“Invisible” Axion Search Methods

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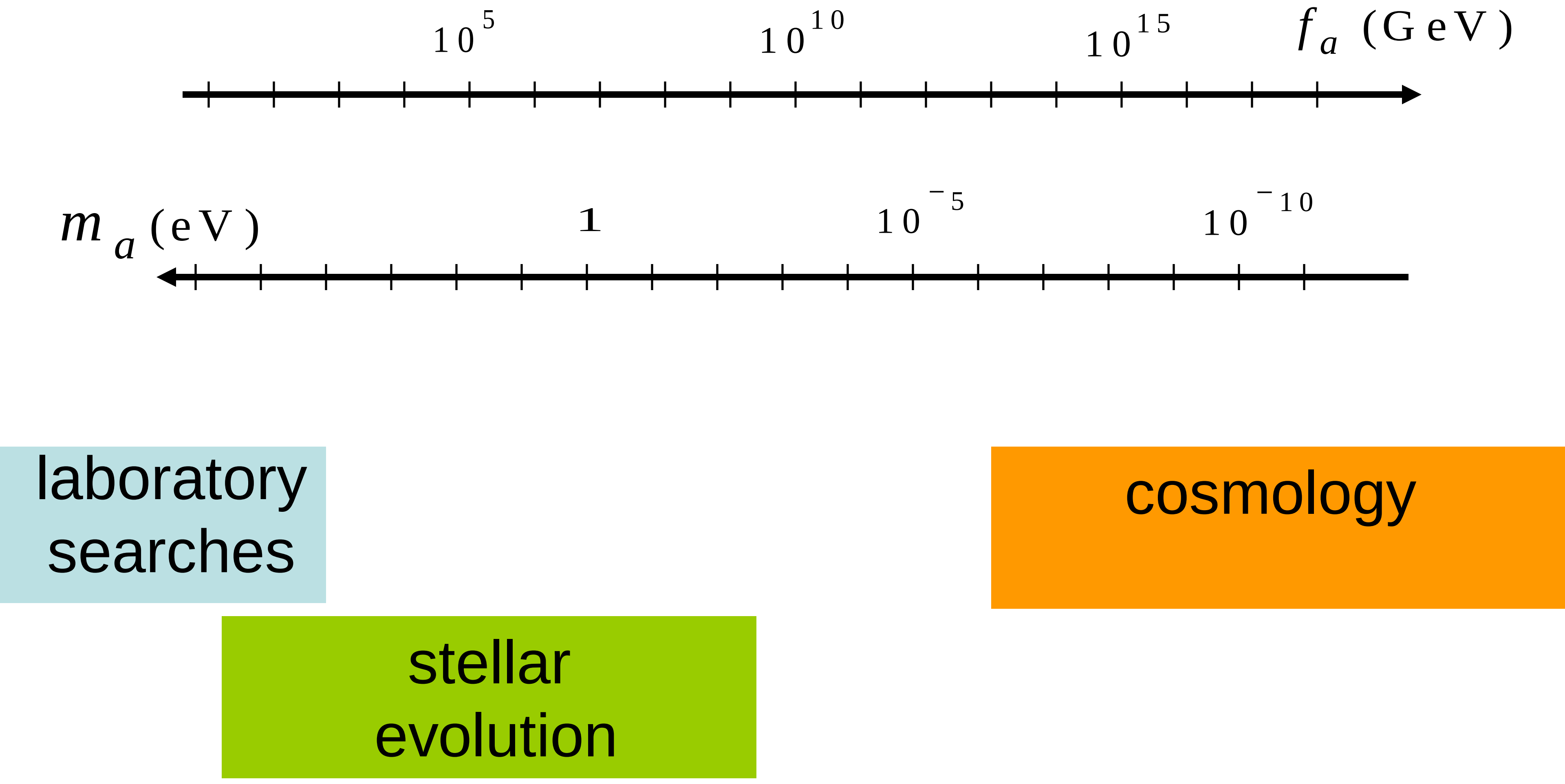
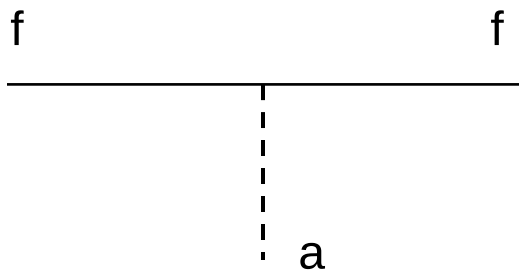
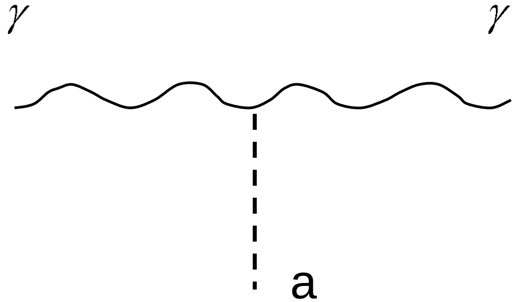
Axion constraints



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



$$\mathcal{L}_{a\bar{f}f} = i g_f \frac{a(x)}{f_a} \bar{f}(x)\gamma^5 f(x)$$



$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a} a(x) \vec{E}(x) \cdot \vec{B}(x)$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model

Outline

axion electrodynamics

the cavity haloscope

solar axion searches

shining light through walls

dielectric haloscopes

NMR methods

axion mediated long-range forces

LC circuit

axion echo

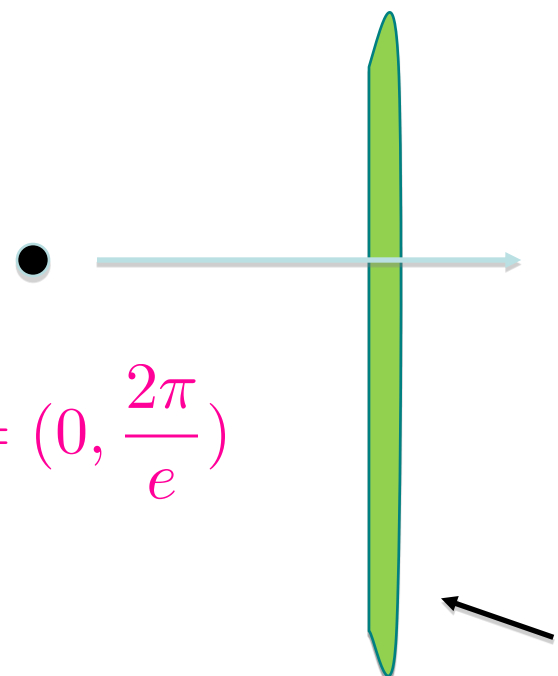
The Witten Effect (1979)

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



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

$$\frac{e^2}{4\pi}\frac{1}{\pi}\frac{2\pi}{e}\;2\pi = e$$

The Witten Effect (1979)

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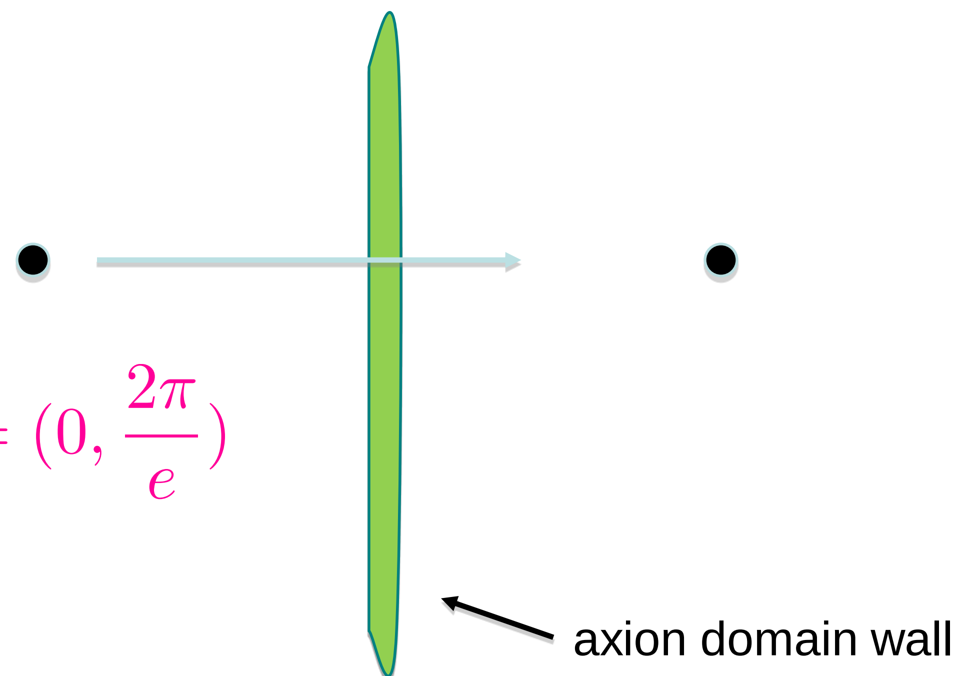
$$q_e = \frac{\alpha}{\pi}\,\theta\, q_m$$

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

with axion



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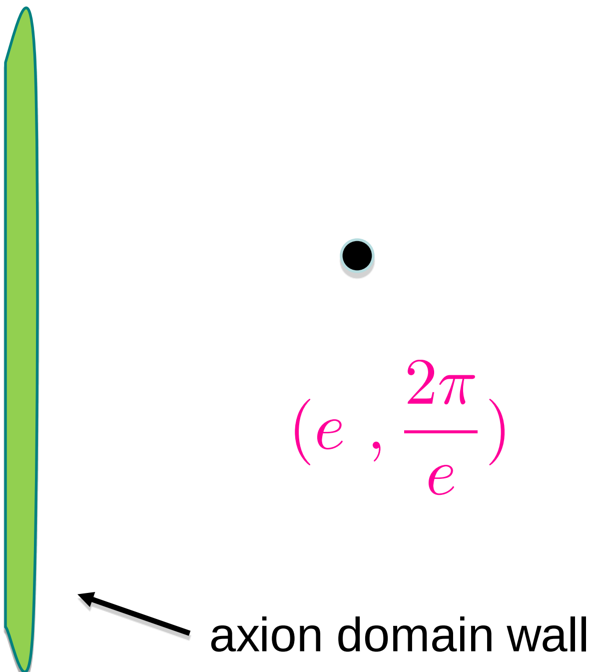
$$q_e = \frac{\alpha}{\pi}\,\theta\,q_m$$

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



Axion Electrodynamics

$$\mathcal{L} = \frac{1}{2}(\vec{E}(x)\cdot\vec{E}(x) - \vec{B}(x)\cdot\vec{B}(x))$$

$$+\frac{1}{2}(\partial_t a(x)\partial_t a(x) - \vec{\nabla} a(x)\cdot\vec{\nabla} a(x))$$

$$-\frac{1}{2}m_a^2 a(x)^2$$

$$-g_\gamma \frac{\alpha}{\pi}\frac{1}{f_a} a(x)\vec{E}(x)\cdot\vec{B}(x)$$

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

Axion Electrodynamics

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

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

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

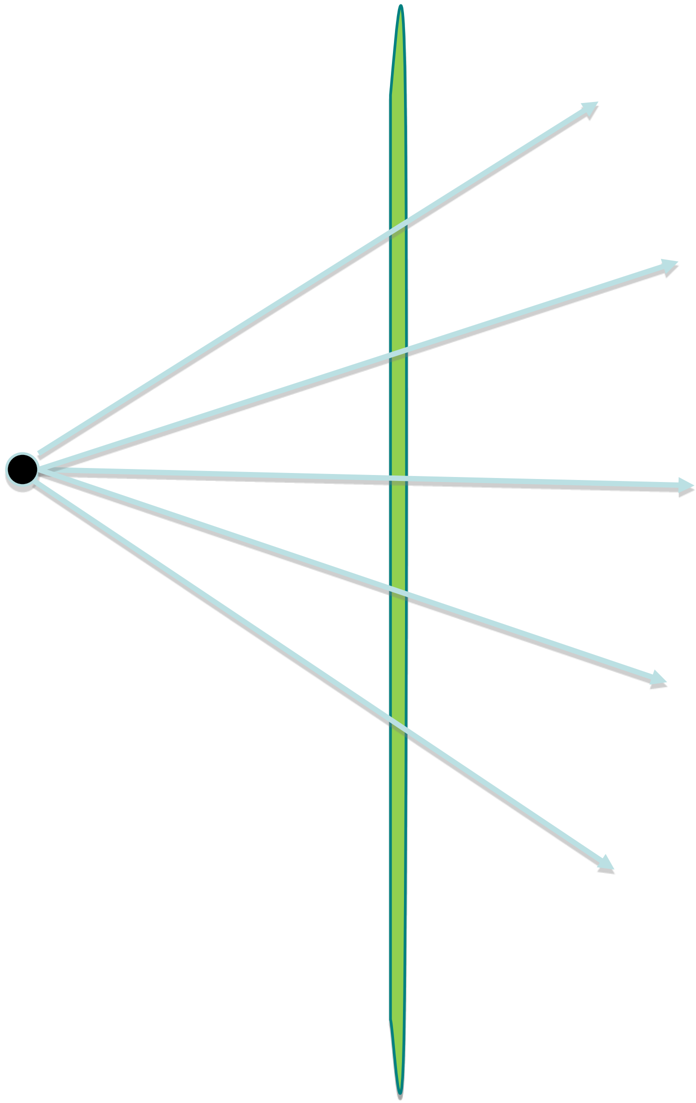
$$\vec{\nabla} \times \vec{E} + \partial_t \vec{B} = 0$$

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

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

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

Witten Effect



electric charge
surface density

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

Axion Electrodynamics

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

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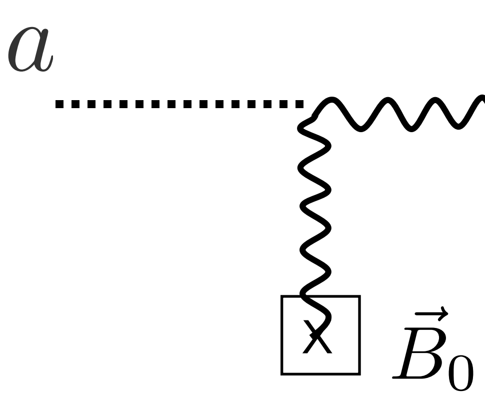
$$\partial_t^2 a - \nabla^2 a + m_a^2 a = -g\vec{E} \cdot \vec{B}$$

$$\vec{\nabla} \times \vec{B} - \partial_t \vec{E} = -g\vec{B}\partial_t a + g\vec{E} \times \vec{\nabla} a$$

In background electric and magnetic fields

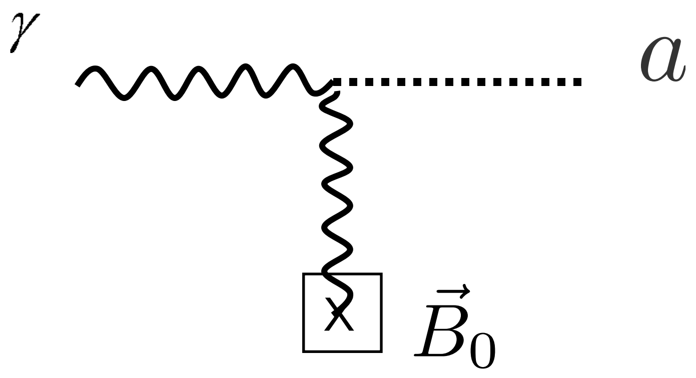
the axion field is a source of electromagnetic radiation

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



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

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



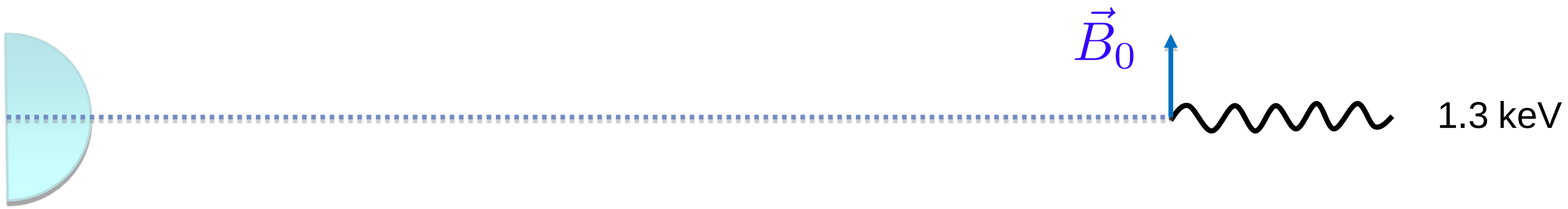
BUT

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

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

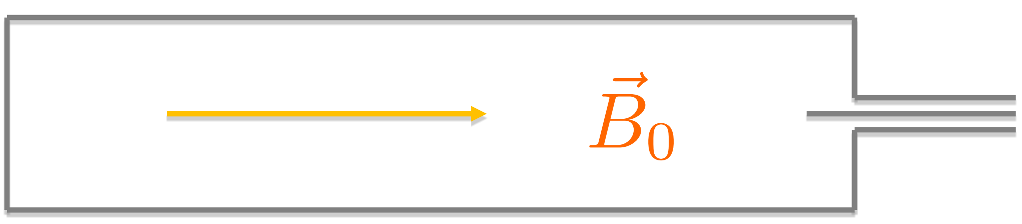
- Axion helioscope

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



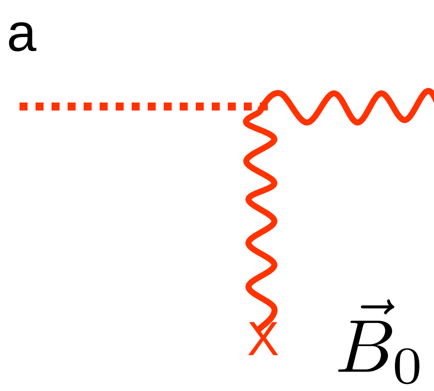
- Axion haloscope

10^{14} axions/cm^3

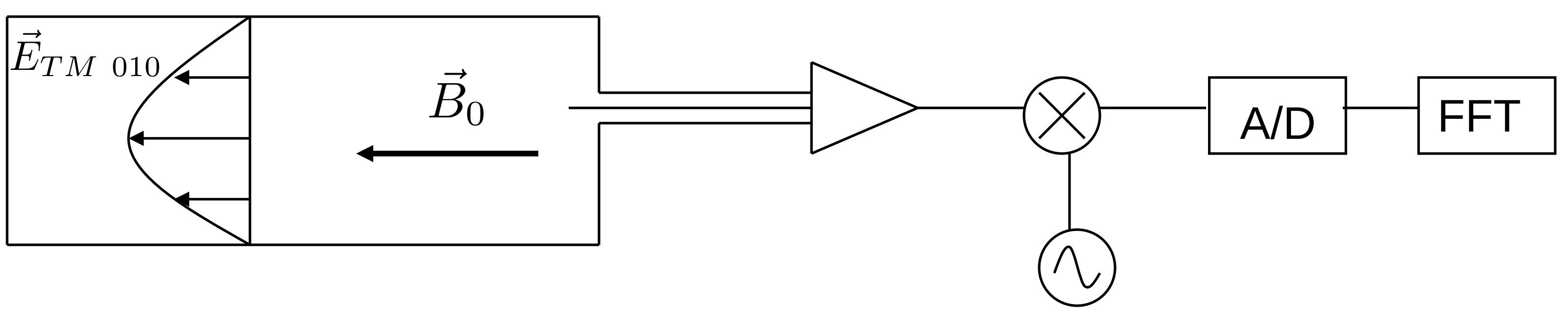


Axion dark matter is detectable

PS, 83



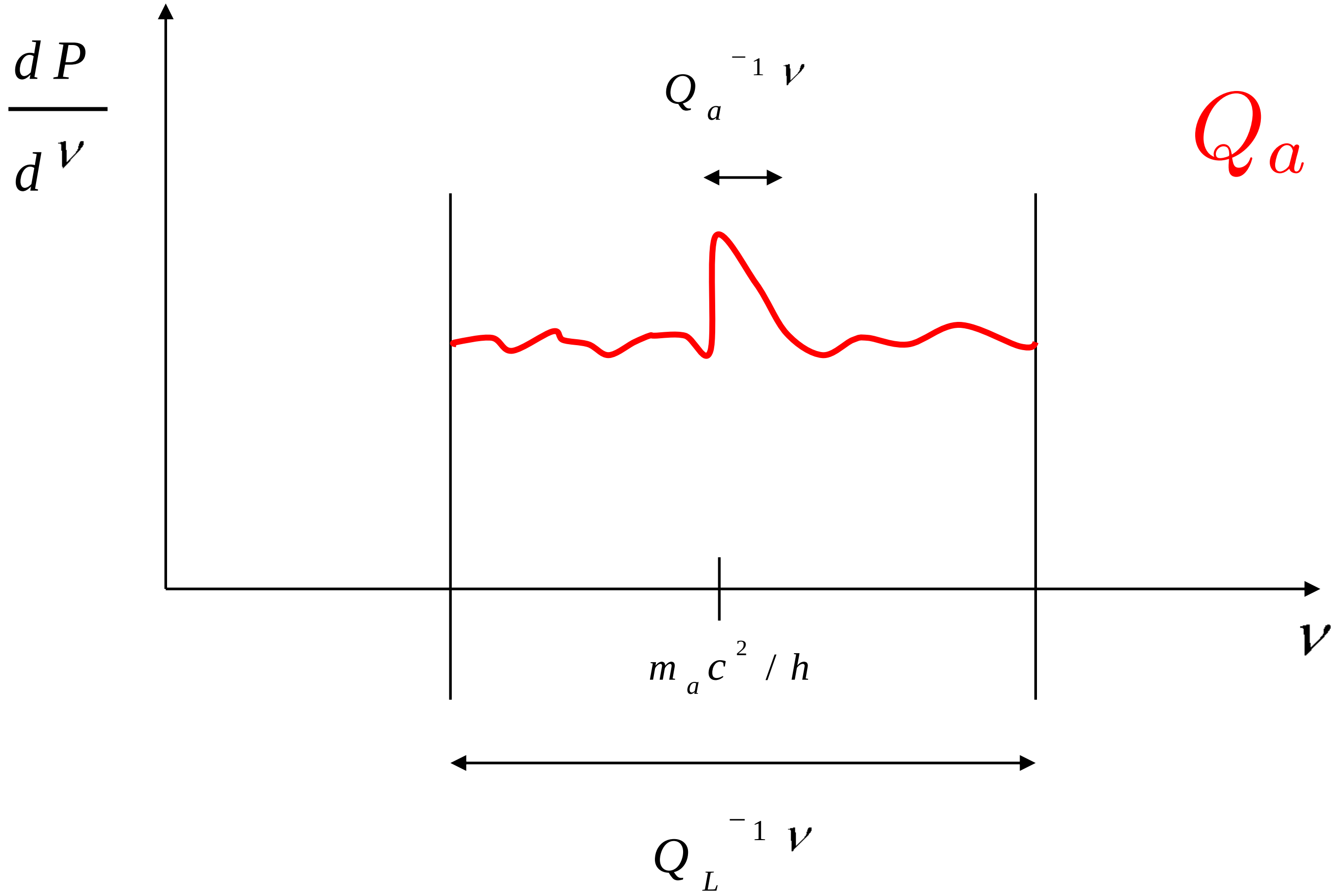
$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a} a(x) \vec{E}(x) \cdot \vec{B}(x)$$



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

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

$$Q_a \simeq 10^6$$



$$a \rightarrow \gamma$$

conversion power on resonance

$$P = \left(\frac{\alpha\, g_\gamma}{\pi\, f_a}\right)^2 V\, B_0^2\, \rho_a\, C\, m_a^{-1}\, Q_L$$

$$= 2 \cdot 10^{-22}\ \mathrm{Watt} \left(\frac{V}{500\ \mathrm{liter}}\right)\left(\frac{B_0}{7\ \mathrm{Tesla}}\right)^2 \left(\frac{C}{0.4}\right)$$

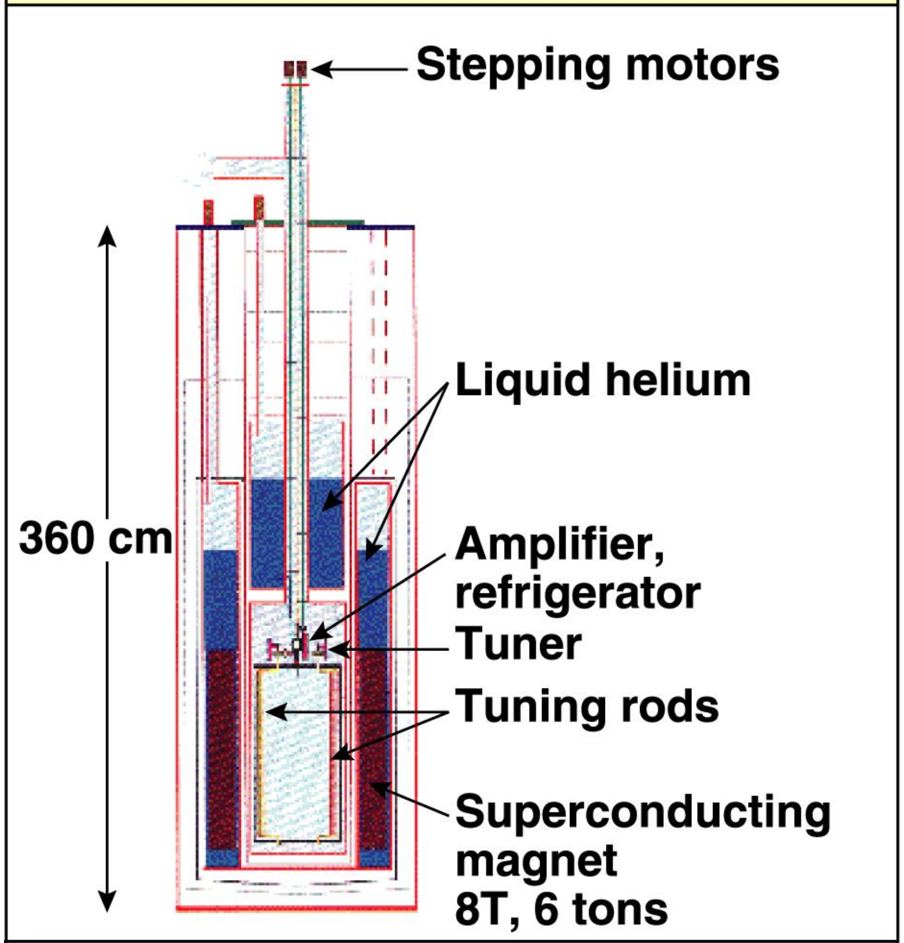
$$\left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho_a}{5 \cdot 10^{-25}\ \mathrm{gr/cm}^3}\right)\left(\frac{m_a c^2}{h\ \mathrm{GHz}}\right)\left(\frac{Q_L}{10^5}\right)$$

search rate for s/n = 4

$$\frac{df}{dt} = \frac{1.2\ \mathrm{GHz}}{\mathrm{year}} \left(\frac{P}{2 \cdot 10^{-22}\ \mathrm{Watt}}\right)^2 \left(\frac{3\ K}{T_n}\right)^2$$

Axion Dark Matter eXperiment

Magnet with Insert (side view)



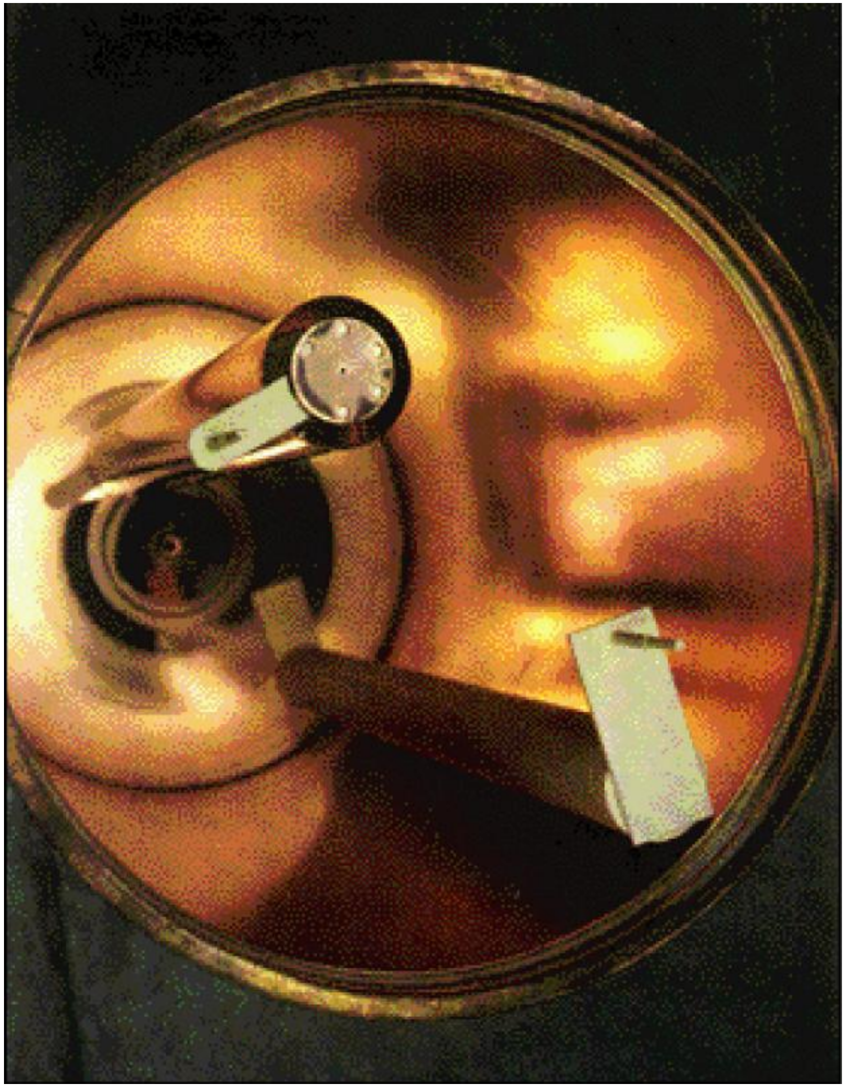
Pumped LHe → T ~ 1.5 k

Magnet

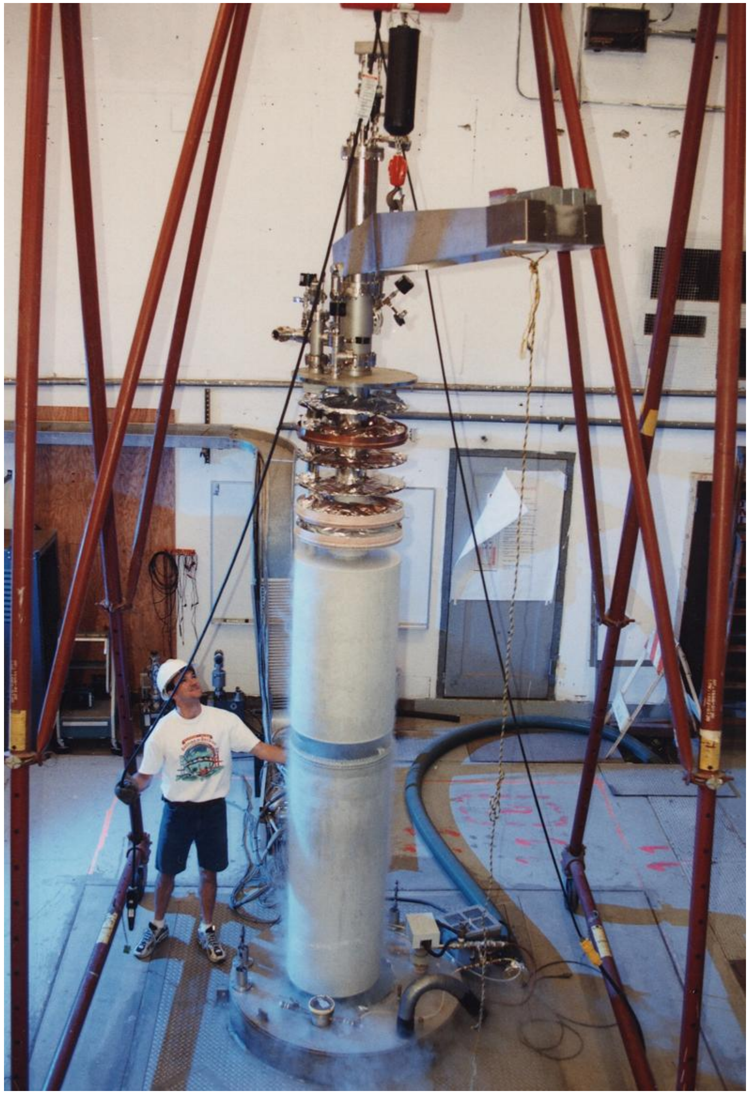
8 T, 1 m × 60 cm ∅

ADMX hardware

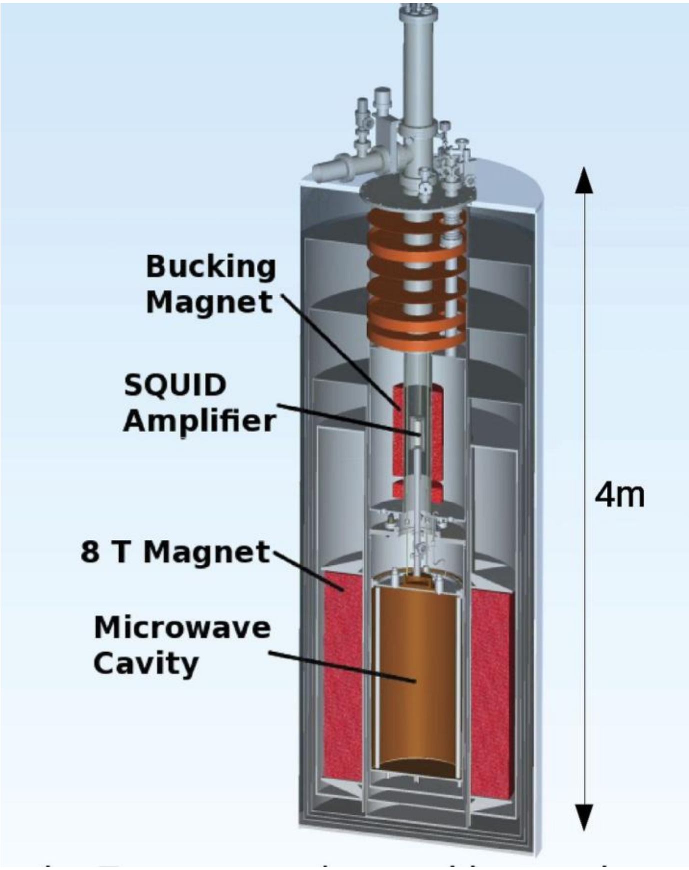
high Q cavity



experimental insert



ADMX 2nd generation



SQUIDs from
J. Clarke's group

Leslie Rosenberg and
Gray Rybka at U. Wash.

ADMX meeting at Fermilab

HAYSTAC at Yale

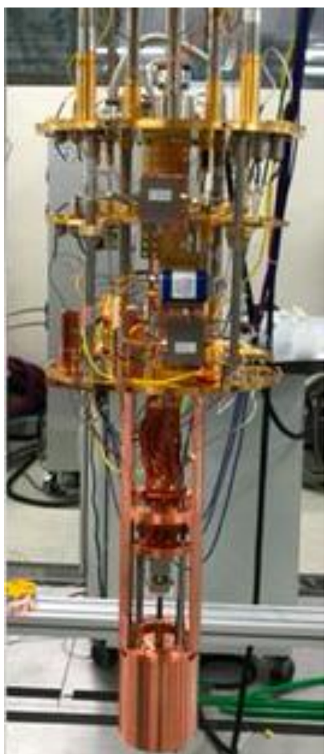
Institute for Basic Science

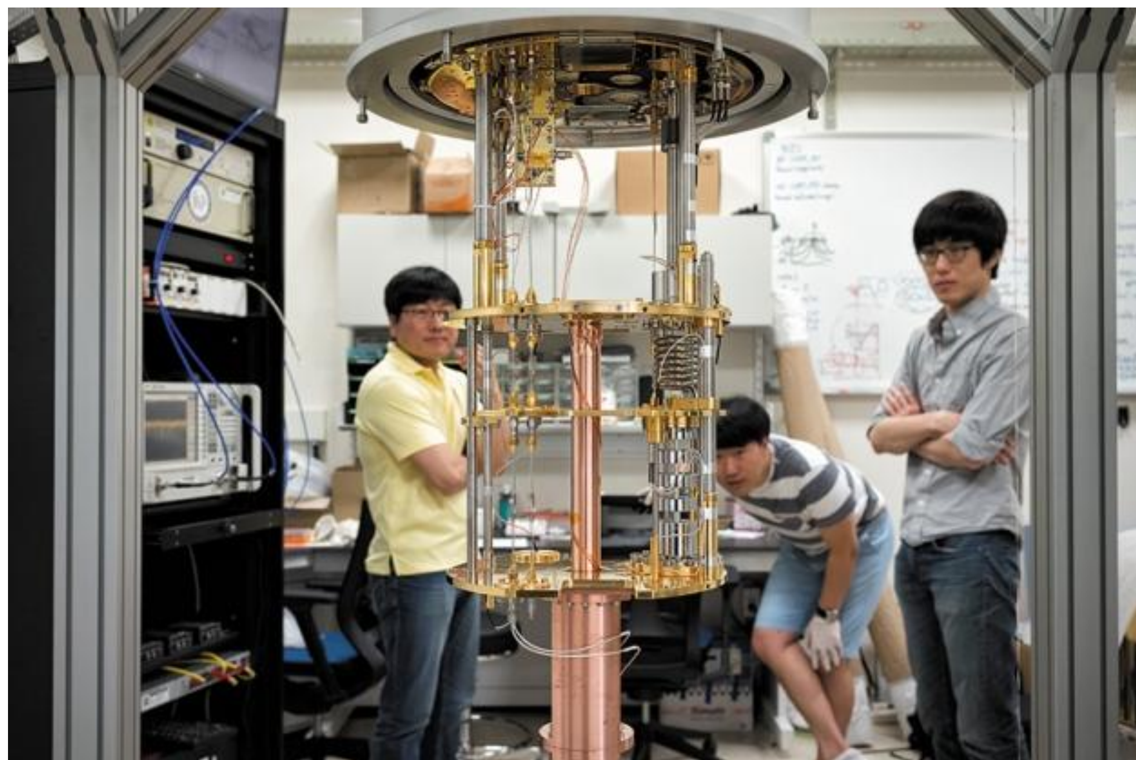
ibs

기초과학연구원

CAPP

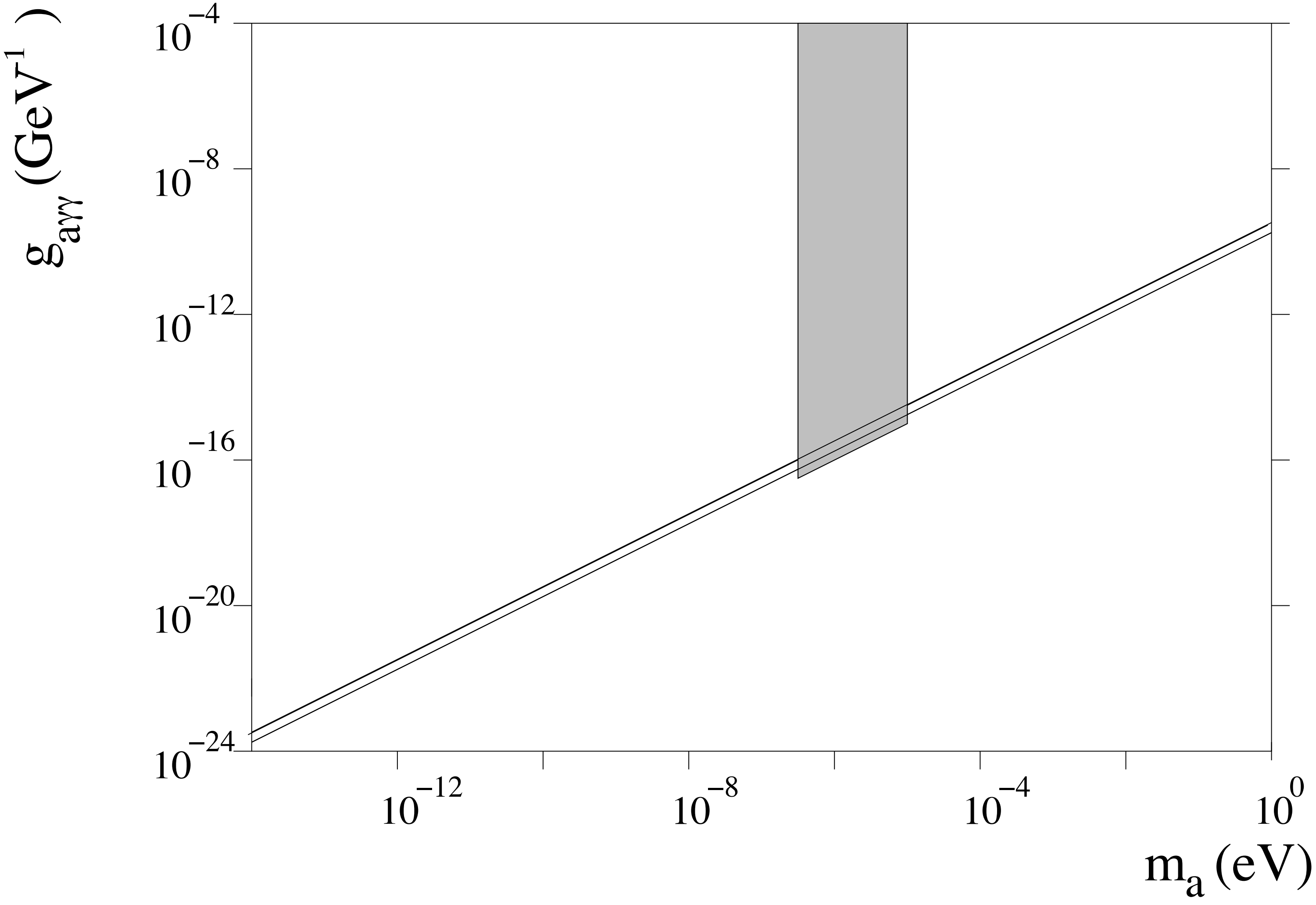
Center for Axion and Precision Physics Research





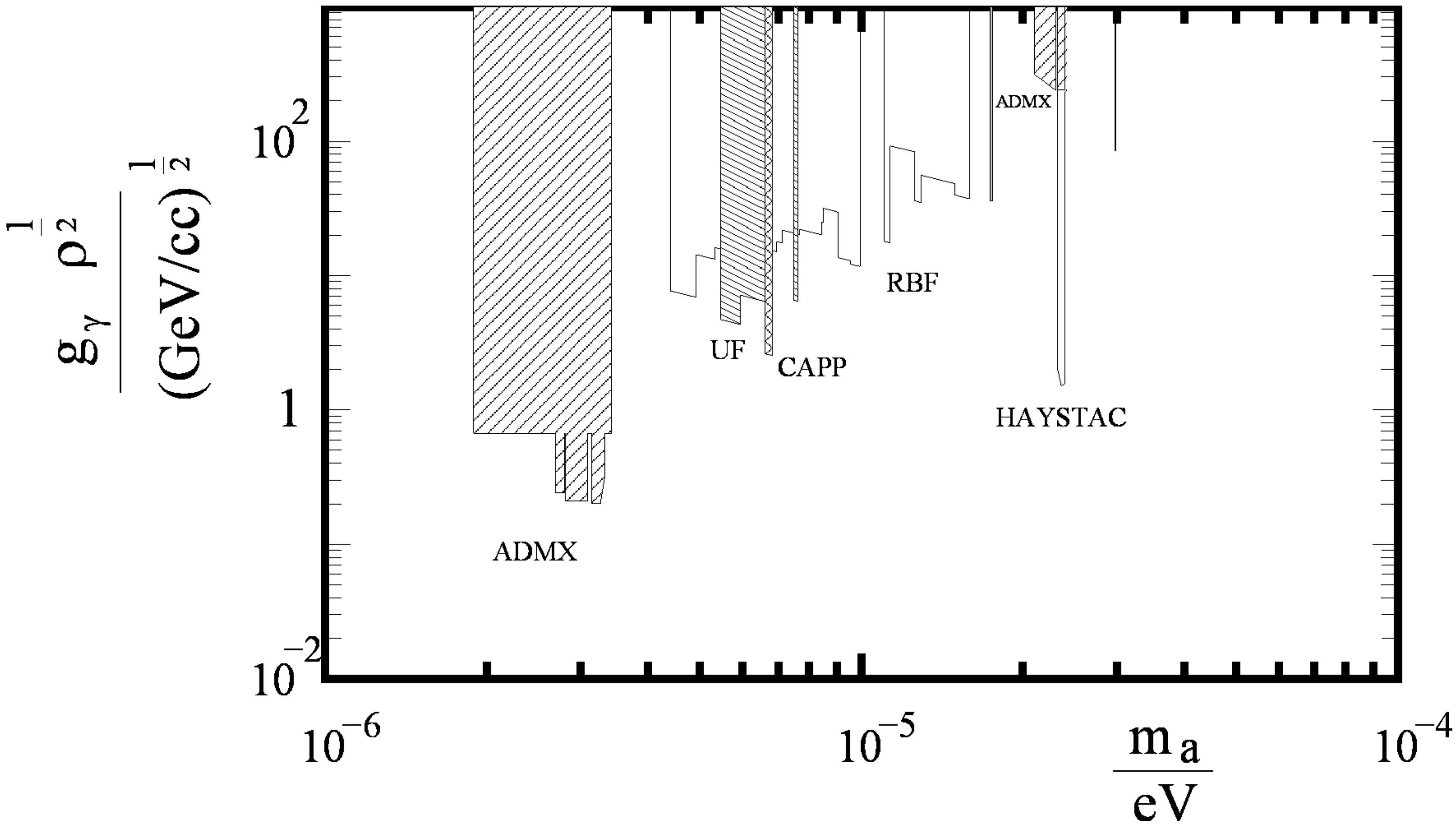
Cavity haloscopes

- 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



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

Constraints on dark matter axions from cavity haloscopes, in 2020



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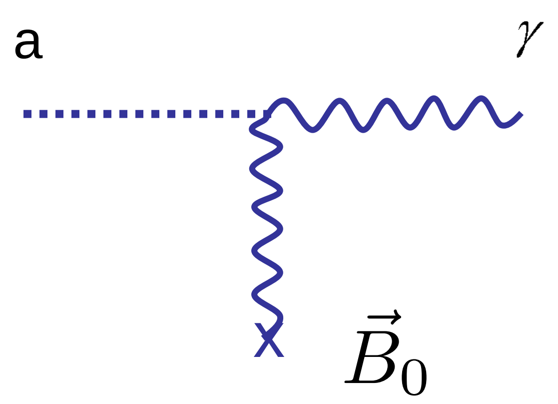
Axion to photon conversion in a magnetic field



Theory

- P. S. '83
- L. Maiani, R. Petronzio and E. Zavattini '86
- K. van Bibber et al. '87
- G. Raffelt and L. Stodolsky, '88
- K. van Bibber et al. '89

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conversion probability

$$p(a \longleftrightarrow \gamma) = \left(\frac{\alpha \quad g_\gamma}{\pi \quad f_a} \right)^2 B_0^2 \left(\frac{\sin \frac{q_z L}{2}}{q_z} \right)^2$$

with

$$q_z = \frac{m_a^2 - \omega_{pl}^2}{2 E_a}$$

Experiment

- D. Lazarus et al. '92
- R. Cameron et al. '93
- S. Moriyama et al. '98, Y. Inoue et al. '02
- K. Zioutas et al. 04
- E. Zavattini et al. 05

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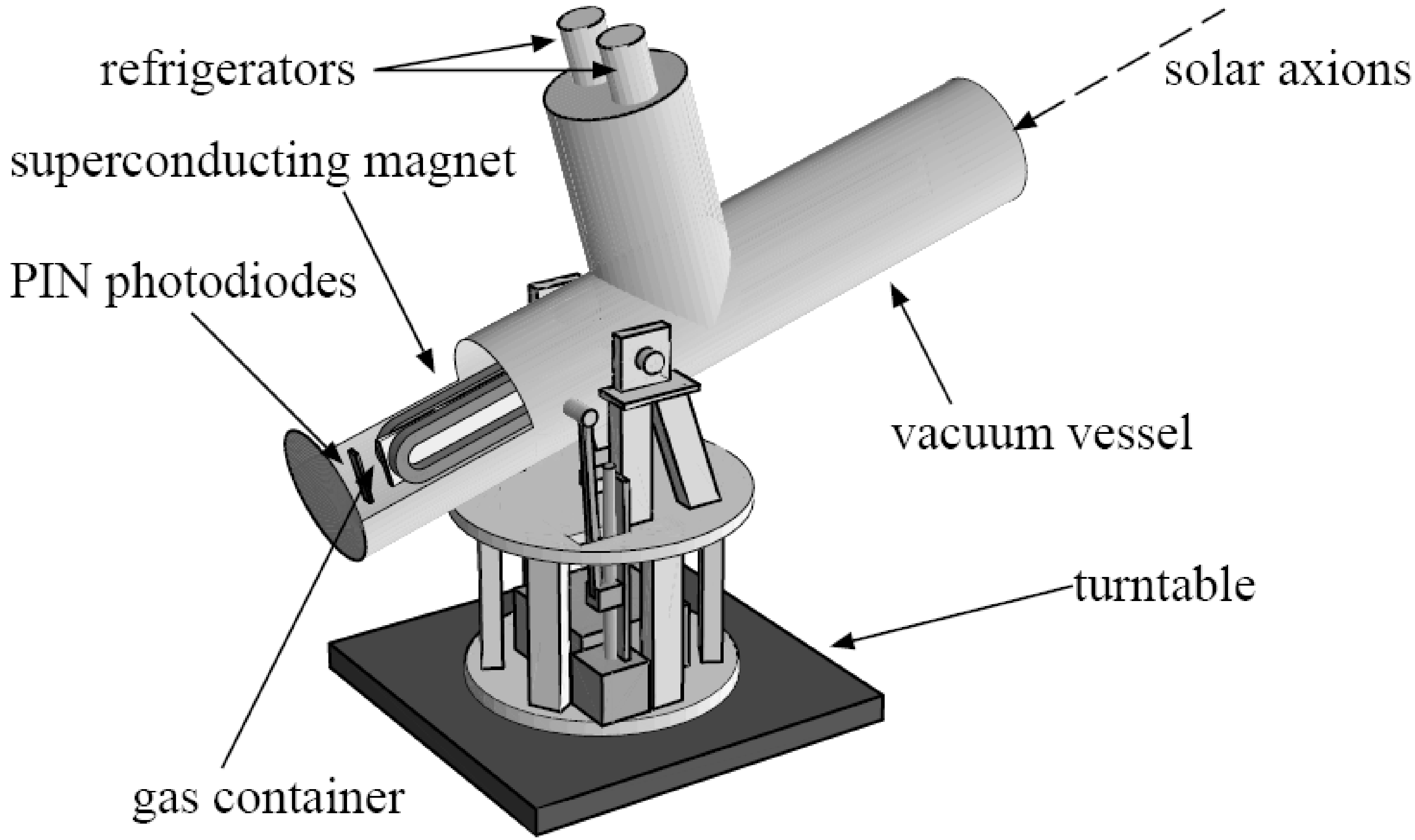
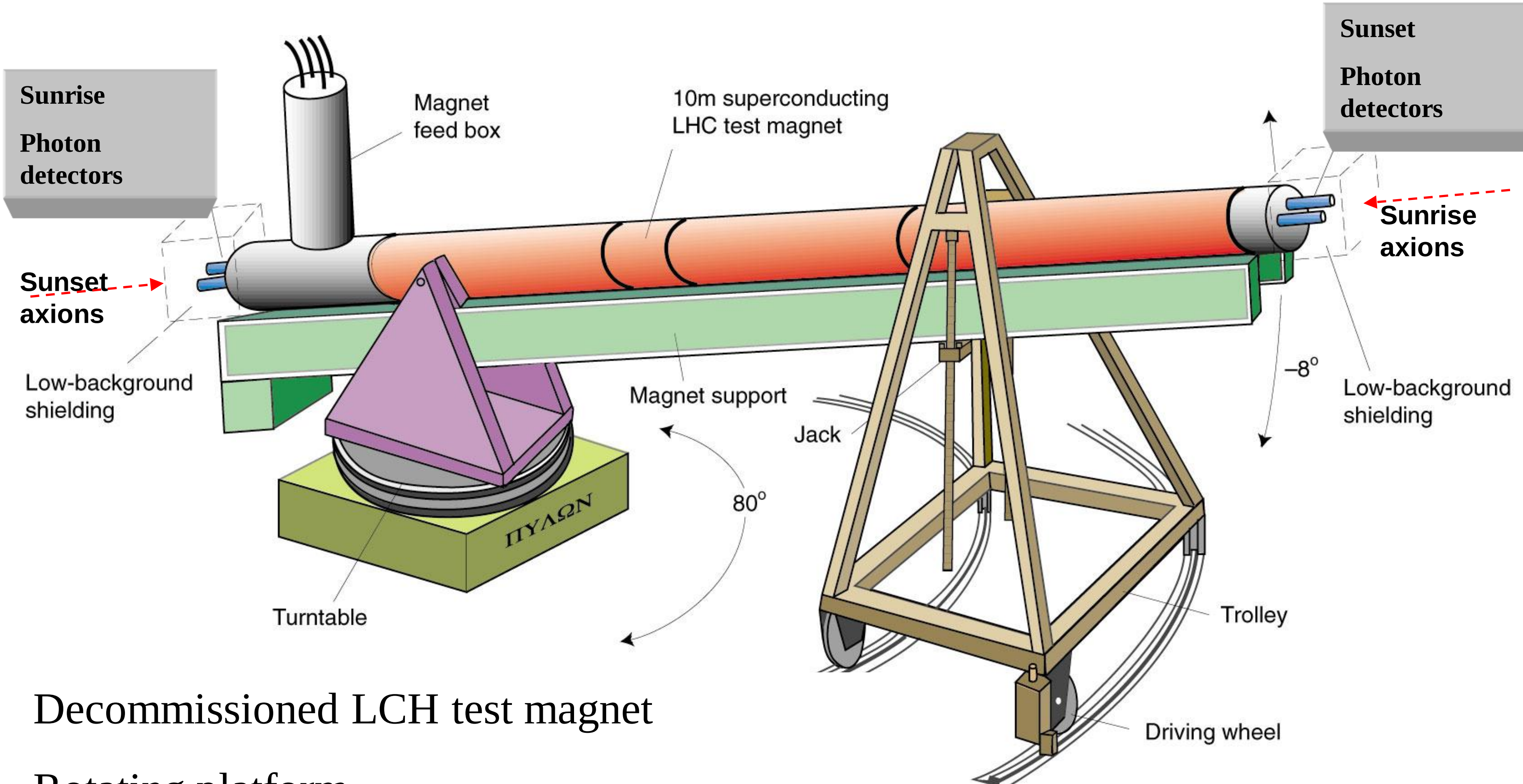
Tokyo Axion Helioscope



Cern Axion Solar Telescope



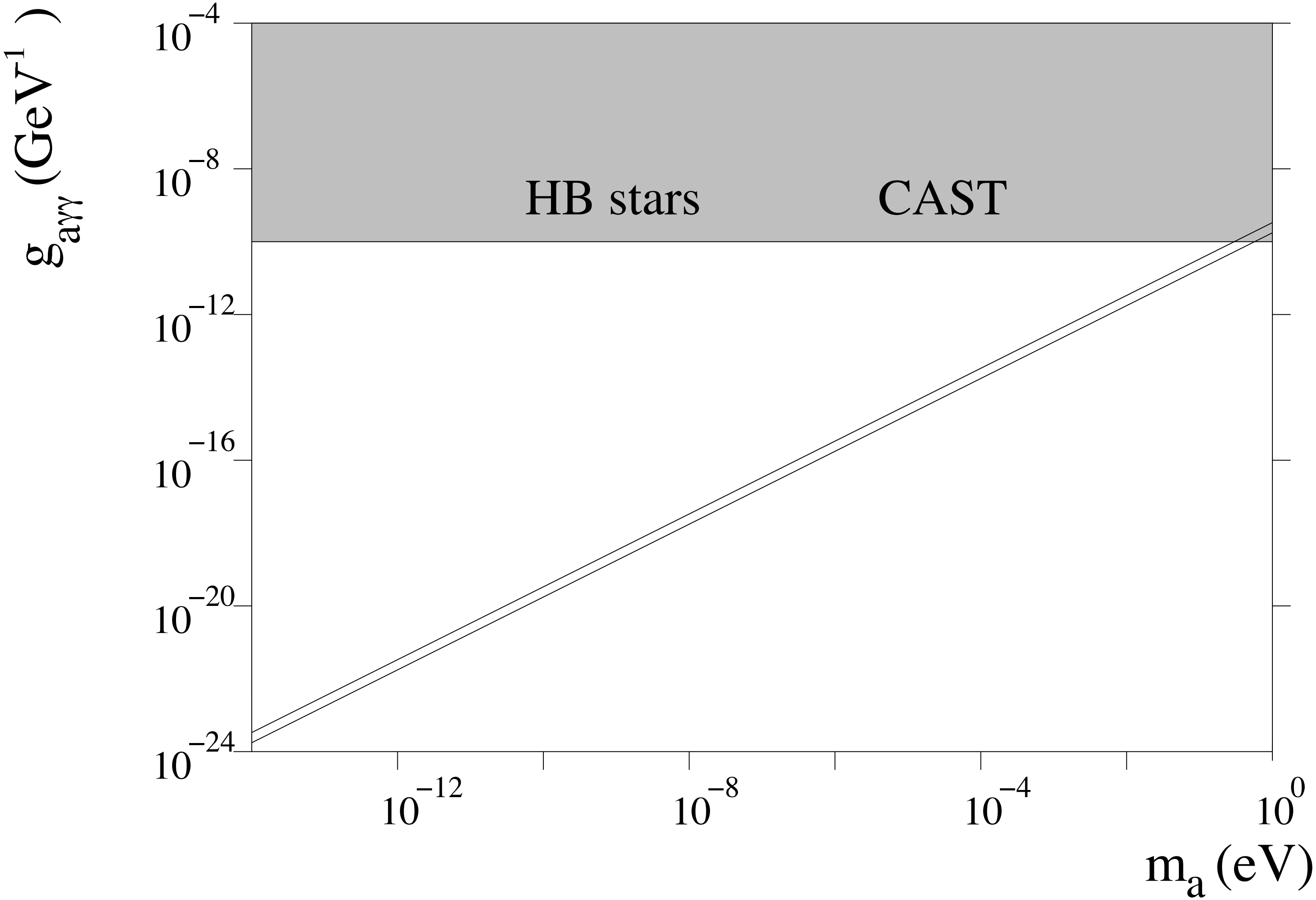
Decommissioned LCH test magnet

Rotating platform

3 X-ray detectors

X-ray Focusing Device

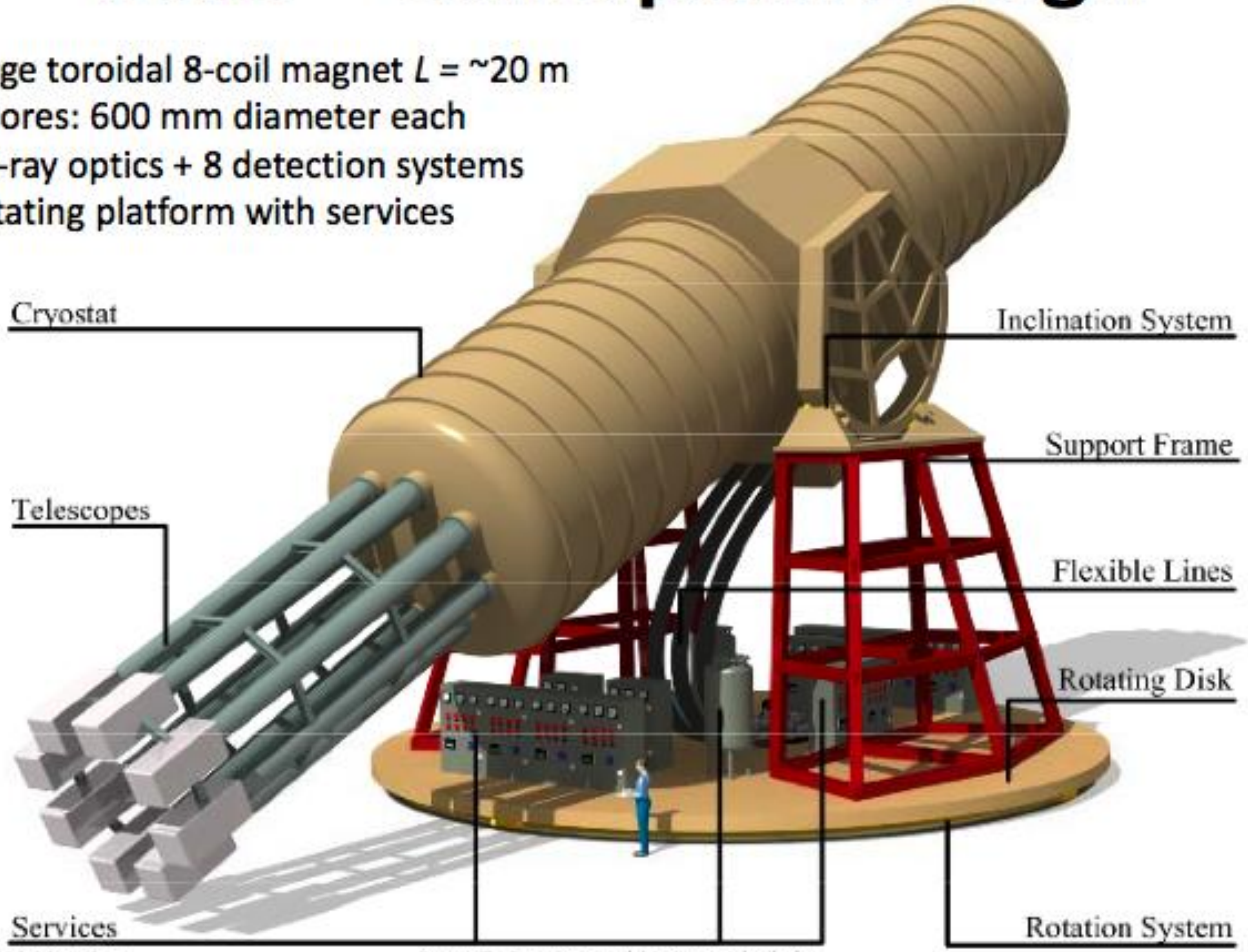

CAST
ANSALDO GIE
EUROPAMETALLI – LMI
E. ZANON

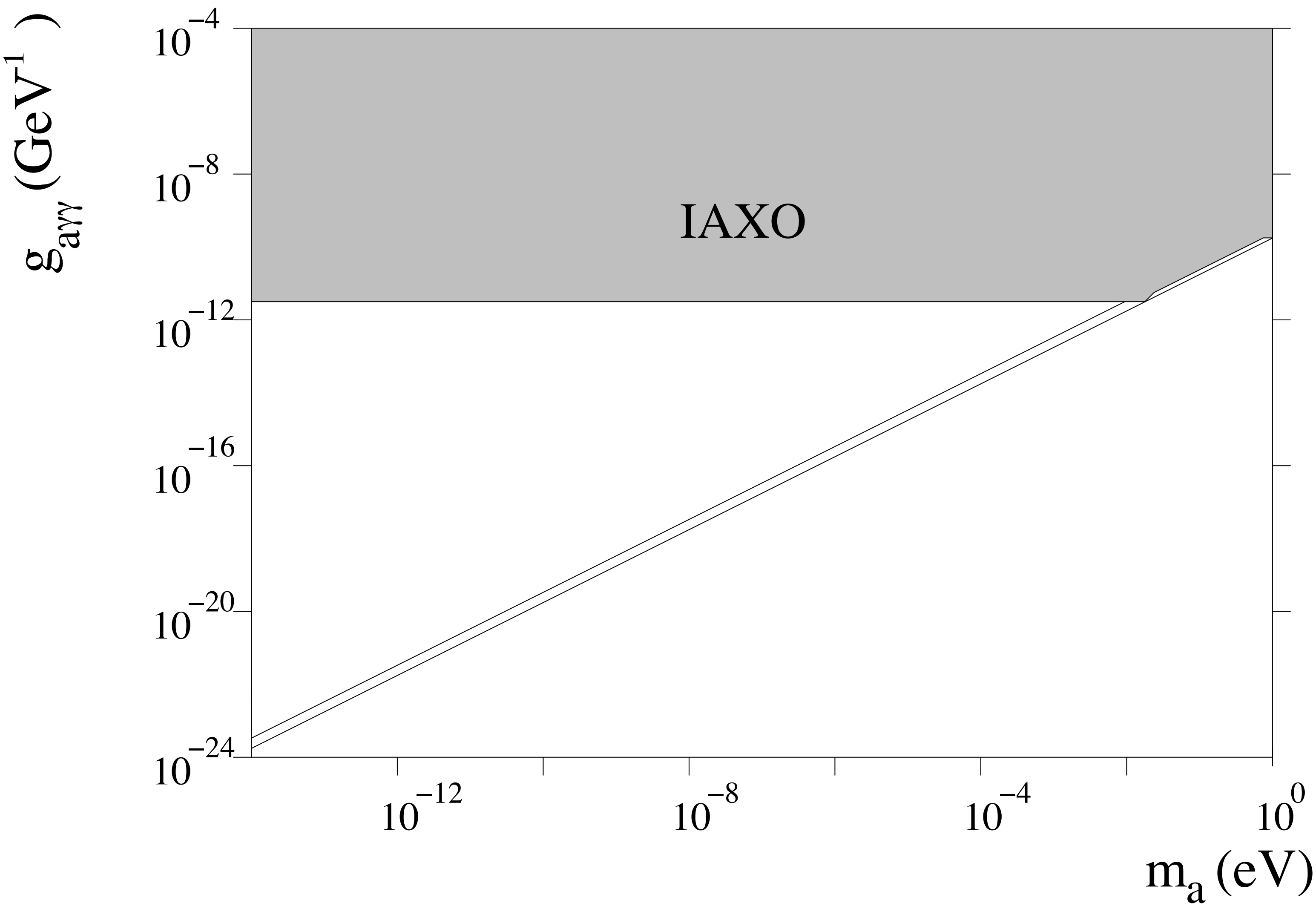


$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
HB stars
CAST
10^{-12}
10^{-8}
10^{-4}
10^{0}
m_a (eV)

IAXO – Conceptual Design

- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services





$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
IAXO
10^{-12}
10^{-8}
10^{-4}
10^{0}
m_a (eV)

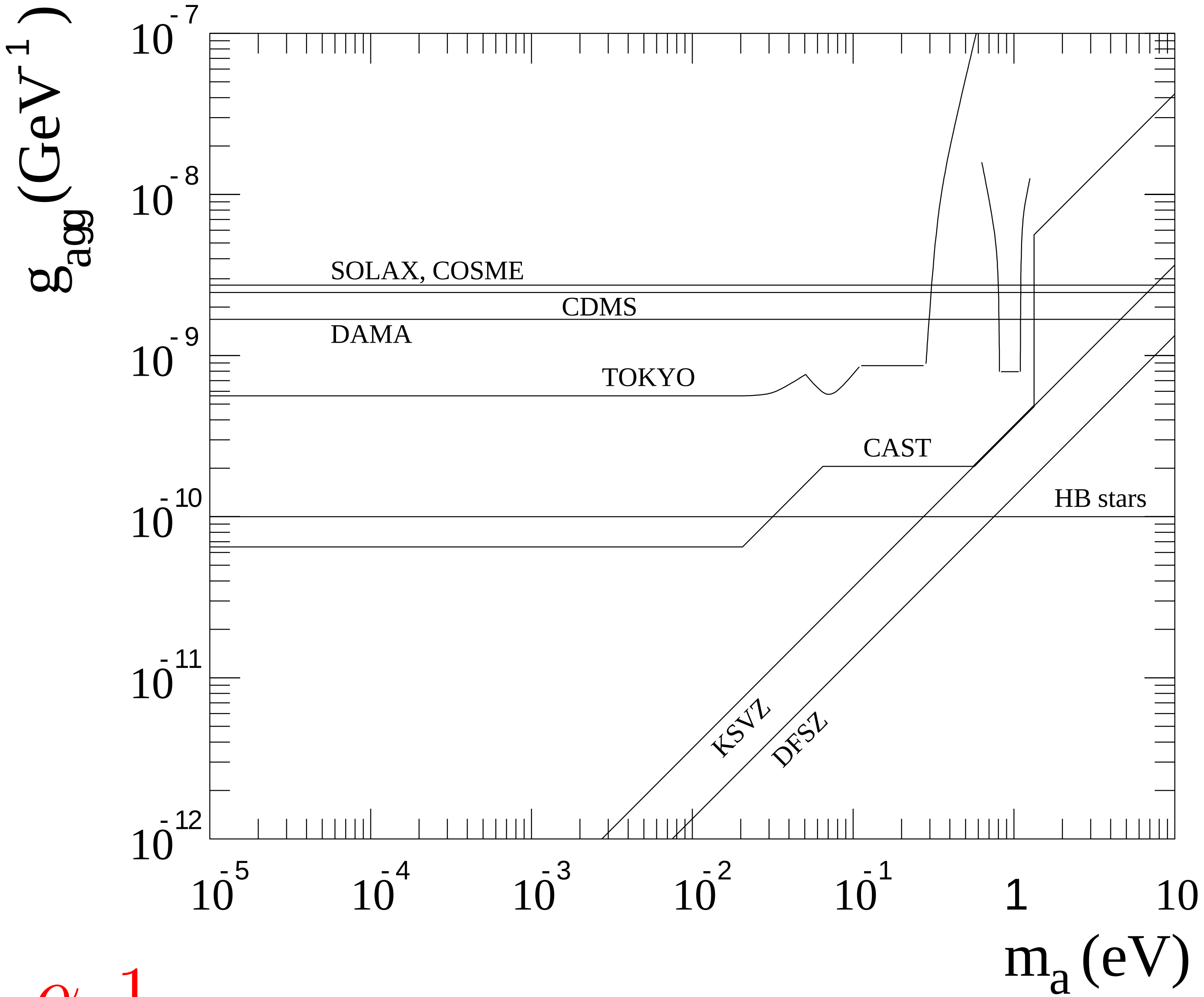
Axio-Electric and Primakoff Effects

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

Dimopoulos, Starkman & Lynn, 1986

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

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



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

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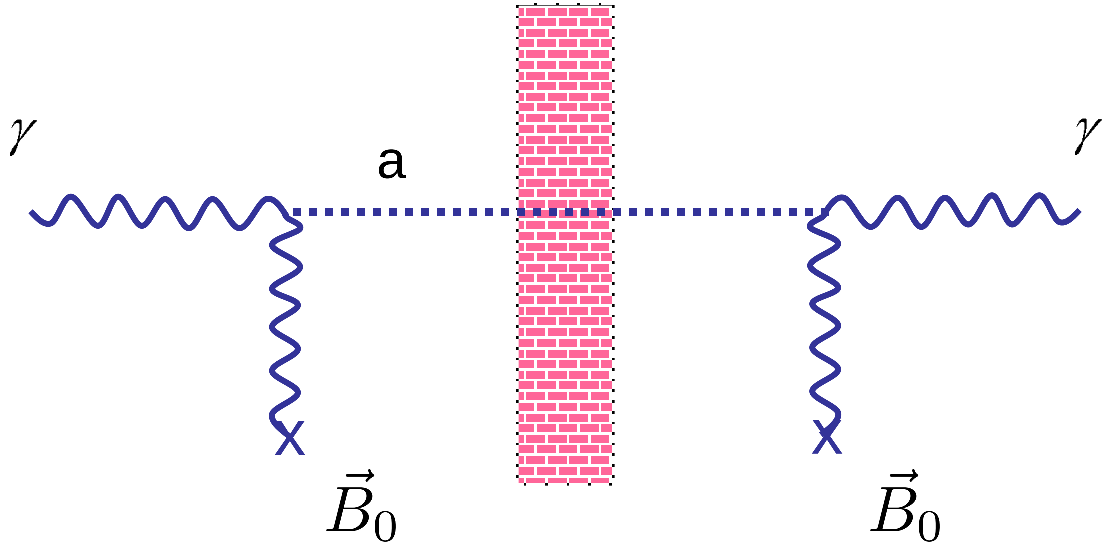


rate $\propto \frac{1}{f_a^{\;4}}$

K. van Bibber et al. ‘87

A. Ringwald ‘03

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

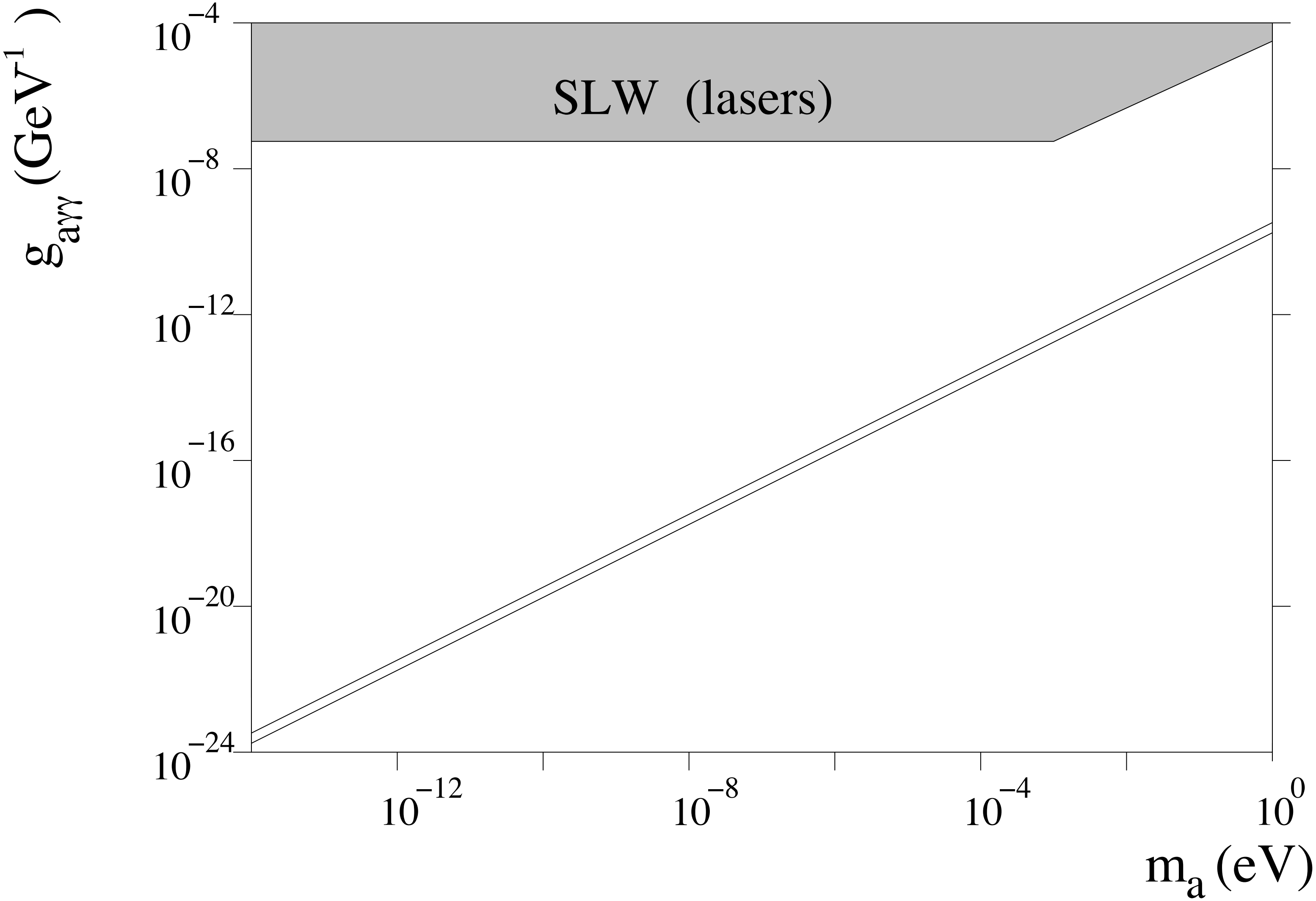
P. Pugnat et al. '05

C. Robilliard et al. '07

A. Afanasev et al. '08

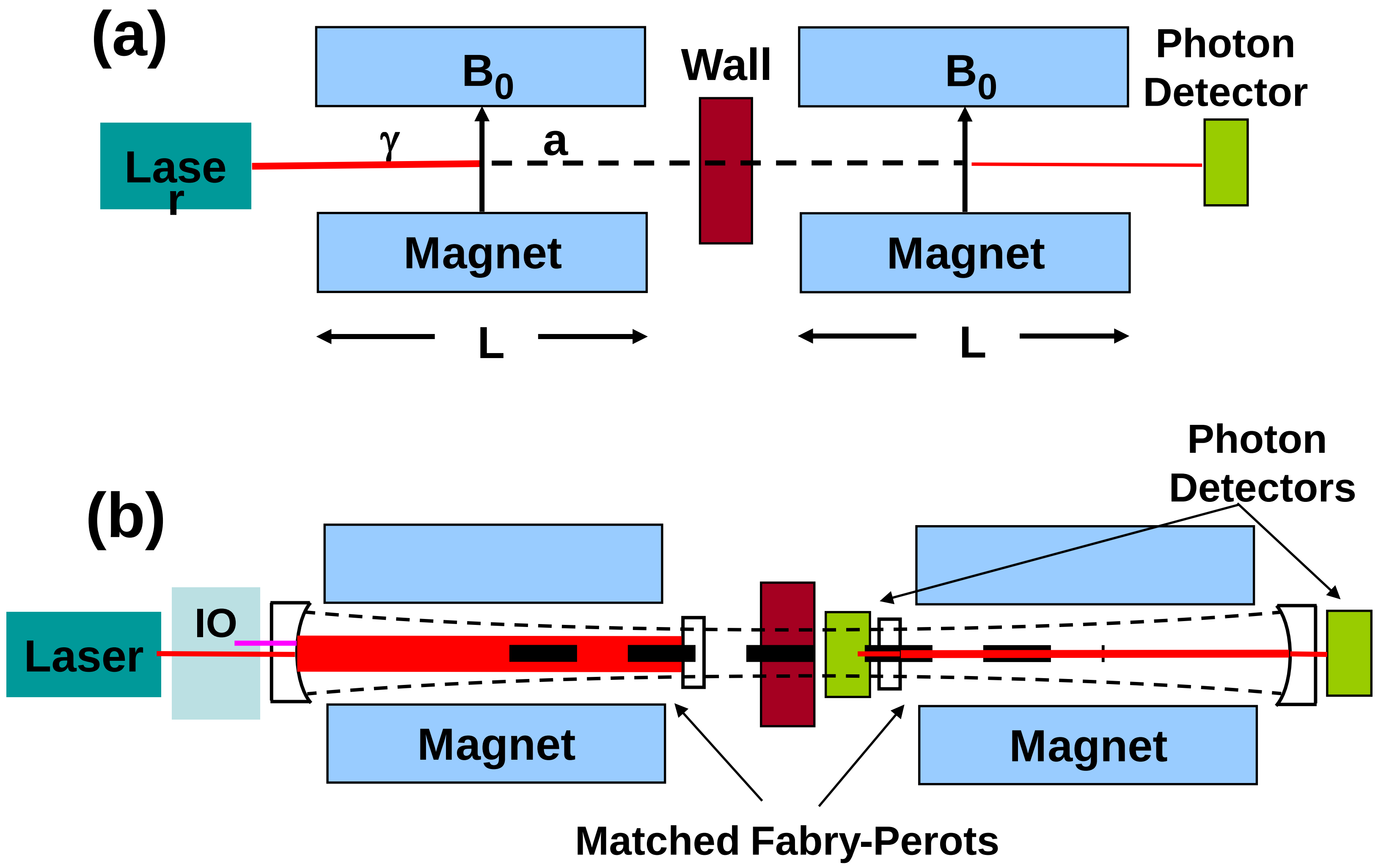
A. Chou et al. '08

K. Ehret et al. '10

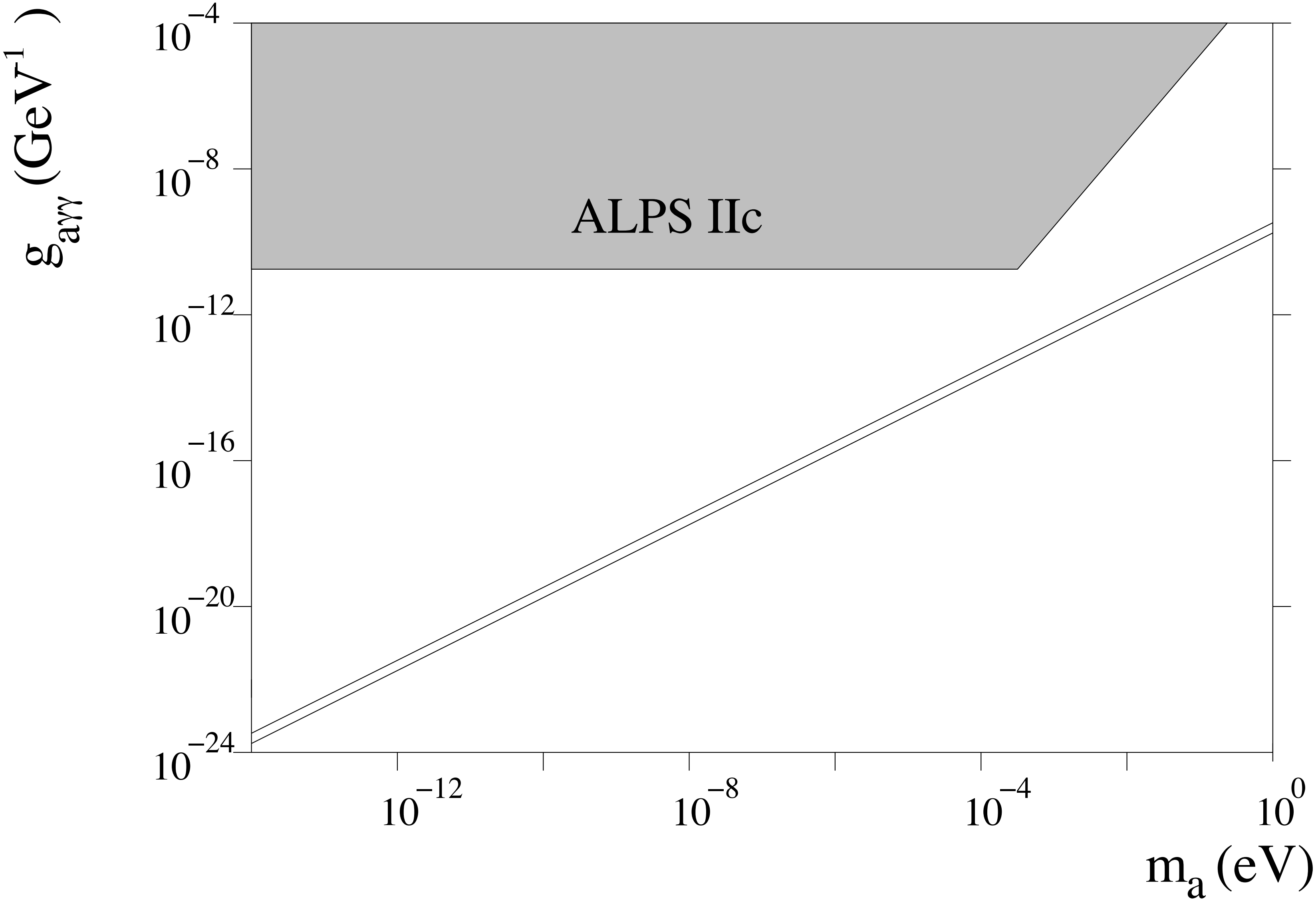


SLW (lasers)
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-12}
10^{-8}
10^{-4}
10^{0}
m_a (eV)

Resonantly Enhanced Axion-Photon Regeneration



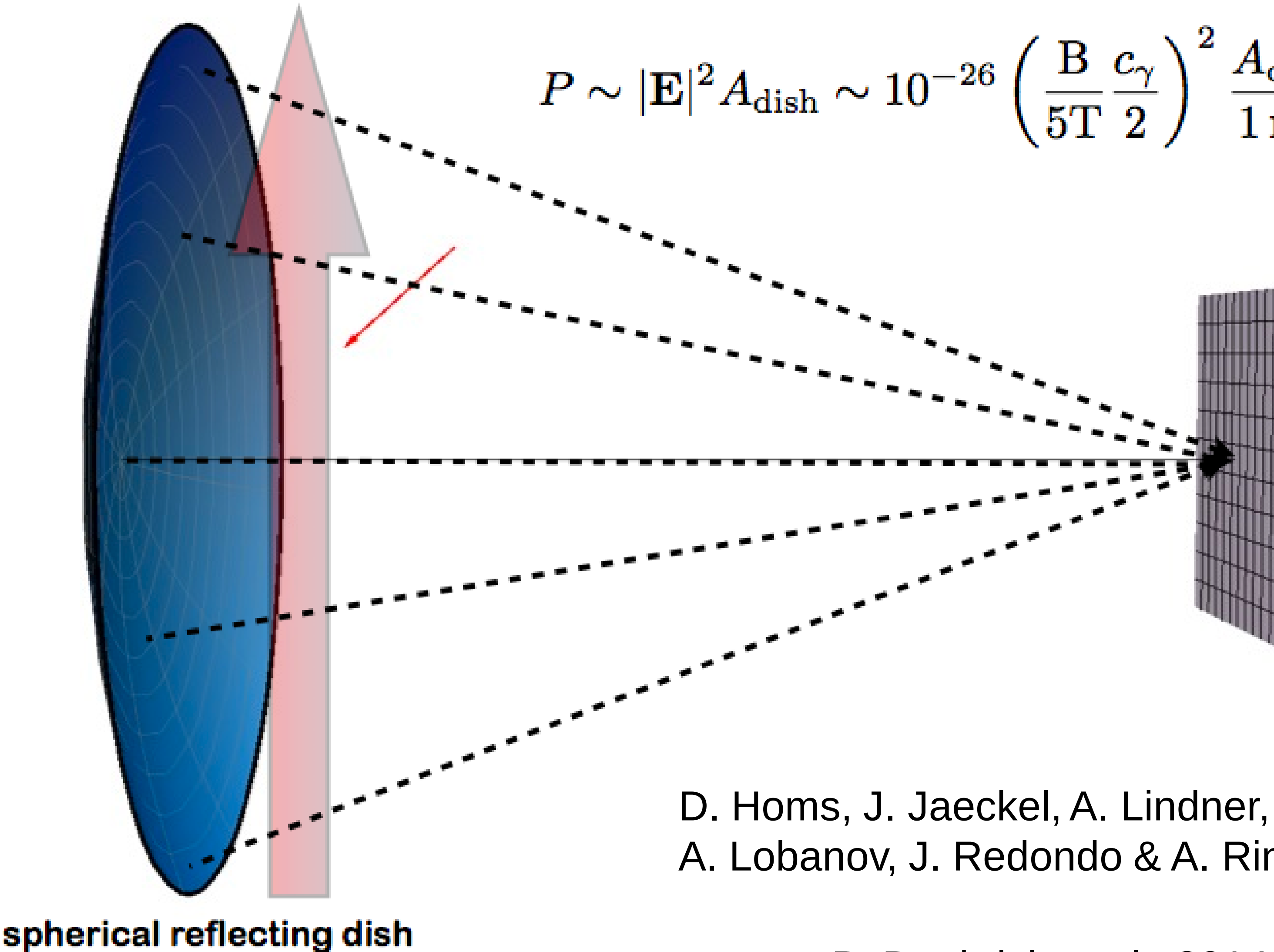
Hoogeveen (1996); P.S., Tanner and van Bibber (2007) & G. Mueller (2009)



ALPS IIc
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-12}
10^{-8}
10^{-4}
10^{0}
m_a (eV)

Dish antenna

$$P \sim |\mathbf{E}|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\frac{c_\gamma}{2}\right)^2 \frac{A_{\rm dish}}{1\,\rm m^2}\,\rm Watt$$



D. Homs, J. Jaeckel, A. Lindner,
A. Lobanov, J. Redondo & A. Ringwald, 2013

B. Doebrich et al. ,2014

Dielectric Haloscope

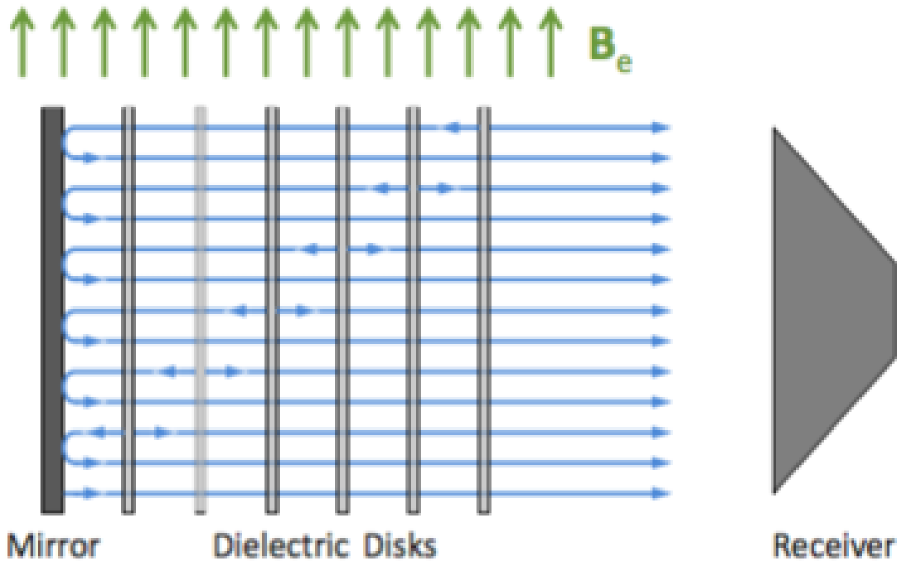


FIG. 1. A dielectric haloscope consisting of a mirror and several dielectric disks placed in an external magnetic field $\mathbf{B}_e$ and a receiver in the field-free region. A parabolic mirror (not shown) could be used to concentrate the emitted power into the receiver. Internal reflections are not shown.

MADMAX

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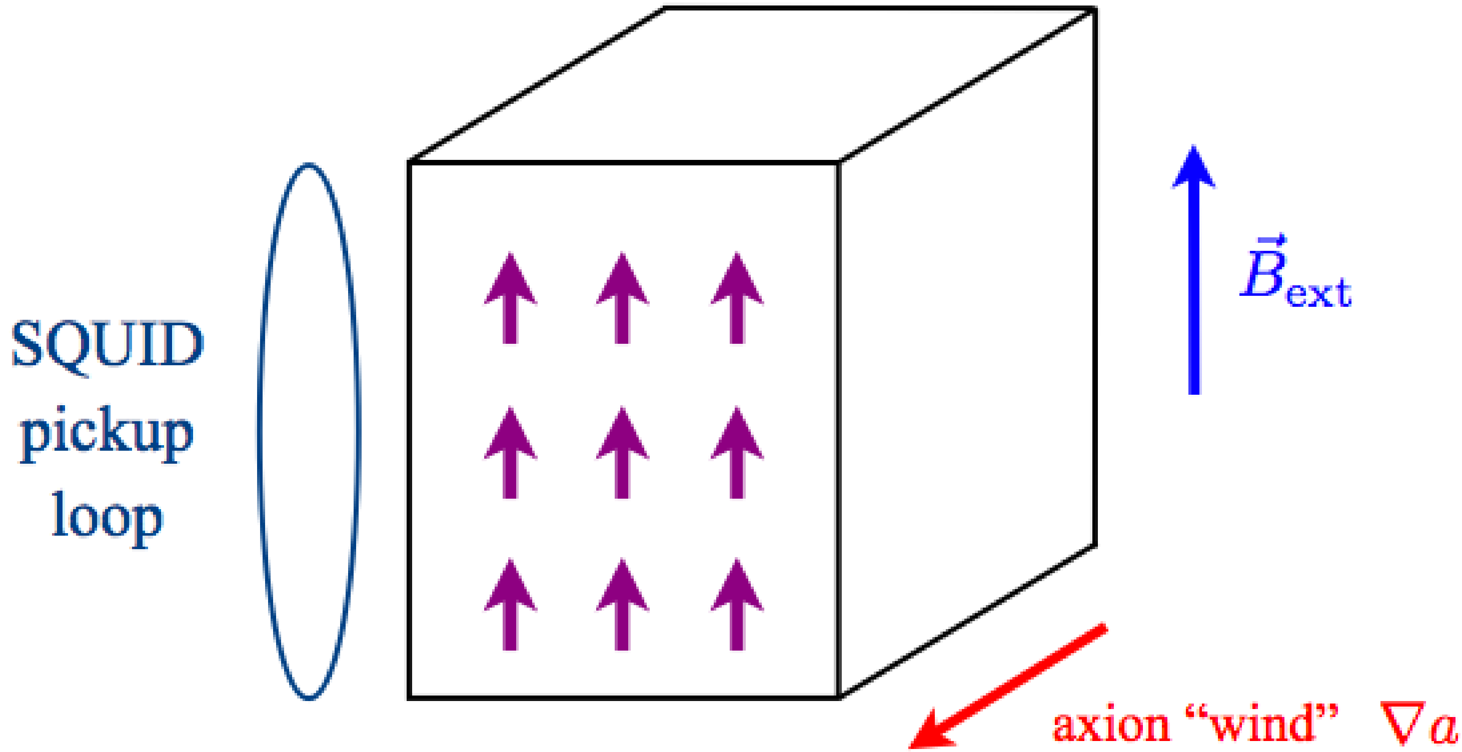
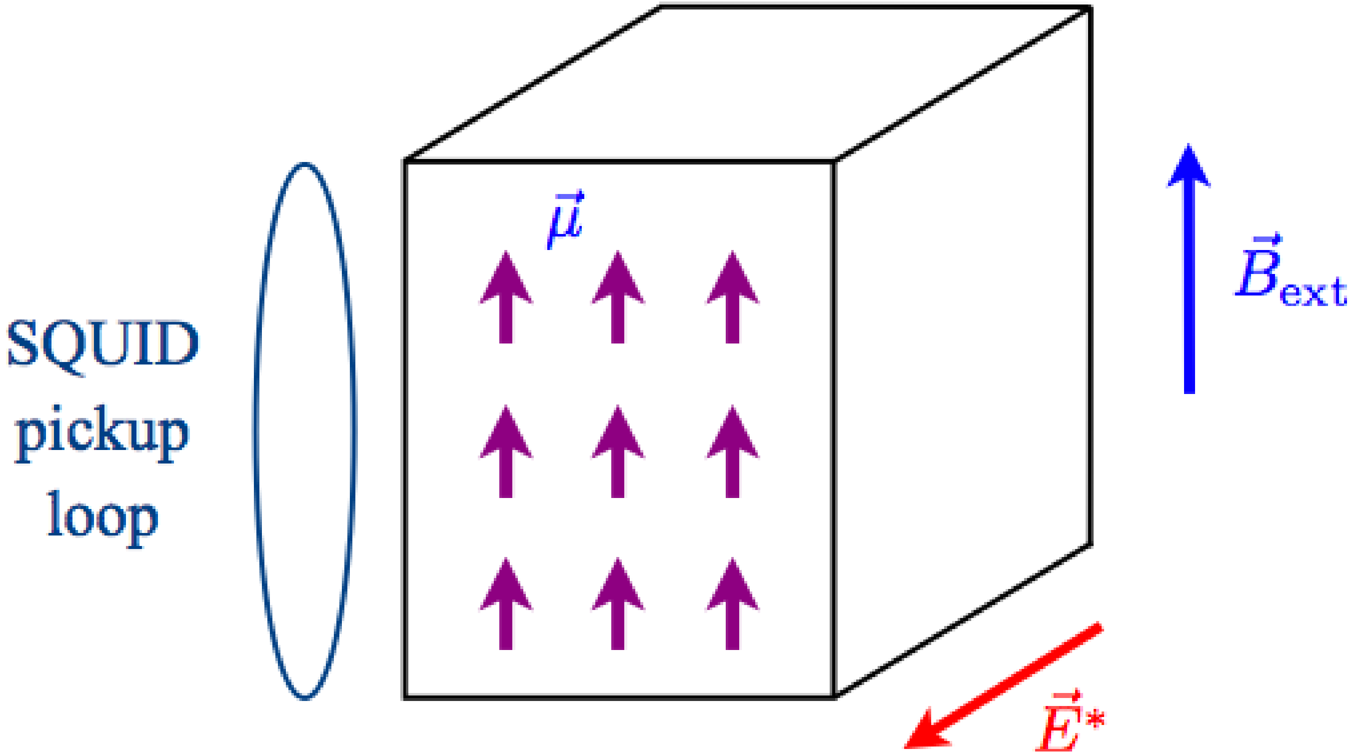
NMR techniques

P. Graham, S. Rajendran; D. Budker, M. Ledbetter, A. Sushkov



use nuclear spins coupled to axion DM

$$g_{\rm aNN}\,(\partial_\mu a)\,\bar{N}\gamma^\mu\gamma_5 N \implies H_N \supset g_{\rm aNN}\vec{\nabla}a.\vec{S}_N$$



the axion field induces an oscillating nuclear electric dipole moment

$$d_e \sim 10^{-16}\ e\ \mathrm{cm}\ \frac{a(x)}{f_a}$$

Macroscopic forces mediated by axions

$$L_{a\bar{f}f} = g_f \frac{m_f}{f_a} a \bar{f} \; i\gamma_5 + \theta_f \; f$$

forces coupled to
the f spin density

background of
magnetic forces

forces coupled to
the f number density

$$\theta_f \sim 10^{-17}$$

Theory:

J. Moody and
F. Wilczek '84

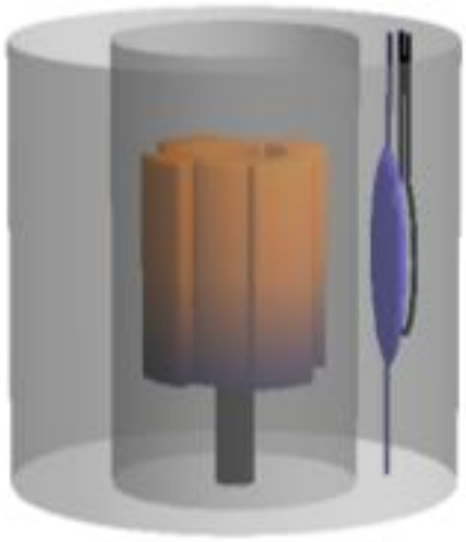
Experiment:

A. Youdin et al. '96
W.-T. Ni et al. '96

NMR with long range axion field

A. Arvanitaki and A. Geraci, 2014

$$H_{\rm int} = \frac{g_f m_f \theta_f}{f_a} a(x)$$



$$H_{\rm int} = \frac{g_f m_f}{f_a} \vec{\nabla} a(x) \cdot \vec{\sigma}$$

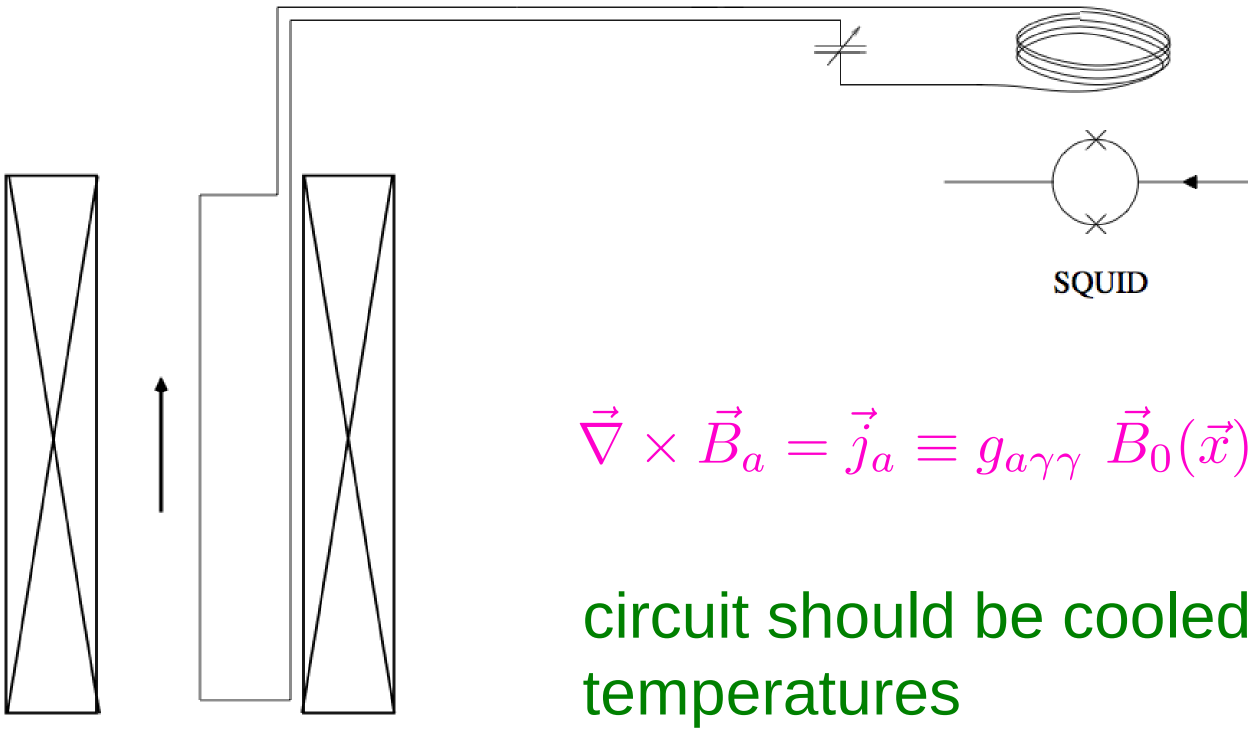
the rotating mass on the left produces an oscillating axion field

the oscillating axion field is an effective magnetic field in an NMR experiment

$$\omega = \gamma_N B_0$$

Axion dark matter detection using an LC circuit

PS, D. Tanner and N. Sullivan, 2013



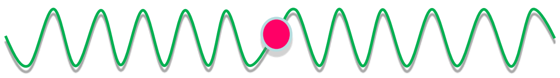
$$\vec{\nabla} \times \vec{B}_a = \vec{j}_a \equiv g_{a\gamma\gamma} \ \vec{B}_0(\vec{x}) \ \partial_t a(\vec{x}, t)$$

circuit should be cooled to milli-Kelvin temperatures

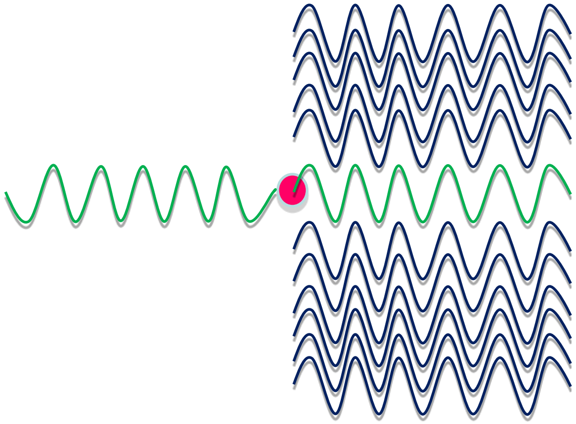
ABRACADABRA, SLIC, DMRadio

Stimulated axion decay

A. Arza & PS, 2019



$$\Gamma(a \to 2\gamma) \sim \frac{1}{10^{51}\ \text{sec}}$$



P_1 P_0

$$\omega = \frac{m_a}{2}$$

$P_0 = \text{outgoing power}$

$P_1 = \text{echo power}$

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