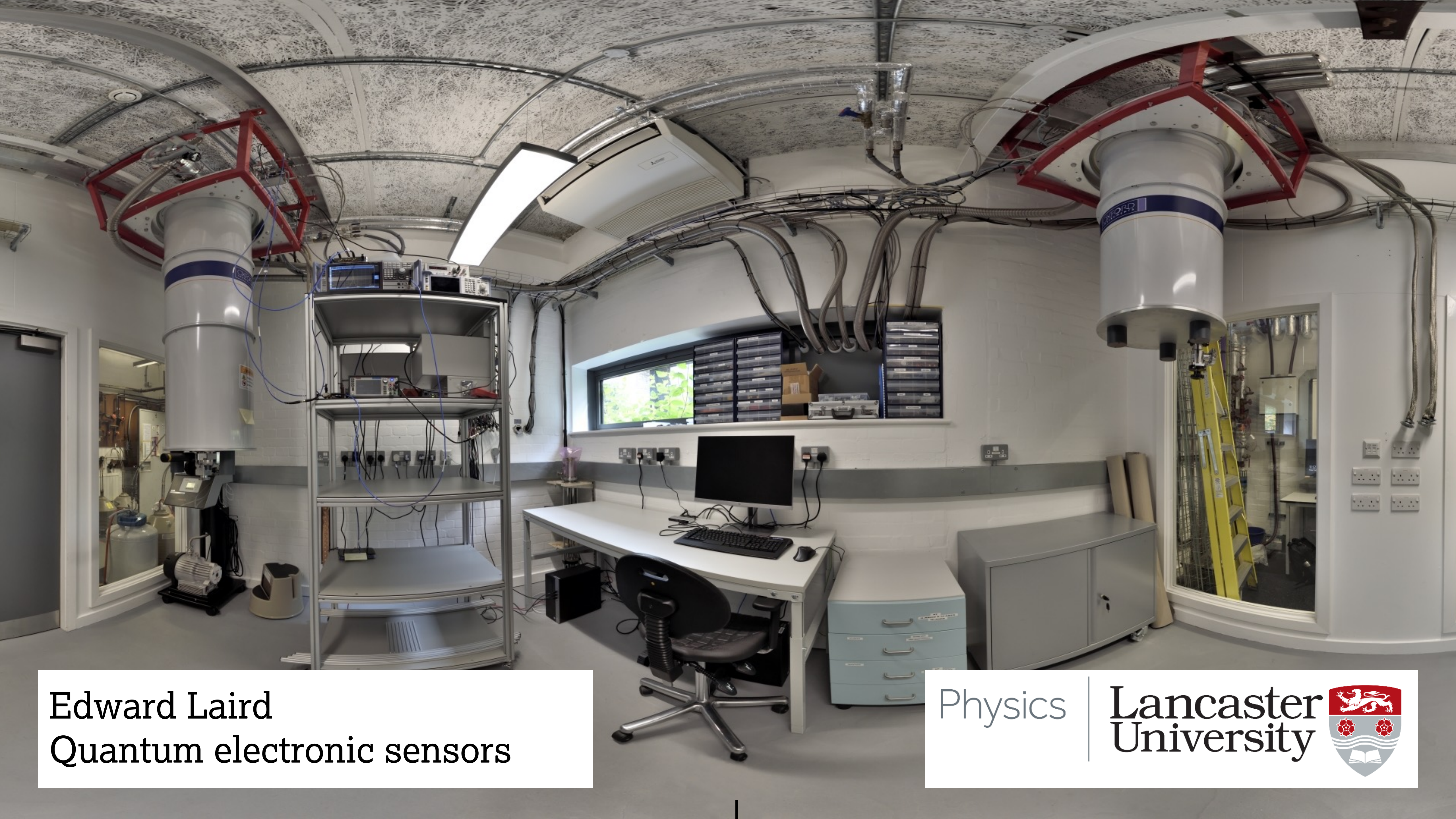
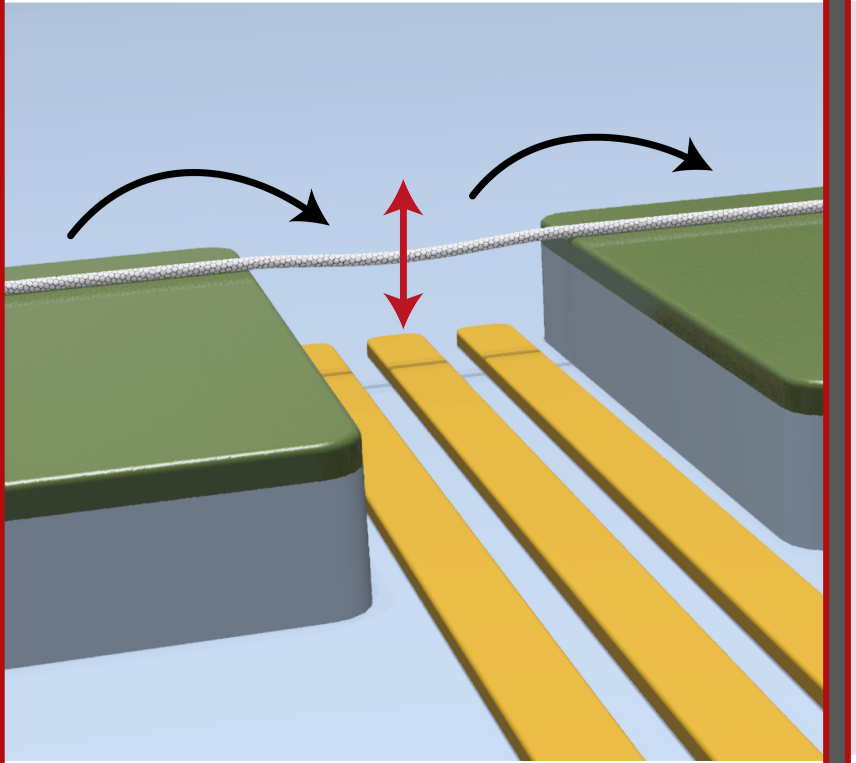


Edward Laird

Quantum electronic sensors

Physics | Lancaster University

Sensing force and motion

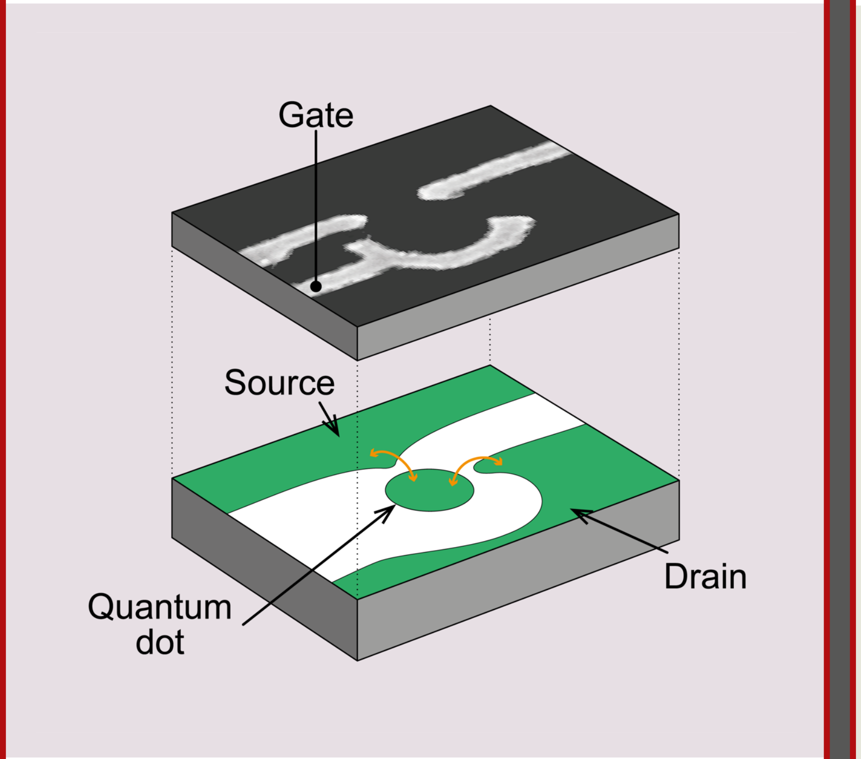


“A coherent nanomechanical oscillator driven by single-electron tunnelling”

Wen et al.

Nature Physics (2020)

Sensing qubits

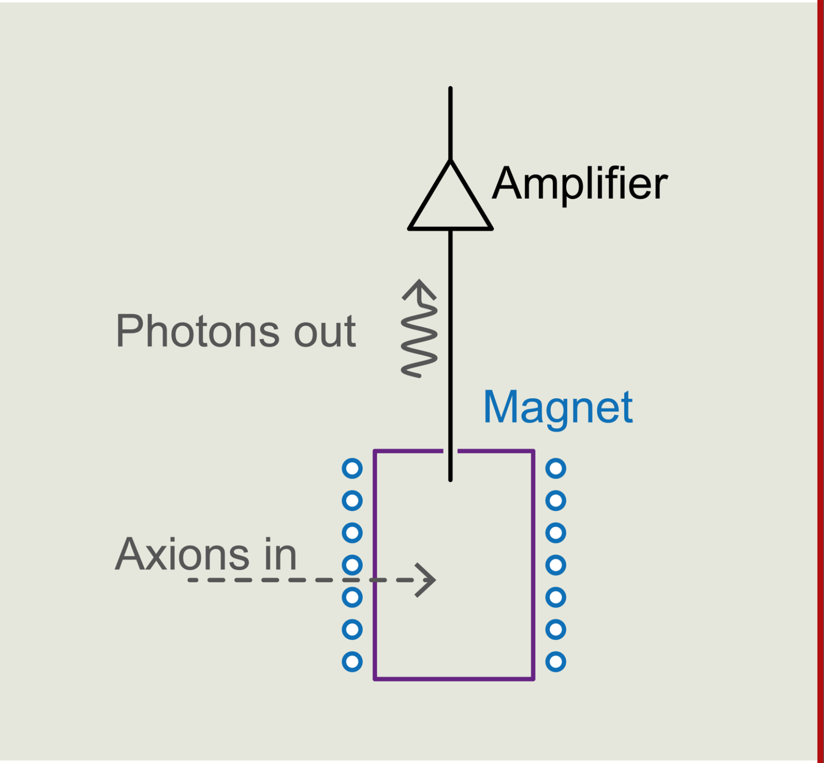


“Sensitive radio-frequency readout of quantum dots using an ultra-low-noise SQUID amplifier”

Schupp et al.

Journal of Applied Physics (2020)

Sensing dark matter



“Searching for wave-like dark matter with QSHS”

Bailey et al.

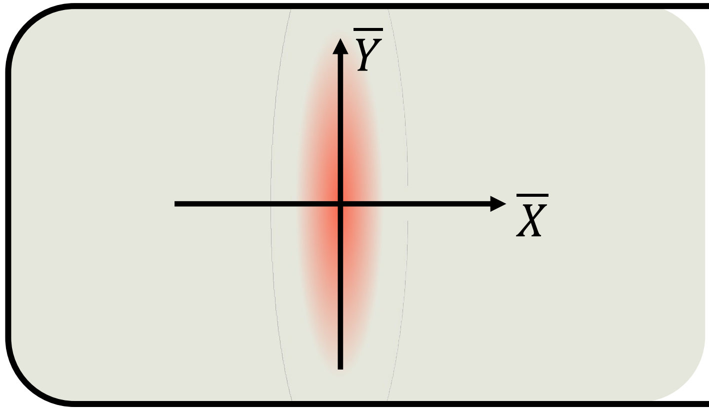
SciPost Physics Proceedings (2023)

Quantum Sensors for the Hidden Sector: An axion search using quantum electronics

Edward Laird
Physics Department, Lancaster University

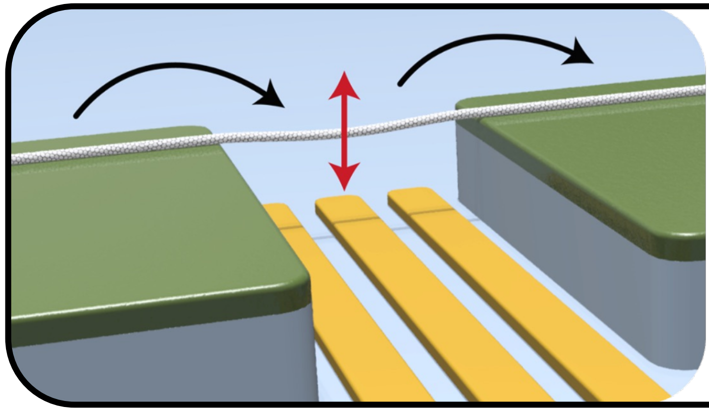
Quantum sensors for the hidden sector

Why should you look for axions?



The QSHS experiment

Looking for axions using quantum technology

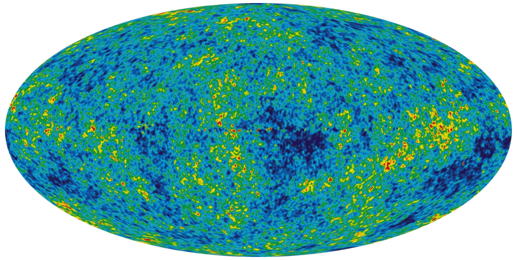


Vibrating nanotubes in superfluid helium

Another device for particle searches?

Is dark matter made from axions?

Evidence from astronomy



Galactic rotation curves
Gravitational lensing
The bullet cluster
Primordial isotopes
Baryon acoustic oscillations

Dark matter

WIMPS

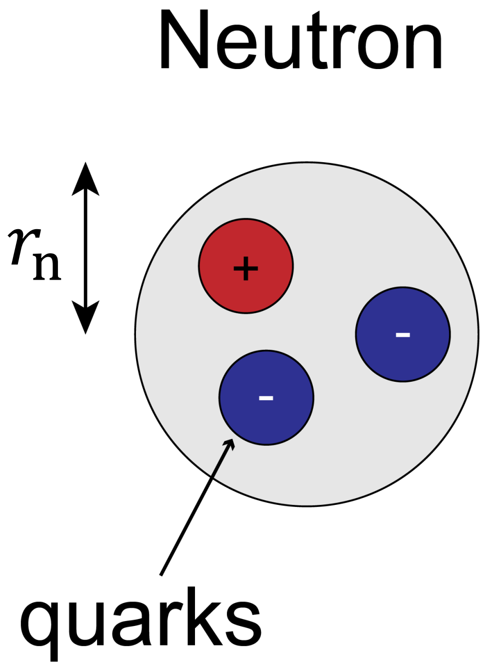
Axions

Something else

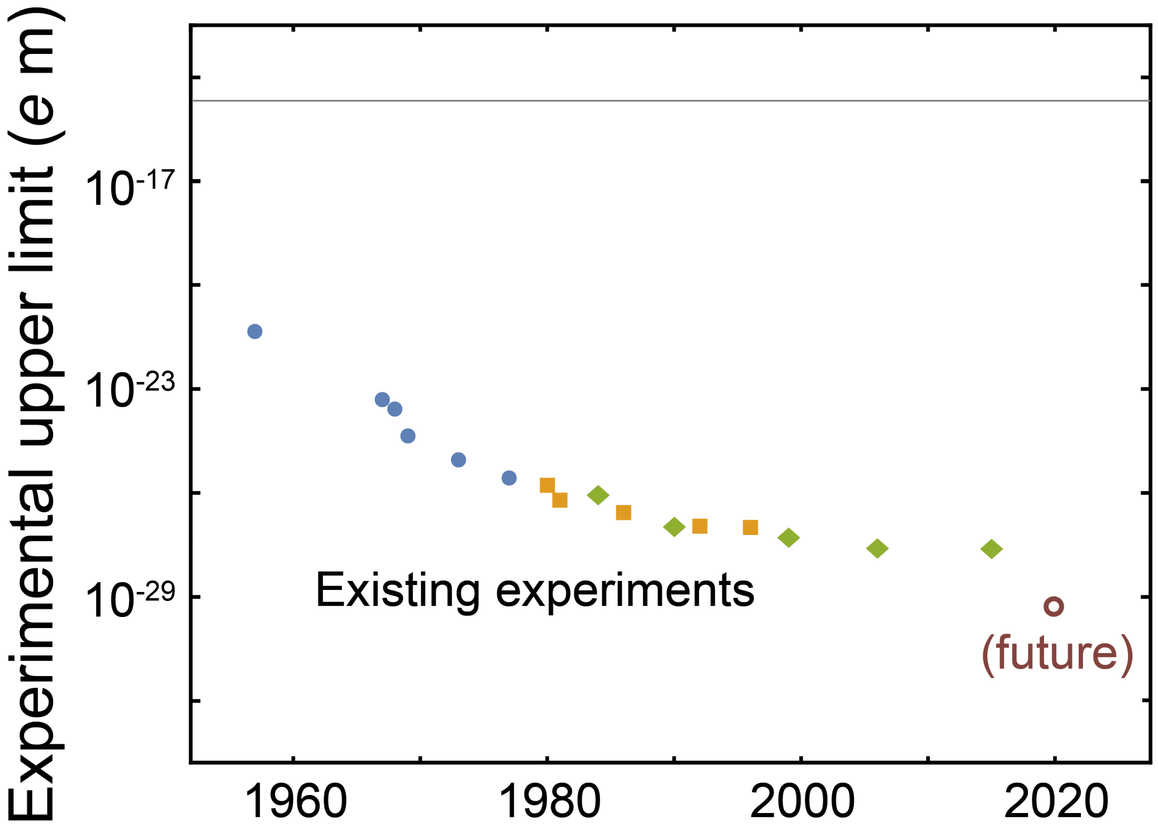
MACHOs
Primordial black holes
Sterile neutrinos
…

Bertone et al, RMP (2018)

Why should you believe in axions?
The strong CP problem



$$d_{\text{expected}} \sim \frac{e}{3} r_{\text{n}}$$
$$\sim 10^{-15}\ e\ \text{m}$$

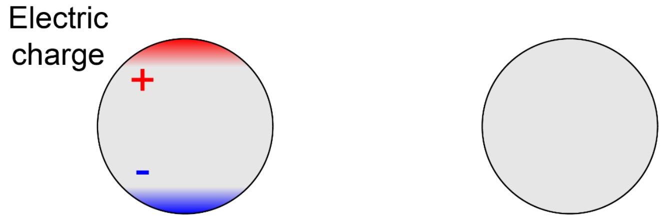


How axions would solve the strong CP problem

Lagrangian of strong nuclear force (simplified):

$$\mathcal{L} = -\frac{1}{4}\underset{\substack{\uparrow \\ \text{Preserves CP symmetry}}}{G_{\mu\nu}}G^{\mu\nu} + \underset{\substack{\uparrow \\ \text{“Dynamic field”}}}{\theta}\,\frac{\alpha_s}{8\pi}\,G_{\mu\nu}\underset{\substack{\uparrow \\ \text{Violates CP symmetry}}}{\tilde{G}^{\mu\nu}}$$

Neutron electric dipole moment



What we expect

What we get

If θ is a number, there is no reason for it to be near zero.

However, if $\theta(\vec{r},t)$ is a field, then there is a mechanism in QCD theory (the Peccei-Quinn mechanism) that holds it near zero.

The axion: a hypothetical particle

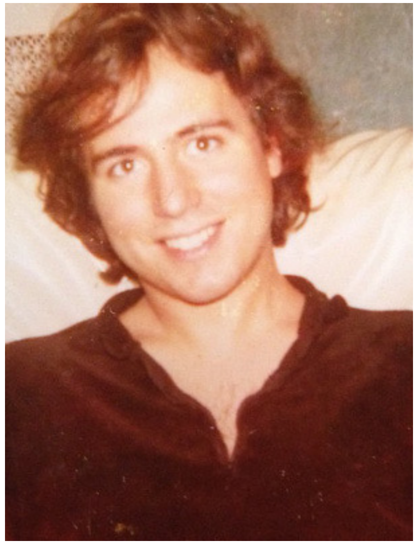
Mechanism
(1977)

Roberto Peccei

Helen Quinn

Particle
(1978)

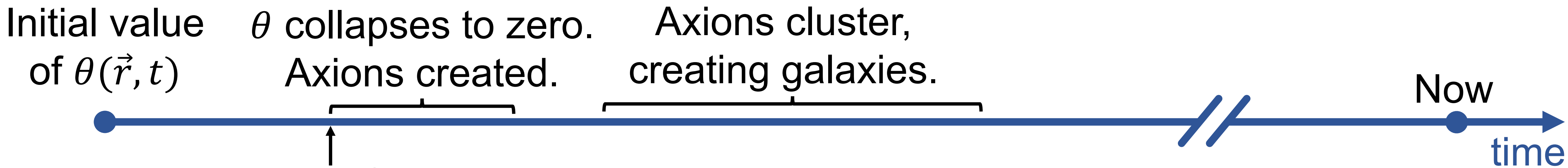
Steven Weinberg



Frank Wilczek

Name

The axion model of dark matter



Initial value
of $\theta(\vec{r}, t)$

θ collapses to zero.
Axions created.

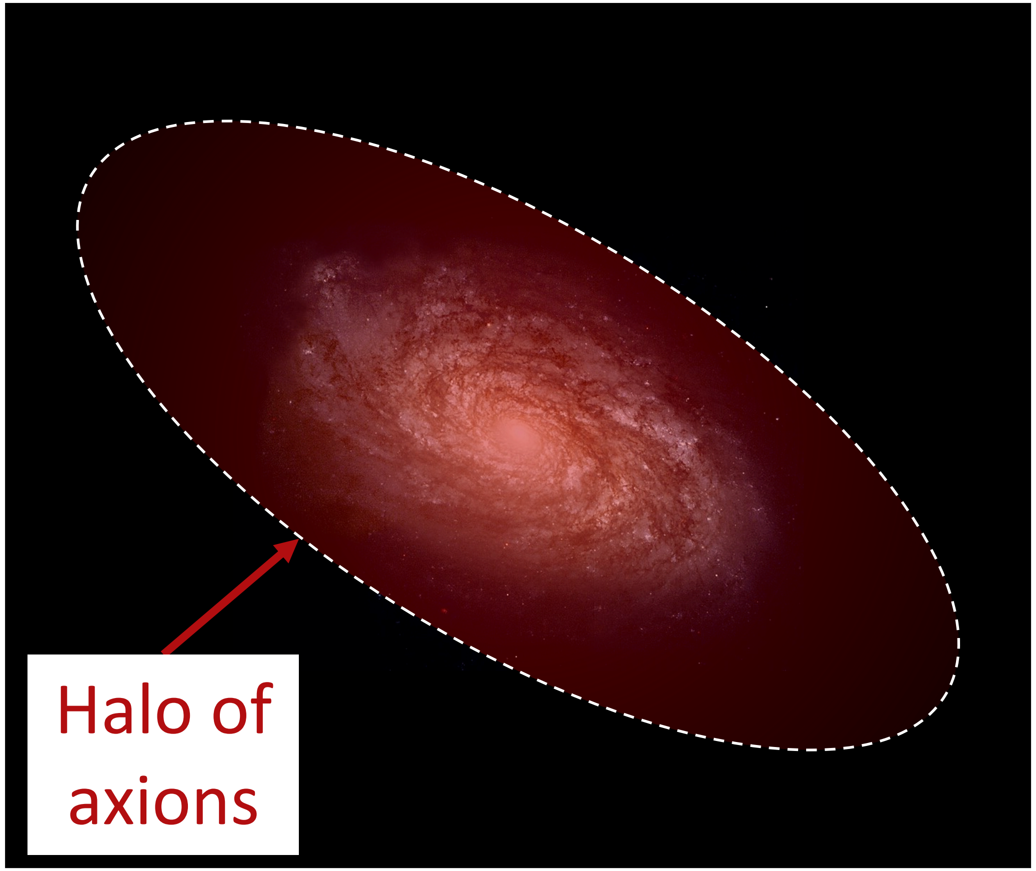
Axions cluster,
creating galaxies.

Now

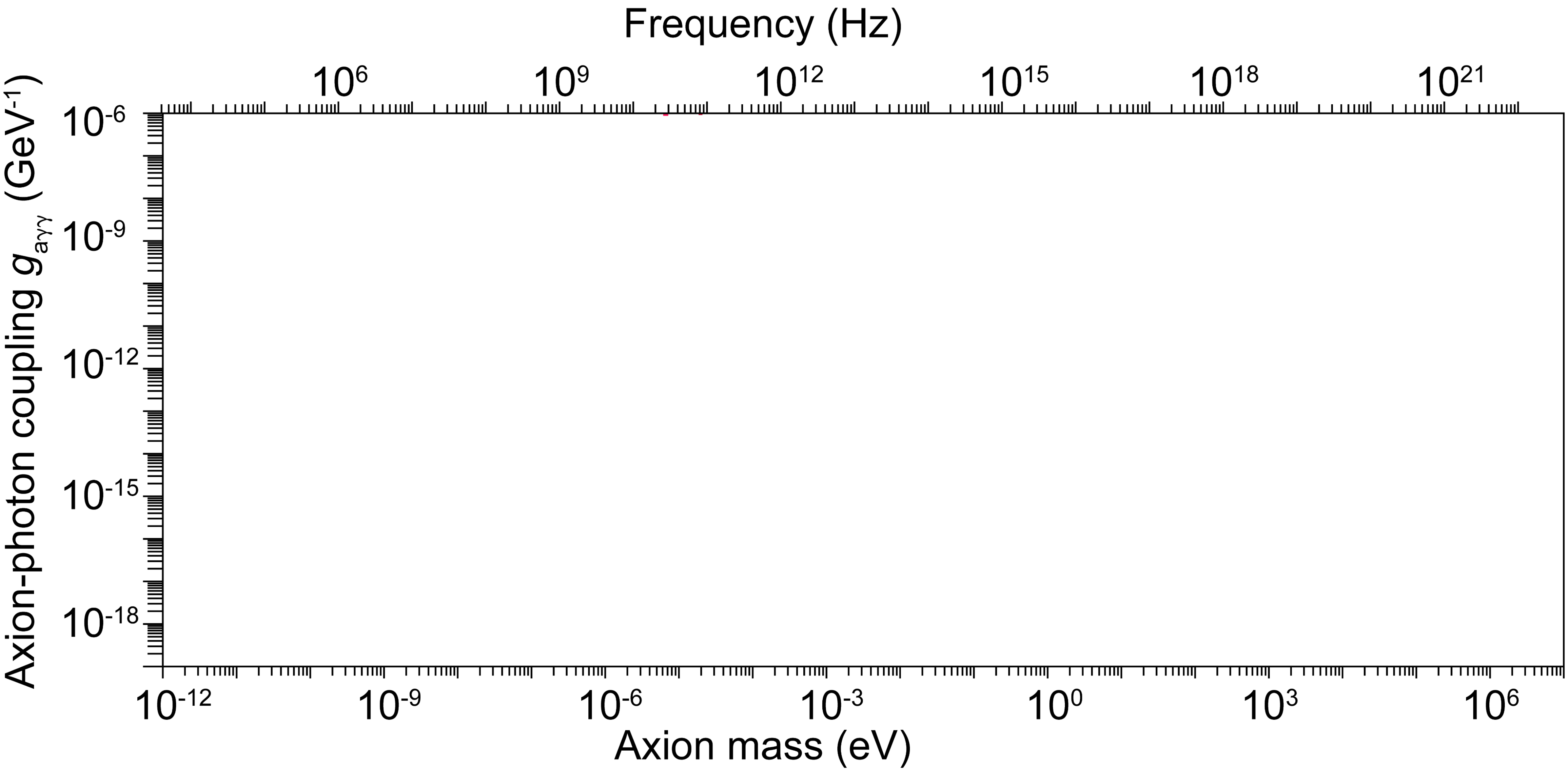
time

Peccei-Quinn
phase transition

If this model is correct, then about 10^{24} axions pass through you every second (depending on the axion mass).



What do we know about the axion's properties?



https://github.com/cajohare/AxionLimits

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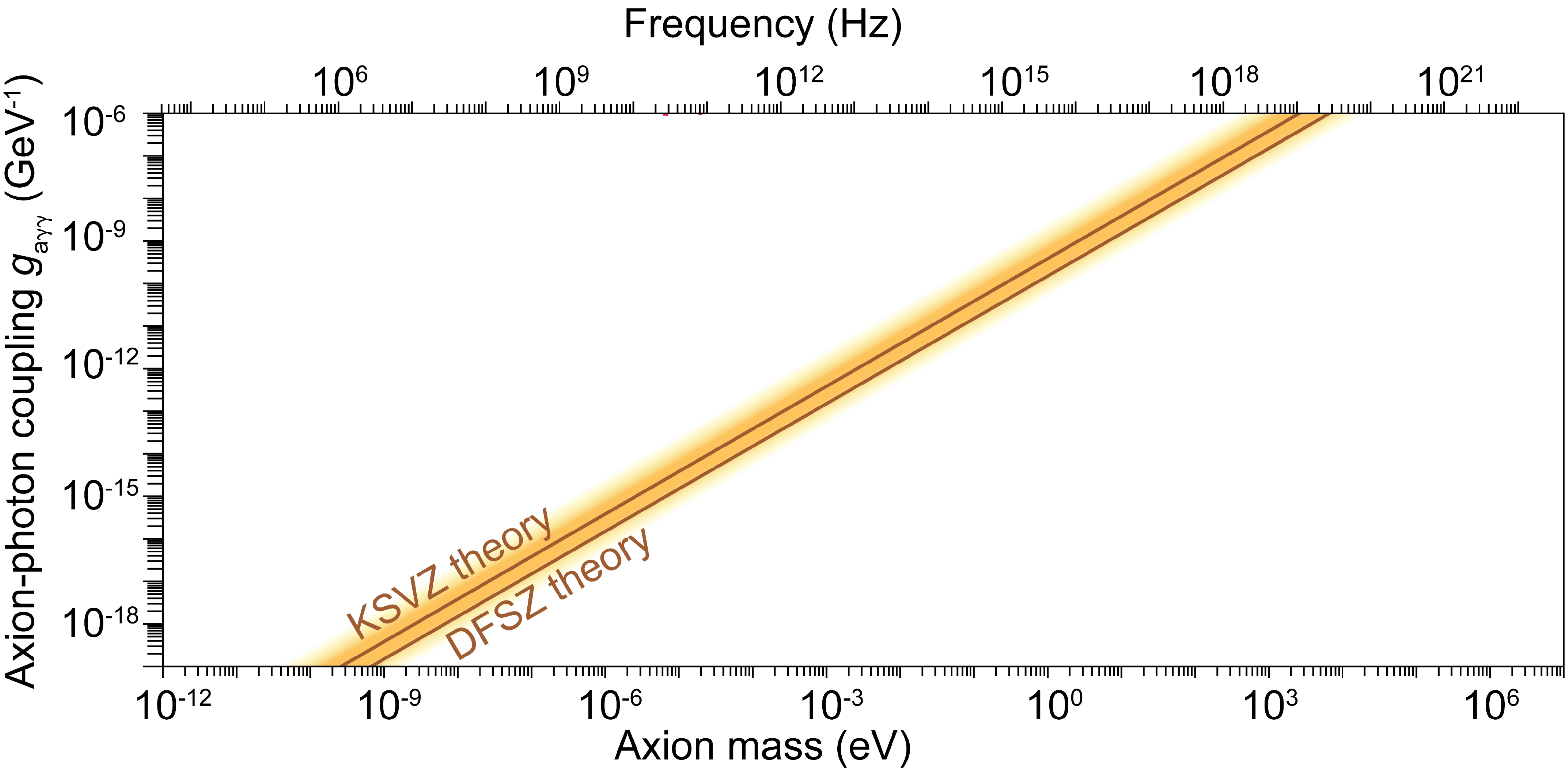

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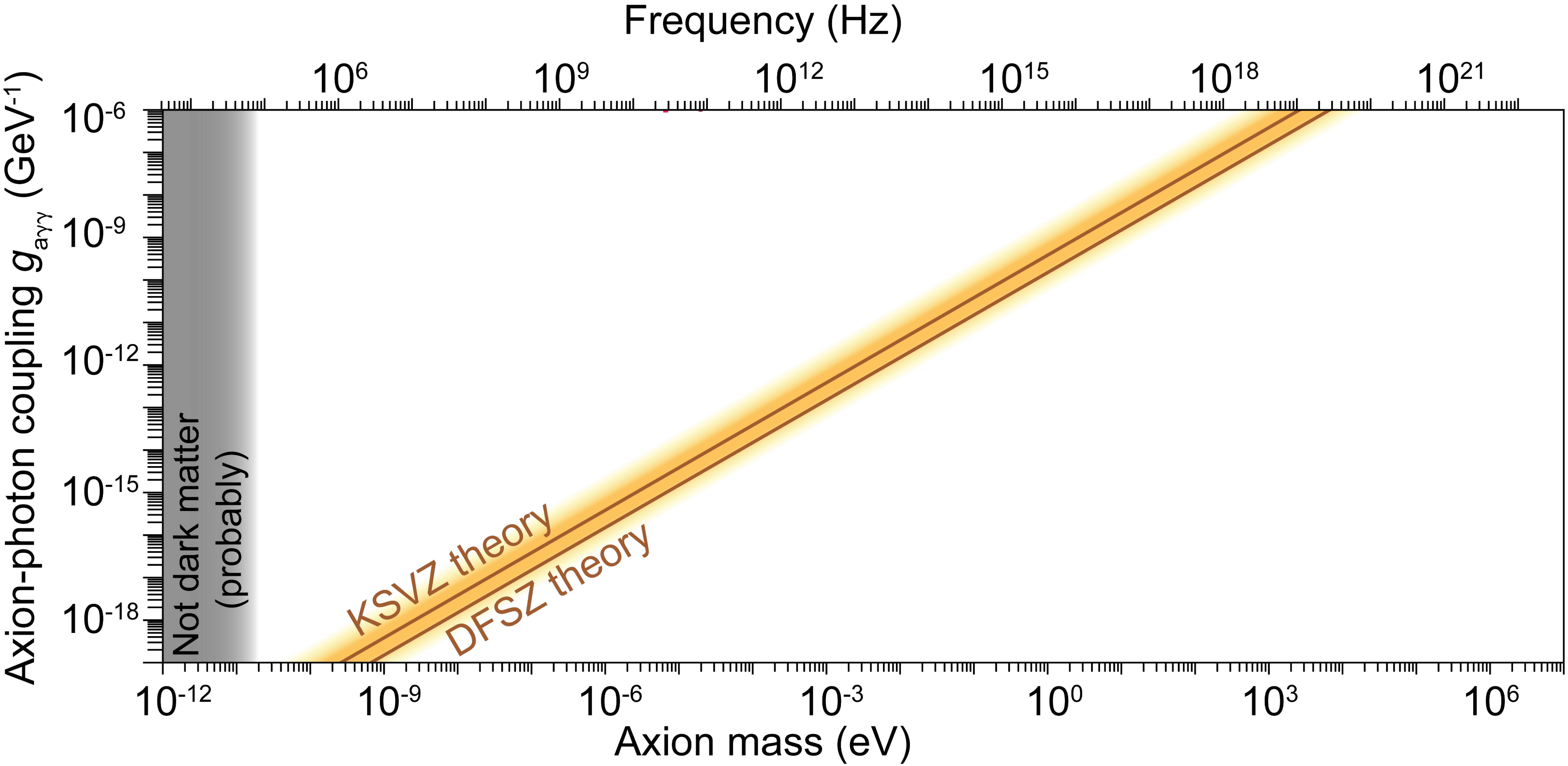

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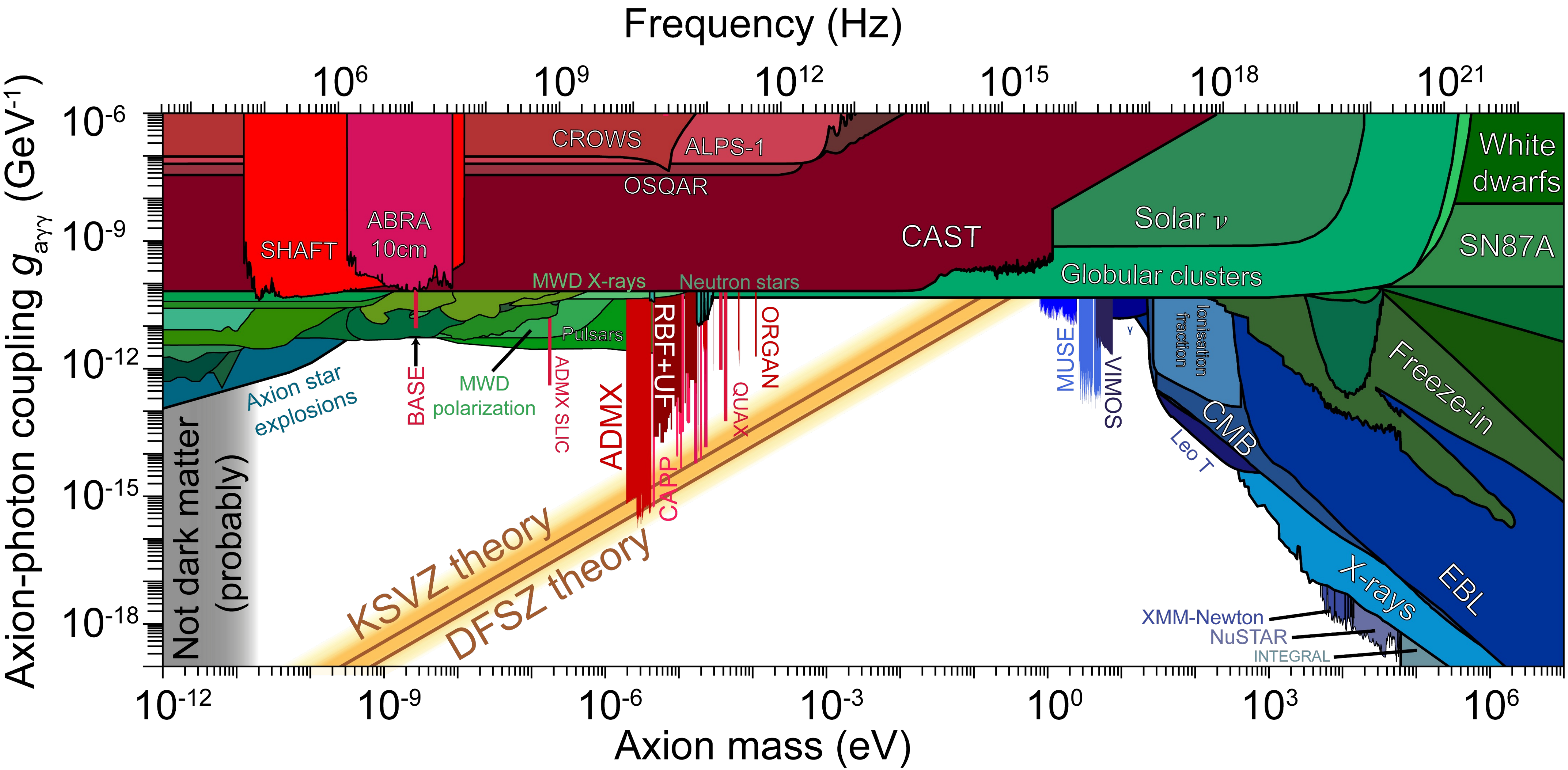

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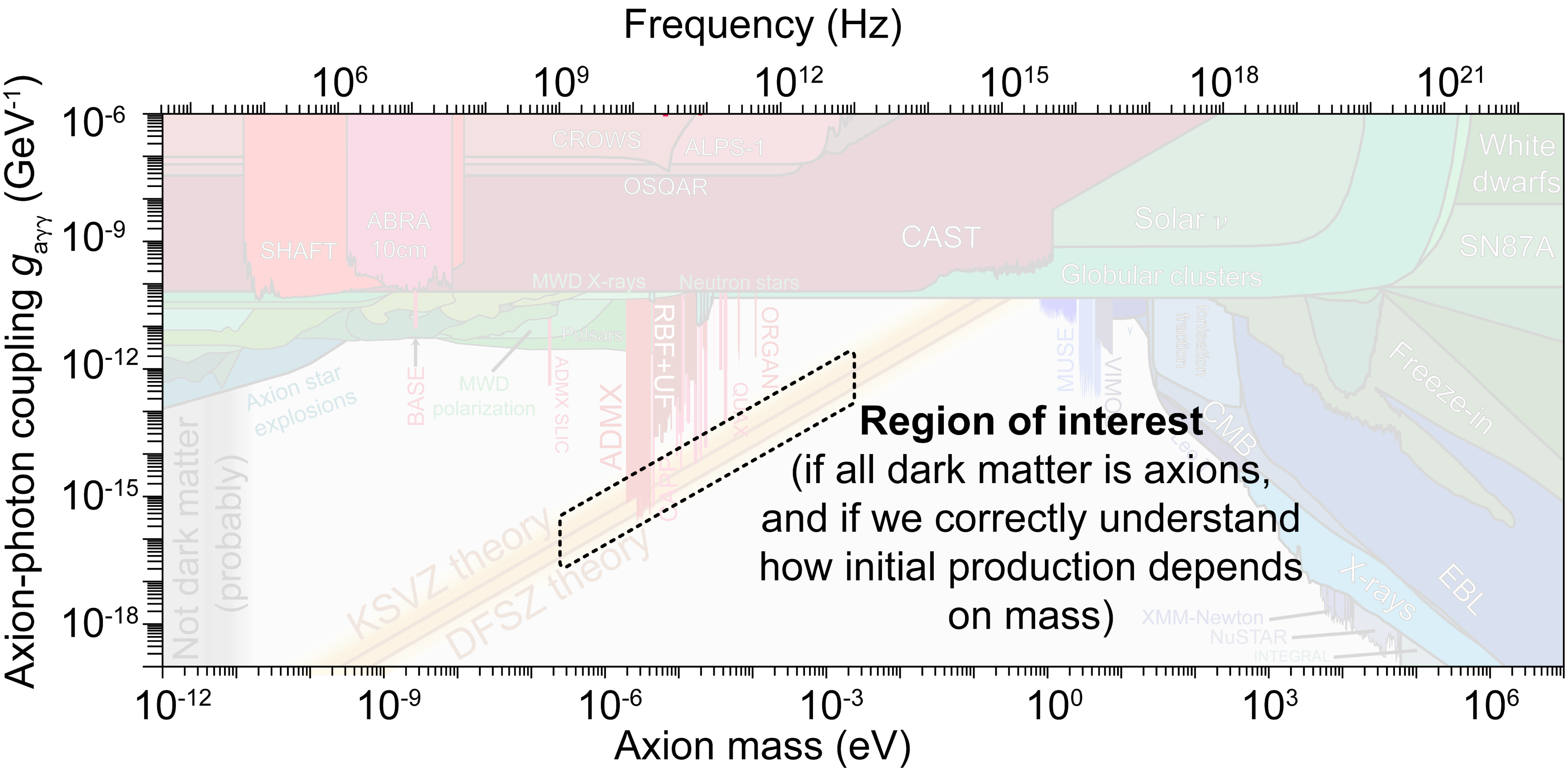
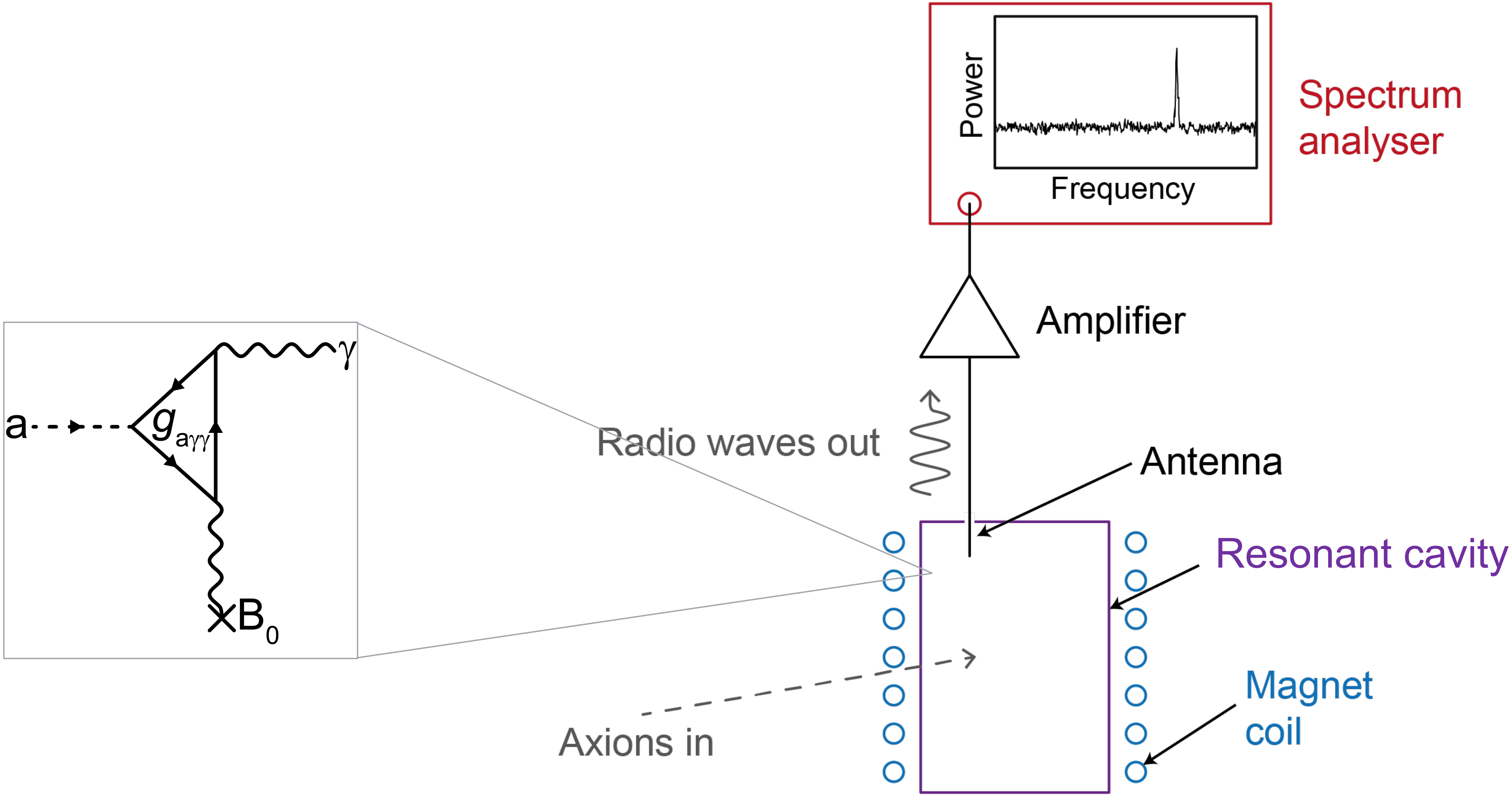


Region of interest
(if all dark matter is axions,
and if we correctly understand
how initial production depends
on mass)

https://github.com/cajohare/AxionLimits

Detecting axions using a haloscope



Spectrum analyser

Amplifier

Radio waves out

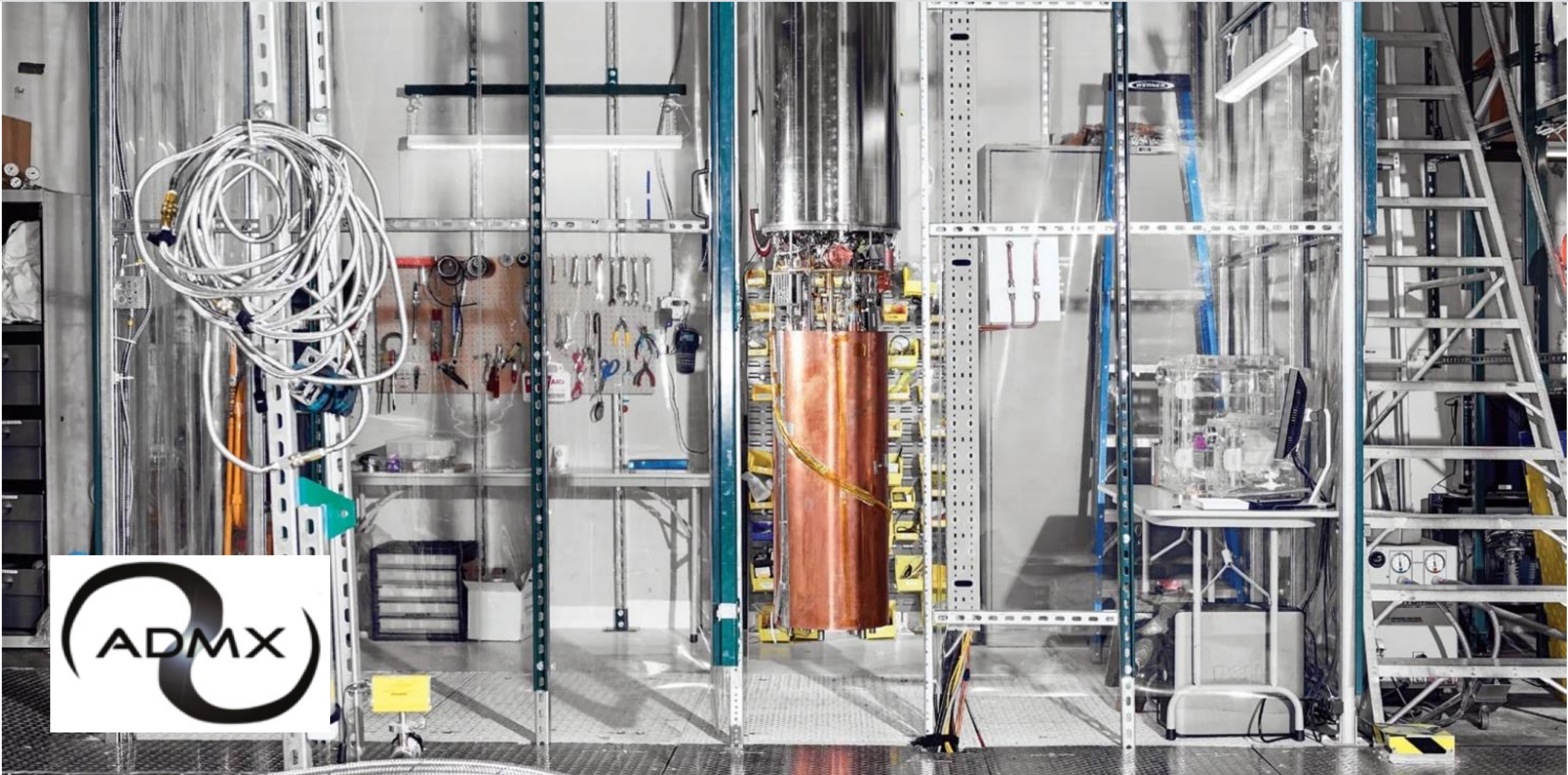
Antenna

Resonant cavity

Magnet coil

Axions in

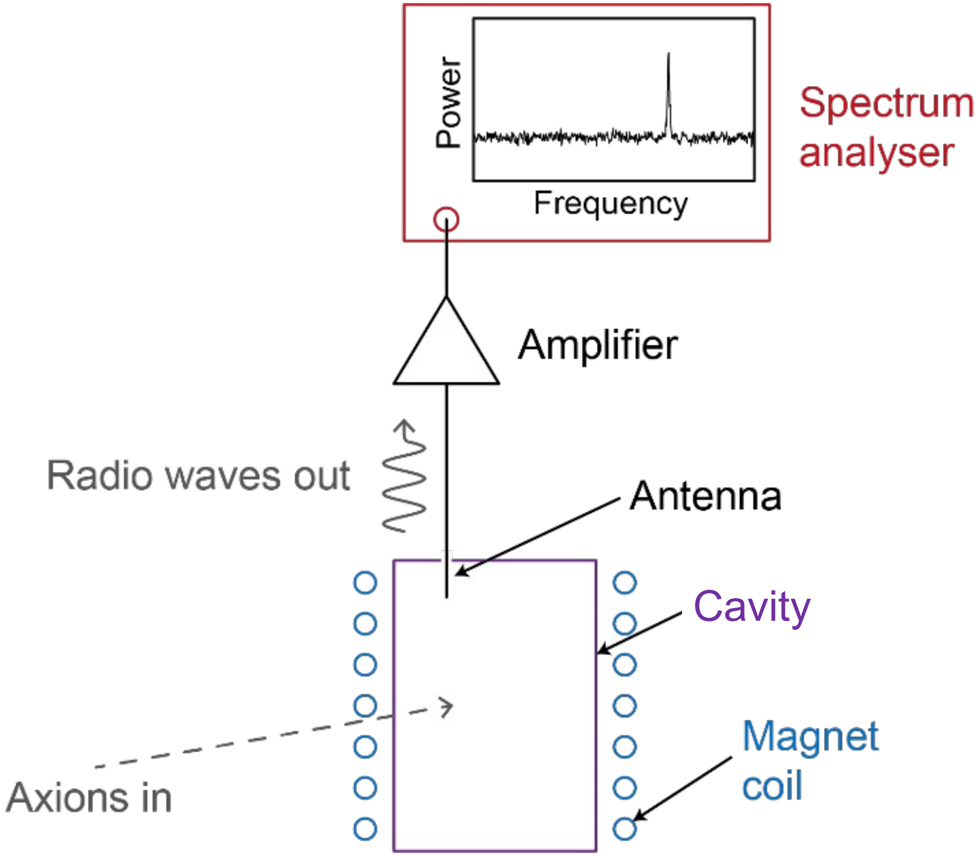
Example of a haloscope: the ADMX experiment (our collaborators)



The challenge: measuring a weak radio signal

Expected signal power in a microwave haloscope:

$$P_{\mathrm{axion}} = 2.2{\times}10^{-23}\ \mathrm{W}$$
$$\times\left(\frac{V}{0.136\ \mathrm{m}^3}\right)\left(\frac{B}{7.6\ \mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{Q}{30{,}000}\right)$$
$$\times\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{0.45\ \mathrm{GeV\ cm}^{-3}}\right)\left(\frac{f}{740\ \mathrm{MHz}}\right)$$



Signal power in other applications:

- Mobile phone: 10^{-6} W
- Radar: 10^{-12} W

See Sikivie RMP (2021) for full calculation

Classical measurement: the Dicke radiometer equation

The signal-to-noise ratio with which an axion peak can be identified is

Signal power

Measurement time

$$\frac{\text{Signal}}{\text{Noise}} = \frac{P_{\text{axion}}}{kT_{\text{N}}}\sqrt{\frac{\tau}{\Delta f}}$$

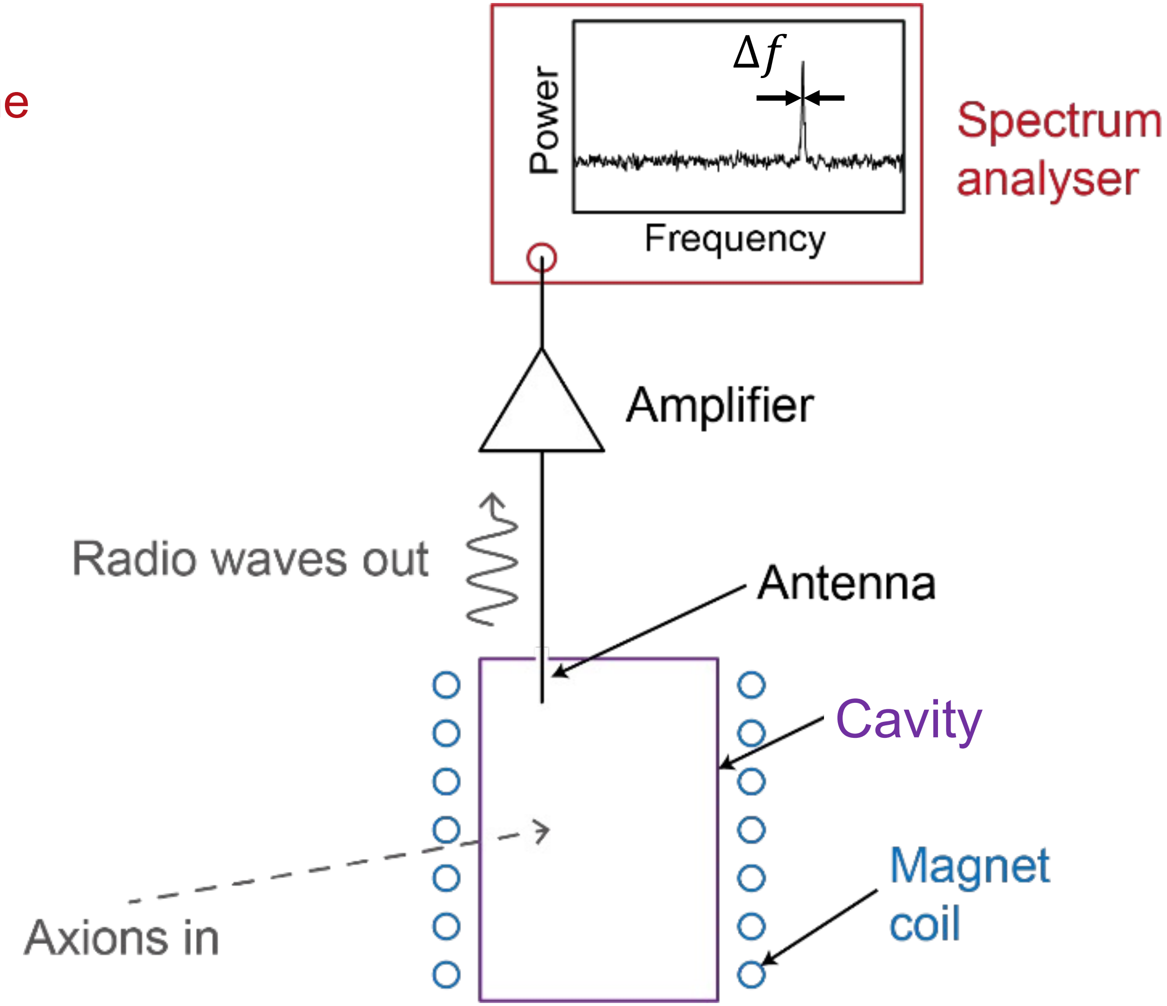
Boltzmann’s constant

Signal bandwidth

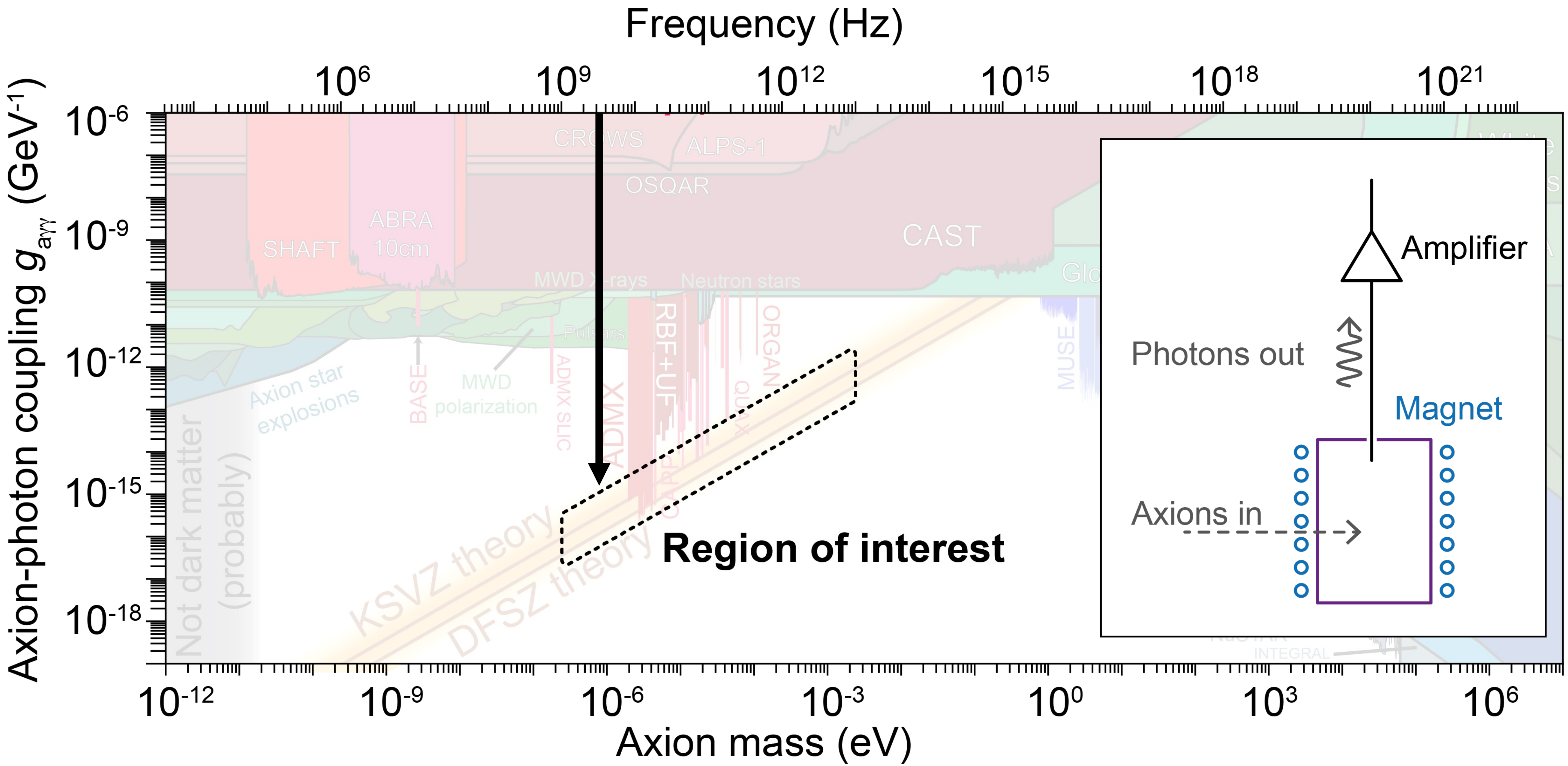
System noise temperature

To discover an axion, we need to tune to the correct frequency and measure until

$$\frac{\text{Signal}}{\text{Noise}} \gtrsim 5.$$



Searching for axions with a haloscope



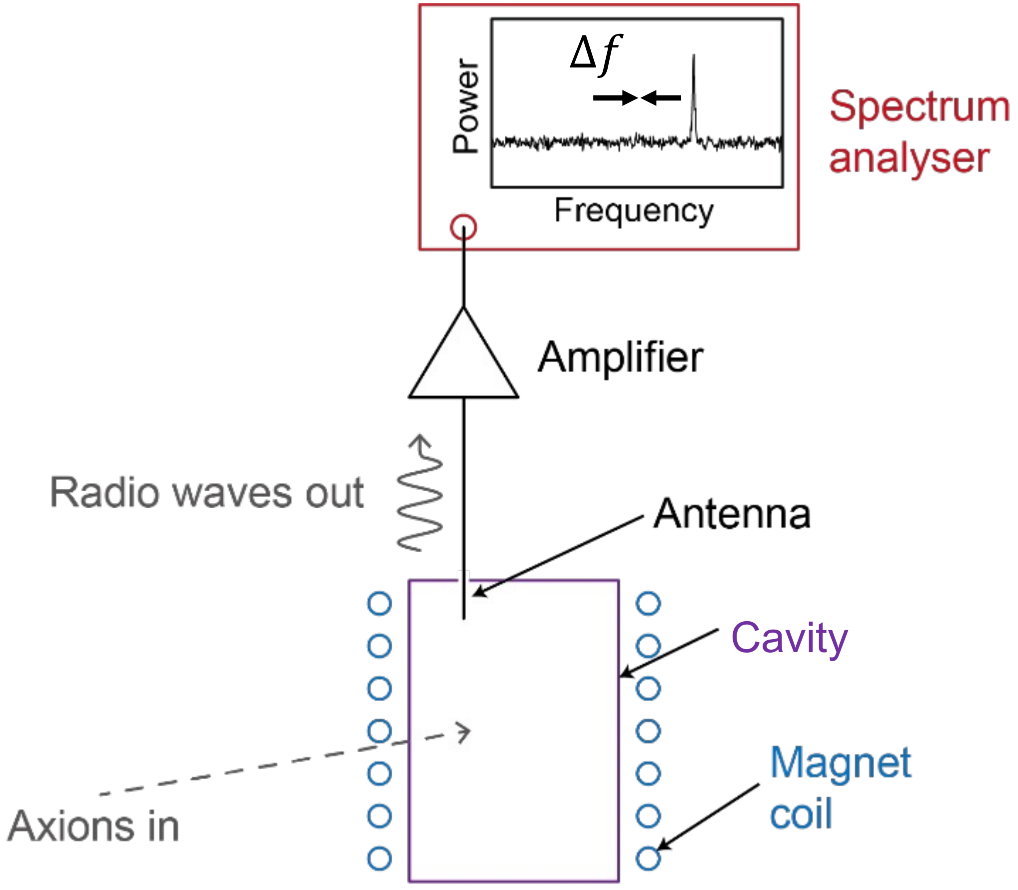
The scan rate and the standard quantum limit

The standard quantum limit for the system noise temperature with a phase-preserving amplifier is:

$$T_N > \frac{hf}{k}.$$

Scan rate for an example detector (10L cavity volume, 8T field, 10GHz centre frequency):

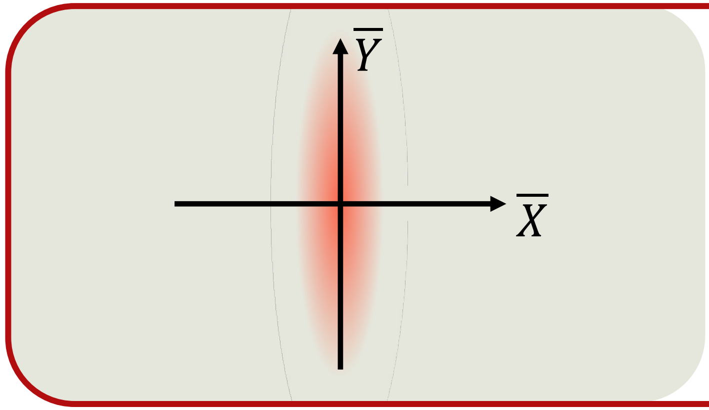
Noise temperature T_N	**Scan rate**
2 K (A good semiconductor amplifier)	90 yr/GHz
0.48 K (Standard quantum limit)	5 yr/GHz



See Sikivie RMP (2021) for full calculation

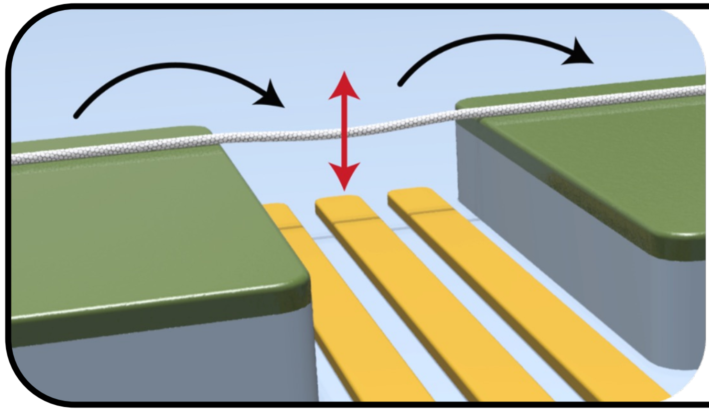
Quantum sensors for the hidden sector

Why should you look for axions?



The QSHS experiment

Looking for axions using quantum technology



Vibrating nanotubes in superfluid helium

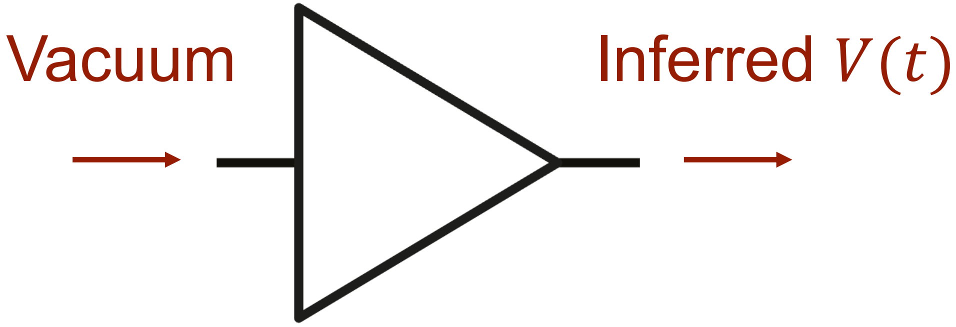
Another device for particle searches?

Squeezing using a parametric amplifier

An oscillating voltage near frequency f has the form

$$V(t) = X(t)\cos 2\pi f t + Y(t)\sin 2\pi f t$$

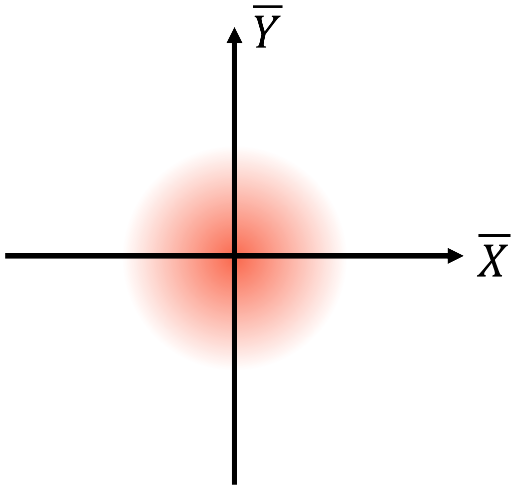
A parametric amplifier can amplify one of these two quadratures while attenuating the other one. This changes the shape of the $(\overline{X}, \overline{Y})$ histogram, but not its area.



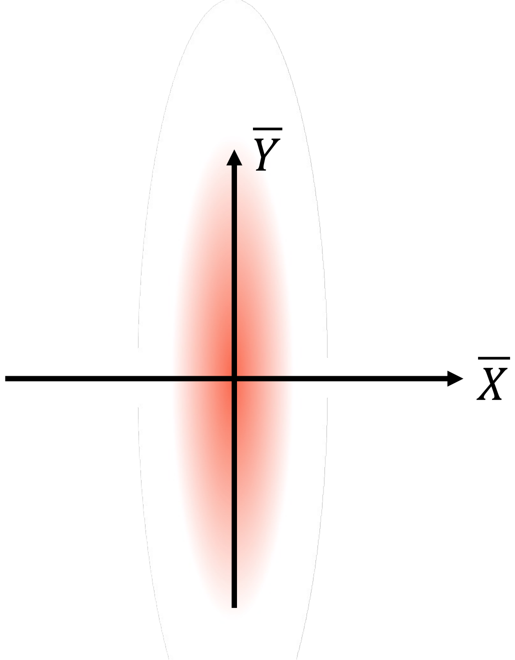
Vacuum

Inferred $V(t)$

Parametric amplifier

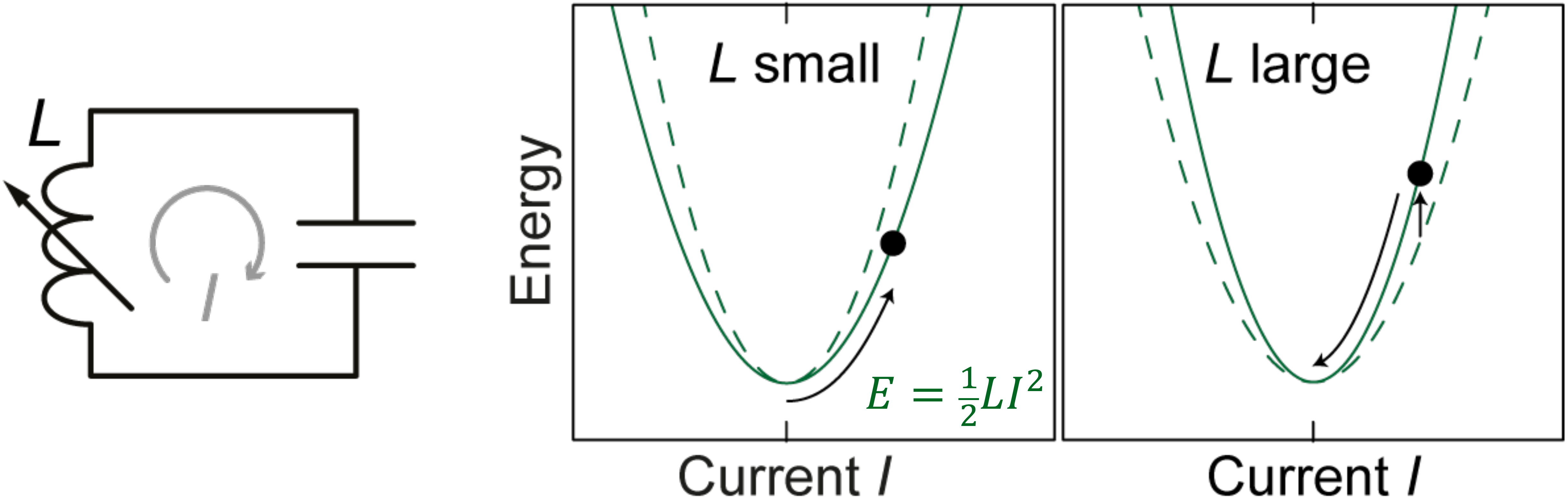


Inferred signal
without squeezing



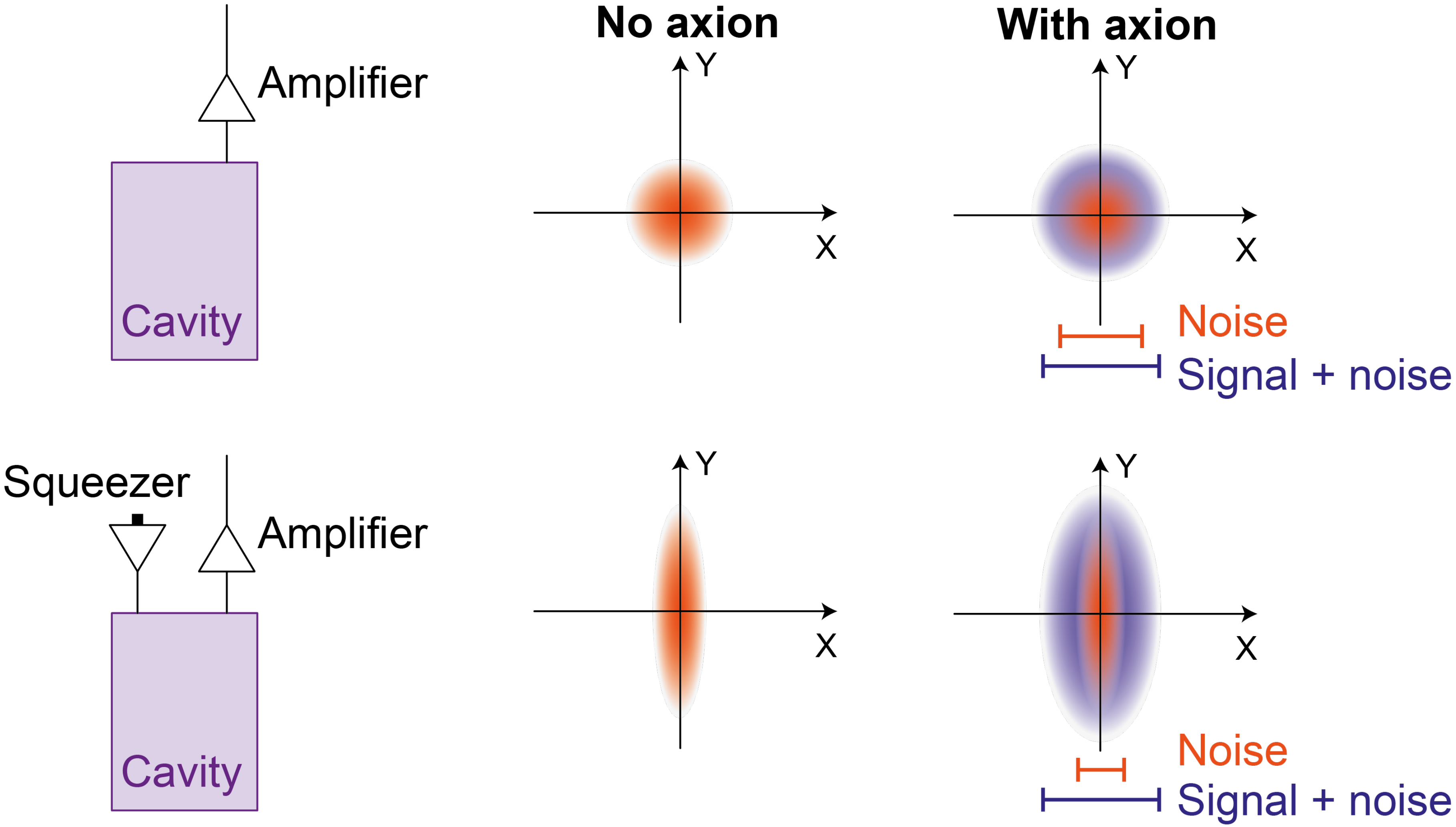
Inferred signal
with squeezing

Principle of parametric amplification



By modulating one parameter of a resonator (such as its inductance) at frequency $2f$, we can pump energy into the signal mode at frequency f.

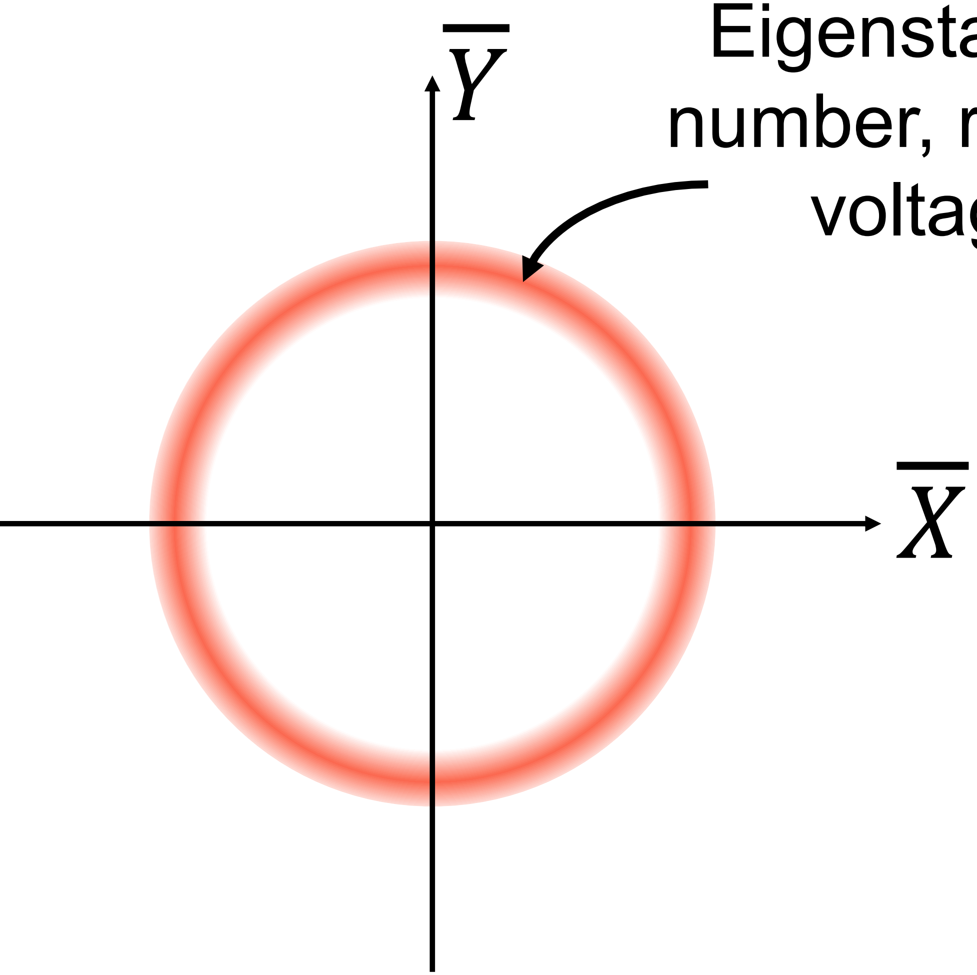
Quantum speed-up method 1: linear squeezing



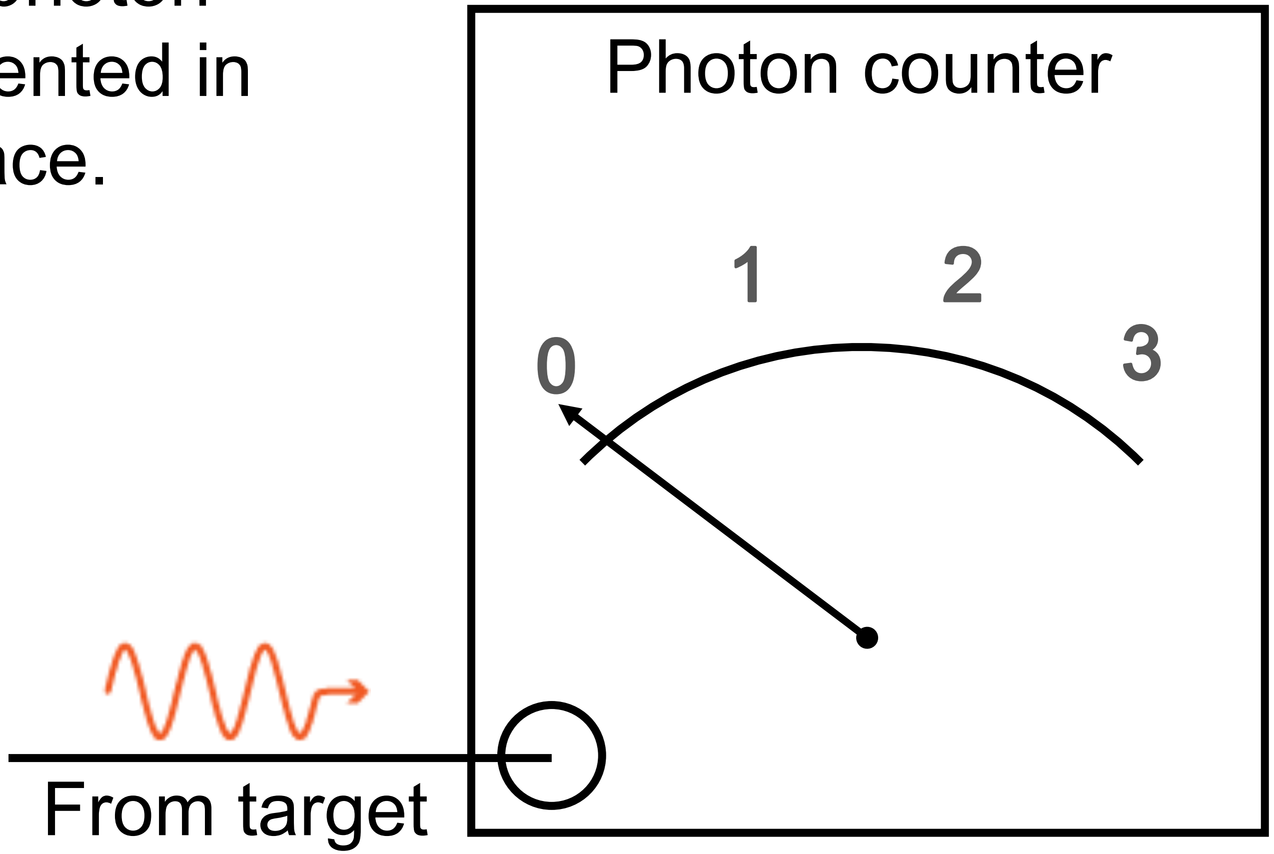
From the HAYSTAC experiment at Yale

Malnou et al, PRX (2019); Backes et al, Nature (2021)

Quantum speed-up method 2: photon counting



Eigenstate of photon number, represented in voltage space.



From Fermilab:
Dixit et al., PRX (2021)

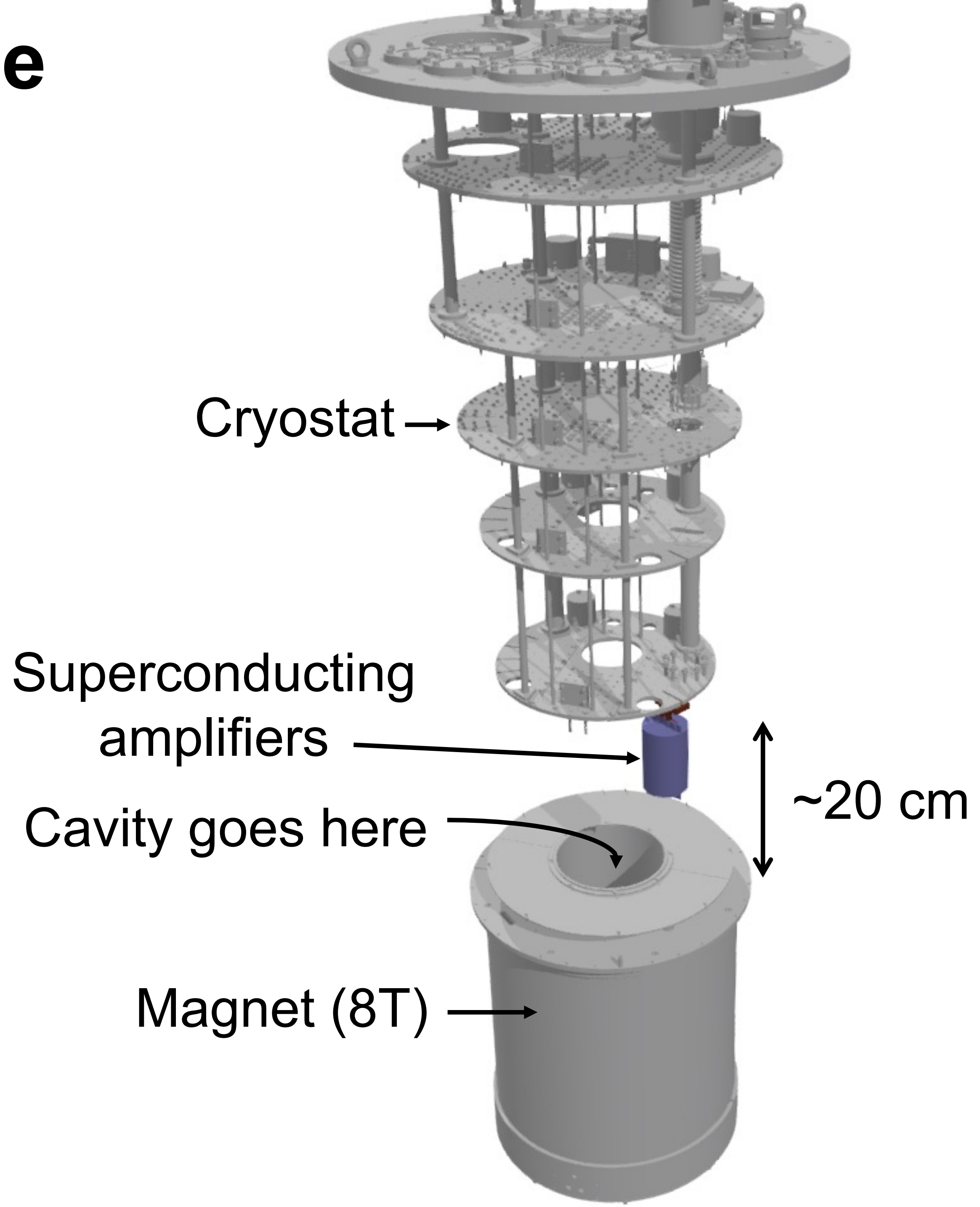
Magnetic field shielding for the QSHS haloscope

Magnetic field shielding is critical to run superconducting amplifiers close to the target cavity.

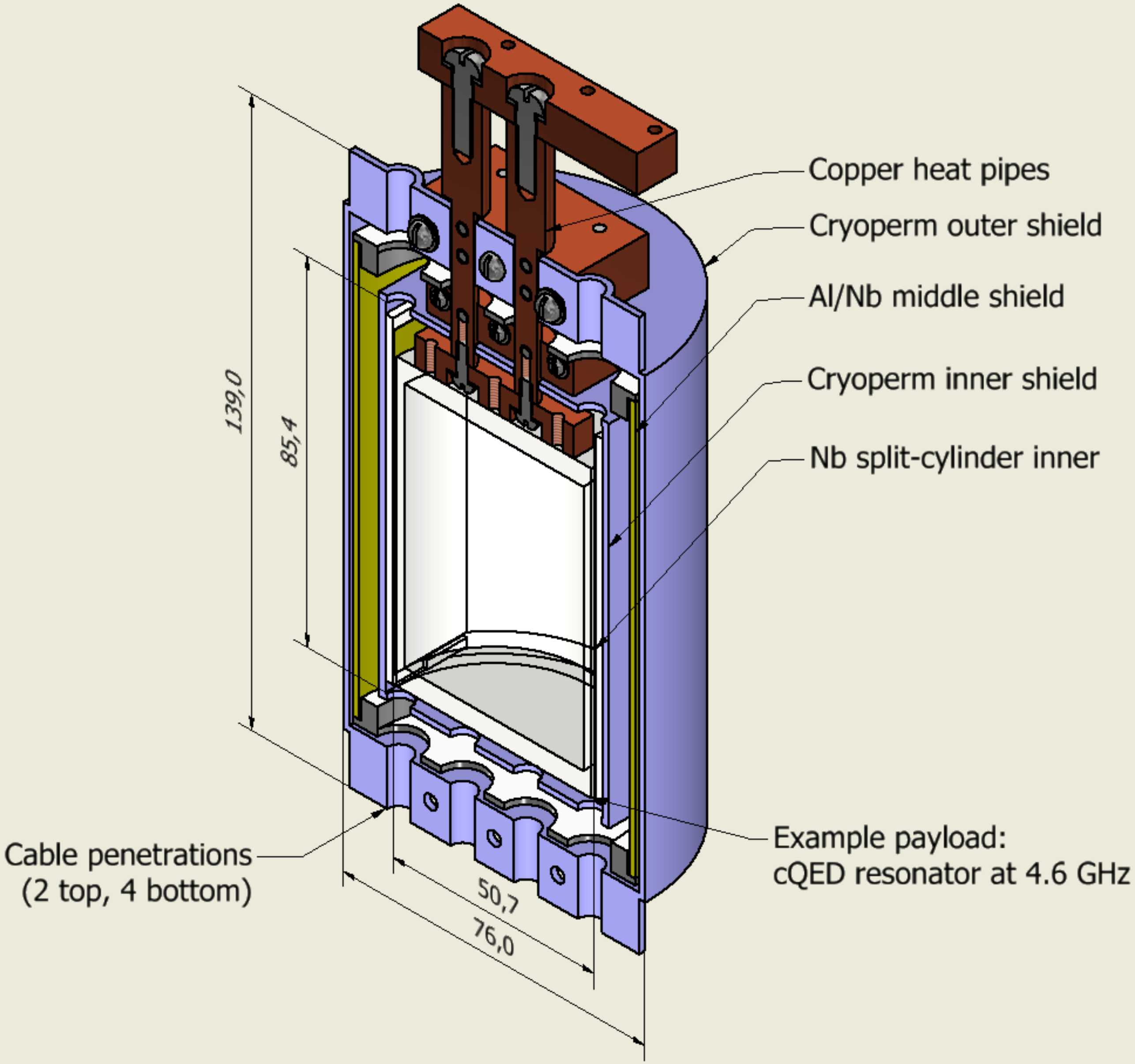
Stray field of main coil:
~10 mT

Operating field of Josephson amplifiers:
~10 nT

(See a thesis from B. Brubaker for information about how this is handled in the HAYSTAC experiment.)



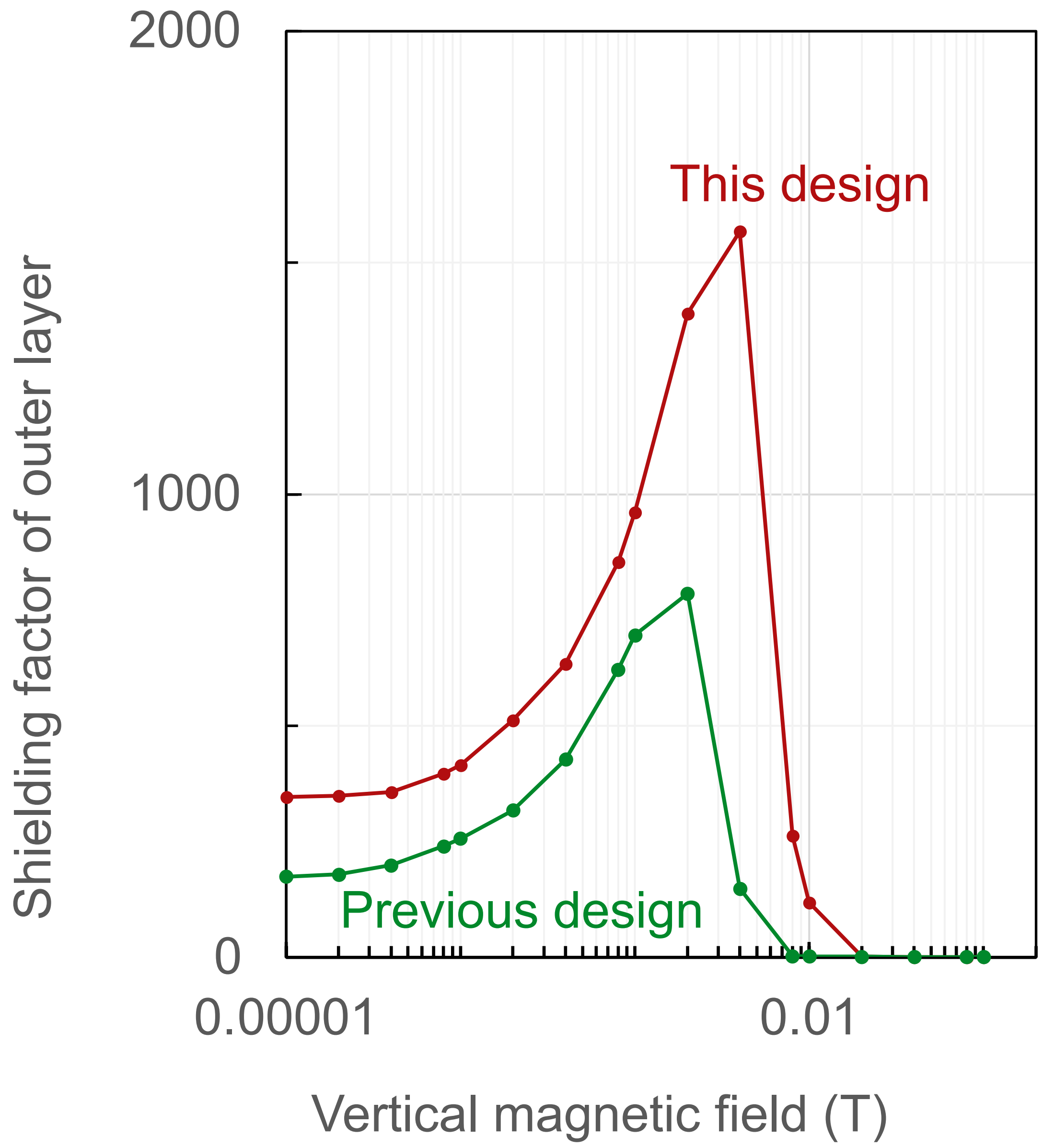
The QSHS field shield

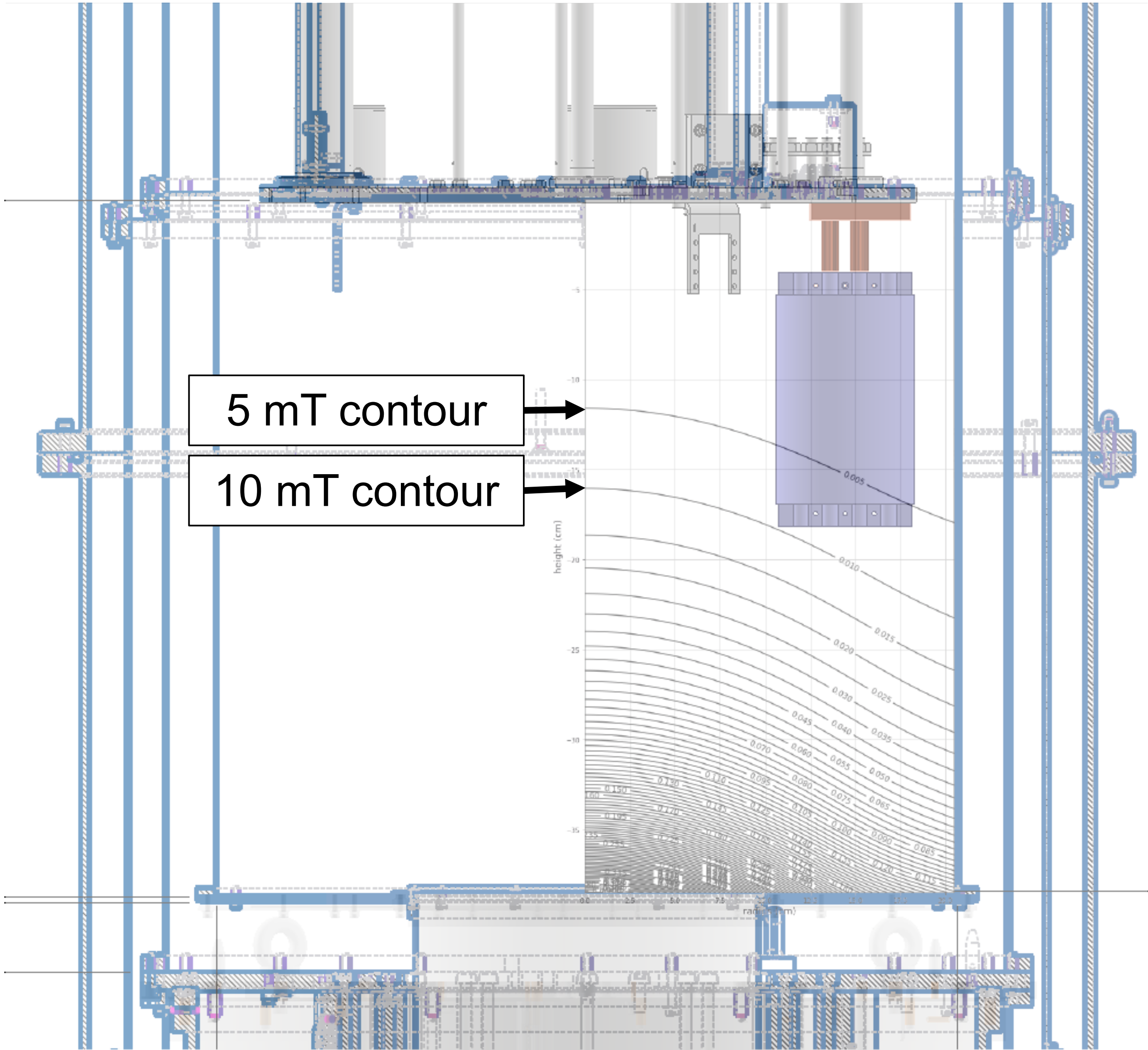


Design criteria:

- Field shielding factor of 10^6 in 10 mT
- Easy access for sample exchange, including a clam-shell design.
- Sufficient sample volume (here 0.17 L)
- Small enough to be tested in our vector magnets.

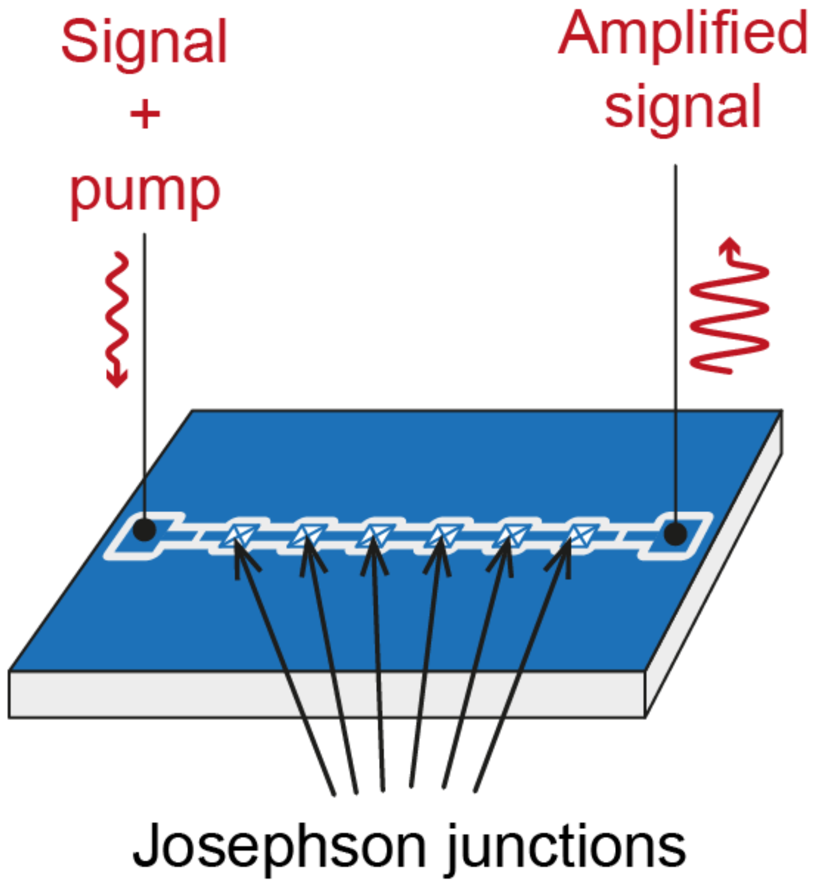
Simulation results



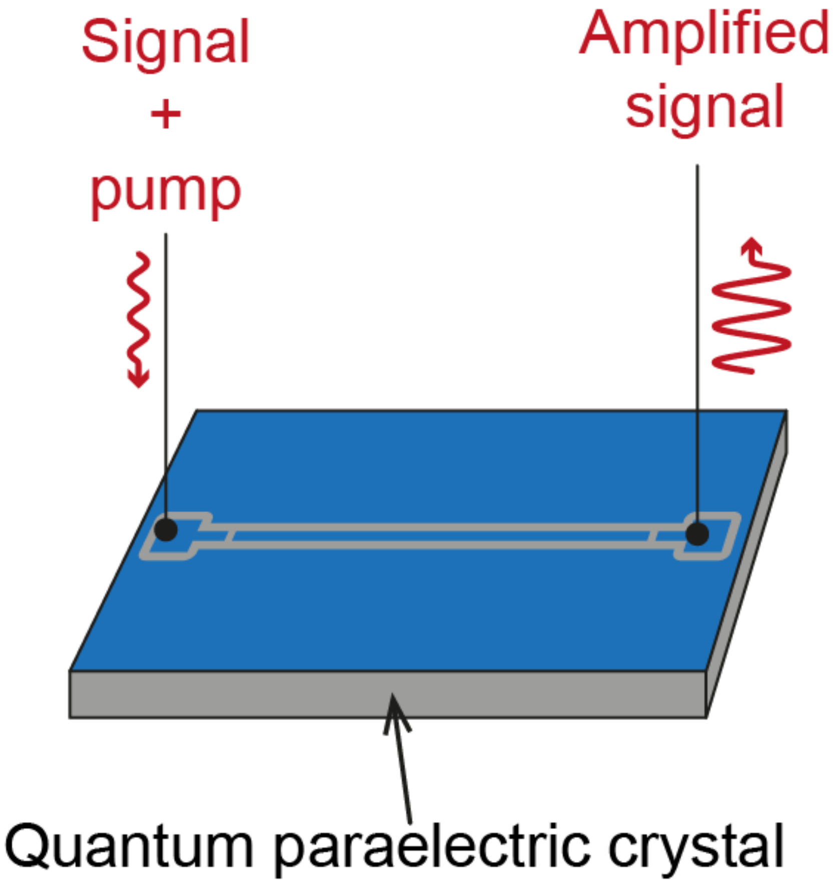


A parametric amplifier that is robust against magnetic fields

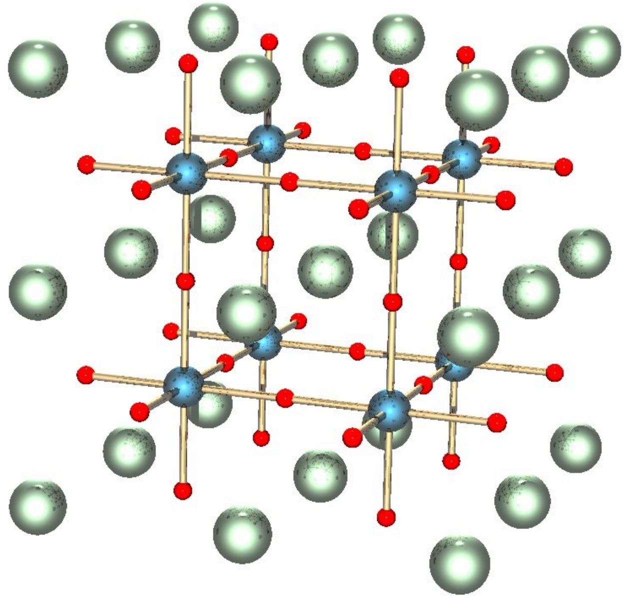
Josephson parametric amplifier



Quantum paraelectric amplifier

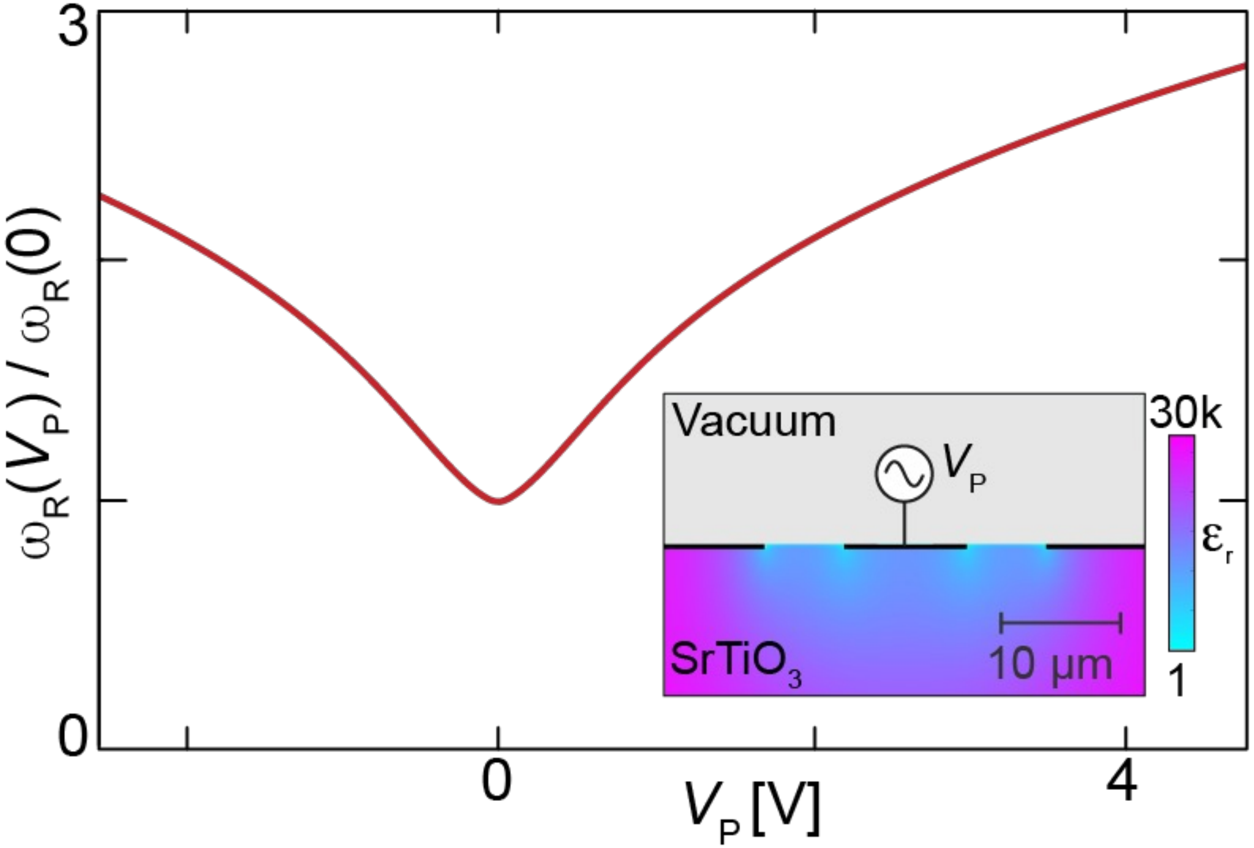


A parametric amplifier that is robust against magnetic fields



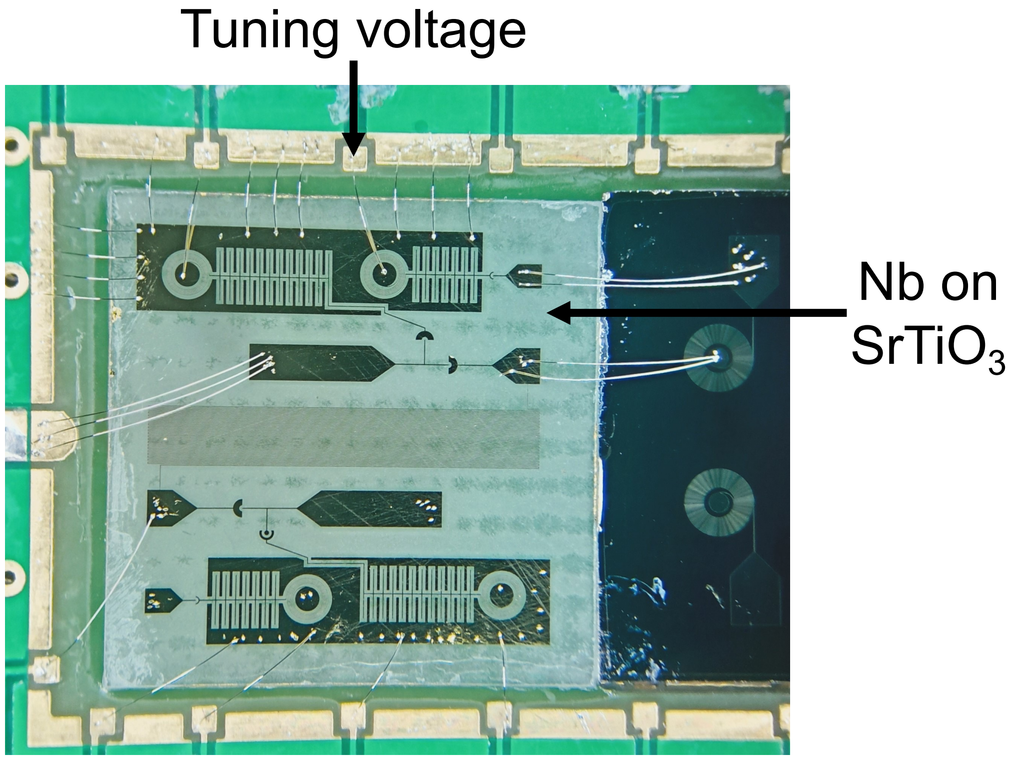
Strontium titanate –
a quantum paraelectric material

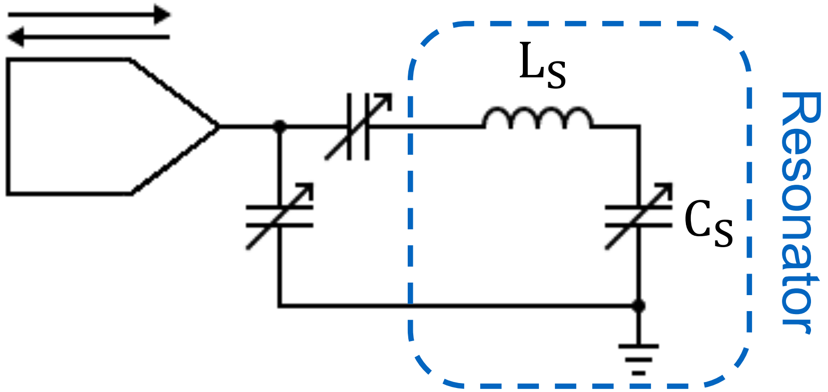
Finite-element simulation

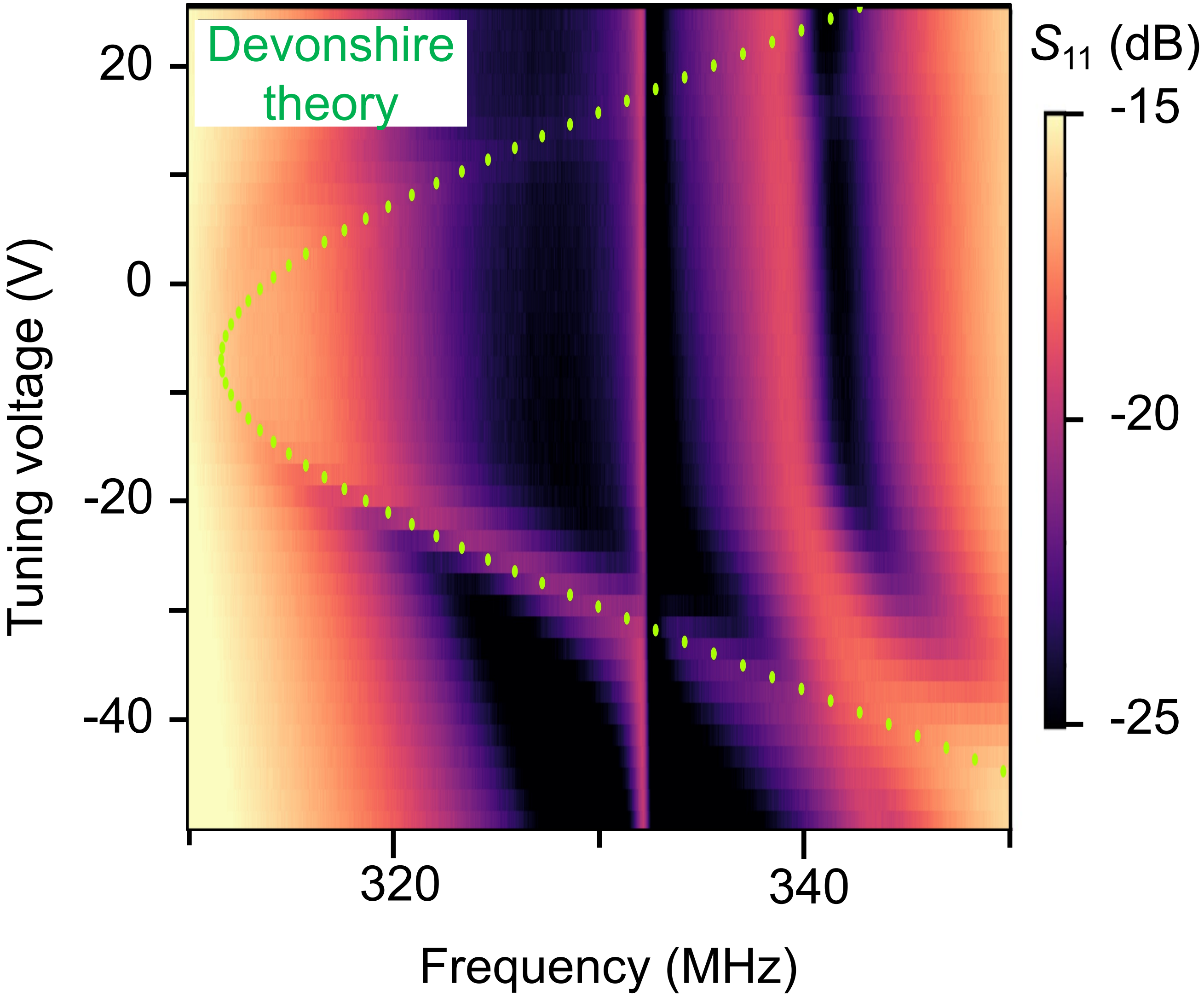


See also experiments by Steele, Buitelaar, Zumbuhl groups

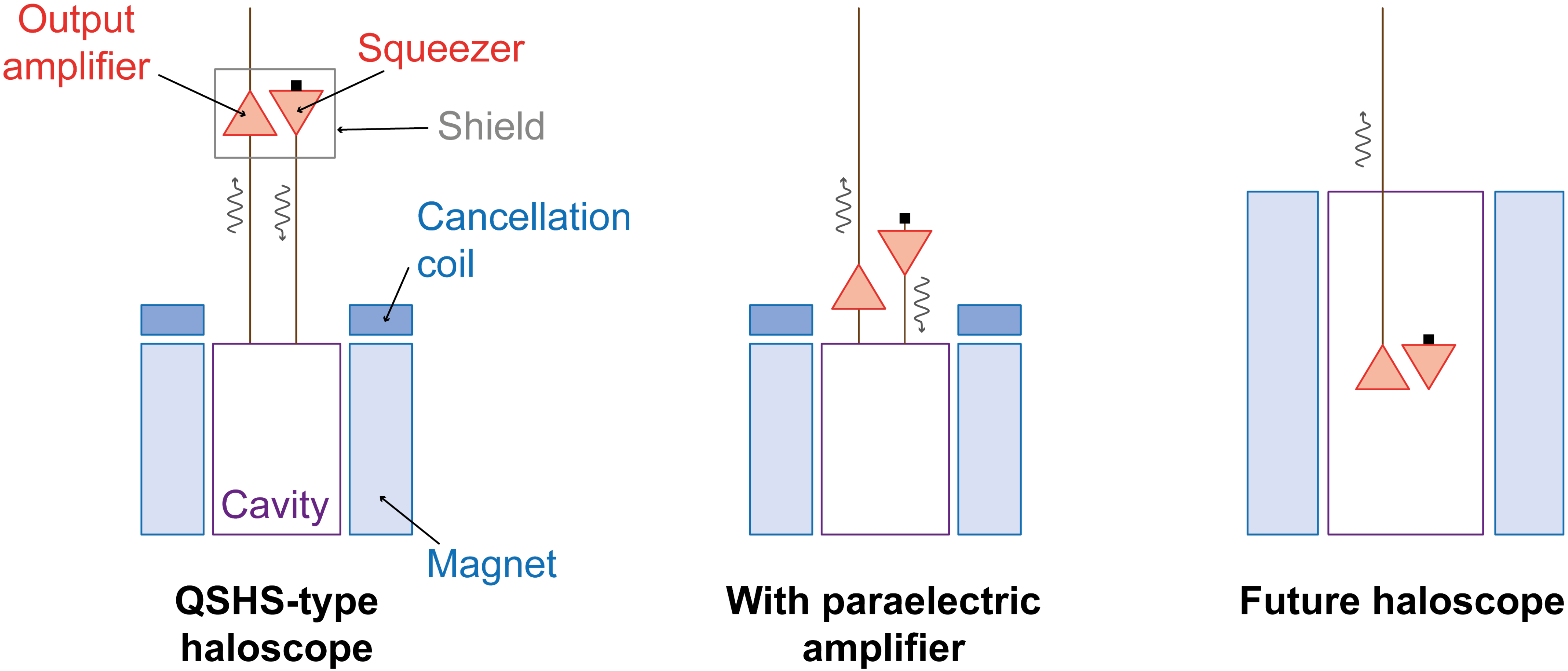
Tuning an RF resonator using paraelectricity





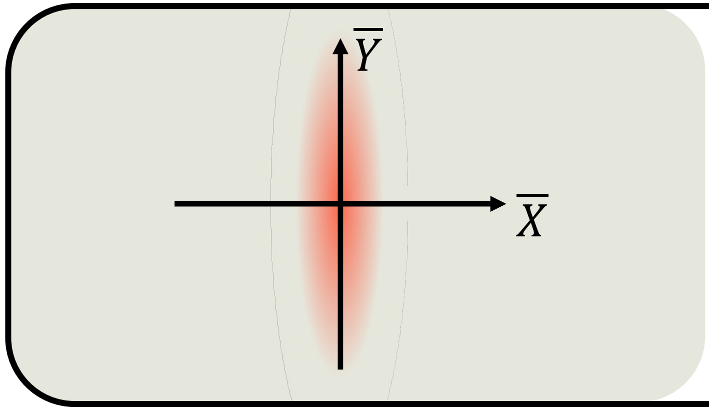


Paraelectric amplifiers for axion searches: the vision



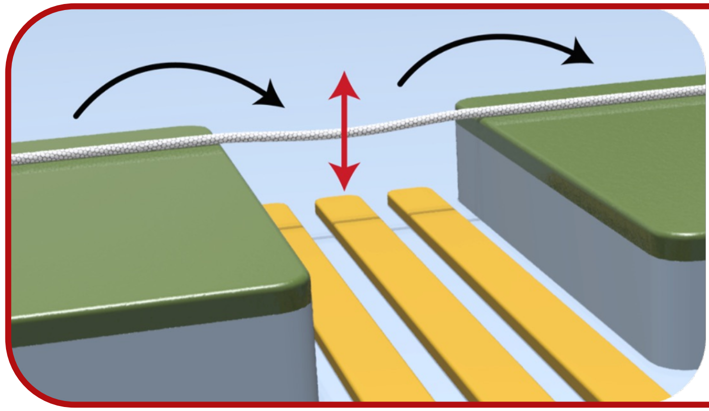
Quantum sensors for the hidden sector

Why should you look for axions?



The QSHS experiment

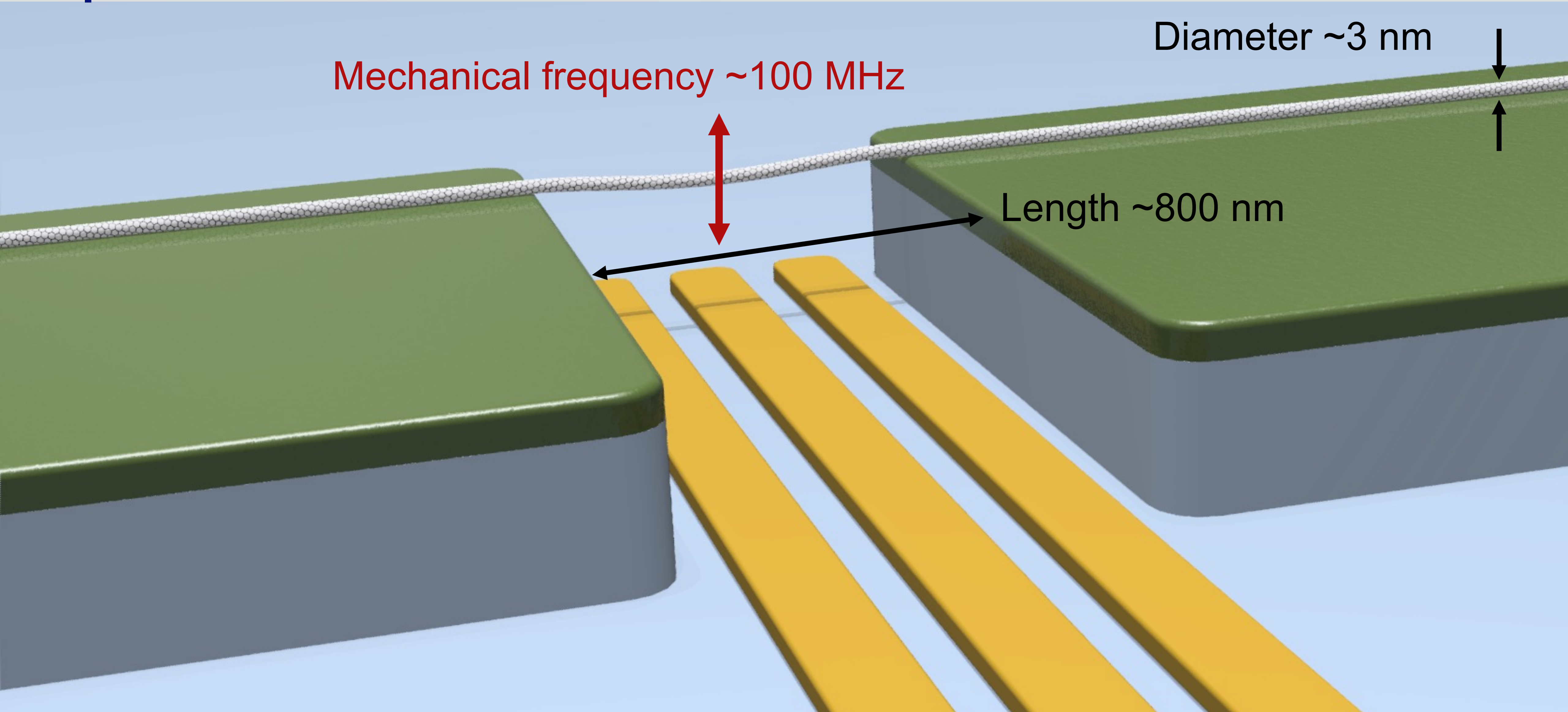
Looking for axions using quantum technology



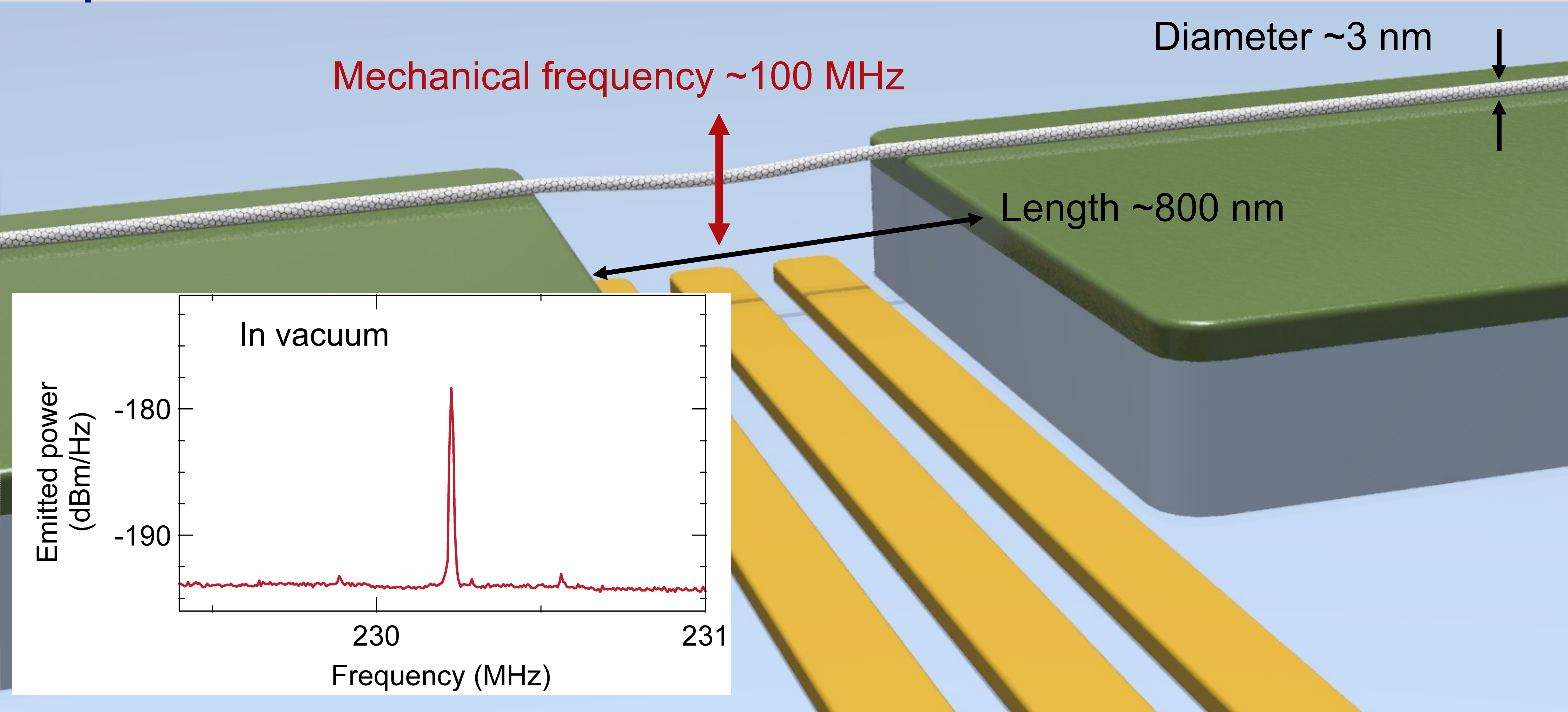
Vibrating nanotubes in superfluid helium

Another device for particle searches?

Carbon nanotube resonators for measuring superfluid helium

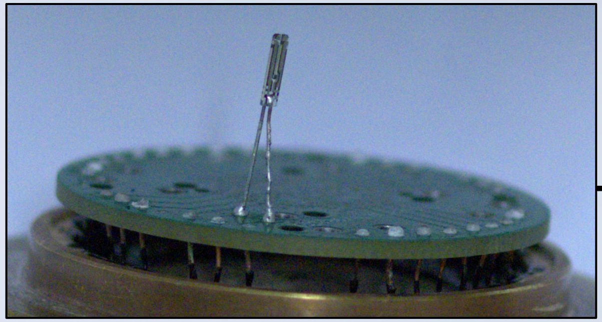


Carbon nanotube resonators for measuring superfluid helium

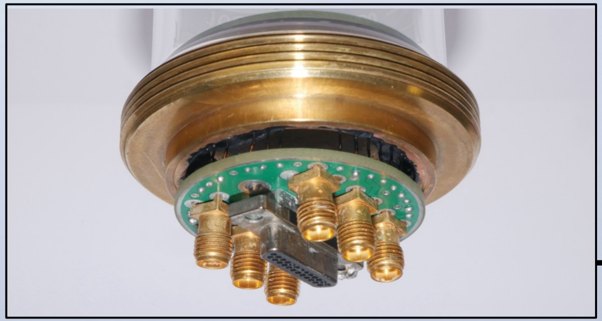


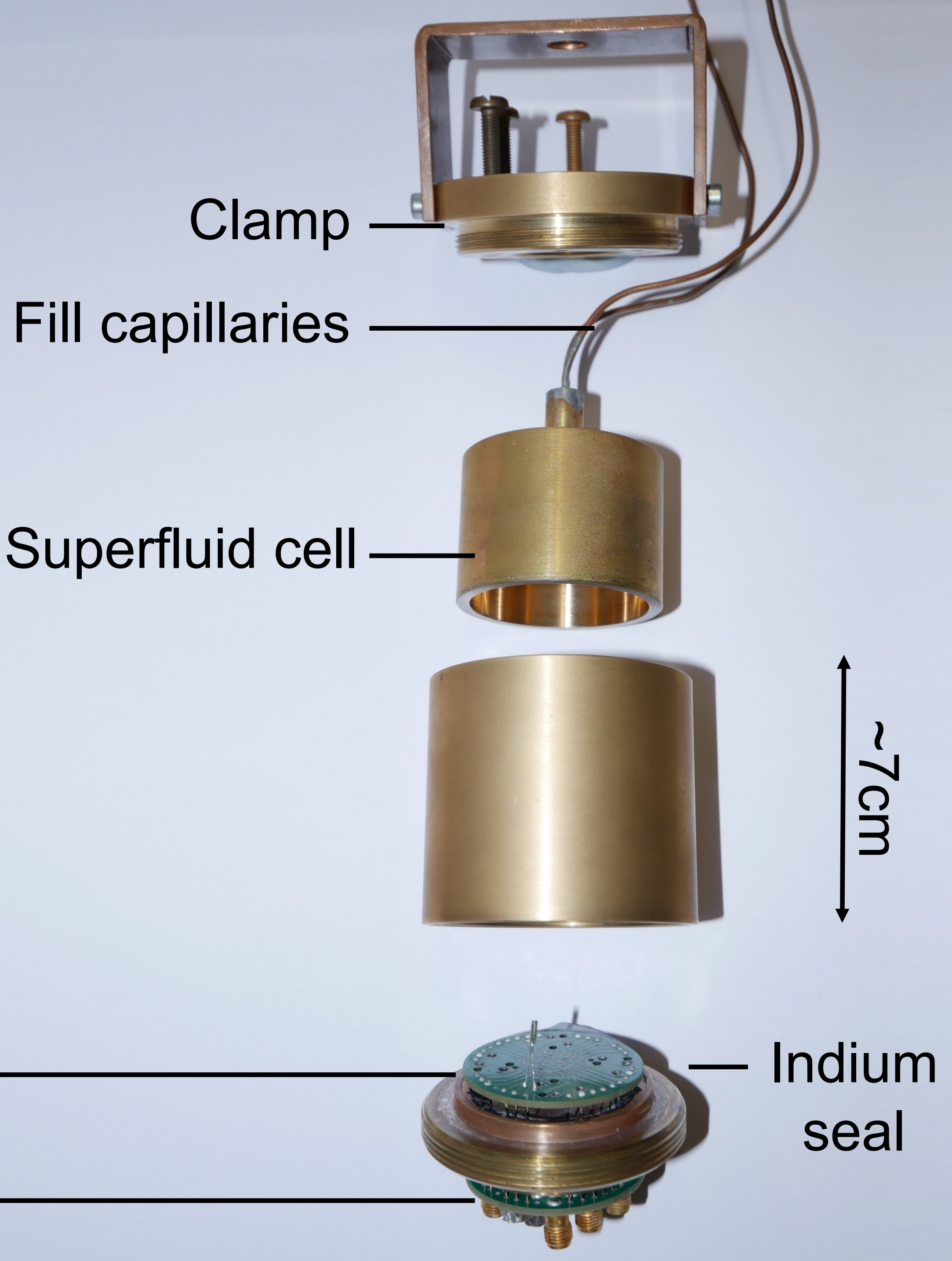
Superfluid plumbing with high-frequency electronics

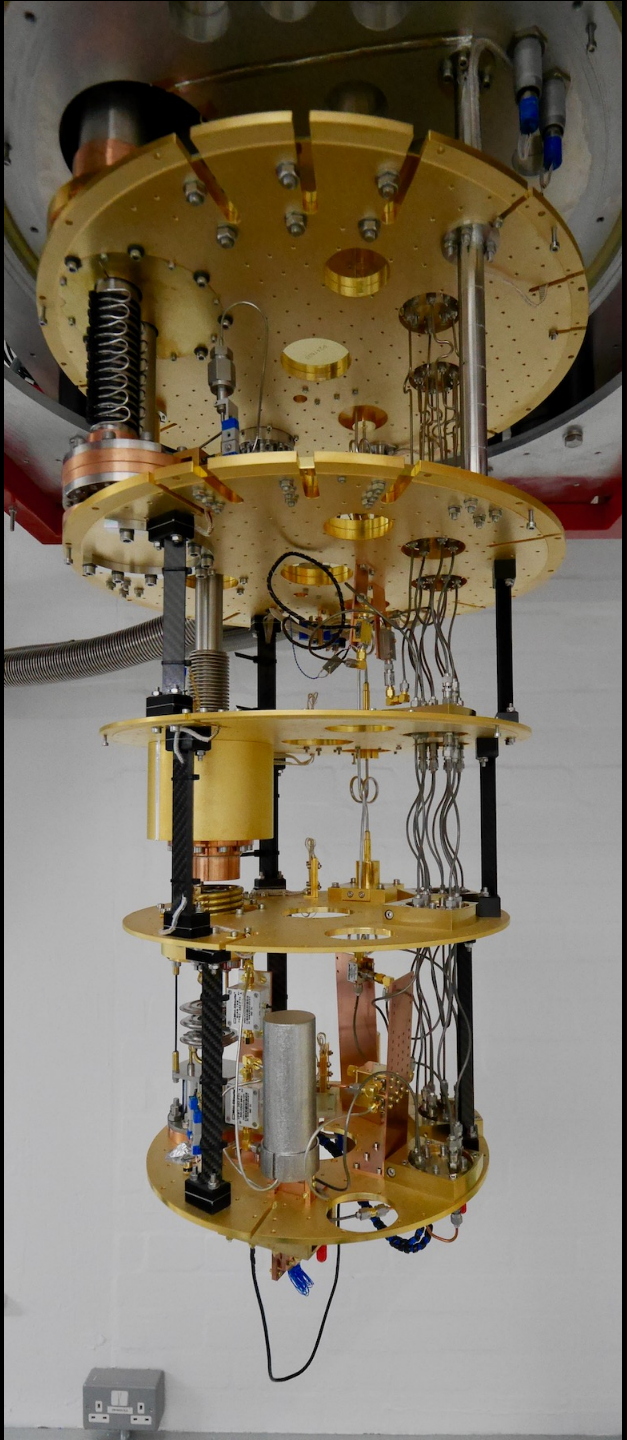
Sample mounting board
(with quartz
level meter/thermometer)



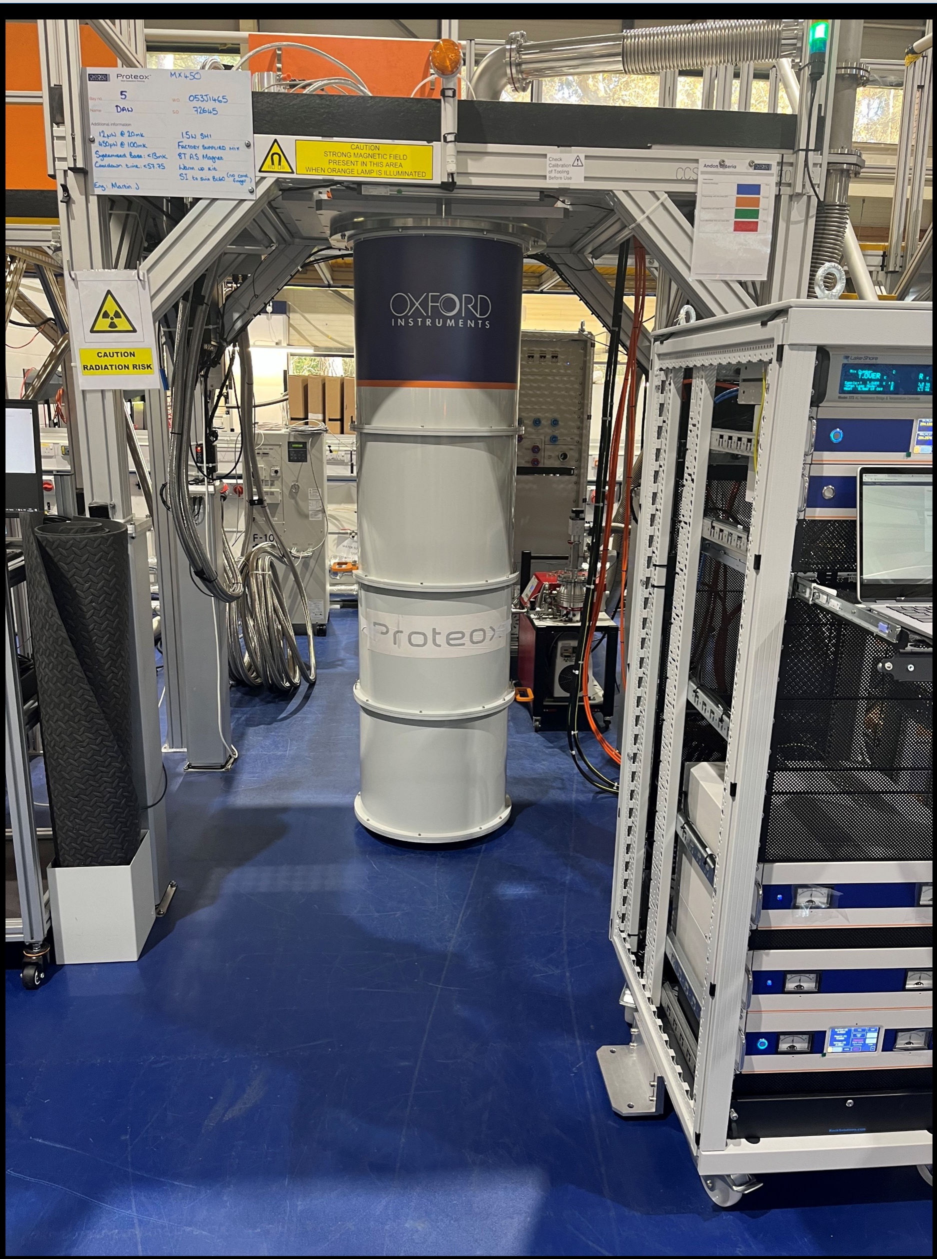
Electrical penetrations



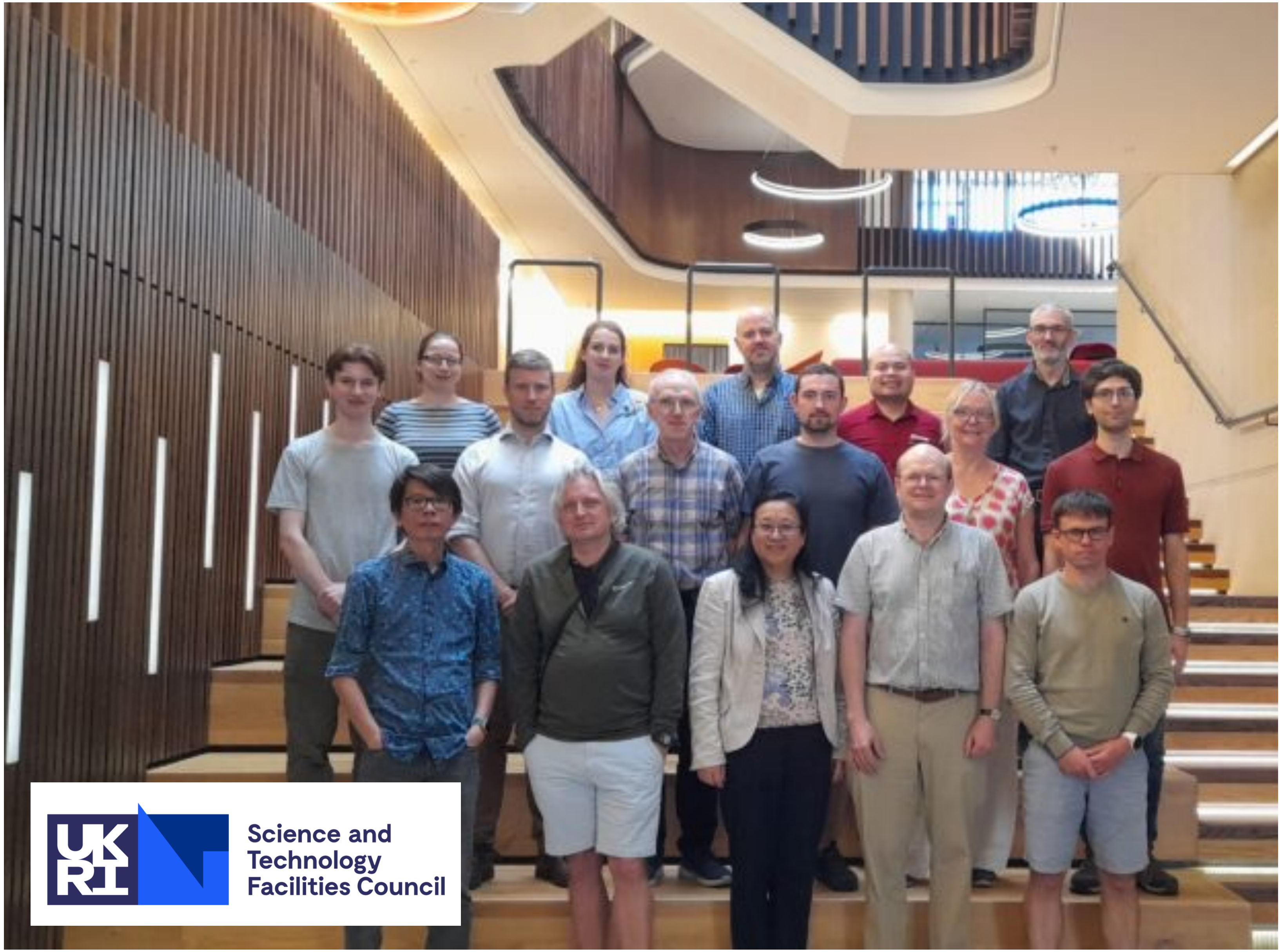




QSHS fridge installation is this month!



The QSHS collaboration



Especially:

- Ed Daw (Sheffield, PI)
- Paul Smith (Sheffield)
- Ian Bailey (Lancaster)
- Yuri Pashkin (Lancaster)
- Ed Romans (UCL)
- Others at qshs.org

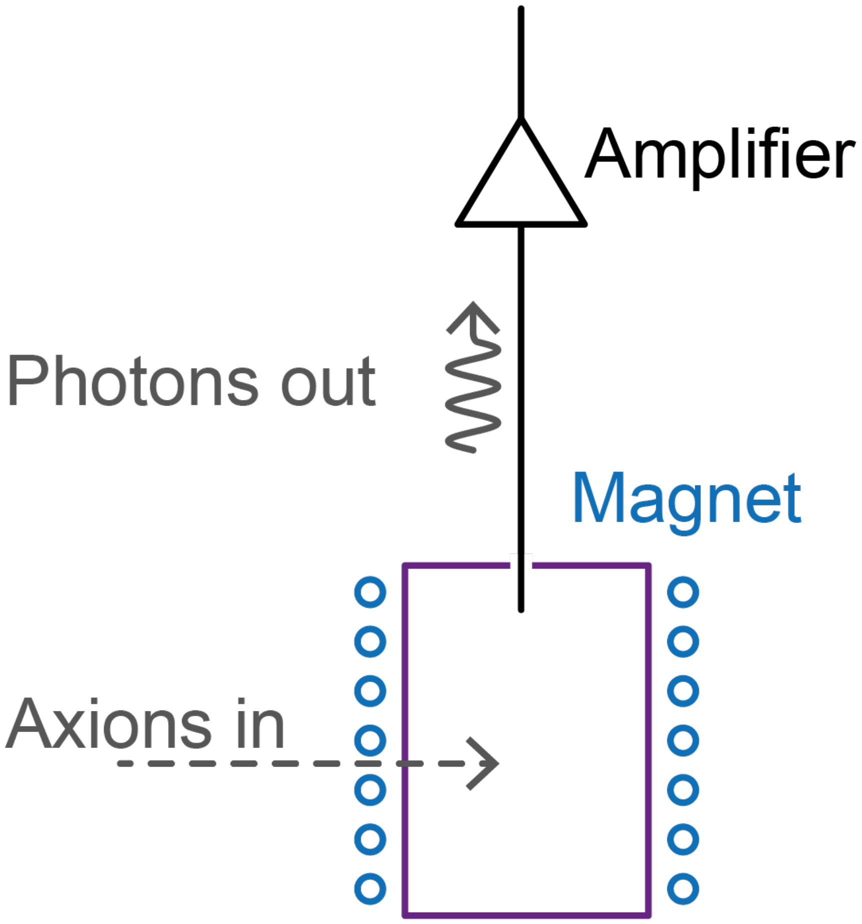
and also my students

- Deepanjan Das
- Scott Henderson
- Saba Khan

and others at Lancaster including Roch Schaanen, Malcolm Poole, Patrick Steger, and Sergey Kafanov

Quantum Sensors for the Hidden Sector

- Axions are an attractive candidate to be dark matter, with a motivated mass search range of 1-100 μeV (= 0.25 - 25 GHz).
- Searches are ongoing using haloscope detectors; however, the search rate is limited by the standard quantum limit on conventional amplifiers.
- Quantum amplifiers can circumvent this limit and allow for much faster searches.
- The QSHS consortium is building a haloscope in which novel quantum electronics will be applied to this challenge.



The QSHS collaboration