Proposal to detect axionic dark matter via their coherent interaction with intrinsic spin

The QUAX R&D - activities

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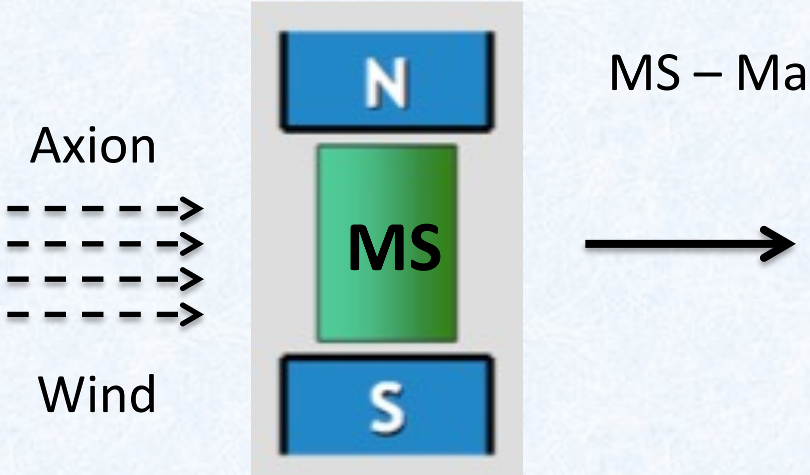
for the QUAX Collaboration

QUAX (lat/gr): QUaerere ʻΑΞιον
or (En): to QUest for AXions

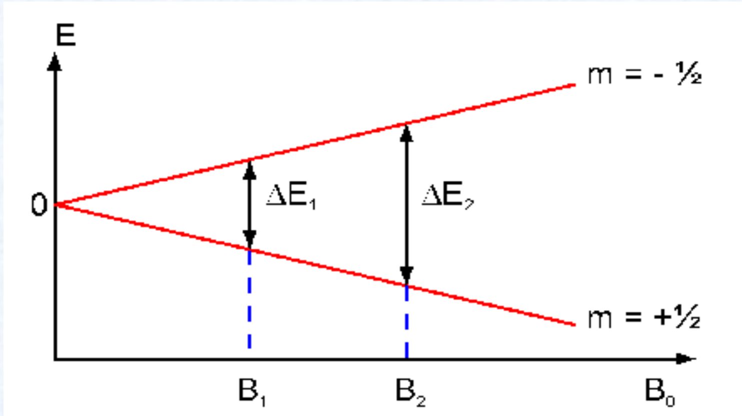
Magnetic detection QUAX (Haloscope)

- A possibility is to exploit the **axion electron coupling**
- **Due to the motion of the solar system** in the galaxy, the axion DM cloud acts as an **effective RF magnetic field on electron spin**
- This field excites **magnetic transition in a magnetized sample**
  (Larmor frequency) and produce a detectable signal
- **The interaction with axion field produces a variation of magnetization which is in principle measurable**

MS – Magnetized sample



Measurable signal



Idea comes from **several old works**:

- L.M. Krauss, J. Moody, F. Wilczeck, D.E. Morris, ”Spin coupled axion detections”, HUTP-85/A006 (1985)
- L.M. Krauss, ”Axions .. the search continues”, Yale Preprint YTP 85-31 (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)

Axion electron interaction

- The interaction of the axion with the a spin ½ particle

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

- In the non relativistic approximation

$$i\hbar\frac{\partial\varphi}{c\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + g_s ca - i\frac{g_p}{2m}\vec{\sigma}\cdot(-i\hbar\vec{\nabla}a)\right]\varphi$$

The interaction term has the form of a **spin - magnetic field interaction** with $\vec{\nabla}a$ playing the role of an effective magnetic field

$$H_{a-e} = -\mu_B\vec{\sigma}\cdot\left[\frac{g_p}{2e}\vec{\nabla}a\right]$$

$$B_a = 9.2\cdot 10^{-23}\left(\frac{m_a}{10^{-4}\mathrm{eV}}\right)\left(\frac{v_E}{270\ \mathrm{Km\,s^{-1}}}\right)\quad \mathrm{T}$$

$$\frac{\omega_a}{2\pi} = 24\left(\frac{m_a}{10^{-4}\mathrm{eV}}\right)\quad \mathrm{GHz}$$

$$\Delta\omega_a/\omega_a \simeq 5\times 10^{-7}$$

Experimental parameters

Axion mass

$$10^{-4}\, eV \le m_a \le 10^{-3}\, eV$$

Equivalent RF magnetic field

$$10^{-22}\, Tesla \le B \le 10^{-21}\, Tesla$$

Working frequency

$$20\ GHz \le \nu \le 200\ GHz$$

Detector bandwidth

$$\Delta\nu \le 100\ kHz$$

Electron Larmor Frequency

$$\nu_{larmor} = \gamma_e B_0 \qquad \gamma_e = 28 GHz / T$$

$$0.7\ T \le B_0(T) \le 7\ T$$

Magnetizing field

Measurement at the quantum limit

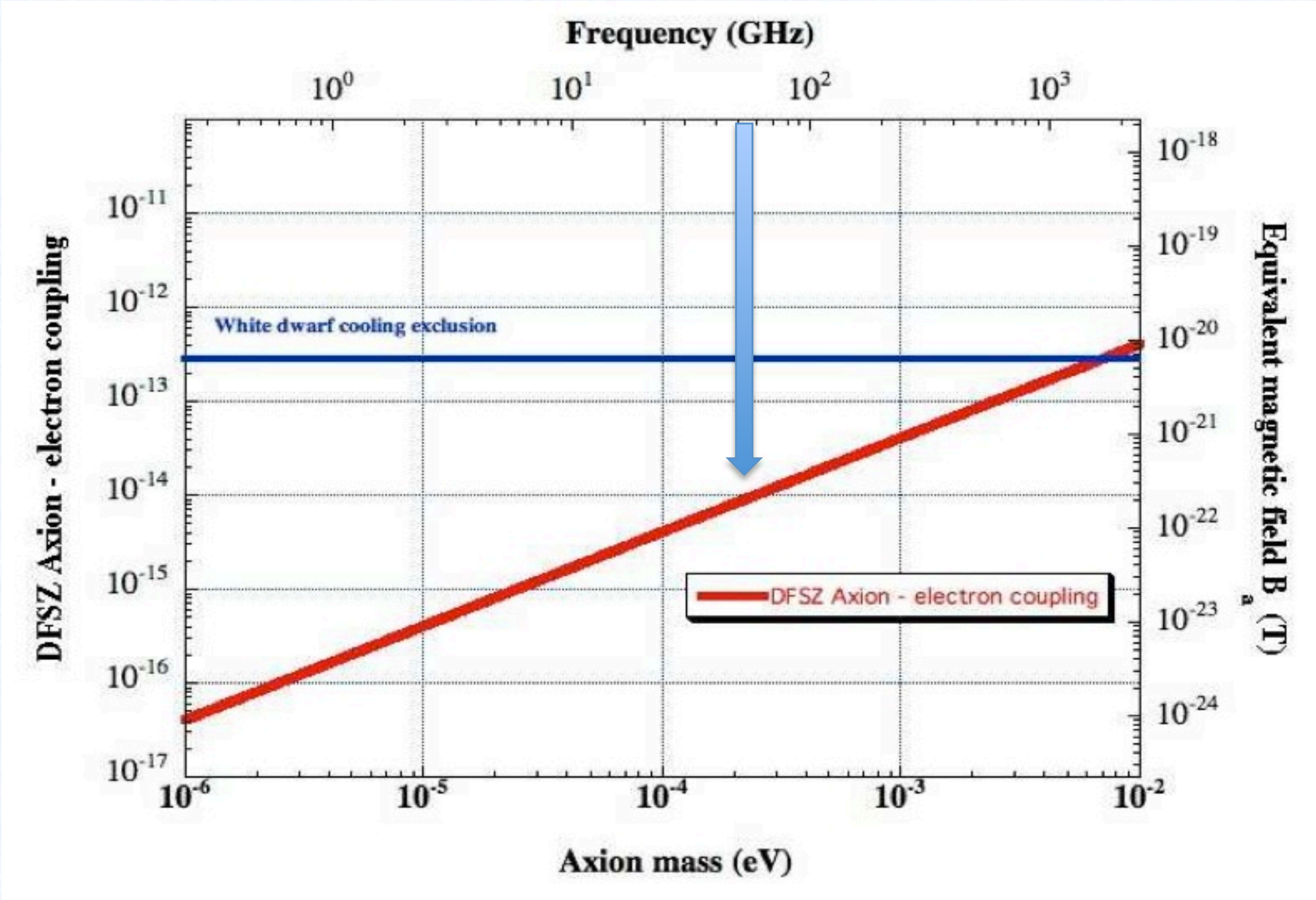
$$T_{spin} \le \frac{\mu_b B_0}{K_b}, T_{lattice} \le \frac{\hbar\nu}{K_b}$$

$$100 mK \le T(K) \le 1K$$

Working temperature

Goal of QUAX prototype

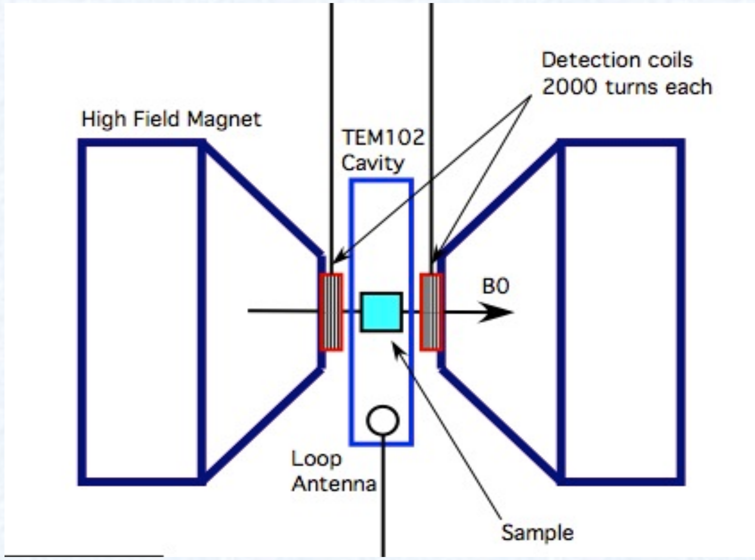
- **Reach the axion model coupling constant within 3-4 years development in a narrow axion mass range**



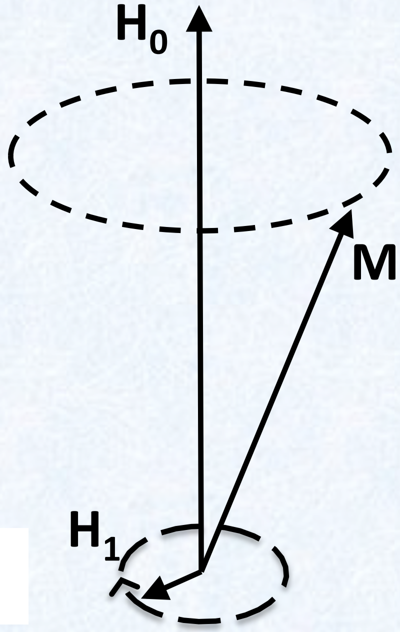
- Key point is to **demonstrate that noise sources are under control** in reasonable amount of time, thus allowing to **extend the mass range in a larger apparatus**

Electron Spin Resonance

Electron Spin Resonance (ESR or EPR) inside a magnetic media (rf receiver) is tuned by an **external magnetizing field H_0;** the rf field $\mathbf{H_1}$ (orthogonal to $\mathbf{H_0}$) in the **GHz range** excites the spin flip transitions at Larmor resonance ν_L . **M** undergo precession!

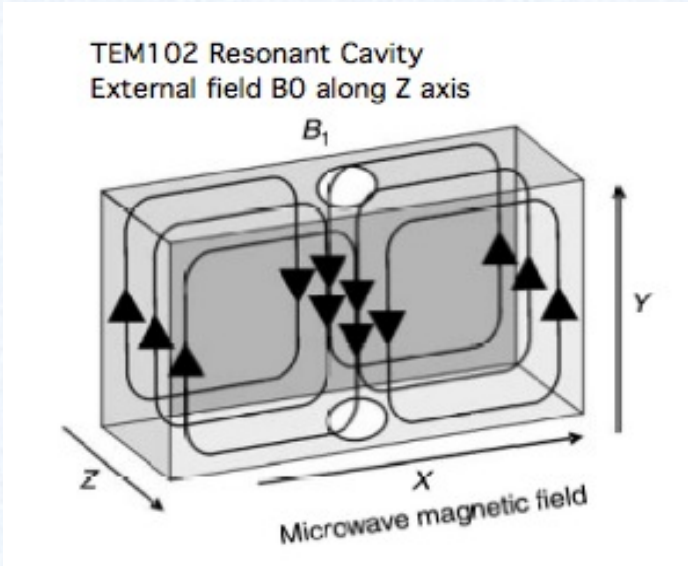


$$\mathbf{H} = \begin{pmatrix} H_1 \cos(\omega t) \\ H_1 \sin(\omega t) \\ H_0 \end{pmatrix}$$



1 T -> ν_L =28 GHz

- We studied the Electron Spin Resonance in 3 experimental situations for the magnetized sample:
  - free space (radiation damping problem)
  - rf cavity with hybridization of cavity-kittel modes (thermal photons problem)
  - waveguide in cutoff $\nu_c > \nu_L$ (under investigation)



The Bloch equations

The evolution of the magnetization **M** **(due to spin transitions)** under the influence of external fields is described by a set of coupled non-linear equations (**H**=Magnetizing field $\mathbf{H_0}$ + driving rf field $\mathbf{H_1}$)

$$\frac{dM_x}{dt} = \gamma(\boldsymbol{M} \times \boldsymbol{H})_x - \frac{M_x}{T_2}$$

$$\frac{dM_y}{dt} = \gamma(\boldsymbol{M} \times \boldsymbol{H})_y - \frac{M_y}{T_2}$$

$$\frac{dM_z}{dt} = \frac{M_0 - M_z}{T_1} + \gamma(\boldsymbol{M} \times \boldsymbol{H})_z$$

Spin-lattice relaxation time $\boldsymbol{T_1}$: establish energetic equilibrium of M_z.

Spin-spin relaxation time $\boldsymbol{T_2} < T_1$: H_1 forces M_x M_y to rotate and T_2 sets equilibrium

At low temperature T < 1 K

T_1 ~ 10^{-6} to 10 s

T_2 ~ 10^{-6} to 0.1 s

depends on spin density

e.g. Magnetization of a paramagnet

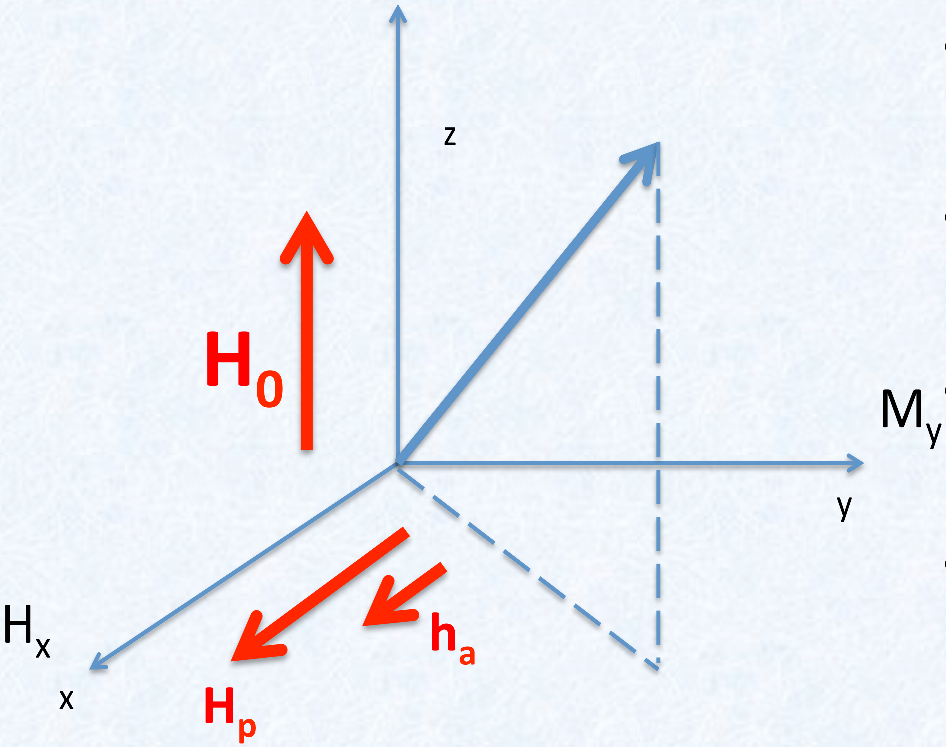
$$M_0 = N_0 \mu_B \tanh[\mu_B H_0 / k_B T]$$

N_0 – spin density

μ_B – Bohr magneton

T – sample temperature

LOngitudinal Detection (LOD) of axion field (1)



- Magnetize the sample along the z-axis orthogonal to the axion direction
- **H_0 amplitude** matches the searched value of the **axion mass**
- Then the equivalent **axion field h_a** is in the transverse direction
- Drive the sample with a **pump field H_p** near the Larmor frequency

Total driving radio-frequency field

$$H_{1,x} = H_p \cos\omega_p t + h_a \cos\omega_a t$$

$$\omega_p \cong \omega_a \cong \omega_{\mathrm{Larmor}} = \gamma H_0$$

$$\omega_D \equiv \omega_p - \omega_a \neq 0$$

Longitudinal detection of axion field (2)

The relevant Bloch equations

$$\dot{M}_z = \gamma\left(M_y H_x\right) + \frac{\left(M_0 - M_z\right)}{T_1}$$

A stationary solution can be obtained.

$$M_y = \frac{\gamma M_0\left(i\omega + \frac{1}{T_2}\right)H_x}{\left(\omega_0^2 + i\frac{\omega}{T_2} - \omega^2 + \frac{1}{T_2^2}\right)} \equiv \chi_y H_x$$

The **magnetization along the z-axis** (longitudinal component) shows a term **modulated at the difference frequency ω_D.**

$$m_z(t) = \frac{1}{2} M_0 \gamma^2 T_1 T_2 H_p h_a \cos\omega_D t$$

for

Saturation parameter s

$$\gamma^2 T_1 T_2 H_p^2 = s << 1$$

$$\omega_D^{-1} << T_1, T_2$$

H_p, h_a in Tesla M_0 , m_z in A/m

Longitudinal detection of axion field (3)

We can define a sort of gain G_r for the **low frequency component Δm_z** with respect to the **high frequency** field **h_a**

$$\Delta m_z(t) = G_r h_a \cos\omega_D t$$

$$G_r = \frac{1}{4} M_0 \gamma^2 T_1 T_2 H_p$$

If we put some relevant numbers (already published for YIG)

$T_1 \approx 10^{-6}$ s
$T_2 \approx 10^{-6}$ s
$M_0 = 0.2$ T

We obtain $G_r > 100$

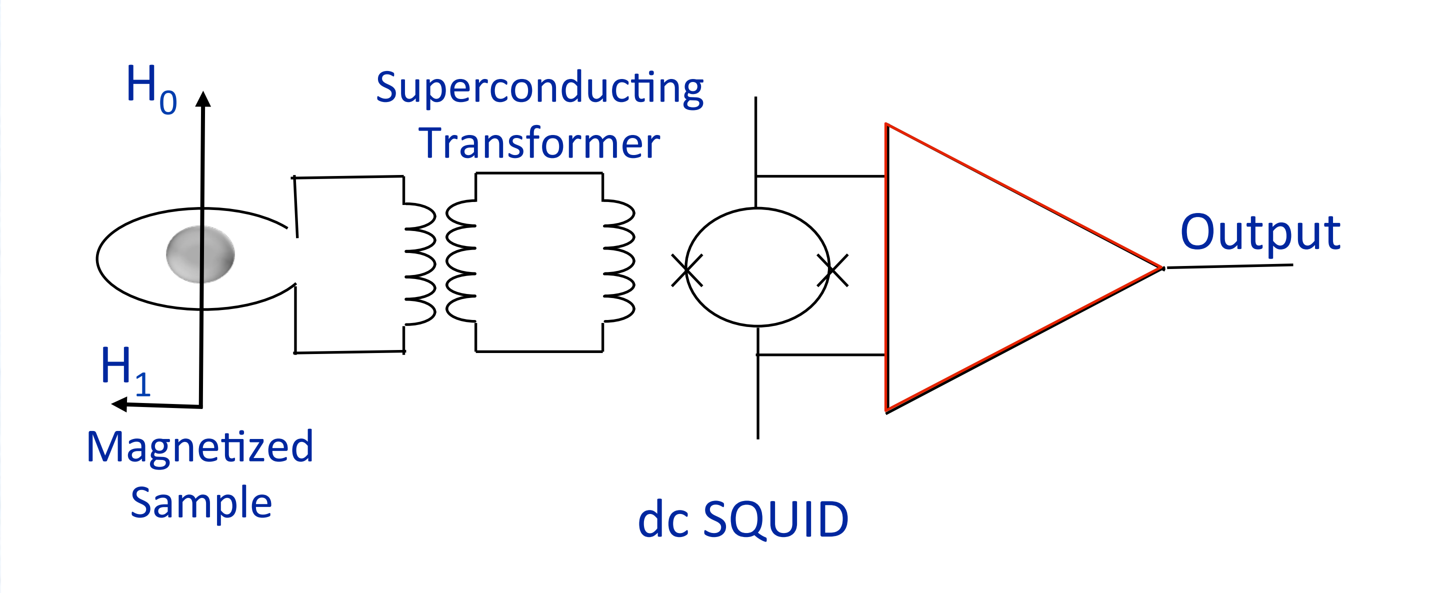
for a pump field $H_p \sim 0.1\ \mu T$

Can we get enough gain G_r to be able to reach a measurable low frequency Δm_z from amplitude axion field $h_a \sim 10^{-22}$ T?

- **find the right material (YIG)**
- **power dissipated in the cryogenic system**
- **noise sources in the system**

Detection of the down converted field

The most sensitive device for measuring magnetic field is the **DC squid** which senses magnetic flux F. The best **SQUID sensitivity is** F_{ns} = 10^{-21} Wb/√Hz



The magnetic flux due to the axion field, and passing through the pick up coil, is

$$F_a = n_L\, G_r\, h_a\, A \quad (Wb)$$

where A is the area covered by the sample and n_L is the number of loops in the pick up coil. If A ~ 10^{-4} m^2, the gain necessary to obtain SNR=1 in 10^4 sec of integration time is:

$$G_r \sim 1000 / n_L$$

To reach this gain, given the material (T_1, T_2), the free parameter is the pumping field.

Pumping field

The **pumping field H_p is limited** by two factors:

- **saturation of the spins** in the material

$$s \equiv \gamma^2 T_1 T_2^* H_p^2 << 1$$

- **power dissipated** into the sample (of volume V)

$$P_{diss} = \frac{1}{2}\omega_p H_p^2 M_0 \gamma T_2^* V \qquad [Watt]$$

The most stringent limitation comes from the power dissipation, which must be lower than the cryogenic power available:

@ 100 mk	P_{cryo} ~ 1 mW
@ 1 K	P_{cryo} ~ 300 mW

QUAX Noise

- We identified 4 main noise sources (our system is in a steady state and not in thermal equilibrium)

1. Fluctuations in magnetization due to relaxation processes in materials
2. Fluctuations associated with the rf pump (dissipation in the driving circuit)
3. Thermal photons (black body in free space or normal modes in a rf cavity)
4. Additive and back-action noises of the SQUID magnetometer

However, other relaxation phenomena may occur in the axion detection bandwidth, for instance, in the down conversion process

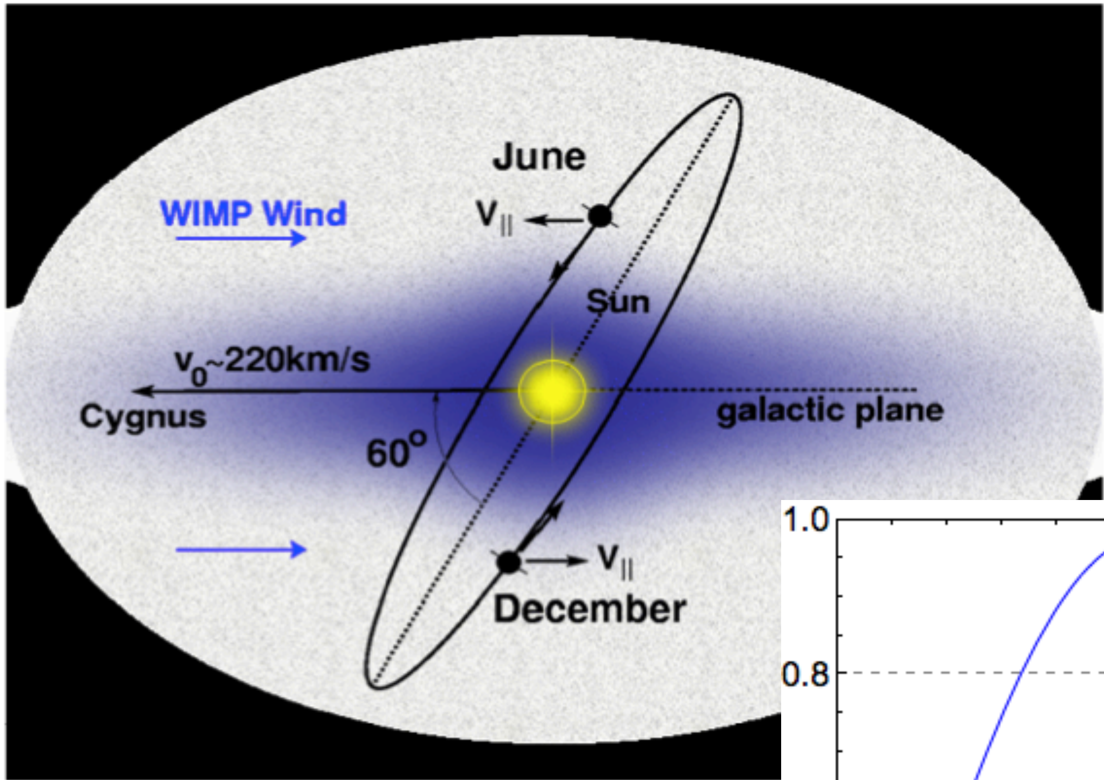
The noise level must be measured experimentally!

We have only this preliminary indication for the noise level

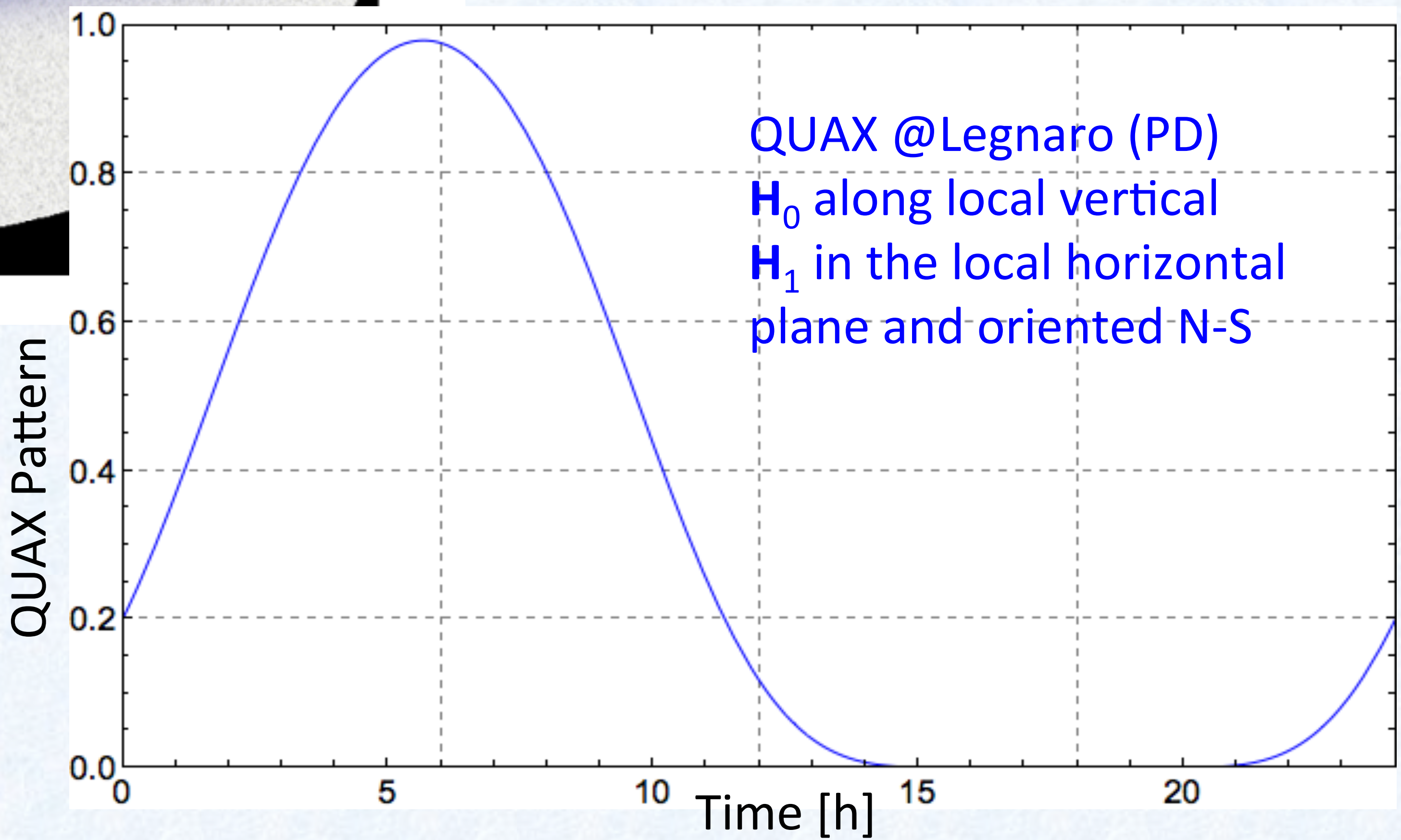
Gd2SiO5 @ 100mK + 1 Tesla magnetizing field + SQUID magnetometer

Magnetization Noise < 10^{-15} T/Hz$^{1/2}$

QUAX Directional Pattern



Due to Earth rotation, the direction of the static magnetic field $\mathbf{H_0}$ and (linearly polarized) pump field $\mathbf{H_1}$ changes with respect to the direction of the axion wind (Vega)



A strong modulation occurs! It is not due to seasonal or Earth rotation doppler effect (few %) but to direction changes (up to 100%)

Experimental tests of the proposed scheme

The LOD technique (Pescia 1965, Ablart and Pescia 1980) is widely used in material science; however, at a **much lower sensitivity level with sample in free space or in rf cavity**.

In addition, LOD is used in **paramagnetic materials** with **low spin density** $N_0 \sim 10^{22}$ spin/m^3.

In order to reach the required gain G_r in the axion bandwidth, we will need **$T_1 \sim$ 1-10 μs, $T_2 \sim$ 1-10 μs, $N_0 \sim 10^{27}$-10^{28} spin/m^3.** The LOD must be verified by experiments in extreme regions of sensitivity (rf field amplitude <10^{-15} Tesla) and with samples in a waveguide.

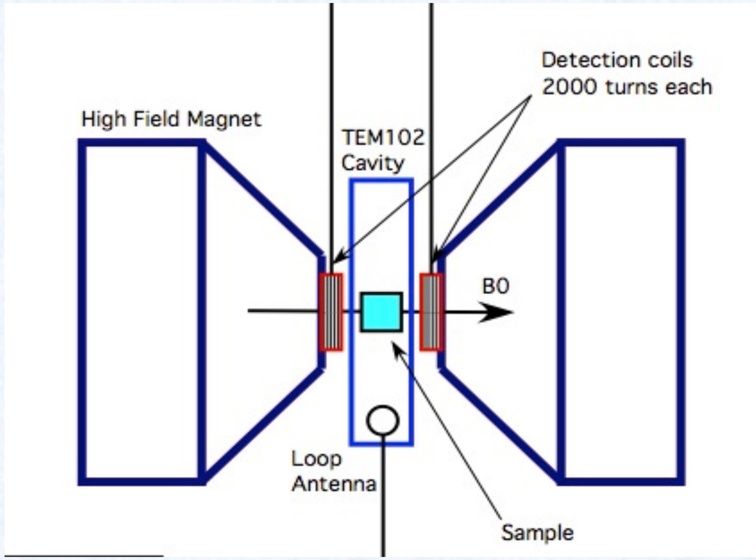
But luckily, an end-to-end calibration of the QUAX prototype, and a measure of the total noise are possible

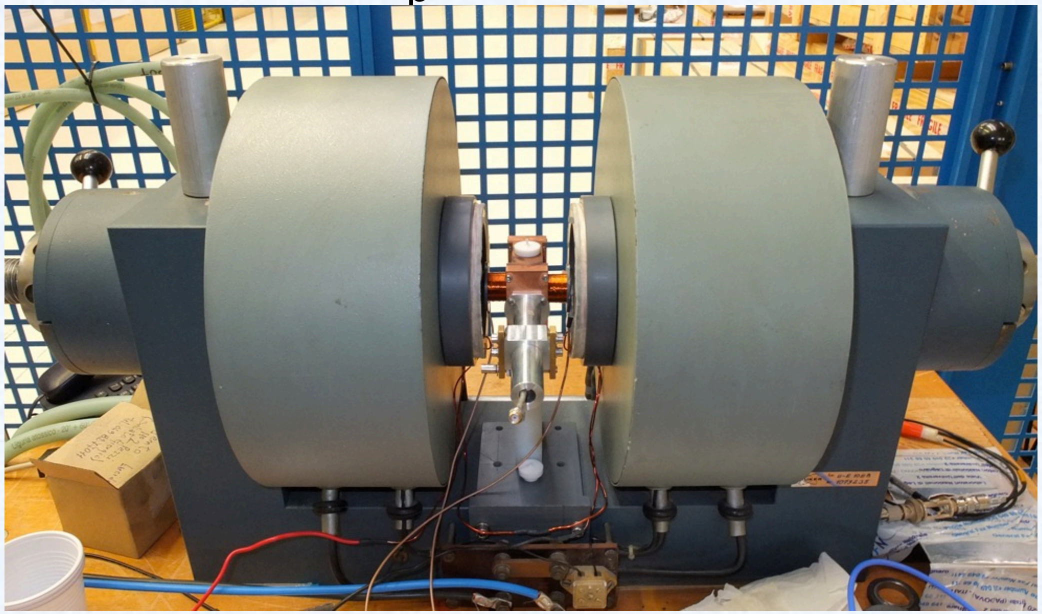
$$H_{1,x} = H_p \cos\omega_p t + h_a \cos\omega_a t$$

Provide h_a with a second rf generator!

Calibrations - First prototype at Legnaro (Italy)

Using an old EPR magnet we have set-up an apparatus to test the measurement scheme at **room temperature**.
The equivalent axion field h_a was generated using a **second RF generator** (coherent source) frequency locked to the pump H_p.





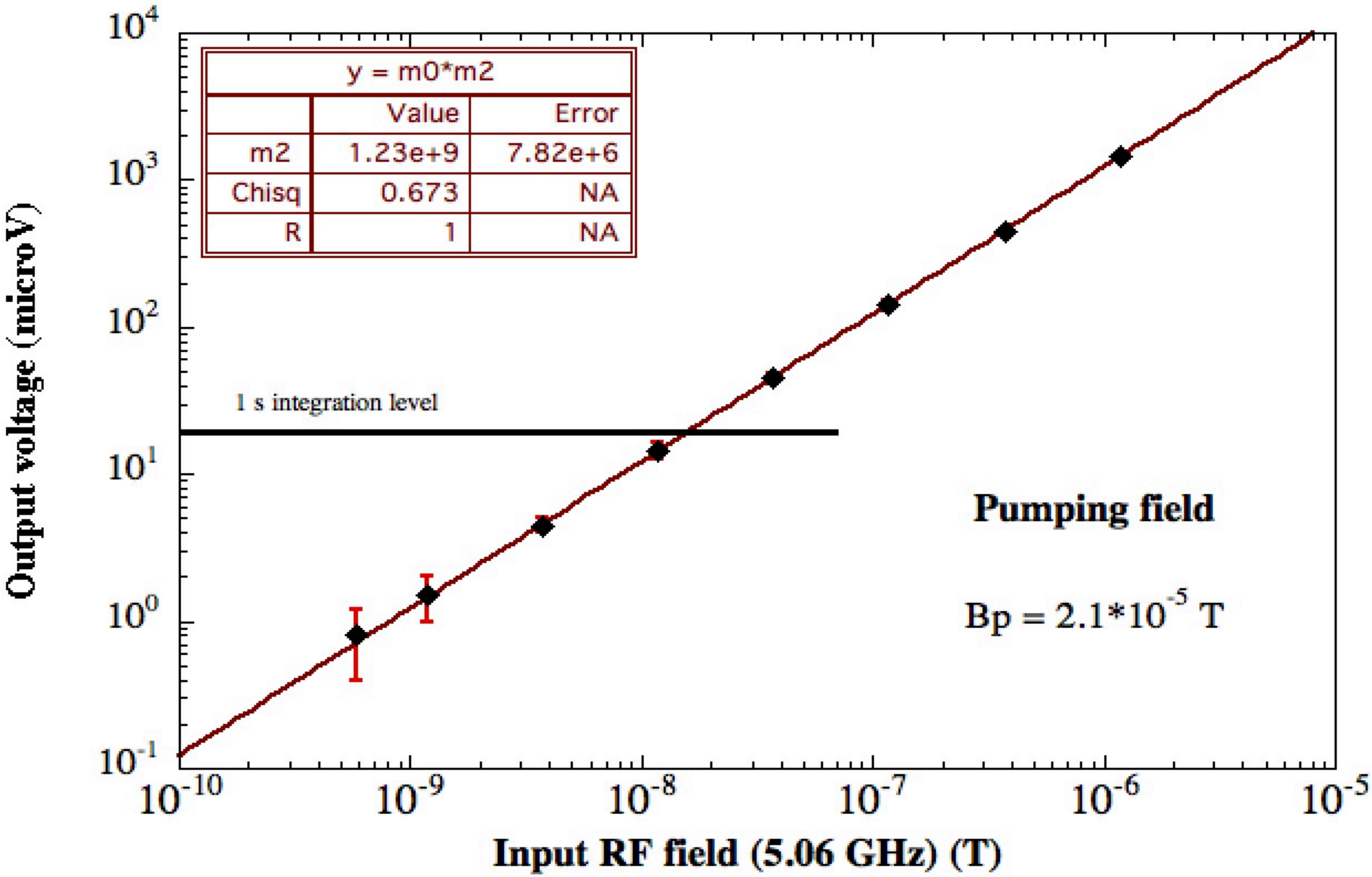
As a magnetized sample we used **DPPH** (2,2-diphenylpicrylhydrazyl) at 300 K.

T_2 = 47 ns (measured by us)
T_1 = 60 ns (from literature)
M_0 = 3.7 A/m   ($N_0 \sim 10^{27}$ m^{-3})

Calibration with coherent source

Calibration with DPPH in a 5 GHz resonant cavity

Detection of low frequency field at 3 KHz with a 3000 loops coil



Expected gain

G_m (th) = 3 10^{-3}

Measured gain

G_m(exp) = 1 10^{-3}

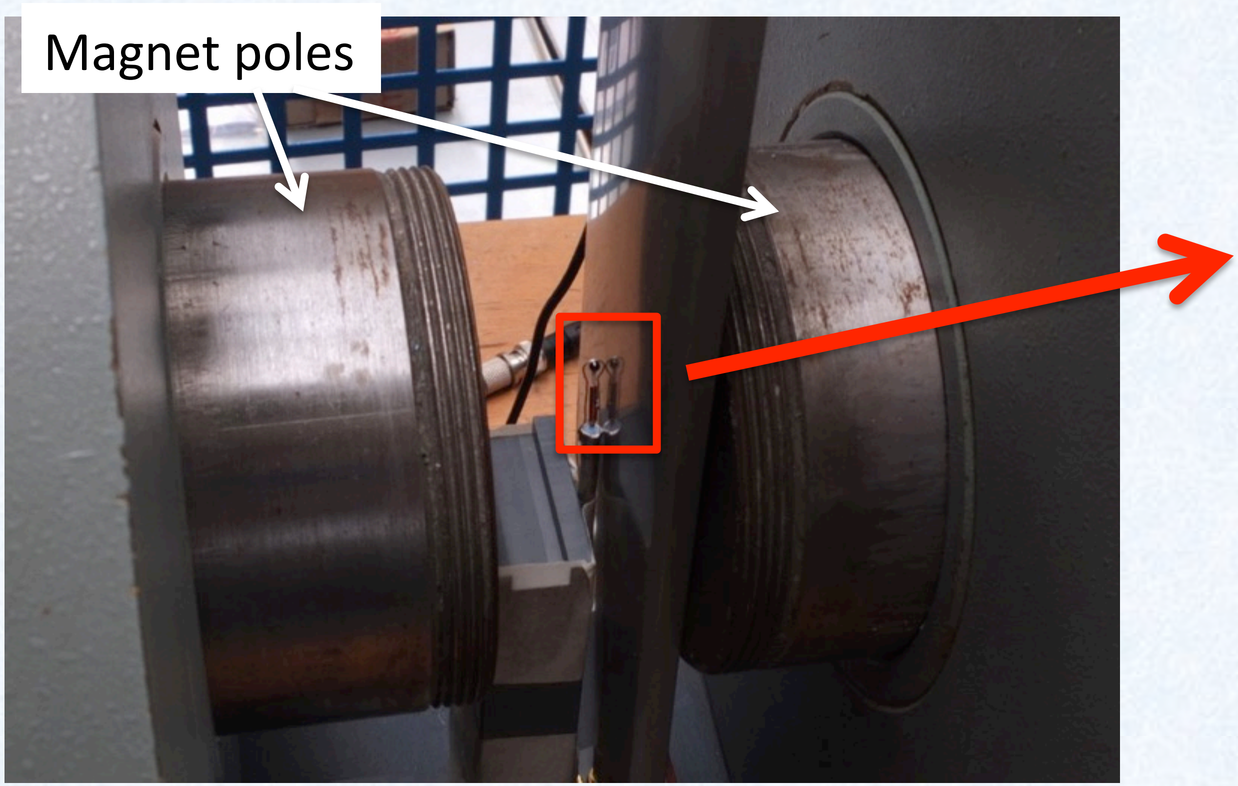
T_2 measured by us

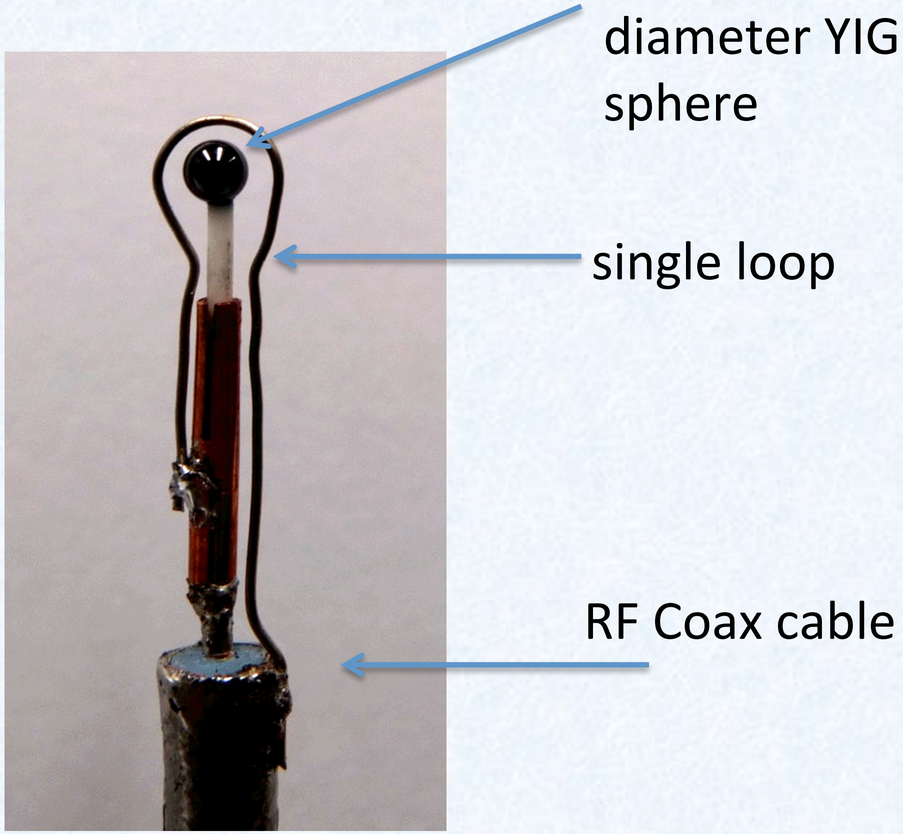
Lower gain possibly due to fields inhomogeneities and worse coupling

Free space measurements

A magnetized sample is placed first in free space inside the magnetic field region and excited by near field in order to test the LOD scheme

rf pumping with two rf generators at ω_a and ω_p within the Larmor linewidth. This has been obtained by a single loop coil enclosing the sample

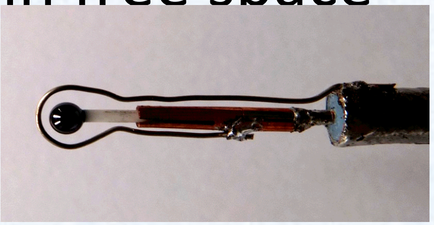




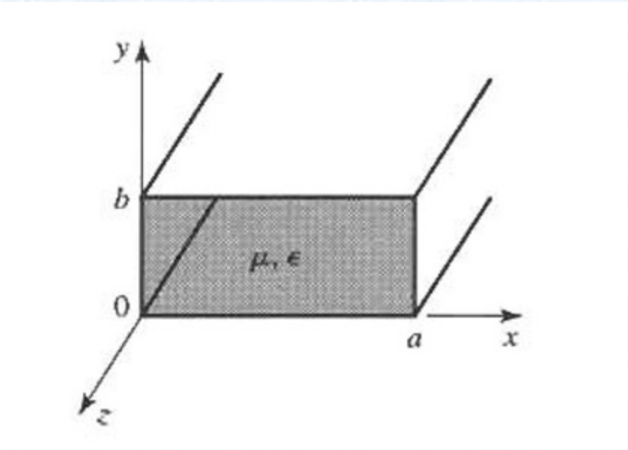
We have checked **the frequency down conversion** feeding the two driving fields. The low frequency signal was picked up with a 3000 loops coil placed close to the sample. **Low frequency signal has been observed**, calibrations of gain G_r are on the way.

Waveguide in cutoff (1)

- A viable solution for the QUAX prototype
  - waveguide reduces radiation damping and thermal photons @ Larmor freq.
  - waveguide isolate the magnetized sample from the environmental rf noise
  - Despite rf photons, axions can penetrate the waveguide because they are massive and thus cause the spin flip of electrons
- We have verified that near field of pump $\mathbf{H_p}$ causes the spin flip of electrons using a single loop enclosing the sample as in free space

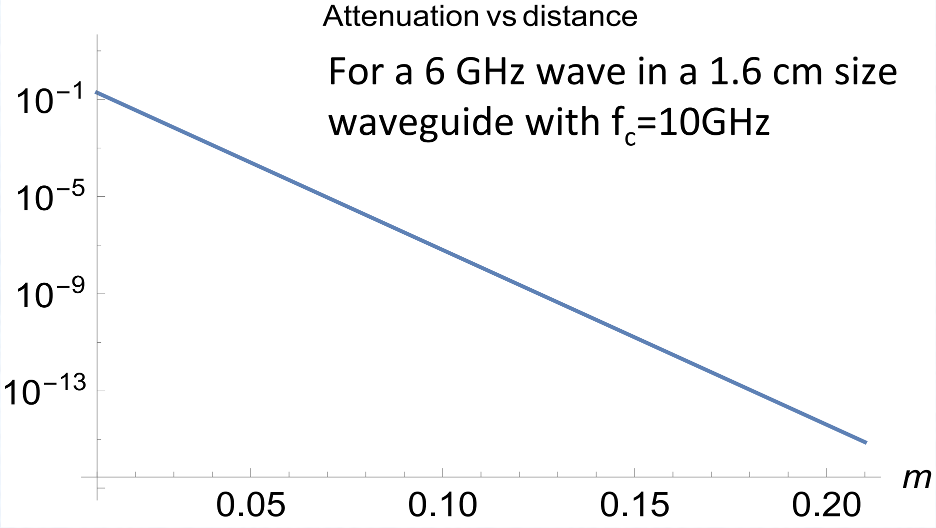


For a > b the lowest cut off frequency is



$$f_{c_{10}} = \frac{1}{2a\sqrt{\mu\epsilon}}.$$

Below cutoff we have an evanescent wave



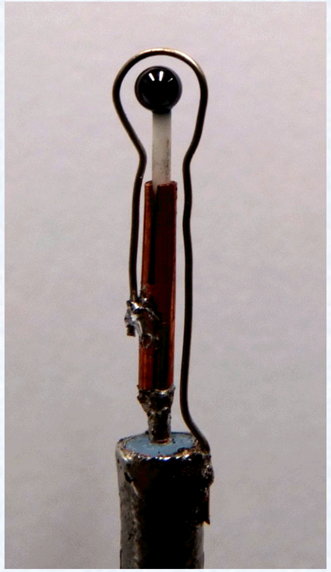
Waveguide in cut off (2)

We have checked the system in the following experimental conditions:

rectangular waveguide with 0.8 x 1.6 cm^2 section
cut off frequency 9.3 GHz
waveguide length 1 m

magnetizing field B_0 = 0.2 T

Larmor frequency 5.6 GHz



We placed **the YIG sphere at the center of 1-m long waveguide**

rf field @ Larmor frequency should be completely suppressed.

The **magnetic field** (near field) produced by the single loop coil excites the spin transitions at the Larmor frequency: strong **absorption peak has been observed at resonance**.
The coil for low frequency detection has not yet been implemented in the waveguide

Short term perspectives

- Build up a prototype apparatus capable of working at cryogenic temperature (at 4 K)
- Find a material with T_1 and T_2 long enough, and with large magnetization at low temperature (YIG seem to be the best one) in order to have $G_r > 10 \div 100$
- In a first step: use as low frequency detector a pick up coil and a low noise GaAs-FET amplifier
- In a second step: integrate a SQUID into the system @ T=4 K
- In one year: reach a sensitivity of 10^{-14} Tesla with pump field of nTesla
- **Measure the material magnetic noise level as soon as possible**

Quantum counter detection scheme

VOLUME 2, NUMBER 3 PHYSICAL REVIEW LETTERS FEBRUARY 1, 1959

SOLID STATE INFRARED QUANTUM COUNTERS*

N. Bloembergen
Harvard University,
Cambridge, Massachusetts,
(Received December 29, 1958)

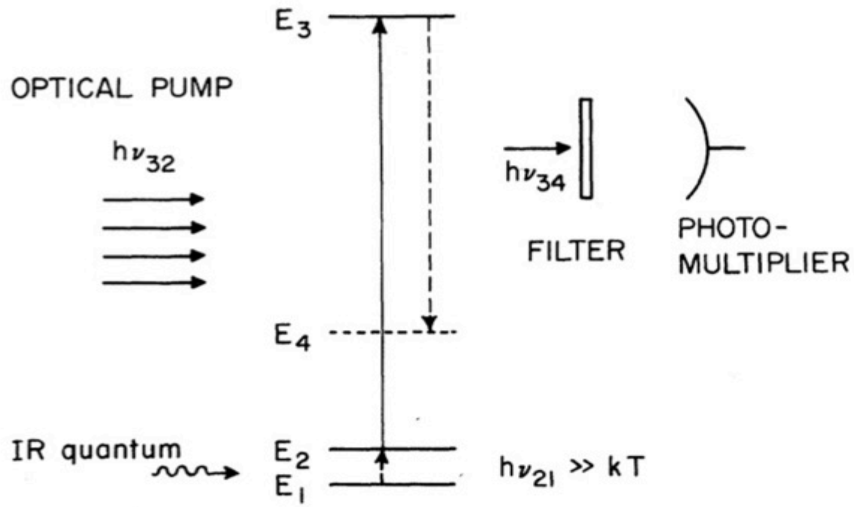


FIG. 1. Infrared quantum counter. Several ions of transition group elements have appropriate energy level diagrams: $h\nu_{21} = 1-5000\ \mathrm{cm}^{-1}$, $h\nu_{32} = 10^4 - 5\times 10^4\ \mathrm{cm}^{-1}$.

Detection of IR photons with high quantum efficiency in the absence of photomultipliers

Extend the same idea into the microwave regime where a Zeeman transition is tuned to the axion mass with an external field.

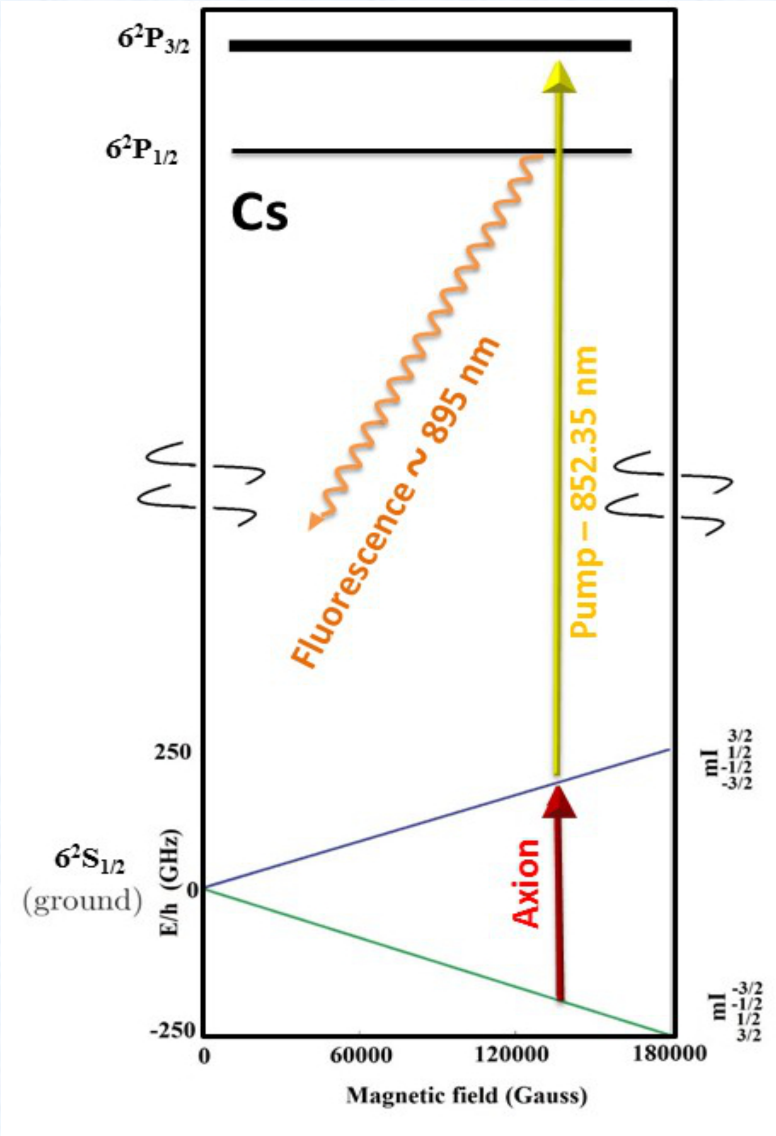
All the atoms must be in the Zeeman lower level.

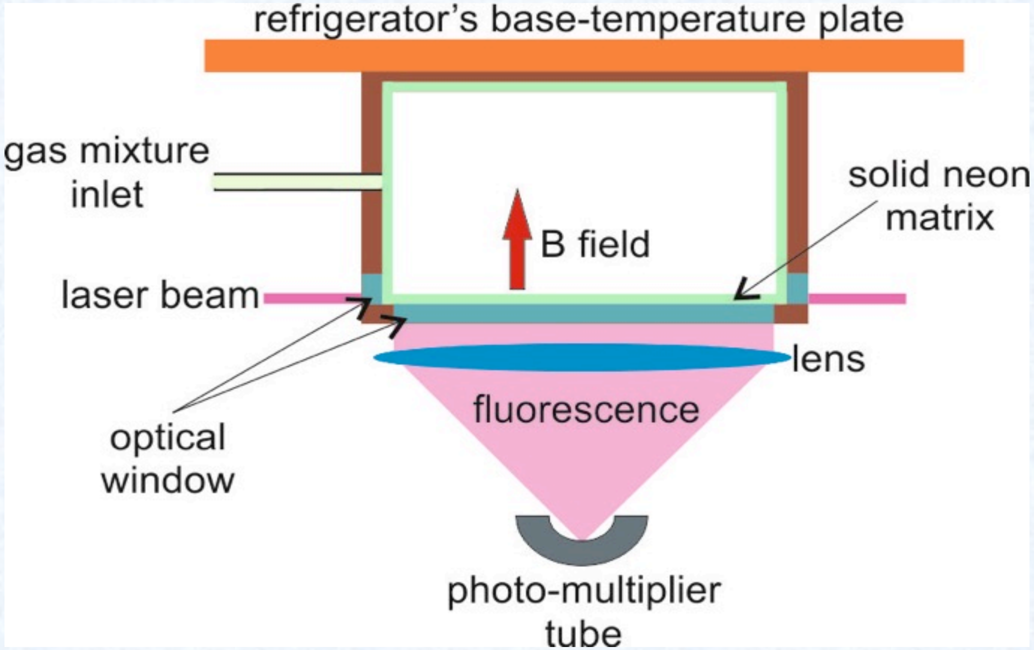
$$T = 12\ \mathrm{mK}\left(\frac{10^{11}\ \mathrm{GeV}}{f_a}\right).$$

(Sikivie, 2014)

Detection with O_2 molecules or Cs atoms?

Together with people in **Pisa, Napoli and Firenze** we are studying the possibility of using **Oxygen molecules or atomic Cesium** cooled to 280 mK (Buffer gas cooling) as magnetized target.





- Work in the higher axion mass range
- Number of available atoms can be an issue
- Find an appropriate detection technique with high efficiency (REMPI – resonance enhanced multiphoton ionization - interrogation scheme?)

(Courtesy of P. Maddaloni)

Conclusions

We have shown a possible approach for detecting galactic axion with magnetic material

- Tune the Larmor frequency of ESR of a magnetic sample to the axion mass
- Perform low frequency conversion of the axion effective magnetic field using the magnetized sample (receiver) as a mixer (rf pump field amplifies the axion signal)
- Measure the low frequency down converted signal (along $\mathbf{H}_0$ direction, i.e. LOngitudinal Detection) using SQUID amplifier coupled with a pick up coil to the receiver (YIG sphere)
- Key issues related to QUAX sensitivity:
  - **waveguide with cutoff frequency > Larmor frequency** to avoid radiation damping (gain of the rf receiver >100) and suppress thermal photons
  - **Measure of magnetic noise of the sample, pump noise, SQUID noise, etc**
- Alternative detection scheme with **quantum counting techniques** for higher axion masses (frequencies > 40 GHz) under study

Back up

- Back up slides

Radiation damping

Radiation damping describes two additional **loss mechanisms in magnetized sample at the Larmor frequency n_L:**

1) the interaction of the magnetized sample with **the driving circuit** $T_R \approx (2\pi\xi\gamma M_0 Q)^{-1}$

2) the **emission of radiation** (magnetic dipole) $T_R \approx \frac{\lambda_L^3}{\gamma M_0 V}$

ξ -> filling factor: geometrical coupling between driving circuit and magnetized sample
Q -> quality factor: accounting for dissipations of rf coils of driving circuit (or rf cavity)
λ_L -> rf wavelength (c/n_L)
V -> sample volume

For frequencies above 10 GHz and large magnetization M_0 the only relevant radiation damping is the emission of em radiation.

$$\frac{dM_x}{dt} = \gamma(\mathbf{M}\times\mathbf{H})_x - \frac{M_x}{T_2} - \frac{M_x M_z}{M_0 T_R}$$
$$\frac{dM_y}{dt} = \gamma(\mathbf{M}\times\mathbf{H})_y - \frac{M_y}{T_2} - \frac{M_y M_z}{M_0 T_R}$$
$$\frac{dM_z}{dt} = \gamma(\mathbf{M}\times\mathbf{H})_z - \frac{M_0 - M_z}{T_1} - \frac{M_x^2 + M_y^2}{M_0 T_R}$$

Bloch Equations modified with non linear terms introduced by Bloom in 1957

Steady state solutions with radiation damping

- Steady state solutions of Bloch Equations in the limit of weak rf field

$$M_x = M_z \frac{\delta\omega (T_2^*)^2}{1+(\delta\omega T_2^*)^2}\gamma H_1$$

$$M_y = M_z \frac{T_2^*}{1+(\delta\omega T_2^*)^2}\gamma H_1$$

$$\delta\omega = \omega - \omega_L$$

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{M_z}{M_0 T_R} \approx \frac{1}{T_2} + \frac{1}{T_R}$$

- For M_z we have to solve a cubic equation:

$$\frac{M_z^3(\delta,t)}{M_0^3} + \left(\frac{2T_R}{T_2} - 1\right)\frac{M_z^2(\delta,t)}{M_0^2} + \left(\delta^2 T_R^2 + \left(\frac{T_R}{T_2}\right)^2 - \frac{2T_R}{T_2} + \frac{\omega_1^2 T_1 T_R^2}{T_2}\right)\frac{M_z(\delta,t)}{M_0} = \left(\delta^2 T_R^2 + \left(\frac{T_R}{T_2}\right)^2\right)$$

- However, in the $\gamma^2 H_1^2 T_1 T_2 << 1$ limit **(far from saturation)** the solution is

$$\Delta m_z \equiv M_0 - M_z = \frac{1}{4} M_0 \frac{T_2^*}{T_2} \frac{\gamma^2 T_1 T_2^*}{1+(T_2^*\delta\omega)^2} H_1^2$$

the component of magnetization along the polarizing field has a quadratic dependence on the rf field $\mathbf{H_1}$. **QUAX exploits this non-linearity for the axion detection**

Longitudinal detection of axion field (2)

H_1 is a linear superposition of two rf fields (**p**ump and **a**xion or **a**ny rf field) with slightly different frequencies ω_p and ω_a with amplitudes $H_p >> h_a$ and $T_1 T_2 \gamma^2 (H_p+h_a)^2 << 1$

IF $\omega_p - \omega_a << \omega_L$ and $(\omega_p + \omega_a)/2 \approx \omega_L$ we can calculate M_z from quasi-stationary solutions

$$\Delta m_z(t) = \frac{1}{4} M_0 \frac{T_2^*}{T_2} \gamma^2 T_1 T_2^* H_p \left[\frac{1+\omega_D^2 T_2^{*2}/4}{\left(1+\omega_D^2 T_1^2\right)\left(1+\omega_D^2 T_2^{*2}\right)} \right]^{1/2} h_a \cos\omega_D t$$

Then M_z oscillates at very low frequency!

Assuming $\omega_D < \min(1/T_1, 1/T^*_2)$
the amplitude of oscillations is

$$\Delta m_z(t) = \underbrace{\left[\frac{1}{4} M_0 \frac{T_2^*}{T_2} \gamma^2 T_1 T_2^* H_p \right]}_{receiver\ gain} h_a \cos\omega_D t$$