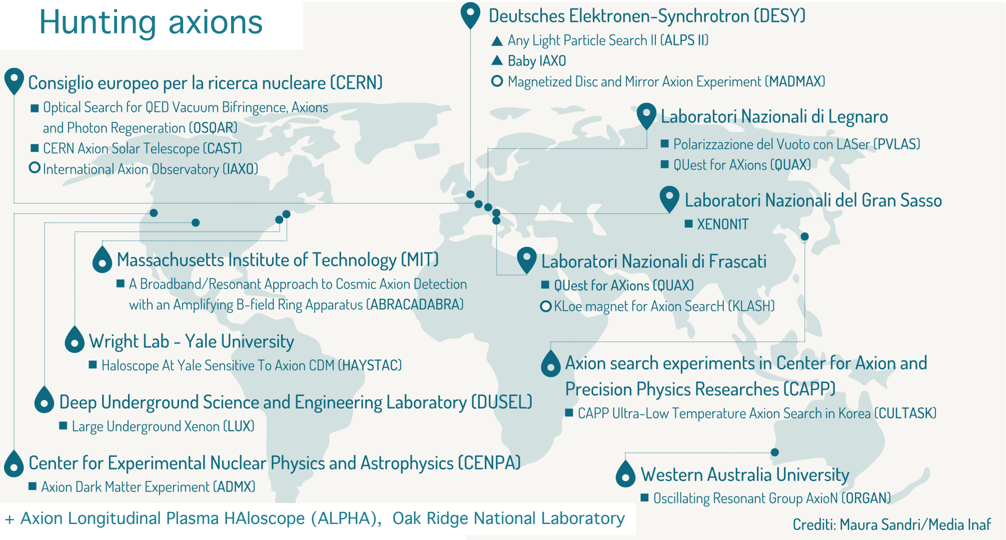
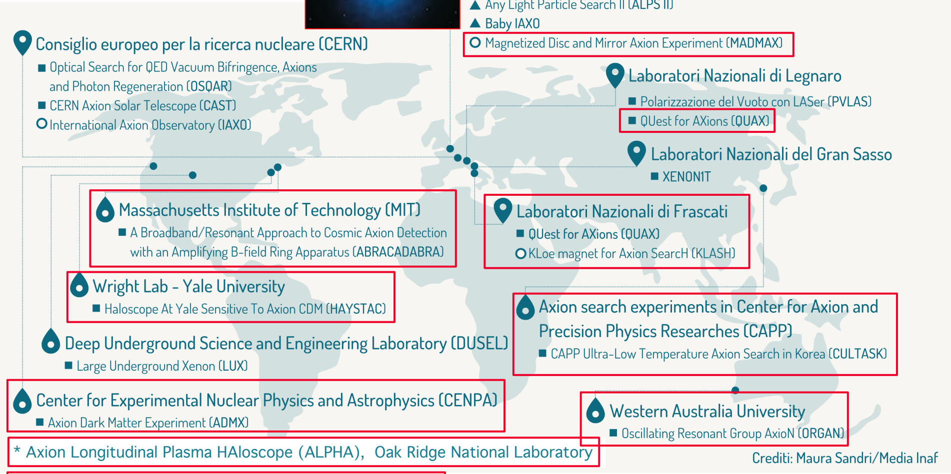
Hunting axions



+ Axion Longitudinal Plasma HAloscope (ALPHA), Oak Ridge National Laboratory
+ Taiwan Axion Search Experiment with Haloscope (TASEH)
+ Cosmic Axion Spin Precession Experiment (CASPEr), Boston and Mainz

DM in the galactic halo



* Axion Longitudinal Plasma HAloscope (ALPHA), Oak Ridge National Laboratory

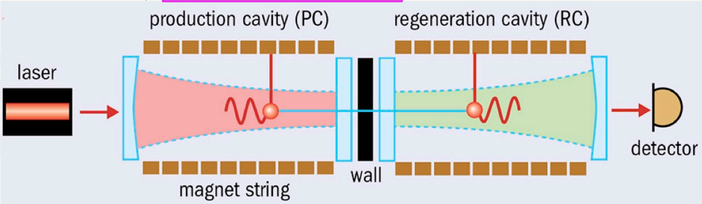
* Taiwan Axion Search Experiment with Haloscope (TASEH)

+ Cosmic Axion Spin Precession Experiment (CASPEr), Boston University and Mainz

Lab axions

Deutsches Elektronen-Synchrotron (DESY)

▲ Any Light Particle Search II (ALPS II)



Consiglio europeo per la ricerca nucleare

- ■ Optical Search for QED Vacuum Bifringence, Axions and Photon Regeneration (OSQAR)
- ■ CERN Axion Solar Telescope (CAST)
- ○ International Axion Observatory (IAXO)

Massachusetts Institute of Technology (MIT)

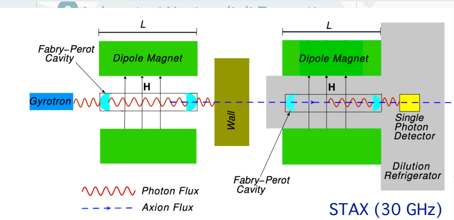
- ■ A Broadband/Resonant Approach to Cosmic Axion Detectio with an Amplifying B-field Ring Apparatus (ABRACADABRA)

Wright Lab – Yale University

- ■ Haloscope At Yale Sensitive To Axion CDM (HAYSTAC)

Deep Underground Science and Engineering Laborator

- ■ Large Underground Xenon (LUX)



Center for Experimental Nuclear Physics and Astrophysics (CENPA)

- ■ Axion Dark Matter Experiment (ADMX)

Western Australia University

- ■ Oscillating Resonant Group AxioN (ORGAN)

■ operativo ▲ in costruzione ○ in progetto

Crediti: Maura Sandri/Media Inaf

Axions from the Sun

Deutsches Elektronen-Synchrotron (DESY)
- ▲ Any Light Particle Search II (ALPS II)
- ▲ Baby IAXO
- ○ Magnetized Disc and Mirror Axion Experiment (MADMAX)

Consiglio europeo per la ricerca nucleare (CERN)
- ■ Optical Search for QED Vacuum Bifringence, Axions and Photon Regeneration (OSQAR)
- ■ CERN Axion Solar Telescope (CAST)
- ○ International Axion Observatory (IAXO)

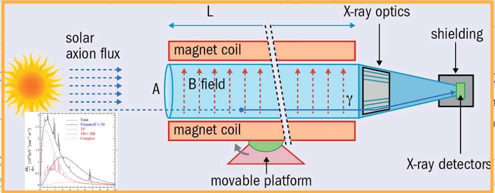
Laboratori Nazionali di Legnaro
- ■ Polarizzazione del Vuoto con LASer (PVLAS)
- ■ QUest for AXions (QUAX)

Laboratori Nazionali del Gran Sasso
- ■ XENON1T

Massac
- ■ A Broa with ar

zionali di Frascati
- ■ ns (QUAX)
- ■ r Axion SearcH (KLASH)

Wright Lab
- ■ Haloscope A



ch experiments in Center for Axion and Precision Physics Researches (CAPP)
- ■ CAPP Ultra-Low Temperature Axion Search in Korea (CULTASK)

Deep Underground Science and Engineering Laboratory (DUSEL)
- ■ Large Underground Xenon (LUX)

Center for Experimental Nuclear Physics and Astrophysics (CENPA)
- ■ Axion Dark Matter Experiment (ADMX)

Western Australia University
- ■ Oscillating Resonant Group AxioN (ORGAN)

■ operativo ▲ in costruzione ○ in progetto

Crediti: Maura Sandri/Media Inaf

Axion interactions with SM particles

Interactions are set by its **pseudo-scalar nature**, and they can be expressed by the nonrelativistic Hamiltonian:

$$\mathcal{H} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\, g_{a\gamma\gamma} \int a\mathbf{E}\cdot\mathbf{B}\, dV + g_{\mathrm{aff}}\, \hbar c\, \nabla a \cdot \hat{\mathbf{S}} + \sqrt{\varepsilon_0 (\hbar c)^3}\, g_{\mathrm{EDM}}\, a \hat{\mathbf{S}} \cdot \mathbf{E}$$

Experimentally how do they look like?

- via $\mathbf{E}\cdot\mathbf{B}$ coupling $\rightarrow$ *additional electric current*
- via coupling to n and e^- **spins** $\rightarrow$ *precession*

Axion interactions with SM particles

Interactions are set by its **pseudo-scalar nature**, and they can be expressed by the nonrelativistic Hamiltonian:

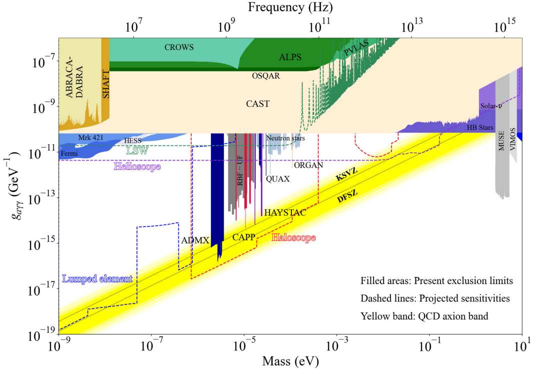
$$\mathcal{H} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\, g_{a\gamma\gamma} \int a \mathbf{E} \cdot \mathbf{B}\, dV + g_{aff}\, \hbar c\, \nabla a \cdot \hat{\mathbf{S}} + \sqrt{\varepsilon_0 (\hbar c)^3}\, g_{EDM}\, a \hat{\mathbf{S}} \cdot \mathbf{E}$$

Experimentally how do they look like?

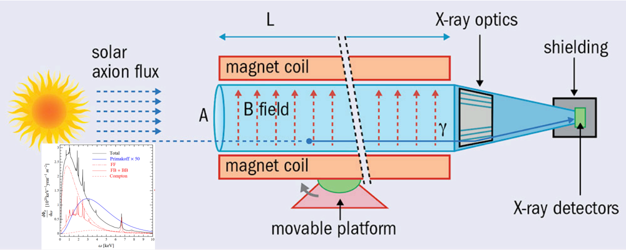
- via $\mathbf{E} \cdot \mathbf{B}$ coupling $\rightarrow$ *additional electric current*
- via coupling to n and e^- **spins** $\rightarrow$ *precession*

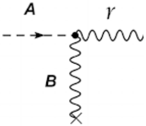
What are the interaction strengths with SM particles?

- $g_i \sim \frac{1}{f_a} \xrightarrow{m_a f_a \sim m_\pi f_\pi} g_i \propto m_a$ true for QCD axion
- ALPs mass could take any value, need not be $\propto g_i$



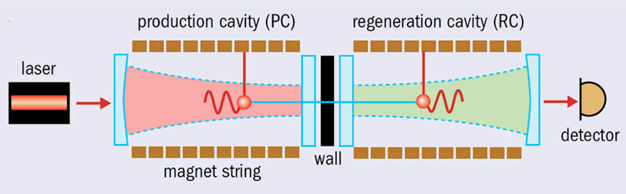
Axions can be produced in the SUN (→ HELIOSCOPE) and in the LAB (→ LIGHT SHINING THROUGH WALL)

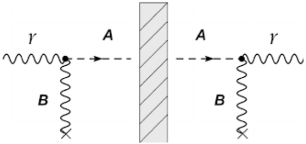




$$g_{a\gamma}^4 \propto \boxed{B^2 L^2 A} \cdot \boxed{\varepsilon_o \alpha^{-1/2}} \cdot \boxed{\varepsilon_d b^{-1/2}} \cdot \boxed{\varepsilon_t t^{-1/2}}$$

Magnet Optics Detector Time

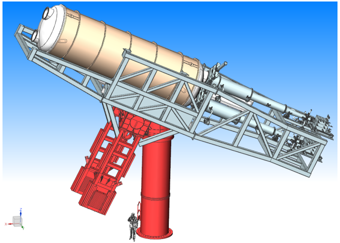


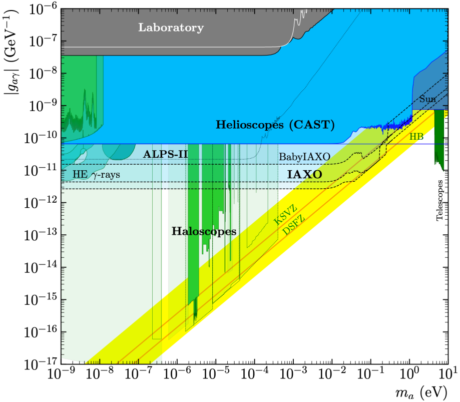


$$N_\gamma = \frac{1}{16}(g_{a\gamma}BL)^4 \frac{\mathscr{P}_i}{\omega} \beta_P \beta_R \tau$$

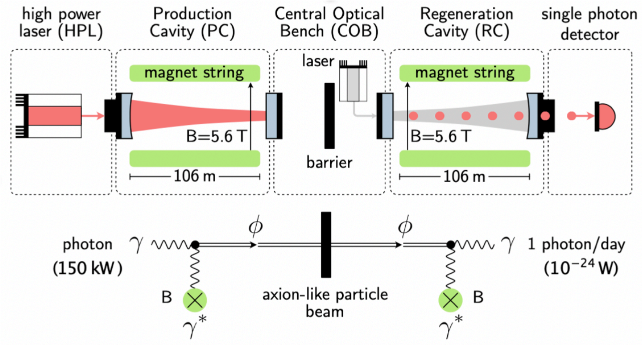
Parameter	Units	CAST	BabyIAXO	IAXO	IAXO+
B	T	9	$\sim$2	$\sim$2.5	$\sim$3.5
L	m	9.26	10	20	22
A	m^2	0.003 (*)	0.77	2.3	3.9
f_M	$T^2 m^4$	21	$\sim$230	$\sim$6000	$\sim$24000
b	$keV^{-1}\,cm^{-2}\,s^{-1}$	1×10^{-6} (**)	1×10^{-7}	10^{-8}	10^{-9}

- High magnetic field B
- Long magnets L
- Large bore A
- $f_M = B^2 L^2 A$
- Ultra low background b X-ray receiver
- Sun tracking





ALPS II - 10^3 better sensitivity than ALPS I



$$\mathrm{sens}(g_{a\gamma\gamma}) \propto \frac{1}{BL}\frac{\omega}{P^{1/4}(F_1F_2)^{1/4}}\frac{N^{1/8}}{t^{1/8}}$$

- Extra gain with the two matched FPs
- Finesses F_1, F_2 larger than 10^4
- TES dark count rate N=10^{-3} counts/sec

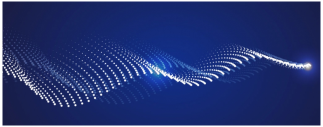
increasing sensitivity with haloscopes

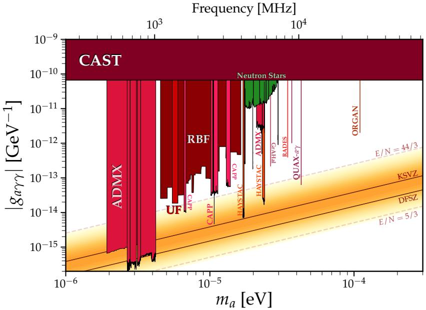
$$m_a \simeq h\nu_a \qquad 1\,\mu\text{eV} \leftrightarrow 0.25\,\text{GHz}$$

particle $\Leftrightarrow$ wave

$$\lambda = \frac{h}{mv}, \qquad h\nu = E = mc^2 + \frac{1}{2}mv^2$$

For **light** and **massless** particles the wavelength can be large.



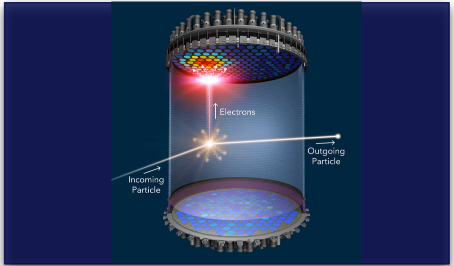


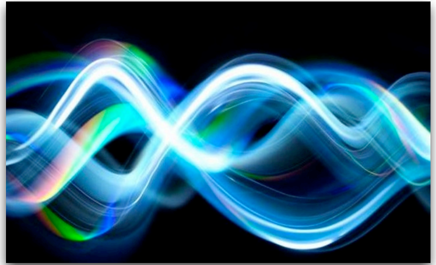
If these particles are also **bosons**, many particles **can occupy the same state**

$$\rho_{\rm DM} = 0.3 - 0.4\,\text{GeV}\,\text{cm}^{-3} \qquad \Longrightarrow \qquad n_a \sim 3\times 10^{12}(10^{-4}\text{eV}/m_a)\ \text{axions/cm}^3$$

it's a **macroscopic wave-like** behavior

AXION VS WIMP DETECTION





WIMP [1-1000 GeV]
— number density is small
— tiny wavelength
— no detector-scale coherence

$\Longrightarrow$ observable: **scattering** of individual particles

AXION [$m_A \ll$ eV]
— number density is large (bosons)
— long wavelength
— **coherence within detector ($\sim$ 1 km for 1 μeV)**

$\Longrightarrow$ observable: classical, oscillating, **background field**

HALOSCOPE SEARCHES - axion DM in the galactic halo

heavy axions

→ *Dielectric haloscope*: periodic structures of dielectric planes allow for an emission of EM waves induced by axions with frequencies (masses) between 10 (40) and 100 (400) GHz (μeV)
Magnetized Disc and Mirror Axion Experiment (MADMAX)

→ *plasma haloscope* (ALPHA, Axion Longitudinal Plasma): use a wire metamaterial to create a tuneable artificial plasma frequencyHAloscope

→ *topological insulator* (TOORAD, TOpolOgical Resonant Axion Detection) make an effective massive photon quasiparticle (polariton) using condensed matter axions

from ~ 3 **up to** $\sim 60\,\mu$**eV**

→ Cavity haloscopes: resonant conversion of axions into cavity photons
high frequency ($5 - 10\,$GHz) challenge is addressed via QIS technologies for signal readout and using dielectric resonators

→ ferromagnetic haloscope (QUAX $a - e$, QUest for AXions)

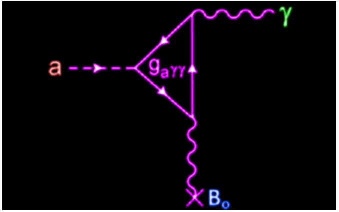
low-mass axion searches

→ Lumped element searches (ABRACADABRA, ...)

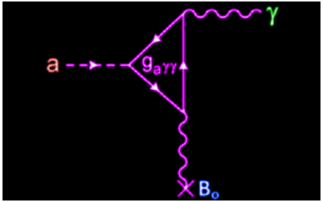
→ NMR-based search (CASPER-wind)

Cavity haloscope - resonant search for axion DM in the Galactic halo

– original proposal by P. Sikivie (1983)
– search for axions as cold dark matter constituent: SHM from Λ_{CDM}, local DM density ρ
  $\rightarrow$ signal is a **line** with 10^{-6} relative width in the energy($\rightarrow$ frequency) spectrum
  $\rightarrow$ + sharp (10^{-11}) components due to non-thermalized
– an **axion** may interact with a **strong** $\vec{B}$ **field** to produce a **photon** of a specific frequency ($\rightarrow m_a$)



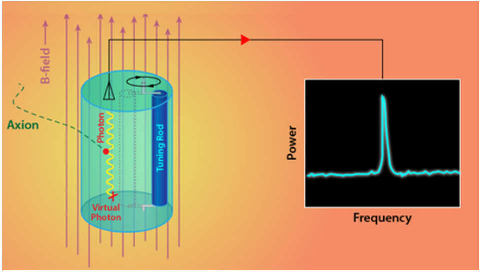
CAVITY HALOSCOPE - resonant search for axion DM in the Galactic halo



1. microwave cavity for resonant amplification
   -think of an HO driven by an external force-
2. with **tuneable frequency** to match the axion mass
3. the cavity is within the bore of a **SC magnet**
4. cavity signal is readout with a **low noise receiver**
5. cavity and receiver preamplifier are kept at base temperature of a **dilution refrigerator** $(10 - 50)$ mK

CAVITY HALOSCOPE - resonant search for axion DM in the Galactic halo

— if axions are *almost monochromatic* then their conversion to detectable particles (photons) can be accomplished using *high-Q* microwave cavities.



- cylindrical cavity frequency of resonance $\nu_c = \frac{115\,\text{GHz}}{r[\text{mm}]}$
- resonant amplification in $[m_a \pm m_a/Q]$
- data in thin slices of parameter space; typically $Q < Q_a \sim 1/\sigma_v^2 \sim 10^6$
- signal power $P_{a\to\gamma}$ is model-dependent

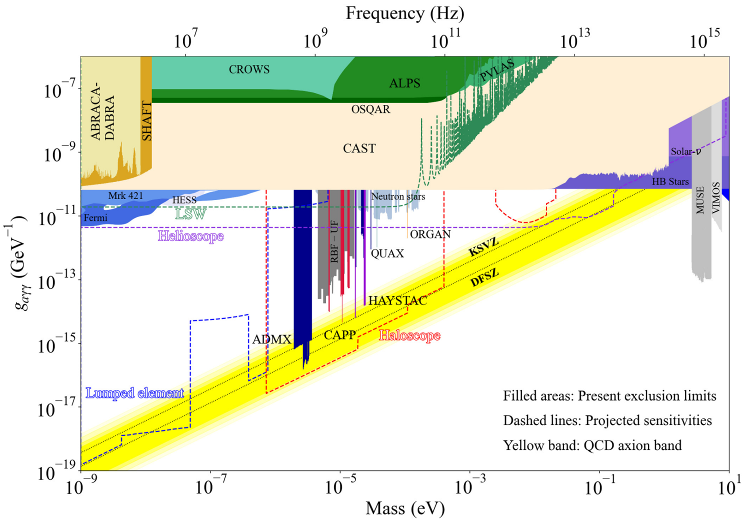
$$P_{a\to\gamma} \propto g_{a\gamma}^2 \frac{\rho}{m_a} B^2 C_{mnl} V Q$$

exceedingly tiny ($\sim 10^{-23}$ W)

- **high frequency**: poor scaling with V and increasing standard quantum limit noise

"The last signal ever received from the 7.5 W transmitter aboard Pioneer 10 in 2002, then 12.1 billion kilometers from Earth, was a prodigious 2.5×10^{-21} *W. And unlike with the axion, physicists knew its frequency!"*

K. V. Bibber and L. Rosenberg, Physics Today 59, 8, 30 (2006) poor scaling of the axion power with V sets a limit at $\sim 20\,\text{GHz}$ for cavity haloscopes



signal power $P_{a\to\gamma}$ and scan rate $\frac{df}{dt}$

how the *cavity performance* and *receiver technology* impact haloscope search

$$P_{a\to\gamma} \approx g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 Q_L C_{mnp} V$$

$$\Sigma = \frac{\text{signal}}{\text{noise}} = \frac{P_{a\to\gamma}}{k_B T_n}\sqrt{\frac{t_m}{b}} \longrightarrow t_m = \Sigma^2 \frac{(k_B T_n)^2}{P_{a\to\gamma}^2}\frac{m_a}{Q_a}$$

$$\Delta t = \frac{\Delta f}{Nb} t_m$$

$$\frac{df}{dt} \approx \left(\frac{g_{a\gamma\gamma}^4}{\Sigma^2}\right)\left(\frac{\rho_a^2 Q_a}{m_a^2}\right)\frac{B^4 Q_L (C_{mnl} V)^2}{(k_B T_n)^2}$$

here draw cavity vs axion linewidth

a time-consuming search

For a target sensitivity $g_{a\gamma\gamma}$, the scan rate is given by:

$$\frac{df}{dt} \propto \frac{B^4\, V_{\text{eff}}^2\, Q_L}{T_{sys}^2}$$

A haloscope optimized at best goes at:

$$\left(\frac{df}{dt}\right)_{\text{KSVZ}} \sim \text{GHz/year}$$

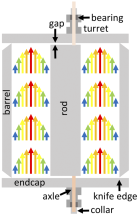
$$\left(\frac{df}{dt}\right)_{\text{DFSZ}} \sim 20\,\text{MHz/year} \qquad \odot\,\odot$$

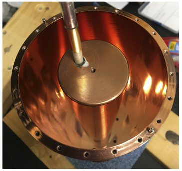
Take-home: to probe the mass range (1-10) GHz at DFSZ sensitivity would require $\gtrsim$ 100 years with 4-5 complementary haloscopes

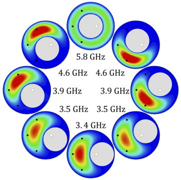
TUNING - SCAN RATE and $g_{a\gamma\gamma}$

Doubling the sensitivity requires reducing the speed by a factor 16

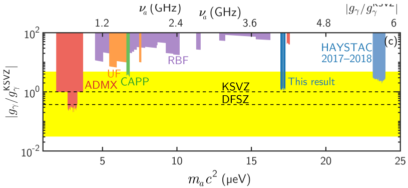
$$\frac{df}{dt} \approx \left(\frac{g_{a\gamma\gamma}^4}{\Sigma^2}\right)\left(\frac{\rho_a^2 Q_a}{m_a^2}\right)\frac{B^4 Q_L (C_{mnl} V)^2}{(k_B T_n)^2}$$







Rev. Sci. Instrum. **92**, 033305 (2021)



sensitivity goal:

$2 \times g_{a\gamma\gamma}^{KSVZ} \Longrightarrow 600\,\mathrm{MHz/year}$

$g_{a\gamma\gamma}^{KSVZ} \Longrightarrow 40\,\mathrm{MHz/year}$ ⊙⊙

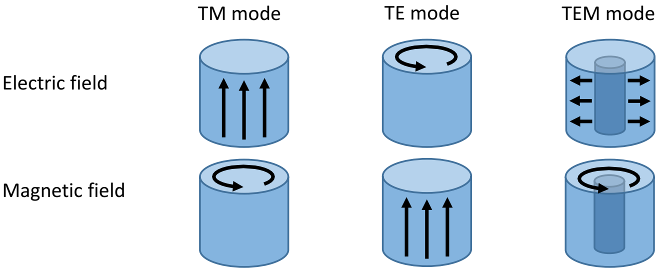
⊙⊙ mode mixing and cavity aspect ratio
arXiv:2006.01248

FORM FACTOR : quantifying the cavity capacity to resonate a signal

$$\propto \int_V dV\, \mathbf{E}_{mnp} \cdot \mathbf{B_0}$$

$$C_{mnp} = \frac{|\int_V dV\, \mathbf{E}_{mnp}(\mathbf{x}) \cdot \mathbf{B_0}|^2}{\mathbf{B}_0^2 V \int d^3x\, \varepsilon(\mathbf{x}) |\mathbf{E}_{mnp}(\mathbf{x})|^2}$$

$$0 < C_{mnp} < 1$$

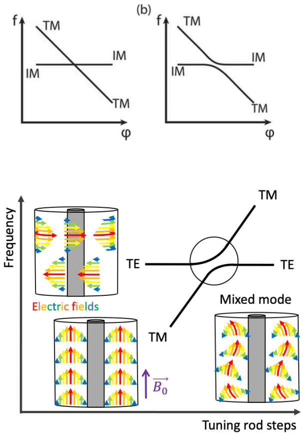


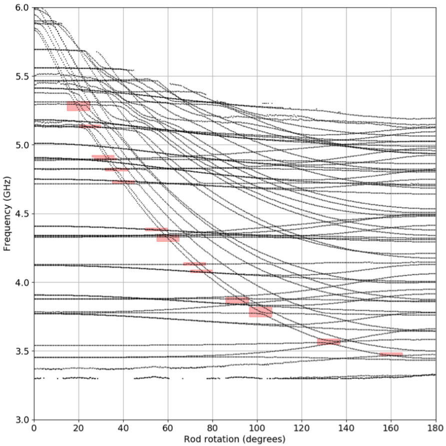
TM (TE), no magnetic (electric) field along the propagation direction

takehome: of all the modes that resonate in a metallic pill box only those that have components **E** along $\mathbf{B}_0$ will yield a signal

MODE MIXING

TE and TM modes are sufficiently close in frequency, they mix and create a mixed hybrid mode

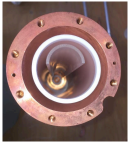




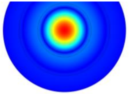
arXiv:2006.01248

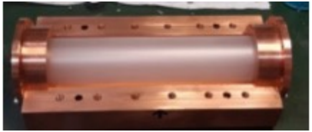
to **maximize the axion signal** we use our **best cavities** $df/dt \propto Q_L$

Transition from copper cavities ($Q_c \ll Q_a = 10^6$) to new solutions that satisfy $Q_c \gg Q_a$



Dielectric resonator

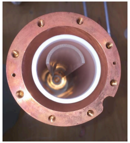




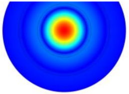
- copper cavity with dielectric shells / "dielectric boosted" resonator concept
  Phys. Rev. Appl. 14, 044051 (2020)
  J. Phys. G47 035203 (2020)
- the shells allow for shaping the cavity fields to suppress ohmic losses at the copper boundaries
  - higher order modes (e.g. TM_{030}) are exploited $C_{030} = 0.03$ (2-shell), upcoming version with 1-shell has $C_{030} = 0.47$ ($df/dt \propto C^2Q$)

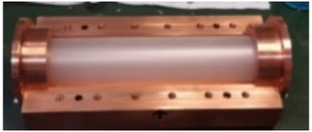
to **maximize the axion signal** we use our **best cavities** $df/dt \propto Q_L$

Transition from copper cavities ($Q_c \ll Q_a = 10^6$) to new solutions that satisfy $Q_c \gg Q_a$



Dielectric resonator





clamshell tuning

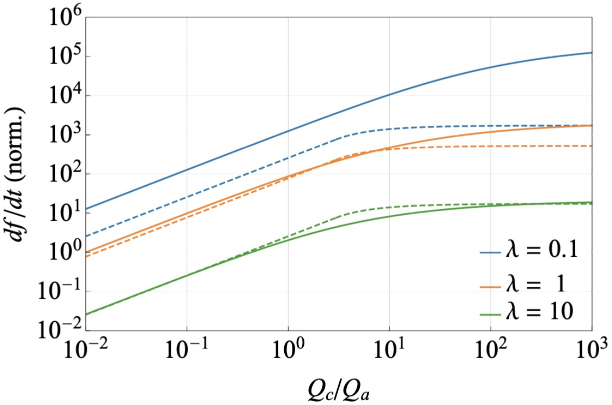
type-II superconductor (ReBCO)

PATRAS Workshop 2022

results from CAPP (Korea)

$Q \sim 10^7$ for any **B** field value we can afford

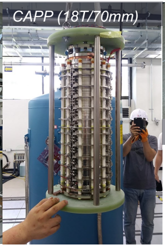
SCAN RATE and CAVITY QUALITY FACTOR

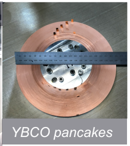


recent improvements in the cavity quality factor → taking into account the impedance mismatch in noise flow to **maximize the axion signal** we use our **best magnets** $df/dt \propto B^4$

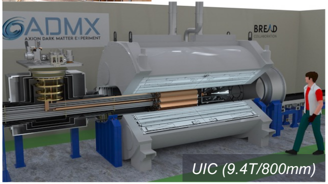

ADMX (8T/600mm)


CAPP (12T/320mm)

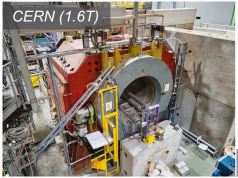

CAPP (18T/70mm)

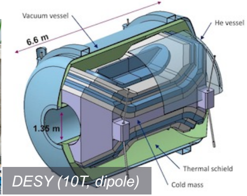

YBCO pancakes

Grenoble (43T/34mm)



UIC (9.4T/800mm)


CERN (1.6T)



DESY (10T, dipole)

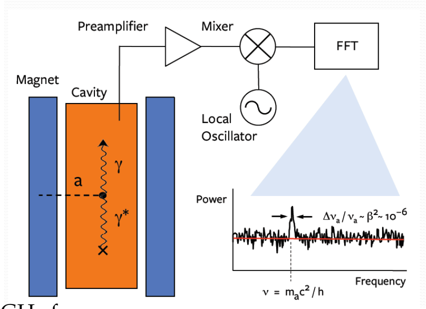
to **minimize noise** we use our **best low noise amplifiers**

and cool down to lowest temperatures in the Universe ($\sim 10\,\text{mK}$) $df/dt \propto T^{-2}$

Josephson Parametric Amplifiers (JPAs) introduce the lowest level of noise, set by the laws of quantum mechanics (Standard Quantum Limit noise)

$T_{sys} = T_c + T_A$
T_c cavity physical temperature
T_A effective noise temperature of the amplifier

$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_a \right)$$



at 10 GHz frequency

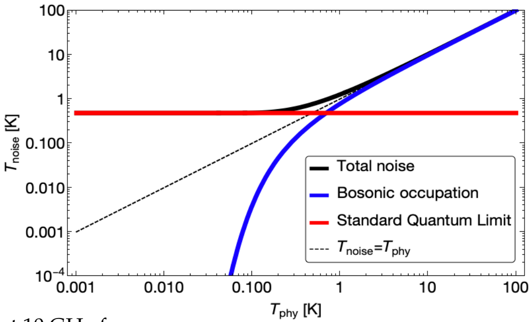
to **minimize noise** we use our **best low noise amplifiers**

and operate at lowest temperatures in the Universe ($\sim 10\,\mathrm{mK}$) $df/dt \propto T^{-2}$

Josephson Parametric Amplifiers (JPAs) introduce the lowest level of noise, set by the laws of quantum mechanics (Standard Quantum Limit noise)

$T_{sys} = T_c + T_A$
T_c cavity physical temperature
T_A effective noise temperature of the amplifier

$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_a \right)$$



at 10 GHz frequency

Standard Quantum limit in linear amplification

Any narrow bandwidth signal $\Delta\nu_c \ll \nu_c$ can be written as:

$$\begin{aligned} V(t) &= V_0[X_1 \cos(2\pi\nu_c t) + X_2 \sin(2\pi\nu_c t)] \\ &= V_0/2[a(t)\exp(-2\pi i\nu_c t) + a^*(t)\exp(+2\pi i\nu_c t)] \end{aligned}$$

X_1 and X_2 signal quadratures
$a, a^* \rightarrow$ to operators $a, a^\dagger$ with $[a, a^\dagger] = 1$ and $N = aa^\dagger$
Hamiltonian of the cavity mode is that of the HO:

$$\mathcal{H} = h\nu_c \left(N + \frac{1}{2}\right)$$

Alternatively, with $[X_1, X_2] = \frac{i}{2}$:

$$\mathcal{H} = \frac{h\nu_c}{2}(X_1^2 + X_2^2)$$

$$kT_{\text{sys}} = h\nu_c N_{sys} = \left(\frac{1}{e^{h\nu/kT}-1} + \frac{1}{2} + N_A\right)$$

Caves' Theorem: $N_A > 1/2$

The quantum noise is a consequence of the base that we want to use to measure the content of the cavity.
A **linear amplifier** measures the amplitudes in phase and in quadrature, while a **photon counter** measures N.

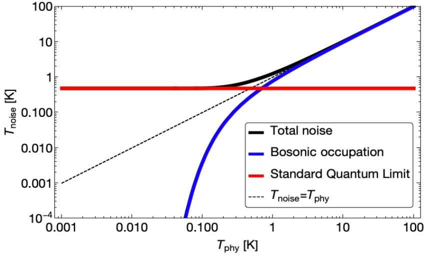
BEYOND SQL THROUGH PHOTON COUNTING

	ν_c GHz	Q	β	B T	V cm^3	C_{nml}	$P_{a\gamma\gamma}$ $\times 10^{-24}$ W	Γ_{sig} Hz
QUAX$_{a\gamma}$	10.48	1×10^6	1	14 T	1150	0.47	439 (KSWZ) 60 (DFSZ)	63 8.7

– **Photon counting** is a game changer at high frequency and low temperatures: in the **energy eigenbasis** there is no intrinsic limit (SQL)

– unlimited (exponential) gain in the haloscope scan rate compared to linear amplification at SQL:

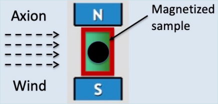
$$\frac{R_{\text{counter}}}{R_{\text{SQL}}} \approx \frac{Q_L}{Q_a} e^{\frac{h\nu}{k_B T}}$$



plot example at 10 GHz, where $T_{\text{SQL}} = h\nu/k_B \to 0.5\,\text{K}$

at 7 GHz, 40 mK $\Longrightarrow 10^3$ faster than SQL linear amplifier readout!

ELECTRON COUPLING – **QUAX** *the FMR haloscope*



the axion DM cloud acts as an **effective RF magnetic field** on the electron spin exciting **magnetic transitions** in a magnetized sample (YIG) $\rightarrow$ **RF photons**

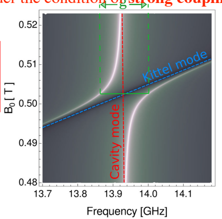
$$P_{\text{out}} = \frac{P_{\text{in}}}{2} = \mathbf{3.8 \times 10^{-26}} \left(\frac{m_a}{200\,\mu\text{eV}}\right)^3 \left(\frac{V_s}{100\text{ cm}^3}\right) \left(\frac{n_S}{2 \cdot 10^{28}/\text{m}^3}\right) \left(\frac{\tau_{\min}}{2\,\mu s}\right) \text{W}$$

ESR (Electron Spin Resonance)
the RF field is actually the axion effective field
—>> axion mass tuning with B field!
1.7 T —> 48 GHz

YIG (Yttrium Iron Garnet)

$\tau_{\min} = \min(\tau_a, \tau_c, \tau_2)$

under the condition of **strong coupling**



$$R_a = \frac{P_{\text{out}}}{\hbar \omega_a} = \mathbf{1.2 \times 10^{-3}}\,\text{Hz}$$

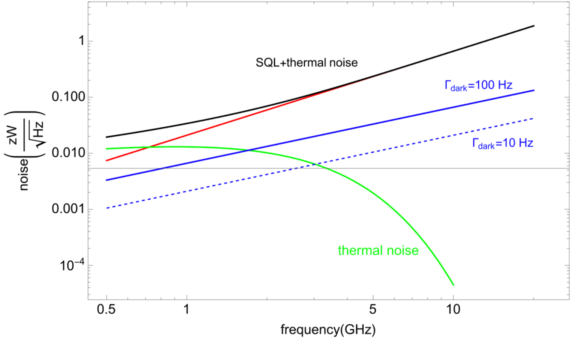
corresponding signal photon rate

Crescini *et al* Phys Rev Lett **124**, 171801 (2020)
Barbieri *et al* Phys Dark Univ **15**, 135-141 (2017)

Why do we need Single Microwave Photon Detectors (SMPD) in haloscope search?

Using quantum-limited **linear amplifiers** (Josephson parametric amplifiers) the **noise set by quantum mechanics** exceeds the **signal** in the high frequency range, whereas **photon counting** has no intrinsic limitations

	ν_c [GHz]	Q_0	B T	V [liter]	$P_{a\gamma\gamma}$ $[10^{-24}$ W]	Γ_{sig} [Hz]
QUAX$_{a\gamma}$	10.48	1×10^6	14 T	1.15	439 (KSWZ) 60 (DFSZ)	63 8.7
Pilot exp.	7.3	1×10^6	2 T	0.11	0.8 (KSWZ) 0.11 (DFSZ)	0.16 0.02



axion linewidth $= \Delta\nu_a$

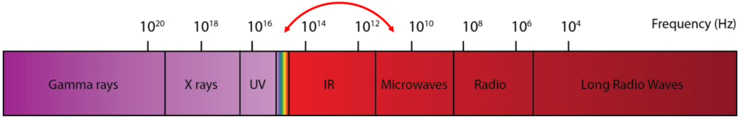
$P_n^{\mathrm{SQL}} = h\nu_a\sqrt{\Delta\nu_a}$

$P_n^{\mathrm{th}} = h\nu_a\bar{n}\sqrt{\Delta\nu_a}$, with $\bar{n} = \frac{1}{e^{h\nu/kT}-1}$, T=50 mK

$P_n^{\mathrm{SMPD}} = h\nu_a\sqrt{\Gamma_{\mathrm{dark}}}$

SMPDs in the microwave range

Detection of individual microwave photons is a challenging task because of their **low energy** e.g. $h\nu = 2.1 \times 10^{-5}\,\mathrm{eV}$ for $\nu = 5\,\mathrm{GHz}$

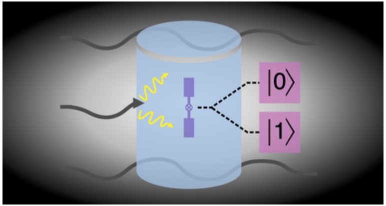


Requirements for axion dark matter search:

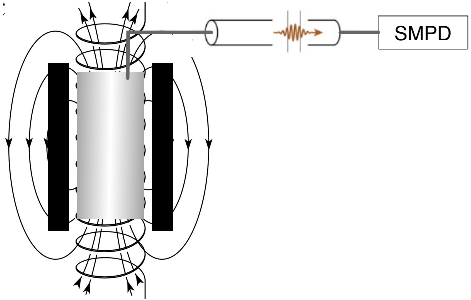
- detection of *itinerant photons* due to involved intense **B** fields
- lowest dark count rate $\Gamma < 100\,\mathrm{Hz}$
- $\gtrsim 40 - 50\,\%$ efficiency
- large "dynamic" bandwidth $\sim$ cavity tunability

ITINERANT and CAVITY PHOTON DETECTION

The detection of *itinerant photons*, i.e. **excitations in a transmission line**, is more challenging compared to the detection of *cavity mode excitations*.



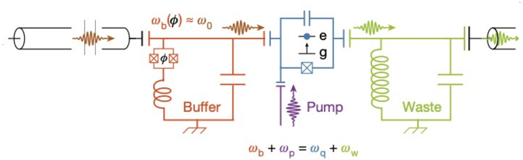
detection of *cavity photons*
applicable to dark photon searches (no B field)



detection of *itinerant photons*
applicable to axion searches (multi-Tesla fields)

Itinerant photon counters for axion detection: most advanced SMPD schemes

- "**artificial atoms**" introduced in circuit QED, their transition frequencies lie in the ∼GHz range



E. Albertinale *et al*, Nature **600**, 434–438 (2021)

R. Lescanne *et al*, Phys. Rev. X 10, 021038 (2020)

- single **current-biased Josephson junction (JJ)**

npj Quantum Information **8**, 61 (2022)

IEEE Tras. Appl. Supercond. **33**, 1-9 (2023)

CHALLENGES and R&D OBJECTIVES

- SMPDs are superconducting circuits, not compatible with magnetic fields above a critical value
  e.g. for Niobium, $B_c = 100\,\mathrm{mT}$

  can they be screened to the required level?
  flux quantum $\Phi_0 = h/(2e) \approx 2.0678... \times 10^{-15}\,\mathrm{Wb}$

- to probe different axion masses tuning of both cavity and SMPD is required

- can we probe the axion parameter space **at reasonable speed**?
  i.e. *best is tuning the whole system at* $\sim 500\,\mathrm{MHz/year}^*$ *for* $\nu_a \gtrsim 5\,\mathrm{GHz}$

* for best haloscopes the signal exceeds few tens of Hz rate (QUAX projected) thus the integration time is short and the search is limited by the speed at which the system can be tuned (e.g. thermal loads . . .)

HALOSCOPE SEARCHES - axion DM in the galactic halo

heavy axions

→ *Dielectric haloscope*: periodic structures of dielectric planes allow for an emission of EM waves induced by axions with frequencies (masses) between 10 (40) and 100 (400) GHz (μeV)
Magnetized Disc and Mirror Axion Experiment (MADMAX)

→ *plasma haloscope* (ALPHA, Axion Longitudinal Plasma): use a wire metamaterial to create a tuneable artificial plasma frequencyHAloscope

→ *topological insulator* (TOORAD, TOpolOgical Resonant Axion Detection) make an effective massive photon quasiparticle (polariton) using condensed matter axions

from ~ 3 **up to** $\sim 60\,\mu$**eV**

→ Cavity haloscopes: resonant conversion of axions into cavity photons
high frequency ($5-10$ GHz) challenge is addressed via QIS technologies for signal readout and using dielectric resonators

→ ferromagnetic haloscope (QUAX $a-e$, QUest for AXions)

low-mass axion searches

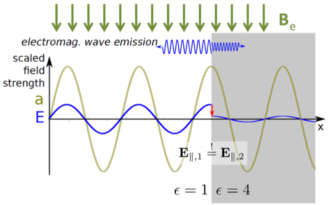
→ Lumped element searches (ABRACADABRA, . . .)

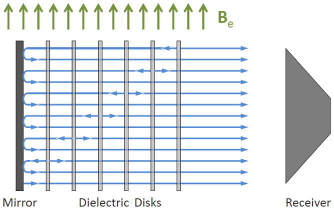
→ NMR-based search (CASPER-wind)

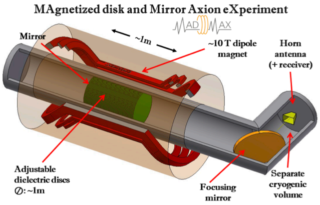
→ *Dielectric haloscope*

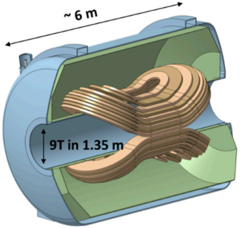
idea: at boundaries between two media (different ϵ) in a **B**-field // to the surface, the axion induced **E**-field oscillation has a discontinuity and EM waves are emitted by the surface

- ⊙ 10^4 power boost factor (tens of disks) is needed
- ⊙⊙ important to know how much is the actual boost factor: direct info is needed on expected signal shape from coherent emission of surfaces
- → solution: reflectivity measurements and study of the noise

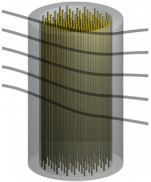








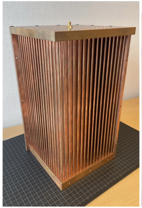
→ *plasma haloscope* (ALPHA, Axion Longitudinal Plasma):
idea: in a plasma the photon has an effective mass corresponding to the plasma frequency → wavelength matching between the massless photon and the axion with mass on much larger resonant system



$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{s^2 \log(s/d)}$$

- *s: inter space*
- *d: wire radius*

$$P_s = \left(\frac{\rho_a}{m_a} g_{a\gamma}^2\right) \kappa B_e^2 Q \mathcal{G} V$$



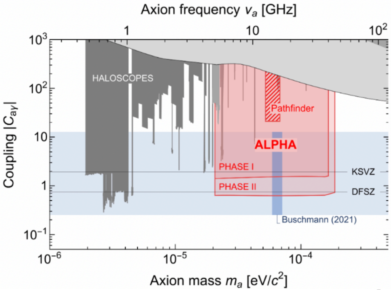
ALPHA PHASE I

- 2 years run
- $(5 \div 40)$ GHz
- HEMT amplifiers
- Single scan (see [8])

ALPHA PHASE II

- 2 years run
- $(5 \div 45)$ GHz
- Quantum limited
- Single scan (see [8])

$(Q \sim 10^4,\ B \sim 10\,\mathrm{T},\ V \approx 0.3\,\mathrm{m}^3)$



Conclusions

- Axions are leading candidates for dark matter

  and the QCD axion solves the strong CP problem
- Theoretically well motivated but experimentally challenging

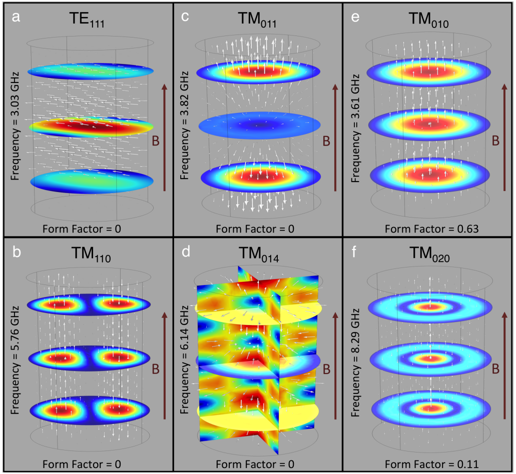
  weak coupling and unknown mass
- Tremendous search efforts

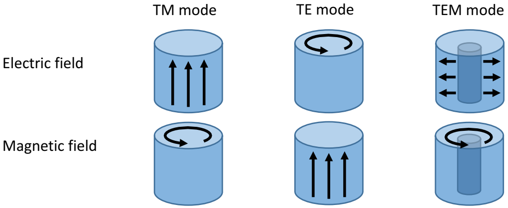
  Different technologies targeting at different mass ranges, quantum sensing
- Axion community is getting larger

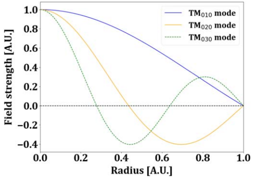
  New results, new groups and new ideas
- Next decade must be critical/exciting

  covering a substantial portion of the parameter space... uncovering the nature of dark matter?

FORM FACTOR : quantifying the cavity capacity to resonate a signal







Mode	f	V	Q	C
TM_{010}	f_{010}	V_{010}	Q_{010}	0.69
TM_{020}	$2.3 \times f_{010}$	V_{010}	$1.5 \times Q_{010}$	0.13
TM_{030}	$3.6 \times f_{010}$	V_{010}	$1.9 \times Q_{010}$	0.05

J. Phys. G: Nucl. Part. Phys. **47** (2020) 035203