Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Boosting Axions Searches With Quantum Sensing

CLAUDIO GATTI LNF-INFN

IEEE 14th Workshop on
Low Temperature Electronics
WOLTE14
Virtual Workshop | April 12-16, 2021

Outline

1. Axions and Axion Haloscopes
2. Amplifiers
    - I. MSA-SQUID
    - II. JPA
    - III. TWJPA
3. Quantum Sensing
    1. Photon in cavities
    2. Sensing magnons with qubits
    3. More counters …
4. Conclusions

Created by Agarunov Oktay-Abraham
from Noun Project

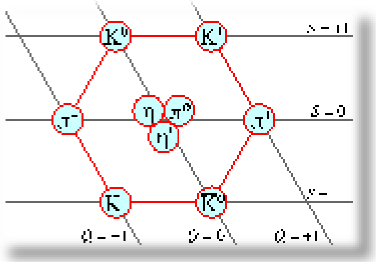
Axions

Origin Of Axions

U(1)$_A$ problem

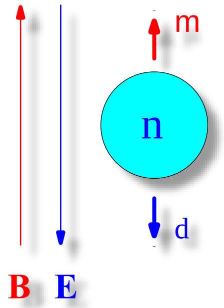
$$M_{\eta'} = 958 \text{ MeV} \gg M_\eta$$

S.Weinberg U(1) problem PRD 11 (1975)



Strong CP problem

$$\mathcal{L}_{QCD}^{\cancel{CP}} = \theta_{QCD} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$



Phys Rev Lett 82, n.5 (1999) p.904

$$d_n < 2.9 \times 10^{-26} e \text{ cm}$$

$$\theta < 10^{-10}$$

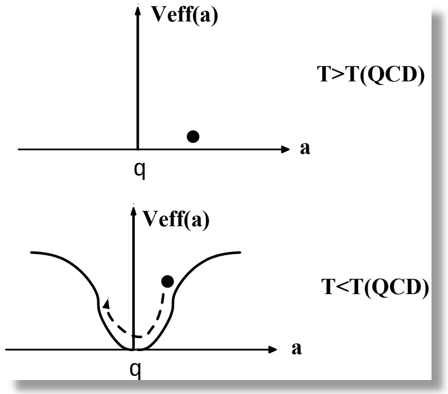
Axions

$$\mathcal{L}_{QCD}^{\cancel{CP}} = \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

R.D.Peccei and H.R.Quinn, Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D 16, 1791 (1977)
S. Weinberg, Phys. Rev. Lett. 40, 223 (1978)
F. Wilczek, Phys. Rev. Lett. 40, 279 (1978)

Axion Dark Matter

Misalignment mechanism

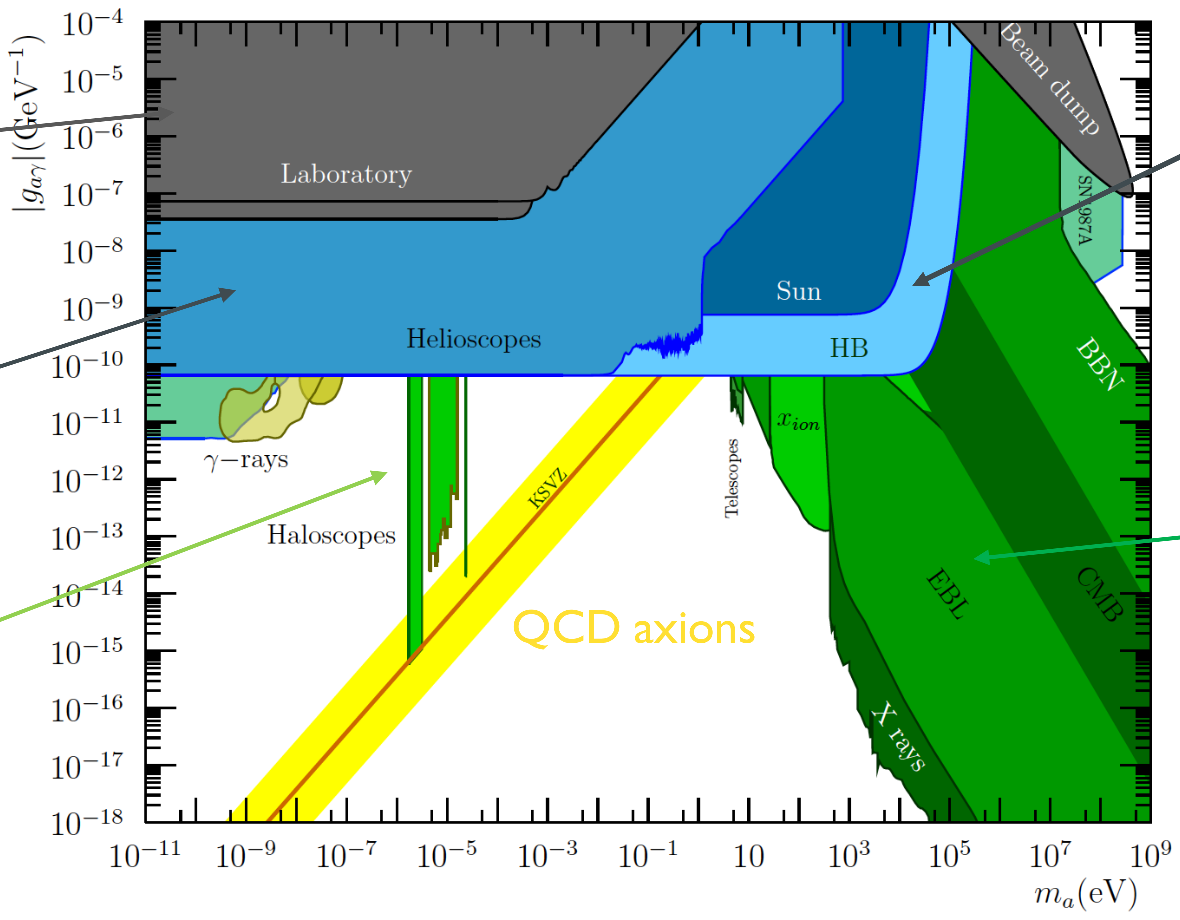


Limits on Axions

Laboratory experiments

Detection of axions from the Sun (Elioscopes)

DM axion detection (Haloscopes)



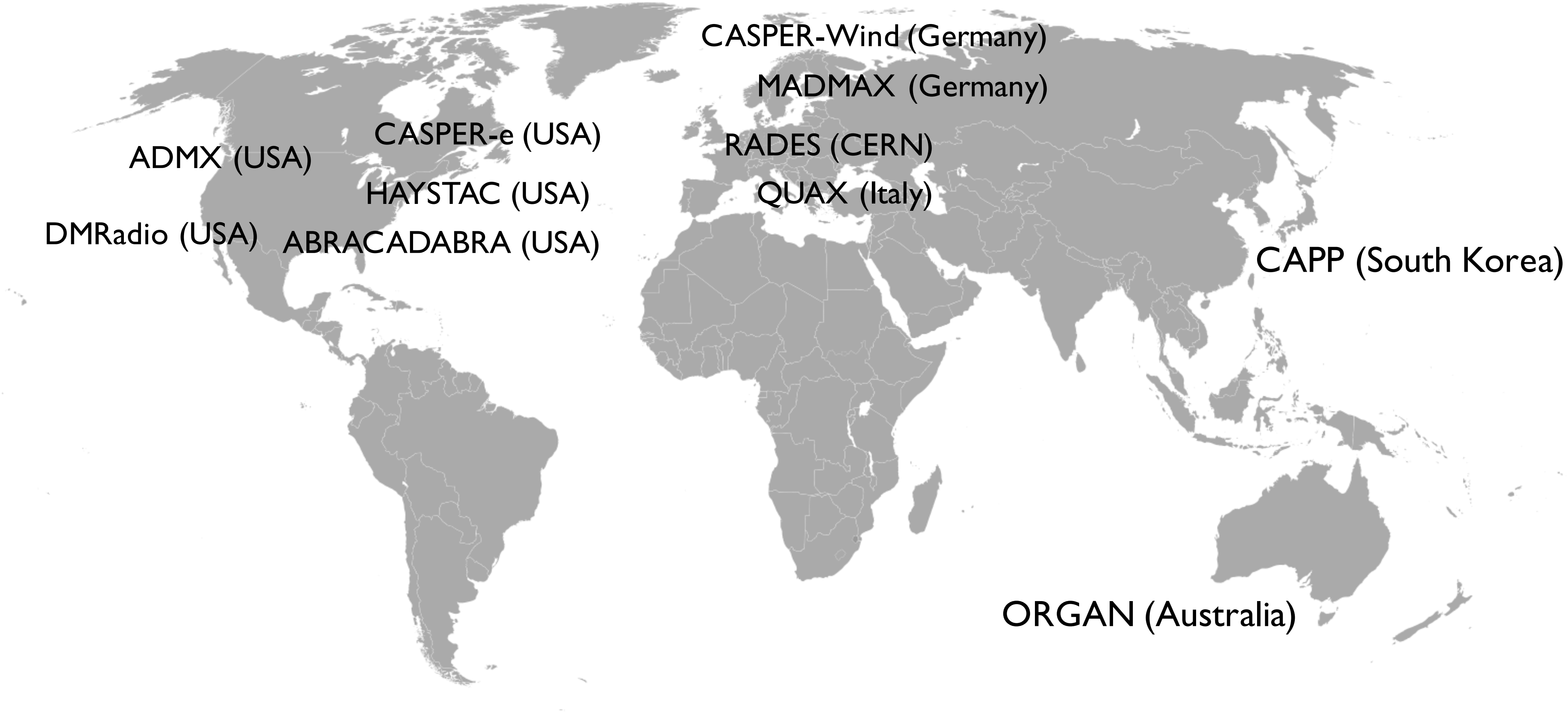
Stellar physics:
Primakoff process in stars $\gamma Ze \rightarrow a Ze$. Constraints on stellar lifetime or energy-loss rates: Sun, HB.

Cosmology:
No DM $a \rightarrow \gamma\gamma$ decays seen in the visible region from galaxies with telecopes. Similar searches with X-rays and extragalactic background light (EBL) or H ionization.

Ringwald et al. PDG 2017

Irastorza Redondo arxiv:1801.08127

Haloscopes



CASPER-Wind (Germany)

MADMAX (Germany)

CASPER-e (USA)

ADMX (USA)

RADES (CERN)

HAYSTAC (USA)

QUAX (Italy)

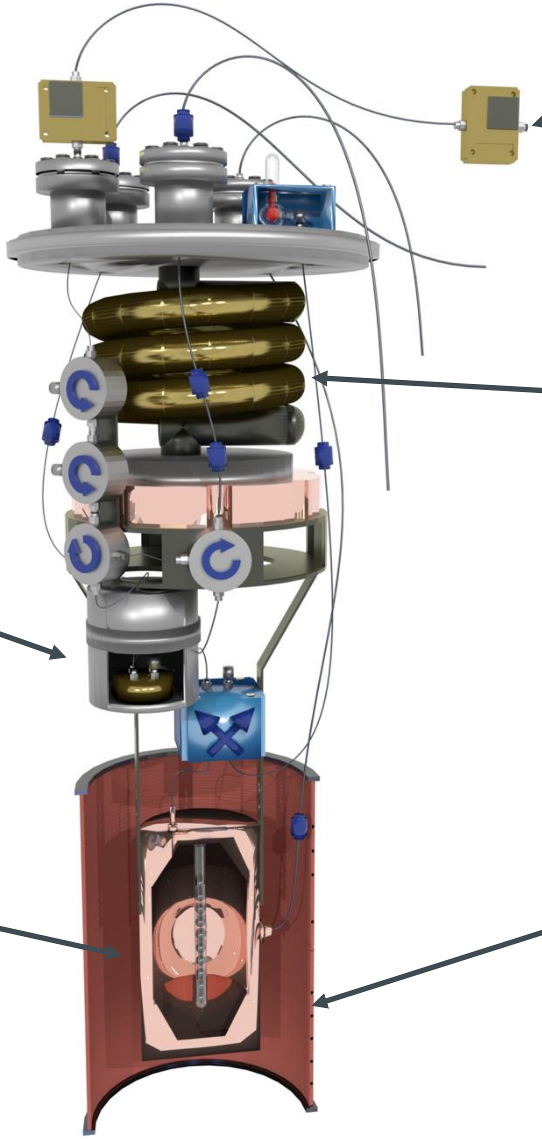
DMRadio (USA)

ABRACADABRA (USA)

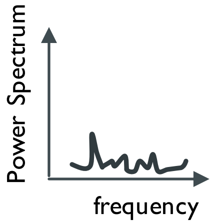
CAPP (South Korea)

ORGAN (Australia)

State of Art Sikivie's Haloscope



Room Temperature Amplifiers



Dilution Refrigeretor T<100 mK

Cryogenic Amplifier (noise at SQL)

Scan rate

$$\frac{df}{dt} \propto \frac{B^4 V^2 Q_L}{T_{sys}^2}$$

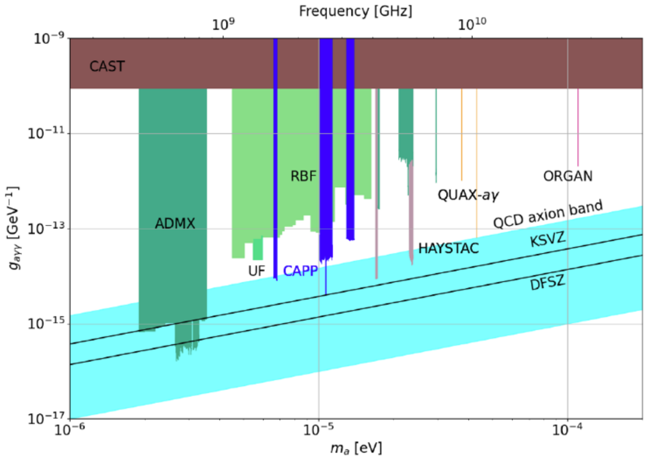
Resonant cavity

SC magnet (~10 T)

Sikivie Phys. Rev. D 32,11 (1985)

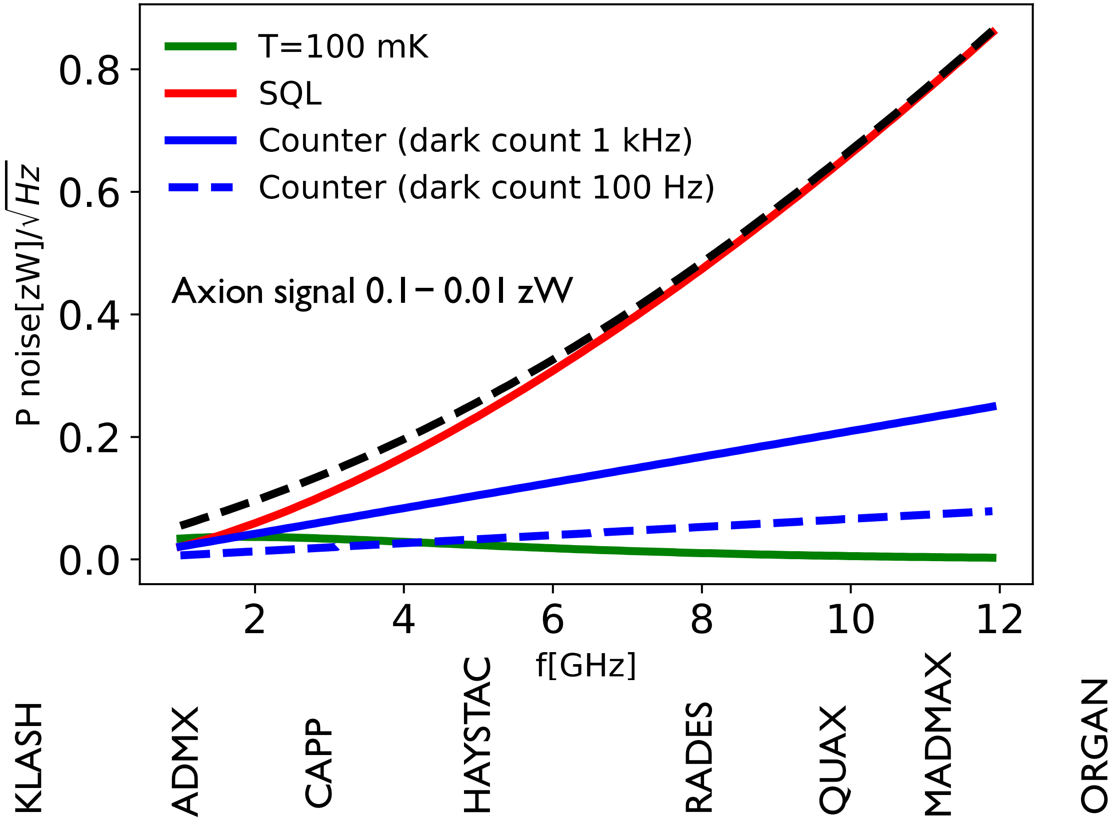
Noise in Haloscopes

Soohyung Lee (IBS/CAPP Axions Beyond Gen 2 Workshop)



Energy spread of galactic axion

$$\frac{\Delta\nu_a}{\nu_a} \sim 10^{-6}$$



Quantum limited amplifiers

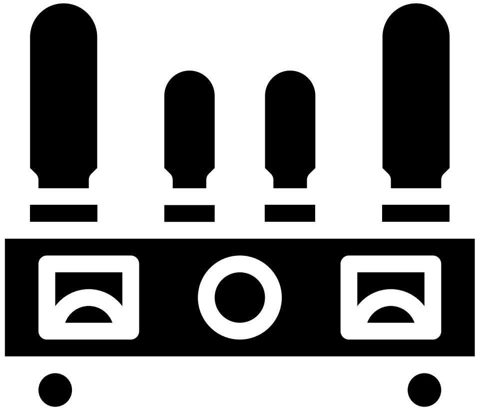
$$\hbar\omega\sqrt{\Delta\nu_a}$$

Photon counters

$$\hbar\omega\sqrt{\Delta\nu_{dark}}$$

Thermal noise

$$n_{th}\sqrt{\Delta\nu_a}$$



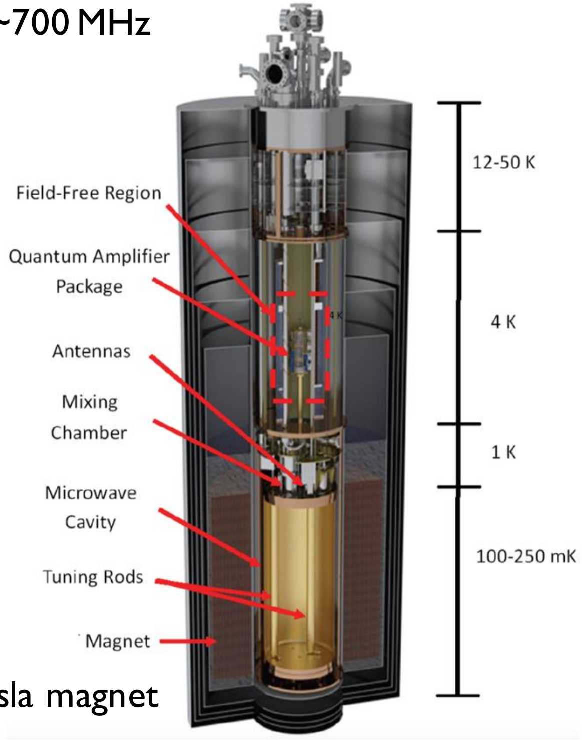
Created by Komkrit Noenp

Quantum Limited Amplifiers

ADMX - Microstrip SQUID Amplifier

ADMX Washington University

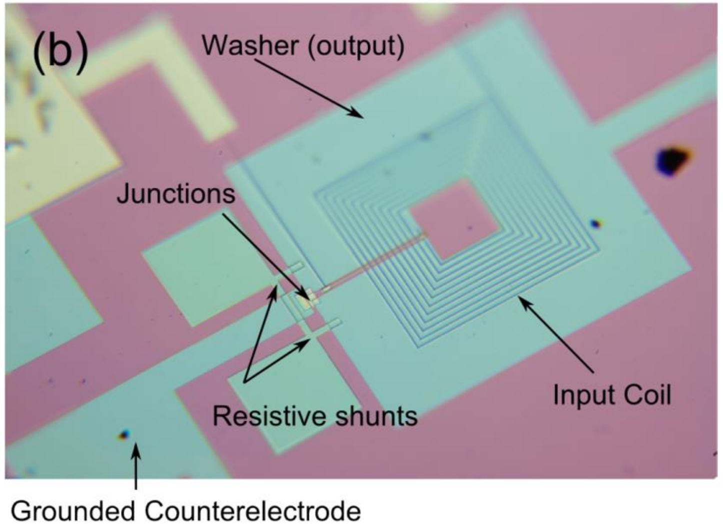
f~700 MHz



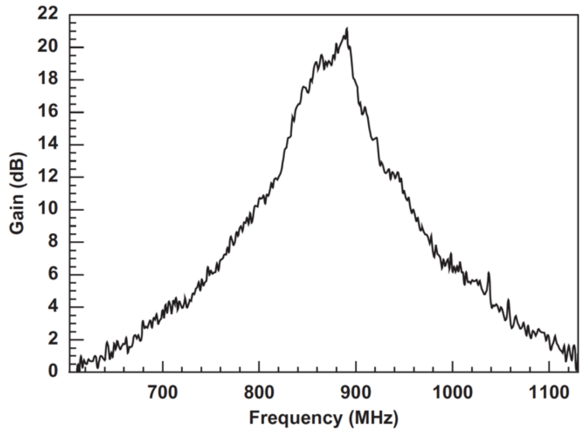
8 Tesla magnet

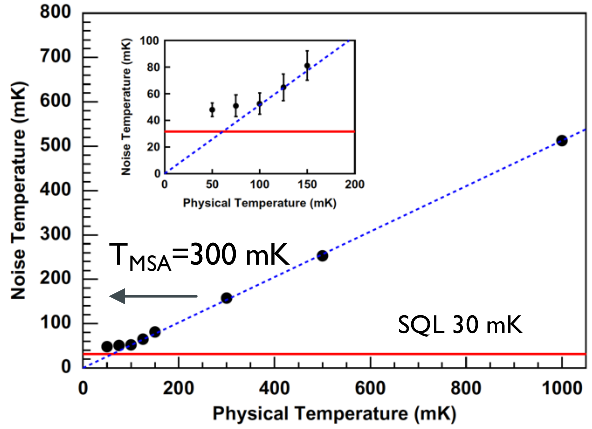
PHYSICAL REVIEW LETTERS 120, 151301 (2018)

For frequency above 100 MHz parasitic capacitance causes drop in SQUID gain. In a MSA the input microstrip coil termination is left open resulting in a $\lambda/2$ resonator.



FERMILAB-PUB-20-331-AD-E-QIS Arxiv:2010.00169



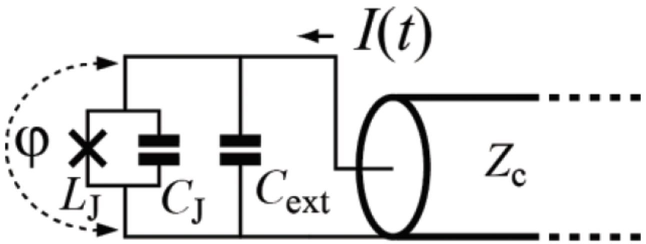


«RF amplifier based on DC SQUID» M. Mück and R. McDermott, Supercond. Sci. Technol. 23 (2010) 093001.

NIM A 656 (2011) 39–44

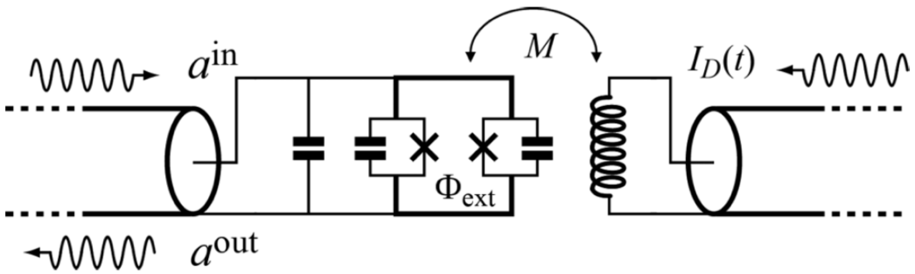
Josephson Parametric Amplifier

Quantum limited parametric amplification is obtained by driving non-linear non-dissipative elements such as Josephson junctions



Current Driven

Parametric amplification achieved by modulating the bias current in the JJ:
$\omega_{pump} \sim \omega_{signal}$ 4 wave mixing



Flux Driven

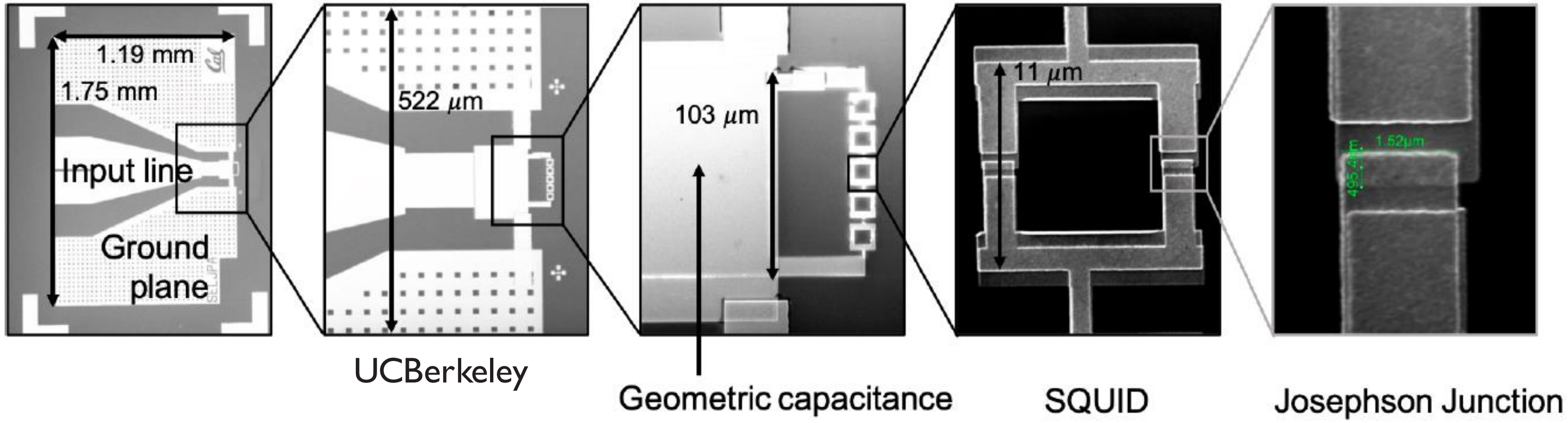
Parametric amplification achieved by modulating the flux in the DC-Squid:
$\omega_{pump} \sim 2\omega_{signal}$ 3 wave mixing

ROY DEVORET PHYSICAL REVIEW B 98, 045405 (2018)

ADMX – JPA

See talk of Yanjie Qiu et al at Workshop on Microwave Cavities and Detectors for Axion Research

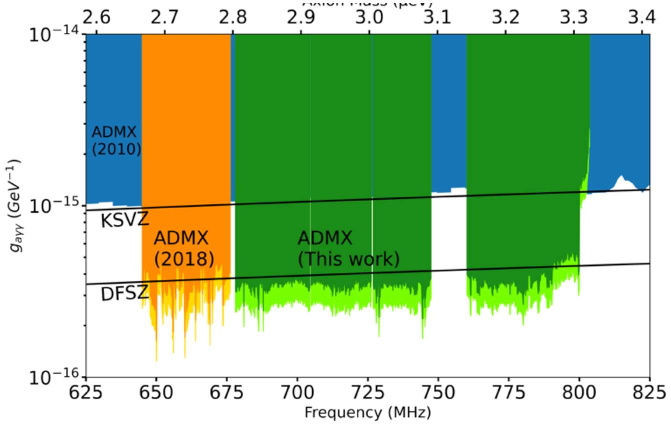
ADMX operates a 4 wave mixing JPA in a phase insensitive mode by pumping with a microwave tone 375 kHz detuned from the cavity resonance.



T_{JPA}	250 mK
mixing	4 wave
Gain	25 dB
BW	5 MHz
Tunability	500 MHz

FERMILAB-PUB-20-331-AD-E-QIS Arxiv:2010.00169

Phys. Rev. Lett. **124**, 101303



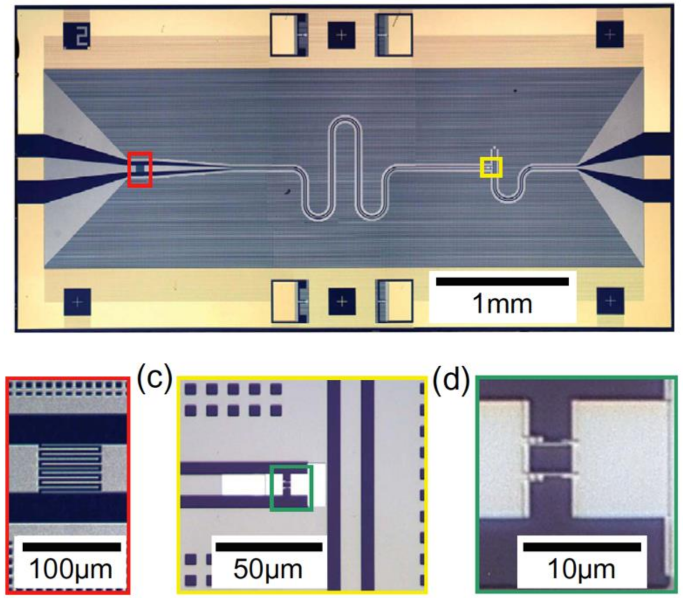
Phys. Rev. D 103, 032002 (2021)

IBS-CAPP – FLUX DRIVEN JPA

3 wave mixing Flux driven JPA

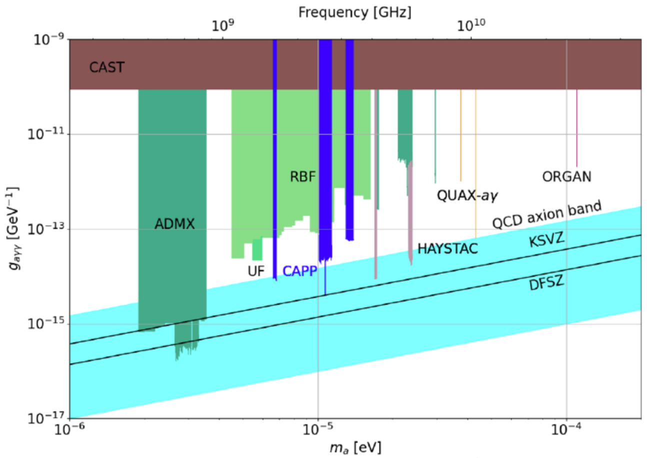
APPLIED PHYSICS LETTERS 93, 042510 2008

L Zhong et al 2013 New J. Phys. 15 125013

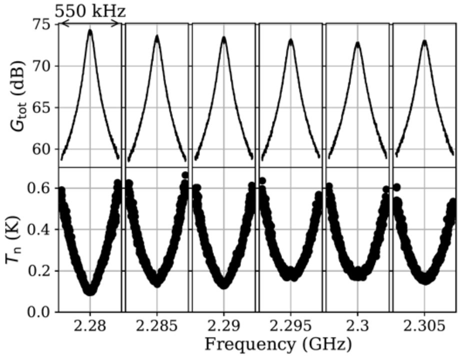


CAPP-MC: For 3.15 - 3.35 GHz, with 9T/125mm PRL 125, 221302 (2020)
CAPP-PACE: For 2.45 - 2.70 GHz, with 8T/125mm arxiv:2012.10764 (2020)
CAPP-8TB: For 1.5 - 1.65 GHz, with 8T/165mm PRL 124, 101802 (2020)
CAPP-12TB: Flagship experiment under development for 1 - 4 GHz with 12T/320mm

T_{noise}	120 mK
mixing	3 wave
Gain	20 dB
BW	100 kHz
Tunability	2.2-2.3 GHz



No JPA yet used here



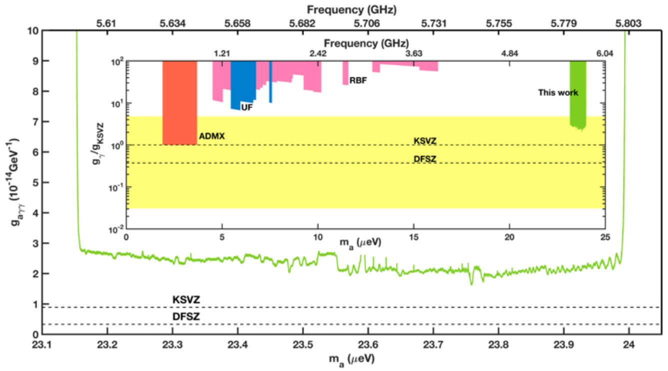
Full chain gain and noise

Characterization of device at CAPP in arXiv:2101.08496

HAYSTAC – 20 SQUID JPA

JPA with series of 20 SQUID in Nb/AlOx/Nb
6.5 GHz max frequency
By applying a DC flux through the SQUID loops, the resonant frequency can be tuned over several gigahertz. System driven near resonance with strong pump.

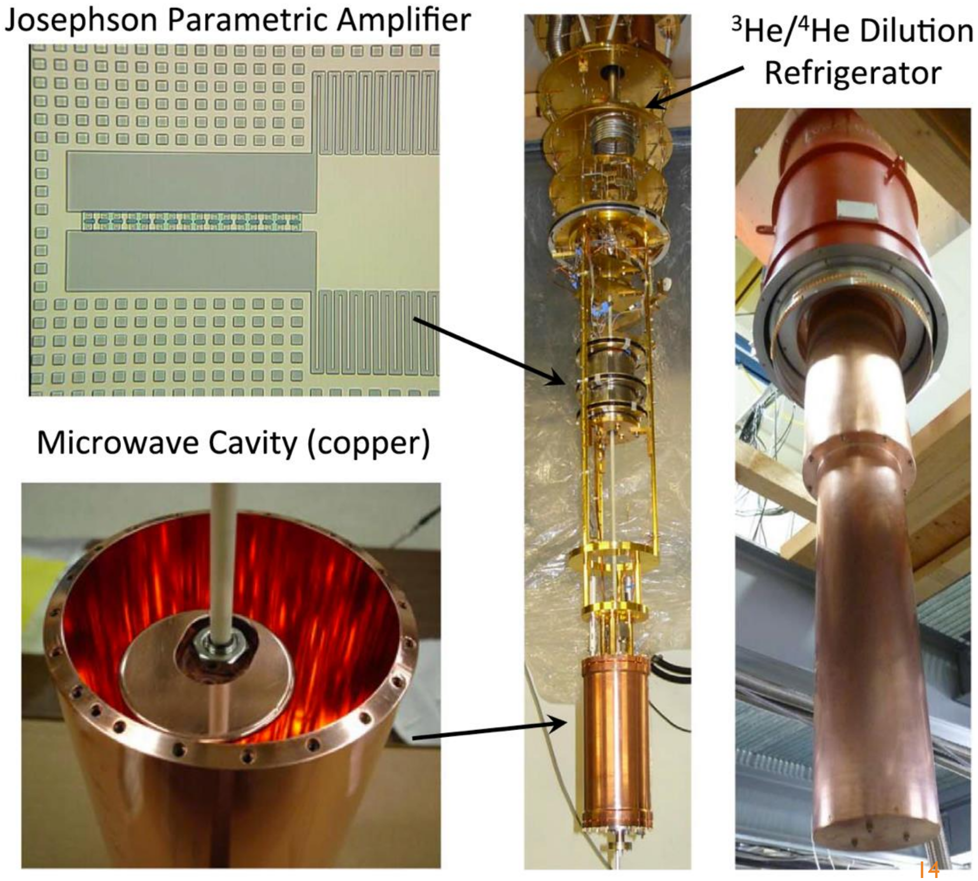
APPLIED PHYSICS LETTERS 91, 083509 2007



PHYSICAL REVIEW D 97, 092001 (2018)

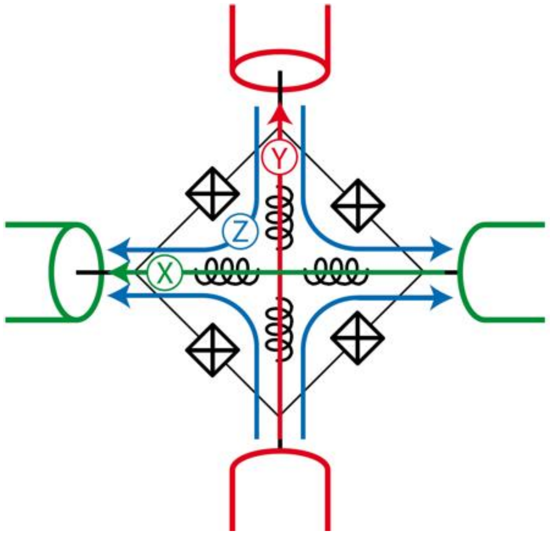
T_{noise}	1.5 hν
mixing	4 wave
Gain	21 dB
BW	2.3 MHz
Tunability	2 GHz

HAYSTAC
Yale University
5.6 GHz frequency
9 T magnet
Tcavity 130 mK

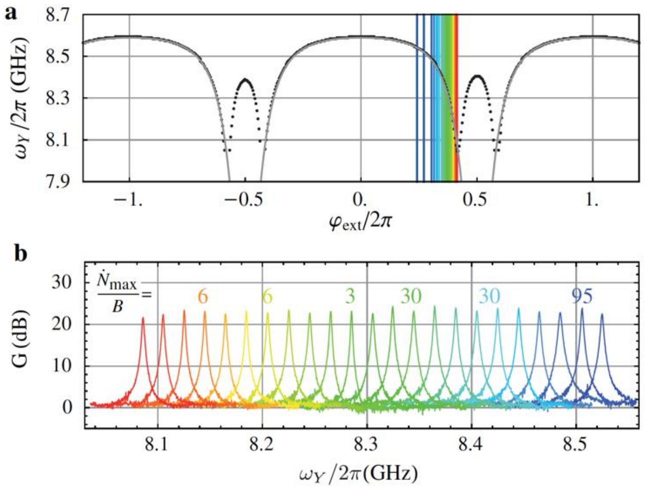


Nuclear Instruments and Methods in Physics Research A 854 (2017) 11–24

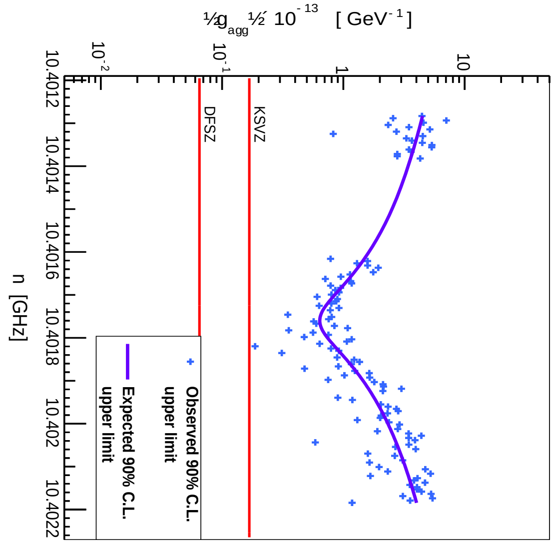
QUAX – RING JPA



N Roch et al. PRL 108, 147701 (2012)



T_{noise}	0.5-1 hν
mixing	3 wave
Gain	21 dB
BW	10 MHz
Tunability	0.5 GHz



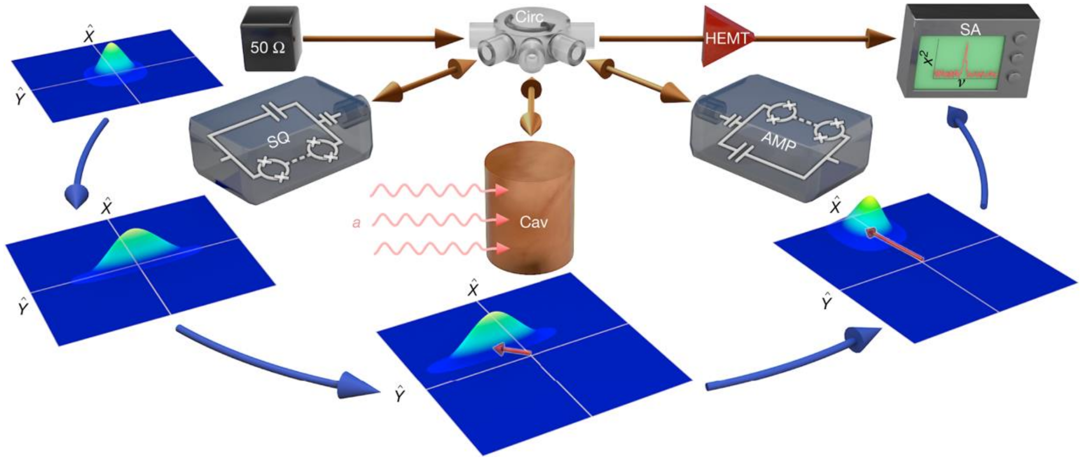
QUAX
INFN Italy
10.4 GHz
Tcavity 100 mK
B 8 Tesla
JPA added noise 0.5-1 hf

PHYSICAL REVIEW LETTERS 124, 171801 (2020)

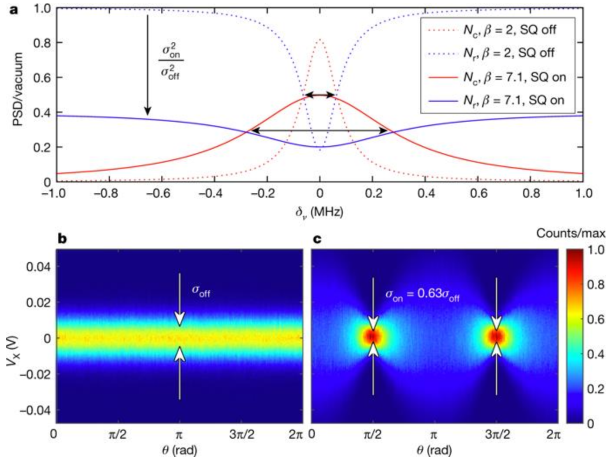
arXiv:2012.09498v1

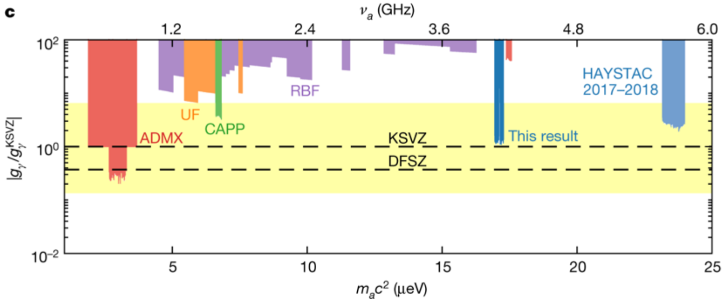
HAYSTAC – A Squeezed State Receiver With JPA

50 ohm noise T 60 mK



Backes *et al.* A quantum enhanced search for dark matter axions. *Nature* **590,** 238–242 (2021).



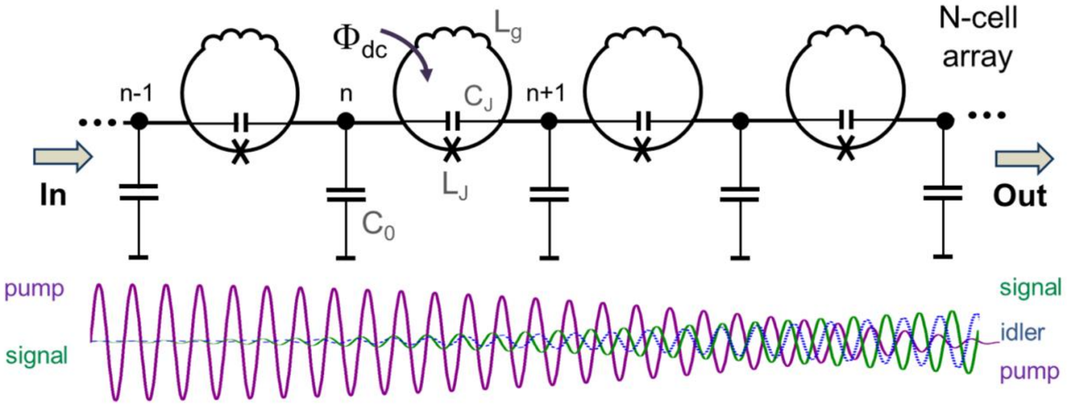


1. JPA operated as phase sensitive amplifier
2. Amplify Y quadrature and squeeze along X
3. $P_X^{out} = (n_T+1/2)/G\,|S_{11}|^2 + (n_T+1/2 + n_{Axion})|X(w)|^2$
4. Squeeze along Y and amplify along X
5. Scan rate increases by a factor 2 thanks to lower noise/larger bandwith

TRAVELING WAVE JPA

Traveling Wave Josephson Parametric Amplifiers amplify microwave signal over a broad range adding the minimum noise set by quantum mechanics. Devices are both 3-wave and 4-wave mixing.

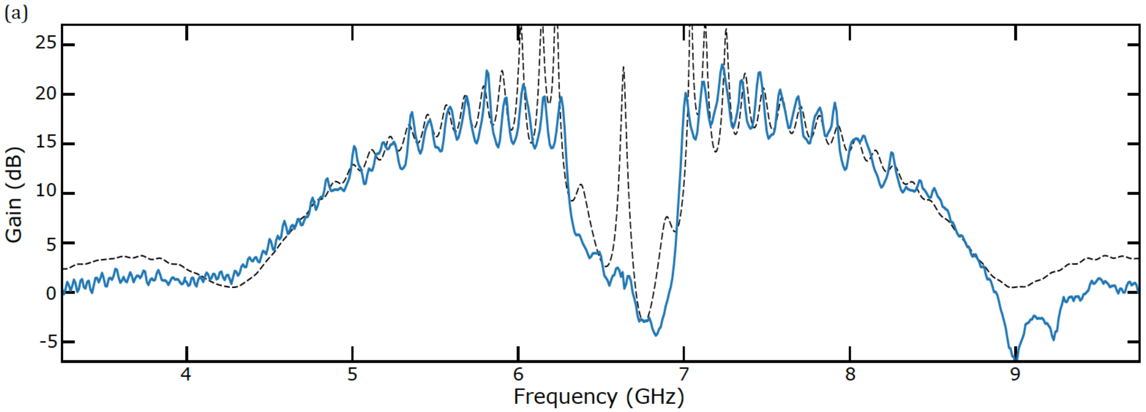
3-wave mixing device



arXiv:1602.02650

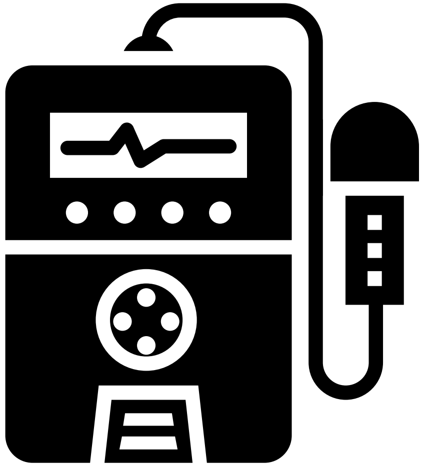
PHYS. REV. APPLIED 12, 044051 (2019)

4-wave mixing device



arXiv:1907.10158

DART WARS Detector Array Readout with Traveling Wave AmplifieRS (See A.Giachero's talk)



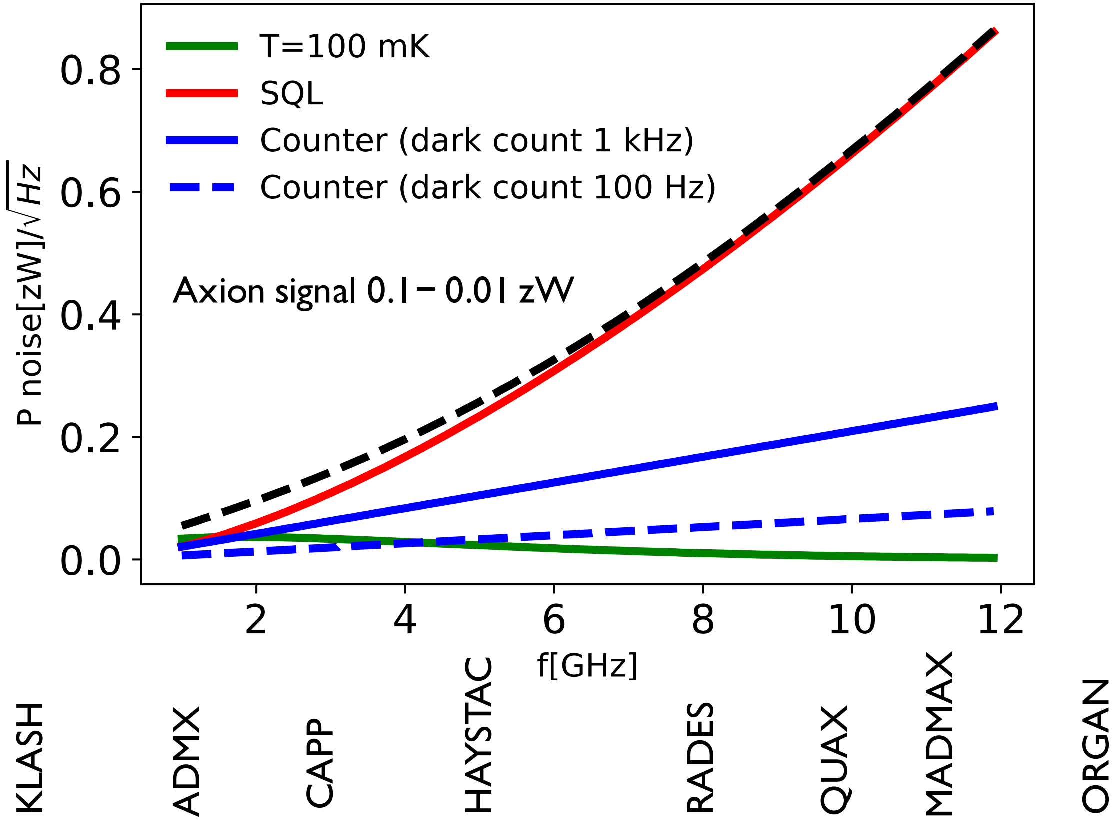
Created by Vectors Point

Photon Counters

Noise In Haloscopes

Scan rate

$$\frac{df}{dt} \propto \frac{B^4V^2Q_L}{\boxed{T^2_{sys}}}$$



Quantum limited amplifiers

$$\hbar\omega\sqrt{\Delta\nu_a}$$

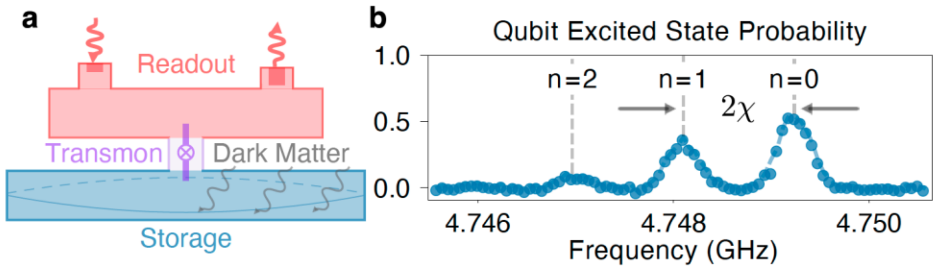
Photon counters

$$\hbar\omega\sqrt{\Delta\nu_{dark}}$$

Thermal noise

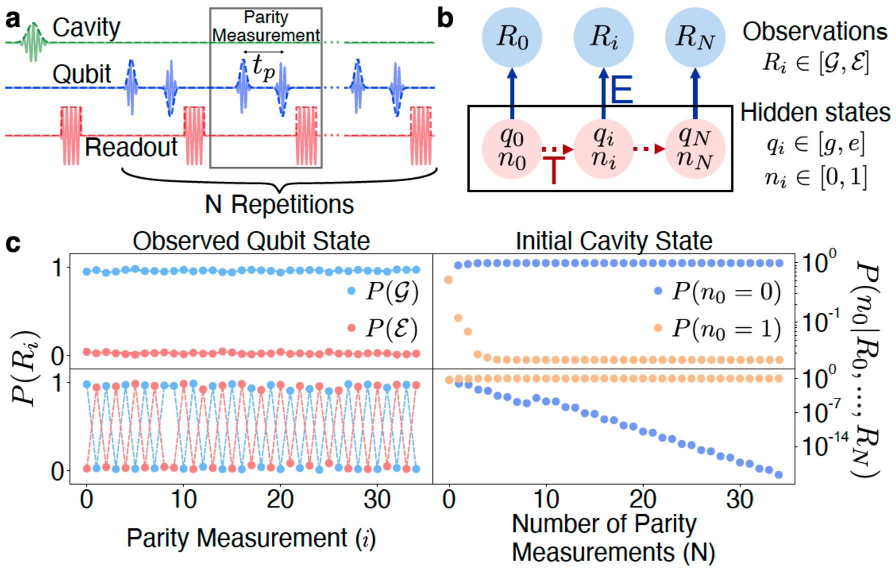
$$n_{th}\sqrt{\Delta\nu_a}$$

Searching DM Dark Photons with SC Qubit



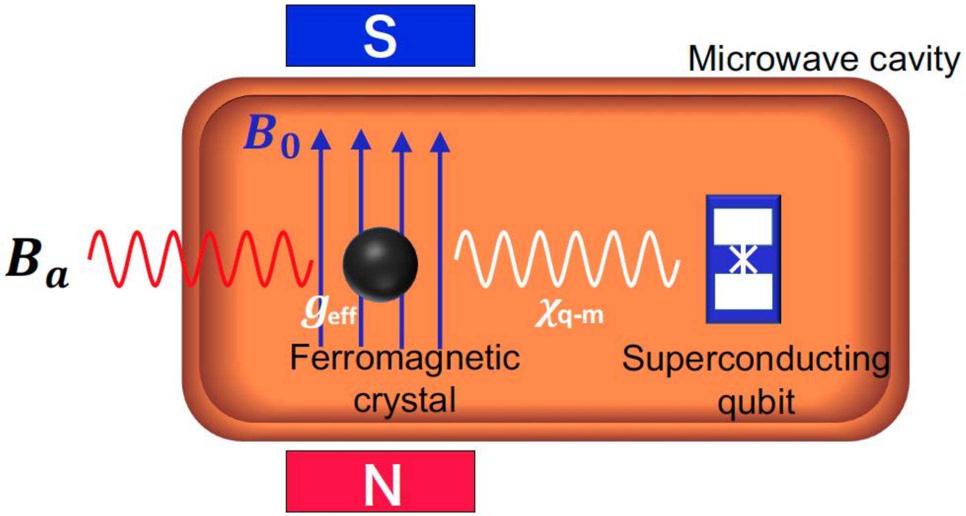
a. Storage and readout cavities bridged by a transmon qubit
b. Storage cavity population is imprinted as a shift of the qubit transition frequency

- Cavity number parity measurement with Ramsey interferometry
- High quality-factor and QND nature of measurement allow 30 repeated measurements and averaging-out of readout errors



Dixit et al arXiv:2008.12231

Axion Search With Quantum Non-demolition Detection Of Magnons



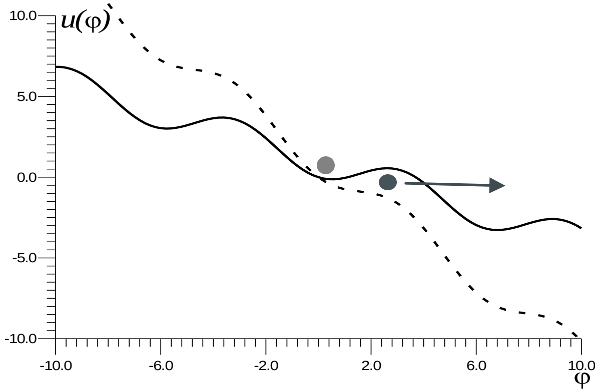
- Prototype detector of a ferromagnetic sphere and a superconducting qubit
- Axion couple to electron spins in ferromagnetic sphere
- Effective qubit-magnon coupling through cavity modes
- Strong dispersive regime ($\chi \gg \gamma$)
- Magnon occupancy number mapped into qubit spectrum S(ω)
- Sensitivity 10^{-3} magnons/sqrt(Hz)

Tomonori Ikeda et al arXiv:2102.08764

S. P. Wolski et al. Phys. Rev. Lett. **125**, 117701

MORE COUNTERS …

Single photon counter based on current biased JJ



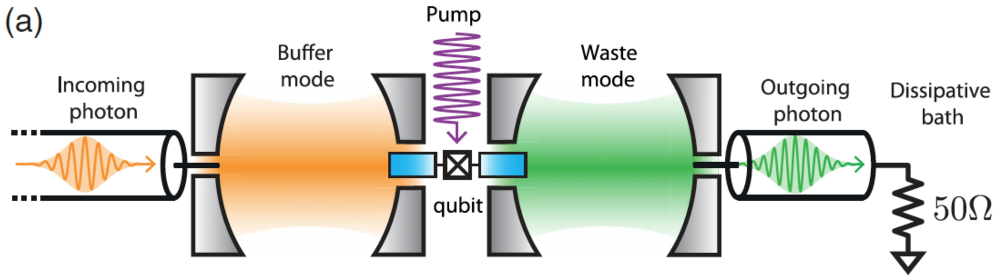
Can potentially reach mHz dark count

L. S. Kuzmin et al in IEEE Transactions on Applied Superconductivity, vol. 28, no. 7, pp. 1-5, Oct. 2018, Art no. 2400505.

Revin et al. Nanotechnol. 2020, 11, 960–965. doi:10.3762/bjnano.11.80

See A. Rettaroli's talk

Irreversible Qubit-Photon Coupling for the Detection of Itinerant Microwave Photons



Reflection of itinerant photon avoided by irreversible absorption with a SC qubit
Reached dark counts below 1 kHz

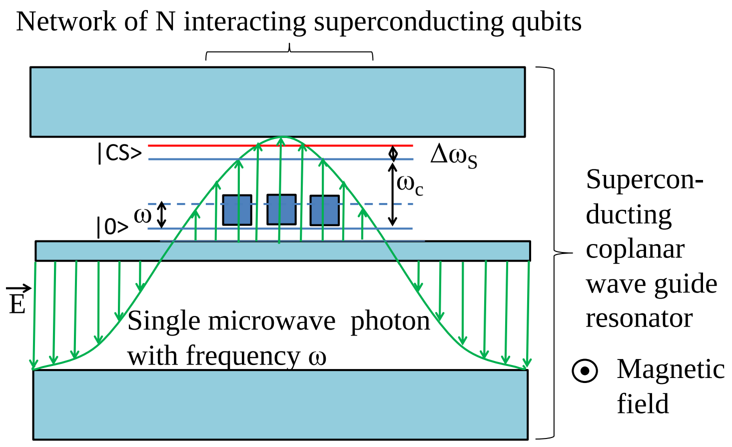
PHYS. REV. X 10, 021038 (2020)

arXiv:2102.01415

SUPERGALAX

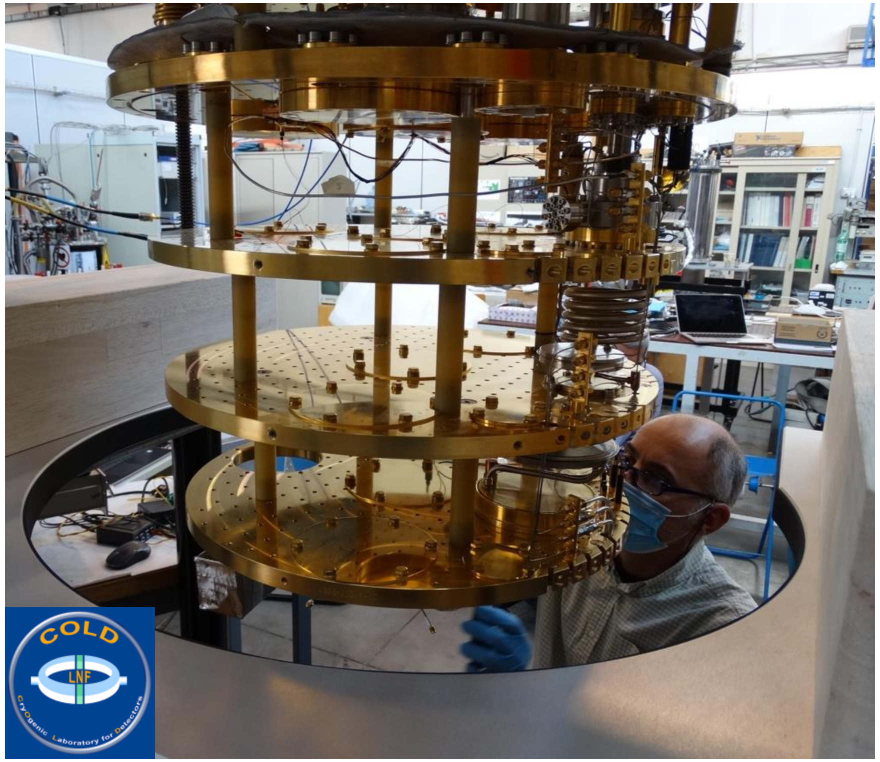
FET OPEN SUPERGALAX
CNR (IT, PI, exp)
INRIM (IT, exp)
INFN (IT, axion exp)
KIT (DE, exp)
Leibniz IPHT (DE, exp)
RUB (DE theory)
LU (UK, theory)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863313. Grant amount 2 456 232.50 Euro.



Develop a single microwave photon detector for axion search in QUAX experiment with an array of SC qubits.

https://supergalax.eu



Conclusion

- The last decade witnessed an increasing interest in axion and axion-like particles with many theoretical works published and many new experimental proposals.
- A major challenge for cosmological-axion discovery is the detection of the faint signals with power as low as a fraction of yoctowatt corresponding to a single microwave photon per minute.
- Microstrip SQUID Amplifiers were operated up to few GHz with a noise temperature close to the standard quantum limit. Josephson Parametric Amplifiers have been recently employed extending the search to higher frequencies while broadband Traveling Wave Parametric Amplifiers are now under study.
- But the ultimate sensitivity, beyond the quantum limit, is however expected from single microwave-photon detectors.