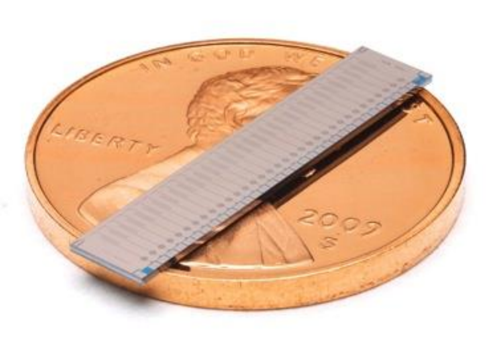
DESIGN EVOLUTION OF A 2000 CHANNEL MICROWAVE SQUID MULTIPLEXER



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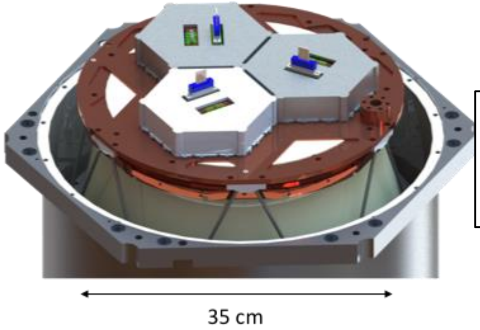
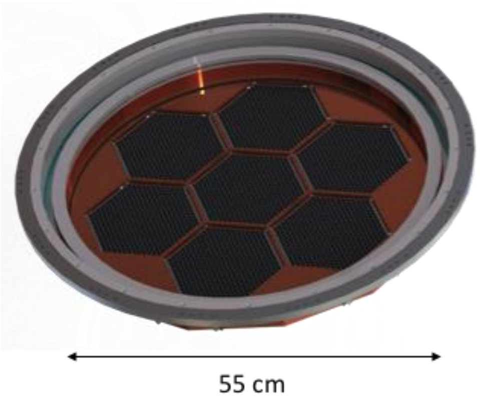
µMUX Design Driven by Upcoming CMB Instruments

- Push Towards Tiled arrays:
  - Require readout to be packed behind focal plane
  - Drives physical channel density on chip
- Readout Noise is Paramount, however:
  - Crosstalk (<0.5%) and Yield (>90%) specs drive design



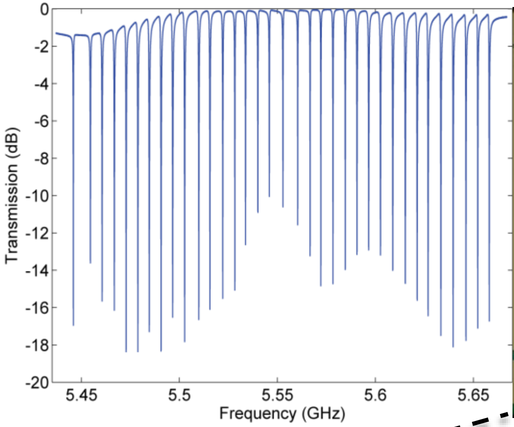
Simons Observatory Large Aperture Optics Tube (x13)

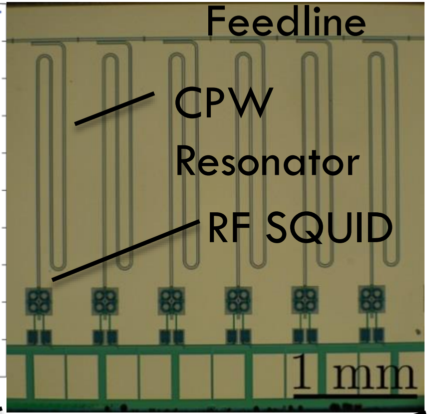


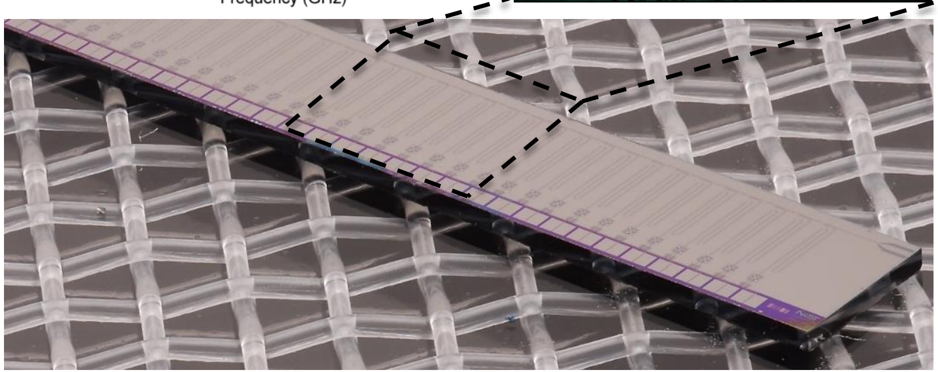
Simons Observatory Small Aperture Telescope (x4)

Where we began: µMUX300k

- Started with Ben Mates' PhD thesis µMUX chip design:
  - 300 kHz BW, 6 MHz spacing, 32 chs / chip
- Dober et al 2017 demonstrated that these chips can read out CMB bolometers
- No where near the frequency or physical densities needed for 2000x

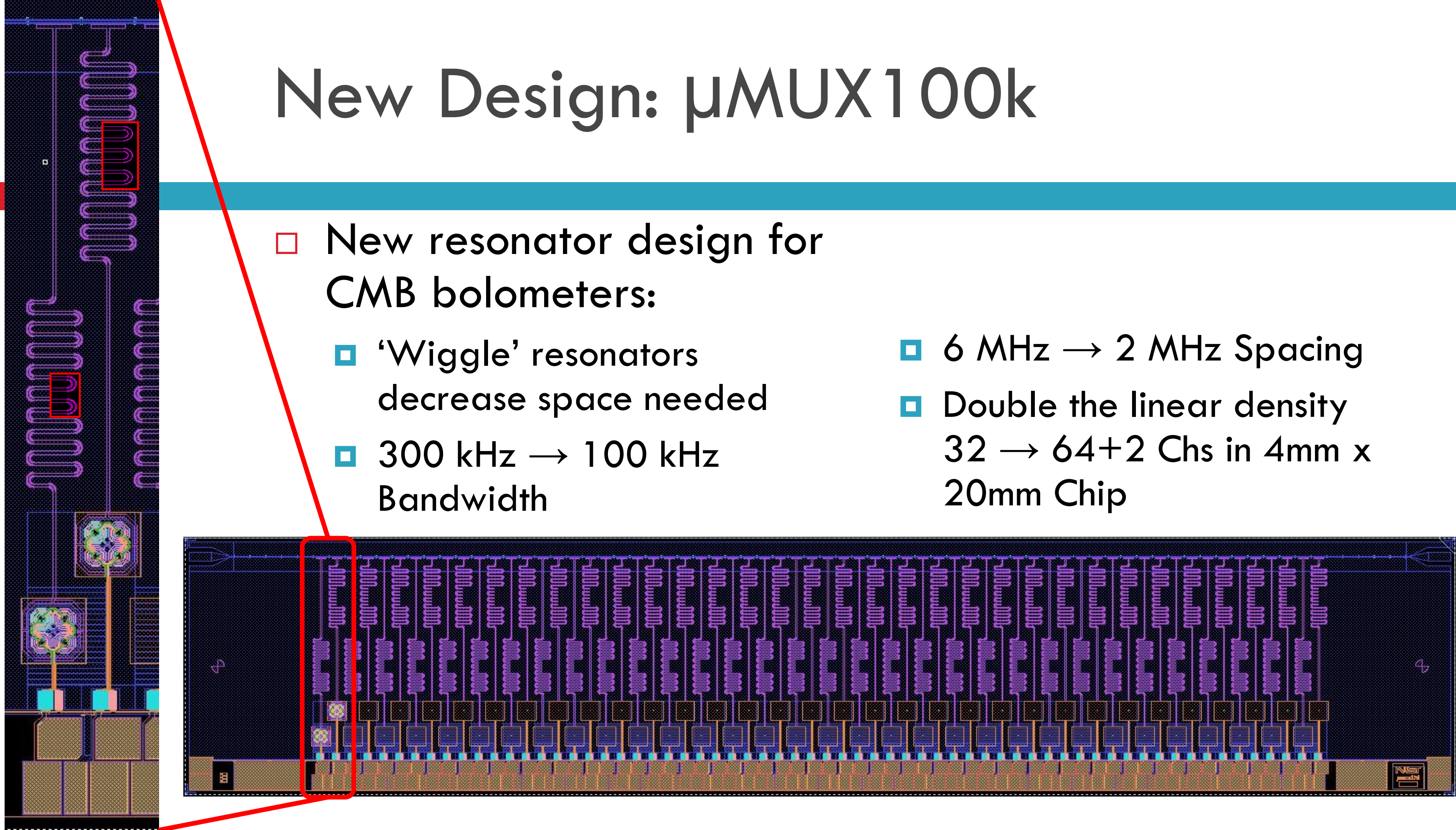






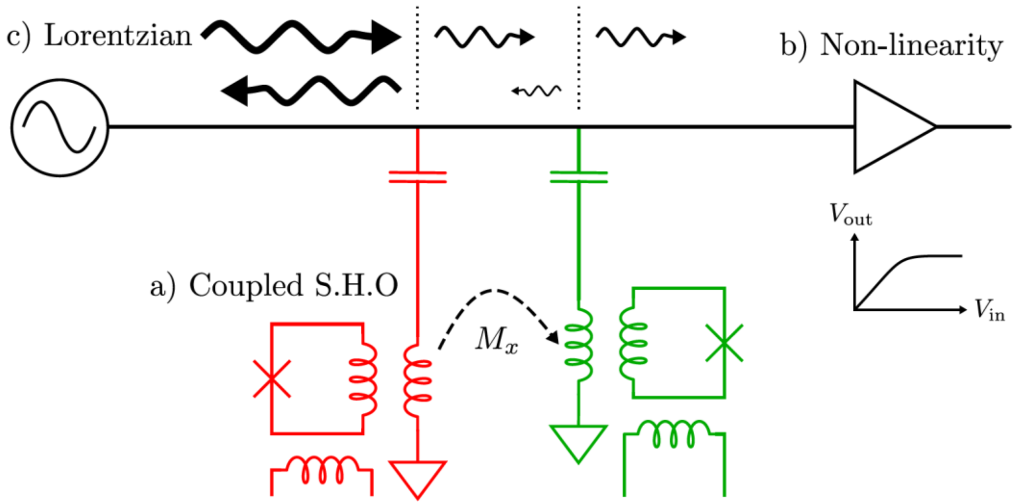
New Design: µMUX100k

- New resonator design for CMB bolometers:
  - ‘Wiggle’ resonators decrease space needed
  - 300 kHz → 100 kHz Bandwidth
  - 6 MHz → 2 MHz Spacing
  - Double the linear density 32 → 64+2 Chs in 4mm x 20mm Chip



Crosstalk Mechanisms

- (c) Lorentzian crosstalk and crosstalk from Amplifier non-linearity (b) is well understood
- Another crosstalk mechanism (a) is due to coupling between SQUIDs on nearest frequency neighbors:
  - $\chi \propto \left(\frac{M_x^2}{(\Delta f)^2}\right)$
  - Nonexistent in μMUX300k and other spectroscopy mux designs

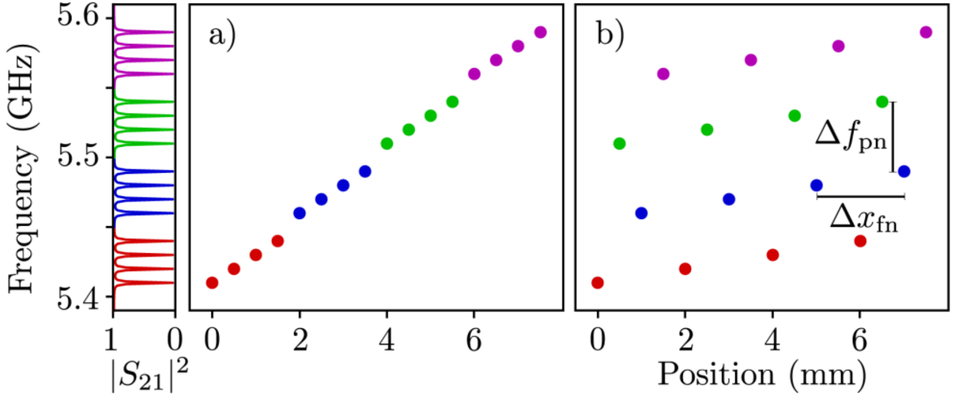


*Mates et. al. APL 2019 (Submitted)

Sub bands to Combat Crosstalk

- Sub bands are a way to map resonant frequencies to physical position on chip
- More Sub bands increases the spacing between nearest frequency neighbors
- Frequency scatter is also dependent on the spacing

4 Sub Band Schematic

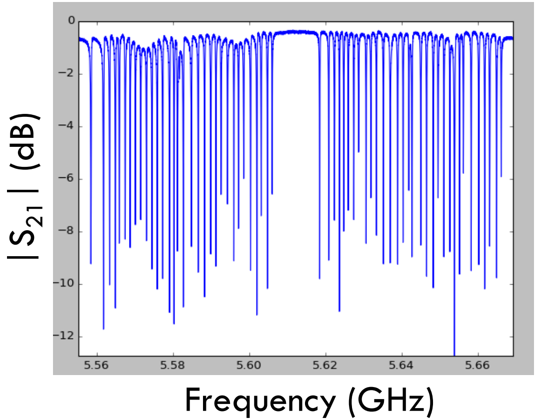


*Mates et. al. APL 2019 (Submitted)

μMUX100k V1.0 – Good Placement, High Crosstalk

- First attempt at constraining SQUID crosstalk by increasing sub bands
- Was too high for SO
  - Doubling sub bands to 8 should fix

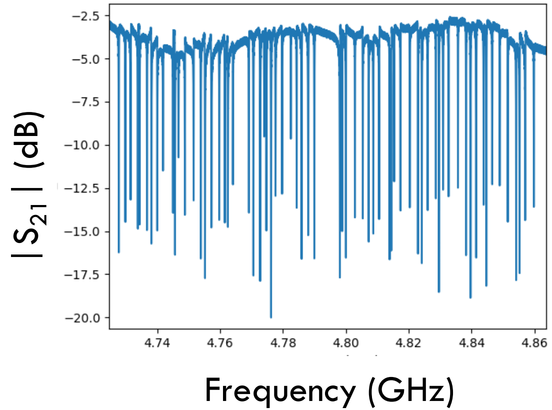
Designed Δf_r	1.6 MHz
# of sub bands (dist.)	4 (1.0 mm)
Frequency Scatter (σ_f)	0.49 MHz
Measured Crosstalk (nearest frequency neighbor)	1.6%



μMUX100k V2.0 – Poor Placement, Low Crosstalk

- Crosstalk now met specifications for SO
- Frequency scatter became large enough to cause non-negligible collision rate
- Can we reduce the SQUID crosstalk to reduce number of sub bands needed?

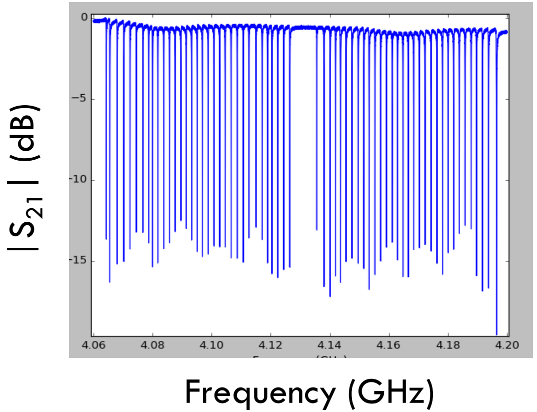
Designed Δf_r	1.8 MHz
# of sub bands (dist.)	8 (2.0 mm)
Frequency Scatter (σ_f)	0.66 MHz
Measured Crosstalk (nearest frequency neighbor)	0.35%



μMUX100k V3.0 –
Amazing Placement, High Crosstalk

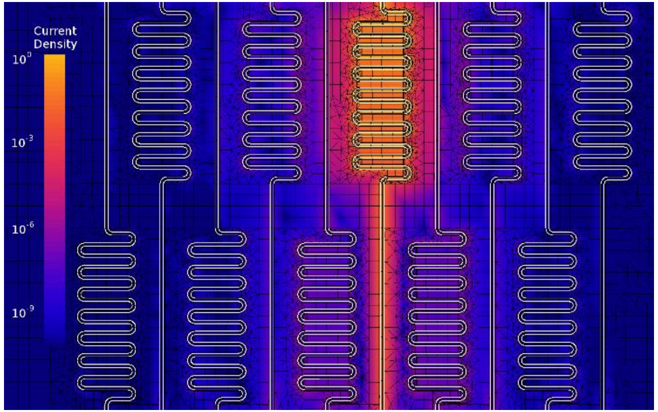
- Redesigned the resonator to SQUID coupling so that we no longer use fringing fields
  - This also reduced the amount of parasitic inductance which should improve frequency placement
- Now major source of coupling is resonator to resonator coupling
  - Back to simulations to model this effect!

Designed Δf_r	2.0 MHz
# of sub bands (dist.)	2 (0.5 mm)
Frequency Scatter (σ_f)	0.22 MHz
Measured Crosstalk (nearest frequency neighbor)	11%

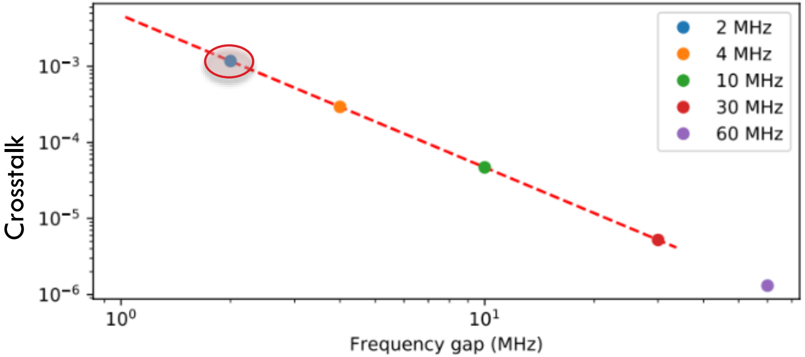


μMUX100k V3.1 – (Designed for) Good Placement, Low Crosstalk

- Microwave Office simulations show increase to 4 sub bands will reduce crosstalk to below SO goals
- Frequency scatter should be further reduced from V1.0 due to reduction of parasitic impedance from old coupler design



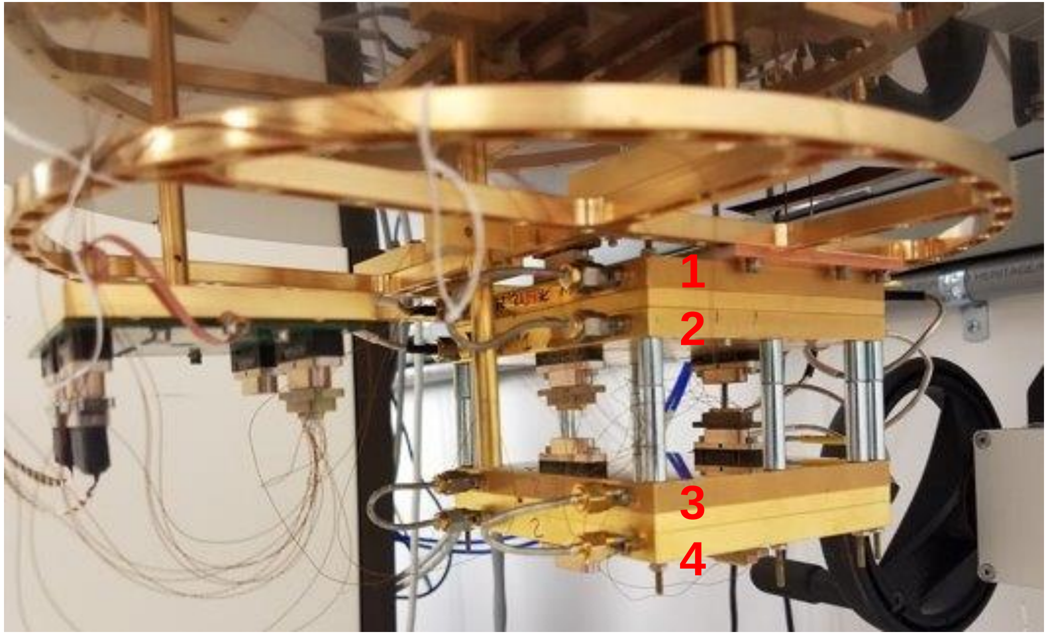
Designed Δf_r	1.8 MHz
# of sub bands (dist.)	4 (1.0 mm)
Frequency Scatter (σ_f)	*Exp.* <0.49 MHz
Designed Crosstalk (nearest frequency neighbor)	*Exp.* ~0.1%



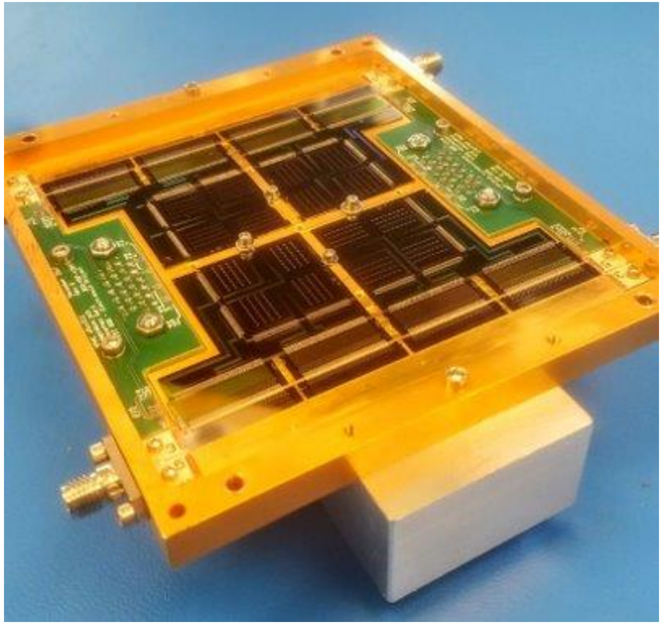
*Microwave Office sims show 10^{-3}crosstalk at 4 sub bands

Now that the design is settled, does µMUX actually work at 2000x?

µMUX 2048k (4x512) demo

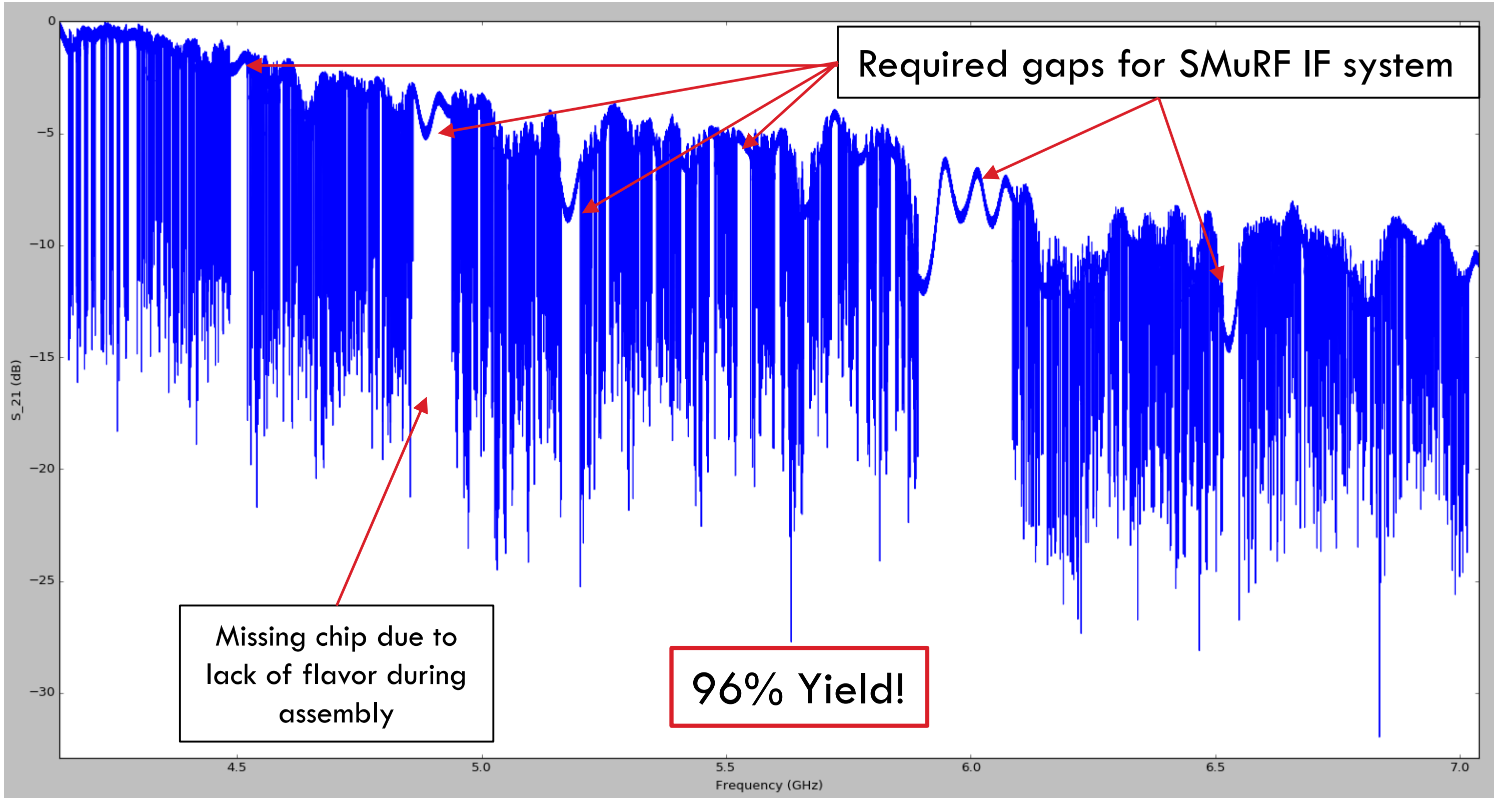


5-6 GHz: V1.0, 4-5 GHz & 6-7 GHz: V2.1, 7-8 GHz: V3.0

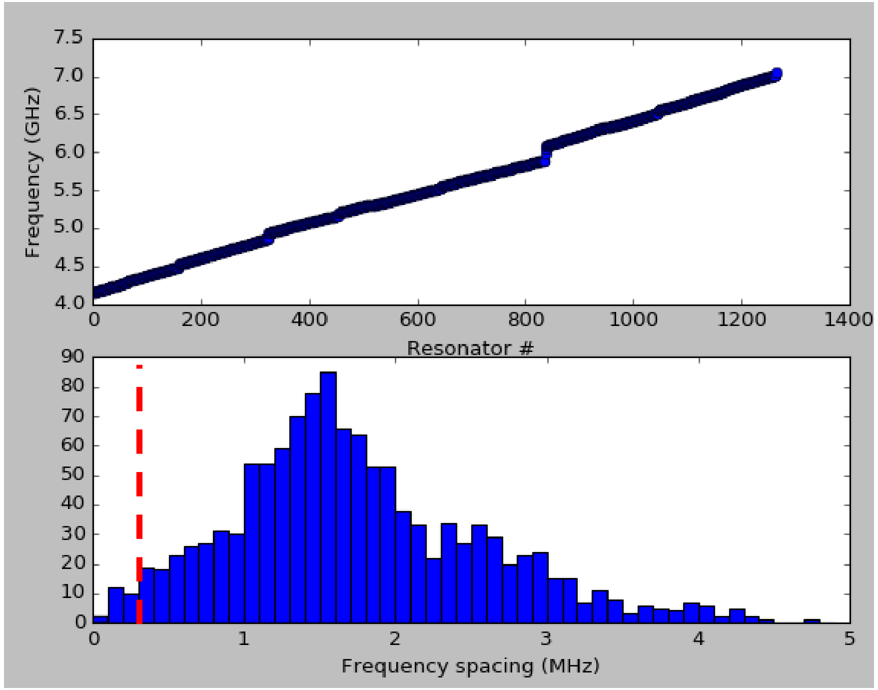


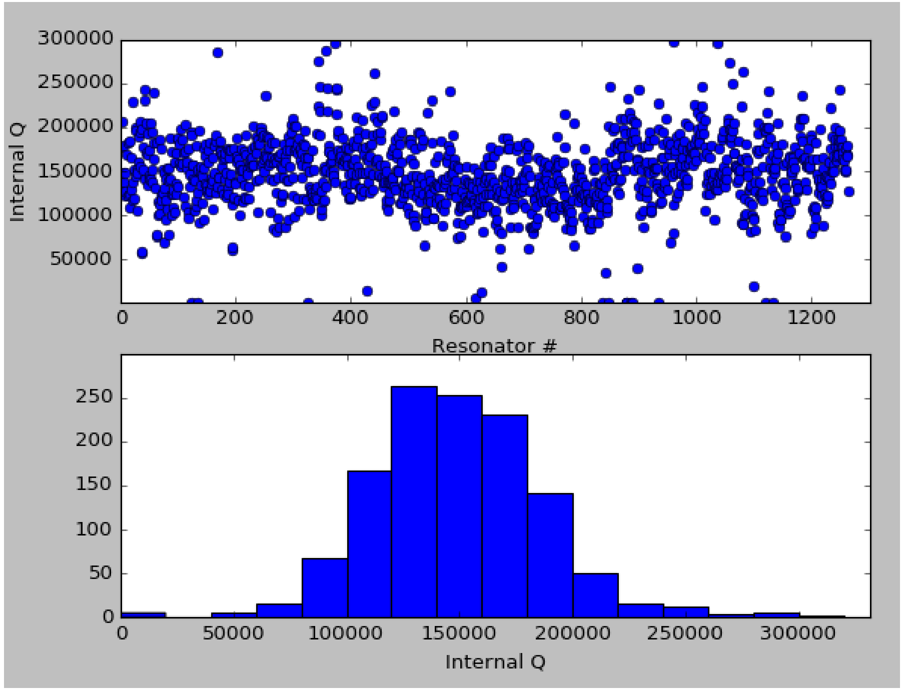
5-6 GHz box containing 8 uMUX chips and 512 TES detectors

4-7 GHz Transmission



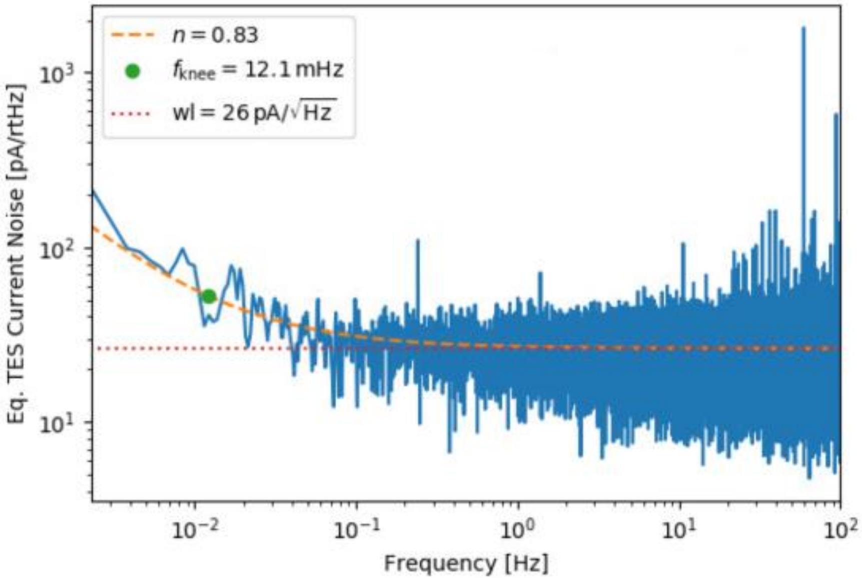
4-7 GHz Spacing and Q_i





23 resonator pairs below 3 linewidths

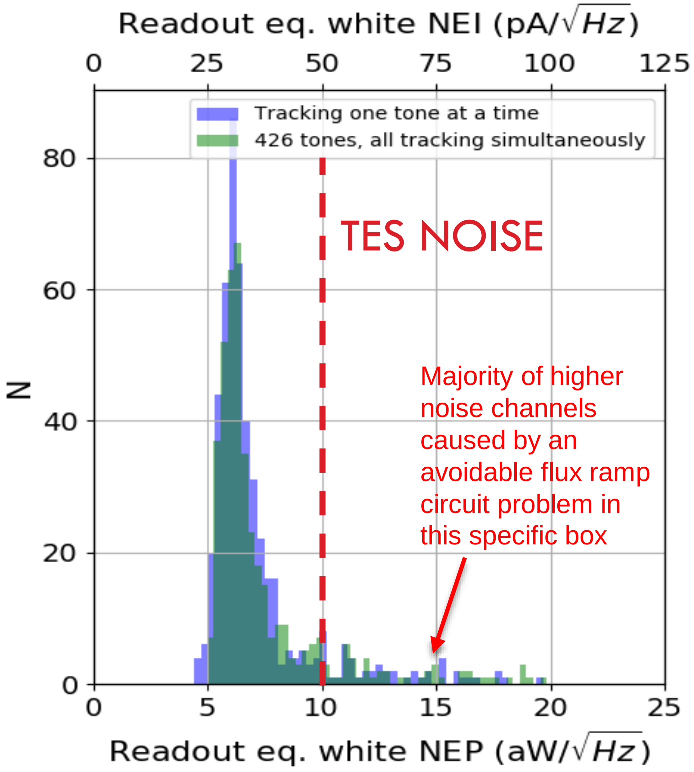
5-6 GHz Noise Analysis



1/f knee is typically ~10 mHz for majority of channels

*Henderson et al., https://arxiv.org/abs/1809.03689

*4-8 GHz noise with SMuRF ongoing at NIST & Princeton

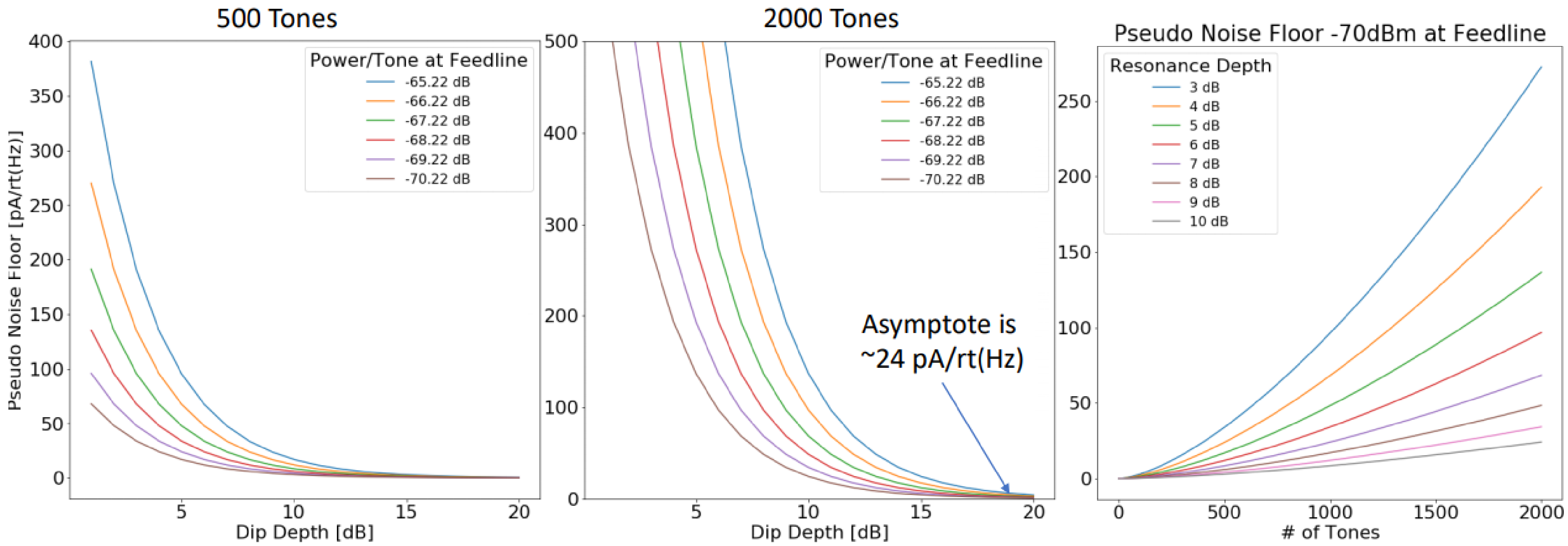


Conclusions

- μMUX100k has demonstrated a clear path for ~2,000 detectors per readout chain
- We expect V3.1 to be the final MUX design configuration when considering noise, crosstalk, and yield
- Enables Simons Observatory, Ali-CPT, BICEP 220/270 GHz Arrays, CCAT-Prime, and CMB-S4

Bonus Slides

What happens at 2000 tones



*Simulations by Max Silva-Feaver