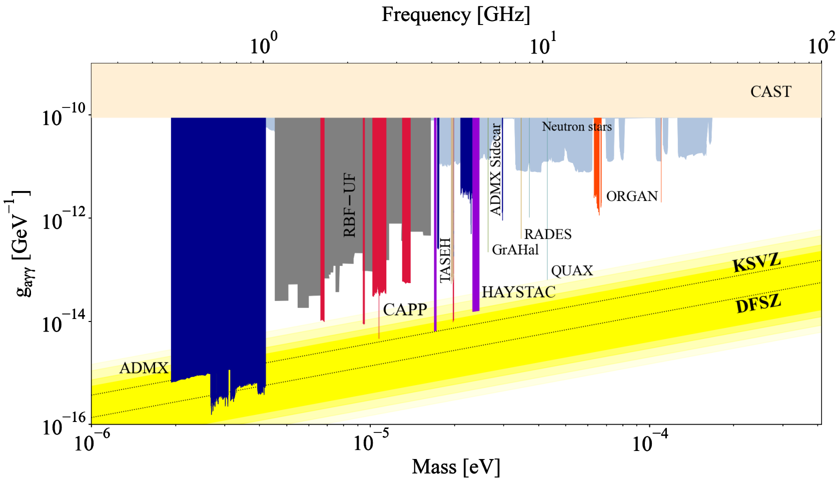
Dark matter search goes quantum: axion searches in PADUA

C. Braggio

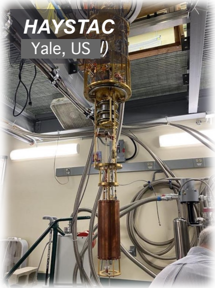
September 12, 2022

cavity haloscope searches of QCD axions are **hopeless**

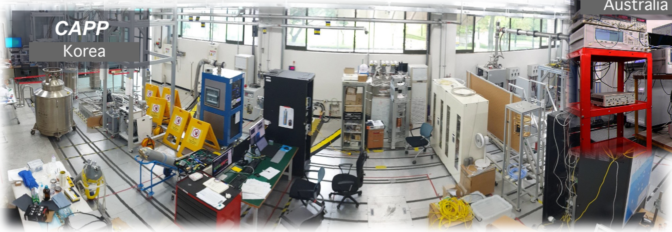
THE MOST SENSITIVE DETECTORS FOR PROBING QCD AXIONS




ADMX
Washington, US


HAYSTAC
Yale, US


QUAX
Italy


CAPP
Korea


ORGAN
Australia

cavity haloscope searches of QCD axions are **hopeless**

unless . . .

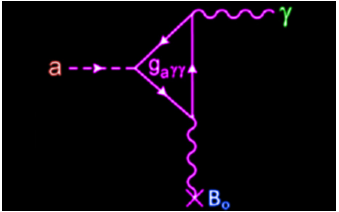
we change the cavity readout paradigm

HALOSCOPE - resonant search for axion DM in the Galactic halo

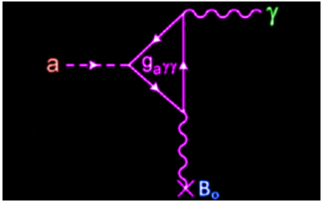
– original proposal by P. Sikivie (1983)

– 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

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



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

Scan rate

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

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

A haloscope optimized at best goes at:

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

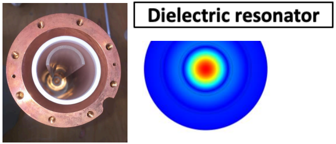
$$\left(\frac{df}{dt}\right)_{\text{DFSZ}} \sim 20\,\text{MHz/year} \qquad \odot\,\odot$$

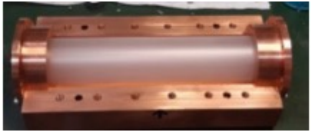
Take-home: to probe the mass range (1-10) GHz at DFSZ sensitivity would require $\gtrsim$ 100 years with 4-5 complementary haloscopes

it's a **hopeless search** even though 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 $Q_c \gg Q_a$





Phys. Rev. Appl. 17, 054013 (2022)

⊙ broad-tuning mechanism demonstrated

QUAX cavity

type-II superconductor (ReBCO)

PATRAS Workshop 2022

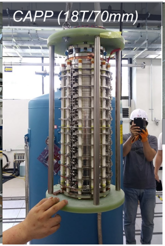
results from CAPP (Korea)

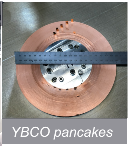
$Q \gtrsim 10^7$ for any **B** field value we can afford

it's a **hopeless search** even though we use our **best magnets** $df/dt \propto B^4$

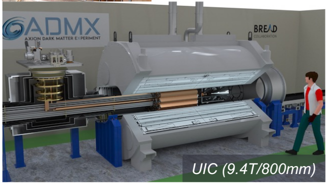

ADMX (8T/600mm)


CAPP (12T/320mm)

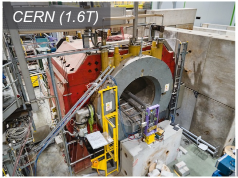

CAPP (18T/70mm)

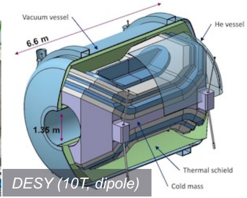

YBCO pancakes

Grenoble (43T/34mm)



UIC (9.4T/800mm)


CERN (1.6T)



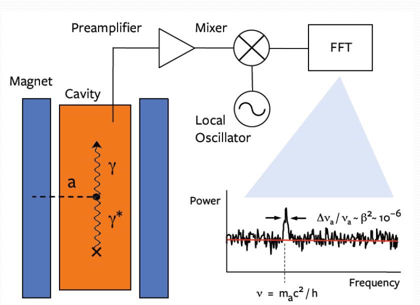
DESY (10T, dipole)

it's a **hopeless search** even when 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

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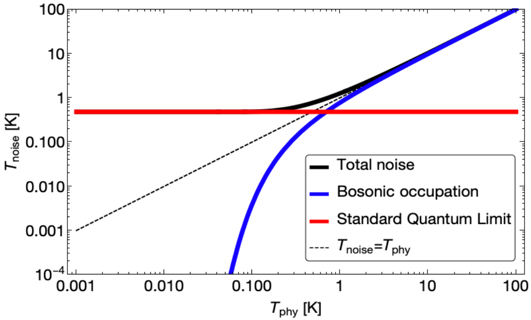


at 10 GHz frequency

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.

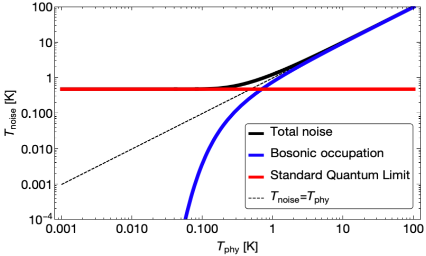
BEYOND SQL: SQUEEZING AND PHOTON COUNTING

	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:

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

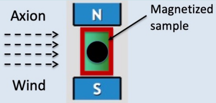


plot example at 10 GHz, where $T_{\text{SQL}} = h\nu/k_B \to 0.5\,\text{K}$

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**

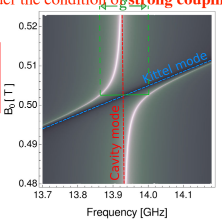
$$P_{\rm out} = \frac{P_{\rm in}}{2} = \mathbf{3.8 \times 10^{-26}} \left(\frac{m_a}{200\,\mu{\rm eV}}\right)^3 \left(\frac{V_s}{100\ {\rm cm}^3}\right) \left(\frac{n_S}{2\cdot 10^{28}/{\rm m}^3}\right) \left(\frac{\tau_{\rm min}}{2\,\mu{\rm s}}\right)\ {\rm W}$$

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)

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

under the condition of **strong coupling**



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

corresponding signal photon rate

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

Real SMPDs have finite efficiency η and dark counts $\Gamma_{dc} > \Gamma_{sig}$

$\delta N_{dc} = \sqrt{\Gamma_{dc}\tau}$ uncertainty in the number of dark counts collected in an integration time τ

$\Sigma = \frac{\eta\Gamma_{sig}\tau}{\sqrt{\Gamma_{dc}\tau}} = \eta\Gamma_{sig}\sqrt{\frac{\tau}{\Gamma_{dc}}}$ the dark count contribution to the fluctuations dominates

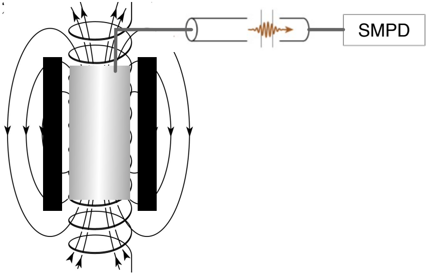
$R_{\text{counter}} = \frac{\Delta\nu_c}{\tau} = \frac{\Delta\nu_c \eta^2 P^2_{a\gamma\gamma}}{h^2\nu^2\Sigma^2\Gamma_{dc}}$ $R_{\text{lin}} = \frac{Q_a}{Q_c}\left(\frac{P_{a\gamma\gamma}}{k_B T\sigma}\right)^2$ scan rates lin. amp. and counter

$$\frac{R_{\text{counter}}}{R_{\text{lin}}} = \left(\frac{k_B T_{sys}}{h\nu}\right)^2 \frac{\eta^2\Delta\nu_a}{\Gamma_{dc}}$$

quantum advantage can be demonstrated even with high dark count rates Γ_{dc}
$\eta \approx 0.4$, $\Gamma_{dc} \approx 100\,\text{Hz} \Longrightarrow$ potential improvement of a factor 11 compared to SQL scan rate

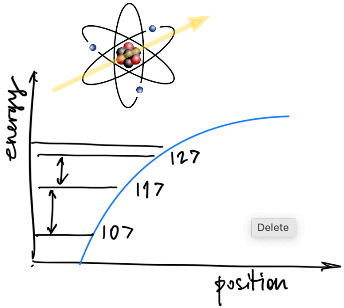
SMPDs FOR ITINERANT PHOTONS

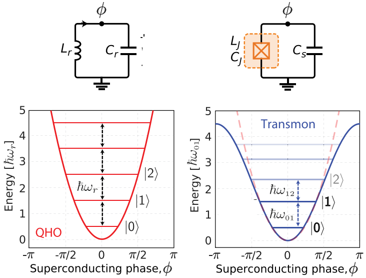
A Single Photon Microwave Counter (SMPD) architecture is significantly different whether it is meant for **cavity photons** or **itinerant (traveling) photons**.
We are interested in the itinerant version due to the intense magnetic fields involved in axion search.



- detection of individual microwave photons is a challenging task because of their **low energy** $\sim 10^{-5}$ eV
- a solution: use "**artificial atoms**" introduced in circuit QED, their transition frequencies lie in the ~GHz range
- or: rely on a single **current-biased Josephson junction** (L. Kuzmin device)

ARTIFICIAL ATOMS: the TRANSMON QUBIT





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

$\rightarrow$ 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)

$\omega_{01} = 1/\sqrt{LC} \sim 10\,\text{GHz} \sim 0.5\,\text{K}$

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

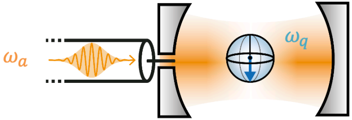
$I_J = I_c \sin \phi \qquad V = \frac{\phi_0}{2\pi}\frac{\partial \phi}{\partial t}$

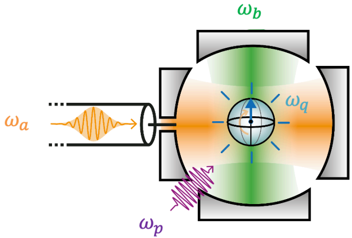
$V = \frac{\phi_0}{2\pi} \frac{1}{I_c \cos \phi} \frac{\partial I_J}{\partial t} = L_J \frac{\partial I_J}{\partial t}$

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

quantum engineers and **particle physicists** joining efforts

A practical transmon-based counter has been recently developed (Quantronics group CEA, Saclay) that we will apply to haloscope signal readout.



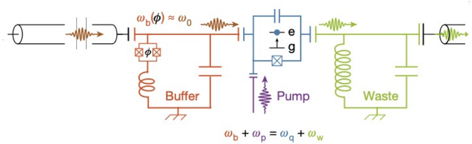


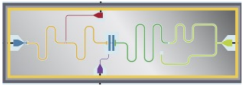
$\omega_a + \omega_p = \omega_q + \omega_b$

R. Lescanne *et al*, Phys. Rev. X 10, 021038 (2020)
E. Albertinale *et al*, Nature 600, 434 (2021)

Quantronics Group
Research Group in Quantum Electronics, CEA-Saclay, France

transmon-based SMPD





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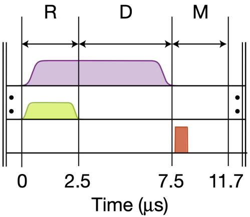
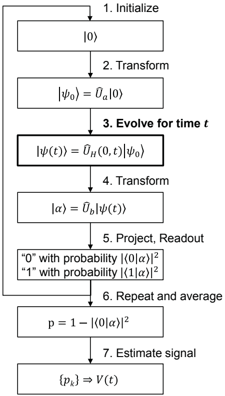


- a three-step process repeated several times
- qubit reset (R) performed by turning on the pump pulse + a weak resonant coherent pulse to the waste port
- detection (D) step with the pump pulse on
- measurement (M) step probes the dispersive shift of the buffer resonator to infer the qubit state

QUANTUM SENSING

"Quantum sensing" describes the use of a quantum system, quantum properties or quantum phenomena to perform a measurement of a physical quantity
Rev. Mod. Phys. 89, 035002 (2017)

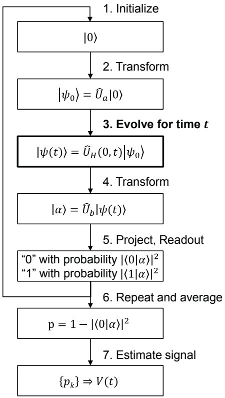
1. Use of a **quantum object** to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels, i.e. electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.
2. Use of **quantum coherence** (i.e., wave-like spatial or temporal superposition states) to measure a physical quantity
3. Use of **quantum entanglement** to improve the sensitivity or precision of a measurement, beyond what is possible classically.



Basic protocol

quantum sensing experiments typically follow a generic sequence of processes known as:

1. sensor initialization into a known basis state
2. interaction with the signal
3. sensor readout
4. signal estimation



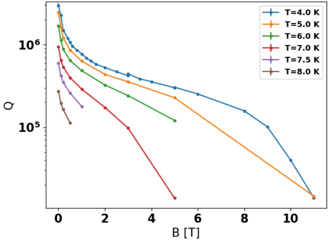
Pilot SMPD-haloscope experiment

- copper cavity **sputtered with NbTi**
  magnetron sputtering in INFN-LNL

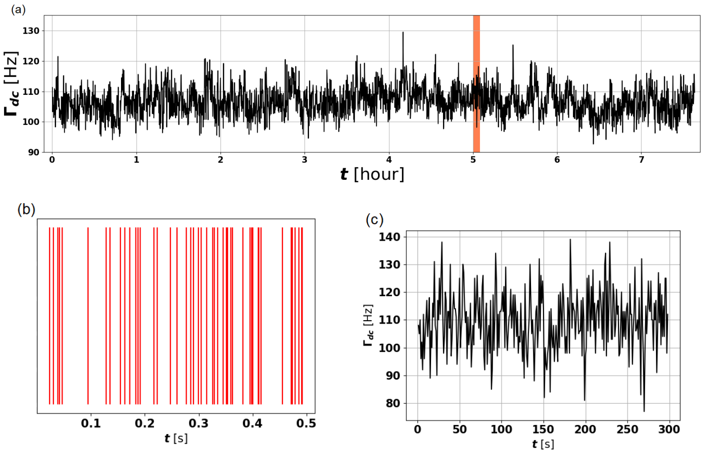
- right cylinder resonator, TM_{010} mode
  $\nu_c \sim 7.3\,\text{GHz}$ to match the new generation SMPD bandwidth
  (7.280 - 7.380) GHz

- **system of sapphire triplets** to tune the cavity frequency
  $\sim$ 10 MHz tuning without impacting Q

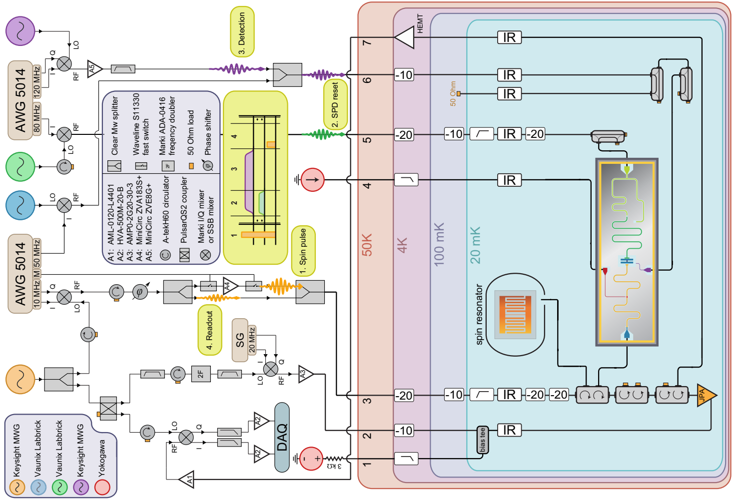
- **Attocube nanopositioner** to change the sapphire rods
  position



the dark count is a **inhomogeneous Poisson process**



Not that **practical** to use ... but that's it!



CONCLUSIONS

- QCD Axions are theoretically well motivated but experimentally challenging

  weak coupling and unknown mass

- Tremendous, definitely not a hopeless search effort

  Different technologies targeting at different mass ranges, quantum sensing

- Next decade must be critical/exciting

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