Experimental Test of the Axion Paradigm using Quantum Sensing

Phase-Resolved Haloscope with Magnetic Tunability

Jeanne BALLY

PhD student in HQC's group, LPENS - LPEM

Exp : C. Fruy, K. Kodama, D. Diez, A. Théry, B. Hue, T. Fauvet, L. Jarjat, T. Philippe Kagan, M.R. Delbecq, T. Kontos
Theory : A. Cottet
RADES Collaboration : I. Irastorza, S. Paraonau, W. Wernsdorfer (Dark Quantum) + B. Döbrich, A. Lindner…

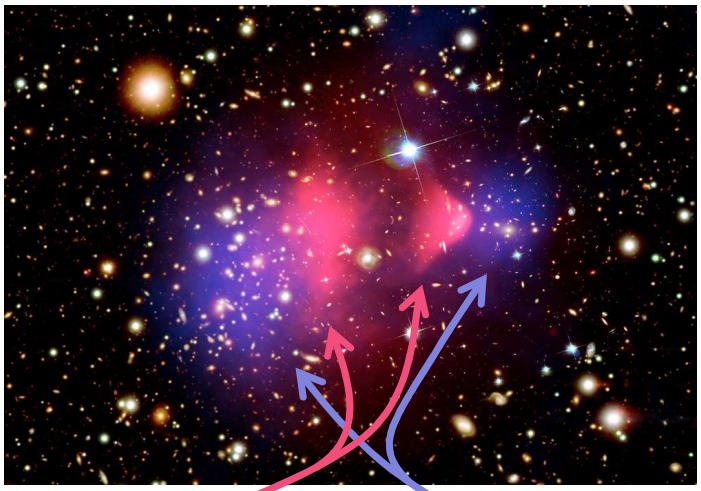
DarkQuantum

22/04/2026

The Dark Universe

Dark matter: hypothetical matter that interacts weakly ordinary matter.

The bullet cluster (ESA)

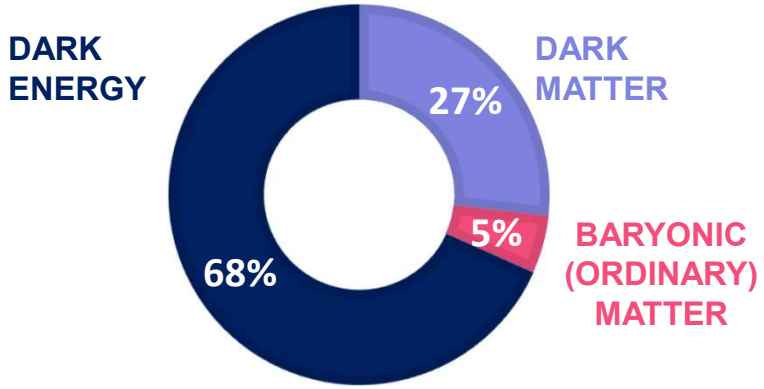


X-ray: NASA/CXC/CfA/M.Markevitch Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe Lensing map: ESO WFI

Hot intracluster gas detected in **X-ray** (contains most of the baryonic matter)

Gravitational lensing detected mass

Estimated matter-energy content of the Universe :



➨ Non-zero local dark matter density, with extremely weak interactions with standard matter

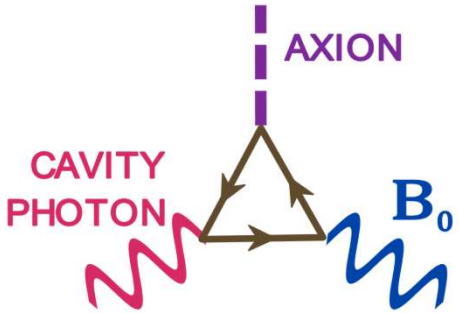
The **AXION** particle
➨ good Dark Matter candidate

The Axion Particle

- Solve the strong charge-parity (CP) problem
- Peccei-Quinn solution: spontaneous breaking of symetry

R.D. Peccei and H.R. Quinn, PRL'77, Weinberg, PRL'78, Wilczek, PRL'78…

Primakoff effect

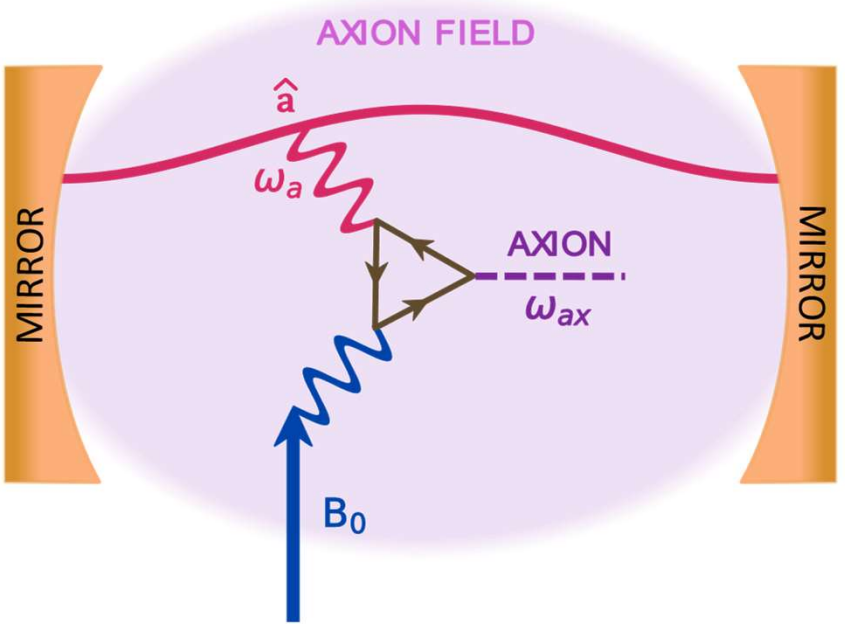


Lagrangian **axion–photon interaction term**:

$$g_{\alpha\gamma\gamma}\,\Phi_{ax}\cos(\omega_{ax}t)\,\vec{E}\cdot\vec{B}_0$$

P. Sikivie, PRL 51, 1415 (1983)

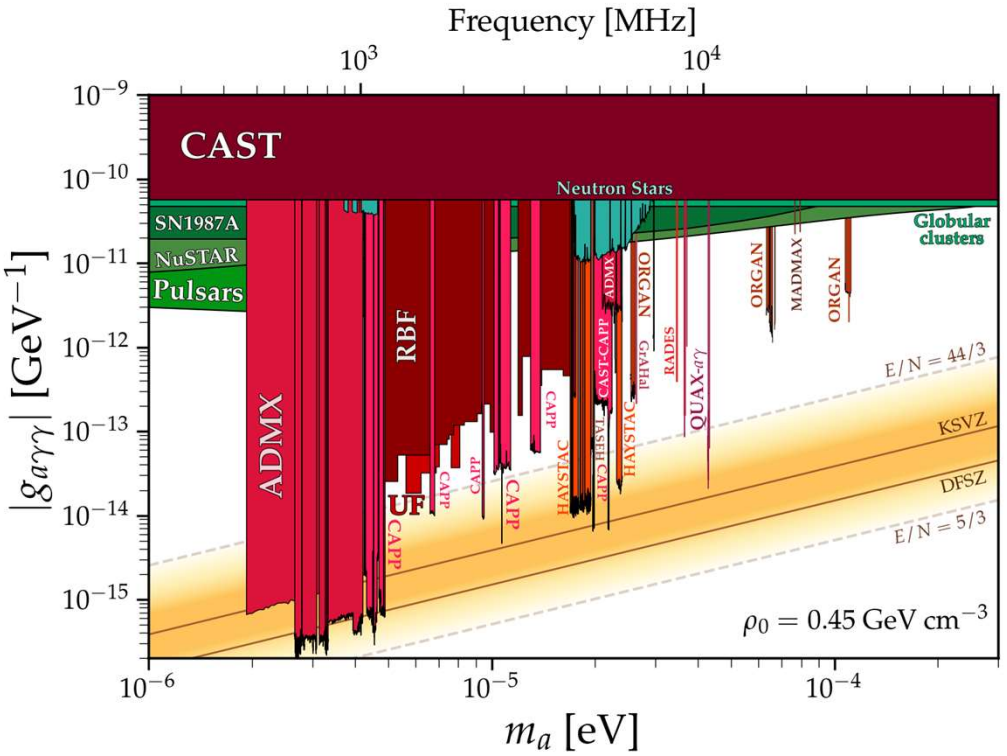
Laboratory searches via electromagnetic conversion experiments: **HALOSCOPES**



$$\omega_a = \omega_{ax}$$

The Axion Search

Parameter space explored by axion experiments benchmarked by **KSVZ** and **DFSZ** predicted axion mass and coupling strength



$g_{\alpha\gamma\gamma}$: coupling constant
m_a : axion mass

Challenges in axion searches:

- Weak signal ~ 10^{-24} to 10^{-22} W
- Narrow linewidth ~1 kHz
- Unknown mass m_a ~ **microwave range** (ω_{ax} ~ 0.1 GHz to 0.1 THz)

Previous experiments have a **low tunablility** with ~ MHz detection bands at fixed cavity frequency

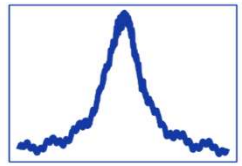
Research Project Goals

Key goals of AXION sensing:

- Expand the **mass scanning range** → **Magnetic materials in resonant cavities**

- Boost the **detection sensitivity** → **Non-linear coupling**

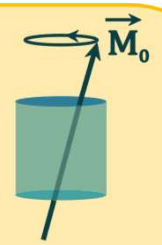
- Simulate a **fake axion** signal → **Phase-jammed signal**



Research Project Goals

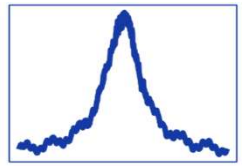
Key goals of AXION sensing:

- Expand the **mass scanning range** → **Magnetic materials in resonant cavities**



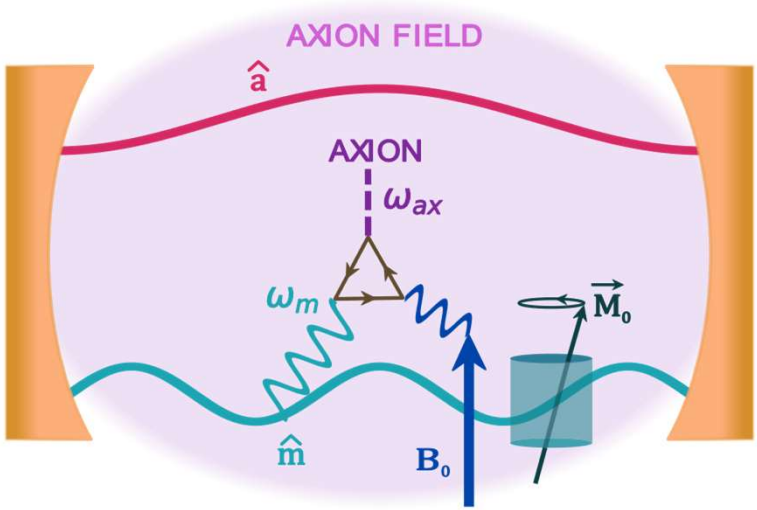
- Boost the **detection sensitivity** → **Non-linear coupling**

- Simulate a **fake axion** signal → **Phase-jammed signal**

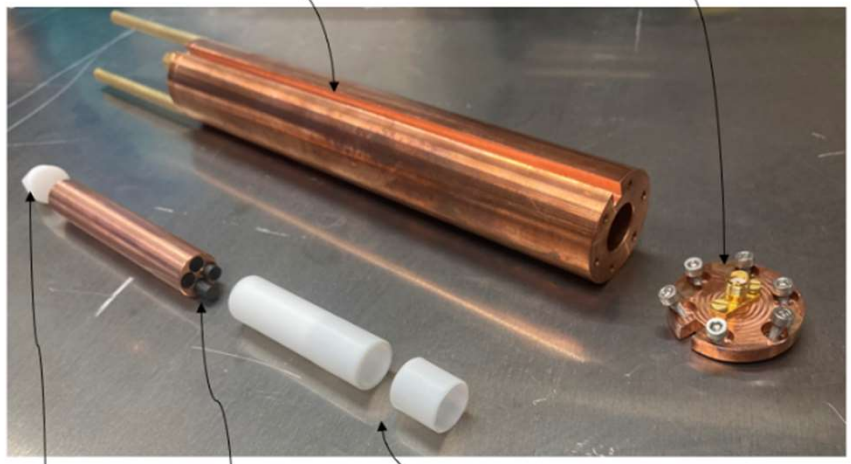


Magnetic Tunability

Ferromagnetic cavity



$\omega_a = \omega_{ax}$ $\quad g_{\alpha\gamma\gamma}\Phi_{ax}\cos(\omega_{ax}t)\vec{E}\cdot\vec{M}_0$



YIG crystals permeability tensor : frequency and magnetic resonnance dependence

$$\check{\mu}(\omega) = \mu_0 \begin{bmatrix} \mu_r(\omega) & i\mu_a(\omega) & 0 \\ -i\mu_a(\omega) & \mu_r(\omega) & 0 \\ 0 & 0 & 1 \end{bmatrix} \xrightarrow[\text{Gilbert equation}]{\text{Landau-Lischitz-}} \mu_r = \frac{\omega_H(\omega_M+\omega_H)-\omega^2}{\omega_H^2-\omega^2} \quad , \quad \mu_a = \frac{\omega\omega_M}{\omega_H^2-\omega^2}$$

$$\omega_M = \mu_0\gamma M_0 \quad , \quad \omega_H = \mu_0\gamma H_0 + i\eta\omega$$

A. Cottet and T. Kontos: New J Phys 28 024504 (2026), Gurevich and Melnikov (1996)

Gyromagnetic Modes

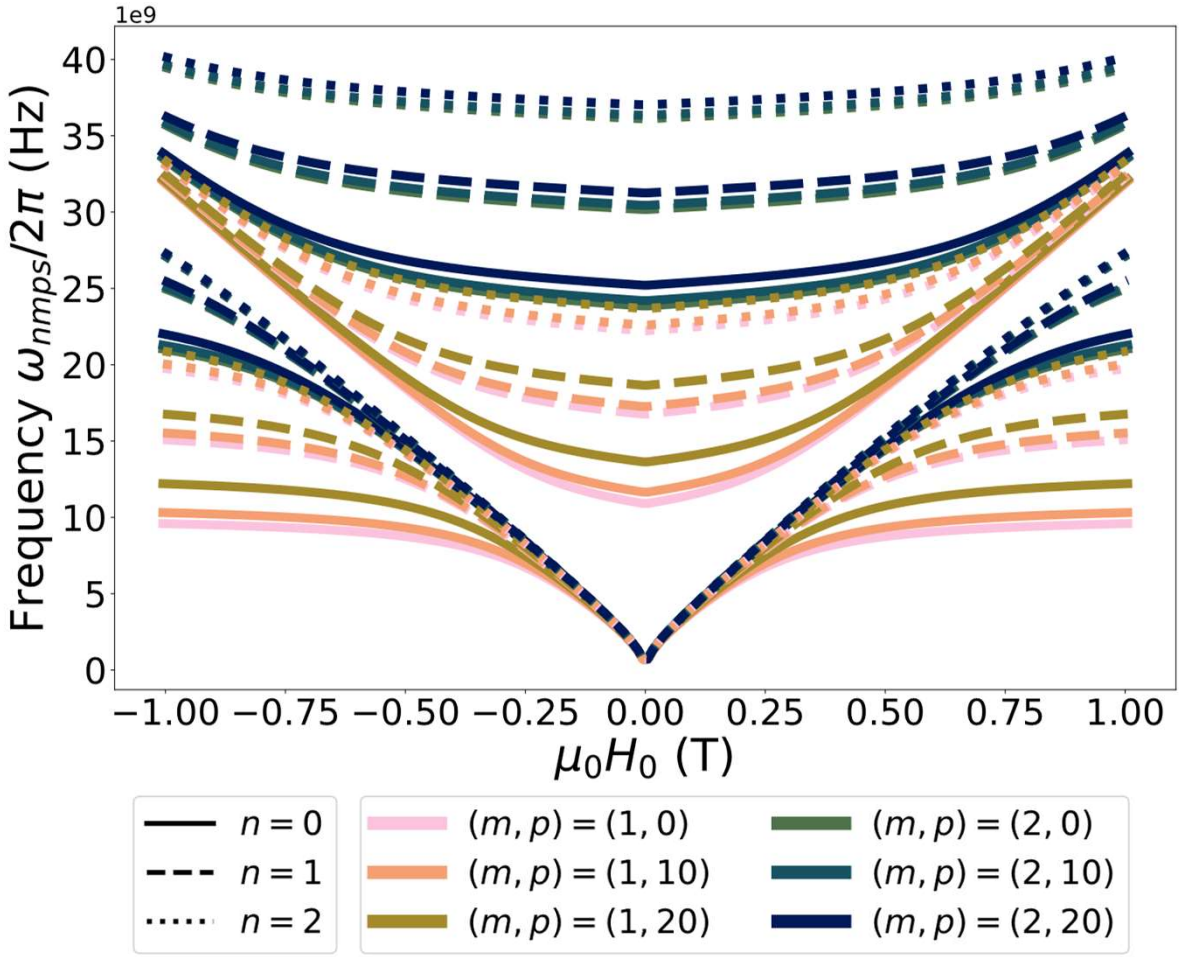
$$\check{\mu}(\omega) = \mu_0 \begin{bmatrix} \mu_r(\omega) & i\mu_a(\omega) & 0 \\ -i\mu_a(\omega) & \mu_r(\omega) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Maxwell equations in a cylindrical cavity

$$\omega_{nmp} = \frac{k_{nmp}}{\sqrt{\mu_\perp \epsilon}} = \sqrt{\left(\frac{z_{nm}}{a}\right)^2 + \left(\frac{p\pi}{L}\right)^2} \frac{1}{\sqrt{\mu_\perp \epsilon}}$$

with $\mu_\perp = \mu_0 \dfrac{\mu_r^2 - \mu_a^2}{\mu_r}$

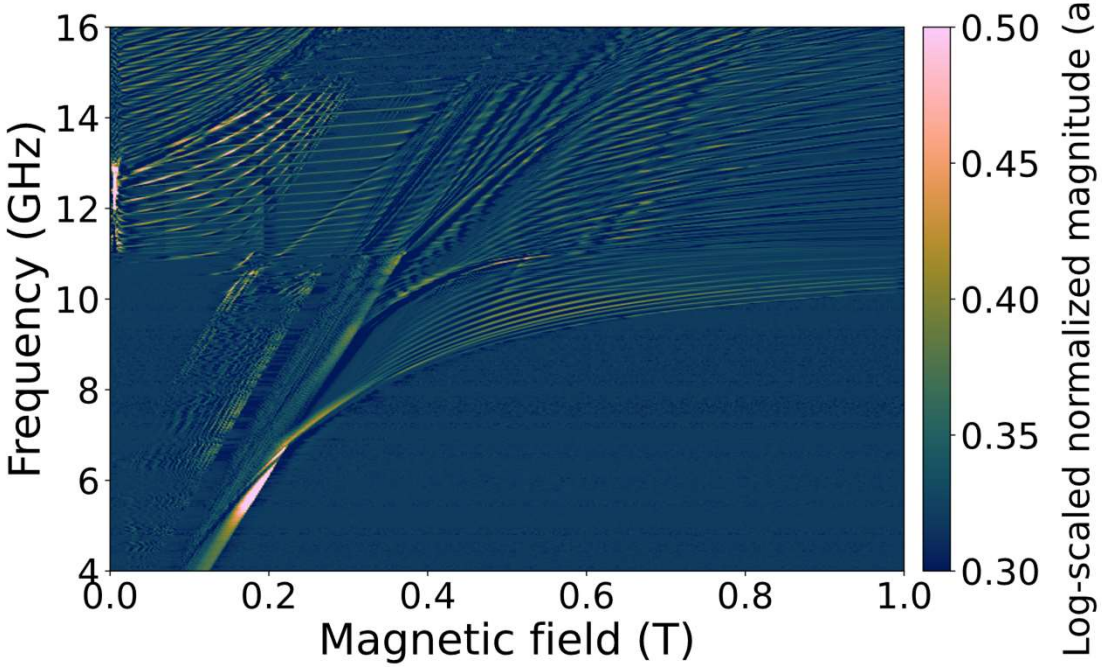
(n, m, p) = angular, radial and longitudinal modes



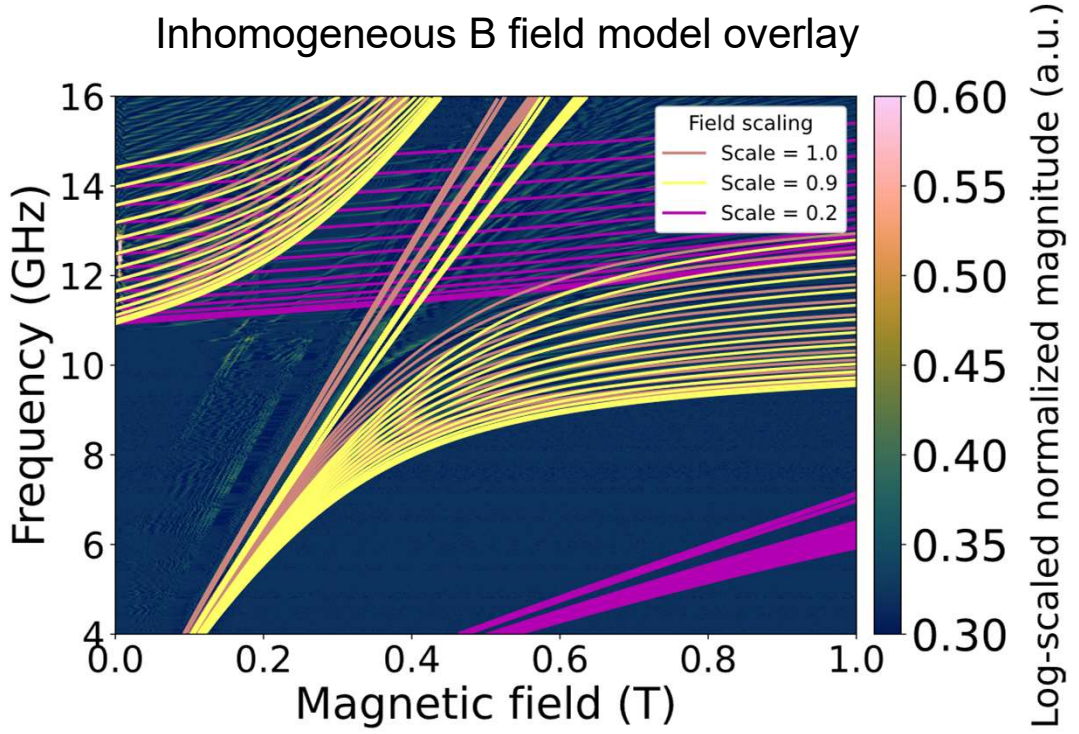
$\omega_{0,1,0,\pm1}$ slope = 28 GHz/T

Experimental Results

YIG magnetospectroscopy 20mK



Inhomogeneous B field model overlay



Achieved $\mathbf{28.4}$ **GHz/T slope**, in addition to good understanding of the dispersion with **analytical** approach

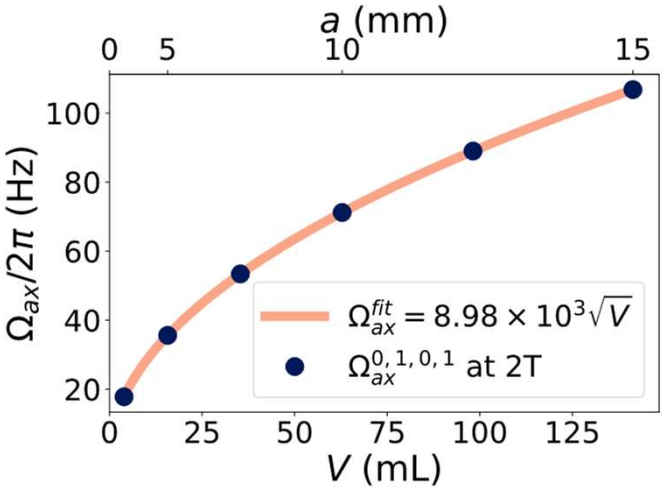
High spectral density of gyromagnetic modes, including modes with lower slope than expected

On-going **analysis** to identify additional, Comsol **simulation**

Axion-Photon Coupling

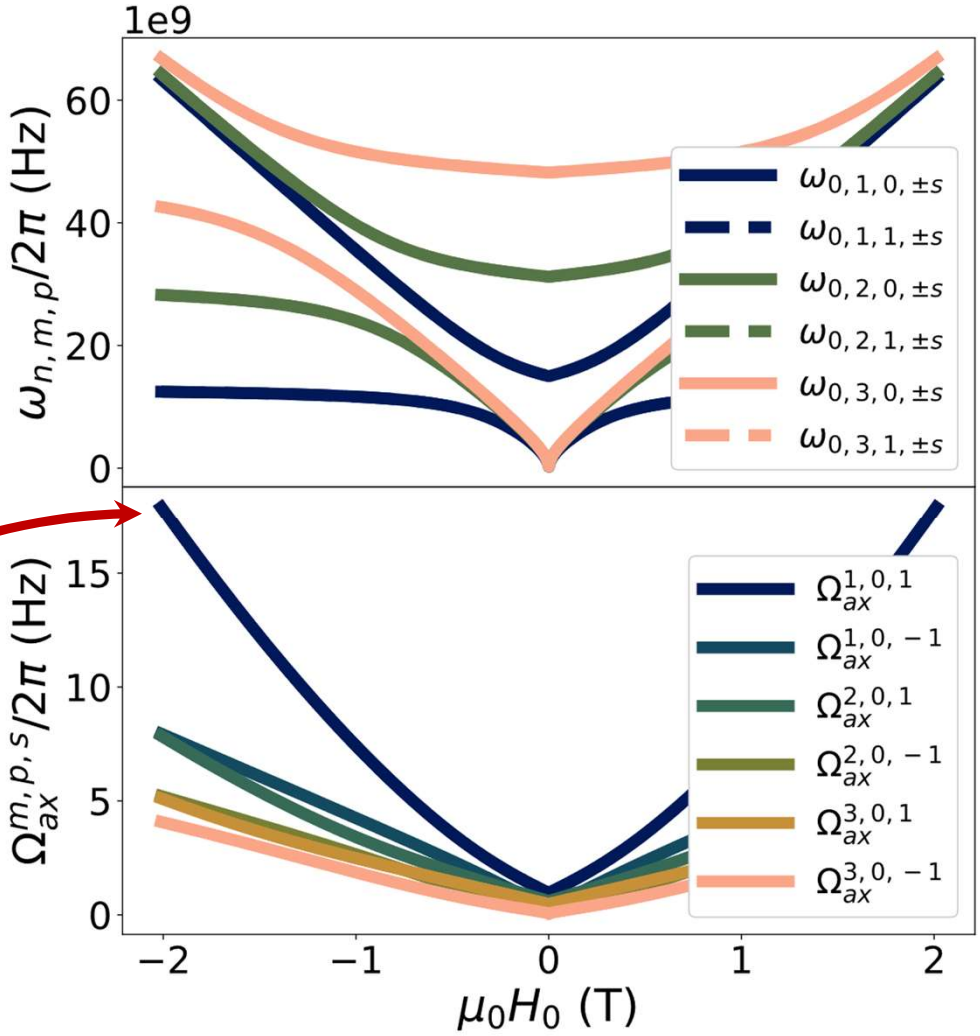
$$\Omega_{ax}^{m} = \frac{1}{\hbar\mu_0 c}\, g_{a\gamma\gamma}\, \mu_0 (M_0 + H_0)\, \frac{1}{z_{0m}} \sqrt{\frac{2V}{\epsilon}}\, \hbar\omega_{0m}$$

- $\frac{1}{m}$ scaling
  - focus on $(n,m,p) = (0,1,0) \equiv TM_{010}$ mode
- $\sqrt{V}$ scaling ⟶ a higher axion field volume leads to a stronger coupling



18 Hz coupling strength for **1 cavity** of radius $a = 2.5$ mm $\equiv \boldsymbol{V \approx 3.9}$ **mL**

Cavity paralleling ?
$V_{eff} = NV_{cav}$



Conventional Haloscope FoM

Figure of Merit (FoM): $F = \frac{1}{T}$ with T the minimum time to get $SNR = 1$

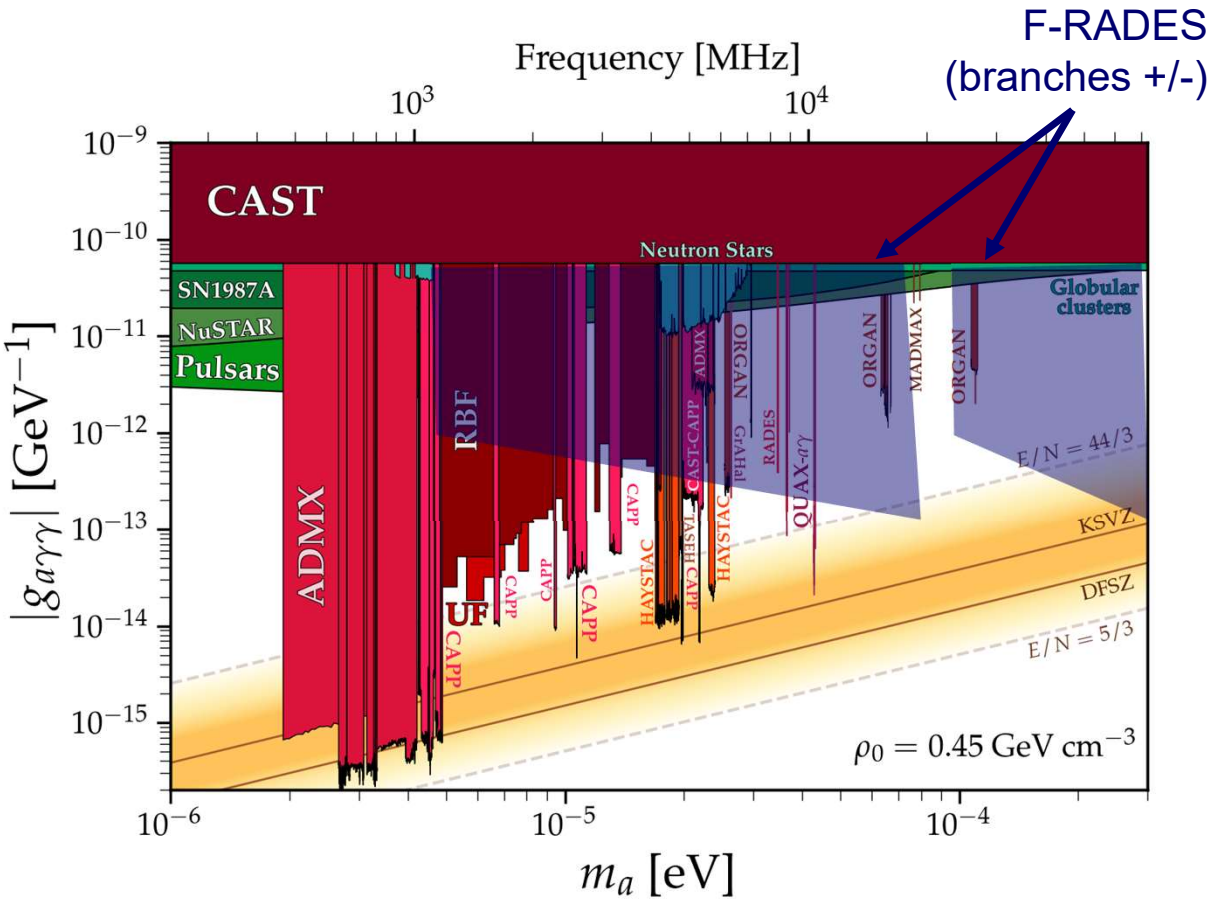
FoM for tunable haloscope: $F_{halo}^{m} = \frac{(\Omega_{ax}^{0})^4}{\Lambda_a^3}$

$$\Omega_{ax}^{0} = g_{a\gamma\gamma} \frac{\mu_0 (M_0 + H_0)}{\hbar \mu_0 c \, z_{0m}} \sqrt{\frac{2V}{\epsilon}} \, \hbar\omega_{0m}$$

➡ Coupling constant in GeV:

$$g_{a\gamma\gamma}^{[eV^{-1}]} = g_{a\gamma\gamma} \frac{m_a^{0m}}{\sqrt{2\rho_{ax}(\hbar c)^3}}$$

- RADES measurement time $F_{halo} = \frac{1}{T_{RADES}} = 10^{-5}\text{Hz}$
- Cavity quality factor $Q = 10^5$
- $SNR = 1$



➡ 1.2 GHz to 66.8 GHz tunability

(Article in preparation)

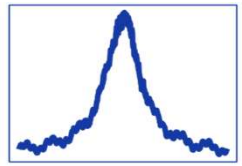
Research Project Goals

Key goals of AXION sensing:

- Expand the **mass scanning range** → **Magnetic materials in resonant cavities**

- Boost the **detection sensitivity** → **Non-linear coupling**

- Simulate a **fake axion** signal → **Phase-jammed signal**

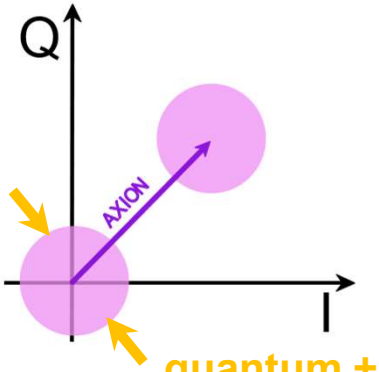


Quantum Detection Scheme

Conventional haloscope

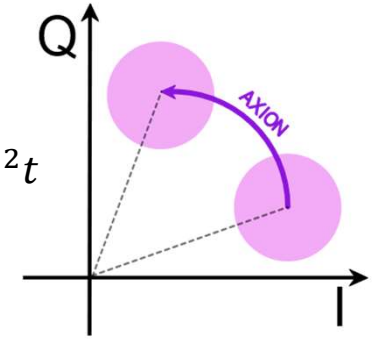
$P \propto |\hat{a} + \hat{a}_{ax}|^2$

with $\hat{a}_{ax} \ll \hat{a}$



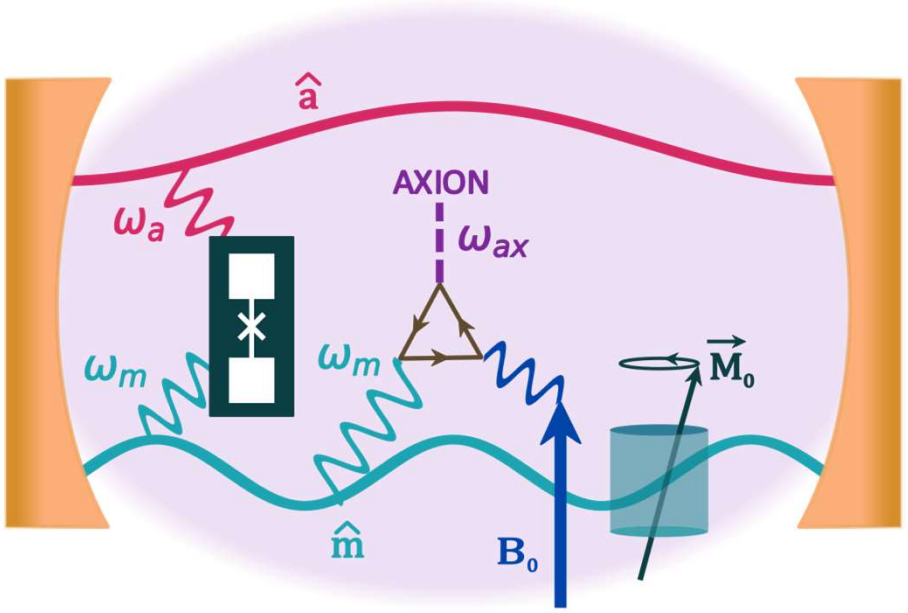
Non-linear coupling

$\Delta\Phi \propto K|\hat{a} + \hat{a}_{ax}|^2 t$



➡ Phase accumulation over time t

Phase-resolved haloscope with magnet tunability scheme



A. Cottet and T. Kontos: New J Phys 28 024504 (2026), Gurevich and Melnikov (1996)

$\hat{a}$: cavity signal

$\hat{a}_{ax}$: axion signal

K : Kerr constant

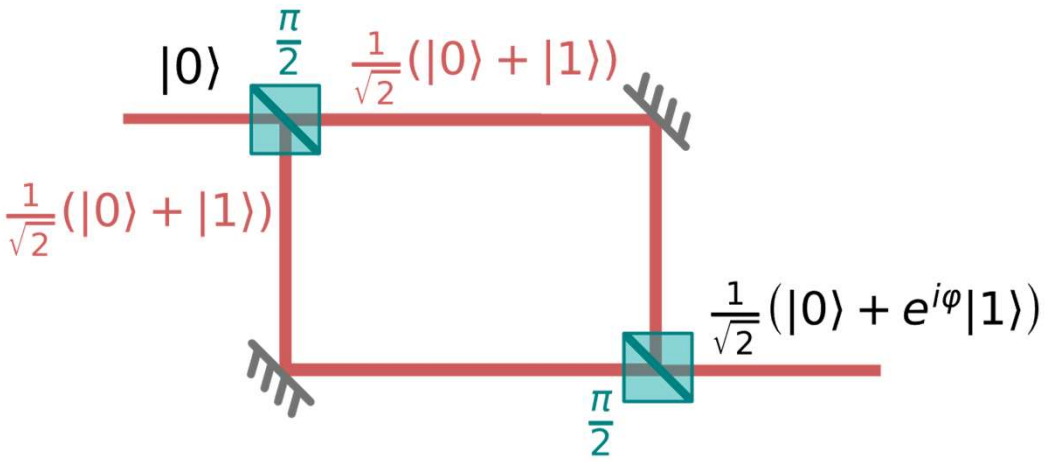
t : interaction time

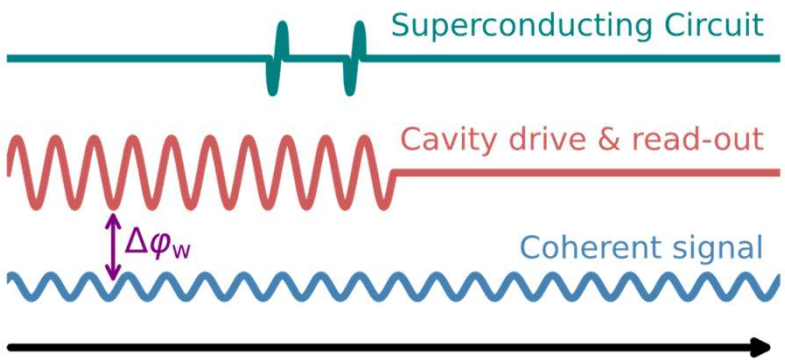
Cavity drive and axion field **interference term** from the superconducting circuit dispersively coupled

$$\Delta\omega_a \approx K[\,|\hat{a}|^2 + |\hat{a}_{ax}|^2 + 2|\hat{a}||\hat{a}_{ax}|\cos(\varphi_{ax})\,]$$

Non-Linear Quantum Interferometry

Ramsey experiment on fake-axion signal

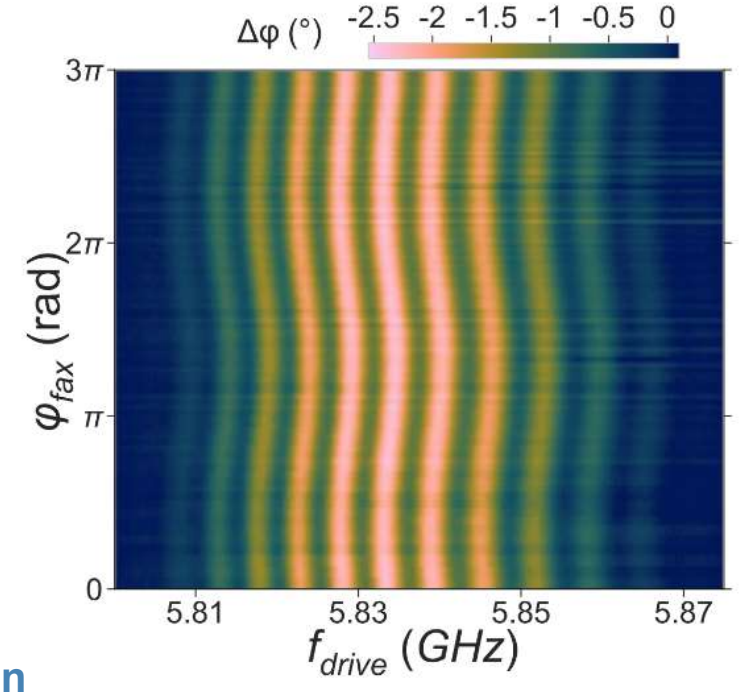




← **Fake axion signal**

$$\Delta\varphi_\omega \sim -\frac{2K}{\kappa}\frac{g^2}{\Delta^2}\left|\sqrt{n_{cav}} + \sqrt{n_\omega}e^{i\varphi_\omega}\right|^2$$

➡ Ramsey fringes are strongly modulated by interfering signal

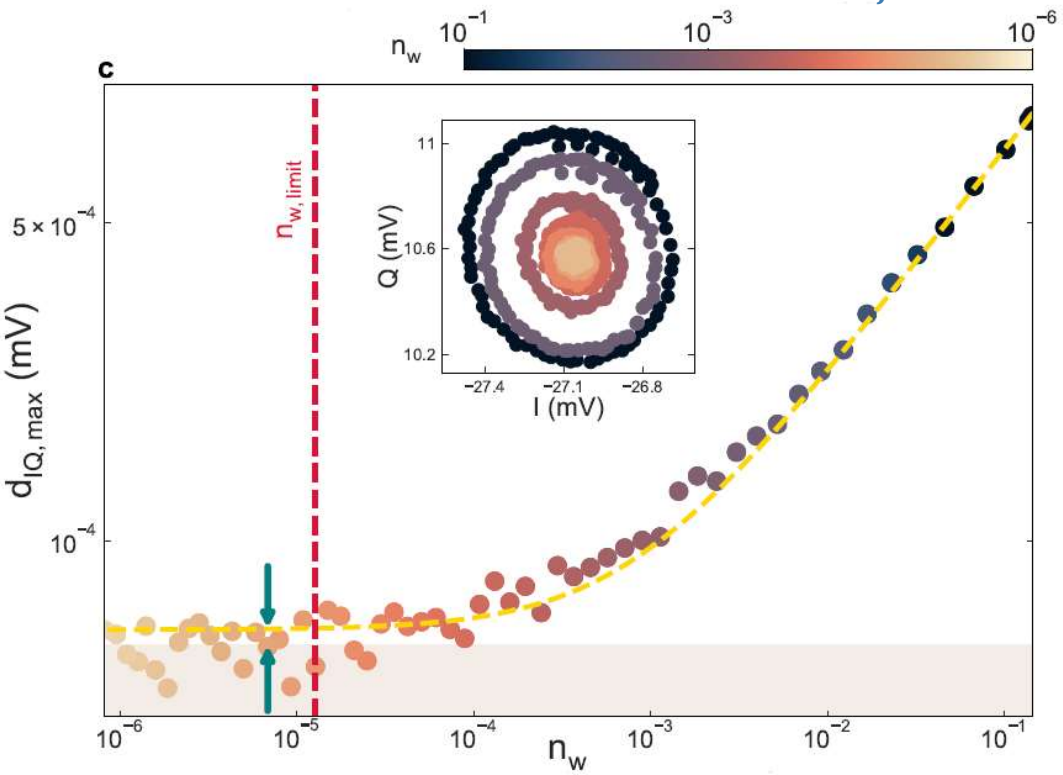


C. Fruy, A, Théry, et al. (2026), Phys. Rev. A 113, 023706

➡ Detection at $\omega_{cav} = \omega_{fax}$

Quantum Enhancement Detection Method

Phase-resolved detection at $\omega_{cav} = \omega_{fax}$



C. Fruy, A, Théry, et al. (2026), Phys. Rev. A 113, 023706

Increased sensitivity at cosmological limit

10^{-5} photons in 400 ms

$\equiv$

$1.2 \times 10^{-2} \quad W/\sqrt{Hz}$

Increased Figure of Merit (FoM)

$$F_{halo} = \frac{(\Omega_{ax}^0)^4}{\Lambda_a^3} \approx \text{mHz}$$

$$\ll$$

$$F_{phase} \approx \frac{\Omega_{ax}^2}{\Lambda_a^3} \approx 0.4 \text{ MHz}$$

A. Cottet and T. Kontos: New J Phys 28 024504 (2026)

n_ω = average photon number in the transmon drive pulse
d_{IQ} = max distance between two points with the same amplitude

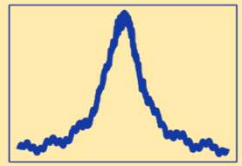
Research Project Goals

Key goals of AXION sensing:

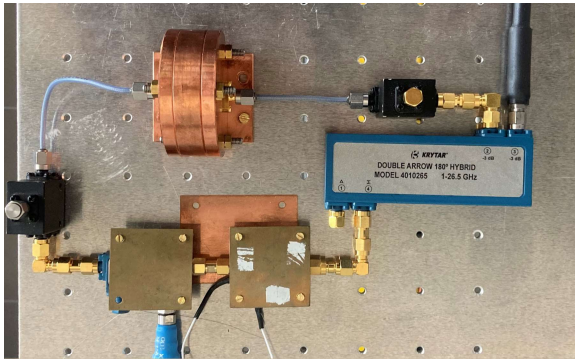
- Expand the **mass scanning range** → **Magnetic materials in resonant cavities**

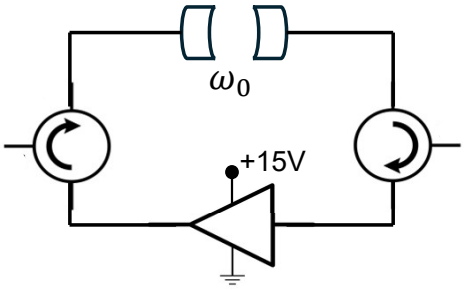
- Boost the **detection sensitivity** → **Non-linear coupling**

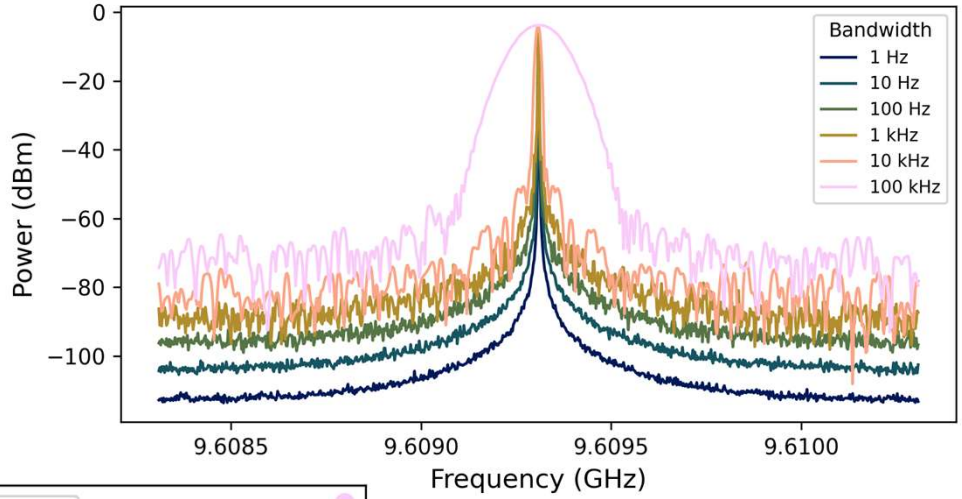
- Simulate a **fake axion** signal → **Phase-jammed signal**



Phase Jamming





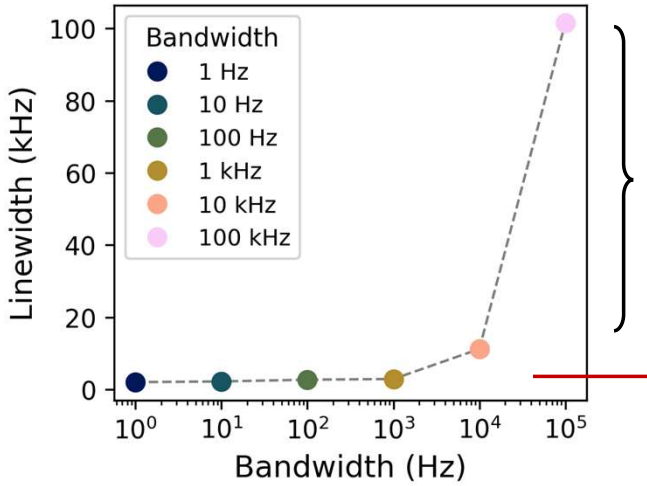


Power spectral density:

$$S(\theta) = \frac{kTF}{P_0}\left(1 + \frac{K\omega_\alpha}{\Delta\omega}\right)$$

- $\theta(t)$: random phase fluctuation
- F: noise figure
- P_0: oscillator output power at ω_0
- $\Delta\omega$: frequency offset relative to ω_0
- K: flicker noise sensitivity (scaling factor)
- ω_α: corner angular frequency between flicker and white phase noise

David M. Pozar, Microwave Engineering, 4th Edition, Wiley, 2012



Measurement instrument- limited

true 1kHz source

more realistic fictitious axion source

Key Points and Outlooks

- **Large tunability** of the phase-resolved haloscope through gyromagnetic materials
- Technical focus on **mode $(0, 1, 0)$ isolation** and manipulation
- Tri – partite coupling by implementing gyromagnetic modes in Chloe's detection setup

- Phase – jammed source to **simulate $\sim kHz$ linewidth axions**
- **Phase-jamming tunability** by using phase shifters in the MASER – like setup

Thank you for your attention !

Benchmarking Parameters

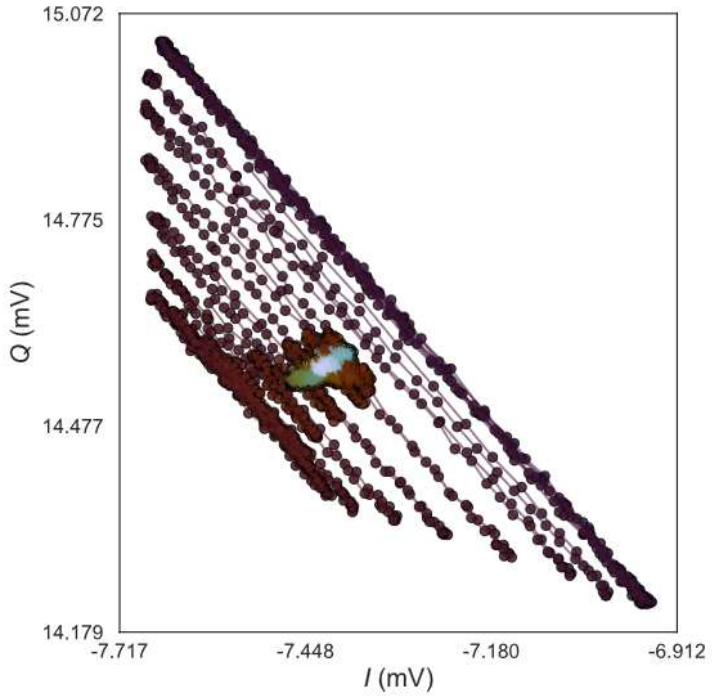
$\epsilon = 12\epsilon_0$	$\gamma = 2\pi \times 28$ GHz.T^{-1}	$\mu_0 M_0 = \mu_0 \rho g \mu_B S = 0.25$ T
$\rho = 4.22 \times 10^{27}$ m^{-3}	$S = 5/2$	$a = 2.5$ mm

Characteristic RADES measurement time	$1/T_{\text{RADES}} = 10^{-5}$ Hz
Magnetic flux density due to static magnetization	$\mu_0 M_0 = 0.25$ T
Cavity volume	$V = 200 \cdot 10^{-3} \cdot \pi \cdot \left(2.5 \cdot 10^{-3}\right)^2 \approx 3.9 \times 10^{-6}$ m^3
YIG permittivity	$\epsilon = 12\epsilon_0$
Gyromagnetic ratio	$\gamma = 2\pi \times 28 \times 10^9$ Hz/T
Axion energy density	$\rho_{ax} = 0.45 \times 10^{15}$ eV/m^3

Quantum Enhancement Detection Method

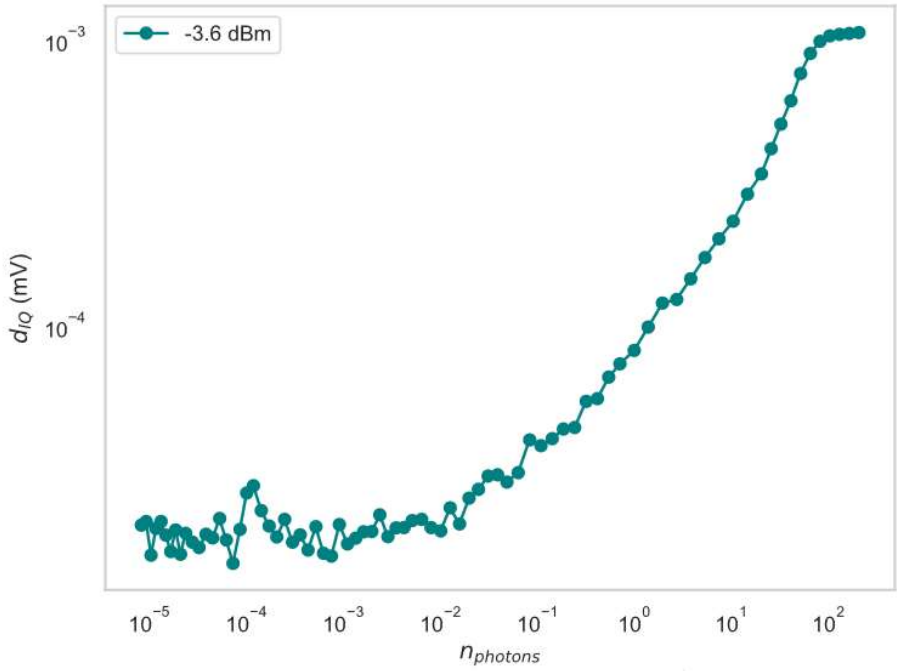
Phase-resolved detection at

$\omega_{cav} = \omega_m = \omega_{fax}$



C. Fruy, A, Théry, et al. (2026), Phys. Rev. A 113, 023706

Increased sensitivity



Sensitivity of 10^{-3} photons in 400 ms

➡ Need to increase the magnetic volume to improve sensitivity

Gyromagnetic Modes in Cylindrical Cavity

Solving the Maxwell equations in a cylindrical cavity with YIG tensor leads to the Helmholtz equation:

$$\frac{\partial^2 e_z}{\partial r^2} + \frac{1}{r}\frac{\partial e_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 e_z}{\partial \theta^2} + k^2 e_z = 0$$

with $k = \omega\sqrt{\mu_\perp \epsilon}$ and

$$\mu_\perp = \mu_0 \frac{\mu_r^2 - \mu_a^2}{\mu_r} = \mu_0 \frac{\gamma^2\mu_0^2(H_0 + M_0)^2 + 2i\eta\gamma\mu_0(H_0 + M_0)\omega - (1+\eta^2)\omega^2}{\gamma^2\mu_0^2 H_0(H_0 + M_0) + i\eta\gamma\mu_0(2H_0 + M_0)\omega - (1+\eta^2)\omega^2}$$

Spatial solution and boundary conditions:

$$e_z^{n,m,p}(r,\theta,z) = \sum_n \sum_m \sum_p \left(A_{nmp}\cos(n\theta) + B_{nmp}\sin(n\theta)\right)\sin(k_{\parallel p} z) J_n(k_{\perp nm} r)$$

with $k_{n,m,p} = \sqrt{k_{\perp n,m}^2 + k_{\parallel p}^2}$ with $\begin{cases} k_{\perp nm} = \frac{z_{nm}}{a}, & \text{where } z_{nm} \text{ is the } m^{\text{th}} \text{ root of } J_n \\ k_{\parallel p} = \frac{p\pi}{L}, & \text{where } p \text{ is an integer} \end{cases}$

Consider $\eta = 0$, the magnetic dissipation, then:

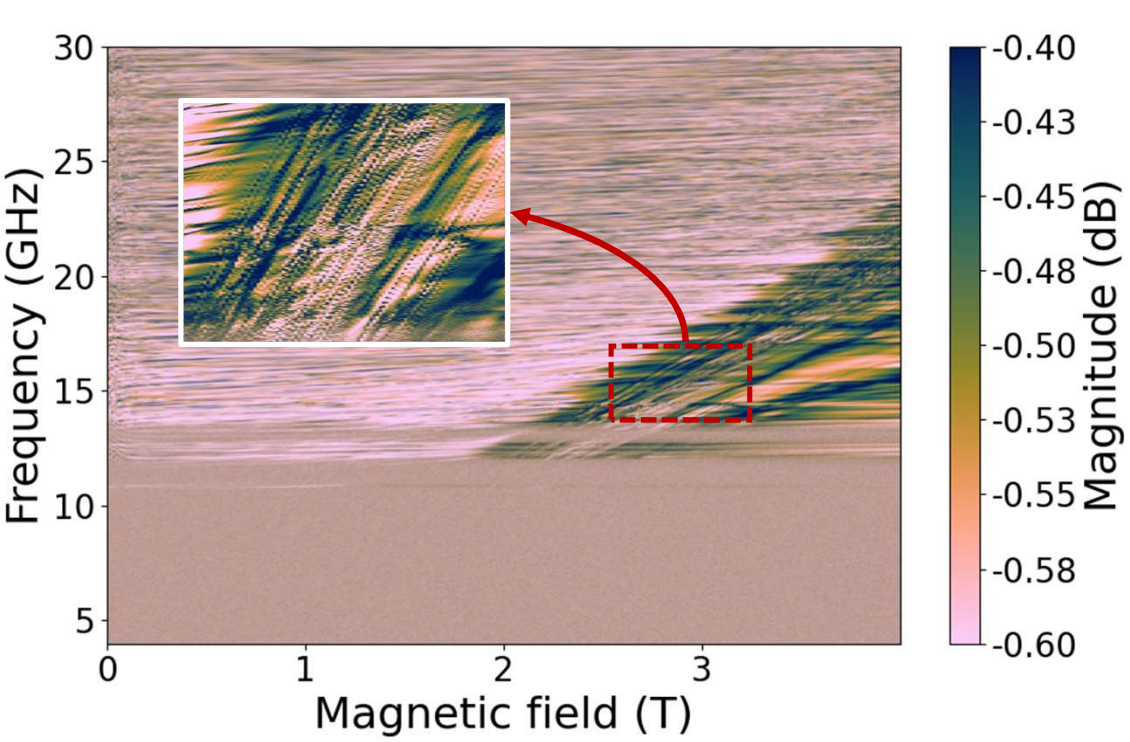
$$\omega_{nmps} = \frac{\sqrt{\mu_0^2\gamma^2\left(H_0 + M_0\right)^2 + \Omega_{nmp}^2 + s\sqrt{\mu_0^4\gamma^4\left(H_0 + M_0\right)^4 - 2\mu_0^2\gamma^2\left(H_0^2 - M_0^2\right)\Omega_{nmp}^2 + \Omega_{nmp}^4}}}{\sqrt{2}}$$

with

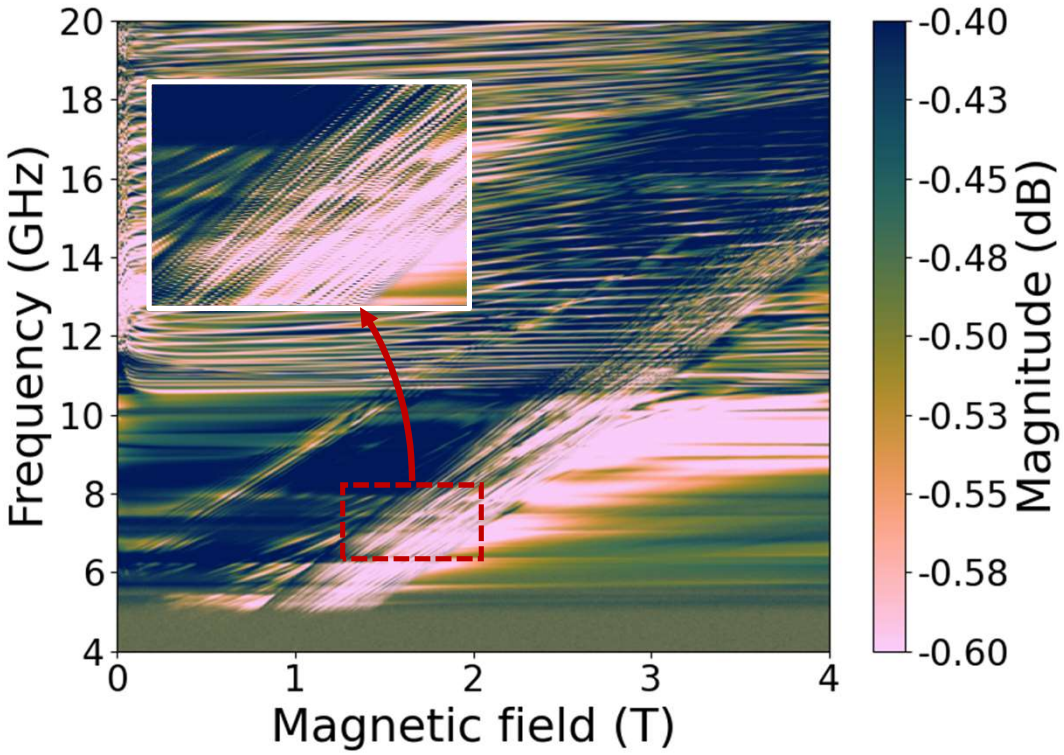
$$s = \pm 1 \quad \text{and} \quad \Omega_{nmp}^2 = \frac{1}{\epsilon\mu_0}\left(\left(\frac{z_{nm}}{a}\right)^2 + \left(\frac{p\pi}{L}\right)^2\right)$$

Gyromagnetic Modes Measurements

Copper barillet and teflon holders



Copper barillet and direct coaxial excitation



Coupling Strength

The coupling Hamiltonian: $$H_c = \frac{1}{\mu_0 c} g_{a\gamma\gamma} \cos(\omega_{ax} t - \varphi_{ax}) \iiint r dr d\theta dz \, \vec{E} \cdot \vec{B}$$

Time harmonic solution to the Helmholtz equation:

$$\vec{E} = \vec{e}(r,\theta,t) = -\sum_{n,m} i\omega_{nm} J_n(k_{nm} r) \left(\sin(n\theta) + B_{nm}\cos(n\theta)\right) \left(A_{nm} e^{i\omega_{nm} t} - A^*_{nm} e^{-i\omega_{nm} t}\right) \hat{z}$$

Magnetic field:

$$\vec{B} = \mu_0 (M_0 + H_0)\hat{z} + \vec{b}(r,\theta,t)$$

$$H_c = \sum_m \hbar \cos(\omega_{ax} t - \varphi_{ax}) \Omega^m_{ax} (\hat{m}_{0m} + \hat{m}^\dagger_{0m})$$

with the coupling strength $$\Omega^m_{ax} = \frac{1}{\hbar \mu_0 c} g_{a\gamma\gamma} \mu_0 (M_0 + H_0) \frac{1}{z_{0m}} \sqrt{\frac{2V}{\epsilon} \hbar \omega_{0m}}$$

Form Factor

$$C = \frac{\langle \mathbf{E}\cdot\mathbf{B}_0\rangle^2_{|\psi\rangle}}{\langle \mathbf{B}_0\cdot\mathbf{B}_0^*\rangle_{|\psi\rangle}\langle \mathbf{E}\cdot\mathbf{E}^*\rangle_{|\psi\rangle}}$$

- $\langle \mathbf{E}\cdot\mathbf{B}_0\rangle^2 = \mu_0^2\left(M_0+H_0\right)^2\hbar\frac{2}{V_a\epsilon}\left\langle\sum_m \frac{1}{z_{0m}}\sqrt{\omega_{0m}}\left(\underbrace{\hat{m}_{0m}^\dagger + \hat{m}_{0m}}_{\left[\hat{m}_{0m}^\dagger,\hat{m}_{0m'}\right]=\delta_{mm'}}\right)\right\rangle^2_{|\psi\rangle} \longrightarrow \langle \mathbf{E}\cdot\mathbf{B}_0\rangle^2_{|0\rangle} = \mu_0^2\left(M_0+H_0\right)^2\hbar\frac{2}{V_a\epsilon}\sum_m\frac{\omega_{0m}}{z_{0m}^2}$

- $\langle \mathbf{B}_0\cdot\mathbf{B}_0^*\rangle_{|0\rangle} = \mu_0^2(H_0+M_0)^2$

- $\langle \mathbf{E}\cdot\mathbf{E}^*\rangle_{|0\rangle} = \hbar\frac{1}{2V_a\epsilon}\sum_m\omega_{0m}$

For one mode (n,m,s) $\quad C^m = \frac{4}{z_{0m}^2}$ with $\quad z_{0m} = \pi\left(m-\frac{1}{4}\right)+\mathcal{O}\left(m^{-1}\right)$ the m^{th} root of J_0

Conventional Haloscope SNR

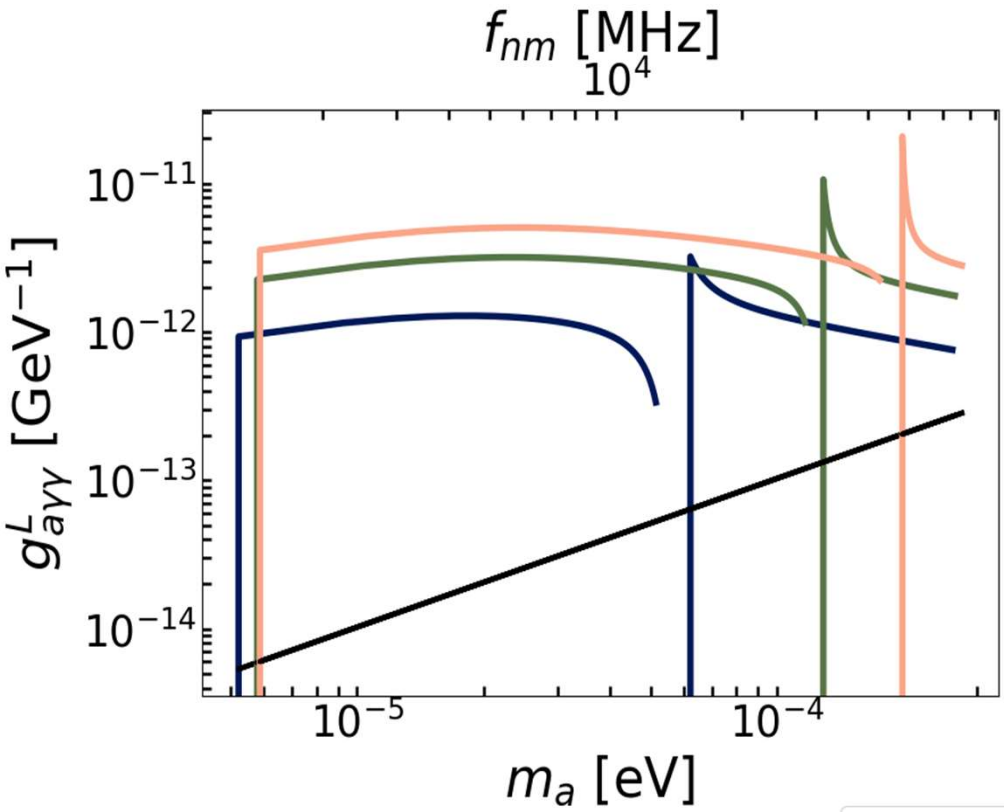
$SNR = \frac{\Delta P_0}{\sqrt{\nu_0}}$ *A. Cottet, kT. Kontos 25'*

- $\Delta P_0 = \frac{2\left(\Omega_{ax}^0\right)^2}{\Lambda_a^2}$ amplitude of the axionic signal at resonance
- $\nu_0 = \frac{4(1+2n_B)}{\Lambda_a T}$ signal variance

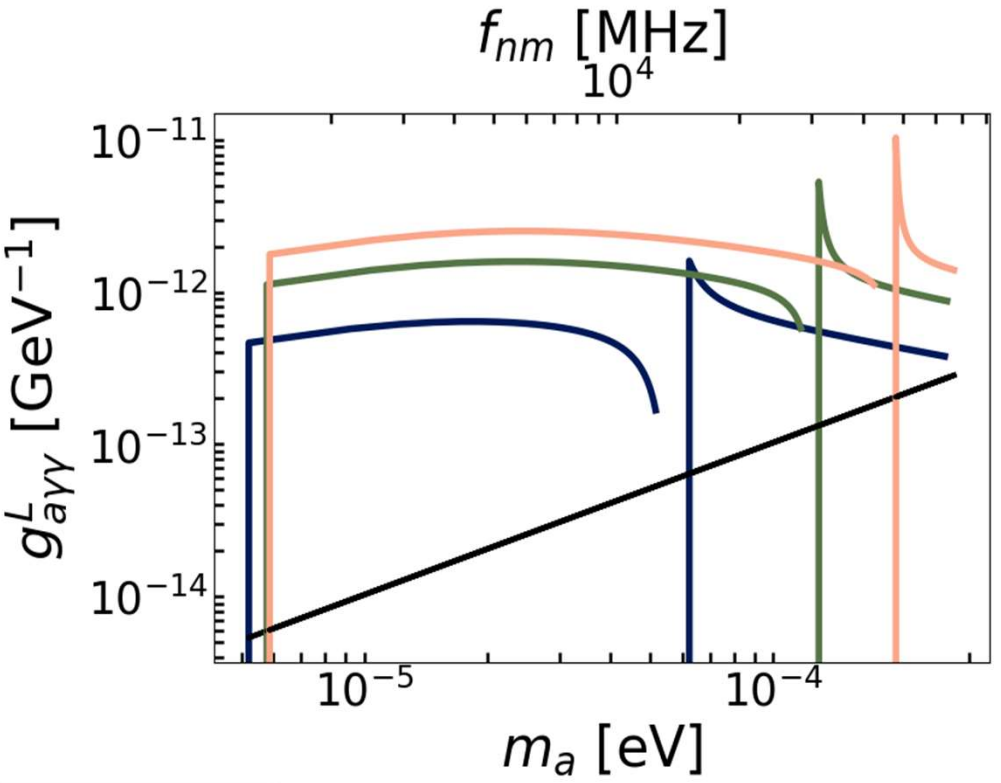
➢ $SNR = 1 \leftrightarrow \frac{\Omega_{ax}^4}{\Lambda_a^3} = \frac{1}{T} = F_{halo}$

First 3 Modes Coupling Constant

1 cavity



4 cavities in parallel



Phase-Jammed Source Setup

Amplifier

https://nardamiteq.com/docs/MITEQ-AFS.PDF

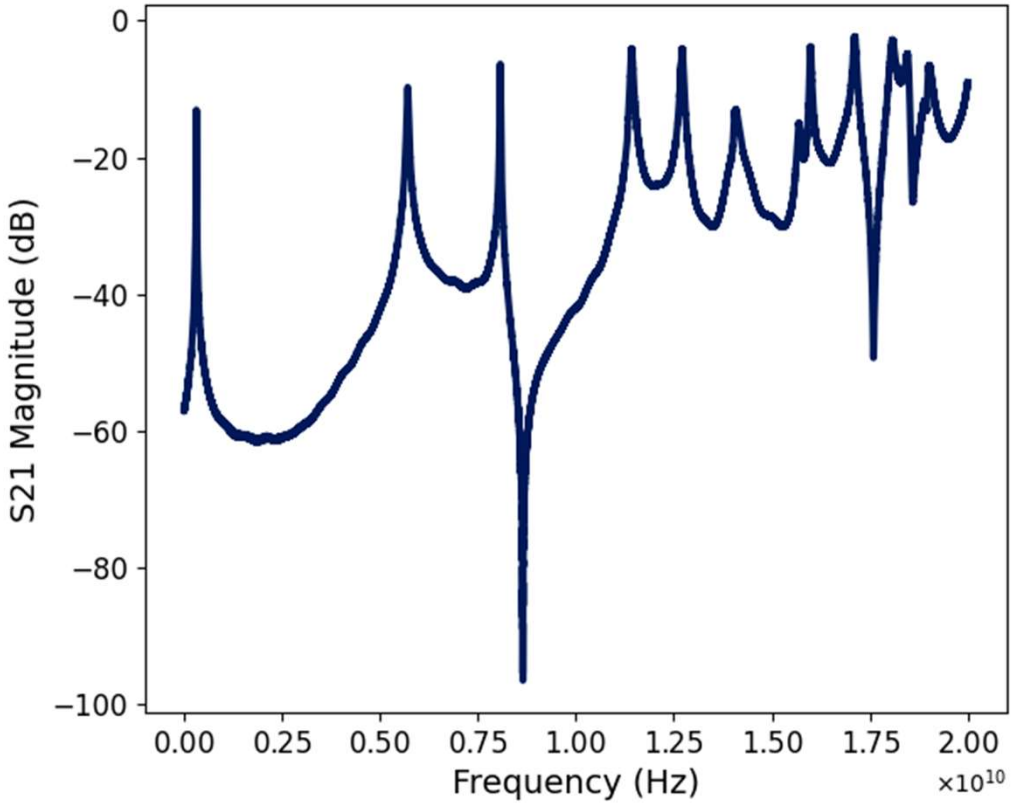
Model : AFS3-04000800-07-10P-4

Freq. range (GHz) : 4 – 8

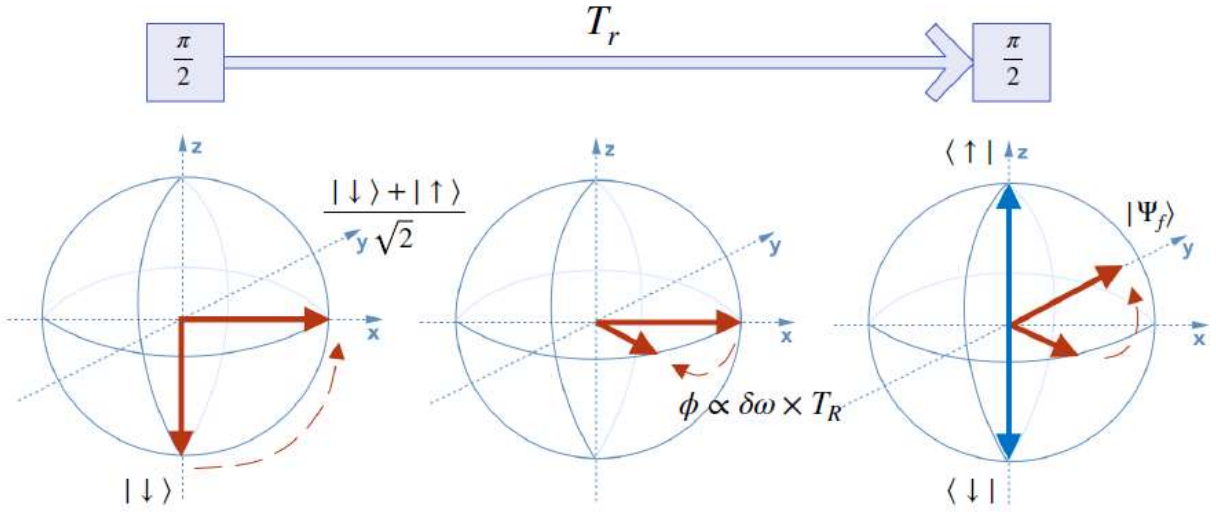
Gain (dB) : 28

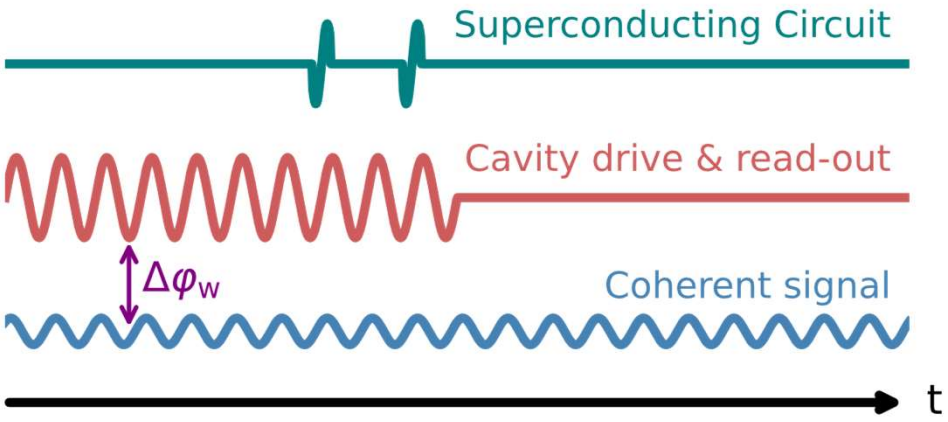
Noise Figure : 0.7

Cavity resonator spectrum



Ramsey Experiment: Bloch Sphere





$$\Delta\varphi_\omega \sim -\frac{2K}{\kappa}\frac{g^2}{\Delta^2}\left|\sqrt{\boldsymbol{n_{cav}}} + \sqrt{\boldsymbol{n_\omega}}e^{i\varphi_\omega}\right|^2$$