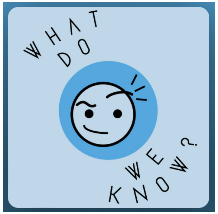
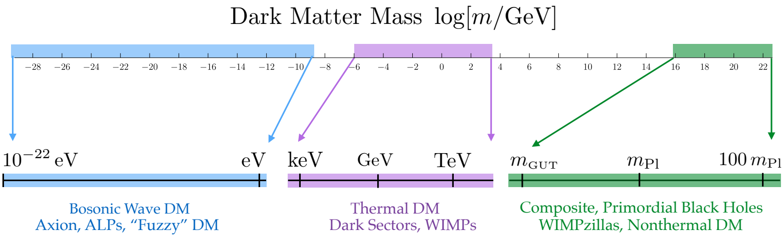
DARK MATTER



- **on a galactic scale it's pretty much like regular matter**
  gravitational pull
- **no non-gravitational interactions**
  feeble interactions with SM particles and itself
- **it's abundant**
  85% of the matter in the Universe
- **spread like a dilute fog through galaxies**
  cold, nonrelativistic
  local density $0.3 - 0.4\,GeV cm^{-3}$*, around* 10^5 *times the average cosmic density*
  local velocity dispersion 200 km/s
- **it isn't made of known particles**
  if it's particles

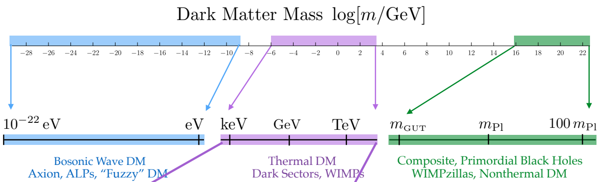
Theoretical particle physicists have cooked up **dozens of hypothetical particles**

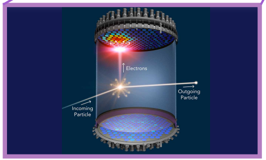


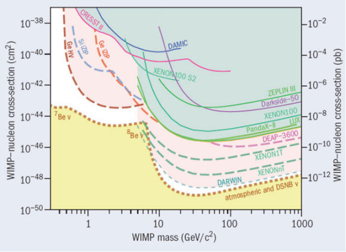
Quantum Sci. Technol. **6** 024002 (2021)

Experimental physicists build and operate detectors **sensitive to specific interactions**.

If they do not see a signal an **exclusion plot** is updated.



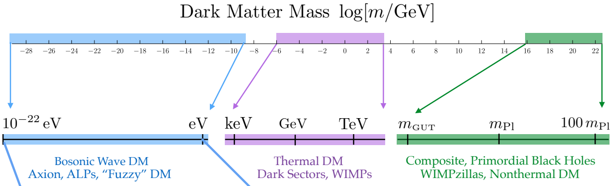


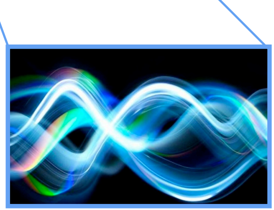


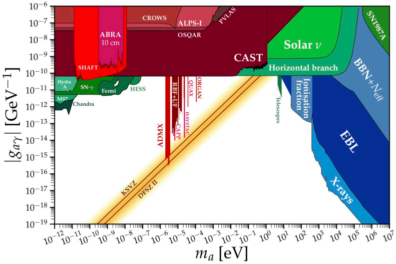
$m \gtrsim 10\,\mathrm{eV}$

individual particles scattering off a detector

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







$m \lesssim 10\,\mathrm{eV}$

classical field oscillating at the Compton frequency

AXION

– number density is large (bosons)

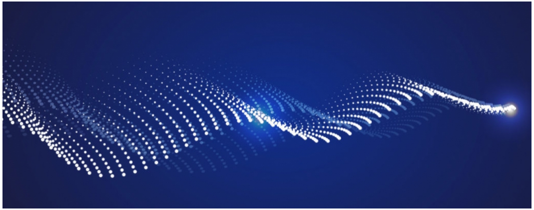
– long wavelength

– coherence ($Q_a = 10^6$) within detector

DARK MATTER AS A COSMIC WAVE

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

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



As these particles are **bosons**, they **can occupy the same state**

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

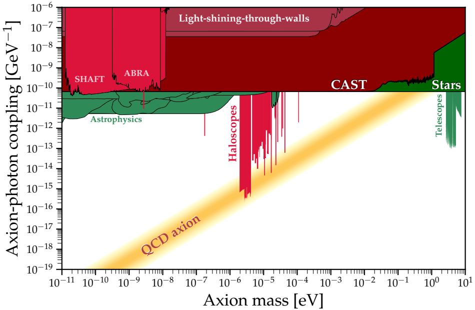
it's a **macroscopic wave-like** behavior

AXION AND ALP

compelling DM candidates with natural early-universe production mechanisms, extremely high energy scales f

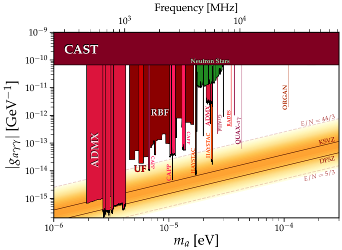
$$m_a = (5.70 \pm 0.007)\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

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



https://cajohare.github.io/AxionLimits/

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



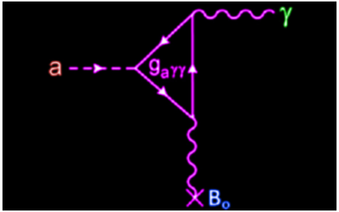
THE HALOSCOPE - a cosmic radio receiver for radio stations from 300 MHz to 15 GHz

axion waves are converted to EM waves as radio waves change to sound waves in a radio

HALOSCOPE - resonant search for axion/dark photon in the Galactic halo

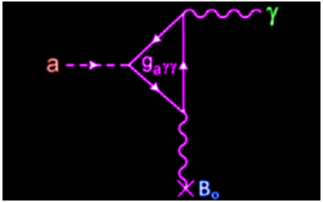
– search for axions as cold dark matter constituent: SHM from Λ_{CDM}, local DM density ρ
  $\rightarrow$ signal is a **line** with 10^{-6} relative width in the energy($\rightarrow$ frequency) spectrum

– an **axion** may interact with a **strong** $\vec{B}$ **field** to produce a **photon** of a specific frequency ($\rightarrow m_a$)



– **dark photons** couple to the SM via kinetic mixing (no B field is required)

HALOSCOPE - resonant search for axion/dark photon in the Galactic halo



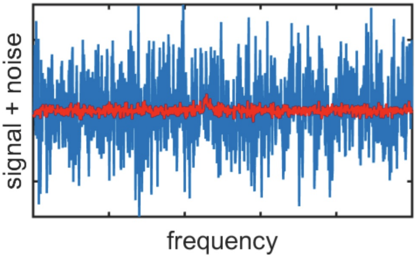
1. 3D microwave cavity for resonant amplification
   -think of an HO driven by an external force-
2. with **tuneable frequency** to match the axion mass
3. the cavity is within the bore of a **SC magnet**
4. cavity signal is readout with a **low noise receiver**
5. cavity and receiver preamplifier are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

NOISE - the analogy with the radio breaks down . . .

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

$$P_n = k_B T \Delta\nu \gg P_s \;\; \propto g_{a\gamma\gamma} \frac{\rho}{m_a} B^2 \, V_{\rm eff} \, Q_L \sim (10^{-22} - 10^{-23})\,\mathrm{W}$$

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

SIGNAL READOUT

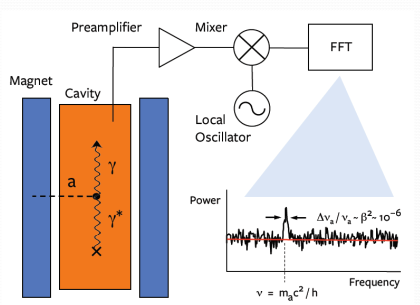
$df/dt \propto V_{\text{eff}}^2 \; Q_L \; T_{sys}^{-2}$

weak interactions with SM particles $\Longrightarrow 10^{-23}$ W signal power
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

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

$N_A \gtrsim 0.5$
S. K. Lamoreaux *et al.*, Phys Rev D **88** 035020 (2013)



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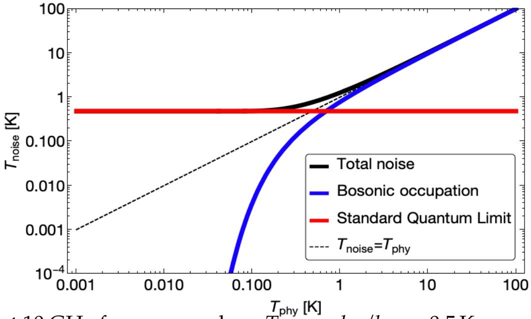

at 10 GHz frequency, where $T_{\rm SQL} = h\nu/k_B \to 0.5\,{\rm K}$

SQL IN LINEAR AMPLIFICATION

The quantum noise is a consequence of the base that we want to use to measure the EM field in the cavity.
A **linear amplifier** measures the amplitudes in phase and in quadrature.
Any narrow bandwidth signal $\Delta\nu_c \ll \nu_c$ can in fact 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

LINEAR AMPLIFIER READOUT

Alternatively, with $[X_1, X_2] = \frac{i}{2}$
the hamiltonian of the HO is written as:

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

PHOTON COUNTER: measuring N

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

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

Photon counting is a game changer (high frequency, low T): in the **energy eigenbasis** there is no intrinsic limit

linear amplification vs photon counting

LINEAR AMPLIFIER READOUT

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the hamiltonian of the HO is written as:

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

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

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

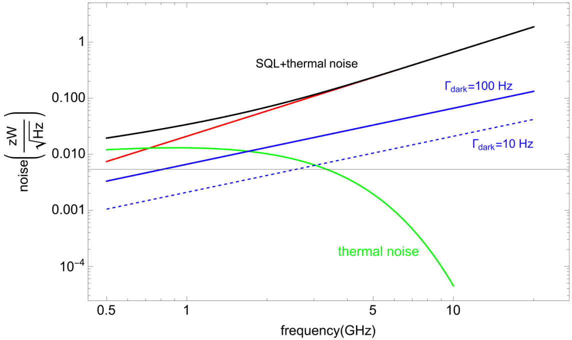
Ex. at 7 GHz, 40 mK
$\Longrightarrow 10^3$ faster than SQL linear amplifier readout with an ideal SMPD (dark count free, unitary efficiency)

S. K. Lamoreaux *et al.*, Phys Rev D **88** 035020 (2013)

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 $= \Delta\nu_a$

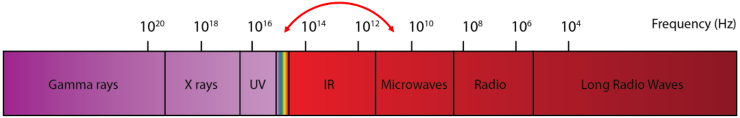
$$P_n^{SQL} = h\nu_a\sqrt{\Delta\nu_a}$$

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

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

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 $\nu = 5\,\text{GHz}$

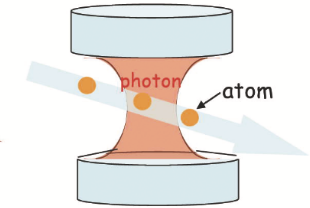


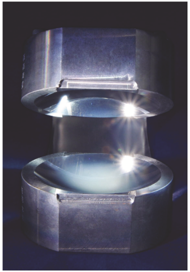
Requirements for axion dark matter search:

- 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

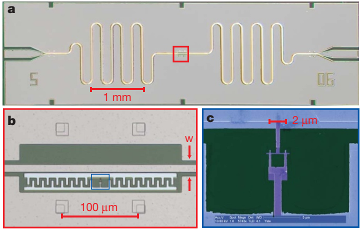
DETECTION OF QUANTUM MICROWAVES

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

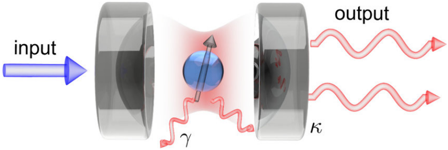
* a quantum oscillator whose quanta are photons

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**

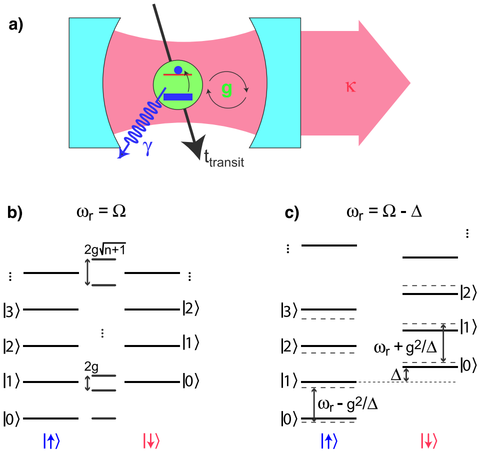
→ **confine the field** in a cavity

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

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)

CAVITY QED SYSTEM

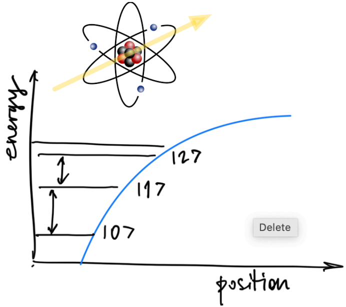


A simple theoretical model (Jaynes-Cummings) describes atoms as two-level, **spin-like systems** interacting with a quantum oscillator

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+)$$

- ω_r cavity resonance frequency
- Ω atomic transition frequency
- g strength of the atom-photon coupling

“Atoms”: (almost) natural qubits



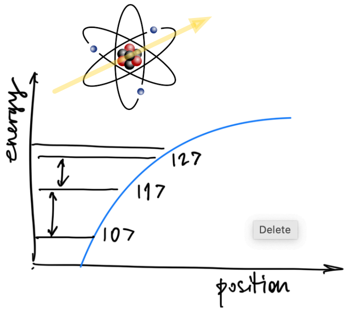
$$E_{01} = E_1 - E_0 = \hbar\omega_{01} \quad \neq \quad E_{02} = E_2 - E_1 = \hbar\omega_{21}$$

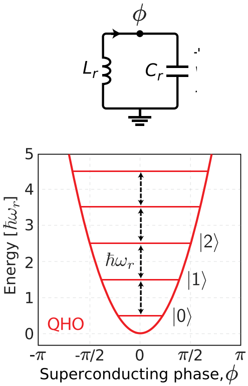
$\rightarrow$ good **two-level atom** approximation

control internal state by shining laser tuned at the transition frequency:

$H = -\vec{d} \cdot \vec{E}(t)$, with $E(t) = E_0 \cos \omega_{01} t$

qubits from "**artificial atoms**": LC circuit





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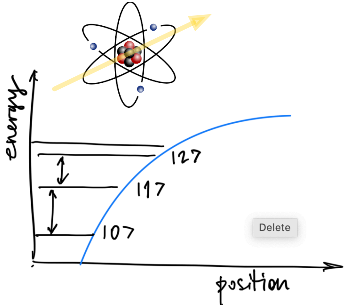
control internal state by shining laser tuned at the transition frequency:
$H = -\vec{d} \cdot \vec{E}(t)$, with $E(t) = E_0 \cos\omega_{01} t$

toolkit: capacitor, inductor, wire (all SC)
$\omega_{01} = 1/\sqrt{LC} \sim 10\,\text{GHz} \sim 0.5\,\text{K}$

$\rightarrow$ simple LC circuit is not a good **two-level atom** approximation

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



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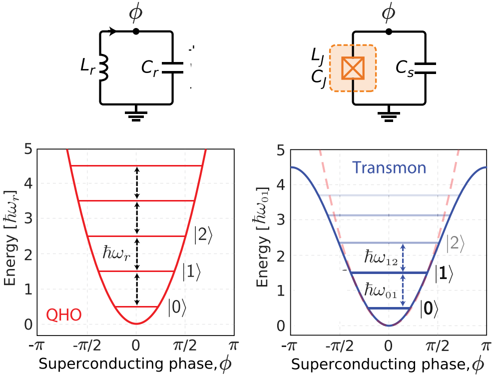


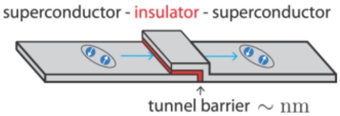
toolkit: capacitor, inductor, wire (all SC) + JJ

JJ is a **nonlinear** and dissipationless element

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

the Josephson Junction

the only circuit element that is both **dissipationless** and **nonlinear** (fundamental properties to make quantum hardware)



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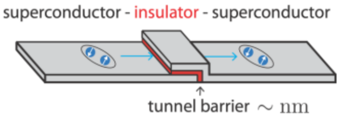
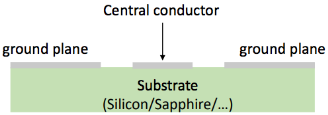
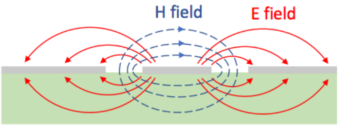


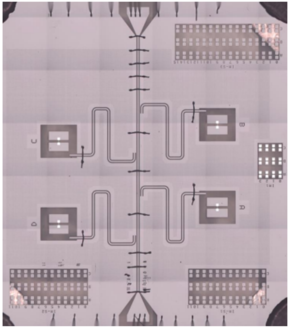
It's integrated in superconducting (SC) circuits, solid state electrical circuits fabricated using techniques borrowed from **conventional integrated circuits**.

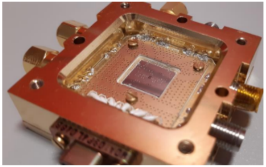


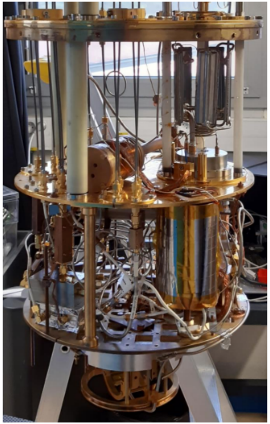


$T = 10 - 20\,\text{mK}$ in dilution refrigerators

$k_B T$ $\quad h\nu$







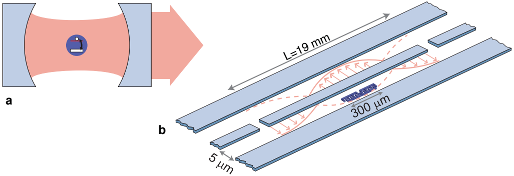
$\Longrightarrow$ low temperature physics

from cavity-QED to circuit-QED

g is significantly increased compared to Rydberg atoms:

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

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

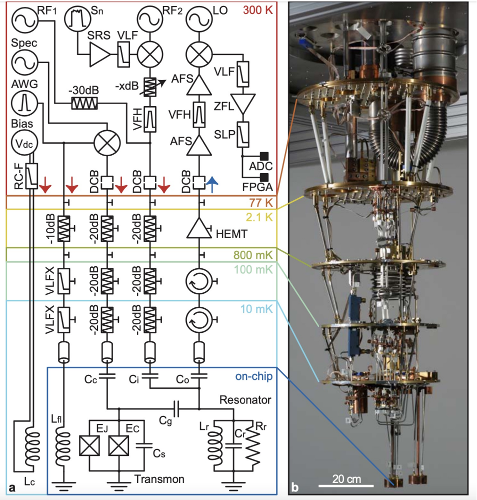


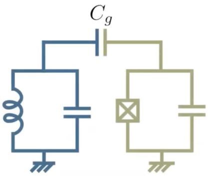
(a) $(g/2\pi)_{\text{cavity}} \sim 50\,\text{kHz}$

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

10^4 larger coupling than in atomic systems

circuit-QED: coupling





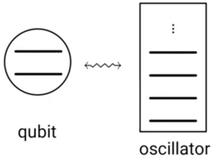
$$\hat{H}_q = 4E_C(\hat{n} - n_g)^2 - E_J \cos\hat{\varphi}$$

$$\hat{H}_r = 4E_C^r \hat{n}_r^2 + \frac{1}{2} E_L \hat{\varphi}_r^2$$

Jaynes-Cummings model

Interaction of a **two state system** with **quantized radiation in a cavity**

$$\mathcal{H}_{\text{JC}} = \frac{1}{2}\hbar\omega_q\hat{\sigma}_z + \hbar\omega_r\hat{a}^\dagger\hat{a} + \hbar g(\hat{a}\hat{\sigma}_+ + \hat{a}^\dagger\hat{\sigma}_-)$$



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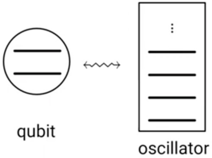
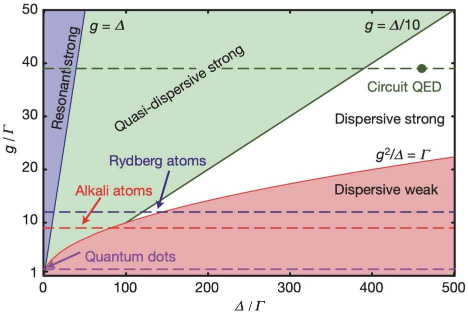


Parameter space diagram for cavity-QED



$$\Delta = |\omega_r - \omega_q|$$

$$\Gamma = \min\{\gamma,\ \kappa,\ 1/T\}$$

– $\omega_r \sim \omega_q$ *resonance* case
– $\Delta = |\omega_r - \omega_q| \gg g$ *dispersive limit* case

JC eigenstates and eigenvalues: detuning

$$\hat{H}_{\mathrm{JC}}^{\mathrm{eff}} = \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_q'}{2}\hat{\sigma}_z + \hbar\chi\hat{a}^\dagger\hat{a}\hat{\sigma}_z$$

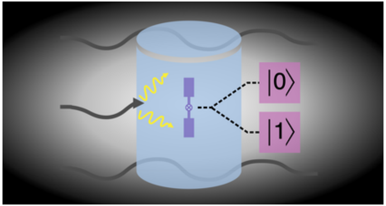
$$= (\hbar\omega_r + \hbar\chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\hbar\omega_q'}{2}\hat{\sigma}_z$$

$$= \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar}{2}(\omega_q' + \cancel{\omega_r}\hat{a}^\dagger\hat{a})\hat{\sigma}_z$$

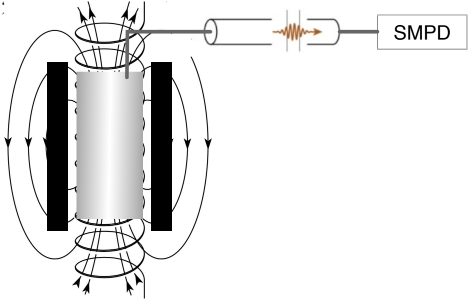
2χ

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)

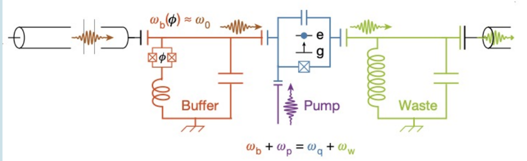


detection of *itinerant photons*
applicable to axion searches (multi-Tesla fields)

Itinerant photon counters for axion detection: the most advanced SMPD

SC qubits

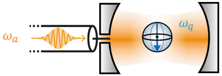
transition frequencies in "**artificial atoms**" lie in the GHz range

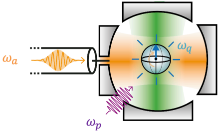


E. Albertinale *et al*, Nature **600**, 434–438 (2021)

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

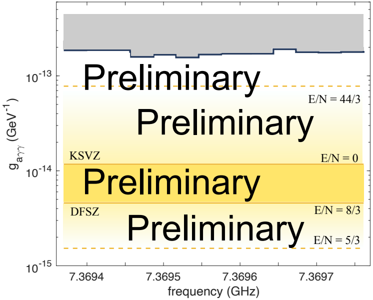
- 2D resonator coupled to a transmon-qubit
- the incoming photon is coupled to the 2D resonator and converted to a qubit excitation via a 4WM nonlinear process
- the state of the qubit is then probed with QIS methods (dispersive readout, $g \ll \omega_r - \omega_q$)

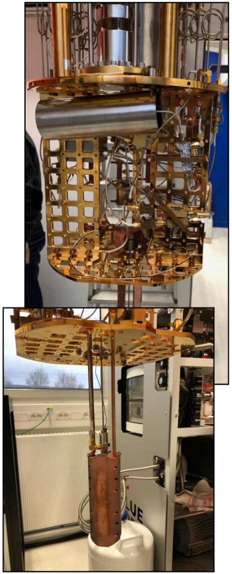




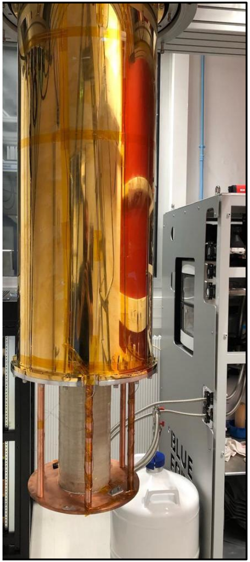
PILOT SMPD-HALOSCOPE experiment
(Feb. 2023, in the Saclay delfridge)

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





SMPD (top) and cavity



SC magnet

building a SMPD-HALOSCOPE

INFN
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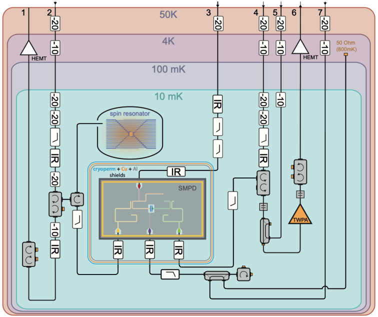
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



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 $\Phi_0 = h/(2e) \approx 2.0678\ldots \times 10^{-15}\,\mathrm{Wb}$

- 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 . . .)