The Abdus Salam International Centre for Theoretical Physics

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1951-24

Workshop on the original of P, CP and T Violation

2 - 5 July 2008

Invisible Axion Searches

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Invisible Axion Searches

P. Sikivie (U. of Florida)

Workshop on the origin of
P, CP and T violation

ICTP, Trieste

July 4, 2008

Outline

- Introduction
- Axion cosmology
- Dark matter axion detection
- Solar axion detection
- Laser experiments
- Other methods

The Strong CP Problem

$$L_{\mathrm{QCD}} = \ \dots + \bar{\theta} \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu}$$

where

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

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

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

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

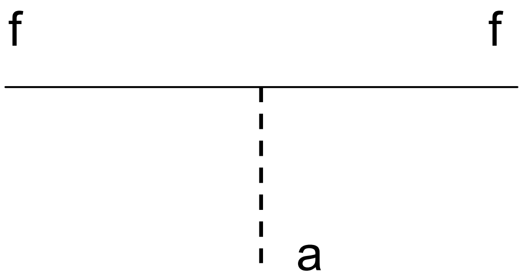
$$L = \ldots + \frac{a}{f_a}\frac{g^2}{32\pi^2} G^a{}_{\mu\nu}\,\tilde{G}^{a\mu\nu} + \frac{1}{2}\partial_\mu a\,\partial^\mu a + \ldots$$

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

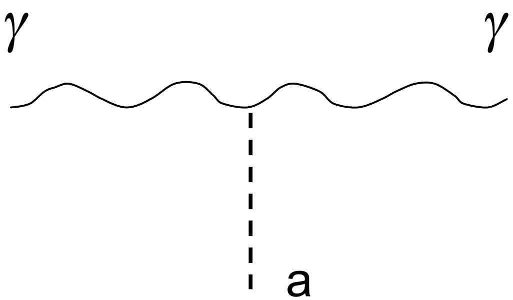
and a light neutral pseudoscalar particle is predicted: the axion.

Weinberg and Wilczek, 1978

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



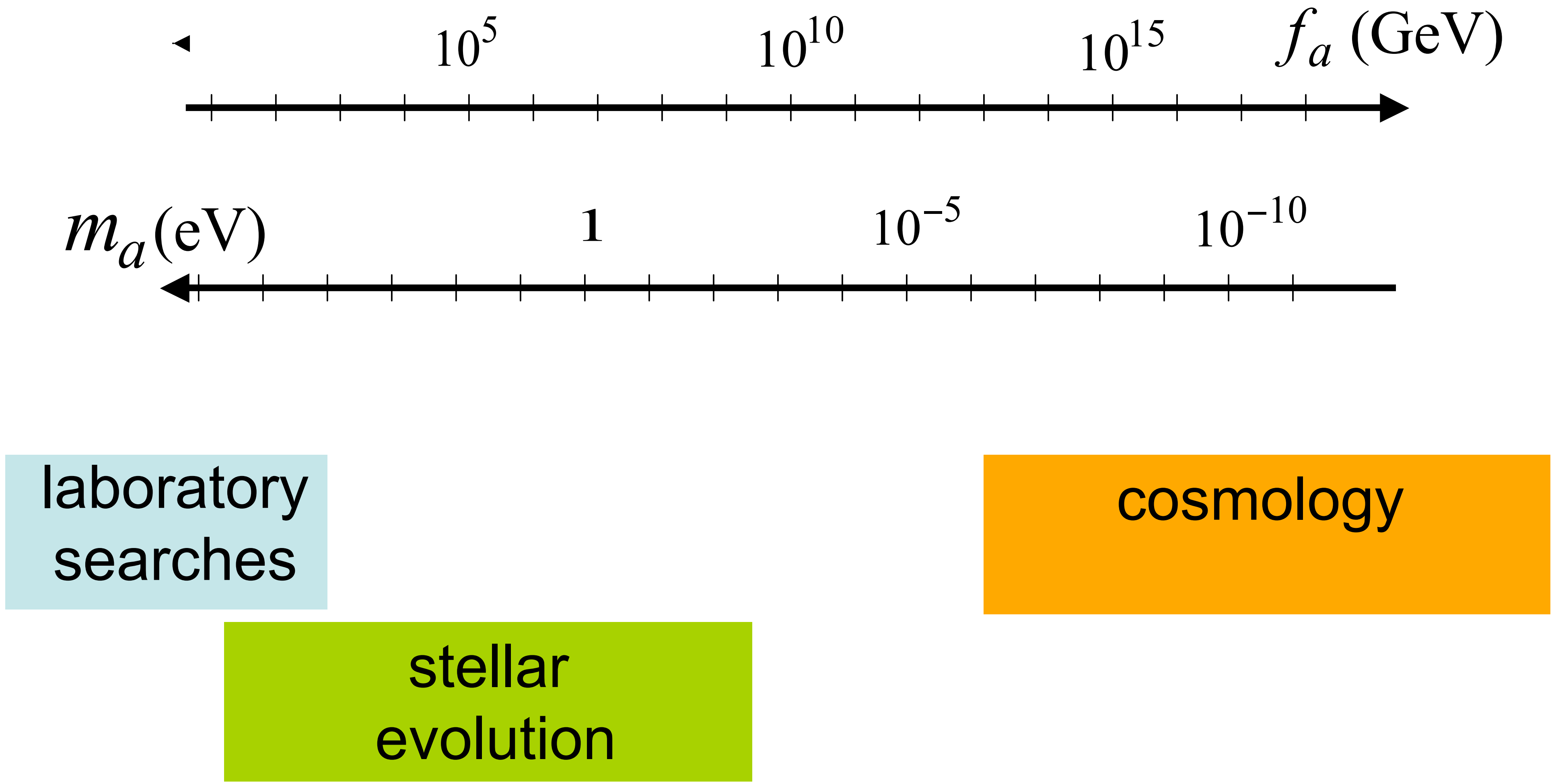
$$L_{a\bar{f}f} = i\, g_f \frac{a}{f_a} \bar{f} \gamma_5 f$$

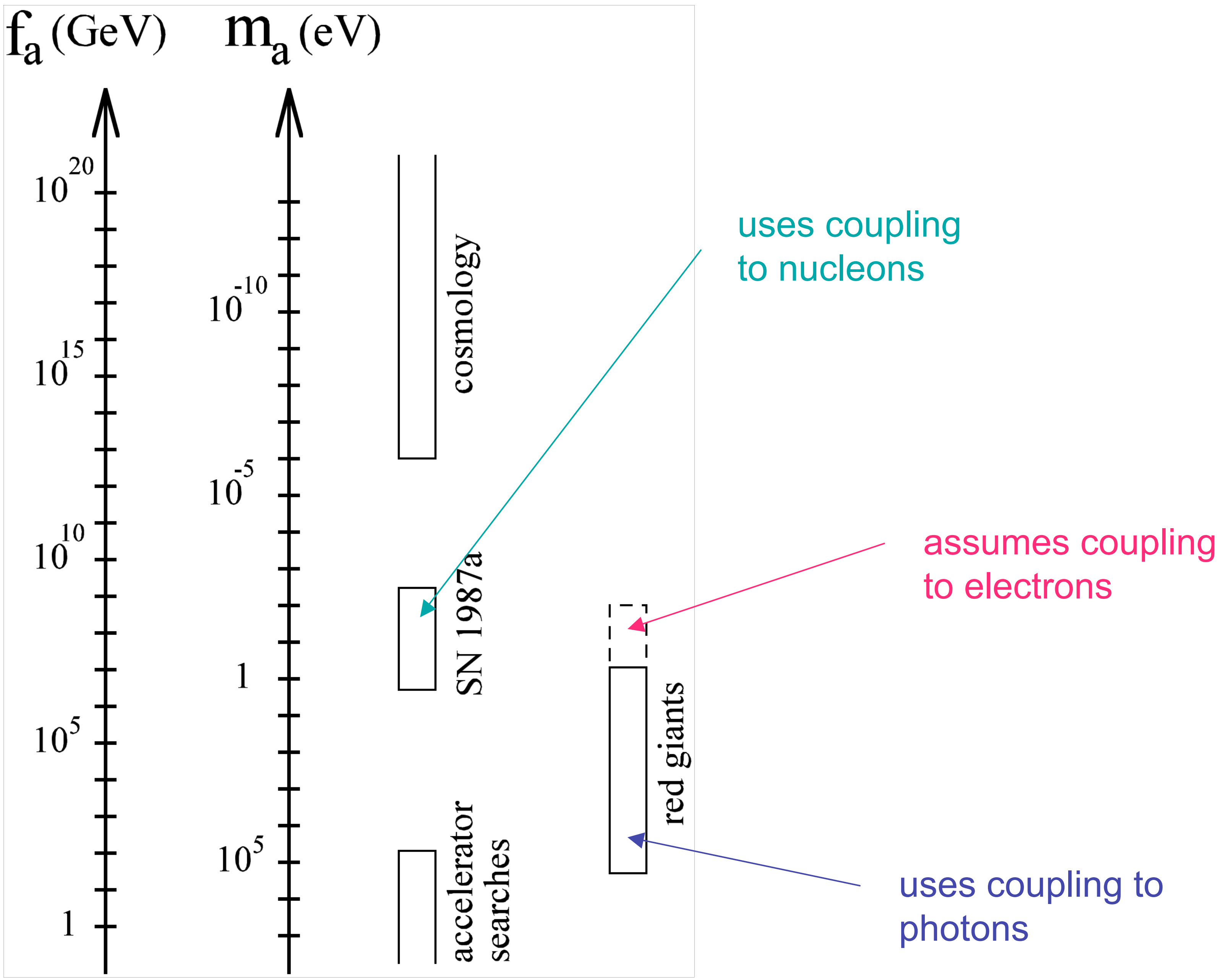


$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model

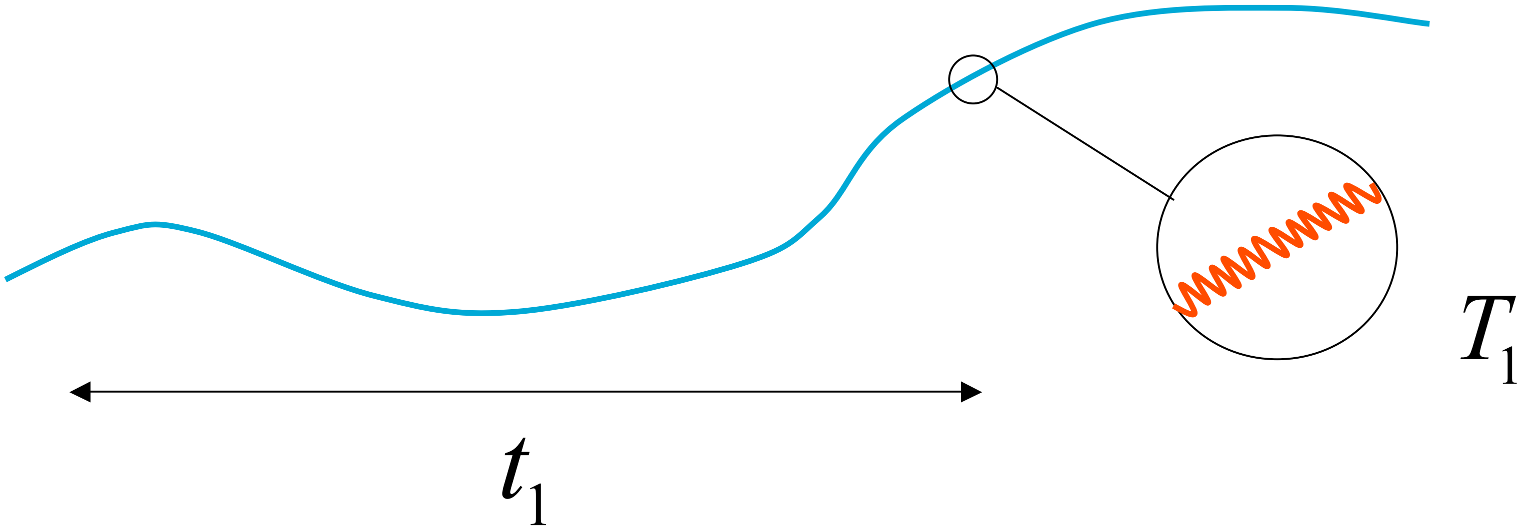
The remaining axion window





f_a (GeV)
m_a (eV)
10^{20}
10^{15}
10^{10}
10^{5}
1
10^{-10}
10^{-5}
1
10^{5}
cosmology
SN 1987a
accelerator searches
red giants
uses coupling to nucleons
assumes coupling to electrons
uses coupling to photons

There are two cosmic axion populations: hot and cold.



When the axion mass turns on, at QCD time,

$$T_1 \quad 1\ \text{GeV}$$

$$t_1 \quad 2 \cdot 10^{-7}\ \text{sec}$$

$$p_a(t_1) = \frac{1}{t_1} \quad 3 \cdot 10^{-9}\ \text{eV}$$

Cold Axions

Density

$$\Omega_a \approx \left(\frac{10^{-5}\ \text{eV}}{m_a}\right)^{\frac{7}{6}}$$

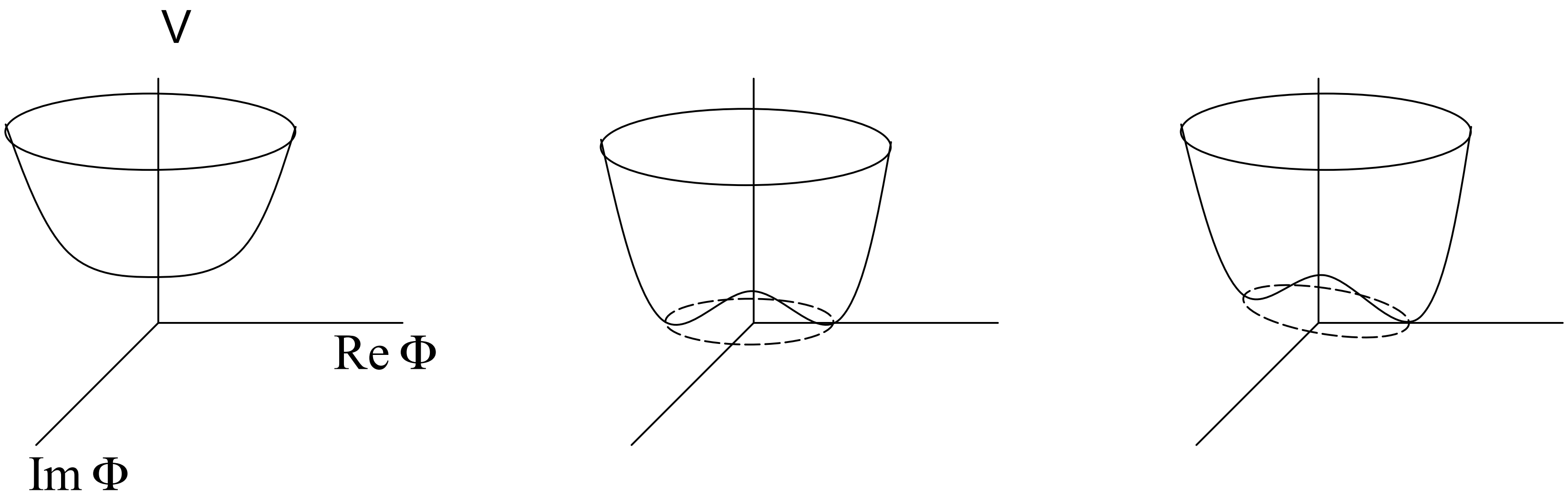
Velocity dispersion

$$\delta \text{v}_a(t_0) \quad 3\cdot 10^{-17}\, c \left(\frac{10^{-5}\ \text{eV}}{m_a}\right)^{\frac{5}{6}}$$

Effective temperature

$$T_{a,\text{eff}}(t_0) \quad 10^{-34}\ \text{K} \left(\frac{10^{-5}\ \text{eV}}{m_a}\right)^{\frac{2}{3}}$$

Effective potential V(T, Φ)

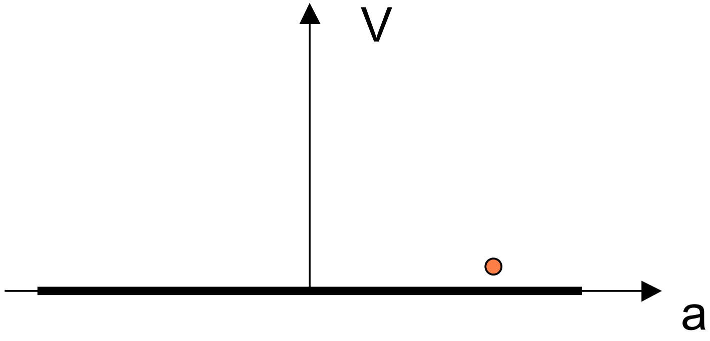


$T > f_a$

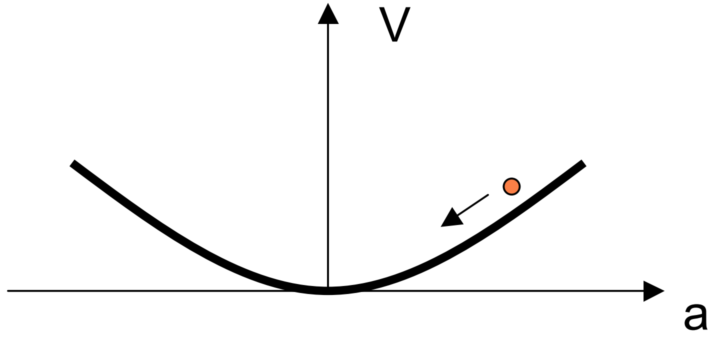
$f_a > T > 1\,\mathrm{GeV}$ → axion strings

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

Axion production by vacuum realignment



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

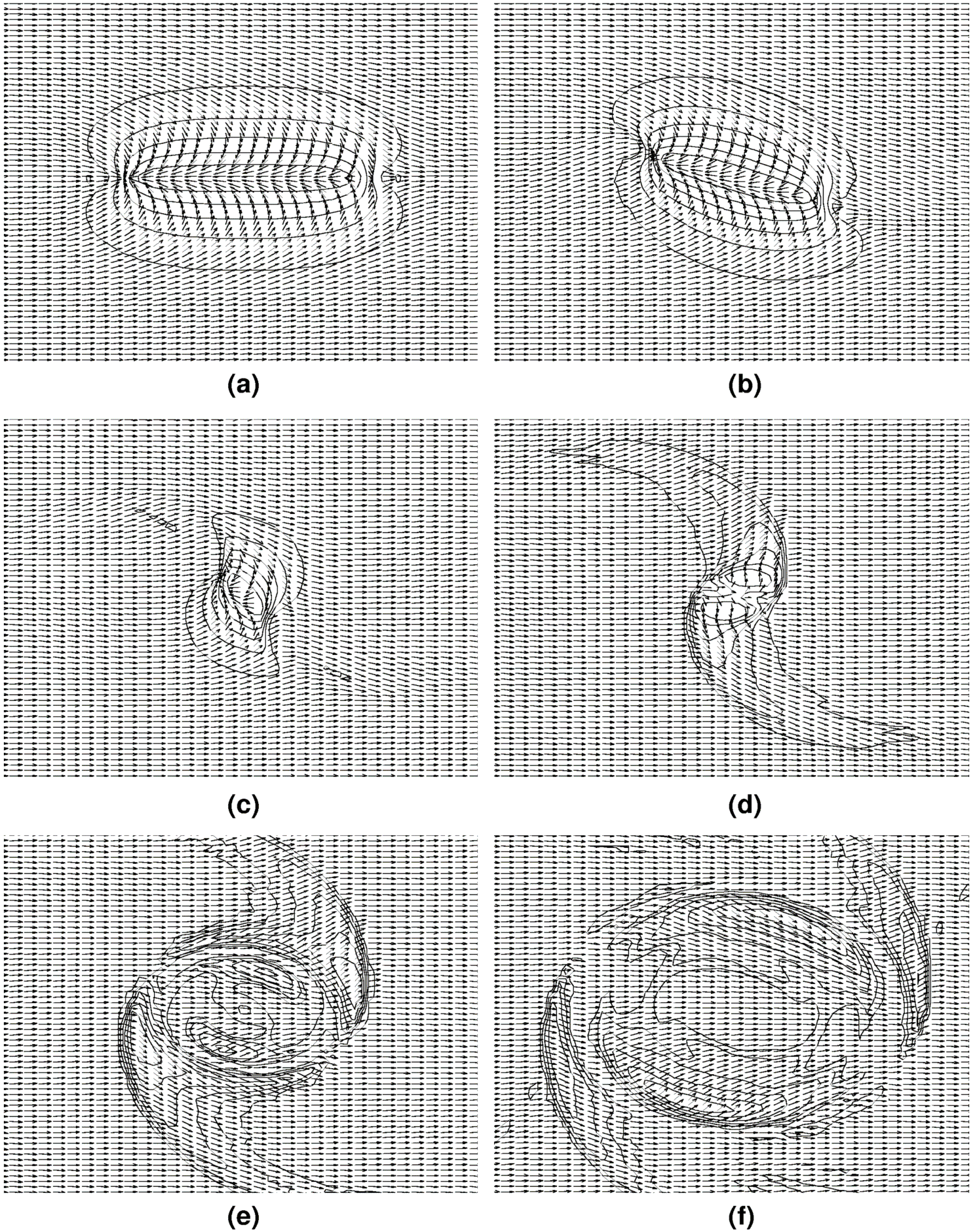


$$T \leq 1\,\mathrm{GeV}$$

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

initial misalignment angle

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



Domain wall bounded by string decaying into axion radiation

If inflation after the PQ phase transition

- $$\Omega_a \qquad 0.25 \left(\frac{10^{-5}\ \text{eV}}{m_a}\right)^{\frac{7}{6}} \alpha(t_1)^2$$

  may be accidentally suppressed

- $$< \sqrt{a^2} > \qquad \frac{H_I}{2\pi}$$

  produces isocurvature density perturbations

$$\left.\frac{\delta\rho_a}{\rho_a}\right|_{\text{iso curvature}} \qquad \frac{H_I}{f_a\,\alpha(t_1)} \leq 10^{-6}$$

CMBR constraint

If no inflation after the PQ phase transition

- cold axions are produced by vacuum realignment, string decay and wall decay

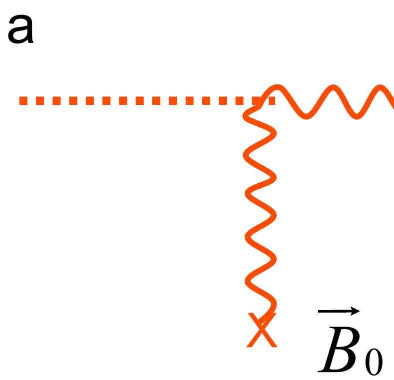
$$\Omega_a \qquad 0.5 \left(\frac{10^{-5}\ \mathrm{eV}}{m_a} \right)^{\frac{7}{6}}$$

- axion miniclusters appear

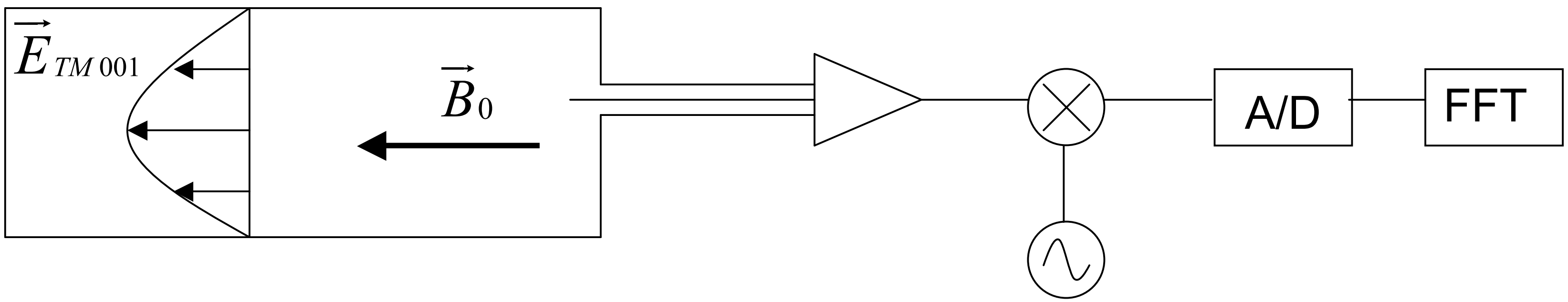
$$M_{\mathrm{mc}} \qquad 10^{-13}\ M \quad \left(\frac{10^{-5}\ \mathrm{eV}}{m_a} \right)^{\frac{5}{3}} \qquad\qquad l_{\mathrm{mc}} \qquad 10^{13}\ \mathrm{cm} \left(\frac{10^{-5}\ \mathrm{eV}}{m_a} \right)^{\frac{1}{6}}$$

Axion dark matter is detectable

PS '83



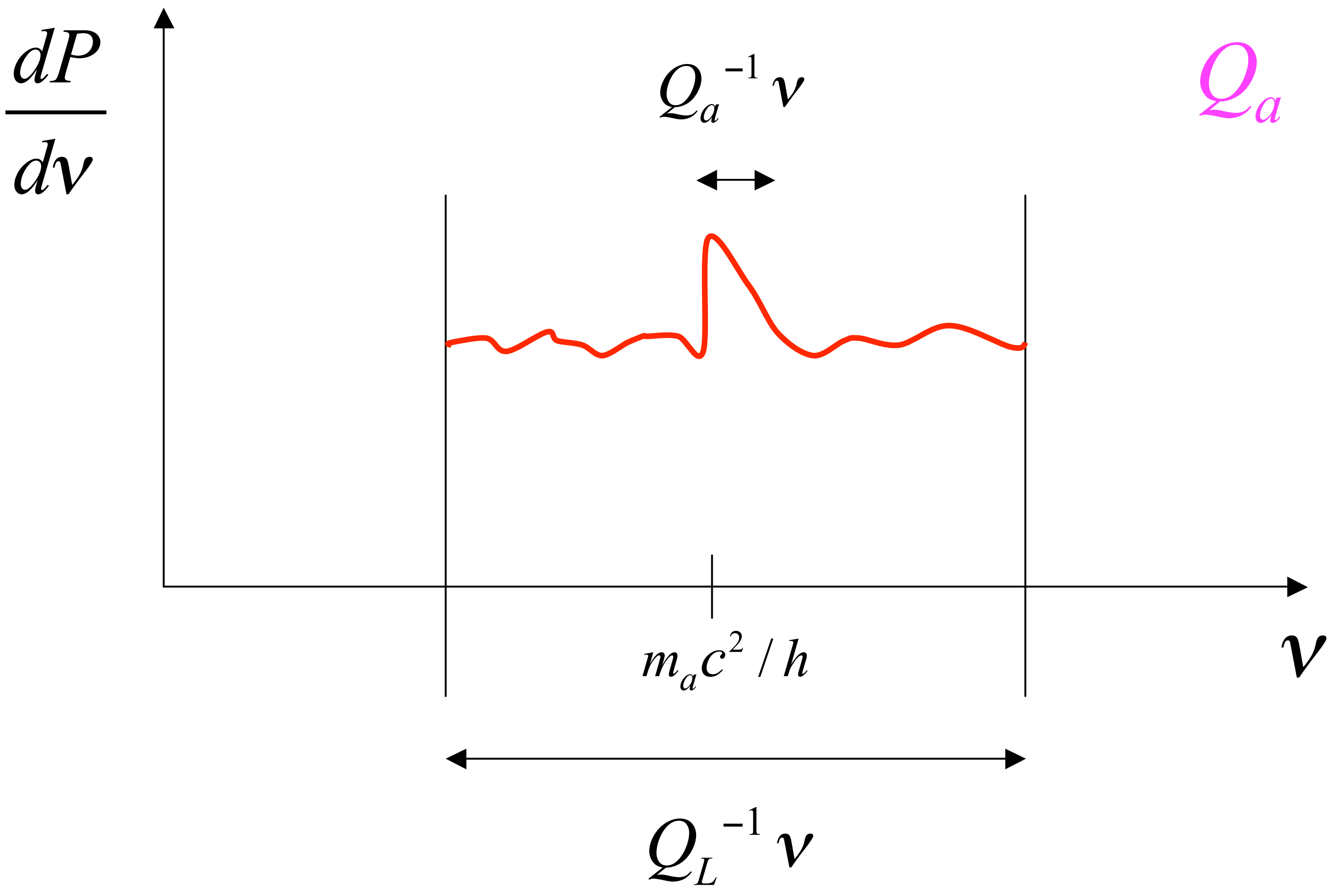
$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



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

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

$$Q_a \quad 10^{-6}$$



ADMX Collaboration

LLNL: S. Asztalos, G. Carosi, D. Carter, C. Hagmann, E. Hartouni, D. Kinion, K. van Bibber

U of Washington: G. Harper, M. Hotz, E. Manrao, A. Myers, L. Rosenberg, G. Rybka, D. Will, T. Wolowiec

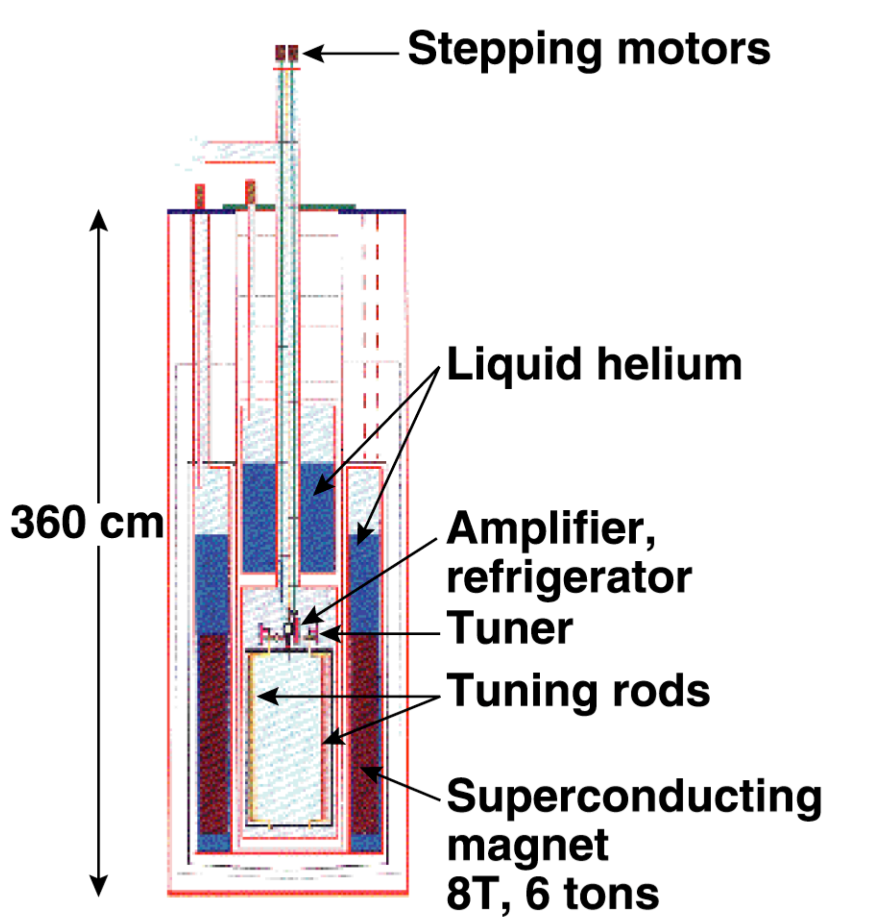
U of Florida: J. Hwang, P. Sikivie, D. Tanner, N. Sullivan

UC Berkeley: J. Clarke

Sheffield U: E. Daw

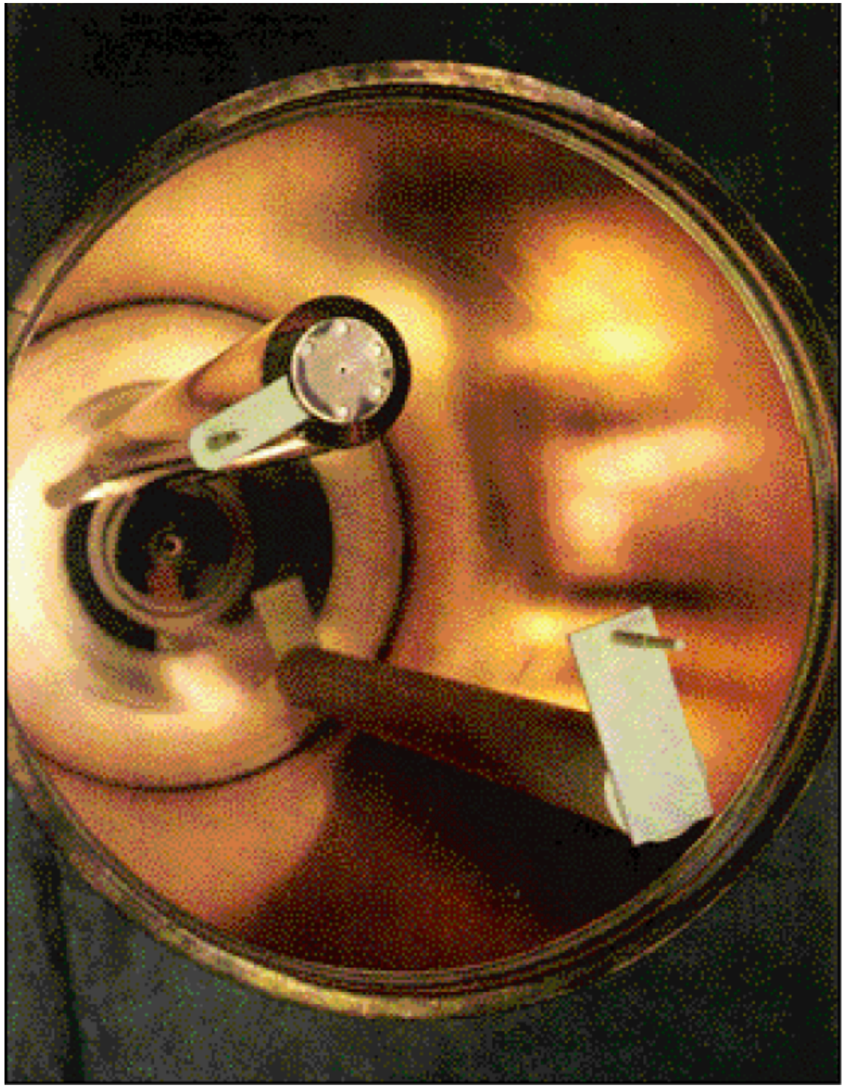
NRAO: R. Bradley

Axion Dark Matter eXperiment

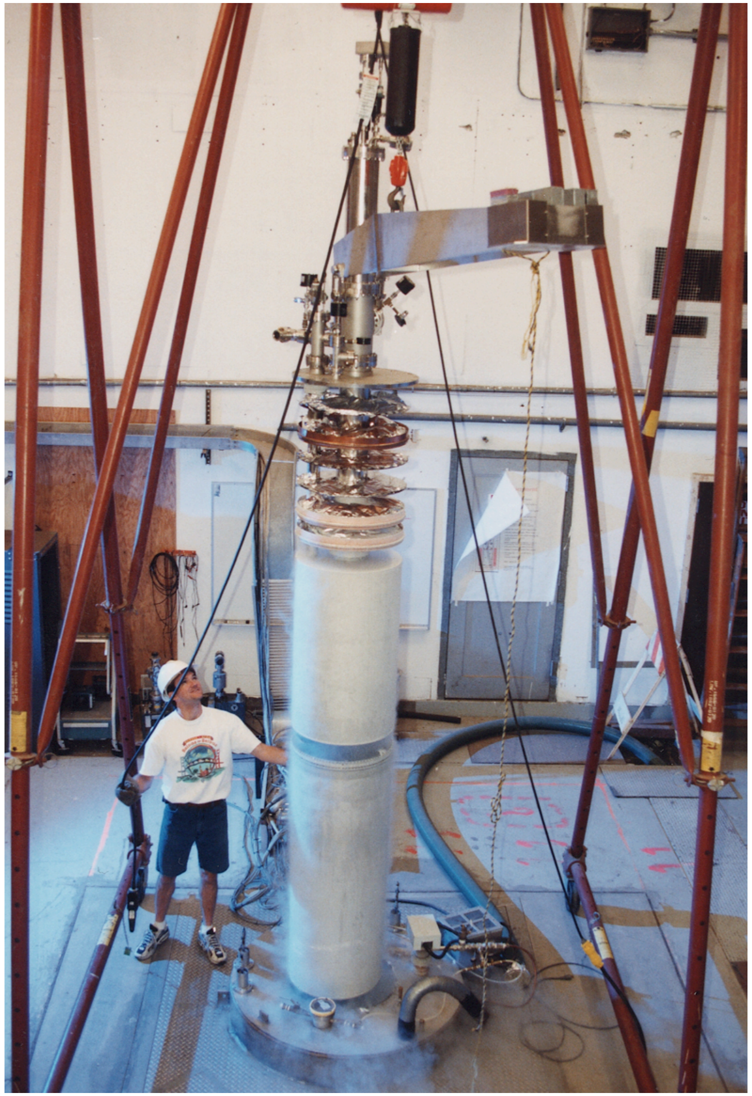
Magnet with Insert (side view)	Magnet
	
Pumped LHe → T ~ 1.5 k	8 T, 1 m × 60 cm ∅

ADMX hardware

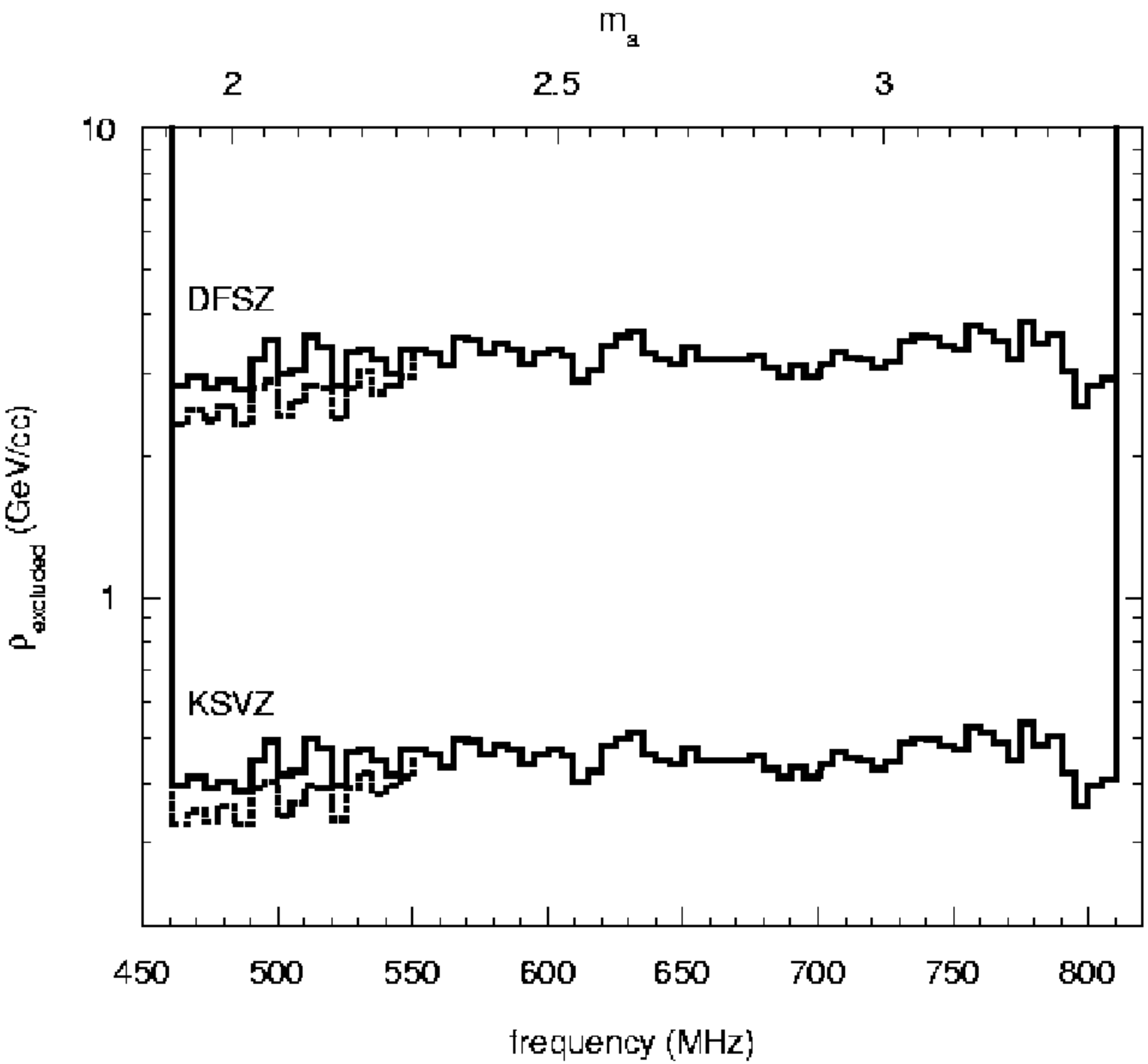
high Q cavity



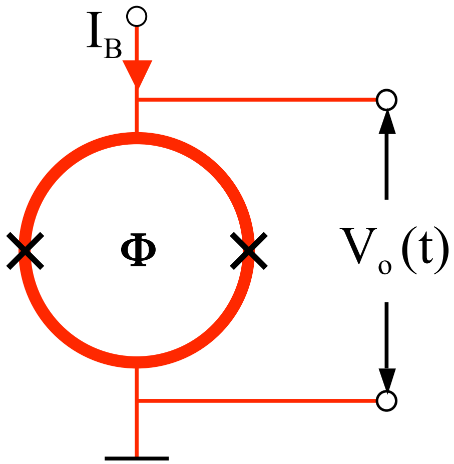
experimental insert



ADMX MedRes limits

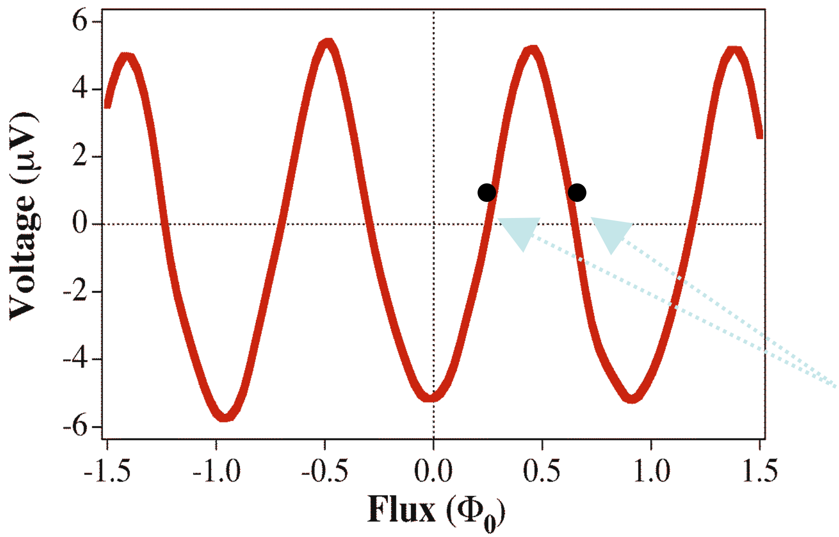


Upgrade with SQUID Amplifiers



The basic SQUID amplifier is a flux-to-voltage transducer

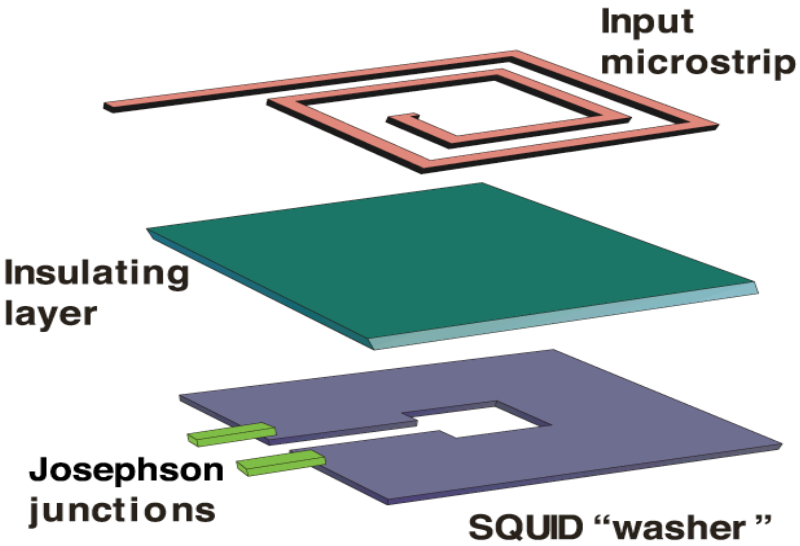
SQUID noise arises from Nyquist noise in shunt resistance scales linearly with T

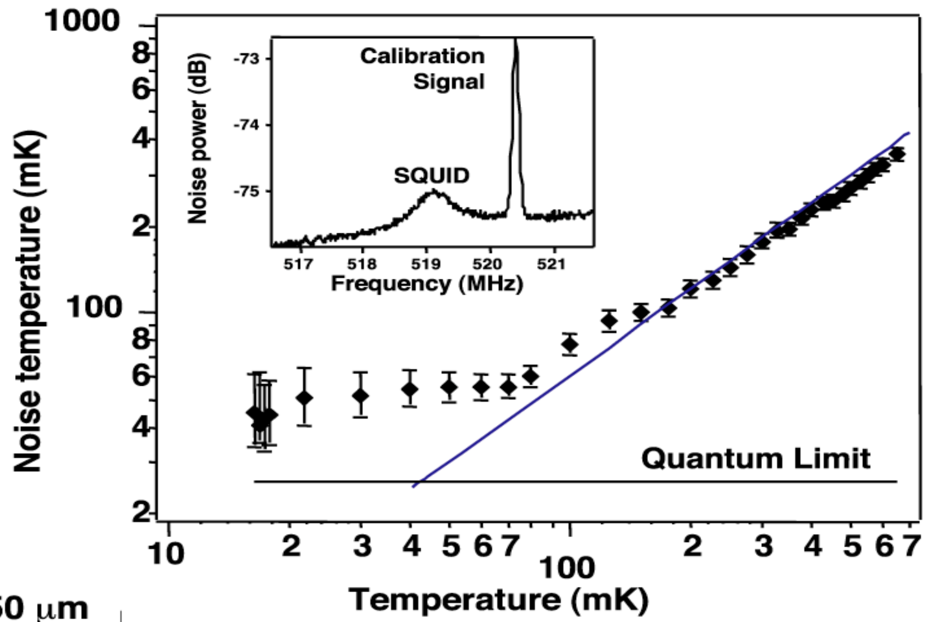


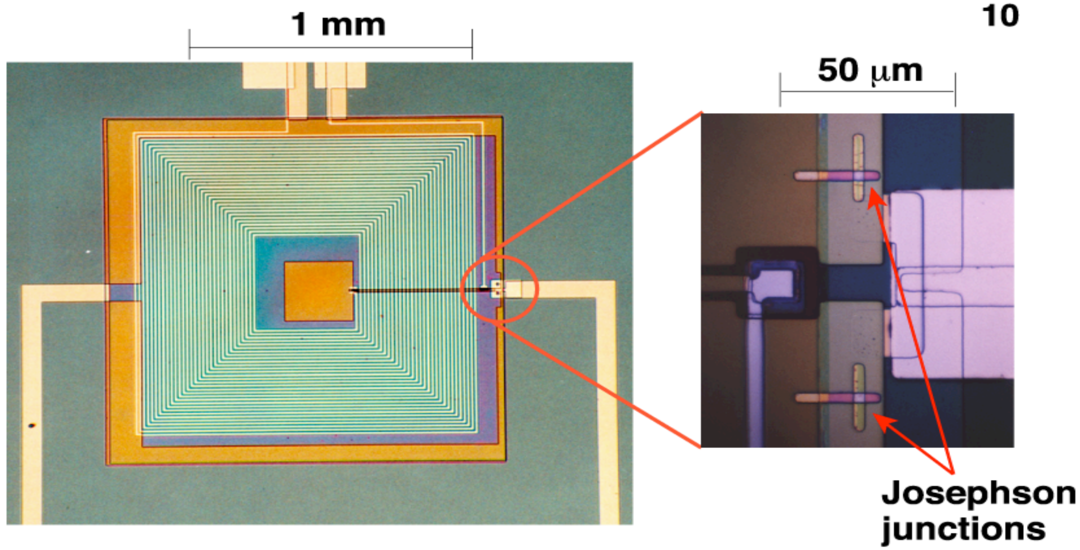
However, SQUIDs of conventional design are poor amplifiers above 100 MHz (parasitic couplings).

Flux-bias to here

ADMX Upgrade: replace HEMTs (2 K) with SQUIDs (50 mK)







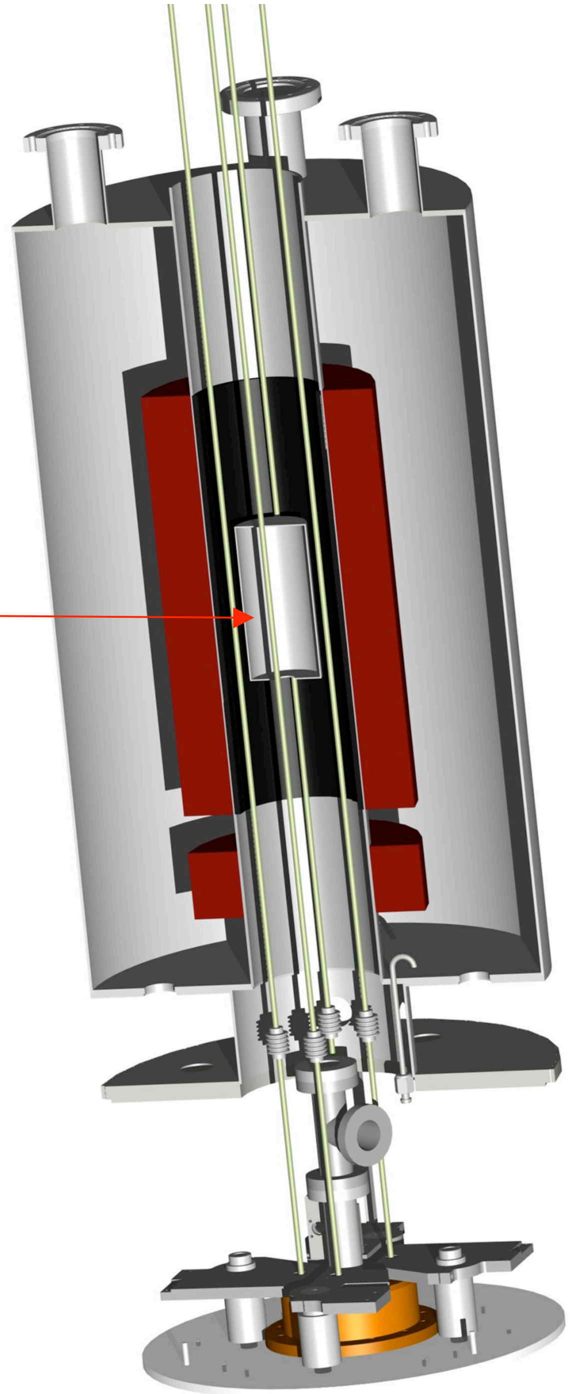
(J. Clarke *et al.*, U.C. Berkeley)

In phase II of the upgrade, the experiment is cooled with a dilution refrigerator.

The magnetic field needs to be cancelled at the location of the SQUID.

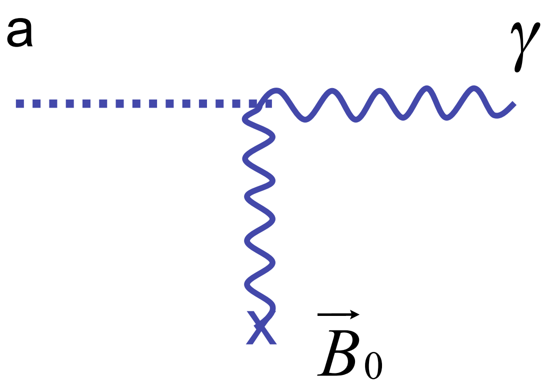
From outwards-in:

Iron shield
Cryoperm (mumetal) shields
Superconducting shields
SQUID amplifier package
SQUIDs



The upgrade will be sensitive to the more pessimistically-coupled axions even if they are a minority fraction of the dark-matter halo.

Axion to photon conversion in a magnetic field



conversion probability

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

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

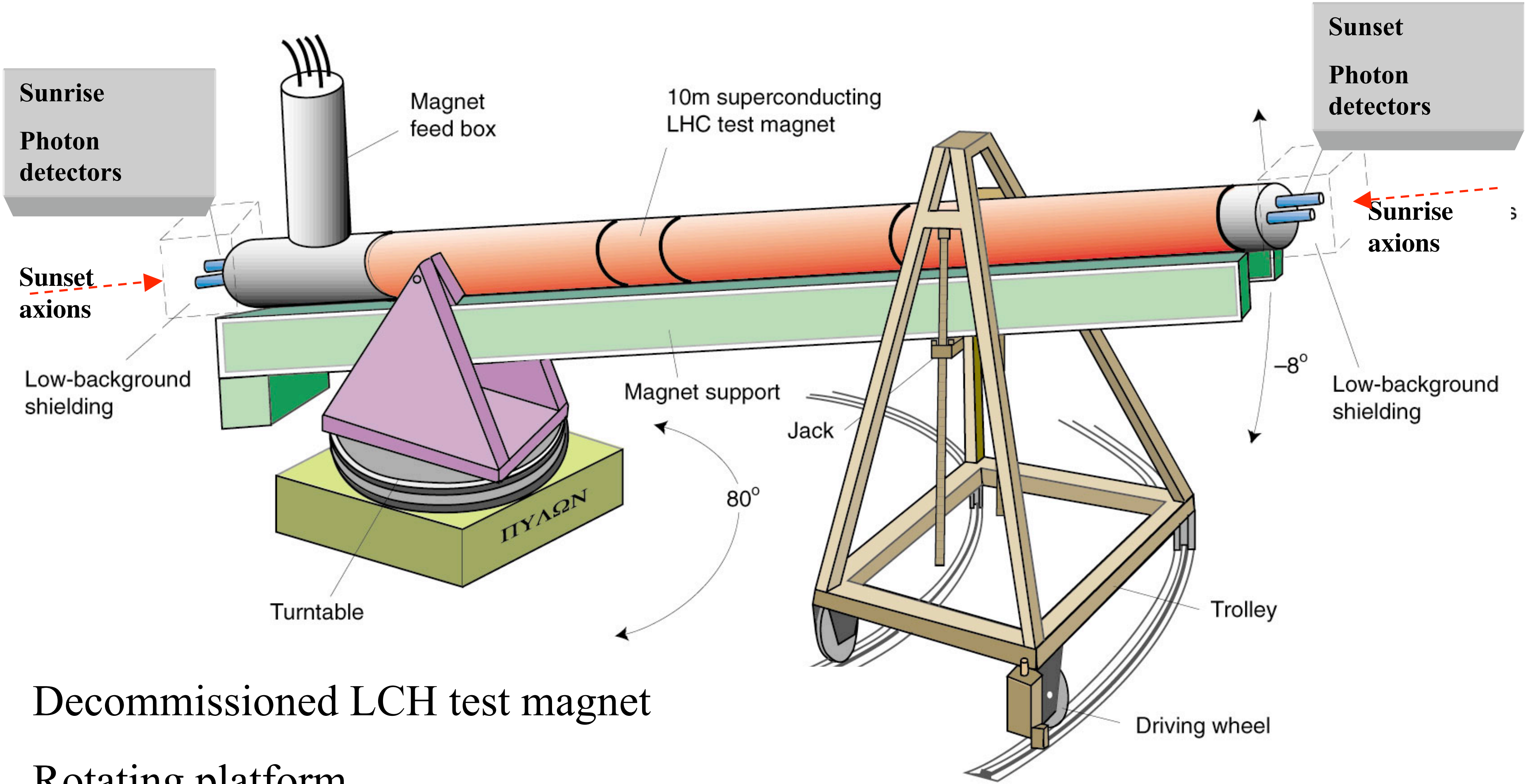
Theory

- 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

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

Cern Axion Solar Telescope



Decommissioned LCH test magnet

Rotating platform

3 X-ray detectors

X-ray Focusing Device

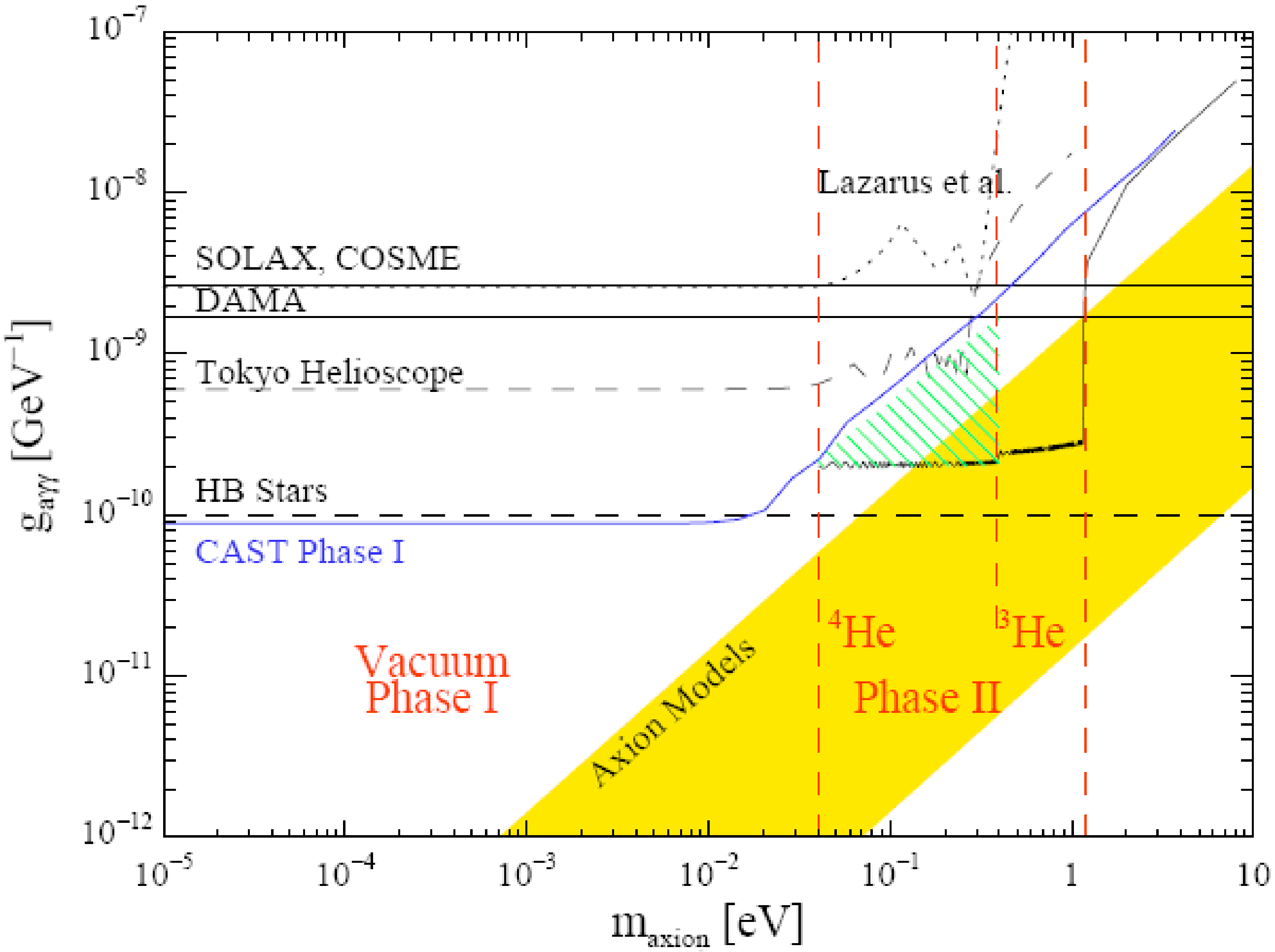

CAST
ANSALDO GIE
EUROPAMETALLI – LMI
E. ZANON

from C. Eleftheriadis (CAST), arXiv: 0706.0637

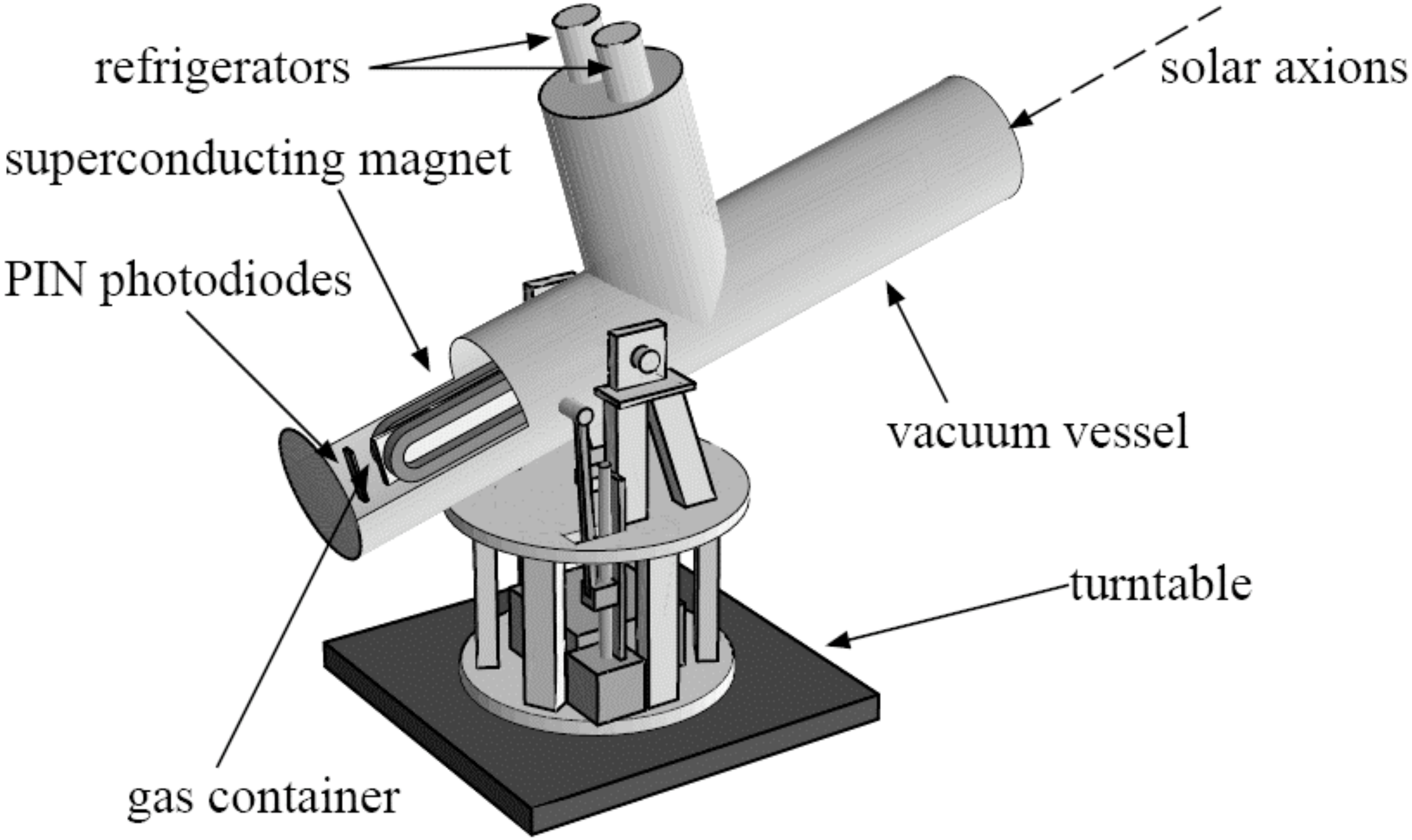
$$L_{a\gamma\gamma} = \frac{1}{M_a} a \vec{E} \cdot \vec{B}$$

$$\frac{1}{M_a} = g_{a\gamma\gamma}$$

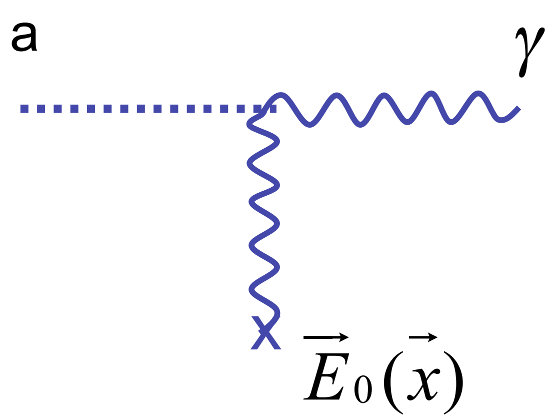
$$= g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a}$$



Tokyo Axion Helioscope



Primakoff conversion of solar axions in crystals on Earth



Solax, Cosme '98

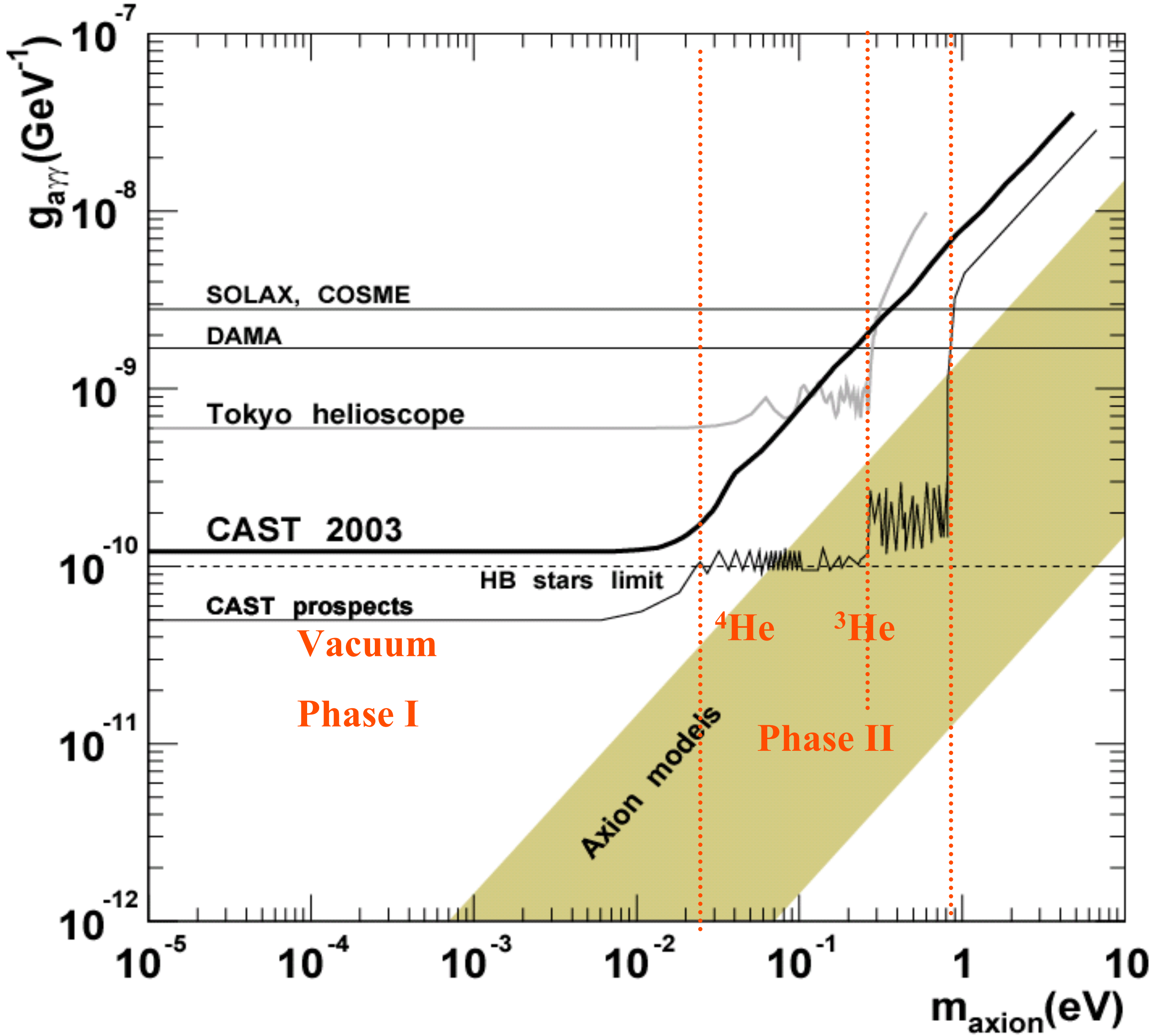
Ge

DAMA '01

NaI (100 kg)

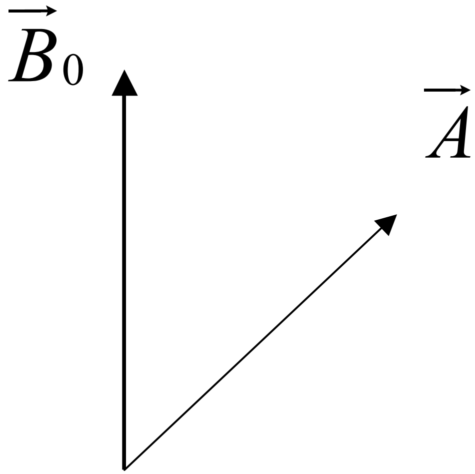
$E_a =$ few keV

Bragg scattering on crystal lattice

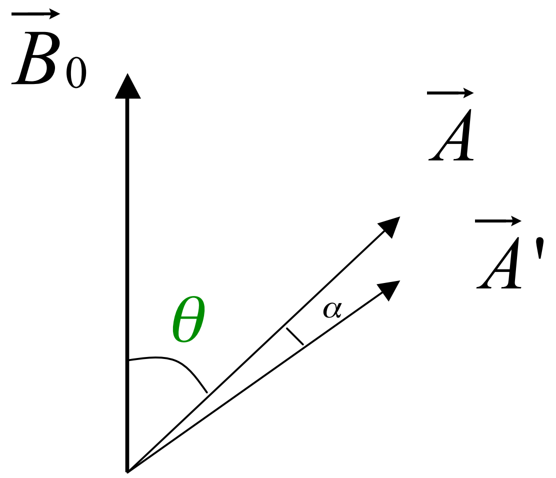


$g_{a\gamma\gamma}$(GeV^{-1})
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
SOLAX, COSME
DAMA
Tokyo helioscope
CAST 2003
HB stars limit
CAST prospects
Vacuum
Phase I
^{4}He
^{3}He
Phase II
Axion models
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion}(eV)

Linearly polarized light in a constant magnetic field



Rotation



$$A'_{//} = A_{//}\,(1 - \frac{1}{2}p - i\psi)$$

$$A'_{\perp} = A_{\perp}$$

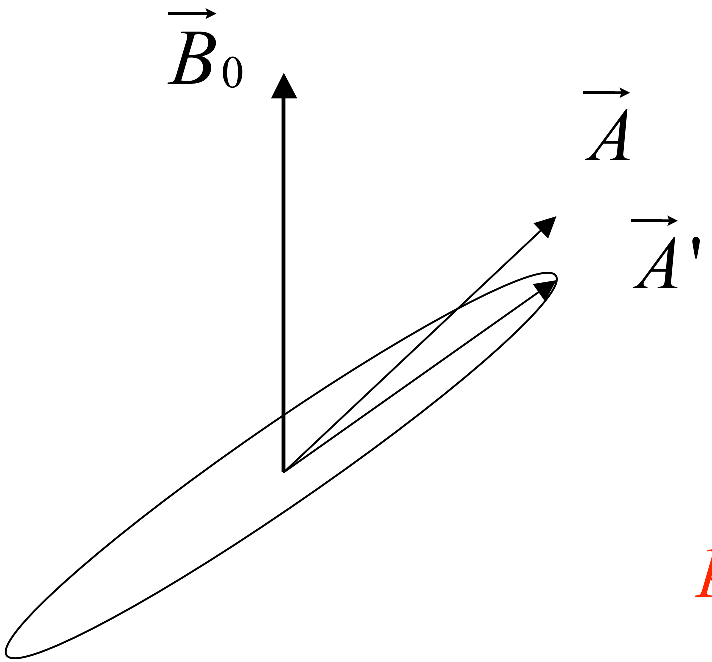
$$p = 4\frac{B_0^{\,2}\omega^2}{M_a^{\,2} m_a^{\,4}}\sin^2\left(\frac{m_a^{\,2}L}{4\omega}\right)$$

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

$$\alpha = -\frac{1}{4}p\sin(2\theta)$$

Rotation and Ellipticity

Maiani, Petronzio and Zavattini, 1986



$$A'_{/\!/} = A_{/\!/}\left(1 - \frac{1}{2}p - i\psi\right)$$

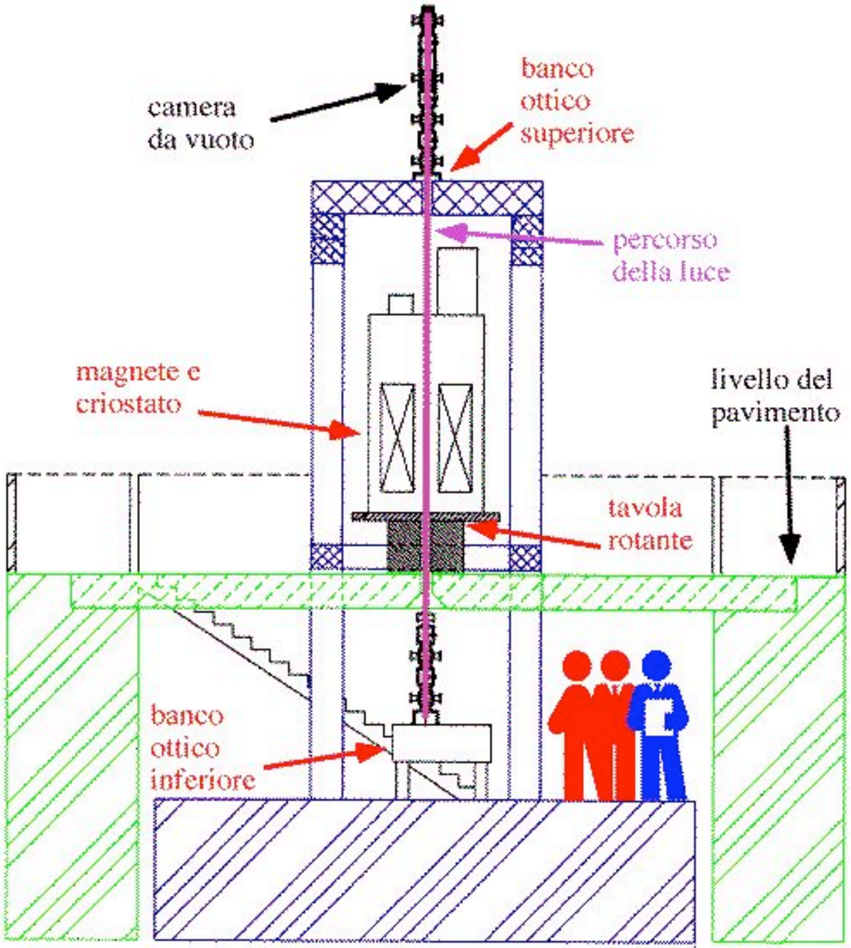
$$A'_{\perp} = A_{\perp}$$

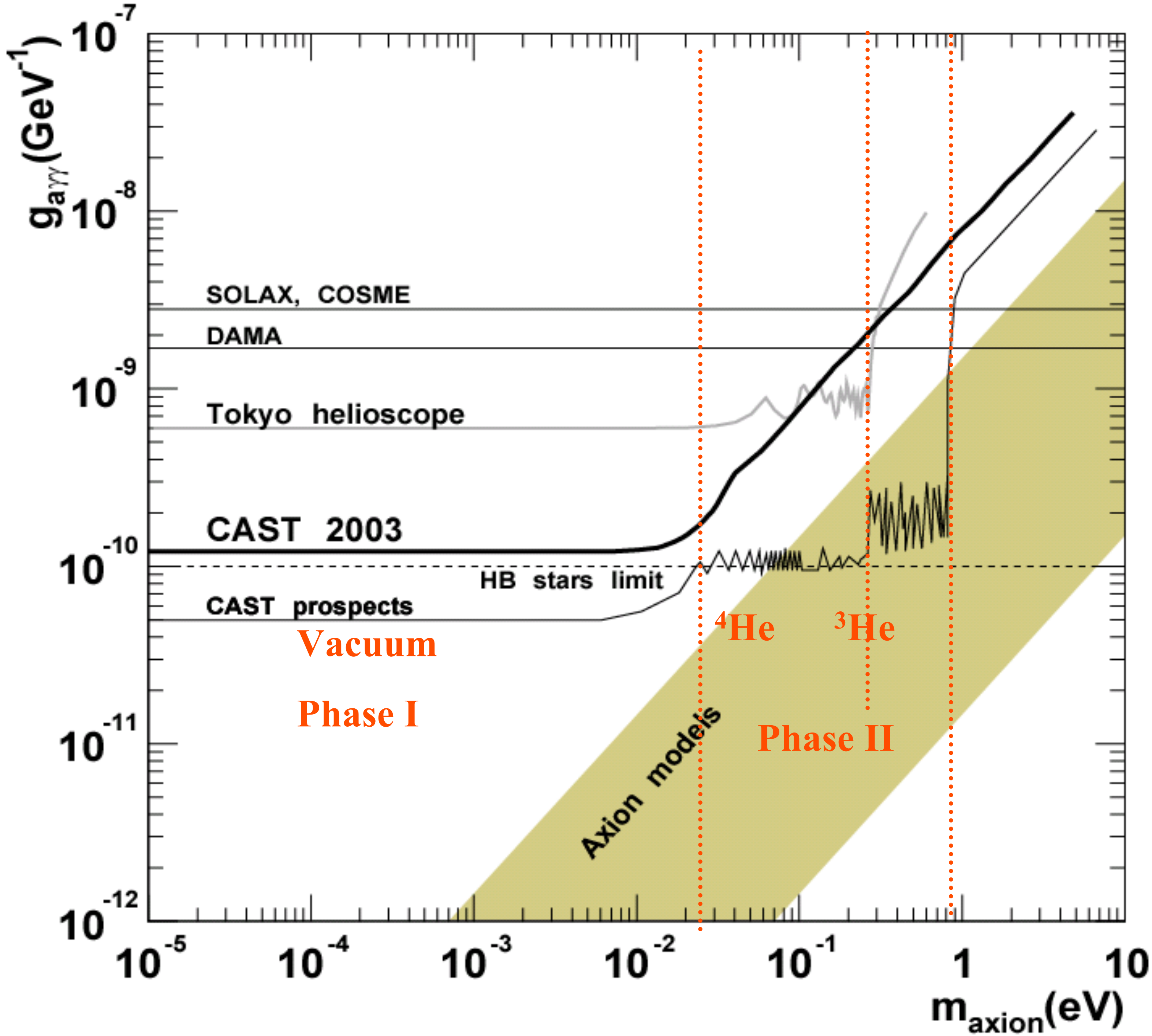
$$p = 4\frac{B_0^{\,2}\omega^2}{M_a^{\,2} m_a^{\,4}}\sin^2\left(\frac{m_a^{\,2}L}{4\omega}\right)$$

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

$$\psi = 2\frac{B_0^{\,2}\omega^2}{M_a^{\,2} m_a^{\,4}}\left[\frac{m_a^{\,2}L}{2\omega} - \sin\left(\frac{m_a^{\,2}L}{2\omega}\right)\right]$$

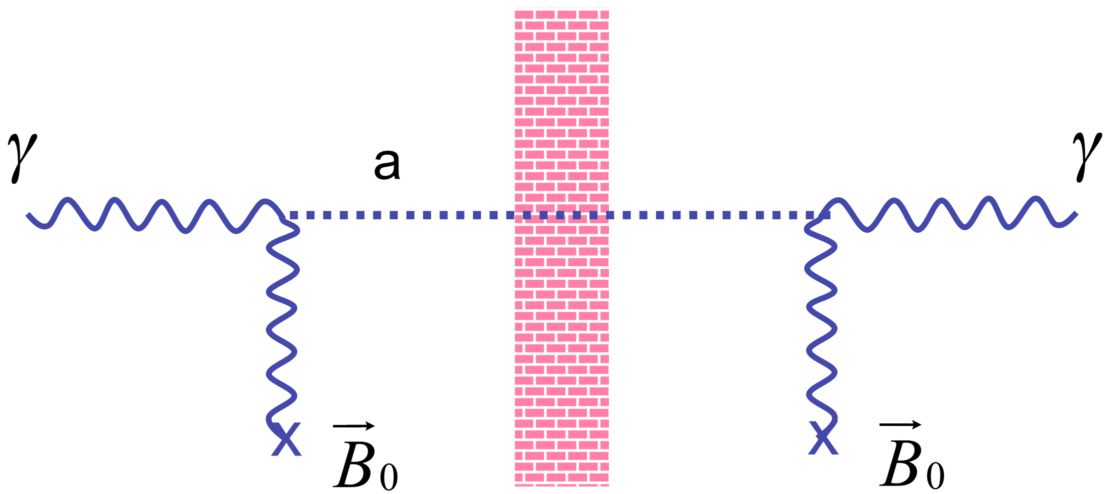
PVLAS


camera
da vuoto
banco
ottico
superiore
percorso
della luce
magnete e
criostato
livello del
pavimento
tavola
rotante
banco
ottico
inferiore



$g_{a\gamma\gamma}$ (GeV^{-1})
SOLAX, COSME
DAMA
Tokyo helioscope
CAST 2003
HB stars limit
CAST prospects
Vacuum
Phase I
^{4}He
^{3}He
Phase II
Axion models
m_{axion}(eV)

Shining light through walls



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

K. van Bibber
et al. '87

A. Ringwald '03

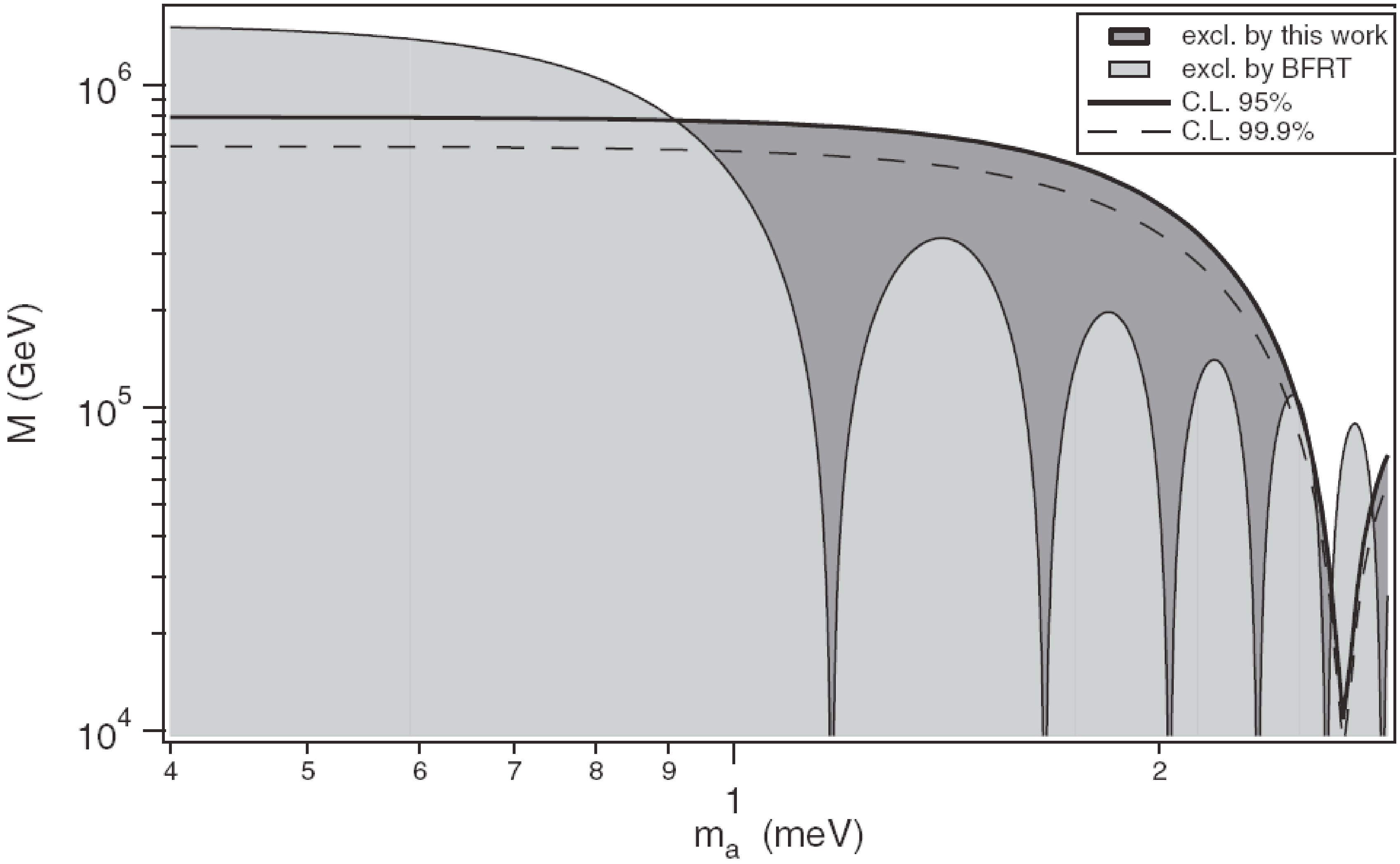
R. Rabadan,
A. Ringwald and
C. Sigurdson '05

P. Pugnat et al. 05

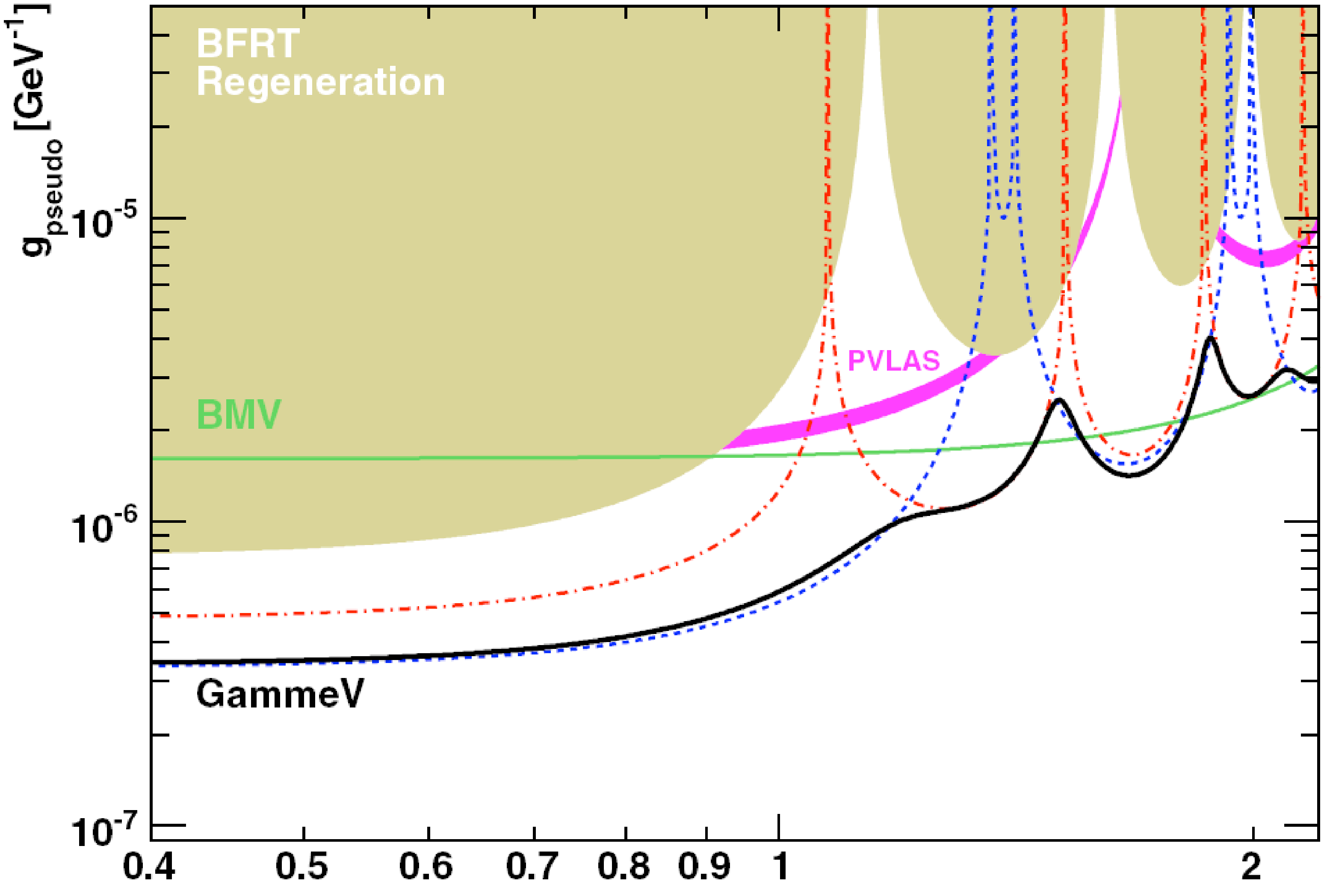
R. Battesti et al.

A. Afanasev et al.

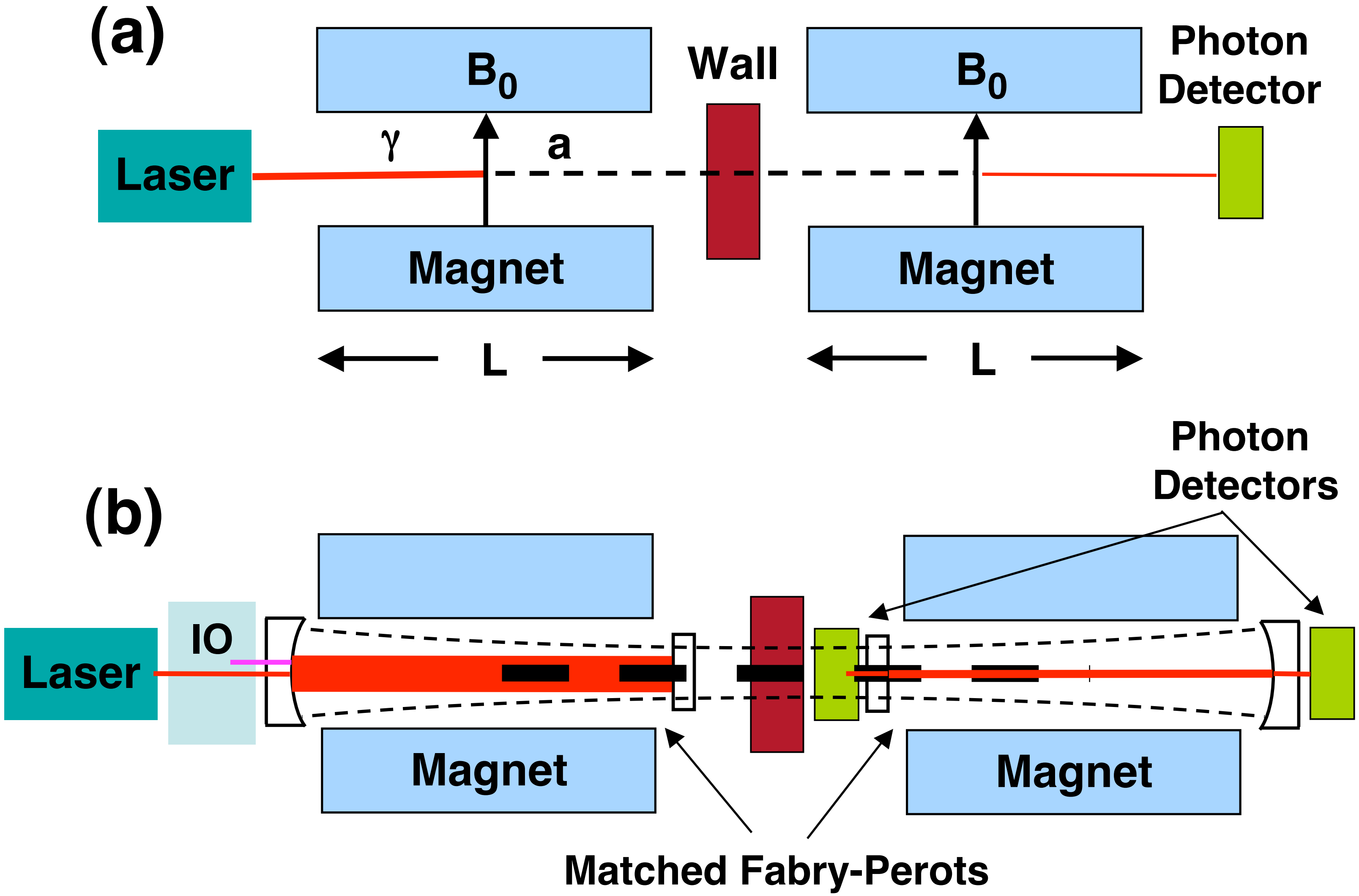
From C. Robilliard et al. (BMV), PRL 99 (2007) 190403



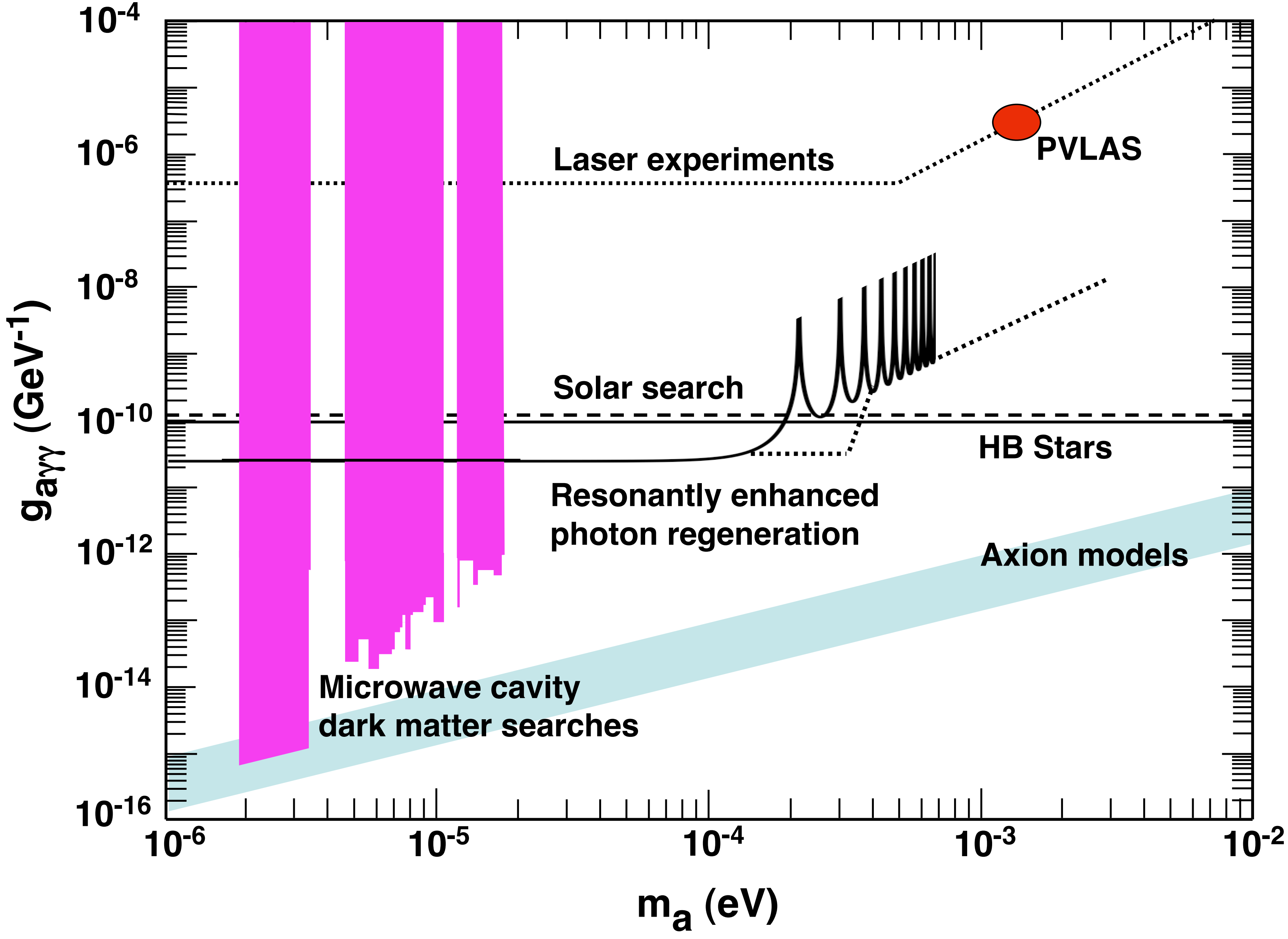
From A. Chau et al. (GammeV) , PRL 100 (2008) 080402



Resonantly Enhanced Axion-Photon Regeneration



Hoogeveen (1996); P.S., Tanner and van Bibber (2007)



Laser experiments
PVLAS
Solar search
HB Stars
Resonantly enhanced
photon regeneration
Axion models
Microwave cavity
dark matter searches
$g_{a\gamma\gamma}$ (GeV^{-1})
m_a (eV)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}

Eduardo Guendelman (2007)

- In a magnetic field $\vec{B}(\vec{x}) = \hat{z}\, B_0(x,y)$, the dynamics of photons $\vec{A} = \hat{z}\, A(x,y,t)$ and axions $a(x,y,t)$ moving parallel to the x-y plane is equivalent to that of a charged scalar particle (charge q) $\varphi = A + i\, a$ in an electric potential $\Phi(x,y)$:

$$q\, \Phi(x,y) = \frac{1}{2} g\, B_0(x,y)$$

- So, a photon beam may be deflected by an inhomogeneous magnetic field.

Macroscopic forces mediated by axions

$$L_{a\bar{f}f} = g_f \frac{m_f}{f_a} a \bar{f} \left(i\gamma_5 + \theta_f \right) f$$

forces coupled to
the f spin density

background of
magnetic forces

forces coupled to
the f number density

$\vartheta_f \quad 10^{-17}$

Theory:

J. Moody and
F. Wilczek '84

Experiment:

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

Conclusions

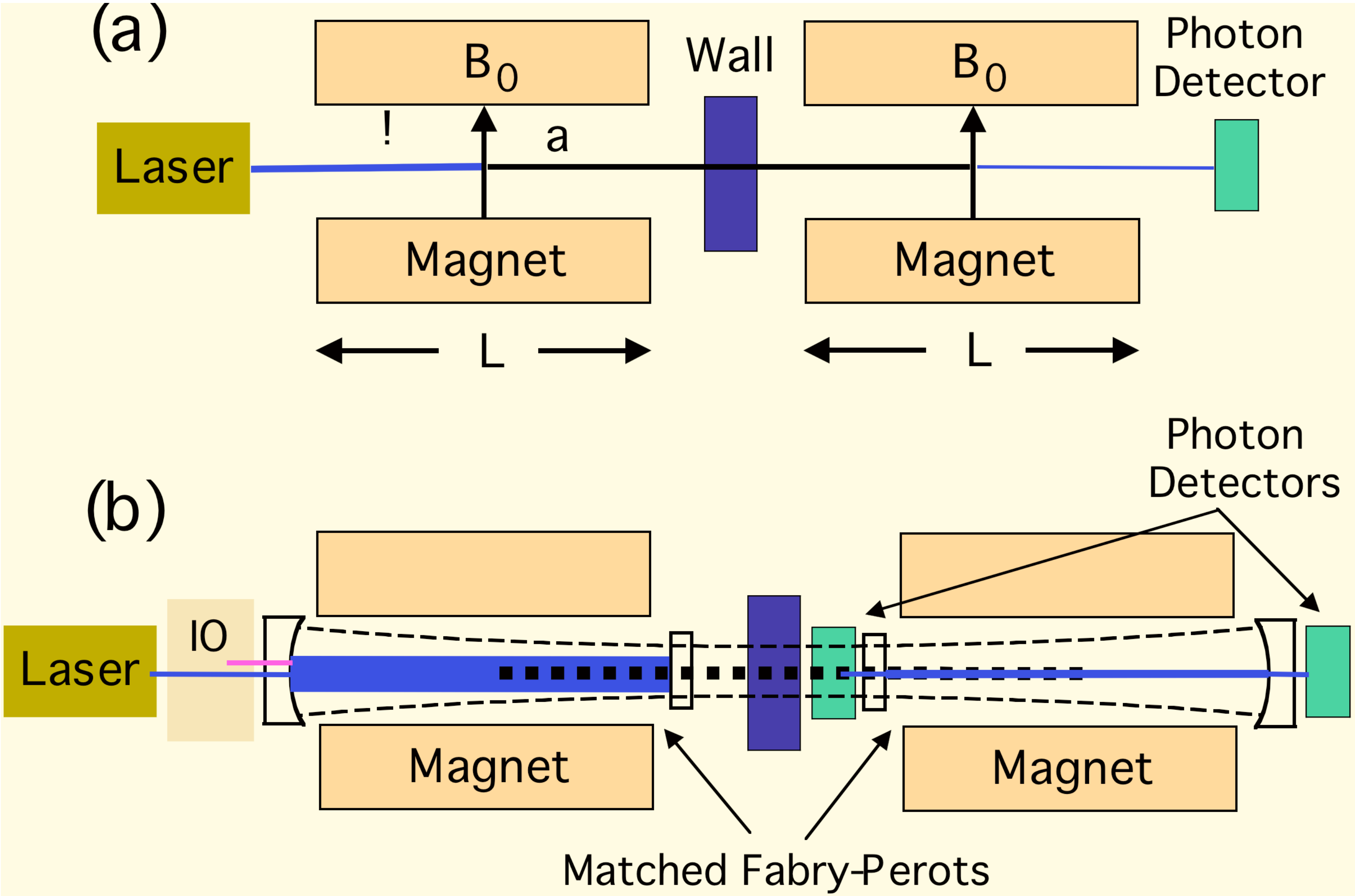
Axions solve the strong CP problem and are a cold dark matter candidate.

Axions haven't been found yet.

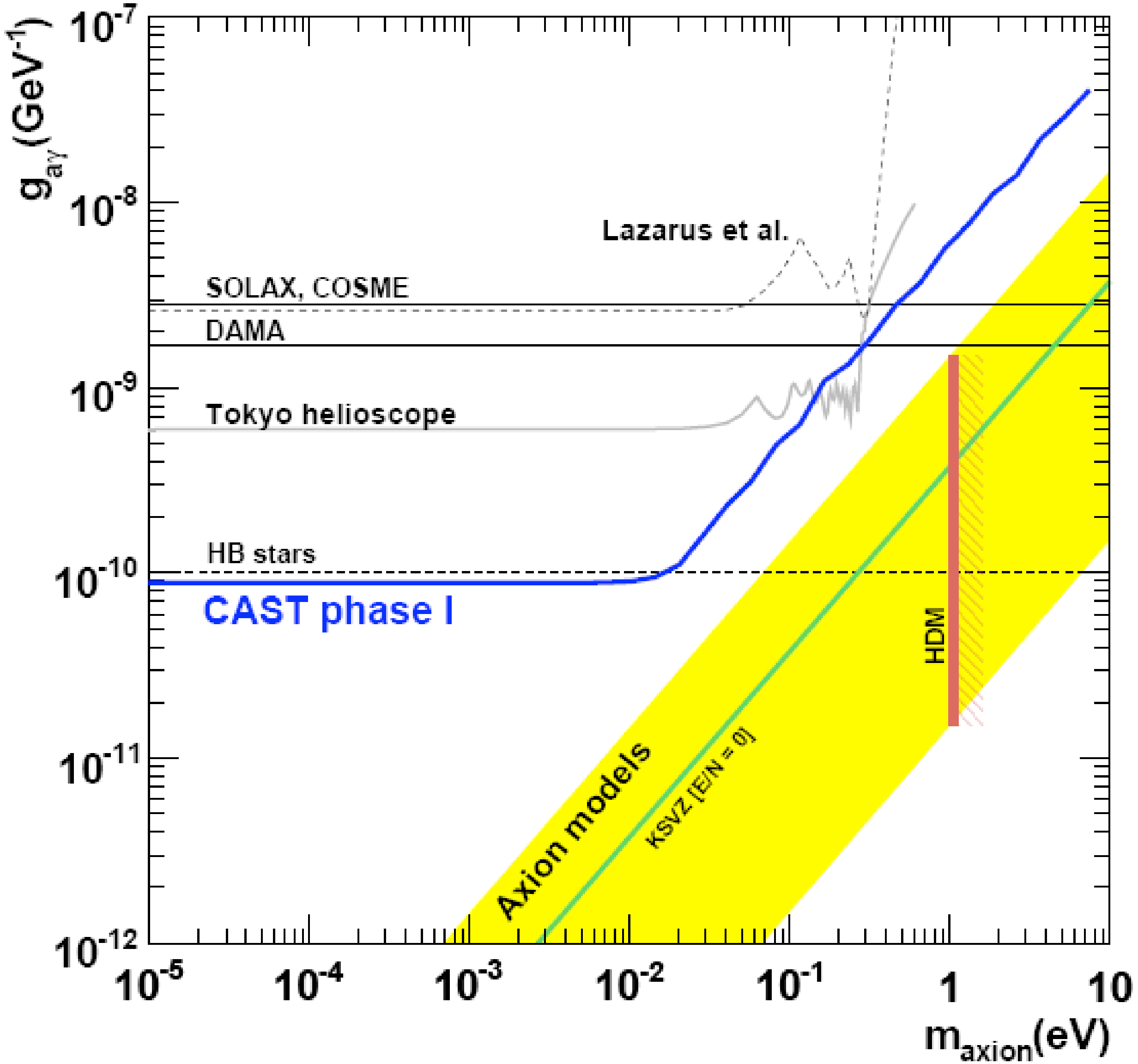
If axions exist, they are present on Earth as dark matter and emitted by the Sun.

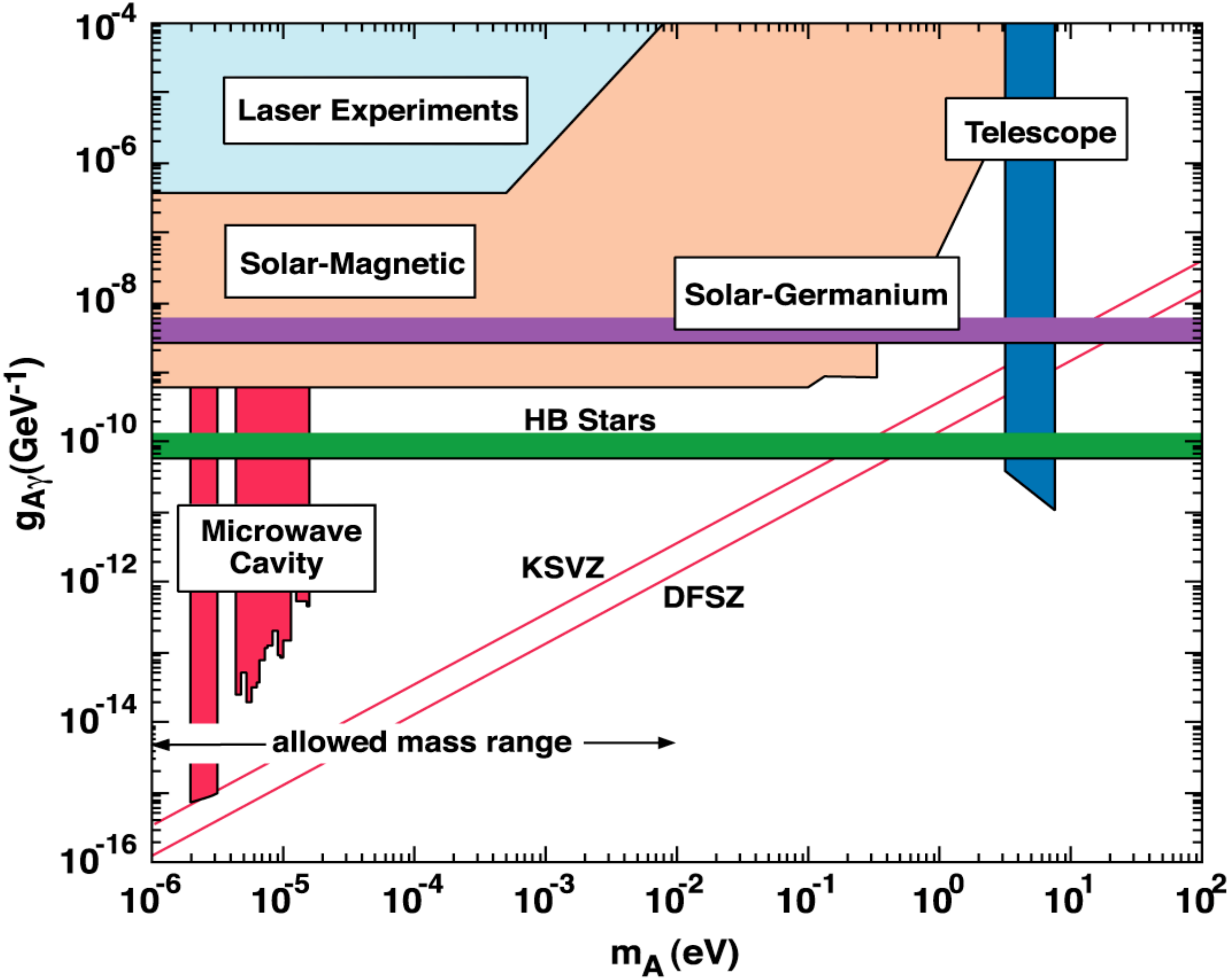
If an axion signal is found, it will provide a rich trove of information on the structure of the Milky Way halo, and/or the Solar interior.

Resonantly Enhanced Axion-Photon Regeneration
P.S., D. Tanner and K. van Bibber, PRL 98 (2007) 172002



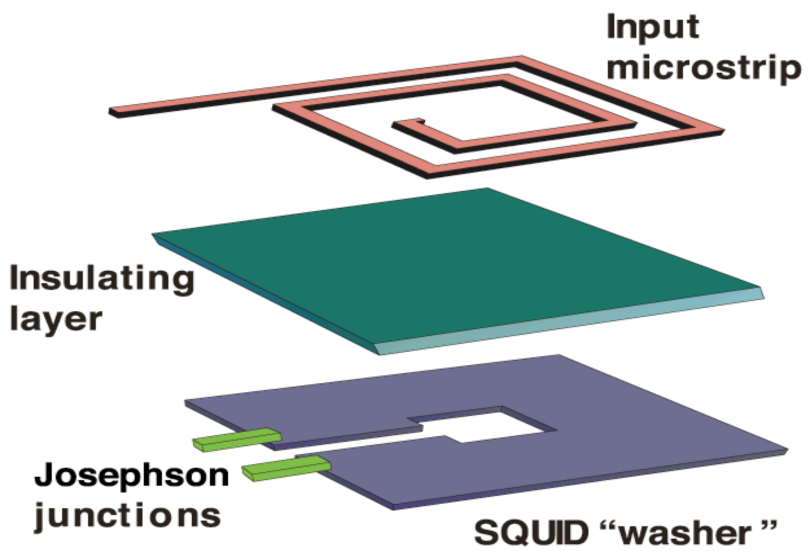
from S. Andriamonje et al. (CAST) , hep-ex: 0702006

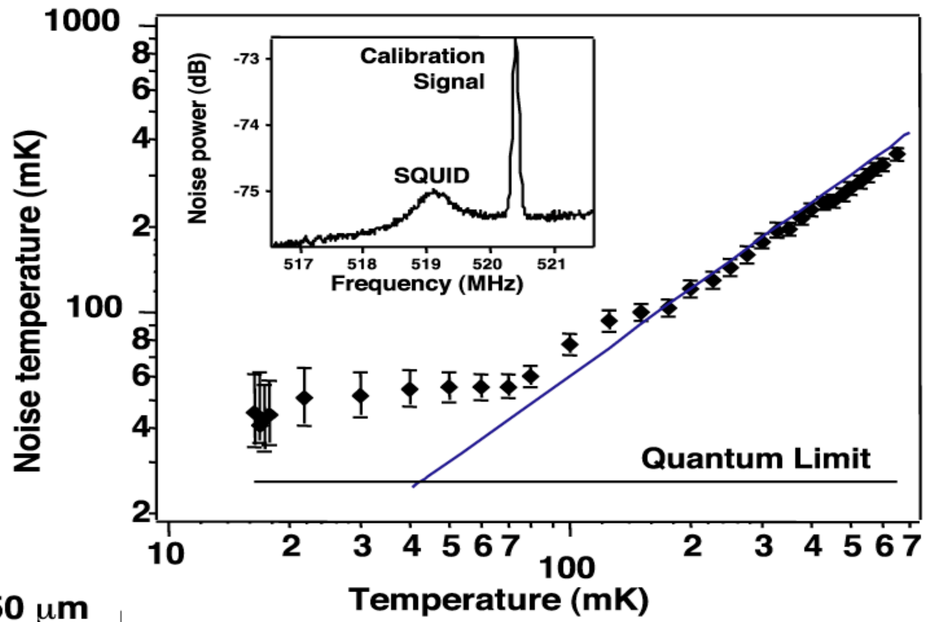


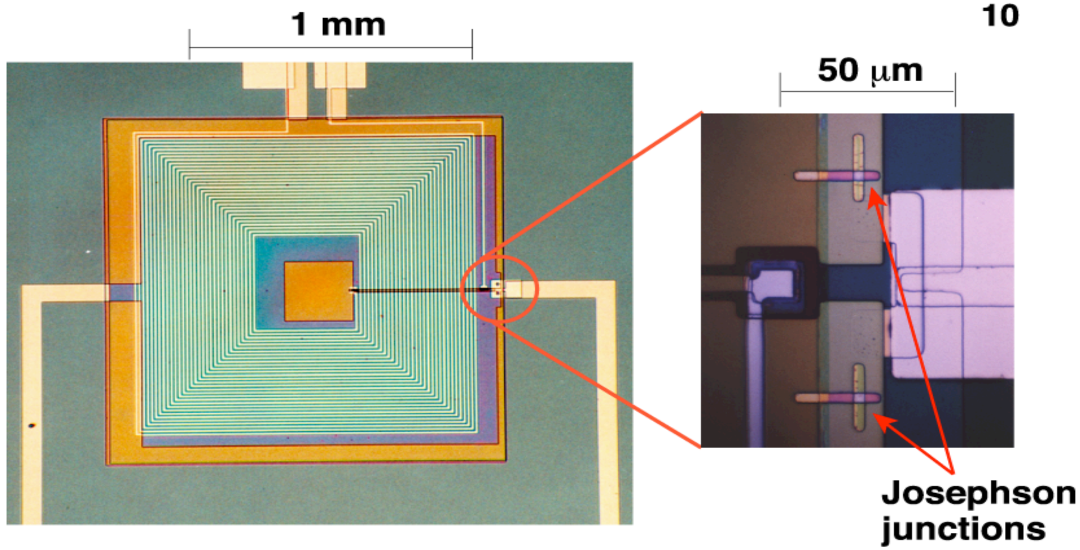


Laser Experiments
Telescope
Solar-Magnetic
Solar-Germanium
HB Stars
Microwave Cavity
KSVZ
DFSZ
allowed mass range
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$g_{A\gamma}(GeV^{-1})$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m_A (eV)

ADMX Upgrade: replace HEMTs (2 K) with SQUIDs (50 mK)



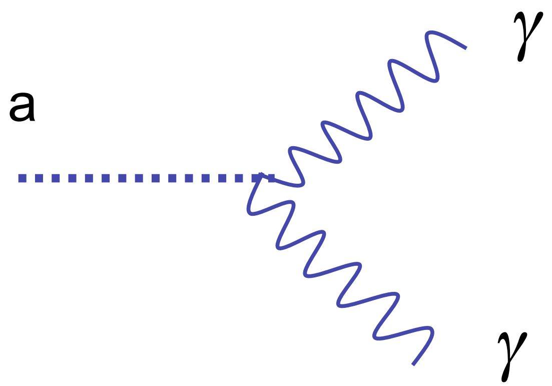




(J. Clarke *et al.*, U.C. Berkeley)

In phase II of the upgrade, the experiment is cooled with a dilution refrigerator.

Telescope search for cosmic axions



M.S. Bershady, M.T.Ressell and M.S. Turner '90

galaxy clusters

3 – 8 eV

B.D. Blout et al. '02

nearby dwarf galaxies

298 – 363 μ eV

$g_{a\gamma\gamma} < 1.0 \cdot 10^{-9}\ \text{GeV}^{-1}$

$$E_\gamma = \frac{m_a}{2}$$

$$\Gamma(a \to 2\gamma) = \frac{1}{0.67 \cdot 10^{25}\ \text{sec}} \left(\frac{m_a}{\text{eV}}\right)^5 \left(\frac{g_\gamma}{0.36}\right)^2$$