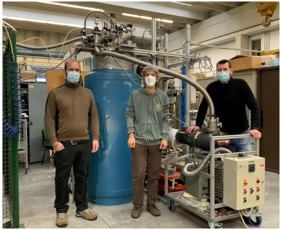
Probing The Axion-Electron and Axion-Photon Couplings with the QUAX Haloscopes

Istituto Nazionale di Fisica Nucleare

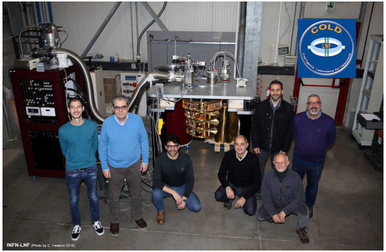
Lab @INFN-**LNL**
C. Braggio, G. Carugno, A. Ortolan, G. Ruoso
A. Lombardi, R. Pengo, L. Taffarello
PhD+PostDoc (2017-2020): N. Crescini
PhD (2018-2020): R. Di Vora

100 μW at 100 mK



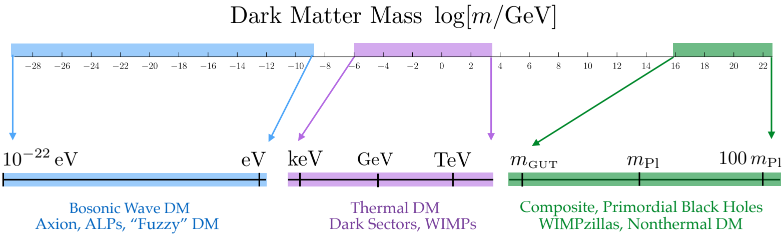
1 mW at 100 mK

Lab @INFN-**LNF**
C. Gatti, D. Alesini, D. Babusci, D. Di Gioacchino, C.Ligi,
G. Maccarrone, D. Morricciani, S. Tocci
PhD (2018-2020): A. Rettaroli



@INFN-**Salerno**
U. Gambardella, G. Iannone, C. Severino, D. D'Agostino
@INFN-**Trento**
P. Falferi, R. Mezzena

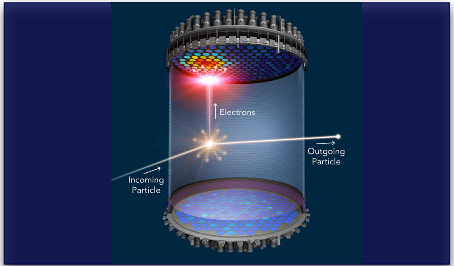
The Landscape of DM masses

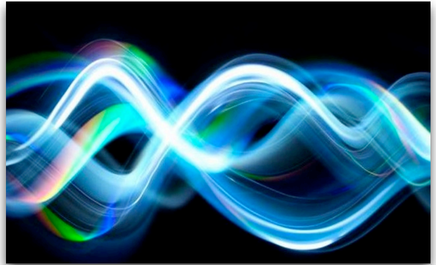


- **60 orders of magnitude** - might even be more, alas -
- which range can be probed with **laboratory searches**?
- $\simeq 10$ eV is considered a fundamental watershed
- **quantum sensing** $\to$ significant opportunities for **ultralight bosonic, wave-like DM** and in the 10 keV-1MeV range

AXION vs WIMP DETECTION

"The axion would be something of a spiritual cousin to the photon, but with just a hint of mass" P. Sikivie





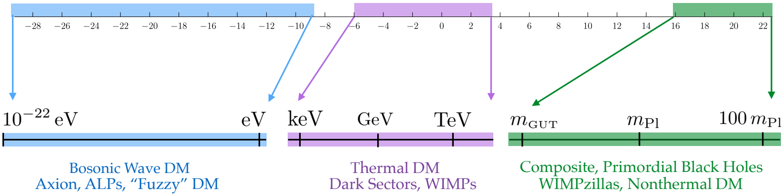
WIMP [4-1000] GeV
— number density is small
— tiny wavelength
— no detector-scale coherence

$\Longrightarrow$ observable: **scattering** of individual particles

AXION [$m_A \lesssim$ eV]
— number density is large (bosons)
— long wavelength
— coherence within detector

$\Longrightarrow$ observable: classical, oscillating, **background field**

THE LANDSCAPE OF DM MASSES



– **60 orders of magnitude** - might even be more, alas -

– which range can be probed with **laboratory searches**?

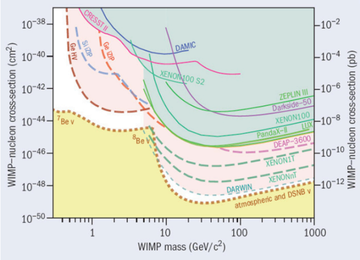
– $\simeq$ 10 eV is considered a fundamental watershed

– **quantum sensing** $\rightarrow$ significant opportunities for **ultralight bosonic, wave-like DM** and in the 10 keV-1MeV range

IS DM MADE OF AXIONS?

⇒ a well motivated scenario:

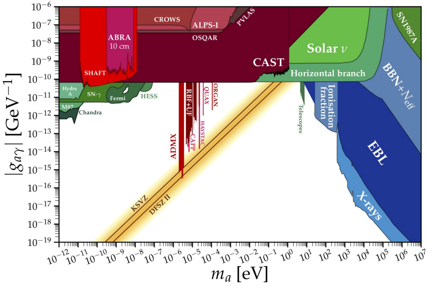
- "three birds with one particle"
  1. a CP problem solution
  2. Dark Matter candidate
  3. barion asymmetry [PRL 124, 111602 (2020)]
- SUSY is failing tests at LHC
- WIMPs searches with next generation of experiments



⇒ axion parameter space

- axions exist in a space of mass m_a and coupling $g_{a\gamma}$ with known **density** and **velocity distribution** throughout the galactic halo
- yellow/white regions not probed
- yellow = QCD axion
- only method for reaching QCD band is with haloscope

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



HALOSCOPE - resonant search for axion DM in the Galactic halo

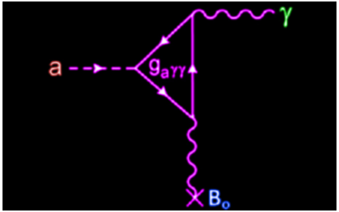
– original proposal by P. Sikivie (1983)

– search for axions as cold dark matter constituent: SHM from Λ_{CDM}, local DM density ρ

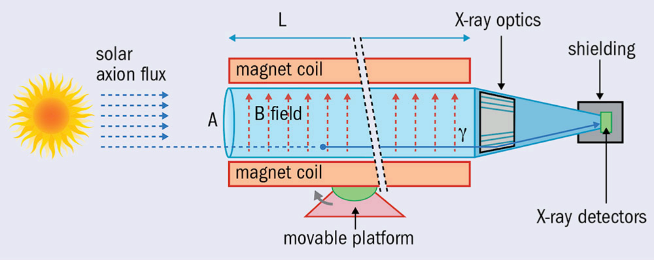
  $\rightarrow$ signal is a **line** with 10^{-6} relative width in the energy($\rightarrow$ frequency) spectrum

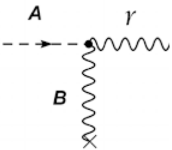
  $\rightarrow$ + sharp (10^{-11}) components due to non-thermalized

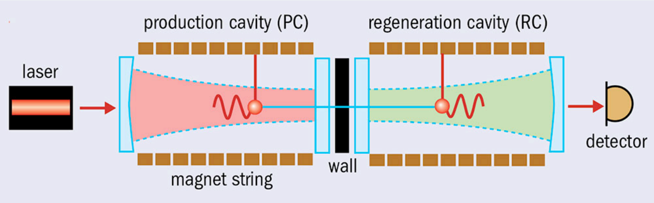
– an **axion** may interact with a **strong $\vec{B}$ field** to produce a **photon** of a specific frequency ($\rightarrow m_a$)

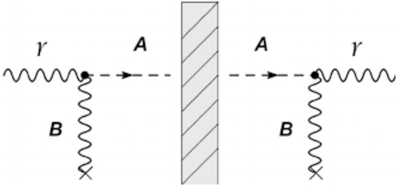


HALOSCOPE - resonant search for axion DM in the Galactic halo

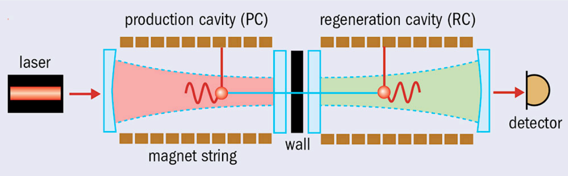


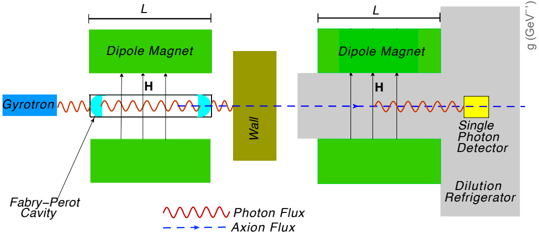


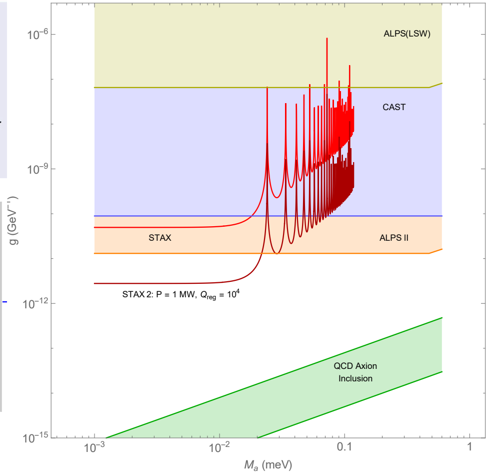




Axions can be produced in the Sun and in the Lab







optical/sub-THz photons → single photon detectors

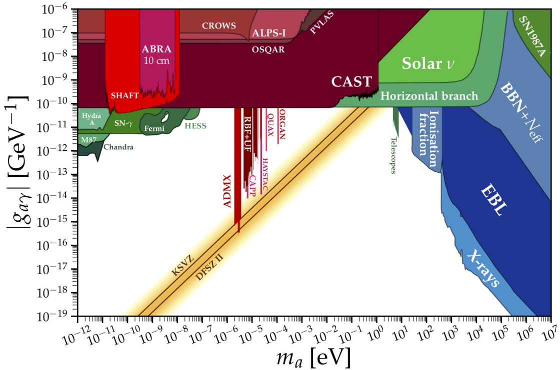
$a \to \gamma$ conversion probability depends on source intensity

Phys. Dark Univ. 12, 37 (2016)

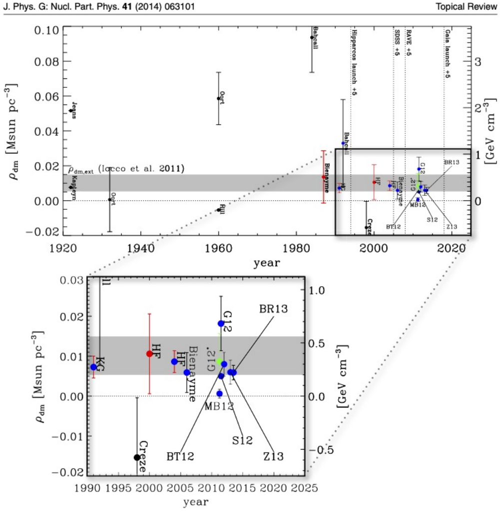
AXION PARAMETER SPACE

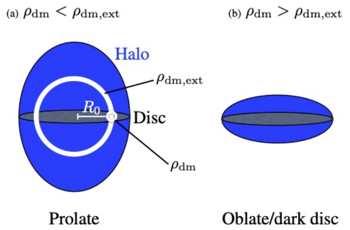
- axions exist in a space of mass m_a and coupling $g_{a\gamma}$ with known **density** and **velocity distribution** throughout the galactic halo
- yellow/white regions not probed
- yellow = QCD axion
- only method for reaching QCD band is with the axion haloscope

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



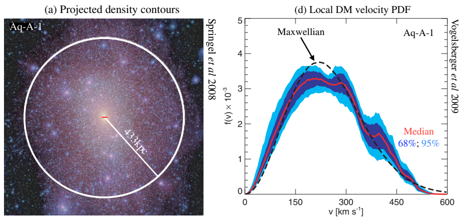
DM: what do we now about its **local** density?

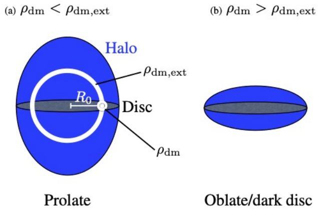




- ρ_{DM} is important for direct detection experiments that hope to find evidence for a DM particle in the lab
- **local** vs **global** measures: errors and assumptions
- 0.45 GeV/cm^3 $\Longrightarrow$ 1 hydrogen atom/$\sim$cm^3

DM particles velocity distribution and axion lineshape





DM cosmological simulation of a halo of Milky Way mass (10^{12} $M_\odot$), run with 4.2 billion dark matter super-particles

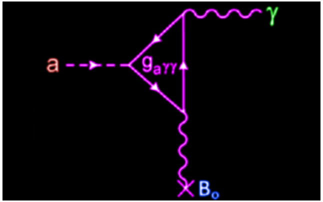
$\rightarrow$ axion linewidth $Q_a = \nu_a/\Delta\nu \simeq 10^6$

– ρ_{DM} is important for direct detection experiments that hope to find evidence for a DM particle in the lab

– **local** and **global** measures: errors and assumptions

– 0.45 GeV/cm^3 $\Longrightarrow$ 1 hydrogen atom/$\sim$cm^3

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-

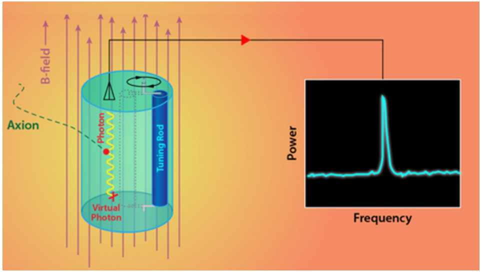
2. with **tuneable frequency** to match the axion mass

3. the cavity is within the bore of a **SC magnet**

4. cavity signal is readout with a **low noise receiver**
   -how much low? depends on the signal amplitude, partly in the hands of the experimentalist

HALOSCOPE - resonant search for axion DM in the Galactic halo

– if axions are *almost monochromatic* then their conversion to detectable particles (photons) can be accomplished using *high-Q* microwave cavities.



– $\omega_{\mathrm{TM}0nl} = \sqrt{\left(\frac{\epsilon_n}{r}\right)^2 + \left(\frac{l\pi}{h}\right)}$

TM_{0nl} are the cavity modes that couple with the axion

– resonant amplification in $[m_a \pm m_a/Q]$

– data in thin slices of parameter space; typically $Q < Q_a \sim 1/\sigma_v^2 \sim 10^6$

– signal power $P_{a\to\gamma}$ is model-dependent

$$P_{a\to\gamma} \propto (B^2 VQ)\left(g_{a\gamma}^2 \frac{\rho}{m_a}\right)$$

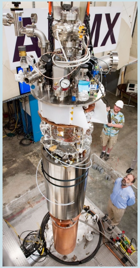
exceedingly tiny ($\sim 10^{-23}$ W)

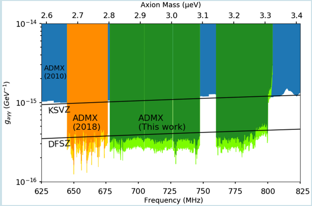
"The last signal ever received from the 7.5 W transmitter aboard Pioneer 10 in 2002, then 12.1 billion kilometers from Earth, was a prodigious 2.5×10^{-21} *W. And unlike with the axion, physicists knew its frequency!"*

K. V. Bibber and L. Rosenberg, Physics Today 59, 8, 30 (2006)

HALOSCOPES: UPDATES

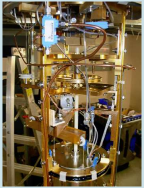
ADMX PRL **124**, 101303 (2020)

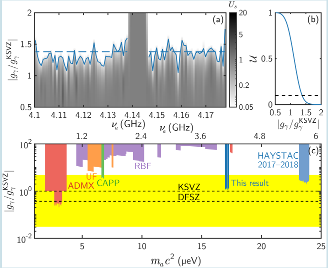




– sensitivity to QCD axion
– 2.82 – 3.31 μeV mass range
– cylindrical cavity at $T = 100\,$mK, $Q_0 \sim 30000$, $V = 136\,l$
– 7.6 T field

HAYSTAC Nature 590, 238 (2021)





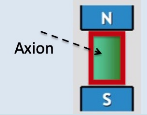
– 17.14 – 17.28 μeV axion mass range
– **squeezing** doubled the search rate
– cylindrical cavity at $T = 60\,$mK $Q_0 \sim 50000$, $V = 1.5\,l$
– 8T magnet

"Roberto and I spent a few months cooking up this theory, and now the experimentalists have spent 40 years looking for it "
H. Quinn

QUAX - QUAERERE AXIONS

Detection of cosmological axions through their **coupling to electrons** or **photons**

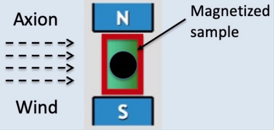
PHOTON COUPLING – QUAX aγ   *high frequency range* (8.5 – 11) GHz



DM axions are converted into **RF photons** inside a **resonant cavity** immersed in a **strong magnetic field**

$$P_{\mathrm{ax}} = 3.3 \cdot 10^{-24}\,\mathrm{W} \left(\frac{V_{\mathrm{eff}}^{\mathrm{Sa}}}{2.3 \cdot 10^{-5}\,\mathrm{m}^3}\right) \left(\frac{B}{8\,\mathrm{T}}\right)^2 \times \left(\frac{g_\gamma}{-0.97}\right)^2 \left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm^{-3}}}\right) \left(\frac{f}{13.5\,\mathrm{GHz}}\right) \left(\frac{Q_L}{145\,000}\right)$$

ELECTRON COUPLING – QUAX   *the FMR haloscope*

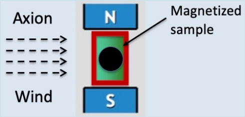


the axion DM cloud acts as an **effective RF magnetic field** on the electron spin exciting **magnetic transitions** in a magnetized sample (YIG) → **RF photons**

$$P_{\mathrm{out}} = \frac{P_{\mathrm{in}}}{2} = 8 \times 10^{-26} \left(\frac{m_a}{2 \cdot 10^{-4}\,\mathrm{eV}}\right)^3 \left(\frac{V_s}{1\ \mathrm{liter}}\right) \left(\frac{n_S}{10^{28}/\mathrm{m}^3}\right) \left(\frac{\tau_{\mathrm{min}}}{10^{-6}\,\mathrm{s}}\right) \mathrm{W},$$

ELECTRON COUPLING – **QUAX**

NEW CONCEPT! *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) → **RF photons**

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

ESR (Electron Spin Resonance)
the RF field is actually the axion effective field
—>> axion mass tuning with B field!
1.7 T —> 48 GHz

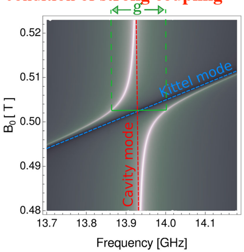
YIG (Yttrium Iron Garnet)

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

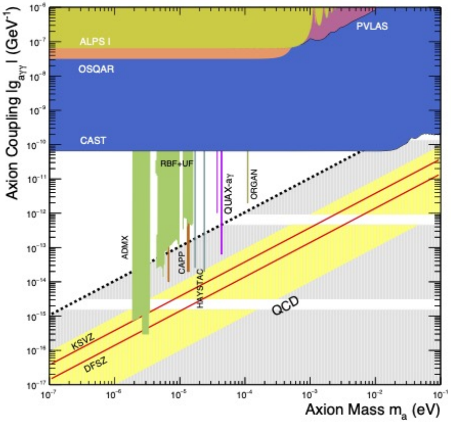
under the condition of **strong coupling**

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

corresponding signal photon rate
microwave photon counter is needed

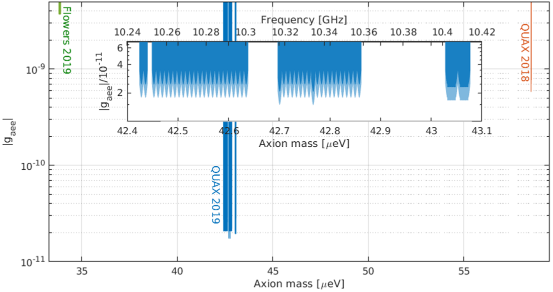


QUAXa – *gamma*



arXiv:2012.09498 (2021)

QUAXa – e

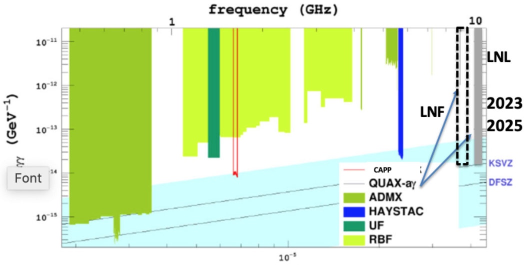


PRL 124, 171801 (2020)

Phys Dark Univ 15, 135–141 (2017)

Today's leading haloscopes would take **centuries** to scan only the 1 – 10 GHz decade at DFSZ sensitivity

QUAX COLLABORATION ROADMAP (2021-2025)



S. Lee et al, PRL 124, 101802 (2020) m_a (eV)

Performance for KSVZ model at 95% c.l. with $N_A = 0.5$		
Noise Temperature	0.43 K	0.5 K
Single scan time	3100 s	69 s
Scan speed	18 MHz/day	40 MHz/day
Performance for KSVZ model at 95% c.l. with $N_A = 1.5$		
Noise Temperature	0.86 K	1 K
Single scan time	12500 s	280 s
Scan speed	4.5 MHz/day	10 MHz/day

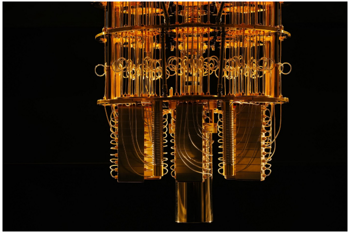
	LNF	**LNL**
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	TM010	pseudoTM030
Single volume	$1.5 \cdot 10^{-4}$ m^3	$1.5 \cdot 10^{-4}$ m^3
Total volume	7⊗0.15 liters	0.15 liters
Q_0	300 000	1 000 000
Single scan bandwidth	630 kHz	30 kHz
Axion power	$7 \otimes 1.2 \cdot 10^{-23}$ W	$0.99 \cdot 10^{-22}$ W
Preamplifier	TWJPA/INRIM	DJJAA/Grenoble
Operating temperature	30 mK	30 mK

SCAN RATE in the past 30 years

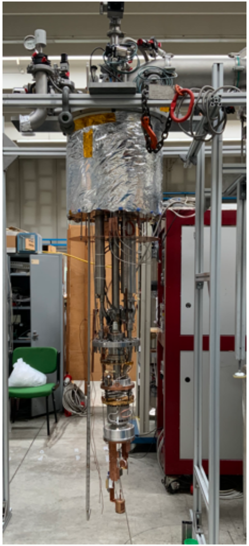
how rapidly an haloscope probes the parameter space at fixed g_γ

$$\frac{df}{dt} \propto \left(\frac{g_\gamma^4}{\mathrm{SNR}^2}\right)\left(\frac{\rho_{\mathrm{DM}}^2 Q_a}{\Lambda^8}\right)\left(\frac{B^4 V^2 C_{mnl}^2 Q_0}{N_{\mathrm{sys}}^2}\right)$$

- B is still within 25-50%
- Q_0 limited by **anomalous skin effect** for normal metals, recently with SC technology (YBCO) gained a factor ~ 10, dielectric cavity
- N_{sys} improved a few hundredfold thanks to dilution refrigerators and the improvement in **amplifier technology** $\rightarrow$ **Circuit QED**

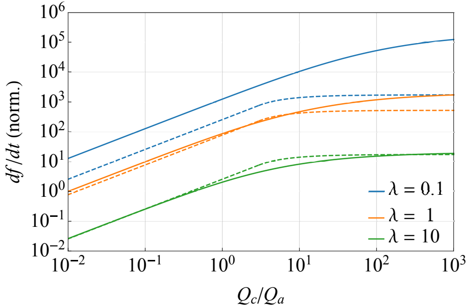


$$T = 10\,\mathrm{mK}$$
$$\sim 1\,\mu\mathrm{eV}$$
$$\sim 200\,\mathrm{MHz}$$
$$k_B T \ll h\nu$$



SCAN RATE:

role of cavity Q_0 and of the receiver noise temperature



$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2}\left(\frac{P_0}{k_B T_{\mathrm{eff}}}\right)^2 \left(\frac{\frac{\beta}{(1+\beta)}}{\frac{4\beta}{(1+\beta)^2}+\lambda}\right)^2 \frac{Q_l Q_a^2}{Q_l + Q_a}$$

$\Longrightarrow$ improve Q
$\Longrightarrow$ improve λ (or change paradigm)

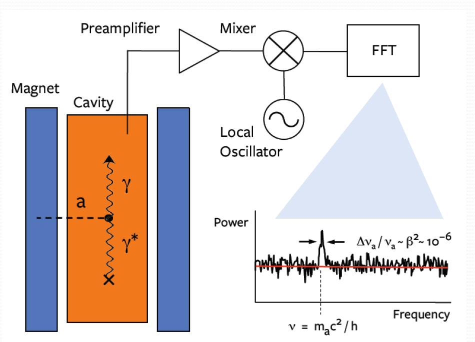
Transitor-based amplification (HEMT)
Josephson Parametric Amplifiers
Squeezing

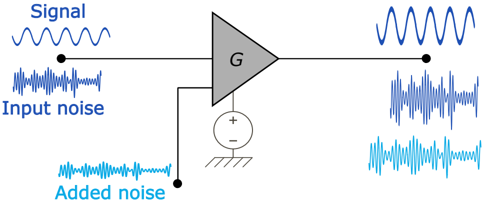
Revisiting the detection rate for axion haloscopes D. Kim et al JCAP03, 066 (2020)

PREAMP NOISE

the Dicke's receiver noise is determined by the preamp:

$$P = k_B T_N \sqrt{\frac{\Delta\nu}{t_m}}$$

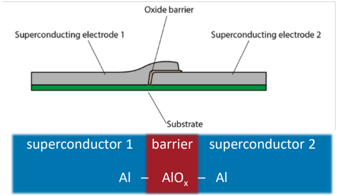


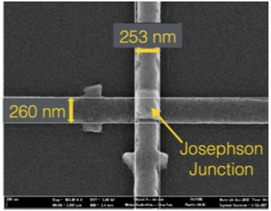


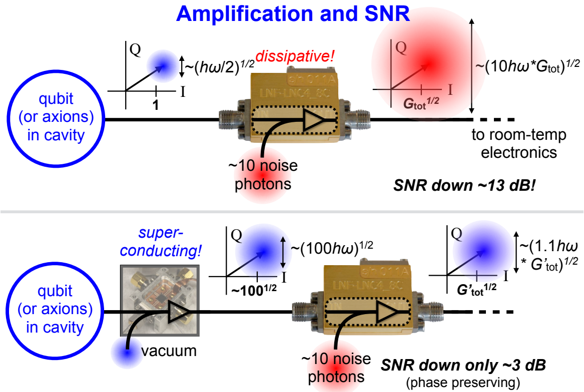
~~thermal~~ + quantum fluctuations
$n(\nu, T) = (\exp(h\nu/k_B T) - 1)^{-1}$
amplifier internal channel

FROM HEMT TO JPA

the Josephson tunnel junction is **non-dissipative** and **non-linear**





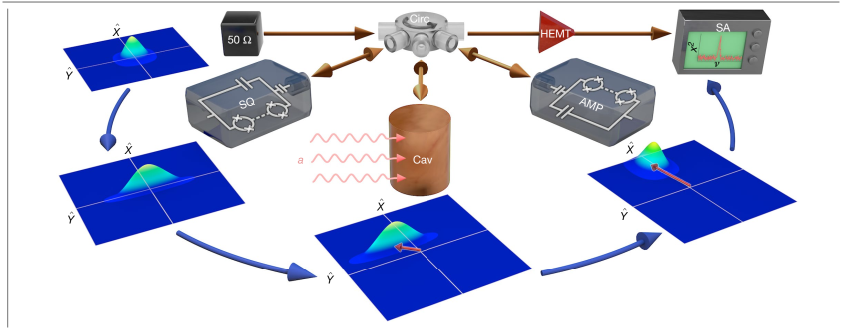


- **JPA improves SNR ~10dB** → **Averaging time reduced ~100x !**

from A. Eddins "*Josephson Parametric Amplifiers: Theory and Application*"

(BLUE LINE): SQUEEZING

1 JPA to squeeze noise added by the amplifier
1 JPA to amplify signal + squeezed noise



mock-haloscope in Phys. Rev. X 9, 021023 (2019)   HAYSTAC cavity in Nature 590, 238–242(2021);

$\Longrightarrow$ Factor **2** faster scanning

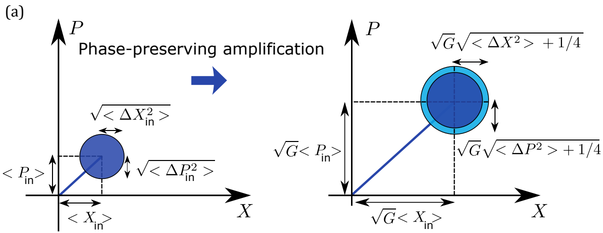
THE STANDARD QUANTUM LIMIT

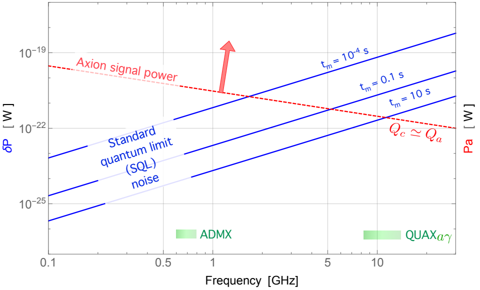
-due to fundamental laws of QM-
any phase preserving amplifier adds at least half a noise photon in the high-G limit

mode of EM field $\Longrightarrow$ HO

$a_{\text{in}} = X_{\text{in}} + iP_{\text{in}}$

$[P_{\text{in}}, X_{\text{in}}] = i\hbar/2$





$\Longrightarrow$ **weeks to months acquisition time** even with quantum-limited amplifiers.

Evading the SQL with photon counters

The counter measures in the **energy eigenbasis** $\Longrightarrow$ change of paradigm

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

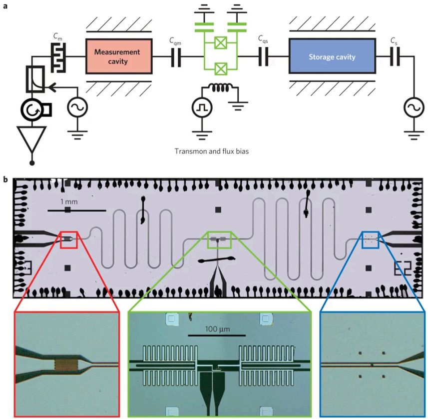
Solution: use "**artificial atoms**" introduced in circuit QED

2010 $\rightarrow$ first QND measurement of single photons
-one **transmon qubit** coupled to two **2D** resonators
Nat. Phys. 6, 663

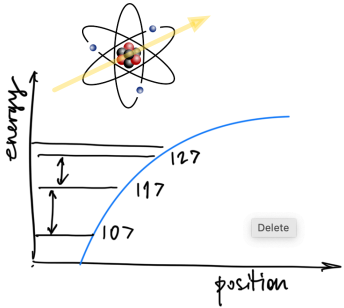
2020 $\rightarrow$ introduction of a practical detector of microwave **itinerant photons** - scheme compatible with axion searches
PRX 10, 021038

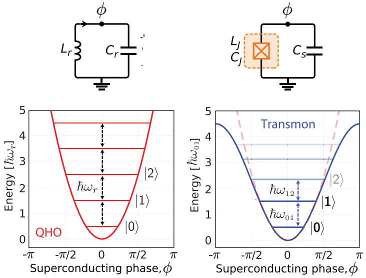
2021 $\rightarrow$ factor 1300 acceleration of **dark photon** search
PRL 126, 141302

! Poisson statistics !
? Dark count rate, efficiency, bandwidth ?



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)

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

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

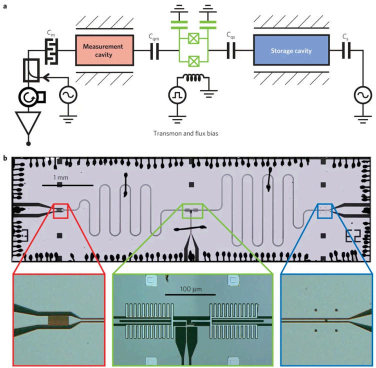
$I_J = I_c \sin\phi \qquad V = \frac{\phi_0}{2\pi}\frac{\partial\phi}{\partial t}$

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

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

SMPD AND TRANSMON QUBITS

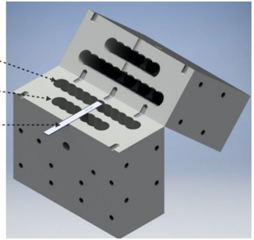
→ detectors for **cavity photons**: the photons interact with the SC transmon qubit, and then you make a measurement on the qubit



Storage Cavity 6.011 GHz

Readout Cavity 8.052 GHz

Qubit on sapphire chip 4.749 GHz



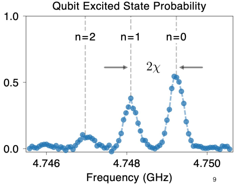
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

Operated in a dilution refrigerator @ 8mK

dispersive regime: $\Delta = \omega_q - \omega_r \gg g$

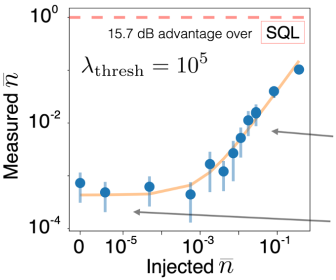
g coupling $\chi = g^2/\Delta$

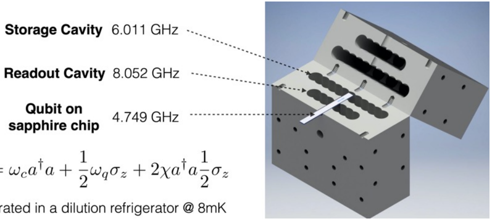
the photons n generated in the cavity shift the frequency of the qubit by $2n\chi$



SMPD and transmon qubits

→ detectors for **cavity photons**: the photons interact with the SC transmon qubit, and then you make a measurement on the qubit





$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

Operated in a dilution refrigerator @ 8mK

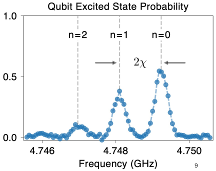
1300X lower background rate than SQL
$\implies$ 1300X less intergration time required

efficiency 40.9%

false positive probability $\delta = 4.3 \times 10^{-4}$

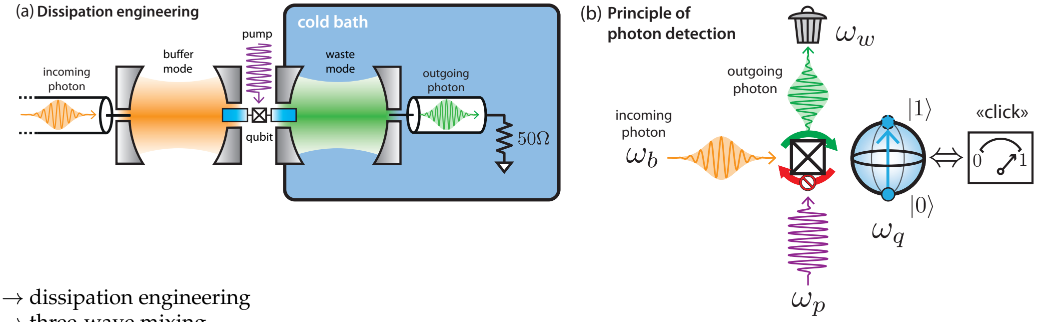
dispersive regime: $\Delta = \omega_q - \omega_r \gg g$
g coupling $\chi = g^2/\Delta$

the photons n generated in the cavity shift the frequency of the qubit by $2n\chi$



SMPD

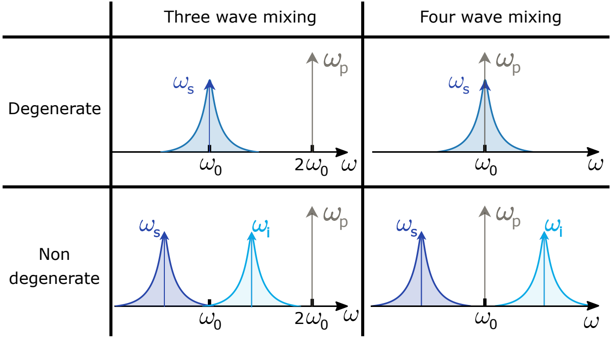
→ detectors for **itinerant** (traveling) microwave photons



→ dissipation engineering
→ three-wave mixing
→ compatible with the haloscope environment (intense B-fields)
→ low dark count rate

Josephson Parametric Amplifier

(quantum optics formalism) Parametric interaction takes place in a **nonlinear medium**, where electromagnetic waves of different frequencies can **mix and generate new frequencies**.



An intense electromagnetic wave with frequency $\omega_p/2\pi$ (the pump), is sent to a nonlinear medium and generates two electromagnetic waves, called signal (idler) of frequency $\omega_s/2\pi$ ($\omega_i/2\pi$)

energy conservation:
(3W) $\omega_p = \omega_s + \omega_i$
(4W) $2\omega_p = \omega_s + \omega_i$

energy transfer between the pump and the signal gives rise to **gain**