TES Readout for Space

2017-12-05

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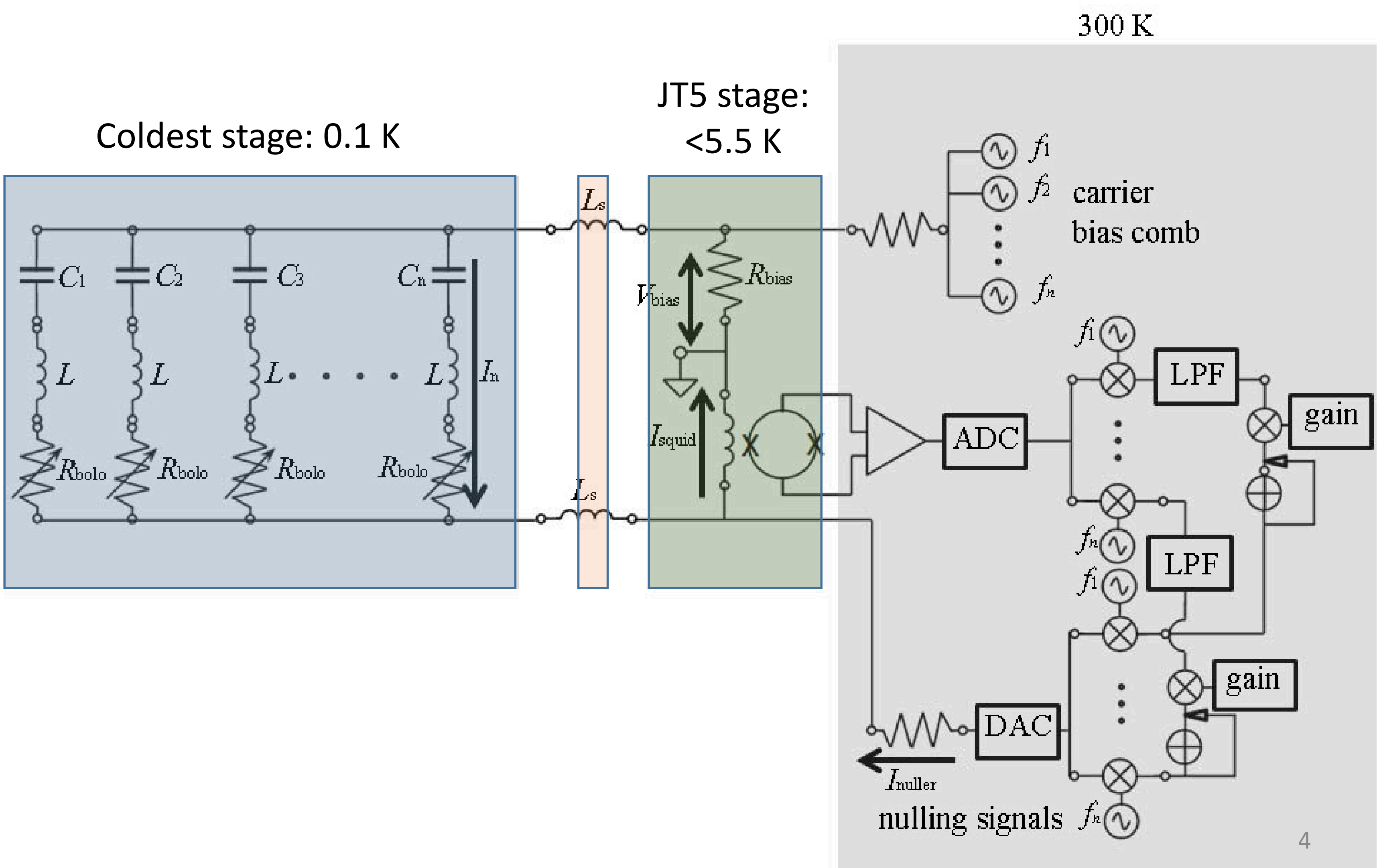
Outline

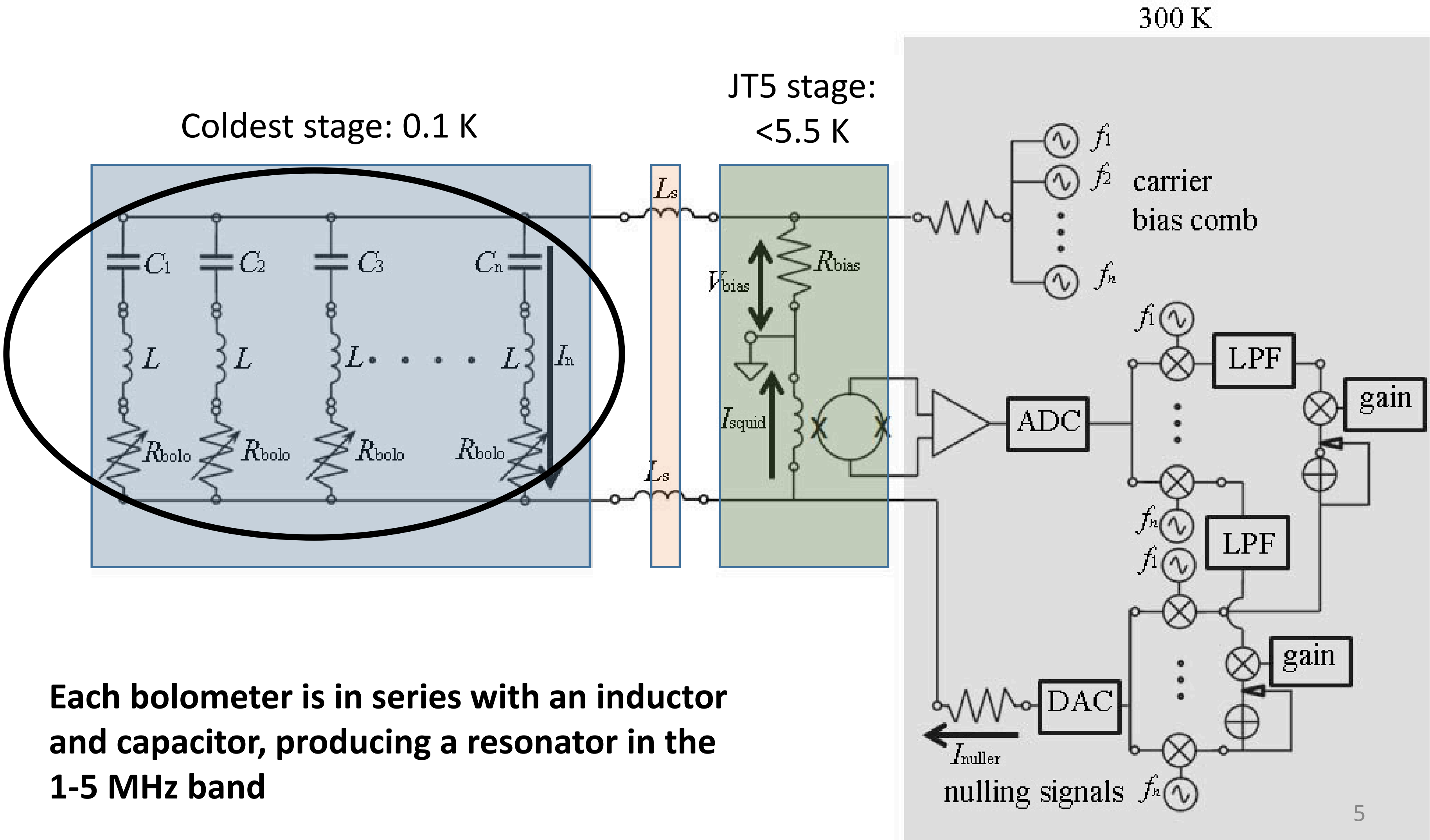
- Digital Frequency-Division Multiplexing (DfMux) – MHz f-mux
  - Overview, Heritage & Status
  - "Warm readout" (outside the cryostat)
    - Existing development efforts for LiteBIRD funded by the Canadian Space Agency
  - "Cryogenic readout" (inside the cryostat)
    - Existing development efforts for LiteBIRD funded by NASA
- Microwave frequency-division multiplexing (μmux) – GHz f-mux
  - Status of this new readout scheme being developed for ground-based instruments

DfMux Overview, Heritage & Status

DfMux Architecture

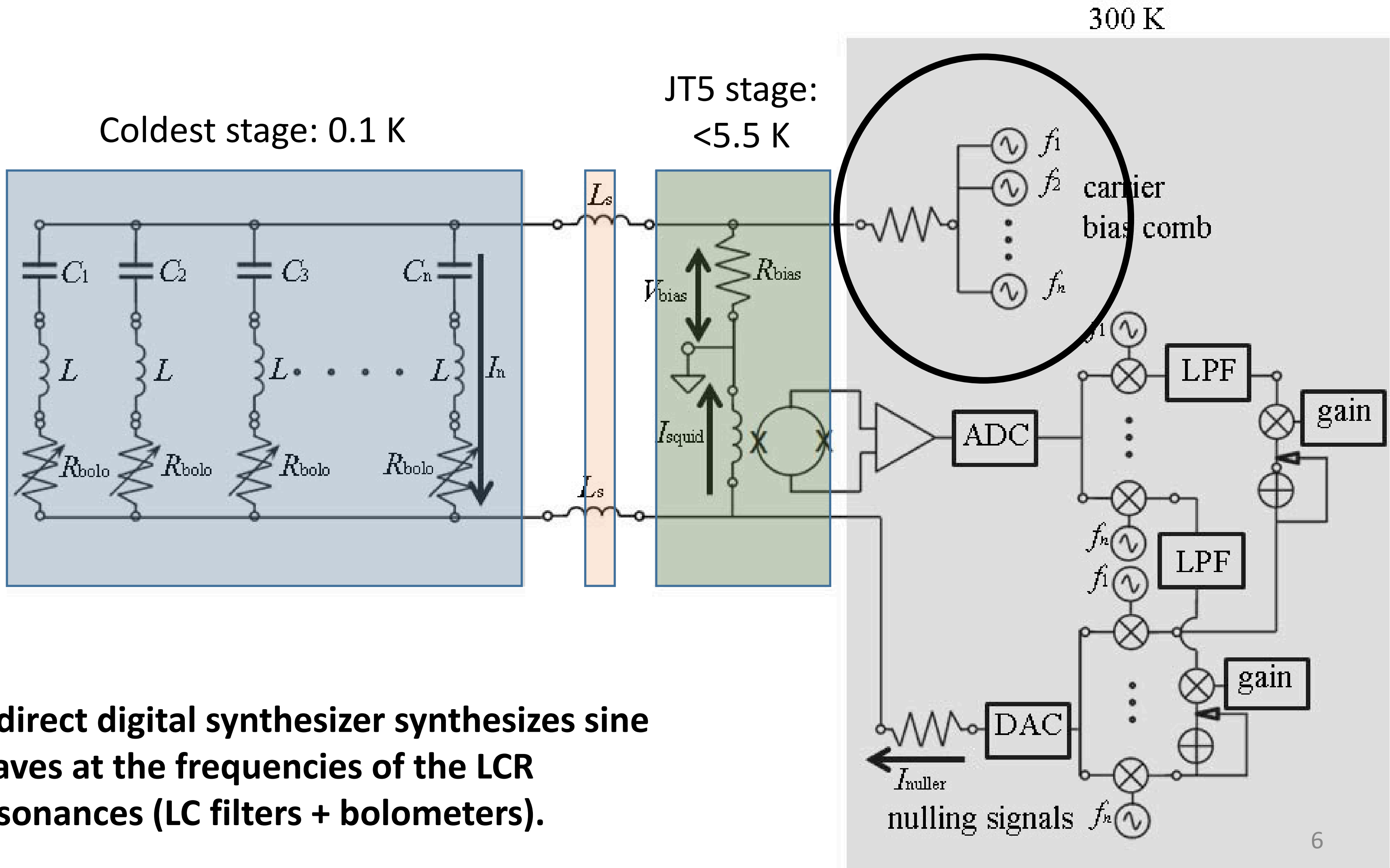


DfMux Architecture



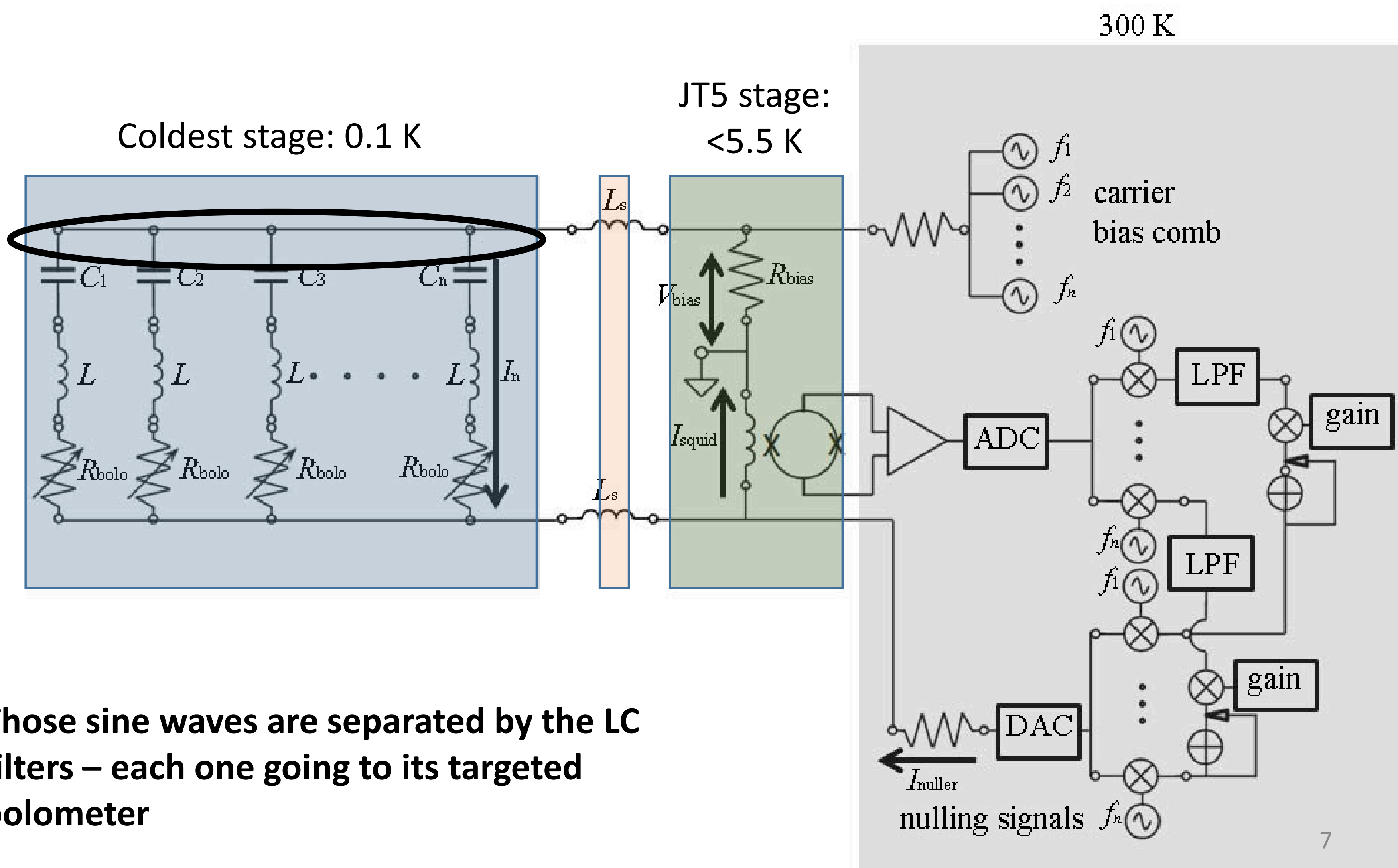
Each bolometer is in series with an inductor and capacitor, producing a resonator in the 1-5 MHz band

DfMux Architecture



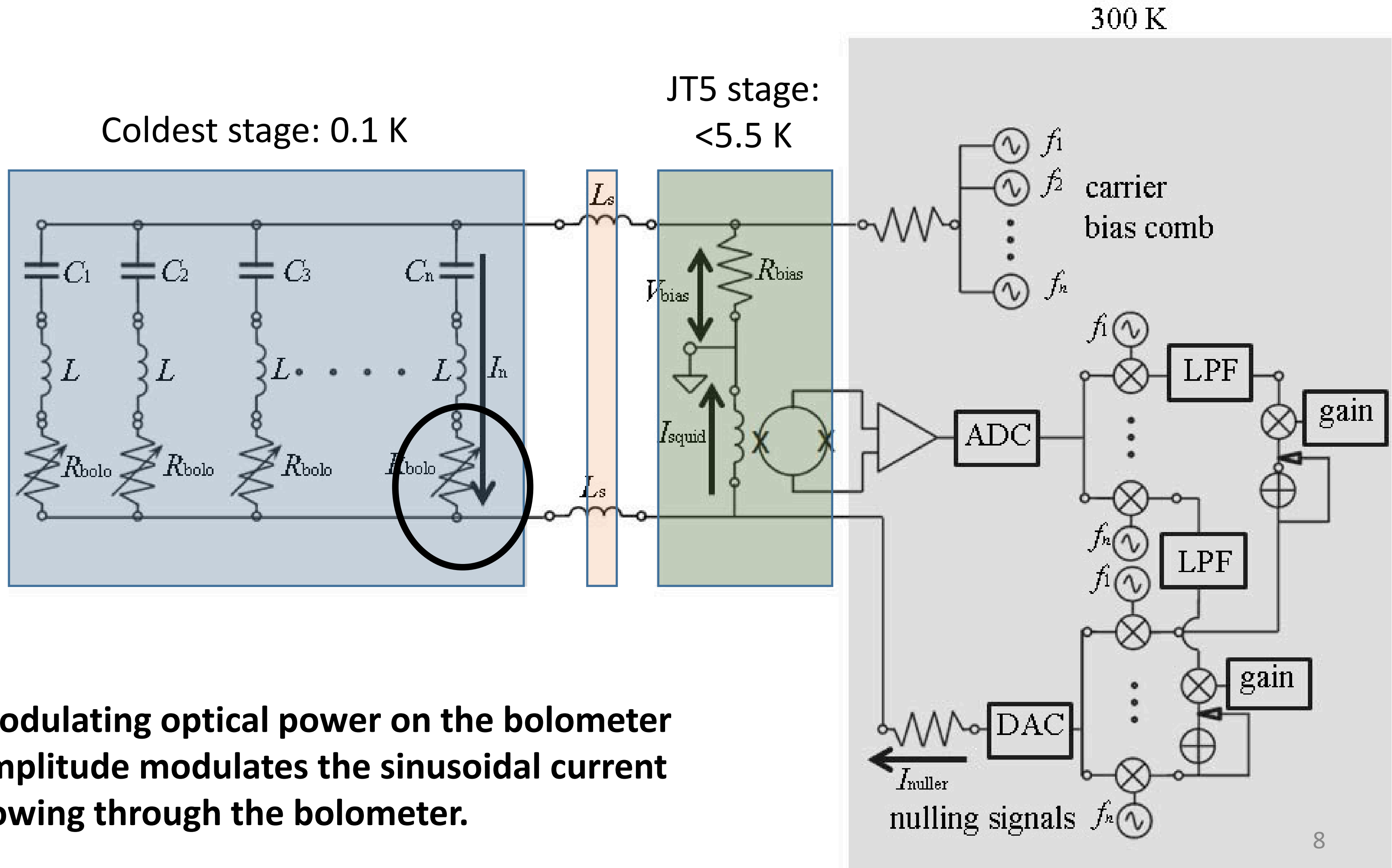
A direct digital synthesizer synthesizes sine waves at the frequencies of the LCR resonances (LC filters + bolometers).

DfMux Architecture



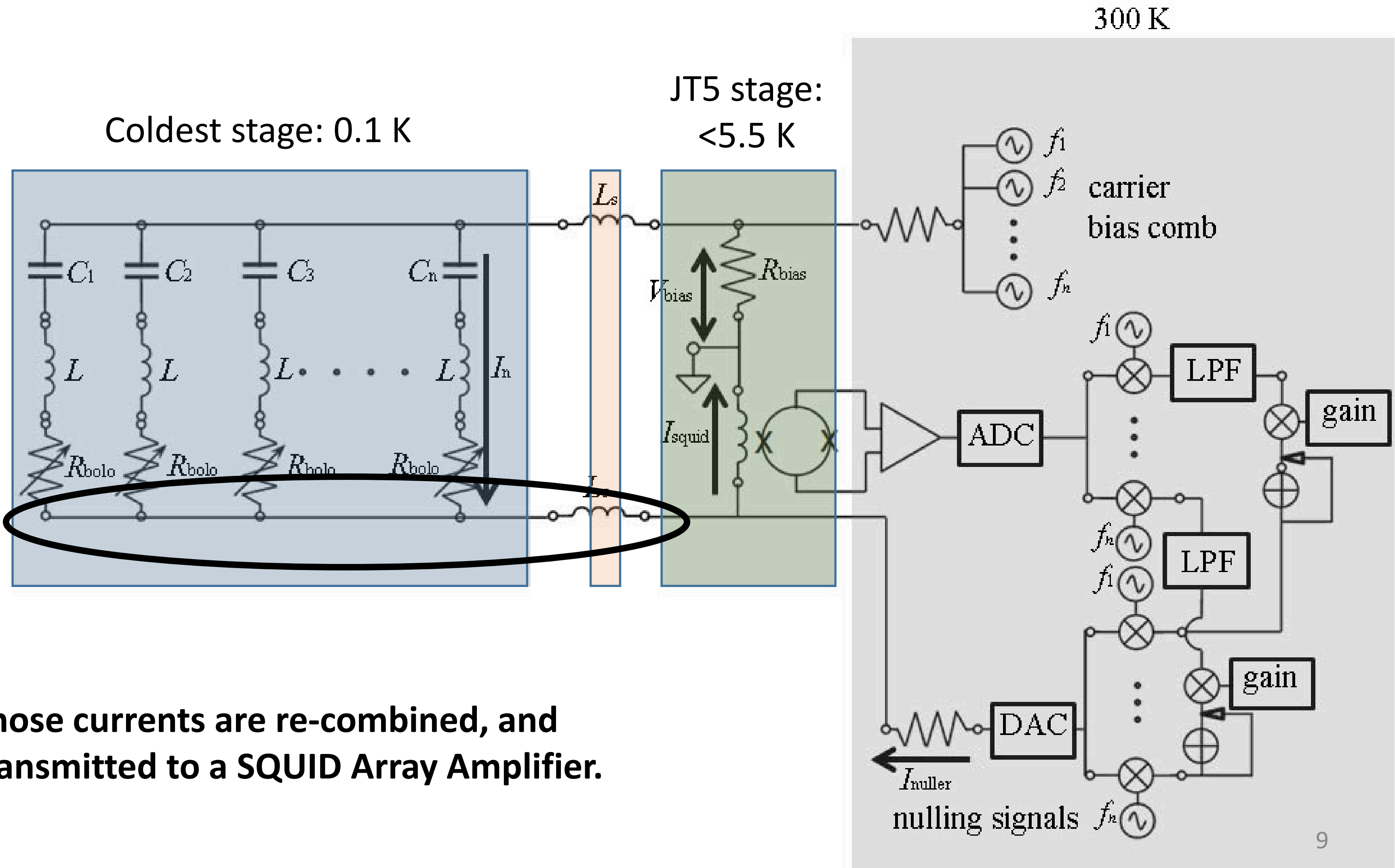
Those sine waves are separated by the LC filters – each one going to its targeted bolometer

DfMux Architecture



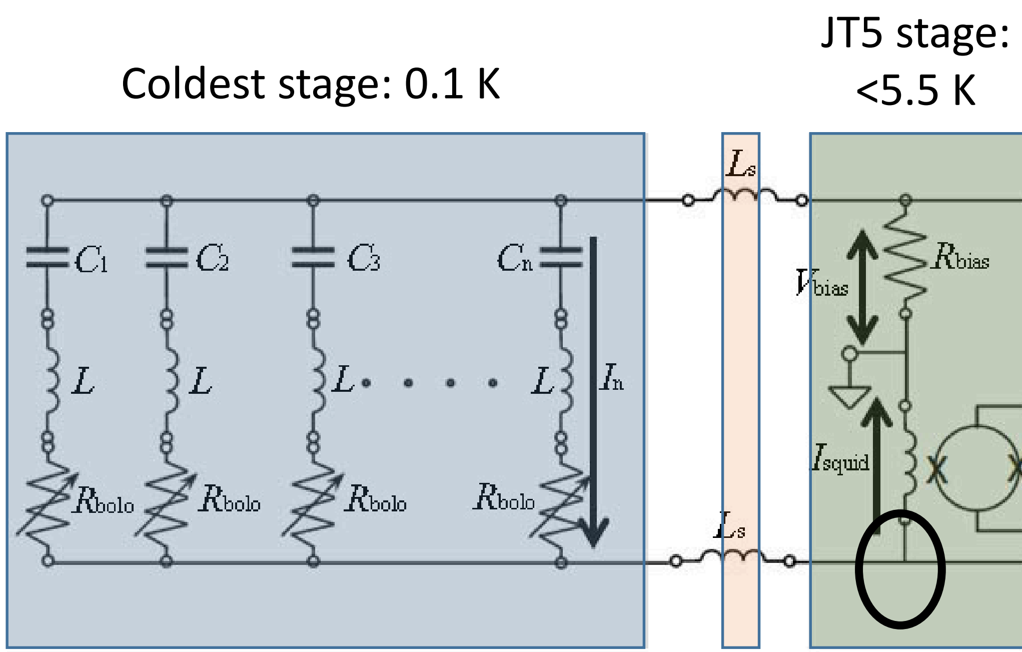
Modulating optical power on the bolometer amplitude modulates the sinusoidal current flowing through the bolometer.

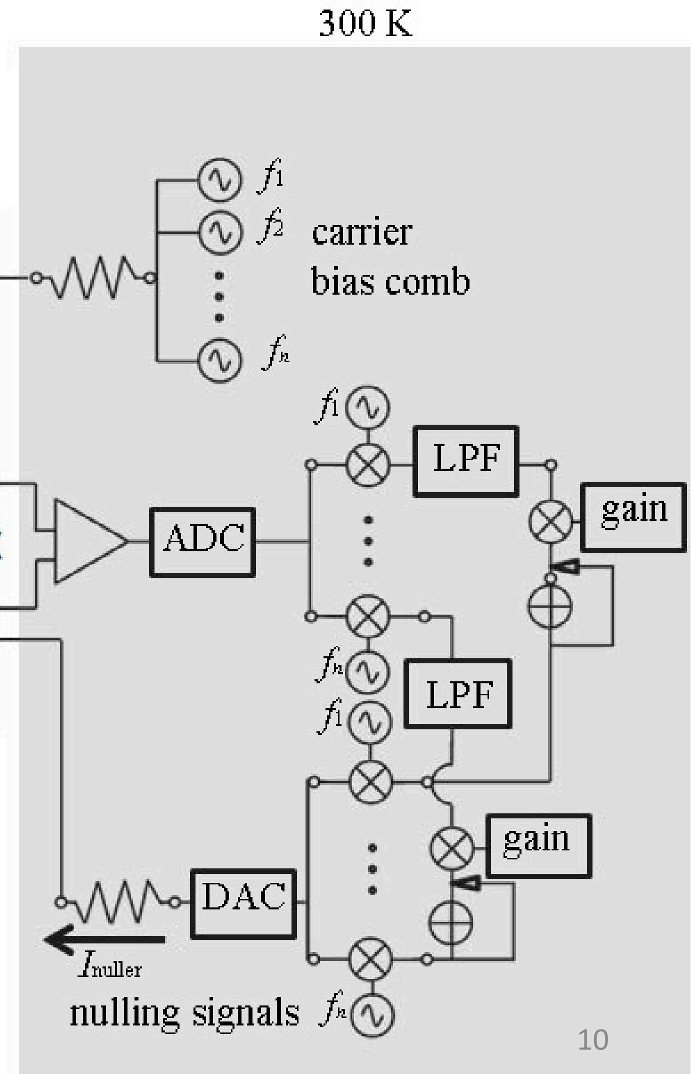
DfMux Architecture



Those currents are re-combined, and transmitted to a SQUID Array Amplifier.

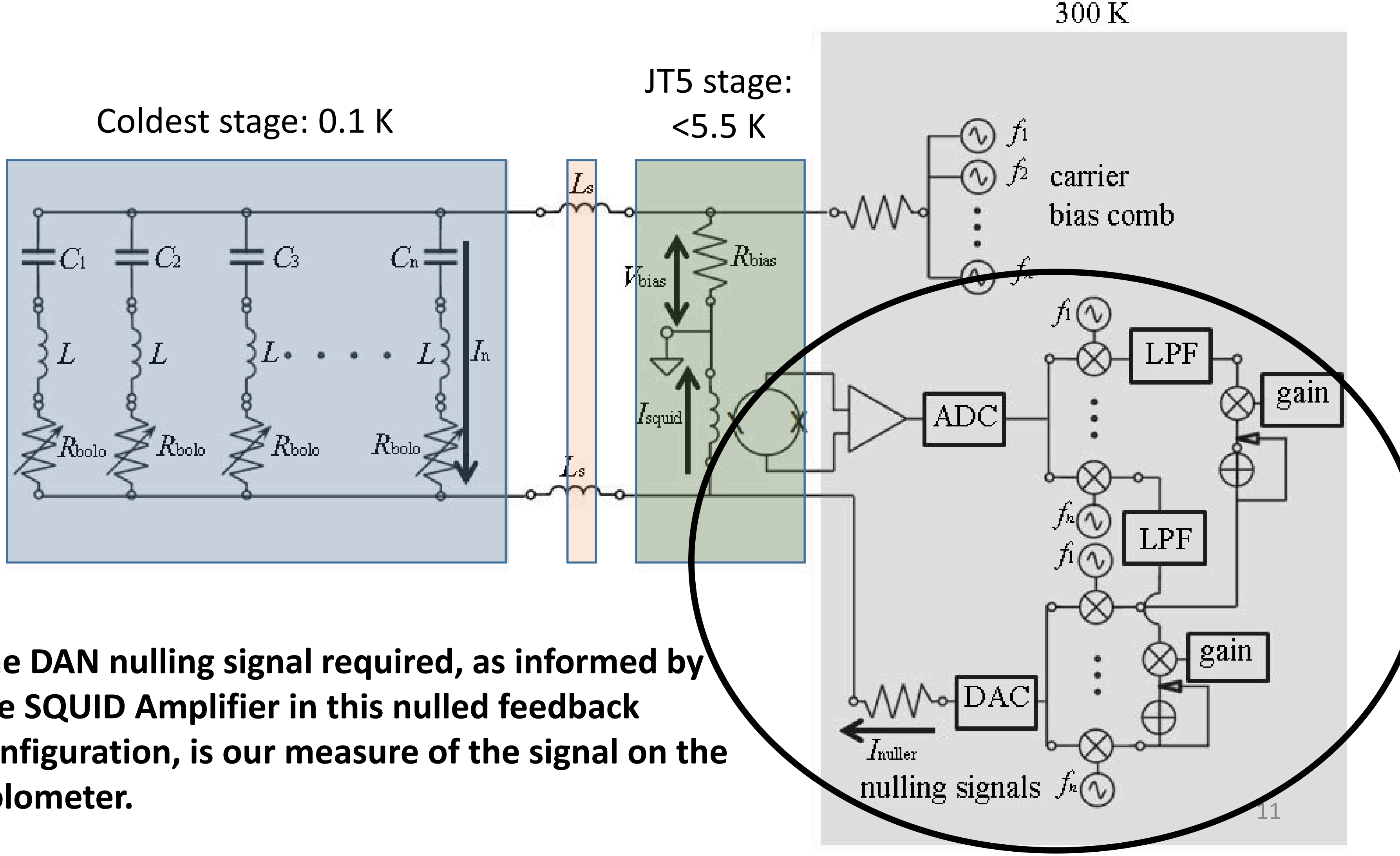
DfMux Architecture





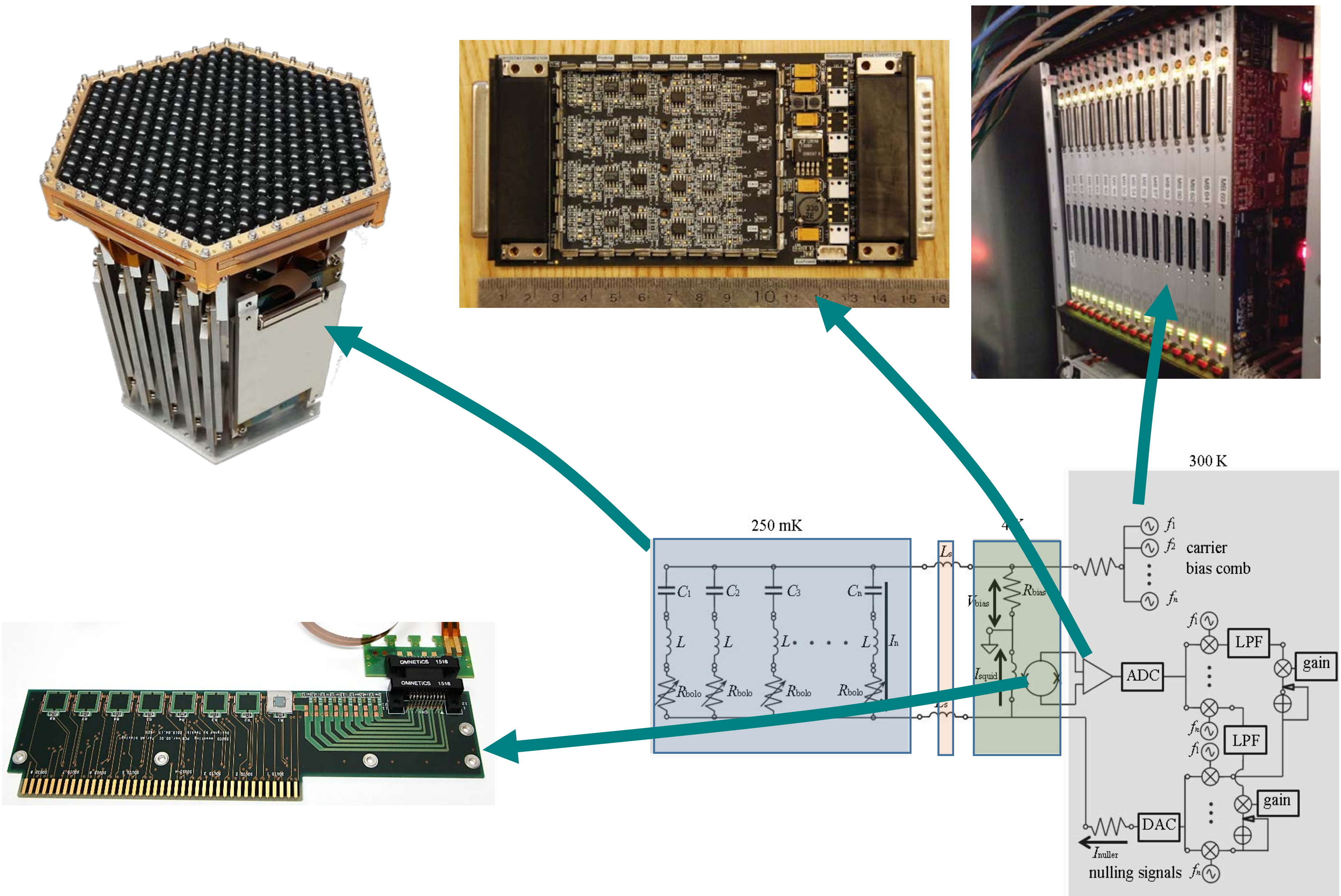
A digital active nulling (DAN) signal is transmitted into the cryostat to null the input of the SQUID Amplifier. This increases the linearity and dynamic range of the SQUID Amplifier.

DfMux Architecture



The DAN nulling signal required, as informed by the SQUID Amplifier in this nulled feedback configuration, is our measure of the signal on the bolometer.

DfMux Readout: Ground-Based System



DfMux: Heritage

Warm Readout Developed at McGill University with industrial partner COMDEV/Honeywell.

- *With strong collaboration from: UC Berkeley, U. Chicago, LBNL, NIST, UC San Diego.*
- See: **A. Bender** *et al.*, **"**Digital frequency domain multiplexing readout electronics for the next generation of millimeter telescopes**", SPIE 2014 arXiv:1407.3161.**

Full Multiplexer → 2nd Generation Digital → Low Power, Flight Worthy → 64x, Lower Power → Satellite

APEX-SZ
320 TES, 2006
Analog fMux

South Pole Telescope
1000 TES, 2007
Analog fMux

POLARBEAR
1274 TES, 2012
SPTpol
2000 TES, 2012/01
Digital fMux

EBEX
1500 TES, 2013
Digital fMux
LD Balloon

Simons Array/PB2
22,768 TES, 2016
New COTS Digital fMUX
SPT3g
15,000 TES, 2016
New Digital fMux

Readout Requirements for Flight

- Given nominal detector parameters, the readout system should not increase the array noise by more than 10%.
  - This noise/sensitivity allocation is included in LiteBIRD sensitivity calculations.
  - Note that assembled yield is just as important, or more important, than fundamental increases in the detector noise.
- Several other requirements about low-frequency noise, gain stability, etc., captured in the US Concept Study Report (CSR)

Current Readout TRL for flight

Intrument component	**TRL**	Sub-Component	TRL
Warm DfMux electronics	**3**		
		SQUID Controller	5
		Analog Mezzaniine Board	5
		FPGA Board	3
		FPGA VHDL Code	4
Harness	**3**		
		Mechanical	9
		Electrical	4
Cryogenic DfMux electronics	**3**		
		inductor/capacitor circuit	3
		inductor/capacitor chips	4
		sub-Kelvin wiring	3
		SQUID circuit	3
		SQUID chips	3

Current Warm Readout TRL - Detail

<table>
<tr><th></th><th>TRL-3</th><th>TRL-4</th><th>TRL-5</th><th>TRL-6</th></tr>
<tr><td>SQUID Controller Board (incorporating DAN)</td><td>Proof of concept test (modified EBEX board with cryo-bolometers)</td><td>a) Updated board design for digital active nulling components
b) Phase 1 boards tested with bolometers</td><td rowspan="2">a) Update board designs with flight representative components
b) Boards tested together over temperature
c) Boards tested with representative cryo bolometers & cryo SQUID</td><td rowspan="4">System Demonstration with flight like boards, harnessing and flight like detector array & SQUIDs
Temperature testing of boards (if required by TRL-5 results).
Other environmental testing as required.</td></tr>
<tr><td>Analog Mezzanine Board (incorporating DAN)</td><td></td><td>a) Updated board design for digital active nulling components
b) Phase 1 boards tested with bolometers</td></tr>
<tr><td>FPGA Board *</td><td>EBEX Boards</td><td>FPGA flight like design (SEU mitigation in place)</td><td>Flight like boards tested with above.</td></tr>
<tr><td>FPGA VHDL Code *</td><td>EBEX VHDL Code</td><td>VHDL code modified for DAN</td><td>SEU monitoring to be demonstrated on EBEX flight</td></tr>
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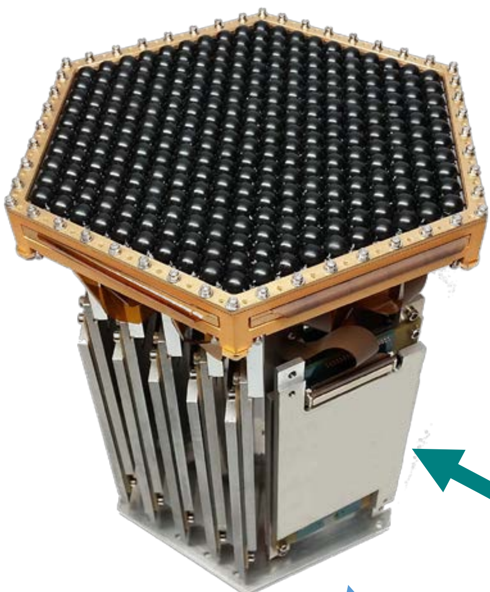
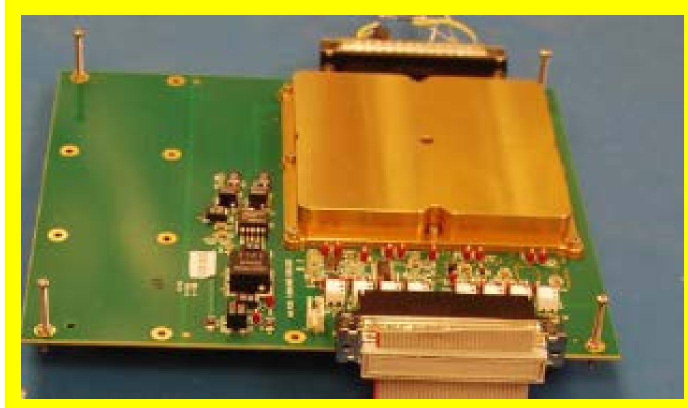
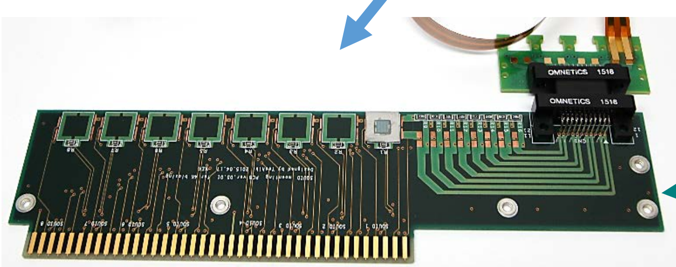
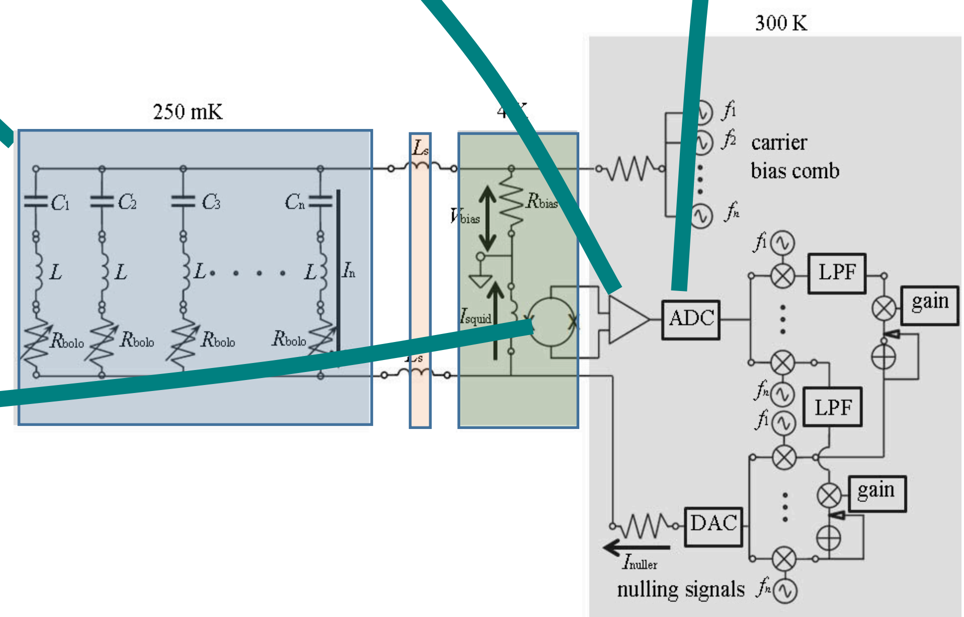
DfMux Readout: Warm analog system at TRL5



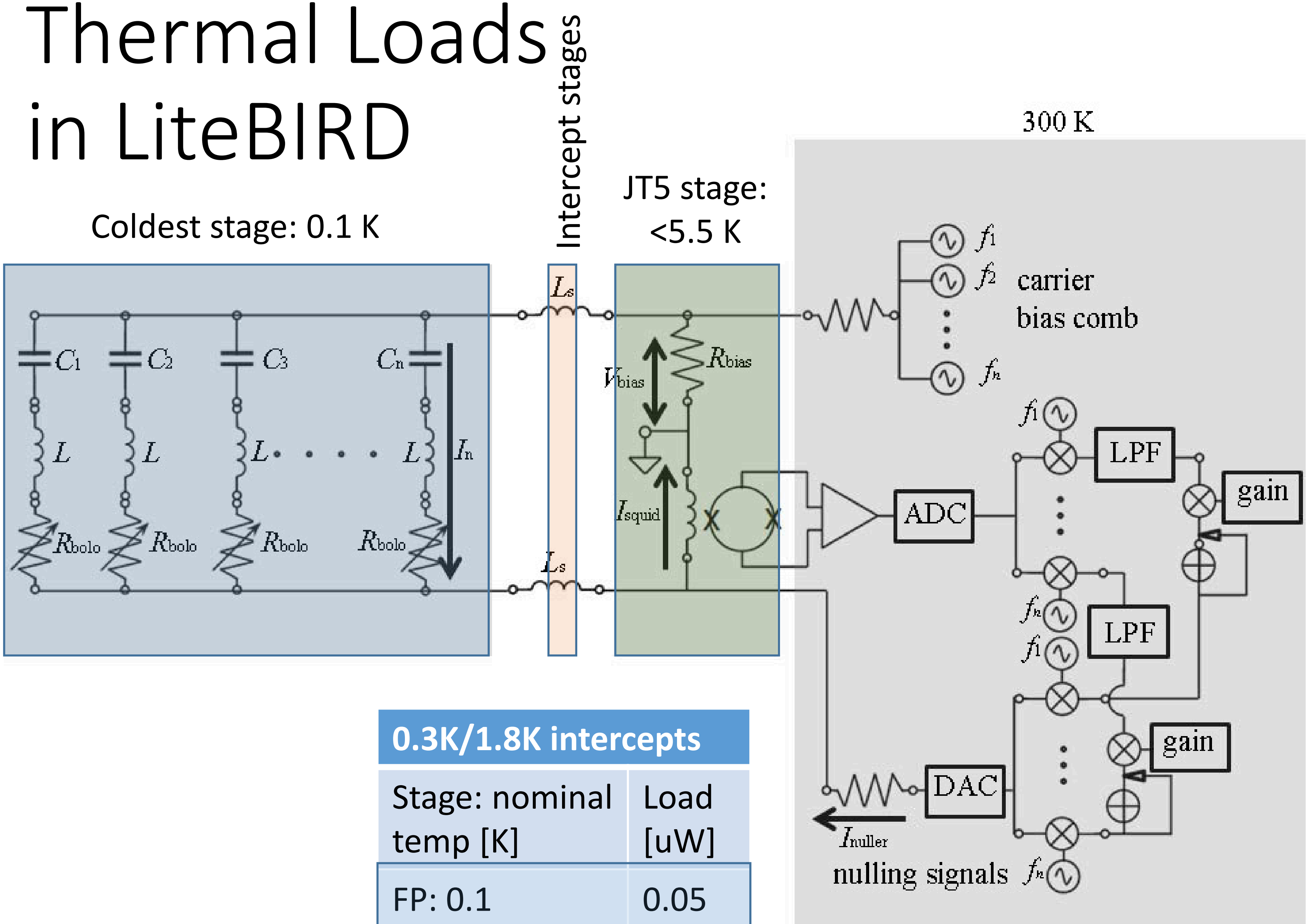


Flight packages to be designed this year as part of US NASA grant



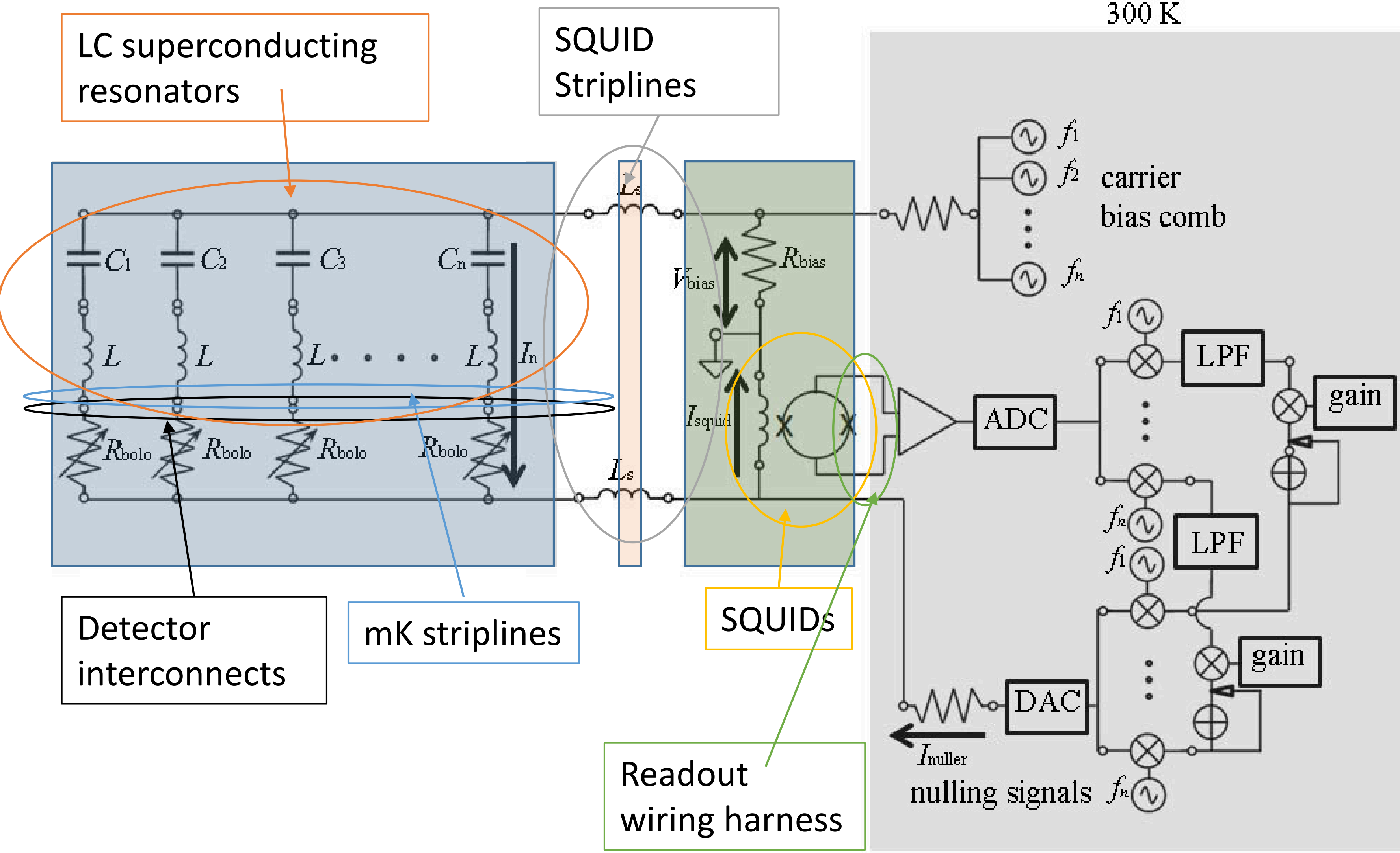


Thermal Loads in LiteBIRD

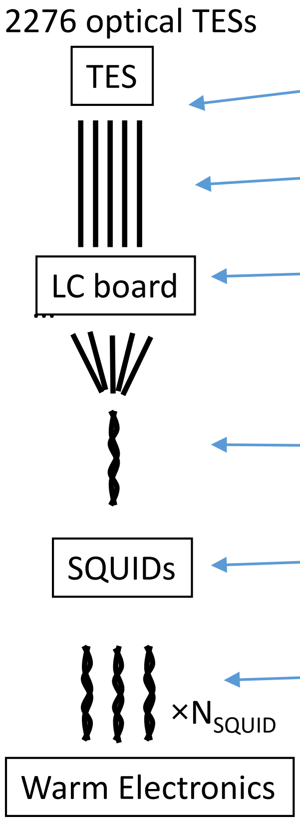


0.3K/1.8K intercepts	
Stage: nominal temp [K]	Load [uW]
FP: 0.1	0.05
CI: 0.3	3.0
JT2: 1.8 K	30

Cryogenic Readout Components

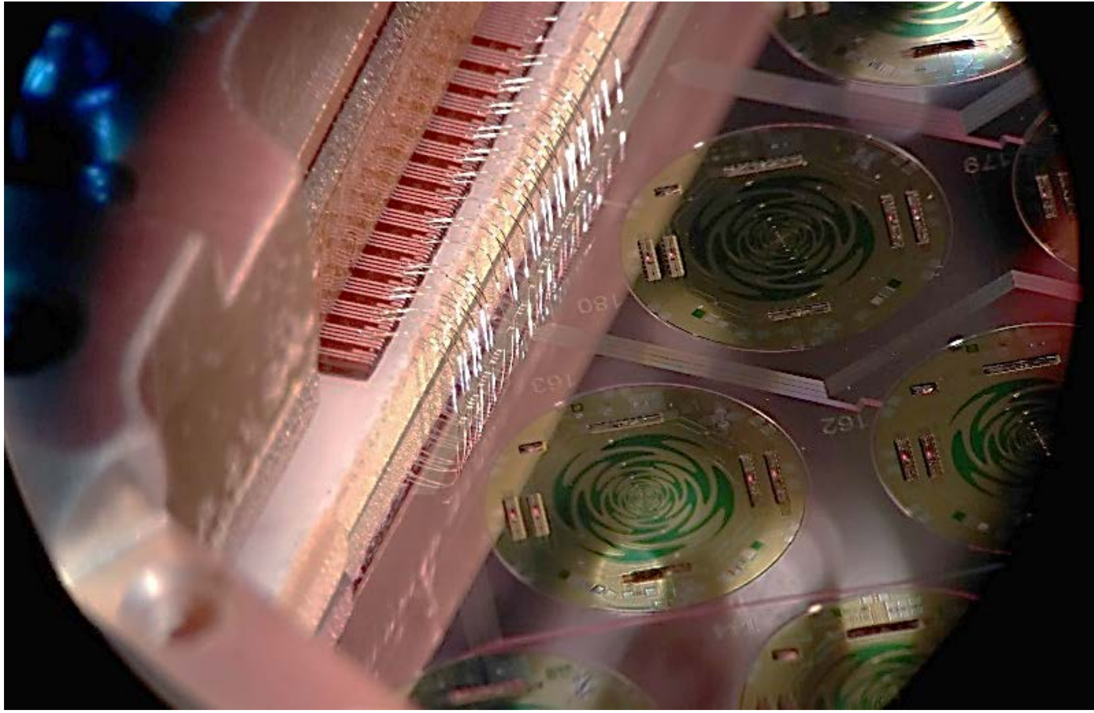


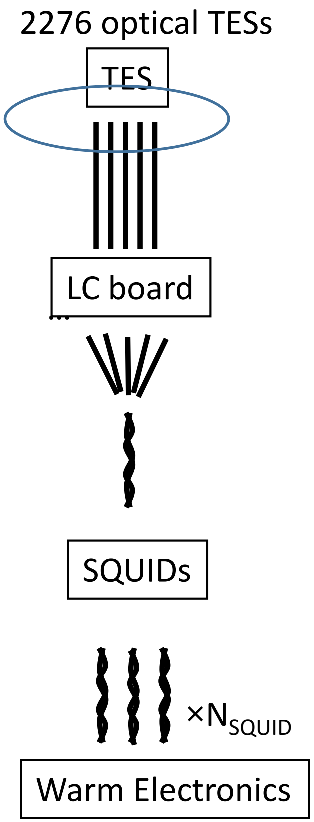
Cryogenic Readout Components



- Detector interconnects
- mK Striplines
- LC superconducting resonators
- SQUID Striplines
- SQUIDs
- Readout wiring harness

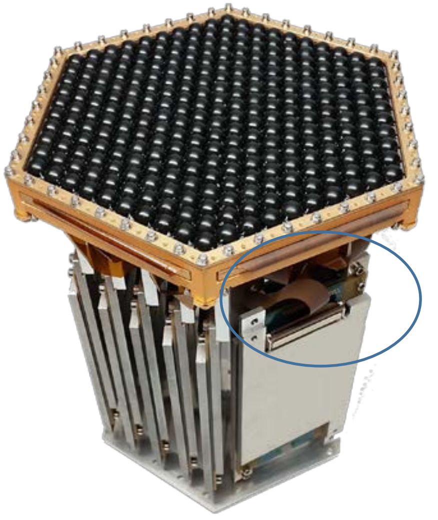
Detector interconnects

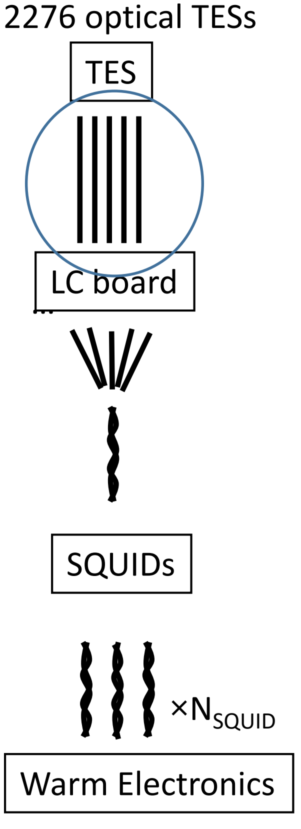




- Polarbear & SPT3G: Robust automatic wirebonding
  - Repeatable pull strength above NASA suggested requirements: https://nepp.nasa.gov/index.cfm/20925
  - Superconducting connection with resistance that is not a significant part of the series resistance budget. Range of series impedance allowed in circuit: **0.05 to 0.2 Ohms**
  - Repeatable inductance, part of inductance variation spec on next slide.
- **Flight Solution to be fully validated**

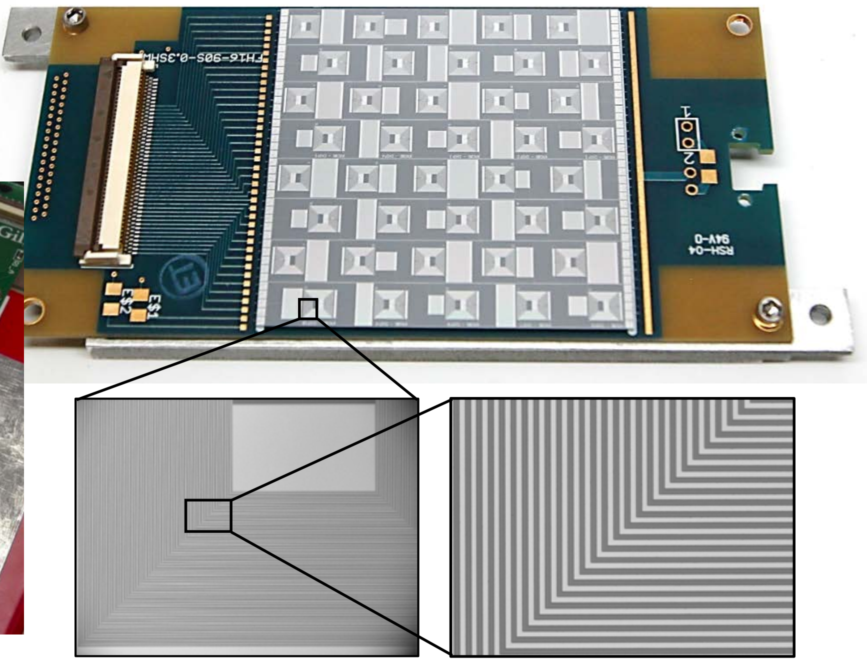
mK Striplines

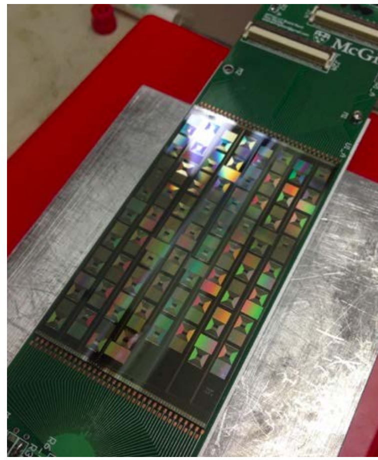


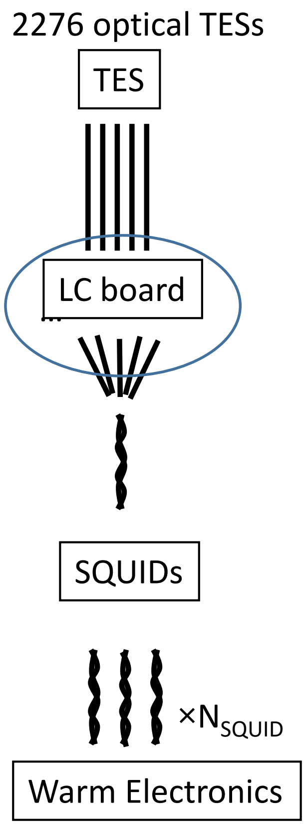


- Polarbear & SPT3G: copper on polyimid. Currently this satisfies requirements.
- Considering lithographed striplines to determine if there is benefit in robustness/packaging.
- **Flight-like components coming in 2018 to reach TRL4**

LC Superconducting Resonators

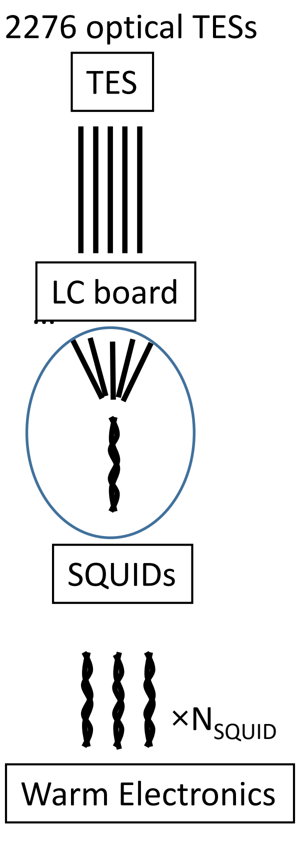






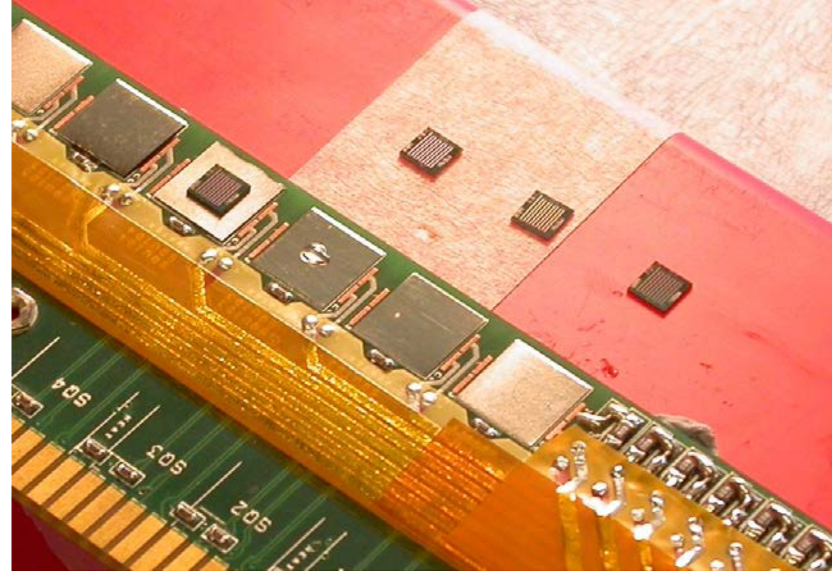
- LiteBIRD: commercial Niobium solution
- Mechanical mounting to be designed.
- Recently demonstrated with 85% yield for POLARBEAR – working on improving this.
- LC Radiation hardness: just Niobium on Si. If SQUIDs are OK, this is definitely OK.
- **Flight-like components coming in 2018 to reach TRL4**

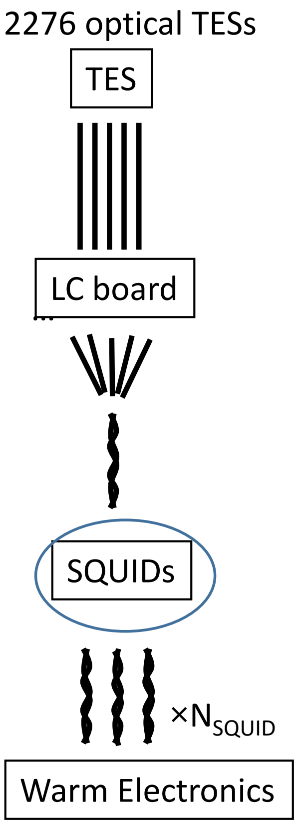
SQUID Striplines



- Polarbear & SPT: NbTi on Kapton – 30 cm sections.
- Currently evaluating a lithographed solution for increased robustness and thermal performance.
- **Flight-like components coming in 2018 to reach TRL4**

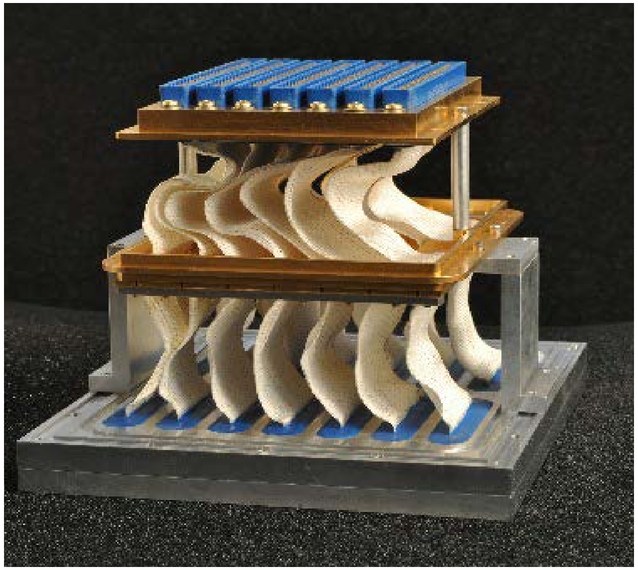
SQUIDs

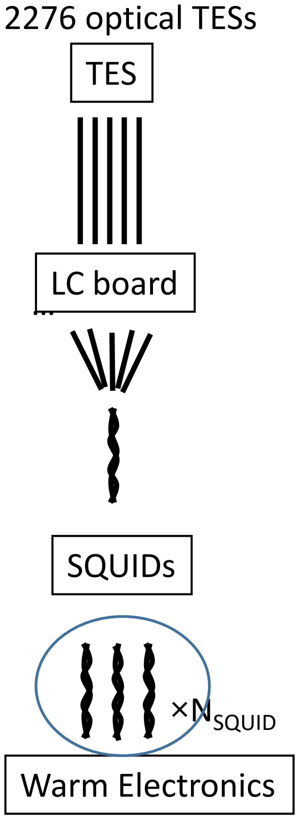




- Current SQUID Array Amplifiers have too much input inductance
  - **Replacement SQUID Array being tested now on PB2 and SPT-3g**
  - **LiteBIRD solution may be to make a 2-stage amplifier: Initial SQUID Amplifier at 0.1 K, then a second-stage amplifier at 4 K.**
  - **As an amplifier system, there is a lot of work for space and ground right now to increase TRL.**

Readout wiring harness





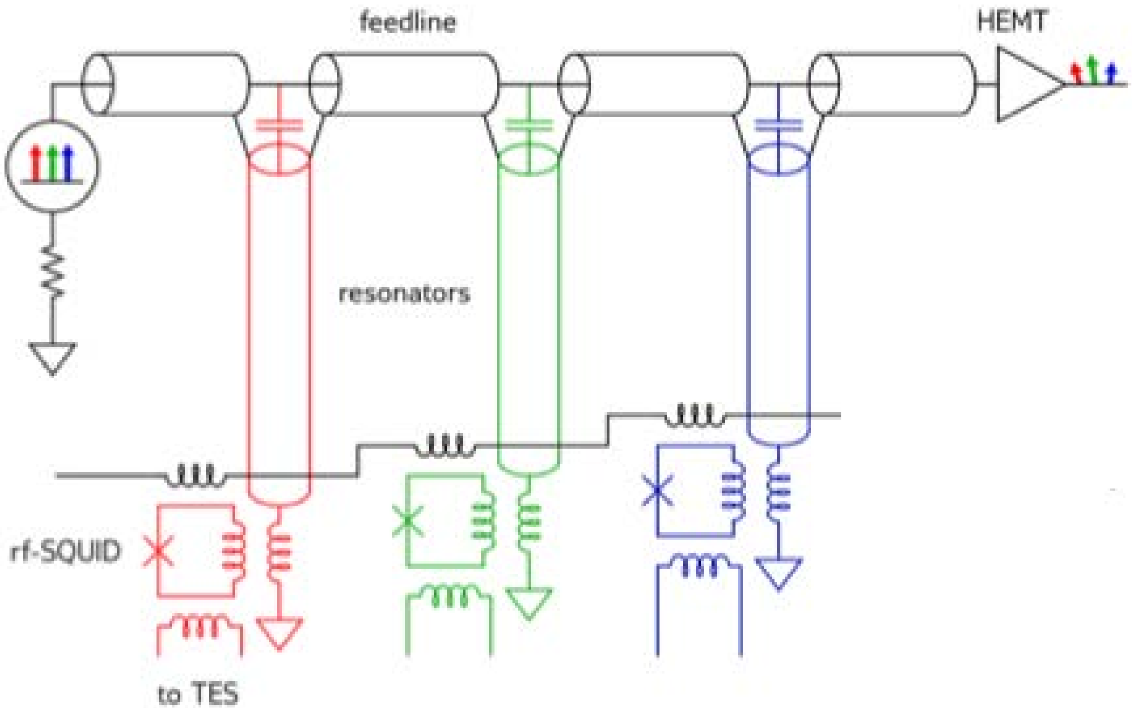
- Current system use short harnesses (see above)
- A spacecraft will require a long harness.
- **Driving signals down the long harness with the SQUID is currently being tested. System will be validated by 2019.**
  - Crosstalk and loss need to be controlled
  - Testing of SQUID Arrays and long harnesses now underway

Near-Term DfMux Readout Development

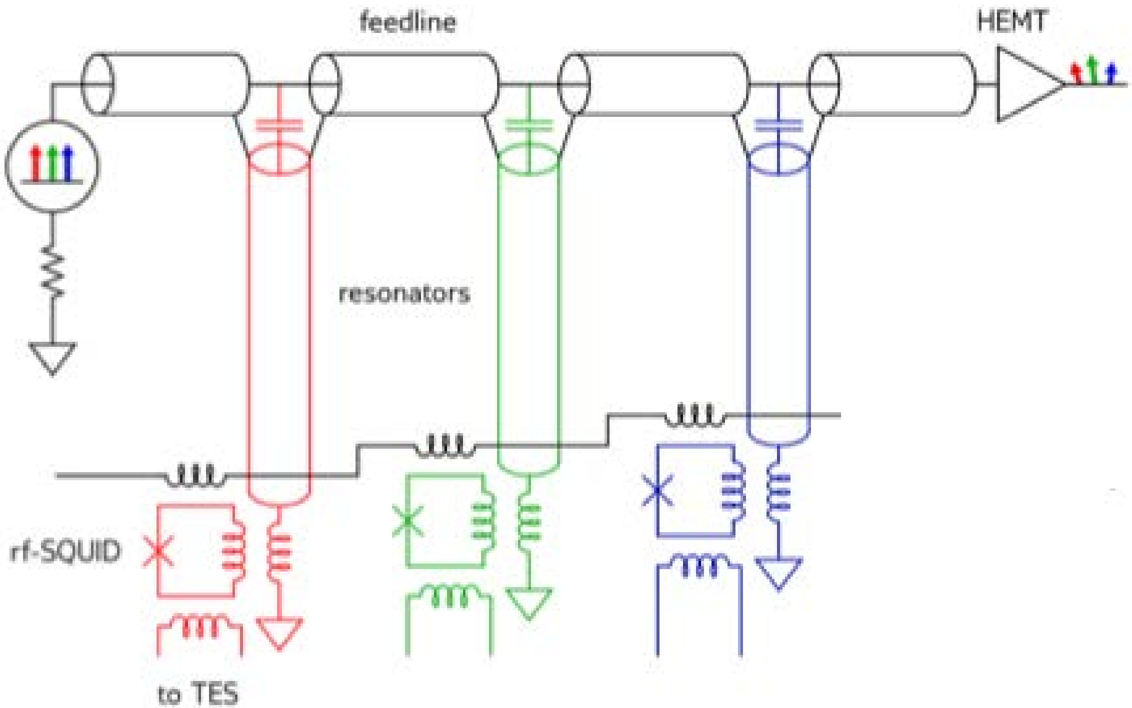
- Warm Readout: McGill funded (last month) by Canadian Space Agency to work on system interface issues
  - Systems-level work, including power converter, etc.
  - Develop FPGA/DSP motherboard to TRL5
    - Question of how to time FPGA work, given how fast the hardware develops here
- Cold Readout: US team funded (kick-off with NASA last week) to bring sub-systems to TRL5. Critical development issues:
  - Readout chain/interconnects: flight design coming in 2018
  - SQUID amplifier chain: input inductance and ability to drive wiring harness
  - Other developments in this program:
    - Bolometer cosmic ray sensitivity mitigation
    - Validate vibration insensitivity: launch survival and observing vibration conditions
    - Simulated observations including critical instrumental systematic effects as input to the LiteBIRD System Requirements Review

μMux – Overview & Status of Development

GHz resonators to multiplex TES bolometers

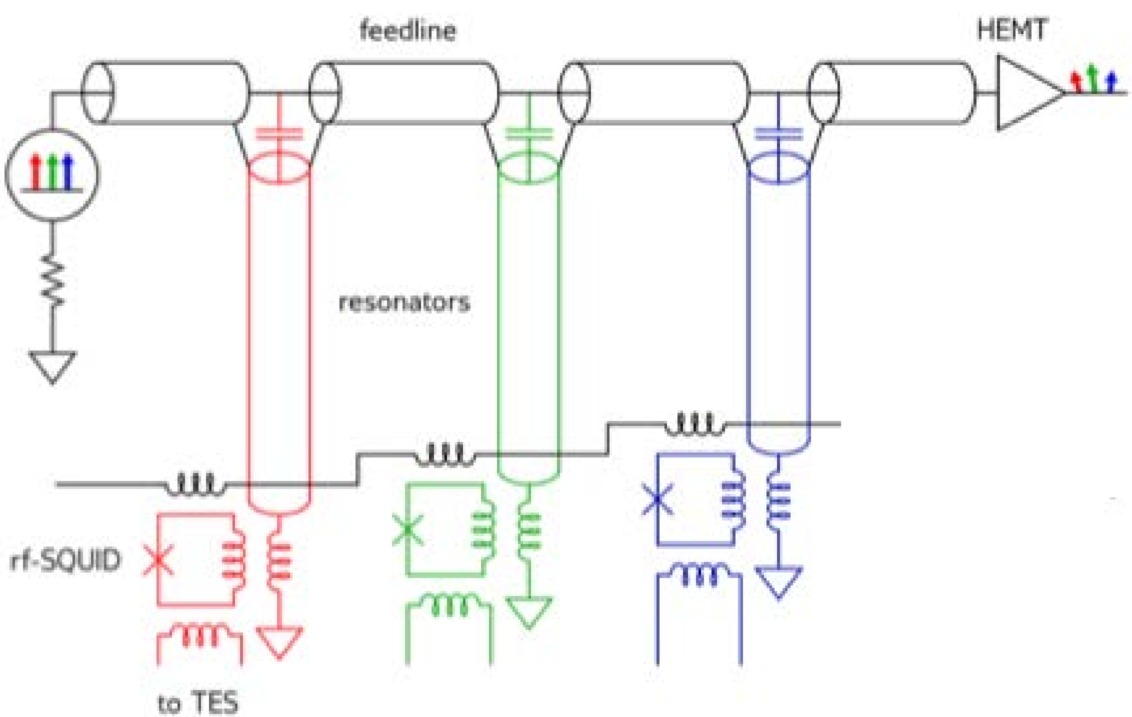


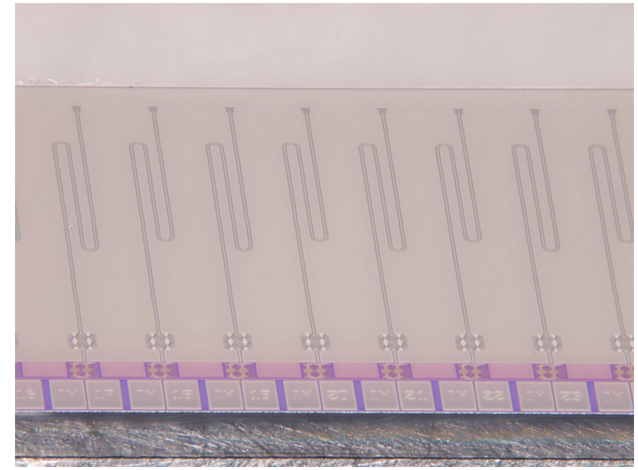
GHz resonators to multiplex TES bolometers

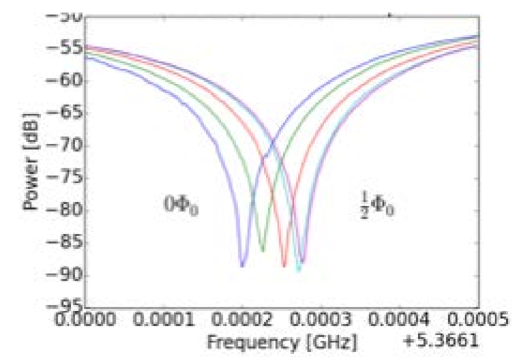


1. Digitally synthesize a sum of sine waves to interrogate the resonators
2. Mix those sine waves up into the 4-8 GHz band
3. Amplify transmitted sine waves with low-noise amplifier at 4 K
4. Mix down and demodulate

GHz resonators to multiplex TES bolometers

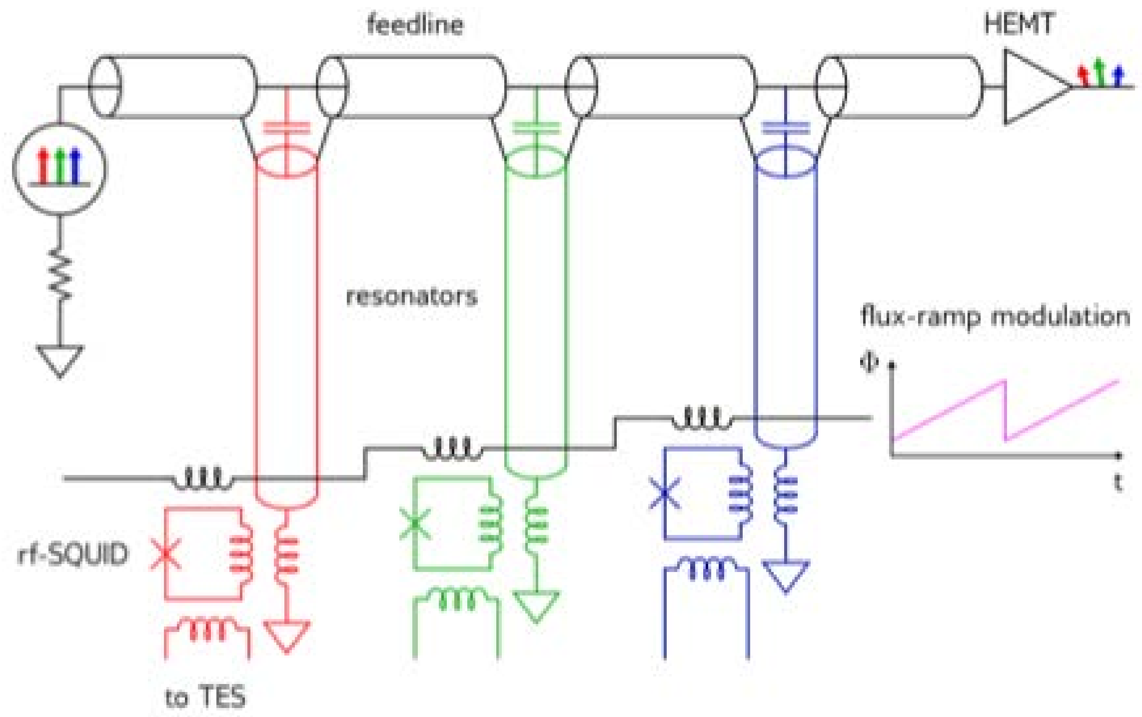


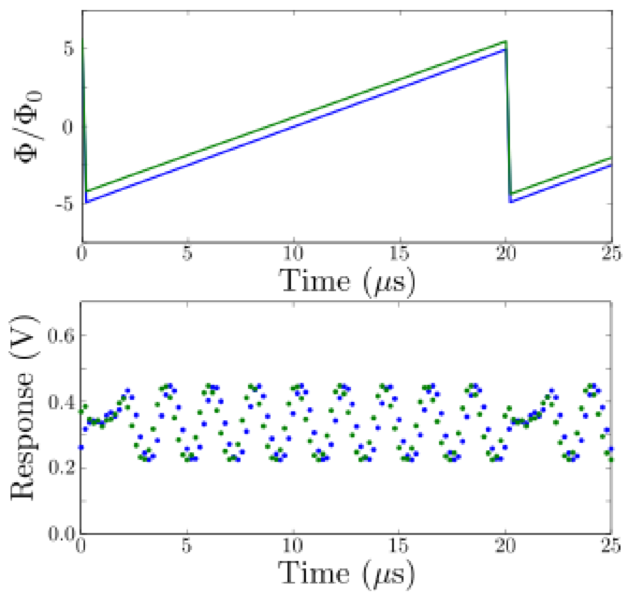




- Combine the immense multiplexability of microwave resonators with the heritage and maturity of TES and SQUIDs
- TES inductively couples to RF-SQUID, which screens a GHz resonator
- Signal in TES changes inductance, hence frequency of resonance. No change in Q

Microwave resonators to multiplex TES bolos (2)



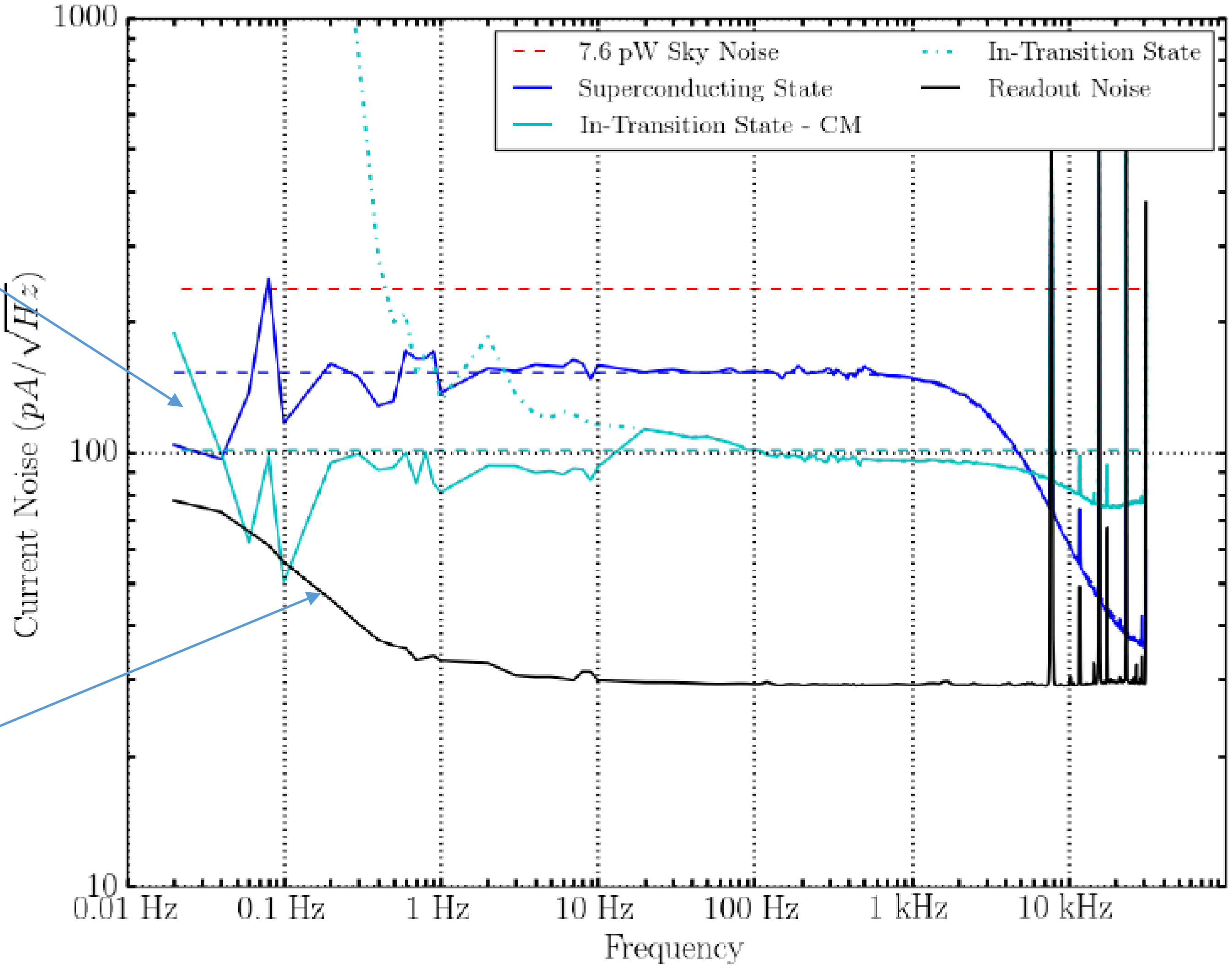


- Flux modulation linearizes SQUID response
- Also mitigates the effect of low-frequency two-level system (TLS) noise in the resonator.

Recently Published lab performance of cold system

Low-frequency detector noise dominated by something that gets removed by common-mode subtraction – likely temperature fluctuations

Low-frequency noise in readout here dominated by voltage source – will be reduced substantially in future systems



https://arxiv.org/abs/1710.04326