an optical resonator made of Lithium Niobate. The RF cavity supports a 9GHz dipole mode. The LN optical resonator supports whispering gallery mode.

The pump optical mode (a_p) is driven to coherently couple the optical signal mode (a_s) with the microwave mode (b), with the electro-optic (EO) coupling strength g about $2\pi \times 60\text{Hz}$. The interaction Hamiltonian to model this system is

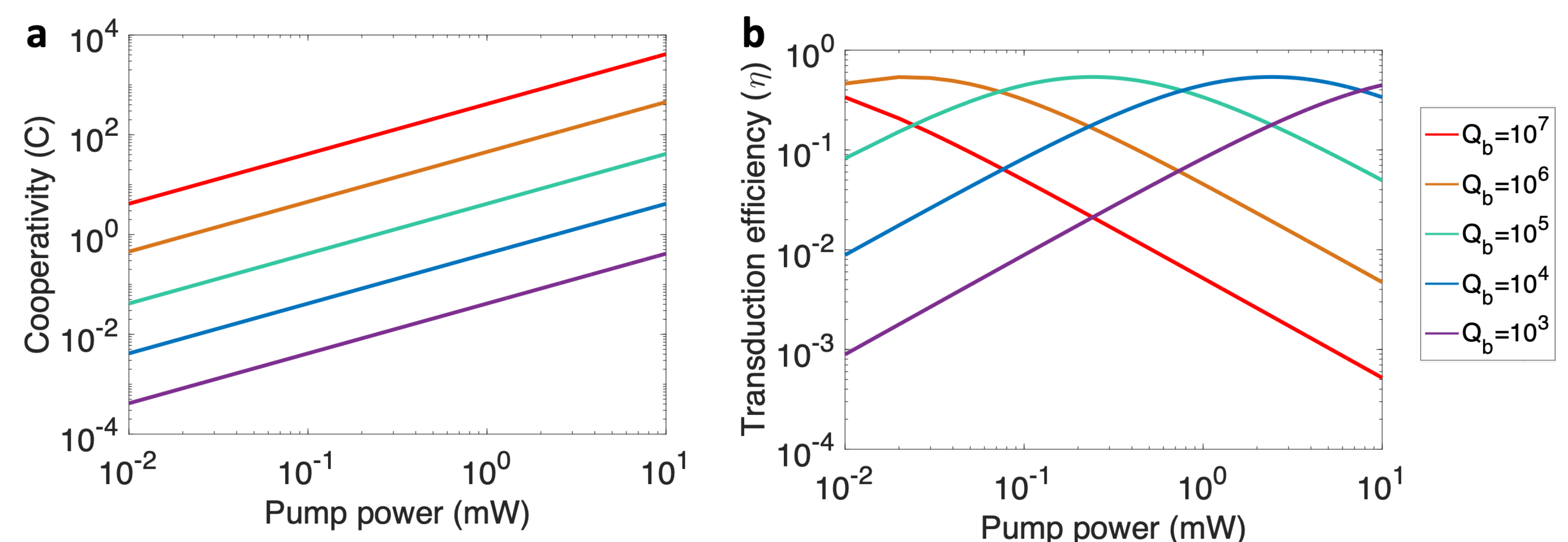
$$H = \hbar g (a_p a_s^\dagger b + a_p^\dagger a_s b^\dagger).$$



3D quantum transduction

The high microwave quality factor and large coupling strength between microwave and optical modes are expected to lead to orders of magnitude enhancements for transduction efficiency at a low pump power.

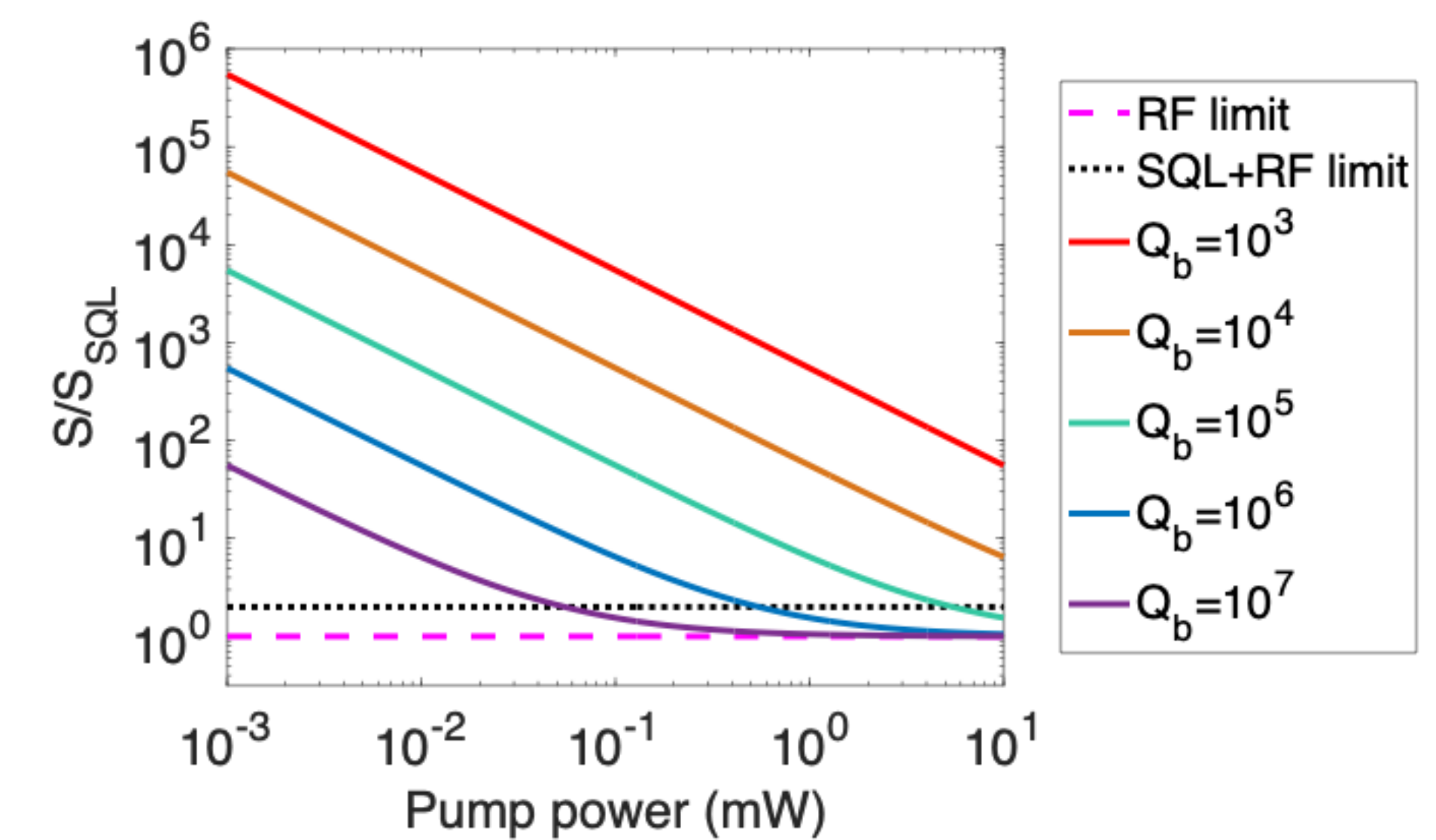
$Q \sim 10^5 \rightarrow 50\%$ efficiency at $150\mu\text{W}$



Enabling technology

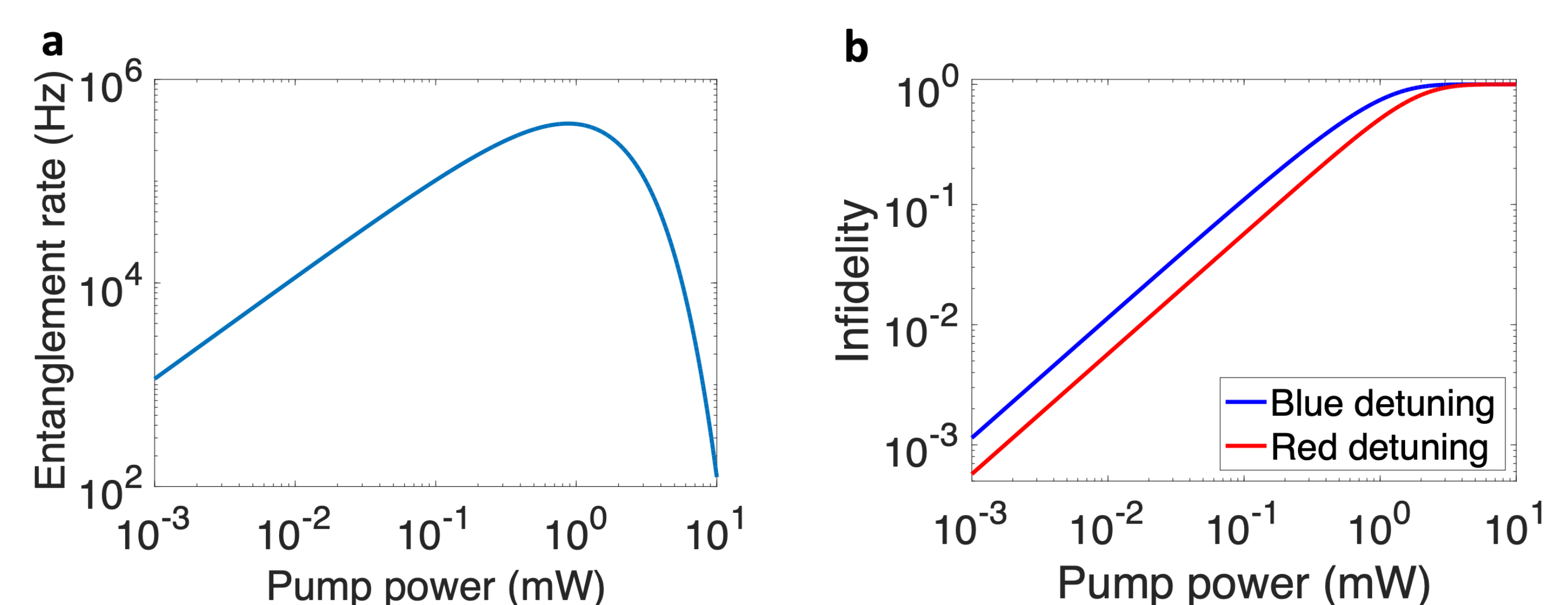
Quantum Sensing

- Single-photon sensing by microwave measurements below the standard quantum limit (SQL)
- Highly sensitive axion and dark photon haloscope searches in the THz regime.



Quantum Networks

High-fidelity heralded quantum entanglement generation between two distant quantum processing units.



References

Pre-prints: [arXiv:2206.15467](https://arxiv.org/abs/2206.15467), [arXiv:2204.13112](https://arxiv.org/abs/2204.13112)
Whitepapers: [arXiv:2203.12714](https://arxiv.org/abs/2203.12714), [arXiv:2204.08605](https://arxiv.org/abs/2204.08605)

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