Axion Searches

Pierre Sikivie (U of Florida)

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Particle Dark Matter and Solar Axion Searches with a small germanium detector at the Canfranc Underground Laboratory

A. Morales[a 1], F.T. Avignone III[b], R.L. Brodzinski[c], S. Cebrián[a], E. García[a], D. González[a], I.G. Irastorza[a], H.S. Miley[c], J. Morales[a], A. Ortiz de Solórzano[a], J. Puimedón[a], J.H. Reeves[c], M.L. Sarsa[a], S. Scopel[a], J.A. Villar[a]

(The COSME Collaboration)

[a] *Laboratory of Nuclear and High Energy Physics, University of Zaragoza, 50009 Zaragoza, Spain*
[b] *University of South Carolina, Columbia, South Carolina 29208 USA*
[c] *Pacific Northwest National Laboratory, Richland, Washington 99352 USA*

Abstract

A small, natural abundance, germanium detector (COSME) has been operating recently at the Canfranc Underground Laboratory (Spanish Pyrenees) in improved conditions of shielding and overburden with respect to a previous operation of the same detector [1, 2]. An exposure of 72.7 kg day in these conditions has at present a background improvement of about one order of magnitude compared to the former operation of the detector. These new data have been applied to a direct search for WIMPs and solar axions. New WIMP exclusion plots improving the current bounds for low masses are reported. The paper also presents a limit on the axion-photon coupling obtained from the analysis of the data looking for a Primakoff axion-to-photon conversion and Bragg scattering inside the crystal.

PACS: 95.35+d; 14.80.Mz
Key words: Dark Matter; Underground detectors; WIMPs; Axions

1 Introduction

Substantial evidence and well-founded arguments exist pointing out that the Universe may well consist of a suitable mixture of cold dark matter (CDM), hot dark matter (HDM) and baryons (in the amount required by the primordial nucleosynthesis), which together with a large component of dark energy could complete the proper gravitational balance of the Universe. Regarding the nature of the dark matter, there are compelling reasons to believe it consist mainly of cold non-baryonic particles. Among these candidates, Weakly

[1]corresponding author: amorales@posta.unizar.es

Axio-Electric and Primakoff Effects

e.g. $$a + \mathrm{Ge} \to e + \mathrm{Ge}^+$$

Dimopoulos, Starkman & Lynn, 1986

Frank Avignone

$$a + (Z, A) \to \gamma + (Z, A)$$

constraints from SOLAX, COSME, DAMA, CDMS, EDELWEISS, XMASS, CUORE, CDEX, Xenon, LUX, PandaX

First results from the CERN Axion Solar Telescope (CAST)

K. Zioutas,[8] S. Andriamonje,[2] V. Arsov,[13,4] S. Aune,[2] D. Autiero,[1,*] F. Avignone,[3] K. Barth,[1] A. Belov,[11] B. Beltrán,[6] H. Bräuninger,[5] J. M. Carmona,[6] S. Cebrián,[6] E. Chesi,[1] J. I. Collar,[7] R. Creswick,[3] T. Dafni,[4] M. Davenport,[1] L. Di Lella,[1,†] C. Eleftheriadis,[8] J. Englhauser,[5] G. Fanourakis,[9] H. Farach,[3] E. Ferrer,[2] H. Fischer,[10] J. Franz,[10] P. Friedrich,[5] T. Geralis,[9] I. Giomataris,[2] S. Gninenko,[11] N. Goloubev,[11] M. D. Hasinoff,[12] F. H. Heinsius,[10] D.H.H. Hoffmann,[4] I. G. Irastorza,[2] J. Jacoby,[13] D. Kang,[10] K. Königsmann,[10] R. Kotthaus,[14] M. Krčmar,[15] K. Kousouris,[9] M. Kuster,[5] B. Lakić,[15] C. Lasseur,[1] A. Liolios,[8] A. Ljubičić,[15] G. Lutz,[14] G. Luzón,[6] D. W. Miller,[7] A. Morales,[6,‡] J. Morales,[6] M. Mutterer,[4] A. Nikolaidis,[8] A. Ortiz,[6] T. Papaevangelou,[1] A. Placci,[1] G. Raffelt,[14] J. Ruz,[6] H. Riege,[4] M. L. Sarsa,[6] I. Savvidis,[8] W. Serber,[14] P. Serpico,[14] Y. Semertzidis,[4,§] L. Stewart,[1] J. D. Vieira,[7] J. Villar,[6] L. Walckiers,[1] and K. Zachariadou[9]

(CAST Collaboration)

[1]*European Organization for Nuclear Research (CERN), Genève, Switzerland*
[2]*DAPNIA, Centre d'Études Nucléaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France*
[3]*Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA*
[4]*GSI-Darmstadt and Institut für Kernphysik, TU Darmstadt, Darmstadt, Germany*
[5]*Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany*
[6]*Instituto de Física Nuclear y Altas Energías, Universidad de Zaragoza, Zaragoza, Spain*
[7]*Enrico Fermi Institute and KICP, University of Chicago, Chicago, IL, USA*
[8]*Aristotle University of Thessaloniki, Thessaloniki, Greece*
[9]*National Center for Scientific Research "Demokritos", Athens, Greece*
[10]*Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
[11]*Institute for Nuclear Research (INR), Russian Academy of Sciences, Moscow, Russia*
[12]*Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada*
[13]*Johann Wolfgang Goethe-Universität, Institut für Angewandte Physik, Frankfurt am Main, Germany*
[14]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany*
[15]*Rudjer Bošković Institute, Zagreb, Croatia*

(Dated: November 3, 2018)

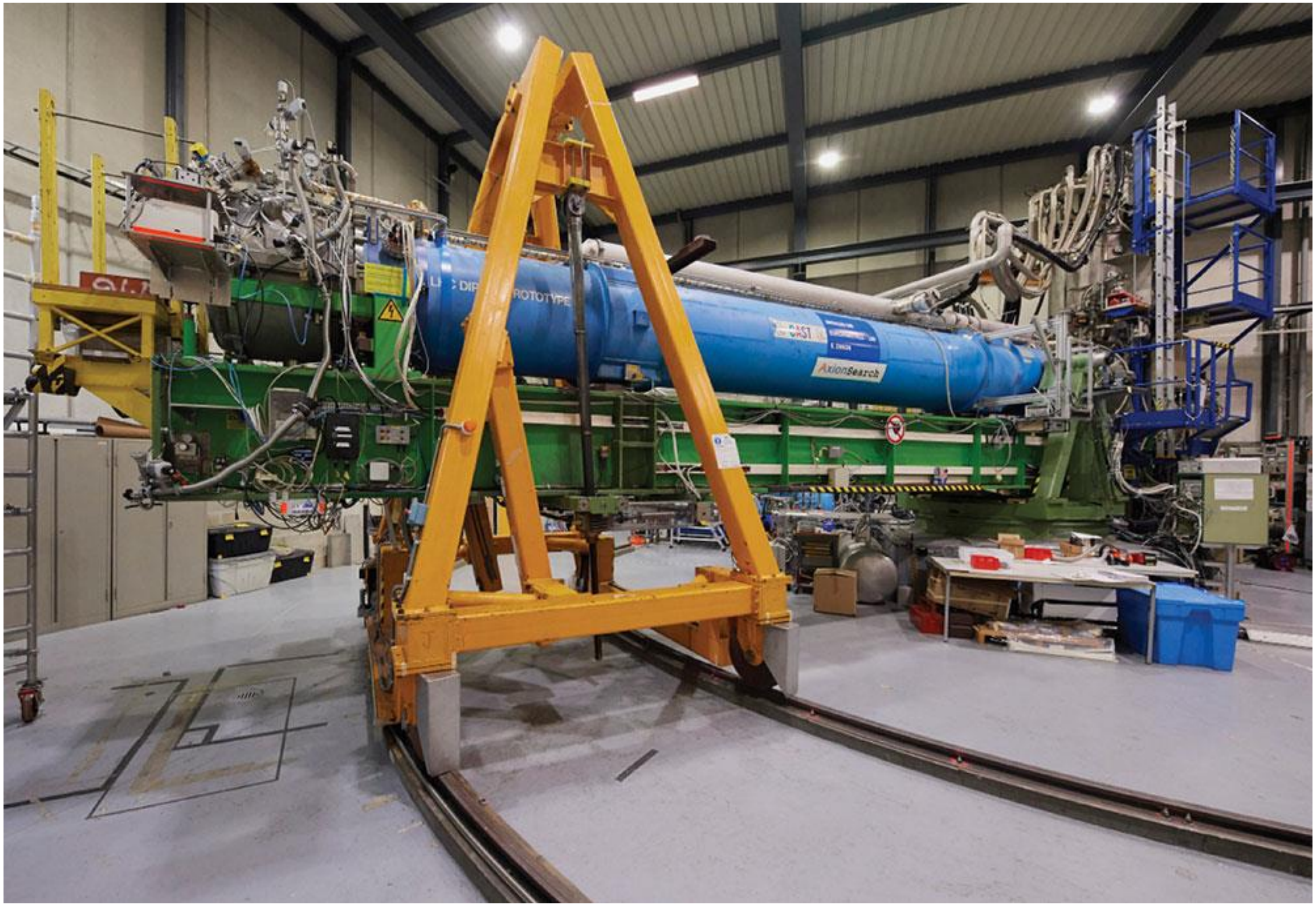
Hypothetical axion-like particles with a two-photon interaction would be produced in the Sun by the Primakoff process. In a laboratory magnetic field ("axion helioscope") they would be transformed into X-rays with energies of a few keV. Using a decommissioned LHC test magnet, CAST ran for about 6 months during 2003. The first results from the analysis of these data are presented here. No signal above background was observed, implying an upper limit to the axion-photon coupling $g_{a\gamma} < 1.16 \times 10^{-10}$ GeV^{-1} at 95% CL for $m_a \lesssim 0.02$ eV. This limit, assumption-free, is comparable to the limit from stellar energy-loss arguments and considerably more restrictive than any previous experiment over a broad range of axion masses.

PACS numbers: 95.35.+d; 14.80.Mz; 07.85.Nc; 84.71.Ba

Introduction.—Neutral pions, gravitons, hypothetical axions, or other particles with a two-photon interaction can transform into photons in external electric or magnetic fields, an effect first discussed by Primakoff in the early days of pion physics [1]. Therefore, stars could produce these particles by transforming thermal photons in the fluctuating electromagnetic fields of the stellar plasma [2, 3]. In laboratory or astrophysical B-fields, transitions between these particles and photons occur [4, 5], an effect that can be observed in the laboratory [6], affects the propagation of cosmic γ-rays [7, 8], and can modify the apparent brightness of distant astronomical sources [9, 10, 11]. Gravitons interact too weakly to be observable in these situations, while pions are too heavy. However, these effects can be crucial for new particles, notably the pseudoscalar axions that arise in the context of the Peccei-Quinn solution to the strong CP problem and are viable cold dark matter candidates [6, 12]. Galactic axions are currently being sought by two large-scale Primakoff-type microwave cavity experiments [12]. Anomalous stellar energy loss by axion emission is constrained by the observed properties of globular cluster stars, implying $g_{a\gamma} \lesssim 10^{-10}$ GeV^{-1} [3] for the axion-photon coupling, where the axion-photon interaction is written in the usual form $\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}\, a$. Axions would also contribute to the magnetically induced vacuum birefringence, interfering with the corresponding QED effect [5, 13]. The PVLAS experiment [14] apparently observes such an effect far in excess of the QED expectation, although an interpretation in terms of axion-like particles requires a coupling strength far larger than existing limits.

On the other hand, the Sun would be a strong axion source and thus offers a unique opportunity to actually detect these particles by taking advantage of

CERN Axion Solar Telescope



Outline

- Axion motivation in particle physics and cosmology
- Axion electrodynamics
- Some axion search strategies

The Strong CP Problem

$$\mathcal{L}_{\text{QCD}} = \ \dots \ + \ \bar{\theta}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

where

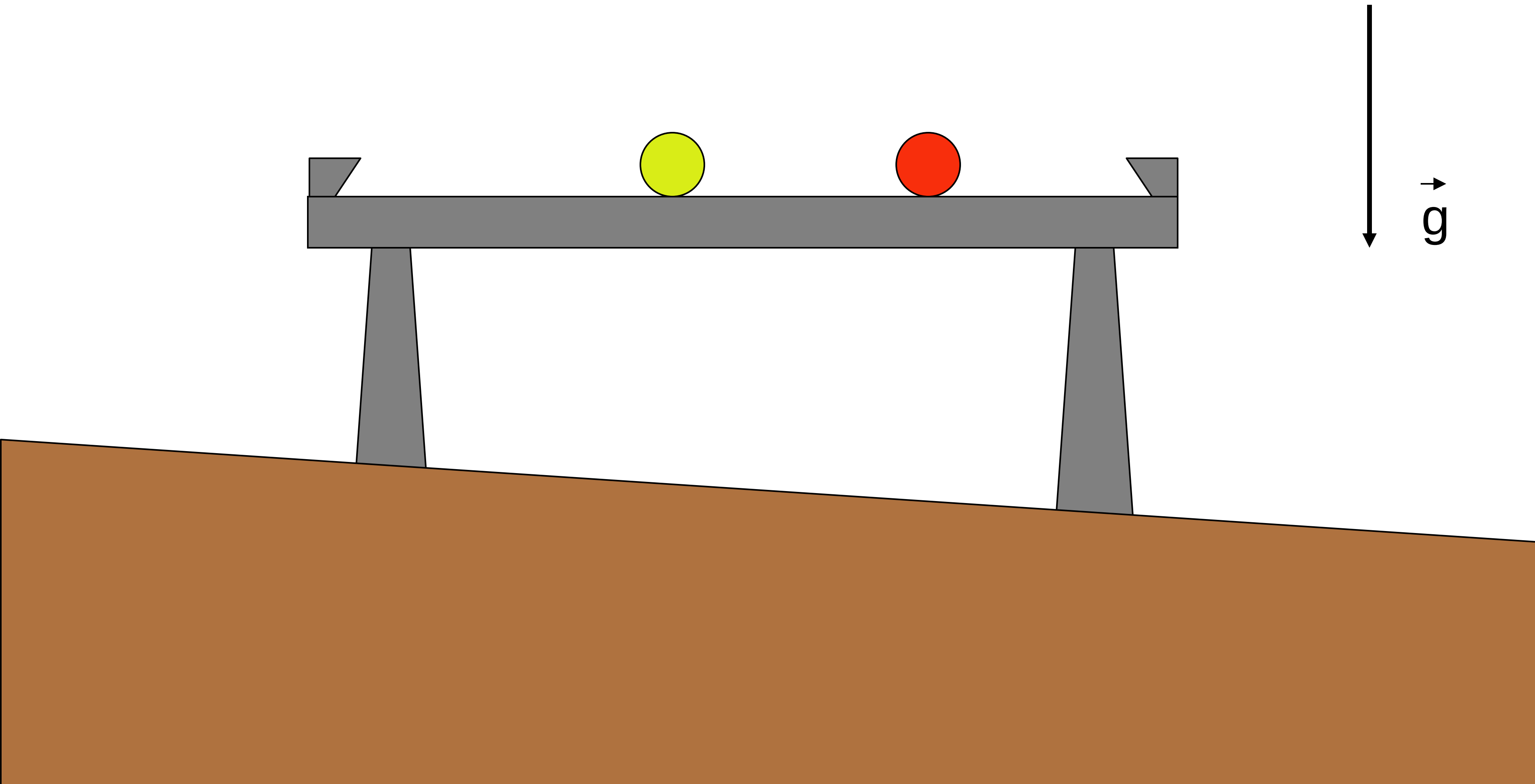
$$\bar{\theta} \ = \theta \ - \ \arg\left(m_u \ m_d \ \ \dots \ \ m_t\right)$$
$$= \ \theta \ - \ \arg\det\left(Y^u \ Y^d\right)$$

The absence of P and CP violation in the strong interactions requires

$$\bar{\theta} \leq 10^{-10}$$

from upper limit
on the neutron electric
dipole moment

A level pooltable on an inclined floor



The Standard Model does not provide a reason for $\bar{\theta}$ to be so tiny,

but a relatively small modification does …

$U_{PQ}(1)$

- is a symmetry of the classical action
- is spontaneously broken
- has a color anomaly

Peccei and Quinn, 1977

Chiral symmetry breaking

in the two flavor quark model (u,d)

$$SU_L(2) \otimes SU_R(2) \otimes U_A(1) \otimes U_V(1)$$

$$\downarrow$$

$$SU_V(2) \otimes U_V(1)$$

4 Nambu-Goldstone bosons $\pi^+ \ \pi^0 \ \pi^- \ \eta$

$$m_\eta < \sqrt{3}\, m_\pi$$

S. Weinberg

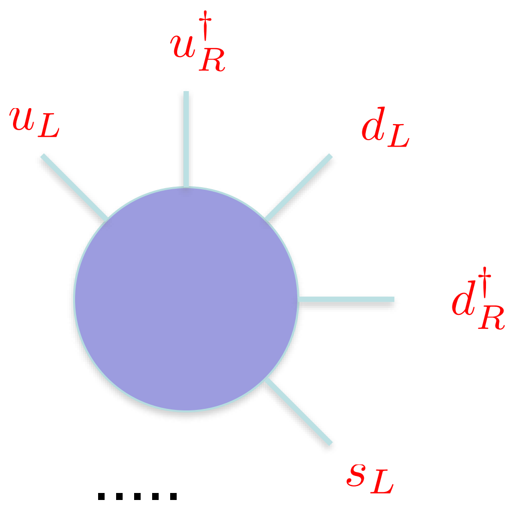
The $U_A(1)$ Problem

In Quantum Chromodynamics (QCD)

$U_A(1)$ has a Adler-Bell-Jackiw anomaly, and is therefore explicitly broken.

Quantum tunneling events, called instantons, produce axial charge for each flavor

't Hooft, 1976



$$\mathcal{L}_{\rm QCD} = \ ... \ + \ \bar{\theta}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta - \arg\,(m_u\, m_d\ \ldots\ m_t)$$

If a $\mathrm{U_{PQ}(1)}$ symmetry is assumed,

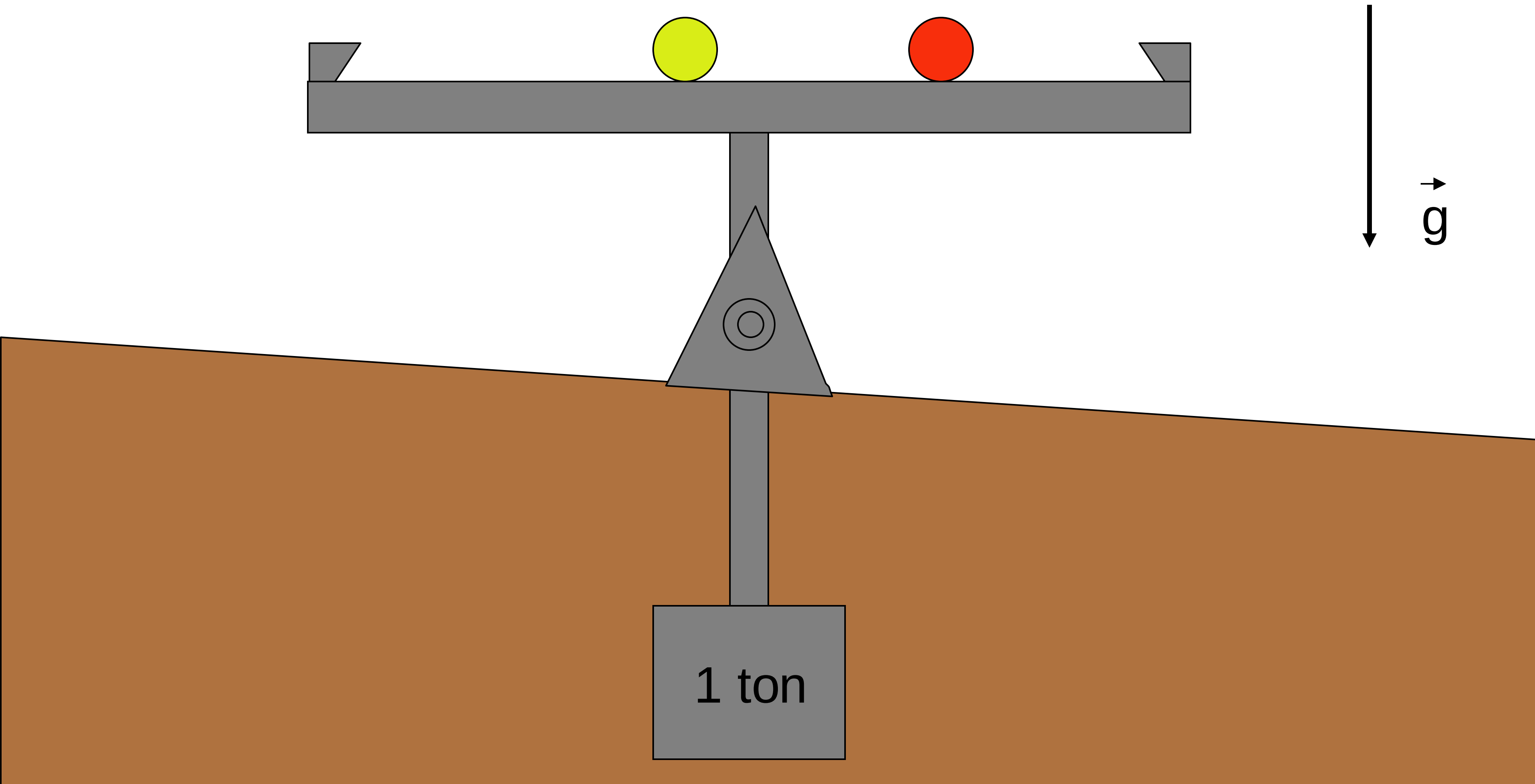
$$\mathcal{L} = \; ... \; + \; \frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \; + \; \frac{1}{2}\partial_\mu a \partial^\mu a$$

$\bar{\theta} = \dfrac{a}{f_a}$ relaxes to zero,

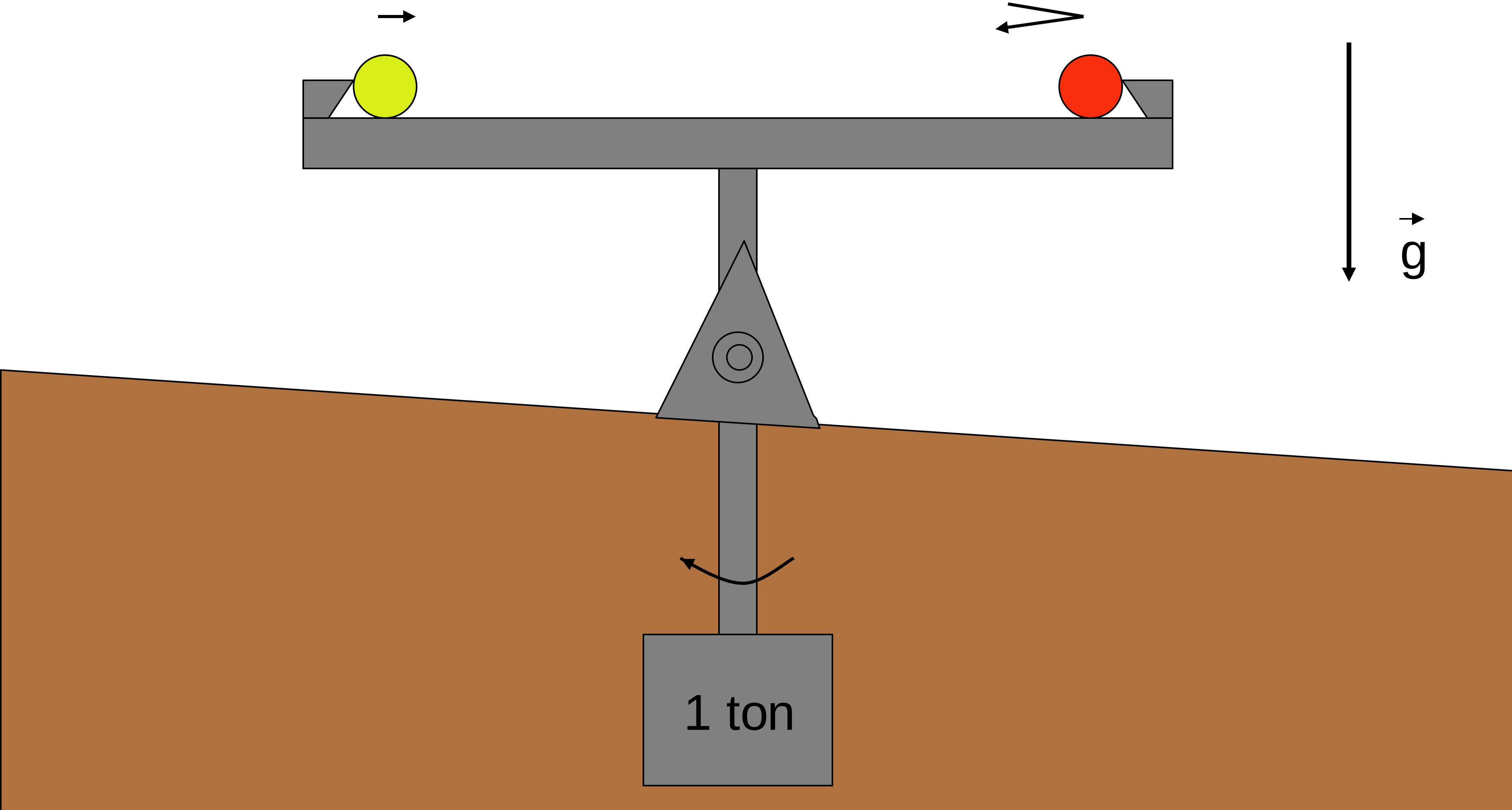
and a light neutral pseudoscalar particle is predicted: the axion.

Weinberg, Wilczek 1978

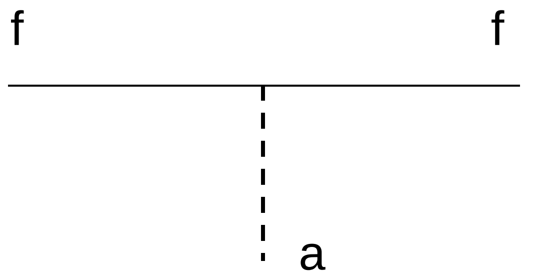
A self adjusting pooltable



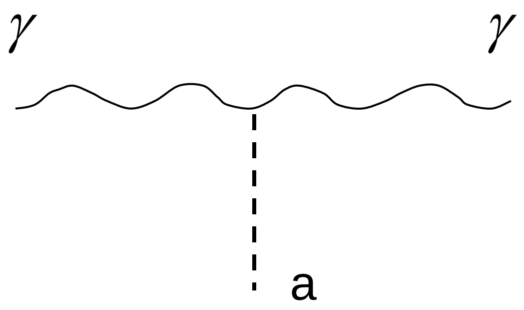
Searching for the pooltable oscillation quantum



$$m_a \simeq 6 \text{ eV} \frac{10^6 \text{ GeV}}{f_a}$$



$$\mathcal{L}_{a\bar{f}f} = i g_f \frac{a}{f_a} \bar{f} \gamma_5 f$$



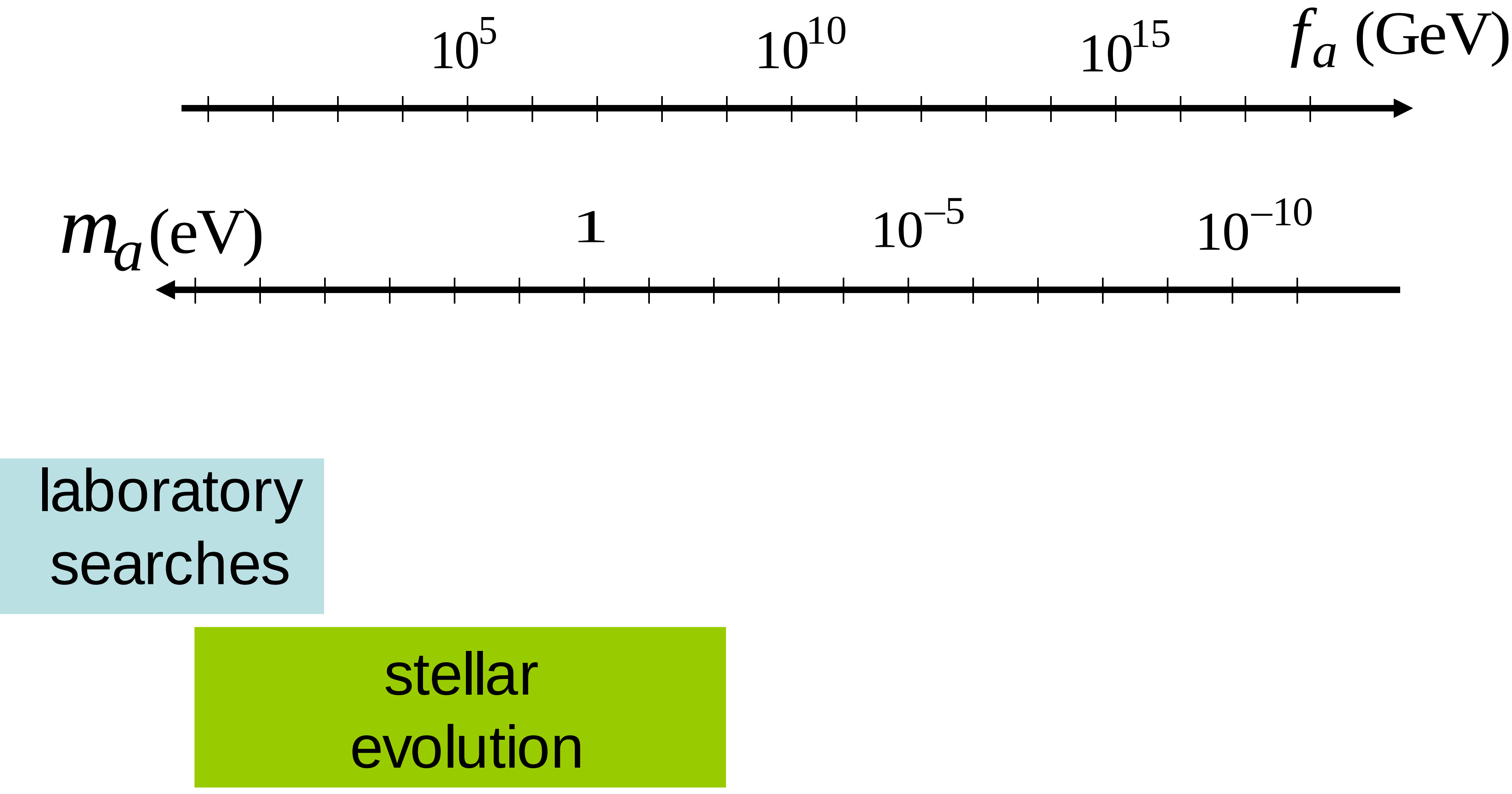
$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model

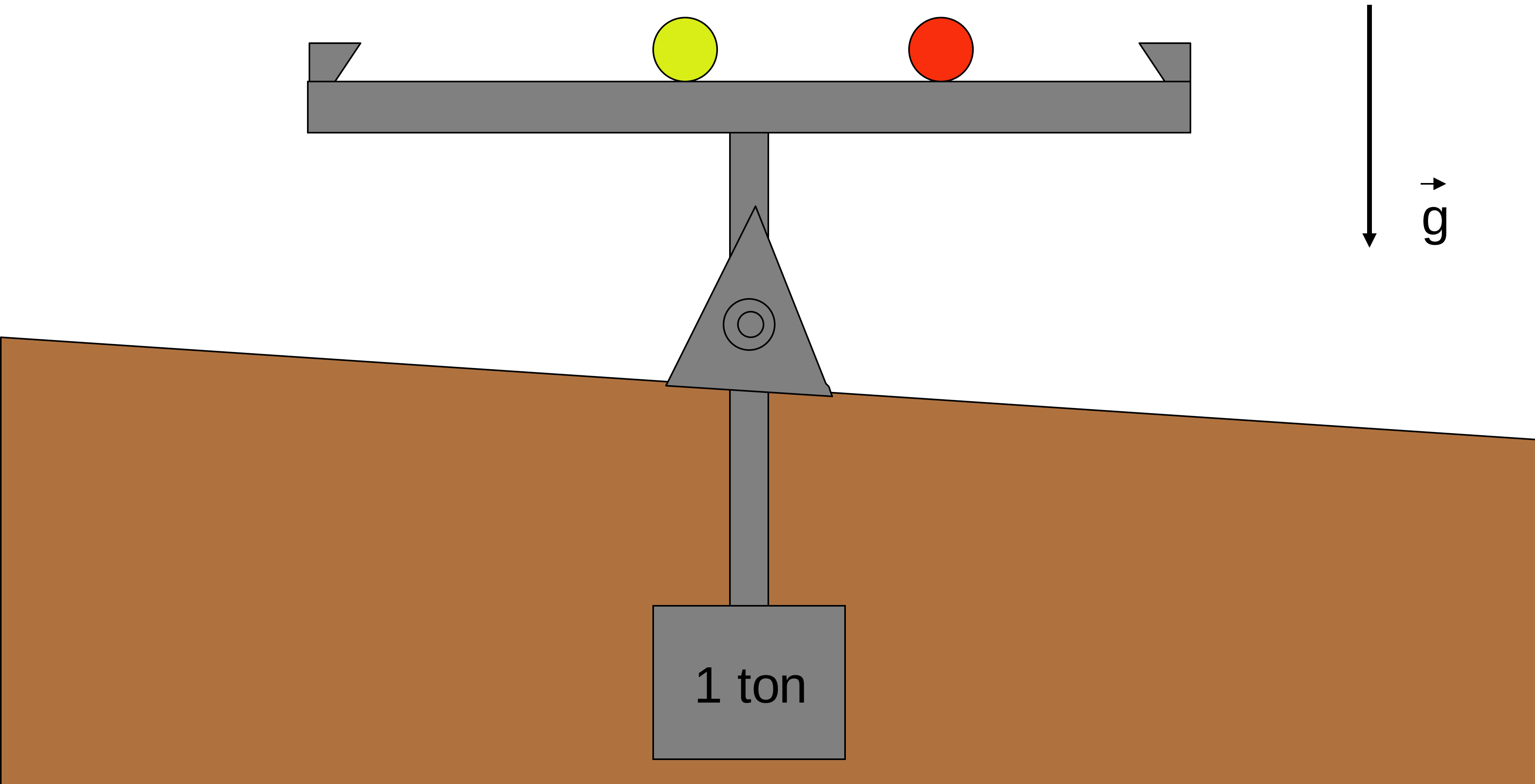
Axions are constrained by

- beam dump experiments
- rare particle decays $(e.g.\ \ K^+ \rightarrow \pi^+\ a)$
- radiative corrections
  $(e.g.\ \ \text{the}\ \mu^-\ \text{anomalous magnetic moment})$
- the evolution of stars

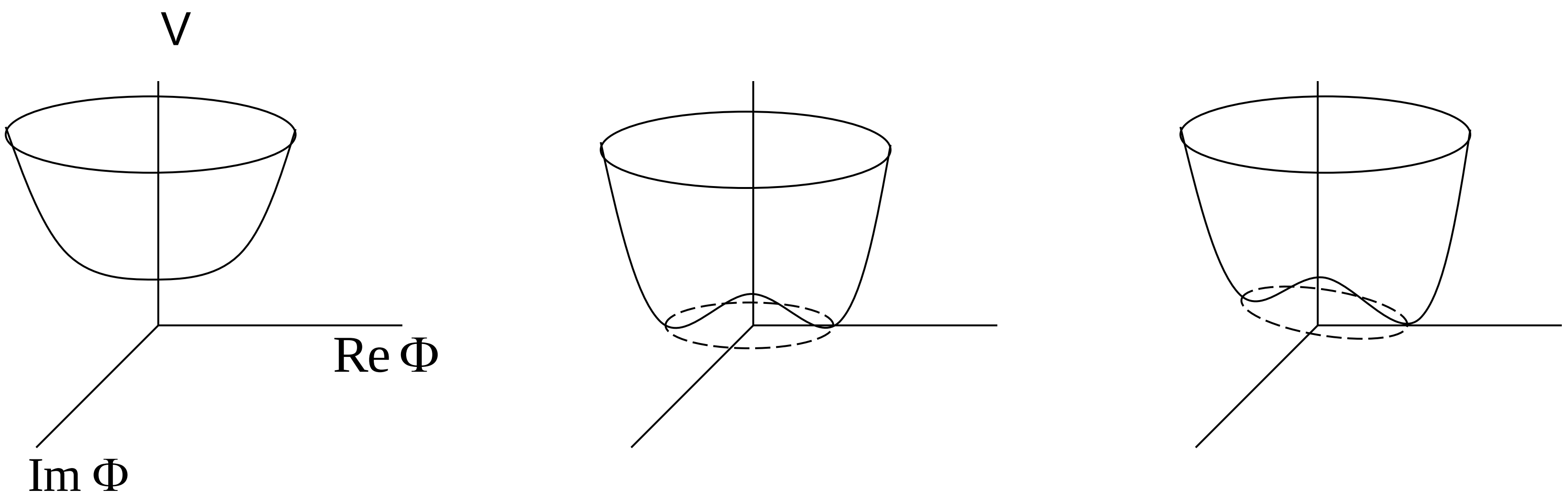
Axion constraints



A self adjusting pooltable



Effective potential V(T,Φ)

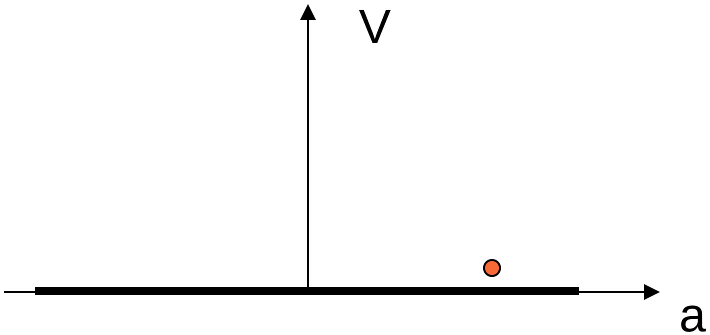


$T > f_a$

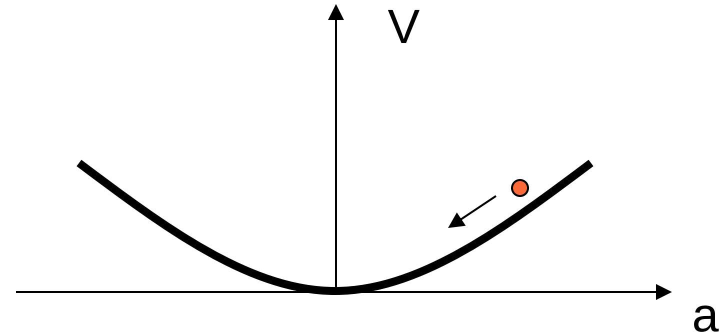
$f_a > T > 1\,\text{GeV}$ → axion strings

$1\,\text{GeV} > T$ → axion domain walls

Axion production by vacuum realignment



$T \geq 1\,\mathrm{GeV}$



$T \leq 1\,\mathrm{GeV}$

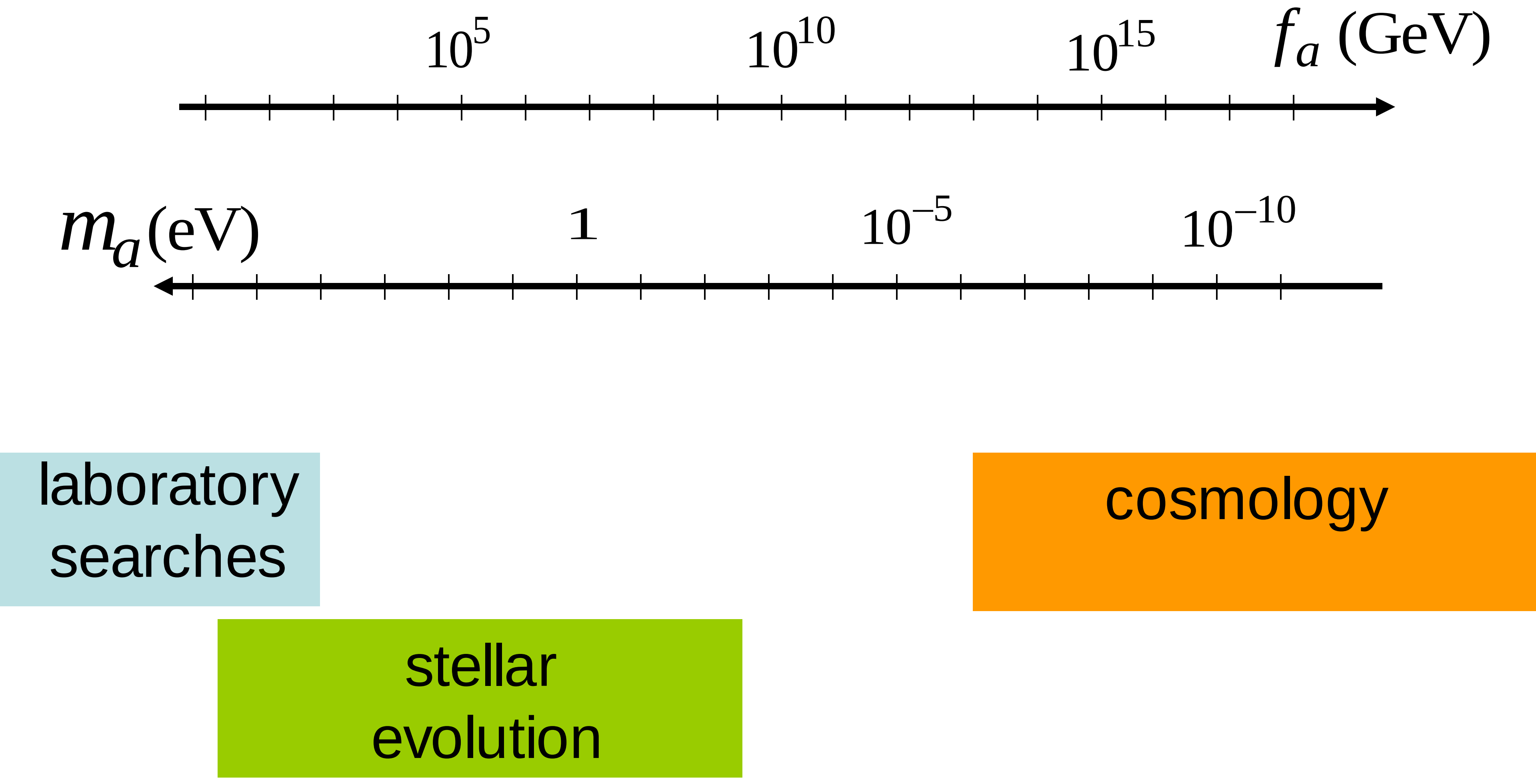
$$n_a(t_1) \simeq \frac{1}{2} m_a(t_1) a(t_1)^2 \simeq \frac{1}{2t_1} f_a^2 \alpha(t_1)^2$$

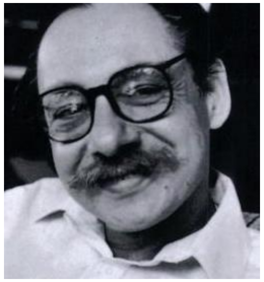
$$\rho_a(t_0) \simeq m_a n_a(t_1) \left(\frac{R_1}{R_0}\right)^3 \propto m_a^{-\frac{7}{6}}$$

initial misalignment angle

J. Preskill, M. Wise & F. Wilczek, L. Abbott & PS, M. Dine & W. Fischler, 1983

Axion constraints





HUTP-82/A032

THE MAGNETIC MONOPOLE FIFTY YEARS LATER*

Sidney Coleman

Lyman Laboratory of Physics
Harvard University
Cambridge, Massachusetts 02138

These lectures were given at the 1981 International School of Subnuclear Physics, "Ettore Majorana". Versions of these lectures were also given at the VI Brazilian Symposium on Theoretical Physics, at Les Houches École d'été de Physique Théorique, and at the Banff Summer Institute on Particles and Fields.

*Research was supported in part by the U.S. National Science Foundation under Grant No. PHY77-22864.

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The Witten Effect (1979)

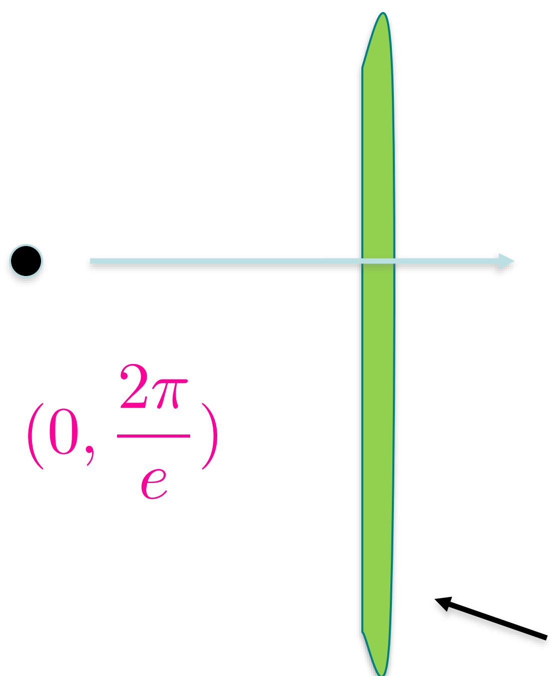
When $\theta \neq 0$ magnetic monopoles acquire electric charge

$$q_e = \frac{\alpha}{\pi}\, \theta\, q_m$$

$$q_e = \frac{\alpha}{\pi}(\theta + \frac{a}{f_a})q_m$$

with axion

$$(q_e, q_m) = (0, \frac{2\pi}{e})$$



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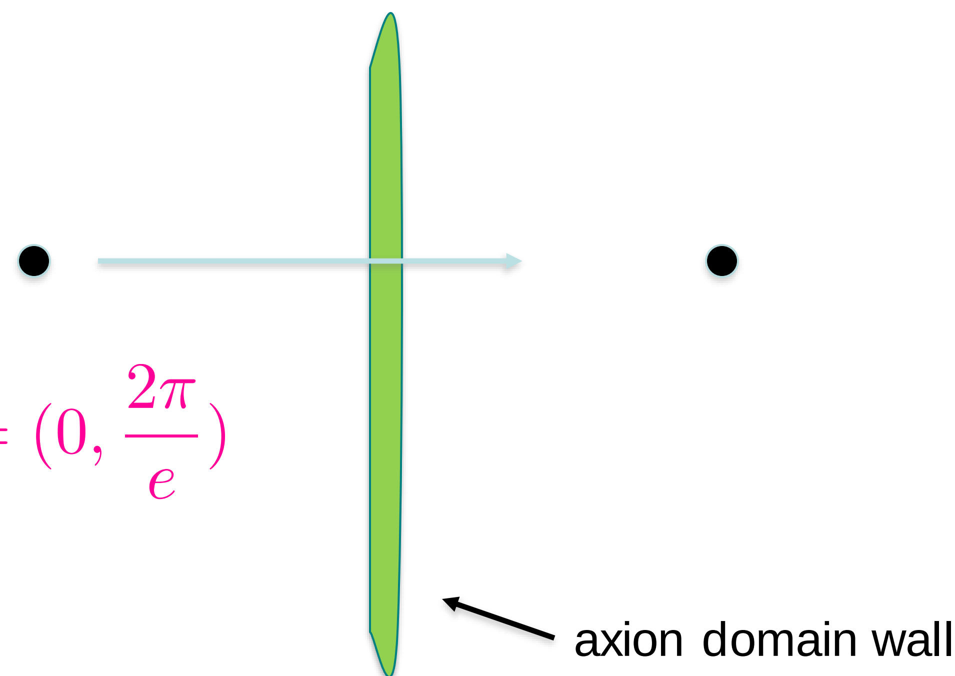

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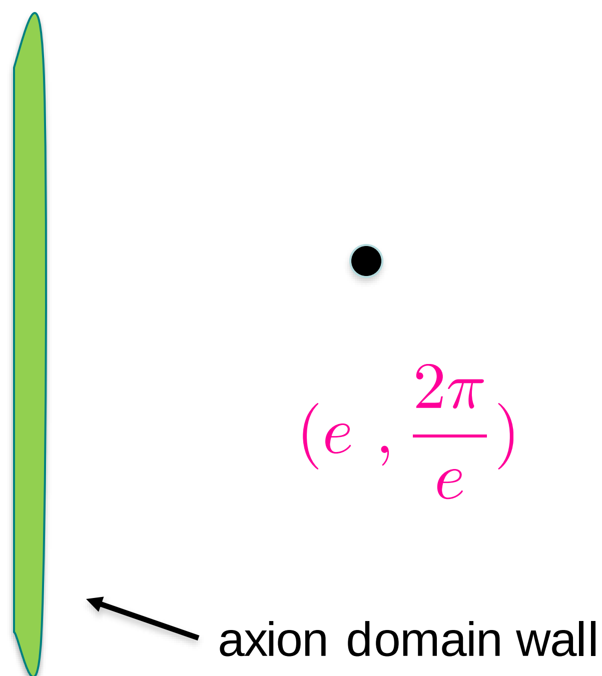


$$\mathcal{L}_{a\gamma\gamma} = g \; a(x) \; \vec{E}(x) \cdot \vec{B}(x)$$

Axion Electrodynamics

$$\vec{\nabla} \cdot (\vec{E} - ga\vec{B}) = \rho_{\rm el}$$

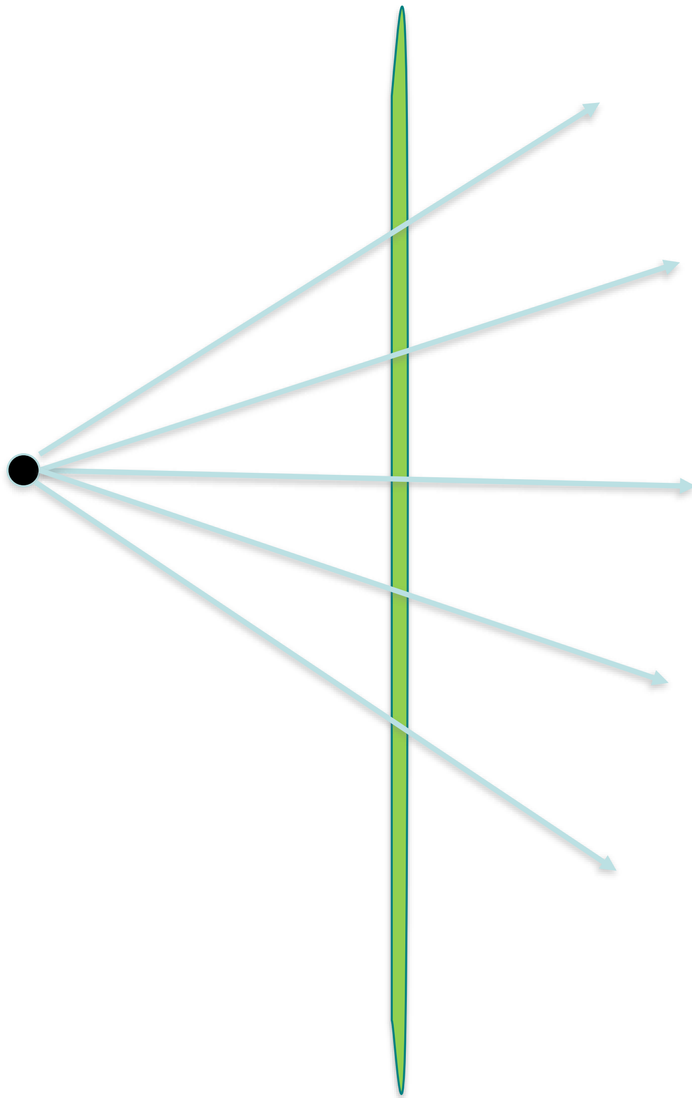
$$\vec{\nabla} \times (\vec{B} + ga\vec{E}) - \partial_t(\vec{E} - ga\vec{B}) = \vec{j}_{\rm el}$$

$$\vec{\nabla} \times \vec{E} + \partial_t \vec{B} = 0$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\partial_t^2 a - \nabla^2 a + m_a^2 a = -g\vec{E} \cdot \vec{B}$$

$$\vec{\nabla} \cdot \vec{E} = g\vec{\nabla} a \cdot \vec{B} + ga\vec{\nabla} \cdot \vec{B}$$



electric charge
surface density

$$\sigma_{\mathrm{el}} = g\Delta a B_{\perp} = 2\alpha B_{\perp}$$

Axion Electrodynamics

$$\vec{\nabla} \cdot (\vec{E} - ga\vec{B}) = \rho_{\rm el}$$

$$\vec{\nabla} \times (\vec{B} + ga\vec{E}) - \partial_t(\vec{E} - ga\vec{B}) = \vec{j}_{\rm el}$$

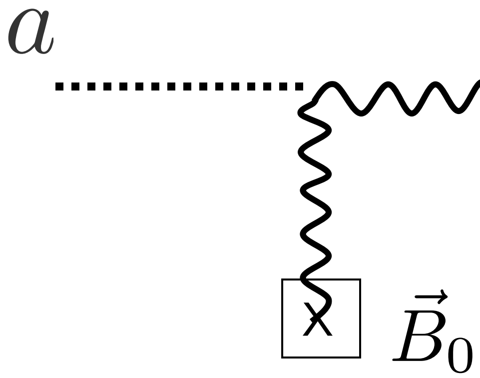
$$\vec{\nabla} \times \vec{E} + \partial_t\vec{B} = 0$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\partial_t^2 a - \nabla^2 a + m_a^2 a = -g\vec{E} \cdot \vec{B}$$

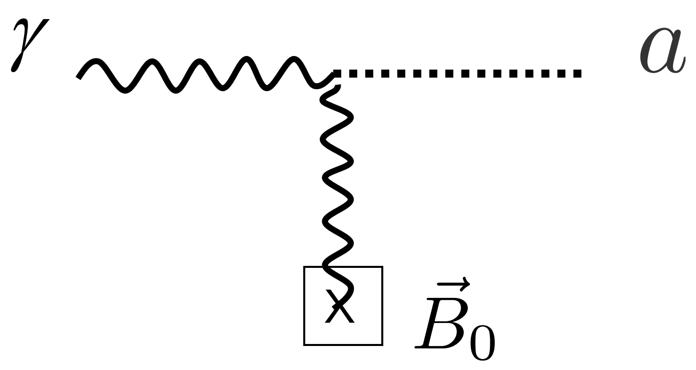
In background electric and magnetic fields
the axion field is a source of electromagnetic radiation

$$\partial_t^2 \vec{A} - \nabla^2 \vec{A} = g(\vec{E}_0 \times \vec{\nabla} a - \vec{B}_0 \partial_t a)$$



Axions convert to photons in a magnetic field and vice-versa

$$\partial_t^2 a - \nabla^2 a = -g\vec{B}_0 \cdot \vec{E}$$



BUT

$$N_{\mathrm{signal}} \sim N_\gamma \left(\frac{\alpha}{\pi}\frac{B_0}{f_a}L\right)^2 \left(\frac{\alpha}{\pi}\frac{B_0}{f_a}L\right)^2 \sim 10^{-48} N_\gamma$$

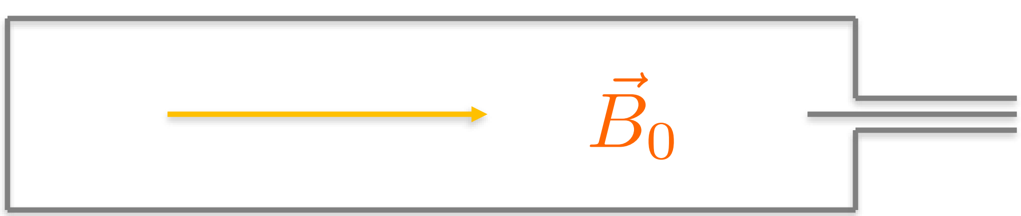
We may search for axions produced in the Sun or present on Earth as dark matter

- Axion helioscope

10^{14} axions/cm^{2}sec

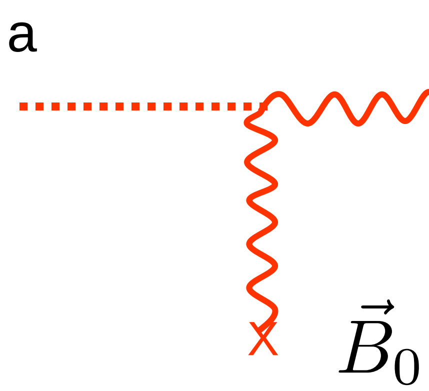
- Axion haloscope

10^{14} axions/cm^3

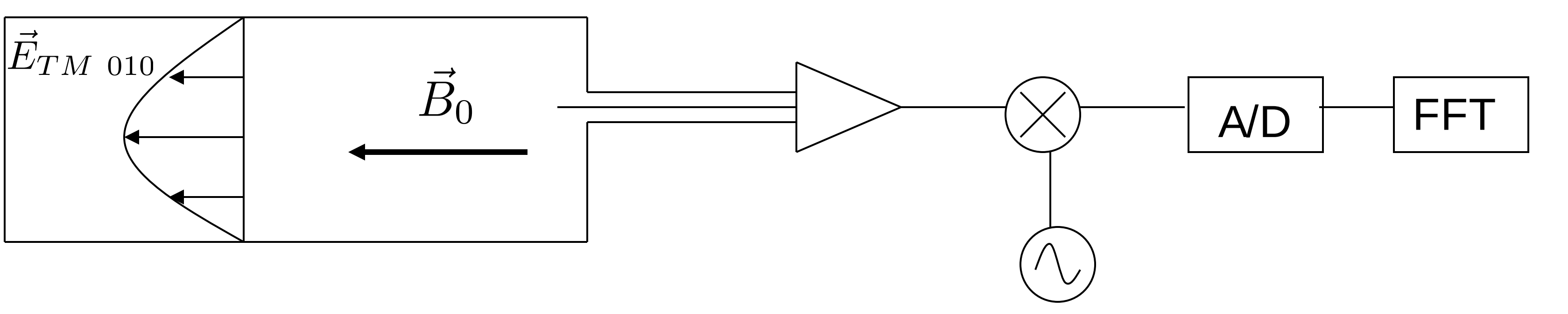


Axion dark matter is detectable

PS '83



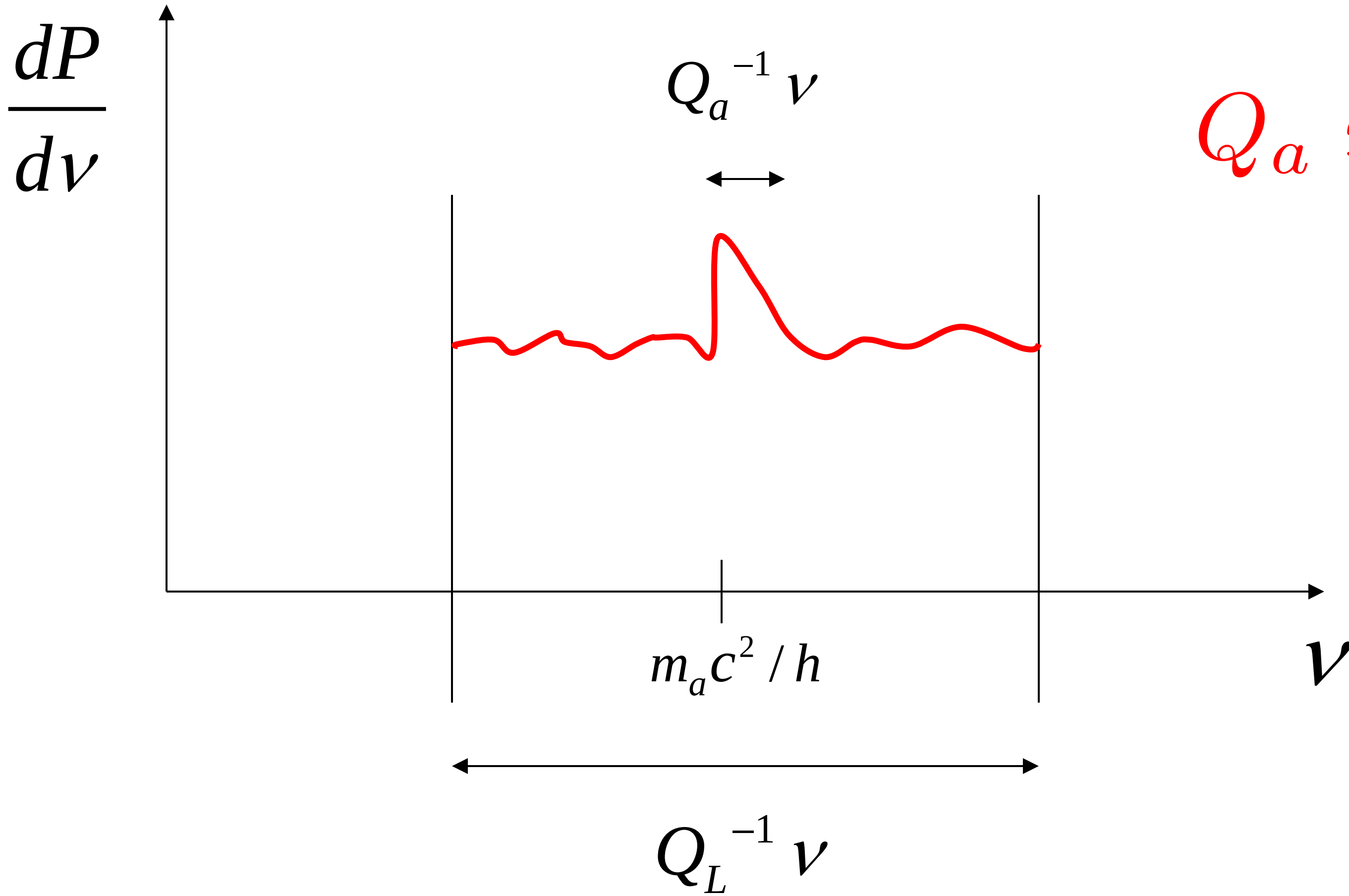
$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi f_a} a(x) \vec{E}(x) \cdot \vec{B}(x)$$



$$h\nu = m_a c^2 (1 + \frac{1}{2}\beta^2)$$

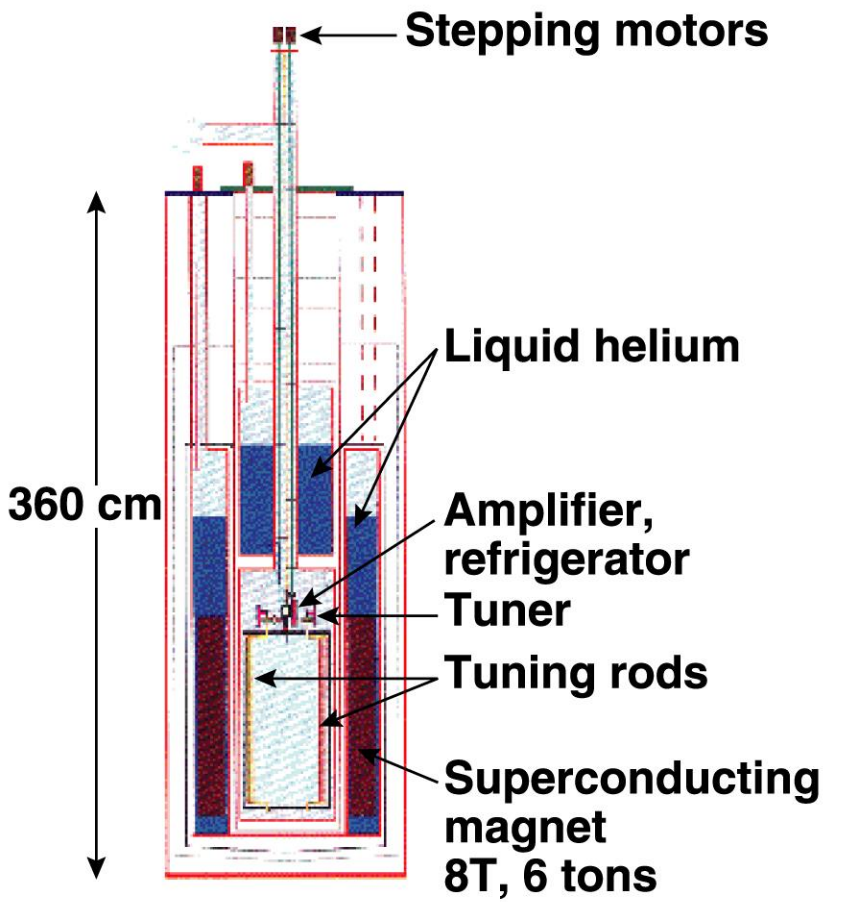
$$\beta = \frac{v}{c} \simeq 10^{-3}$$

$$Q_a \simeq 10^6$$



Axion Dark Matter eXperiment

Magnet with Insert (side view)

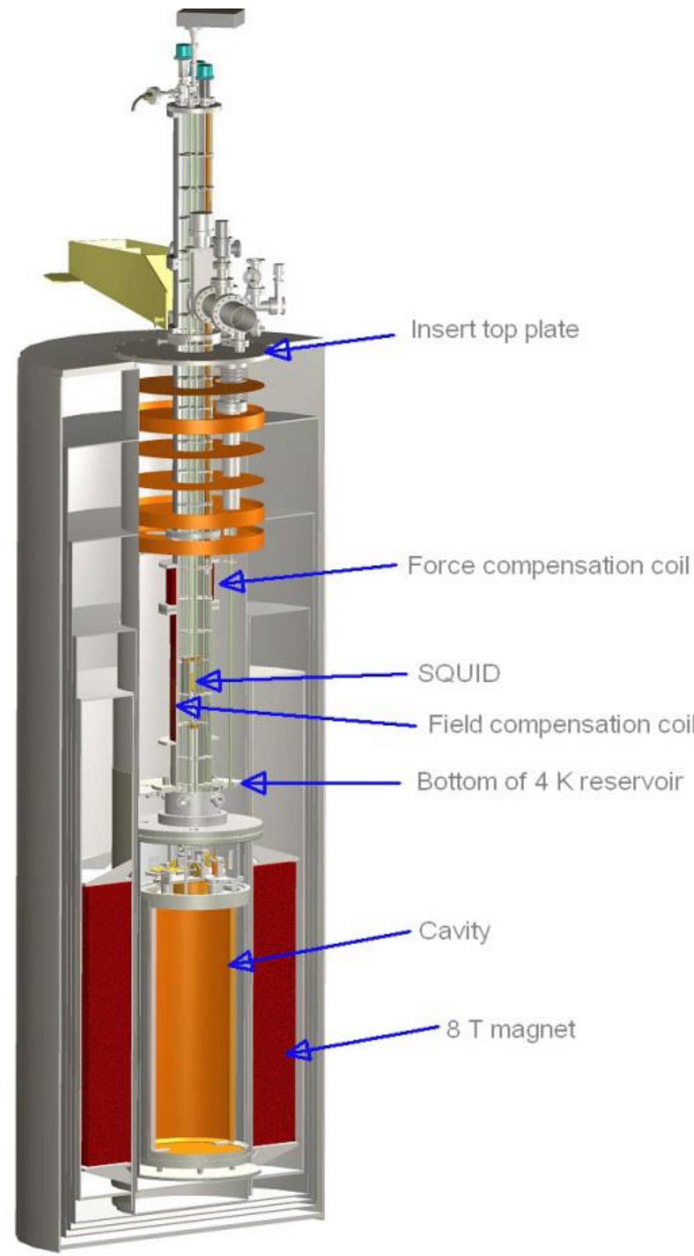


Pumped LHe → T ~ 1.5 k

Magnet

8 T, 1 m × 60 cm ∅

ADMX in its second generation



*Supported by DOE Grants DE-FG02-97ER41029, DE-FG02-96ER40956, DE-AC52-07NA27344, DE-AC03-76SF00098, NSF Grant PHY-1067242, and the Livermore LDRD program

HAYSTAC at Yale

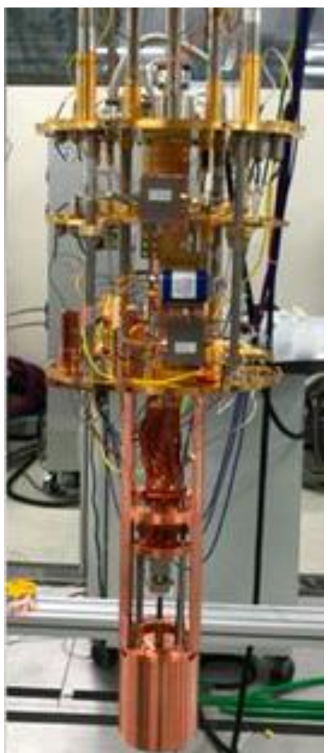
Institute for Basic Science

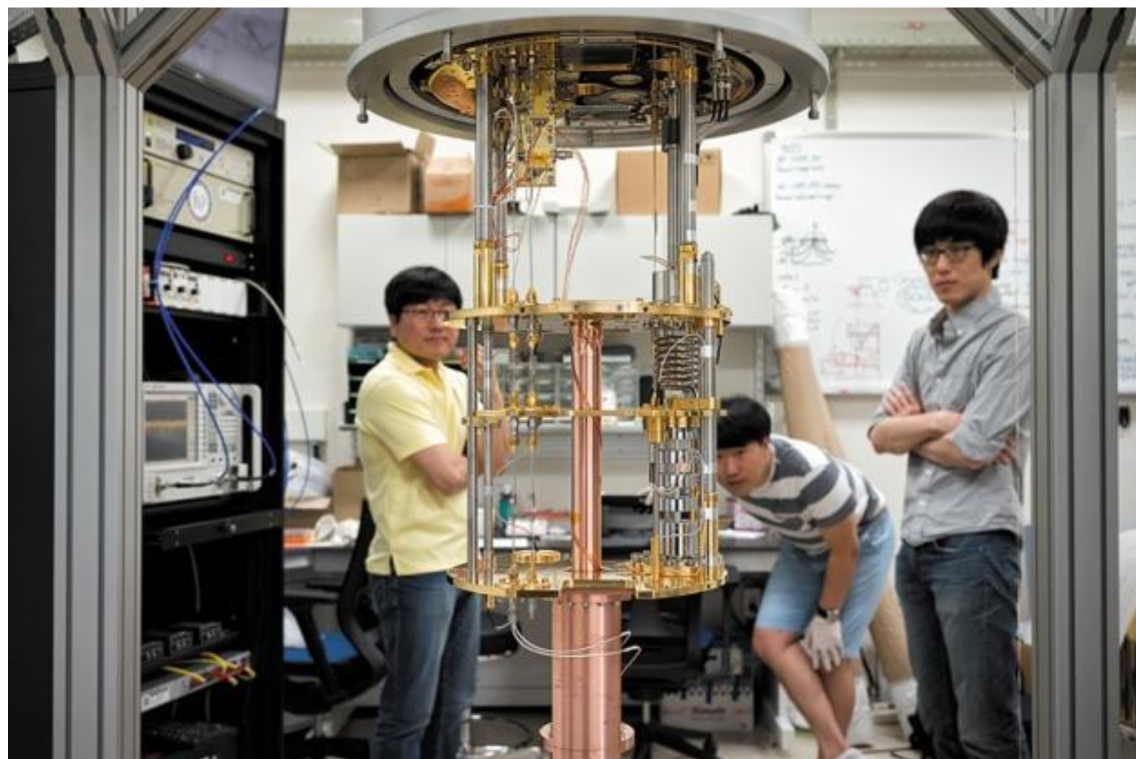
ibs

기초과학연구원

CAPP

Center for Axion and Precision Physics Research





Cavity haloscopes

- ADMX in Seattle & FNAL
- HAYSTAC at Yale
- CAPP in Korea
- QUAX at INFN laboratory in Legnaro
- ORGAN at University of Western Australia
- RADES at CERN
- TASEH in Taiwan

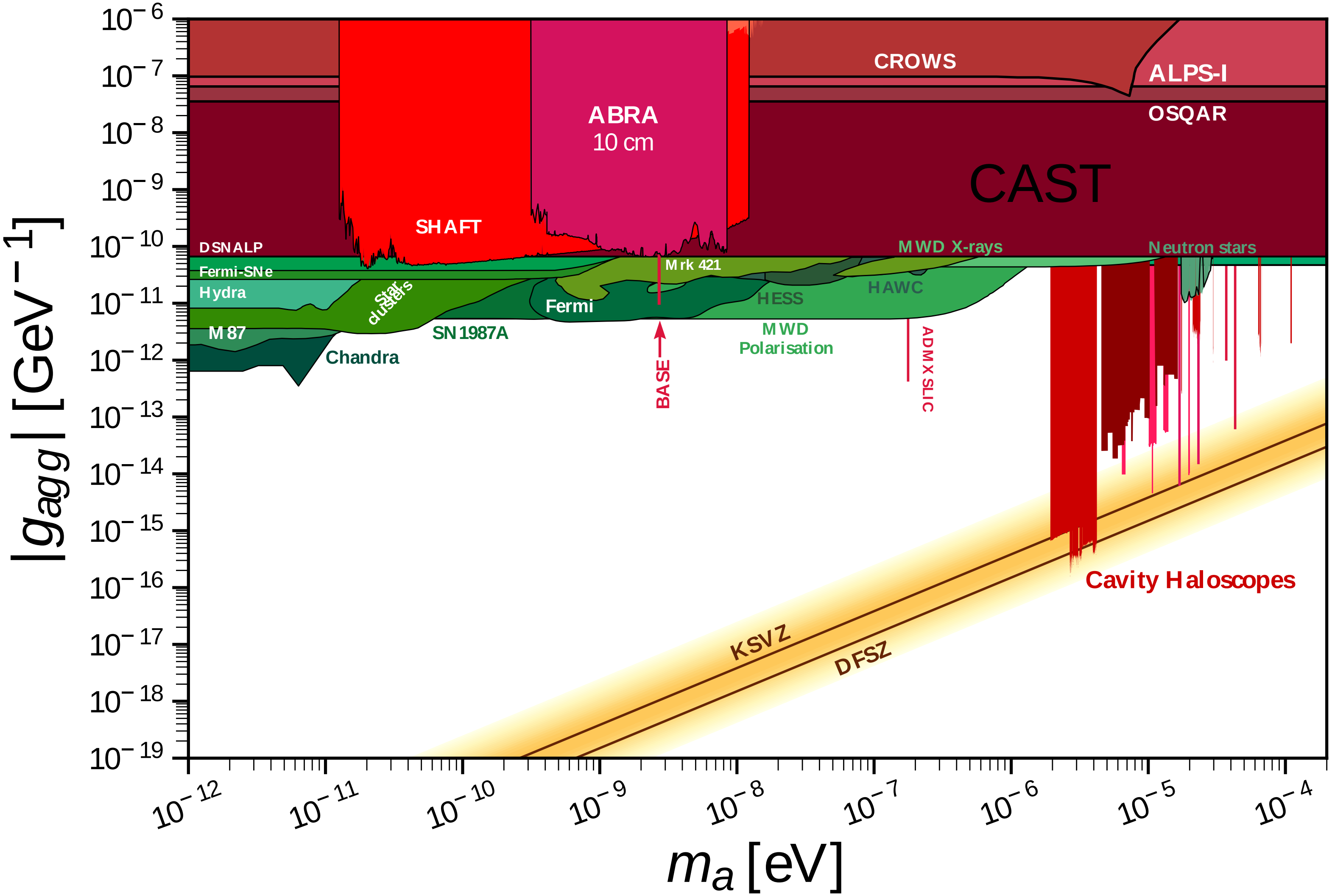
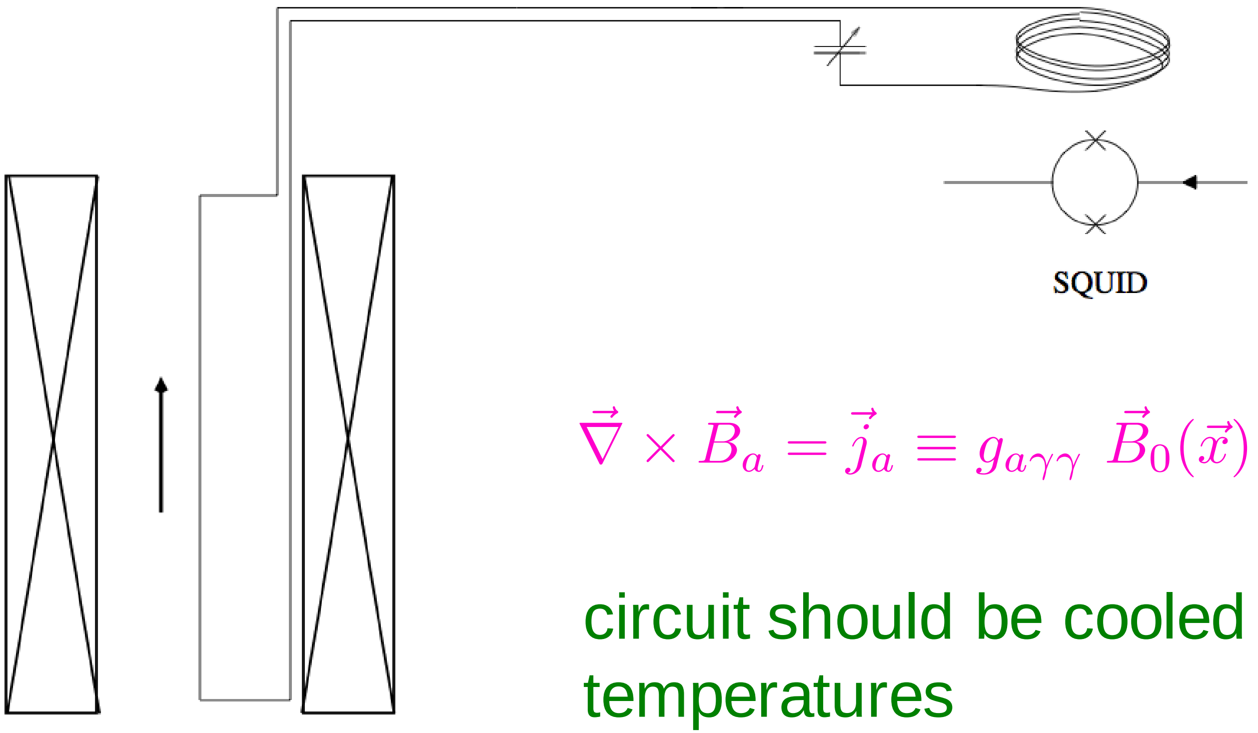


Figure by Ciaran O'Hare, available at https://github.com/cajohare/AxionLimits

Axion dark matter detection using an LC circuit

PS, D. Tanner and N. Sullivan, 2013

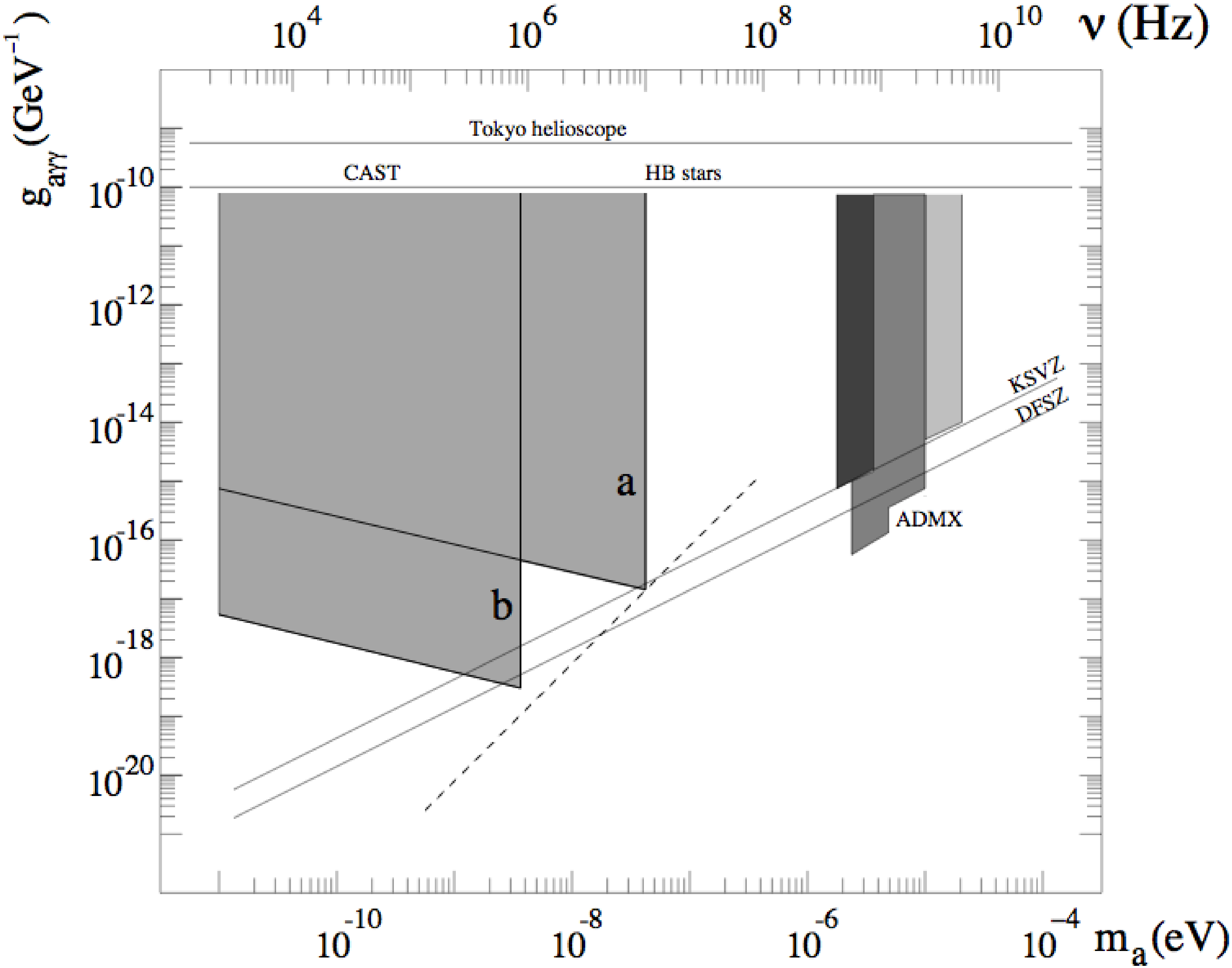


$$\vec{\nabla} \times \vec{B}_a = \vec{j}_a \equiv g_{a\gamma\gamma}\ \vec{B}_0(\vec{x})\ \partial_t a(\vec{x}, t)$$

circuit should be cooled to milli-Kelvin temperatures

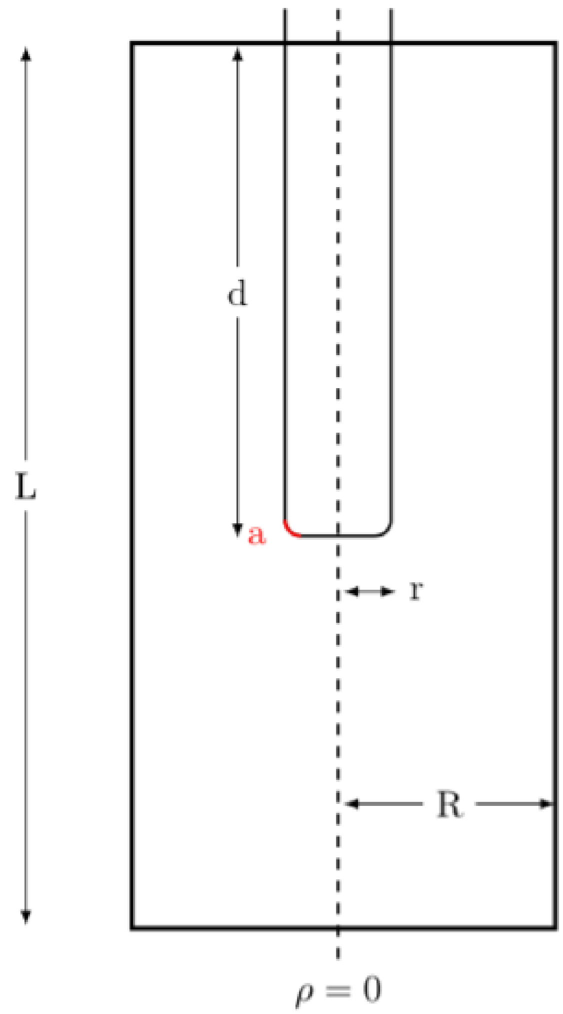
see talk by Lindley Winslow

ABRACADABRA, SLIC, DMRadio



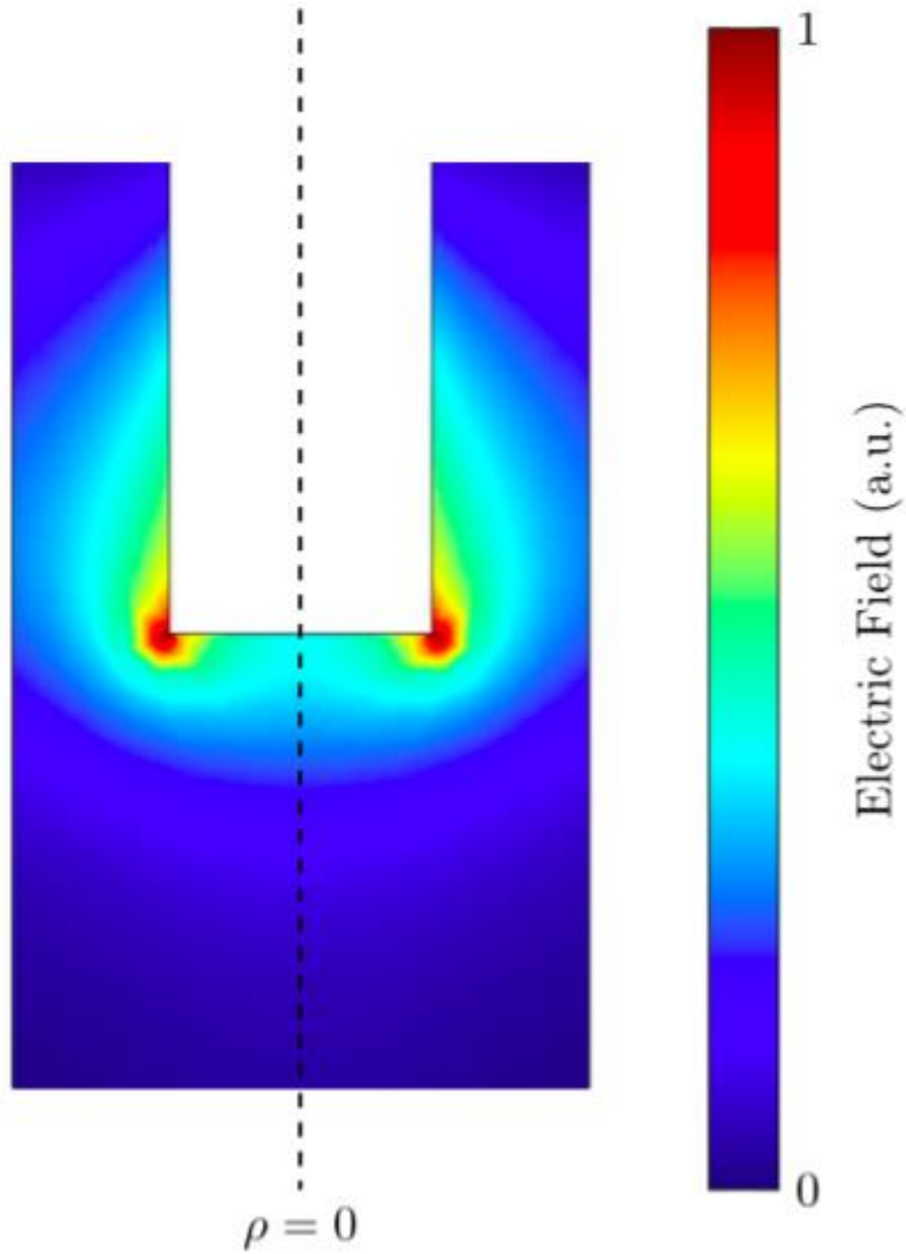
$g_{a\gamma\gamma}$ (GeV^{-1})
ν (Hz)
10^{4}
10^{6}
10^{8}
10^{10}
Tokyo helioscope
CAST
HB stars
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
a
b
KSVZ
DFSZ
ADMX
10^{-10}
10^{-8}
10^{-6}
10^{-4}
m_a (eV)

Reentrant Cavity

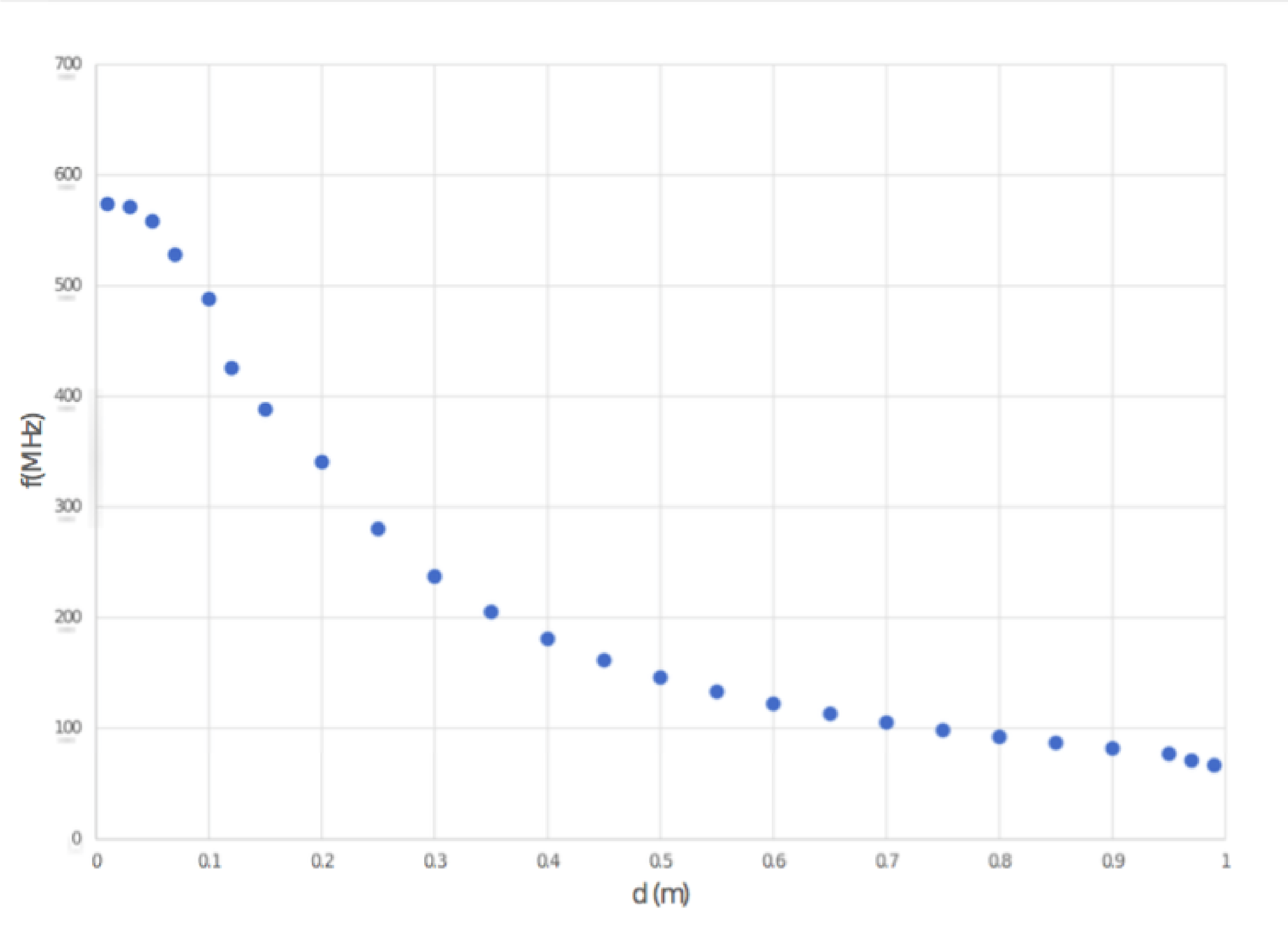


S. Chakarabarty et al. (ADMX Colloab.) 2303.07116

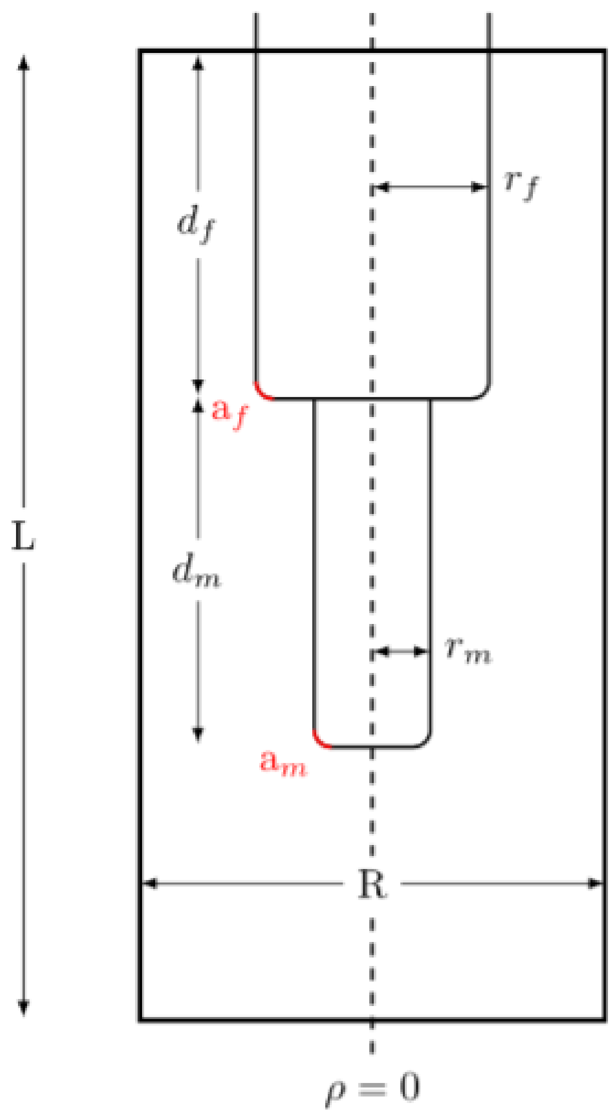
"Low frequency (100 – 600 MHz) searches with axion cavity haloscopes"



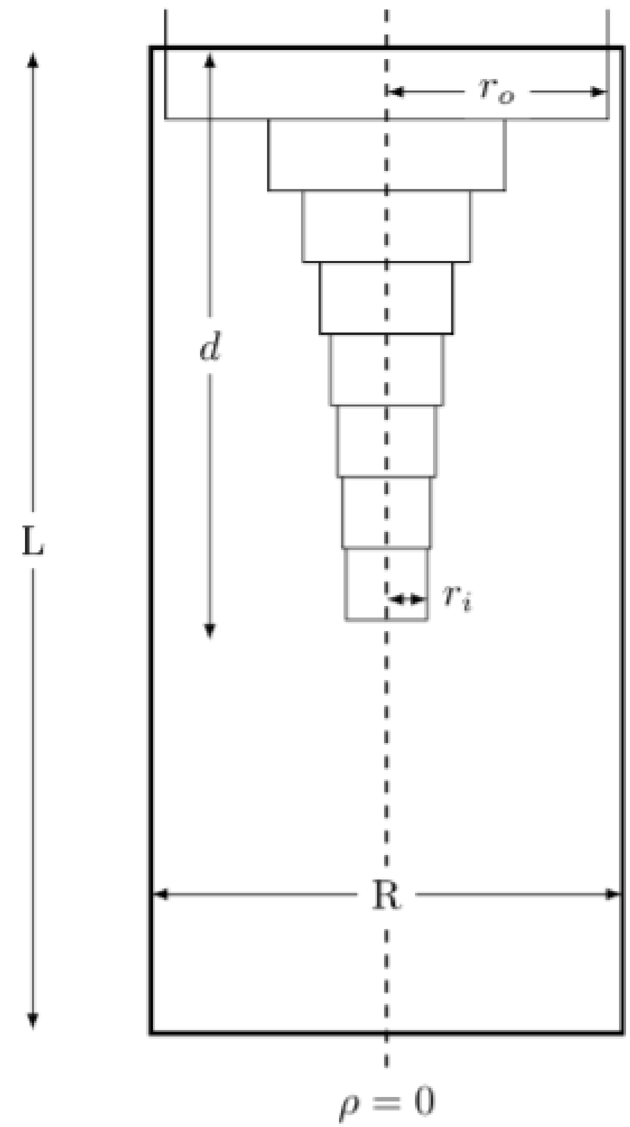
1
Electric Field (a.u.)
0
$\rho = 0$



700
600
500
400
300
200
100
0
f(MHz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d (m)



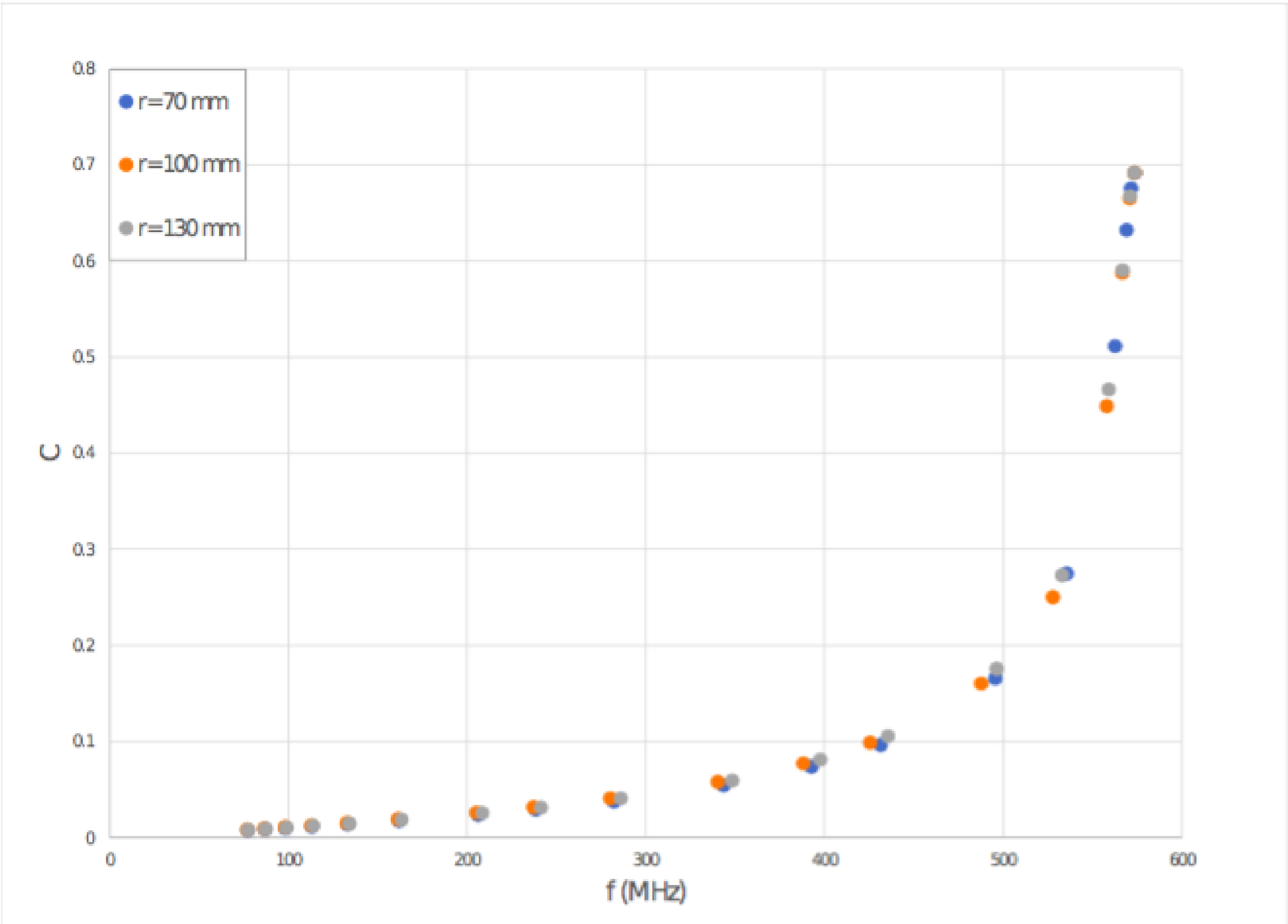
L
d_f
r_f
a_f
d_m
r_m
a_m
R
$\rho = 0$



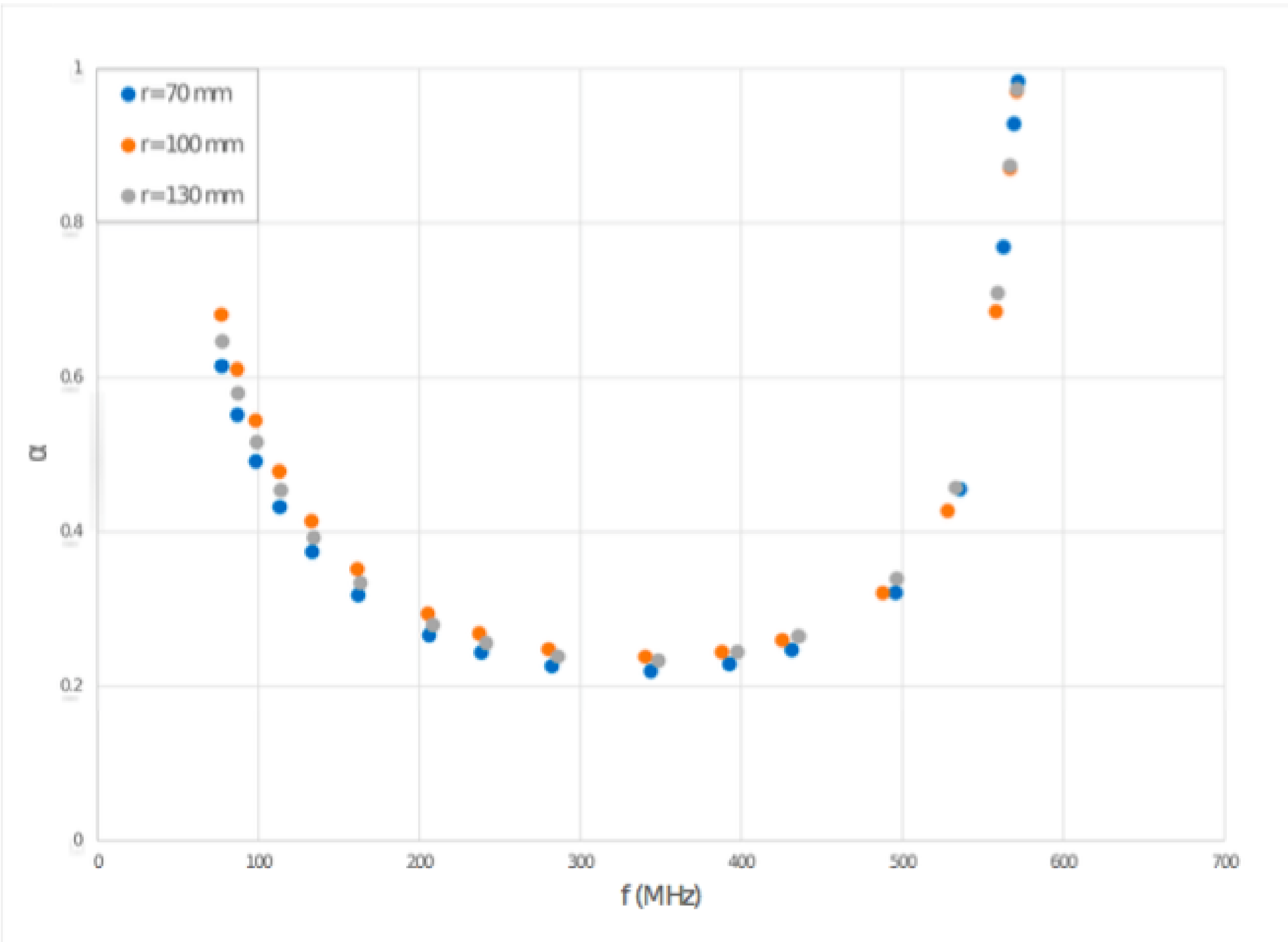
L
r_o
d
r_i
R
$\rho = 0$

Form factor

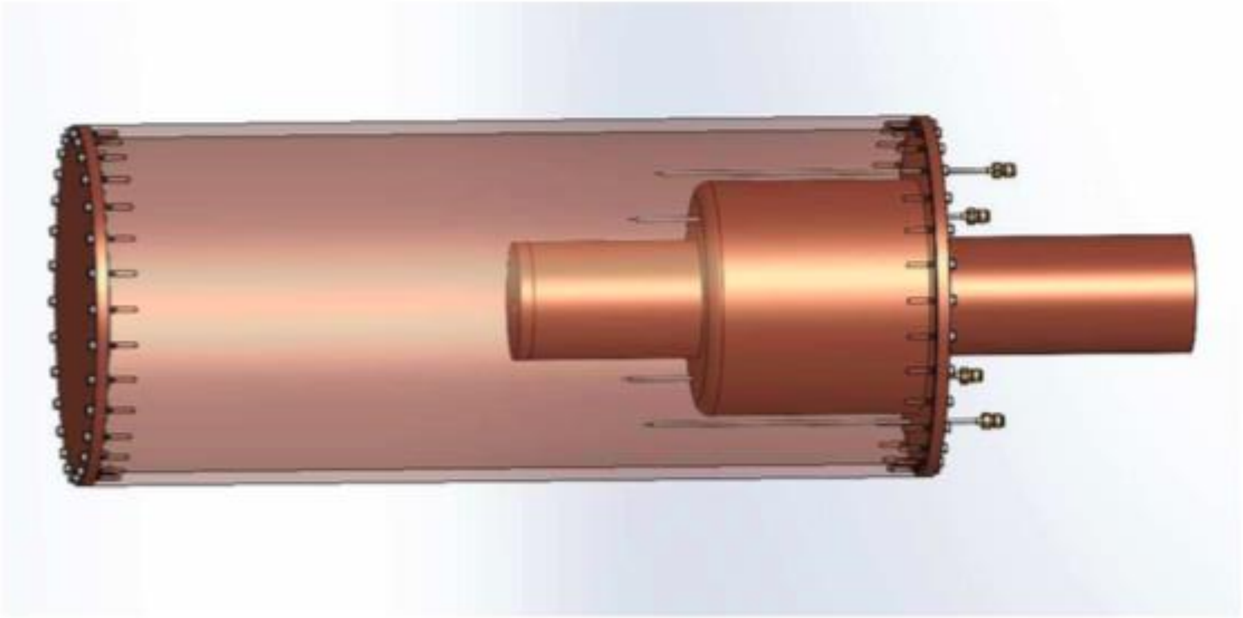
$$C(f) \sim f^2$$



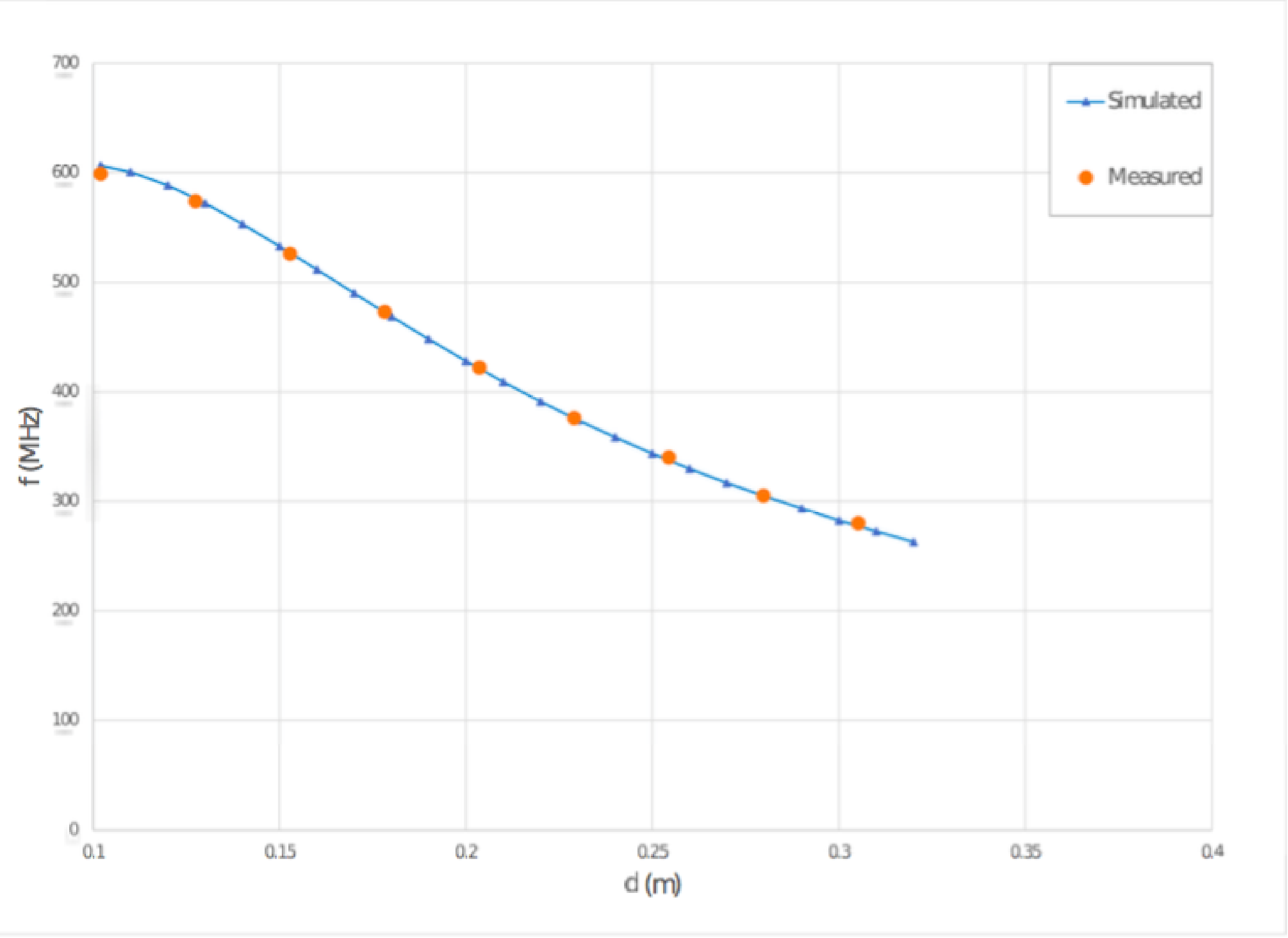
$$C(f) \equiv C_0 \left(\frac{f}{f_0} \right)^2 \alpha(f)$$



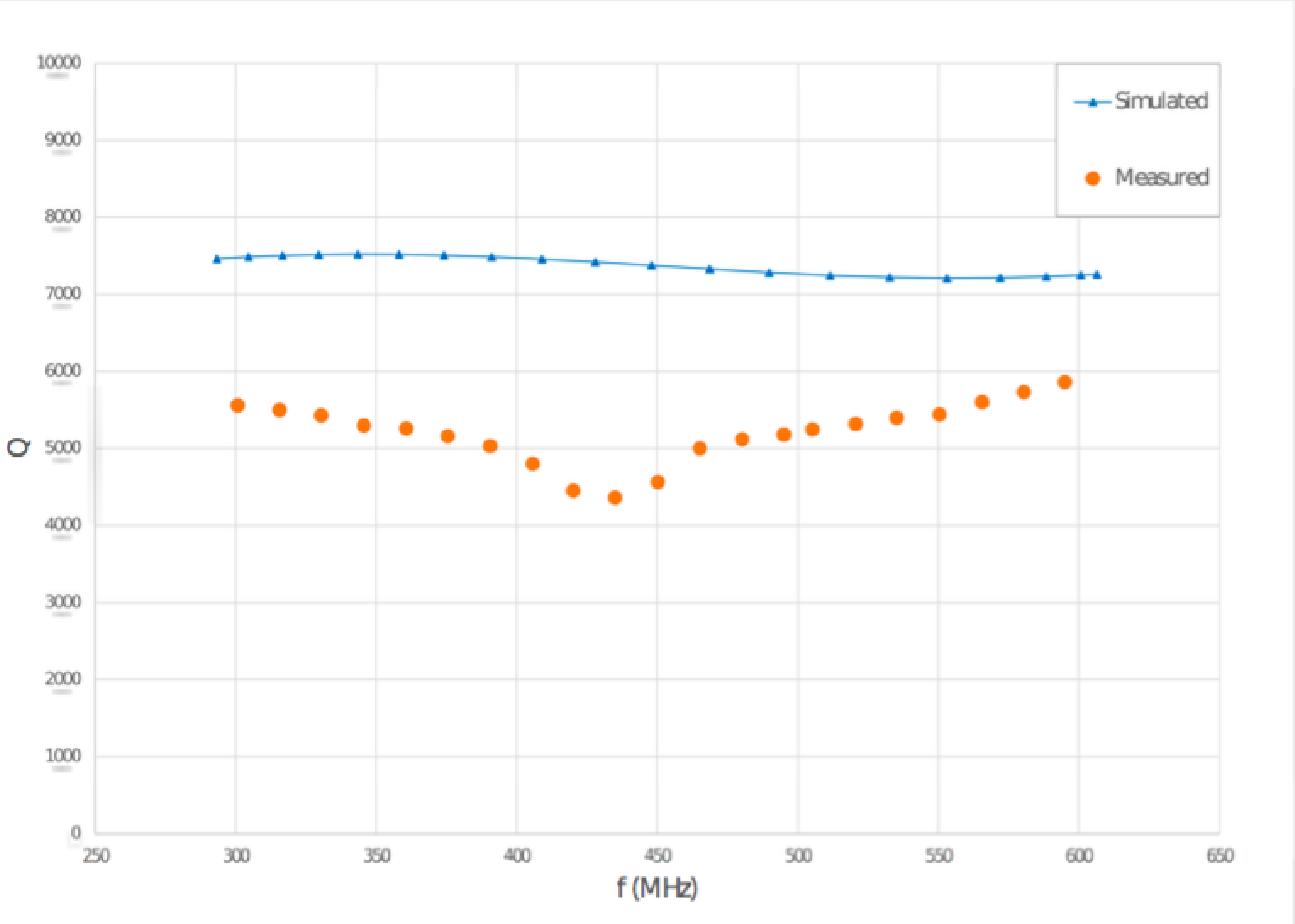
Prototype cavity

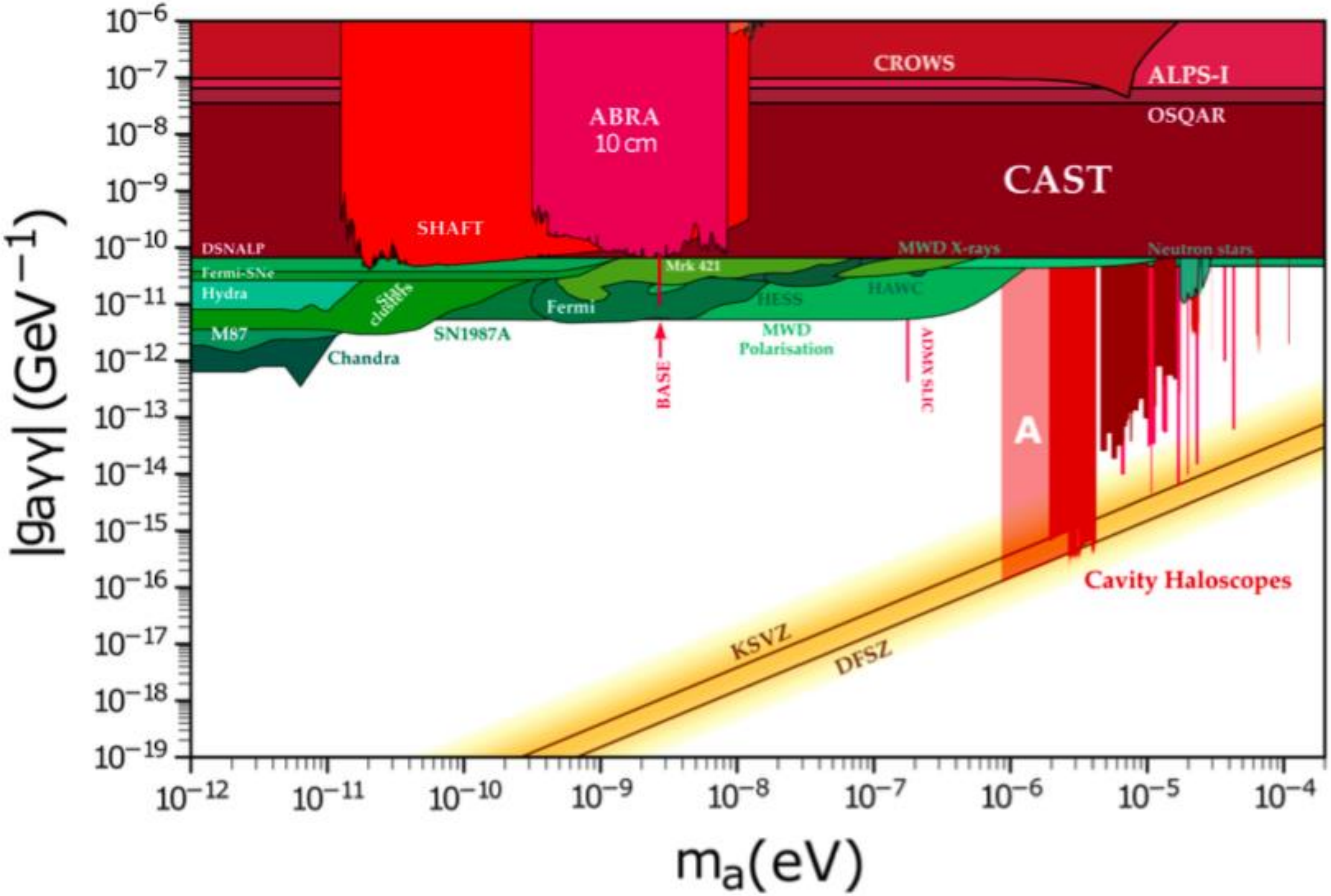


Prototype cavity



Prototype cavity





Area A can be ruled out using a reentrant cavity inside the EFR magnet (9 T, 65 cm diam) to be installed at Fermilab

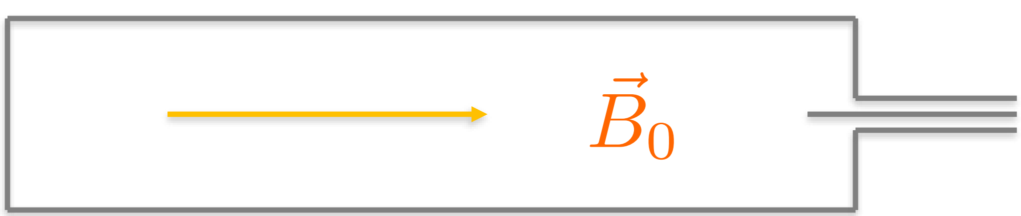
We may search for axions present on Earth as dark matter or axions produced in the Sun

- Axion helioscope

$$10^{14}\ \mathrm{axions/cm^2sec}$$

- Axion haloscope

$$10^{14}\ \mathrm{axions/cm^3}$$

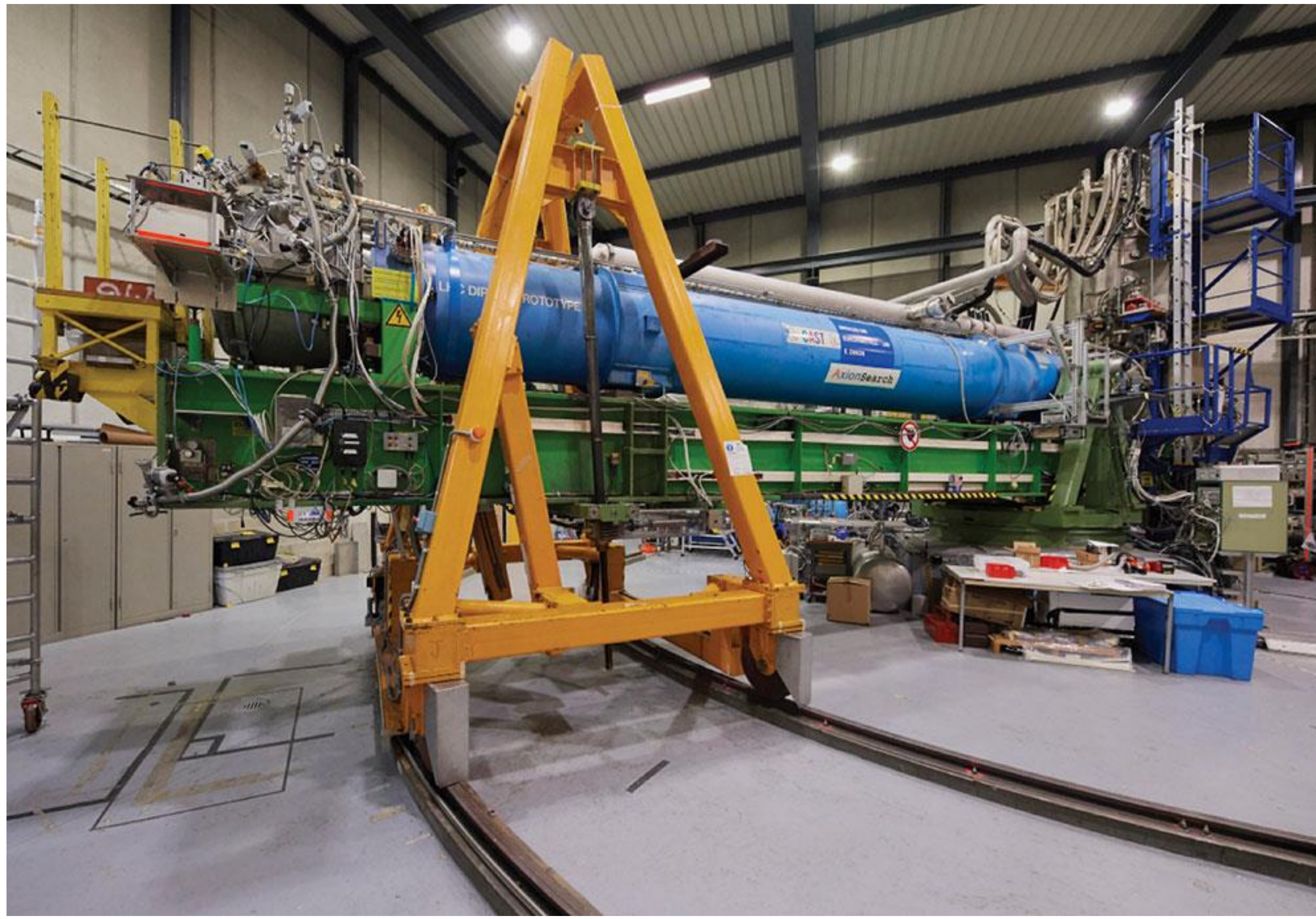


Tokyo Helioscope - Sumico

Makoto Minowa
et al.

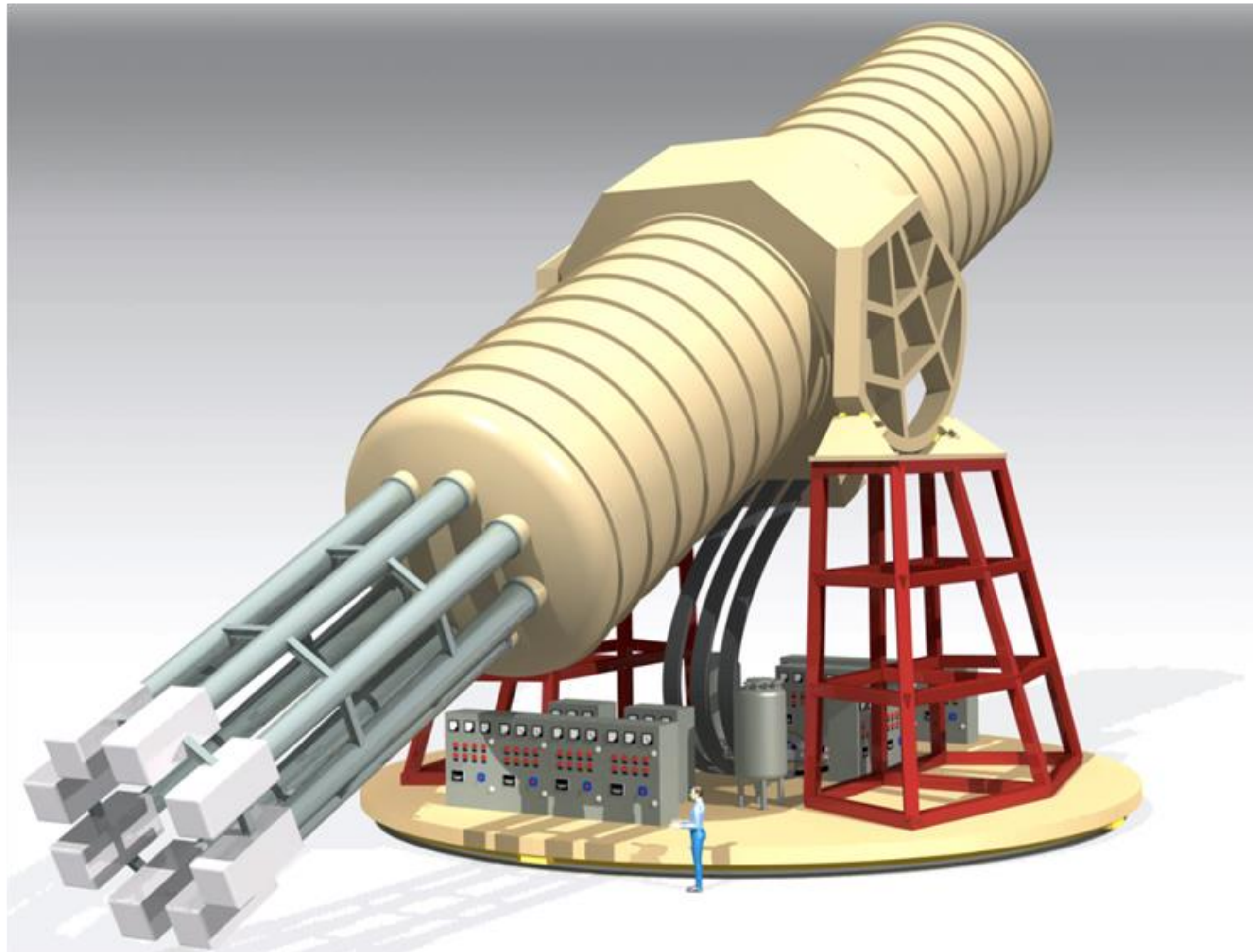
CERN Axion Solar Telescope

Konstantin Zioutas
et al.

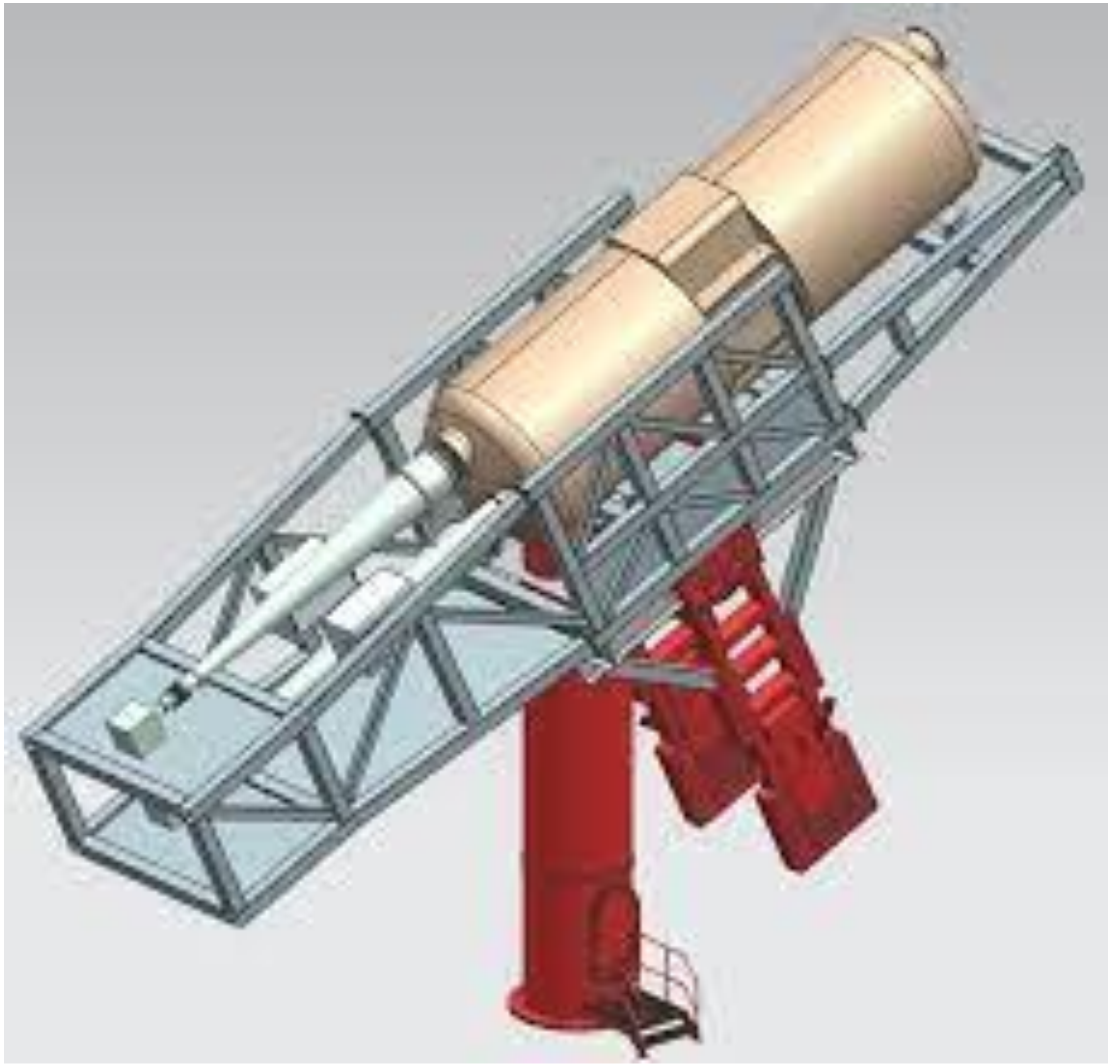


International AXion Observatory

Igor Irastorza
et al.



Baby IAXO at DESY



Axio-Electric and Primakoff Effects

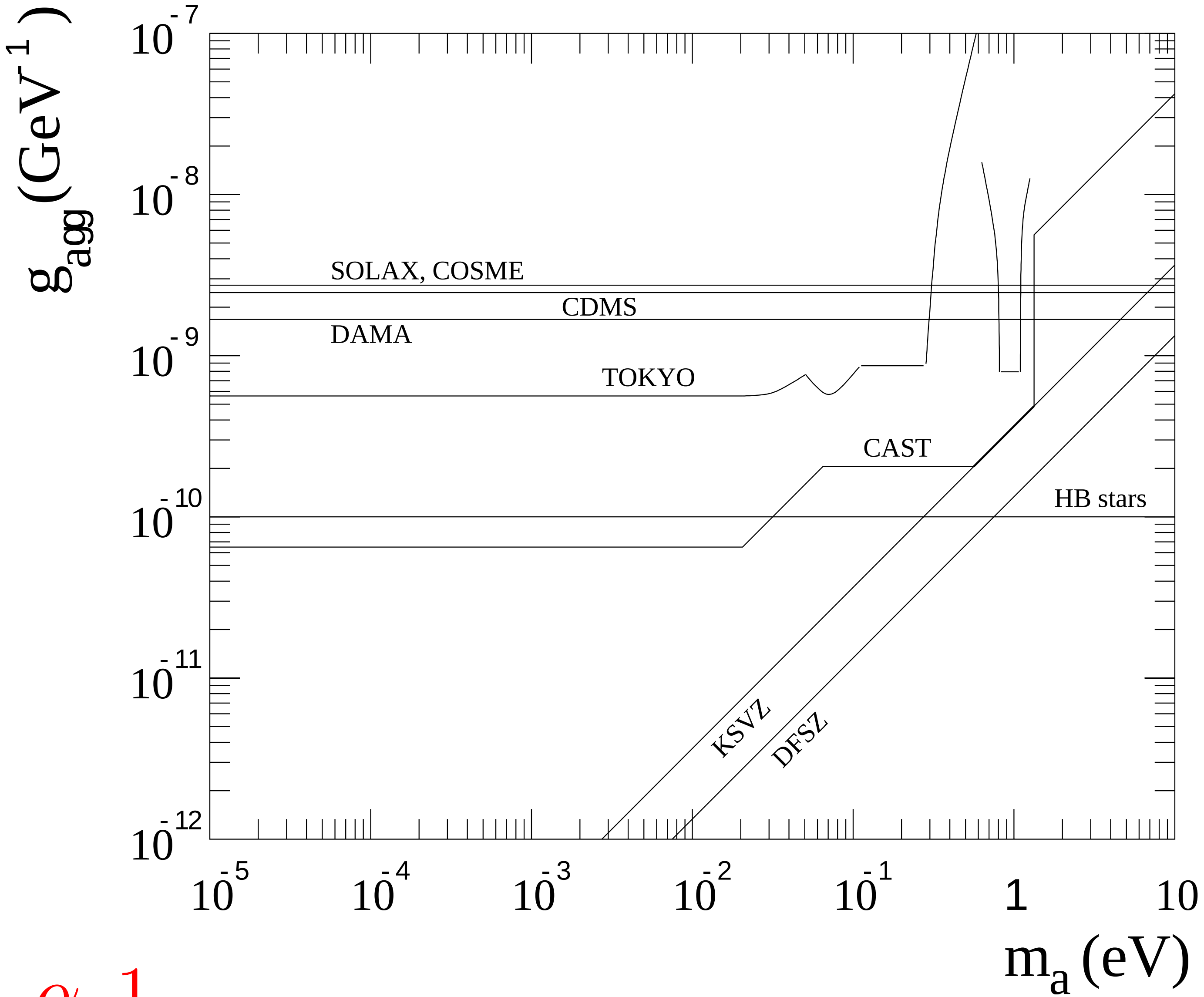
Frank Avignone

e.g. $$a + \mathrm{Ge} \to e + \mathrm{Ge}^{+}$$

Dimopoulos, Starkman & Lynn, 1986

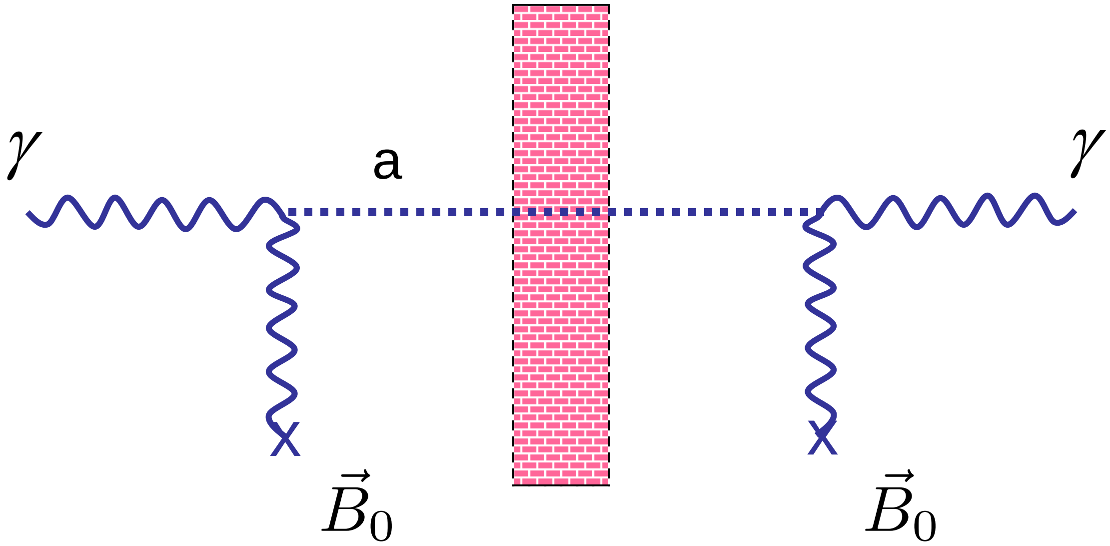
$$a + (Z, A) \to \gamma + (Z, A)$$

constraints from SOLAX, COSME, DAMA, CDMS, EDELWEISS, XMASS, CUORE, CDEX, Xenon, LUX, PandaX



$$g_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a}$$

Shining light through walls



$$\text{rate} \propto \frac{1}{f_a{}^4}$$

K. van Bibber et al. ‘87

A. Ringwald ‘03

R. Rabadan,
A. Ringwald and
C. Sigurdson ‘05

P. Pugnat et al. '05

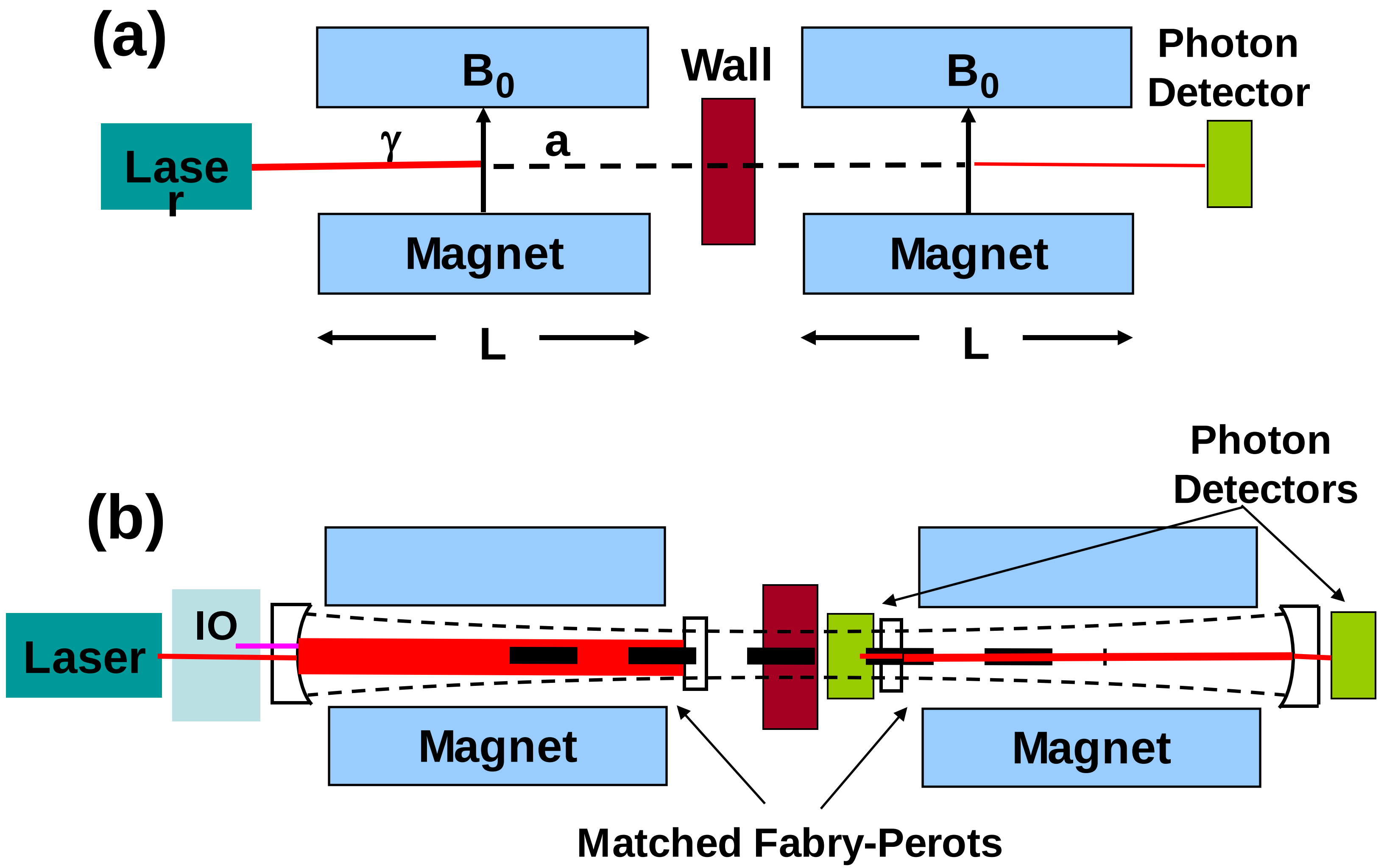
C. Robilliard et al. '07

A. Afanasev et al. '08

A. Chou et al. '08

K. Ehret et al. '10

Resonantly Enhanced Axion-Photon Regeneration



Hoogeveen (1996); P.S., Tanner and van Bibber (2007) & G. Mueller (2009)

ALPS II at DESY

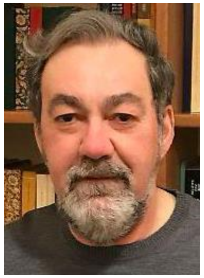
A. Ringwald, A. Lindner et al.

$B_0 = 5.3\ \mathrm{T} \qquad L = 2 \times 120\ m$ in HERA tunnel

Many approaches to axion detection

Dielectric haloscopes	MADMAX
Nuclear Magnetic Resonance	CASPEr
Axion to magnon conversion	QUAX
LC circuit	ABRACADABRA, SLIC, DMradio
Axion echo	
Shining light through walls (SLW)	... ALPs, OSQAR
Long range forces	ARIADNE
Stellar evolution constraints	white dwarf cooling
SLW in astrophysical magnetic fields	

Axel Lindner



Marco Roncadelli

Axions relate to

- particle physics
- nuclear physics
- astrophysics
- cosmology
- solid state physics (topological insulators)
- atomic physics
- statistical mechanics (Bose-Einstein condensation)
- ...

Conclusions

- Axions solve the strong CP problem
- A population of cold axions is naturally produced in the early universe which may be the dark matter today
- Axion dark matter is detectable

Happy Birthday, Frank!