



**PROJECT 8**

# Front-End Readout for Project 8

April 14, 2026

**Noah S. Oblath**  
For the Project 8 Collaboration



PNNL is operated by Battelle for the U.S. Department of Energy

# Brief Introduction to CRES and Project 8

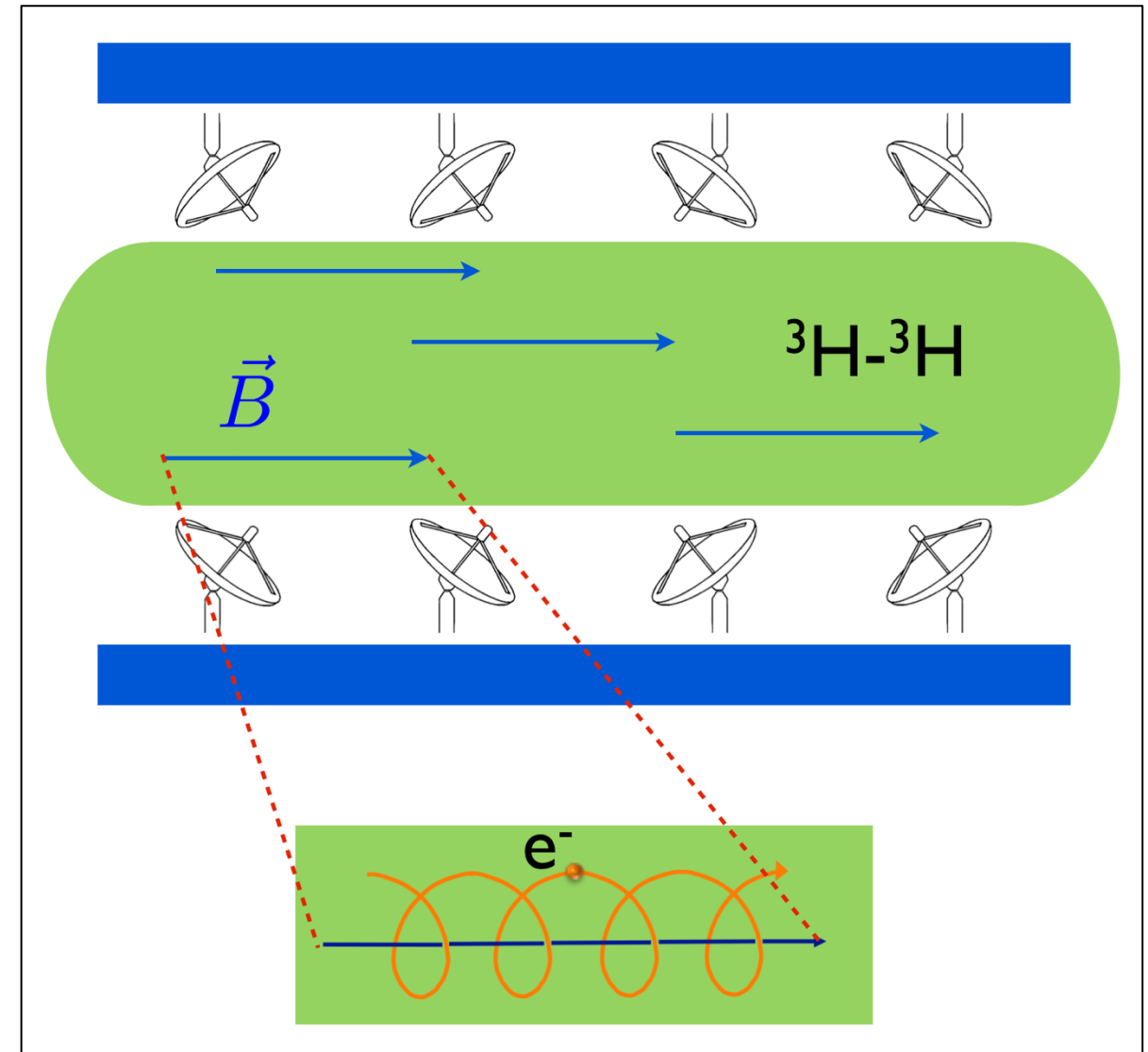
- CRES = Cyclotron Radiation Emission Spectroscopy

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e} \quad \text{Cyclotron radiation frequency}$$

- Tritium endpoint frequencies:

$B$	0.95 T	0.02 T
$\omega_\gamma$	26 GHz	560 MHz

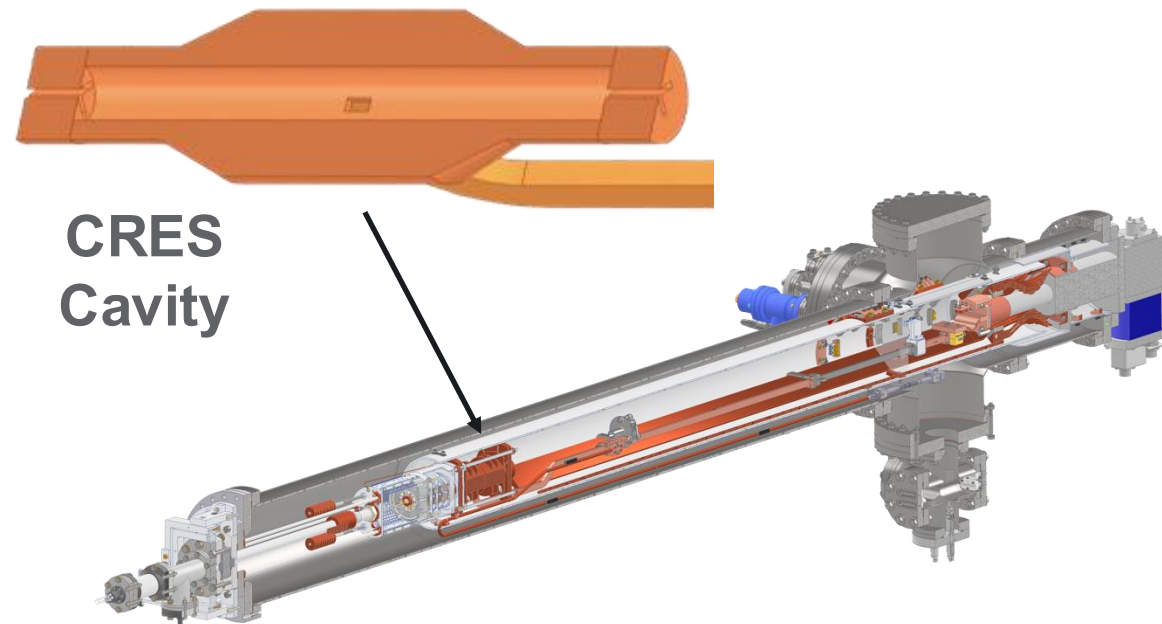
- Experiment requires careful radiation detection and readout chain
- Project 8 will combine CRES with an atomic tritium source to be the next-generation of tritium neutrino mass measurement



# Two Cavity-Based CRES Experiments

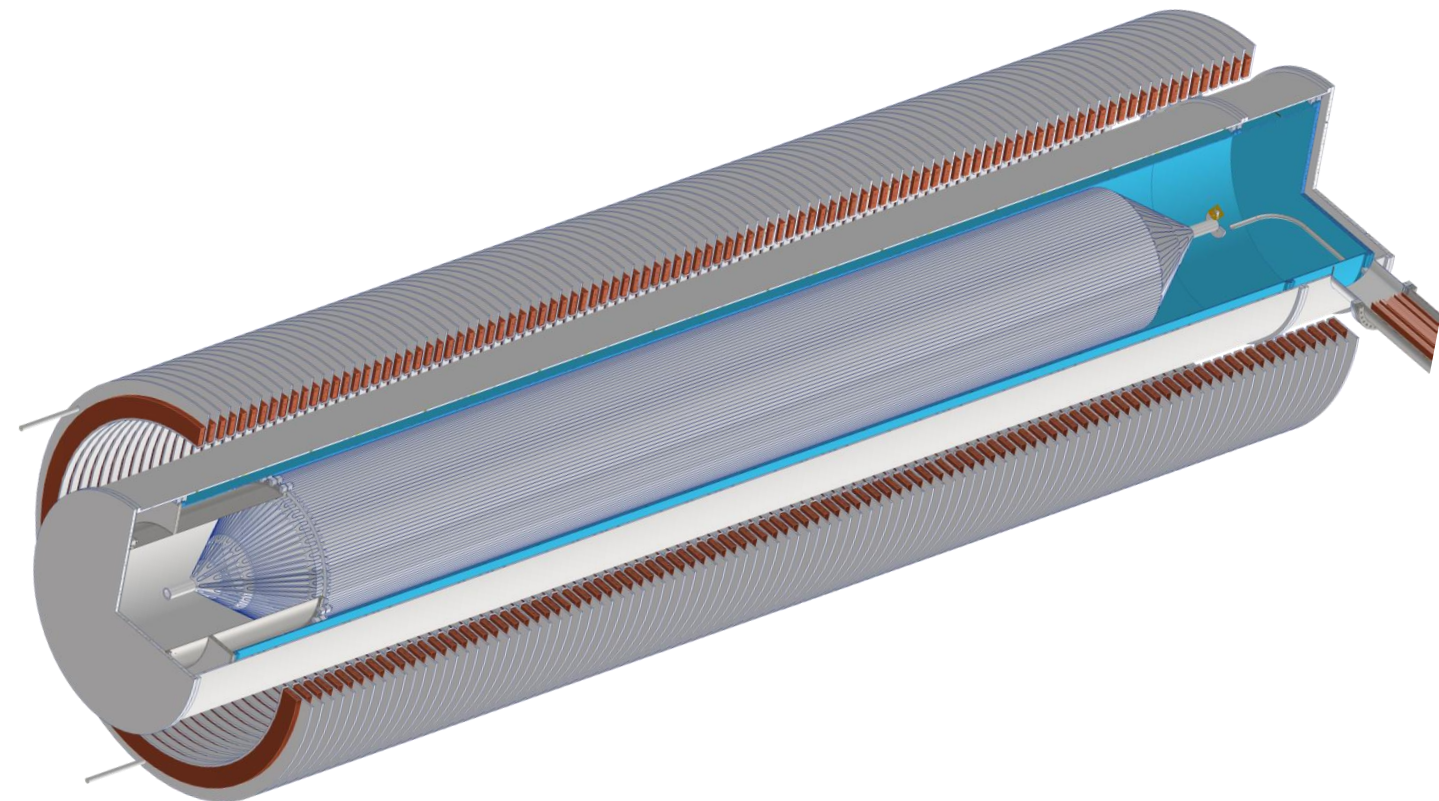
## Cavity CRES Apparatus (CCA)

- Signal extraction: rectangular waveguide
- Frequency: 26 GHz

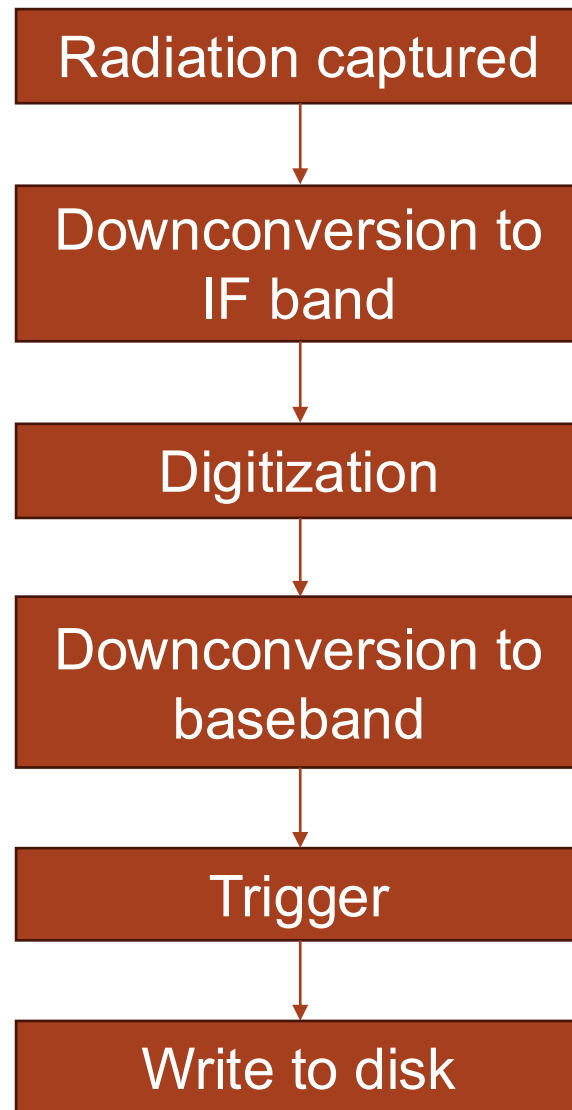


## Low Frequency Apparatus (LFA)

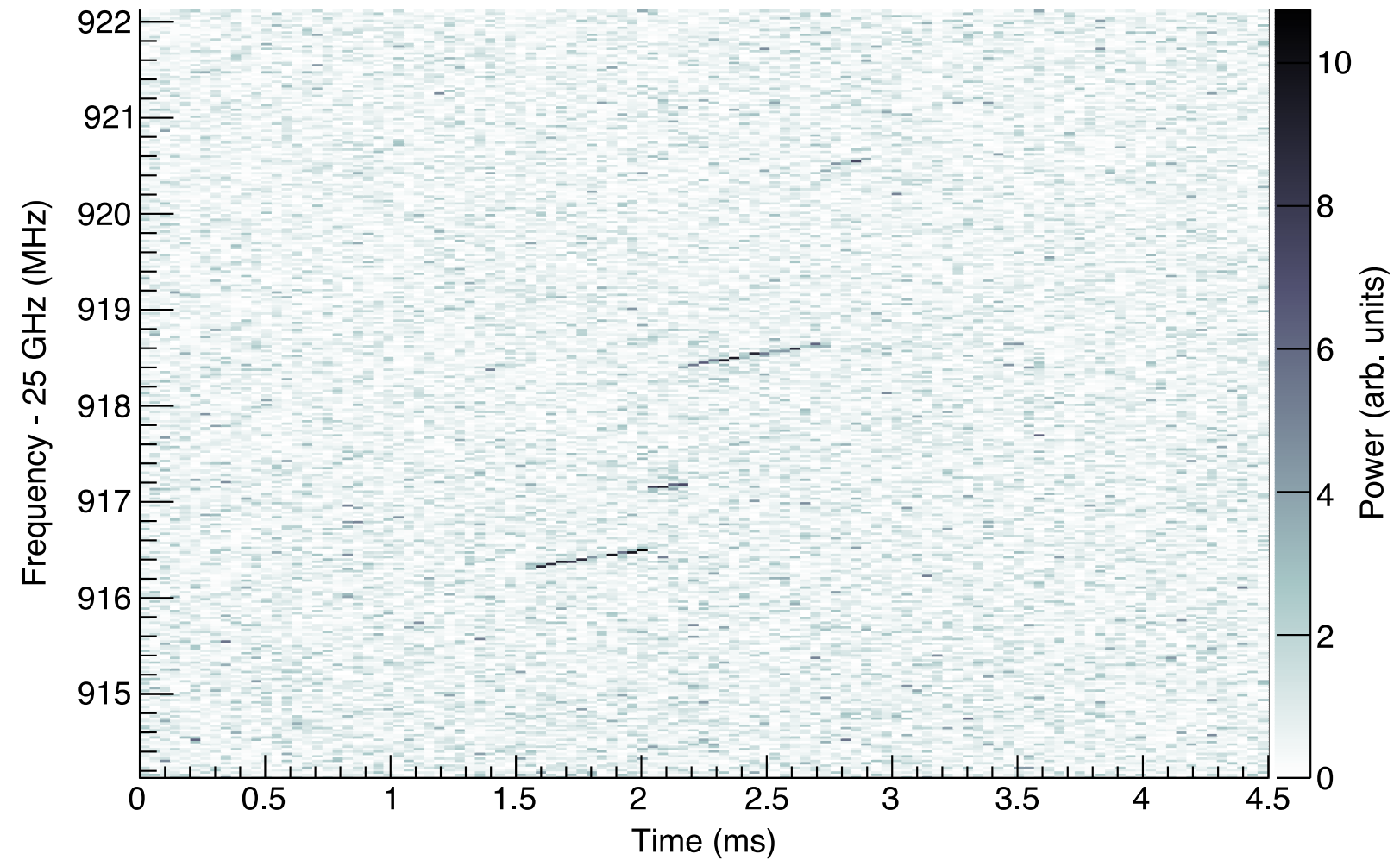
- Signal extraction: patch antennas
- Frequency: 560 MHz



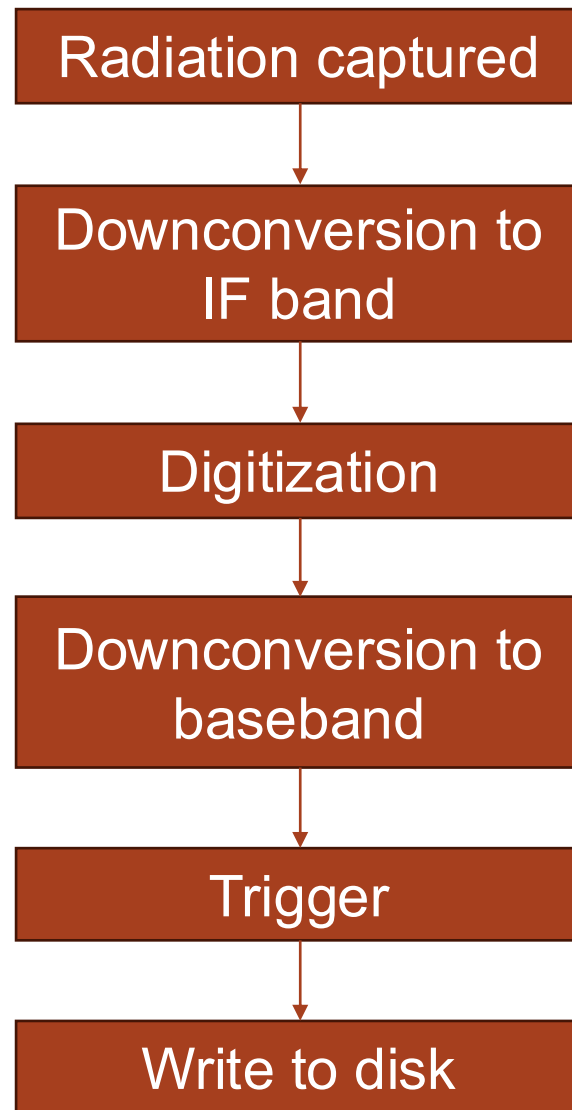
# Reading out CRES Data



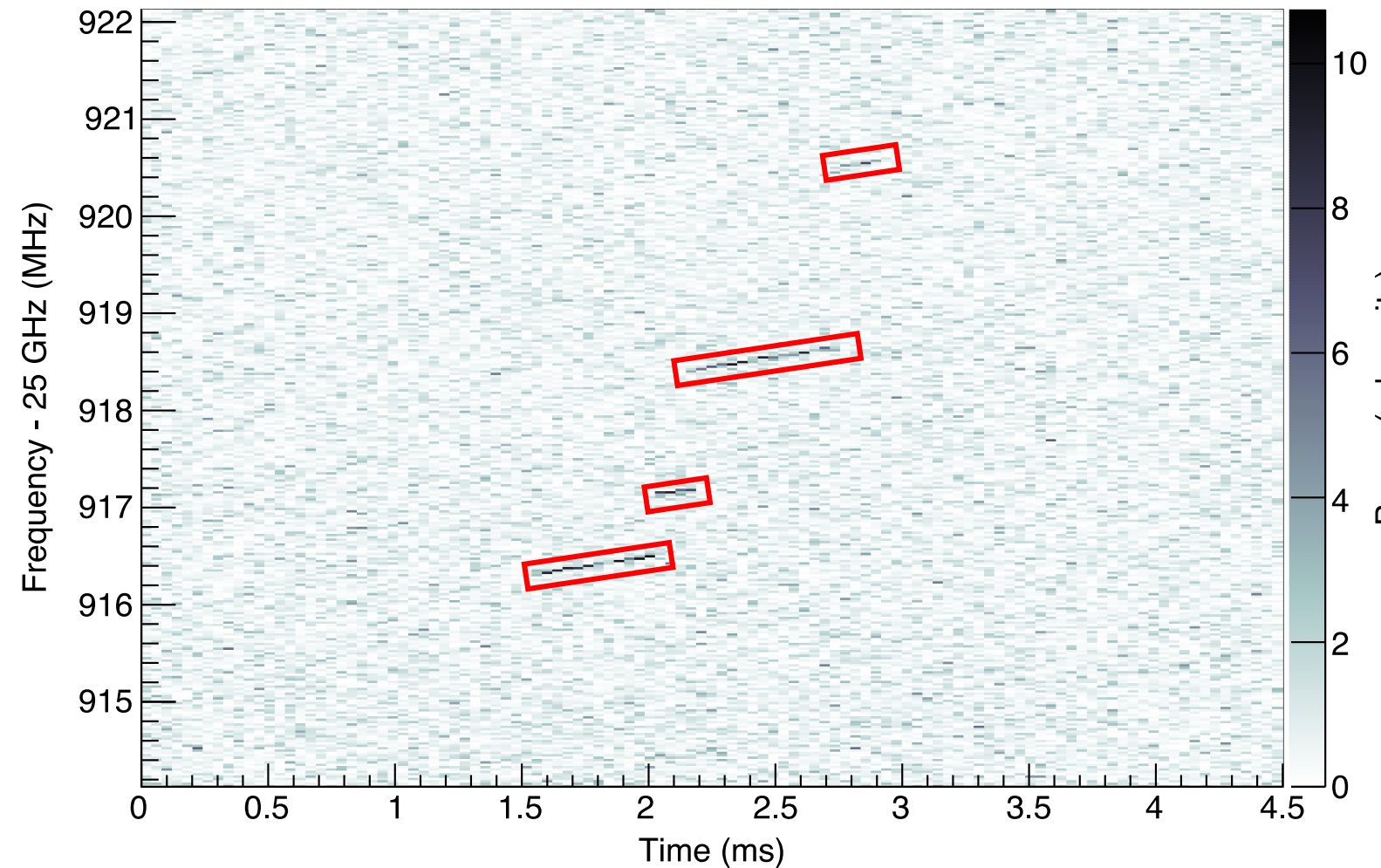
Phase II Tritium Event



# Reading out CRES Data



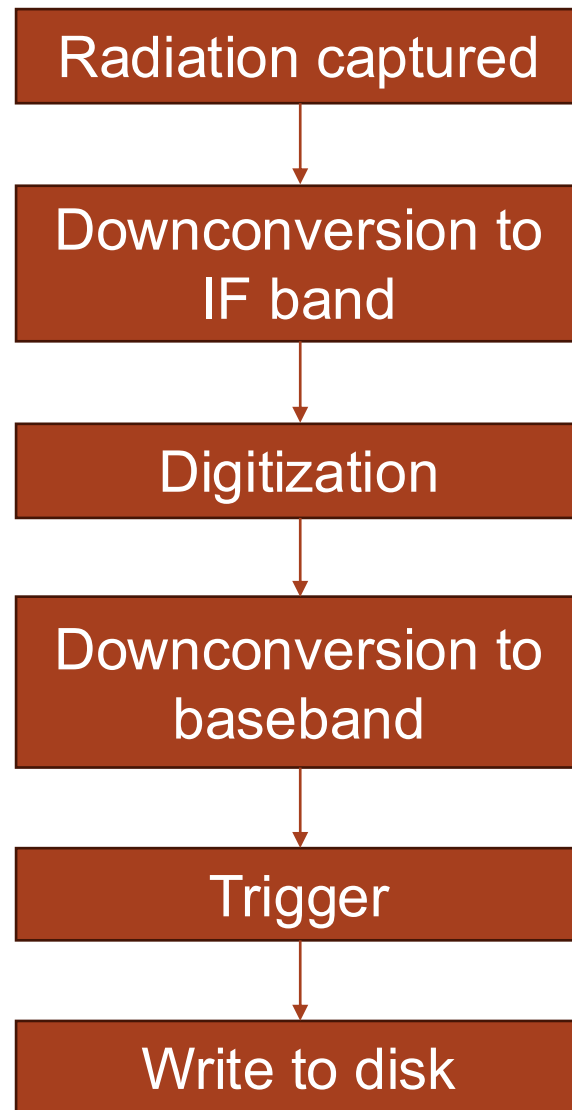
Phase II Tritium Event



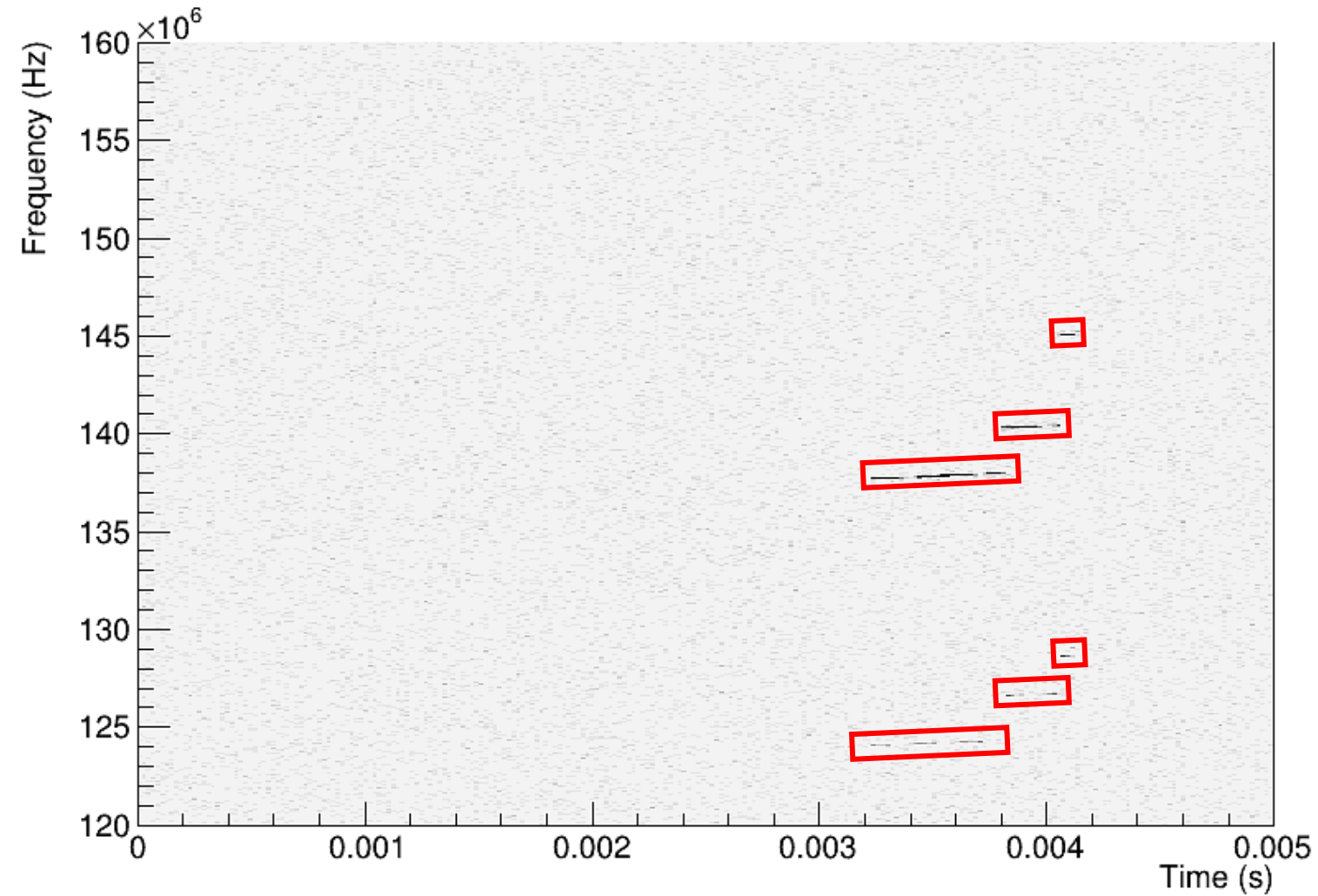
## Features

- ✓ Set of tracks represents electron lifetime in the detector
- ✓ Jumps are from scattering
- ✓ Slope is energy loss

# Reading out CRES Data



CCA Simulated Electron



## Features

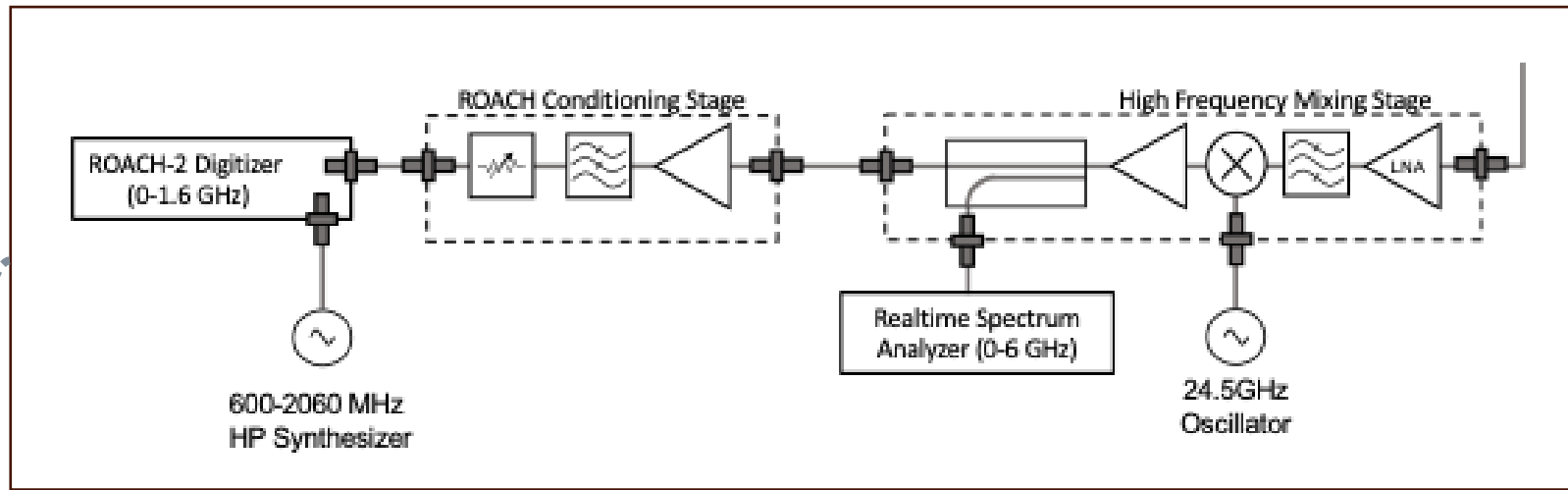
- ✓ Set of tracks represents electron lifetime in the detector
- ✓ Jumps are from scattering
- ✓ Slope is energy loss
- ✓ Sidebands due to axial motion

# CCA\* Signal Processing

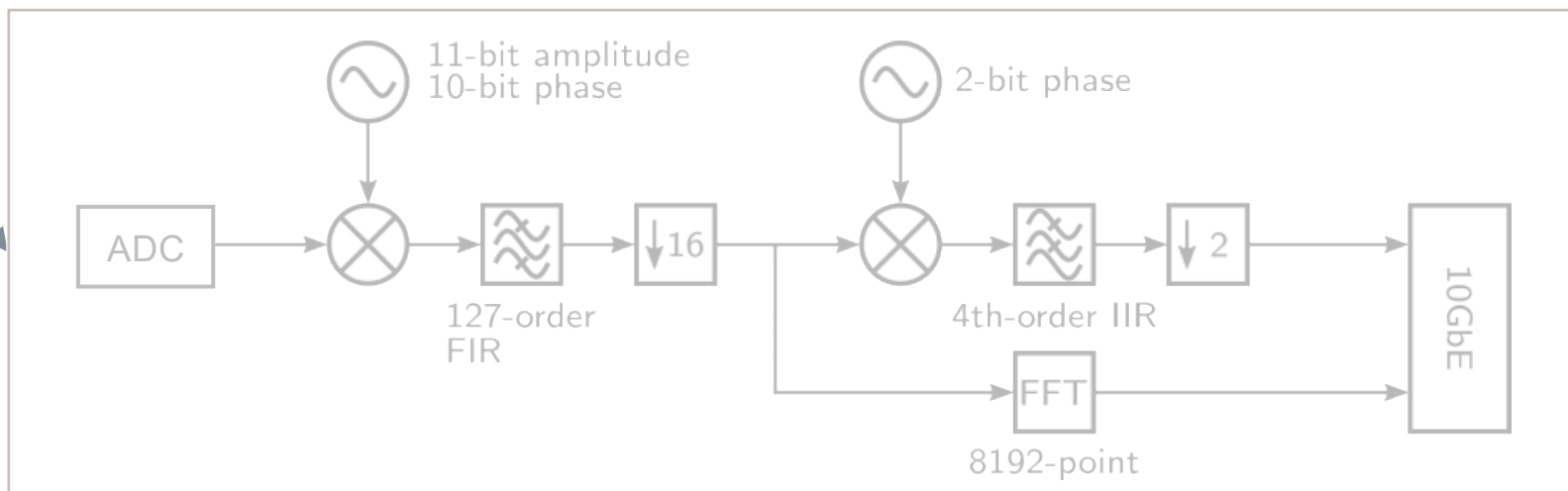
\* Inherited directly from Phase II

**0. Signal input:**  
~26 GHz

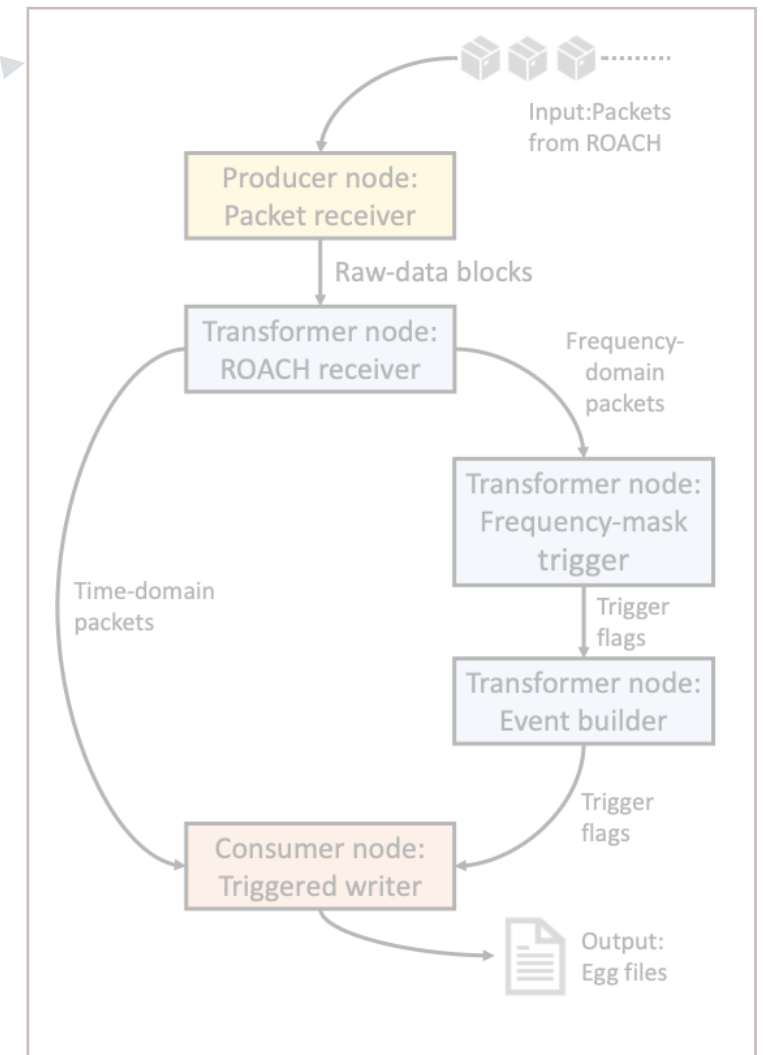
## 1. Analog Signal Chain



## 2. Digital (FPGA) Signal Chain



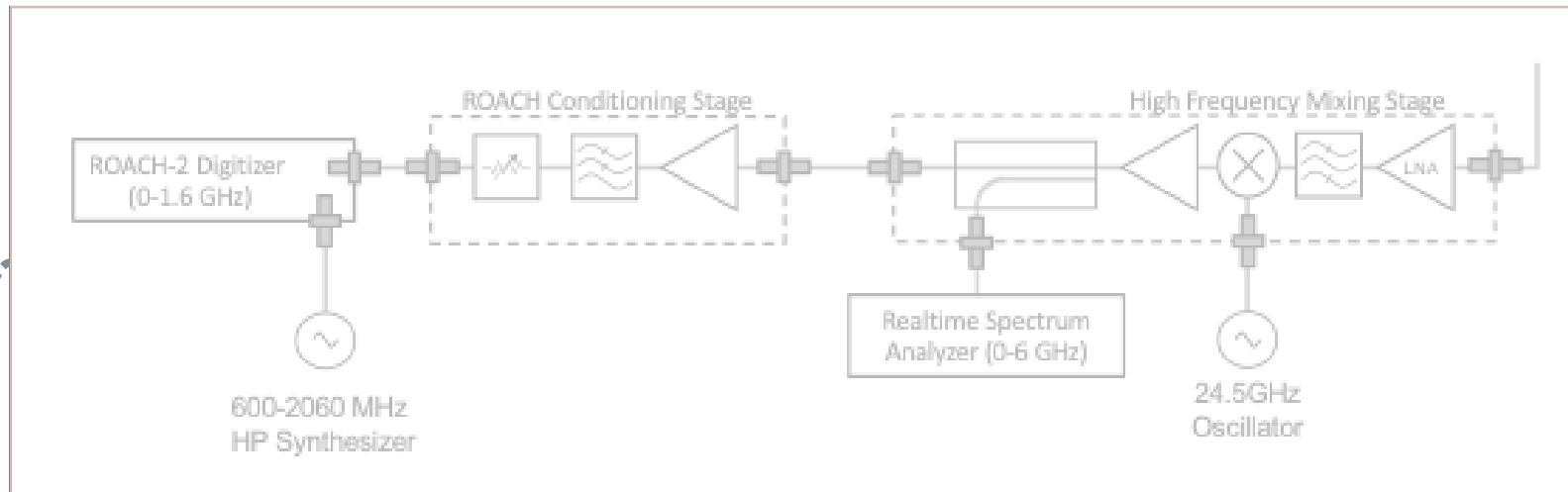
## 3. Digital (Software) Signal Chain



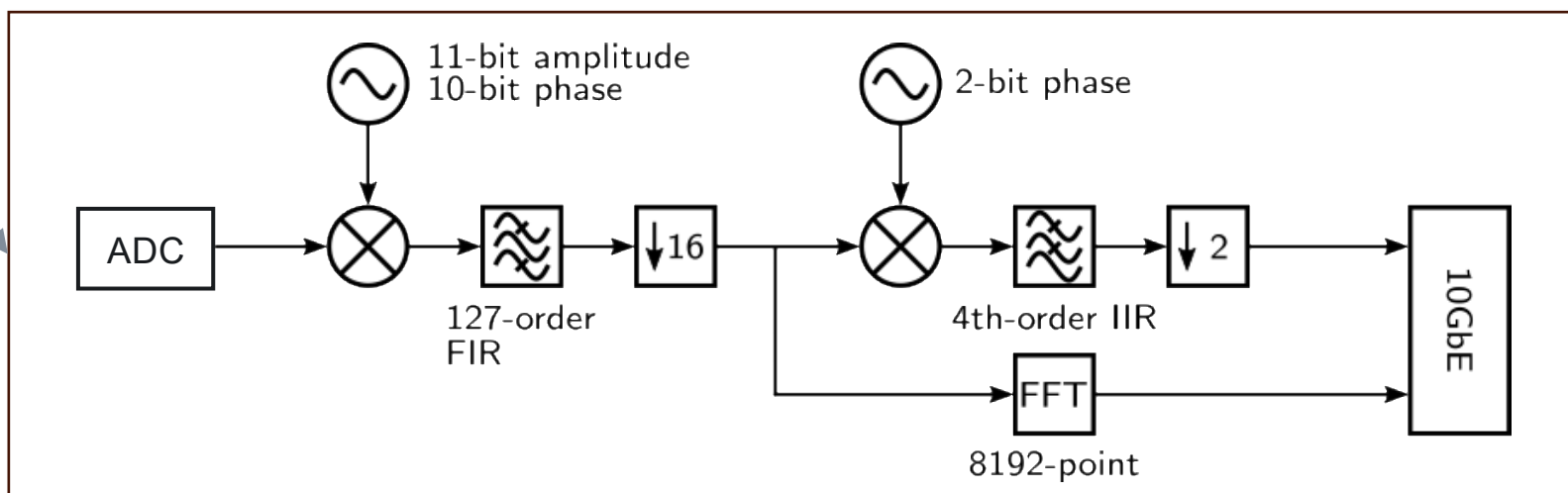
# CCA Signal Processing

0. Signal input:  
~26 GHz

## 1. Analog Signal Chain

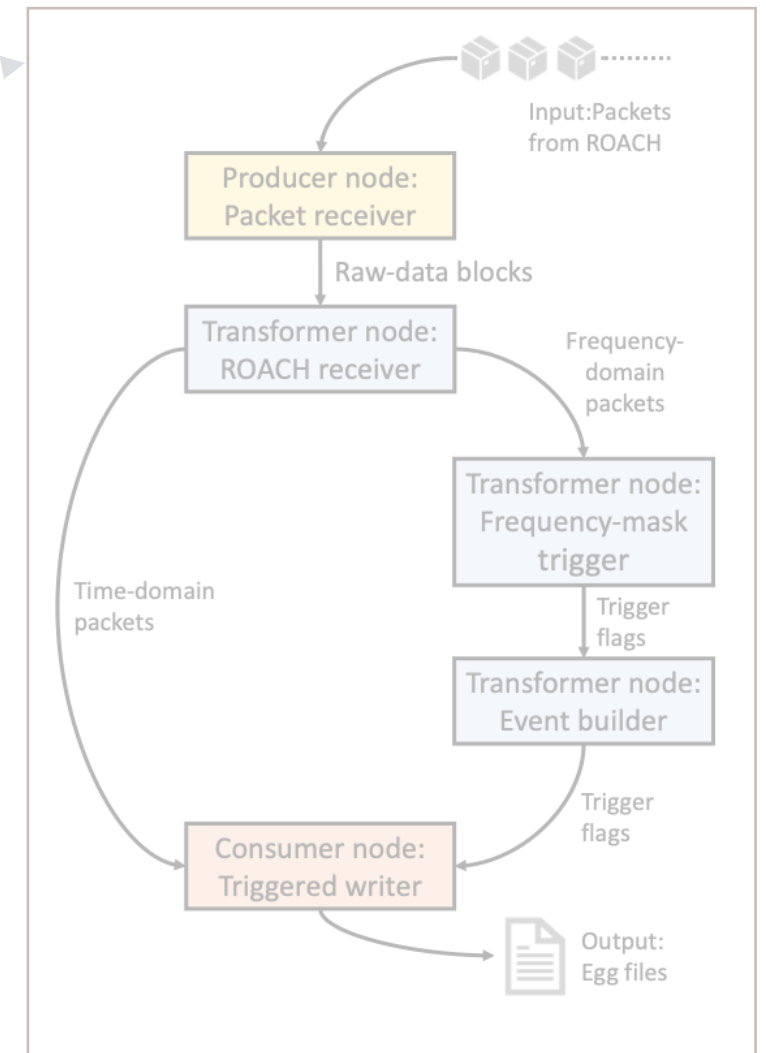


## 2. Digital (FPGA) Signal Chain



Nucl. Instrum. Meth. A 1081 (2026)

## 3. Digital (Software) Signal Chain

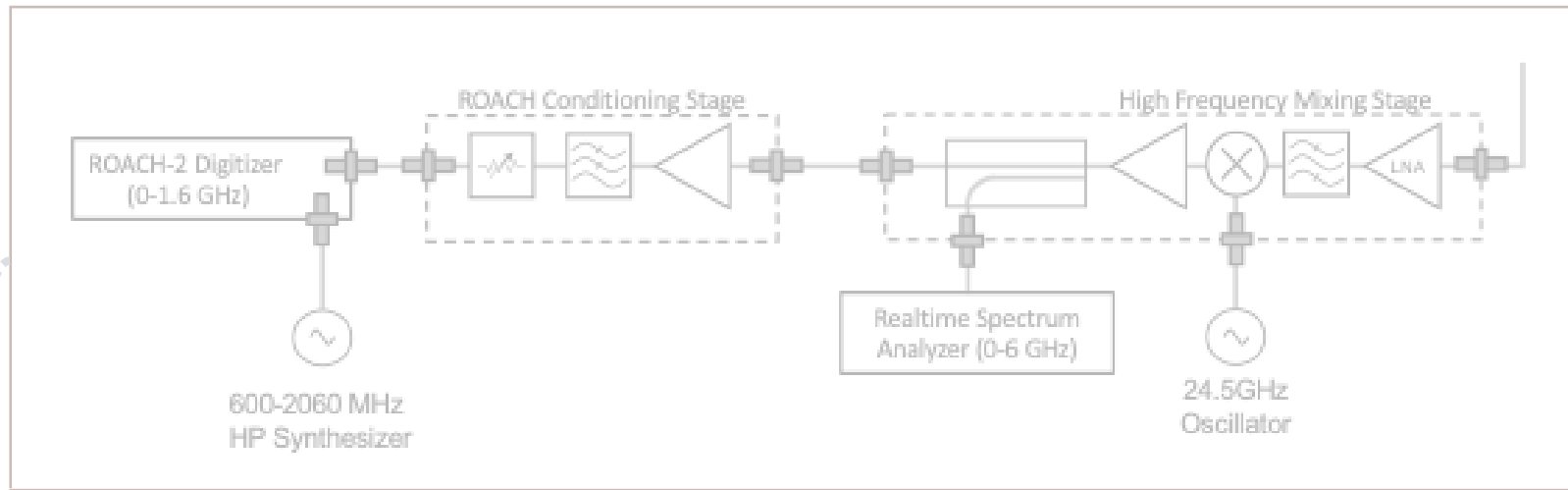


Nucl. Instrum. Meth. A 1081 (2026)

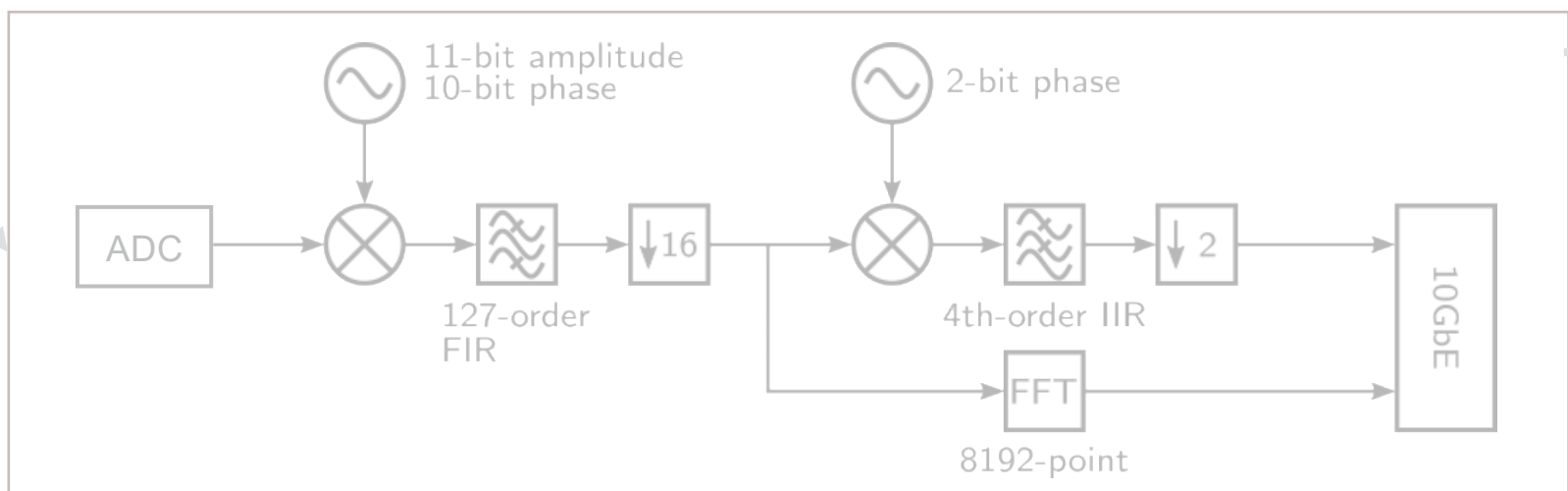
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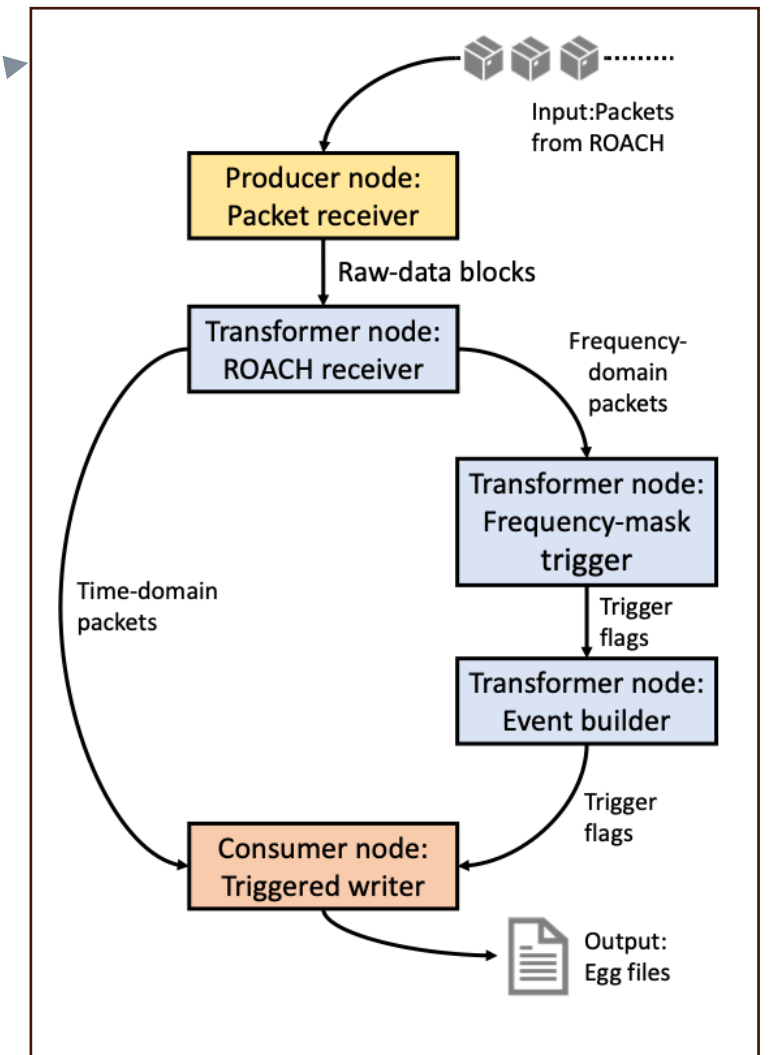
## 1. Analog Signal Chain



## 2. Digital (FPGA) Signal Chain

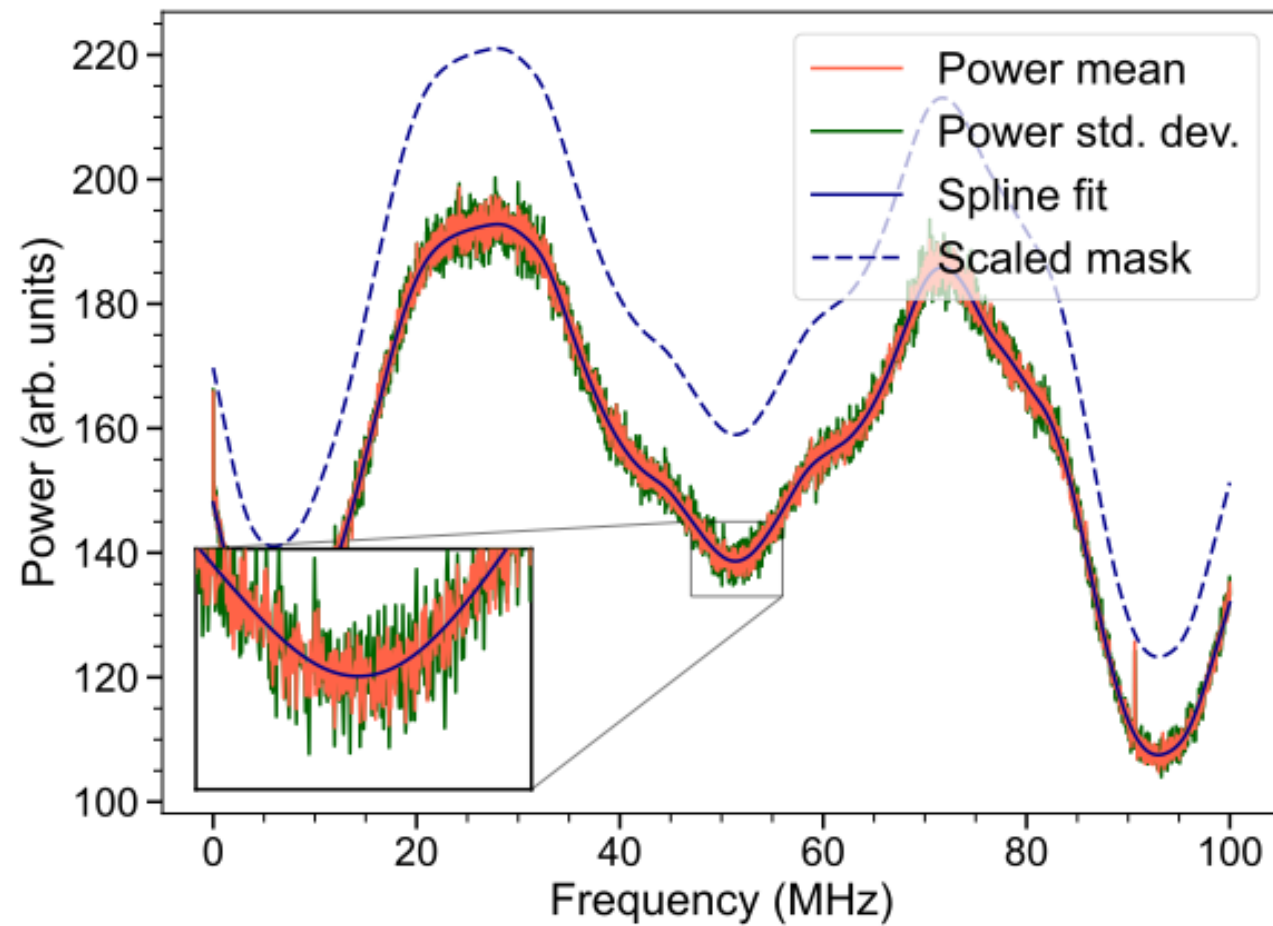


## 3. Digital (Software) Signal Chain

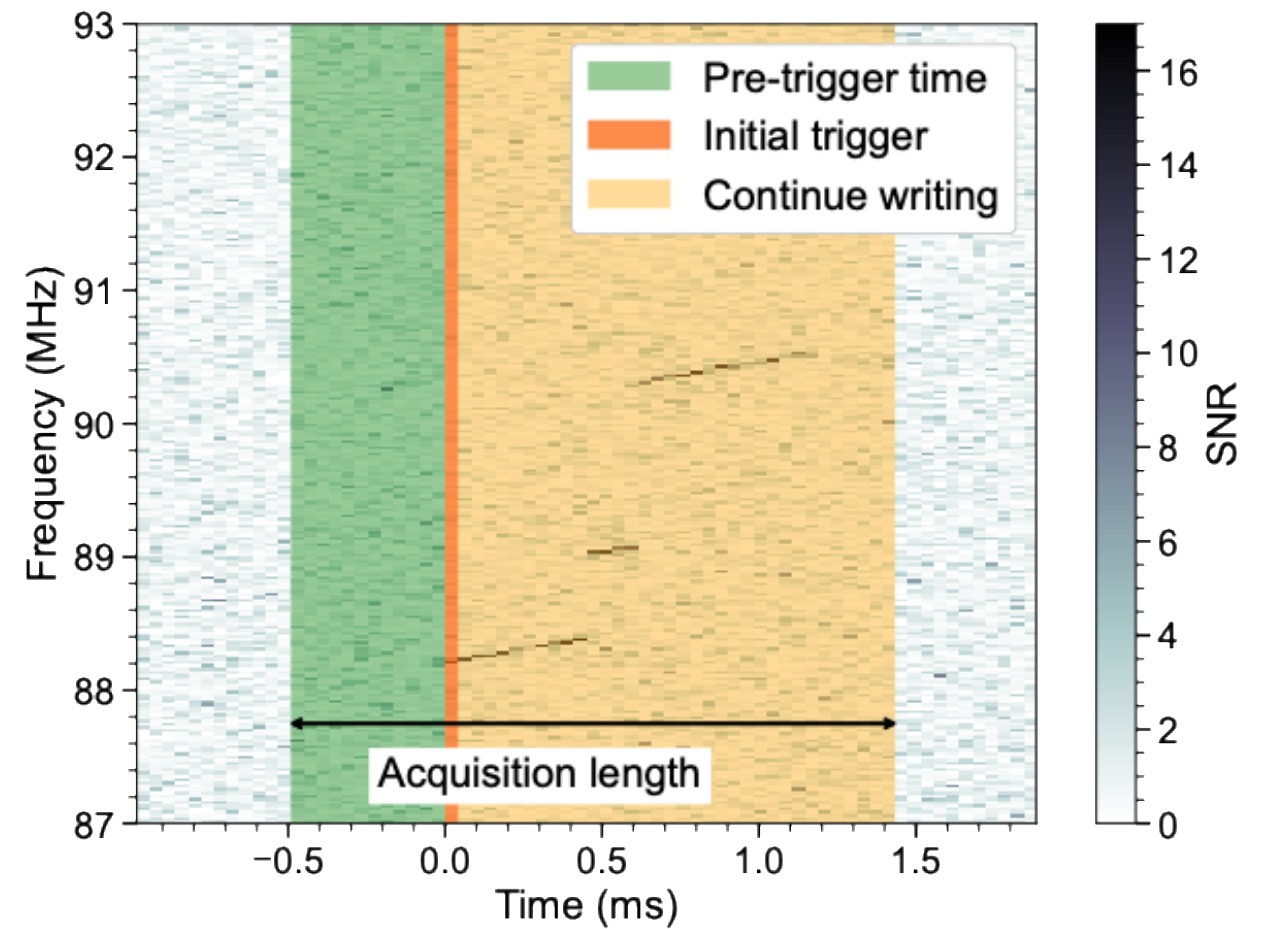


# CRES Event Trigger

### Average Spectrum + Trigger Mask



### Event Trigger Window



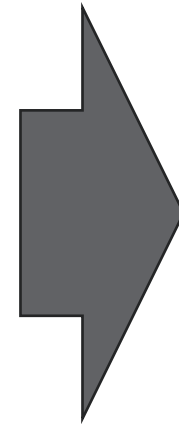
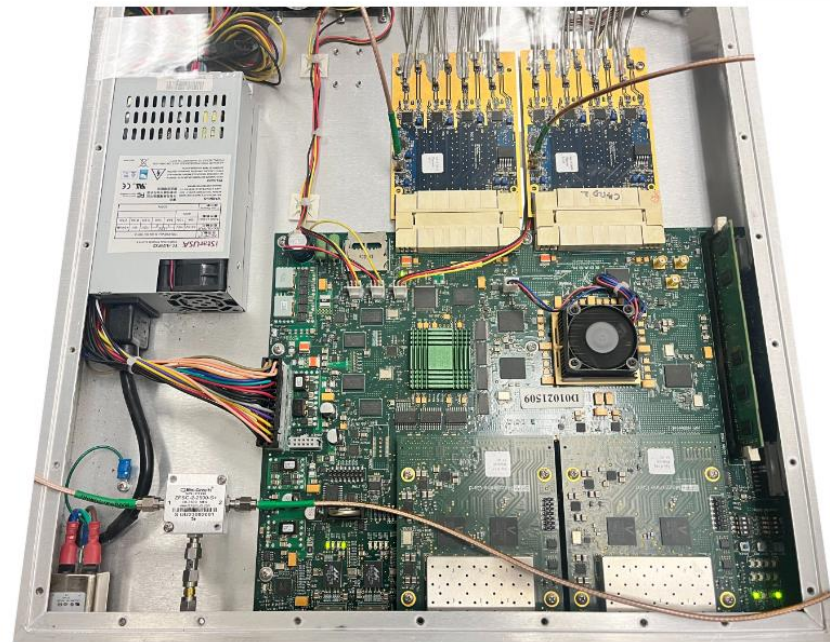
Nucl. Instrum. Meth. A 1081 (2026)

# Hardware Systems

## For the CCA:

### Reconfigurable Open Architecture Computing Hardware v2 (ROACH2)

- FPGA + ADC daughter boards
- Developed by the CASPER\* collaboration



## For the LFA:

### RF System on Chip (RFSoc)

- FPGA + ADC + DAC
- Made by Xilinx

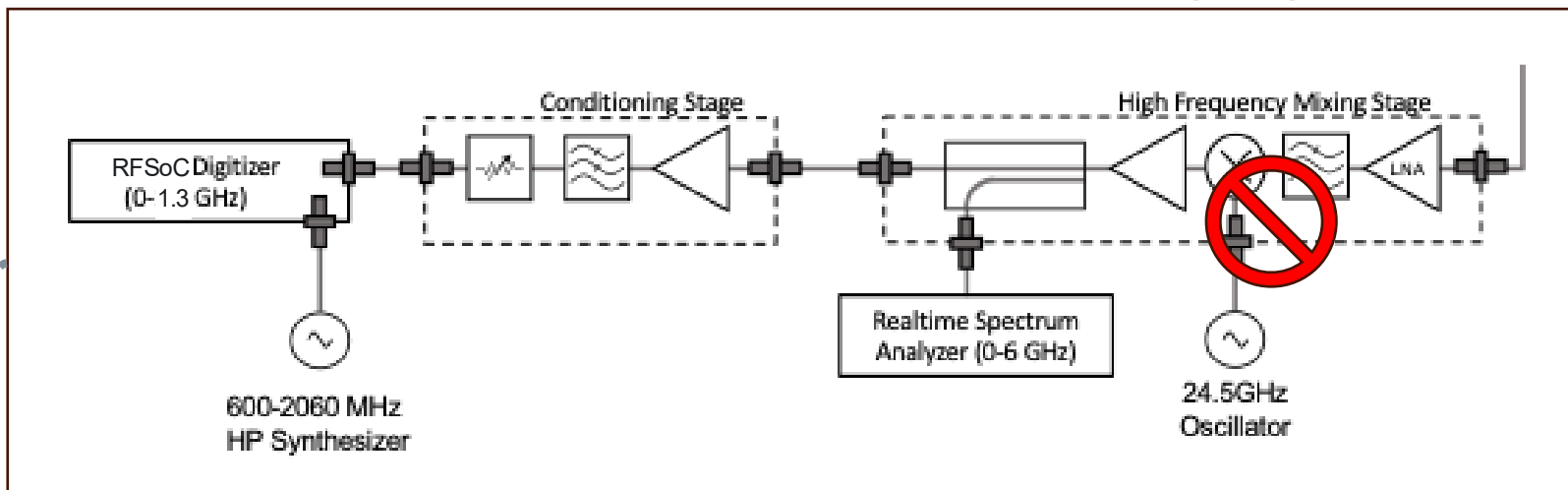


\* Collaboration for Astronomy Signal Processing and Electronics Research

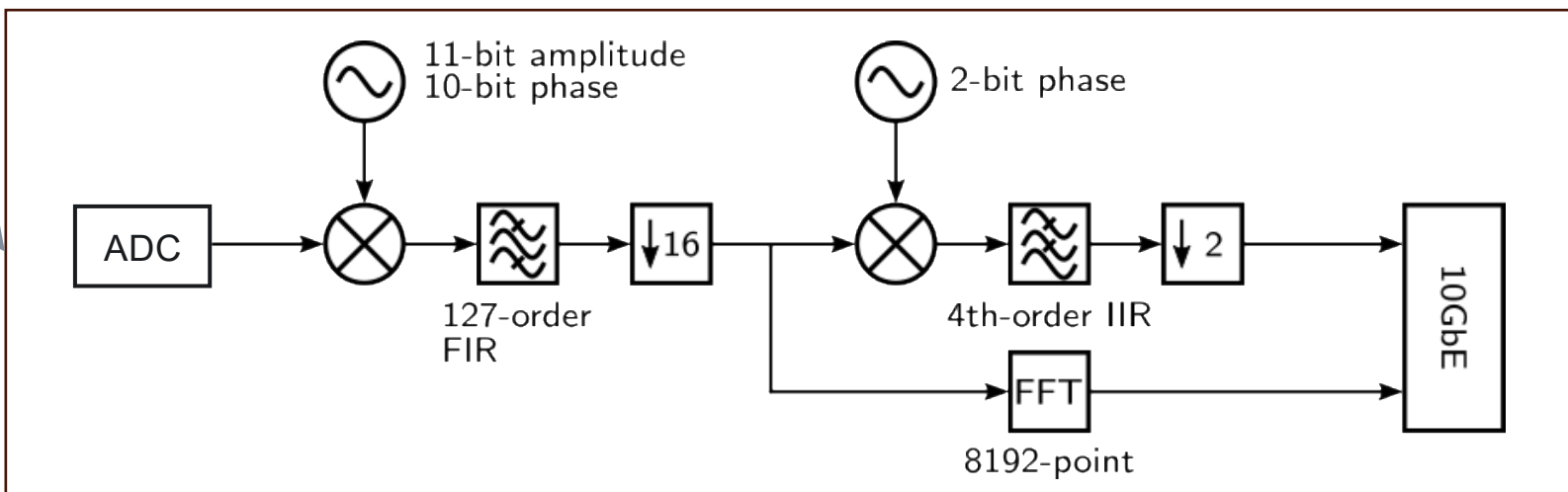
# LFA Signal Processing

**0.** Signal input:  
~560 MHz

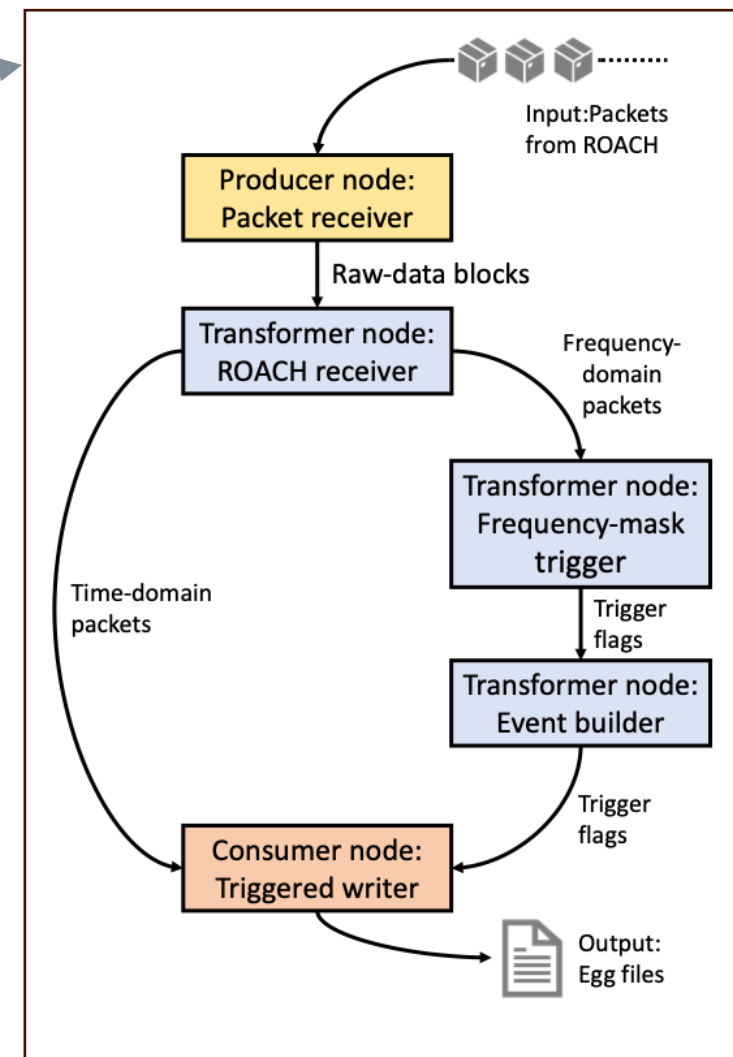
## 1. Analog Signal Chain



## 2. Digital (FPGA) Signal Chain

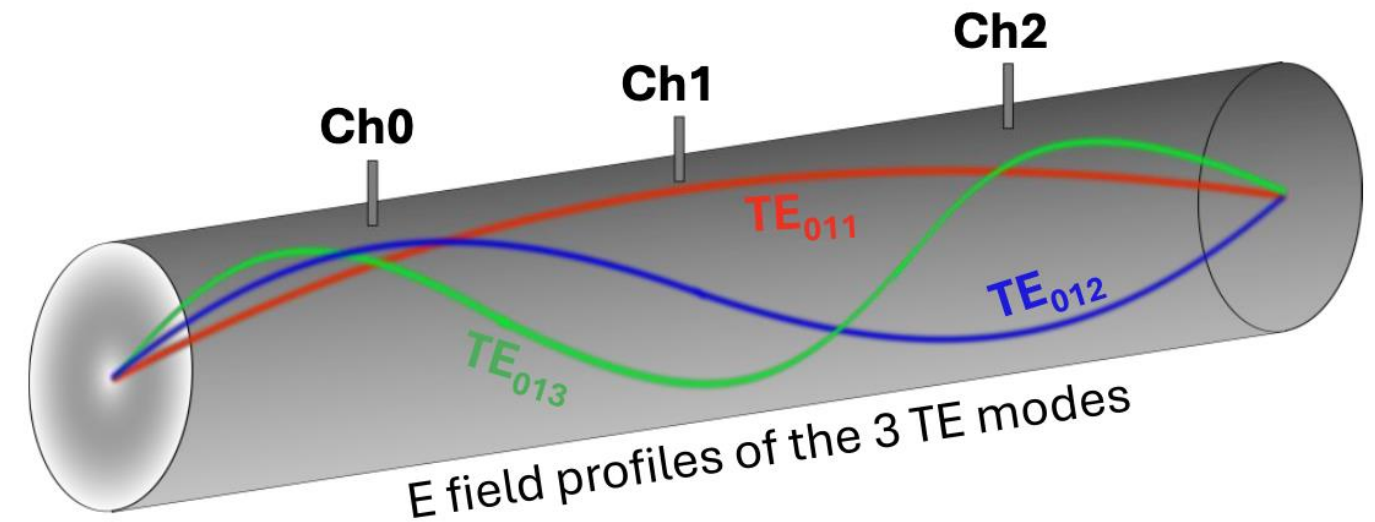


## 3. Digital (Software) Signal Chain



# Reading out Multiple Modes

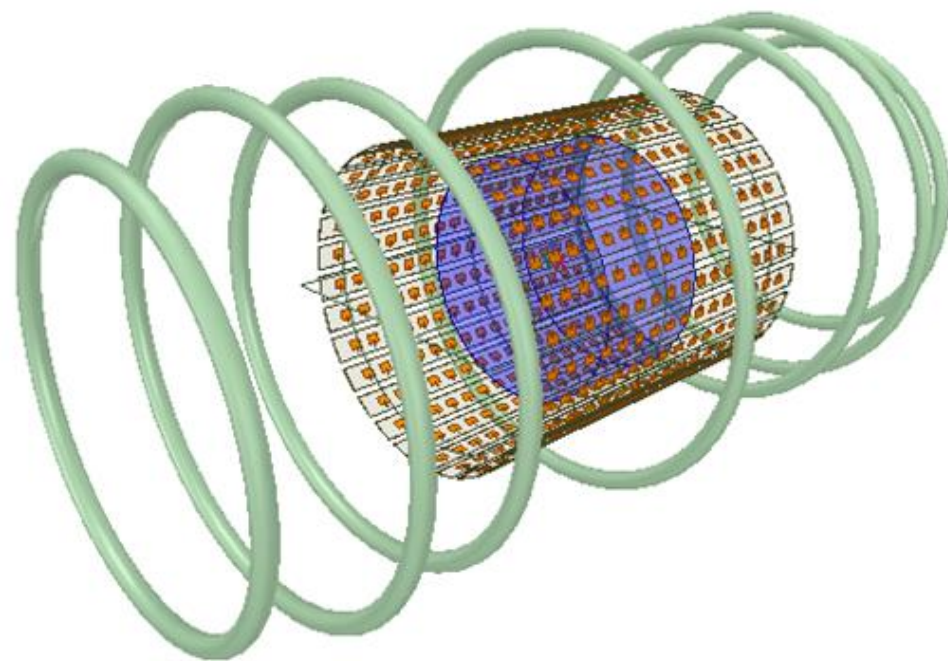
- Different modes have different spatial sensitivities
  - Can help us understand position in the detector
- Use readout at different locations to be sensitive to each mode (or a linear combination) of the modes
- Channels digitized independently but recorded with timestamps
- Analyze coherently



# Antenna Array: the Path Not Taken

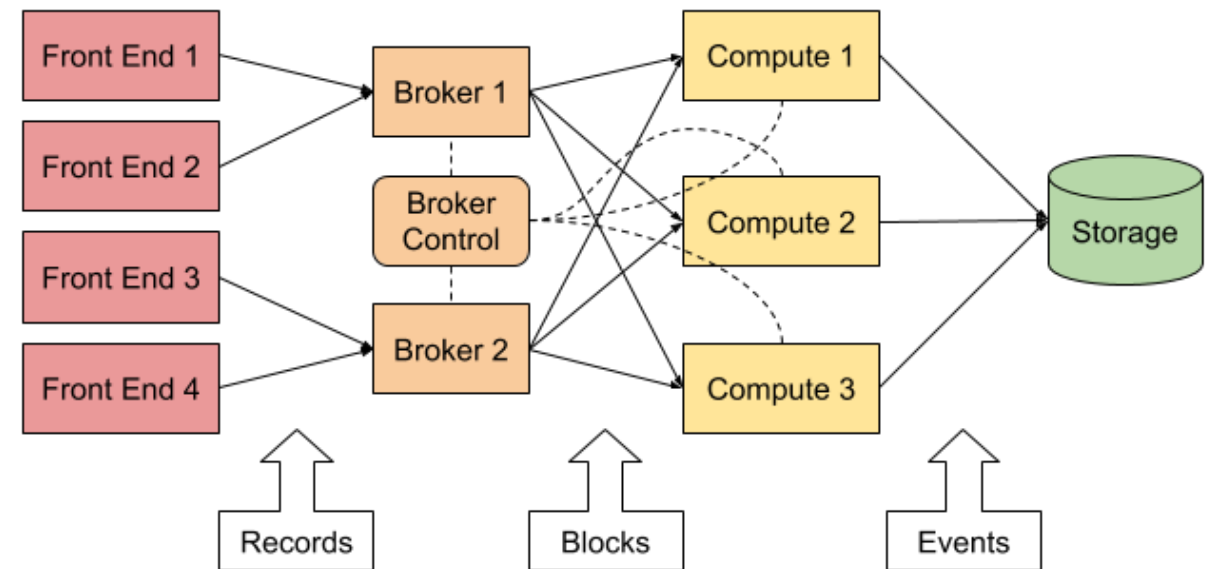
## Experimental Concept

- Inward-looking antenna array
- Beamforming used to identify electron locations



## Signal Processing Architecture

- Digitize data by antenna channel
- Linear combinations of channels form “beams”
- Analyze beams for signals

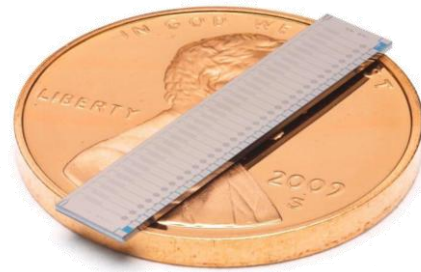


**Conclusion:** Cavity-based experiment DAQ is vastly simpler!

# Summary

- Signals from CRES electrons are microwave RF radiation
- The front-end system has its roots in the technologies developed for radioastronomy
- We use modern RF signal processing techniques to identify and record transient femtowatt signals
- Current signal processing for the CCA uses the previous phase's system
- Future signal processing for the LFA will be simpler, with no analog downconversion needed
- We're studying the use of multiple cavity modes and multiple channels to optimize signal detection

# Multiplexing readout schemes for low temperature detectors



# Why do we multiplex?

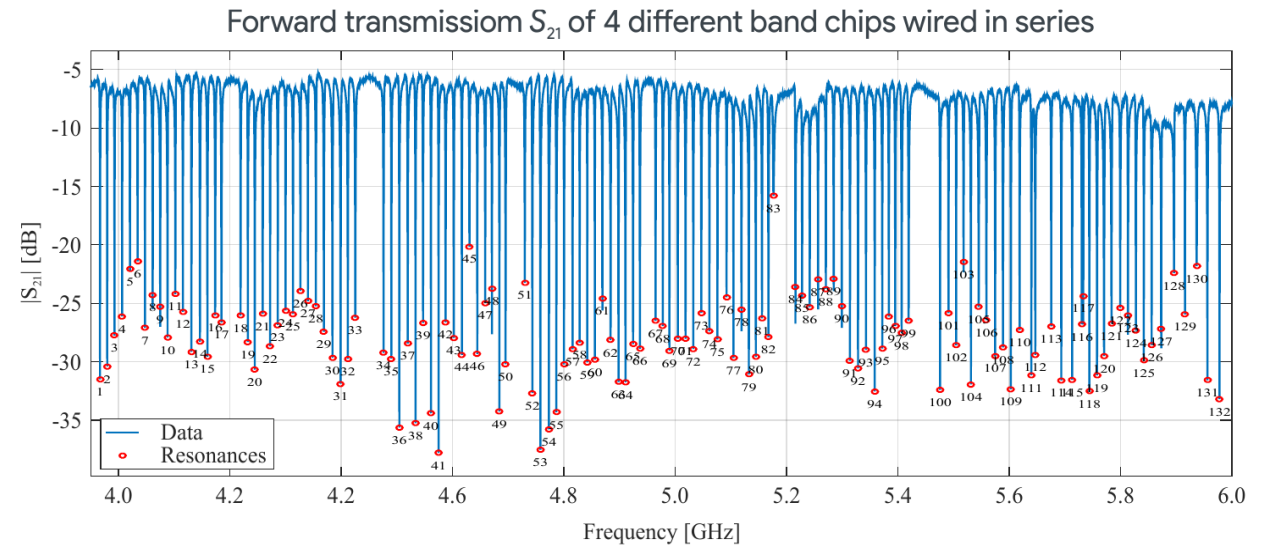
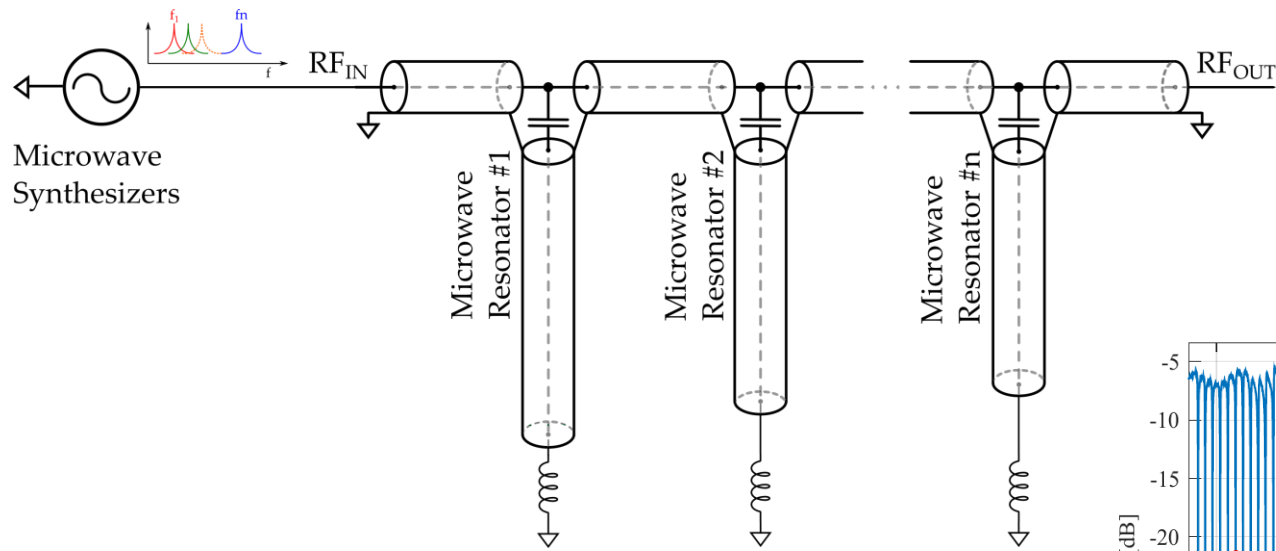
- each LTD requires readout wiring between room temperature and the cold stage of a dilution refrigerator at **tens of mK**
- there are a few multiplexing schemes available for both TESs and MMCs (both rely on a current signal)
- a good candidate needs to provide a large bandwidth and a good multiplexing factor, along with low x-talk
- two are of particular interest
  - microwave SQUID multiplexing (*Appl. Phys. Lett.* (2013) 103, 202602) → already in use for keV detectors by HOLMES
  - Kinetic Inductance Current Sensors (KICS) (*Commun. Eng.* 3 (2024) 1, 160) → demonstrated for NIR TESs, under development for keV TESs

# Disclaimer

I'll refer here to the multiplexing applied to TES, but similar arguments can be made for MMCs (with a few differences)

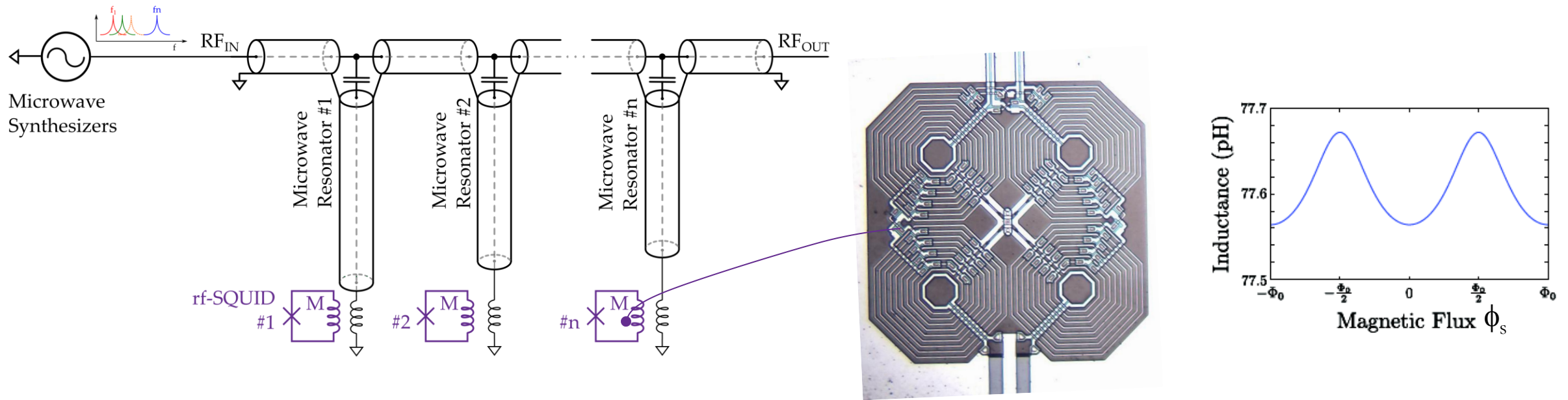
# Microwave SQUID multiplexing

- the multiplexing is naturally achieved with microwave microresonators:



# Microwave SQUID multiplexing

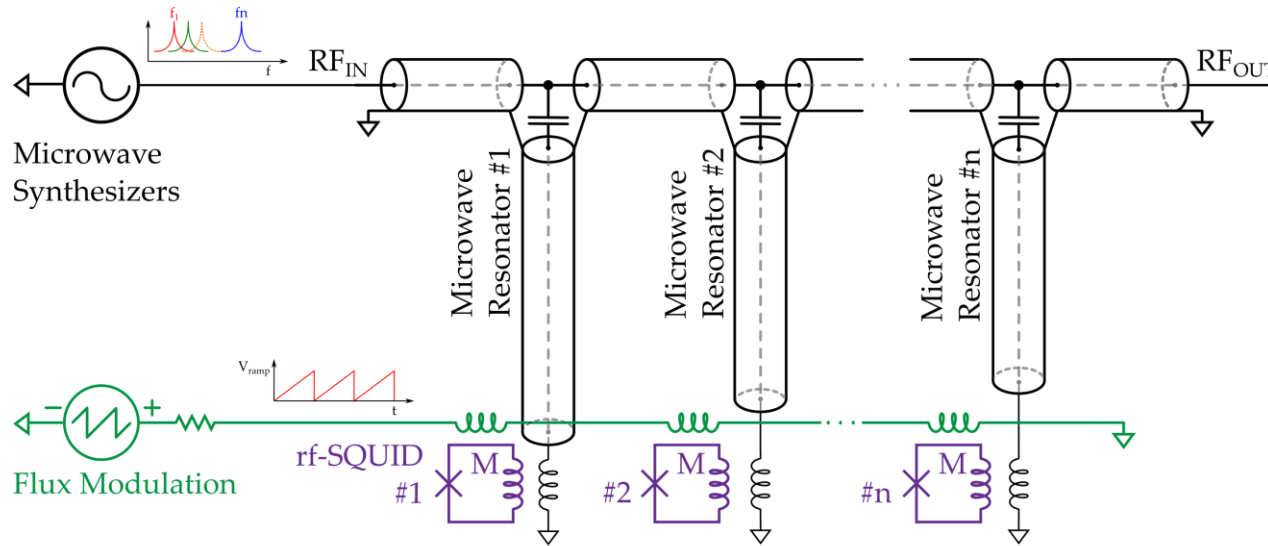
- the objective is to detect a current signal: a rf-SQUID translates the current information into magnetic flux, and hence mutual inductance



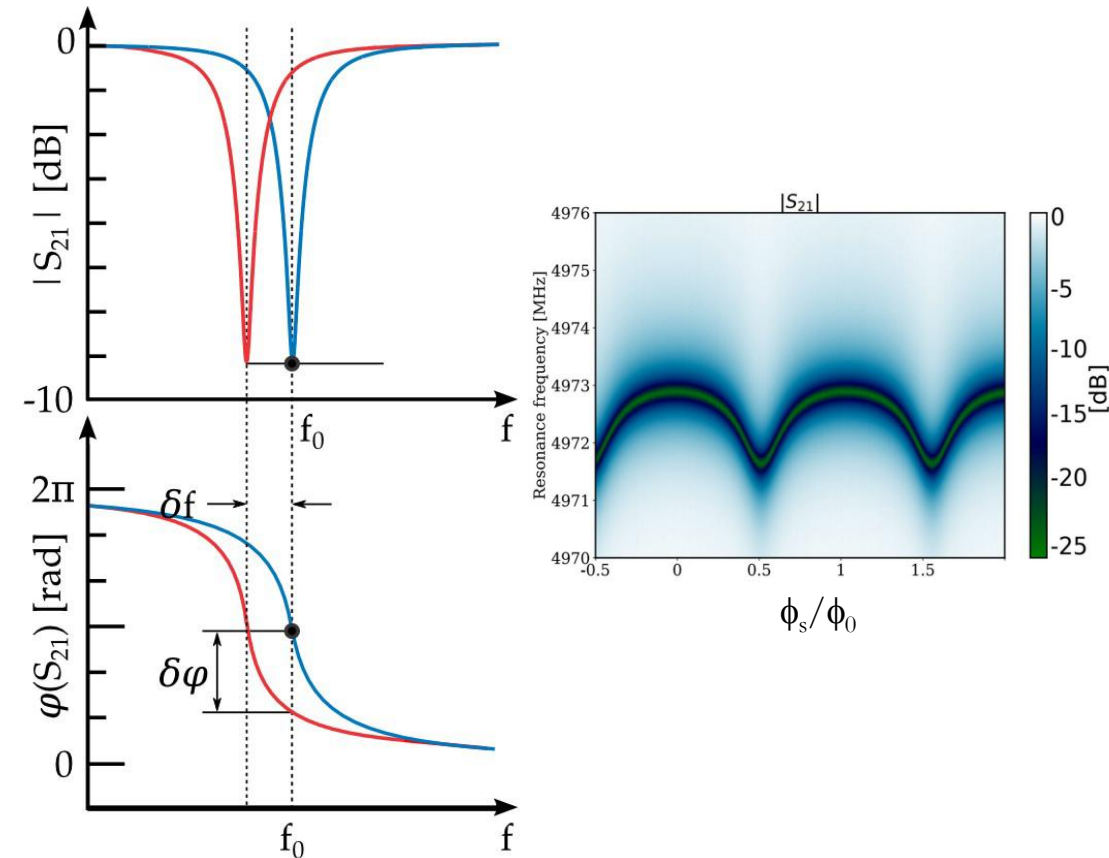
SQUIDs are very sensitive to current signals, but have a non-linear (periodic) response  $\rightarrow$  it is necessary to linearize its response

# Microwave SQUID multiplexing

- the objective is to detect a current signal: a rf-SQUID translates the current information into magnetic flux, and hence mutual inductance

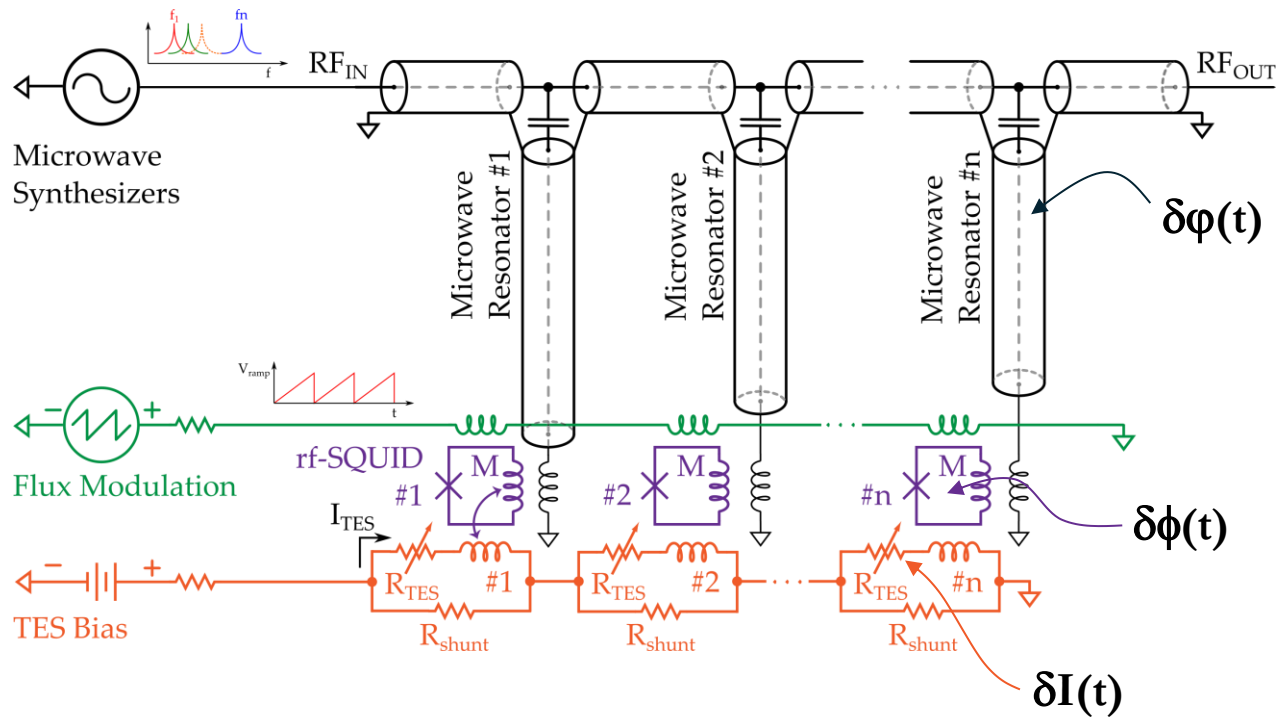


a periodic, linearly increasing, signal (the ‘ramp’) is applied to the SQUID  
 → the frequencies of the resonators oscillate continuously

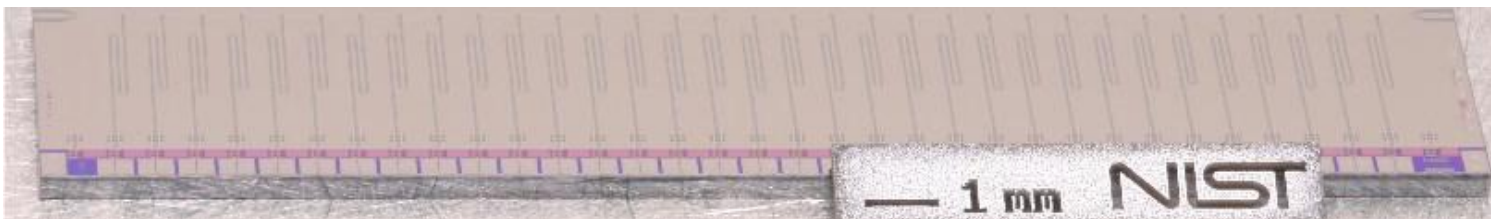
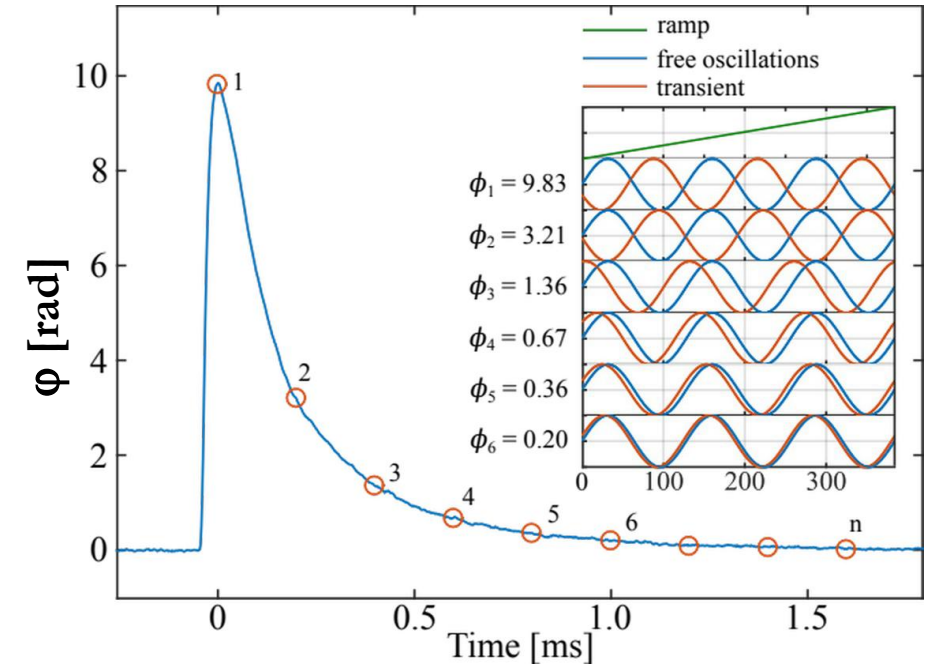


# Microwave SQUID multiplexing

- $\delta I(t) \rightarrow \delta\phi(t) \rightarrow \delta\varphi(t)$



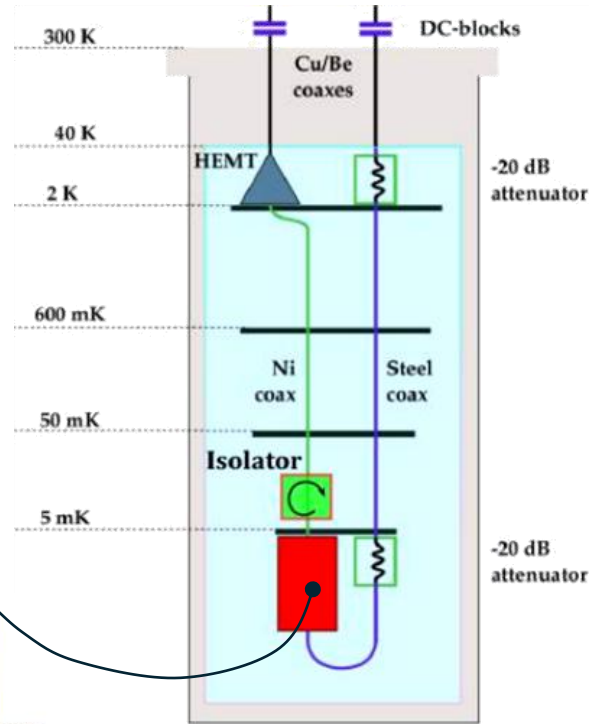
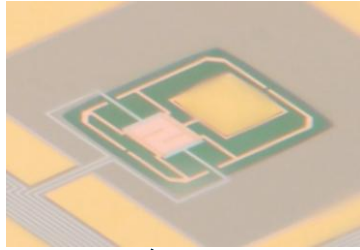
**in this scheme the ramp frequency is the signal sampling frequency**



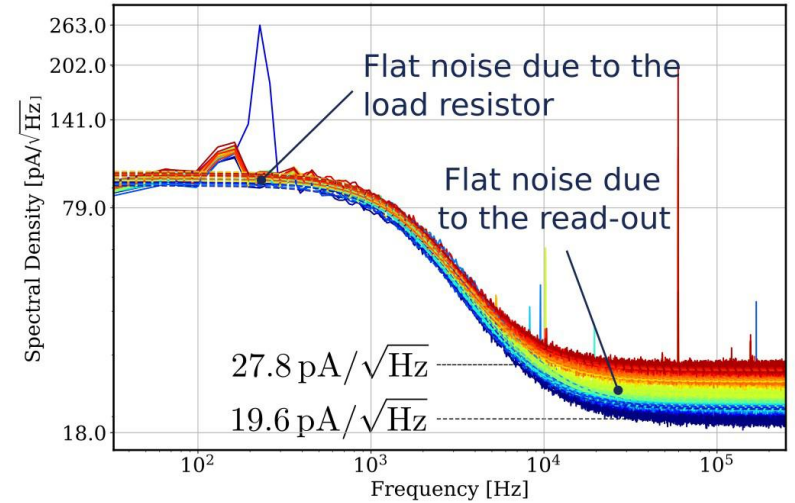
scheme currently in use in HOLMES for acquiring physics data, such as Phys. Rev. Lett. 135 (14), 141801

# Microwave SQUID multiplexing

## HOLMES



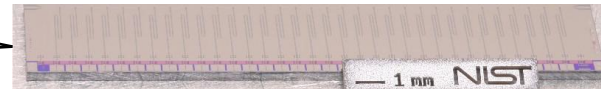
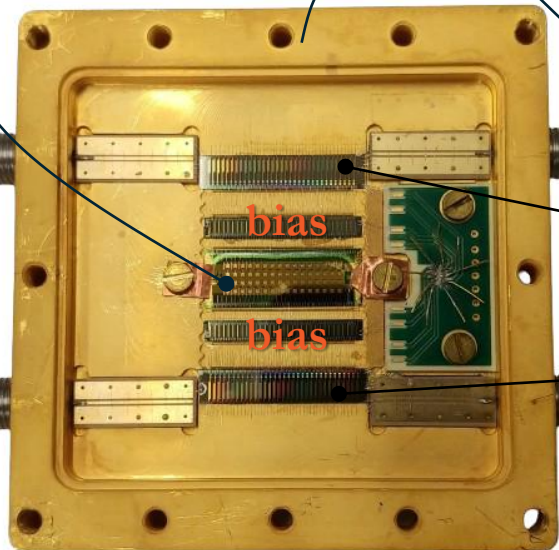
**Read out noise**  
32 Channels, no TES bias applied



64 TESs

RF probe in

RF (carrier + TES signal) out



# Microwave SQUID mux: BW considerations

- $\Delta f_{\text{res}} \geq 2f_{\text{ramp}} n_{\phi_0}$   $n_{\phi_0} = 2$  flux quanta per ramp period
- $f_{\text{ramp}} (= f_{\text{sampl}}) \geq \frac{5}{\tau_{\text{rise}}}$  requirement to avoid distortion
- $f_n \geq 8\Delta f_{\text{res}}$  crosstalk suppression
- each resonator requires a BW equal to  $f_n \approx \frac{160}{\tau_{\text{rise}}}$
- the current SDR-based DAQ used in HOLMES (ROACH2) has a total BW  $f_{\text{ADC}} = 512$  MHz

$$\Rightarrow \frac{f_{\text{ADC}}}{f_n} = \frac{f_{\text{ADC}} \tau_{\text{rise}}}{160} \xrightarrow{\tau_{\text{rise}} = 10 \mu\text{s}} = 32 \text{ TESs/ROACH2 board}$$

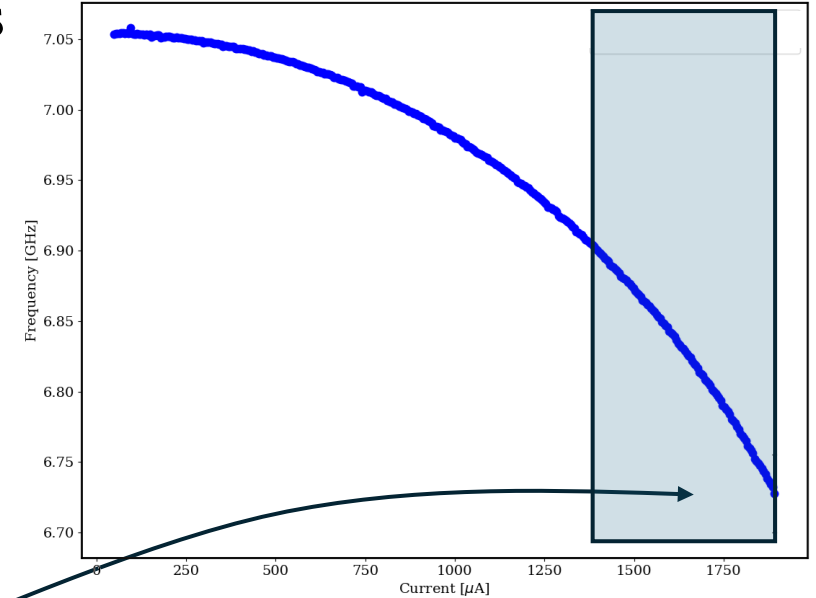
$\tau_{\text{rise}}$  slowed down electrically on purpose to match the BW of the readout. **The underneath thermal signal is much faster  $\rightarrow$  time resolution limited by the sampling time**

# Kinetic Inductance Current Sensors (KICS)

- novel scheme, so far demonstrated for NIR photons
- relies on kinetic inductance vs current flowing in a superconductor:

$$L(I) \approx L_0 \left( 1 + \frac{I^2}{I_*^2} + \dots \right)$$

- when patterned into a resonator,  $f_r$  depends on the current
- at low currents, the response is basically flat
- to work in the **current-sensitive region**, an additional persistent current is added
- any additional current from the detectors is detected as a frequency shift

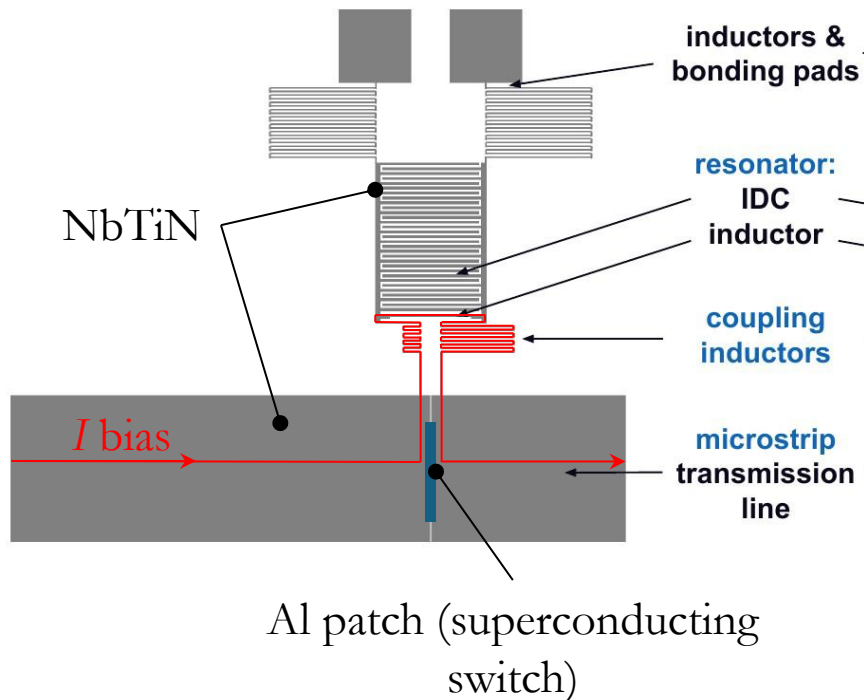


$$f_r(I) = \frac{1}{2\pi\sqrt{L(I)C}}$$

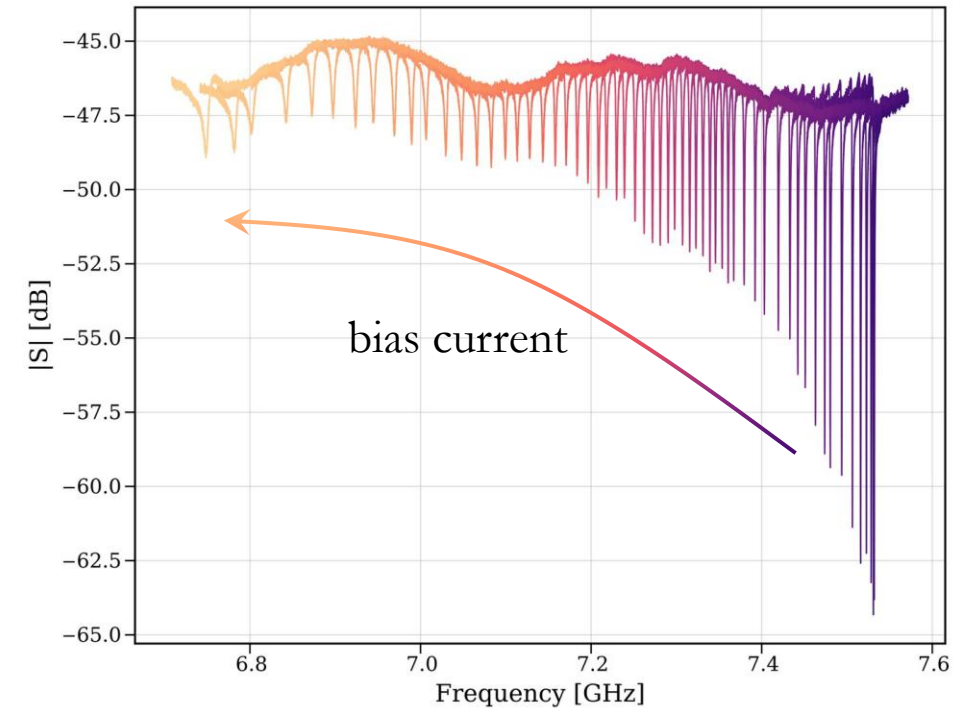
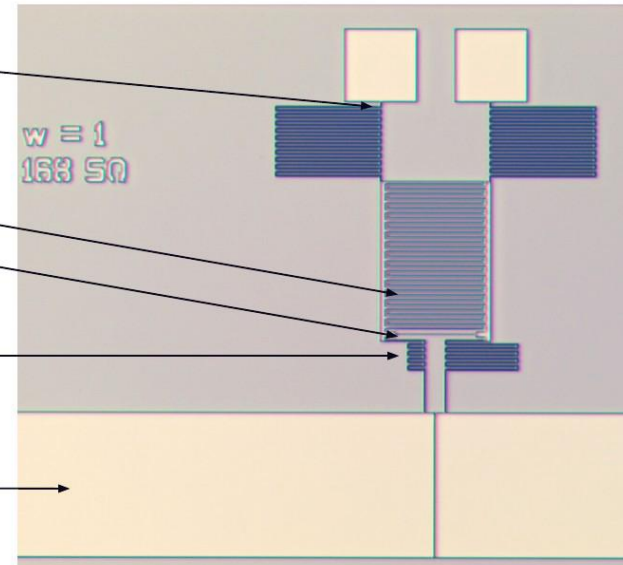
# Kinetic Inductance Current Sensors (KICS)

- first prototype produced at FBK within the HOLMES+ collaboration

Design (GDS) of KICS



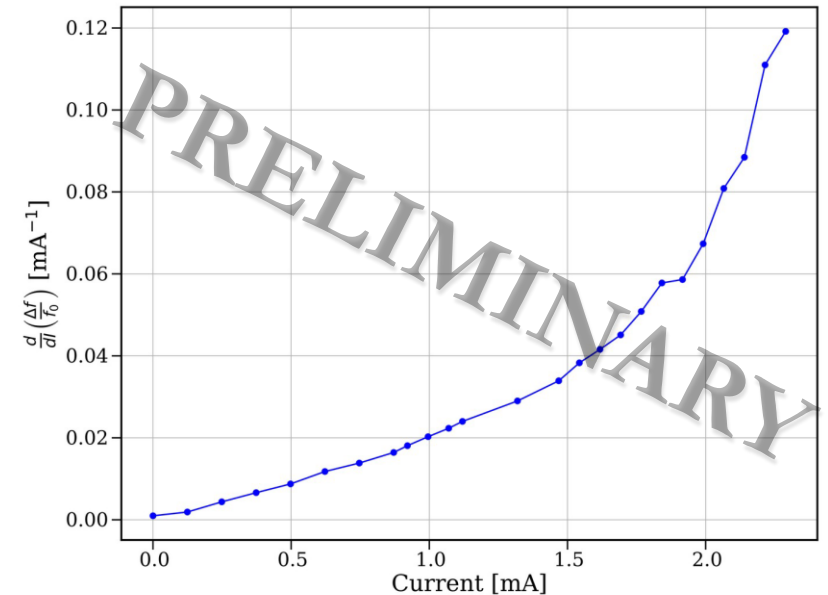
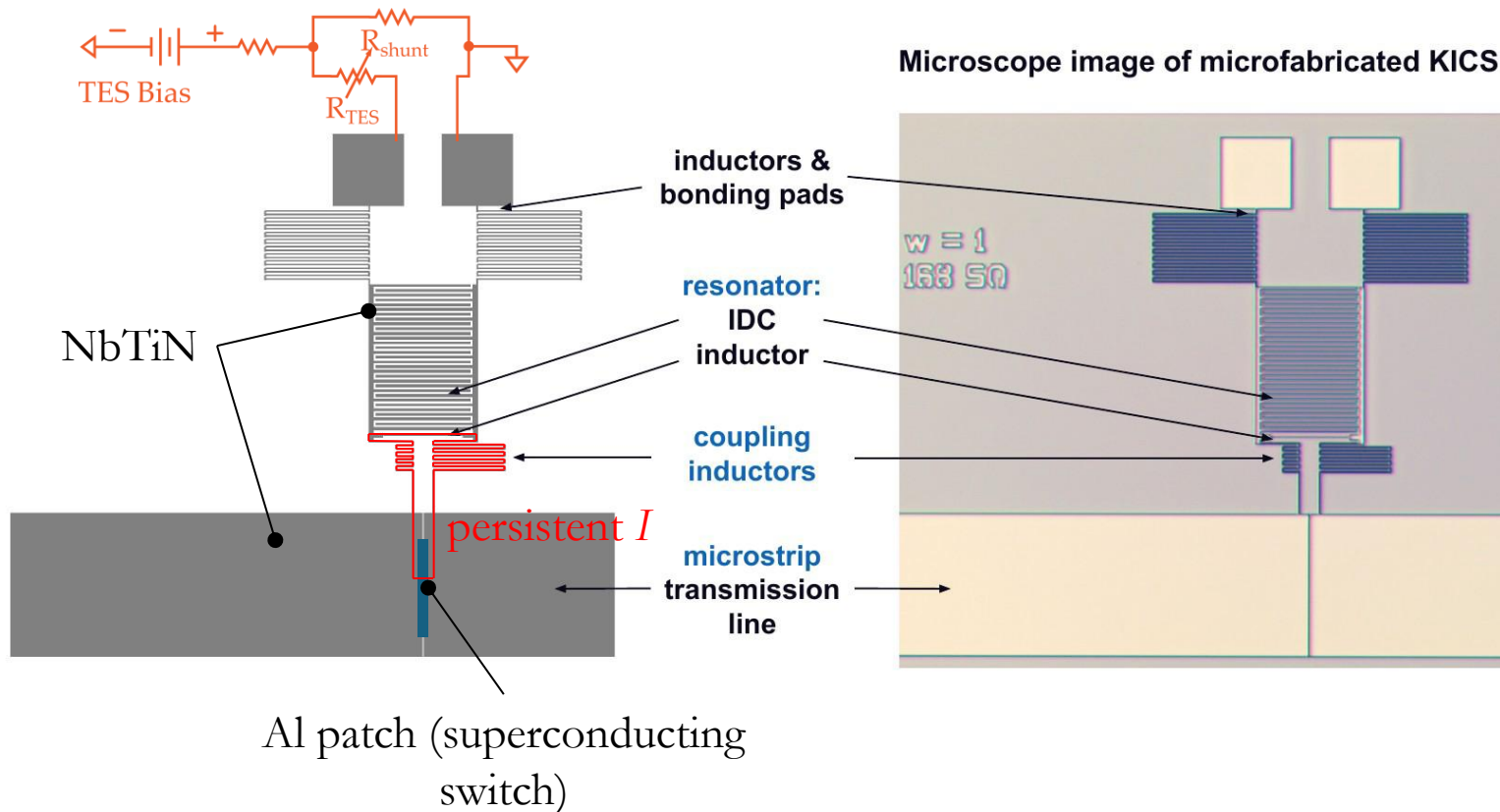
Microscope image of microfabricated KICS



step 1: apply a bias current while keeping the temperature  $T_c^{KICS} > T > T_c^{switch}$  of the superconducting switch (in the current prototype:  $T_c^{KICS} \approx 11.8K$ ,  $T_c^{switch} \approx 1.2K$ )

# Kinetic Inductance Current Sensors (KICS)

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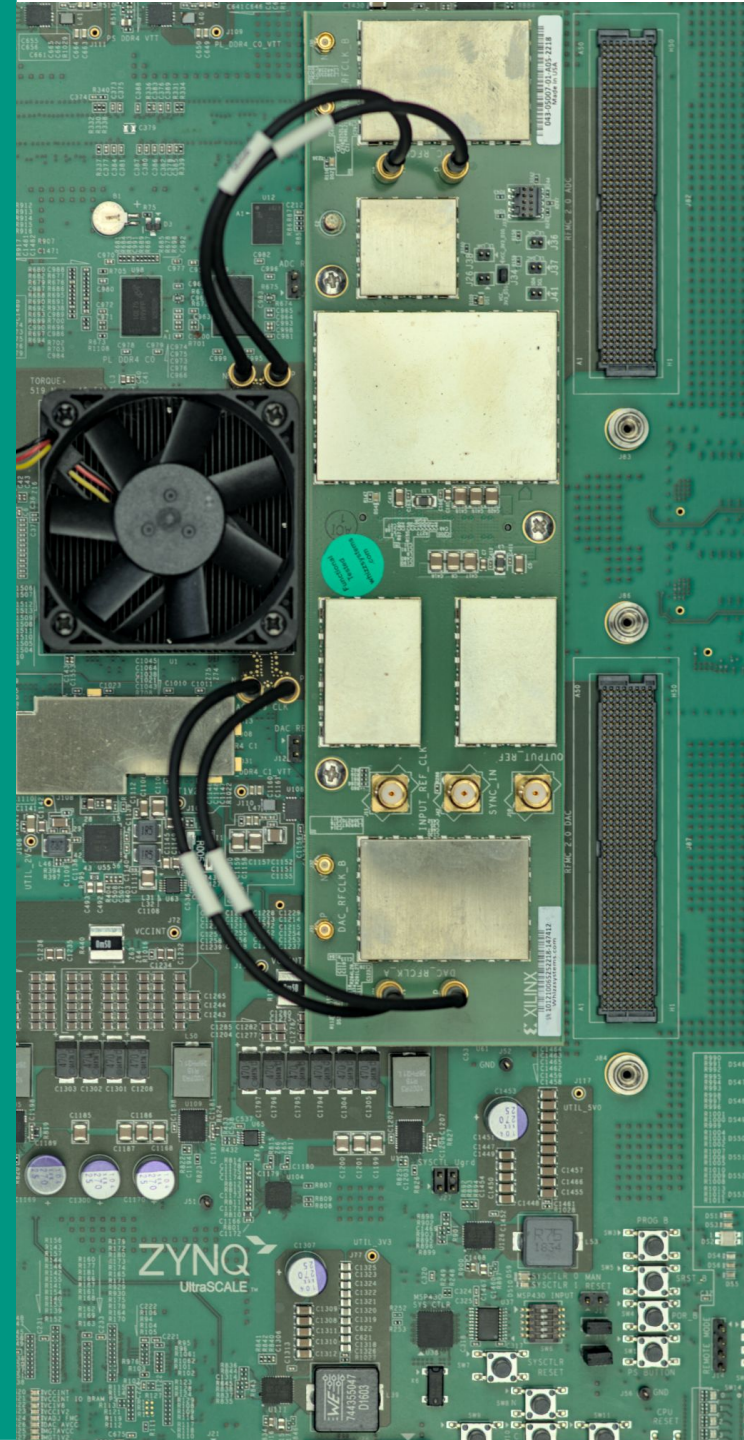


step 2: lower  $T$  below  $T_c^{\text{switch}}$  and remove the bias: the resonator will detect a current signal from a TES w/o ramp modulation

→ current prototypes successfully tuned with persistent current

# KICS: BW considerations

- ~~$\Delta f_{\text{res}} \geq 2f_{\text{ramp}} n_{\phi_0}$~~   ~~$n_{\phi_0} \equiv 2$  flux quanta per ramp period~~
  - $\Delta f_{\text{res}} \geq \frac{1}{\pi\tau_{\text{rise}}}$  requirement to avoid distortion
  - $f_n \geq 8\Delta f_{\text{res}}$  crosstalk suppression
  - each resonator requires a BW equal to  $f_n \approx \frac{8}{\pi \cdot \tau_{\text{rise}}} \Rightarrow$  **a factor 60**
- increase in the mux factor respect to SQUID mux**
- additional benefit from new RF-SoC boards, with larger BW
  - sampling time 0.1  $\mu\text{s}$   $\rightarrow$  lower pup contribution



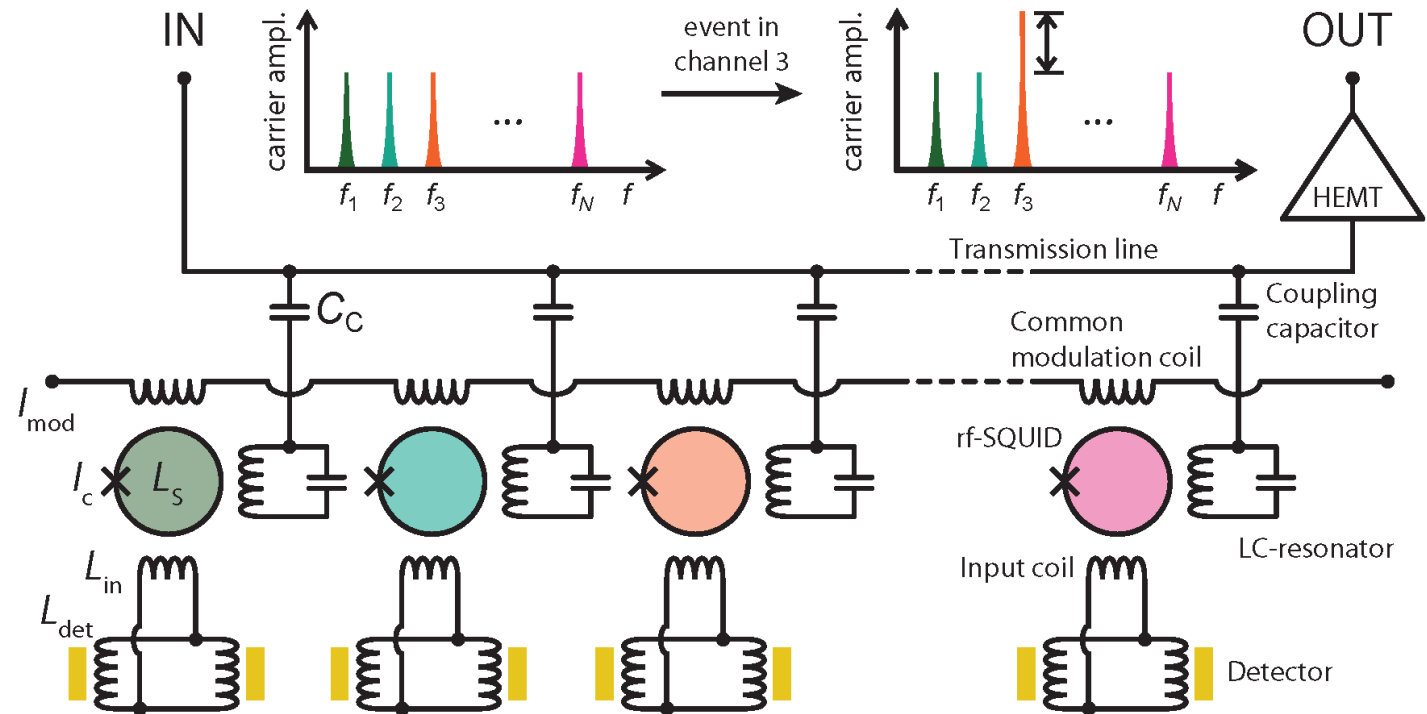
# ECHO electronics for $\mu$ MUX readout

Timo Muscheid, Robert Gartmann,  
Daniel Crovo, Luis E. Ardila-Perez

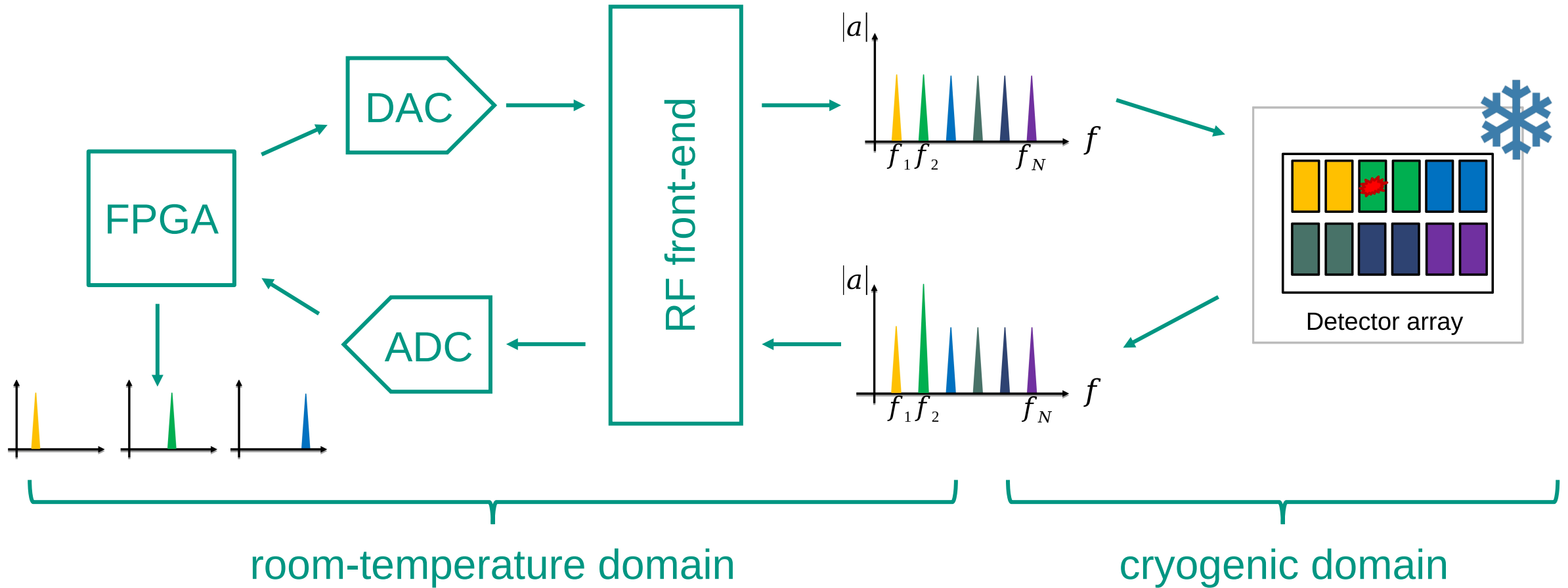
14.04.2026

# ECHo-100k Detector Design

- Frequency band: 4-8 GHz
- 400 Channels, 800 MMCs
- Spacing 10 MHz
- Detector bandwidth: 1.6 MHz
- 15 systems for 12k detectors



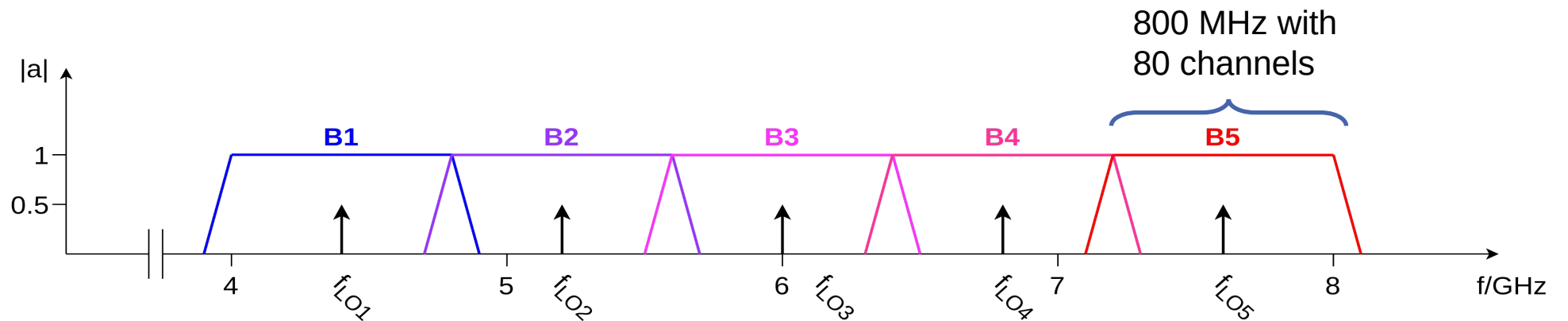
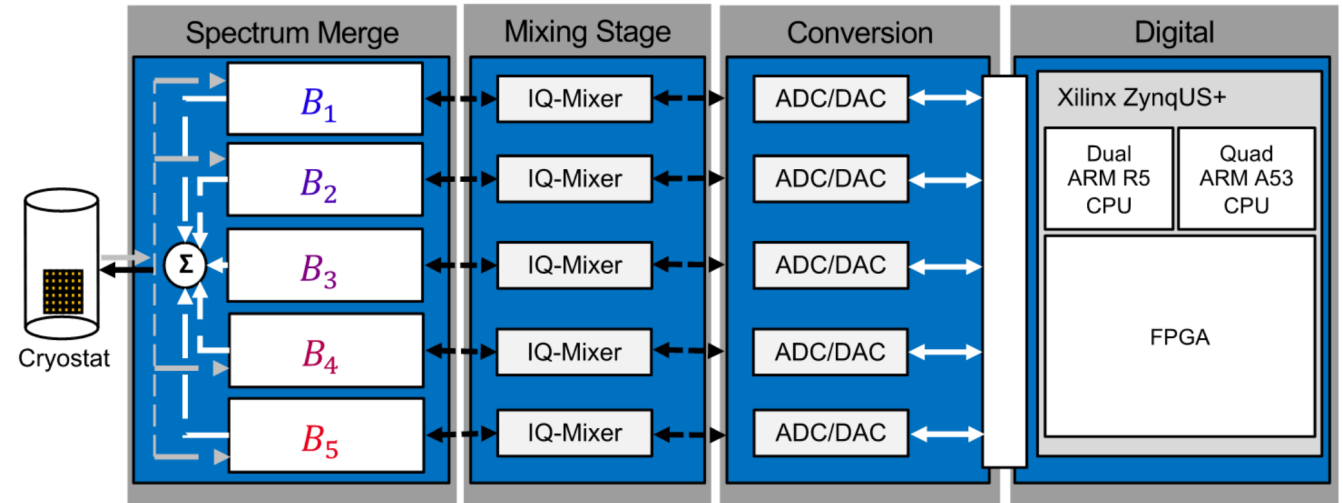
# Software-Defined Radio approach



Usable for readout of microwave SQUID multiplexed MMC and TES, as well as KID and KICS

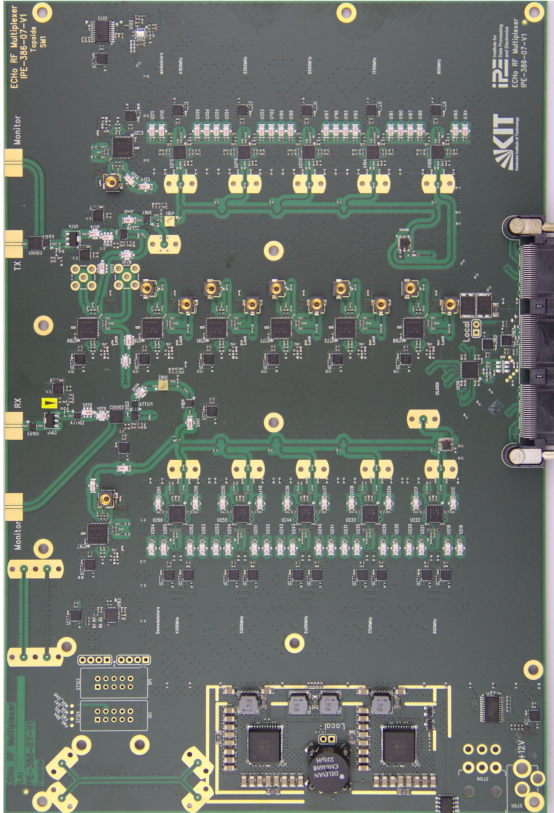
# ECHo-100k DAQ Architecture

- Digital signal processing on FPGA
- DAC + ADC operate at 1 GS/s
- Merge 5 bands of 800 MHz
- Mix from baseband to RF

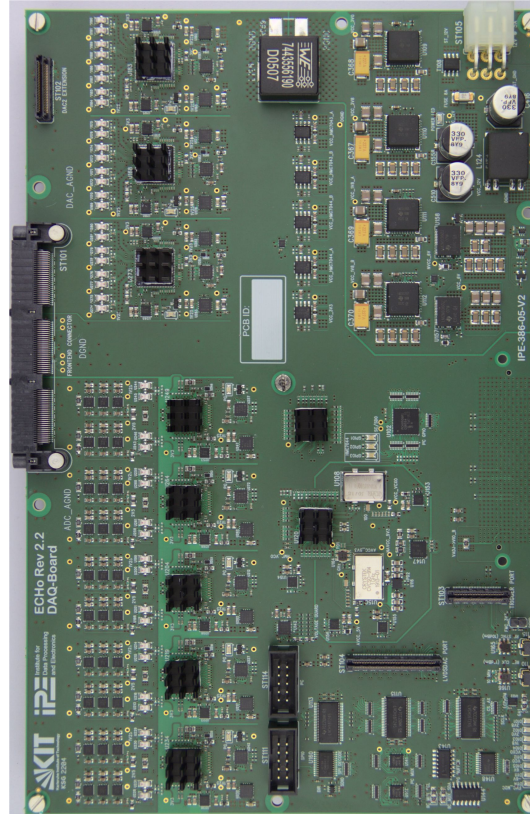


# EChO-100k Hardware

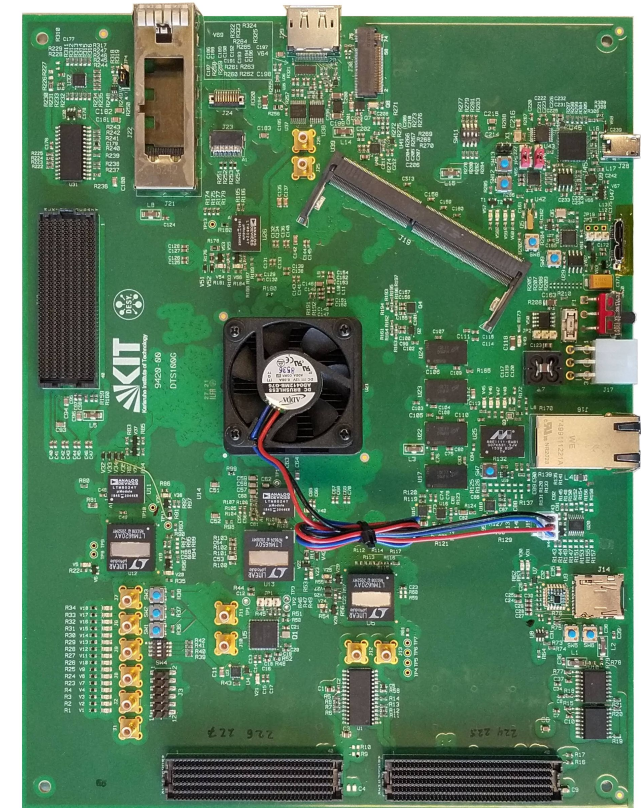
## RF-Frontend



## Conversion Stage

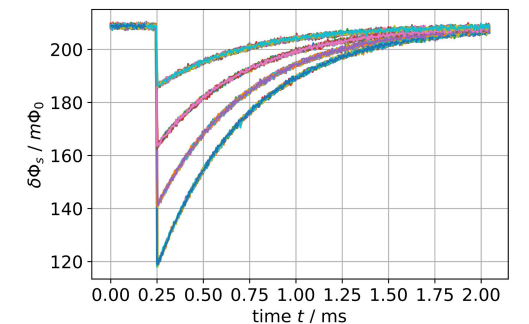
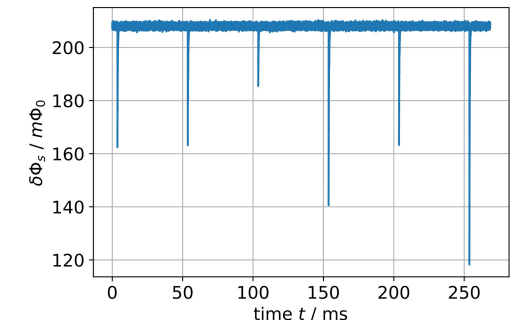
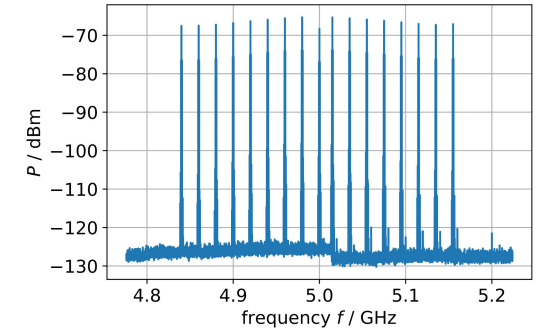
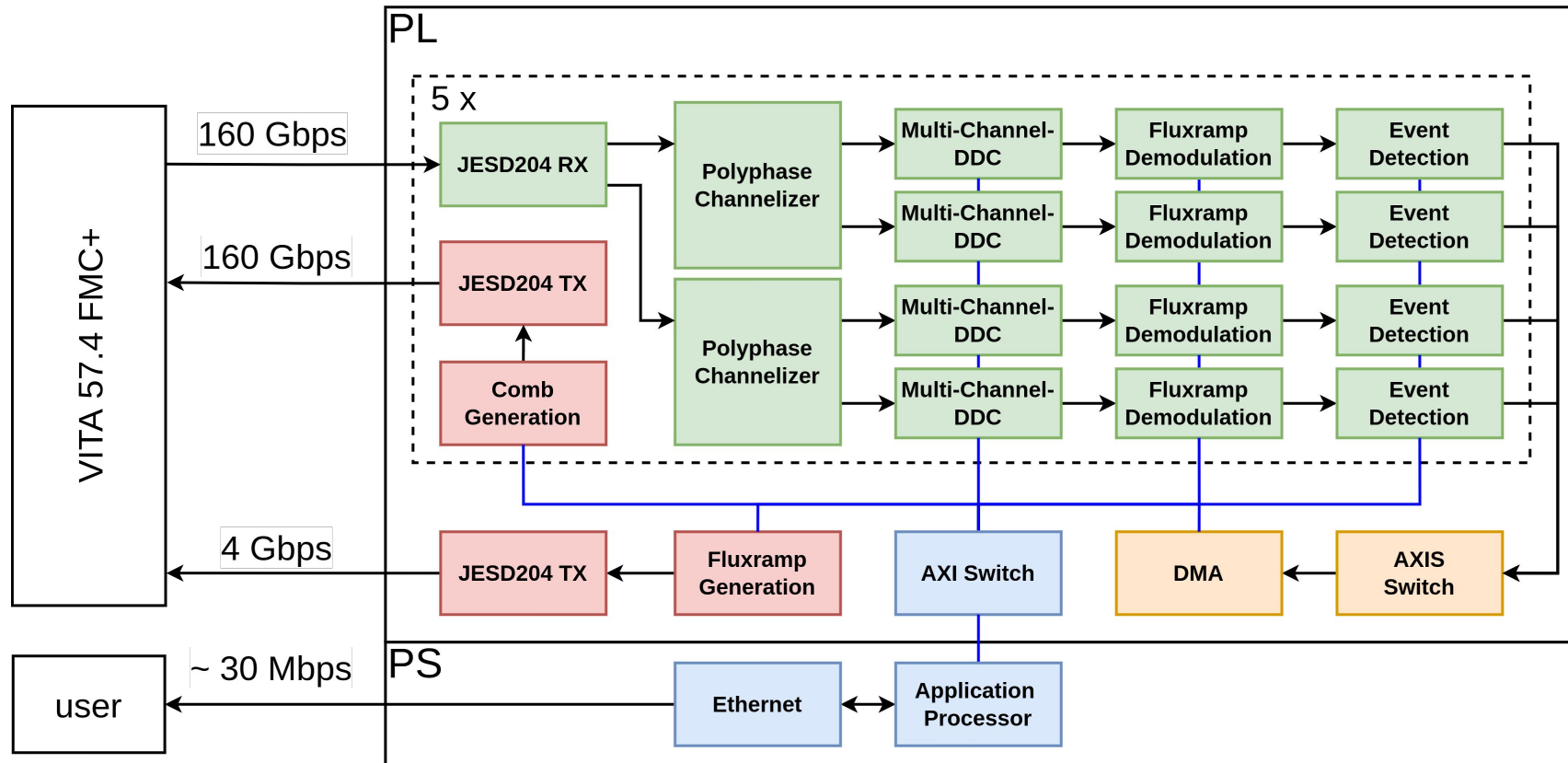


## FPGA-Board



Three custom boards for modular architecture

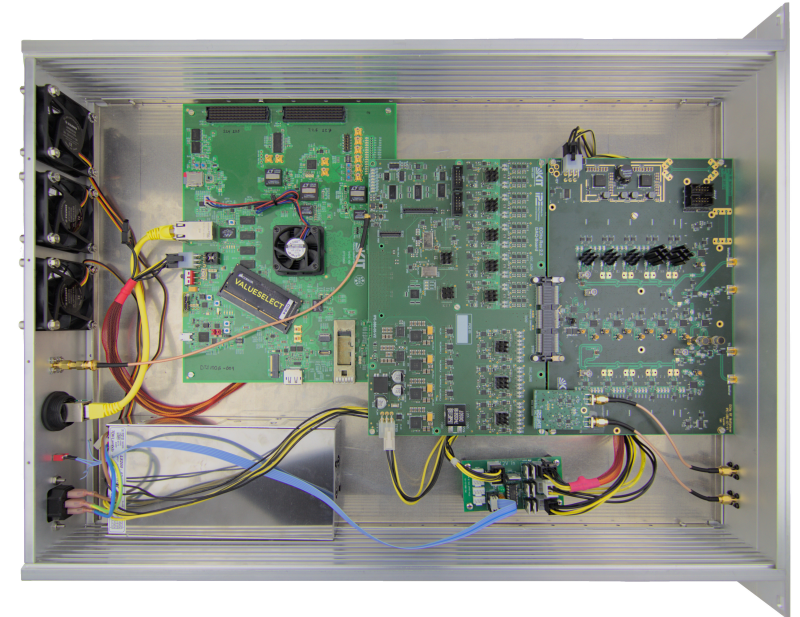
# ECHo-100k Firmware



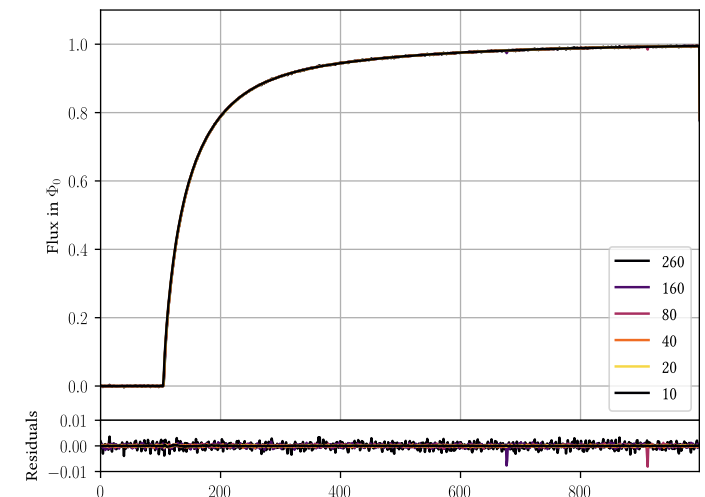
Real-time data processing on FPGA to reconstruct detector signals and reduce data rate

# Current status

- 15 Units assembled & commissioned
- Fully functional firmware
  - Carrier tone generation
  - Fluxramp generation
  - Frequency demultiplexing
  - Trigger System
- Successfully used in small-scale measurements
- Verification with digital detector emulator



Analysis of reconstructed pulse:



# ECHo-LE Requirements

- Goal: Readout of 20.000 MMCs
- 800 detectors per MUX: 25 systems
- DAQ work packages from ERC Grant:
  - Assembly of 10 additional systems
  - Integration of Tone Tracking feature

## Lessons learned from ECHo-100k DAQ:

- Development of custom hardware is laborious
- FPGA – Converter interface is difficult to setup
- Complex hardware architecture, not adaptive

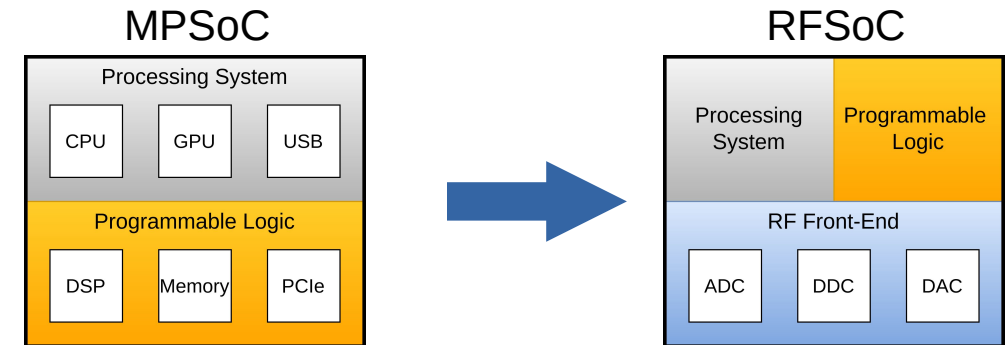
## Enhanced readout capability:

- Extension of FPGA firmware
- Static readout tones limit multiplexing factor

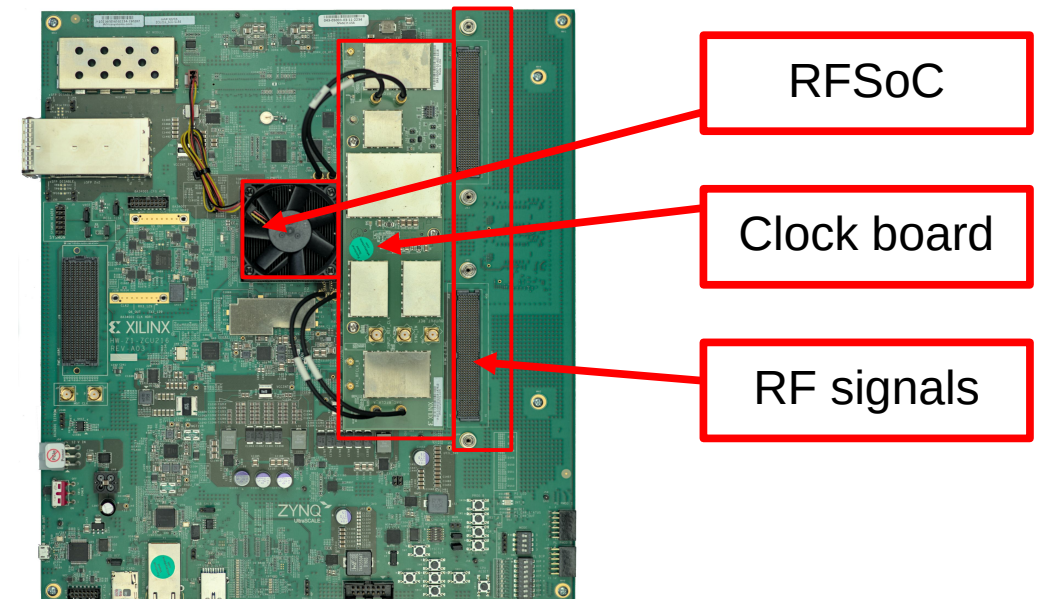
New DAQ systems will be improved using previous knowledge

# ECHo-LE Hardware Proposal

- AMD offers single-chip solution: RFSoc
- Advantages:
  - Higher integration
  - Easier interface to converters
  - Higher sampling rates
- Same architecture (Zynq UltraScale+)
- XCZU49DR device:
  - 16 DAC with 10 GS/s
  - 16 ADC with 2.5 GS/s

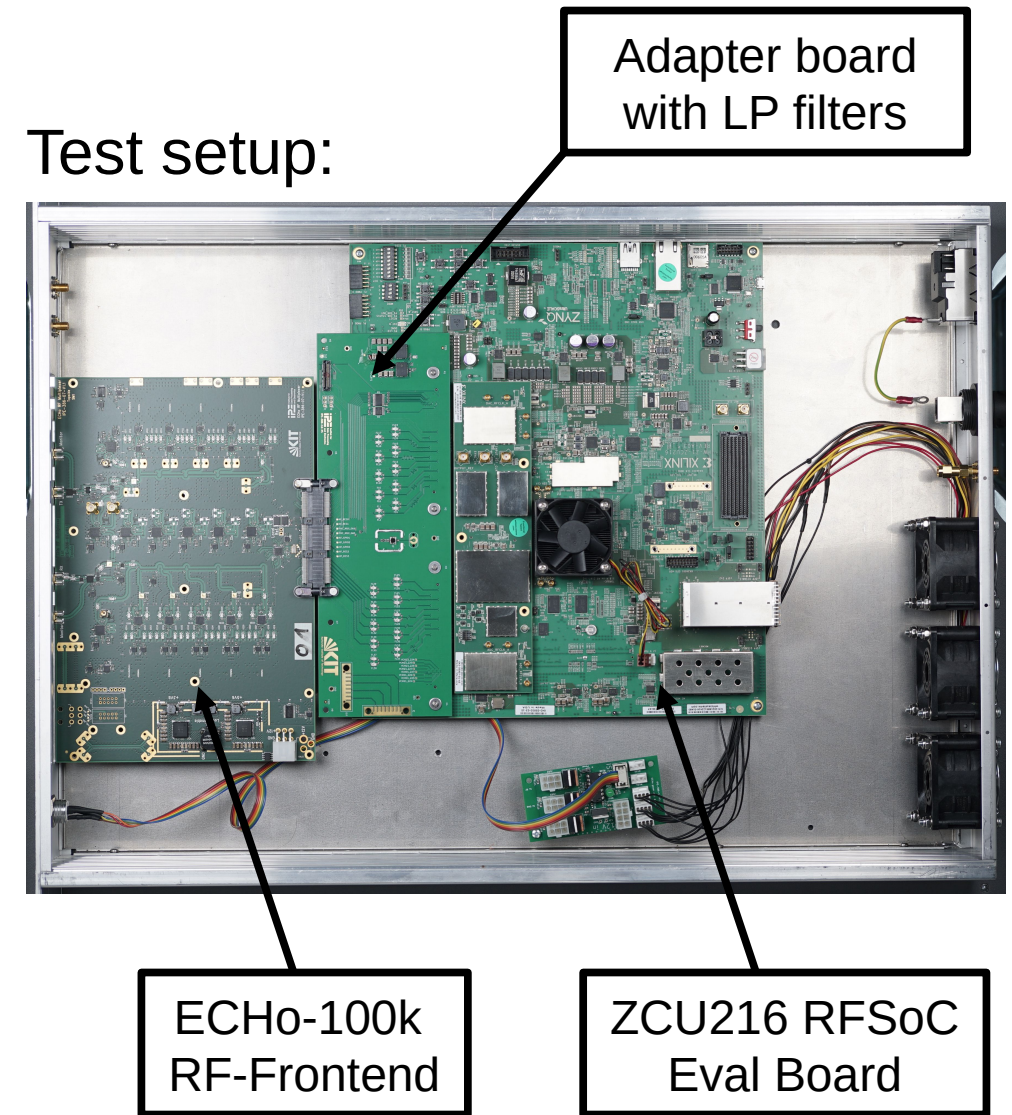


AMD ZCU216 Eval board:



# ECHo-LE Hardware Architecture

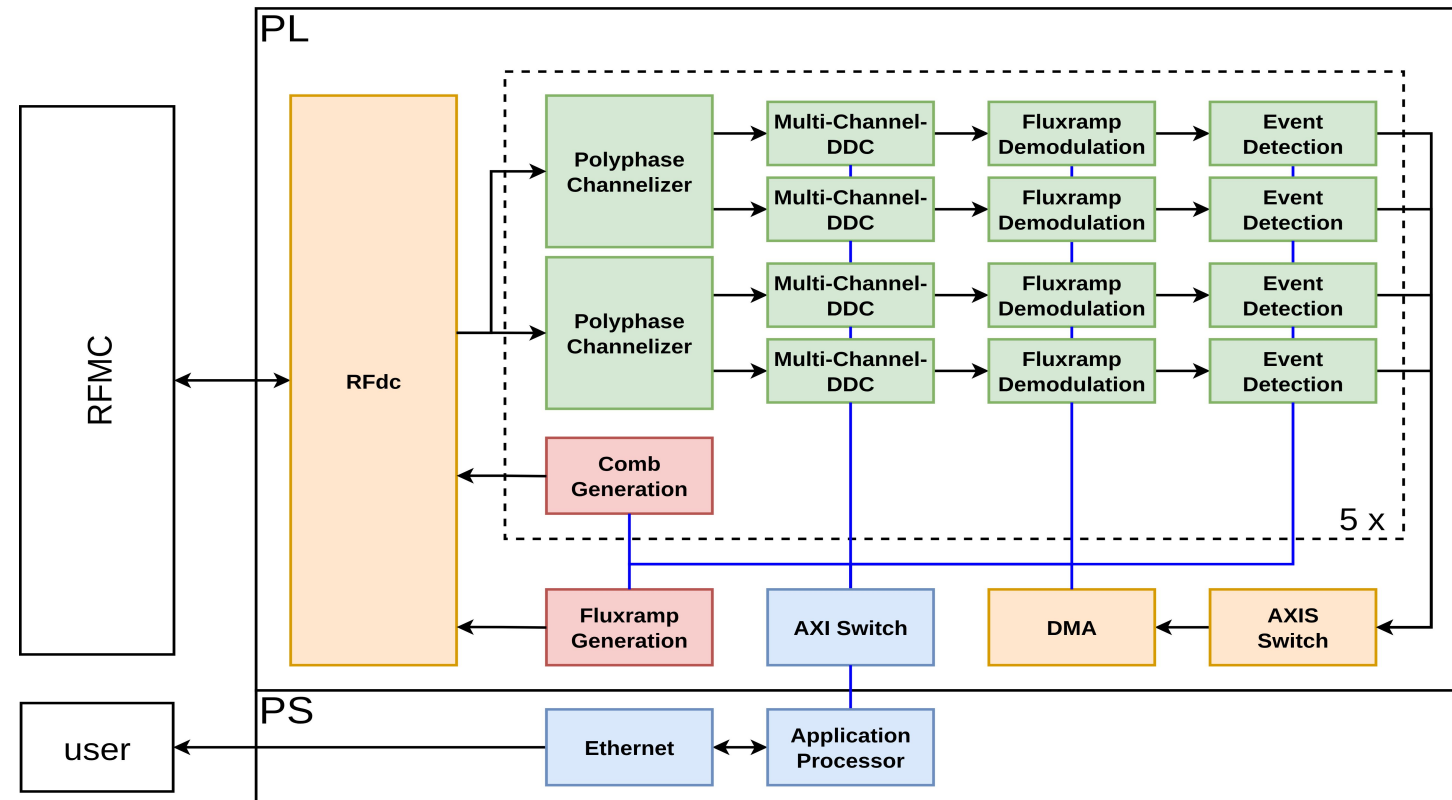
- RFSoc system
  - ZCU216 Evaluation board
  - SoM with custom base board
- Custom adapter card
  - Map DAC / ADC to RF channels
  - Low pass filter for signal conditioning
  - Connector for fluxramp board
- Analog front-end from ECHo-100k



RFSoc-based setup to evaluate performance

# ECHo-LE Firmware

- Replace JESD204 Protocol
- Use RFdc (AMD IP-Core)
  - Up-/ Downmixing
  - Interpolation/ Decimation
- Firmware migration complete
- More DSPs enable additional algorithms



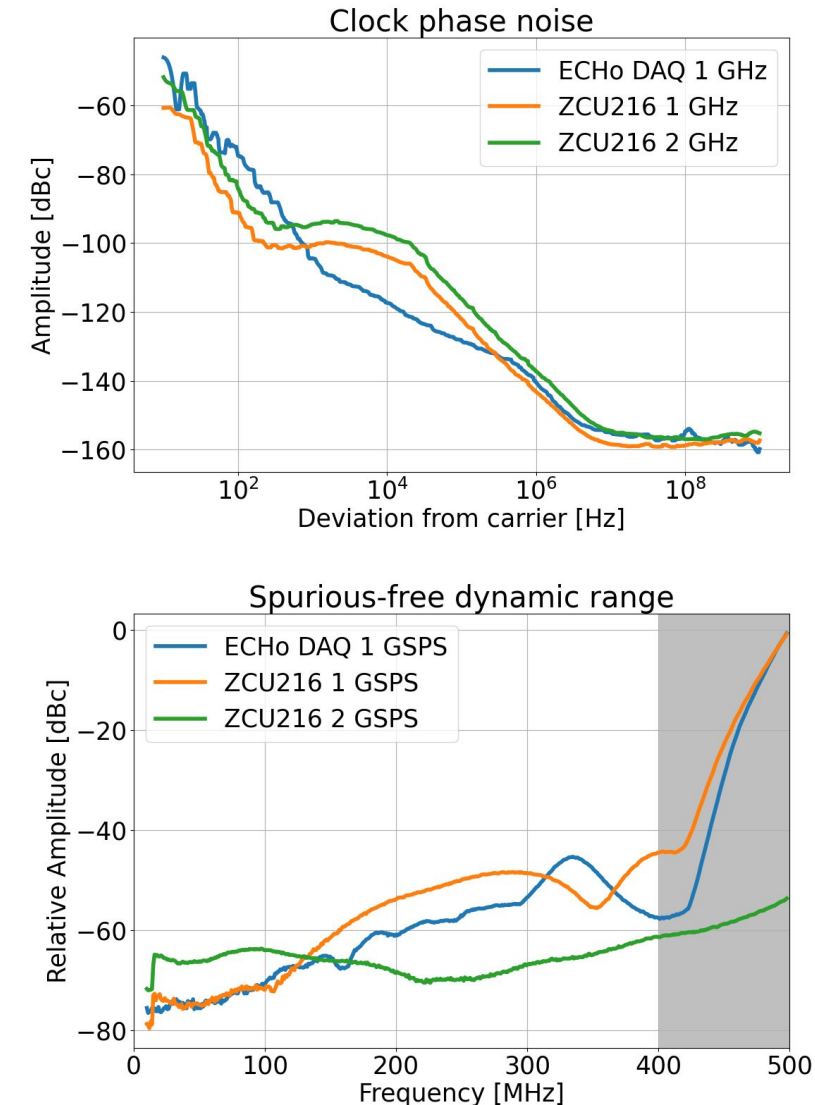
Type	MPSoC (ZU19EG)	RFSoc (ZU49DR)	ECHo-LE FW
LUT	523k	425k	323k
Logic cells	1143k	930k	544k
Memory	80.4 Mb	73.5 Mb	34.8 Mb
DSP	1968	4272	1334

# RFSoc Characterization

- ZCU216 comparable to ECHo hardware
- Clock quality limited by eval card, could be improved with custom clock board
- Higher sampling rates of DAC and ADC improve SFDR

## Previous work:

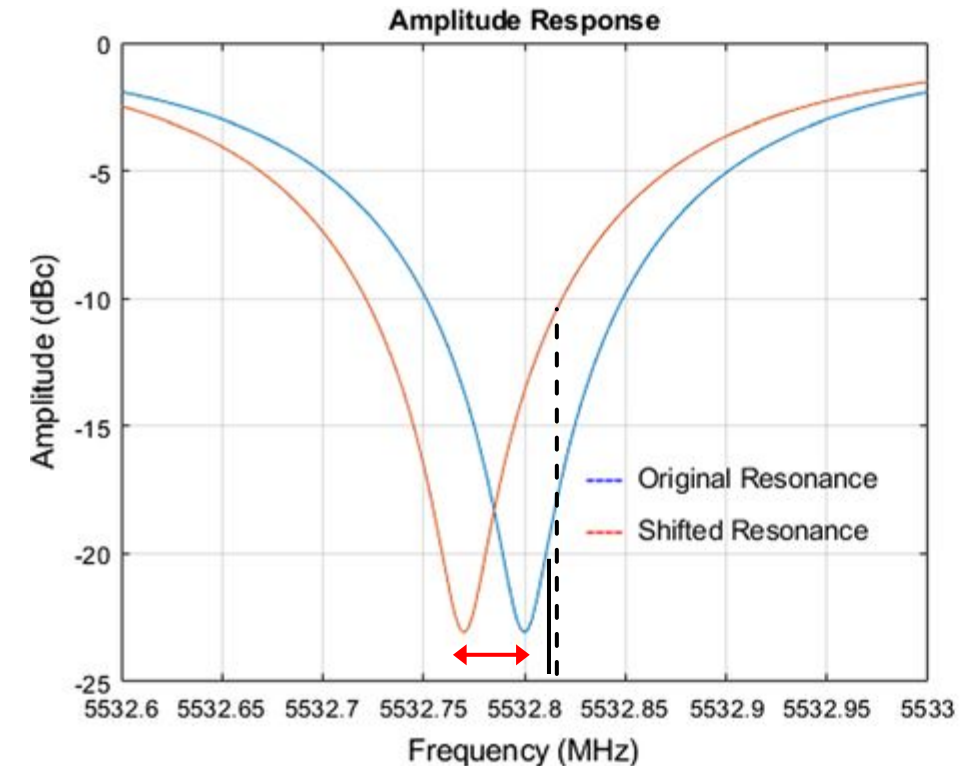
M. Garcia *et al.*, "RFSoc Gen3-based SDR Characterization for the Readout System of Low-Temperature Bolometers"  
R. Gartmann *et al.*, "Evaluating the RFSoc as a SDR readout system for Magnetic Microcalorimeters"



RFSoc-based DAQ shows comparable performance as custom hardware

# Tone Tracking

- Resonance frequency moves periodically
- Variable input power at HEMT amplifier, may lead to clipping
- Track resonance frequency with readout tone
- Requirements:
  - adaptive tone generation
  - control loop to correct frequency error



Firmware feature currently under active development

# Conclusions

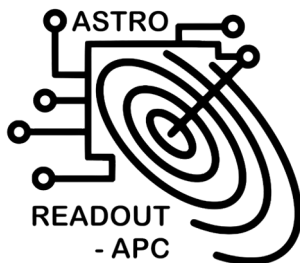
- 15 ECHo-100k DAQ systems ready for use
- 10 additional systems for ECHo-LE
- New systems will be based on RFSoc
- Similar performance, higher clock rates
- Tone Tracking under active development



# Low-noise and low-drift Front-end ASICs design

for astronomical telescopes QUBIC, ATHENA, (CMB-S4)

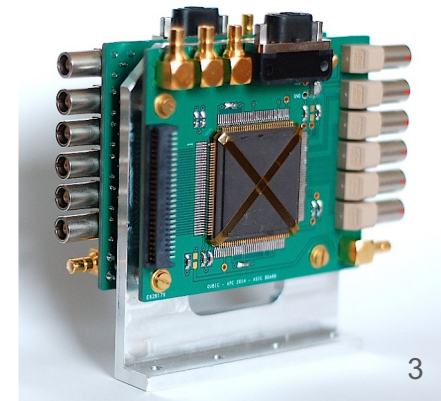
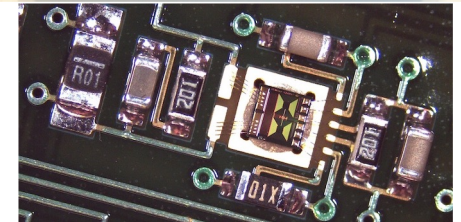
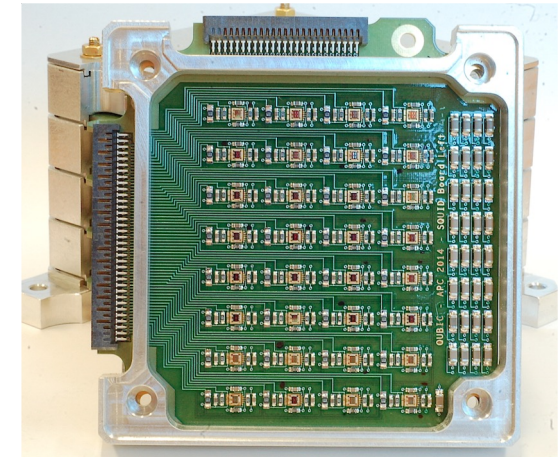
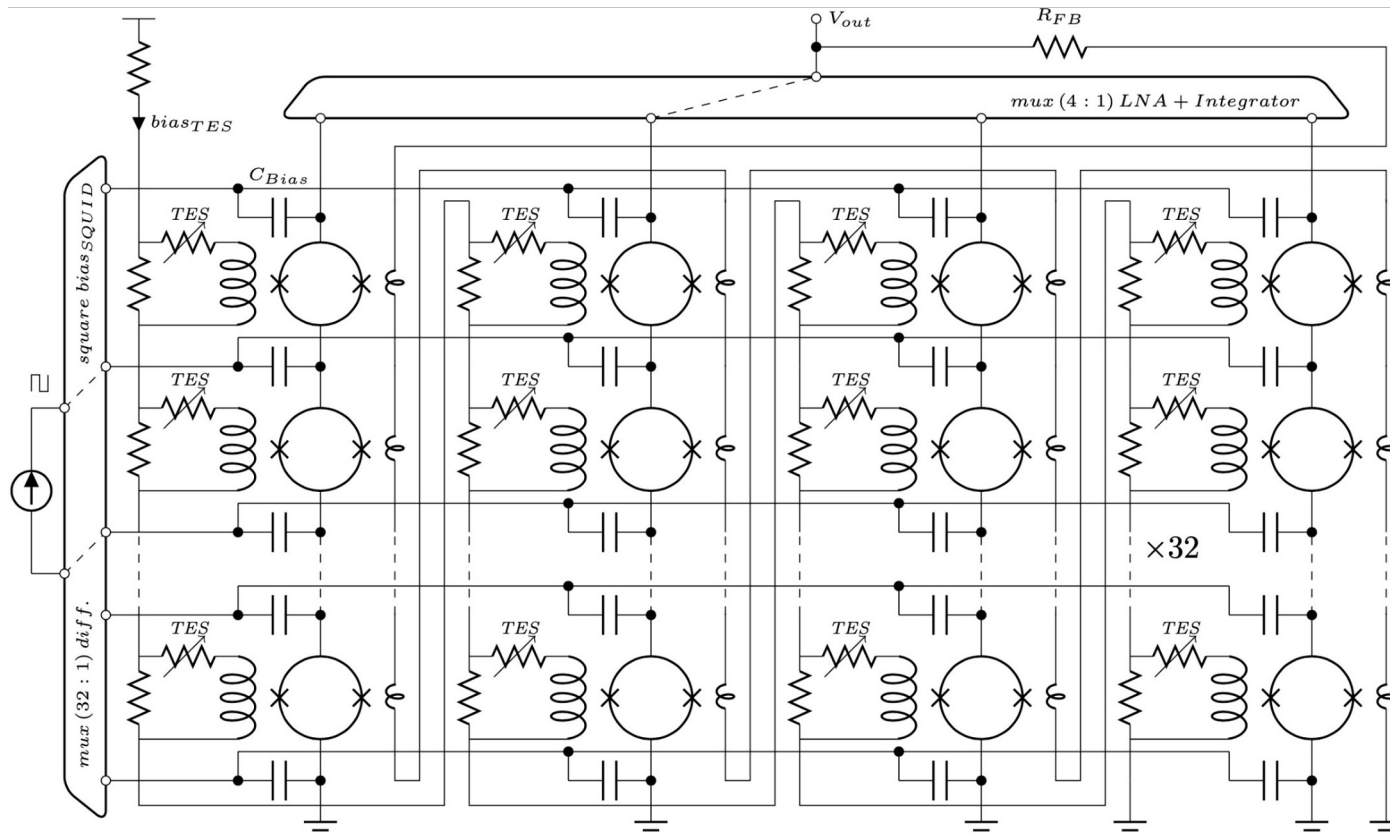
Damien PRELE - APC CNRS IN2P3 / Univ. Paris Cité  
14th of April 2026 - NuMass 2026 - KIT Karlsruhe  
Topical session *Front-end electronics*



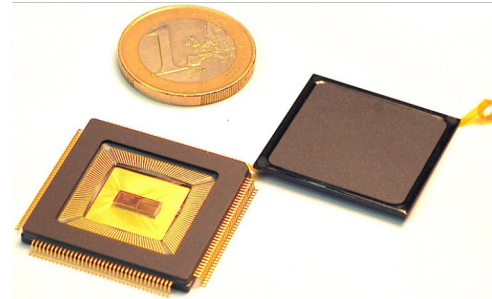
**QUBIC readout**

# QUBIC readout chain : SQUID multiplexing

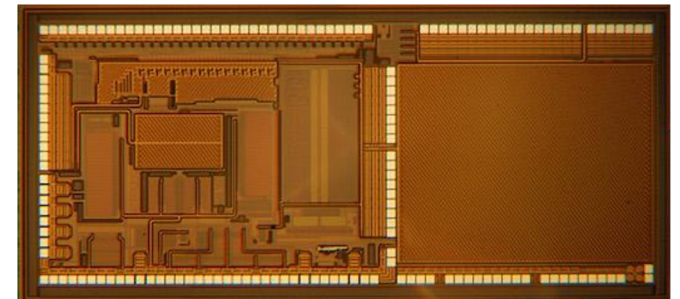
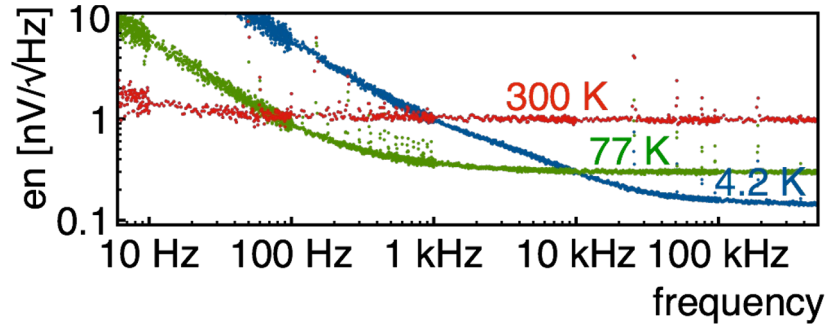
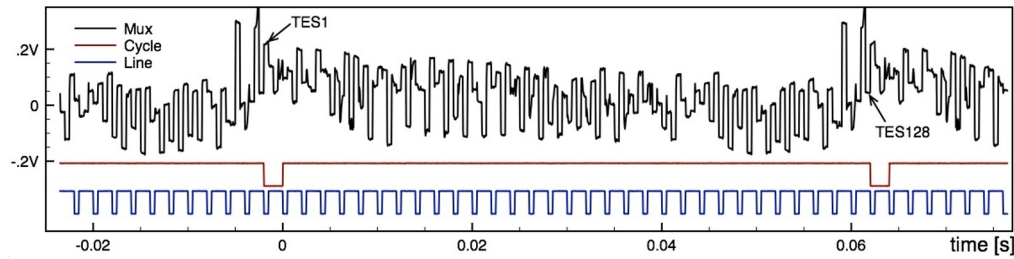
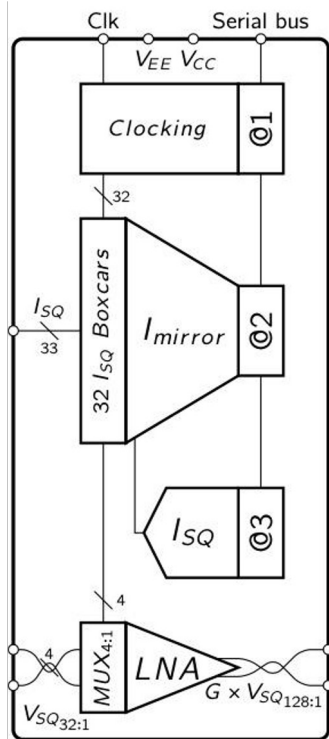
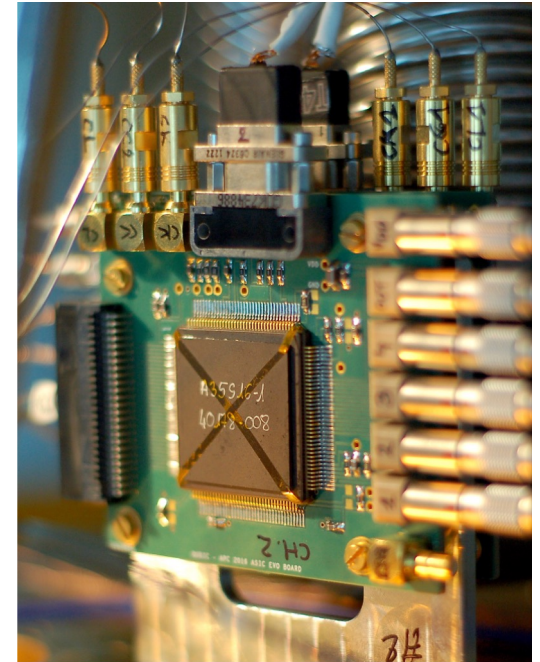
D. Prêle et al. Capacitively-Coupled SQUID Bias for Time Division Multiplexing doi 10.1007/s10909-014-1129-1



# QUBIC : ASIC SQmux128



D. Prêle et al A 128 Multiplexing Factor Time-Domain SQUID Multiplexer DOI DOI 10.1007/s10909-015-1449-9  
 M. Piat et al. QUBIC IV: Performance of TES Bolometers and Readout Electronics arXiv:2101.06787

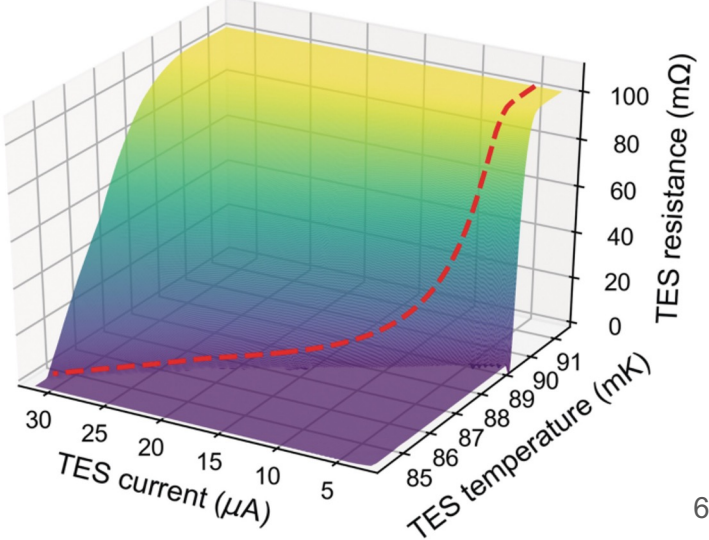
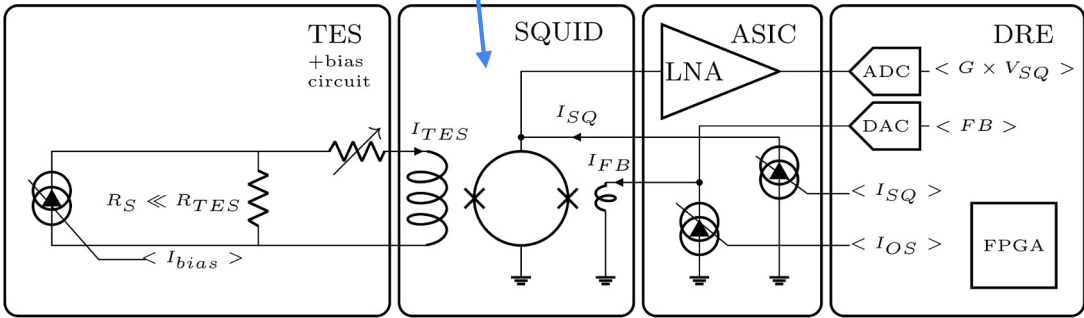
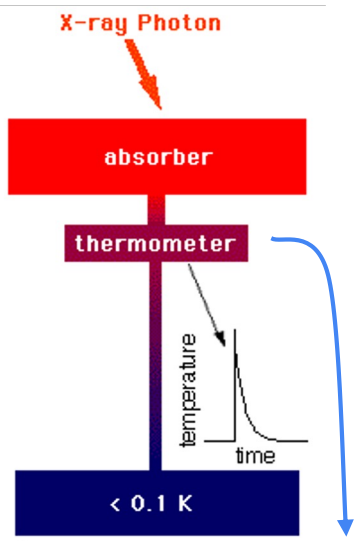
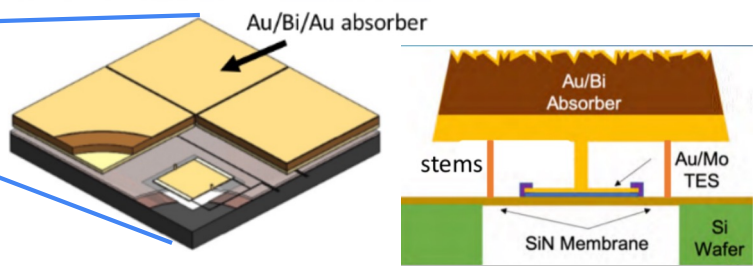
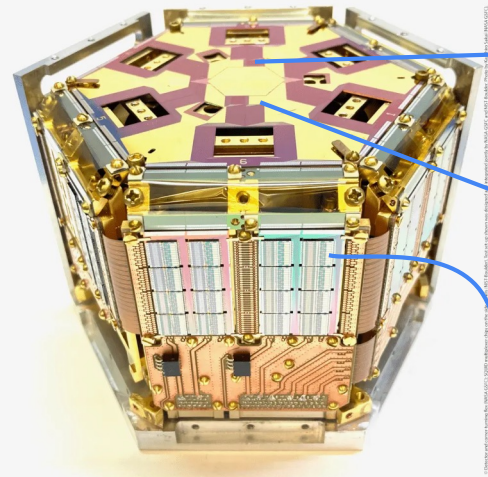


**ATHENA readout**



# X-IFU - Detectors and readout

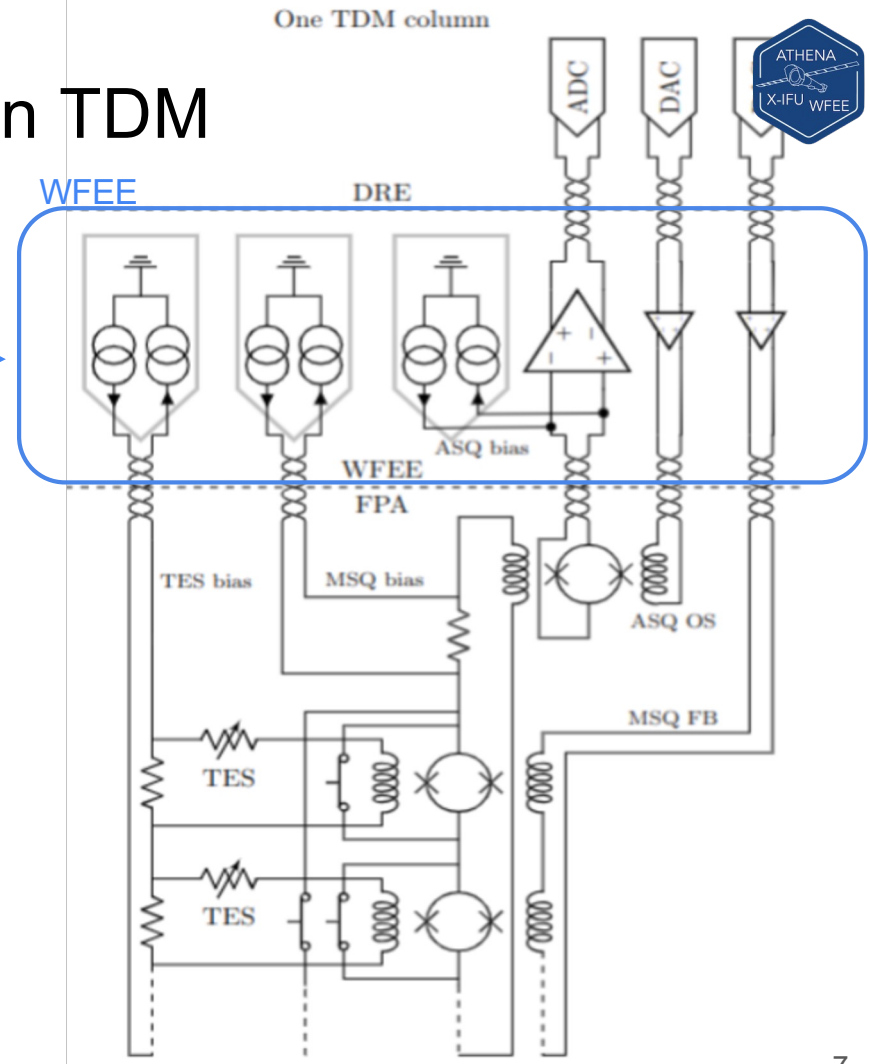
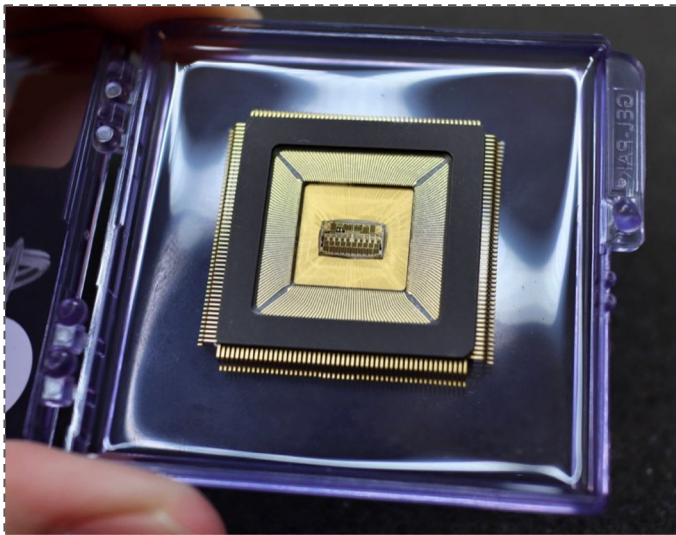
Micro-calorimeters based on transition edge sensors (TES)



L. Gottardi & S. Smith Transition-Edge Sensors for Cryogenic X-ray Imaging Spectrometers DOI 10.1007/978-981-16-4544-0\_22-1

# X-IFU - readout / multiplexing chain TDM

The warm front-end electronics - WFEE @ 300 K





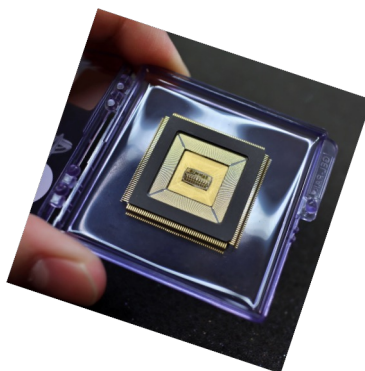
# WFEE ASIC developments

## ● ASIC technology consolidation

✓ AwaXe\_v3 full ASIC using AMS350nm BiCMOS tech. (2020)

used in WFEE demonstration models

build an AMS ASIC with TMR



-> dose & latch up tests->

-> last opportunity in 2025 to

AwaXe\_v4ana, v4.5DAC, v4.5LNA, v5bus, AwaXe\_v6/EM using ST130nm BiCMOS tech. (2

-> Dose test up to

200 krad end 2023 (report delivered)

-> SEE tests



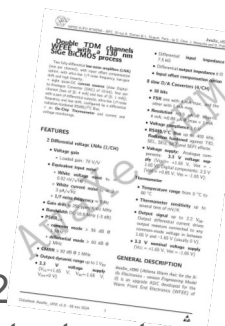
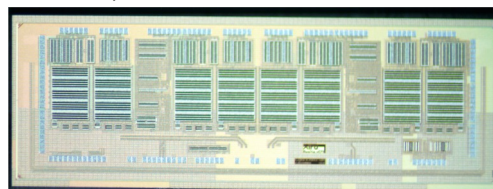
see -> ASIC design evolution of ATHENA X-IFU warm front-end electronics.

S. Chen, D. Prêle, M. Gonzalez, J. Mesquida, B. Courty, M. Punch, L. H. Arnaldi, B. Ton, J. Lesrel, Proc. Volume 13093,

Space Telescopes and Instrumentation 2024:

Ultraviolet to Gamma Ray; 130934J (2024)

doi. 10.1117/12.3020115



Highlight ASIC technology

# The ASICs

**SQmux128** AMS350 2016 (SQUIDbias+Row@+LNA 40-50K)

-> Integrated in **QUBIC (50K)**

see technical Design Report : <https://arxiv.org/pdf/1609.04372>

**AwaXe\_v3** AMS350 2020 (2ch SQUIDs+TES bias+LNAs+HK 300K)

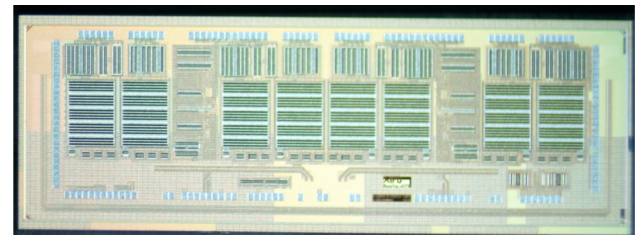
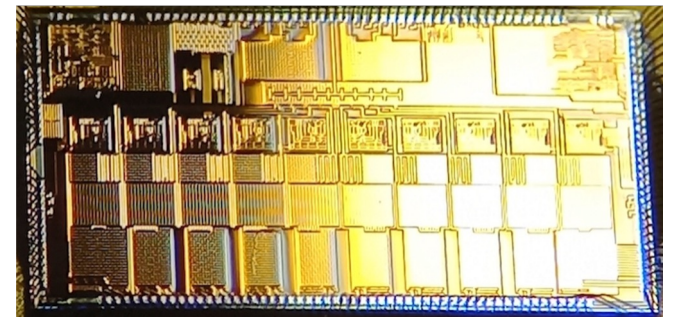
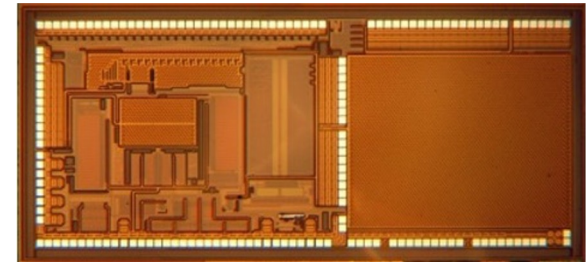
-> Integrated in **X-IFU WFEE DM (300K)**

**AwaXe\_vEM** ST130 2024 (2ch SQUIDs+TES bias+LNAs+HK 300K)

-> not yet tested

S. Chen, D. prèle, M. Gonzalez, J. Mequida et al. doi. 10.1117/12.3020115

1mm



Bipolar technology for low-noise IC front-end

# Bipolar (BJT/HBT) vs MOS for low-noise analog electronics

Flicker noise :

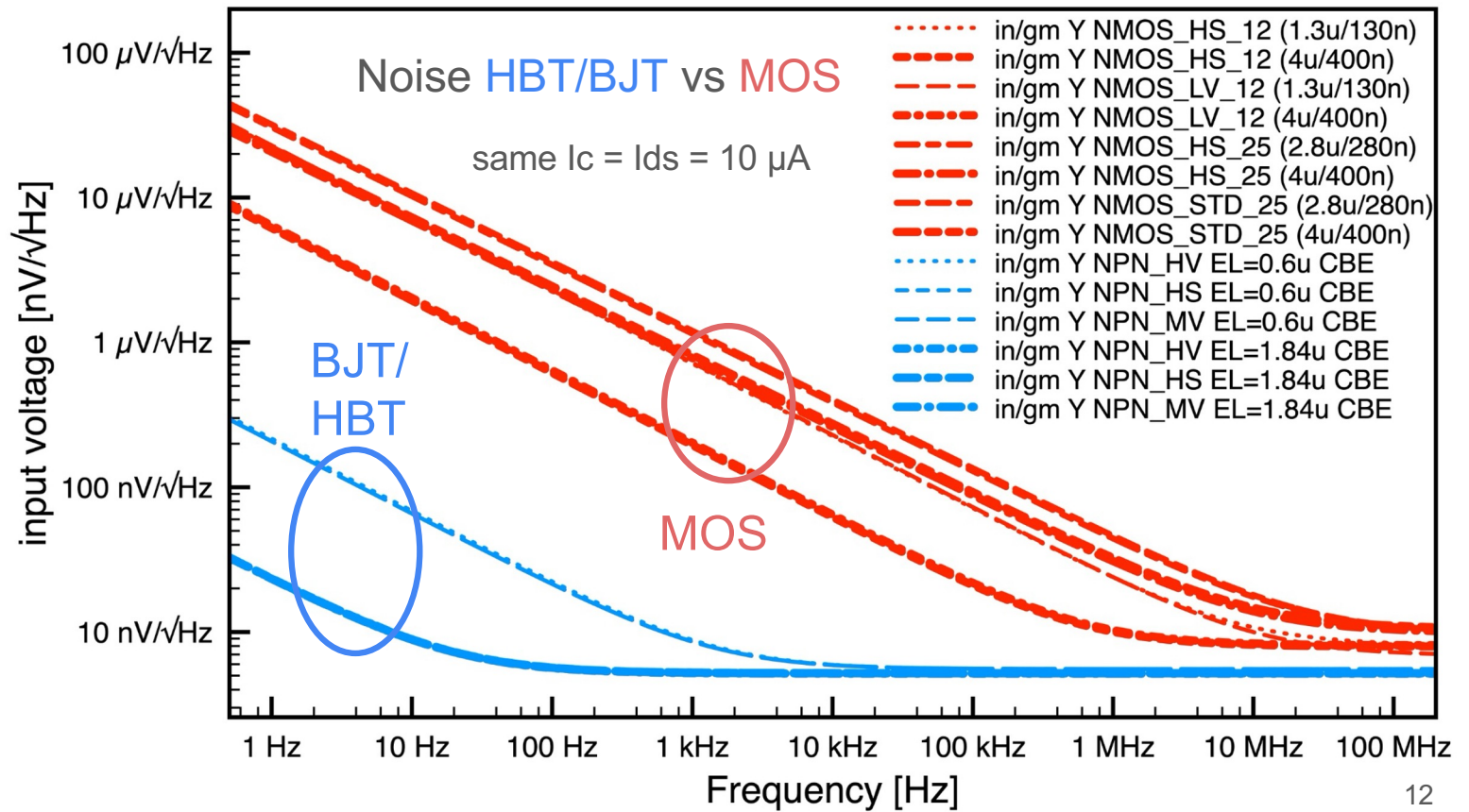
MOSFET

$$\overline{i_{df}^2} = \frac{K}{C_{ox}WL} \frac{1}{f^c} g_m^2 \Delta f$$

$$f_c = \frac{K}{C_{ox}WL} g_m \frac{3}{8k_B T}$$

BJT & HBT

$$\overline{i_{fb}^2} = \frac{KI^a}{f^b} \Delta f$$



## FET vs Bipolar noise - a large transconductance ( $g_m$ ) is required

**FET noise = THERMAL noise of the channel resistance**

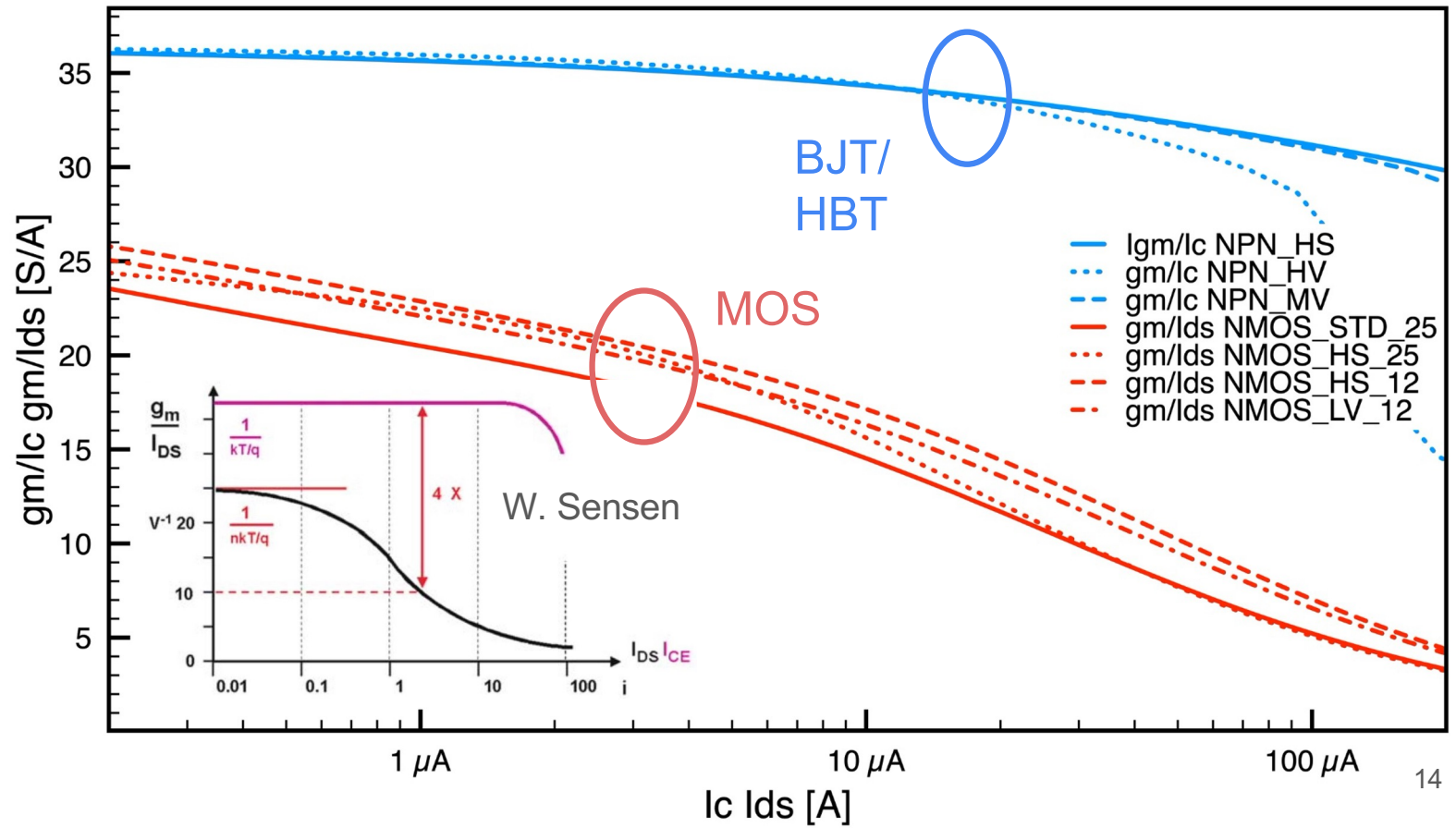
- ▶ Output current noise :  $S_{i_D} = 4k_B T \frac{2g_m}{3} + K \frac{I_D^{\alpha \approx 2}}{f^{\gamma \approx 1}}$
- ▶ **Input voltage noise** :  $S_{v_{GS}} = \frac{S_{i_D}}{g_m^2} = \frac{8k_B T}{3g_m} + \frac{K}{g_m^2} \frac{I_D^{\alpha \approx 2}}{f^{\gamma \approx 1}}$

**Bipolar noise = SHOT noise of the junctions**

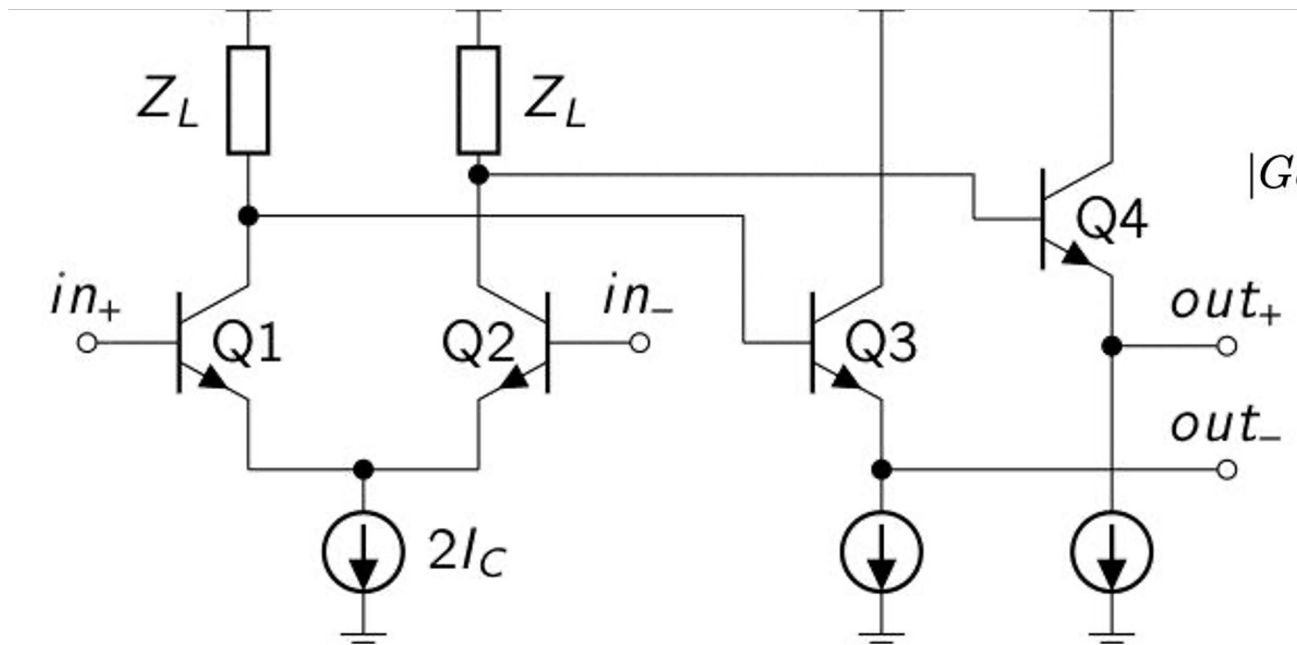
- ▶ **Input voltage noise**  $S_{v_{BE}} = 4k_B T R_{BB'} + \frac{2qI_C}{g_m^2} + K \frac{R_{BB'} I_B^{\alpha \approx 2}}{f^{\gamma \approx 1}}$   
 $\approx \frac{4k_B T}{2g_m} + K \frac{R_{BB'} I_B^{\alpha \approx 2}}{f^{\gamma \approx 1}}$
- ▶ Input current noise  $S_{i_B} = 2qI_B + K \frac{I_B^{\alpha \approx 2}}{f^{\gamma \approx 1}}$

# Transconductance $\mu\text{S}/\mu\text{A}$ (BJT/HBT 38 $\mu\text{S}/\mu\text{A}$ , MOS 30 $\mu\text{S}/\mu\text{A}$ )

“The  $g_m/I$  ratio is also better with a bipolar transistor” - Analog Design Essentials, Willy M. C. Sansen Textbook



## typical differential LNA topology



input gain :

$$|Gain_R| = g_m \times R_L = \frac{qI_C}{k_B T} \times R_L$$

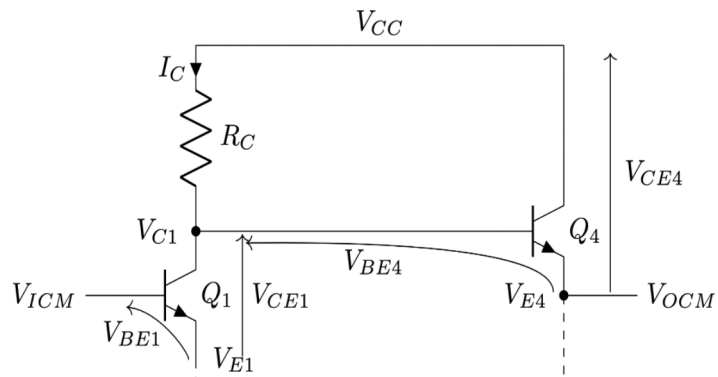
$Z_{in} = \beta/g_m$

output drivers :

$$Z_{out} = 1/g_m = k_B T/q$$

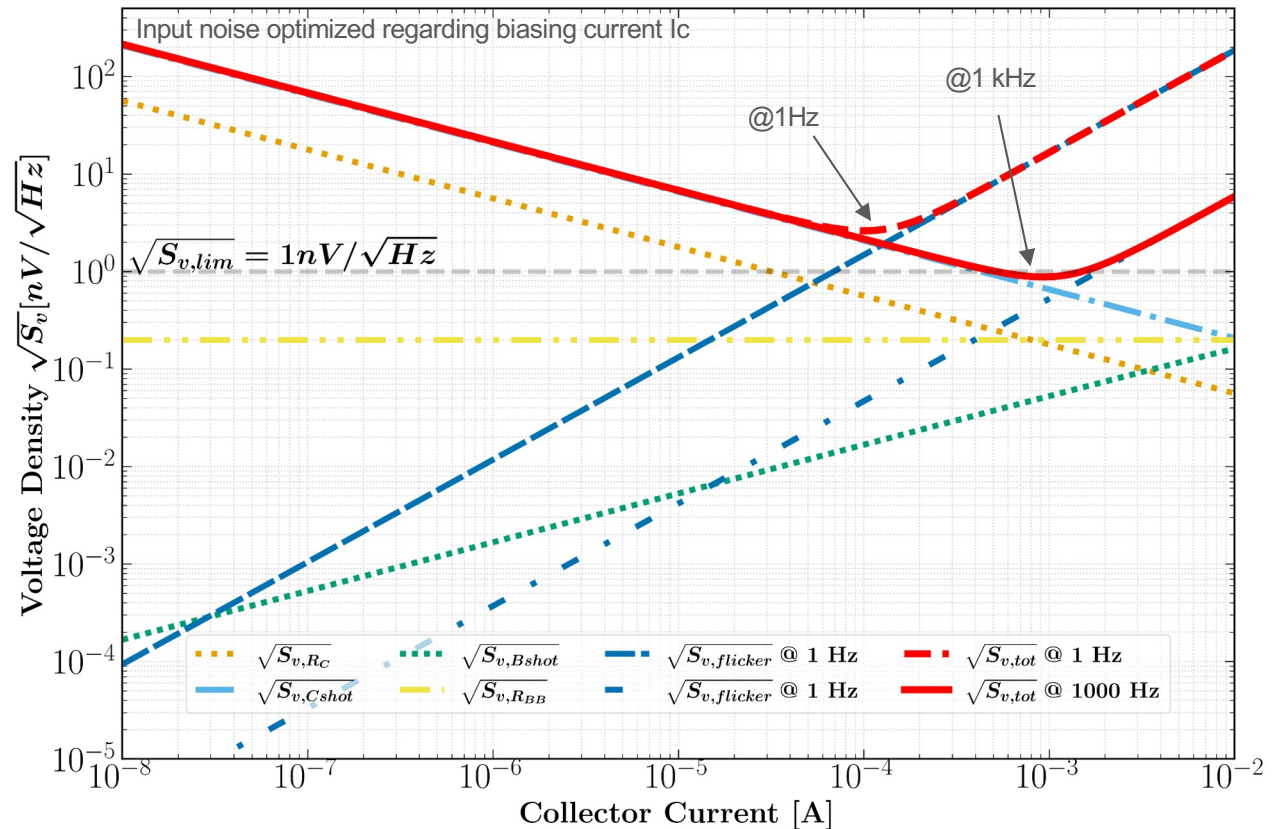
$$\sqrt{S_v} = \sqrt{2} \times \sqrt{4k_B T R_{BB'} + 2qI_B \times \left( \frac{(R_{BB'} + R_S)h_{11}}{R_{BB'} + R_S + h_{11}} \right)^2 + \frac{2qI_C}{g_m^2} + \frac{4k_B T/R_L}{g_m^2}}$$

# Optimisation regarding Flicker noise Bao TON PhD thesis (2023-2026)



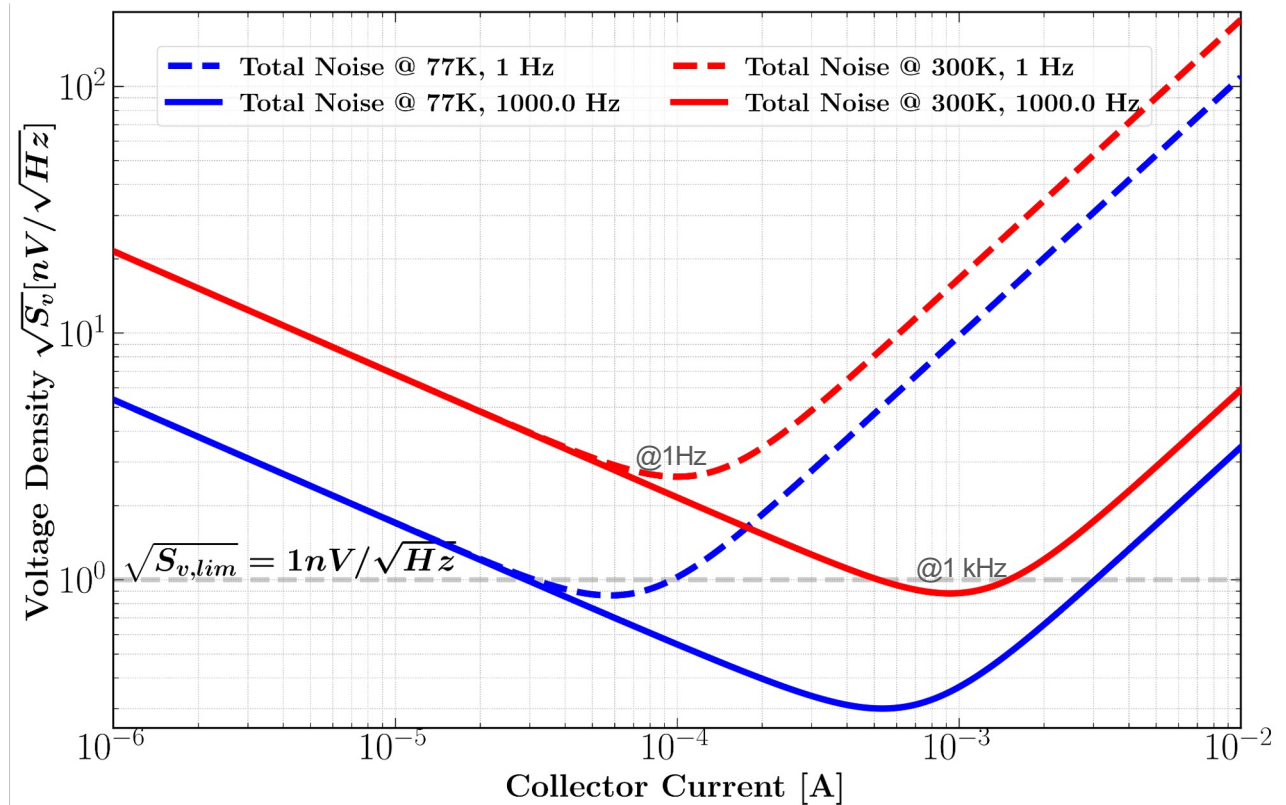
$$V_{OCM} = V_{CC} - I_C R_C - V_{BE4}$$

with DC coupling, output common mode is linked with the gain

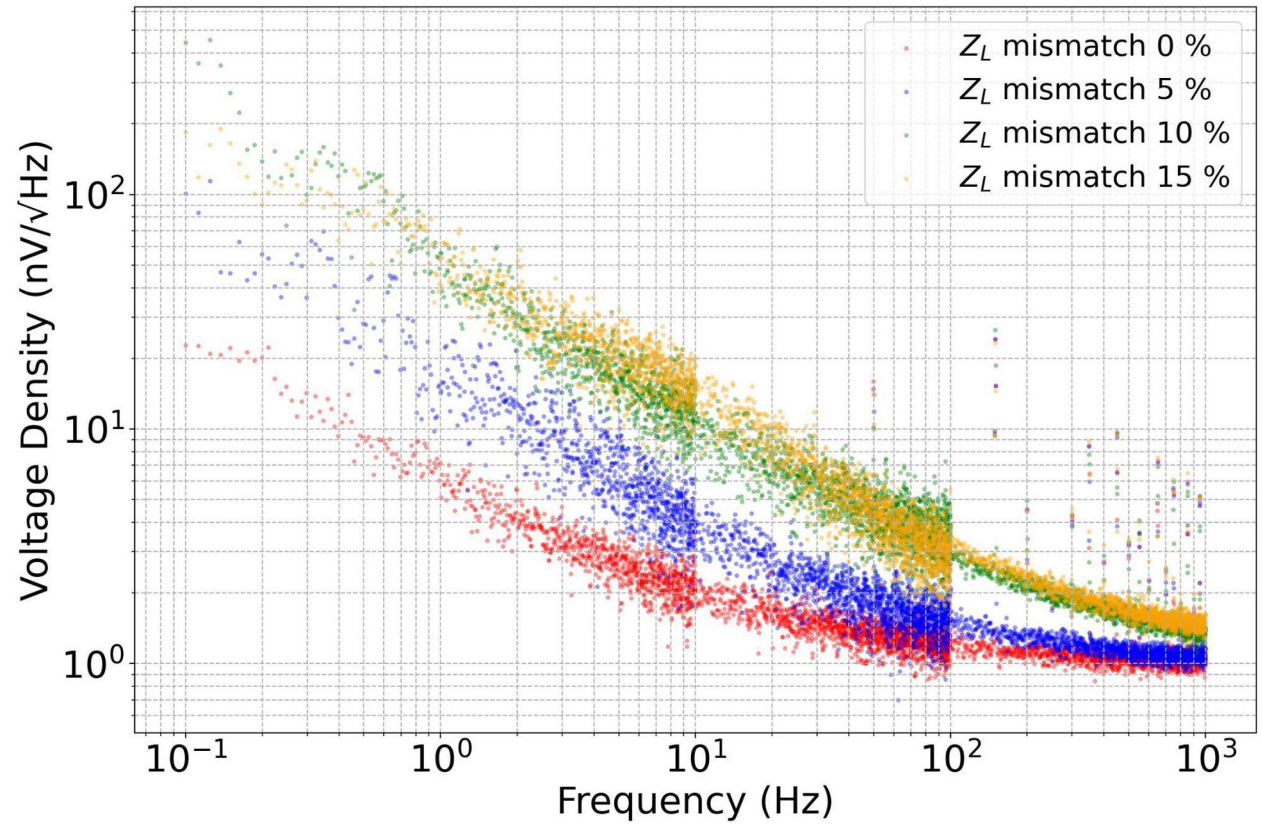
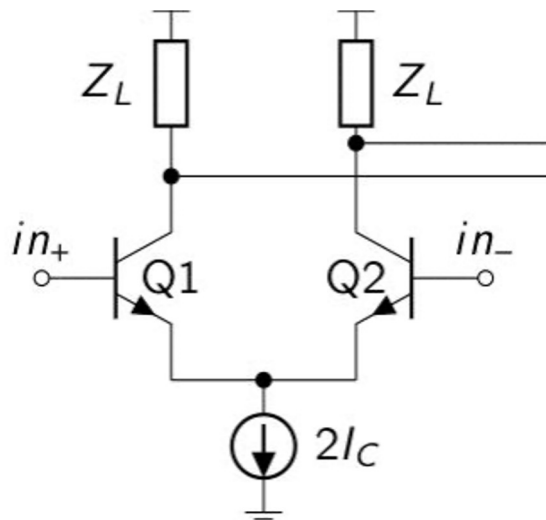


# Optimisation regarding Flicker noise Bao TON PhD thesis (2023-2026)

*and this  
depend with the  
temperature*

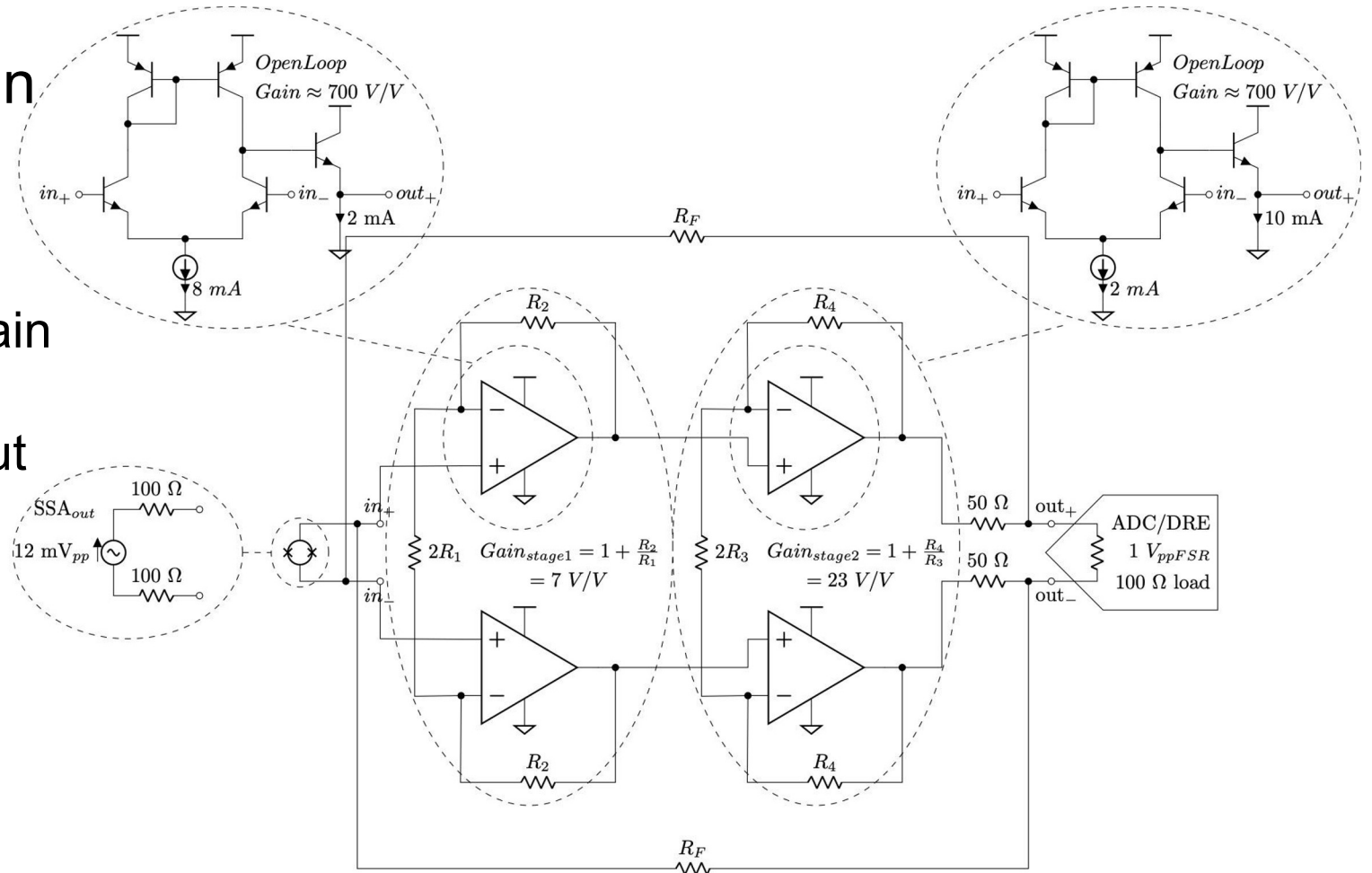


# Mismatch vs Flicker noise Bao TON PhD thesis (2023-2026)



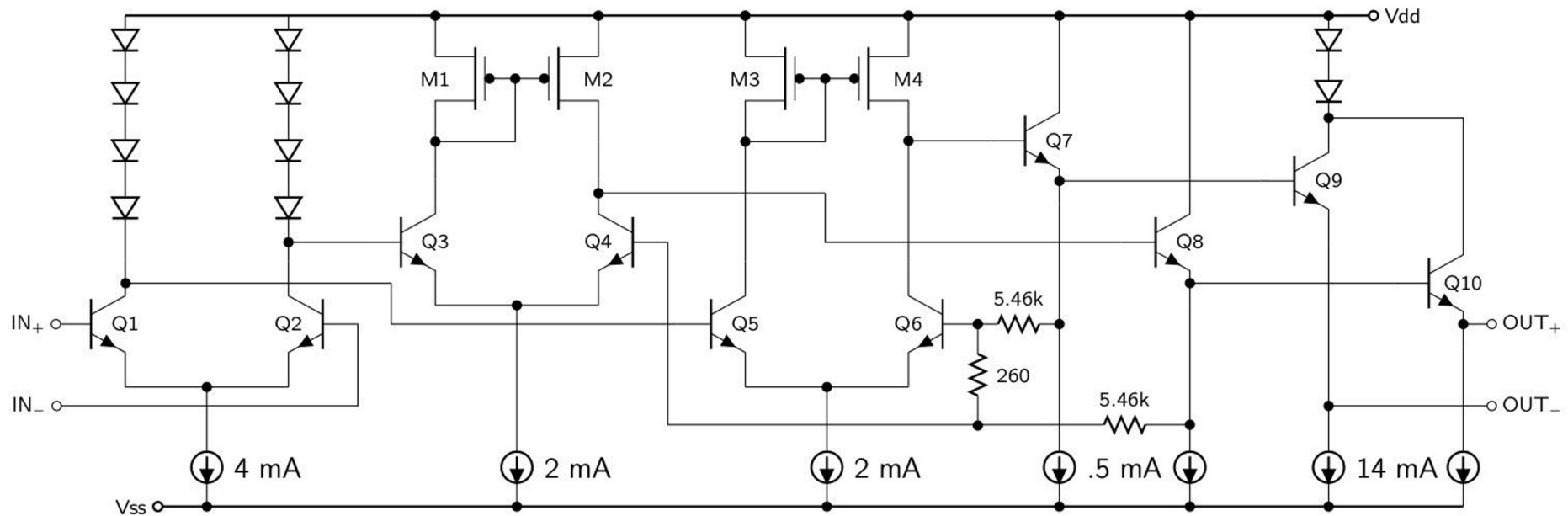
# Instrumentation amplifier

- Fixed differential gain
- matched input impedance
- Low noise (low  $R_1$ )



$$i_n R_S = e_n \rightarrow 2q \frac{I_{C_{opt}}}{\beta} R_S^2 = \frac{2(k_B T)^2}{q I_{C_{opt}}} \rightarrow I_{C_{opt}} = \frac{k_B T}{q} \times \frac{\sqrt{\beta}}{R_S}$$

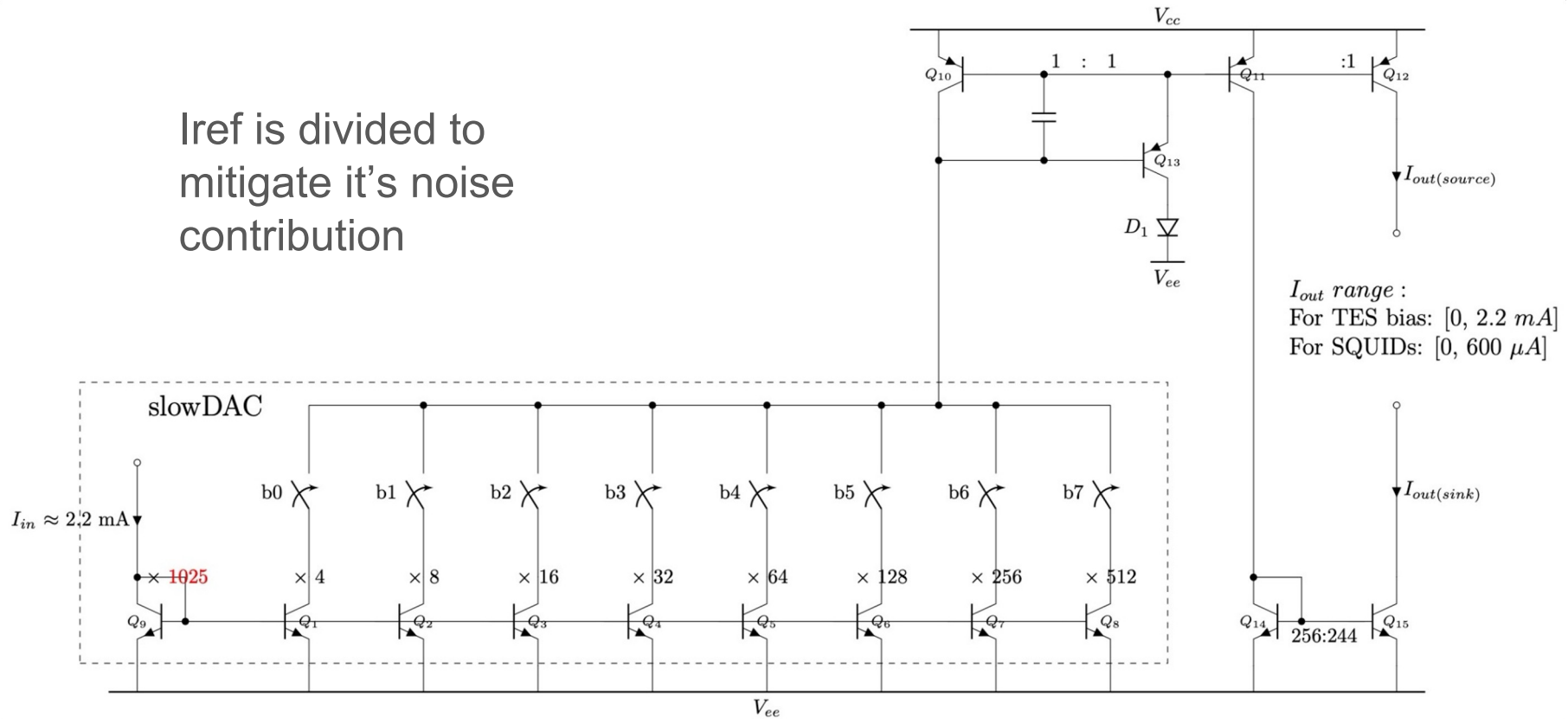
# Diff LNA AMS : Low noise / low gain drift LNA (AwaXe\_v3)



$$|Gain_D| = g_m \times n_D \times \frac{k_B T}{q I_C} = n_D \quad \forall I_C \text{ and } T$$

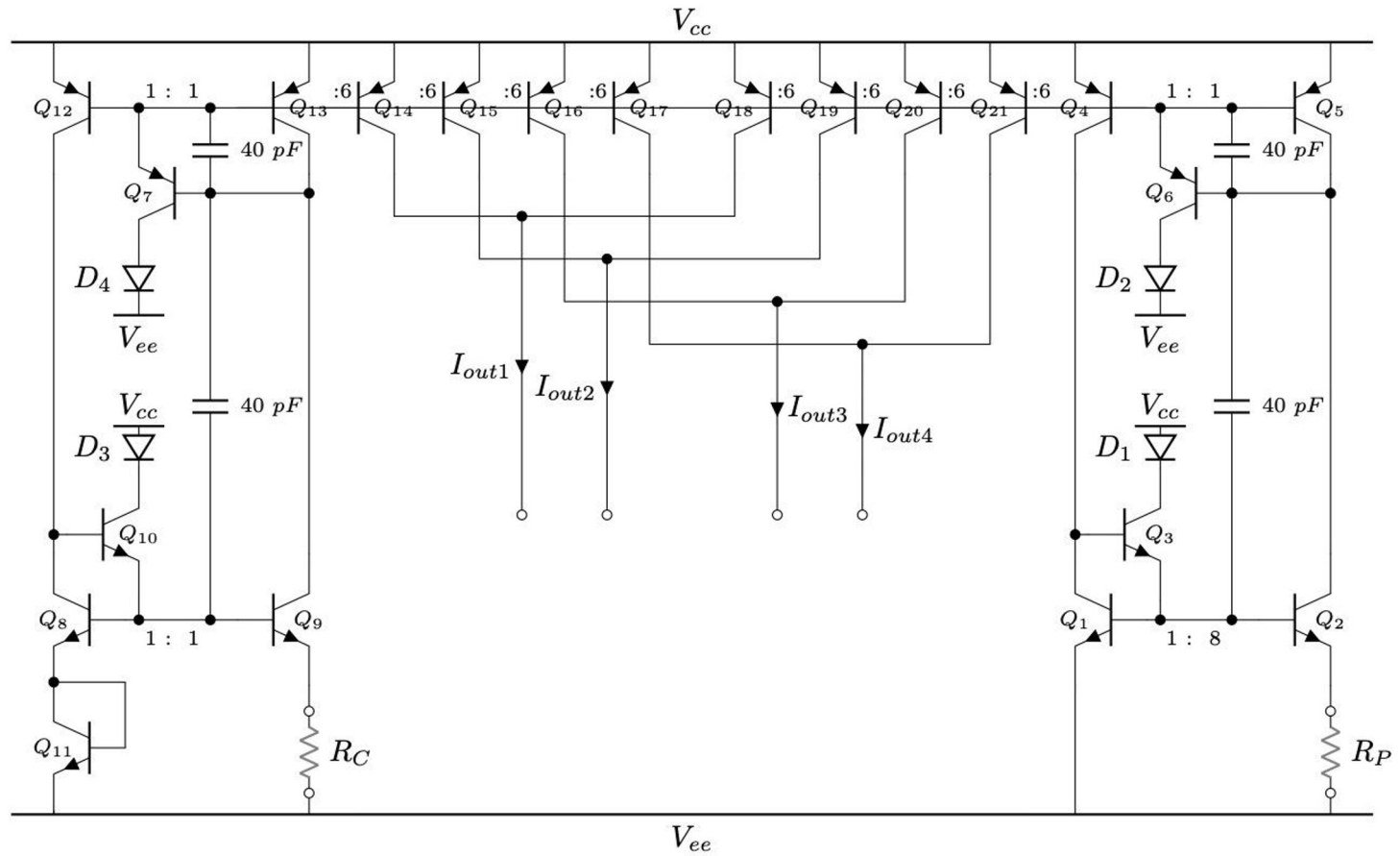
# Low Noise Diff binary DAC - Reference division

I<sub>ref</sub> is divided to mitigate its noise contribution

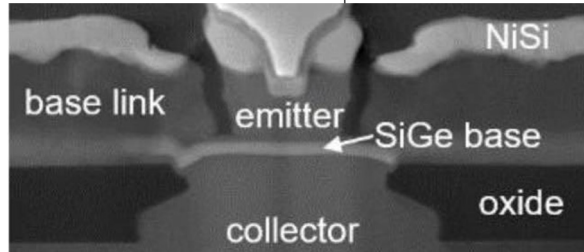


# Low thermal drift current reference

$CTAT \propto 1/T$   
 $V_{be}$   
  
 $PTAT \propto T$   
 $V_t$



# ASIC technologies



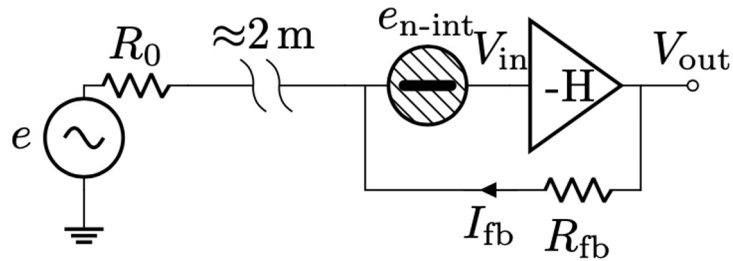
credit D. Charrier

	node, nm	nodes thicker/thinner, nm	MP accessibility, Europractice CMP	run/year	Ft NPN, GHz	$\beta$ NPN	Ft PNP, GHz	$\beta$ PNP	vertical PNP	Bipolar breakdown voltage $B_{vce0}$ , NPN/PNP V	CMOS core voltage, V	high res. poly.	cost, kEuro/mm <sup>2</sup> / min surf. mm <sup>2</sup>
GF, SiGe 8XP	130	180/90	E	4	250	?	X	X	no	3.3	1.2/2.5	yes	4/9
XFAB, XH035	350	1k/130	E	4	?	52	?	77	yes	5.5/45	3.3/5	yes	1/10
<del>XFAB, XT018</del>	180	1k/130	E	5	?	90	?	75	yes	5.5-20/5.5-20	1.8/5	yes	1.6/2.3
IHP, SGB25V	250	250/130	E	2(3)	75	?	X	X	no	2.5-3.3-7 ?	2.5 ?	?	2/.8
IHP, SG13S	130	250/130	E	4	250	?	X	X	no	?	1.2 ?	?	4.4/.8
Tower, SiGe	180	250/130	X	1	?	?	?	?	yes	?	?	?	
NXP	250	?	X	?	?	?	?	?	yes	?	?	?	
ST, 9MW	0.13	.13/.055	C	3	230	1k	?	?	no	1.2?	1.2	yes	1/210
AMS, S35D4	0.35	0.35	C,E	4	65	200	?	?	no	2.4	3.6	yes	0.8/7

last year

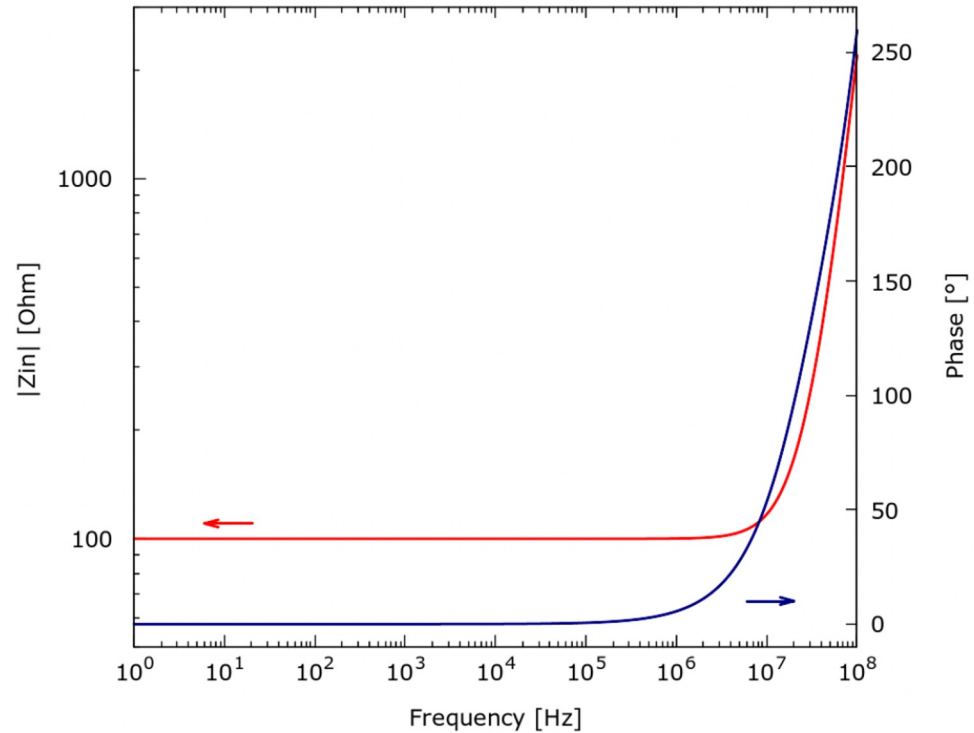
# Low-noise input impedance matching

# Low noise active input impedance matching (Miller effect)

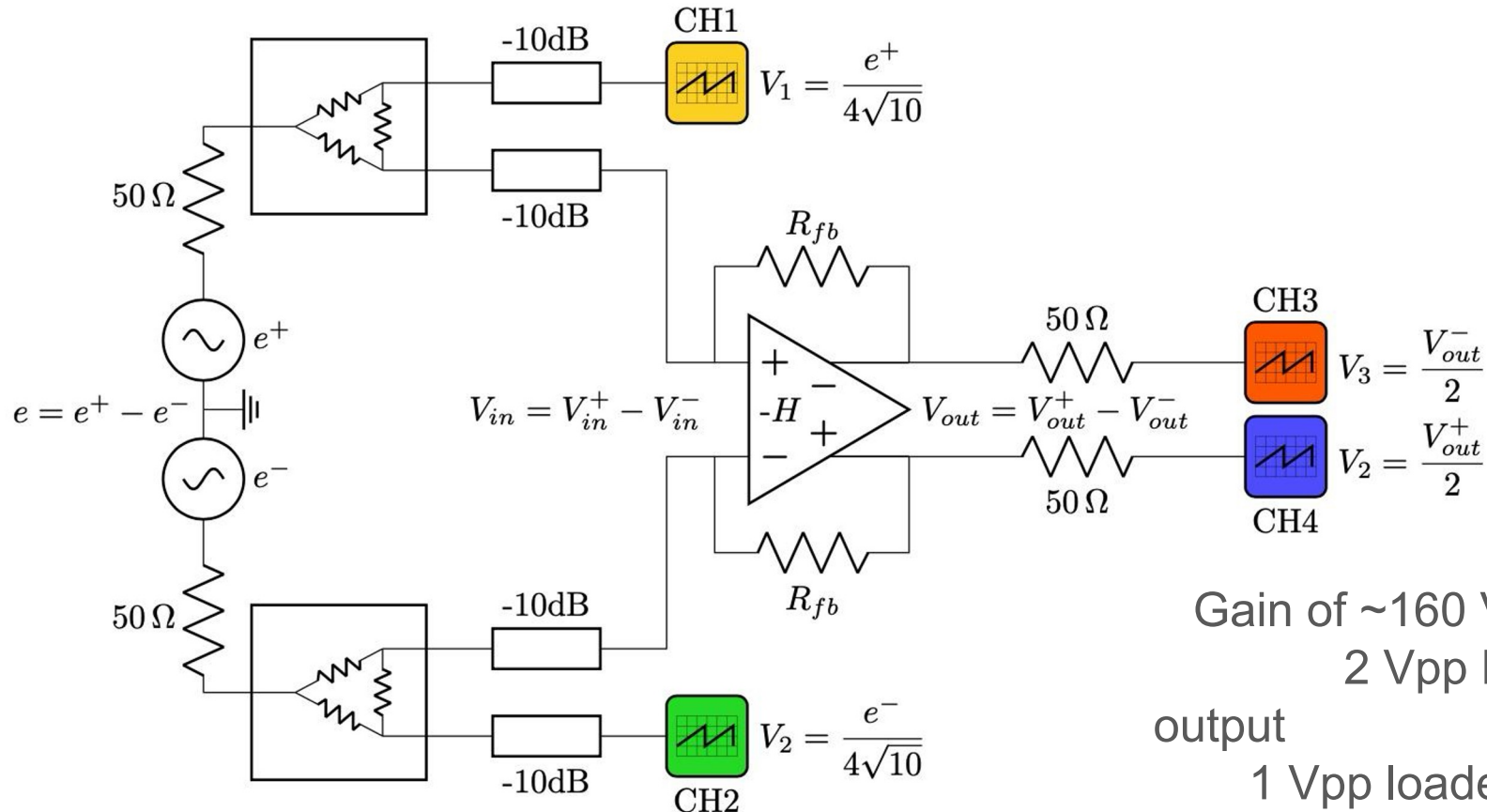


$$\left. \frac{V_{out}}{e} \right|_{e_{n=0}} = \frac{-H(f)}{1 + [1 + H(f)] \frac{R_0}{R_{fb}}}$$

$$Z_{in} = \frac{V_{in}}{-I_{fb}} = \frac{V_{in}}{-V_{out} + V_{in}} = \frac{R_{fb}}{1 + H(f)}$$



# Differential gain bandwidth measurements with matching

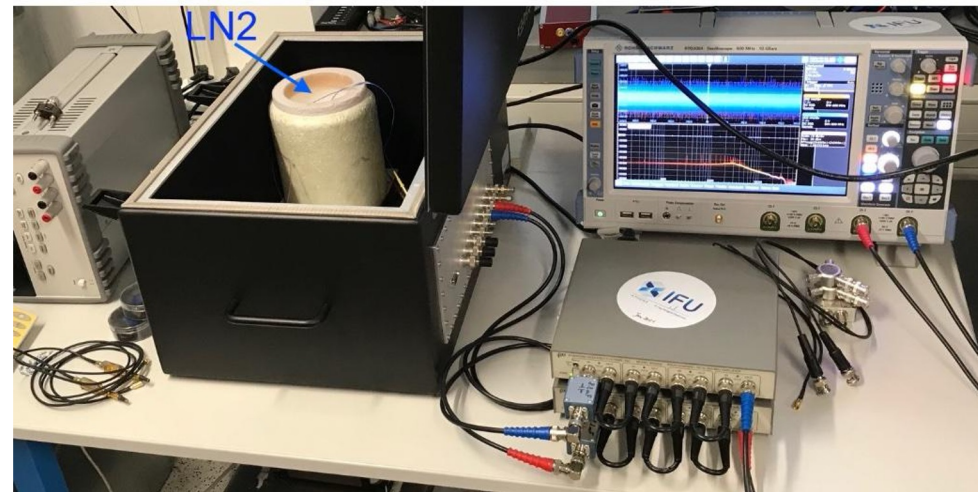
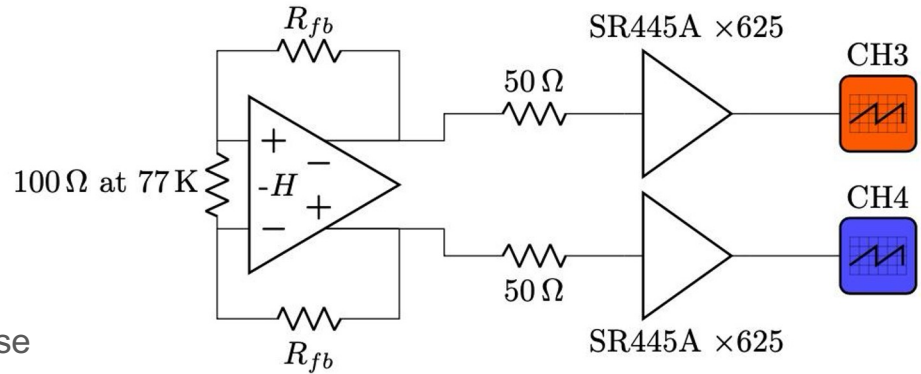
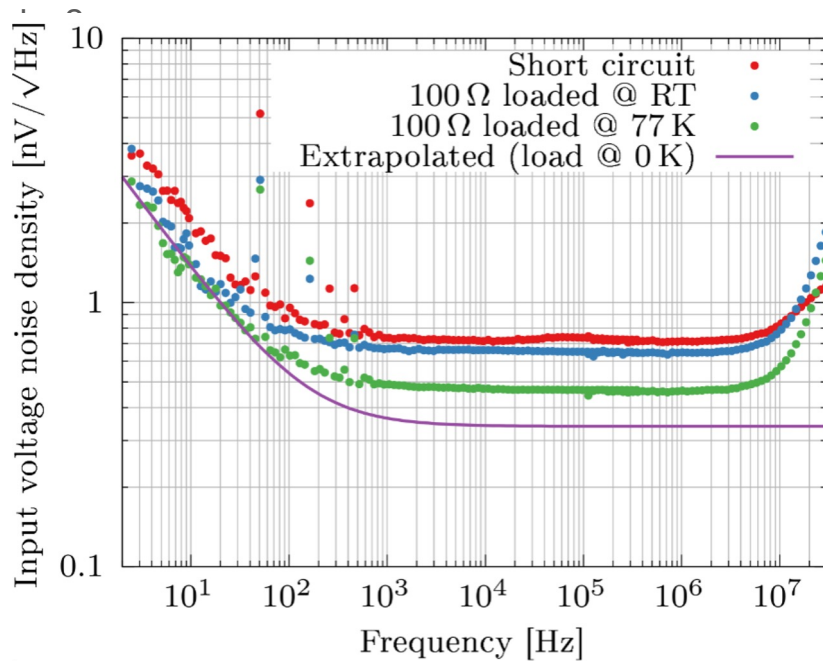


Gain of  $\sim 160$  V/V  
 2 Vpp LNA  
 output  
 1 Vpp loaded output  
 12.5 mVpp

# Low noise measurements

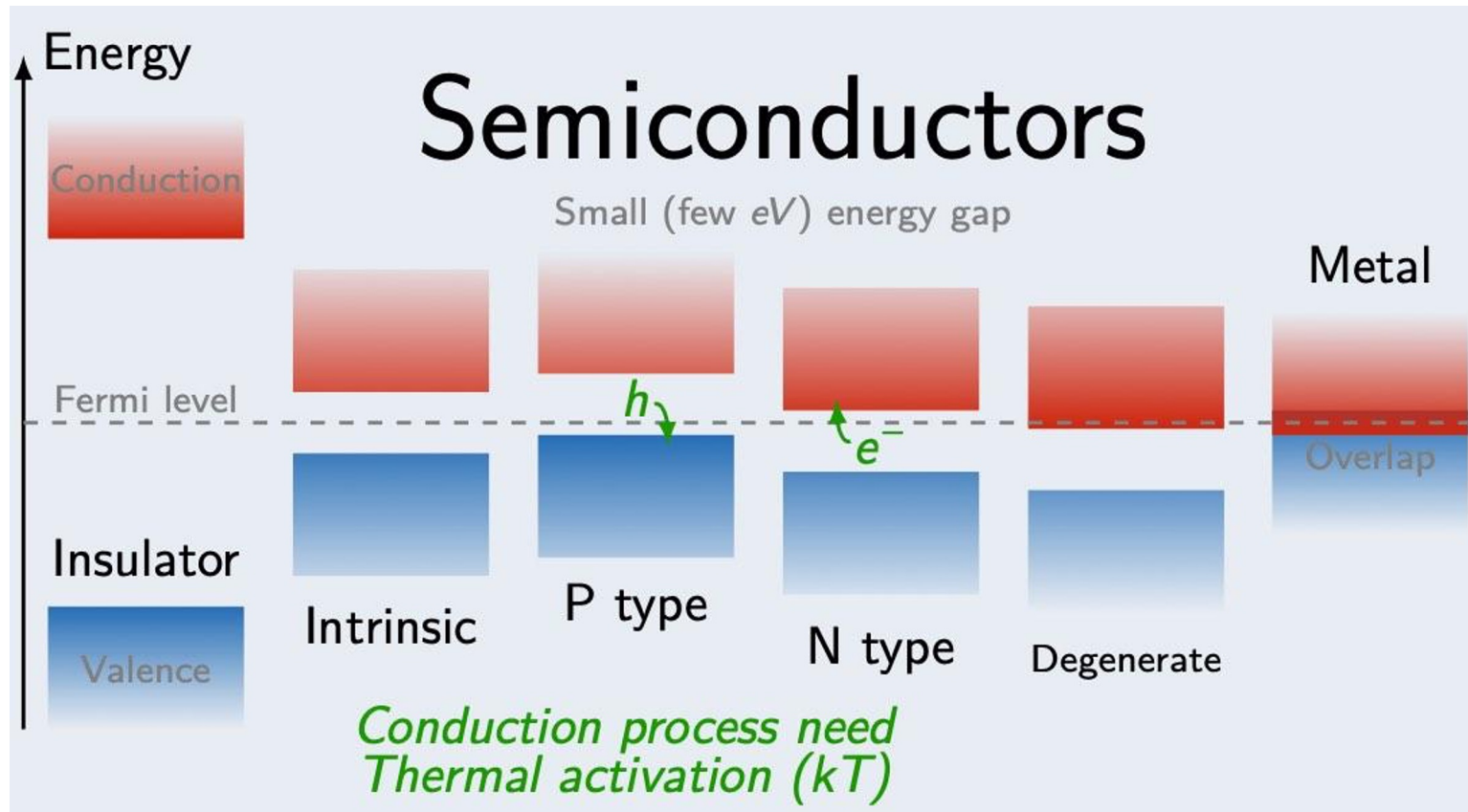
100  $\Omega$  thermal noise  $\sqrt{4kTR}$  :  
 1.3 nV/ $\sqrt{\text{Hz}}$  @ 300 K / RT  
 0.65 nV/ $\sqrt{\text{Hz}}$  @ 77 K

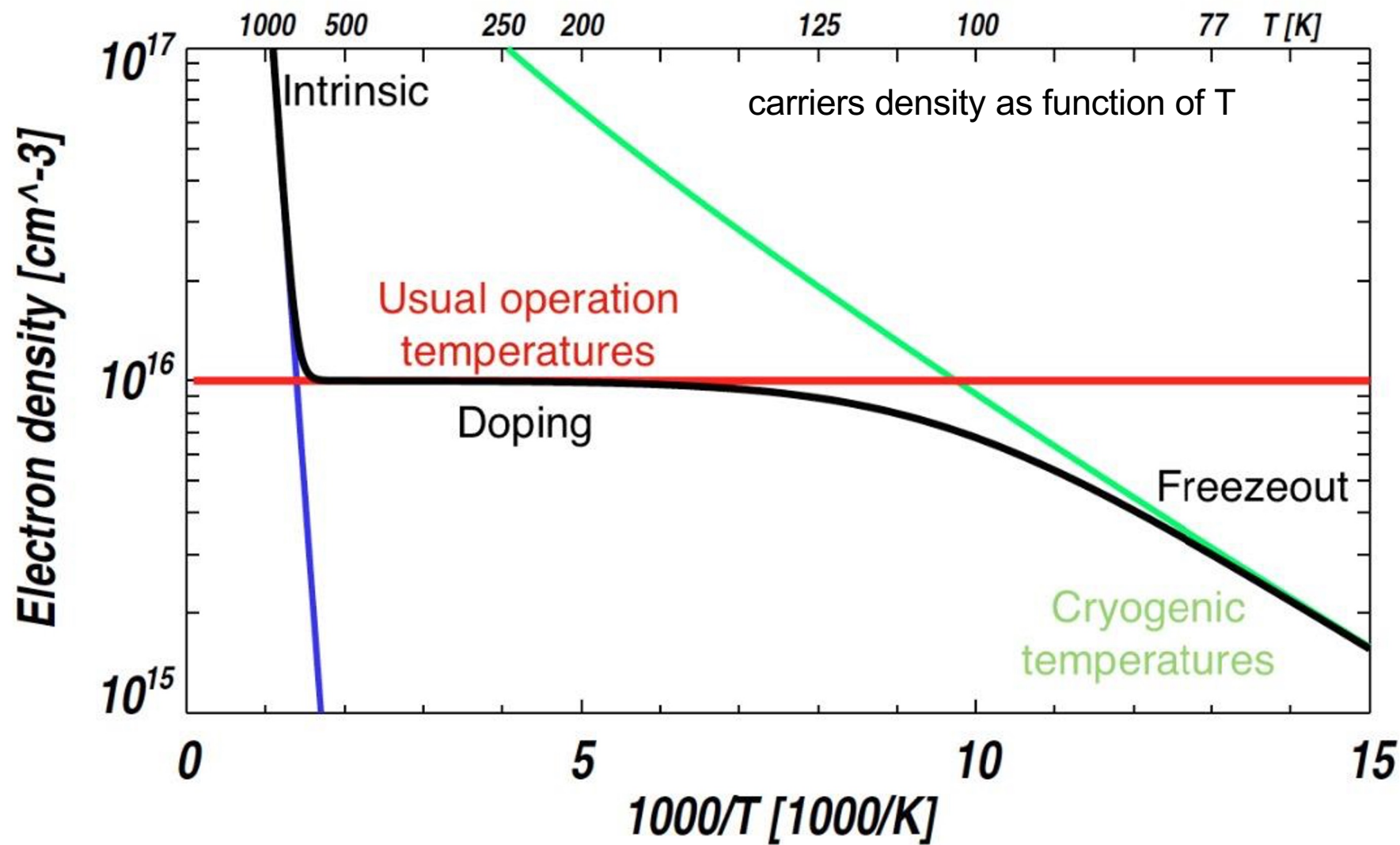
-> active matching divide the signal AND the noise

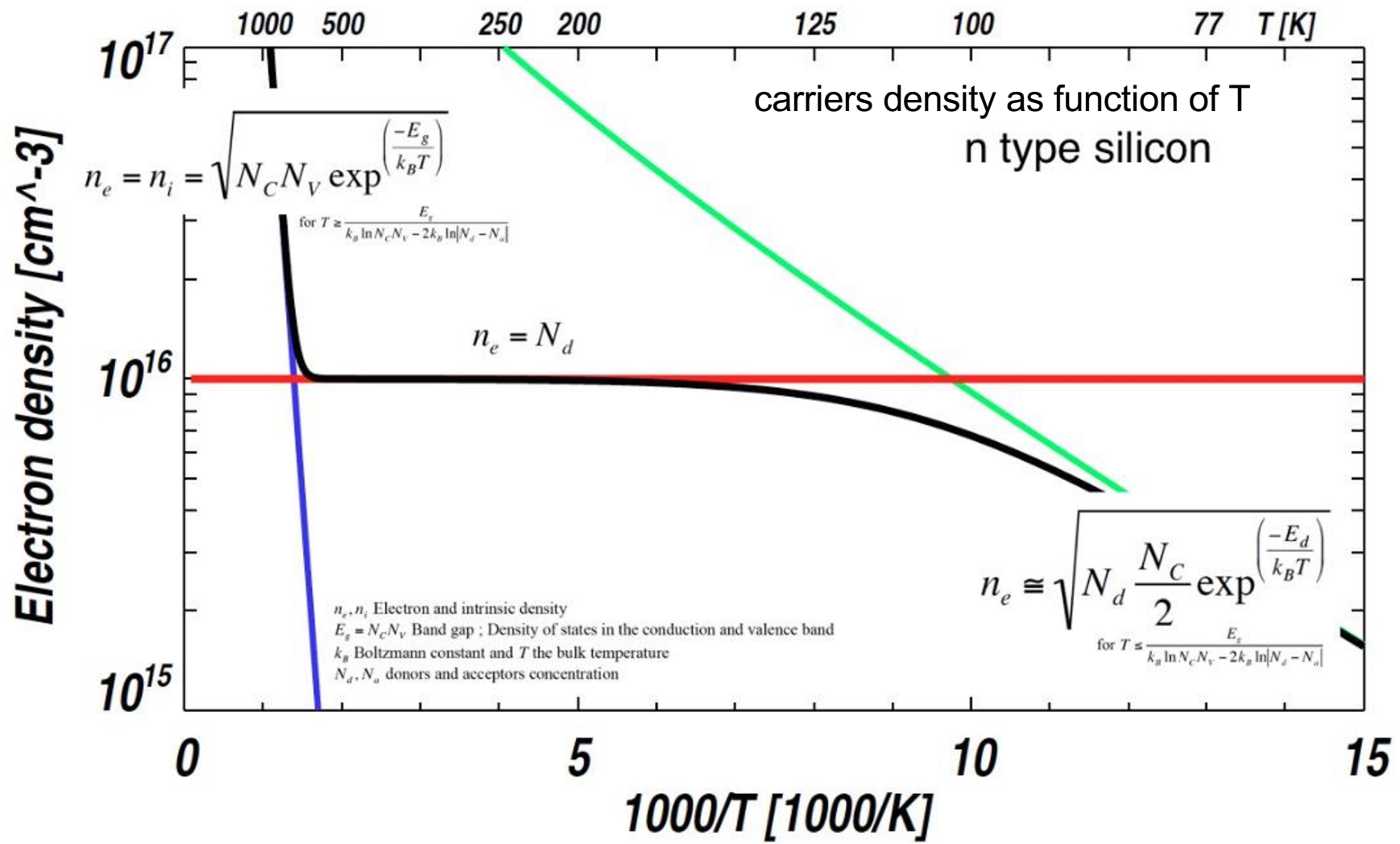


# Cryogenic front-end IC design

# Solid-state physics and semiconductors



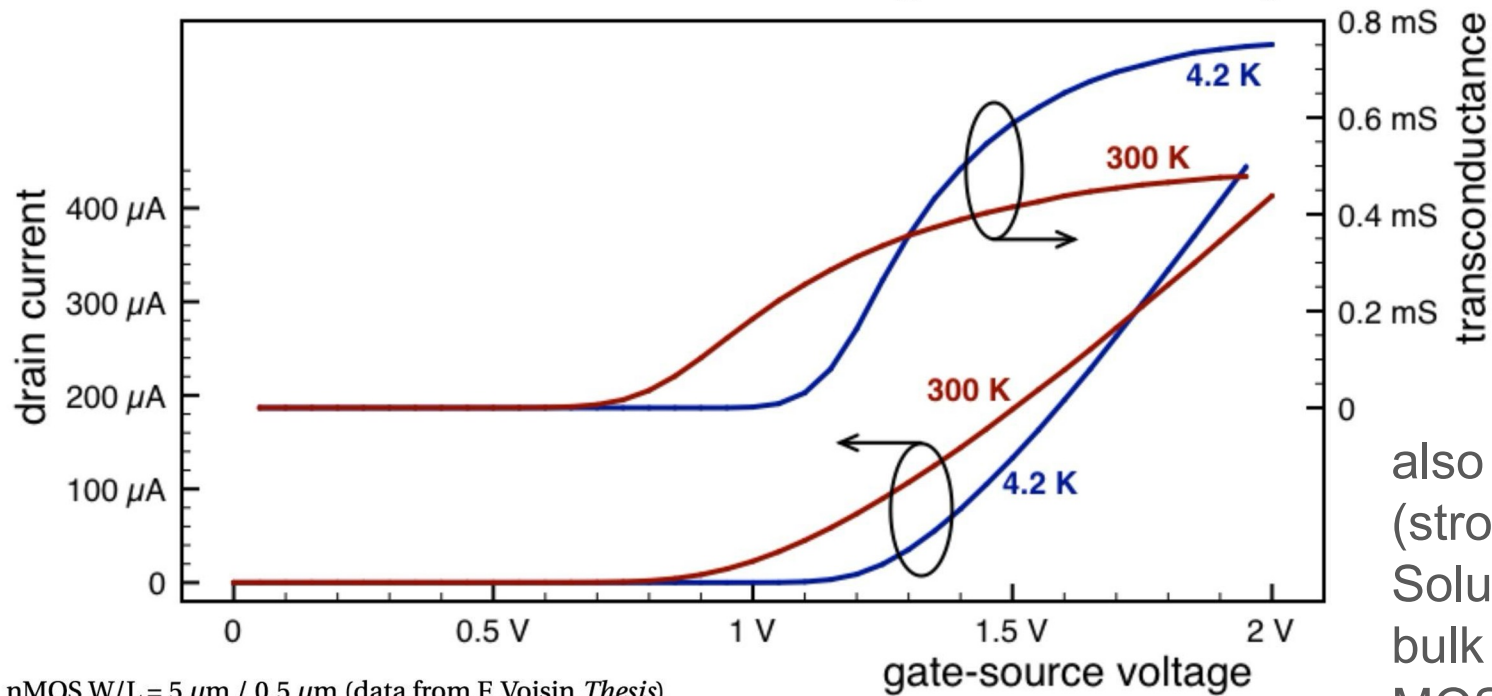




# MOS transistor as function of temperature

$$I_D(V_{DS}) \approx \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{GS} - V_{th})^2$$

$$\Rightarrow |g_m| \approx \mu C_{ox} \frac{W}{L} (V_{GS} - V_{th}) \propto \frac{\sqrt{I_D}}{T^\alpha}$$



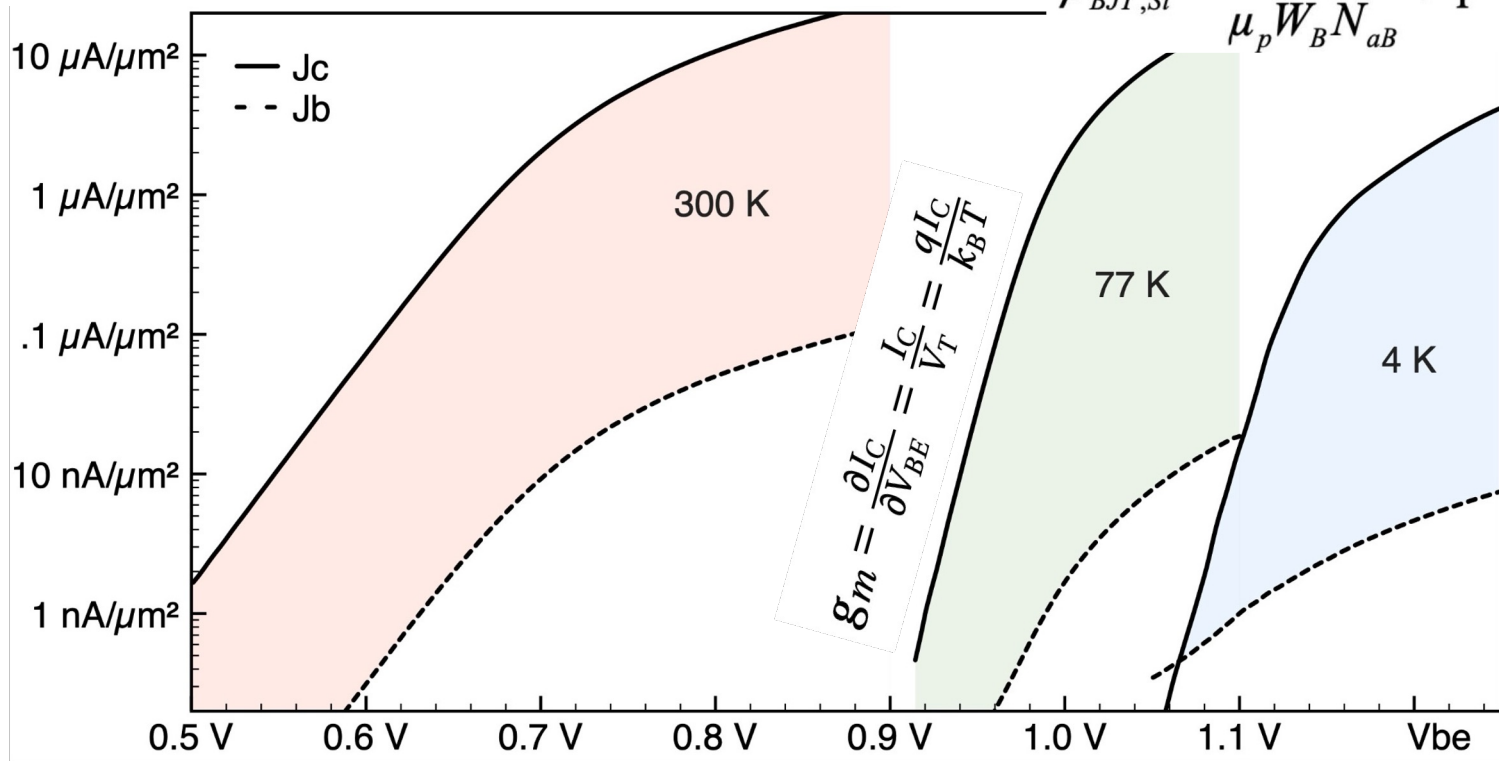
nMOS W/L = 5 μm / 0.5 μm (data from F. Voisin Thesis)

also Kink effect  
(stronger in nMOS)  
Solution : adding many  
bulk contacts around  
MOS transistors

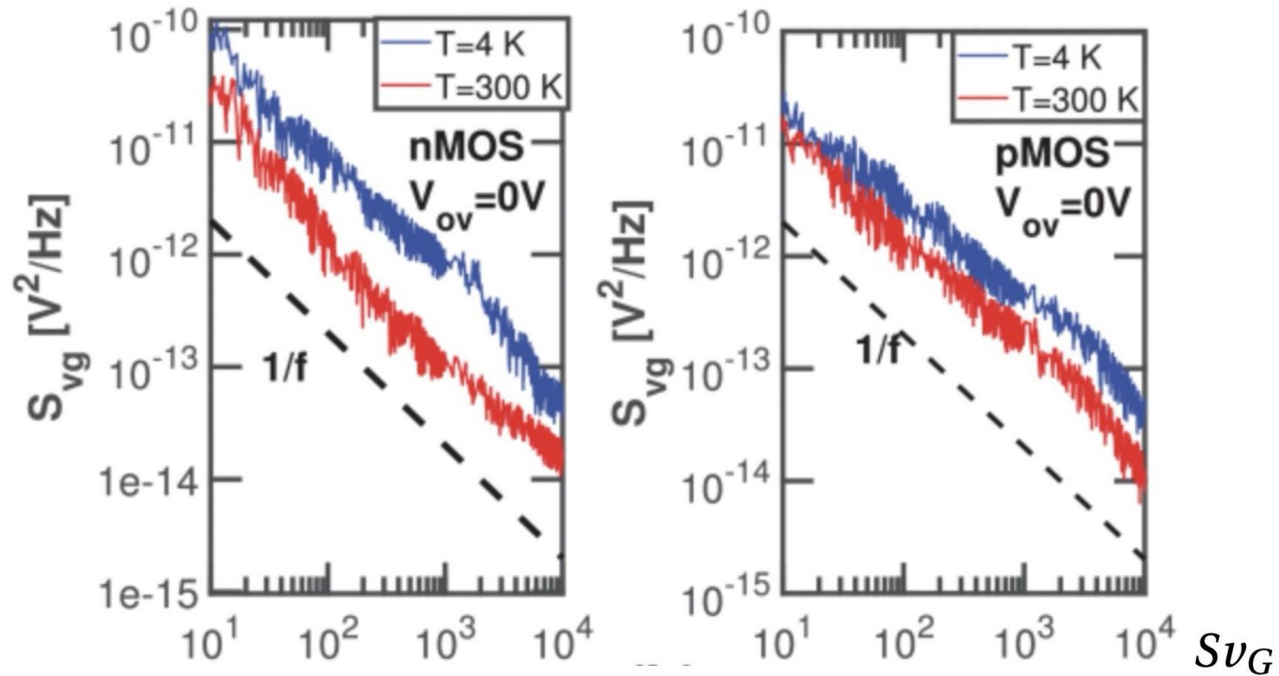
# SiGe Bipolar transistor (T)

$$\beta_{HBT, SiGe} = \frac{\mu_n L_p N_{dE}}{\mu_p W_B N_{aB}} \exp \frac{\Delta E_{gSi/SiGe} - \Delta E_{gEapp}}{k_B T}$$

$$\beta_{BJT, Si} \approx \frac{\mu_n L_p N_{dE}}{\mu_p W_B N_{aB}} \exp \frac{-\Delta E_{gEapp}}{k_B T}$$



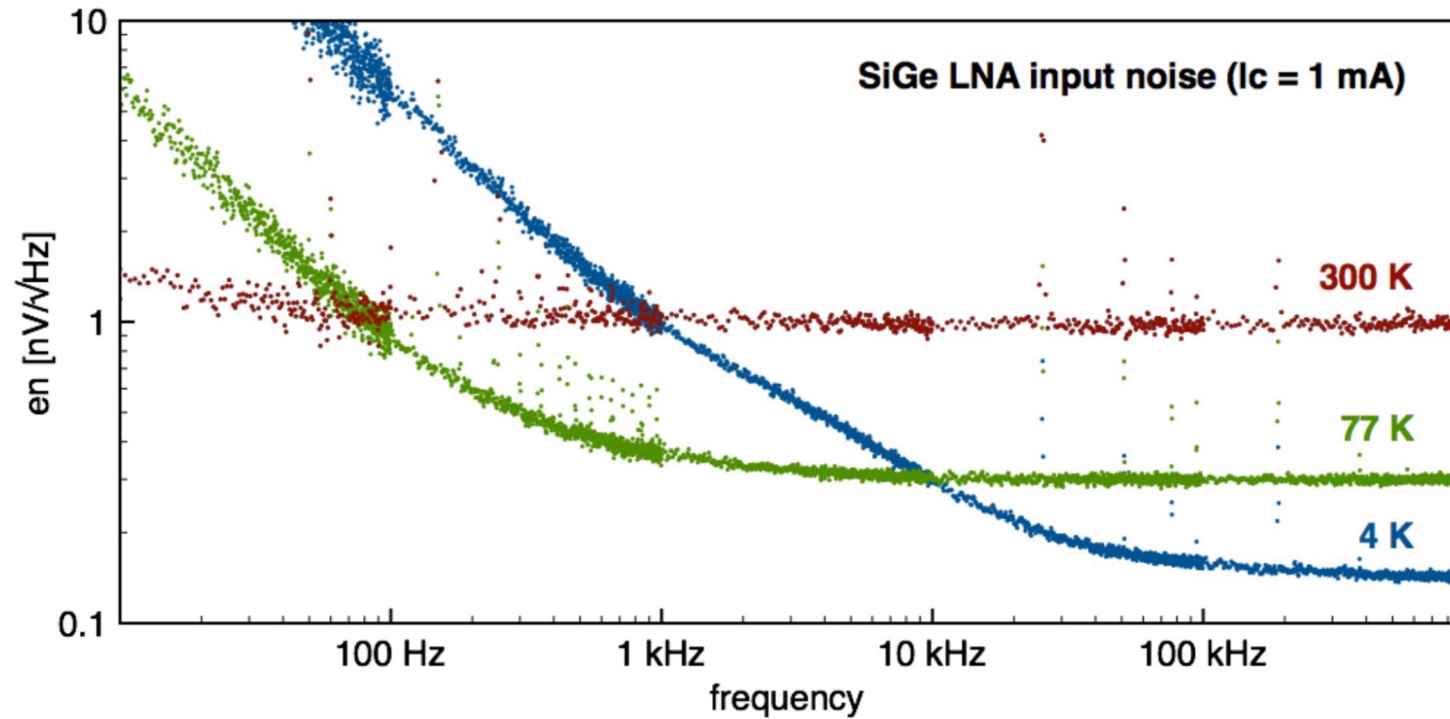
# Flicker noise (T) in MOS



measurements 28nm technology (a) nMOS and (b) pMOS at 300 and 4 K for  $V_{ov} = 0$  V and  $V_{ds} = 20$  mV. Notice that the noise amplitude at 4 K is higher than the one at 300 K

Ruben Asanovski et al. Understanding the

# Flicker noise (T) in HBTs



$$e_n \approx \frac{\sqrt{2qI_C}}{g_m} \quad \text{with } g_m \approx \frac{qI_C}{k_B T} \Rightarrow I_C \text{ fixed by the required input noise}$$



# From MHz range TDM/FDM readout to $\mu$ Mux/KIDs readout (Manuel Gonzalez – APC – Research perspectives)

- Develop **cryogenic RF low-noise amplifiers (LNAs)** in the 1–8 GHz range using SiGe BiCMOS ASIC technologies
- **Identify key system requirements:** noise performance, dynamic range, power consumption, footprint, and channel count
- **Target applications:** superconducting detector readout (TES, MKIDs) and quantum computing
- Design and evaluate integrated, **scalable cryogenic LNAs** for high-multiplexing architectures