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ITeDA
Instituto de Tecnologías en Detección y Astropartículas

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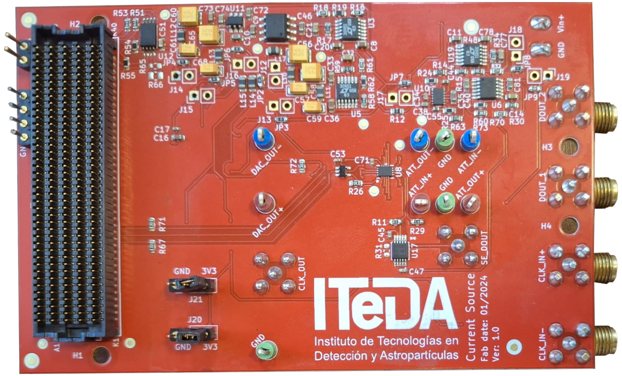
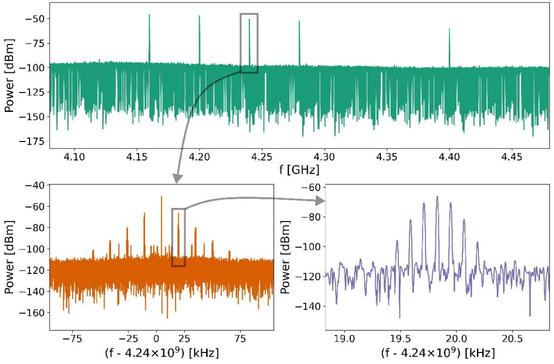
Signal Processing in the Microwave SQUID Multiplexer-based Readout System for Magnetic Microbolometer Detector Arrays

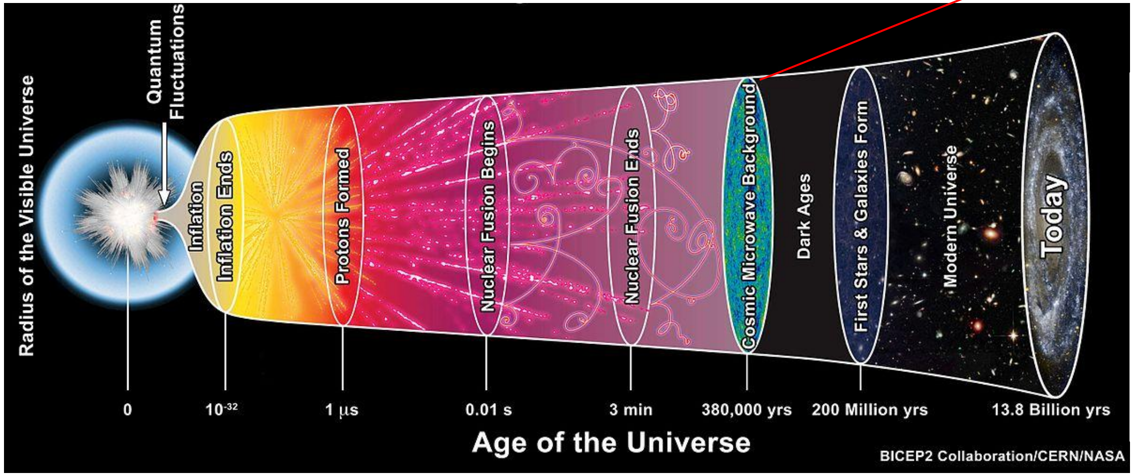
Eng. Juan Manuel Salum



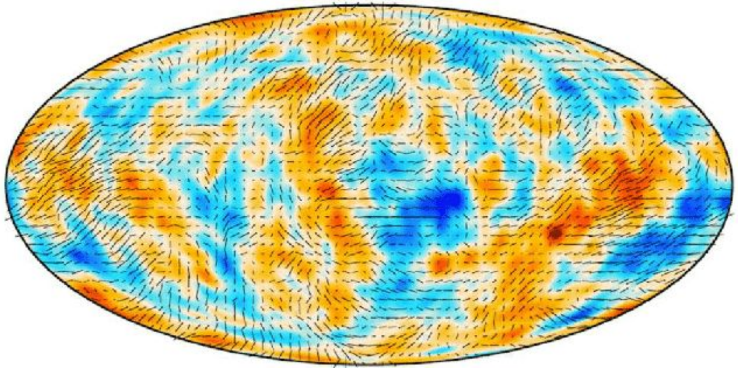


Motivation

Photons propagate freely



The Cosmic Microwave Background (CMB)



Credits: Planck collaboration

<u>Inflation Theory</u>

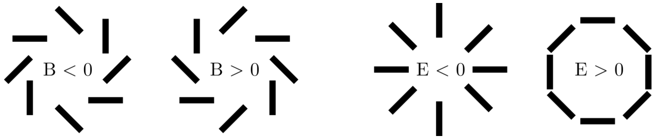
➔ The Universe expanded exponentially, leading to its cooling

➔ Photons enabled to freely propagate after recombination epoch

➔ The footprint of this process is in the CMB polarization

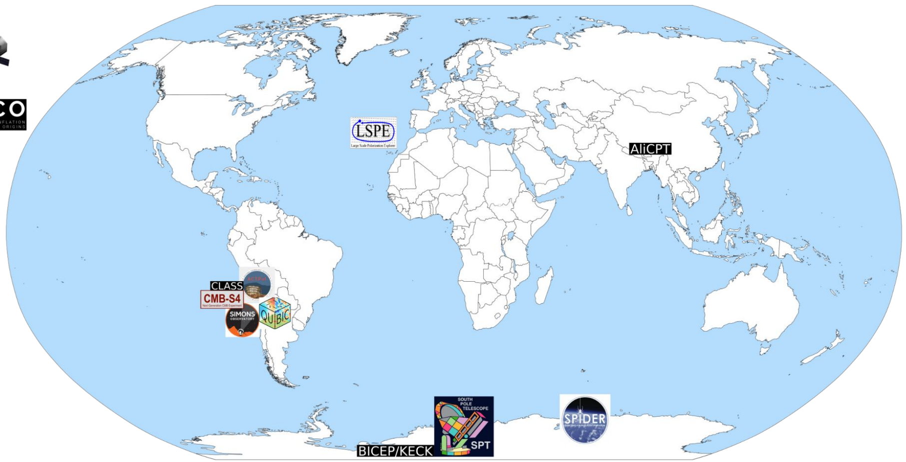
➔ CMB is B- and E-mode polarized

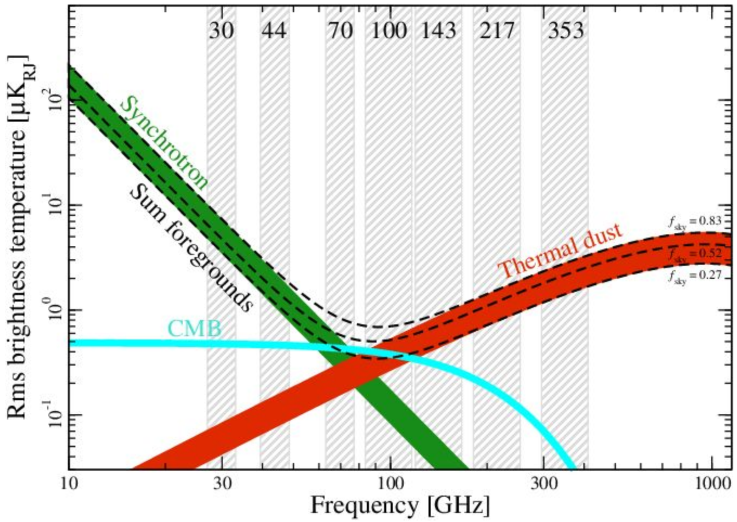
➔ <u>**Detecting B modes provides direct evidence of the inflationary period**</u>



B modes *E modes*

Challenges for B modes detection



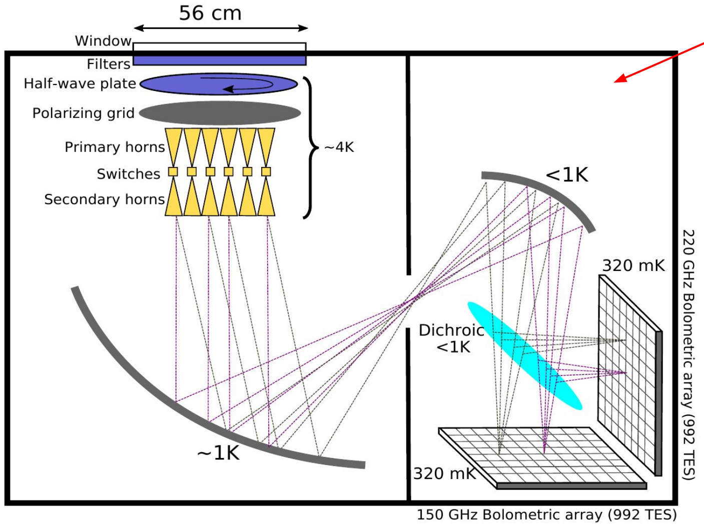


Credits: Planck collaboration

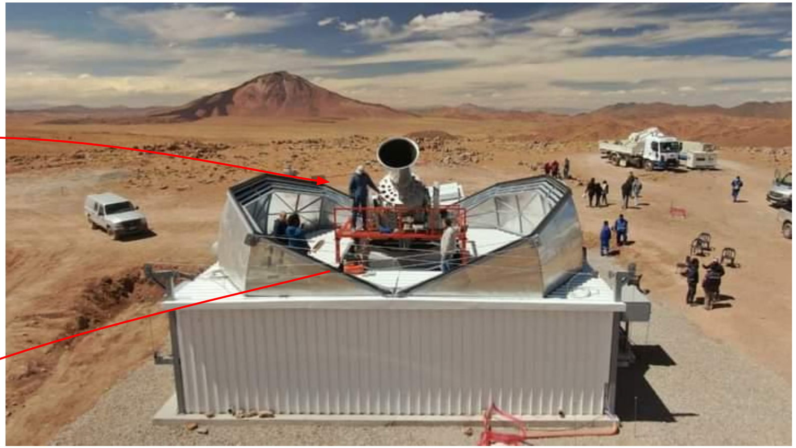
- ➔ Effort by the scientific community to measure B-modes
- ➔ Measurement challenges:
  - ◆ B-mode is a weak signal ⟶ Low-temperature bolometer arrays
  - ◆ Foregrounds ⟶ Additional bands for foregrounds removal
  - ◆ Systematic effects ⟶ Calibration

Bolometric Interferometry

Bolometric Interferometry and QUBIC



The QUBIC telescope



- ➔ QUBIC is the first bolometric interferometer for CMB
- ➔ Two 1024 bolometer arrays for 150GHz and 220GHz
- ➔ Back-to-back horns calibrates the interferometer pattern
- ➔ The system is housed in a cryostat at low temperatures to reduce detection noise
- ➔ QUBIC <u>challenges</u>:
  - ◆ **<u>Designing the dichroic plate for simultaneous 150GHz and 220GHz operation</u>**
  - ◆ **<u>Readout system scalability</u>**

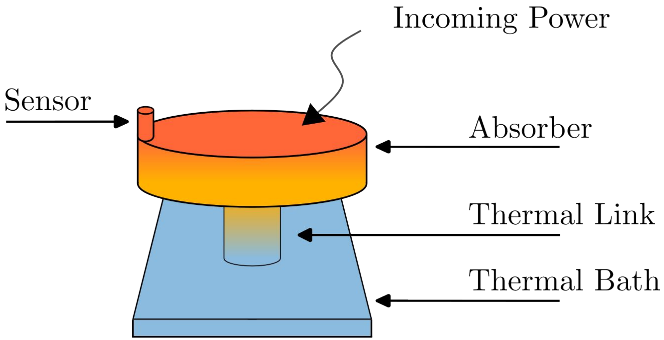
A proposal for QUBIC next generation

- ➔ Multichroic antenna-coupled Magnetic Microbolometer (MMB)
  - Multiple observation bands in a single pixel avoid the use of the dichroic
  - Novel detector based on the Magnetic Microcalorimeter (MMC)

- ➔ A microwave SQUID multiplexer readout system
  - Promising technology for high-sensitivity readout
  - High-multiplexing factor

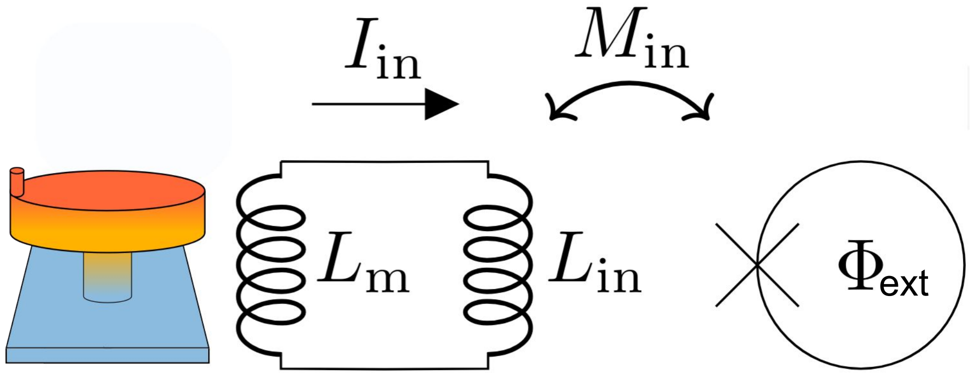
- ➔ Room temperature electronics
  - A system based on a software-defined radio scheme is proposed due to its adaptability to different experiments requirements
  - FPGA-based system enables high scalability and flexibility

Novel detector: Magnetic Microbolometer (MMB)



- ➔ Photons absorption increase the absorber temperature
- ➔ A Au:Er paramagnetic sensor embedded in a magnetic field changes its magnetization with the temperature
- ➔ The magnetic flux passing through the sensor changes, generating a measurable signal

MMB readout

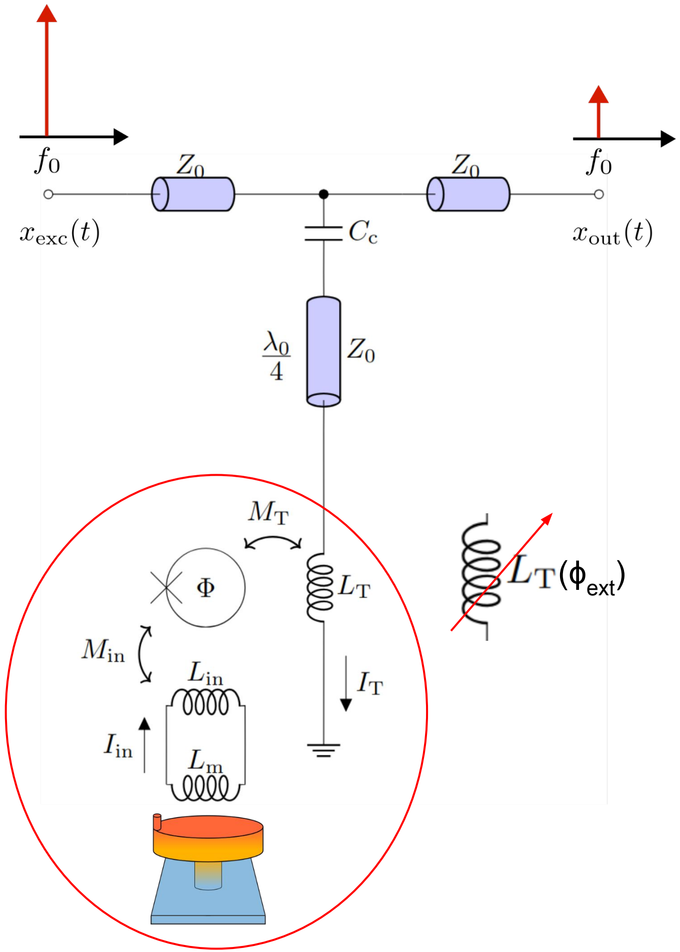


- ➔ Magnetic flux is readout with a radio frequency Superconductive Quantum Interference Device (rf-SQUID)
- ➔ The supercurrent in the rf-SQUID follows

$$I_{\rm s} = -I_{\rm c} \sin\left(\frac{2\pi\Phi_{\rm ext}}{\Phi_0} + \frac{2\pi L_{\rm s} I_{\rm s}}{\Phi_0}\right)$$

Detector Signal

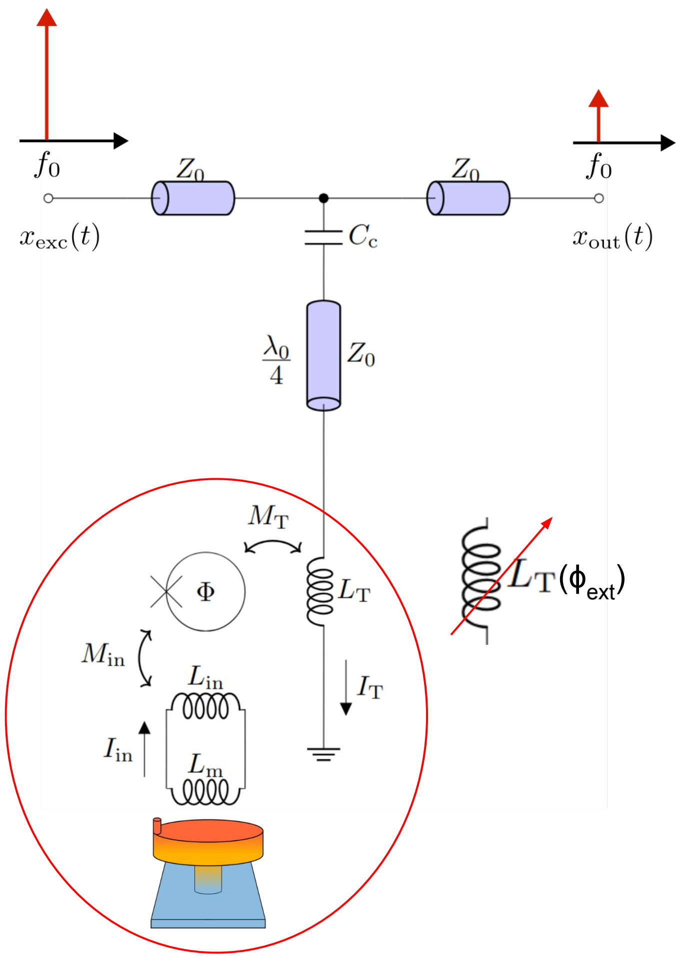
rf-SQUID readout



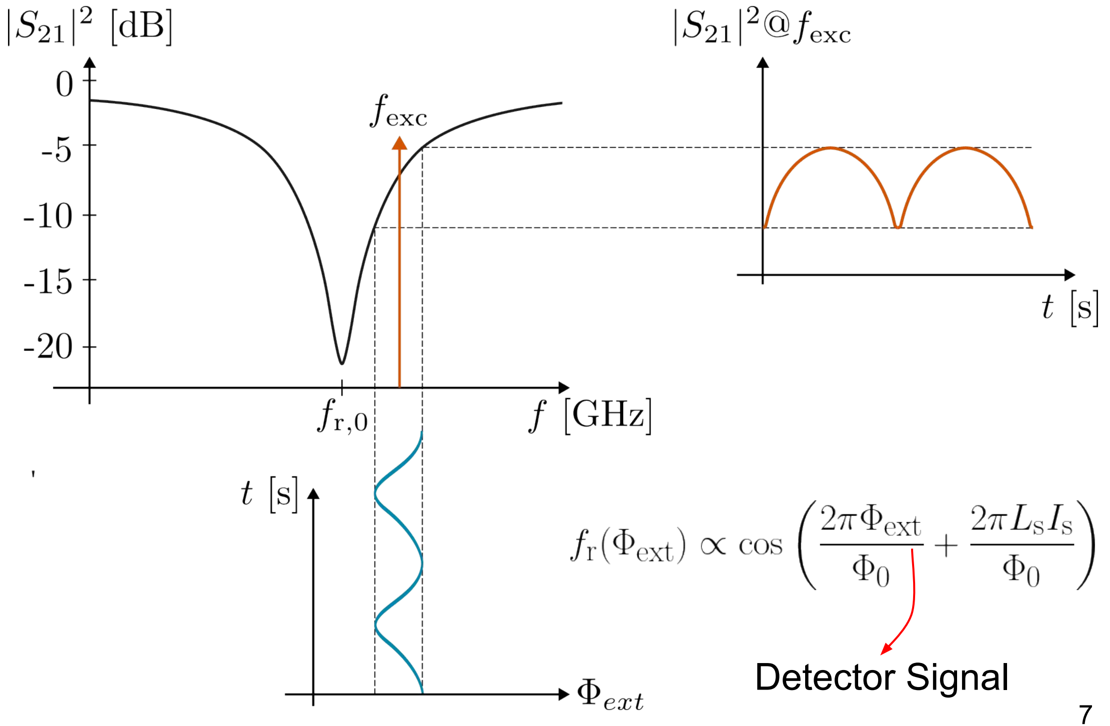
➔ rf-SQUID coupled to a resonator

➔ Inductance as a function of external magnetic flux

rf-SQUID readout



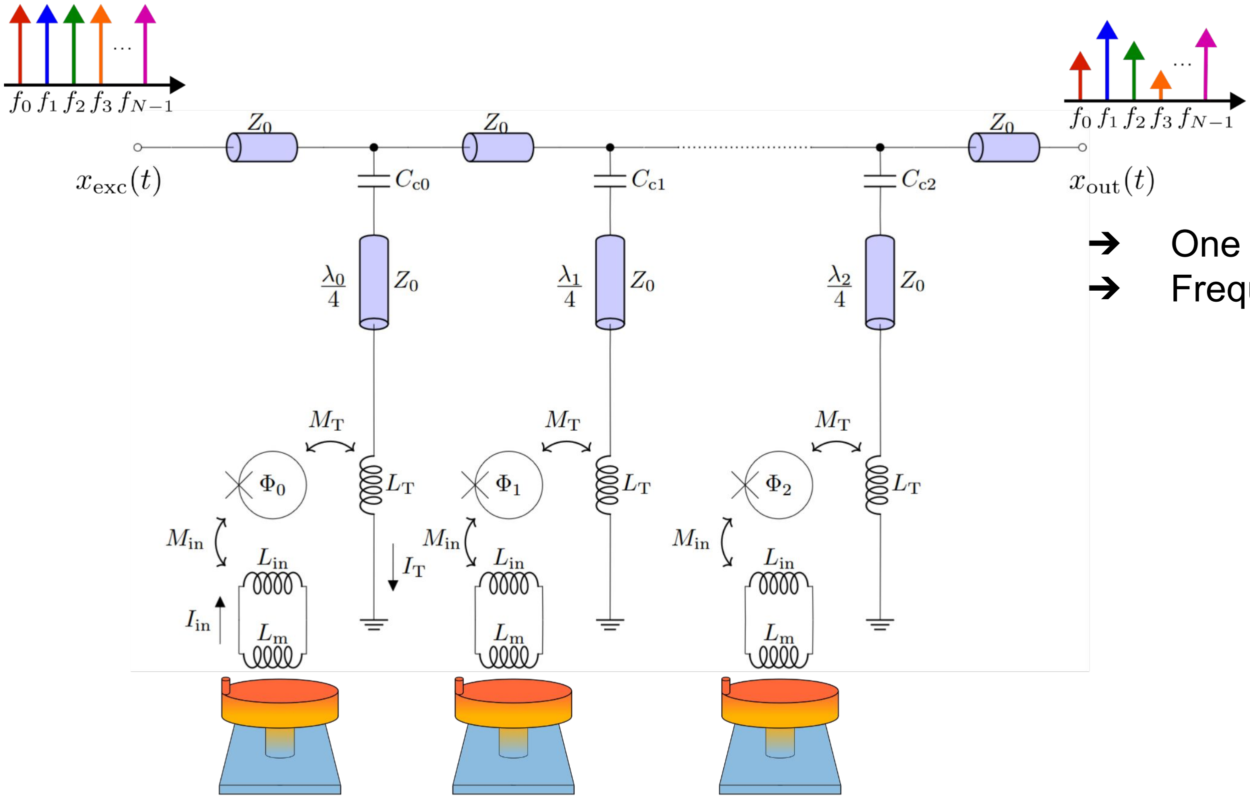
- ➔ rf-SQUID coupled to a resonator
- ➔ Inductance as a function of external magnetic flux
- ➔ Detector signal shifts the resonator response (s_{21})
- ➔ **A readout tone monitors the resonator state**



$$f_r(\Phi_{ext}) \propto \cos\left(\frac{2\pi\Phi_{ext}}{\Phi_0} + \frac{2\pi L_s I_s}{\Phi_0}\right)$$

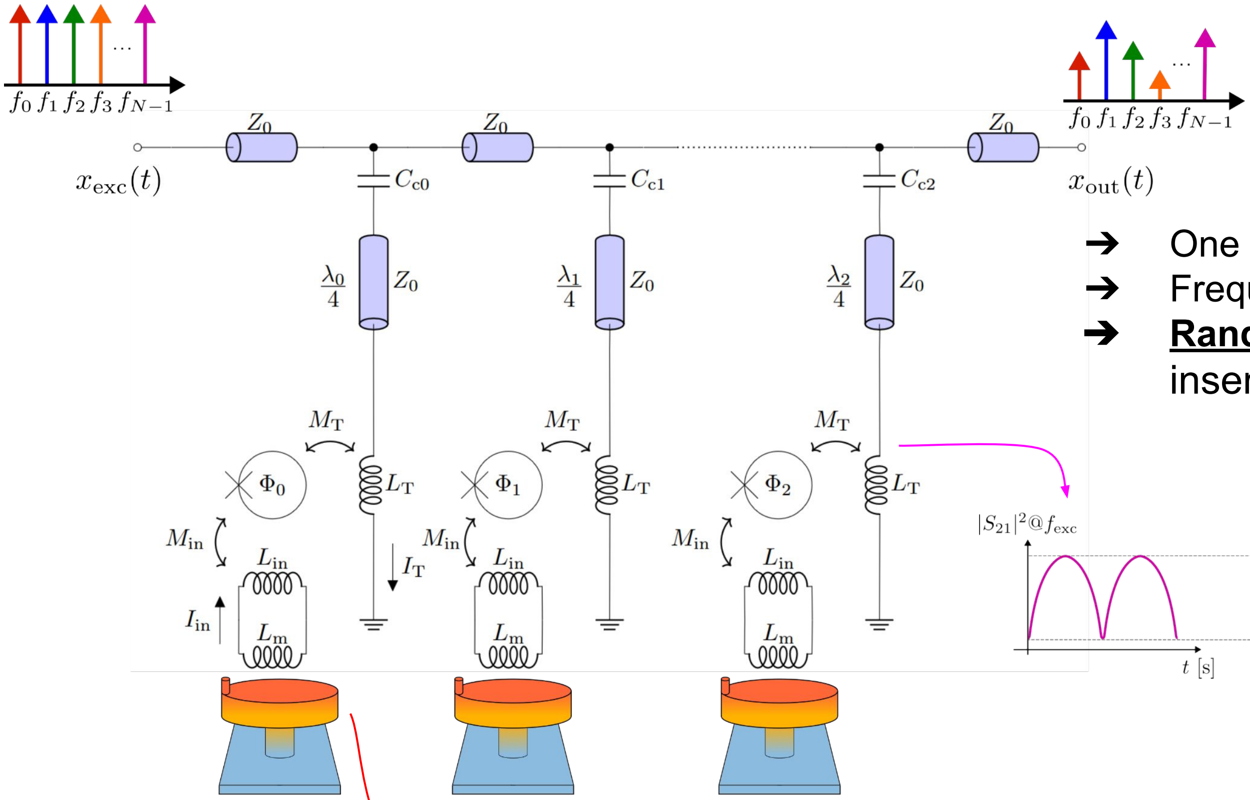
Detector Signal

The Microwave SQUID Multiplexer

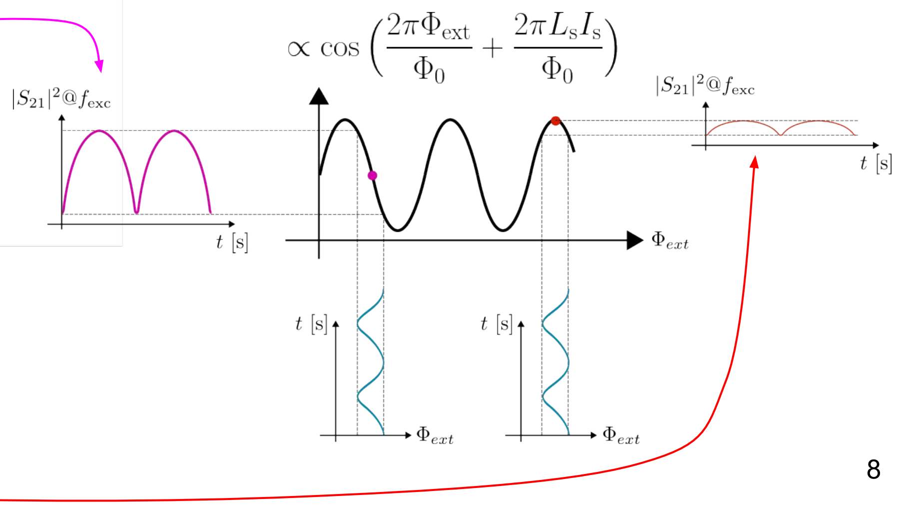


- ➔ One readout tone per channel
- ➔ Frequency division multiplexing

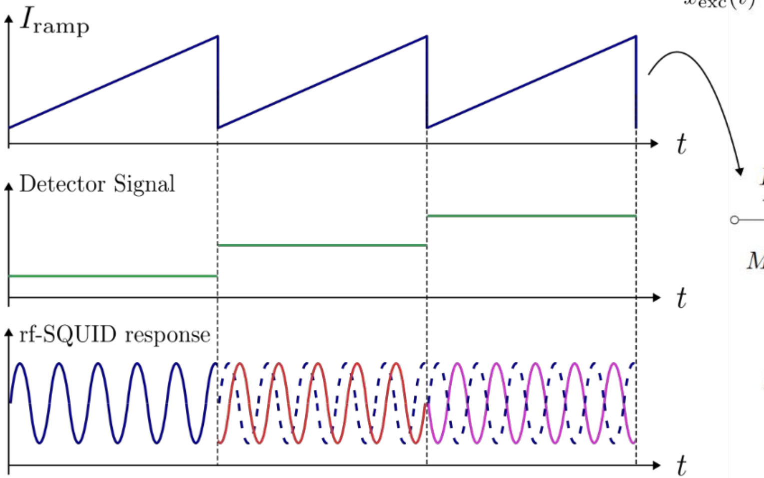
The Microwave SQUID Multiplexer

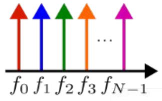


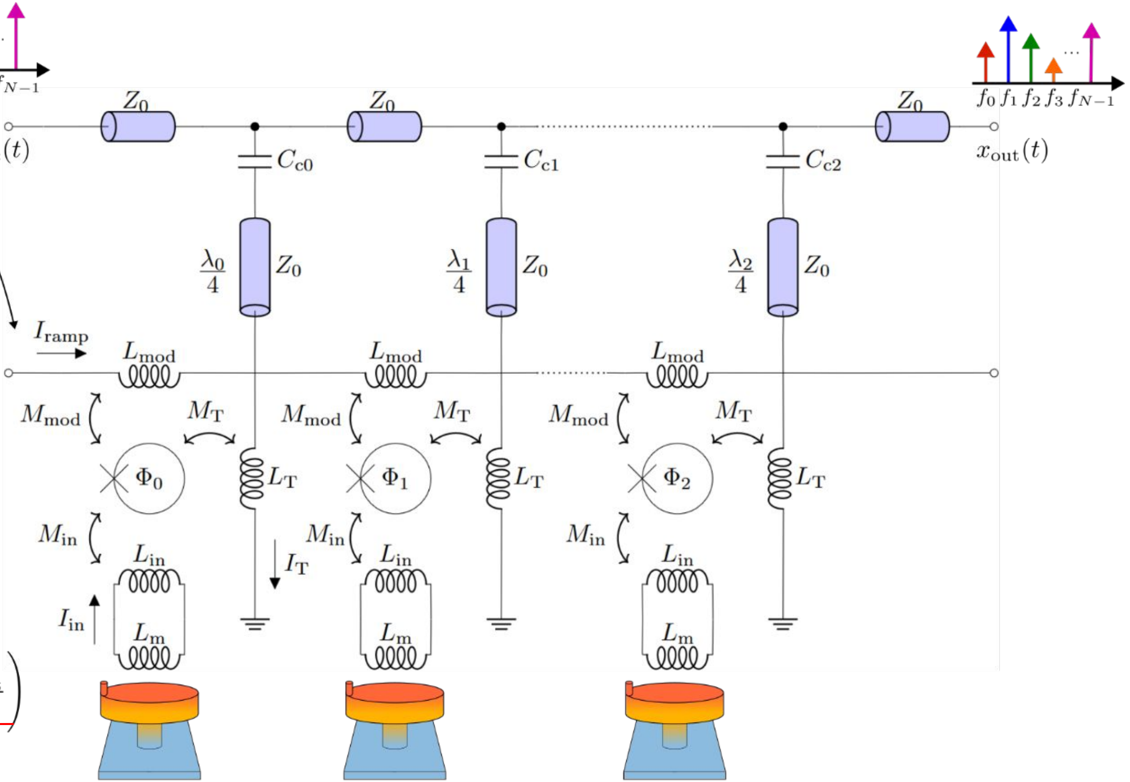
- ➔ One readout tone per channel
- ➔ Frequency division multiplexing
- ➔ **Random external flux problem:** insensitive SQUIDs



The µMUX: Fluxramp modulation







$$f_r(\Phi_{ext}) \propto \cos\left(2\pi \frac{I_{ramp} M_{mod} f_{ramp}}{\Phi_0} t + 2\pi \frac{\Phi_{det}}{\Phi_0} + 2\pi \frac{L_S I_S}{\Phi_0} + 2\pi \frac{\Phi_{init}}{\Phi_0}\right)$$

Fluxramp Signal

Detector Signal

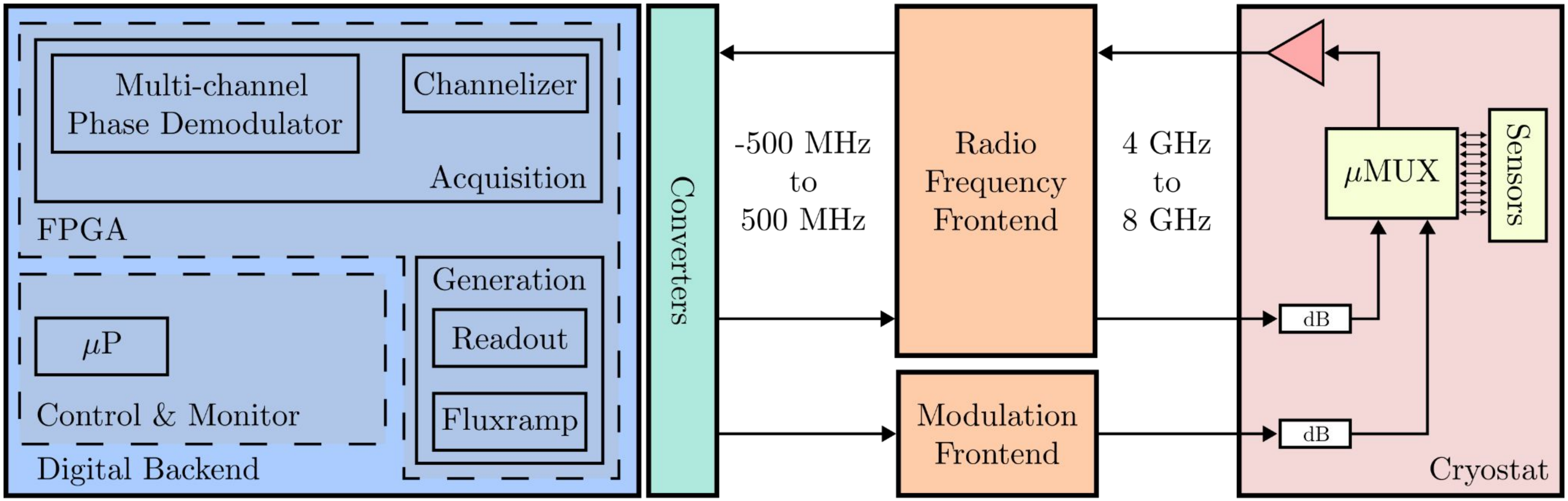
Random Phase

➔ Additional ramp signal periodically coupled flux to SQUID

➔ The detector signal modulates the SQUID signal's phase

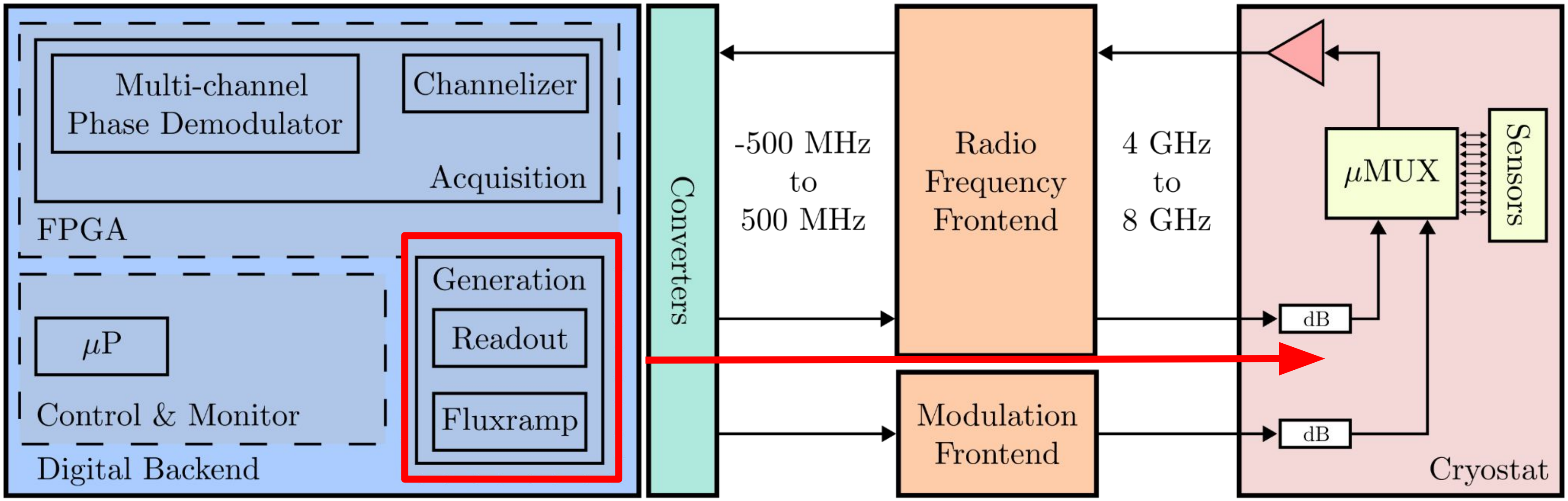
➔ <u>**A phase demodulator is required**</u>

Software-defined radio scheme



- ➔ Fluxramp and multi-tonal readout signals generation
- ➔ The readout tones are converted to analog by multiple DACs, each covering a complex bandwidth from -500 MHz to 500 MHz
- ➔ Readout signal up- and down-conversion from MHz to GHz band
- ➔ Signal acquisition and processing
  - ◆ Channelizer: signal sub-band splitting, filtering, down-sampling, and rf-SQUID recovery.
  - ◆ Fluxramp demodulation

Software-defined radio scheme



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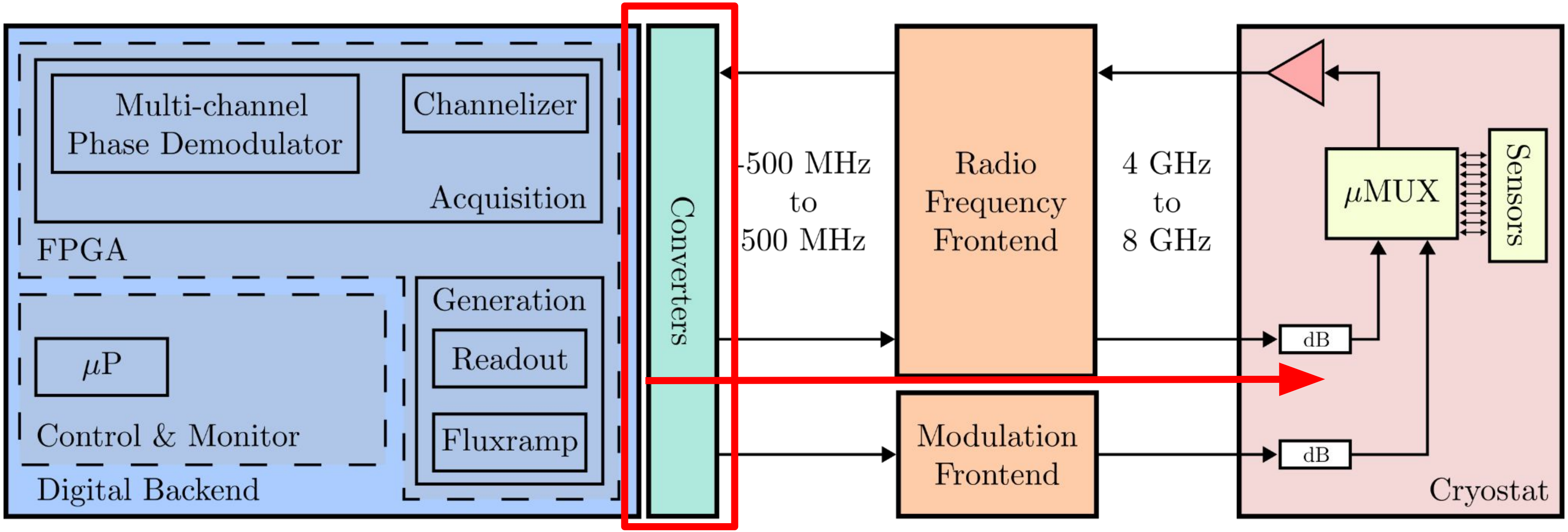

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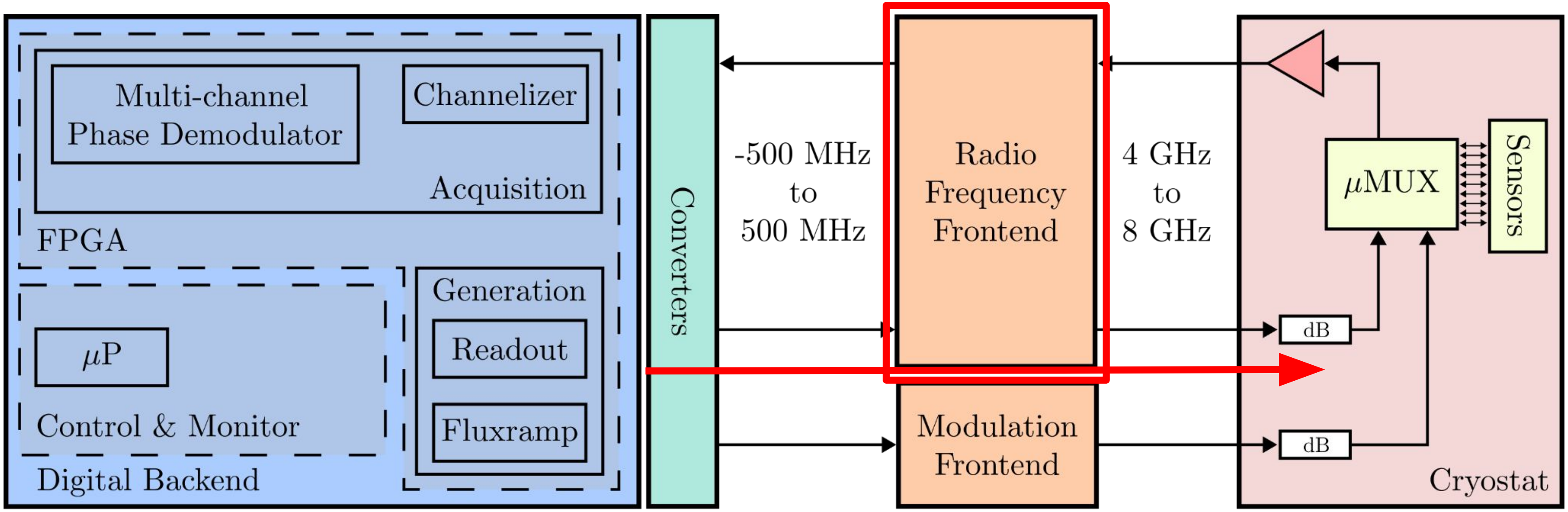

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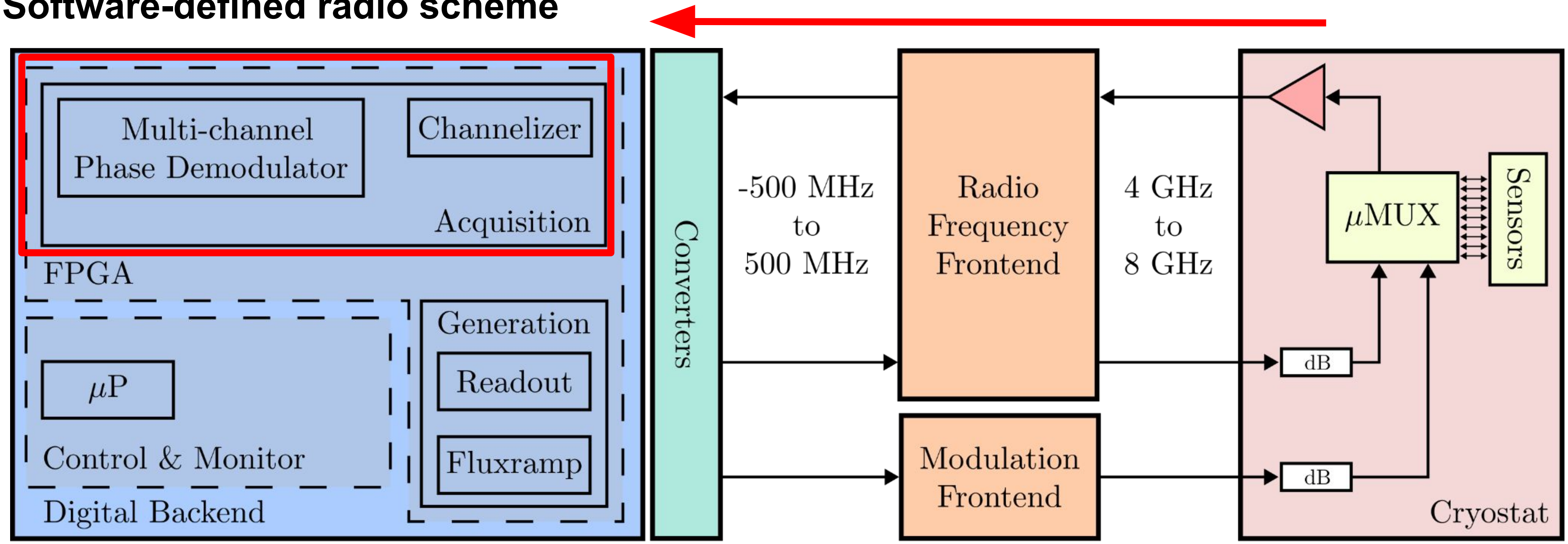

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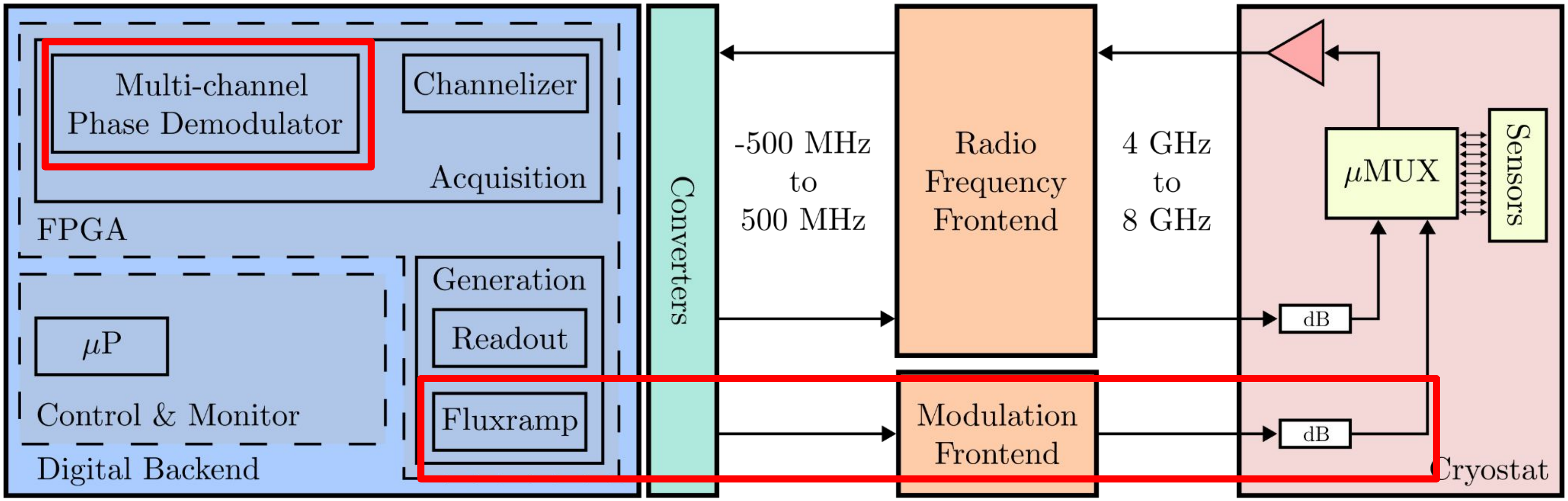
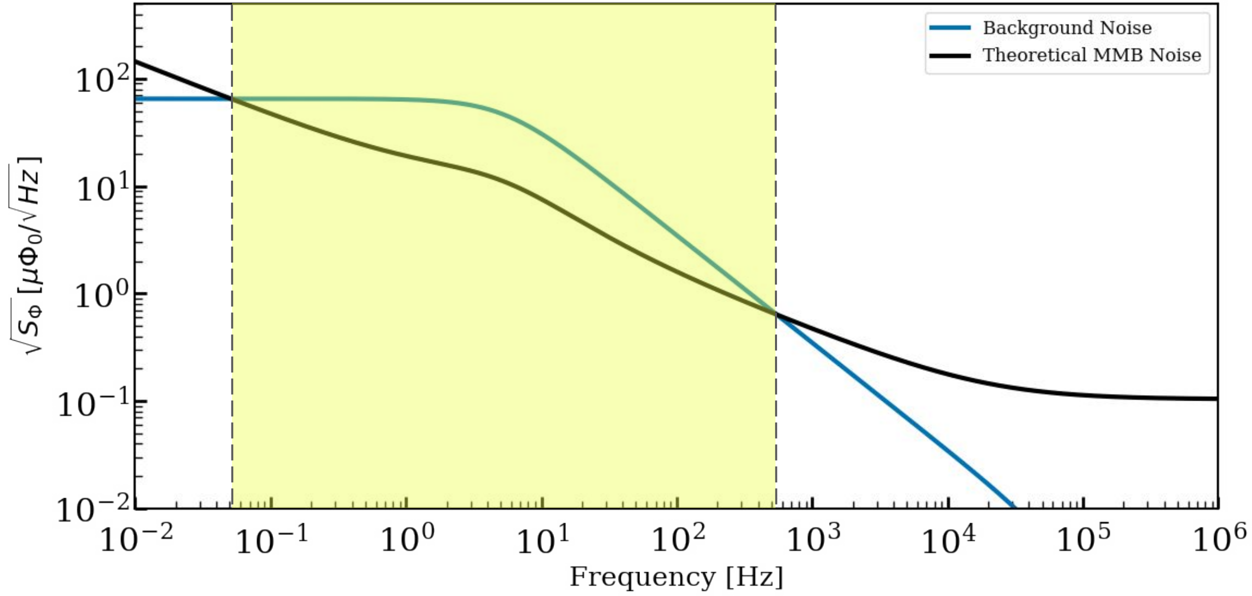
This work objectives



- ➔ Generation sub-system
  - ◆ **Fluxramp signal chain design**
  - ◆ **Integrate the signal generation system**
- ➔ Acquisition & Processing sub-system
  - ◆ **Demodulation of multichannel detector signals**
  - ◆ **Acquisition chain integration**
- ➔ **Readout System Validation**

Fluxramp signal noise requirement

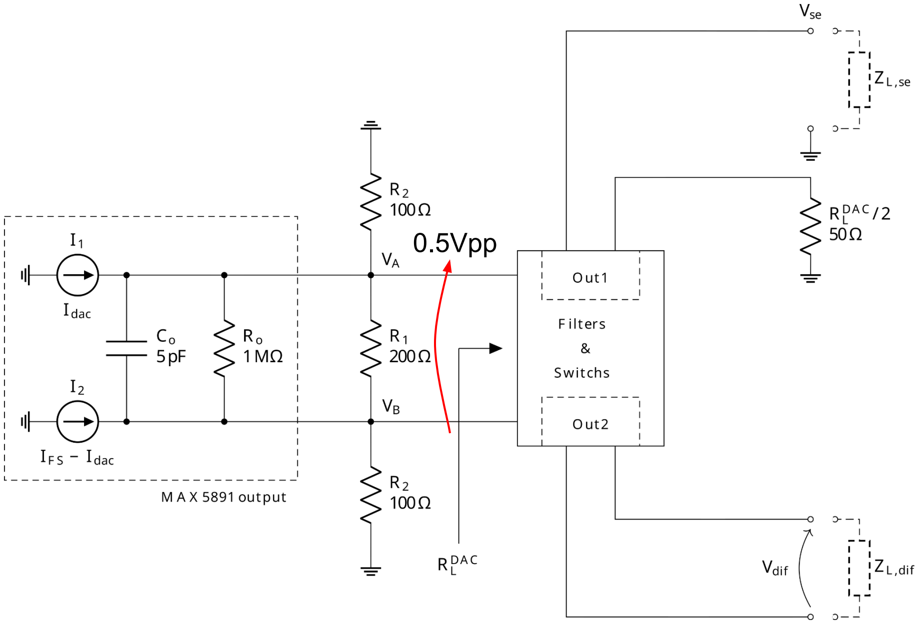
- ➔ Background noise > Detector noise > Readout noise
- ➔ Background Limited Photometry (BLIP) condition achieved from 0.045 Hz to 760 Hz

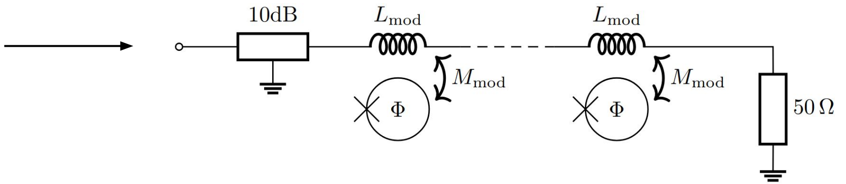


- ➔ **Fluxramp noise much less than 0.6 $\mu\Phi_0/\sqrt{Hz}$**

MSS analog frontend

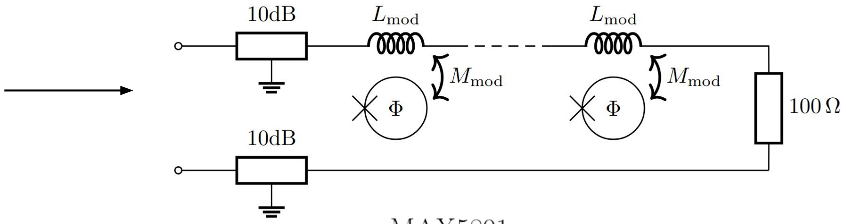
➔ Modulation Signal Synthesizer (MSS) around the 16 bits DAC MAX5891





Cryogenic single-ended setup

Cryogenic differential setup



➔ Theoretical noise spectral density

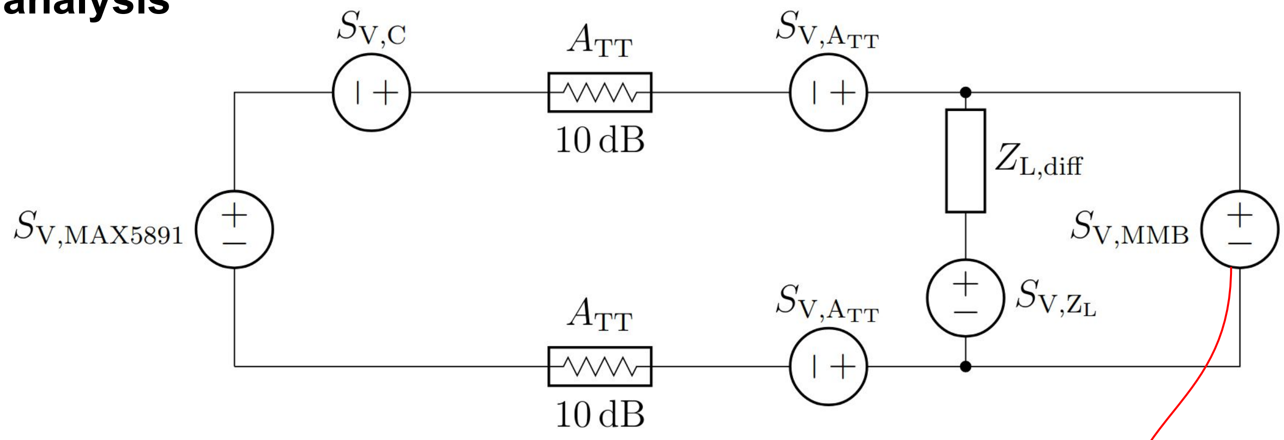
$$S_{\mathrm{MAX5891}}\Big|_{\mathrm{dBm}} = 1\,\mathrm{dBm} - \mathrm{SNR}_{\mathrm{dB}} - 10\log_{10}\left(\frac{f_s^{\mathrm{MAX5891}}}{2}\right) = -164\,\frac{\mathrm{dBm}}{\mathrm{Hz}}$$

20mA full scale current in a double-terminated 100Ω load

10MHz clock signal

➔ 10dB attenuation enables coupling of 1 to 8 ϕ_0 and reduces fluxramp noise

MSS: Noise analysis



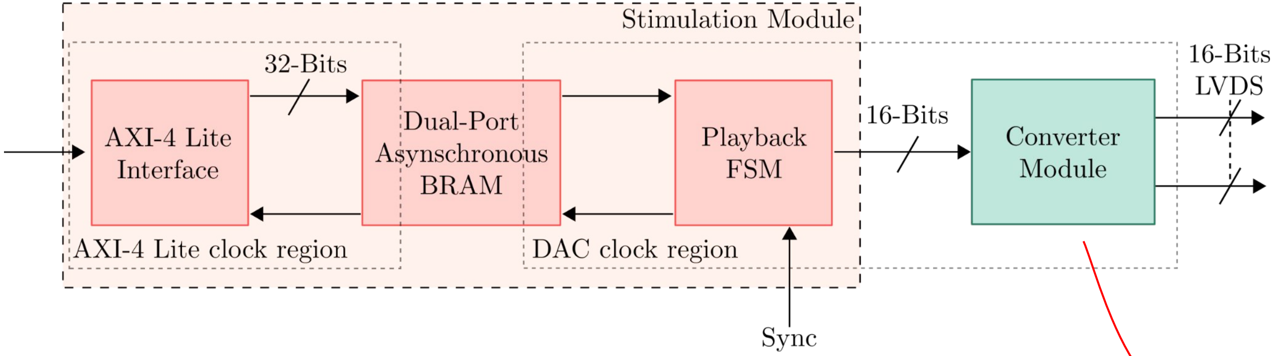
Source	Voltage Spectral Density (nV/√Hz)
DAC quantized noise	0.630 (considering attenuator)
Current to voltage converter	0.204 (considering attenuator)
Cryogenic attenuator	0.053
MSS load	0.149
Total Noise	0.683

Modulation line coupling
(Mmod = 2291 ϕ_0/A)

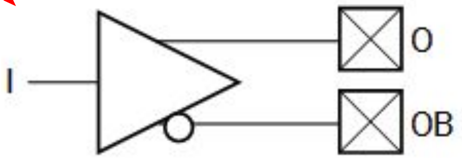
$$S_{V,MMB} = \frac{\sqrt{S_{\Phi,MMB}}}{M_{mod}} \cdot 100\,\Omega = 26.2 \frac{\mathrm{nV}}{\sqrt{\mathrm{Hz}}}$$

<u>MMB signal degraded by 0.034%</u>

MSS digital backend



MPSoC ZCU102

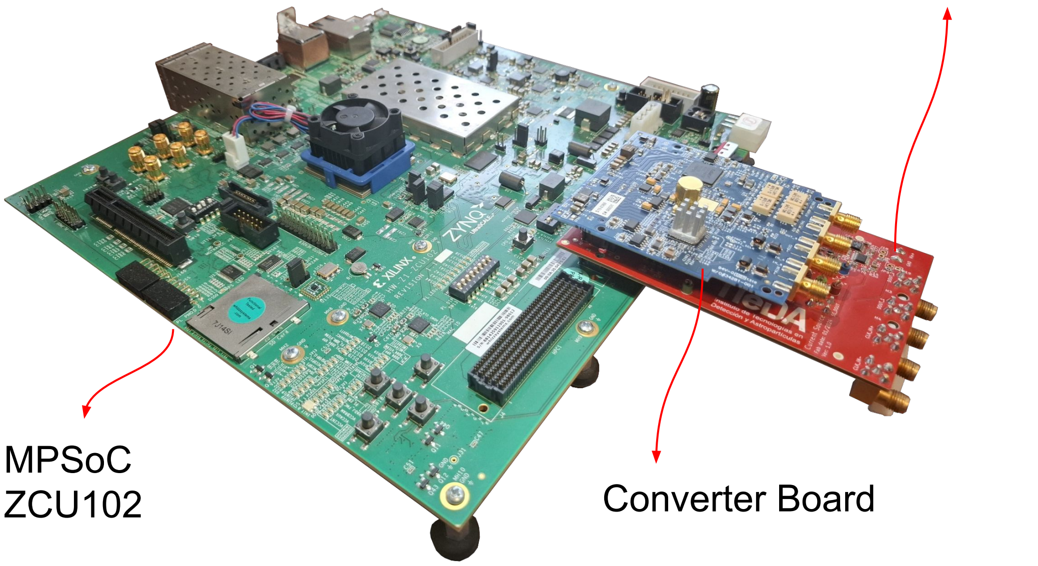


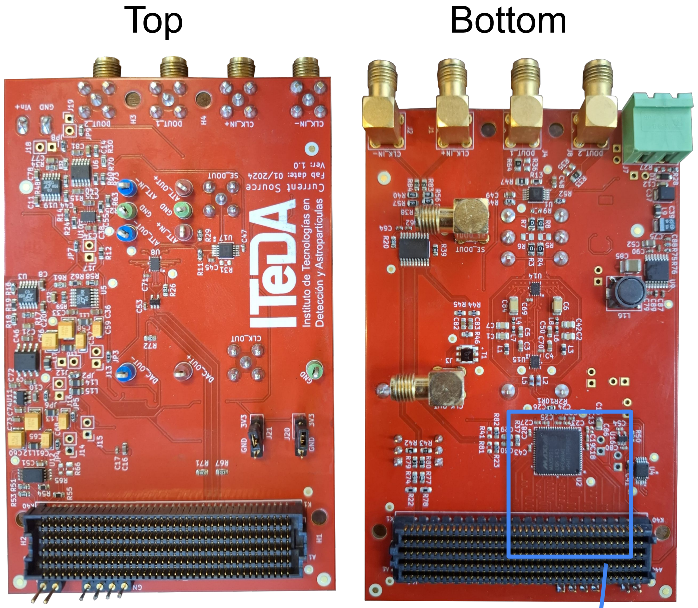
Differential Signaling Output Buffer

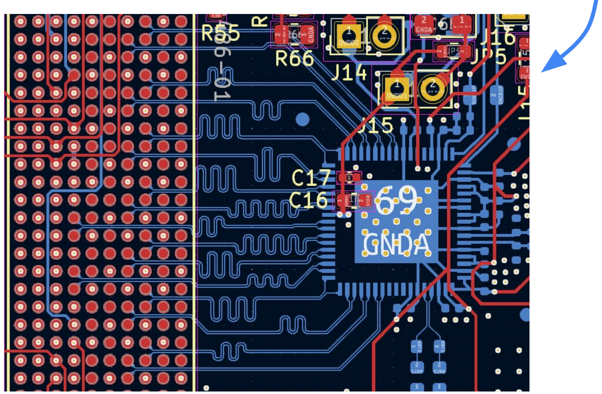
- ➔ MPSoC ZCU102 selected as digital backend
- ➔ Dual-port BRAM
  - ◆ Arbitrary waveform generation
  - ◆ Playback continuous signal
  - ◆ Real-time configuration using AXI-Lite protocol
- ➔ Synthesizable signal frequencies

$$\frac{f_{\mathrm{clk}}}{\mathrm{L}_{\mathrm{bram}}} \geq f_{\mathrm{out}} > \frac{f_{\mathrm{clk}}}{2}$$

Signal generation system

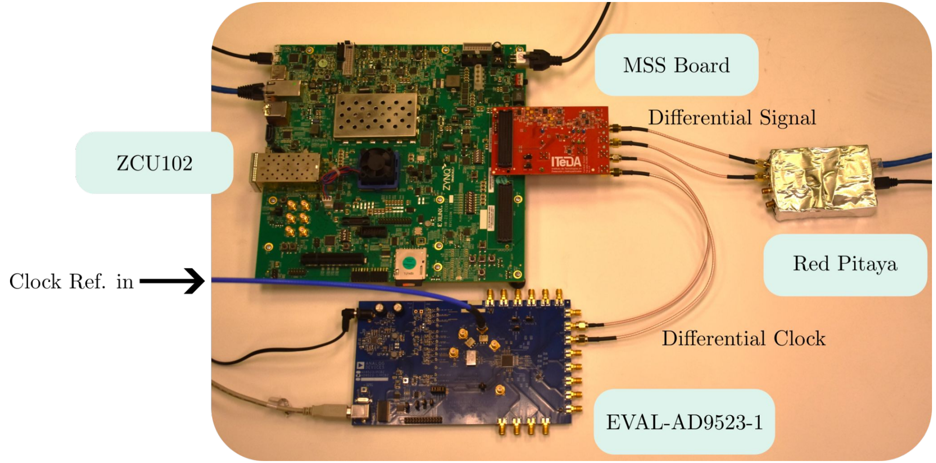




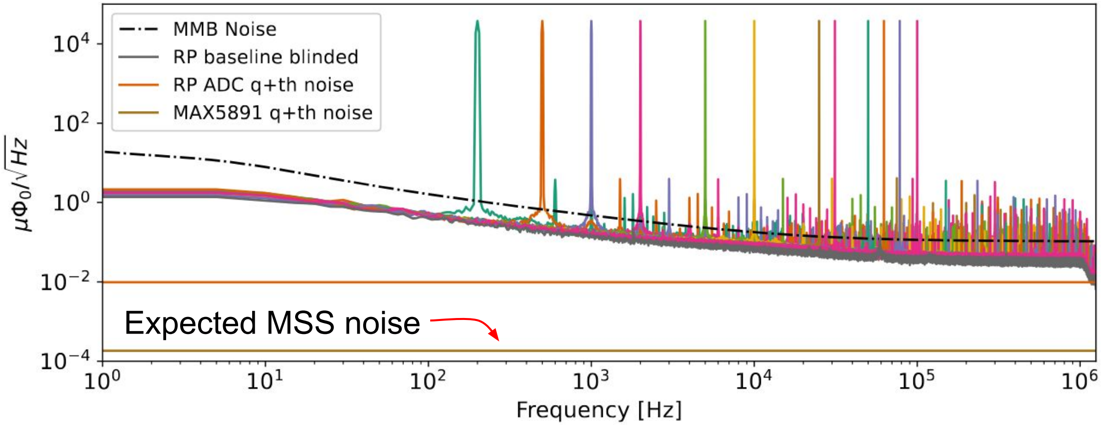


- ➔ Stackable board system (MPSoC-MSS-Converter board)
  - ◆ Dual high density FMC+ connector
  - ◆ Via-in-pad for FMC+ male-female connection
- ➔ 16 differential microstrip transmission lines
- ➔ Intra- and inter-line delay matching

MSS characterization

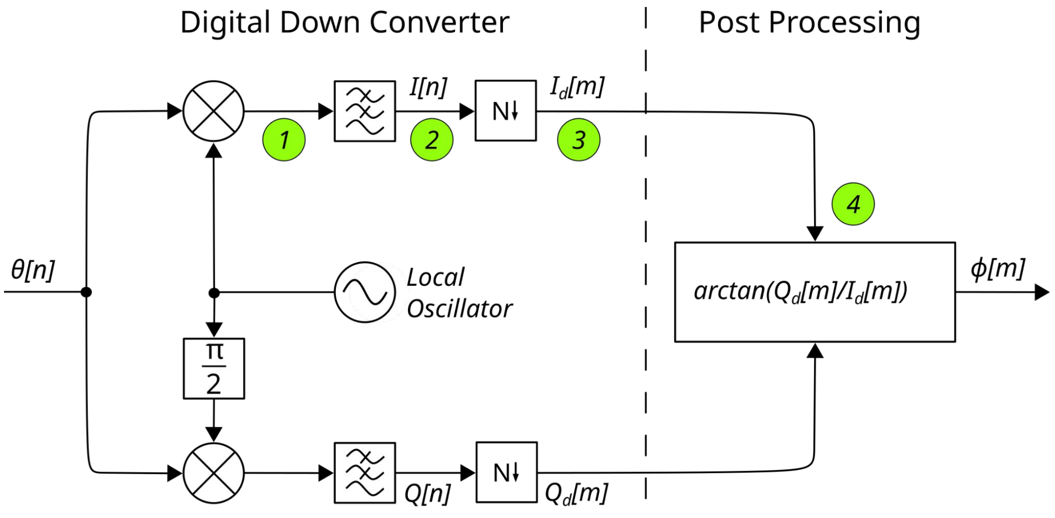


- Clock generated by the EVAL-AD9523-1 board
- Signal acquisition using Red Pitaya
- 200Hz to 100kHz signal generation
- Spurious free dynamic range (SFDR) and total harmonic distortion (THD) characterization
- SFDR=80dBc and THD < 0.02% consistent with specified in datasheet
- Red Pitaya noise is dominant (added 26dB gain amplifier)



<u>Baseline noise below MMB noise</u>

Multi-channel quadrature demodulator



$$\phi[m] = \arctan\left(-\frac{\sum_{n=0}^{N-1} \theta[n] \sin(\Omega_{\text{mod}} n)}{\sum_{n=0}^{N-1} \theta[n] \cos(\Omega_{\text{mod}} n)} \right)$$

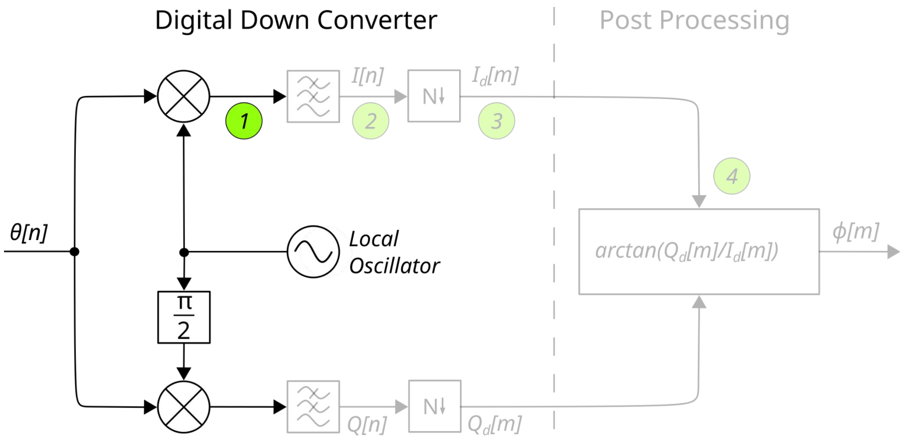
➔ Correlation method with the rf-SQUID signal for phase demodulation

$$f_{\text{mod}} = \frac{I_{\text{ramp}} M_{\text{mod}}}{\Phi_0} f_{\text{ramp}}$$

➔ Phase recover from the arctan function of the real and imaginary signal relation

➔ Time-division Multiplexing (TDM) of multiple rf-SQUID signals through a buffer

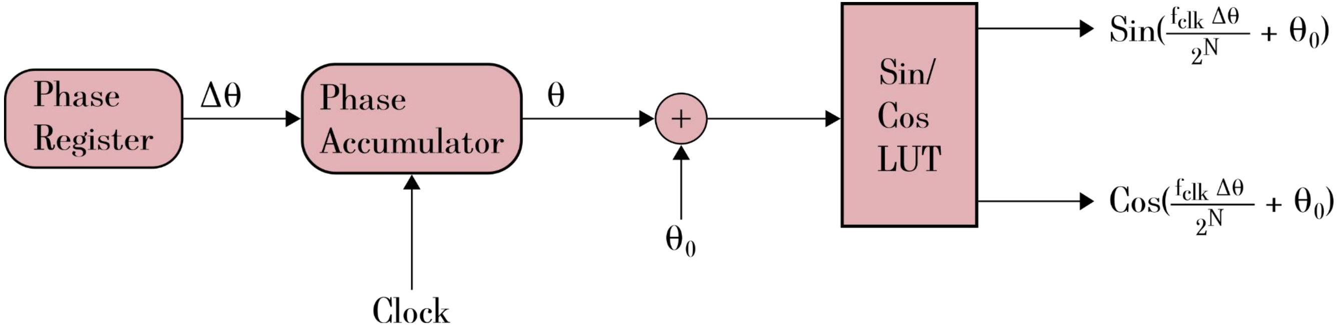
Down-conversion implementation



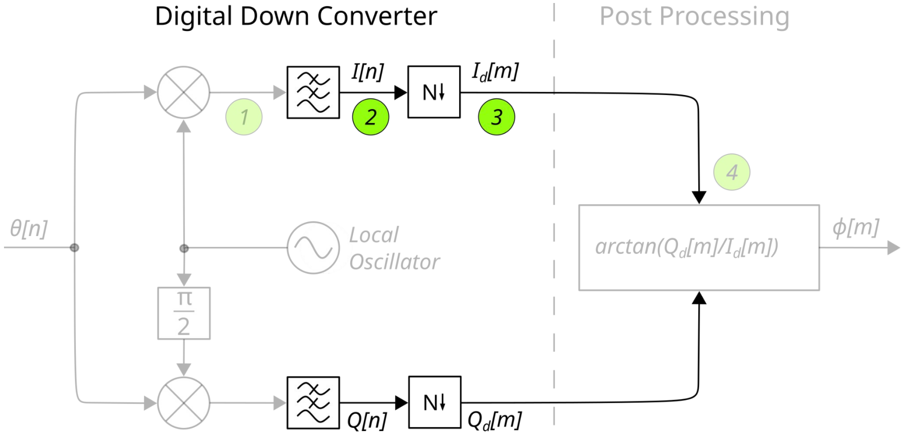
1 Down-conversion

- ➔ DSP slice for efficient multiplication
- ➔ Complex signal generated by a DDS
- ➔ A phase value is generated as the index for a memory preloaded with sine and cosine samples
- ➔ The phase value is generated by cyclically adding the Phase Register value to the Phase Accumulator
- ➔ θ_0 sets the initial phase
- ➔ One phase register for each input signal to be multiplexed in time

<u>Direct Digital Synthesizer</u>



Filter implementation



$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + \dots + b_N z^{-N}}{1 + a_1 z^{-1} + a_2 z^{-2} + \dots + a_N z^{-N}}$$

General Digital Filter Form

$a_x = 0$

$b_x = 1$

$$H(z) = 1 + z^{-1} + z^{-2} + \dots + z^{-N}$$

Average Filter

2 Filtering

➔ No multiplier needed

➔ Rectangular window function

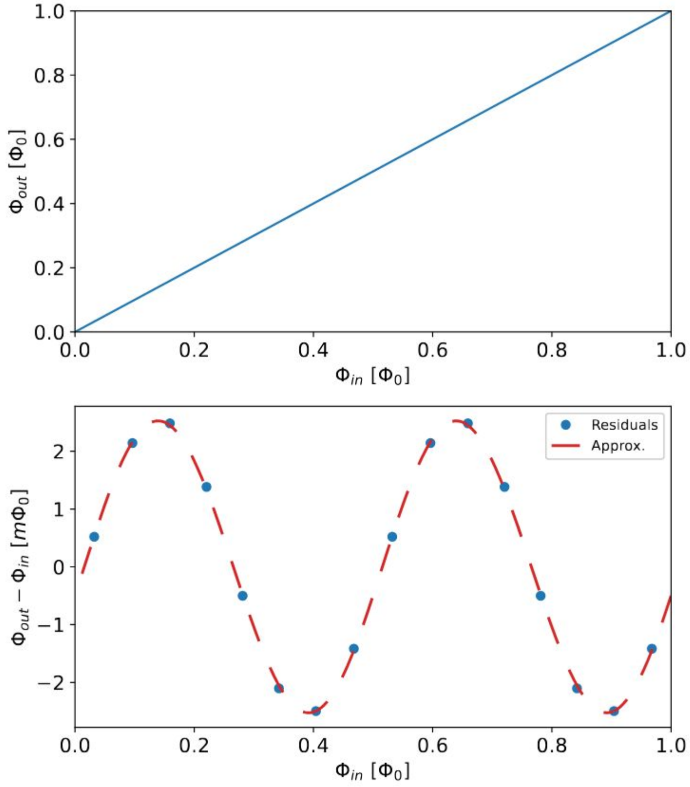
➔ A buffer stores the sum of the N elements in the FPGA implementation

3 Downsampling

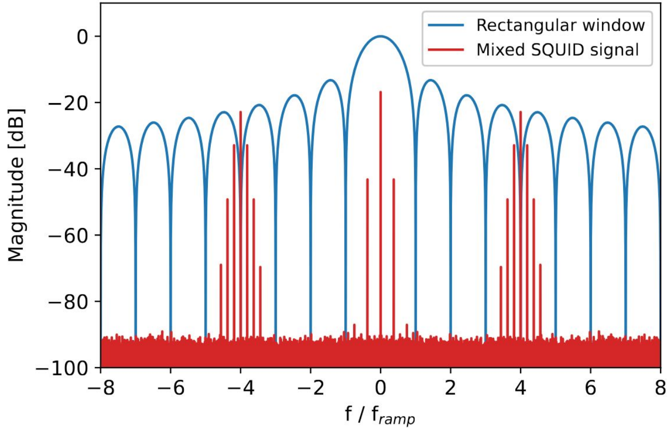
➔ One sample is output every N elements

➔ **Spectral aliasing**

Nonlinear error

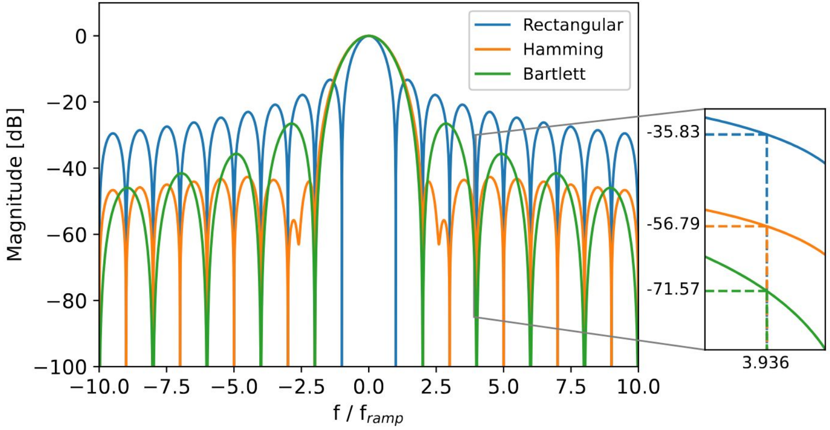


- ➔ Many groups reported non-linearities in the readout system
- ➔ Detector signal simulated as a linear signal
- ➔ Residuals observed at twice the detector signal frequency after the demodulator output
- ➔ **<u>Conclusions: aliasing effects produced by the phase demodulator</u>**

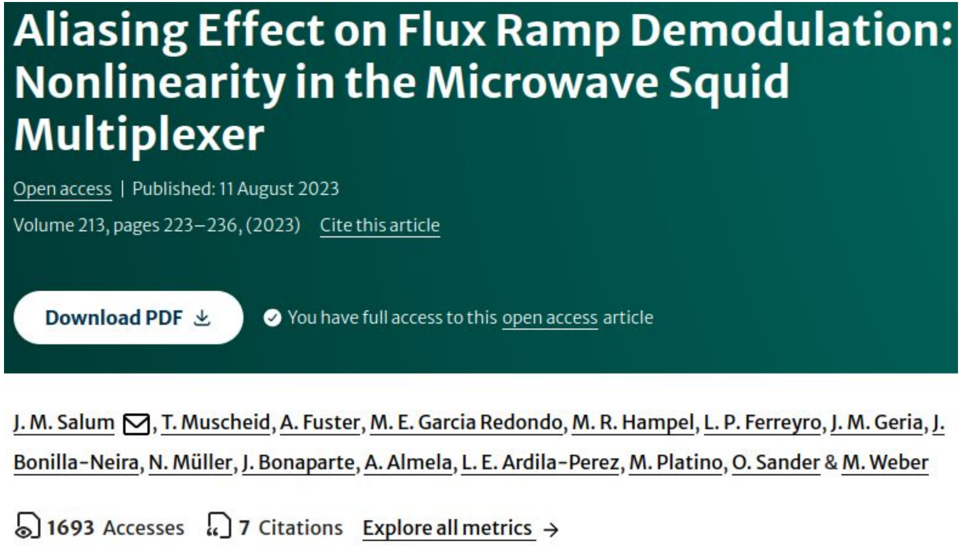


Weighted filter implementation

$$\phi[m] = \arctan\left(-\frac{\sum_{n=0}^{N-1} \theta[n]\ \sin(\Omega_{mod} n) W[n]}{\sum_{n=0}^{N-1} \theta[n]\ \cos(\Omega_{mod} n) W[n]}\right)$$



- ➔ Adding a window function improves the attenuation at the expense of higher FPGA resource usage
- ➔ An improvement of **more than 35dB** achieved with the Bartlett window
- ➔ **<u>This work contributes with a publication</u>**



Aliasing Effect on Flux Ramp Demodulation: Nonlinearity in the Microwave Squid Multiplexer

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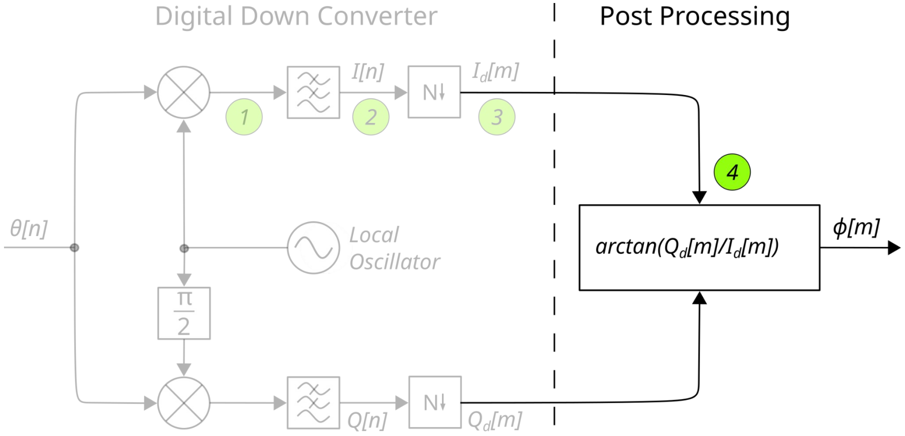
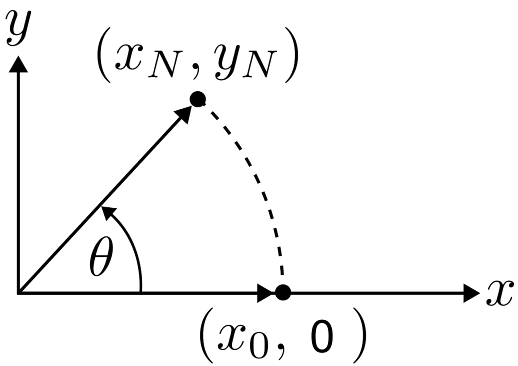
Arctan implementation



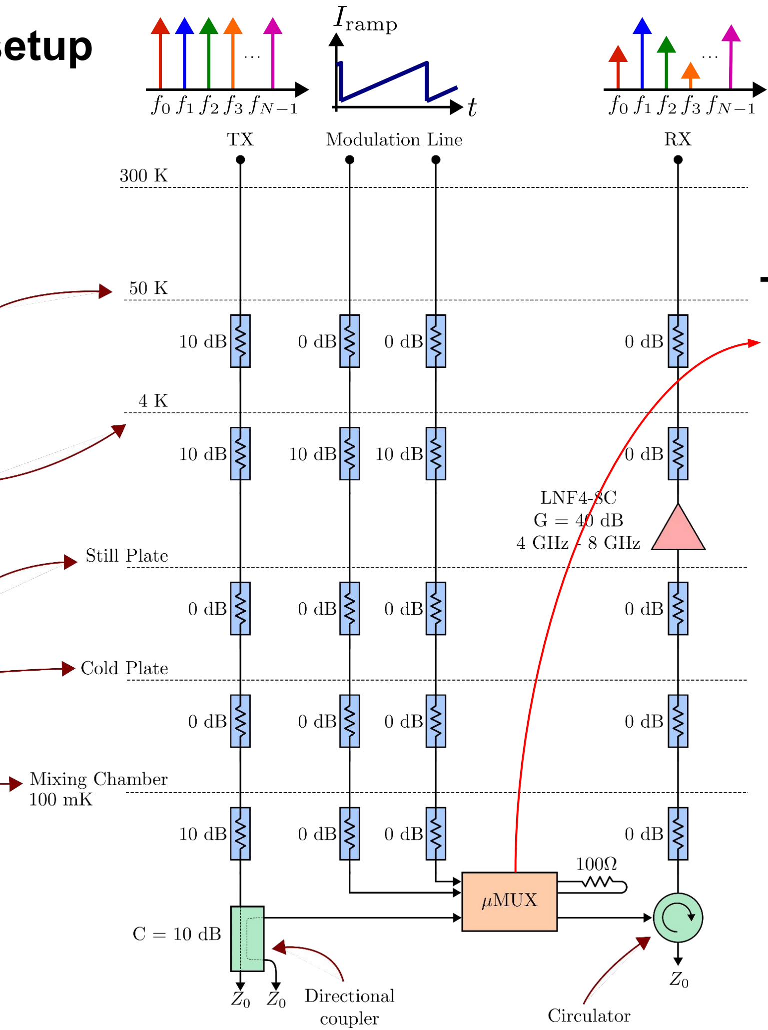


$$x[n+1] = x[n] - d[n] \cdot 2^{-n} \cdot y[n]$$
$$y[n+1] = y[n] - d[n] \cdot 2^{-n} \cdot x[n]$$

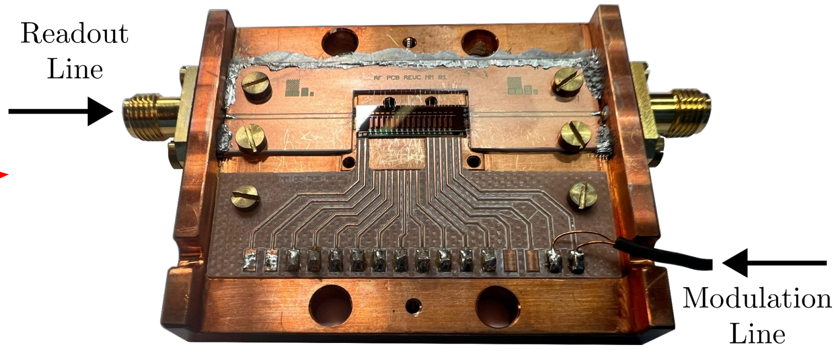
4 CORDIC algorithm

- ➔ Hardware efficient: requires only additions, subtractions and binary shifts
- ➔ A starting vector (x_0, 0) is iteratively rotated to the angle corresponding to arctan(y_N/x_N)
- ➔ The accumulated sum of the rotated angles provides the final result for the arctangent
- ➔ Adjustable precision: number of iterations determines the precision of the result

Cryogenic setup

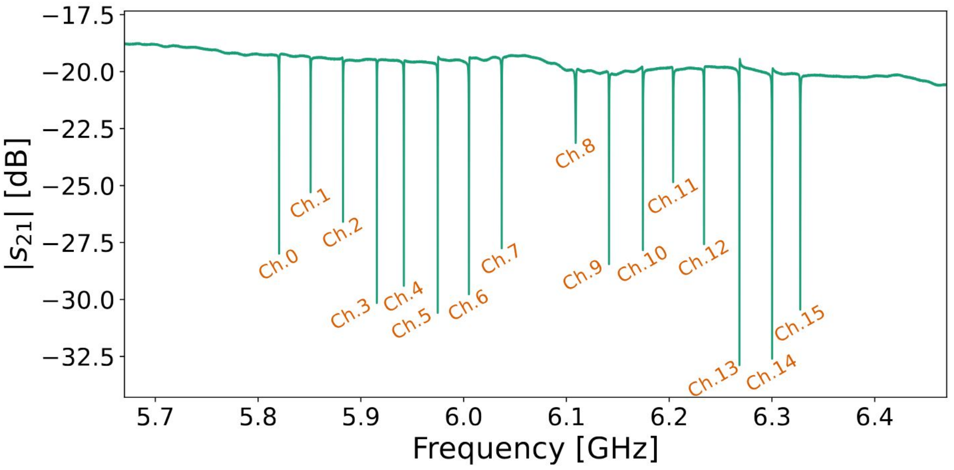


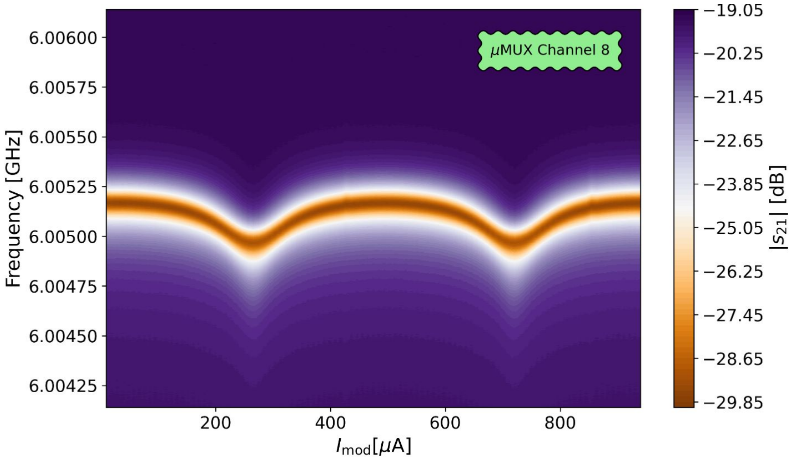
Microwave SQUID Multiplexer



- ➔ Cryostat to cooldown at sub-K temperatures
- ➔ 16-ch Microwave SQUID Multiplexer located at 100mK
- ➔ Readout signal attenuation to achieve -70dBm μMUX measurement
- ➔ The readout signal is amplified on the return path for optimal acquisition
- ➔ Differential fluxramp signal chain

µMUX characterization

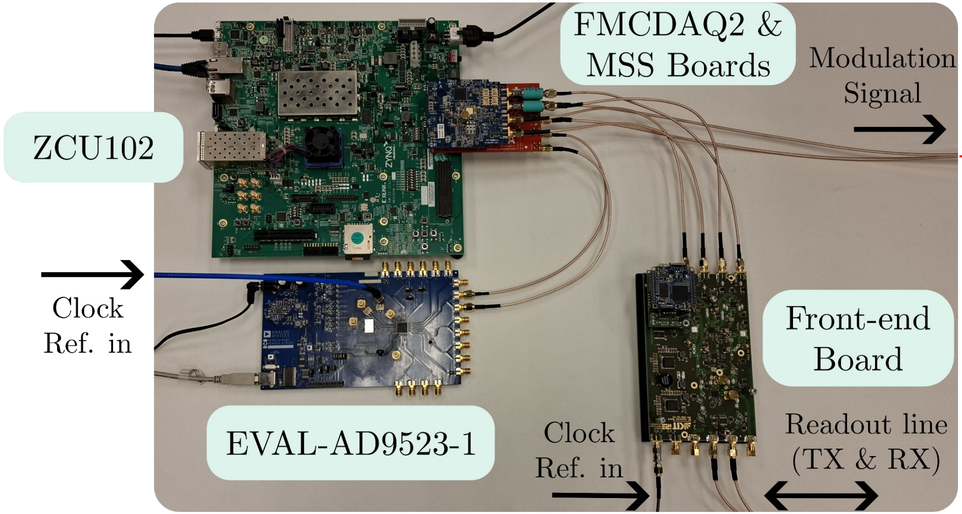


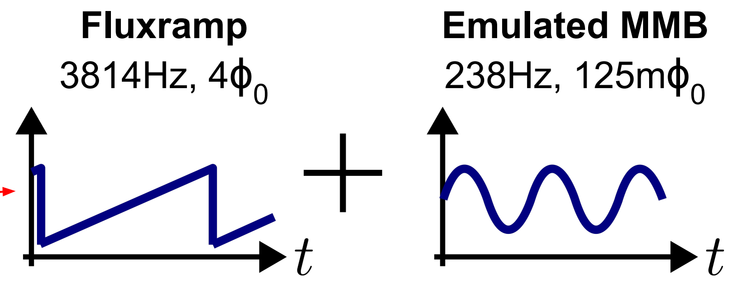


- ➔ µMUX channel measurement using commercial VNA and no modulation signal
- ➔ Obtained channel parameters:
  - ◆ Resonance frequencies
  - ◆ Bandwidths
  - ◆ Transmission depths

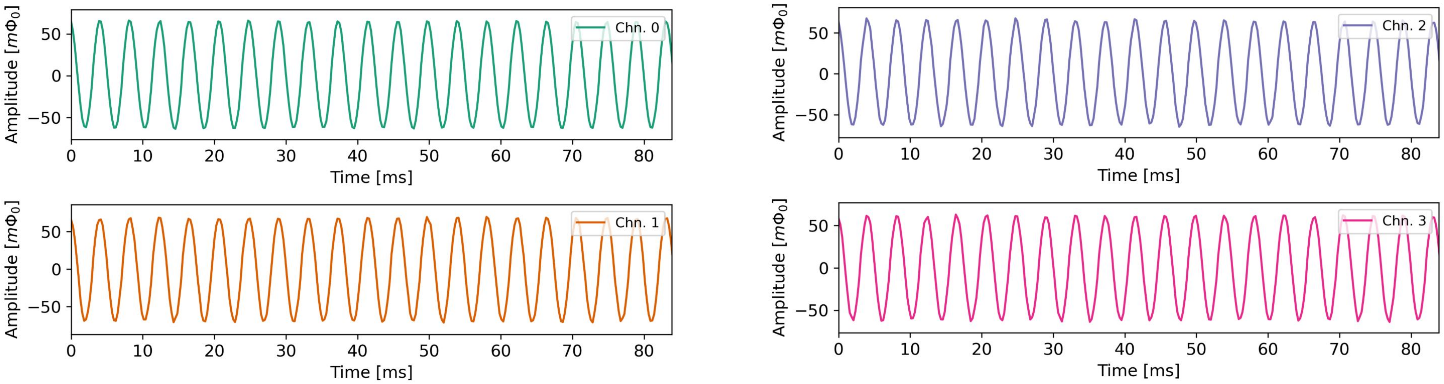
- ➔ Adding a DC current to the modulation line
- ➔ Swept over two SQUID periods
- ➔ Resonator response as a function of the flux signal
- ➔ Mmod calculated

System integration and validation

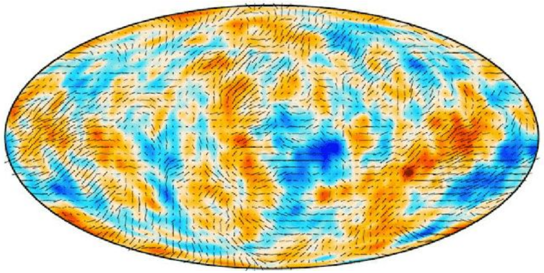




- ➔ Multi-channel quadrature demodulator integrated with a 4-channel channelizer.
- ➔ Complete readout assembly
- ➔ A 238 Hz, 125 $m\phi_0$ MMB signal was emulated (added to the modulation signal in the BRAM)
- ➔ **Successful detector signal demodulation**

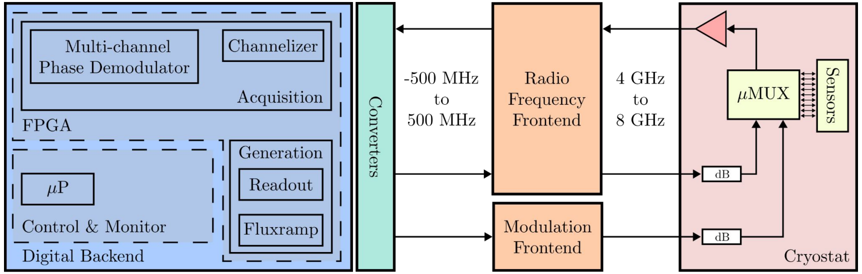


Summary



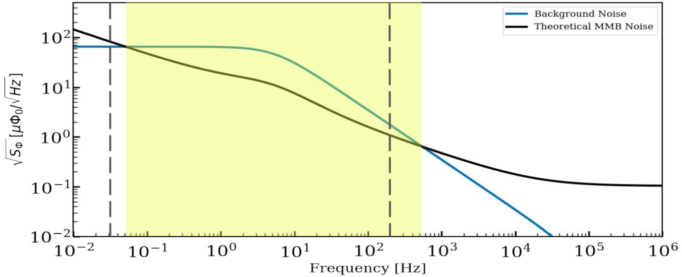
<u>Scientific motivation</u>

B-modes detection for inflation theory validation



<u>Experimental strategy</u>

Bolometric interferometry, Magnetic Microbolometer, Microwave SQUID Multiplexer, Software-defined radio



<u>Experimental requirement</u>

Integrated readout system

Background limited photometry

<u>Contributions</u>

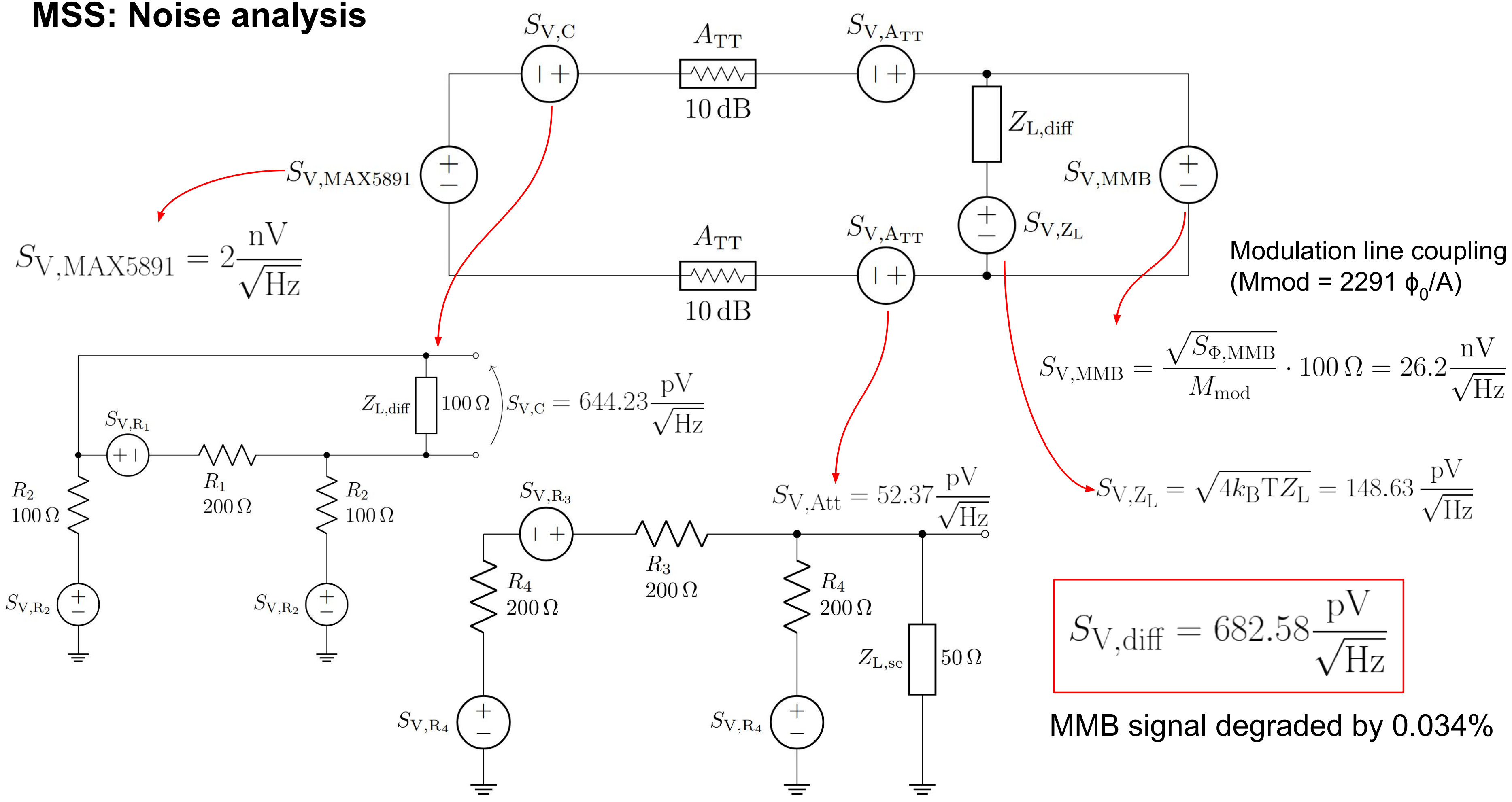
Integrated signal generation sub-system

Integrated acquisition & processing sub-system

Proposal for aliasing effect mitigation

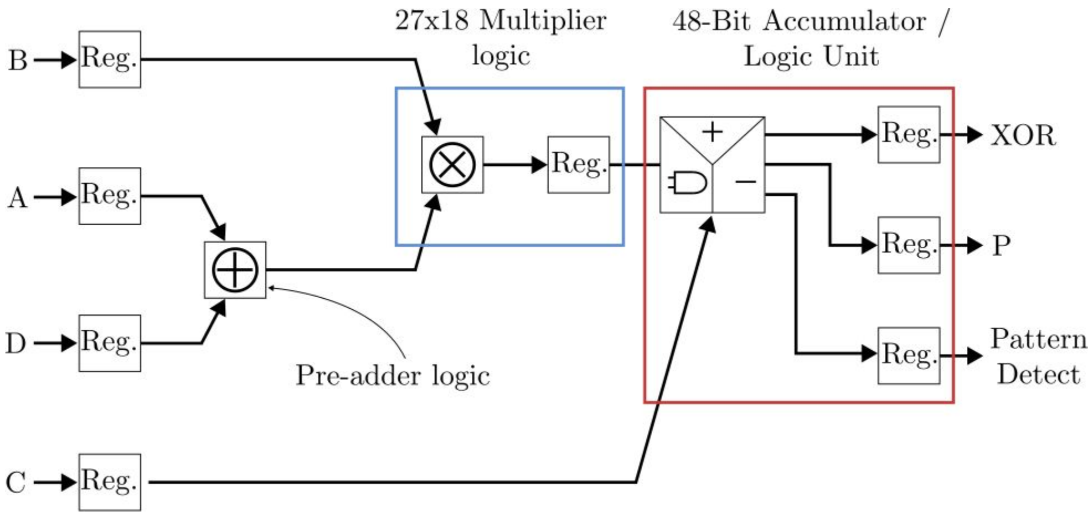
Back-up

MSS: Noise analysis



Multiplication implementation

1 Multiplier



- ➔ Intellectual Property Core DSP48E2
- ➔ Specialized block for efficient multiplication and accumulation (MAC operations)

Background noise

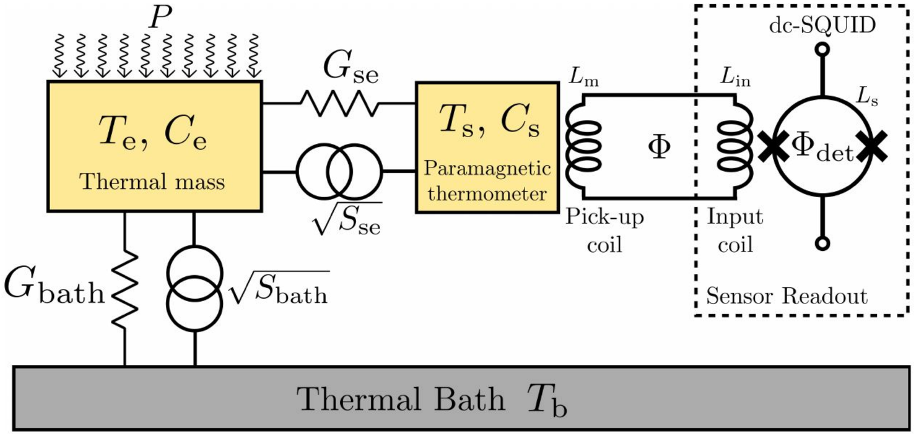
Center frequency

$$\mathrm{NEP}_{\gamma}^{2} = 2hf\,P_{\mathrm{opt}} + \frac{2P_{\mathrm{opt}}^{2}}{m\Delta f}$$

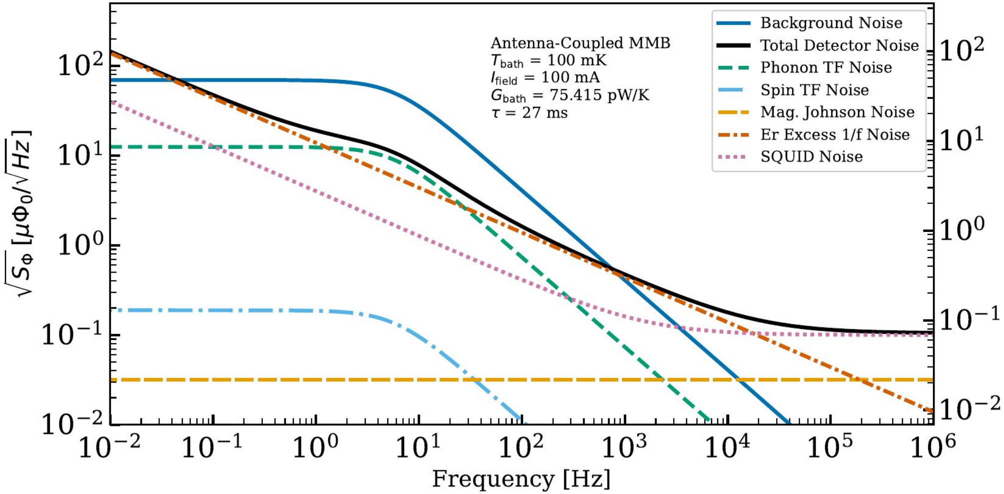
Signal power
absorber by the MMB

Bandwidth

MMB noise



P
G_{se}
T_e, C_e
Thermal mass
$\sqrt{S_{se}}$
T_s, C_s
Paramagnetic thermometer
L_m
Φ
Pick-up coil
L_{in}
Input coil
dc-SQUID
L_s
Φ_{det}
Sensor Readout
G_{bath}
$\sqrt{S_{bath}}$
Thermal Bath T_b



Antenna-Coupled MMB
T_{bath} = 100 mK
I_{field} = 100 mA
G_{bath} = 75.415 pW/K
τ = 27 ms
Background Noise
Total Detector Noise
Phonon TF Noise
Spin TF Noise
Mag. Johnson Noise
Er Excess 1/f Noise
SQUID Noise
$\sqrt{S_\Phi}$ [$\mu\Phi_0/\sqrt{Hz}$]
Frequency [Hz]

Fluxramp demodulator implementation