Detection of cosmological axions
The QUAX-AXIOMA R&D Activities

Giovanni Carugno UNIPD/INFN

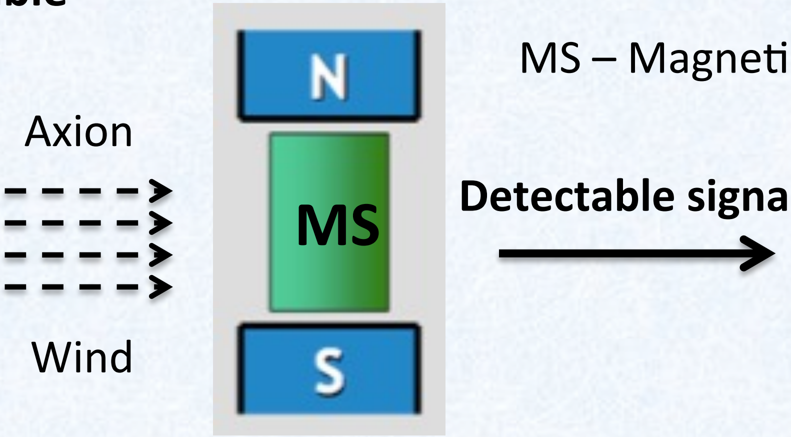
for the QUAX and AXIOMA Collaborations

QUAX (lat/gr): QUaerere ‘ΑΞιον

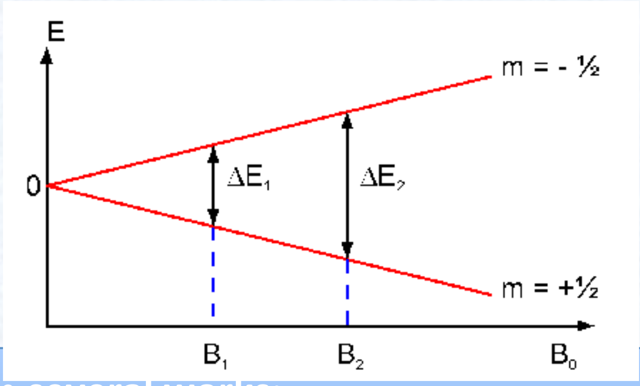
or (En): to QUest for AXions

QUAX-AXIOMA Detector (Haloscope)

- The idea for the axion detection 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** **(causing the spin flip)**
- An external polarizing magnetic field H_0 set their Larmor frequency
- The equivalent magnetic (rf) field excites **transition in a magnetized sample** which behaves as a **rf receiver** tuned at the Larmor frequency
- **The interaction with axion field produces a variation of magnetization which is in principle measurable**



MS – Magnetized Sample (YIG)



Idea to exploit Electron Spin Resonance (ESR) in not new and comes from **several 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

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

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

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

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

Experimental parameters

Axion mass $10^{-4}\,eV \leq m_a \leq 10^{-2}\,eV$

Equivalent RF magnetic field $10^{-22}\,Tesla \leq B \leq 10^{-20}\,Tesla$

Working frequency $20\,GHz \leq \nu \leq 280\,GHz$

Detector bandwidth $\Delta\nu \leq 1\,MHz$

Electron Larmor Frequency

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

$$0.7\,T \leq B_0(T) \leq 10\,T$$

Magnetizing field

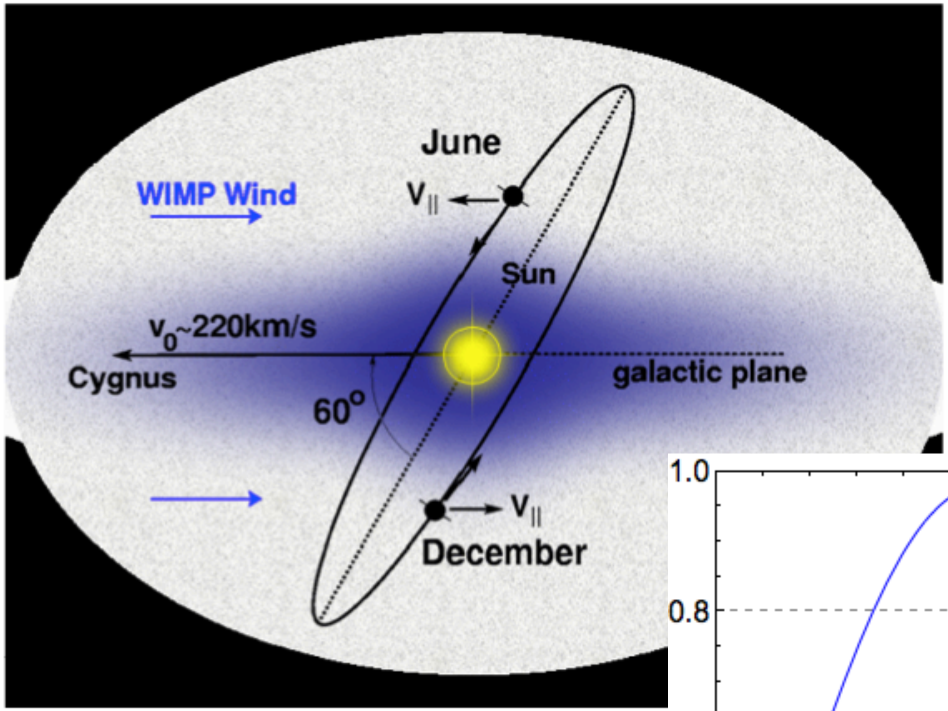
Measurement at the quantum limit

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

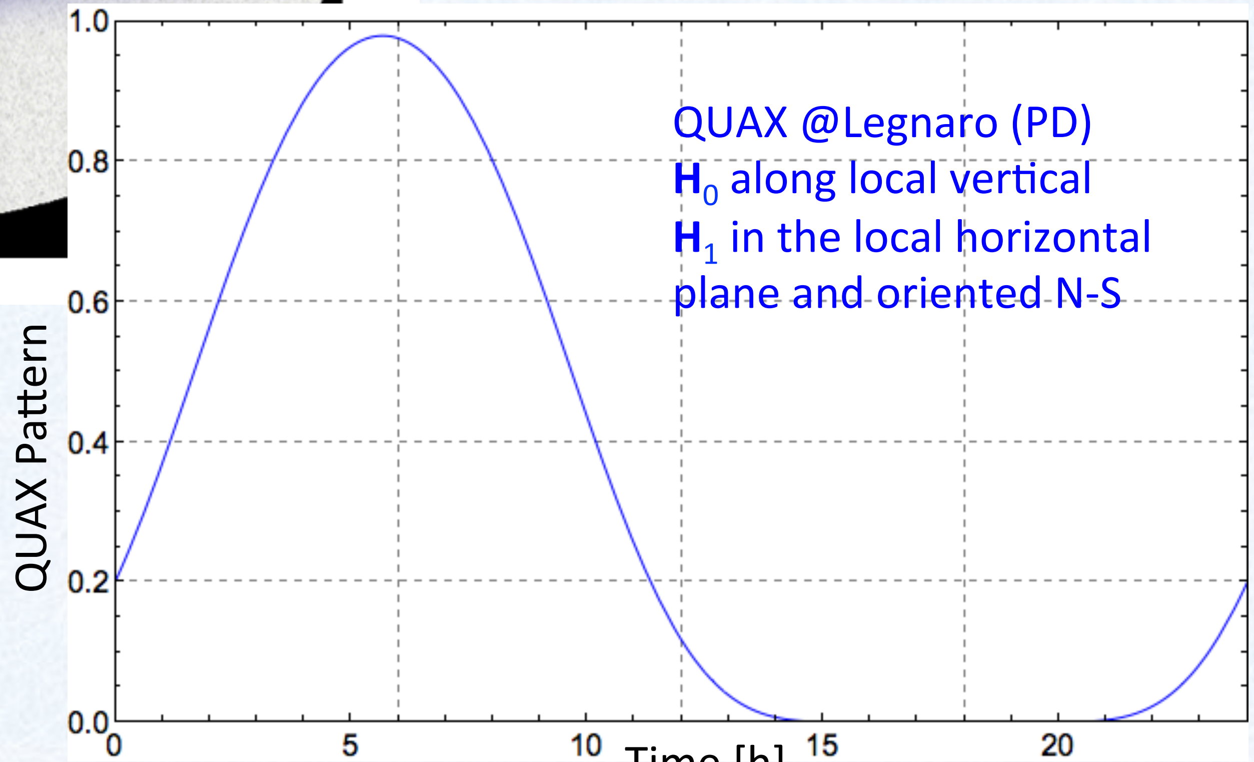
$$\boxed{100mK \leq T(K) \leq 1K}$$

Working temperature

Directional Pattern



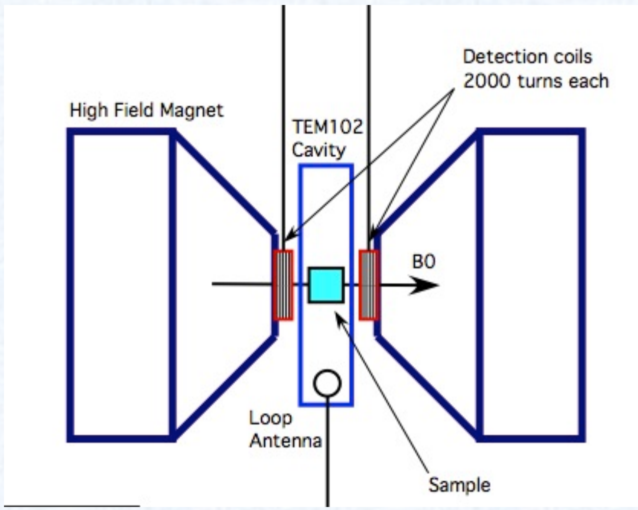
Due to Earth rotation, the direction of the static magnetic field $\mathbf{H_0}$ and (linearly polarized) pump field $\mathbf{H_1}$ changes with respect to the direction of the axion wind (Vega)



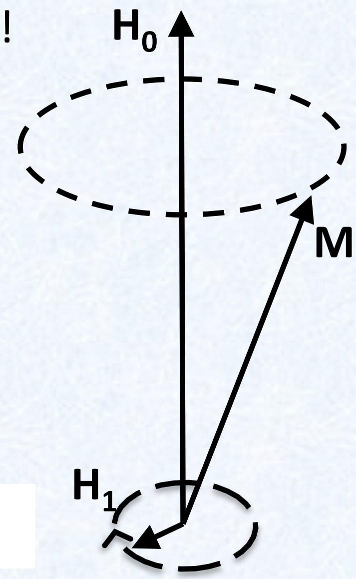
A strong modulation occurs! It is not due to seasonal or Earth rotation doppler effect (few %) but to direction changes (up to 100%)

QUAX : 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!

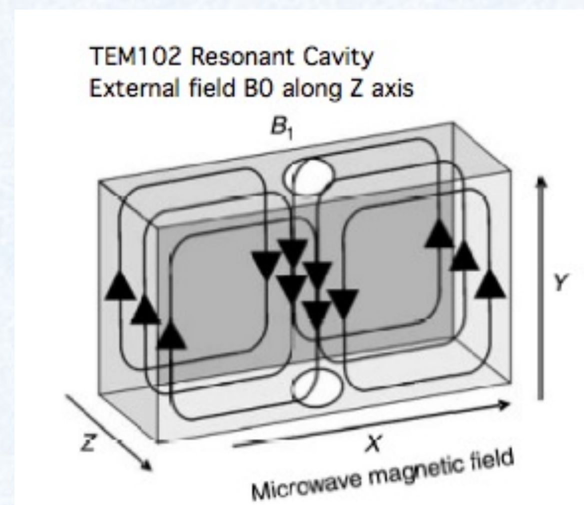


$$\mathbf{H} = \begin{pmatrix} H_1 \cos(\omega t) \\ H_1 \sin(\omega t) \\ H_0 \end{pmatrix}$$



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
  - 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 T_1:
establish energetic equilibrium of M_z.

Spin-spin relaxation time $T_2 < T_1$:
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

Radiation damping

Radiation damping describes two additional **loss mechanisms in magnetized sample at the Larmor frequency ν_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/ν_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

Two Detections Approaches

- 1) Measure the Power emitted in the cavity directly through:

  a) Linear Amplifier

  b) Microwave Counter

- 2) LOngitudinal Detection (LOD)
  Signal Down Converted @ Low Frequency

Axion power

- The axion interacting with the electron spin will induce spin-flips, i.e. a change in the material magnetization.
- Effect due only the component of the axion magnetic field orthogonal to the magnetizing field – **directional detector**

Axion induced magnetization

$$M_a(t) = \gamma \mu_B B_a n_S \tau_{\text{sig}} \cos(\omega_a t)$$

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

$$B_a = 9.2 \cdot 10^{-23} \left(\frac{m_a}{10^{-4}\text{eV}} \right) \ \text{T}$$

$$\tau_{\text{sig}} = \min\left(\tau_a, \tau_2, \tau_r\right)$$

Axion coherence t_a

Material relaxation t_2

Radiation damping t_r

Axion power 2

Axion coherence t_a → $$\tau_a = 6.3 \left(\frac{2\times 10^{-4}\,\mathrm{eV}}{m_a}\right)\left(\frac{Q_a}{1.9\times 10^6}\right)\ \mu\mathrm{s}$$

Material relaxation t_2 → Typical values from ns to a few ms

Radiation damping t_r → $$\frac{1}{\tau_r} = \frac{1}{4\pi}\frac{\omega_L^3}{c^3}\gamma\mu_0 M_0 V_s$$ Free space

-> Radiation damping mechanism is suppressed inside a microwave cavity.

Power released by the axion wind

$$\begin{aligned} P_{\mathrm{in}} &= B_a \frac{dM_a}{dt} V_s \\ &= \gamma \mu_B n_S \omega_a B_a^2 \tau_{\mathrm{sig}} V_s \end{aligned}$$

$$P_{\mathrm{out}} = \frac{P_{\mathrm{in}}}{2} = 8\times 10^{-26}\left(\frac{m_a}{2\cdot 10^{-4}\,\mathrm{eV}}\right)^3\left(\frac{V_s}{1\ \mathrm{liter}}\right)\left(\frac{n_S}{10^{28}/\mathrm{m}^3}\right)\left(\frac{\tau_{\mathrm{sig}}}{10^{-6}\,\mathrm{s}}\right)\ \mathrm{W}$$

Axion power detection

- **Linear amplifier**
  - measures the power associated with the magnetic field inside the cavity
  - limited by the amplifier noise temperature
  - A Standard quantum limit amplifier minimum is $1/2\ \hbar\omega_a$
  - SQL amplifier built for GHz regime, minimum power about $10^{-23} - 10^{-24}$ W

- **Microwave quantum counter**
  - Measures single photon produced in the cavity from the re-emission after axion induced spin flips
  - Re-emission is electromagnetic if radiation damping is shorter than other mechanism (practically always true for large sample volumes)
  - Limited by the photons emitted by the fluctuations of the thermal bath, having average photon number

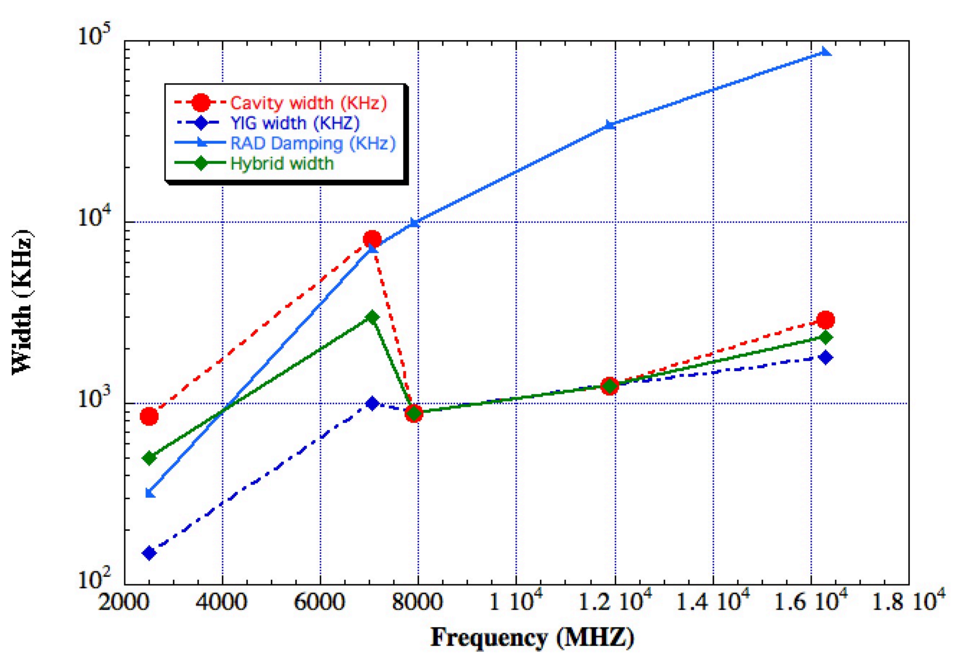
$$\bar{n} = \frac{1}{e^{\frac{\hbar\omega_c}{k_B T_c}} - 1}$$

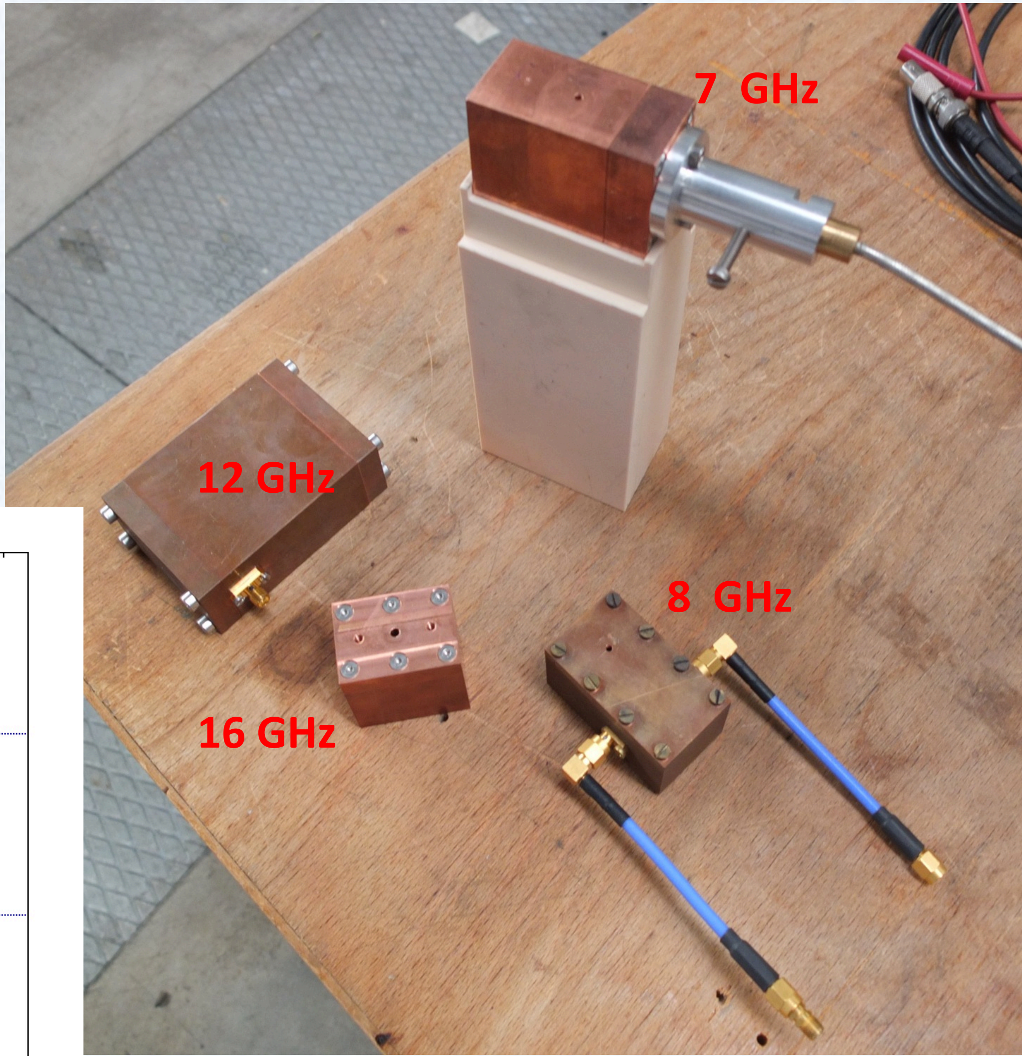
  - **Counters not yet available, but feasibilty demonstrated even below SQL**

Radiation damping

Radiation damping (RF emission) linewidth is expected to increase with frequency.

We have verified it is limited by the cavity linewidth.

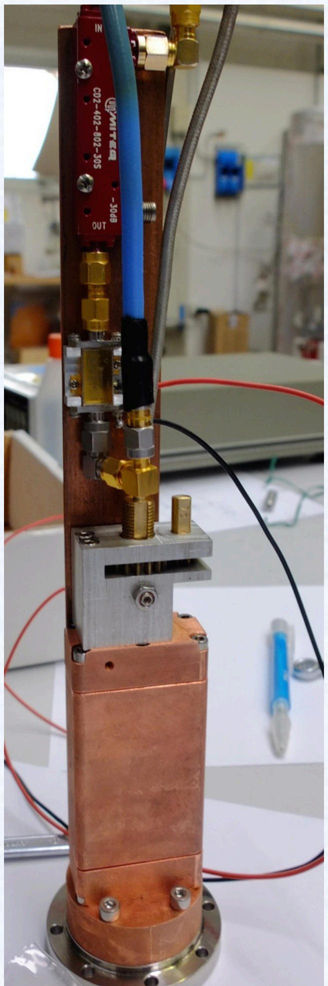


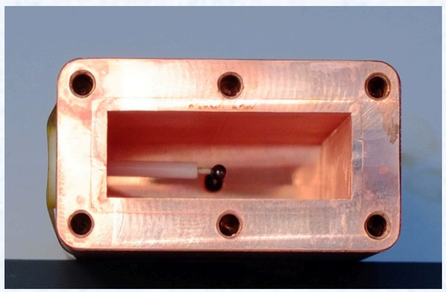


Strong coupling

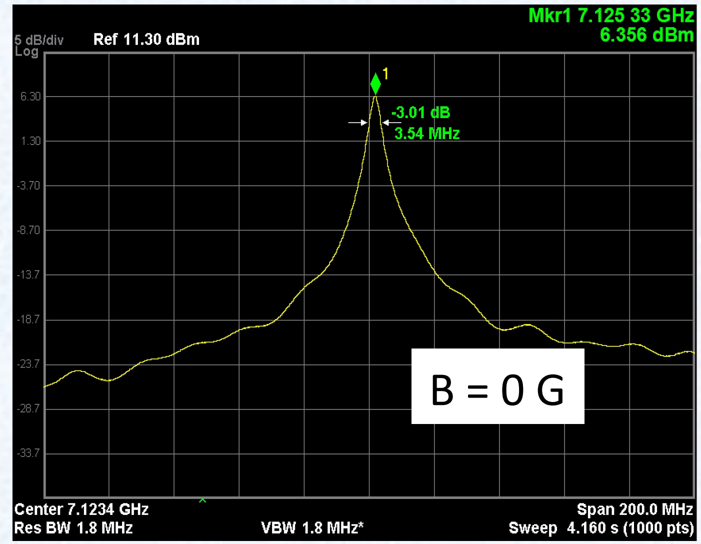
In order to provide a large signal a strong coupling regime is necessary between the Larmor resonance and the cavity resonance.

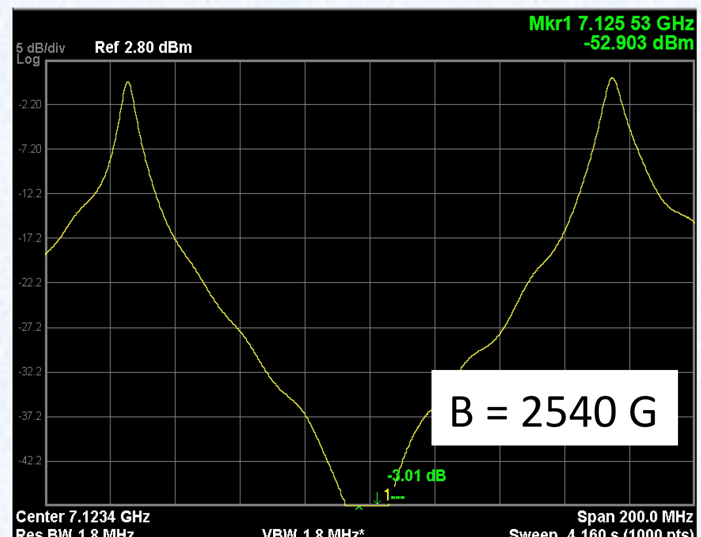
This results in **hybridization**





7.1 GHz Cavity with 2 mm diameter YIG sphere

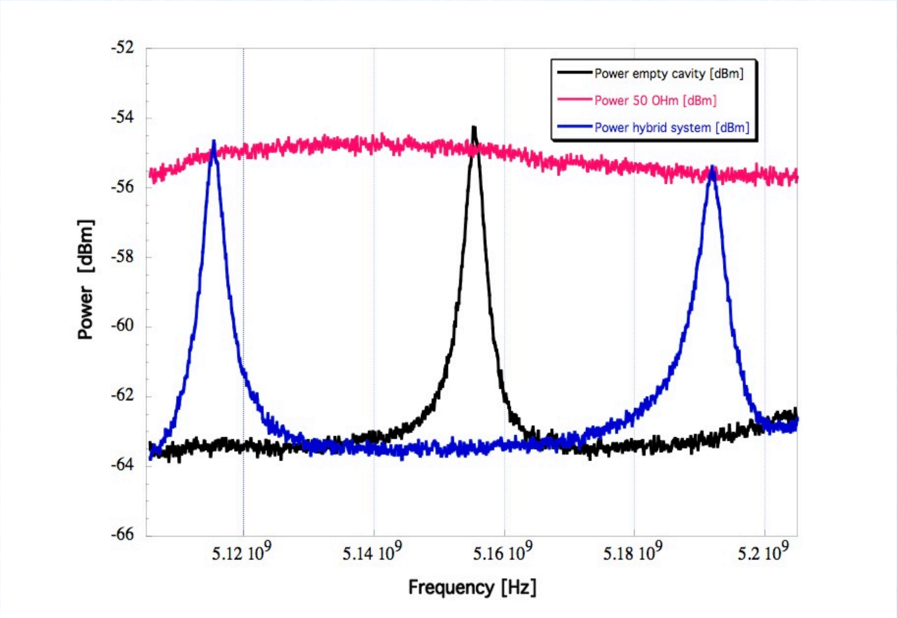




Thermal background

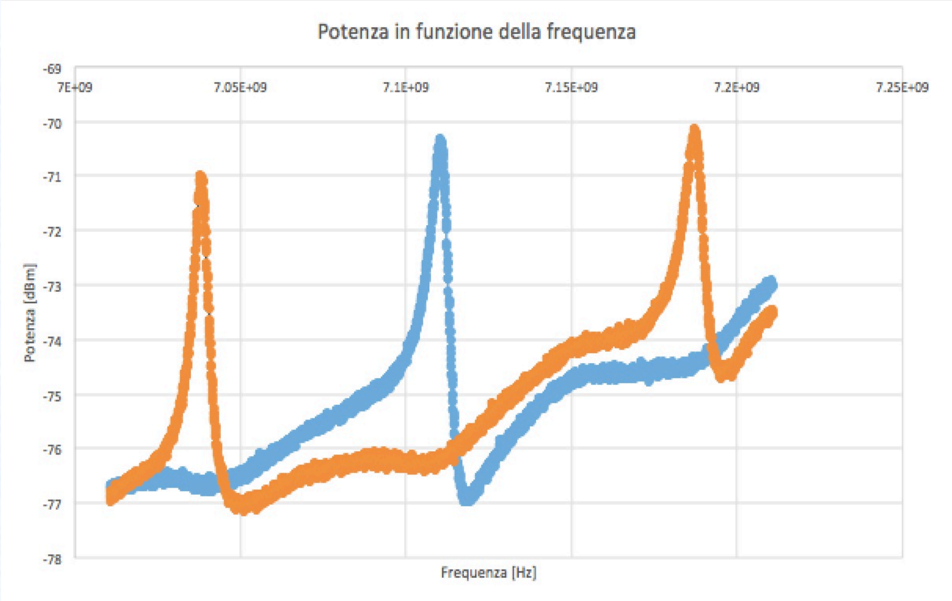
- The presence of the thermal photon bath is the limit sensitivity for all measuring techniques. We have to verify that in the strong coupling regime no extra noise is added to the system at the resonance frequency.
- Measurements have been performed to identify the system resonance excited by the thermal background.
- **No difference has been seen between cavity modes and hybridized system modes**

5 GHz system at 300 K



Amplifier chain gain = 69 dB
RBW = 100 kHz

7.1 GHz system at 77 K



Amplifier chain gain = 69 dB
RBW = 10 kHz

Quantum counter

The expected rate from axion spin flips

$$R_a = \frac{P_{\rm out}}{\hbar\omega_a} = 2.6 \times 10^{-3} \left(\frac{m_a}{2 \cdot 10^{-4}\,{\rm eV}}\right)^2 \left(\frac{V_s}{1\ {\rm liter}}\right) \left(\frac{n_S}{10^{28}/{\rm m}^3}\right) \left(\frac{\tau_{\rm sig}}{10^{-6}\,{\rm s}}\right)\ {\rm Hz} \tag{16}$$

The thermal photon rate

$$R_t = \bar{n}/\tau_c$$

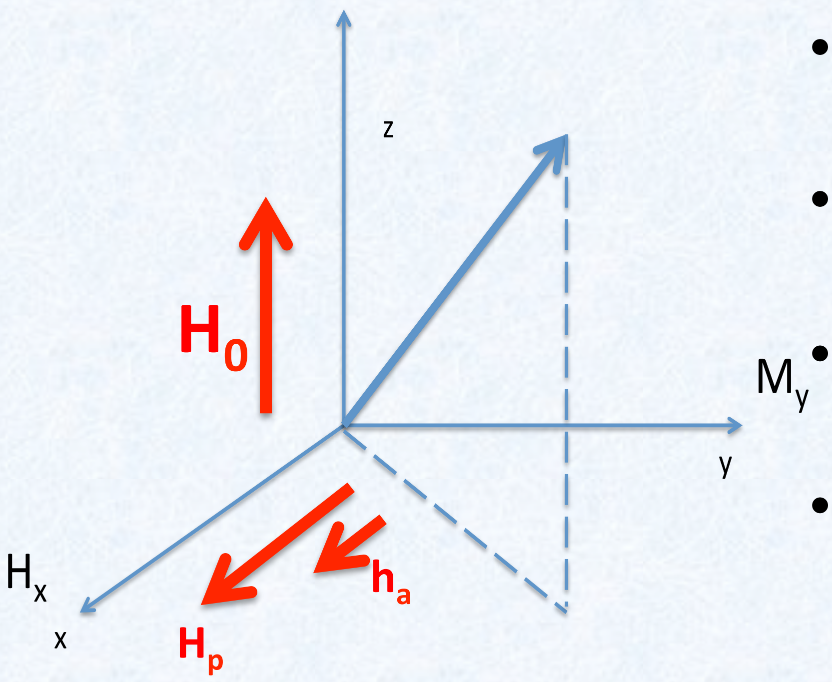
$${\rm SNR} = \frac{\eta R_a t_m}{\sqrt{\eta(R_a + R_t)t_m}} = \frac{R_a}{\sqrt{R_a + R_t}}\sqrt{\eta t_m}$$

For a SNR = 3 this implies a working temperature of 13 mK for $t_m = 10^4$ s

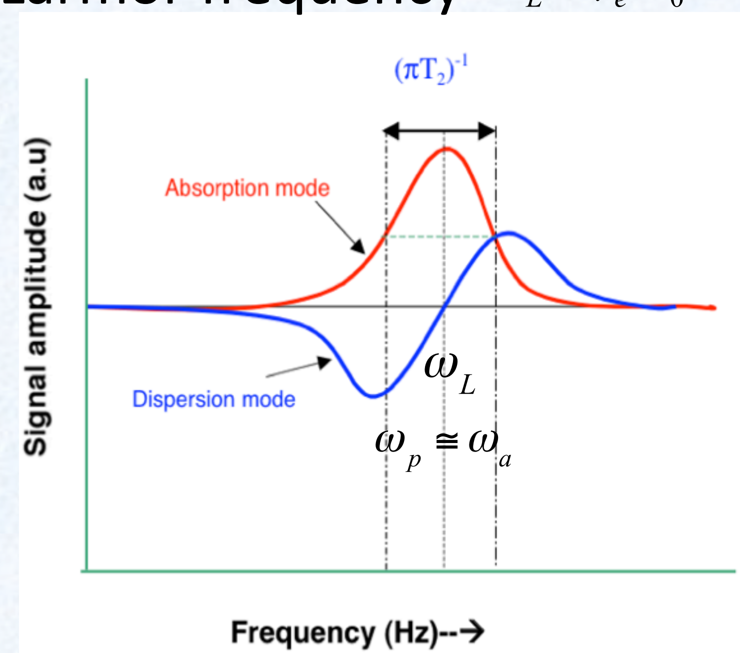
Comparison with ADMX like experiment (Sikivie's detector)

Sikivie's detector	QC - QUAX
Axion coupling to **photon**	Axion coupling to **electrons**
Signal proportional to **cavity volume and Q factor**	Signal proportional **to material volume and cavity Q factor**
Static magnetic field increases signal strength	Static magnetic field determines axion mass but not signal strength
Large volumes at high frequency hard to realize: magnetic field must follow microwave profile	Large volumes easily achievable with long solenoidal field
Magnetic field uniformity and stability not very important	Magnetic field uniformity and stability very crucial
High Q factor cavity **limited** from external magnetic field	High Q factor cavity **possible** due to lower external magnetic field
Non directional	**Directional**

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 $\omega_L = \gamma_e H_0$



Total driving radio-frequency field

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

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

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 $T_1T_2\gamma^2(H_p+h_a)^2<<1$

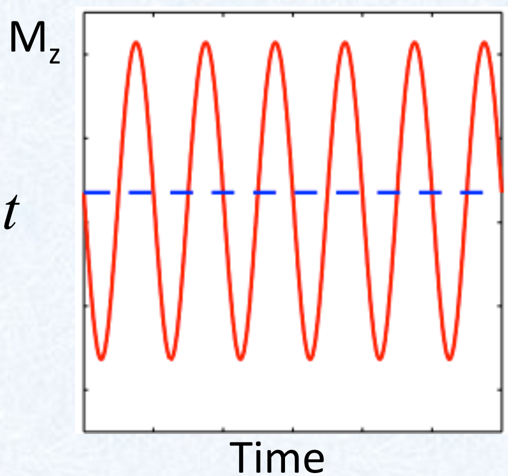
IF $\omega_p - \omega_a << \omega_L$ we can calculate M_z from quasi-stationary solutions

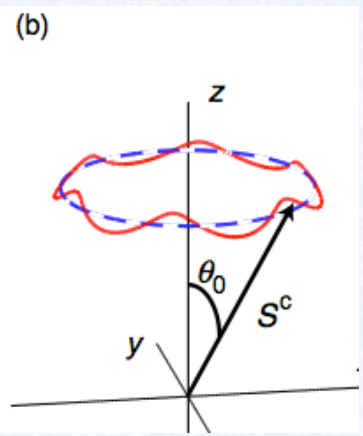
$$\Delta m_z(t) = \frac{1}{4} M_0 \frac{T_2^*}{T_2} \gamma^2 T_1 T_2^* H_p \left[\frac{1+\omega_D^2 T_2^{*2}/4}{\left(1+\omega_D^2 T_1^2\right)\left(1+\omega_D^2 T_2^{*2}\right)} \right]^{1/2} h_a \cos \omega_D t$$

Then M_z oscillates at very low frequency!

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

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





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**

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

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

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 $G_r > 100$

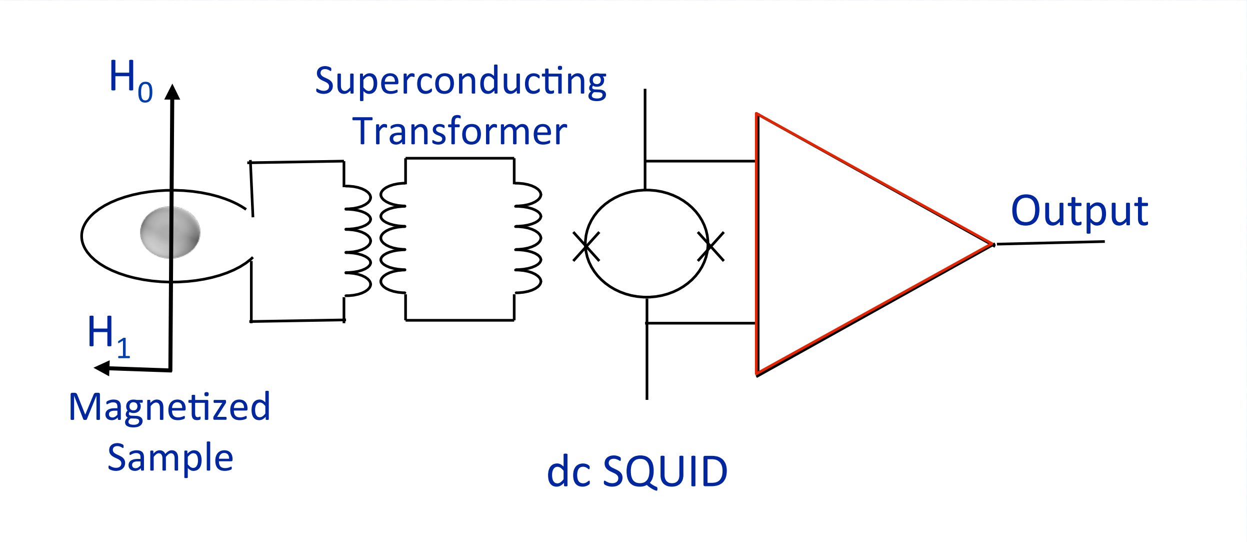
for a pump field $H_p \sim 0.1\ \mu T$

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 Φ. The best **SQUID sensitivity is** $\Phi_{ns} = 10^{-21}$ Wb/√Hz



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

$$\Phi_a = n_L G_r h_a A \quad (\mathrm{Wb})$$

where A is the area covered by the sample and n_L is the number of loops in the pick up coil. If $A \sim 10^{-4}$ 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 $\quad P_{cryo}$ ~ 1 mW
@ 1 K $\quad P_{cryo}$ ~ 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/$Hz^{1/2}$

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.

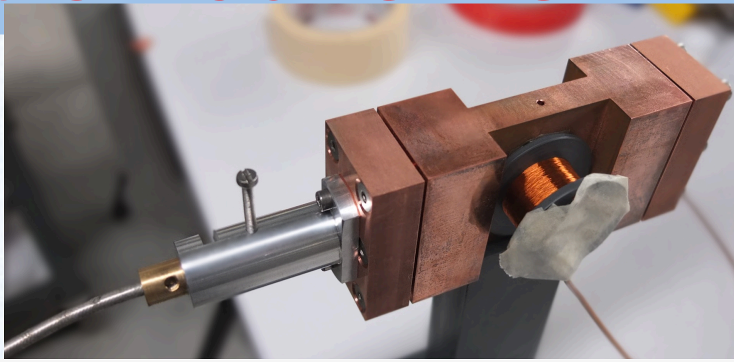
In order to reach the required gain G_r in the axion bandwidth, we will need **$T_1 \sim$ 1-10 μs, $T_2 \sim$ 1-10 μs, $N_0 \sim 10^{27}$-10^{28} spin/m^3.** The LOD must be verified by experiments in extreme regions of sensitivity (rf field amplitude <10^{-15} Tesla) and with samples in a waveguide.

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

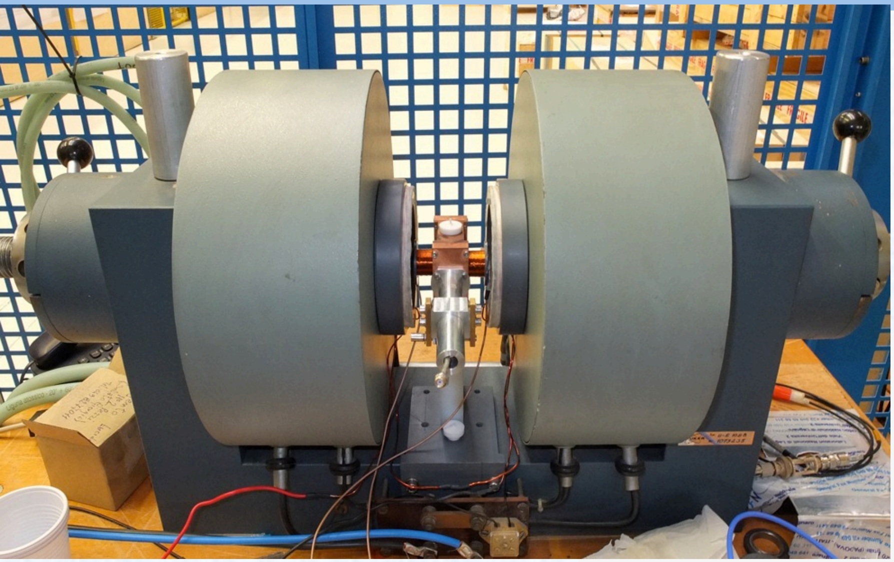
$$H_{1,x} = H_p \cos \omega_p t + h_a \cos \omega_a t$$

Provide h_a with a second rf generator!

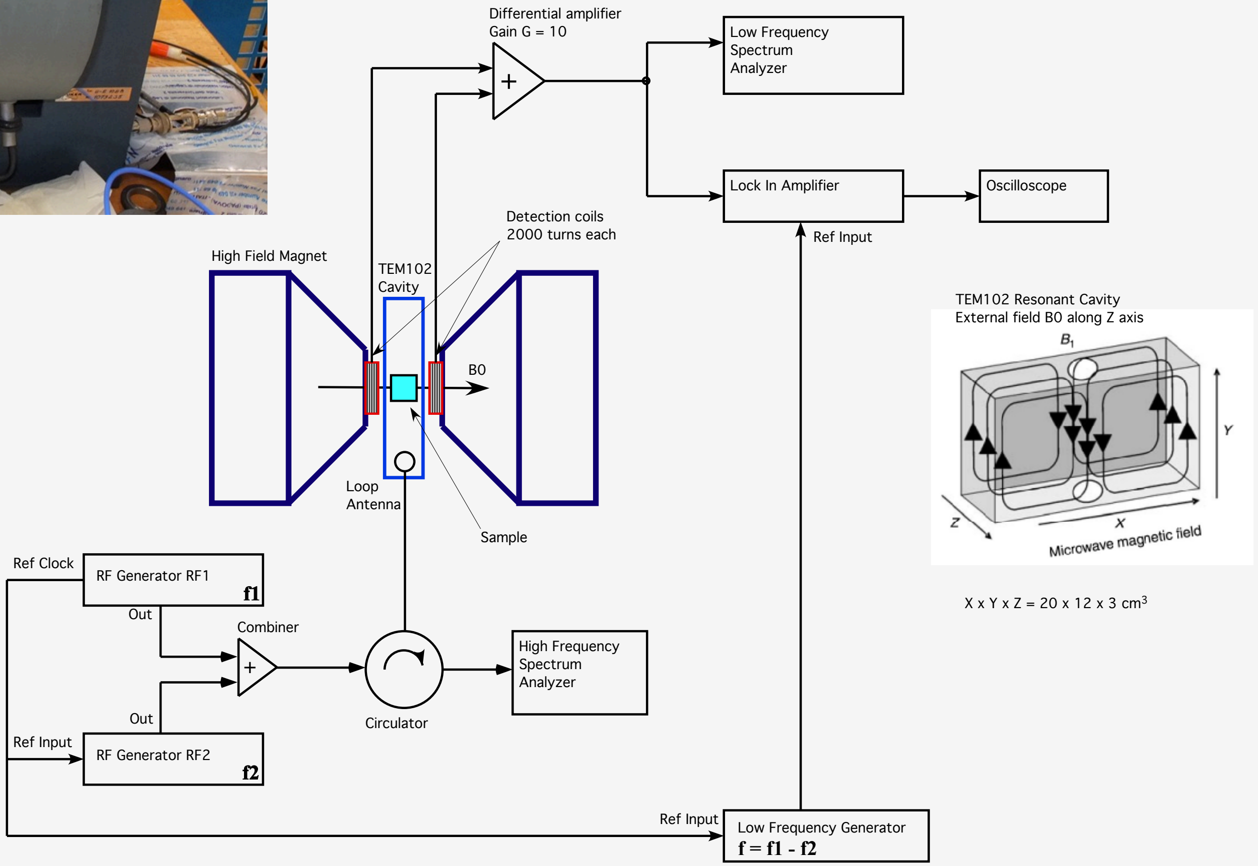
Calibration/Detection scheme



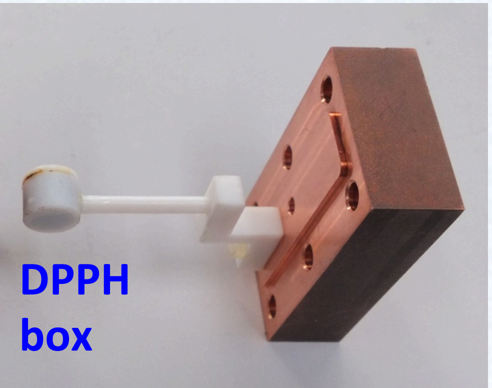
5 GHz cavity



Magnetic field source



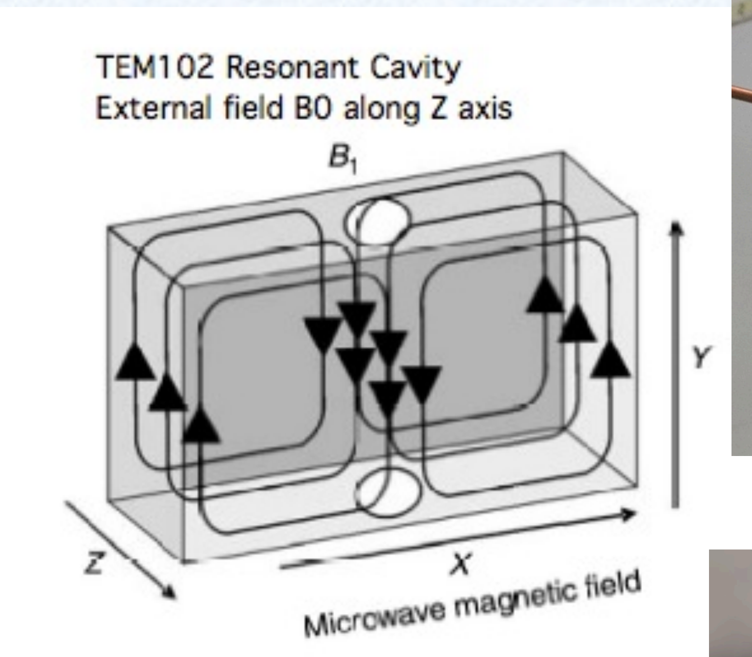
Paramagnetic sample



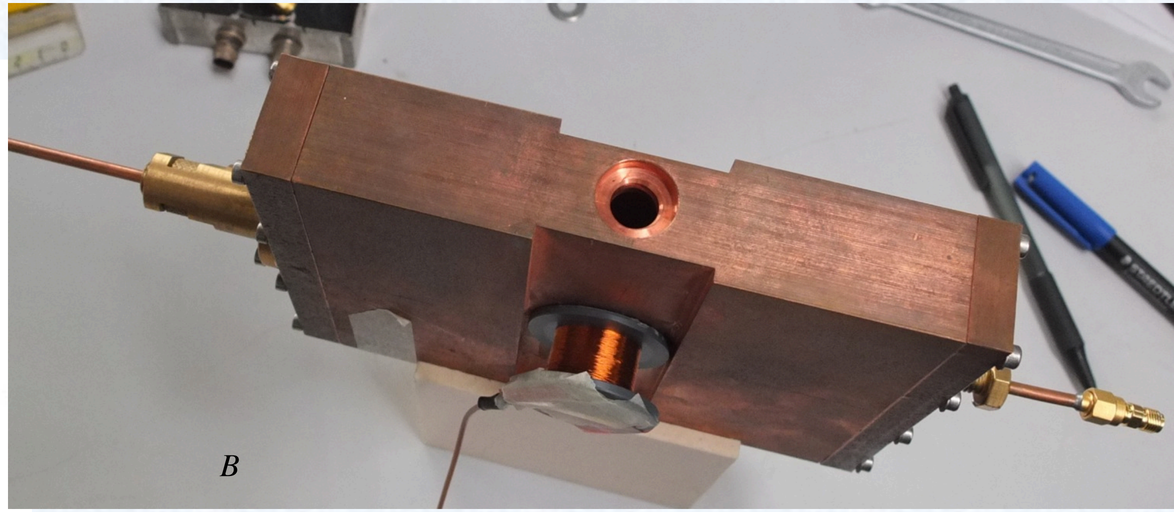
DPPH box

Cavities

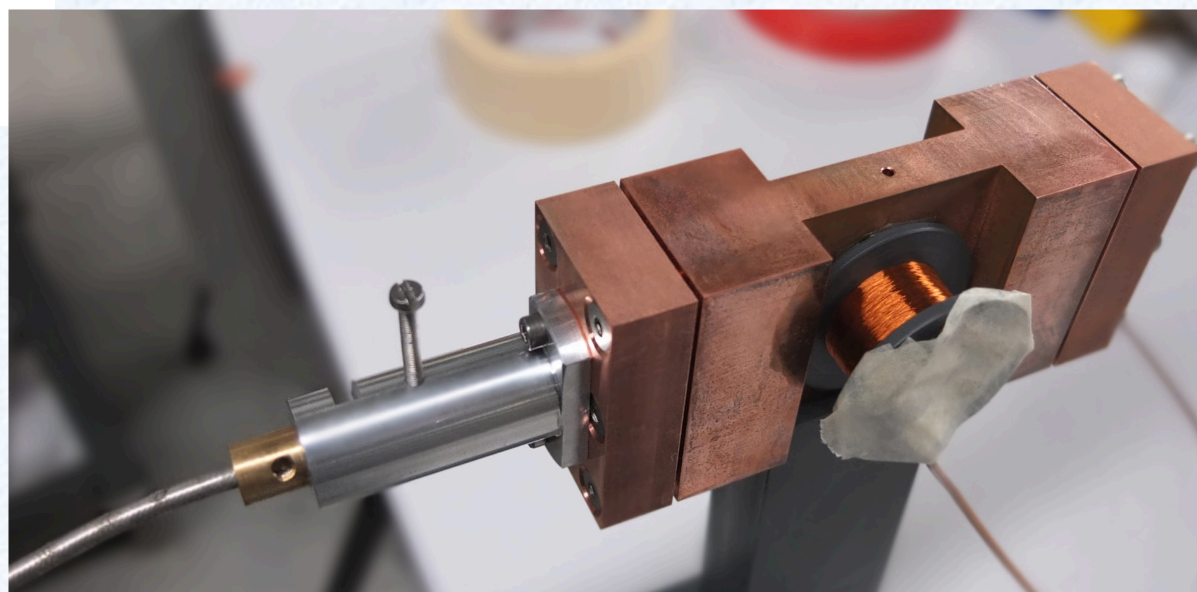
TE102 mode



2.5 GHz



5.0 GHz



At critical coupling

$$B_{sample} = k_c \sqrt{P_{in} / Q}$$

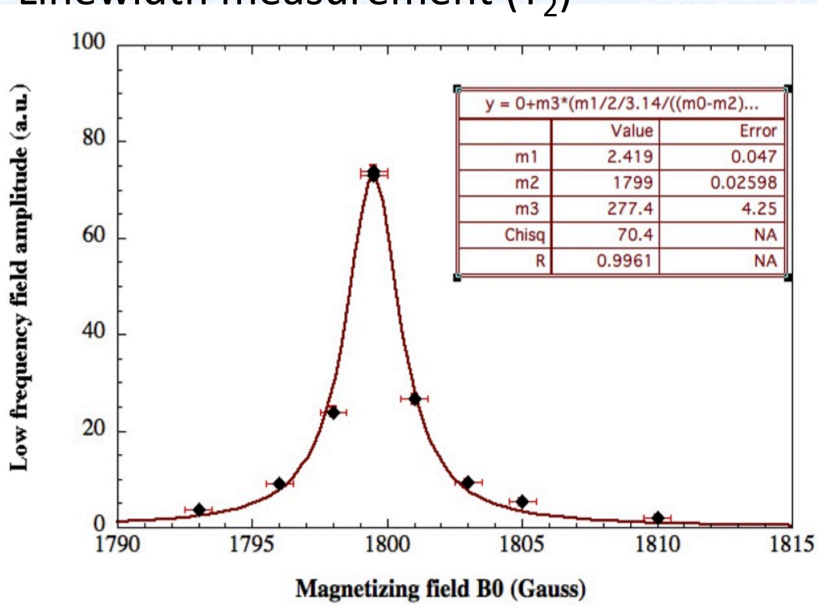
$$k_c \cong 6 \cdot 10^{-6}$$

B in Tesla

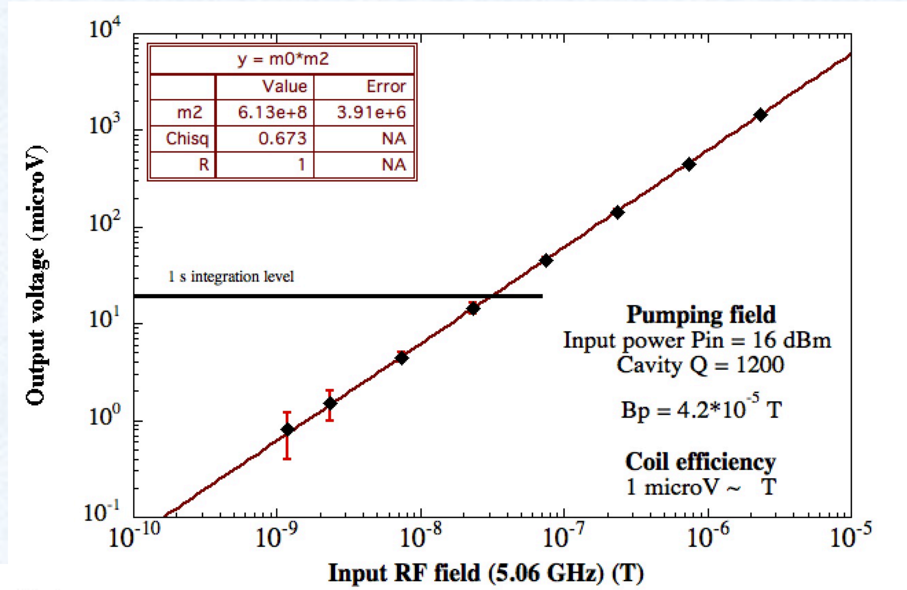
From Poole 1967

Paramagnetic sample @ 5.0 GHz

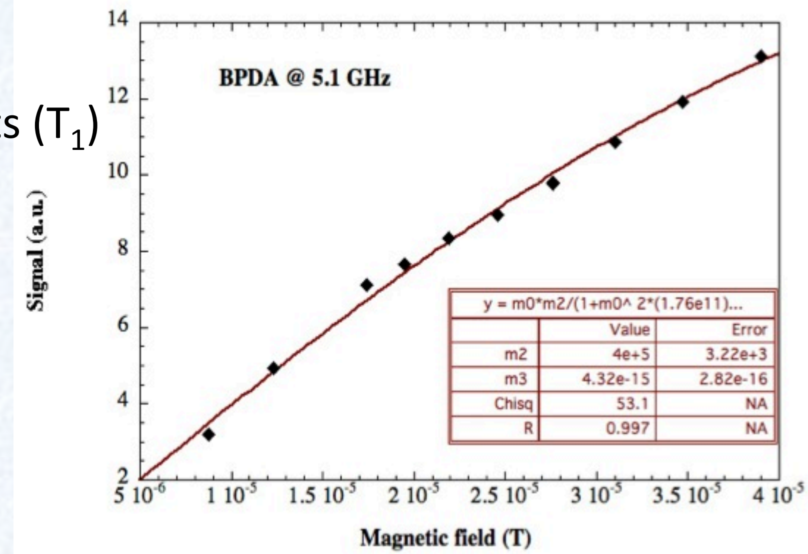
Linewidth measurement (T_2)



Linearity measurements



Saturation measurements (T_1)



We have check the formula for the gain:
Correct within a factor about 2

AXIOMA: Zeeman – Optical Transition

PRL 113, 201301 (2014) PHYSICAL REVIEW LETTERS week ending 14 NOVEMBER 2014

Axion Dark Matter Detection Using Atomic Transitions

P. Sikivie
Department of Physics, University of Florida, Gainesville, Florida 32611, USA
(Received 9 September 2014; published 14 November 2014)

Dark matter axions may cause transitions between atomic states that differ in energy by an amount equal to the axion mass. Such energy differences are conveniently tuned using the Zeeman effect. It is proposed to search for dark matter axions by cooling a kilogram-sized sample to millikelvin temperatures and count axion induced transitions using laser techniques. This appears to be an appropriate approach to axion dark matter detection in the 10^{-4} eV mass range.

$$\mathcal{L}_{a\bar{f}f} = -\frac{g_f}{2f_a}\partial_\mu a\ \bar{f}(x)\gamma^\mu\gamma_5 f(x)$$

$$H_{a\bar{f}f} = +\frac{g_f}{2f_a}\left(\vec{\nabla}a\cdot\vec{\sigma} + \partial_t a\ \frac{\vec{p}\cdot\vec{\sigma}}{m_f}\right)$$

ZEEMAN TRANSITION RATE With 1 Mole of Polarized Electrons

$$N_A R_i = g_i^2 N_A v^2 \frac{2\rho_a}{f_a^2}\min(t,t_1,t_a)$$

$$N_A R_i = \frac{2*10^3}{\sec}\left(\frac{\rho_a}{GeV/cm^3}\right)\left(\frac{10^{11}GeV}{f_a}\right)^2\left(\frac{v^2}{10^{-6}}\right)\left(\frac{\min(t,t_1,t_a)}{\sec}\right)$$

Hz Rate

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)

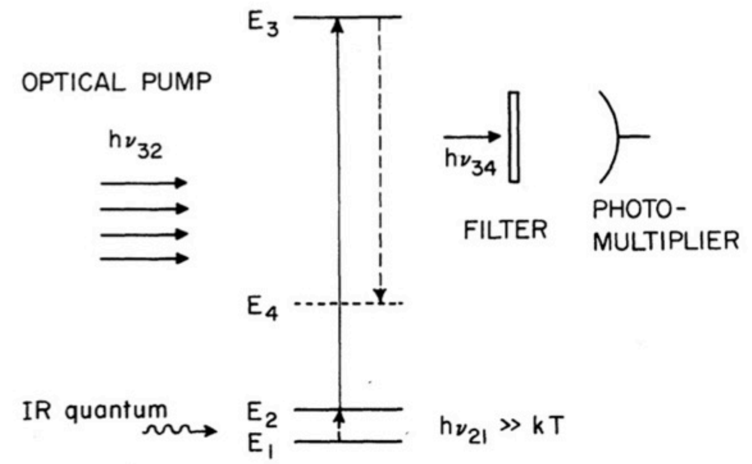


FIG. 1. Infrared quantum counter. Several ions of transition group elements have appropriate energy level diagrams: $h\nu_{21} = 1 - 5000\ \text{cm}^{-1}$, $h\nu_{32} = 10^4 - 5\times 10^4\ \text{cm}^{-1}$.

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.

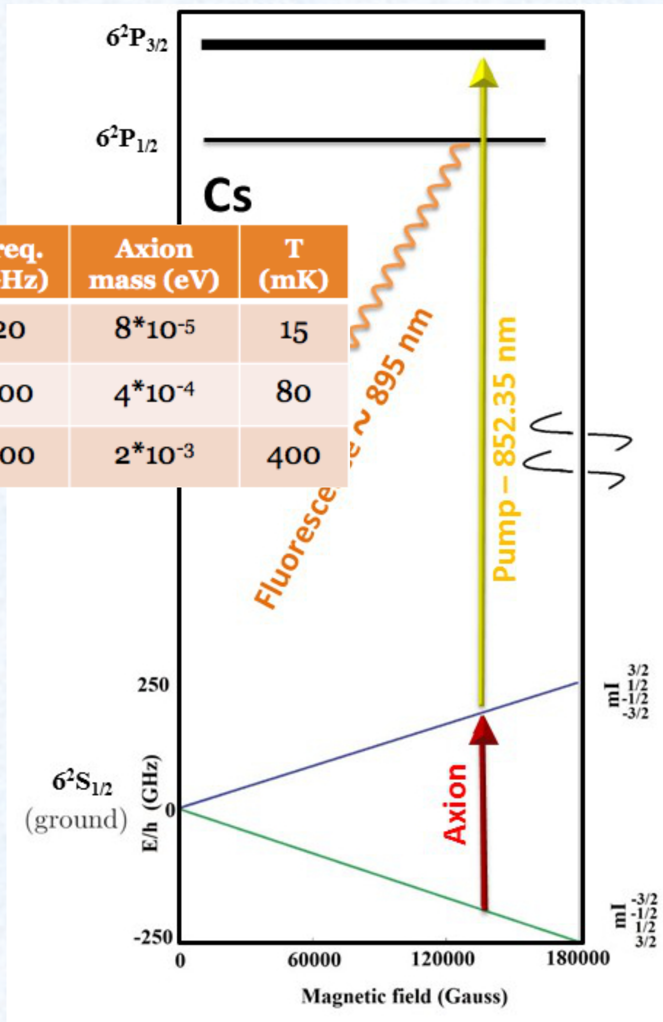
All the atoms must be in the Zeeman lower level.

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

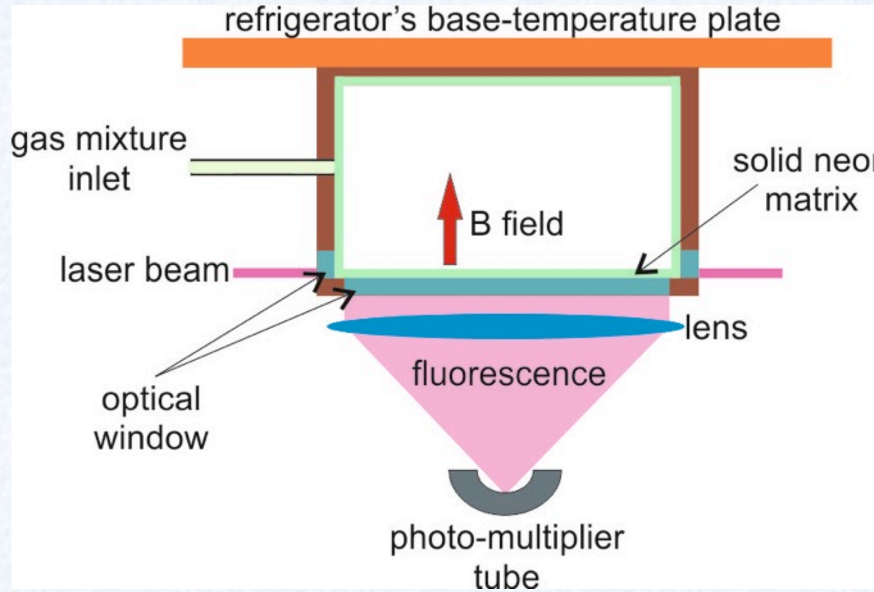
(Sikivie, 2014)

Detection with O_2- Cs - RE crystals

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.



B (T)	Freq. (GHz)	Axion mass (eV)	T (mK)
0,8	20	$8*10^{-5}$	15
3,5	100	$4*10^{-4}$	80
18	500	$2*10^{-3}$	400



- 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

- Measure the emitted power from the microwave cavity with an Amplifier or a Quantum Counter (frequencies > 30 GHz)

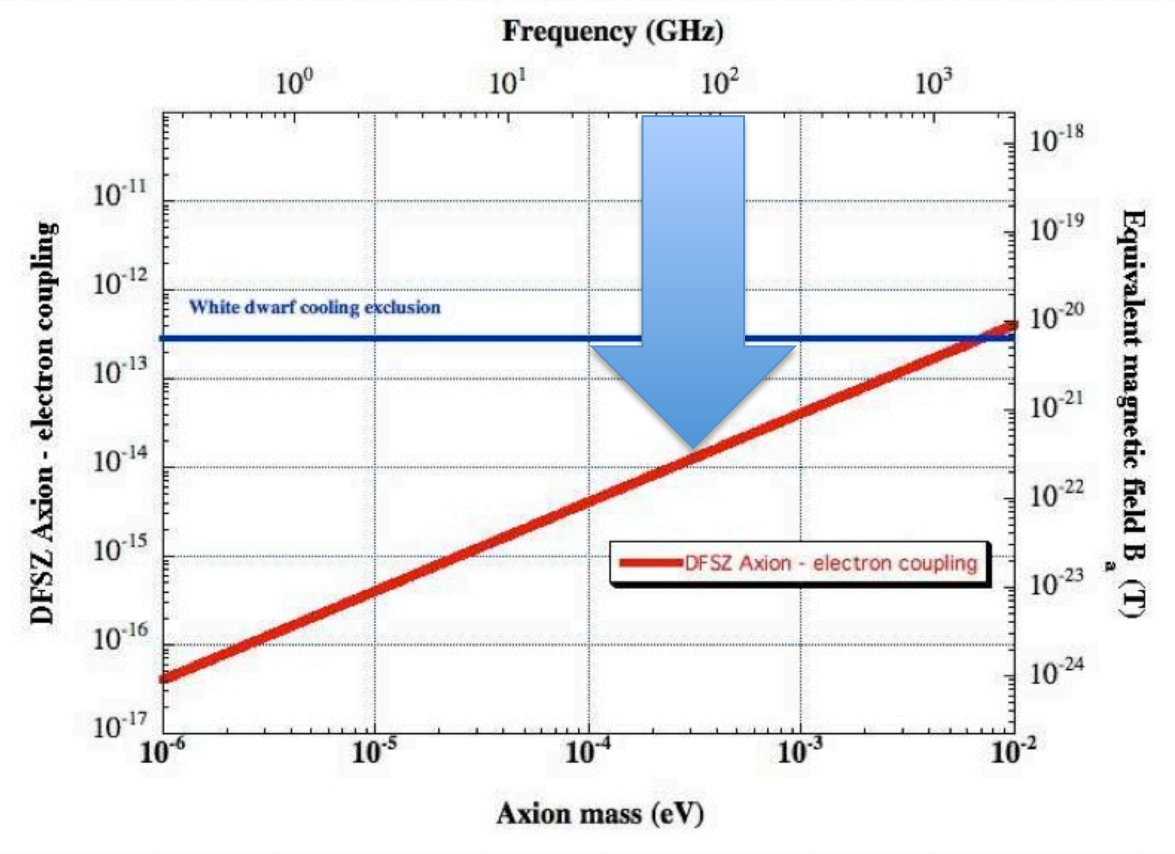
- Measure the low frequency down converted signal (along $\mathbf{H_0}$ direction, i.e. LOngitudinal Detection) using SQUID amplifier coupled with a pick up coil to the receiver (YIG sphere)

- Alternative detection scheme with **Up-Conversion technique** for higher axion masses (frequencies > 100 GHz) under study

- Spin Coupling is related also to neutrino interaction through Polarized Target

Goal of QUAX-AXIOMA R&D

- **Feasibility study to reach axion-electron 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**

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

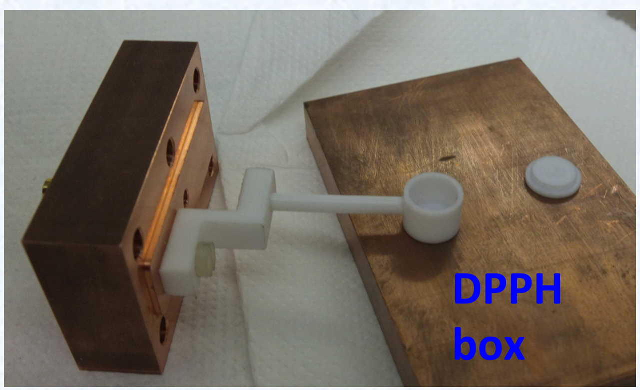
$$\Delta m_z \equiv M_0 - M_z = \frac{1}{4} M_0 \frac{T_2^*}{T_2} \frac{\gamma^2 T_1 T_2^*}{1+(T_2^*\delta\omega)^2} H_1^2$$

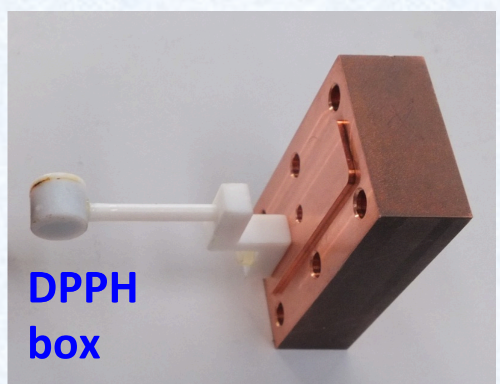
the component of magnetization along the polarizing field has a quadratic dependence on the rf field $\mathbf{H_1}$. **QUAX exploits this non-linearity for the axion detection**

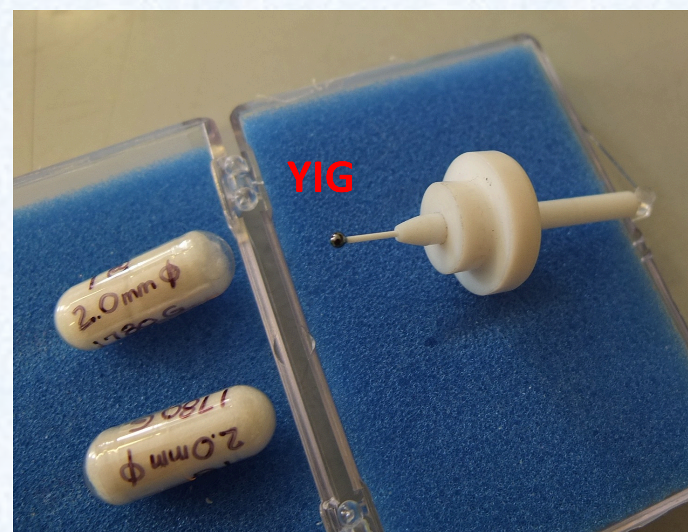
Magnetic samples

Material	Spin density	M0	T1	T2	Size
DPPH	2.1 x 10^{27} [$1/m^3$]	8 A/m	60 ns	60 ns	Cylinder 8 mm diameter 8 mm length
YIG	2.1 x 10^{28} [$1/m^3$]	1.4 10^5 A/m	0.16 μs		Sphere 2 mm radius

All values at room temperature



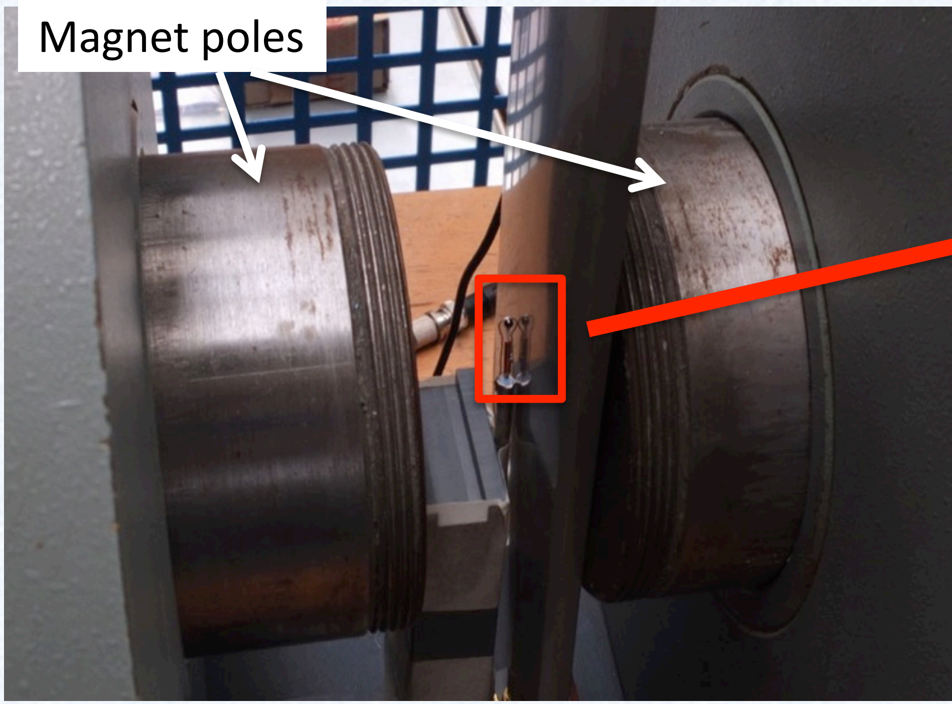


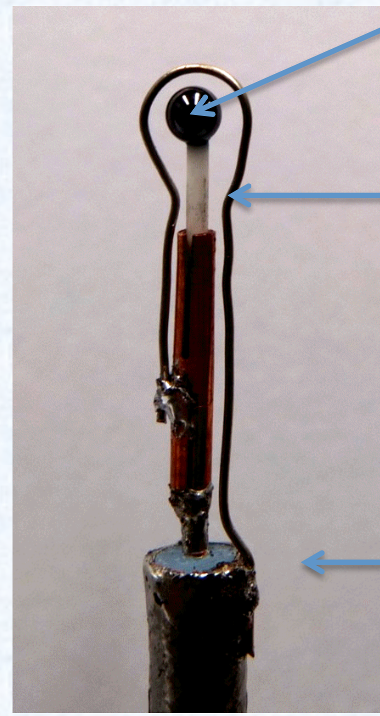


Free space measurements

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

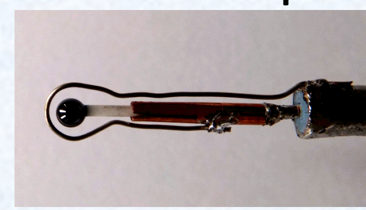




We have checked **the frequency down conversion** feeding the two driving fields. The low frequency signal was picked up with a 3000 loops coil placed close to the sample**. Low frequency signal has been observed**, calibrations of gain G_r are on the way.

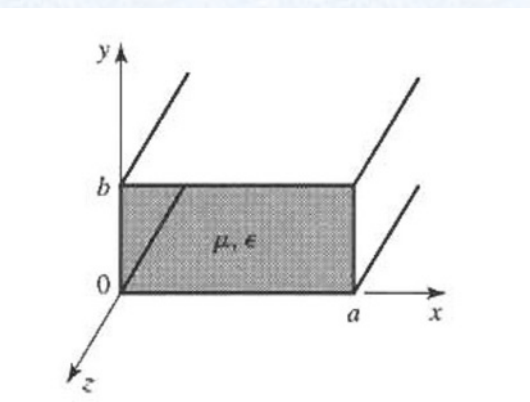
Waveguide in cutoff (1)

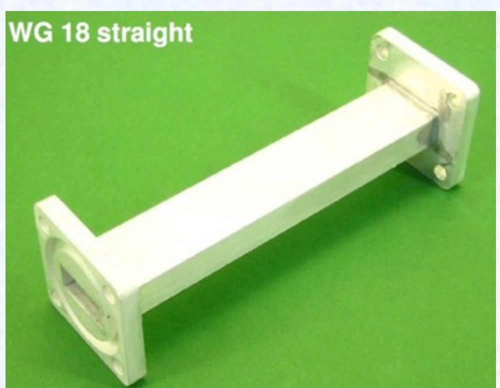
- A viable solution for the QUAX prototype
  - waveguide reduces radiation damping and thermal photons @ Larmor freq.
  - waveguide isolate the magnetized sample from the environmental rf noise
  - Despite rf photons, axions can penetrate the waveguide because they are massive and thus cause the spin 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



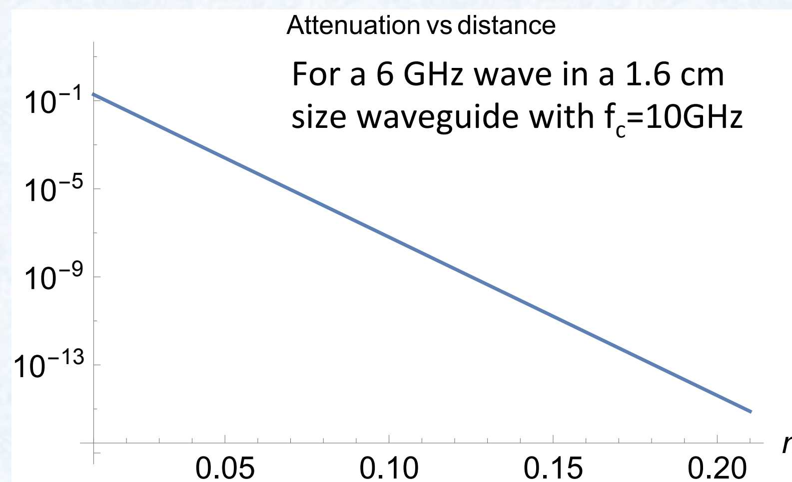
For a > b the lowest cut off frequency is

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





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