Nonstandard Uses for Axion Haloscopes: Transient Signals and Parametric Resonance

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Part I:
Transient Signals and Axion Haloscopes

I have recently been asked by multiple people about the ability for axion haloscopes to detect transient signals

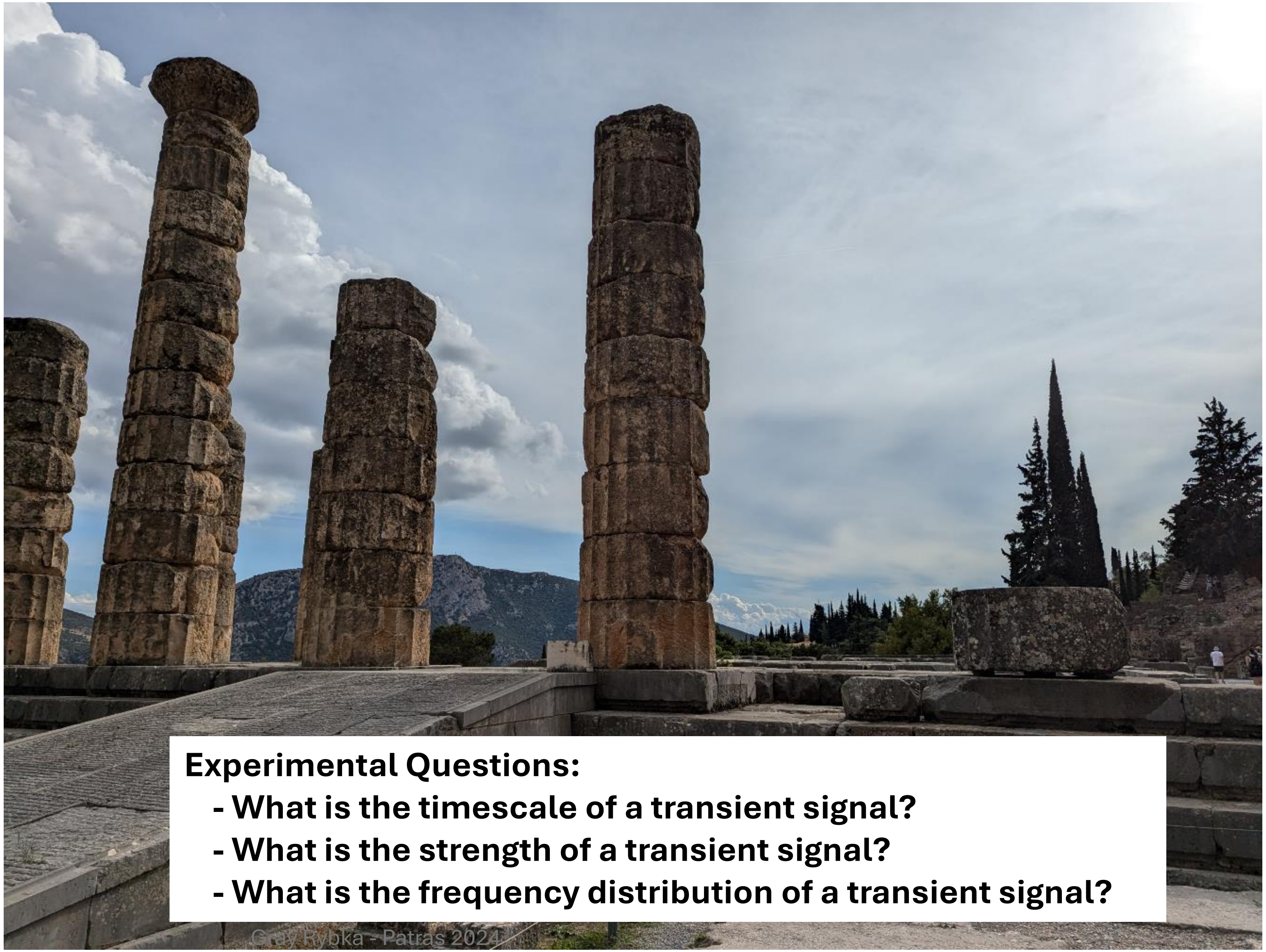
As more creative ideas for haloscope signals are developed, I give a bit of pedagogy to help theorists and modelers understand what is easy and what is hard to do with an Axion Haloscope

Work supported by DOE DE-SC0011665 & NSF 2208847)

Sources

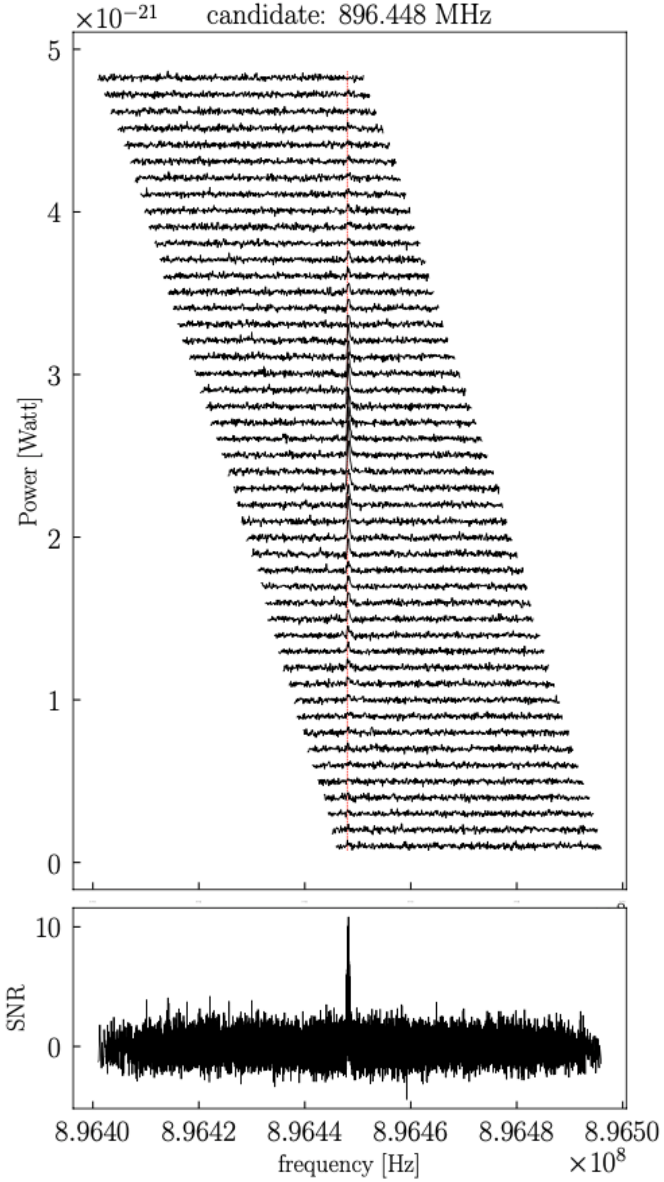
Clumps of axion dark matter:
- cold flows
- miniclusters
- minihalos
- axteroids
- axion stars

Astrophysical sources providing relativistic, time-varying axion blasts.



Experimental Questions:
- **What is the timescale of a transient signal?**
- **What is the strength of a transient signal?**
- **What is the frequency distribution of a transient signal?**

Review: how haloscopes take data



Example from ADMX:

Voltage vs time signals are turned into 100 second long power spectra (though they can be sliced finer)

The cavity is tuned past a single frequency on a timescale of 20 minutes

A single frequency is usually covered in 2 to 3 sweeps, roughly a week apart

Signals that appear in one sweep but not the next are rejected as transient.

Take-away: signals that persist at a single frequency for weeks will be detected in a standard analysis*. Signals that do not will require special analysis.

Transient Difficulty: Ring-up

- Haloscopes rely on resonant enhancement for their extreme sensitivity.

Frequency Domain View

Short signals are spread out over a frequency band 1/dt. If that is wider than the resonance bandwidth, the signal is suppress.

Time Domain View

The cavity takes a time Q/f to ring up and get full resonant enhancement. Times shorter than that are suppressed

Some typical values: f0=1 GHz Q=50,000

Take-away: Signals that last less than a millisecond require significant hardware changes in a haloscope to not be suppressed

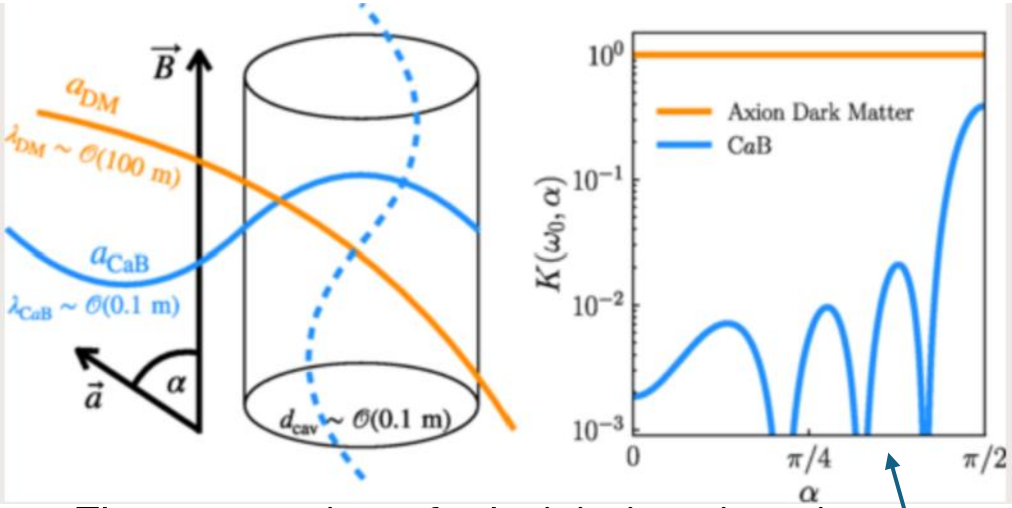
Transient Difficulty: Indistinguishability from RFI

- Radio Frequency Interference (RFI): Cellphone, TV, and Wifi signals are all in the haloscope frequency range. The can and do leak into the datastream.
- Transient power excesses from astrophysical sources cannot be distinguished from the above.
- If a signal is there one week and gone the next week, we must discount it as RFI.
- What logging and reporting would provide conclusive evidence for clumpy axion dark matter?

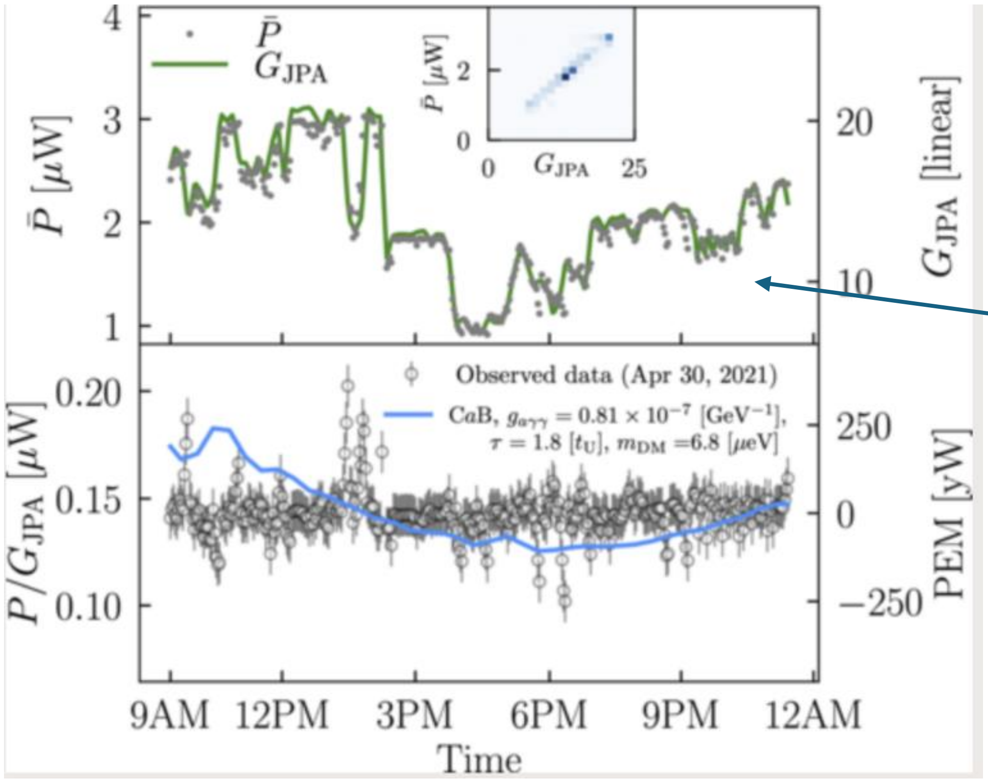
Case Study: CaB axions

Work by T.Nitta, J.A. Dror, H. Murayama, N.L. Rodd, and the ADMX collaboration
Nitta et al. PRL 131, 101002 (2023)

Relativistic axions could be produced by exotic processes in the center of the galaxy "Cosmic Axion Background"



The conversion of relativistic axions in a haloscope is angle-and-time dependent



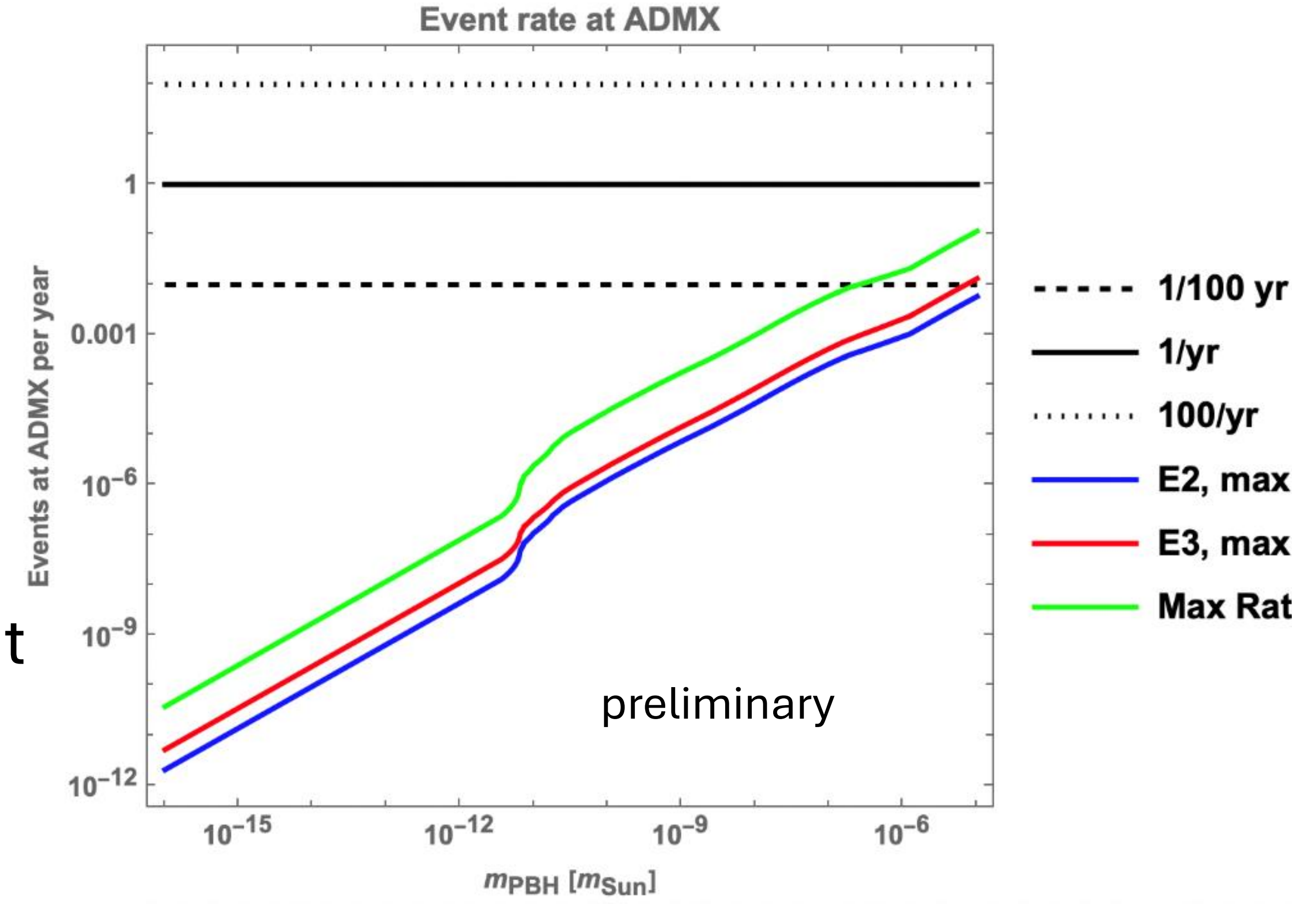
Amplifier gain is modified frequency between measurements. This must be corrected in the analysis.

Dedicated searches for this type of signal would benefit from a change in operations procedure – keep the amplifier gain stable for days!

Case Study: Gravitational Waves

Work with H. Su (UW/U.Mass.Amherst), S. Profumo, L. Brown, S. Ricarte (UC Santa Cruz)

- Merging black holes produce gravitational waves
- Early in the merger, they sit at one frequency (nontransient signal)
- Late in the merger, they chirp through many frequencies (transient signal)
- Better sensitivity to continuous signals. ADMX has a low predicted event rate, but ADMX-EFR may do much better.
- Do we need a PBH binary early warning system? Maybe.



Optimization and alternate signal model work is ongoing

Case Study: Pulsars

Work with T. Dyson (Stanford), A. Prabhu (Princeton)

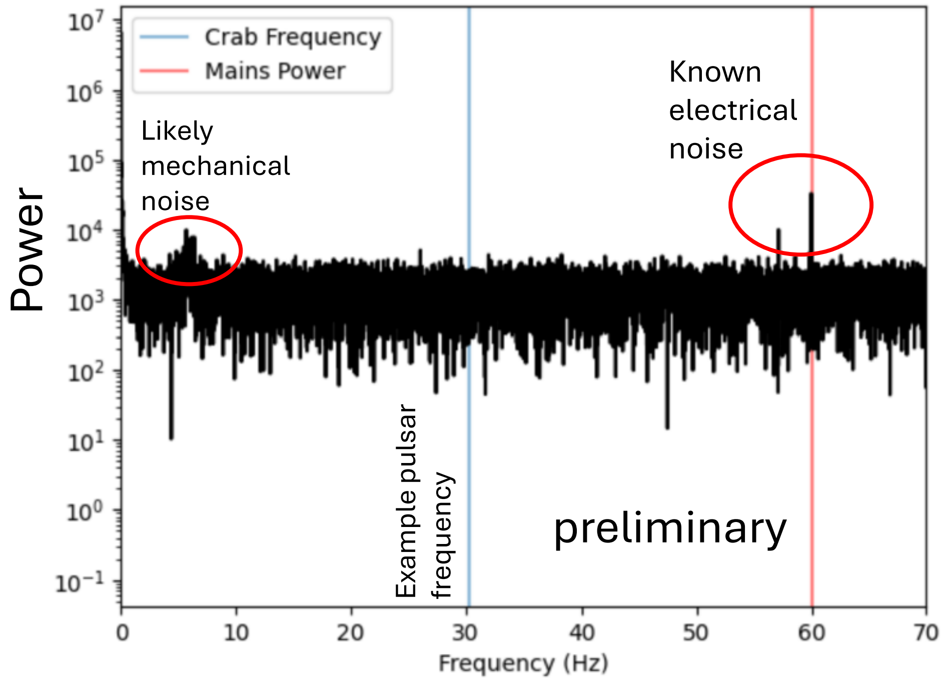
Pulsars have a lot of microwave photons, a big magnetic field, and turn on and off: Transient (probably relativistic) axion signal

Signal is broadband -> cavity tuning doesn't matter

The relative phase of the pulsar signal is very well known from radio observations, tracking over years.

Hence, data from years of haloscopes could be combined and sensitivity scales linearly with time!

Example autocorrelation of haloscope data



This shows how we would search for periodic transient signals in the ~Hz range

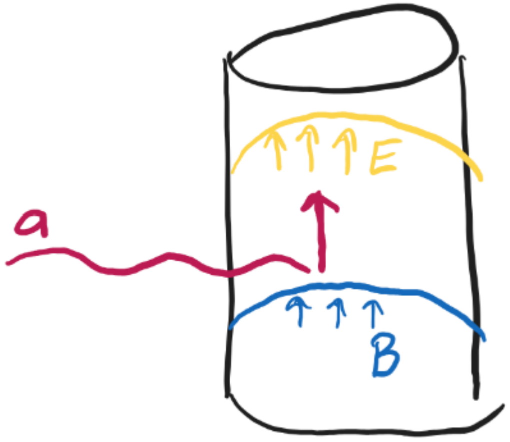
Alas, the pulsars are very far away, and the signal in a haloscope appears far too small to be relevant.

Part II
Axion Parametric Resonators

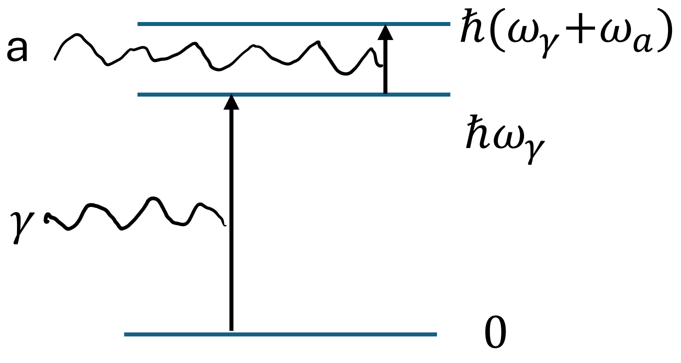
Work with K. Ruffin, U. Virginia, as part of the NSF REU Program

(NSF REU #2243362)

RF Axion Haloscope Review



RF Axion Haloscope Cartoon



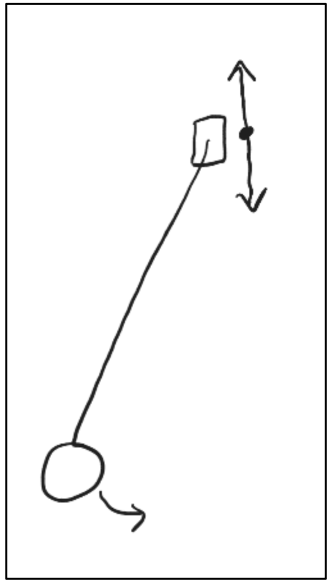
Axion haloscopes can use a time varying magnetic field instead of a static field

It works best when two resonant modes that have good $\vec{E}\cdot\vec{B}$ overlap are spaced apart by the $\hbar\omega_a = m_a$.

P. Sikivie, (2013), arXiv:1009.0762
Z. Bogorad et al. PRL 123, 021802 (2019)

Parametric Resonance Review

Child on swing



Pendulum with movable pivot

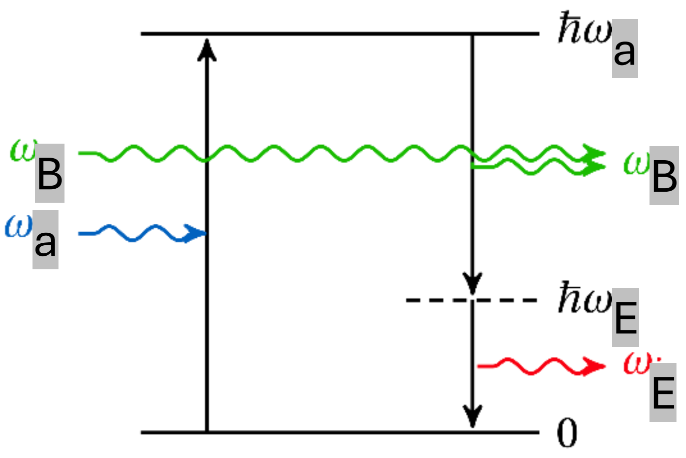
Josephson Parametric Amplifier

Nonlinear interactions allows power at one frequency to be transferred to another frequency

Axion Cavity Parametric Resonance

$$H_{int} = g_{a\gamma\gamma} a E \cdot B$$

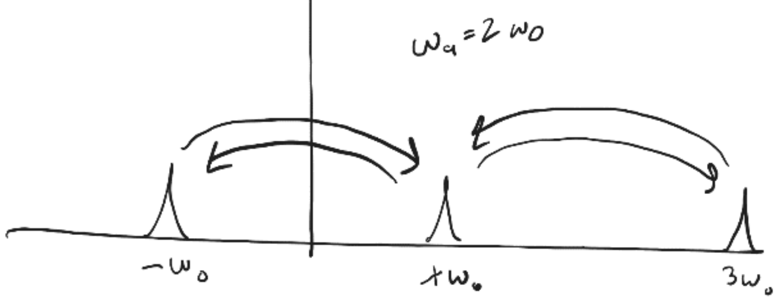
Nonlinear coupling if E and B are related



Optical parametric amplifier (Wikipedia picture), hacked for axions.

Axion is stimulated to decay point of view

$$\sin\omega_0 \sin\omega_a = \frac{1}{2}\cos(\omega_0 + \omega_a) + \frac{1}{2}\cos(\omega_0 - \omega_a)$$

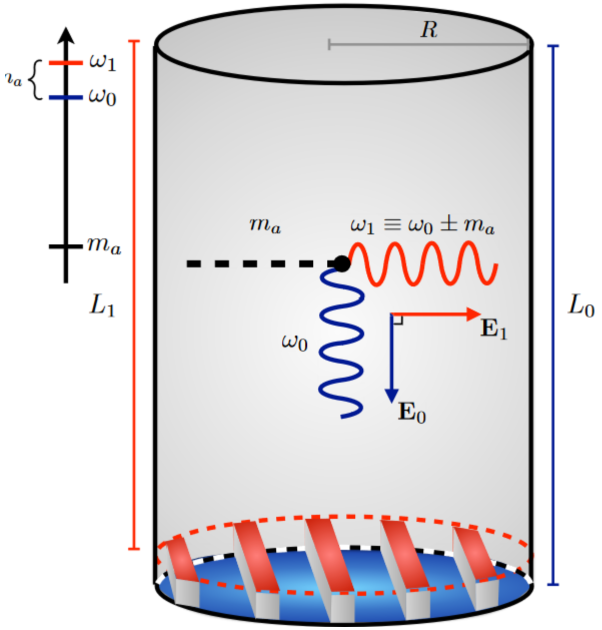


RF amplifier point of view. Axion is pump tone for a parametric amplifier

The Concept

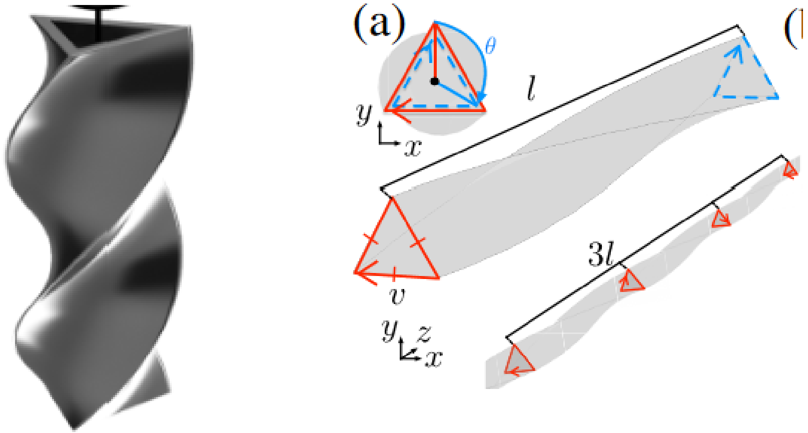
- We'd like to use parametric resonance to convert axions into photons faster than normal – stimulated emission is almost always better than spontaneous emission.
- We learned after the fact that someone had already studied the possibility of axion parametric resonance in free-floating clumps of axions. M. P. Hertzberg and E. D. Schiappacasse, JCAP 2018 (11), 004.
- Can we arrange a terrestrial experiment to trigger this process?

Axion Parametric Resonator Design and Mode Structure



A. Berlin, et al, JHEP 2020, 88 (2020).

Cavities can be engineered with the desired frequency splitting between TE and TM modes



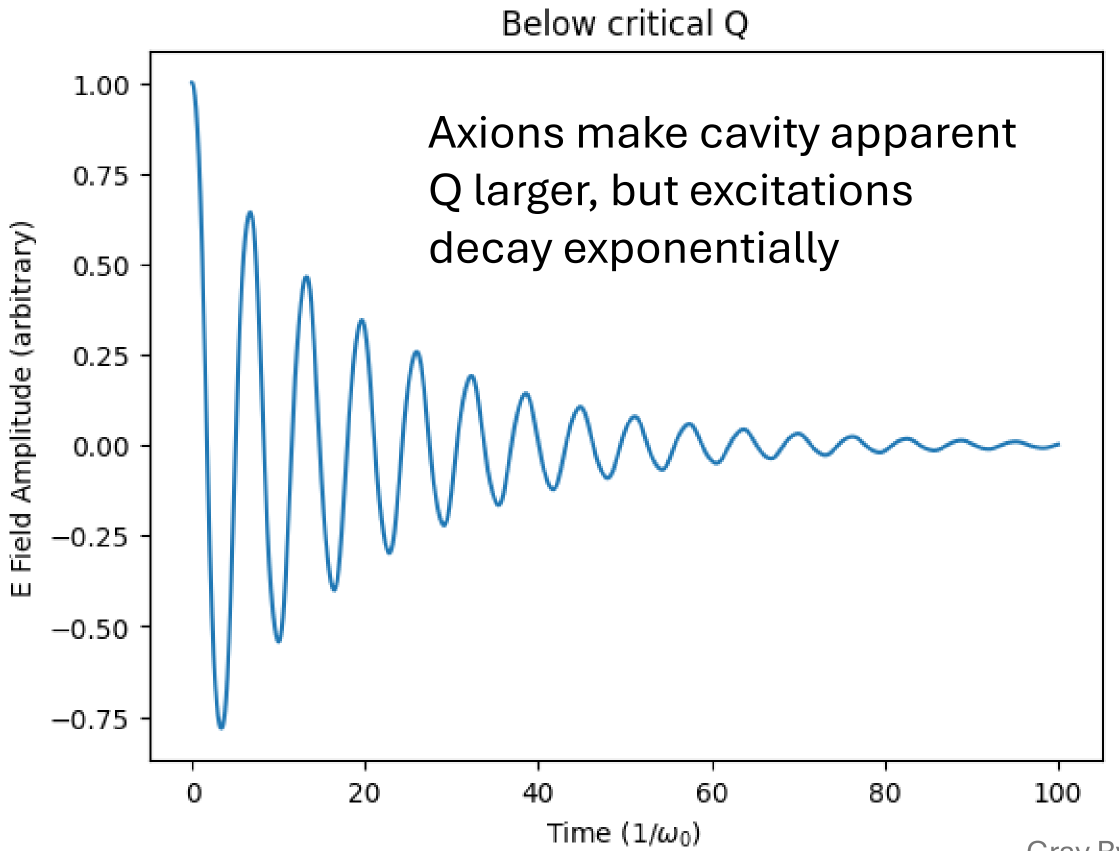
J. F. Bourhill, et. al Phys. Rev. D 108, 052014 (2023)

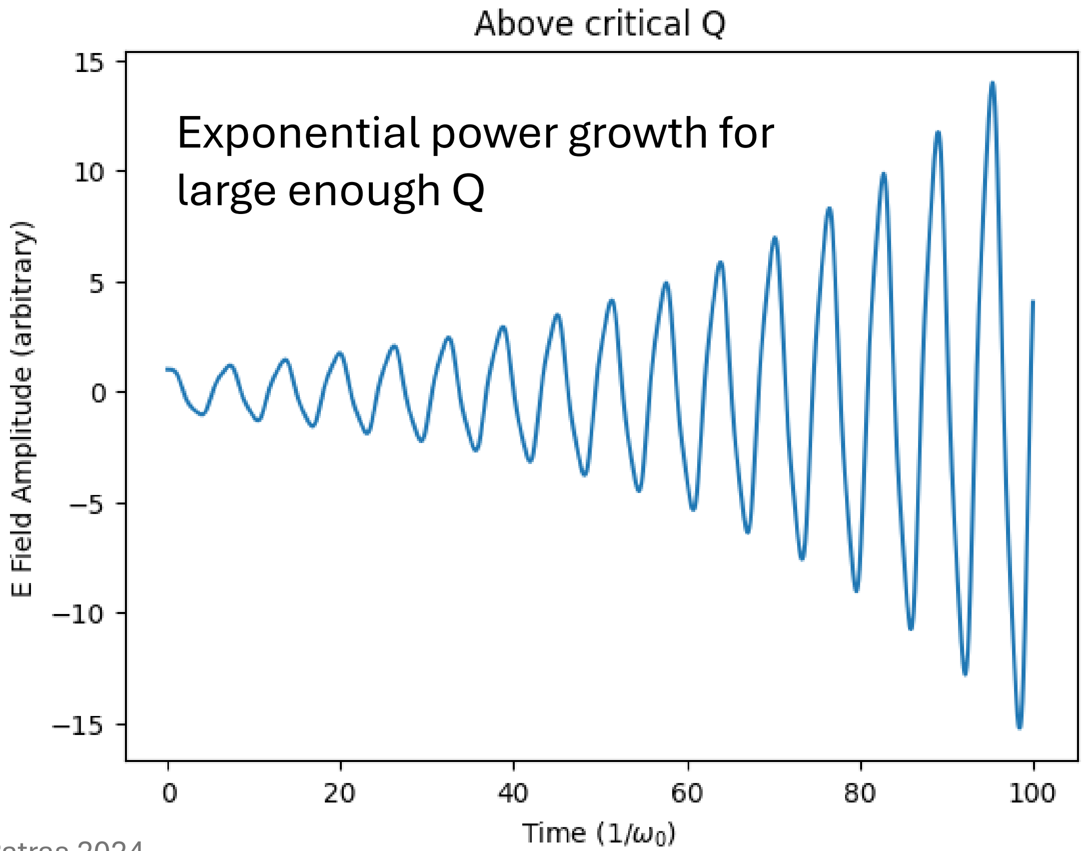
Cavities with chiral properties have modes with nonzero EB, and have already been proposed for axion searches

Either should work, but the math for the chiral cavities is easier to visualize

Cavity Response

If the rate of photons gained from axion conversion exceeds the rate of losses in the cavity, the stored energy of the cavity grows exponentially





Can we build one?

Condition for unstable growth:

$$g \eta Q \sqrt{\rho_a} > 2\omega_a$$

Axion Mass

Axion coupling

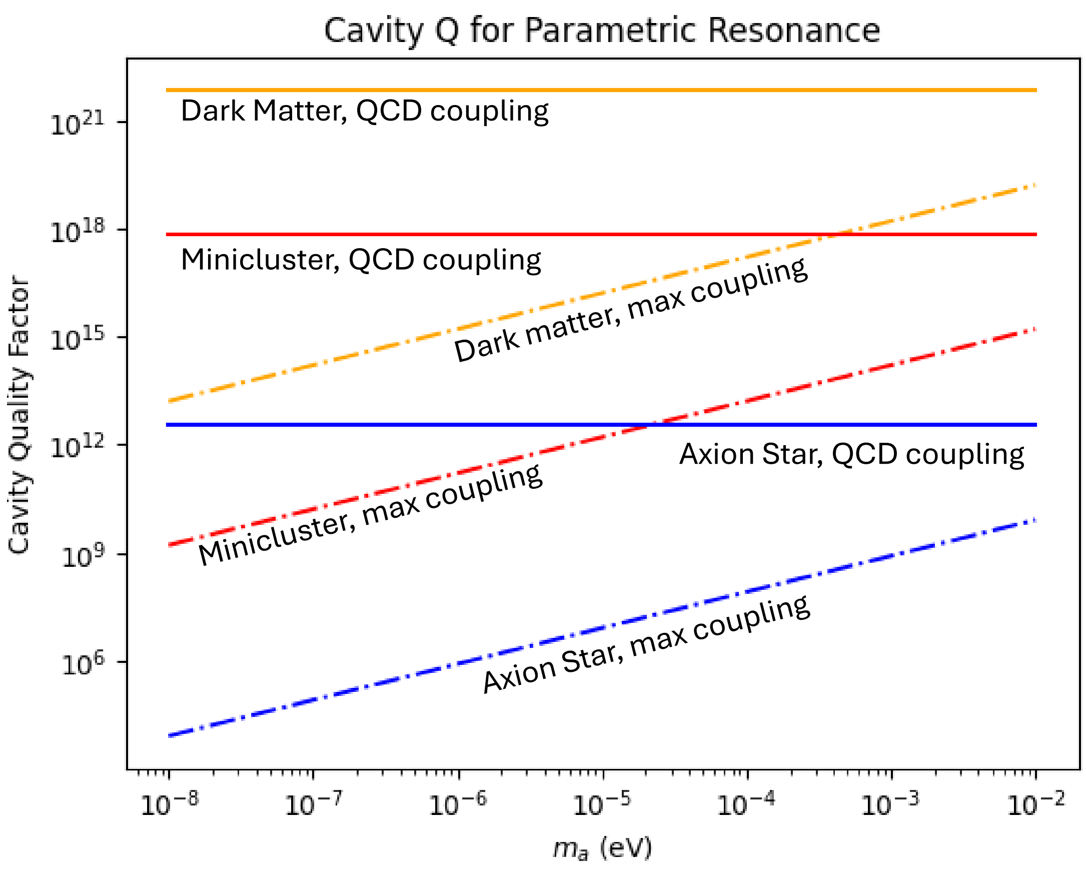
Mode Overlap

Cavity Q

Axion Density

Achievable resonator Q's are only usable for large couplings and high axion densities.

Conclusion: Not useful for an axion search, but if you need to extract power from the center of an axion star, please give us a call.



Conclusions

- A variety of new physics signals in axion haloscopes vary with time.
- Detecting transient signals present unique challenges for current haloscope analysis procedures – don't assume a signal can be excluded without a dedicated analysis.
- An understanding of how to distinguish new physics signals from transient RFI is critical for any test of theory.
- There is still room to grow in terms of leveraging interactions between wavelike dark matter and normal matter.