RF Electronics Study

November 18, 2020

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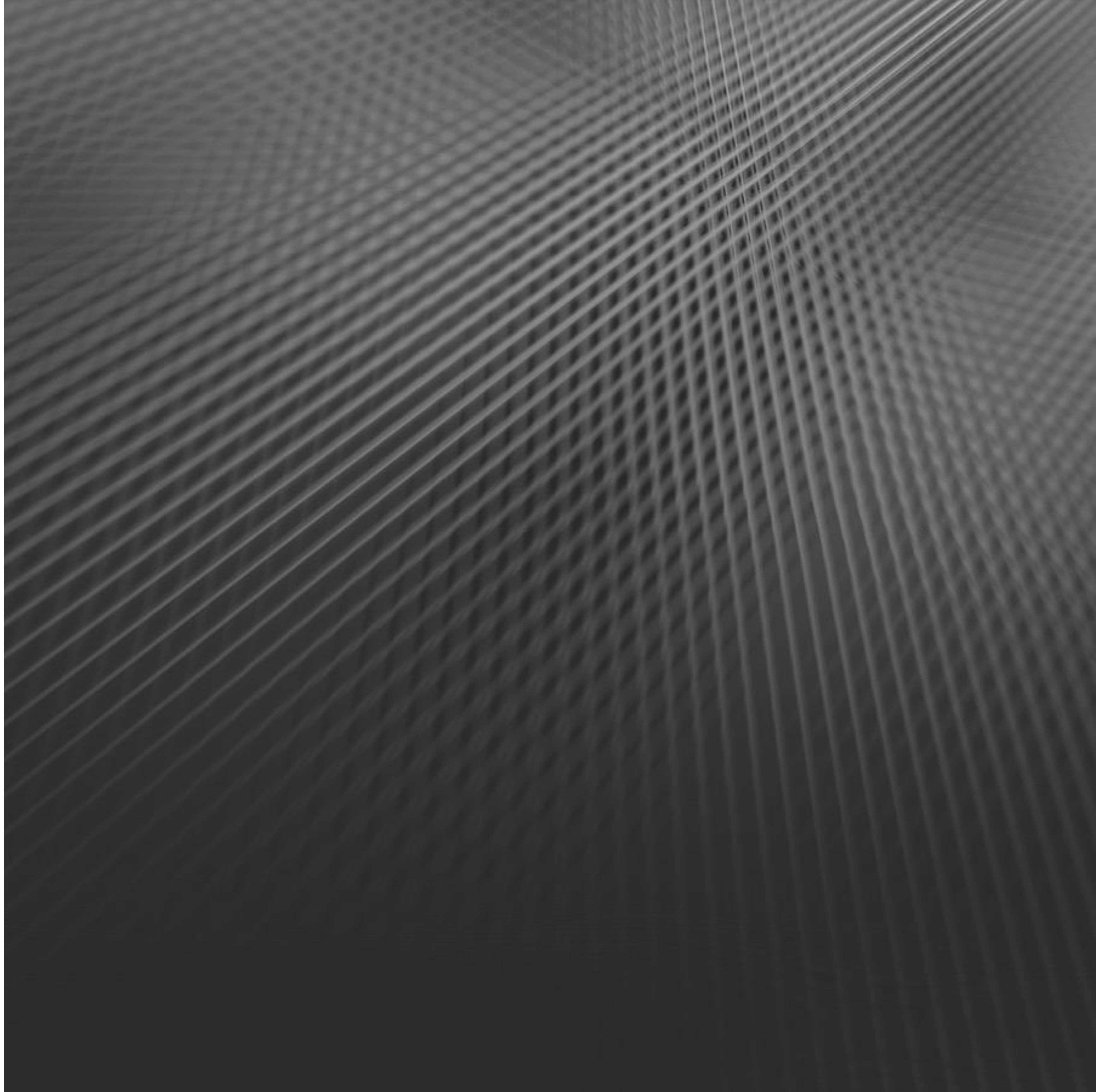
RF Engineer



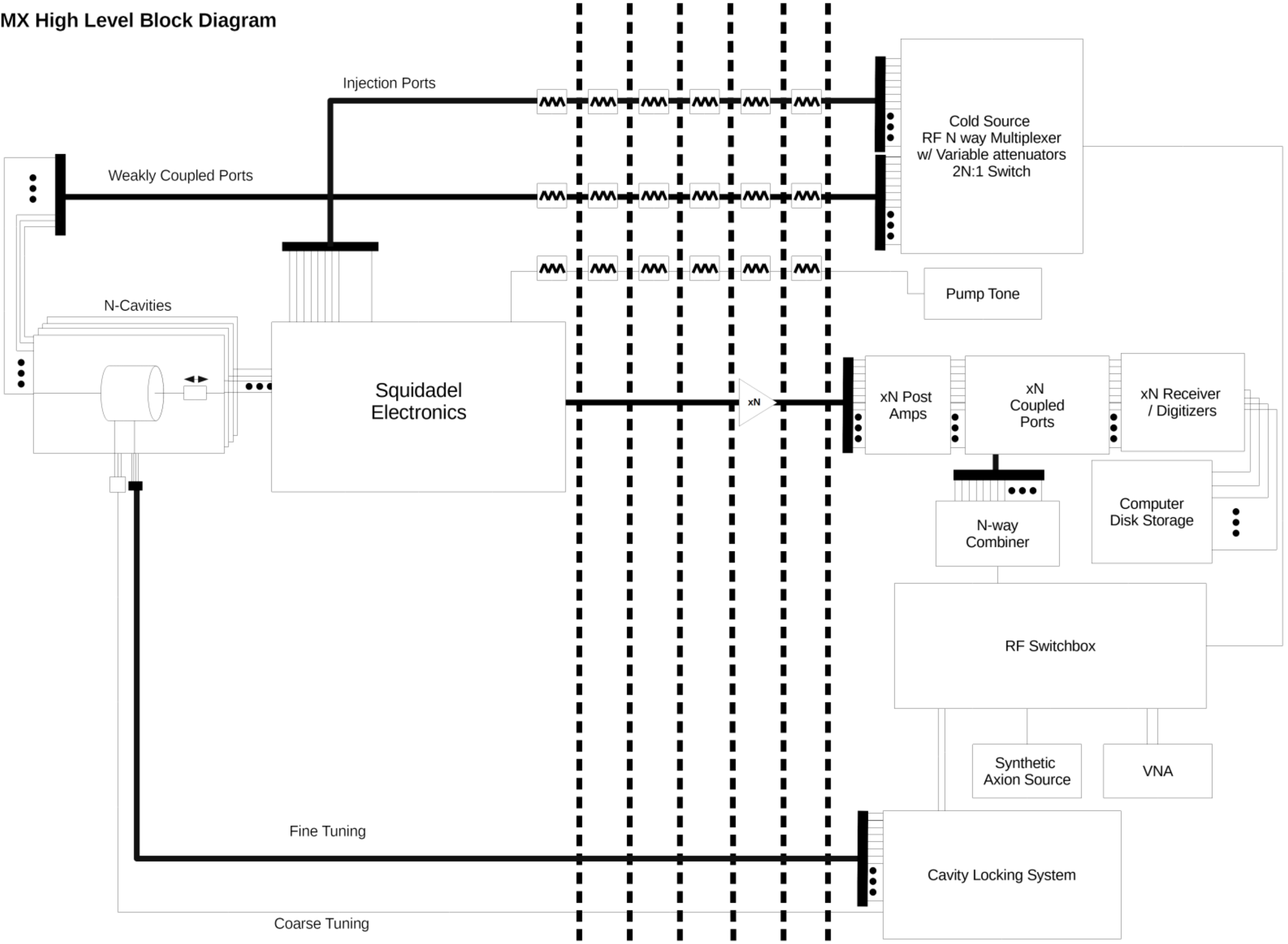
Outline

- ADMX 2-4 GHz RF System Level Architecture
- RF Architecture
  - Trade study Analog vs. Digital Combination
- RF System sensitivity tools
  - Effect of quantum thermal limit on measurements
  - Effects of loss before JPA
  - Calculating/Estimating/Using system integration time as a metric
- Using noise waves for cascading components
- Summary

ADMX 2-4 GHz RF System Level Architecture

- ADMX 2-4 GHz experiment:
  - Nominally 14 cavities
  - All 14 cavities must be coherently summed together.
    - Three possibilities:
      - Digital summation post processing.
      - Analog summation vis passive combiner
      - Combination of the above two methods.
  - Any phase or amplitude error when summing cavities will degrade system SNR.
  - Approach must allow for tuning/locking cavities.
  - Approach must allow for calibration

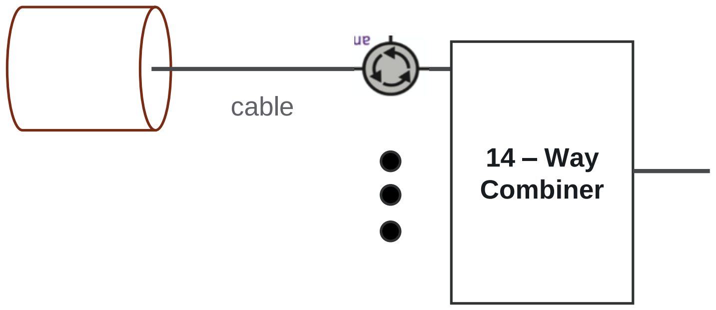
ADMX High Level Block Diagram



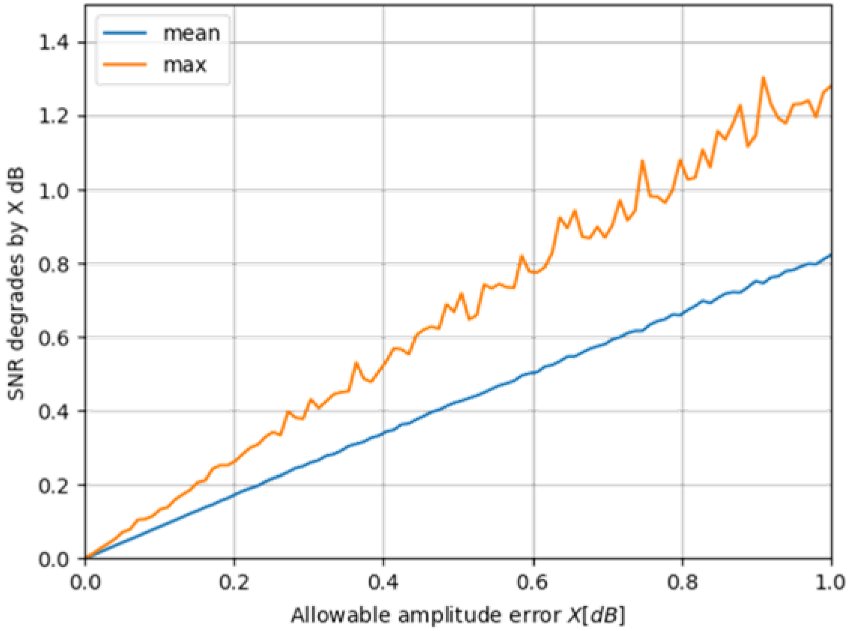
Based on ADMX run 2A Layout

RF Architecture Trade study – Passive Combination

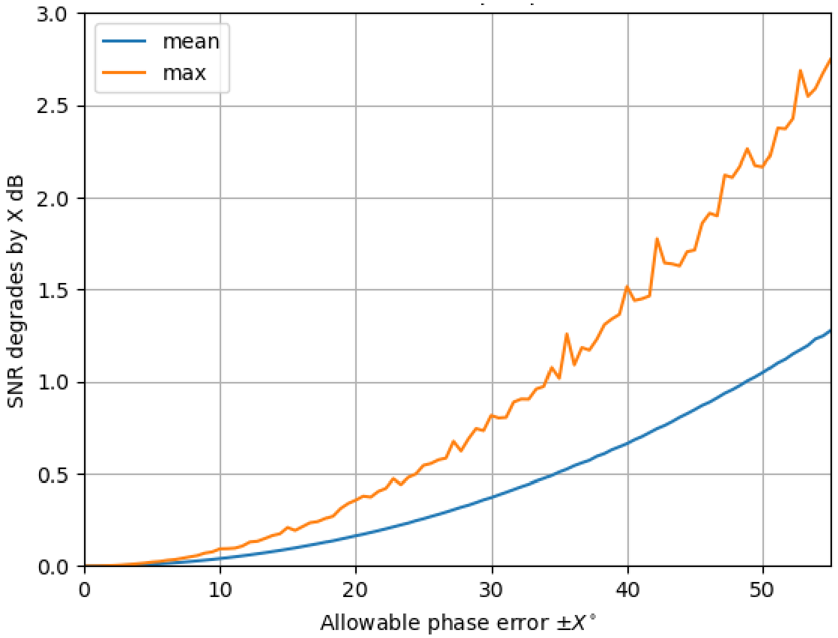
Assume random phase/amplitude errors on each channel of a 14-channel combiner



Amplitude

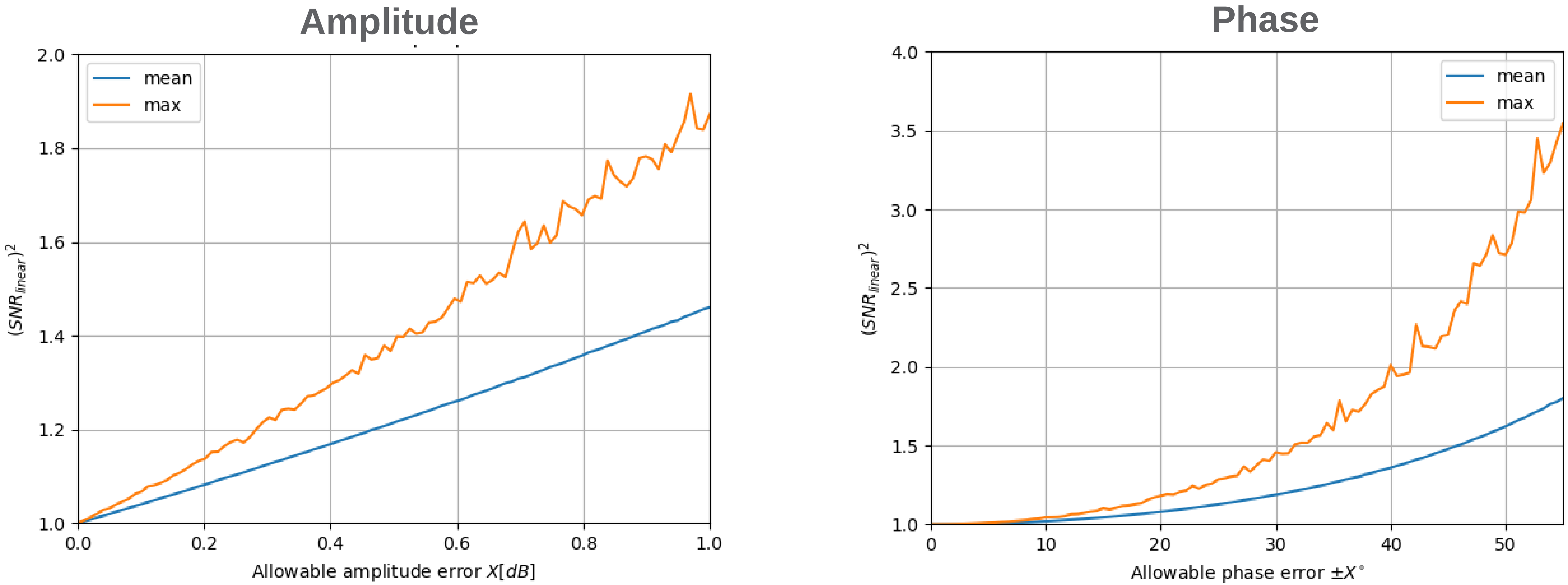


Phase



- The plots above are monte-carlo simulations 10,000 runs per point on a 14-way combiner
    - Randomly distributed phase or amplitude
- SNR result represents total system variation budget across all cables, circulators, couplers, and interfaces leading to combiner as well as in the combiner itself.
- **At 4 GHz in a cable (dk=2.1) 20 degrees of phase is 2.87 mm**
- **At 4 GHz in a cable (dk=2.1) 40 degrees of phase is 5.74 mm**

Same Data in Terms of SNR^2

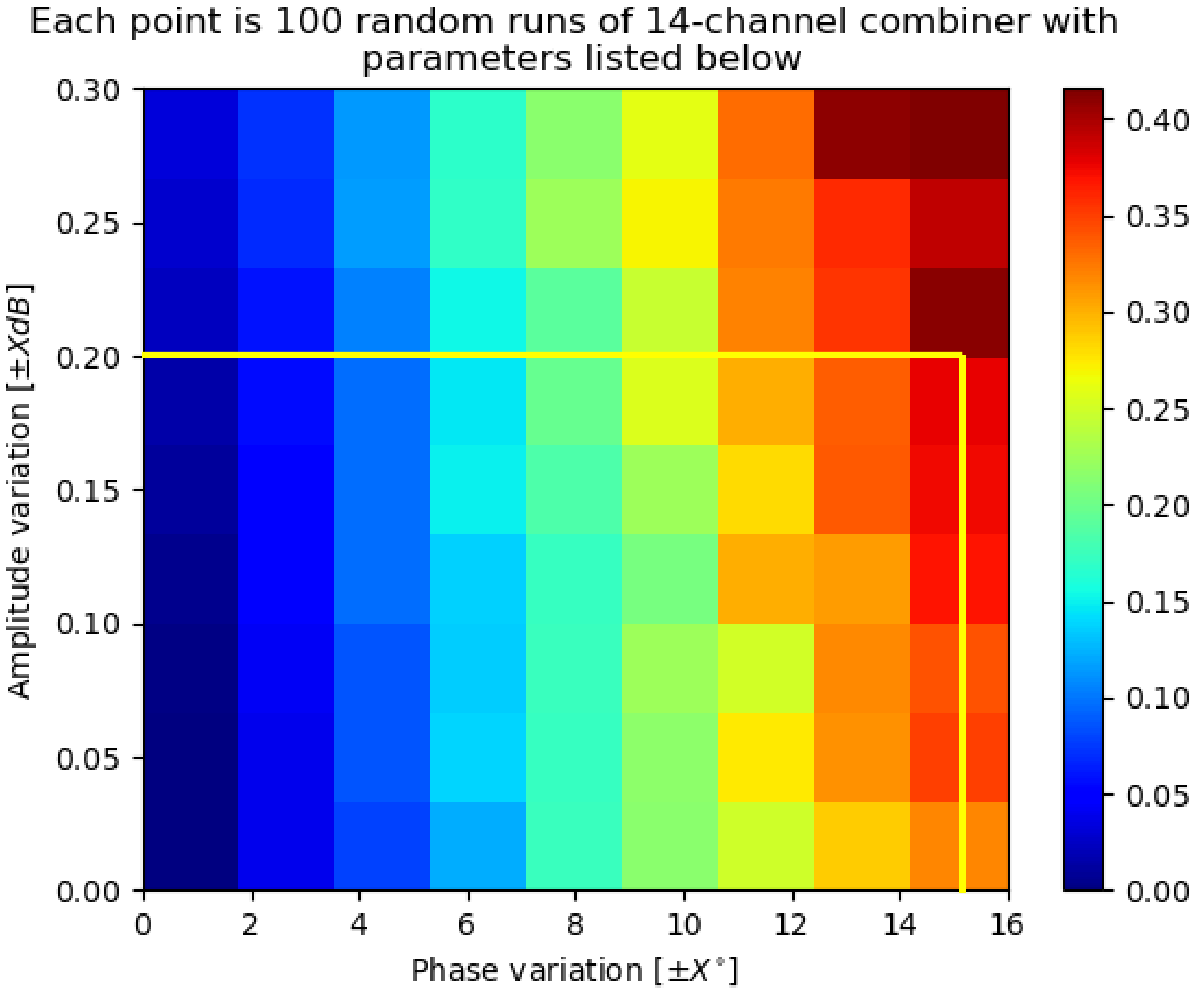


- Useful since integration time is proportional to SNR^2
- SNR is linear here if you are comparing to previous plot
- **At 4 GHz in a cable (dk=2.1) 20 degrees of phase is 2.87 mm**
- **At 4 GHz in a cable (dk=2.1) 40 degrees of phase is 5.74 mm**

Requirements Analysis combining: Amplitude and Phase

- I want a maximum SNR degradation of 0.5 dB (1.26 SNR^2)
  - Budget half to phase and half to amplitude
  - Each channel must be within ±15º phase and channel amplitude within ±0.2 dB variation
- Digital combiner can calibrate
  - There will be some errors from the calibration setup.
  - More investigation is needed to analyze tolerances of calibration schemes

SNR degradation



Digital Vs. Analog Combining Decision Matrix

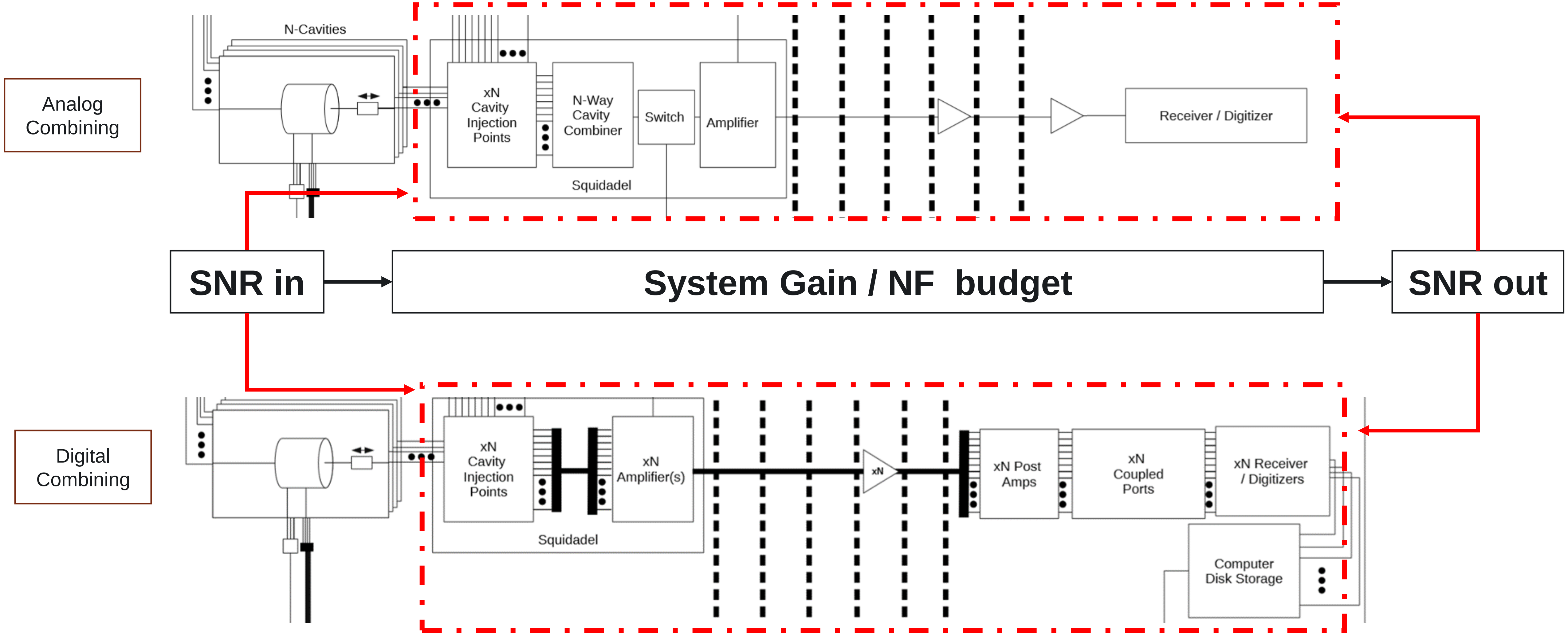
	Digital Combining	**Analog Combining**
Pros	• Better resiliency against a failed cavity • Easier to calibrate and verify each cavity is critically coupled • Lower T_{sys} → More margin on cavity temperature	• Less data to collect and process • Fewer cables routed out of the dilution fridge
Cons	• More data to disk (14-channels) • More data to post-process • More JPAs • x14 more RF cables routed out of dilution fridge	• **Harder to calibrate** • Phase and amplitude errors before combiner directly affect SNR

- This table captures where we left the Analog Vs. Digital combination discussion.
- Theoretically we should be able to calibrate out the individual channel phase differences using the digital approach.
- **Its safe to say we are leaning heavily toward digital combination but**….
    - Still need a good method of calibrating out channel phase differences for digital scheme.

RF System Sensitivity

- Already discussed channel-to-channel sensitivity to amplitude and phase variations on SNR.
  - That discussion also applicable to the digital combining calibraton method.
- This next section will concentrate on
  - Effect of Quantum thermal limits on measurements
  - Effects of loss before JPA
  - Calculating/Estimating/Using system integration time as a metric

Requirements Flow down for Two Approaches



Analog Combining

Digital Combining

SNR in

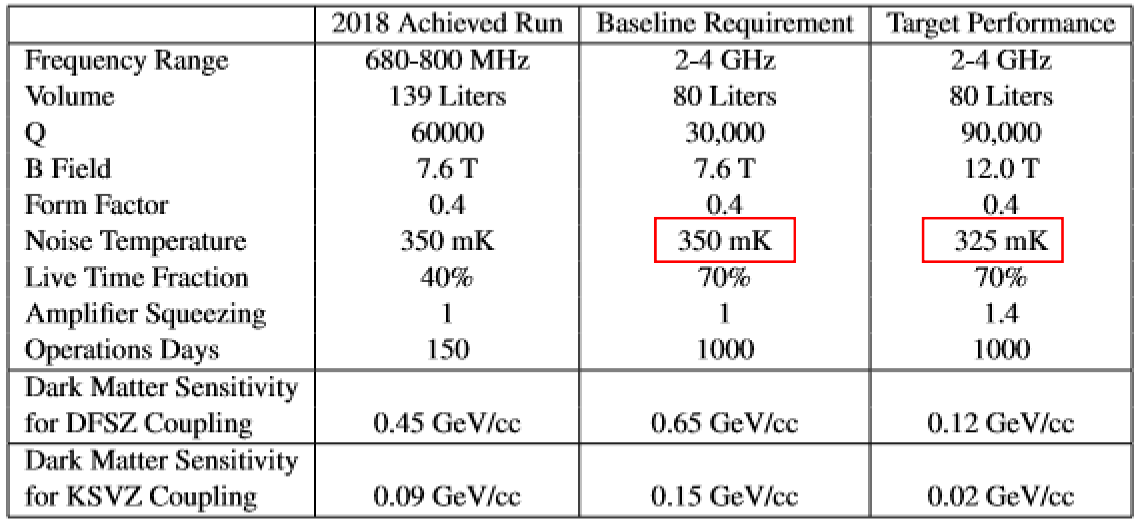
System Gain / NF budget

SNR out

- Overall System Noise Temperature requirements will set how much can be allocated to each subsystem regardless of approach.

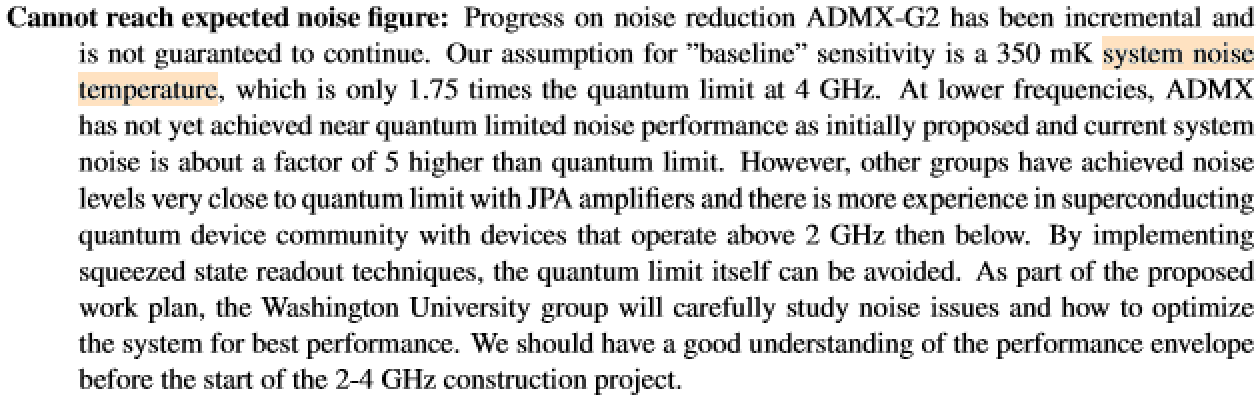
Proposal System Noise Budget

- Assume Desired 350 mK system noise temperature requirement
- Also compare to goal of 325 mK system noise temperature



	2018 Achieved Run	Baseline Requirement	Target Performance
Frequency Range	680-800 MHz	2-4 GHz	2-4 GHz
Volume	139 Liters	80 Liters	80 Liters
Q	60000	30,000	90,000
B Field	7.6 T	7.6 T	12.0 T
Form Factor	0.4	0.4	0.4
Noise Temperature	350 mK	350 mK	325 mK
Live Time Fraction	40%	70%	70%
Amplifier Squeezing	1	1	1.4
Operations Days	150	1000	1000
Dark Matter Sensitivity for DFSZ Coupling	0.45 GeV/cc	0.65 GeV/cc	0.12 GeV/cc
Dark Matter Sensitivity for KSVZ Coupling	0.09 GeV/cc	0.15 GeV/cc	0.02 GeV/cc

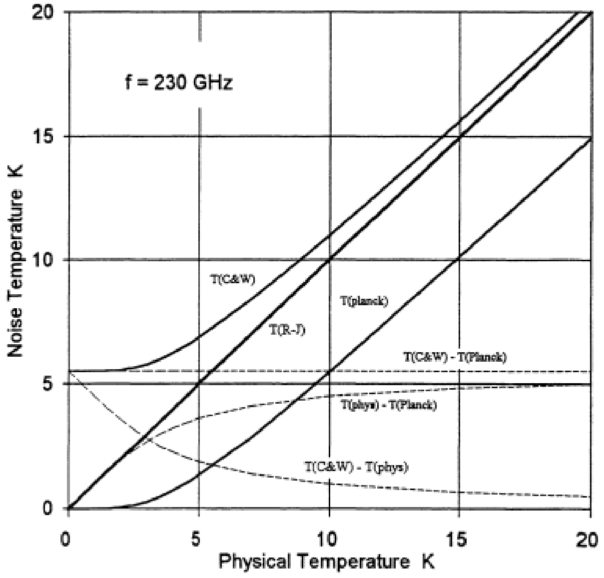
Table 1: Parameters for the most recent operation of ADMX and an example parameter set with enhanced quality factors, squeezing, and a new magnet that would allow completion of the proposed frequency ranges in a reasonable operations time.

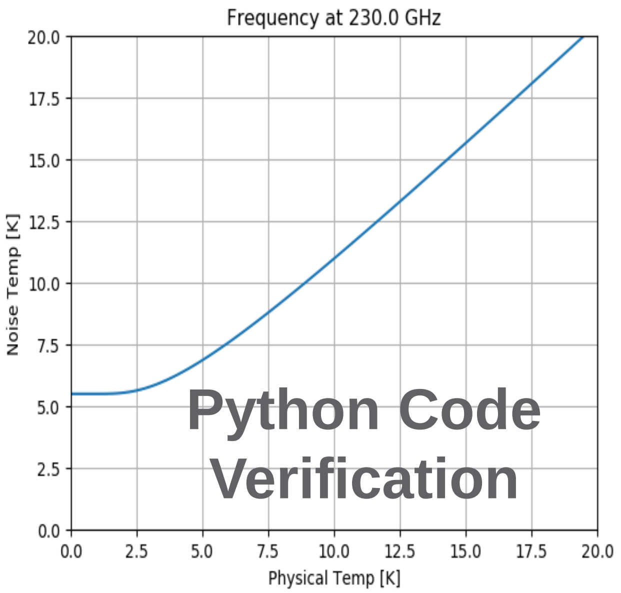


Cannot reach expected noise figure: Progress on noise reduction ADMX-G2 has been incremental and is not guaranteed to continue. Our assumption for ”baseline” sensitivity is a 350 mK system noise temperature, which is only 1.75 times the quantum limit at 4 GHz. At lower frequencies, ADMX has not yet achieved near quantum limited noise performance as initially proposed and current system noise is about a factor of 5 higher than quantum limit. However, other groups have achieved noise levels very close to quantum limit with JPA amplifiers and there is more experience in superconducting quantum device community with devices that operate above 2 GHz then below. By implementing squeezed state readout techniques, the quantum limit itself can be avoided. As part of the proposed work plan, the Washington University group will carefully study noise issues and how to optimize the system for best performance. We should have a good understanding of the performance envelope before the start of the 2-4 GHz construction project.

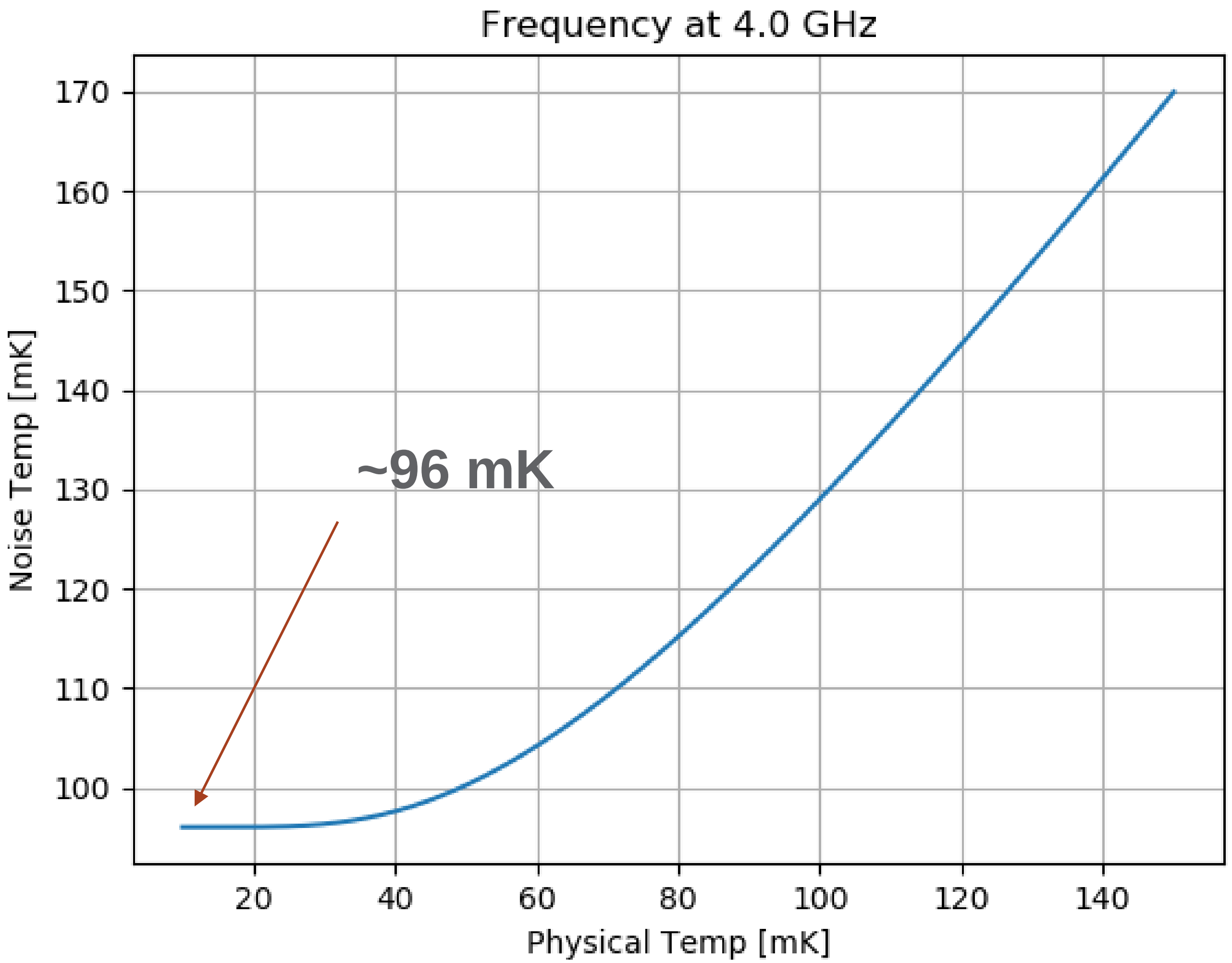
Thermal Noise Model

$$T^{C\&W} = T\left[\frac{\frac{hf}{kT}}{\exp\left[\frac{hf}{kT}\right]-1}\right] + \frac{hf}{2k} = \frac{hf}{2k}\coth\left(\frac{hf}{2kT}\right)$$





Python Code Verification



~96 mK

- This is the thermal noise model for all the data from this slide onward

Noise Temperature Friis Cascade Parameters

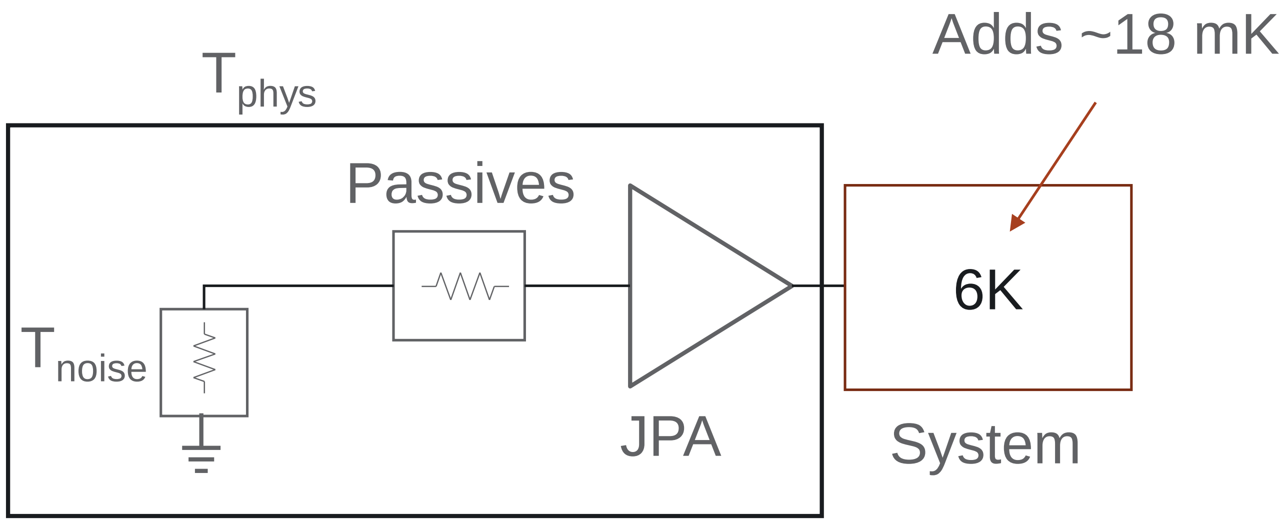
Variable	Value
Tsys	350 mK (goal 325 mK)
Gain JPA	26 dB (398 linear)
Noise Temp JPA	From Cave eq 3.4b: $T_{n0} \geq \frac{\hbar\omega_I}{k}\left[\ln\left(\frac{3 \mp G^{-1}}{1 \mp G^{-1}}\right)\right]^{-1} \longrightarrow \frac{\hbar\omega_I}{k\ln 3}$
Remaining System Noise Temp budget	6 K (includes cables, HEMT amp, and external electronics)

$$T_{sys} = T_{noise} + T_{rx\ cascade}$$

$$T_{noise} = \frac{hf}{2k}\coth\left(\frac{hf}{2kT_{phys}}\right)$$

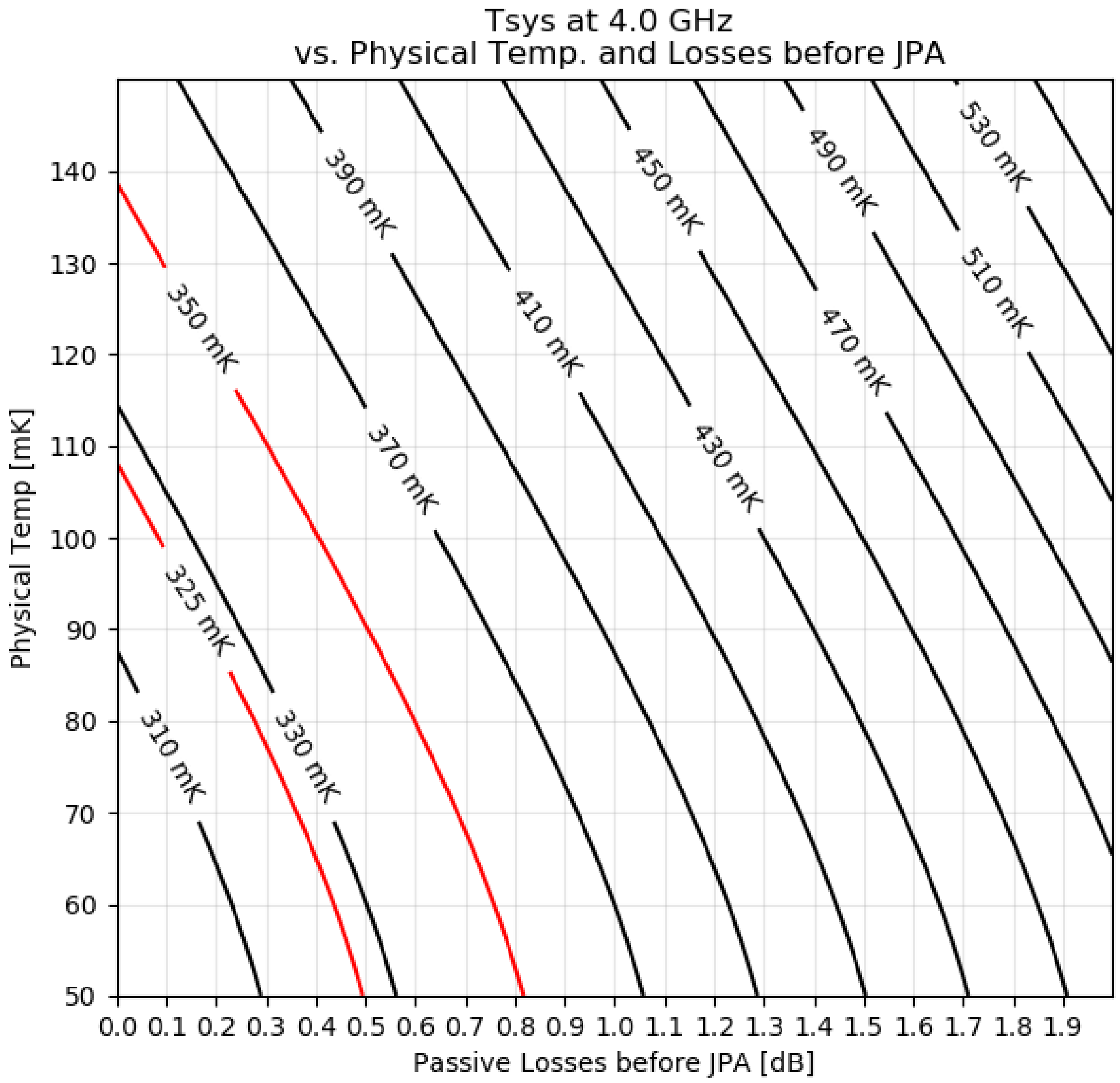
$$T_{rx\ cascade} = (A-1)*T_{noise} + A\,(T_{JPA}) + A*(T_{HEMT}/G_{JPA})$$

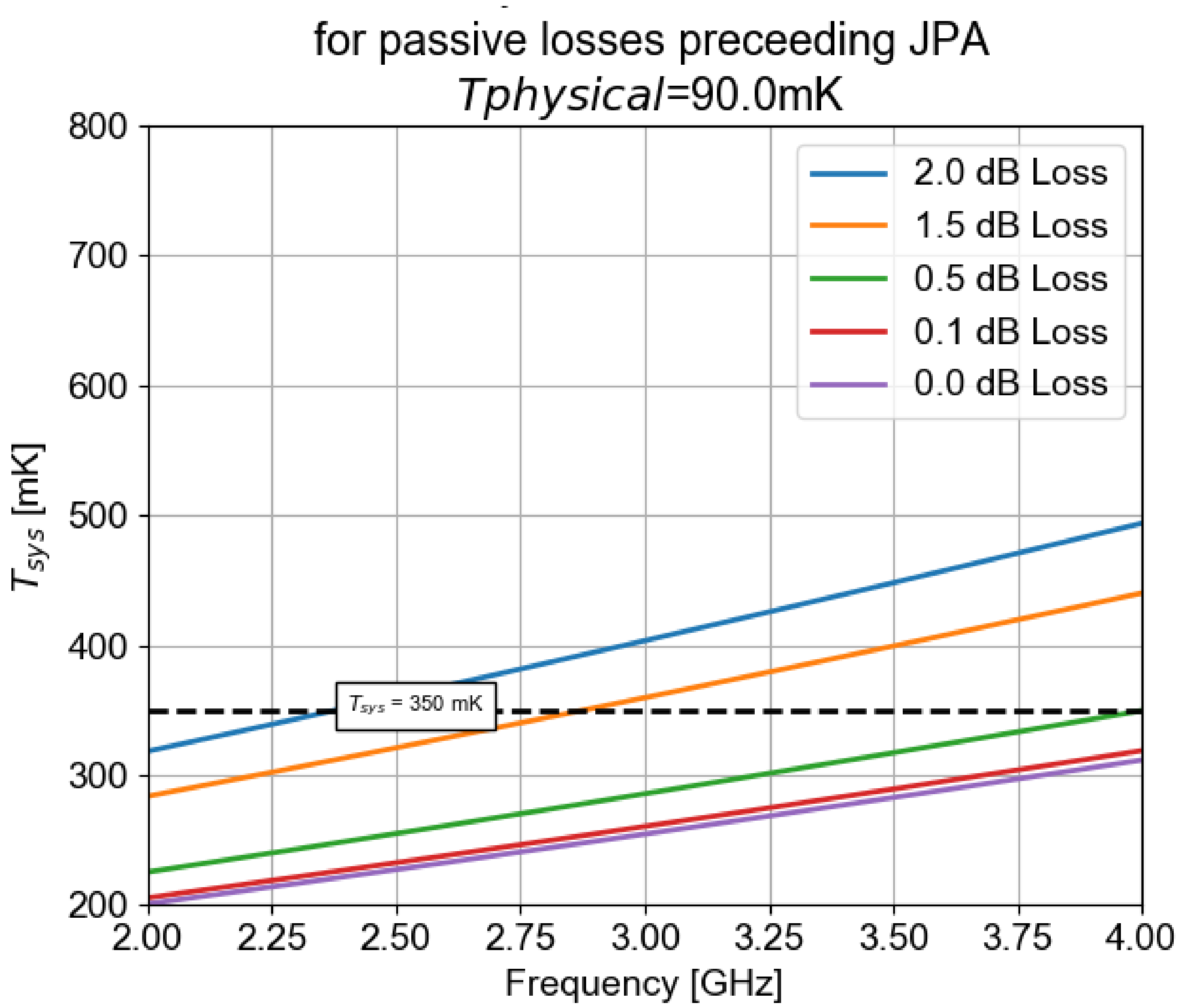
- Where $A = 1/(G_{passive})$, $A \geq 1$



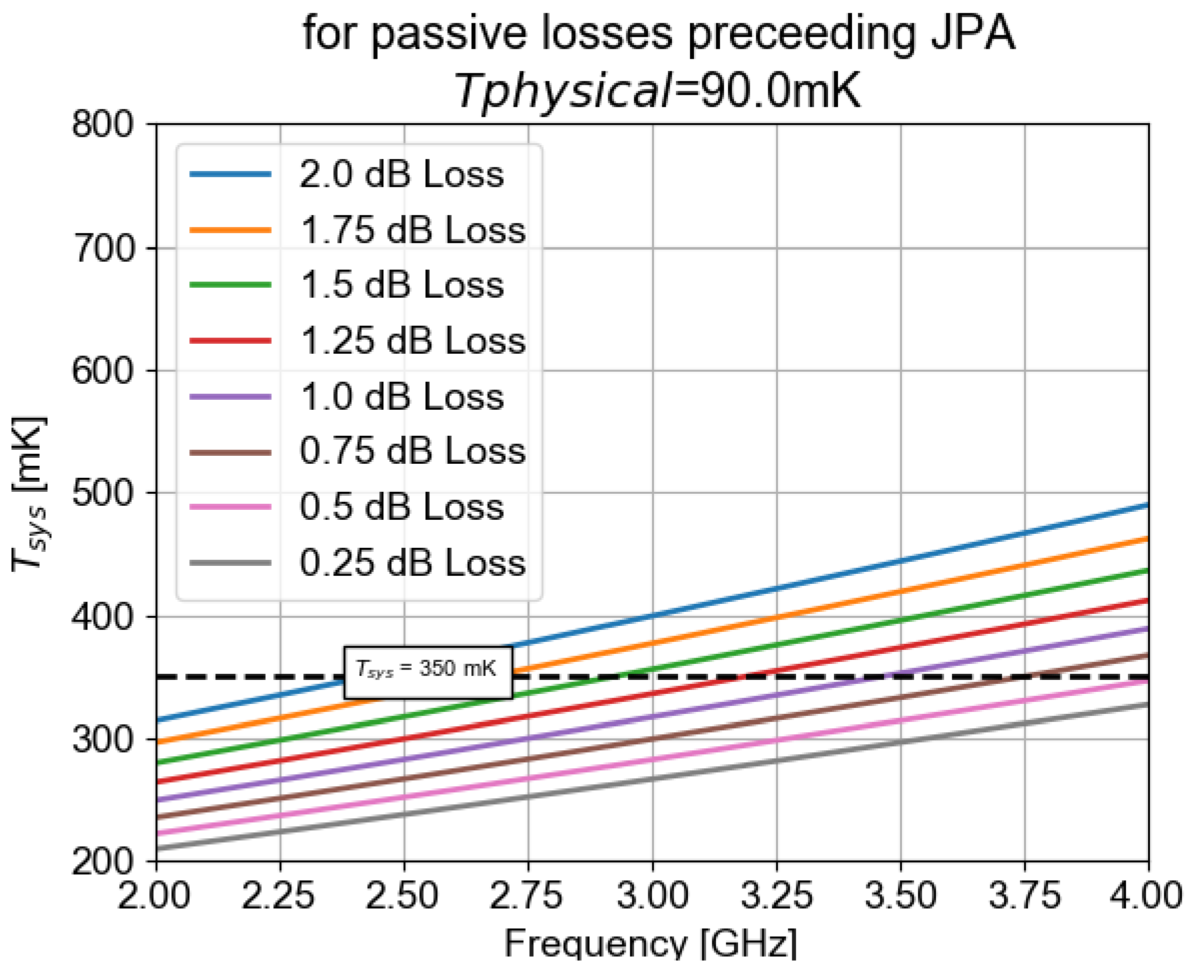
Simple model of $T_{rx\ cascade}$

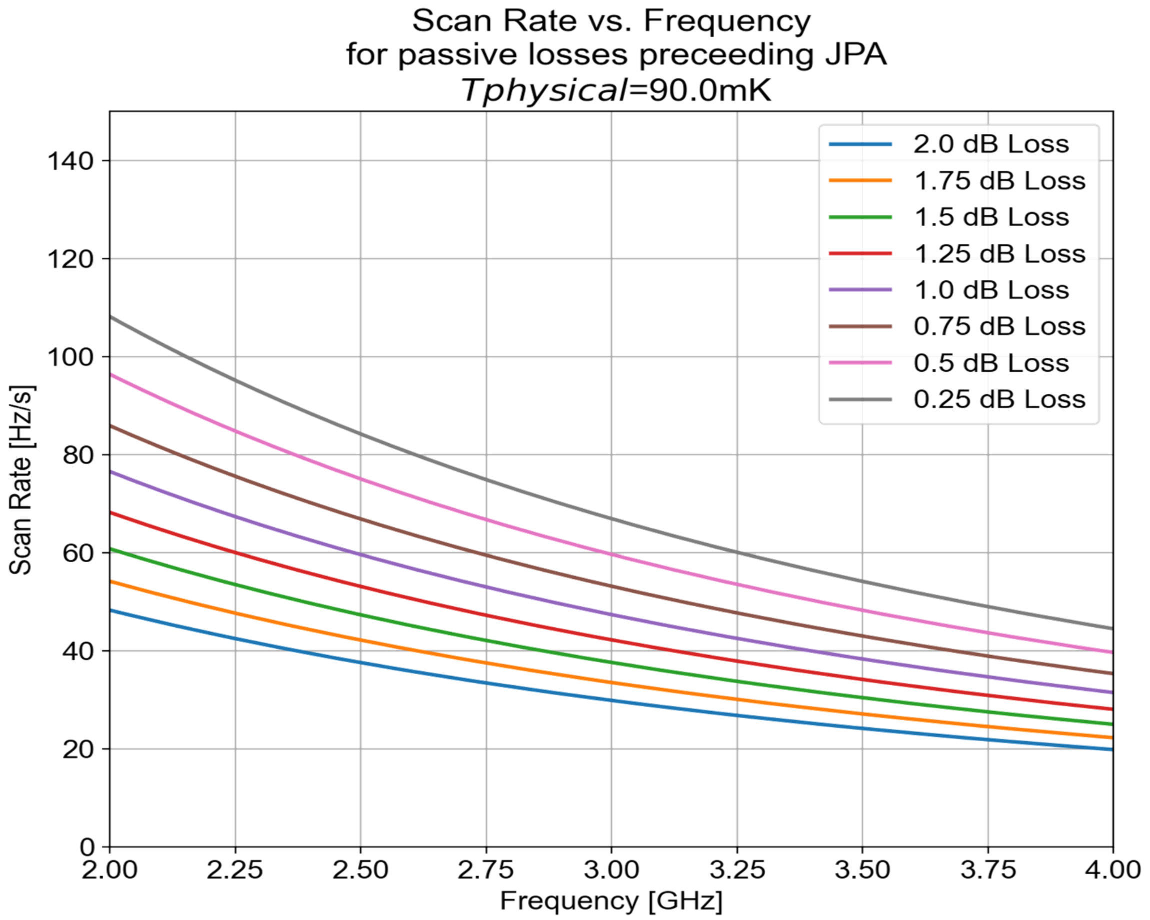
Updated Noise Temperature





Move Metric From Noise Temperature to Integration Time


for passive losses preceeding JPA
Tphysical=90.0mK


Scan Rate vs. Frequency
for passive losses preceeding JPA
Tphysical=90.0mK

- Decided to use scan rate to score different RF approaches
  - Also open to using the integral of the curves on the right to get a total scan time.
  - This is an unimpeded scan rate (no down time is currently considered)

How I Measure Scan Rate

- Calculate Tsys for a given architecture – covered in my previous slides.
- Use mean axion power
- Calculate Integration time for:
  - 6 dB SNR
  - Mean axion power
  - Tsys from RF stackup
  - BW = F[GHz]/(1e6) as an approximation
- Scan rate = (F[Hz]/Q) / integration time

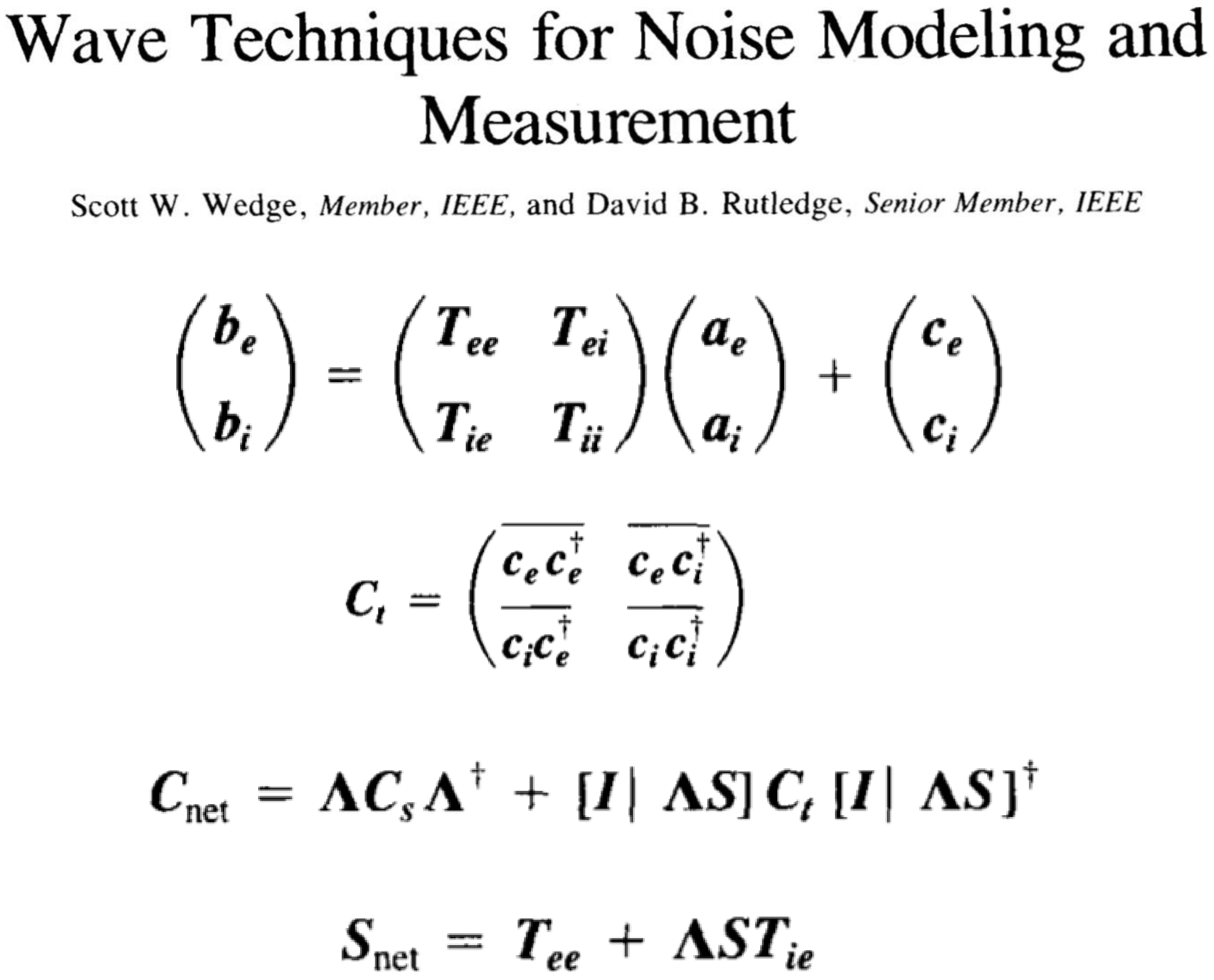
$$SNR = \frac{P_{out}}{k_B T_{sys}} \sqrt{\frac{t}{B}}$$

```
Ga = .36
B = 7.6 #Magnet in T
V = 80 # volume liters
Q = 30000 #Q of the cavity
FF = 0.4 # form factor
kappa = 0.5 #power transfer

Ps = AxionPower(Ga, B, V, F*(1e9), Q, FF,kappa)
Ps = np.mean(Ps)
```

Using Noise Wave Techniques for Cascading Components

- Part of Christians LDRD to explore RF architectures for high frequency (>4 GHz) axion detection.
- Developed a <u>multi-port cascade version</u> that is currently integrated into a personal fork of scikit-rf.
  - Pull request for scikit started mid-October
    - ✓ Will include noise waves
    - ✓ Will include thermal noise model
- Used papers provided by collaboration to develop python code.



Wave Techniques for Noise Modeling and Measurement

Scott W. Wedge, *Member, IEEE,* and David B. Rutledge, *Senior Member, IEEE*

$$\begin{pmatrix} b_e \\ b_i \end{pmatrix} = \begin{pmatrix} T_{ee} & T_{ei} \\ T_{ie} & T_{ii} \end{pmatrix} \begin{pmatrix} a_e \\ a_i \end{pmatrix} + \begin{pmatrix} c_e \\ c_i \end{pmatrix}$$

$$C_t = \begin{pmatrix} \overline{c_e c_e^\dagger} & \overline{c_e c_i^\dagger} \\ \overline{c_i c_e^\dagger} & \overline{c_i c_i^\dagger} \end{pmatrix}$$

$$C_{\text{net}} = \Lambda C_s \Lambda^\dagger + [I \mid \Lambda S] C_t [I \mid \Lambda S]^\dagger$$

$$S_{\text{net}} = T_{ee} + \Lambda S T_{ie}$$

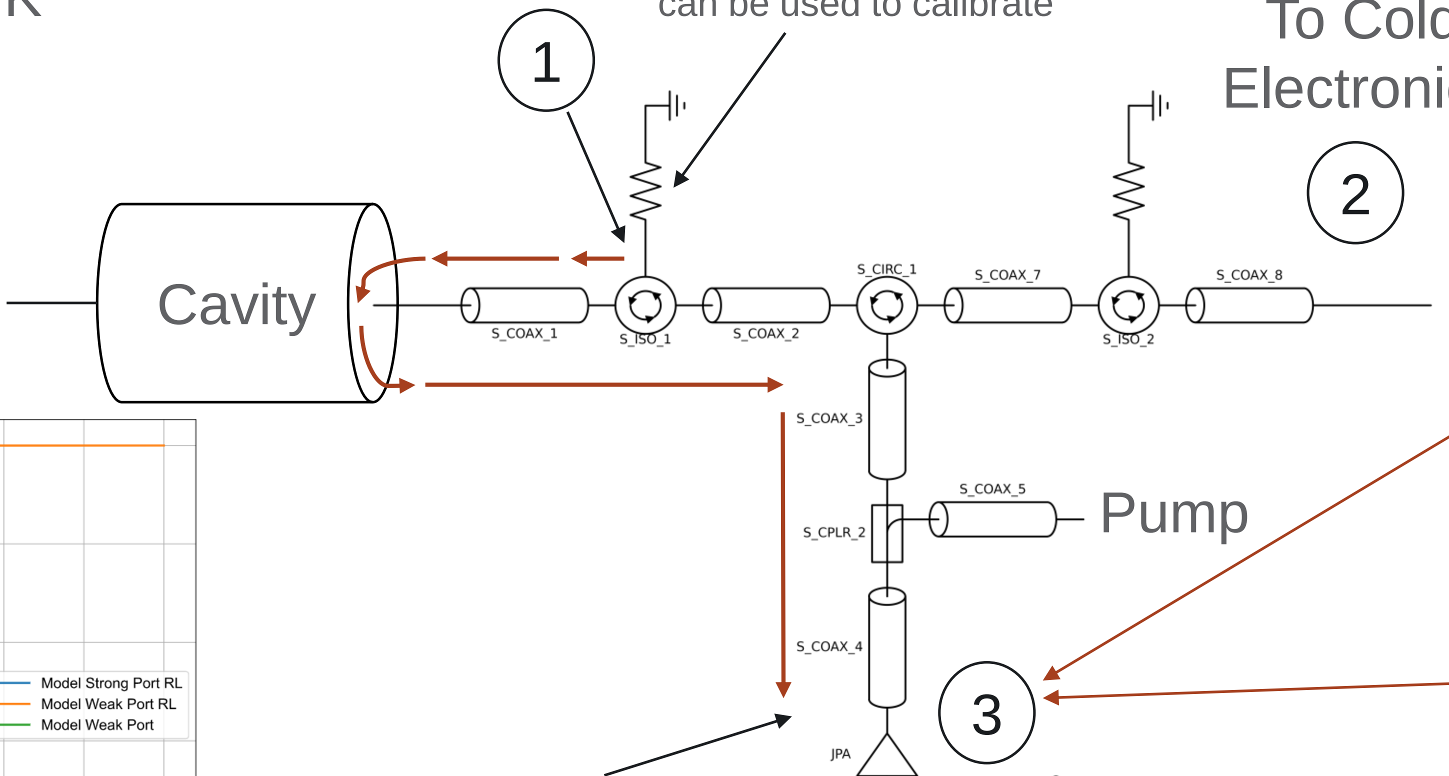
In progress Example #2

T phys = 290 K currently

Weakly Coupled Port (Terminated)

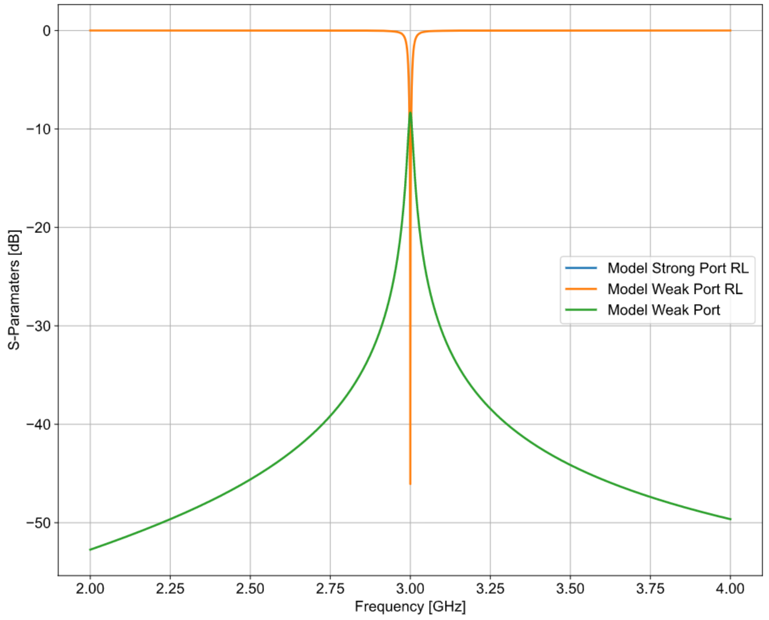
Heat load up and see if it can be used to calibrate

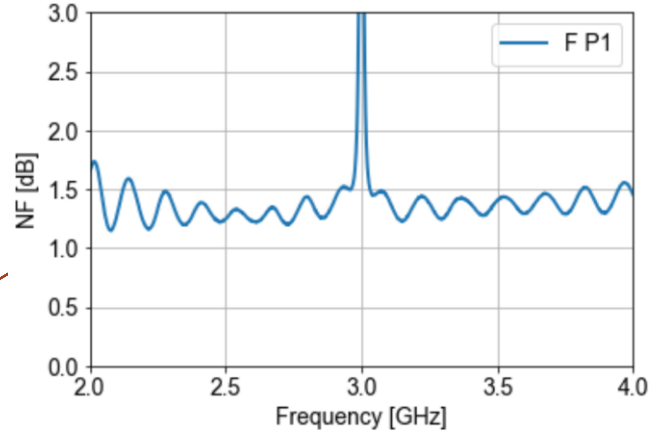
To Cold Electronics

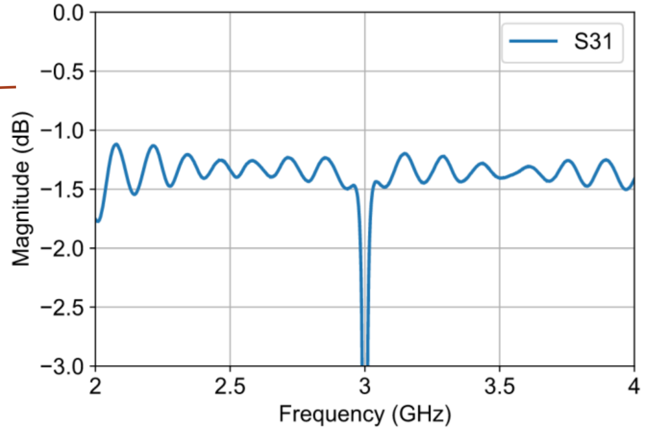


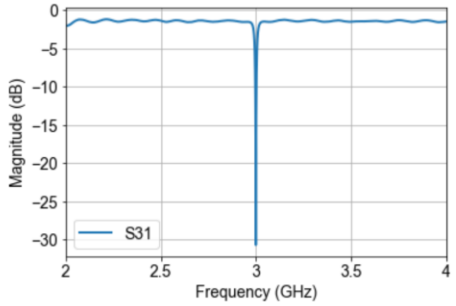
Pump

Current sim looks at input to JPA.





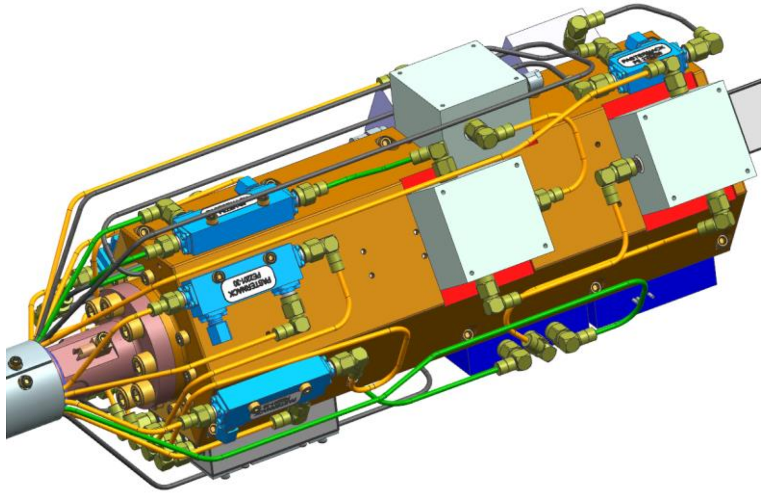




- This example, proposed by GP last cold electronics meeting is still being worked out.
- Plans are to try a measurement at room temp to verify noise cascade chain.

Summary

- Analog vs. Digital combiner
  - Digital is the current leading design
    - Still need a good calibration method for coherent summation of all channels.
- Toolbox
  - Friis cascade good for initial calculations
    - Solid basis for understanding and allocating loss/NF budget to different subsystems
    - Minimizing loss before JPA is critical.
  - Noise wave cascading
    - Can have deeper fidelity into noise temperature of the system
    - Takes mismatches and directional components isolation into account
  - Integration Time as a metric
    - Consistent metric for all RF Architecture approaches.
    - Good way to score design changes
- Current/Future work
  - RF Architecture of Squidadel electronics
    - Schematic and BOM of modular design proposed by Andrew.
    - Use above toolbox to evaluate metrics



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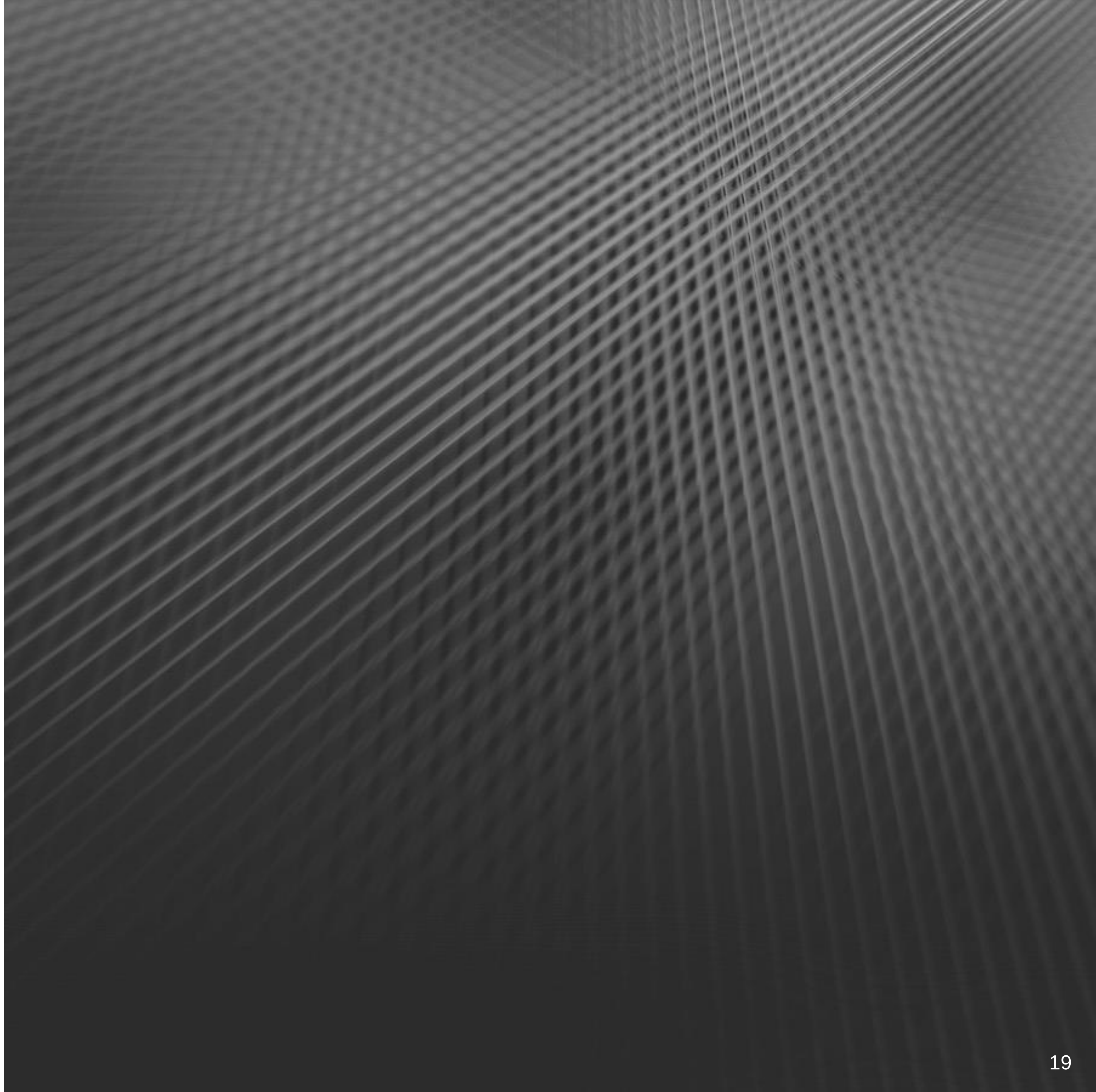
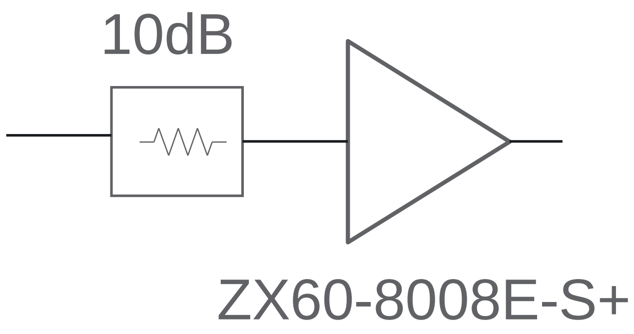
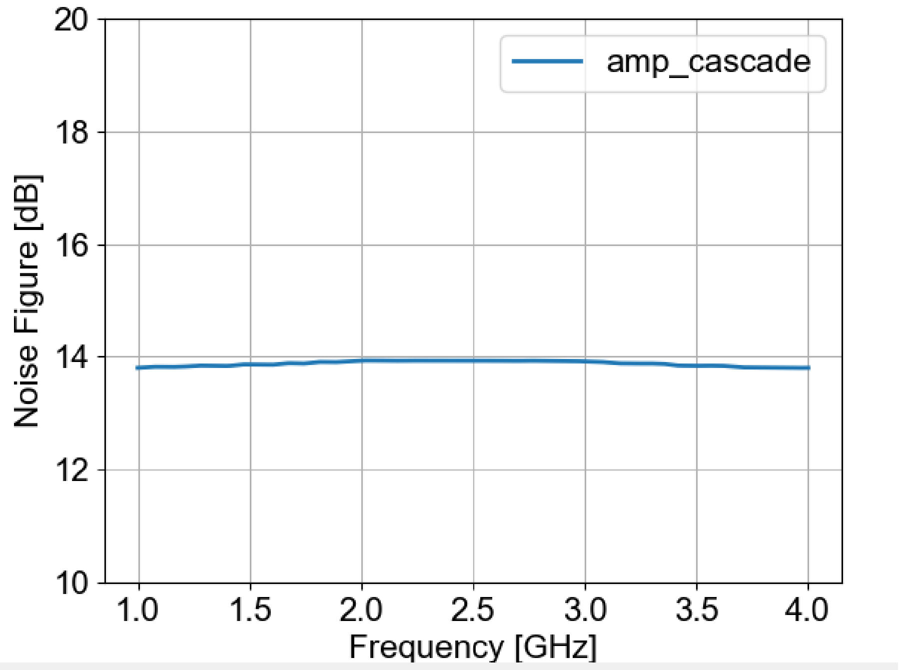
Thank you

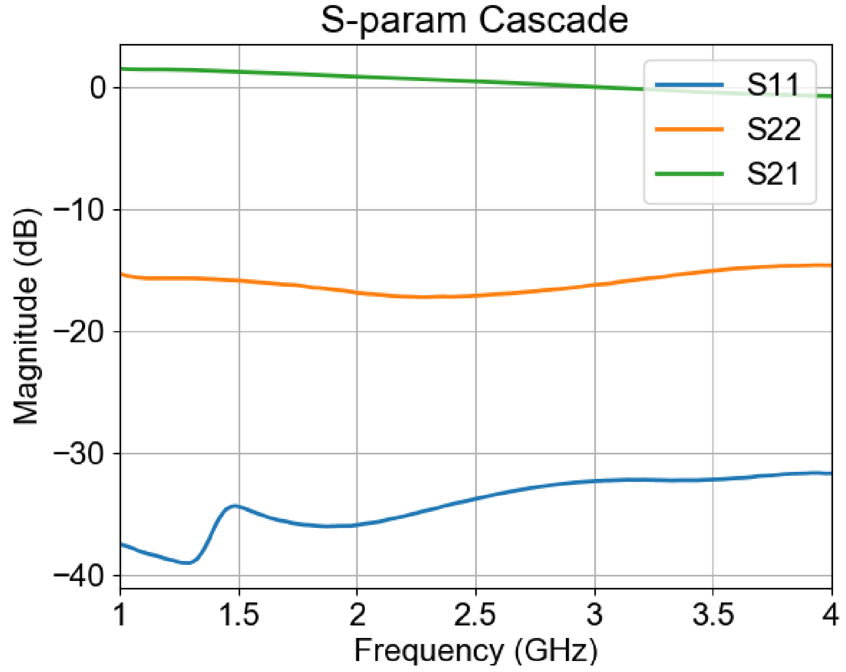


Small Example #2

$$F_i = \frac{1}{k_B T_0} \frac{k_B T_0 \mathbf{SAS}^\dagger + \overline{\mathbf{cc}^\dagger}\}_{ii}}{\mathbf{SAS}^\dagger\}_{ii}} = 1 + \frac{\overline{\mathbf{cc}^\dagger}\}_{ii}}{k_B T_0 \mathbf{SAS}^\dagger\}_{ii}}, \tag{13}$$







- This example is a toy problem to test out cascade program
  - Amp noise figure @3GHz is 4.0 dB / Gain 10 dB
  - Expected noise figure at 3GHz 13.9 dB
  - This shows that we can at least approximate the noise covariance matrix from an Amp
  - More investigation required so far everything at room temp.