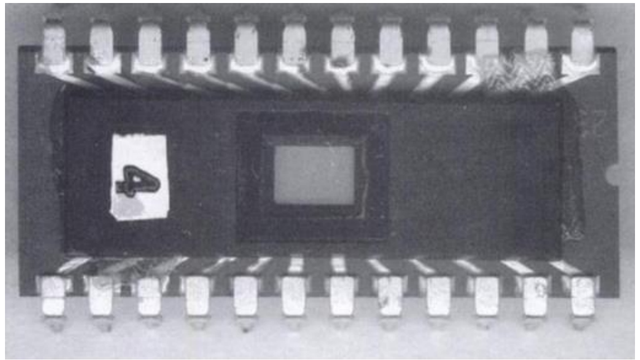
An Affordable and Easily Programmable Homodyne Readout System

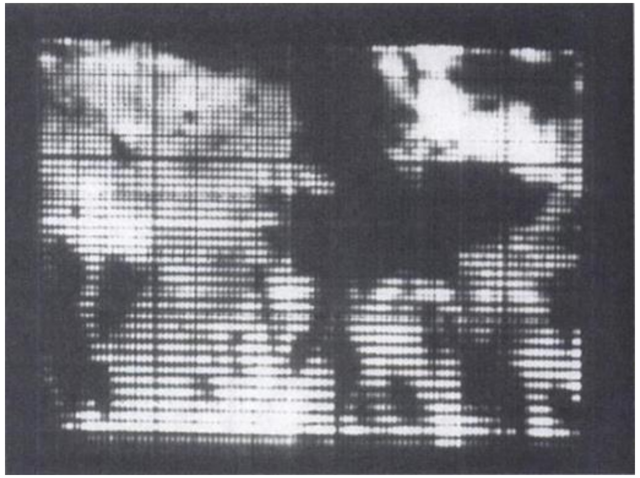
(For Readout and Characterisation of Prototype MKIDs (Microwave Kinetic Inductance Detectors) for UVOIR Astronomy and Astrophysics)

Colm Bracken, Mario de Lucia, Gerhard Ulbricht, Cathal McAleer, Gary Donegan, and Tom Ray

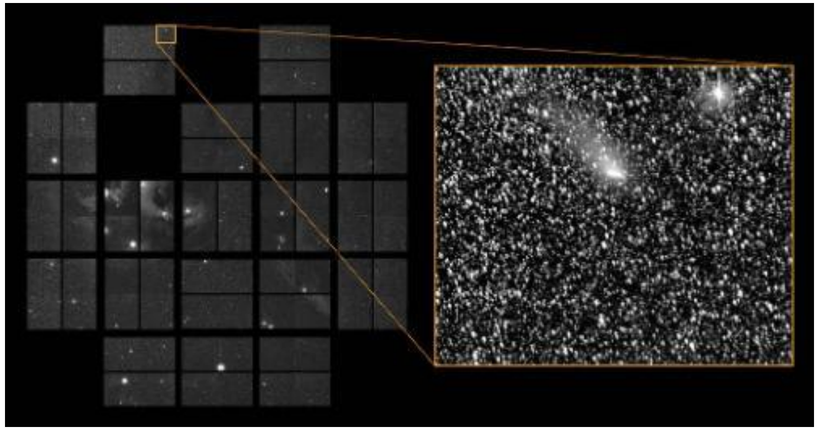
- Astronomy & Astrophysics with digital cameras (or CCDs)
- Limitations of CCDs
- Improvements with superconducting detectors
- Superconducting Microwave Kinetic Inductance Detectors (MKIDs)
- Electronic Readout for MKIDs
- Student-Led Design and Construction of an Affordable, Easily Programmable Single Pixel Readout System

Astronomy & Astrophysics with digital cameras (or CCDs) - Imaging



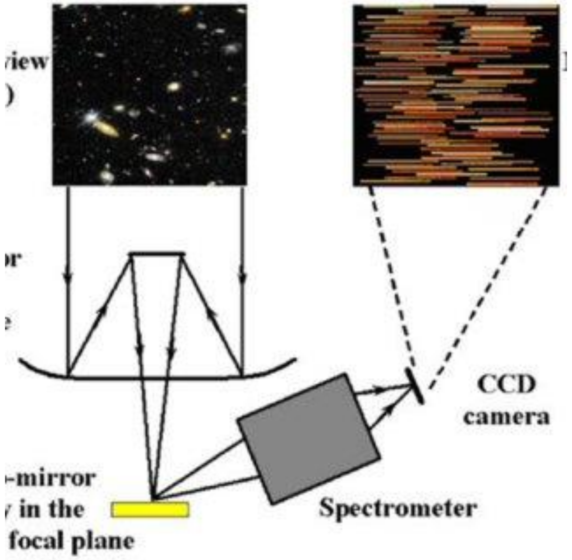


1974:
100 x 100 pixel Fairchild CCD, and the early image of moon craters taken with it. Image credit: Scientific chare-coupled devices, J.R. Janesick, 2001. ISBN: 9780819436986

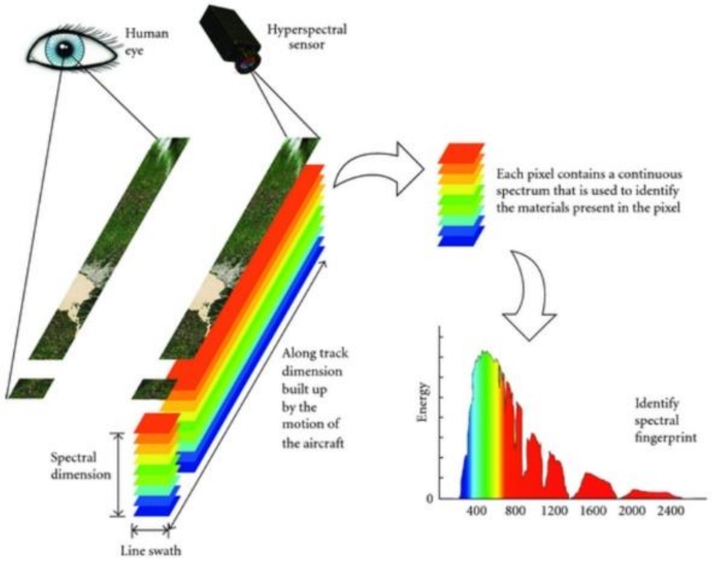


Recently:
Comet Siding Spring observed in October 2016 as it passed across the field of view of NASA's Kepler spacecraft. Credit: NASA Ames/W Stenzel; SETI Institute/D Caldwell

Astronomy & Astrophysics with digital cameras (or CCDs) - Spectroscopy

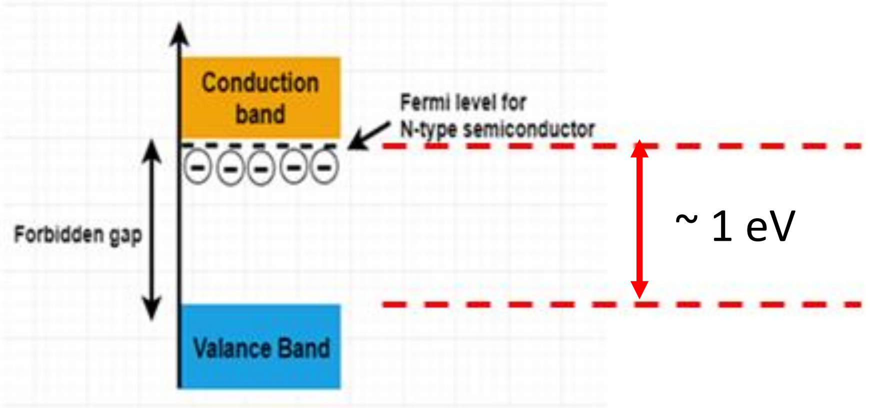


If you want spectral information, you often have to sacrifice at least one dimension of spatial information.



We can get around this by sweeping across the other spatial dimension, but this takes time!

Limitations of CCDs

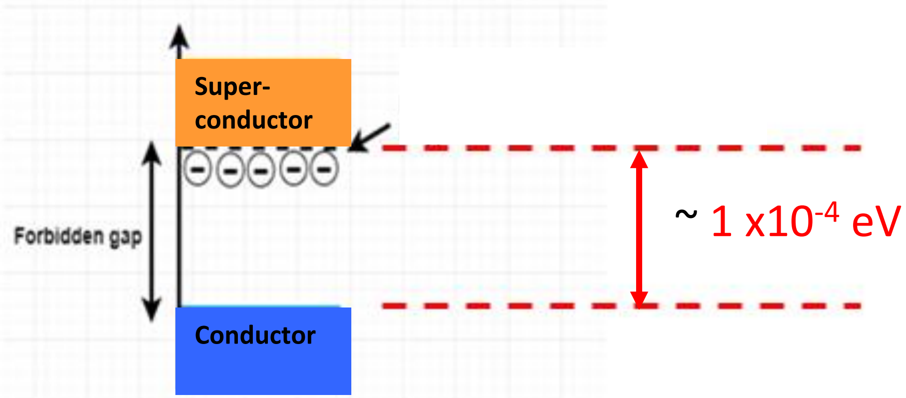


Silicon, for example, has a bandgap of 1.14 eV.

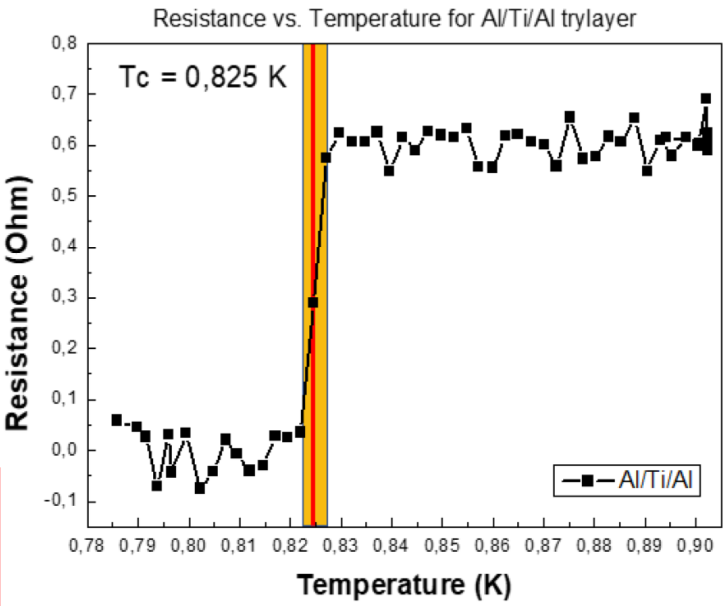
Colour	Wavelength [nm]	Energy [eV]
NIR	750	1.65
Red	625	~ 2.00
Green	540	2.30
Blue	450	2.75
UV	350	3.55
FIR	100,000 (100 um)	0.0124

Detection not even possible at far-IR wavelengths, as photons just **do not enough energy**.

Move to superconducting detectors



Aluminium, for example, has a bandgap of 3.4 x10^{-4} eV.



Colour	Wavelength [nm]	Energy [eV]
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Blue	450	2.75
UV	350	3.55
FIR	**100,000 (100 um)**	**0.0124**

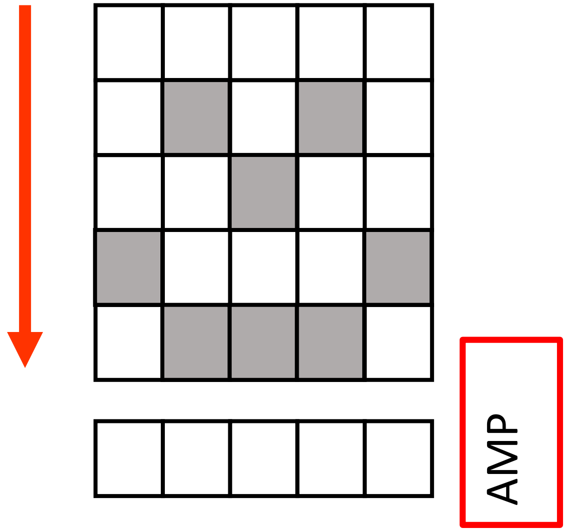
Now, for <u>every **optical** photon absorbed</u>, we can get **10's of thousands of charge-carriers** for our signal.

And, lower-energy wavelengths can now be detected, e.g. Far-IR/Sub-mm.

Comparing CCDs with MKIDs

$$\Delta \approx 1.76\, k_B T_c \qquad f_r = \frac{1}{2\pi\sqrt{LC}}$$

- CCDs are semiconducting detectors
- Current transport with resistance
- Energy gap Δ for electron excitation in Si is about 1.2 eV (~ to optical/near-IR photon)



- MKIDs are superconducting detectors
- Current transport with resistance
- Current transport with zero resistance
- No electrical fields → Can't operate like a CCD
- Instead: LC resonator (tank circuit): Classic harmonic oscillator with well defined resonant frequency f_r

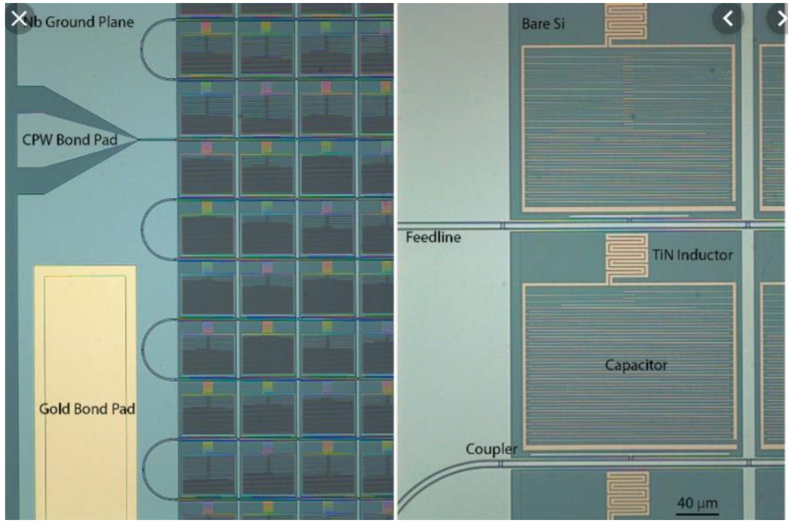
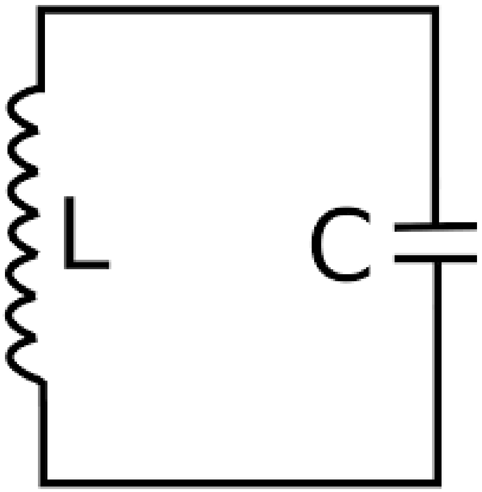
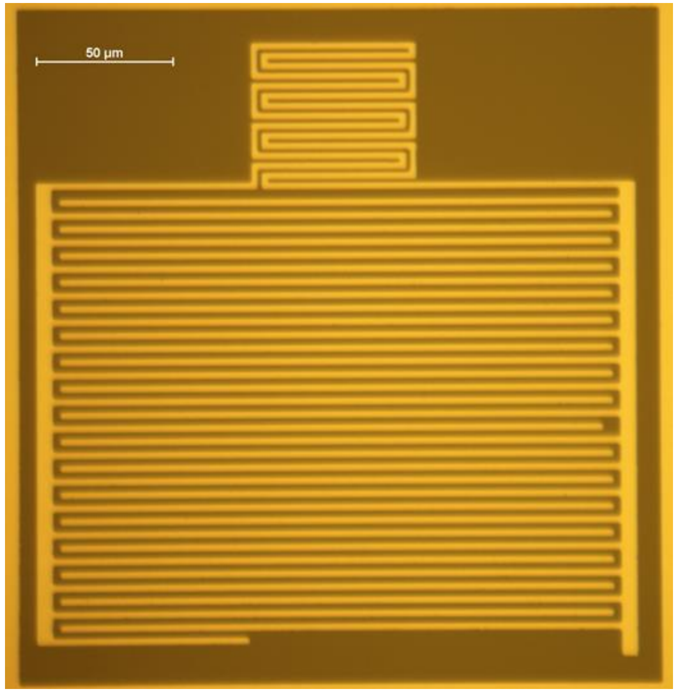
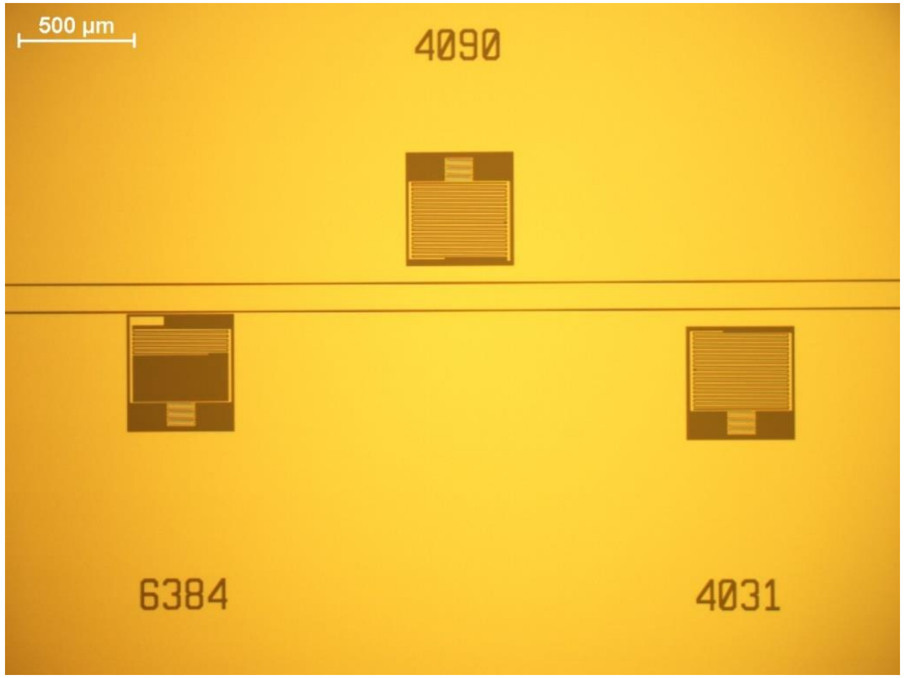


Image credit: Ben Mazin (UCSB), et al., 2013.

What is an MKID?



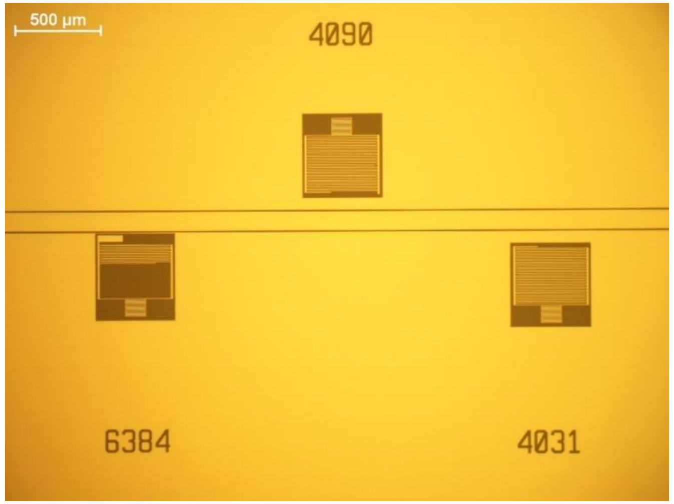


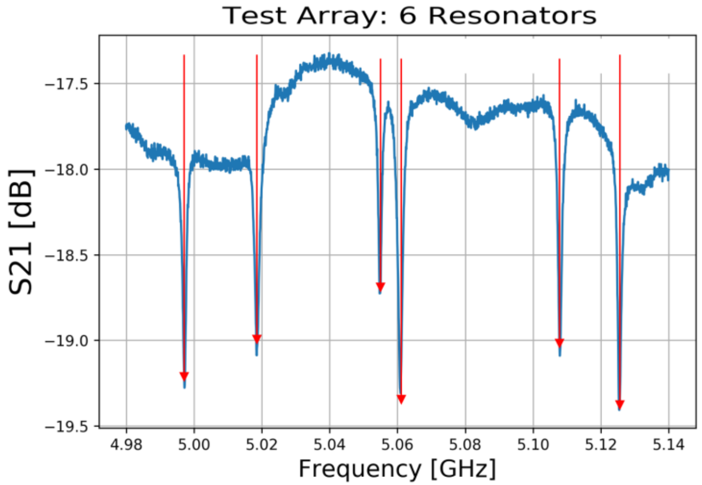


- Each pixel/detector is fabricated as a LC micro-resonator, with unique res. frequency
- We can thus drive and measure each resonator/pixel at its specific resonance
- Create large arrays of detectors, using **frequency division multiplexing (FDM)**

How Do We Use FDM?

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$





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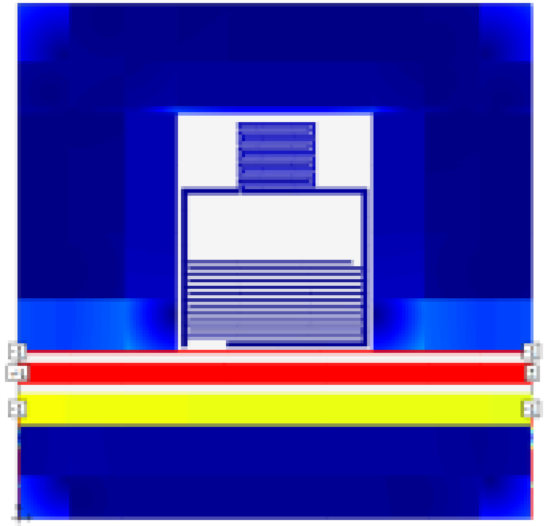
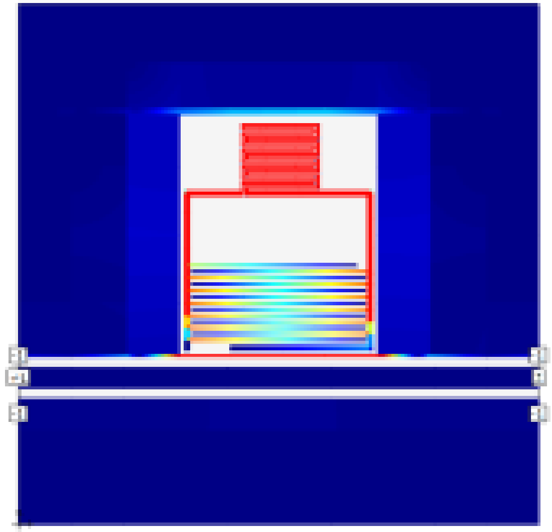
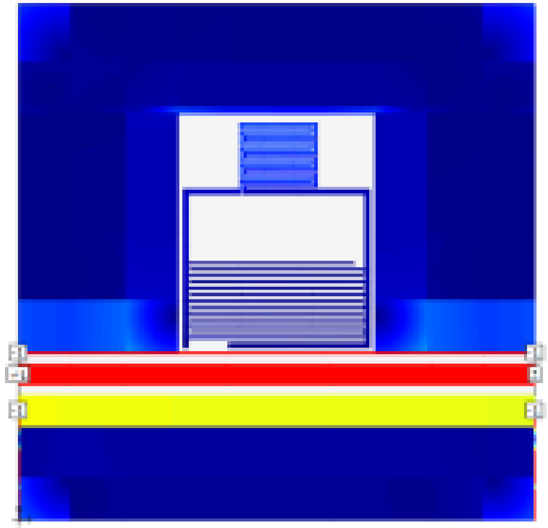


Tone Frequency: 5.3 GHz



Tone Frequency: 5.33816 GHz

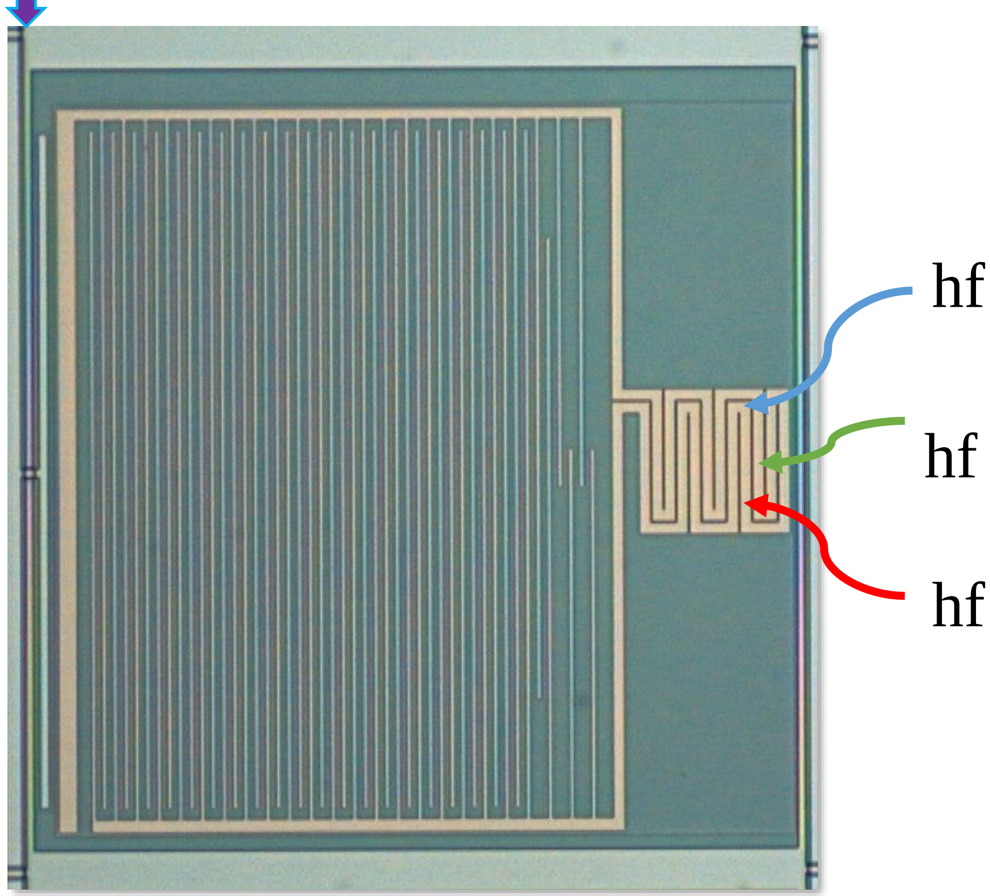


Tone Frequency: 5.4 GHz

- Probe tone frequencies not matching resonator resonance will pass by.
- Only tones with frequency matching resonator will couple to resonator.
- Also, notice that on resonance, the current density is overwhelmingly in the inductor.

MKID Operation

f ~ 4 - 8 GHz



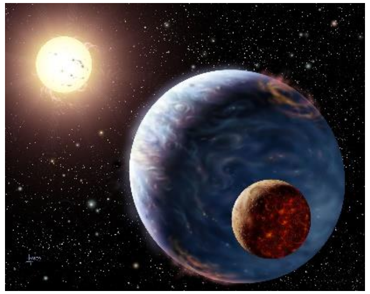
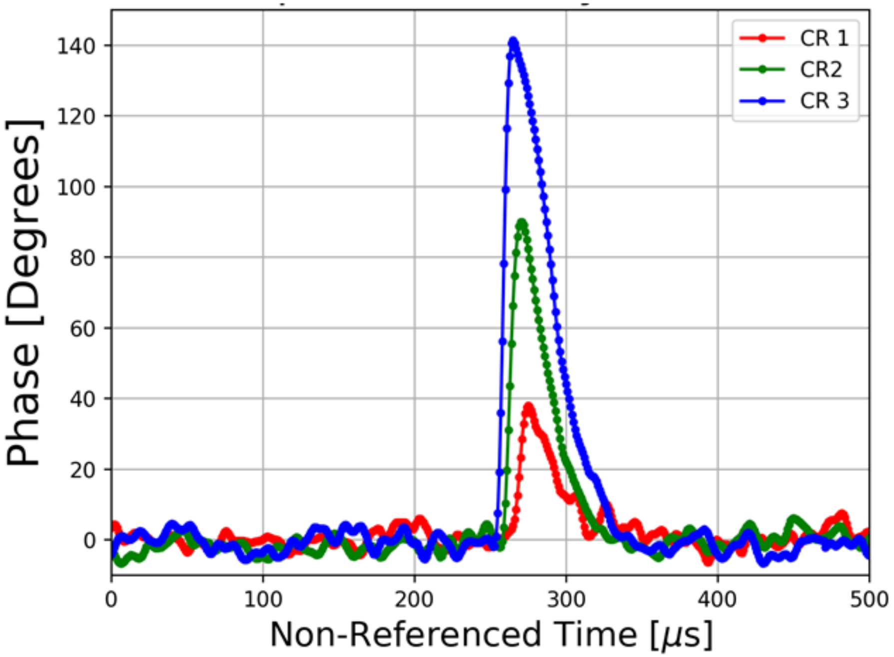
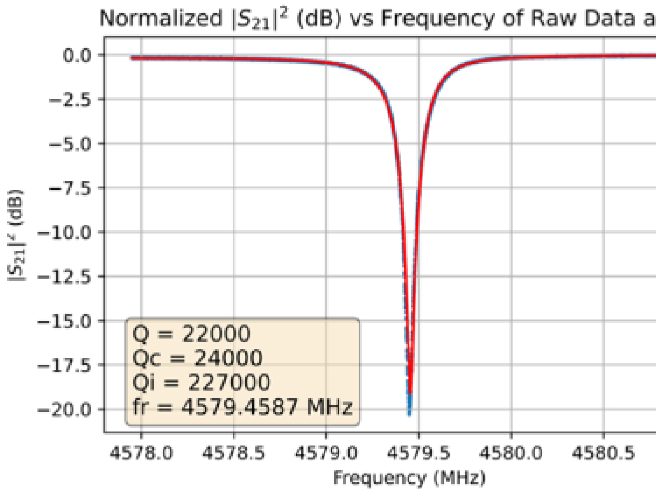


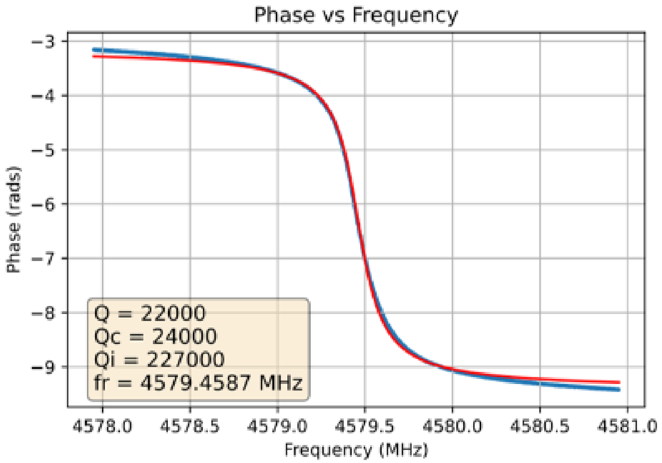
Image Credit:
www.universetoday.com



Monitoring re-normalized phase as function of time

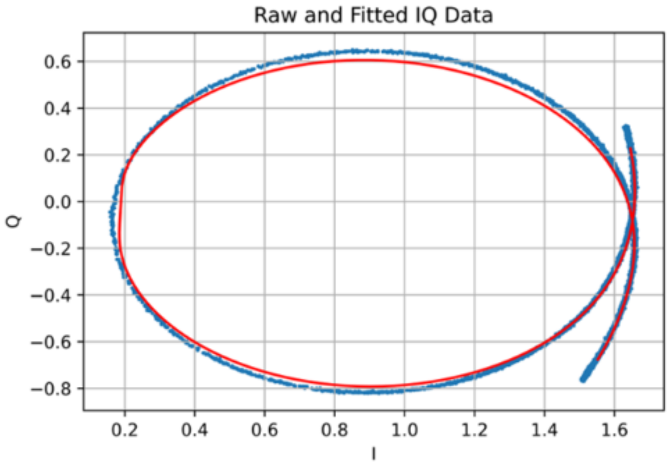
Options for monitoring/reading an MKID





Sweeping Frequency from:

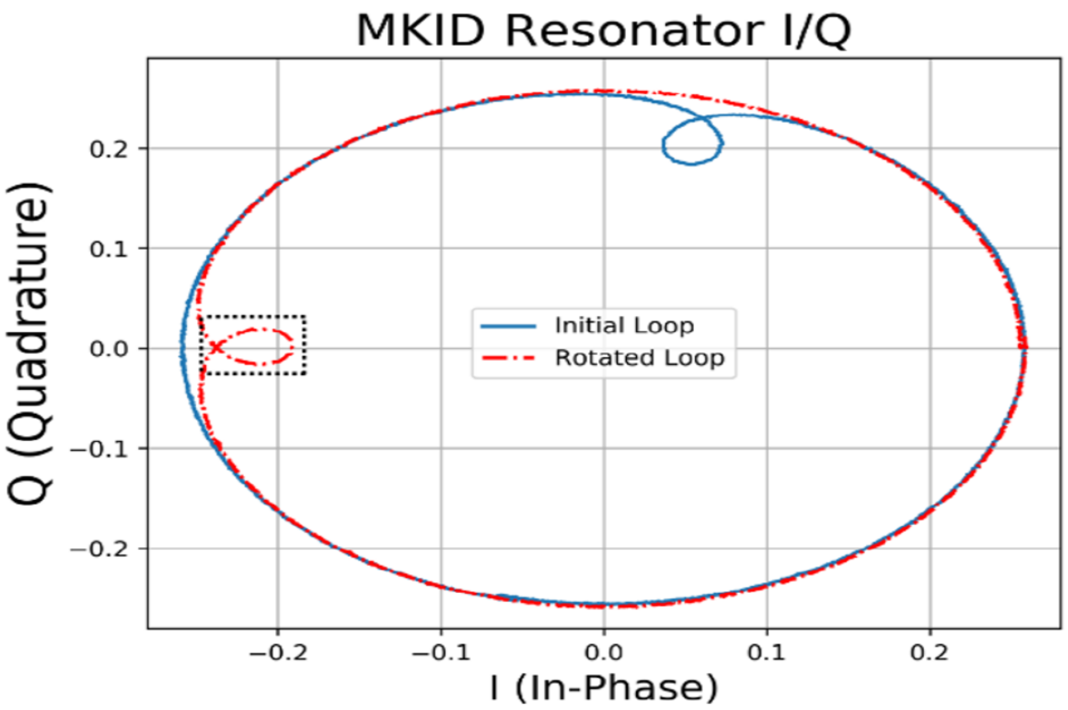
$f = f_r - 1.5$ MHz, to $f_r + 1.5$ MHz

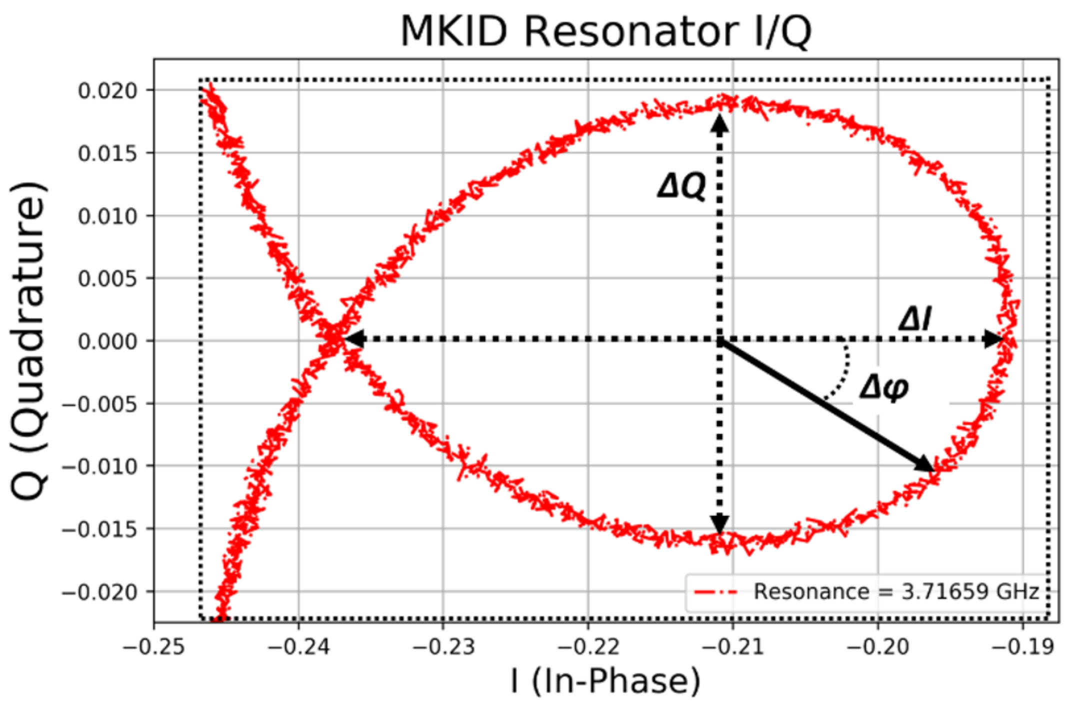


Choice to monitor the MKID in:

1. Absolute Magnitude
2. Absolute Phase
3. Re-normalised phase (and/or amplitude)

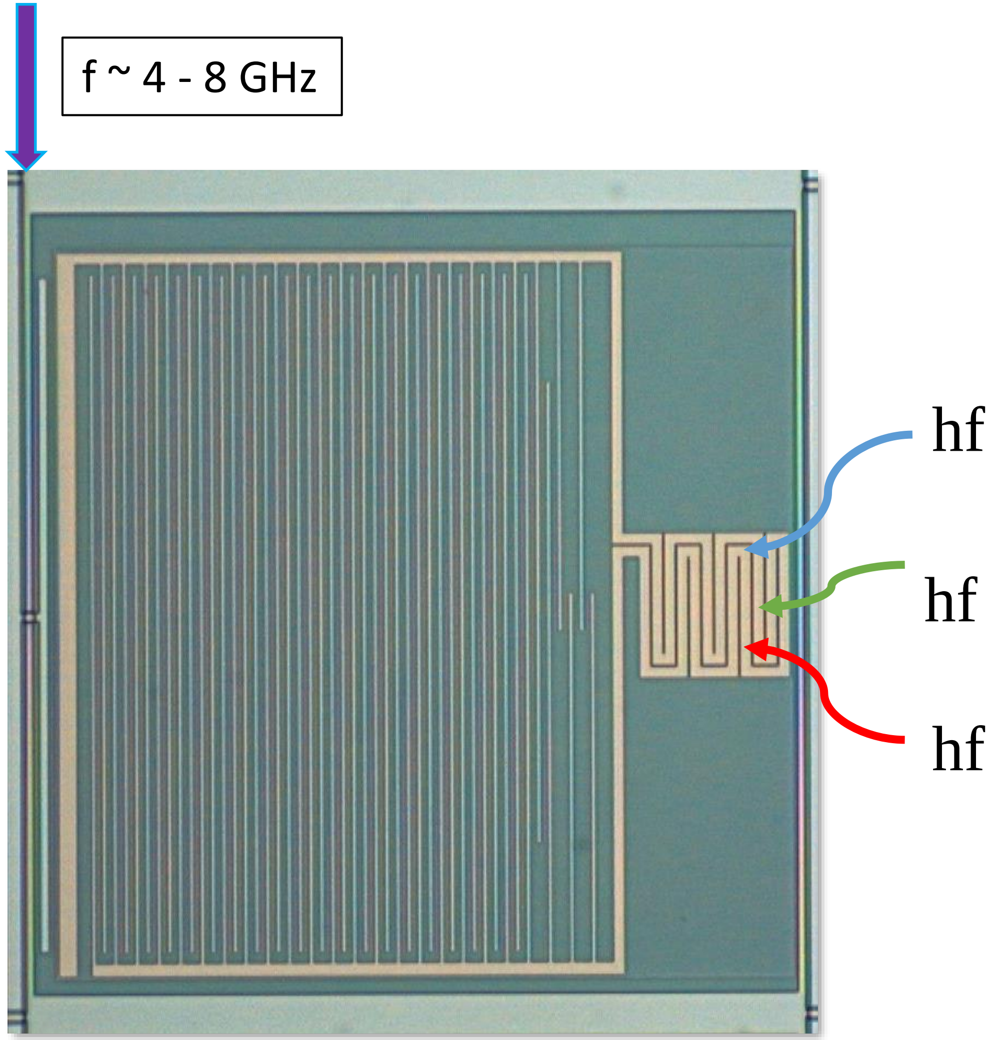
Phase Rotation and Renormalisation





MKID Operation

f ~ 4 - 8 GHz



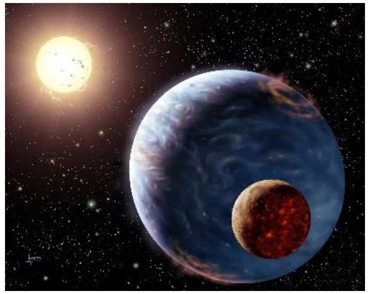
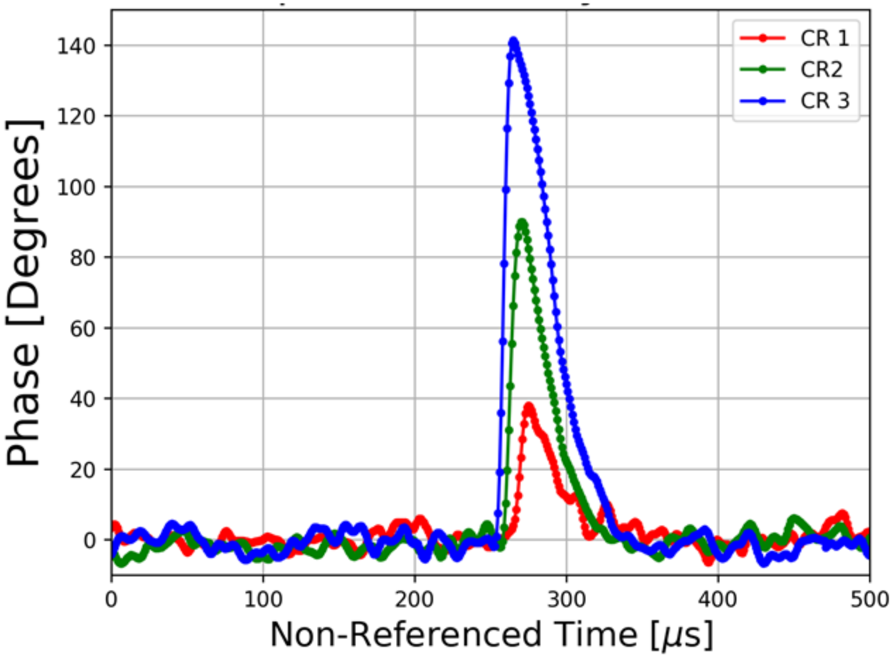
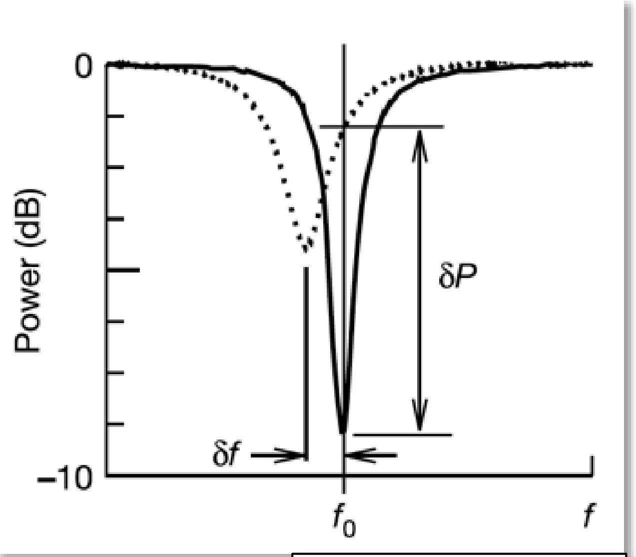


Image Credit:
www.universetoday.com

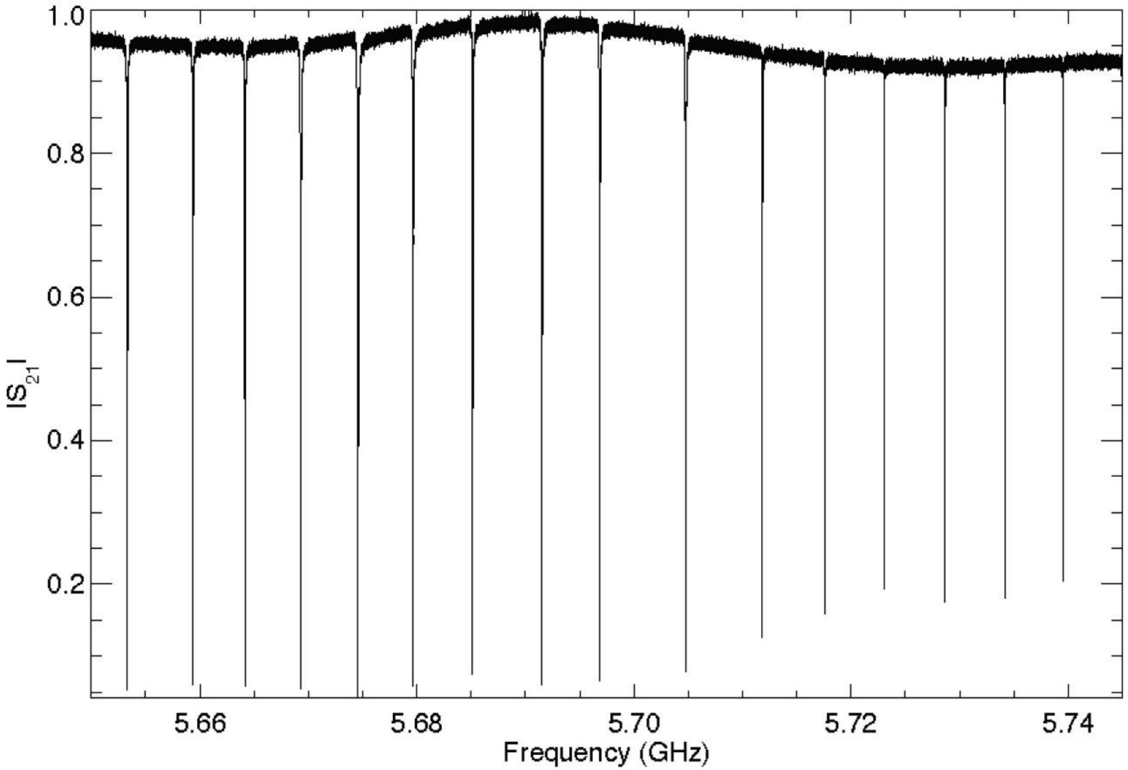


Monitoring re-normalized phase as function of time

Frequency domain multiplexing: one **fixed** frequency per pixel



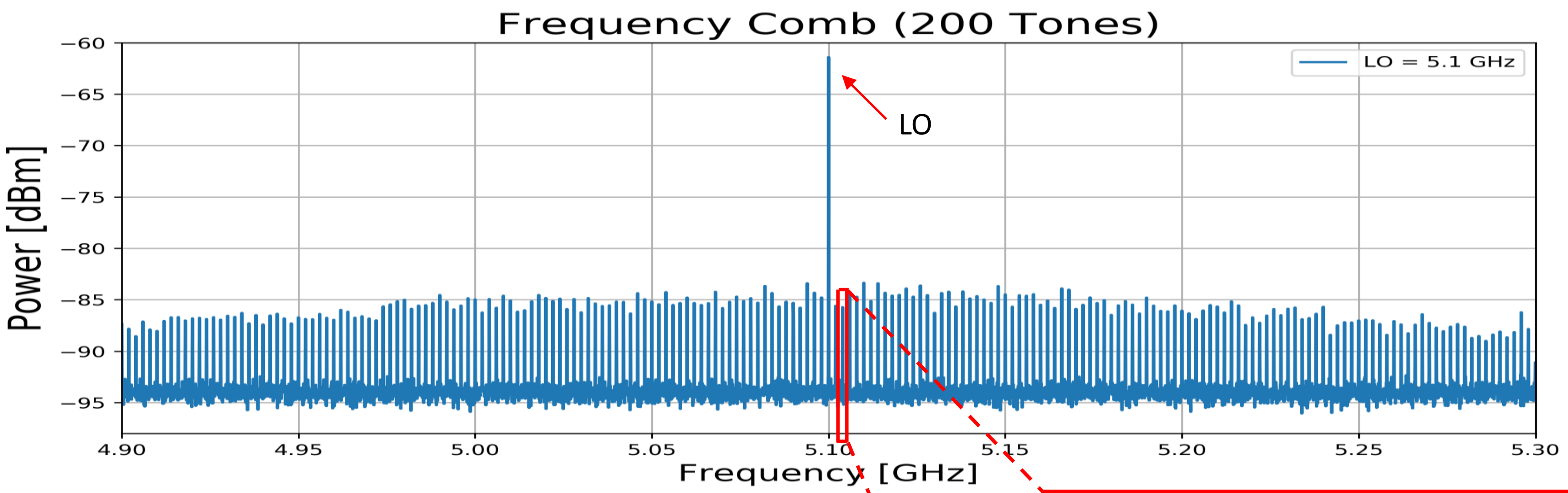
P. Day et. al., Nature 425, 817

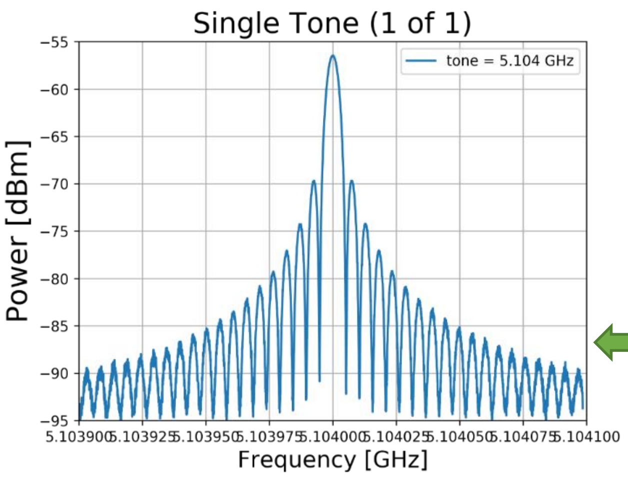


- Every pixel is monitored at its resonant frequency.
- Superconducting resonator → Very little damping, very high Q
  → Very sharp resonances, no effect on signals with different frequencies.

➔ Multiplexibility: Every single pixel has its unique, lithographically defined resonant frequency in the GHz range.

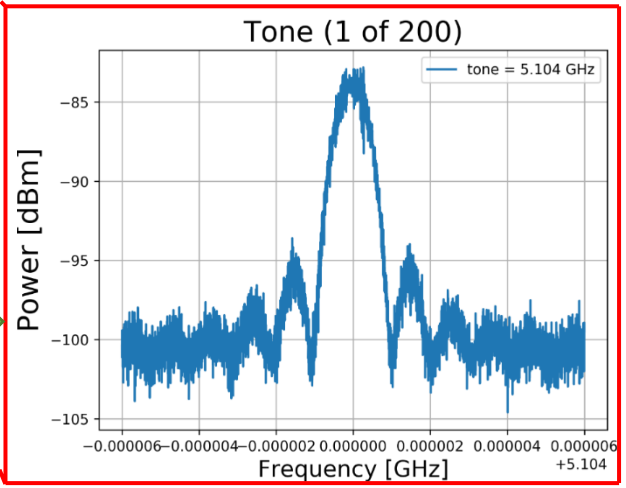
Drive signals (frequency comb waveform)





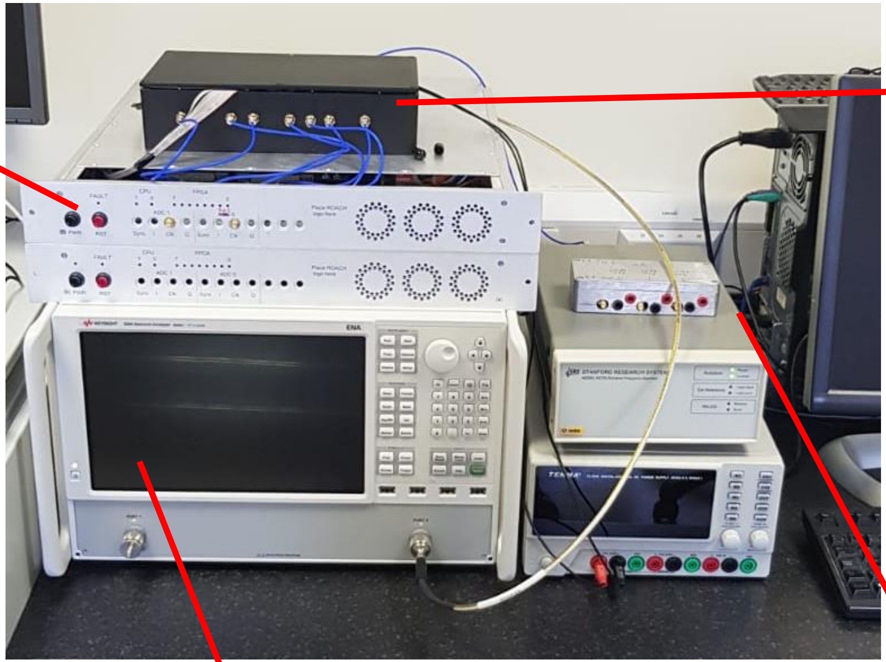
Each ROACH and DAC can output 256 tones with ~ -86 dBm per tone

~ -58 dBm for single tone



Our Current Readout: ROACH 1 (Deprecated, but pre-existing firmware and control software)

- ROACH 1 FPGA board
- ADC: 550 MSPS, 12 bit
- DAC: 1000 MSPS, 16 bit



- IF/RF Board

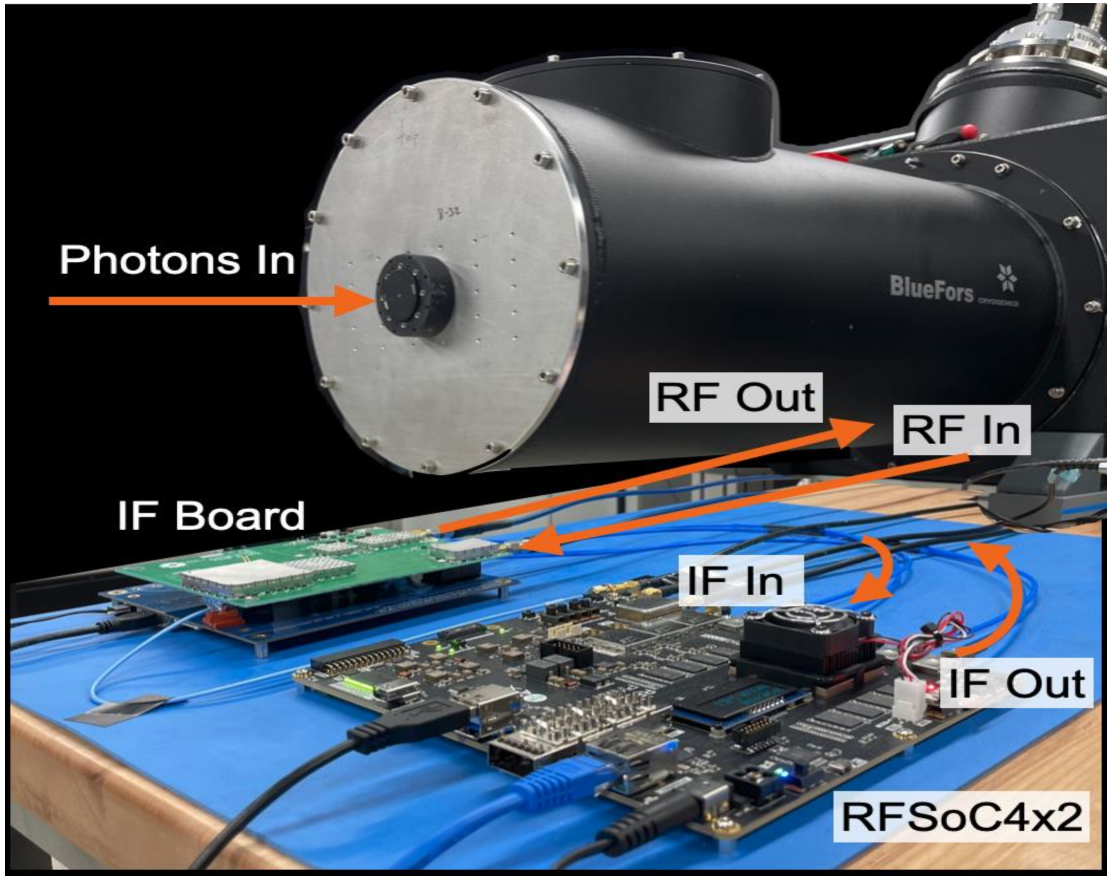
- Each ROACH 1 can read ~ 250 pixels

- Rubidium Frequency Standard (Stable 10 MHz) & 1PPS
- VNA

State of the Art MKID Readout (for UV/O/IR)

- UCSB/Mazin Labs, & FermiLab
- AMD/Xilinx RF SoC 4x2 Board
- ADCs: 4 x 9.85 GSPS, 14 bit
- DACs: 2 x GSPS, 14 bit
- Significant DSP, Logic and Memory

- Each system can read ~ 2,000 pixels



A single RF SoC 4x2-based MKID readout, Jennifer Smith, et al. 2024

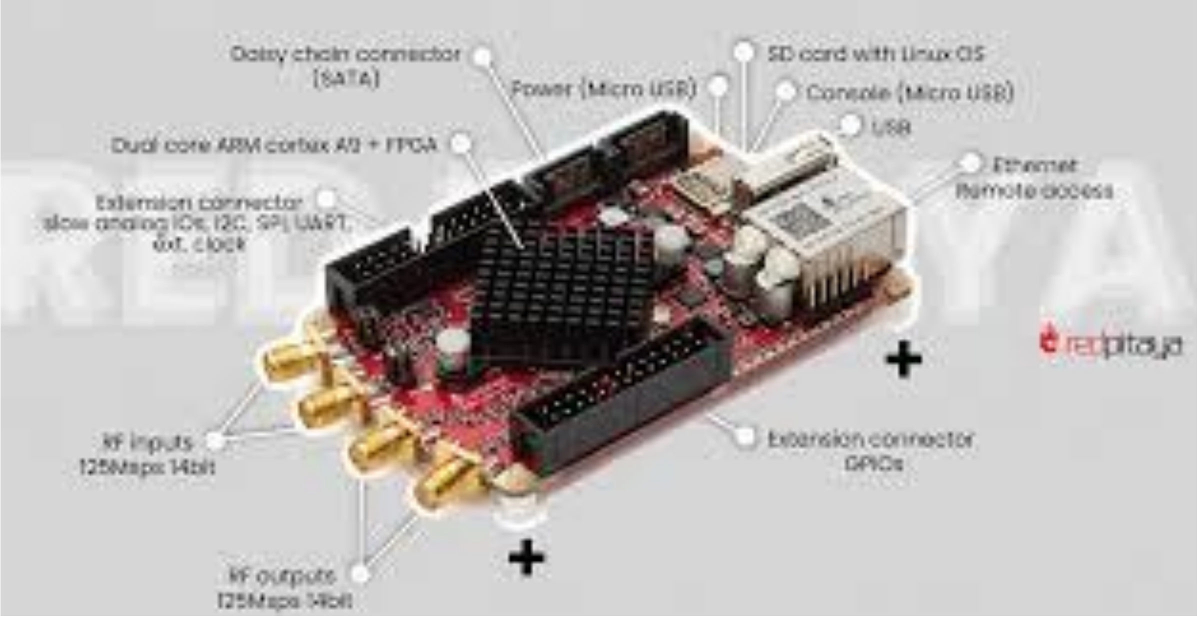
Primary Challenge for Early Work (Prototyping)

- Early prototyping work on requires only one/(a few) channels
- Each resonator can be measured and characterised individually
- A full FDM readout system is overkill for prototyping
- Significant learning curve for FDM readout
- Typically requires an electronic engineer, proficient with FPGA/GPUs

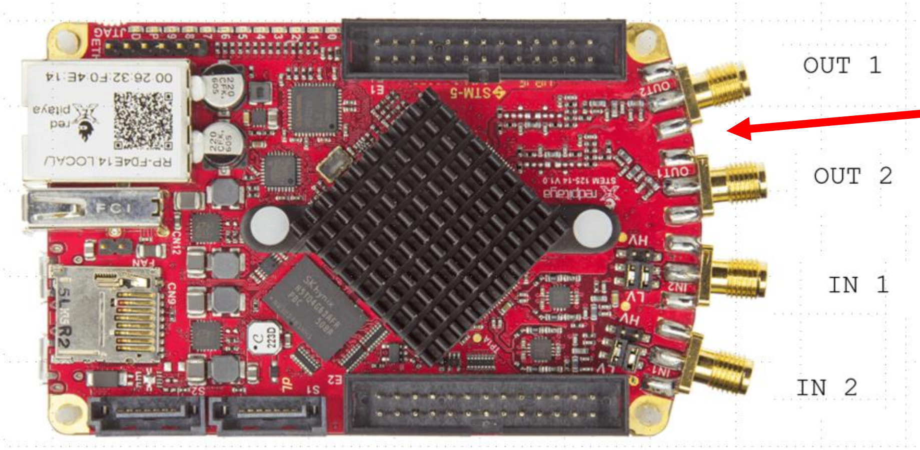
Aim of Single Channel Homodyne Readout

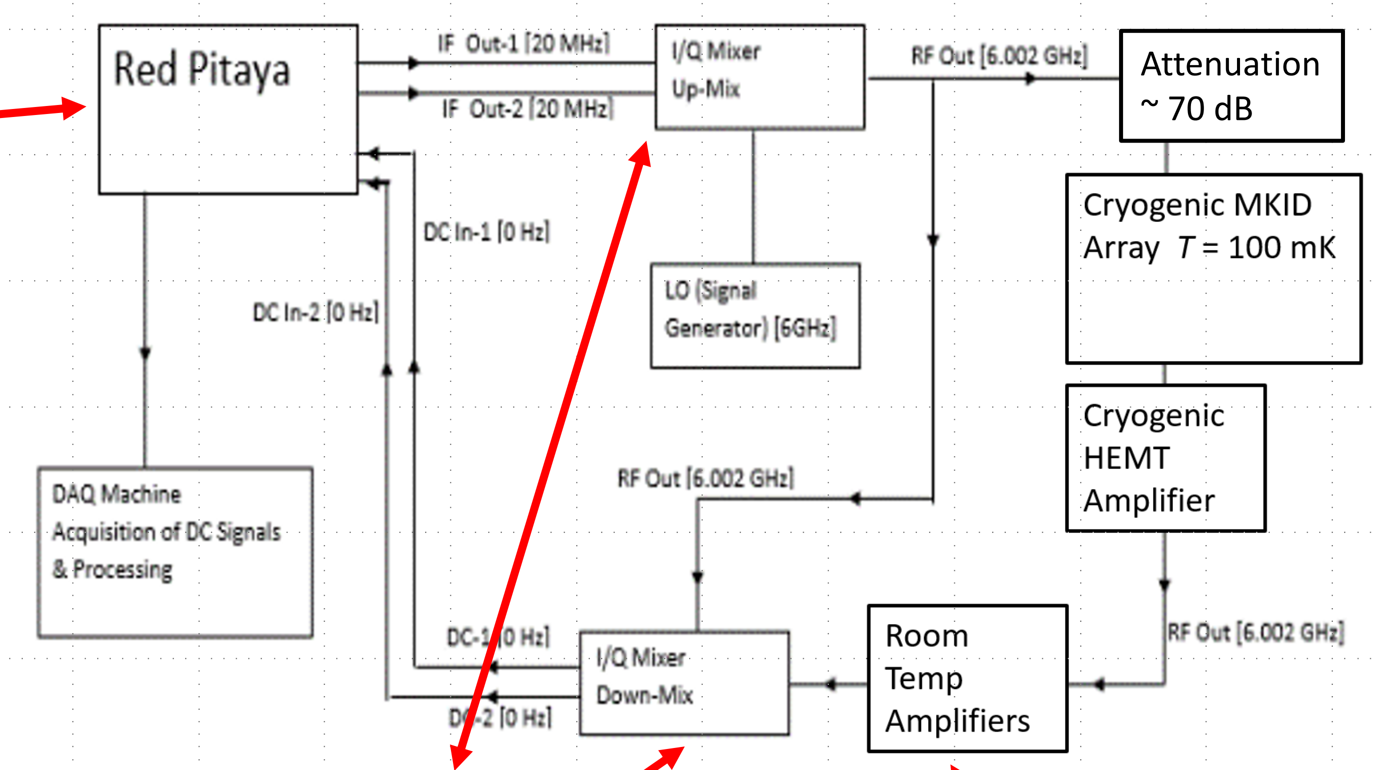
- Student driven – part of final year undergraduate project
- Affordable – budget ~ 2K (Euro)
- Easily programmable – And Open Access (Python, on Github)
- Modular – components easily replaceable/upgradable

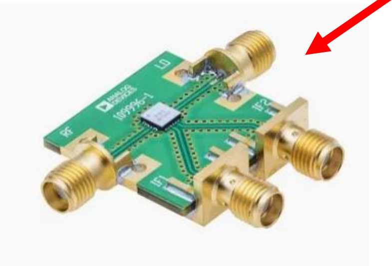
- We chose the core of the readout to be the Red Pitaya
- So-called Swiss Army Knife of test equipment



Block Diagram for Homodyne Readout

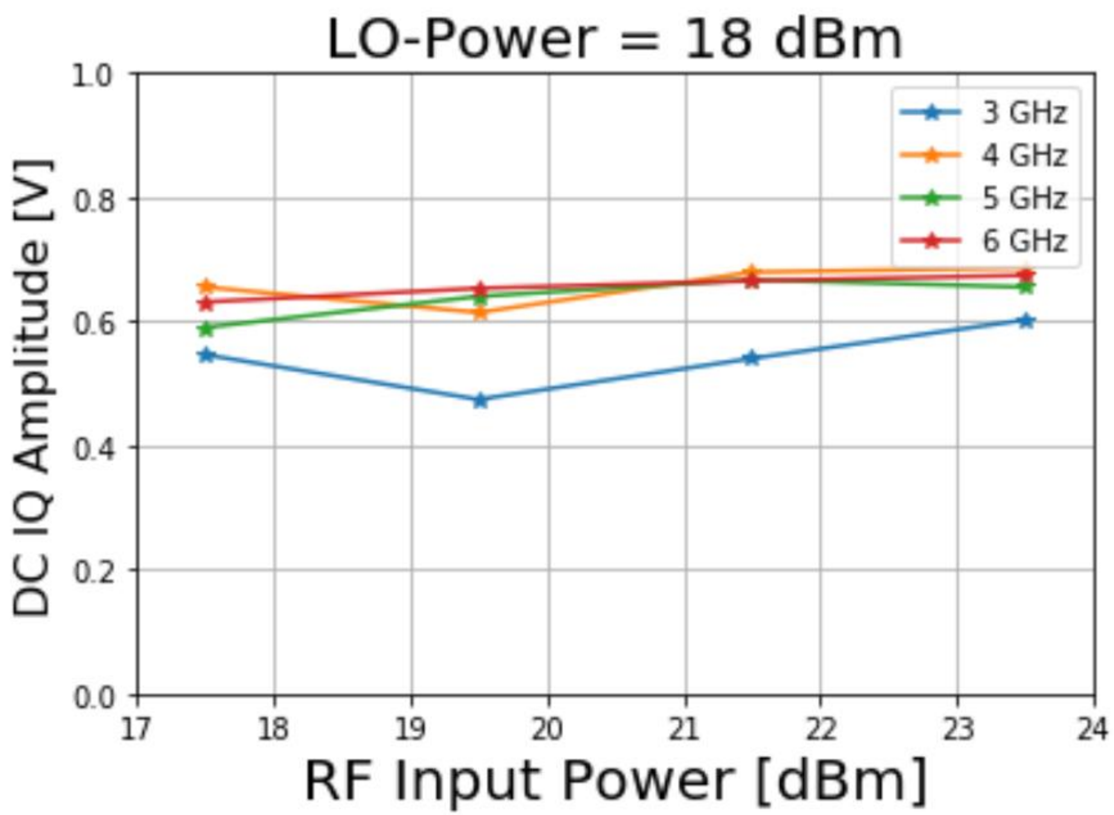




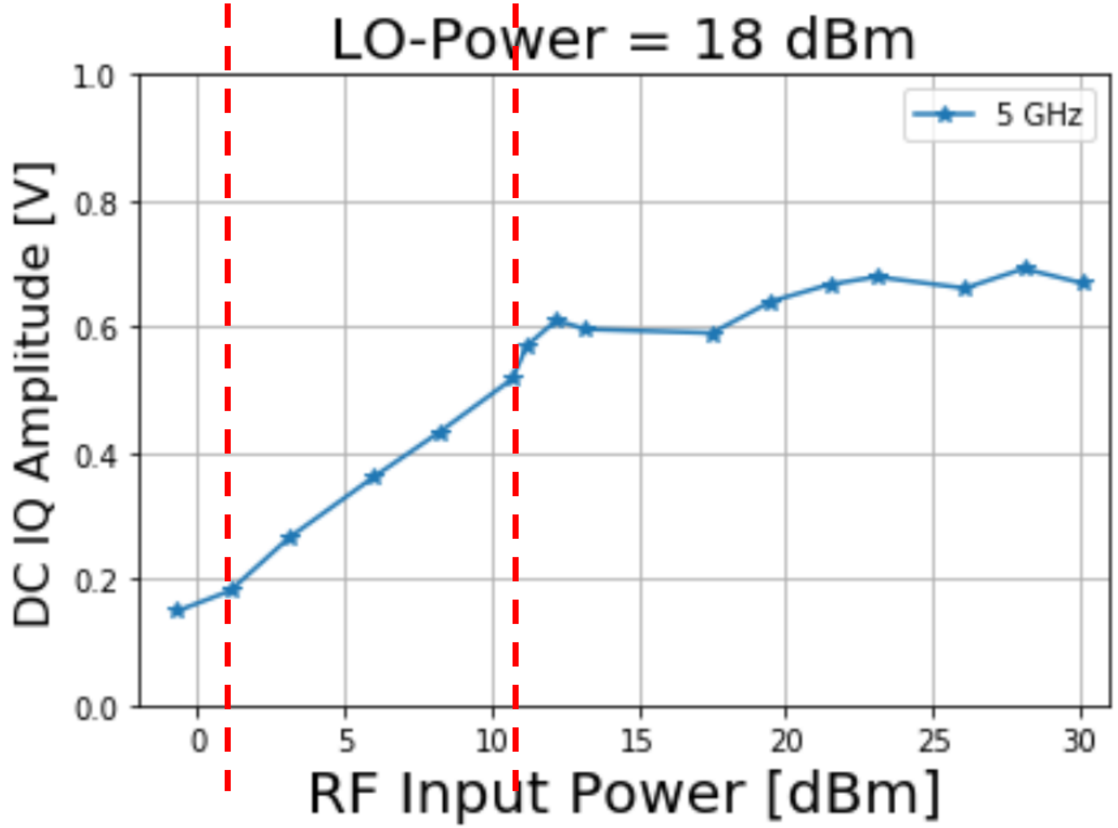


- Red Pitaya ~ 500 Euro
- Mixers ~ 300 Euro
- Amps ~ 200 Euro each
- LO Signal Generator ~ 500 Euro
- Attenuators & Filters ~ 200 Euro
- Total < 2 K

Characterisation of Homodyne Readout (Mixer)

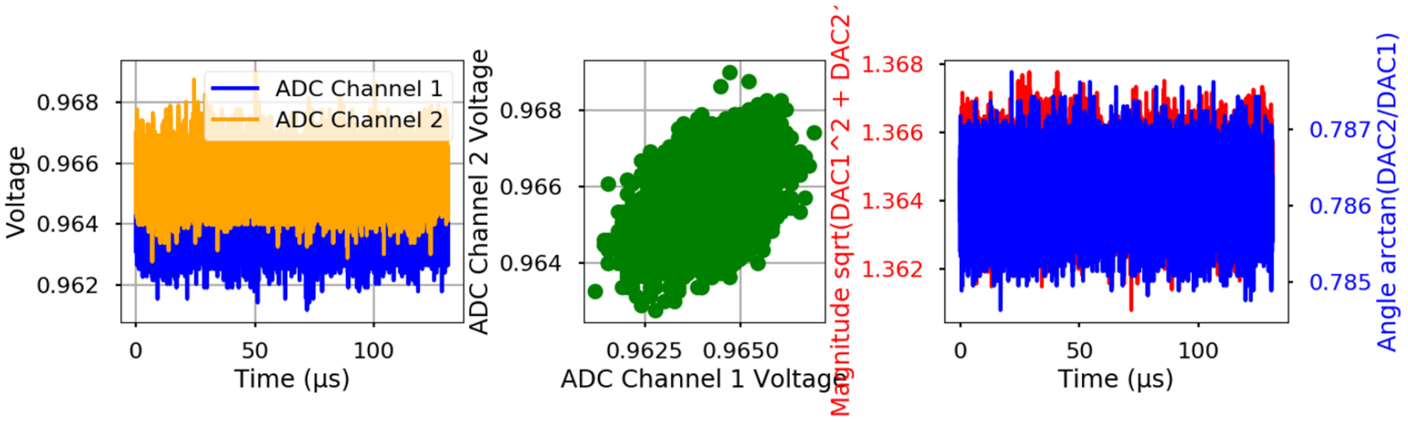


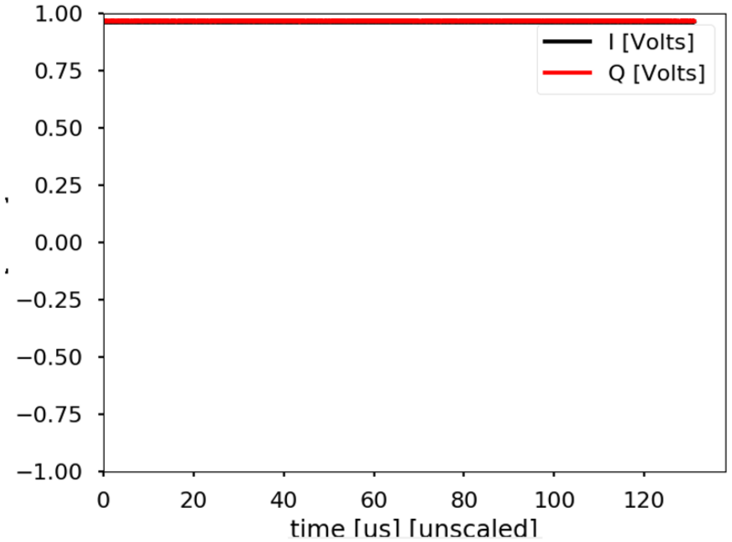
Mixer: RF Input Power ~ to LO Input Power

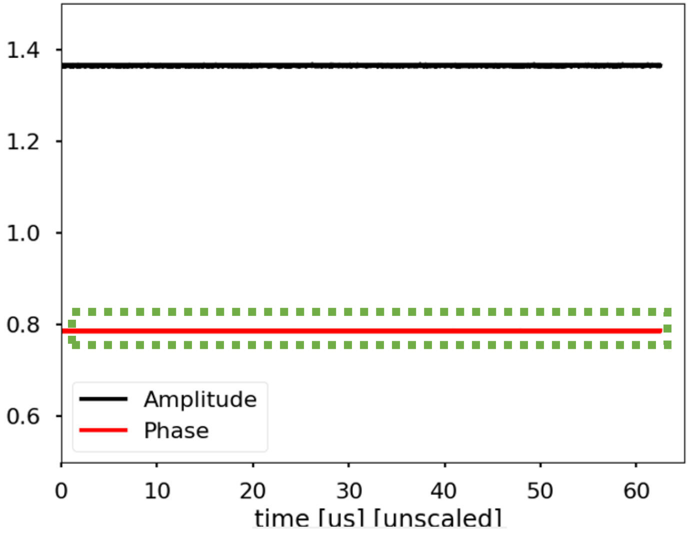


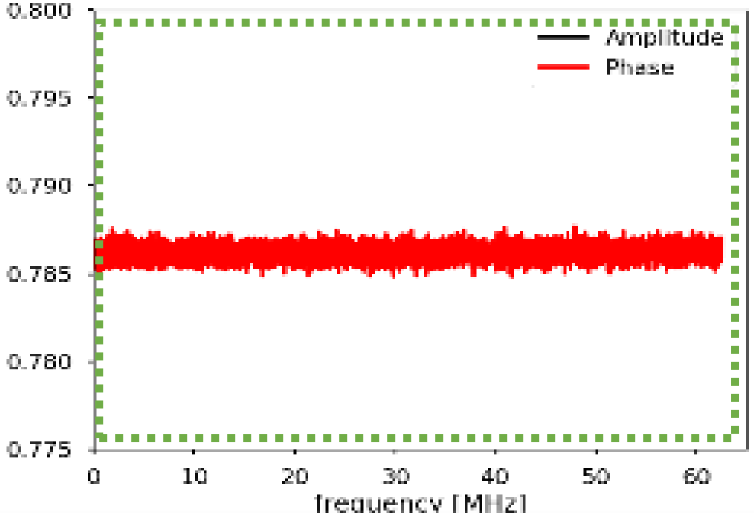
Mixer: Lower RF Input Powers

Characterisation of Homodyne Readout (ADCs)

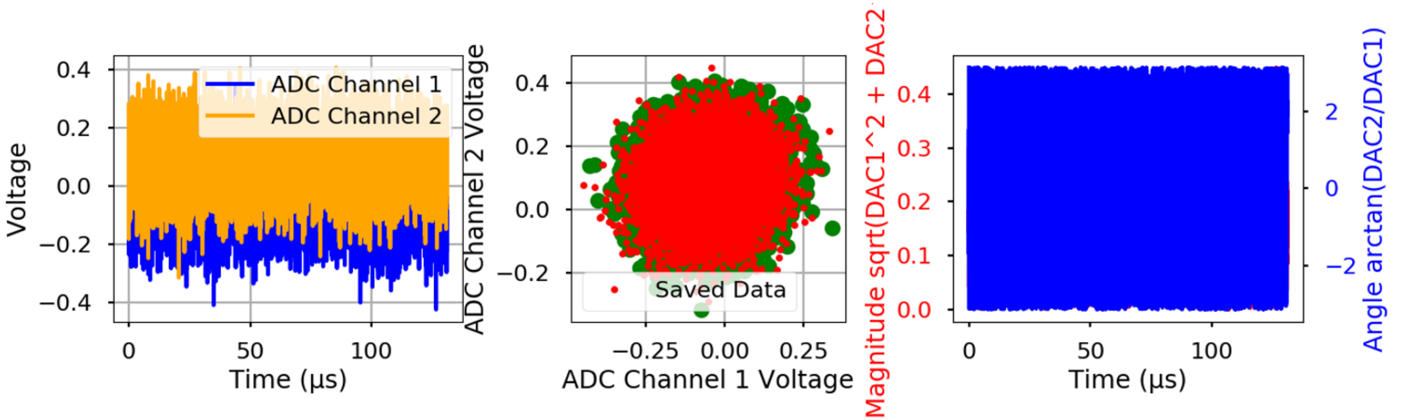


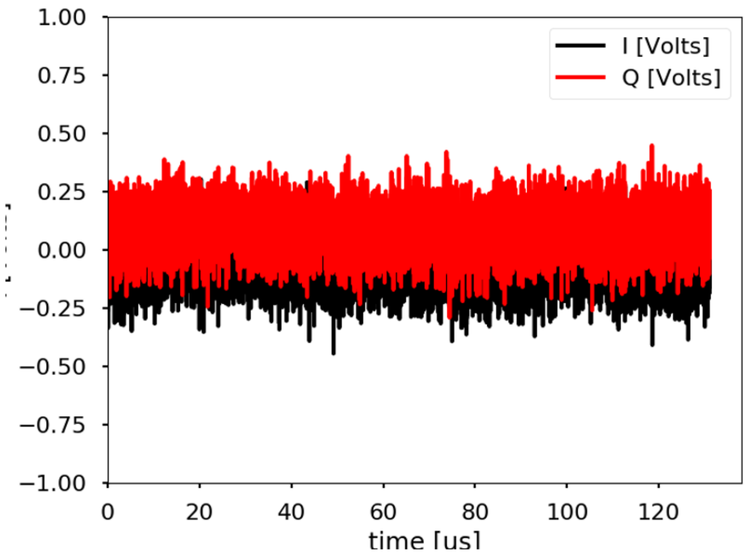


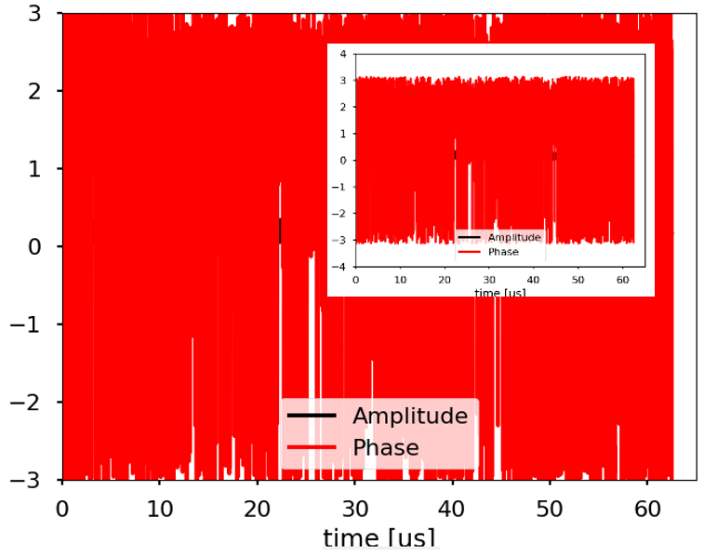




Characterisation of Homodyne Readout (Amps)





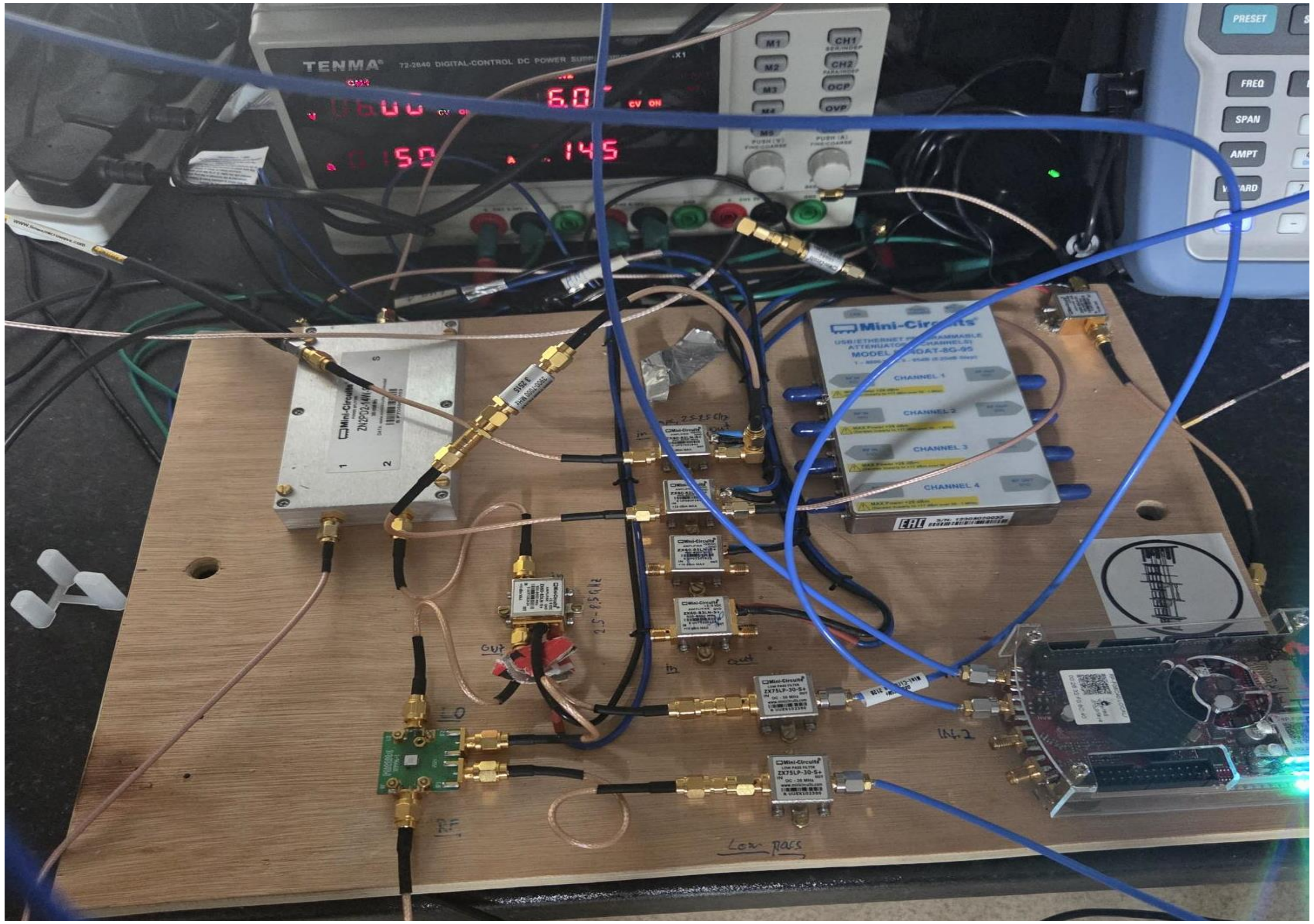


- Because we drive our resonators at extremely low powers (P ~ -90 dBm), we need a lot of amplification
- Need to daisy chain 3 room-temperature amps
- Huge noise introduced along the analogue signal line

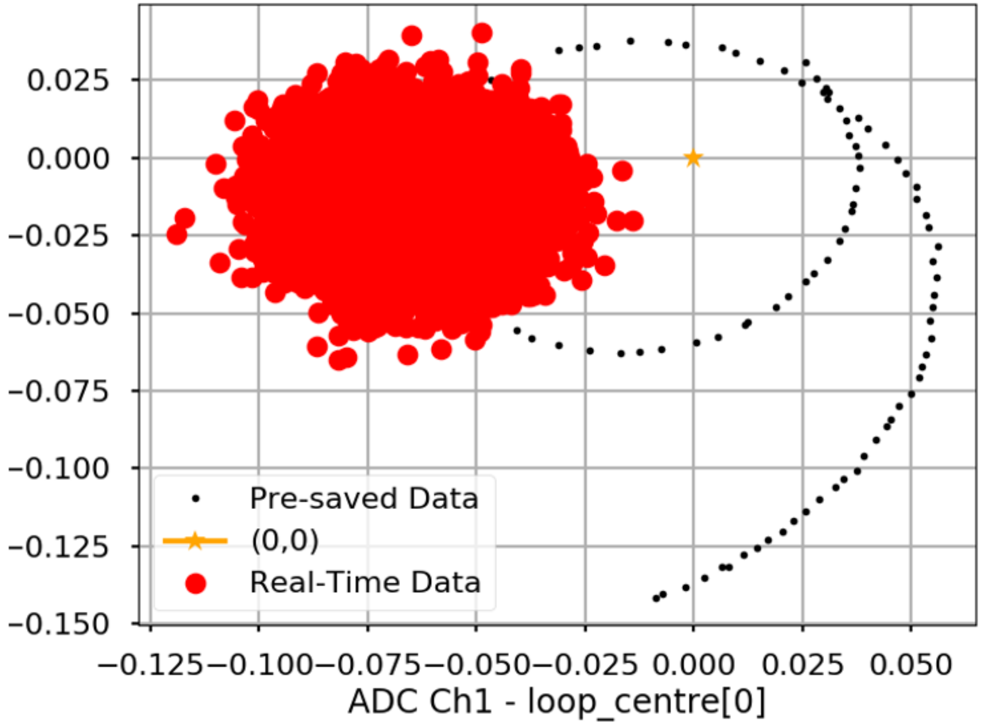
Optimisation of Homodyne Readout (Noise)

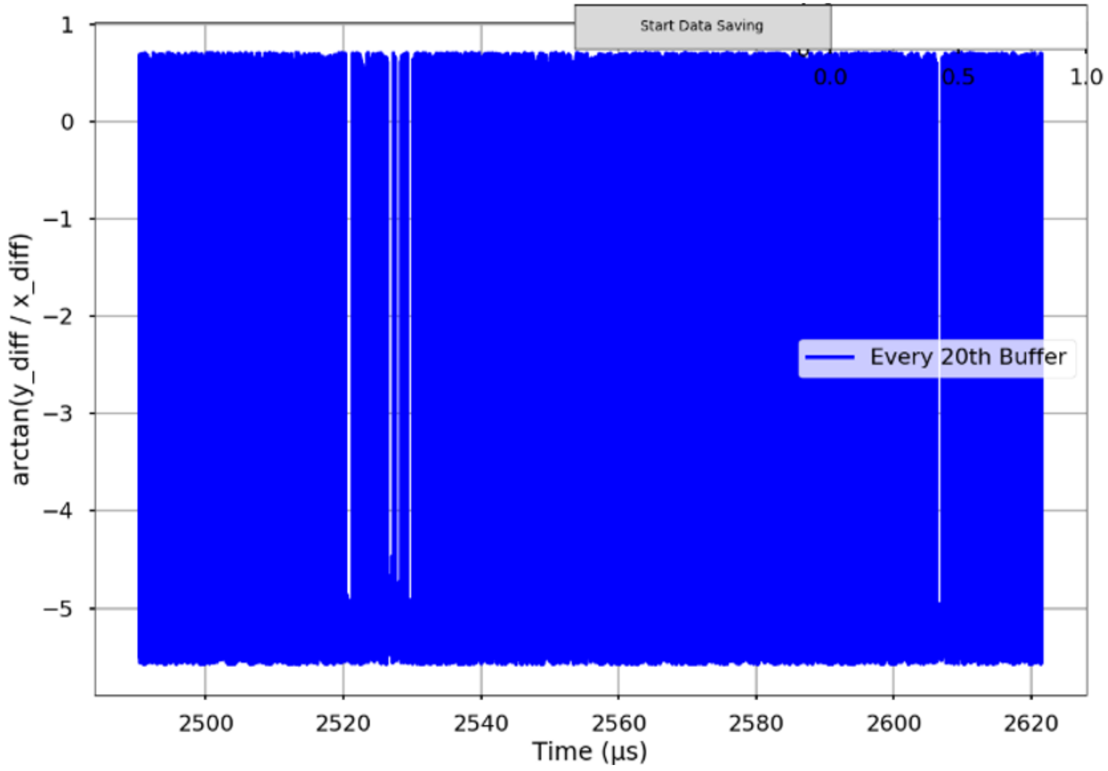
- We found that low frequency noise was being amplified in the amp chain
- - Simple high-pass filers before each amp

- We also found the mixer was leaking LO at high level
  - Required low-pass filters on down-converted DC signals (LO leakage from mixer).



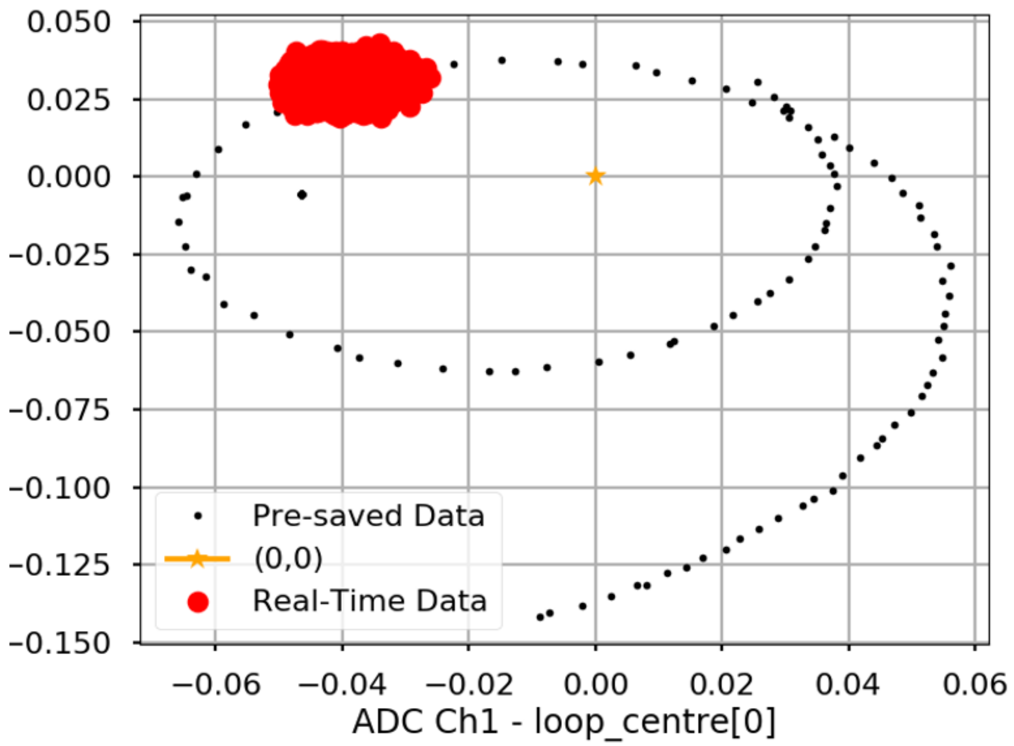
Optimisation of Homodyne Readout (Noise)

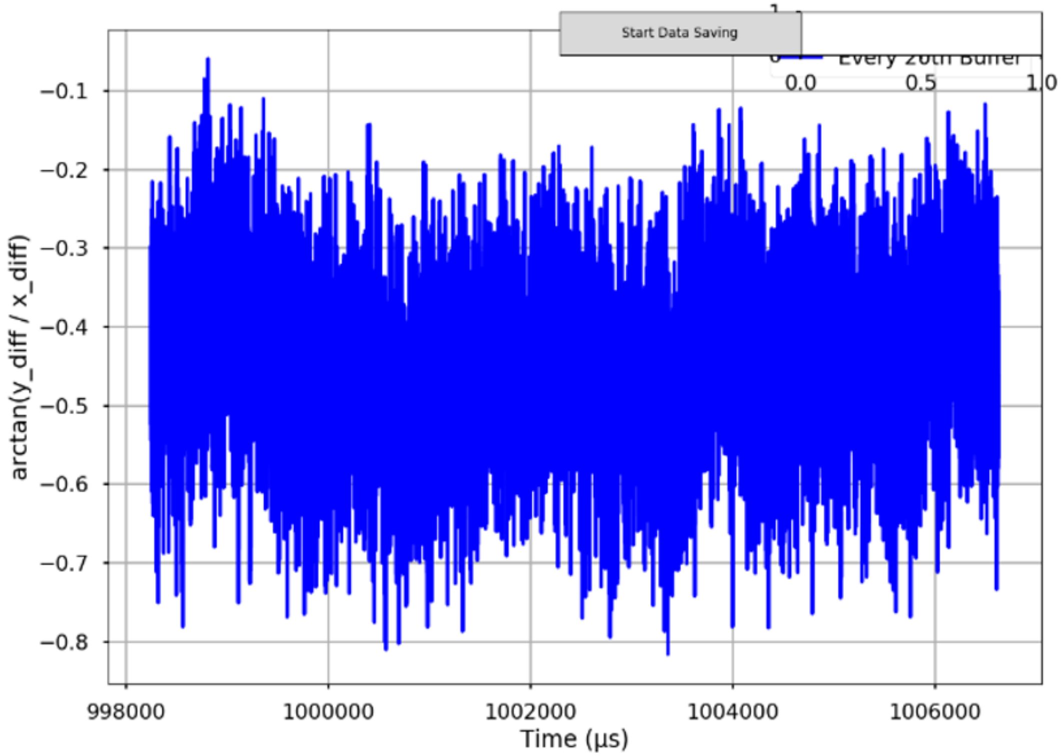




- Even after filtering of analogue signals, the noise was still dominating the signal, particularly in phase

Optimisation of Homodyne Readout (Noise)

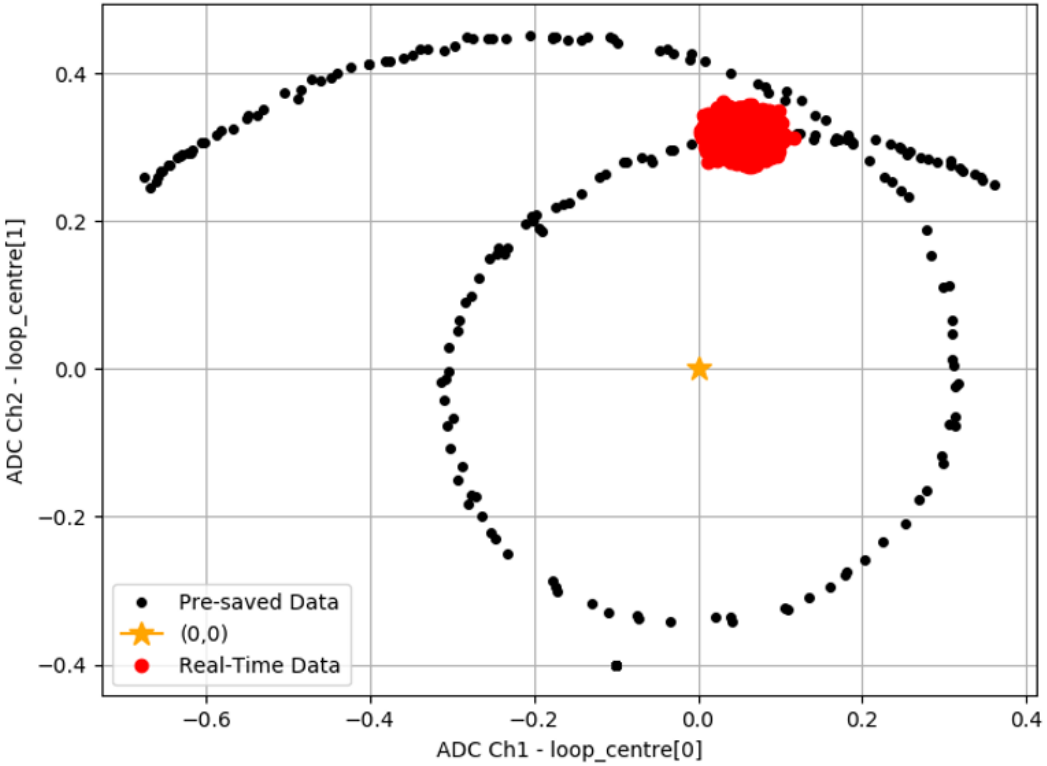


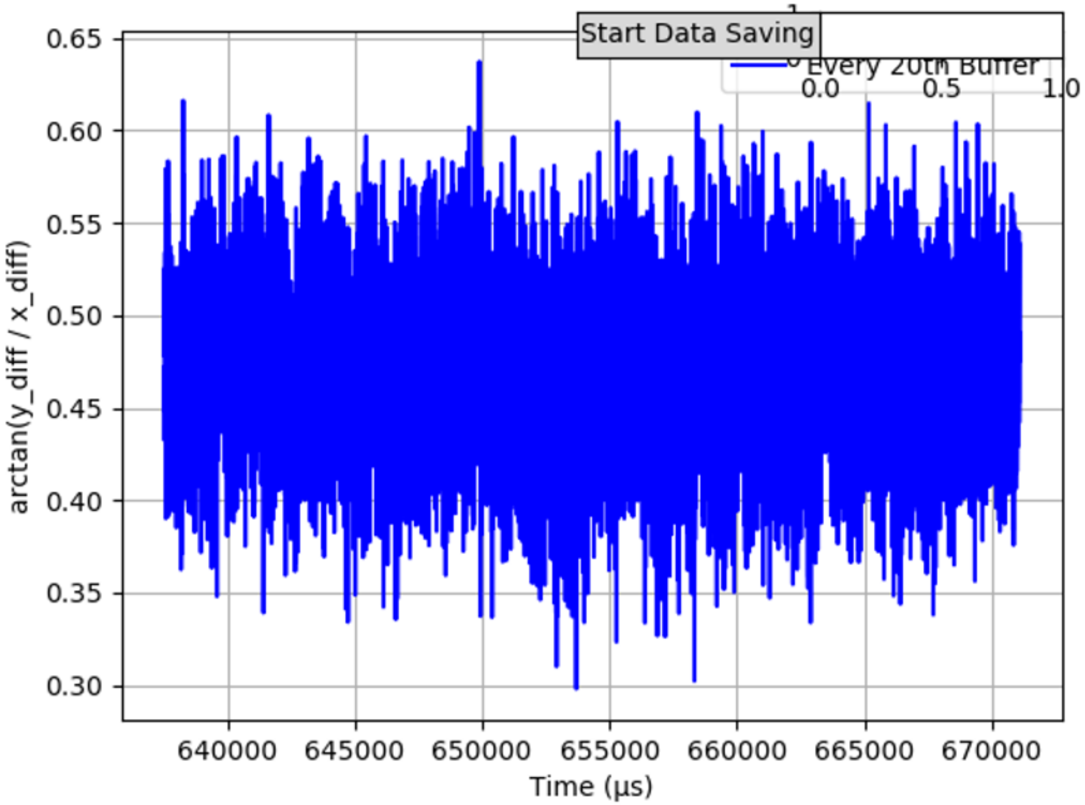


Decimation (averaging) set to 64

- Solution: The sampling speed of the ADCs is roughly 100 times faster than what we need (Sampling = 125 MSPS). So, decimate/average.

Final Results

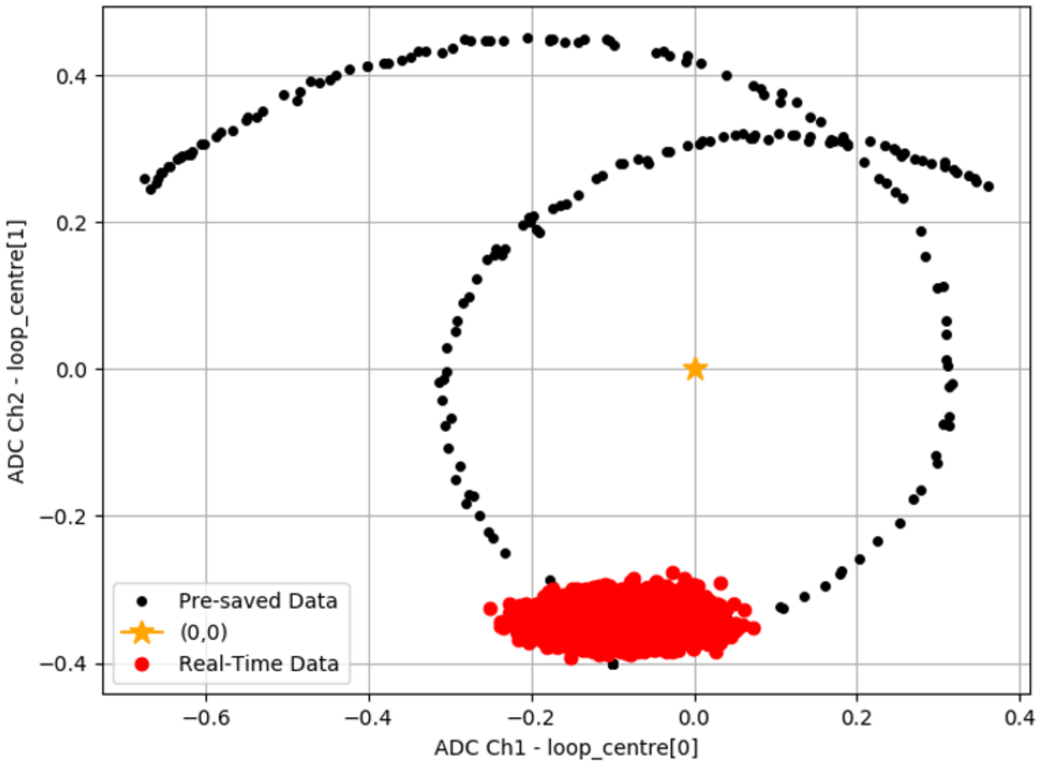


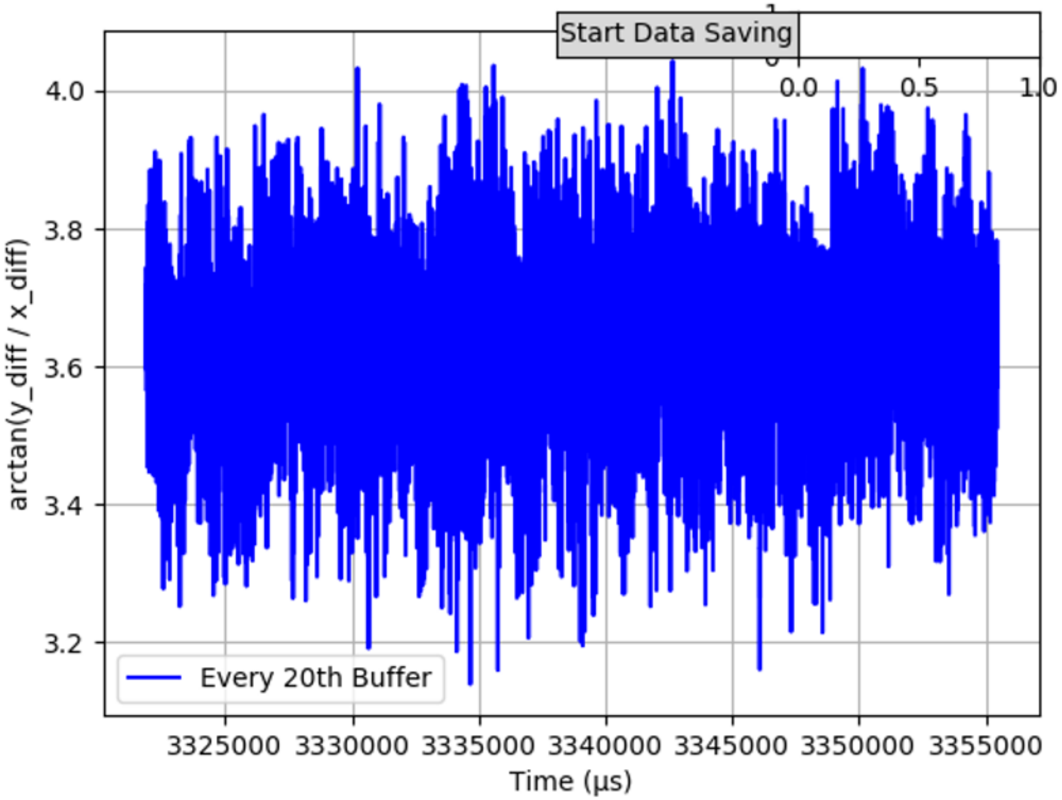


Decimation (averaging) set to 128

- Off resonance the noise cloud is now acceptably small.

Final Results of Readout

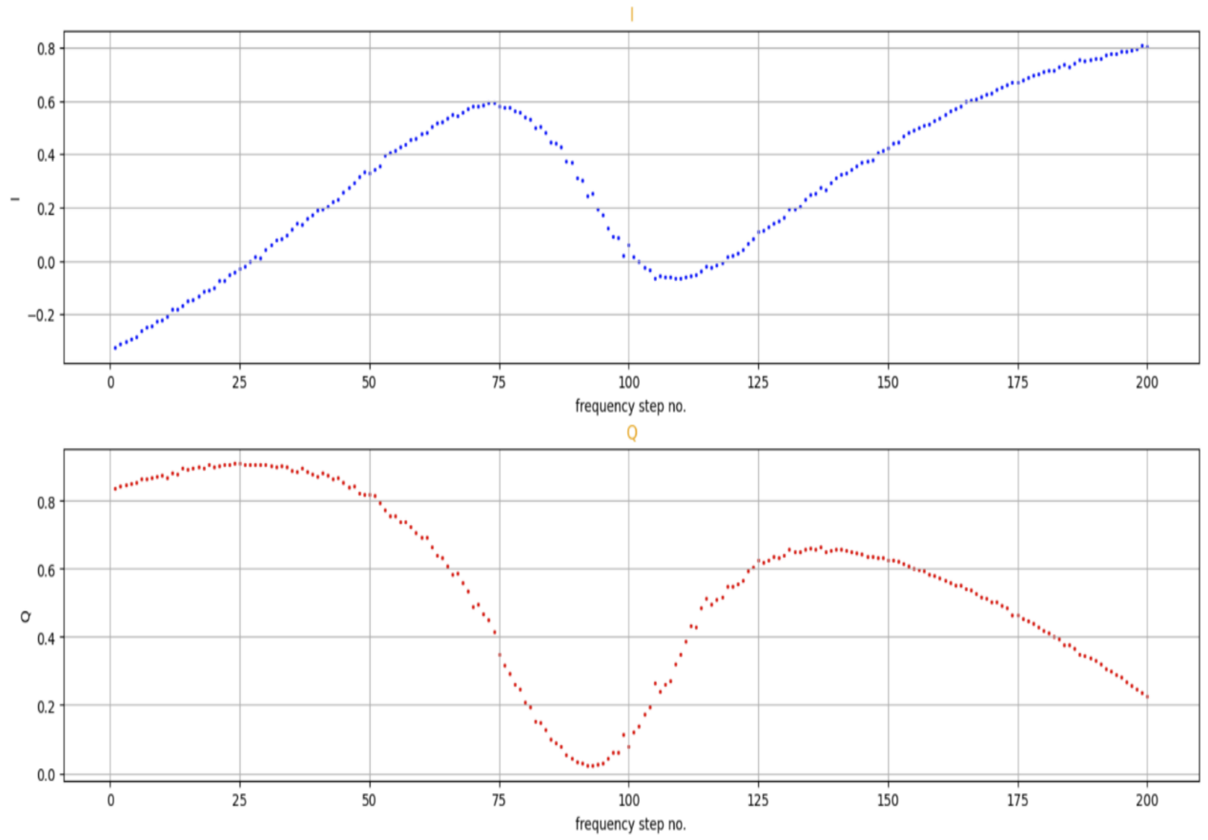


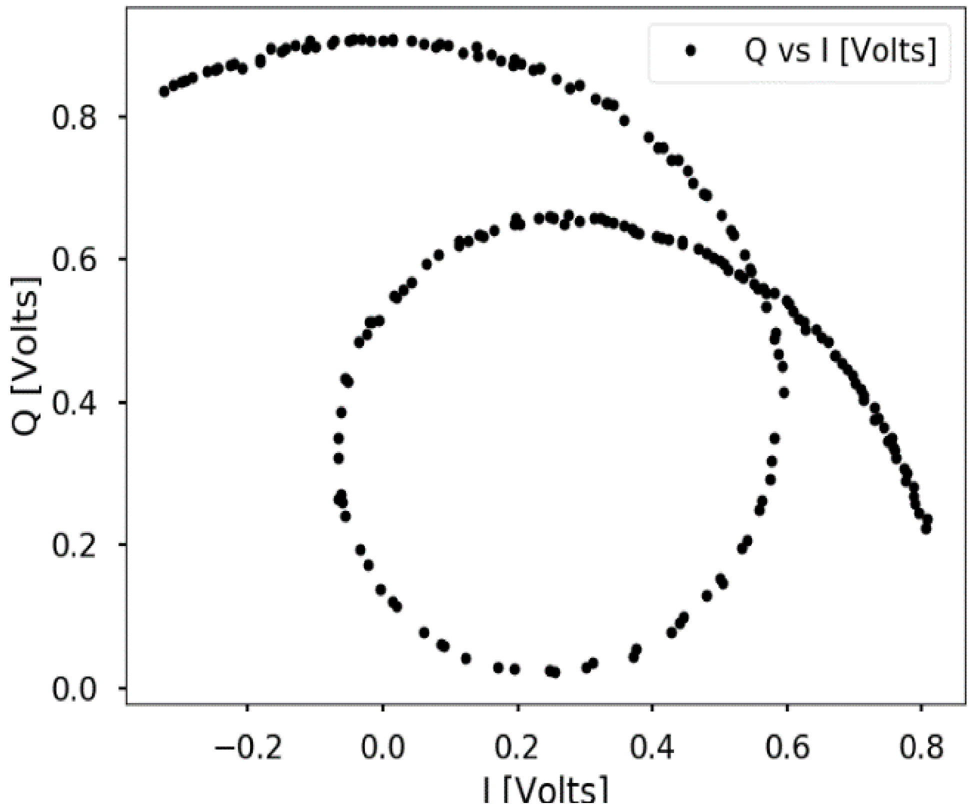


Decimation (averaging) set to 128

- On resonance the phase noise cloud is larger, but this is detector noise.

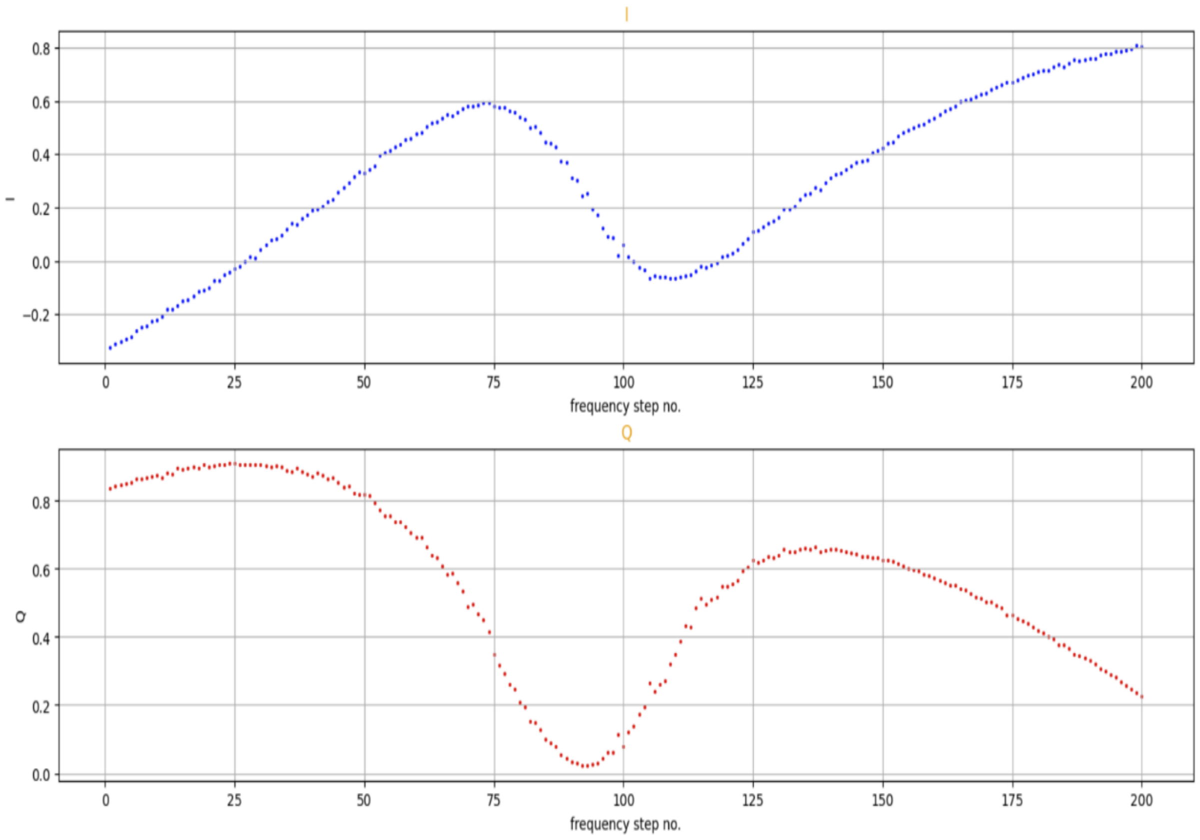
Operation of System: Step 1 – Sweep Mode

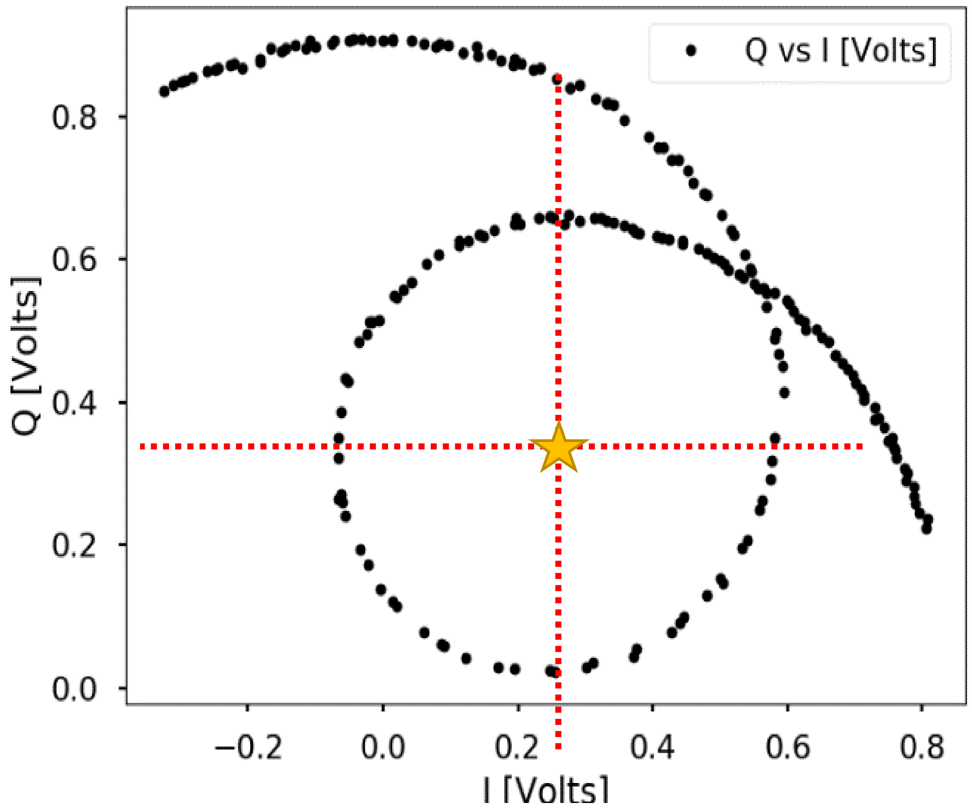




- Sweep frequency through ~ 5 MHz (sweep centred of f_r)

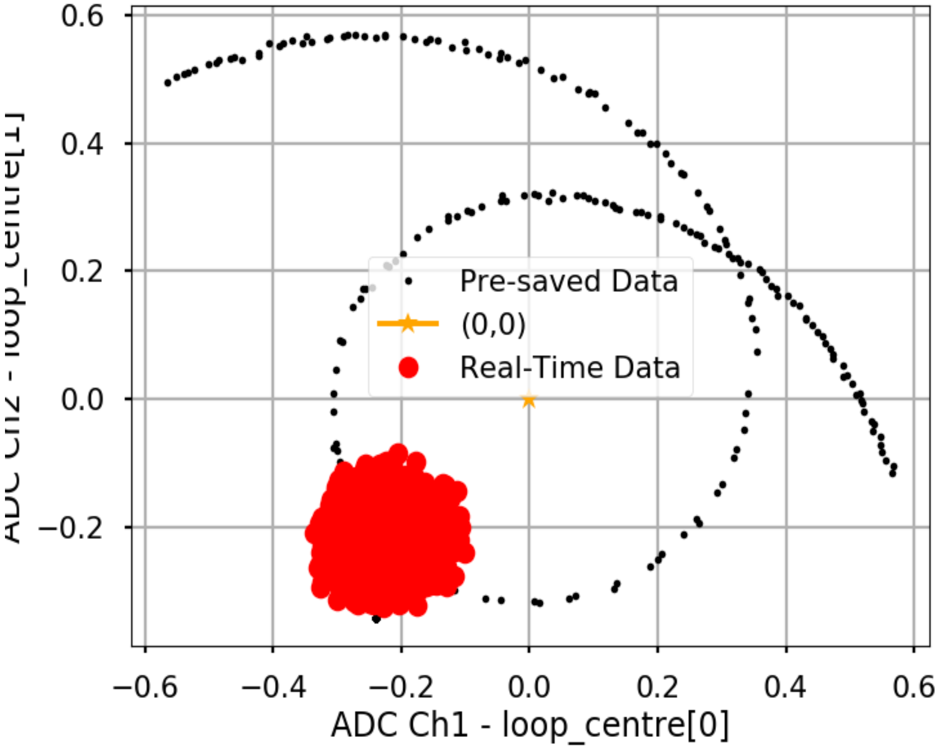
Operation of System: Step 1 – Sweep Mode

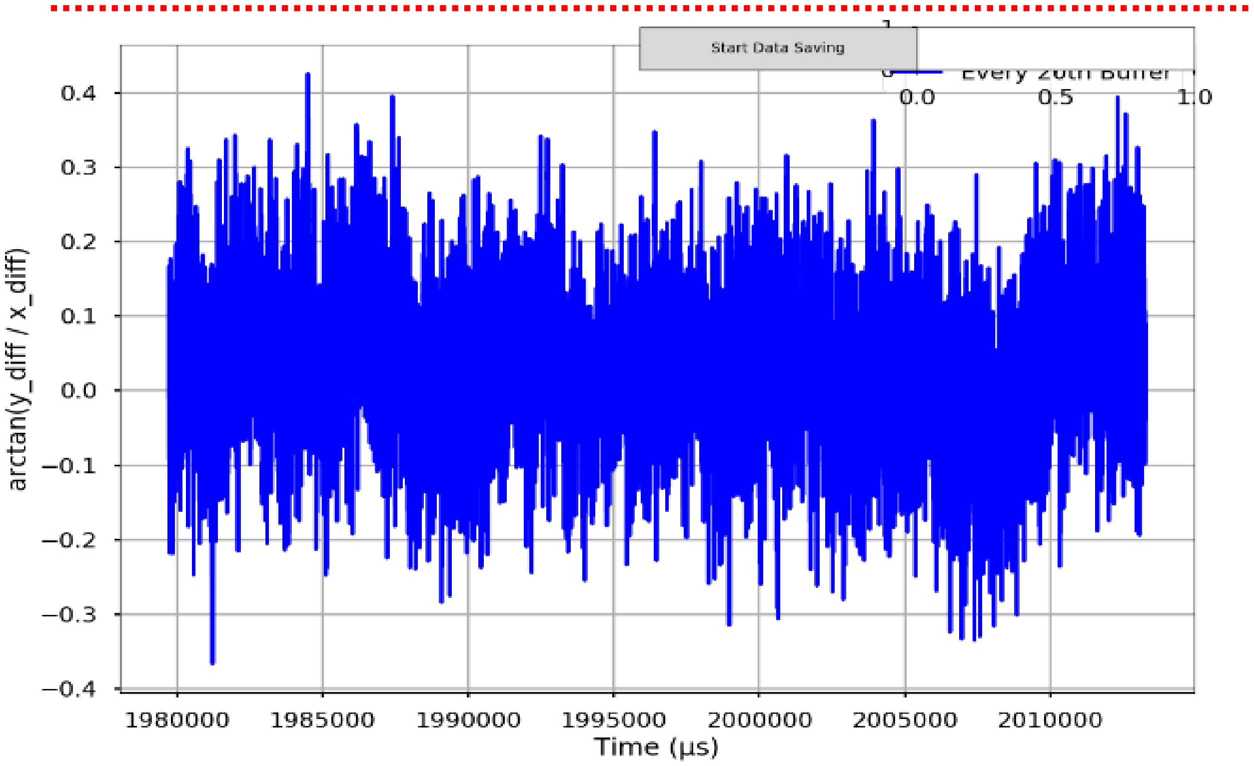




- Sweep frequency through ~ 5 MHz (sweep centred of f_r)

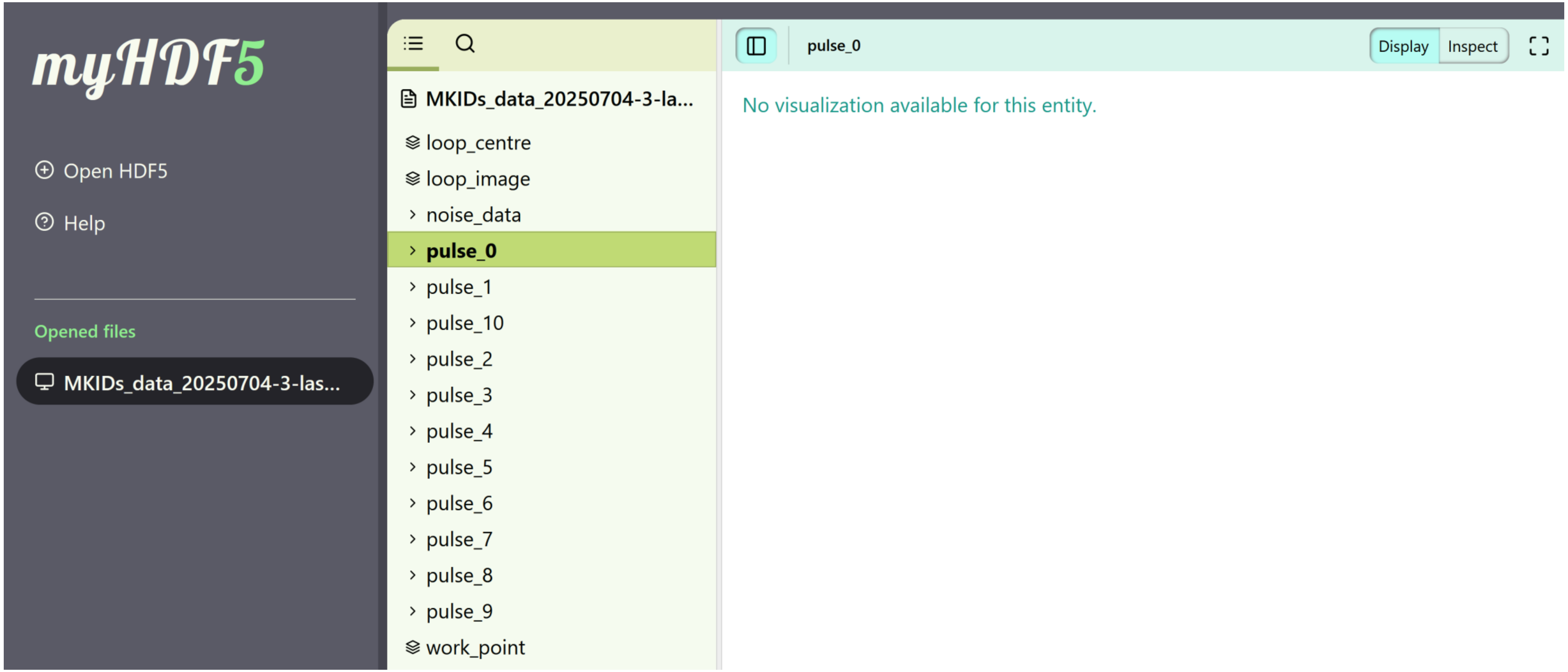
Operation of System: Step 2 – Pulse Mode



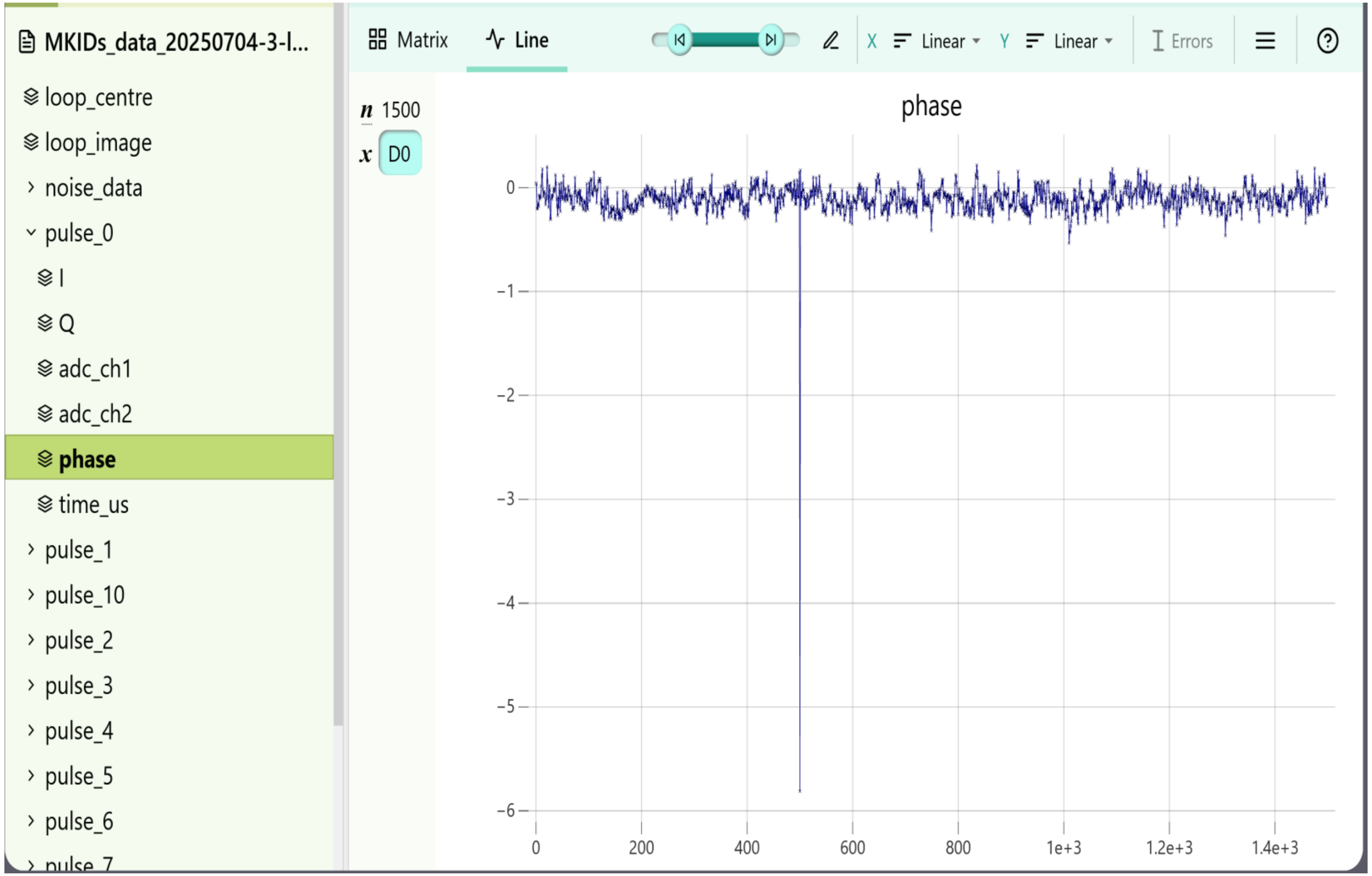


- Set trigger threshold value.
  If phase breaches threshold, data file written for each pulse (HDF5 format).

Pulse-Triggered Data Format



Pulse-Triggered Data Format



- Records '*n*' data points per file (*n* is user defined)
- Raw ADC1, ADC2 data file
- Re-normalised I, Q data
- **Phase 'vs' time data**
- Every nth (say, 20th) data buffer for real-time noise analysis

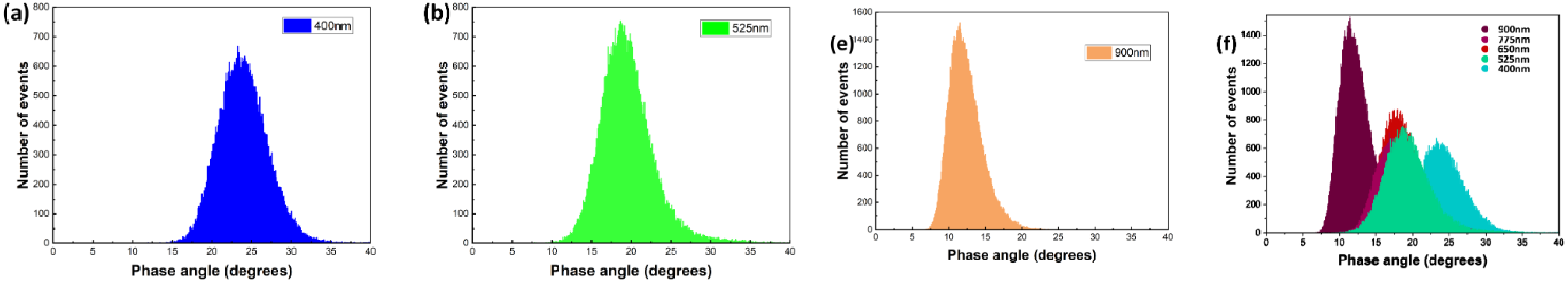
- Data shown here is artificial phase injection

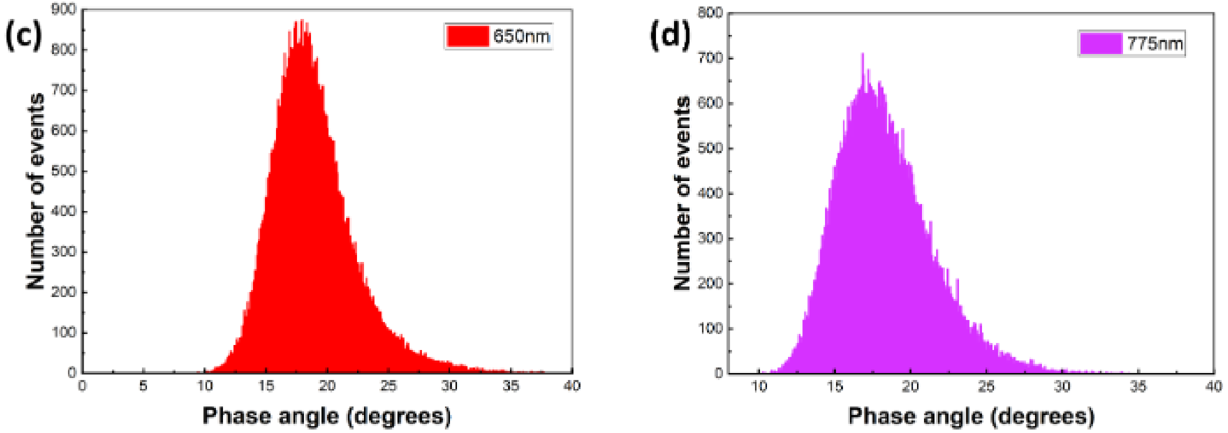
Summary/Conclusions

- Hardware component list and control software (python) will be made available on Github
- Easy access to readout system for prototype MKID devices
- Modular design with replaceable/updateable components
- System noise is below detector noise, as required
- Control software comes in two modules:
    - 1. VNA/Sweep mode: Sweep frequency to find resonator of choice
    - 2. Pulse mode: Monitor phase of a single probe frequency, and write data file if phase threshold is triggered.

Supplemental Slides

Detector Results





wavelength (nm)	Resolving Power
400nm	3.14
525nm	3.01
650nm	2.60
775nm	2.57
900nm	2.45

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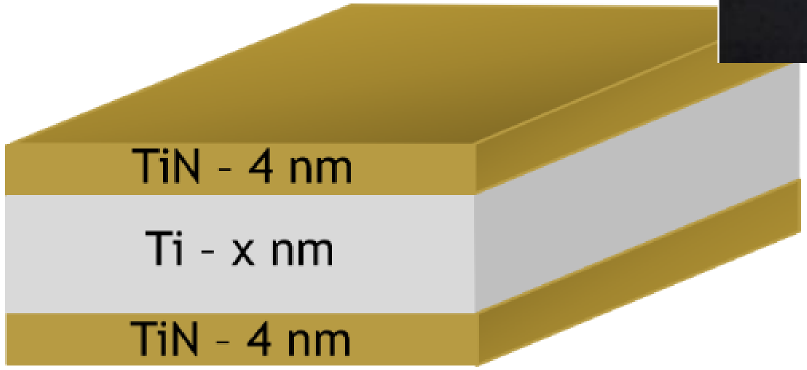
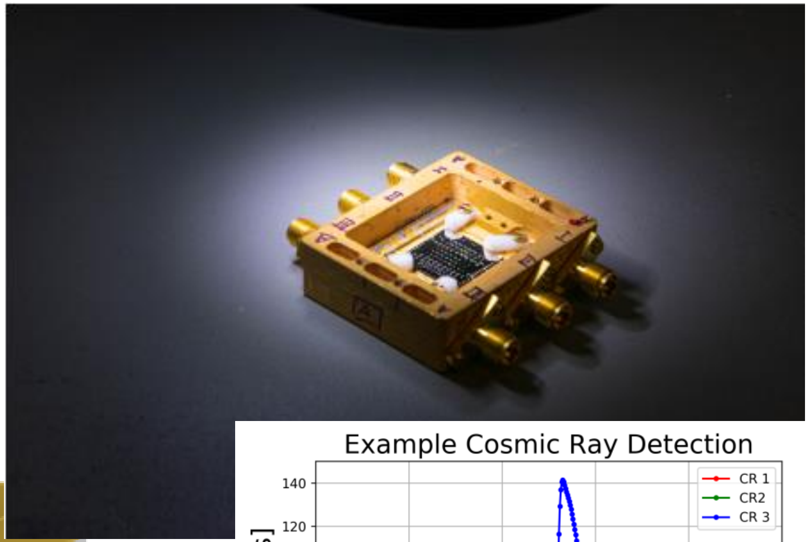
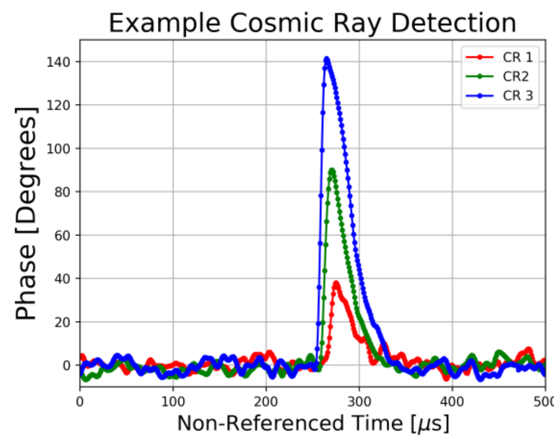
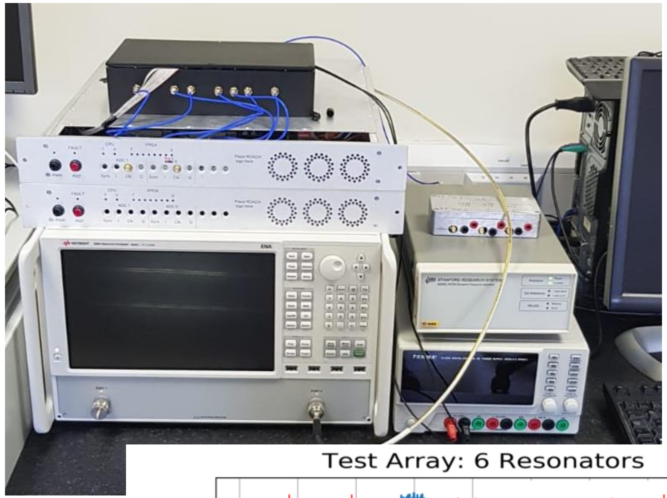
New Camera for Finding Exoplanets

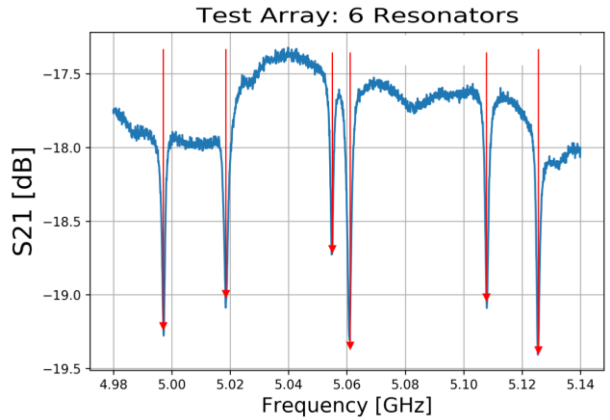
Superconducting Materials for Better Instruments





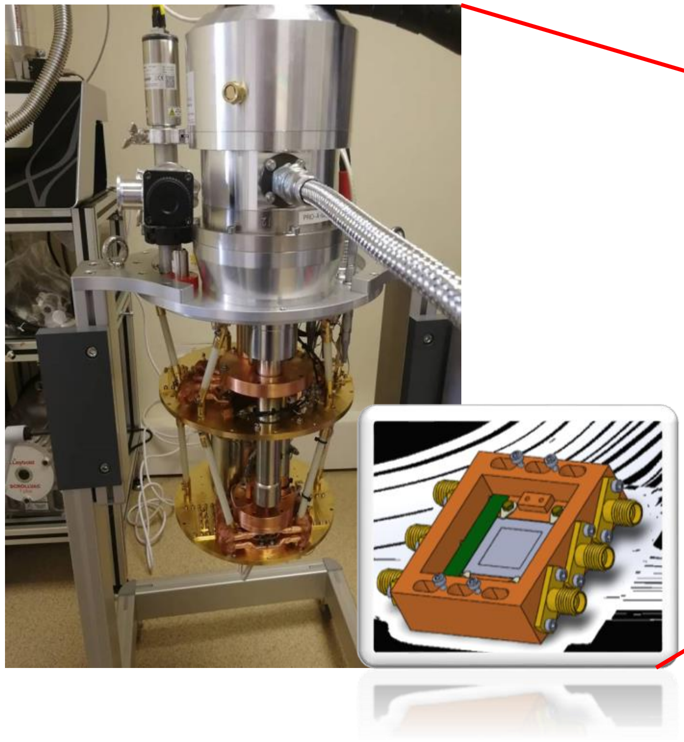






Plans for Applications for our MKID Instrument

- Our future (albeit optimistic) plans, will ideally see our future arrays on large class observatories such as the E-ELT, with <u>coronagraph and advanced AO</u>



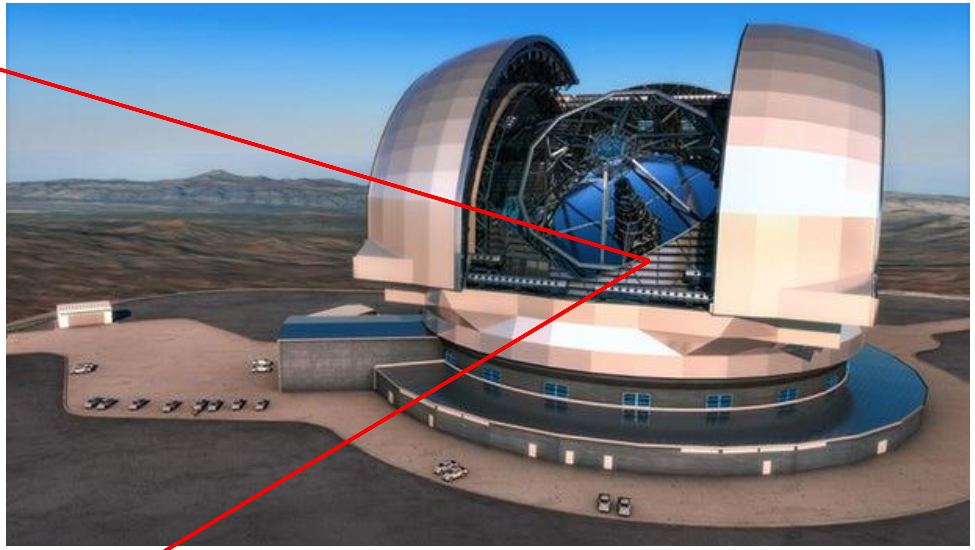
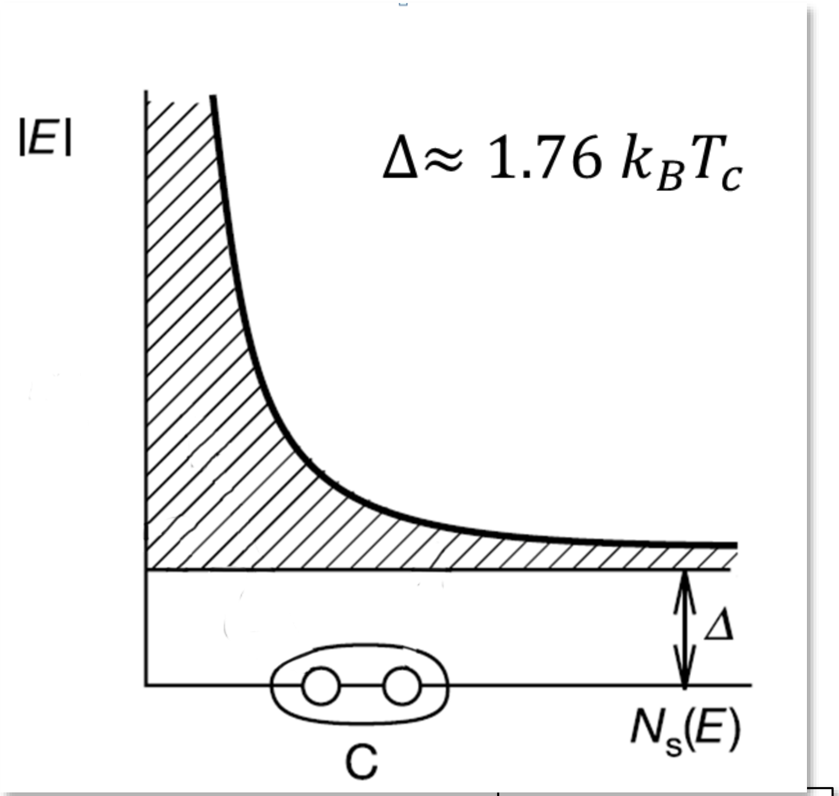


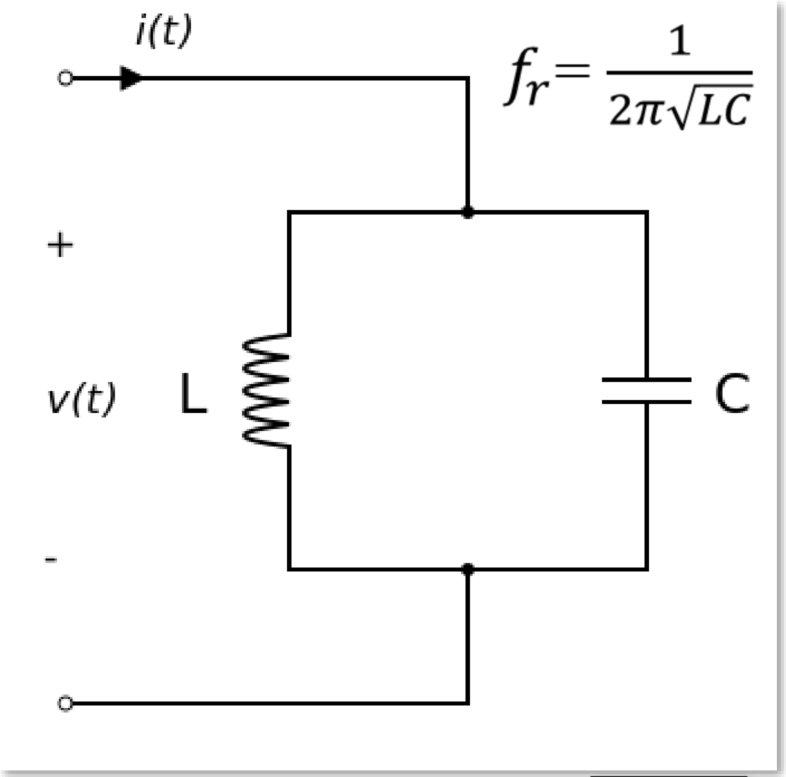
Image credit: ESO

Ireland officially joined ESO in September, 2018

- MKIDs are <u>superconducting</u> detectors
- Current transport without resistance
- Energy gap Δ for Cooper pair splitting is about 4 orders of magnitude smaller then e.g. the band gap in Si



P. Day et. al., Nature 425, 817



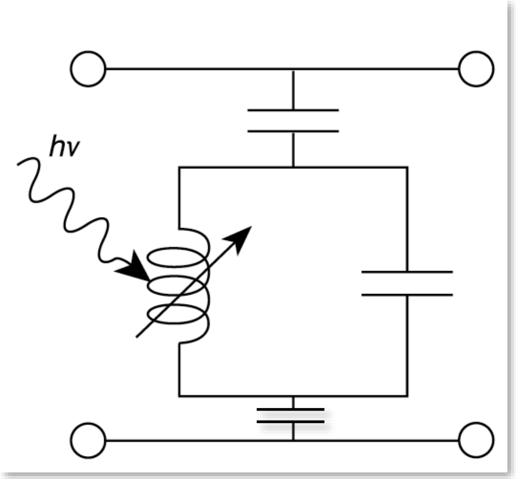
Wikipedia

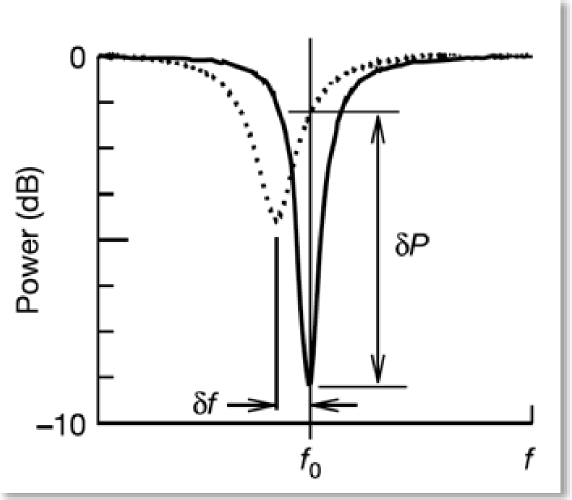
- No electrical fields → Can't operate like a CCD
- Instead: LC resonator (tank circuit): Classic harmonic oscillator with well defined resonant frequency f_r

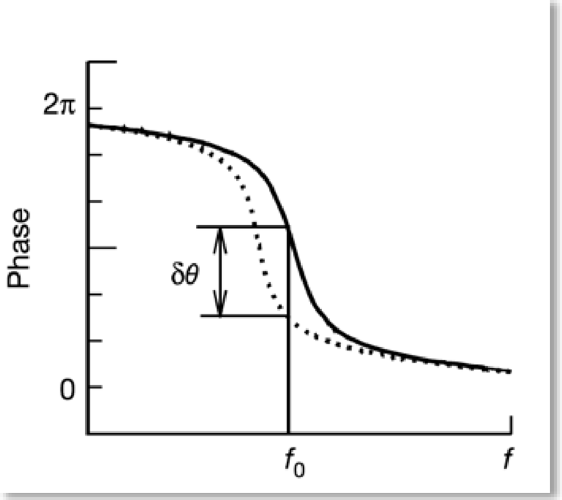
MKIDs are superconducting LC resonators:

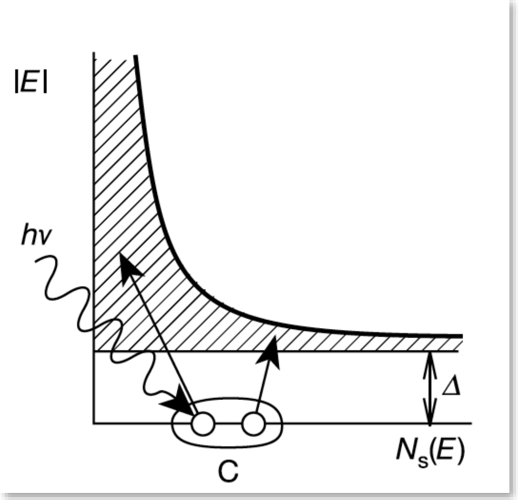
- Photon absorption breaks many Cooper pairs.
- Lower charge carrier concentration
  → higher Cooper pair velocity
  → higher kinetic inductance
  → $\Delta L_{total} > 0$ → ***$\Delta f_r < 0$***

- We are only monitoring at a single frequency!

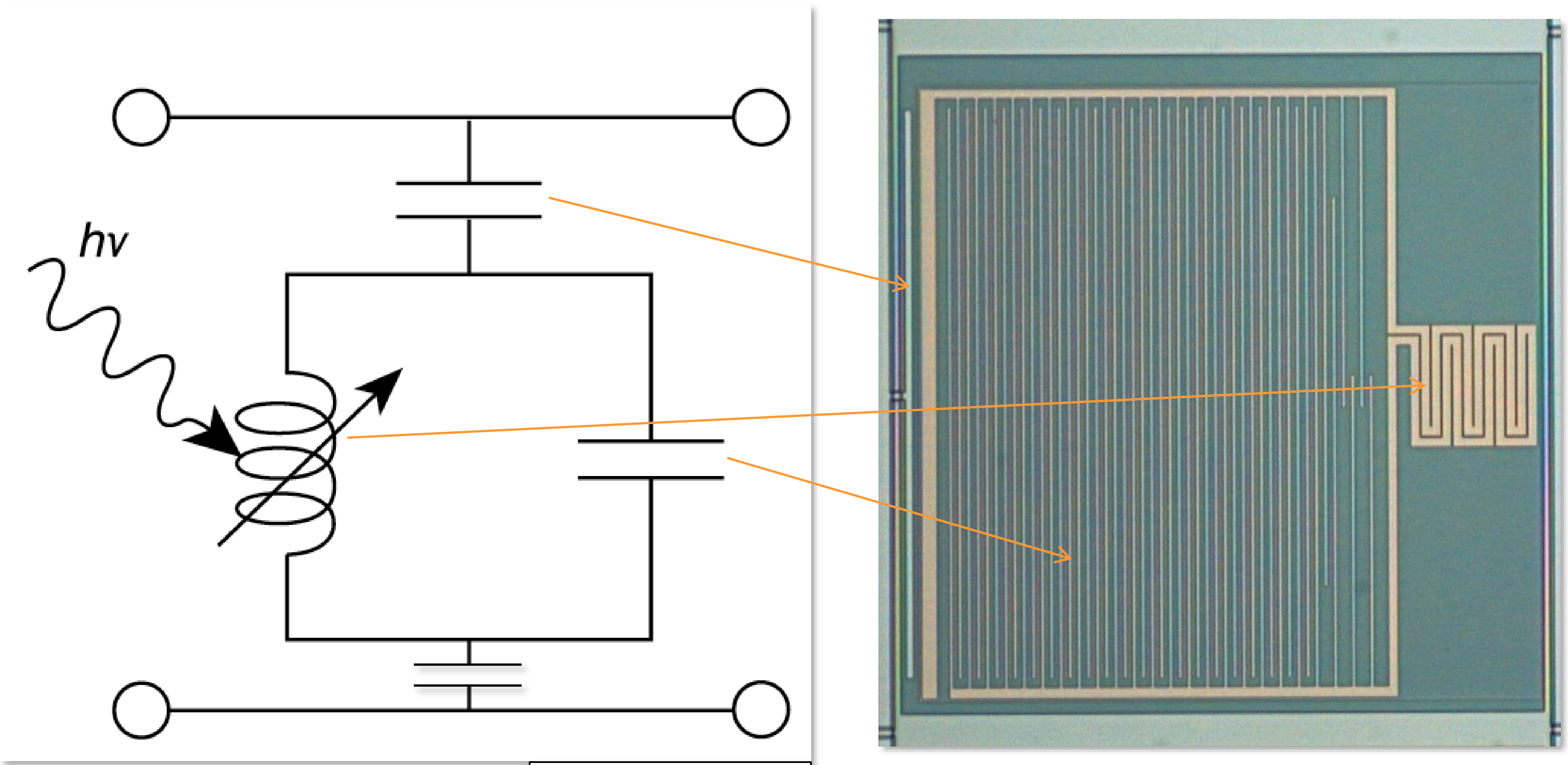








P. Day et. al., Nature 425, 817



P. Day et. al., Nature 425, 817

- Substrate: High resistivity silicon or sapphire.
- A square microlens array focuses the photons on the inductor and improves the effective fill factor to > 90%

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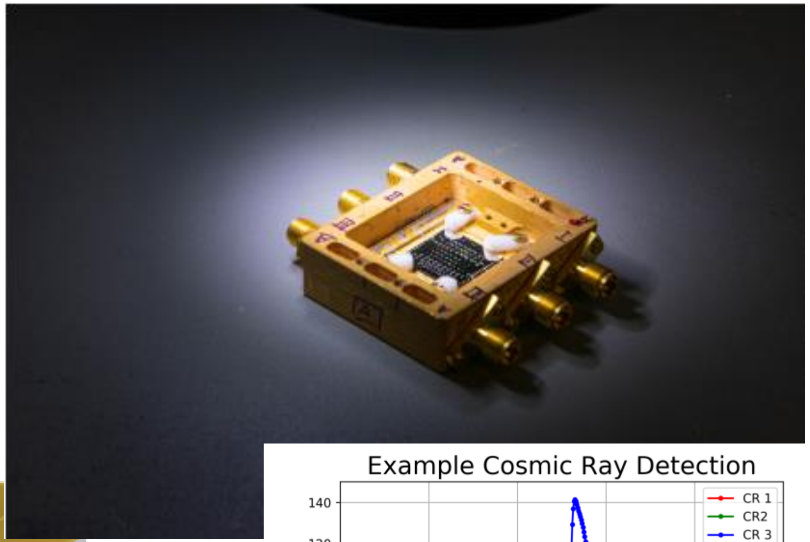
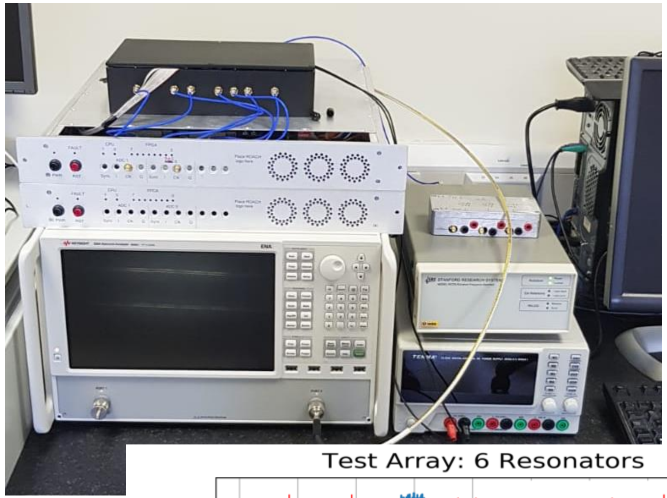
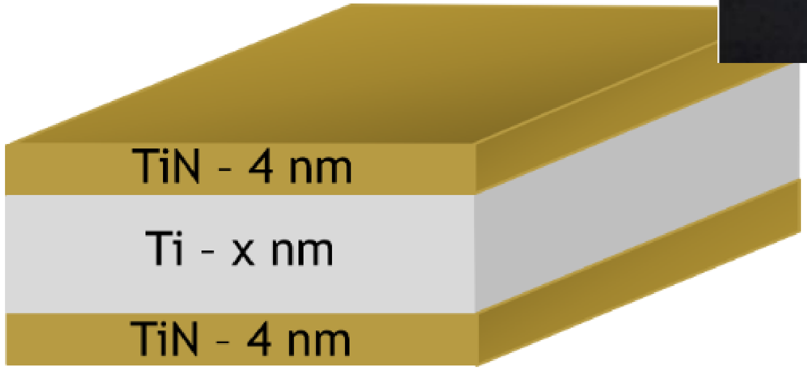
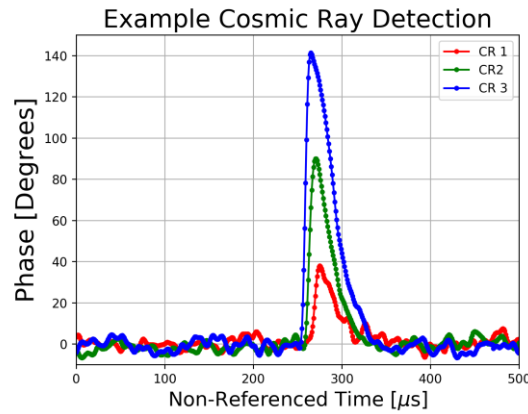
New Camera for Finding Exoplanets

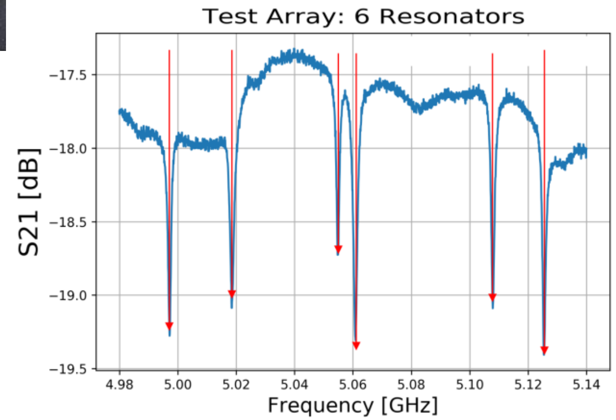
Superconducting Materials for Better Instruments











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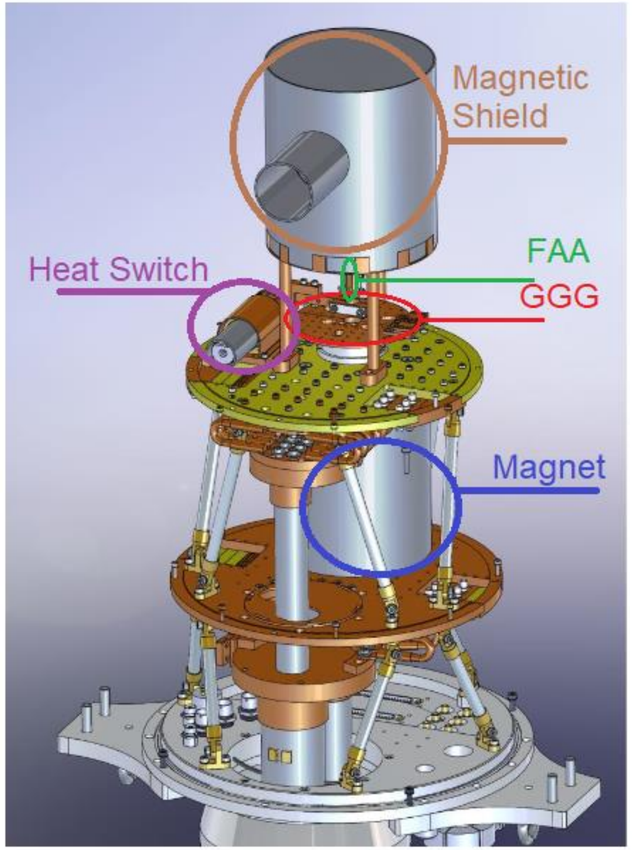

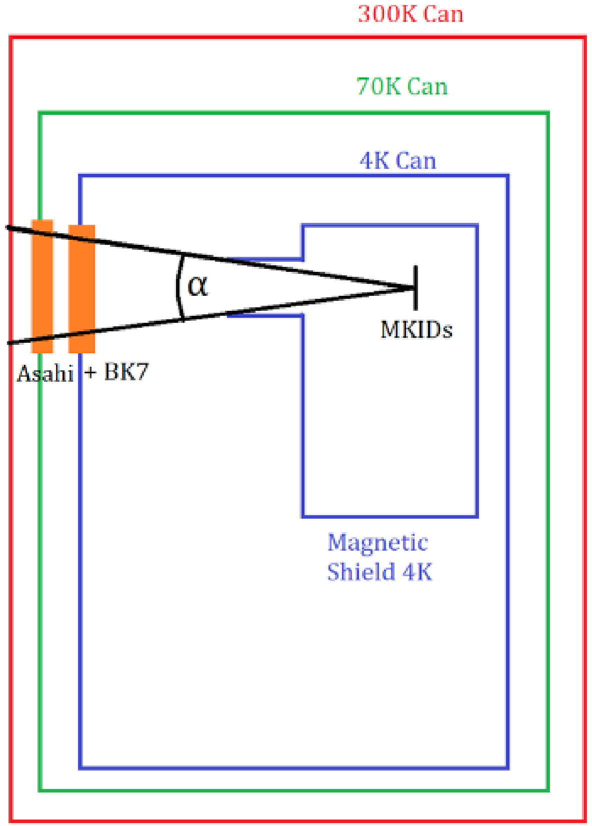

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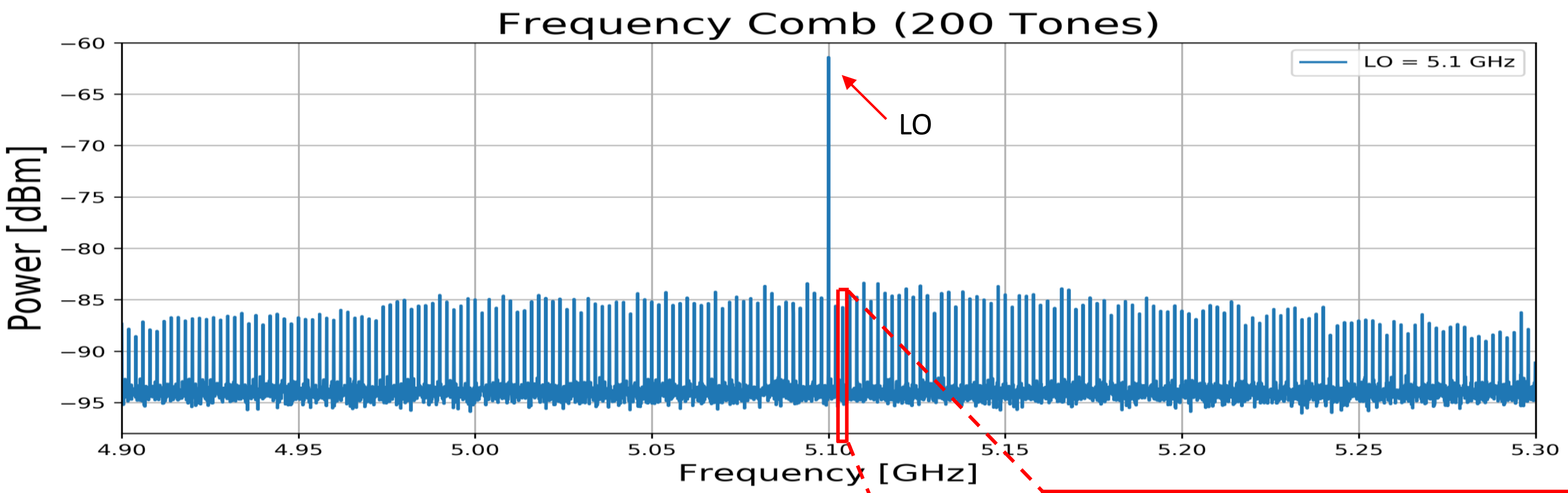
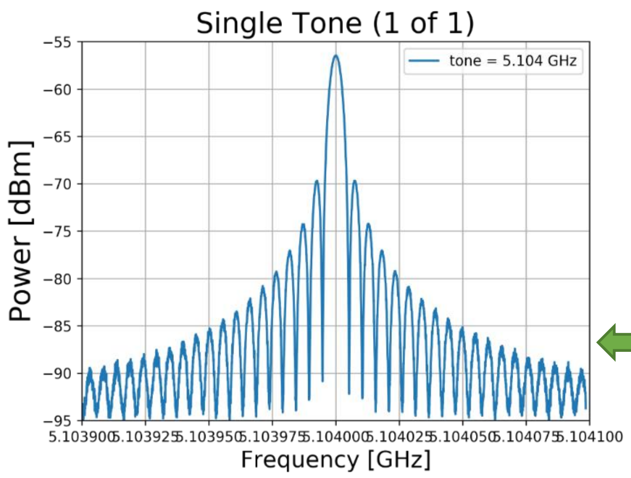
National University of Ireland Maynooth

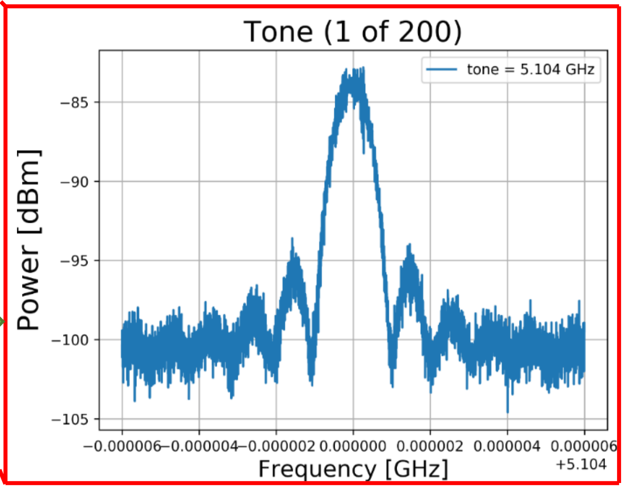
Tone Stability & Noise Reduction



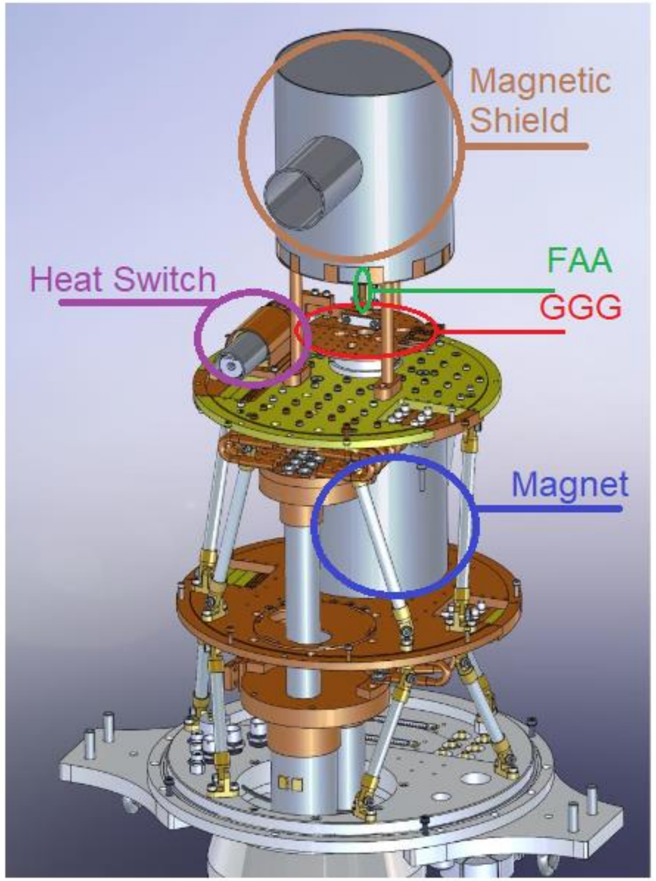


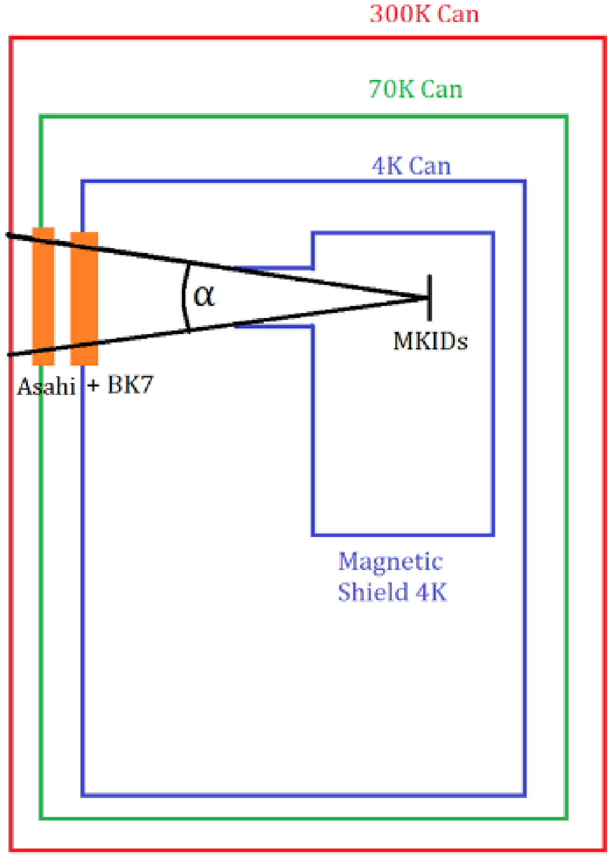
Each ROACH and DAC can output 256 tones with ~ -86 dBm per tone

~ -58 dBm for single tone



Ongoing Tests, Measurements, and Calibration





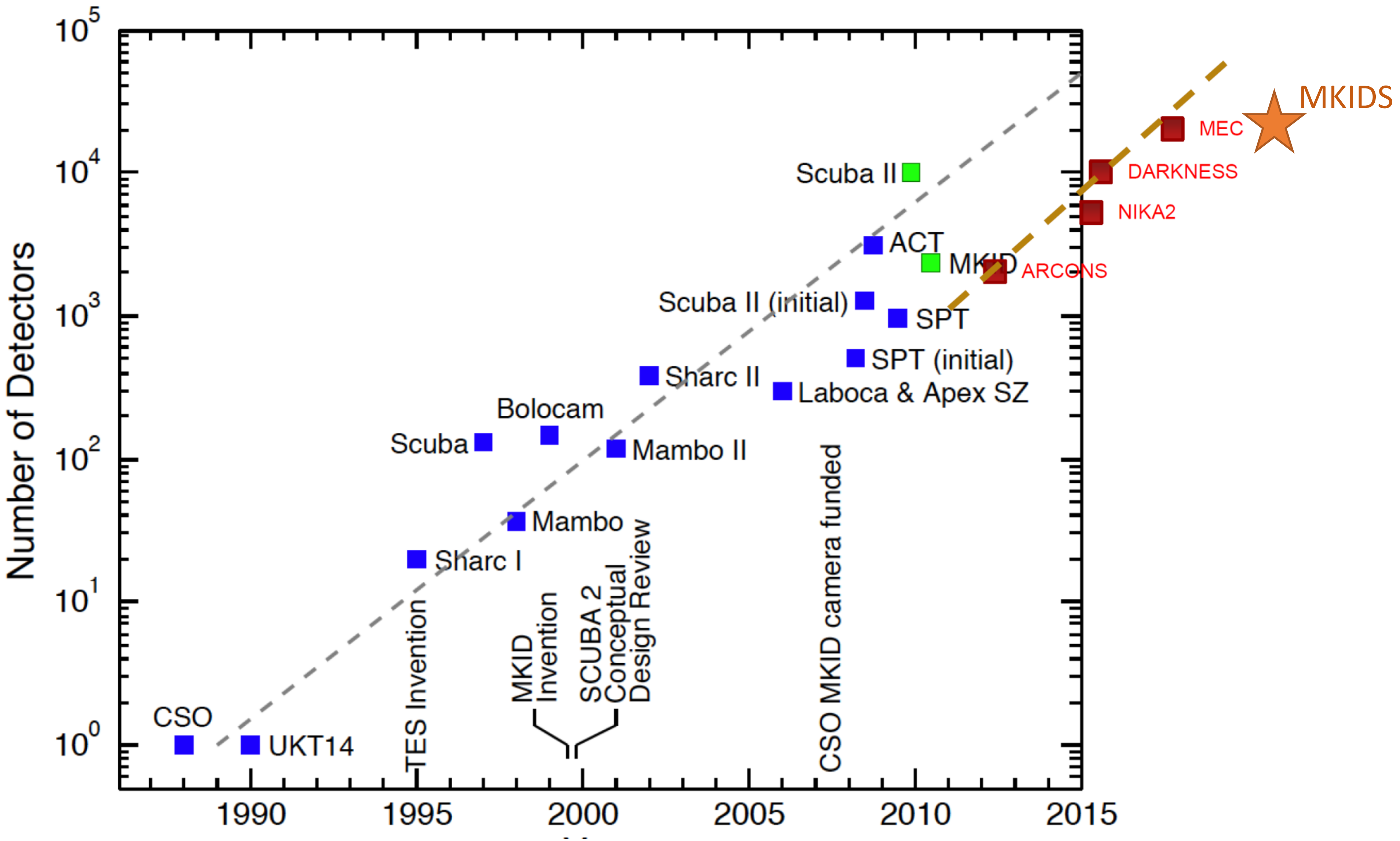
Material

$T_C \approx 0.8\ K$

Operation

$T_{op} \approx 0.1\ K$

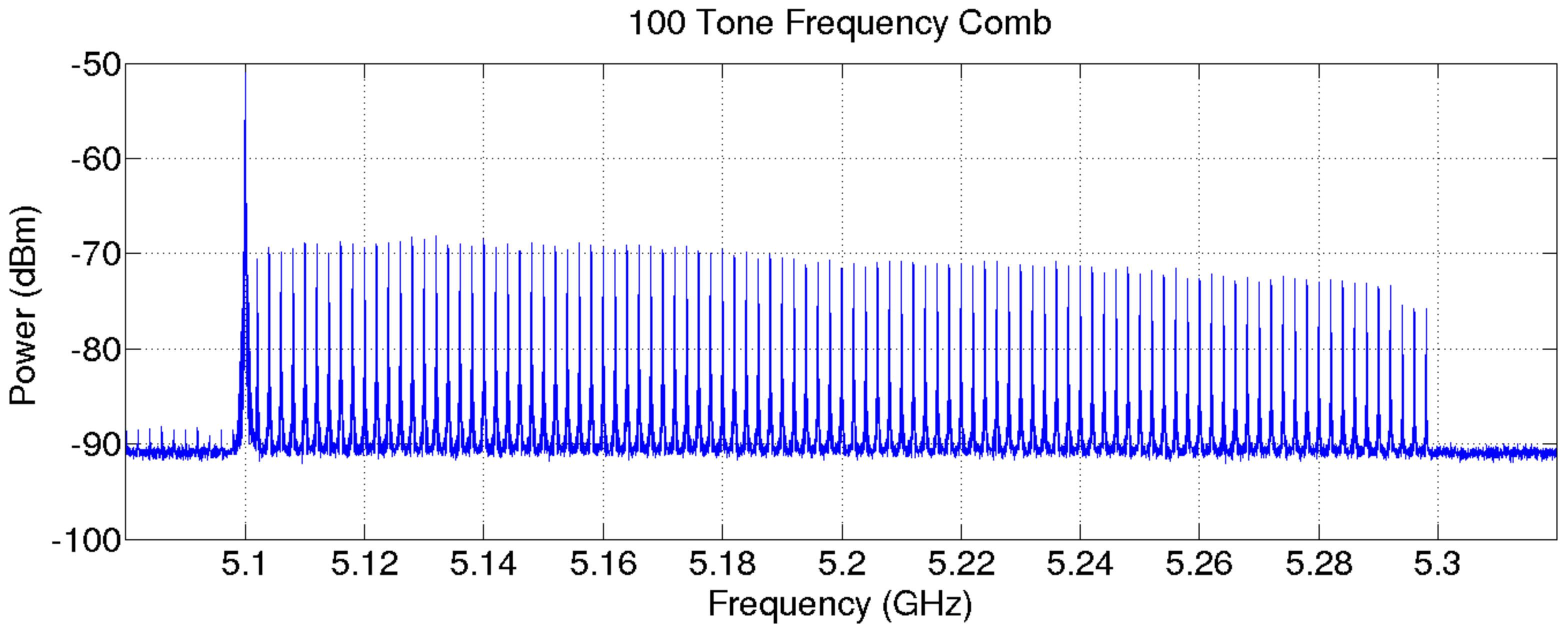
MKIDS at DIAS



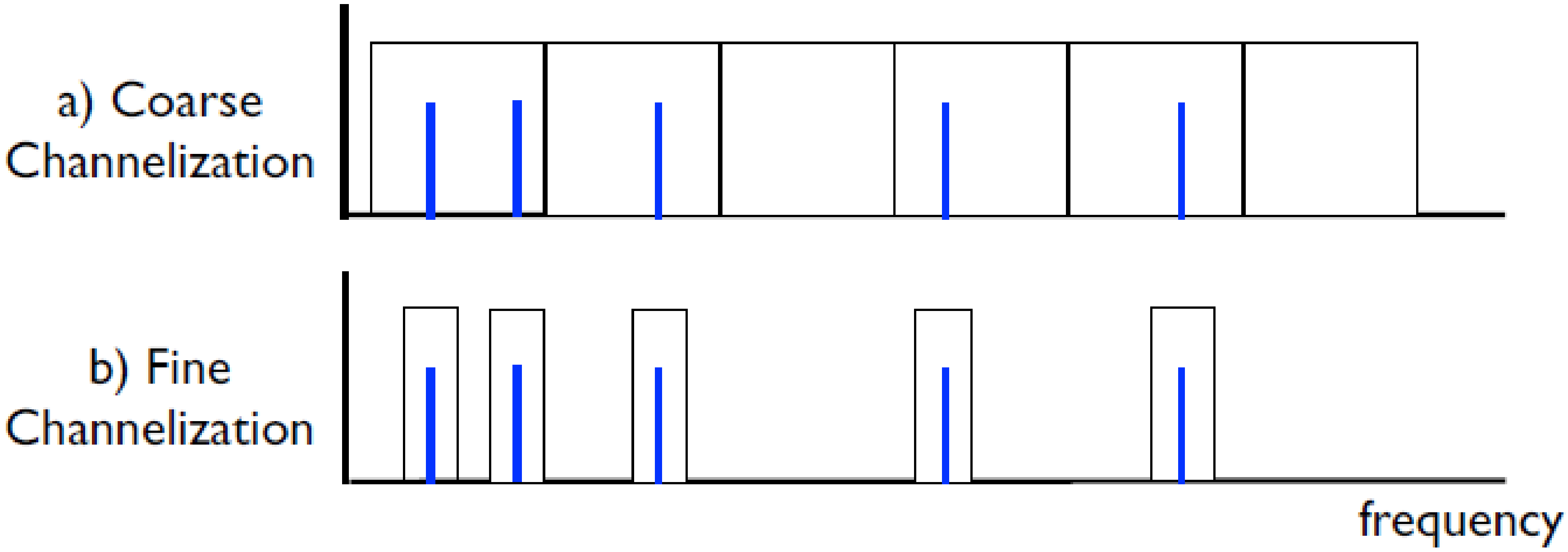
Original plot from J. Zmuidzinas
Modified from B. Mazin

MKID Readout

- Frequency comb is generated and up-mixed to pixel frequencies.
- Tones pass through MKIDs, exciting resonators.
- Detectors imprint phase and amplitude changes on resonant probe tones from photon event.
- Output tones are down-mixed and digitized.
- Down-mixed data is separated into individual channels by Field Programmable Gate Array (FPGA).



Channelization



P. Strader, PhD Thesis, UCSB, 2016.