Development of Josephson Parametric Amplifiers for CAPP's Axion Dark Matter Search Experiments

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OUTLINE

- Cryogenic amplifiers for haloscopes
- Josephson Parametric Amplifier (JPA)
- Read-out and test setup
- 2.3 GHz JPA
- 1.8 GHz JPA
- 6 GHz JPA
- Implementation to PACE experiment
- Summary

Scan Rate

- theoretical parameters
- experimental parameters

- **Conversion power ($a \rightarrow \gamma\gamma$)**

$$P_{a\rightarrow\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$$

Coupling constant

Axion number density

Magnetic field

Effective volume

Cavity Q factor

Axion Q factor

- **Signal-to-noise ratio (SNR)**

$$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\rightarrow\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{\text{int}}}{\Delta f_a}}$$

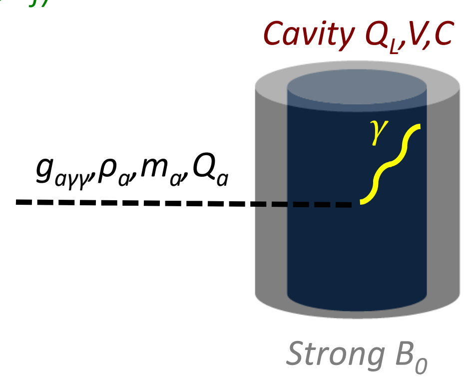
Integration time

Axion bandwidth ($\sim 10^{-6} f$)

System noise temperature

- **Scan rate (F.O.M.)**

$$\frac{df}{dt} = \left(\frac{1}{SNR}\right)^2 \left(\frac{P(f)}{k_B T_{syst}}\right)^2 \cdot \frac{Q_a}{Q_L} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$



Standard quantum limitE

AMPLIFIERS FOR HALOSCOPES

Cryogenic HEMT Amplifiers

Easy to operate: high bandwidth, frequency and temperature stability
Noise high above quantum limit 0.9-3.6 K for 0.6 -10 GHz
heat dissipation >10 mW

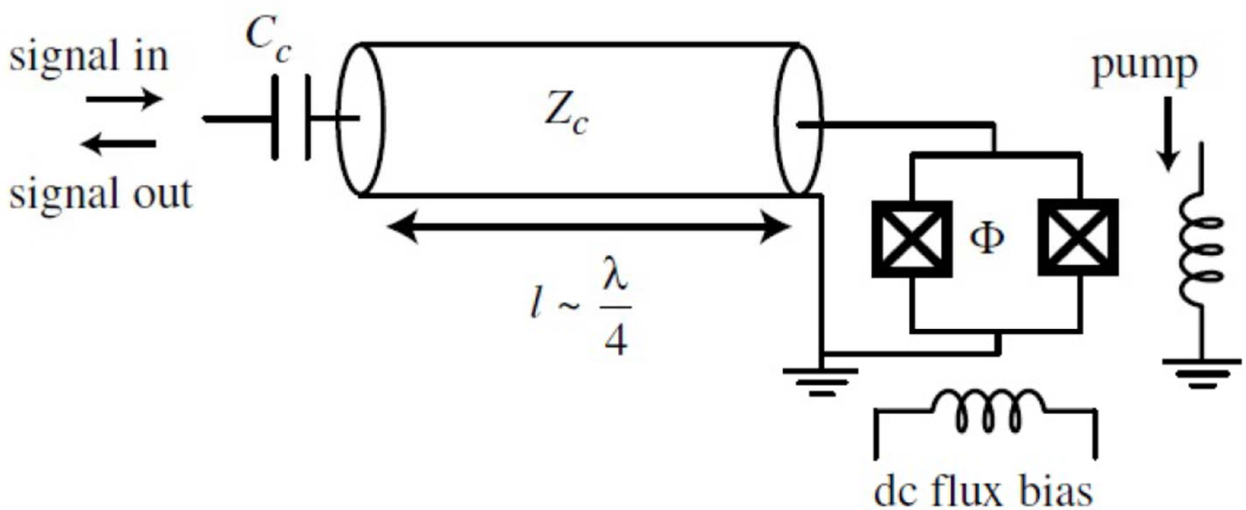
Microstrip SQUID amplifiers

Near to quantum limit noise demonstrated
Difficult to operate: frequency stability, temperature stability, heat dissipation

Josephson Parametric Amplifiers (JPAs)

Quantum limit noise demonstrated (>6 GHz), no heat, better frequency and temperature stability
Mostly for frequency about 10 GHz, unusual operation, limited bandwidth

Josephson Parametric Amplifiers (JPA)

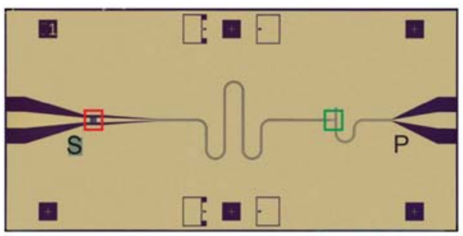


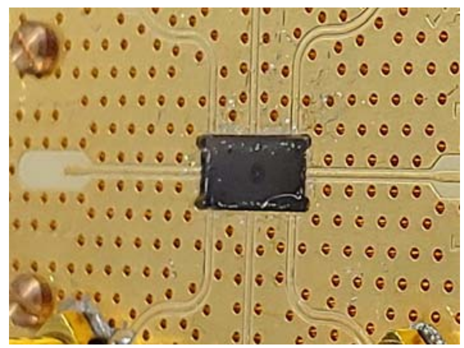
$$L(I) = L_0\left[1 + \frac{1}{2}\frac{I^2}{I_c^2}\right], L_0 = \frac{\Phi_0}{2\pi I_c}$$

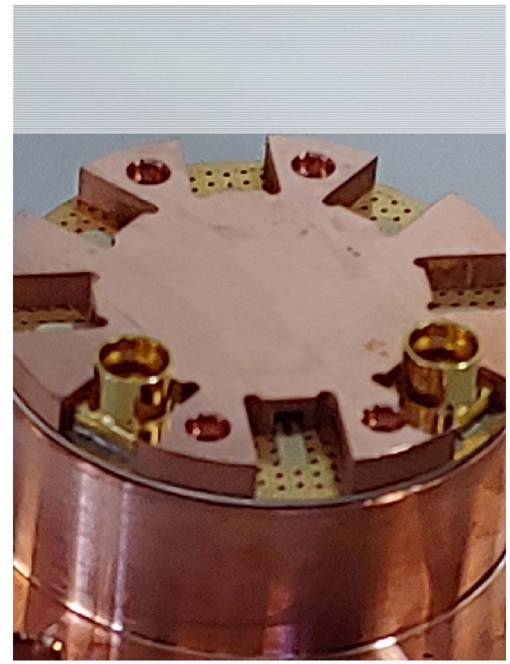
Inductance of a SQUID depend from flux bias Φ $I_C = I_{C0}cos(\pi\Phi/\Phi_0)$ **- frequency adjustment**

The nonlinear current-dependent inductance of a Josephson junction **- amplification**

JPAs: Collaboration with University of Tokyo and RIKEN

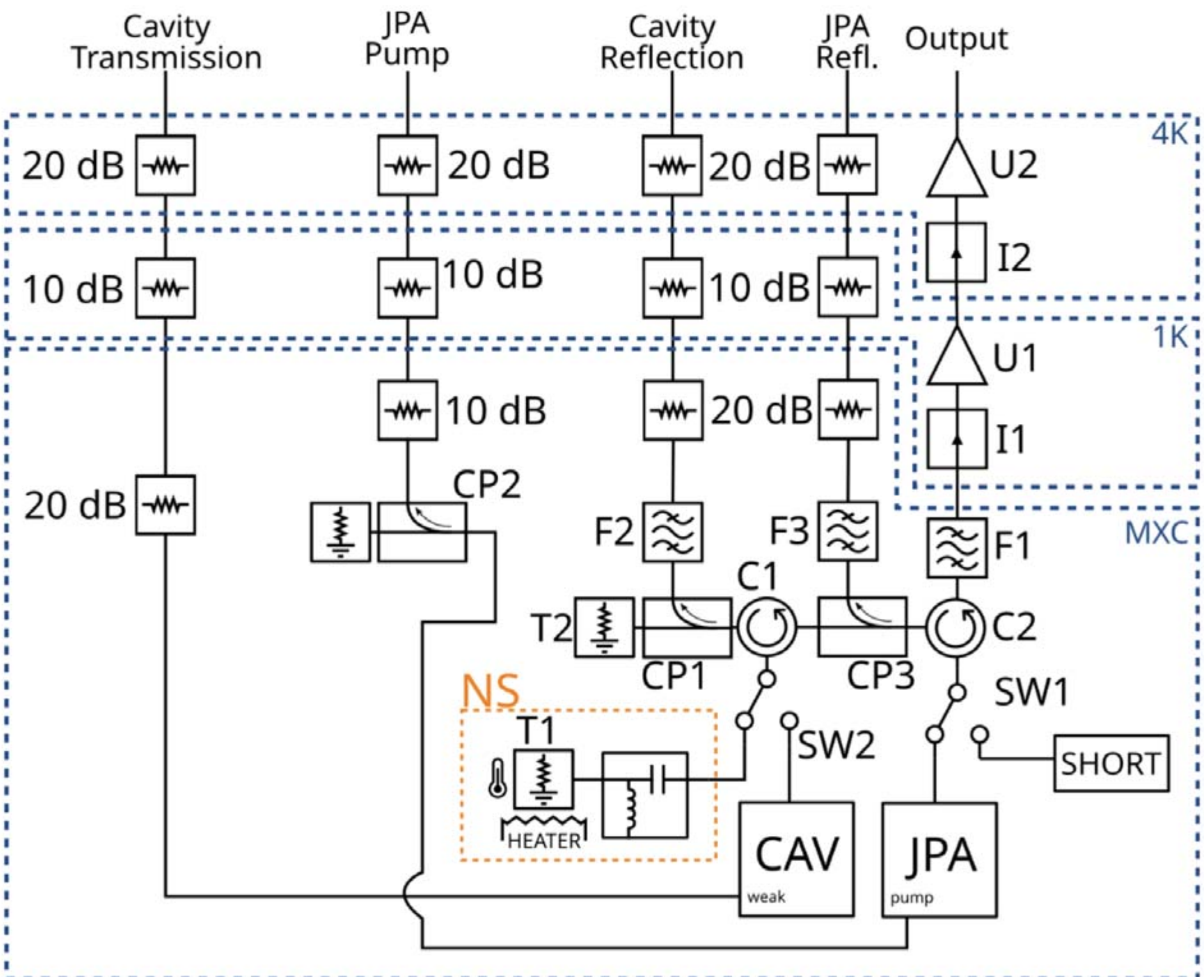






RiIKEN: 196mK @ 5.6 GHz

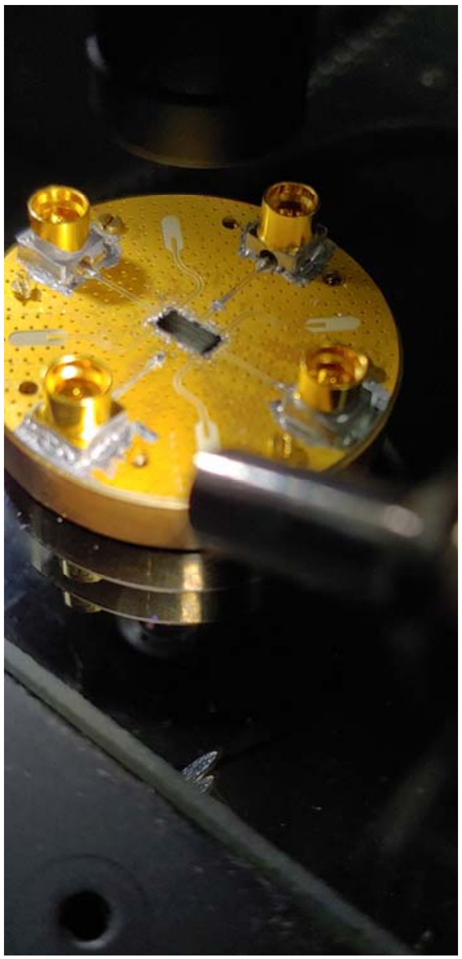
JPA Read-Out Setup



Test:

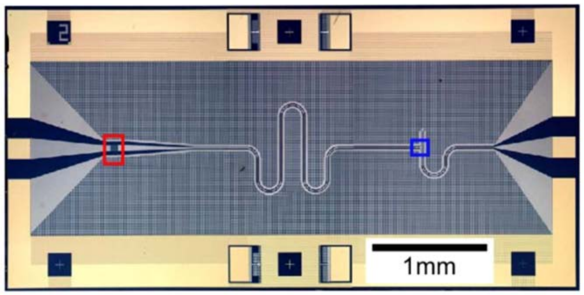
1) Gain
2) Noise temperature

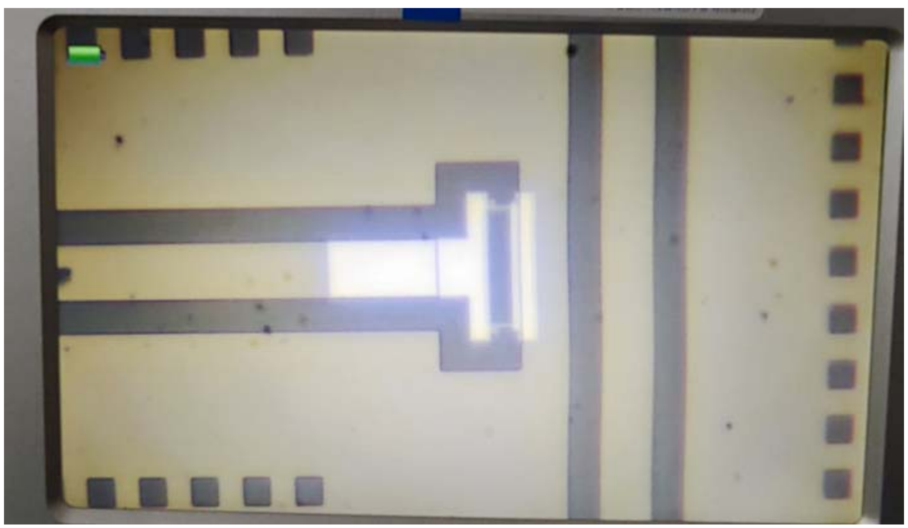
JPA Test setup

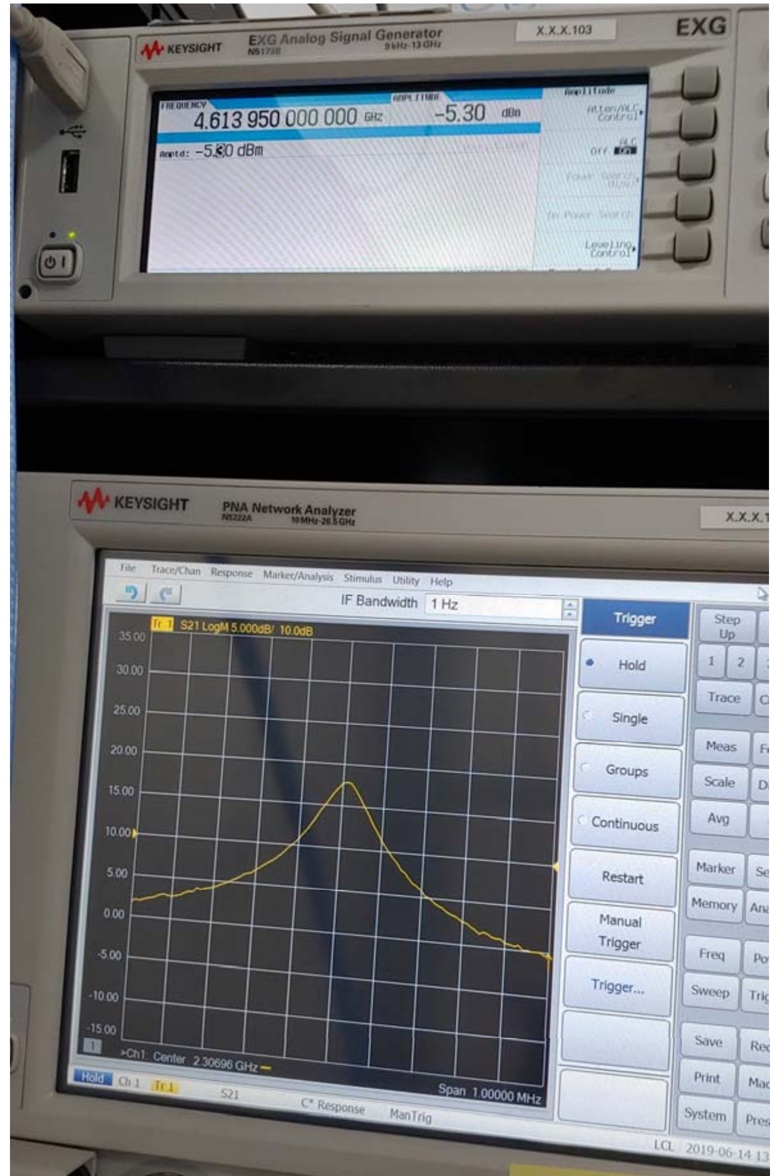


JPA 2.3GHz

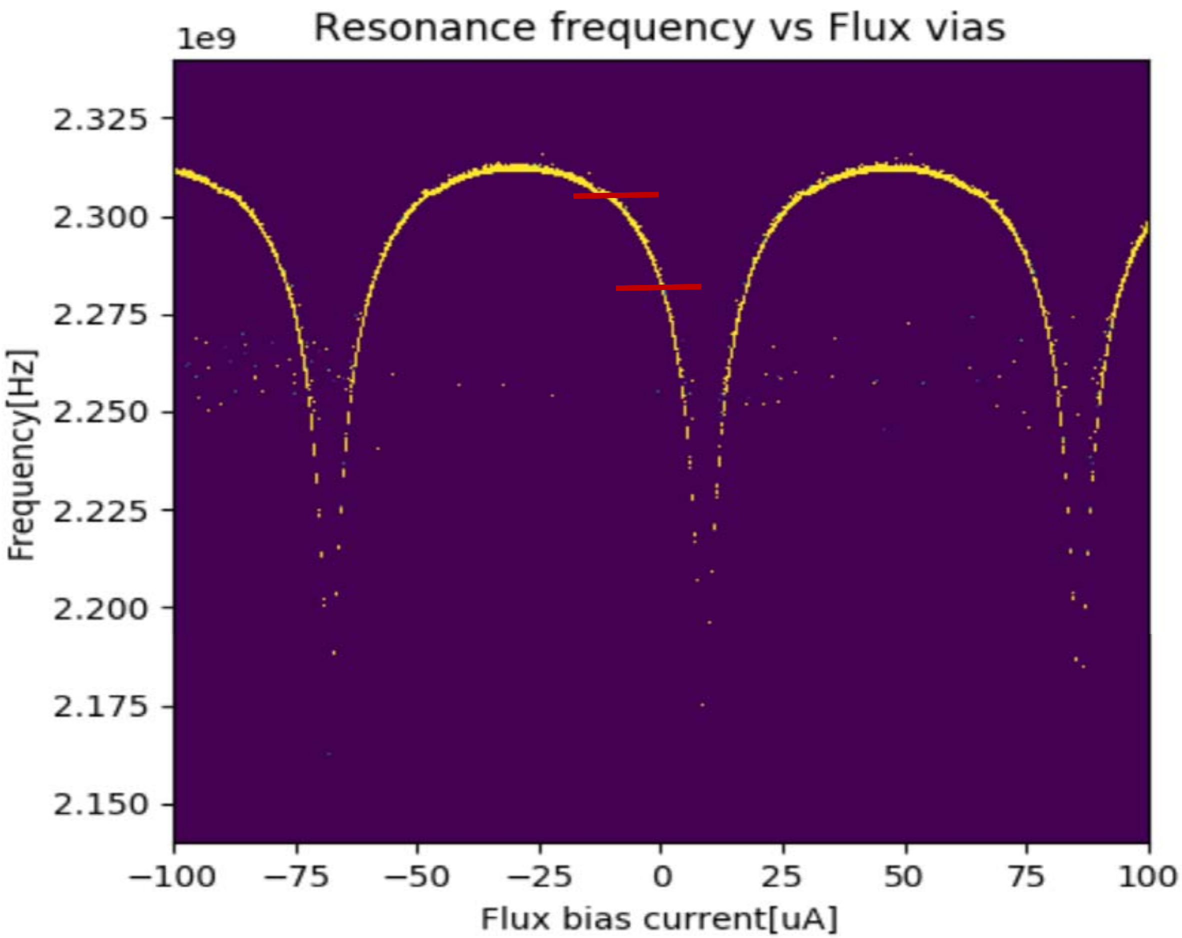
2.3 GHz amplifier





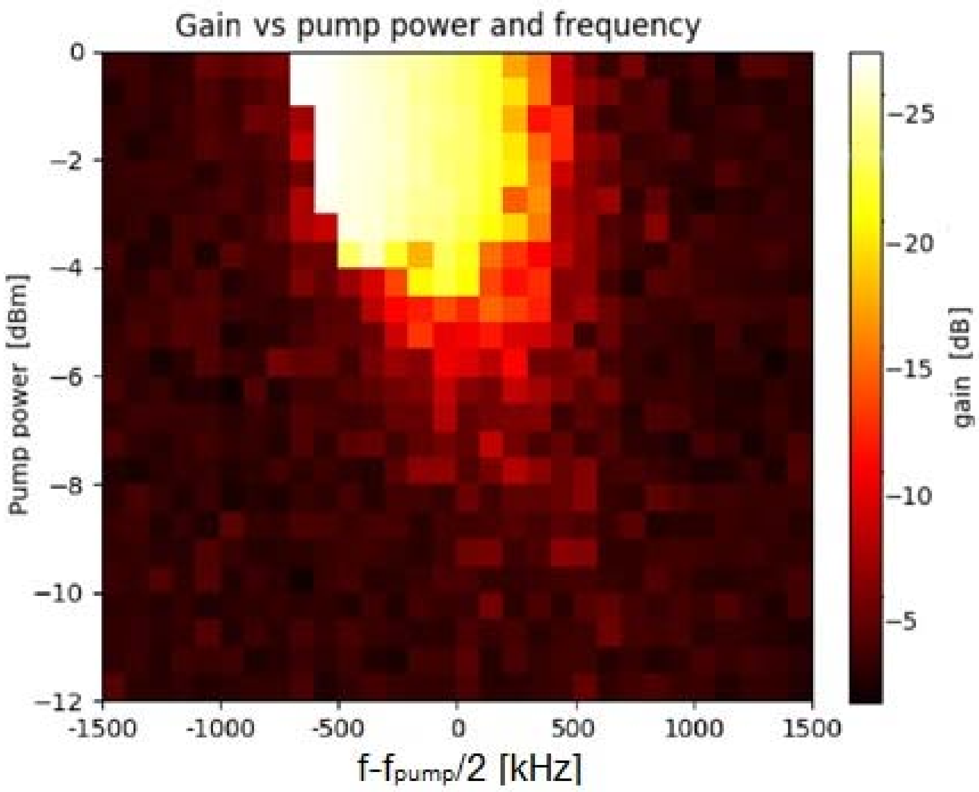


JPA Resonance Frequency vs. Bias Flux



Operating range about 30 MHz

Gain vs pump power and frequency at fix resonance frequency

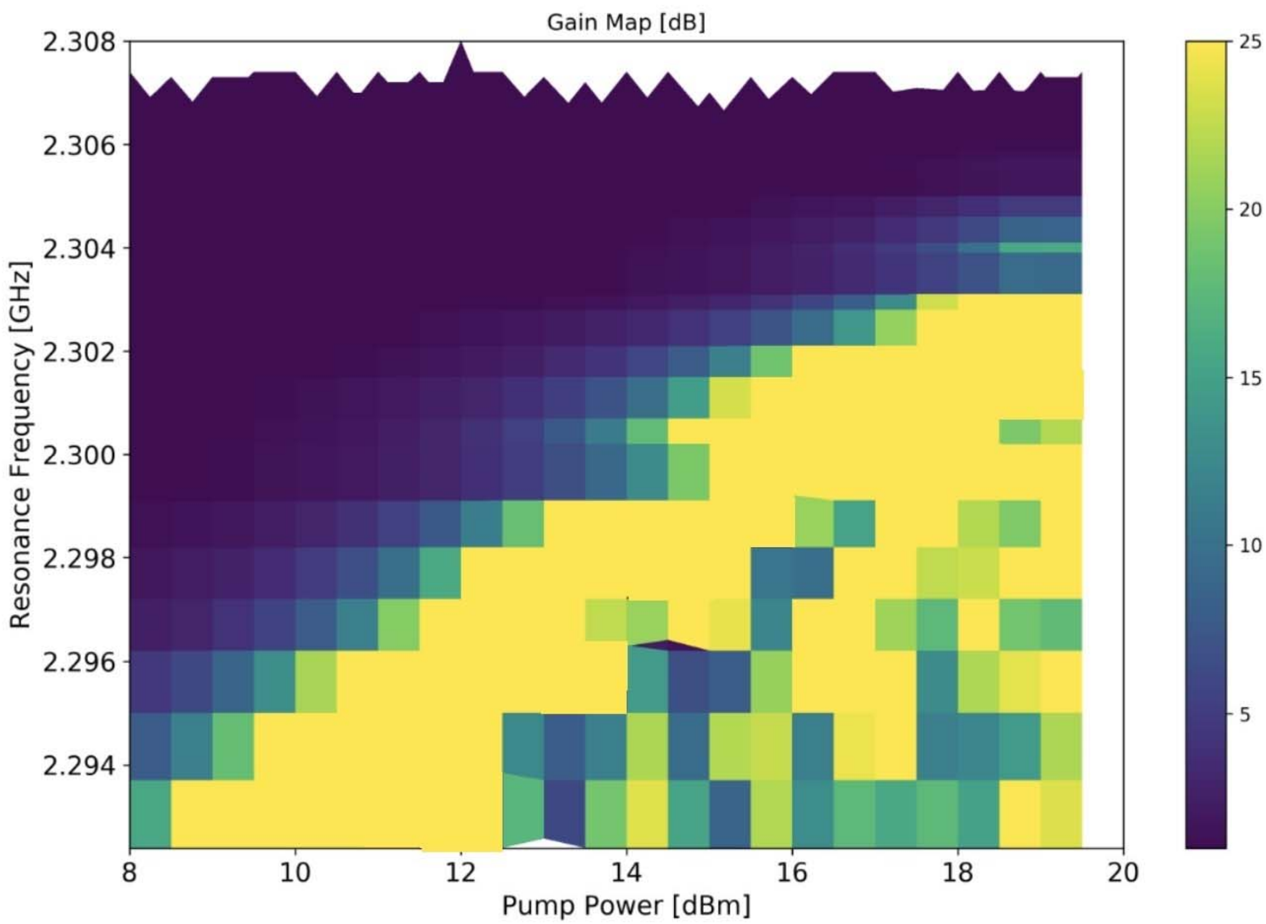


Instant bandwidth

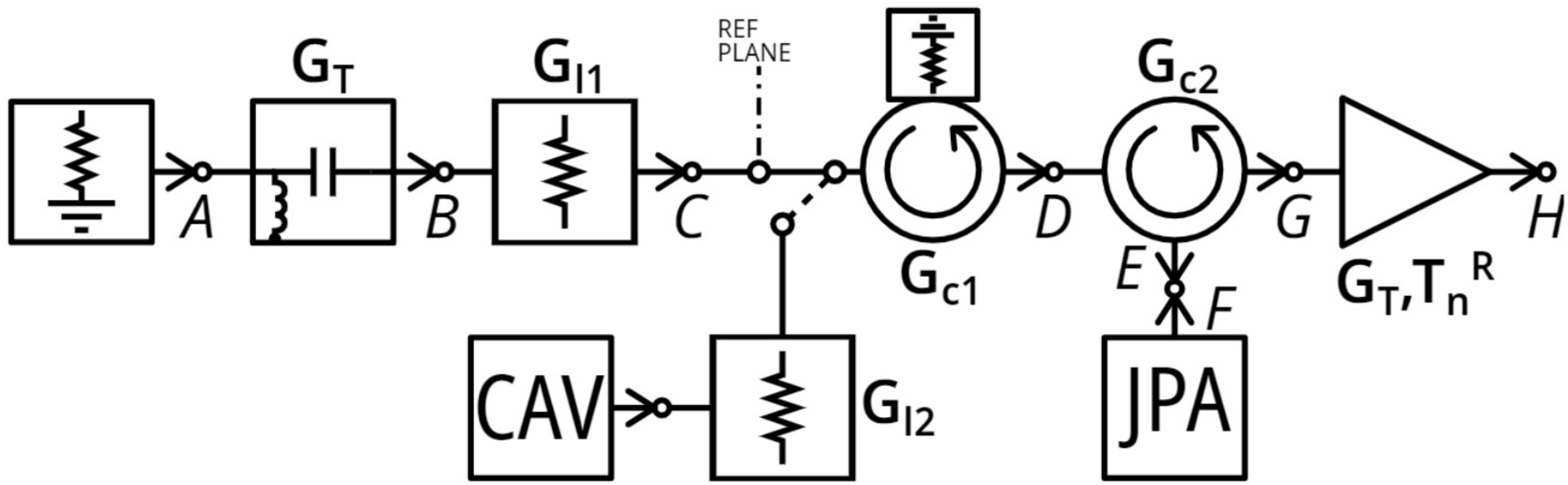
~ 180 kHz @ 18 dB gain

Maximum gain > 25dB

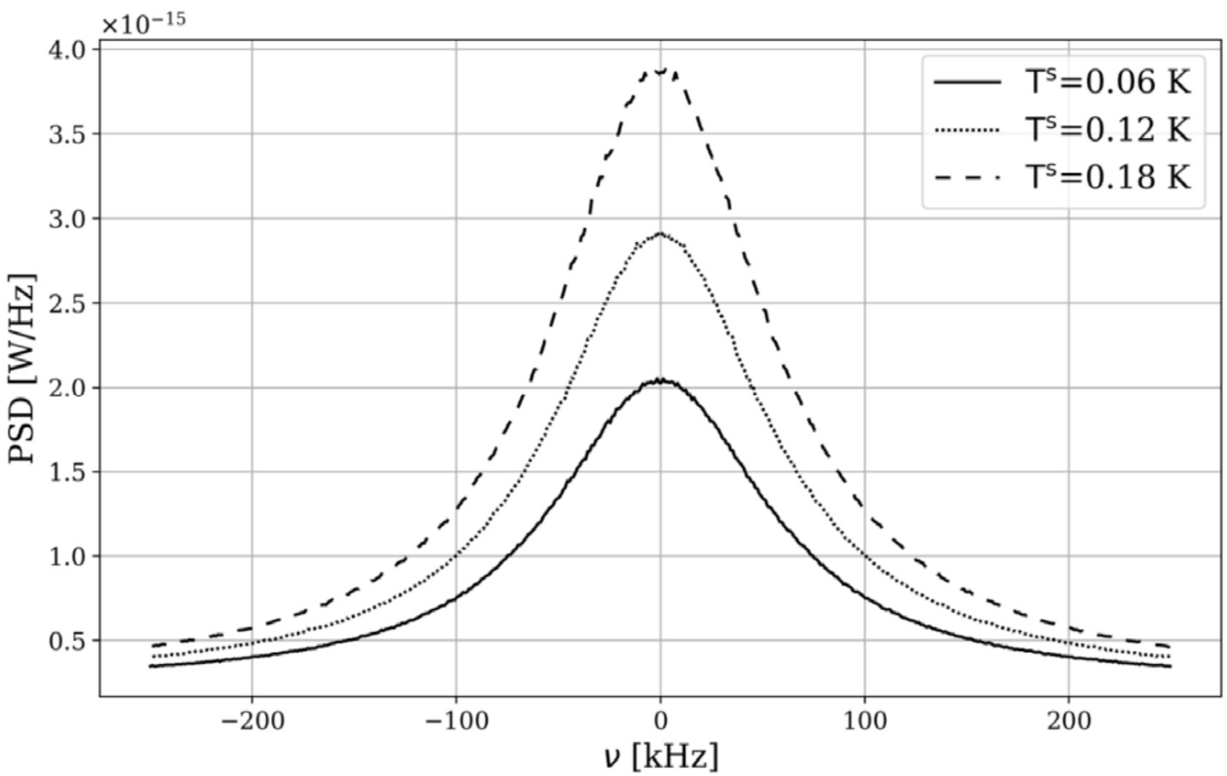
Gain vs pump power at different resonance frequency



Noise temperature measurement
Y-method implemented



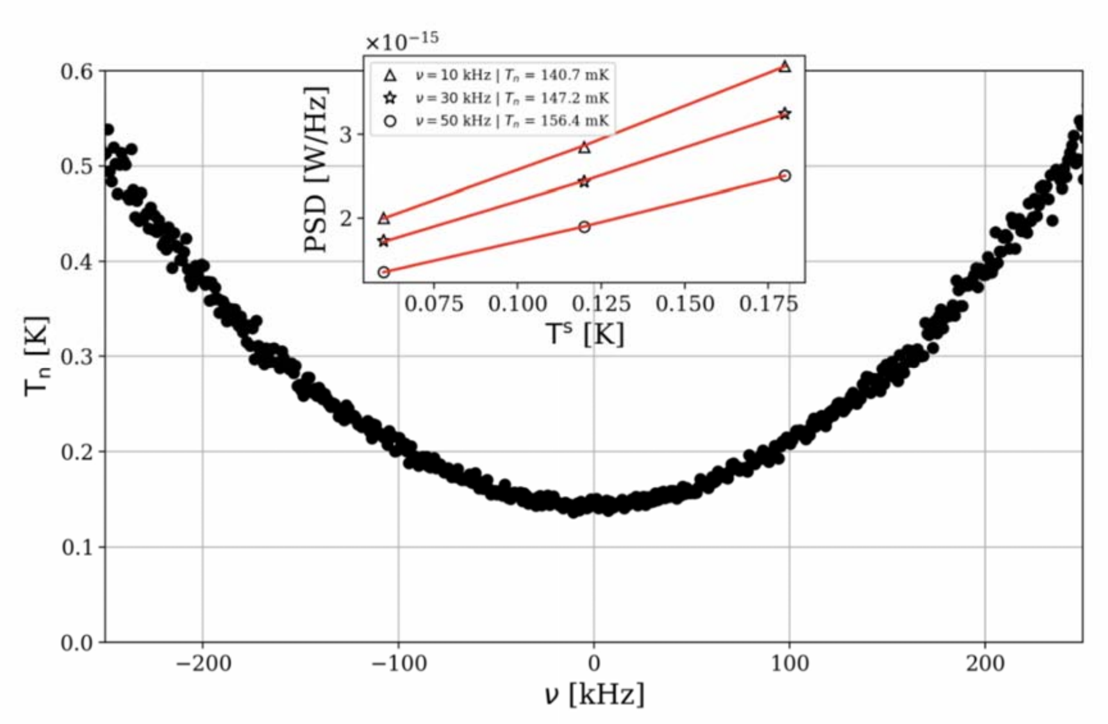
Raw data of noise measurements: Power Spectrum Density vs detuning



Detuning:

$$\nu = f - f_{pump}/2$$

Results of noise measurements, 2.3GHz

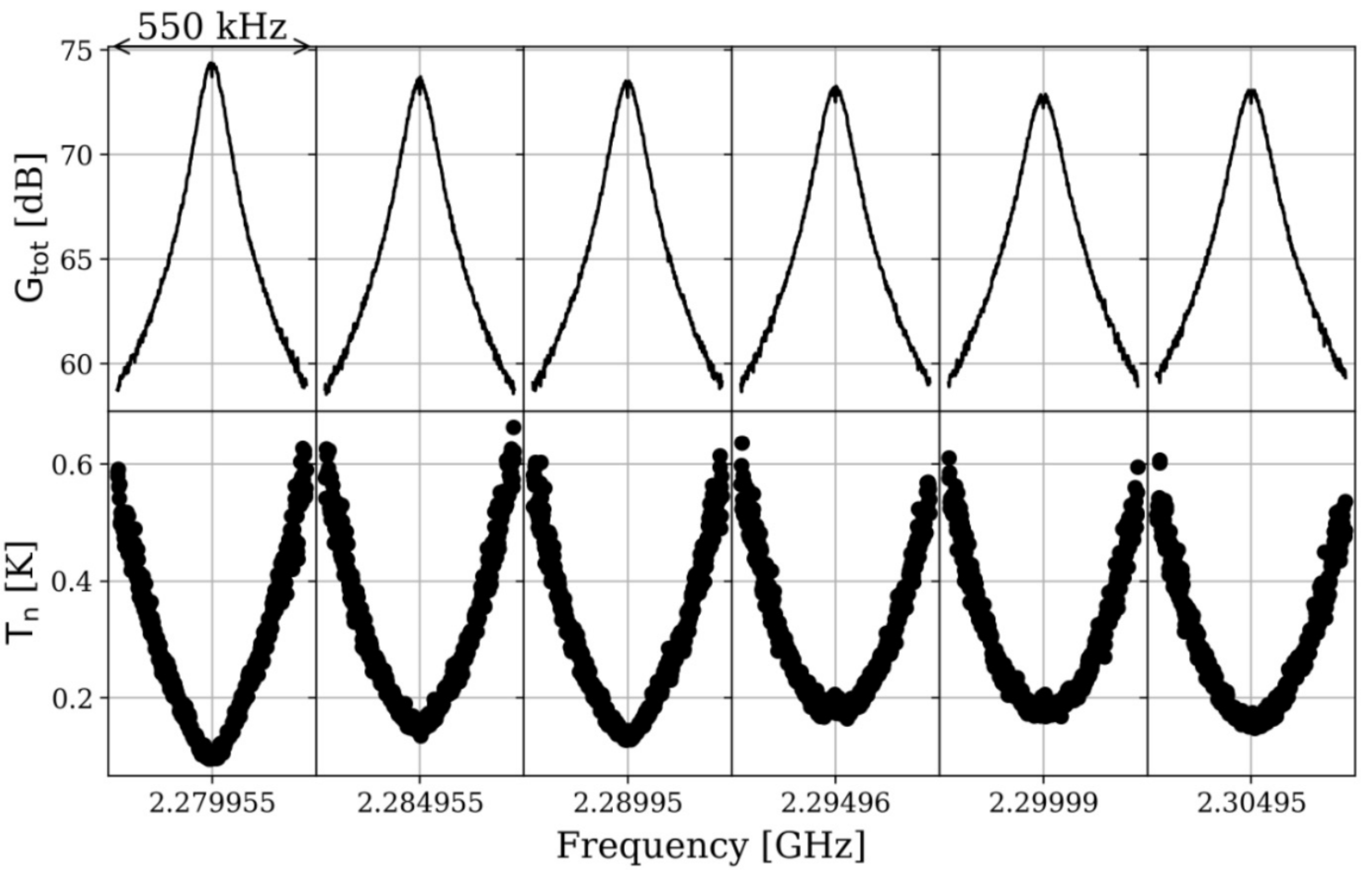


Standard Quantum limit for system noise temperature for 2.3 GHz:

$$T_N = \frac{\hbar\omega}{k_B} = 110\ mK$$

Result: 140 mK

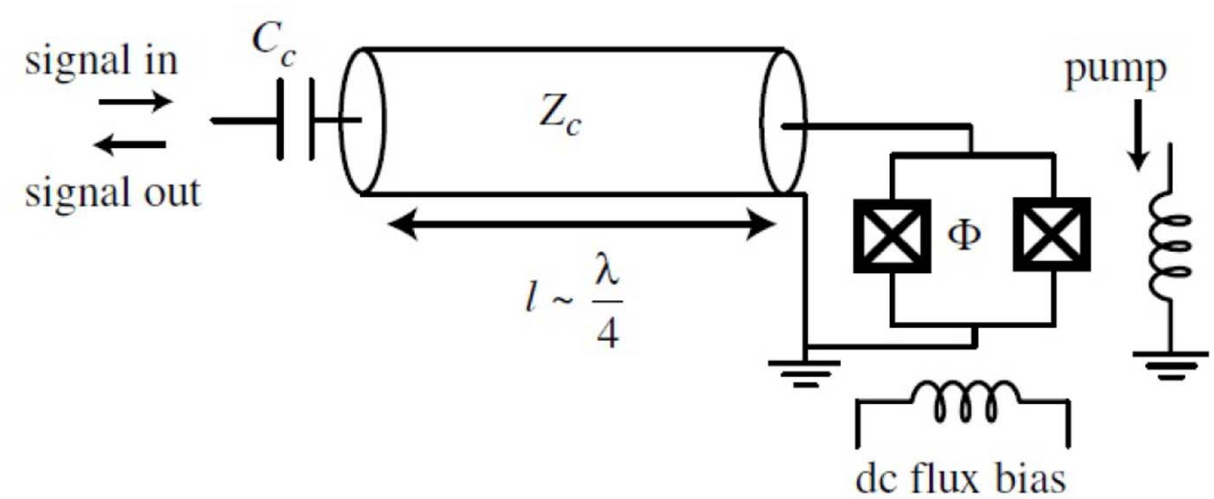
Gain and Noise vs resonant frequency



2.3 GHz JPA results

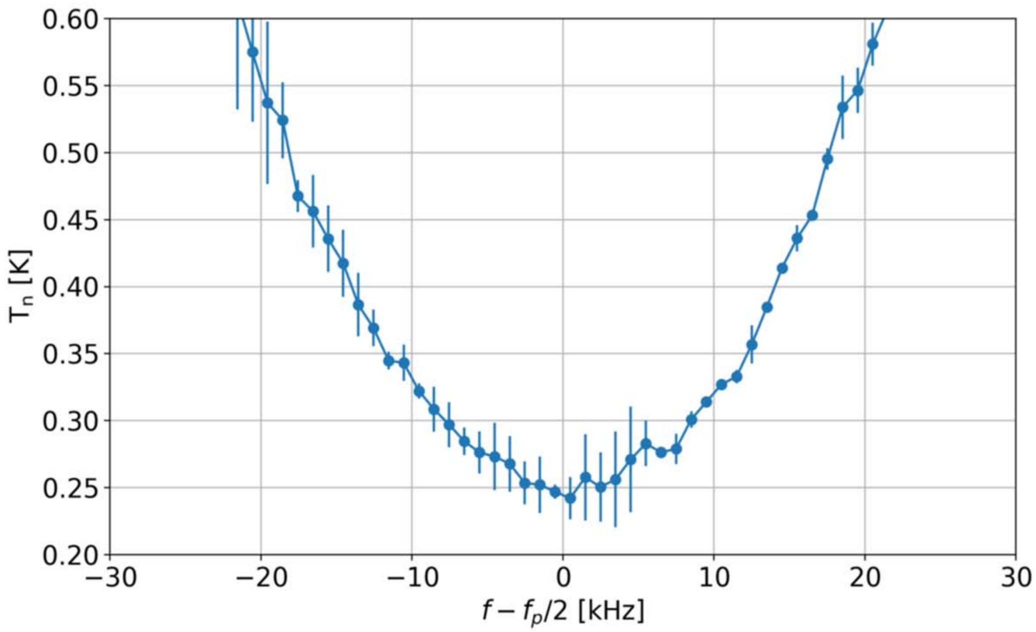
- Show near quantum limit noise (130-140 mK)
- Reasonable gain for noiseless amplification with HEMT cold amplifier (>17 dB)
- Instant bandwidth about 150-200 kHz
- Useful tunable operation frequency band about 30 MHz
- Useful for PACE experiment

JPA 1.8GHZ



Length l define resonance frequency, l~λ/4

Results of noise measurements, 1.82GHz



Standard Quantum limit for system noise temperature for 1.82 GHz:

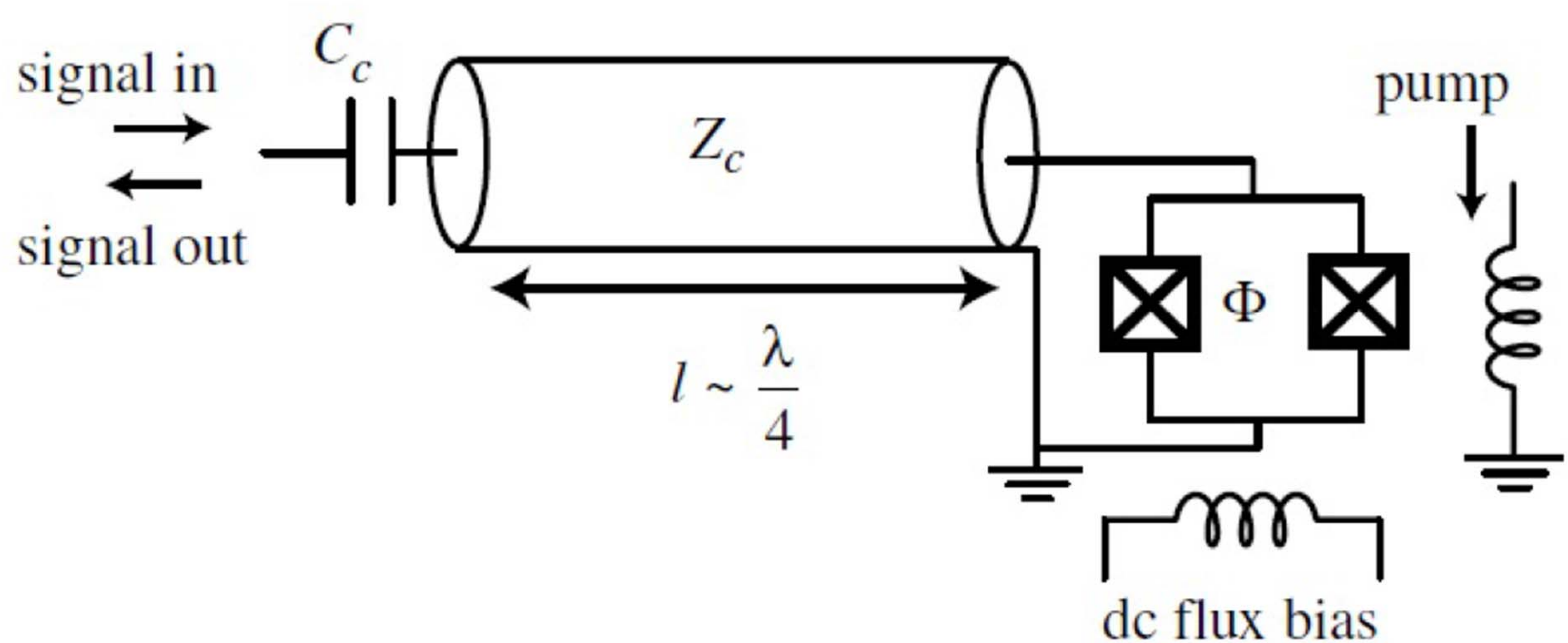
$$T_N = 87.4\ mK$$

Results: 250 mK

Instant bandwidth
25 kHz@20dB

Tuning range 10 MHz

Coupling capacitor, SQUIDs number



C_c~1/f, L=n*Lsq

1.82 GHz JPA results

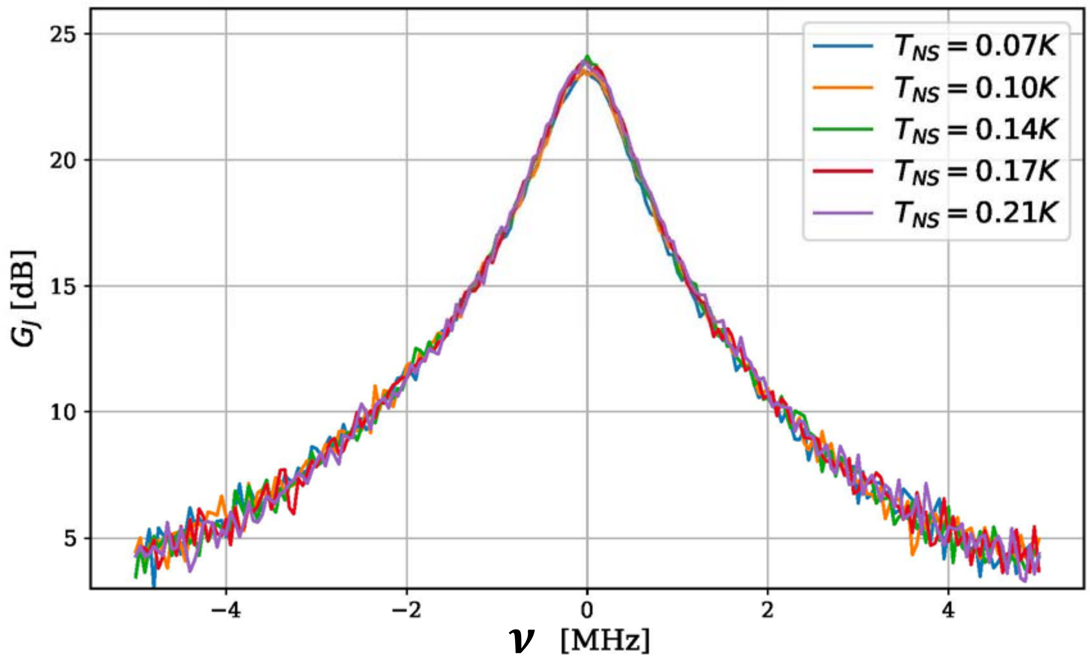
- Show near quantum limit noise (250 mK)
- Reasonable gain for noiseless amplification with HEMT cold amplifier (>17dB)
- Useful tunable operation frequency band about 10 MHz, can be improve by design change
- Instant bandwidth about 25 kHz @ 20dB

JPA 6 GHz

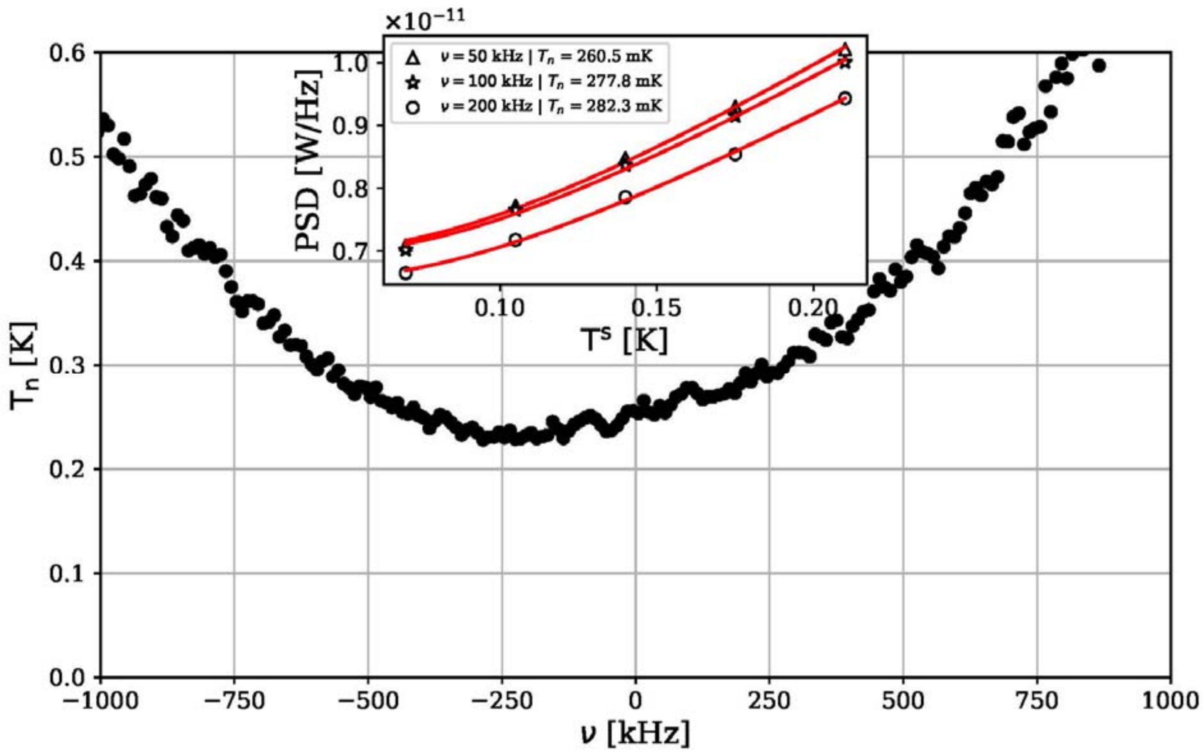
- Range of operation about 1 GHz
- Useful operation range 0.5-0.7 GHz

- Reasonable G and T_N

  G > 24 dB @1 MHz bandwidth



JPA 6 GHz: Noise temperature, 5.8 GHz

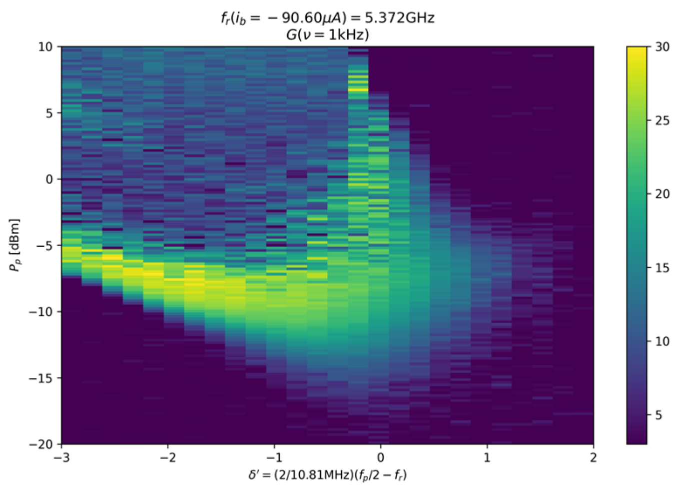


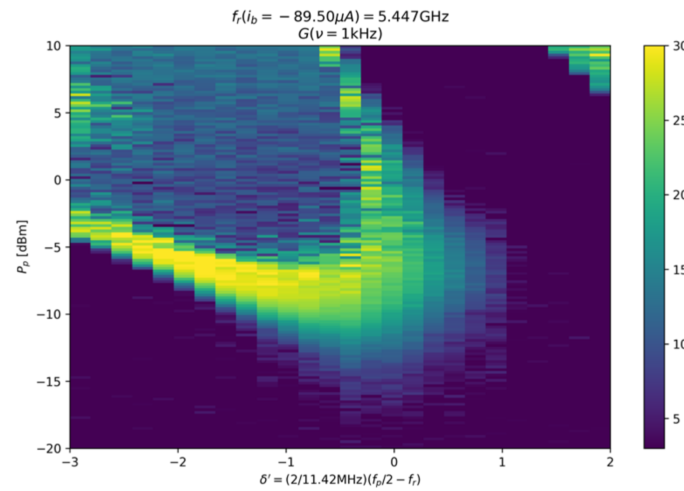
Standard Quantum limit for system noise temperature for 5.8 GHz @20dB gain:

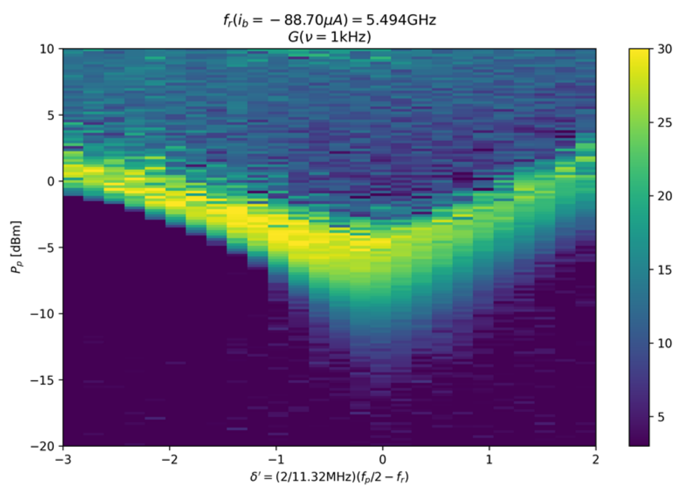
$$T_N = 278\ mK$$

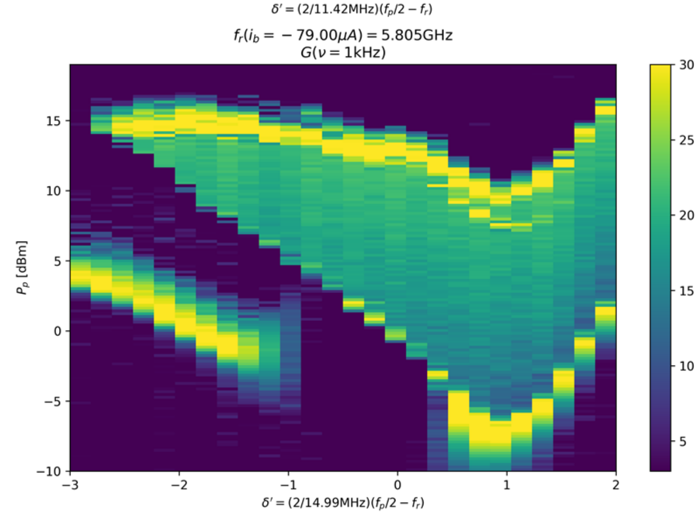
Result:
230 mK @20dB @1.5MHz

JPA 6 GHZ: choice of operation point: Gain vs Pump Power and Detuning









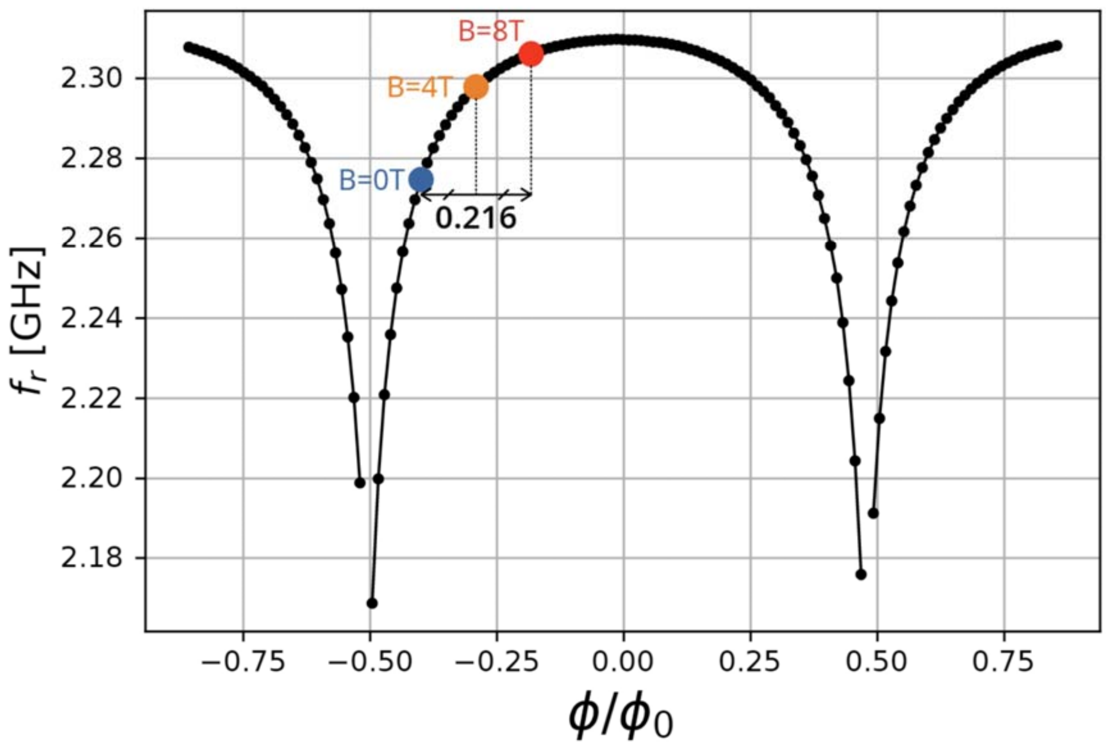
6 GHz JPA results

- Show near quantum limit noise (230 mK)
- Reasonable gain for noiseless amplification with HEMT cold amplifier (>17dB)
- Tunable operation frequency band about 1 GHz
- Instant bandwidth about 1-1.5 MHz @ 20dB
- Very promising for PACE experiment

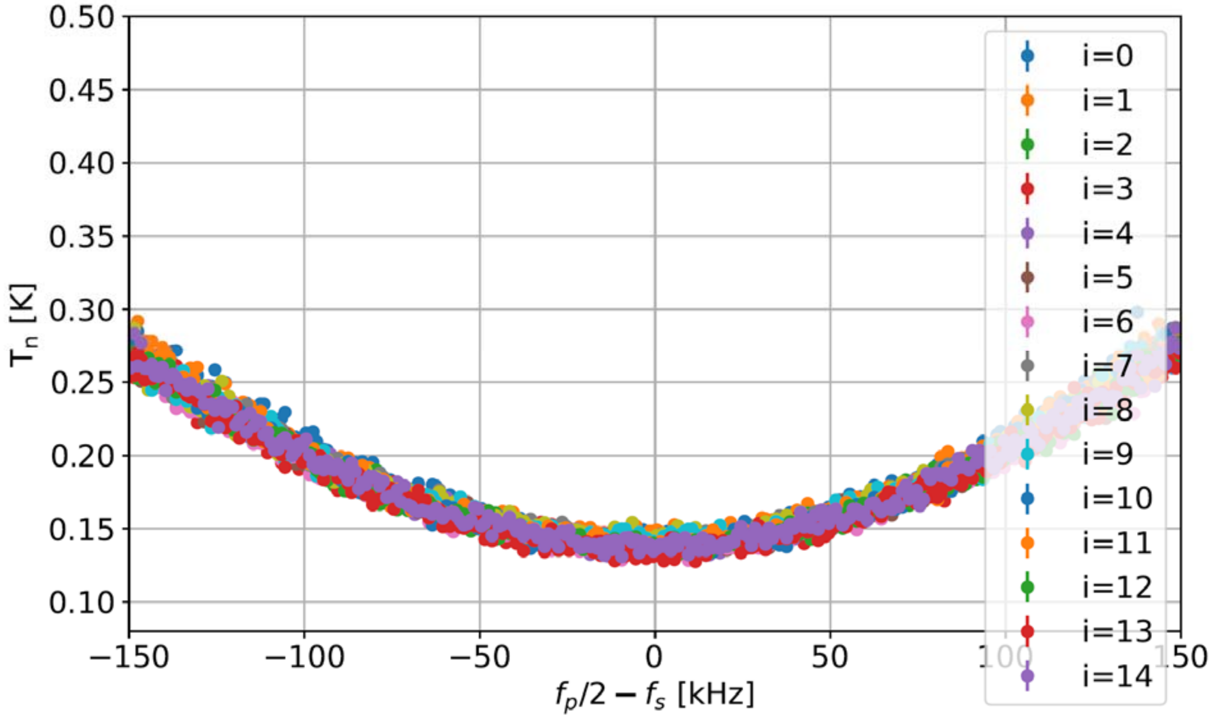
Implementation 2.3 GHz JPA in PACE experiment

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

Resonance frequency drift



Noise temperature stability



14 measurements
2.300 GHz:

Result: 130-155 mK

During experiment:
control noise temperature
every 2 MHz

CAPP/PACE 2,3GHz JPA runs

- Two run finished
- Entire sensitivity level 2 KSVZ
- Working on bigger cavity/higher Q
- Working on analysis

SUMMARY

- CAPP has successfully tested JPAs for haloscope axion dark matter experiments in three frequency range
- Near quantum limit noise characteristics were achieved
- CAPP developed experience in JPA operation in high magnetic field environment
- 2.3 GHz JPA runs reliable about two month with clear operation procedure developed, regular noise temperature check
- 6 GHz JPAs showed wideband amplification up to 1 GHz. Design of 6 GHz cavities is ongoing. New cavity expected in 1-2 months.

Thank You For Your Attention!