European high-frequency detectors for CMB instruments

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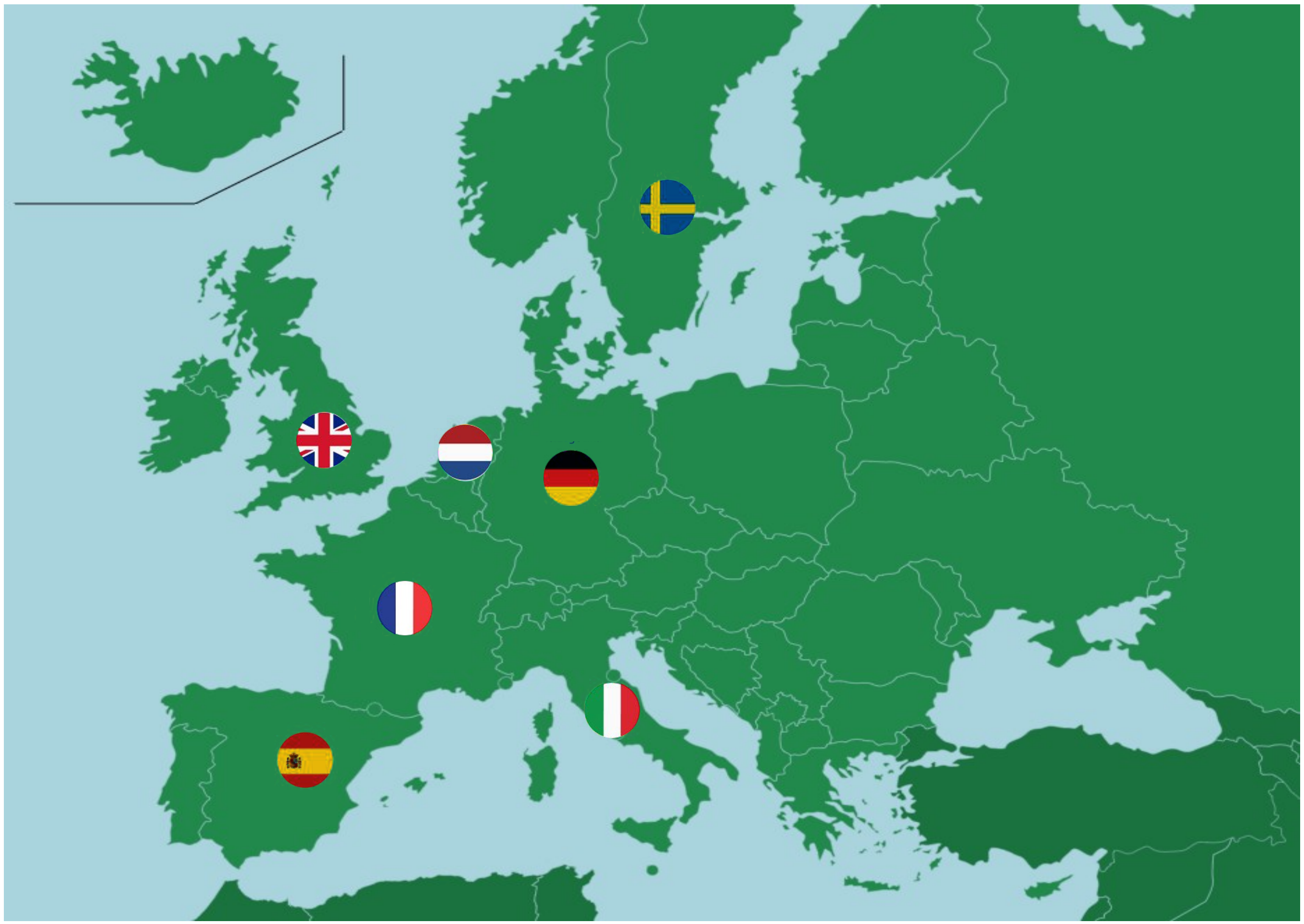
Outline

HF detectors in Europe



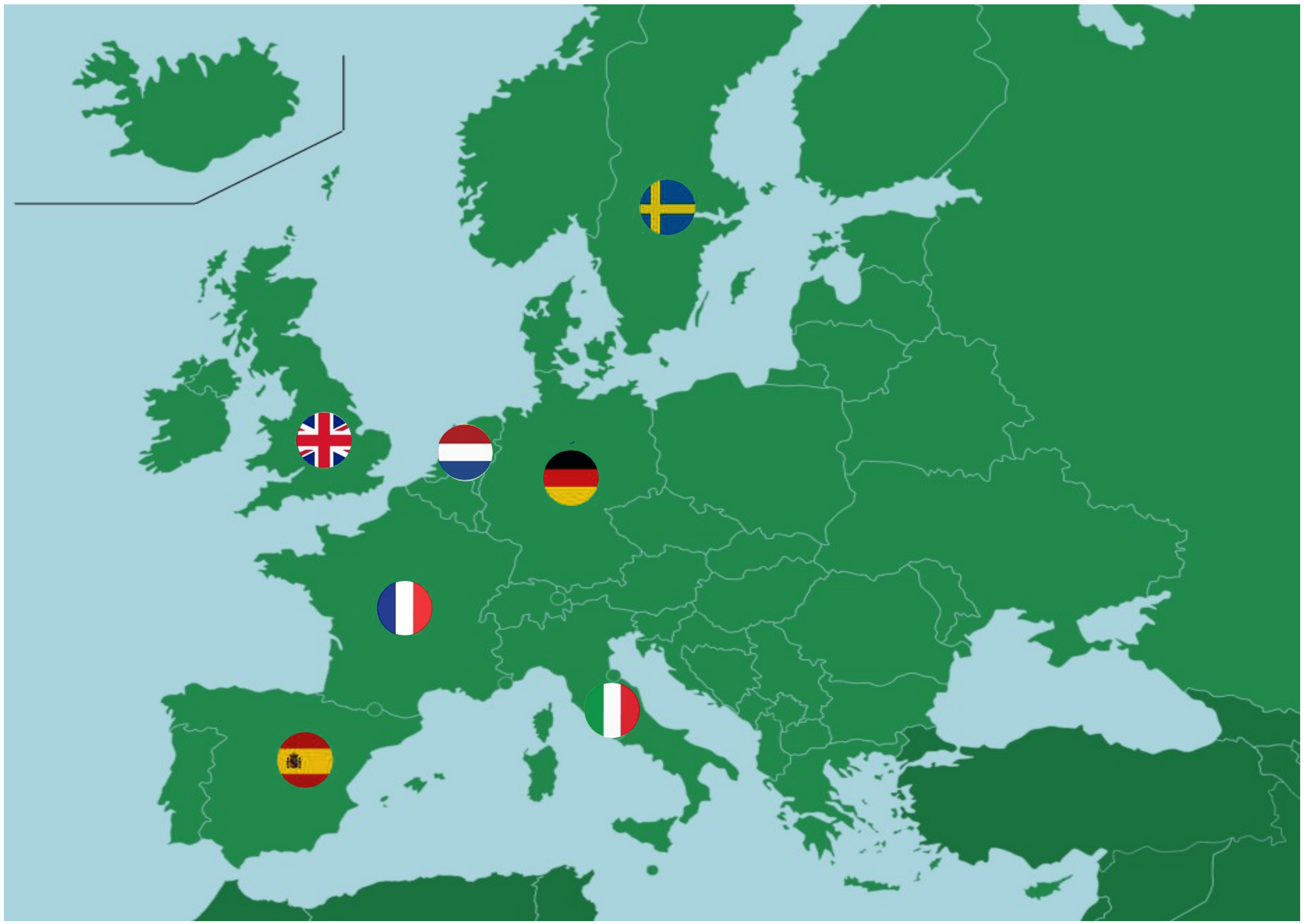
Many actors:

- *France*
- *Italy*
- *UK*
- *Netherlands*
- *Spain*
- *Sweden*
- *Germany*
- *...*

Different options:

- *KID*
- *Bolometers (TES)*
- *Other (eg CEB)*

HF detectors in Europe



Many actors:

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- *...*

Different options:

- *KID*
- *Bolometers (TES)*
- *Other (eg CEB)*

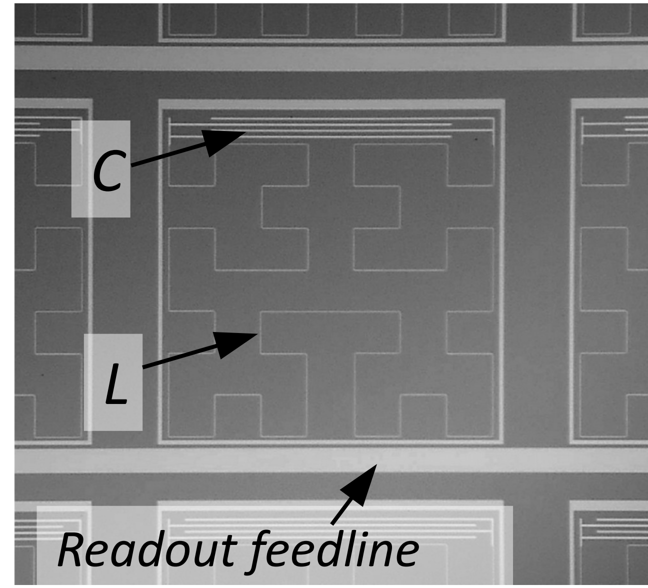
Kinetic Inductance Detectors

KID = superconducting resonator

Incoming light breaks CP

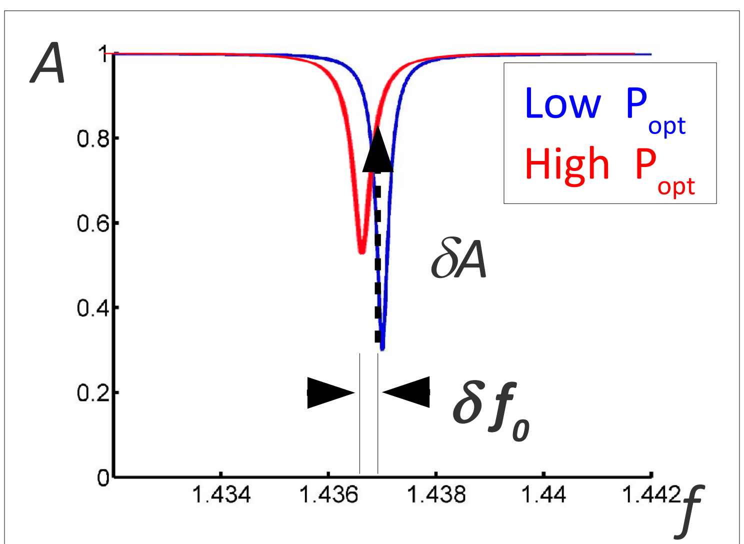
→ change in A, φ and f_0

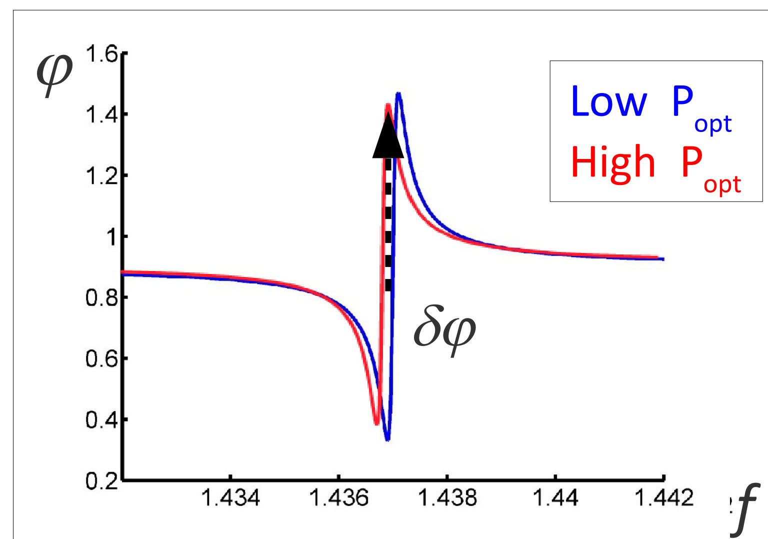
$$\delta f_0 \propto \delta L_k \propto \delta P_{abs}$$



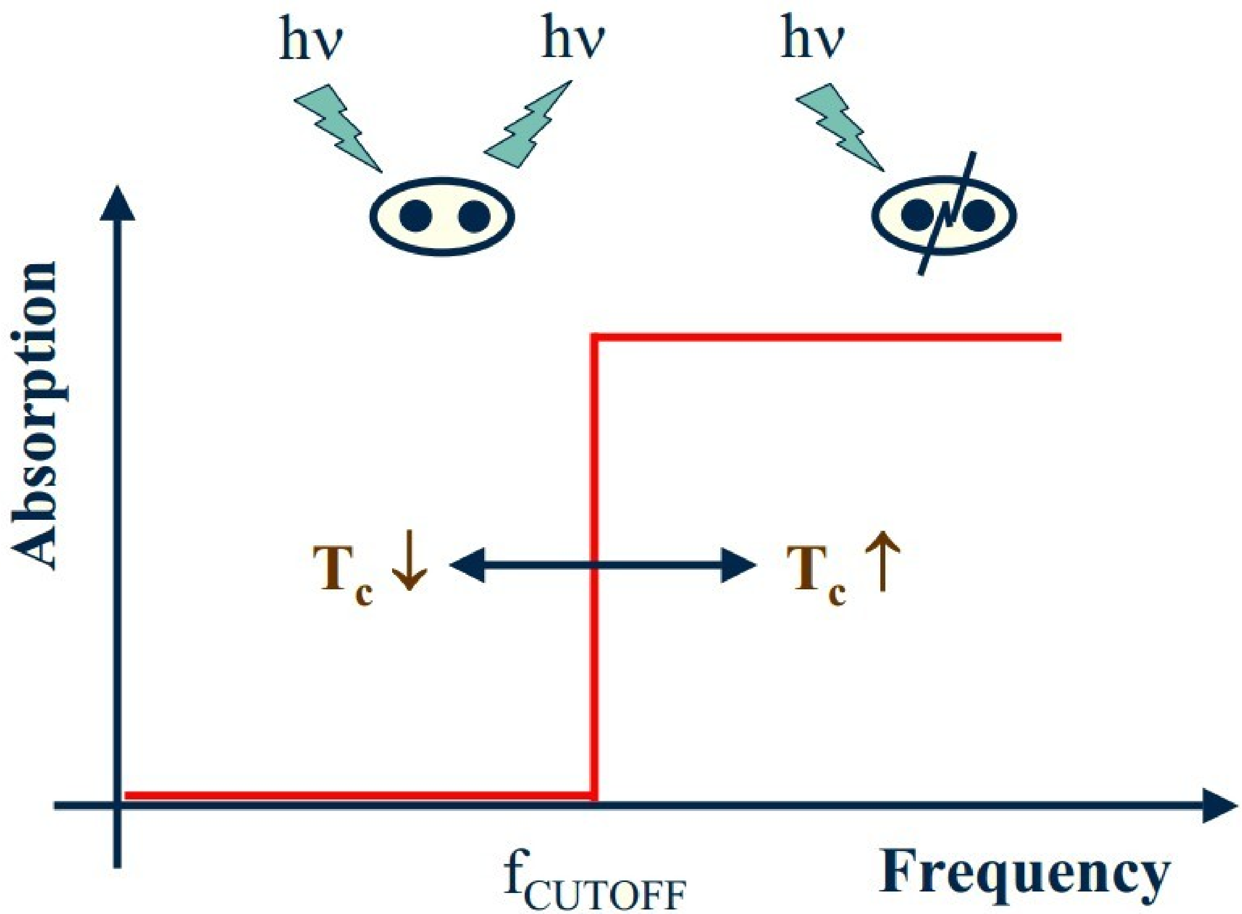
Hilbert LEKID design, 2-pol

M. Roesch et al., 2012, ArXiv 1212.4585





KIDs absorption spectrum



$f_C \approx 100$ GHz $\cdot(T_c/1.3K)$

$T_{base} < T_c/6 \rightarrow 0.2K$ @ 100GHz

Ti → $f_c \approx 40$ GHz

Al → $f_c \approx 100$ GHz

Nb → $f_c \approx 700$ GHz

NbN → $f_c \approx 1.2$ THz

…

TiN_x → adjustable

Nb_xSi → adjustable

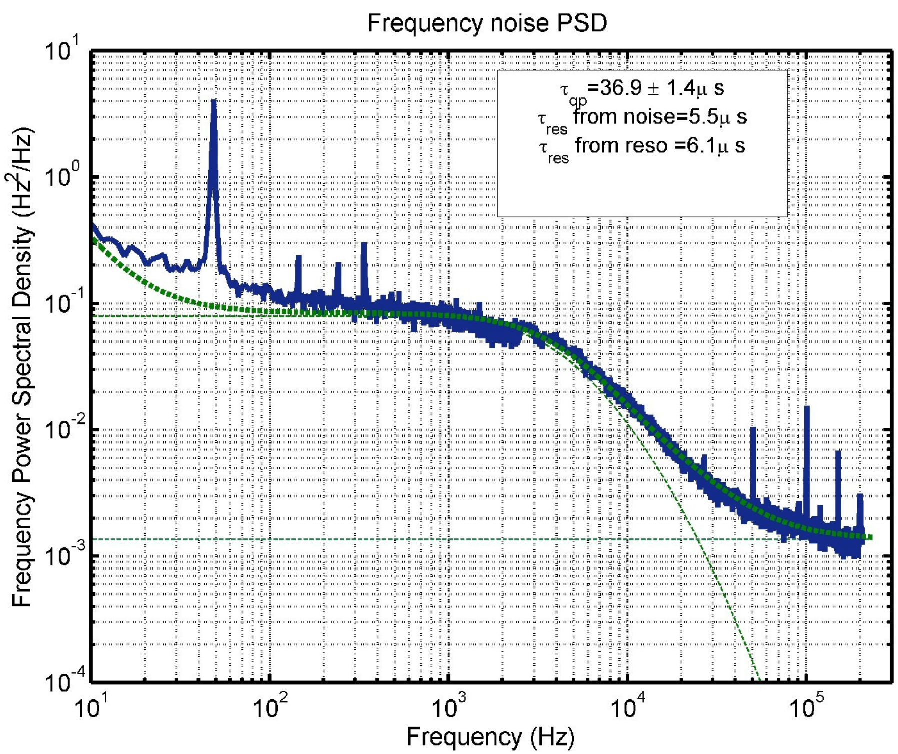
TiV_x → adjustable

Multilayers → adjustable

Note: applies to ***phonons*** as well!

KIDs time constant

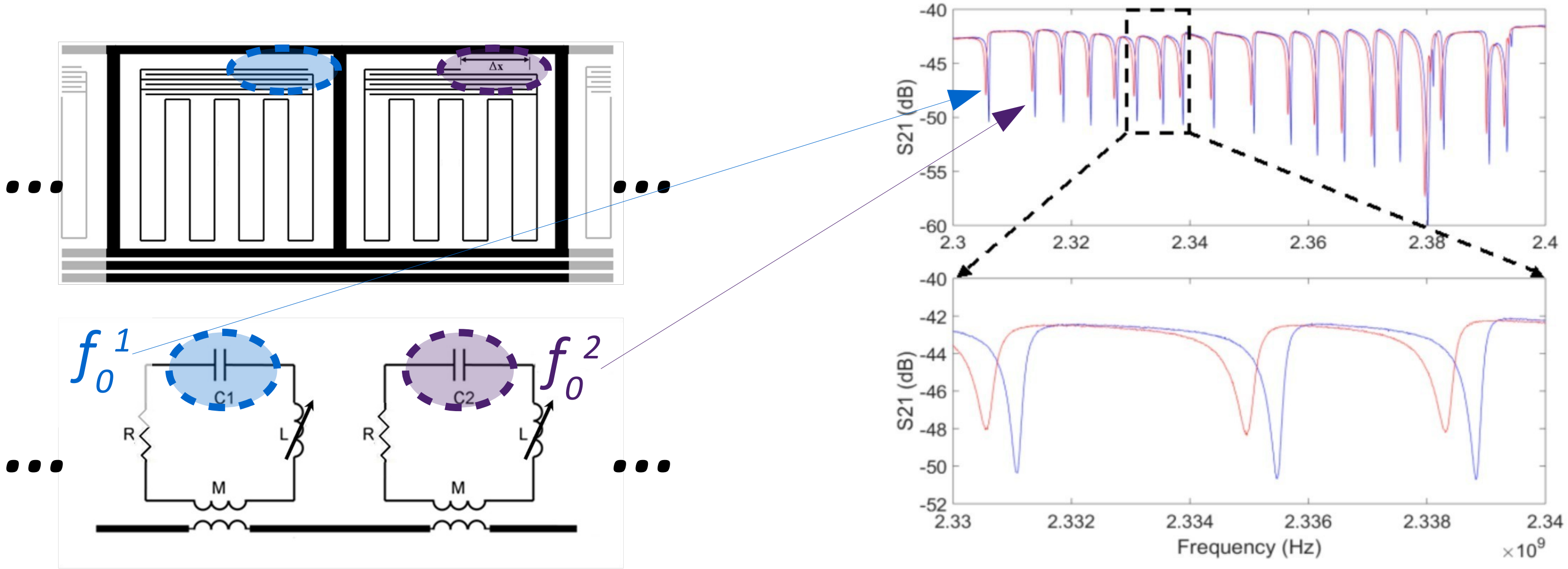
- KID are non-thermal detectors
- Largely insensitive to bath temperature/thermal phonons
- Time constant τ dominated by QP dynamics

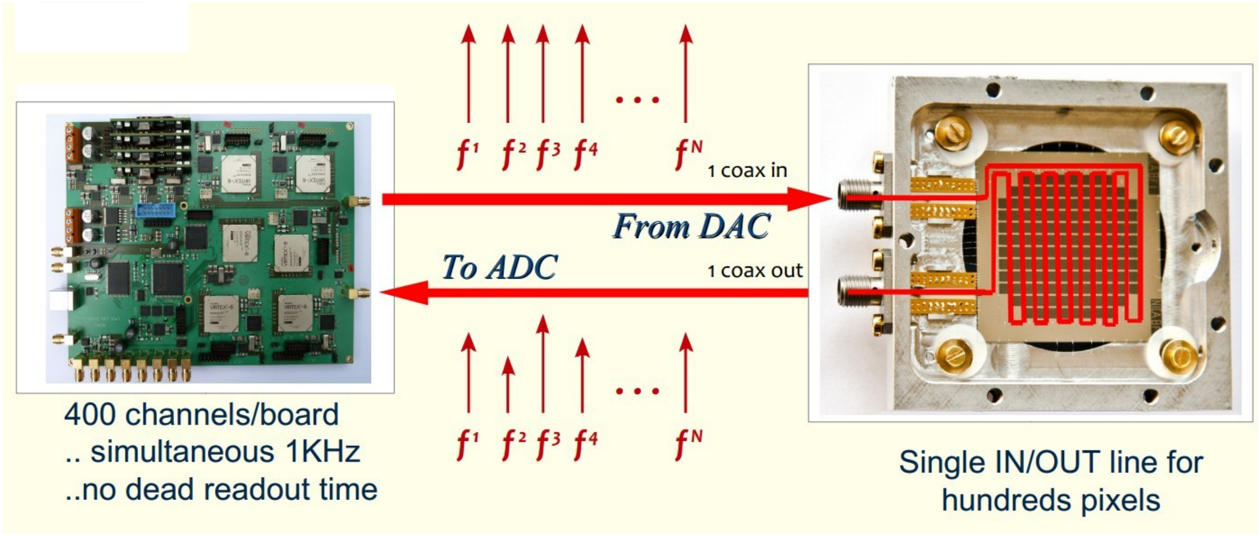


Typical τ : (10 -- 100)μs

Exact value depends on material, optical load, ...

KIDs multiplexing





MUX is 'built-in'

MUX≈300
demonstrated on-sky!

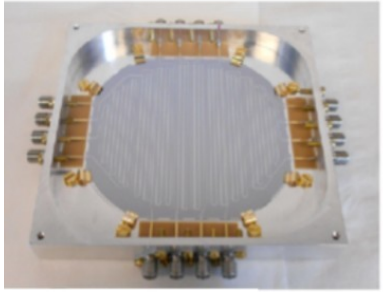
KIDs summary

KID have many desirable features:

- *Fast time constant*
- *Ease of multiplexing*
- *Ease of fabrication, moderate cost*
- *Small effects of thermal drifts/phonons*
- *But.. Mind the gap!*

A natural choice for CMB HF!

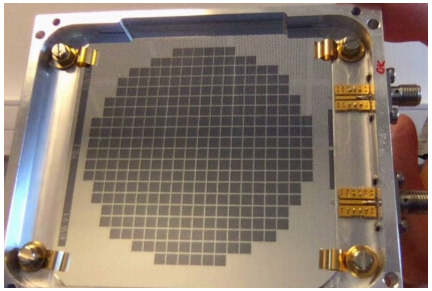
KIDs in Grenoble: instruments



2014-today →

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

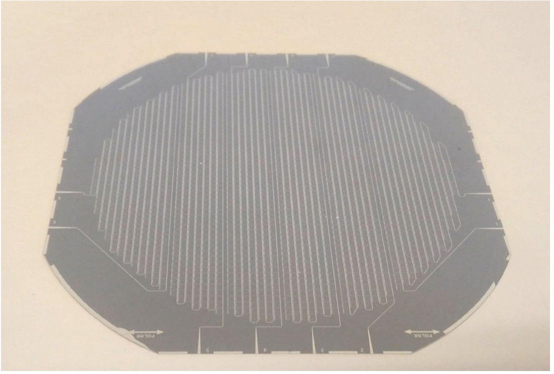
→ NIKA2



2018-today →

316x2 pixels
@ 1.25…3 mm
+ spectrometry!

→ KISS



Today⟶ →

2000x2 pixels
@ 1…2.2 mm
+ spectrometry!

→ CONCERTO

NIKA2: a fully mature instrument

- Commissioning phase completed
- Open to external astronomers since 2018 via *open pools*
- Final tweaks ongoing (handover → IRAM)
- Papers starting to appear (ie: good work!)

Adam et al., A&A 609, A115 (2018)
→ instrument

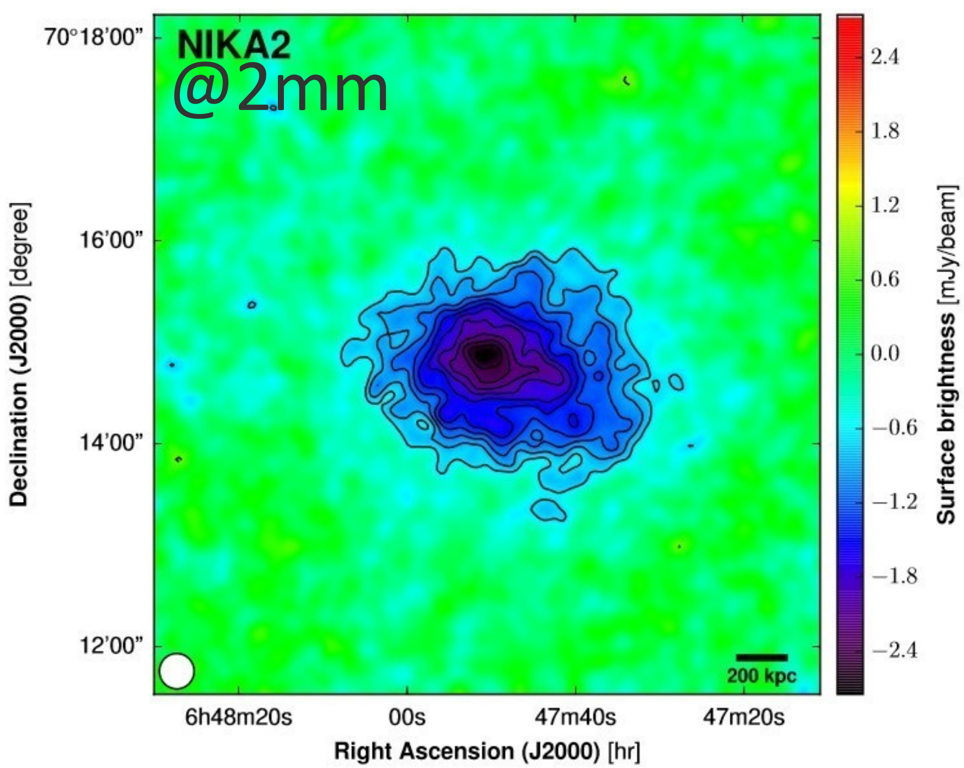
Perotto et al., submitted to A&A (2019)
→ performance + 'howto'

Ruppin et al., A&A 615, A112 (2018)
→ SZ with NIKA2

+ various NIKA papers

NIKA2: a fully mature instrument

PSZ2G144.83+25.11 (run 10)



Integration time: ≈ 11h

Ruppin et al., A&A 615, A112 (2018)

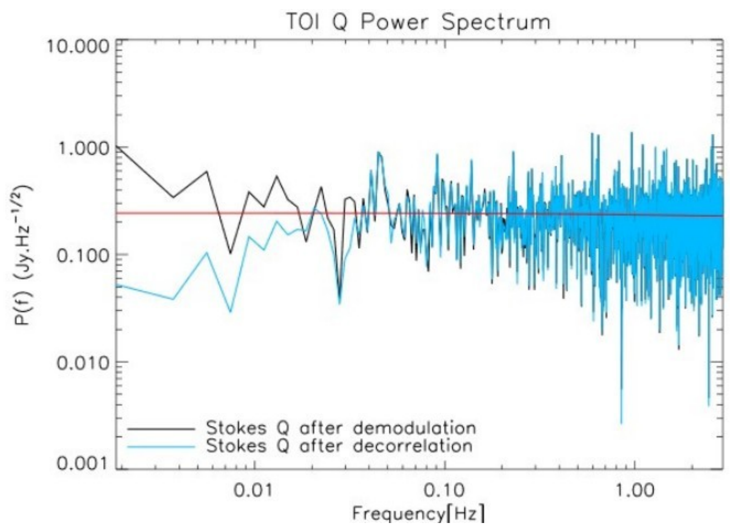
	Array 1&3	Array 2	Reference
Reference Wavelength [mm]	1.15	2.00	
Reference Frequency [GHz]	260	150	Sect. 8.1.1
Frequency [GHz]	254.7&257.4	150.9	Sect. 2.5
Bandwidth [GHz]	49.2&48.0	40.7	
Number of designed detectors	1140&1140	616	Sect. 2.3
Number of valid detectors[a]	952&961	553	Sect. 5.3
Fraction of valid detectors [%]	84	90	
Pixel size in beam sampling unit[b] [λ/D]	1.1	0.87	Sect. 5.2
FWHM[c] [arcsec]	11.1 ± 0.2	17.6 ± 0.1	Sect. 6.2
Beam efficiency[d] [%]	55 ± 3	77 ± 2	Sect. 6.3
Rms FWHM across the FOV [arcsec]	0.6	0.6	Adam et al. (2018)
Reference FWHM[e] [arcsec]	12.5	18.5	Sect. 8.1.1
Reference Beam efficiency[f] [%]	70 ± 4	85 ± 3	Sect. 8.1.3
Rms pointing error [arcsec]	< 3	< 3	Sect. 3.2
Absolute calibration uncertainty [%]	5	5	Sect. 9.1, App. A.1
Systematic calibration uncertainty[g] [%]	0.6	0.3	Sect. 9.1.3
Rms calibration uncertainty [%]	5.7	3.0	Sect. 9.2
α noise integration in time[h]	0.5	0.5	Sect. 10.3
NEFD[i] [$\mathrm{mJy \cdot s^{1/2}}$]	30 ± 3	9 ± 1	Sect. 10.3
M_s[j] [$\mathrm{arcmin^2 \cdot mJy^{-2} \cdot h^{-1}}$]	111 ± 11	1388 ± 174	

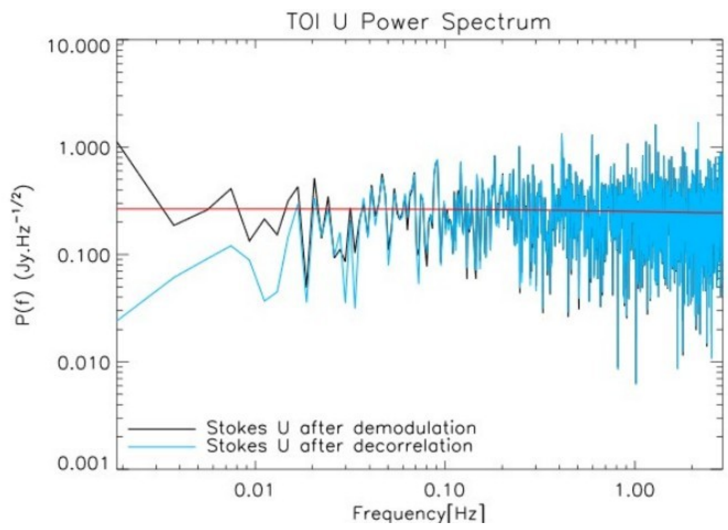
Perotto et al., submitted to A&A (2019)

The first KID-based camera worldwide (and ***fully European***!)

Future of NIKA2

- Solve remaining open issues (ie dichroic)
- Finish polarization commissioning + get data





Flat spectrum thanks to fast KID + rotating HWP
Already demonstrated by NIKA

Future of NIKA2

- Solve remaining open issues (ie dichroic)
- Finish polarization commissioning + get data
- On the longer term, upgrades are possible

Eg: more, smaller pixels @1mm, but need 1GHz band electronics

Shu et al., JLTP 193, 141-148 (2018)

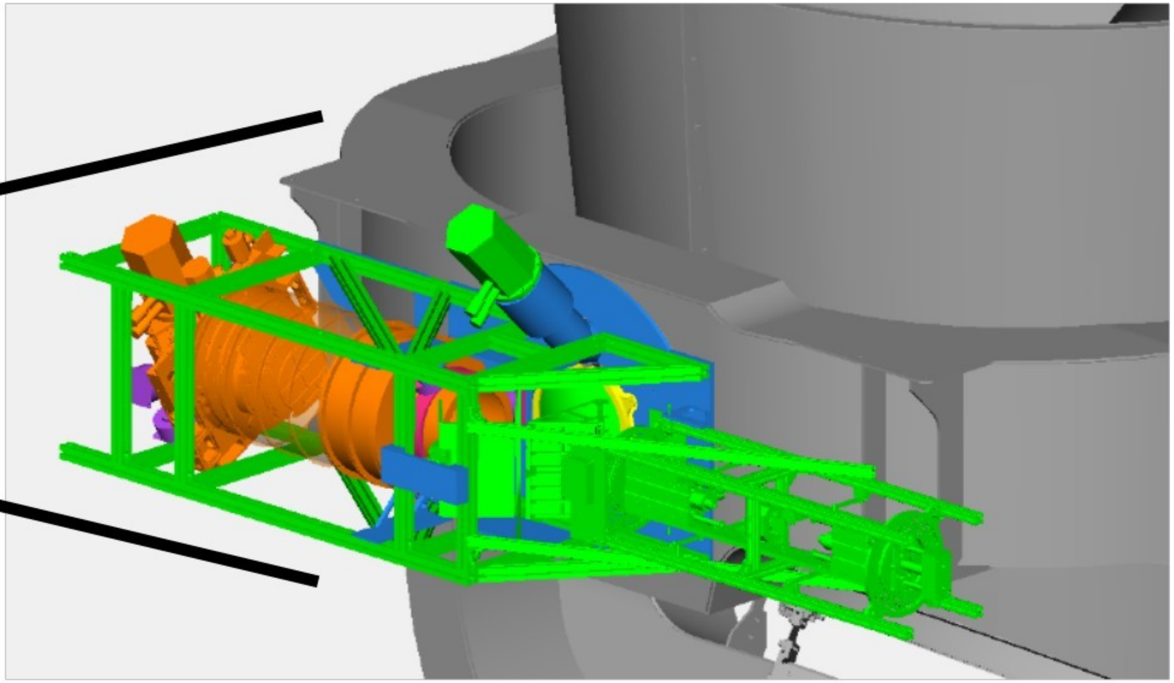
KISS: low-res spectroscopy for SZ

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



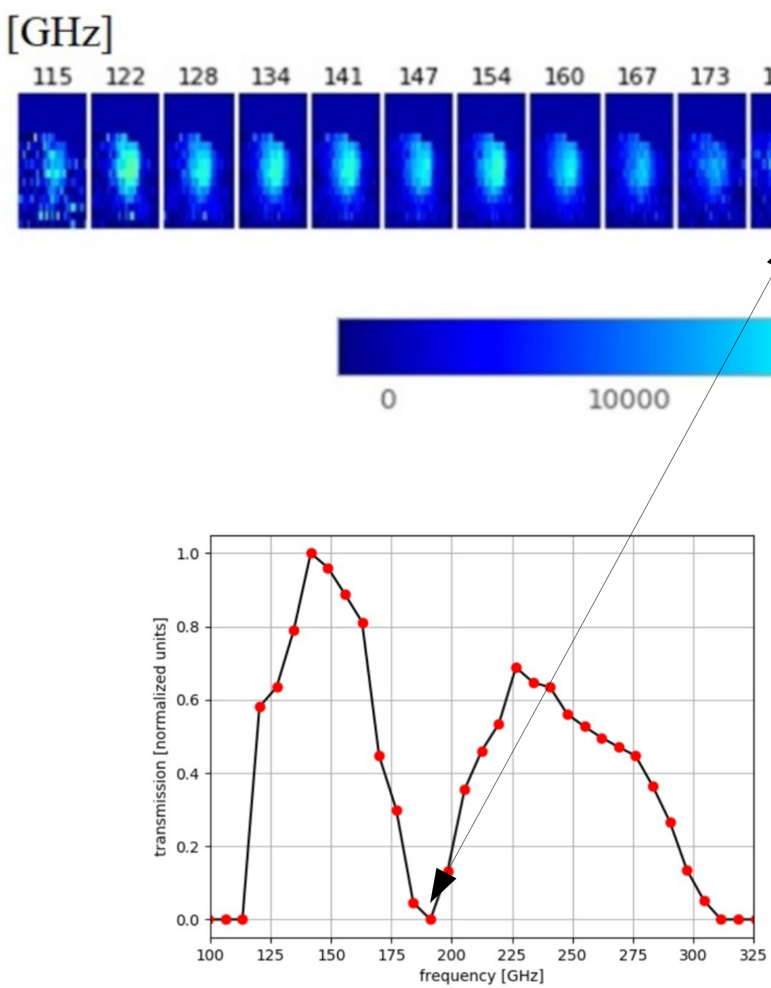
KISS: current status

- Installation went smoothly
- Commissioning was hard! (but a lot of feedback)

Eg: installation and weight compensation, pointing model, alignment…

KISS: current status

- Now ready for scientific data taking!



Jupiter

The next step: CONCERTO

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

KISS

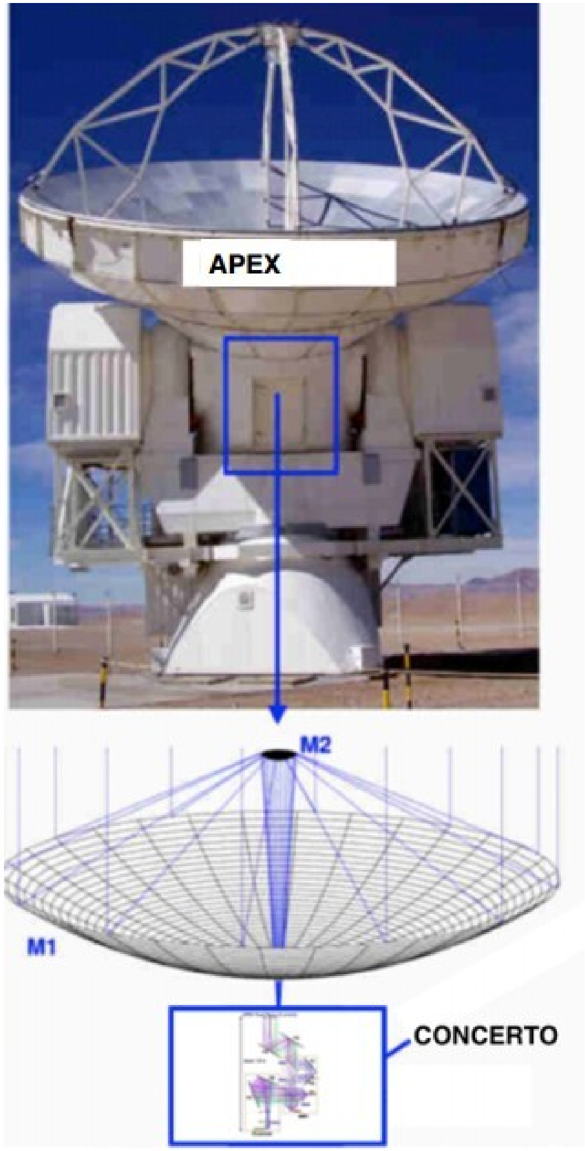
Averaged sky angular resolution	3.5 arcmin	Number of KIDS	600
Spectral range GHz	80 - 250 GHz	Frequency resolution δ_ν	1.5 GHz
Quijote telescope size	2.5 m	Round FOV, Diameter	1 deg
End-to-end optical efficiency	0.3	^{3}He-^{4}He dilution cryostat	100 mK
# of expected observed clusters	10	Expected integration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

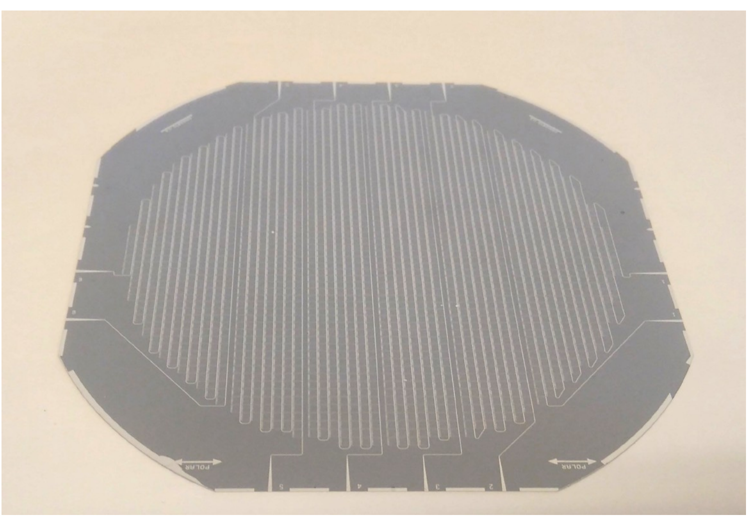
Timeline

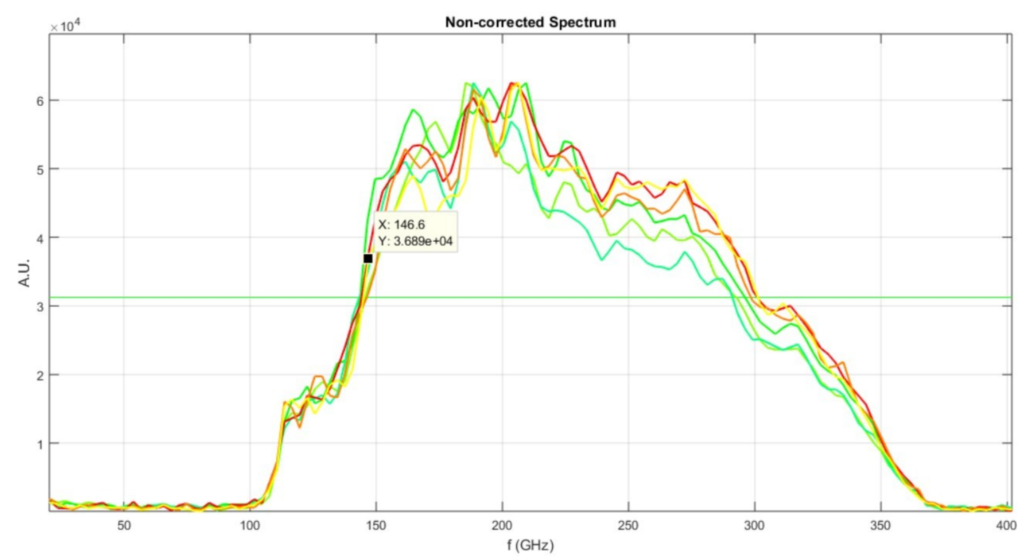
- **2018:** Pre-study and Design ✓
- **October 2018:** Acceptance meeting from APEX ✓
- **2019:** Fabrication, sub-system qualification and integration ✓
- **2020:** Calibration of the final model in lab
- **January 2021:** Installation at the APEX telescope



CONCERTO update

- Already many arrays tested with good performance
- Cryostat to be assembled this fall
- First test in CONCERTO instrument by end of the year





KID instruments in Europe/US

- We are definitely not alone! A lot of other instruments:

Flown or operating

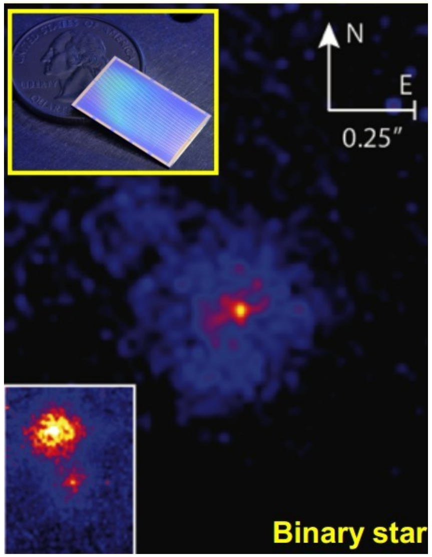
- OLIMPO
- DARKNESS
- DESHIMA

Instruments for CMB frequencies

- AMKID
- TOLTEC
- MUSCAT
- BLAST-TNG

Planned or commissioning

OLIMPO



DARKNESS

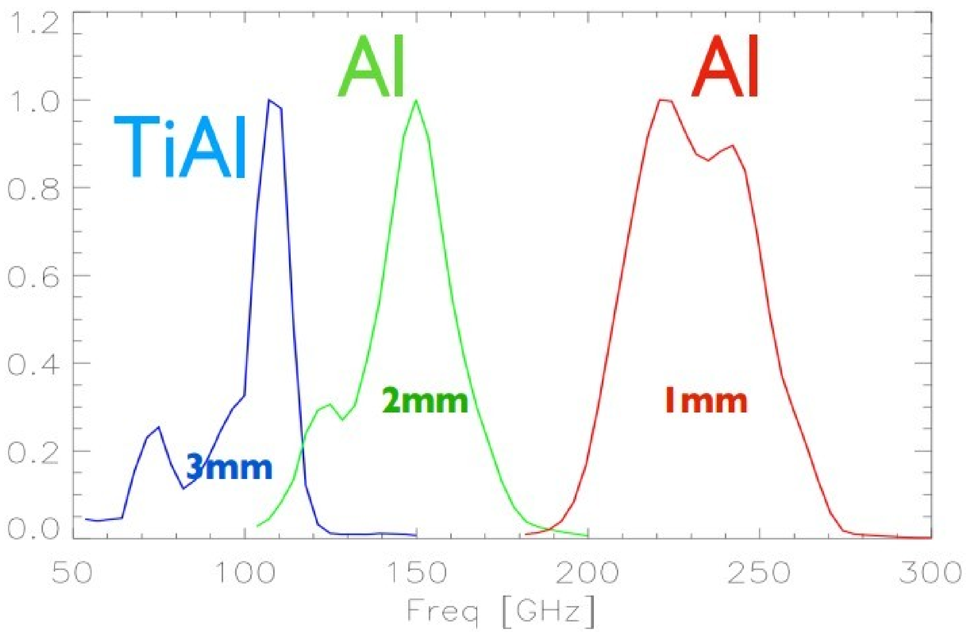
KIDs in Grenoble: developments

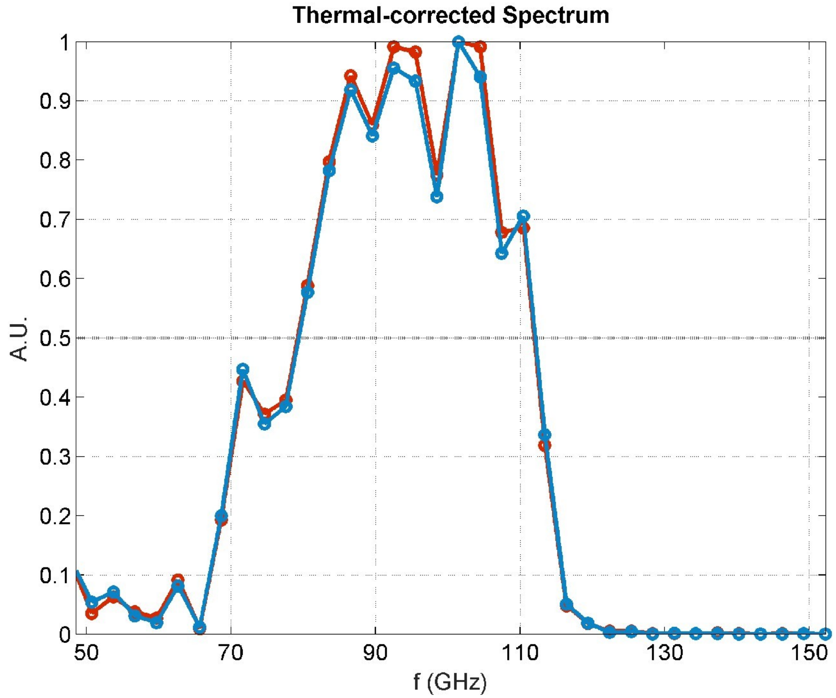
In recent years, we have assessed the main points to increase KID TRL with respect to a possible CMB satellite mission

- Spectral coverage?
- NEP? Are we at the photon noise limit?
- Effect of CR? Is it ok? Do we have to improve further?
- Electronics: lower power, larger band?

Enlarging the KID spectral band

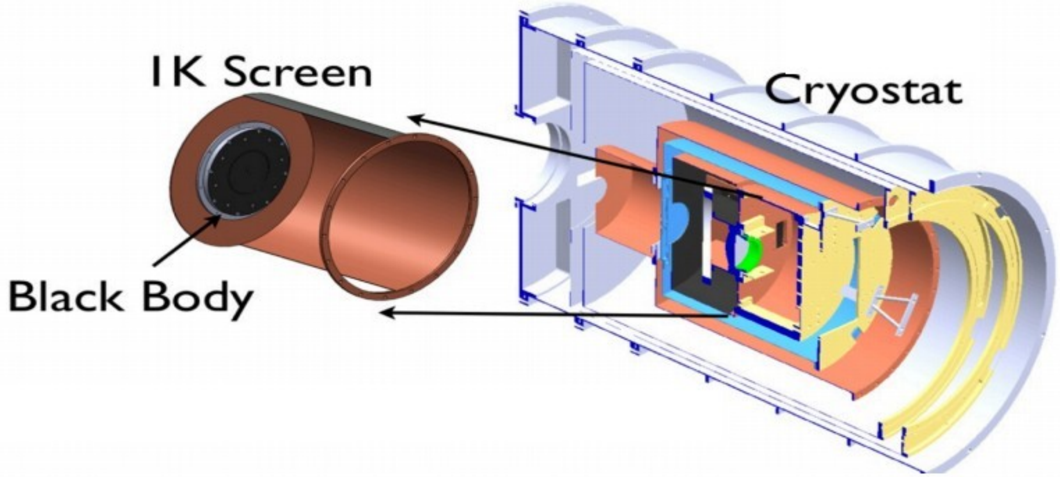
- Already ok up to ~600GHz
- Main issues is going lower than ~100GHz
- **Ti/Al** bi-layers seem promising for CMB



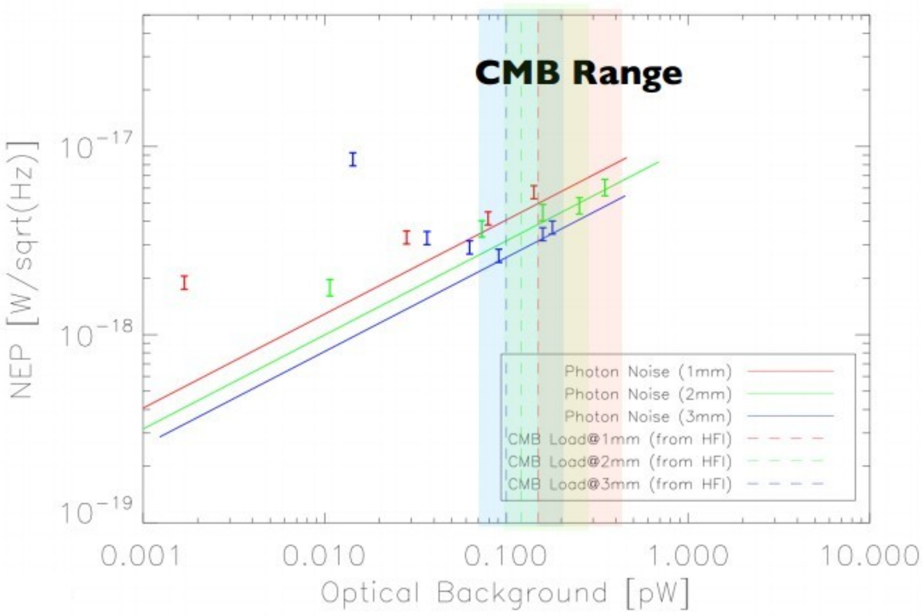


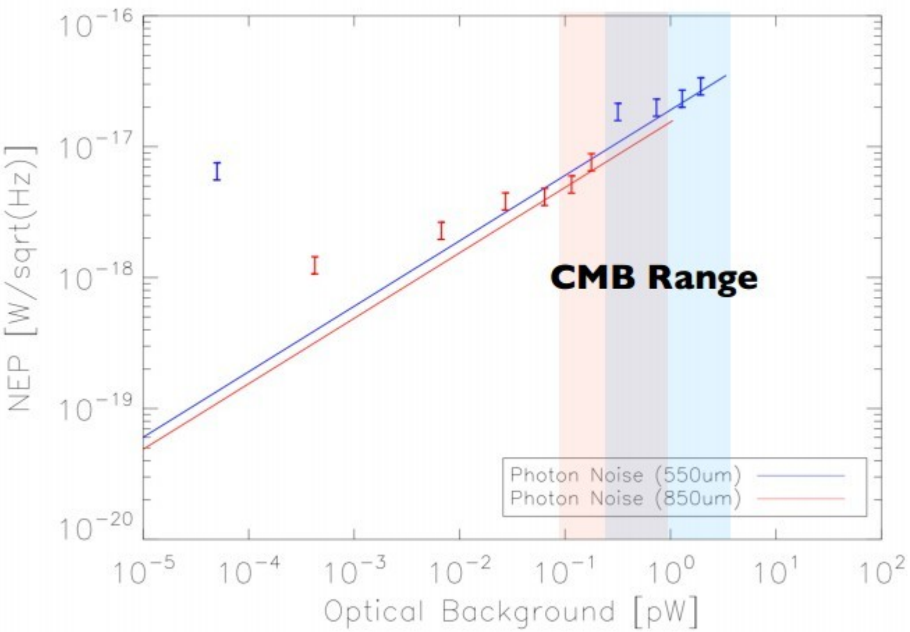
Other options are available (grAl, Ti/TiN, ..), but lower TRL (in Europe)

NEP at low background

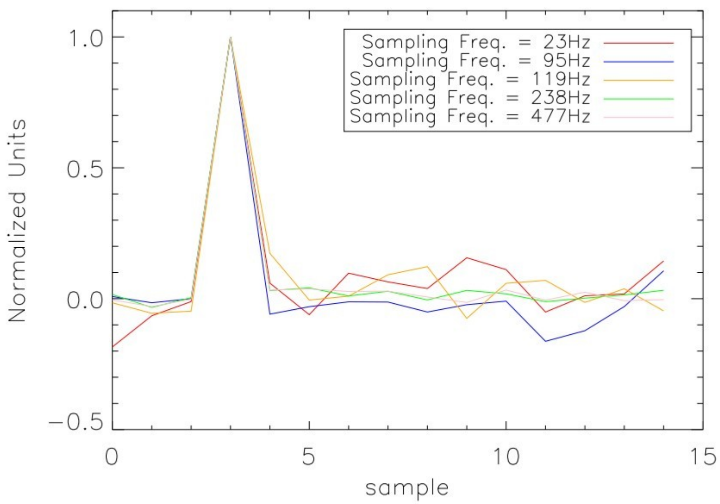


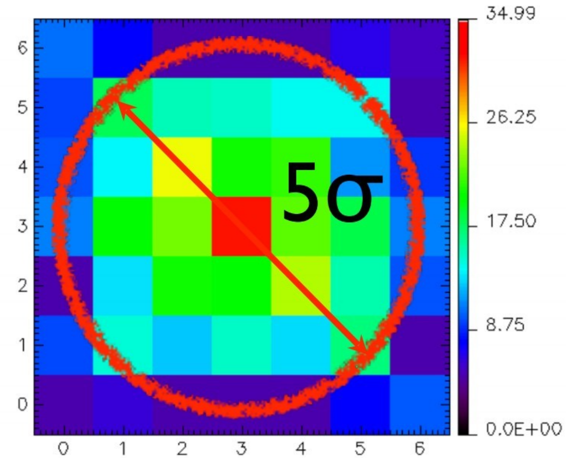
Under space typical background conditions KID show NEPs in line with CMB photon noise.





CR impacts on KID arrays



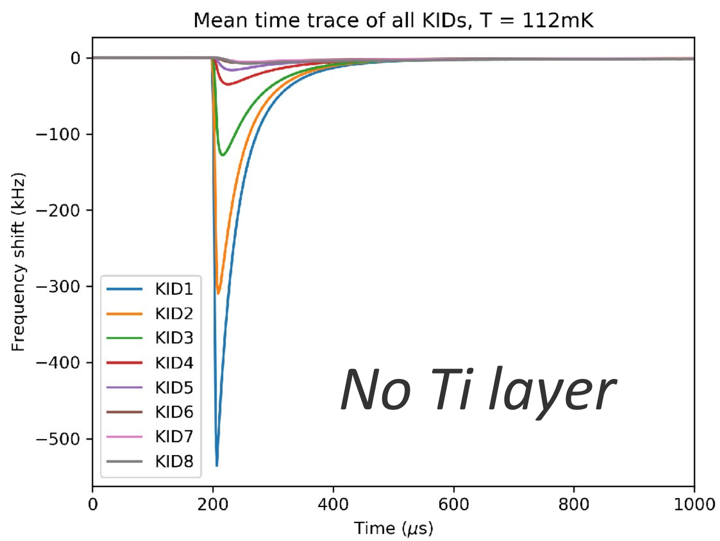


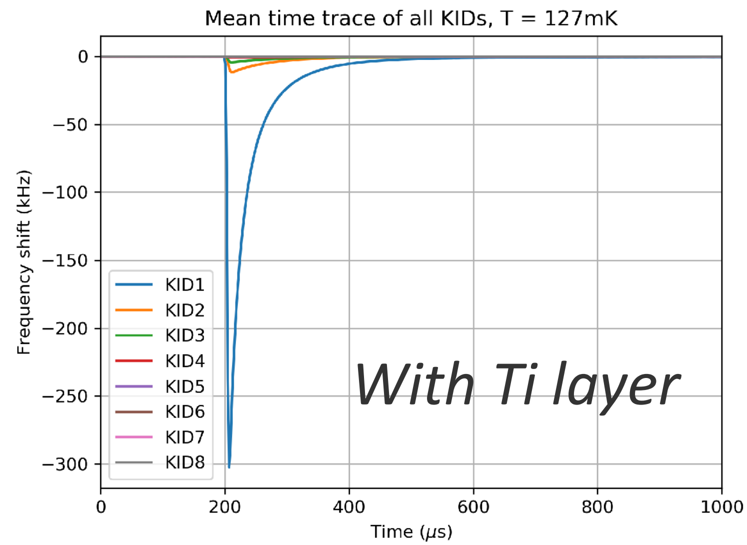
KID time constants:

τ ≈ 100μs

+ no effect of thermal phonons!

Can improve further with <u>phonon absorbing layers</u>

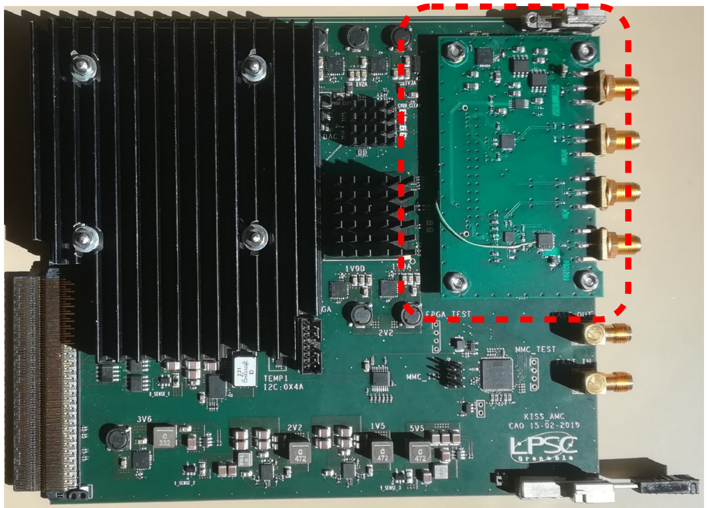




See eg: *Monfardini et al., Proc SPIE 9914 (2016)* *Karatsu et al., APL **114**, 032601 (2019)*

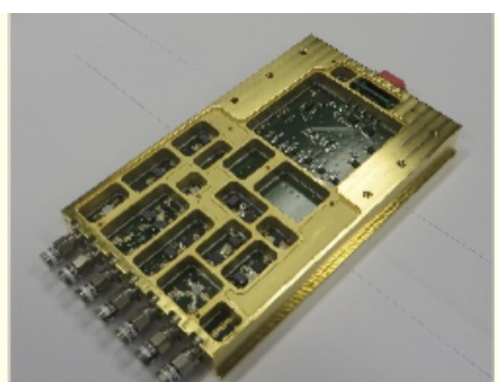
KIDs readout: NIKEL (et al!)

- New NIKEL board: larger bandwidth + lower consumption



- *1GHz band*
- *~30W total power*
- *Modular approach*

- Also available: SRON readout board



- Now up to 8kchannel!

A large EU KID community!

- KID are relatively easy to do
- KID have already confirmed their potential on ground
- KID have intrinsic advantages

    - More and more groups involved
    - More and more good results, ideas…
    - More and more a viable solution!

A positive feedback in place!

OLIMPO: KID on a balloon

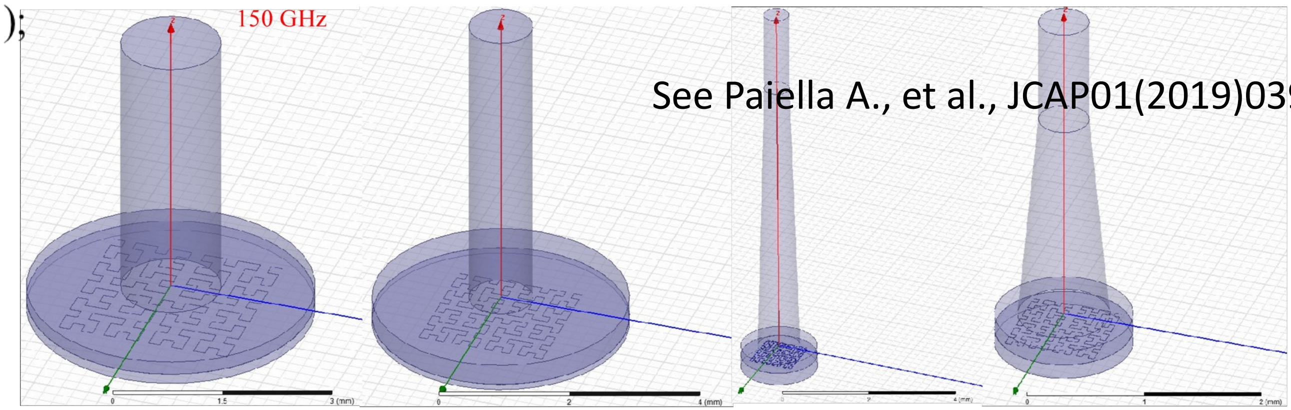
- Horn-coupled Al LEKID

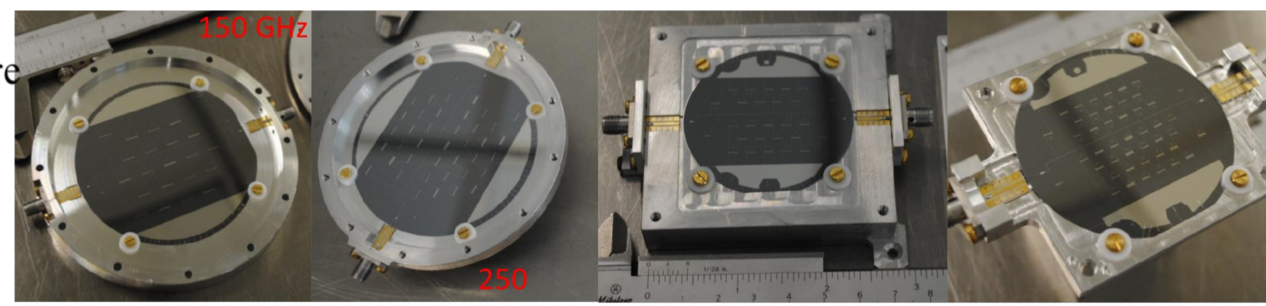
Credit: A. Paiella

- Absorber/Inductor: IV order Hilbert in Al 30nm thick (T_c = 1.31 K, $R_{\square}$ = 1.21 Ω/□);
- Substrate: Si with different thickness depending on the observed wavelenght.
- Radiation coupling: front–illuminated via single–mode (flared) circular waveguide;
- Electrical coupling: via capacitors to a 50Ω −matched microstrip feedline and to the ground, and such that Q_c~15000.
- Readout: two ROACH2-based systems menaging about 60 detectors each (firmware and software developed by ASU).
- Cryogenic LNAs developed by ASU.

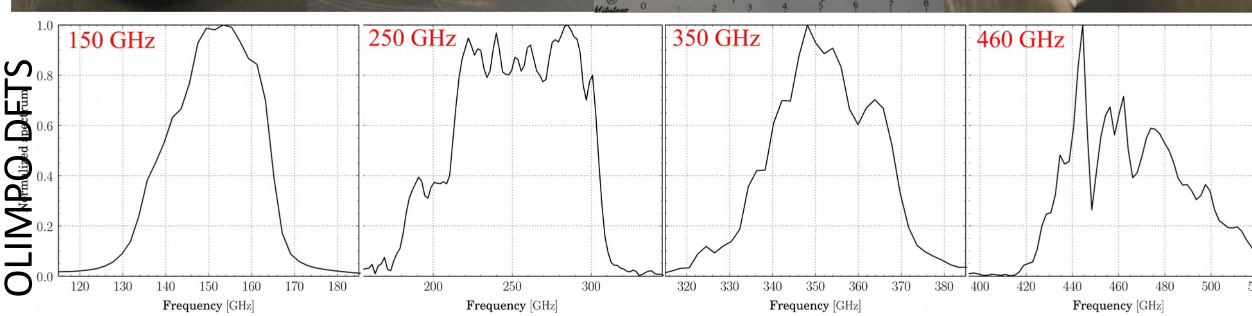
Channel [GHz]	Si wafer $d['']\times t\,[\mu m]$	# (+ dark)	ν_r [MHz]
150	3 × 135	19 + 4	[146; 267]
250	3 × 100	37 + 2	[150; 335]
350	2 × 310	23 + 2	[362; 478]
460	2 × 135	41 + 2	[288; 487]

See Paiella A., et al., JCAP01(2019)039



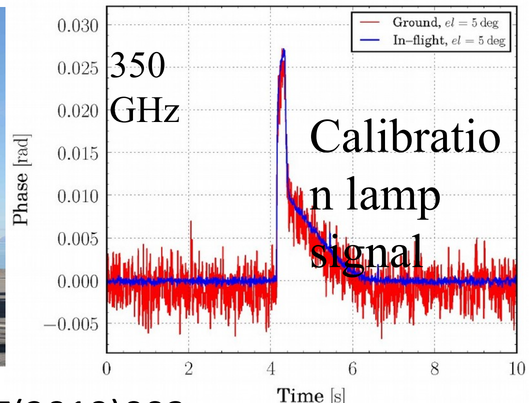


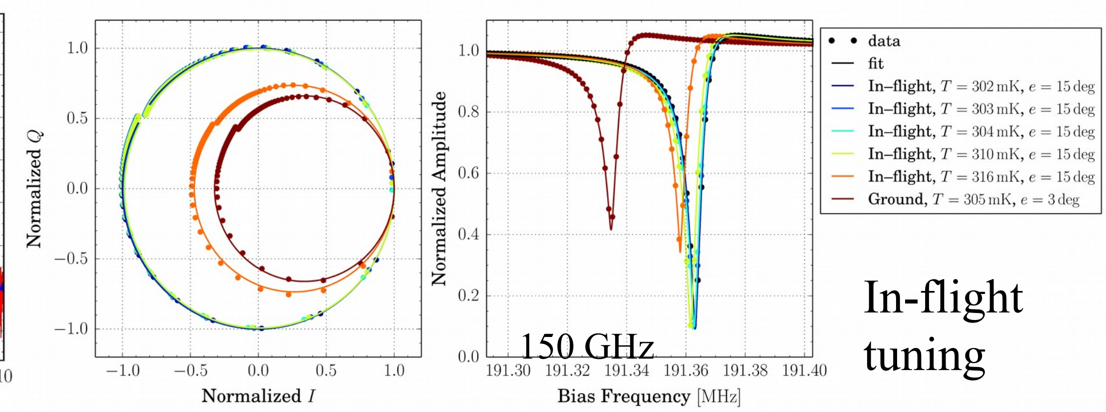
Measured with OLIMPO DFTS



OLIMPO: KID on a balloon

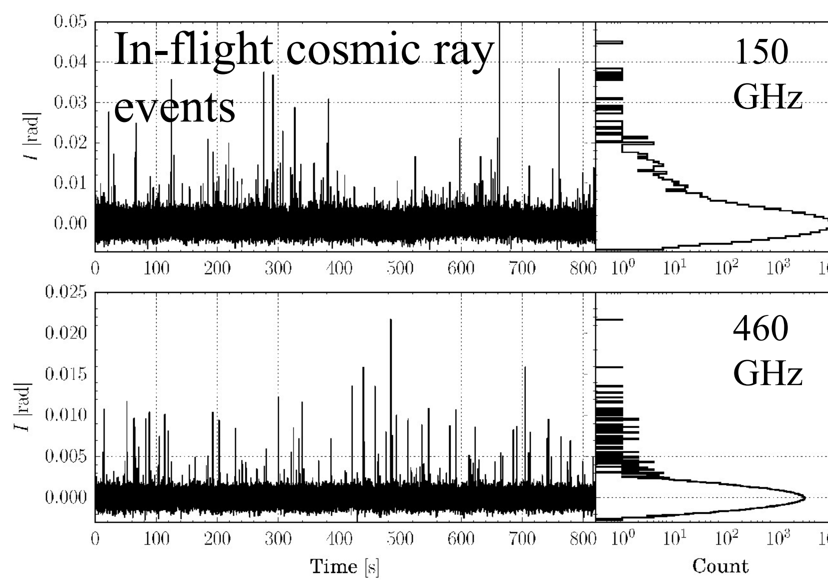
- First demonstration of KIDs in (quasi-)space





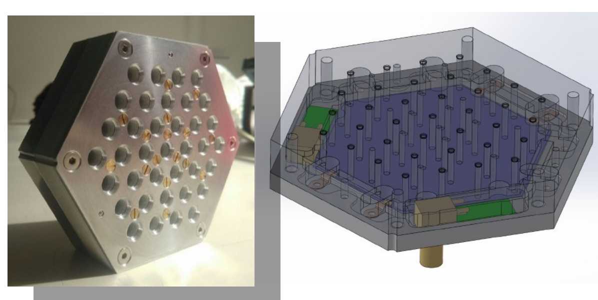
See Masi S. et al., JCAP**07**(2019)003

Channel [GHz]	Active Pixels (+ dark)	FWHM [GHz]	photon–noise NET_{RJ} [$\mu K\sqrt{s}$]	average NET_{RJ} [$\mu K\sqrt{s}$] ground	average NET_{RJ} [$\mu K\sqrt{s}$] in–flight	Fraction of contaminated data
150	16 + 4 (87%)	25	70	201 ± 26	91 ± 18	<2.7%
250	32 + 2 (87%)	90	30	243 ± 27	31 ± 6	<2.8%
350	21 + 2 (92%)	30	80	243 ± 8	71 ± 14	<0.1%
460	41 + 2 (100%)	60	90	336 ± 28	73 ± 15	<0.2%



Other activities:

- development of dual-polarization LEKIDs (via OMT) for large focal planes in space applications (national collaboration, Sapienza + CNR + UniMI + UniMiB;
- development of multi-mode KIDs for COSMO (founded by PNRA and PRIN);
- development of KIDs for the W-band.

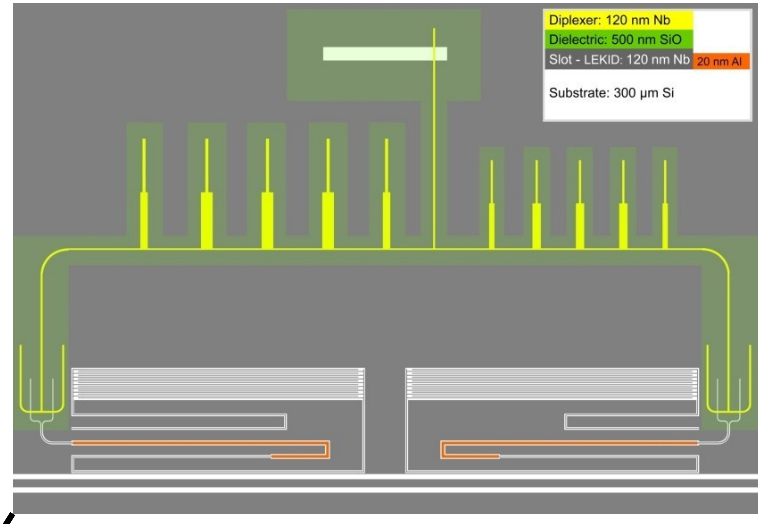


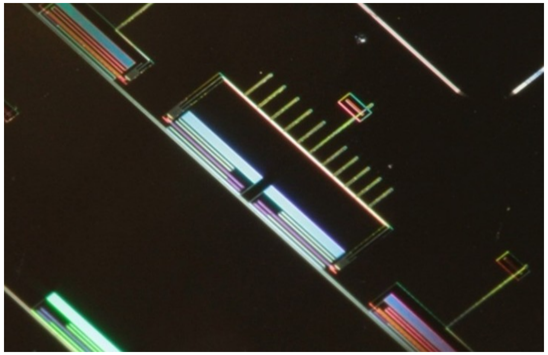
Credit: A. Paiella

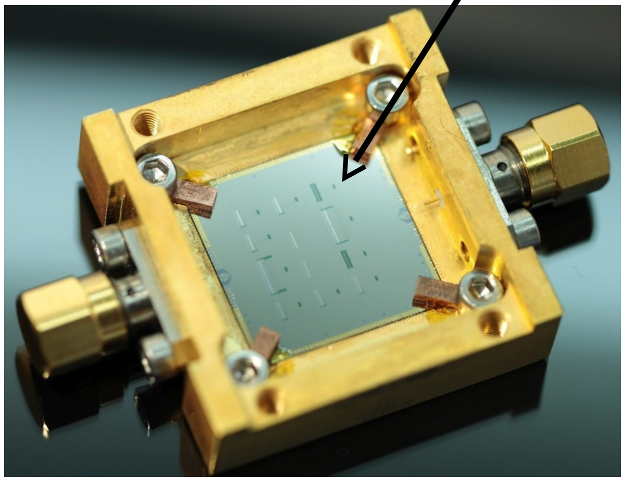
Dual-colour LEKID @APC

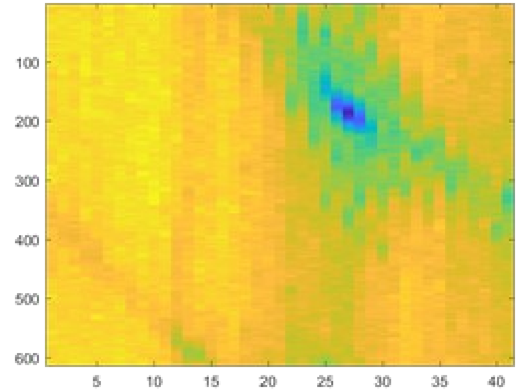
- LEKID + on-chip band splitting

- Design
  - Wide band slot antenna
  - Diplexer: N=5 Chebyshev open-stub bandpass
    - 10% bandwidth
  - Capacitive coupling to LEKID
- First samples made and tested
- Sensitive to direct light?







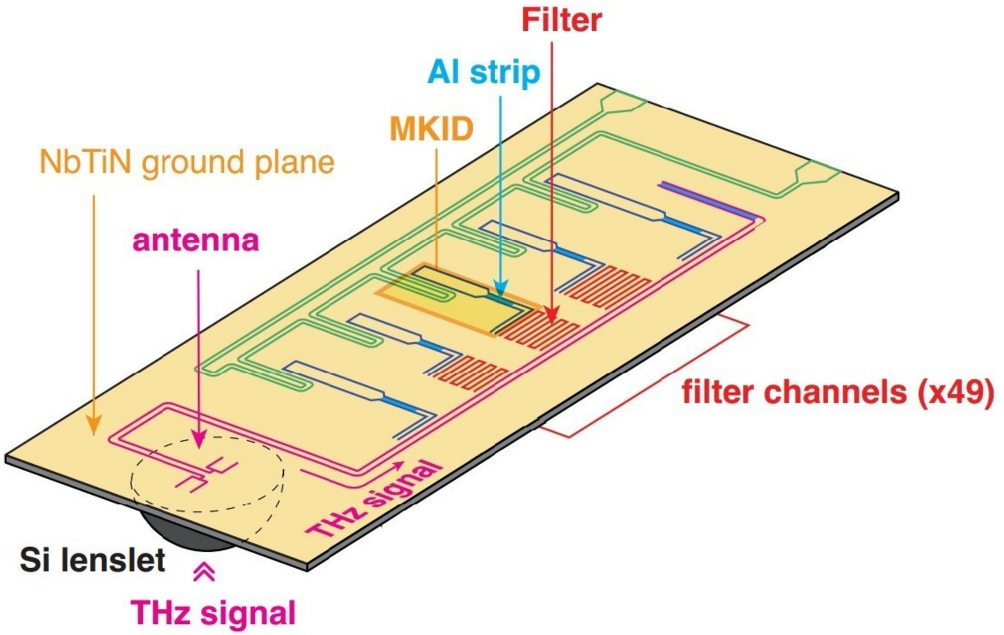


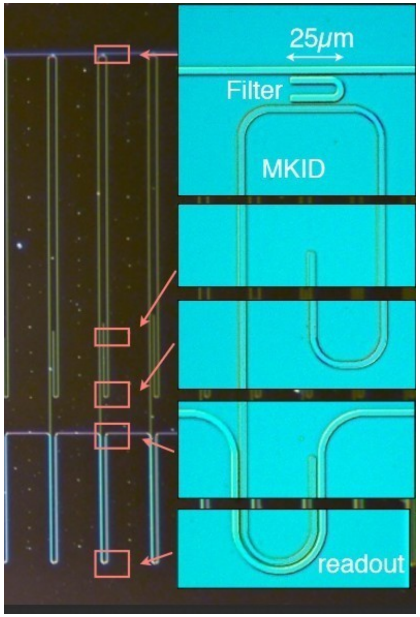
Beam at 150GHz

Credit: M. Piat

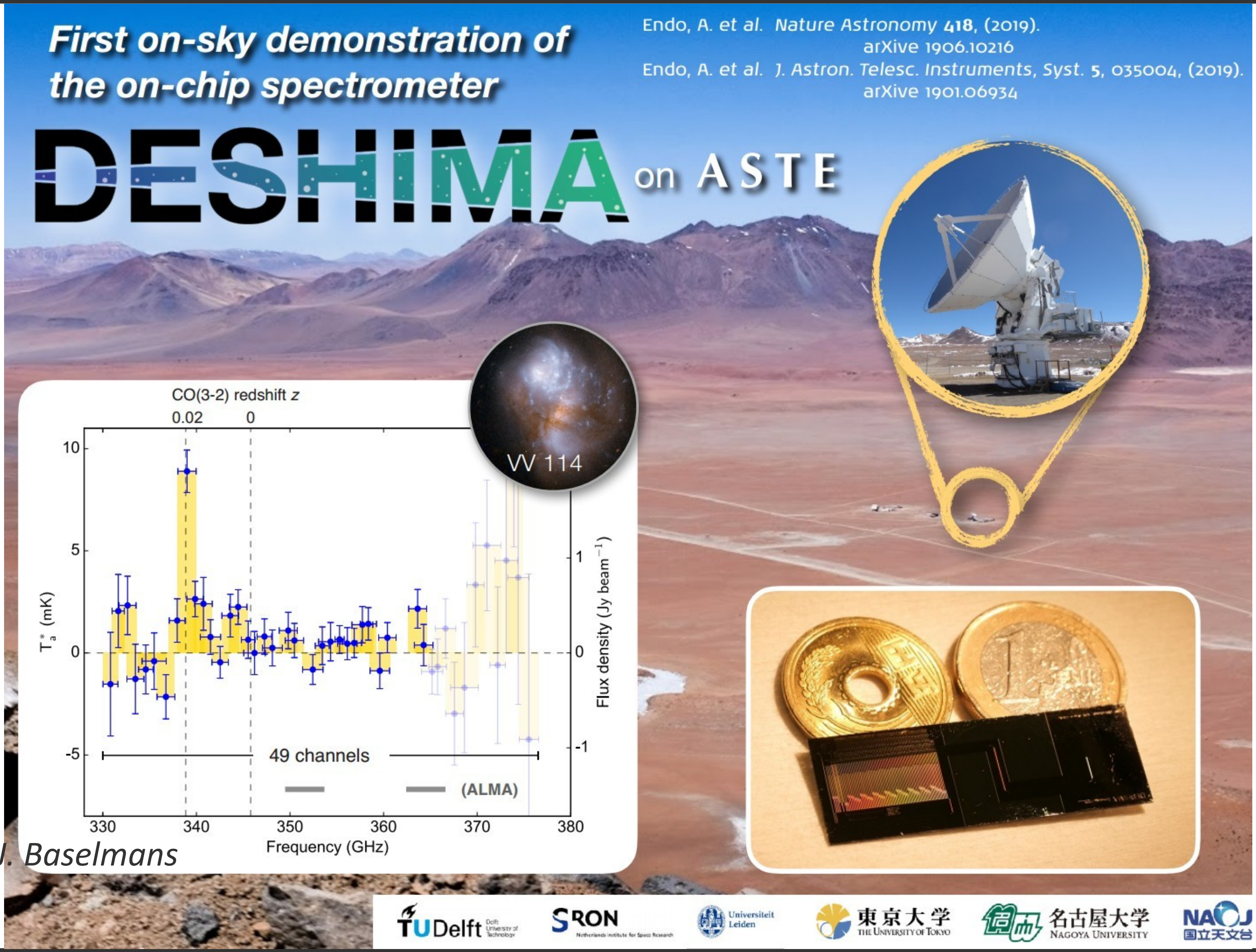
On-chip spectrometry: DESHIMA

- Alternative to the FTS/MPI approach
- An on-chip filter bank spectrometer
- Ideally suited for compact sources (#channels = #pix x #bands)





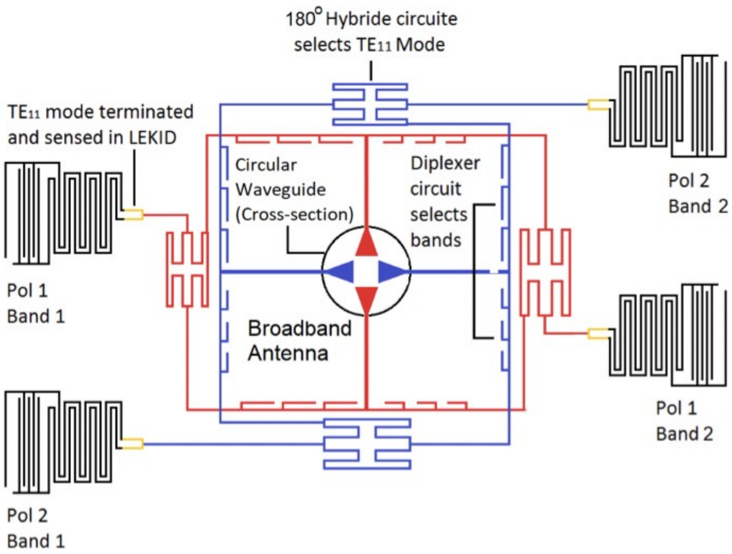
On-chip spectrometry: DESHIMA

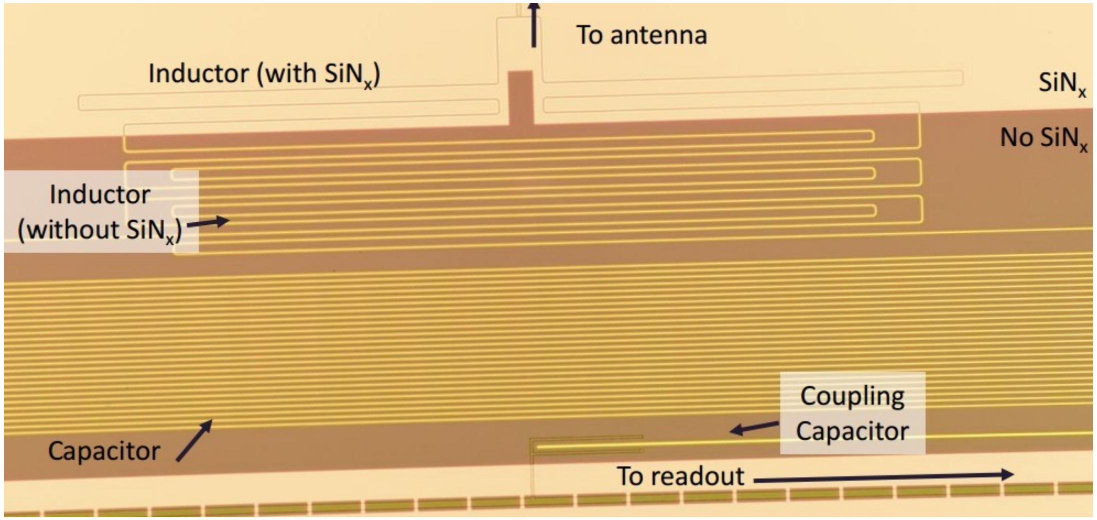


Credit: J. Baselmans

Antenna-coupled LEKID in UK

- Antenna-coupled, dual-pol+dual-band LEKID





Credit: S. Doyle

- Strong involvement in MUSCAT (LMT)

BiKID in Spain

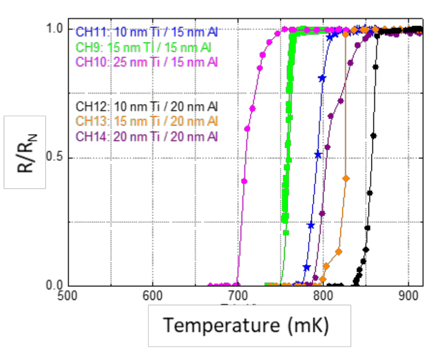
- Continuing the development of the BiKID approach:

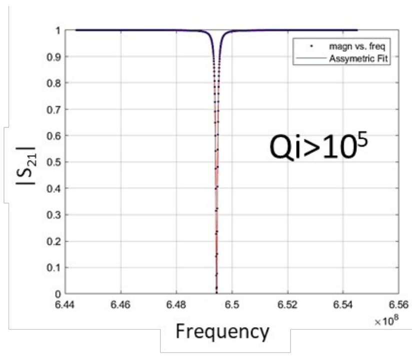
SINGLE CHIP POLARIZATION DETECTION WITH Ti/Al BiKIDS AT FREQUENCIES BELOW 90 GHz

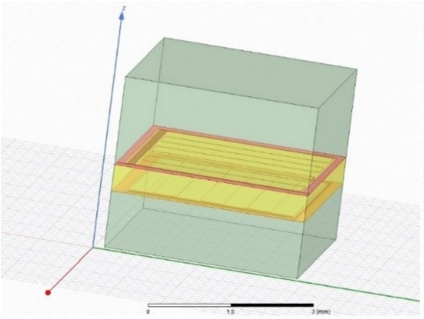
CENTRO DE ASTROBIOLOGÍA CSIC · instituto imdea nanociencia · IFCA Instituto de Física de Cantabria · DICOM · UC Universidad de Cantabria

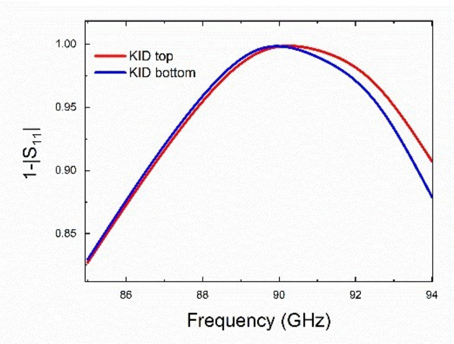
➢ Ti/Al Bilayers for low frequency detection

➢ Double-side LeKIDs: First design at 90 GHz.

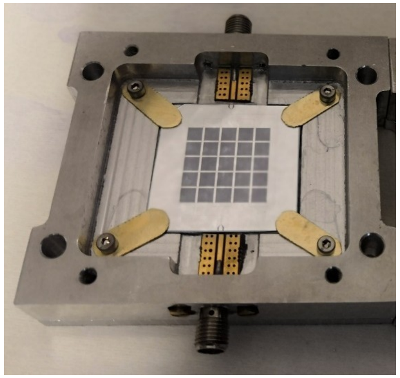


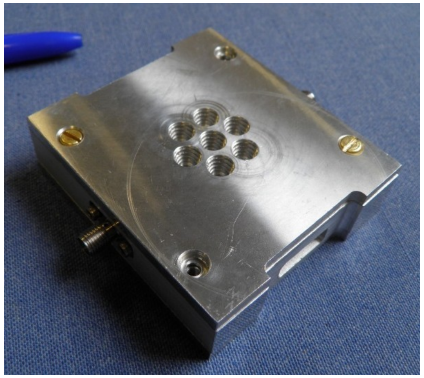


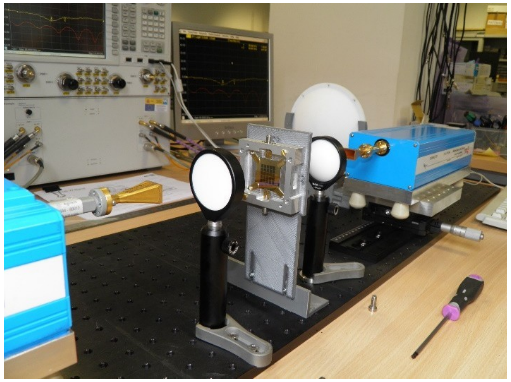




➢ Direct absorption vs. Horn coupling to be tested at room and low temperature (*In progress*)



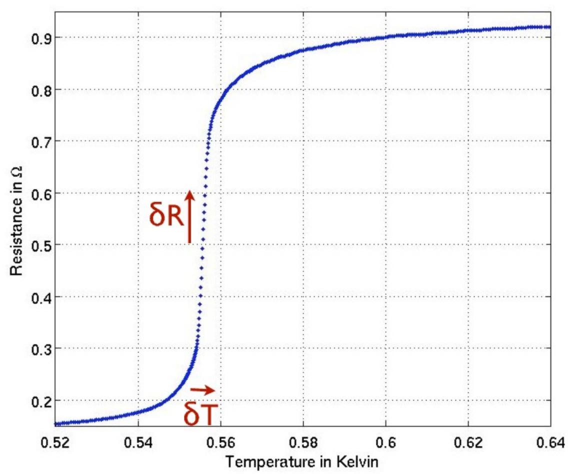


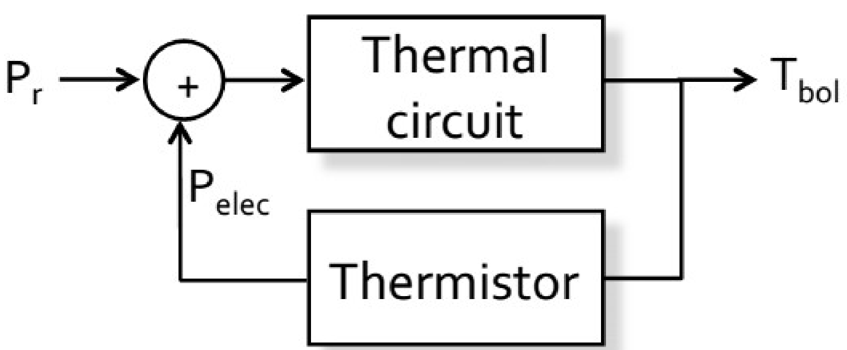


Credit: A. Gomez

TES in Europe

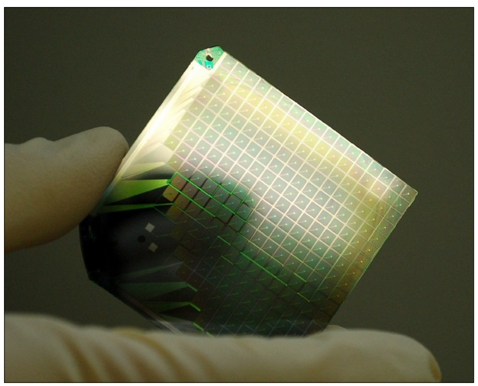
- TES are bolometers → no cutoff frequency
- Can be a solution for 'low-HF'
- Disadvantages: harder to make, moderate EU involvement
- But: promising ongoing work and results!



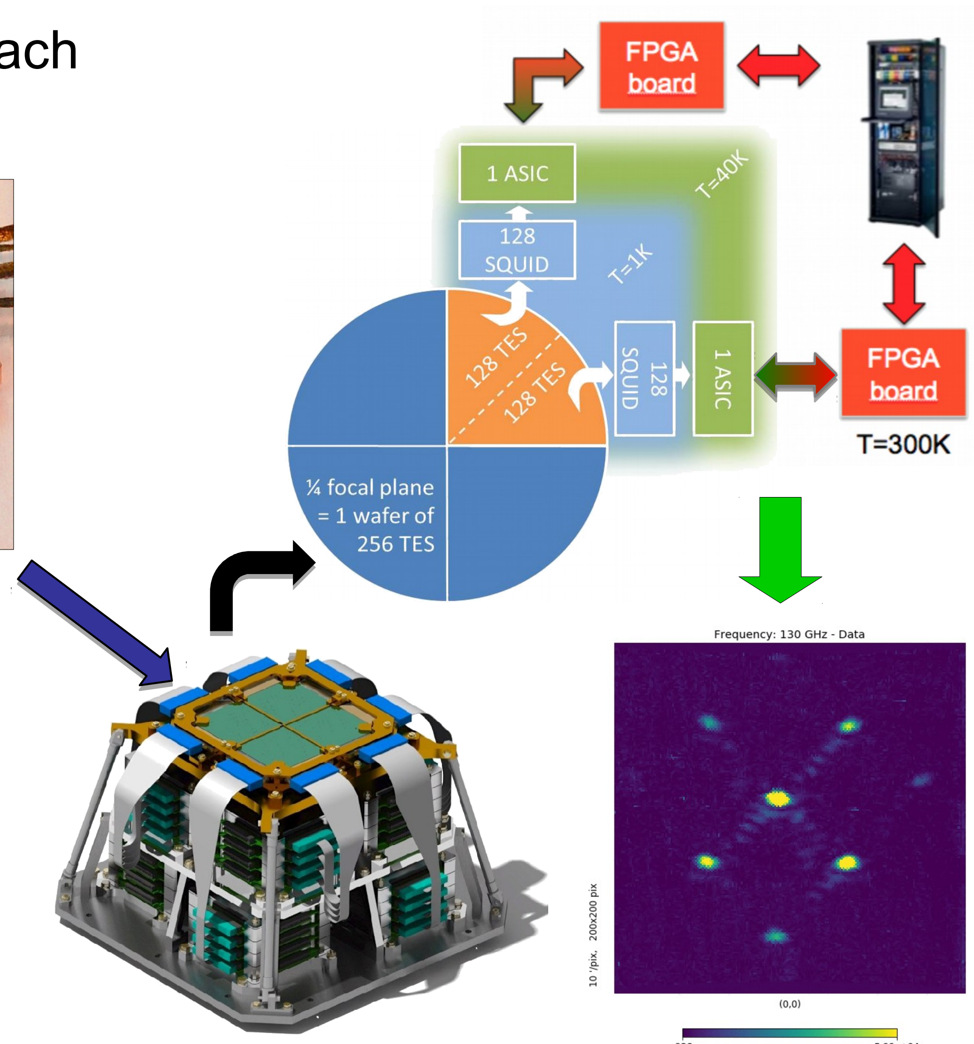


TES for QUBIC

- NbSi TES filled array @ 350mK
  - 2 focal planes with 1024 detectors each
  - 150GHz and 220GHz

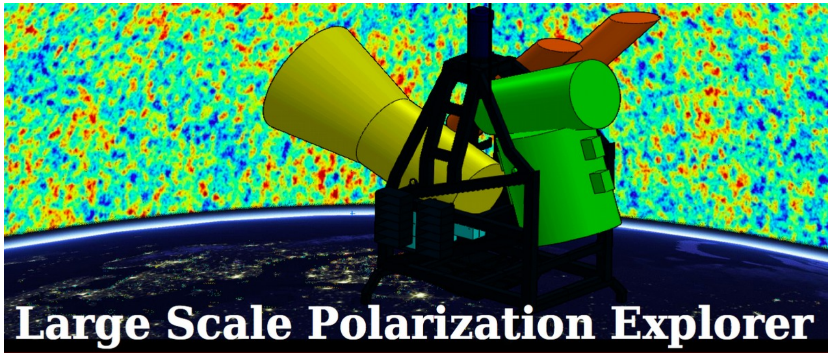


- Time Domain Multiplexing 128:1
  - SiGe ASIC @ 40 K
- Warm readout: FPGA board
- Ongoing optical measurements & characterization!

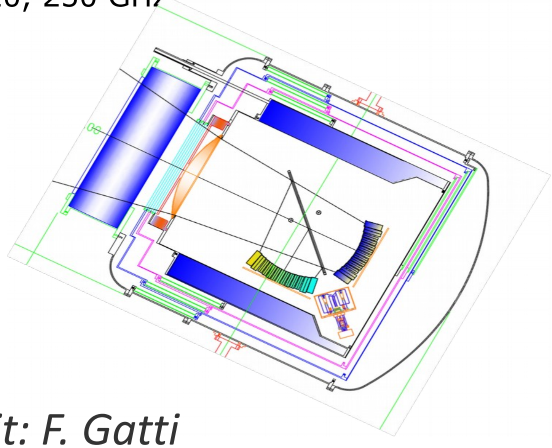


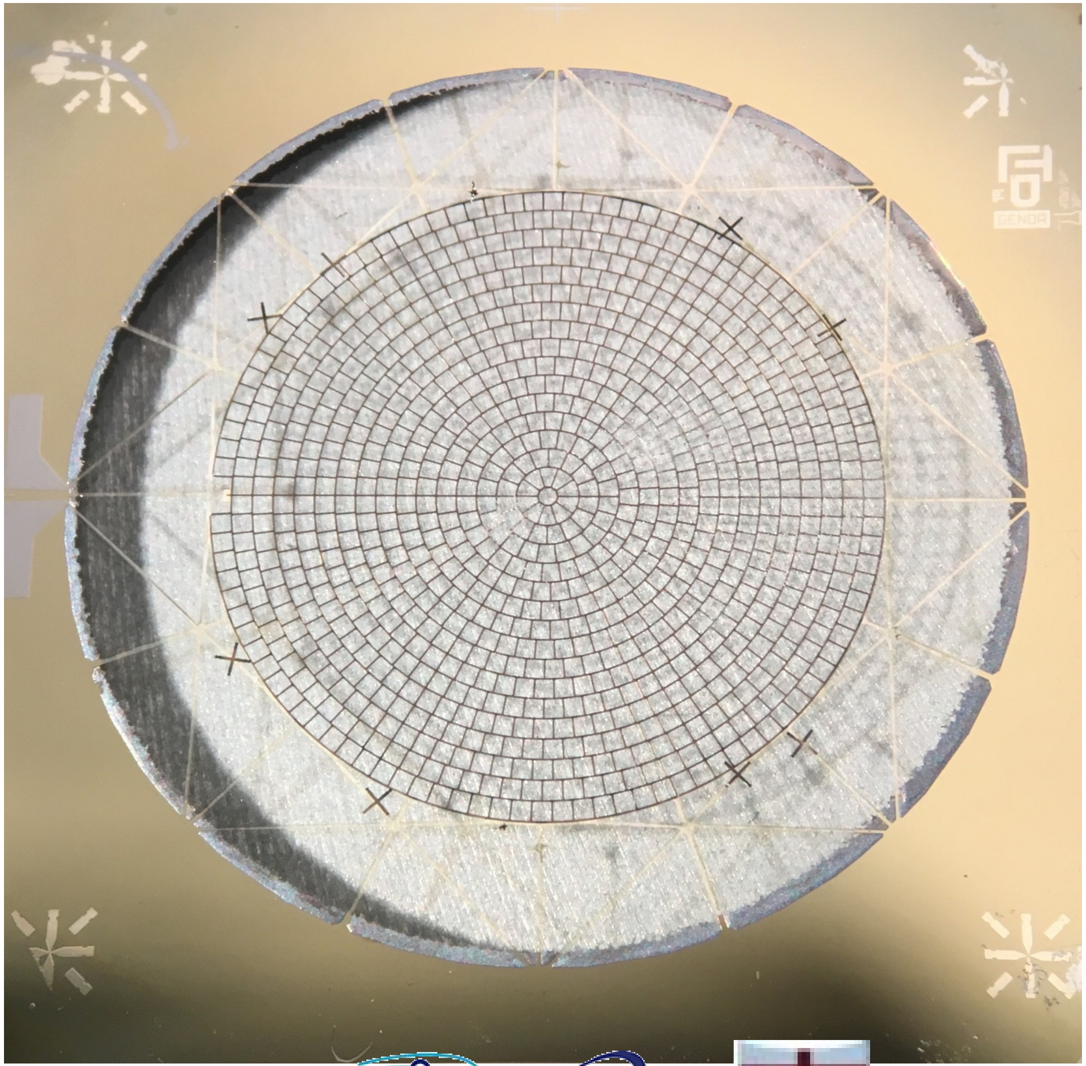
Credit: M. Piat

TES for LSPE



- TES Bolometers for the SWIPE telescope of the LSPE balloon born mission(PI - P. De Bernardis)
- Very-Large Area Spider-Web absorber (8mm dia.) for a multi-mode horn coupled cavity. Full bolometer diameter: 1 cm.
- Focal plane with 330 bolometers, 3 frequency bands: 140, 220, 250 GHz

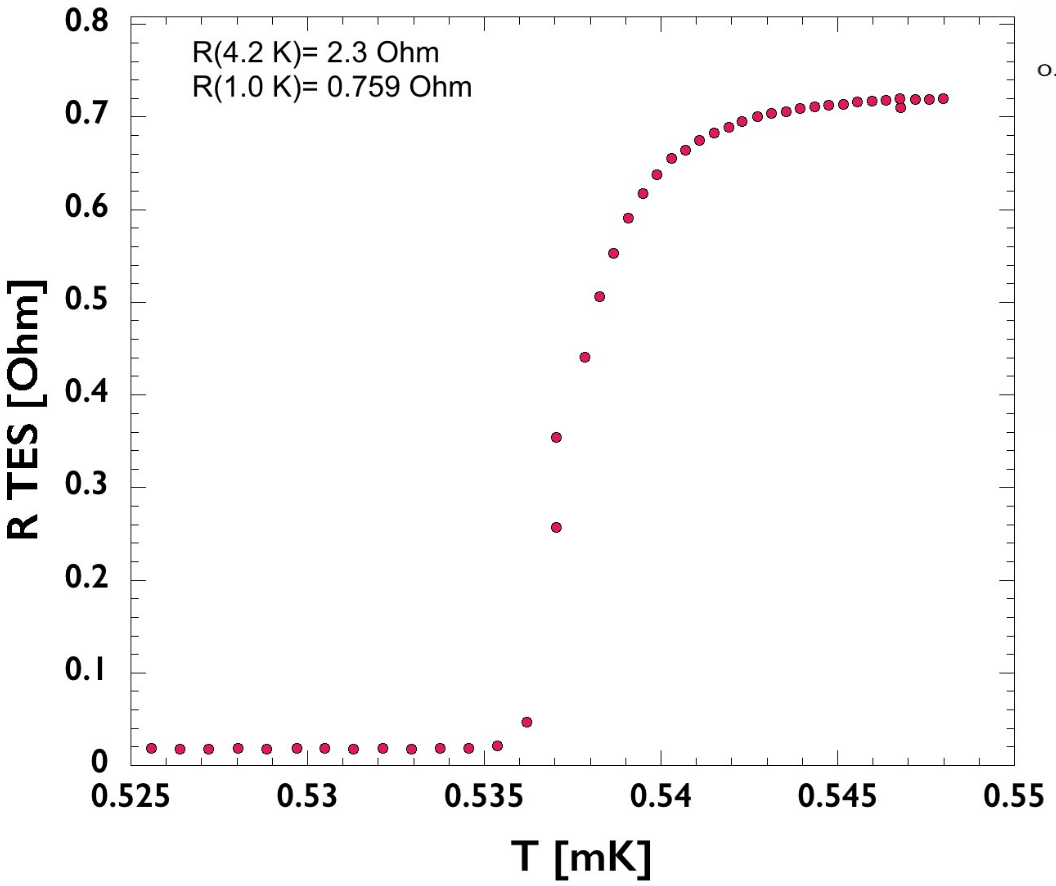


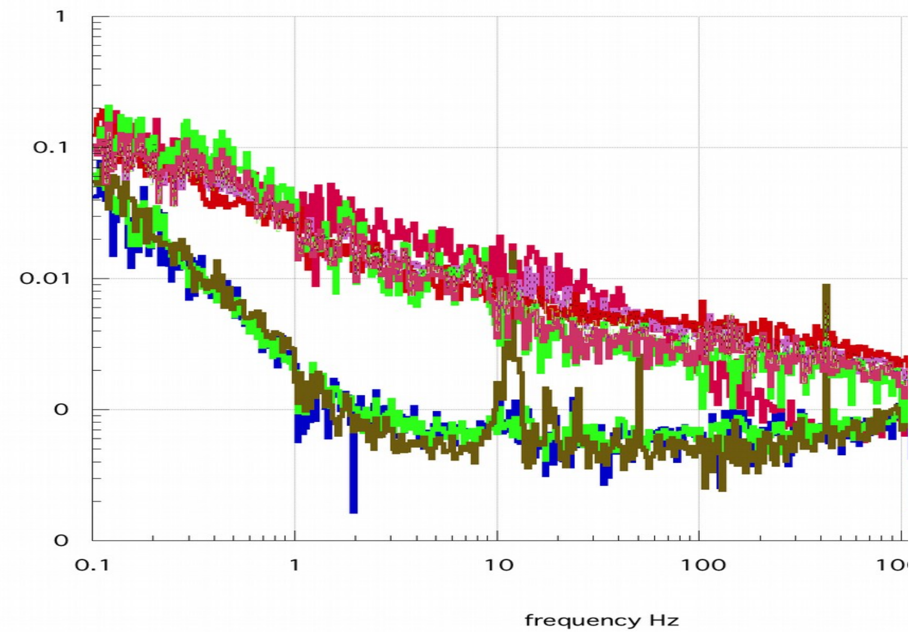


Credit: F. Gatti

TES for LSPE

- TiAu TES with Tc≈530 mK
- NEP ≈ 2-6 x10^{-17} W/sqrt(Hz)





Vbias (uV)	G pW/K	NEP aW/Hz$^{0.5}$
0.5	50	26
1.0	100	38
1.5	200	53
2.0	280	63

Credit: F. Gatti

Conclusions

- Strong European involvement in HF detectors
- Performance of KID for CMB-like missions demonstrated
- A European KID focal plane is possible, and can fit the budget constraints of a (large) European project
- TES are also advancing fast and look promising
- European detectors are an option to be pursued!
- *Need to find the ideal framework!*