COSMO fast readout system

Mario Zannoni
University of Milano Bicocca
Italy

In collaboration with:
Massimo Gervasi, Andrea Passerini,
Andrea Limonta, Giulia Conenna
and Stefano Meinardi

Cosmic Microwave Background (CMB)

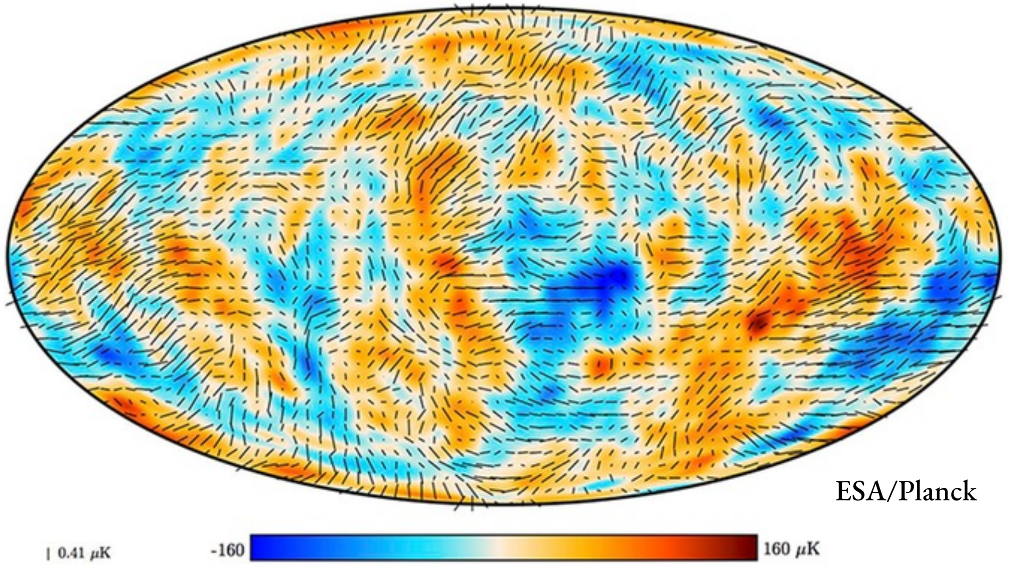
Discovered by Arno Penzias and Robert Wilson in 1965

→ important evidence of the Big Bang theory and ΛCDM model

- blackbody spectrum at 2.7260±0.0013K [Fixen, 2009]

What we measure:

B-modes polarization → cosmological inflation

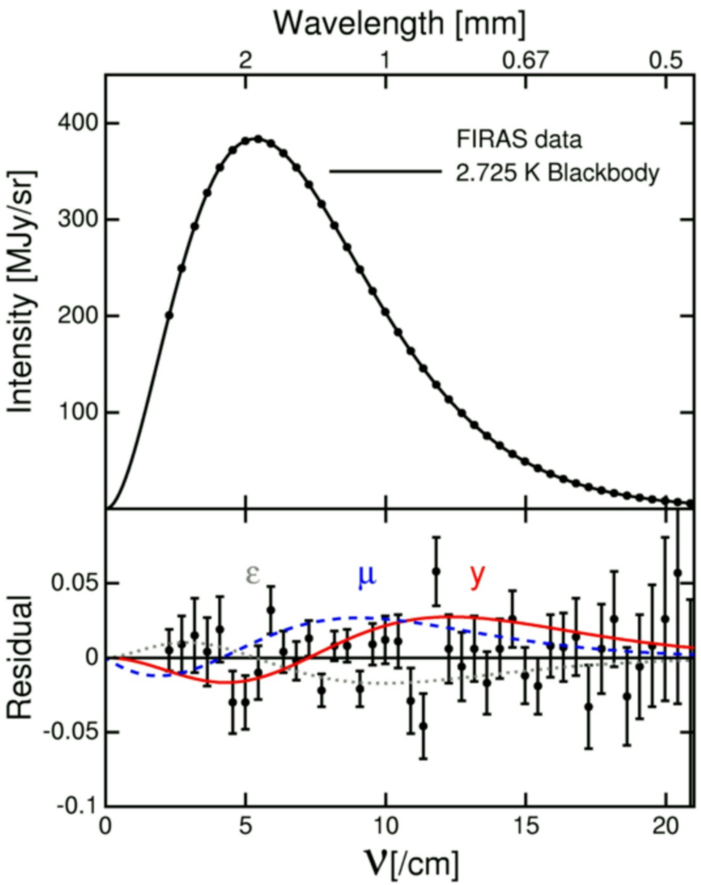


ESA/Planck

spectral distortions

→ thermal history of the Universe

(see FIRAS and TRIS experiments)



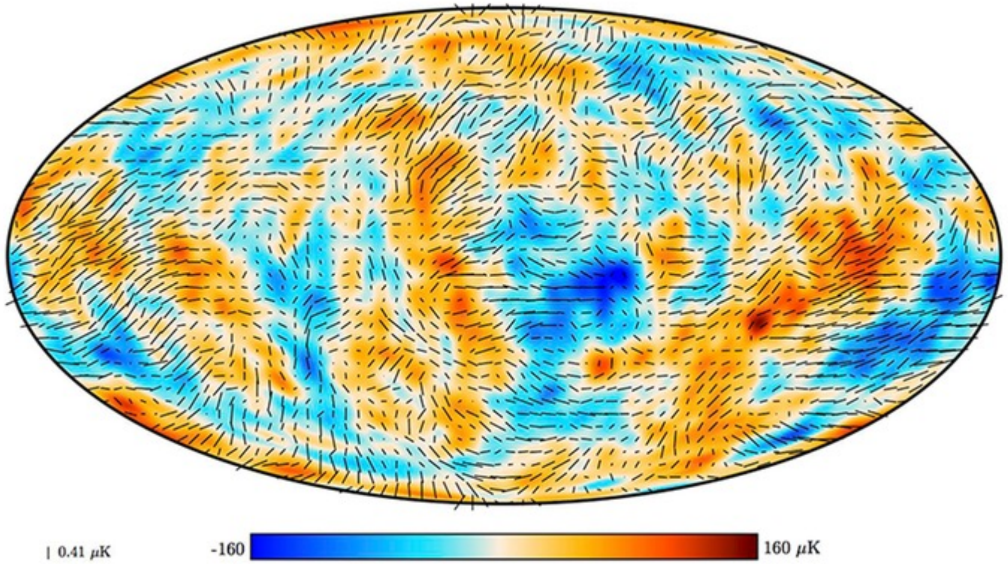
Mather et al. (1990) Ap.J.L 354 37

Cosmic Microwave Background (CMB)

Discovered by Arno Penzias and Robert Wilson in 1965
→ important evidence of the Big Bang theory and ΛCDM model

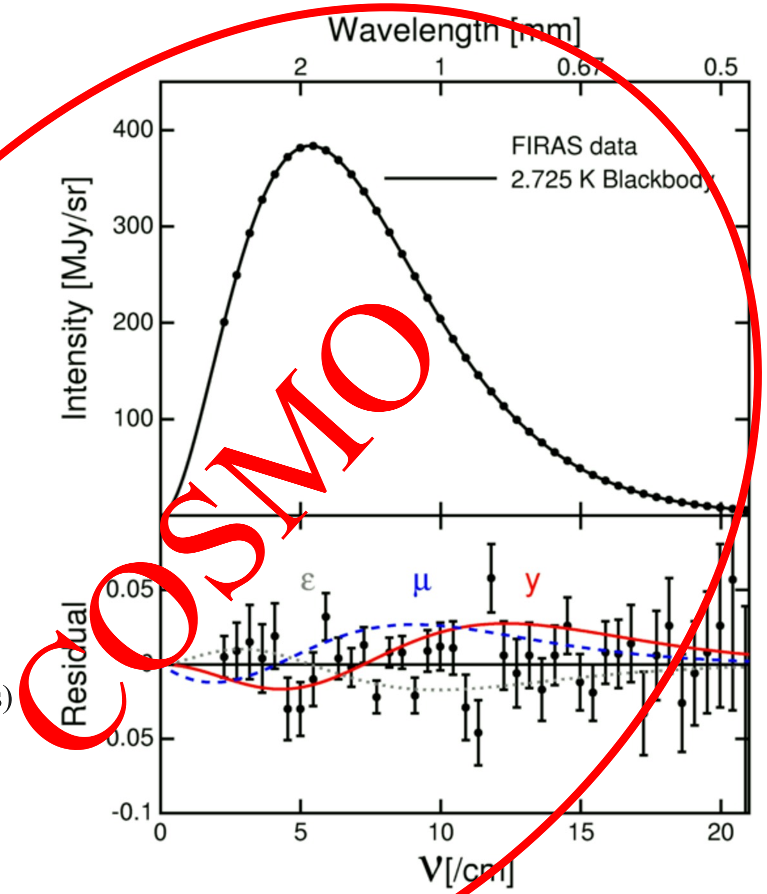
- blackbody spectrum at 2.7260±0.0013K [Fixen, 2009]

What we measure:
B-modes polarization → cosmological inflation



spectral distortions
→ thermal history of the Universe

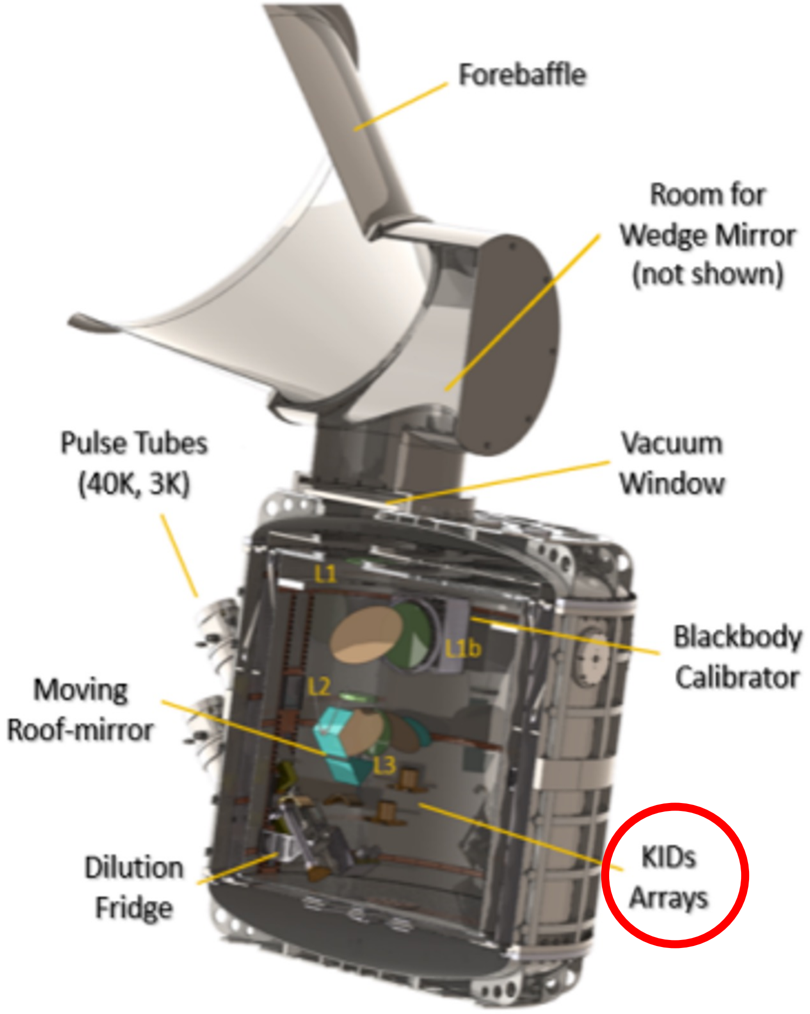
(see FIRAS and TRIS experiments)



Mather et al. (1990) Ap.J.L 354 37

COSMO (COSmic Monopole Observer)

- pathfinder ground-based experiment to measure the isotropic *y* spectral distortions
- cryogenic differential Fourier Transform Spectrometer (FTS) in Martin Puplett interferometer configuration to measure the spectral brightness of the sky compared to the brightness of an internal blackbody
- two frequencies ranges:
    - 120-180 GHz
    - 210-300 GHz

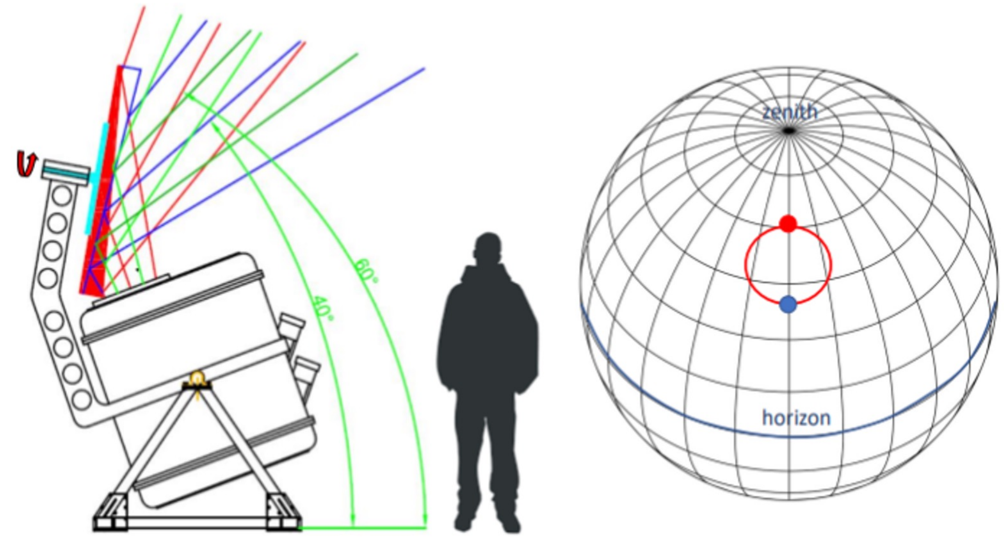


L. Mele et al. (2021) COSMO: Measuring CMB spectral distortions from Antarctica

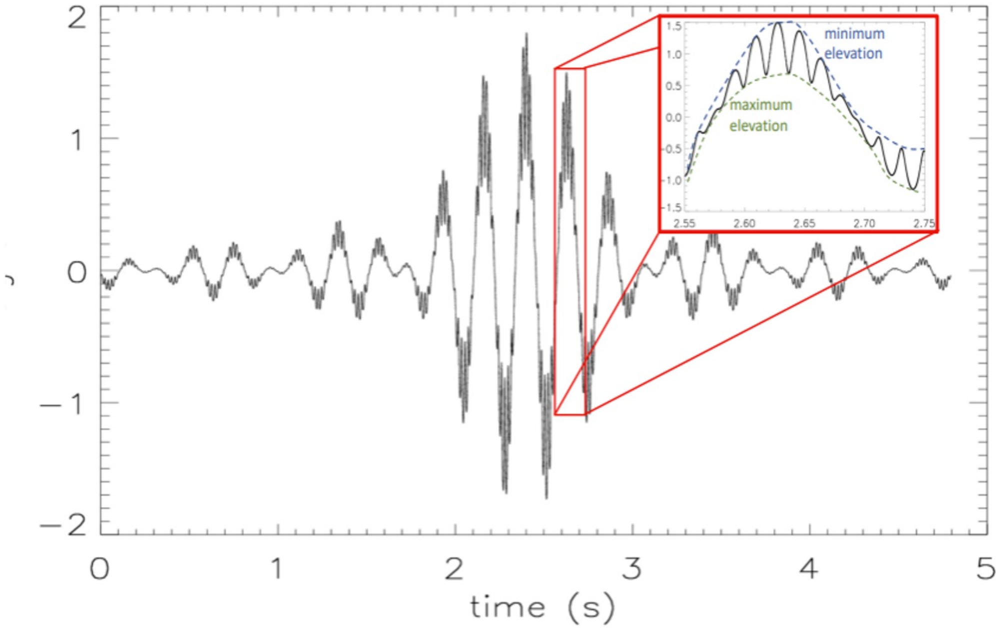
Deal with atmospheric emission

-Fast elevation scans → separate atmospheric emission and its fluctuations from the monopole
-Fast spinning flat mirror (>1000 rpm) on a circle 20° in diameter, scanning a range of elevations while the cryogenic interferometer scans the optical path difference

$$I_{sky}(x) = R \int_0^{\infty} A\Omega(\sigma)\left[B_{sky}(\sigma) - B_{ref}\left(T_{ref}, \sigma\right)\right] e(\sigma)\left[1 + \cos(4\pi\sigma x)\right] d\sigma$$

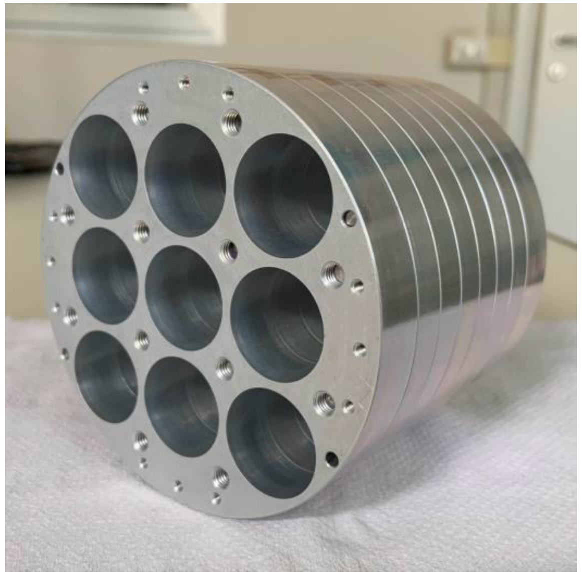
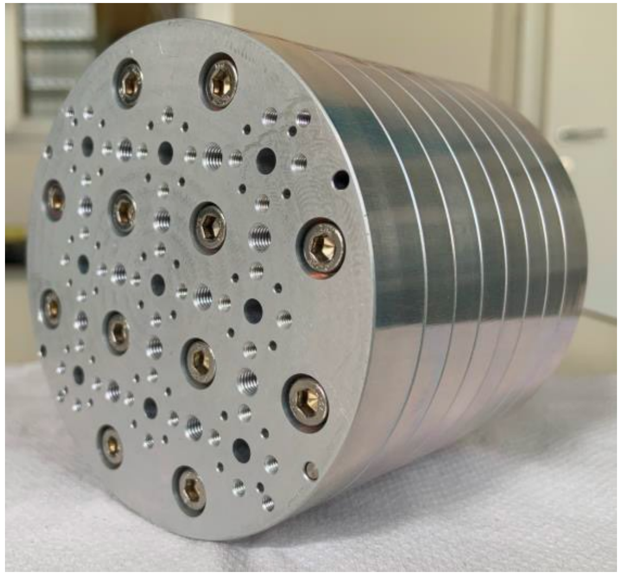


S. Masi et al. (2021) The COSmic Monopole Observer (COSMO)

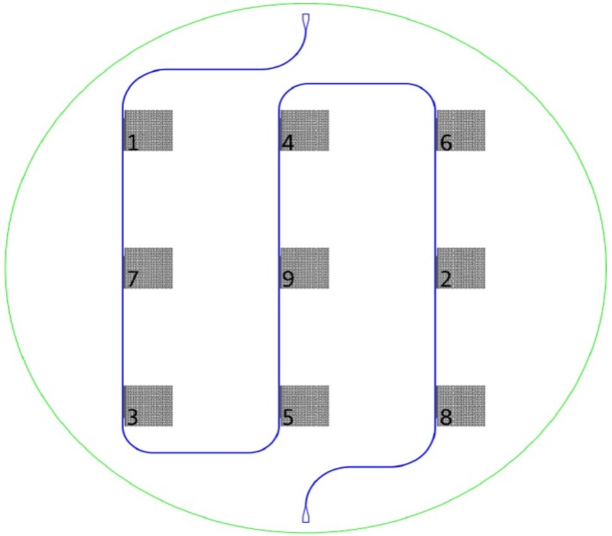


Fast Scans → Fast Detectors → Fast Readout

Multimode Aluminium KIDs (Kinetic Inductance Detectors) for sensitivity
Fast detectors and fast readout to track atmospheric fluctuations and glitches:
- ACQUISITION RATE TARGET 50 kHz (to resolve CP recovery time)

Low Frequency Array (feed horns + detectors)

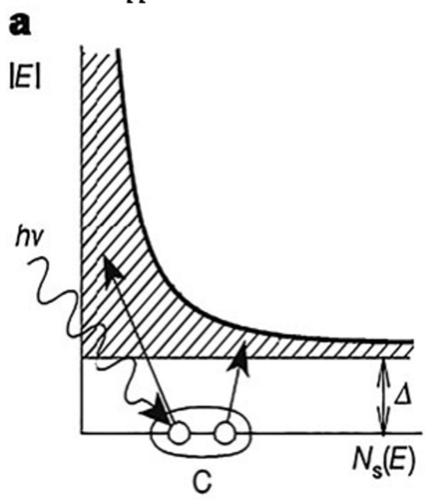


Index	Freq. [MHz]
1	85.1
2	88.1
3	91.4
4	95.1
5	99.4
6	104.2
7	109.9
8	116.6
9	124.6

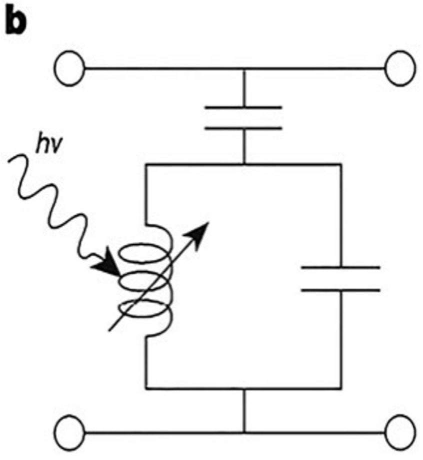
Fast Scans → Fast Detectors → Fast Readout

$T \ll T_c$

a. Incoming photon with $h\nu > 2\Delta$
→ CPs are broken
→ $N_{qp} = \eta h\nu/\Delta$

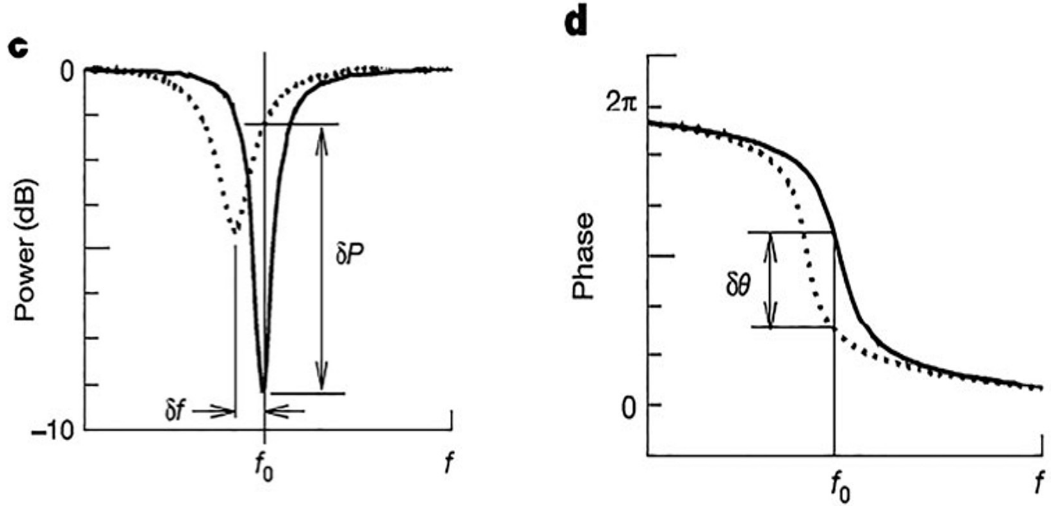


b. KID as a RLC circuit
→ $Z = R + i\omega L$



Inductance in superconductors depends on both the geometry and Cooper pairs density

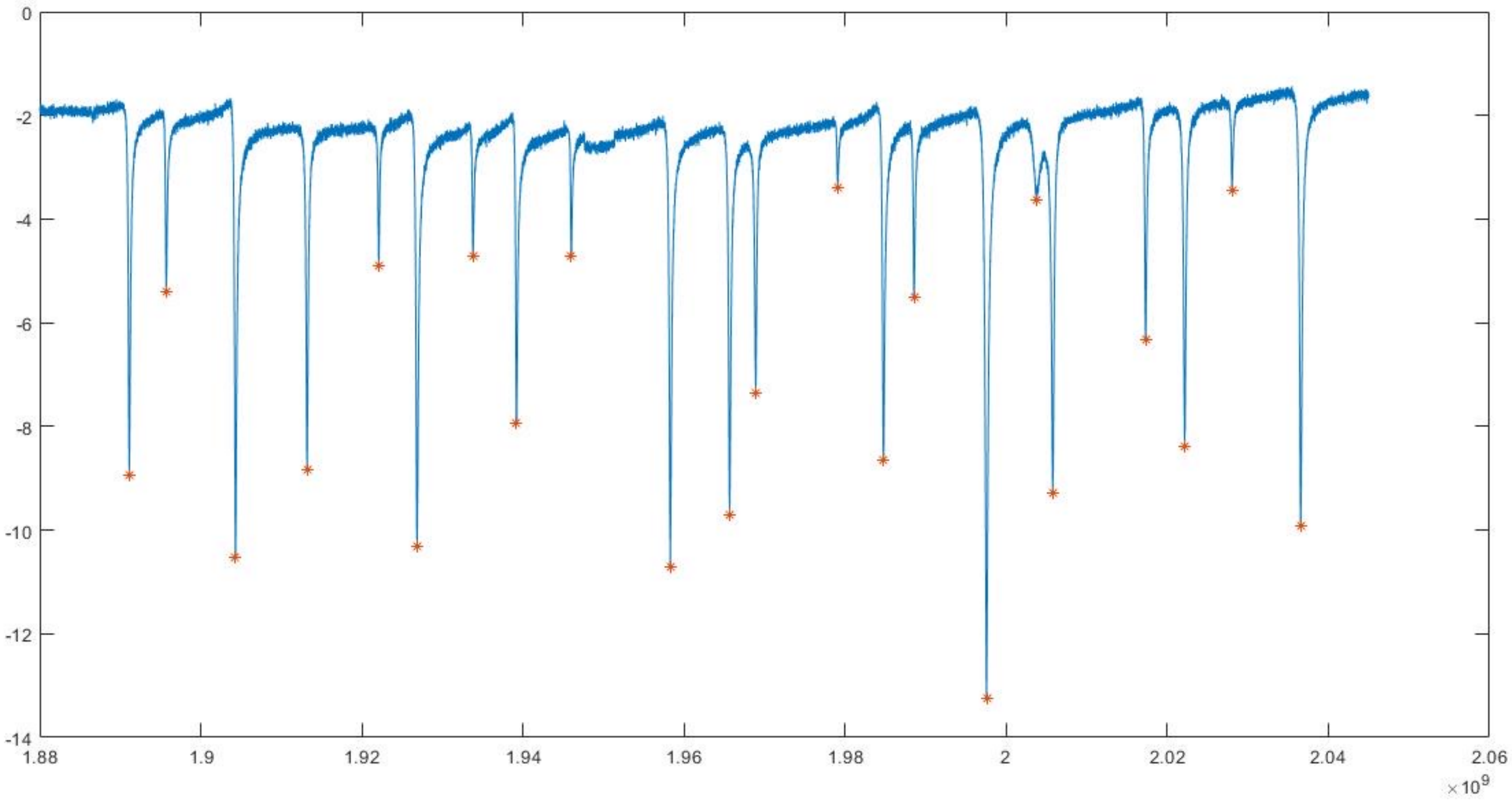
c.&d. QPs production: L and R grow
→ the resonant frequency is smaller
→ the peak is larger and less deep
→ amplitude and phase change



B. Mazin (2004) Microwave Kinetic Inductance Detectors

Fast Scans → Fast Detectors → Fast Readout

Kinetic Inductance Detectors: how do they look like to a VNA



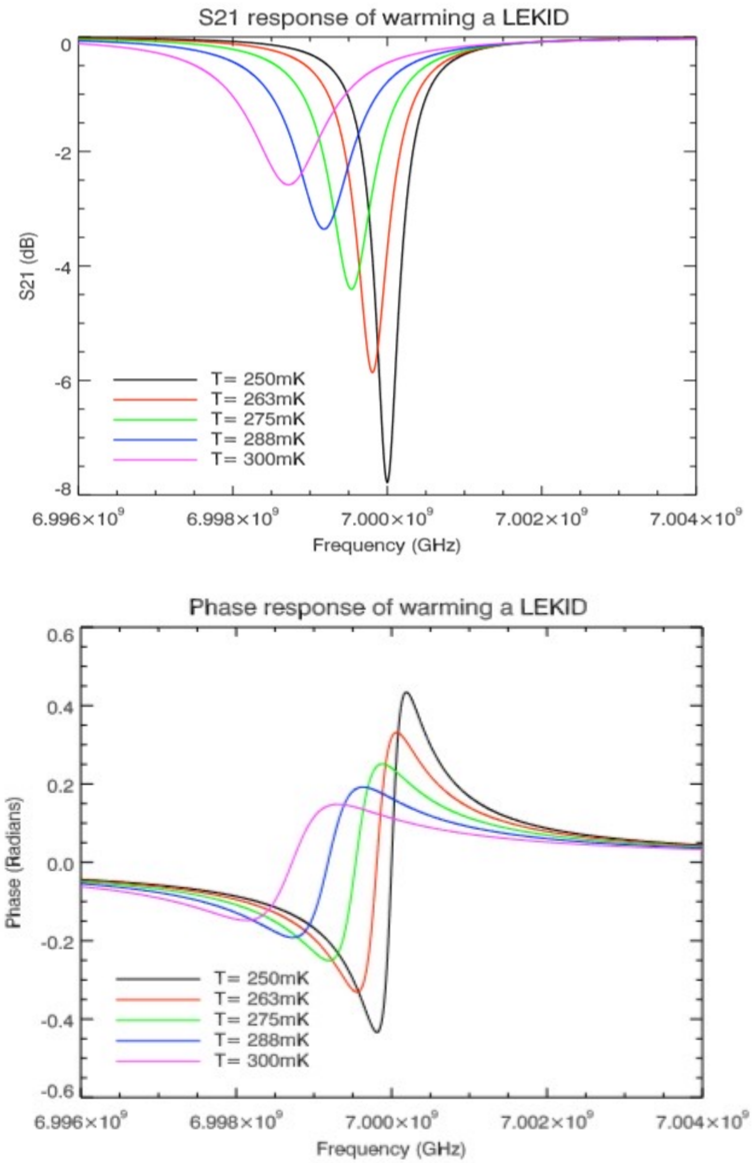
KIDs are resonant circuits

Each pixel has its own resonance frequency

Energy deposited on the pixel lower the resonance and quality factor

Nb test KIDs (courtesy of Boussaha Faouzi Paris Obs)

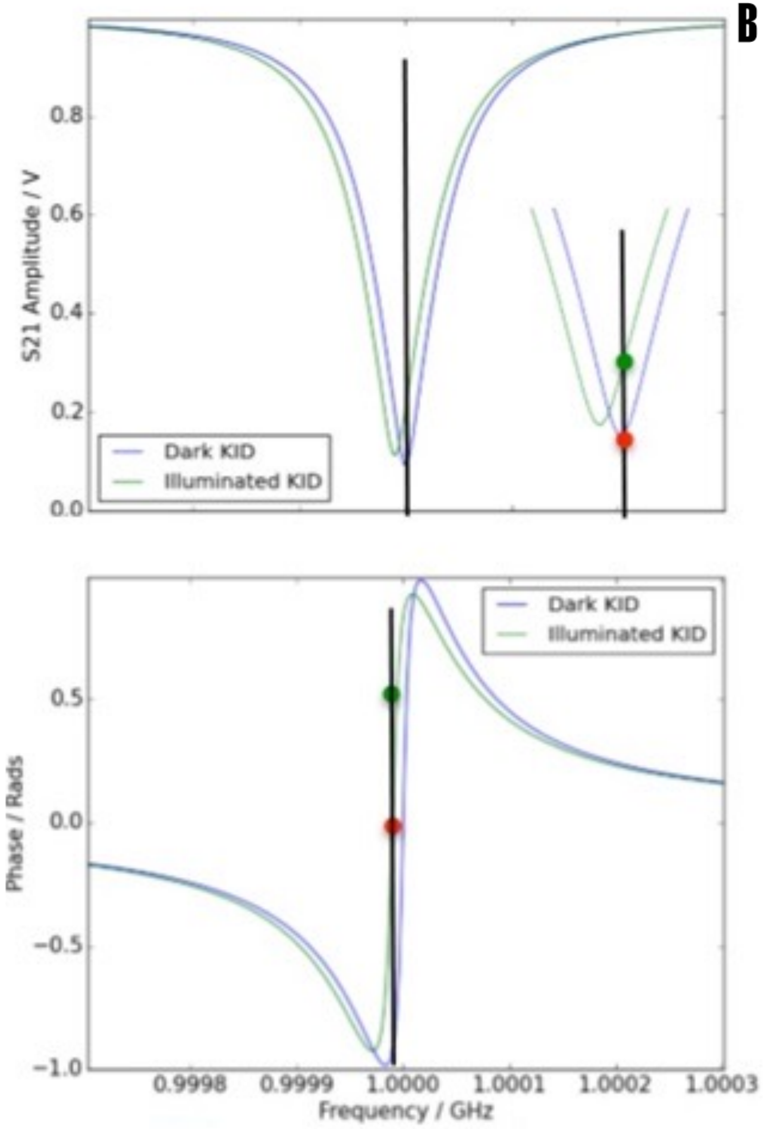
Fast Scans → Fast Detectors → Fast Readout



We can either track the amplitude and phase variation

or (better and less computational demanding)

use **comb of tones**



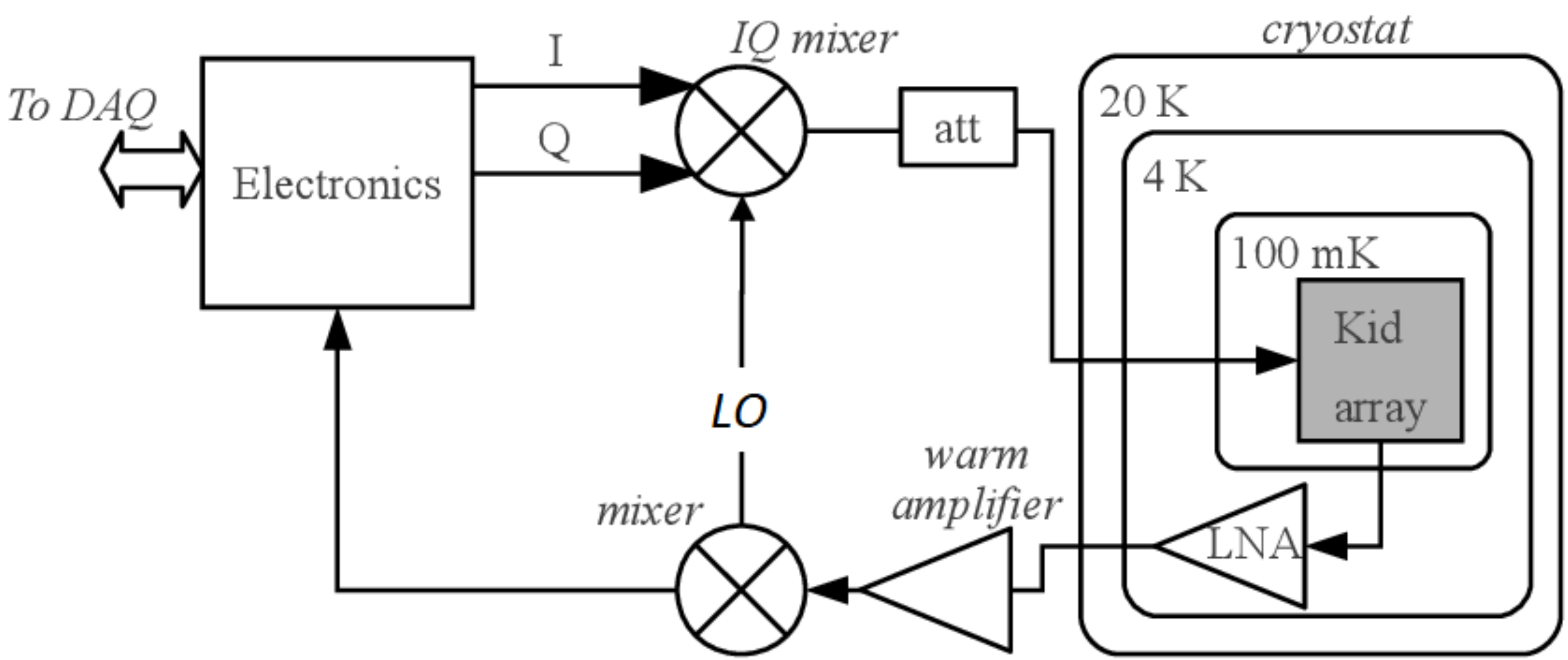
Pictures from Simon Doyle PhD thesis

Fast Scans → Fast Detectors → Fast Readout

To have phase under control the preferred approach is to generate In-phase and Quadrature signals

$$|A| = \sqrt{I^2 + Q^2}$$

$$\phi = \arctan\left({}^{Q}/_{I}\right)$$



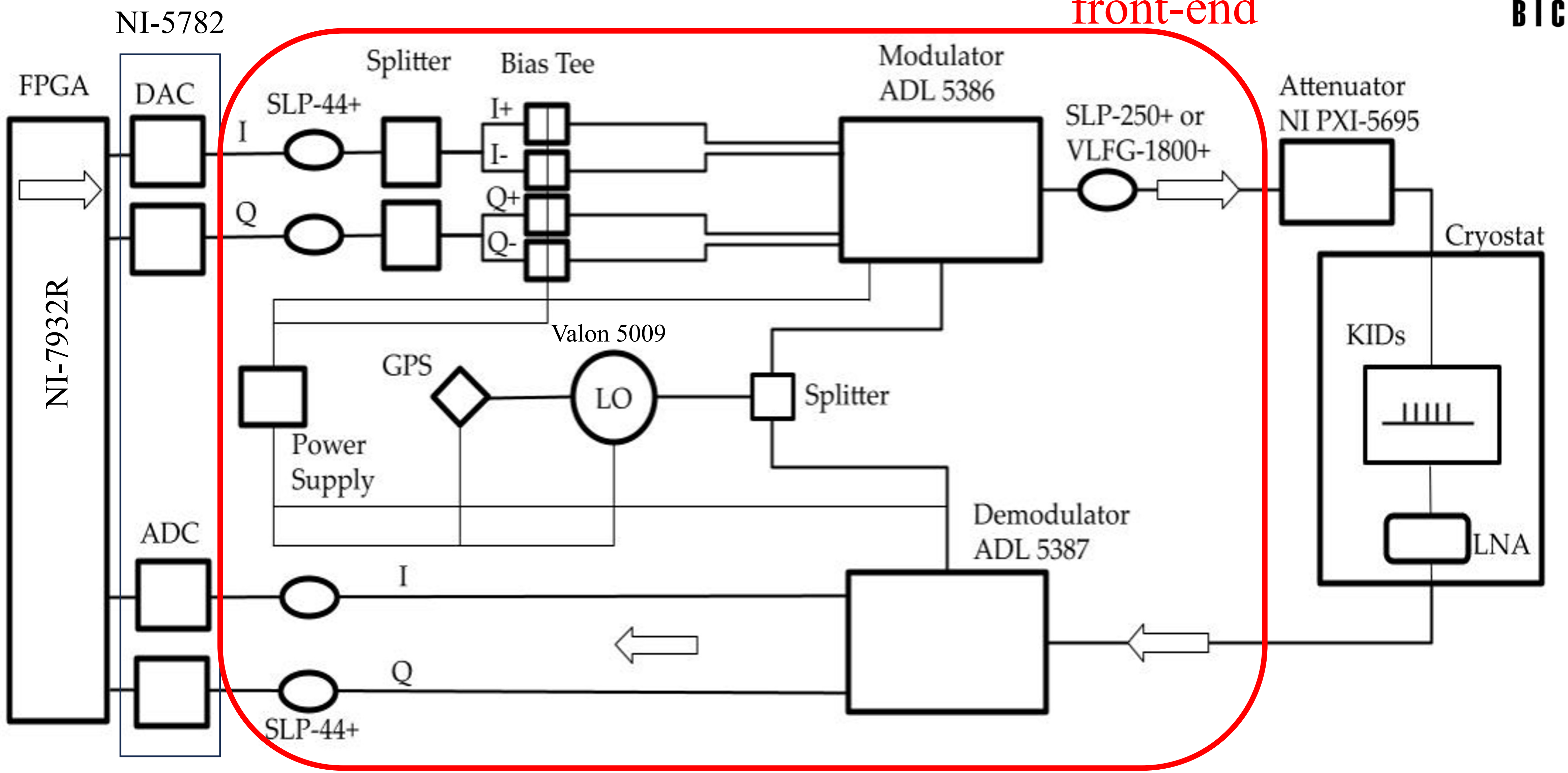
Fast Scans → Fast Detectors → Fast Readout

COSMO realization:

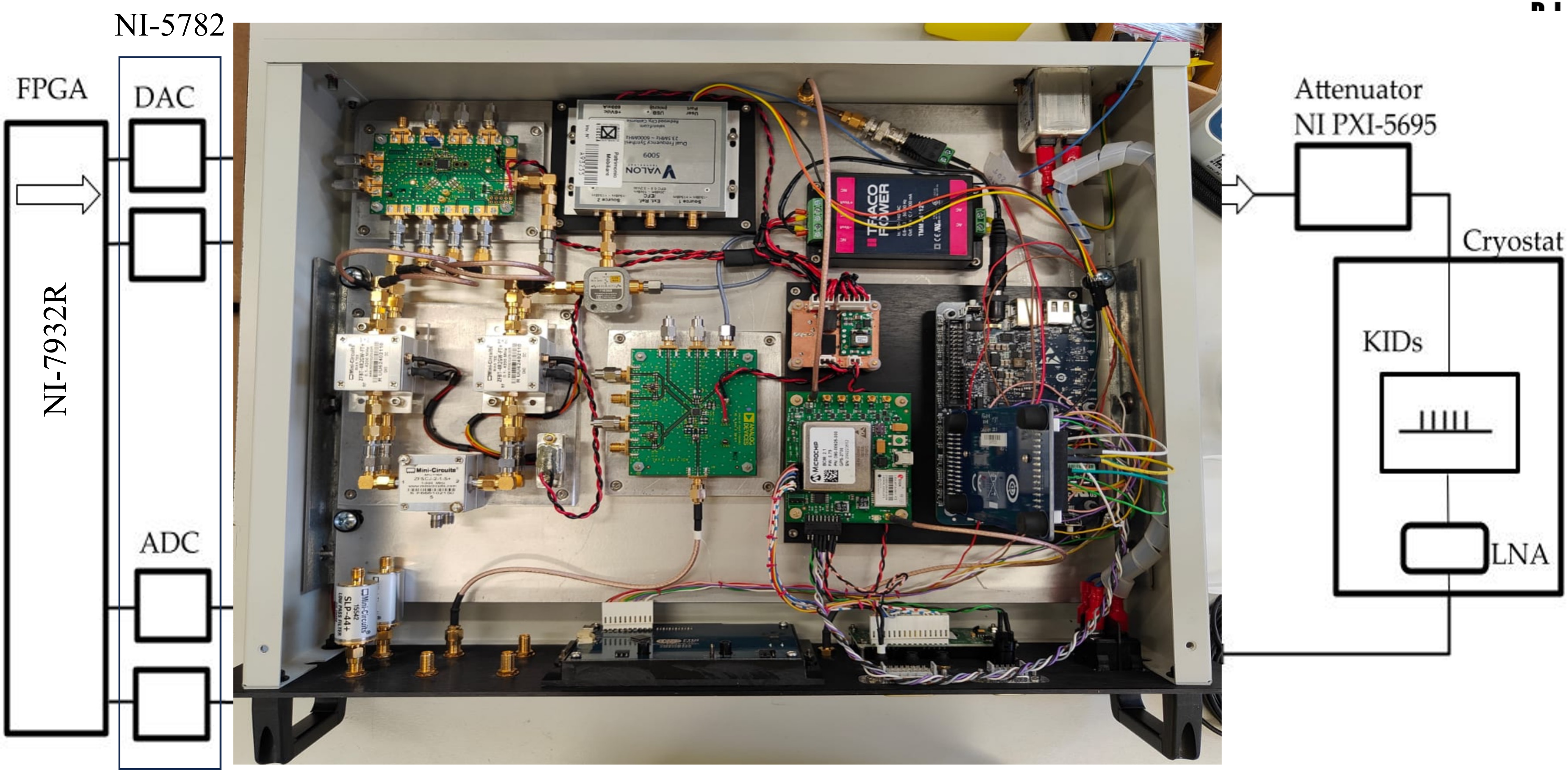
- Thermally shielded rack
- National Instruments PXI rack PXIe-1088
- NI Xilinx Virtex-7 FPGA module NI-7932R
- NI Scala Double Transceivers NI-5782 (I-Q)
- NI Variable Attenuator NI PXI-5695
- NI Analog output VDC NI-793XR (for LNA bias)
- Modular in-house assembled vectorial front-end
- DELL Rack workstation fully redundant
- UPS

Fast Scans → Fast Detectors → Fast Readout

Modular vectorial front-end

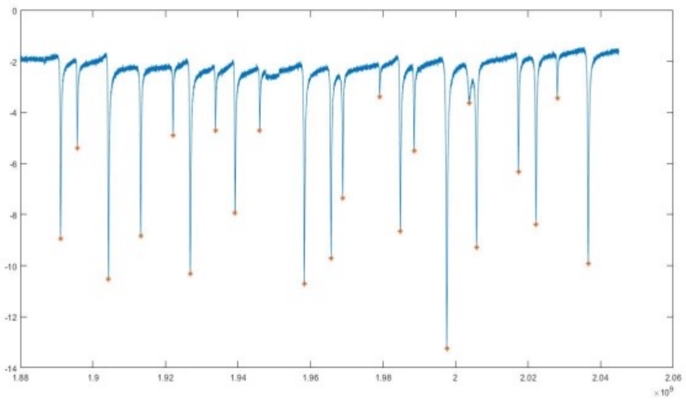


Fast Scans → Fast Detectors → Fast Readout

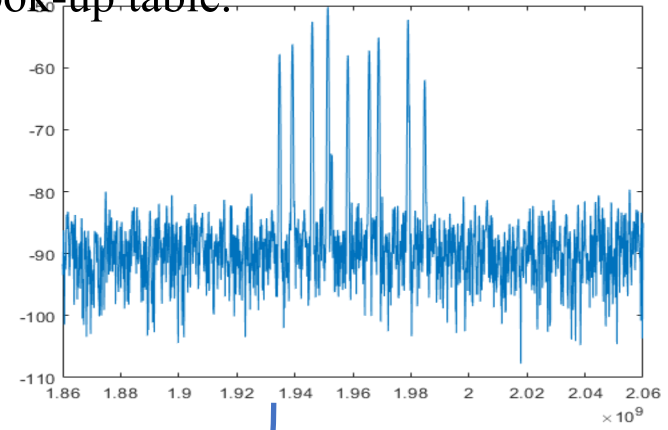


The FPGA is programmed as a three-state machine

1 Resonant frequencies are found and saved.

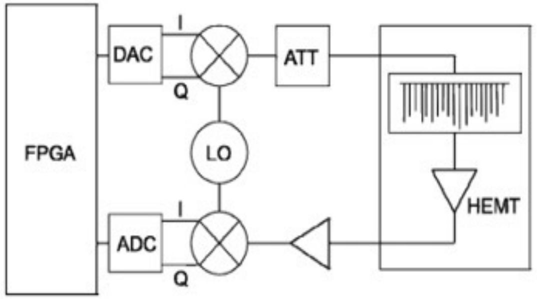


2 The tones to be transmitted in the MKIDs are generated by means of CORDIC algorithm and stored in a look-up table.



Signal generated ...

3 The tones are transmitted, received and analyzed.

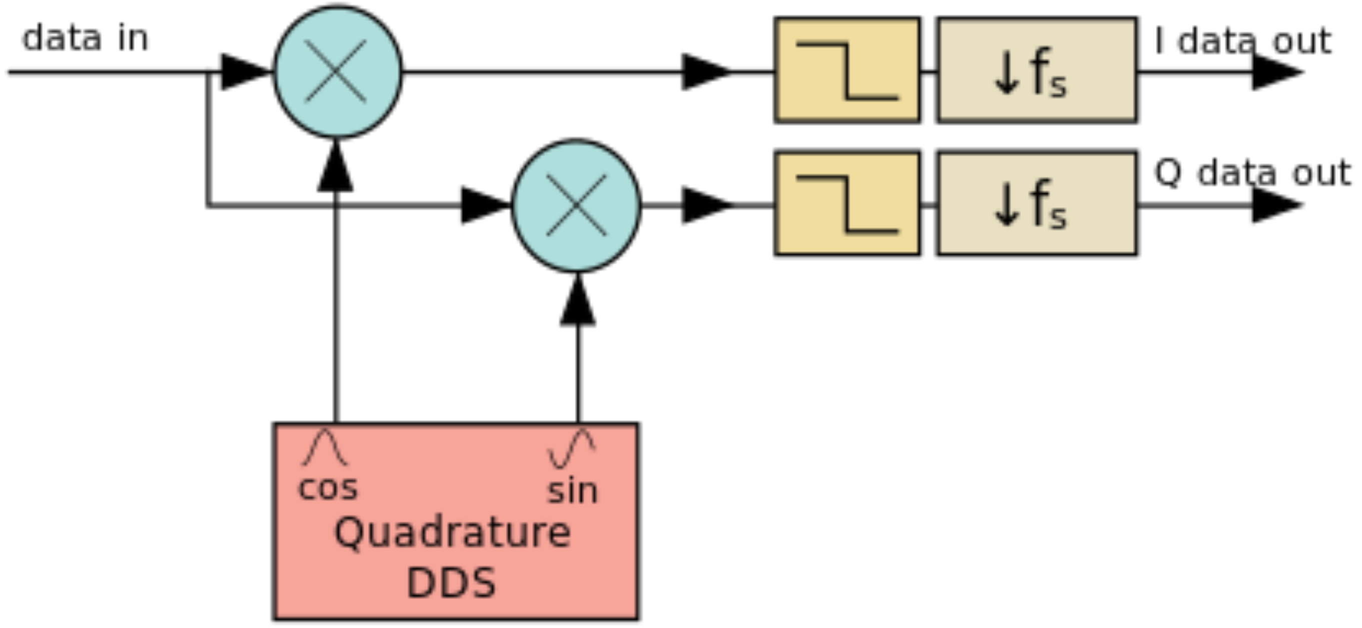


Periodically, if there are changes in the system (like the detectors' temperature)

Fast Scans → Fast Detectors → Fast Readout

Tones detection via Digital Down Conversion (DDC)

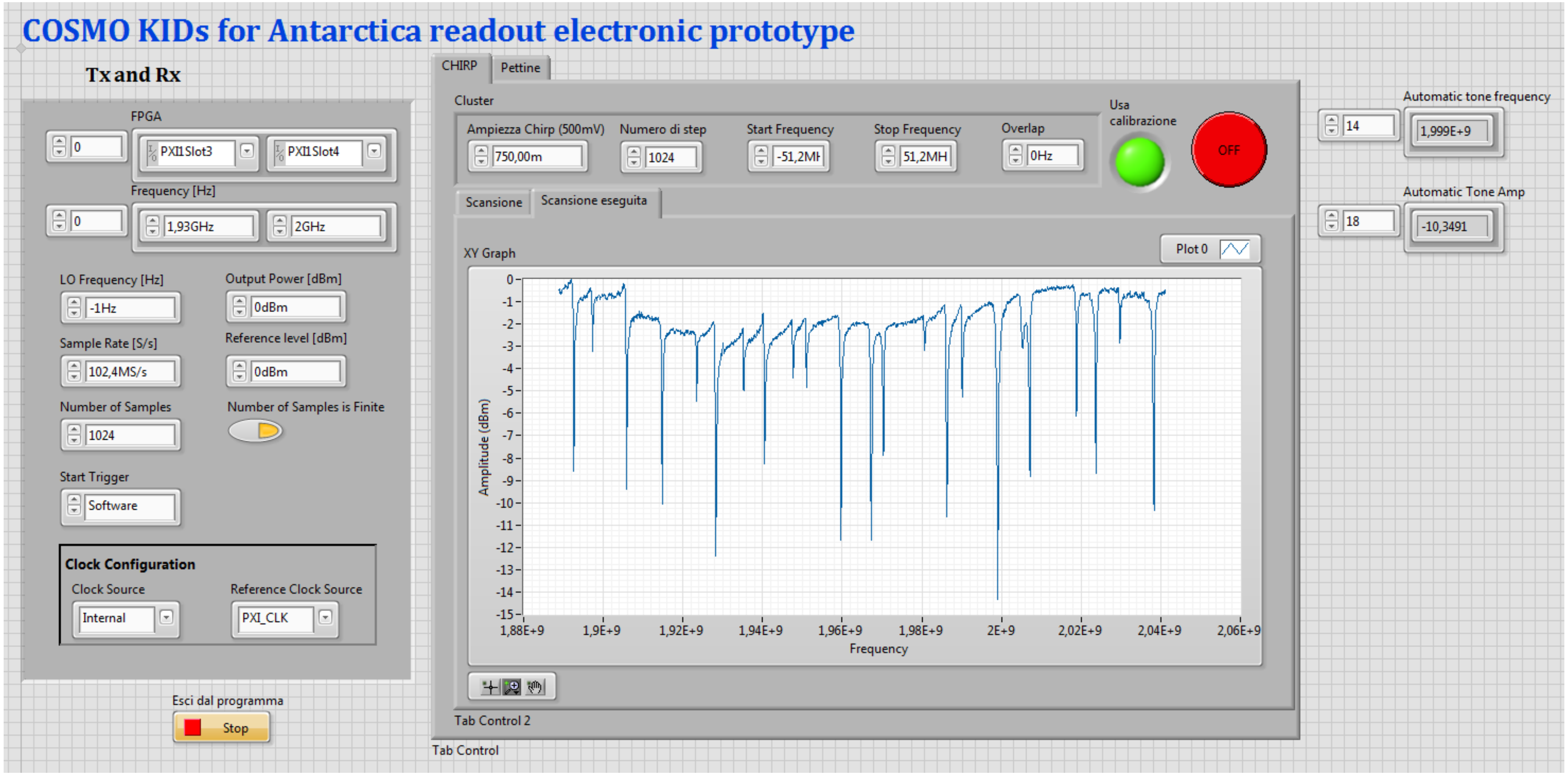
If the number of tones is limited DDC is an efficient numerical Homodyne detection with intrinsic decimation



Direct Digital Synthesiser

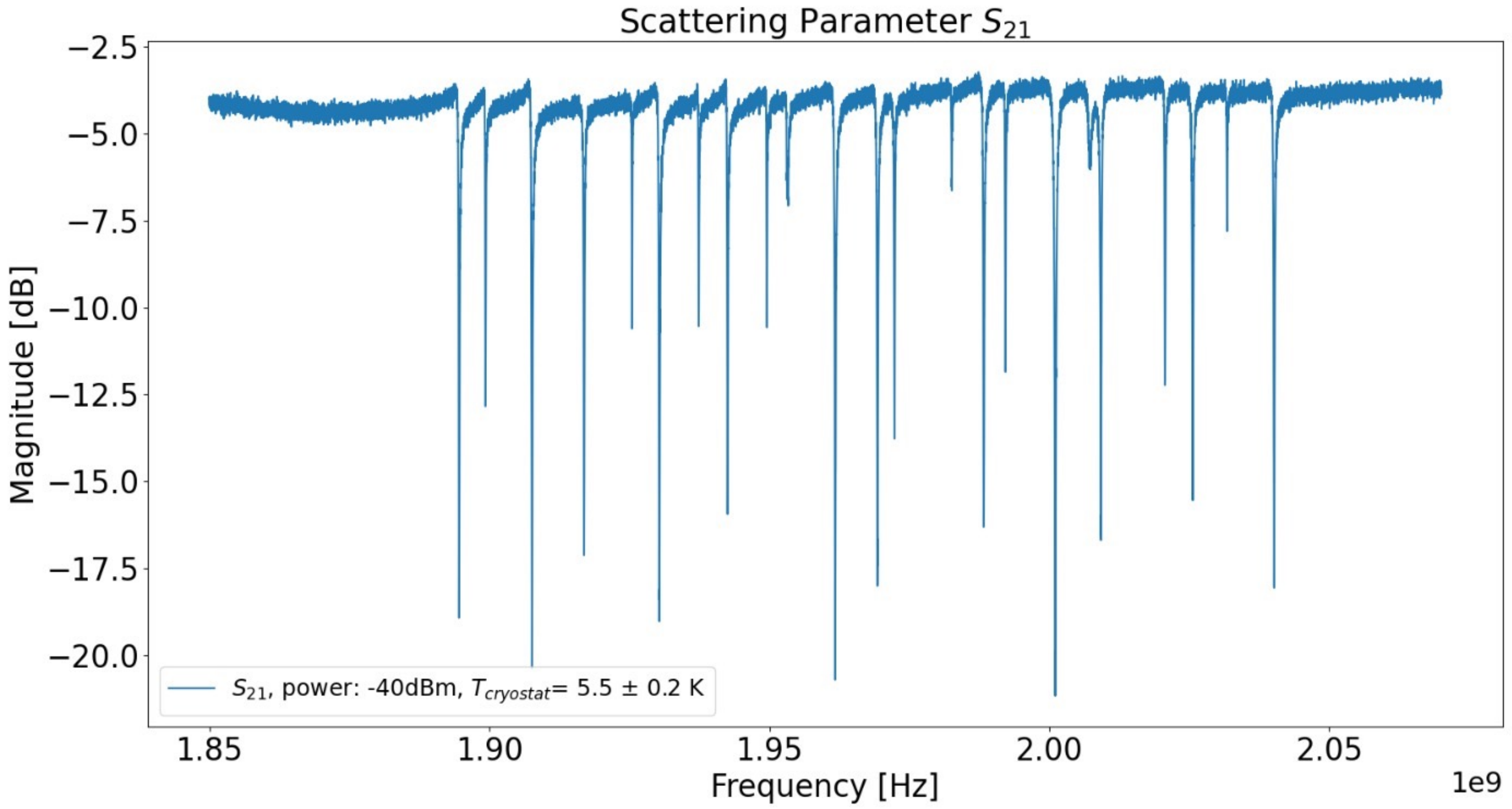
Fast Scans → Fast Detectors → Fast Readout

Tones detection



Fast Scans → Fast Detectors → Fast Readout

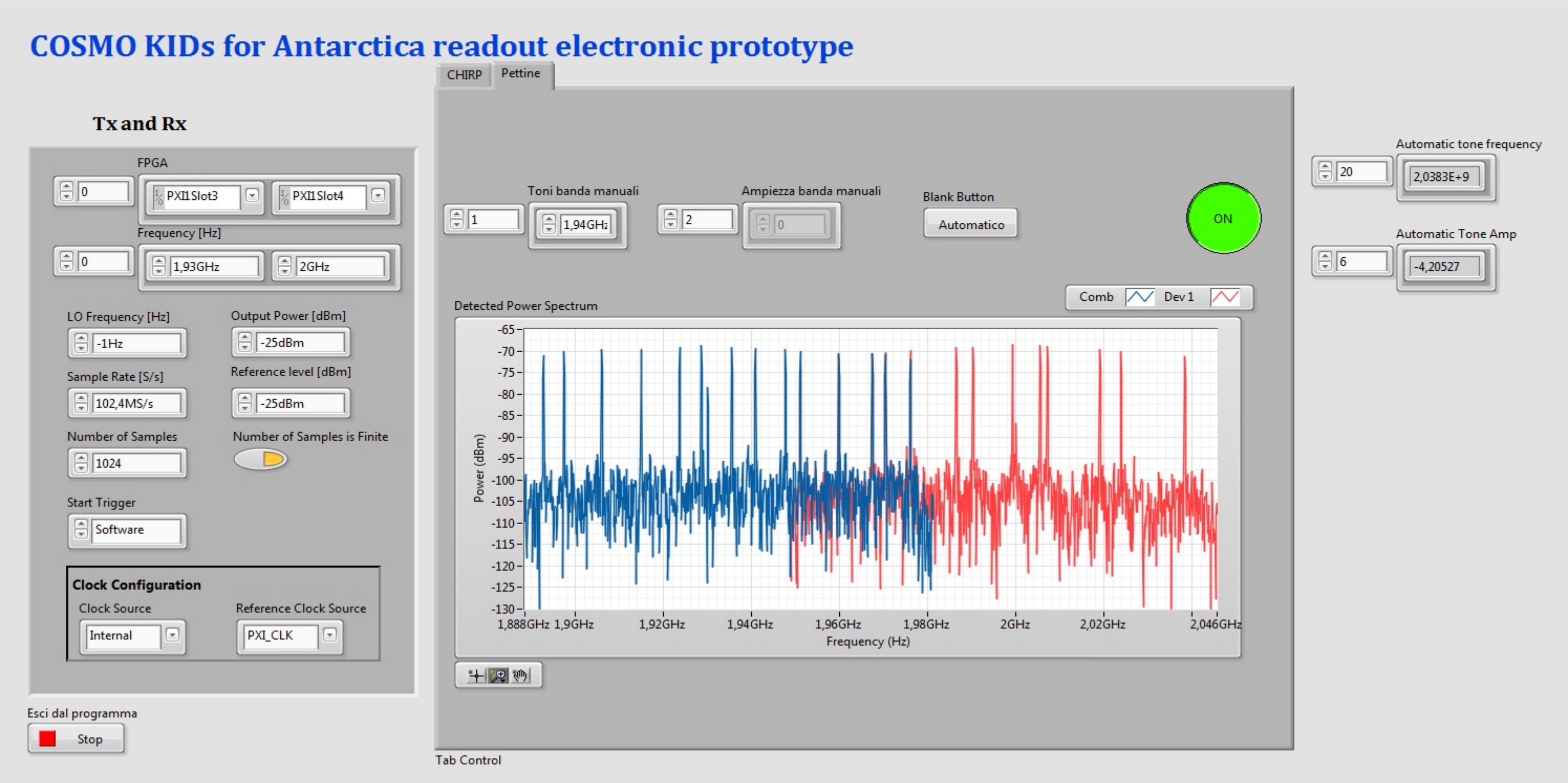
Tones detection



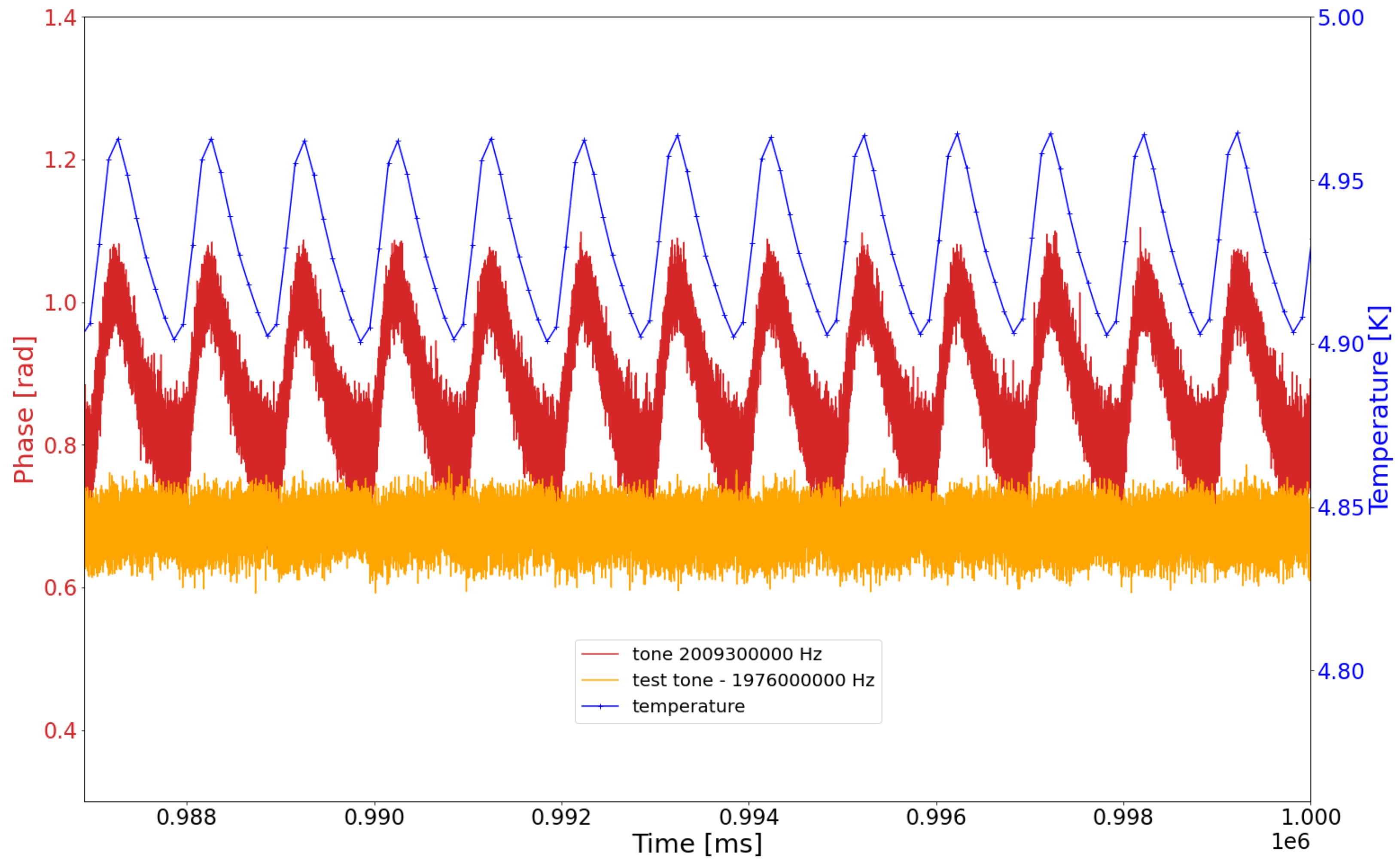
Tones of a Nb KID array as seen by the VNA

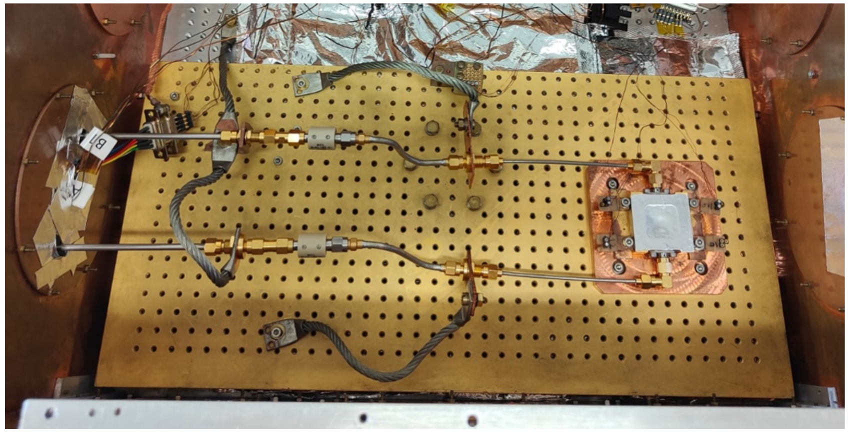
Fast Scans → Fast Detectors → Fast Readout

Tones generation



Fast Scans → Fast Detectors → Fast Readout



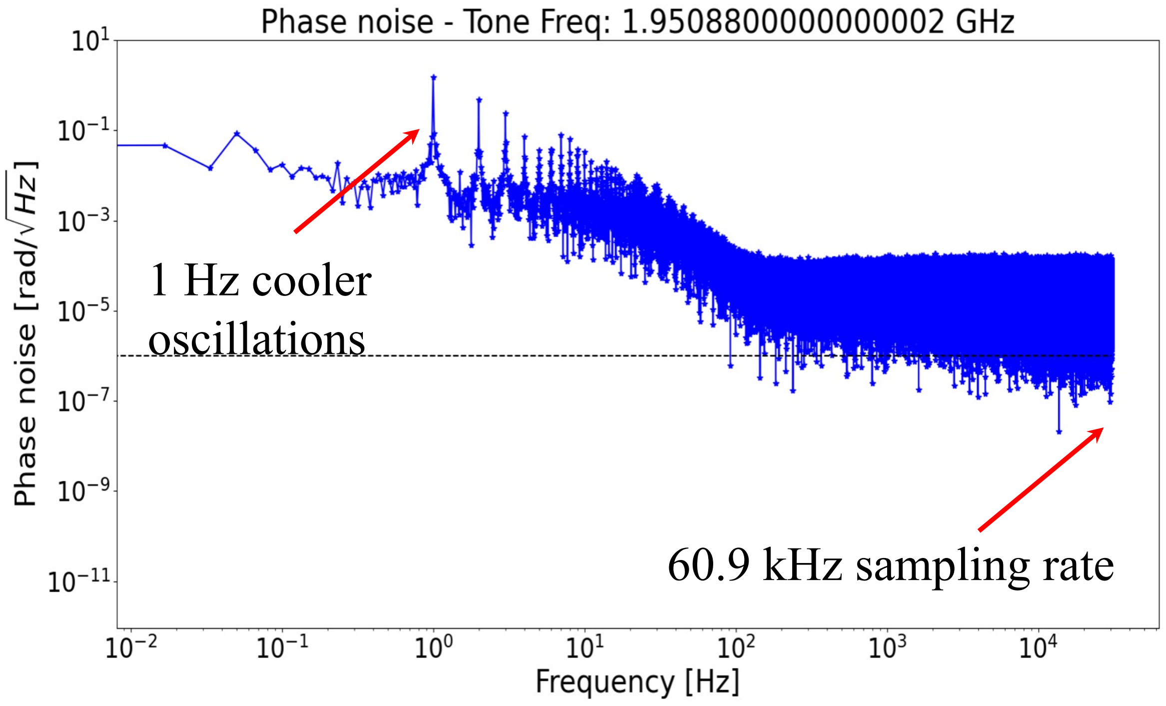


We test the readout using the cooler oscillations (1 Hz):
KIDs variations track the temperature

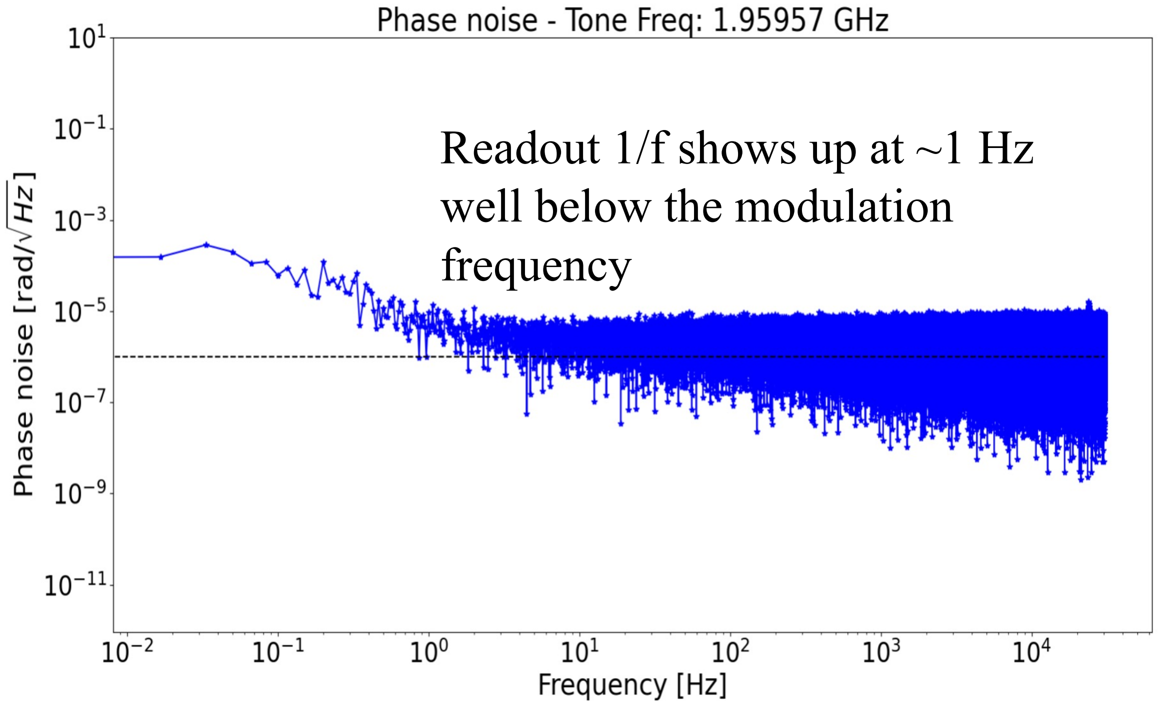
A tone out of any resonance is stable.

Fast Scans → Fast Detectors → Fast Readout

PSD of one tone with Nb kids

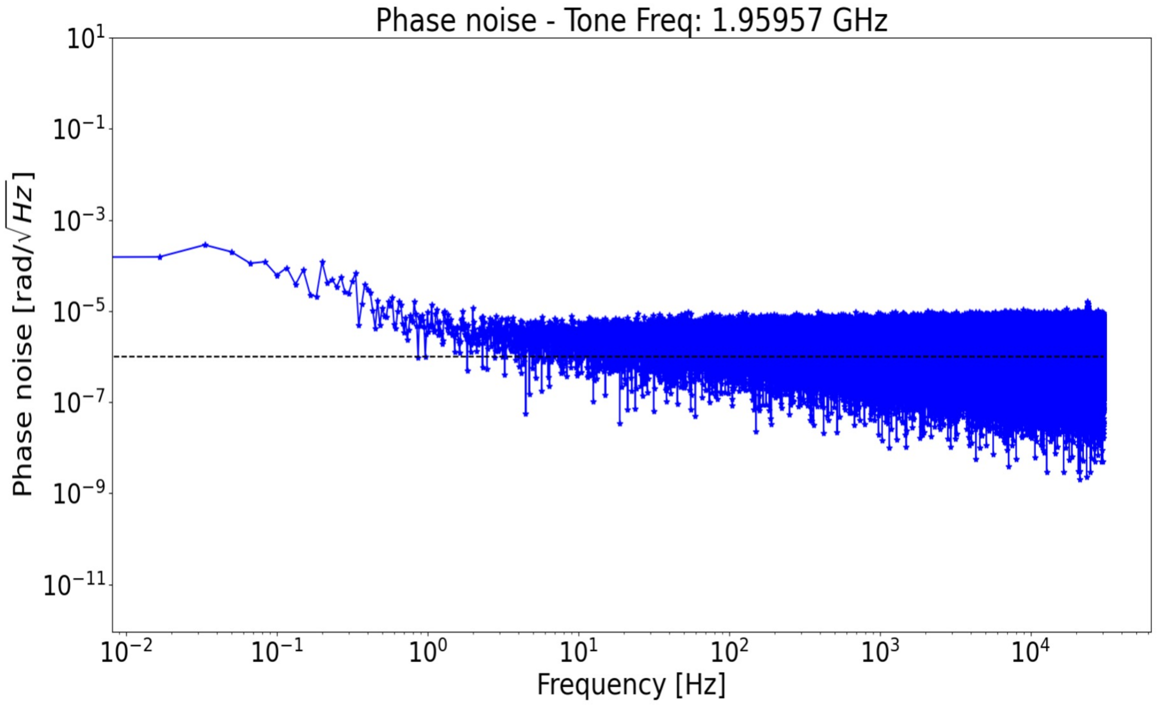


PSD in loop-back
(just readout no detectors)

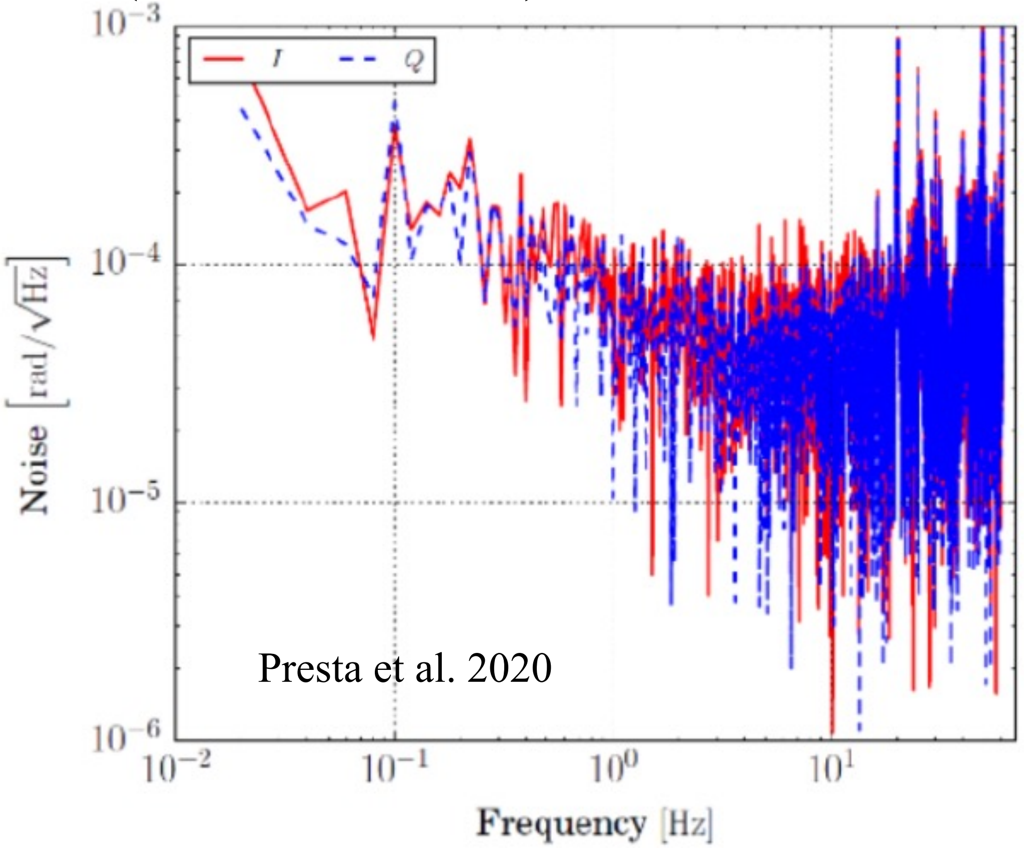


Fast Scans → Fast Detectors → Fast Readout

PSD in loop-back (just readout)



OLIMPO phase noise as a reference (ROACH board)



Fast Scans → Fast Detectors → Fast Readout

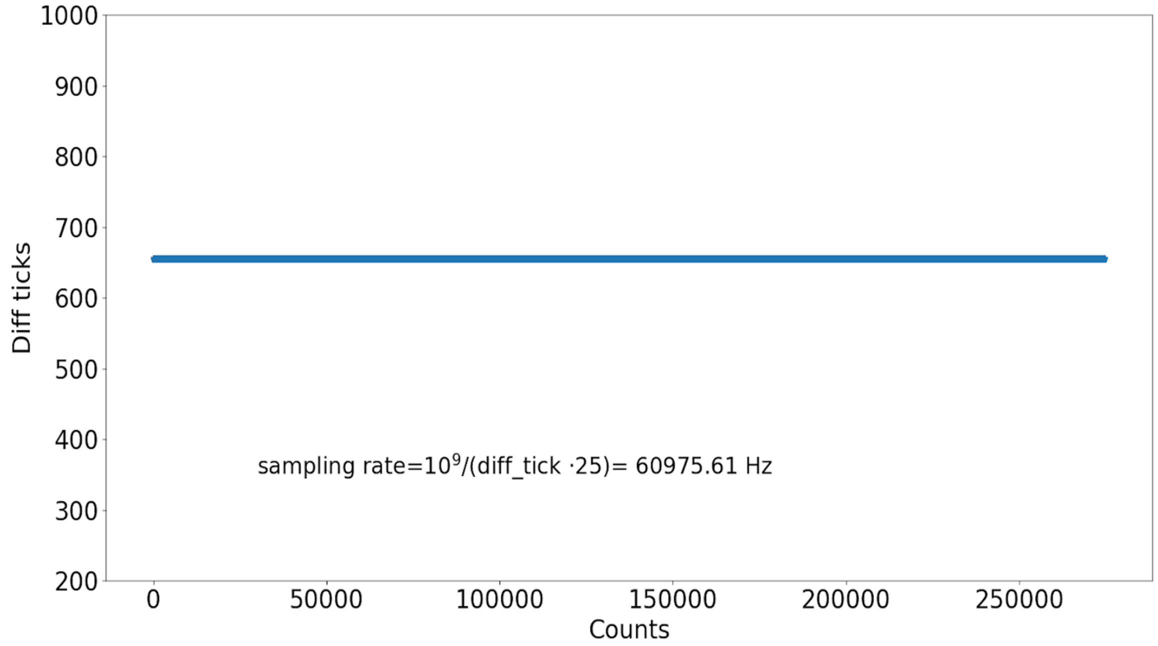
Stream of deterministic data with nanosecond precision

Acquisition rate is bit by FPGA clock (40 MHz)

Package of data:

Binary file (HDF5) at 64 bit with 40 rows:

- 36 rows for I&Q (18 tones)
- 37th row: posix time
- 38th row: tick-sampling rate
- 39th row: zeros
- 40th row: end of package



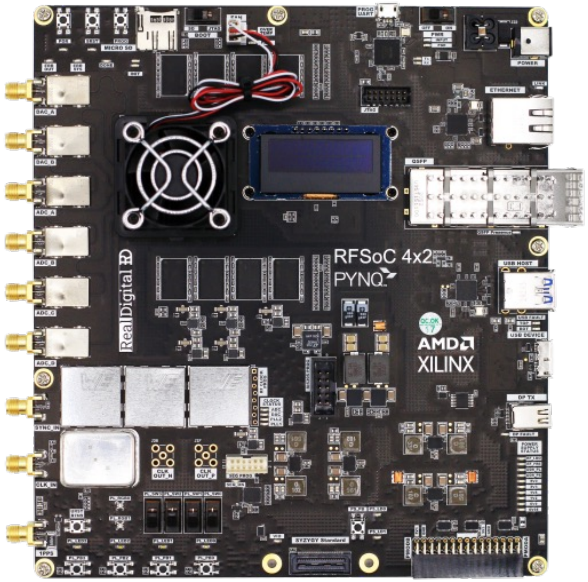
60s of data taking: 1.1 Gb! Need for a decimation strategy

Conclusions

- We built and successfully tested a mKID readout electronics with **commercial components**
- We have **under control** all the aspects from **hardware** to **firmware**
- For a few (**tens**) **pixels** experiment with detectors spanning ~120 MHz bandwidth we can acquire as fast as **60 kHz**
- Noise performances are in line with state-of-the-art systems

Next steps:

- test with the real COSMO detectors and further debug
- Data decimation/compression
- GUI finalization



Perspective: start to play with a powerful RFSoC 4x2 board for a fully digital signal generation and processing