# QUAX – QUEST for AXIONS

### CONCEPTS, STATUS AND PERSPECTIVES

Axion cosmology 2020 @ MIAPP February 24th



ALESSIO RETTAROLI

*Università degli Studi Roma Tre INFN – LNF*



- § USELESS INTRO
- **QUAX EXPERIMENT** 
	- **COUPLING TO ELECTRONS**
	- **COUPLING TO PHOTONS**
- NEXT STEPS



# INTRODUCTION

## AXIONS IN ΛCDM MODEL





$$
n_a = 3 \times 10^{12} \left(\frac{100~\mu\text{eV}}{m_a}\right)~1/\text{cm}^3
$$

### AXIONS IN ΛCDM MODEL

- **Nelocity distribution approximately Maxwellian** adion application and
- **Velocity dispersion**  $\sigma \approx$ <sup>*o*</sup>  $\sigma_v \approx 270\,\, {\rm km/s}$
- **E** Axion linewidth *h*  $\delta E/E \approx 5.2 \times 10^{-7}$

**E** Axion figure of merit  $Q_a \simeq 1.9$  $\sqrt{10}$  $Q_a \simeq 1.9 \times 10^6$ 

[Turner, Phys. Rev. D 42 (1990)]



### AXION WINDOW



$$
\boxed{10^{-6}~{\rm eV} < m_a < 10^{-3}~{\rm eV}}
$$

$$
0.25~\mathrm{GHz} < \nu_a < 250~\mathrm{GHz}
$$

[C. Giunti, C. W. Kim]

### QUAX IS A HALOSCOPE

### *<sup>L</sup>* <sup>=</sup> <sup>ψ</sup>¯(*x*)(*i*!∂/ <sup>−</sup> *mc*)ψ(*x*) <sup>−</sup> *igpa*(*x*)ψ¯(*x*)γ5ψ(*x*) Axion-electron spin interaction Axion-photon coupling

INCREASING VOLUME: 3 SPHERES IN A RESONANT CAVITY OF THE SECOND SERVICE OF THE SECOND SERVICE OF THE SECOND SE





∇*a* \$= 0 ⇒ β \$= 0 Resonant RF cavities



# SEARCHING AXIONS WITH MAGNETIZED MEDIA

AXION COUPLING

QUAX  $a - e$ 

AXION-FERMION interaction

rare-earth doped materials

- $\frac{1}{\sqrt{2}}$  and  $\frac{1}{\sqrt{2}}$ **Energy levels of a two-state system are split**
- *|*0i ! *|i*i in which axions are absorbed **Think of an electron spin under the effect of magnetic field**  $\blacksquare$ 
	- **EXTERN** An axion tuned to the Larmor frequency causes a transition (generates a magnon in multi-spin system)
		- **Then the system relaxes emitting radiation**



(*x*) is the spinor field of the fermion with mass *m*

 $\mathbb{E}[\mathbf{E}(\mathbf{X})]$ 

#### THE COUPLING WIND AS AN EFFECTIVE MAGNETIC FIELD THE AXION WIND AS AN EFFECTIVE MAGNETIC FIELD AS AN EFFECTIVE MAGNETIC FIELD AS AN EFFECTIVE MAGNETIC FIELD AN<br>The action of the action o The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the Lagrangian: The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the Lagrangian: *<sup>µ</sup>* are the 4 Dirac matrices, <sup>5</sup> = *i*012<sup>3</sup> **given by dimensionless pseudo-scalar coupling constant constant constant constant constant constant constant co THE COUPLING AN EFFECTIVE MAGNETIC MAGNET** *gp* dimensionless pseudo-scalar coupling constant The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the Lagrangian: THE AXION WIND AS AN EFFECTIVE MAGNETIC FIELD AS AN EFFECTIVE MAGNETIC FIELD AS AN EFFECTIVE MAGNETIC FIELD AN<br>The action of the action o

THE AXION WIND AS AN EFFECTIVE MAGNETIC FIELD AS AN EFFECTIVE MAGNETIC FIELD AS AN EFFECTIVE MAGNETIC FIELD AS

 $\mathcal{H}(\mathcal{H})$  and  $\mathcal{H}(\mathcal{H})$  and  $\mathcal{H}(\mathcal{H})$  and  $\mathcal{H}(\mathcal{H})$  and  $\mathcal{H}(\mathcal{H})$  and  $\mathcal{H}(\mathcal{H})$  and  $\mathcal{H}(\mathcal{H})$ 

 $\sim$ 

*<sup>L</sup>* <sup>=</sup> ¯(*x*)(*i*~*µ*@*<sup>µ</sup> mc*) (*x*) *igpa*(*x*) ¯(*x*)<sup>5</sup> (*x*)

**Q**<br>Quax *Quax Quax Quax Qu* 

Non-relativistic limit of the Euler-Lagrange equation:  $\mathcal{L}_{\mathcal{A}}$ 

The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the



The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the Lagrangian:

 $R_{\rm eff}$  :RUNVKRS  $R_{\rm eff}$  is a dyly  $\rm H_{\rm eff}$ 

*gp* dimensionless pseudo-scalar coupling constant

*<sup>L</sup>* <sup>=</sup> ¯(*x*)(*i*~*µ*@*<sup>µ</sup> mc*) (*x*) *igpa*(*x*) ¯(*x*)<sup>5</sup> (*x*)

INTRODUCTION AXIOMATIC INTRODUCTION AXIOMATIC INTERNATIONAL AXIOMATIC INTERNATIONAL AXIOMATIC INTERNATIONAL AXIO

INTRODUCTION AXIOMA QUAX BkUP

*<sup>L</sup>* <sup>=</sup> ¯(*x*)(*i*~*µ*@*<sup>µ</sup> mc*) (*x*) *igpa*(*x*) ¯(*x*)<sup>5</sup> (*x*)

The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the

The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the

The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the

THE AXION WIND AS AN EFFECTIVE MAGNETIC FIELD AS AN EFFECTIVE MAGNETIC FIELD AS AN EFFECTIVE MAGNETIC FIELD AS

Introduction introduction  $\mathcal{L}_\mathcal{A}$  is a set of  $\mathcal{L}_\mathcal{A}$  introduction  $\mathcal{L}_\mathcal{A}$ 

Introduction is a set of  $\mathcal{L}_\mathcal{A}$  introduction  $\mathcal{L}_\mathcal{A}$  introduction  $\mathcal{L}_\mathcal{A}$ 

The AXION WIND AS AN EFFECTIVE MAGNETIC FIELD  $\mathcal{A}^{\mathcal{A}}$ 

The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the

Introduction introduction  $\mathcal{L}_\mathcal{A}$  is a set of  $\mathcal{L}_\mathcal{A}$  introduction  $\mathcal{L}_\mathcal{A}$ 

In the control  $\mathcal{L}_\mathcal{A}$  is a set of  $\mathcal{L}_\mathcal{A}$  introduction  $\mathcal{L}_\mathcal{A}$  is a set of  $\mathcal{L}_\mathcal{A}$ 

Lagrangian:

*<sup>µ</sup>* are the 4 Dirac matrices, <sup>5</sup> = *i*012<sup>3</sup>

*gp* dimensionless pseudo-scalar coupling constant

(*x*) is the spinor field of the fermion with mass *m*

 $N_{\rm eff}$  is the Euler-Lagrange equation:  $\Gamma_{\rm eff}$  is the Euler-Lagrange equation:

Introduction introduction  $\mathcal{L}_\mathcal{A}$  is a set of  $\mathcal{L}_\mathcal{A}$  introduction  $\mathcal{L}_\mathcal{A}$ 

The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the

(*x*) is the spinor field of the fermion with mass *m*

The interaction of a spin 1/2 particle with the axion field *a*(*x*) is described by the

*<sup>L</sup>* <sup>=</sup> ¯(*x*)(*i*~*µ*@*<sup>µ</sup> mc*) (*x*) *igpa*(*x*) ¯(*x*)<sup>5</sup> (*x*)

*<sup>µ</sup>* are the 4 Dirac matrices, <sup>5</sup> = *i*012<sup>3</sup>

the spin magnetic moment and a magnetic field (as in the Zeeman effect in atomic physics),

#### USE MAGNETIZED MATERIALS  $\overline{\phantom{a}}$ AN EXPERIMENT PERFORMED IN THE STRONG COUPLING REGIME where (*x*) is the spinor field of the fermion with mass *m*. Here *µ* **are the 4 Dirac matrices, 5 and 2 3, and 3 4, and 3 4** where (*x*) is the spinor field of the fermion with mass *m*. Here *<sup>µ</sup>* are the 4 Dirac matrices, <sup>5</sup> = *<sup>i</sup>* <sup>0</sup> <sup>1</sup> <sup>2</sup> 3, and *<sup>a</sup>*(*x*) is coupled



interaction of a spin 1/2 particle with the axion field *a*(*x*) reads

interaction of a spin 1/2 particle with the axion field *a*(*x*) reads

to matter by the dimensionless pseudo-scalar coupling constant *gp*.

300 MeV*/*cm3, and we will suppose that axions are the dominant

 $A\rightarrow B$  and the best example of non-thermal data matrix  $\mathcal{A}$ 

*,* (2.3)  $M_a(t) = \gamma \mu_B B_a n_S \tau_{\min} \cos(\omega_a t)$ ter candidate  $[24]$ . The expected data matter dark matter dark matter dark matter dark matter density is  $\frac{1}{2}$  $\frac{1}{\sqrt{2}}$ 

8

axion wind coherence ⌧*<sup>a</sup>* ⇠

⌧r*<sup>a</sup>* ' <sup>0</sup>*.*<sup>68</sup> ⌧*<sup>a</sup>* <sup>=</sup> <sup>17</sup>✓200µeV

⌧r*<sup>a</sup>* ' <sup>0</sup>*.*<sup>68</sup> ⌧*<sup>a</sup>* <sup>=</sup> <sup>17</sup>✓200µeV

and correlation length for the QUAX detector read

by

by

◆

In the framework of  $D_{\rm 15}$  axion model  $\sim$ 

In the framework of  $D_{\rm{eff}}$  axion model  $\sim$ 

coupling constant *gp* with electrons can be expressed as *gp* =

*<sup>p</sup><sup>E</sup>* sin✓*p*<sup>0</sup>*ct <sup>p</sup><sup>E</sup>* · *<sup>x</sup>*

coupling constant *gp* with electrons can be expressed as *gp* =

time of the magnetic system with respect to the axion driving

 $\mathcal{G}(\mathcal{G})$  or more case, radiation damping is dominated in dominated in dominated in dominated in dominated in

to account for the electromotive force induced in the rf coils of

a driving circuit by magnetization changes without taking into

#### **OUTPUT POWER**  $\overline{\phantom{a}}$ account the dynamics of the ref coils. In our case the ref coils. In our case the ref coils. In our case the ref coils. In this damping term of the ref coils. In the ref coils. In our case the ref coils. In thi is affecting the maximum allowed coherence hence the integration  $\bigcirc$  we that the material spin–lattice relaxation time  $\bigcirc$  is greaterial spin–lattice relaxation time  $\bigcirc$ than ⌧*h*, so that now ⌧min = min *(*⌧r*<sup>a</sup>,* ⌧*h)*.

Axion properties

\n
$$
P_a = \mu_0 \mathbf{H} \cdot \frac{d\mathbf{M}}{dt} = B_a \frac{dM_a}{dt} V_s = \gamma \mu_B \eta_S \omega_a B_a^2 \overline{t_{\text{min}} V_s}
$$
\nExperimental design

scribed by the hybrid mode characteristic time ⌧*<sup>h</sup>* = <sup>1</sup>*/kh*. Radia-

than ⌧*h*, so that now ⌧min = min *(*⌧r*<sup>a</sup>,* ⌧*h)*.

absorbed by the material in each cycle is easily for  $\alpha$  in each cycle is easily for  $\alpha$ 

In the presence of the axion wind, the axion wind, the axion wind, the average amount of  $\mu$ 

magnetization **Magnetization** *Machine ensures that* **a steady state ensures the power balance ensures that the power balance ensur**  $n_s V_s =$  number of spins

 $\tau_n$ *P*in will be emitted as rf radiation, and so *P*in*/*2 can be collected by spin relaxation time (next slide) coherence length of the axion field is much larger than the typical  $\mathbf{u}$  $\tau_{min} =$  spin relaxation time (next slide)

### LIMITING FACTORS

 $\tau_{min} =$ minimum time between:



YIG

### Yttrium Iron Garnet

Synthetic garnet, ferrimagnetic material







tion, *ns* its spin density, g is the gyromagnetic ratio of the

rial an amount of power *P*in

electron, and tmin the minimum relaxation time of the sys-**I** When  $\omega_c \simeq \omega_L$  the modes hybridize **■** When  $\omega_c \simeq \omega_L$  the modes hybridize **Strong coupling regime:**  $\sum_{i=1}^{n}$  in the minimum relation time  $\sum_{i=1}^{n}$ and the resonance splits into two **in frace to one space the season is matter to one one one one one one of the structure one of the signal signa** ation damping mechanisms (i.e. magnetic dipole emission of the hybrid resonant modes, the extracted power is *P*out = of the sample) [47–49], with values much smaller than the  $10^{-6}$ Hybridization of a microwave cavity with Larmor resonance of 1, 2 and 3 spheres of YIG No sphere **having 1 mm diameter**  $\frac{1}{1}$  **having 1 mm diameter** 0.61  $\begin{bmatrix} 1 & \cdots & 1 \\ 1 & \cdots & 1 \end{bmatrix}$  mode (see text for details).  $\Box$  Cavity  $\blacksquare$   $V_s$  $\blacksquare$  5 $V_s$  $\mathbf{f}$ Amplitude [W]  $\mathbf 0$ amplitude. The GaYIG spheres are placed on the cavity axis at the cav  $0.60$  $-10$ <br>  $-20$ <br>  $-20$ <br>  $-30$ <br>  $-40$ <br>  $-50$  $-90$  $\frac{1}{100}$  -90<br>  $\frac{1}{100}$  -100<br>  $\frac{1}{100}$  -110<br>  $\frac{1}{100}$  -120 maximum of the rf magnetic field.  $\begin{bmatrix} 0.59 \\ -0.58 \end{bmatrix}$ 1 sphere  $-\lambda$ 2 spheres ->  $\sqrt{2}\Delta$ 3 spheres  $\rightarrow \sqrt{3\Delta}$ 0.58  $p_{\text{ref}}$  and the properties we studied the properties we studied the properties of  $\mathbb{R}$ of several paramagnetic samples and some ferrites. Highest  $0.57$ values of *ns* together with long relaxation times have been  $-60$ 0.56  $\mathcal{F}$ found  $\mathcal{F}$   $1.385 \times 10^{10}$  $1.395 \times 10^{10}$  $1.405 \times 10^{10}$ 13.9 14.0 13.7 13.8 14.1  $10^{9}$  avoid  $1.38810^{10}$  and  $1.39210^{10}$  and  $1.39610^{10}$  and  $1.40^{10}$  and  $1.40410^{10}$ Frequency [Hz] Frequency [GHz] **Frequency (Hz)**  $\mathcal{F}_{\mathcal{A}}$  Power spectrum of the cavity (blue line), and hybrid modes calare shaped as highly polished spheres. Five GaYIG spheres 1 coupled antenna anten  $k_{\rm hybr}$   $\simeq$  $\frac{1}{2}(k_c + k_m)$ of 1 mm diameter have been placed in the mag $k_{\text{hvbr}} \simeq \frac{1}{2} (k_c + k_m)$ .  $p^2$ <sup>V</sup> e and contract to the coupling with case of  $\sim 2$  MHz mental values of  $\mathbb{Z}^{\times}$  $\overline{a}$   $\overline{b}$   $\overline{a}$   $\overline{b}$   $\overline{c}$   $\overline{a}$   $\overline{a}$   $\overline{b}$   $\overline{c}$   $\overline{a}$   $\overline{b}$   $\overline{a}$   $\overline{b}$   $\overline{c}$   $\overline{a}$   $\overline{b}$   $\overline{a}$   $\overline{b}$   $\overline{c}$   $\overline{a}$   $\overline{b}$   $\overline{a}$   $\overline{b}$   $\overline{c}$   $\overline{$  $\sim$  2 MHz  $\sim$  600 MHz  $\sim$  2 *MHz* 

form factor x . The linewidths of the hybrid modes *k*+*,* are an average of the linewidth of the cavity *kc* and of the ma-

hybrid modes are more sensitive to the power deposited by

### OUTPUT AND NOISE POWER

$$
P_{\text{out}} \simeq 6 \times 10^{-30} \left(\frac{m_a}{200 \text{ }\mu\text{eV}}\right)^3 \left(\frac{V_s}{10^{-3} \text{ cm}^3}\right) \left(\frac{n_s}{2 \times 10^{28} \text{ m}^{-3}}\right) \left(\frac{\tau_{\text{min}}}{0.2 \text{ }\mu\text{s}}\right) \text{ W}
$$

Johnson noise uncertainty:

Johnson noise uncertainty:

\n
$$
\delta P = k_B T_{\text{sys}} \sqrt{\frac{\Delta \nu}{t}} \sim 5 \times 10^{-23} \text{ W}
$$
\n
$$
\begin{pmatrix}\nT_{\text{sys}} = 1 \text{ K} \\
v = 48 \text{ GHz} \\
t = 1 \text{ h}\n\end{pmatrix}
$$

take as an example

$$
\left(\begin{array}{c}\nT_{sys} = 1 K \\
v = 48 GHz \\
t = 1 h\n\end{array}\right)
$$

### RESULTS

Eur. Phys. J. C (2018) 78:703 https://doi.org/10.1140/epjc/s10052-018-6163-8 **THE EUROPEAN** CrossMark PHYSICAL JOURNAL C

Regular Article - Experimental Physics

#### Operation of a ferromagnetic axion haloscope at  $m_a = 58 \mu eV$

N. Crescini<sup>1,2,a</sup> ®, D. Alesini<sup>3</sup>, C. Braggio<sup>1,4</sup>, G. Carugno<sup>1,4</sup>, D. Di Gioacchino<sup>3</sup>, C. S. Gallo<sup>2</sup>, U. Gambardella<sup>5</sup>, C. Gatti<sup>3</sup>, G. Iannone<sup>5</sup>, G. Lamanna<sup>6</sup>, C. Ligi<sup>3</sup>, A. Lombardi<sup>2</sup>, A. Ortolan<sup>2</sup>, S. Pagano<sup>5</sup>, R. Pengo<sup>2</sup>, G. Ruoso<sup>2,b</sup> o, C. C. Speake<sup>7</sup>, L. Taffarello<sup>4</sup>



- 5 YIG spheres (1mm)
- $\tau_{hybr} \approx 0.11 \,\mu s$
- $T_{sys} \approx (4 + 11) K$

 $B = 0.5$  T **COL** 

 $\Box$  $t \approx 2.3 h$ 





 $m_a = 58 \text{ }\mu\text{eV}$  $\sum_{i=1}^n a_i = \infty$  for  $\mu$ 

 $\mathcal{L} = 11 \, \text{C}$ U-cm3. The green shaded area is excluded as  $\mathcal{L} = 11 \, \text{C}$  $f = 14 \text{ } GHz$ 

### RECENT RESULTS

#### arXiv:2001.08940

#### Axion search with a quantum-limited ferromagnetic haloscope

N. Crescini,<sup>1, 2, \*</sup> D. Alesini,<sup>3</sup> C. Braggio,<sup>2, 4</sup> G. Carugno,<sup>2, 4</sup> D. D'Agostino,<sup>5</sup> D. Di Gioacchino,<sup>3</sup> P. Falferi,<sup>6</sup> U. Gambardella,<sup>5</sup> C. Gatti,<sup>3</sup> G. Iannone,<sup>5</sup>

 $d = 10^{-11}$  is 5*.5*  $\mu$  axion-time, corresponding to a limit on the axion-time, corresp  $g_{aee} \leq 1.7 \times 10^{-11}$  at 95% CL.

 $\overline{\phantom{a}}$  ferromagnetic axion haloscope searches for Dark Matter in the form of axions by exploiting by exploiting  $\overline{\phantom{a}}$ 

their interaction with electronic spins. It is composed of an axion-to-electromagnetic field transducer  $\mathcal{L}$ coupled to a sensitive ref detector. The former is a photon-magnon hybrid system, and the latter  $\alpha$ is based on a quantum-limited Josephson parameter. The hybrid system  $\mathcal{L}_\text{max}$  $2.1$  mm diameter  $\mathcal{L}_\mathrm{M}$  spheres coupled to a single microwave cavity mode by means of a static mode by means magnetic field. Our setup is the most sensitive realized  $\epsilon$  spin-magnetometer ever  $r$ 



#### Quax – magnetized media



# SEARCHING AXIONS THROUGH PRIMAKOFF CONVERSION

−<br>−1

systematic disturbances.

reported in blue. A part of the bandwidth was removed due to

 $\overline{\phantom{a}}$  for  $\overline{\phantom{a}}$  ,  $\overline{\phantom{a$ 

×

degree 5 polynomial to account for the off-resonance particle

#### NO NEED FOR A TITLE EEL  $\frac{1}{\sqrt{2}}$ We set the magnetic field to 2 T and measured the cavity of 2 T and measured the cavity of 2 T and measured the

<sup>−</sup><sup>10</sup> <sup>10</sup> <sup>−</sup><sup>9</sup> <sup>10</sup> <sup>−</sup><sup>8</sup> <sup>10</sup> <sup>−</sup><sup>7</sup> <sup>10</sup> <sup>−</sup><sup>6</sup> <sup>10</sup> <sup>−</sup><sup>5</sup> <sup>10</sup> <sup>−</sup><sup>4</sup> <sup>10</sup> <sup>−</sup><sup>3</sup> <sup>10</sup> <sup>−</sup><sup>2</sup> <sup>10</sup> <sup>−</sup><sup>1</sup> <sup>10</sup> <sup>1</sup> <sup>10</sup> <sup>2</sup> <sup>10</sup>

QCD

<sup>−</sup><sup>16</sup> 10



 $\mathcal{F}_{\mathcal{A}}$  fig.  $\mathcal{F}_{\mathcal{A}}$  is the axion-photon coupling. The axion-photon coupling. The reduced  $\mathcal{F}_{\mathcal{A}}$ 

geneous magnetic field of intensity *B<sup>e</sup>* to trigger the conversion of DM axions into photons. Figure 14

$$
P_{\rm a} = 1.85 \times 10^{-25} \,\mathrm{W} \left(\frac{V}{0.0361}\right) \left(\frac{B}{2\,\mathrm{T}}\right)^2 \left(\frac{g_{\gamma}}{-0.97}\right)^2 \left(\frac{C}{0.589}\right) \left(\frac{\rho_{a}}{0.45\,\mathrm{GeV}\,\mathrm{cm}^{-3}}\right) \left(\frac{\nu_{c}}{9.067\,\mathrm{GHz}}\right) \left(\frac{Q_{L}}{201000}\right) \qquad \mathrm{C} \times V = \mathrm{effective\ volume}
$$

 $\equiv$   $\equiv$   $\equiv$   $\equiv$ 

:

### COPPER AT HIGH FREQUENCIES



### **• Performance of copper** saturates at a certain temperature

**•** Performance of copper decreases with frequency



of the mode TM010 are parallel to the applied field, were coated, as evidenced by the different colors of the different colors of the lower different colors of the lower

urement of the reflection and transmission and transmission waveforms,  $\mathcal{L}_{\mathcal{A}}$ 

#### SUPERCONDUCTING CAVITIES - NbTi **SUPERCUIY** WIDED CONDINICTING WERCONDUCTIN and that the superconductor is in the flux flow state [21]. UMVITILJ = IND IT

 $[PRD 99, 101101(R) (2019)]$  $\pi$ modes resonant frequencies are inversely proportional proportional proportional propor- $[PRD 99, 101101(R) (2019)]$ 

tivity [13].<br>Tivity [13].





factor of approximately 3.3 better than a copper cavity.  $C$  and  $\mathcal{L}_\mathcal{F}$  and  $\mathcal{L}_\mathcal{F}$  and  $\mathcal{L}_\mathcal{F}$  and  $\mathcal{L}_\mathcal{F}$  and  $\mathcal{L}_\mathcal{F}$  and  $\mathcal{L}_\mathcal{F}$  and  $\mathcal{L}_\mathcal{F}$ 







## PHOTONIC CAVITY

#### arXiv:2002.01816 <sup>3</sup>

- $Q_0 = 290\,000$ , TM010 mode at  $v_c \approx 13.6\,GHz$
- **FIG. 36 sapphire rods of 2mm diameter** and the field of the field resonant modes: TM010 (a) and TM011 (b).

FIG. 2. Magnitude of the electric field of the first two TM

- No concern about spoiling superconductivity with  $\Box$ high magnetic fields ng suberconductivity wit  $\overline{\phantom{a}}$  No concern about spoiling superconductivity with  $\overline{\phantom{a}}$  $\begin{bmatrix} 10^{-9} \end{bmatrix}$
- $C_{nml} \times V$  comparable with copper cavities of same  $v$  $\alpha$  copper cavities of same  $\nu$   $\parallel$   $\rightarrow$ **P**  $\frac{1}{2}$  = 2<sup>.3</sup> *·* 2.4 **·** 2.4 **·** 2.4 **·** 2.4 **·** 2.5  $\mathbb{R}$  C  $\sim$   $\times$  U comparable with copper cavities  $em<sub>l</sub>$  value volume of the system of the system, essential to deduce the system of the system. and  $C_{mnl} \times V = 2.3 \cdot 10^{-5} \text{ m}^3$ able with copper cavities of same  $V = \begin{bmatrix} \frac{1}{3} \\ \frac{1}{3} \end{bmatrix}$  Spurious

TM011

TM010

■ Can be coupled to a JPA <sup>e</sup>↵ = 2*.*<sup>3</sup> *·* <sup>10</sup><sup>5</sup> <sup>m</sup><sup>3</sup>.



the one expected from simulations.





### cavities. In this paper, we deal with the last issue, presenting the result of a search for galactic axions using  $\sim$ haloscope based on a 36 cm $36$  NbTi superconducting cavity. The cavity worked at T  $_{\rm eff}$  in a  $2$   $_{\rm eff}$

PRD 99, 101101(R) (2019)



is a NbTi compensated solenoid, 15 cm bore and 50 cm height, generating a central field of 2 T with homogeneity better than 20 ppm on a 20-mm-long line along the central axis. A superconducting switch is installed to perform installed to perform  $\mathcal{L}$ measurements also in persistent current mode. The bias current of 50 A is supplied by a high-stability current of 50 A is supplied by a high-stability current of 50 A generator. The magnet and the vacuum chamber are immersed in a LHe bath at the temperature of 4.2 K. The cavity is instrumented with two antennas. A weakly coupled one is used to inject probe signals in the cavity with

axion a mass in the range  $\sim$  103   $\mu$ the monitoring of resonant cavity modes with frequency above 5  $G_{\rm eff}$  GHz, where several experimental experimental experimental experimental experimental experimental experimental experimental experimental experimental

limitations occur due to linear amplifiers, small volumes, and low quality factors of copper resonants of copp

### JPA + DILUTION PERFORMANCE



 $\mathcal{A} = \{ \mathcal{A} \mid \mathcal{A} \in \mathcal{A} \mid \mathcal{A} \neq \emptyset \}$  and  $\mathcal{A} = \{ \mathcal{A} \mid \mathcal{A} \neq \emptyset \}$ mounted in the experimental site at Laboratori Nazionali di Legnaro (LNL), which hosts an apparatus capable of searching for galactic axions [17]. The scheme of the apparatus is shown in Fig. 4. The SCC is inside a vacuum in Fig. 4. The SCC is inside a vacuum in SCC is inside chamber inserted in a superconducting magnet. The magnet

#### | IMPROVEMENTS height, impd $\bigcap$ iemeneit  $\blacksquare$  better than  $20$  ppm on a 20-mm-long than  $20$ axis. A superconduction is installed to perform room temperature amplifiers (A3I;Q) with G<sup>3</sup> ≃ 50 dB each and accuracy acquired by a 16  $\mu$  bit analog to digital converter (ADC) and  $\mu$ sampling at 2 MHz. The acquisition program controls both



the output of a resistor (RJ). The temperature of the resistor is kept constant by a heater and read by a thermometer.



## (OPTIMISTIC) CONCLUSION



## THANK YOU!

### The End.



backup





$$
C_{mnl} = \frac{\left[\int_V dV \mathbf{E}_{mnl} \cdot \mathbf{B}\right]^2}{VB^2 \int_V dV \epsilon_r E_{mnl}^2}
$$







TABLE I. Results of the measurements on the cavity.

### Photonic cavity, bead pulling





 $\mathcal{L}_\text{max}$  accordingly. Moreover, probably due to changes of the changes