Tuning in to Dark Matter with ALPHA

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Fermilab

Axion-Maxwell Equations

- Easiest to just think of the axion as modifying Maxwell equations
- Note: ϵ, μ are complex and can be less than 1, or even negative
- External B-field $\mathbf{B}_e$ induces small effective current
- Use the coherence to resonantly excite E-fields

$$\begin{aligned} \nabla \cdot (\epsilon \mathbf{E}) &\simeq \rho_f \,, \\ \nabla \times (\mathbf{B}/\mu) - \epsilon \dot{\mathbf{E}} &\simeq \mathbf{J}_f + \boxed{g_{a\gamma} \mathbf{B}_e \, \dot{a} \,,} \\ \nabla \cdot \mathbf{B} &= 0 \,, \\ \nabla \times \mathbf{E} + \dot{\mathbf{B}} &= 0 \,, \end{aligned}$$

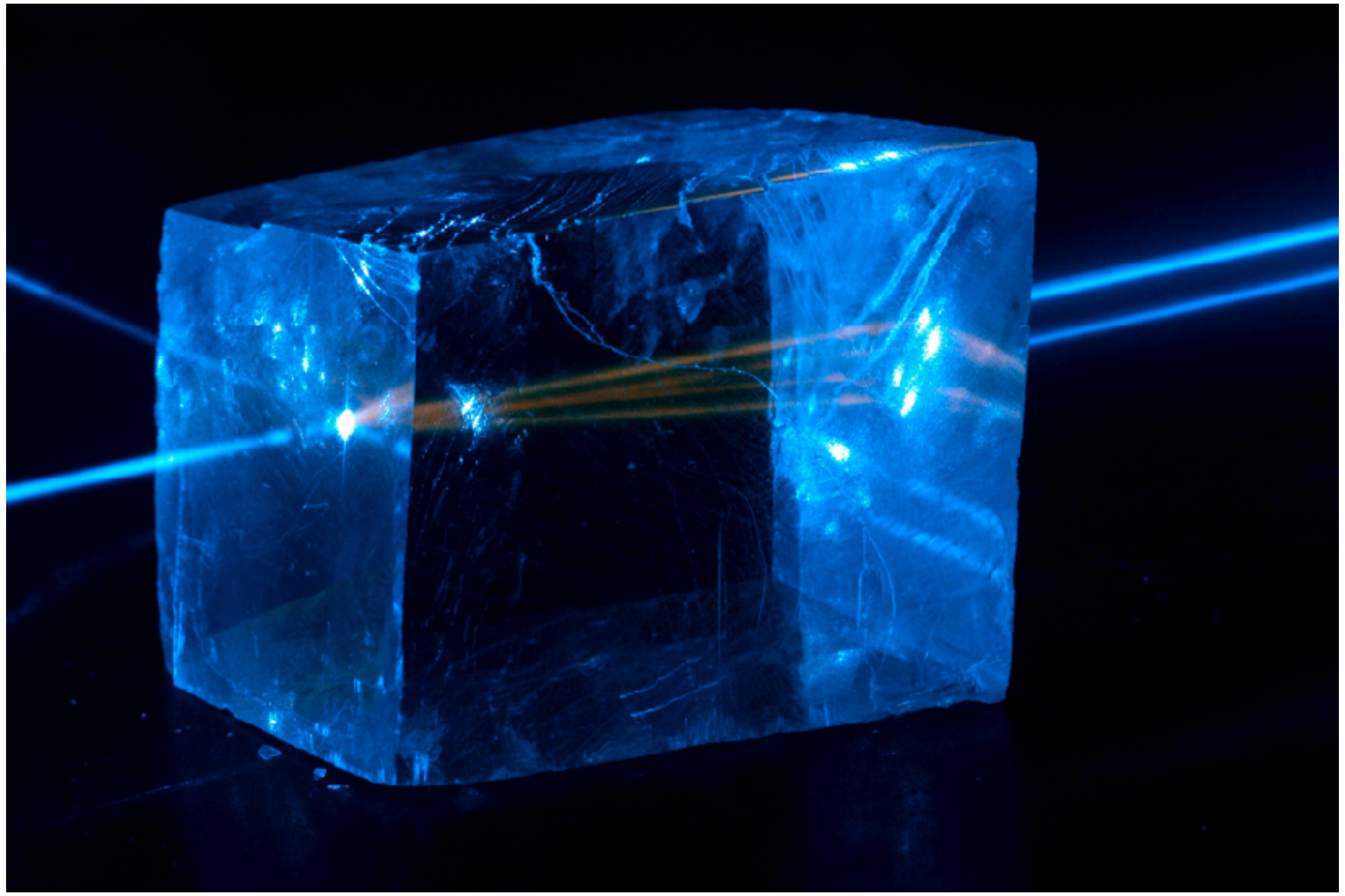
Looks like a current!

Medium Effects

- The induced E-field depends on the medium

$$\mathbf{E} = -\frac{g_{a\gamma}\mathbf{B}_{\rm e}a}{\epsilon}$$

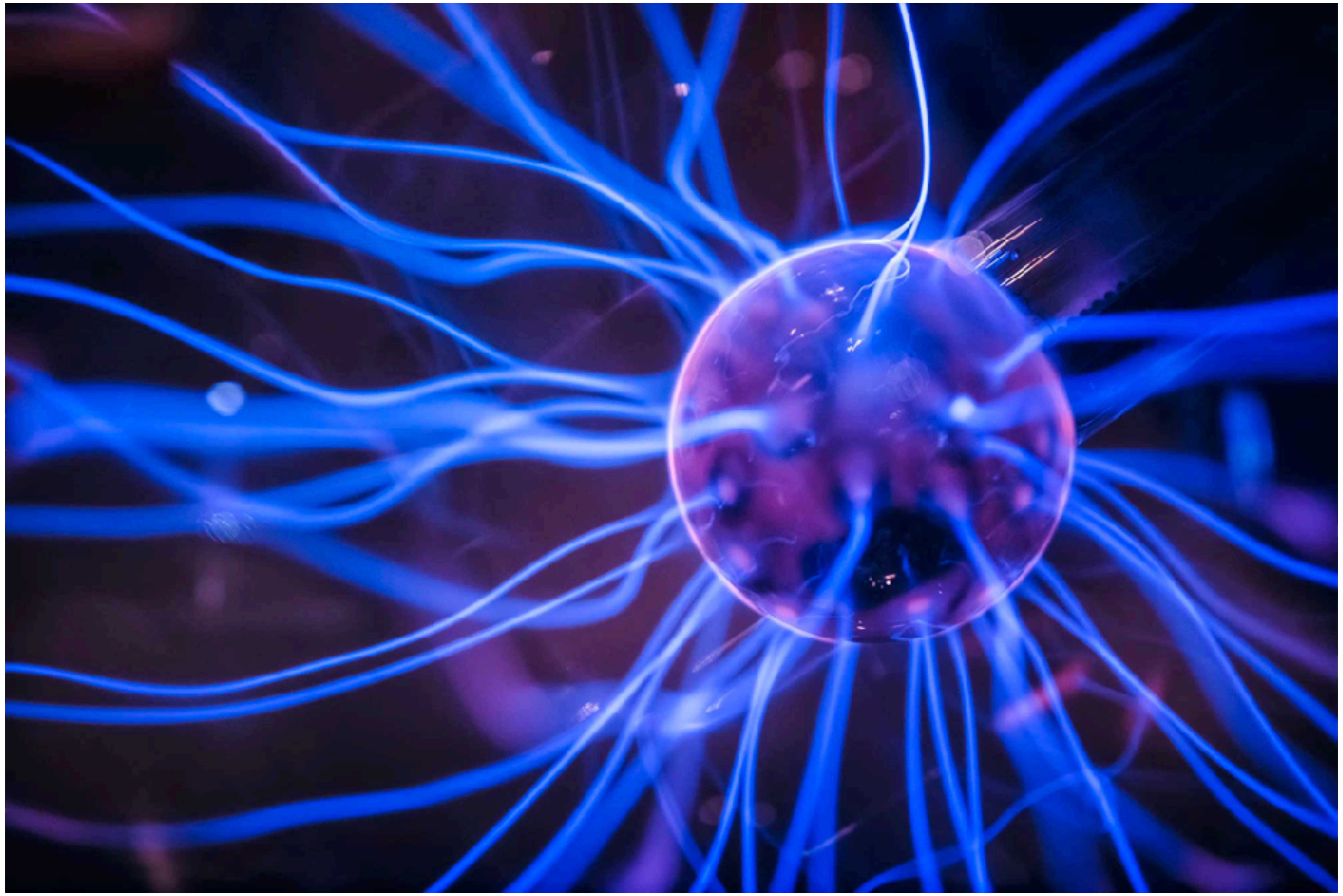
- What if ε is very small?
- Resonant enhancement



WikiCommons

What Do You Want in a Material?

- Cryogenic temperatures
- Preferably a tunable mass
- Large volume
- “Low” mass
- Low material losses



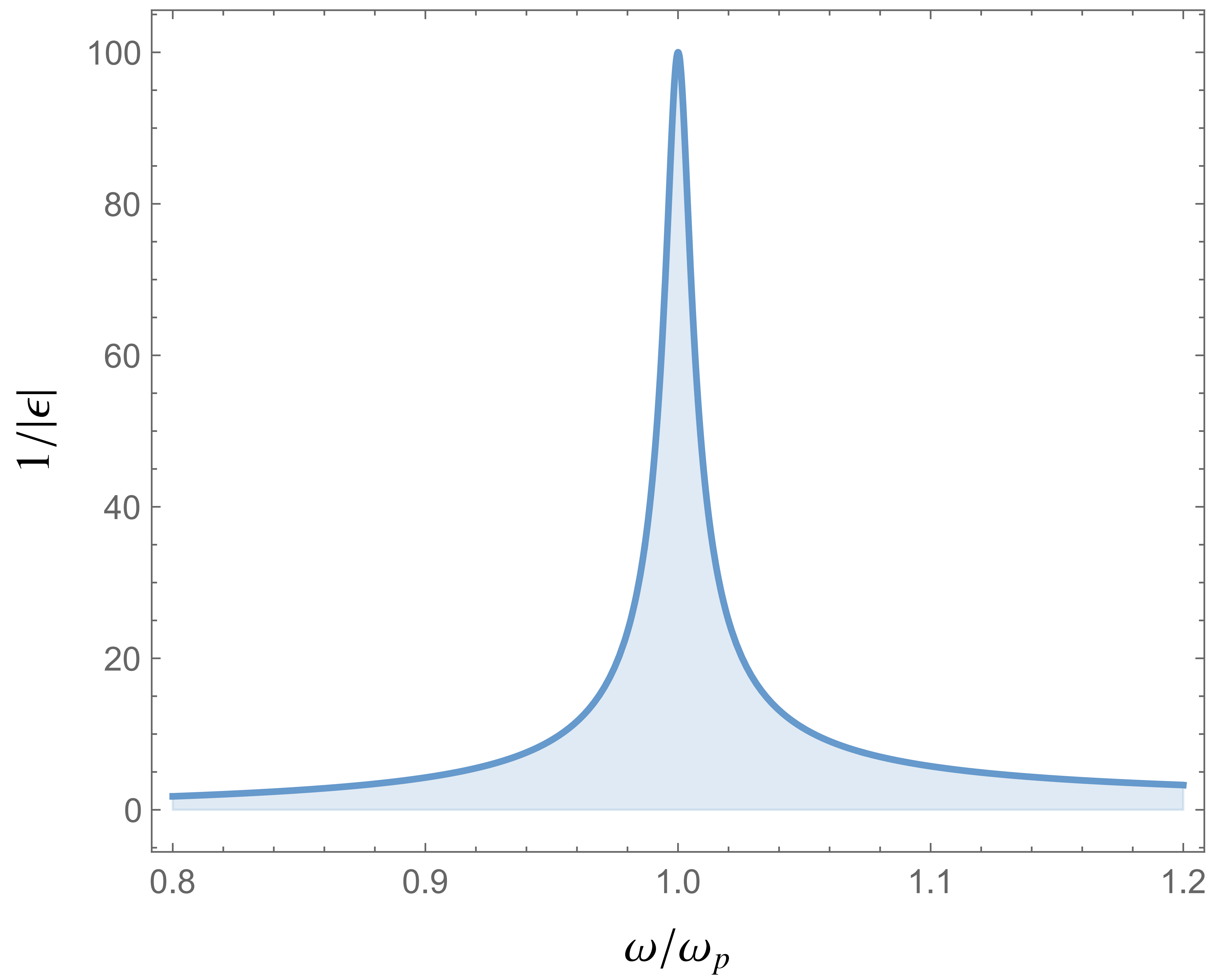
https://www.agro-chemistry.com/

Classic Case: a Plasma

- Collective motion of electrons give an effective mass (plasma frequency ω_p)

$$\epsilon = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma}$$

- Hot plasmas in astrophysical environments give axion production
- Cold plasmas also exist
- Low losses, $\Gamma \ll \omega_p$, gives good resonance

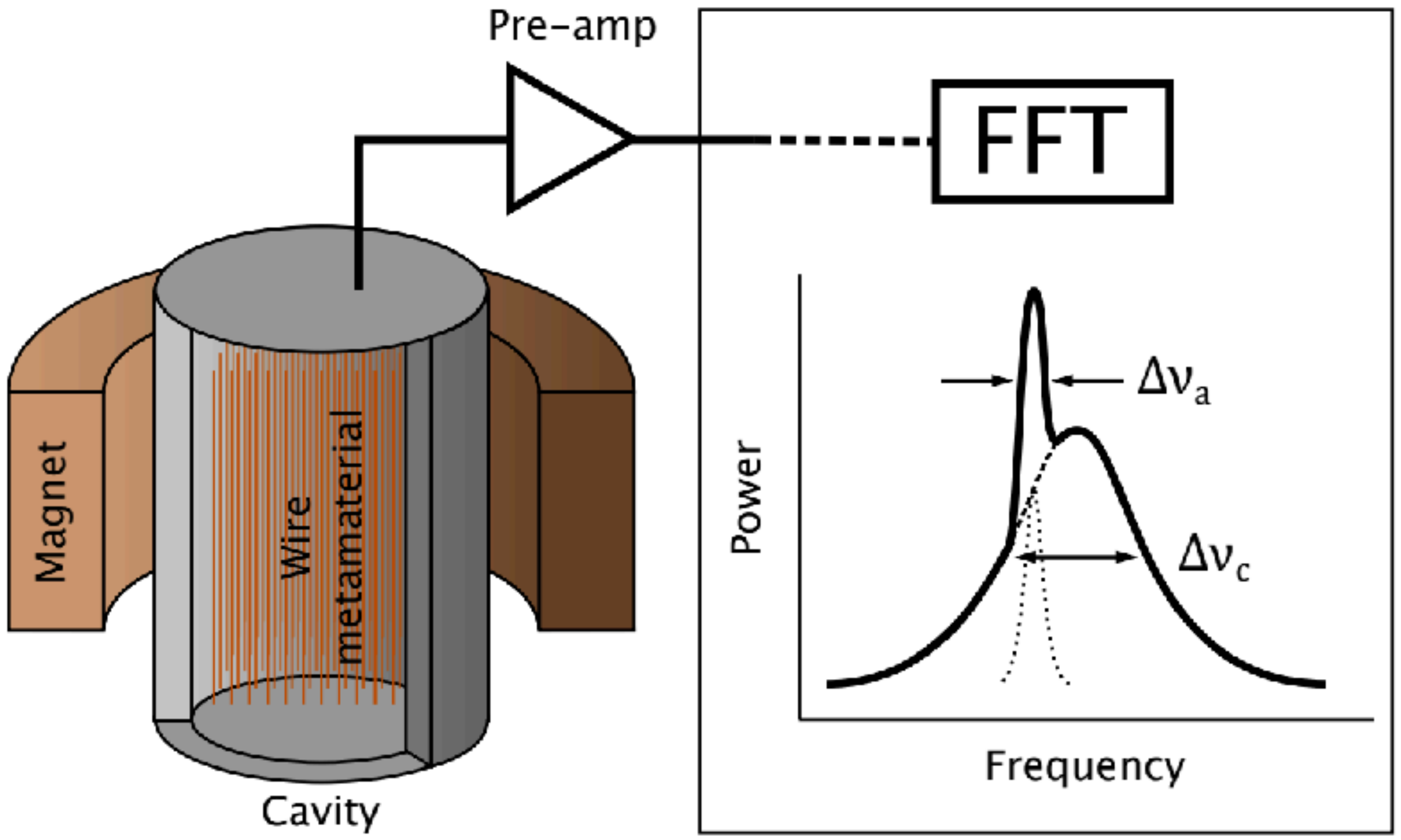


Wire Metamaterials

- One of the first metamaterials
- Plasma frequency determined by two factors: effective electron number density and mass
- Wires mutually induct, changing the plasma frequency
- cm spacing gives ~$\mathcal{O}(10\ \mu\text{eV})$ plasma frequency

The Road to Experiment

- Idea in Lawson, AM, Pancaldi, Vitagliano and Wilczek, *Phys. Rev. Lett.* 123 (2019)
- Designing tuning systems, optimizing Q…
- Much larger volumes/higher power for high frequencies than traditional approaches
- Working on new quantum detectors for readout



Kowit et al, *Phys.Rev.Applied* 20 (2023)

ALPHA

- Newly formed collaboration
- Funded by the Simons and Templeton Foundations in the States and the Wallenberg Foundation in Sweden
- 16 T Magnet provided by Yale, where ALPHA will be operated
- Future plans include a sub quantum limited amplification and a larger magnet being acquired at Oak Ridge National Laboratory

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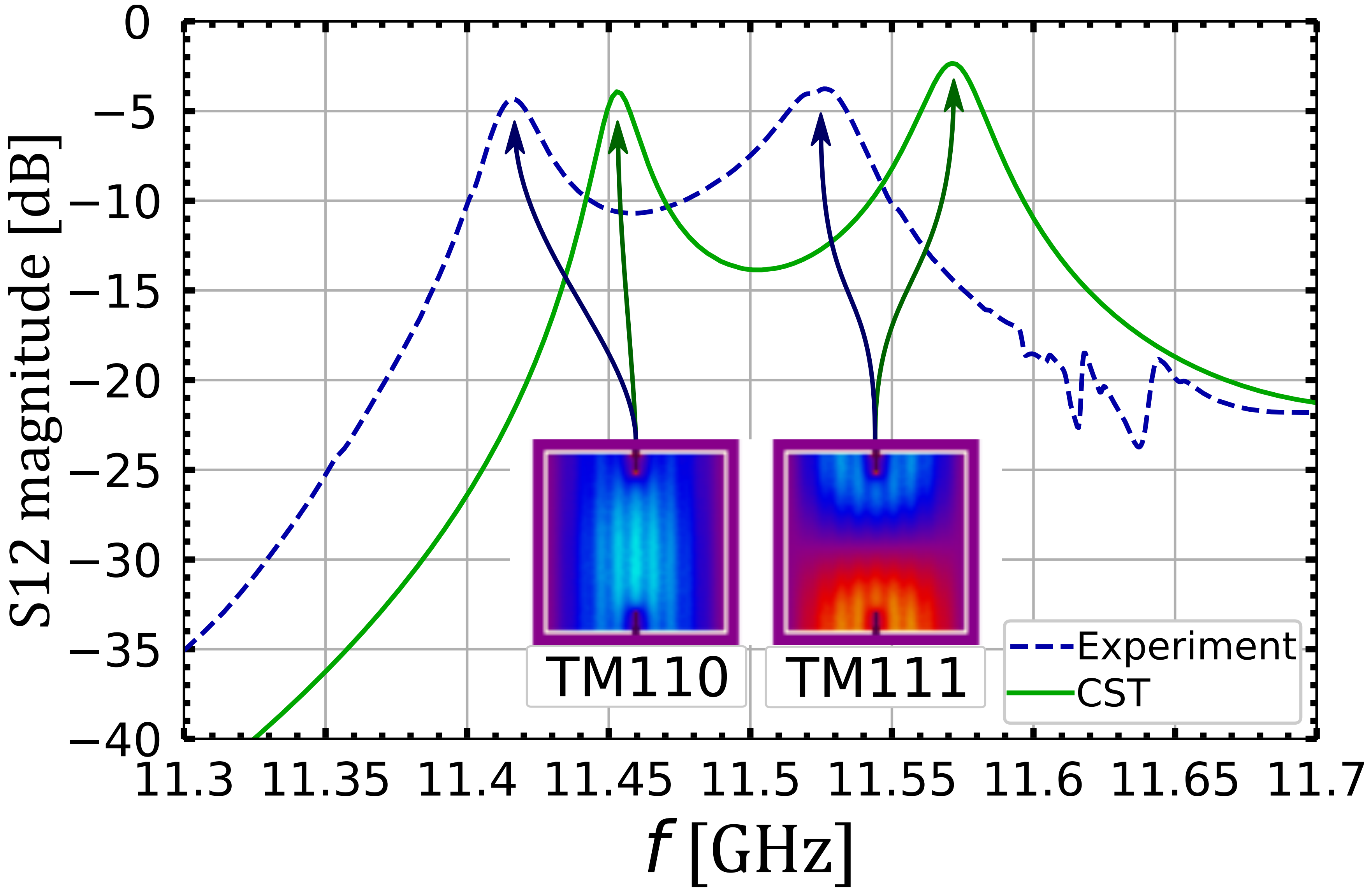
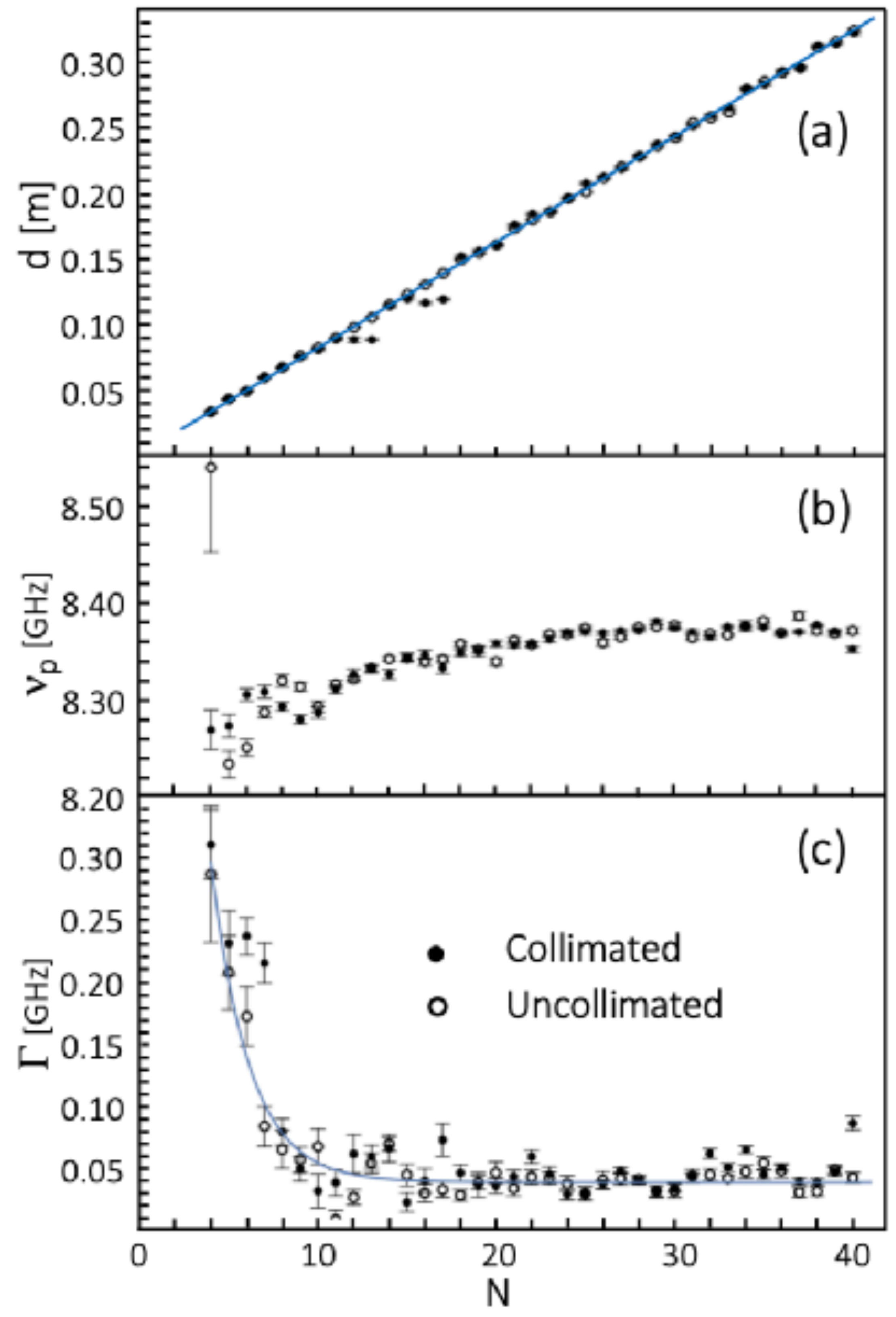
ALPHA

- Developed new analytic and simulations of metamaterials
- Early prototyping shows good agreement between theory and experiment



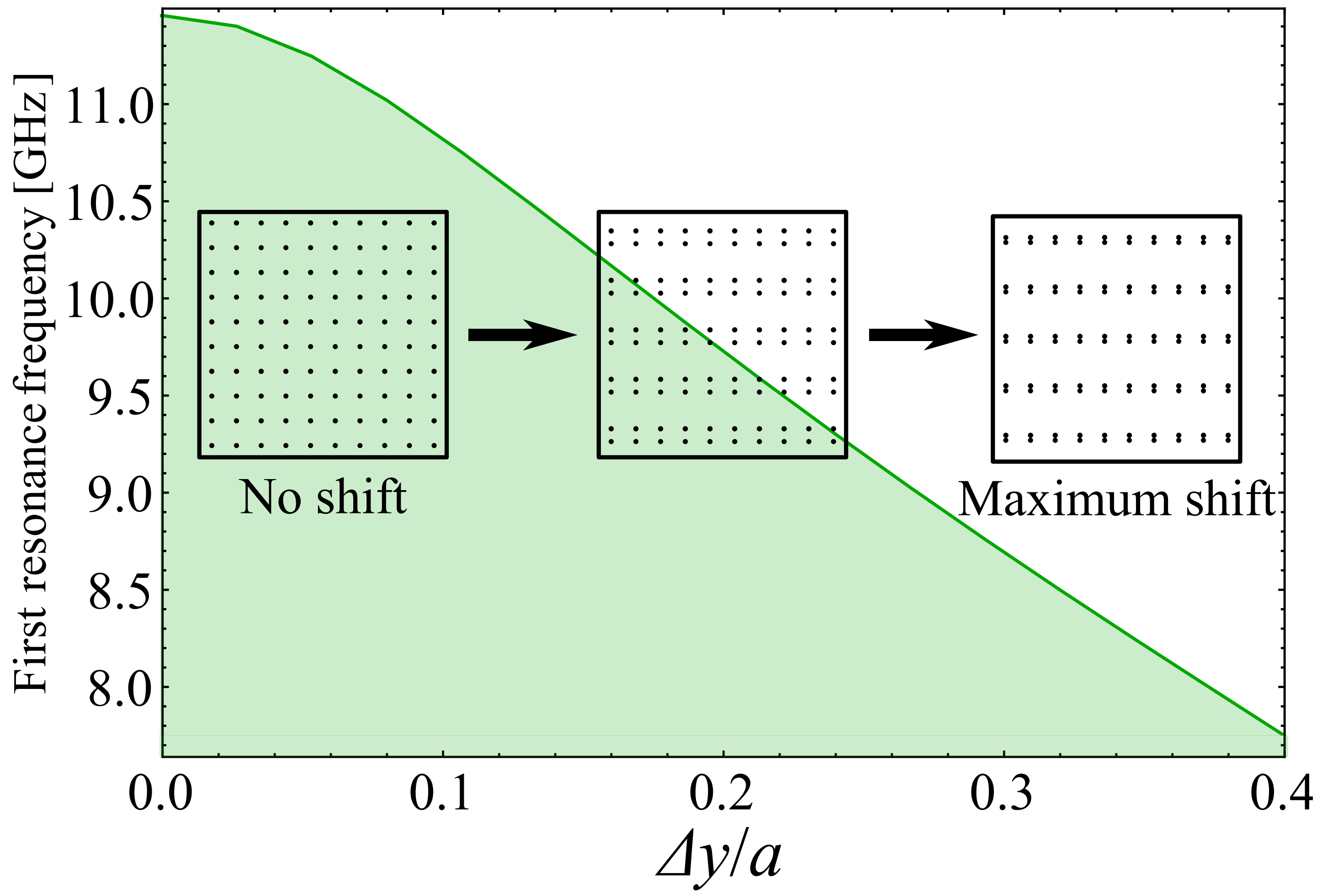
arXiv:2203.10083



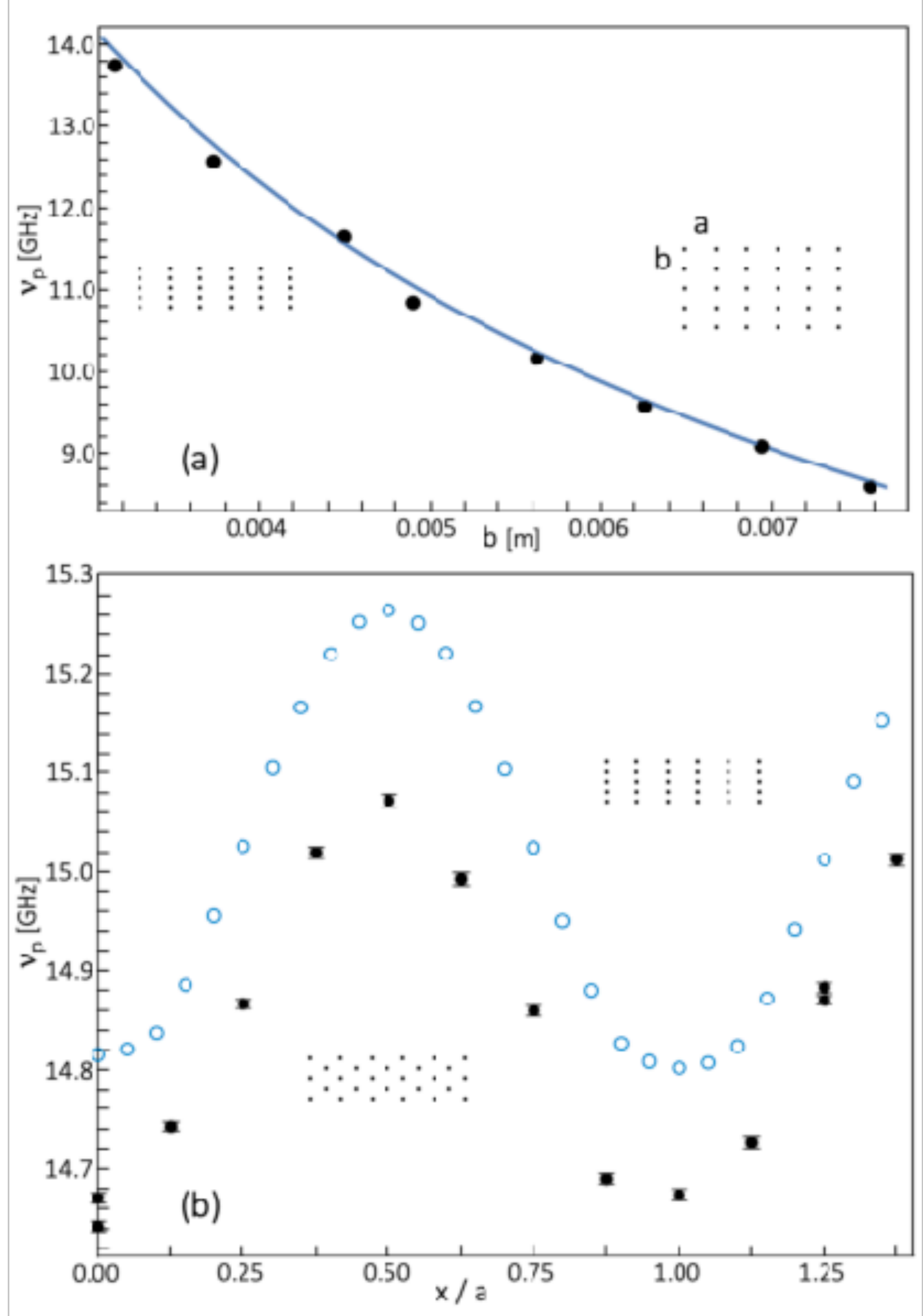
arXiv:2203.13945

Tuning

- Tuneable by modifying wire geometry
- Possibilities including moving planes of wires or pairs of wires closer together and rotating elongated wires



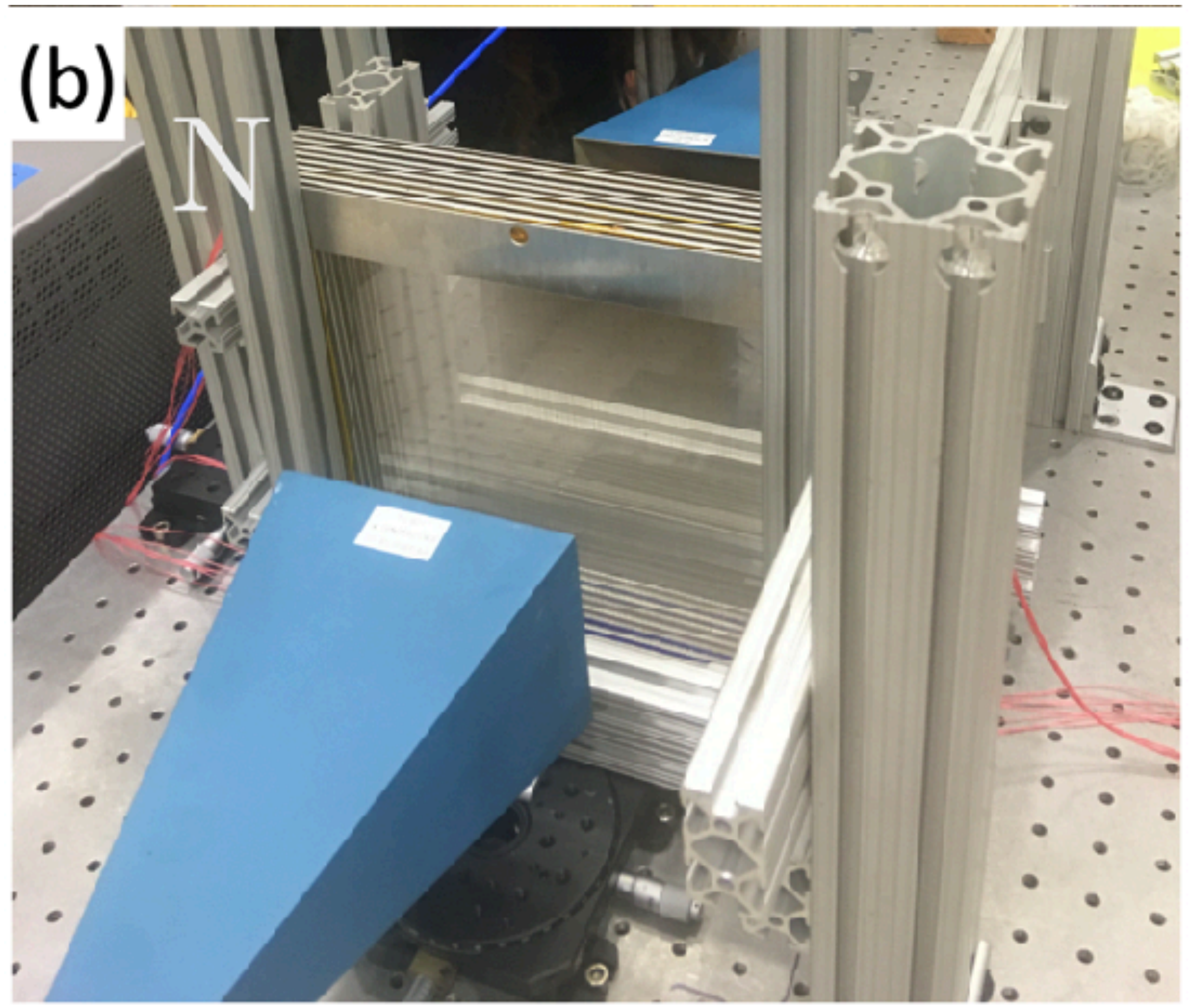
arXiv:2210.00017

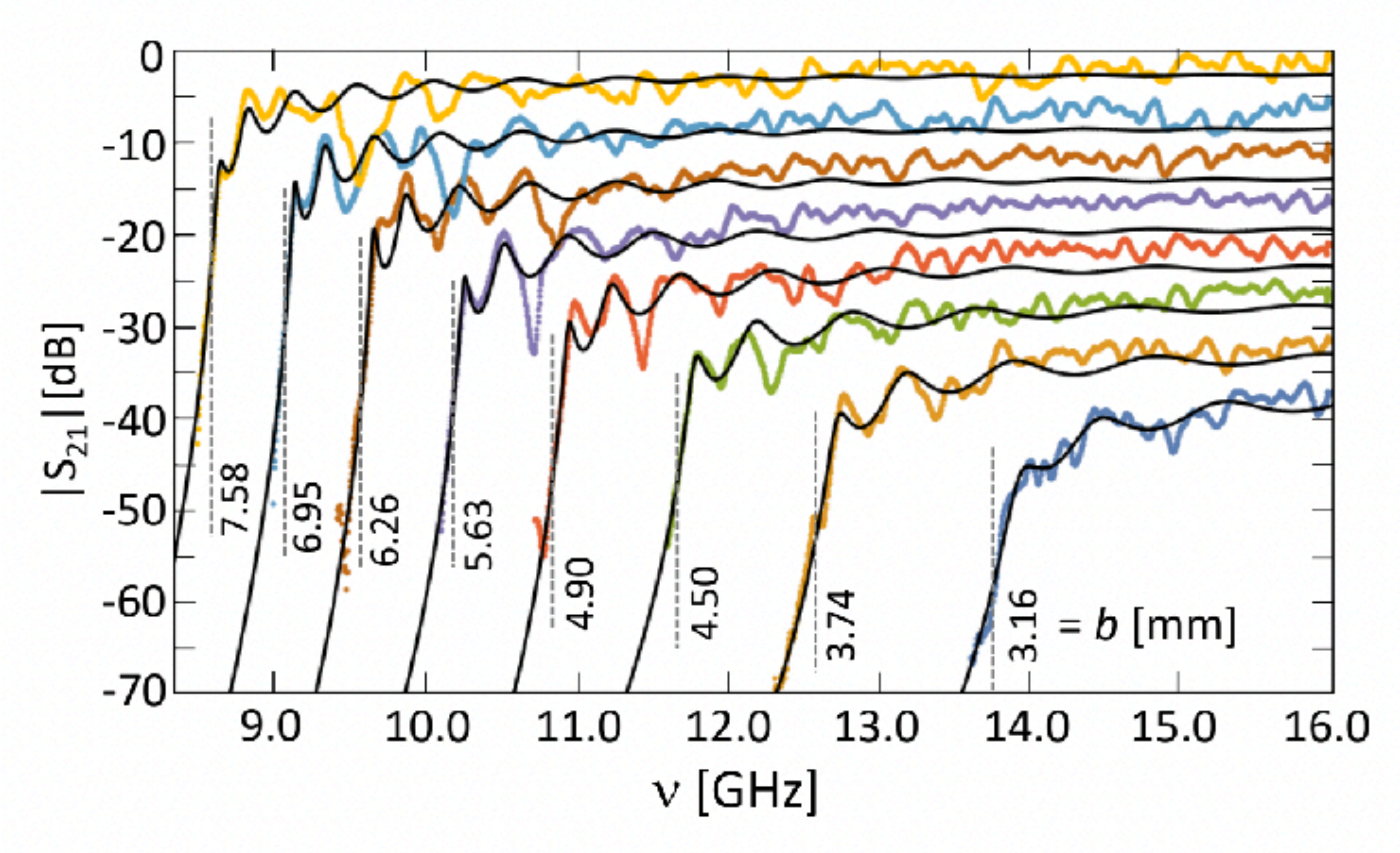


arXiv:2203.13945

Tuning

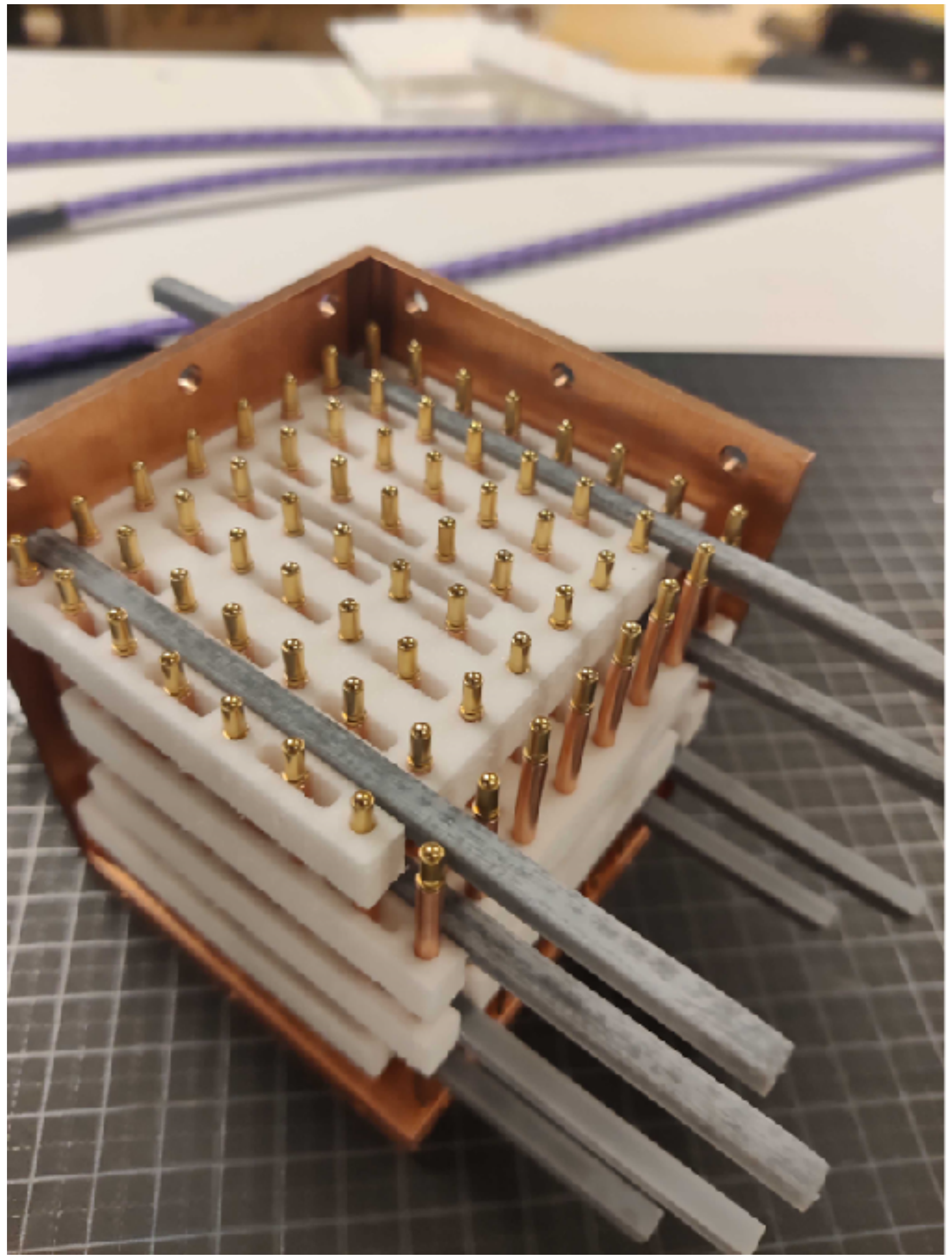
- Early prototypes show excellent agreement with theory
- Tested with thin wires at Berkeley with analytic and simulations from ITMO (arXiv:2306.15734)

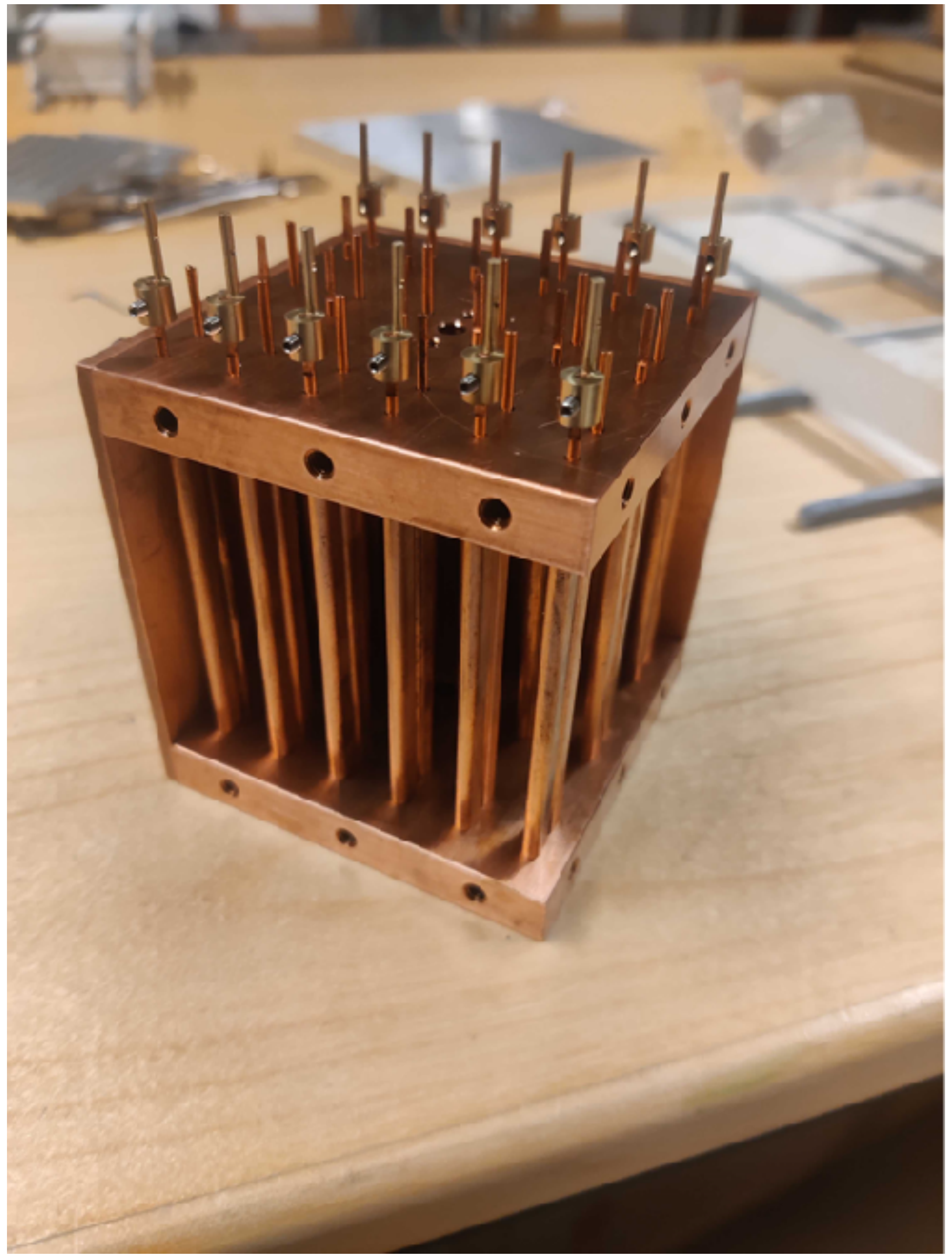





Physics

Prototyping

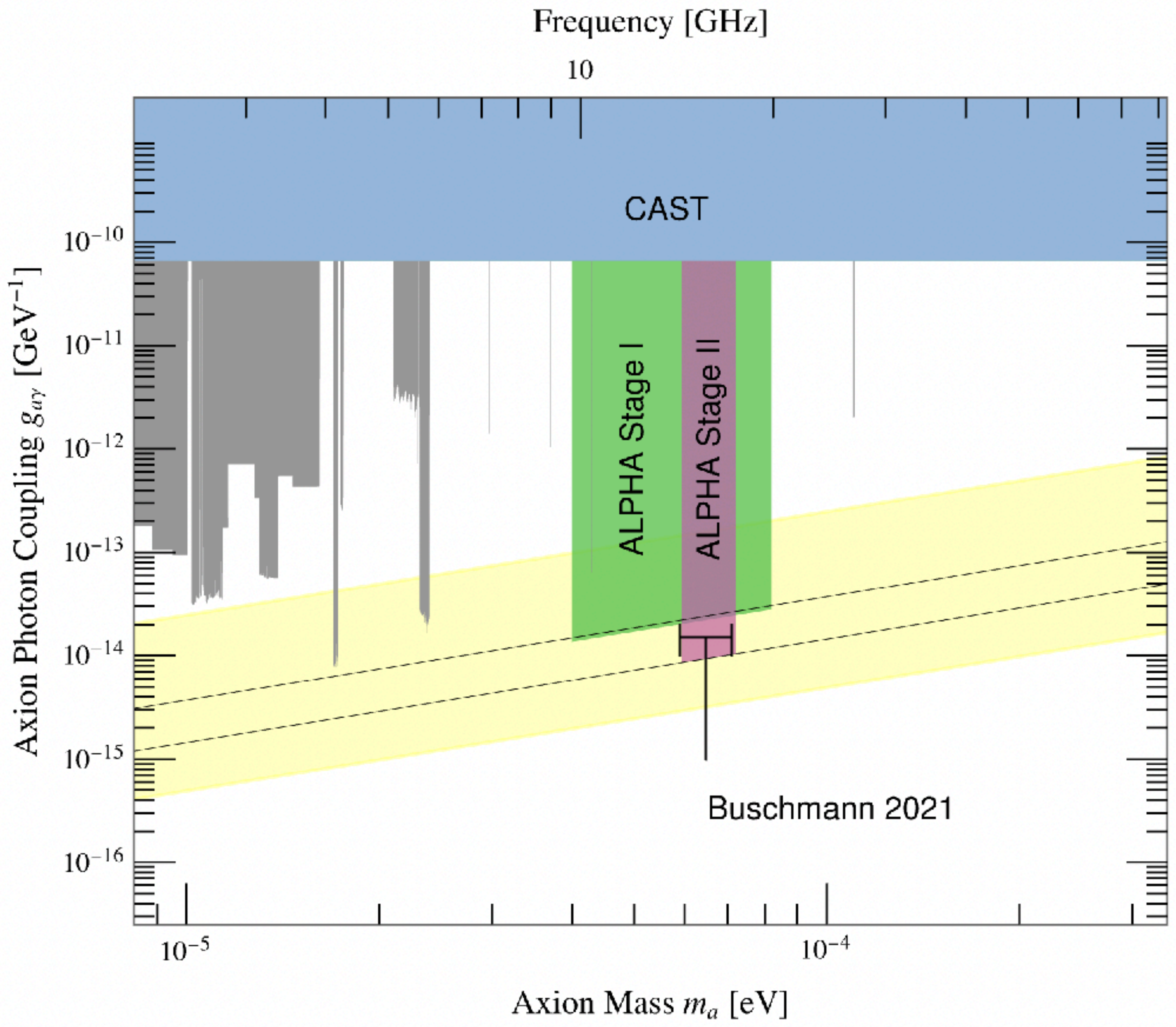




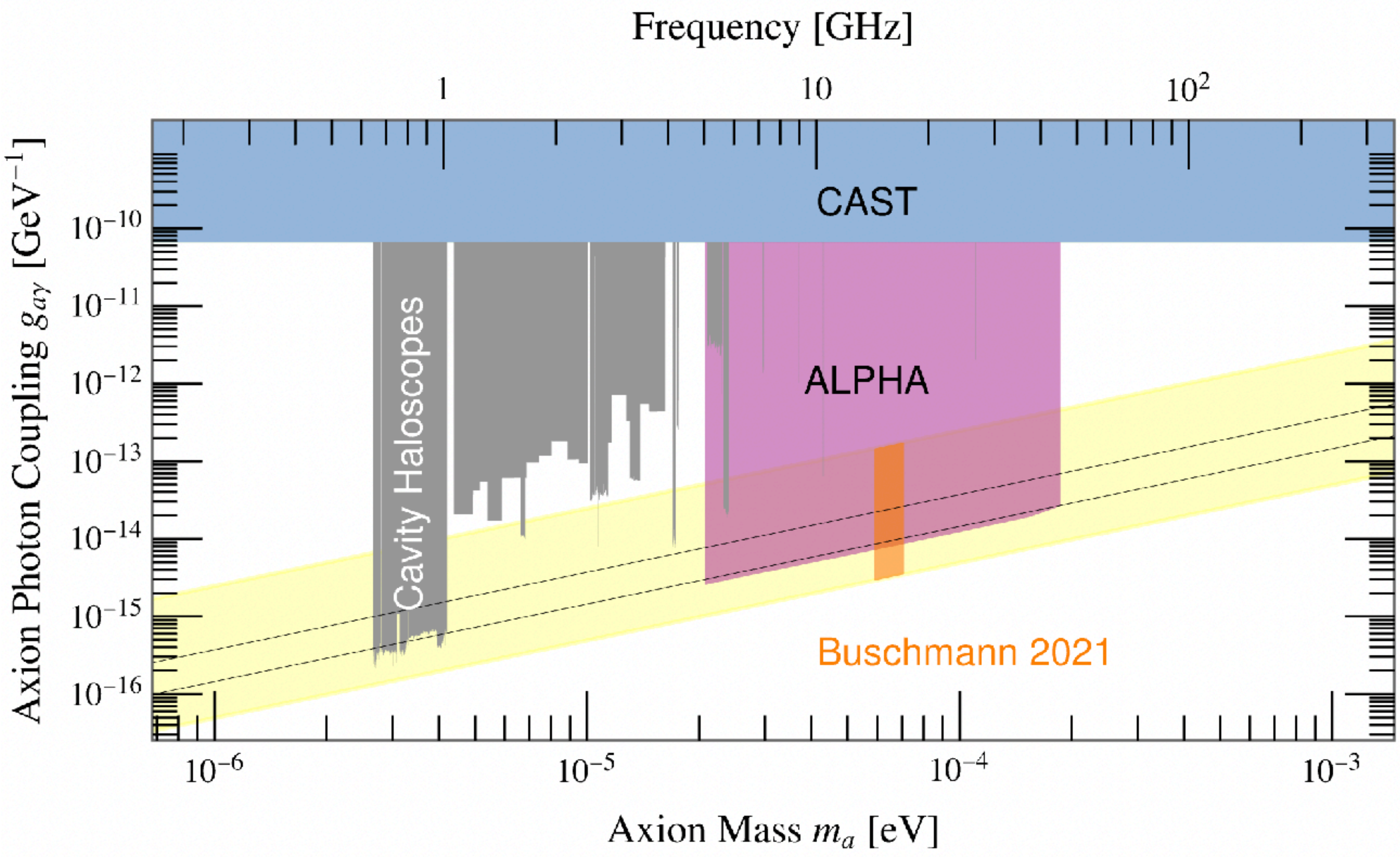
ALPHA R&D Consortium

- Looser group of people interested in broader physics
- Exploring superconducting materials and novel resonator designs
- Locally being investigated by Sam Posen and Grigory Eremeev at SQMS
- Exploring non-mechanical and mechanical tuning options, interesting mode shapes etc

Discovery Potential (Near Term)



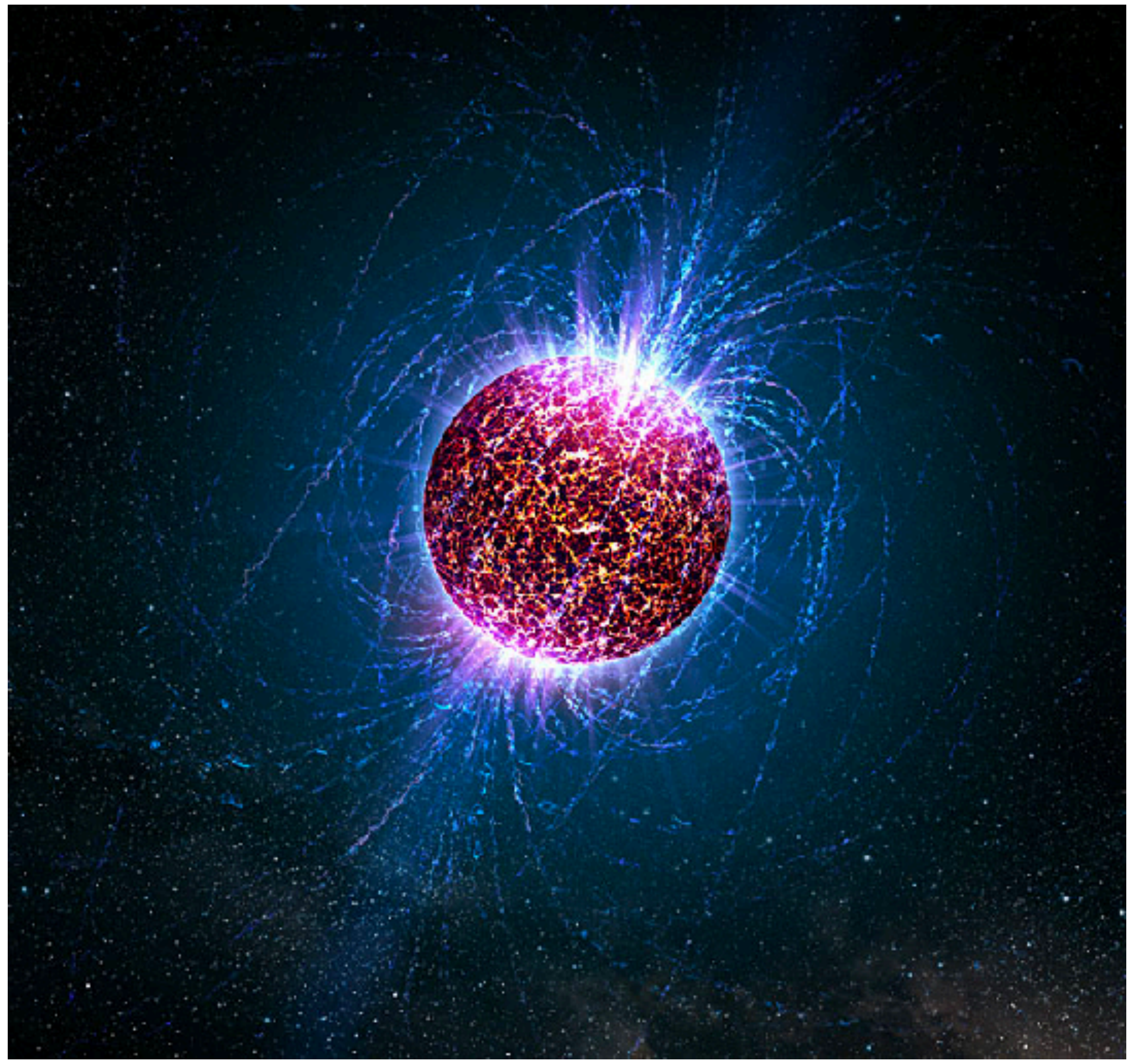
Discovery Potential (Long Term)



Adapted from Millar et al, *Phys.Rev.D* 107 (2023)

Outlook

- Wavelike dark matter sits at the exciting intersection of particle physics, astrophysics, condensed matter physics and quantum detection
- Plasmas and other quasiparticles are a great new way to look for light dark matter
- The same systems also work for other new physics searches such as gravitational waves
- Outstanding synergy with advances in qubits and single photon counting



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