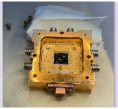
Electroweak Interactions & Unified Theories
March 15 - 22

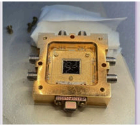
# Quantum sensing in axion dark matter searches

Caterina Braggio, *University of Padova and INFN*



# OUTLINE

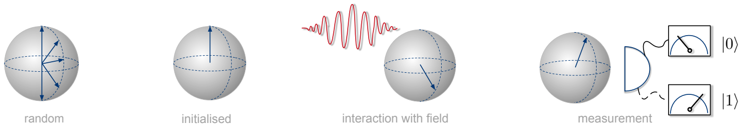
1. what is a Quantum Sensor (QS)?
2. why they are needed in **cavity-based DM search**
   $S/N \ll 1 \rightarrow$ *time-consuming* search
3. state of the art for signal readout
   **quantum-limited superconducting amplifiers** $\Longrightarrow$ **PRL 135, 211002 (2025)**
4. how do QSs work?
5. QSs **accelerate the search** by $\times 100$
6. pathfinder with a **transmon-based** sensor
   new exclusion limit + $\times 20$ acceleration $\Longrightarrow$ **PRX 15, 021031 (2025)**

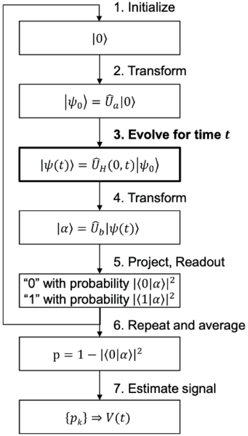


# What is a quantum sensor?

*(academic)*
"Quantum sensors are individual systems or ensembles of systems that use **quantum coherence**, **interference** and **entanglement** to determine physical quantities of interest."
*Rev. Mod. Phys. 89, 035002 (2017)*

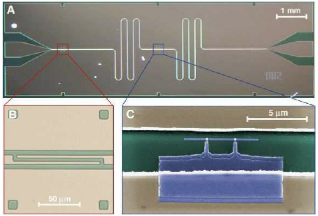
*(operational)*
"A device whose measurement (sensing) capability is enabled by our ability to **manipulate and readout its quantum states**."
*M. Safranova and D. Budker*



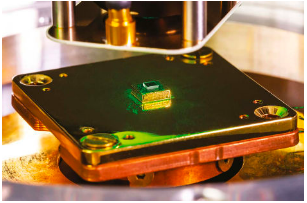



## THE QUANTUM SENSING LANDSCAPE

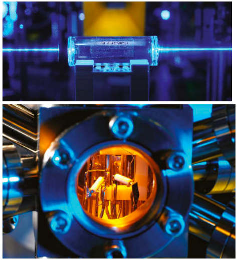
Quantum sensing has been demonstrated across diverse physical platforms, each with unique advantages




Superconducting circuits



Solid-state spins



Atomic ensembles

✓ **Current status:** Proven in laboratory settings with gains of **100-1000**× over conventional sensors

! **Challenge:** Transitioning to practical devices

# HALOSCOPE DETECTORS

- asm: axions as **exclusive component** of the DM in the Milky Way

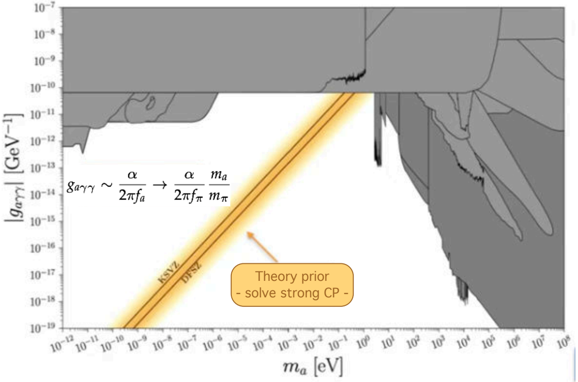
$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F\tilde{F}$$

$\rightarrow$ detectors reply upon coupling to EM

- targeting the well motivated **QCD axion**

$\rightarrow$ theory prior: a solution to the long-standing strong CP problem

$$g_{a\gamma\gamma} \sim \frac{\alpha}{2\pi f_a} \rightarrow \frac{\alpha}{2\pi f_\pi}\frac{m_a}{m_\pi}$$



## AXION-PHOTON

do not require $a = \text{DM}$

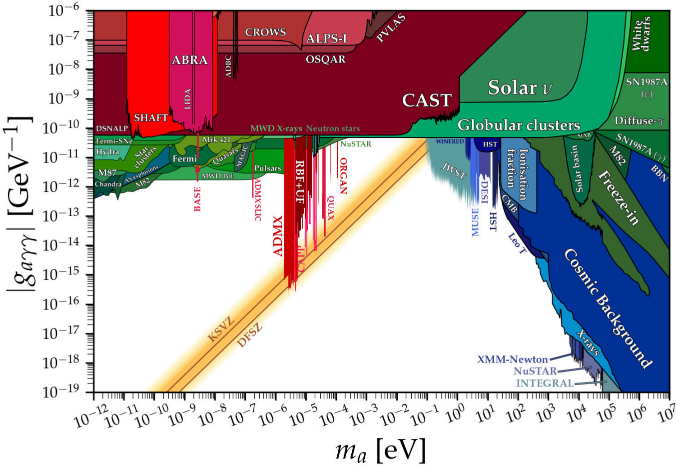
→ anomalous cooling of stars or direct production

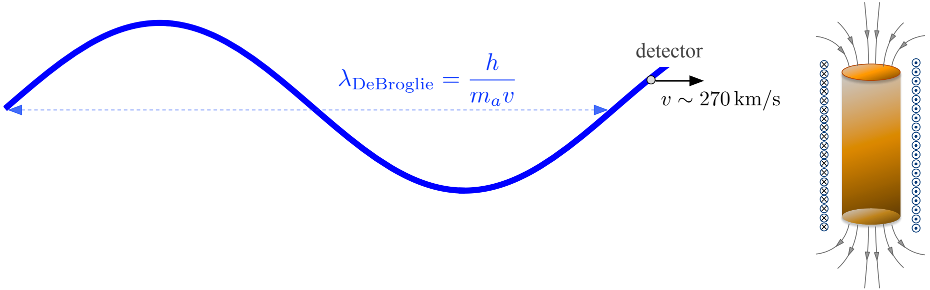
→ CAST: axions from the Sun

need $a = \text{DM}$

→ photons from regions where DM is observed
$\tau \propto m_a^3$

→ **haloscope bands**: resonant enhancement in 3D microwave cavities






dimension $\lesssim$ meter

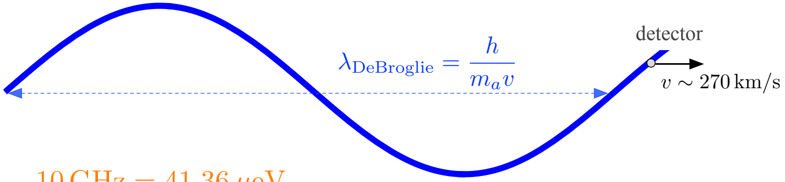
## DE BROGLIE WAVELENGTH AND WAVE-LIKE DM

Example: $m_a = 20\,\mu\text{eV} \implies \lambda_{\text{DeBroglie}} \sim 70\,\text{m}$

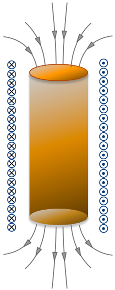
Number of particles that share the same quantum state:

$$\mathcal{N} = n_a \lambda^3_{\text{DeBroglie}} = \frac{\rho_{\text{DM}}}{m_a} \lambda^3_{\text{DeBroglie}} \sim 10^{25}$$

$\rightarrow$ at the scale of the lab detector axions can be searched as a classical field




$10\,\text{GHz} = 41.36\,\mu\text{eV}$



dimension $\lesssim$ meter

## De Broglie wavelength and **coherence time**

Example: $m_a = 20\,\mu\text{eV} \implies \lambda_{\text{DeBroglie}} \sim 70\,\text{m}$

$\rightarrow$ a detector takes a **coherence time** $\tau_a$ to shift in a region where the axion field oscillation gets out of phase:

$$\tau_a = \frac{\lambda_a}{v} = 200\,\mu\text{s}$$

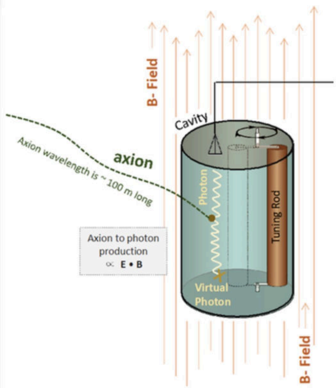
## "Signal linewidth"

$$\Delta\nu = \frac{1}{\tau_a}$$

$$Q_a = \frac{\nu}{\Delta\nu} = \frac{c^2}{h} m_a \tau_a = \frac{c^2}{v^2} \sim 10^6$$

# DM field coherence and resonant enhancement

- as the DM field is **coherent** for $\sim 10^6$ periods $\Longrightarrow$ **resonant enhancement** in microwave cavities (P. Sikivie, 1987)



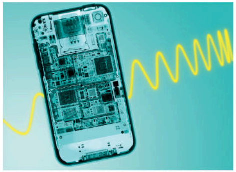

$$\mathcal{L} \propto g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}$$

- cylindrical cavity frequency of resonance $\nu_c = \frac{11.5\,\text{GHz}}{r[\text{cm}]}$
- enhancement in $[m_a \pm m_a/Q_c]$, typically $Q_c < Q_a$
- signal power $P_{a\to\gamma}$ is model-dependent

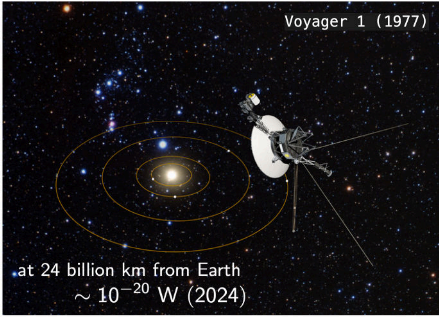
$$P_{a\to\gamma} \propto g_{a\gamma}^2 \frac{\rho}{m_a} B^2\, C_{mnl}\, V\, Q$$

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

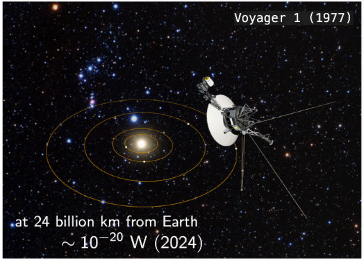
$\sim 1\,\mathrm{kW}$

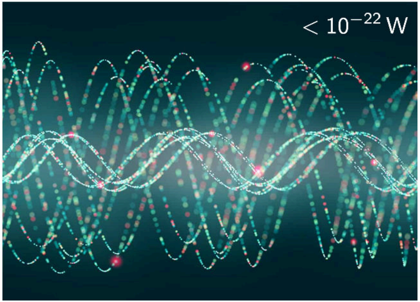


$\sim 0.1 - 0.5$ W



# Dark Matter: an extreme detection challenge

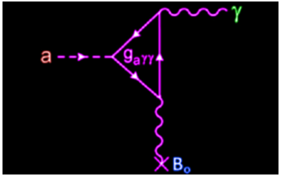



$\Downarrow$

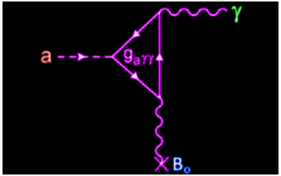
**Dark Matter wave-like fields**
oscillating at (unknown) **GHz frequencies** with power $\lesssim 10^{-22}$ **W** $\Leftrightarrow$ **few photons/s**

1. **3D** microwave **resonator** for resonant amplification
   -think of an HO driven by an external force-
2. the **resonator** is within the bore of a **SC magnet** $\rightarrow$ **$B_0$**
   multi-tesla field
3. it is readout with a **low noise receiver**




signal **S** set by **$B_0$** and 3D cavity at specified $g_{a\gamma\gamma}$, the noise **N** is set by the receiver

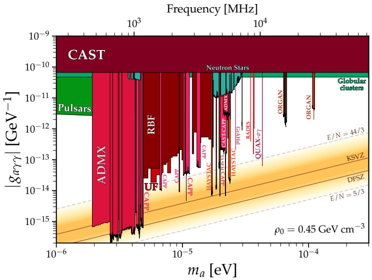
1. 3D microwave **resonator** for resonant amplification
   -think of an HO driven by an external force-
2. the **resonator** is within the bore of a **SC magnet** $\rightarrow$ $\mathbf{B}_0$
   multi-tesla field
3. it is readout with a **low noise receiver**




signal **S** set by $\mathbf{B}_0$ and 3D cavity at specified $g_{a\gamma\gamma}$, the noise **N** is set by the receiver

$S/N \ll 1$ time integration to reach $S/N \sim 3-5$

# heavier (axions) & harder (life)




- heavier axions are well motivated,
  BUT
  the *scan rate df/dt scales unfavourably with f*

$$\frac{df}{dt} \propto \frac{g_{a\gamma\gamma}^4 B^4 V_{\text{eff}}^2 Q_L}{T_{sys}^2} \propto f^{-4}$$

  (best scenario asm. **SQL**, SC cavities, relax $r/L$)

- $(df/dt)_{DFSZ} \sim$ **50** $(df/dt)_{KSVZ}$

PROBLEM: WAY TOO SMALL SEARCH SPEED

A haloscope optimized at best goes at:

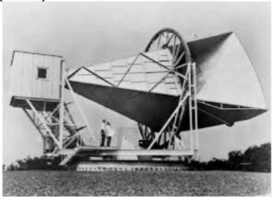
$$\left(\frac{df}{dt}\right)_{\text{KSVZ}} \sim 100\,\text{MHz/year} \qquad \left(\frac{df}{dt}\right)_{\text{DFSZ}} \sim 2\,\text{MHz/year}$$

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

# Microwave receivers

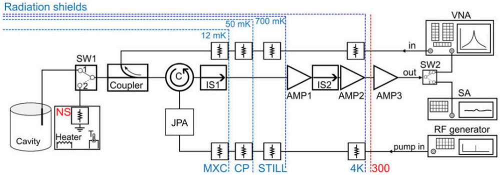
Dicke receiver —> heterodyne receiver

(1965) Penzias and Wilson



Green Bank telescope

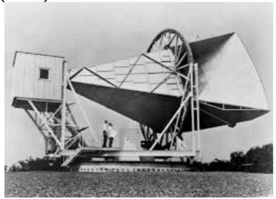
Haloscope receiver



# Microwave receivers

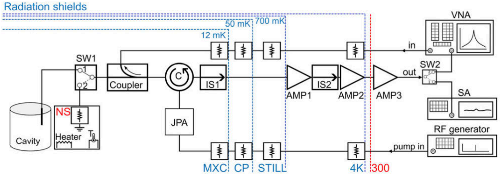
Dicke receiver —> heterodyne receiver

(1965) Penzias and Wilson

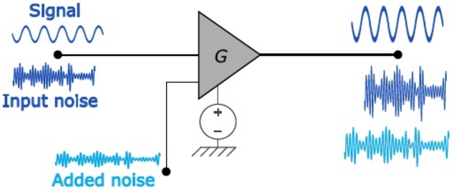


Green Bank telescope

Haloscope receiver




Amplifiers introduce noise




→ Johnson noise $P_n = kTB$
in cryogenic HEMT amplifiers $T_{eq} = 3 - 5\,K$

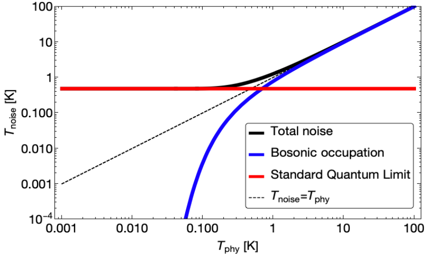
→ quantum noise (fundamental limit)
in parametric amplifiers (i.e. superconducting circuits): $1/2\hbar\omega$

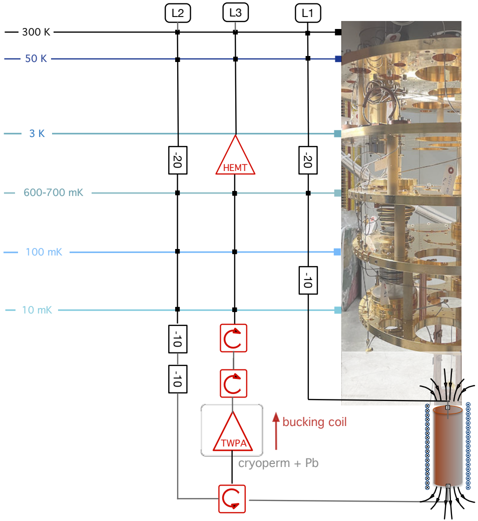
# **Ultralow noise receiver:** SC paramps and DR operation ($\sim 10\,\text{mK}$) $df/dt \propto T_{sys}^{-2}$

quantum-limited readout: SC amplifiers introduce the minimum amount of noise allowed by QM

$$k_B T_{sys} = h\nu \left( \frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_a \right), \; N_a \geqslant 0.5$$

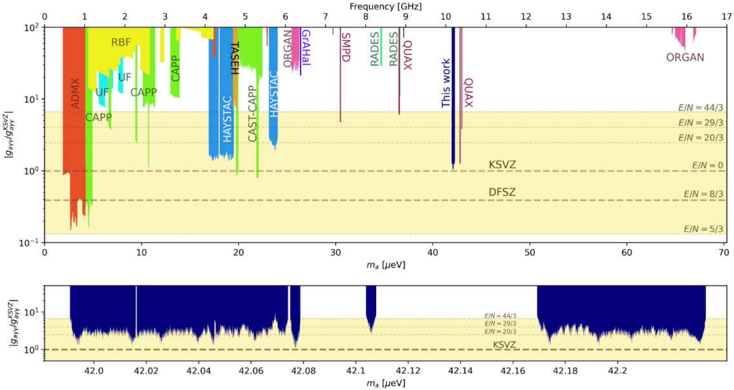
$T_{sys} = T_c + T_a$
$T_c$ cavity temperature
$T_a$ effective noise temperature of the amplifier



# PROBING THE DM HALO WITH QUAX

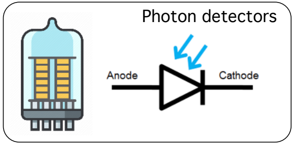
QUest for AXions is a haloscope detector, readout with **quantum-limited amplifiers**

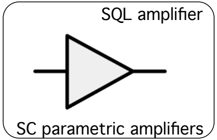



Phys Rev Lett 135, 211002 (2025)

- best sensitivity for heavier axions
- 38 MHz range probed, no candidates in the 225 hours long acquisition

## **photon counting** vs parametric amplification at standard quantum limit (**SQL**)




### IDEAL PHOTON DETECTOR

$$\frac{(df/dt)_{\text{counter}}}{(df/dt)_{\text{SQL}}} \approx \frac{Q_L}{Q_a} e^{\frac{h\nu}{k_B T}}$$

Ex. at 7 GHz, 40 mK $\rightarrow$ gain by $10^3$

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

### REAL DETECTOR WITH DARK COUNTS $\Gamma_{dc}$

$$\frac{(df/dt)_{\text{counter}}}{(df/dt)_{\text{SQL}}} \approx \eta^2 \frac{\Delta\nu_a}{\Gamma_{dc}}$$

$\Gamma_{dc}$ dark counts

$\eta$ photon counter efficiency
$\Delta\nu_a$ axion linewidth

$\rightarrow$ ($\times$100s) gain [$\Gamma_{dc} \sim$ 10s count/s, $\eta^2 \sim 70\%$]

- can probe in a day the same range a linear amplifier at SQL would take more than 3 months-

## PHOTON DETECTION

Light* is typically detected **by destroying it**

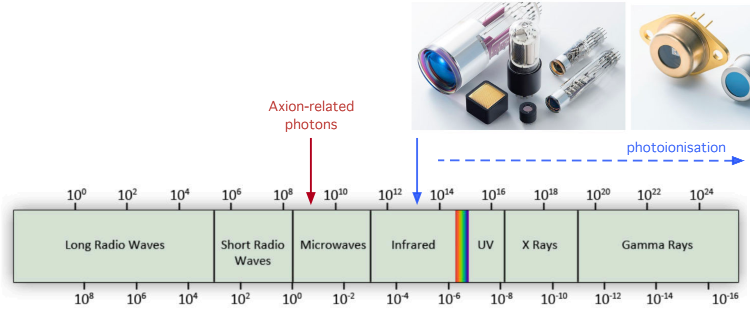
 

observable: generation of an electrical pulse when it absorbs (and so destroys) a photon

* holds for photons more energetic than IR

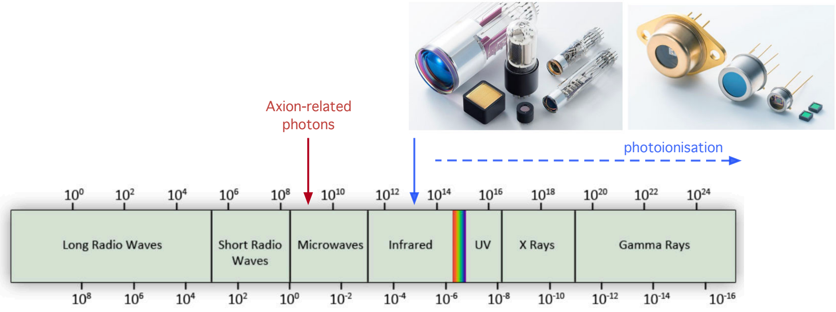
# MICROWAVE PHOTON DETECTION

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



## MICROWAVE PHOTON DETECTION

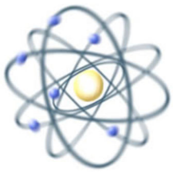
Detection of individual microwave photons is a challenging task because of their **low energy** e.g. $h\nu = 2.1 \times 10^{-5}\,\text{eV at } 5\,\text{GHz}$

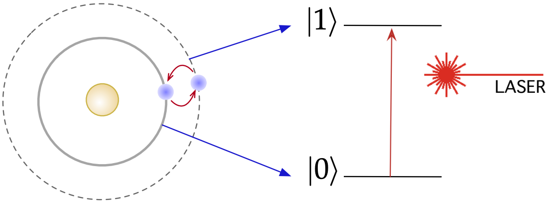



**Requirements** for dark matter search:

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

# Using atoms as detectors

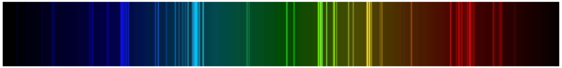





→ discrete energy levels

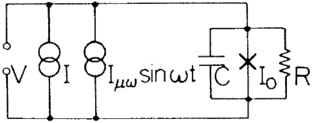
→ coupling to EM fields

→ anharmonic spectrum



**Rydberg atoms** have transitions in the microwave range, but they're not that practical

# Building atoms from superconducting circuits: "Atoms with wires"

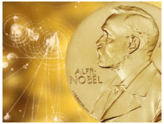


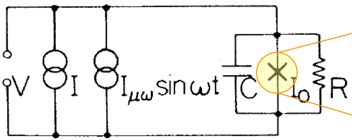

The **2025 Nobel Prize in Physics**

*"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"*

John M. Martinis, Michel H. Devoret, and John Clarke


Phys Rev Lett **55**, 1543 (1985)
Phys Rev Lett **55**, 1908 (1985)



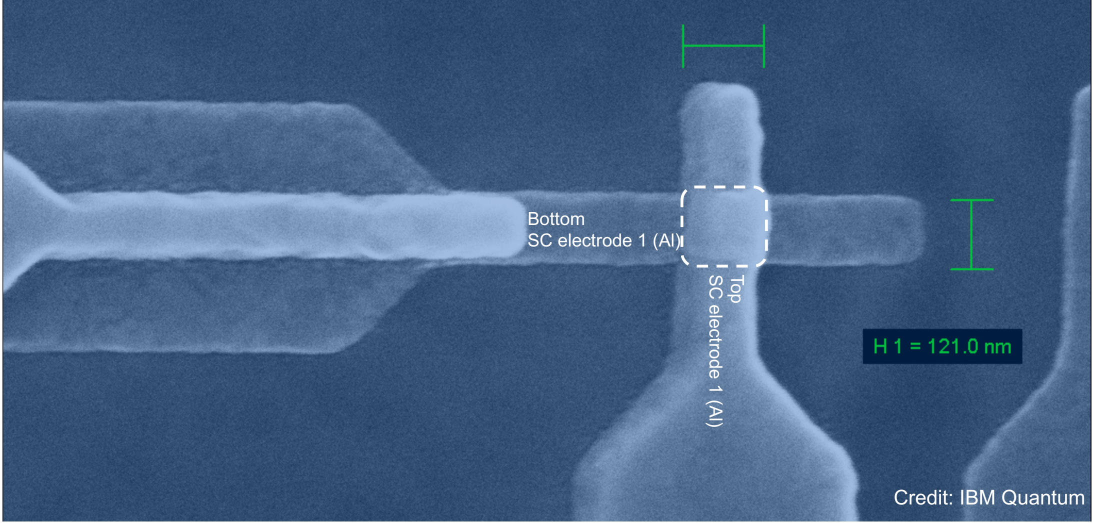


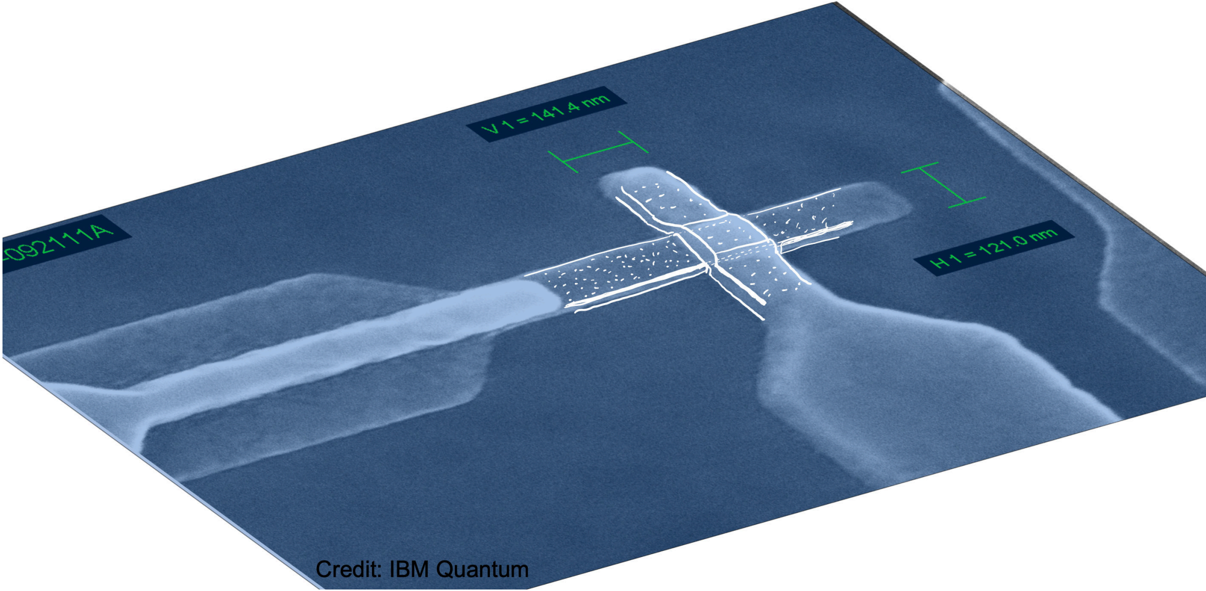
*"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"*

John M. Martinis, Michel H. Devoret, and John Clarke

Phys Rev Lett **55**, 1543 (1985)
Phys Rev Lett **55**, 1908 (1985)

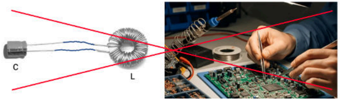
# Josephson Junction



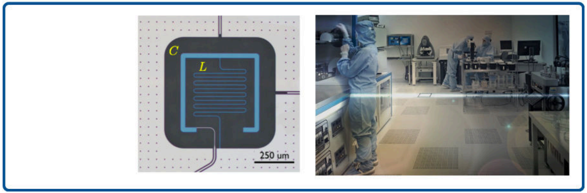



Credit: IBM Quantum

# fabrication of superconducting circuits




SC circuit fabrication facilities

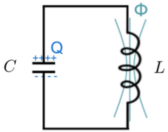



Superconducting circuits leverage standard silicon nanofabrication technology, with critical challenges in:

→ achieving **high-quality Josephson junctions**

→ minimizing dielectric losses in Si/Sapphire substrates

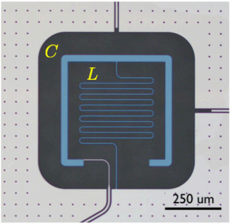
# Building atoms from superconducting circuits

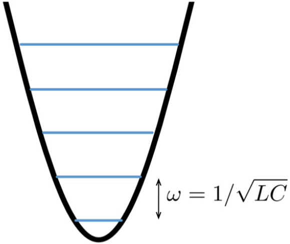



$$I = \Phi / L$$

$$\dot{\Phi} = V$$

$$E = \int dt\, P = \int dt\, I\, V = \int dt\, \frac{d\Phi}{dt}\, \Phi = \frac{\Phi^2}{2L}$$




$$[\Phi, Q] = i\hbar$$

$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

charging energy  inductive energy

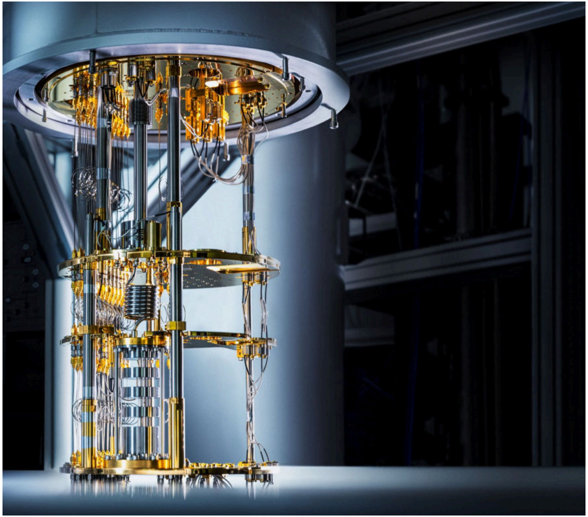
$$= \hbar\omega\left(a^\dagger a + \tfrac{1}{2}\right)$$

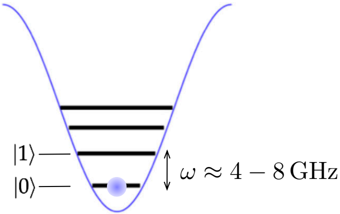
→ discrete energy levels

→ coupling to EM fields

→ ~~an~~harmonic spectrum

suppressing $|0\rangle \longrightarrow |1\rangle$ thermal excitation

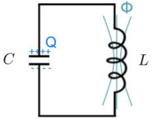


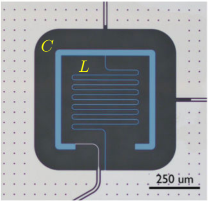


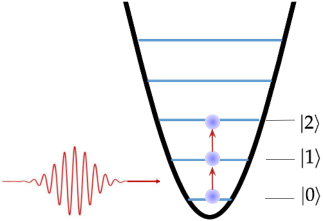

$$k_B T \ll \hbar\omega$$

$$T \sim 10\,\mathrm{mK} \Longrightarrow \omega_q/2\pi \approx 4-8\ \mathrm{GHz}$$

# Building quantum bits from superconducting circuits




$$[\Phi, Q] = i\hbar$$

$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

charging energy   inductive energy

$$= \hbar\omega \left(a^\dagger a + \tfrac{1}{2}\right)$$

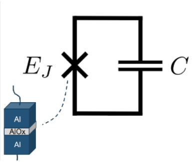
→ discrete energy levels

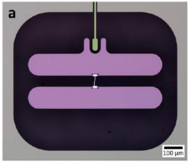
→ coupling to EM fields

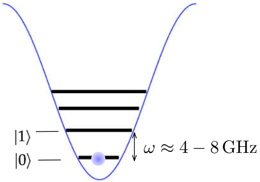
→ ~~an~~harmonic spectrum

not a good qubit

# Building quantum bits from superconducting circuits




$$I = I_c \sin\theta = I_c \sin(2\pi\Phi/\Phi_0)$$

$$\dot{\theta} = \frac{2\pi}{\Phi_0} V \quad \Leftrightarrow \quad \dot{\Phi} = V$$

$$E_J = \int dt\, P = \int dt\ \dot{\Phi}\ \sin(2\pi\Phi/\Phi_0) =$$

$$= -\frac{I_c\Phi_0}{2\pi}\cos(2\pi\Phi/\Phi_0)$$

$$\hat{H} = \frac{\hat{Q}^2}{2C} - E_J \cos\left(\frac{2\pi}{\Phi_0}\hat{\Phi}\right)$$

$$= 4E_C\hat{n}^2 - E_J\cos\hat{\varphi}$$

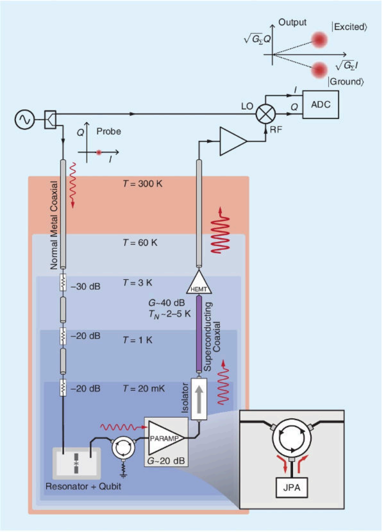
$E_C = e^2/2C$

→ discrete energy levels

→ coupling to EM fields

→ anharmonic spectrum

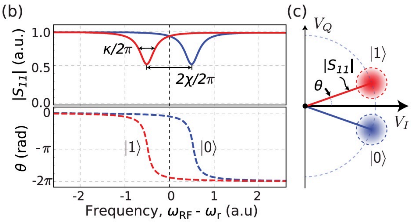
# qubit state detection




$\Delta = |\omega_r - \omega_q| \gg g$ *dispersive limit,*

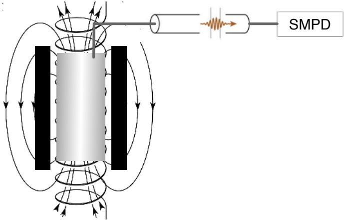
with $g$ coupling between the qubit and the cavity mode

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

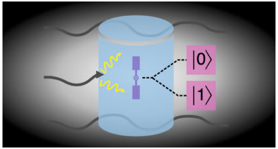


## TRAVELING QUANTUM MICROWAVES

ITINERANT PHOTONS

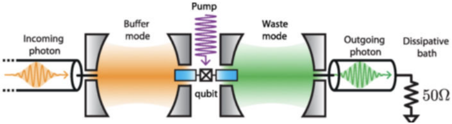



CAVITY PHOTONS




Phys. Rev. Lett. 126, 141302 (2021)

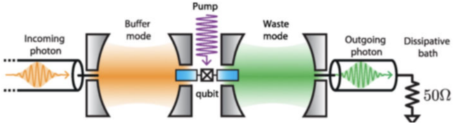
# COUNTING ITINERANT MICROWAVE PHOTONS




Phys. Rev. X 10, 021038 (2020) ← 1.3 counts/ms
Nature **600**, 434–438 (2021) ← spin fluorescence detection
Nature **619**, 276–281 (2023) ← single spin flip
Phys. Rev. Appl. 21, 014043 (2024) ← 85 counts/s

and more at https://iramis.cea.fr/en/spec/gq/

# COUNTING ITINERANT MICROWAVE PHOTONS




Phys. Rev. X 10, 021038 (2020) ← 1.3 counts/ms
Nature **600**, 434–438 (2021) ← spin fluorescence detection
Nature **619**, 276–281 (2023) ← single spin flip
Phys. Rev. Appl. 21, 014043 (2024) ← 85 counts/s

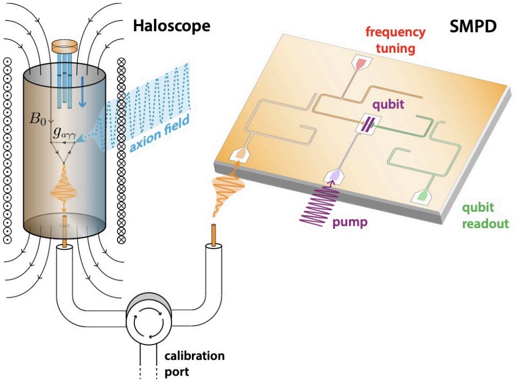
and more at https://iramis.cea.fr/en/spec/gq/

- wave mixing (4WM) process: the incoming photon is converted into an excitation of the qubit
  $\omega_b + \omega_p = \omega_q + \omega_w$
- readout of the qubit state with quantum information science (QIS) methods
- efficiency $\eta \sim 0.5$,
  dark counts $\Gamma_d \sim 85\,\mathrm{s}^{-1}$
- $\sim 100\,\mathrm{MHz}$ tuning range
- on/off resonance → monitor the **dark counts**

# PATHFINDER

- a **transmon qubit-based** single microwave photon detector (SMPD) is used to readout the cavity mode
- TWPA for dispersive readout of the qubit state
- hybrid (normal-superconducting) cavity
  $TM_{010}$ at 7.37 GHz
  **tunable** by a triplet of rods
  $Q_0 = 9 \times 10^5$ at 2 T-field
- T=14 mK
  @ fridge Quantronics lab (CEA, Saclay)

→ investigated the background,
and set a limit to $g_{a\gamma\gamma}$ [0.5 MHz band]

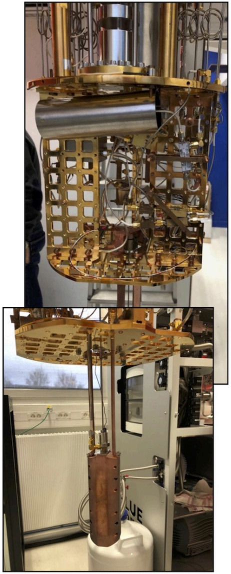



Phys. Rev. X 15, 021031 (2025)

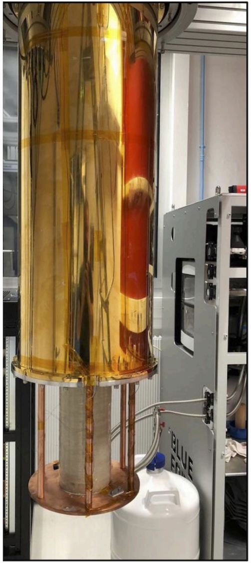
## PATHFINDER

- a **transmon-based** single microwave photon detector (SMPD) is used to readout the cavity mode
- TWPA for dispersive readout of the qubit state
- hybrid (normal-superconducting) cavity
  $TM_{010}$ at 7.37 GHz
  **tunable** by a triplet of rods
  $Q_0 = 9 \times 10^5$ at 2 T-field
- T=14 mK
  @ fridge Quantronics lab (CEA, Saclay)

→ investigated the background,
and set a limit to $g_{a\gamma\gamma}$ [0.5 MHz band]

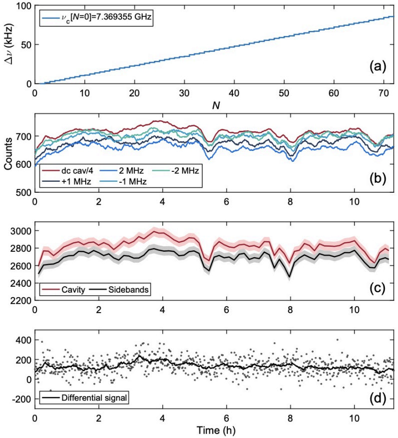


SMPD (top) and cavity



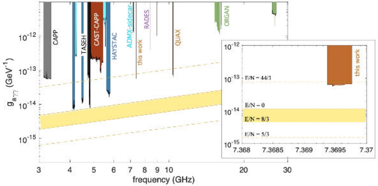
SC magnet

# A background-limited search: dark counts




- counts at $\omega_b = \omega_c$ registered in a time interval of 28.6 s (set by readout protocol structure) $\Longleftrightarrow$ **average dark count rate** $\alpha \sim 90$ **counts/s**
- both the counts at resonance and on sidebands $\omega_b = \omega_c \pm 1, 2$ MHz vary **beyond statistical uncertainty** expected for poissonian counts
- and a systematic **excess** at cavity frequency $\rightarrow$ the cavity sits at a slightly higher T (few mK)

$\rightarrow$ $\alpha = \alpha_q + \alpha_{th} + \alpha_{4WM}$
dominated by $\alpha_{th} \leftrightarrow$ **effective temperature of the input line** (30 − 40 mK)



# CONCLUSIONS

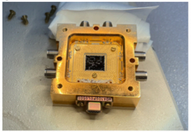
- → **Cavity-based DM searches** are inherently time-consuming, calling for smarter readout strategies
- → **State of the art:** quantum-limited SC amplifiers (great! but…microwave photon counters can do better)
- → Quantum Sensors (QS) represent a **new paradigm** for detecting ultra-weak signals in physics experiments
- → QS dramatically enhance sensitivity
- → pathfinder with a transmon-based quantum sensor
  new exclusion limit + $\times 20$ **acceleration** of the search $\Longrightarrow$ PRX 15, 021031 (2025)

INFN PADOVA


National Laboratories of Legnaro

G. Carugno
G. Ruoso
C. Braggio
A. Ortolan
R. Di Vora
A. Danho
G. Sardo Infirri
D. Maiello
P. Falferi
G. Lilli

SMPD



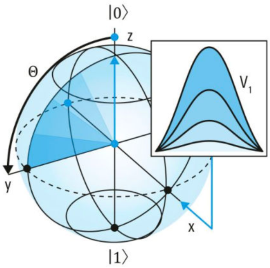
P. Bertet, E. Flurin lab

spec cea iramis cnrs université PARIS-SACLAY

# BACKUP SLIDES

# qubit control & readout

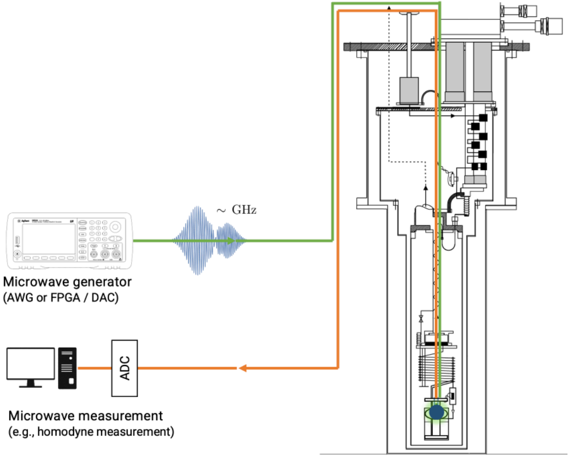
a qubit can exist in an arbitrary superposition of $|0\rangle$ and $|1\rangle$




Bloch sphere

$\rightarrow$ $\pi$-pulse, $\pi/2$-pulse: rotations of the state vector in the Bloch sphere

qubit calibrations: finding the right amplitude, duration and shape of the control pulse

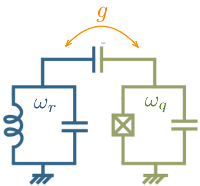


# qubit state detection

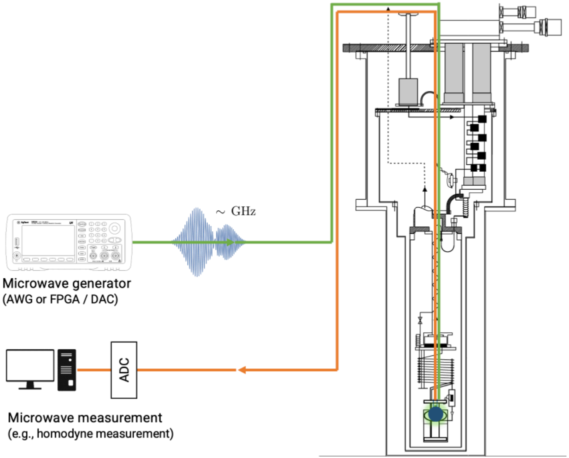
Readout can be accomplished in the **dispersive regime** of the Jaynes-Cummings Hamiltonian

Model: **two state system** interacts with **quantized radiation in a cavity**

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




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



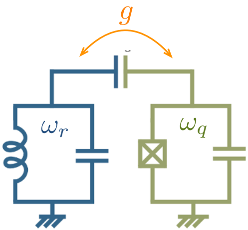
# qubit state detection

Readout can be accomplished in the **dispersive regime** of the Jaynes-Cummings Hamiltonian

Model: **two state system** interacts with **quantized radiation in a cavity**

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

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




$\chi = g^2/\Delta$ qubit-state dependent frequency shift