Detection of cosmological axions QUAX R&D

QUAX (lat/gr): QUaerere Αξιον
or (En): QUest for Axions

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on behalf of the QUAX Collaboration

Axion (&) Cosmology

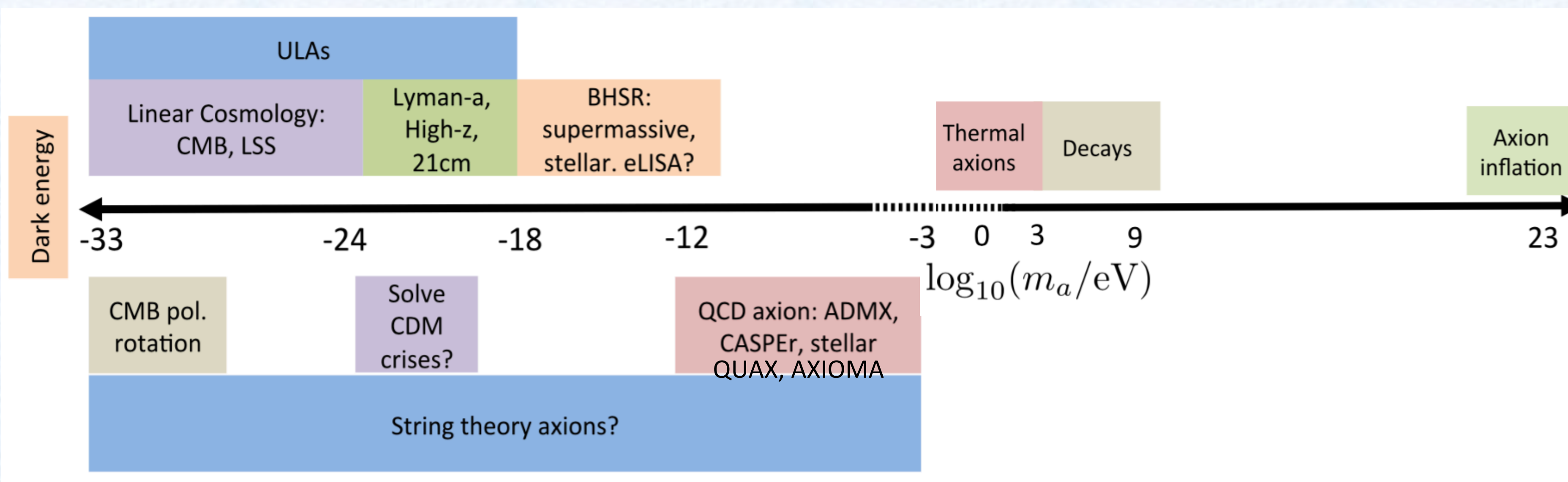
D.J.E. Marsh / Physics Reports **643** (2016) 1–79

"Precision Cosmology":

- Cosmic Microwave Background (CMB)
- Large Scale Structure (LSS),
- Galaxy formation (local Universe, high redshift, epoch of reionization (EOR)).

''Axion'' can take on a variety of meanings:

- QCD axion: the Peccei–Quinn solution to the strong-CP problem $m_a \alpha\ 1/f_a$.
- ALP: any pseudoscalar Goldstone bosons of spontaneously broken global chiral symmetries, giving a two parameter model (m_a,f_a)
- ST&SUGRA: either matter fields or pseudoscalar fields associated to the geometry of compact spatial dimensions



QCD axion couplings to the standard model

For the purpose of our discussion, the relevant interactions of the axion are described by an effective Lagrangian

Almost model independent prediction

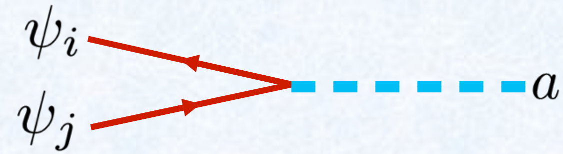
$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\frac{f_\pi m_\pi}{f_a} = \left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right) 0.60\,\mathrm{meV}$$

- Free axion:

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a\,\partial^\mu a + \frac{1}{2}m_a^2 a^2$$

- Interactions with matter:

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

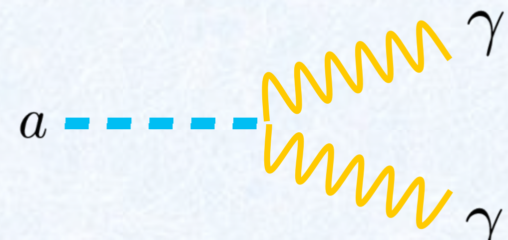


- Interaction with electromagnetic field:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{\alpha}{2\pi} f_a^{-1} c_{a\gamma\gamma}\vec{E}\cdot\vec{B}\,a$$

$$c_{a\gamma\gamma} = N\left(\frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_u + m_d}\right) = O(1)$$

-1.92 (KSVZ)   0.75 (DFSZ)



Primakoff effect: Sikivie proposal to detect the “invisible” axion. Macroscopic B-field can provide a large coherent transition rate over a big volume (low-mass axions)

If axions exist, they are very light and VERY weakly interacting ($g_{aj} \alpha\ 1/f_a$)!!!

Interaction of DFSZ axion and electron spin

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

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

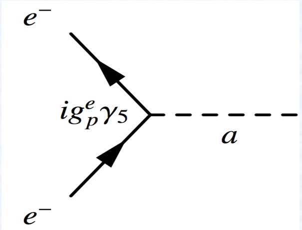
$$g_p \cong \frac{m_e}{3 f_a} \cos^2 \beta$$

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

- In DFSZ axion model, coupling with non relativistic (v/c<<1) electron interaction energy and EOM read

$$\mathrm{H}_{\mathrm{int}} = \frac{g_{aee}}{f_a} \left(\vec{\nabla} a \cdot \vec{\sigma} + \partial_t a \frac{\vec{p} \cdot \vec{\sigma}}{m_e} \right)$$

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



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

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

Note: Frequency of the effective magnetic field proportional to axion mass
Amplitude of the effective magnetic field proportional to DM density

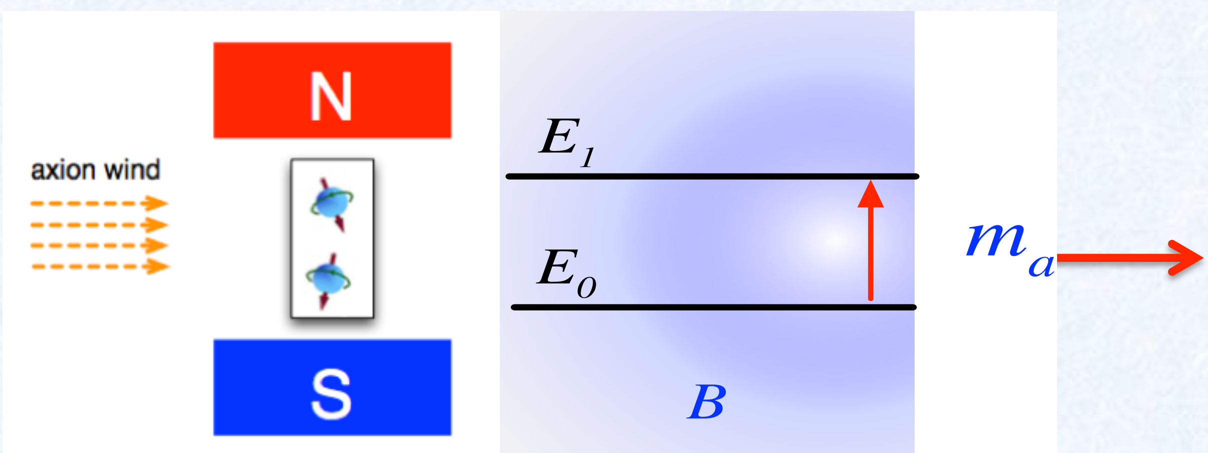
QUAX detector (Haloscope)

- The idea for the axion detection is to exploit Larmor precession of a magnetized sample (YIG or other ferrimagnetic and paramagnetic materials)
- An external polarizing magnetic field $\mathbf{B_0}$ defines the Larmor frequency i.e. $\mathbf{B_0}$ tunes the apparatus with the axion mass: **the magnetized sampled behaves as a rf receiver**

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

- **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** **and the axion gradient causes the spin flip**
- The equivalent magnetic (rf) field with amplitude proportional to ρ_{DM} and v_E, (oriented in the direction of the axion gradient) excites **spin transitions E_1-E_0≈m_a c^2 in the magnetic samples**

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

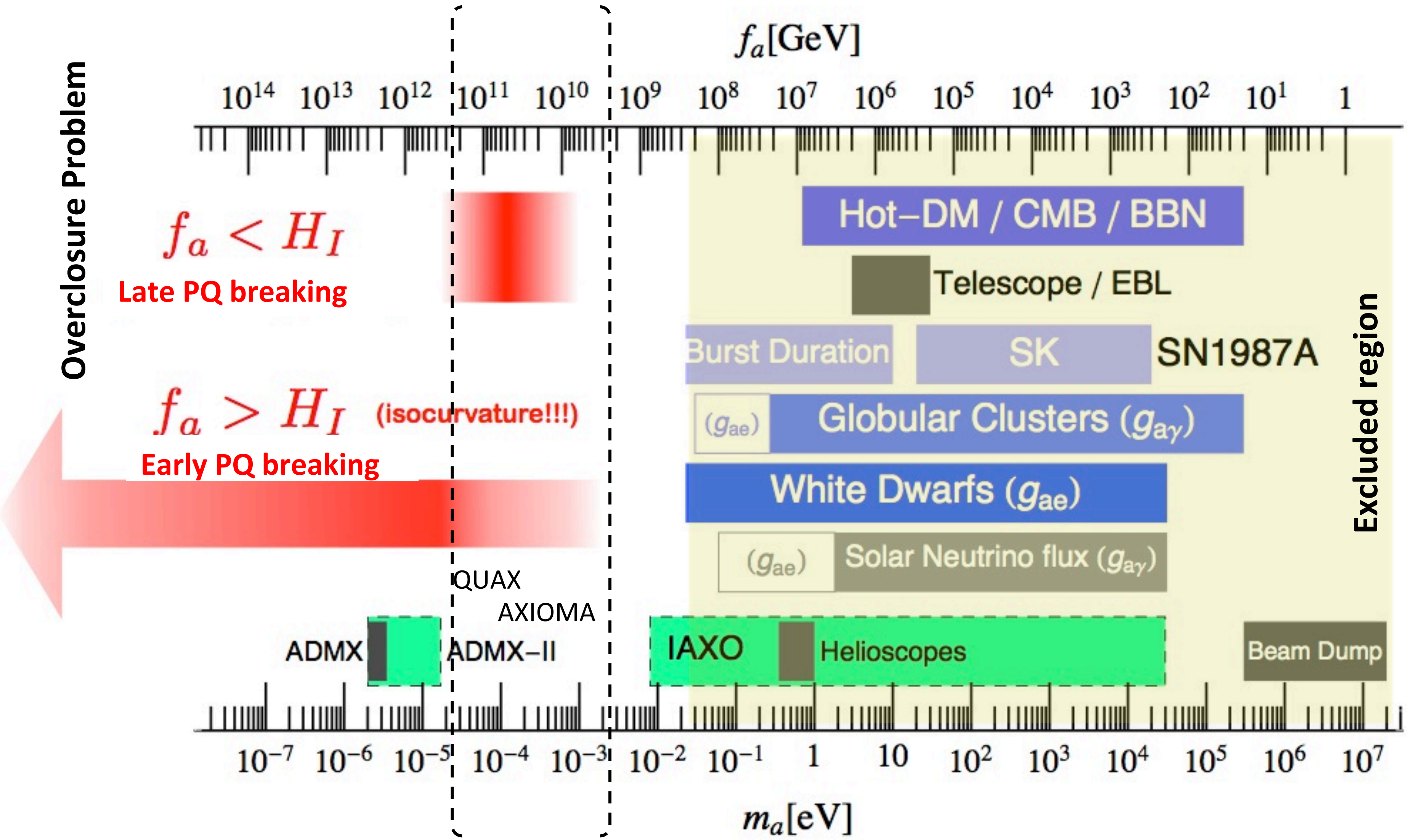


Detectable signal: magnetization changes

[R. Barbieri, et al. Phys. Lett. **B 226**, 357 (1989); QUAX coll Phys. Dark Univ. **15** (2017)]

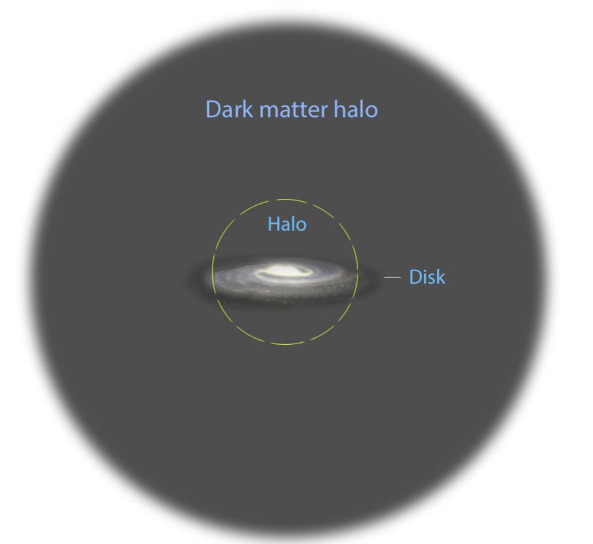
What we know from Cosmology, Astrophysics and QCD@FT

"Calculation of the axion mass based on high-temperature lattice quantum chromodynamics" [Nature **539** 69 (2016)] **(50÷1500 µeV -> 12÷363 GHz)**



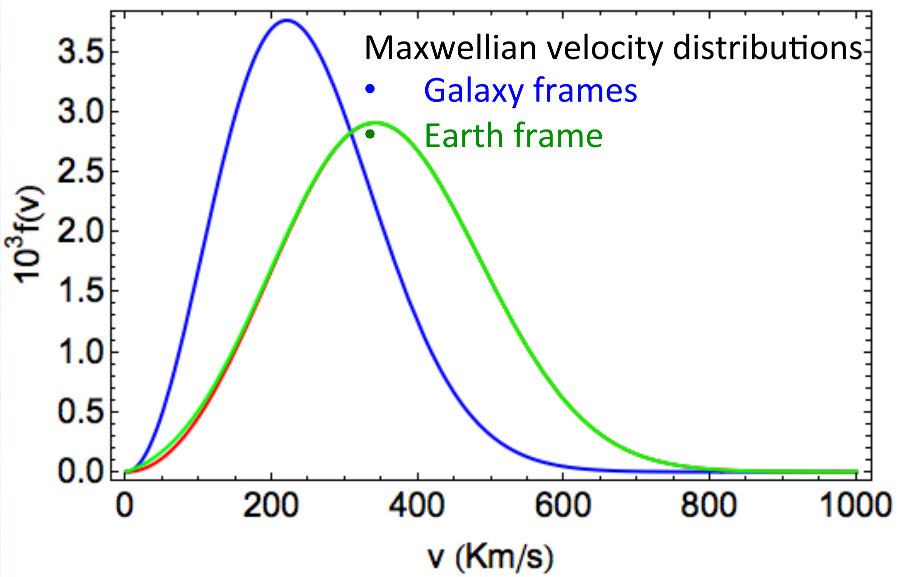
Standard Halo Model for ρ_{DM} and $f(v_a)$

Standard Halo Model: Isothermal, isotropic Maxwell-Boltzmann Distribution of DM assuming ρ_{DM} =0.3 Gev/cm^3



Milky Way model

$$f(v) = 4\pi \left(\frac{\beta}{\pi}\right)^{3/2} v^2 \exp(-\beta v^2)$$



Observed axion velocity $\mathbf{v}_a = \mathbf{v} - \mathbf{v}_E$, where the Earth velocity $\mathbf{v}_E = \mathbf{v}_{sun} + \mathbf{v}_{orb}$

$$f(v_a) = 2\left(\frac{\beta}{\pi}\right)^{1/2} \frac{v_a}{v_E} \exp(-\beta v_a^2 - \beta v_E^2) \sinh(2\beta v_E v_a)$$
$$\simeq 2\left(\frac{\beta}{\pi}\right)^{1/2} \frac{v_a}{v_E} \exp(-\beta(v_a - v_E)^2)$$

Expected signal from galactic halo axions

$$a(t,\vec{x}) = \iiint d^3k \; e^{i[\omega(\vec{k})t + \vec{k}\cdot\vec{x}]} a(\vec{k})$$

$$\langle a(\vec{k}) \rangle = 0$$

$$\langle a(\vec{k}) a(\vec{k}')^* \rangle = f(|\vec{k}|)\delta^3(\vec{k} - \vec{k}')$$

Homogeneous and isotropic maxwellian distribution

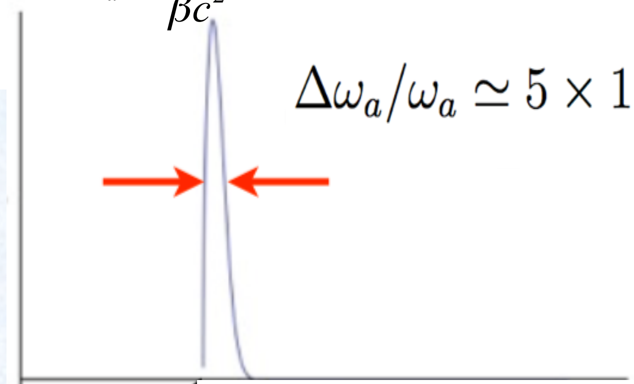
Axion dispersion relations

$$E = \hbar\omega = m_a c^2 + \frac{1}{2} m_a v_a^2$$

$$\vec{p} = \hbar\vec{k} = m_a \vec{v}_a$$

$$P_a(\omega) \propto \left(\frac{|\omega| - \omega_a}{\Delta\omega_a}\right)^{1/2} \exp\left(\frac{|\omega| - \omega_a}{\Delta\omega_a}\right) \theta(|\omega| - \omega_a)$$

$$\Delta\omega_a = \frac{\omega_a}{\beta c^2}$$



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

m_a

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

Coherence time

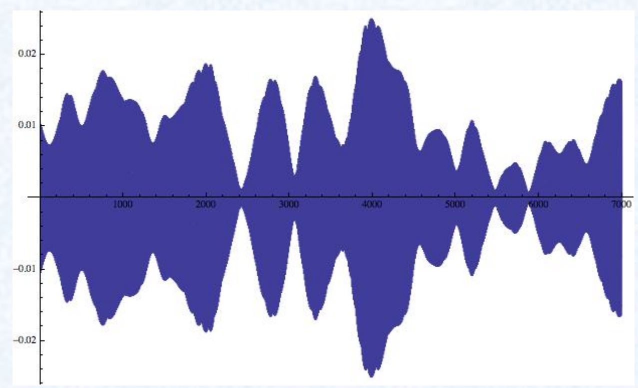
$$\tau_{\nabla a} = 0.68\,\tau_a \cong 34\ \mu s \left(\frac{10^{-4}\, eV}{m_a}\right)$$

Correlation length

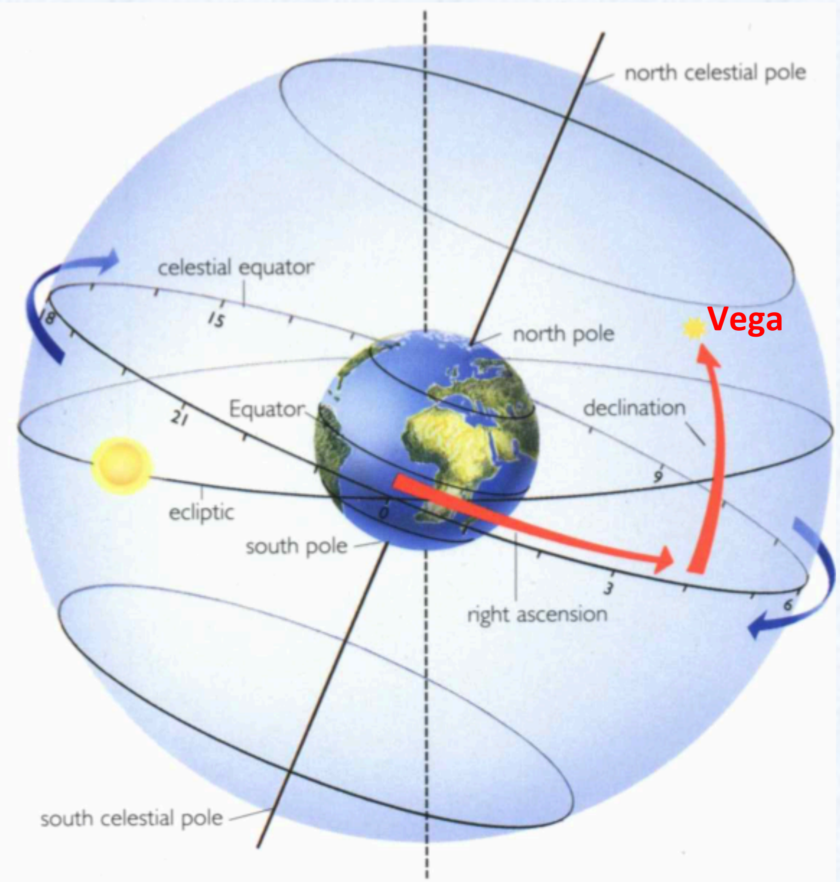
$$\lambda_{\nabla a} = 0.74\,\lambda_a \cong 10.2\ m \left(\frac{10^{-4}\, eV}{m_a}\right)$$

Coherence time is set by power spectrum linewidth:

For optimal SNR, relaxation times of magnetized materials must not exceed coherence time



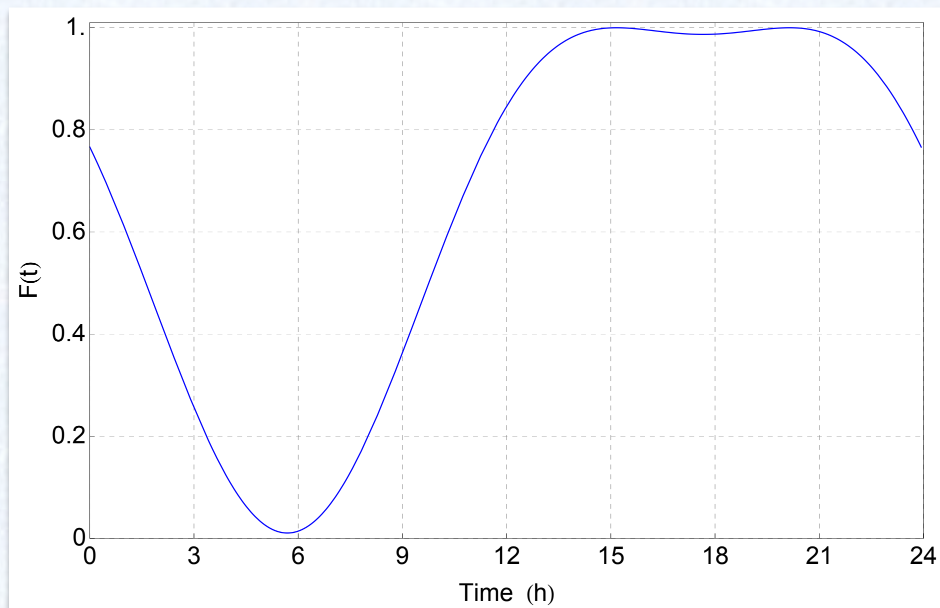
QUAX polarized target and axion gradient anisotropy: Strong Directional Pattern



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%)!

Doppler effect is not relevant (few %):

- 50 KHz/year
- 1 KHz/day

Experimental parameters of QUAX for the hunt of QCD axions

Axion Masses

$$50\,\mu eV \leq m_a \leq 1.5\,meV$$

Equivalent RF magnetic field

$$10^{-23}\,Tesla \leq B_a \leq 10^{-21}\,Tesla$$

Working frequency

$$12\,GHz \leq \nu \leq 300\,GHz$$

Electron Larmor Frequency

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

$$0.4\,Tesla \leq B_0 \leq 12\,Tesla$$

Magnetizing field

Measurement at the quantum limit:
Thermal fluctuations below quantum fluctuations

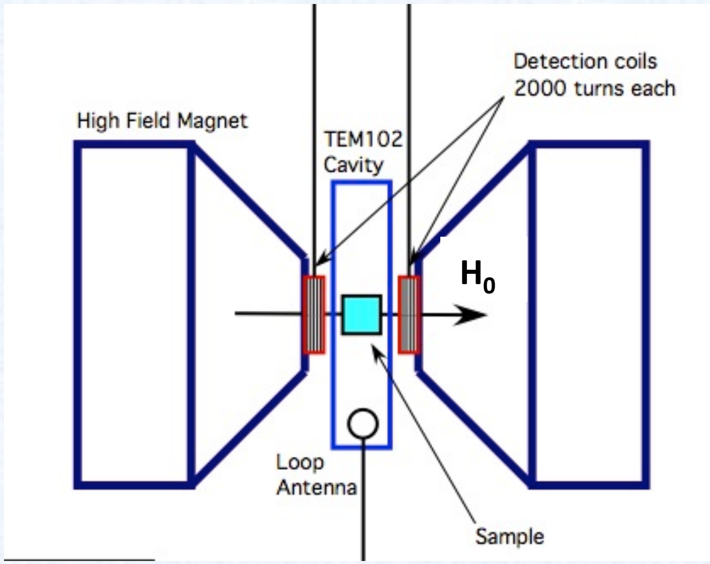
$$T \leq \frac{\mu_b B_0}{K_b} \quad and \quad T \leq \frac{\hbar\nu}{K_b}$$

$$100\,mK \leq T \leq 1\,K$$

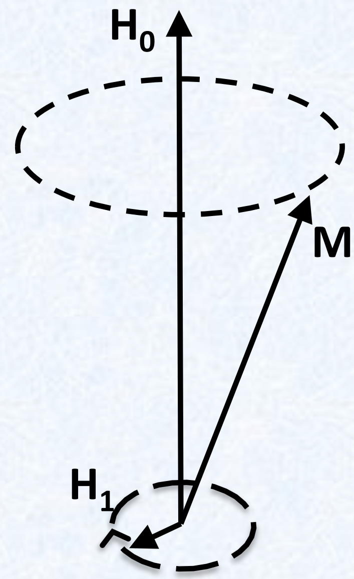
Working temperature

Experimental technique of QUAX: Electron Spin Resonance

Electron Spin Resonance (ESR or EPR) in 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 transitions at Larmor resonance ν_L



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

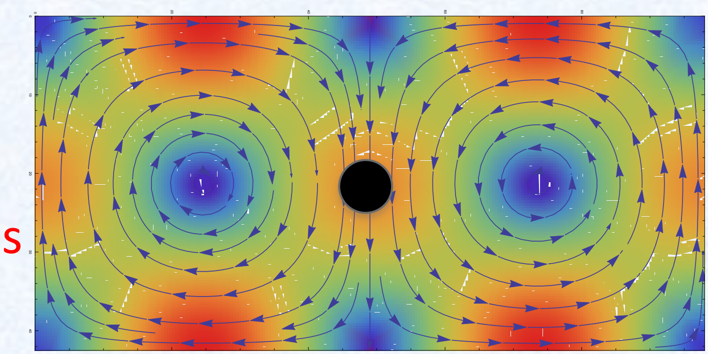


1 T -> ν_L =28 GHz

We can exploit the Electron Spin Resonance in different experimental setups for the magnetized sample:

- free space (radiation damping problem)
- waveguide in cutoff $\nu_c > \nu_L$
  (avoid radiation damping but bad coupling)
- rf cavity with hybridization of cavity-Kittel modes
  (good coupling and avoid radiation damping)

TM102 Resonant Cavity
H_0 along z axis (normal to the figure)



The Bloch equations

The dynamics of magnetization is described by a set of coupled non-linear equations due to Bloch (Polarizing field $\mathbf{H_0}$ along z-axis, driving rf field $\mathbf{H_1}$ in the (x,y) plane)

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

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

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

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} or better

T_2 ~ 10^{-6} or better

(**depends on spin density**)

e.g. static magnetization per unit volume of a paramagnet

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

n_s – spin density

μ_B – Bohr magneton

T – sample temperature

Radiation damping issue

Radiation damping in ESR describes additional **loss mechanisms in magnetized sample with spins precessing 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 in free space) $T_R \approx \dfrac{\lambda_L^3}{\gamma \mu_0 M_0 V}$

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

Absorbed rf power in steady state with radiation damping: 1) free space

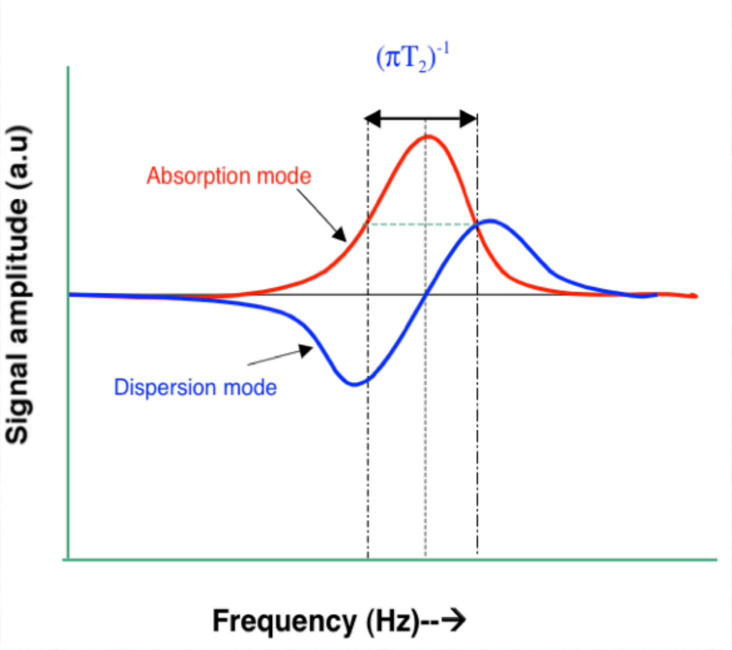
- Steady state solutions of Bloch Equations in the limit of weak rf field B_1

$$M_x = M_0 \frac{\delta\omega (T_2^*)^2}{1+(\delta\omega T_2^*)^2}\gamma B_1$$

$$M_y = M_0 \frac{T_2^*}{1+(\delta\omega T_2^*)^2}\gamma B_1$$

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

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



At the resonance

$$M_x = 0$$

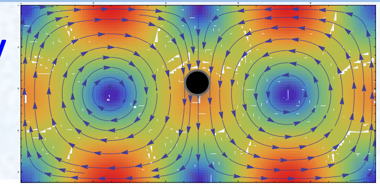
$$M_y = M_0 T_2^* \gamma B_1$$

$$P_{abs} = \left\langle -\mathbf{M}\cdot\frac{d\mathbf{B}_1}{dt}\right\rangle = \frac{\gamma M_0 V_s \omega_0 T_2^* B_1^2}{\left[1+\left(T_2\delta\omega\right)^2\right]} \xrightarrow{\delta\omega\to 0} \gamma M_0 V_s \omega_0 T_2^* B_1^2$$

$$if\ T_2^* \to T_R \approx 4\pi\frac{c^3}{\omega_0^3}\frac{1}{\gamma\mu_0 M_0 V_s} \to P_{abs} = 4\pi\frac{c^3}{\omega_0^2}\frac{B_1^2}{\mu_0} \approx 10^{-40}\,Watt$$

Absorbed rf power in steady state with radiation damping: 2) rf cavity

- Steady state solutions of Bloch Equations coupled with a rf cavity



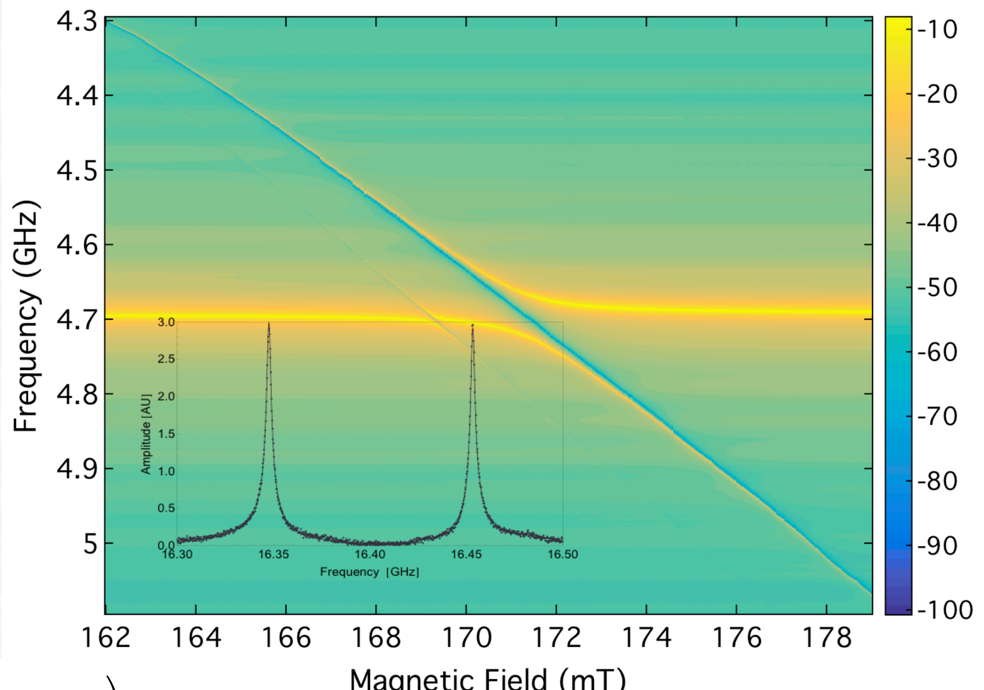
Kittel mode hybridization

$$M_x + iM_y = M_z \frac{\gamma M_0 T_2}{1 + i(\delta\omega T_2)} K' I \equiv \chi\, K' I$$

$$I = M_z \frac{i\omega / L}{\omega^2 - \omega_c^2 - i\omega_c / (2T_c) + 4\pi\,\chi\,\omega}\gamma H_1$$

$$\chi = \chi' + i\chi''$$

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



When hybridized modes are present (strong coupling)

$$\omega_\pm + \frac{i}{2T_\pm} = \omega_L \pm \frac{1}{2}\left[\frac{4}{T_c}\left(\frac{1}{T_2} + \frac{1}{T_r}\right) - \left(\frac{1}{T_c} + \frac{1}{T_2}\right)\right]^{1/2} + \frac{i}{2}\left(\frac{1}{T_c} + \frac{1}{T_2}\right)$$

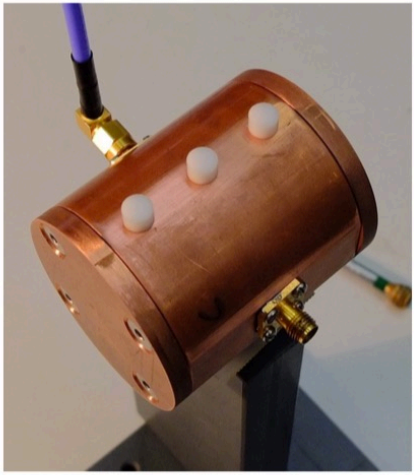
IF NO radiation damping then material properties get back in the game

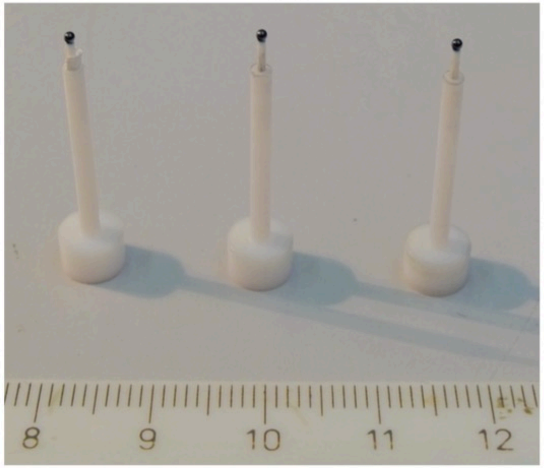
$$P_{abs} = \left\langle -\mathbf{M} \cdot \frac{d\mathbf{B}_1}{dt} \right\rangle = \gamma M_0 V_s \omega_0 \bar{T}_2 B_1^2$$

Assuming: $V_s \approx 0.1$ litre; $n_s \approx 10^{28}$ spin/m^3; $T_2 \approx 1$ μs

$B_1 = B_a \approx 10^{-22}$ T **$P \approx 10^{-25}$ Watt**

(a) Signal issues: volume, materials, n_s, T_2

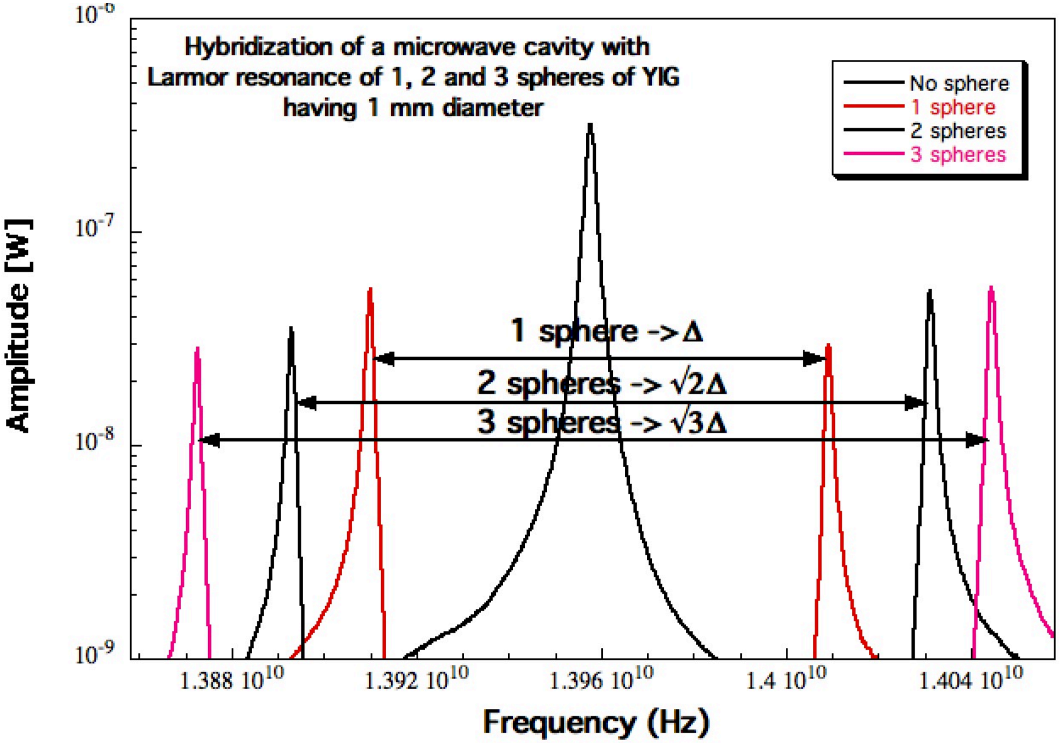




One idea to increase volume is to have several YIG spheres

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



(b) Signal issues: volume, materials, n_s, T_2

- A long cylinder could show a narrow linewidth?
  - Demagnetization issue
  - RF homogeneity

- We have realized a long BDPA sample to be tested inside the 14 GHz cavity.

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

- Very preliminary: lineiwidth of high purity YIG measured @ 4 K → about 1 MHz as at room Temp.

We are planning to check other materials: K_3CrO_8 (potassium peroxochromate (paramagnet)),
Lithium ferrite (Ferrimagnet, n_s ~ 2 n_s of YIG)

QUAX Noise Sources

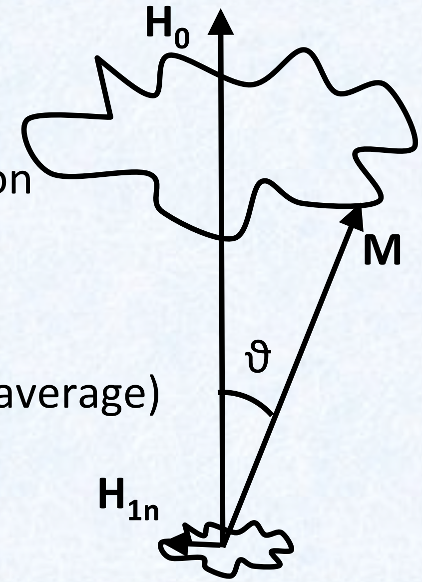
We identified 3 main noise sources

1. Fluctuations in magnetization due to relaxation processes in materials
2. Thermal photons (normal or hybridized modes in a rf cavity)
3. If **linear detection:** additive and back-action noises of the rf amplifier (SQL issue)
4. If **quantum counter**: dark count rate

The total noise power must be checked!

1. Spontaneous fluctuations of magnetization

Fluctuations of magnetization away from z direction
due to dissipations in the magnetized material and/or radiation damping
For small angle ϑ<<1 , fluctuations are described by the Langevin equation



$$\frac{d\vartheta}{dt} + \frac{\vartheta}{T_2} = \gamma B_{1n}$$

For the mean square deviation from the z direction (<> is the ensemble average)

$$\left\langle \frac{d\vartheta^2}{dt} \right\rangle + \left\langle \frac{2\vartheta^2}{T_2} \right\rangle = 2\gamma \left\langle \vartheta B_{1n} \right\rangle \xrightarrow{\text{steady state}} \left\langle \frac{\vartheta^2}{T_2} \right\rangle = \gamma \left\langle \vartheta B_{1n} \right\rangle$$

At equilibrium absorption and dissipation are balanced!

$$\left\langle \mathbf{M} \cdot B_0 \right\rangle - M_0 B_0 = M_0 B_0 \cos\vartheta - M_0 B_0 \cong \frac{1}{2} M_0 B_0 \left\langle \vartheta^2 \right\rangle$$

Using the Equipartition Theorem

$$\frac{1}{2} M_0 B_0 \left\langle \vartheta^2 \right\rangle = \frac{\hbar\omega_L}{V_s} \coth\left(\frac{\hbar\omega_L}{2k_B T}\right) \Longrightarrow \left\langle \vartheta^2 \right\rangle_{eq} = \frac{2\hbar\omega_L}{M_0 B_0 V_s} \coth\left(\frac{\hbar\omega_L}{2k_B T}\right)$$

From stationary solutions of Bloch equations

$$\left\langle B_{1n}^2 \right\rangle = \frac{2\hbar}{\gamma M_0 V_s T_2^2} \coth\left(\frac{\hbar\omega_L}{2k_B T}\right) \xrightarrow{k_B T << \hbar\omega_L} \frac{2\hbar}{\gamma M_0 V_s T_2^2}$$

$$\left\langle \vartheta^2 \right\rangle = \frac{\left\langle M_x^2 \right\rangle + \left\langle M_y^2 \right\rangle}{M_0^2} = \gamma^2 \left\langle B_{1n}^2 \right\rangle T_2^2 \Longrightarrow P_M = \gamma M_0 V_s \omega_L \left\langle B_{1n}^2 \right\rangle T_2 = 2\hbar \frac{\omega_L}{T_2} \approx 10^{-28}\, Watt$$

2. Fluctuations due to thermal photons: SQL issue

In a rf cavity + magnetized material with hybridized Kittel+cavity modes

Zero point energy of em field: a problem for detection with linear amplifier

$$P_{th} \approx 2k_B T\sqrt{\frac{\Delta\nu}{t_m}}$$

$$P_{SQL} \approx \hbar\omega\sqrt{\frac{\Delta\nu}{t_m}}$$

- $P_{th}>P_{SQL}$ However, with a **linear amplifier** and at very low temperature we can reach the SQL: Assuming $\omega \approx \omega_L$ = 40 GHz, $\Delta\nu \approx 10^{-6}\,\omega_L$, $t_m \approx 10^4$ s

→ $P_{SQL} \approx 10^{-24}\,Watt$

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

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

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

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

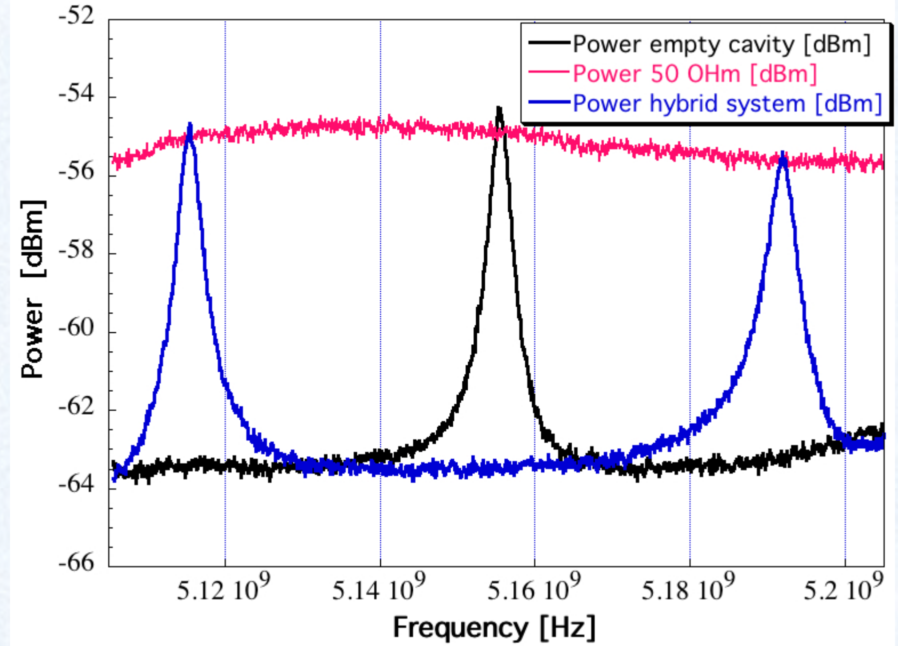
That is a single 48 GHz photon, emitted with a rate $R_a = 10^{-3}$ Hz.

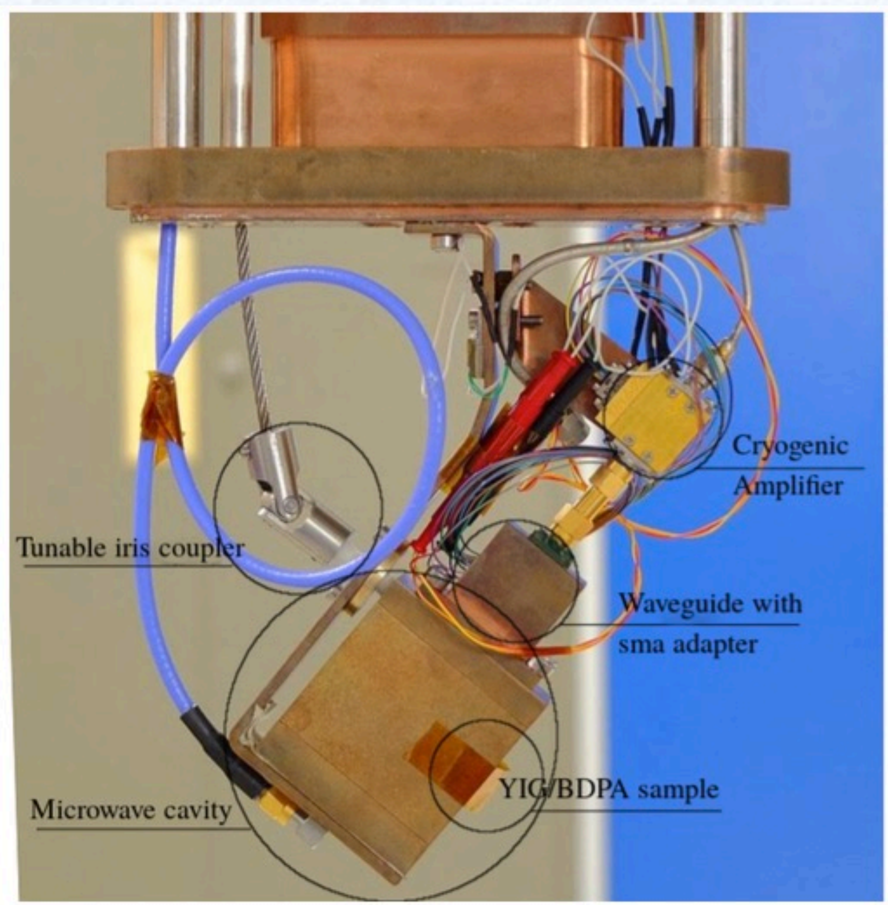
PHOTON COUNTERS CAN OVERCOME THE SQL PROBLEM

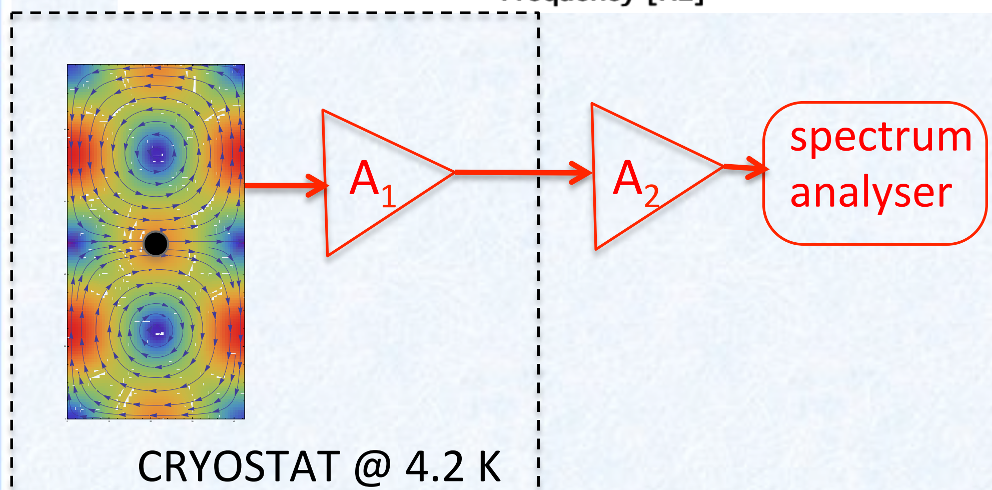
3. Preliminary study of noise with linear amplifier

we showed that, at **room temperature**, **no extra noise** is added in the system when it is **hybridized**

We have to demonstrate that it holds at low temperature with BDPA in a 5GHz rf cavity







The cryogenic set-up now works properly. A single fill allows about 4 hours of measurements

3. Preliminary study with linear amplifier @ 4K

At Liquid Helium there is a matching problem between cavity and amplifier. Now on a separate apparatus we are studying how to optimize it.

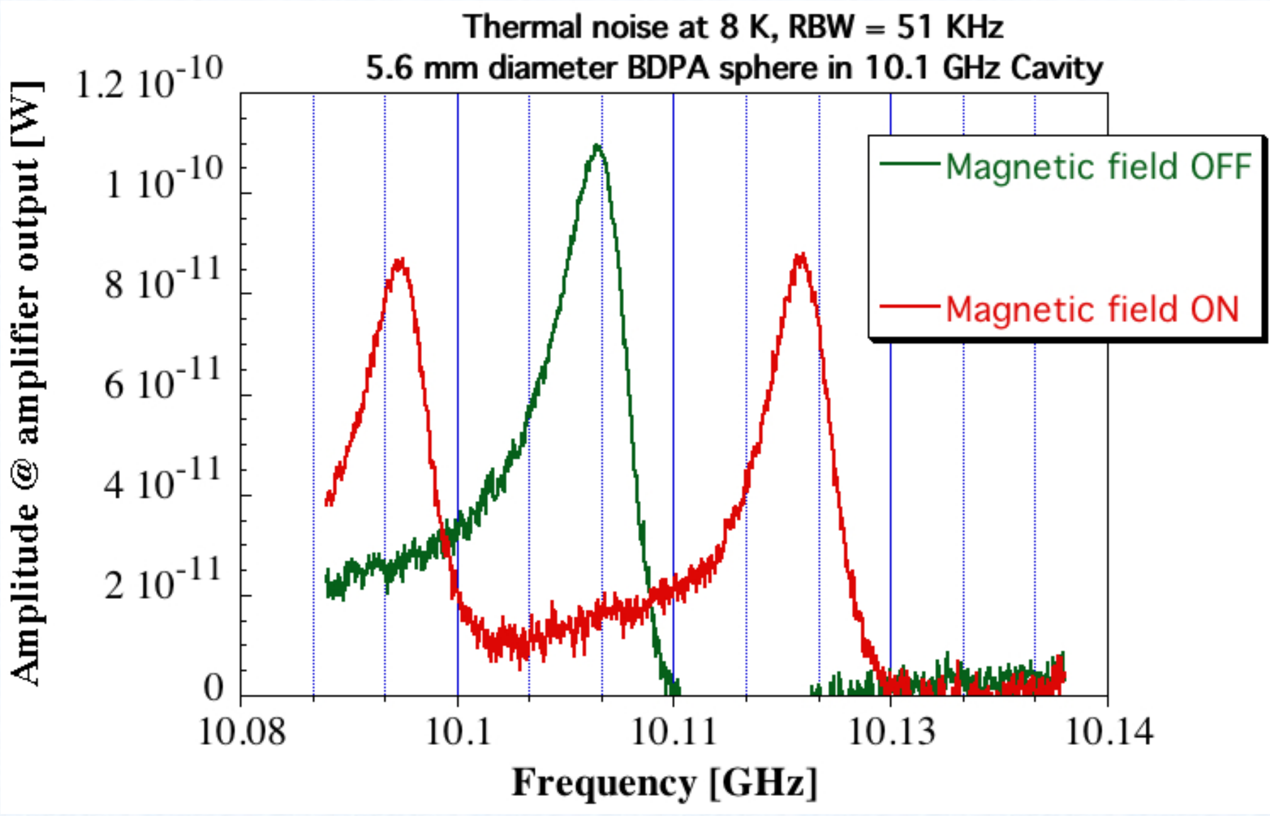
Preliminary results with a DBPA sphere @ 4 K

NEXT STEPS

Repeat the test also with a YIG sphere (with a better control of T)

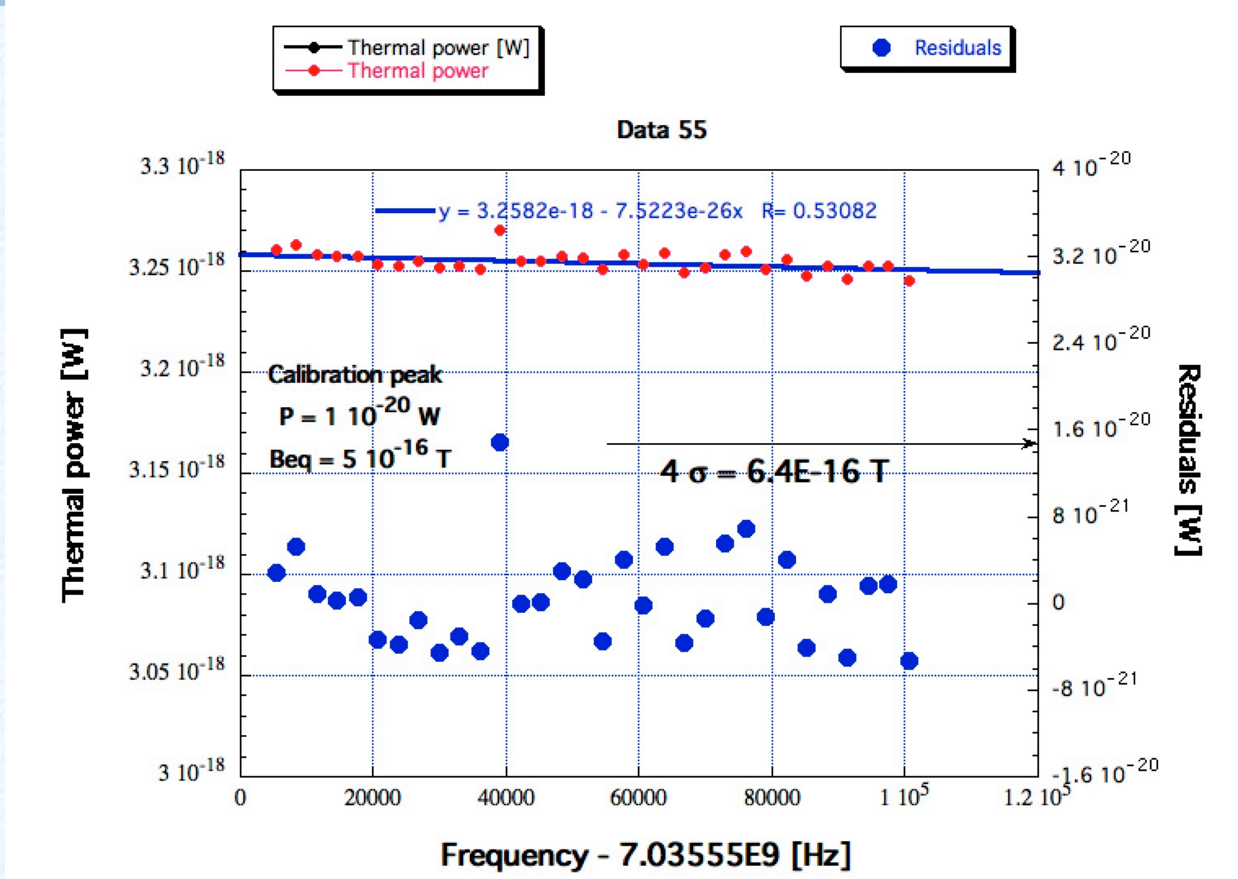
Optimization of detector chain

Long measurements to fully exploit the detector sensitivity and give some preliminary upper limits on axion coupling



3. Preliminary study with linear amplifier

Down conversion of the rf signal at 7 GHz with a mixer followed by a FFT spectrum analyzer



More effective use of the collected data

Available FFT instruments limit the analysis to 100 kHz bandwidth

Frequency bin 3kHz = axion linewidth

Axion Effective Magnetic field sensitivity

$$B_a^{\text{sens}} = \sqrt{\frac{P_{\text{residual}}}{\gamma \mu_B n_S \omega_a \tau_{\min} V_s}}.$$

4. SNR of an ideal (negligible dark count rate) photon counter

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

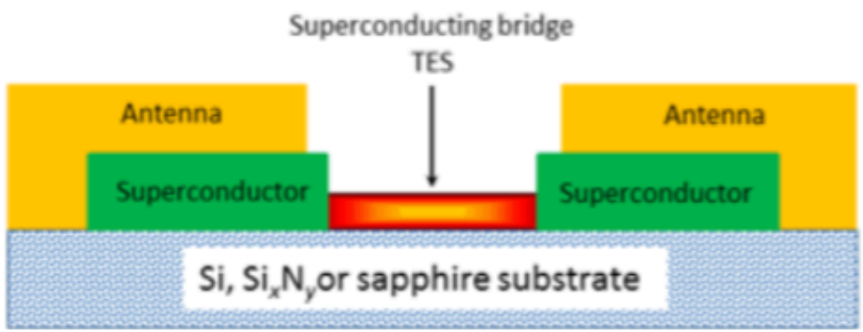
At $T \neq 0$ the single-photon detector is subject to noise from fluctuations in the number of detected *thermal photons*. Noise is determined by the thermal photon rate $R_{th} = \bar{n}\tau_c$

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

→ SNR = 4 for T = 116 mK and $t_m = 10^4$ s (i.e. 17 counts) in a 150 KHz bandwidth

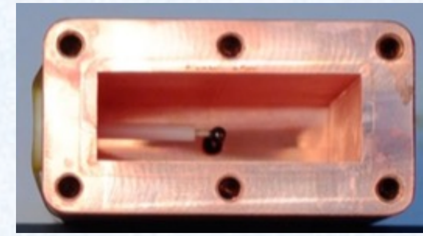
http://arxiv.org/abs/1606.02201

Single photon detector in the microwave range yet not developed.
Capparelli L.M. *et al* Phys. Dark Universe **12** 37 (2016)

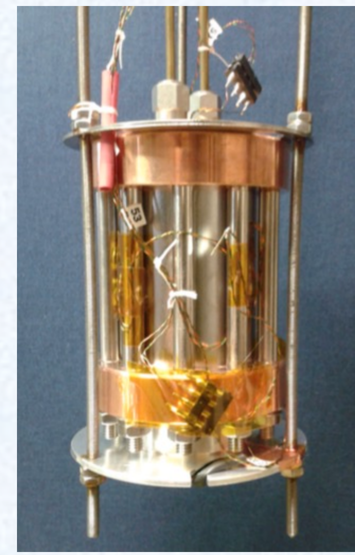


Conclusions

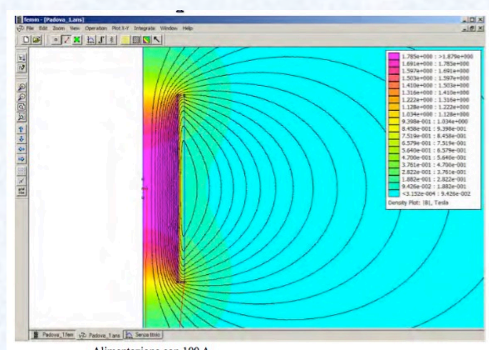
QUAX R&D Activities 2017 - 2019



- **Study of materials (PD, LNL) – linewidth and spin density**
  behaviour of materials (YIG, LiF, BDPA and other paramagnets) at low temperatures.



- **Cavity design for magnetic field operation (LNF, LNL, PD)**
  design of a high-Q (~ 10^6) cavity with a geometry useful to maximize the signal and operating in 2 T magnetic field.



- **Static magnetic field source (NA/Salerno)**
  realization of a highly uniform magnetic field (up to 10ppm for a 2 T field).