QUAX – QUEST for AXIONS

CONCEPTS, STATUS AND PERSPECTIVES

Axion cosmology 2020 @ MIAPP
February 24th

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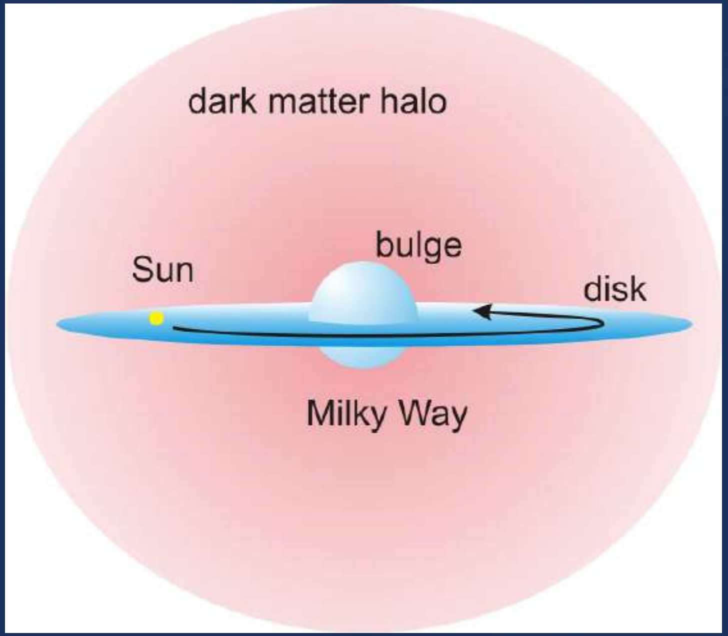
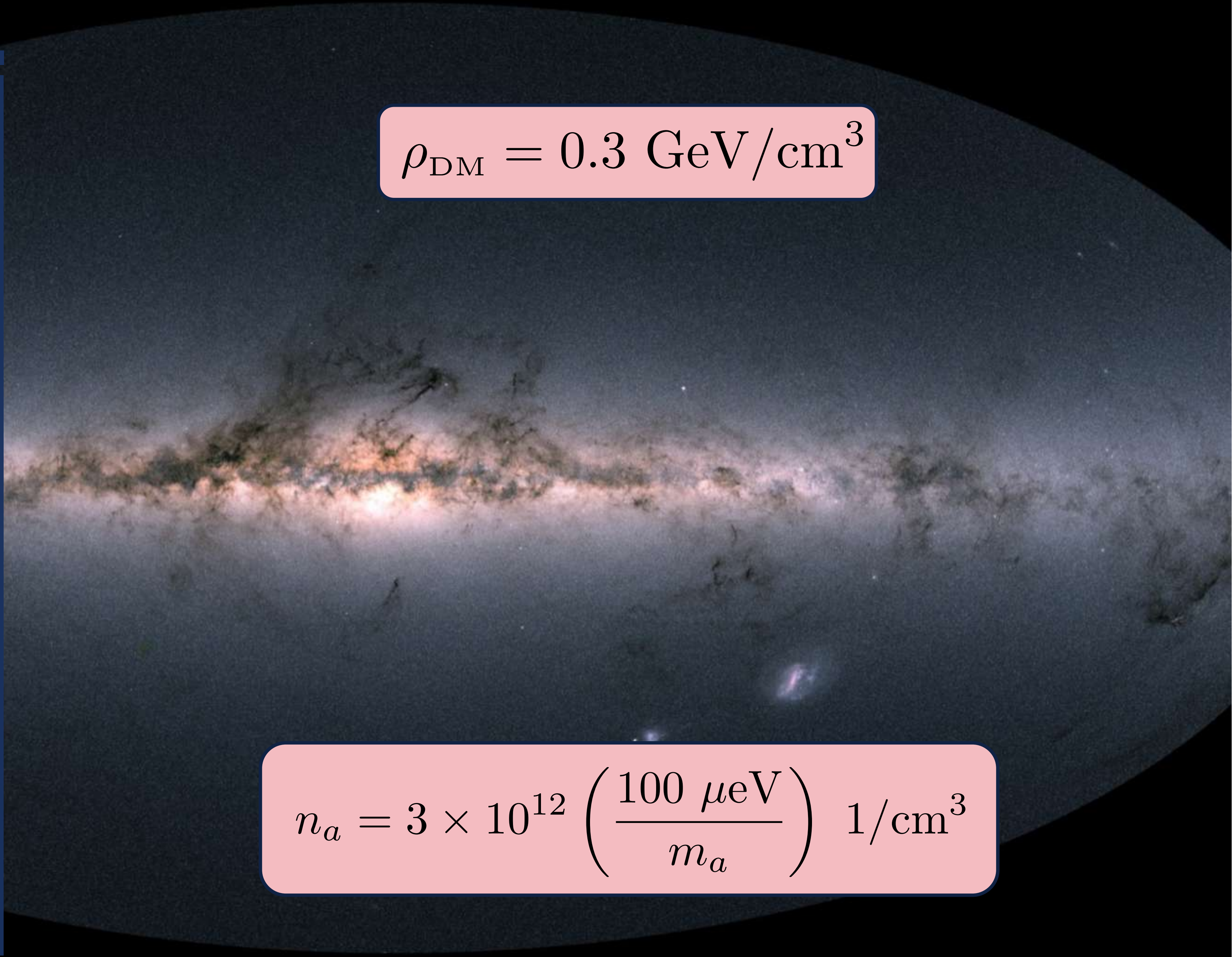
OUTLINE

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

INTRODUCTION

AXIONS IN $\Lambda\mathrm{CDM}$ MODEL





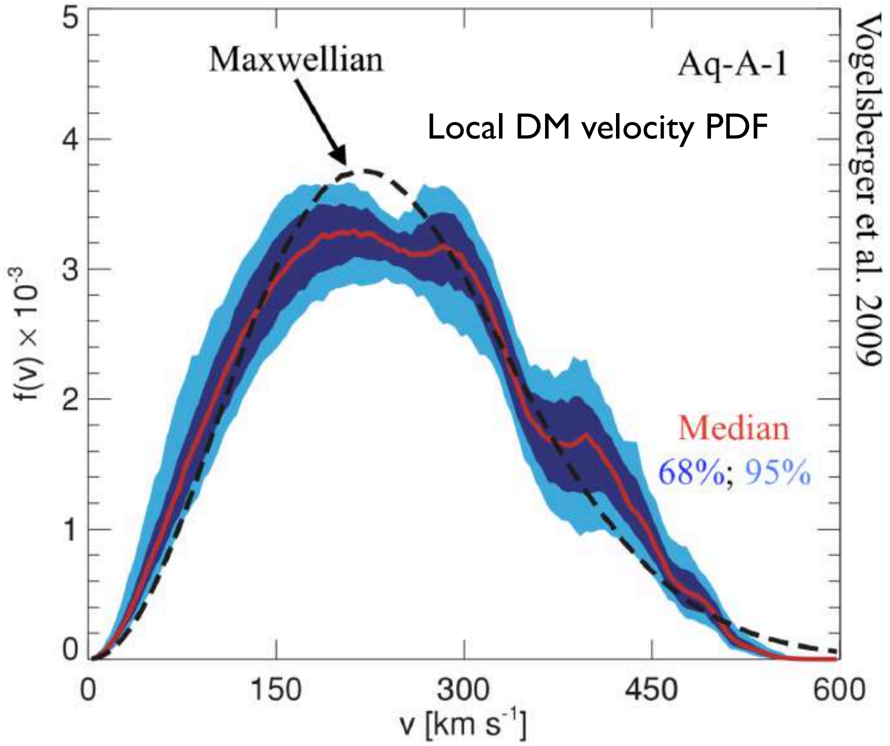
$$\rho_{\mathrm{DM}} = 0.3\ \mathrm{GeV/cm^3}$$

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

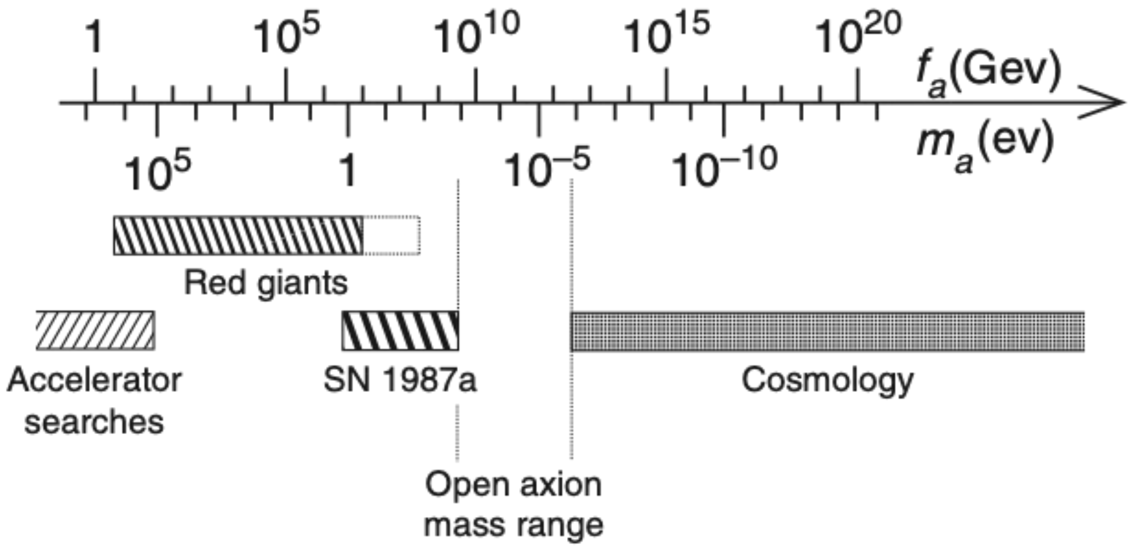
AXIONS IN ΛCDM MODEL

- Velocity distribution approximately Maxwellian
- Velocity dispersion $\sigma_v \approx 270\ \mathrm{km/s}$
- Axion linewidth $\delta E/E \approx 5.2 \times 10^{-7}$
- Axion figure of merit $Q_a \simeq 1.9 \times 10^6$

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



AXION WINDOW



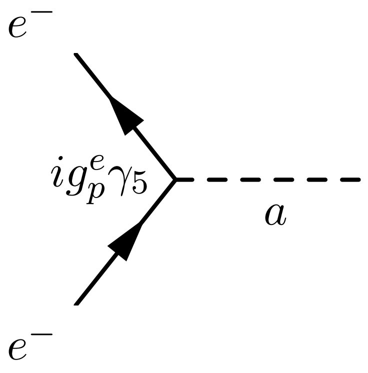
[C. Giunti, C. W. Kim]

$$10^{-6}\ \mathrm{eV} < m_a < 10^{-3}\ \mathrm{eV}$$

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

QUAX IS A HALOSCOPE

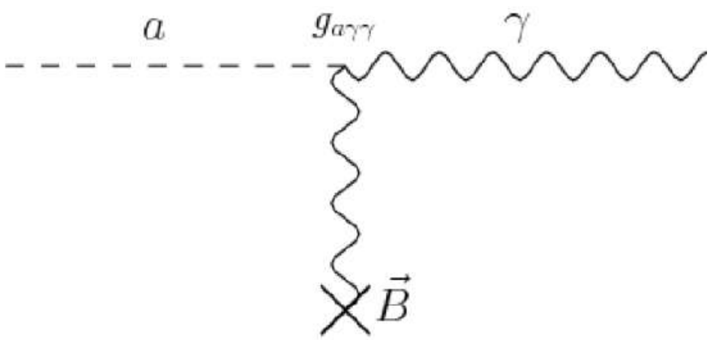
Axion-electron spin interaction



$\Longrightarrow$ Magnetized media

Resonant RF cavities

Axion-photon coupling

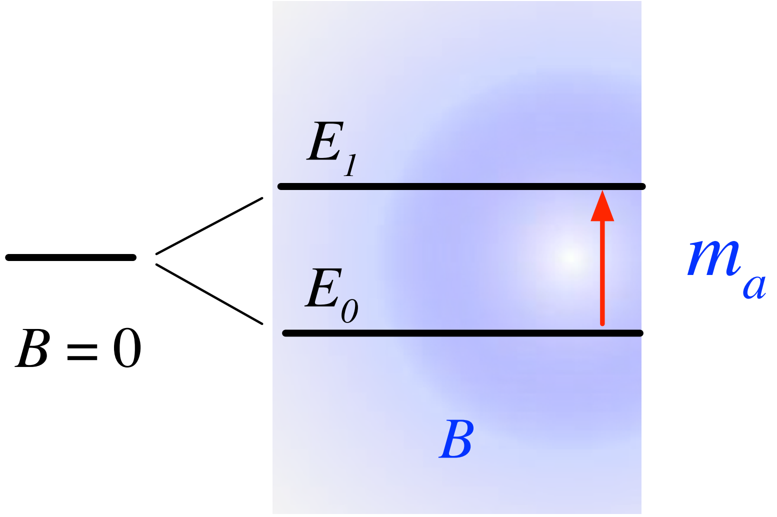


$\Longrightarrow$ Magnetic fields

SEARCHING AXIONS WITH MAGNETIZED MEDIA

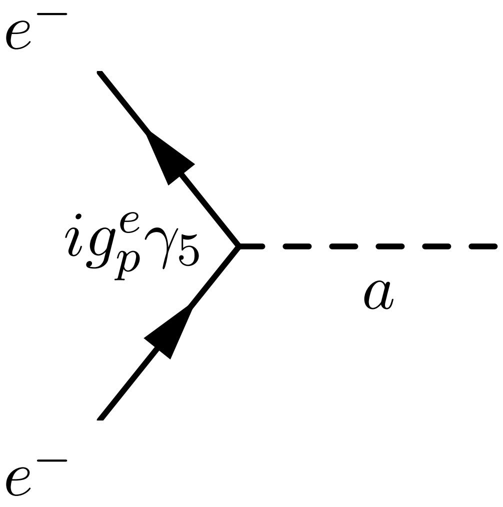
QUAX $a - e$

- Energy levels of a two-state system are split
- Think of an electron spin under the effect of magnetic field
- An axion tuned to the Larmor frequency causes a transition (generates a magnon in multi-spin system)
- Then the system relaxes emitting radiation



$$B_0 = \frac{\omega_L}{\gamma} = \frac{m_a c^2}{\gamma \hbar}$$

THE COUPLING



[Barbieri et al., Phys. Dark Univ. 15 (2017)]

$$L = \bar{\psi}(x)(i\hbar\gamma^\mu\partial_\mu - mc)\psi(x) - ig_p a(x)\bar{\psi}(x)\gamma_5\psi(x)$$

(DFSZ axions)

Euler-Lagrange equations in non-relativistic limit

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

$$-\frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a \equiv -2\frac{e\hbar}{2m}\boldsymbol{\sigma}\cdot\left(\frac{g_p}{2e}\right)\boldsymbol{\nabla}a$$

$-2\mu_B\boldsymbol{\sigma}$,

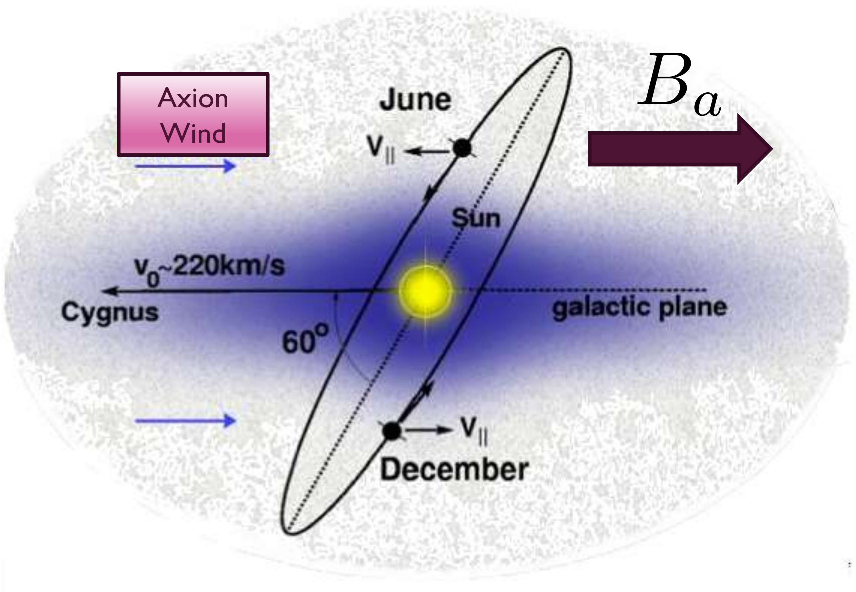
μ_B the Bohr magneton

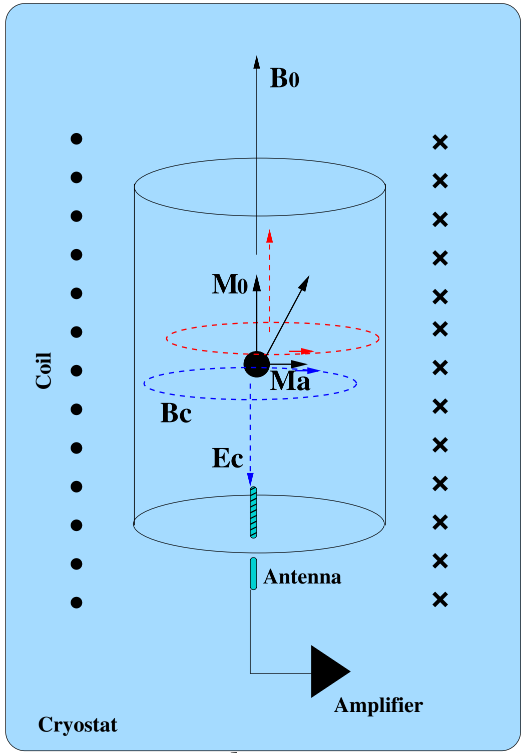
$$B_a \equiv \frac{g_p}{2e}\boldsymbol{\nabla}a$$

effective magnetic field

USE MAGNETIZED MATERIALS

$$-2\mu_B \boldsymbol{\sigma} \cdot \boldsymbol{B}_a$$





- $B_0 = 1.7 \left(\frac{m_a}{200\ \mu\text{eV}} \right)$ T
- $B_a = 2.0 \cdot 10^{-22} \left(\frac{m_a}{200\,\mu\text{eV}} \right)$ T
- $\frac{\omega_a}{2\pi} = 48 \left(\frac{m_a}{200\,\mu\text{eV}} \right)$ GHz

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

OUTPUT POWER

Axion properties

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

Experimental design

$n_s V_s$ = number of spins

τ_{min} = spin relaxation time (next slide)

LIMITING FACTORS

τ_{min} = minimum time between:

τ_1 spin-lattice relaxation time

τ_2 spin-spin relaxation time

τ_R radiation damping → Resonant cavity

τ_a axion decoherence time

$$\tau_1 > \tau_2$$

$$\tau_2 \sim 0.1 \ \mu\text{s}$$

$$\tau_c = \frac{Q}{\omega_a} \sim 10 \ \mu\text{s} \left(\frac{10 \text{ GHz}}{\omega_a}\right)\left(\frac{Q}{10^6}\right)$$

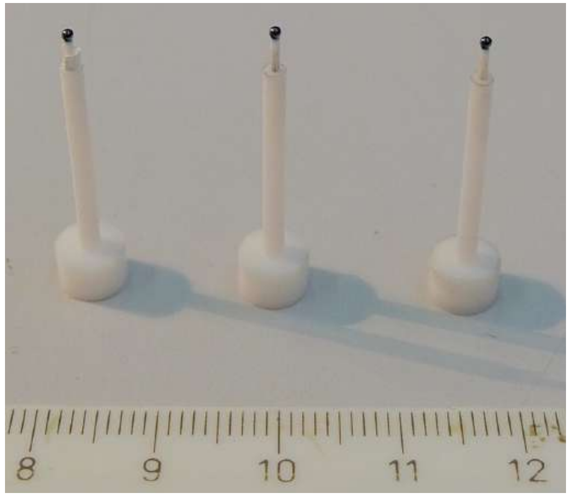
$$\tau_a = \frac{1.9 \times 10^6}{\omega_a} \sim 30 \ \mu\text{s} \left(\frac{10 \text{ GHz}}{\omega_a}\right)$$

YIG

Yttrium Iron Garnet

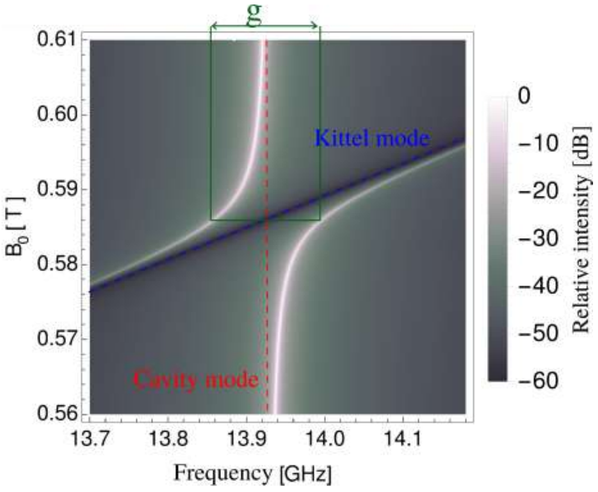
Synthetic garnet,
ferrimagnetic material

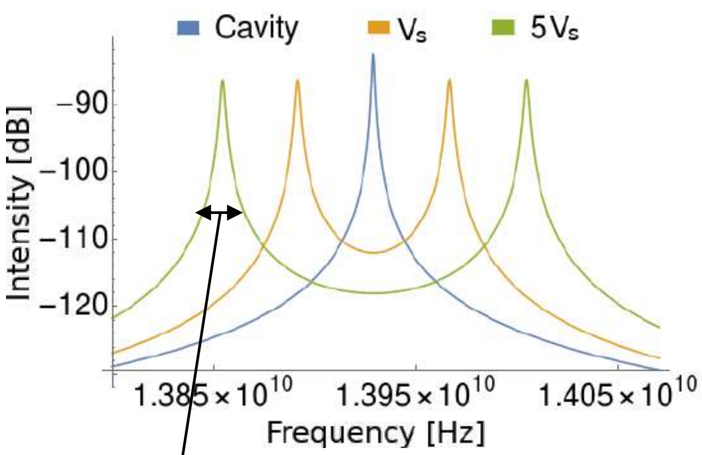
n_s	τ_2	Size	Linewidth
$\sim 2 \times 10^{28}\ \mathrm{m}^{-3}$	$\sim 0.2\ \mu\mathrm{s}$	Spheres of ϕ $1\ mm, 2\ mm$	$\sim 1\ \mathrm{MHz}$



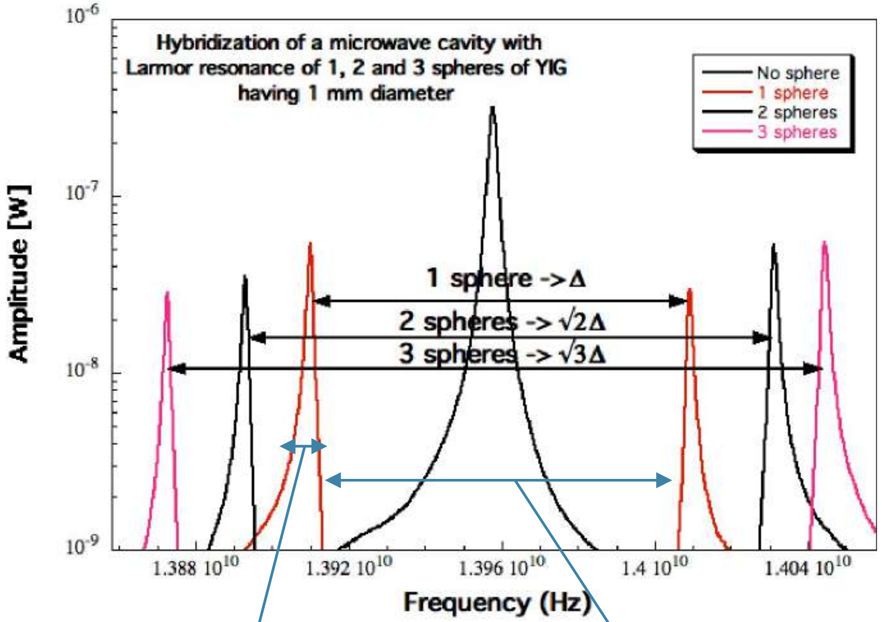
- When $\omega_c \simeq \omega_L$ the modes hybridize and the resonance splits into two

- Strong coupling regime:





$$k_{\text{hybr}} \simeq \frac{1}{2}(k_c + k_m)$$



$\sim 2\ MHz$ $\quad$ $\sim 600\ MHz$

OUTPUT AND NOISE POWER

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

Johnson noise uncertainty:

$$\delta P = k_B T_{\text{sys}} \sqrt{\frac{\Delta\nu}{t}} \sim 5 \times 10^{-23}\ \text{W}$$

take as an example

$$\begin{pmatrix} T_{sys} = 1\ K \\ \nu = 48\ GHz \\ t = 1\ h \end{pmatrix}$$

RESULTS

Eur. Phys. J. C (2018) 78:703
https://doi.org/10.1140/epjc/s10052-018-6163-8

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Experimental Physics

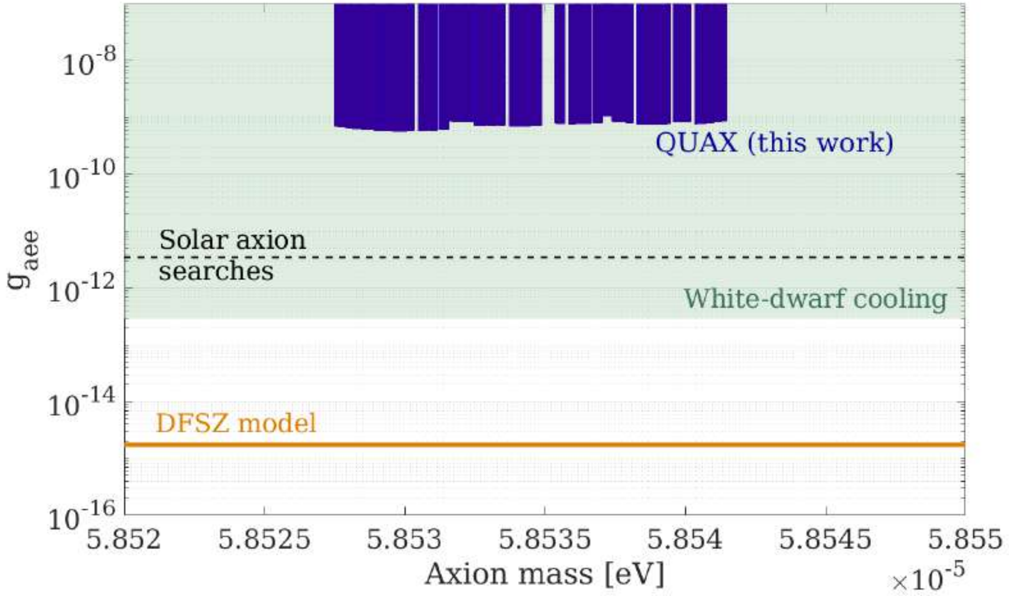
Operation of a ferromagnetic axion haloscope at $m_a = 58\ \mu\text{eV}$

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

- LHe thermal bath
  $T = 4\ K$
- HEMT amplifier
  $T_n = 11\ K$

- 5 YIG spheres (1mm)
- $\tau_{hybr} \approx 0.11\ \mu s$
- $T_{sys} \approx (4 + 11)\ K$
- $B = 0.5$ T
- $t \simeq 2.3\ h$

$g_{aee} < 4.9 \times 10^{-10}$ at 95% CL



$m_a = 58\ \mu\text{eV}$

$f = 14\ GHz$

RECENT RESULTS

arXiv:2001.08940

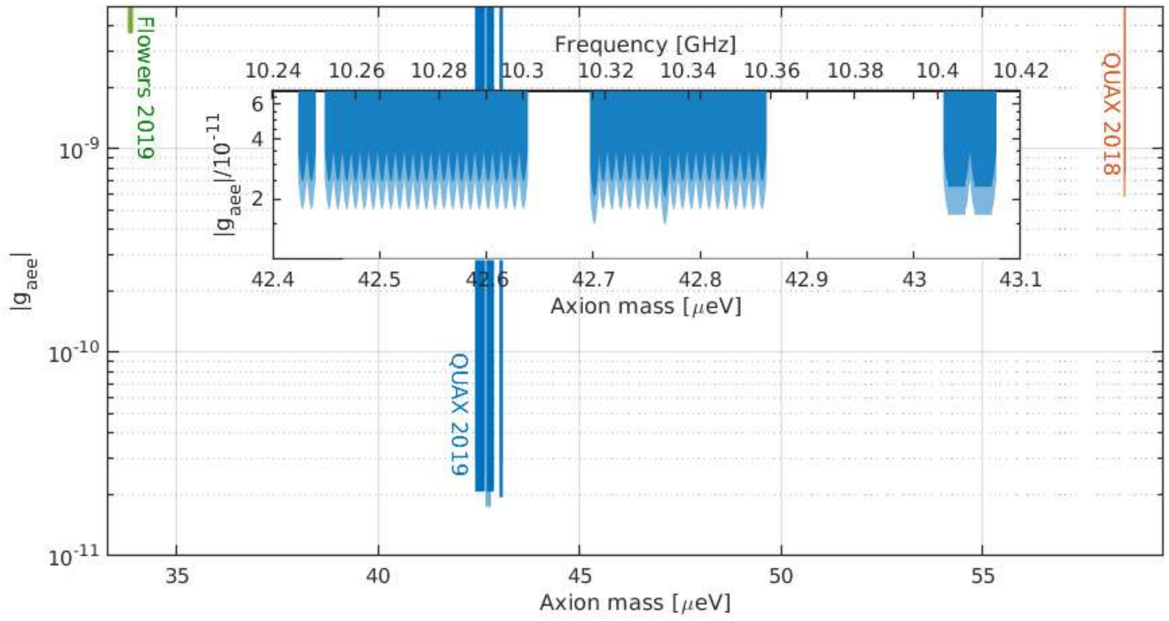
Axion search with a quantum-limited ferromagnetic haloscope

N. Crescini,[1,2,*] D. Alesini,[3] C. Braggio,[2,4] G. Carugno,[2,4] D. D'Agostino,[5]
D. Di Gioacchino,[3] P. Falferi,[6] U. Gambardella,[5] C. Gatti,[3] G. Iannone,[5]
C. Ligi,[3] A. Lombardi,[1] A. Ortolan,[1] R. Pengo,[1] G. Ruoso,[1,†] and L. Taffarello[7]
(QUAX Collaboration)

- Dilution refrigerator
  $T_{base} = 90\ mK$
- **JPA** amplifier
  $T_n = (0.5 \div 1)\ K$

- **10** YIG spheres (2,1mm)
- $\tau_{hybr} \approx 0.084\ \mu s$
- $T_{sys} \approx (0.12 + 0.99)\ K$
- $t \simeq 74\ h$
- $\nu_c \simeq 10.7\ GHz$

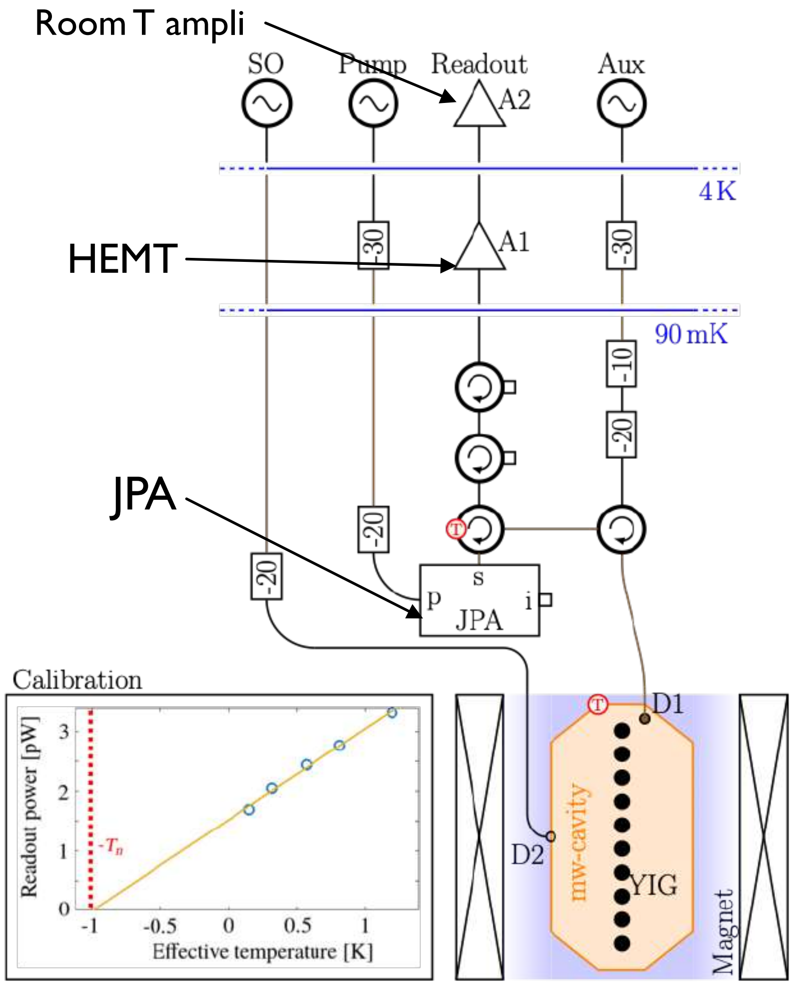
$g_{aee} \leq 1.7 \times 10^{-11}$ at 95% CL



$42.4\ \mu\text{eV} < m_a < 43.1\ \mu\text{eV}$

120 MHz span

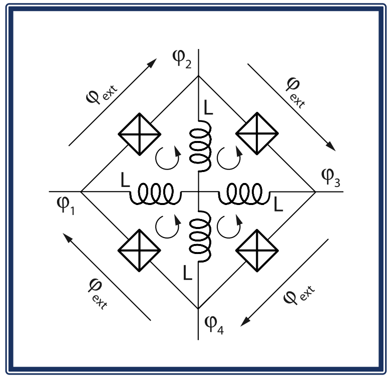
Quax – magnetized media



$T_{noise} \approx 1\ K$

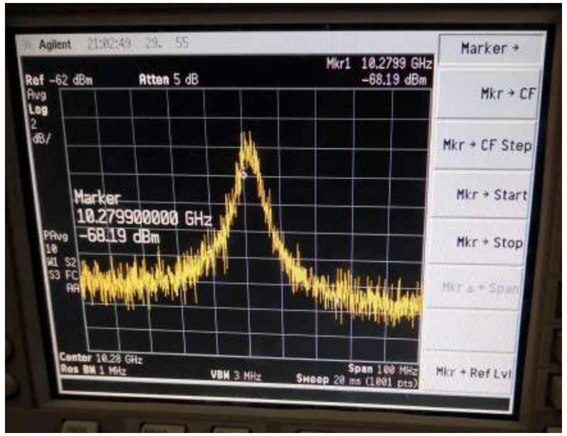
$G \approx 70\ dB$

[PRL 108, 147701 (2012)]



Pb

JPA resonance



Tunability
200-400 MHz

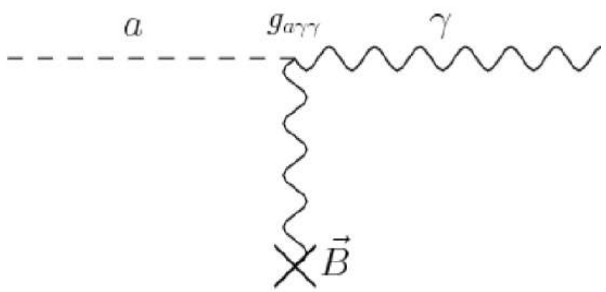
Bandwidth
$\sim 20\ MHz$

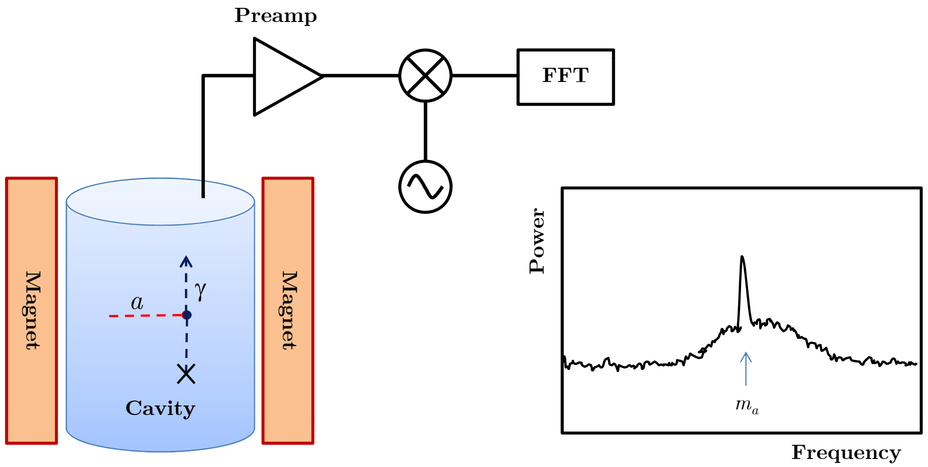
Peak height
$\sim 10\ dBm$

SEARCHING AXIONS THROUGH PRIMAKOFF CONVERSION

NO NEED FOR A TITLE

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma}a(x)\vec{E}\cdot\vec{B}$$





(image stolen from Javier)

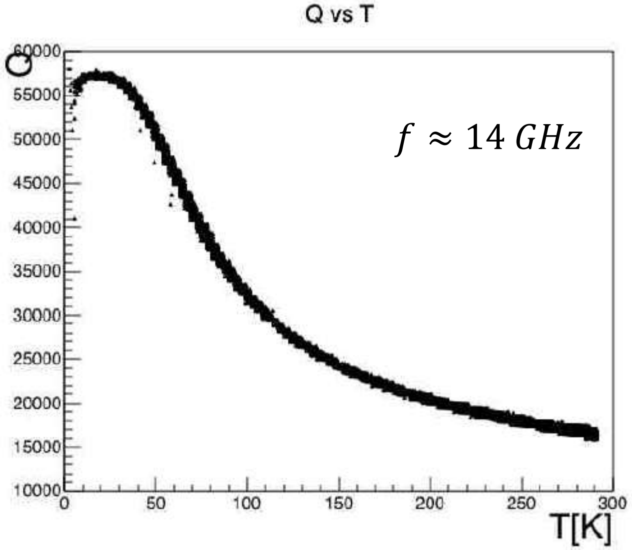
$$P_a = 1.85\times10^{-25}\,\mathrm{W}\left(\frac{V}{0.0361}\right)\left(\frac{B}{2\,\mathrm{T}}\right)^2\left(\frac{g_\gamma}{-0.97}\right)^2\left(\frac{C}{0.589}\right)\left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\nu_c}{9.067\,\mathrm{GHz}}\right)\left(\frac{Q_L}{201000}\right)$$

$C\times V$ = effective volume

$0 < C < 1$

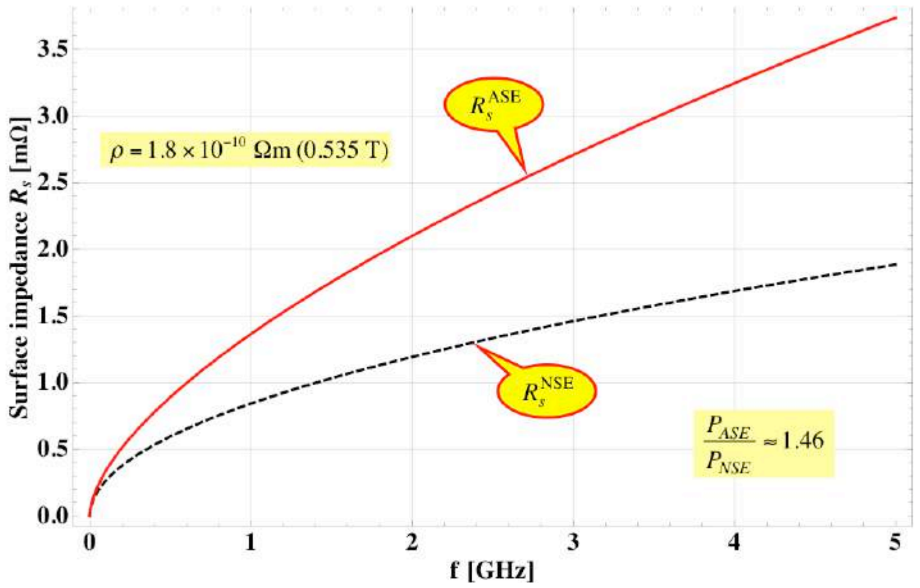
COPPER AT HIGH FREQUENCIES

- Performance of copper saturates at a certain temperature
- Performance of copper decreases with frequency



Anomalous skin effect:

arXiv:1108.1643

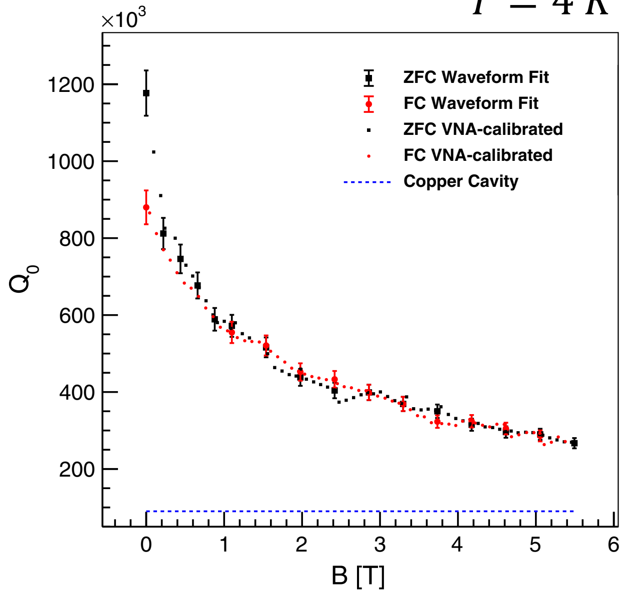


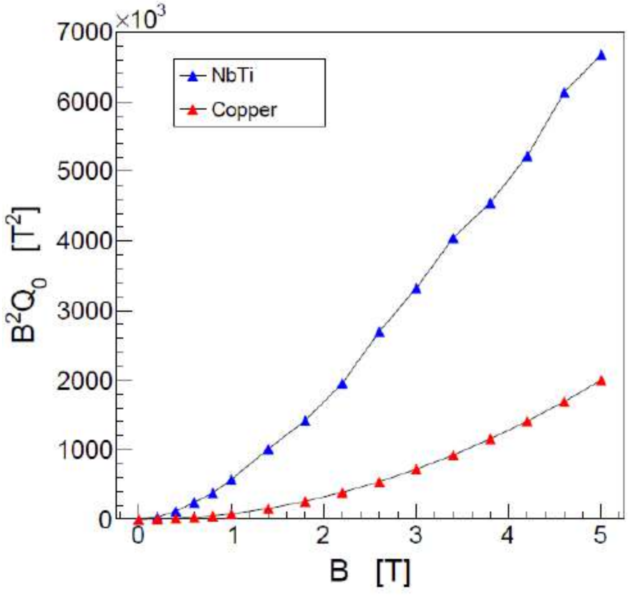
SUPERCONDUCTING CAVITIES - NbTi

[PRD 99, 101101(R) (2019)]

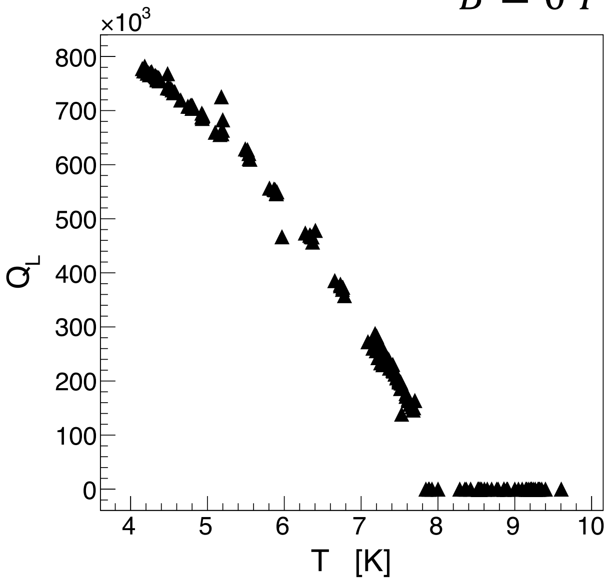
[IEEE TRANS. APP. SUPERCOND., 29, 5, (2019)]

$T = 4\ K$





$B = 0\ T$



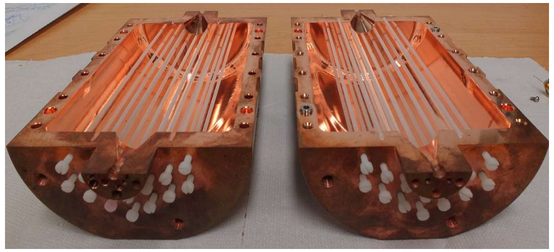
PHOTONIC CAVITY

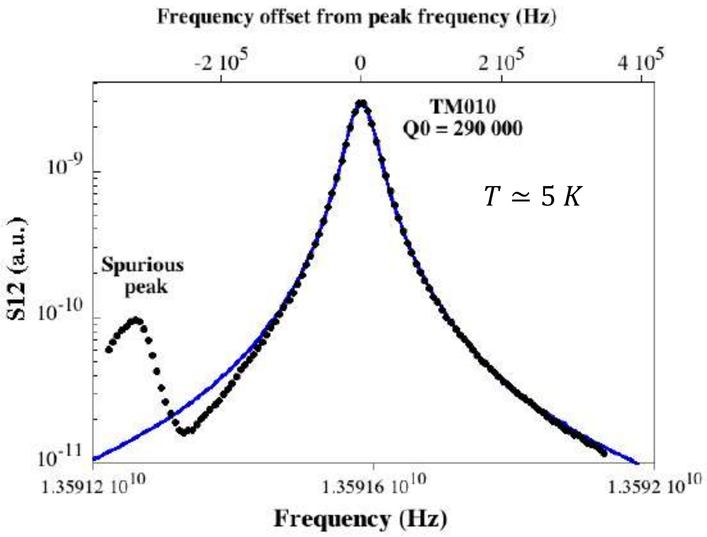
arXiv:2002.01816

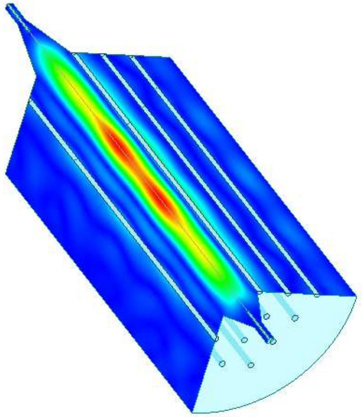
- $Q_0 = 290\ 000$, TM010 mode at $\nu_c \simeq 13{,}6\ GHz$
- 36 sapphire rods of 2mm diameter
- No concern about spoiling superconductivity with high magnetic fields
- $C_{nml} \times V$ comparable with copper cavities of same ν

$$C_{mnl} \times V = 2.3 \cdot 10^{-5}\ \mathrm{m}^3$$

- Can be coupled to a JPA

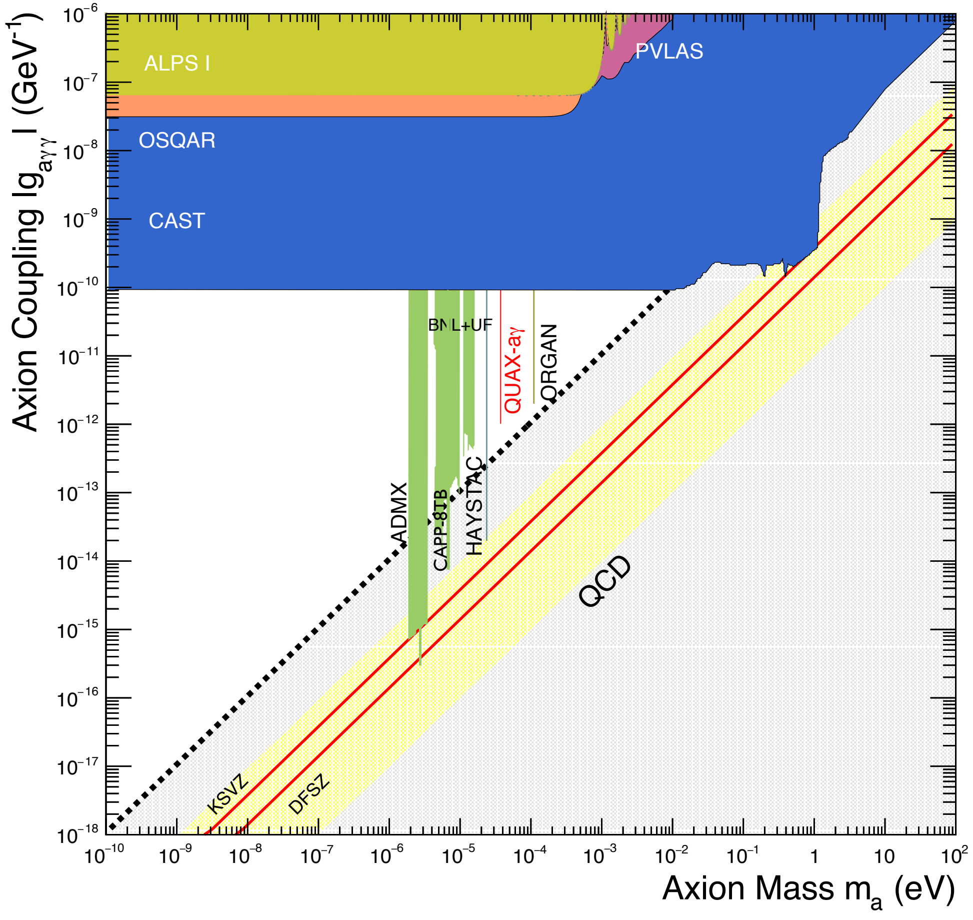






DEMONSTRATOR WITH NbTi

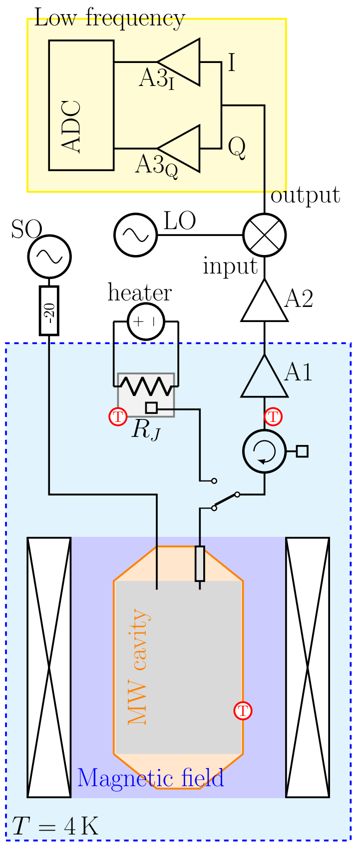
PRD 99, 101101(R) (2019)



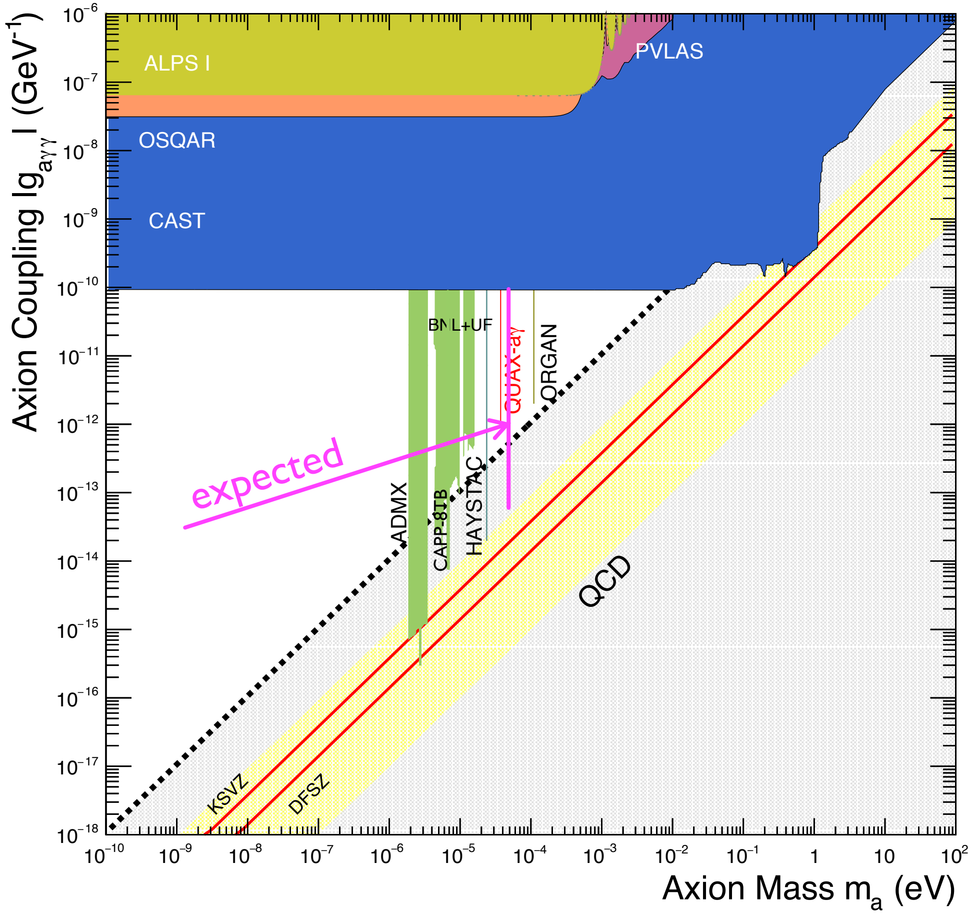
$$g_{a\gamma\gamma} < 1.03 \times 10^{-12}\ \mathrm{GeV}^{-1}$$
$$m_a = 37.5\ \mu\mathrm{eV}$$

$T_{sys} = (4 + 11)\ K$
$B = 2\ T$
$\nu = 9.07\ GHz$
$Q = 4{\times}10^5$
$t = 20\ min$
Linear ampli

- Lhe thermal bath $T = 4\ K$
- HEMT amplifier $T_n = 11\ K$
- $B = 2\ T$

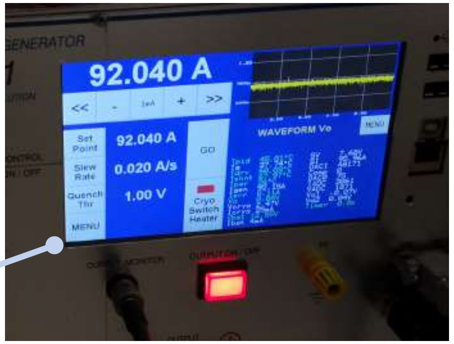


JPA + DILUTION PERFORMANCE



$$g_{a\gamma\gamma} < 6 \times 10^{-14} \text{ at } 1\ \sigma\ ??$$
$$m_a \simeq 43\ \mu\text{eV}$$

[data taking: Jan 2020]

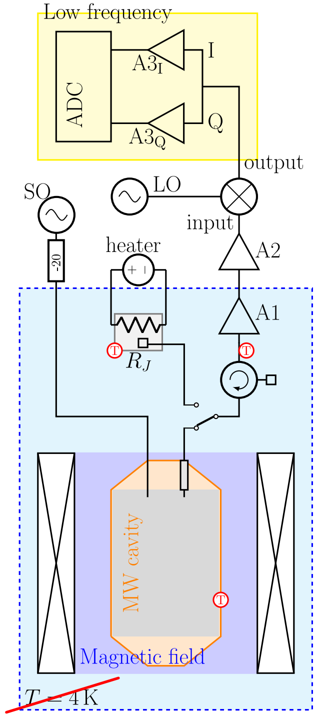


$T_{sys} = (0.12 + 1)\ K$
$B = 8.1\ T$
$\nu = 10.4\ GHz$
$Q = 76\ 000$
$t \approx 1\ h$
JPA

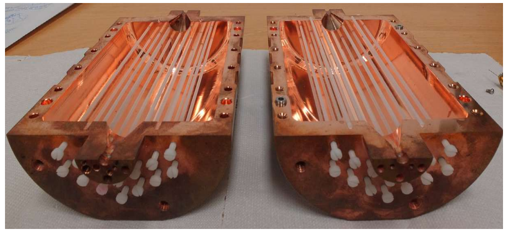
- Dilution refrigerator $T_{base} = 90\ mK$
- JPA amplifier $T_n = (0.5 \div 1)\ K$
- Higher B field $B = 8.1\ T$

IMPROVEMENTS

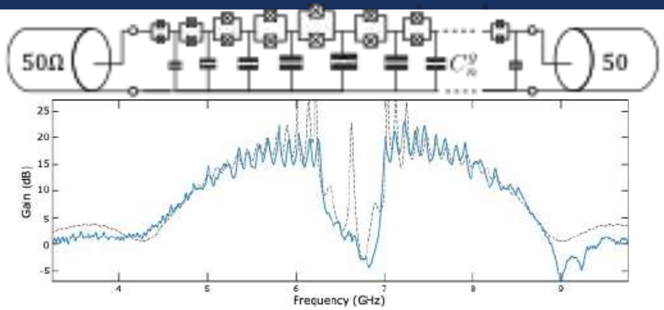
Build haloscope in Frascati!



8 mK

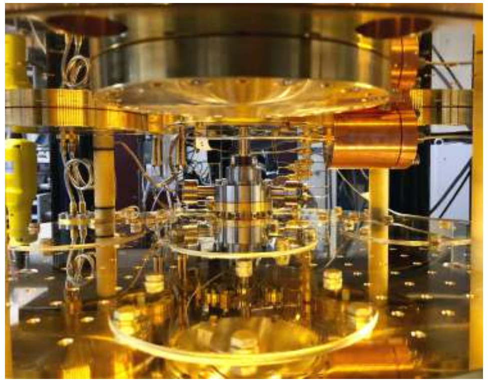


Other sapphire geometries

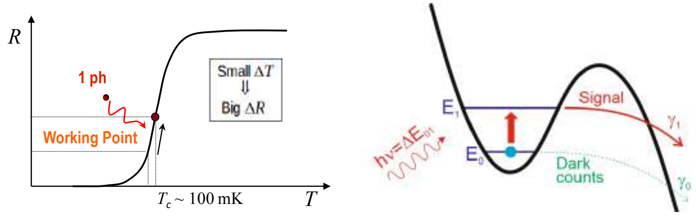


Travelling wave ampli, broader scan

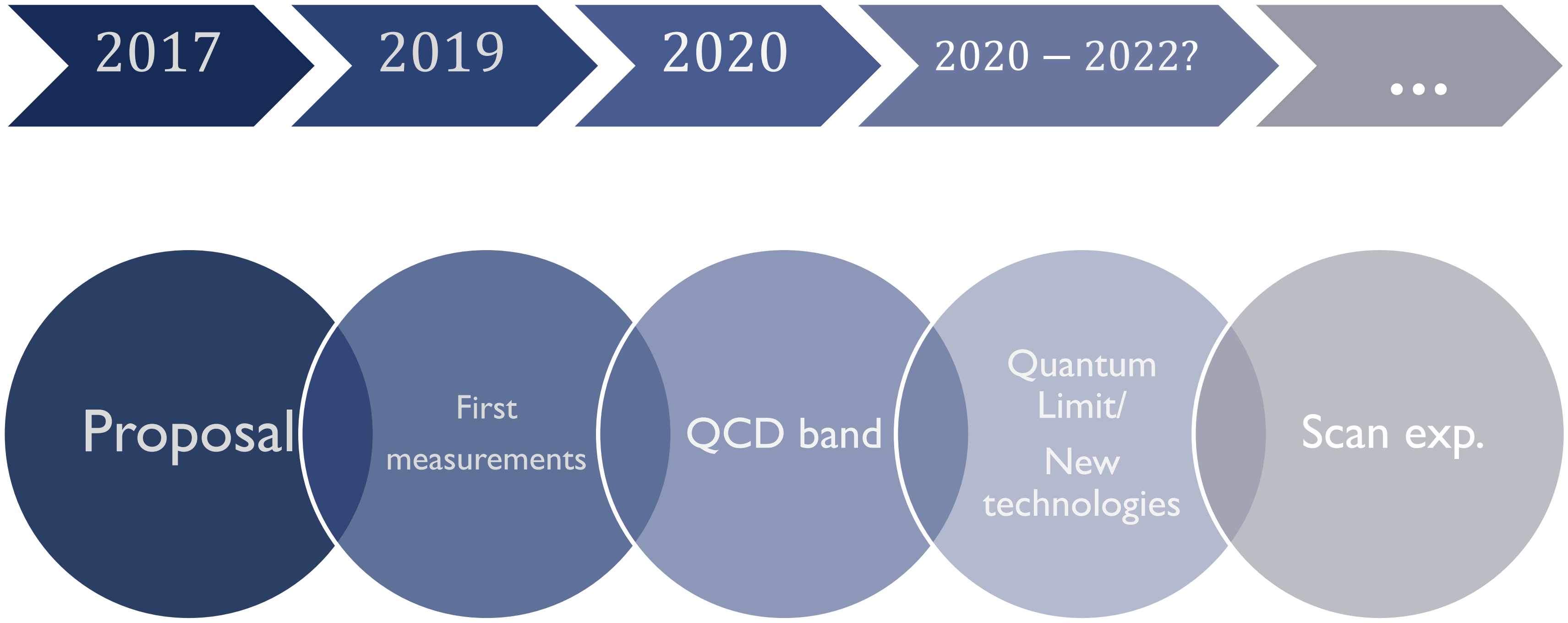
New fridge, 8 mK base temp.

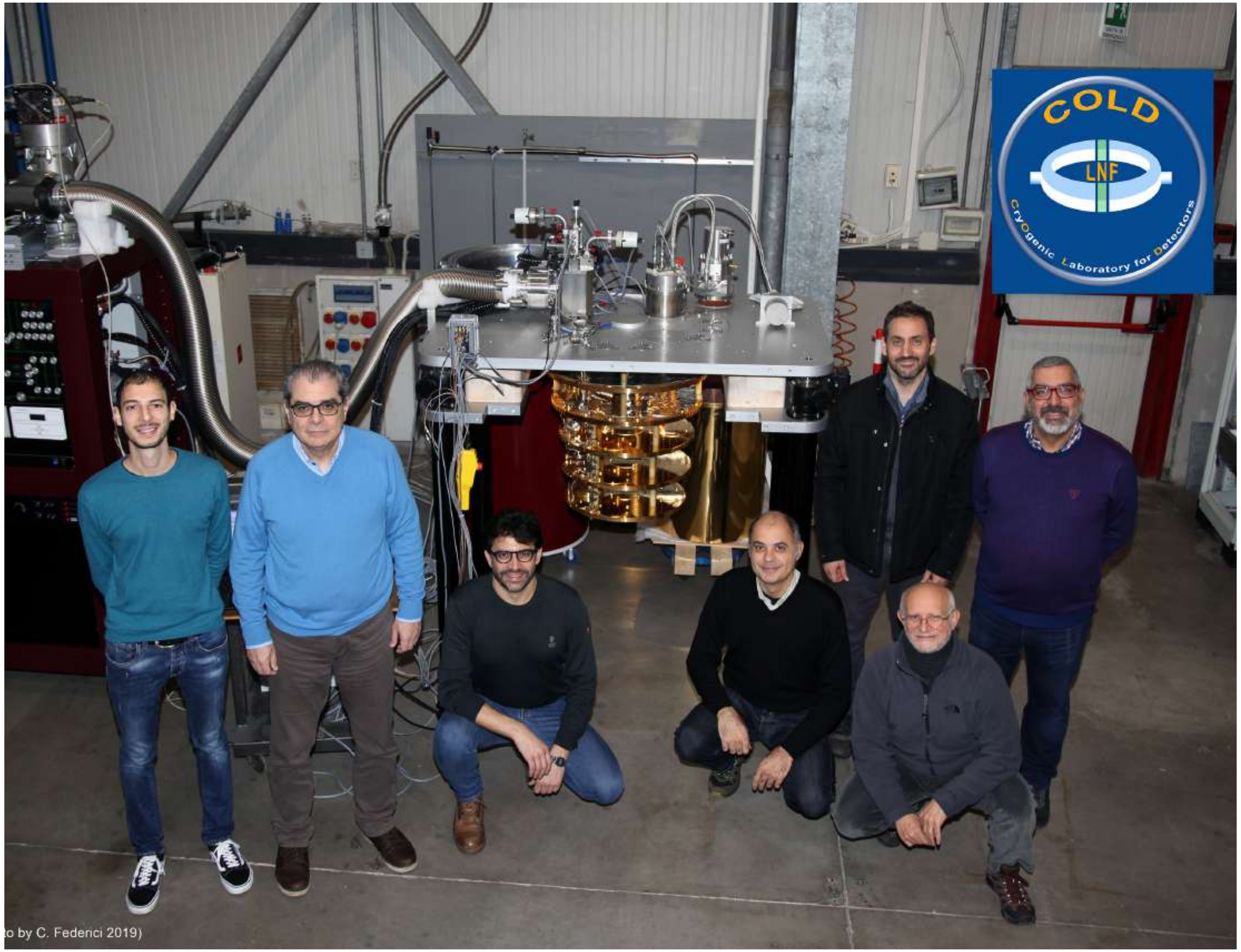


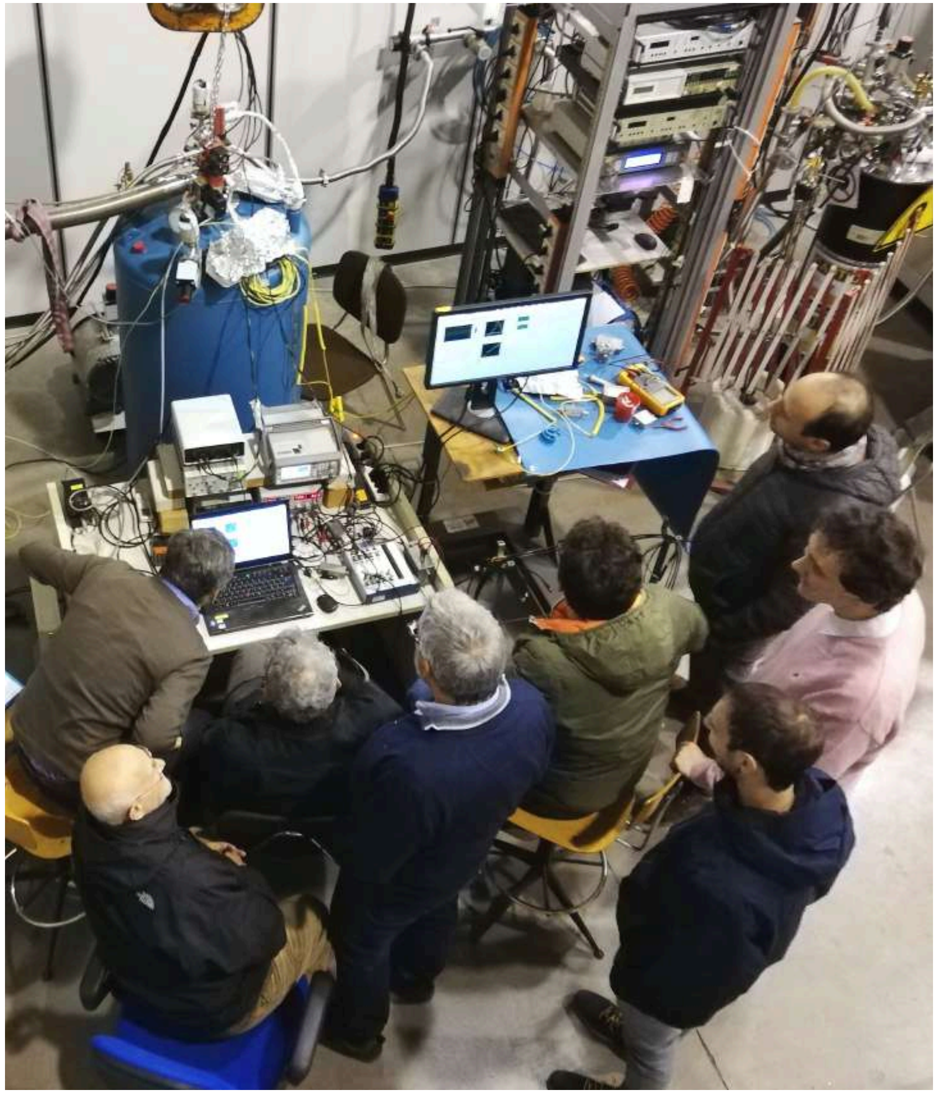
Single photon counter (SIMP project)



(OPTIMISTIC) CONCLUSION



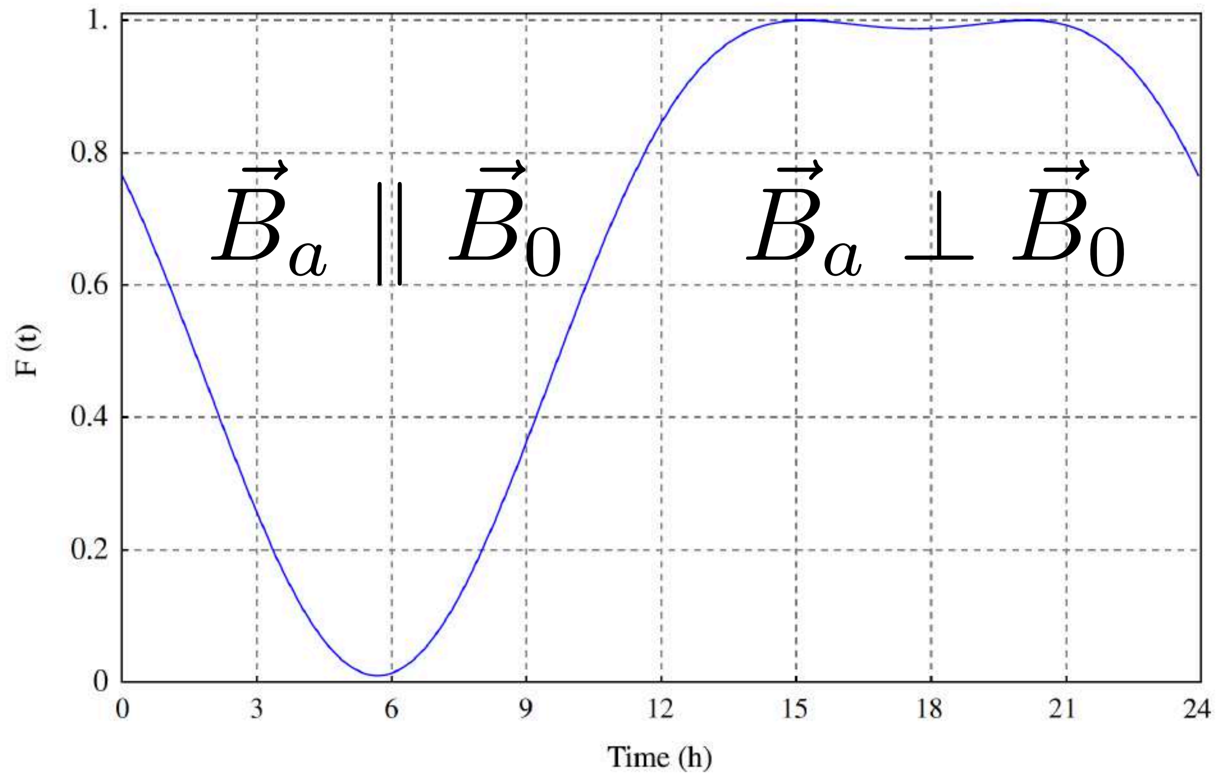

COLD
LNF
CryOgenic Laboratory for Detectors
to by C. Federici 2019)

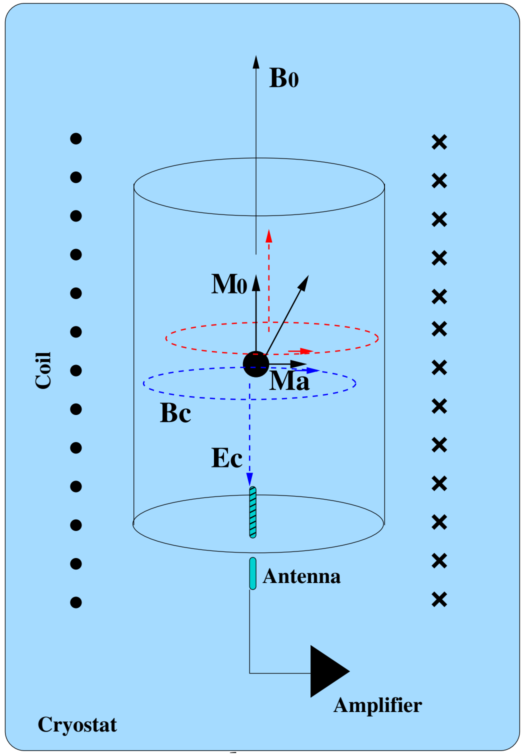


THANK YOU!

backup

Daily signal modulation

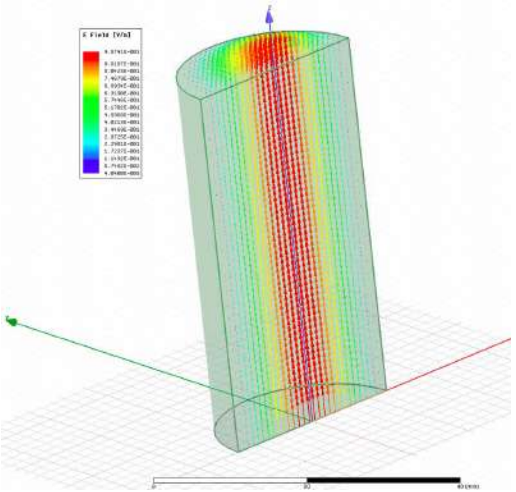




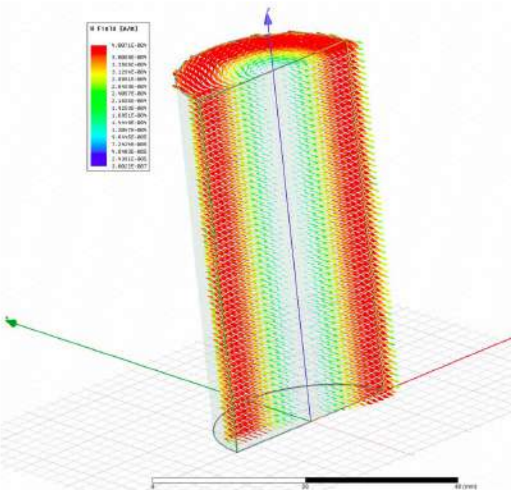
TM010

TM110

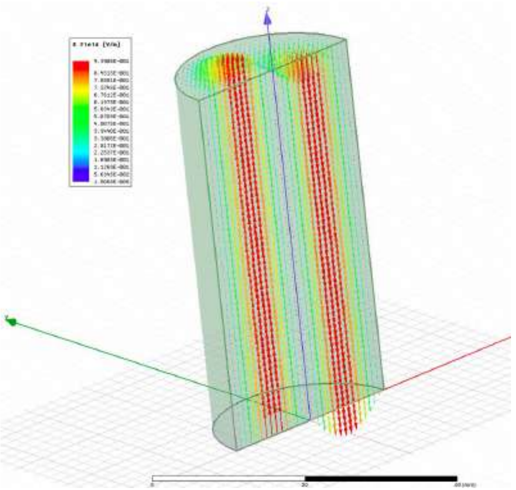
E field



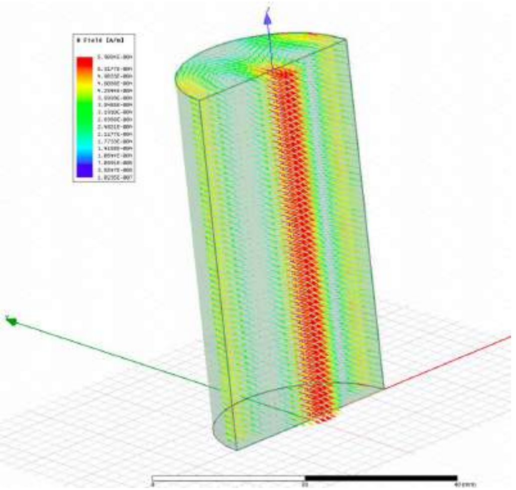
H field



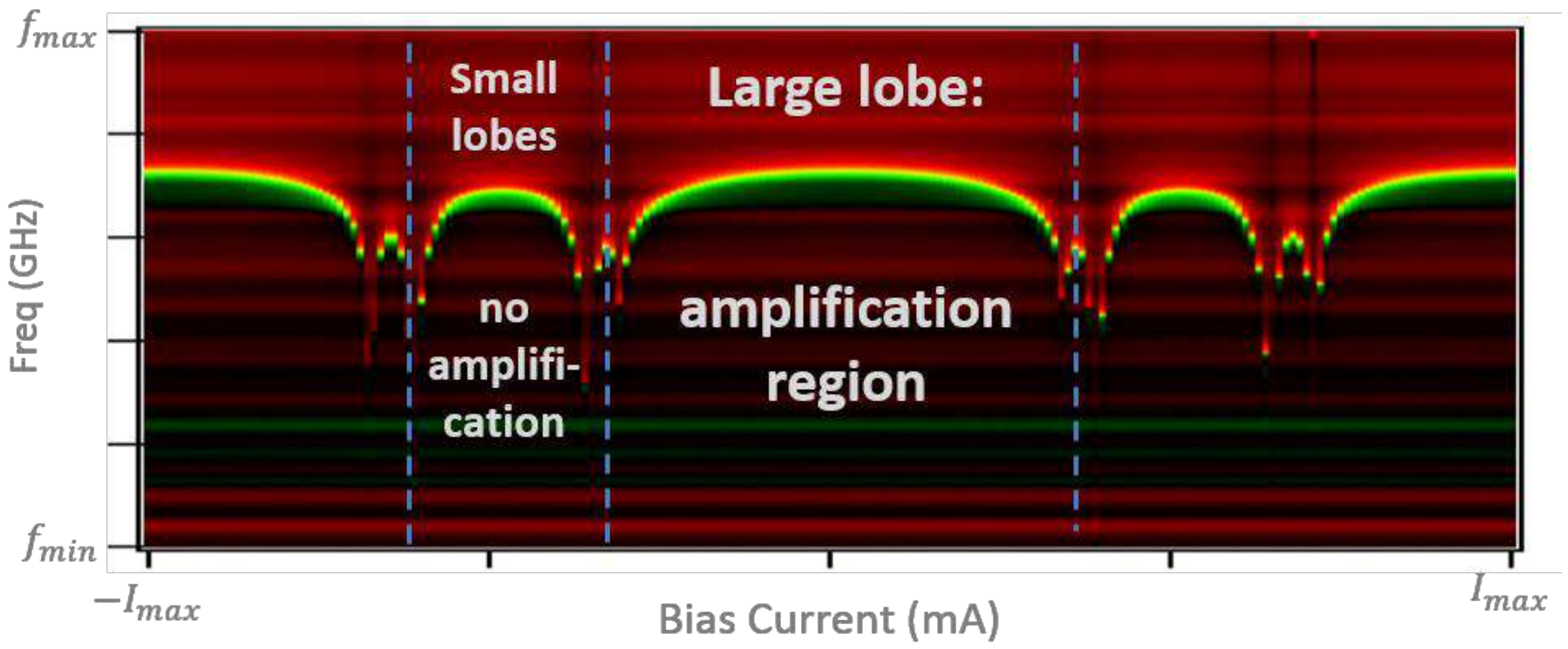
E field

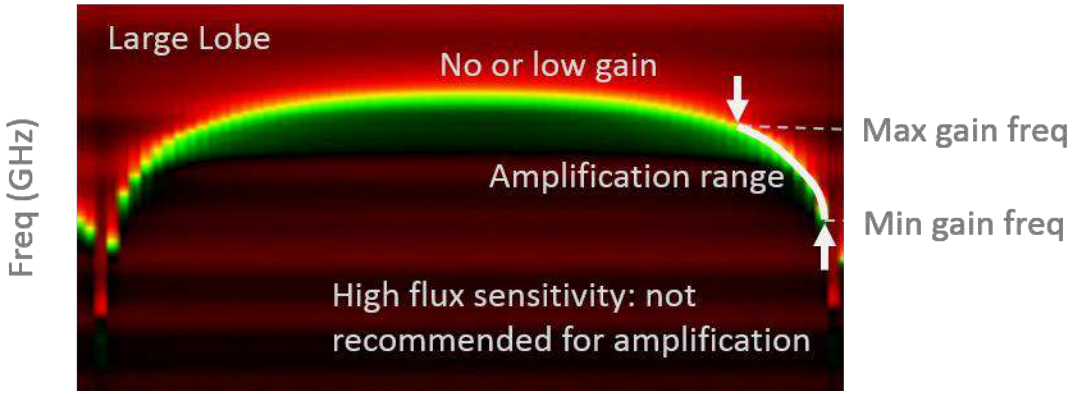


H field



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


f_{max}
f_{min}
Freq (GHz)
Small lobes
no amplifi-cation
Large lobe:
amplification region
$-I_{max}$
I_{max}
Bias Current (mA)


Freq (GHz)
Large Lobe
No or low gain
Max gain freq
Amplification range
Min gain freq
High flux sensitivity: not recommended for amplification

System	Cavity Temperature	TM010 Q_0	TM011 Q_0
Room T	298 K	173 000	94 000
Liquid He	5.5 K	290 000	520 000

Photonic cavity, bead pulling