UK Technical R&D for Future CMB Experiments

Matt Griffin

Cardiff University

Main UK Institutes and Capabilities

Institutes

- University of Cambridge
- Cardiff University
- Imperial College London
- University of Manchester
- University of Oxford
- RAL-Space (Rutherford Appleton Laboratory)

Interests/Capabilities/Experience

- Detectors (TES, KID)
- Quasi-optics
- Mechanical coolers

- Earth-based and space-borne experiments
- Calibration/systematics/foregrounds
- Data processing

TES Detector Development

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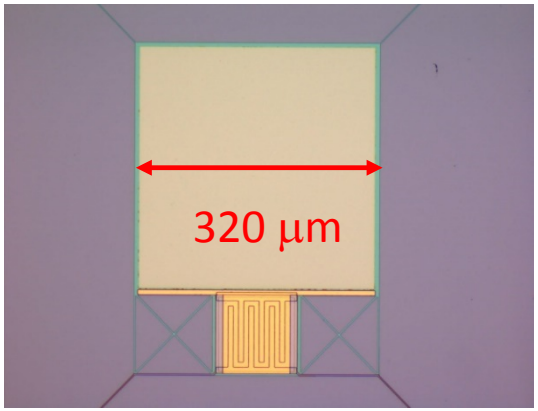
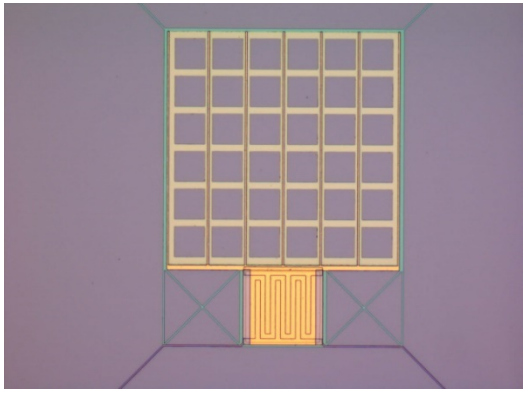
ESA-CTP Programme (Cambridge, Cardiff)

- Feedhorn-coupled TES arrays
- Objectives
  1. Explore fabrication of ultra-low NEP arrays for future space instruments
  2. Raise the TRL of arrays integrated with horn antennas
- Directed initially at developing focal plane technology for SPICA-SAFARI
- Cambridge: TES array manufacture and testing
- Cardiff : Filters and feedhorn manufacture and optical testing

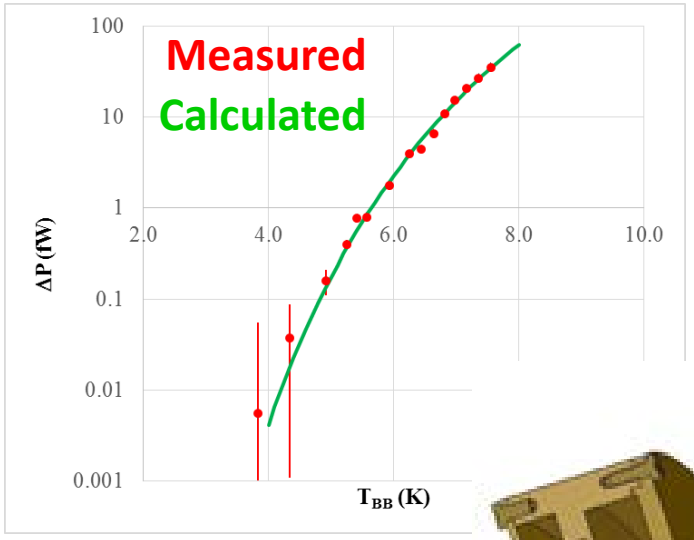
Ultra-Low Noise TES Measurements

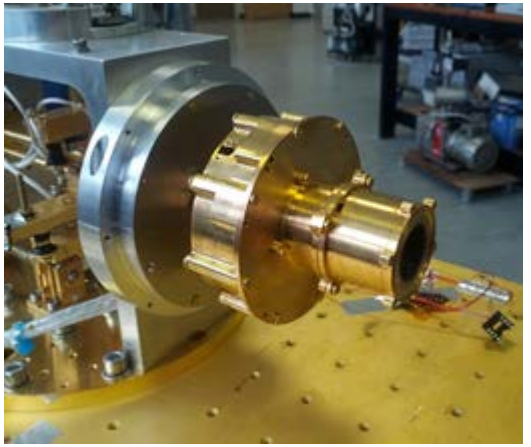


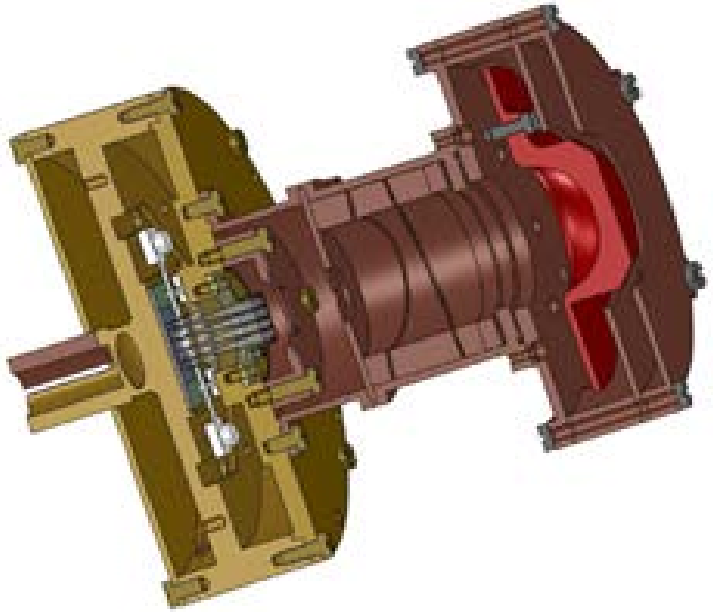


Absorber coupled TESs with full and patterned absorbers for 160 μm

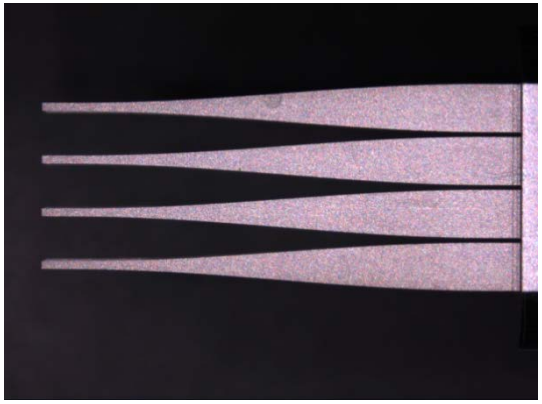
- High TES absorption efficiency

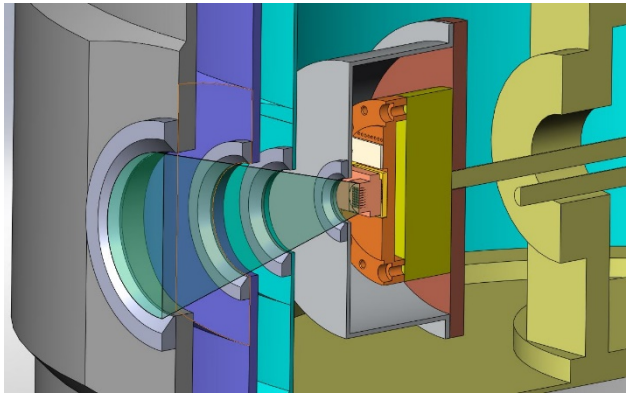


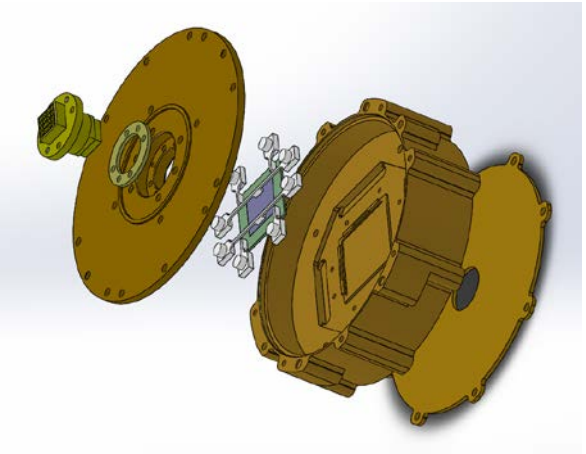


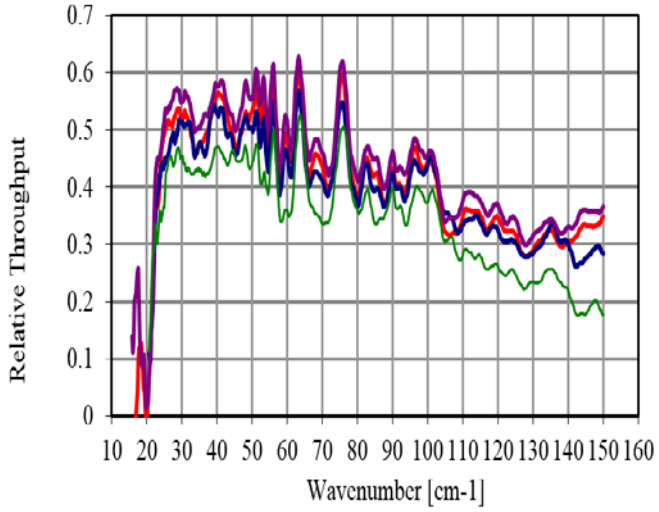


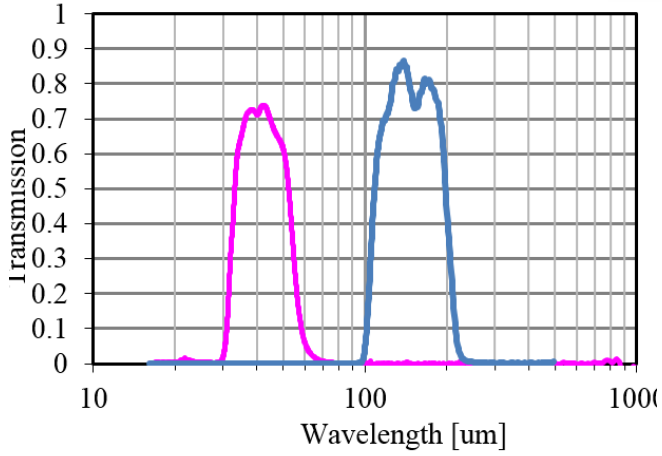
Horn and Filter Performance

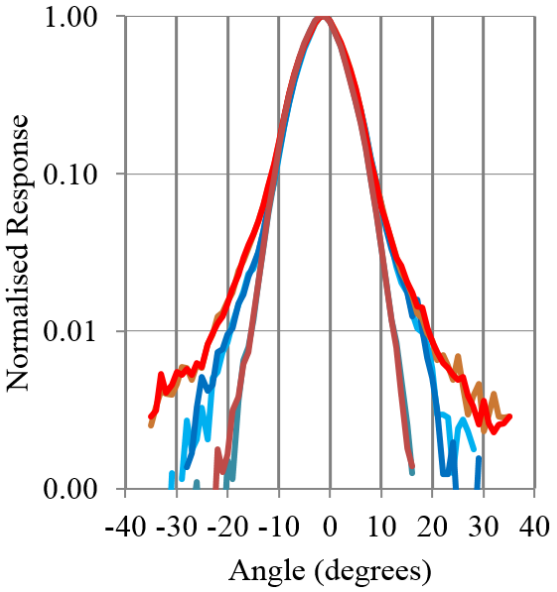






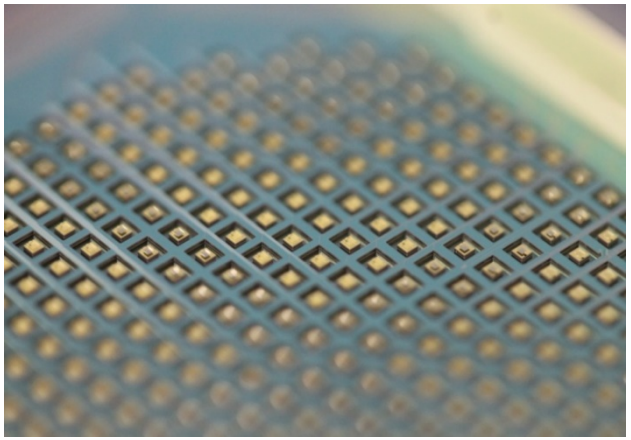




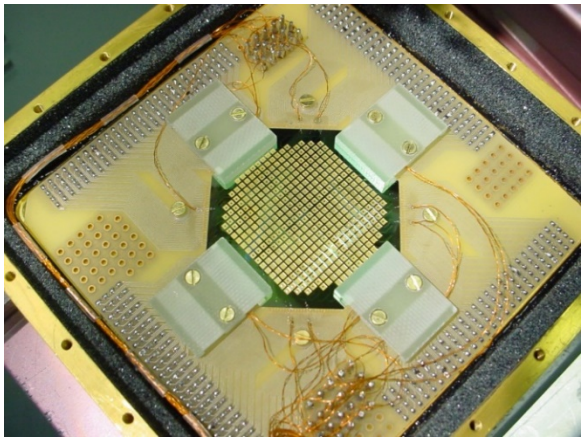


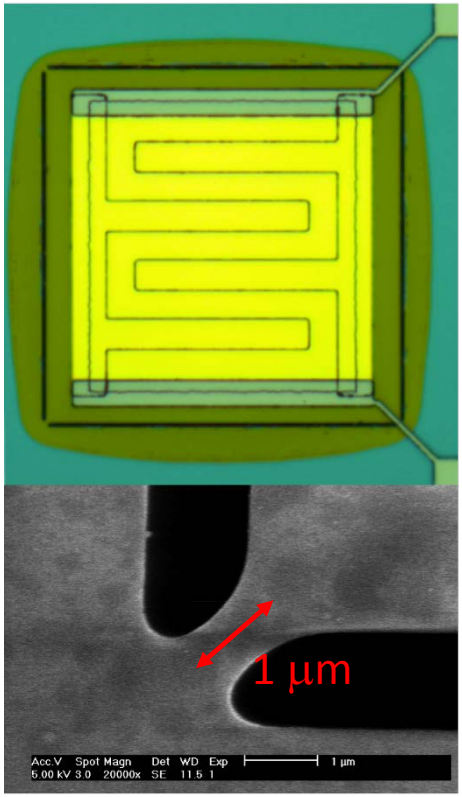
Ultra-Low Noise TES Arrays

Absorber-coupled TES Array with micro-machined back-shorts



384 element array
NEP ~ 4×10^{-19} W/$\sqrt{\text{Hz}}$
T_c =120 mK





Ballistic phonon isolated TESs

- **0.5-µm wide SiN support legs**
- **Only low-order phonon modes contribute to transport**
- **T_c = 100 – 500 mK**
- **NEP ~ 1 x 10^{-18} W $Hz^{-1/2}$**
- **Very close-packed arrays**
- **Suitable for space-borne or ground-based CMB polarimetry**

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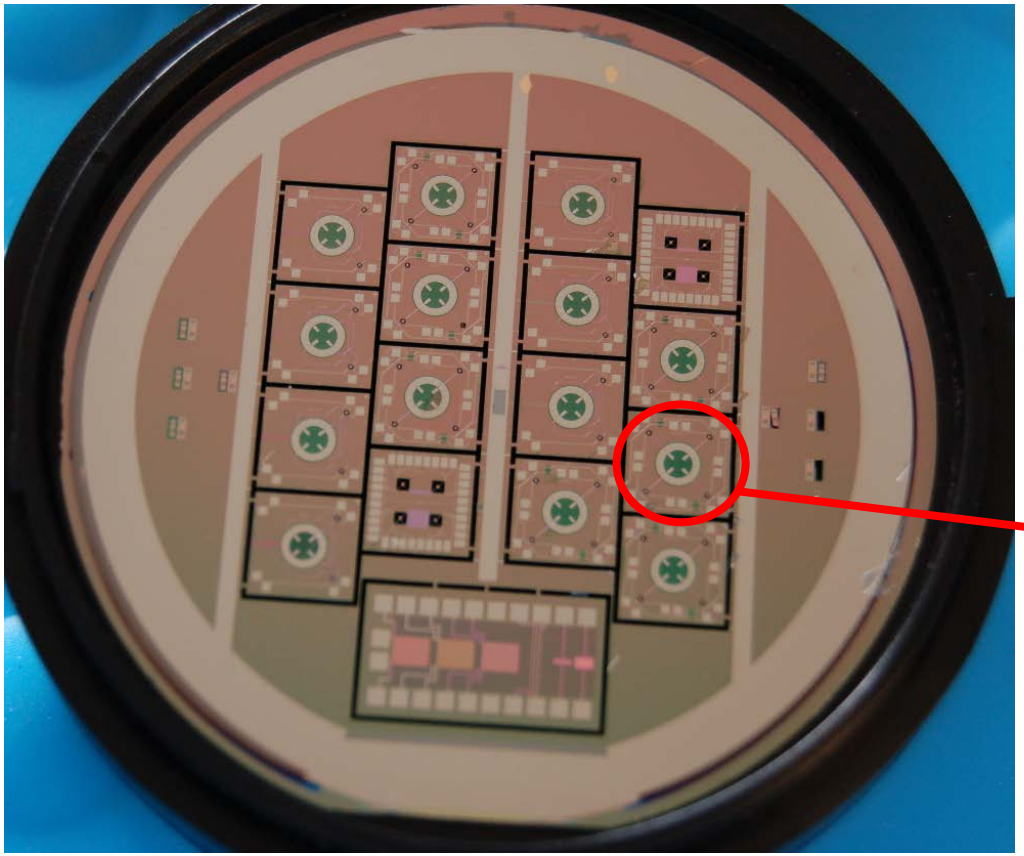
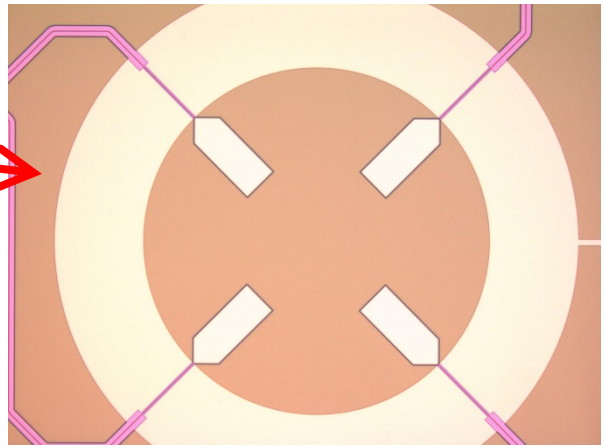
Probe-Coupled TES for CMB Polarimetry



- NEP ~ 2×10^{-17} W Hz$^{-1/2}$
- T_c = 300 mK



Four-probe design with microstrip transition for circular waveguide

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Kinetic Inductance Detector Development

spaceKIDS
Kinetic Inductance Detectors for Space

SPACEKIDS

SEVENTH FRAMEWORK PROGRAMME

- UK, Netherlands, France, Spain
- Three-year EU FP-7 programme (ends Dec. 2015)
- Develop KID technology for space applications
  - Astronomy
  - Earth observing
- KID sensors and arrays
- Optical coupling methods
- Readout electronics
- Two lab demonstration systems in representative regimes
  - Low background (astronomy)
  - High background (Earth observation)
  - Instrument concept studies (Astrophysics/CMB/EO)

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Kinetic Inductance Detectors for Space

Key Objectives

1. Photon noise limited sensitivity
2. Broadband optical coupling with high efficiency
3. Low cosmic ray susceptibility → small data loss due to glitches
4. Low microwave crosstalk between readout channels allowing high pixel count

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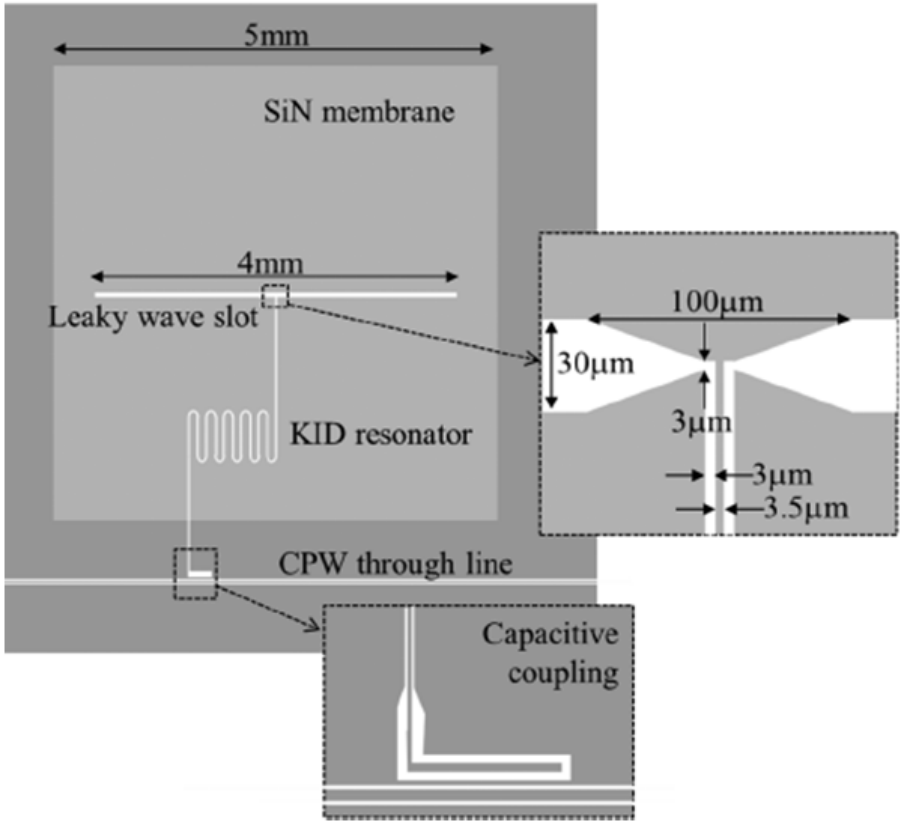
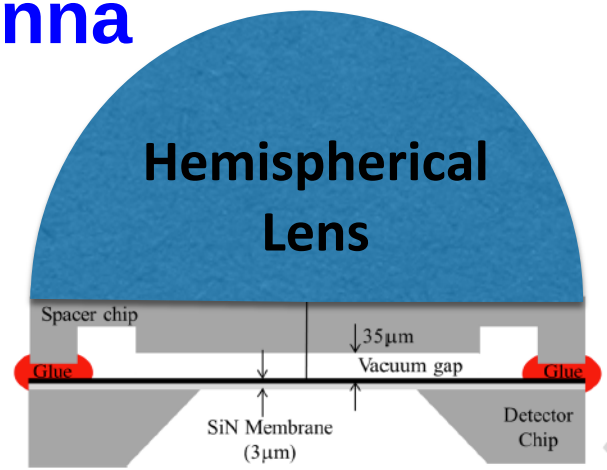
Kinetic Inductance Detectors for Space

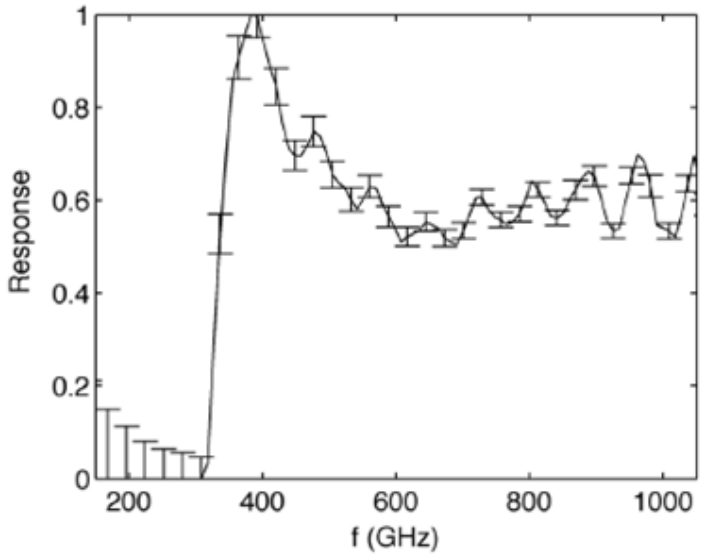
Key Requirements for Demonstrator Systems

	Low background	High background
$P_{Background}$	5 fW	2 pW
NEP	$< 5 \times 10^{-19}$ W $Hz^{-1/2}$	$< 4 \times 10^{-17}$ W $Hz^{-1/2}$
Time const.	1 ms	15 ms
Array size	> 500	> 500
Crosstalk	< 20 dB	< 20 dB
CR data loss	< 10%	< 10%

Broadband Response: Leaky Lens Antenna

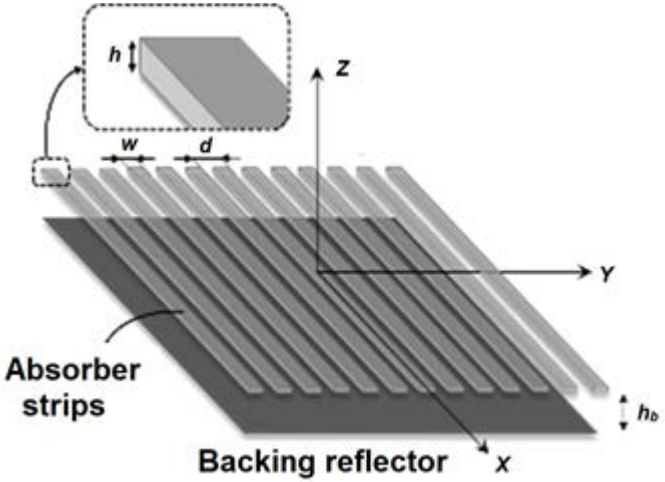


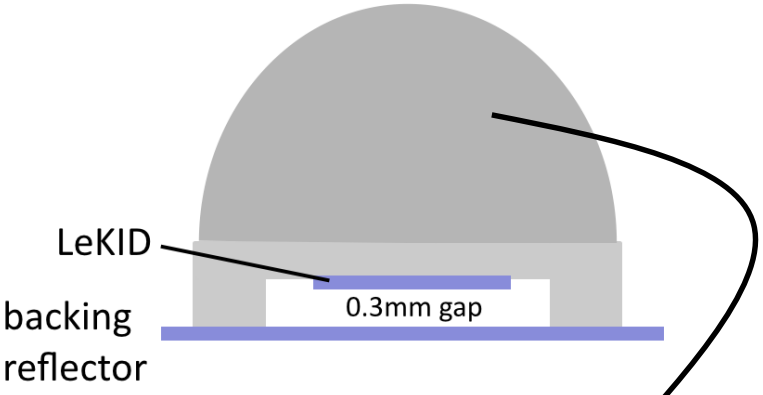


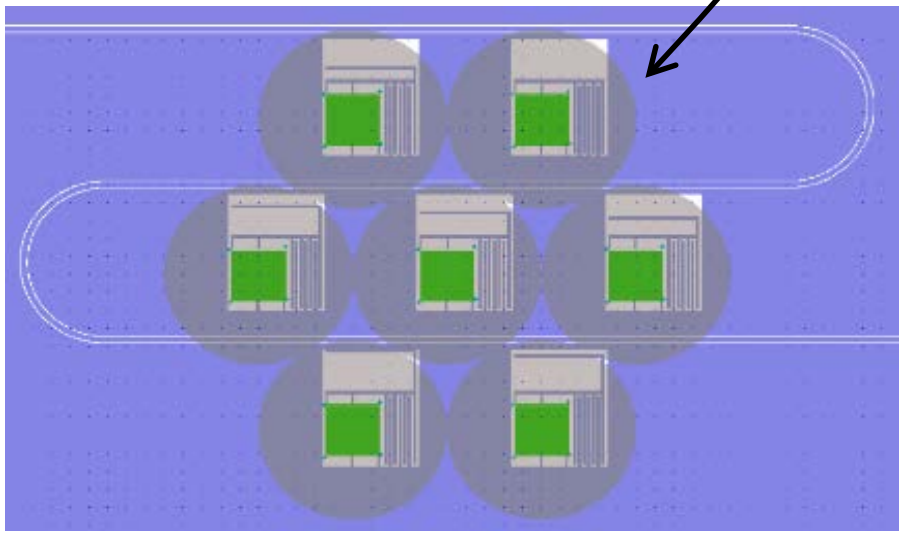


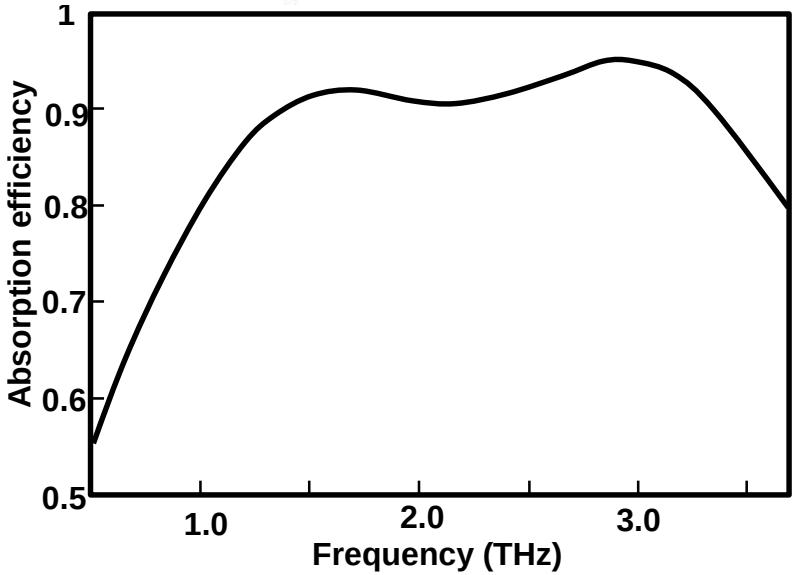
Neto et al. IEEE Trans THz Sci. Technol., 121, 2013.

Broadband Response: Absorber-Coupling









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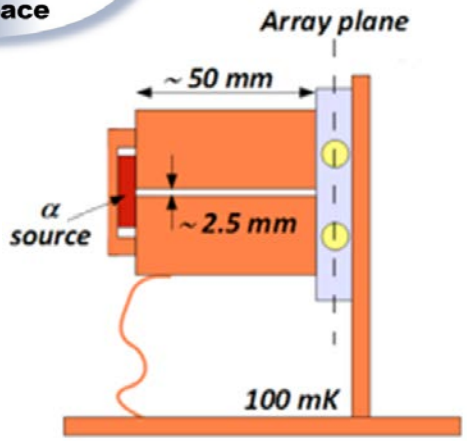
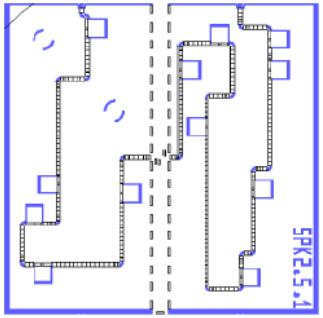
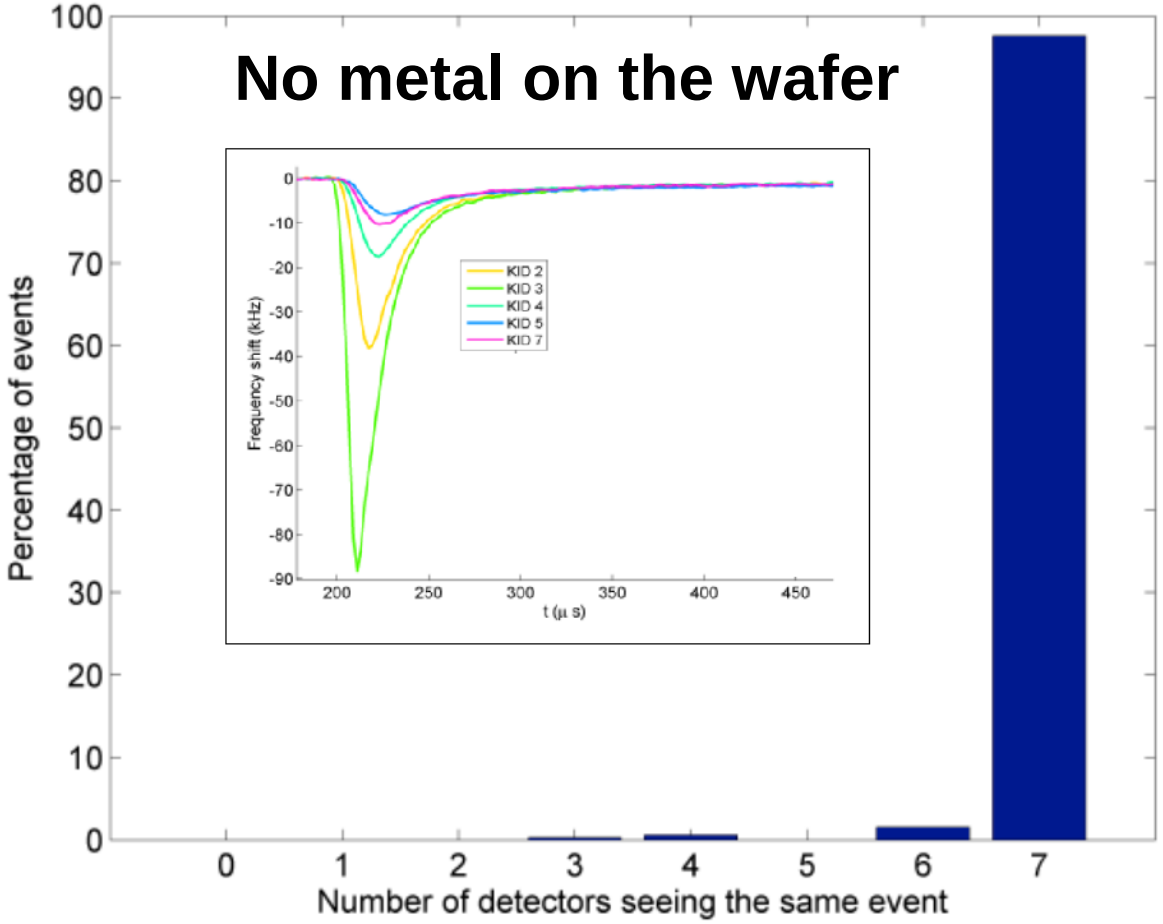
Kinetic Inductance Detectors for Space

Cosmic Ray Rejection



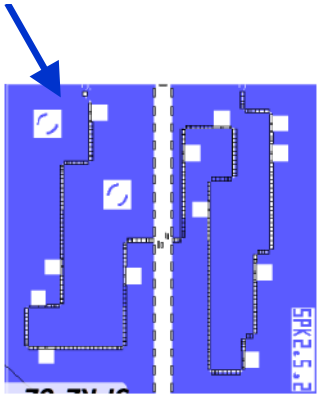


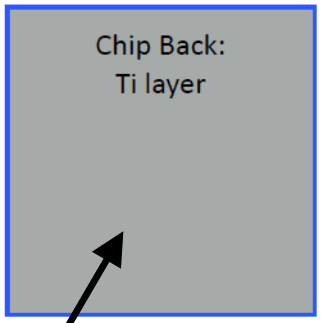
Chip Back:
bare Si



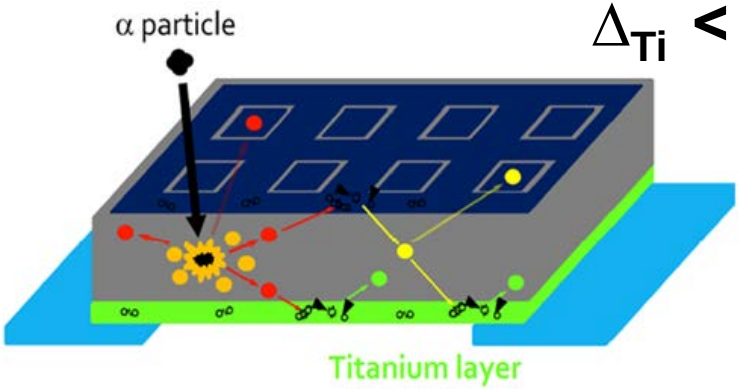
Cosmic Ray Rejection

Al on front side

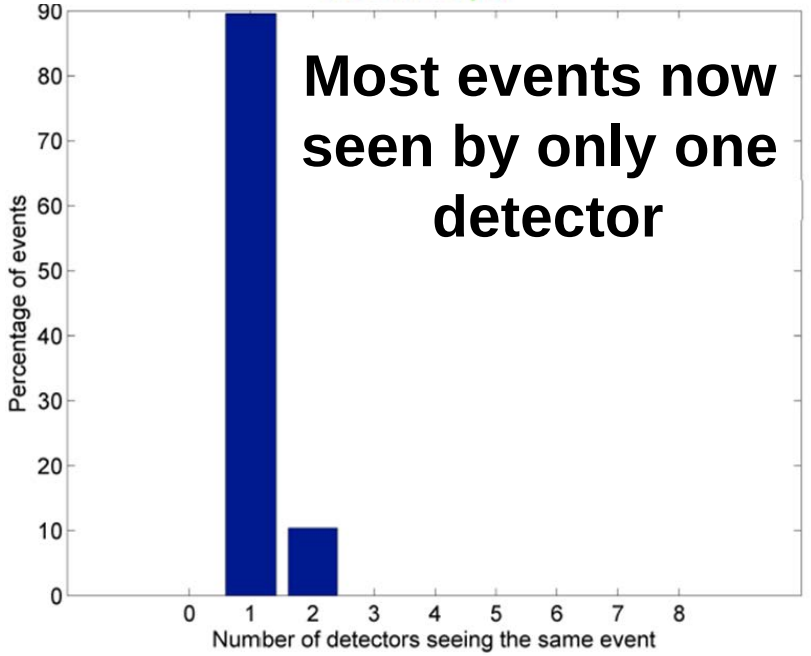


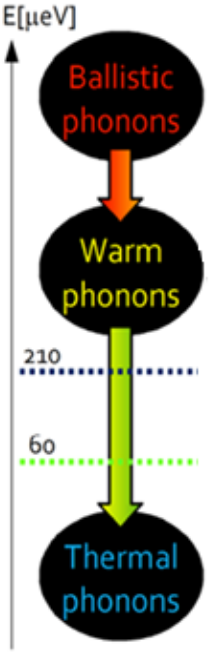


Ti on back side



$\Delta_{Ti} < \Delta_{Al}$





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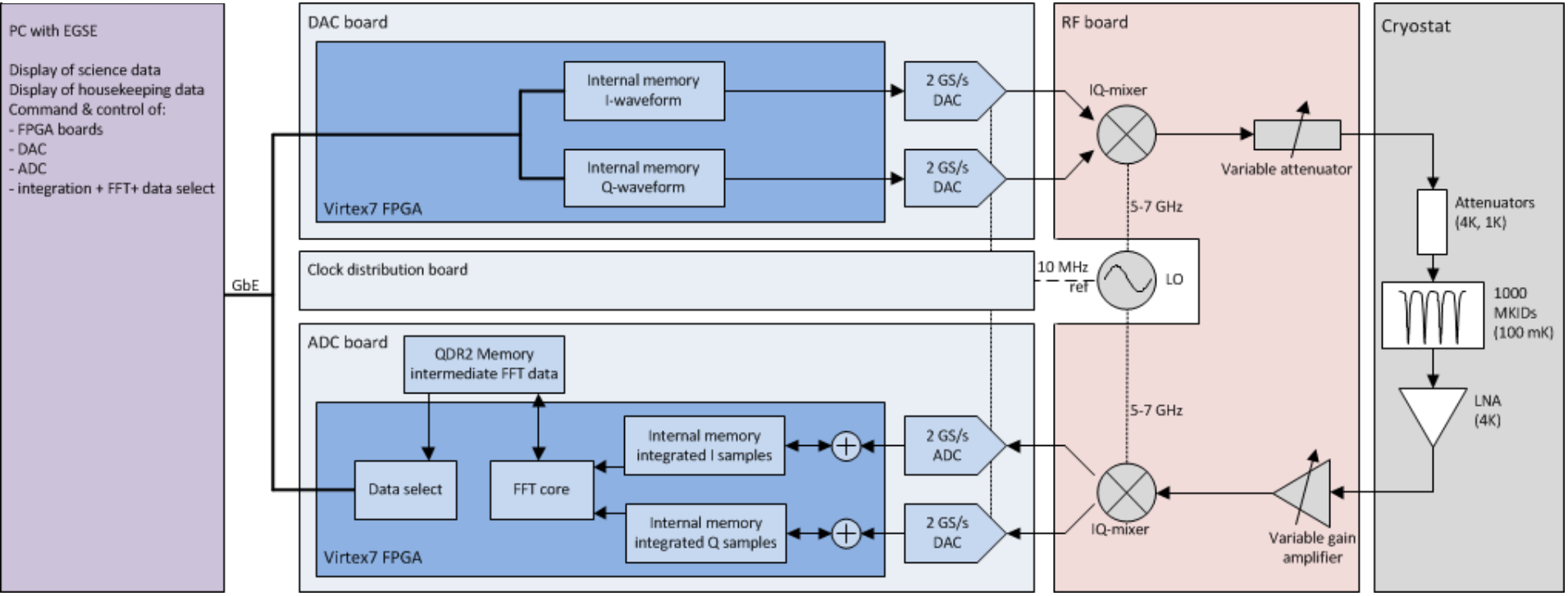
Readout Electronics Architecture



- **Number of tones: up to 2200**
- **Band: 2-4 or 4-8 GHz**
- **Further work at SRON to develop a space-worthy version**

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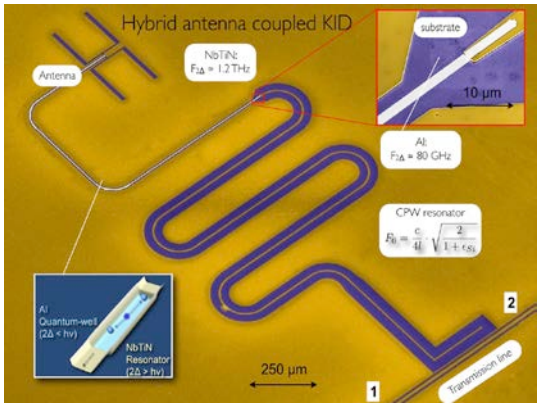
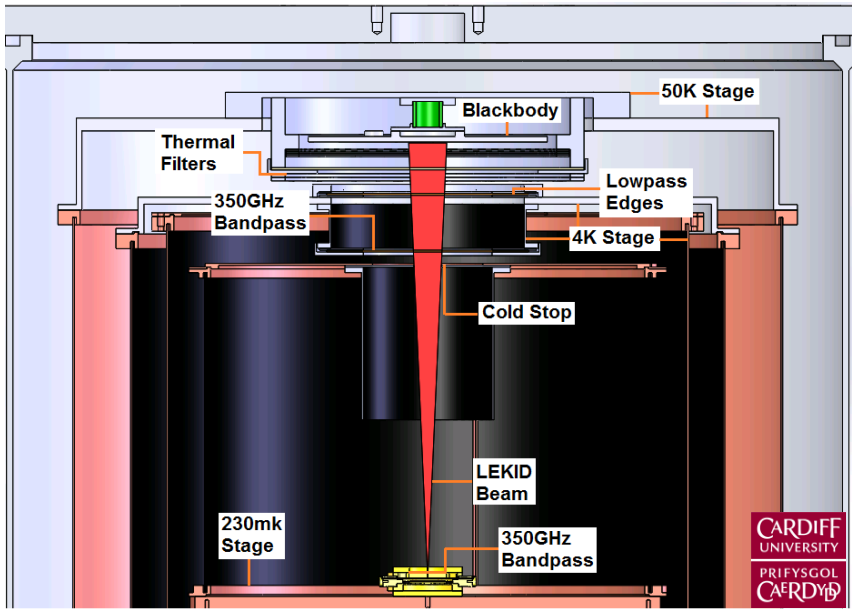
Kinetic Inductance Detectors for Space

Med-High Background Test Programme

- **AMKID-type 350 GHz array**
  - **~ 800 pixels**
  - **NbTiN / Al hybrid MKIDs**
- **Dual-polarisation LEKID 350 GHz array**





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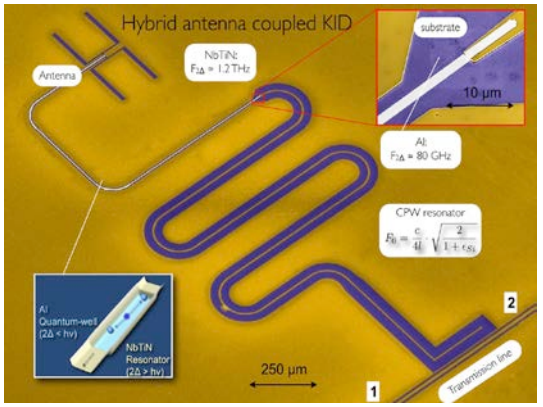
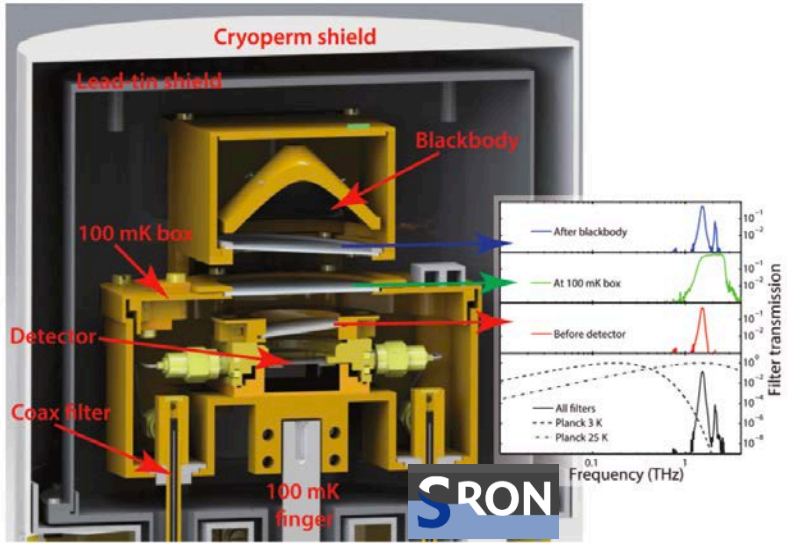
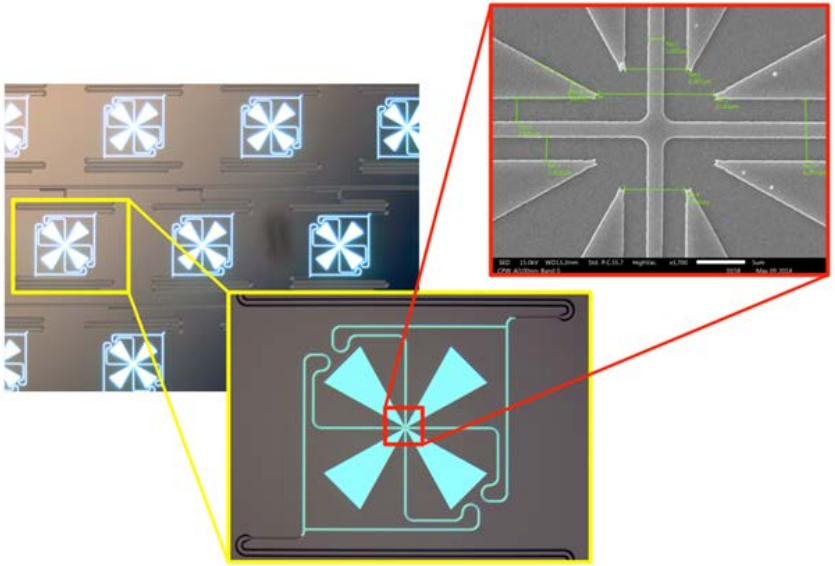
Low Background Test Programme

- 1000-pixel 850-GHz Array
  - Twin-slot antenna-coupled
  - NbTiN/Al hybrid MKIDs
- ~800-pixel 1.6 THz Array (broadband leaky wave lens antenna-coupled)







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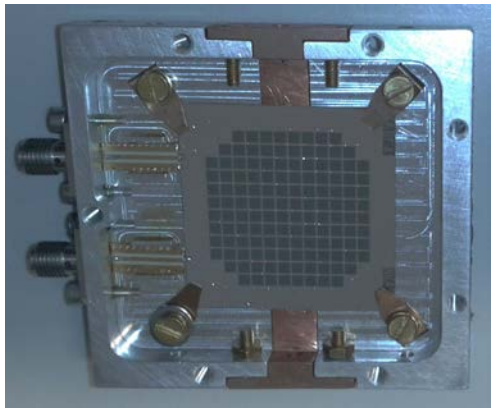
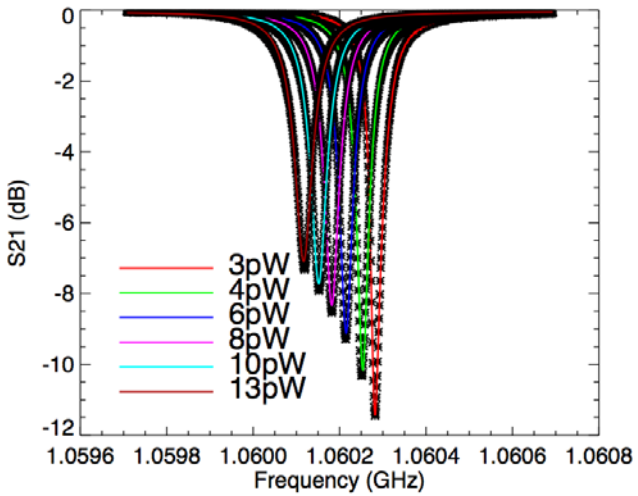
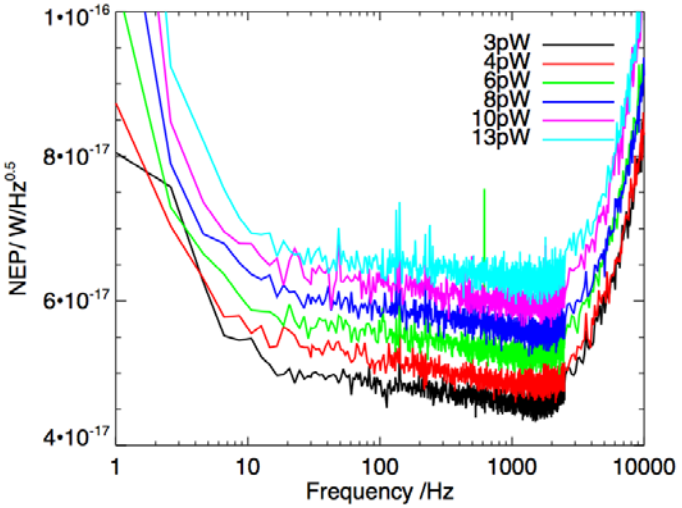
Large-format Imaging Arrays for NIKA

- **Photon noise limited performance under loads typical of a CMB experiment**
- **Spectral band can be tuned to by adjusting wafer thickness and back-short distance**
- **Possible to optimize for a single polarization**







Mauskopf, et al, 2014,

KID Development at Cambridge

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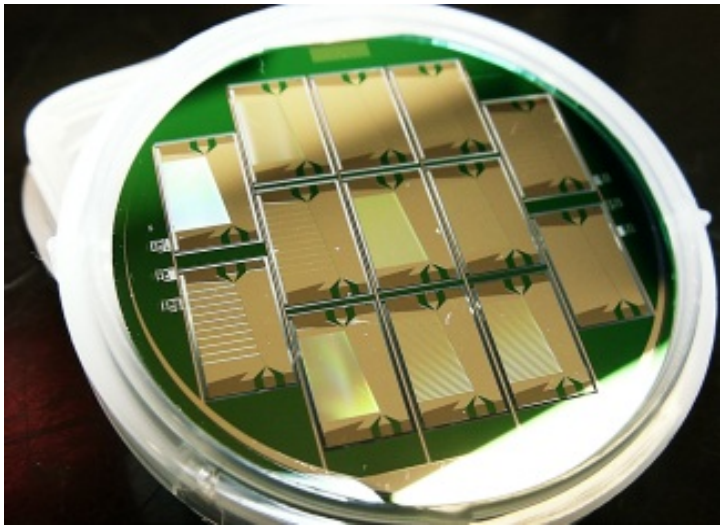
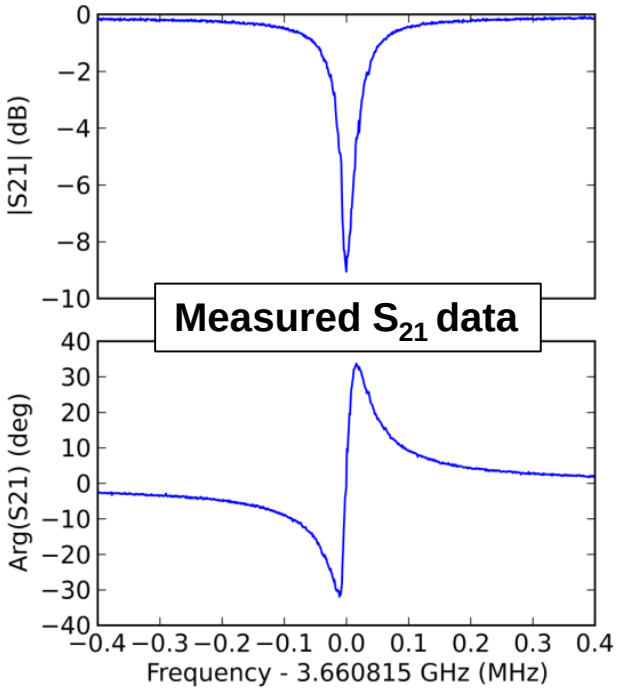
- CAMELS (Cambridge EMission Line Surveyor)
  - Collaboration with Harvard CfA
  - Pathfinder instrument for on-chip spectrometry
  - 103-115 GHz range with R ~ 1000
- KIDs fabricated and tested at Cambridge





KID Development at Cambridge

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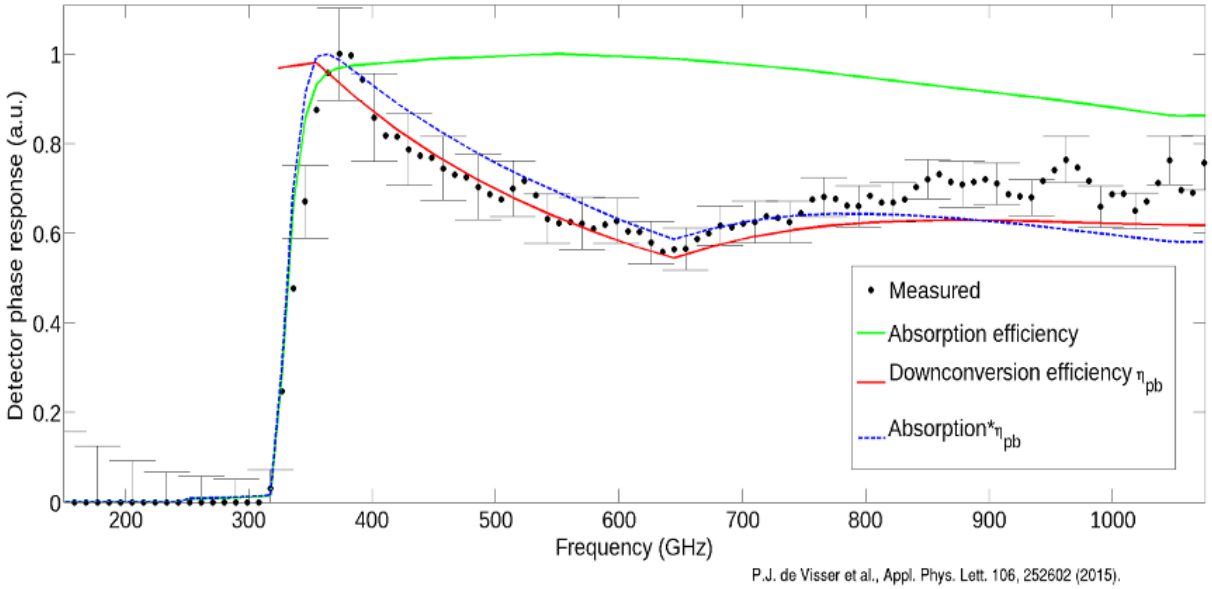
- **Simulation and theory**
  - **Simulations of non-equilibrium quasiparticle distribution and dynamical behaviour of resonators in presence of readout- and optical-forcing**
  - **Large and small-signal electro-thermal models of KIDs, including noise and feedback mechanisms**



Model calculated using Cambridge non-equilibrium code.

KID Development at Cambridge

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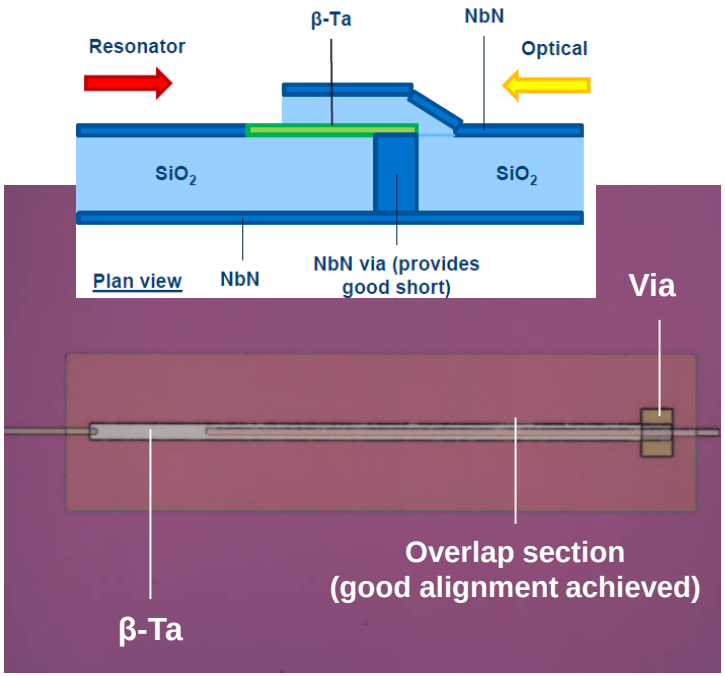
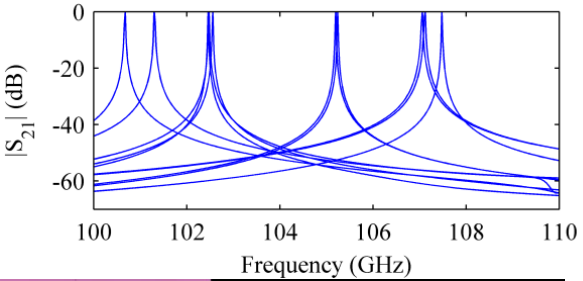
Low-frequency operation

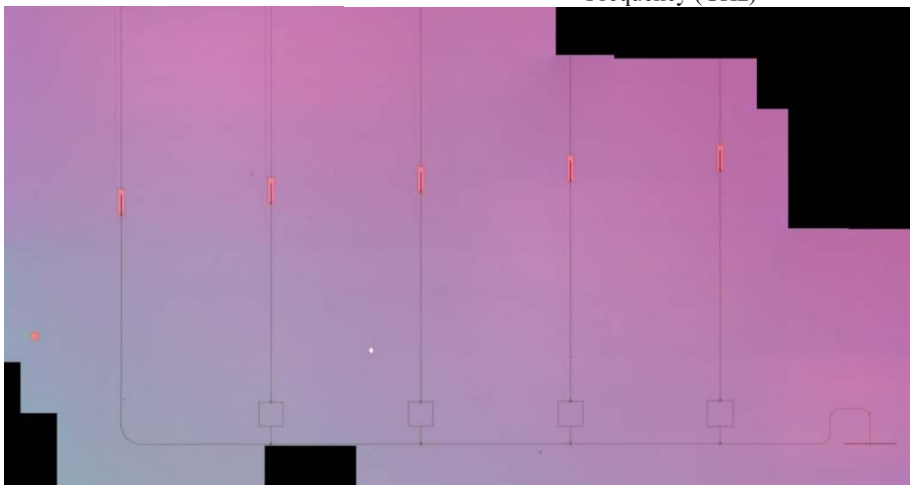
- Investigating materials for 70-110 GHz operation
- Devices with β-Ta sensing sections fabricated and in testing
- Thermal KIDs (TKIDs)
  - Theory and simulation effort



Filterbank spectrometers

- On-chip filter-bank with high R for CAMELS.
- Multiple low-R channels could be useful for foreground removal





Multiband Horn-Coupled Polarimetry

- Plan to demonstrate multi-band probe-coupled pixel with planar filters feeding LEKIDs in both polarizations and across a several photometric bands
- Study
  - Feedhorn vs lens coupling
  - Band-defining filter architectures (distributed vs lumped element) coupled to LEKID absorbers
- Design, fabrication and characterization
  - Spectral response
  - End-to-end optical efficiency
  - NEP
  - Cross-polarization

Optical Modelling and Measurement

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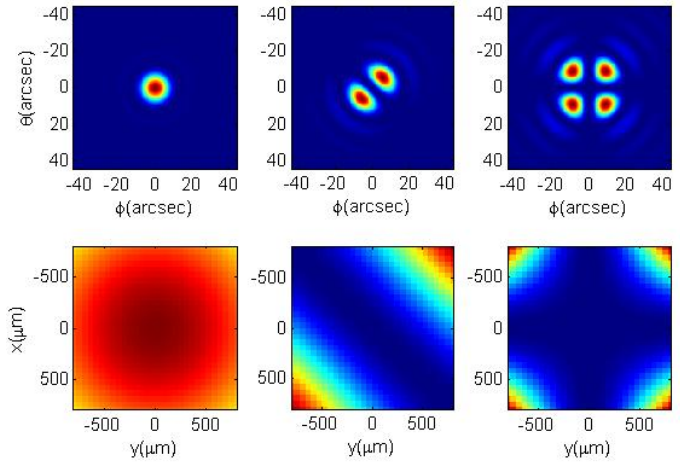
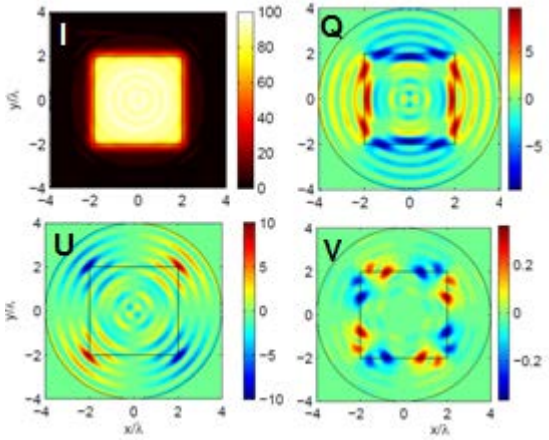
- **Few-mode simulations of SPICA/SAFARI and optical test system, including photon noise and polarisation response.**



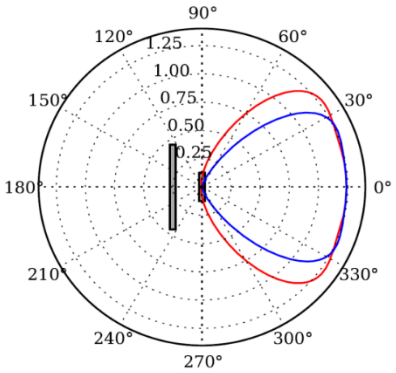
Simulated response of highest-order modes on sky and at SPICA focal plane

- **Few-mode simulations of free-space coupled and waveguide-mounted absorbers**

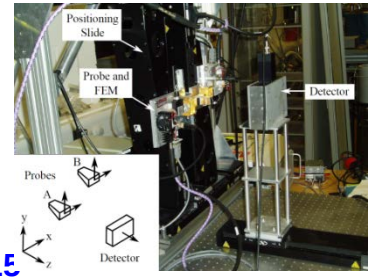


Stokes response of a waveguide mounted absorber.

- **Experimental methods for optical characterisation of few-mode detectors**



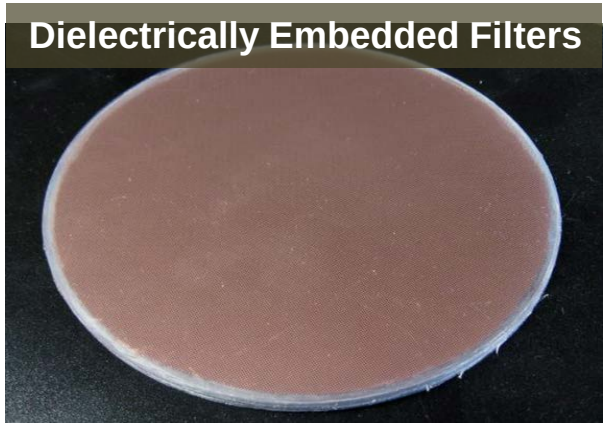
Beam pattern of small, back-shorted, absorber

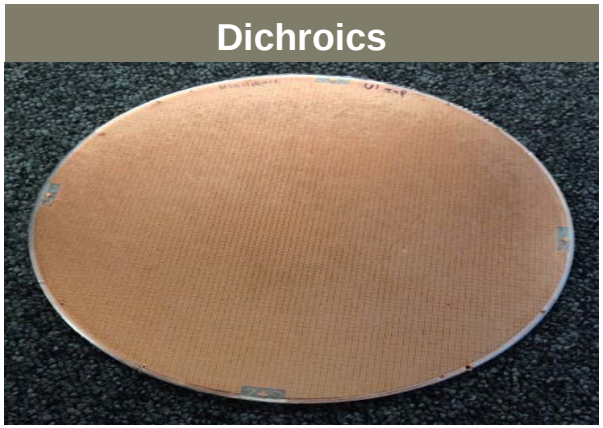


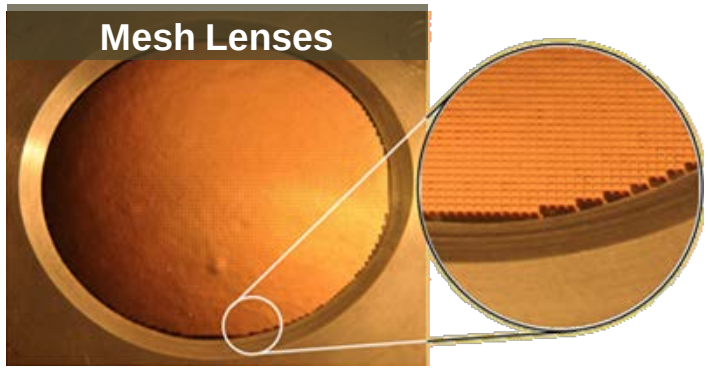
Quasi-Optical Components

Quasi-Optical Components

- Filters
- Polarisers
- Beam dividers
- Lenses
- Windows
- Waveplates
- AR Coatings
- Etc.

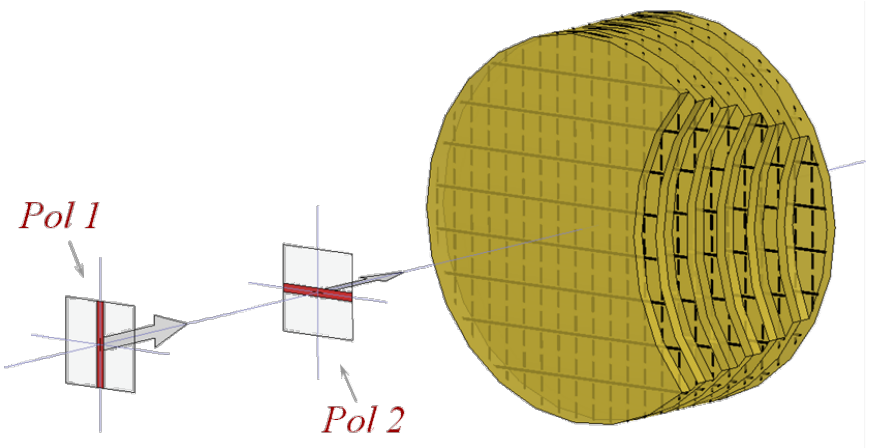


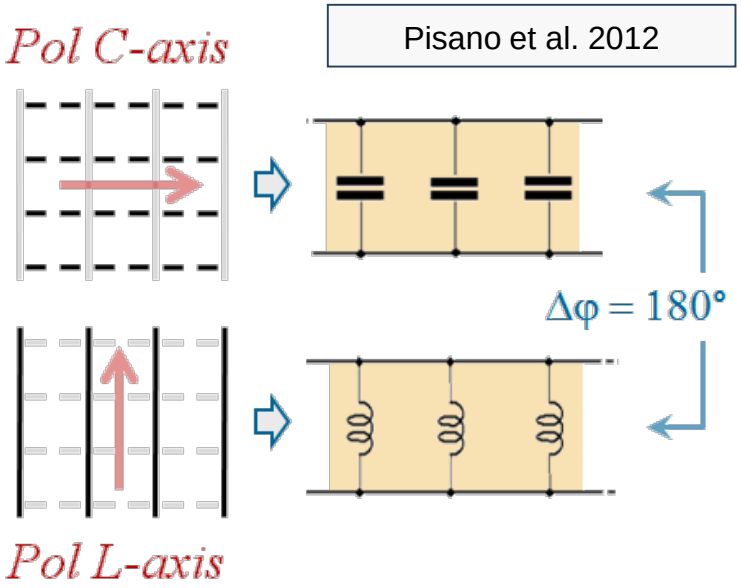


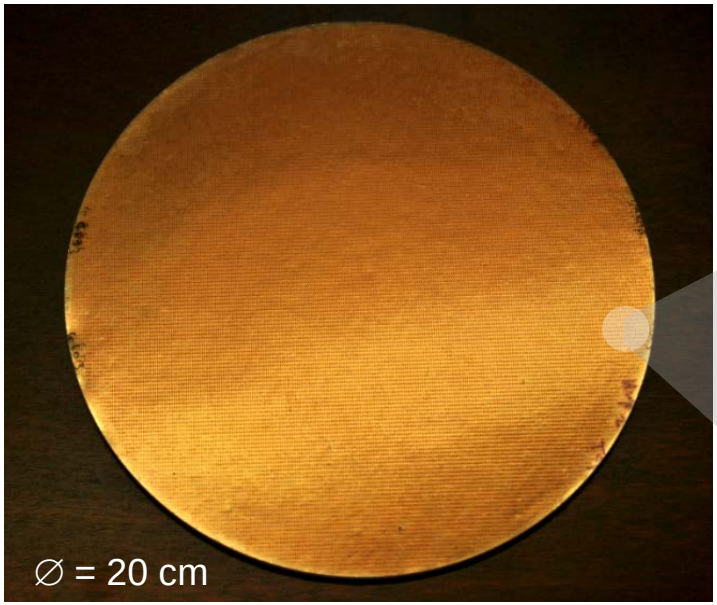


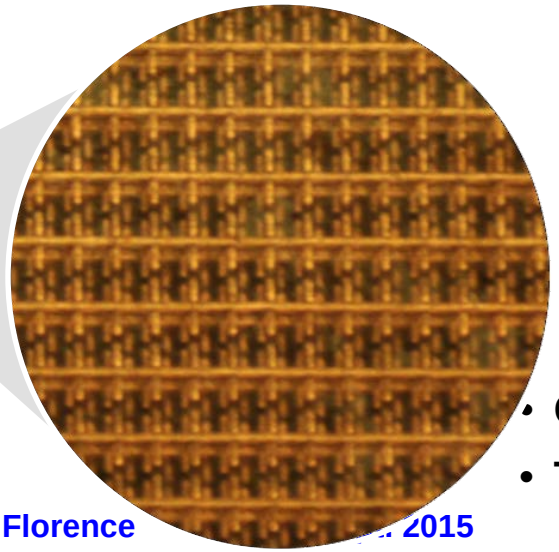
- Design, modelling, manufacturing and test facilities
- Including large (> 0.5-m) components

Dielectrically Embedded Mesh Half Wave Plates





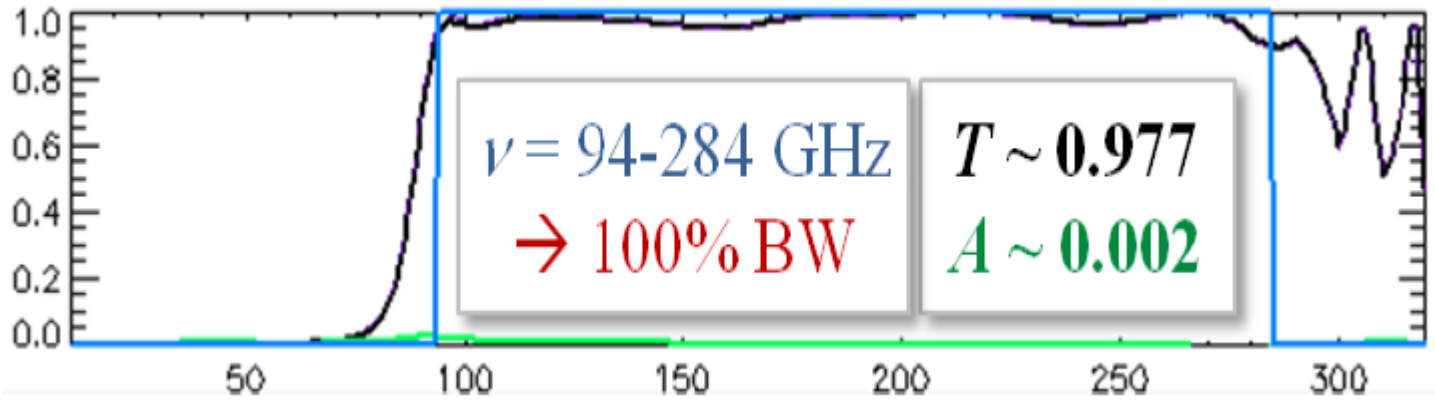


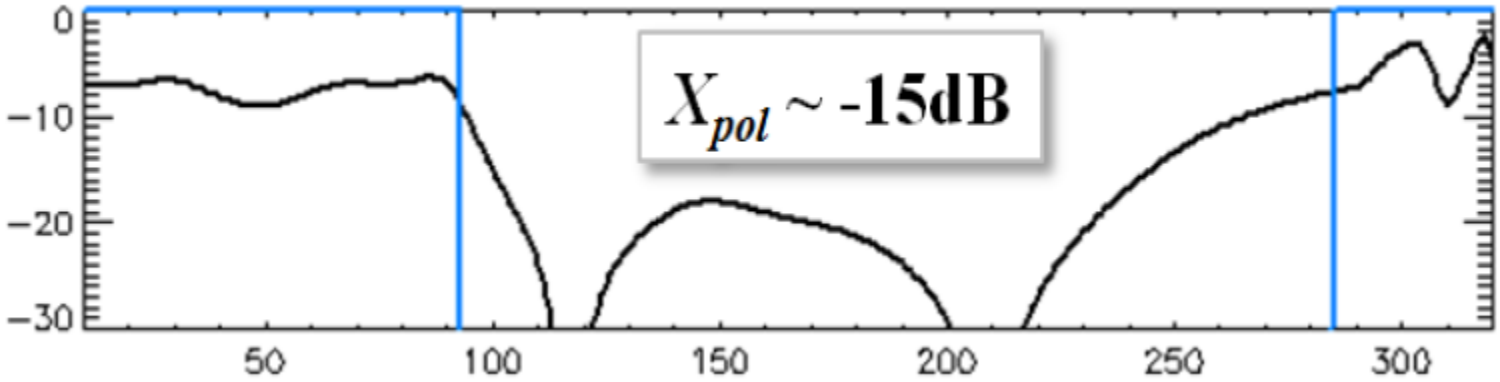


Other devices:

- **QWPs** (linear ↔ circular)
- **TPRs** (pol rotation)

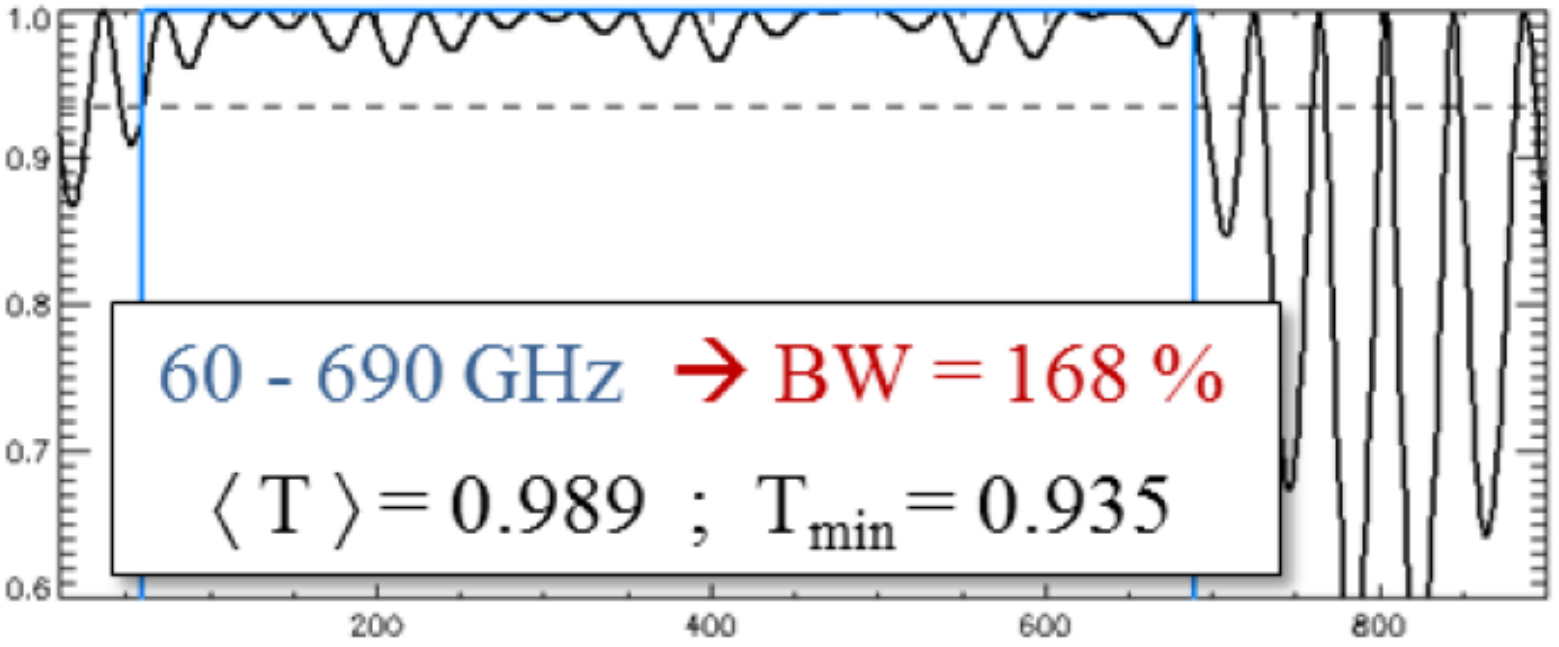
Large-Bandwidth HWPs



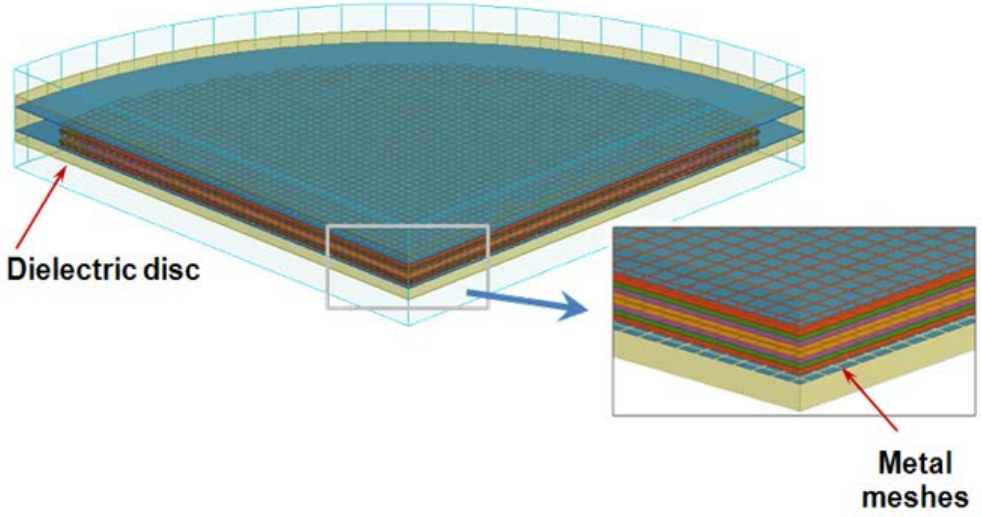


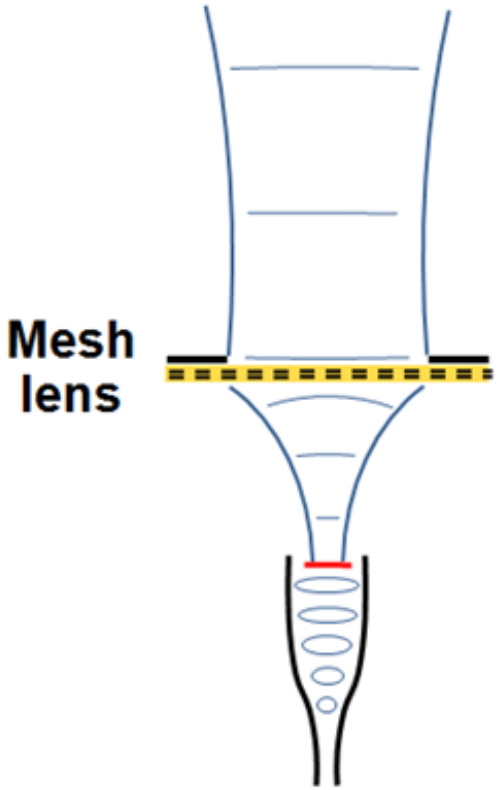
Mesh Antireflection Coatings

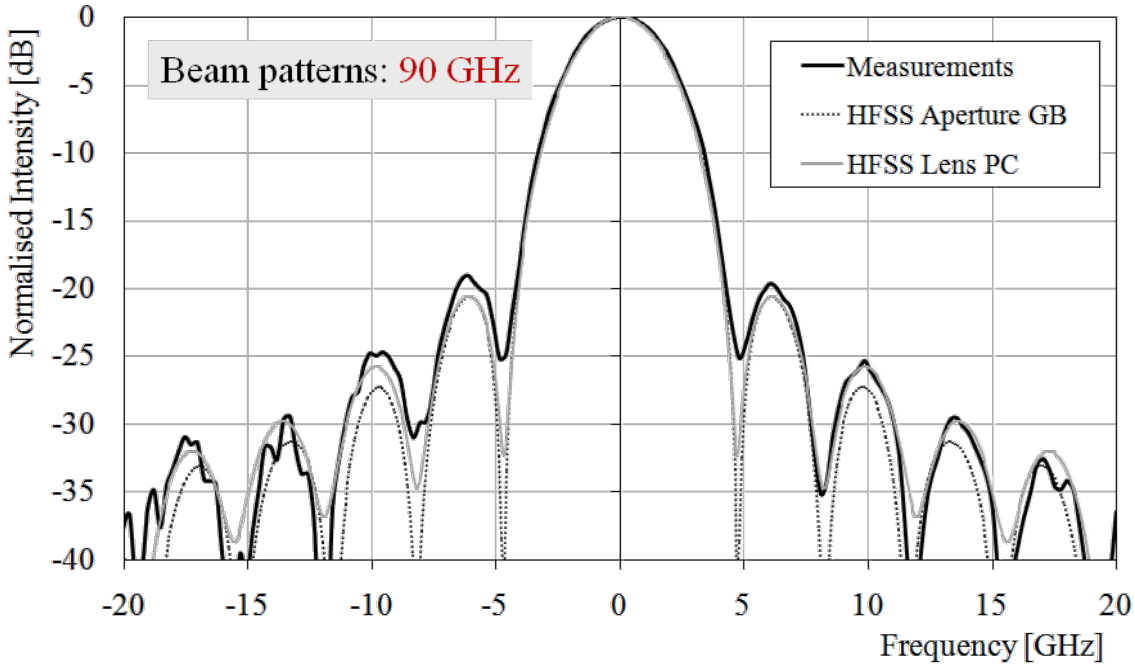
- **Mesh-based artificial dielectrics with specifically tuned refractive indices**
- **Large bandwidth (>160%) polypropylene-based ARC**



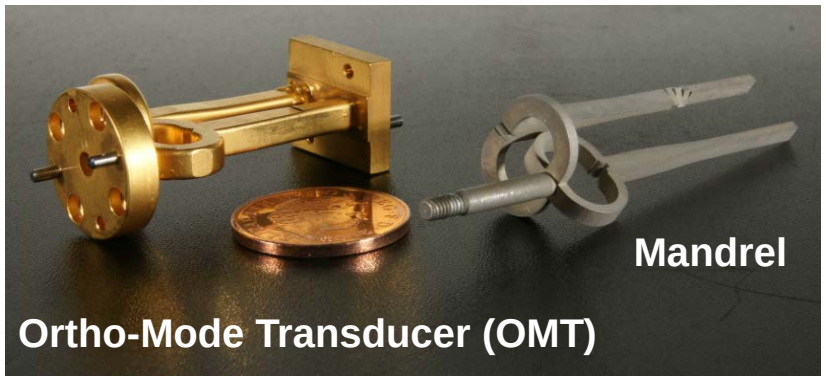
Flat Lenses

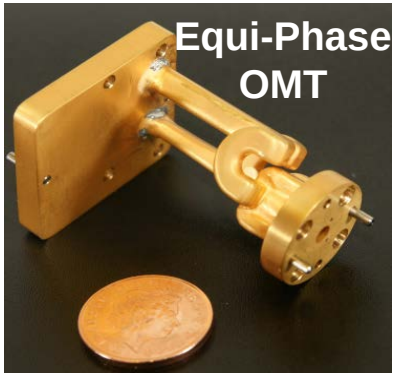

Dielectric disc
Metal meshes

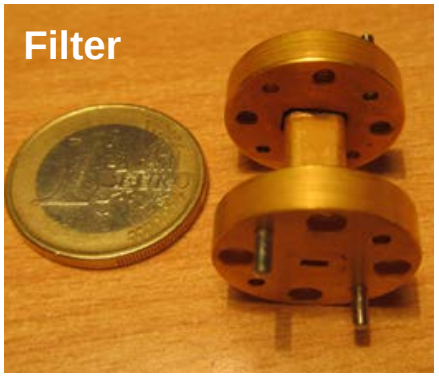

Mesh lens

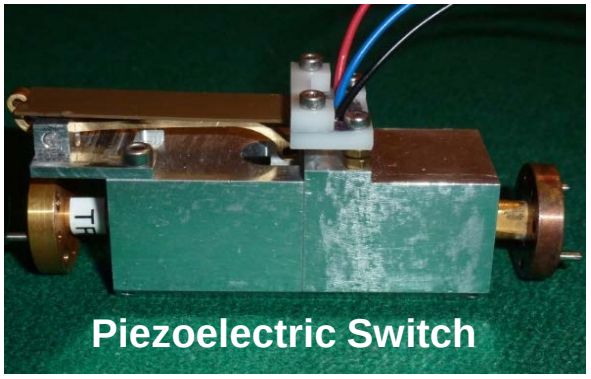

Beam patterns: 90 GHz
Measurements
HFSS Aperture GB
HFSS Lens PC
Normalised Intensity [dB]
0
-5
-10
-15
-20
-25
-30
-35
-40
-20
-15
-10
-5
0
5
10
15
20
Frequency [GHz]

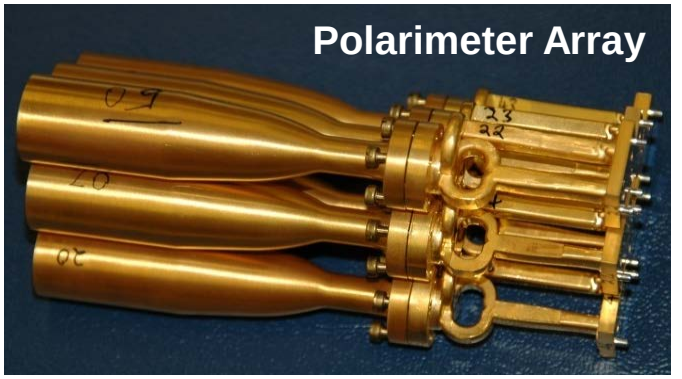
RF Components





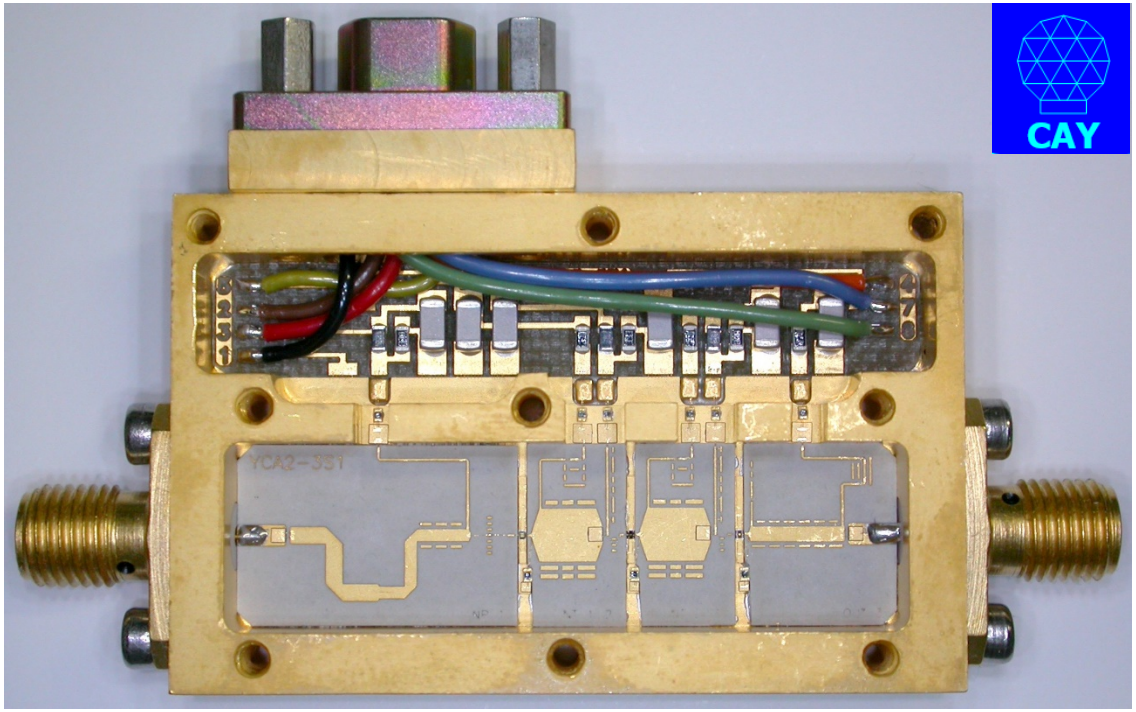






Low-noise Microwave Amplifiers

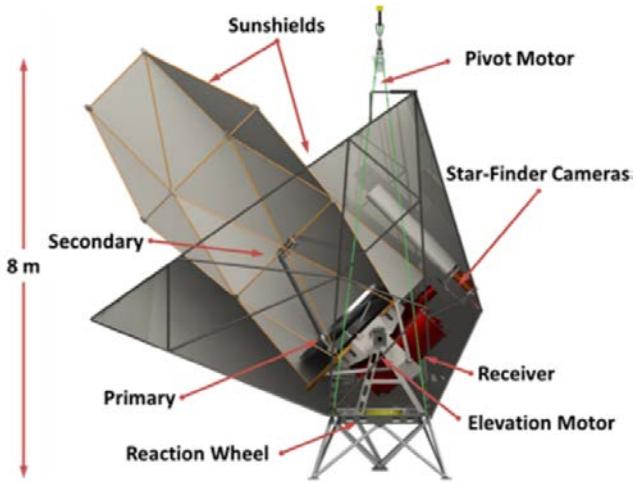
- **4-8 GHz amplifiers (from Centro Astronómico de Yebes)**
- **T_{noise} ~ 3.5 K at 20 K operating temperature**
- **Flat across the band to 0.5 dB**

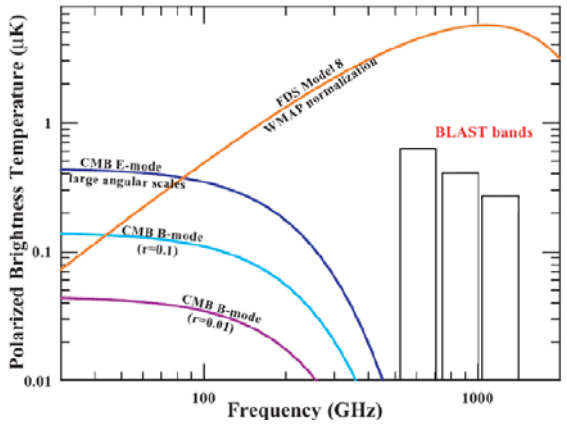


Participation in US Balloon Experiments

BLASTPol and BLAST-TNG

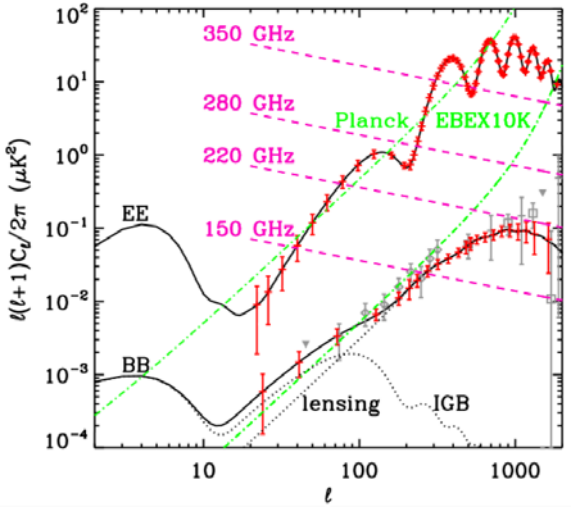
BLASTPol and BLAST-TNG



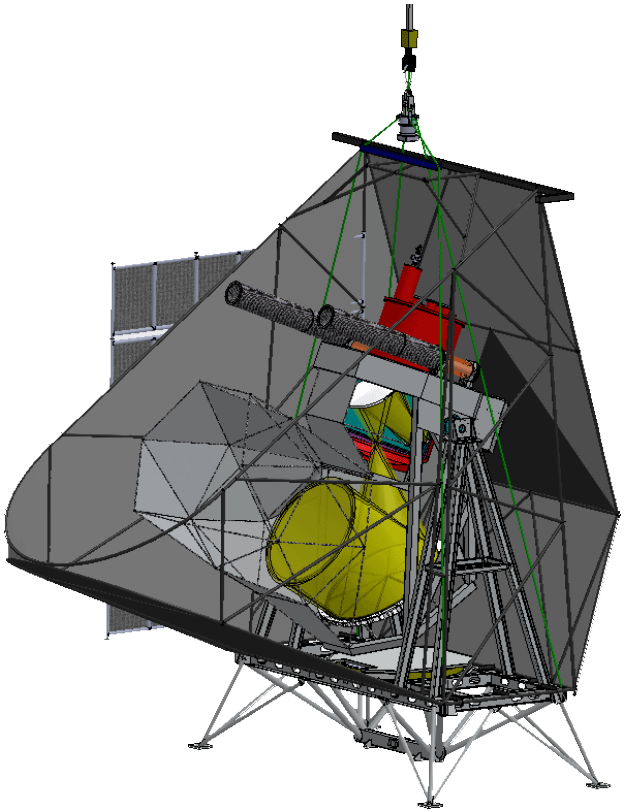


EBEX and EBEX10K

- **11,000 detectors**
- **Lens-coupled sinuous antenna multichroic pixels**
- **150, 220, 280, and 350 GHz**



BFORE

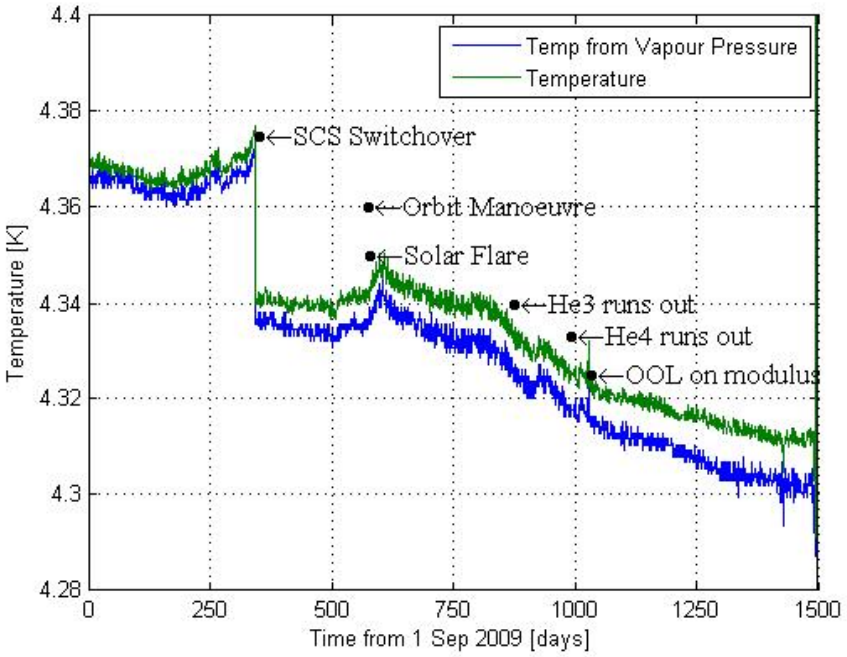


- ~ 8,000 TES detectors (270, 350 GHz)
- ~5 000 KID detectors (600 GHz)
- 1.35-m telescope with 4 K secondary
- Long-duration (> 28 day) Antarctic flight
- 10,000 deg^2 overlapping ACT, BICEP2,
- CLASS, PolarBear and SPT
- Proposed first flight – Dec. 2018

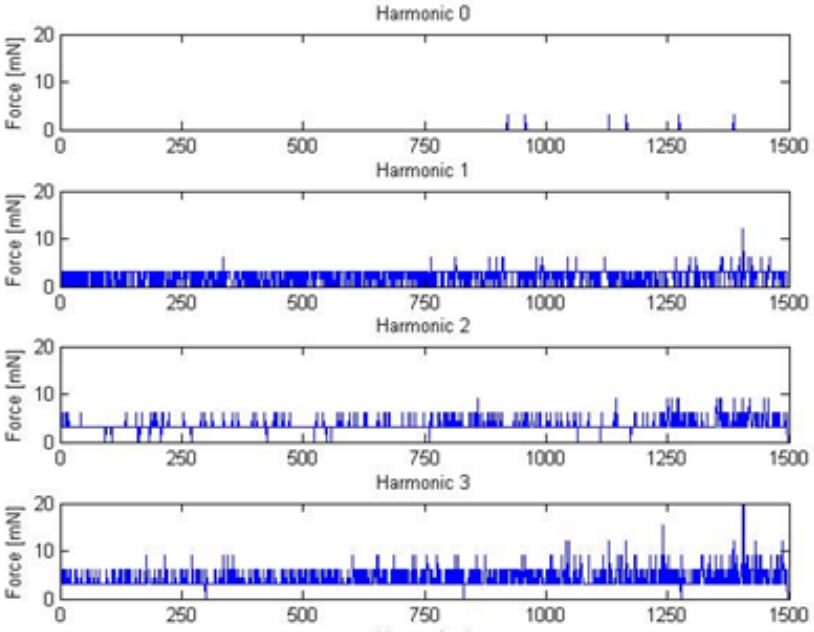
Mechanical Coolers

Planck 4-K Cooler

- **Low vibration**
- **Temperature stability ~3.6 mK/year**



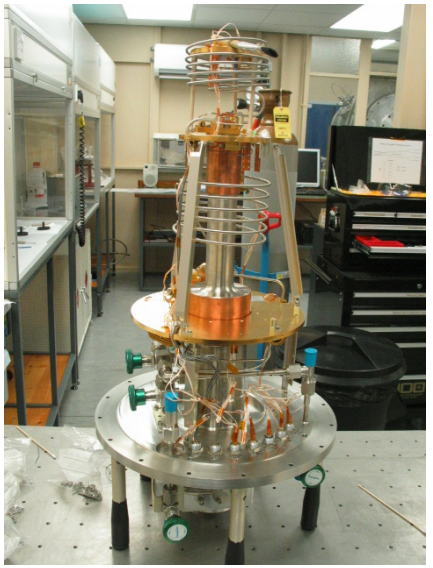
Temperature evolution over the mission

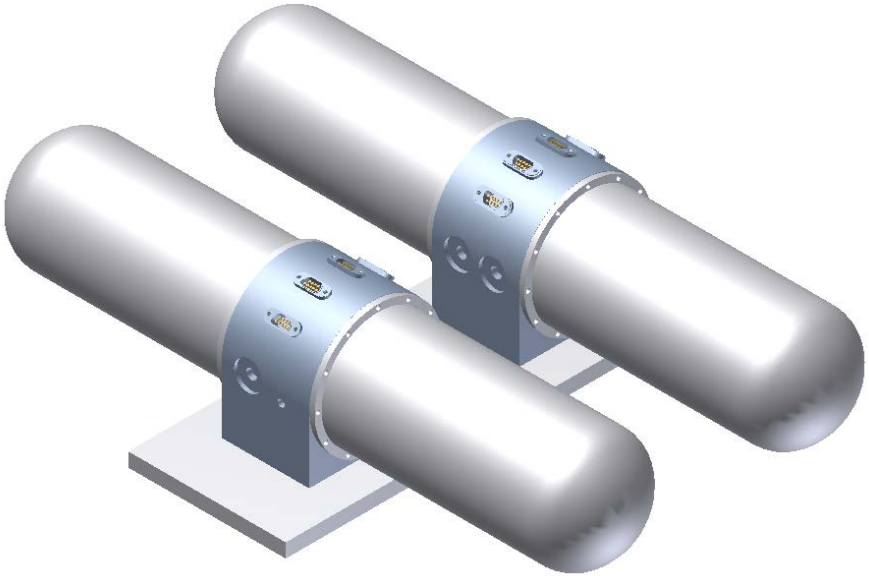


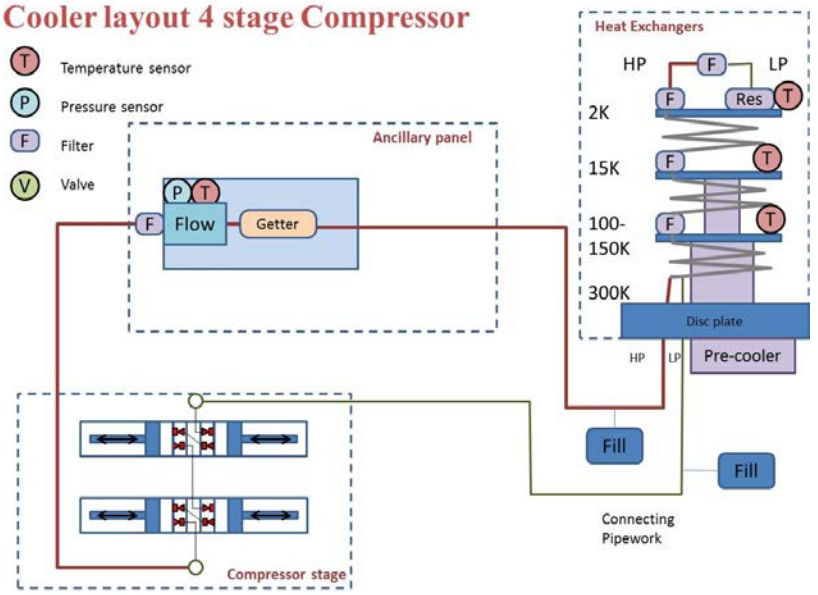
Very low exported vibration from the cooler to the spacecraft

2-K Cooler Development

- **Aimed at future cryogen-free science missions requiring cooling chain to < 100 mK**
- **Builds on *Planck* design, with improved mechanisms and low vibration systems**
- **Cold plumbing tested**
- **Manufacture of compressors underway**
- **To be used by ESA to demonstrate 50-mK cryogenics chain for use in missions such as Athena+, CoRE+**

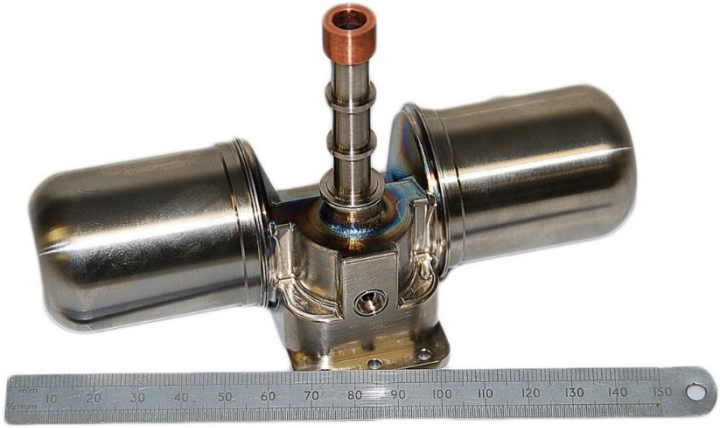






Miniaturisation and Integration with Sub-K Coolers

- **Looking at cooler miniaturisation using new motor mechanisms**
- **Also looking at additions of further stages to get down to 50-300 mK**



SMALL SCALE COOLER PRODUCT SPECIFICATION	
Mass (excluding CDE)	650g
Size Envelope (excluding DCE)	144 x 61 x 93mm
Input power (750mW@77K, +20°C rejection)	25W
Operating environment range	-30°C to +50°C
Lifetime	>50 000hrs

All-sky Foreground Characterisation from the Ground

- **Foregrounds key for accurate CMB measurements**
- **C-BASS has demonstrated that it's possible to do all-sky maps with high accuracy at low ℓ from the ground**
- **Oxford ERC-Advanced proposal for ground-based wide-field mapper for high-*z* CO and CMB foregrounds**
  - **6-m compact range telescope**
  - **Receiver with 10-20 and 20-40 GHz feeds**
  - **Wideband (> 10 GHz inst.) digital spectrometer/polarimeter backed based on SKA technology**