Readout for PICO

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University of Minnesota
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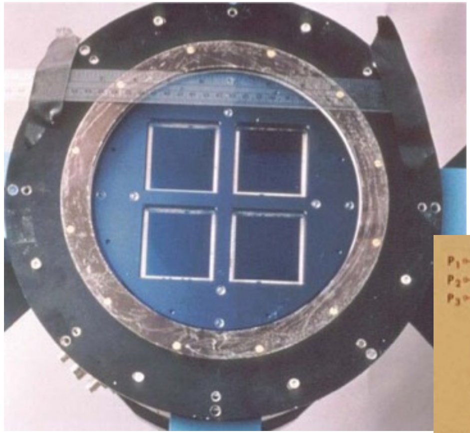
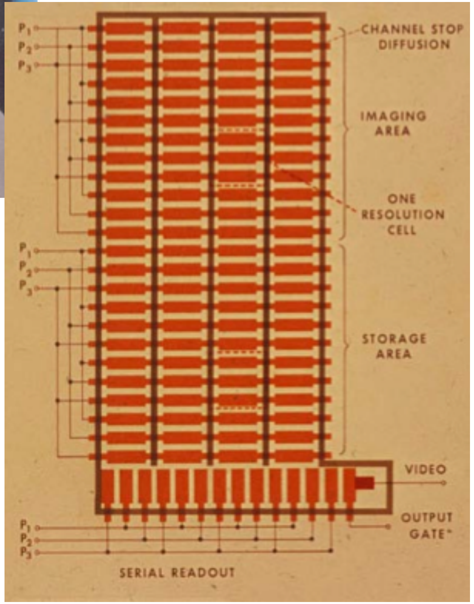
(Multiplexed) Readout is Important

- Multiplexing is ubiquitous
- Charged-coupled devices (CCDs)
  - Revolutionized astronomy
  - Boyle and Smith received 2009 Nobel Prize "for the invention of an imaging semiconductor circuit - the CCD sensor".
  - Enabled by bucket-brigade readout
- Situation no different with superconducting detectors
- Readout is the major challenge for upcoming/planned bolometric focal planes



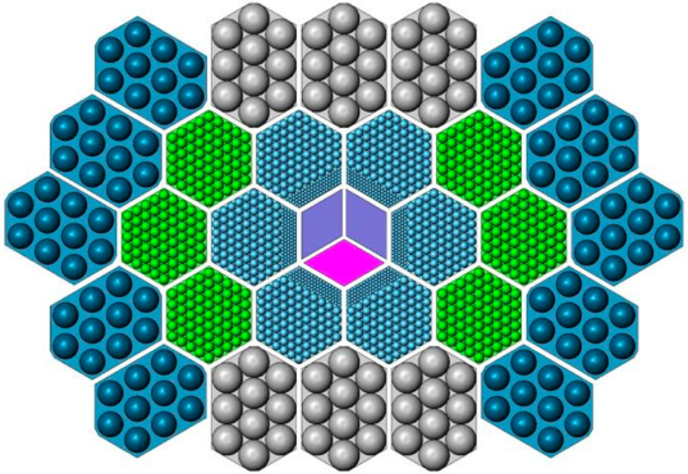
4 1Megabite CCD arrays

Area imaging CCD geometry



Is Readout Technology for PICO Mature?

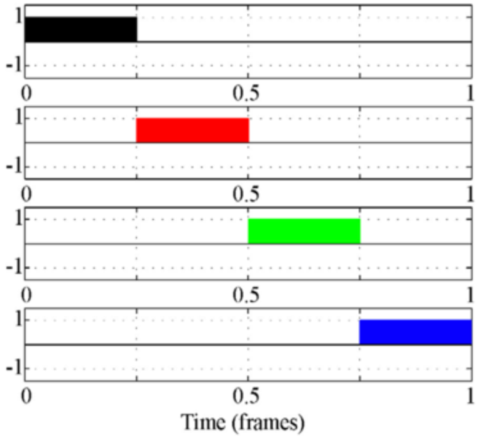
- Challenges
  - 13,000 readout channels
  - noise requirements (both white and low frequency)
    - NEP readout ~ 1 aW/√Hz
    - ~10 mHz and potentially lower important
- Current multiplexing technologies for TES readout (TDM, DfMUX) would work for PICO, but are suboptimal.
  - Case in point, we are already baselining a multiplexing factor beyond what has been demonstrated
- PICO current baseline is TDM at 128x, but clear trend in LTD readout is to use FDM in RF/microwave regime. On timescale relevant to PICO, expect significant maturation.



PICO focal plane: 13,000 sensors (K. Young)

Three Basis Sets

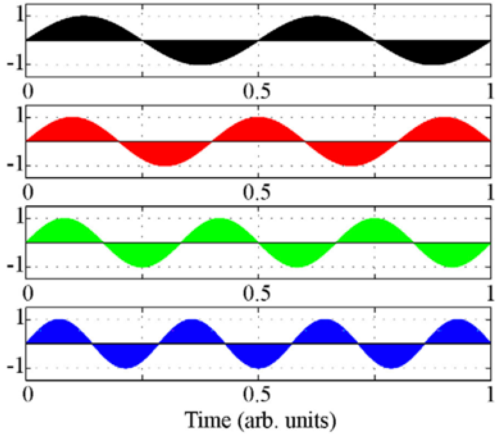
Time Division



ACT, ACTPol, Advanced ACTPol, ABS, BICEP2/KECK, BICEP3, CLASS, HAWK+, PIPER, GISMO1, GISMO2, MUSTANG, MUSTANG2, SCUBA2, SPIDER, ZEUS2

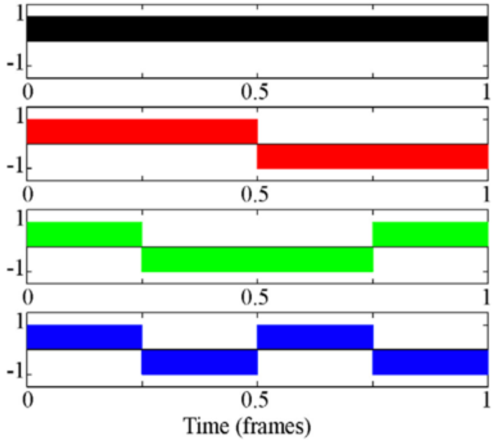
Current PICO baseline.

Frequency Division



- MHz FDM: APEX-SZ, SPT, SPTpol, SPT-3G, EBEX, PB1, PB2/Simons Array, LiteBIRD
- Microwave SQUID multiplexer (μmux): MUSTANG2, Simons Observatory, ALI-CPT, BFORE (proposed)
- All MKID Instruments

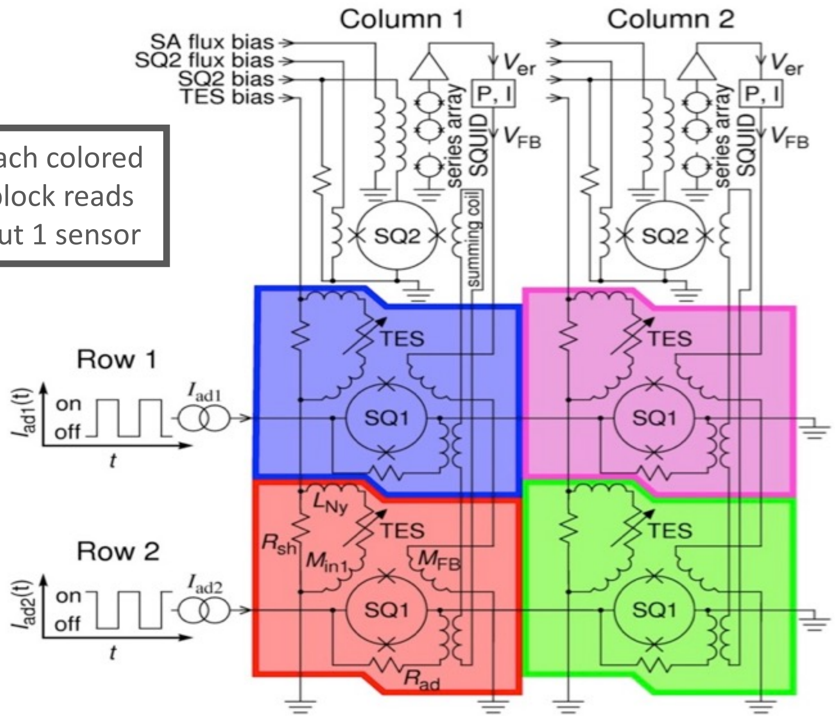
Code Division



Lab-based + x-ray sensor readout demonstrations. Technique better suited to high pixel bandwidth applications.

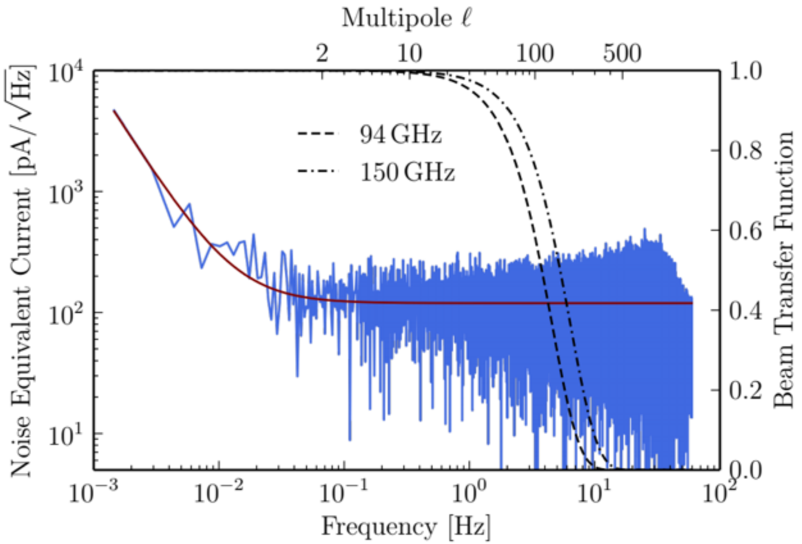
Time Division SQUID Multiplexing (TDM)

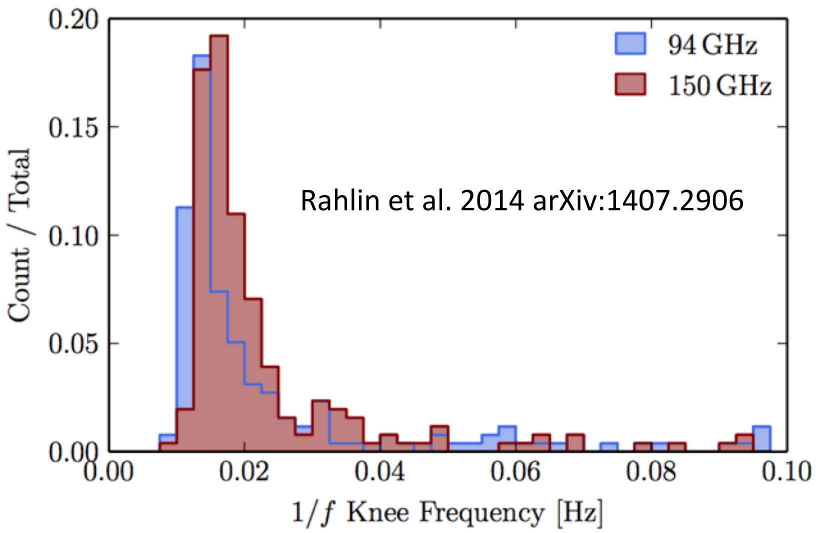
each colored block reads out 1 sensor



- DC biased TES
- Each TES coupled to one SQ1
- Rows of SQ1s turned on and off sequentially
- Highest multiplexing factor: 66, Advanced ACTPol
- TRL = 6 (33 rows per column) in SPIDER balloon flight 2015
- Noise aliasing increases base readout noise by $\sqrt{N_{rows}}$

TDM Performance





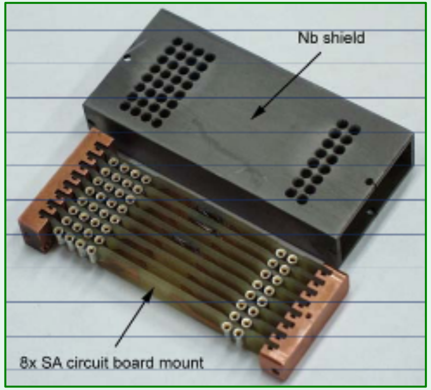
- White noise levels consistent with predictions (many examples)
- ~17 mHz 1/f knee (SPIDER preflight data). Other published examples also exist.
- Cross-talk: 0.25% nearest neighbor, <0.03% for rest (deKorte 2003, BK-II, BK-III)

TDM Readout Chain – PICO Implementation

300K

3,916 DC wires*

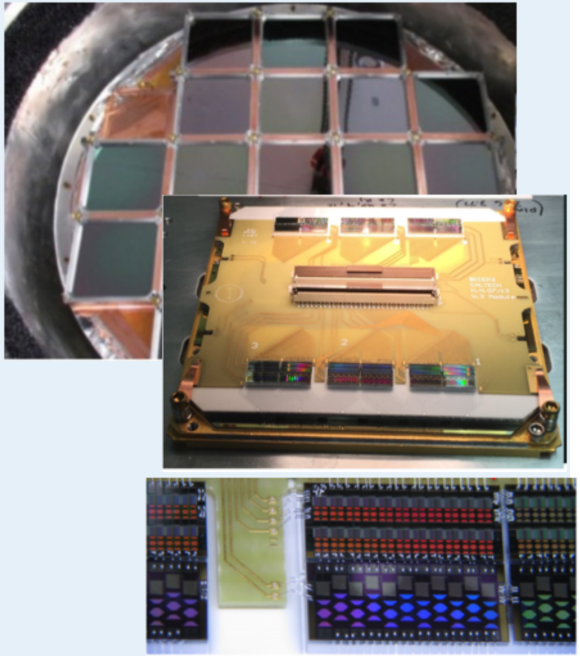
4K



3,256 DC wires*

100mK

BICEP3, Hui et al. 2016



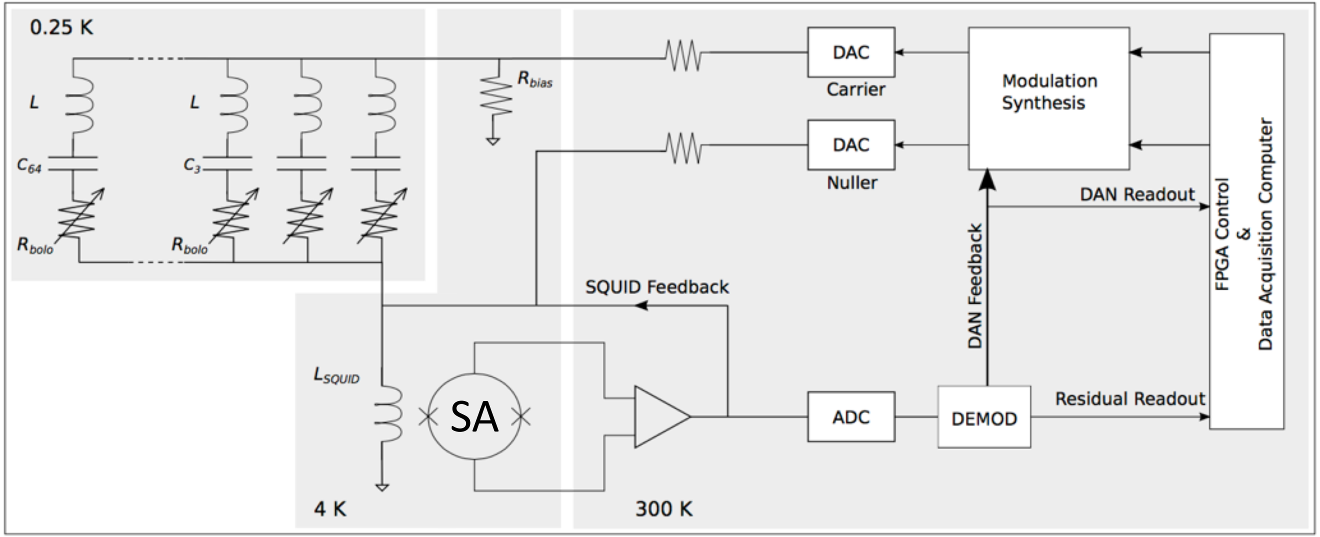
- Multi-Channel Electronics (MCE), University of British Columbia
- 37mW/channel (assuming 2000 channels/crate)
- 480W total power dissipation (note this number may be incorrect for 128 rows!)
- ~7 crates required

- SQUID Amplifier (SA) module, NIST
- One SA per 128 channels
- 102 total SA
- ~10 µW total power dissipation

* assumes 11 128 x10 multiplexers,
1 detector bias per column,
room temperature RS switching

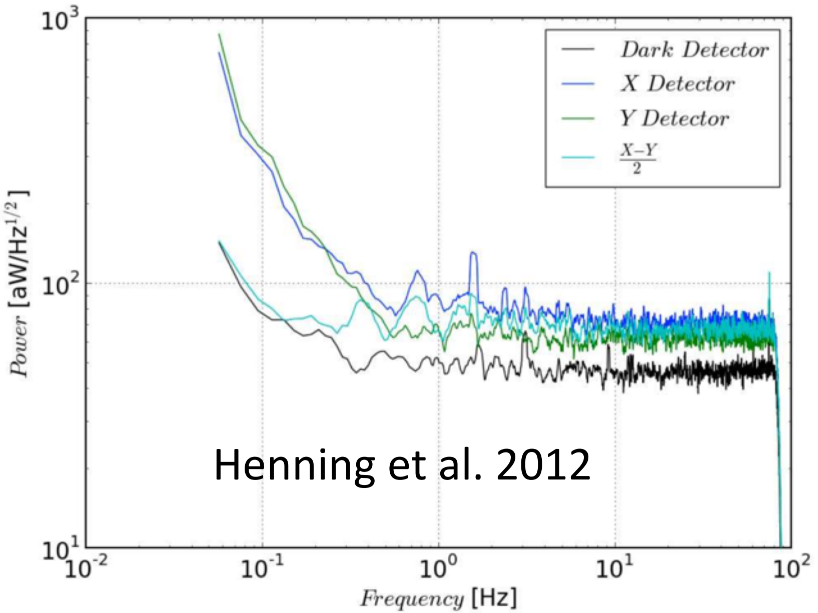
- Readout components = mux + “interface” chip
- Total power dissipation ~ 70 nW
- Silicon readout component footprint = 470 cm^2

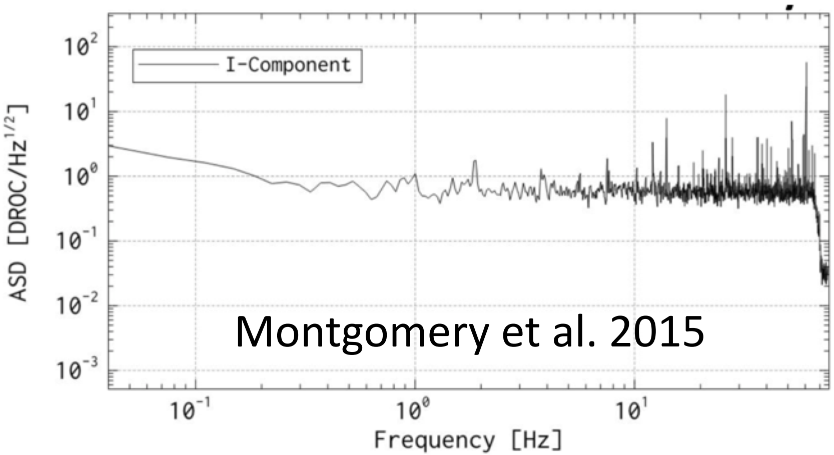
MHz Frequency Division SQUID Multiplexing



- AC biased TES
- LC for each sensor (~1 – few MHz)
- N sensors coupled to one SQUID Array
- Two separate development efforts/architectures: UC Berkeley/McGill ("DfMUX") and SRON
- TRL = 6 (EBEX flight 2013)
- Highest multiplexing factor: 68 (SPT-3G), 160 (lab-based demonstration, R. Hijmering 2016)
- Readout architecture for LiteBIRD

MHz FDM Performance



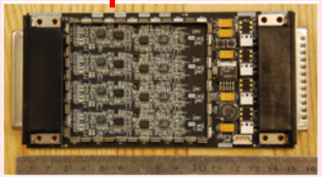


- White noise levels consistent with predictions (many examples)
- Published data show 1/f knee ~ 100 mHz for both differenced and individual readout channels (see above + Kermish et al. arXiv: 1210.7768)
- Cross-talk < 1% from nearest neighbors (Hattori 2016)

MHz FDM Readout Chain – PICO Implementation

300K

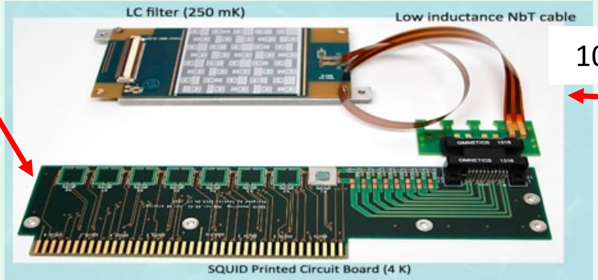
306
twisted
pairs*



SQUID controllers mounted to cryostat wall

- 26 x DfMUX "ICE" boards (McGill)
- 26 x SQUID controller boards mounted to cryostat wall
- 1.6W/module x 102 modules = 163W
- Radiation hardened electronics (work done by McGill)

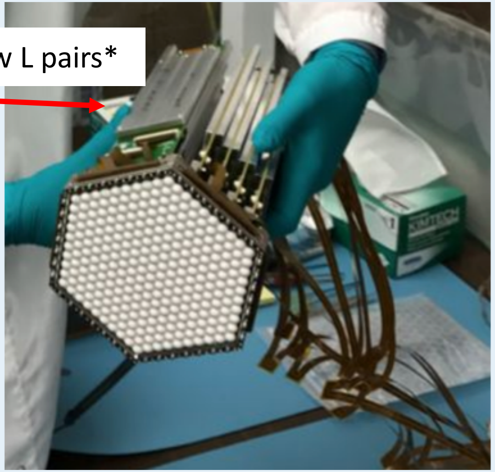
4K



- SQUID card containing SQUID Amplifiers (SAs) (same as TDM components)
- One SA per 128 channels
- 102 total SA
- ~10 μW total power dissipation in SA
- Power dissipation in detector bias resistors, but this is also small

100mK

102 low L pairs*

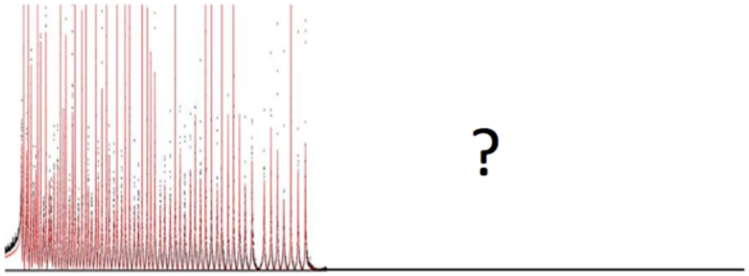


SPT-3G, Benson et al. 2014

- Readout components consist of LC resonators
- Power dissipation = in band optical load ~ 10 nW
- Readout footprint = 7,800 cm^2

Trend Toward Microwave Readout

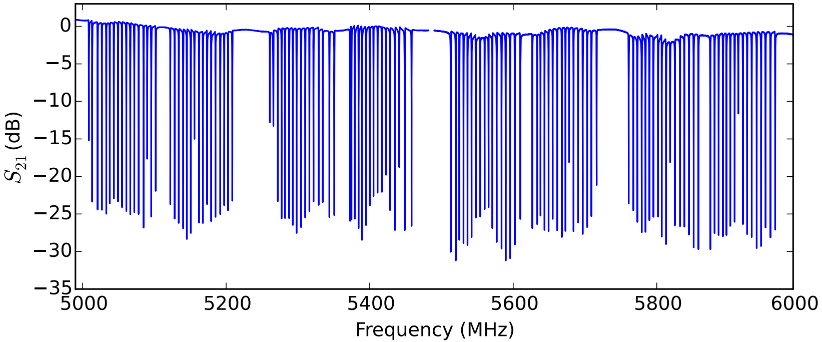
Concepts to scale DfMUX up to 50 MHz under investigation



Cartoon plot for increasing total bandwidth

from Suzuki CPAD Instrumentation Workshop 2017

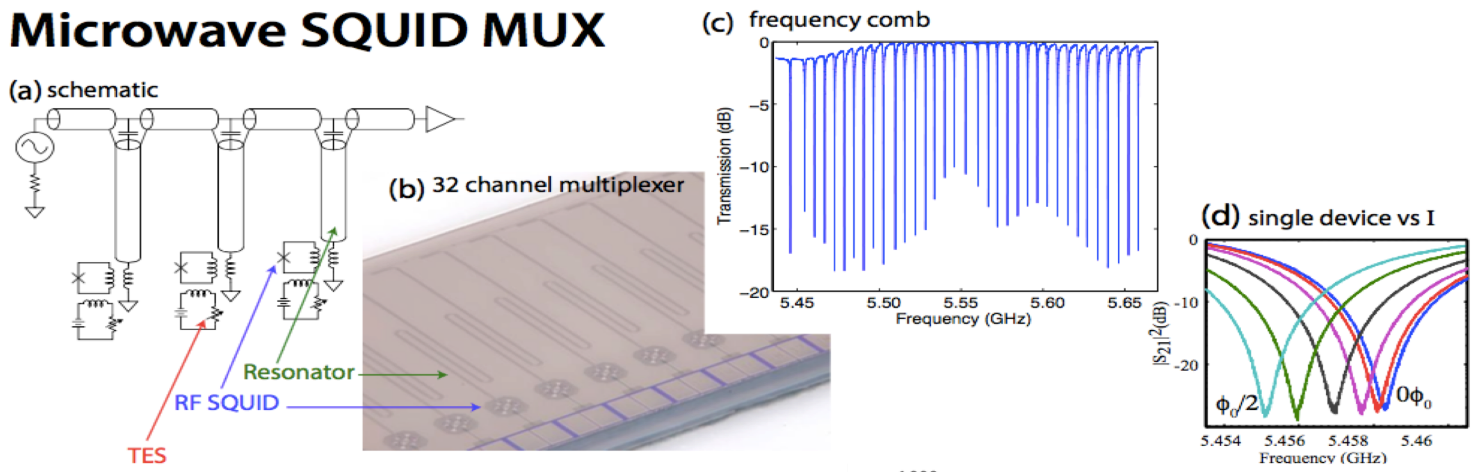
Microwave SQUID Multiplexer Survey



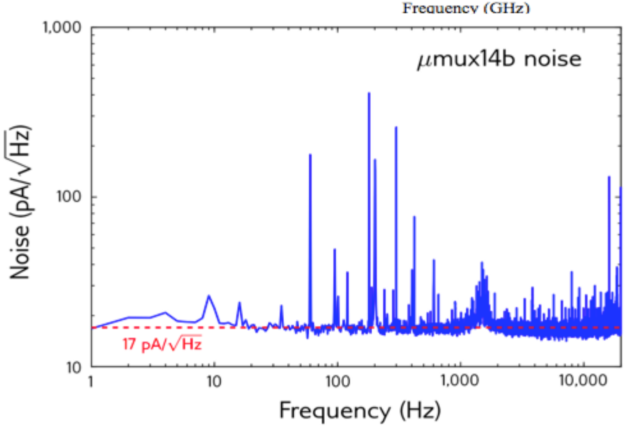
Mates et al. APL 111, 062601 (2017)

Include all MKID work here as well

Microwave SQUID Multiplexer (μmux)

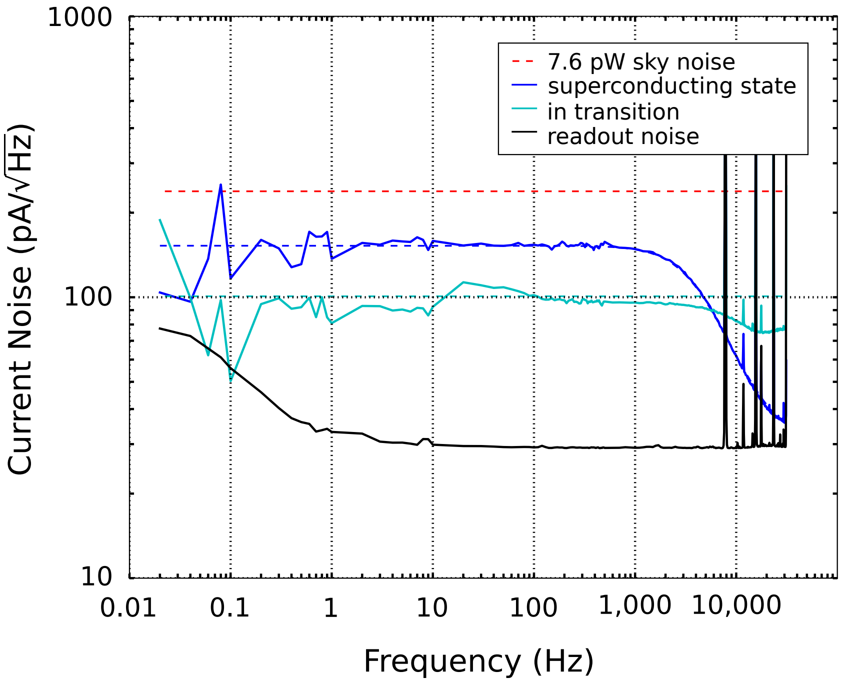


- Multiplexing capability of MKIDs + proven sensitivity of TES
- DC biased TES
- Irwin and Lehnert 2004, Mates thesis 2011



μmux development status

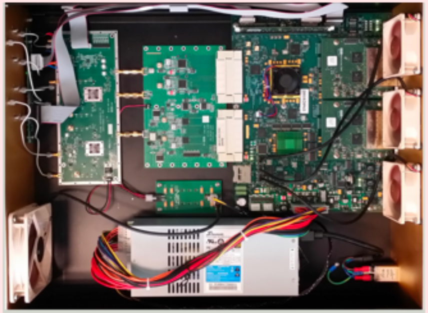
- 128 channel x-ray detector readout demonstration: Mates et al. APL 111, 062601 (2017)
- Proven on-sky with 215 TES MUSTANG-2 array on the GBT (4 x 64-channel multiplexers)
- Successful readout of CMB-optimized bolometer
  - TES in transition noise matched expectations
  - Noise flat to 100 mHz
  - Crosstalk < 0.3%
- Currently under development for Simons Observatory to achieve 2000 channels in 4-8 GHz
- 512-channel demonstration within 1 GHz of readout bandwidth underway
- Room temperature electronics:
  - Tone-tracking - SLAC.
  - Low power consumption - ASU
- Baseline readout for the proposed BFORE balloon-borne payload



Dober et al. APL 111, 243510 (2017)

μmux readout chain – PICO implementation

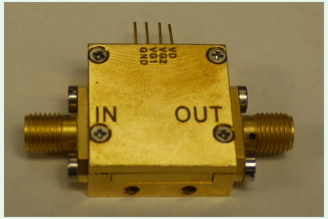
300K



7 coax pairs + 77 twisted pairs

- 7 readout boards, each 4-8 GHz
- Power consumption = 2.5 kW based on scaling of ROACH2 platform

4K

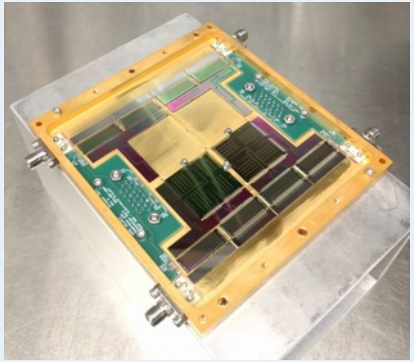


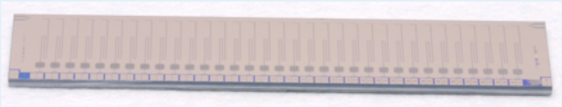
HEMT
2-12 GHz
+35 dB
$T_N \approx 5$ K

- 7 x Large bandwidth LNAs
- Total power dissipation ~70 mW

7 coax pairs + 70 twisted pairs

100mK





- Readout components consist of μmux + interface chips
- Power dissipation ~ 100 nW
- Readout footprint = 315 cm^2

Development Activities (non-exhaustive list)

- Demonstrate required readout noise level on long time scales and at the multiplexing factor baselined for PICO
- Detector-to-readout packaging
  - development of superconducting high density flex
  - magnetic shielding
  - array thermal management
- Substantial increase in multiplexing factor over the state-of-the-art.
  - High density, uniform readout channel frequency spacing
  - Maintain low cross-talk
  - Several GHz bandwidth, low IP3 preamplifier (HEMT, SiGe, para-amp, …)
  - Room temperature electronics
    - low power consumption
    - multi-tone software defined radio

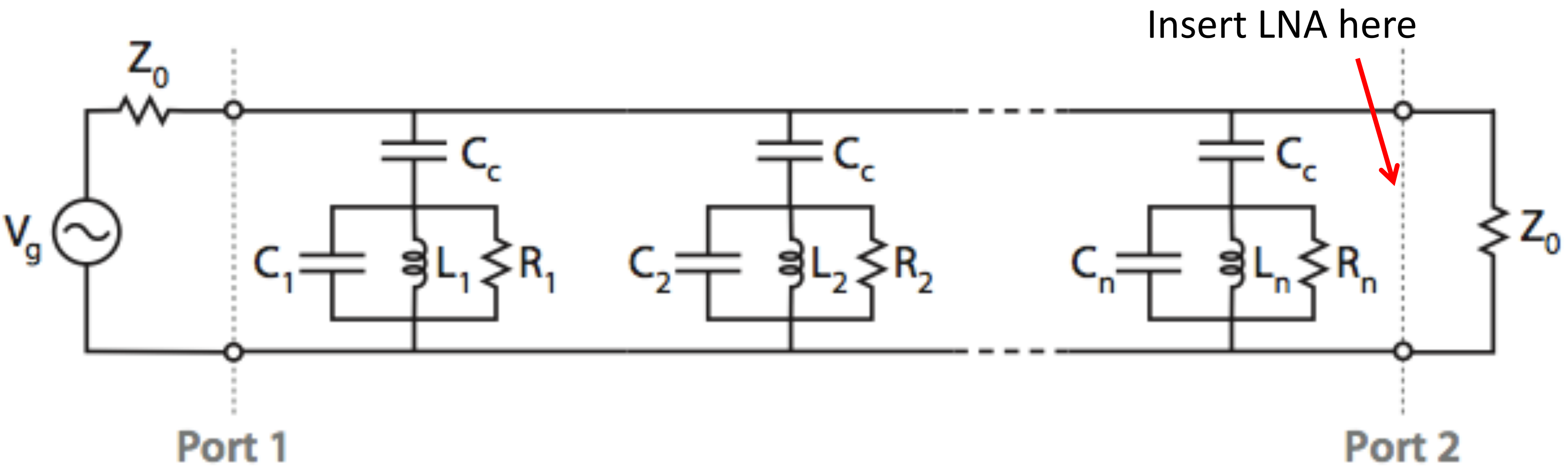
Summary

- Although not discussed here, don't count MKIDs out--could provide significant simplifications.
- Brute force application of existing SQUID-based multiplexing techniques for TES arrays can get the job done for PICO. However, to do so requires system changes that need to be verified.
- Trend toward microwave readout which will enable much larger arrays of low temperature sensors. On timescale relevant for PICO these techniques will be as mature as TDM/DfMUX and provide more capability.
- Few questions (perhaps for the discussion section):
  - In our report, how do we balance stating that a technical solution for readout exists versus conveying that R&D funds to develop readout would make PICO a lot easier/cheaper/more robust?
  - NASA has been excellent in providing support for detector and readout development, to the great benefit of the CMB community. We should argue that this should continue in the next decade. Is PICO report the place to do this?

Thank You

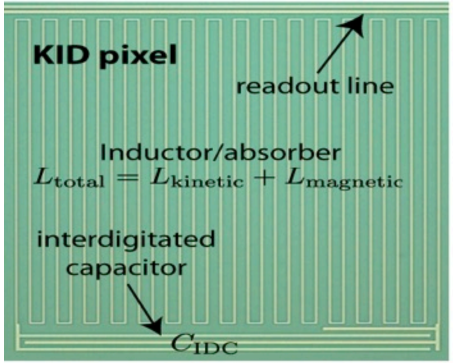
backup

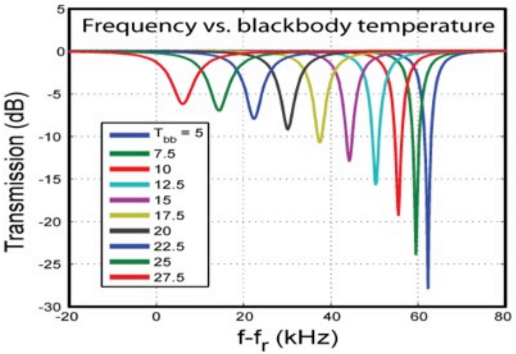
Microwave Kinetic Inductance Detectors (MKIDS)

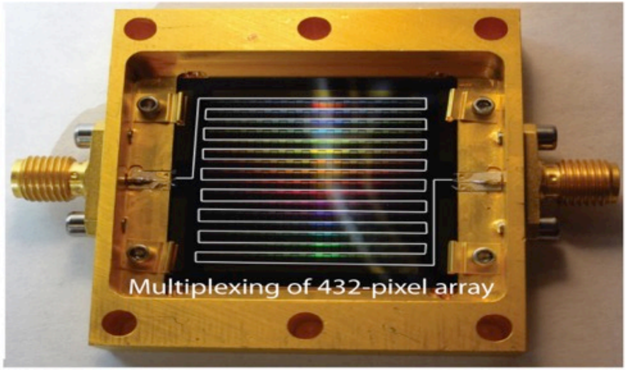


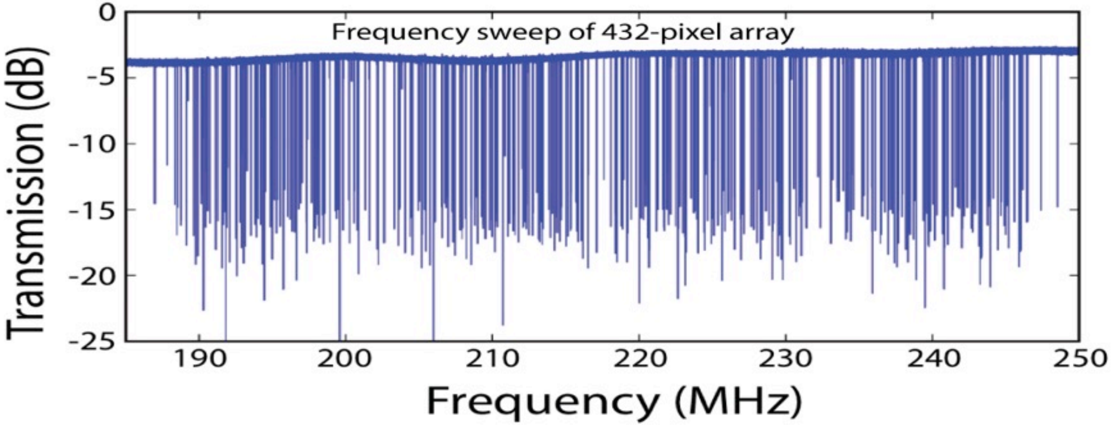
- Day et al. 2003
- Surface impedance altered by absorbed mm-wave radiation
- Transduces light from sky to frequency shift and quality factor reduction of microwave resonator
- Charm of approach is large multiplexing factor

KIDS: basic concept







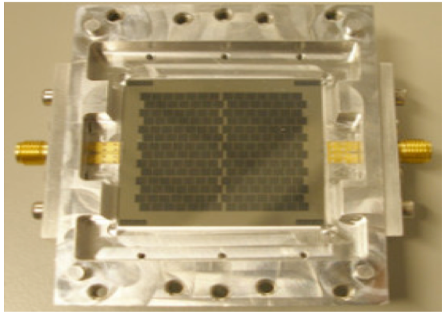


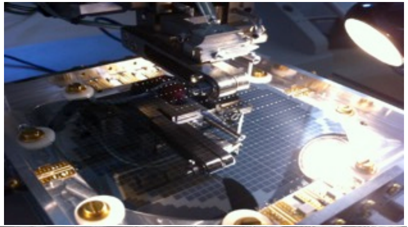
From J. Zmuidzinas

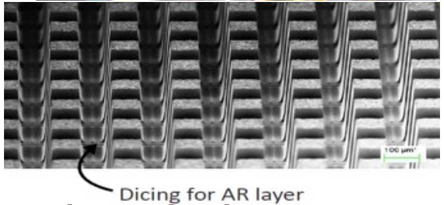
NIKA and NIKA2 cameras for IRAM 30m

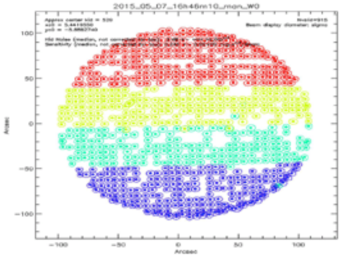
(A. Monfardini et al.)

From J. Zmuidzinas



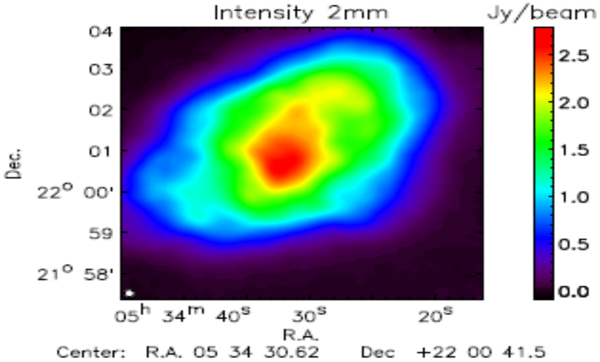


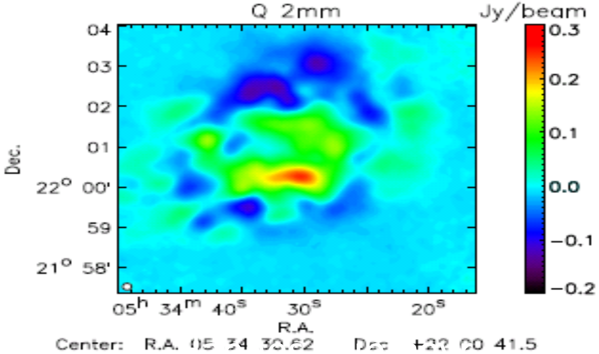


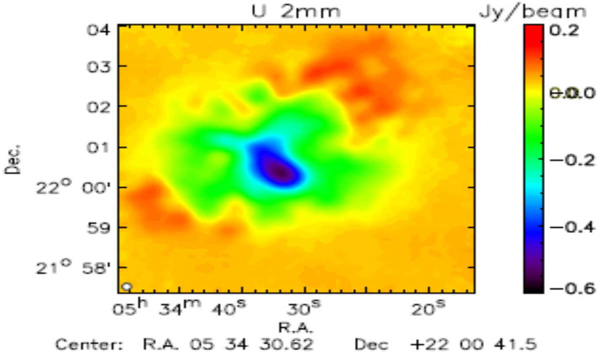


Arrays and beams-map

NIKA polarization maps of the Crab Nebula at 150 GHz

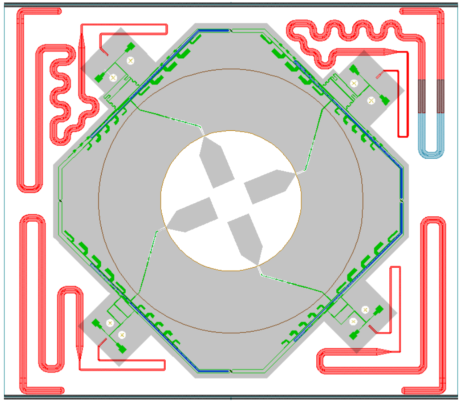






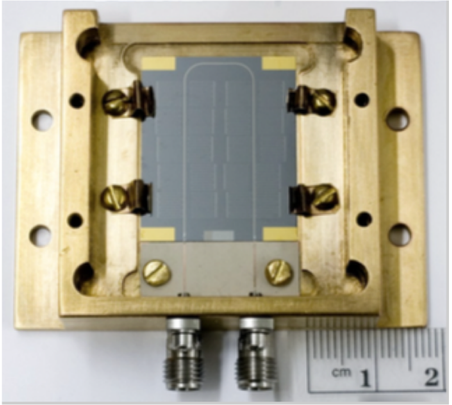
MKIDs for CMB

OMT-coupled



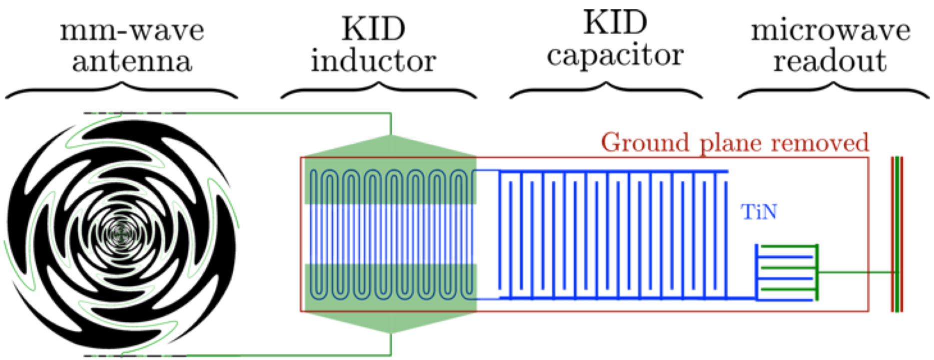
B. Johnson, Columbia
Sekimoto, NAOJ
Tajime, KEK

Direct Absorber



Wisconsin/GSFC

Lenslet/Sinuous Antenna-coupling



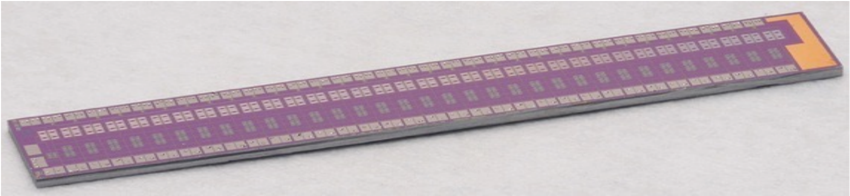
U. Chicago, E. Shirokoff

TDM Room Temperature Electronics

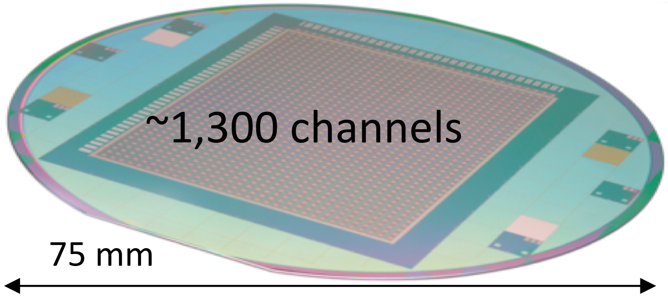
- Multi Channel Electronics (MCE) developed at University of British Columbia
- 37 mW/channel
  - 2048 channels/crate (assuming 64 rows per column)
  - 75W/crate
- SCUBA2, ACT, ACTPol, Advanced ACTPol, ABS, SPIDER, NIST THz imager, BICEP2, KECK ARRAY, BICEP3
- TRL=6 (SPIDER 2015)

TDM: performance

33x1 SQUID multiplexer



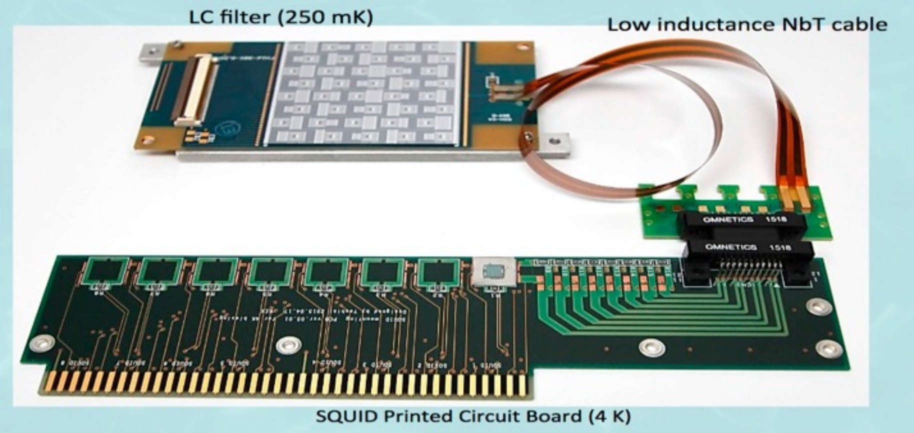
2D multiplexer



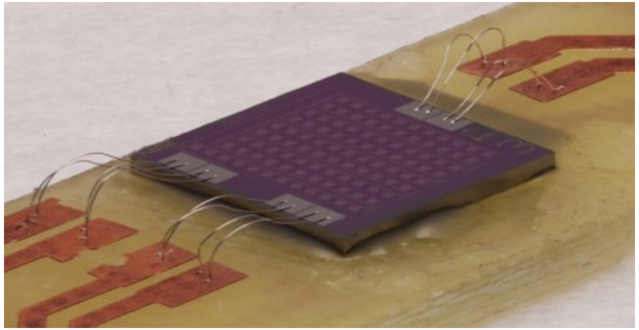
HAWK+, PIPER, SCUBA2

- Multiplexing factor: 64 (advanced ACTPol, Henderson et al 2016)
- highest pixel-count array demonstrated on the sky: 10,000 SCUBA2
- When bias circuit optimized, negligible noise degradation due to readout
- cross-talk
  - 0.25% nearest neighbor, <0.03% for rest (deKorte 2003, B2 instrument paper)

MHz FDM: performance



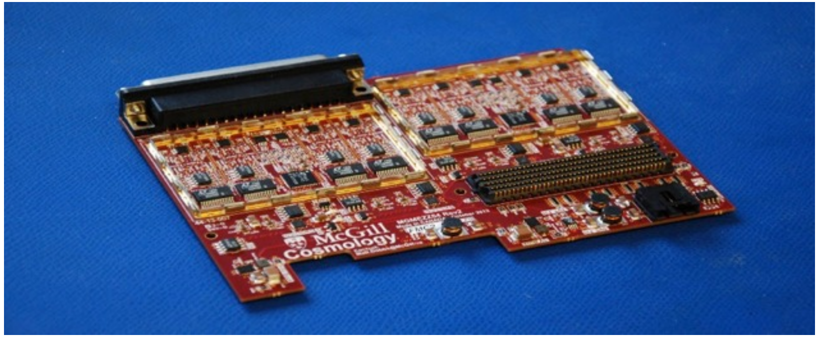
Hattori LTD16

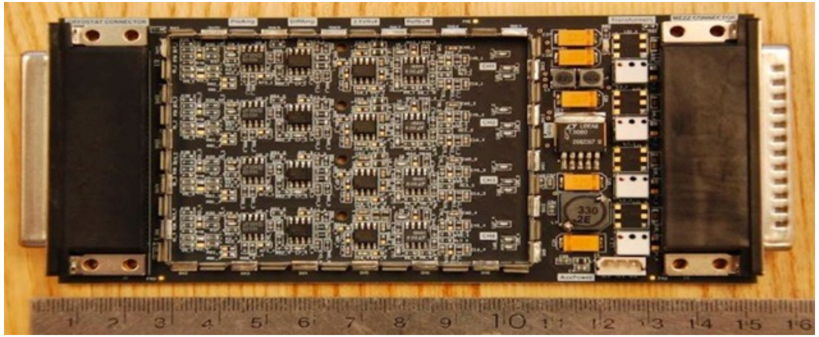


SQUID Series Array

- Used in mm/sub-mm instruments APEX-SZ, EBEX, PolarBear/Simmon's Array, SPT, SPTpol, SPT-3G, LiteBIRD
- highest mux factor achieved in deployed instrument: 68 (SPT-3G)
- highest pixel-count array demonstrated on the sky: 1,536 (SPTpol, Austermann 2012)
- When bias circuit optimized, negligible noise degradation due to readout
- Readout area per channel at mK stage = 60 mm^2 (silicon LC chips only)
- Xtalk: <1% (Hattori 2016)

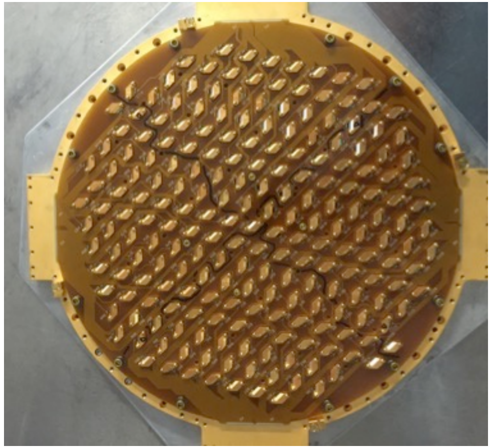
MHz FDM: readout



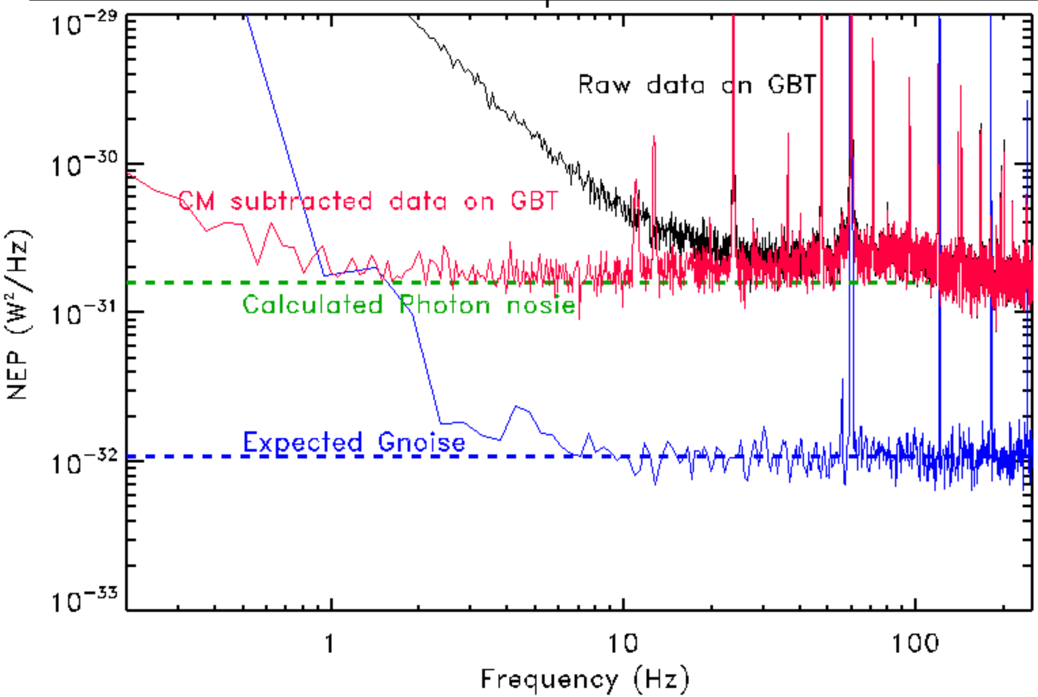


- Developed at McGill University and UC, Berkeley
- x68 demonstrated
- Readout bandwidth = 6 MHz
- Power consumption
  - 330 mW/channel (x16 MUX, EBEX 2013, McDermid 2014)
  - 49 mW/channel with new FPGA chips and x64 MUX (Bender et al. 2014)
- EBEX, SPTpol, PolarBear, PolarBear2/Simon's Array, SPT-3G, LiteBIRD
- Spaced optimized hardware shown on the left. Key components brought to TRL5.

MUSTANG2 µMUX Demo



On-sky, end-to-end demonstration of uMUX readout



Dicker et al. SPIE 2016