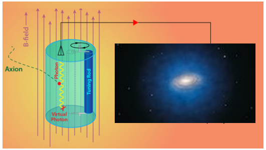
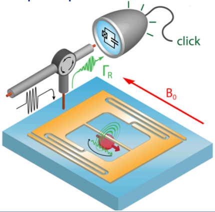
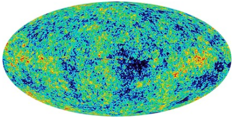
Haloscopes: axion detection



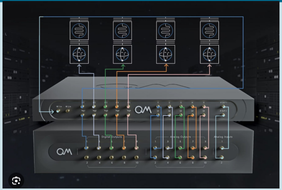
Single spin-flip detection



CMB



ROOM TEMP. INSTRUMENTATION (VAT incl.)



- **OPX machine**: hardware and software platform for designing **quantum control protocols**, executing them on a wide range of quantum hardware platforms
  $\sim$ 72 keuro
- **vector network analyser**:
  testing two-ports equipment
  $\sim$ 53 keuro
- **SC magnet** $\sim$ 55 keuro

Haloscopes

Axion interactions with SM particles are expressed by the Hamiltonian:

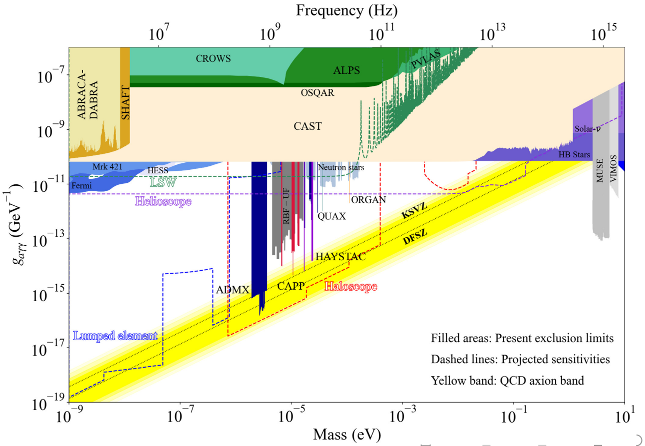
$$\mathcal{H} = \sqrt{\frac{\varepsilon_0}{\mu_0}} g_{a\gamma\gamma} \int a \mathbf{E} \cdot \mathbf{B} dV + g_{aff} \hbar c \nabla a \cdot \hat{\mathbf{S}} + \sqrt{\varepsilon_0 (\hbar c)^3} g_{EDM} a \hat{\mathbf{S}} \cdot \mathbf{E}$$

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?

- $g_i \sim \frac{1}{f_a} \xrightarrow{m_a f_a \sim m_\pi f_\pi} g_i \propto m_a$
  true for QCD axion
- ALPs mass could take any value



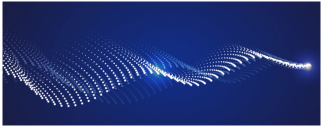
wave-like DM

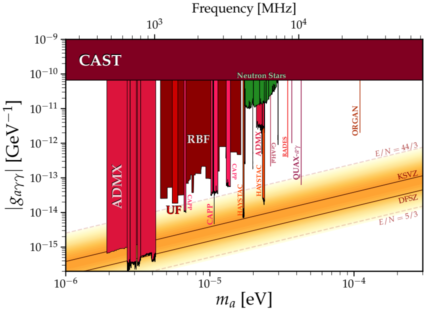
$m_a \simeq h\nu_a \qquad 100\,\mu\text{eV} \leftrightarrow 25\,\text{GHz}$

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.



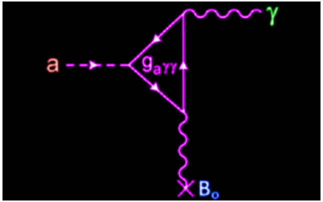


If these particles are also **bosons**, many particles **can occupy the same state**

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

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

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

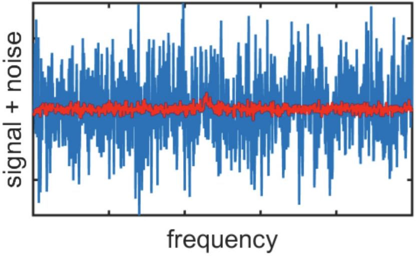


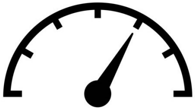
1. microwave cavity for resonant amplification
   -think of an HO driven by an external force-
2. with **tuneable frequency** to match the axion mass
3. the cavity is within the bore of a **SC magnet**
4. cavity signal is readout with a **low noise receiver** $S \ll N$
5. cavity and receiver preamplifier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

In these searches, **the signal is much smaller than noise**

$$P_n = k_B T \Delta\nu \gg P_s \;\propto\; B^2\, V_{\text{eff}}\, Q_L \sim (10^{-22} - 10^{-23})\,\text{W}$$

To increase sensitivity we rely on **averaging several spectra** recorded at the same cavity frequency **over a certain integration time**.





Thus a figure of merit for haloscope search is the **scan rate** :

$$\frac{df}{dt} \propto \frac{B^4\, V_{\text{eff}}^2\, Q_L}{T_{sys}^2} \qquad \text{for a target sensitivity } g_{a\gamma\gamma},\ \chi$$

A haloscope optimized at best goes at:

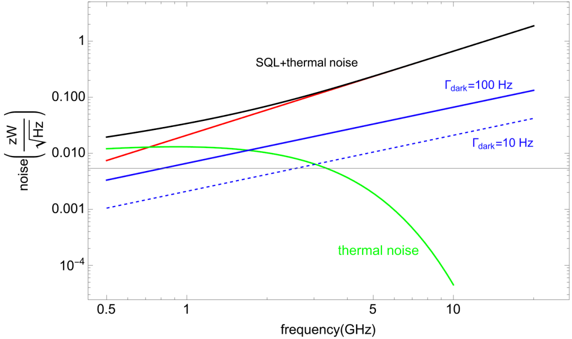
$$\left(\frac{df}{dt}\right)_{\text{KSVZ}} \sim \text{GHz/year} \qquad\qquad \left(\frac{df}{dt}\right)_{\text{DFSZ}} \sim 20\,\text{MHz/year}$$

To probe the mass range (1-10) GHz at DFSZ sensitivity would require $\gtrsim 100$ **years with current technology**

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 $= \Delta\nu_a$

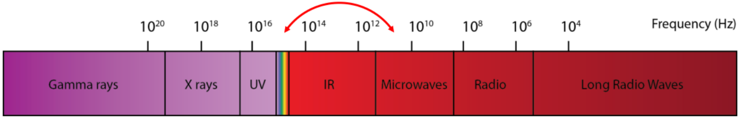
$$P_n^{\mathrm{SQL}} = h\nu_a\sqrt{\Delta\nu_a}$$

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

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

SMPDs in the microwave range

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

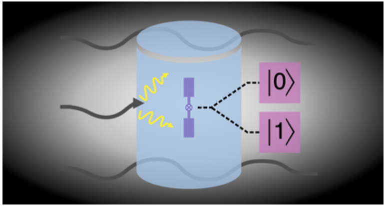


Requirements for axion dark matter search:

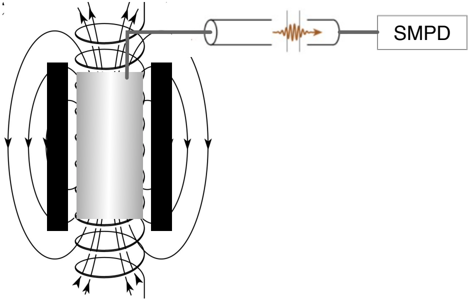
- detection of *itinerant photons* due to involved intense **B** fields
- lowest dark count rate $\Gamma < 100\,\text{Hz}$
- $\gtrsim 40 - 50\,\%$ efficiency
- large "dynamic" bandwidth $\sim$ cavity tunability

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*.



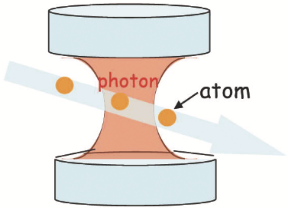
detection of *cavity photons*
applicable to dark photon searches (no B field)

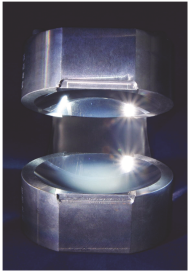


detection of *itinerant photons*
applicable to axion searches (multi-Tesla fields)

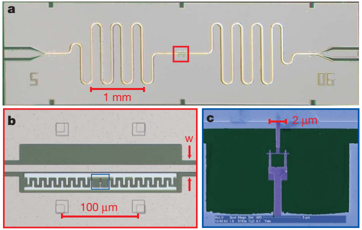
DETECTION OF QUANTUM MICROWAVES

The detection of individual **microwave photons** has been pioneered by **atomic cavity quantum electrodynamics experiments** and later on transposed to **circuit QED experiments**





Nature **400**, 239–242 (1999)



Nature **445**, 515–518 (2007)

In both cases **two-level atoms** interact directly with a **microwave field mode*** in the cavity

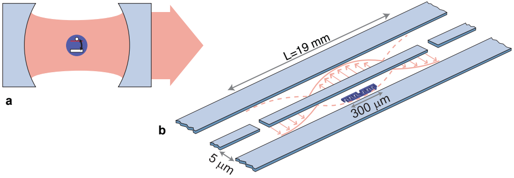
* a quantum oscillator whose quanta are photons

from cavity-QED to circuit-QED

g is significantly increased compared to Rydberg atoms:

$\rightarrow$ artificial atoms are large ($\sim 300\,\mu$m)
$\Longrightarrow$ large dipole moment

$\rightarrow$ $\vec{E}$ can be tightly confined
$\vec{E} \propto \sqrt{1/\lambda^3}$
$\omega^2\lambda \approx 10^{-6}\,\mathrm{cm}^3$ (1D) versus $\lambda^3 \approx 1\,\mathrm{cm}^3$ (3D)
$\Longrightarrow 10^6$ larger energy density



(a) $(g/2\pi)_{\text{cavity}} \sim 50\,\text{kHz}$

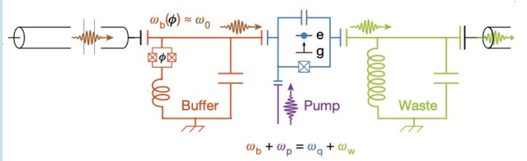
(b) $(g/2\pi)_{\text{circuit}} \sim 100\,\text{MHz}$ (typical)

10^4 larger coupling than in atomic systems

Itinerant photon counters for axion detection: the most advanced SMPD

SC qubits

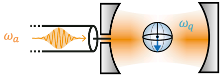
transition frequencies in "**artificial atoms**" lie in the GHz range

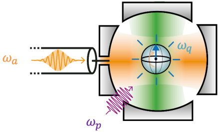


E. Albertinale *et al*, Nature **600**, 434–438 (2021)

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

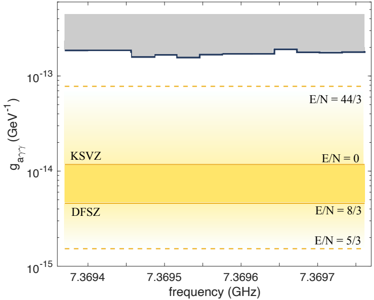
- 2D resonator coupled to a transmon-qubit
- the incoming photon is coupled to the 2D resonator and converted to a qubit excitation via a 4WM nonlinear process
- the state of the qubit is then probed with QIS methods (dispersive readout, $g \ll \omega_r - \omega_q$)

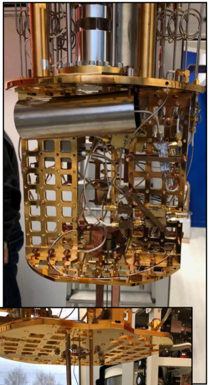




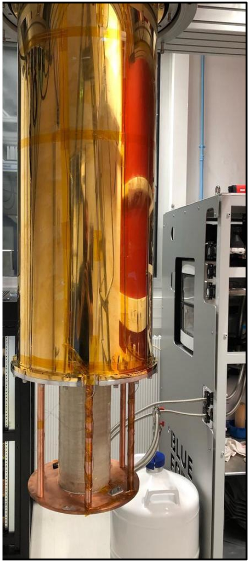
PILOT SMPD-HALOSCOPE experiment
(Feb. 2023, in the Saclay delfridge)

- right cylinder 3D resonator, TM_{010} mode $\nu_c \sim 7.3\,\text{GHz}$
- **ultra-cryogenic nanopositioner** to change sapphire rods position
- **2 T** (60 A) SC magnet






SMPD (top) and cavity



SC magnet

building a SMPD-HALOSCOPE experiment in Padova

pre-existing hardware: the dilution refrigerator

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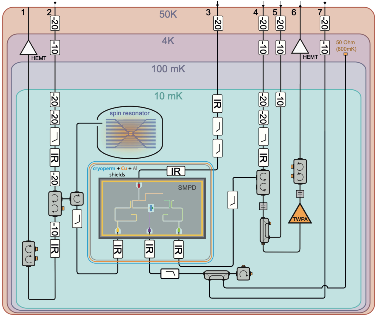
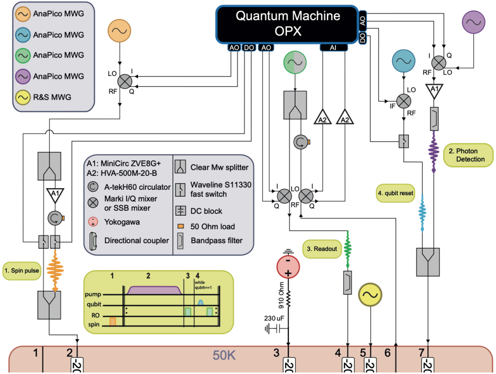


WISHLIST



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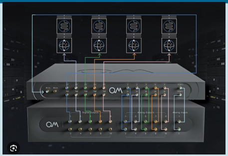

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∼ 72 keuro

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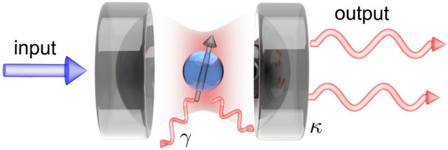
Cavity-QED

Can the field of a single photon have a large effect on the artificial atom?

Interaction: $H = -\vec{d} \cdot \vec{E}$, $E(t) = E_0 \cos \omega_q t$

It's a matter of increasing the **coupling strength** g between the atom and the field $g = \vec{E} \cdot \vec{d}$:



→ work with **large atoms**

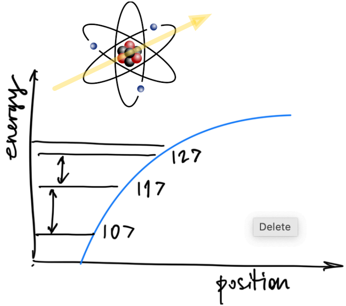
→ **confine the field** in a cavity

$$\vec{E} \propto \frac{1}{\sqrt{V}}, \; V \;\text{volume}$$

κ rate of cavity photon decay
γ rate at which the qubit loses its excitation
to modes $\neq$ from the mode of interest

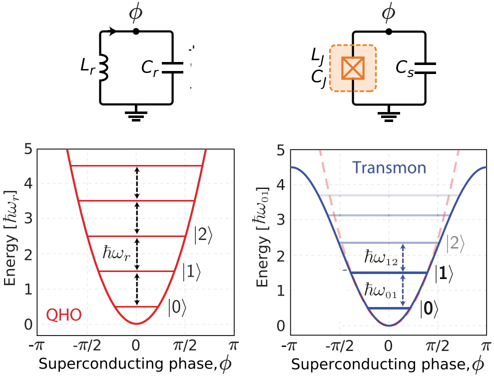
$g \gg \kappa, \gamma \iff$ regime of strong coupling
coherent exchange of a field quantum between the atom (matter) and the cavity (field)

qubits from "**artificial atoms**": LC circuit **with NL inductance** of the Josephson Junction



$E_{01} = E_1 - E_0 = \hbar\omega_{01} \neq E_{02} = E_2 - E_1 = \hbar\omega_{21}$
$\rightarrow$ good **two-level atom** approximation

control internal state by shining laser tuned at the transition frequency:
$H = -\vec{d} \cdot \vec{E}(t)$, with $E(t) = E_0 \cos \omega_{01} t$



toolkit: capacitor, inductor, wire (all SC) + JJ
JJ is a **nonlinear** and dissipationless element

$$L_J = \frac{\phi_0}{2\pi} \frac{1}{I_c \cos \phi}$$