I Laboratori Nazionali di Legnaro
LNL

INFN
Istituto Nazionale di Fisica Nucleare

Dipartimento di Fisica e Astronomia Galileo Galilei

Searching Axions through coupling with spin: the QUAX experiment

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for the QUAX collaboration
7 December 2016

Introduction

1. Introduction
2. Axion-Spin interaction
   Axionic field acting on magnetized materials: the effective magnetic field.
3. Dark matter properties
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4. Cavity detection and hybridization
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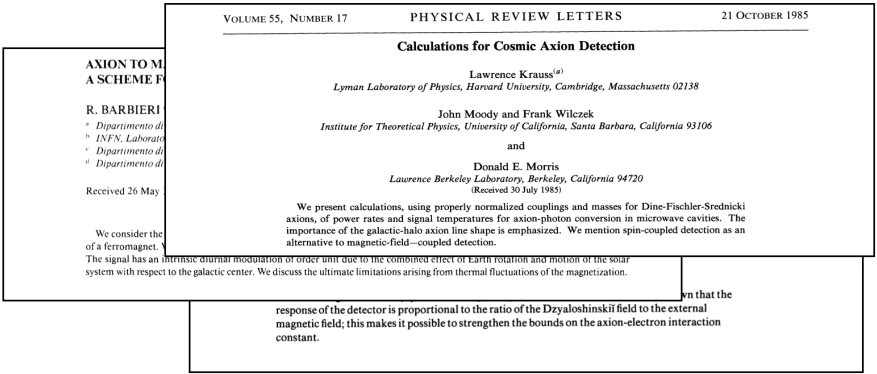
5. First experimental results
   Cavity-sample coupling and noise measurement.
6. Limitation and possibilities
   SQL and linear amplification vs. single microwave photon counter.
7. Conclusions

Theoretical suggestions



VOLUME 55, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1985

Calculations for Cosmic Axion Detection

Lawrence Krauss[(a)]
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

John Moody and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

and

Donald E. Morris
Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 30 July 1985)

We present calculations, using properly normalized couplings and masses for Dine-Fischler-Srednicki axions, of power rates and signal temperatures for axion-photon conversion in microwave cavities. The importance of the galactic-halo axion line shape is emphasized. We mention spin-coupled detection as an alternative to magnetic-field–coupled detection.

AXION TO M
A SCHEME F

R. BARBIERI

[a] Dipartimento di
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[c] Dipartimento di
[d] Dipartimento di

Received 26 May

We consider the
of a ferromagnet.
The signal has an intrinsic diurnal modulation of order unit due to the combined effect of Earth rotation and motion of the solar system with respect to the galactic center. We discuss the ultimate limitations arising from thermal fluctuations of the magnetization.

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First paper: 1985 by L.M. Krauss, J. Moody, F. Wilczek, D.E. Morris.

Theoretical suggestions

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AXION TO MAGNON CONVERSION.
A SCHEME FOR THE DETECTION OF GALACTIC AXIONS

R. BARBIERI [a], M. CERDONIO [b], G. FIORENTINI [c] and S. VITALE [d]

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[c] *Dipartimento di Fisica and INFN, I-09100 Cagliari, Italy*
[d] *Dipartimento di Fisica and INFN, I-38050 Trento, Italy*

Received 26 May 1989

We consider the possibility of detecting axions in the halo of our Galaxy by means of converting them into collective excitations of a ferromagnet. We calculate that, under optimal conditions, one can convert about 6000 axions per day in a 1 m^3 ferromagnet. The signal has an intrinsic diurnal modulation of order unit due to the combined effect of Earth rotation and motion of the solar system with respect to the galactic center. We discuss the ultimate limitations arising from thermal fluctuations of the magnetization.

Second paper: 1986 by R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale.

Theoretical suggestions

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Antiferromagnetic axion detector

A. I. Kakhidze and I. V. Kolokolov

Institute of Nuclear Physics, Siberian Branch of the Academy of Sciences of the USSR

(Submitted 21 November 1990)
Zh. Eksp. Teor. Fiz. **99**, 1077–1081 (April 1991)

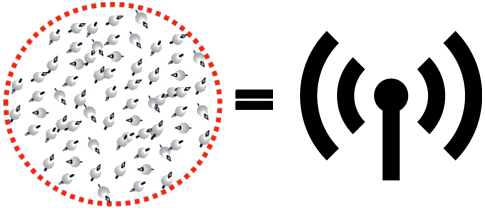
Antiferromagnets with easy-plane anisotropy are proposed as axion detectors. It is shown that the response of the detector is proportional to the ratio of the Dzyaloshinskiĭ field to the external magnetic field; this makes it possible to strengthen the bounds on the axion-electron interaction constant.

Third paper: 1991 by A.I. Kakhizde, I.V. Kolokolov.

Interaction with matter

Axions interacts with ordinary matter :

- Interaction with photons (Primakoff and inverse Primakoff effects)
- Interaction with electronic spin (only DFSZ)



L.M. Krauss, J. Moody, F. Wilczek, D.E. Morris, *Spin coupled axion detections* (1985)
R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett. B 226, 357 (1989)
A.I. Kakhizde, I.V. Kolokolov, Sov. Phys, JETP 72 598 (1991)

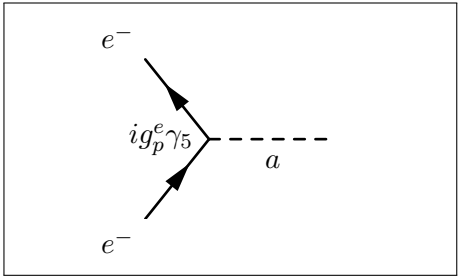
The interaction can change the magnetization in a magnetized sample.

↓

It can be treated as an effective magnetic field.

Axion-fermion interaction is described by

$$\mathcal{L} = \bar{\psi}(x)(i\hbar\partial\!\!\!/ - mc)\psi(x) - ig_p a(x)\bar{\psi}(x)\gamma_5\psi(x)$$



Using non-relativistic Euler-Lagrange

$$i\hbar\partial_t\varphi = \left[-\frac{\hbar^2}{2m}\nabla^2 - \frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a \right]\varphi,$$

where the interaction term is

$$-\frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a \equiv -2\frac{\hbar e}{2m}\boldsymbol{\sigma}\cdot\left(\frac{g_p}{2e}\right)\boldsymbol{\nabla}a$$

$\frac{\hbar e}{2m} = \mu_B$ is Bohr's magneton, describing the behavior of the spin.

$B_a = \frac{g_p}{2e}\boldsymbol{\nabla}a$ is the axion effective magnetic field, which acts on the sample.

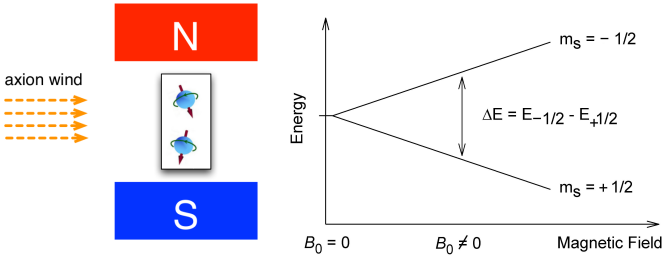
How to tune the receiver: ESR

For an axion mass of $\sim 200\,\mu$eV, $m_a c^2 = \hbar\omega \Rightarrow \omega/2\pi \sim 48$ GHz

The effective magnetic field $B_a = \frac{g_p}{2e}\nabla a$ is actually an RF field.

$\downarrow$

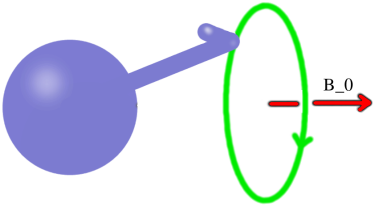
The sample is tuned at a chosen ω_L with a static field B_0



For example, $\omega_L/2\pi = 48$ GHz $\Rightarrow B_0 = 1.7$ T

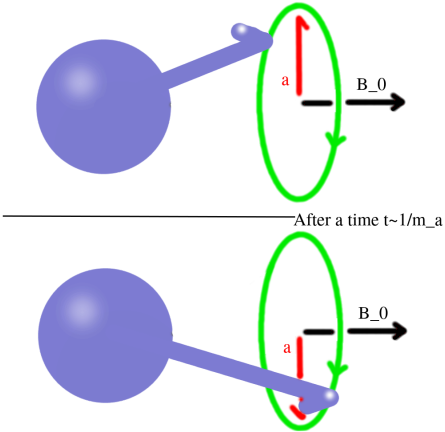
∇a
RF field
$\Downarrow$
$\omega \Leftrightarrow m_a$
Mass
$\Downarrow$
ESP
$\Downarrow$
ω_L
Larmor
$\Downarrow$
B_0
Static field

A classical description:
If subjected to magnetic fields, the electronic spins start to precede at the Larmor frequency $\omega_L = -\gamma B_0$.



If the frequency of the rf axion field is close to the one of the EPR, ω_L...

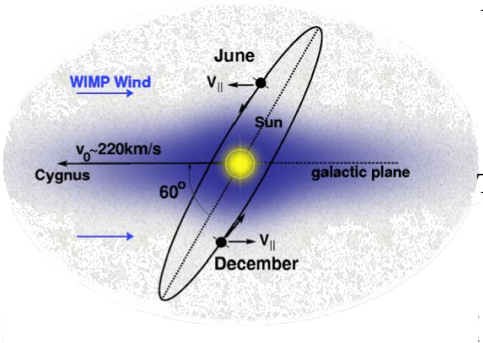
...the axion field increases the EPR amplitude at the frequency ω_a.



Quantum description→ spin flips

Axion background

What are the features of this effective field B_a?
An earth-based laboratory is moving in a dark matter (hp: axions) halo.



The so-called "axion wind" provides:

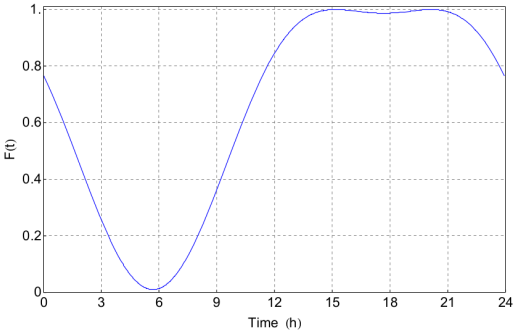
1. $\beta \simeq 10^{-3}$
2. $\lambda = \frac{\hbar}{m_a \beta c} \gg \lambda_{\text{exp}}$
3. $Q_a \simeq 2 \cdot 10^6$

That is:

1. $\nabla a \neq 0$
2. coherent axion field interaction
3. natural figure of merit

Signal signature

It also provides a signature



Daily modulation of the axion flux for the QUAX detector located at Legnaro (PD)

Different acquisitions runs during day provide different results.

⇓

Measurement

↓

Is it still not possible to make a measurement in this condition

In a free-field environment, for $f \gtrsim$GHz, radiation damping is dominated by magnetic dipole emission from magnetized the sample.

Radiation damping and microwave cavities

The axion-electron interaction is extremely weak $g_p^e \sim 10^{-13}\,\mathrm{GeV}^{-1}$

The signal is anomalous oscillations of the magnetization $\boldsymbol{M}$ $B \sim 10^{-22}\,\mathrm{T}$

↓

The dynamics is described by Bloch's equations:

$$\frac{\mathrm{d}M_x}{\mathrm{d}t} = \gamma(\boldsymbol{M}\cdot\boldsymbol{B})_x - \frac{M_x}{\tau_2} - \frac{M_x M_z}{M_0\tau_r}$$
$$\frac{\mathrm{d}M_y}{\mathrm{d}t} = \gamma(\boldsymbol{M}\cdot\boldsymbol{B})_y - \frac{M_y}{\tau_2} - \frac{M_y M_z}{M_0\tau_r}$$
$$\frac{\mathrm{d}M_z}{\mathrm{d}t} = \gamma(\boldsymbol{M}\cdot\boldsymbol{B})_z - \frac{M_0 - M_z}{\tau_1} - \frac{M_x^2 + M_y^2}{M_0\tau_r}$$

Relaxation times:

- τ_r = radiation damping
- τ_1 = longitudinal (spin-lattice)
- τ_2 = transverse (spin-spin)

In free field the maximum allowed coherence is limited by τ_r

---

Limited phase space $\Rightarrow$ inhibition of the damping mechanism

$$\Downarrow$$

Sample embedded in a microwave cavity: $\tau_{\text{min}} = \min(\tau_a, \tau_c, \tau_2)$

$$\frac{\mathrm{d}M_x}{\mathrm{d}t} = \gamma M_y B_0 - \frac{M_x}{\tau_2} - \frac{M_x}{\tau_2}$$

$$\frac{\mathrm{d}M_y}{\mathrm{d}t} = \gamma(M_z K I -) M_x B_0 - \frac{M_y}{\tau_2}$$

$$\frac{\mathrm{d}M_z}{\mathrm{d}t} = -\gamma K' I M_y - \frac{M_0 - M_z}{\tau_1}$$

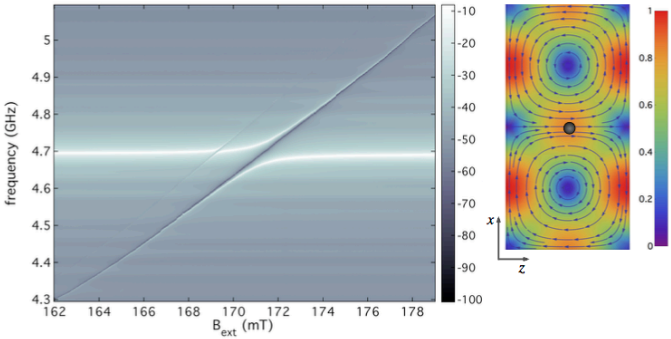
$$L\frac{\mathrm{d}I}{\mathrm{d}t} = K\frac{\mathrm{d}M_x}{\mathrm{d}t} - RI - \frac{1}{C}\int_0^t I\mathrm{d}t + V_{\text{rf}}$$

New Bloch equation:

- R,L,C cavity parameters
- K and K' are geometrical coupling factors
- $I = B_1/K'$ is the equivalent current generating B_1 field

N. Bloembergen and R. V. Pound, Phys. Rev. **95**, 8 (1954)

Strong coupling regime $\Rightarrow$ equations can be solved $\Rightarrow$ hybridization $\omega_c \simeq \omega_L$

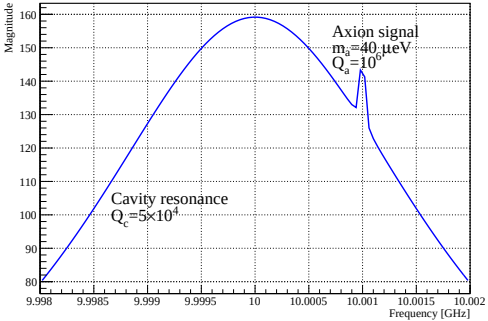


The radiation damping contributes to the frequency separation of the cavity and kittel modes.

$$S_{21}(\omega) \simeq \frac{1}{i(\omega-\omega_c) - \frac{k_c}{2} + \frac{|g_m|^2}{i(\omega-\omega_m)-k_m/2}}$$

$k_m = 1/\tau_2,\ k_c = 1/\tau_c,\ k_h = (k_c + k_m)/2$
$g_m =$ coupling strength (volume, # spins)

The signal is an excess of magnetization driven by the axion field.



Cavity hybridized with ESR resonance fueled by the thermal noise.

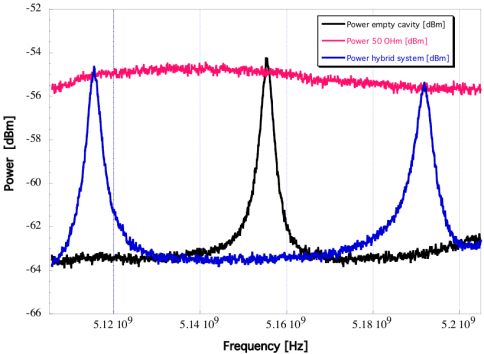
The axionic effective rf field driving the magnetization manifests as a spike in the resonance spectrum.

↓

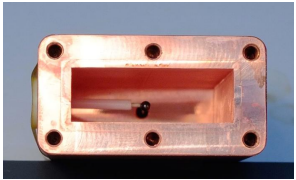
A residual analysis provides a limit on the effective field B_a.

First experimental results

First measures with a YIG sphere coupled to the cavity → No excess noise



Next step: cryogenic measurements



YIG properties:

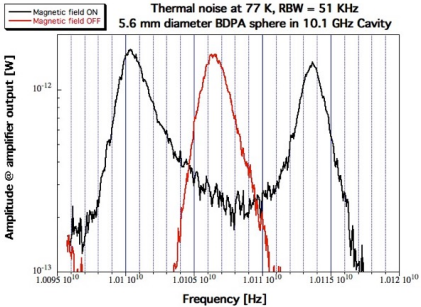
- Ferrimagnet
- High spin density $n_S = 10^{28}\ \mathrm{m}^{-3}$

$\Downarrow$

Good coupling strength achieved

Lower $T \Rightarrow$ larger YIG linewidth

First cryogenic measures with BDPA

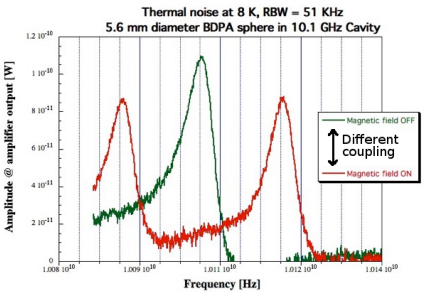


Thermal noise spectra at lower T

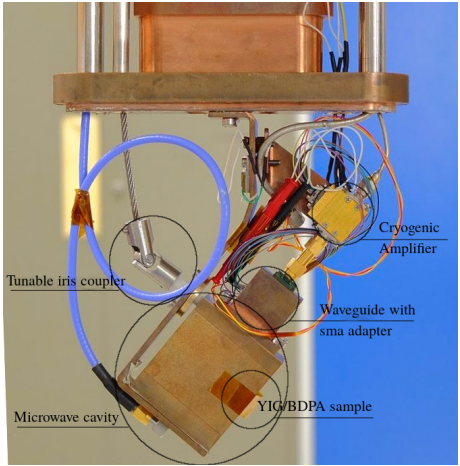
BDPA properties:

- paramagnet
- high spin density $n_S = 10^{27}\,\mathrm{m}^{-3}$

Lower coupling caused by lower spin density and sample volume.

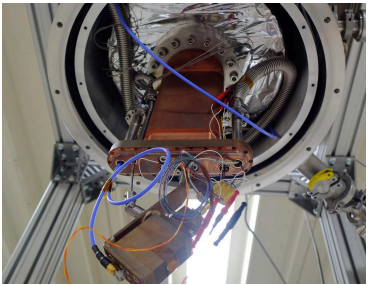


Experimental apparatus (inner parts)

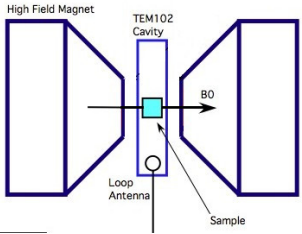


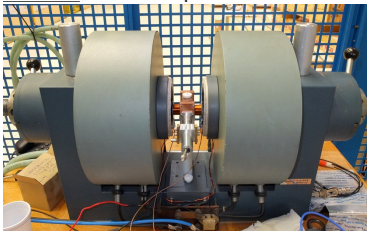
Pictures of the apparatus, with the ← different parts labelled.

Bottom view of the apparatus housed into the cryostat. ↓

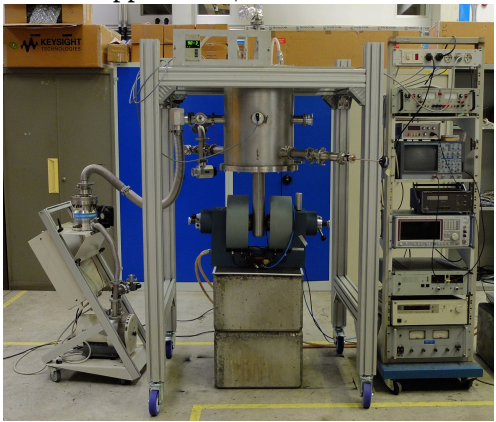


Experimental apparatus (outer parts)



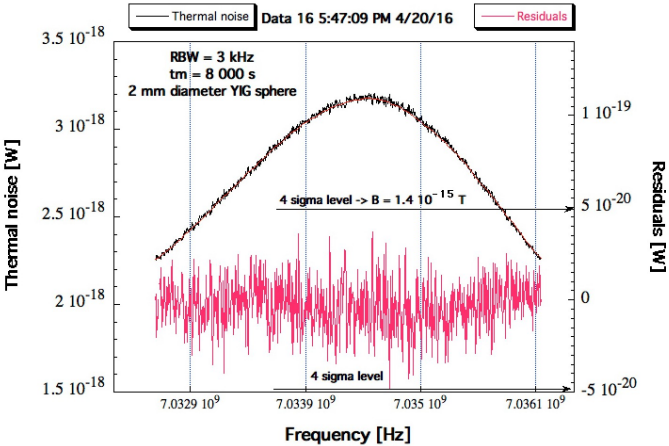


←Static magnetic field with electromagnets and full apparatus. ↓



A preliminary measurement

The axion search is performed averaging subsequent power spectra:

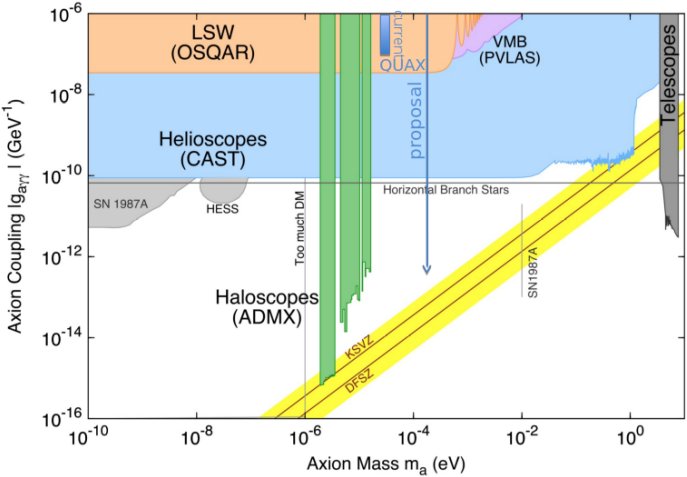


The axion signal is a sharp peak over the resonance spectra, $Q_a \simeq 2 \cdot 10^6$.

An analysis of the residuals provides the measured limit.

This measure requires magnetic field stability at the $1/Q_c$ level over the entire integration time.

Comparison in the axion-photon coupling space: previously reported measures and proposed sensitivity.



Note that the sensitivity of QUAX is limited to the electron coupling

↓

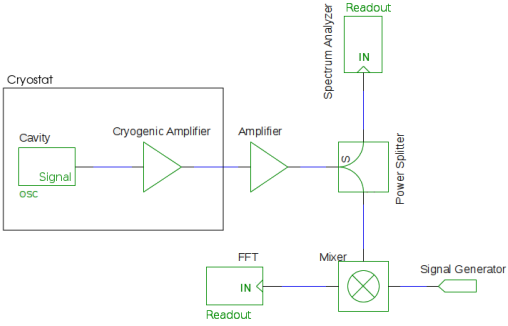
$g_{a,ee}$

This figure has the only purpose of make a comparison with different experiments.

Optimizing the performances

Easy direct analysis → each bin is computed separately.

Analyze every bin in parallel → Signal down conversion



More effective use of time

↓

Further FFT online analysis possible after collecting the down converted signal.

↓

Digital acquisition @ 1 MHz

The way to the quantum counter

The average power P_{in} absorbed by the material from the axion wind is

$$P_{\text{in}} = B_a \frac{\mathrm{d}M_a}{\mathrm{d}t} V = \gamma \mu_B n_S \omega_a B_a^2 \tau_{\text{min}} V$$

With an antenna critically coupled $P_{\text{in}}/2$ is collected as rf radiation.

$$P_{\text{out}} = \frac{P_{\text{in}}}{2} = 3.8 \times 10^{-26} \left(\frac{m_a}{200\,\mu\text{eV}}\right)\left(\frac{V}{100\,\text{cm}^3}\right)\left(\frac{n_S}{2 \cdot 10^{28}/\text{m}^3}\right)\left(\frac{\tau_{\text{min}}}{2\,\mu\text{s}}\right) \text{W}$$

That is a single 48 GHz photon, emitted with a rate $R_a = 10^{-3}$ Hz.

Note: switching to TE110 or TE120 mode of a rectangular cavity, the QUAX apparatus can detect Primakoff or spin flip photons, distinguishing DFSZ and KSVZ axions.

Linear amplification

Axion signal peak $\Delta\omega_a/2\pi$

Detected with a RBW $= \Delta f = \Delta\omega_a/2\pi$

How far can a linear amplifier go?

$$P_{\text{min}}^{\text{thermal}} = 2k_B T\sqrt{\frac{\Delta f}{t}} \simeq 5\times 10^{-25}\,\text{W}$$

$$P_{\text{min}}^{\text{SQL}} = \hbar\omega_a\sqrt{\frac{\Delta f}{t}} \simeq 5\times 10^{-24}\,\text{W} \leftarrow \text{larger}$$

$T = 10\,\text{mK}$, $\Delta f = 30\,\text{kHz}$, $t = 10^4\,\text{s}$, $\omega_a/2\pi = 30\,\text{GHz}$

The Standard Quantum Limit limits the sensitivity of a linear amplification.

Or we can reduce the noise level...

The way to the single microwave photon counter to detect spin-flip photons

Specifics of the Single Microwave Photon Detector

Advantages of the SMPD:

- Immunity to the standard quantum limit
- Possibility to detect very small amounts of power

Disadvantages of the SMPD:

- Non-zero probability of recording false counts (dark counts)
- Effective continuous detection (duty cycle)

Features searched in a SMPD:

- Possibility of performing real-time measurements
- Very low dark count ($\sim 0.1\,\mathrm{Hz}$)

Conclusions

Currently working on:

- Study of the materials
  behaviour of materials (YIG, BDPA and other paramagnets) at low temperatures.
- Cavity in a magnetic field
  design of a high-Q ($\sim 10^5$) cavity with a geometry useful to maximize the signal.
- External field
  realization of a highly uniform magnetic field (up to 10ppm for a 2 T field).

The R&D phase of the project is approved and will last 2-3 more years. If the goals are reached the building of the final apparatus will start.

Reference and collaboration

Details of the experiment are described in:
R. Barbieri et al, "*Searching for galactic axions through magnetized media: the QUAX proposal*" http://arxiv.org/abs/1606.02201

This is a collaboration between Laboratori Nazionali di Legnaro, University of Padova, Laboratori Nazionali di Frascati, University of Salerno and University of Birmingham.

Thank you for your time.