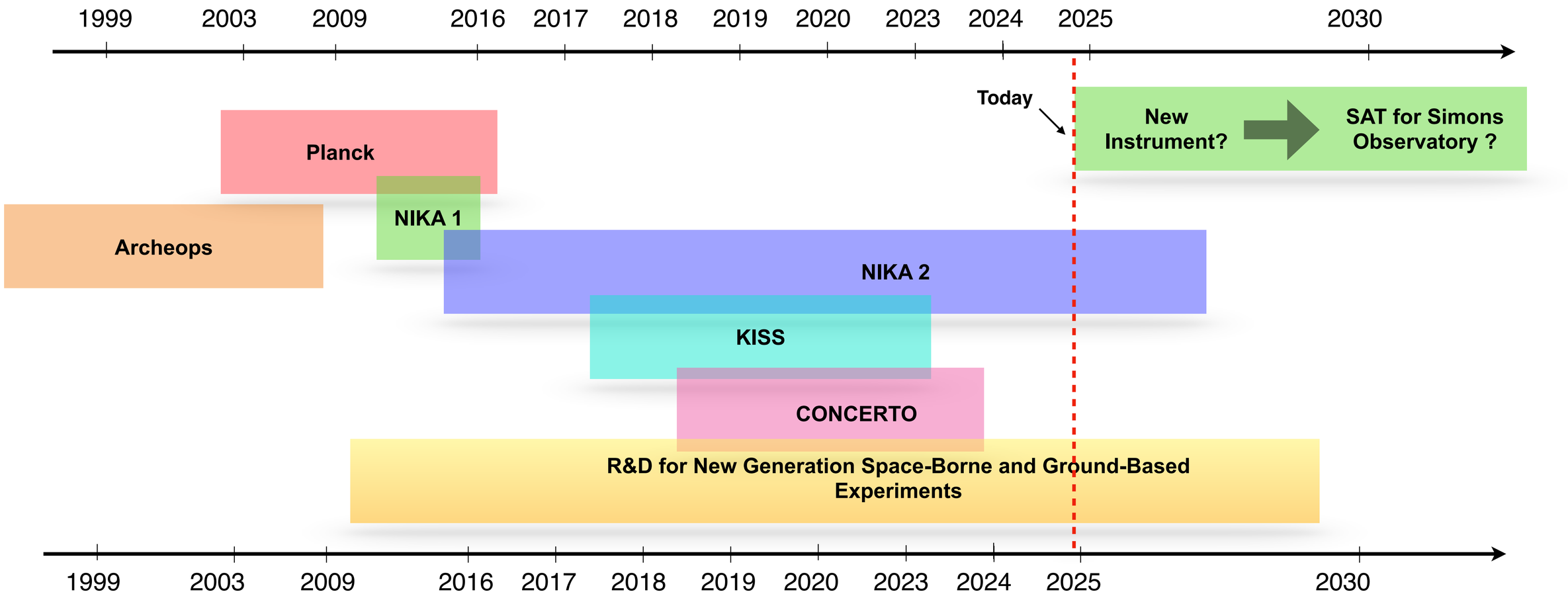
Observations of the early Universe at millimeter wavelengths: The Grenoble GIS Contribution

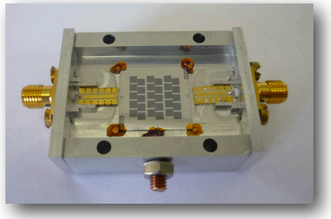
GIS KIDS

The GIS-KID: our activities are always driven by real instruments…



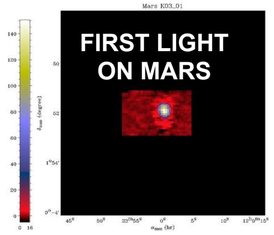
Most of this work has been developped in a strong collaboration between institut Néel (INP), LPSC (IN2P3) and IPAG (INSU). These three labs together with IRAM are consolidated through a GIS (Groupement d'intérêt scientifique)
https://ipag.osug.fr/~ponthien/GIS_Website/research.html

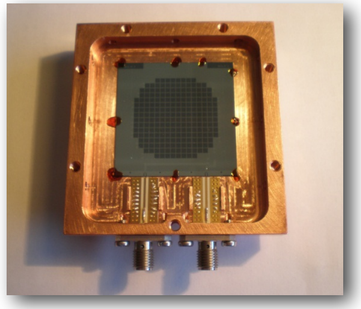
KID Development



2009

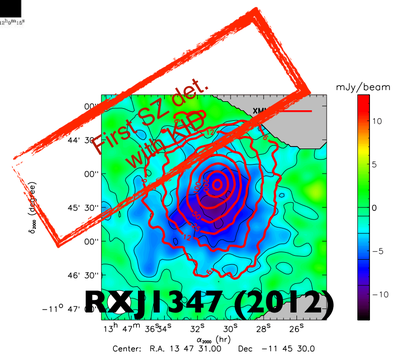
30 Pixels

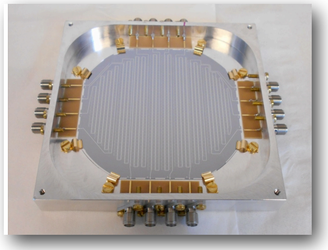




2010-2013

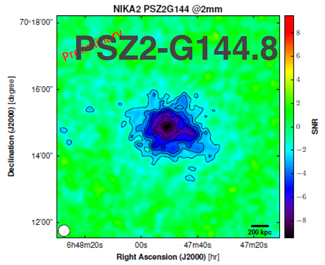
200 Pixels

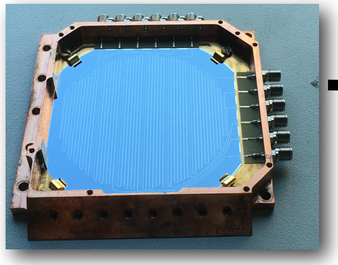




2014-2015

1000 Pixels





2015-2022

2000 Pixels

8000 Pixels

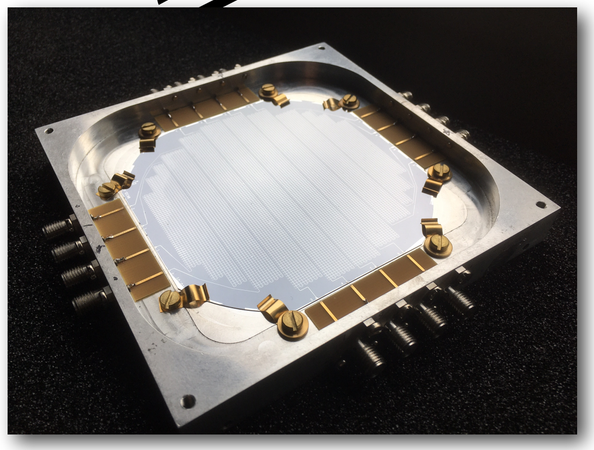
Today

Prototype

Photon noise Detectors in 6 bands (3mm - 550 µm)
for ground-based or space borne typical optical loads
[Catalano et al.,A&A 2020]

Acquiring a new evaporation machine. Up to 20 cm wafer

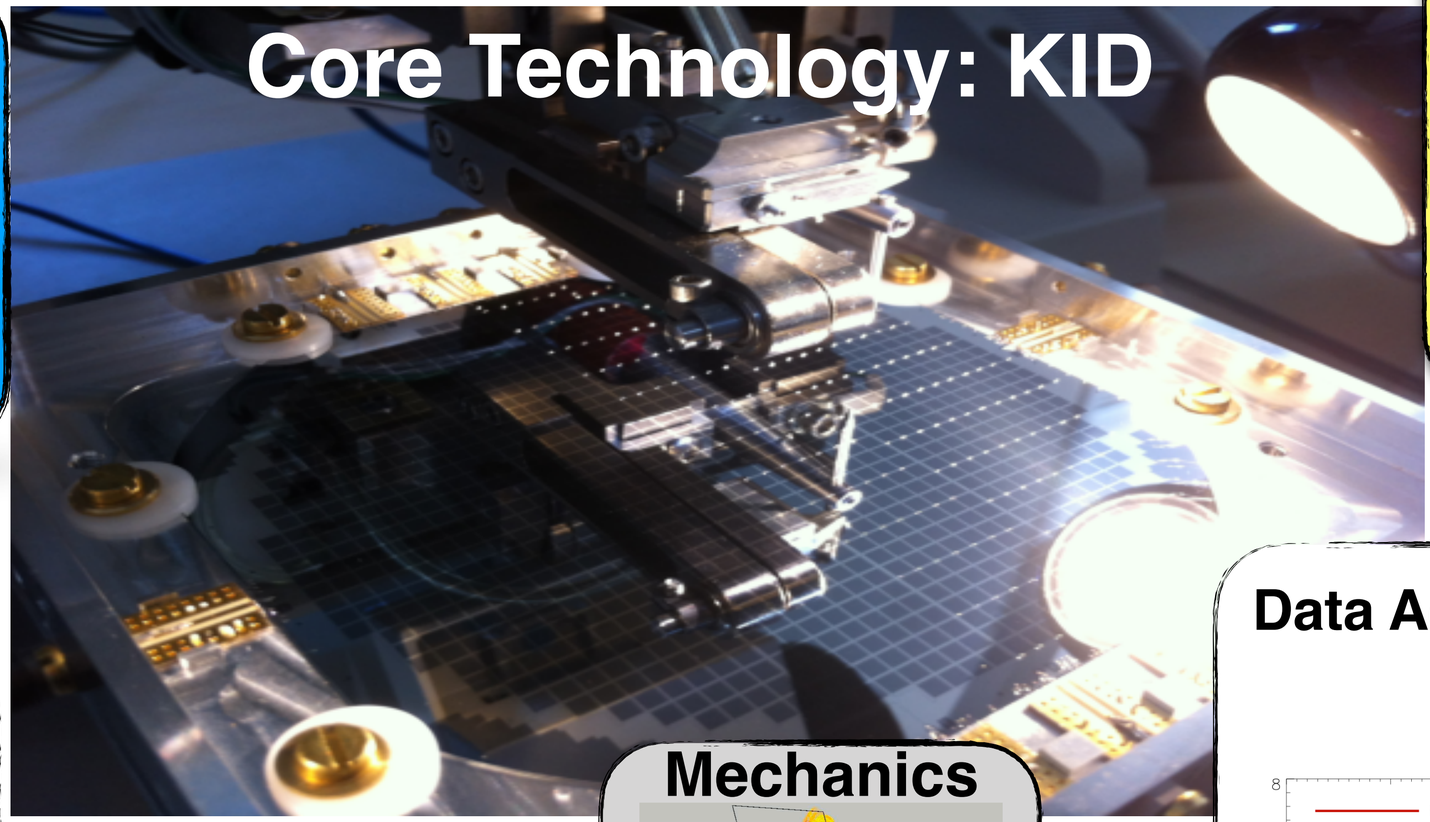
2025-2030



Instrumental Development

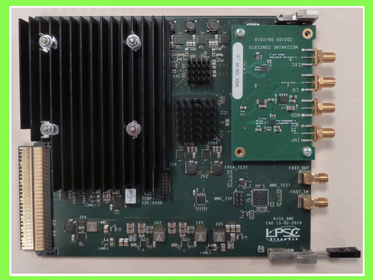
Cryogenics

Core Technology: KID

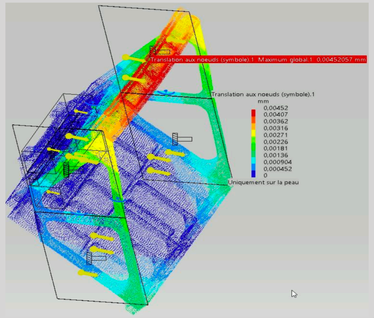


Optics

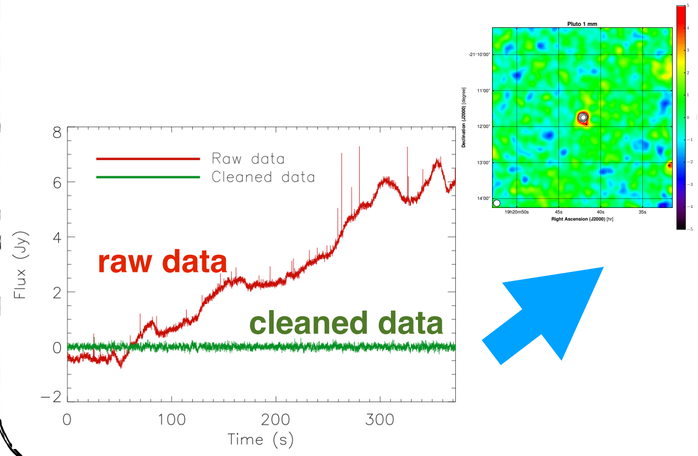
Electronics



Mechanics

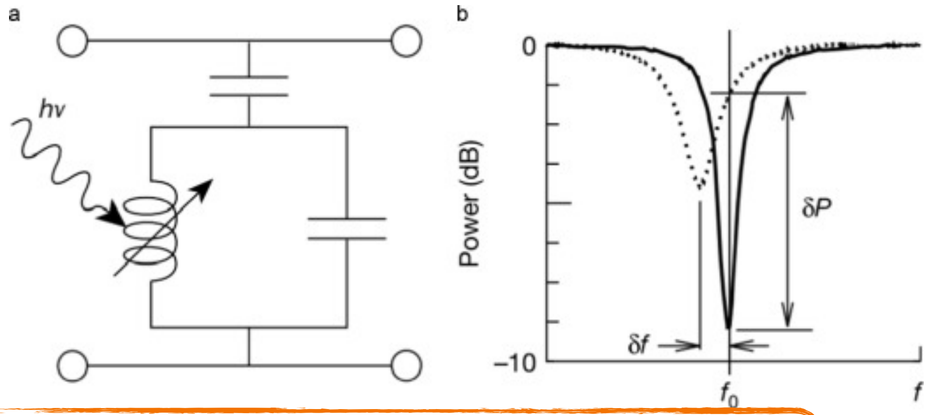


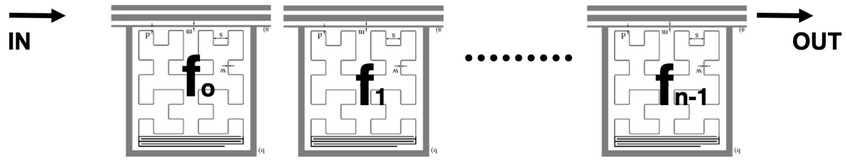
Data Acquisition-Pipeline

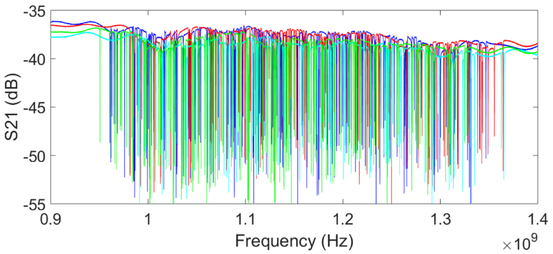


KID Operation and Photometry

The incoming photons break Cooper pairs (supercurrent carriers) in a superconducting LC resonator → measurable signals

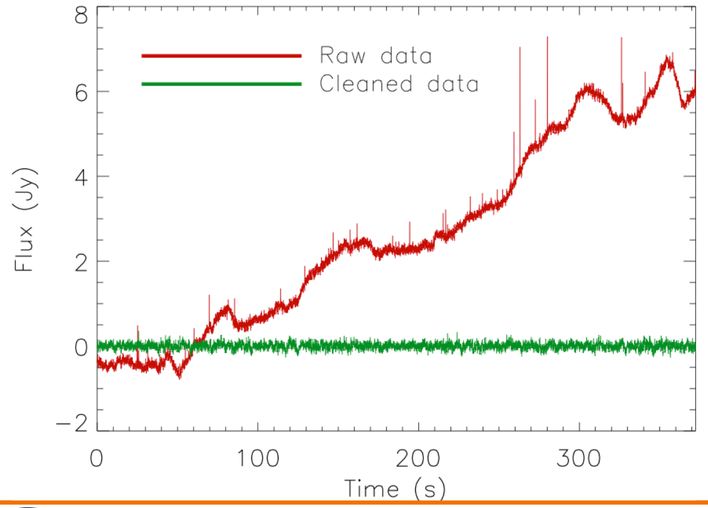






- *Very few steps in the manufacturing process (1 for Al KID)*
- Frequency multi-plexing (600 per feedline)
- *Time constant from 0.01 to 0.2 ms*
- *Very good linearity (about 1/10^5)*
- *Not vey sensitive to the temperature fluctuation, mechanical vibrations and cosmic rays (1000 time less than Planck bolometers).*

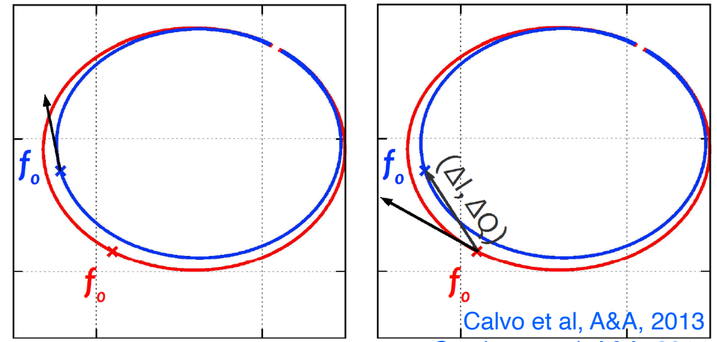
Difficult challenges in operating with KIDs: convert the observed in phase (I(t)) and in quadrature (Q(t)) components to absorbed optical power.



Approach for Photometers / Polarimeters

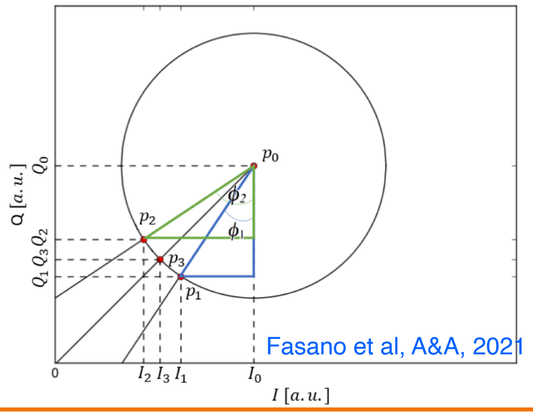
Modulate continuoisly the LO carrier frequency

- Evaluate for each point I,Q,dI/df,dQ/df
- Mesure ΔI,ΔQ
- Evaluate $\delta\mathbf{f} \propto \delta\mathbf{P}$ projecting ΔI,ΔQ on the reference gradient



Calvo et al, A&A, 2013

Catalano et al, A&A, 2014



Fasano et al, A&A, 2021

Approach for FTS

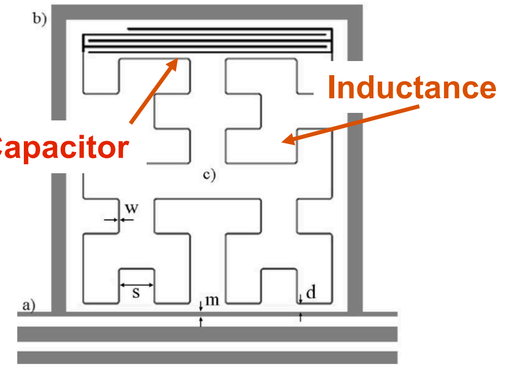
Modulating the signal first and then sky integration with no modulation.

- Evaluate for each point I,Q,dI/df,dQ/df
- Mesure ΔI,ΔQ
- Evaluate $\delta\mathbf{f} \propto \delta\mathbf{P}$ projecting ΔI,ΔQ on the reference gradient

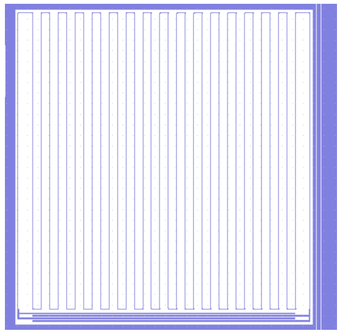
Our approach on KID development: Photometers / Polarimeters

Lumped Element KID

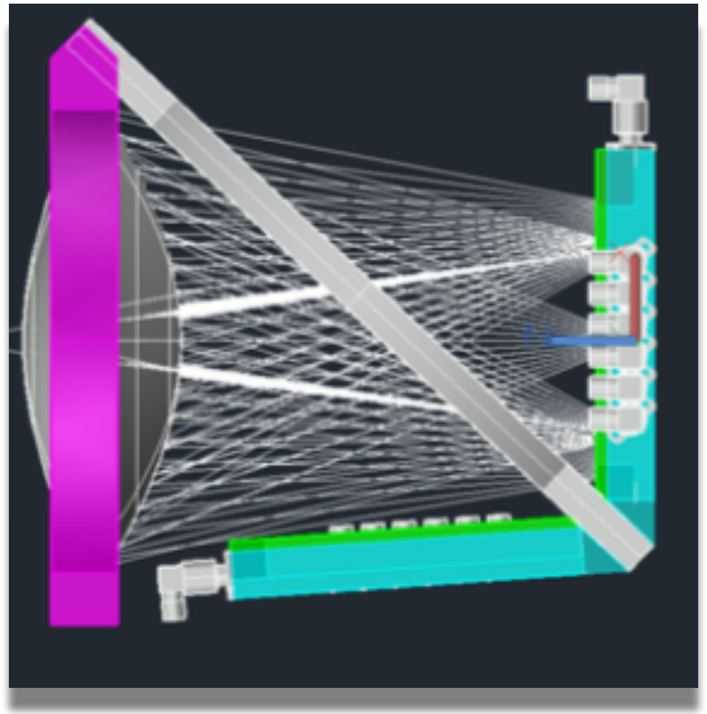
Dual Polarisation
(3rd-order Hilbert pattern)



Single Polarisation

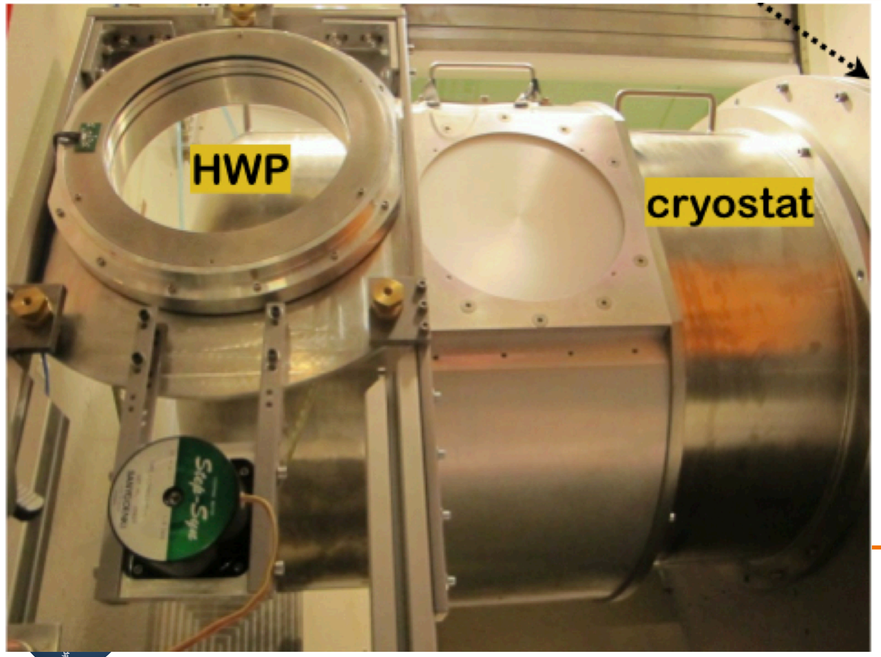


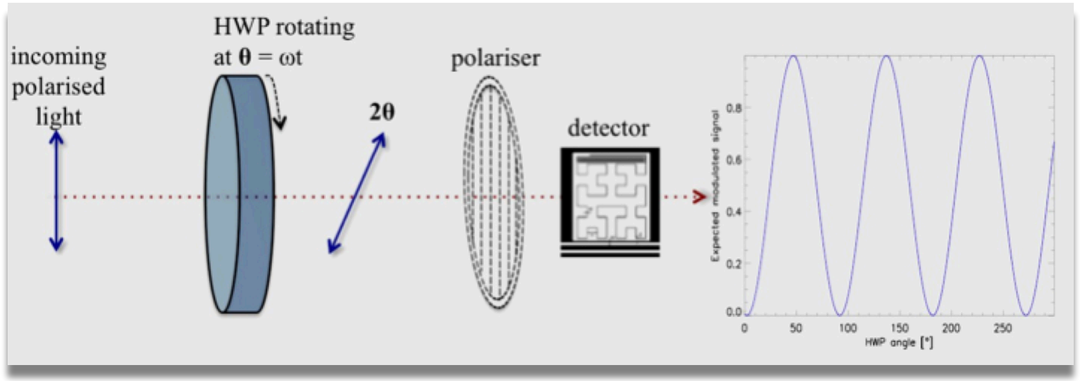
More details in Sofia's Talk…..



Filled arrays LEKID:

- Large filling factor
- Very high quantum efficiency in a 30% mm-band
- Easy to fabricate

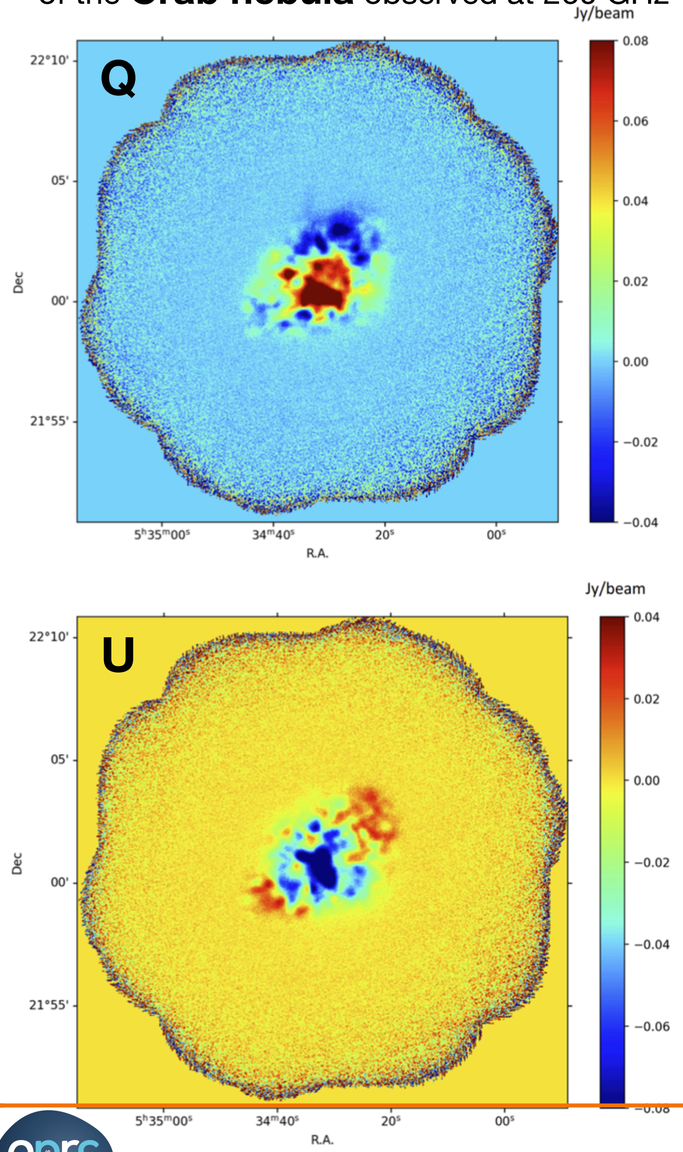




Continuous Rotation of an HWP permits quasi-simultaneous Observations of I,Q,U Stokes parameters

State of the Arts: Polarisation with NIKA2

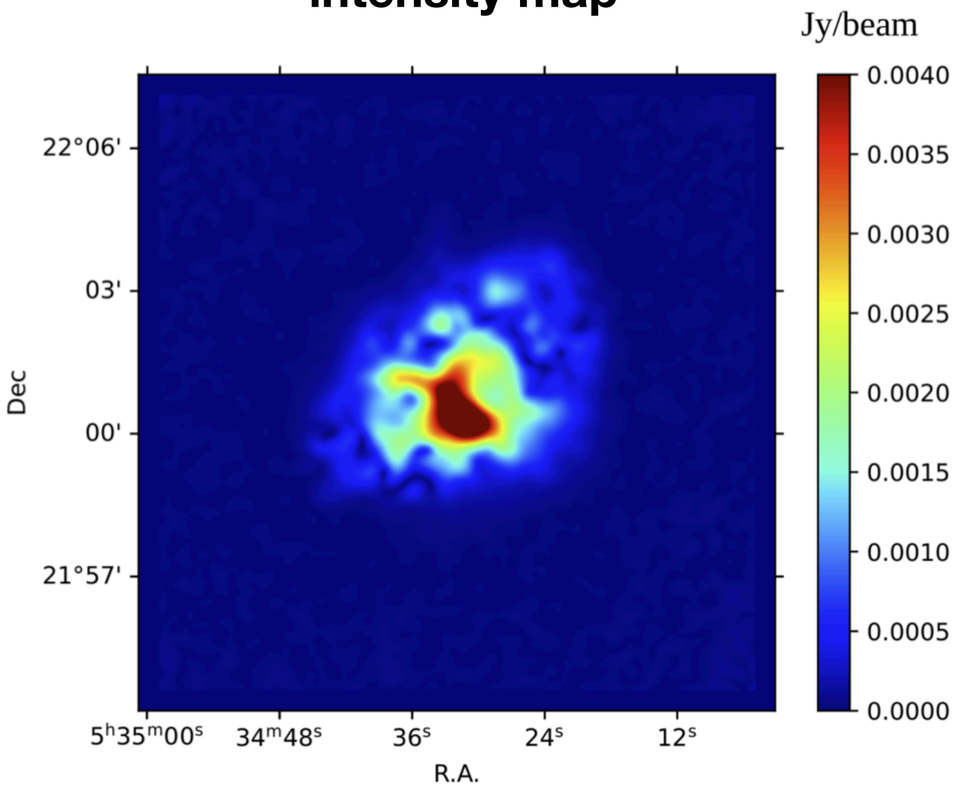
Stokes Q and U maps
of the **Crab nebula** observed at 260 GHz



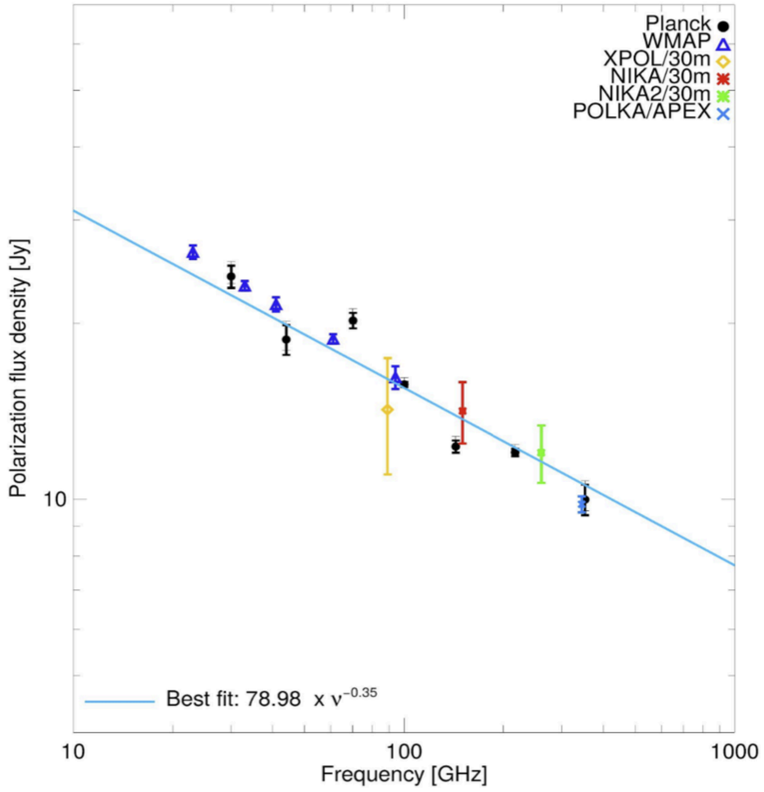
- **Final Sensitivity: ~20mJy*sqrt*(s) (better than phot. Sensitivity)**
- **Polarization Leakage : < 1% (mainly due to the Tel.)**
- **Error on the pol. angle reconstruction : ~ +/- 0.5 Deg.**

Ritacco et al. (2022), EPJ WC 257, 00042
Ritacco et al. (2024) - in preparation…

NIKA2 polarized intensity map



Spectral energy distribution obtained by previous measurements accounting for the new value obtained from NIKA2 (green).



CONCERTO Project

Main Goals:
- Observations (COSMOS field) of the [CII]-emission line at high redshift
- SZ signal from galaxy clusters
- 12 open time programs (Galactic regions, SMC, galaxy clusters)

Fundings : ERC Advanced Grant
Duration of operation: April 2021 - May 2023
P.I. : G. Lagache (LAM) / A. Monfardini (IN)

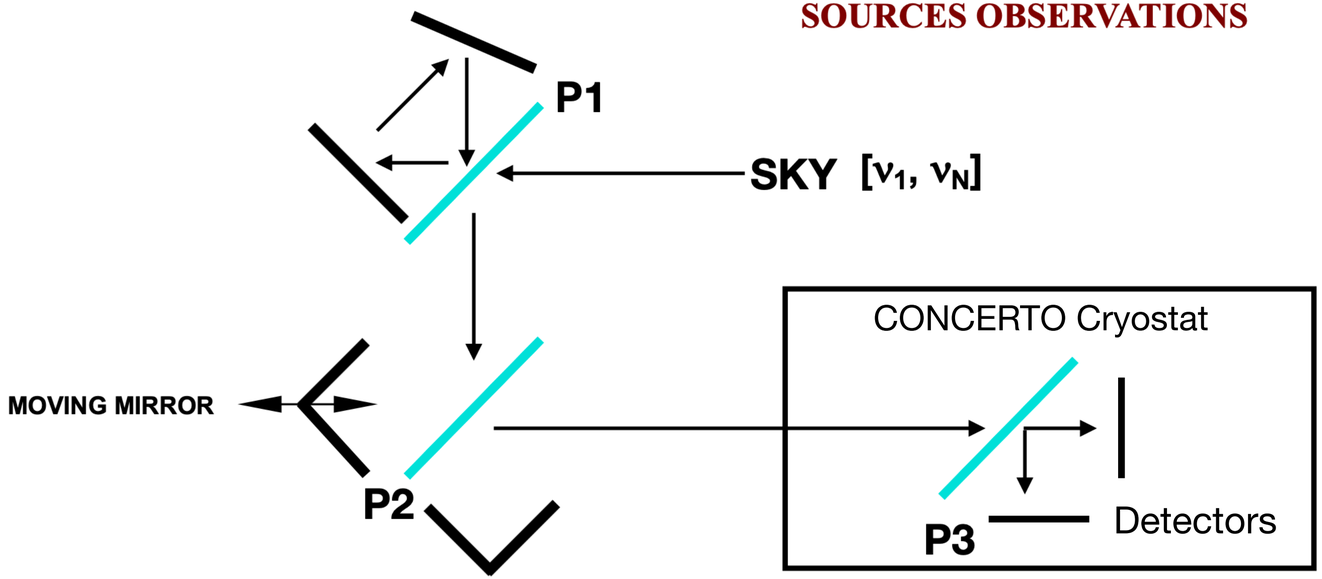
Original optical design adopted for CONCERTO:

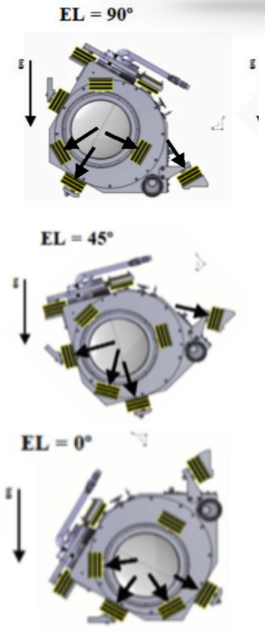
European Research Council
Established by the European Commission

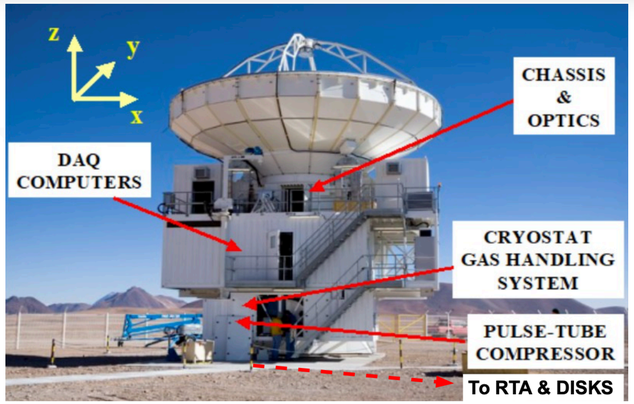
Telescope primary mirror diameter [m]	12
Field-of-view diameter [arcmin]	20
Absolute spectral resolution [GHz]	≥ 1
Relative spectral resolution R [#]	1–300
Frequency range HF | LF [GHz]	195–310 | 130–270
Pixels on Sky HF | LF [#]	2,152 | 2,152
Instrument geometrical throughput [sr m^2]	2.5×10^{-3}
Single Pixel geometrical throughput [sr m^2]	1.16×10^{-6}
Data rate [MBytes/sec]	128

"Two Skies"

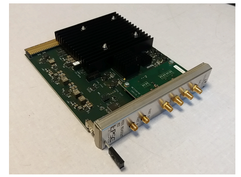
BEST FOR COMPACT SOURCES OBSERVATIONS



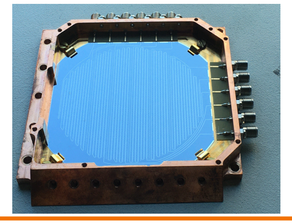




12 REU Boards



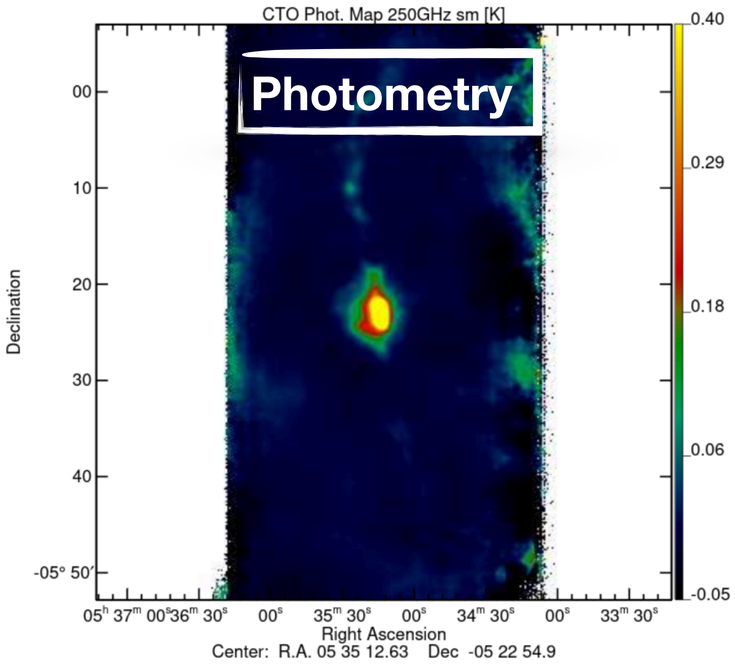
2 KID Arrays (4304 pixels)



CONCERTO : few preliminary results and spectral calibration

ORION

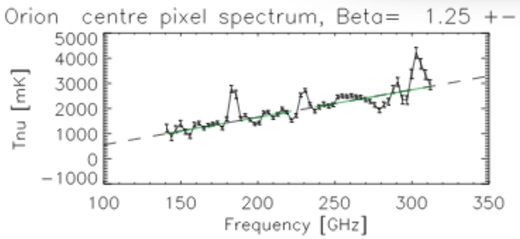
Photometry

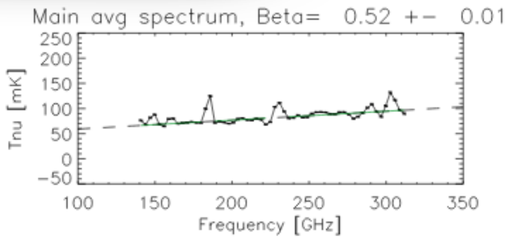


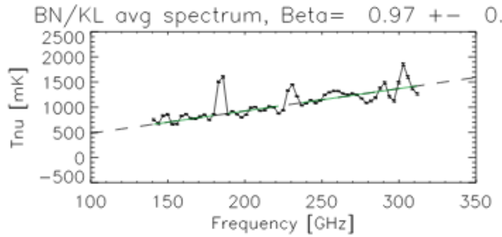
- **Photometric : 1 hour integration**
- **Size: 1° x 0.5°**

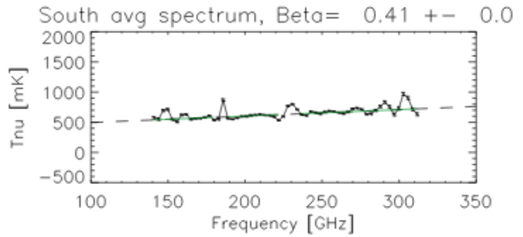
[Désert et al. in preparation]

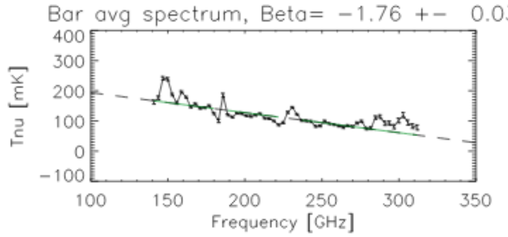
Spectroscopy

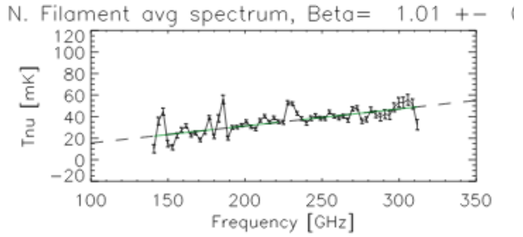




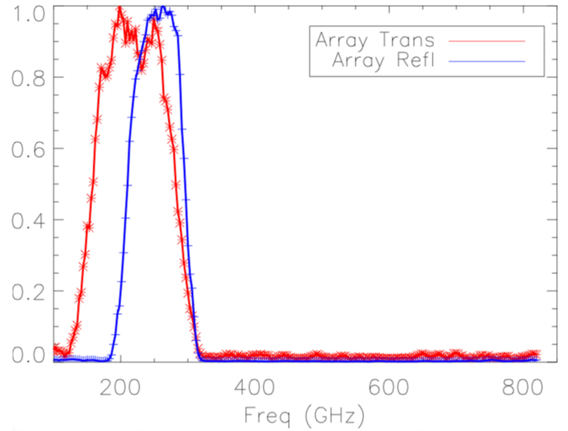


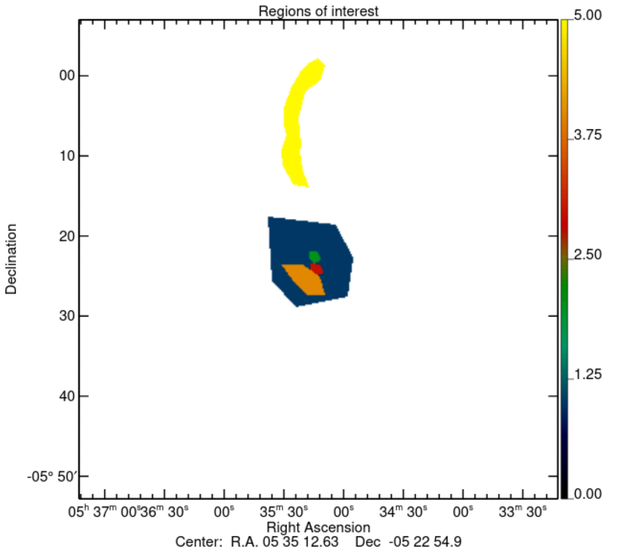






Band-Passes
(raw + RJ source)



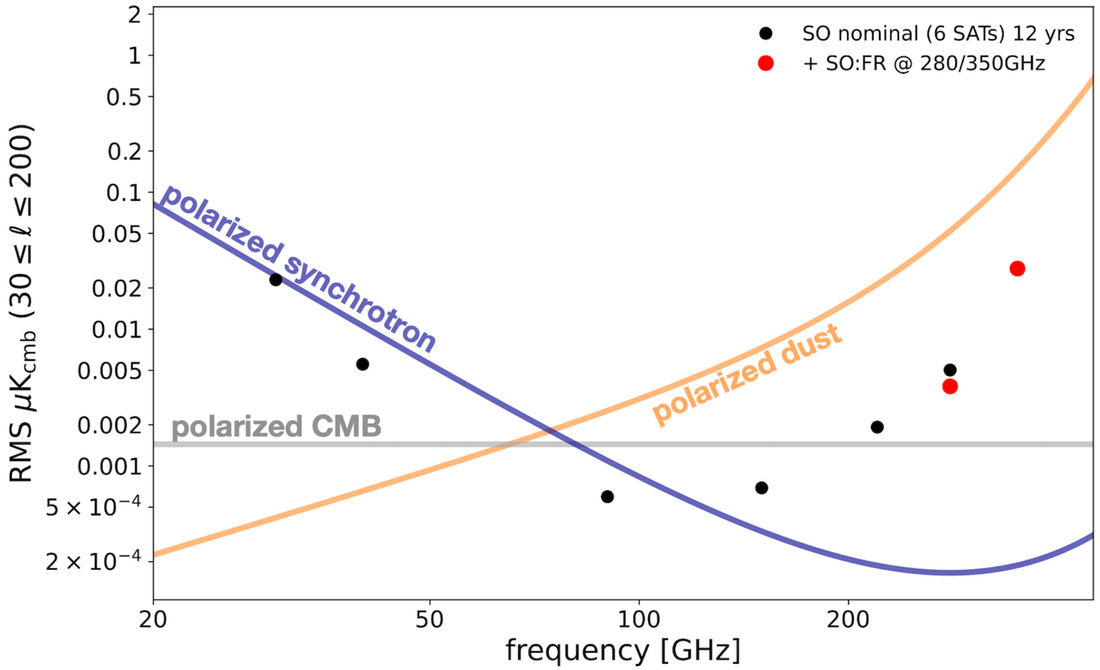


KAIROS

Perspectives : Polarimeters → The French SAT for SO

In early 2024 we proposed for funding to add a high frequency Small Aperture Telescope (SAT) to Simons Observatory existing telescope

More precise measurement of the contamination of galactic dust emissions



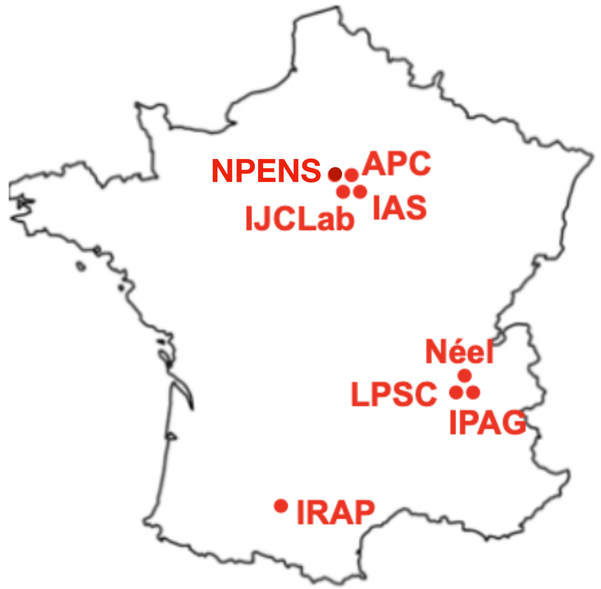
- **Increase the lever arm on the dust SED fit**
- **Lower the noise on the dust template**

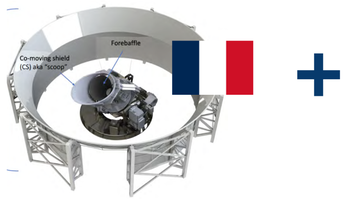
Status

In France:
Participation to the CNRS M.I.P.N RI[2]
Final decision End 2024/ Beg. 2025

With Simons:
Common consensus between the OEO and Kairos Consortium

Consortium





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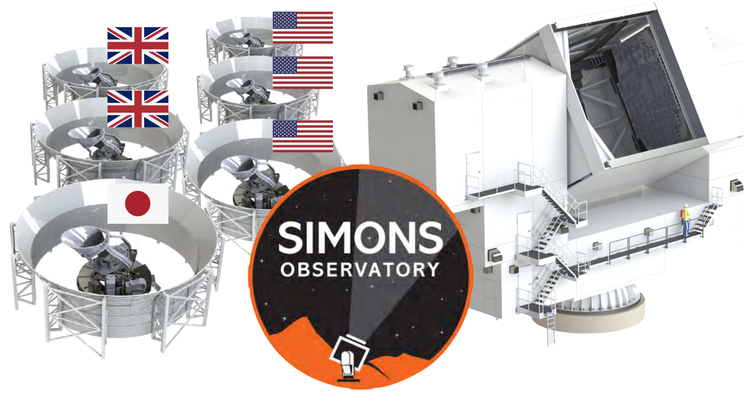
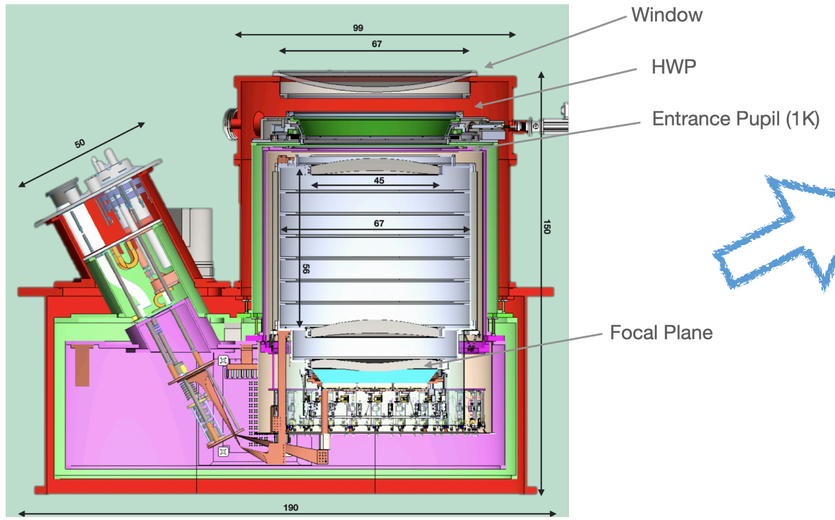


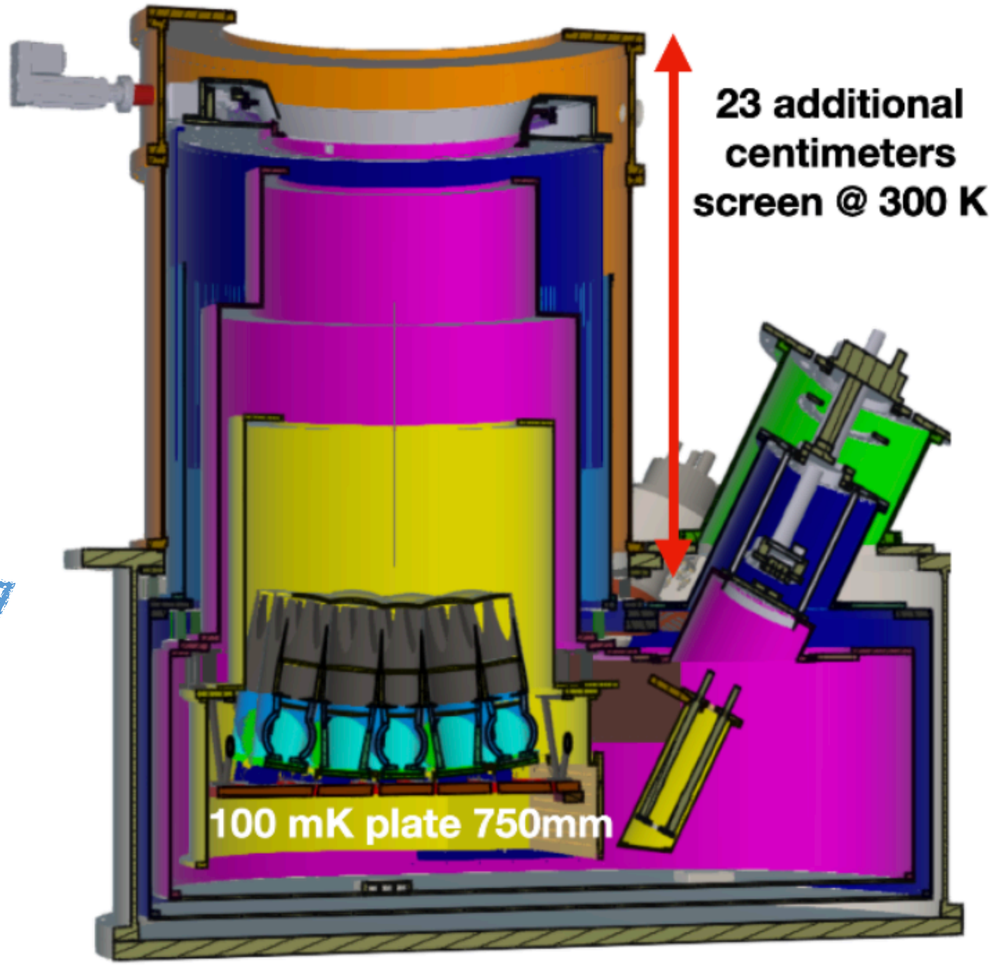
KAIROS

Perspectives : Polarimeters → The French SAT for SO

Starting from the constraints imposed by SO, we propose to adapt the French SAT to host a 30k-KID focal plane with adapted optics

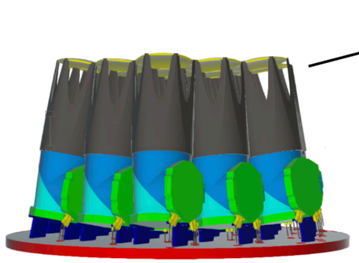


from US SAT …

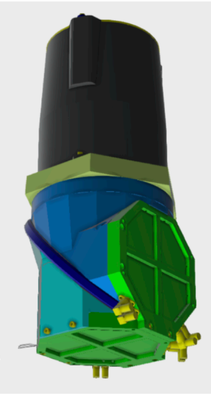


…. to French SAT

Entrance Pupil = 420 mm
Total F.o.V. = 35 Deg.
# of channels = 2
BandPass = 200-400 GHz
# of Optical Tubes = 19
F.o.V per Tube = 6 Deg
Total # of Si lenses per Tube = 5
Total # of Det. ~ 30k
# of LEKID array = 36 (4-inches wafer)
# of Readout Boards = 50-70
(multiplex. Factor~ 600-800)
Total Data Rate ~ 100 MBytes/s



100 mK FP



Conclusions

- **KID Technology**

  - French KID technology represents the state-of-the-art worldwide for mm and sub-mm astrophysics.
  - GIS LEKID technology has today a TRL high enough to be used for the next generation CMB experiments.

- **Photometers/Polarimeters/FTS Instruments**

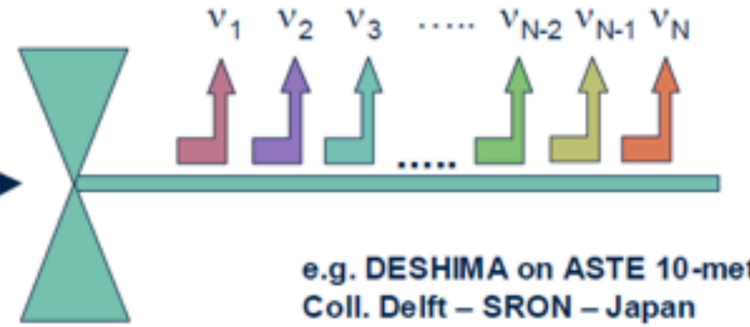
  - Several scientific results thanks to **NIKA 2** for our collaboration but also for the mm astrophysical community worldwide
  - FTS Spectroscopy analysis with **CONCERTO** is in progress, first spectral results are coming out soon.

- **Perspectives**

  - Sensitivity for photometers and Polarimetry applications is in line with the expectations of **S3 and S4 effort.**
  - Big effort of the French community to contribute to the **Simons Observatory project** by adding a 100% French technology instrument to the SO telescopes

Our approach on KID development: Spectrometers

ON-CHIP $[\nu_1, \nu_N]$

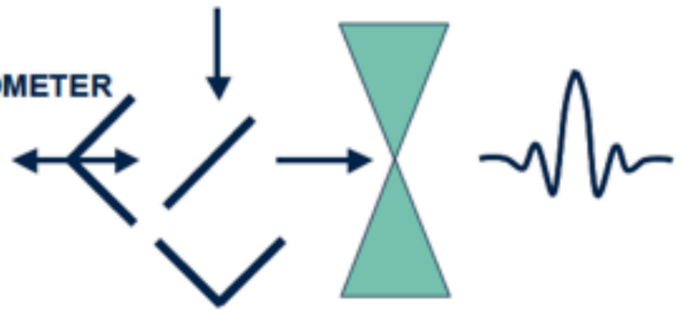


e.g. DESHIMA on ASTE 10-meters telescope
Coll. Delft – SRON – Japan
OR SuperSpec US coll.

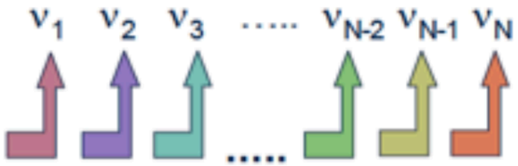
BETTER FOR **SMALL NUMBER OF BEAMS (FOV)** AND **R=100 ÷ 1000**

$[\nu_1, \nu_N]$

INTERFEROMETER



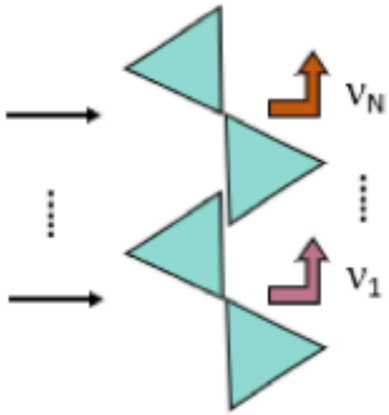
FFT



e.g. CONCERTO on APEX

BETTER FOR **MEDIUM NUMBER OF BEAMS (FOV)** AND **R = 10 ÷ 100**

HYPERSPECTRAL $[\nu_1, \nu_N]$

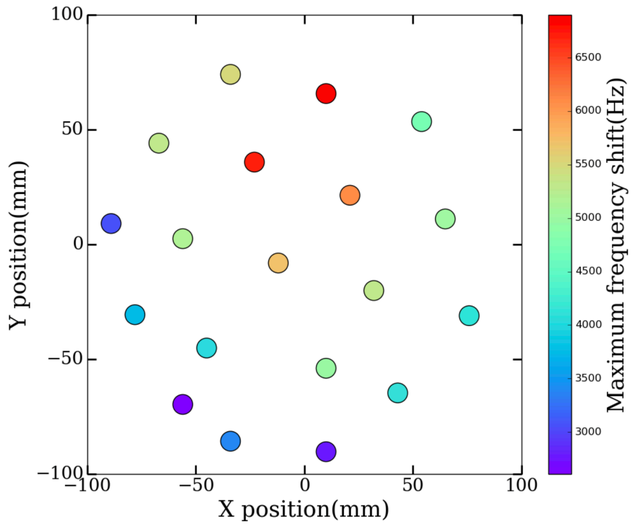


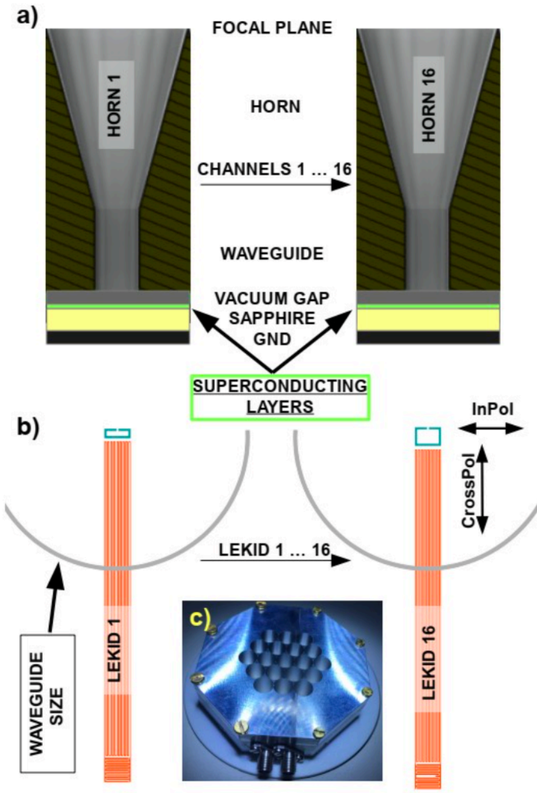
FABRY-PEROT ≡ HYPERSPECTRAL

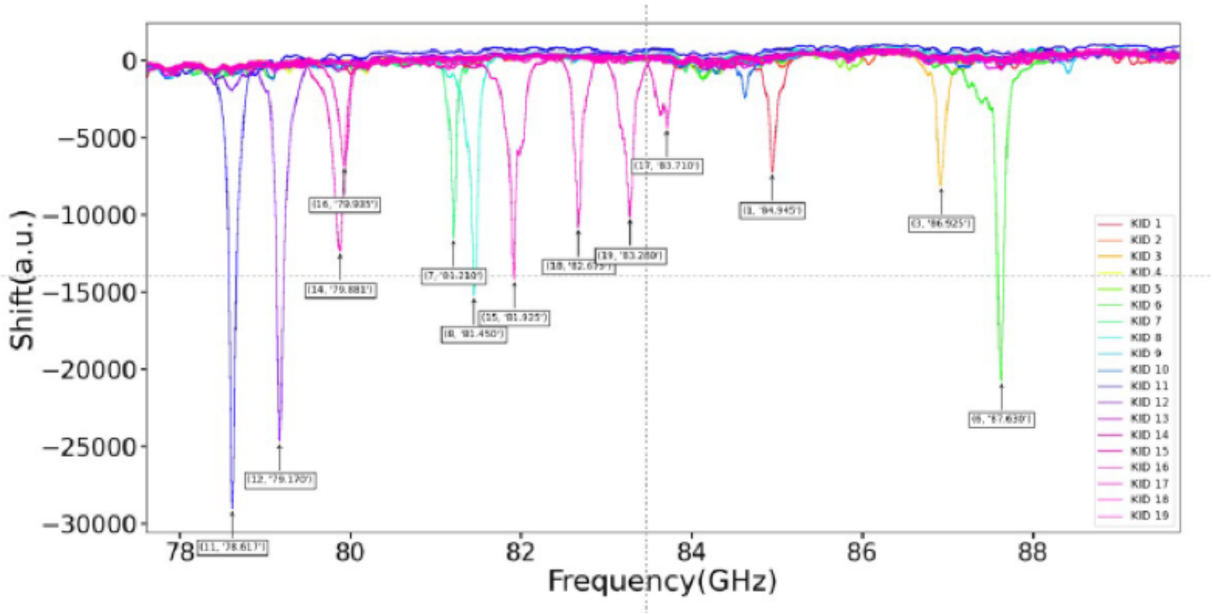
BETTER FOR **VERY LARGE NUMBER OF BEAMS (FOV)** AND **R = 100 ÷ 1000**

Perspectives : Spectrometers → R&D on KID detectors in progress….

HYPKID = Hyperspectral Kinetic Inductance Detector





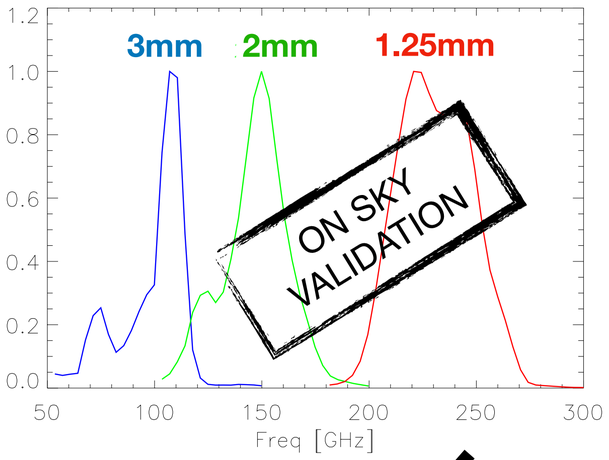


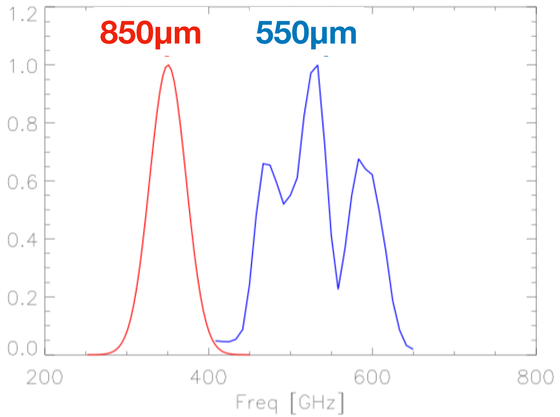
- **Direct Coupling of the Horne with the resonant filter**
- **Horn-Microstrip transition removed**
- **Very interesting for low resolution spectra on-chip**
- **NEP very raw: 1.10^-17 W/sqrt(Hz)**

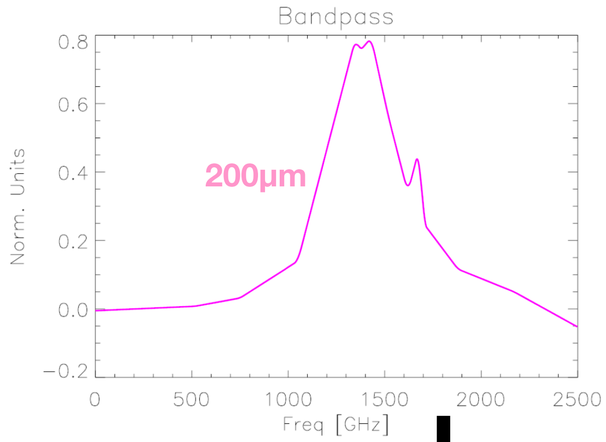
KID/Readout Development : Sensitivity

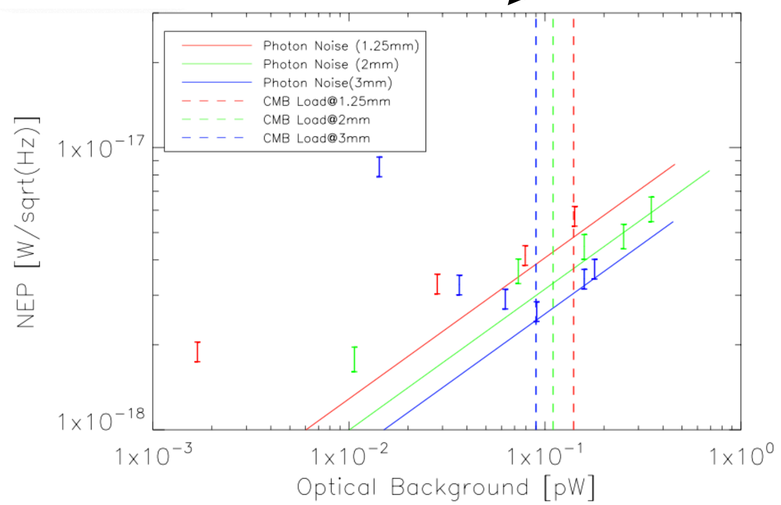
[Catalano et al.,A&A 2020]

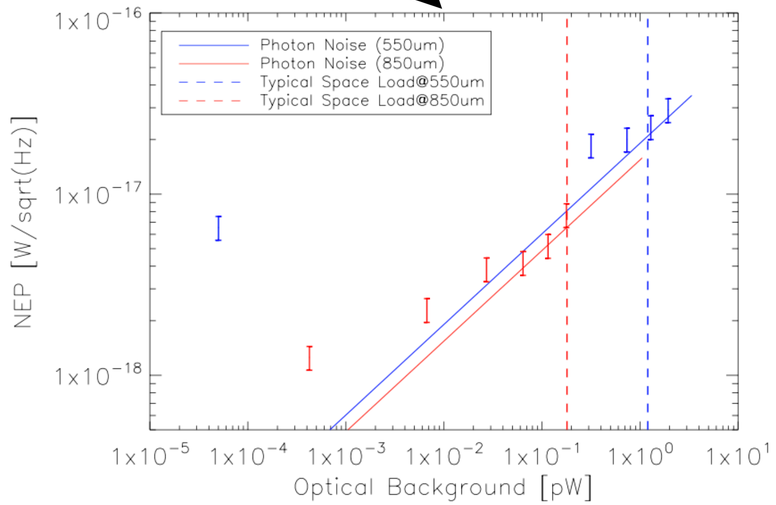
Spectral range covering, sensitivity, Cosmic Rays impact, polarisation study

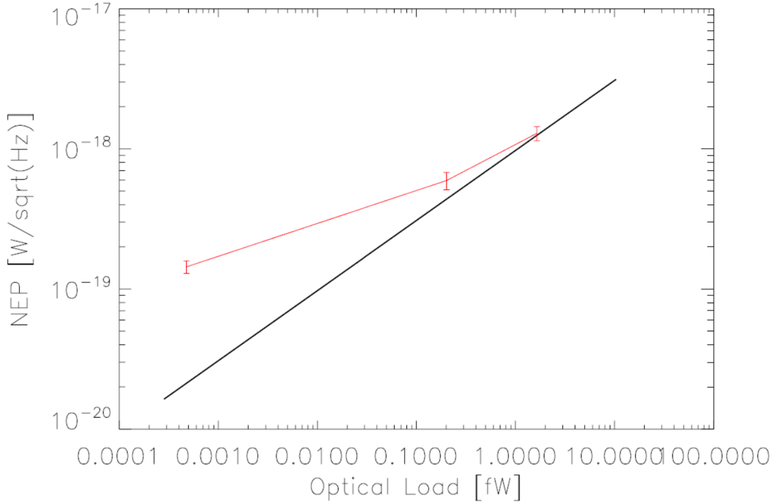










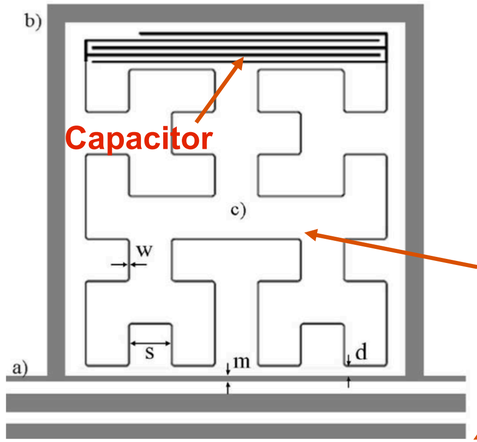


The **K**inetic **I**nductance **D**etectors

The incoming photons break Cooper pairs (supercurrent carriers) in a superconducting LC resonator → measurable signals

Dual Polarisation
(3rd-order Hilbert pattern)

Roesch, M. et al. 2012, ArXiv 1212.4585



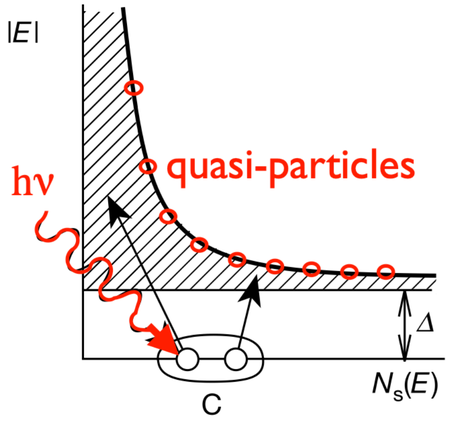
Capacitor

Inductance ($L_K + L_G$)

Feedline 50Ω

photon detection principle :

$h\nu > 2\Delta$

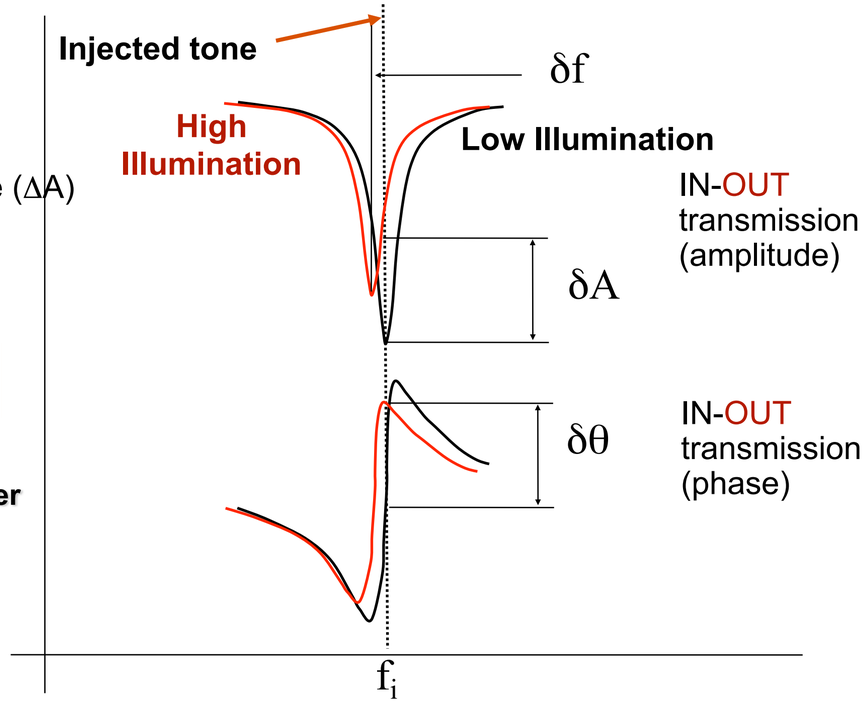


Dark, $T << T_c$

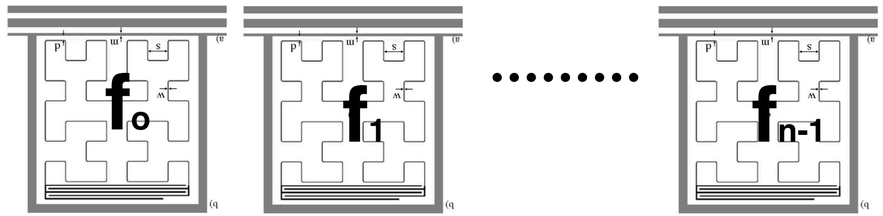
Light: **increase in R**
Change in amplitude (ΔA) and phase

$\delta f \propto \delta L_K \propto \delta P$

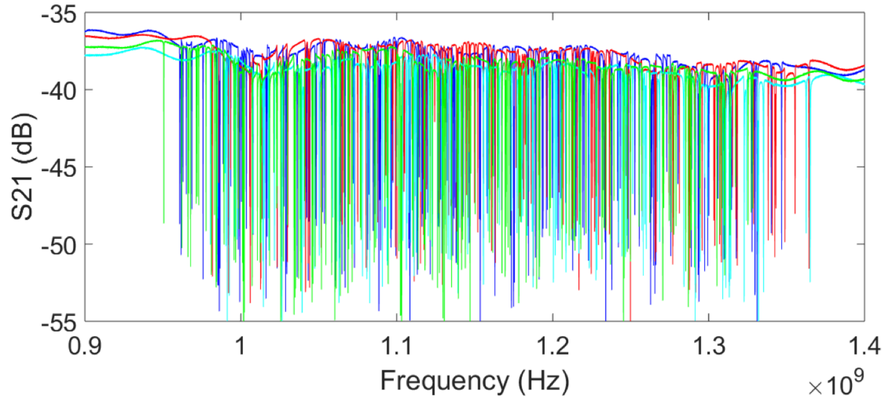
δf = frequency shift
δP = incoming power



IN → OUT

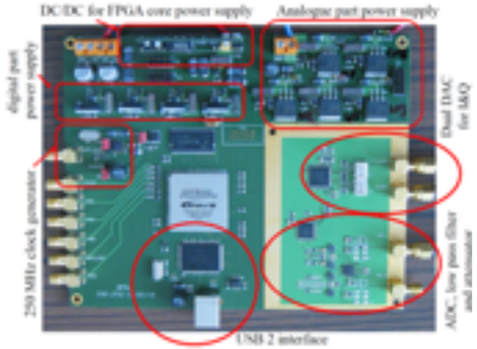


Each 400 pixels are connected to a single transmission line



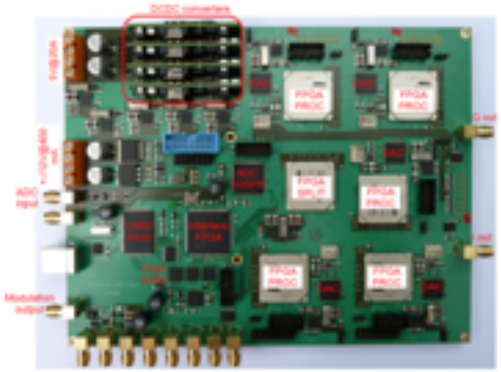
READOUT Development

2011: NIKEL proto



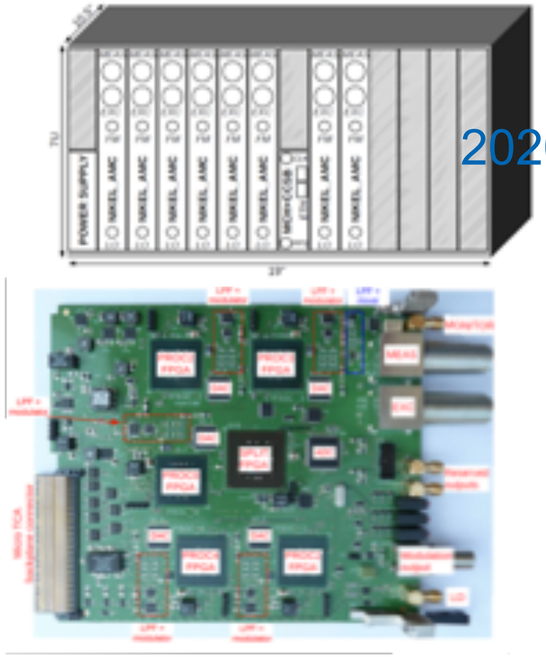
128 pixels
500 MHz bandwidth
external RF

2012: NIKEL (NIKA)



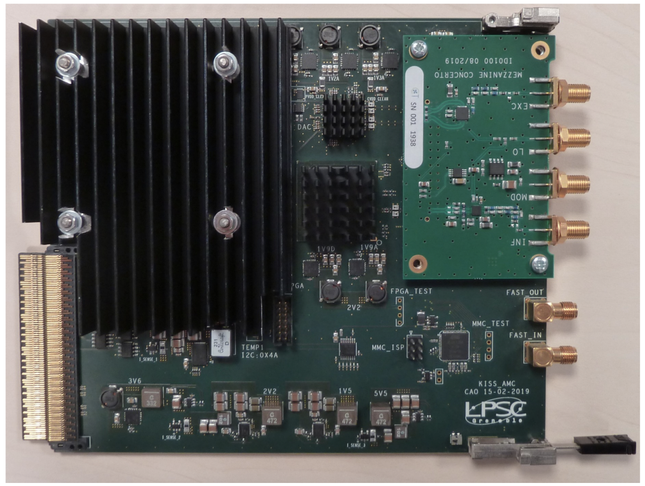
400 pixels
500 MHz bandwidth
external RF

2016: NIKEL AMC (NIKA2/KISS)



400 pixels
500 MHz bandwidth
RF in the board
Compact crate with up to 10 boards

2020: NIKEL AMC v2 (CONCERTO)



400 pixels
1 GHz bandwidth
30 watts power

[Bourrion+2011, 2012, 2016, 2022, Bounmy+2022]

NIKA2 collaboration

NIKA2 Worldwide

- 163 scientists from 33 Institutes in 9 countries (France, Spain, Italy, Ireland, Belgium, Greece, UK, Iran & USA).
- specialists in instrumentation, data analysis, and scientific interpretation in astrophysics and cosmology

NIKA2 France

- 112 specialists from 13 laboratories affiliated with IN2P3, INSU, INP, CEA and IRAM
- Origin: Synergy IN2P3-INSU-INP that has proven its efficiency since 20 yrs (Archeops, Planck, NIKA, KISS, NIKA2, Concerto)
- Leading position: Principal Investigator: A. Monfardini I. Néel, INP; Project Scientist: J.F. Macías-Pérez LPSC/IN2P3

NIKA2 IN2P3

- 23 scientists at LPSC and IP2I-Lyon (~2-3 FTE/yrs since 15 yrs)
- Leading responsabilities : Project Scientist (J.F. Macías-Pérez), President of the Editorial Board (L. Perotto) …
- Major contributions to the construction: Readout electronics (O. Bourrion) + strong involvement of the services
- Key role in the scientific exploitation (PI of a Large Program)

NIKA2 MoU

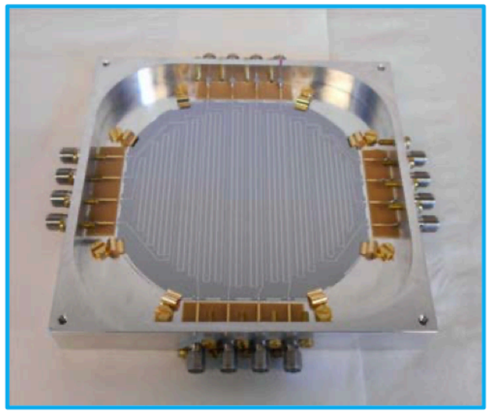
- Responsability of the construction, commissioning, maintenance & upgrades until ~2030
- 1300 hours of Guaranteed Time at the IRAM 30-m telescope distributed in 5 *Large Programs, one of which led by IN2P3*

NIKA2 in a nutshell

A millimetric continuum camera of 2 900 Kinetic Inductance Detectors (KID), operating at 150 and 260 GHz, installed at the IRAM 30-meter telescope, and operating since 2017

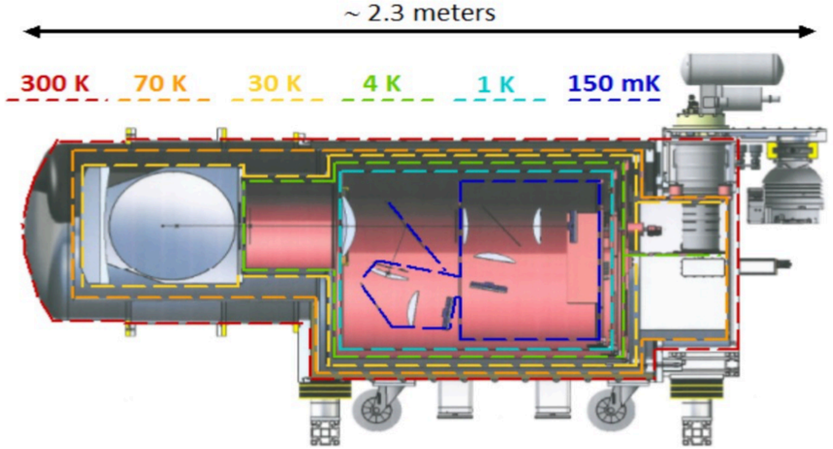
Bourrion et al. (2016) Jinst, 11, 11
Adam et al. (2018) A&A 609, A115
Perotto et al. (2020) A&A 637, A71

Thousands KID-based camera…



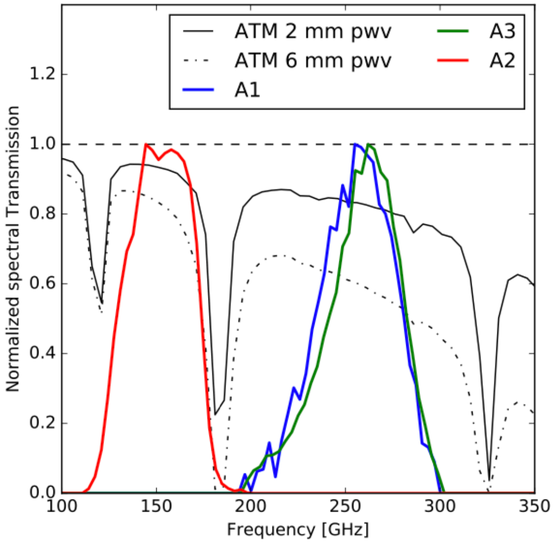
One of the two 1140 KID arrays at 260 GHz

…cooled at 150 mK…



Design of the cryogenic stages

… operating at 150 and 260 GHz …



Measured spectral transmission

IRAM 30-meter telescope at Pico Veleta, 2870m, Spain

…with an angular resolution < 20″ and an instantaneous field of view of 6.5′ in diameter…

…and sensible to polarization at 260 GHz

CONCERTO Project

Fundings : ERC Advanced Grant
Duration of the project : 60 months
Staring : 1st January 2019
P.I. : Guilaine Lagache (LAM)

- Spectro-Interferometer (spectral resolution R > 100)
- Observing between 120 GHz - 350 GHz from 12 m APEX Tel.
- Large Field of View (20 Arcmin)
- LEKID Technology
- Collaboration LAM - Inst. Néel - LPSC - IPAG

Telescope primary mirror diameter [m]	12
Field-of-view diameter [arcmin]	20
Absolute spectral resolution [GHz]	≥ 1
Relative spectral resolution R [#]	1–300
Frequency range HF | LF [GHz]	195–310 | 130–270
Pixels on Sky HF | LF [#]	2,152 | 2,152
Instrument geometrical throughput [sr m^2]	2.5×10^{-3}
Single Pixel geometrical throughput [sr m^2]	1.16×10^{-6}
Data rate [MBytes/sec]	128

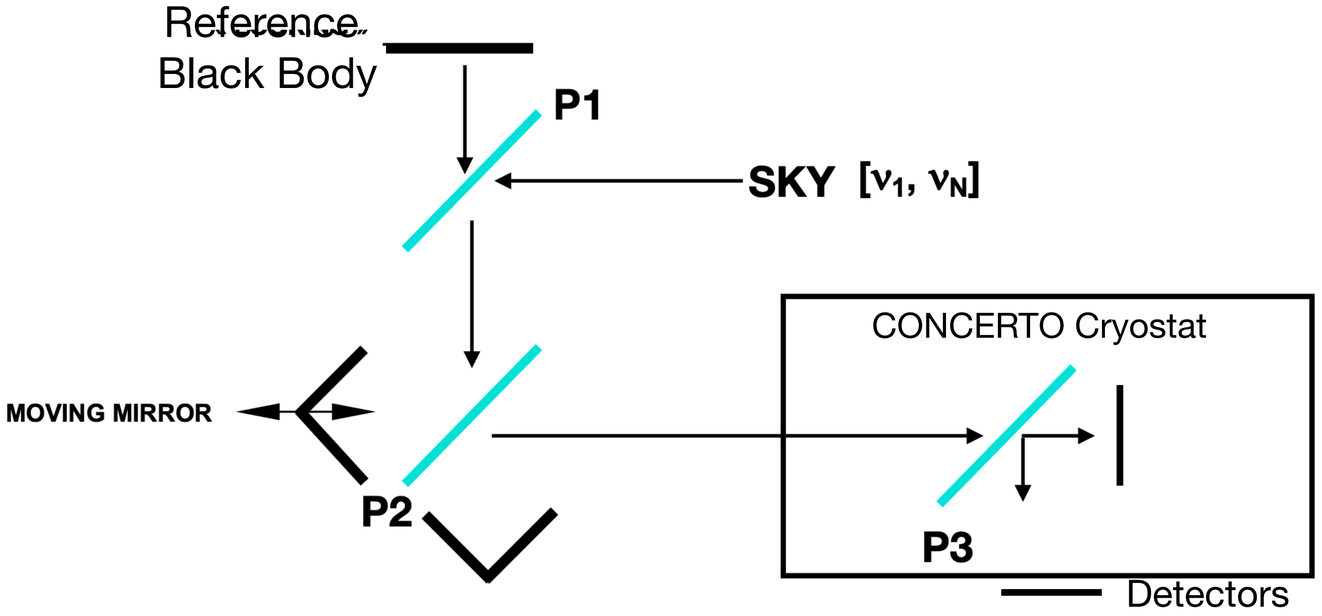
Main Goals: 1200 hours Observations of the [CII]-emission line at high redshift
20 hours SZ signal from galaxy cluster RXJ1347–1145 (z = 0.45)

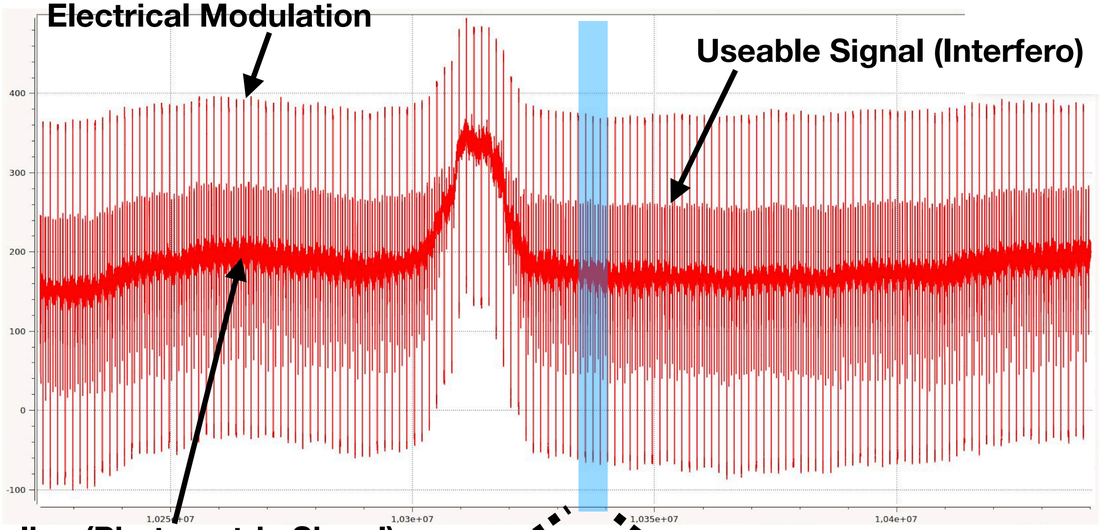
Pathfinder: KISS installed at Qujiote (Tenerife) since end of 2018. Still observing

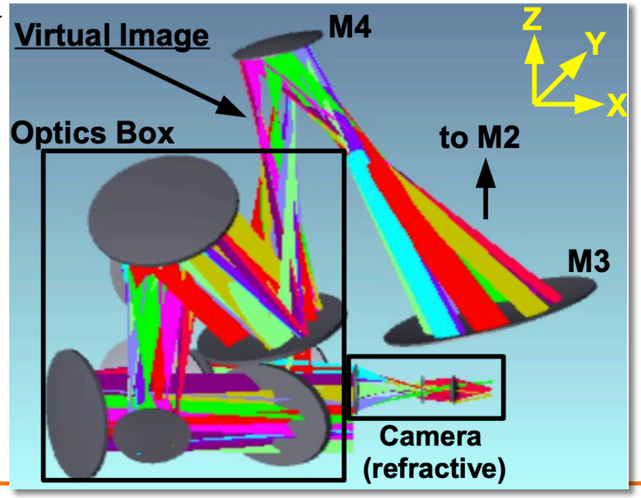
Status: Concerto is installed at 12 m APEX telescope since April 2021

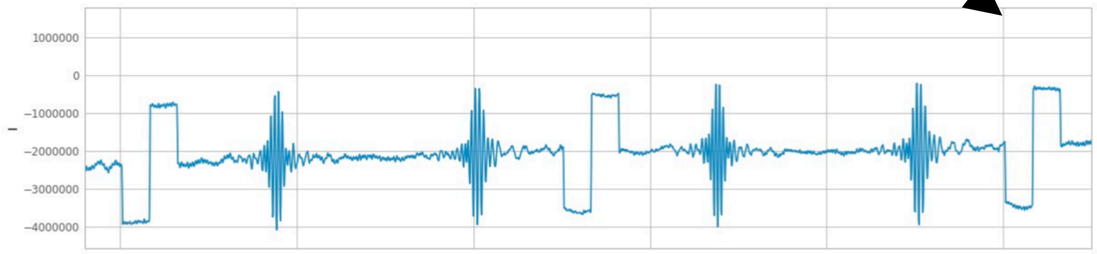
Schedule: Science Verification in June (2 weeks), Regular observations started in August 2021 until June 2023.

CONCERTO Design & Signal Processing





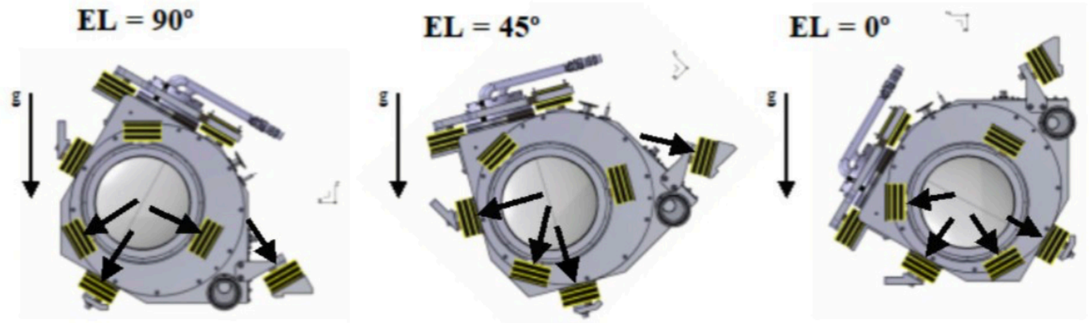


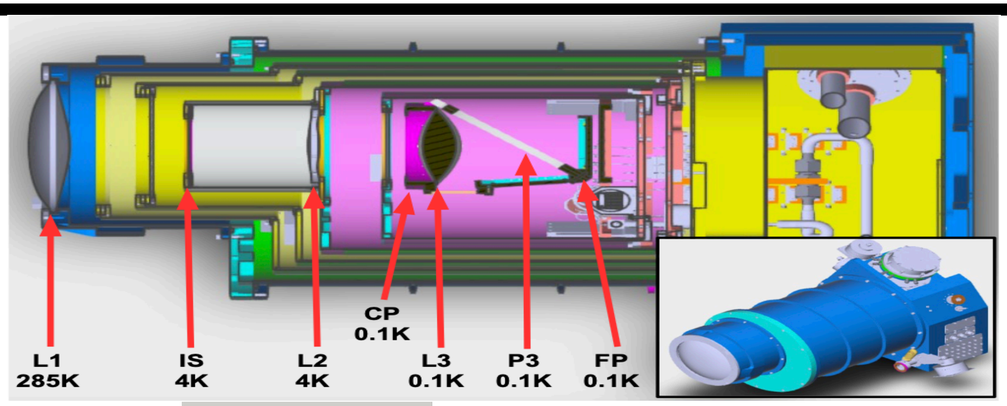


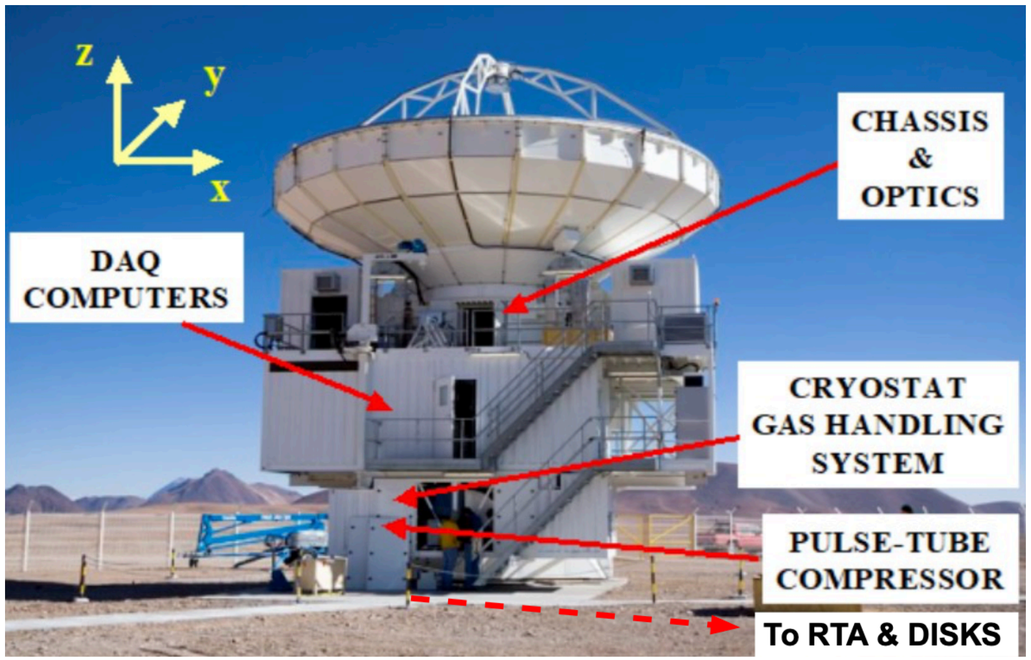
We modulate the frequency on the local oscillator before each interferogram producing some dead time at each block of data.

CONCERTO Enslavements

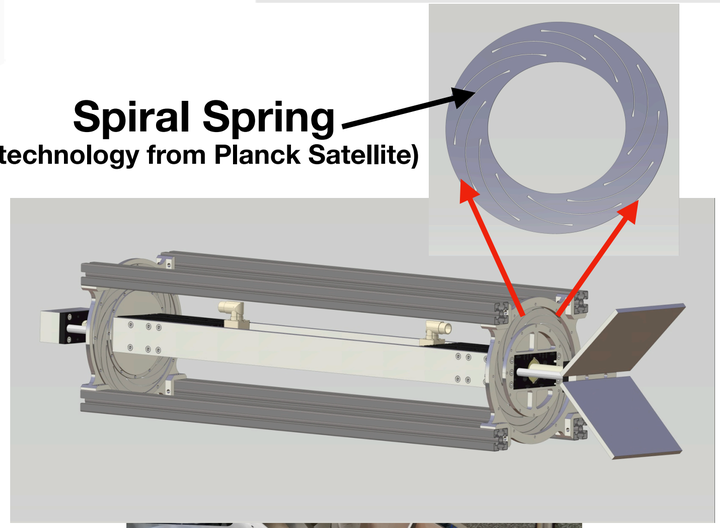
Rotation of the cryostat (and optics) following the telescope elevation







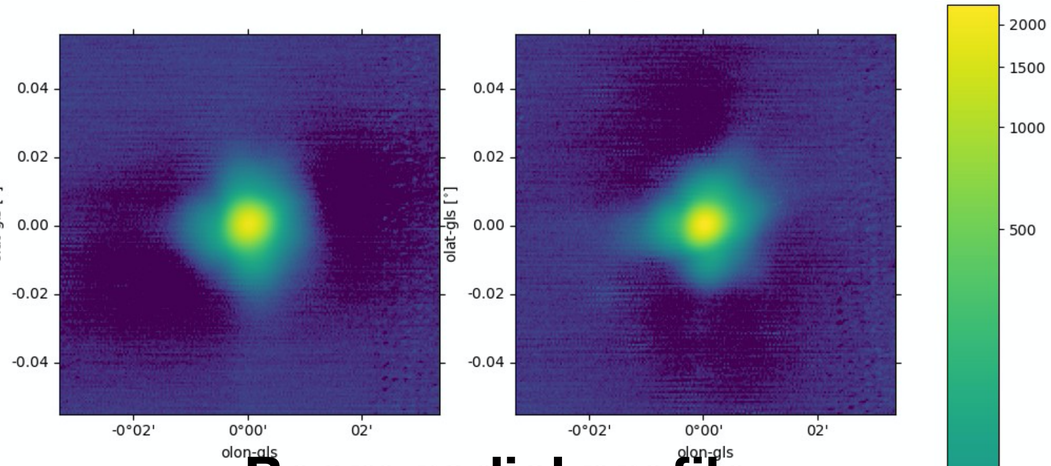
Spiral Spring
(technology from Planck Satellite)



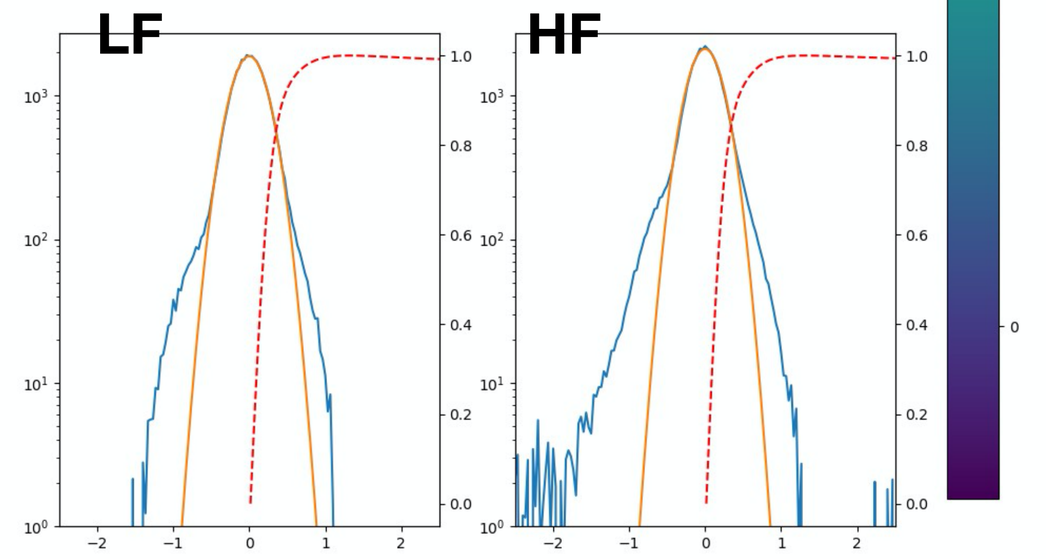
- 100mK Dilution Cryostat fully remote controlled
- MPI moveable roof mirrors with very low vibration level
- Large Size Polarizers
- Polypropylene Lenses with Geometrical AR.
- 10 Al Mirrors

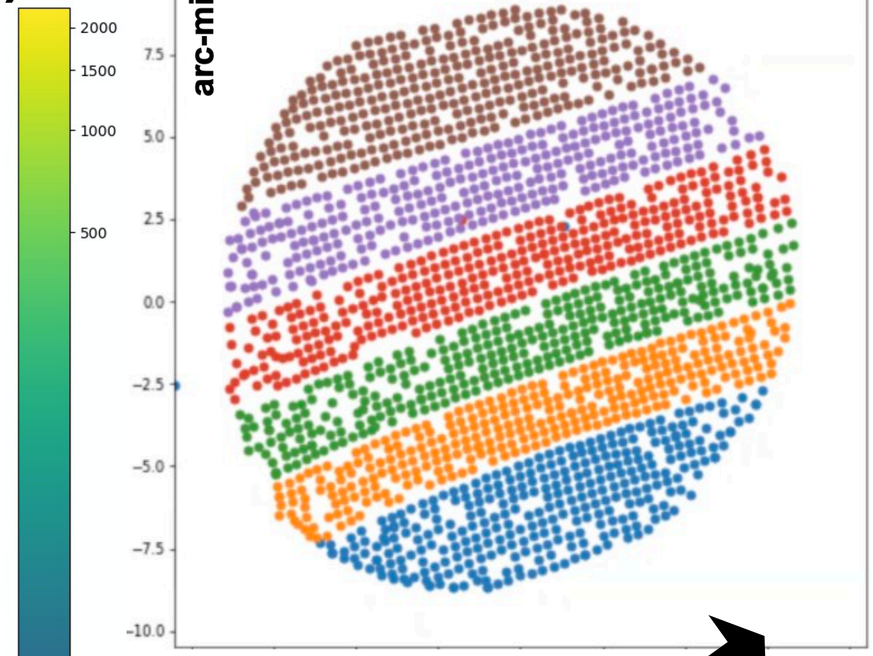
CONCERTO Commissioning

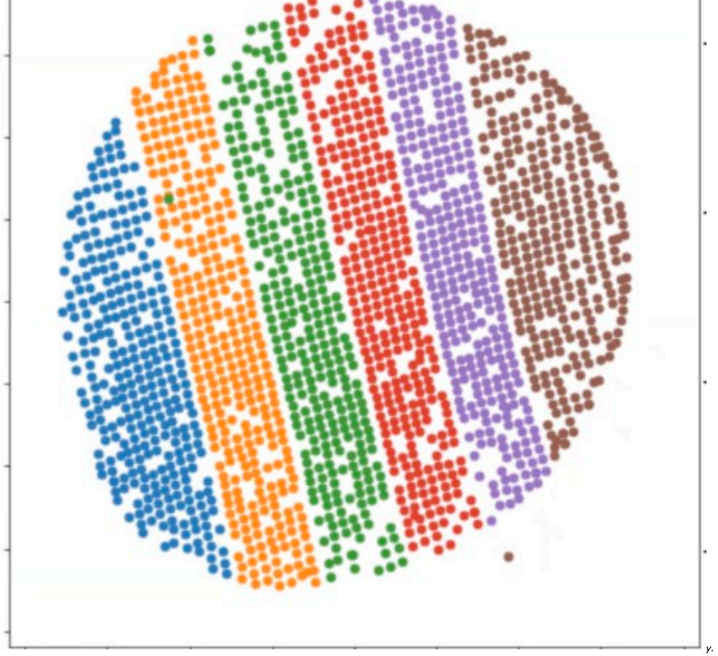
Mars Beam Map (02/05/2021)



Beam radial profile.

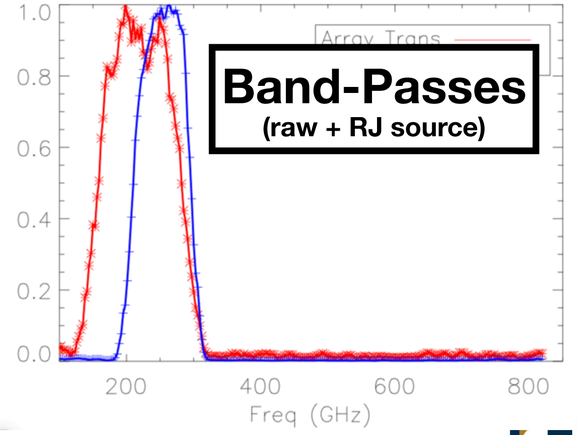






Focal Plane Geometry

> 90 % Functional pixels



CONCERTO First Photometric Observations

Cats Paws (NGC6334)

- 16 minutes integration
- LF Array (Blue)
- HF Array (Red)