Detection of cosmological axions experimental issues

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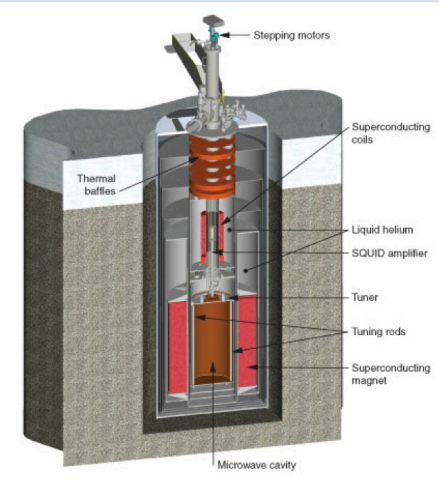
for the QUAX Collaboration

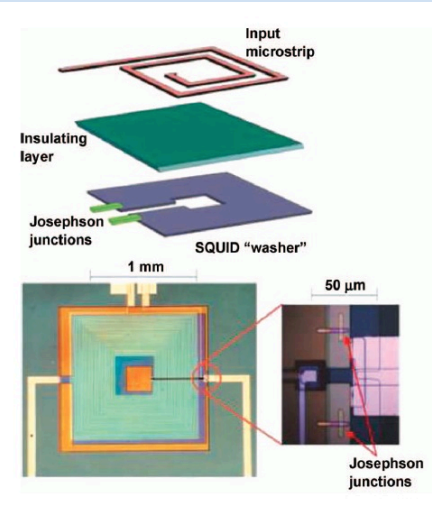
Haloscope detectors

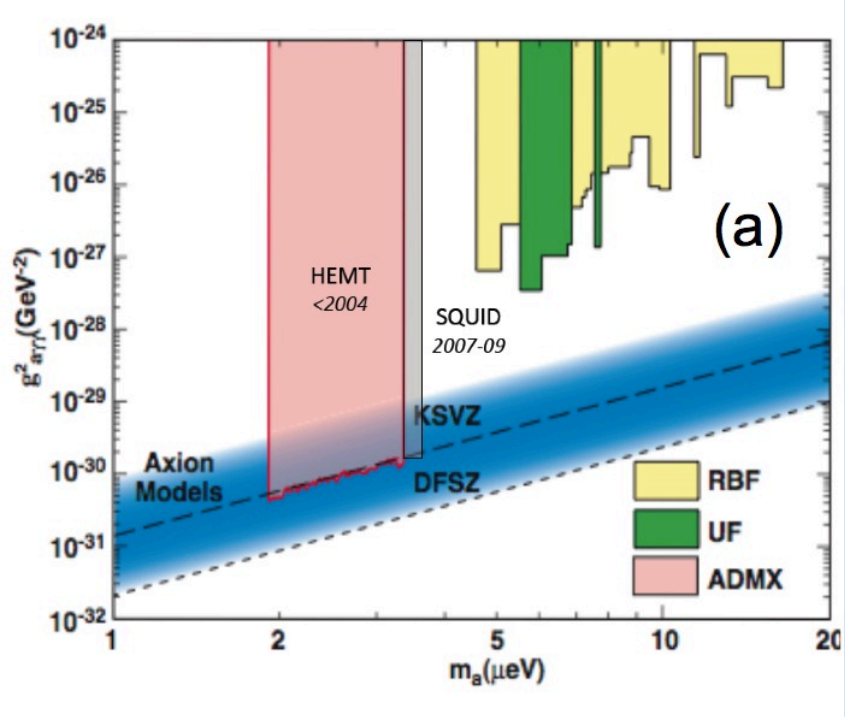
- Pilot experiments in Brookhaven (1988) and University of Florida (1990)
- Second generation experiments:
  - ADMX @ Lawrence Livermore employing low noise amplifier detectors
  - CARRACK @ Kyoto employing Rydberg atom detectors

ADMX – Axion Dark Matter eXperiment

- High Q microwave cavity inside an 8.5 T magnet
- Almost Quantum Limited SQUID detector







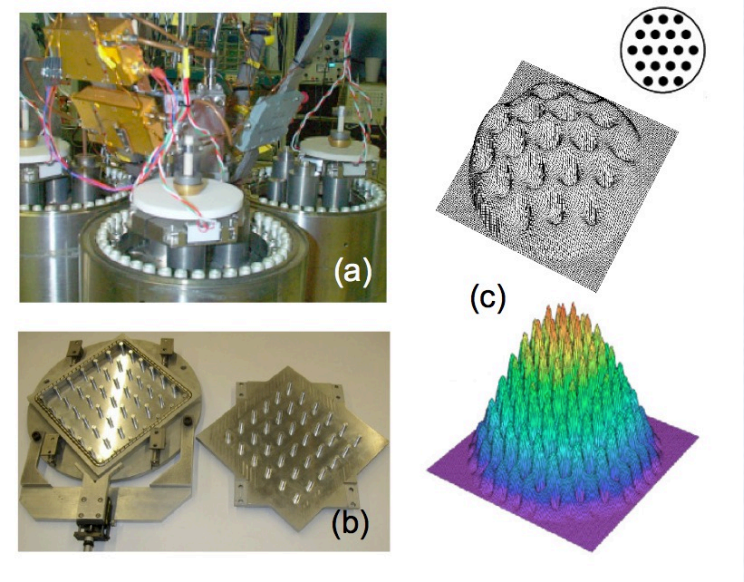
Reached sensitivity for **probing DM axion**:

- If all galactic DM is all made of axion
- If we assume KSVZ model right
- If the axion has the right mass, i.e. resonant with the cavity

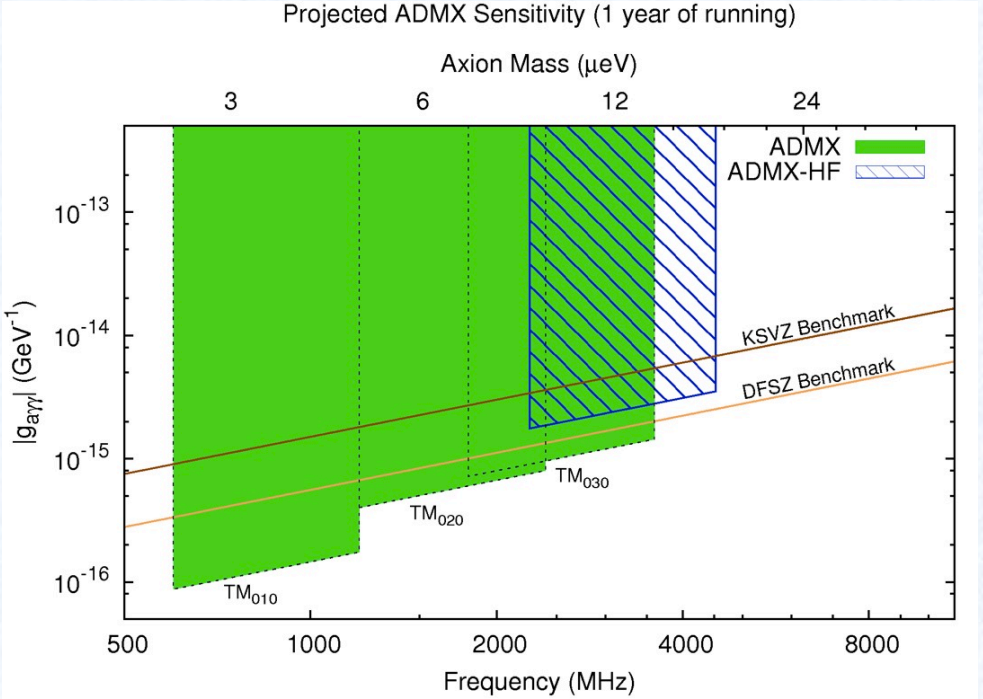
ADMX recent progress and prospects

- The experiment goes to a second stage with a collaboration between University of Washington and Yale

- New scheme to employ SQUID at higher frequency
- New type of amplifier at frequencies above a few Ghz
- Use higher order modes in the resonant cavity
- Optimize cavity material to obtain higher Qs – hybrid superconducting cavities



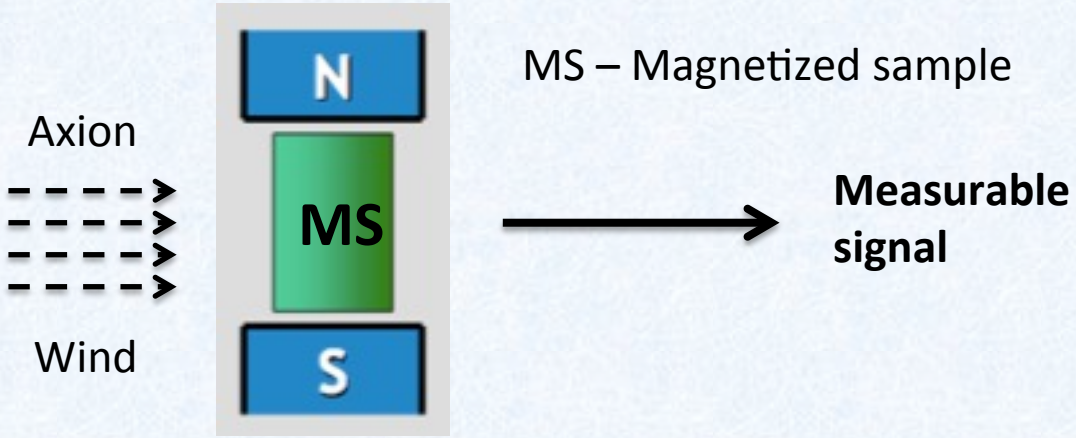
Photonic band gap cavity in the multi-GHz range



http://www.phys.washington.edu/groups/admx/future.html

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



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

$$H_a = -\vec{S}\cdot\left[\frac{g_p}{m_e}\nabla a\right]$$

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

Experimental parameters

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

Equivalent RF magnetic field $10^{-22}\,\mathrm{Tesla} \le B \le 10^{-21}\,\mathrm{Tesla}$

Working frequency $20\ \mathrm{GHz} \le \nu \le 200\ \mathrm{GHz}$

Electron Larmor Frequency

$$\nu_{\mathrm{Larmor}} = \gamma_e B_0 \quad ; \quad \gamma_e = 28\ \mathrm{GHz/T}$$

$$0.7\ \mathrm{T} \le B_0 \le 7\ \mathrm{T}$$

Magnetizing field

Measurement at the quantum limit

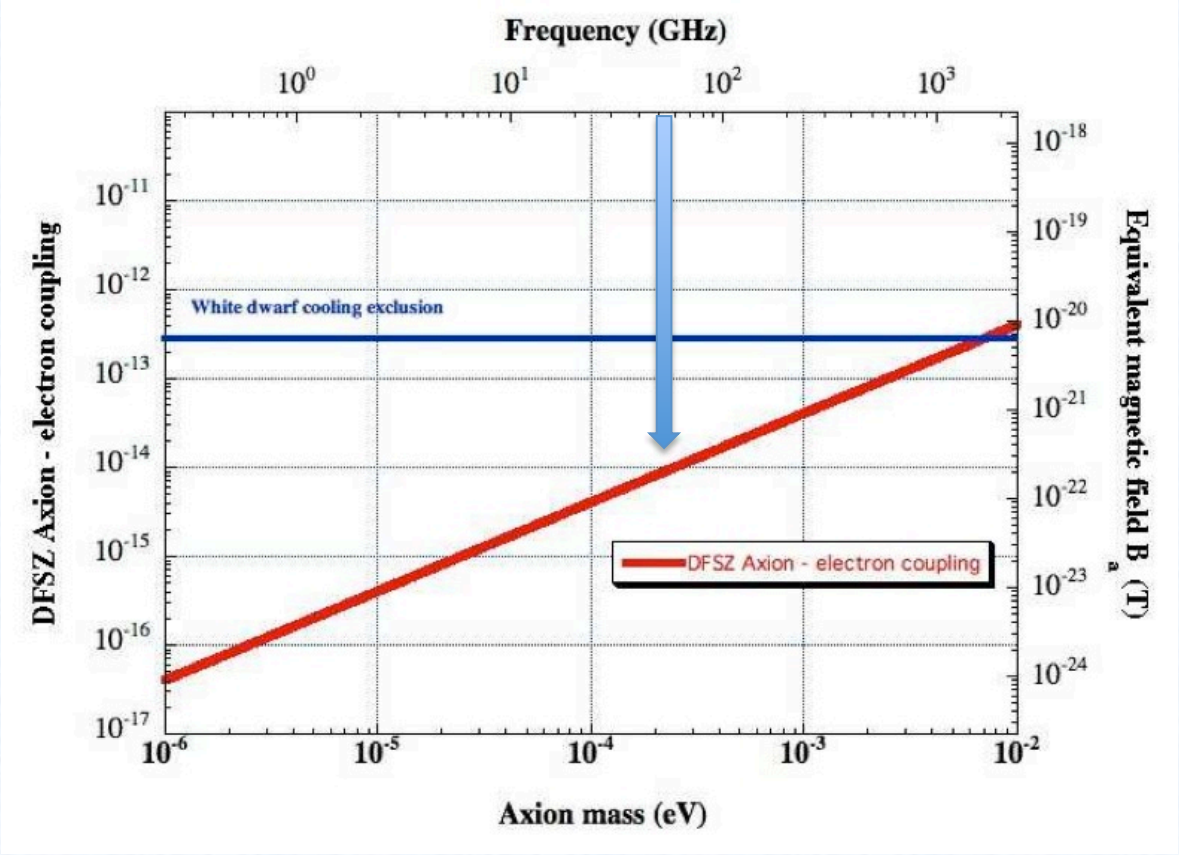
$$T_{spin} \le \frac{\mu_b B_0}{K_b}, T_{lattice} \le \frac{\hbar\nu}{K_b}$$

$$100\ \mathrm{mK} \le T \le 1\ \mathrm{K}$$

Working temperature

QUAX goal

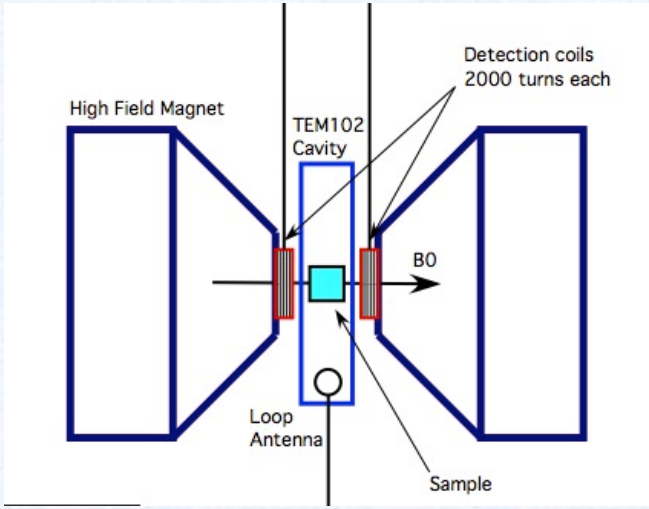
- **Reach the axion model coupling constant within a 5 year development in a narrow axion mass range**

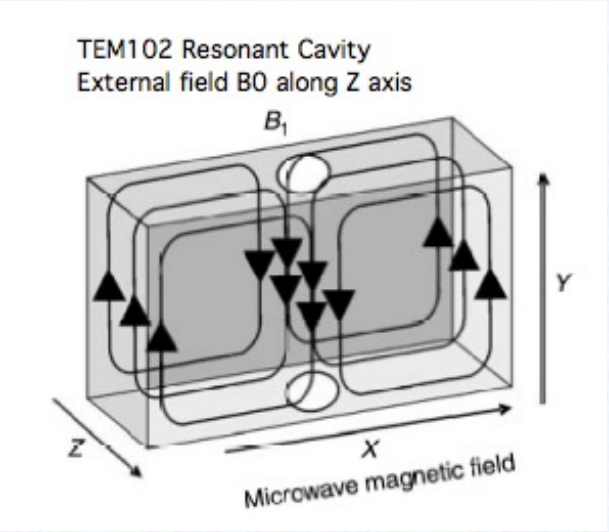


- Major issue is to **demonstrate that noise sources are under control** in reasonable amount of time, thus allowing to **extend the mass range in a larger apparatus**

ESR / MR magnetometry

- We exploit the Magnetic Resonance (MR) inside a magnetized material (Electron Spin Resonance - ESR)





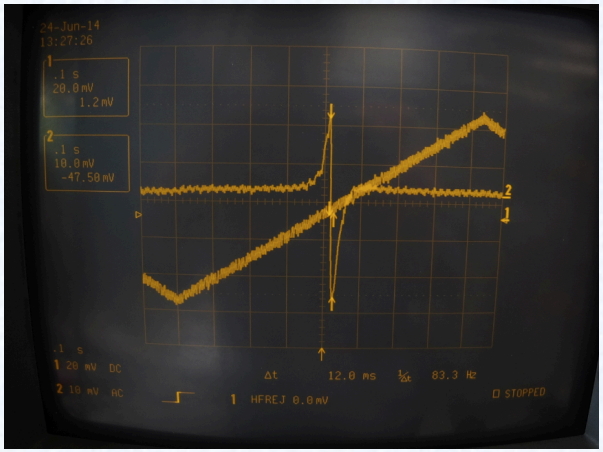
ESR/MR resonances inside a magnetic media can be tuned by an **external magnetizing field** and lies in the **multi GHz range** (radio frequency)

Bohr magneton $\mu_B = \frac{e\hbar}{2m_e} = 9.27 \cdot 10^{-24}$ J T^{-1}

Gyromagnetic ratio $\gamma_e = ge/(2m) = g_e\mu_B/\hbar = 1.76 \cdot 10^{11}$ rad s^{-1} T^{-1}

Larmor frequency $\omega_L = \gamma_e B_0$

1 T -> 28 GHz



The Bloch equations

The evolution of the electron spin (**spin precession**) under the influence of external fields is described by a set of coupled non-linear equations due to Bloch (Magnetizing field H_0 along z-axis)

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

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

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

T_1 – longitudinal relaxation time

T_2 – transverse relaxation time

Radiation Damping to be checked

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

Magnetization

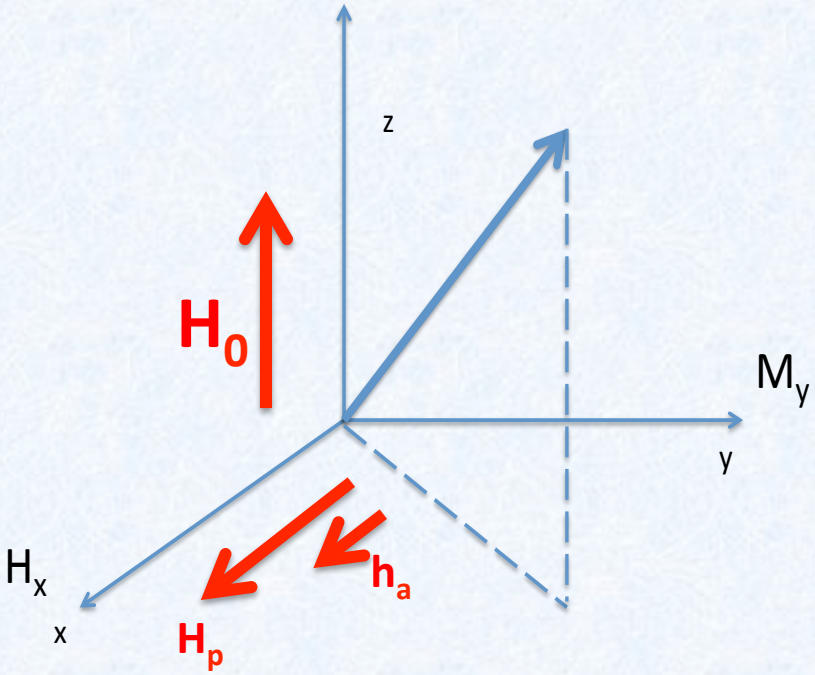
$$M_0 = N_0 \mu_B \tanh[\mu_B B_0 / k_B T_S]$$

N_0 – spin density

μ_B – Bohr magneton

T_s – sample temperature

Longitudinal detection of axion field



- We magnetize the sample along the z-axis and orient the sample in order to have the equivalent **axion field h_a** in the transverse direction
- **H_0 amplitude** matches the searched value of the **axion mass**
- We drive the sample with a **pump field H_p** at the Larmor frequency

The total driving radio-frequency field is then

$$H_x = H_p \cos\omega_p t + h_a \cos\omega_a t$$

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

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

$$\omega_p + \omega_a \cong 2\omega_p$$ **Also Present**

Longitudinal detection of axion field II

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 III

We can define some sort of gain G_m for the **low frequency field component $\mu_0 m_z$** with respect to the **high frequency** one **h_a**

$$\mu_0 m_z(t) = \frac{1}{2}\mu_0 M_0 \gamma^2 T_1 T_2 H_p h_a \cos\omega_D t$$
$$= G_m h_a \cos\omega_D t$$

$$G_m = \frac{1}{2}\mu_0 M_0 \gamma^2 T_1 T_2 H_p$$

If we put some relevant numbers (already published)

$T_1 = 10^{-3}$ s

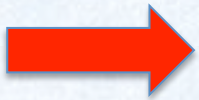
$T_2 = 3 \times 10^{-7}$ s

$M_0 = 200$ A/m

We obtain $G_m > 1$

for a pump field of $H_p \sim 1$ nT

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



- **find the right material**
- **power dissipated in the cryogenic system**
- **noises in the system**

Detection of LF field

The most sensitive device for measuring magnetic field is the **DC squid**. Squid measures magnetic flux Φ, the best **sensitivity Φ_s** obtainable is:

$$\Phi_s = 10^{-22}\ \mathrm{Wb}/\sqrt{\mathrm{Hz}}$$

The flux that can be obtained at low frequency is:

$$\Phi_{lf} = n_L\, G_m\, h_a\, A$$

where A is the area covered by the sample and n_L is the number of loops in the pick up coil.

For $A \sim 10^{-4}\ m^2$, the gain necessary to obtain a signal $1/100 \times \Phi_s$ is:

$$G_m \sim 100 / n_L$$

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

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

- **power dissipated** into the lattice (having volume V_s)

$$P_{diss}(W) = \frac{1}{2\mu_0}\omega_p H_p^2 M_0 \gamma T_2 V_S$$

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

Noise

Supposing to reach the limiting sensitivity for the detector, residual intrinsic noise will be present as magnetization noise δm_z in the sample.

A first guess of its level can be calculated **using Fluctuation-Dissipation theorem**. This is in general correct for system at the equilibrium, which in principle is not our situation (stationary system).

$$\delta m_z = \left[2 \frac{\chi_{0s}}{\mu_0 V_S} \frac{1}{\omega_a T_2} \hbar \coth\left(\frac{\hbar \omega_a}{2 k_B T_S} \right) \right]^{1/2} \qquad \text{(A/m)}$$

$Gd_2Si_5O_2$ @ 100mK + 1 Tesla => SQUID, Noise @ 10^{-15} T/√Hz

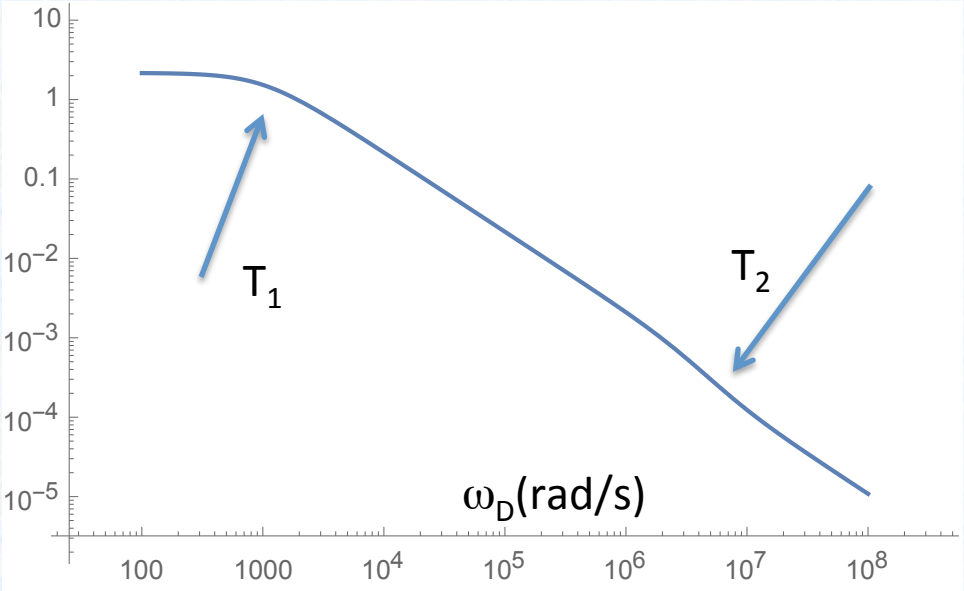
The noise level must be measured experimentally!

Frequency prescriptions

The general solution for the variable component of the magnetization is:

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

For large values of T_1 and T_2 ($T_1 > T_2$) the gain drops off as $1/\omega$ above $\omega_1 \sim 1/T_1$.



This has to be taken into account in order to keep the largest gain-bandwidth.

Pick – up coils

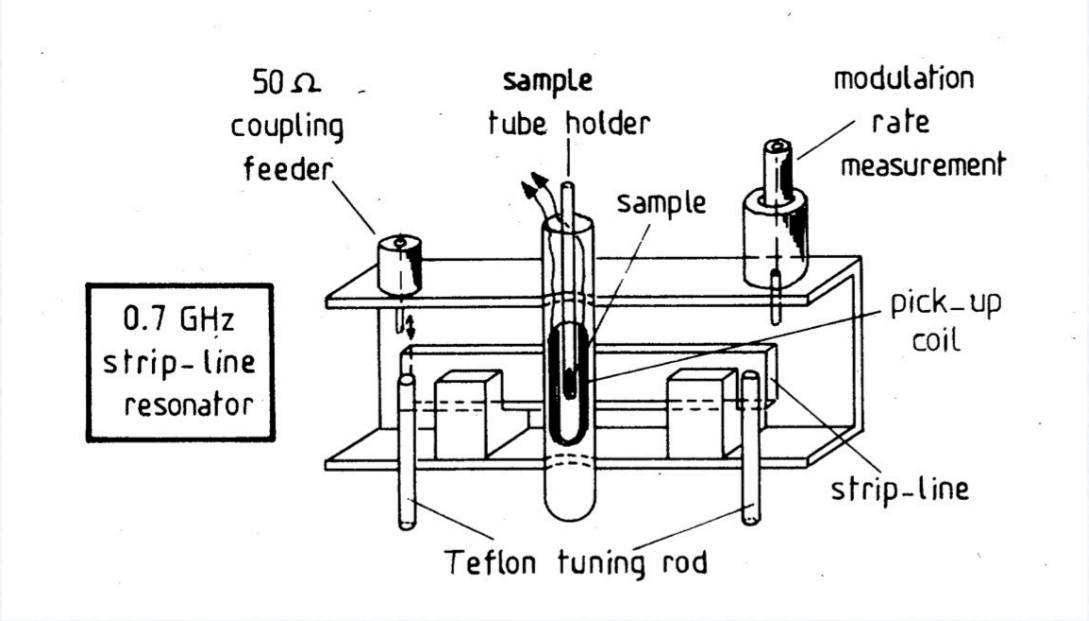
Before using squids the system can be studied with a pick-up coil.

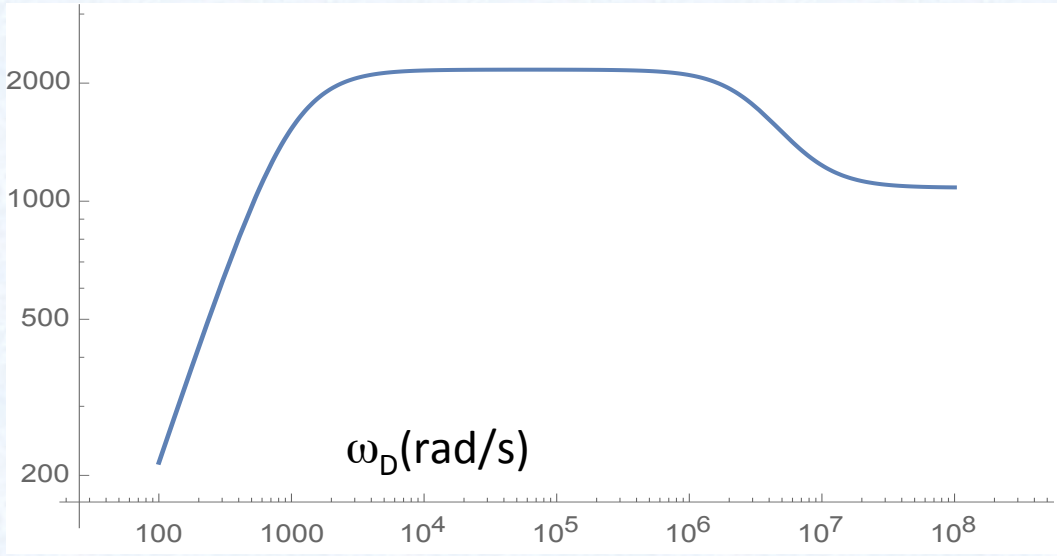
A pick-up coil surrounding the magnetized sample will produce an **induced voltage** which is:

$$V(t) = n\frac{\partial \Phi}{\partial t} = n\mu_0 A\omega_D m_z(t)$$

Which has now the form:

there is a different frequency behavior, but sensitivity is in general much worse than squids





Calibration

We have illustrated a technique which is not new (Pescia 1965, Ablart and Pescia 1980), however it has been normally **used with very small values of relaxation times**: T_1, $T_2 < 1$ μs.

Moreover, the theoretical framework is correct for **paramagnets** with **small spin density** $N_0 \sim 10^{26}$ m^{-3}. For higher densities **radiation damping mechanisms** and **coupling to the external world** must be taken into account.

In order to reach the necessary gain G_m, we will need **T_1 ~ 1-10 μs, $N_0 \sim 10^{26}$-10^{28} m^{-3},** or a strong pump field (~ μT)

The system must be verified, both from an experimental and a theoretical point of view, in this extreme regions. **Calibration is possible**:

$$H_x = H_p \cos\omega_p t + h_a \cos\omega_a t$$

Provide h_a with a second RF generator

Radiation damping

Radiation damping describes two **loss mechanisms at the Larmor frequency ν_L:**

1) the interaction of the magnetic sample with **a detector tuned to ν_L**

2) the **emission of radiation** (magnetic dipole)

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

Modified Bloch equations with T_R

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

$$T_R \approx \frac{\lambda^3}{\gamma M_0 V}$$

V – sample volume

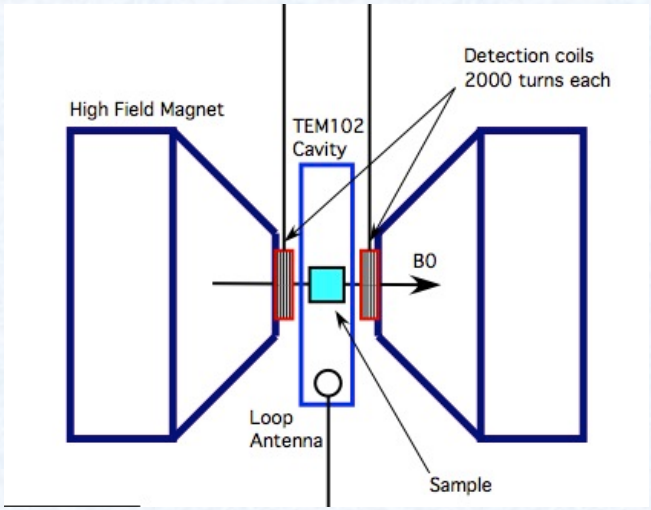
Modified Gain

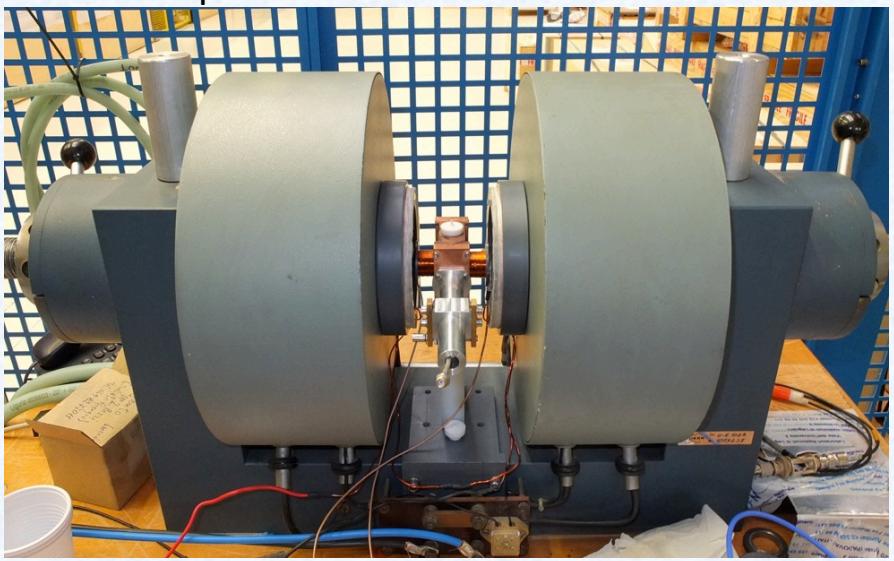
$$G_m = \frac{1}{4}\mu_0 M_0 \frac{T_2^*}{T_2}\gamma^2 T_1 T_2^* H_p$$

$$T_2^* = 1/(T_2^{-1} + T_R^{-1})$$

Calibrations - First prototype at Legnaro

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

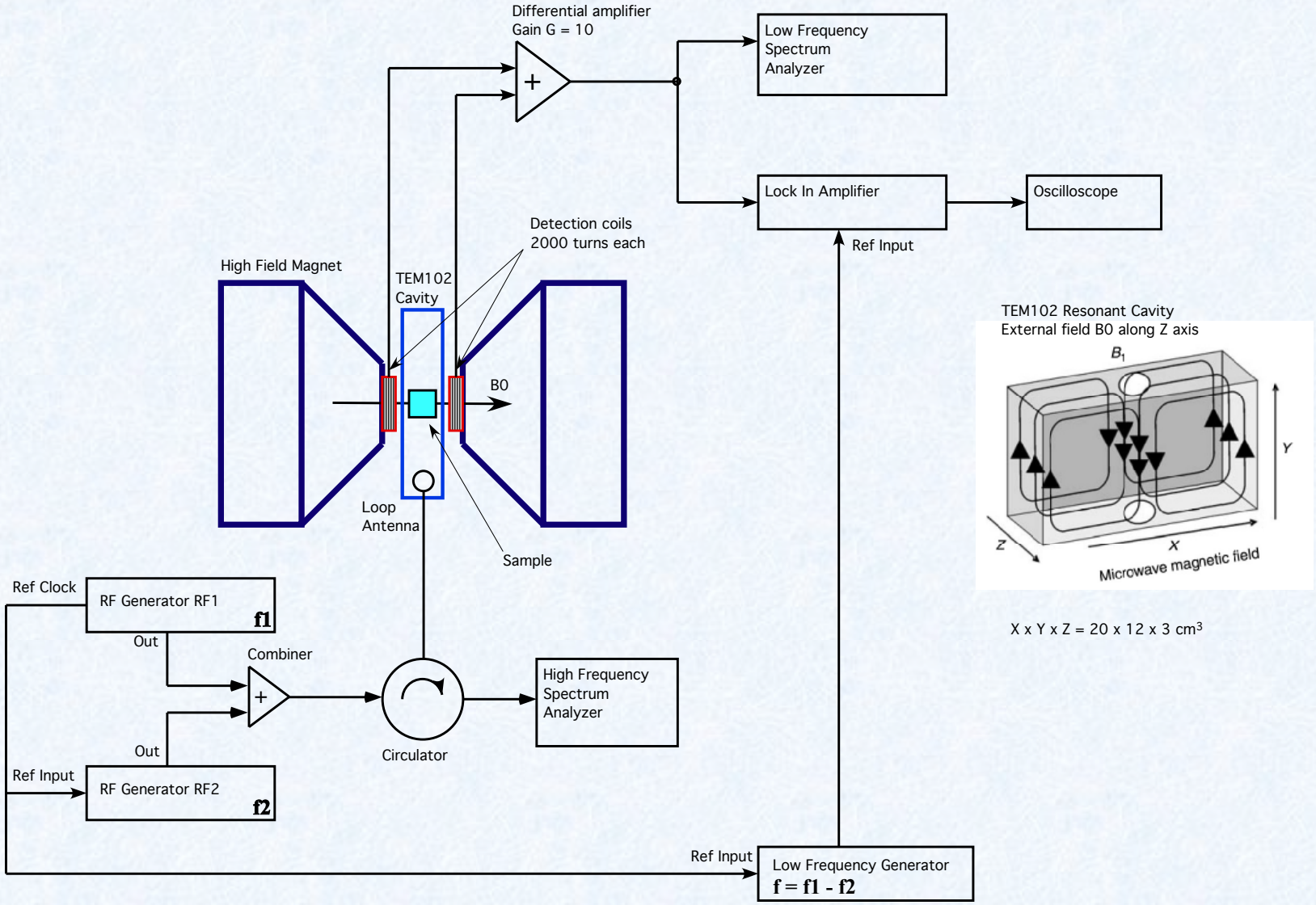




As a magnetized sample we used **DPPH** (2,2-diphenylpicrylhydrazyl) at 300 K.

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})

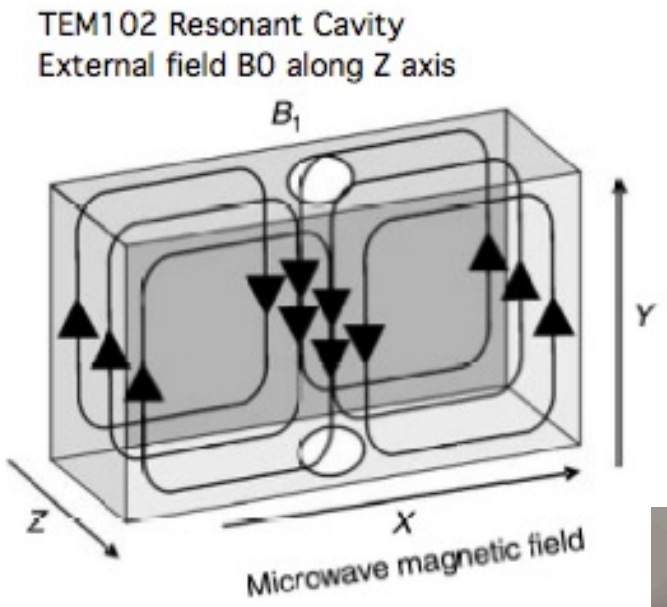
Detection scheme



X x Y x Z = 20 x 12 x 3 cm^3

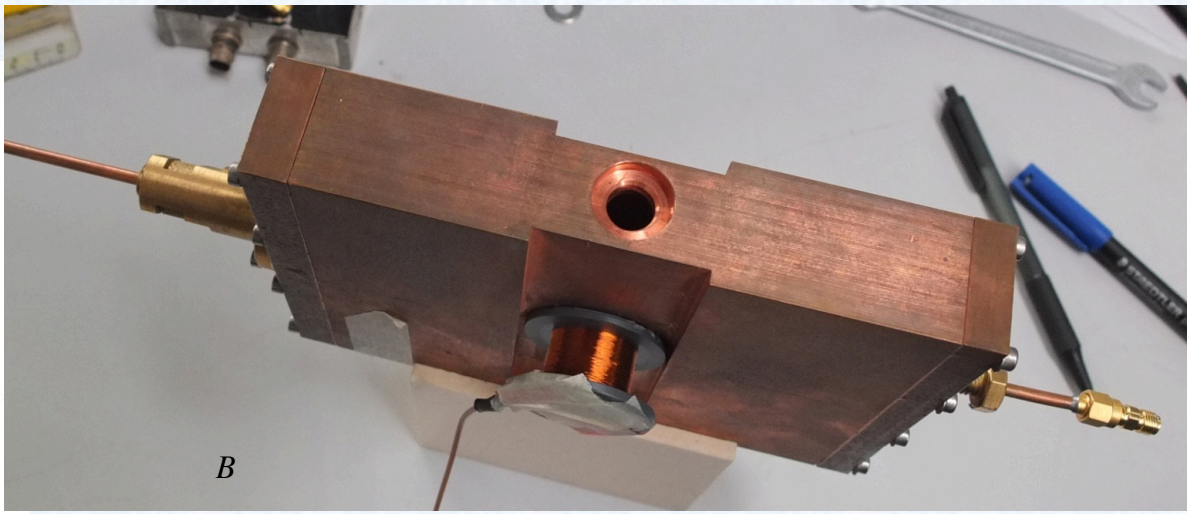
Cavities

TE102 mode

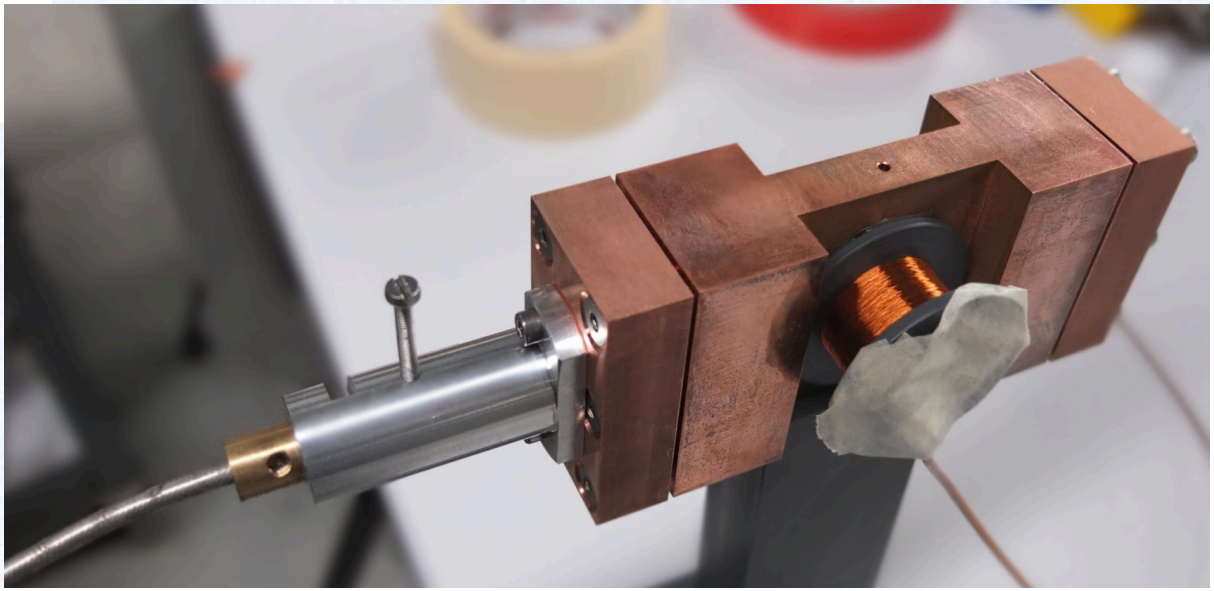


We are using a resonant cavity for a better driving of the magnetized sample, but in principle it is not necessary

2.5 GHz

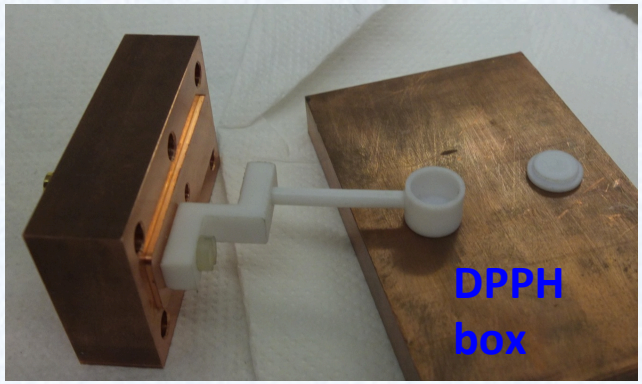


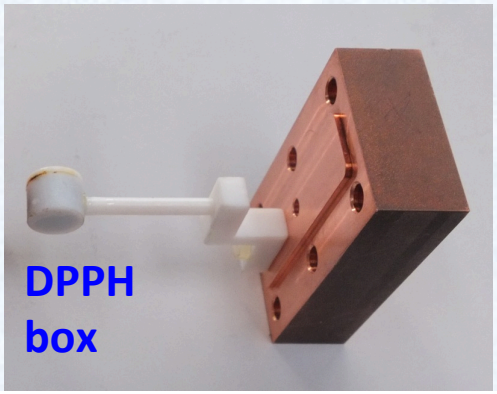
5.0 GHz

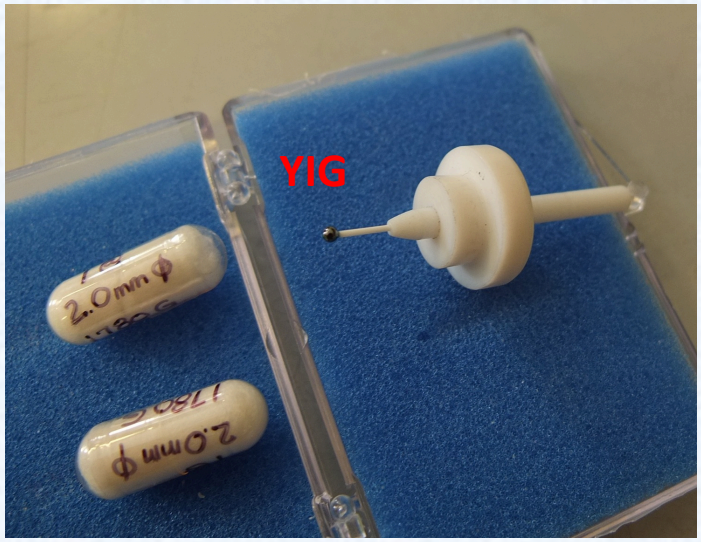


Magnetic samples

Material	Spin density	M0	T1	T2	Size
		All values at room temperature			
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 diameter



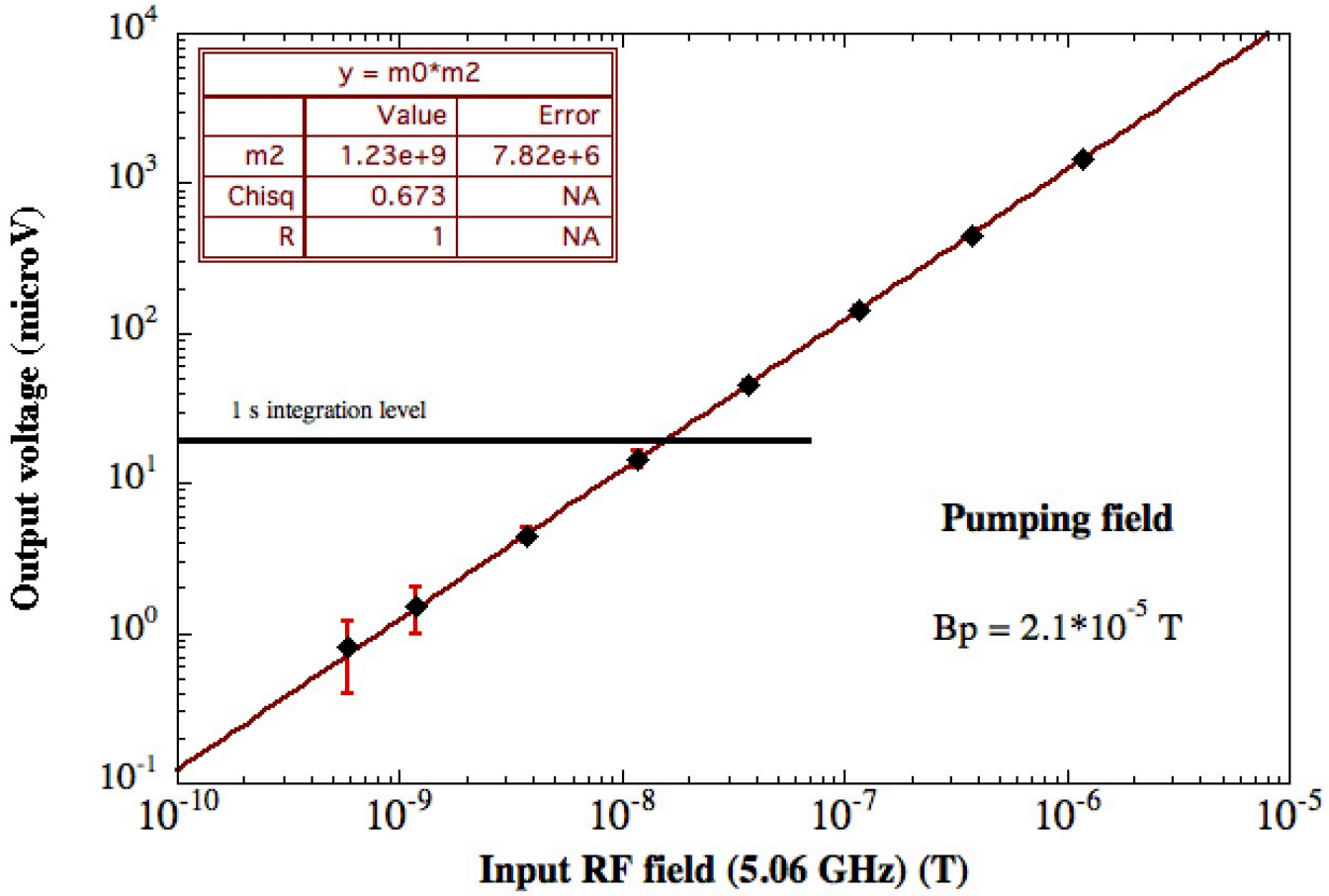




DPPH @ 5.0 GHz

Calibration with DPPH in a 5 GHz resonant cavity

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



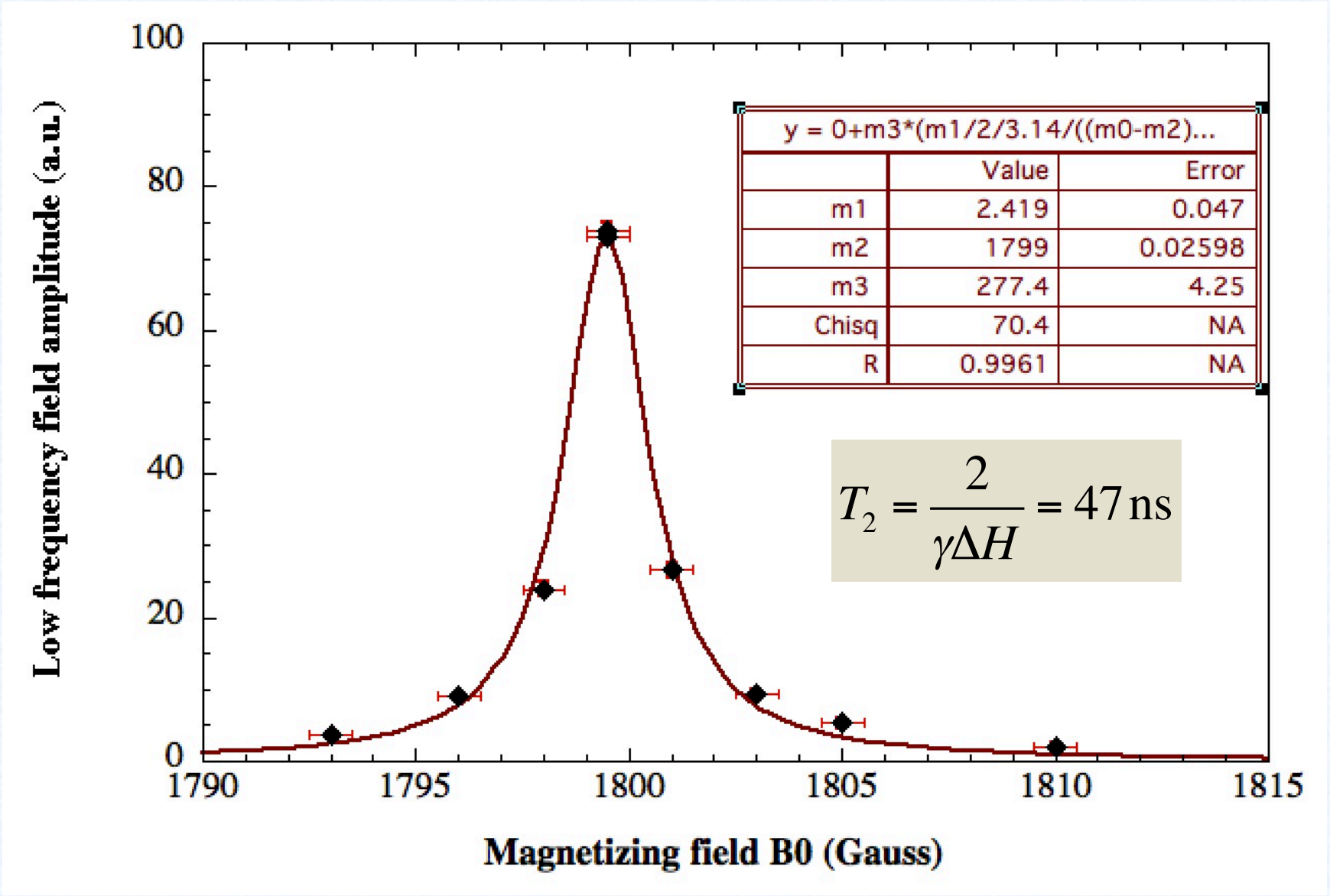
Expected gain
G_m (th) = 6 10^{-3}

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

T_2 measured by us

Lower gain possibly due to fields inhomogeneities and worse coupling

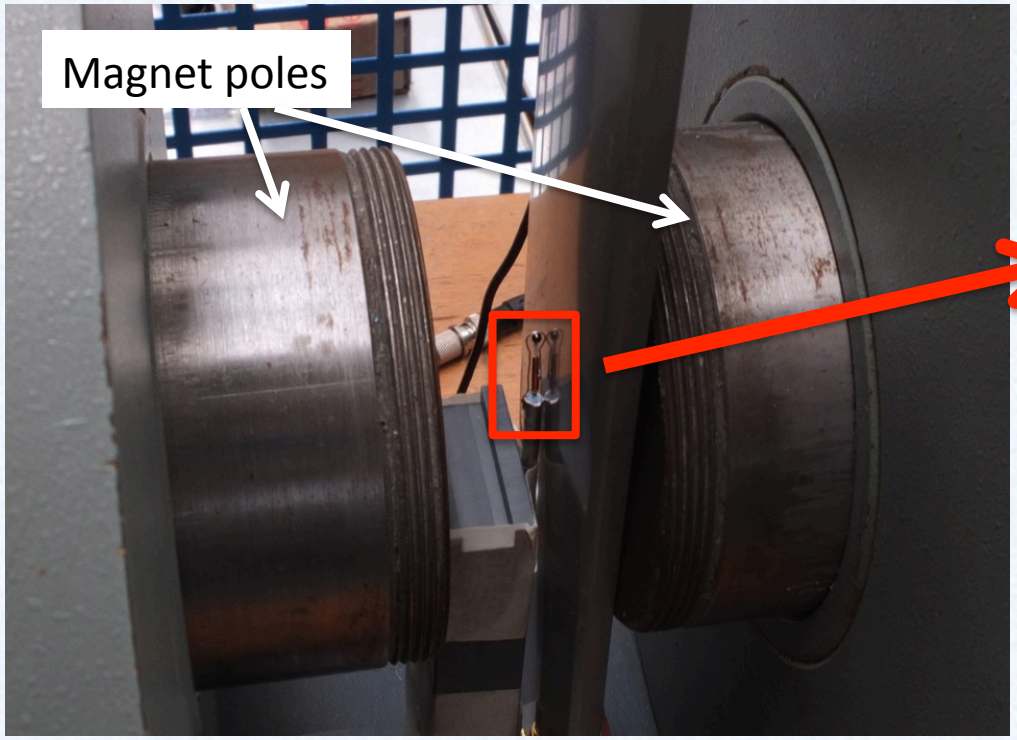
DPPH linewidth @ 5 GHz



Free field detection

Resonant cavities pump **thermal photons** into the magnetic material. In order to avoid this effect the sample will be placed free inside the magnetic field region.

Pumping is made by a single loop coil enclosing the sample



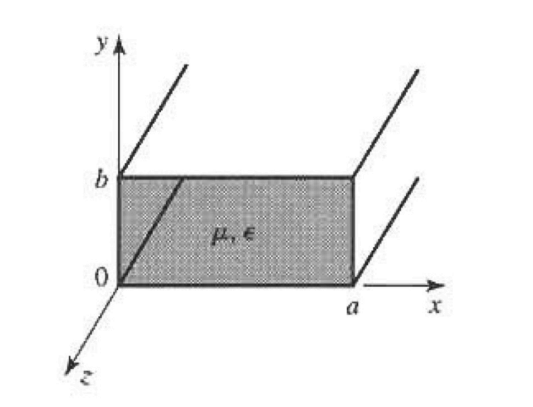
We have checked **the low frequency down conversion** feeding two driving fields at the Larmor frequency. The signal was picked up with a 3000 loops coil placed close to the sample**. Low frequency signal has been observed**, calibrations are on the way.

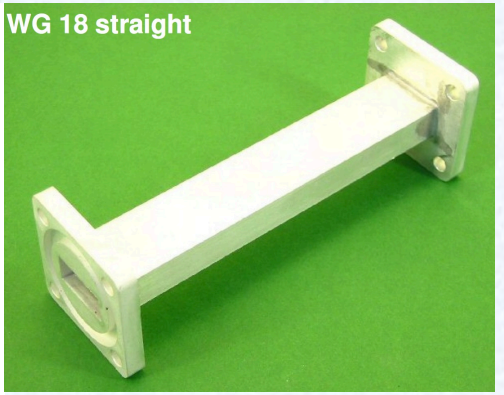
Cut-off waveguide

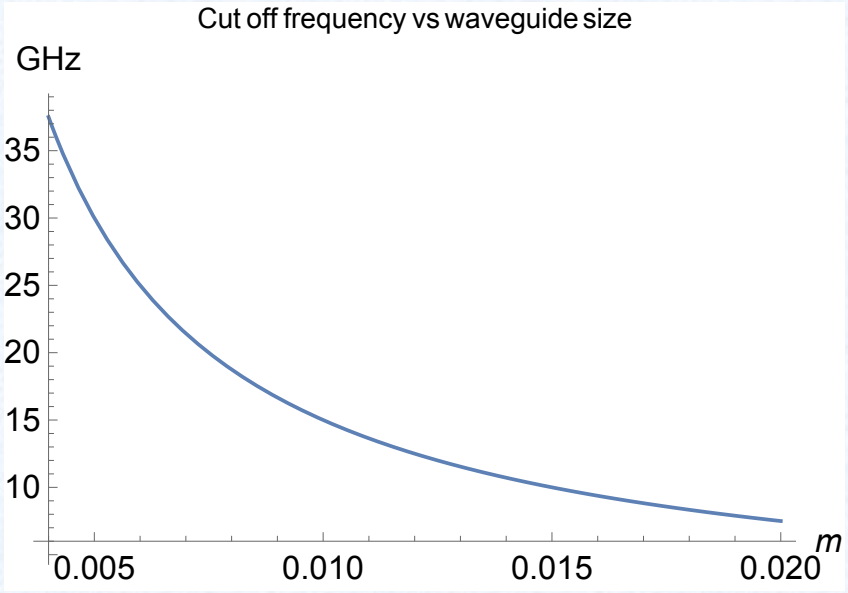
- The magnetic sample must be isolated from the outer world
- Possible solution to reduce radiation damping @ Larmor frequency

For a > b the lowest cut off frequency is

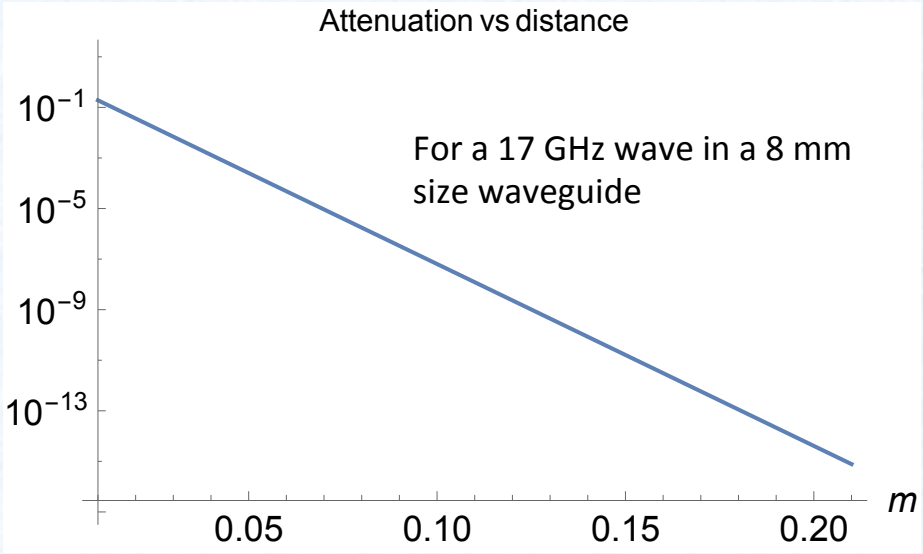
$$f_{c_{10}} = \frac{1}{2a\sqrt{\mu\epsilon}}.$$







Below cutoff we have an evanescent wave



Measurement with cut off waveguide

We have checked the system in the following conditions:

rectangular waveguide with 8 x 16 mm^2 section
cut off frequency 9.3 GHz
length 1 m

magnetizing field B0 = 2 T

Larmor frequency 5.6 GHz

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

RF @ Larmor frequency completely suppressed.

The **magnetic field** (near field) produced by the single loop coil excites the spin precession 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 low temperature (at 4 K)
- Find a material with long T1 and large magnetization at low temperature
- In a first step: use as low frequency detector a resonant pick up coil.
- We will integrate a SQUID into the system in a second step/phase.
- One year goal: reach a sensitivity at 10^{-14} Tesla
- **Assess the material magnetic noise level as soon as possible**

Detection of axion with atomic transitions

Volume 263, number 3,4 PHYSICS LETTERS B 18 July 1991

Direct detection of galactic axions with Rydberg atoms in an inhibited cavity regime

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and

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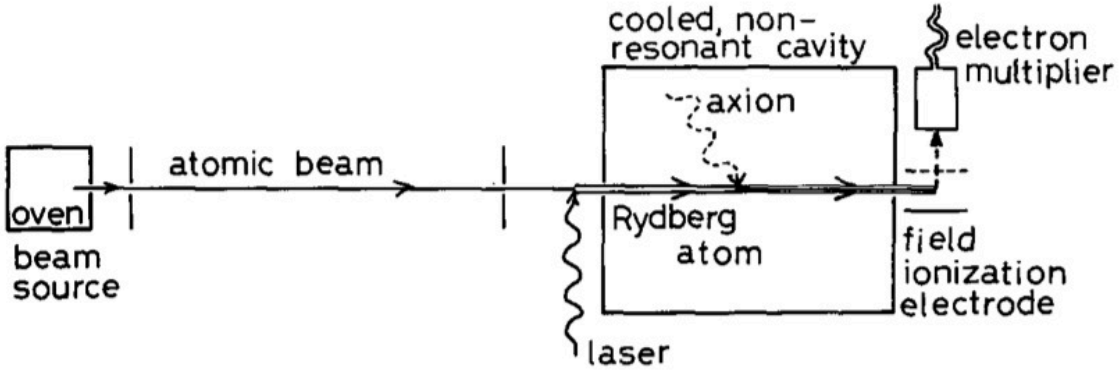
Only proposal, no experiment done



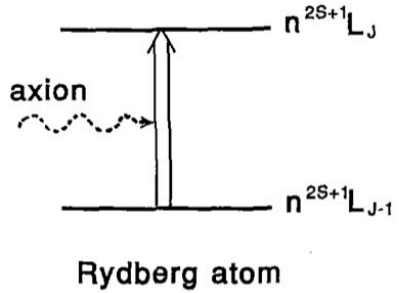


Fig. 2. Transition due to the axion absorption between the fine-structure splitting components of the Rydberg atom.

A new scheme to detect galactic axions directly with Rydberg atoms is proposed and discussed. Rydberg atoms are excited from the lower to the upper fine-structure states by absorbing the axions in an inhibited (non-resonant) cavity regime. The weak transition rate in axion absorption could be enormously enhanced due to the huge occupation number of the axions if the axions constitute our galactic halo, while the transition rate in photon absorption could be strongly suppressed in a cooled, inhibited cavity regime. Thus it would be possible to get a good signal-to-noise ratio for axion hunting.

Expected **sensitivity not sufficient to reach axion models**, just improved limits on electron-axion coupling

Detection of axion with atomic transitions – 2

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

Axion Dark Matter Detection Using Atomic Transitions

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(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.

Coupling to fermions

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

Interaction energy

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

Search for Zeeman transition induced by axion absorption. External B field tuned to the axion mass. The expected rate for 1 mole of polarized electrons

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

Hz Rate

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

$$m_a \simeq 0.6\times10^{-4}\ \text{eV}\left(\frac{10^{11}\ \text{GeV}}{f_a}\right)$$

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)

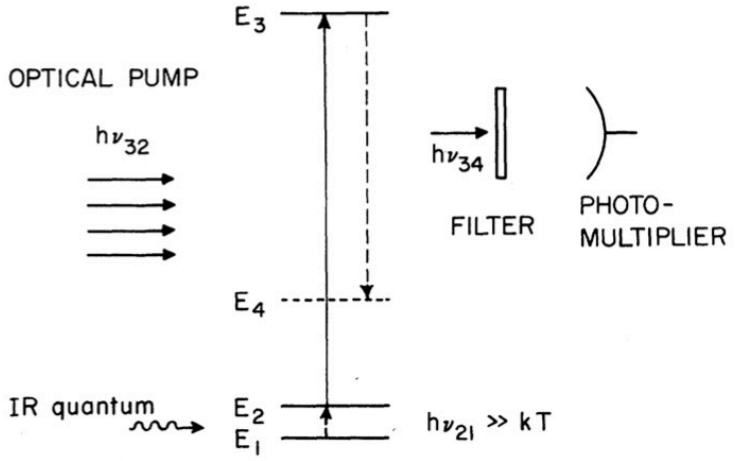

FIG. 1. Infrared quantum counter. Several ions of transition group elements have appropriate energy level diagrams: $h\nu_{21} = 1 - 5000\ \text{cm}^{-1}$, $h\nu_{32} = 10^4 - 5\times 10^4\ \text{cm}^{-1}$.

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 Oxygen molecules?

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

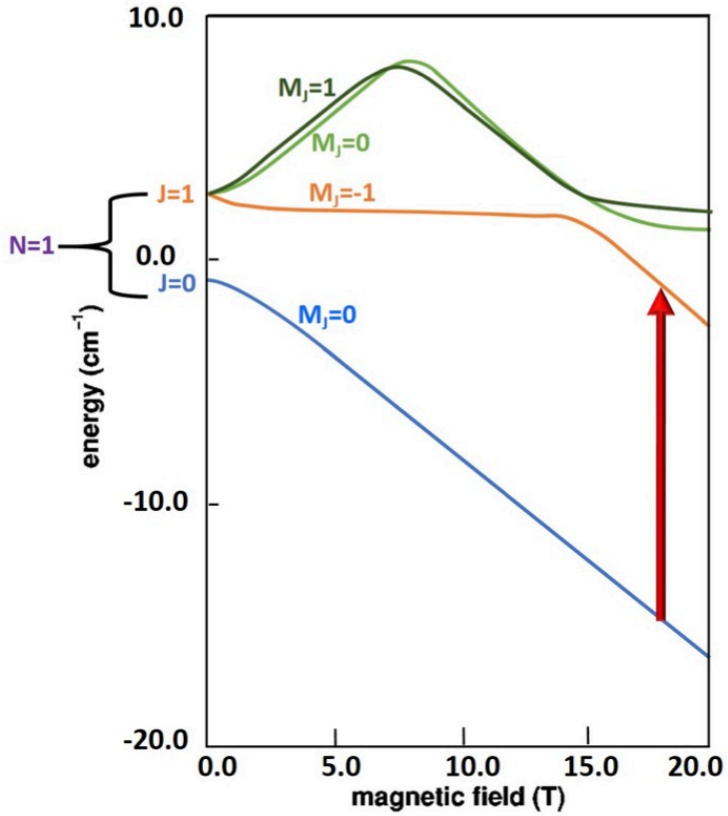

Figure 1. $N = 1$ rotational levels in the $X^3\Sigma_g^-(\upsilon = 0)$ ground state of $^{16}O_2$. $J = 2$ is omitted for a clear view. The axion transition is indicated by the red arrow.

(Courtesy of P. Maddaloni)

- Buffer gas cooling in ^{3}He environment
- Work in the higher axion mass range to satisfy temperature prescription
- Number of available atoms can be an issue
- Find an appropriate detection technique with high efficiency (REMPI – resonance enhanced multiphoton ionization - interrogation scheme?)

Conclusions

We have shown possible schemes for detecting galactic axion with magnetic material

- Tune the Larmor frequency of a magnetic sample and perform low frequency conversion of the axion effective magnetic field
- Low frequency detection using SQUID
- **Magnetic noise of the sample is the key issue**
- Alternative detection scheme with **quantum counting techniques** for **higher axion masses**