Readout for CMB Detection

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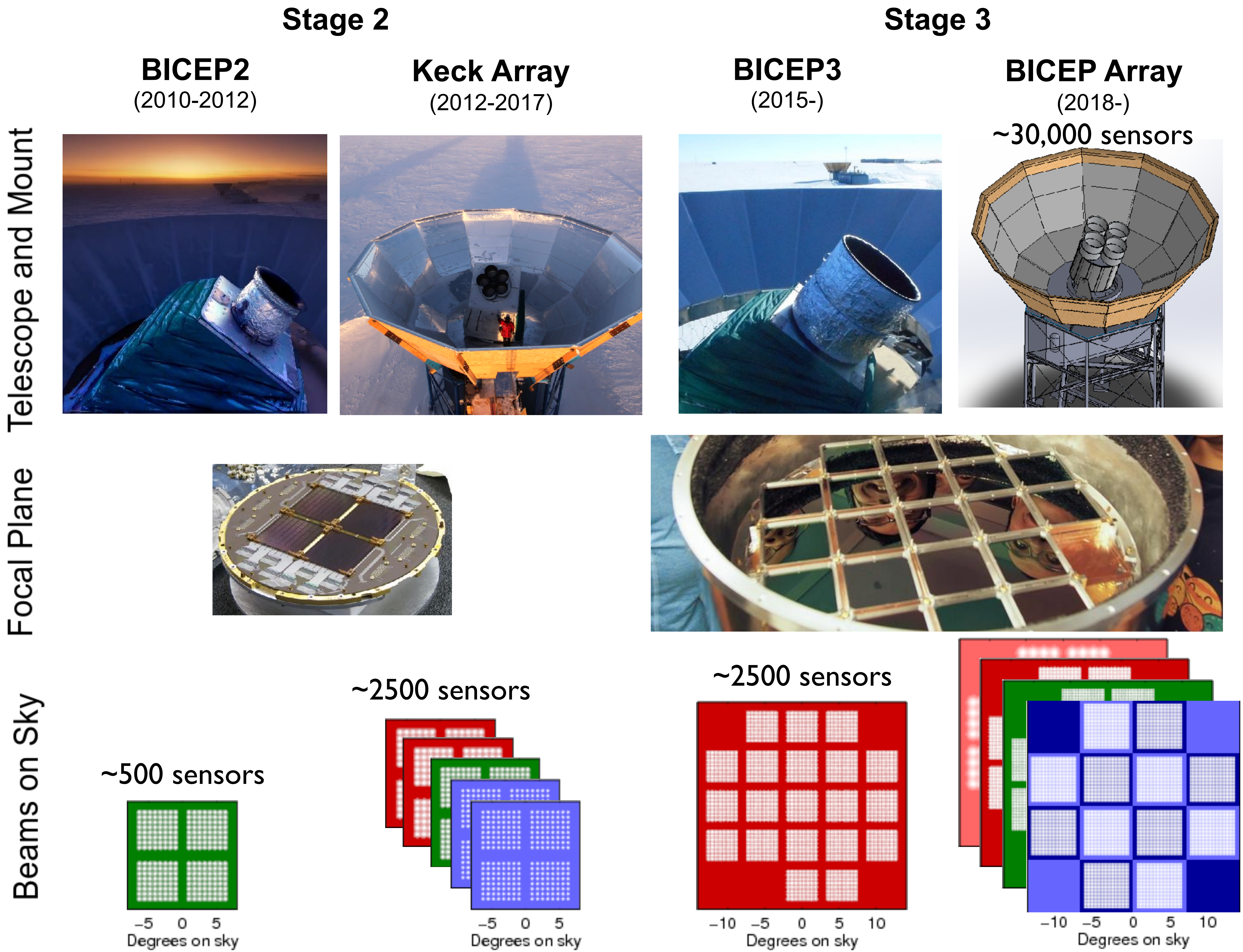
Workshop on Quantum Sensing for High Energy Physics

Argonne National Laboratory

Outline

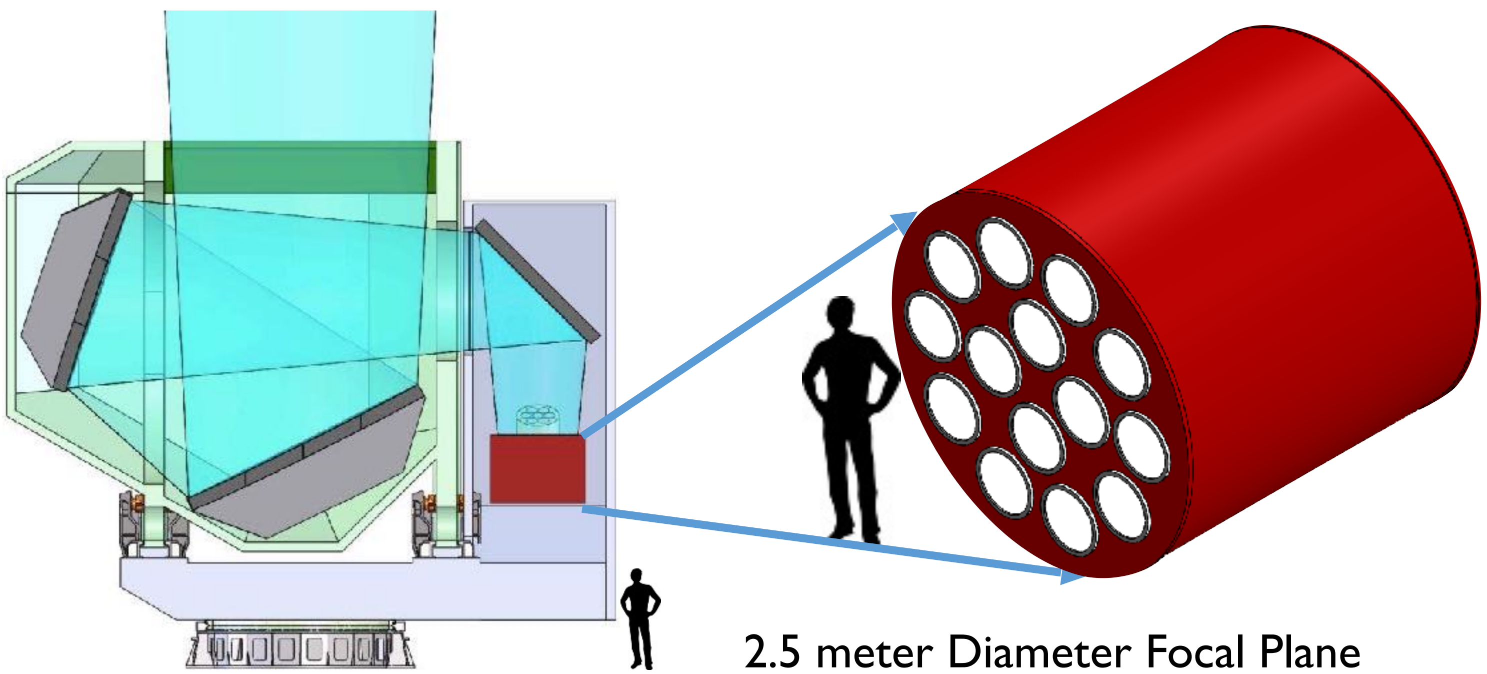
- Motivation
- Readout of CMB quantum sensors: basics and taxonomy
- Traditional readout techniques for TES bolometers
  - DC-SQUID serial switching (Time Divison)
  - In-series LC resonators (Frequency Division)
- Cold: Next-gen Microwave resonator techniques
  - MKIDs
  - Microwave resonators for TES readout using RF-SQUIDs
  - Challenges and opportunities
- Warm: Readout electronics for microwave resonators
  - FPGA+ADC/DAC for multi-channel software-defined radio
  - SLAC Microresonator RF Electronics
  - Challenges and opportunities



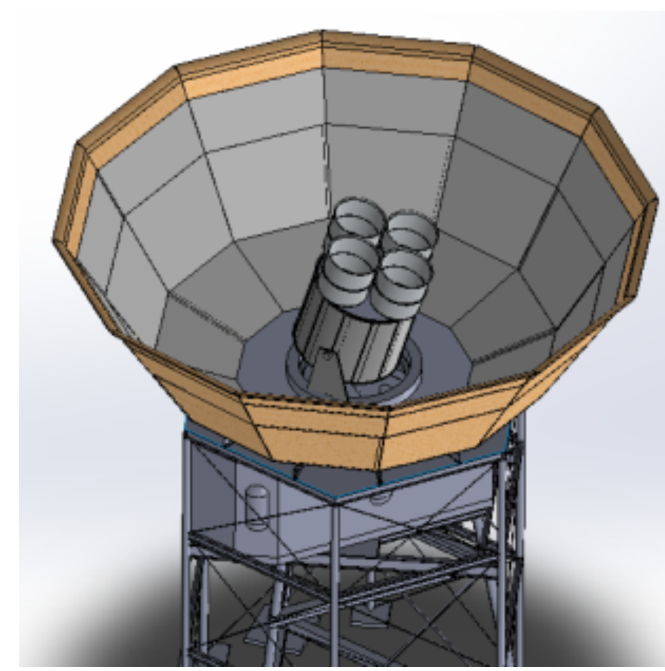
Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2017)
BICEP3
(2015-)
BICEP Array
(2018-)
~30,000 sensors
Telescope and Mount
Focal Plane
Beams on Sky
~500 sensors
~2500 sensors
~2500 sensors
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 −5 0 5 10
Degrees on sky

CMB-S4

- 500,000 sensors
- 8 optical bands from 30-300 GHz
- Multiple cameras for inflation, dark relics, neutrino mass, dark energy, cosmological parameters



2.5 meter Diameter Focal Plane
with 100,000+ detectors

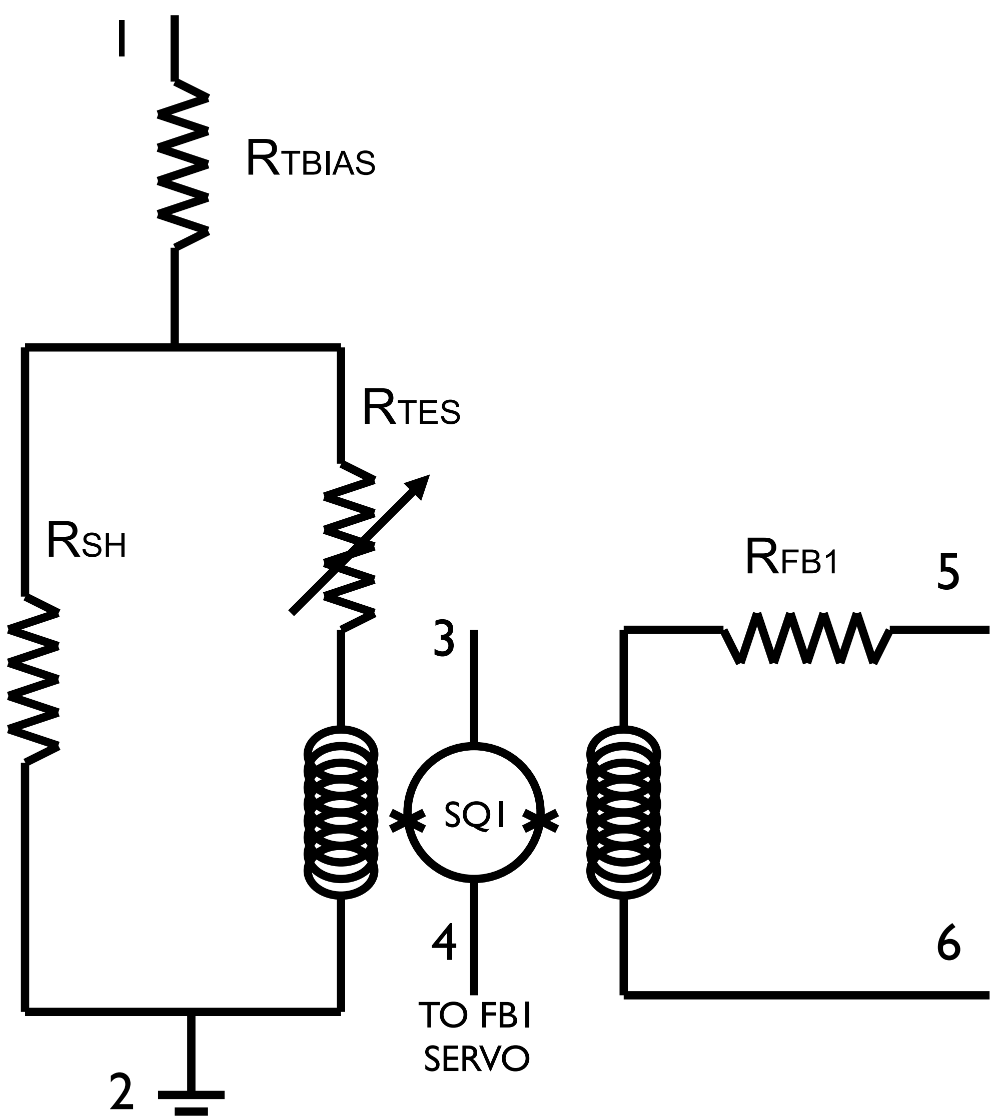


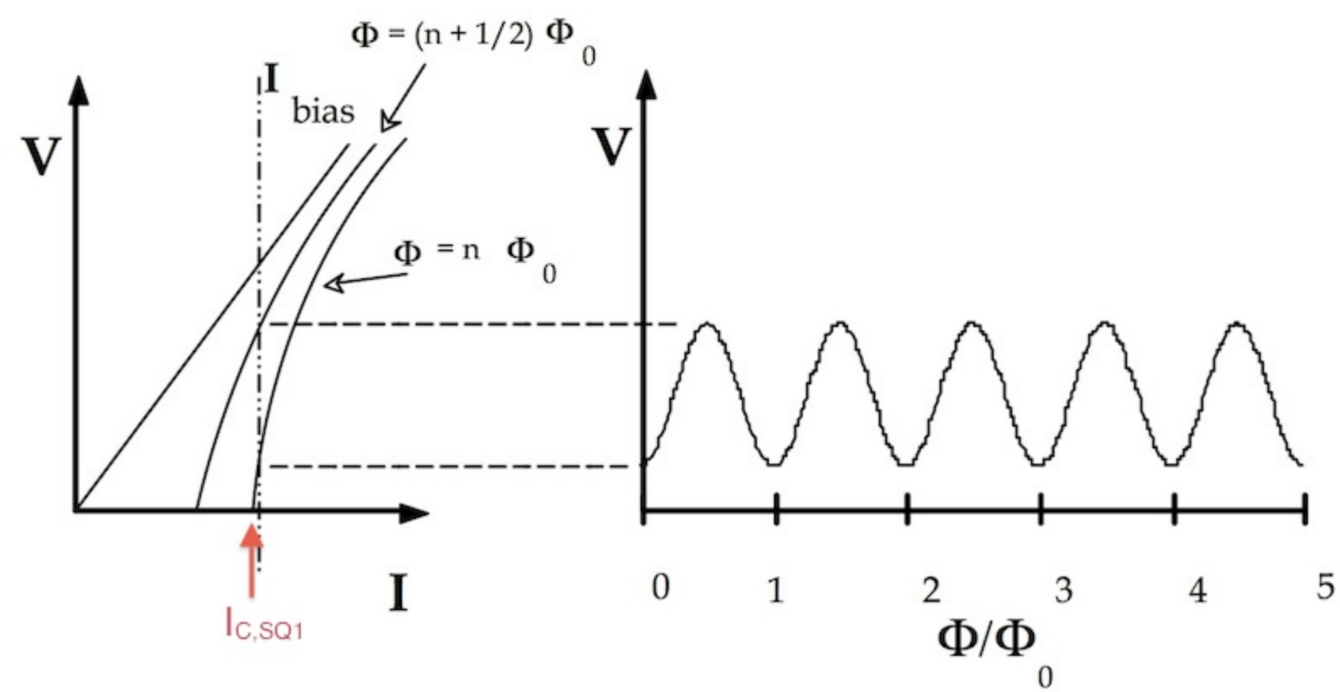
High-resolution Science + de-lensing:
300,000 sensors
on 3-4 large telescopes

Low-resolution B-mode Science:
200,000 sensors
on ~12 small telescopes

CMB Readout basics (1)

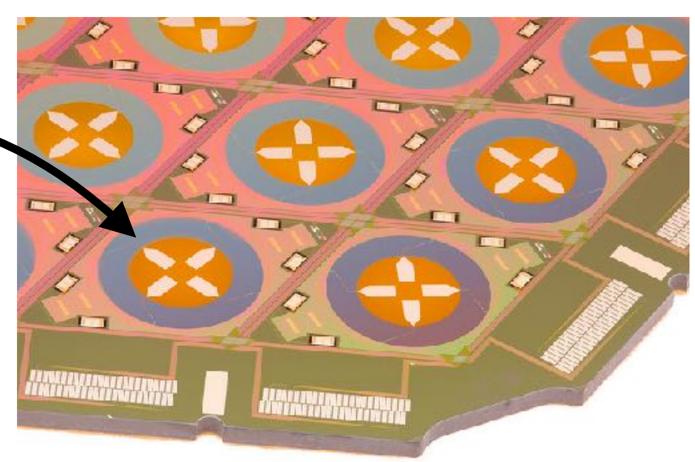
- TES bolometers with SQUID amplifiers have provided sufficiently low noise and sensitivity for CMB cameras in the past decade
  - SQUID has periodic response, so needs to be linearized.
  - Thus end up with many wires to read out one TES bolometer





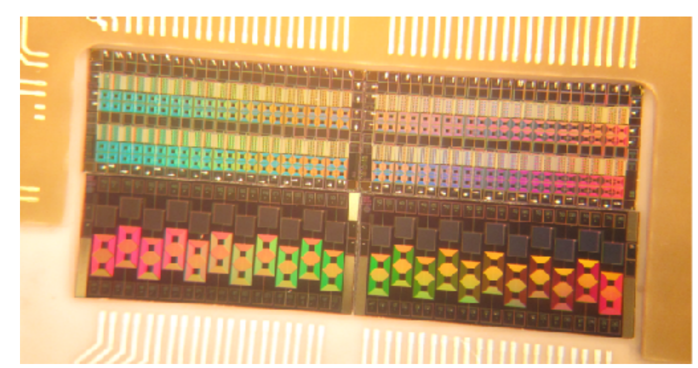
CMB Readout basics (II)

- Share sensor bias and signal wiring across many sensors of the instrument.
    - TES & other quantum sensors are operated at subkelvin temperatures. So need to minimize heat load from room temperature
    - Reduce system complexity and reduce integration burden
- Signals are multiplexed at or close to the temperature stage that houses the sensors.
- **MUX factor** = number of sensor signals carried per unit set of wires to room temperature



AdvACT sensors

+

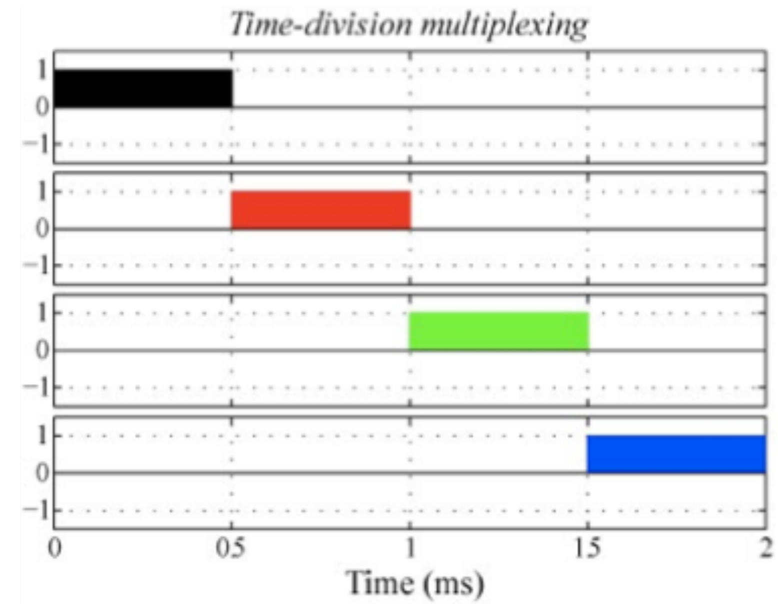


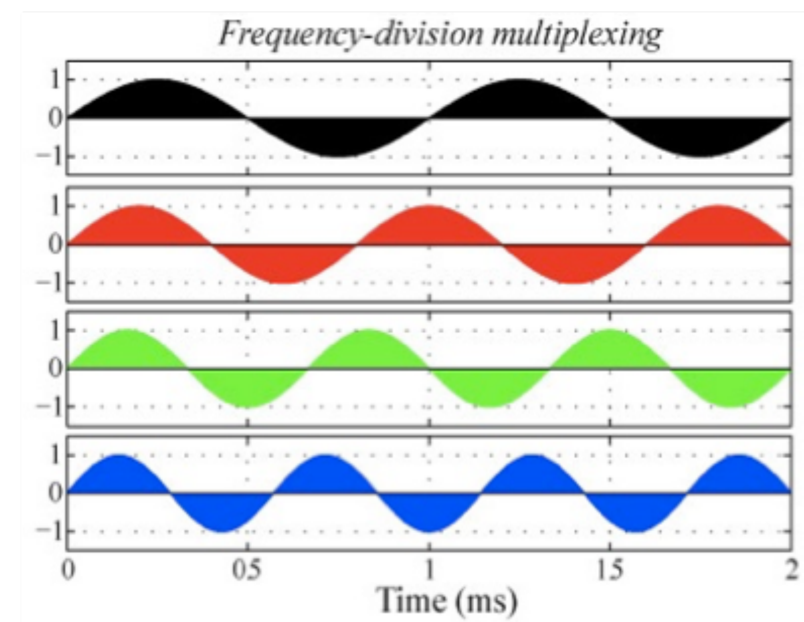
SQUID multiplexer

CMB readout multiplexers

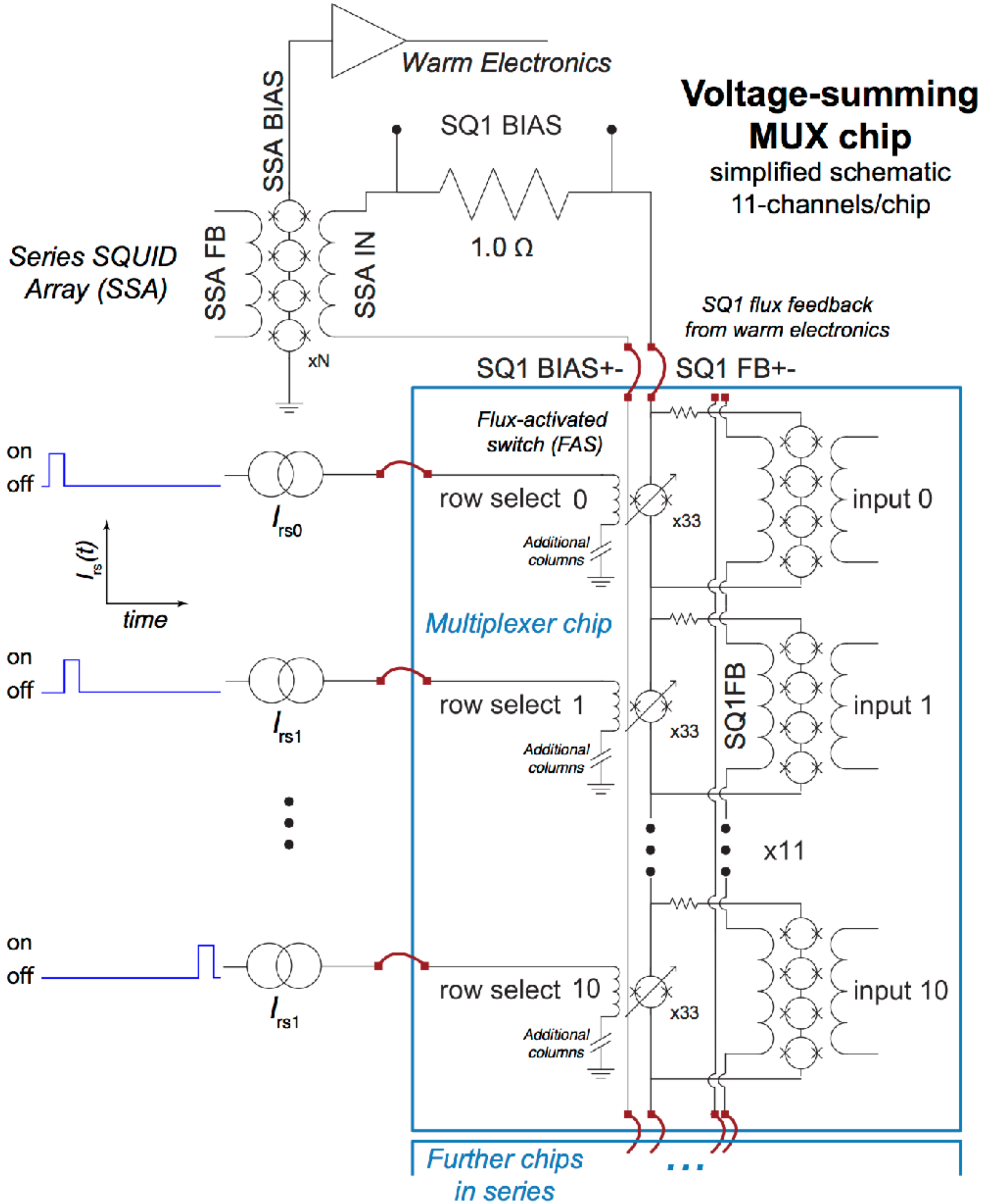
- RF time division and frequency division MUX are common in CMB cameras today

MUX basis/ Frequency regime	**~RF** O(1-100) MHz	**~Microwave** O(300MHz)+
Time-division	1. DC-SQUIDs used as switches to cycle through TESes (aka TDM)	--
Frequency-division	1. LC resonators in series with TESes (aka dfMUX) 2. MKIDs	1. LC resonators inductively coupled to TESes (aka microwave MUX) 2. MKIDs



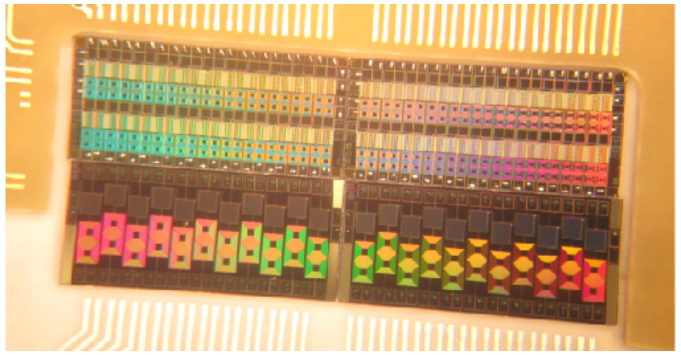


DC-SQUID serial switching of TES bolos



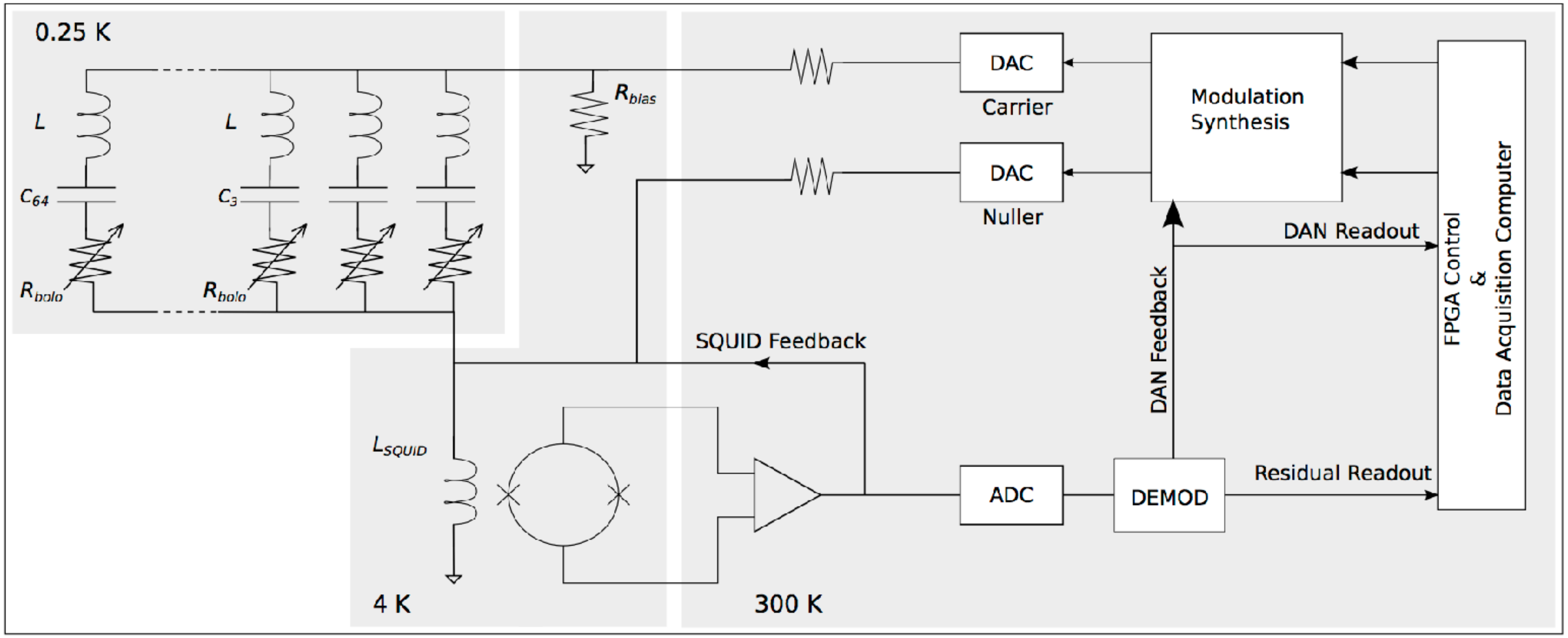
- TES bolo connected to inputs. Inputs amplified by SQUIDs
- MUX Factor = 64
  - 64 bolos per "column".
  - Switch between "rows" serially.
- All columns read out at once, but only one row at a time.
- Active feedback linearizes SQUID response

Rev. Sci. Instrum. 74, 3807 (2003)



SQUID multiplexer chip

LC resonators in series with TES bolos



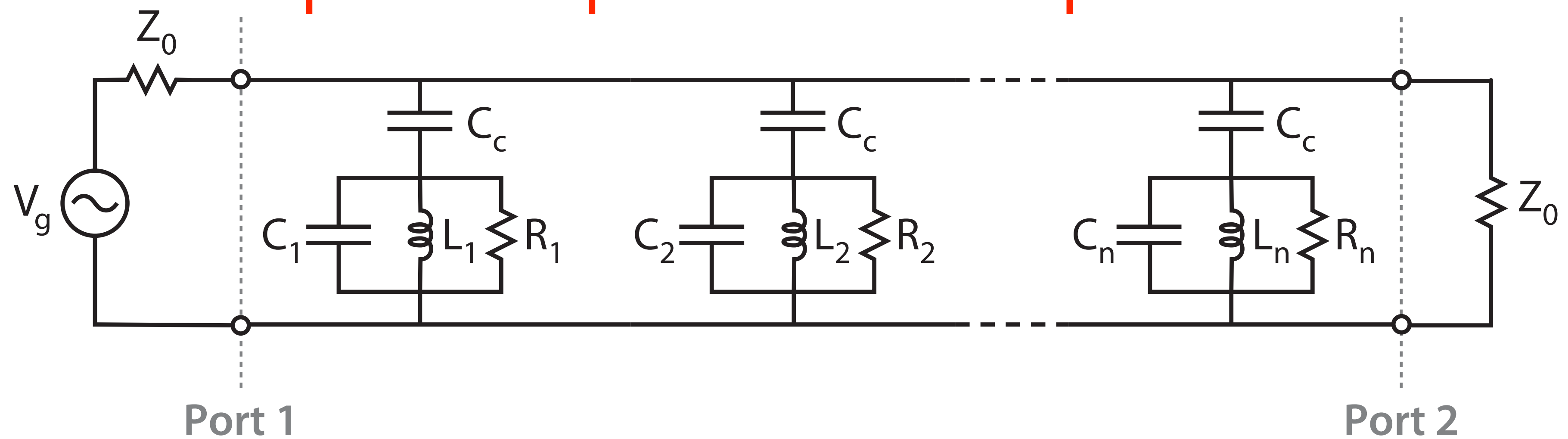
- TES bolos are dissipative elements in ~MHz resonators at unique frequencies in parallel
- MUX factor = 64
  - Bolos on one frequency comb, amplified by single SQUID.
- Active feedback linearizes SQUID response

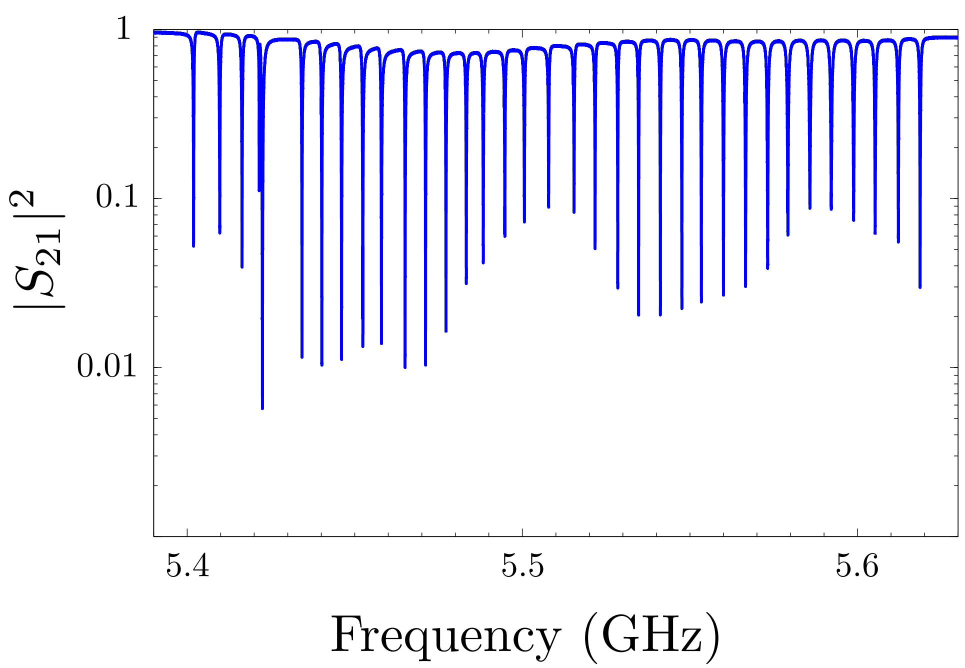
dfMUX LC board

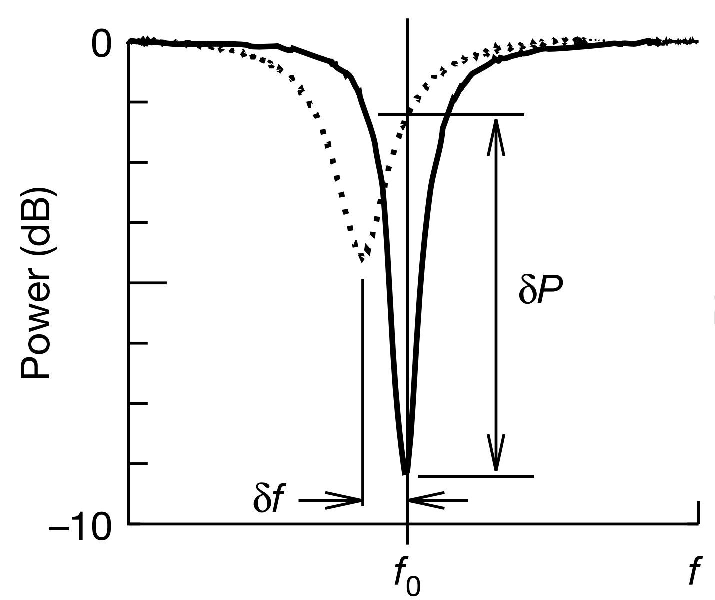
Rev. Sci. Instrum. 83, 073113 (2012)

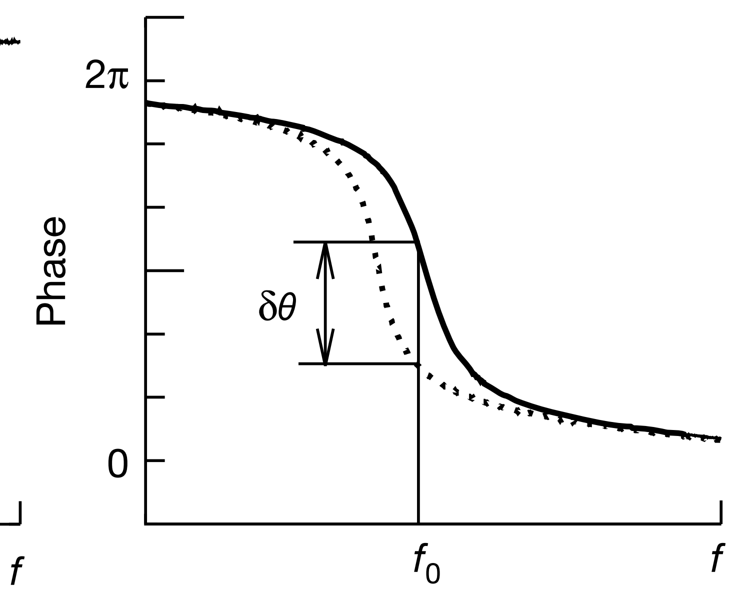
Superconducting Microresonators

- O(0.1-10) GHz superconducting resonators
- Pack 100s-1000s in reasonable bandwidth
- Signals can be captured in phase and/or amplitude modulation



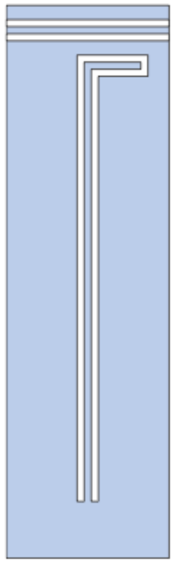




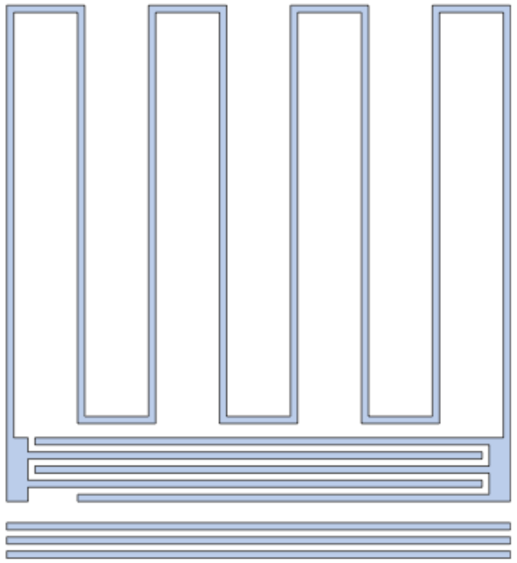


Annu. Rev. Condens. Matter Phys. 2012. 3:169–214

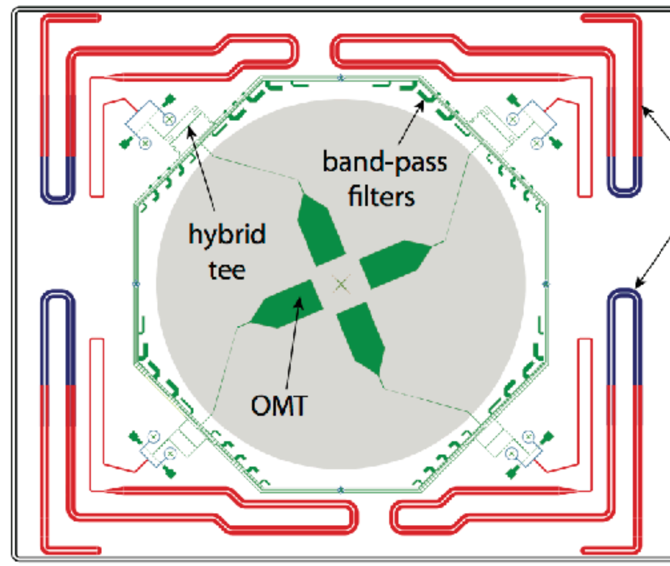
MKID multiplexing



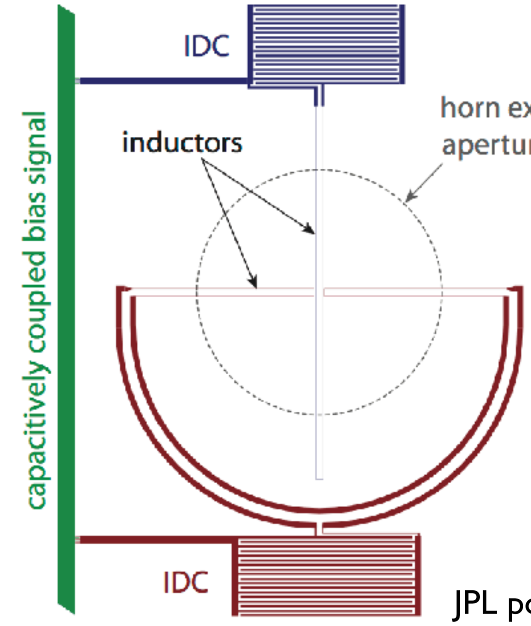
λ/4 CPW resonator



Meander inductor plus interdigitated capacitor resonator

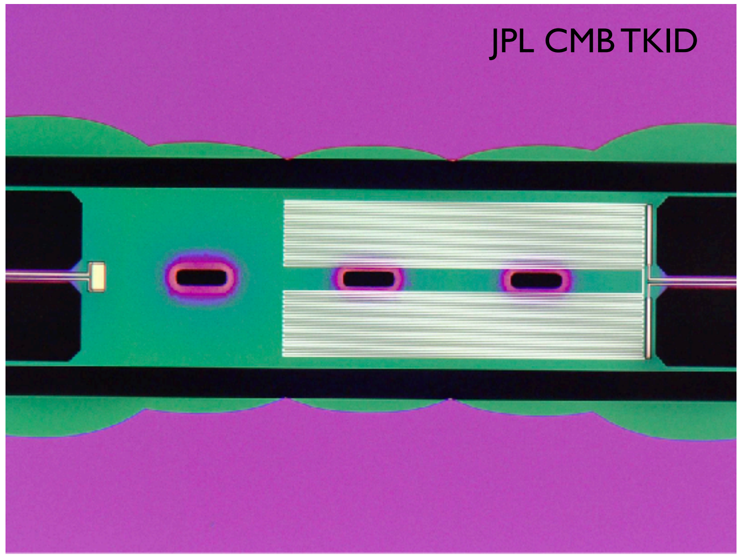


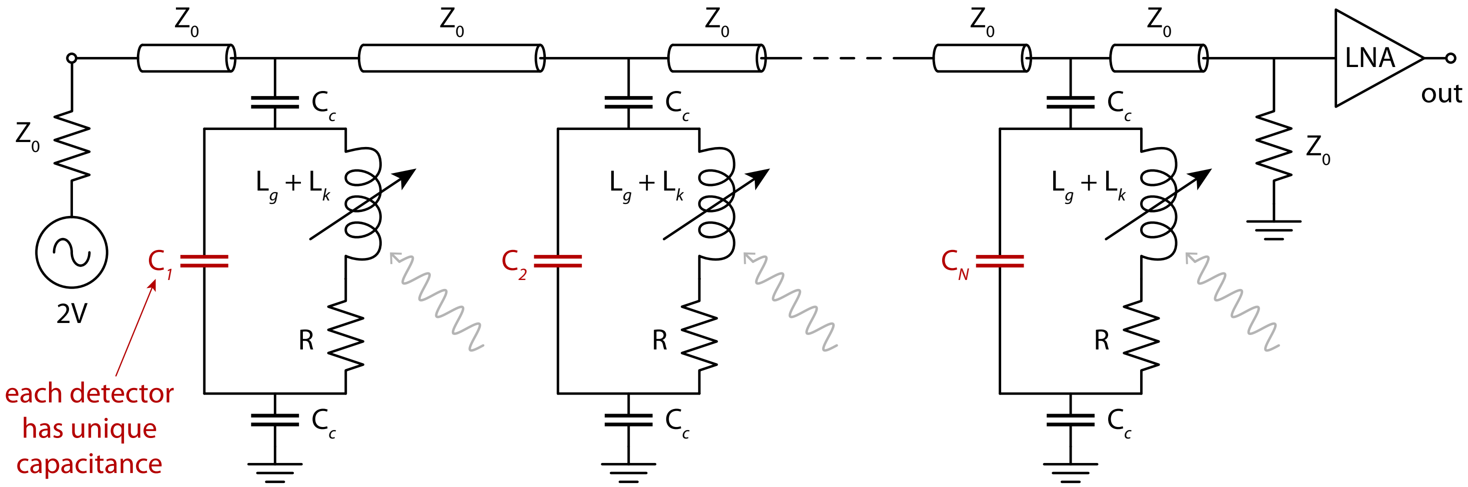
SLAC/NIST OMT-coupled KIDs



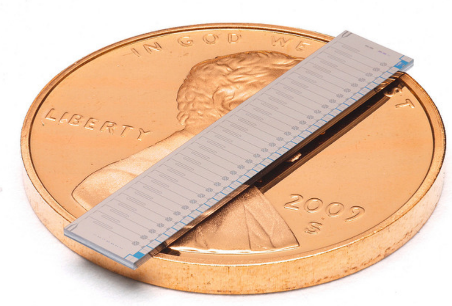
JPL pol-MKIDs

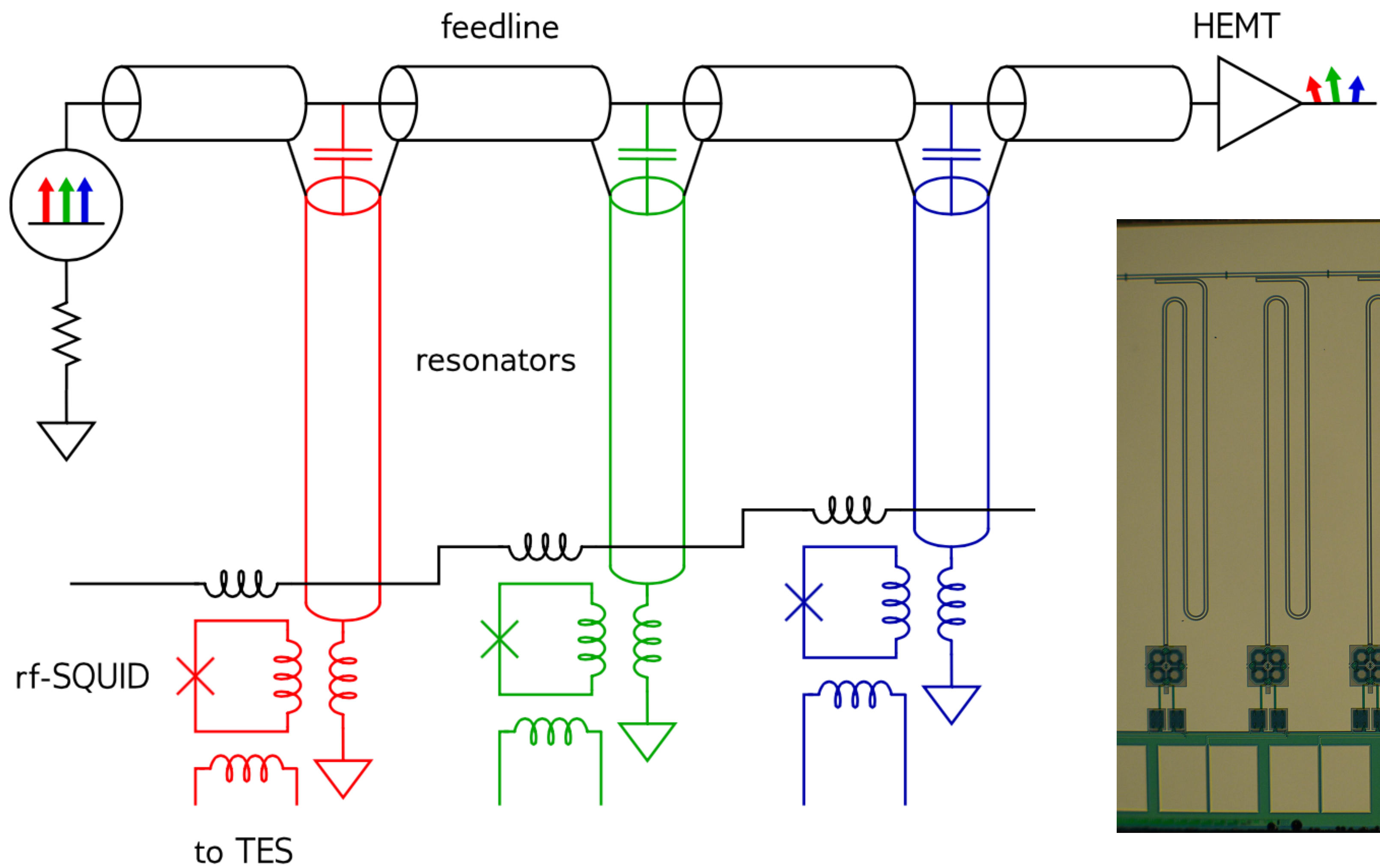
- Resonator inductor is sensor for photons or coupled optical power
- Cold amplification by LNA at ~few K
- MUX factor: ~1000

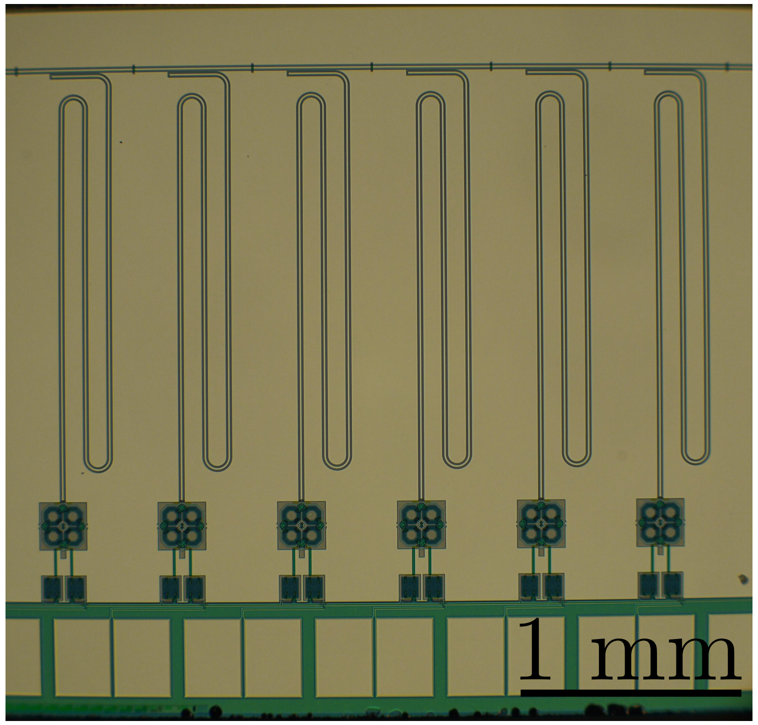




Microwave resonators to multiplex TES bolos (1)



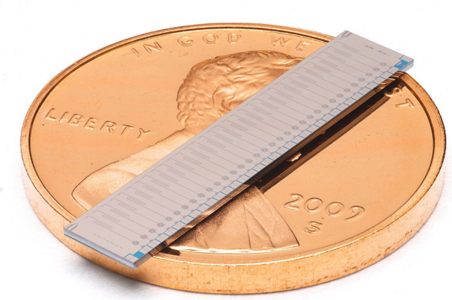


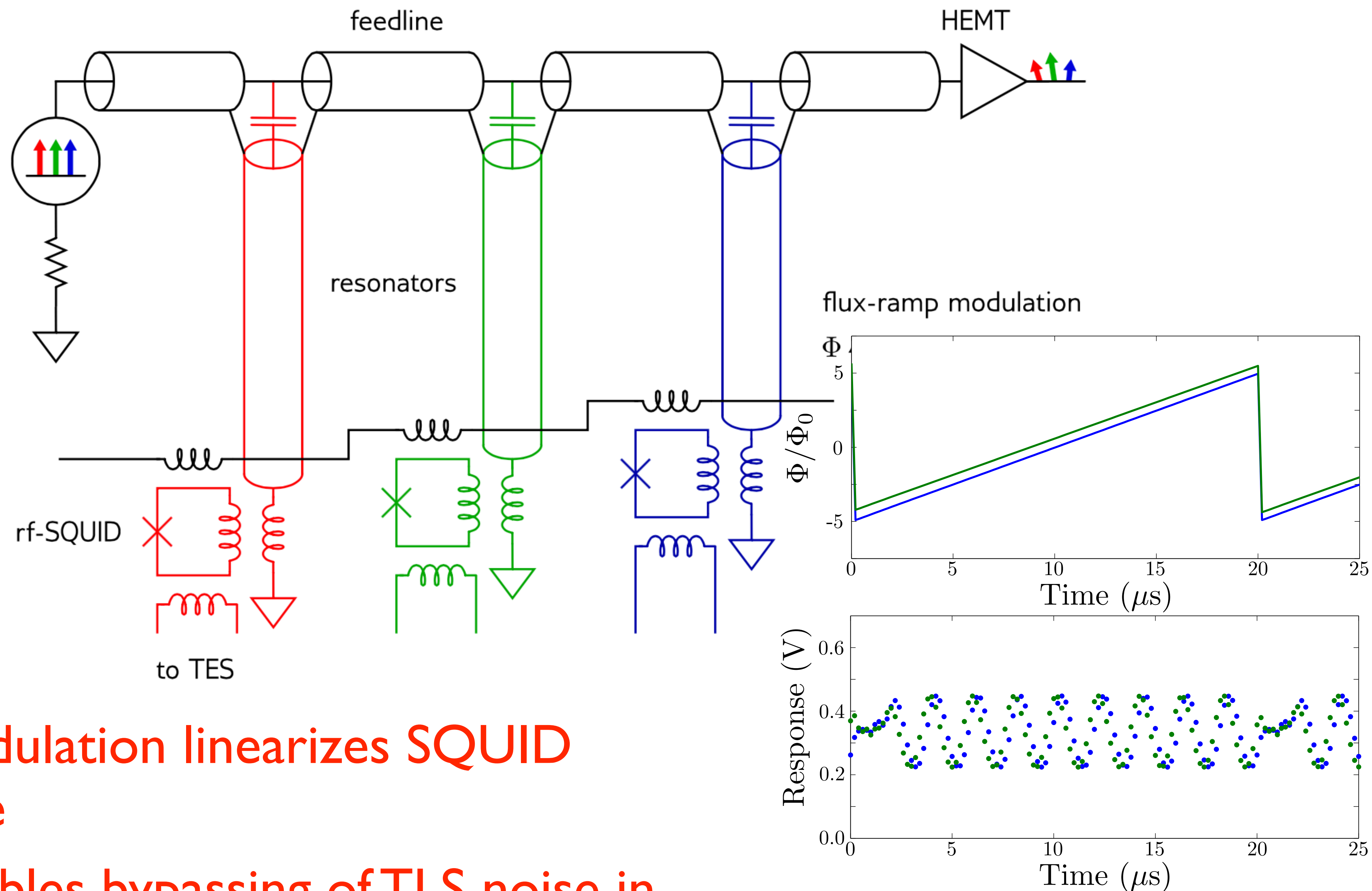


- Use microwave resonators to multiplex TES
- TES inductively couples to RF-SQUID, which screens a GHz resonator
- Signal in TES changes inductance, hence frequency of resonance. No change in Q

Irwin & Lehnert, Appl. Phys. Lett. 85, 2107 (2004

Microwave resonators to multiplex TES bolos (2)

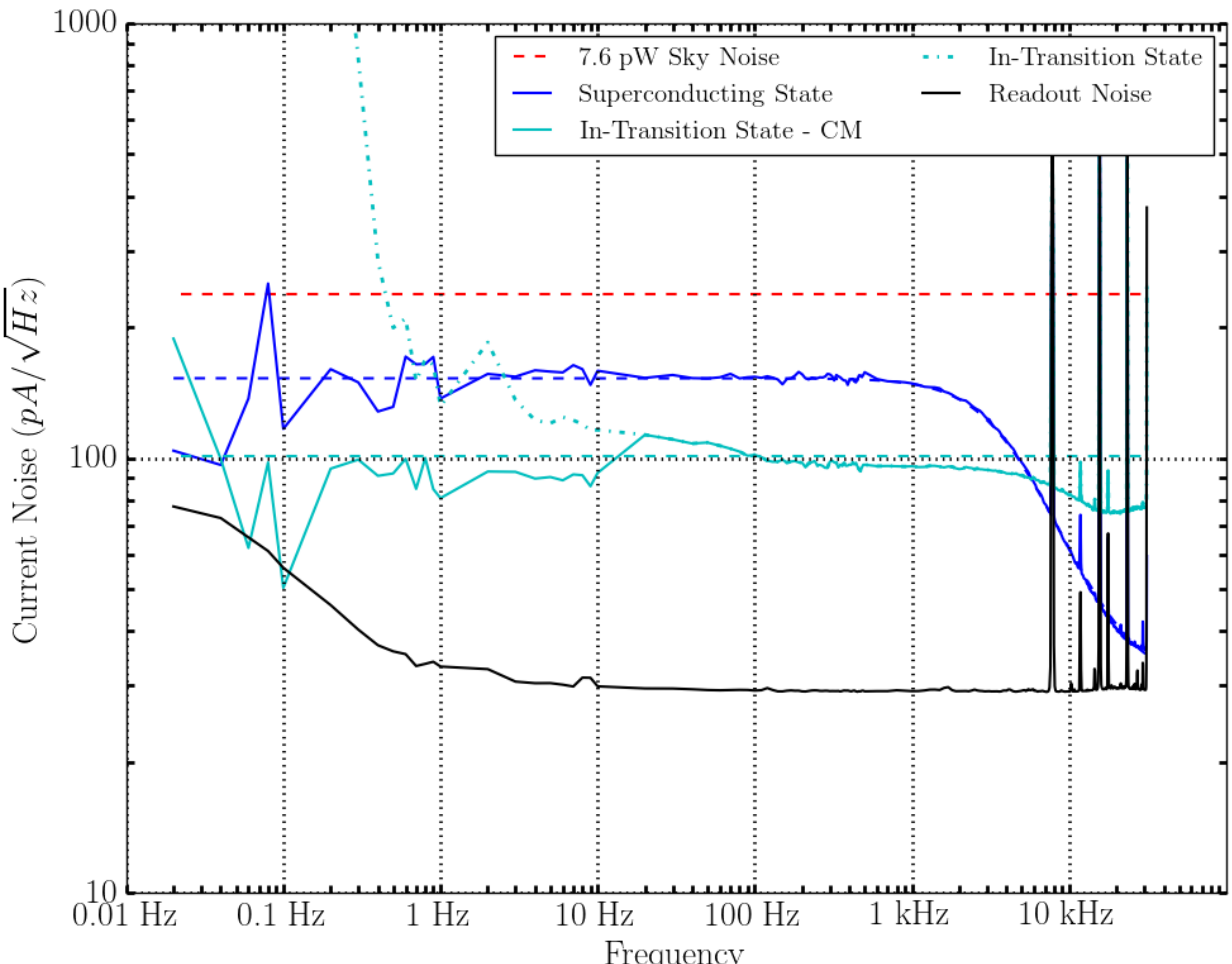




- Flux modulation linearizes SQUID response
- Also enables bypassing of TLS noise in resonator capacitor
- MUX factor: ~1000

B. Mates dissertation (2011)

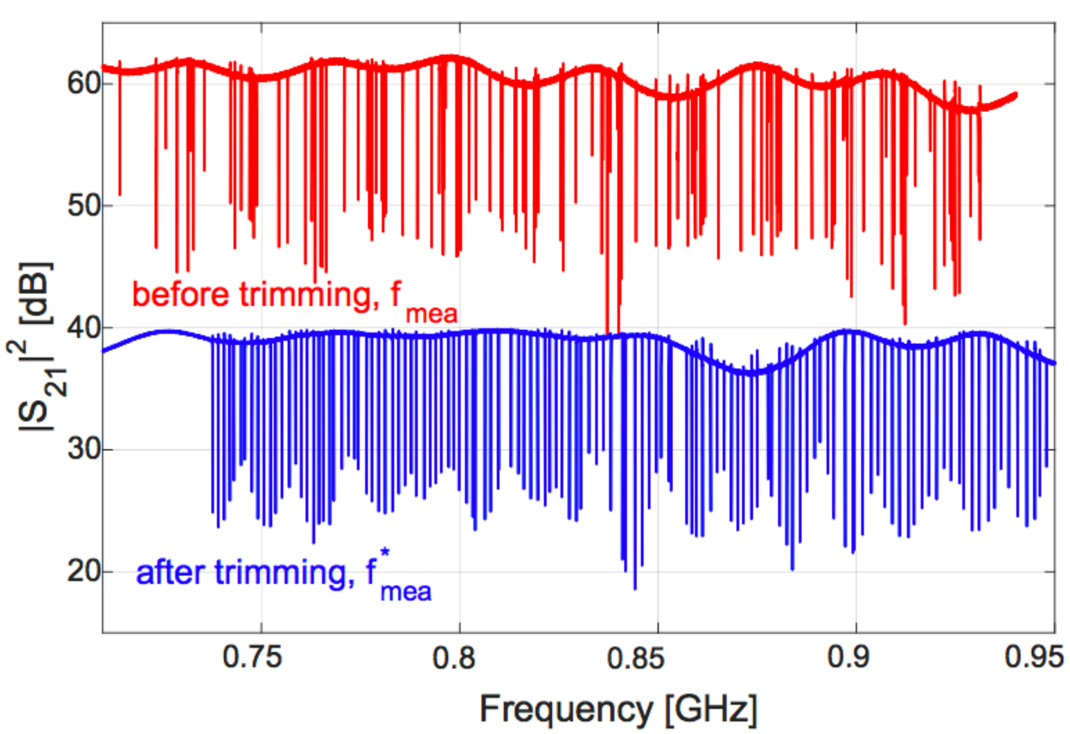
Noise performance of microwave-multiplexed TES bolos

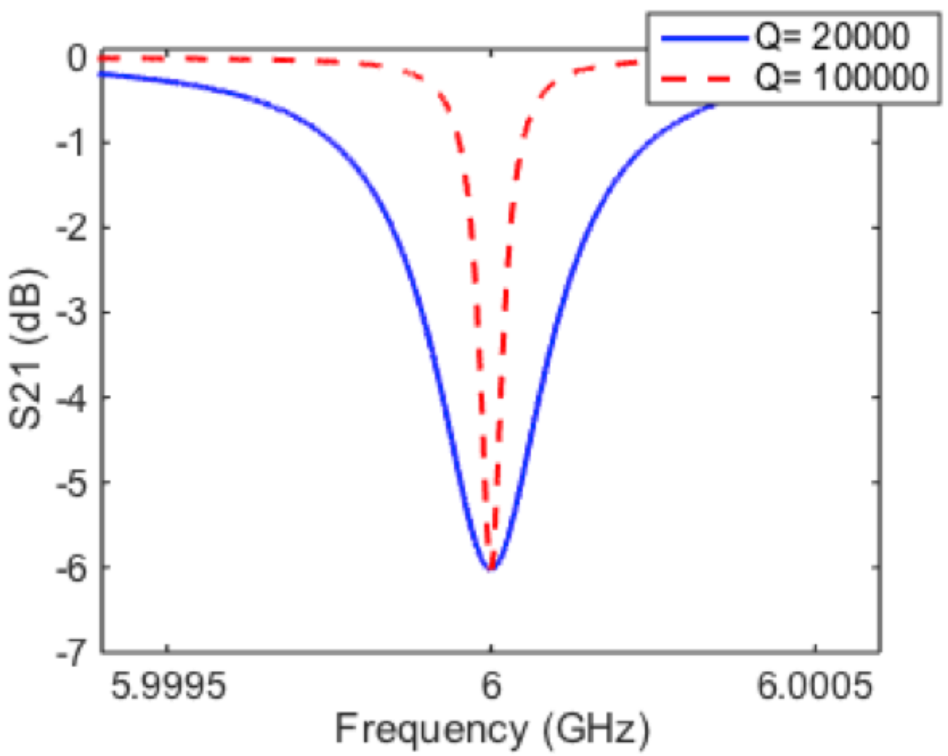


Dober et al, arXiv:1710.04326 (2017)

Challenges & opportunities for next-gen cold readout

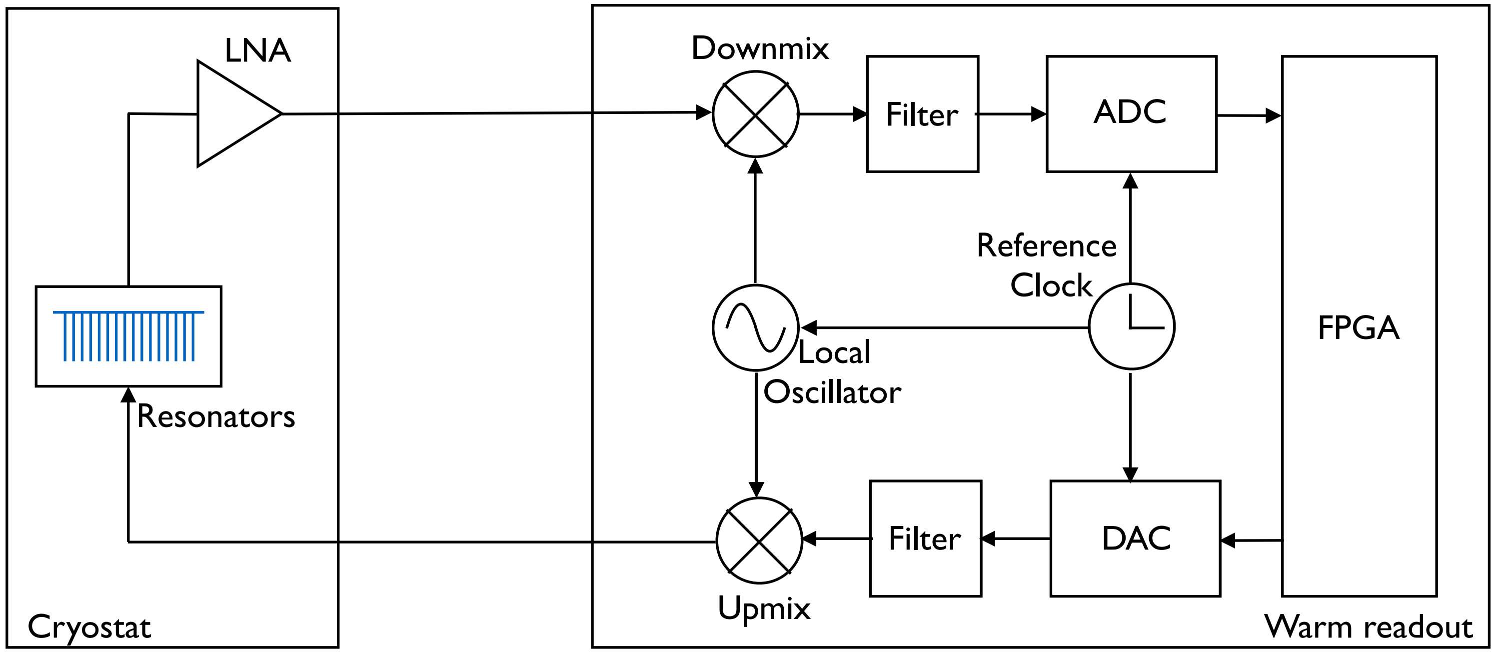
- Can go to extremely large MUX factors and cryogenic arrays with superconducting microresonators
- Resonator fabrication
  - Frequency placement
  - Quality factors/bandwidths or df/f
- Materials, geometry
  - For MKIDs, suitable band gaps for optical bands of interest
  - Resonator noise (TLS, g-r etc.)





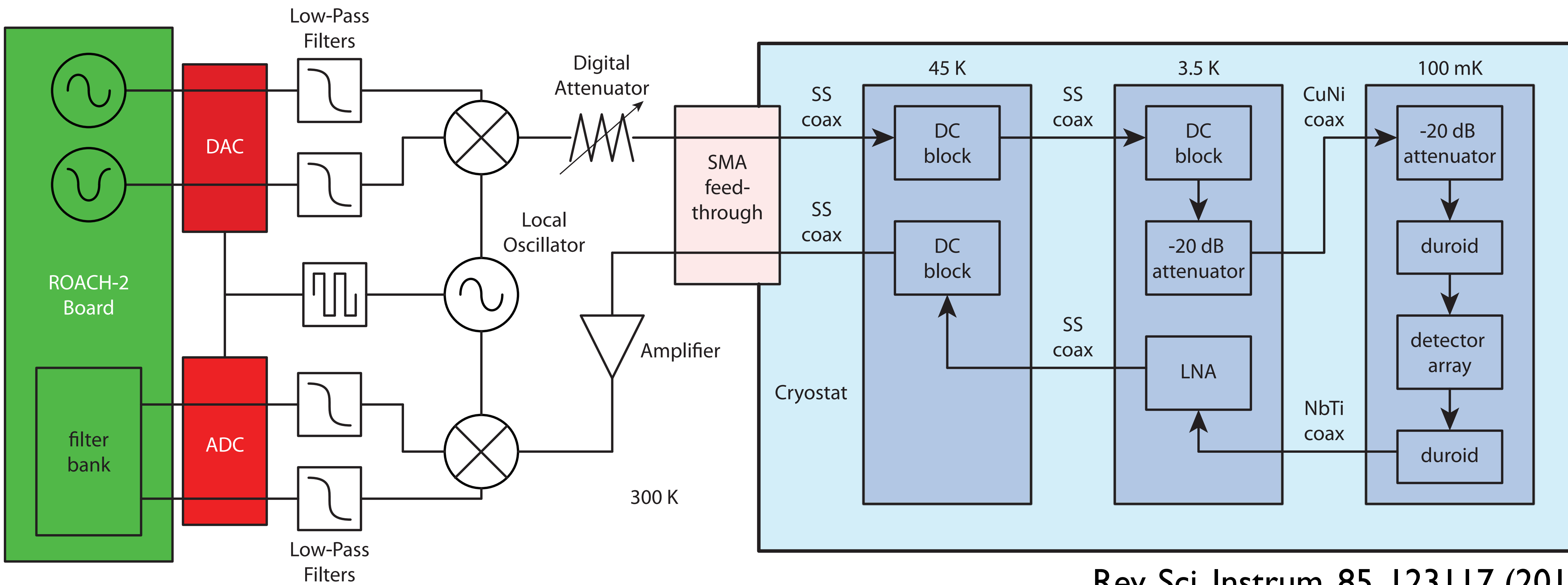
Liu et al, arXiv:1711.0791(2017)

Warm readout electronics for microwave resonators

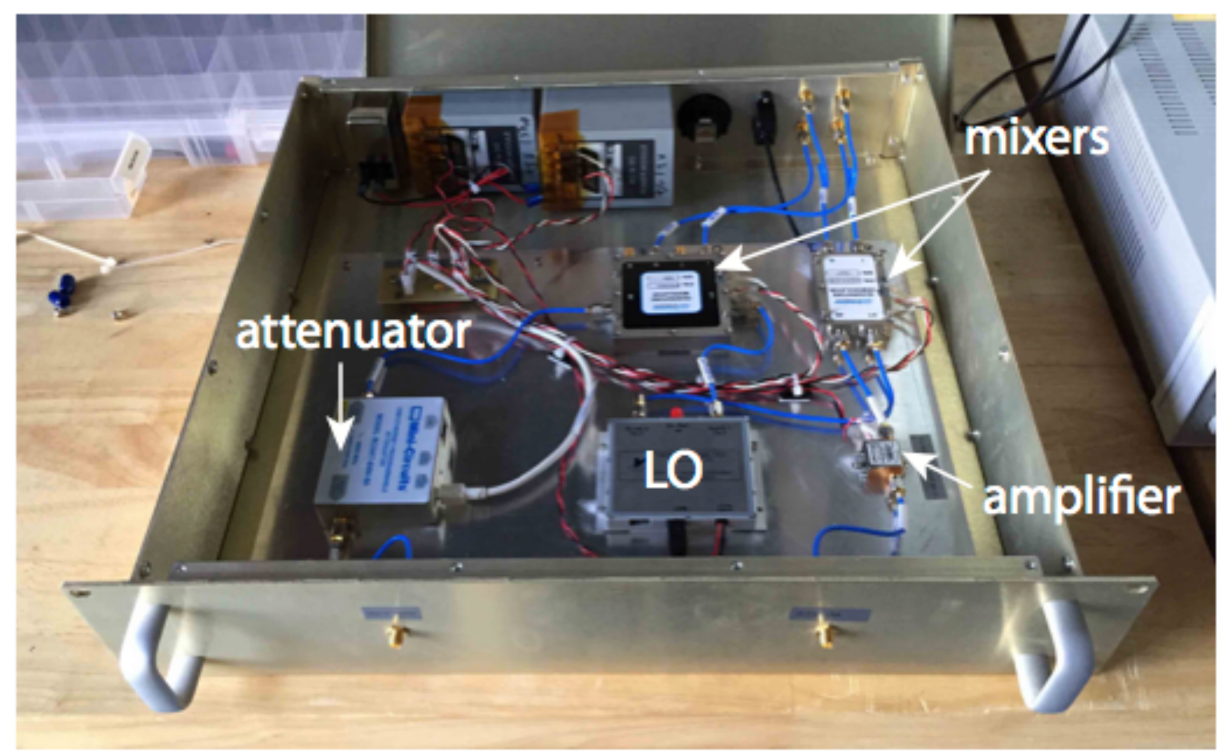


- Warm (300 K) digital electronics synthesize input microwave tones to drive the resonators and channelize and demodulate the output microwave tones
  - ADC, DACs, FPGAs
- ADCs, DACs not sufficiently high bandwidth today
  - Operate in baseband (DC-MHz/GHz) and up-/downmix for signal band
  - Optionally use IQ scheme
- Industry-driven fast-paced growth in FPGA/ADC/DAC capability

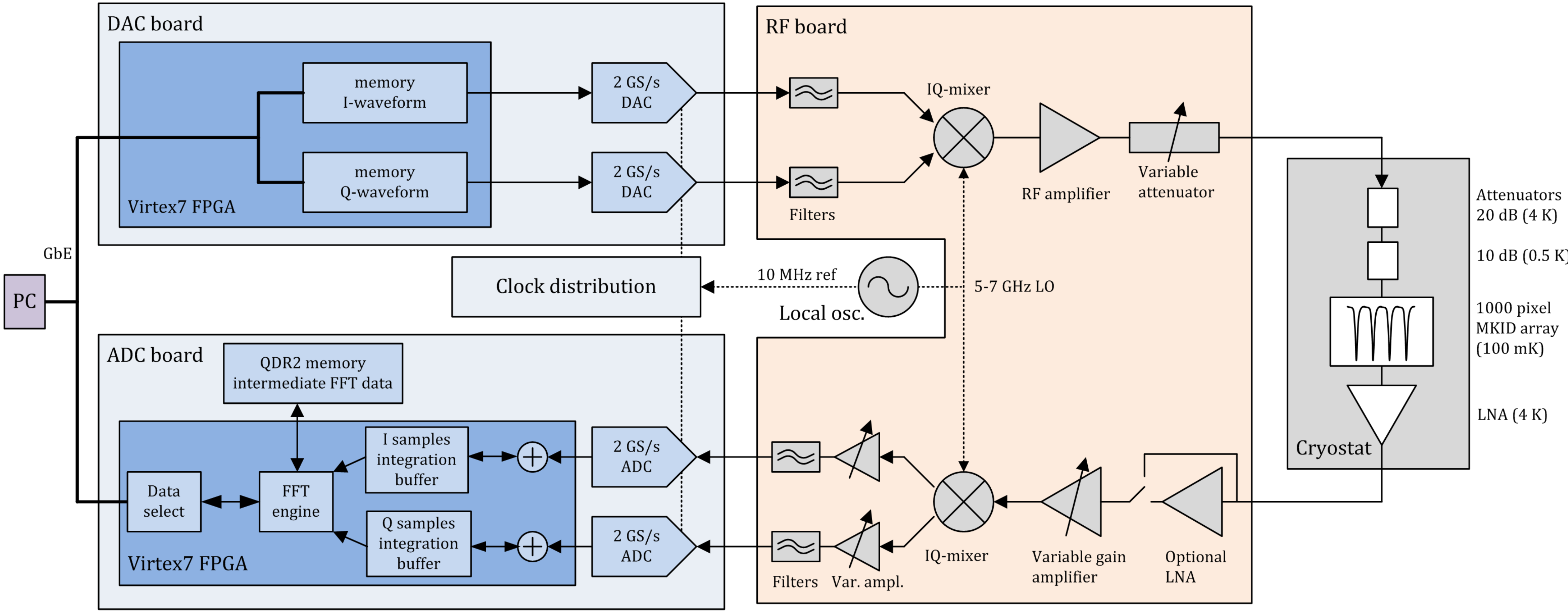
ROACH-2 + 500 MHz ADC/DACs

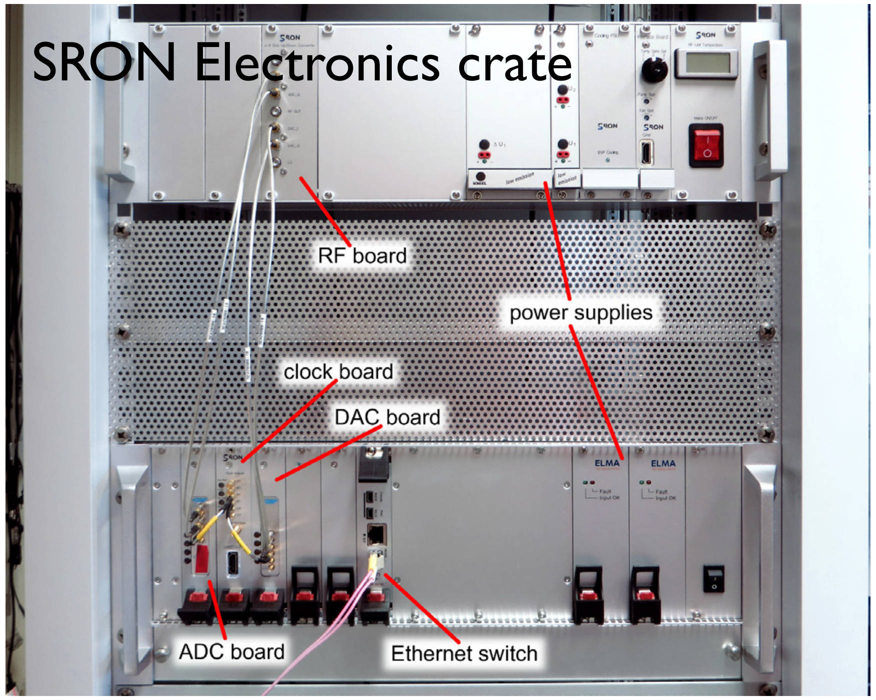


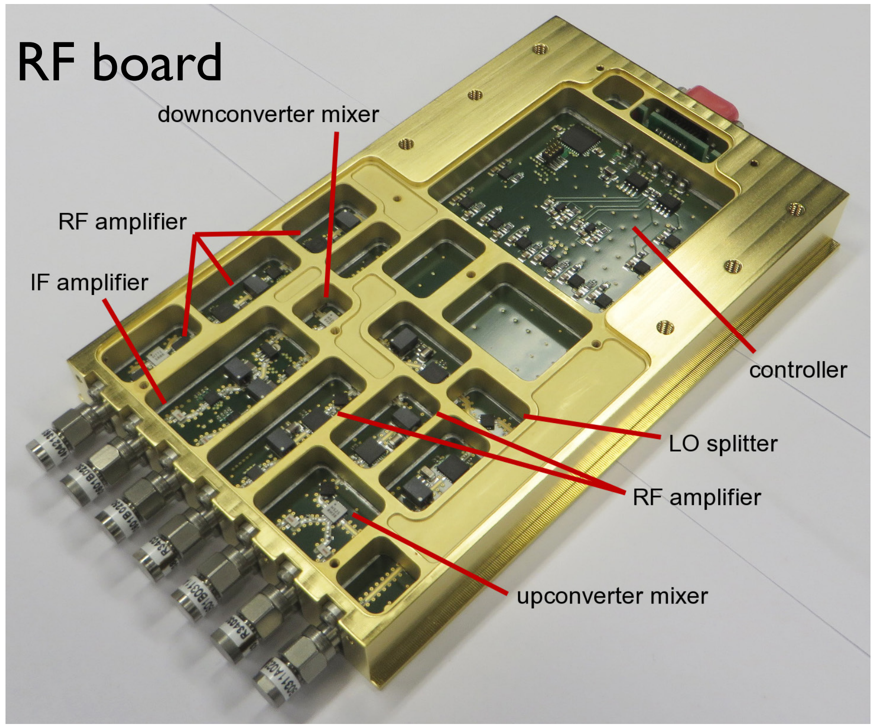
Rev. Sci. Instrum. 85, 123117 (2014)



SRON system (2 GHz bandwidth)

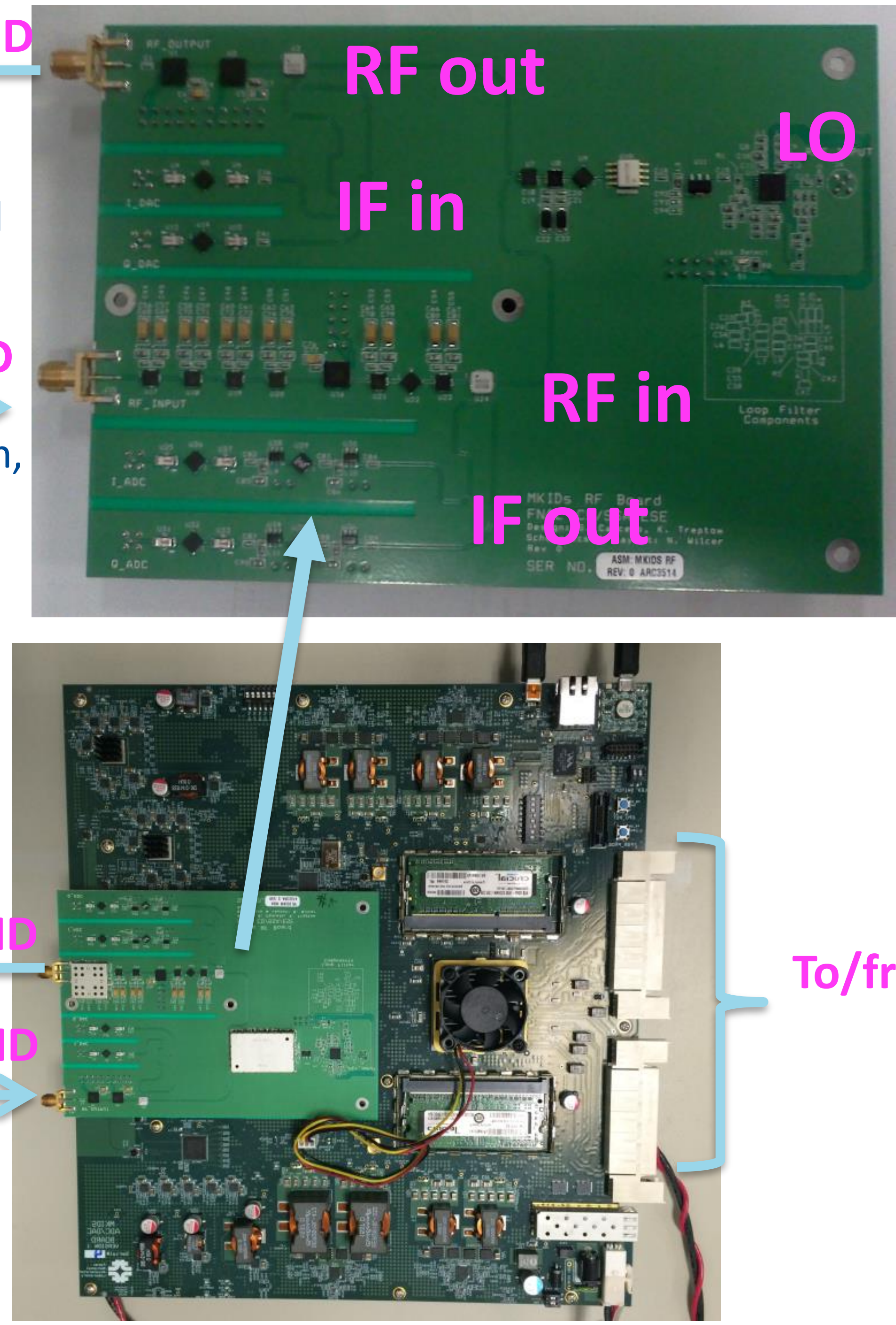




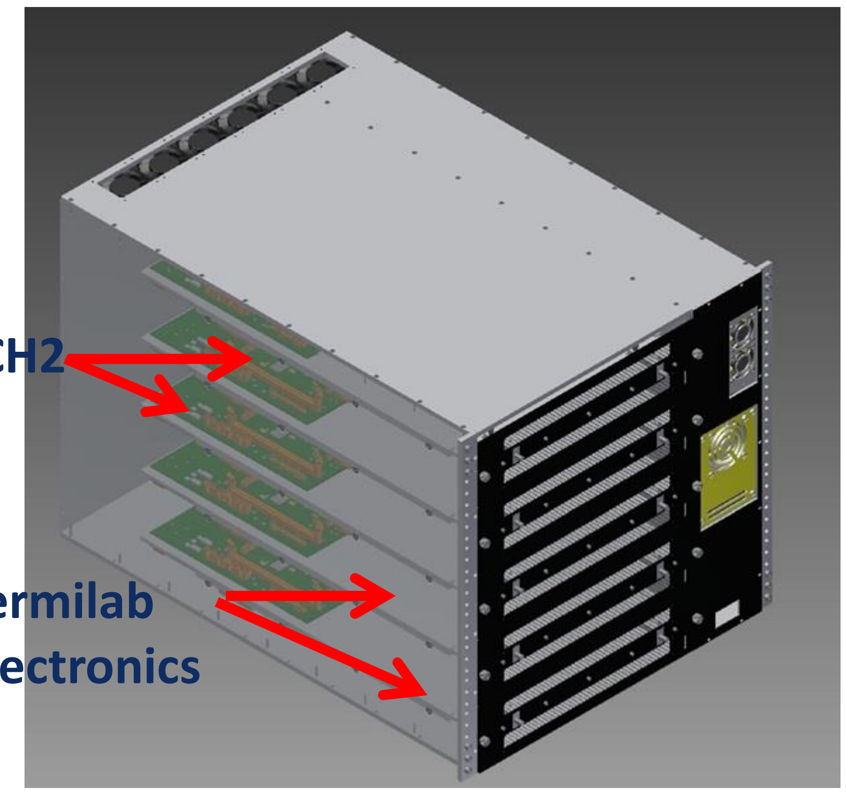


arXiv: 1507.04151

Fermilab: ROACH-2 + 4 GHz bandwidth



10 K pixels crate

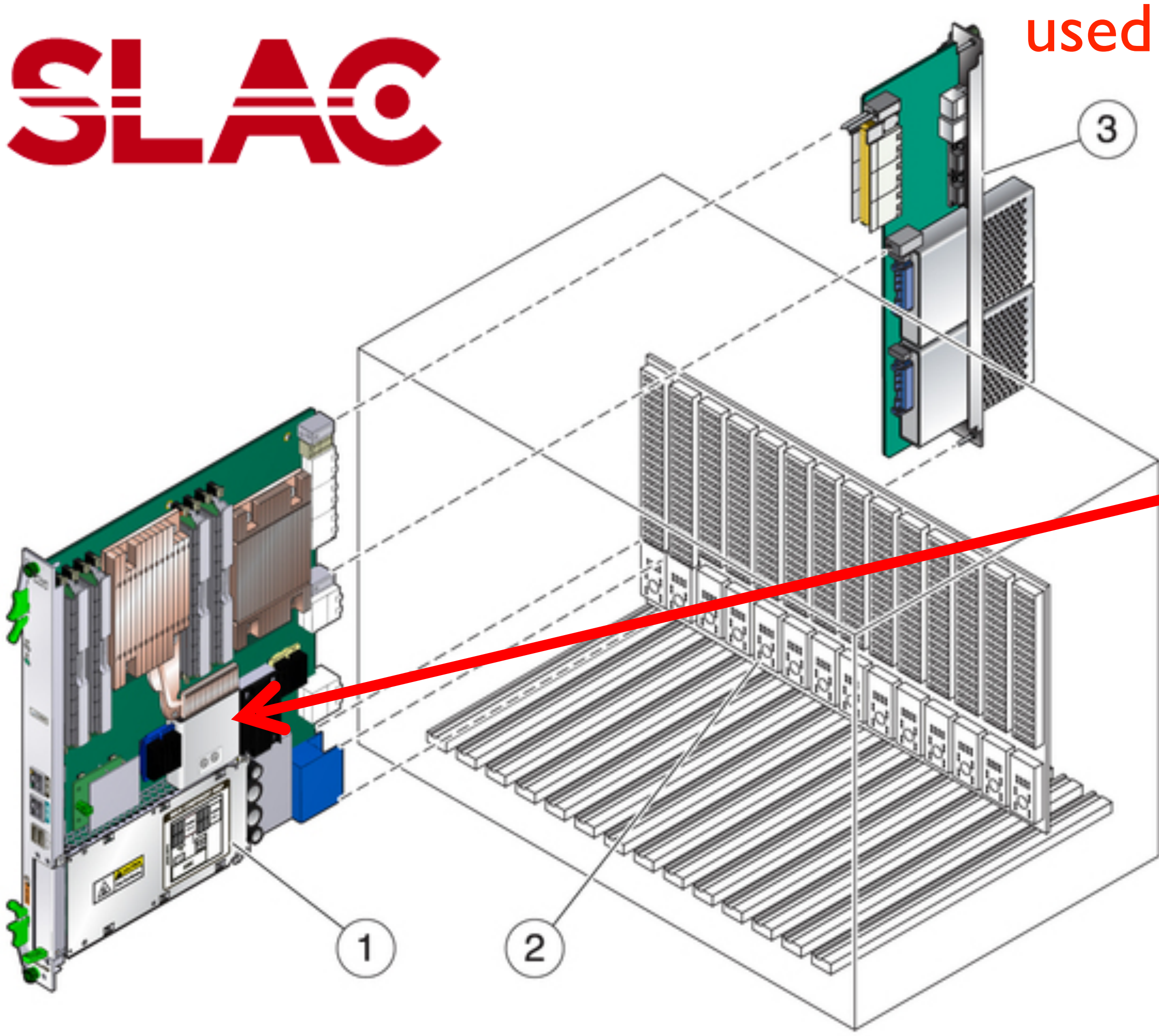


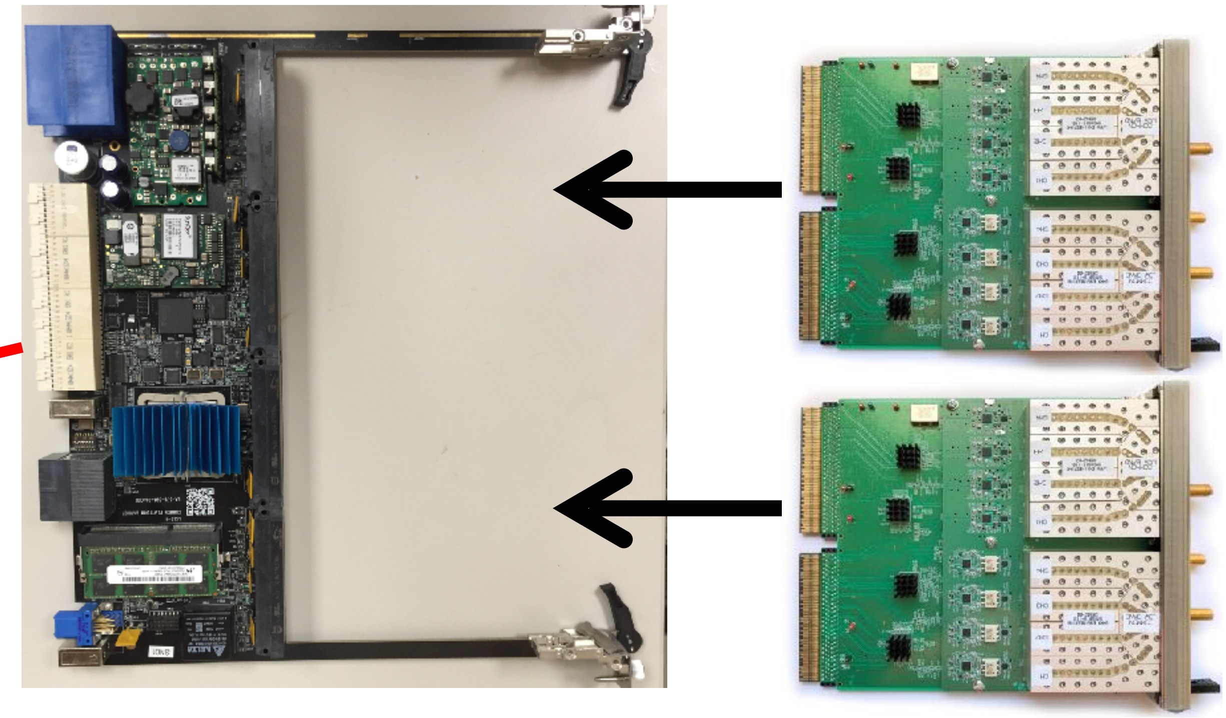
MKIDs for optical require a detector with a BW of ~250 KHz.
CMB ~100Hz. (More channels per ADC and more resolution).

Gustavo Cancelo, CPAD 2017 slides

SLAC Microresonator RF Electronics (4 GHz bandwidth)

Special application of SLAC's RCE "common platform" used in particle and neutrino physics, and in cosmology





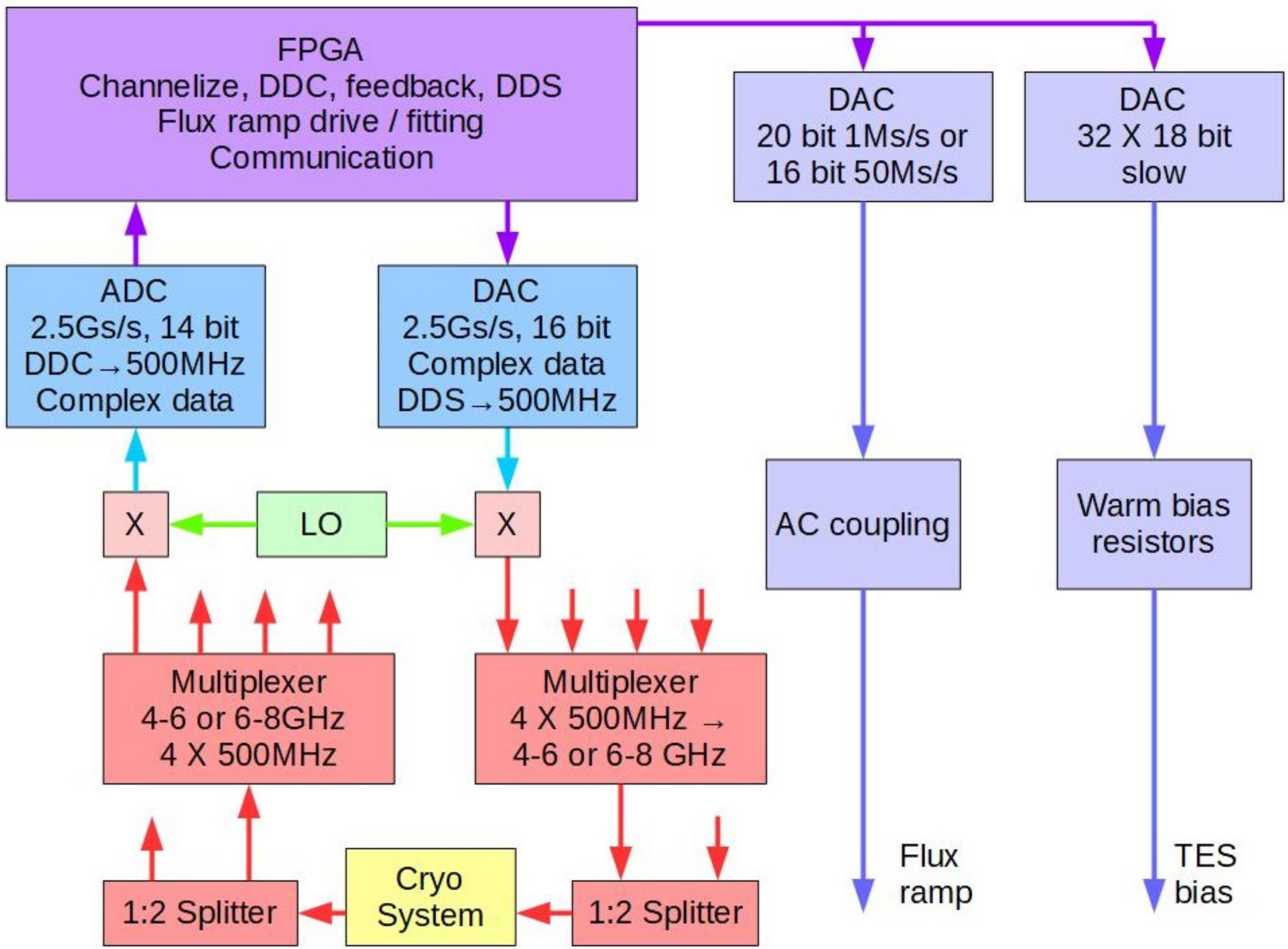
1: Carrier Card (Xilinx KU060, 2.7K slices)
2: Crate (ATCA, 1-14 slot available)
3: RTM
Each carrier supports 2 AMC application cards

Carrier card: FPGA, memory, backplane connections

AMC cards: (double-wide full height) ADCs, DACs, high performance front end electronics

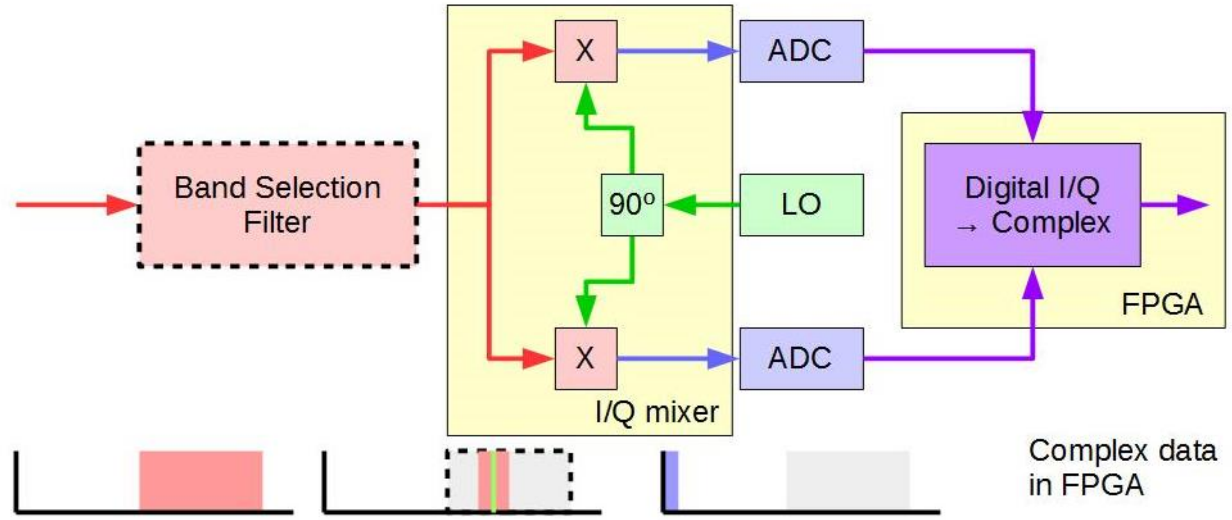
RTM: General purpose IO, extra networks, miscellaneous

SLAC Microresonator RF Electronics (4 GHz bandwidth)

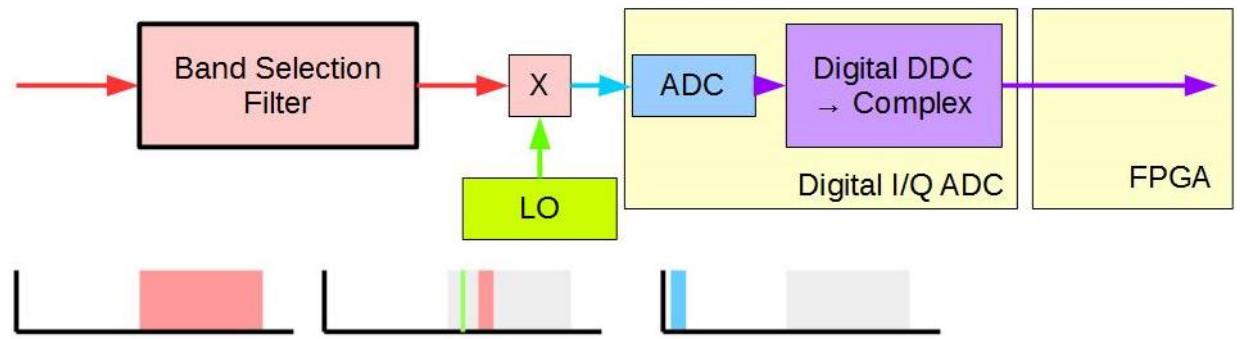


Digital IQ vs. Analog IQ

Analog I/Q scheme used for many systems



Digital I/Q scheme used in SMuRF



- For a single band, analog I/Q provides more efficient use of ADC.
    - Continuous calibration of I/Q mixer require to reject out of band signals
- For multiple bands, channel splitting filters eliminate ADC efficiency advantage.
    - Single 4GHz band beyond current ADC / DAC state of the art
- Digital I/Q chosen for SLAC electronics to eliminate calibration complexity

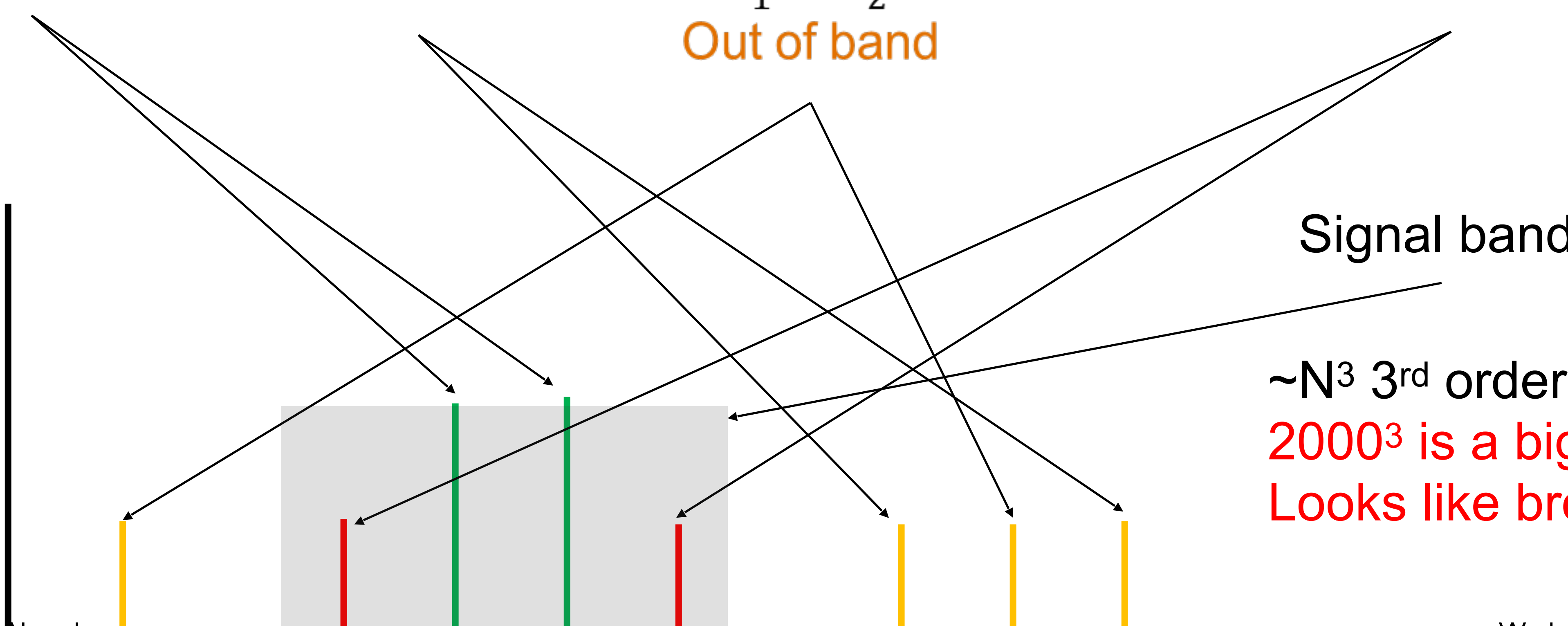
Noise and dynamic range

- LNA (HEMT) noise, 2-4K, ultimate limit
- For large MUX systems, **dynamic range** is the problem
  - Limited by linearity, intermodulation products can mimic broadband noise!

$$A = \sin(w_1 t + \varphi), \qquad B = \sin(w_2 t + \phi)$$

$$Y = C_1 A + C_2 B + C_3 A^2 + C_4 B^2 + C_5 AB + C_6 A^2 B + C_7 AB^2 + \cdots$$

- $C_1 A + C_2 B$: w_1, w_2 — Original tones
- $C_3 A^2 + C_4 B^2$: $2w_1, 2w_2$ — Out of band
- $C_5 AB$: $w_1 + w_2$, $w_1 - w_2$ — Out of band
- $C_6 A^2 B + C_7 AB^2$: $2w_1 - w_2, 2w_2 - w_1, other\ f$ — In band!



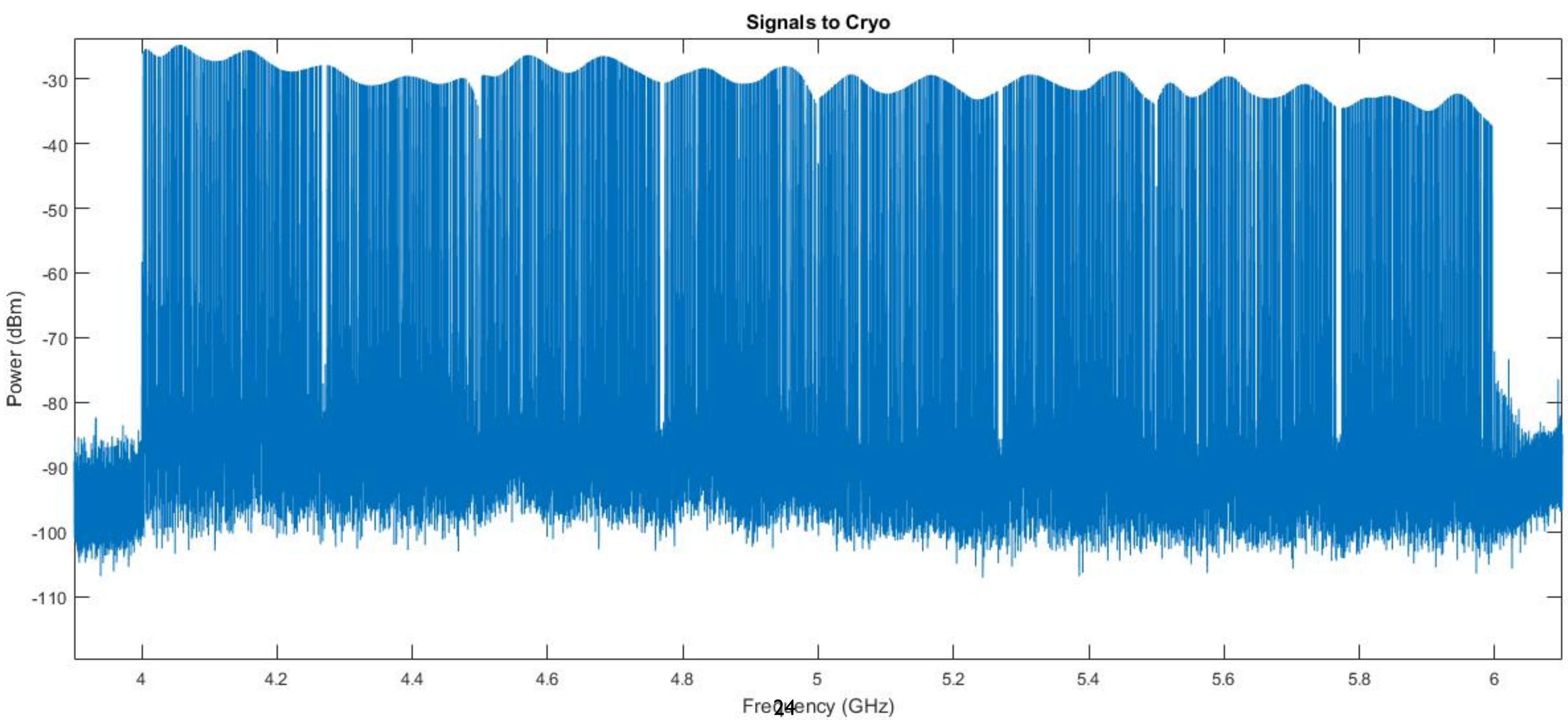
~N^3 3rd order terms!

2000^3 is a big number!

Looks like broadband noise

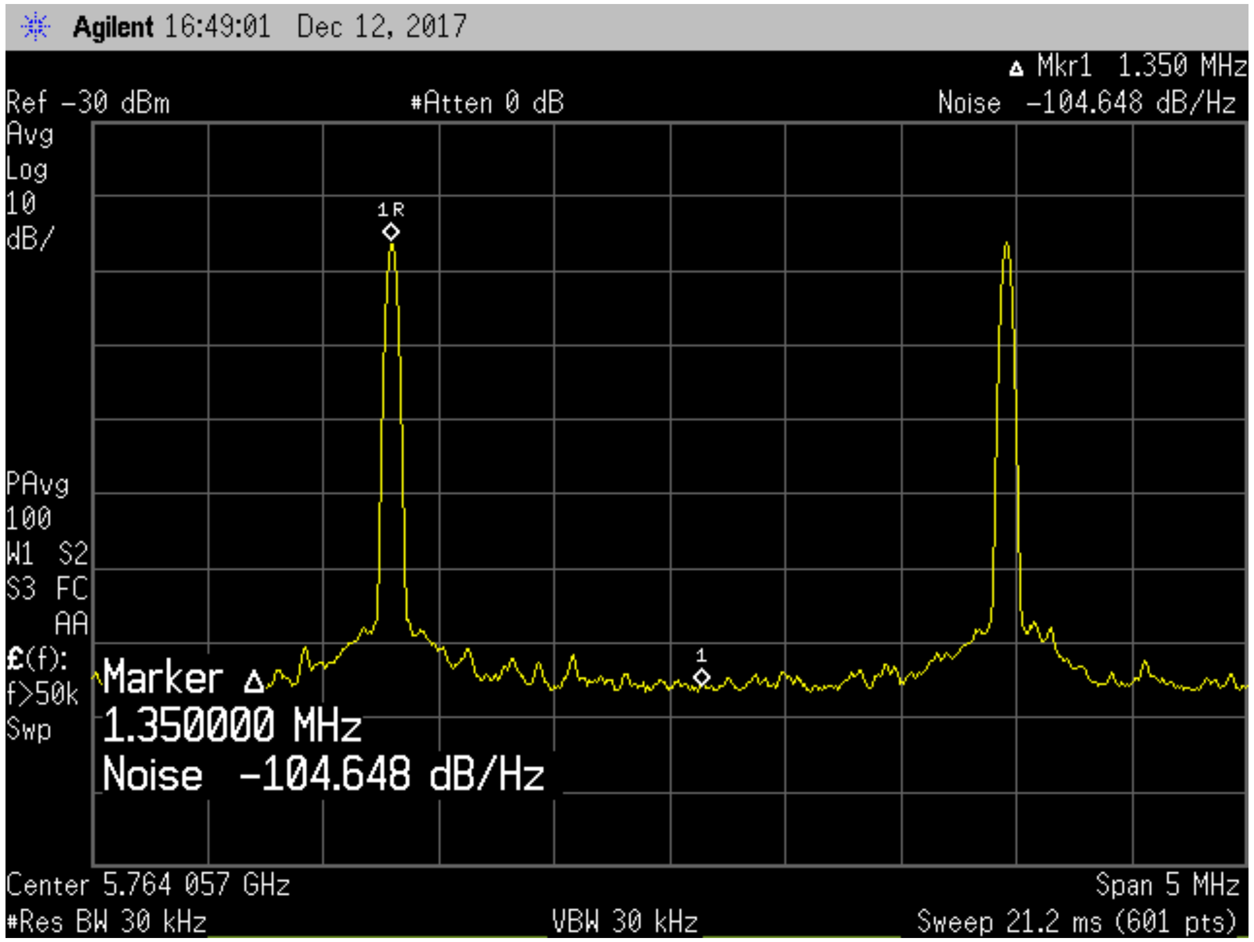
DAC and Upmix system

- Generating 1000 lines in 2GHz bandwidth from 4-6GHz
  - Gaussian random frequency errors added
  - Note: Gaps are put in spectrum for noise testing.
- This is after the last active device and filter in the system. Combining with 6-8 GHz is not expected to add spectral distortion or non-linearity
- Final system will add equalizers to level overall spectrum



Signal generation noise in detection band

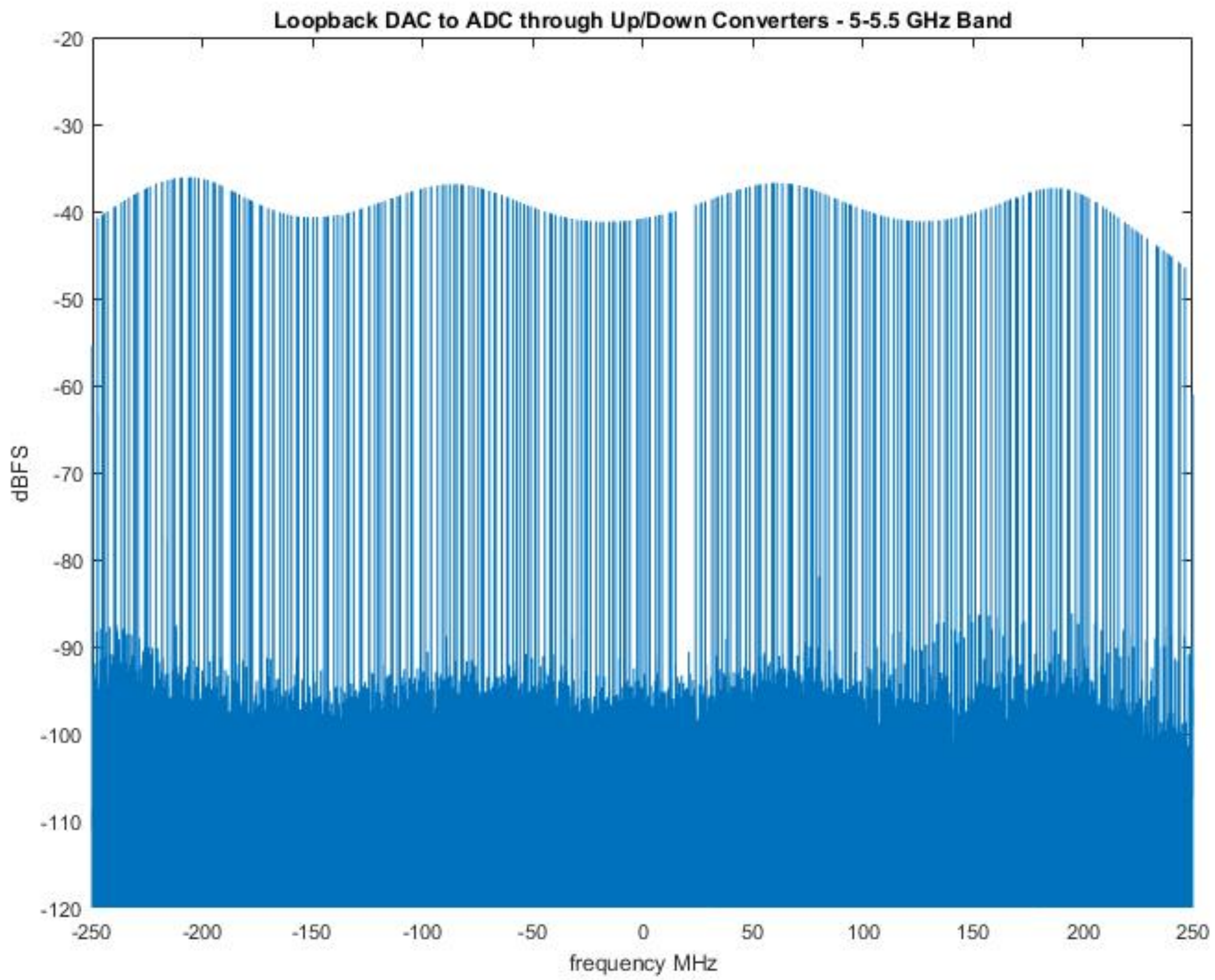
- Measurement shows >100dBc/Hz
- LO noise, nonlinearity etc. all included
- Measurement done with 2000 lines generated (not equally spaced, obviously!)
- Tests with real SC resonators now in progress!



-104dBc/Hz noise between lines

Full Loopback test: DAC + upmix + downmix + ADC

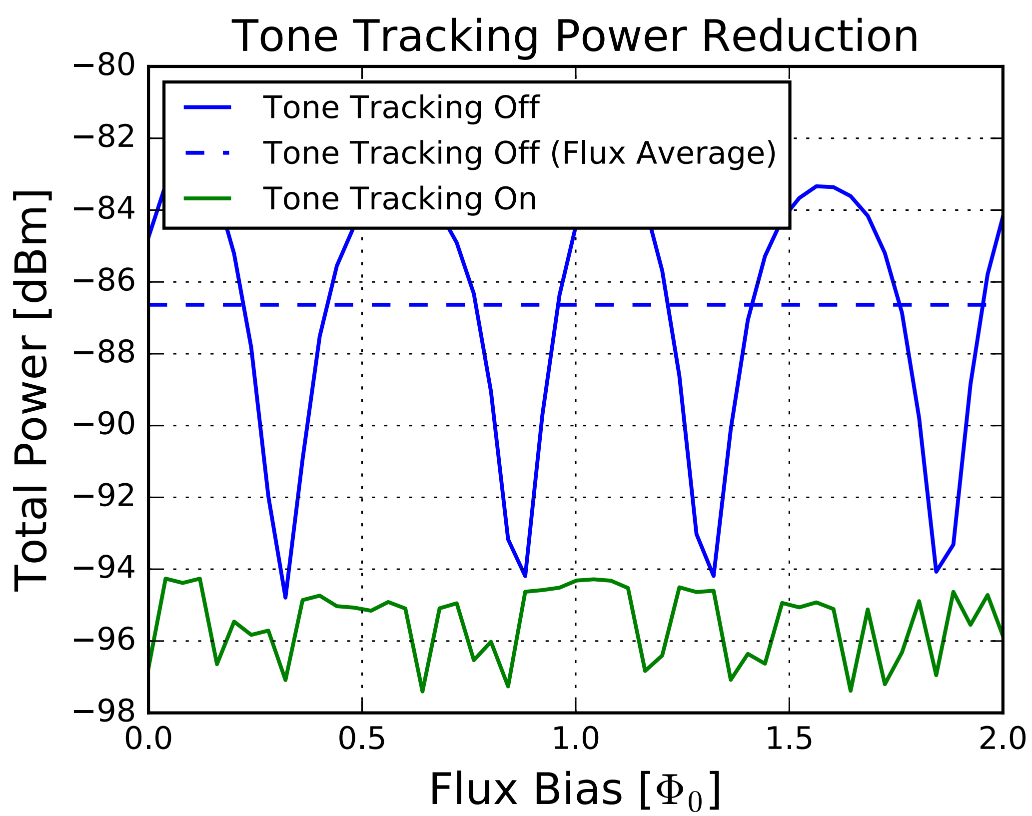
- Single 500MHz block, 5.5-6GHz shown.
  - 2000 lines being generated and received
  - Gap is used for noise calibration
- Full SMuRF system, everything except the cryogenic system

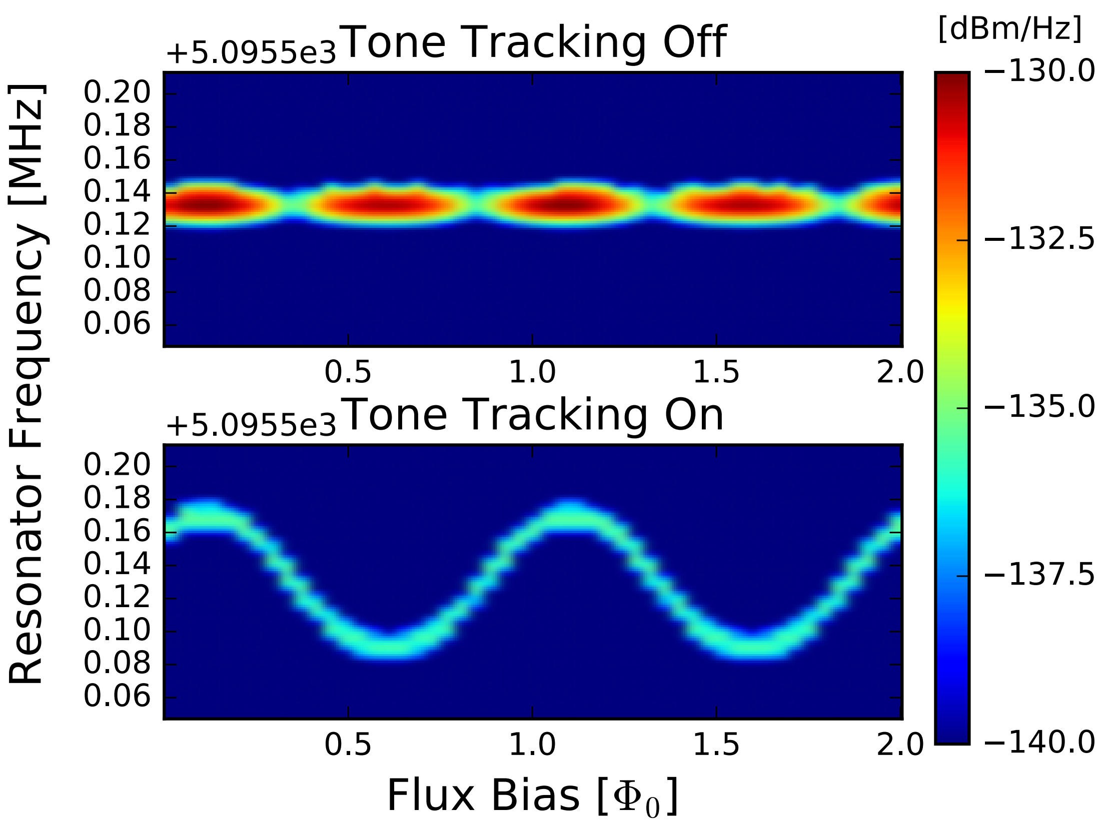


Maximizing Dynamic Range — HEMT, tone tracking

- HEMT is normally the limit to system dynamic range
  - Replace HEMT with low gain modification and add 50K amplifier stage
- Dynamically track resonance dips to reduce power in HEMT an additional ~10-15dB without degrading signal to noise
  - Line tracking reduces dynamic range requirement in ADCs (but not DACs).

Tone tracking demo with SLAC electronics

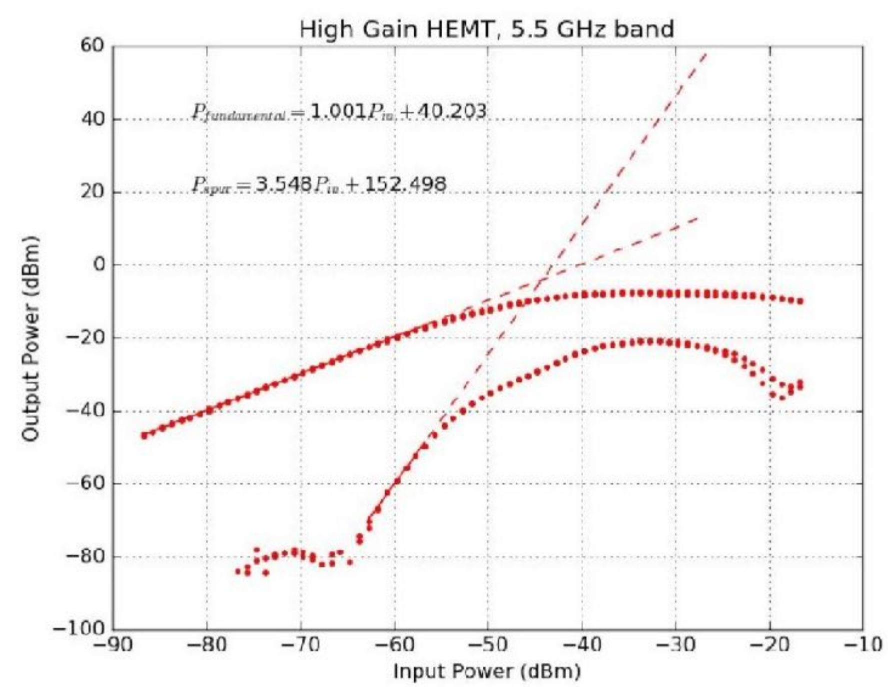




Kernasovskiy et al. LTD-17, submitted

Challenges & opportunities for next-gen warm readout

- FPGAs, ADCs, DACs will become more and more capable
  - RFSoCs (RF System on Chip) will combine these components
- Fully digital systems without analog mixing around the corner!
  - ADC/DAC bandwidth increasing
- Component costs are dropping
- Linearity is a challenge for large MUX factors for CMB-S4
  - LNA linearity improvements might be possible if trade off with noise
  - Tone tracking, feed forward, chirped readout etc.



Conclusions

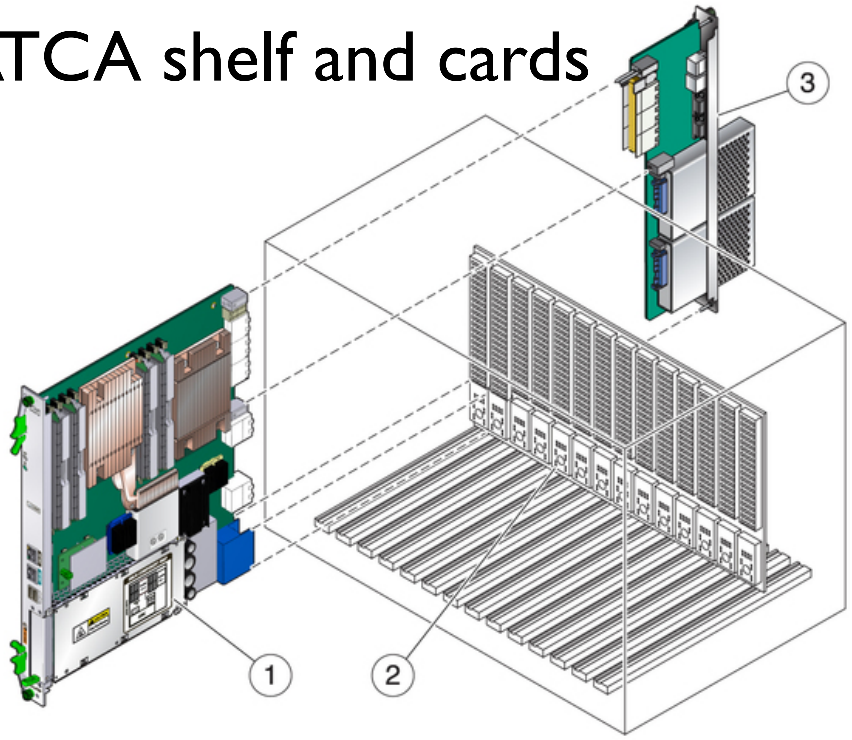
- Traditional cold & warm readout has served 2 generations of CMB cameras, but no more!
- Microwave resonators will enable larger camera sensor counts
  - TES, MKIDs are starting to take advantage
  - MUX ~1000 being achieved, several 1000 around the corner
- Warm readout
  - ADC, DAC and FPGA technology advancing quickly to take advantage of superconducting resonators
- CMB-S4 and next-generation CMB experiments will take advantage of this progress in cold and warm readout technology for quantum sensors.

Backup slides

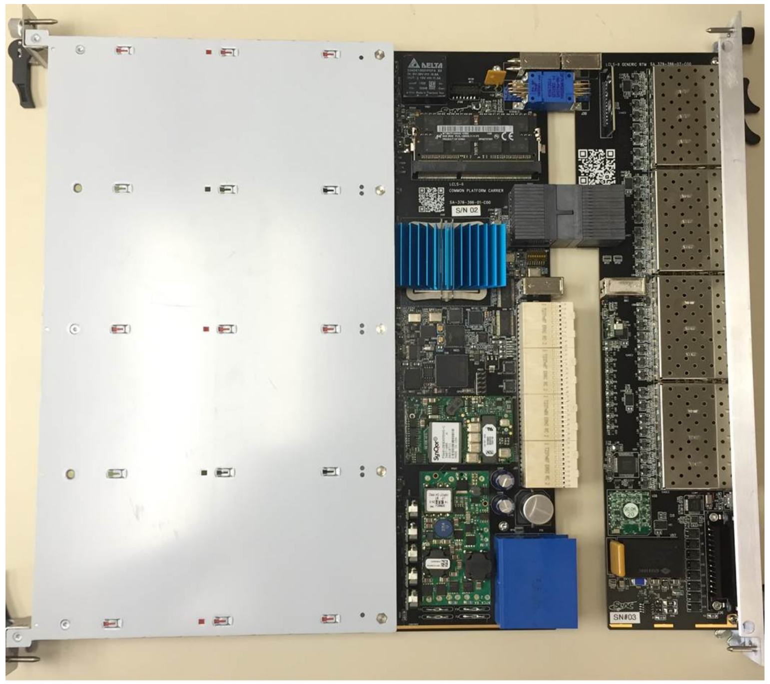
SLAC Microresonator RF Electronics (4 GHz)

- Frequency of probe tones is actively adjusted to track resonance.
- Enables packing more resonances in a given RF power budget.
- Direct digital synthesis and demod (no IQ)
- Being built for LCLS-II based on existing ATCA heritage at SLAC for particle physics and RF engineering in LCLS-I.
- A carrier card provides
  - 4GHz bandwidth
  - Upto 4000 channels
- Full hardware prototype now being tested
- Plans to make this general purpose and serve TES/MKID applications

ATCA shelf and cards



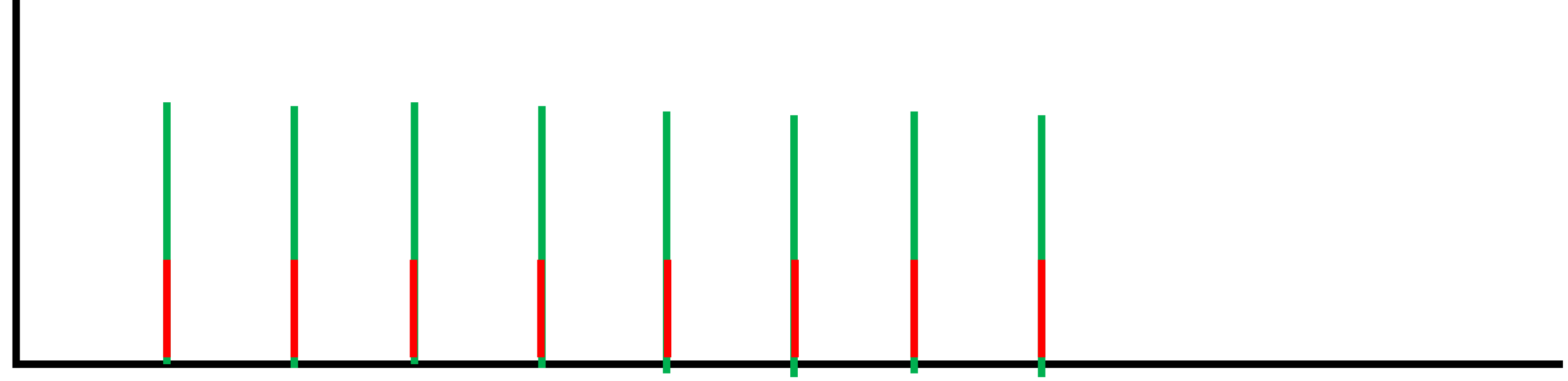
Carrier cards



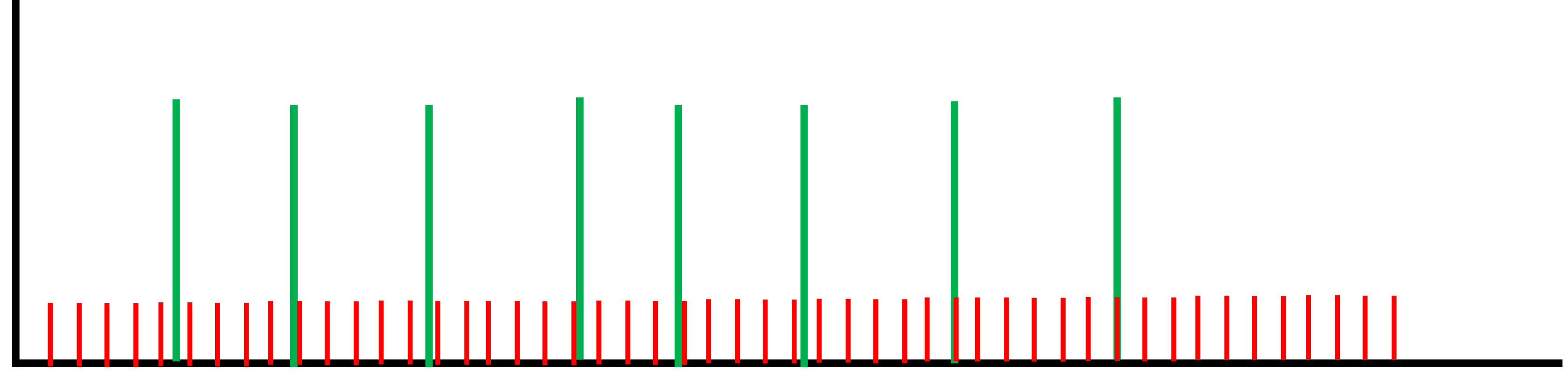
Linearity:

- If the system bandwidth includes an octave or more bandwidth, 2nd order non-linear products are important (f1-f2) is in-band.
- Otherwise the first important nonlinear terms are 3rd order (f1+f2-f3) which are typically smaller.
  - This can still work but requires careful design.
- Signal levels need to trade off noise vs nonlinearity throughout the design
  - Generally implies low gain amplifier stages
  - SMuRF uses a low gain HEMT and 50K amplifier
- SMuRF design avoids octave bandwidths.

With evenly spaced lines the intermodulation products are “**hidden**” underneath the main lines, invisible but still there



With randomly spaced lines, the intermodulation products look like broadband noise

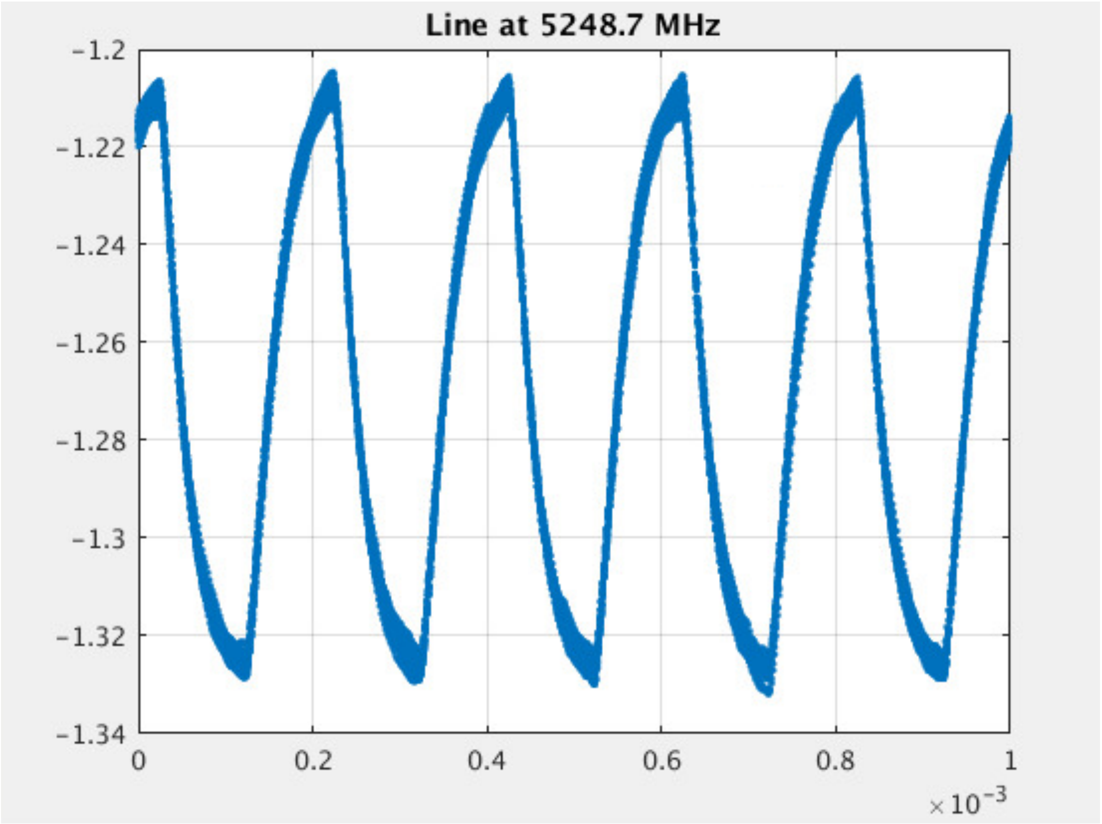


Linearity needs to be tested with random line spacing

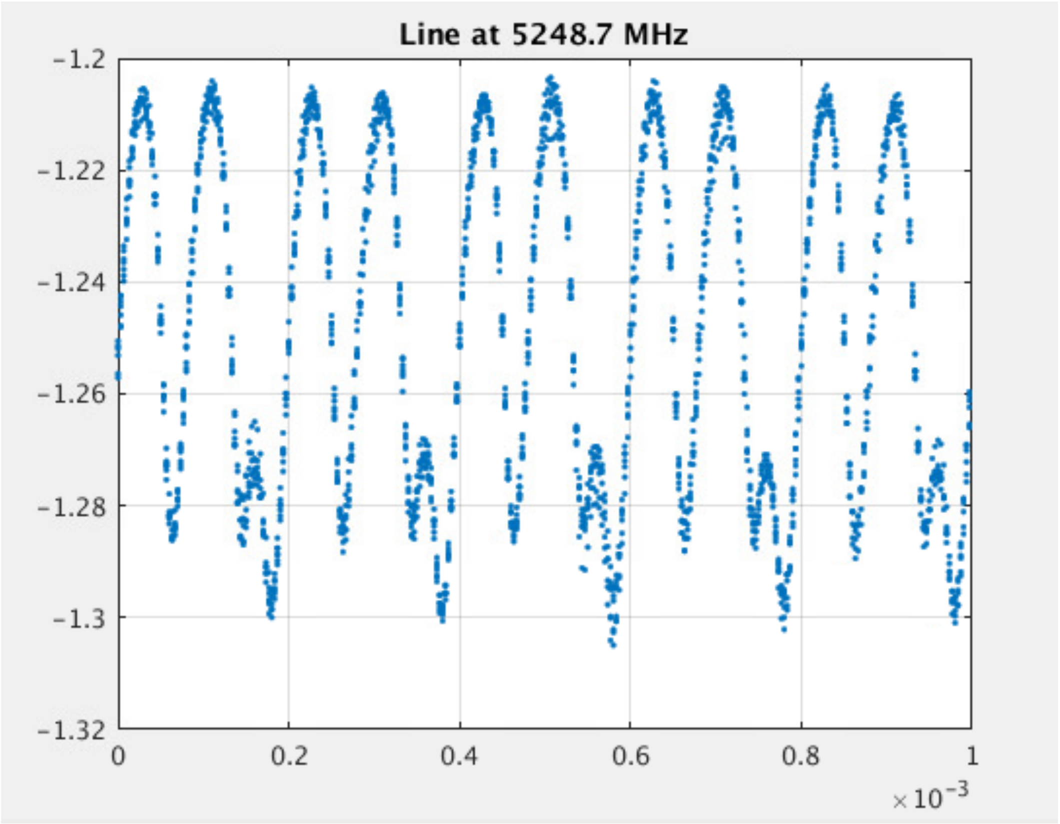
Cold MUX tests: Flux Ramp Tracking Demonstration

SLAC

- All lines operational, single line frequency vs time shown.
- Performance good for 5KHz flux ramp
- For faster flux ramp will need feed-forward
  - Electronics and algorithm latency limit bandwidth
  - Already in development for 1MHz X-ray sensor
  - For CMB, physics signal is small (icy blackness of space)
  - Flux ramp very reproducible -> feed forward should work easily!



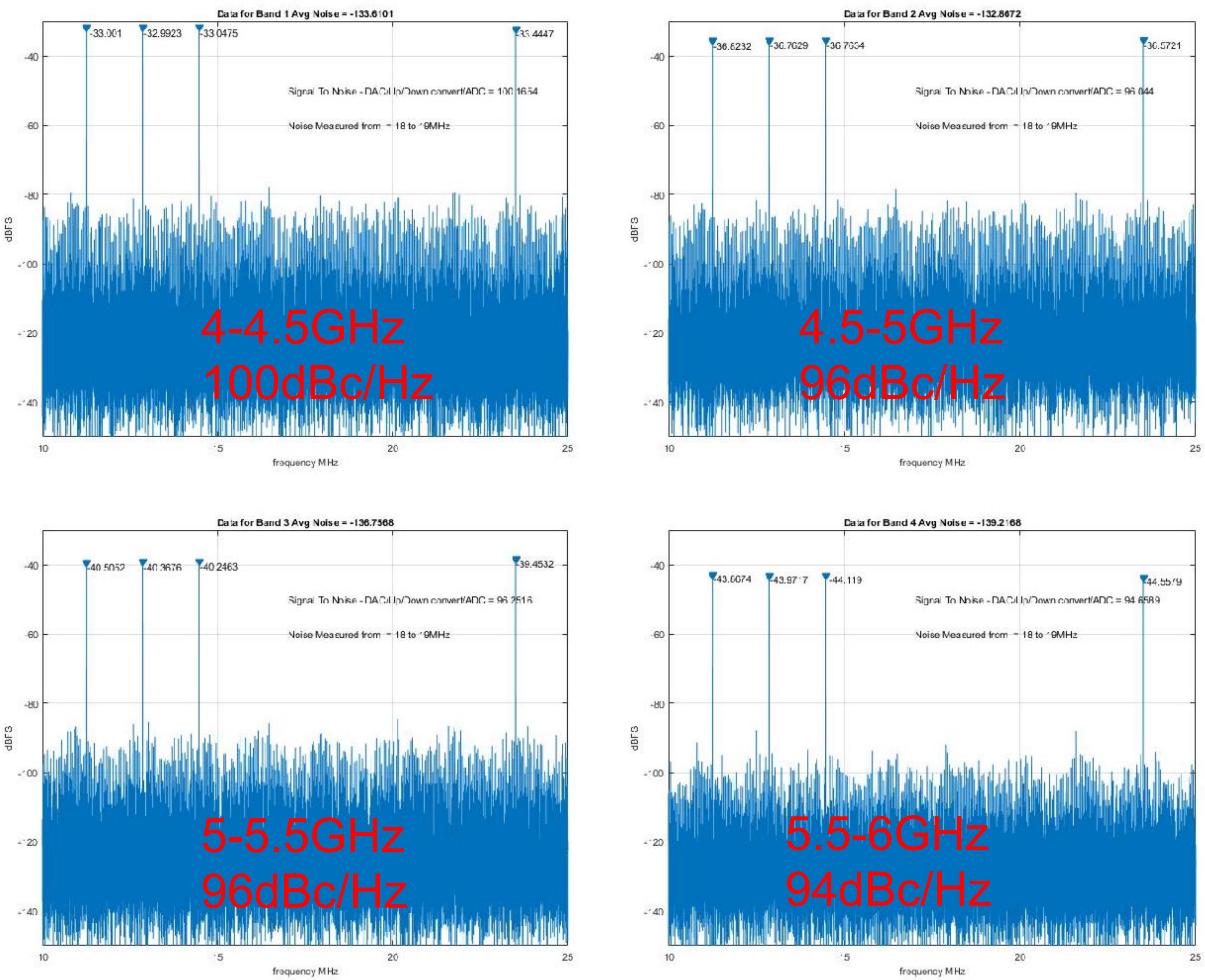
Response time test: 5KHz square wave flux ramp



Flux ramp $2\Phi_0$ ramp, 5KHz ramp, 10KHz Φ_0

Full loopback test: noise measurement

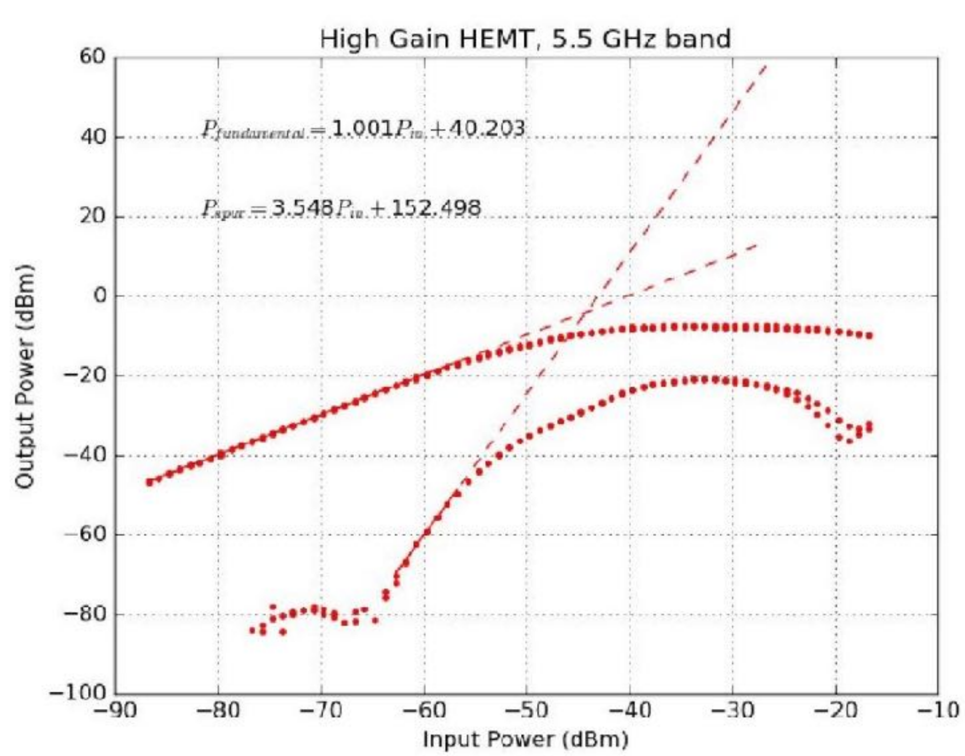
- Noise measurements on all 4 blocks.
- Receive requirements **85dBc/Hz**, 15dB below transmit requirements due to line tracking



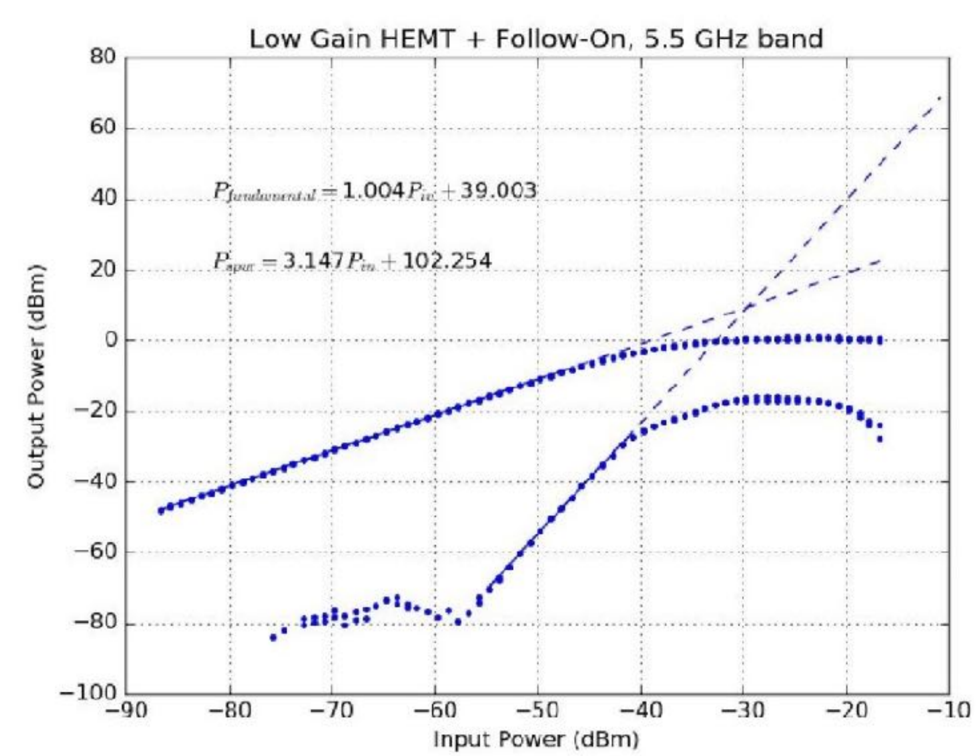
- Noise measured in 1MHz band around "missing line"
- Full 2GHz bandwidth operating for each measurement

Results: Improved HEMT linearity

- HEMT has low noise noise (-194dBc/Hz) but poor linearity: **-44.1dBm input IP3**
- **Low Gain HEMT**: HEMT IP3 is limited by the output stage, so by removing one stage (out of 3 total) and get 13dB less gain, 13dB higher input IP3 and the same noise. **-29.5dBm input IP3**
- Line tracking reduces signal by ~15dB due to resonance dips
- For 2000, -70dBm input lines, reduced to -85dBm by line tracking:
  - Original HEMT: 83dBc/Hz (want total system >85dBc/Hz on receiver)
  - Low gain HEMT: 113dBc/Hz – no longer limiting!



High Gain, IIP3 = **-44.1dBm**



Low Gain, IIP3 = **-29.5dBm**