New detectors for axions

C. Braggio, G. Carugno, M. Guarise, A.F. Borghesani
University of Padova and INFN
L. Santamaria, V. Di Sarno, P. Maddaloni
CNR-INO
A. Di Lieto, M.Tonelli
University of Pisa and INFN
A. Ortolan, G. Ruoso
INFN-LNL

December 17, 2015

PROPERTIES OF THE AXION

- Peccei and Quinn (1977) proposed to solve the strong CP problem by postulating the existence of a global UPQ(1) quasisimmetry (it is spontaneously broken).
- The axion (Weinberg 1978, Wilczeck 1978) is the pseudo Goldstone boson associated with the spontaneous breakdown of the PQ-simmetry.
- The axion is a light pseudoscalar boson, the light cousin of the π_0

$$m_a f_a \approx m_\pi f_\pi \qquad m_\pi = 135\,\mathrm{MeV},\ f_\pi = 93\,\mathrm{MeV}$$

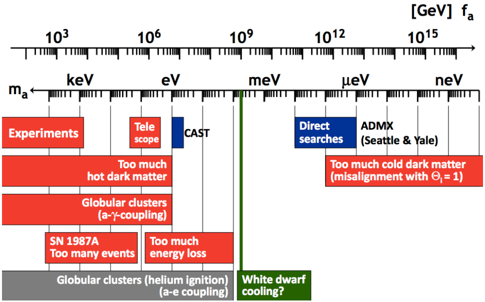
$$m_a \simeq 0.6\,\mathrm{eV}\,\frac{10^7\,\mathrm{GeV}}{f_a}$$

- f_a, the SSB scale of the PQ-symmetry, is the one important parameter in the theory.

Originally it was thought that $\quad f_a \approx f_{EW} \Longrightarrow m_a \simeq 100\,\mathrm{keV}$
but this axion was RULED OUT by accelerator experiments

PROPERTIES OF THE AXION II

- While the standard Peccei Quinn Weinberg Wilczeck (PQWW) axion was soon ruled out, the other axion (DFSZ, KSVZ) **continues to evade all current experimental limits**
- A reduced window of possibilities is actually left for discovery:



EXCLUDED
SEARCHES
HINT

$$10^{-(5 \text{ to } 6)}\ \text{eV} < m_a < 10^{-(2 \text{ to } 3)}\ \text{eV}$$

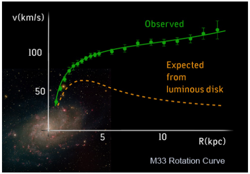
From G. Raffelt talk in Vistas in Axion Physics, INT, Seattle, 23–26 April 2012

AXIONIC DARK MATTER

A SUB-EV MASS AXION IS A GOOD DM CANDIDATE

In new models (two main ones):

Kim-Shifman-Vainstein-Zakharov **(KSVZ)**
(Kim 1979; Shifman, Vainstein, and Zhakharov 1980) Dine-Fischler-Srednicki-Zhitnitskii **(DFSZ)**
(Zhitnitskii 1980; Dine, Fischler, and Srednicki, 1981a, 1981b)



f_a is **arbitrarily large**
$\Longrightarrow$ extraordinarily weak couplings (m_a, $g_{aii} \propto f_a^{-1}$) INVISIBLE AXION!
$\Longrightarrow$ cosmological abundance ($\Omega_a \propto f_a^{7/6}$) DM CANIDATE!

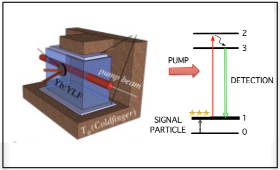
Axions are expected to be uniformly distributed with a density of around 10^{14} axions/cm^3 [P. Sikivie, Phys Rev D, **32**, 2988 (1985)].
+ motion of E in the galaxy $\Longrightarrow$ they can be seen as a wind with $v \sim 10^{-3}\, c$

AXIOMA: A SEARCH FOR GALACTIC HALO AXIONS

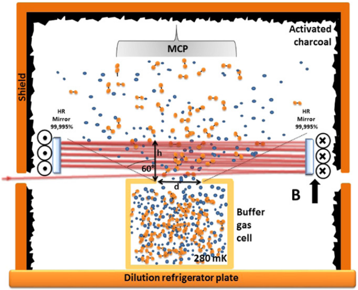
Detectors based on **laser-induced transitions** in the *active detecting material*:

1. gas system – ultracold molecular oxygen $^{16}O_2$
2. solid neon matrix
3. rare-earth doped crystals

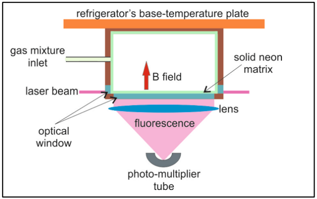
3.



1.



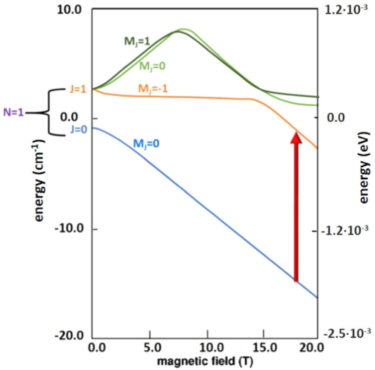
2.



1. GAS SYSTEM – ULTRACOLD MOLECULAR OXYGEN $^{16}O_2$

DM axions may induce *dipolar transitions between Zeeman states in an atomic system, which differ by m_a*
(P. Sikivie, Phys. Rev. Lett. **113** 201301 (2014))

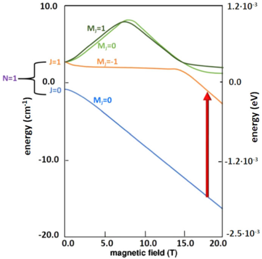
- axion transition $a \rightarrow b$
- Zeeman effect for $N = 1$ rotational levels in the GS of $^{16}O_2$
- mole-sized population of $^{16}O_2$molecules in a



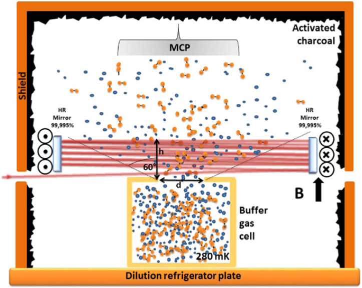
1. ULTRACOLD MOLECULAR OXYGEN $^{16}O_2$

- axion transition $a \to b$
- Zeeman effect for $N = 1$ rotational levels
- mole-sized population of $^{16}O_2$molecules in a

New J. Phys. **17** (2015) 113025

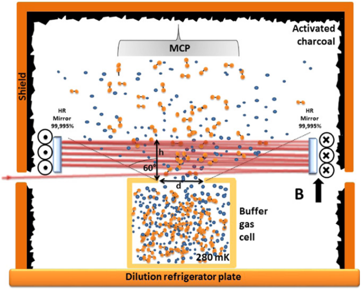


- BGC (buffer gas cooling). $^{16}O_2$ cooled by collisions with a helium-3 thermal bath at temperature $T_{He} \simeq 280\,\text{mK} \Longrightarrow W_{ba}(B_{\min}) = 11\,\text{cm}^{-1}$ (1.4 eV)
- magnetic field region:
  W_{ba} saturates for $B > B_{\max} = 18\,\text{T}$
  $1.4\,\text{eV} < m_a < 1.9\,\text{eV}$
- detection: REMPI (resonance-enhanced multi-photon ionization spectroscopy)

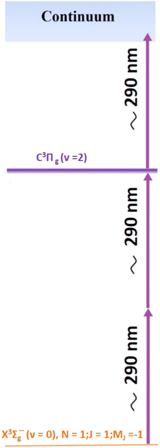


1. GAS SYSTEM: ULTRACOLD MOLECULAR OXYGEN $^{16}O_2$

- BGC (buffer gas cooling). $^{16}O_2$ cooled by collisions with a helium-3 thermal bath at temperature $T_{He} \simeq 280\,\mathrm{mK} \Longrightarrow W_{ba}(B_{\min}) = 11\,\mathrm{cm}^{-1}$ (1.4 eV)
- magnetic field region:
  W_{ba} saturates for $B > B_{\max} = 18\,\mathrm{T}$
  $1.4\,\mathrm{eV} < m_a < 1.9\,\mathrm{eV}$
- detection: REMPI (resonance-enhanced multi-photon ionization spectroscopy)
- $N_{\text{refl}} = 13500$ to maximize the fraction of molecules that interacts with the laser beam
  $\mathcal{F} = (N_{\text{refl}}\, \pi\, w^2)/(h\, d + h^2 \tan\theta)$



(2+1)REMPI
2 ph to intermediate state
+1 ph to ionize



1. GAS SYSTEM: ULTRACOLD MOLECULAR OXYGEN $^{16}O_2$

In 1 s, the number of oxygen molecules that have been exposed to the axion field is

$$N_{\mathrm{molec}} = \frac{n_{\mathrm{max}}}{4}\pi (d/2)^2 v_m,$$

where $v_m = \sqrt{(8\,k_B\,T)/\pi\,m}$
and $n_{\mathrm{max}} \simeq (1/30)\,n_{\mathrm{He}} = 10^{15}\,\mathrm{cm}^{-3}$ max molecular density that can be cooled to T_{He}

$\Longrightarrow$ the axion-induced absorption event number

$$N = N_{\mathrm{molec}}\frac{\bar{h}}{v_m}\mathcal{R}_{ab}\mathcal{F}(n_{\mathrm{days}}\cdot 24\cdot 3600)$$

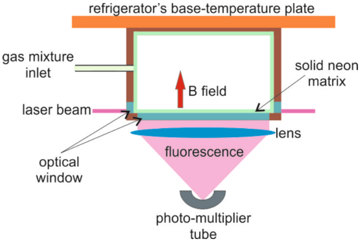
In the worst case $\mathcal{R}_{ab} = 1\,\mathrm{Hz}/N_A \rightarrow N \simeq 1$ for an acquisition time of 10 days

...is it possible to increase the density?

2. SOLID NEON MATRIX

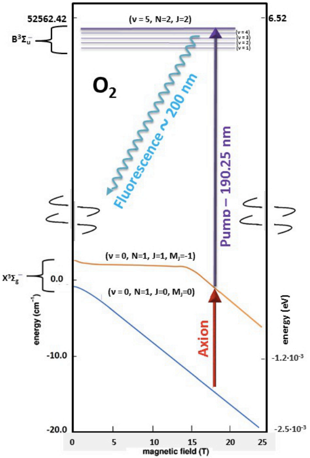
Alkali atom or molecular oxygen embedded in a condensed phase according to the matrix-isolation spectroscopy technique (MIS).

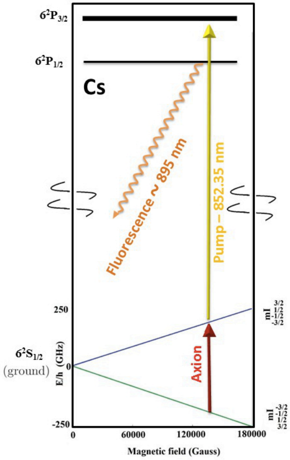
- 80 mK in **B** up to 18 T
- copper cell $1 \times 3 \times 3\,\mathrm{cm}^3$
- inject noble gas N and atomic/molecular species D (1:100 to 1:1000)



After a few hours of deposition, a 1-mm-thick noble gas matrix, incorporating species D is grown on each side of the walls.

2. SOLID NEON MATRIX: DOPANT SPECIES





Number of axion-induced absorption events:

$$N \cdot N_A = \mathcal{R}_{ab}\, n_{\mathrm{Ne}}\, V_c\, d\, (3600\,\mathrm{s}) n_h$$

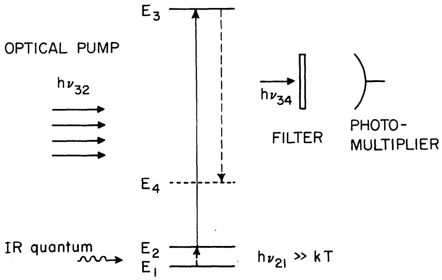
some reasonable values:
$\mathcal{R}_{ab} = 1\,\mathrm{Hz}$;
$n_{\mathrm{Ne}} = 4.6 \cdot 10^{22}\,\mathrm{cm}^{-3}$ neon density;
$V_c \sim 1\,\mathrm{cm}^3$ crystal volume;
$d = 1\%$ doping ratio;
n_h acquisition time [hours]=4

$$\Longrightarrow N \cdot N_A = 10$$

3. RE-DOPED CRYSTALS

basic idea: **diminish w-value** in an **all-optical scheme** based on the IRQC concept

N. Bloembergen, *Phys. Rev. Lett.* **2**, 84 (1959)

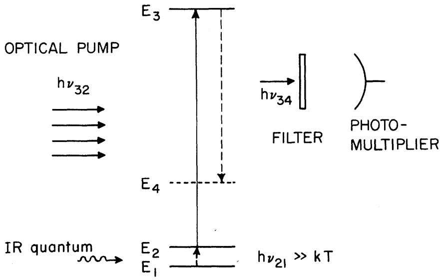


- pump laser resonant with transition $2 \rightarrow 3$
- material transparent to the pump until an IR photon is absorbed ($1 \rightarrow 2$)
- level 3 is fluorescent $\Longrightarrow$ detection can be accomplished via conventional detectors (PMT or PD)
- such energy level scheme can be realized in wide bandgap materials doped with trivalent rare-earth ions

3. RE-DOPED CRYSTALS

basic idea: **diminish *w*-value** in an **all-optical scheme** based on the IRQC concept

N. Bloembergen, *Phys. Rev. Lett.* **2**, 84 (1959)

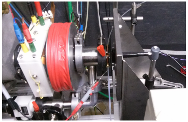


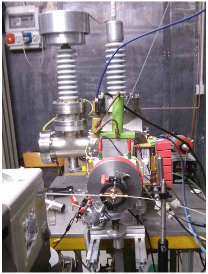
- pump laser resonant with transition $2 \rightarrow 3$
- material transparent to the pump until an IR photon is absorbed $(1 \rightarrow 2)$
- level 3 is fluorescent $\Longrightarrow$ detection can be accomplished via conventional detectors (PMT or PD)
- such energy level scheme can be realized in wide bandgap materials doped with trivalent rare-earth ions

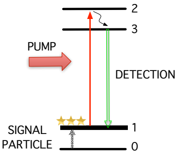
the whole field of **upconversion** can be traced back to this idea
(with applications in lasing, laser cooling, up-conversion based weak infrared photon detection, infrared imaging and so on)

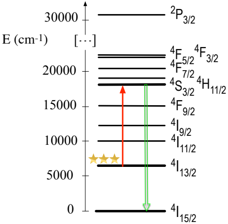
3. THE IRQC IDEA APPLIED TO PARTICLE DETECTION: A DEMONSTRATION

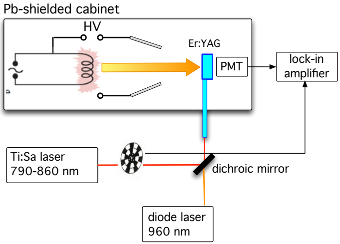
- an **electron gun** as a signal source (wideband)
- YAG:Er^{3+}, $E_1 = 0.74\,\text{eV}$ ($^4I_{15/2} \longrightarrow {}^4I_{13/2}$ transition)
- **room temperature** $\rightarrow N_1/N_0 \sim 10^{-14}$
- **lock-in detection** to select fluorescent photons originated only from double resonance







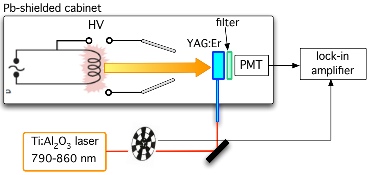


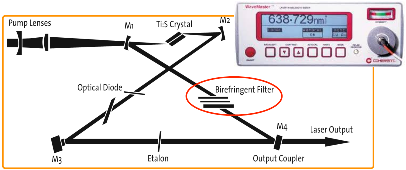


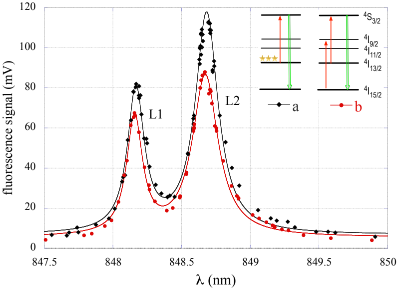
Appl. Phys. Lett. **107** (issue 9 nov 2015)

Appl. Phys. Lett. **107** (issue 9 nov 2015)

L1, L2 transitions between sublevels in the $^4I_{13/2}$ and $^4S_{3/2}$ manifolds





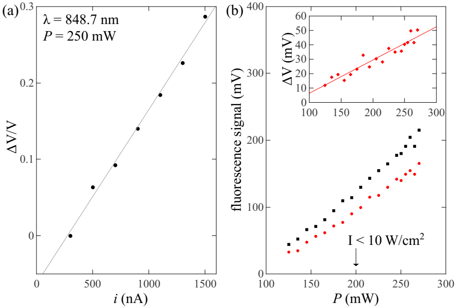


		λ_{max} (nm)	*area*
L1	p.l.	848.16 ± 0.01	12.8 ± 0.8
	p.l. + e^-	848.17 ± 0.02	16.5 ± 1.1
L2	p.l.	848.67 ± 0.01	28.8 ± 1.1
	p.l. + e^-	848.68 ± 0.01	34.8 ± 1.1

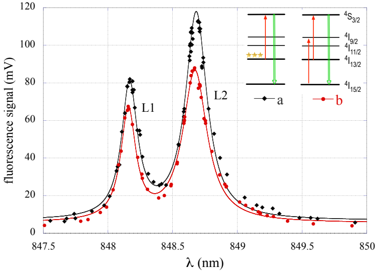
- the fluorescence signal is greater when the electron gun excites the crystal
- a significant fraction of the fluorescence is determined by the pump laser double resonance
- e^- excitation geometrically unfavorite as compared to pump laser double resonance
- host crystal (YAG) has a weak IRQC output

LINEARITY TESTS

the fluorescence is linearly dependent on:
⋆ the pump laser intensity
⋆ the electron gun current

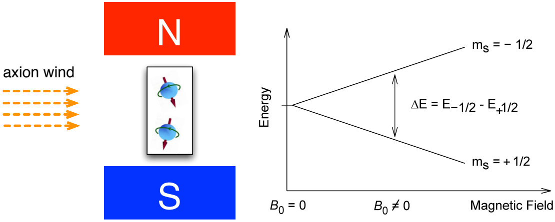


L1, L2 transitions between sublevels in the $^4I_{13/2}$ and $^4S_{3/2}$ manifolds



QUAX

- interaction of the axion field with the spin of electrons in a magnetized sample



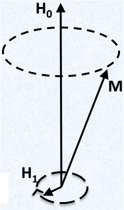
- the axion DM acts as as **effective RF magnetic field** on the electron spin ($\nu_{RF} \longleftrightarrow m_a$, $A_{RF} \longleftrightarrow f_a$)
- the RF receiver module of the detector consists of magnetized samples with **Larmor frequency tuned to the axion mass** by a polarizing magnetic field
- the equivalent magnetic RF field excites a **transition** in the magnetized sample $\longrightarrow$ **variation in the magnetization**

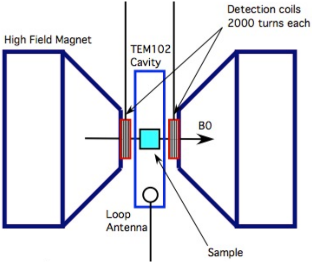
L. M. Krauss, J. Moody, F. Wilczek, D.E. Morris, *Spin coupled axion detections* (1985)

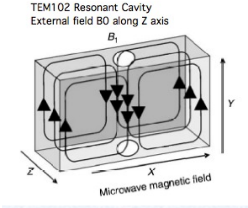
R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett. B **226**, 357 (1989)

A.I. Kakhizde, I.V. Kolokolov, Sov. Phys, JETP **72** 598 (1991)

EPR (or ESR electron paramagnetic/spin resonance) inside a magnetic media is tuned by an external field H_0; the RF field H_1 ($\perp H_0$) in the GHz range excites the spin flip transition at $\nu_L \implies$ **M** undergoes precession



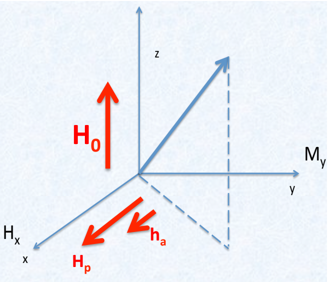




axion mass	$10^{-4}\,\text{eV} \leqslant m_a \leqslant 10^{-3}\,\text{eV}$
equivalent RF magnetic field	$10^{-22}\,\text{Tesla} \leqslant B \leqslant 10^{-21}\,\text{Tesla}$
frequency	$20\,\text{GHz} \leqslant f \leqslant 200\,\text{GHz}$
magnetizing field	$\nu_L = \gamma_e B_0$, with $\gamma_e = 28\,\text{GHz/Tesla}$ $\rightarrow 0.7\,\text{T} \leqslant B \leqslant 7\,\text{T}$
detector bandwidth	$\leqslant 100\,\text{kHz}$
temperature	$T_{\text{spin}} = \frac{\mu_b B_0}{k_B}, \; T_{\text{lattice}} = \frac{\hbar\nu}{k_B}$ $\rightarrow 100\,\text{mK} \leqslant \text{T (K)} \leqslant 1\,\text{K}$

LONGITUDINAL DETECTION OF THE AXION FIELD

the axion effective field produces **oscillations in the magnetization** of the sample, a very small field that can be detected with the LOD technique



- magnetize the sample along the z-axis orthogonal to the axion direction
- $\mathbf{H}_0$ amplitude matches the searched value of the axon mass
- the equivalent axion field $\mathbf{h}_a$ is in the transverse direction
- drive the sample with a pump field $\mathbf{H}_p$ near the Larmor frequency $\omega_L = \gamma_e \mathbf{H}_0$

$\Longrightarrow$ total driving RF field

$$\mathrm{H}_{1,x} = \mathrm{H}_p \cos \omega_p t + \mathrm{h}_a \cos \omega_a t$$

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

$\mathrm{H}_{1,x}$ is a linear superposition of two RF fields (pump and axion/any field) with slightly different frequencies ω_p, ω_a and amplitudes $\mathrm{H}_p \gg \mathrm{h}_a$

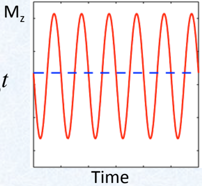
LONGITUDINAL DETECTION OF THE AXION FIELD

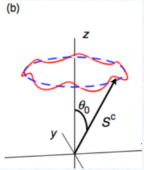
$$\Delta m_z(t) = \frac{1}{4} M_0 \frac{T_2^*}{T_2}\gamma^2 T_1 T_2^* H_p \left[\frac{1+\omega_D^2 T_2^{*2}/4}{\left(1+\omega_D^2 T_1^2\right)\left(1+\omega_D^2 T_2^{*2}\right)}\right]^{1/2} h_a \cos\omega_D t$$

Then M_z oscillates at very low frequency!

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

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





Def:= gain G_r for the low frequency component Δm_z for the high frequency field h_a in

YIG: $T_1 \approx T_2 \approx 10^{-6}$ s, $M_0 = 2$ T $\Longrightarrow G_r > 100$ for $H_p \sim 0.1\,\mu$T

Can we get G_r so as to measure Δm_z from an axion field $h_a \sim 10^{-22}$ T?

If we assume that the relaxation times satisfy $\tau_1 \sim \tau_2$ and $\tau_r < \tau_2$, the transduction gain will depend only on τ_r: $G_m \simeq \mu_0 M_0 \tau_r^2 \gamma^2 B_p \approx 1/(8\pi^2)(\lambda_L^3/V_s)\gamma\tau_r B_p$, where $\lambda_L \equiv 2\pi c/\omega_L$ is the wavelength corresponding to the Larmor frequency. Thus to obtain a gain $G_m > 1$ in free space, the sample volume must satisfy the inequality $V_s < 1/(8\pi^2)\lambda_L^3 \tau_r \gamma B_p$. On the other hand, the pump field amplitude must be far from saturation $\gamma^2 B_p^2 \tau_r \tau_1 << 1$, which implies $\gamma \tau_r B_p << 1$. This is the reason why we can't get $G_m > 1$ in free space with realistic sample volumes and pumping fields.

Inside an rf cavity, this problem could be solved but the thermal noise in the hybridized system formed by cavity and magnetized sample is much greather than the axion equivalent field. The solution is to detect axions by placing the sample in a waveguide with a cutoff frequency ω_c above the Larmor frequency of the sample. For instance, we can place the sample at a distance ℓ from the aperture of a rectangular waveguide of cross section ab. The lowest cut-off frequency for an open waveguide ($a > b$) is given by (the waveguide behaves as a high pass filter): $\omega_c = 1/(4\pi a\sqrt{\epsilon\mu})$.

Due to boundary conditions, if the Larmor frequency is lower than ω_c, the magnetic resonant mode cannot propagate inside the waveguide, but only evanescent waves can exist. We expect then a reduction of the radiation damping mechanism for the selected magnetic resonance.