Application of **superconducting technologies** (cavities, electronics) to **particle detection**

Caterina Braggio

Workshop on Quantum technologies for HEP

1 – 4 November 2022, CERN

OUTLINE

→ probing the Universe at large energy scale: wave-like dark matter
axion, ALP, dark photon, scalar moduli

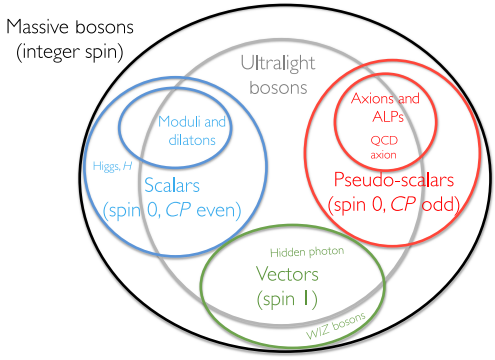
– 3D superconducting cavities
bulk Nb, type II films

– signal readout:
  - superconducting parametric amplifiers (JPA, TWPA)
  - single microwave photon detectors → quantum sensing

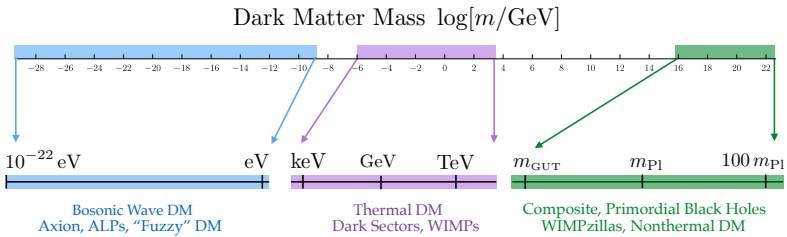
Open questions in Particle Physics

Reasons for **Beyond Standard Model**

1. **Observations require it**
   - Dark Matter
   - Baryogenesis
2. **Parameters of SM are "funny"**
   - cosmological constant
   - Higgs mass
   - Strong CP angle (nucleon EDM)
   - mass of quarks + leptons



Chadha-Day *et al.*, Sci. Adv. **8** eabj3618 (2022)



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

$m \gtrsim 10\,\mathrm{eV} \rightarrow$ individual particles scattering off a detector
ultra-sensitive, quantum-enhanced detectors for photons, phonons, magnons (collective excitations)

$m \lesssim 10\,\mathrm{eV} \rightarrow$ classical field oscillating at the Compton frequency with 10^{-6} coherence
resonant detectors of tiny EM fields (haloscopes)

Quantum sensing $\rightarrow$ significant opportunities for both **wave-like DM** and in the 10 keV-100 MeV range
Phys. Rev. Lett. **124**, 201801 (2020) arXiv:2209.12909 (2022)

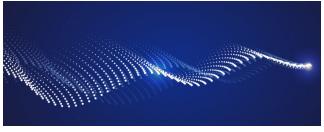
DM WAVES

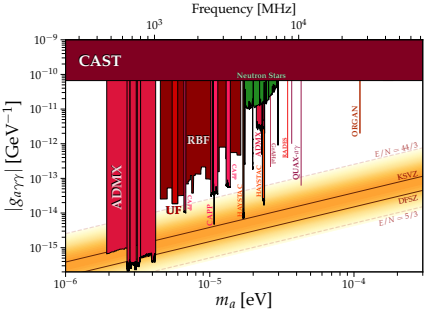
$m_a \simeq h\nu_a \qquad 1\,\mu\text{eV} \leftrightarrow 0.25\,\text{GHz}$

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**

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

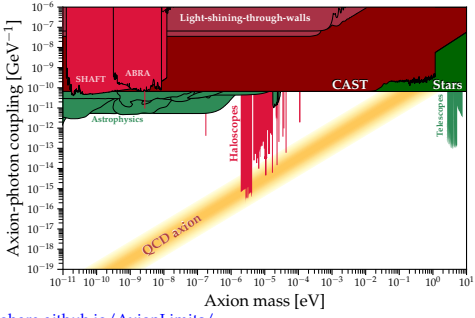
it's a **macroscopic wave-like** behavior

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/

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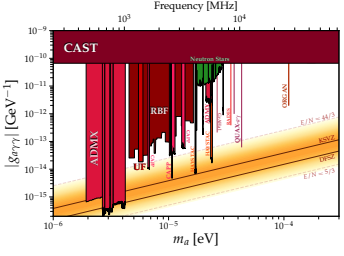
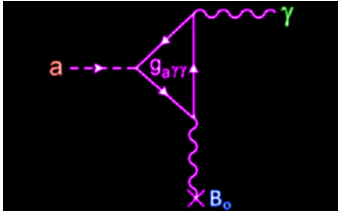


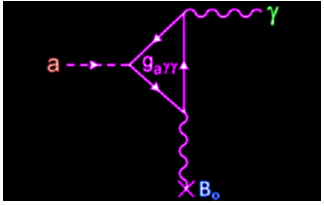
HALOSCOPE - resonant search for axion/dark photon in the Galactic halo

- 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 ($\rightarrow m_a$)



- **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

SIGNAL POWER and SCAN RATE

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:

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

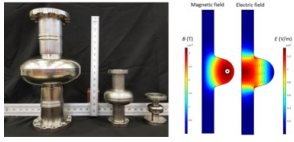
Take-home: to probe the mass range (1-10) GHz at DFSZ sensitivity would require $\gtrsim 100$ years with 4-5 complementary haloscopes with current technology

SUPERCONDUCTING 3D RESONATORS: Niobium

$df/dt \propto V_{\rm eff}^2\ Q_L\ T_{sys}^{-2}, \quad Q_L = G_s\, R_s^{-1}$

- – building up resonant power to detect tiniest signals created by potential **dark matter candidates**
- + efficient transfer of large RF power in modern **particle accelerators**
- + housing and reading out **qubits** in the QIS community

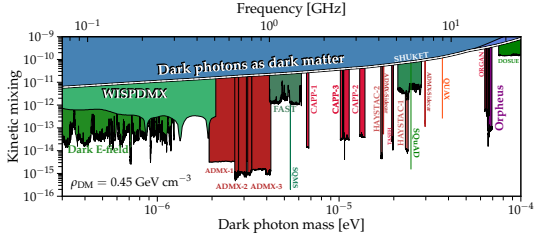
TESLA-shaped single cell niobium cavities
$Q_L \sim 10^9 - 10^{11}$



A. Romanenko *et al.*, Phys. Rev. Applied 13, 034032 (2020)

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Deepest sensitivity to wave-like dark photon DM

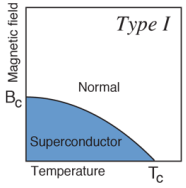


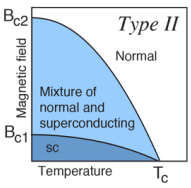
R. Cervantes *et al.*, arXiv:2208.03183v3

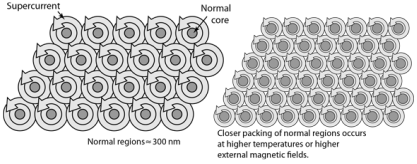
SUPERCONDUCTING 3D RESONATORS: type II films

$df/dt \propto V_{\rm eff}^2\ Q_L\ T_{sys}^{-2}, \quad Q_L = G_s\, R_s^{-1}$

Type II superconductivity compatible with operation in intense **magnetic fields** (axion-photon conversion, polarize magnetic materials)







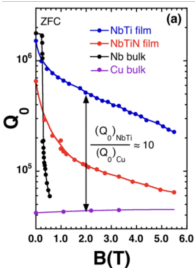
Requirements:

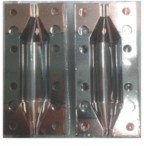
- critical field B_{c2} > applied magnetic field (up to 14 T, and even more)
- RF surface resistance R_s smaller than that of copper

	$R_s, B = 0$	H_{c2} [T]
OFHC Cu	$\sim 7 \times 10^{-3}\ \Omega$	-
(LTS) **$NbSn_3$**	∼nΩ	25
(LTS) **NbTi**	∼nΩ	13
(HTS) **REBCO**	$\sim 10^{-5}\ \Omega$	$> 100(\|\|ab)$

→ the dominant source of surface resistivity is **vortex motion**

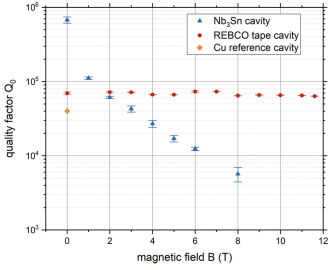
vortex motion resistivity depends on the **angle** between the applied B field and the SC surface
$\rightarrow$ surfaces parallel to B do not contribute to increasing surface resistance + hybrid surface

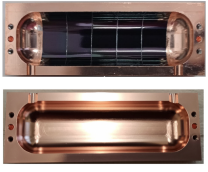




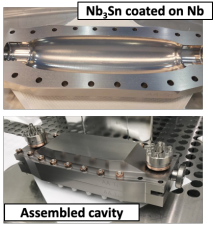
RF cavity
2 Cu semi-cells+NbTi film

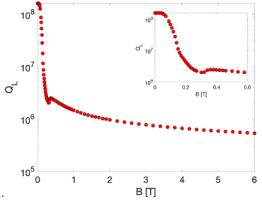
(QUAX collaboration)
IEEE Trans. Appl. Super. **29**, 3500605 (2019)



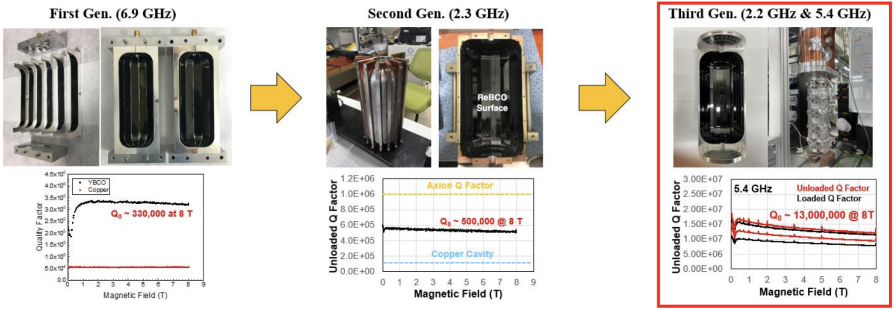


(RADES collaboration)
IEEE Trans. Appl. Super. **32**, 1500605 (2022)





(SQMS, Fermilab)
arXiv:2201.10733 (2022)



Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	~ 500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	1.5	2.2	4,500,000 @ 0 T Waiting for Magnet Test
	EuBCO + APC	Hastelloy	0.2	5.4	~ 13,000,000 @ 8 T

17th Patras Workshop, Mainz 2022 D. Ahn, CAPP (Korea)

many aspects still to be clarified!

SIGNAL READOUT

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

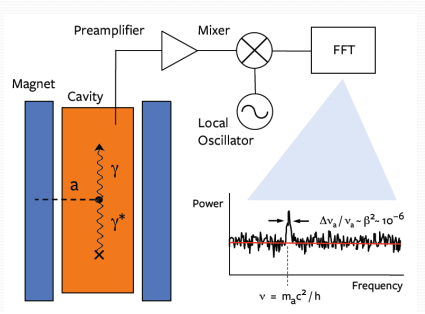
weak interactions with SM particles $\Longrightarrow 10^{-23}$ W signal power
Josephson Parametric Amplifiers (JPAs) introduce the lowest level of noise, set by the laws of quantum mechanics (Standard Quantum Limit noise)

$T_{sys} = T_c + T_A$
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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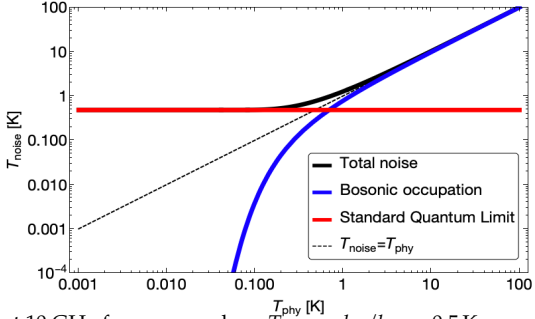

at 10 GHz frequency, where $T_{\rm SQL} = h\nu/k_B \rightarrow 0.5\,{\rm K}$

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:

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

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:

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

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

linear amplification vs photon counting

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

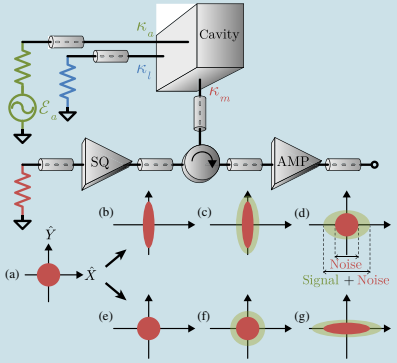
$$\frac{R_{\text{counter}}}{R_{\text{SQL}}} \approx \frac{Q_L}{Q_a} e^{\frac{h\nu}{k_B T}}$$

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)

BEYOND SQL: squeezing and photon counting

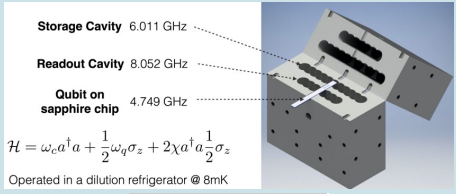
SQUEEZING - phase sensitive amplification

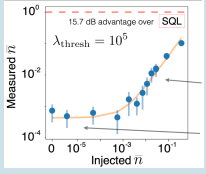


X 2 the search rate for axions around 4.14 GHz (±80 MHz range)

K. Bakes *et al.*, Nature **590** 238-242 (2021)

SMPD - qubit coupled to 3D resonators



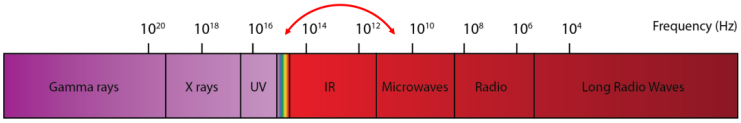


potential **X 1300** scan rate
exclusion limit for dark photons at fixed freq. (6 GHz)

A. Dixit *et al.*, Phys. Rev. Lett. **126**, 141302 (2021)

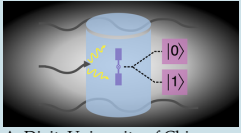
SMPDs IN THE MICROWAVE RANGE

Detection of individual microwave photons is a challenging task because of their **low energy** $\sim 10^{-5}$ eV



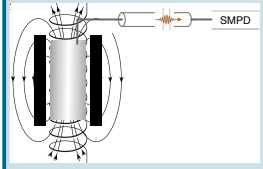
A Single Photon Microwave Counter (SMPD) architecture is significantly different whether it is meant for **cavity photons** or **itinerant (traveling) photons**.

CAVITY PHOTONS



A. Dixit, University of Chicago

ITINERANT PHOTONS = transmission line excitations



:) applies also where $B \neq 0$
:(more challenging to develop

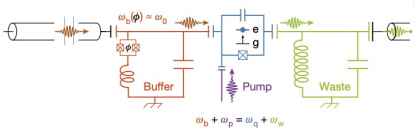
Requirements and challenges for SMPD application to axion search

$\Longrightarrow 10^{-23}\,\mathrm{W}$ signal power $\longleftrightarrow \lesssim$ Hz signal rate at 10 GHz

- lowest dark count rate
- $\gtrsim 40 - 50\,\%$ efficiency
- large BW (or tunability)

Itinerant photon counters for axion detection: some examples of ongoing R&D

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

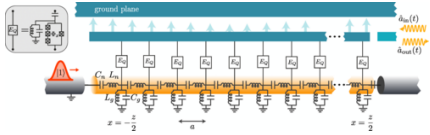


Nature **600**, 434–438 (2021)

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

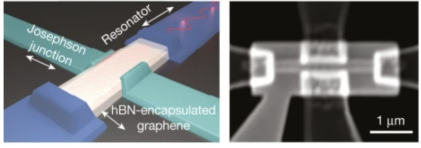
npj Quantum Information **8**, 61 (2022))

- quantum metamaterial (large number of JJ)



Phys. Rev. Applied **15**, 034074 (2021)

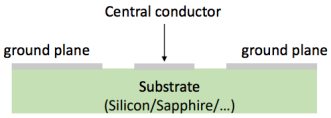
- Graphene-based JJ microwave bolometer

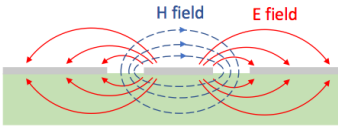


Nature **586**, 42–46 (2020)

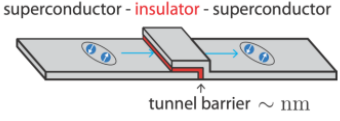
SUPERCONDUCTING CIRCUITS and the JOSEPHSON JUNCTION

SC circuits are solid state electrical circuits fabricated using techniques borrowed from **conventional integrated circuits**.

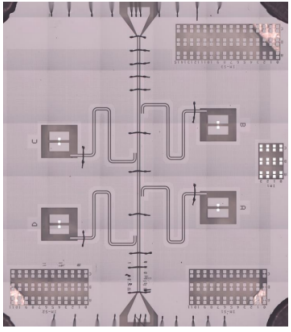


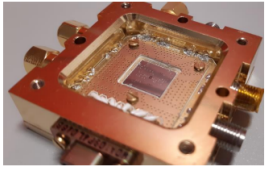


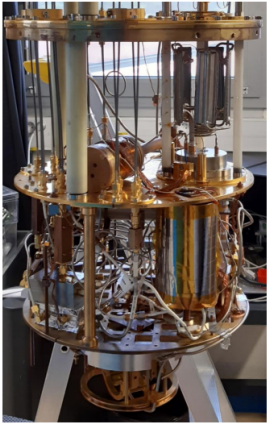
Devices useful for circuit QED are fabricated starting from a **non-dissipative**, **non-linear element**: the Josephson tunnel junction



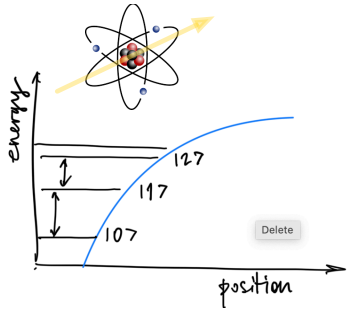
$10 - 20\,\mathrm{mK}$ temperatures $k_B T < h\nu$







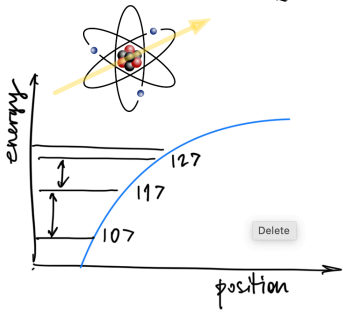
ARTIFICIAL ATOMS: the TRANSMON QUBIT

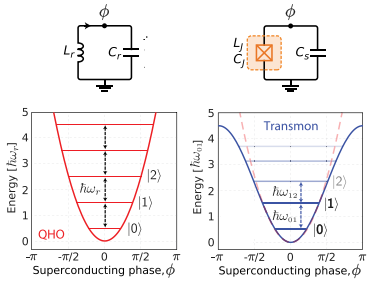


$E_{01} = E_1 - E_0 = \hbar\omega_{01} \neq E_{02} = E_2 - E_1 = \hbar\omega_{21}$
$\rightarrow$ good **two-level atom** approximation

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

ARTIFICIAL ATOMS: the TRANSMON QUBIT





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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

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

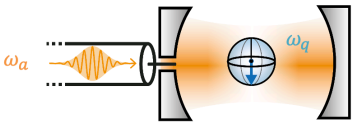
$V = \frac{\phi_0}{2\pi}\frac{1}{I_c\cos\phi}\frac{\partial I_J}{\partial t} = L_J\frac{\partial I_J}{\partial t}$

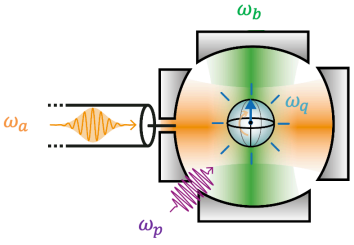
$L_J = \frac{\phi_0}{2\pi}\frac{1}{I_c\cos\phi}$ NL Josephson inductance

transmon-based SMPD

The detection of individual microwave photons has been pioneered by **atomic cavity quantum electrodynamics experiments** [Nature **400**, 239–242 (1999)] and later on transposed to circuit QED experiments [Nature **445**, 515–518 (2007)]

- the incoming photon is converted to a qubit excitation
- the state of the qubit is then probed with QIS methods (dispersive readout)

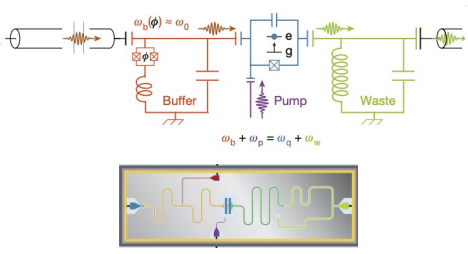




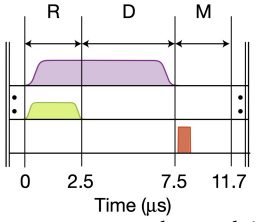
$$\omega_a + \omega_p = \omega_q + \omega_b$$

Nature **600**, 434–438 (2021)
Phys. Rev. X **10**, 021038 (2020)

transmon-based SMPD



Nature **600**, 434–438 (2021) Phys. Rev. X **10**, 021038 (2020)

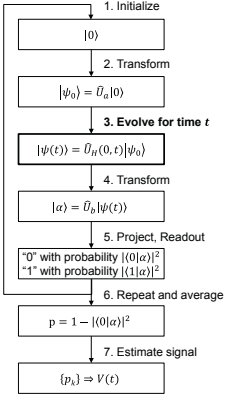


- a three-step process repeated several times
- qubit reset (R) performed by turning on the pump pulse + a weak resonant coherent pulse to the waste port
- detection (D) step with the pump pulse on
- measurement (M) step probes the dispersive shift of the buffer resonator to infer the qubit state

QUANTUM SENSING: a definition

"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.



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

$$R_{\text{counter}} = \frac{\Delta\nu_c}{\tau} = \frac{\Delta\nu_c\eta^2 P_{a\gamma\gamma}^2}{h^2\nu^2\Sigma^2\Gamma_{dc}} \qquad R_{\text{lin}} = \frac{Q_a}{Q_c}\left(\frac{P_{a\gamma\gamma}}{\Sigma\, k_B T}\right)^2$$ 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

SUMMARY

- Theoretically well motivated DM candidates, but experimentally challenging

  weak coupling and unknown mass

- Tremendous R&D efforts

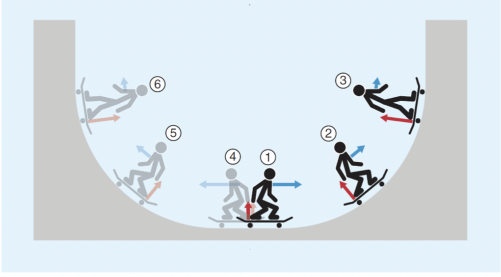
  Different technologies targeting at different mass ranges, quantum sensing
  - **high quality factor, tunable cavities in multi-Tesla fields**
  - **single microwave photon counters**
  - **Josephson parametric amplifiers at SQL in the high frequency range** ($\sim 10\,\mathrm{GHz}$)

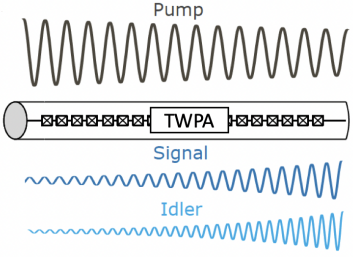
- Next decade must be critical/exciting

  opportunities for quantum sensing! …

Traveling Wave Parametric Amplifiers

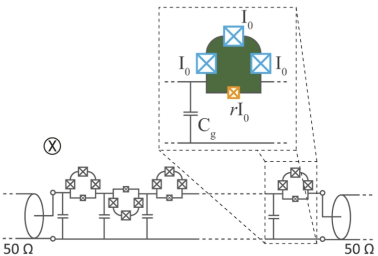
In haloscope search amplifiers with **quantum-limited noise performance** and $\sim$**GHz amplification bandwidth** are needed.
Standard resonant parametric amplification puts a constraint on the amplification bandwidth. This limitation can be overcome with TWPAs.

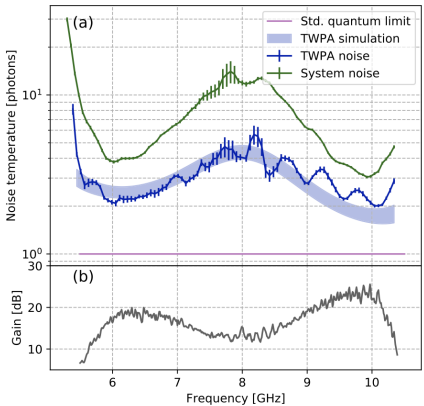




Josephson metamaterial and Reversed-Kerr phase matching

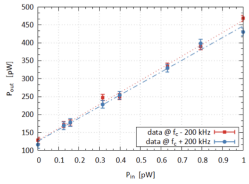
- **tunable**, **nonlinear** unit element is the "snail"
- phase matching between pump, signal and idler fields is accomplished via **reversed kerr** phase matching



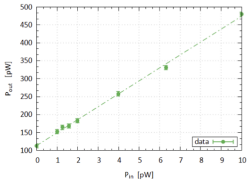


A. Renadive *et al*, Nat. Commun. 13, 1737 (2022)
M. Esposito *et al* Appl. Phys. Lett. 119, 120501 (2021)
M. Esposito *et al* Phys. Rev. Lett 128, 153603 (2022) $\Longleftarrow$ **broadband squeezing!**

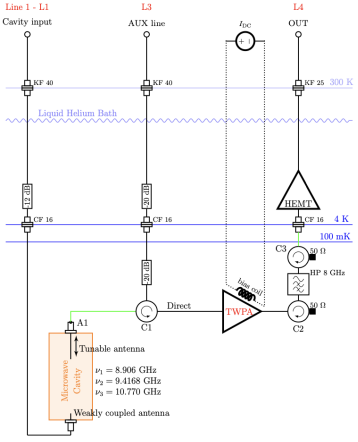
Measuring TWPA performance in a haloscope setup



➢ Fit L3 → L4



➢ Fit L1 → L4



arXiv:2205.02053

- figures of merit for the **complete detection chain**

$$g_4(\mathrm{dB}) = (76.4 \pm 0.1) \qquad T_{sys} = (2.01 \pm 0.06)\,\mathrm{K}$$

- figures of merit for the **TWPA**

$$G_{\mathrm{TWPA}}(\mathrm{dB}) = 24 \qquad T_{\mathrm{TWPA}} \approx 1.8\,\mathrm{K}$$