Josephson Parametric Amplifiers for Axion Search Experiments in CAPP

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For PCS meeting 2021-10-25

OUTLINE

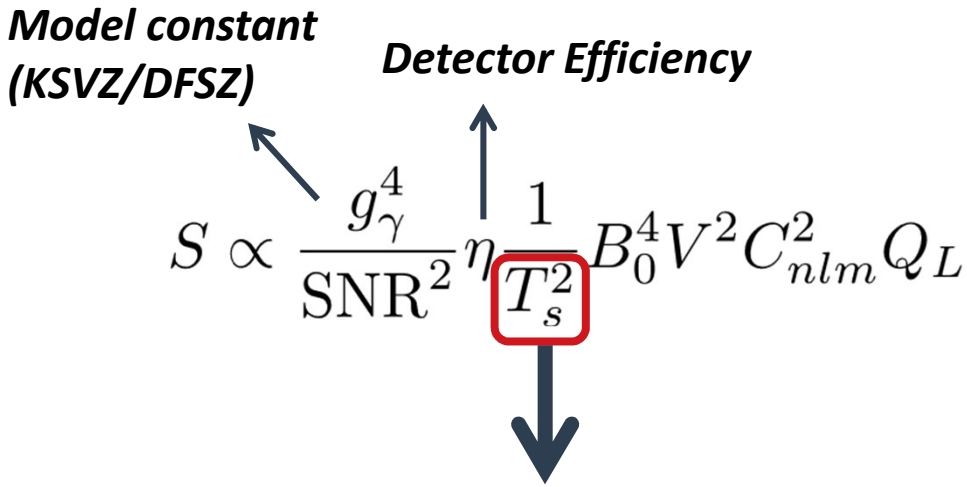
- *Axion search with Haloscopes*
- *JPA in CAPP*
- *JPA in CAPP Experiments*
- *Summary*

Haloscope Scan Rate

Increasing scan rate

The mass is unknown, so we have to scan.

The scan rate, i.e. the rate at which we can cover a range in axion mass parameter space:

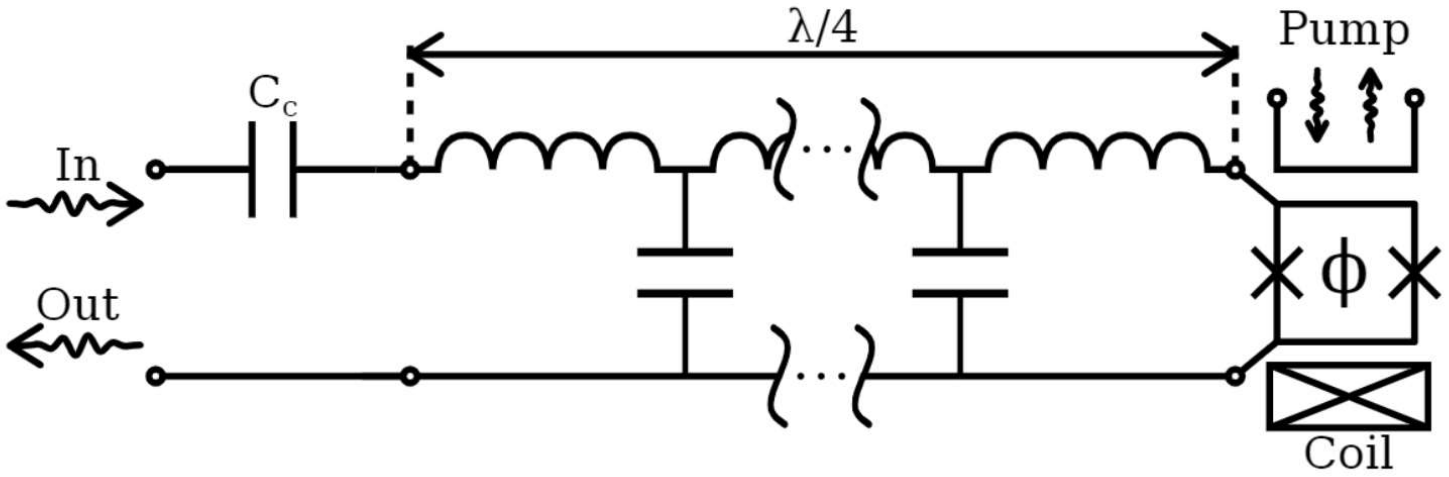


Lower T_s → Quantum limited amplifiers → flux driven JPAs

Flux-driven JPA in CAPP

Started: May, 2019

Flux-driven Josephson Parametric Amplifiers (JPA)



The nonlinear current-dependent inductance of a Josephson junction

Inductance of a SQUID depends from flux bias Φ $I_C = I_{C0}cos(\pi\Phi/\Phi_0)$

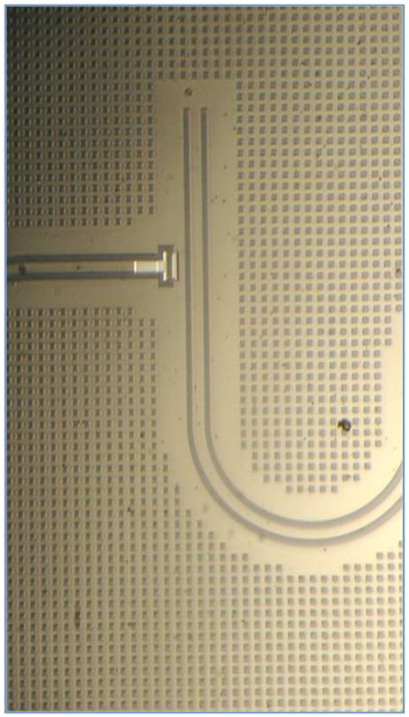
- amplification

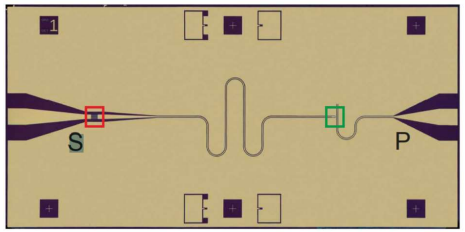
- frequency adjustment

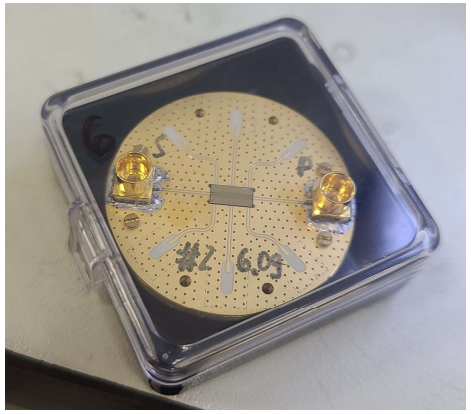
$$L(I) = L_0\left[1 + \frac{1}{2}\frac{I^2}{I_c^2}\right], L_0 = \frac{\Phi_0}{2\pi I_c}$$

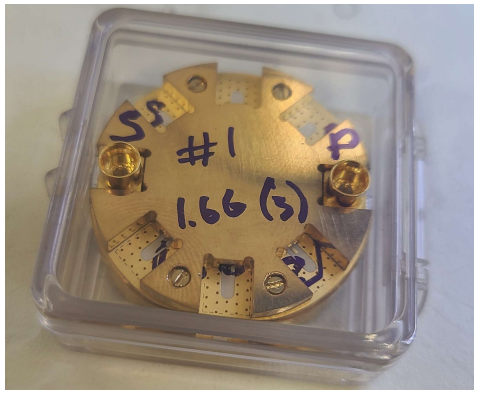
Ic –critical current of the SQUID,
Φ0 – flux quantum, 2.069·10^{-15} Wb
I – dc persistent current, created by dc flux

JPAs: Collaboration with University of Tokyo and RIKEN





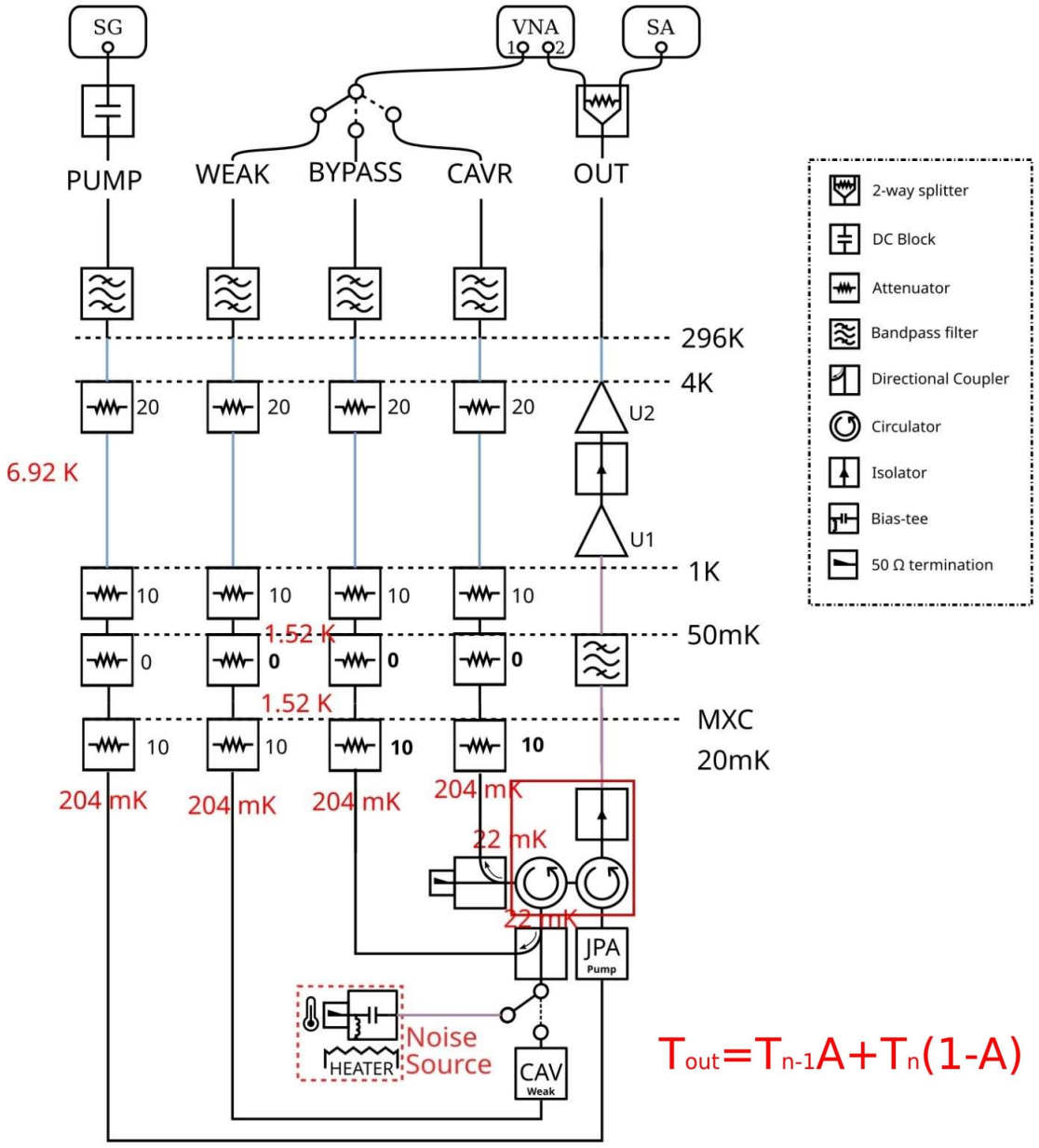




JPA Read-Out Setup for Test and Measurements

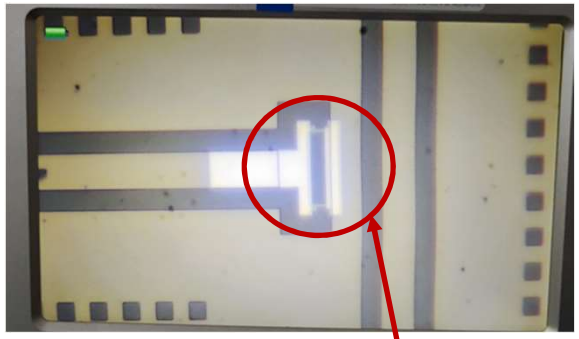
- ***Test:***
  - ***Tuning frequency range***
  - ***Gain***
  - ***Instant bandwidth***
  - ***Noise temperature***

- ***Experiment:***
  - ***Cavity test***
  - ***JPA test***
  - ***Run experiment***

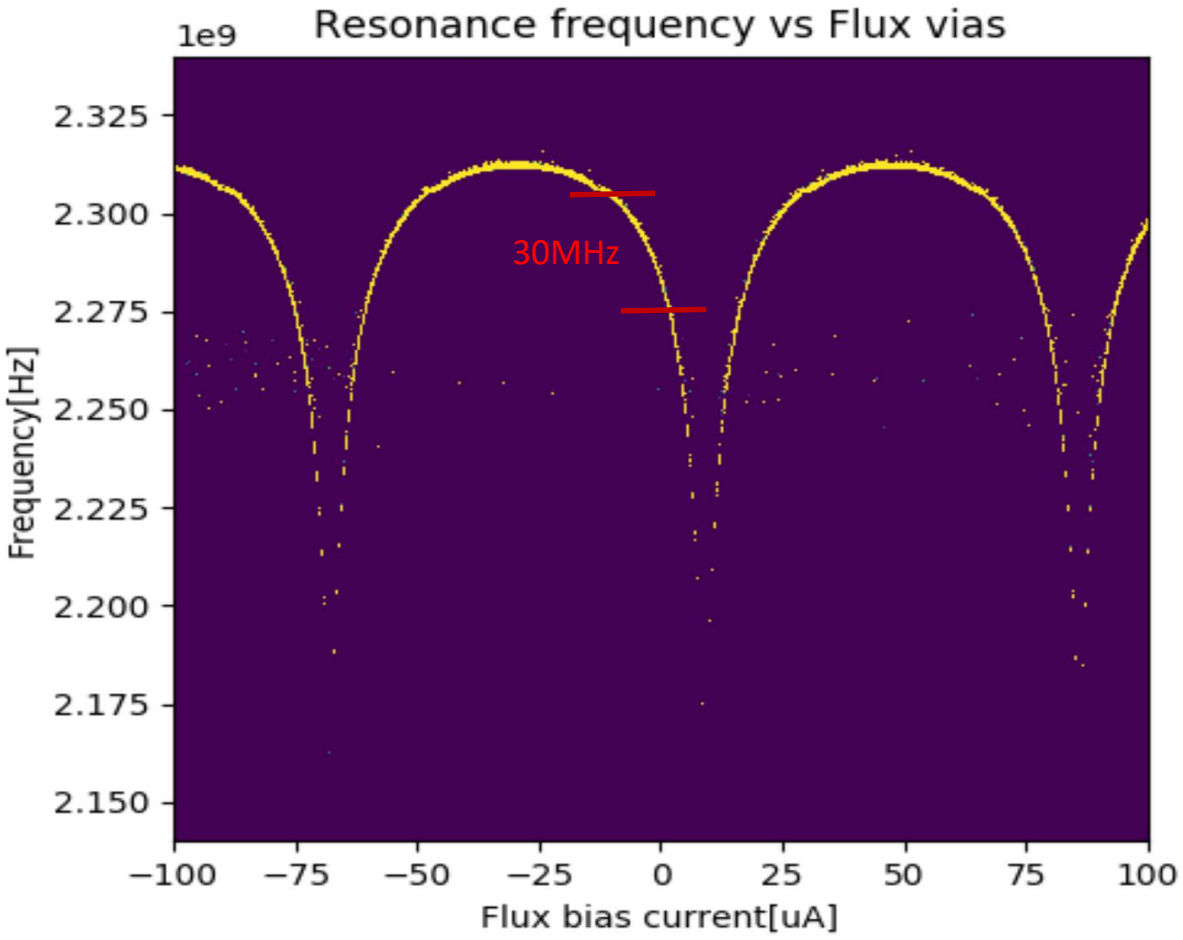


$T_{out}=T_{n-1}A+T_n(1-A)$

2.3 GHz JPA Resonance Frequency vs. Bias Flux

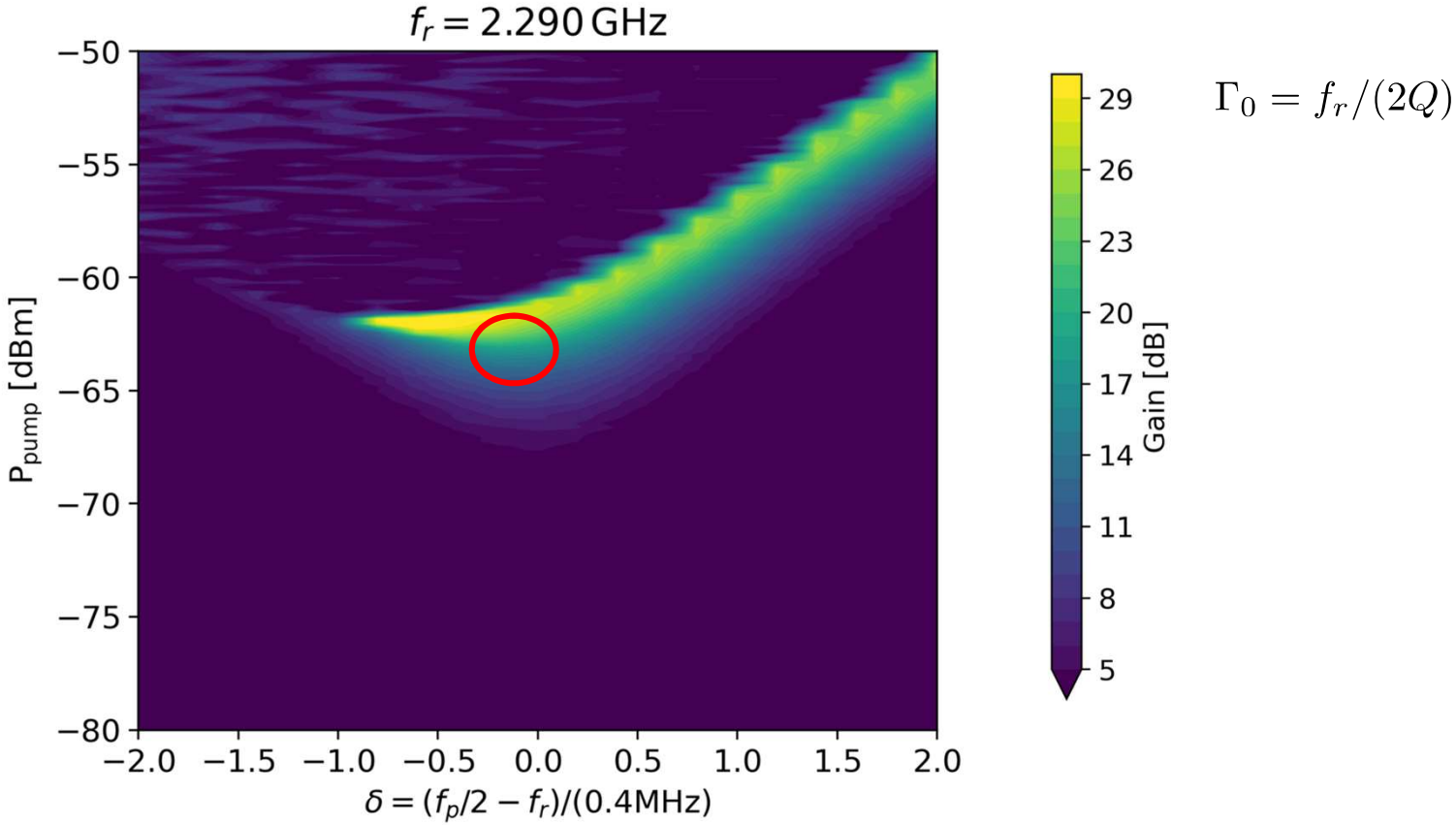


Apply flux into SQUID loop to get operating range about 30 MHz



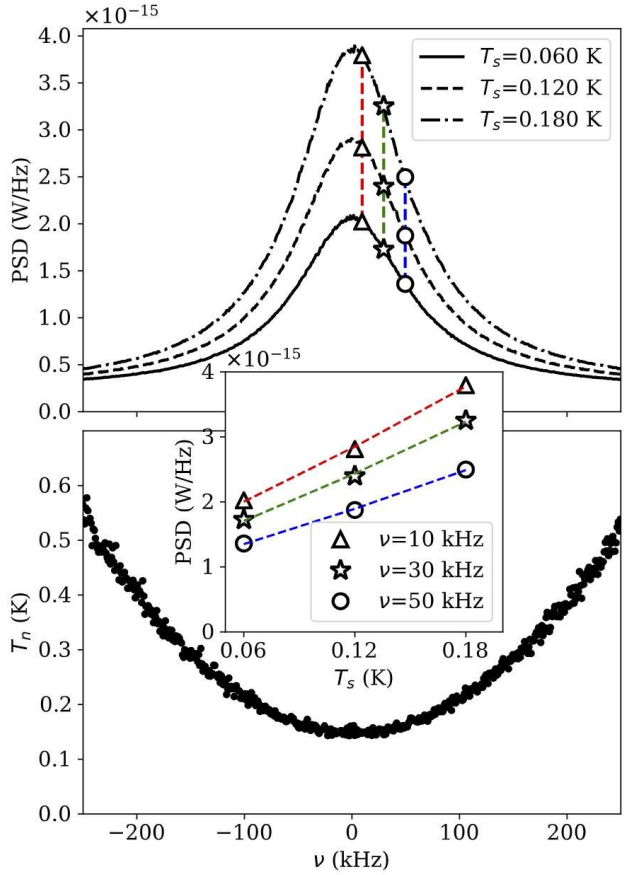
2.3 GHz JPA Operation: Gain

- ***Fix f_r***
- ***Sweep pump power (P_p)***
- ***Sweep pump frequency via:*** $\delta = (1/\Gamma_0)\left(\frac{f_p}{2} - f_r\right)$



$\Gamma_0 = f_r/(2Q)$

Results of noise measurements, 2.3GHz



Quantum limit for amplifier added noise for 2.3 GHz:

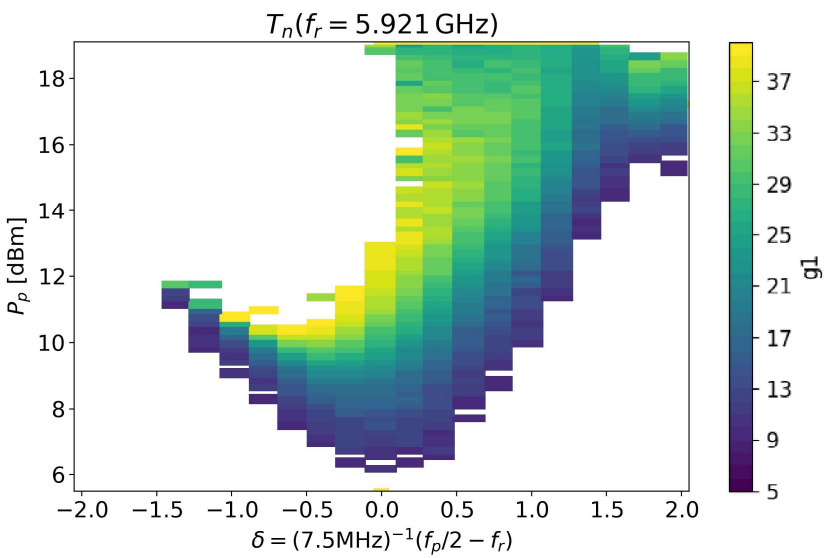
$$T_N = \frac{\hbar\omega}{2kB} = 55\ mK$$

Measured added noise of JPA: 120 mK

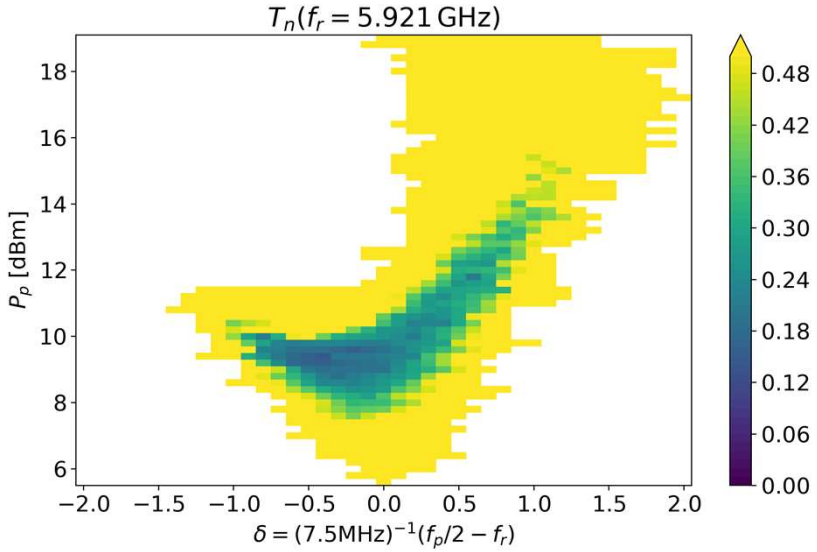
Çağlar Kutlu, Arjan F van Loo, Sergey V Uchaikin, Andrei N Matlashov, Doyu Lee, Seonjeong Oh, Jinsu Kim, Woohyun Chung, Yasunobu Nakamura and Yannis K Semertzidis. 2021 Supercond. Sci. Technol. 34 085013
Jinsu Kim et al. Will be published.

JPA 6 GHZ: choice of operation point: Minimal noise

Gain map



Noise map



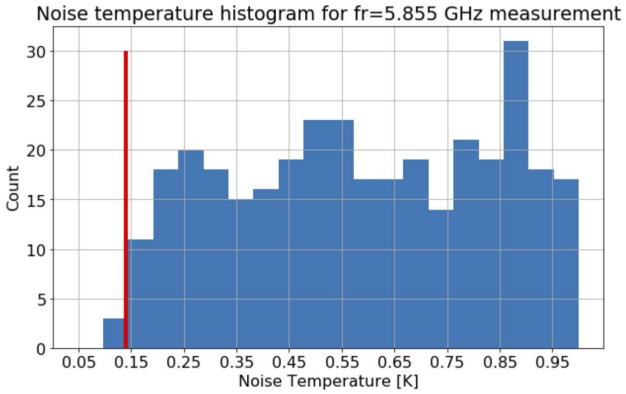
Working point corresponds to minimal noise temperature. Gain at working point about 15-20 dB

Quantum limit for amplifier added noise for 6 GHz – 139mK:

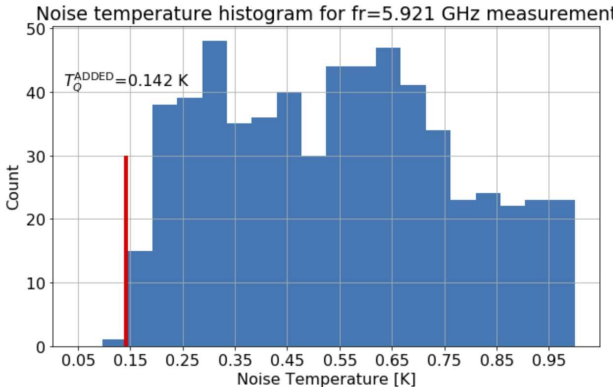
Measured added noise:

About 150 mK or 1.07 of $\frac{\hbar\omega}{2kB}$

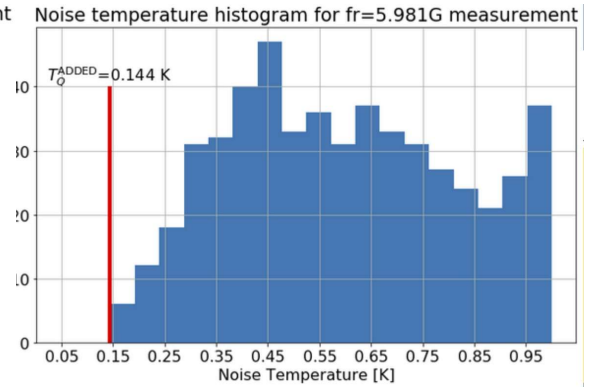
JPA 6 GHZ: choice of operation point: Frequency Dependence



5.855 GHz



5.921 GHz



5.981 GHz

JPA characteristics

20 working JPAs for range of 0.98-1.3, 2.1-2.4 and 5-6.1 GHz

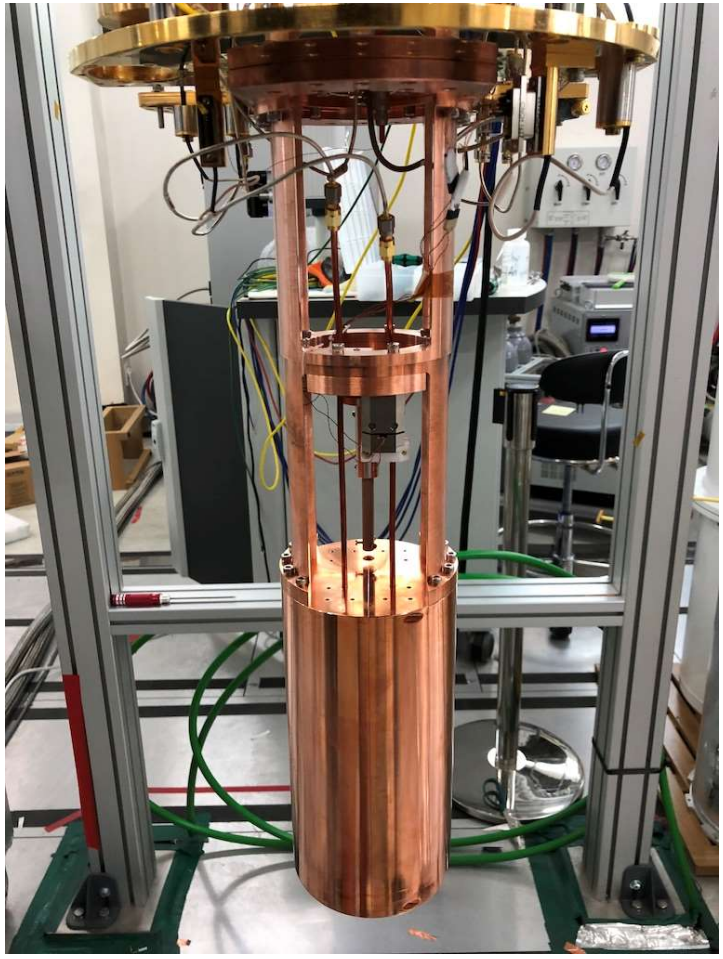
JPA	2010-1.05G	2010-1.1G	2010-1.2G	1910-1.6G	2010-2.25G	1904-2.4G	1910-2.5G	1910-6.09G	1910-7G
Frequency Low-High (GHz)	0.98 – 1.018	1.07-1.12	1.13-1.165	1.74-1.83	2.06-2.157	2.27-2.31	2.30-2.45	5.1- 5.4	5.5-6.0
T_N (mK)	100	100	95	250	150	120	130	145	150
$hf/(2k_B)$	24	26	28	43	50	55	58	127	139
$T_N/(hf/(2k_B))$	4.2	3.8	3.4	5.8	3	2.1	2.24	1.14	1.07
BW (kHz)	>100	>100	>100	~30	>100	~100	~100	>200	>200

Physical temperature of JPA 30mK

JPA in CAPP experiments

2.3 GHz JPA in PACE experiment (done)

- *1.12 liter copper cavity*
- *Sapphire adjustment rod*
- *8 T magnet*
- *Double superconducting shield*
- *~50 mK MXC temperature*



2.3 GHz JPA results (2020)

- *JPA shows near quantum limit noise (120-150 mK added noise)*
- *System show very low system noise, down to 1.7 SQL (185 mK)*
- *~ 2 runs with about 2.3 KSVZ sensitivity*
- *7.5 times speed improvement compare with HEMT run*
- *Experience is the most important result*
- *Will be published this year*

Protection from magnet field

JPA Operation: Assembled JPA magnetic shield



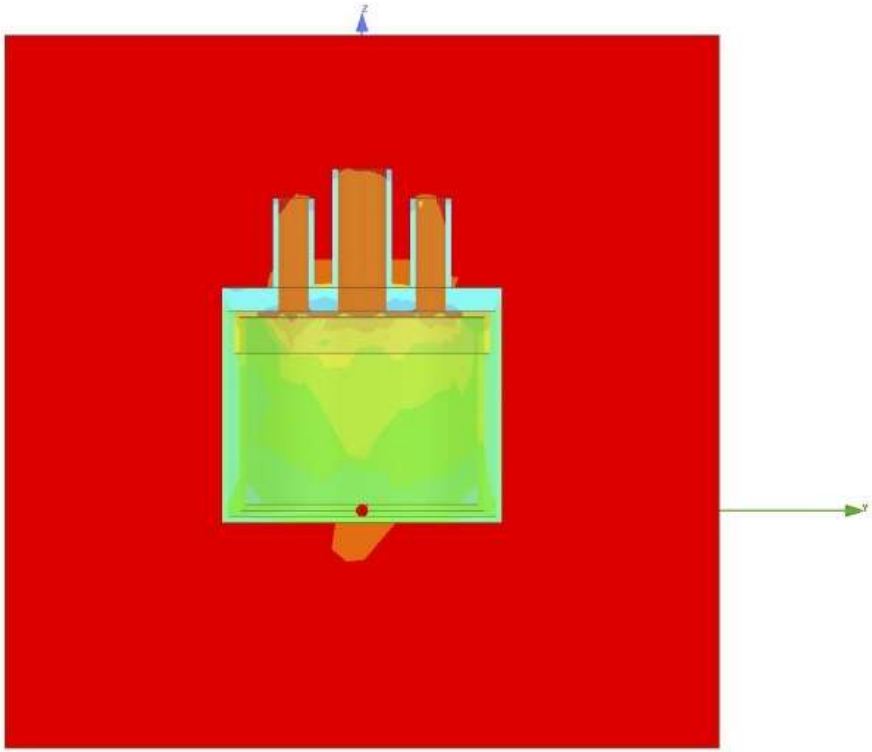
3 layer shield:

1) *NbTi shield, up to 0.1 T*
2) *Mu-metal shield*
3) *Al SC shield*

Magnet field change: 0-8 T
Shift of SQUID working point <0.01Φ_0

Stable operation of the JPA during a few weeks

Shield simulation



Component shielding



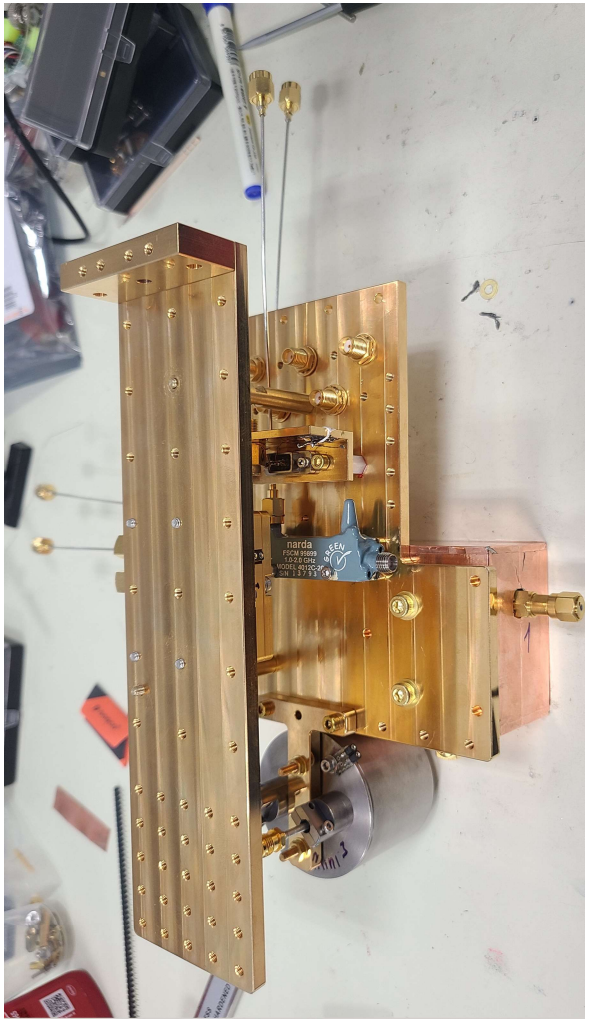
Switches, circulator

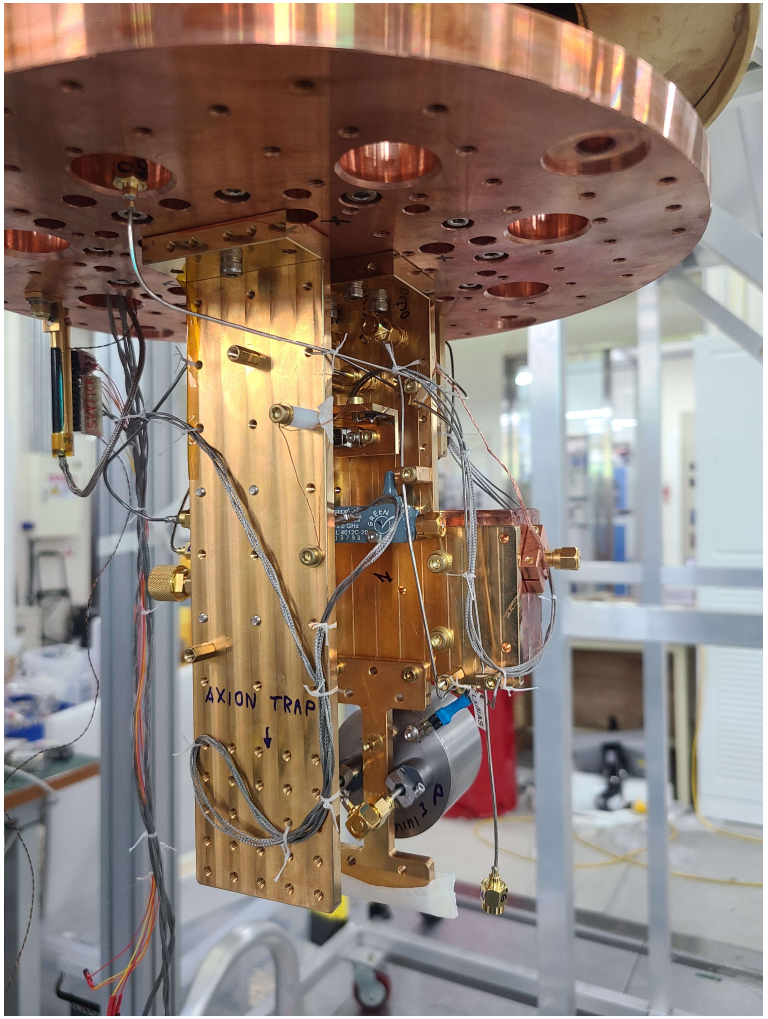
Up to 0.1 T

1-1.2 GHz experiment

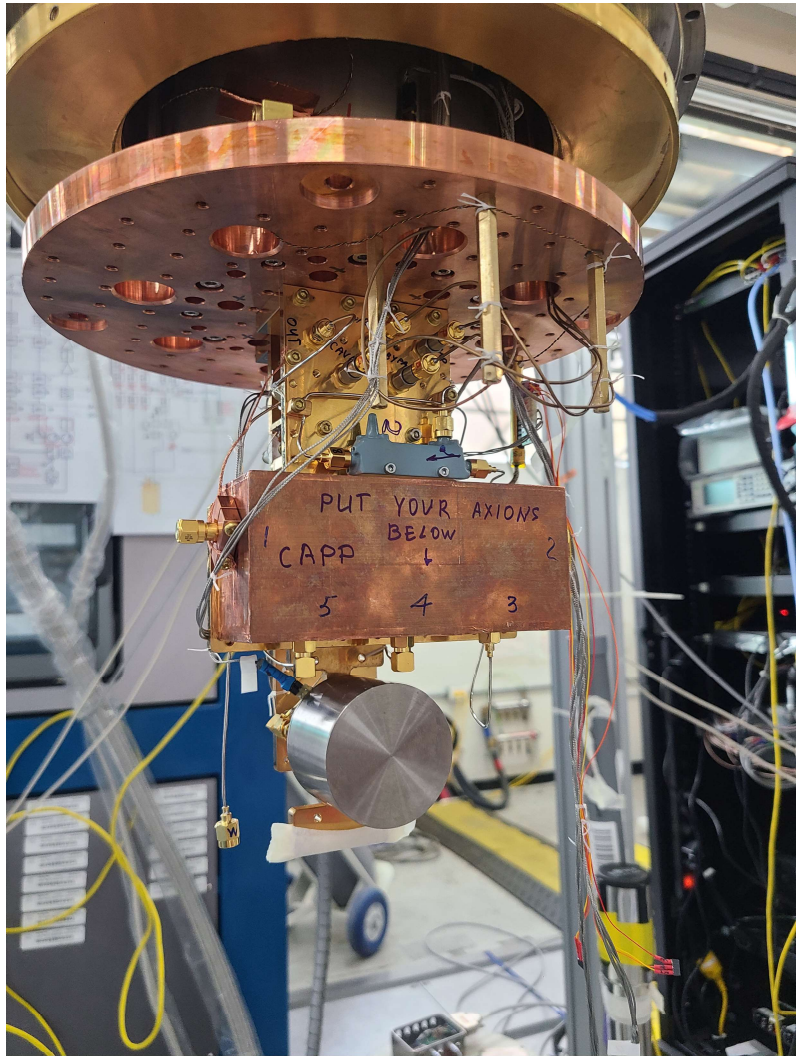
Haloscope based on 1-1.2 GHz cavity (Leiden wet fridge)

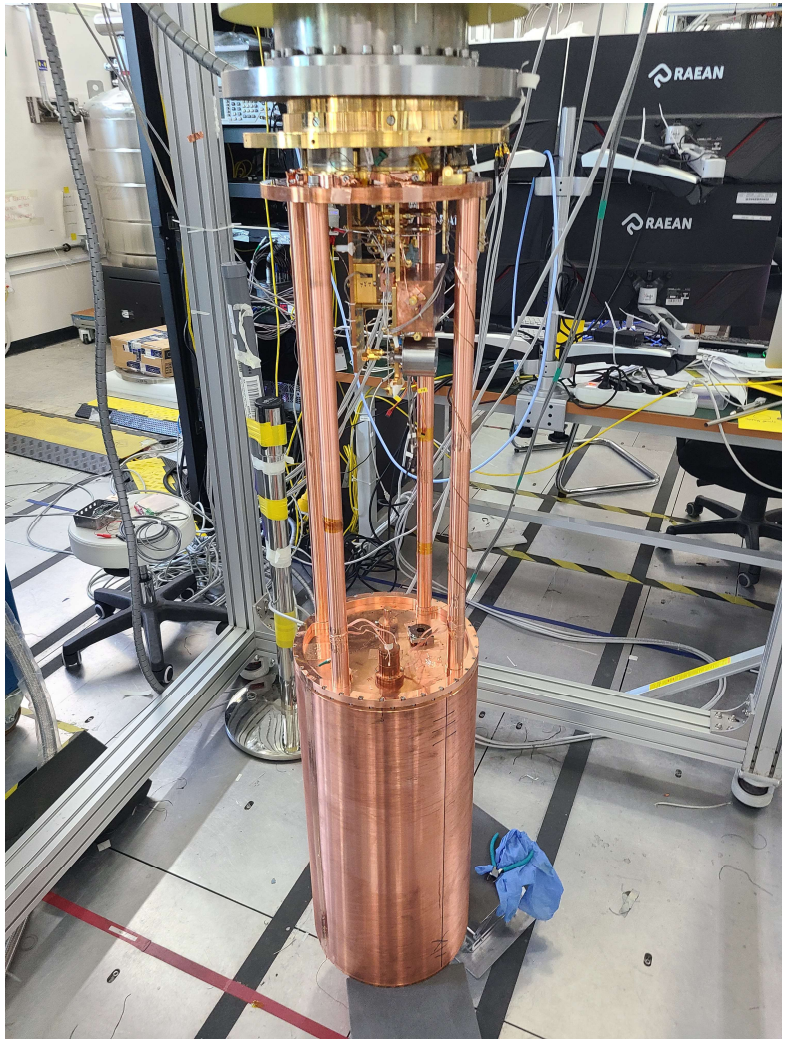
- Modular design



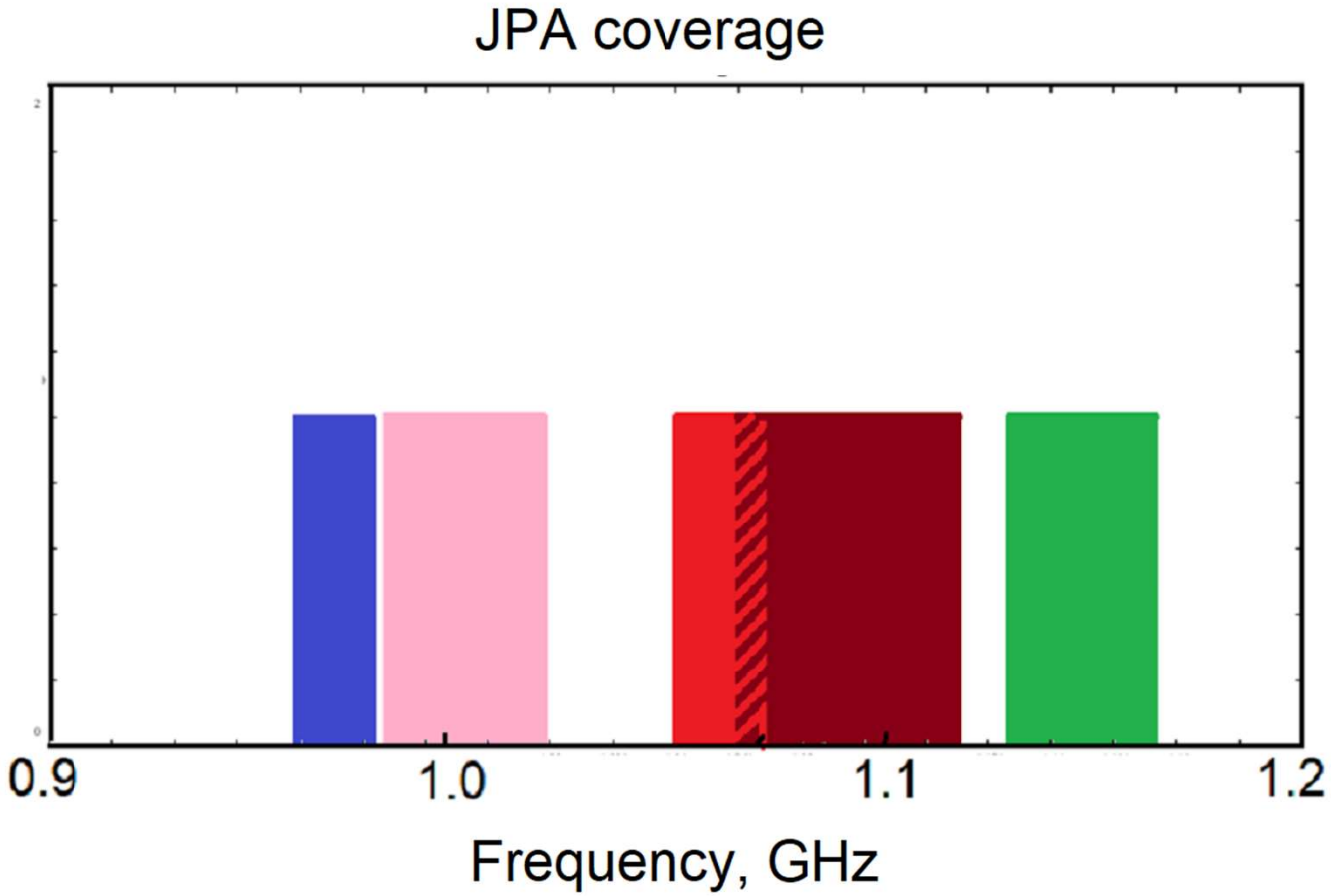


Haloscope based on 1-2 GHz cavity (Leiden wet fridge)



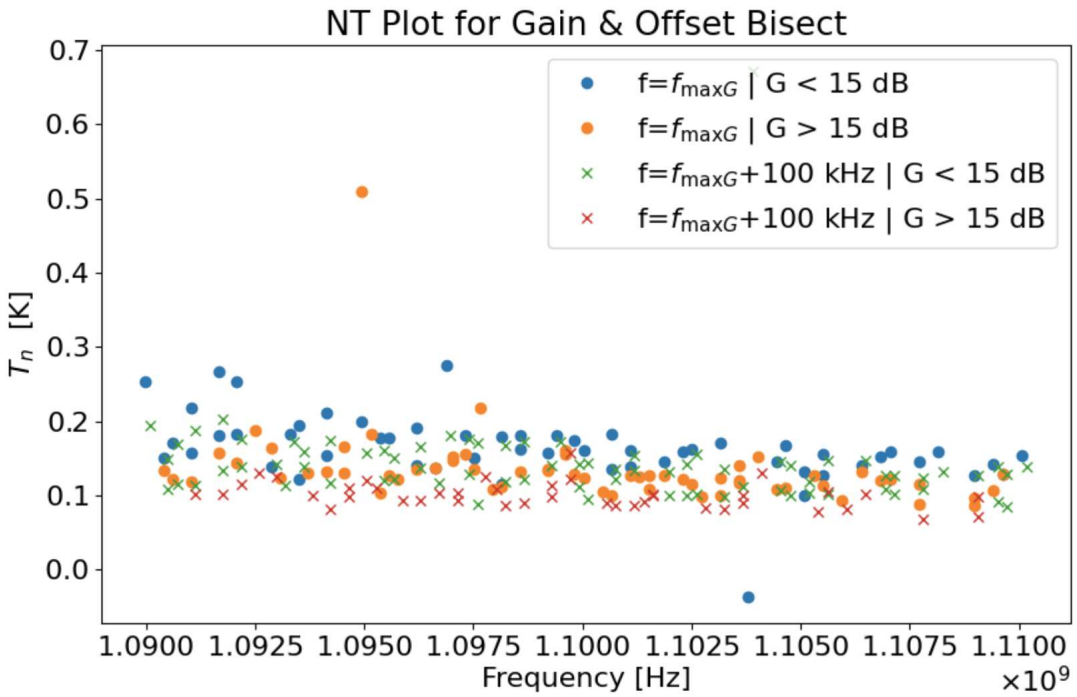


JPA coverage for 12T experiment



8 JPAs tested

1.09-1.11 GHz range



50 MHz JPA tuning range, at the fist experiment will use 20 MHz

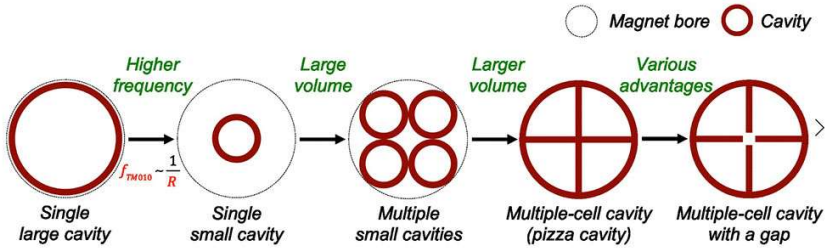
SQL for added noise 24 mK @ 1 GHz

Noise 80-100 mK

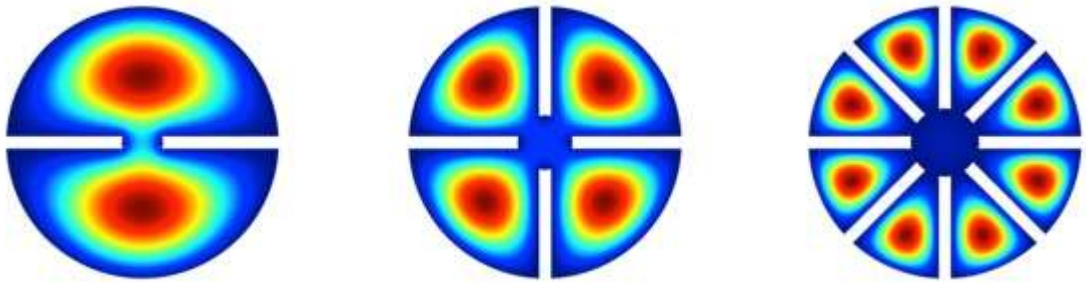
Haloscopes for frequency >2 GHz

Pizza cavity

Increasing volume for high frequency range to use magnet efficiently

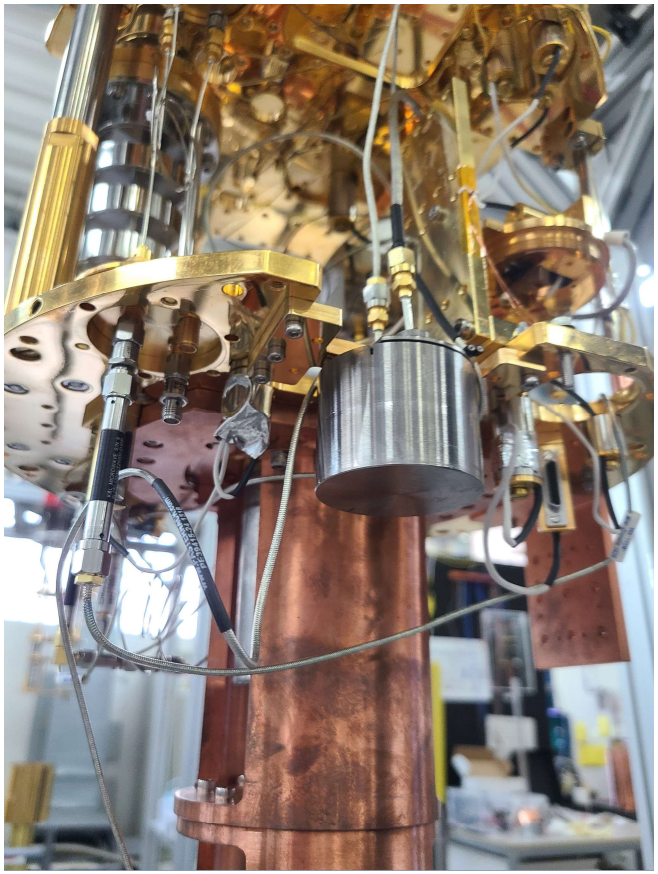


Magnetic field in pizza cavities



Junu Jeong, SungWoo Youn, Sungjae Bae, Jingeun Kim, Taehyeon Seong, Jihn E. Kim, and Yannis K. Semertzidis, Search for invisible axion dark matter with a Multiple-Cell Cavity, Physical Review Letters. DOI: 10.1103/PhysRevLett.125.221302

Haloscope based on 6 GHz 6-cell pizza cavity

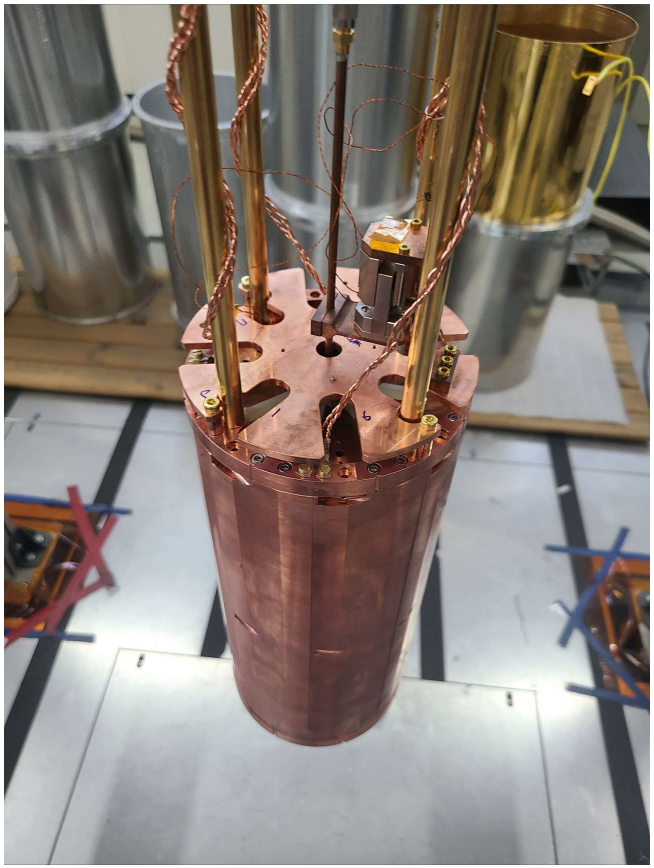




Test measurements started in March, 70MHz scanned

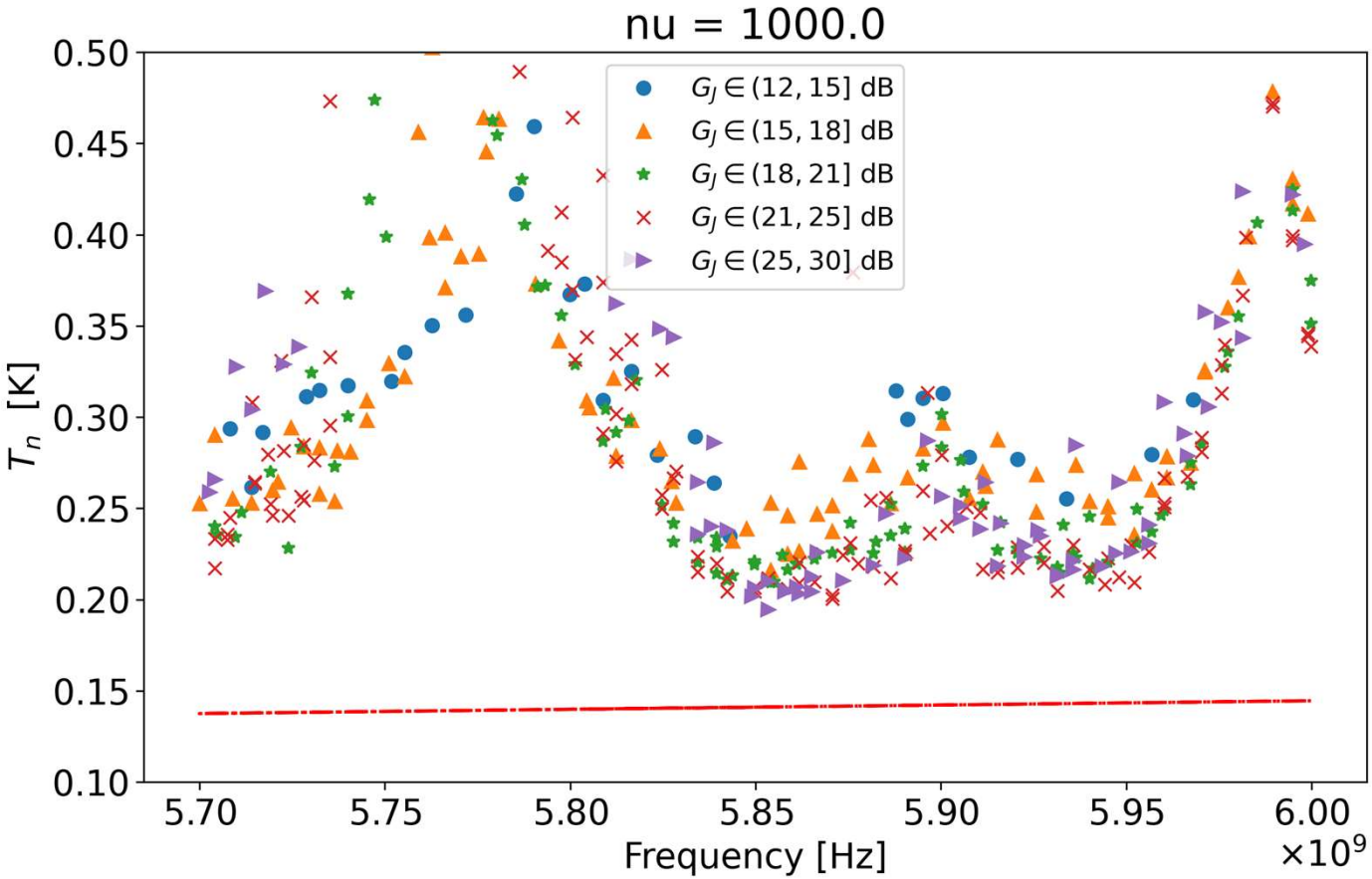
Haloscope based on 6 GHz 8-cell pizza cavity





Plan: start test measurement in the end of August

JPA noise in 8TB



Summary: CAPP experiments with JPAs

- 8T PACE 2.3 GHz, 1.12 l - finished, 30MHz scanned, 2-3KSVZ
- 8T PACE, 5.5-6 GHz 2 l - running, 70 MHz scanned, 3-4KSVZ
- 8TB, 5.5-6 GHz, 3.6 l - start in the end of August
- 12TB PACE, 1-1.2GHz, >37 l - start in the end of August

CAPP JPA/Cavity Team

- *IBS/CAPP: Çağlar Kutlu, Jinsu Kim, Andrei Matlashov, Seonjeong Oh, Jinmyeong Kim, Soohyung Lee, Sungwoo Youn, Woohyun Chung, HeeSu Byun, Saebyeok Ahn, Danho Ahn, Kiwoong Lee, Ohjoon Kwon, Prof. Yannis K. Semertzidis*
- *U.of Tokyo, RIKEN: Arjan van Loo, Yoshiro Urada, Shingo Kono, Prof. Y.Nakamura*

Thank You For Your Attention!