Axion Theory

P. Sikivie (U. of Florida)

Fourth Patras Workshop on Axions, WIMPs and WISPs

DESY

June 18, 2008

Outline

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

The Strong CP Problem

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

Because the strong interactions
conserve P and CP, $\theta \leq 10^{-10}$.

The Standard Model does not provide a
reason for θ to be so tiny,

but a relatively small modification of the
model does provide a reason …

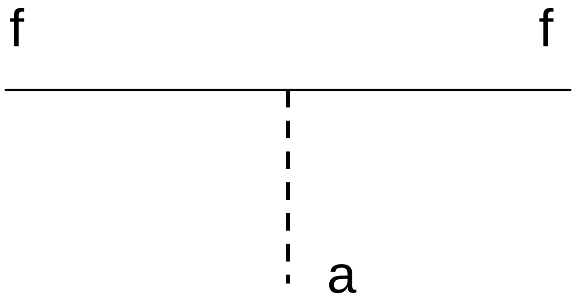
If a $U_{PQ}(1)$ symmetry is assumed,

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

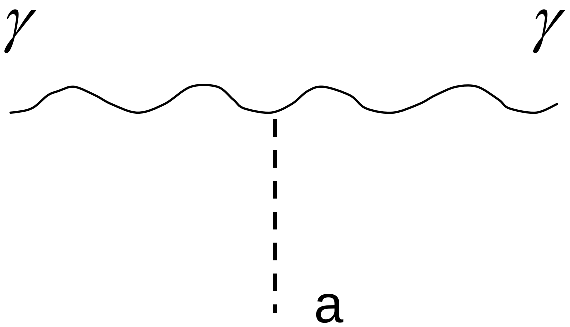
$\theta = \dfrac{a}{f_a}$ relaxes to zero,

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

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



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

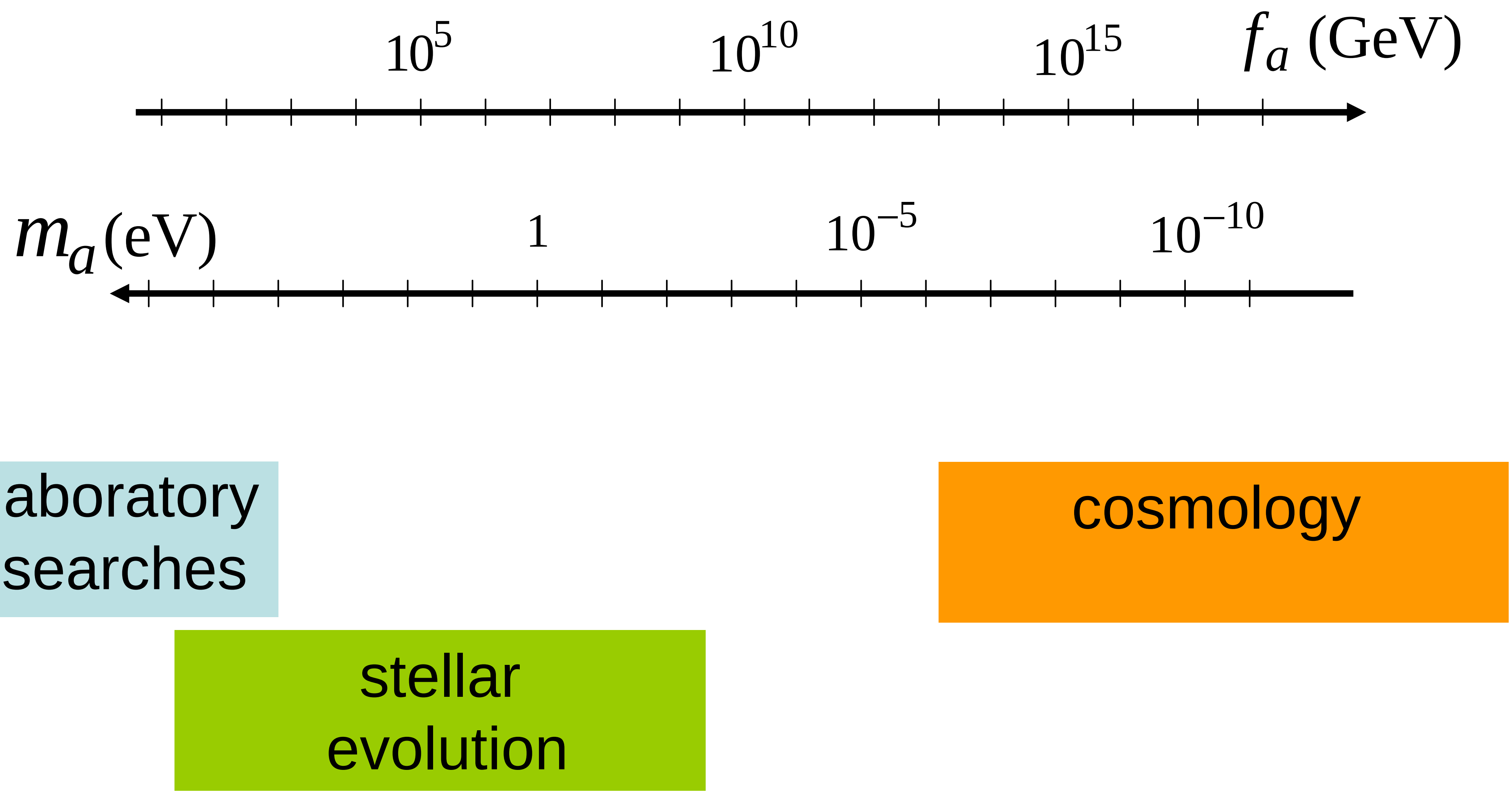


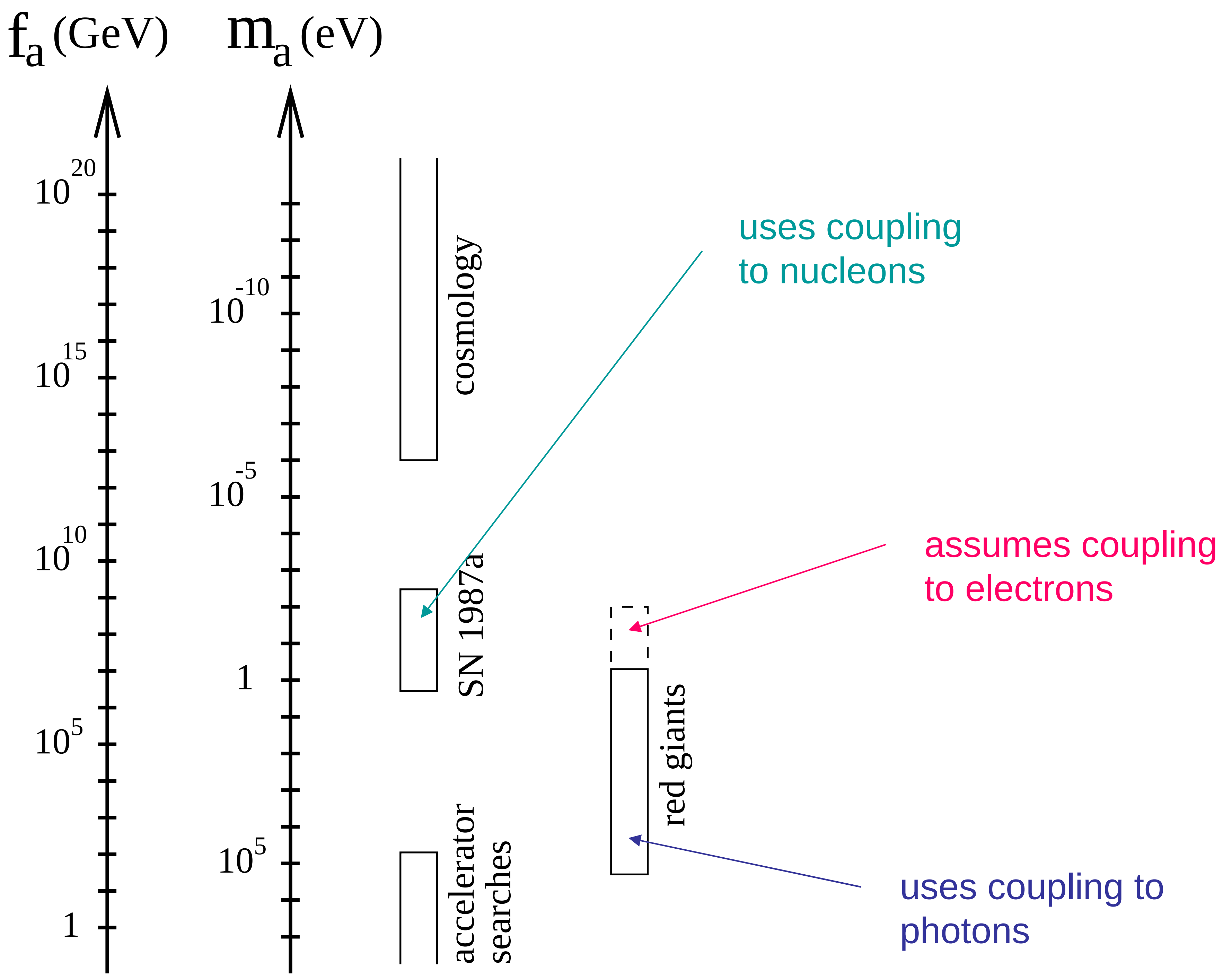
$$L_{a\gamma\gamma} = g_\gamma\, \frac{\alpha}{\pi}\, \frac{a}{f_a}\, \vec{E} \cdot \vec{B}$$

g_γ = 0.97 in KSVZ model

0.36 in DFSZ model

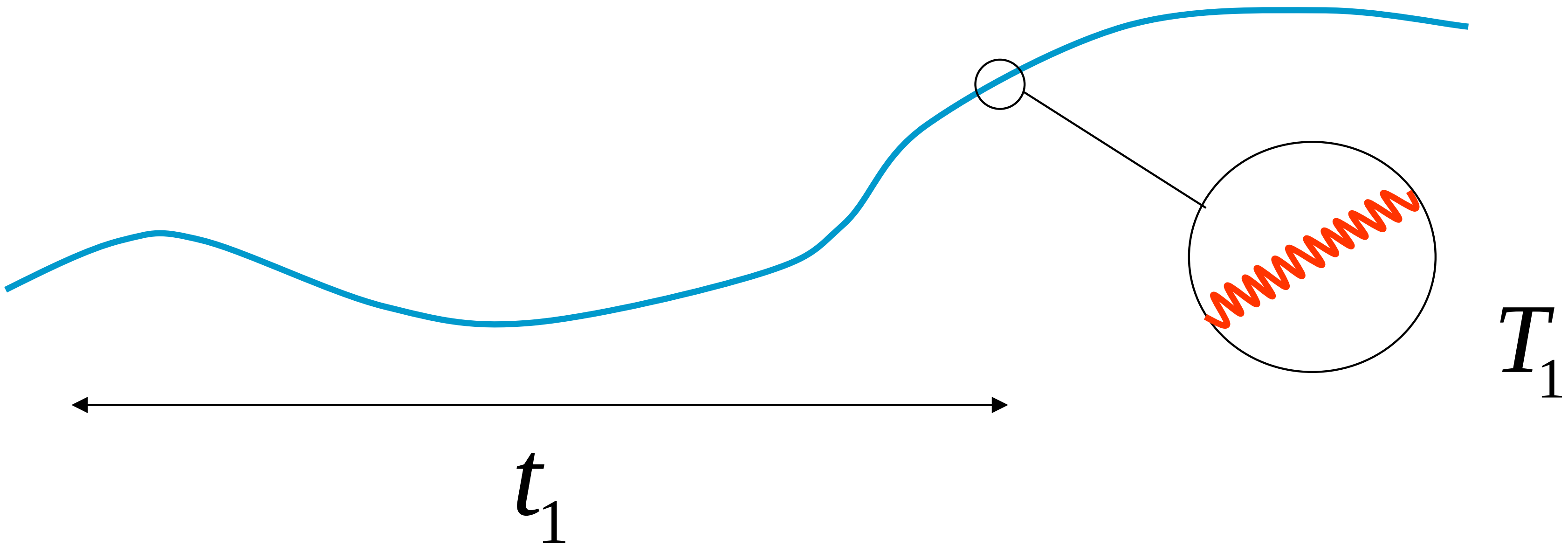
The remaining axion window





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,

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

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

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

Cold Axions

Density

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

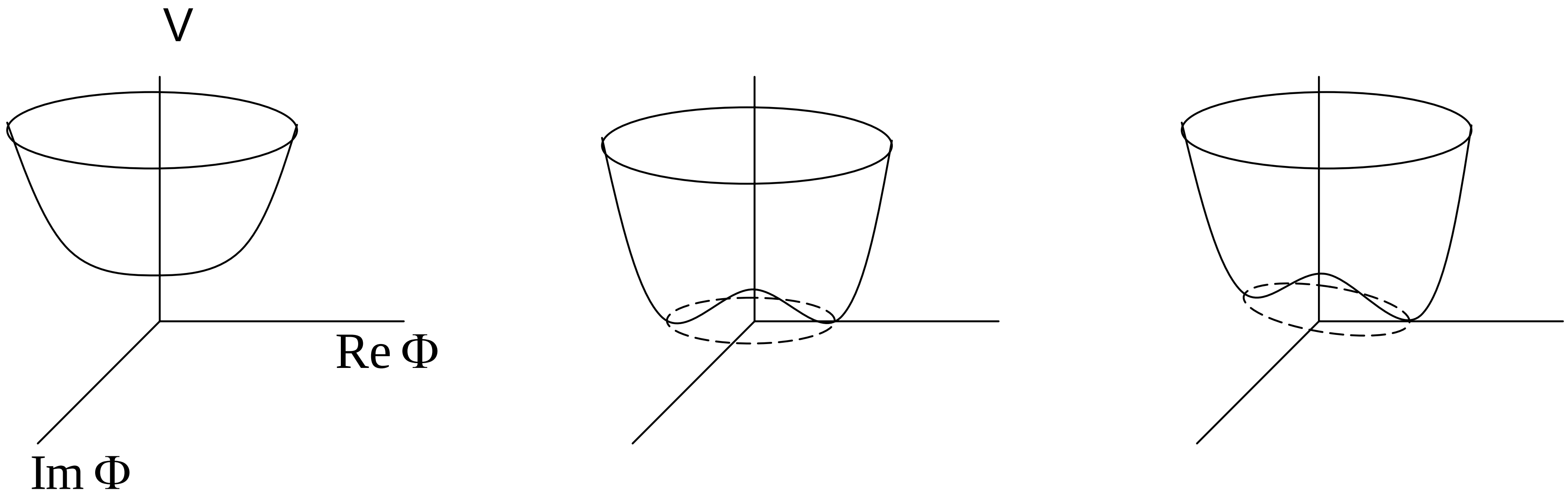
Velocity dispersion

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

Effective temperature

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

Effective potential V(T,Φ)

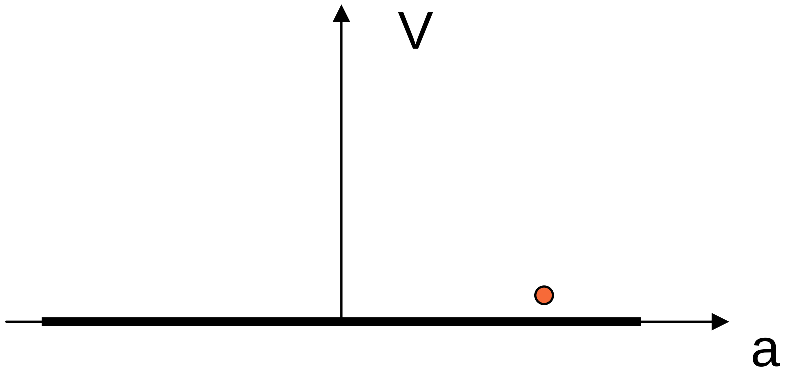


$T > f_a$ $\qquad$ $f_a > T > 1\,\mathrm{GeV}$ $\qquad$ $1\,\mathrm{GeV} > T$

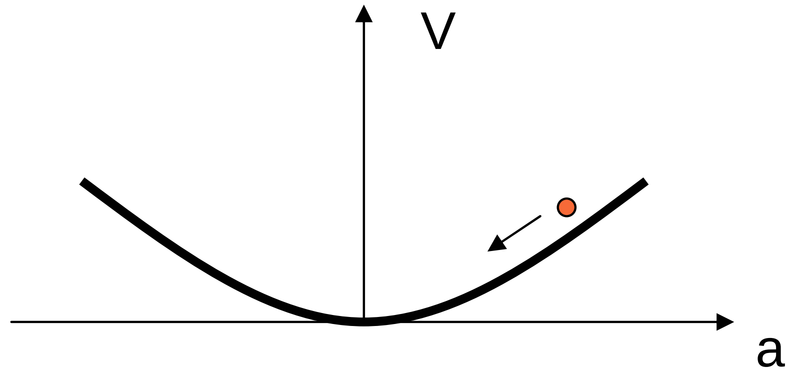
↓ axion strings

↓ axion domain walls

Axion production by vacuum realignment



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

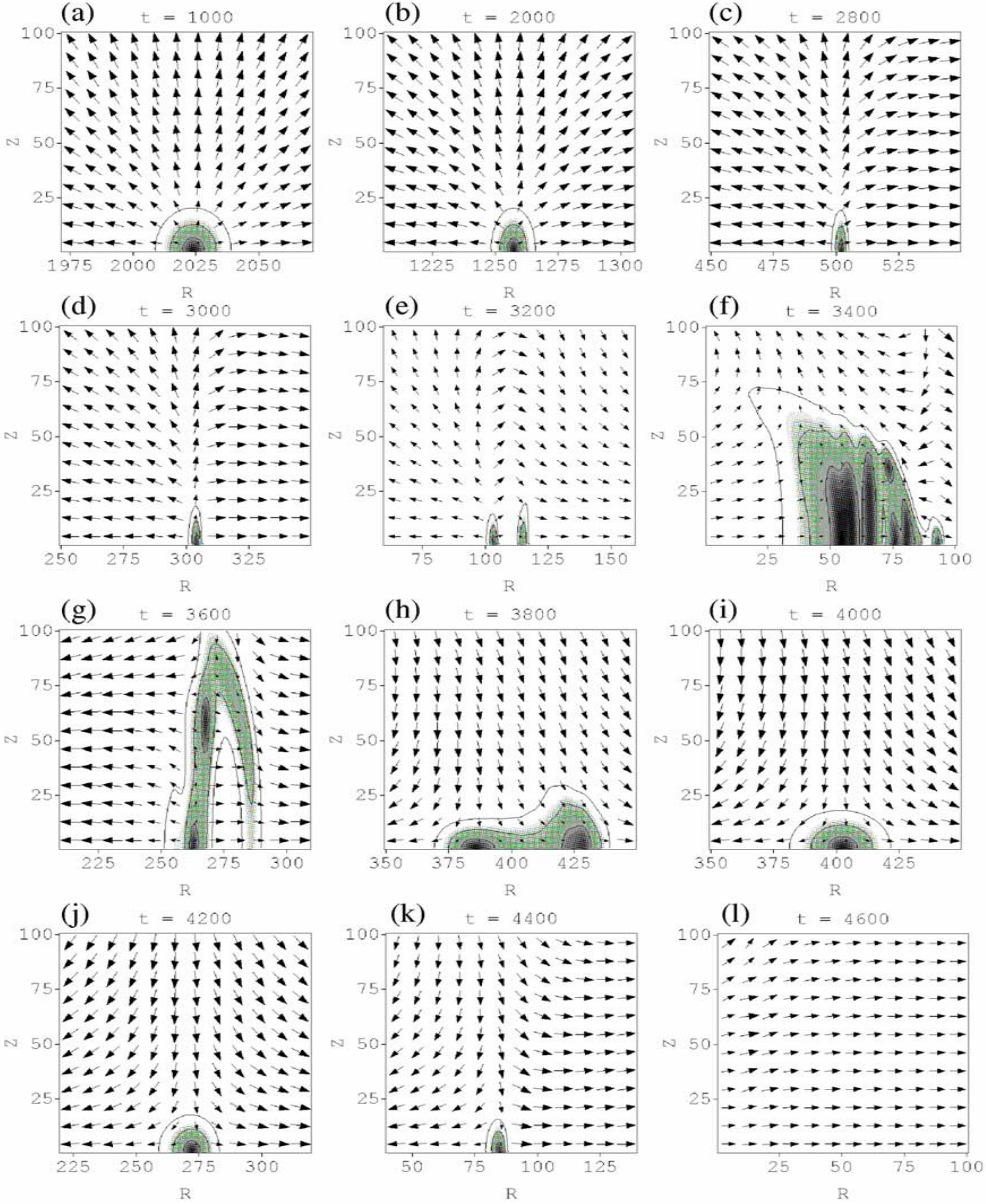


$$T \leq 1\,\mathrm{GeV}$$

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

initial misalignment angle

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

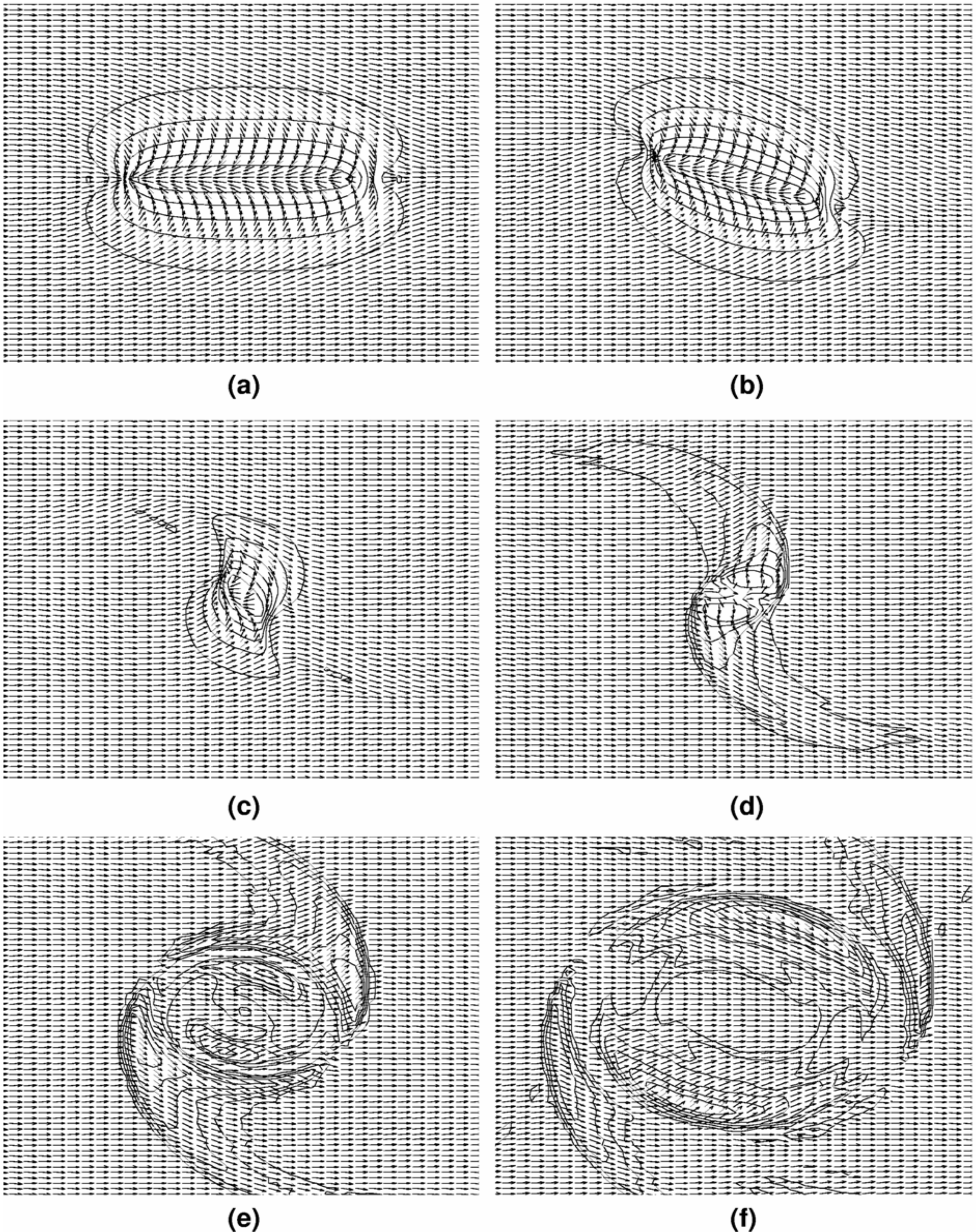


String loop decaying into axion radiation

simulation by
S. Chang, C. Hagmann and PS

see also:
R. Battye and P. Shellard;

M. Yamaguchi, M.Kawasaki and J. Yokoyama



Domain wall bounded by string decaying into axion radiation

If inflation after the PQ phase transition

- $$\Omega_a \sim 0.25 \left(\frac{10^{-5}\ \text{eV}}{m_a} \right)^{\frac{7}{6}} \alpha(t_1)^2$$ may be accidentally suppressed

- $$< \sqrt{a^2} > \sim \frac{H_I}{2\pi}$$ produces isocurvature density perturbations

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

CMBR constraint

Axion isocurvature constraints

$$\text{iff} \quad T_{\text{reheat}} < T_{\text{PQ}}$$

$$\Omega_a < 0.22$$ implies $$\Lambda_I < 5 \cdot 10^{14}\,\text{GeV} \left(\frac{f_a}{10^{12}\,\text{GeV}} \right)^{\frac{5}{24}}$$

$$\delta\rho^{\text{iso}} < 0.3\ \delta\rho_{\text{cdm}}$$ implies

$$\Lambda_I < 10^{13}\,\text{GeV} \ \ \Omega_a^{-\frac{1}{4}} \left(\frac{f_a}{10^{12}\,\text{GeV}} \right)^{\frac{5}{24}}$$

$\Lambda_I = V_I^{\frac{1}{4}}$ = scale of inflation

If no inflation after the PQ phase transition

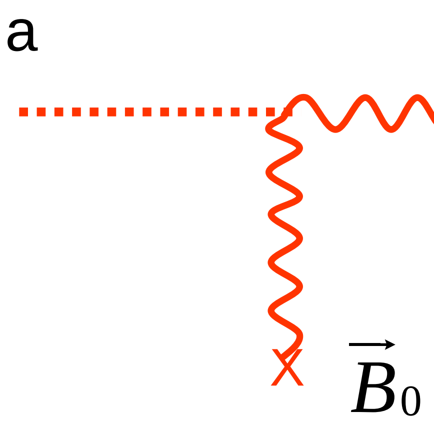
- cold axions are produced by vacuum realignment, string decay and wall decay

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

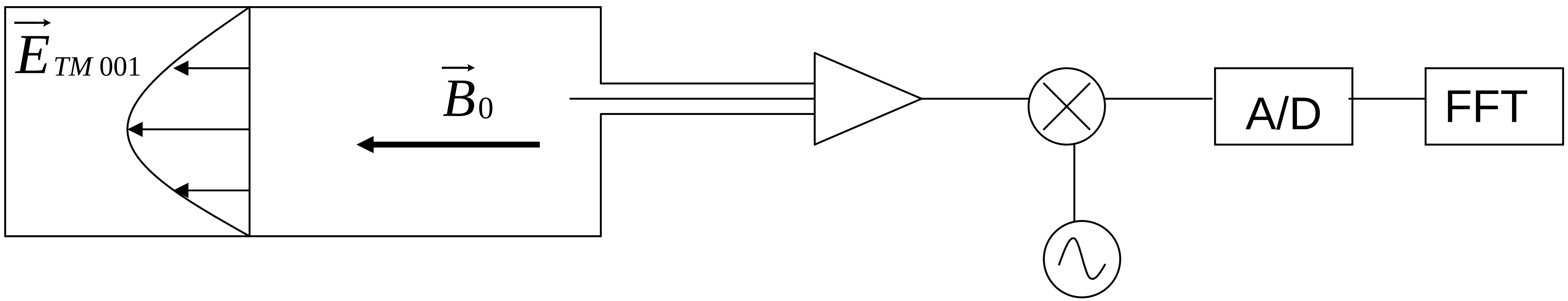
- axion miniclusters appear

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

Axion dark matter is detectable



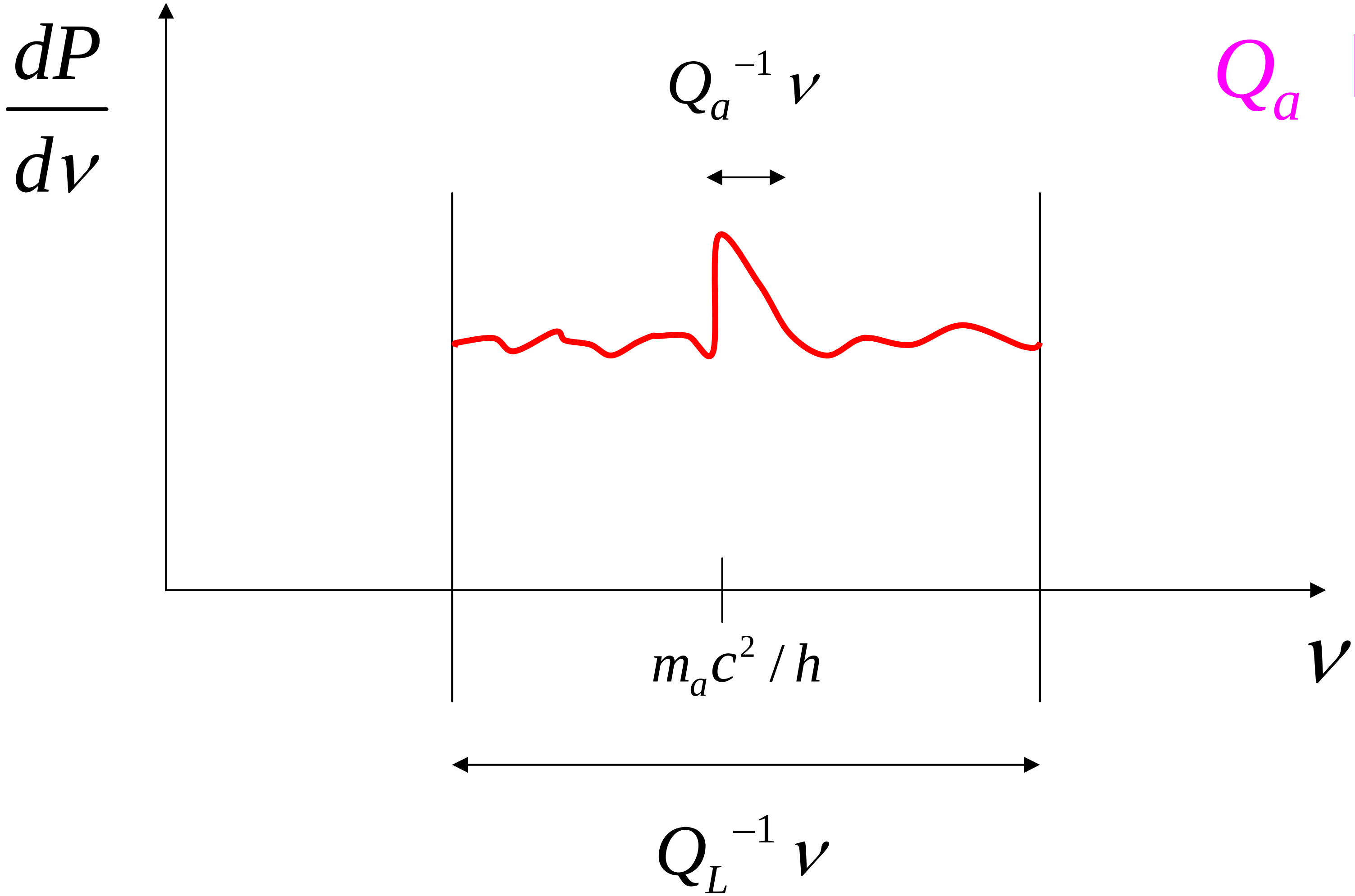
$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



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

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

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



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

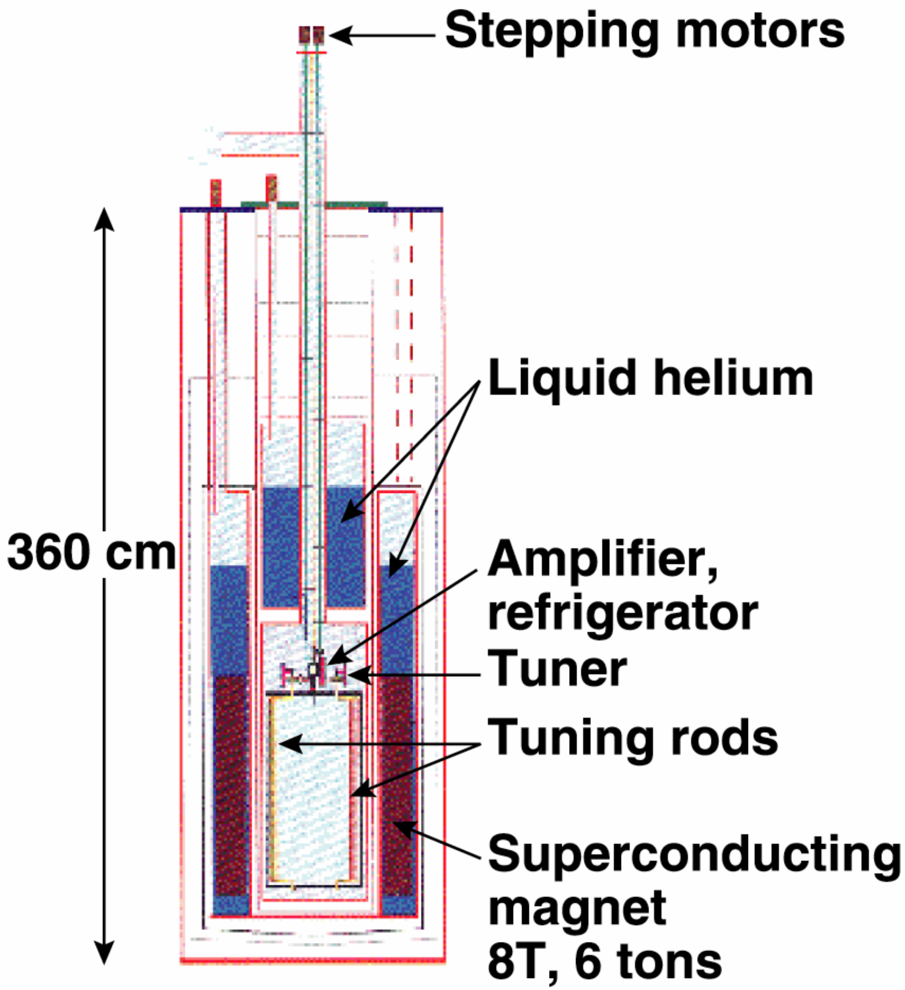
UC Berkeley: J. Clarke

Sheffield U: E. Daw

NRAO: R. Bradley

Axion Dark Matter eXperiment

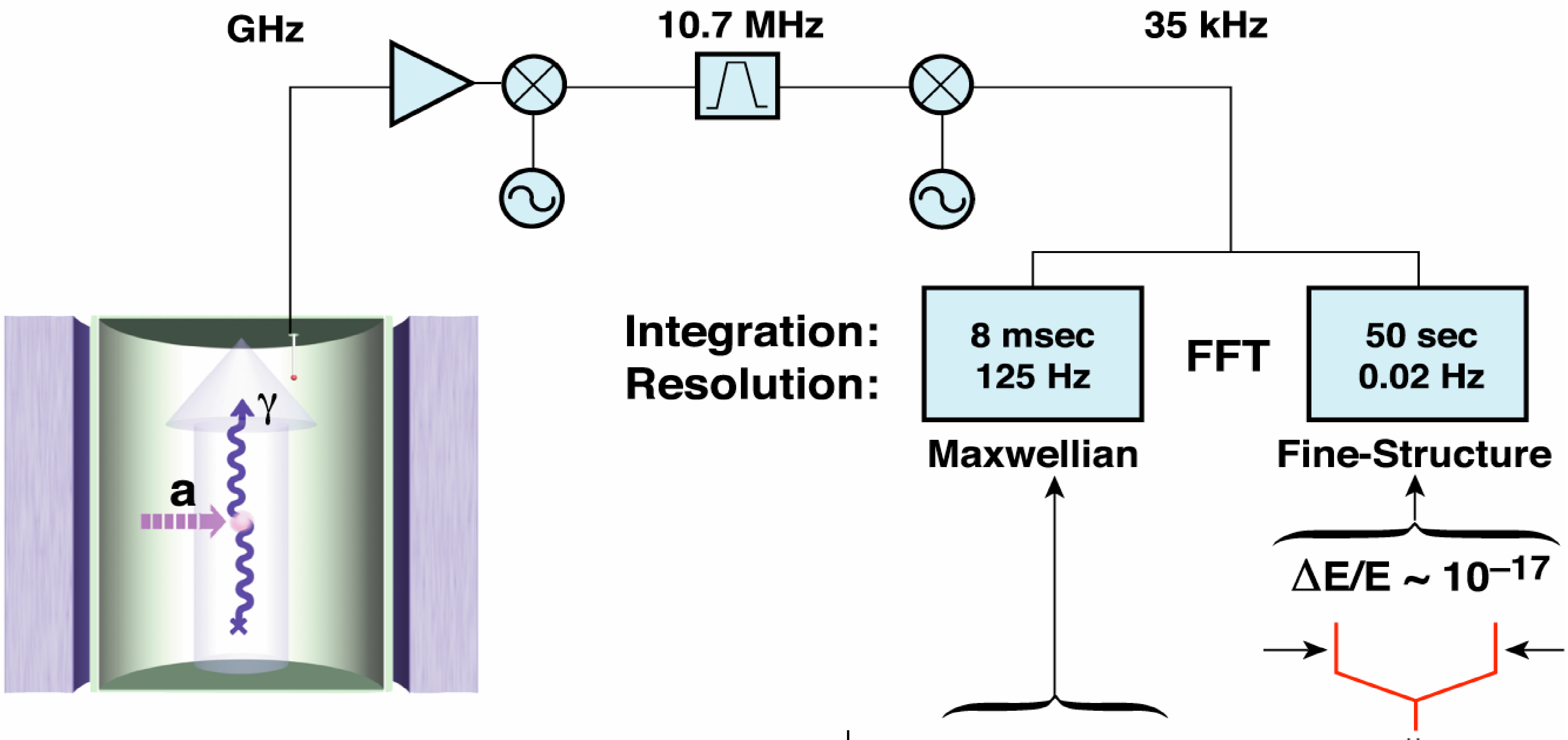
Magnet with Insert (side view)

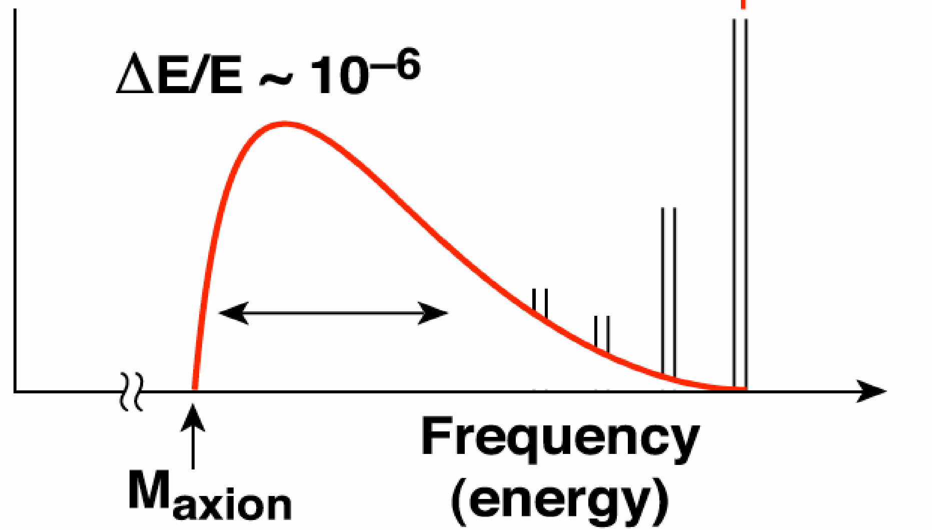


Pumped LHe → T ~ 1.5 k

Magnet

8 T, 1 m × 60 cm ∅



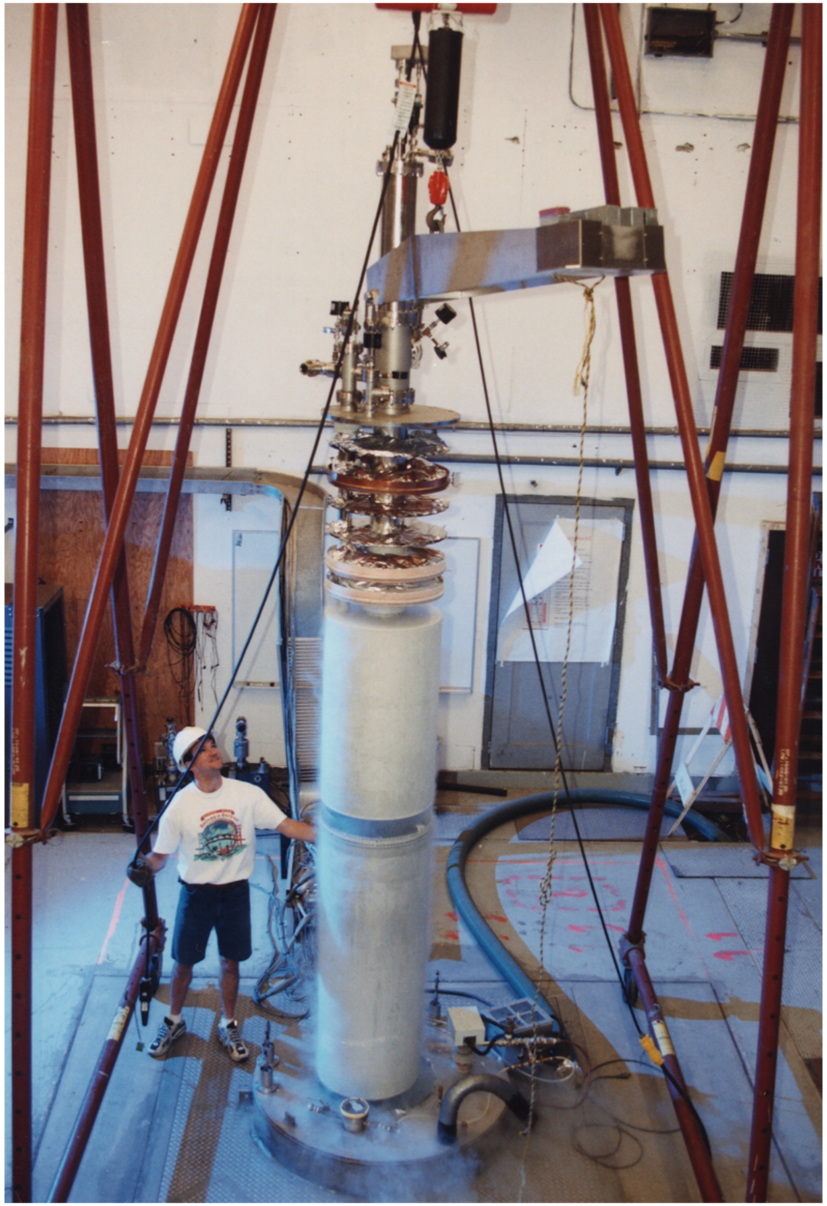


High resolution analysis of the signal may reveal fine structure …

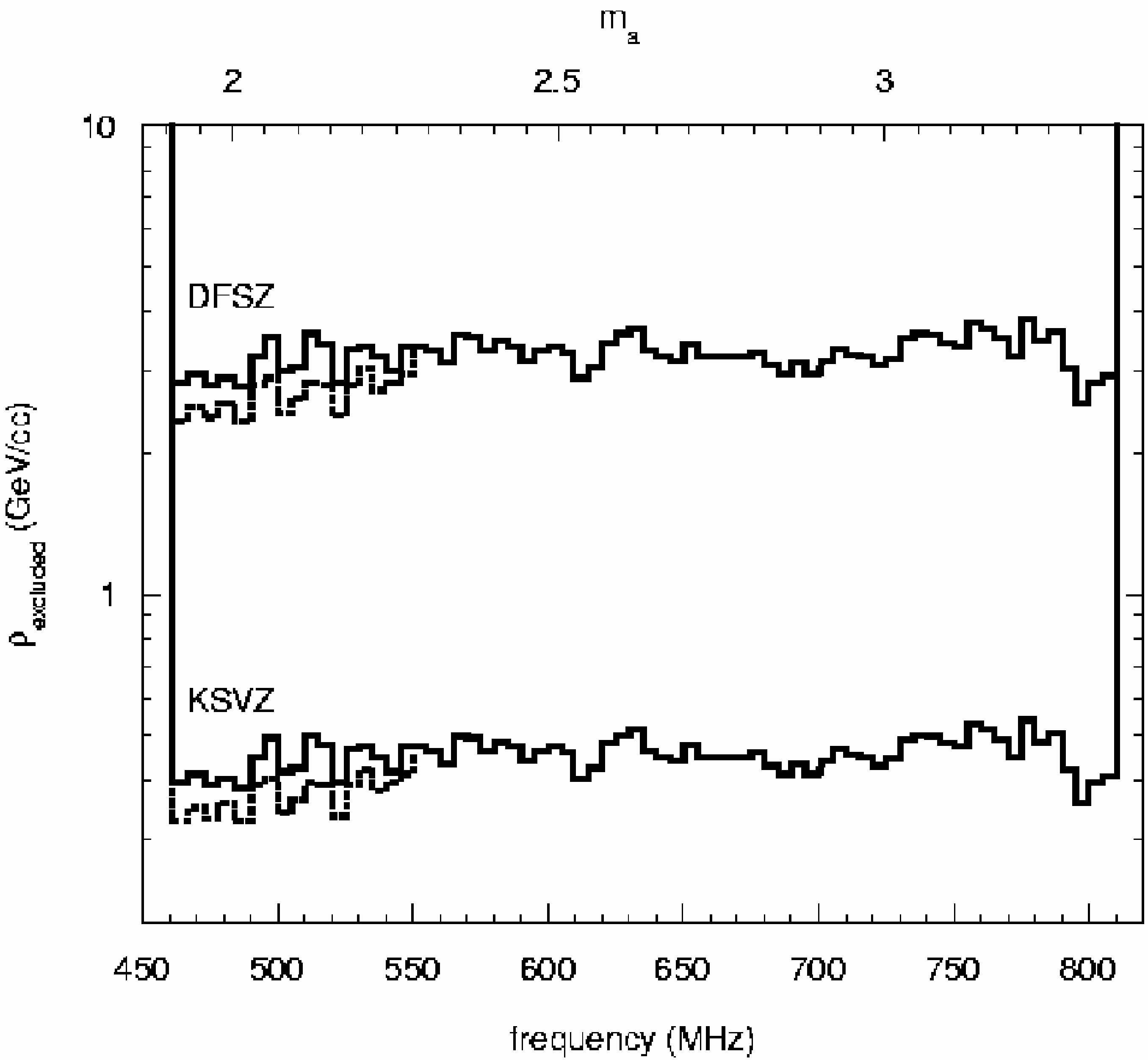
ADMX hardware

high Q cavity

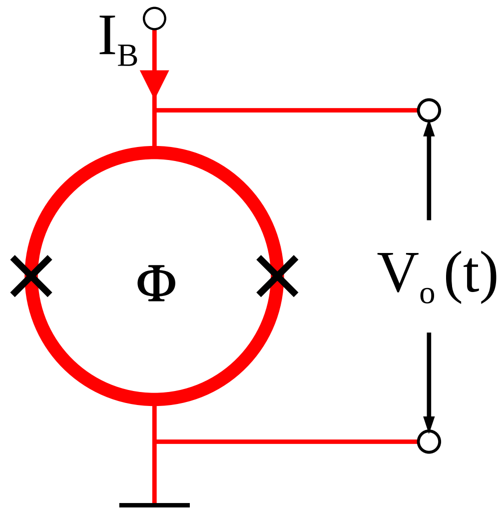
experimental insert



ADMX MedRes limits

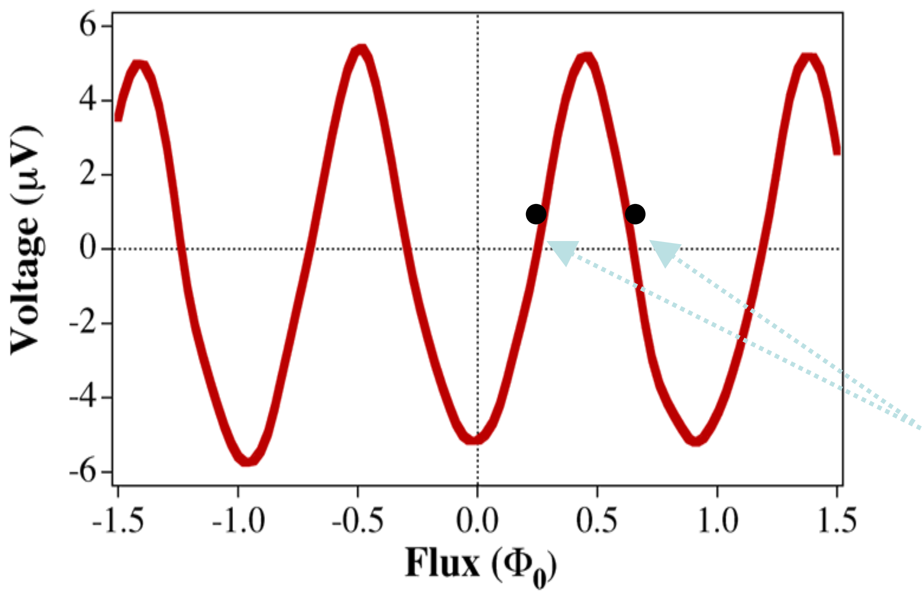


Upgrade with SQUID Amplifiers



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

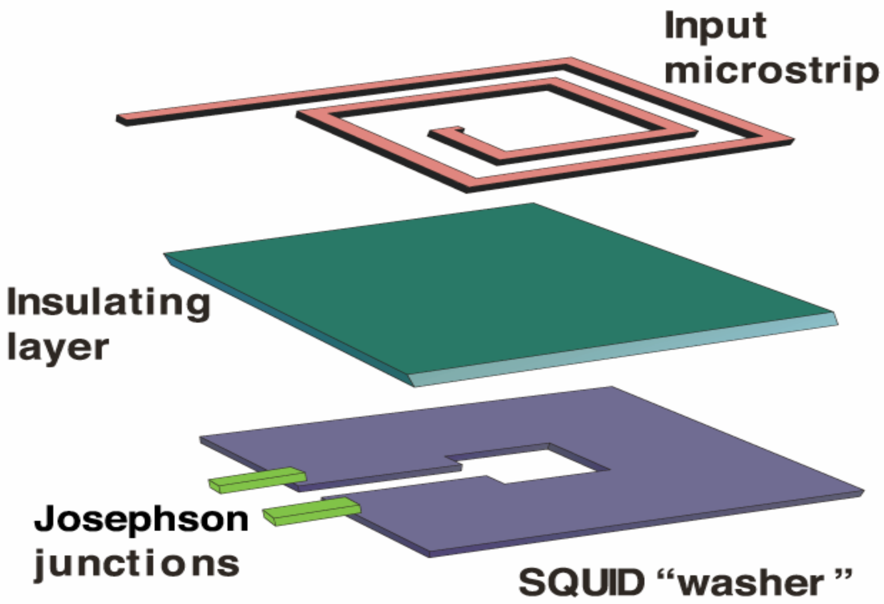
SQUID noise arises from Nyquist noise in shunt resistance scales linearly with T

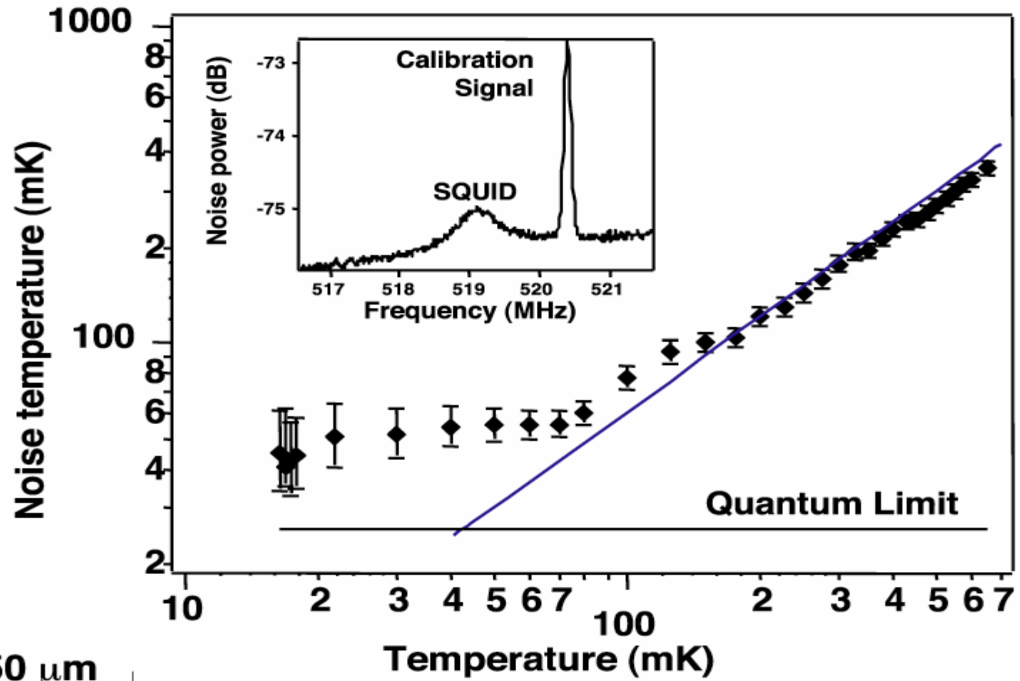


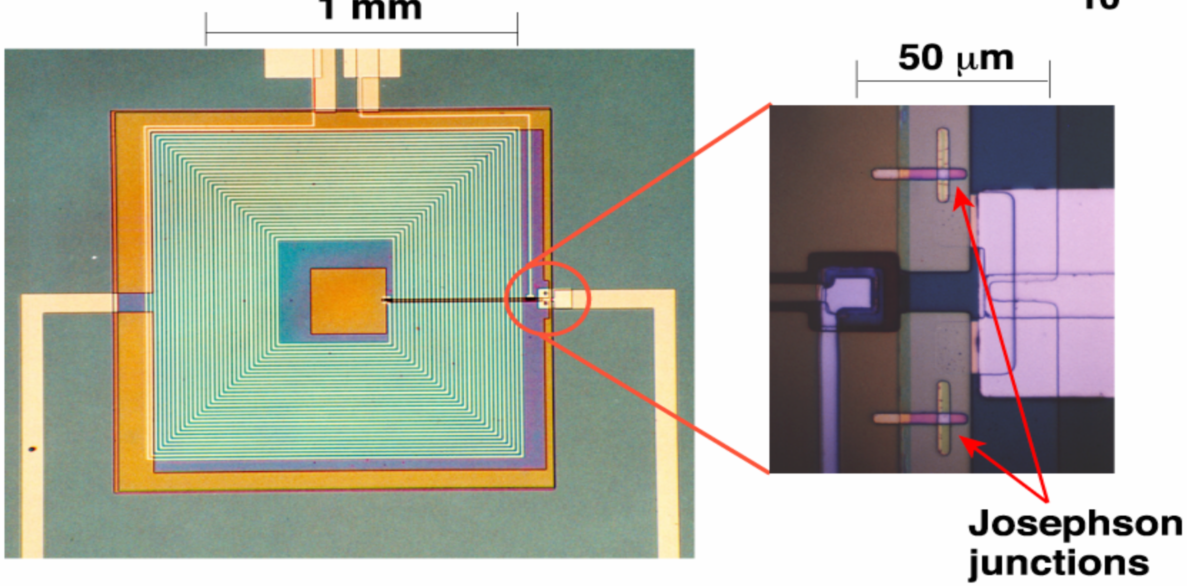
However, SQUIDs of conventional design are poor amplifiers above 100 MHz (parasitic couplings).

Flux-bias to here

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







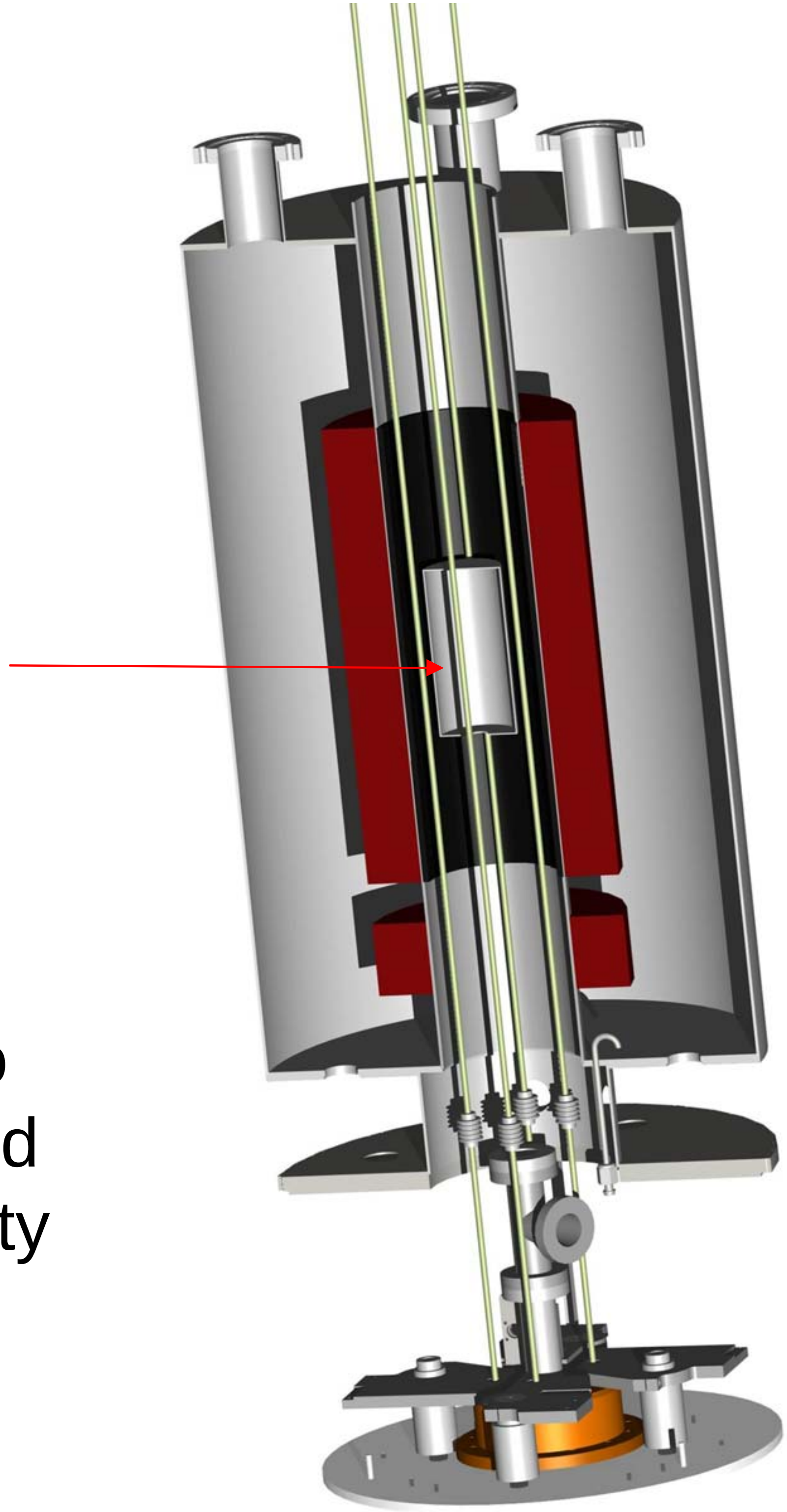
(J. Clarke *et al.*, U.C. Berkeley)

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.

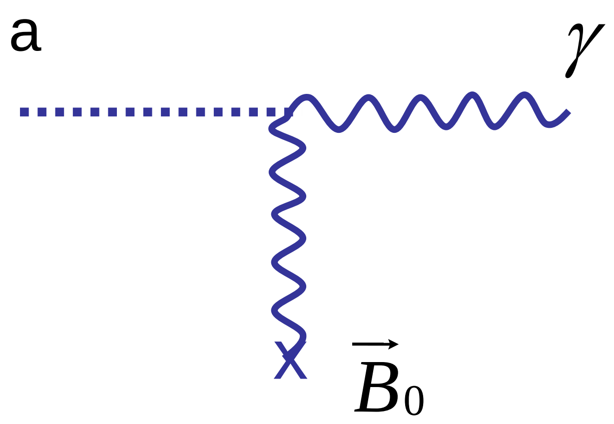
From outwards-in:

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

$$p(a \longleftrightarrow \gamma) = \left(\frac{\alpha \; g_\gamma}{\pi \;\; f_a} \right)^2 \mathrm{B}_0^{\;2} \left(\frac{\sin \frac{q_z L}{2}}{q_z} \right)^2$$

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

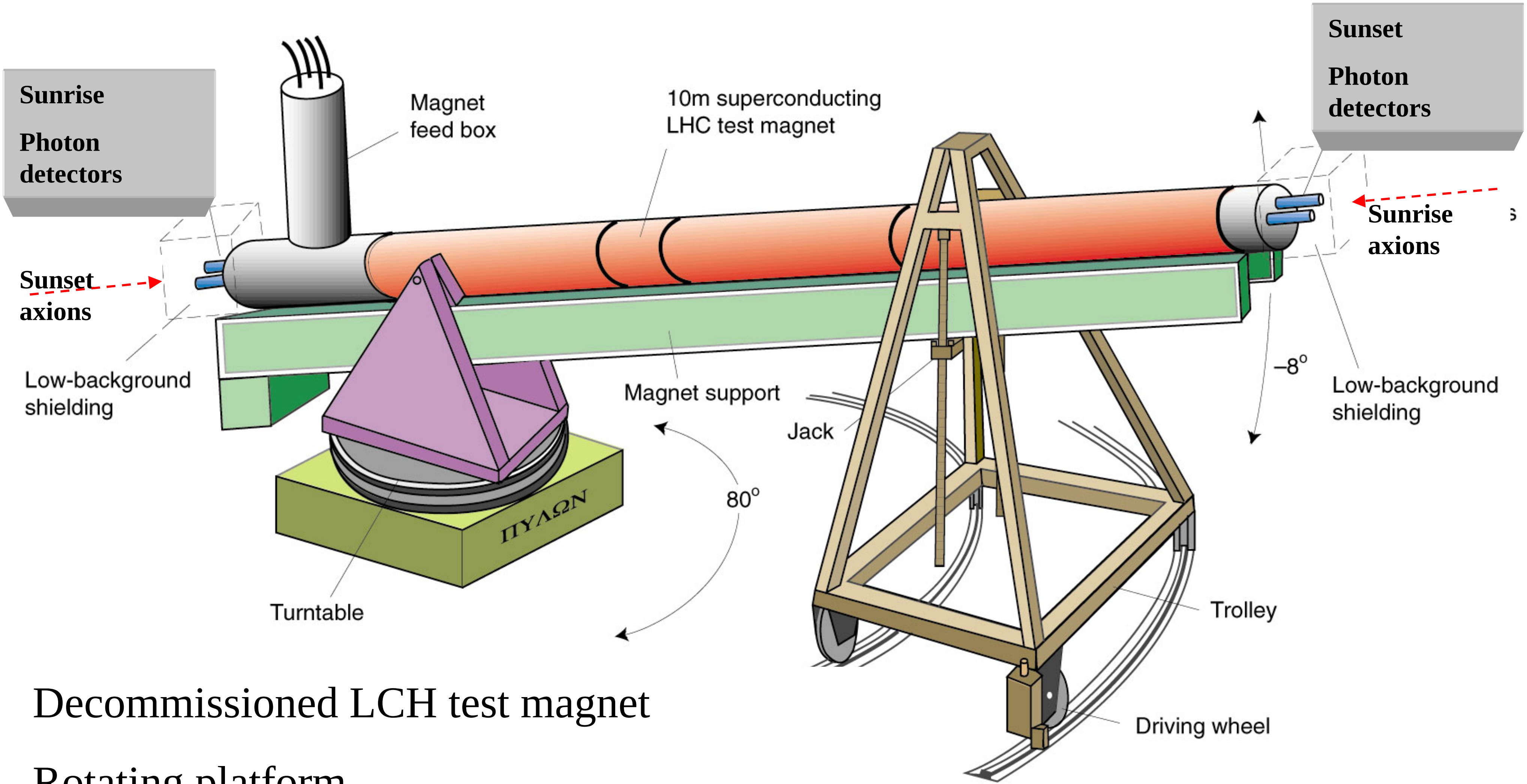
Theory

- 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

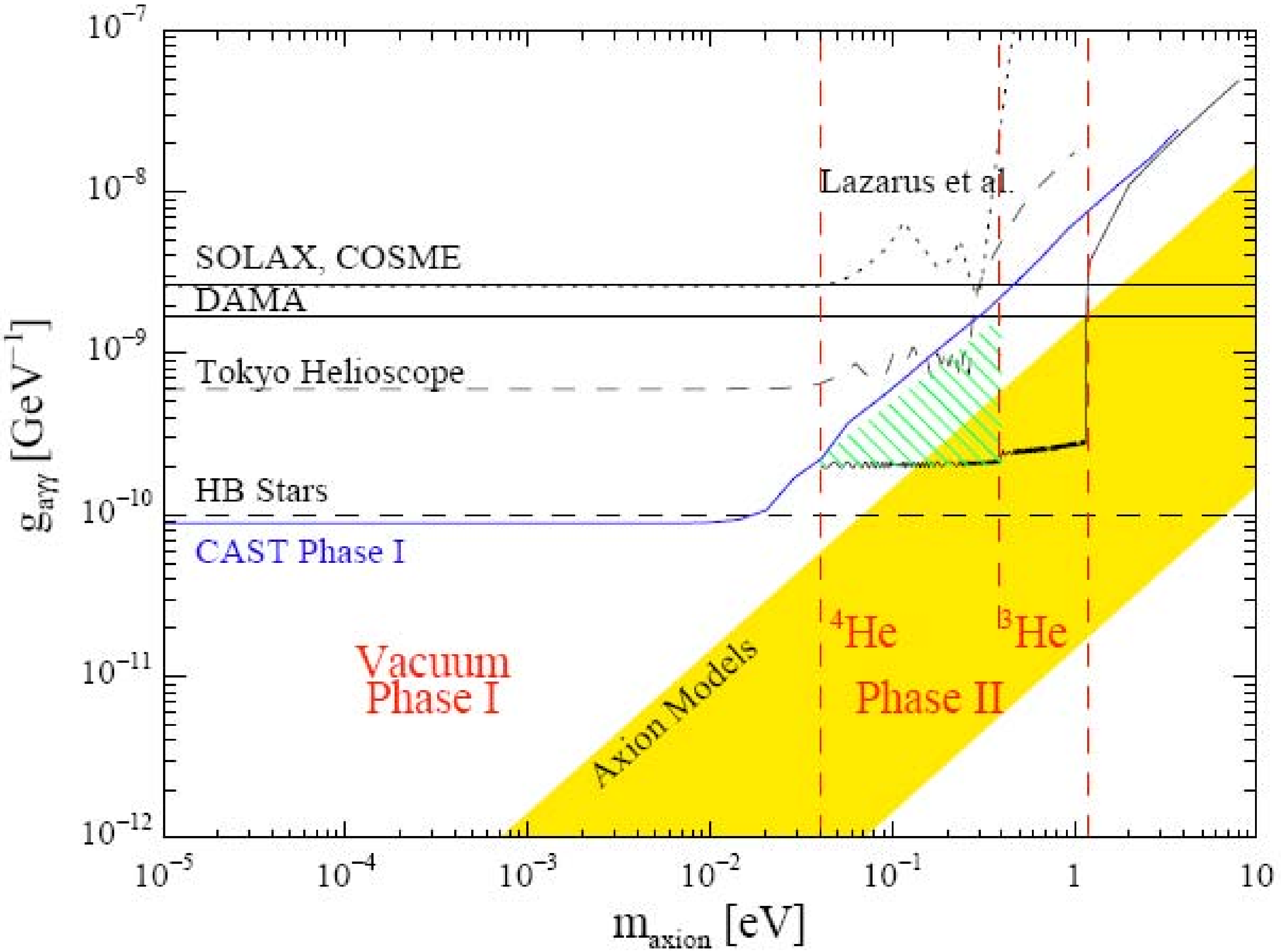

CAST
ANSALDO GIE
EUROPAMETALLI – LMI
E. ZANON

from C. Eleftheriadis (CAST), arXiv: 0706.0637

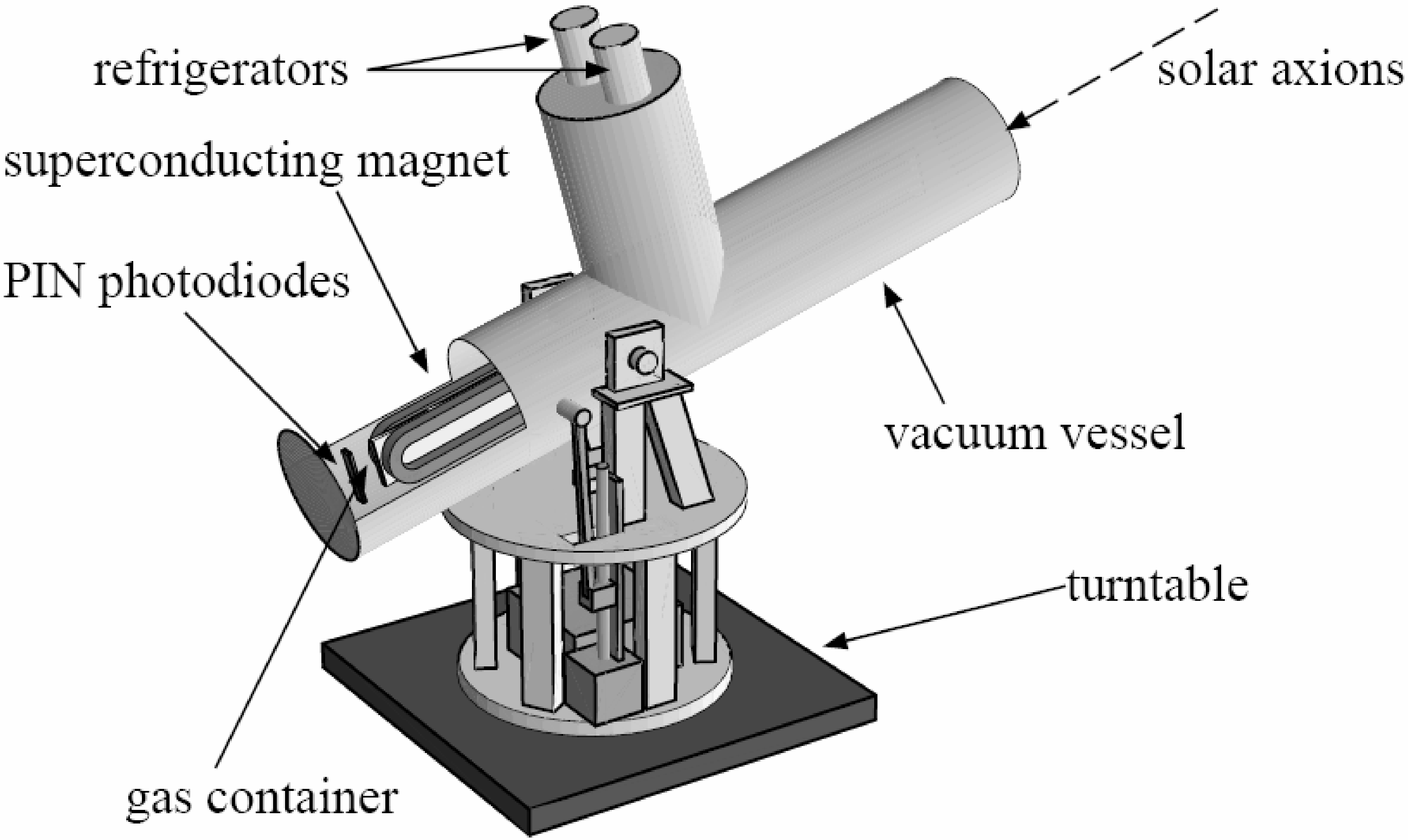
$$L_{a\gamma\gamma} = \frac{1}{M_a} a \vec{E} \cdot \vec{B}$$

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

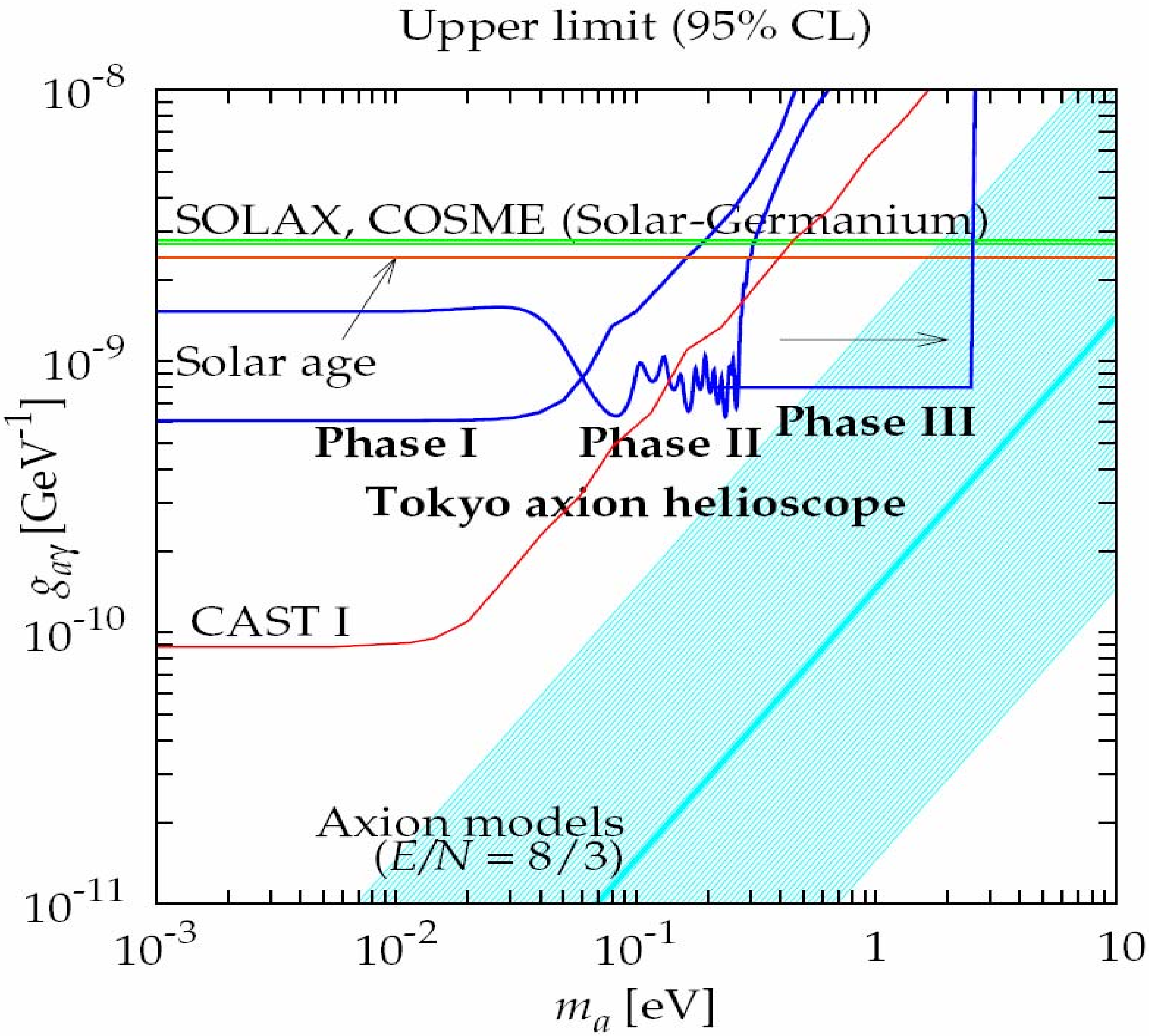
$$= g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a}$$



Tokyo Axion Helioscope



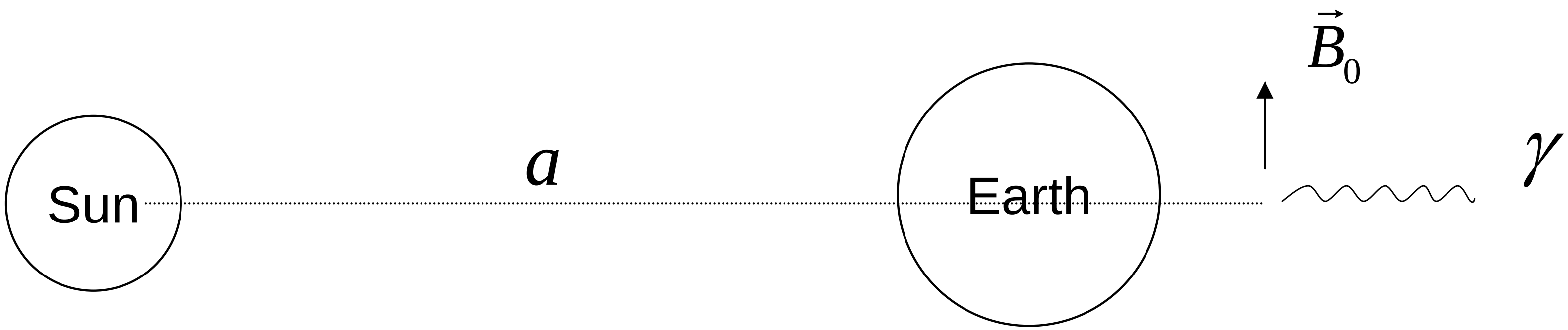
from S. Inoue et al., arXiv:0806.1471



Detecting solar axions using Earth's magnetic field

by H. Davoudiasl and P. Huber

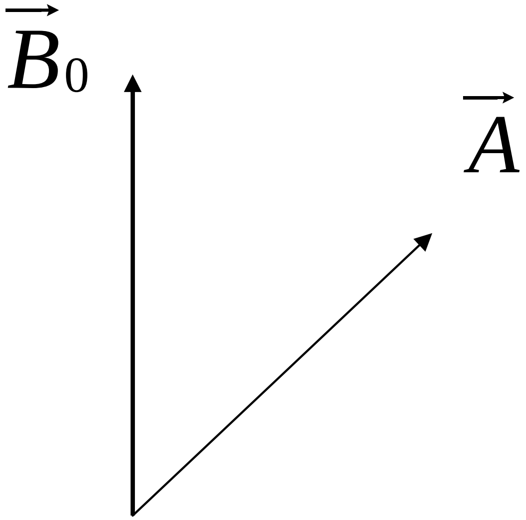
hep-ph/0509293



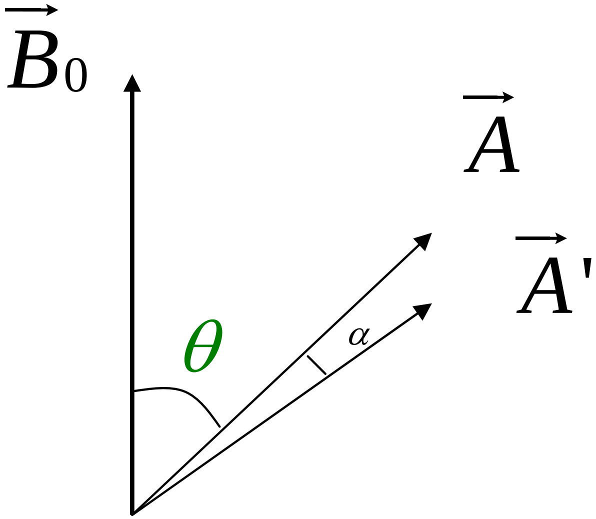
For axion masses $m_a \leq 10^{-4}\,\mathrm{eV}$, a low-Earth-orbit x-ray detector with an effective area of $10^4\ \mathrm{cm}^2$, pointed at the solar core, can probe down to $M_a \sim 10^{11}\ \mathrm{GeV}$, in one year.

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

Linearly polarized light in a constant magnetic field



Rotation



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

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

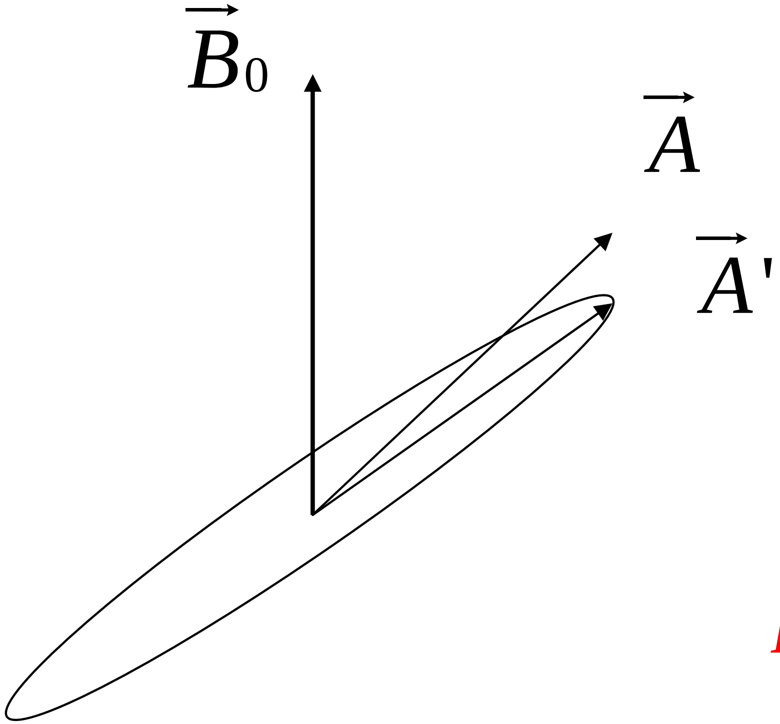
$$p = 4\frac{B_0^{\,2}\omega^2}{M_a^{\,2} m_a^{\,4}}\sin^2\left(\frac{m_a^{\,2}L}{4\omega}\right)$$

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

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

Rotation and Ellipticity

Maiani, Petronzio and Zavattini, 1986



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

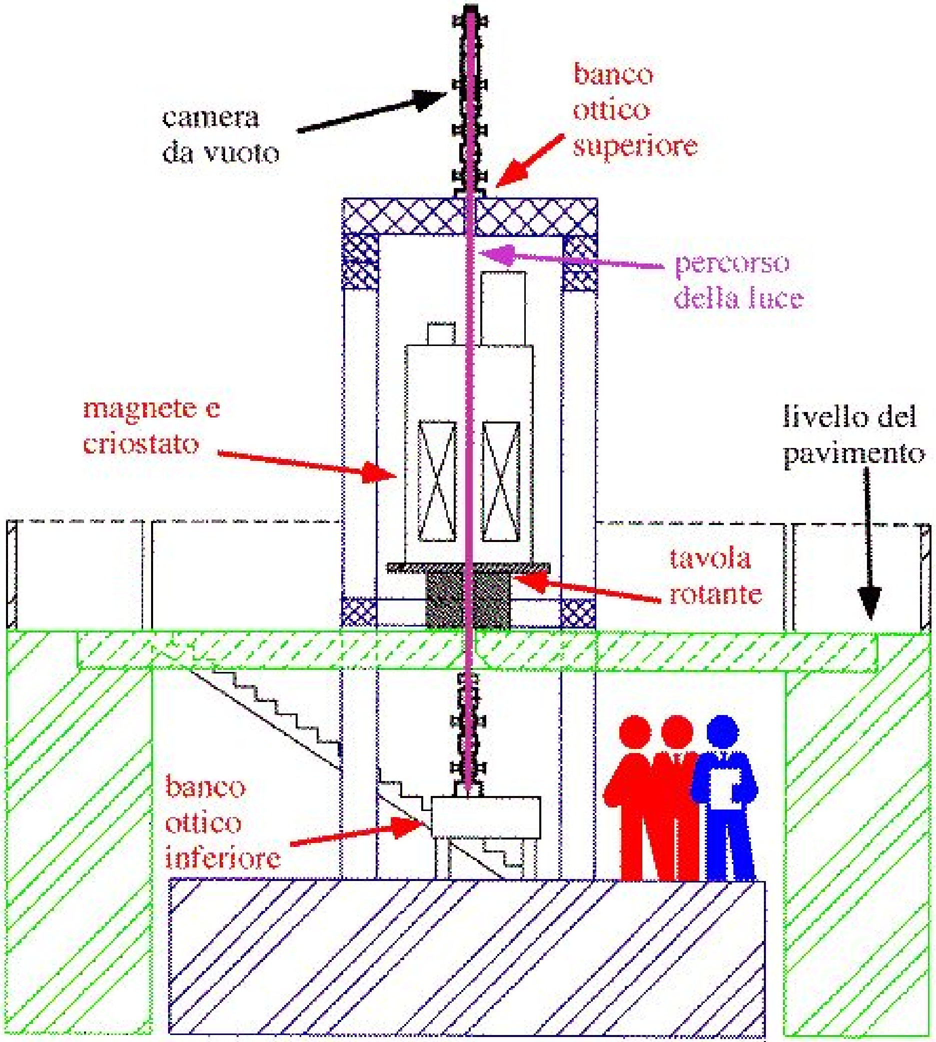
$$A'_{\perp} = A_{\perp}$$

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

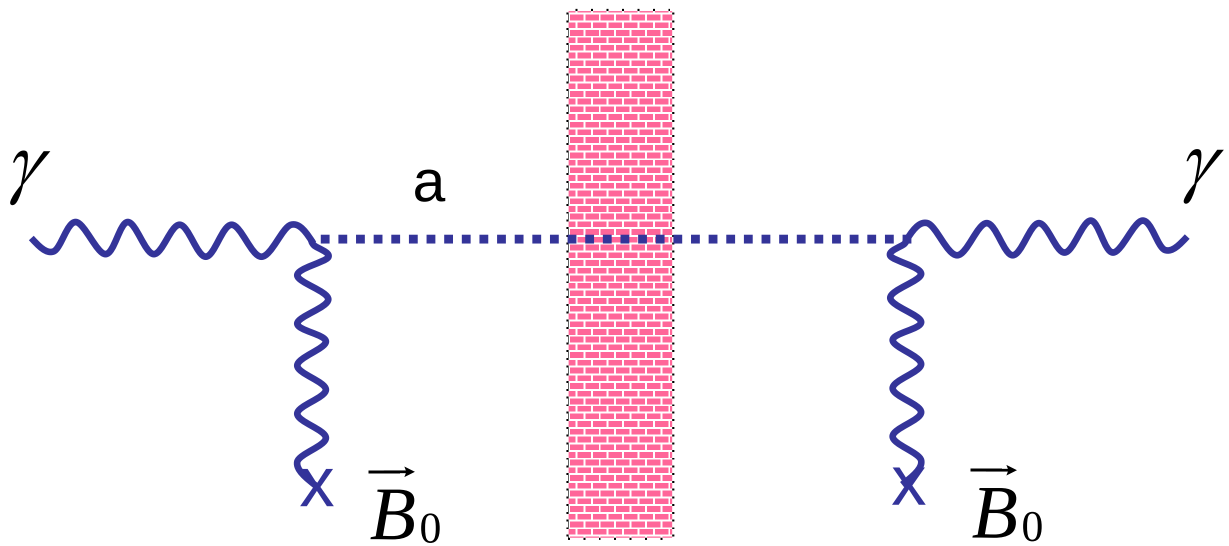
$$\frac{\alpha g_\gamma}{\pi f_a} = g_{a\gamma\gamma} = \frac{1}{M_a}$$

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

PVLAS


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

Shining light through walls



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

K. van Bibber
et al. '87

A. Ringwald '03

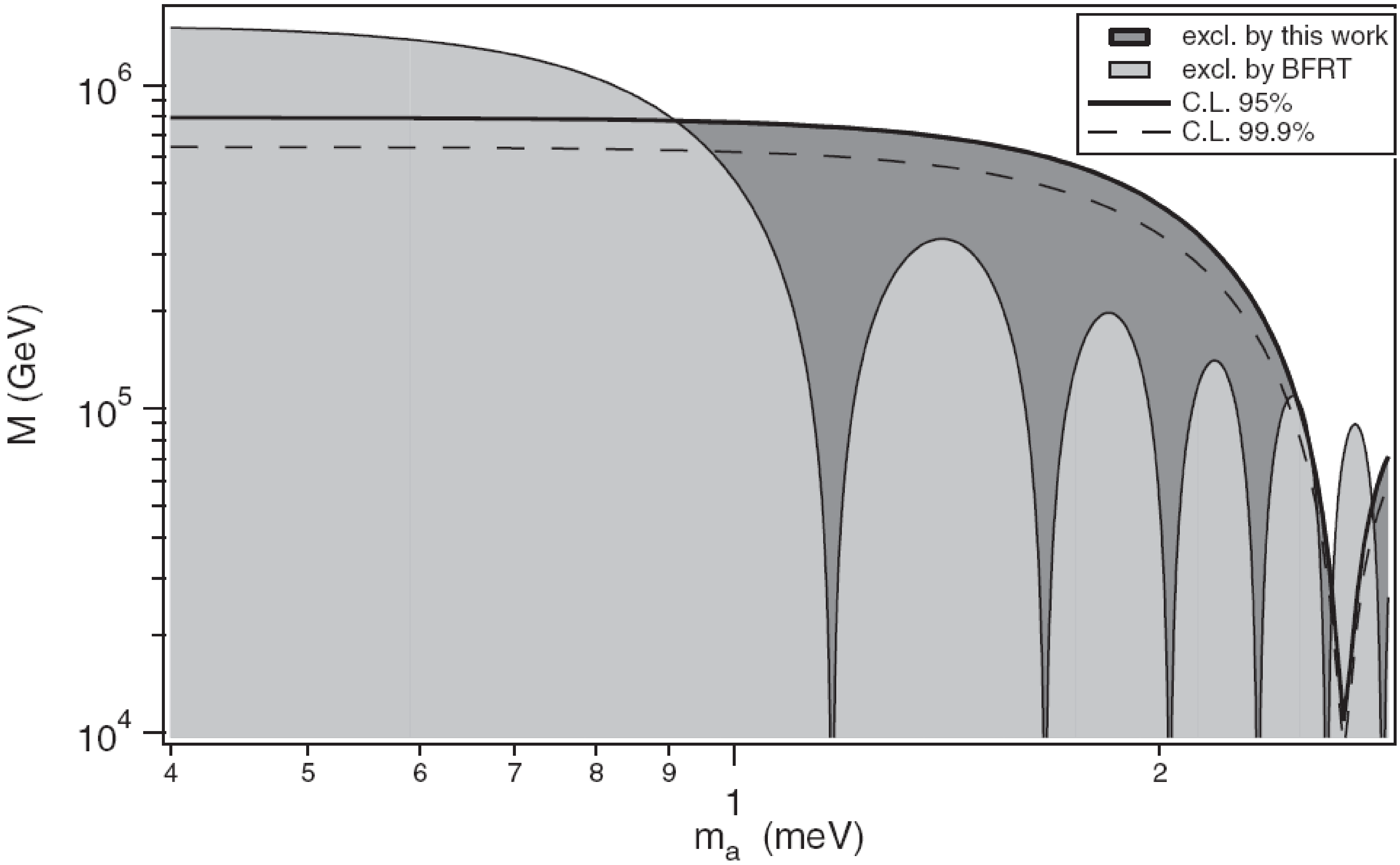
R. Rabadan,
A. Ringwald and
C. Sigurdson '05

P. Pugnat et al. 05

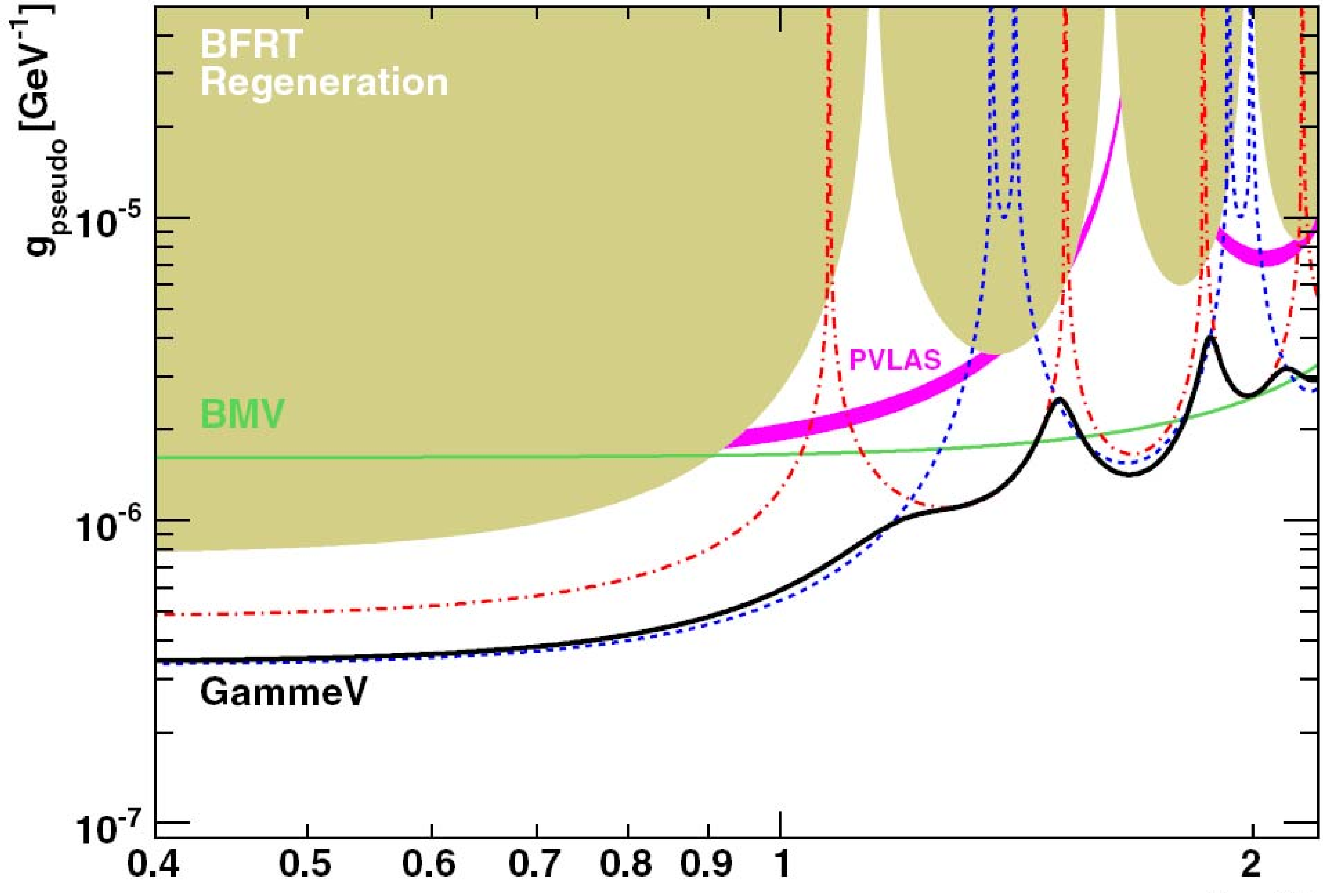
R. Battesti et al.

A. Afanasev et al.

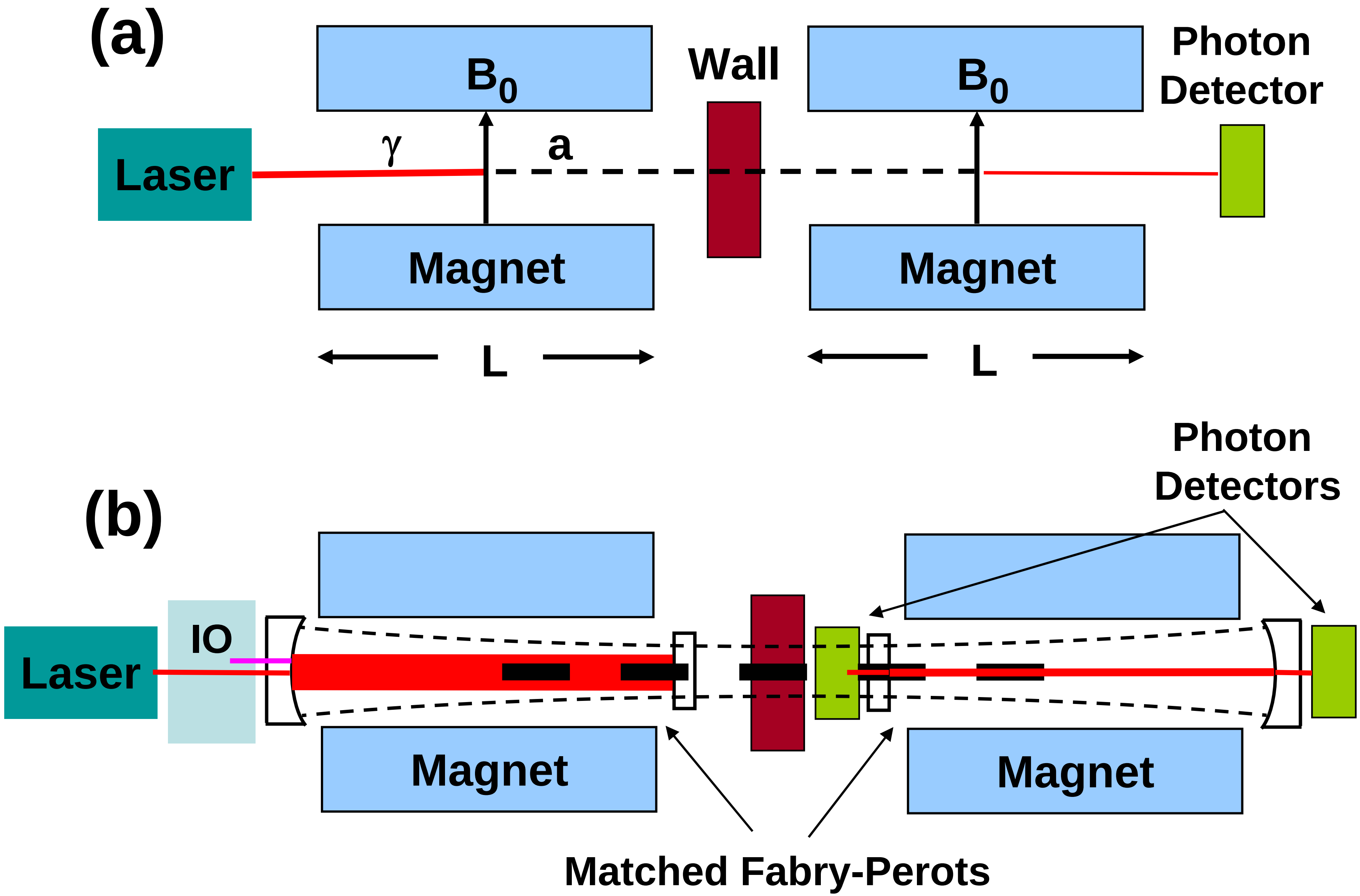
From C. Robilliard et al. (BMV), PRL 99 (2007) 190403



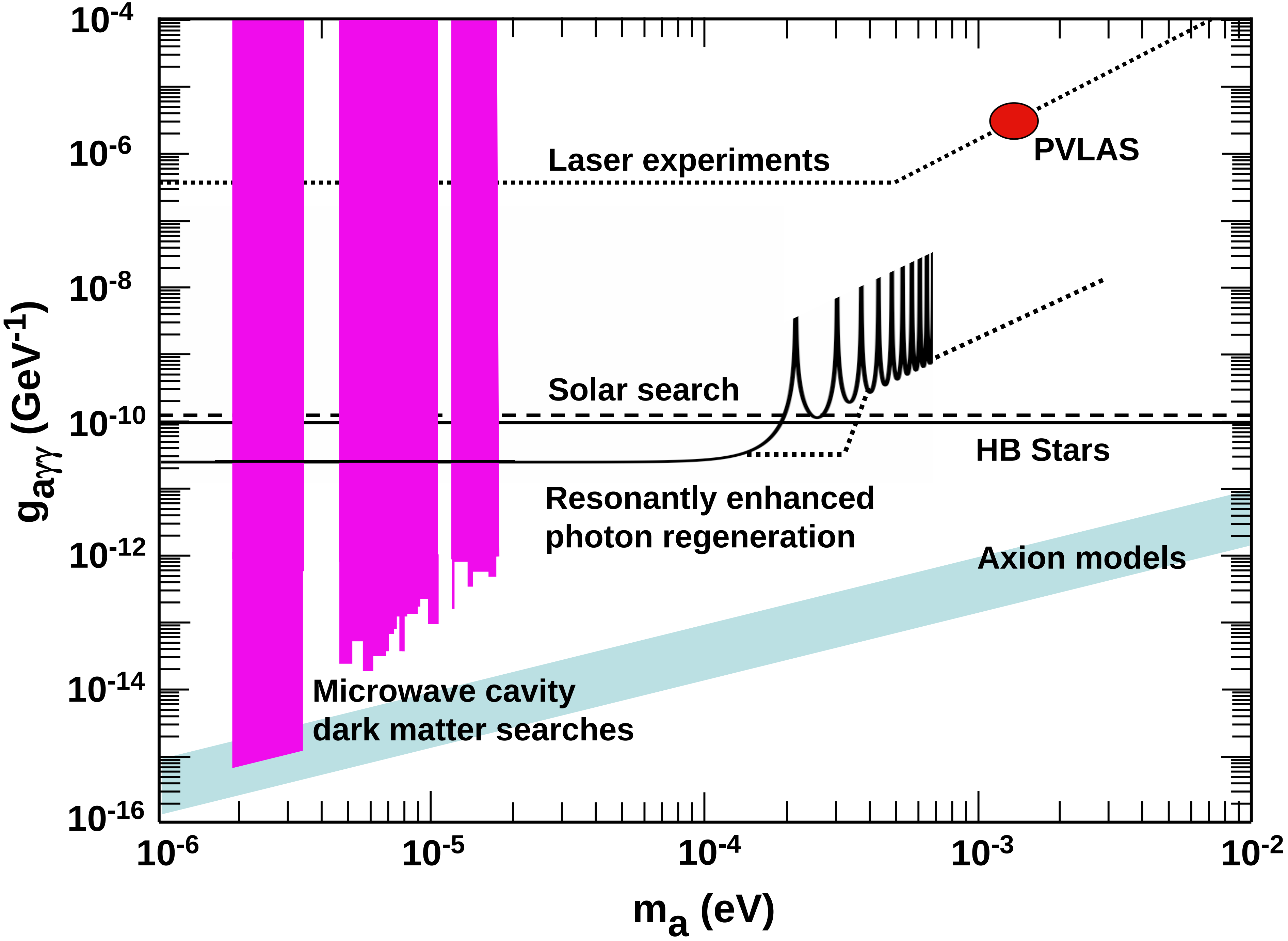
From A. Chau et al. (GammeV) , PRL 100 (2008) 080402



Resonantly Enhanced Axion-Photon Regeneration



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



10-4
10-6
10-8
10-10
10-12
10-14
10-16
g aγγ (GeV-1)
Laser experiments
PVLAS
Solar search
HB Stars
Resonantly enhanced
photon regeneration
Axion models
Microwave cavity
dark matter searches
10-6
10-5
10-4
10-3
10-2
m a (eV)

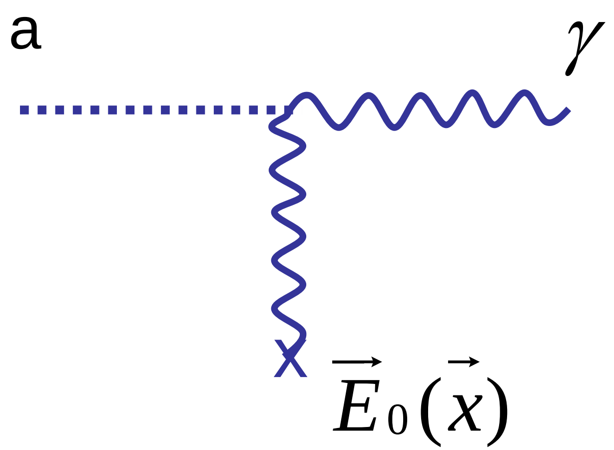
Eduardo Guendelman (2007)

- 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.

Primakoff conversion of solar axions in crystals on Earth



Solax, Cosme '98

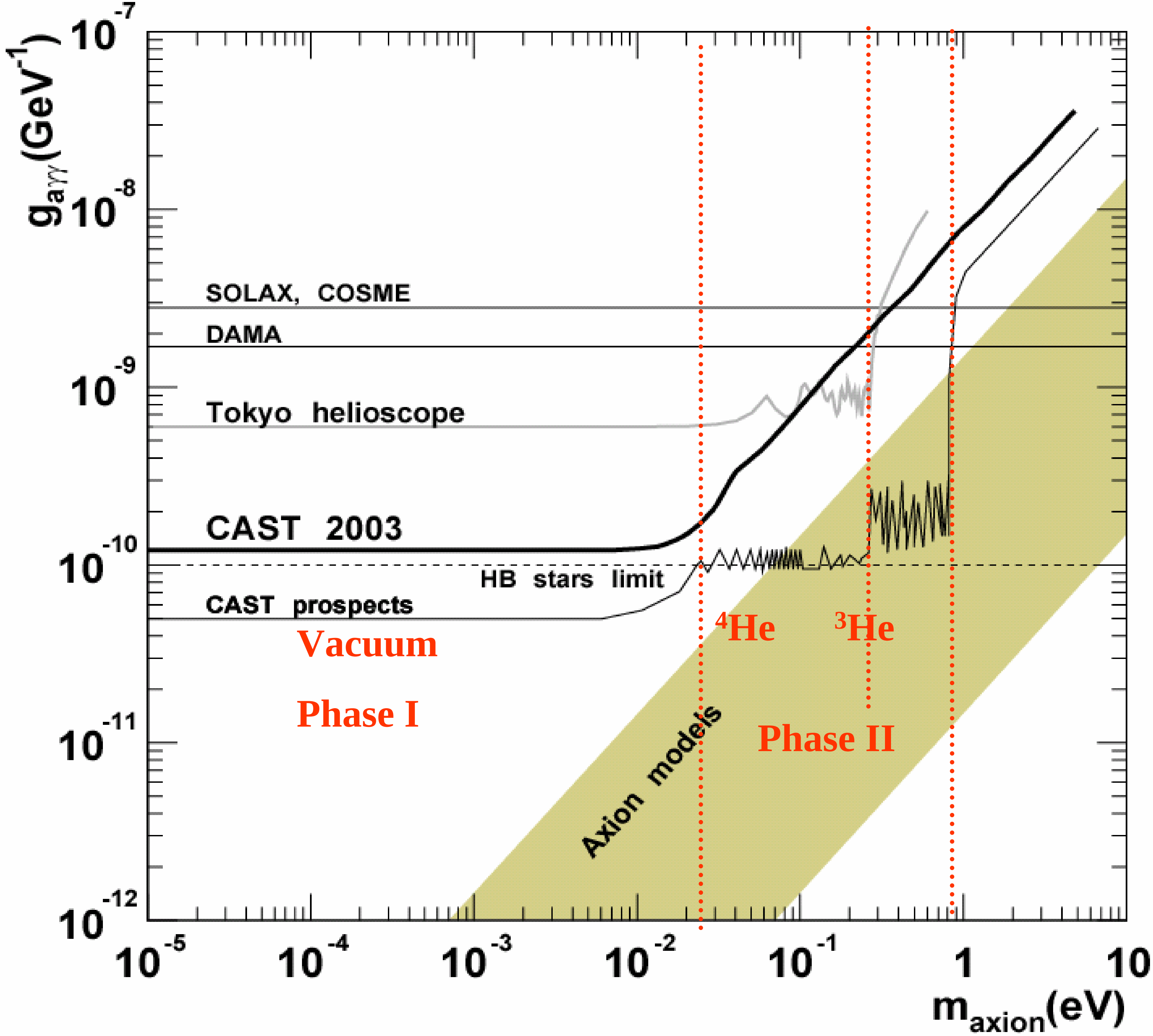
Ge

DAMA '01

NaI (100 kg)

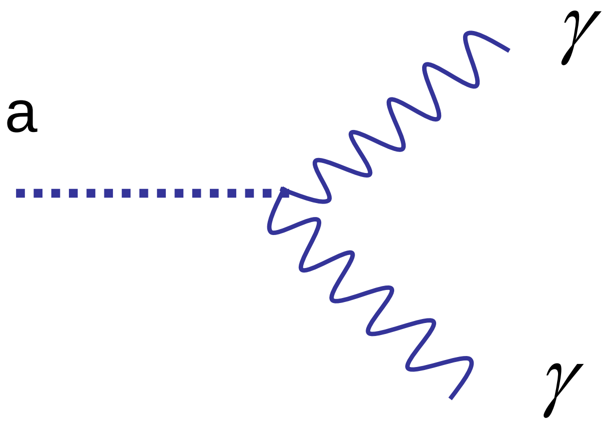
$E_a =$ few keV

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
^{4}He
^{3}He
Vacuum
Phase I
Axion models
Phase II
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion}(eV)

Telescope search for cosmic axions



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

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 μeV

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

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

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

$$\vartheta_f \;\square\; 10^{-17}$$

Theory:

J. Moody and
F. Wilczek ’84

Experiment:

A. Youdin et al. ’96
W.-T. Ni et al. ‘96

Conclusions

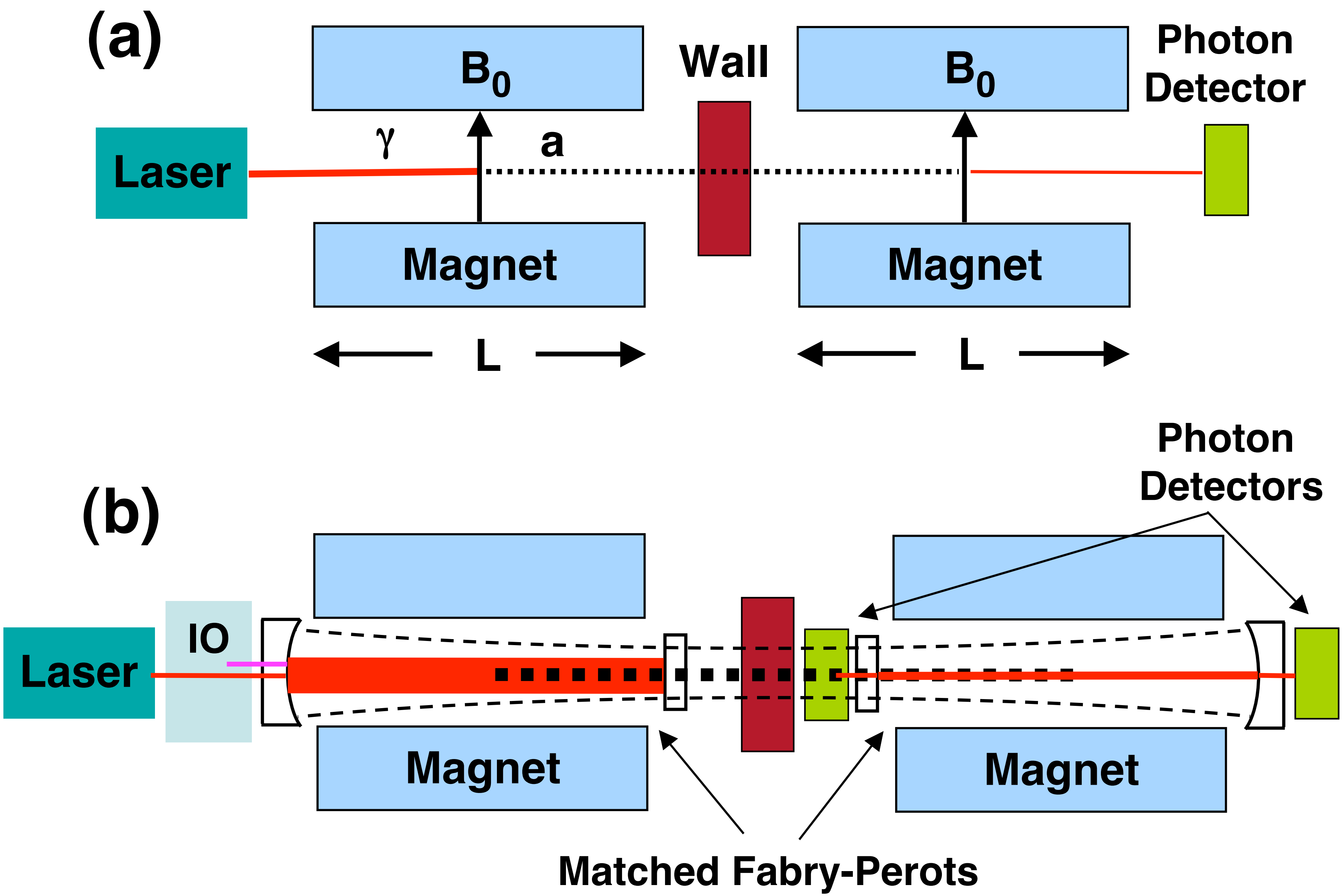
Axions solve the strong CP problem and are a cold dark matter candidate.

Axions haven't been found yet.

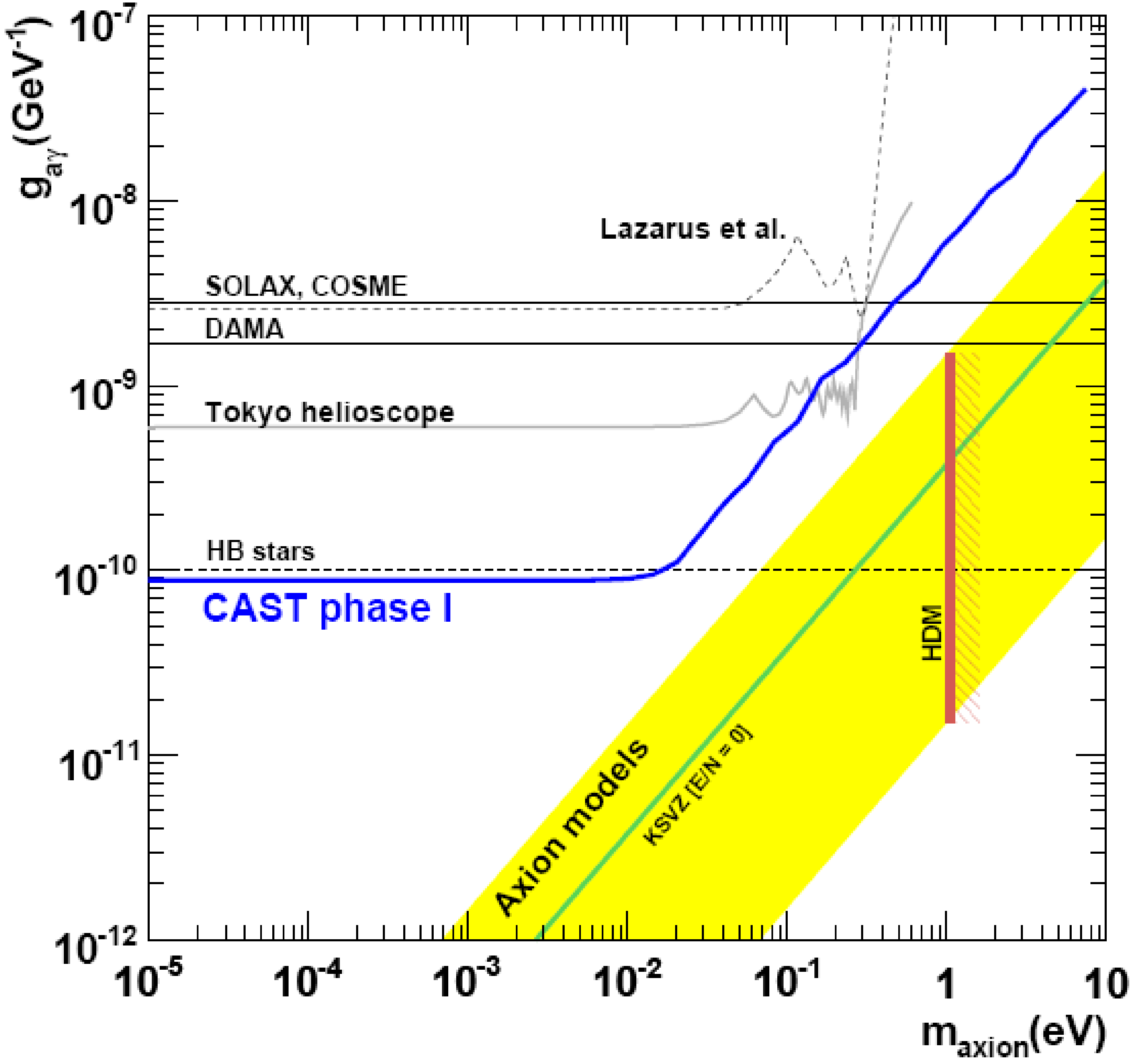
If axions exist, they are present on Earth as dark matter and emitted by the Sun.

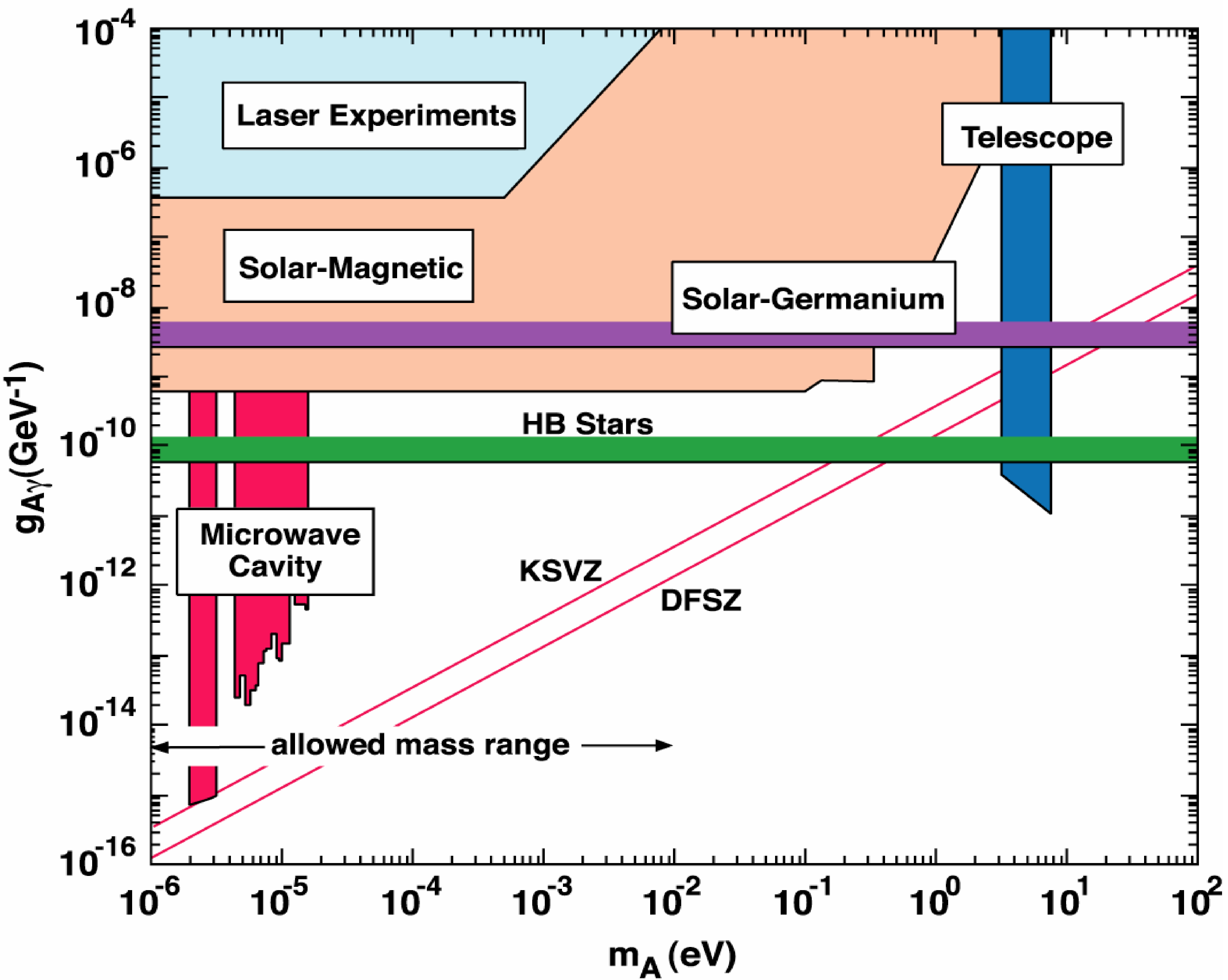
If an axion signal is found, it will provide a rich trove of information on the structure of the Milky Way halo, and/or the Solar interior.

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



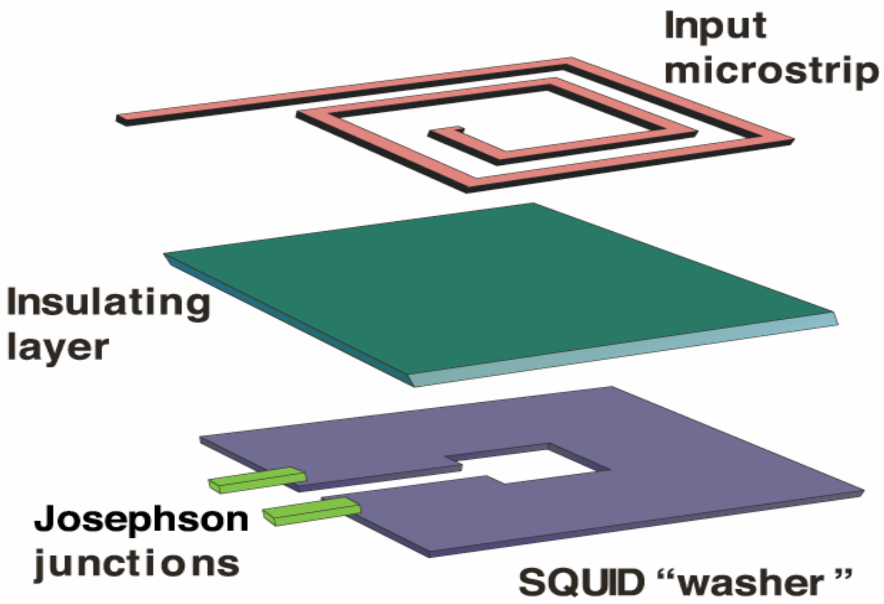
from S. Andriamonje et al. (CAST) , hep-ex: 0702006

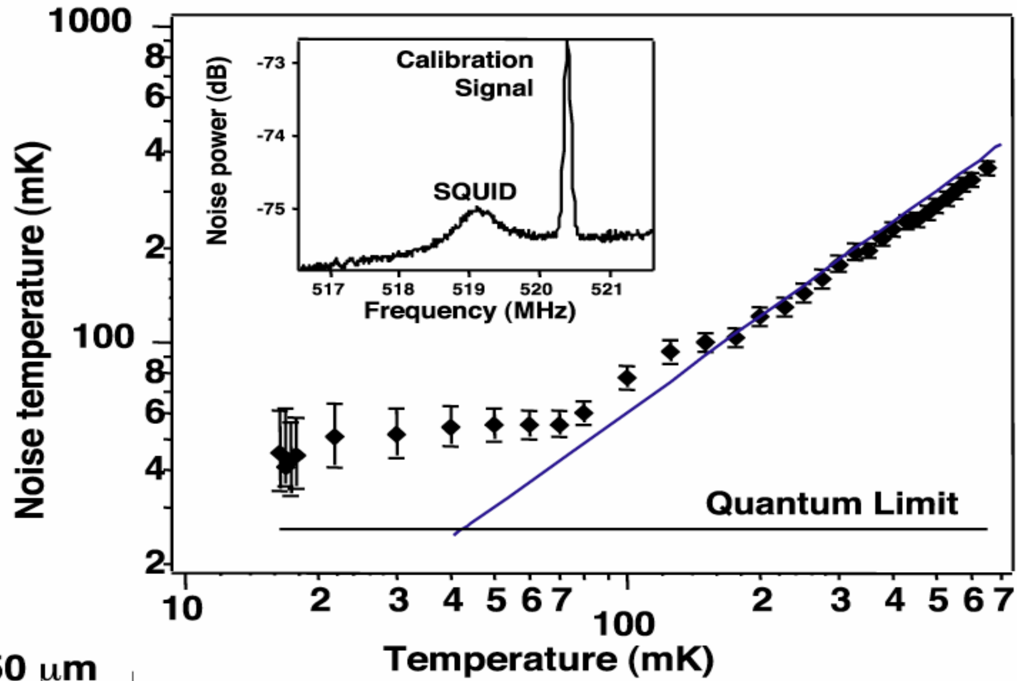


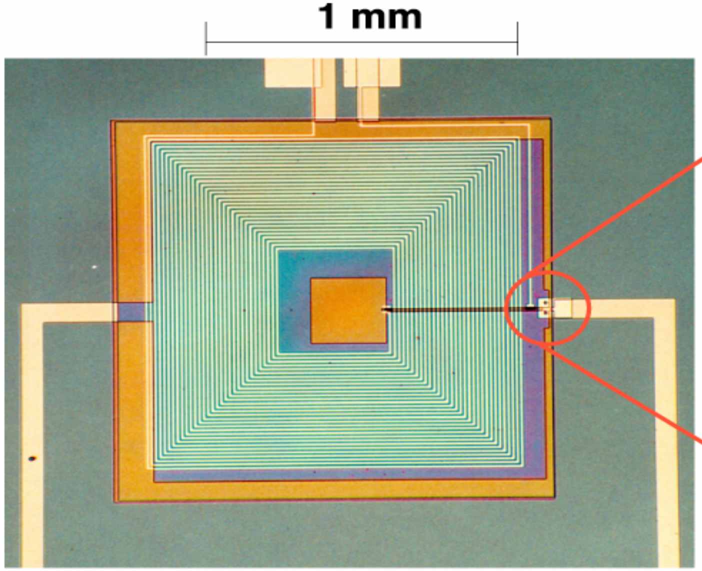


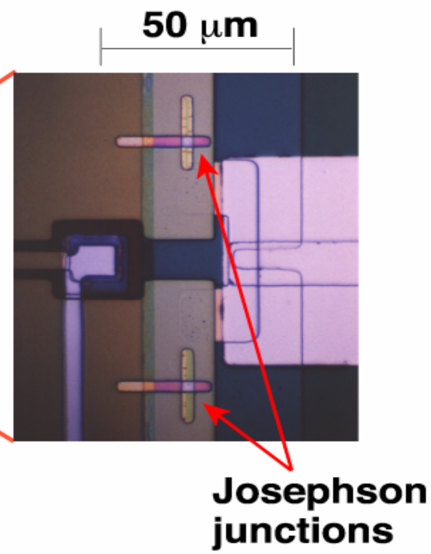
Laser Experiments
Solar-Magnetic
Telescope
Solar-Germanium
HB Stars
Microwave Cavity
KSVZ
DFSZ
allowed mass range
$g_{A\gamma}(GeV^{-1})$
m_A (eV)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

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.