Searching for Galactic Axions
QUAX Status

QUest for AXions

Giovanni Carugno

on behalf of the QUAX Collaboration

Overview

- Axion-electron coupling: DFSZ models (in KSVZ models $1/\alpha$ suppression)
- Detection principle: electron spin resonance (ESR)
- Experimental challenges: current R&D @ INFN
- Current sensitivity of the QUAX prototype
- Axion-Photon coupling sensitivity with QUAX set up

Interaction of DFSZ axion and electron spin

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

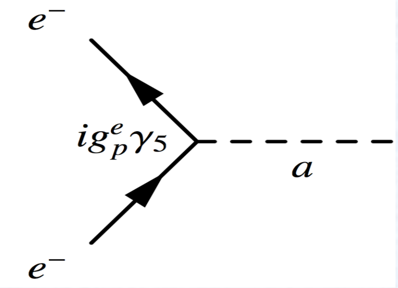
$$\mathcal{L}_{a,\text{matter}} = f_a^{-1} g_{aij} \overline{\psi}_i \gamma^\mu \gamma^5 \psi_j \, \partial_\mu a$$

$$g_p \cong \frac{m_e}{3 f_a} \cos^2 \beta$$

$$g_p \approx 3 \times 10^{-11} \left(\frac{m_a}{1\, eV} \right)$$

- DFSZ axion coupling with non relativistic (v/c << 1) electron: equation of motion reduces to the Schroedinger equation

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



- Cold Dark Matter of the Universe may consists of axions and they can be searched for

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

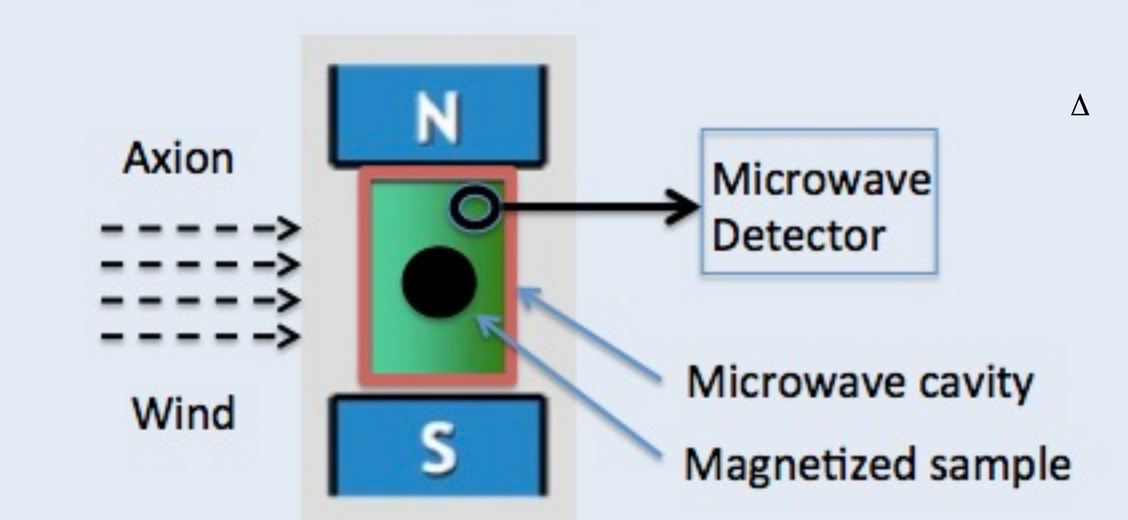
$$\mathrm{H}_{\text{int}} = -2\mu_B \vec{\sigma} \cdot \left[\frac{g_p}{2e} \vec{\nabla} a \right]$$

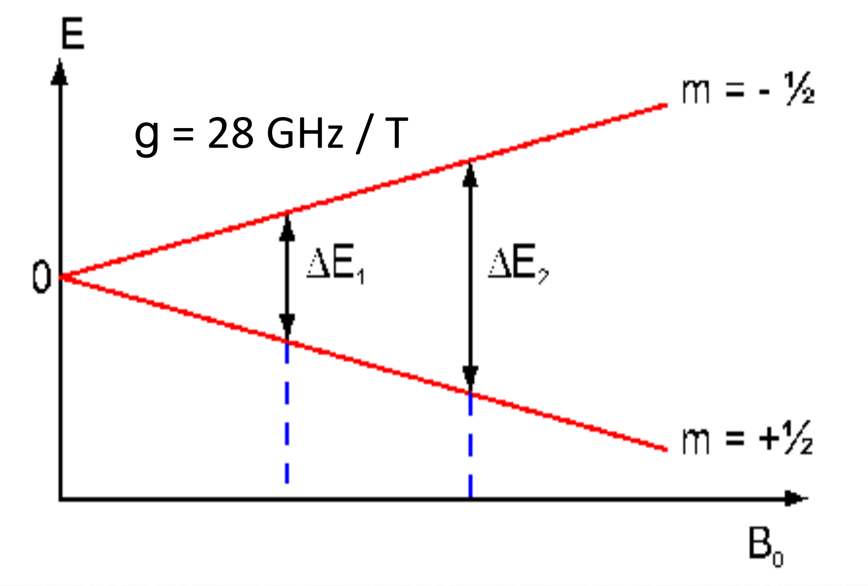
$$\mathrm{B}_a = \frac{g_p}{2e} \vec{\nabla} a$$

-- **Frequency** of the effective magnetic field proportional to **axion energy**
-- **Amplitude** of the effective magnetic field proportional to **axion density**

The axion wind

- **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**
- RF field excites **magnetic transition in a magnetized sample** (Larmor frequency) with a static magnetic field $\mathbf{B_0}$ and can produces a detectable signal
- **The interaction with axion field produces a variation of magnetization which is in principle measurable**





Idea is 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)
- R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett. B 226, 357 (1989)
- F. Caspers, Y. Semertzidis, “Ferri-magnetic resonance, magnetostatic waves and open resonators for axion detection”, Workshop on Cosmic Axions, World Scientific Pub. Co., Singapore, p. 173 (1990)
- A.I. Kakhizde, I. V. Kolokolov, Sov. Phys. JETP 72 598 (1991)

The axion effective magnetic field

- R. Barbieri et al., *Searching for galactic axions through magnetized media: The QUAX proposal* [Phys. Dark Univ. **15,** 135 - 141 (2017)]

The effective magnetic field associated with the axion wind

$$B_a = \frac{g_p}{2e}\left(\frac{n_a h}{m_a c}\right)^{1/2} m_a \mathrm{v}_E$$

n_a – axion density $\sim$ 0.4 Gev/cm^3
v_E – Earth velocity $\sim$220 km/s
axion velocity dispersion $\sim$270 km/s

Using from standard model of Galactic Halo:

$$\boxed{B_a = 2.0 \cdot 10^{-22}\left(\frac{m_a}{200\,\mu\mathrm{eV}}\right)\quad \mathrm{T},}$$

$$\boxed{\frac{\omega_a}{2\pi} = 48\left(\frac{m_a}{200\,\mu\mathrm{eV}}\right)\quad \mathrm{GHz},}$$

$$\tau_{\nabla a} \simeq 0.68\,\tau_a = 17\left(\frac{200\,\mu\mathrm{eV}}{m_a}\right)\left(\frac{Q_a}{1.9\times 10^6}\right)\quad \mu\mathrm{s};$$

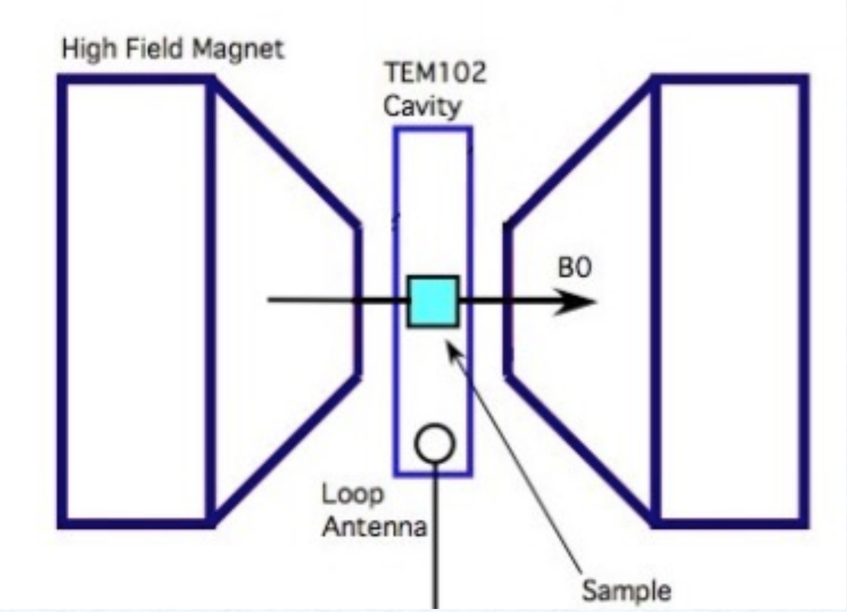
Coherence time

$$\lambda_{\nabla a} \simeq 0.74\,\lambda_a = 5.1\left(\frac{200\,\mu\mathrm{eV}}{m_a}\right)\quad \mathrm{m},$$

Correlation length

Detection strategy: Electron Spin Resonance

Electron spin resonance (ESR) arises when energy levels of a quantized system of electronic moments are **Zeeman split** (the **magnetic system** is placed in a uniform magnetic field B_0) and the system absorbs/emits EM radiation (in the microwave range) at the **Larmor frequency n_L** of the **ferromagnetic resonance**.

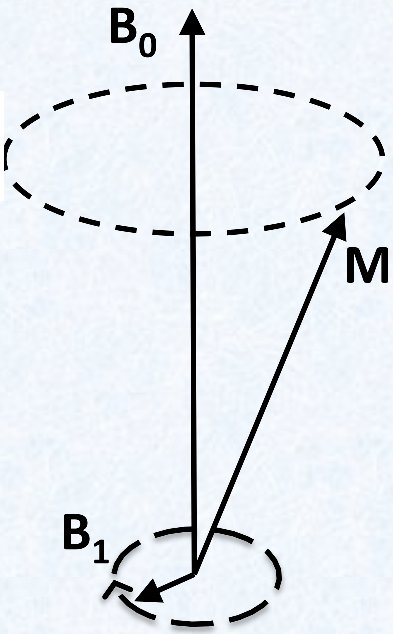


$$B = \begin{pmatrix} B_1 \cos(\omega t) \\ B_1 \sin(\omega t) \\ B_0 \end{pmatrix}$$

$$\nu_L = \mathbf{g}\, \mathbf{B_0}$$

g = 28 GHz / T

1.7 T -> v_L = 48 GHz



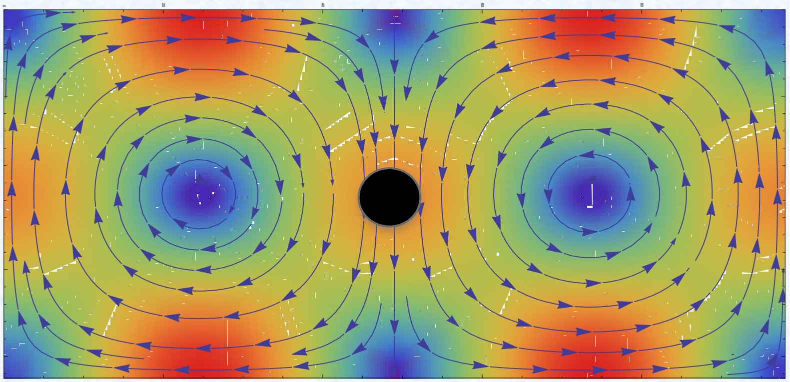
An experimental geometry with **crossed field** is needed:

- **B_0** along the z direction, defines the Larmor resonance
- **RF field B_1** in the x-y plane excites the Magnetization modes

The system macroscopic dynamics is given by **Bloch equations** which describe the evolution of **each component** of the magnetization vector **M.** **No radiation damping in a resonant cavity and in strong coupling regime of Kittel/cavity modes.**

TEM102 Resonant Cavity

B_0 along z axis (normal to the figure)

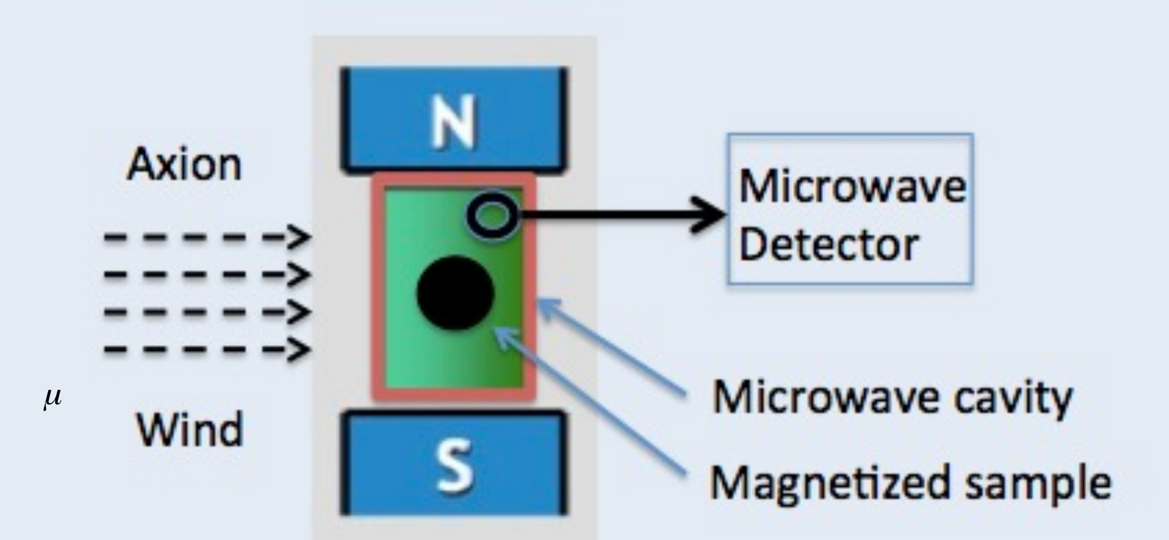


Axion driving of magnetization

The axion wind mimics the transverse rf magnetic field inducing a **time dependent magnetization of the uniform or Kittel mode** of the magnetized sample

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

at resonance



τ_{min} is the shortest coherence time among:

- **axion wind** coherence $\tau_{\nabla a}$
- magnetic material **relaxation time τ_2**
- **radiation damping τ_r**

n_s – material spin density

μ_B – Bohr magneton

A **volume V_s of magnetized material** will absorb energy from $\mathbf{B}_a$ at a rate

$$P_{\text{in}} = \mu_0 \mathbf{H} \cdot \frac{d\mathbf{M}}{dt} = B_a \frac{dM_a}{dt} V_s = \gamma \mu_B n_S \omega_a B_a^2 \tau_{\min} V_s$$

this power will excite magnetization/cavity modes and could be possibly detected

Anticipated signal strength

Expected signal as a function of relevant experimental parameters

Working @ m_a = 200 μeV-> 48 GHz

Larmor frequency tuning by magnetizing field
B_0 = 1.7 T => 48 GHz

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

Such a low power level is out of reach of linear amplifiers → **Single photon microwave detection** To be developed

See discussion in *S.K. Lamoreaux et al., Phys. Rev. D 88 (2013) 035020.*

The corresponding **signal photon rate**

$$R_a = \frac{P_{\text{out}}}{\hbar \omega_a} = \mathbf{1.2 \times 10^{-3}}\,\text{Hz}$$

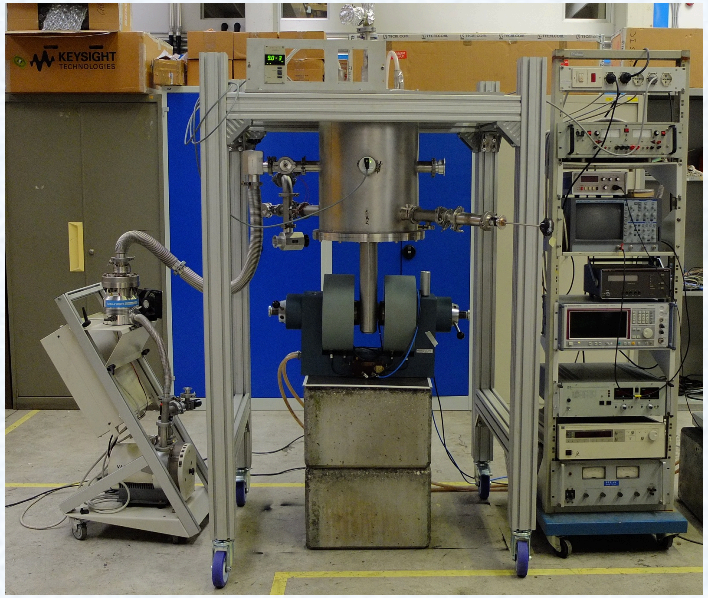
this rate establishes the required dark count rate of the photon counter

QUAX experimental challenges

- **Magnetized material**
  - Spin density 2 x 10^{28} / m^3
  - Ferromagnetic linewidth ~150 kHz (i.e. $\tau_2 \sim \mu s$)
  - Total volume ~100 cm^3
- **Microwave cavity**
  - Q factor $\gtrsim 10^6$
  - To be operated in a few Tesla static magnetic field
  - Must house a 100 cm^3 magnetic sample (use replica?)
- **Magnetizing field**
  - Up to 2 T magnetic source
  - High uniformity and high stability – at the ppm level
- **Microwave receiver**
  - Single photon counter with a dark count rate $\lesssim 10^{-3}$ Hz
- **Complete apparatus**
  - Working temperature around 100 mK
  - Noise dominated by thermodynamic fluctuations
  - Frequency tunability (to search for different axion masses)

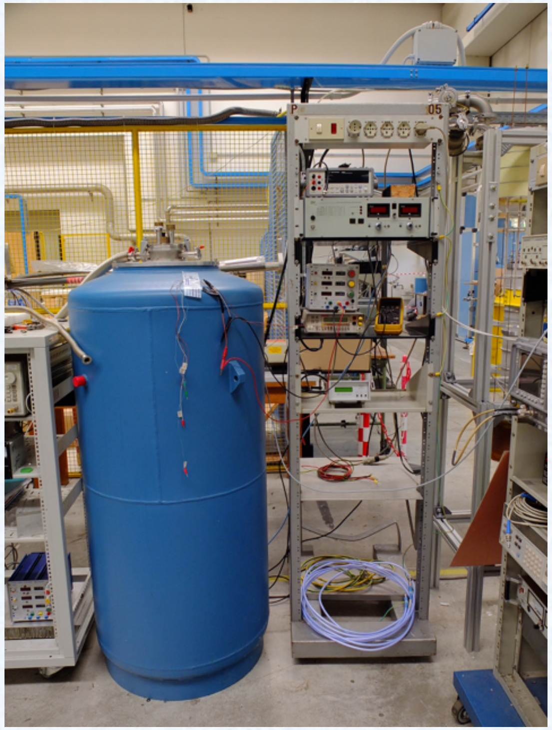
Work in progress

We are working on almost all these points to address the feasibility of the experiment



Cryogenic system #1 in **Legnaro**

External magnetic source



Cryogenic system #2 in **Legnaro**
Superconducting magnet

Cryogenic system in **Frascati**

Superconducting magnet

All present systems works with LHe

A dilution refrigerator is on the way

During R&D we are working in the 10 – 15 GHz range

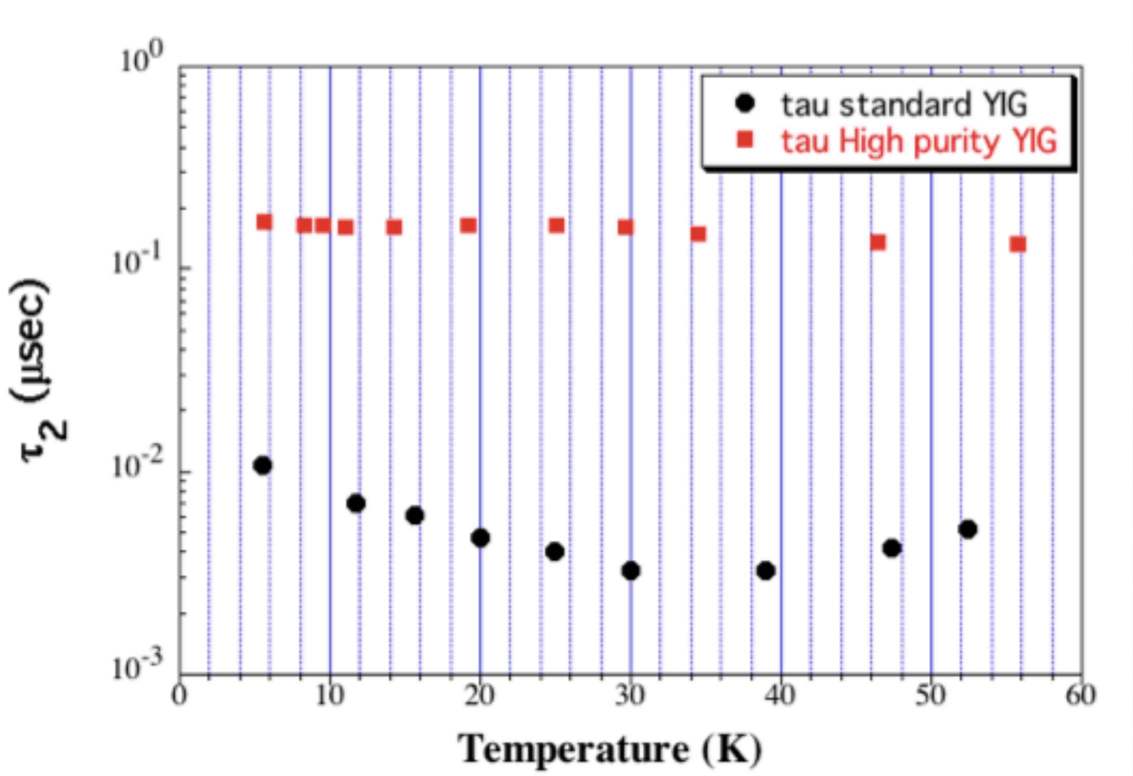
Magnetic Material

Material	Spin density	M0	τ_1	τ_2	Size
YIG	2.1×10^{28} [1/m^3]	$1.4\ 10^5$ A/m	0.16 μs	0.16 μs	Spheres 1 mm, 2 mm and 3 mm diameter

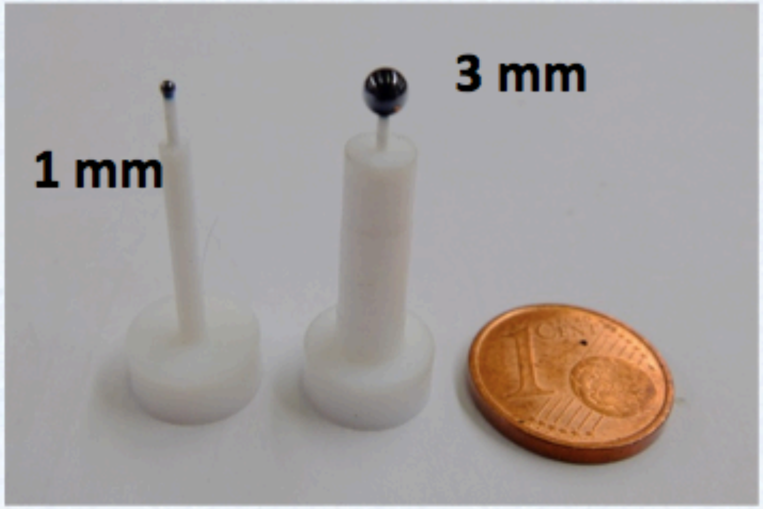
All values at room temperature

YIG – Yttrium Iron Garnet is a ferrimagnetic synthetic garnet with chemical composition $Y_3Fe_5O_{12}$.

Its **ferromagnetic linewidth** ($= 1 / 2\pi\tau_2$) depends on temperature, **sample purity** and geometry (highly polished spheres)



Typical application: rf filters and synth

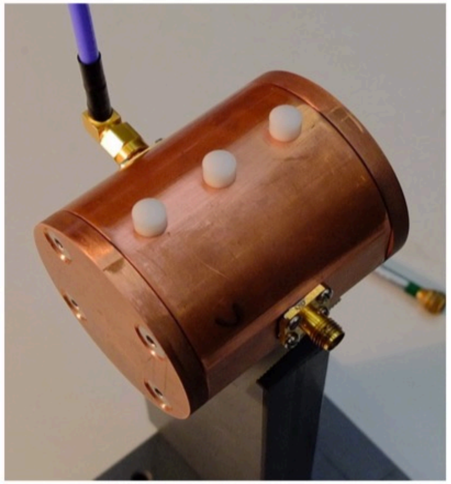


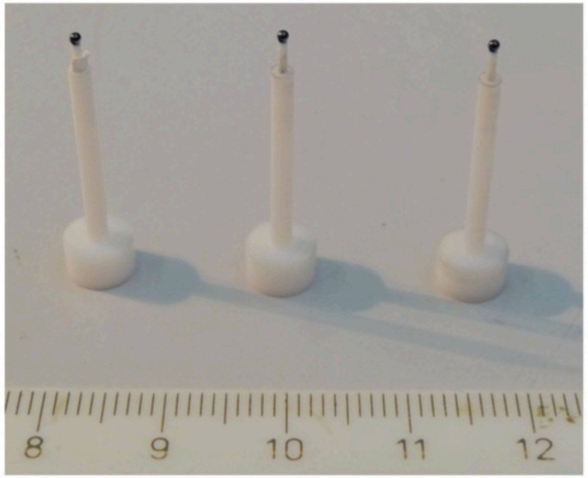
High purity YIG:
rare earth content below **1 ppm**

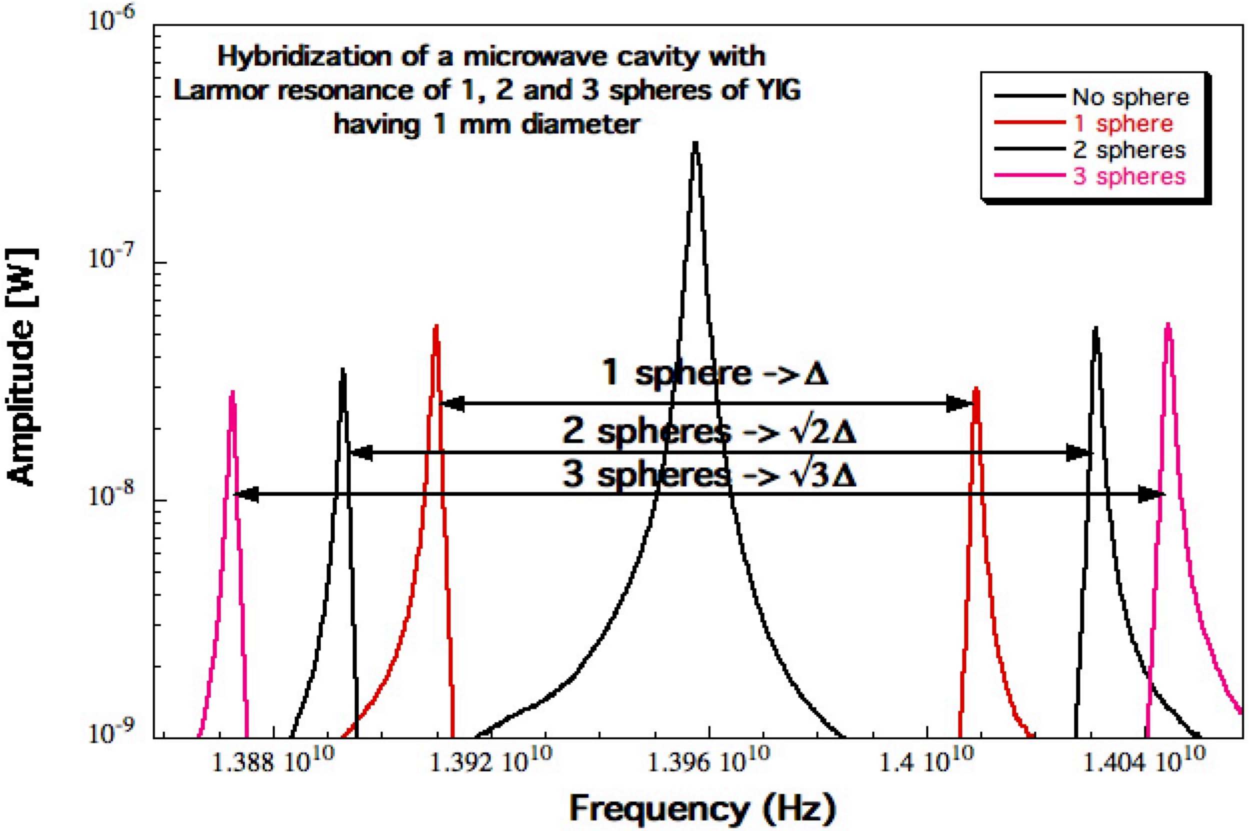
Magnetic material: volume issue

A possible idea to increase volume is to have several YIG spheres

Test with 3 identical spheres in a cavity







The wavelength for this frequency is **21.4 mm**, the YIG spheres are placed in the middle and 8 mm from the end faces, so the **separation between the outermost spheres is 34 mm**. The cavity is placed inside a homogeneous static magnetic field parallel to the cavity main axis.

No effect on the linewidth

Signal issues: volume, materials, number of spins, $\tau 2$

- Can we build a long cylinder and have a small linewidth?
  - Demagnetization issue
  - RF homogeneity

- We have realized a long BDPA sample to test inside a 14 GHz cavity.

- Worsening of linewidth of standard YIG at low temperature (8-10 MHz) → due to rare earth contamination

- Line width of high purity YIG measured @ 4 K → about 1 MHz

- We are checking other materials: **BDPA, K_3CrO_8** (paramagnets), **Lithium ferrite** (Ferrimagnet, spin density 4 x 10^{28} /m^3)

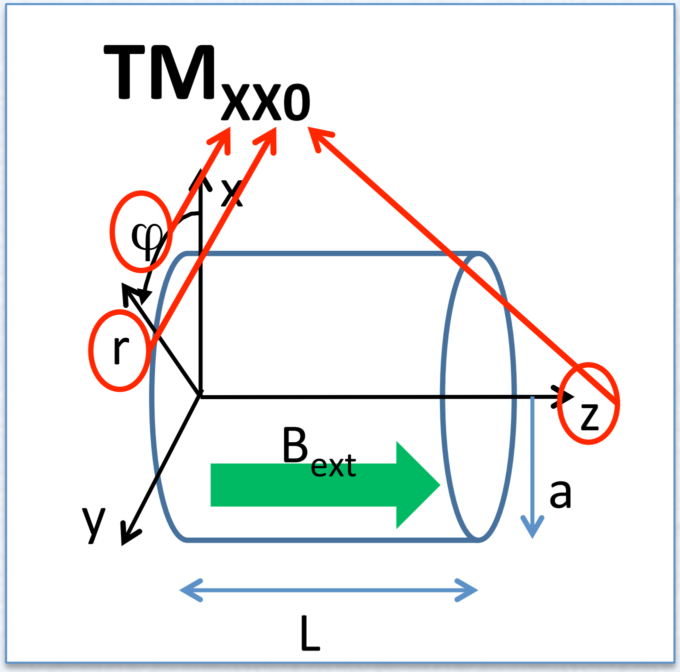
- Problems with the procurement of high quality YIG

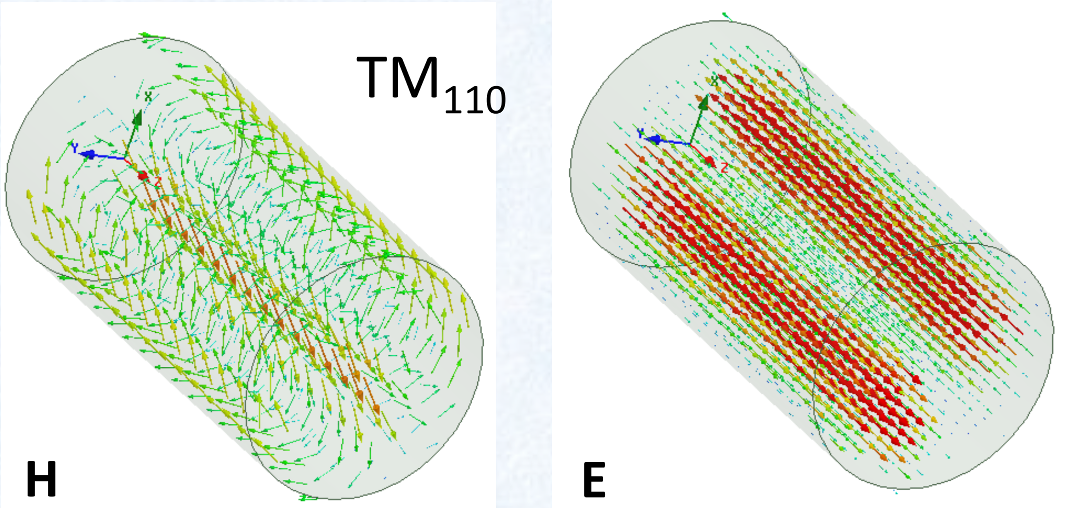
→ Produce YIG spheres by our own

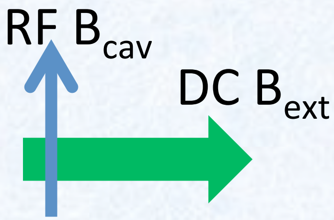
Microwave cavity: geometry

Basic geometry: **cylindrical cavity** working in the **TM_{XX0} mode**

- Simple design
- RF field uniform along the longitudinal coordinate
- Resonance frequency fixed by the radius of the cell







To increase the volume of the cavity (for YIG or other material insertion) we have to increase the **cavity length.** This does not change the resonance frequency.

This **increases the number of nearest modes** (hybridization can couple different modes?)

Cylindrical geometry produces mode degeneracy for the chosen mode

Solved by employing structure cuts

Microwave cavity: composition to work in high magnetic field

NC: Copper

PROS

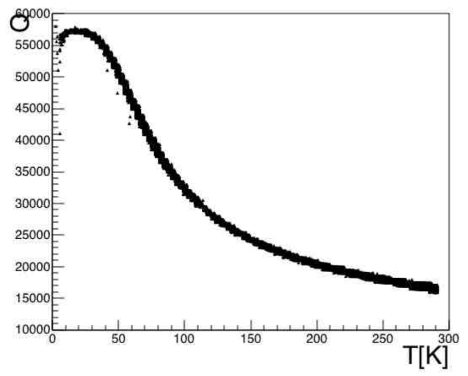
arbitrary H fields can be applied

H field (DC) can penetrate inside the cavity volume

Low cost, simple fabrication (brazing, welding,…)

CONS

Low quality factor even at cryogenic temperatures (6-8x10^4 because of the anomalous skin depth effect)



SC: Nb Ti

PROS

High quality factor ~10^6 (measured at 10GHz)

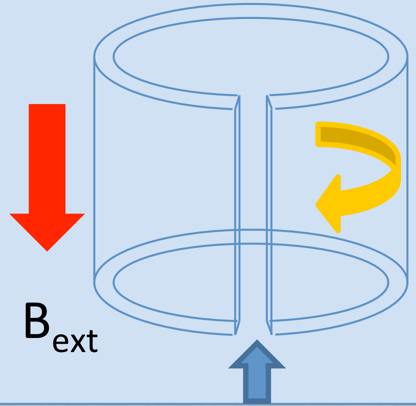
CONS

H fields below H_{c2} can be applied. **Q-factor deterioration** when H field are applied (between H_{c1} and H_{c2}) (**no model for R_s**, measurements to be done, preliminary results on Nb).

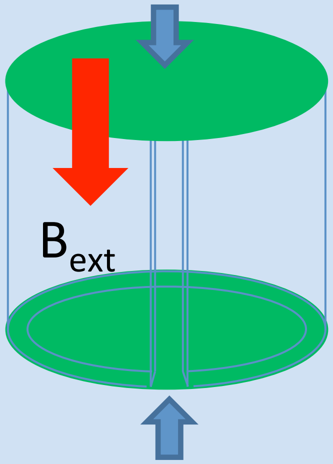
external H field can, in principle, penetrate inside the cavity volume but **measurements of the field penetration and uniformity have to be done** (different regimes ZFC and FC can be explored).

POSSIBLE SOLUTIONS

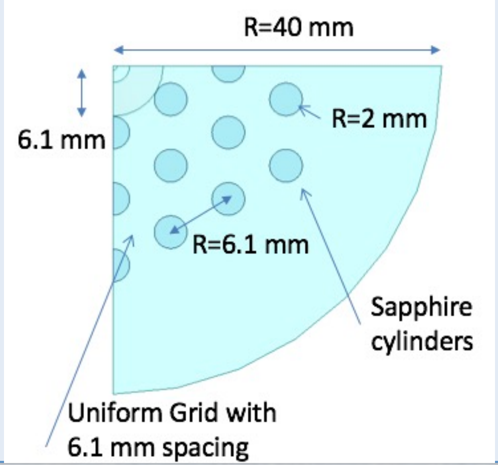
Cut on the cavity wall to interrupt surface DC currents that obstacle the penetration of the H field into the cavity (measurements to be done)

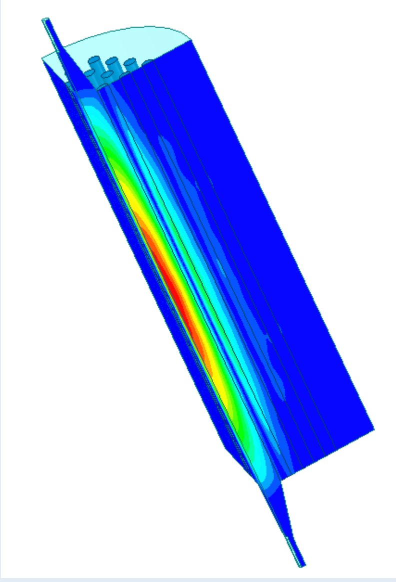


Two **copper plates** to allow penetration of the H field



Photonic cavity



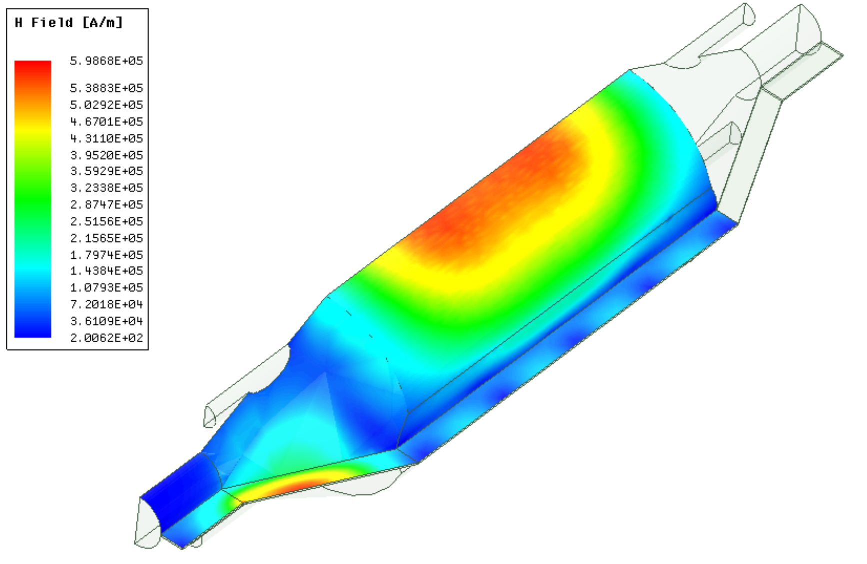


Microwave cavity: composition to work in high magnetic field

Copper cavity with conical end-caps

Two halves kept separated by lower conductivity material

NbTi sputtering in central cylinder



Preliminary measurements: Q factor 150 000 @ 4 K For the TM110 – 14 GHz mode with no external magnetic field. Small degradation of Q with a 0.5 T field along axis.
Field penetration OK. Field homogeneity still to be checked.

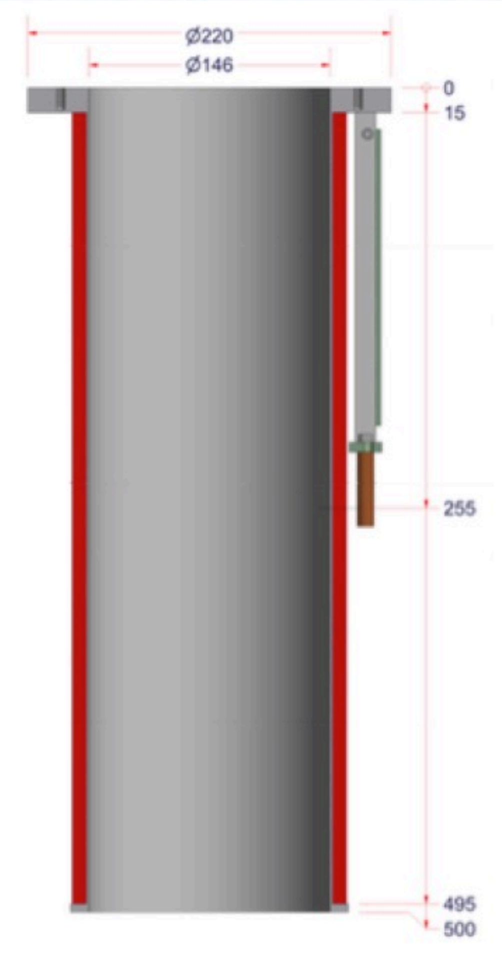
Static Magnetic field: current magnet

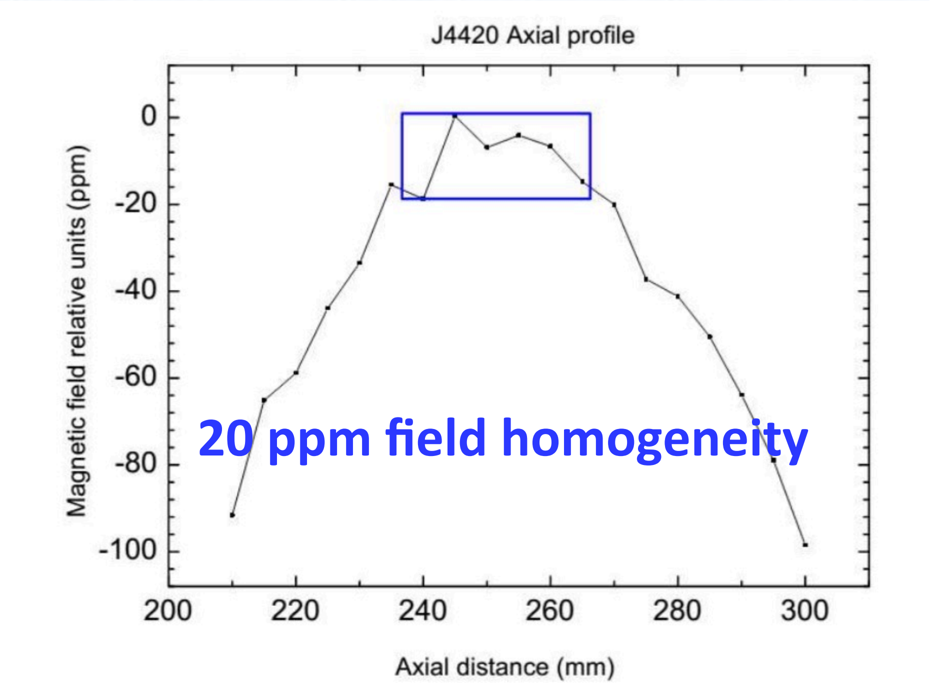
Other solution: increase ratio length / radius

Homogeneity depends on cost

20 ppm solution from private company

Superconducting coil NbTi





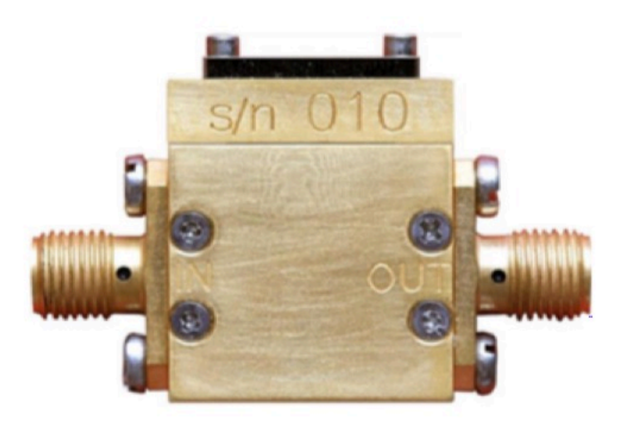
20 ppm field homogeneity

The current magnet can work up to 4 T

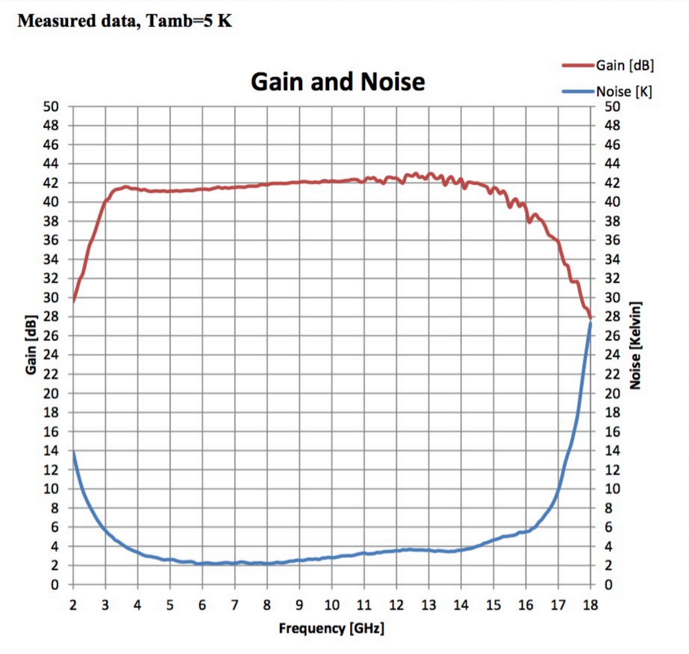
Magnetic field 1 T for 25 A

Microwave Receivers: HEMT, JPA, SPD

- All our tests for the moment are conducted with a **low noise linear amplifier**



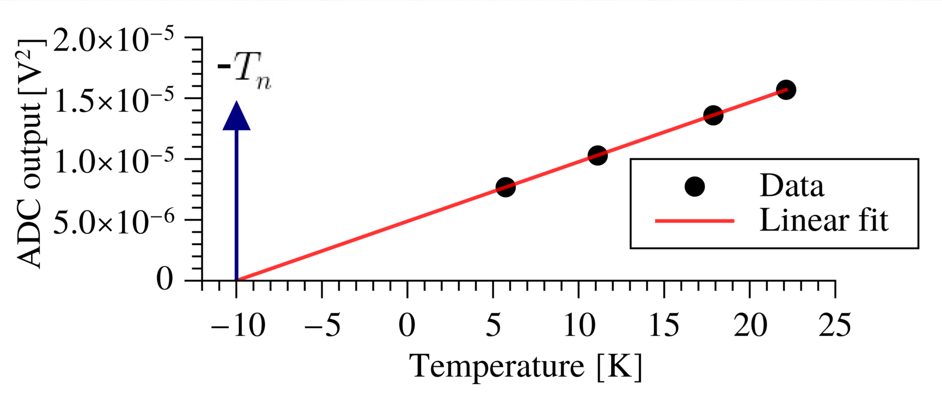
HEMT
High Electron
Mobility
Transistor

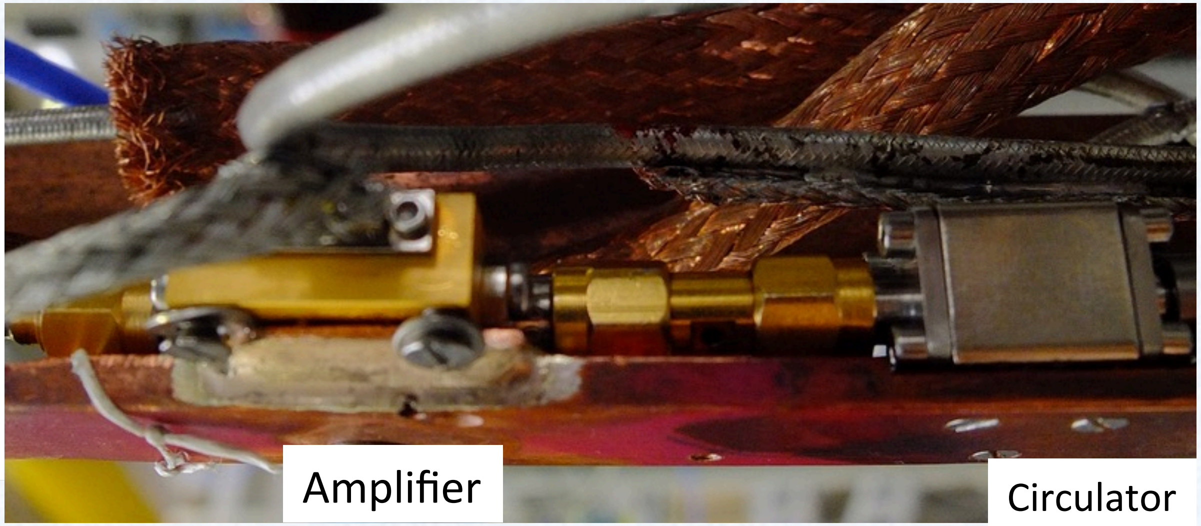


@ 14 GHz
@ 5 K

T_n = 4 K

Amplifier noise Temperature @ 5 K



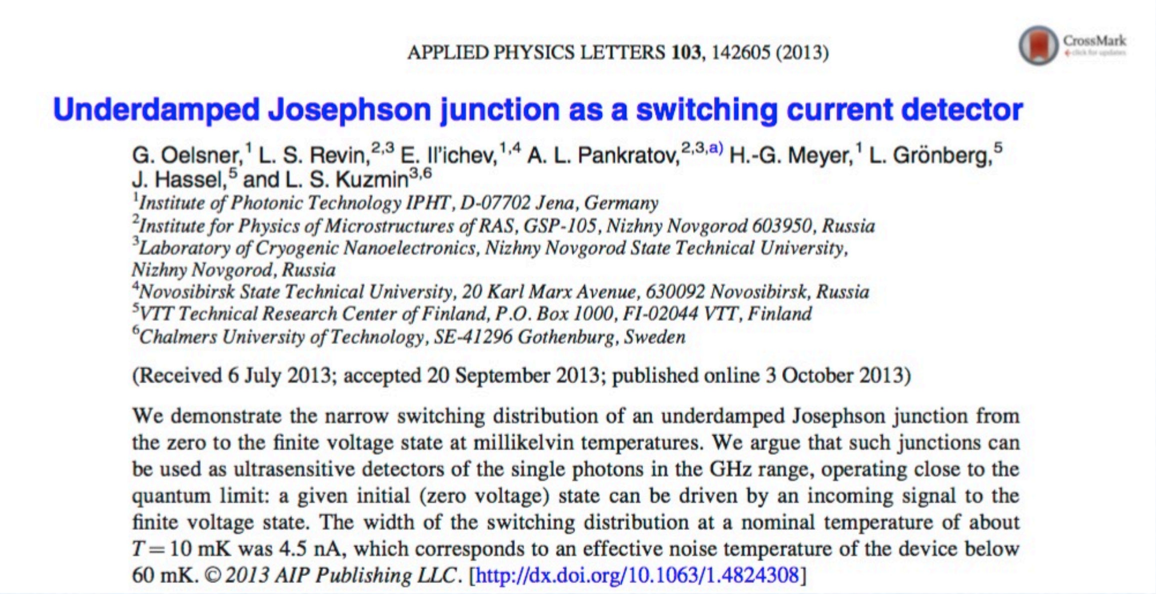


Mounted amplifier has a T_n about two times bigger than specification

JPA from QCI Company under test

Single Photon Microwave Detector

- The request for the final apparatus is to use a **microwave quantum counter**. World wide researches are under way in this direction outside our collaboration. Contact have been established with a group in Chalmers University that are interested in collaborating with us.



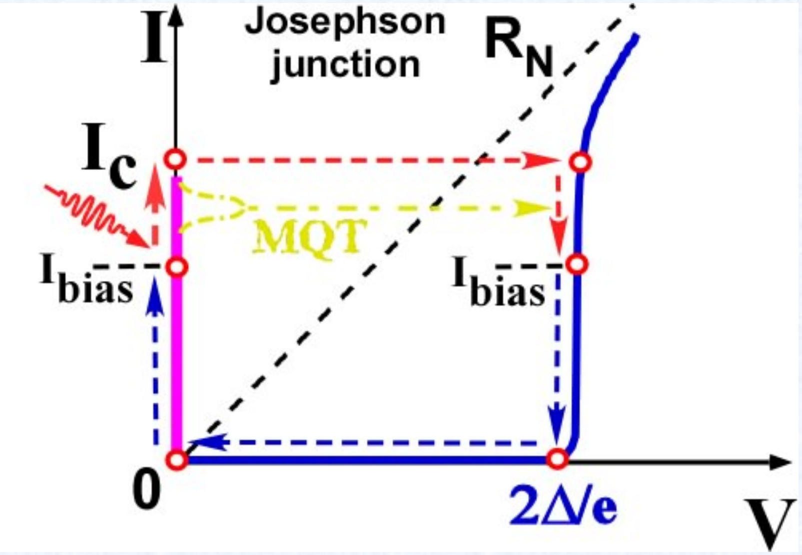
APPLIED PHYSICS LETTERS **103**, 142605 (2013)

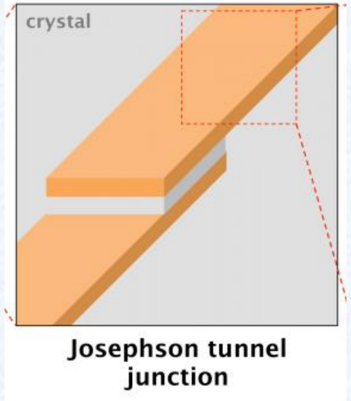
Underdamped Josephson junction as a switching current detector

G. Oelsner,[1] L. S. Revin,[2,3] E. Il'ichev,[1,4] A. L. Pankratov,[2,3,a)] H.-G. Meyer,[1] L. Grönberg,[5] J. Hassel,[5] and L. S. Kuzmin[3,6]
[1]*Institute of Photonic Technology IPHT, D-07702 Jena, Germany*
[2]*Institute for Physics of Microstructures of RAS, GSP-105, Nizhny Novgorod 603950, Russia*
[3]*Laboratory of Cryogenic Nanoelectronics, Nizhny Novgorod State Technical University, Nizhny Novgorod, Russia*
[4]*Novosibirsk State Technical University, 20 Karl Marx Avenue, 630092 Novosibirsk, Russia*
[5]*VTT Technical Research Center of Finland, P.O. Box 1000, FI-02044 VTT, Finland*
[6]*Chalmers University of Technology, SE-41296 Gothenburg, Sweden*

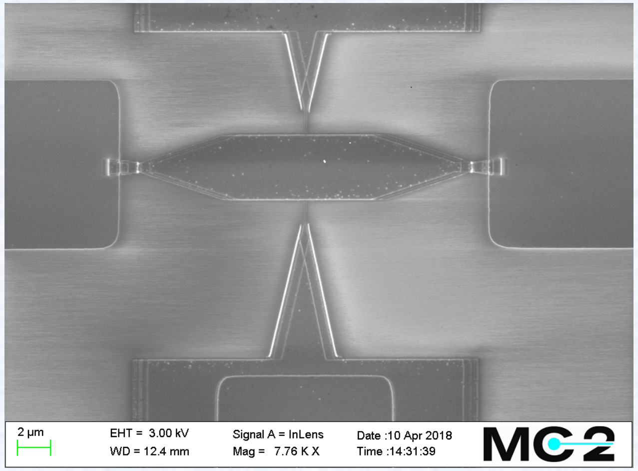
(Received 6 July 2013; accepted 20 September 2013; published online 3 October 2013)

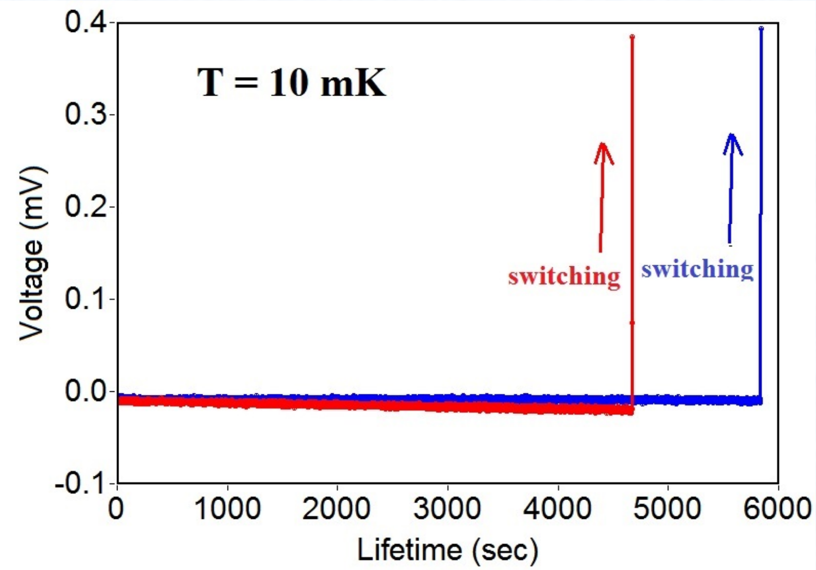
We demonstrate the narrow switching distribution of an underdamped Josephson junction from the zero to the finite voltage state at millikelvin temperatures. We argue that such junctions can be used as ultrasensitive detectors of the single photons in the GHz range, operating close to the quantum limit: a given initial (zero voltage) state can be driven by an incoming signal to the finite voltage state. The width of the switching distribution at a nominal temperature of about $T = 10$ mK was 4.5 nA, which corresponds to an effective noise temperature of the device below 60 mK. © 2013 *AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4824308]





Josephson tunnel junction





First results @ 14 GHz with lifetime in excess 10^3 s

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2018.2850019, IEEE Transactions on Applied Superconductivity

Single Photon Counter based on a Josephson Junction at 14 GHz for searching Galactic Axions

Leonid Kuzmin, Alexander S. Sobolev, Claudio Gatti, Daniele Di Gioacchino, Nicolò Crescini, Anna Gordeeva, Eugeni Il'ichev

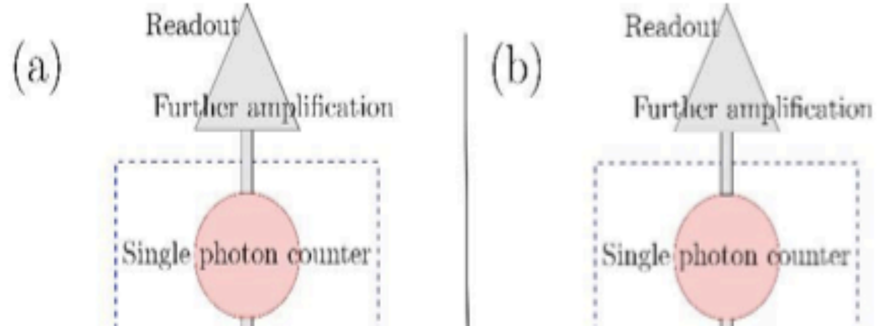
Abstract— **Axions and axion-like particles appear in well-motivated extensions of the Standard Model of particle physics and may be the solution to the long-standing puzzle of the Dark Matter in our Universe. Several new experiments are foreseen in the next decade searching them in a wide range of the parameter space. In the mass region from few to several tens of microelectronvolt, detector sensitivity will be limited by the Standard Quantum Limit of linear amplifiers and a new class of single microwave-photon detector will be needed.**

We have developed a single photon counter based on the voltage switching of an underdamped Josephson junction that is coupled to a coplanar waveguide. By measuring the switching voltage, we can register single photons at 14 GHz with the rate less than 1 photon per 3000 sec.

Index Terms—**Single Photon Counter, Josephson Junction, Axions, Critical current, Coplanar waveguide.**

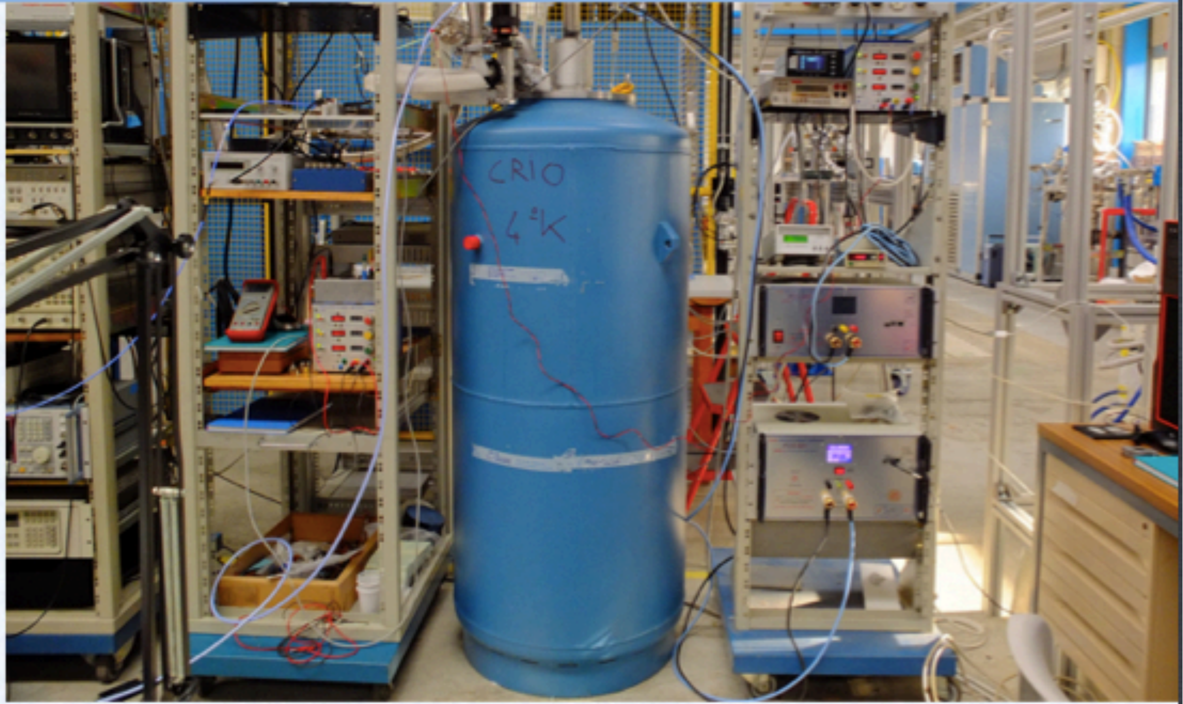
electromagnetic signals. In particular, experiments searching in the mass range from few to hundreds of μeV must be able to detect single microwave photons with a rate of a fraction of Hz and no dark counts.

In the following, we will discuss the requirements for haloscope searches using the standard axion conversion in a magnetic field (Primakoff conversion), as well as the axion conversion through the interaction with a magnetized media [8]. The detection scheme is schematically shown in figure 1.

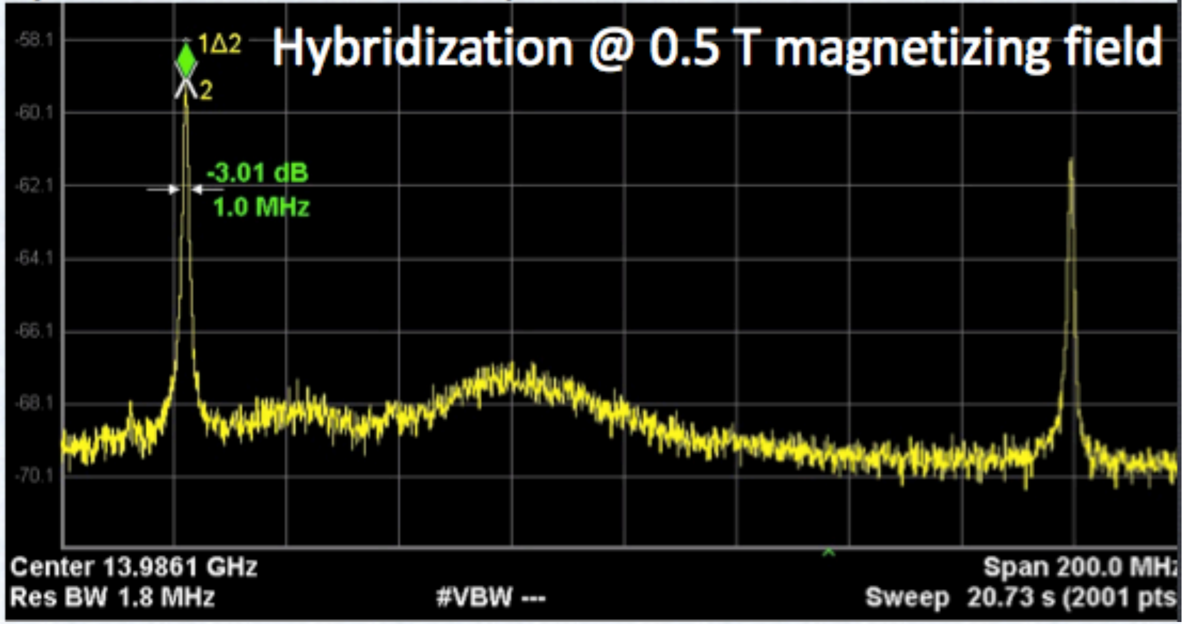


QUAX R&D experimental set-up

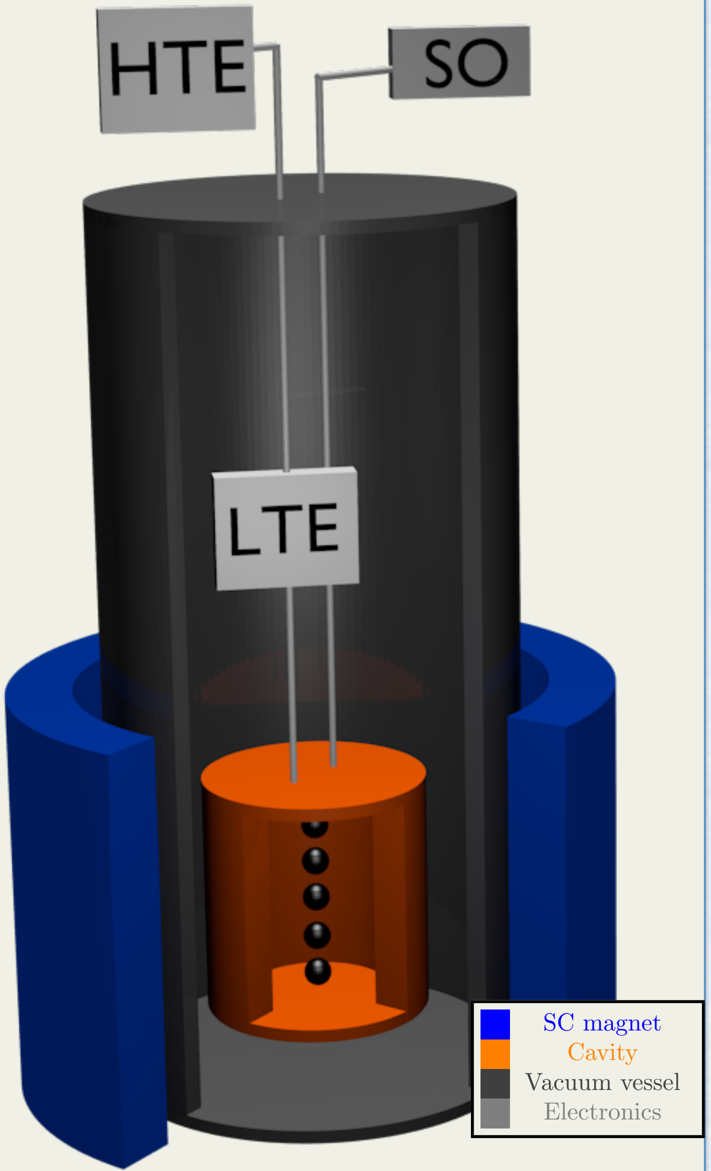
- Cylindrical cavity $\nu_c = 14$ GHz (26 mm diameter, 50 mm length)
- 5 spheres of GaYIG – 1 mm diameter – spin density 2.1×10^{28} 1/m^3 (measured from coupling/mode separation)
- HEMT amplifier – system noise temperature 9K
- High-precision and stability current generator (up to 20 A ± 0.3 mA)
- Highly uniform magnetic field (tens of ppm) with superconducting magnet (0.5 T field with 12.5 A)
- Fast ADC for data taking (2 Ms/s) – 16 bit



System transmission spectrum

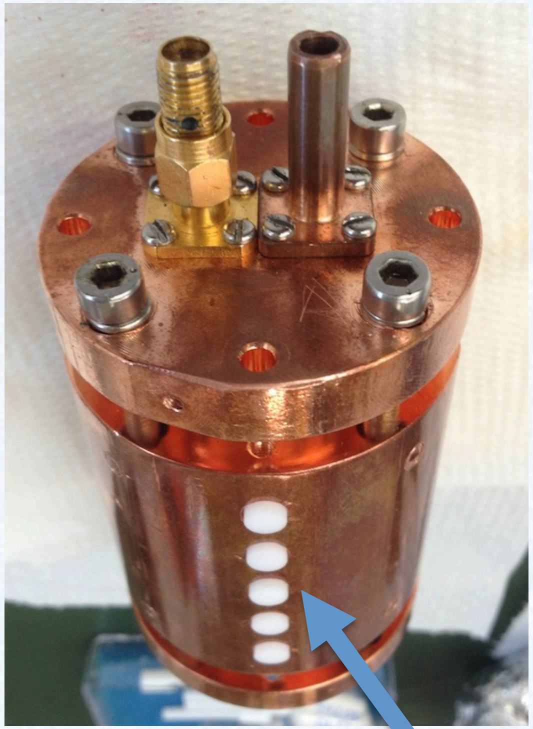

Hybridization @ 0.5 T magnetizing field

QUAX R&D experimental set-up

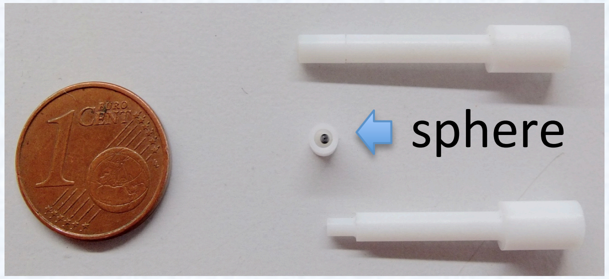


HTE – high temp electronics
LTE – low temp electronics
SO – source generator

Resonant cavity with 5 GaYIG spheres inside

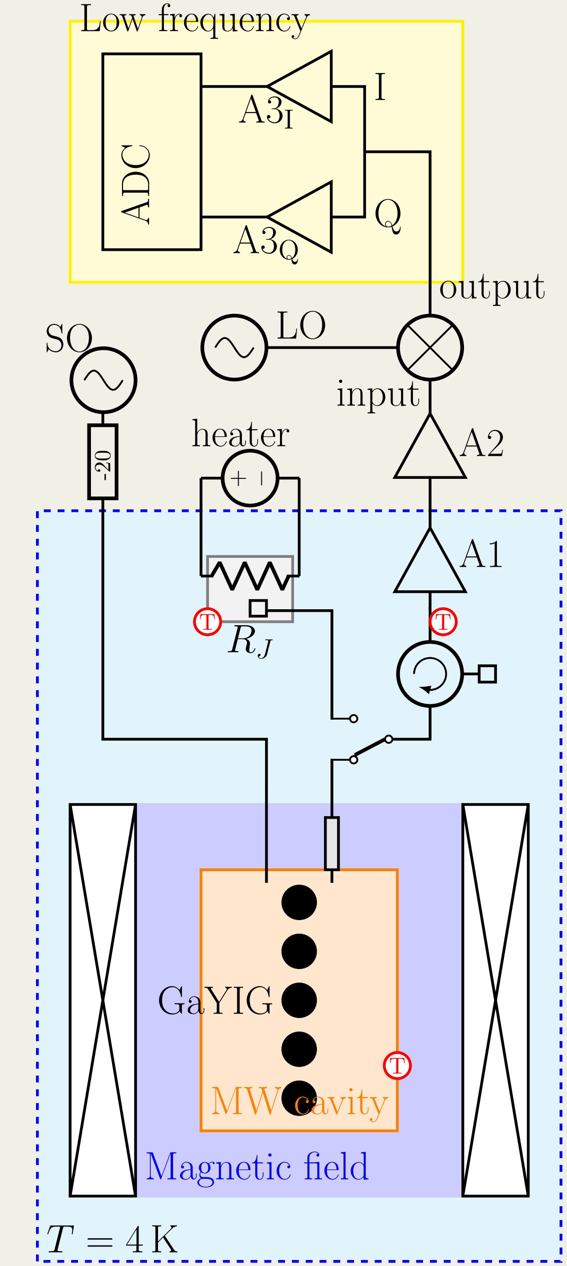


GaYIG holders



Spheres are free to rotate for correct alignment (easy axis || B)

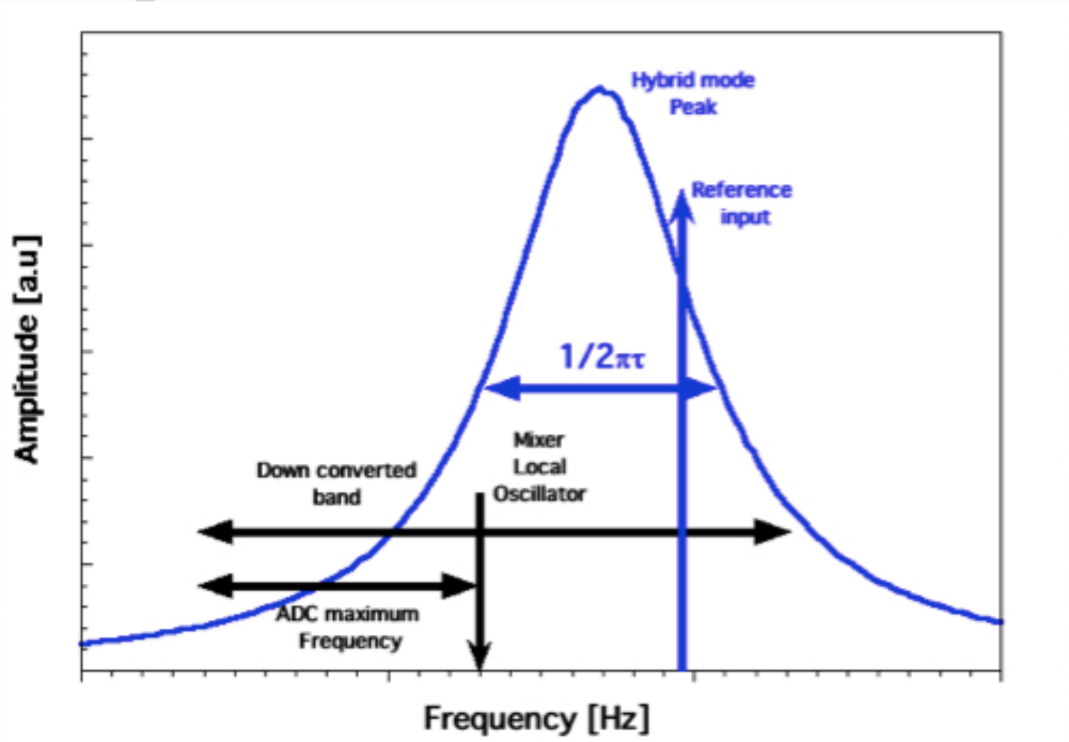
Detection chain



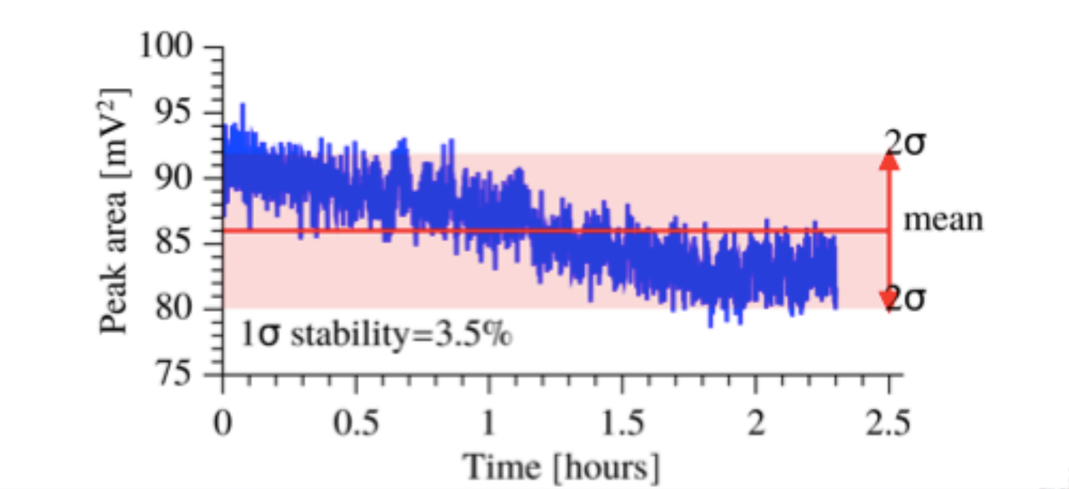
Improved set-up: measurements

- Several 2-3 hours runs performed in 'axion search mode'
- System **noise temperature** $\mathbf{T_n}$ and **gain G** measured for each run
- Hybrid cavity transmission measured to obtain mode resonance frequency f_{h+} and characteristic time τ_{h+}
- Reference signal input inserted @ about f_h
- Down converted data (I and Q channel), with mixer frequency set to $f_h - 0.5$ MHz, acquired with fast ADC
- Data record 5 s long stored for off line analysis

Signal down conversion scheme



Stability of the reference peak during single run



Improved set-up: first results[arXiv:1806.00310]

Typical gain and noise T

- G ≅ 107 dB
- T_n ≅ 9 ÷ 11 K

Down converted data records Fourier transformed and RMS averaged

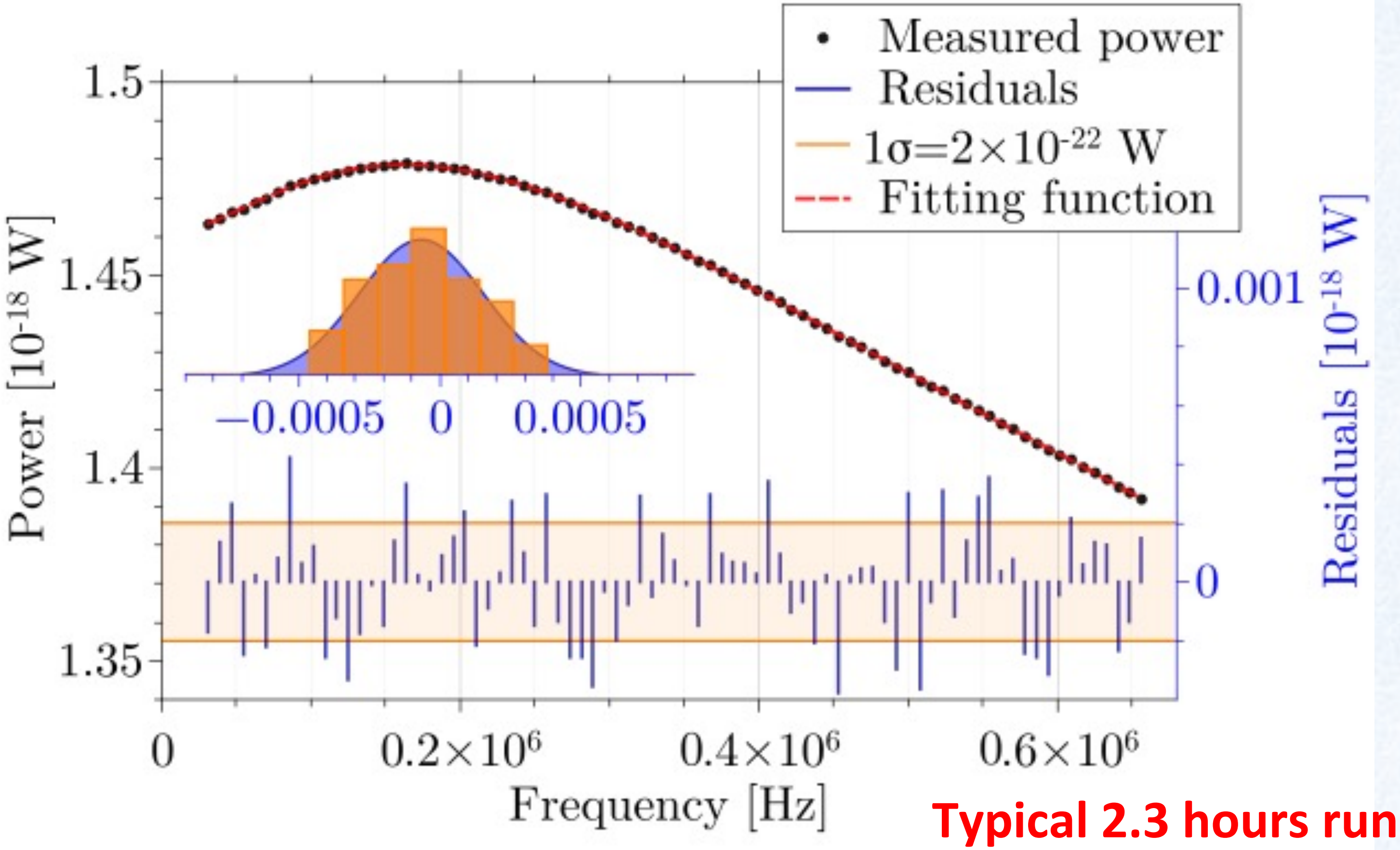
Final spectrum rebinned with 7.8 kHz resolution bandwidth (axion bandwidth)

Look for single bins out of the 'flat' noise

Noise is not 'flat' due to ADC non linear gain

Measured power level @ cavity output

$$P_n = 1.65\times 10^{-18}\left(\frac{T_c+T_n}{5.2\,\mathrm{K}+10.1\,\mathrm{K}}\right)\left(\frac{\Delta f}{7.8\,\mathrm{kHz}}\right)\mathrm{W}$$



Typical 2.3 hours run

Improved set-up: noise levels

Analysing the residuals:

$$< P > = -4.6 \times 10^{-23}\ \mathrm{W} \qquad \sigma_P = 2.2 \times 10^{-22}\ \mathrm{W}$$

The standard deviation is compatible with the value coming from Dicke radiometer equation, that sets the maximum sensitivity for a thermal limited power measurement with integration time t

$$\sigma_P = k_B T \sqrt{\frac{\Delta f}{t}} = 2.1 \times 10^{-22} \sqrt{\left(\frac{\Delta f}{7.8\,\mathrm{kHz}}\right)\left(\frac{8400\,\mathrm{s}}{t}\right)}\,\mathrm{W},$$

This values can then be converted in equivalent magnetic field

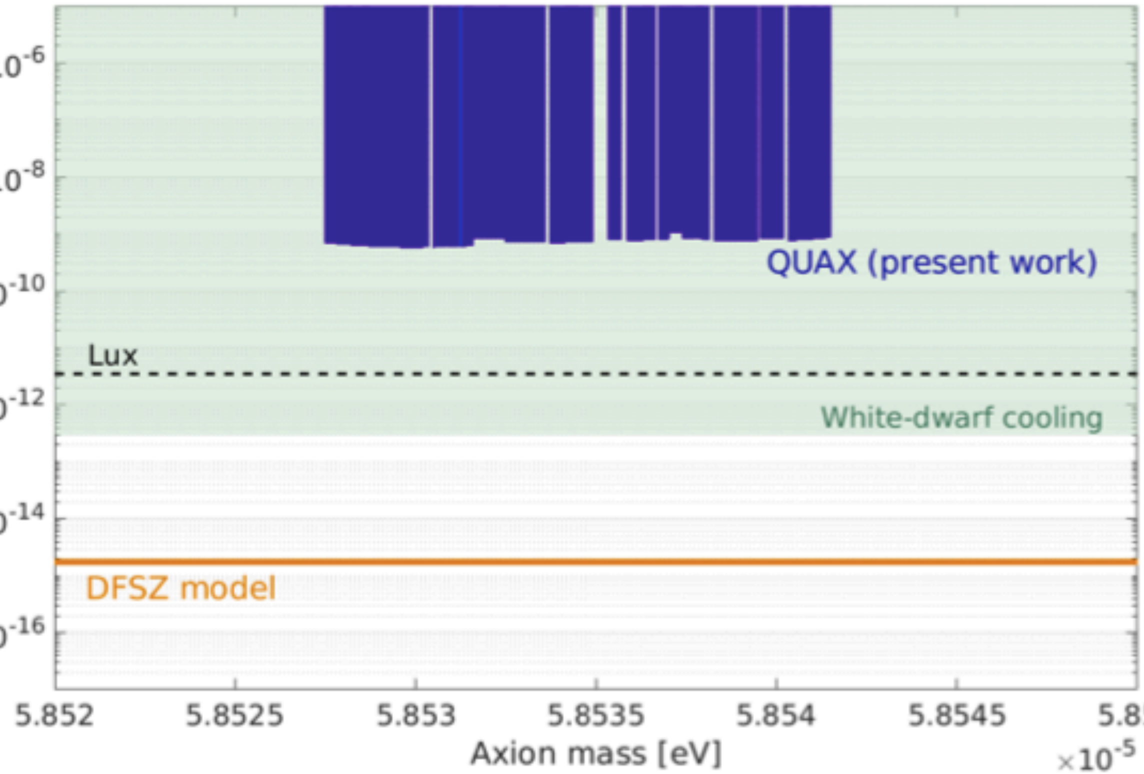
$$B_a = \left(\frac{P_{\mathrm{out}} = 2\sigma'_P}{2\pi\gamma\mu_B n_S f_a \tau_h V_s}\right)^{1/2} = 3.7 \times 10^{-17} \sqrt{\left(\frac{2.13 \cdot 10^{28}/\mathrm{m}^3}{n_S}\right)\left(\frac{14\,\mathrm{GHz}}{f_a}\right)\left(\frac{0.1\,\mu\mathrm{s}}{\tau_+}\right)\left(\frac{2.6\,\mathrm{mm}^3}{V_s}\right)}\,\mathrm{T}.$$

The magnetic field is directly related to the axion coupling. We have seen that sensitivity scales exactly with $t^{1/4}$ as expected up to 6 hours. Longer integration time on a single frequency is then not effective. Scanning must be employed to search for larger parameter space.

Current sensitivity

Residual power sensitivity can be recast directly into axion coupling, taking also into account the mode Lorentzian shape

$$g_{aee} > \frac{e}{\pi m_a v_a}\sqrt{\frac{2\sigma'_P}{\mu_B \gamma n_a n_s V_s \tau_+}},$$



First limit in the parameter space $\{m_a, g_{aee}\}$ obtained from an experiment searching for axions as the dominant Dark Matter component of Galactic halo

Sensitivity is still poor but:	This results	QUAX R&D (2019)	QUAX (Goal)
• Material volume	2.6 mm^3	42 mm^3	10^5 mm^3
• System equiv. noise temp.	15 K	0.2 K	counter (T_{eff} <1 mK)
• Relaxation time	0.1 μs	0.3 μs	2 μs

Ultra cryogenic system

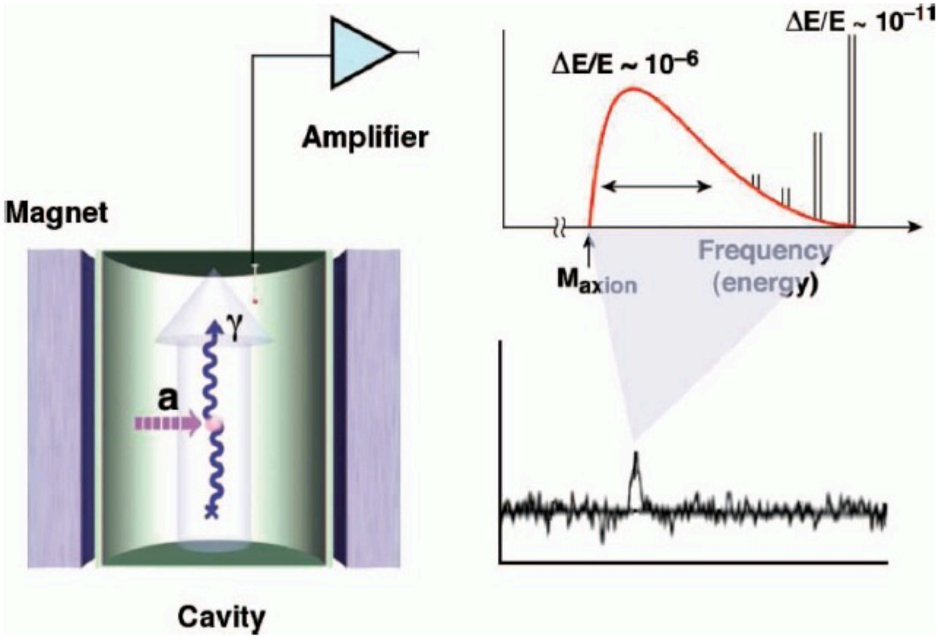
Commissioning of Ultra Cryo System for JPA installation

Start of measurements with ultra low temperature

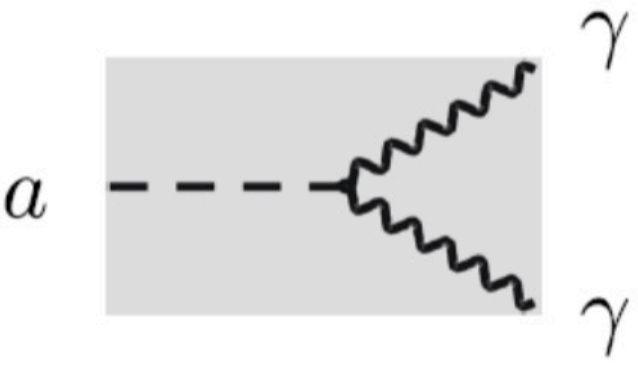
Study of YIG below 1 K

Studying the axion – photon coupling

The same set-up can be operated as a Sikivie's haloscope to study Axion-Photon coupling



$$-\frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$

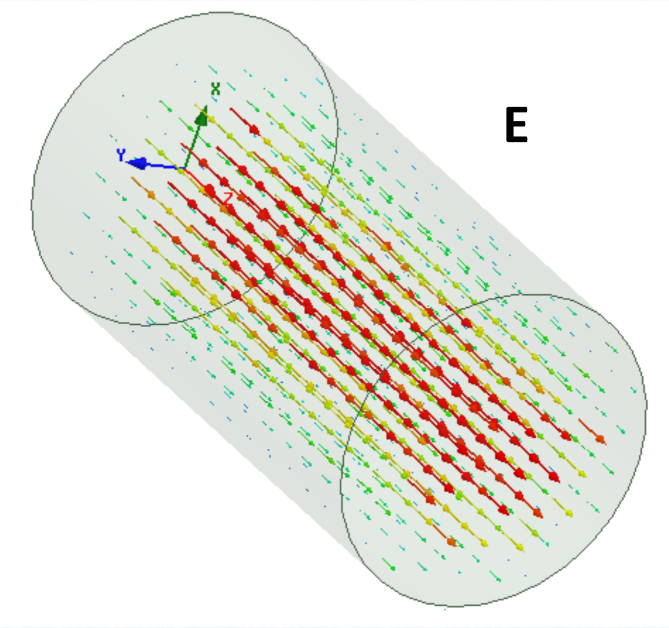


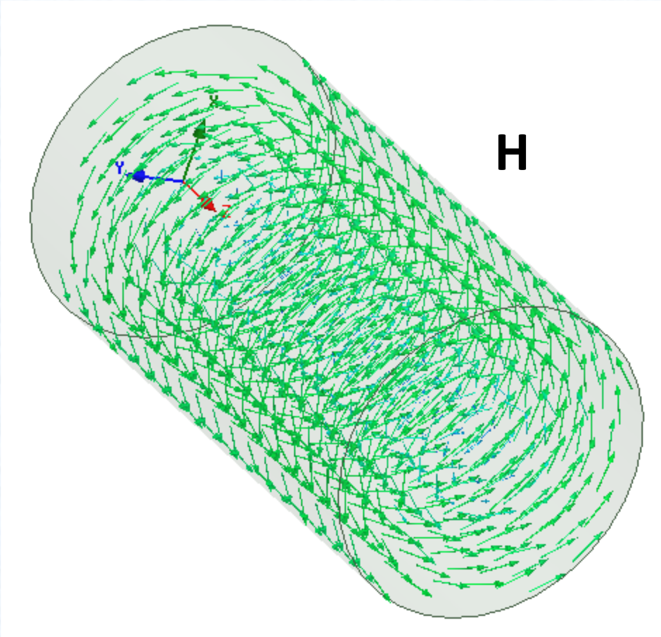
$$P_{\mathrm{axion}} = 1.9\times10^{-22}\mathrm{W}\left(\frac{V}{136\ l}\right)\left(\frac{B}{6.8\ \mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_{\mathrm{a}}}{0.45\ \mathrm{GeV\,cm^{-3}}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\left(\frac{Q}{50{,}000}\right)$$

- Avoid the use of the magnetic material
- Find appropriate resonant cavity mode
- Operate the magnet at highest magnetic field amplitude
- Detection chain is the same

Cavity mode for Axion Photon coupling

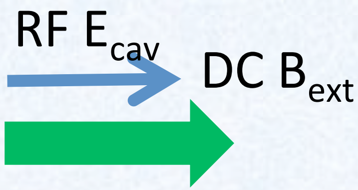
If we have the rf field aligned with the external static field we can probe Primakov effect





TM_{010}

(ADMX-like)


RF E_{cav}

DC B_{ext}

Neglecting the presence of the material and running for the maximum magnetic field

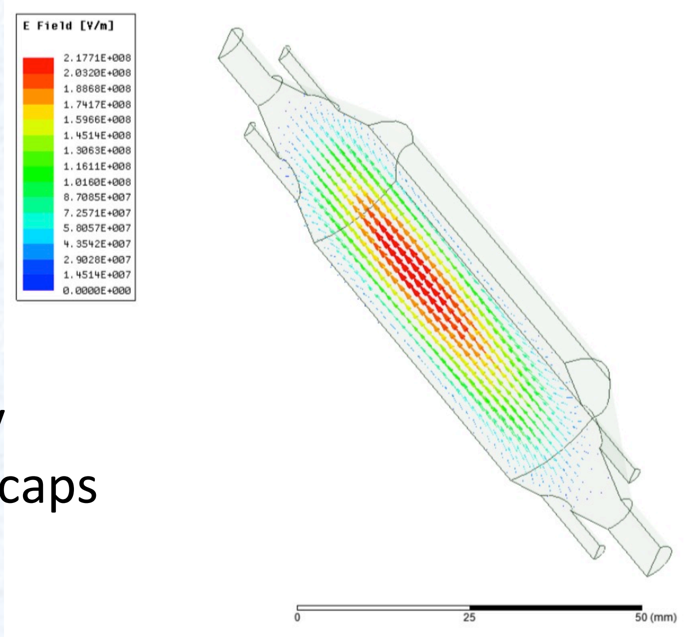
The equivalent rate with QUAX-like system

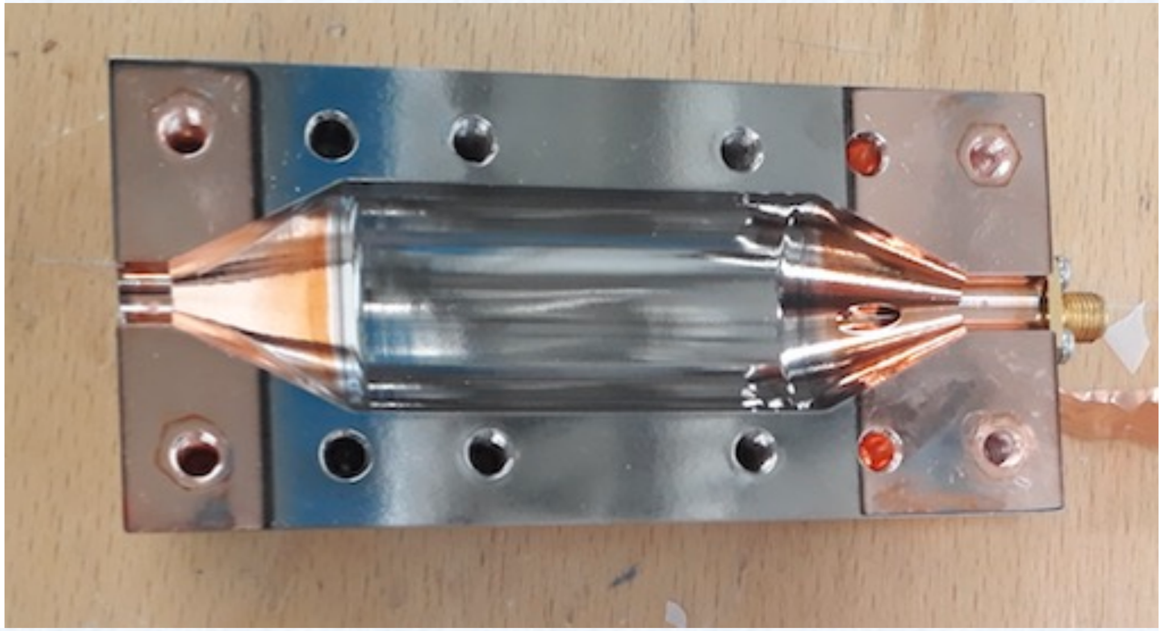
$$R_a^{\gamma} \simeq 10.0 \times 10^{-3}\, C_{nl} \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{V_s}{100\ \mathrm{cm}^3}\right) \times \left(\frac{B_0}{2\,\mathrm{T}}\right)^2 \left(\frac{\tau_{\min}}{2\,\mu\mathrm{s}}\right)\ \mathrm{Hz},$$

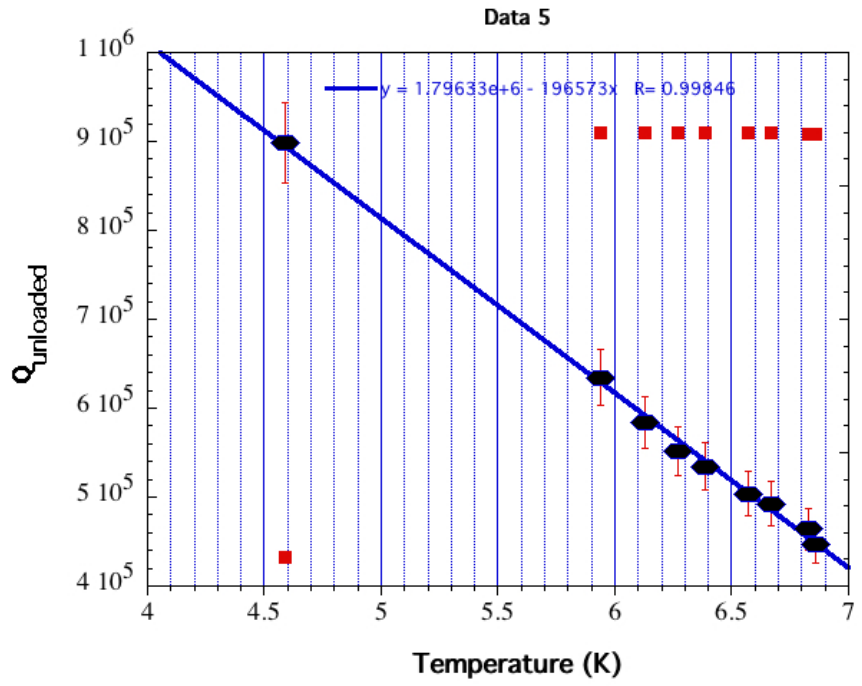
High Q cavity in external field

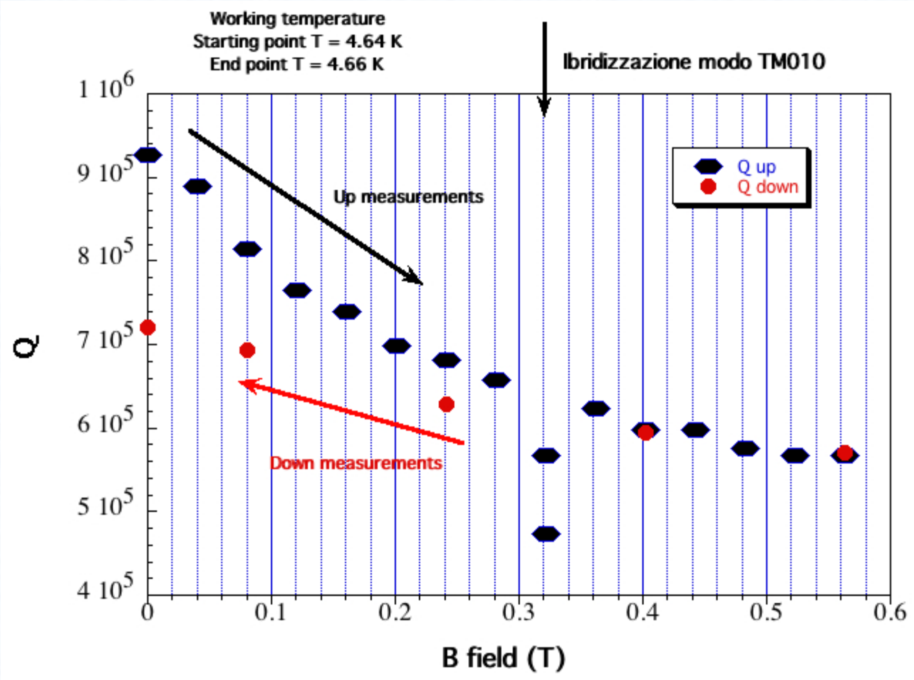
TM010 MODE

Cylindrical cavity
with conical endcaps

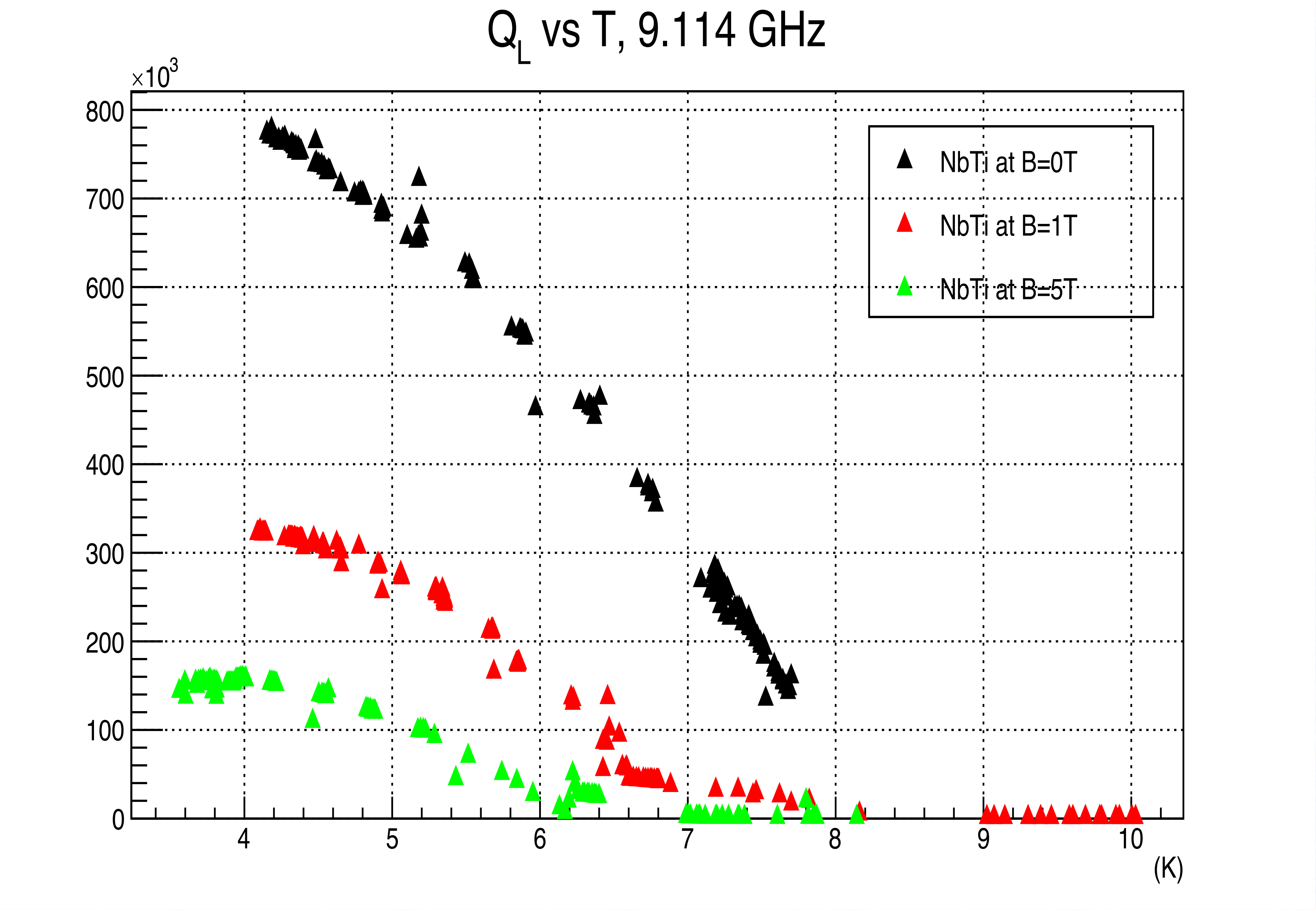




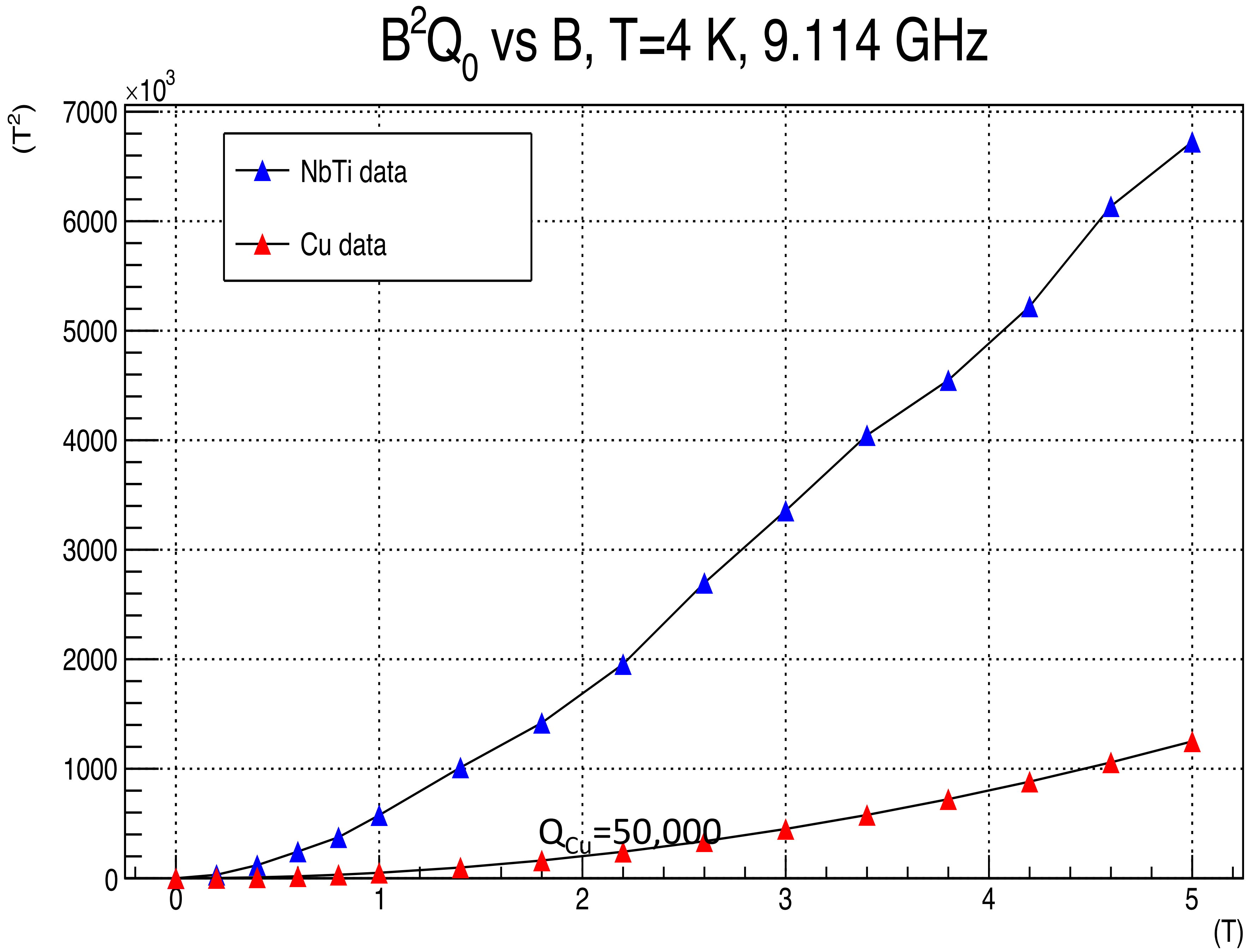




Q_{loaded} vs Temperature and Field

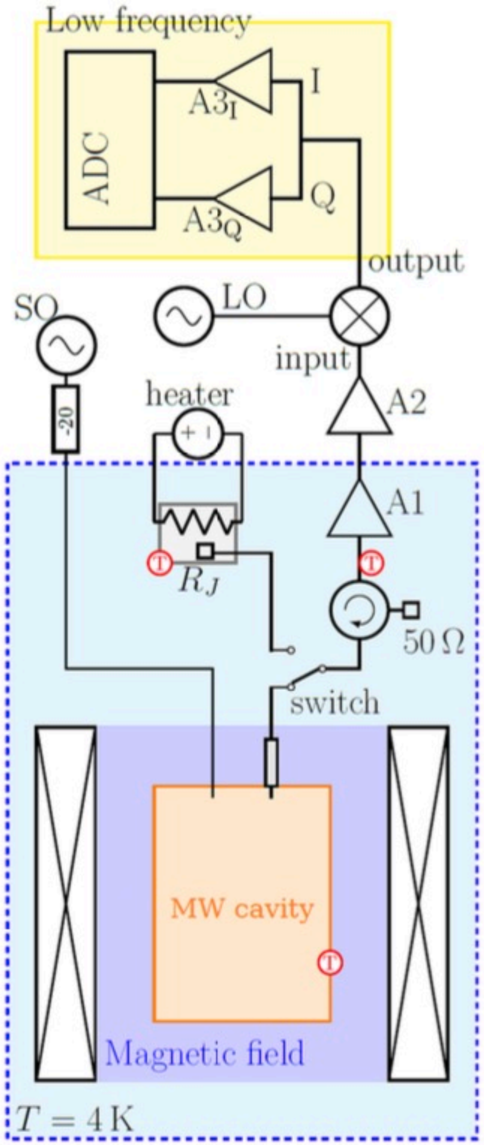


Confronto B^2Q_0 tra NbTi e Cu



First measurement @ 4K

Same set-up, no YIG



TM010 mode @ 9.06 GHz
Magnetic field = 2 T (max safety value)
About 10 minutes run
Detector noise temperature T = 11 K
Loaded Q value in magnetic field = 176 000

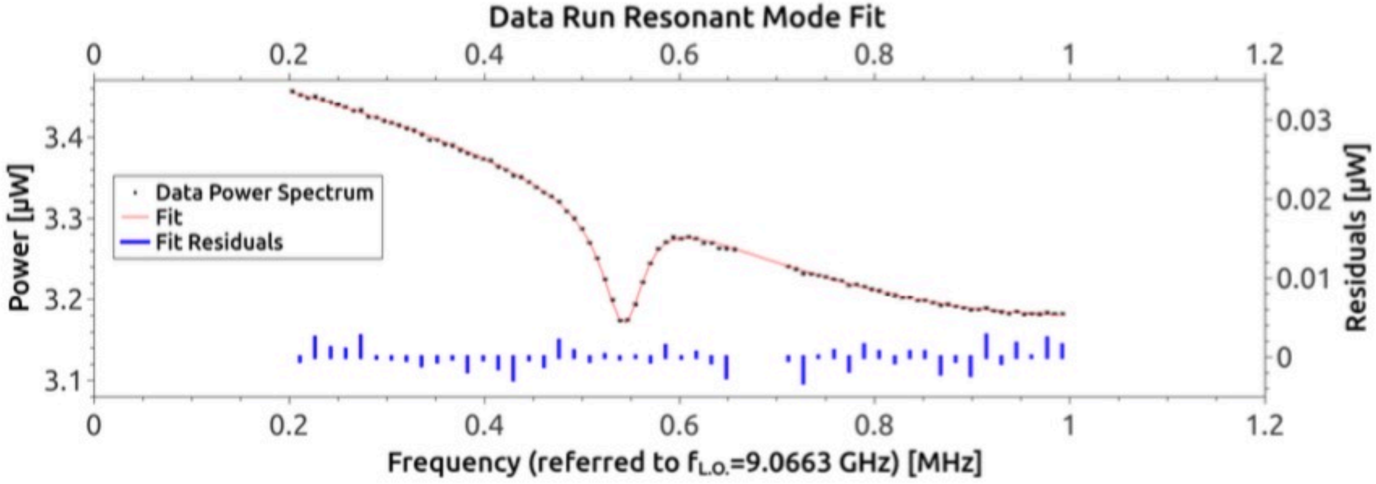


Figura 1.10: Comprehensive fit of our data

Power level @ ADC input, total gain about 126 dB

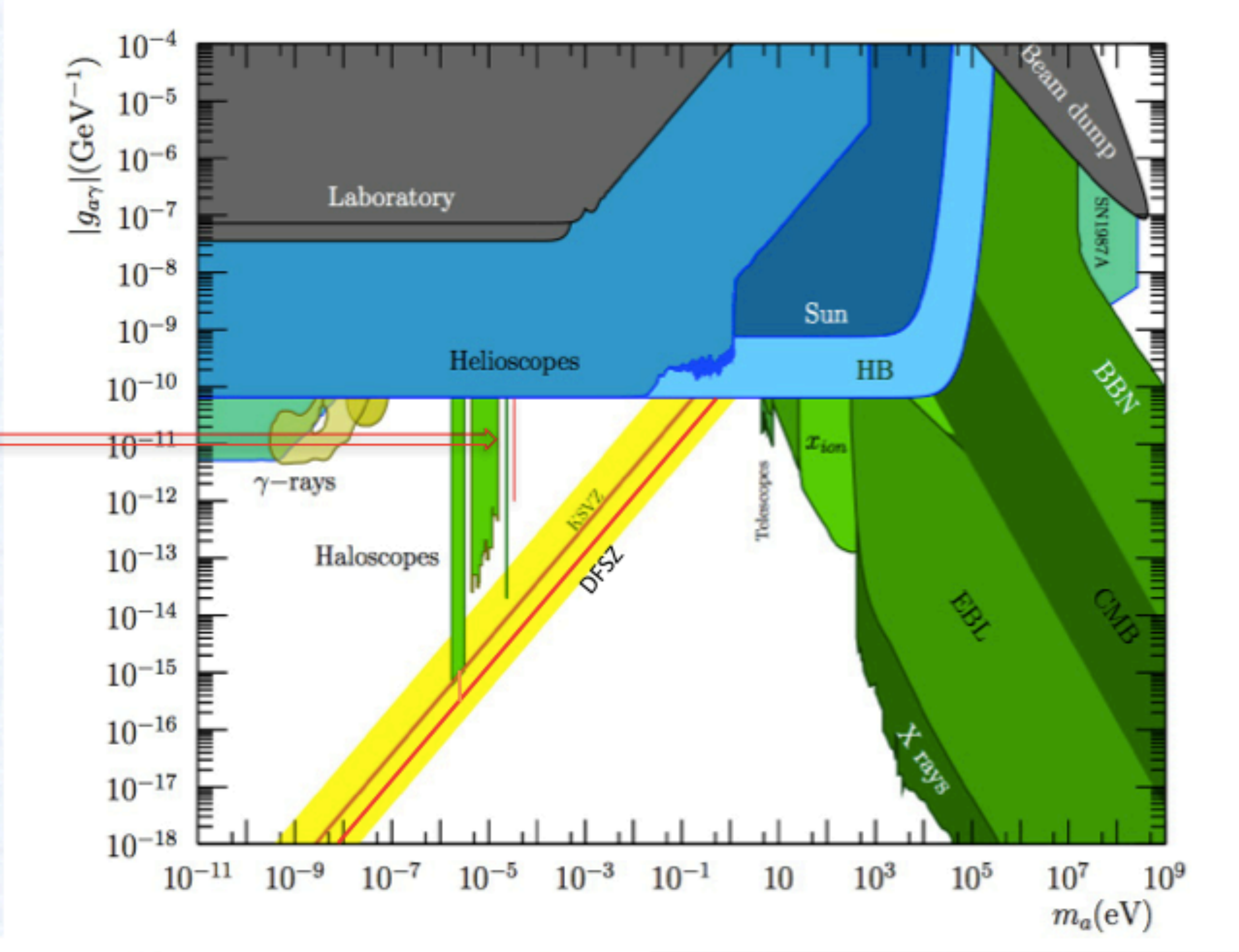
Very preliminary analysis

Where we are

Final sensitivity for excess power

σ_P = 6 x 10^{-22} W

For a bandwidth of 50 kHz,
At about 38 microeV



Expected axion signal

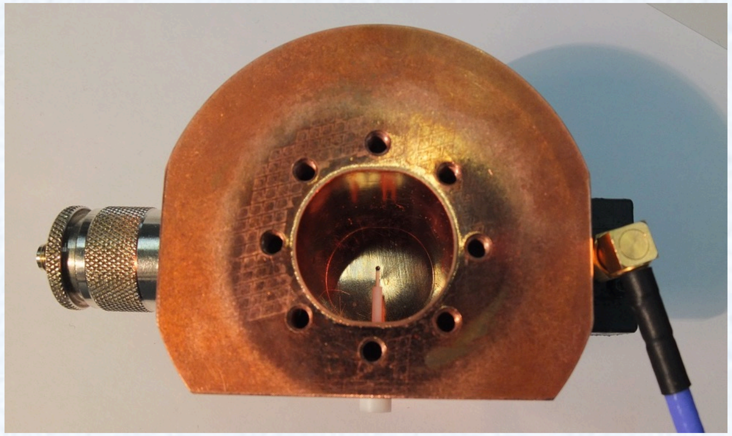
$$P_{axion} = 2.7\cdot 10^{-25}\,W \left(\frac{V}{0.0268\,l}\right)\left(\frac{B}{2\,T}\right)^2\left(\frac{C}{0.69}\right)\left(\frac{g_\gamma}{-0.97}\right)^2\cdot$$

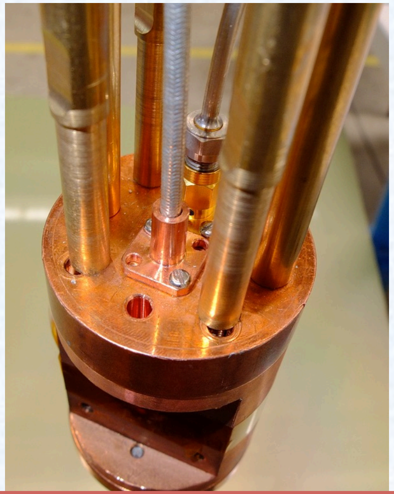
$$\cdot\left(\frac{\rho_a}{0.45\,GeV\,cm^{-3}}\right)\left(\frac{f_c}{9.06685\,GHz}\right)\left(\frac{Q}{176000}\right),$$

PRELIMINARY

The R&D phase of QUAX will last 1 more year.

Funding agency of QUAX:
INFN – CNS2– Italy



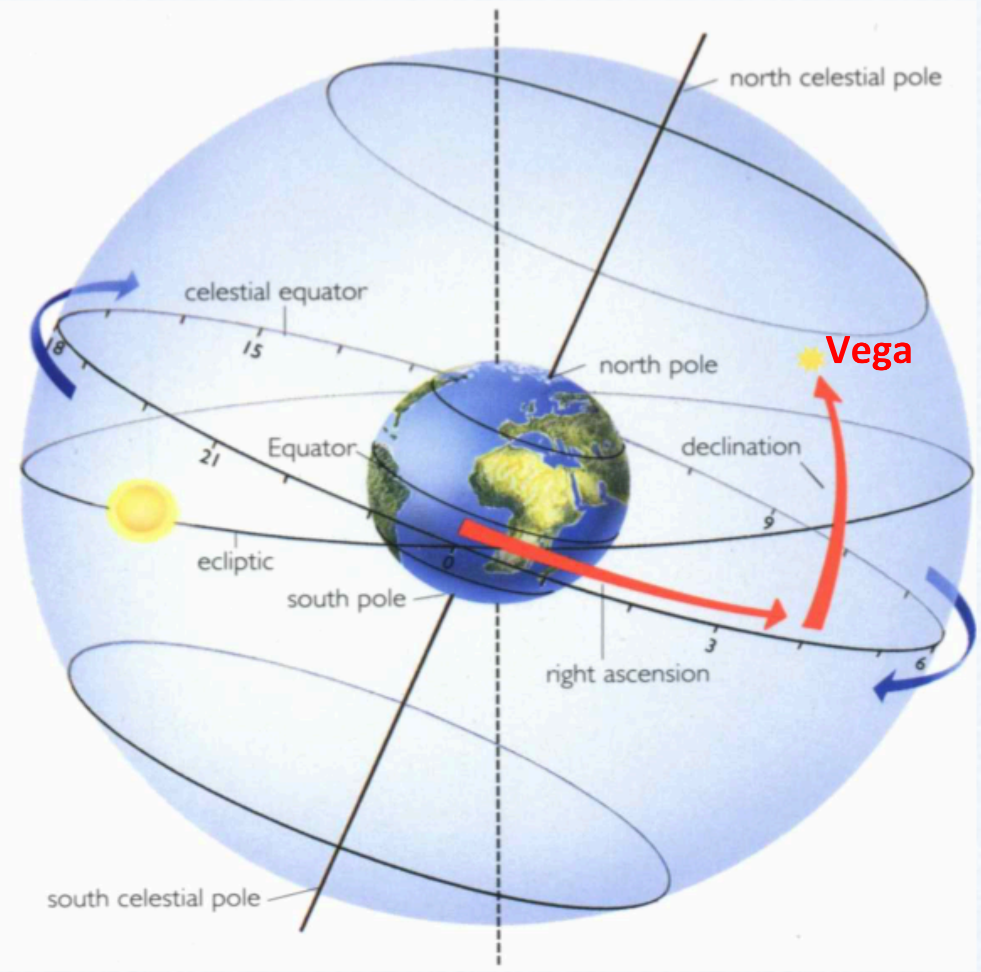


G. Carugno (PI), C. Braggio, S. Gallo, L. Taffarello, A.Pepato – Padova
N. Crescini, A. Ortolan, R. Pengo, A. Lombardi, G. Ruoso – LNL
C. Gatti, D. Alesini, D. Di Gioacchino, G. Lamanna,A.Rettaroli, C.Ligi, S. Tocci – LNF
U. Gambardella, G. Iannone, S. Pagano, A. Saggese – Salerno
P. Falferi, R. Mezzena – Trento; C. Speake - Birmingham

Thanks for your attention

- Back up slides

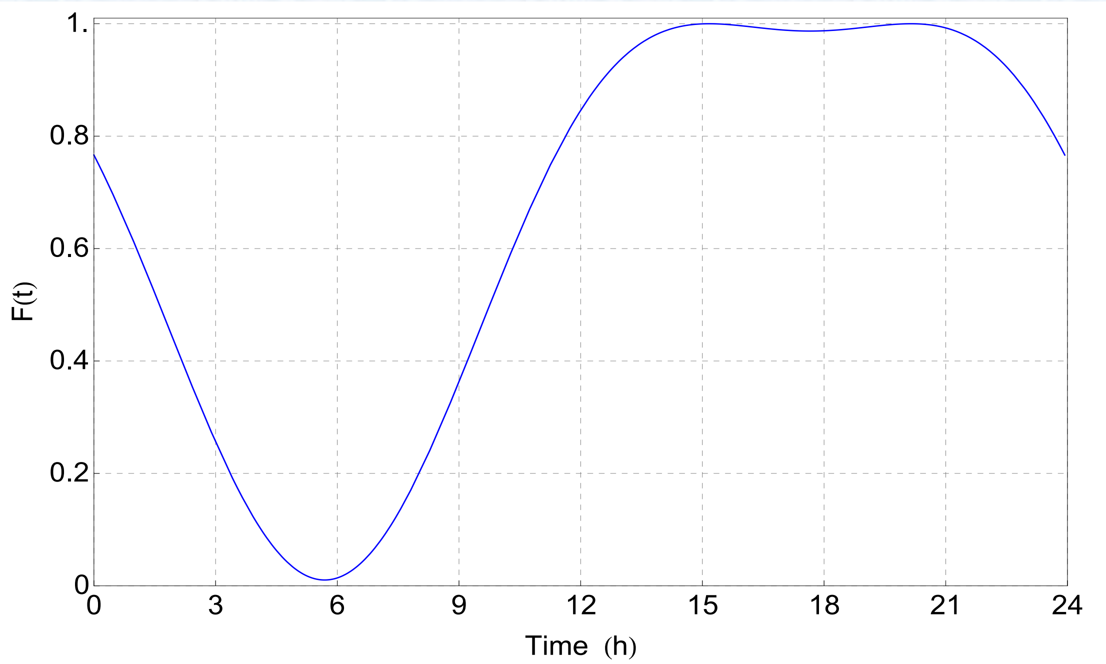
Polarized matter: directional DM search



Due to Earth rotation, the direction of the static magnetic field $\mathbf{B}_0$ changes with respect to the direction of the axion wind (Vega in Cygnus)

e.g. QUAX located @Legnaro (PD)
$\mathbf{B}_0$ in the local horizontal plane and oriented N-S (the local meridian)

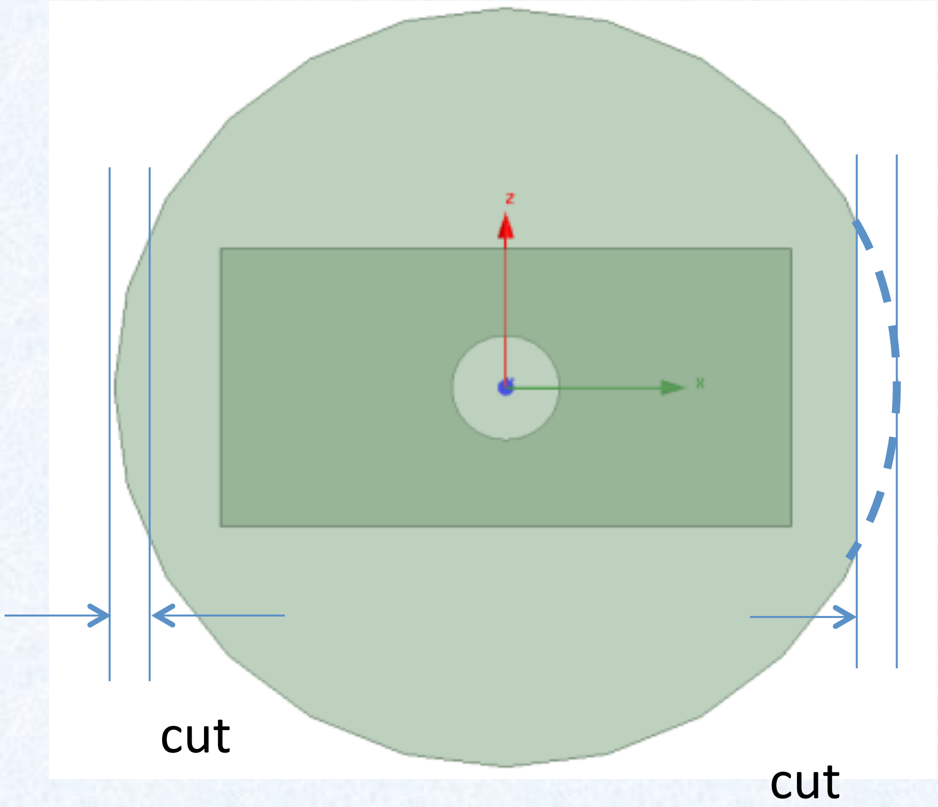
QUAX Pattern



Strong modulation (up to 100%)!
Not due to seasonal or Earth rotation Doppler effect (few %) but to relative direction change of magnetic field respect to axion wind

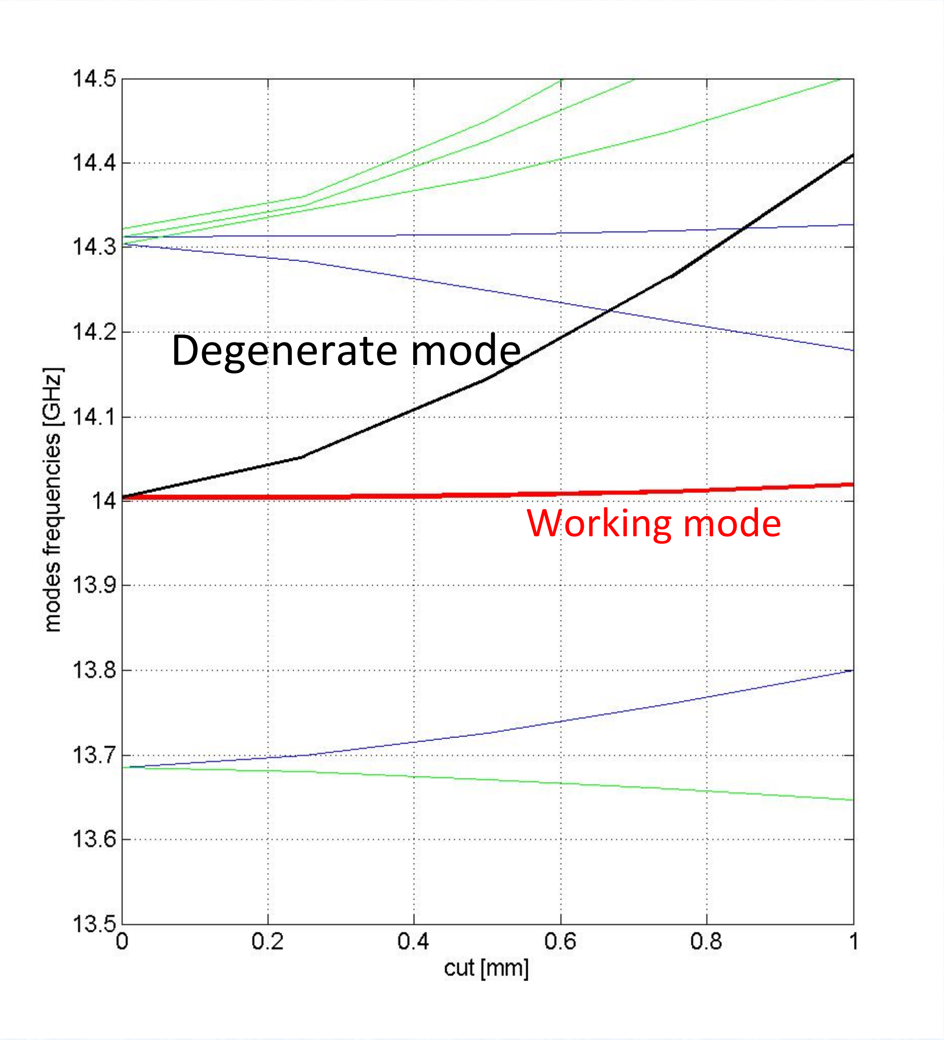
Microwave cavity: degeneracy removal

By placing a symmetric cut (left – right) it is possible to remove the mode degeneracy while keeping all the other modes well separated in frequency.



Simulations for a cavity with diameter 26 mm

Mode resonance frequencies



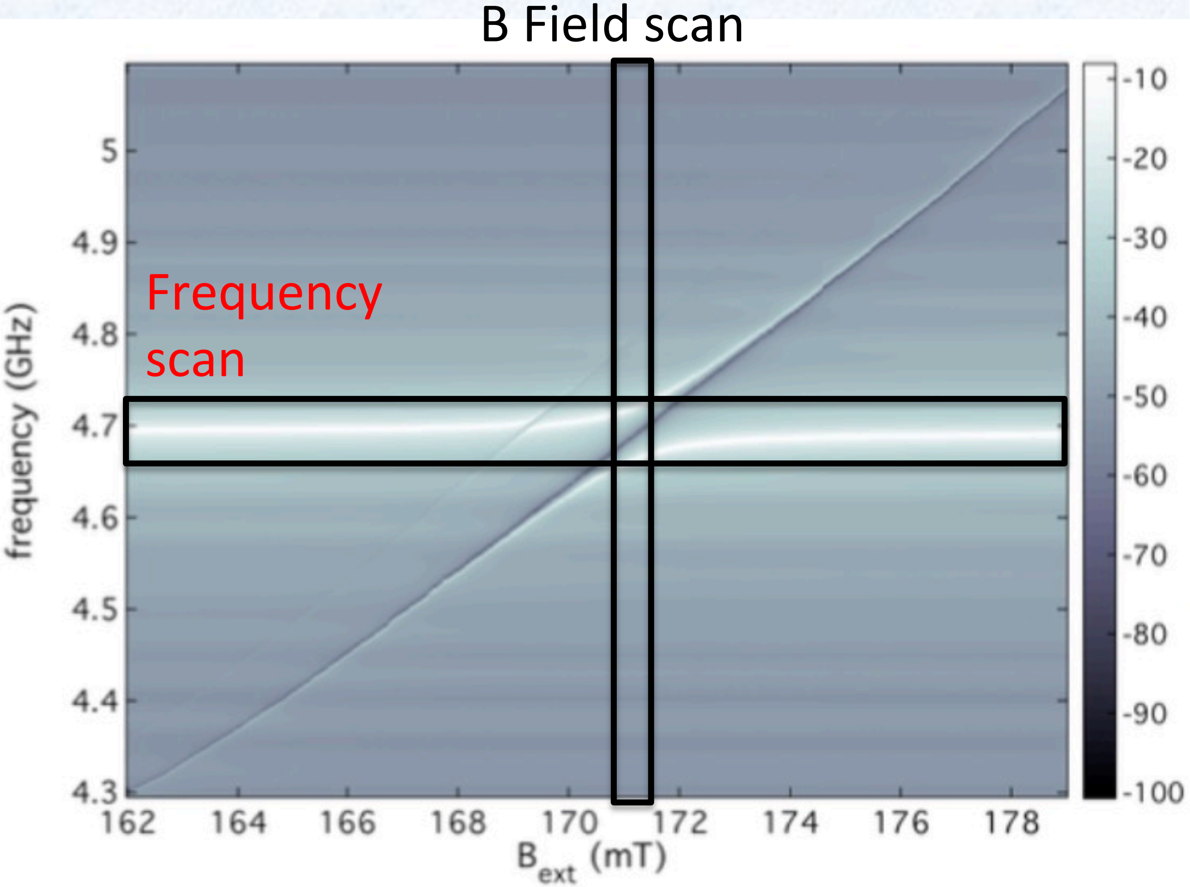
Small frequency tuning

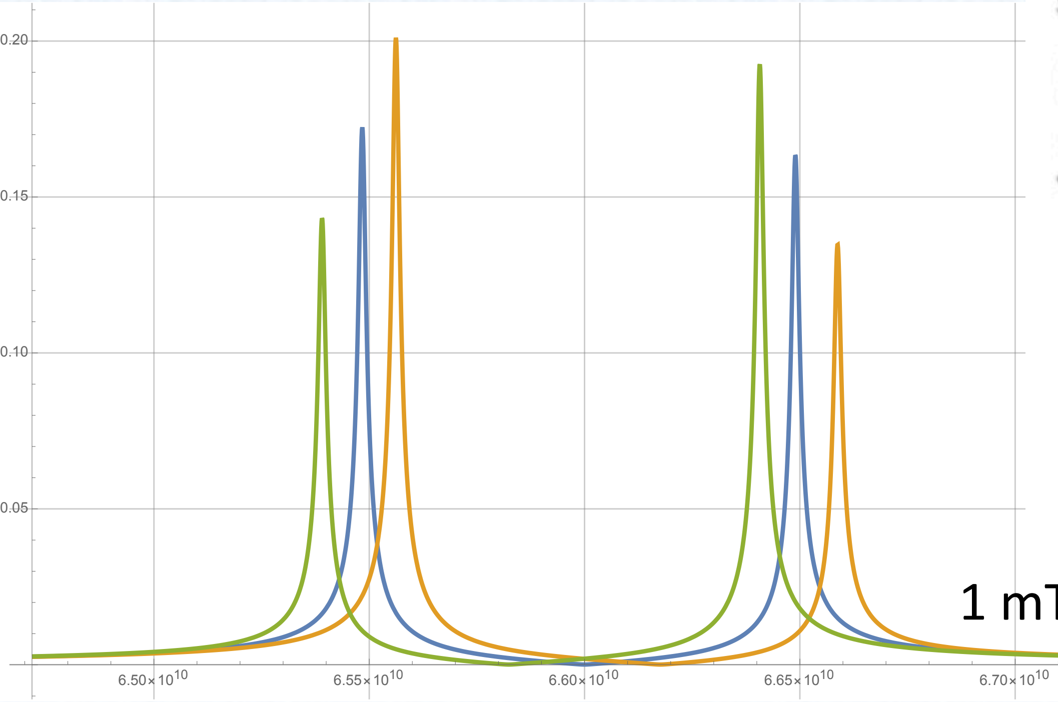
In order to **scan different mass values**, a frequency tuning of the system must be present

With the QUAX apparatus this can be easily achieved by changing the magnetizing field.

The minimum separation of the peaks is

$$g_m = \gamma \sqrt{\mu_0 \hbar \omega_m n_S V_S / V_c}$$





1 mT difference

Check coupling with material