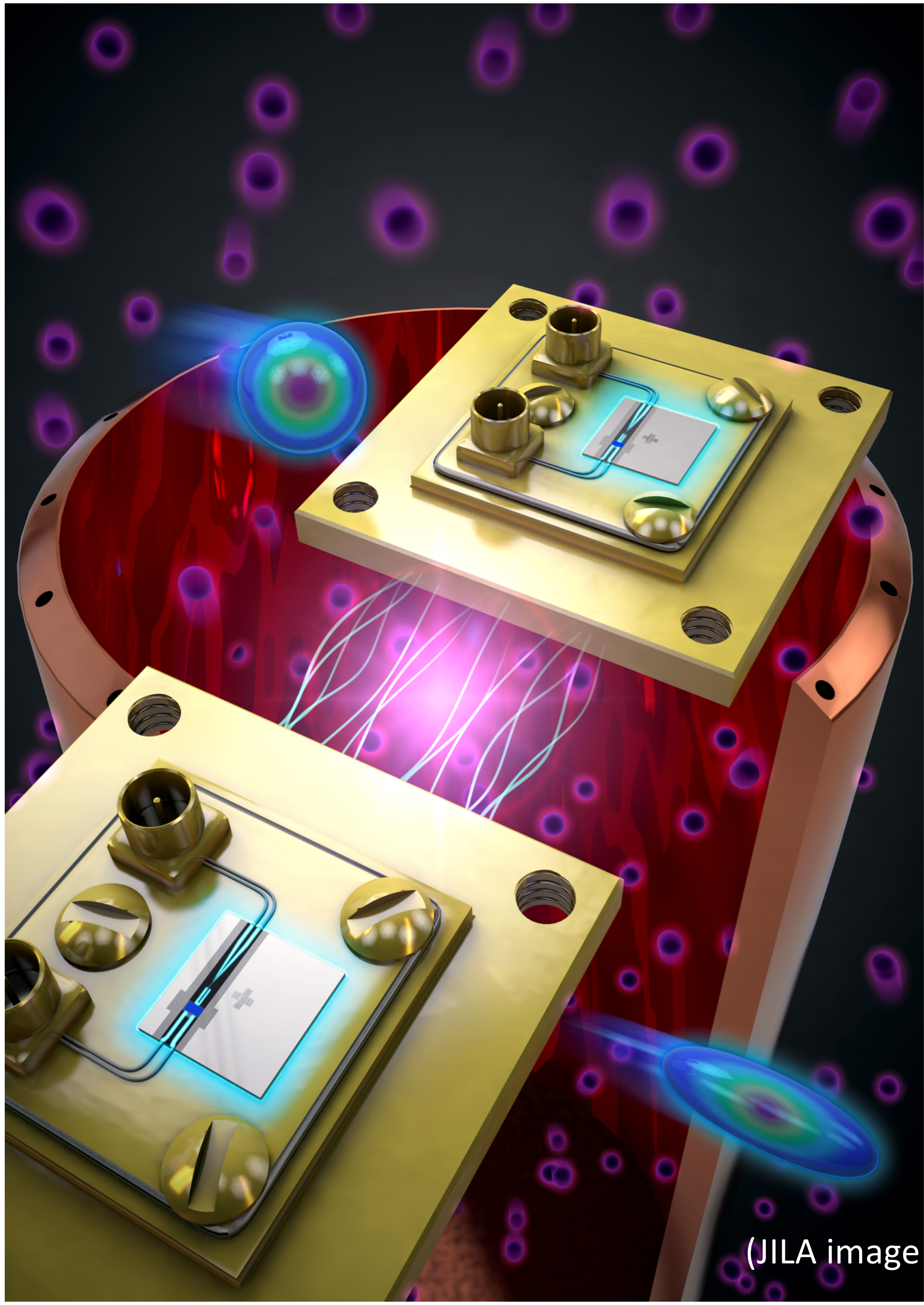


A Tribute to Georg

Some New Developments in the Microwave Dark Mark Axion Search

Karl van Bibber
University of California Berkeley

November 10, 2022

(JILA image courtesy Lehnert Group and Steven Burrows)

Outline

- An Apology
- A Brief Reminiscence
- The Microwave Cavity Search for Dark Matter Axions
- Searching from Top to Bottom
- Final Thoughts

Berkeley Axion Works™

An Apology

Up until a few days ago, I was planning on being with you in person.

But when you are Department Chairman, sometimes things blow up, and disrupt your most cherished personal plans.

An Apology

Up until a few days ago, I was planning on being with you in person.

But when you are Department Chairman, sometimes things blow up, and disrupt your most cherished personal plans.

However, when you are Chairman of the Nuclear Engineering Department, you should at least be thankful that things only blow up *figuratively*, and not *literally!*

My first foray in the axion world (1987): Photon Regeneration (a.k.a. Light Shining through Walls)

VOLUME 59, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1987

Proposed Experiment to Produce and Detect Light Pseudoscalars

K. Van Bibber
Lawrence Livermore National Laboratory, Livermore, California 94550

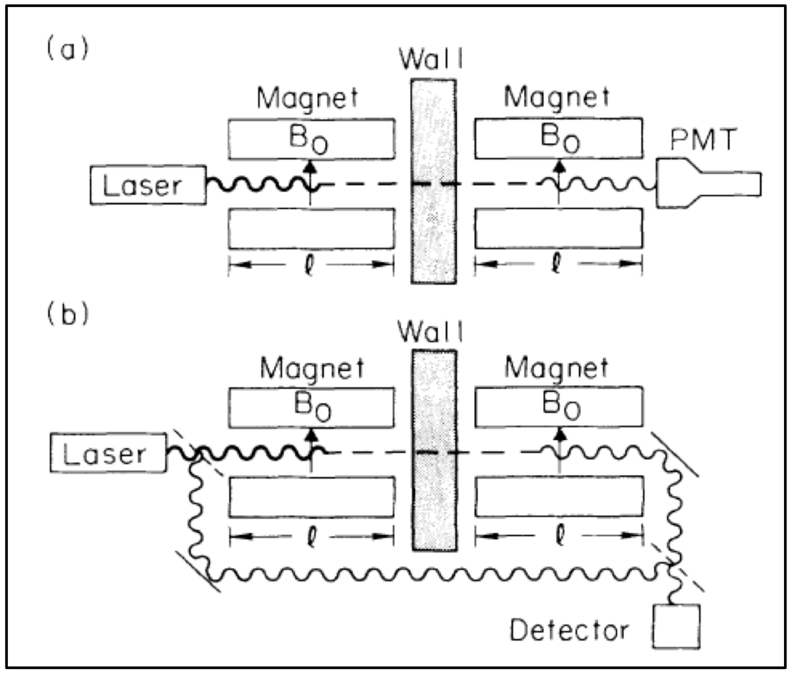
N. R. Dagdeviren and S. E. Koonin
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

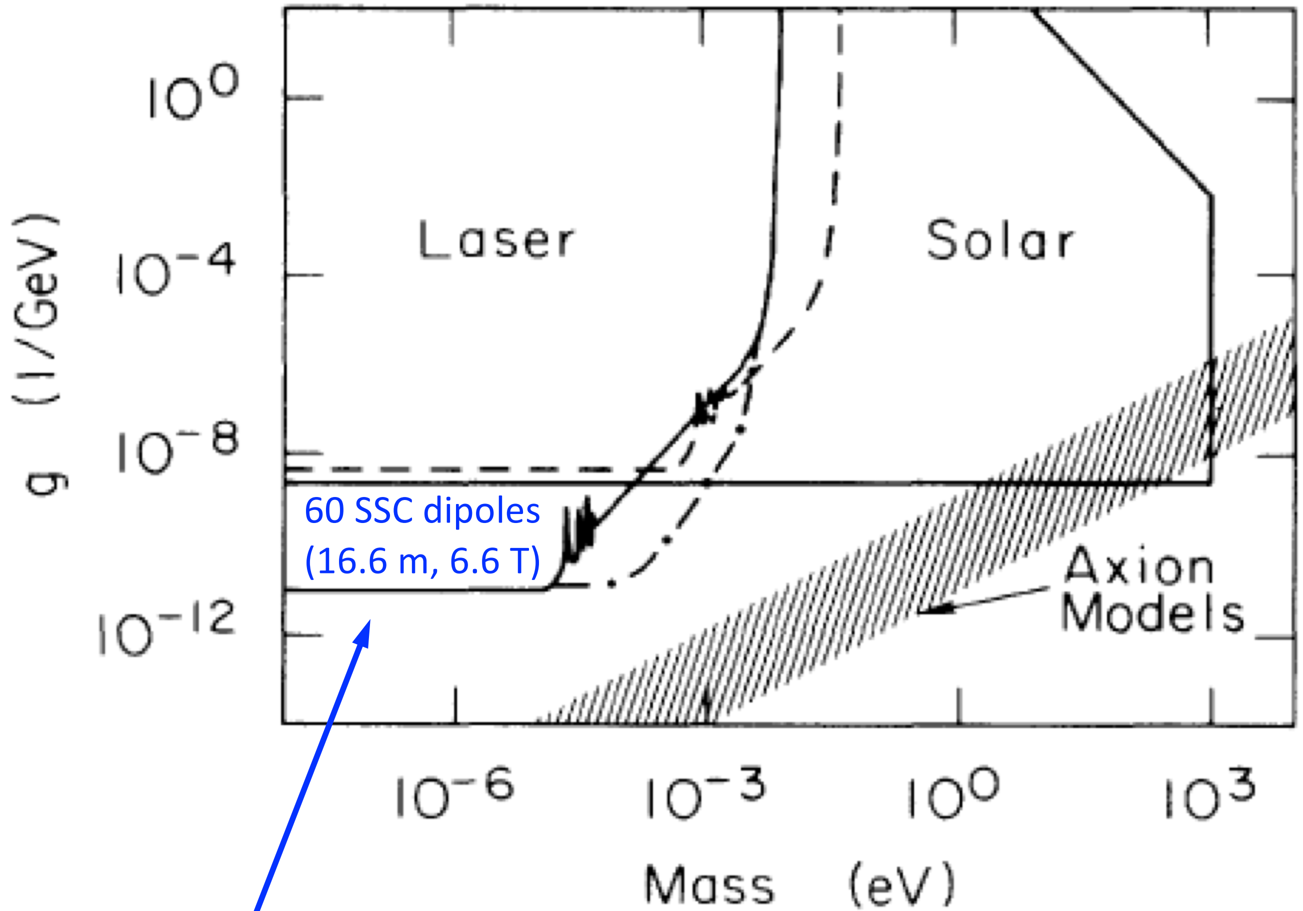
A. K. Kerman
Center for Theoretical Physics, Department of Physics, and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

H. N. Nelson
Department of Physics and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 12 May 1987)

We propose a laboratory experiment to produce and detect a light neutral pseudoscalar particle that couples to two photons. The pseudoscalar would be produced by a (real) photon from a laser beam interacting with a second (virtual) photon from a static magnetic field; it would be detected after it reconverts to a real photon in a duplicate magnetic field. The bounds on the coupling constant that could be obtained from a null result in such an experiment compete favorably with astrophysical limits and would substantially improve those from direct measurements.





Exactly where ALPS-II will be – 35 years later!

The beginning of a long friendship: Giving the photon an effective mass (1989)

PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 39, NUMBER 8 15 APRIL 1989

Design for a practical laboratory detector for solar axions

K. van Bibber
Physics Department, Lawrence Livermore National Laboratory, University of California, Livermore, California 94550

P. M. McIntyre
Physics Department, Texas A&M University, College Station, Texas 77843

D. E. Morris
Physics Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

G. G. Raffelt
Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, University of California, Livermore, California 94550
and Astronomy Department, University of California, Berkeley, California 94720
(Received 19 September 1988)

The beautiful paper of Georg & Leo's, which all my students read (1988)

PHYSICAL REVIEW D VOLUME 37, NUMBER 5 1 MARCH 1988

Mixing of the photon with low-mass particles

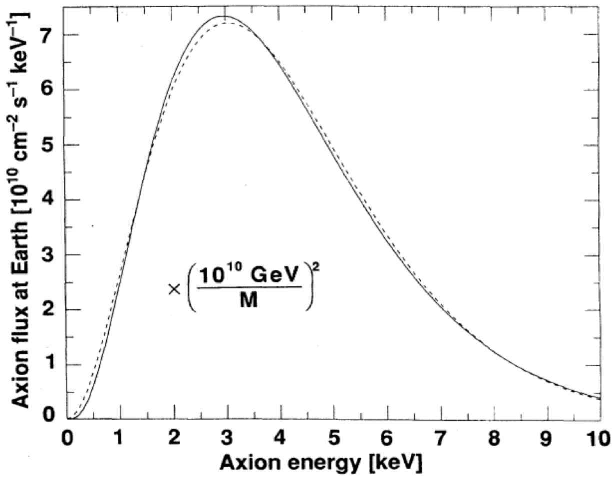
Georg Raffelt
Astronomy Department, University of California, Berkeley, California 94720
and Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, California 94550

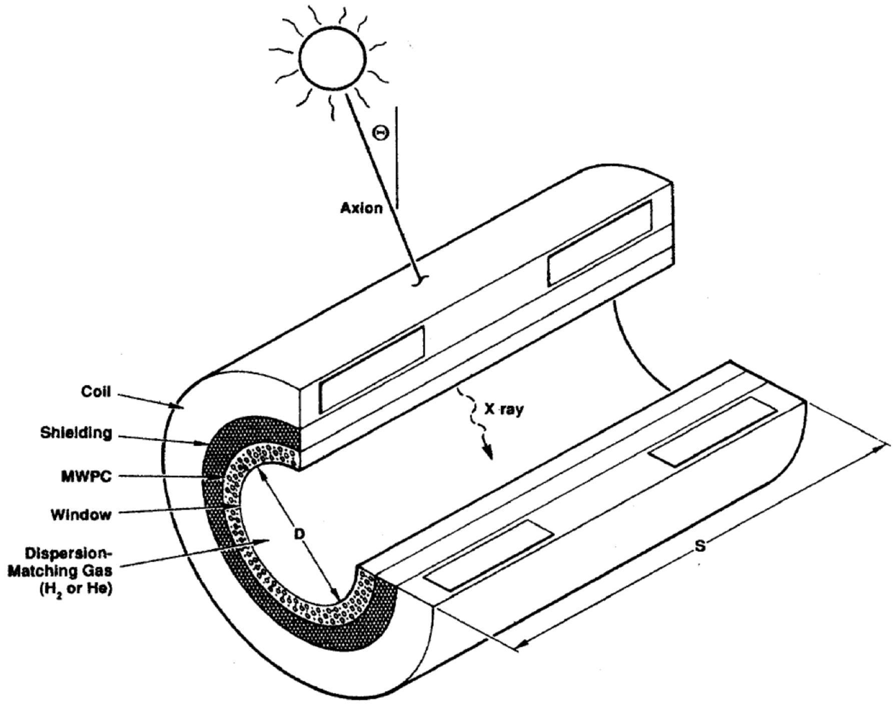
Leo Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Postfach 401212, 8000 München 40,
Federal Republic of Germany

(Received 21 August 1987)

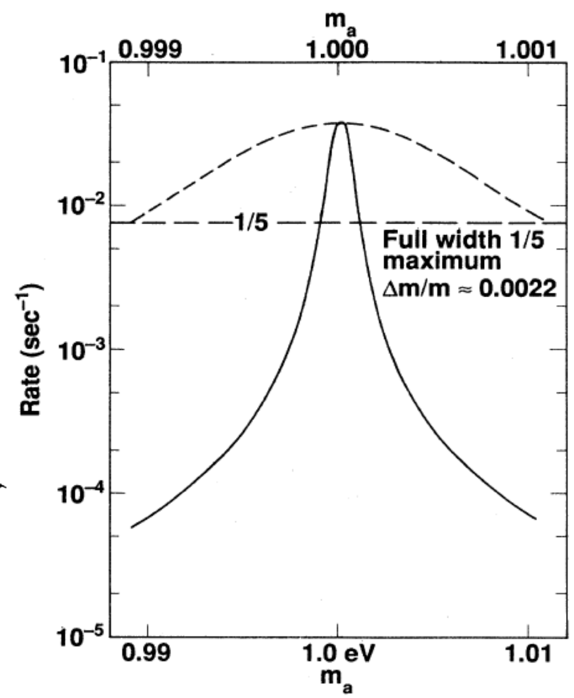
Photons can mix with low-mass bosons in the presence of external electromagnetic fields if these particles—not necessarily of spin 1—couple by a two-photon vertex. Important examples are the hypothetical axion (spin 0) and graviton (spin 2). We develop a formalism which is adapted to study the evolution of a photon (axion, graviton) beam in the presence of external fields. We apply our results to discuss the possibility of detecting axions by a measurement of the magnetically induced birefringence of the vacuum. We also discuss photon-axion (graviton) transitions in pulsar magnetic fields. The QED-induced nonlinearity of Maxwell's equations causes magnetic birefringence effects which are much stronger than the axion-induced effects in the range of axion parameters allowed by astrophysical constraints. Also, this QED effect induces an index of refraction for photons in vacuum which is so large near pulsars that photon-axion (graviton) transitions are strongly suppressed. However, this QED effect can be canceled by plasma refractive effects, leading to degeneracy between photons and axions so that resonant transitions can occur in analogy with the Mikheyev-Smirnov-Wolfenstein effect. The adiabatic condition can be met only in spatially extended systems, possibly in the magnetosphere of magnetic white dwarfs. Our conclusions differ substantially from several recent discussions of various aspects of these mixing phenomena.

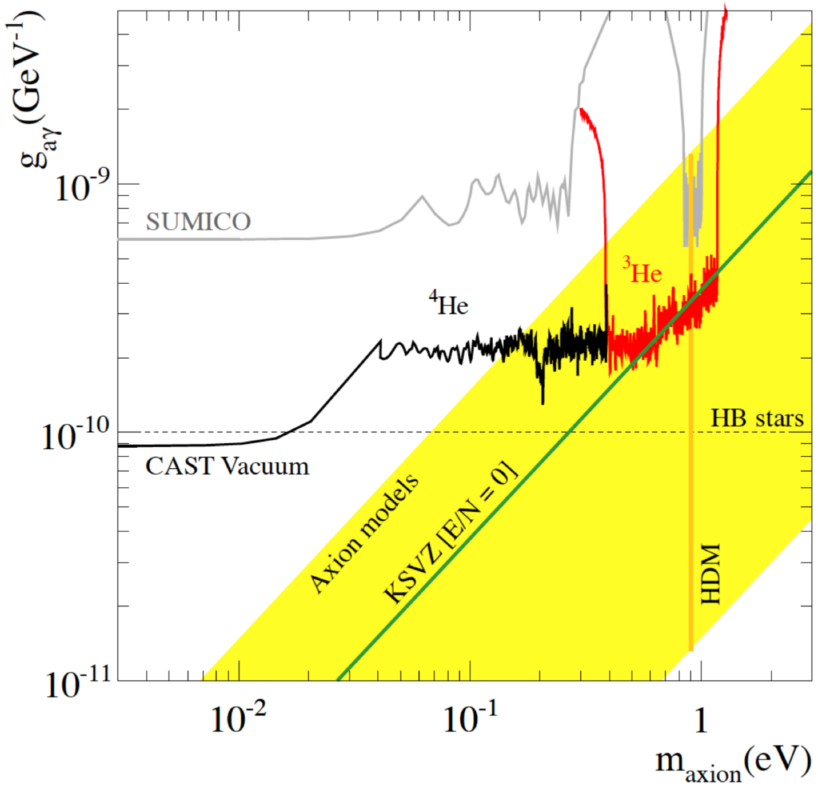
Extending the helioscope mass sensitivity by filling the conversion volume with gas





$$\omega_{pe} = \left(4\pi n_{e0} e^2 / m_e\right)^{1/2}$$





M. Arik et al., Phys. Rev. Lett. 112 (2013) 091302

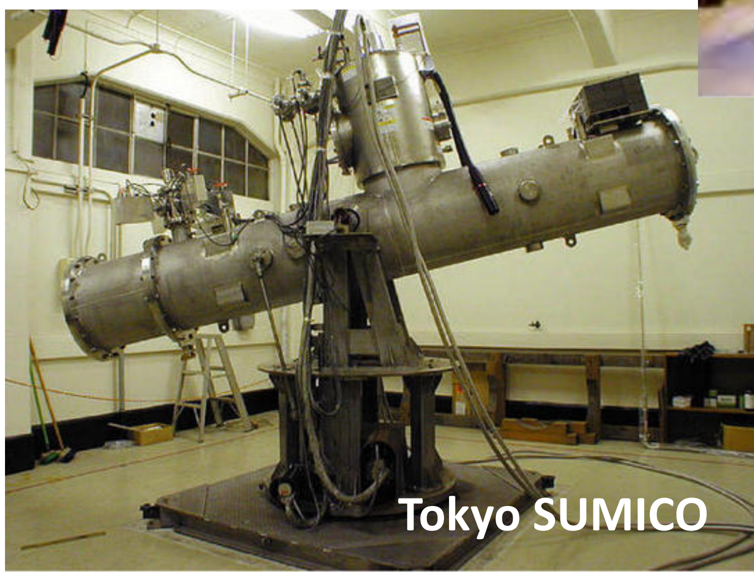
However, Georg, we still do need to publish an Erratum to our paper …

Design for a practical laboratory detector for solar axions

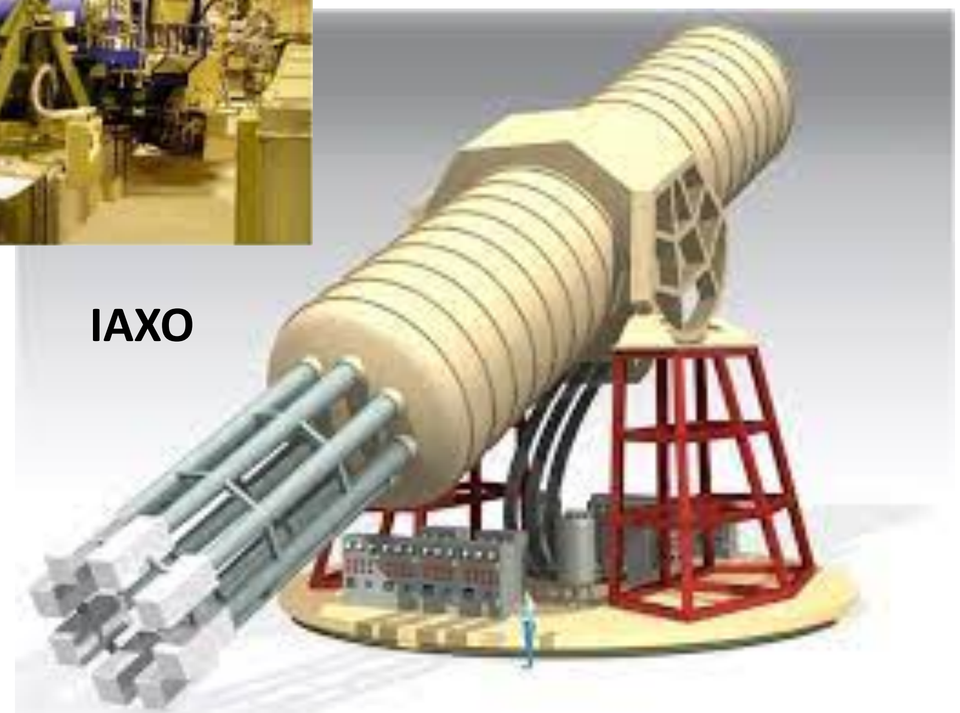
The title of the paper needs to be changed to:

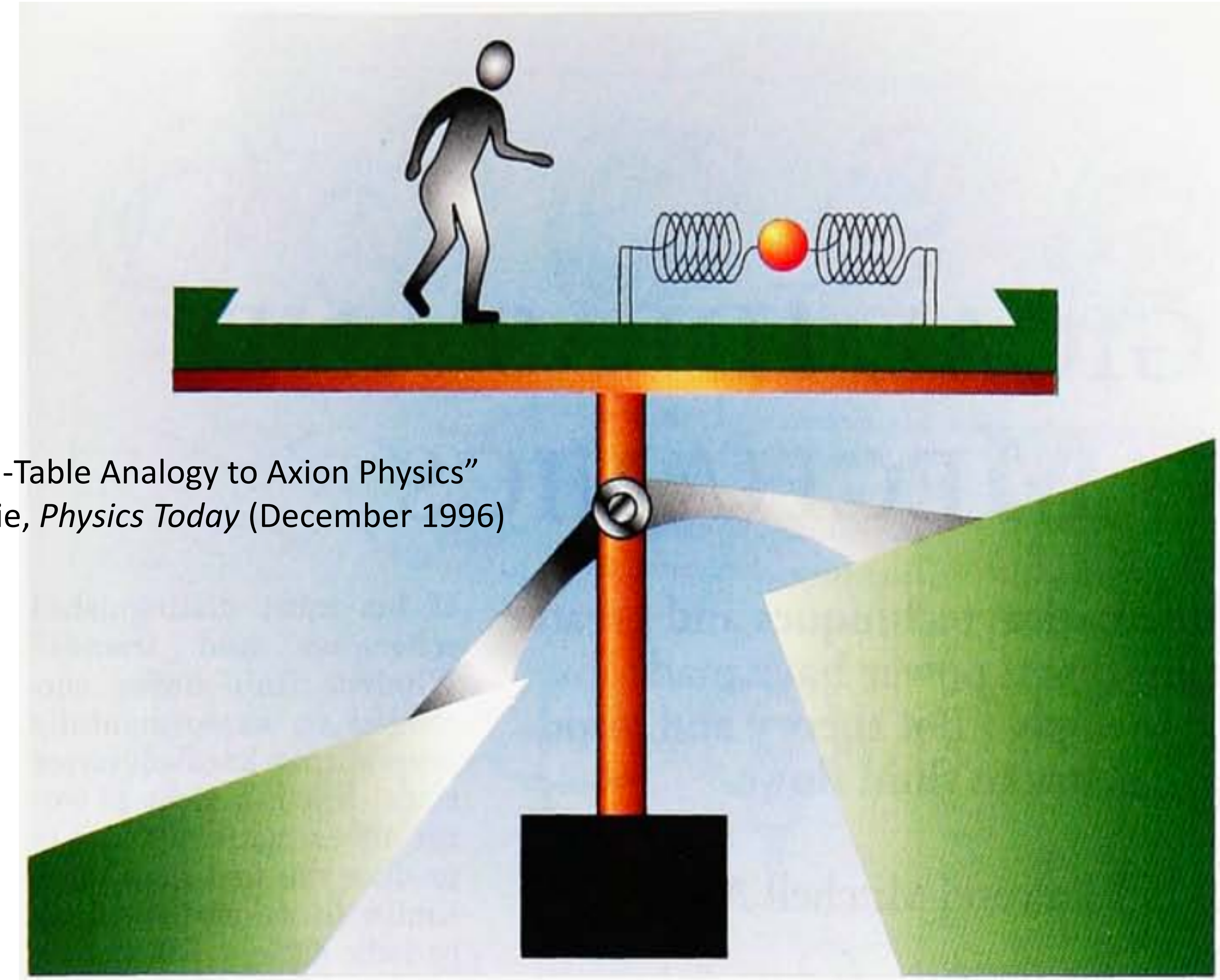
an impractical

Design for a ~~practical~~ laboratory detector for solar axions

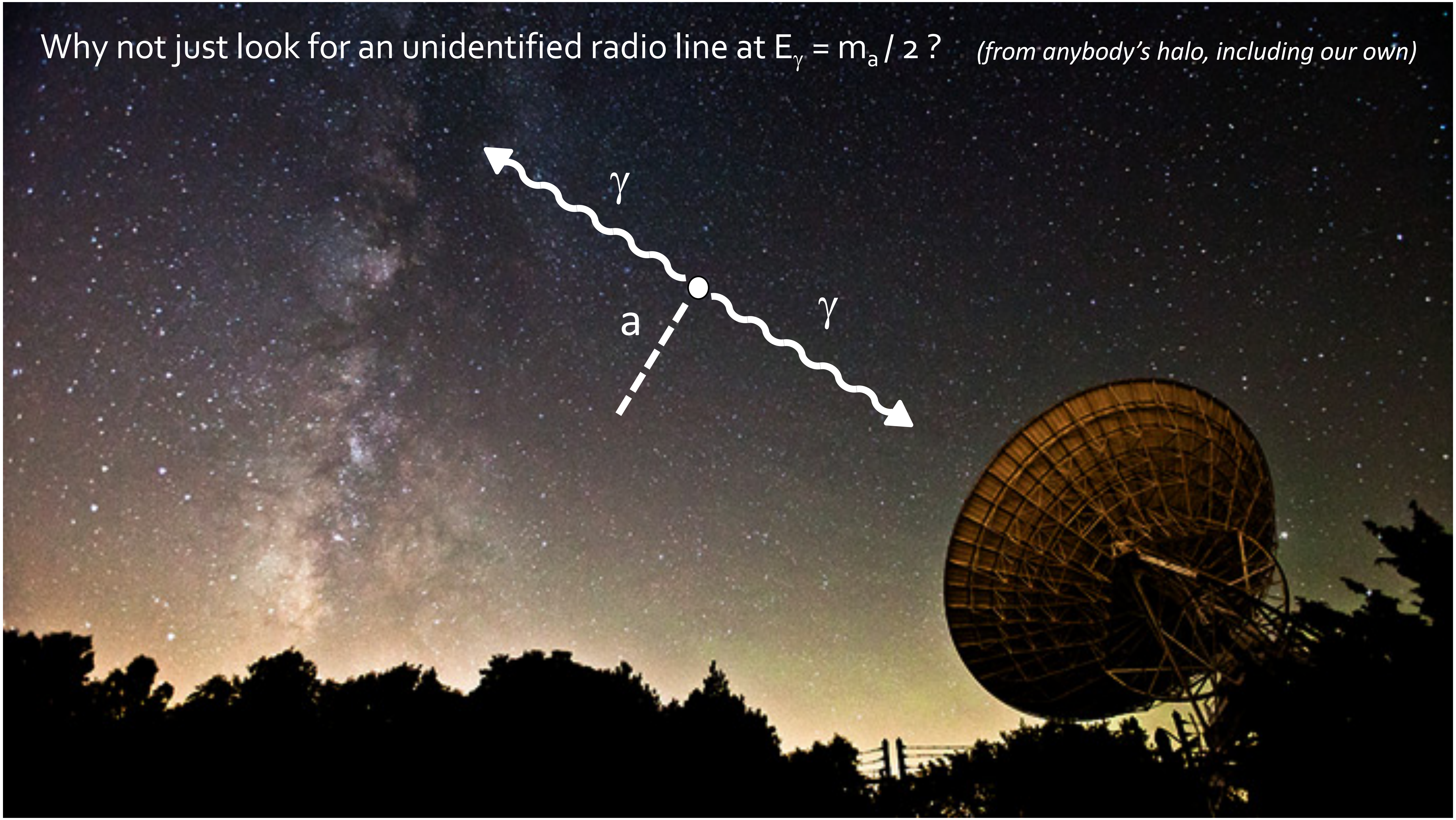


All helioscopes beginning with RBF (D.M. Lazarus et al.) have employed our trick with gas, but have sensibly used transverse dipole magnets !

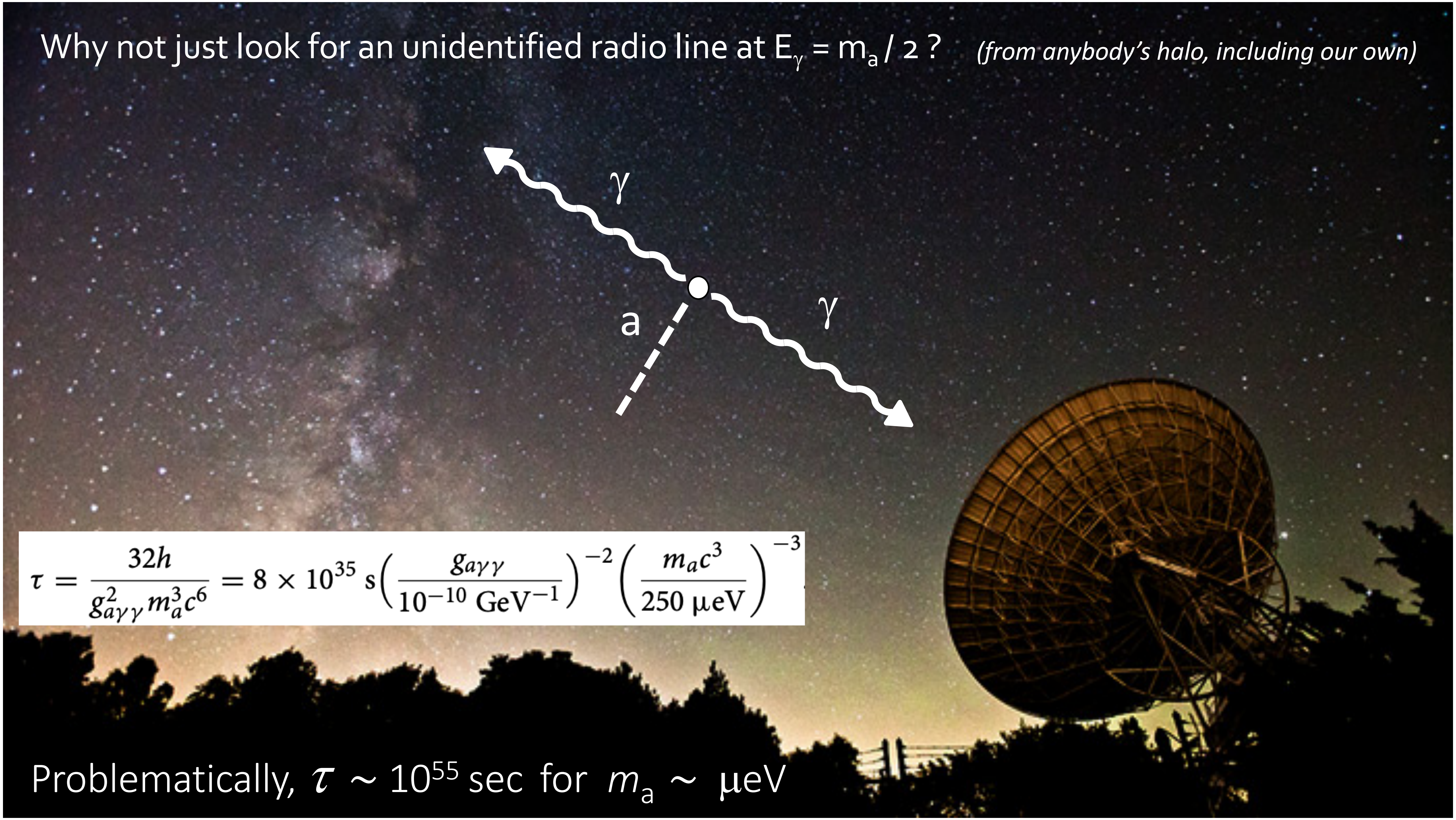




“The Pool-Table Analogy to Axion Physics”
Pierre Sikivie, *Physics Today* (December 1996)


Why not just look for an unidentified radio line at $E_\gamma = m_a / 2$?
(from anybody's halo, including our own)
γ
γ
a

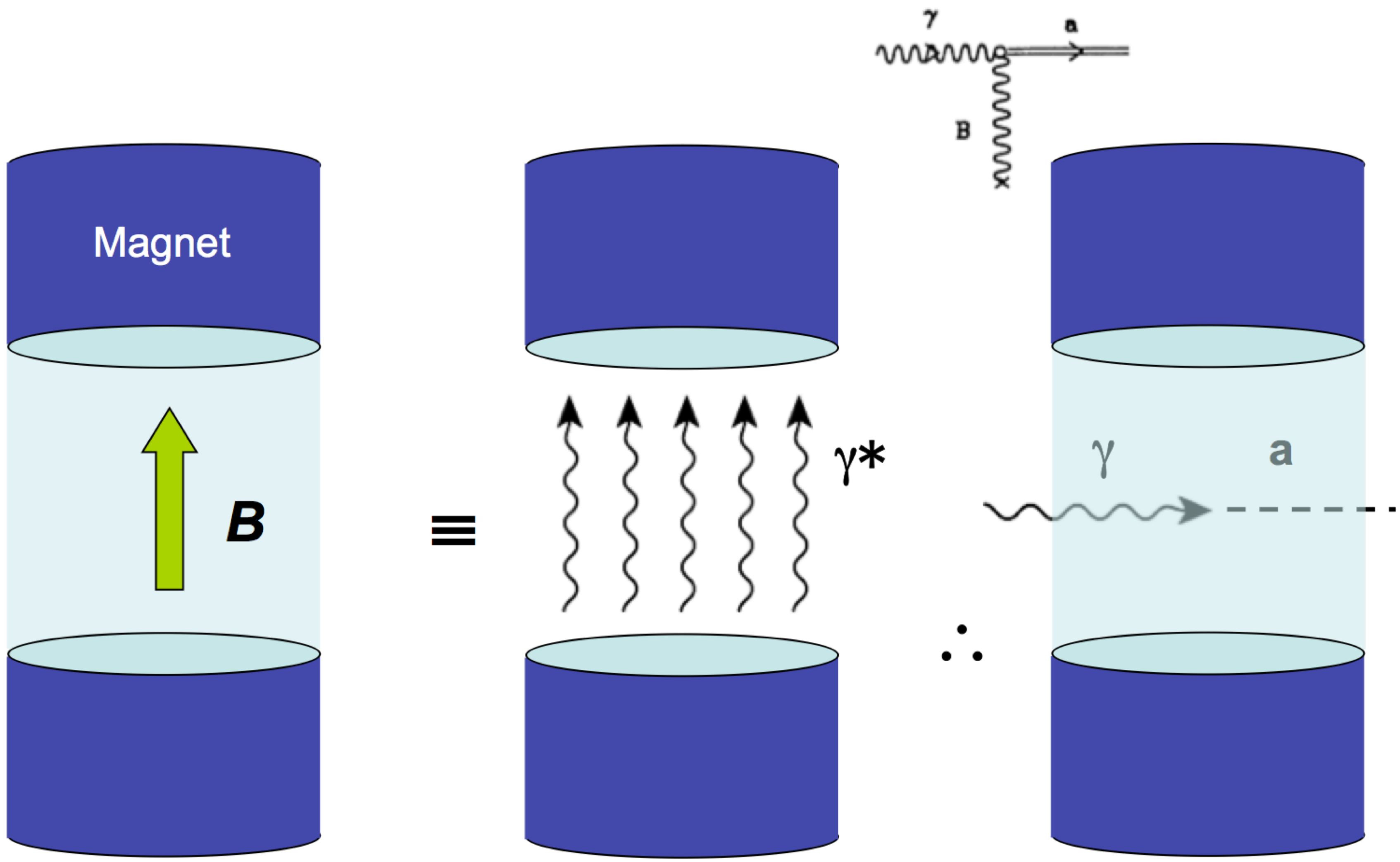
Why not just look for an unidentified radio line at $E_\gamma = m_a / 2$? *(from anybody's halo, including our own)*



$$\tau = \frac{32h}{g_{a\gamma\gamma}^2 m_a^3 c^6} = 8 \times 10^{35}\ \mathrm{s} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{m_a c^3}{250\ \mu\mathrm{eV}}\right)^{-3}$$

Problematically, $\tau \sim 10^{55}$ sec for $m_a \sim \mu\mathrm{eV}$

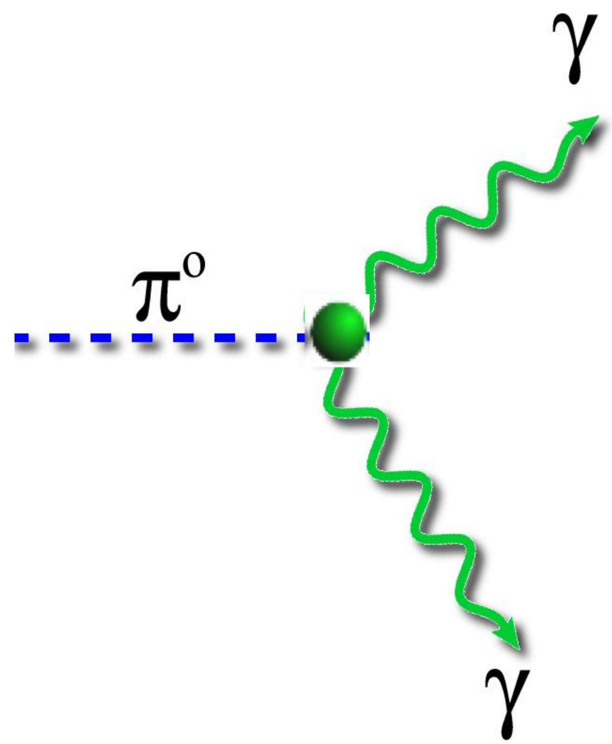
The Primakoff Effect



Classical EM field *Sea of virtual photons* *Primakoff Effect*

Primakoff effect *(H. Primakoff, Phys. Rev. 81 (1951) 899)*

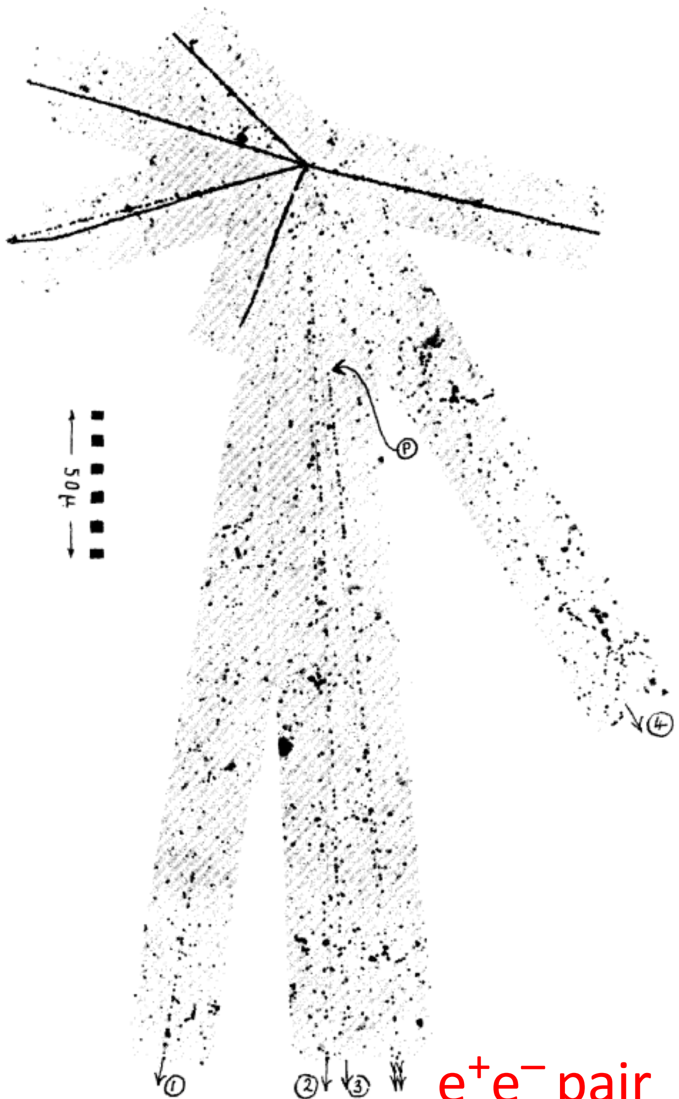
How to accurately measure the lifetime of the neutral pion, τ_{π^0} which was very short?



Early experimental limits on the lifetime of the neutral pion

A. G. CARLSON et al. Phil. Mag. Ser. 7 Vol. 41, Pl. XXIV.

LXIII. Nuclear transmutations produced by cosmic ray particles of great energy. — Part V. The neutral mesons (1950)



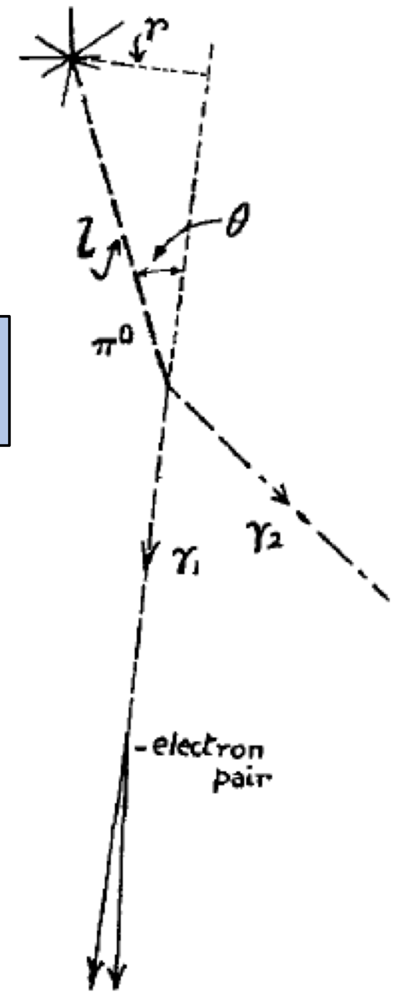
A large shower of mesons (6+4p) showing the origin of a related pair very close to the star. The pair has been marked by an arrow in the microphotograph.

Observer: Miss E. James. *To face page 724*

$$\tau\,(\pi^0) < 5 \times 10^{-14}\ \text{sec}$$

About a factor of x700 longer than its currently accepted value, 8.5×10^{-17} sec

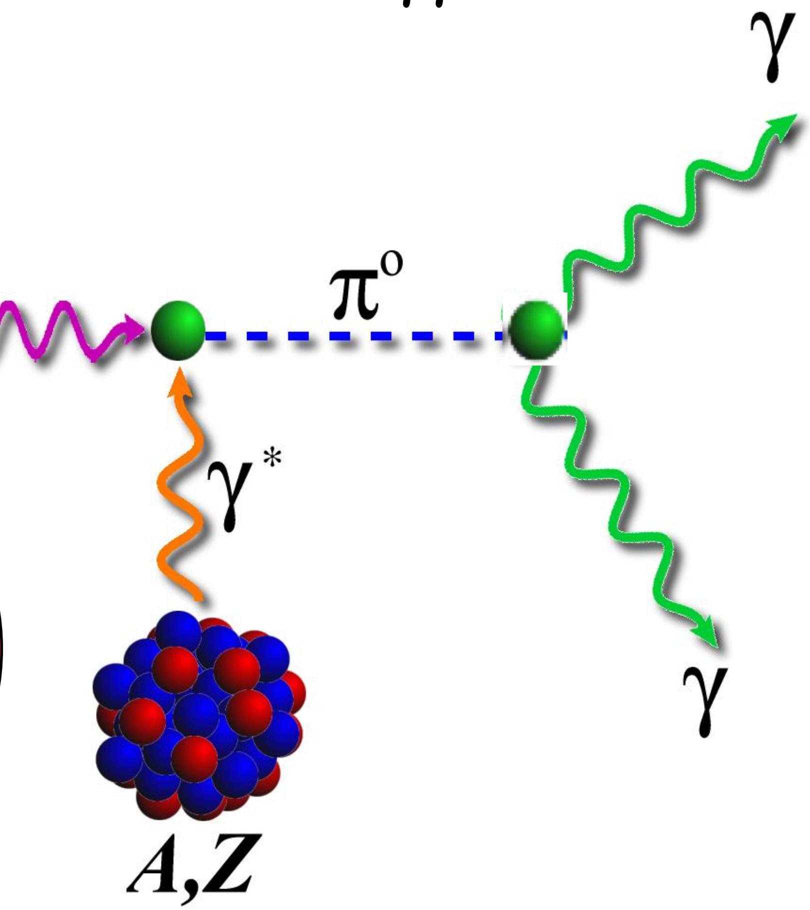
Fig. 8.



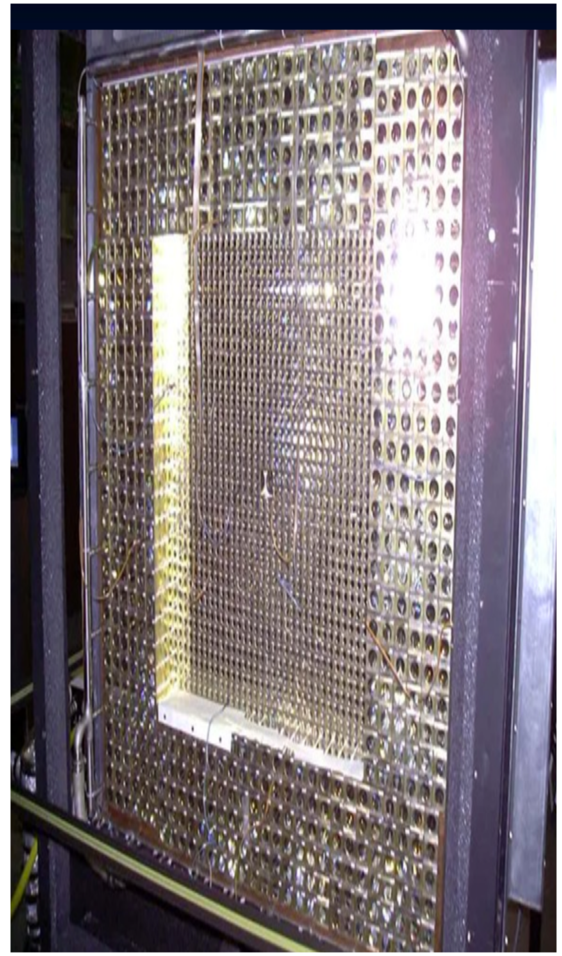
Principle of the method for the determination of the lifetime of the neutral meson.

Primakoff – experiment (1965): $\tau \sim 8.7 \times 10^{-17}$ sec

$$\sigma \leftarrow g_{\pi\gamma\gamma} \rightarrow \tau$$



No clock needed!



A curiously delicious irony …

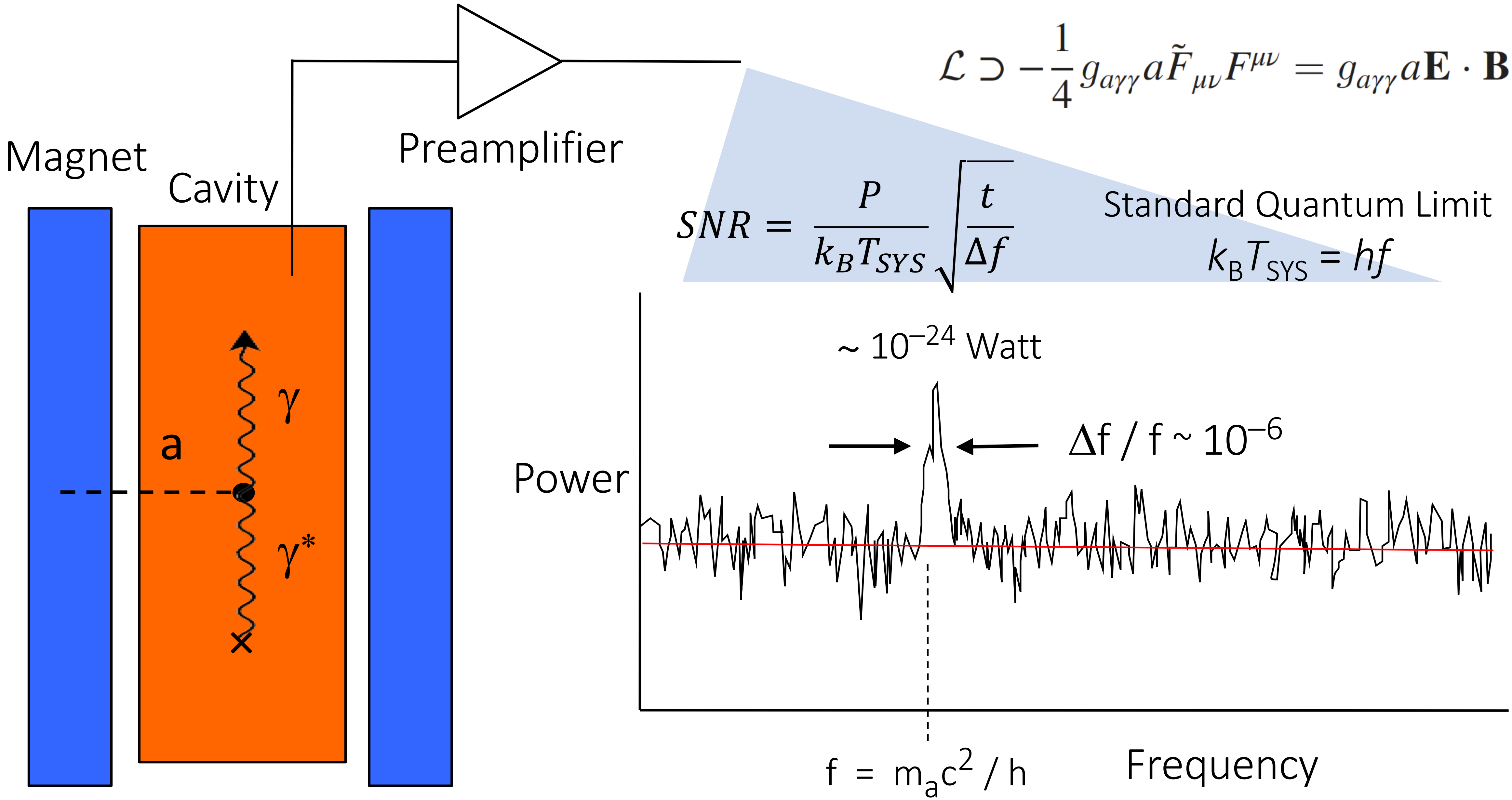
The same Primakoff interaction which enables us to measure the lifetime of a particle that *lives too short to be seen*, also enables us to measure the lifetime of a particle that *lives too long to be seen* …

… differing by a mere 70 orders of magnitude in lifetime.

Thank you, Henry!

Microwave cavity dark matter axion searches (a.k.a. haloscopes)

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



$$SNR = \frac{P}{k_B T_{SYS}} \sqrt{\frac{t}{\Delta f}}$$

Standard Quantum Limit

$$k_B T_{SYS} = hf$$

Prehistory: Pierre's PRL, UF & RBF pilot experiments, and Adrian's BNL workshop (1989)

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

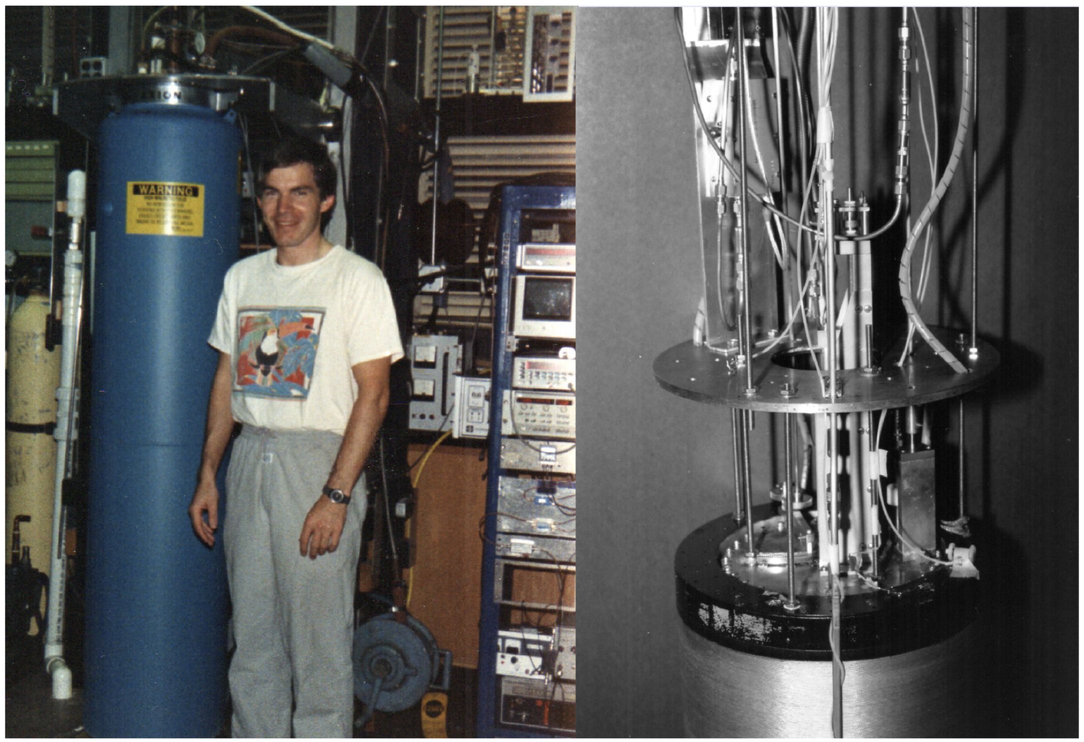
Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611

(Received 13 July 1983)

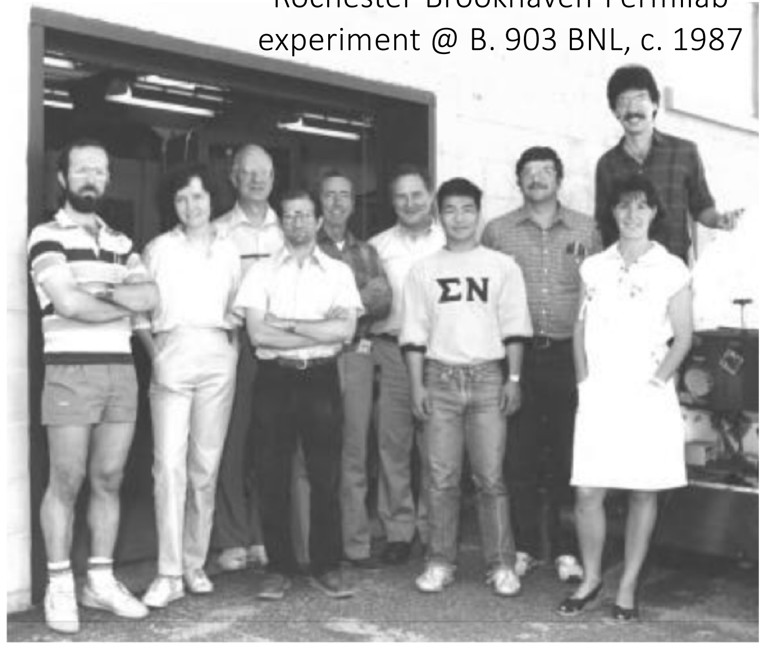
Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

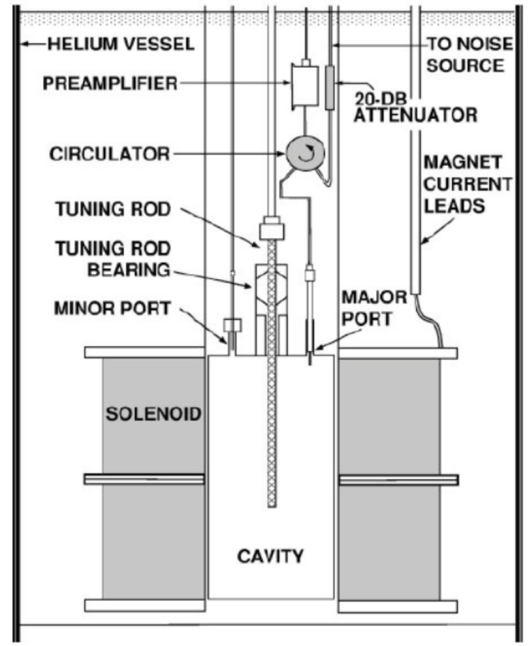
PACS numbers: 14.80.Gt, 11.30.Er, 95.30.Cq

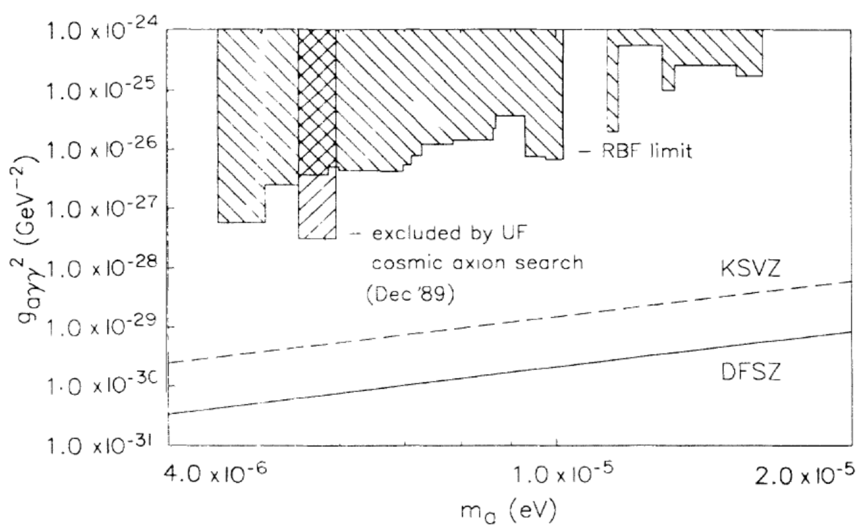


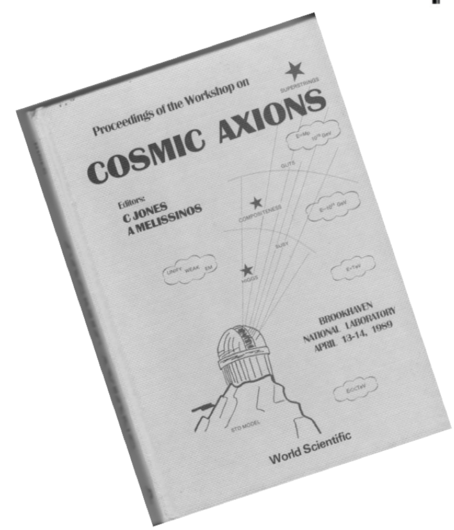
U. Florida experiment, c. 1989; Chris Hagmann, Ph.D. student

Rochester-Brookhaven-Fermilab experiment @ B. 903 BNL, c. 1987

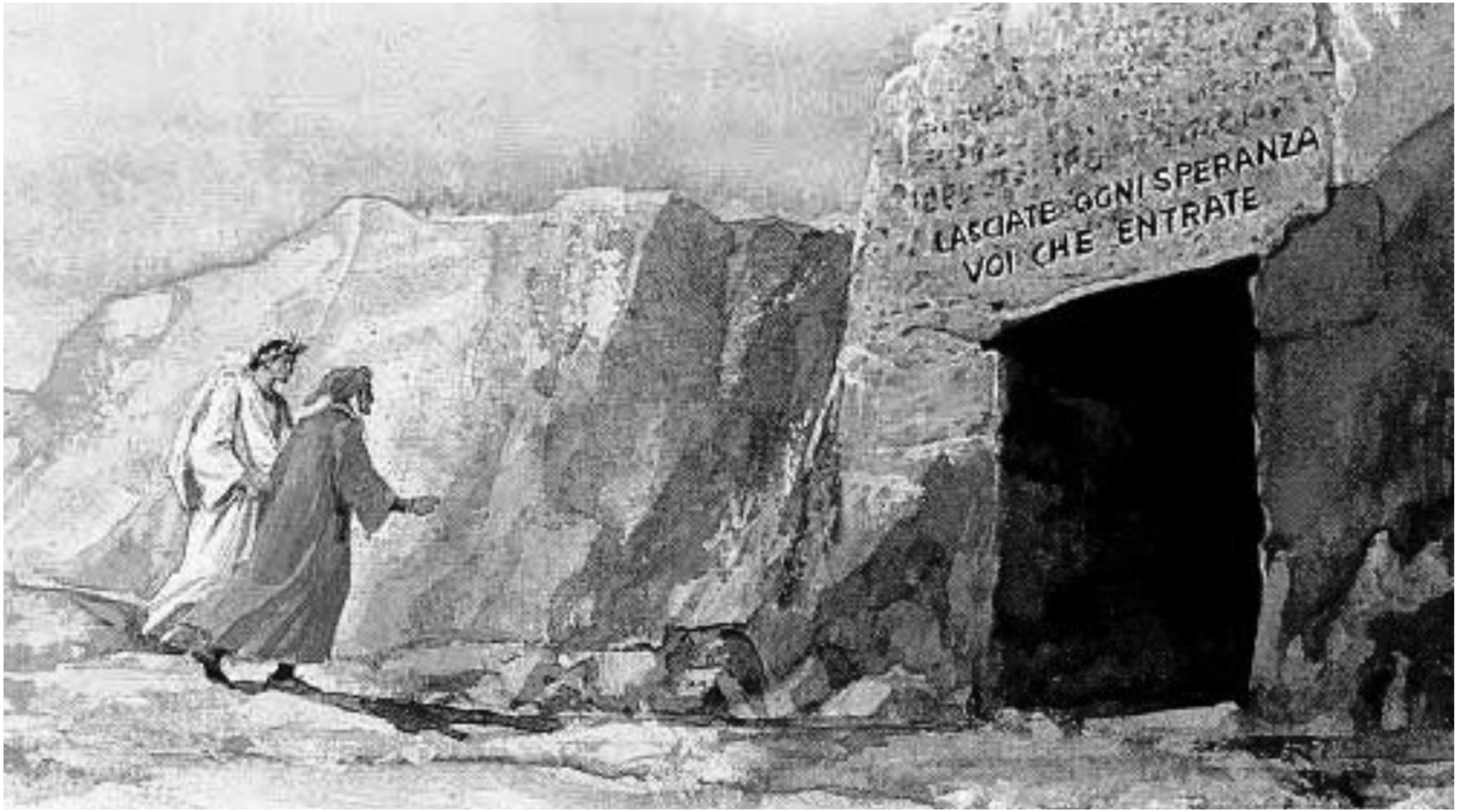








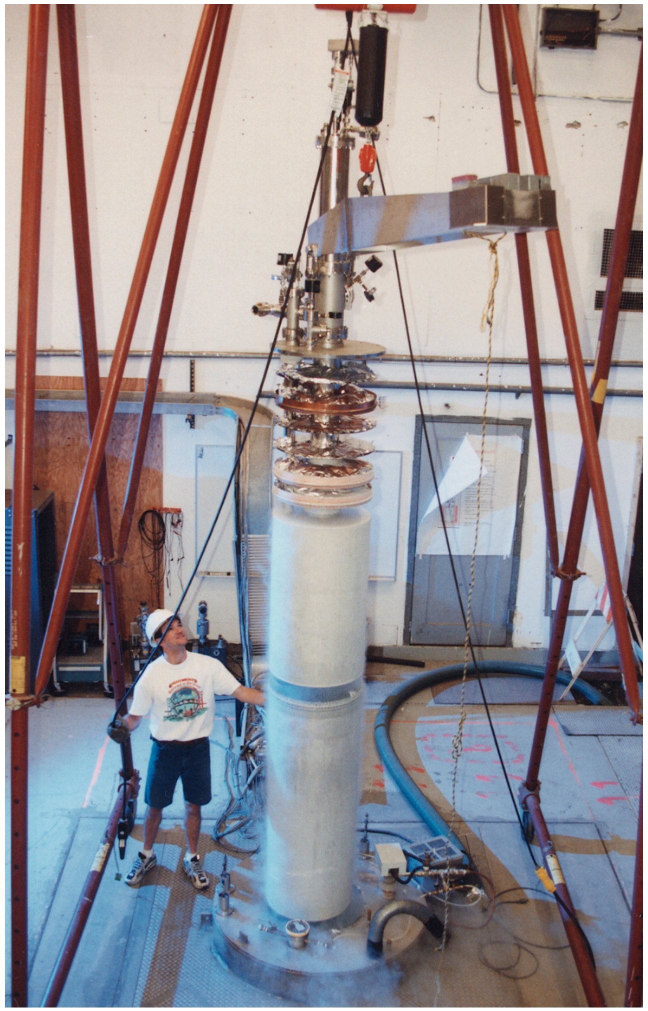
The younger scientists may derive a different lesson from this …



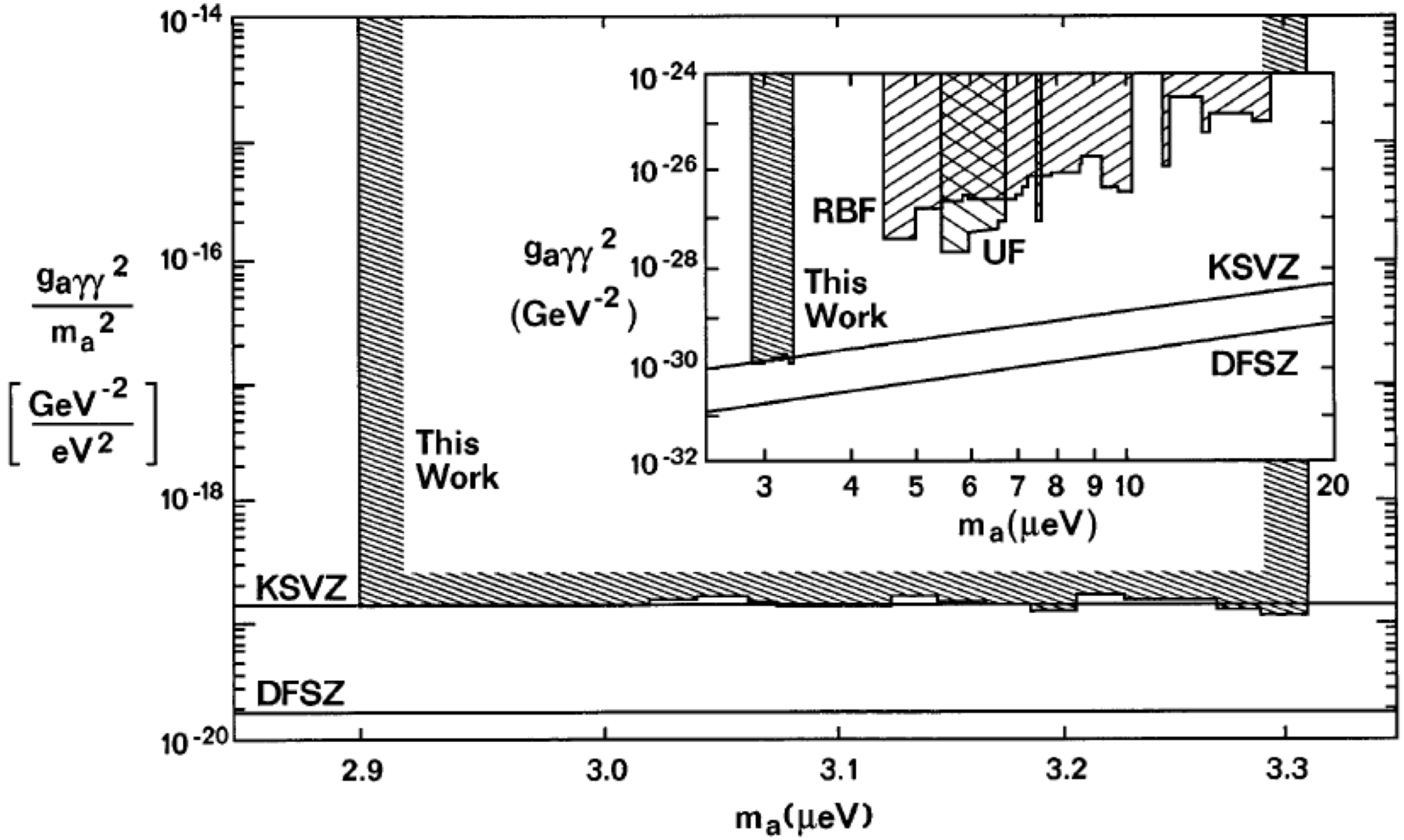
*

* *Abandon all hope, ye who enter here* (*Dante's Inferno, Canto iii*)

The Axion Dark Matter eXperiment (ADMX) – The Livermore Era (1993-2011)

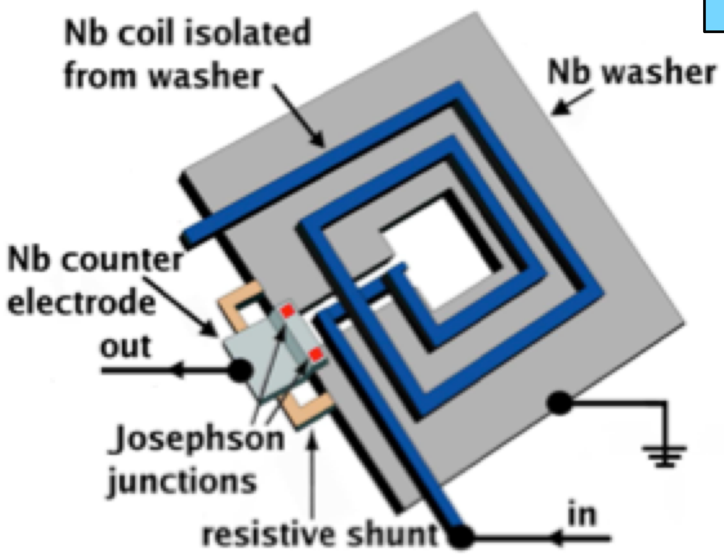


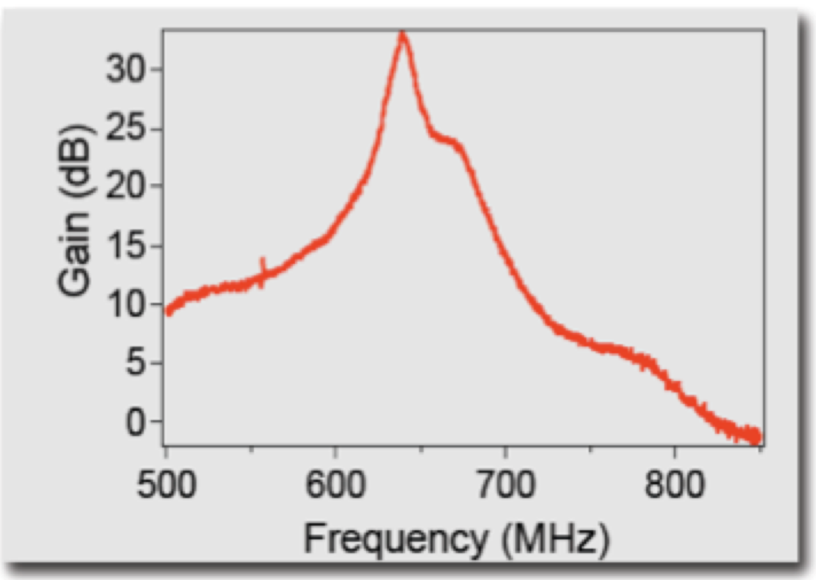
C. Hagmann et al., Phys. Rev. Lett. 80 (1998) 2043

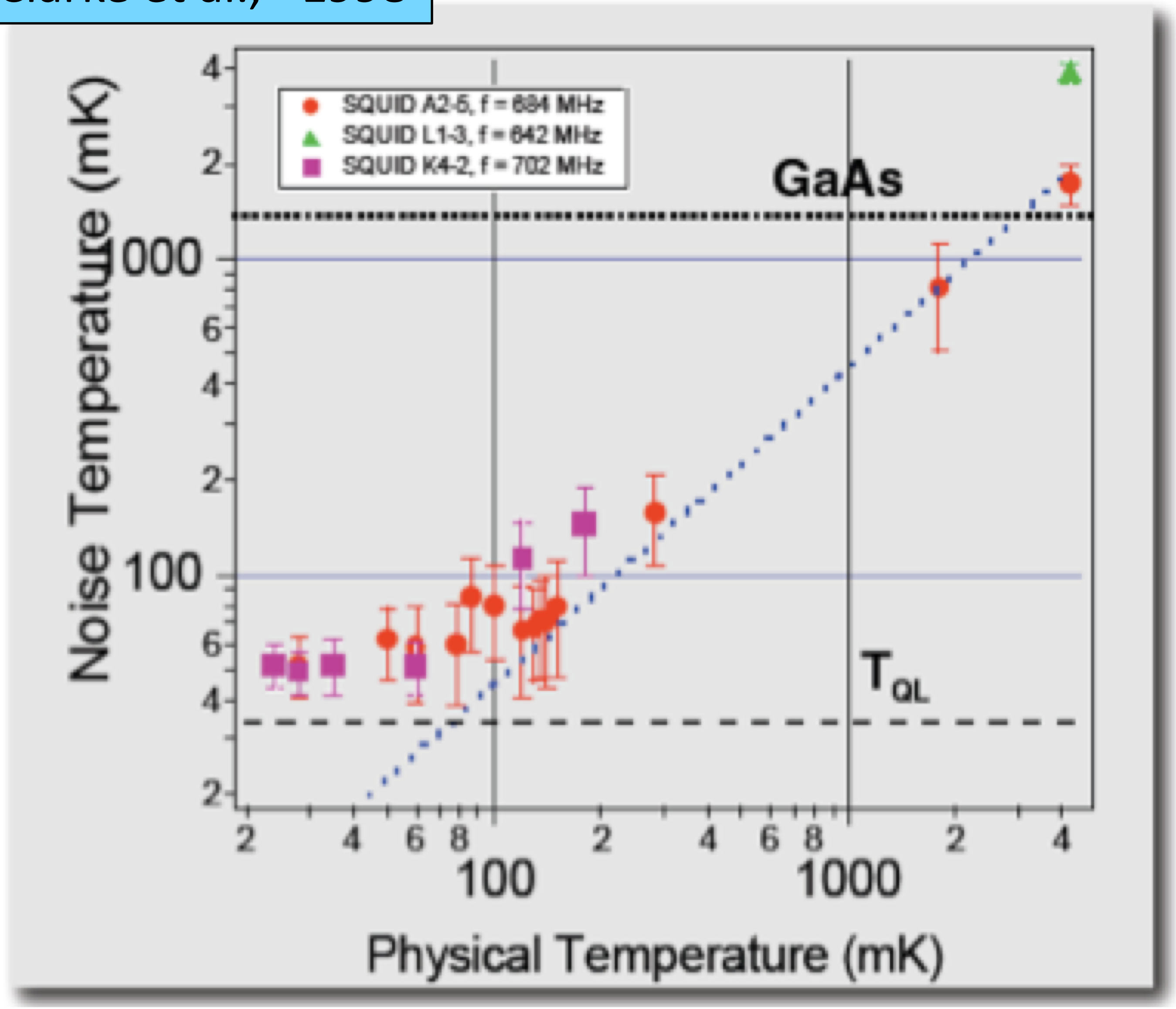


Pivotal moment in the history of the field – the Microstrip SQUID Amplifier

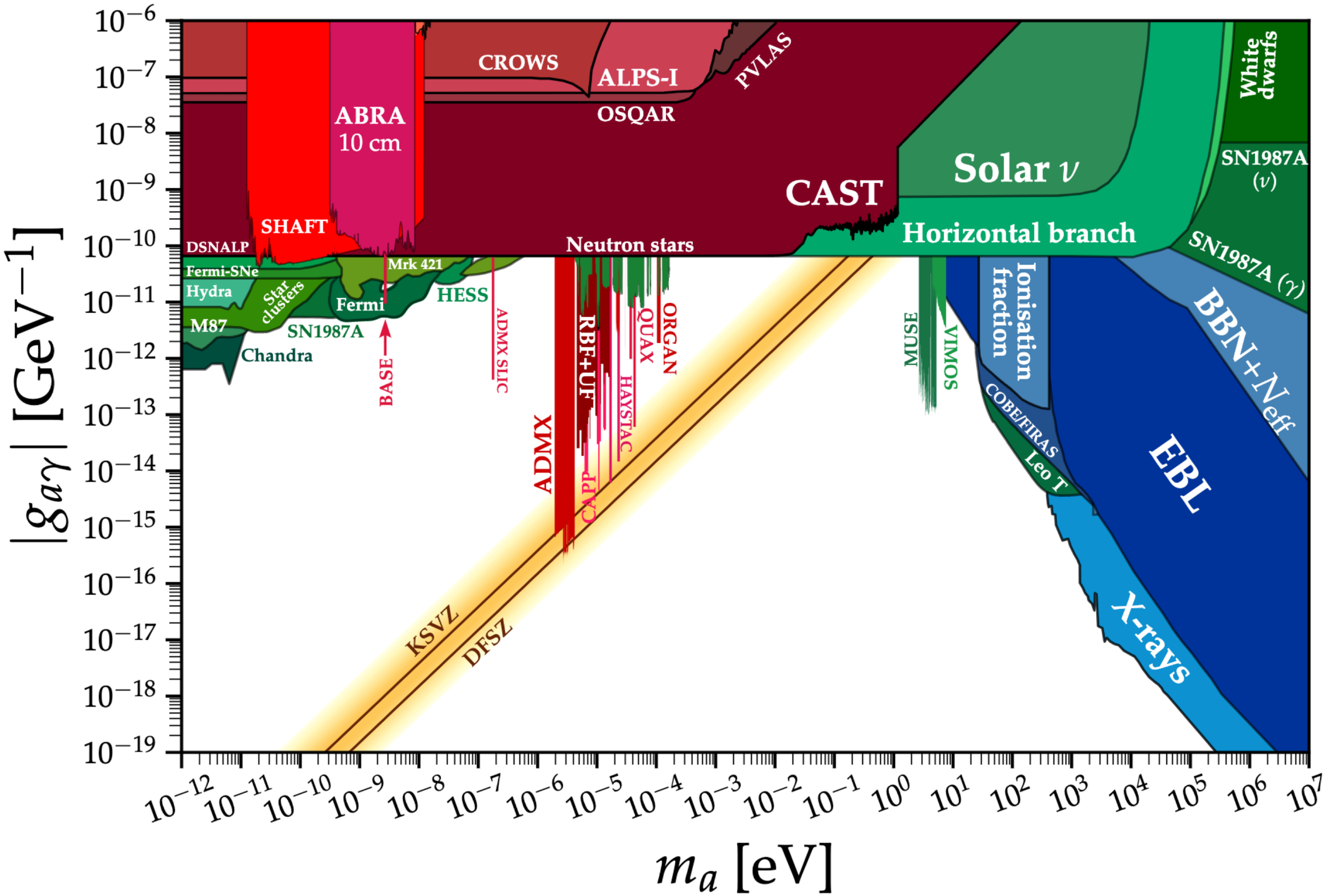
John Clarke et al., ~1998

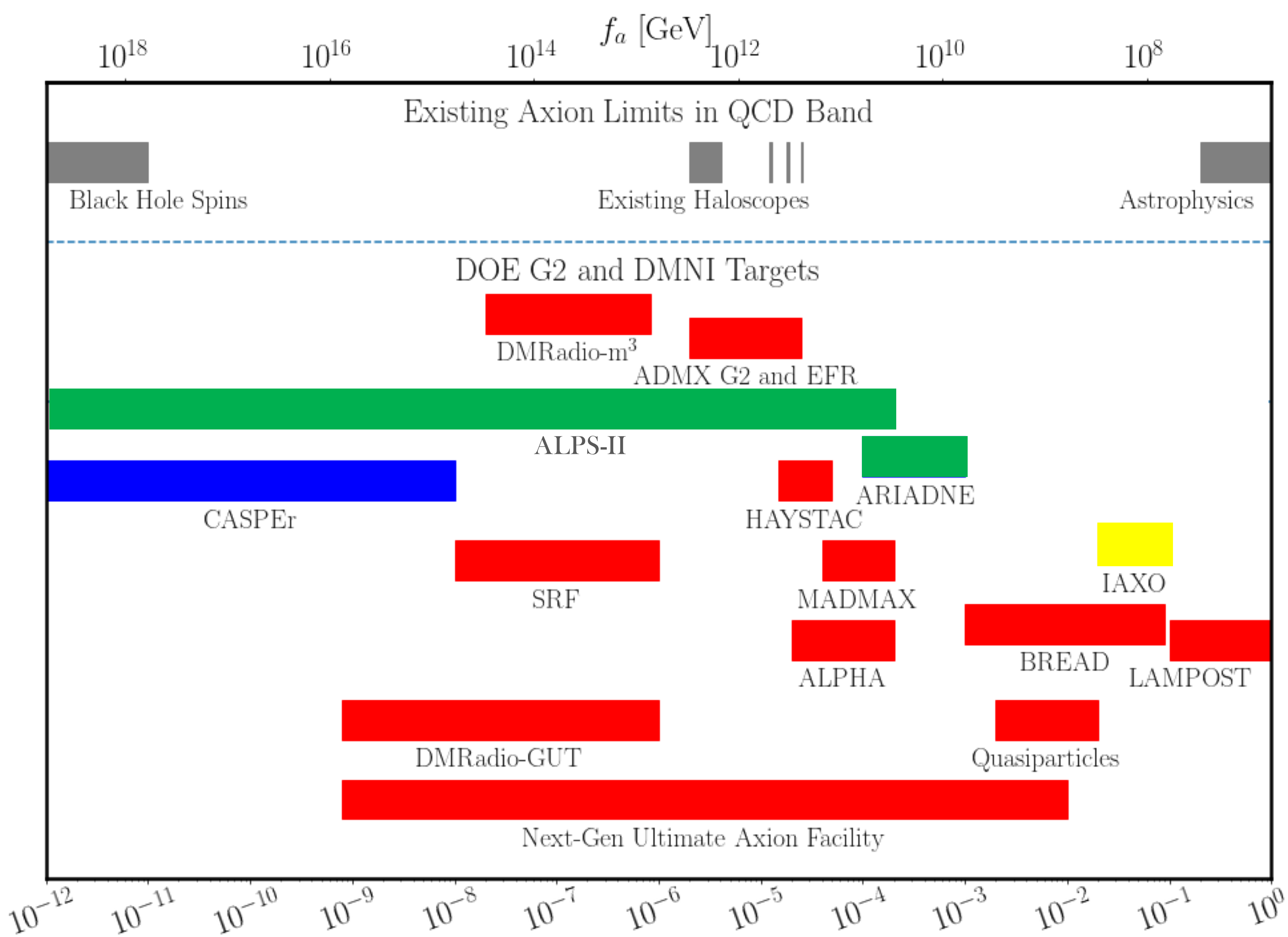






From PDG 2022





Adapted from Snowmass CF2 Wavelike DM Report

The field is crowded – good

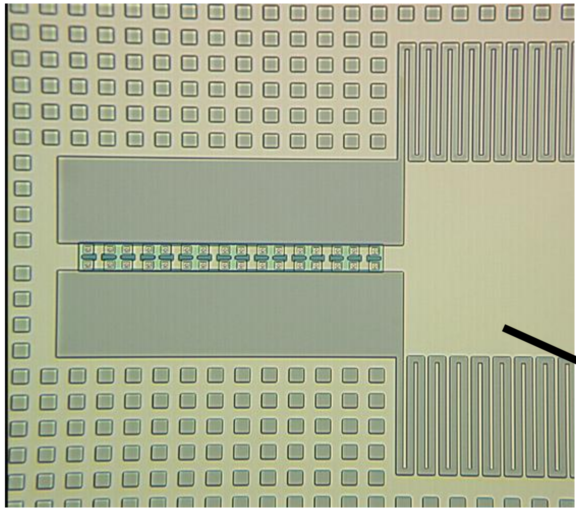
Includes axions & ALPs

All experiments are relevant and important to do

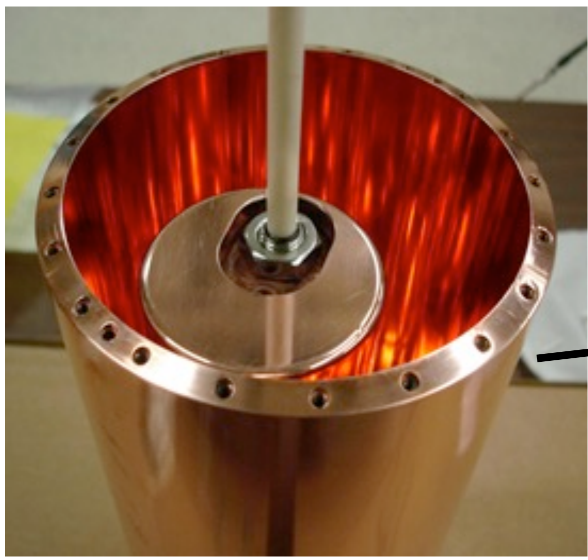
Need to be open to surprise

HAYSTAC: To the Quantum Limit and below (Yale-Colorado-Berkeley-Johns Hopkins)

JPA-based Squeezed-State Receiver



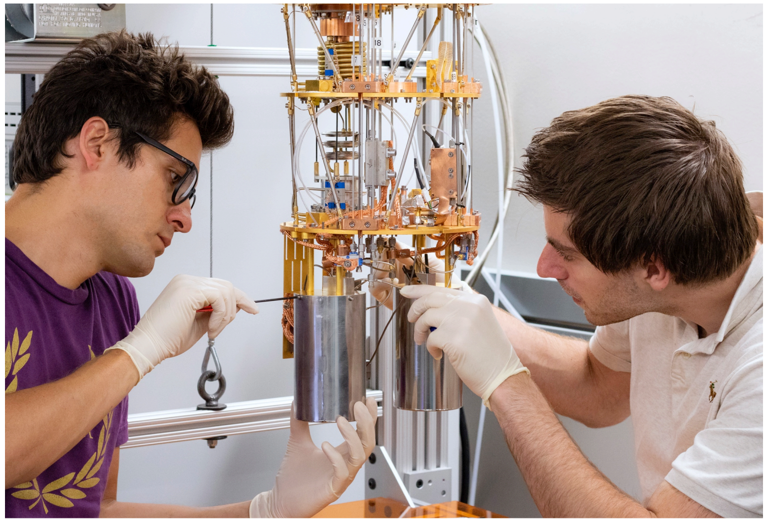
Microwave Cavity (copper)

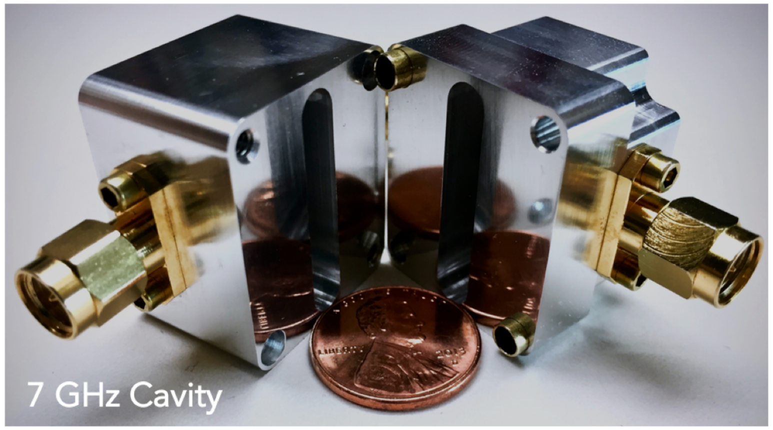


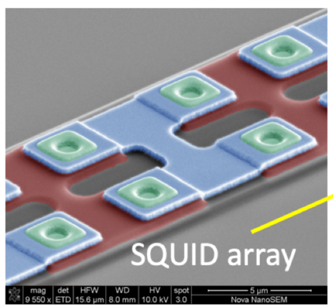
$^3He/^4He$ Dilution Refrigerator

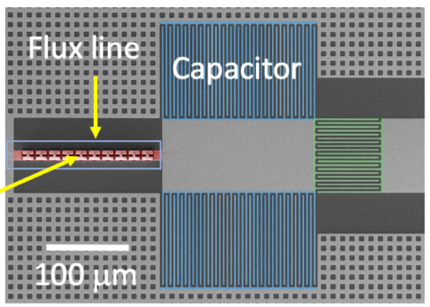
9.4 Tesla, 10 Liter Magnet

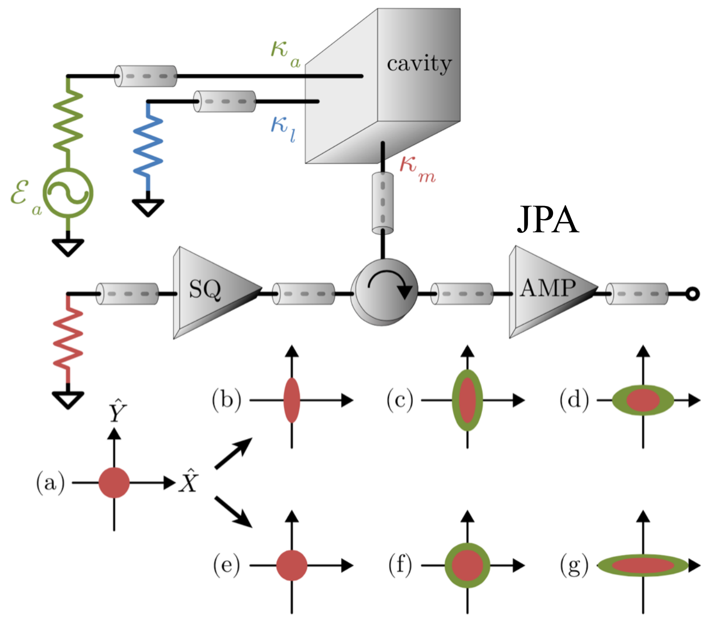
The microwave cavity experiment has been a driver of quantum-enhanced sensing

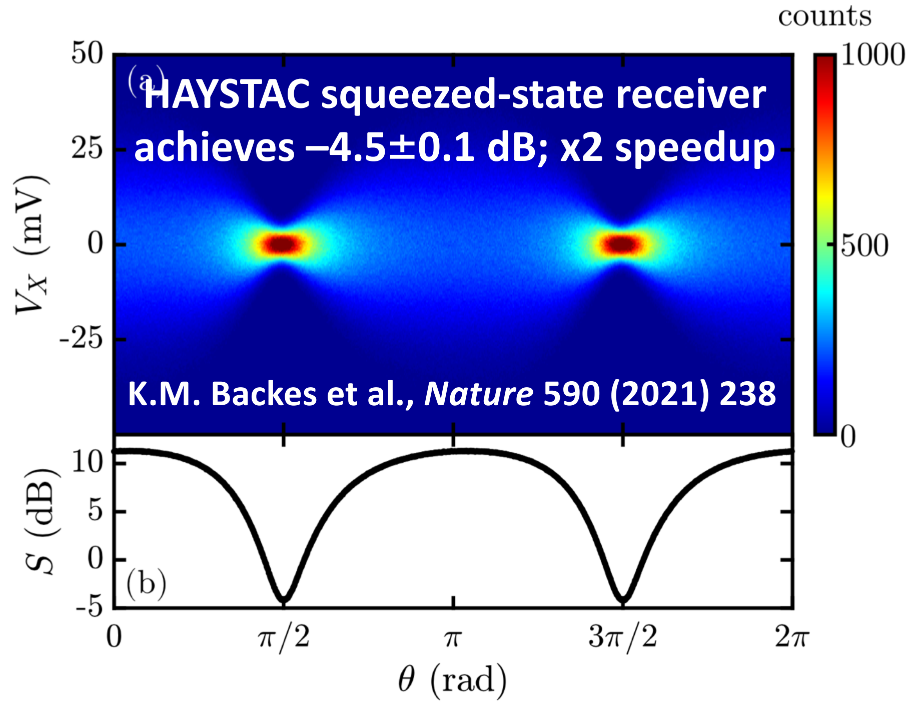


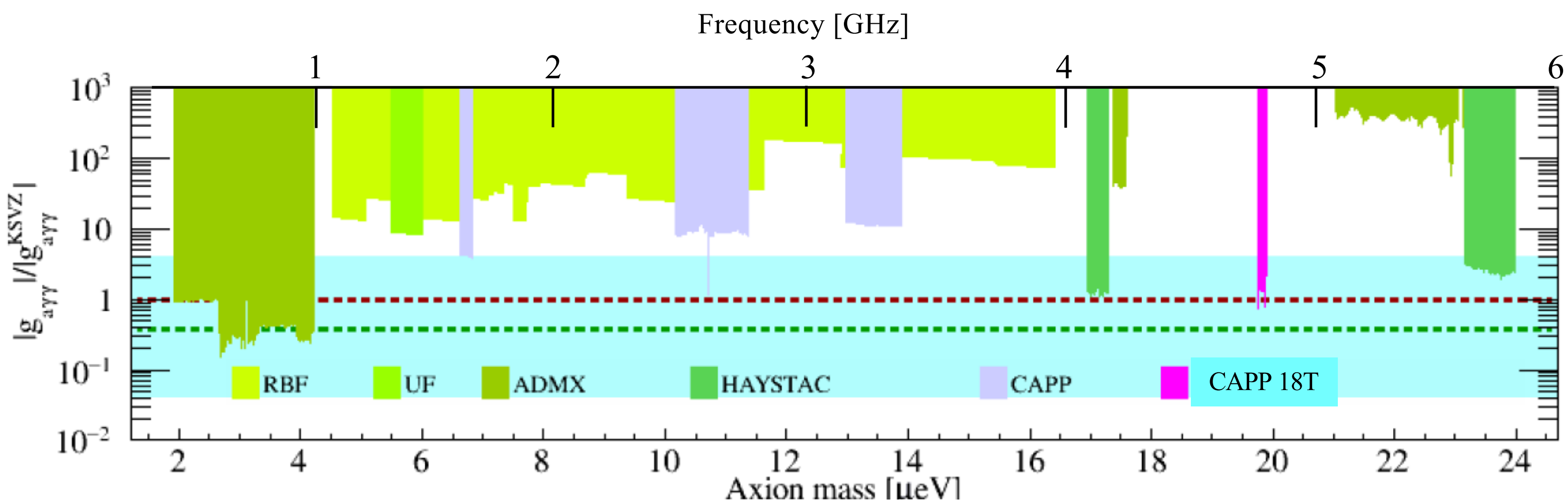






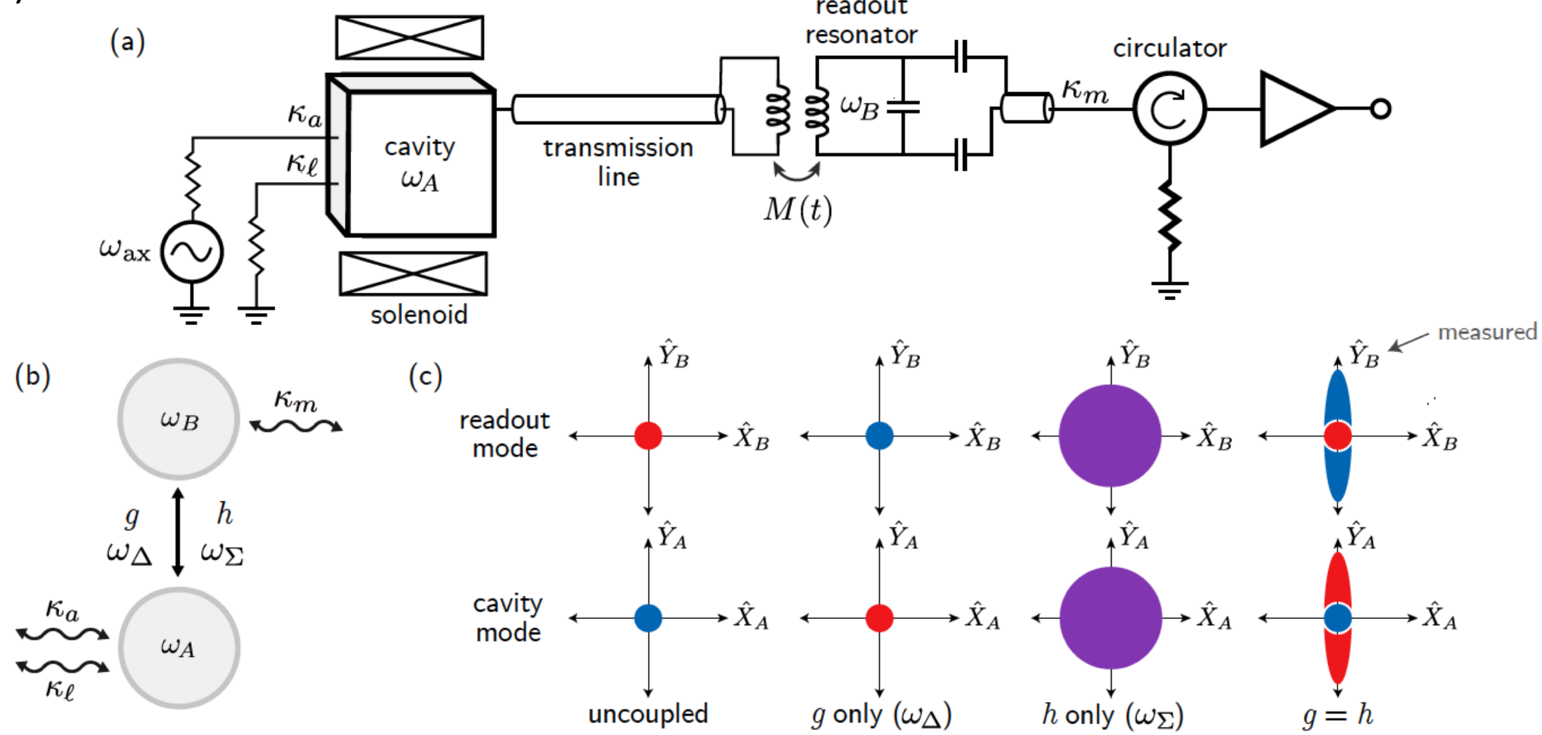






CEASEFIRE: Cavity Entanglement and State Exchange for Improved Readout Efficiency

K. Wurtz et al., PRX Quantum 2 (2021) 040350



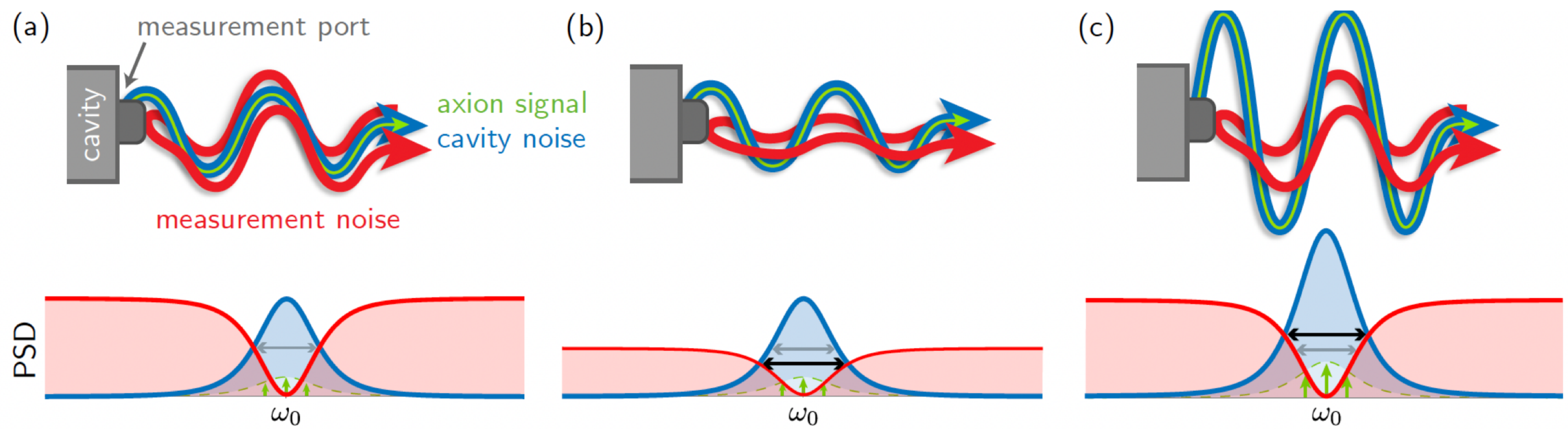
Projected to speed up the search by x15

To be deployed in HAYSTAC mid-2023

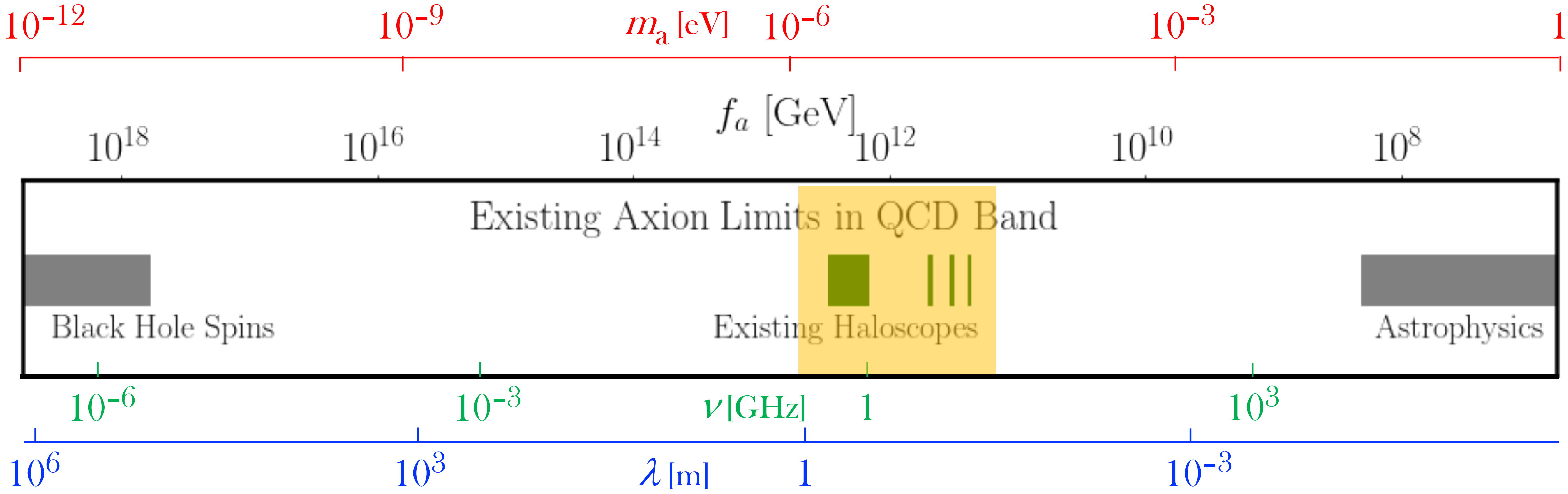
(a) Linear amplifier

(b) Squeezing

(c) Squeezing with state exchange



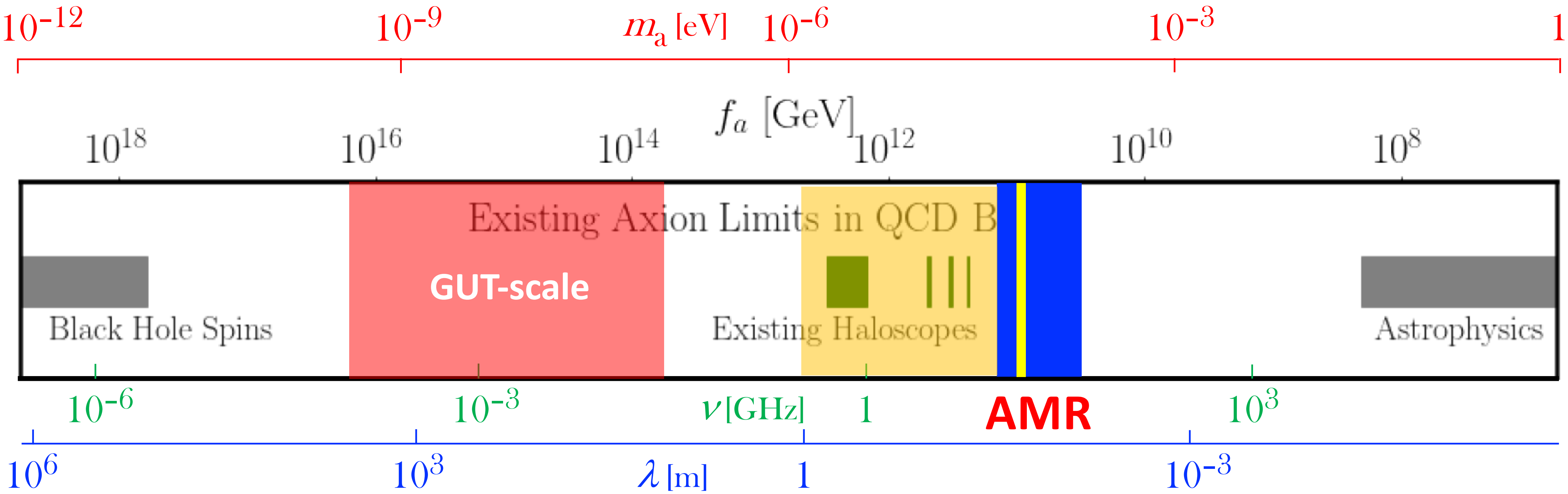
Microwave cavities



The conundrum:

- You can detect an arbitrarily weakly coupled particle with (i) a high-Q amplifier, (ii) sensitive amplifier, (iii) sufficient time
- But at the price of bandwidth, i.e. the search becomes a tuning experiment
- And furthermore, there are practical limitations on all three

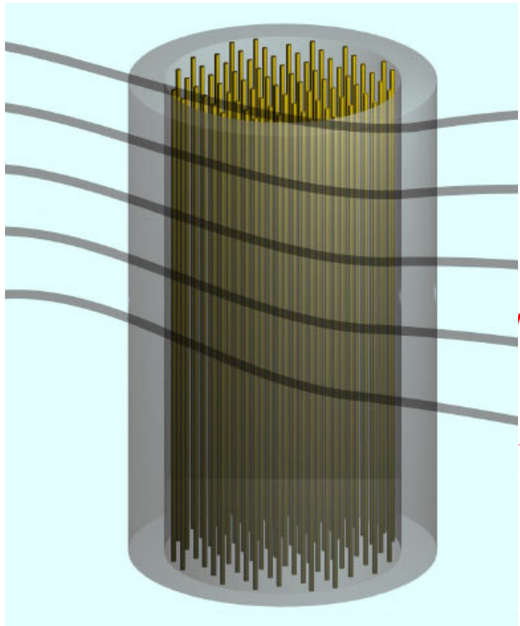
The post-inflation axion

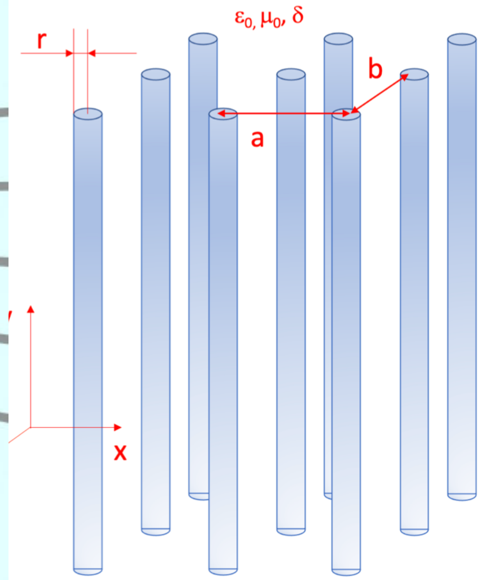


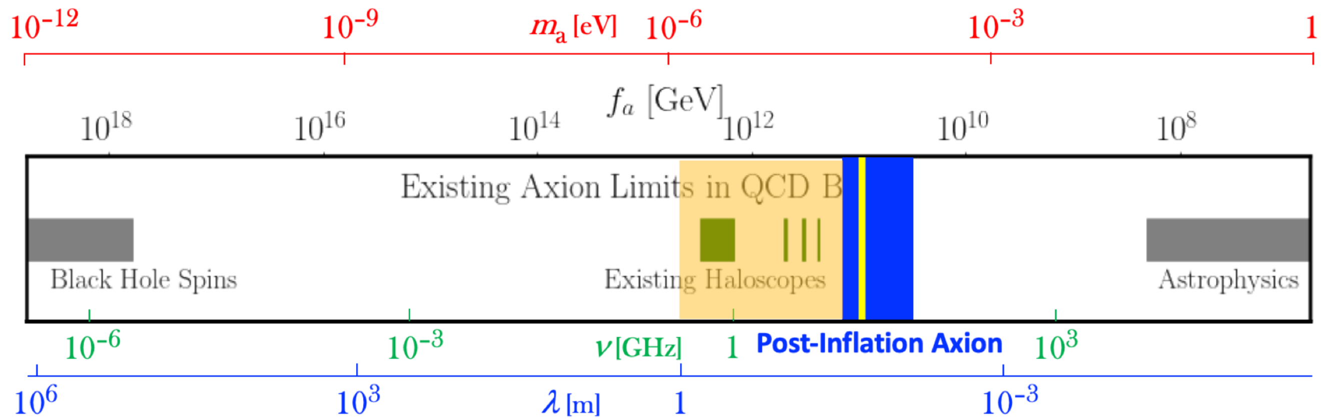
- A special case is the post-inflation axion whose mass is uniquely determined; our knowledge of the mass is limited only by our ability to calculate
- Recent simulations using Adaptive Mesh Refinement find m_a = 40–180 μeV (~10–45 GHz, blue), with 65 ± 6 μeV (14.3–17.2 GHz, yellow) preferred (M. Buschmann et al., *Nat. Comm.* 13 (2022) 1049)
- These predictions will be significantly sharpened within the next two years

Towards the post-inflation axion: The tunable plasmonic haloscope

(M. Lawson *et al.*, PRL 123 (2019) 141802)



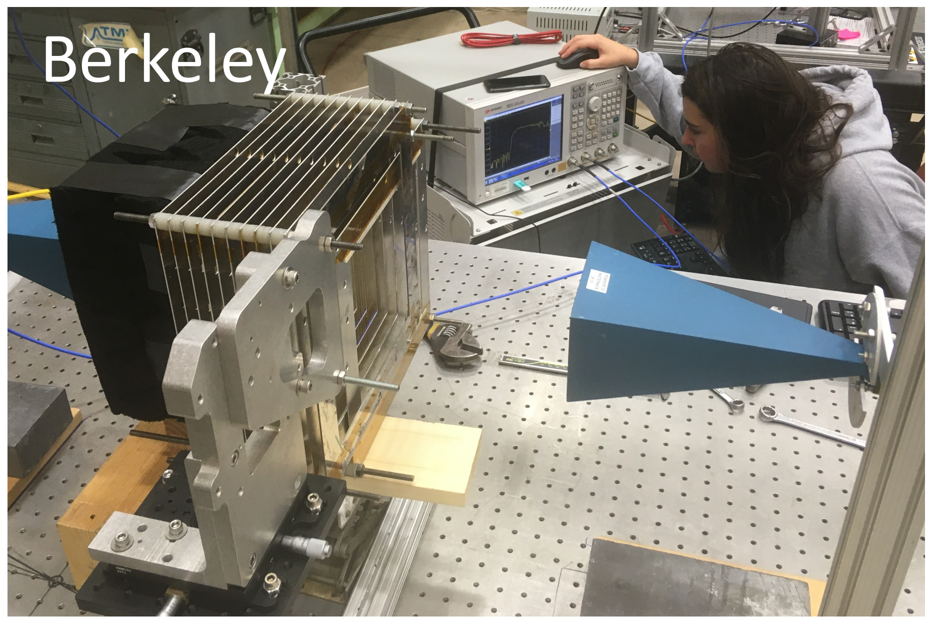




AMR sims: m_a = 40-180 μeV (10–45 GHz), with 65 ± 6 μeV preferred (M. Buschmann et al., *Nat. Comm.* 13 (2022) 1049)

Wire-array metamaterials with the plasma frequency in the 10-100 GHz range can readily be designed; R&D at Stockholm & Berkeley is promising

(M. Wooten et al., arXiv:2203.13945)



The Tunable Plasma Haloscope (M. Lawson *et al.*, PRL 123 (2019) 141802)

Cavity and dielectric haloscopes use broken translation invariance to convert massive axions to massless photons. Plasma haloscopes instead match the axion mass and photon mass (plasma frequency) to conserve energy and momentum unrelated to boundary conditions, i.e. $m_a = \omega_{plasma}$.

$$c^2k^2 = \omega^2 - \omega_{plasma}^2$$

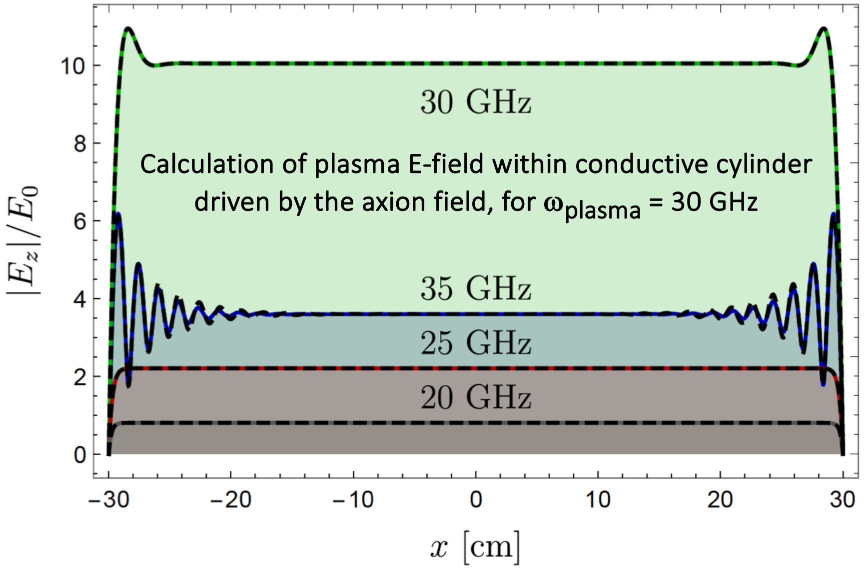
$$\omega_{plasma}^2 = \frac{Ne^2}{m\epsilon_0}$$

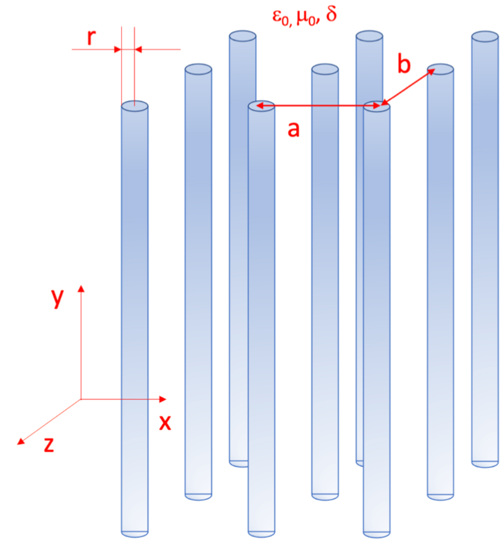
Wire array metamaterials exhibit plasmonic behavior, and may be feasible as resonators for a dark matter axion experiment, to higher frequencies. See:

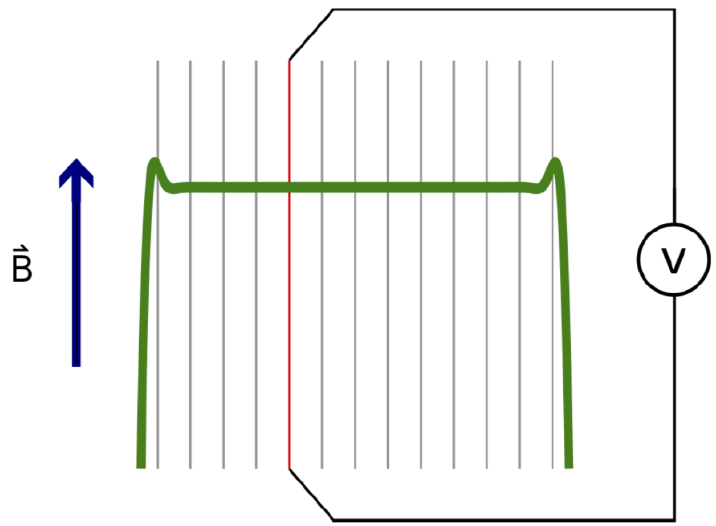
– J.B. Pendry *et al.*, J. Phys.: Condens. Matter 10 (1998) 4785

– P.A. Belov *et al.*, Phys. Rev. B 67 (2003) 113103

– R. Balafendiev *et al.*, arXiv:2203.10083v1







Schematic of the plasmonic haloscope

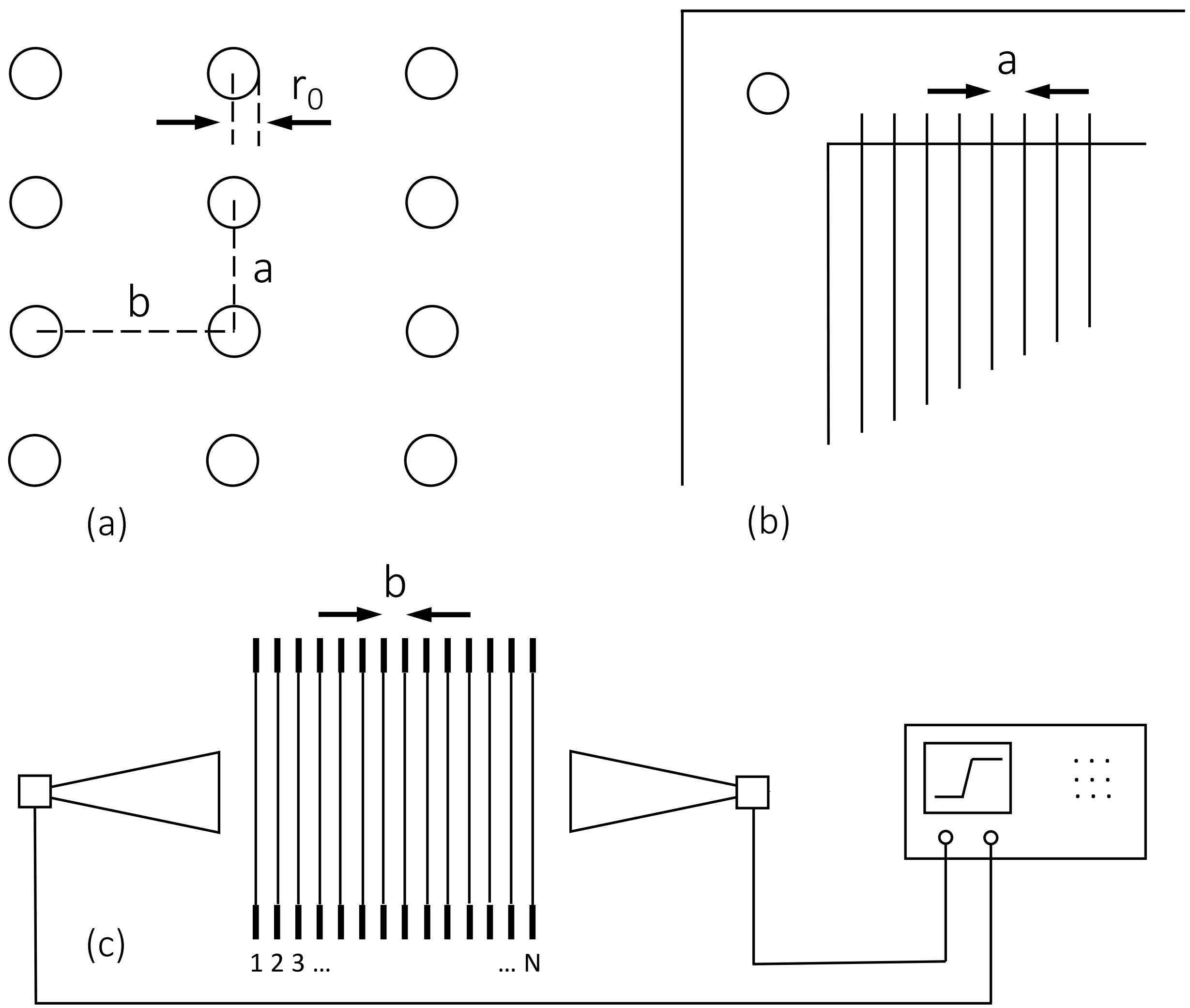
For square lattice of wires, of radius r and spacing a :

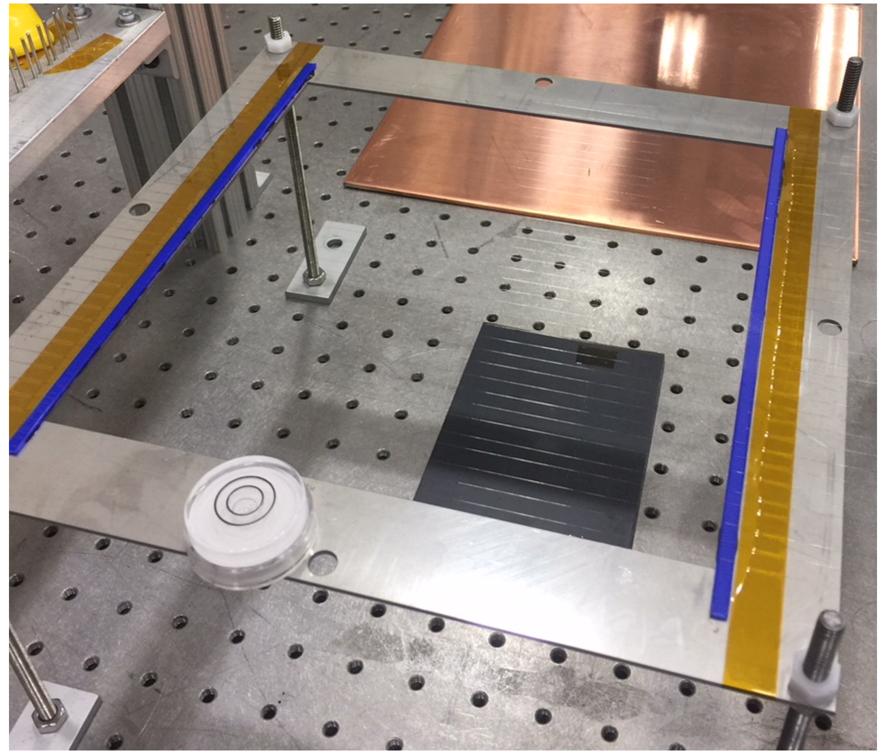
$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{a^2 \log(a/r)}$$

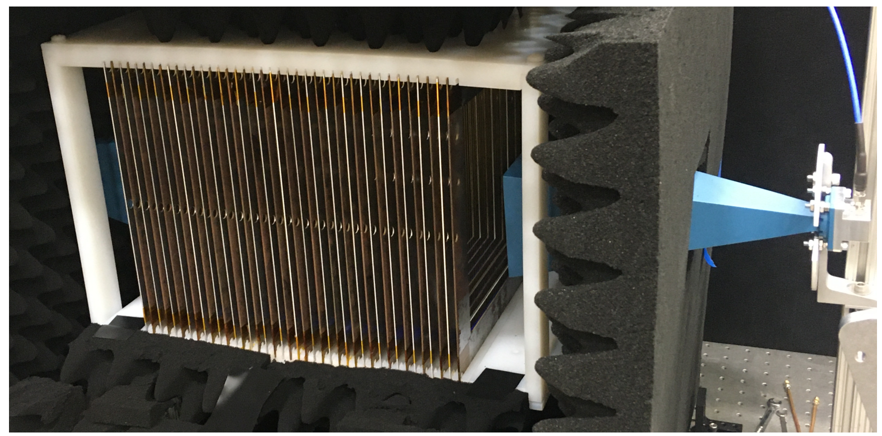
For r = 25 μm & a = 5 mm, the plasma frequency f_{pl} = 10 GHz

Looks like a HEP wire chamber

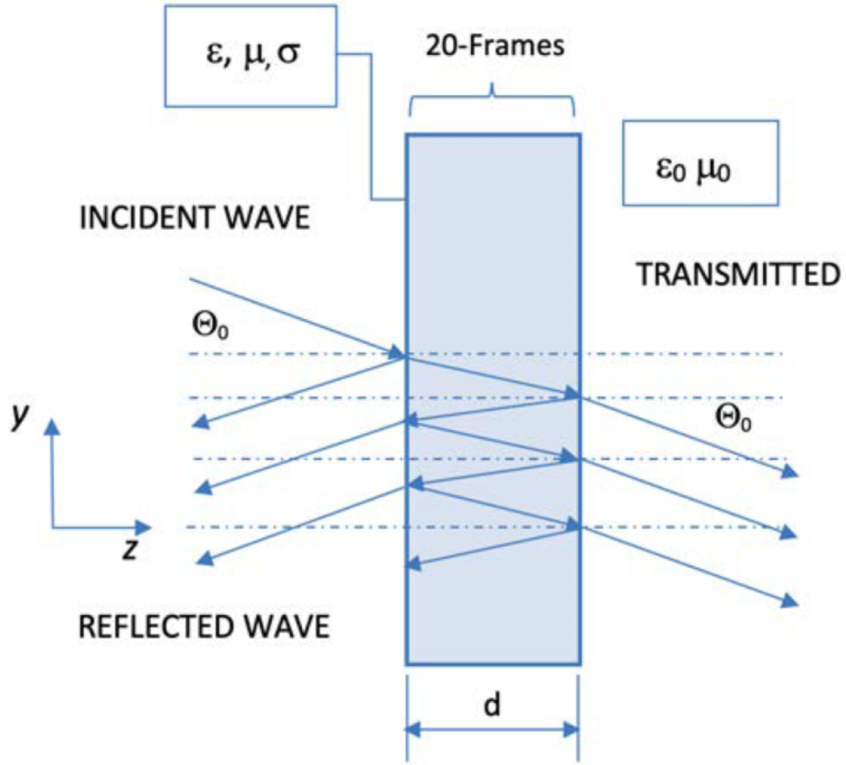
S_{21} measurements on 3D wire arrays at Berkeley





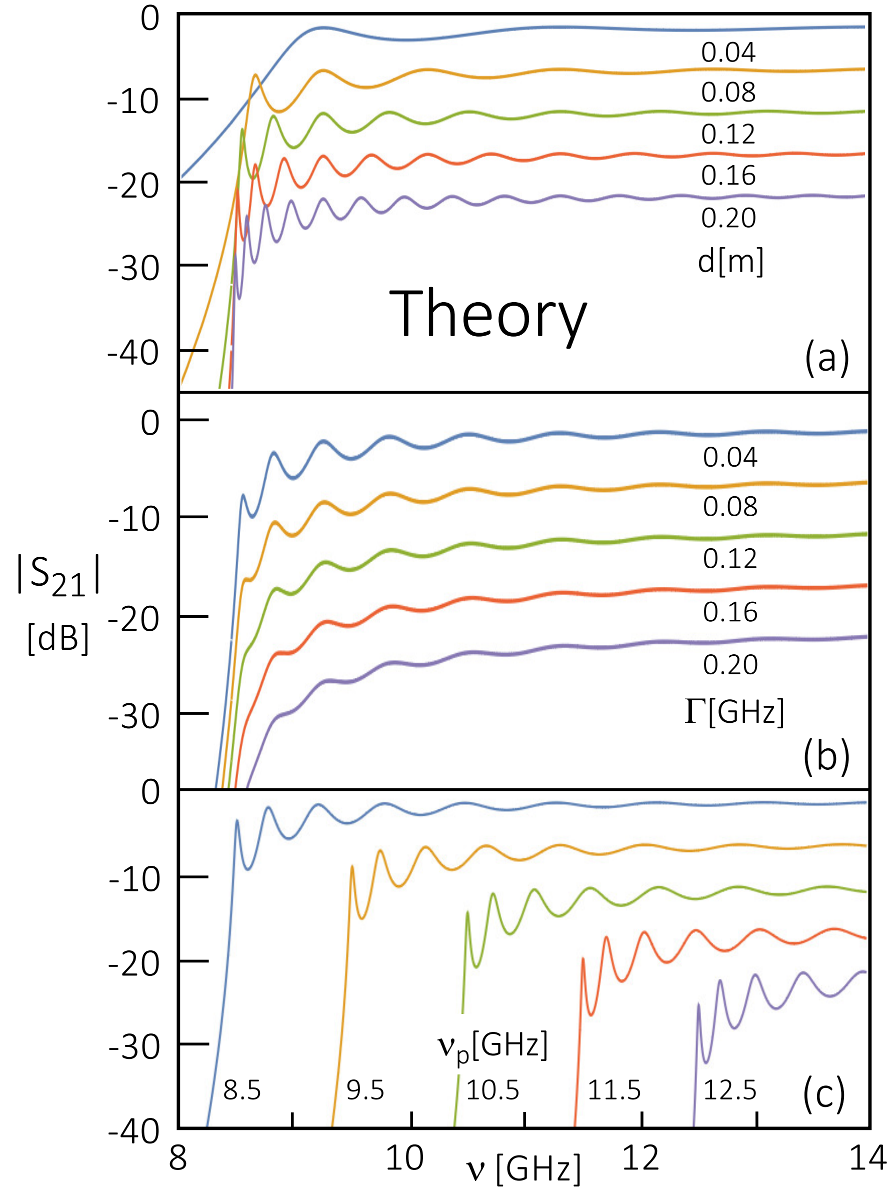


Formalism for fitting the data: S_{21} is a good tool to extract the key parameters

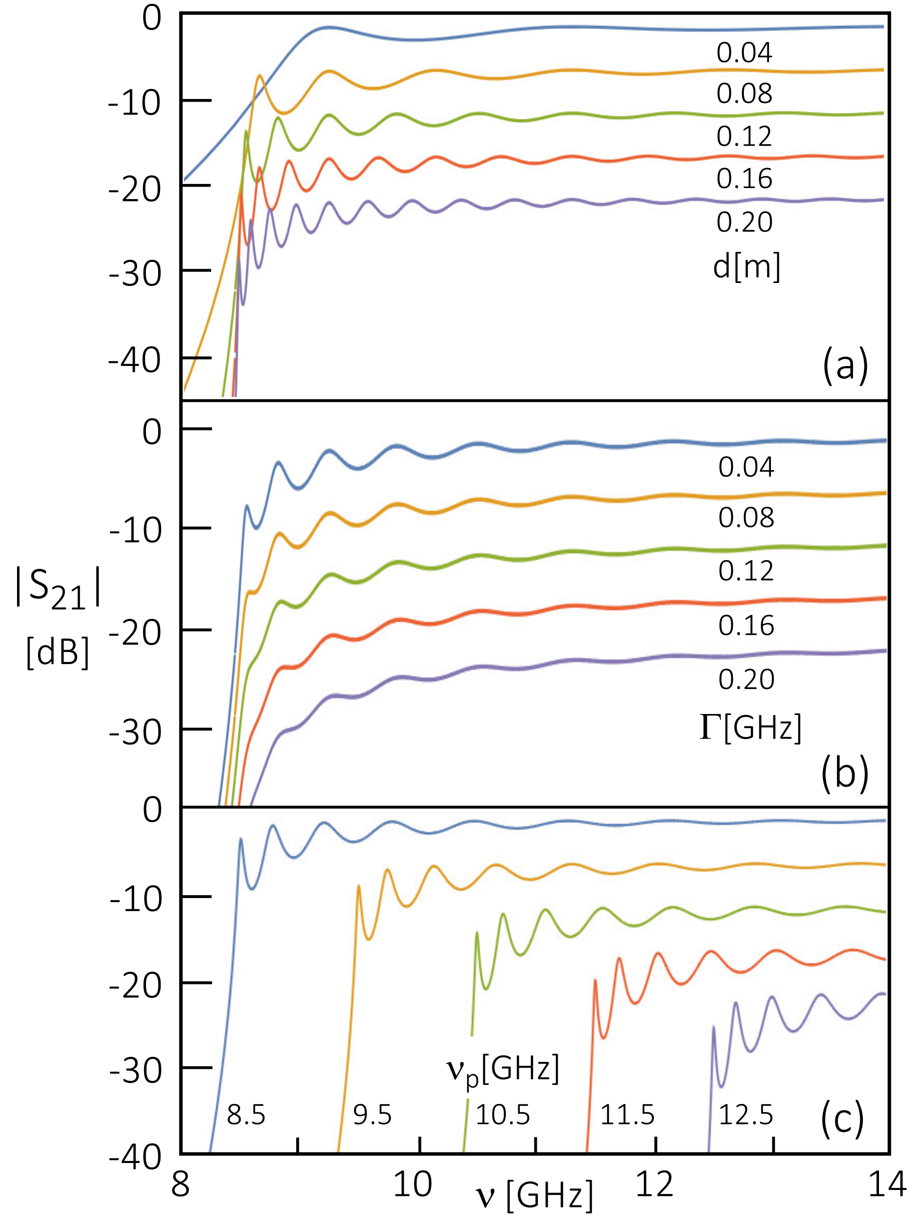


The metamaterial is a complex dielectric slab, which we represent in a Drude model:

$$\epsilon_r = 1 - \frac{\omega_p^2}{\omega^2\left(1 - j\frac{\Gamma}{\omega}\right)} \Rightarrow \quad \epsilon' = \left(1 - \frac{\omega_p^2}{\omega^2 + \Gamma^2}\right) \qquad \epsilon'' = \left(\frac{\Gamma}{\omega}\right)\frac{\omega_p^2}{\omega^2 + \Gamma^2}$$



Is S_{21} the right tool? Yes!

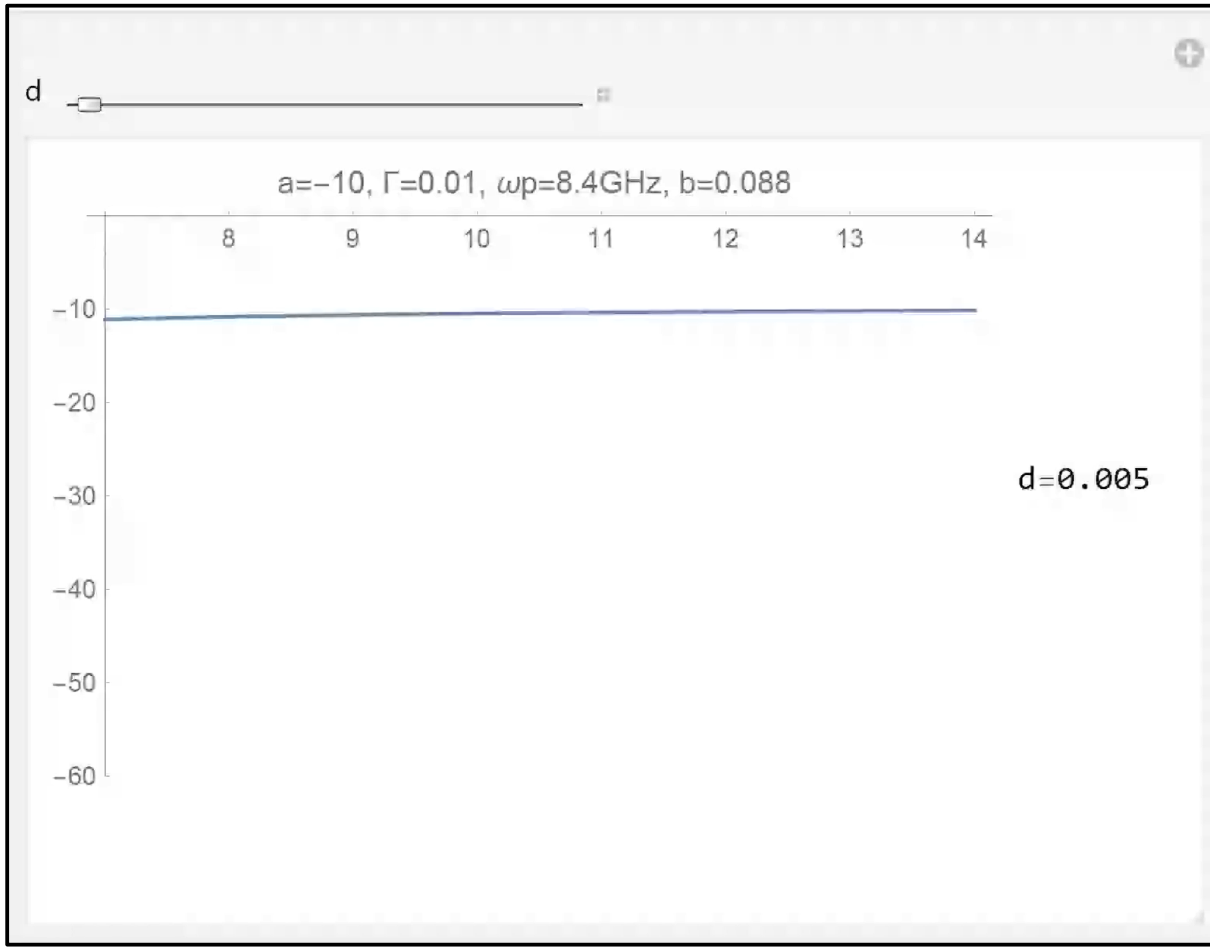


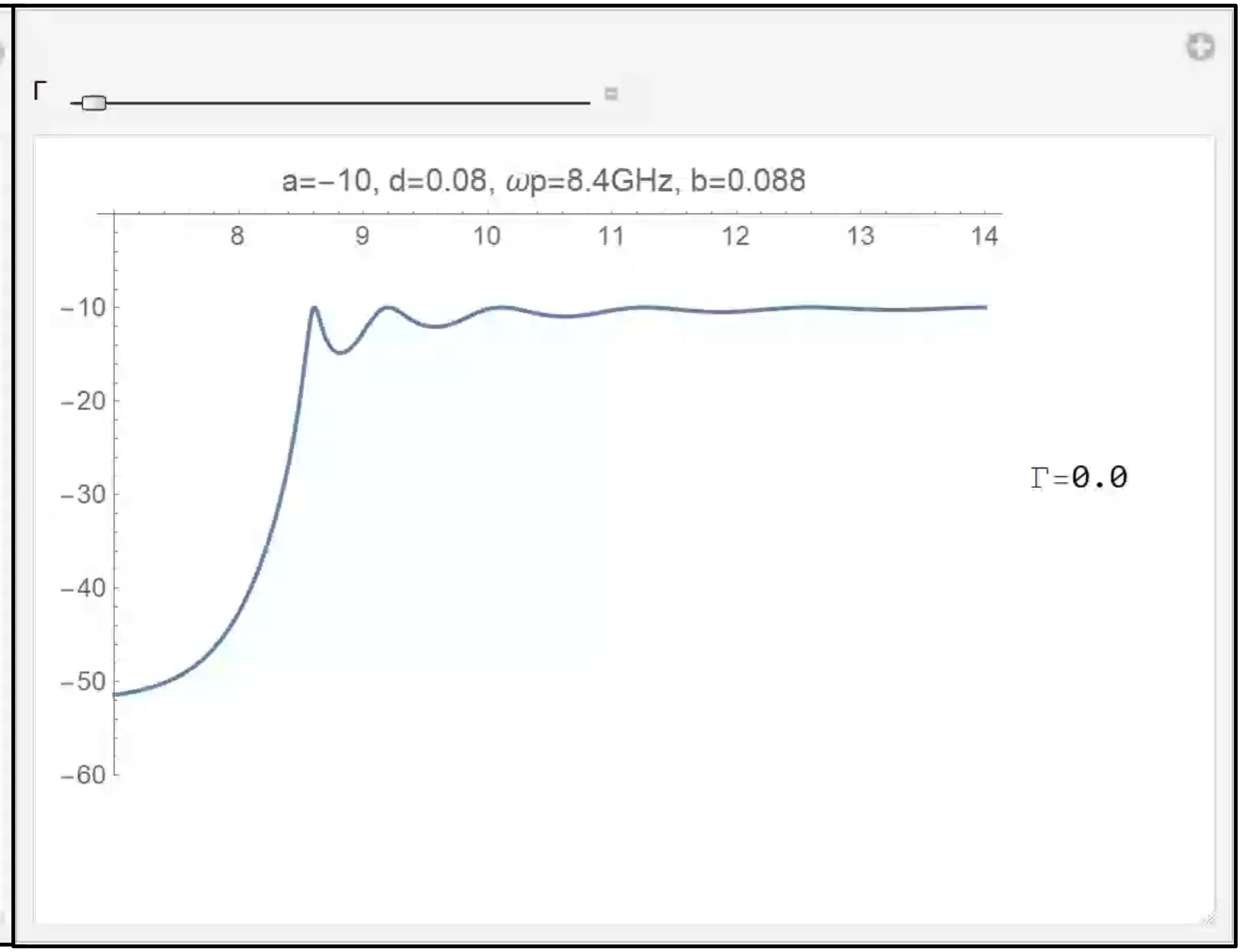
One of the four scattering parameters, for a two-port device, $S_{21} = V_2^+/V_1^+$.

Here, two of three parameters are fixed, the third is varied (ν_p = 8.5 [GHz], d = 0.12 [m], Γ = 0.01 [GHz]).

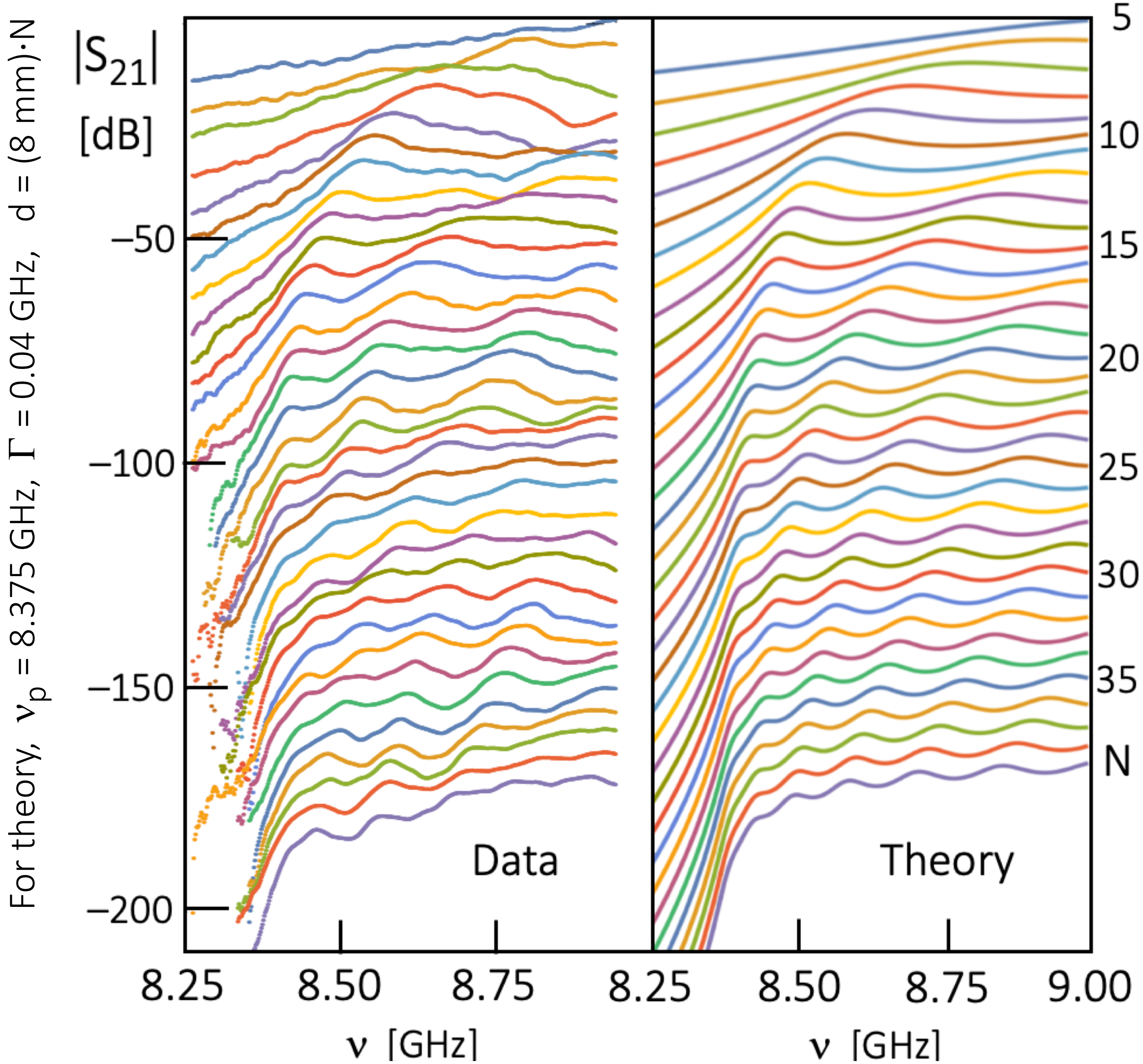
Curves in (a) sequentially offset by –7.5 dB for clarity; for (b) and (c), offset by –5 dB.

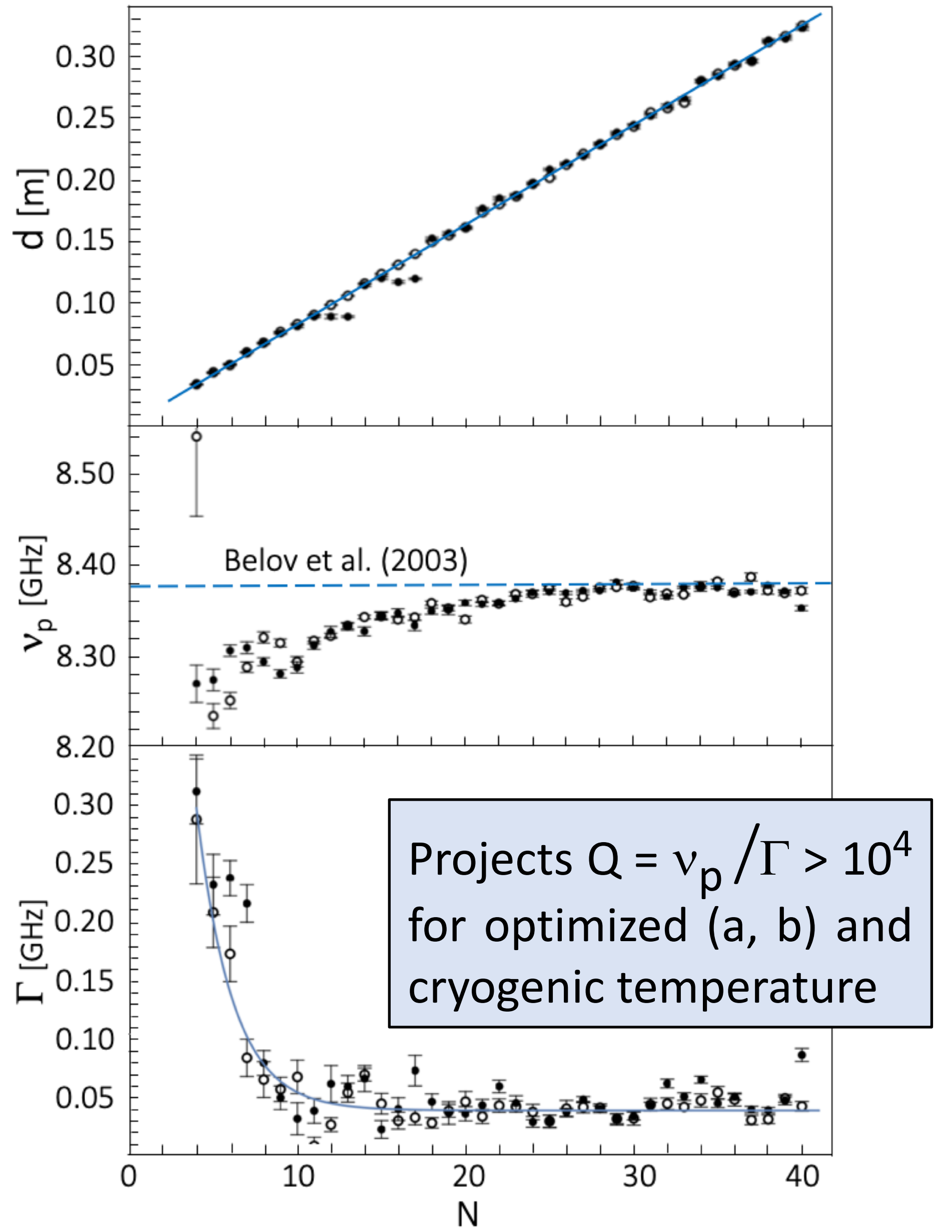
S_{21} animated



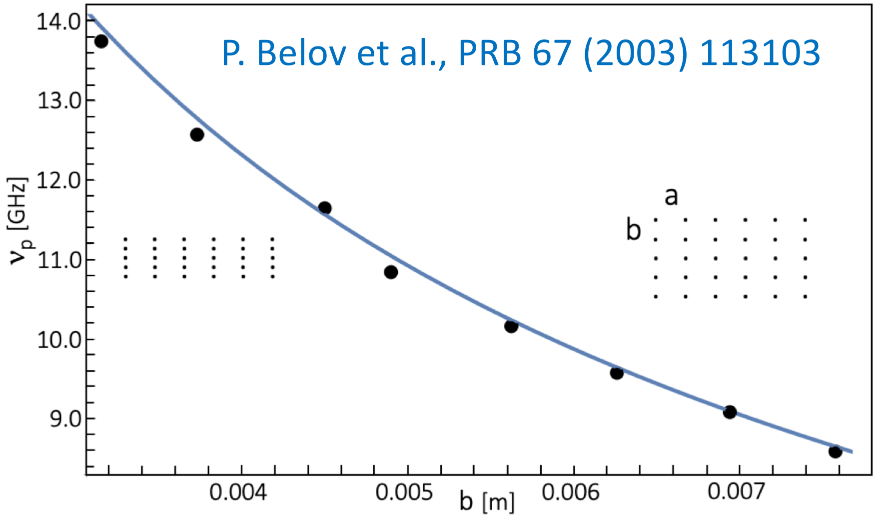


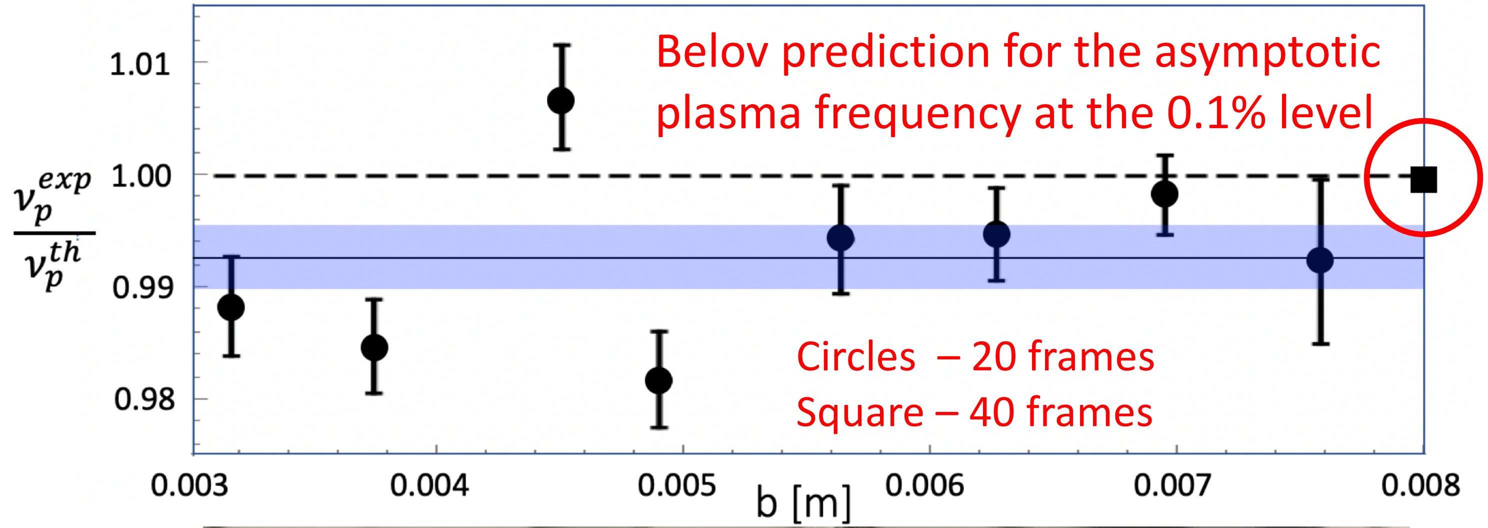
Early onset of plasmonic behavior & key systematics (M. Wooten et al., arXiv:2203.13945)

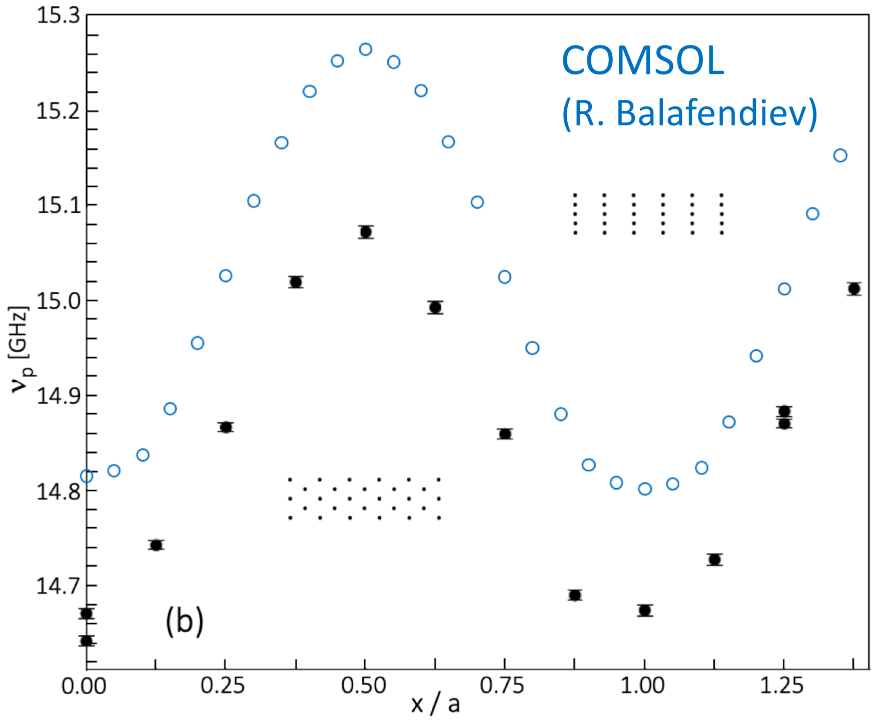


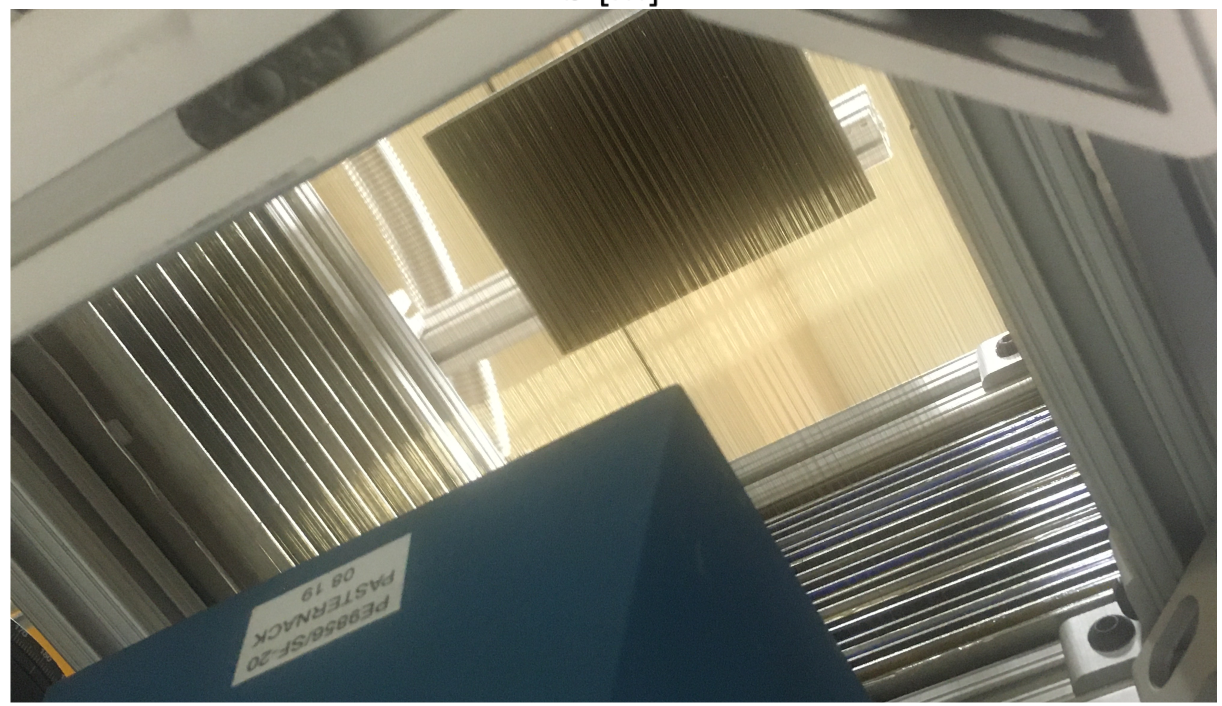


Tuning the haloscope by modifying the unit cell

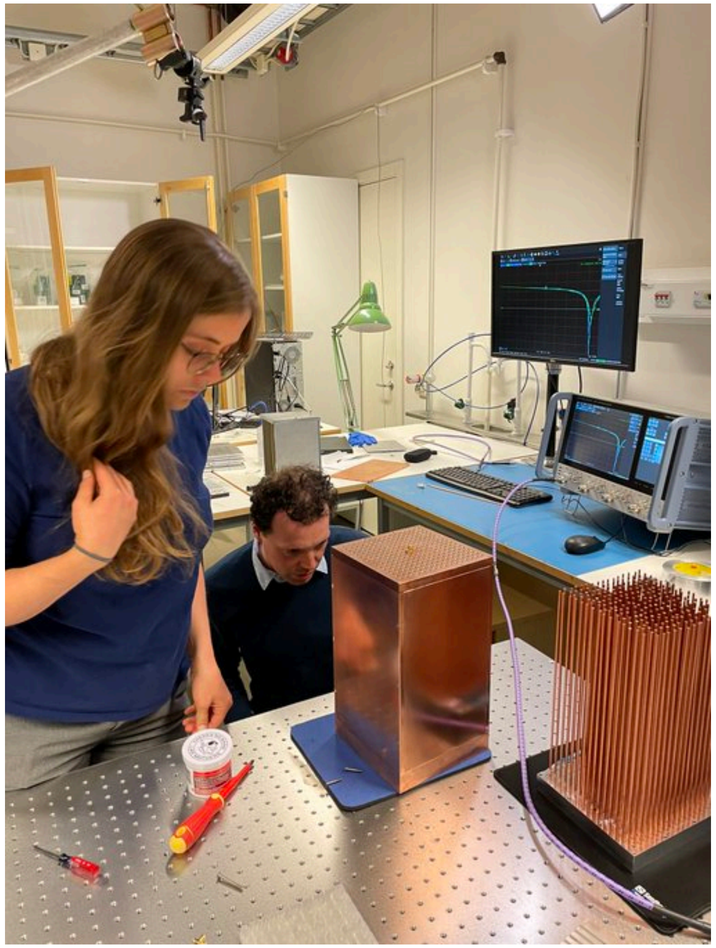


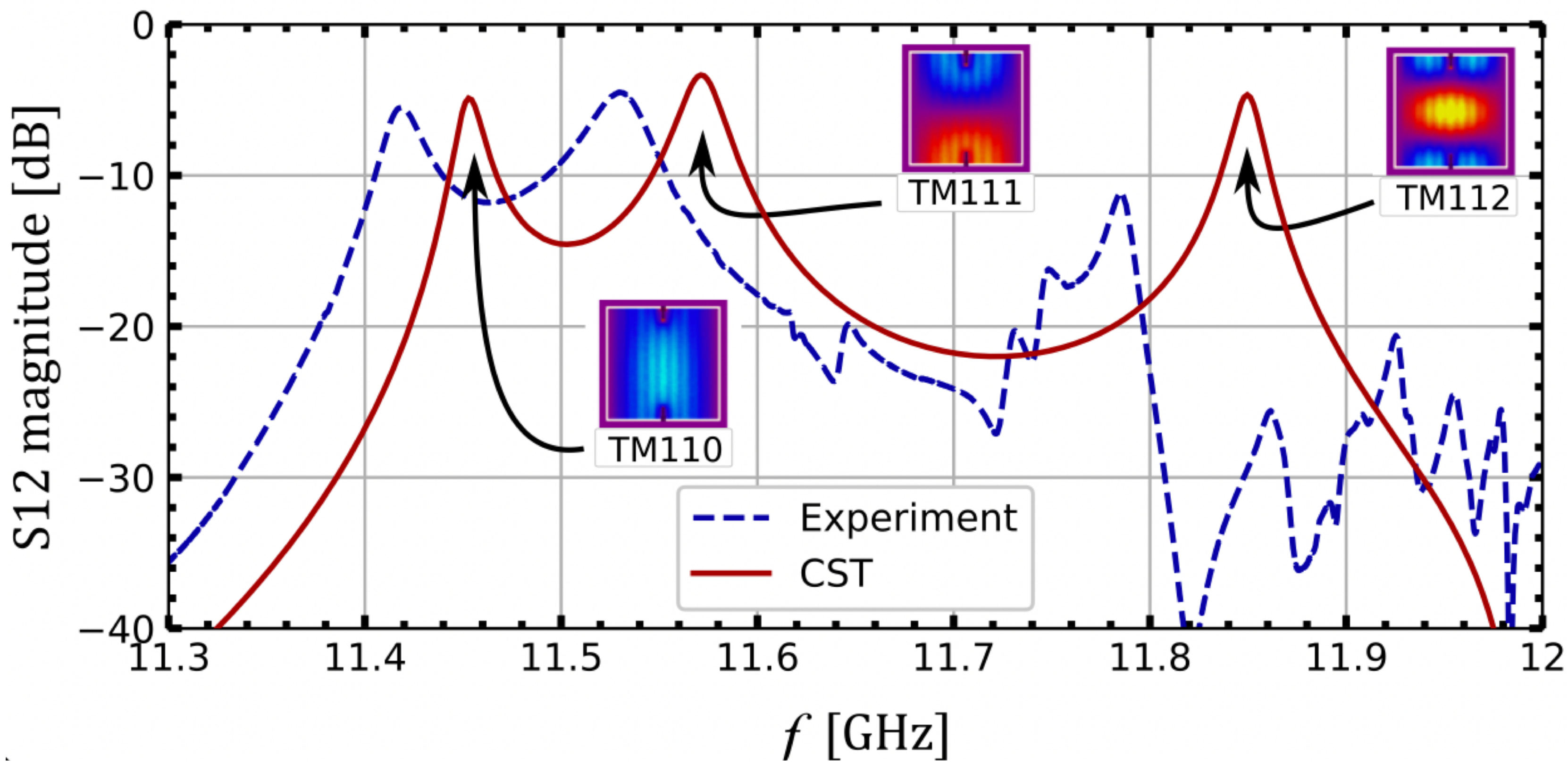




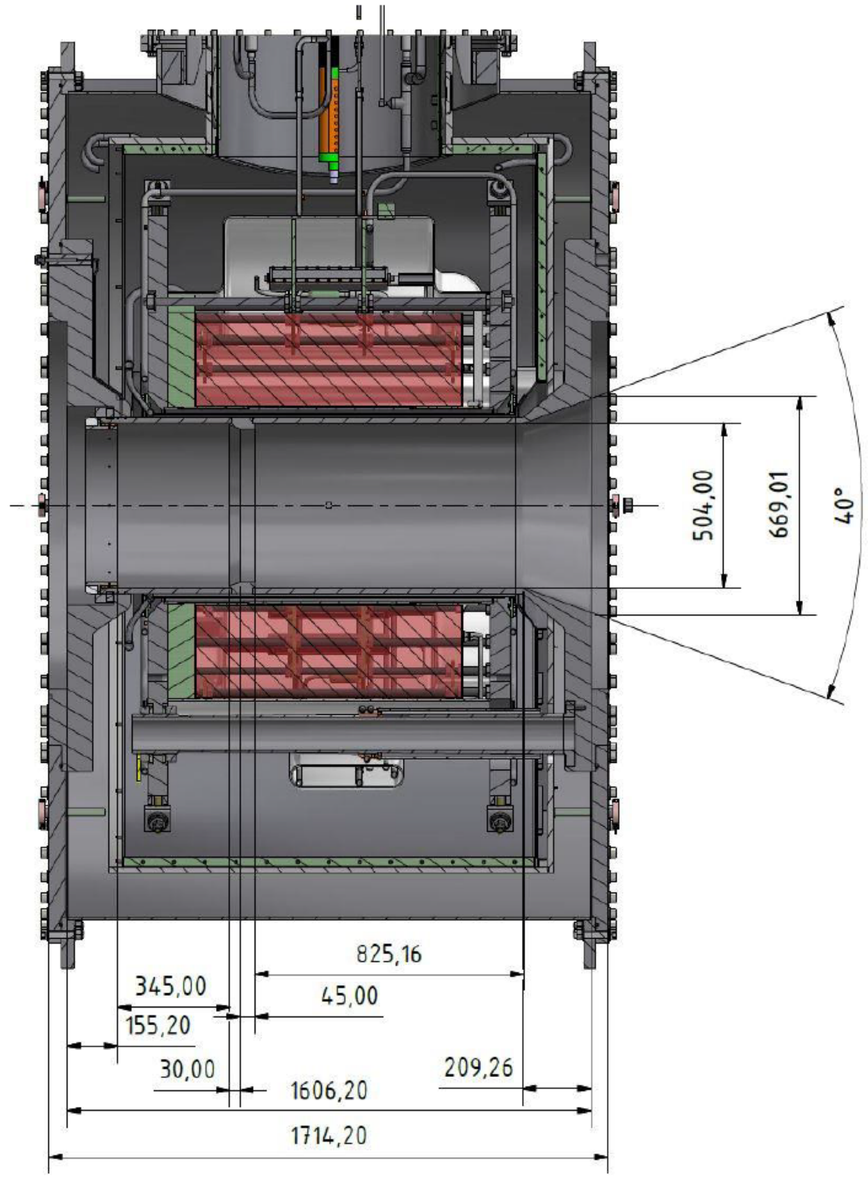


Stockholm prototyping





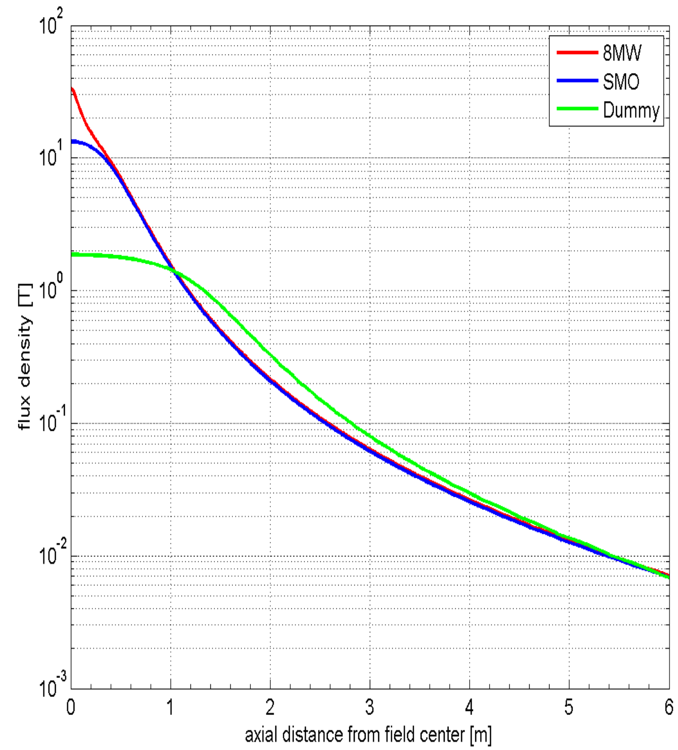
The ALPHA consortium; the Helmholtz Zentrum Berlin 13 T magnet



13 T, 50 cm ∅ × 170 cm

Coming to ORNL in 2023

Available for the ALPHA experiment for 10 years

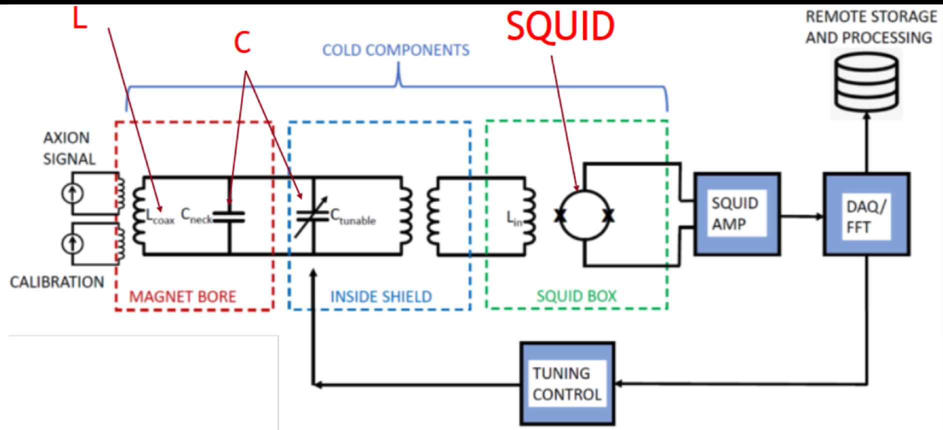


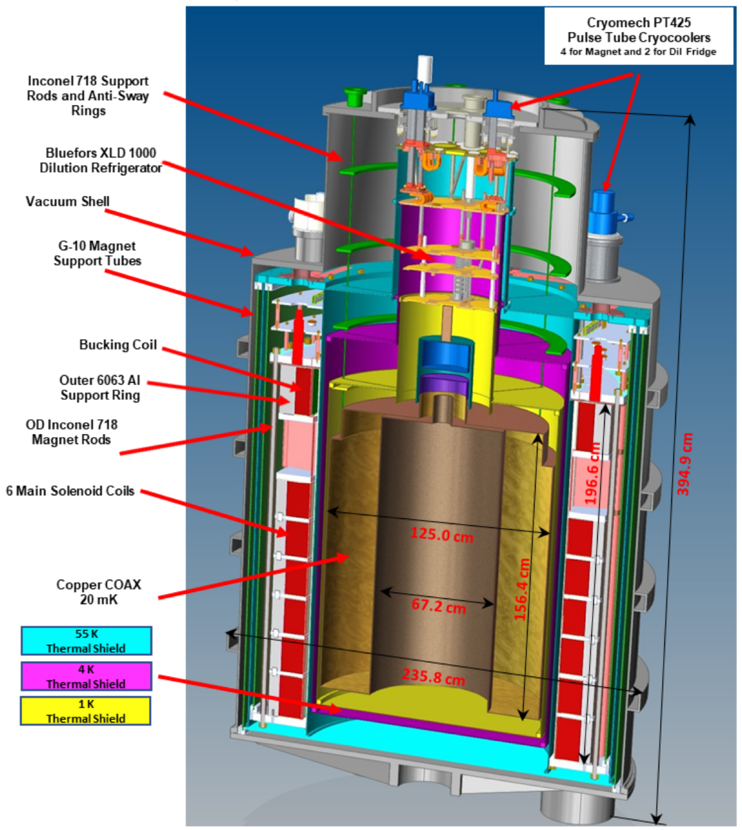
Exercise #1 for Wavy Dark Matter Summer School Students

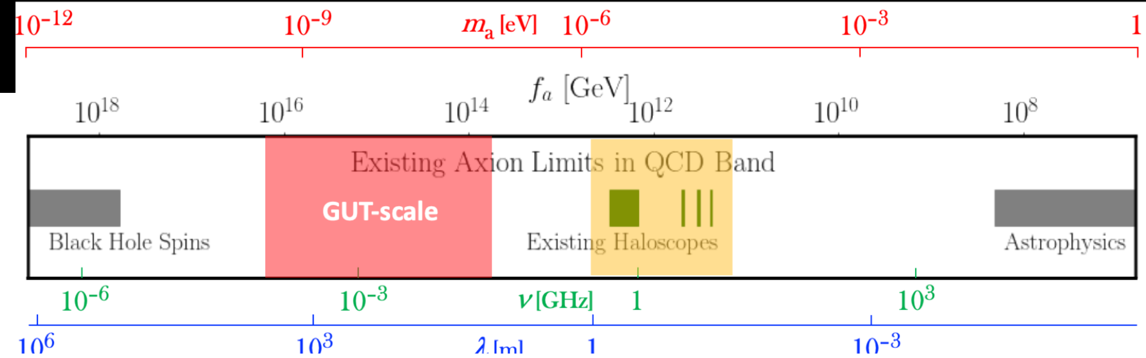
- ❑ Find the local hardware store here in town
- ❑ Buy a spool of copper wire and a soldering gun
- ❑ Have a paper up on the arXiv by Friday setting limits on hidden sector photons between 10-20 GHz
- ❑ You may work in small teams

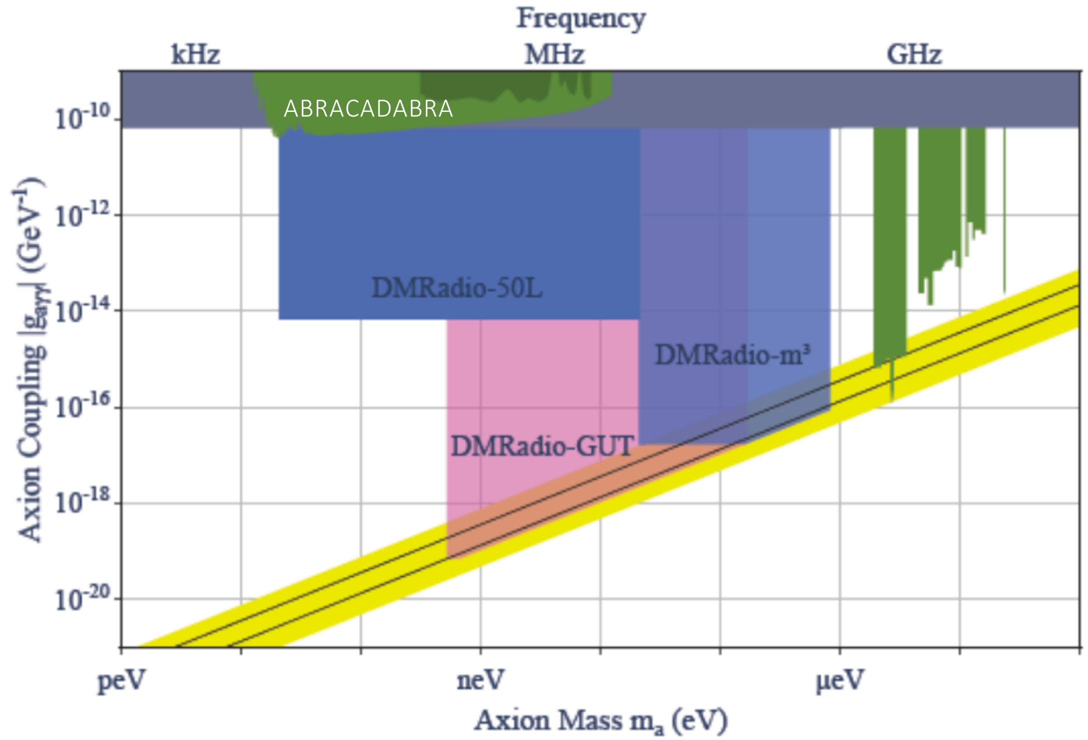
Helpful hint: You don't need a magnet.

Towards GUT-scale axions: DM Radio









Lumped-element LC resonator: *coax* supplants *cavity* for conversion volume

Program includes 50 Liter (late 2023) and Cubic meter (~2027)

DMRadio-m3, L. Brouwer et al, Physical Review D 106 (2022) 103008

DMRadio-GUT, L. Brouwer et al, arXiv:2203.11246 *(accepted, PRD)*

Final remarks

A healthy attitude is to shed all theoretical prejudice of dark matter models.

- ➥ DM may be found with virtually any mass and coupling.
- ➥ All experiments are valuable, of whatever mass range & sensitivity.
- ➥ "But between going deep and going wide, pick mass coverage any day!" *Bruce Winstein*

Quantum sensing has played and will continue to play an essential role in DM experiments.

These are exciting times for axions and ALPS, so ….

Stay "Tuned" !

And thank you, Georg, for your friendship,
the physics you have taught us,
the joy of physics we have done together,
and the papers we hope to write together in the future!