KID Focal Plane for CMB Observations

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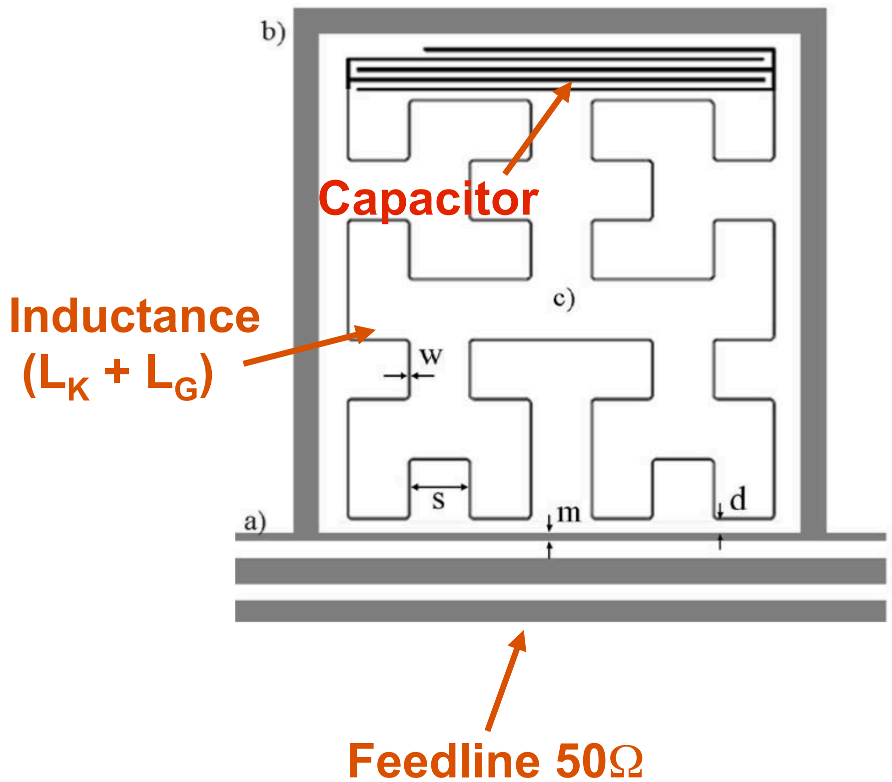
On behalf of the Grenoble Team

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

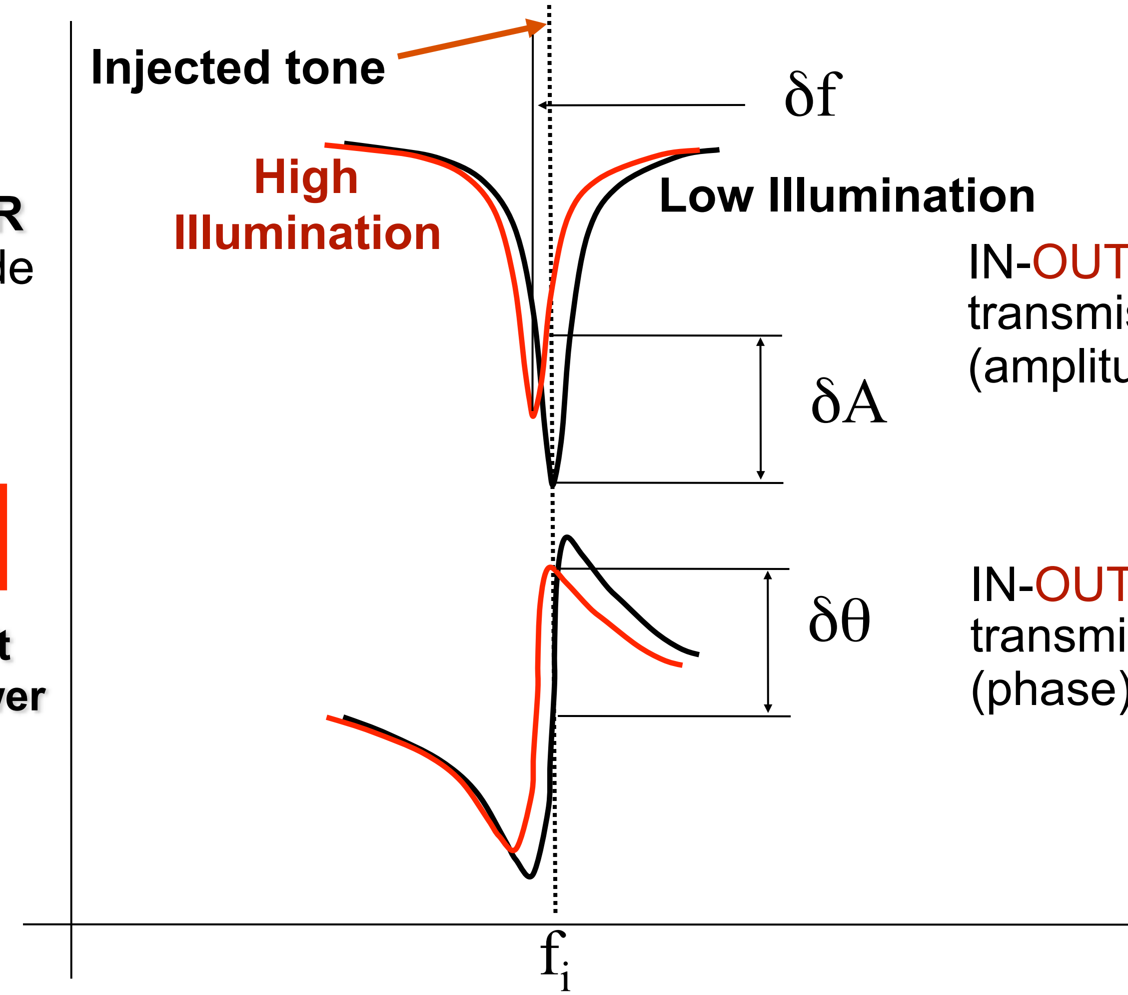


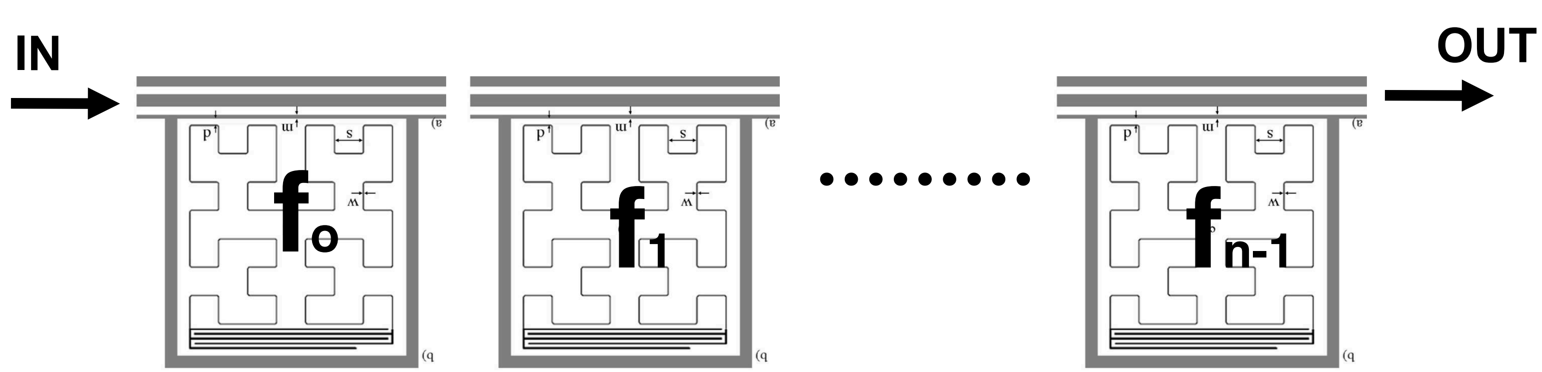
Dark, $T << T_c$

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

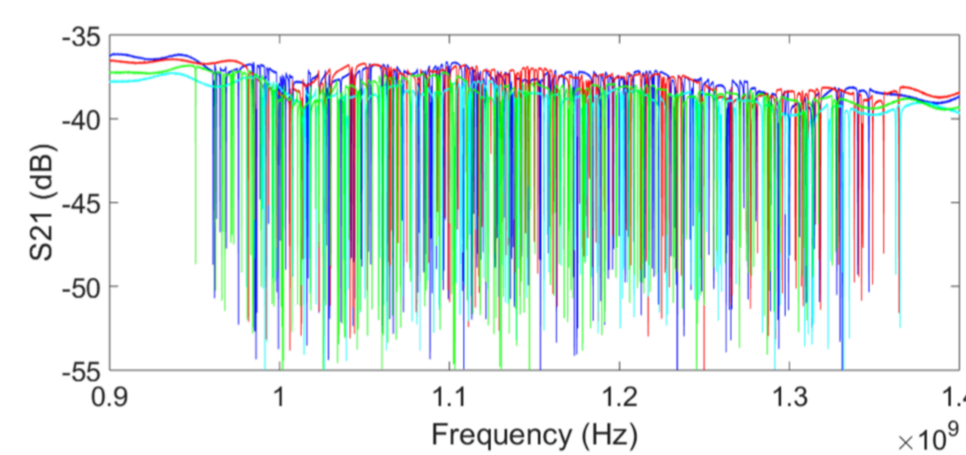
$$\delta f \propto \delta L_K \propto \delta P$$

δf = frequency shift
δP = incoming power





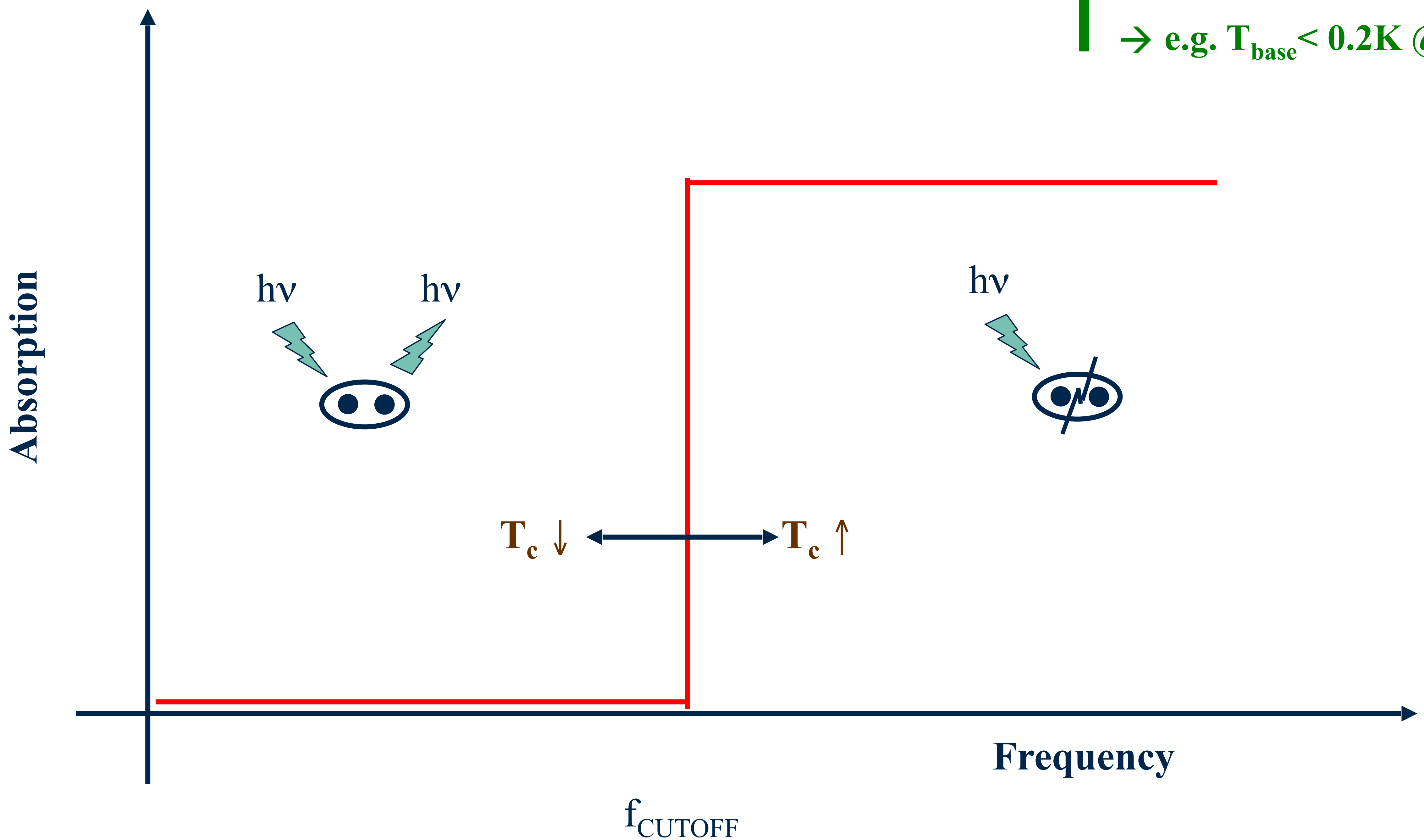
Each NIKA array is connected to a single transmission line



The Expected Spectral Response

$f_C \approx 100$ GHz · (T_c / 1.3)

→ e.g. $T_{base} < 0.2$K @ 100GHz

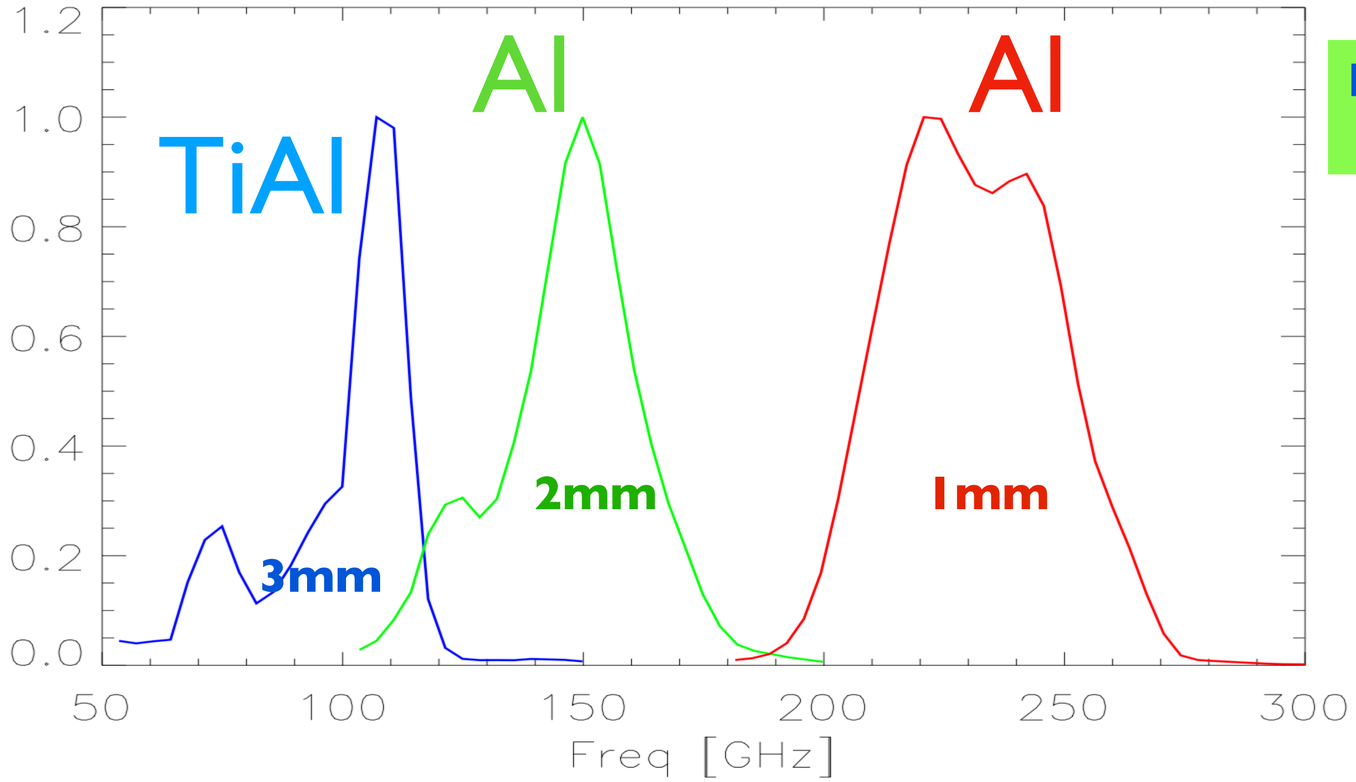


Why KID for CMB Observations?

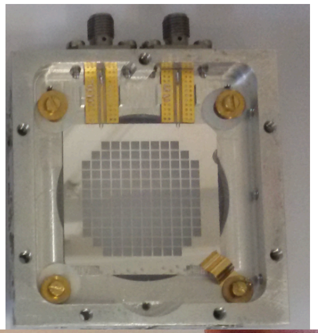
They have reached a Technology Readiness Level high enough for ground, balloon and space applications:

- *CMB photon noise limited detectors for ground and possible space observation.*
- *Linearity and fast time constants.*
- *Thousands pixel array produced and tested on sky.*
- *Calibration and Control of systematics effects.*
- *The cost of a KID camera is compatible with standard (despite very competitive) EU calls*
- *The technology is mature* ***in Europe***

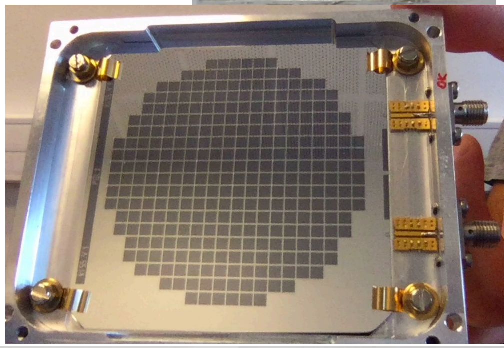
Maturity in terms of Spectral Response

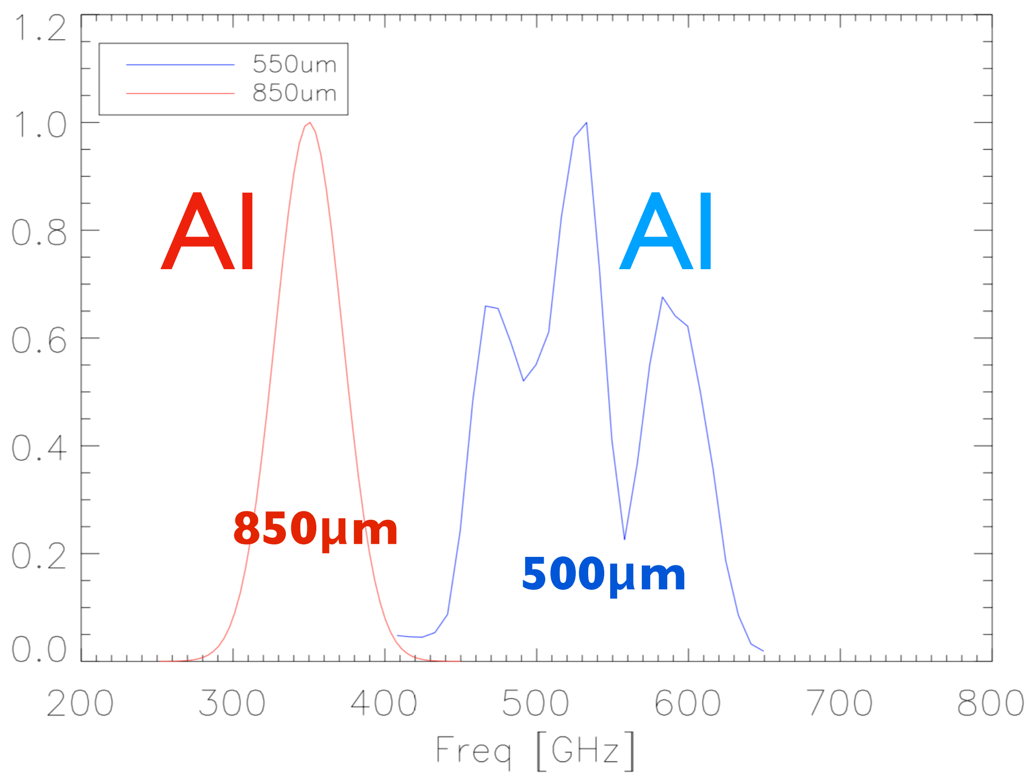


LEKID Demonstrators for space (132pix)
3mm - 2mm - 1mm - 850µm - 500µm

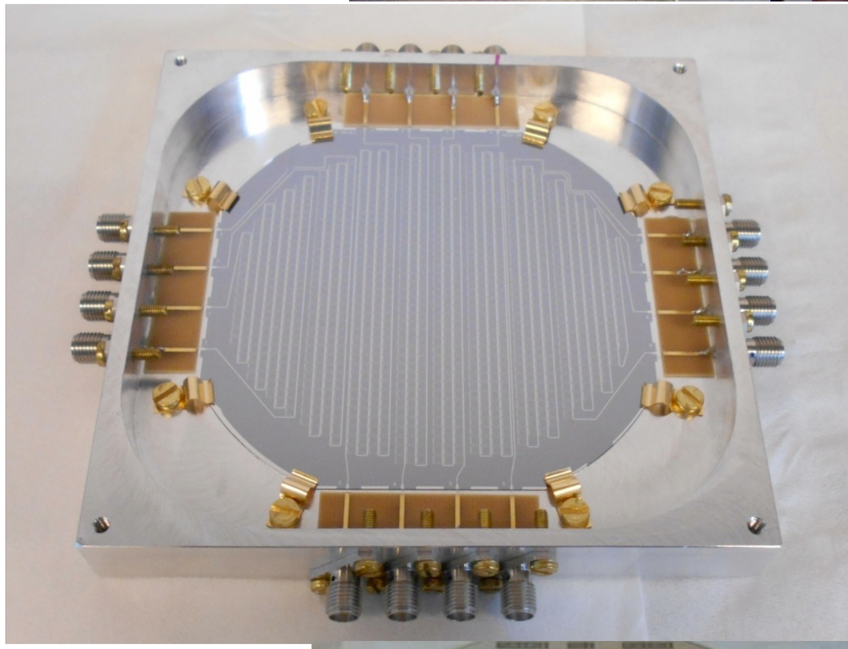


LEKID Array for KISS Interferometer (300pix) TiAl@3mm

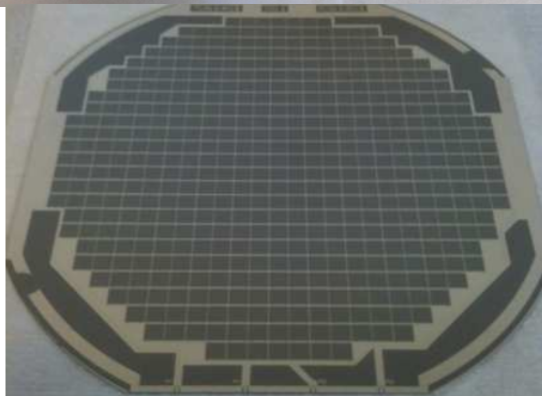




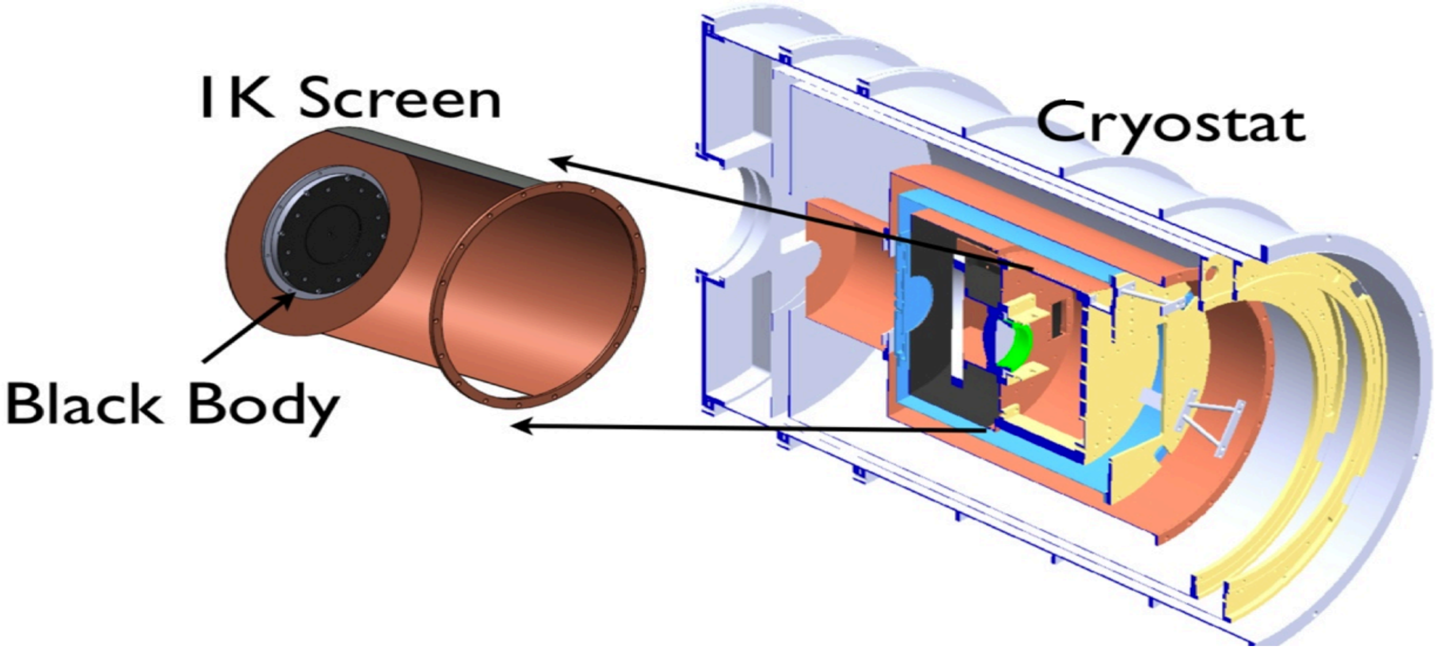
LEKID Array for NIKA2 (2000pix) Al@3mm



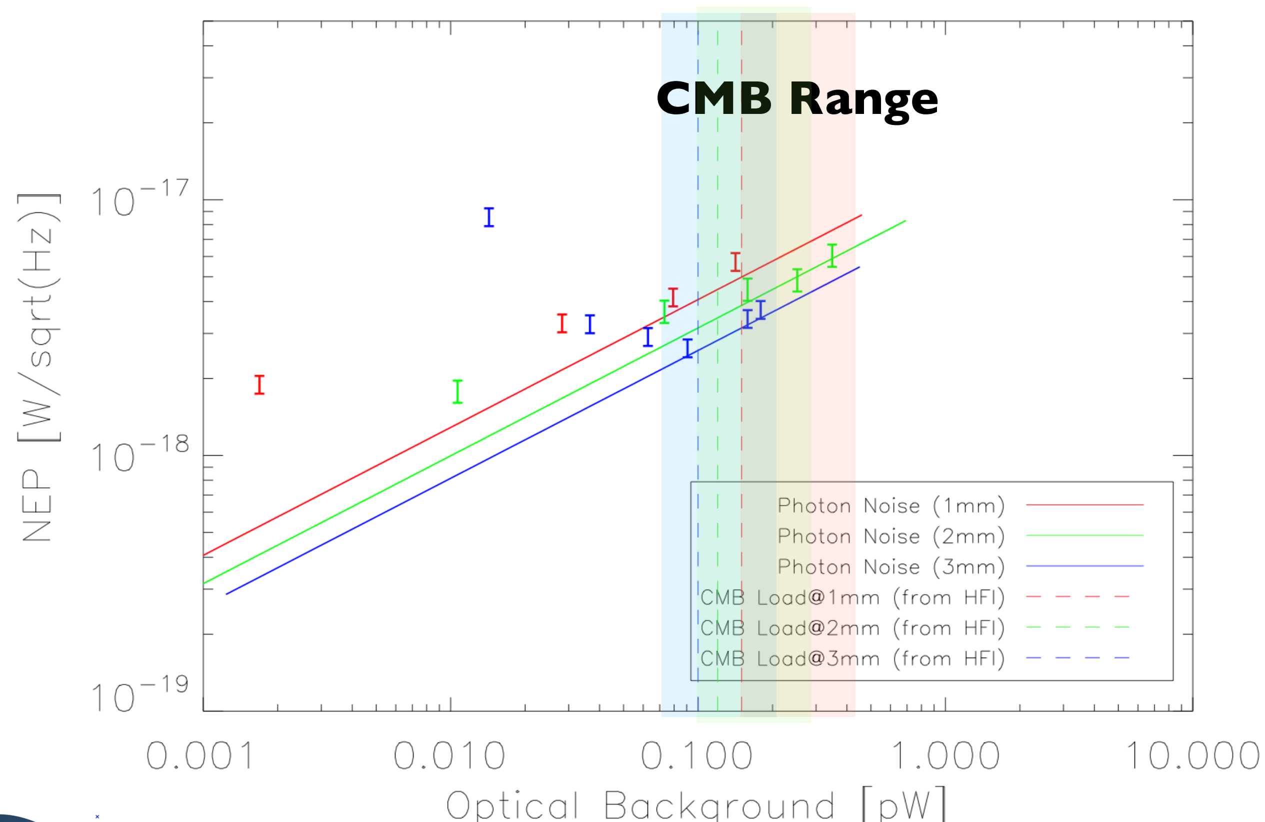
LEKID Array for Ballon (500 pix) Al@500µm

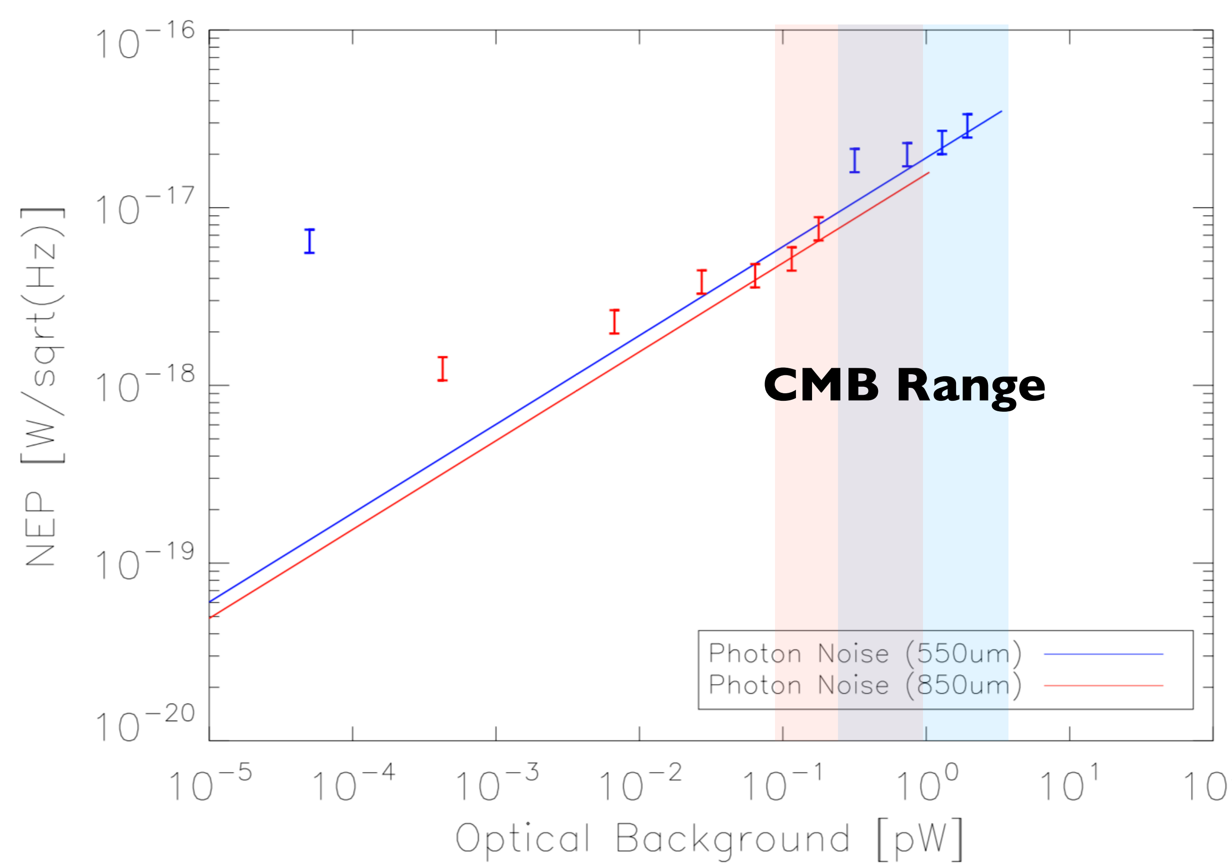


Maturity in terms of Sensitivity - Space

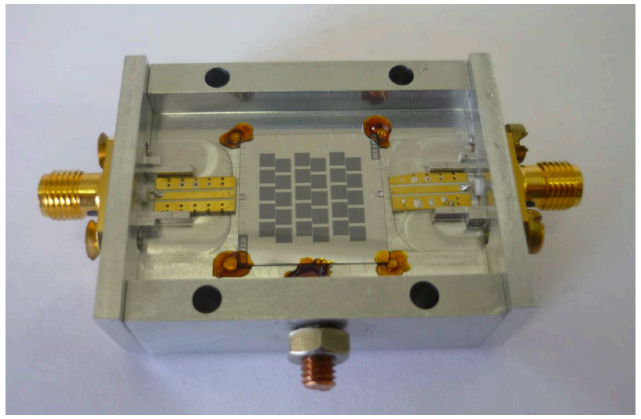


Under space typical background conditions KID show NEPs in line with CMB photon noise.

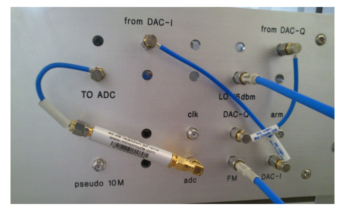


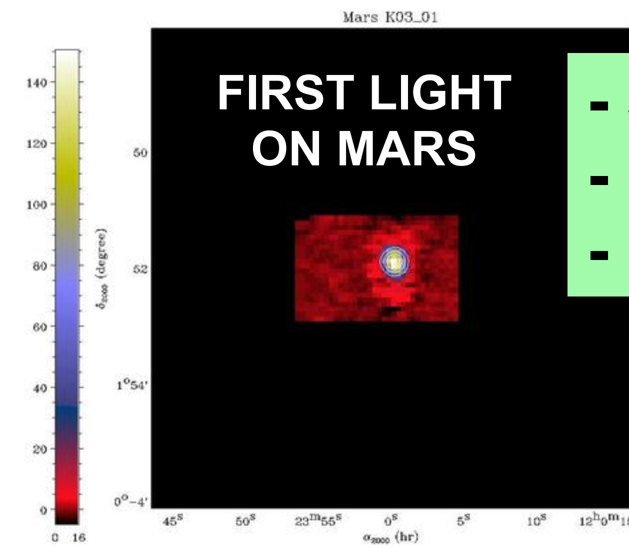


Maturity in terms of Sensitivity - Ground: NIKA2



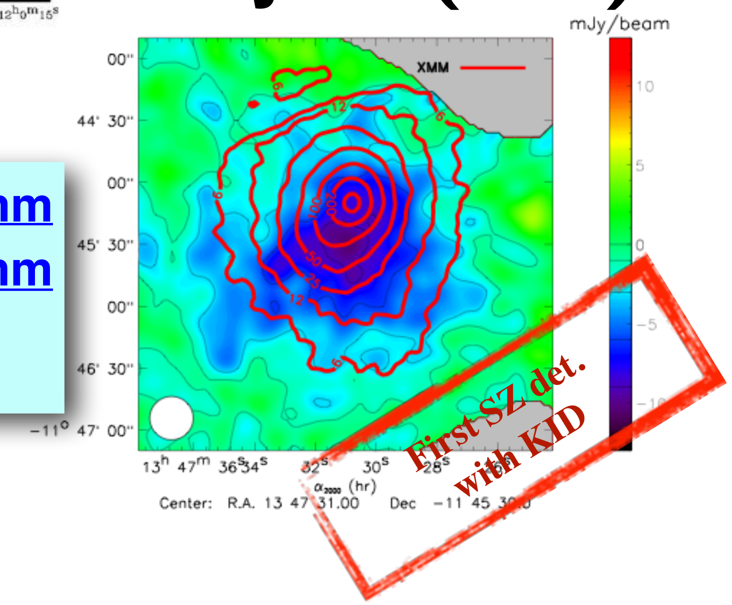
2009

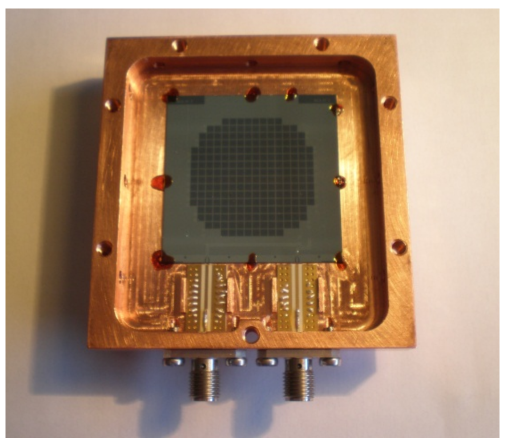




- 30 Pixels
- 120 mJy*s^0.5/beam
- Roach (Berkley) REU

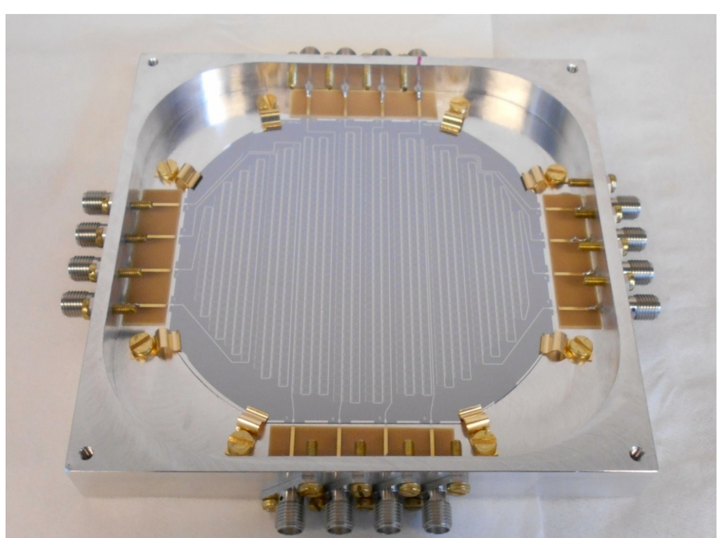
RXJ1347(2012)



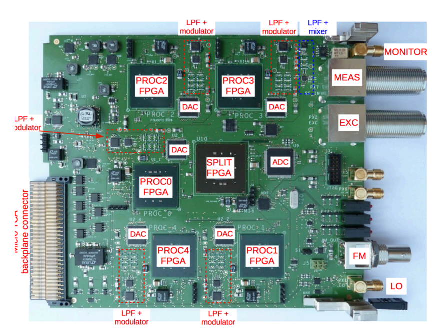


2010-2013

- 190 valid pixel @ 1.25mm
- 125 valid pixel @ 2.14mm
- 35-15 mJy*s^0.5/beam
- NIKEL USB - REU



2014-today



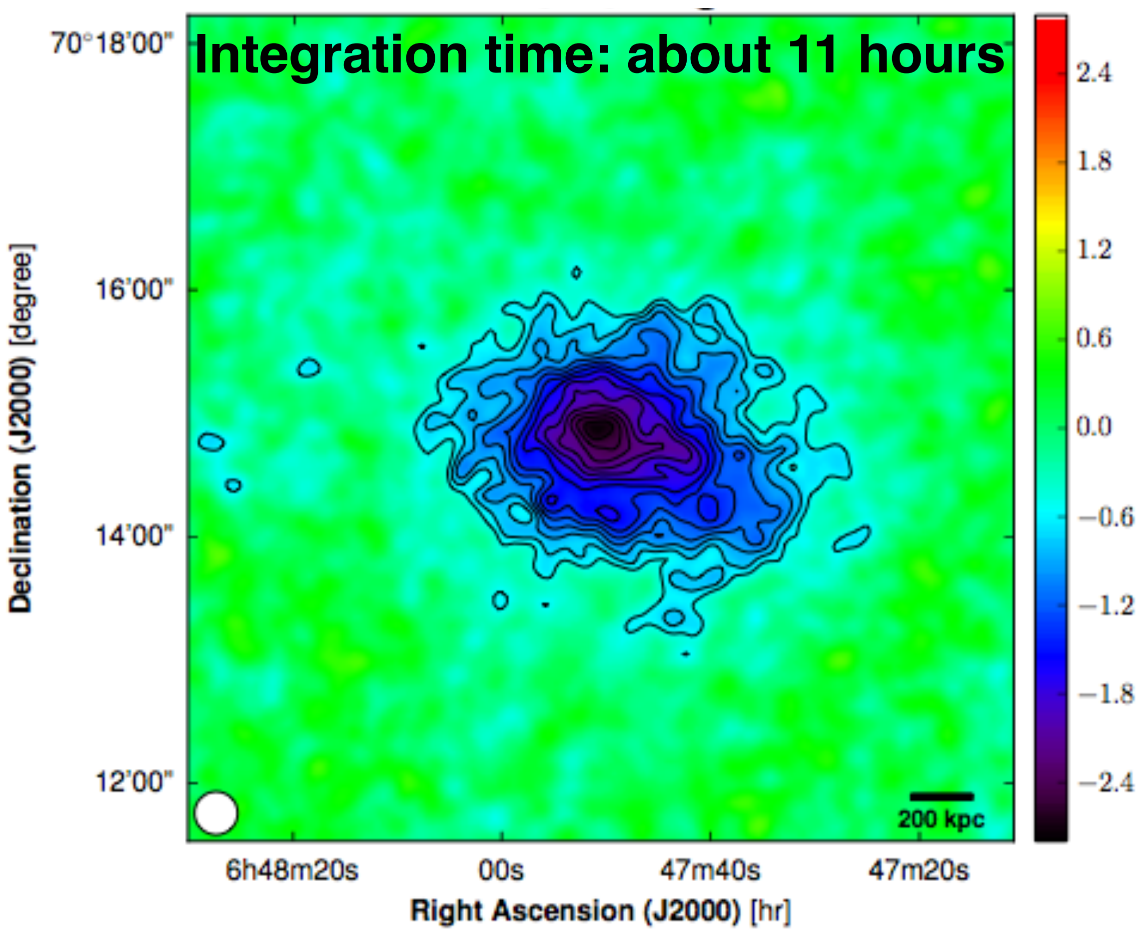
- 1140X2 pixels @ 1.25mm
  33 mJy*s^0.5/beam
- 652 pixels @ 2.14mm
  8 mJy*s^0.5/beam
- NIKEL AMC

Maturity in terms of Sensitivity - Ground: NIKA2

The NIKA2 instrument is installed at the 30 m IRAM since September 2015.
Acceptance meeting scheduled early September 2017 ended officially the Commissioning Phase.

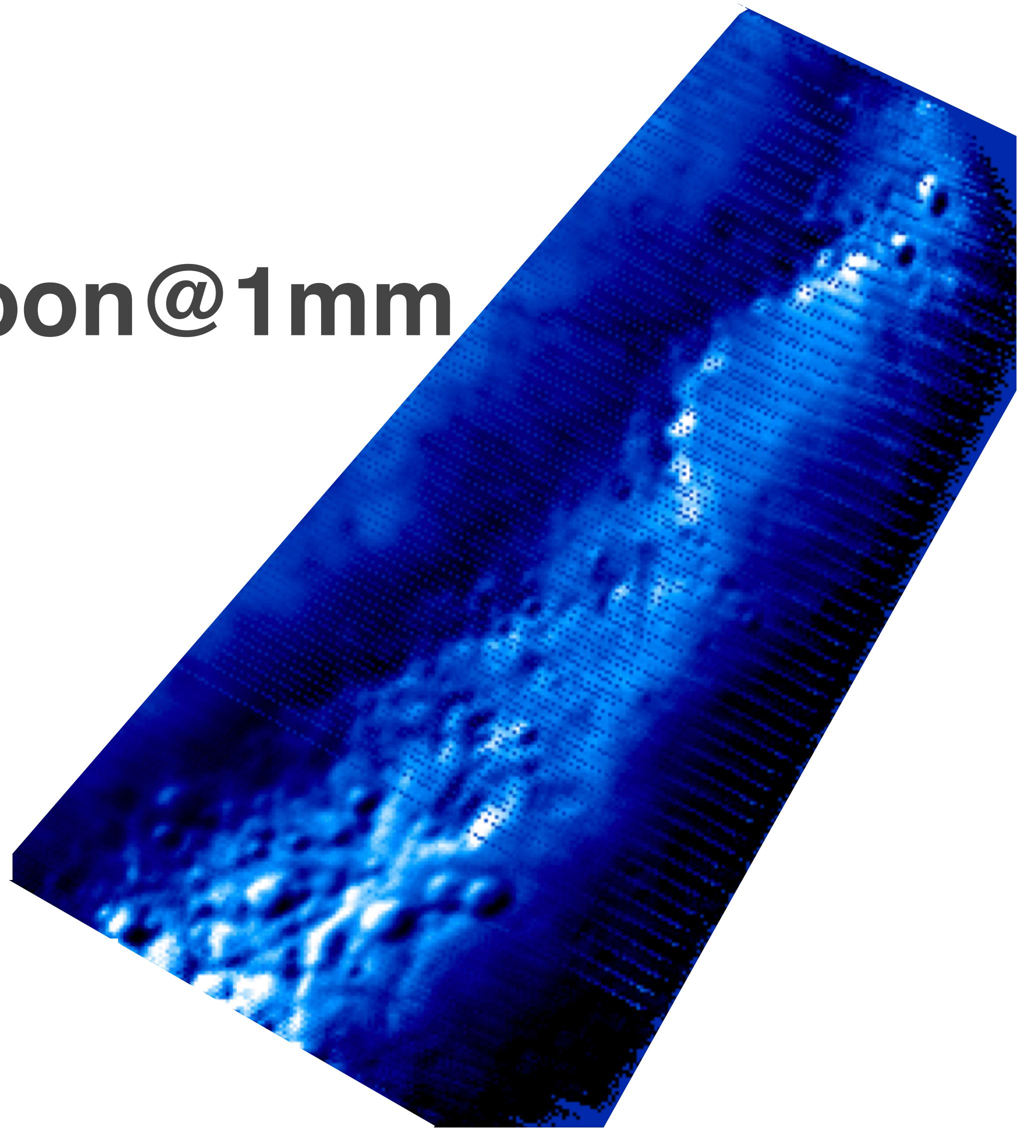
10 Clusters of galaxy have been already observed and detected after the end of commissioning phase.

PSZ2-G144.8@2mm



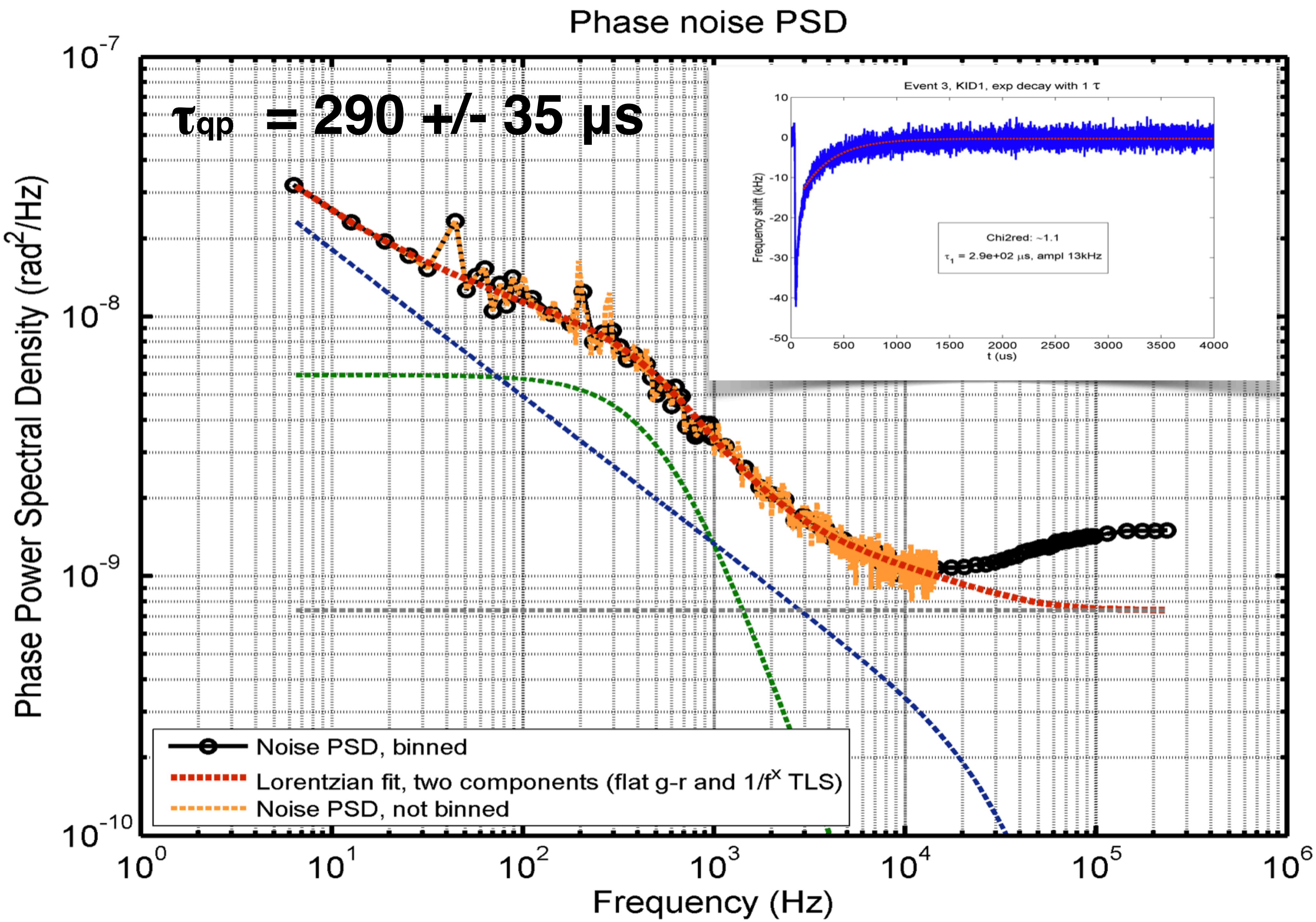
Ruppin A&A, 615, A112 (2018)

Moon@1mm



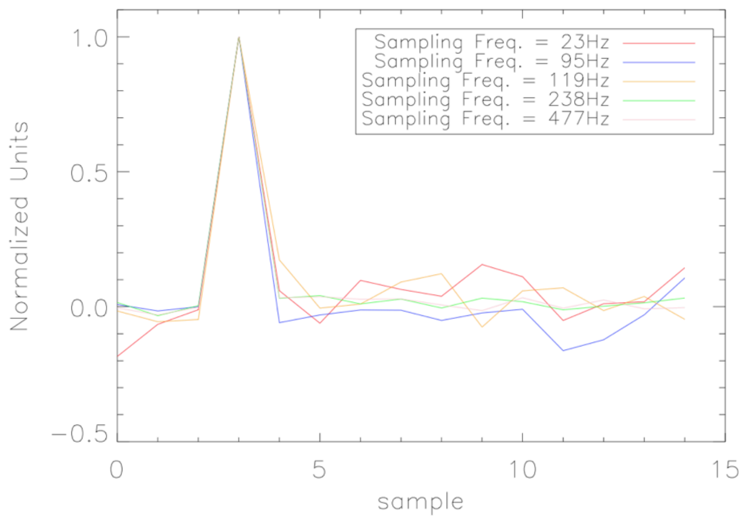
Time Response - Control of Systematics

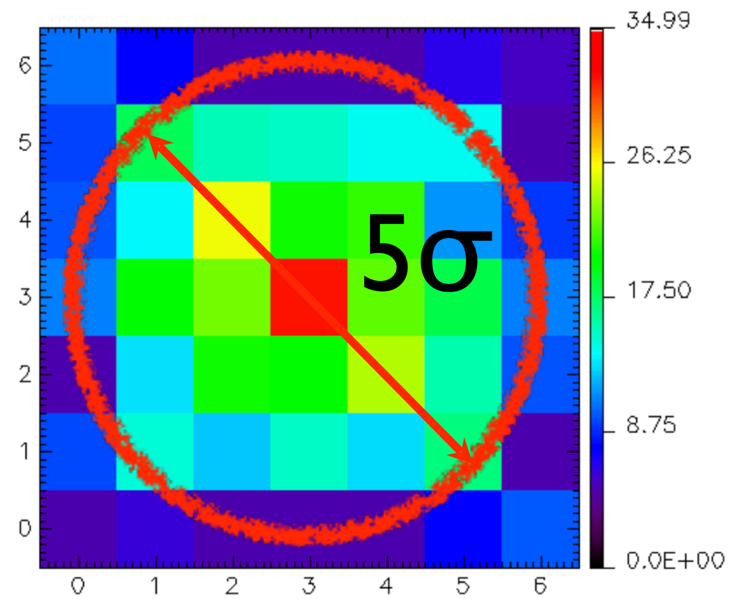
Noise measurements using homodyne acquisition with picoscope in a range of frequencies between few Hz up to fraction of MHz



A Fast Time Response gives for example…

- ***An attenuation of the impact of the CRs***

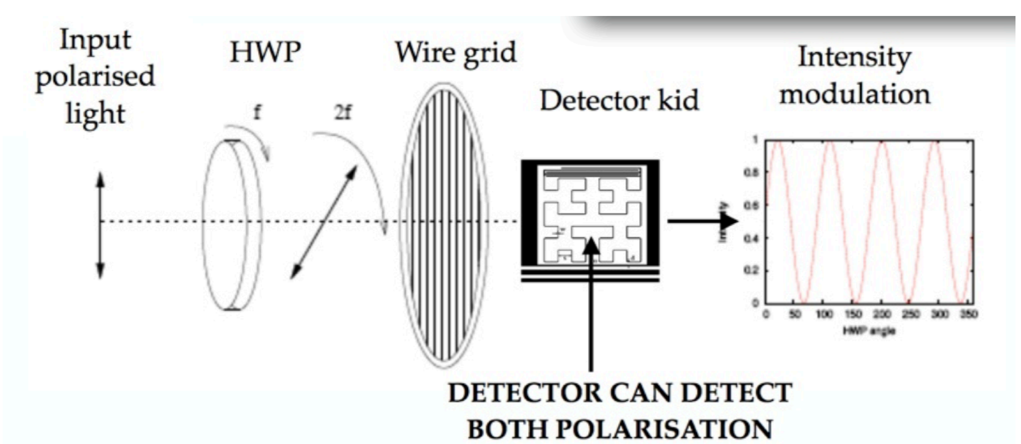


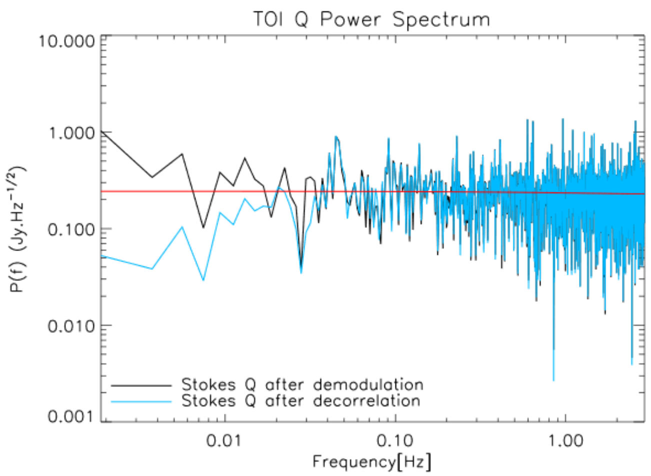


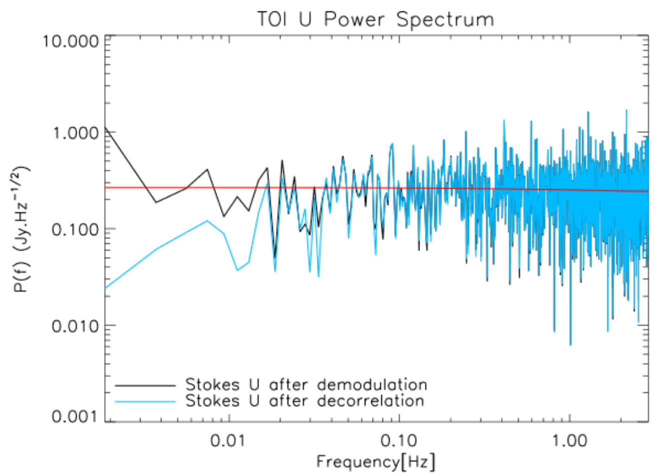
the surface of the silicon wafer impacted by a typical 200 MeV CR never exceeds a square of about 6x6 detectors (about 1.4 cm^2).

- ***Use of a fast rotating optical element in front of the detector***

NIKA2 polarisation strategy



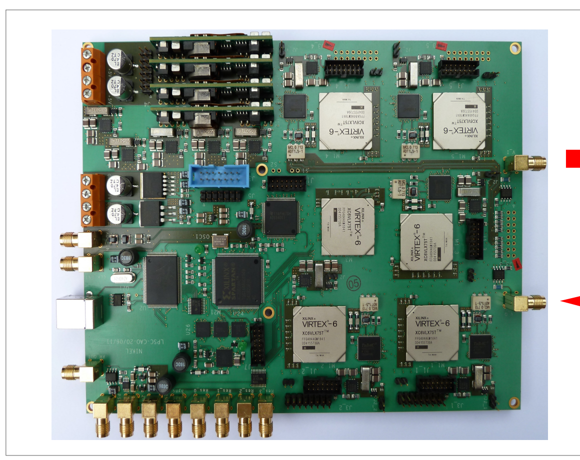


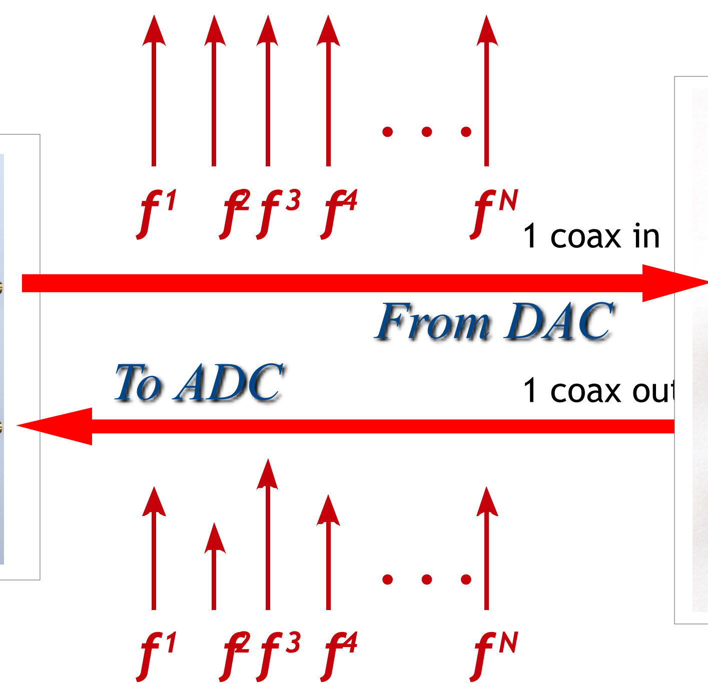


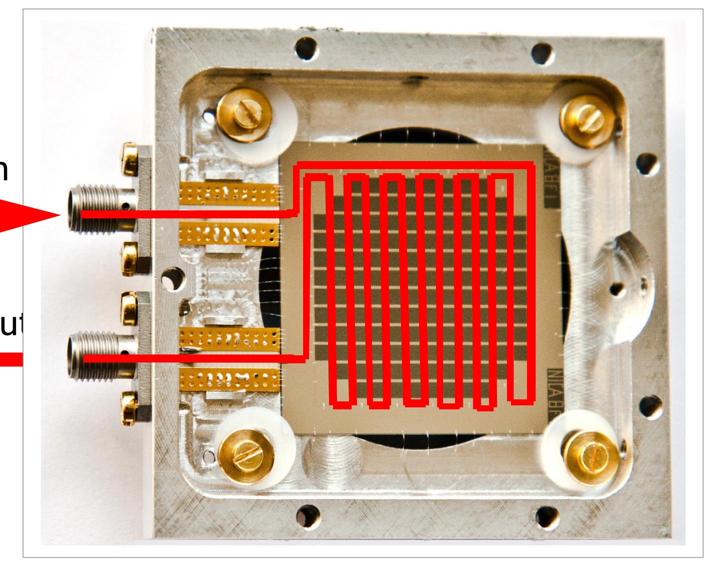
Flat noise spectrum thanks to the fast rotating half-plate (polarisation modulated at 12 Hz)

Maturity in terms of Readouts Electronics

Natural f-domaine multiplexing → **High MUX factor (hundreds to thousands)**





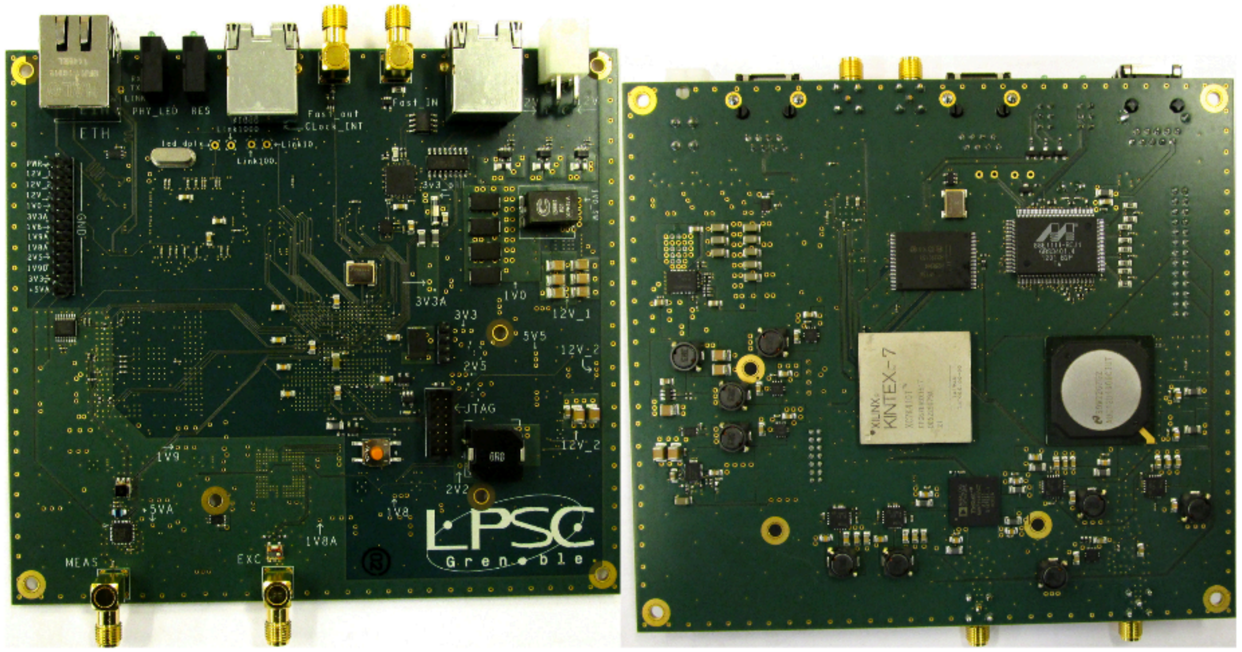


400 channels/board
.. simultaneous 1KHz
..no dead readout time

Single IN/OUT line for
hundreds pixels

Journal of Instrumentation 7, Issue 07, 7014 (2012)
Journal of Instrumentation 8, Issue 12, C12006 (2013)
Journal of Instrumentation, submitted, arXiv:1602.01288

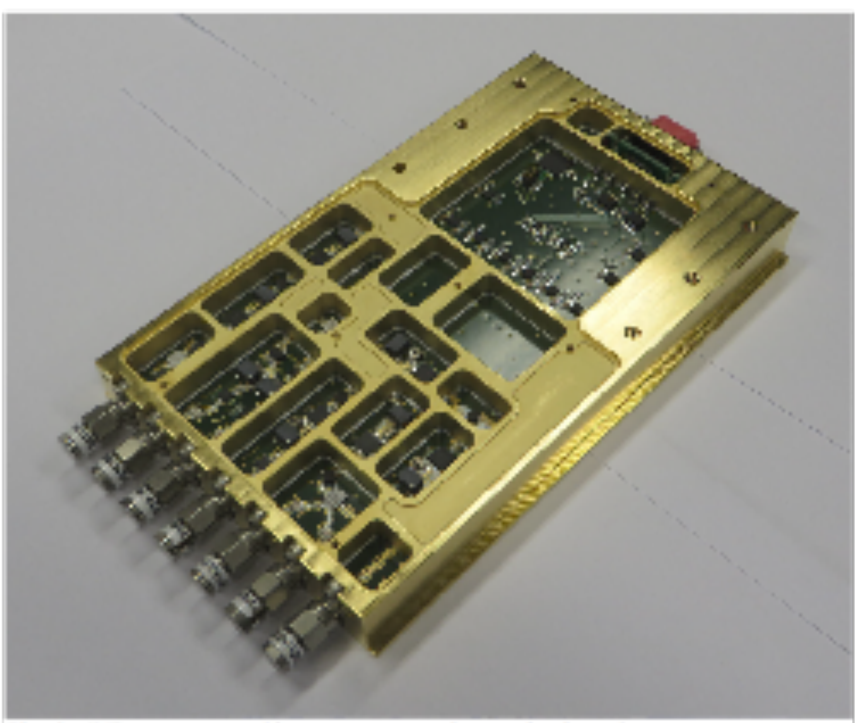
Maturity in terms of Readouts Electronics



Board dimension 135 mm × 150 mm

Grenoble electronics

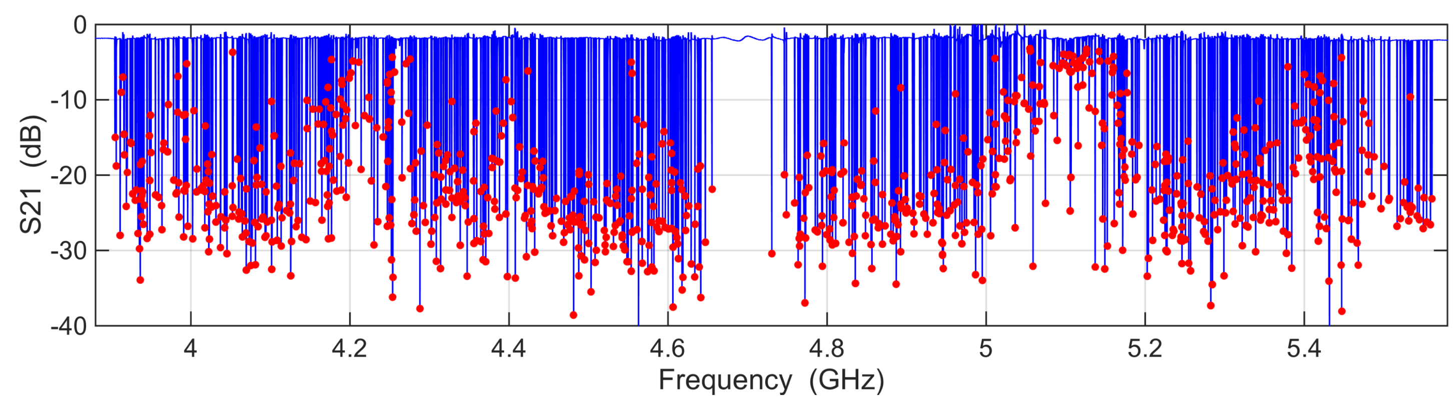
	NIKA2	BSIDE
Max KID/board	300	300
Excitation range	1.3-2.8 GHz	0-1.0 GHz
Max analog bandwidth	500 MHz	1000 MHz
Effective bandwidth	500 MHz (hard)	450 MHz (firm)
Average resonnance separation	2-3 MHz	1-2 MHz
Effective KID/board	160-250	up to 300
Optical frequencies	120-300 GHz	450-650 GHz
Readout max power	54 W	29 W



SPACEKIDS electronics (SRON)

2 GHz band

1000 channels



KID-based Instruments for Astrophysics (mostly in Europe)

CMB related Instr.
Not CMB related Instr.

Operating:

- **NIKA 2 : (**3.2 kpixels@150-260GHz bands) at 30m IRAM tel.

Commissioning Phase:

- **AMKID :** (25 kpixels@350-850 GHz) at APEX 12m telescope
- **OLIMPO :** (0.1 kpixels@150-200-350-480GHz bands) at 2.5m aperture
- **DESHIMA :** (9 pixels X 920 colors between 350-850 GHz) at ASTE 10m telescope

In preparation:

- **GroundBIRD :** (0.5 kpixels@150-220 GHz) at Tenerife with $6 < l > 300$
- **MUSCAT :** (2 kpixels@240 GHz) at LMT 50m telescope
- **KISS :** (0.6 kpixels X 200 colours from 80 to 250 GHz) at Qujiote 2.5m telescope
- **CONCERTO :** (4 kpixels x 200 colors *interferometer* from 120 to 350 GHz) at APEX-12m

…..Others?

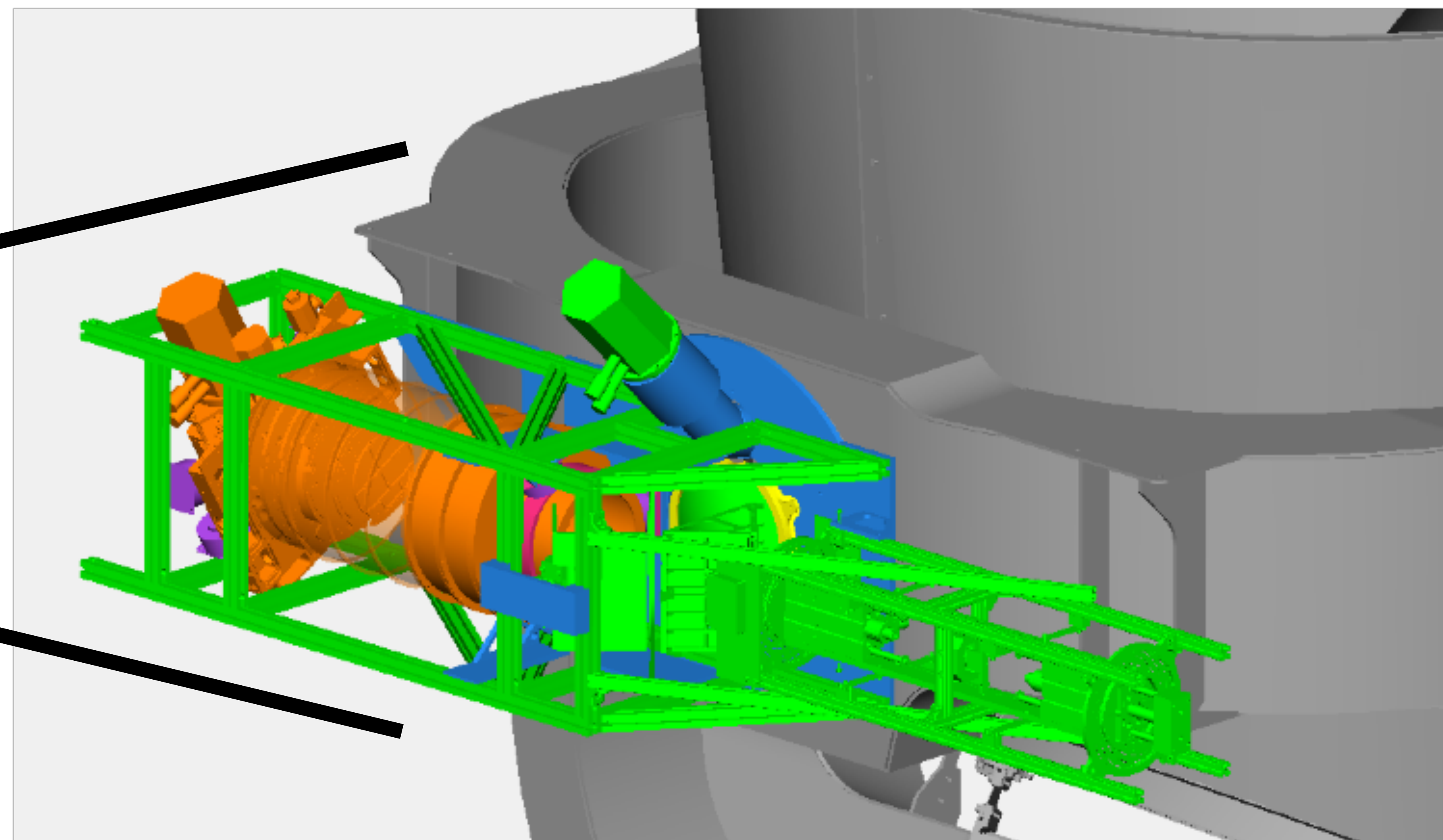
Step Forward from NIKA2 : Low Resolution Spectroscopy for S-Z

KISS:

1) Large FOV and band 80-270
2) Low Spectral resolution
(~1.5-10GHz at least 20 bins)
3) Low angular Resolution
4) Maximum Sensitivity
(Photon noise detectors)

1) Telescope : 2.5m - Quijote
***(**from about 2 to 5 arcmin)*
2) FTS Technique - Fast MPI
(10 cm excursion, fast acquisition, avoid 1/f noise)
4) 2 Arrays of 300 pixels.

Installation November 2018



Final Instrument : CONCERTO@APEX

KISS is a pathfinder of the CONCERTO instrument which will observe at the focal plate of the Cassegrain cabin APEX 12-meter antenna.

KISS

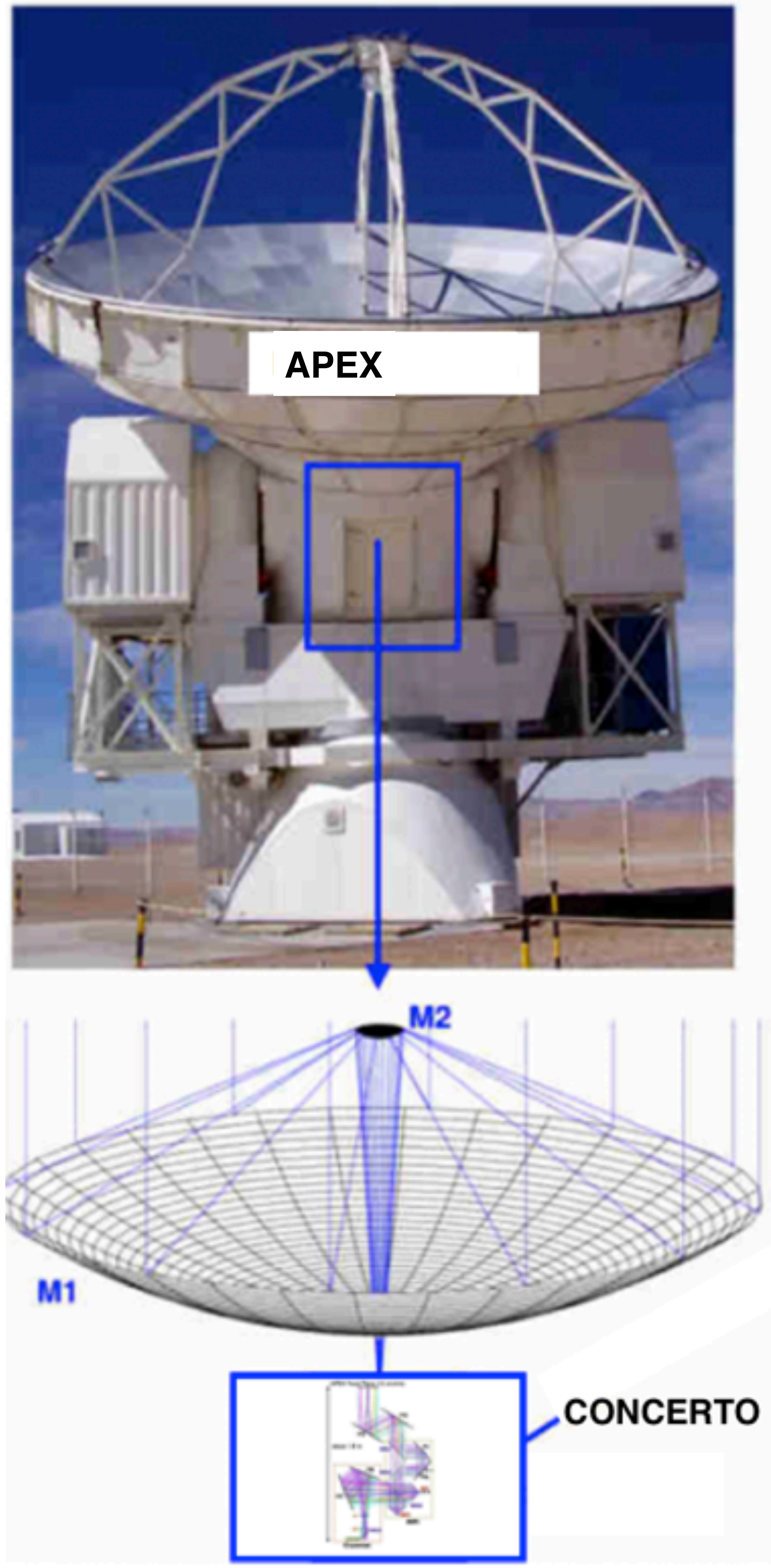
Averaged sky angular resolution	3.5 arcmin	Number of KIDS	600
Spectral range GHz	80 - 250 GHz	Frequency resolution δ_ν	1.5 GHz
Quijote telescope size	2.5m	Round FOV, Diameter	1 deg
End-to-end optical efficiency	0.3	^{3}He-^{4}He dilution cryostat	100 mK
# of expected observed clusters	10	Expected integration time	3000 hours

CONCERTO

Averaged sky angular resolution	27 arcsec	Number of KIDS	4000
Spectral range GHz	120-300 GHz	Frequency resolution δ_ν	1.5 GHz
LLAMA telescope size	12 m	Round FOV, Diameter	12 arcmin
End-to-end optical efficiency	0.3	^{3}He-^{4}He dilution cryostat	100 mK
[CII] survey field size	2 deg^2	[CII] survey integration time	1500 hours

Timeline

- **2018:** Pre-study and Design
- **October 2018:** Acceptance meeting from APEX
- **2019:** Fabrication, sub-system qualification and integration
- **2020:** Calibration of the final model in lab
- **January 2021:** Installation at the APEX telescope

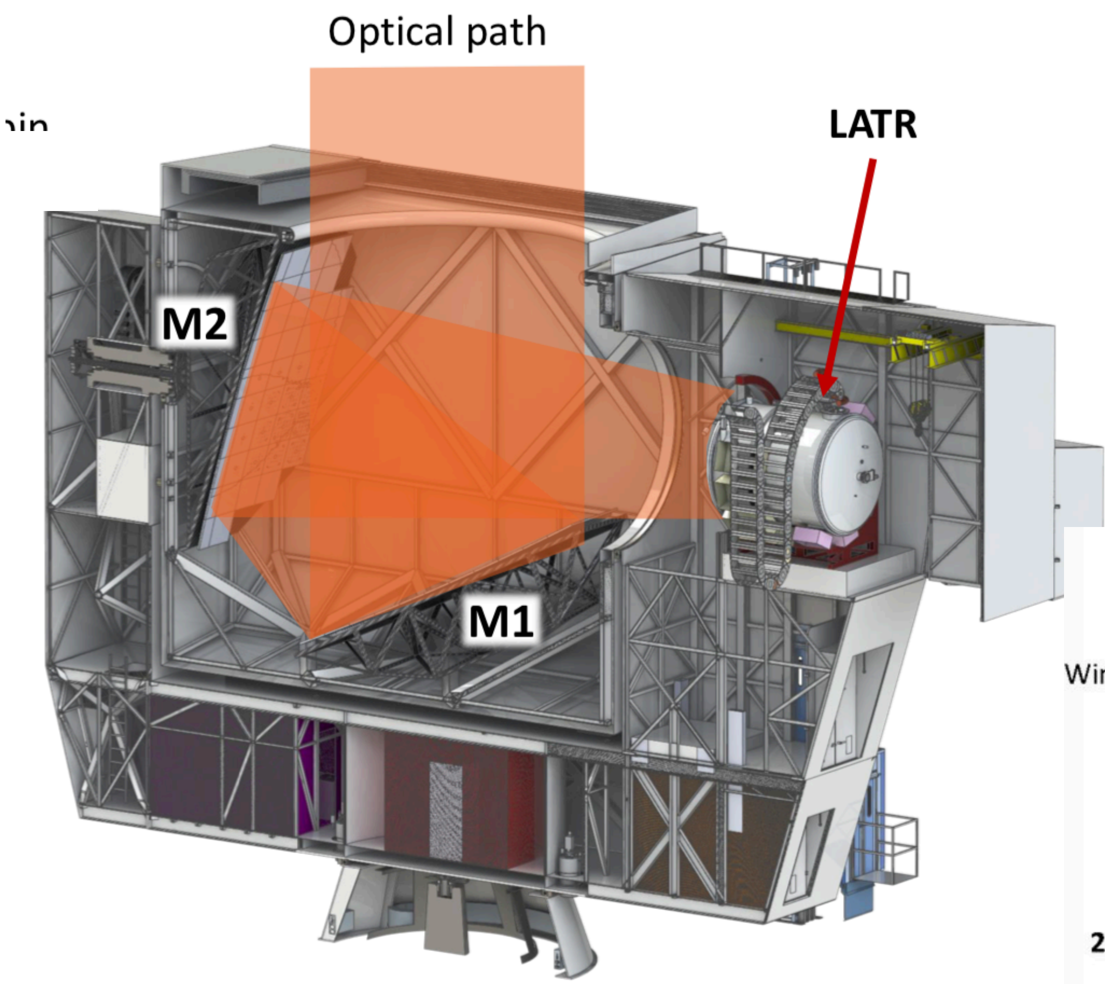


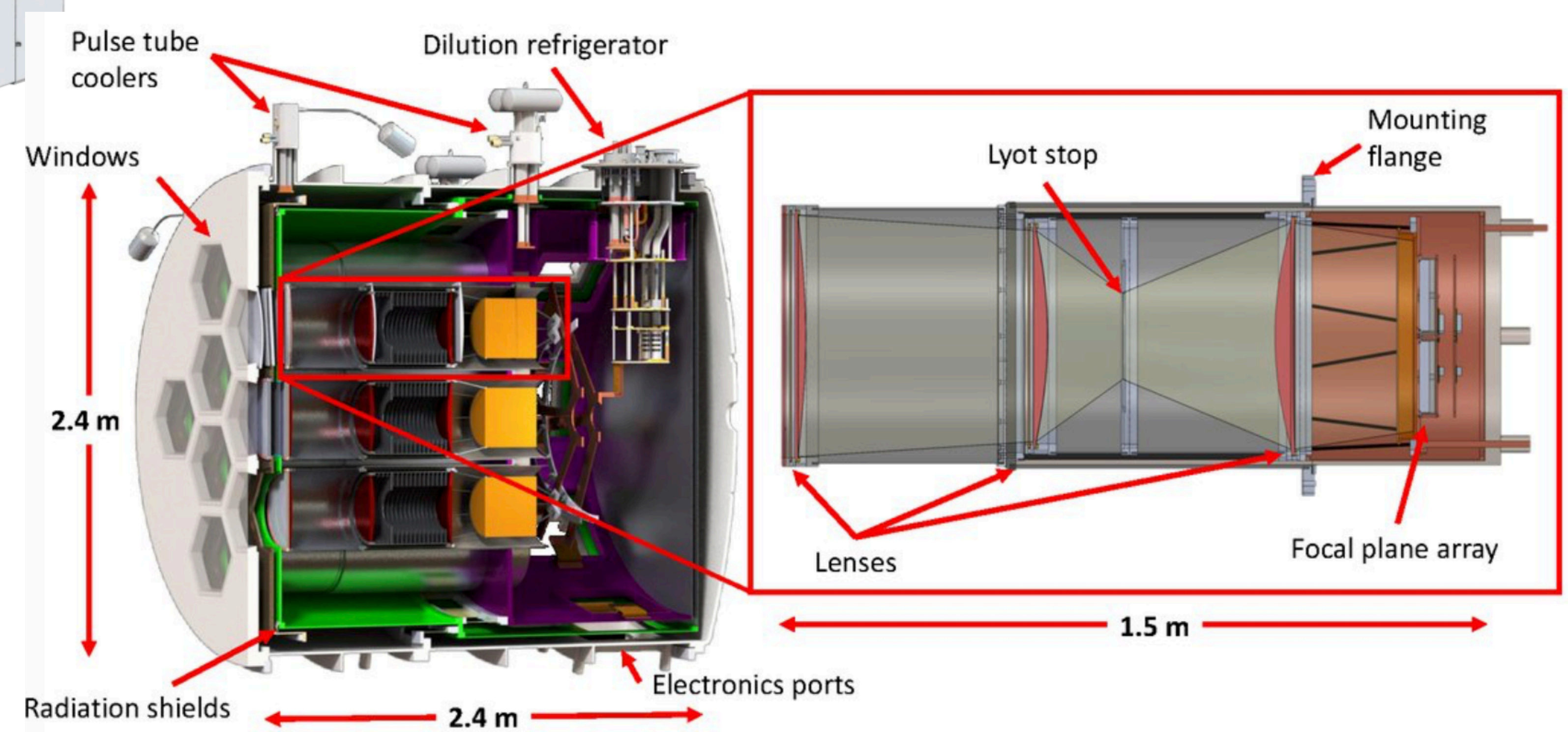
Other possible future implications - (SO?-LAT?)

Large Aperture Telescope to map the CMB 10 x faster (6 m diameter Cross Dragone design)

optical tubes
(36 cm each - FOV = 1.3°)

3mm ~ 1100 x 2 Pixels (Fλ ~ 1)
2mm ~ 2500 x 2 Pixels (Fλ ~ 1)
1mm ~ 10000 x 2 Pixels (Fλ ~ 1)
850µm ~ 13000 x 2 Pixels (Fλ ~ 1)





Conclusions

- KIDs seem to be a good and natural candidate for European next generation CMB observations.
- Several labs in Europe are working on KID development or are going to…
- There are already at least two operational cameras (fully European) observing CMB

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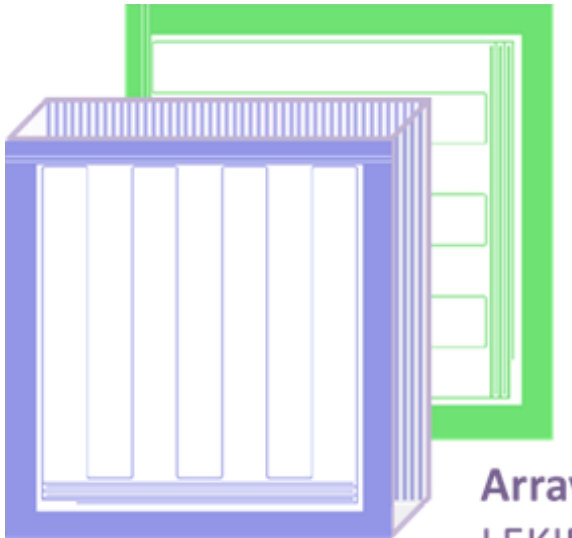
Polarisation with KIDs

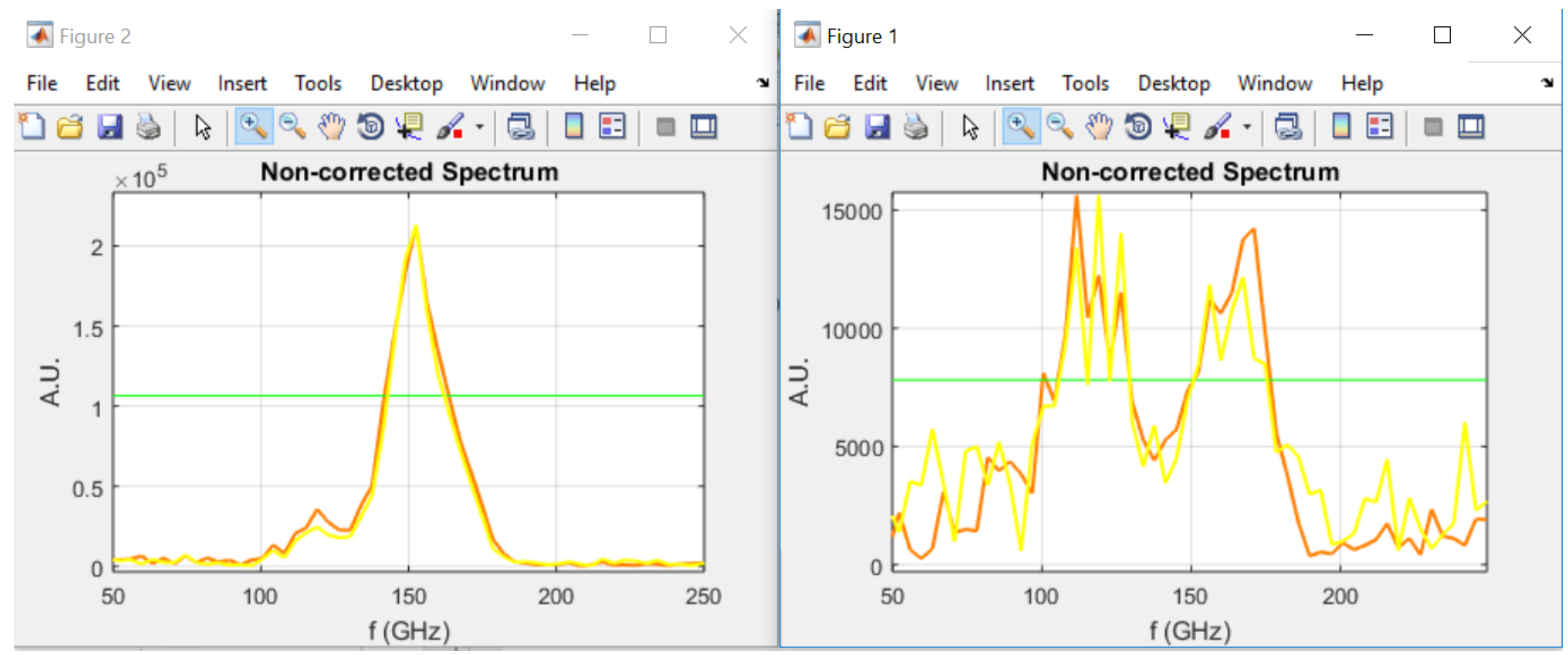
1) Stacked Arrays

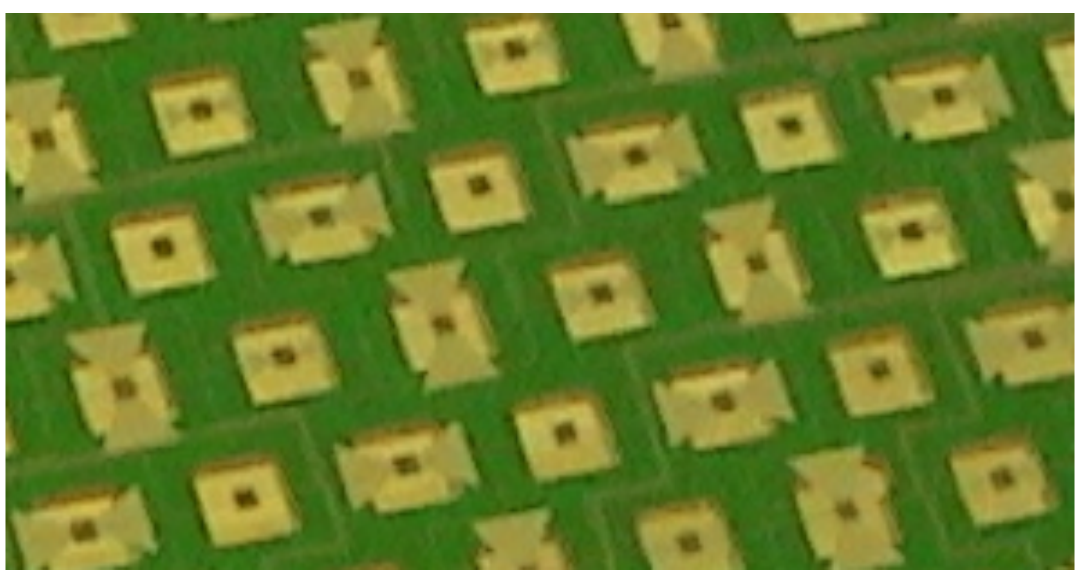


Array Top:
LEKID+Backshort

Array Bottom:
LEKID+Polariser

Cross-polarisation of the order of 2-5%
Best values 2% at 150 GHz





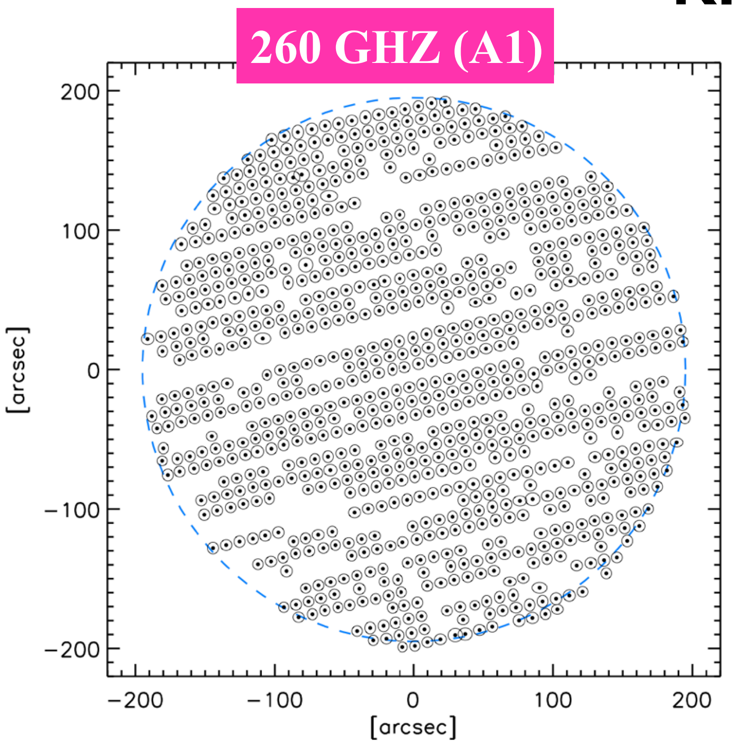
2) Antenna-Coupled KID

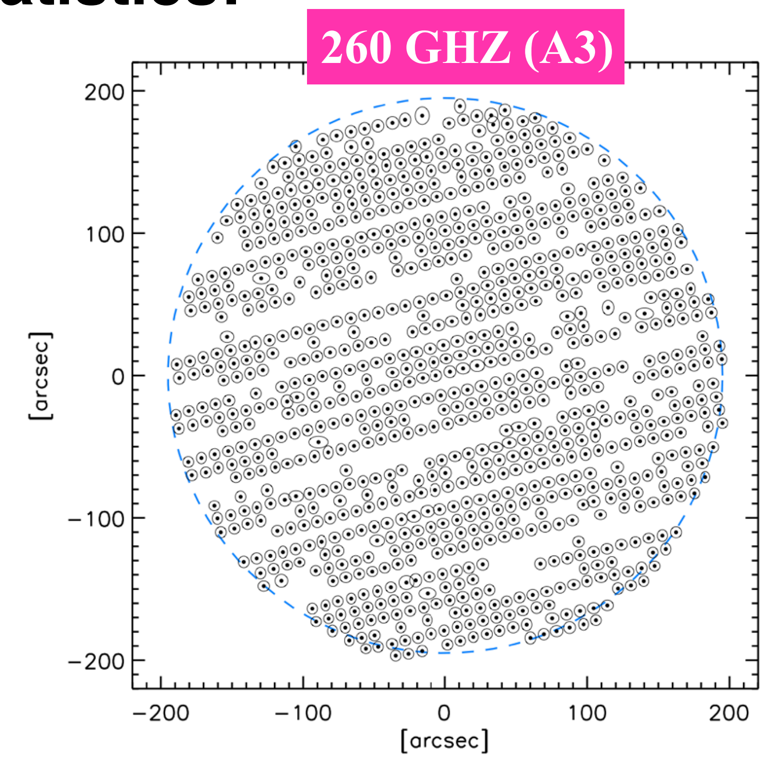
Encouraging even if not yet in the wanted range (<1% for a large band)

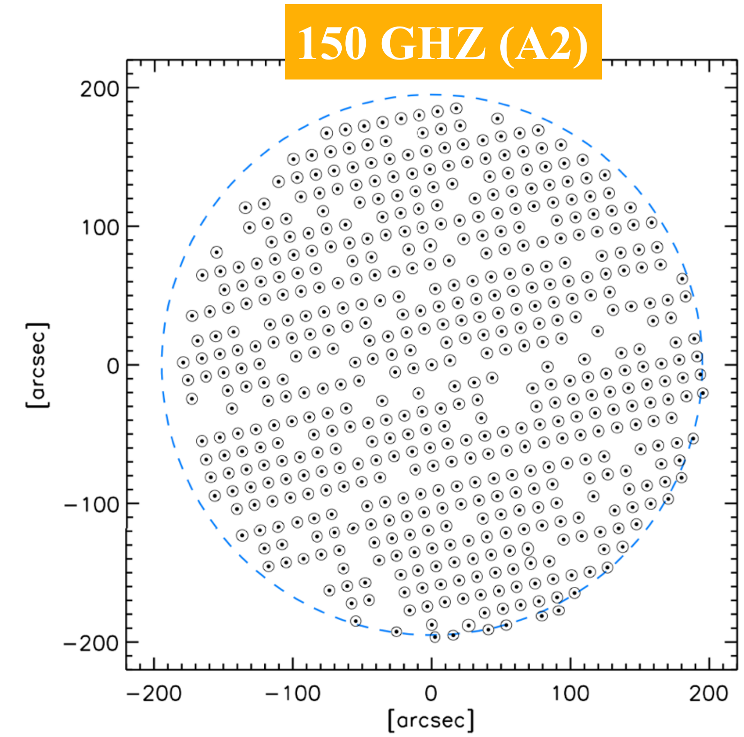
Commissioning Phase : Photometry

KID statistics:

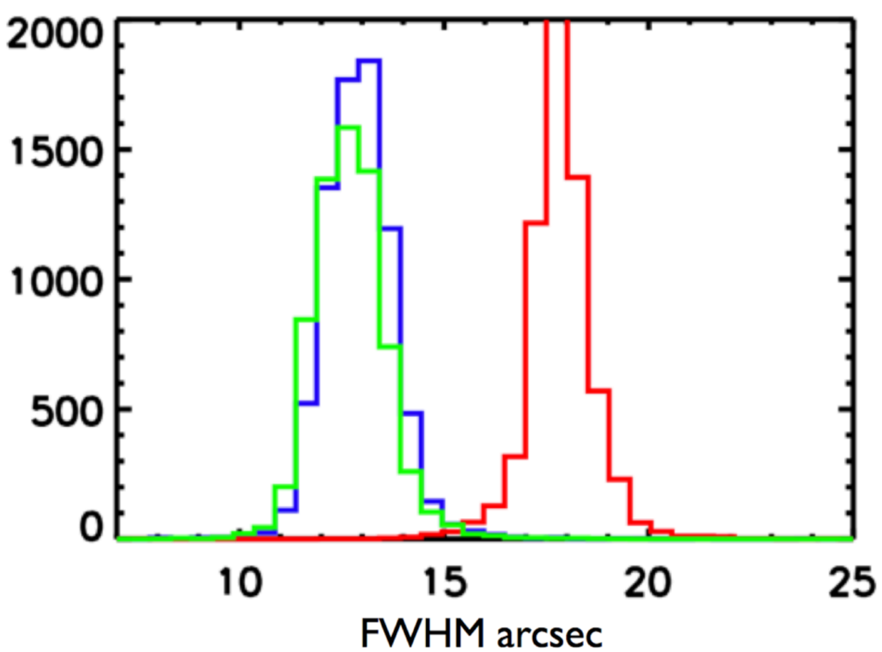
Between 83-85 % of valid KIDs





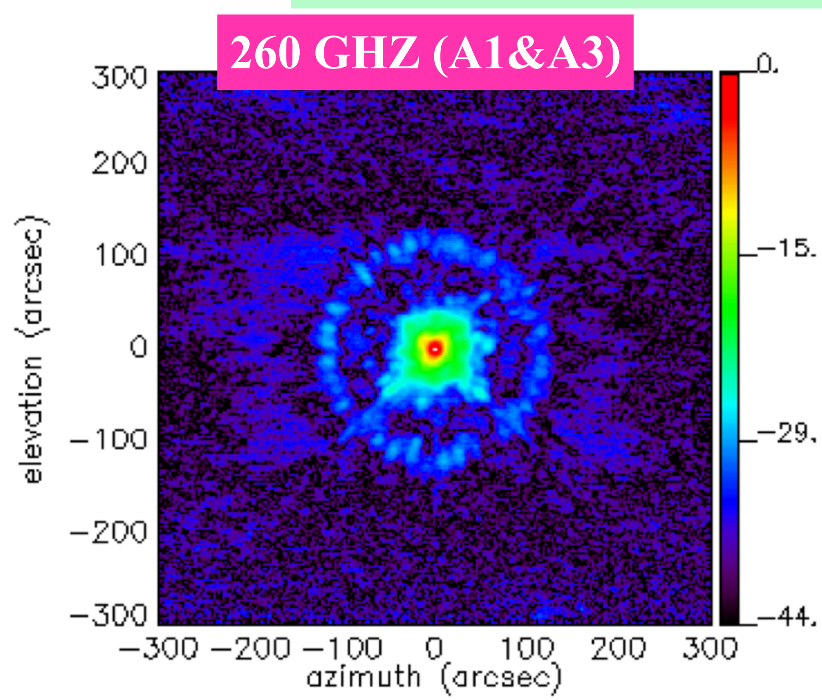


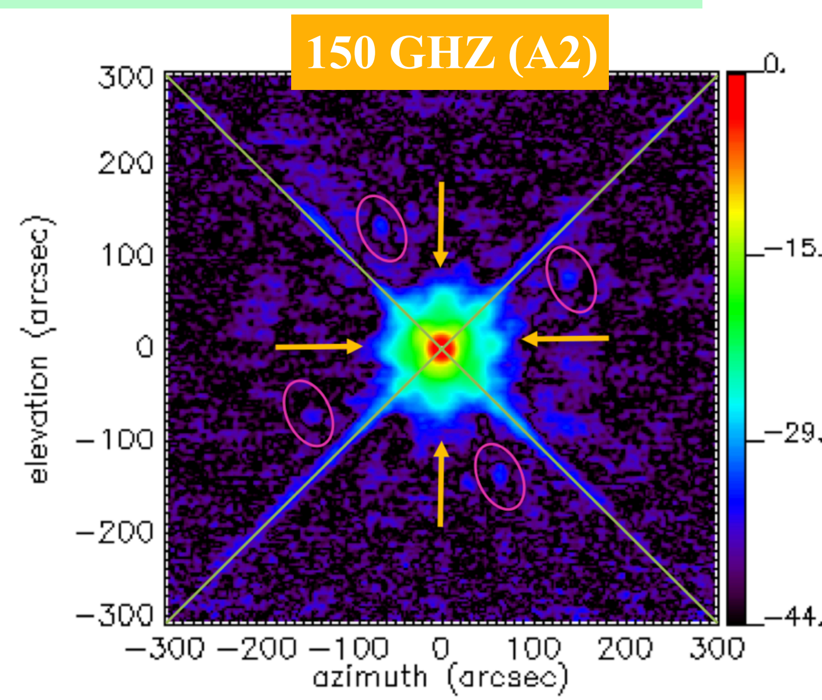
Main Beam FWHM distribution



FWHM (260 GHz) = 11.3”
FWHM (160 GHz) = 17.45”

Beam Efficiencies : ~ 55% @ 260 GHz (model 54.0 %)
~ 70% @ 150 GHz (model 74.1 %)





Commissioning Phase : Results

Weak Sources (10 mJy)

NEFD

260 GHz: 20 mJys$^{1/2}$

150 GHz: 6 mJys$^{1/2}$

Opacity = 0.2
Elevation = 60°

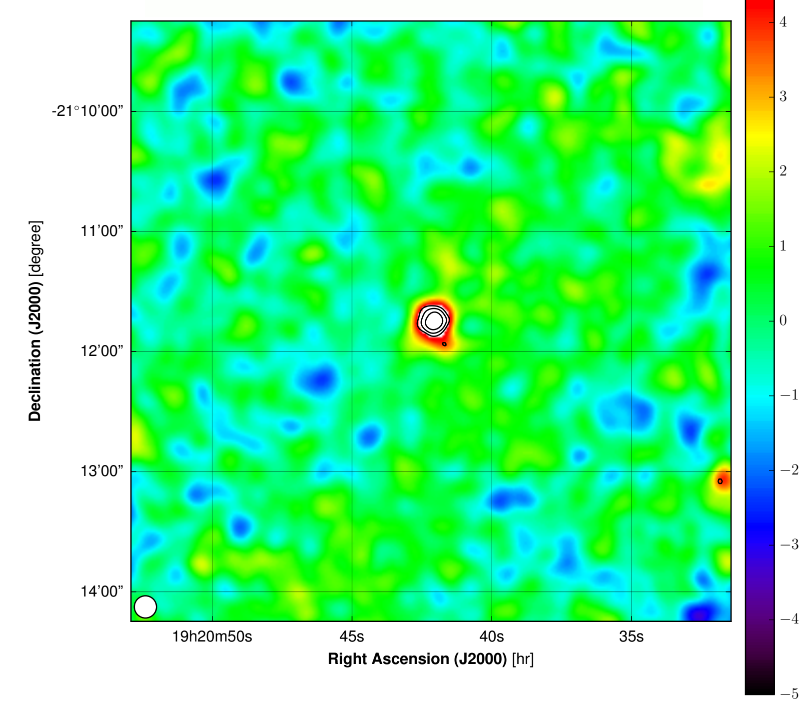
Caveats

Correlated noise observed in the maps

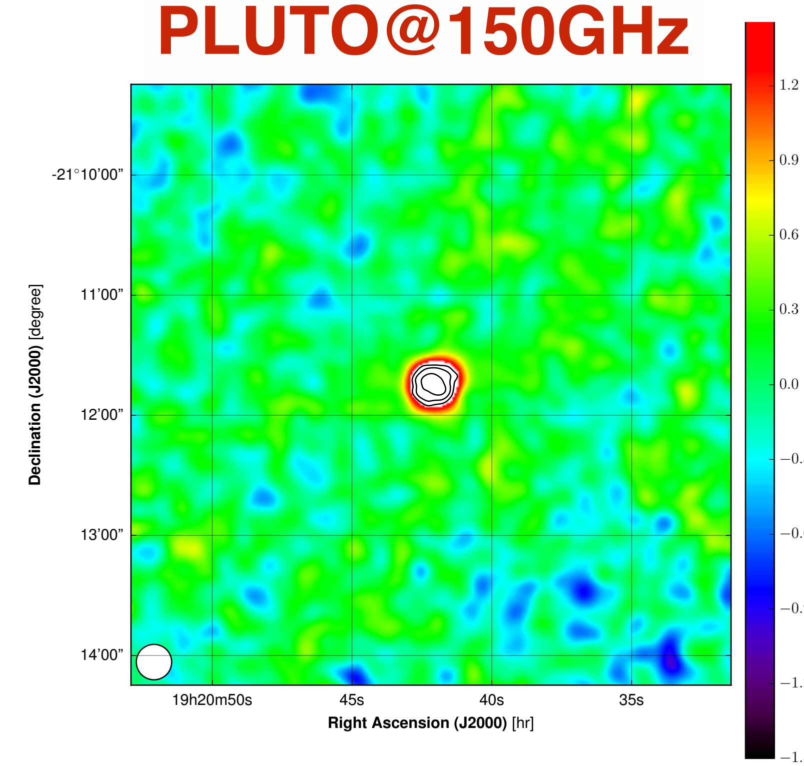
Positive

better than specifications, approacching goals.

PLUTO@260GHz

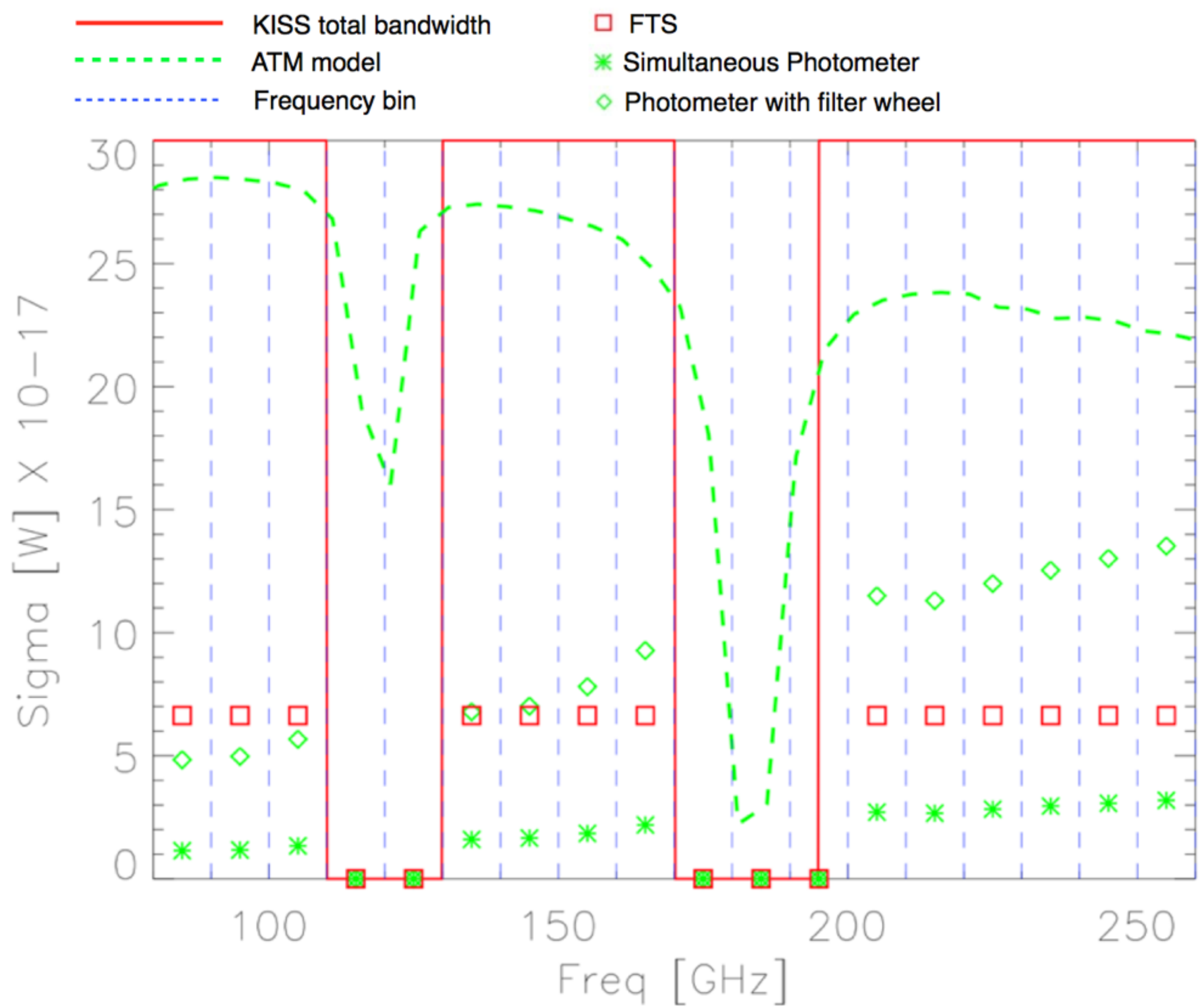


PLUTO@150GHz



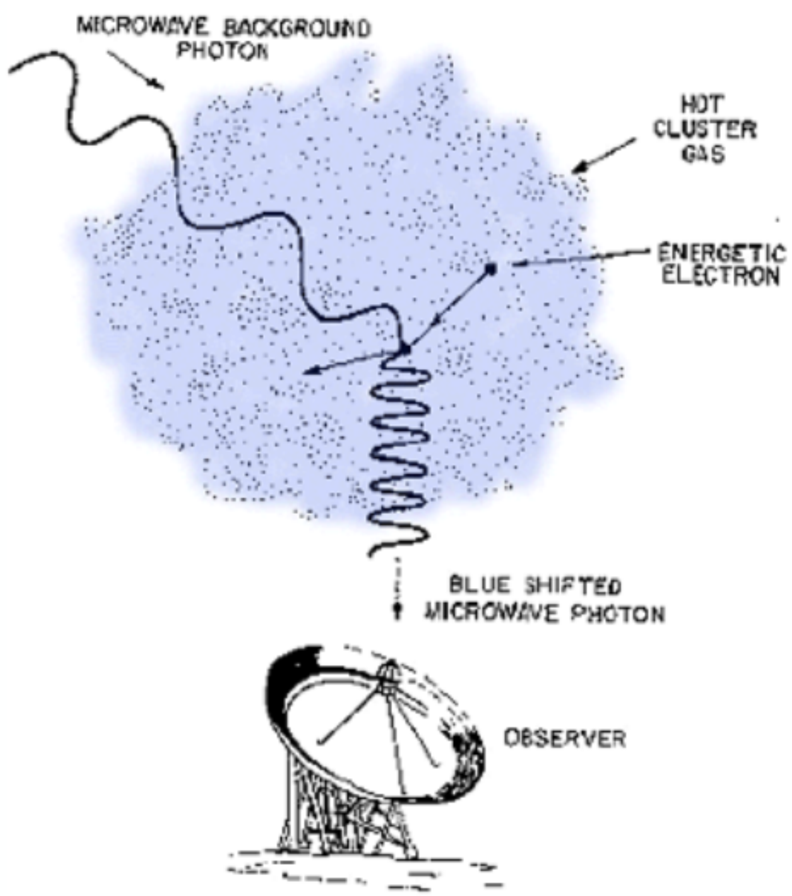
Channel	260 GHz 1.15 mm			150 GHz 2 mm
Arrays	A1	A3	A1&3	A2
Number of designed detectors	1140	1140		616
Number of valid detectors[1]	952	961		553
FOV diameter [arcmin]	6.5	6.5	6.5	6.5
FWHM [arcsec]	11.3 ± 0.2	11.2 ± 0.2	11.2 ± 0.1	17.7 ± 0.1
Beam efficiency[2] [%]	55 ± 5	53 ± 5	60 ± 6	75 ± 5
rms calibration error [%]	4.5	6.6		5
Model absolute calibration uncertainty [%]	5			
rms pointing error [arcsec]	< 3			
NEFD [mJy.s$^{1/2}$] [3]			20	6
Mapping speed [arcmin^2/h/mJy^2] [4]			222	1885

Principle of measurements (1) - MultiBands or FTS?

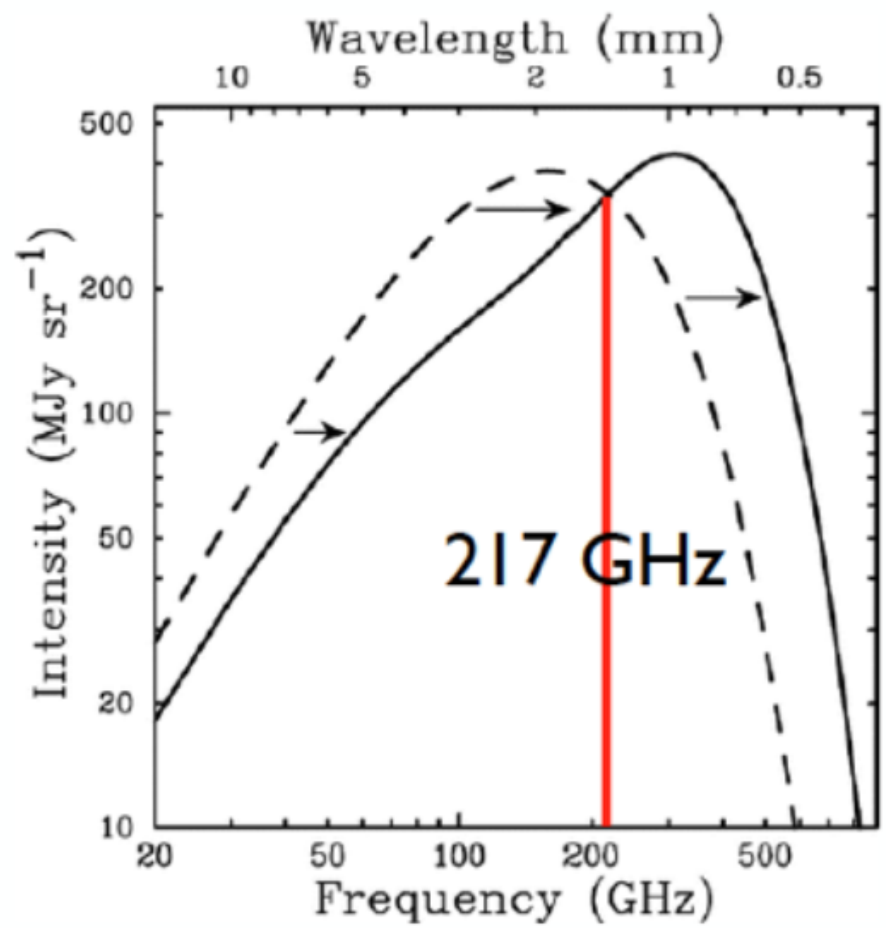


Science KISS - SZ effect

Spectral distortion of the CMB by the inverse Compton scattering of CMB photon with hot electrons in clusters of galaxies



[L.Van Speybroeck]

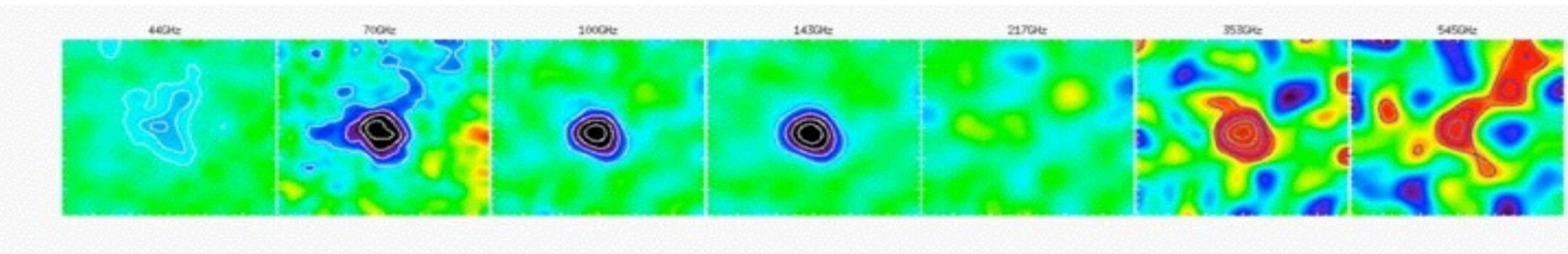


[J. E. Carlstrom et al. (2002)]

$$\frac{\Delta T_{TSZ}}{T_{CMB}} = f(x)y = f(x)\int n_e \frac{K_B T_e}{m_e c^2}\sigma_T dl \qquad f(x) = \left(x\frac{e^x+1}{e_x-1} - 4\right)$$

Science KISS - tSZ Measured by Planck

- The particular spectral signature of the tSZ makes it detectable
- The Planck satellite has been specially designed to map the tSZ signal



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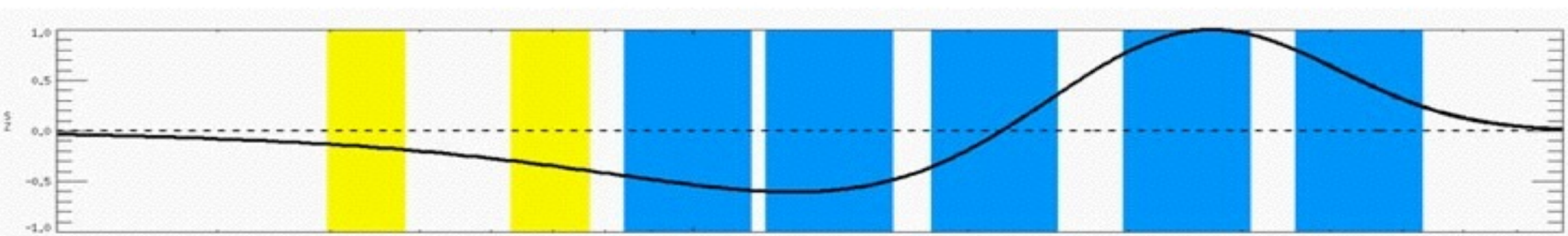
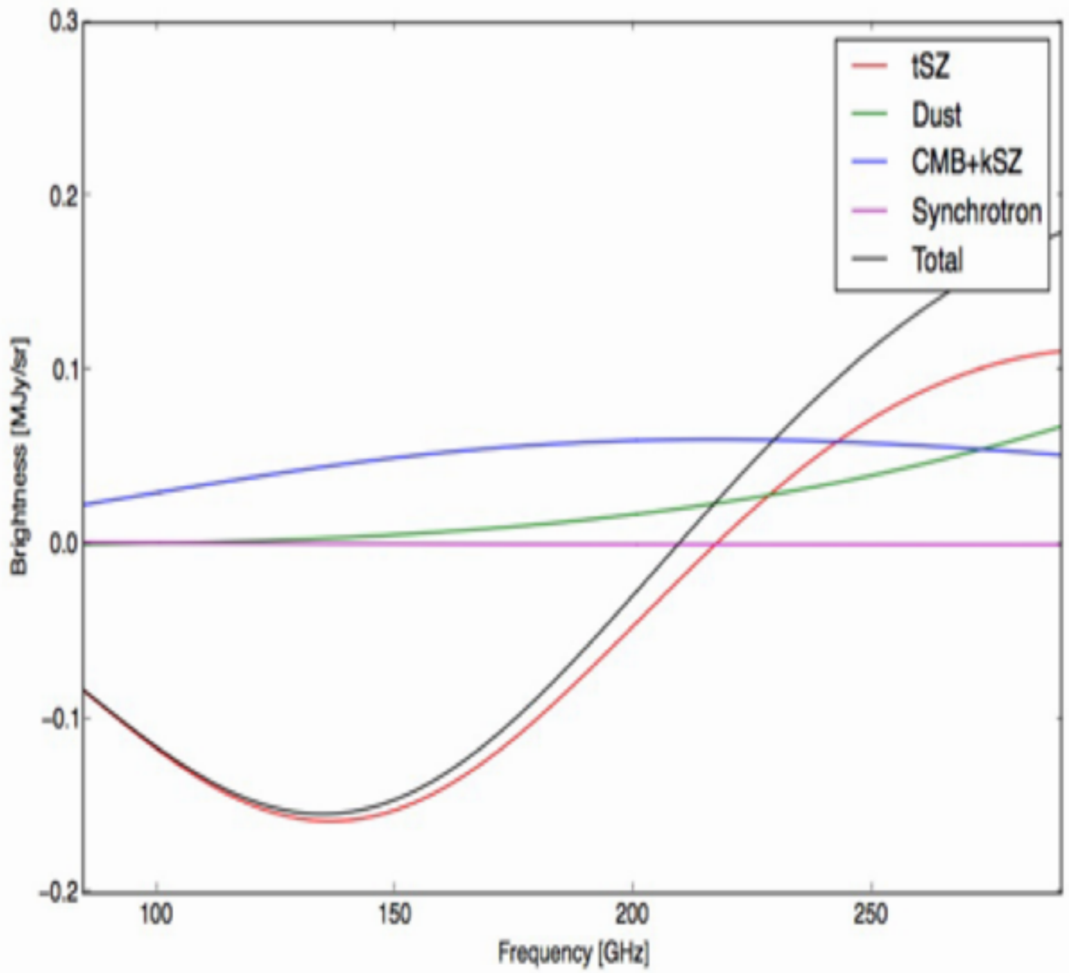


Science KISS - Many sources of foreground

Several components must be considered when we integrate a mm/sub-mm signal along the line of sight of a cluster:

- **Cluster parameters :** y, v, T_e, τ_t, τ_{nt}, p_1
- **LOS signal parameters :** T_d, τ_d, I_s, I_{ff}, ΔI_{CMB}



Contribution of various physical components:

- thermal SZ (electron pressure) + relativistic corrections (cluster temperature)
- kinetic SZ (cluster LOS velocity)
- CMB
- thermal dust (emissivity and temperature)
- synchrotron, free (spectral index, spatial variations)

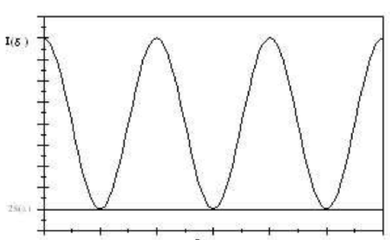
Use spectroscopy to fully separate different components and extract physical information from spectral distortions: pressure, temperature, density, mass, LOS velocity

Martin-Puplett Interferometer

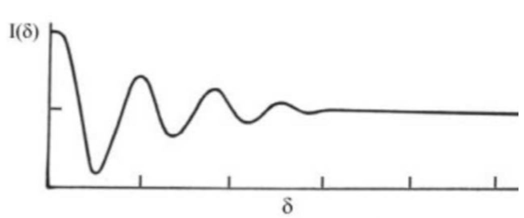
A Martin–Puplett interferometer measures the difference between the powers of two input beams (wikipedia).

Mueller Matrix of a MPI

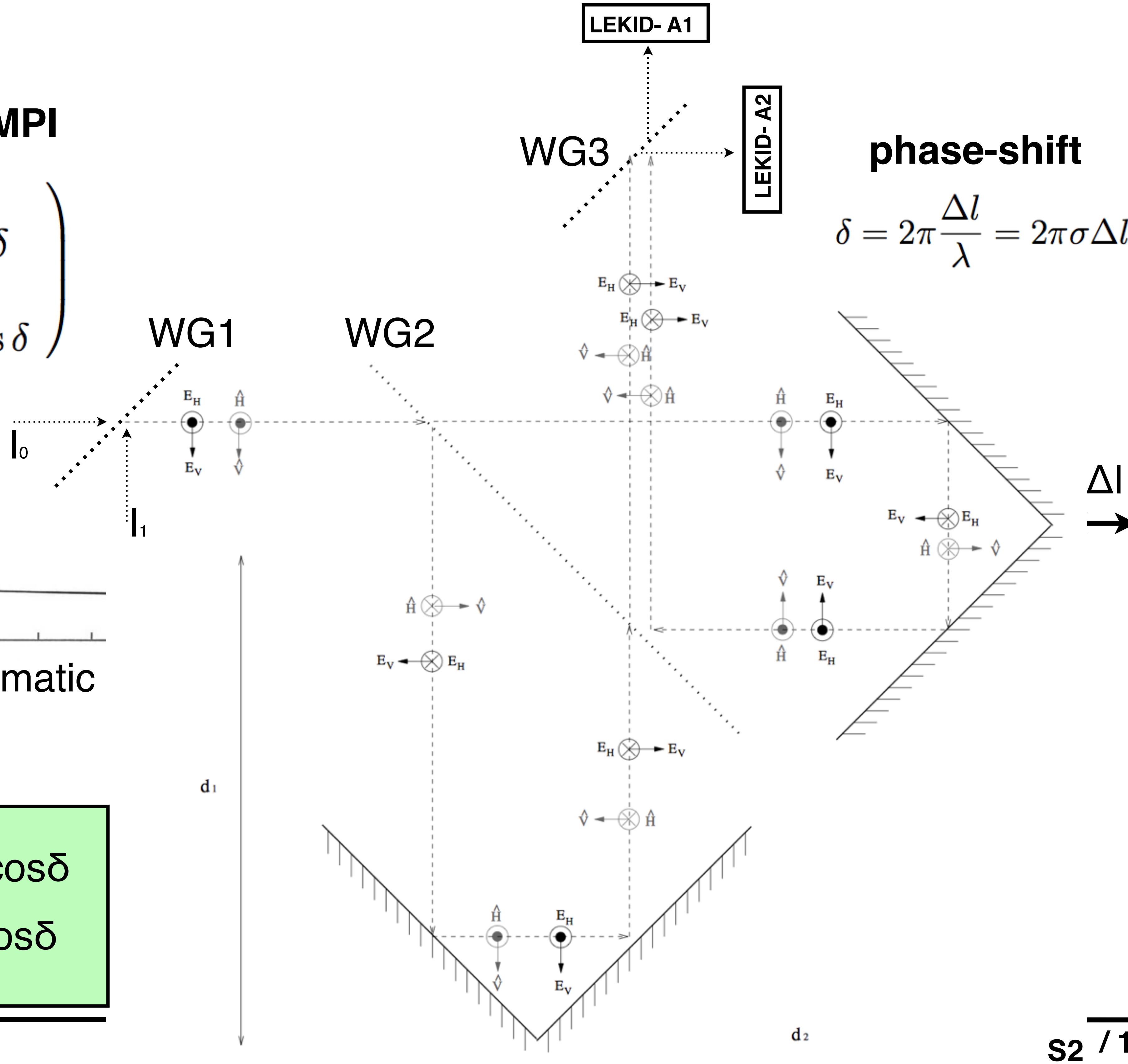
$$\mathbf{I}_{MP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\delta & 0 & \sin\delta \\ 0 & 0 & -1 & 0 \\ 0 & \sin\delta & 0 & -\cos\delta \end{pmatrix}$$



monochromatic



polychromatic



phase-shift

$$\delta = 2\pi\frac{\Delta l}{\lambda} = 2\pi\sigma\Delta l$$

$I_R = 1/2\,(I_0 + I_1) + 1/2\,(I_0 - I_1)\cos\delta$

$I_T = 1/2\,(I_0 + I_1) - 1/2\,(I_0 - I_1)\cos\delta$