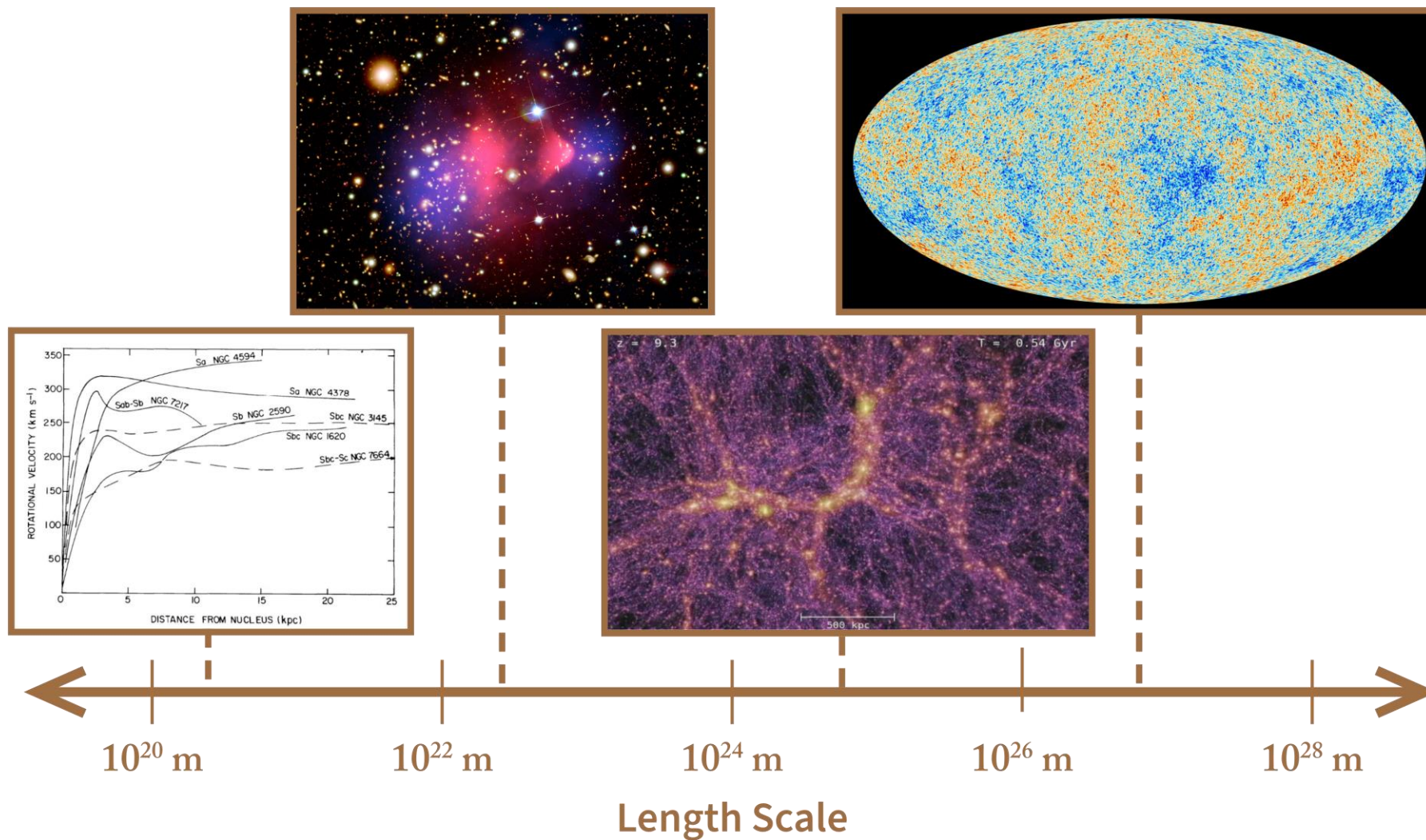




QUANTUM AMPLIFIERS FOR AXION DARK MATTER DETECTION

DARK MATTER EVIDENCE

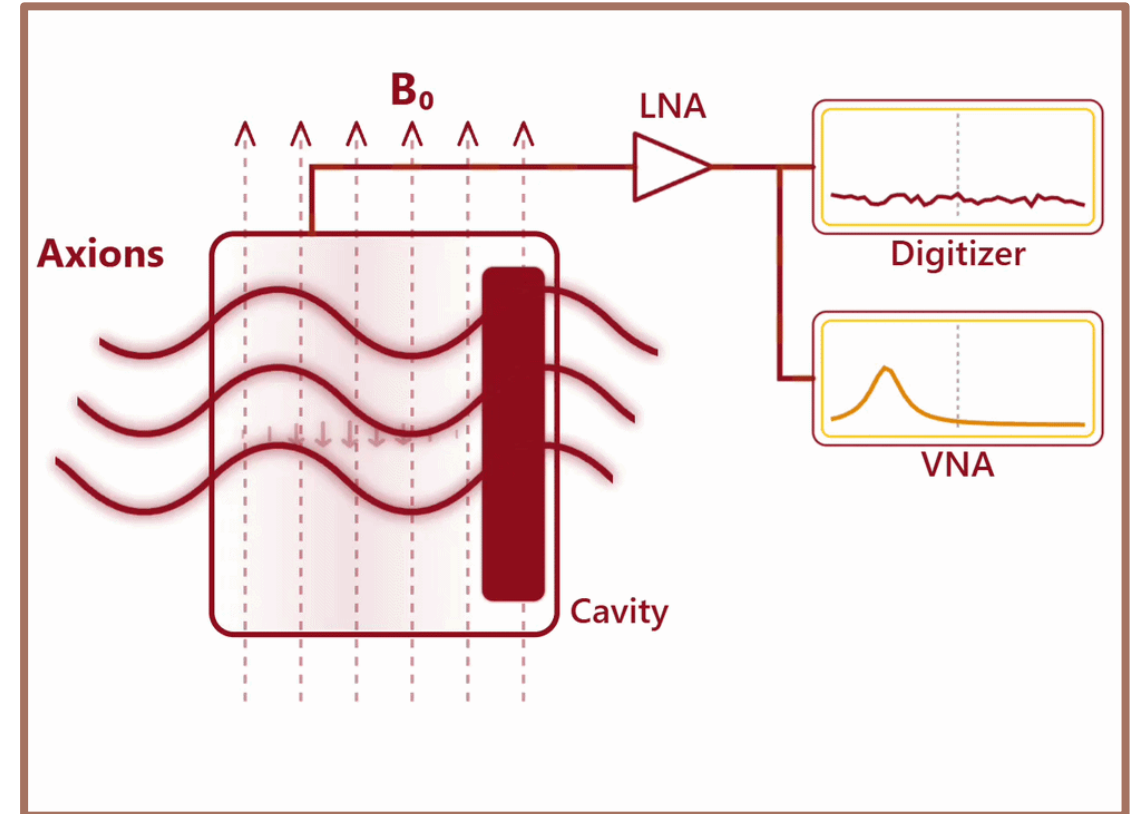


THE AXION

- QCD contains CP violations that are not observed in experiments
- Introducing a new axial $U(1)$ symmetry cancels CP violation
- The axion appears as a pseudo-Goldstone boson when the $U(1)$ symmetry is broken at low energy
- Axions acquire small mass below QCD phase transition
- Axions can be produced in large enough quantity to be dark matter
- Axions have small couplings to standard model particles

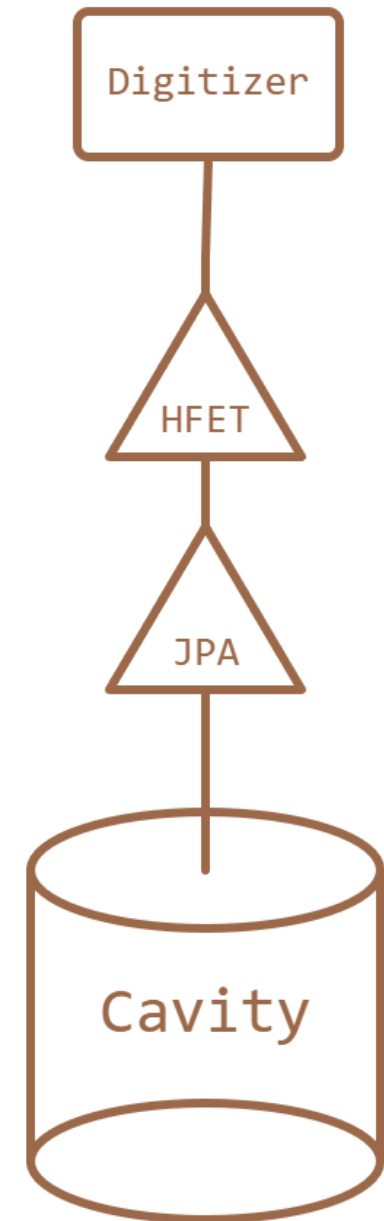
THE AXION HALOSCOPE

- Probe axion-photon coupling
- Resonant cavity and strong magnetic field enhance axion to photon conversion
- Tune cavity to search parameter space



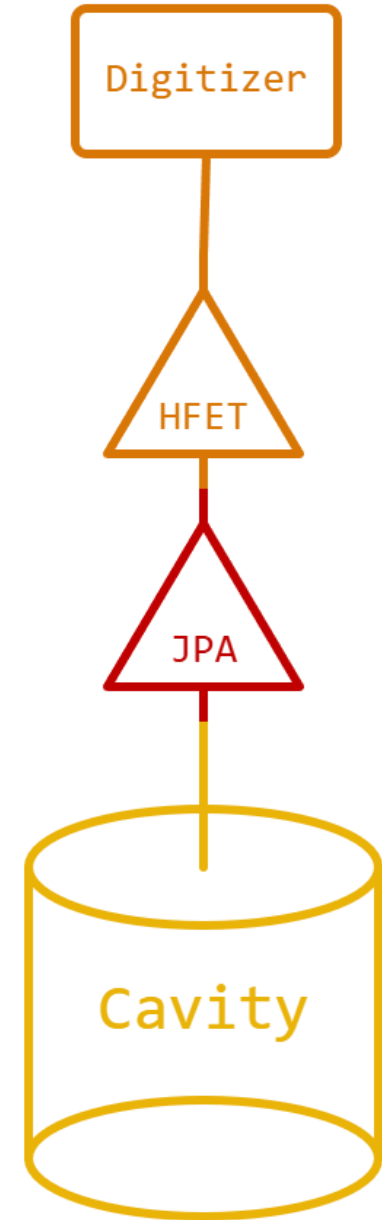
ADMX RECEIVER

- Axion haloscope background comes from thermal and electronic noise
- Low noise, high gain amplifiers suppress noise contributions from downstream electronics
 - Josephson parametric amplifier (JPA) produces large gain with near-quantum limited performance
- Digitizer records power output



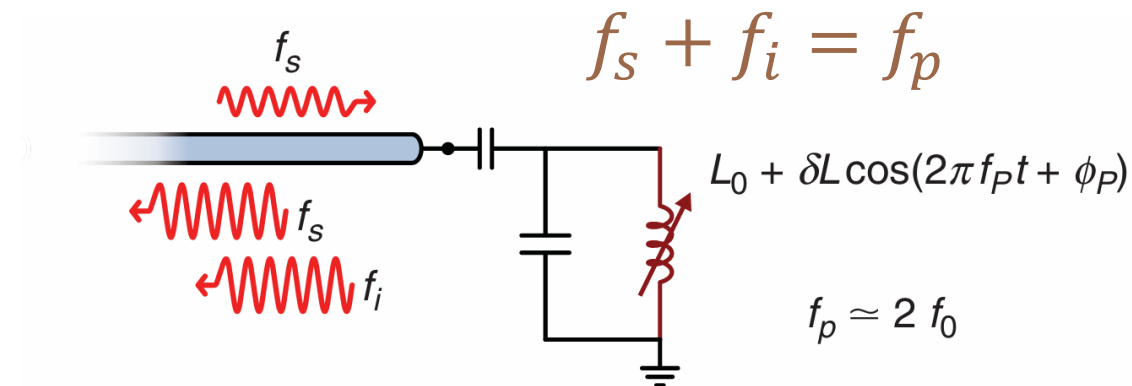
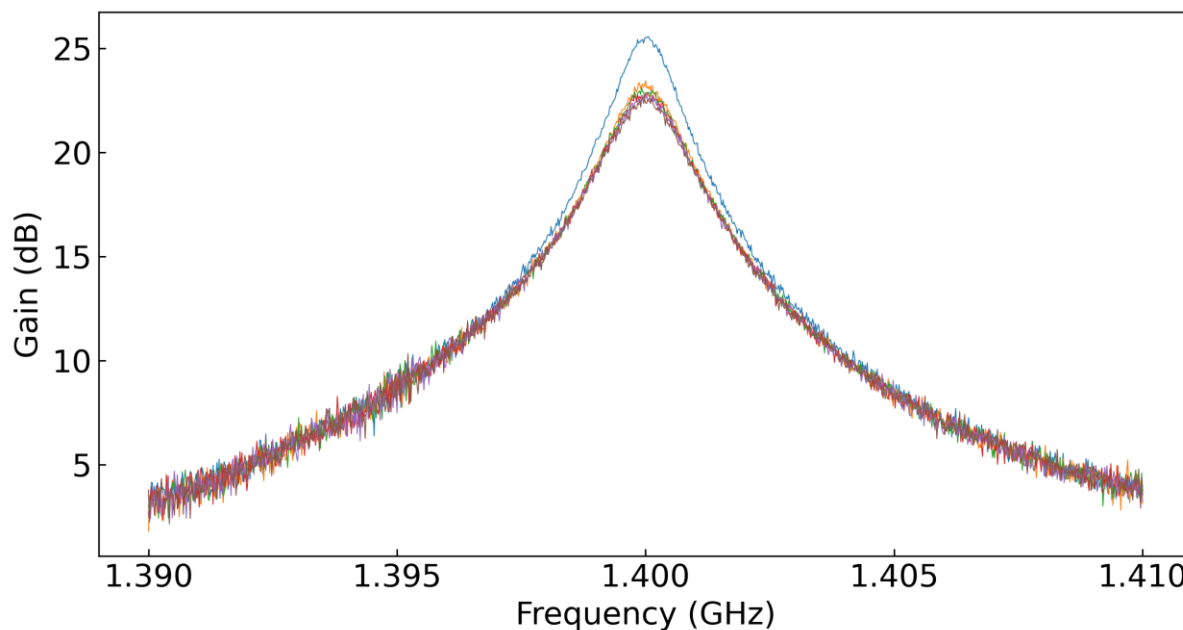
ADMX NOISE BACKGROUND

- $\text{SNR} = \frac{P_{\text{axion}}}{k_B T_{\text{noise}} b}$
- $T_{\text{noise}} = T_{\text{cavity}} + (T_{\text{cavity}} + T_{\text{JPA}}) + \frac{T_{\text{HFET}}}{G_{\text{JPA}}}$



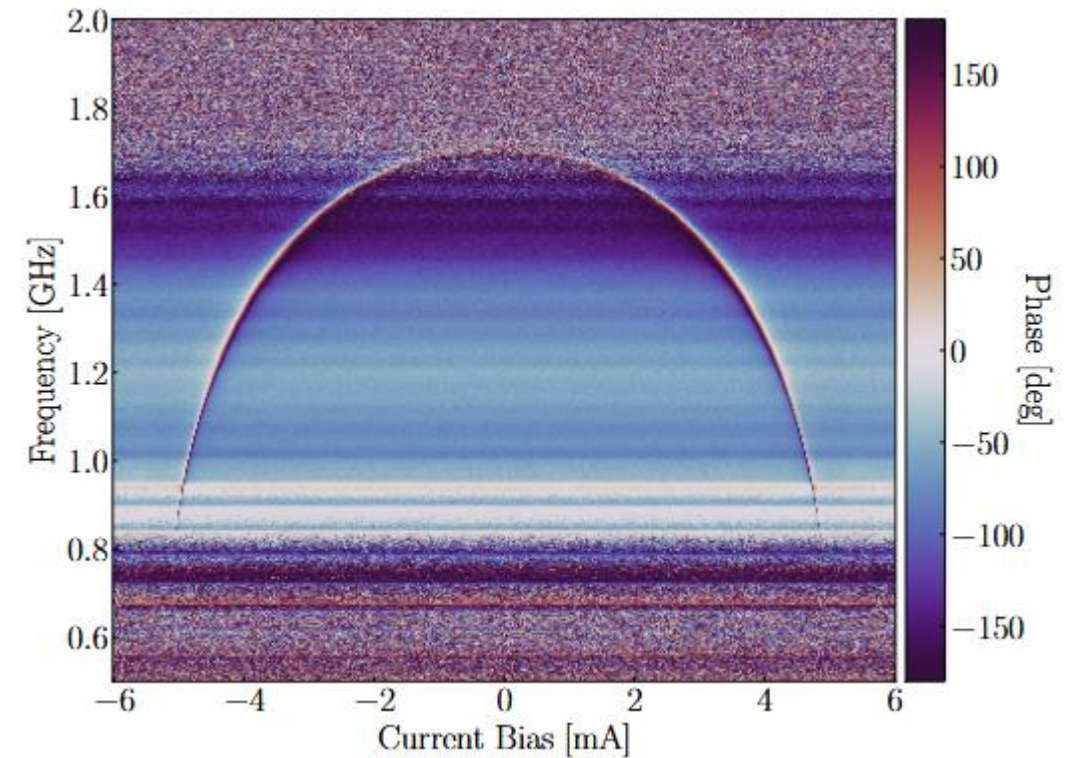
JOSEPHSON PARAMETRIC AMPLIFIER

- Superconducting LC circuit
- High, quantum limited gain over narrow bandwidth
- Parametric pumping of Josephson inductance
- Mixing generates photons at two different frequencies
- Noise mixed in from idler channel satisfies standard quantum limit (SQL) for noise added during amplification



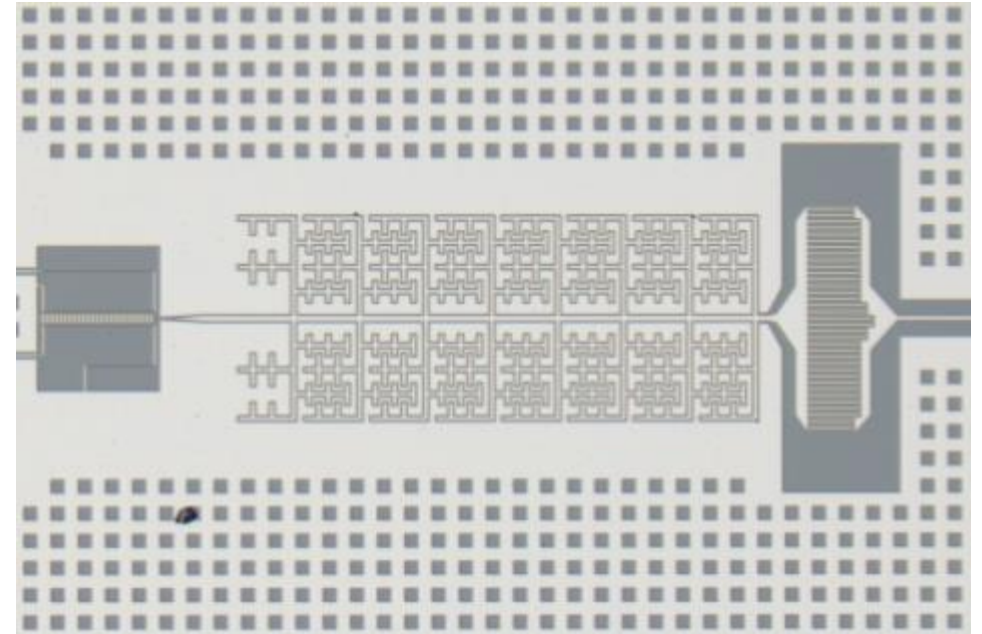
JPA TUNING

- JPA must be tunable to cover parameter space
- DC current bias sets L_0
- AC pump varies the inductance to put power into the mode



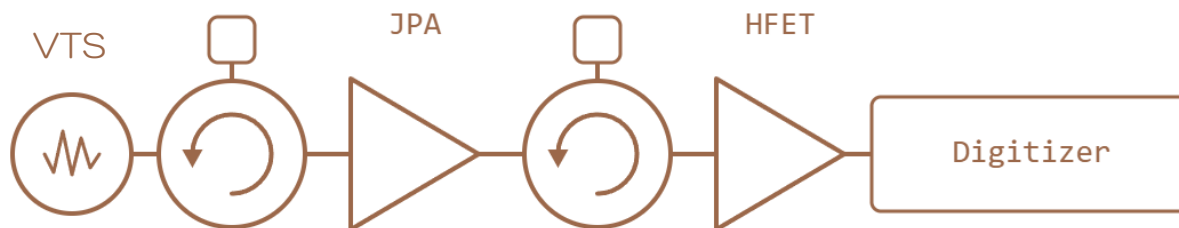
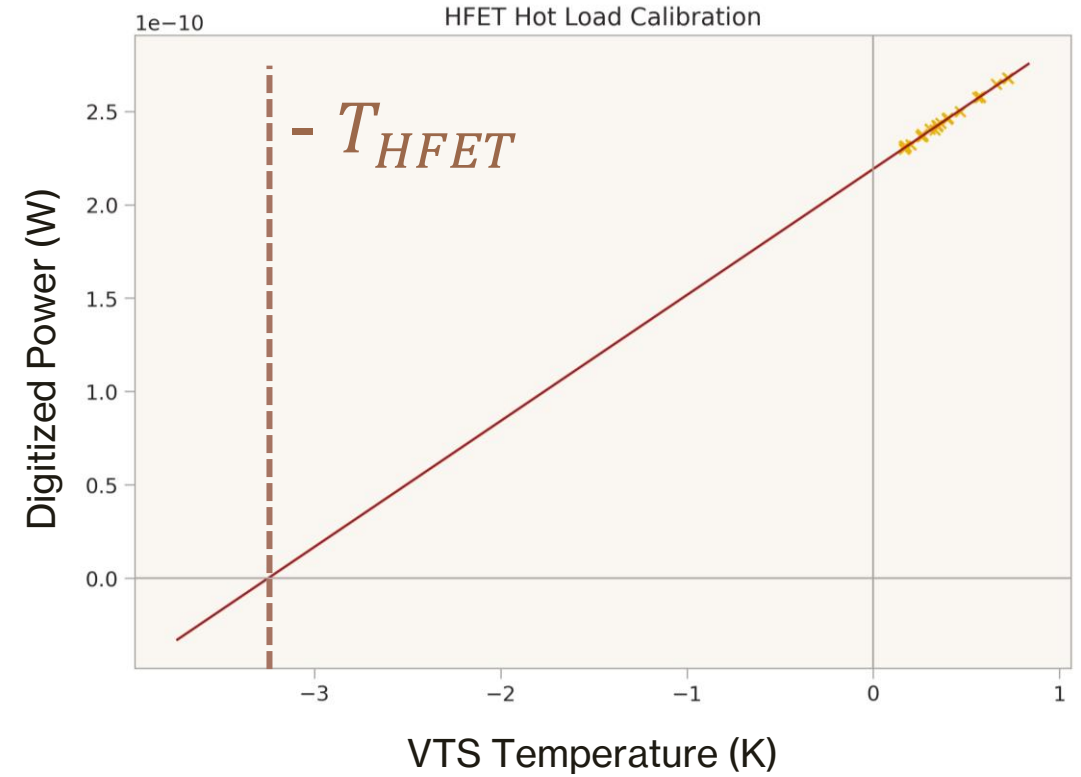
JPA OPERATION

- Up to 35 dB of gain
- Continuous biasing and noise monitoring
 - JPA performance may change with frequency, temperature, etc.
 - Automated biasing keeps the JPA resonance near the cavity resonance
 - Regular noise measurements monitor changes in noise performance and trigger re-biasing when noise gets too high
- Improvements to receiver chain and controls have improved stability of JPA performance and reduced time spent on JPA biasing and monitoring

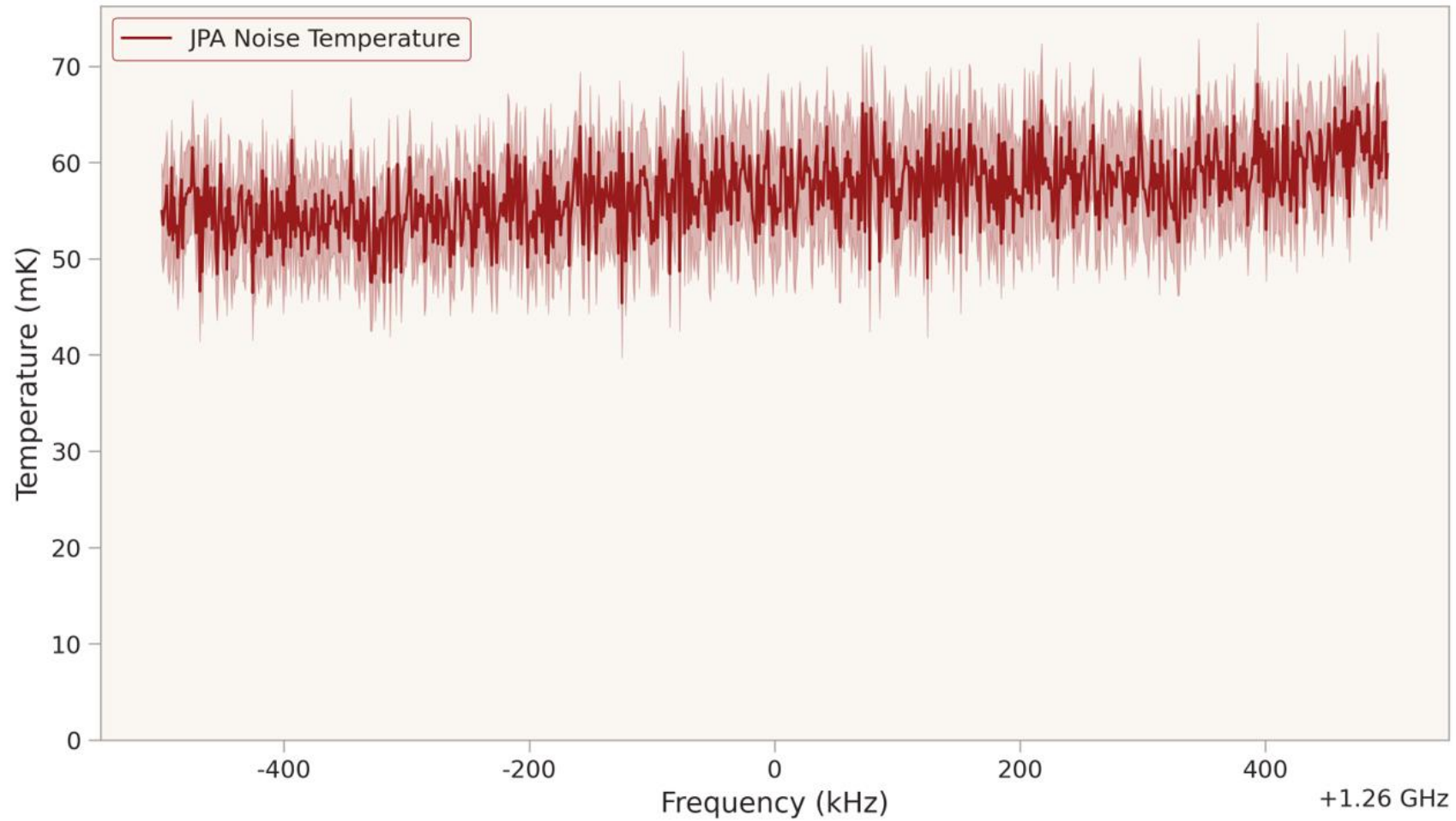


NOISE TEMPERATURE CALIBRATION

- Variable temperature stage (VTS) inputs known noise into receiver chain
- Fitting scatter of VTS temperature and power output constrains noise added by receiver
- Can isolate noise added by JPA and HFET



JPA NOISE CALIBRATION



TOTAL SYSTEM NOISE TEMPERATURE

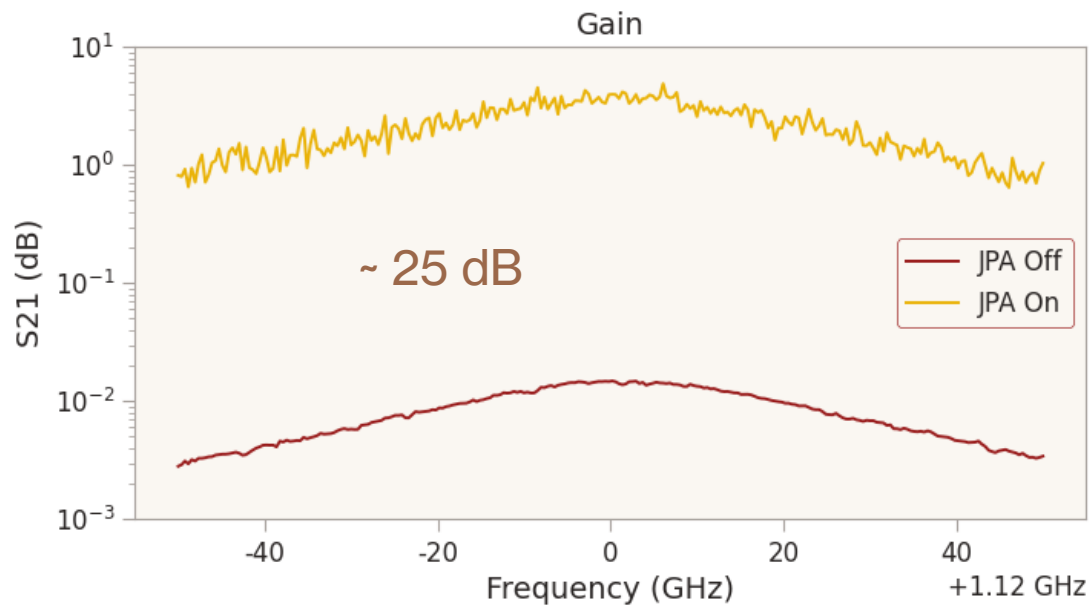
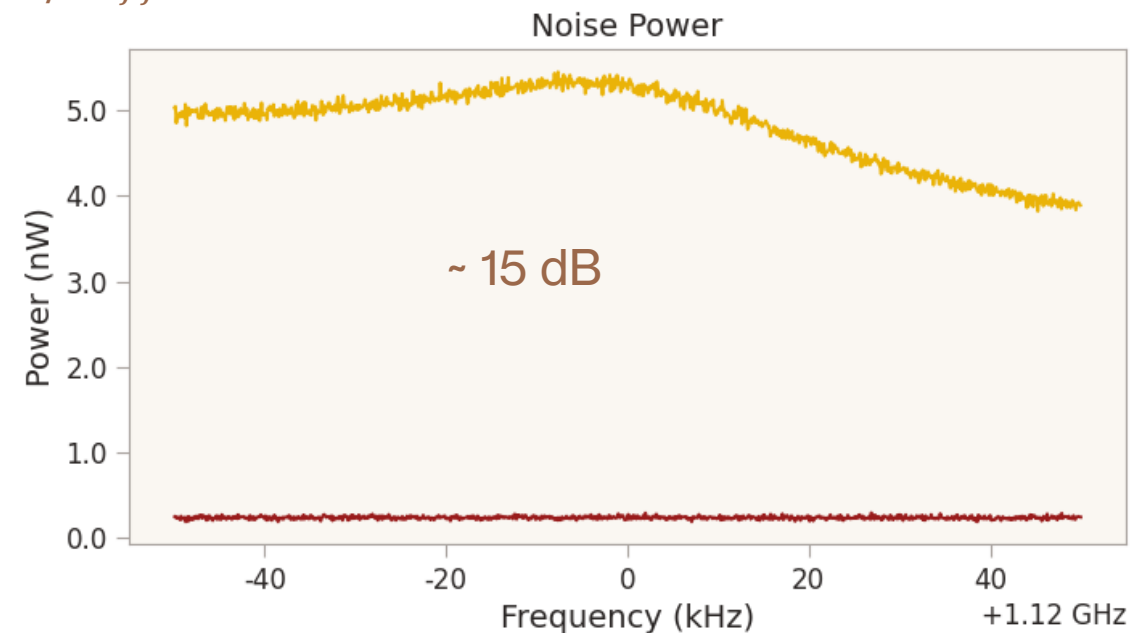
- 3 methods of determining total system noise temperature
 - SNR Improvement (SNRI)
 - Gain based noise model
 - Idler correlation noise model

SNRI NOISE MEASUREMENT

- Measure SNR Improvement (SNRI) from turning JPA on

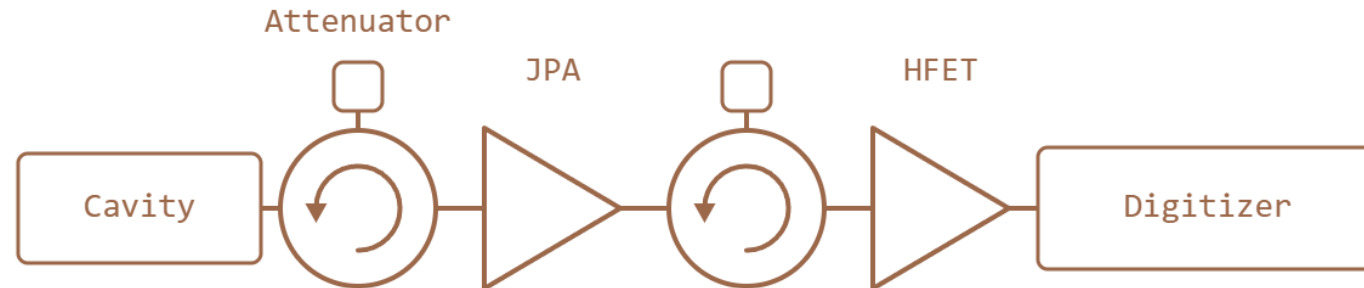
- $T_{sys} = \frac{T_{HFET}}{SNRI}$

$$SNRI = \frac{G_{JPA}}{P_{on}/P_{off}} \approx 10 \text{ dB}$$



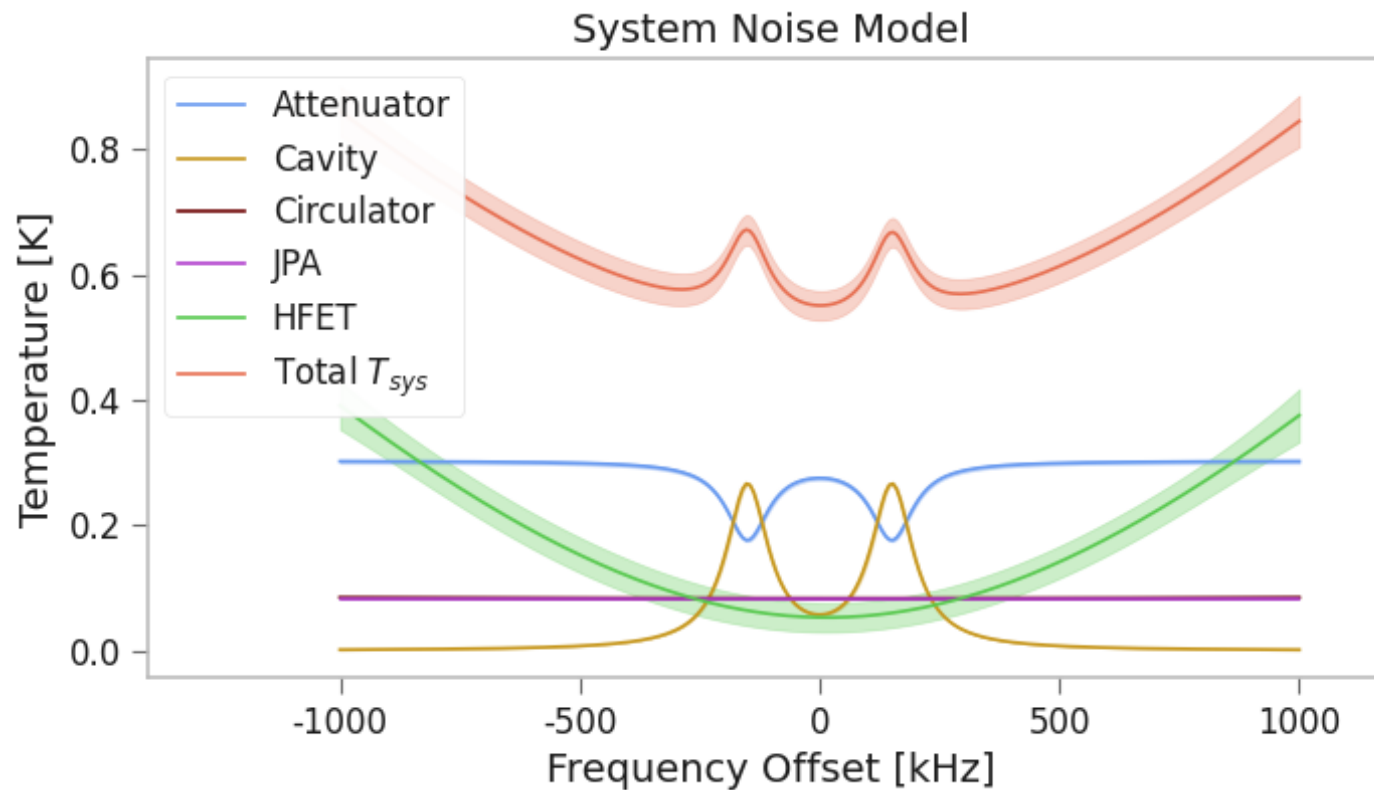
SYSTEM NOISE MODEL

- $T_{noise} = T_{cavity} + T_{attenuator} + T_{circulator} + T_{JPA} + \frac{T_{HFET}}{G_{JPA}}$



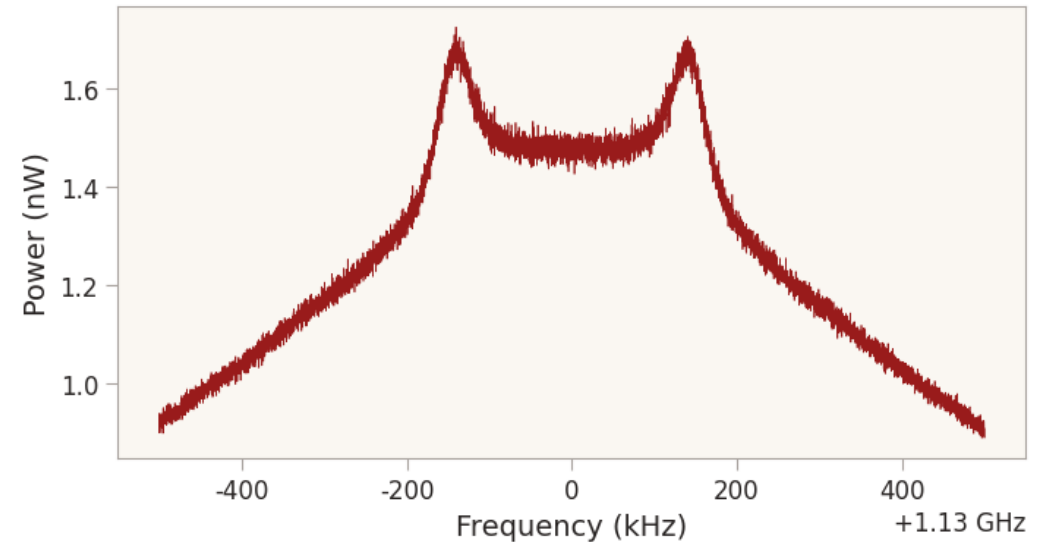
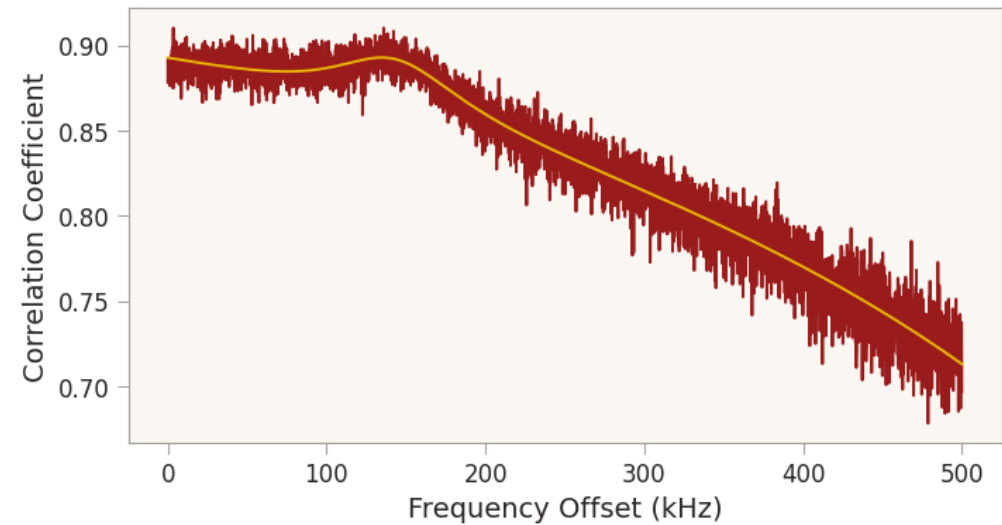
SYSTEM NOISE MODEL

- $$T_{noise} = T_{cavity} + T_{attenuator} + T_{circulator} + T_{JPA} + \frac{T_{HFET}}{G_{JPA}}$$



IDLER COMBINATION

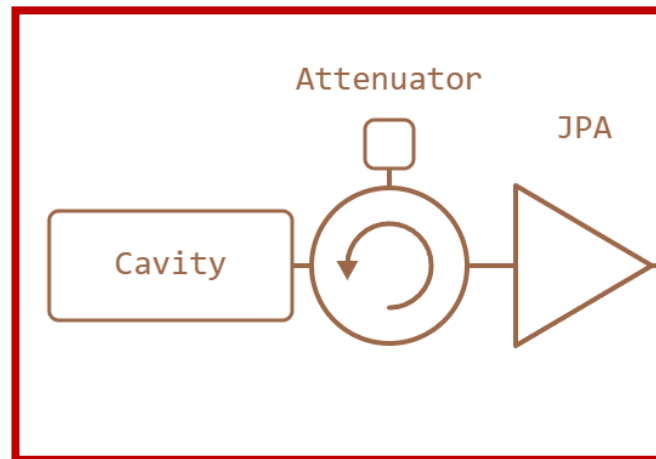
- JPA entangles signal and idler channels
- Noise added after the JPA is uncorrelated
- Averaging signal and idler bands reduces uncorrelated noise
 - 3-5% increase in SNR
- Signal and idler correlation provides independent measurement of noise temperature



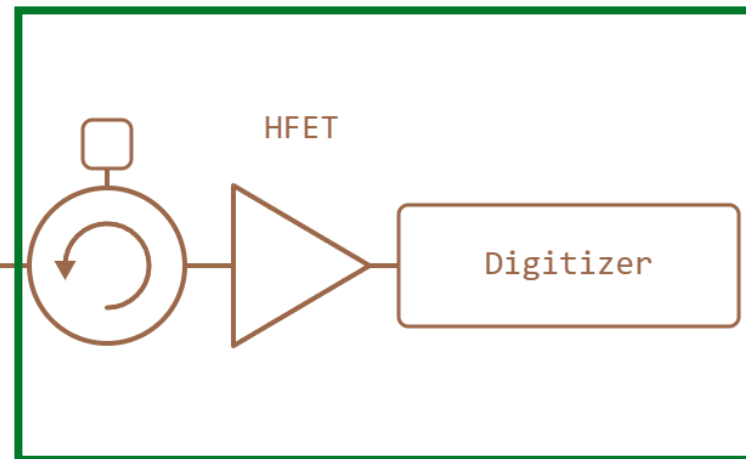
IDLER CORRELATION NOISE MODEL

- Idler correlation contains information about portion of noise coming from JPA, HFET
- $$T_{sys} = \frac{T_{cavity} + T_{attenuator} + T_{circulator} + T_{JPA}}{\sqrt{\rho}}$$
- Accounts for effects not considered in other two measurements such as standing waves and off-resonance behavior

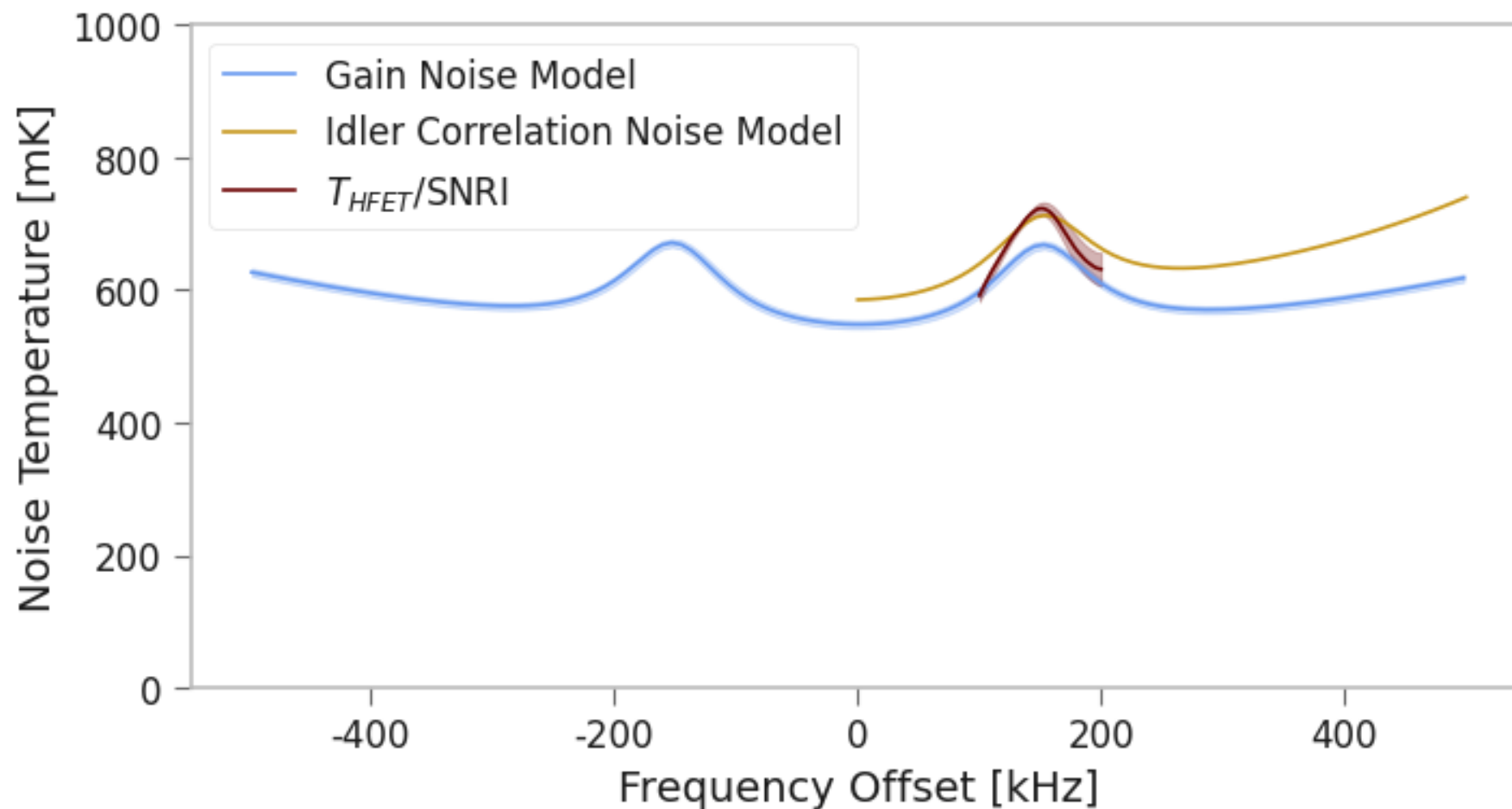
Noise Correlated by JPA



Noise Not Correlated by JPA

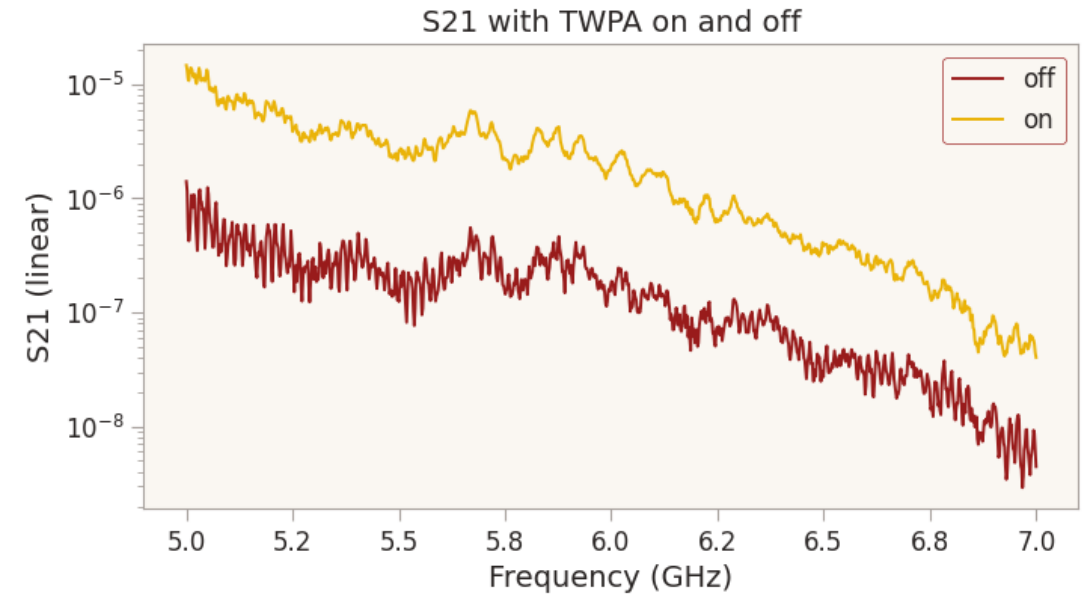


NOISE TEMPERATURE COMPARISON



KINETIC INDUCTANCE TRAVELING WAVE PARAMETRIC AMPLIFIER (KI-TWPA)

- Parametric amplification as signal propagates along transmission line
 - No resonant structure so gain is more broadband
- Kinetic inductance used instead of Josephson inductance
 - Less sensitive to magnetic fields
- Testing in ADMX-Sidecar
 - Operates without magnetic shielding
 - Achieved 13 dB of gain
 - Observed large attenuation in receiver chain



SUMMARY

- Quantum sensors enable haloscopes to be sensitive to QCD axion dark matter
- ADMX uses a JPA to approach quantum limited performance
- Several complimentary noise calibration methods determine noise sensitivity

Collaborating Institutions:

University of Washington
Washington University St. Louis
University of Western Australia
University of Florida
University of Sheffield
Illinois Institute of Technology

Swinburne University of Technology
Stanford University / SLAC
UC Berkeley
Harvard University
Fermilab
Pacific Northwest National Laboratory

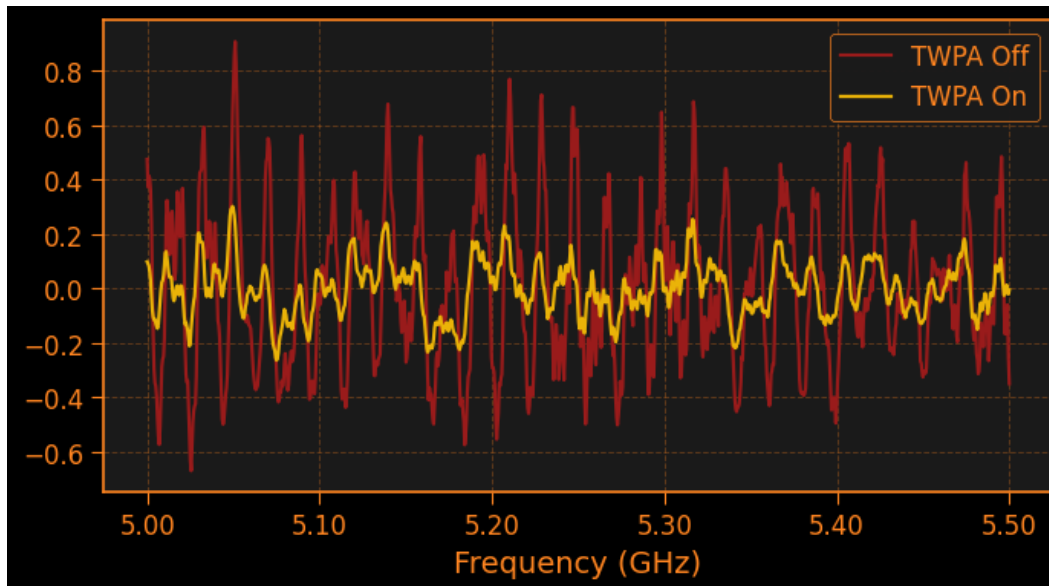
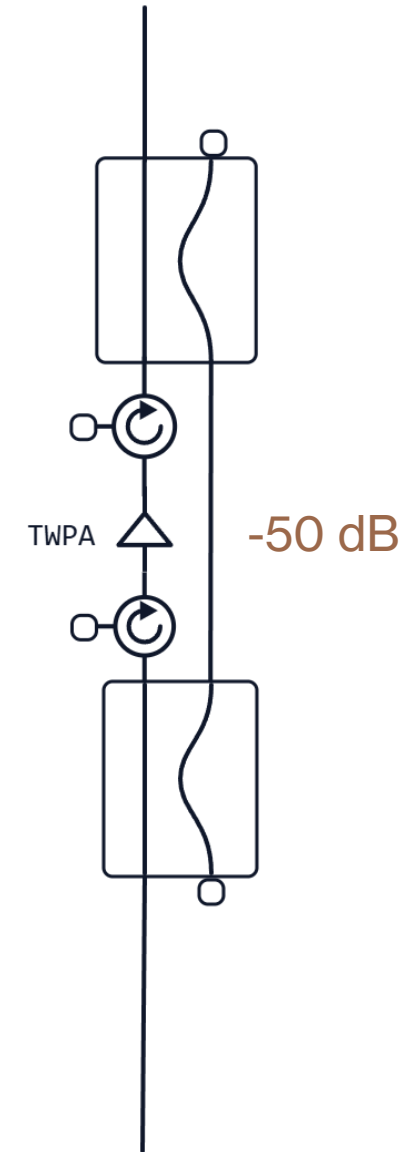
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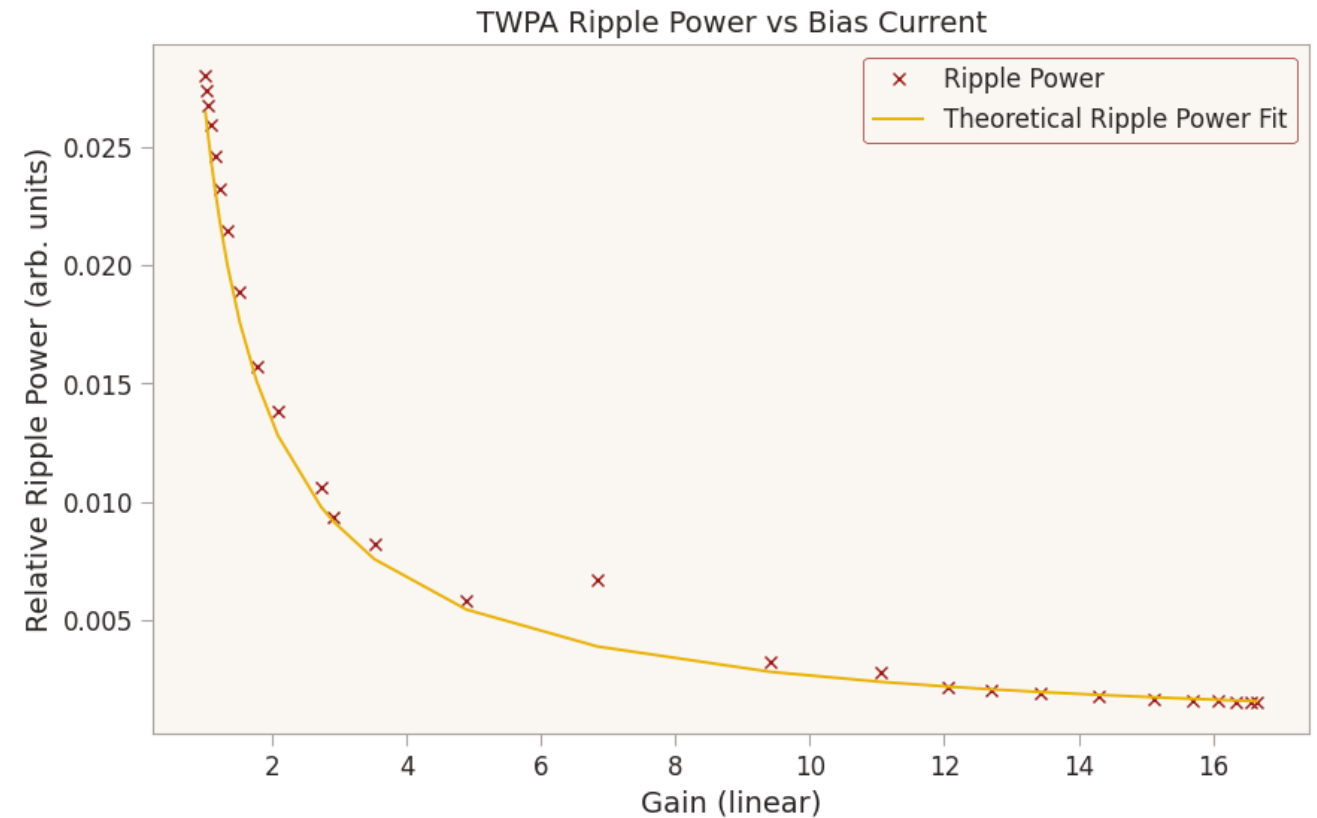
TWO PATH INTERFERENCE MODEL

- Two path interference between TWPA path and directional coupler path
 - Interference is large when power transmission through the two paths is similar in magnitude
 - Interference is small when the TWPA is on because much more power goes through the TWPA path
 - Requires large attenuation on the TWPA path



GAIN TEST

- Ripple power decreases with gain
- For gain G and power ratio between TWPA path and directional coupler R
- Ripple power $\propto \frac{GR}{(G+R)^2} \approx \frac{1}{G}$



CURRENT BIAS TEST

- Use current bias to vary electrical length of TWPA
 - Changes relative phase where signals are combined
 - Should see phase of interference fringes change
- Electrical length $L \propto L_0 + \alpha I^2$ for bias current I
 - Expect quadratic dependence of fringe phase on TWPA bias current

