Superconducting Sensors and Electronics for Fundamental Physics

12 April 2021

Stafford Withington

Quantum Sensors Group, University Cambridge

- *Brief historical time line*
- *Device types and sensitivities*
- *Materials and fabrication*
- *Transition Edge Sensors*
- *Travelling Wave Parametric Amplifiers*
- *The future*

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1910-1970 First half of the 20th century, the physics of the superconducting state first became a rich area of study.

Superconducting materials support a wealth of physical processes, some of which are highly desirable and can be used to create devices, and others cause endless problems.

1970s Superconducting device physics started to emerge following the discovery of pair tunnelling, and the invention of the SQUID. Josephson junction parametric amplifiers (JJPA) started to appear.

1980s Refinement of superconducting device physics as an enabling technology for fundamental physics began in the context of devising low-noise first-stage mixers (SIS) for submillimetre-wave astronomy (200 GHz -1 THz) .

Ground-based spectroscopy and interferometry (JCMT, CSO, IRAM, KOSMA, ALMA), and space-based platforms (Herschel) were enabled through major technological refinement of mixers.

Opening up the submillimetre-wave Universe led to major discoveries in star and galaxy formation, and the evolution of large scale structure in the Universe.

1990s. Demonstration of superconducting bolometers in the form of a transition edge sensor (TES).

Large arrays of bolometers (100-600 GHz) have revolutionised ground-based observations of the intensity and polarimetric anisotropies of the CMB, leading to numerous detailed observations of the early Universe.

Search for B-modes in the early inflationary phase of the Big Bang is a major challenge, which will be enabled by large superconducting polarimetric imaging arrays (CMB-S4, LightBIRD).

Considerable innovation and success in the development of ultra-low-noise superconducting readout electronics for large arrays – time domain and frequency domain multiplexing.

2000s saw the invention of kinetic inductance detectors (KID) for large format imaging arrays across the whole of the spectrum – more elegant way of achieving multiplexing - SDR

2010 saw the introduction of the travelling wave parametric amplifier (TWPA) for quantum noise limited coherent amplification of large bandwidths.

2020 Superconducting qubits for quantum computing, superconductor/spin-system quantum memory elements.

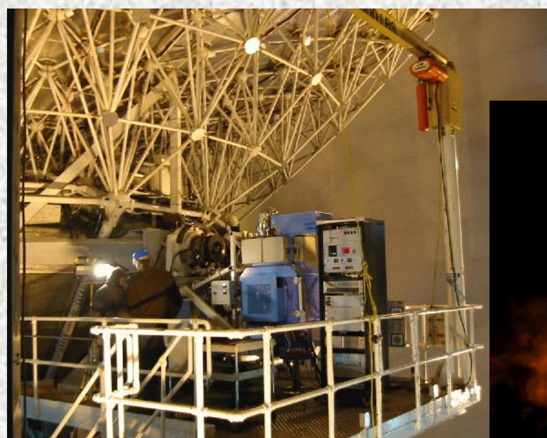
- Submillimetre-wave wave and FIR astronomy would not exist, and its numerous discoveries would not have happened, if it were not for superconducting electronics.

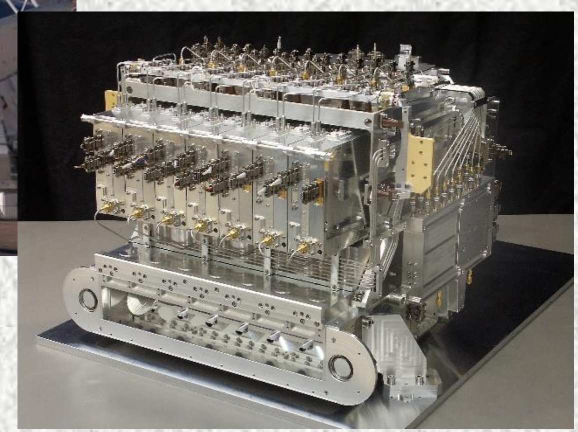
  Recently, the direct imaging of the event horizon of the black hole in M87 – Event Horizon Telescope (VLBI) – was performed using superconducting mixers

- Many future ground-based and space observatories (including x-ray) are entirely reliant on the existence and further development of superconducting electronics – cannot be uninvented!

- Many future space-based astronomy platforms will be launched with superconducting electronics (Athena, SPICA, LightBIRD, Earth Observation).

- None of this technology was provided by industry – all of it comes out of university and government laboratories – responsibility for continuity of supply.





2020 (50 years later)…

Massive opportunities for quantum-limited performance and *enhanced functionality* in astronomy.

The application of superconducting sensors/electronics to further advance fundamental physics.

2020-2024

Quantum Technology for Fundamental Physics - £31M investment by UKRI (STFC)
(Coordinated by Ian Shipsey, Oxford)

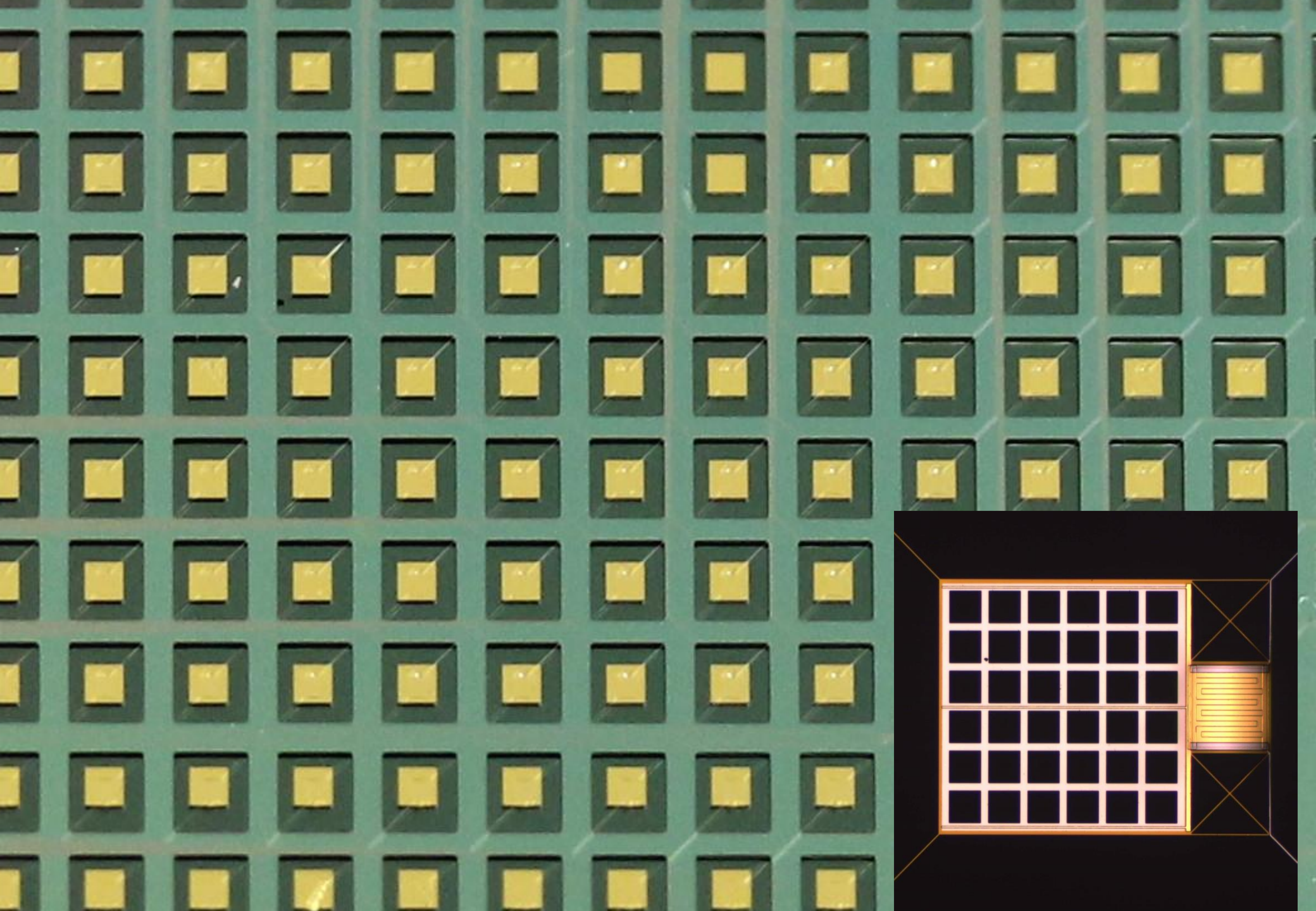
3 out of the 7 projects funded are enabled by superconducting electronics:

- Quantum Sensors for the Hidden Sector – vacuum state of activity radiation (QSHS)
  (JJPA's, QUBITs, Bolometers)
- Quantum Technology for measurement of Neutrino Mass through CRES (QTNM)
  (SQUID amplifiers, and TWPA for quantum noise limited spectroscopy)
- Quantum Enhanced Interferometry for New Physics
  (SNSPD as optical photon counters to enable new advances in laser interferometry)

Primary device types (an electromagnetic perspective):

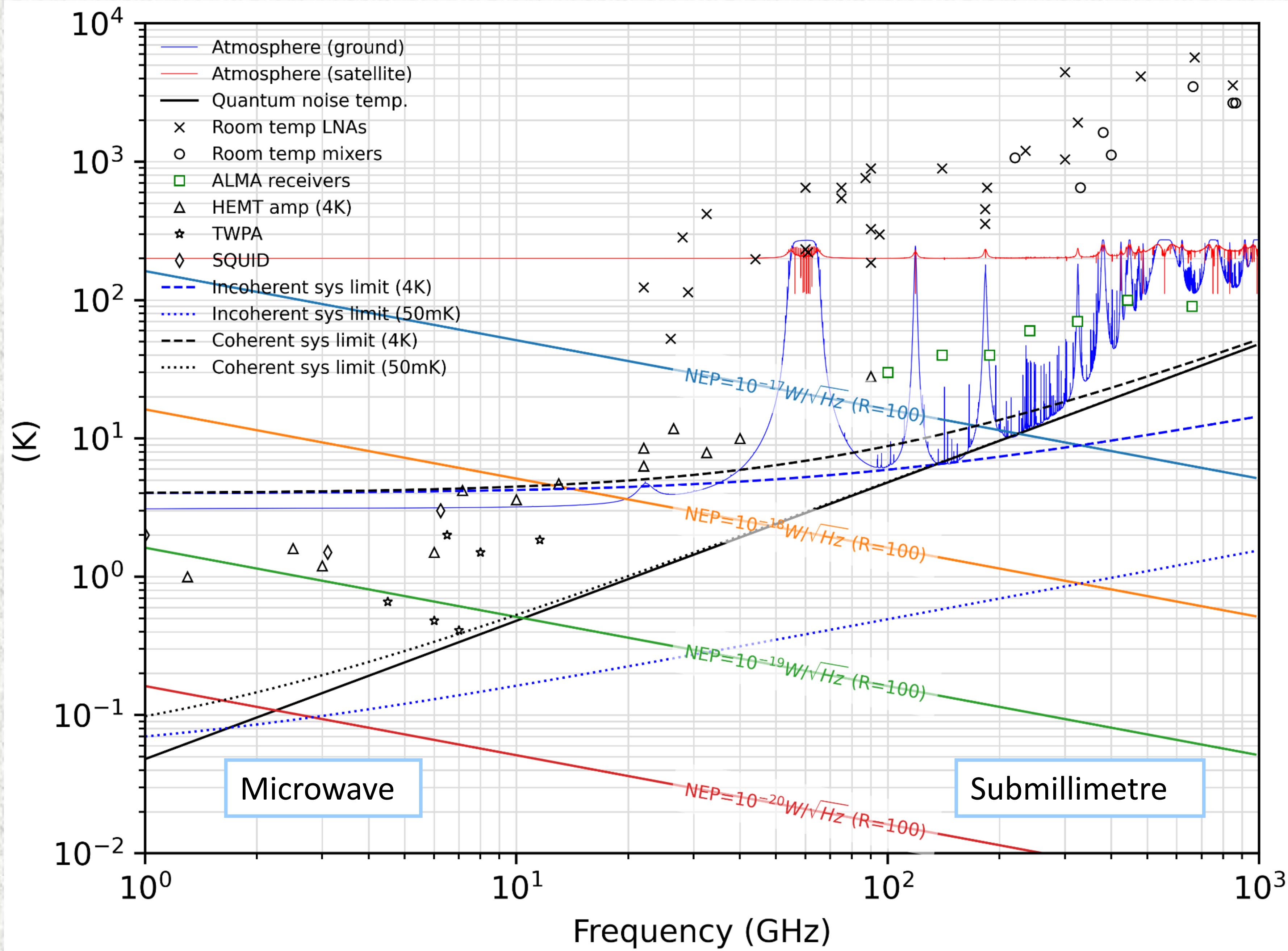
- survived evolutionary down-selection
- some use the superconducting coherent state, some use pair breaking

	Microwave	Submillimetre	Far infrared	Optical	High energy
	10 – 100 GHz 3 cm- 3 mm	100 GHz – 1 THz 3 mm – 300 μm	1 – 10 THz 300 – 30 μm	2 μm – 300 nm	UV, Ɣray and Xray
SIS mixers		●			
HEB			●		
CEB		●			
TES	●	●	●	●	●
KID	●	●	●	●	
SNSPD			●	●	
SQUID	●				
JJPA	●				
TWPA	●	●			



Sensitivity measuring photon flux - C.N. Thomas and S. Withington

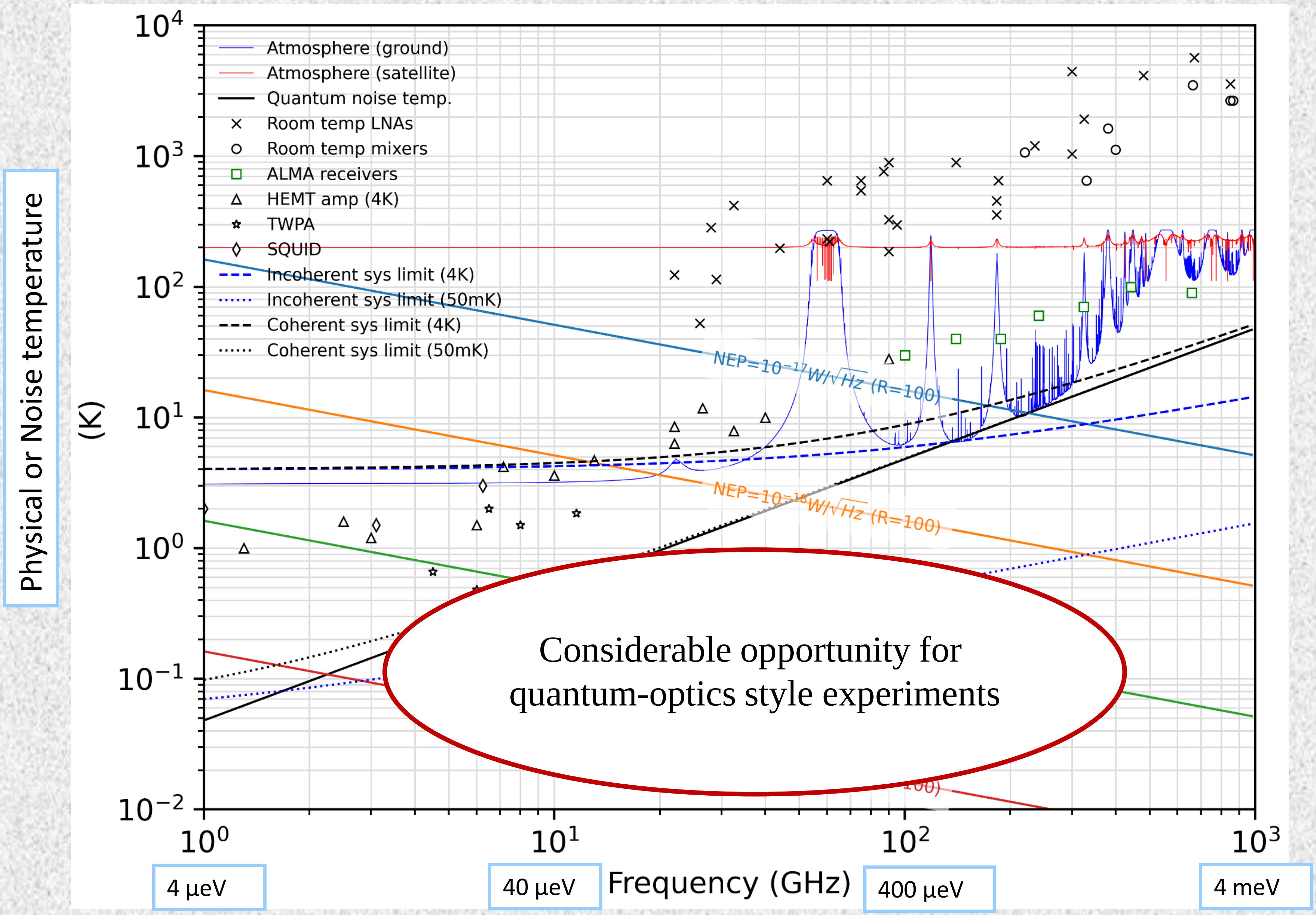
Physical or Noise Temperature



Microwave

Submillimetre

Sensitivity measuring photon flux - C.N. Thomas and S. Withington



	Ti	Nb	Al	Mo	Ta (bcc)	Ta (β)
T_c (K)	0.55	9.2	1.2	1.1	4.5	0.47 - 0.57
f_c (GHz)	40	676	88	81	327	35-42
σ_N (MS/m)	5.88	11.4	132	10.9	24.4	0.5
ξ (nm)	57	30	189	100	11 – 60	17 (?)
j_c (GA/m^2)	6.5	400	100	14	200-1100	1.7
j_* (GA/m^2)	19	1200	280	40	600-3300	5

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Elemental BCS superconductors (courtesy Songyuan Zhao):

Tc critical temperature – cool to about 10% of Tc
fc gap frequency calculate from Tc using BCS – pair breaking, not pair breaking
σ_N – normal state conductance
ξ – coherence length
jc – critical current
j* - calculate from jc

Alloys – the nitrides (reactive deposition)

	TiN	NbTiN	NbN
T_c (K)	4	14	10
f_c (GHz)	300	1000	750
σ_N (MS/m)	1	1 - 2.5	
ξ (nm)			
j_c (GA/m^2)	4	4	20
j_* (GA/m^2)	11	11	143 (expt) 56 (theory)

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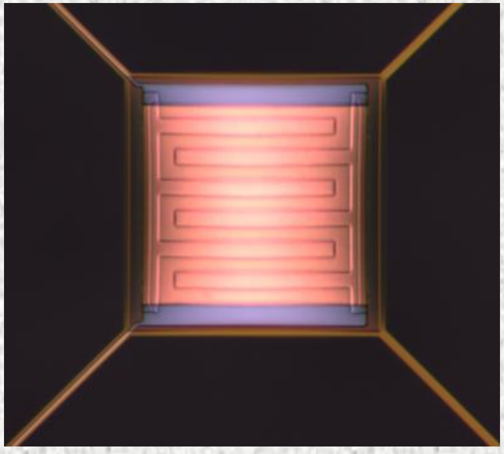
Also silicides, such as WSi

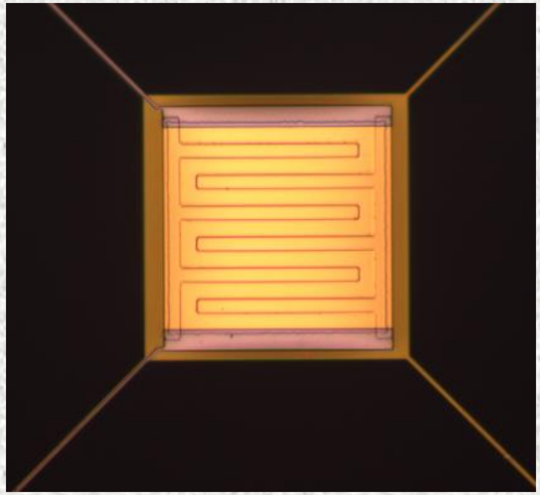
Bilayers and multilayers used extensively for `tuning' the Tc and gap:

MoAu, TiAu, TiAl, MoCu

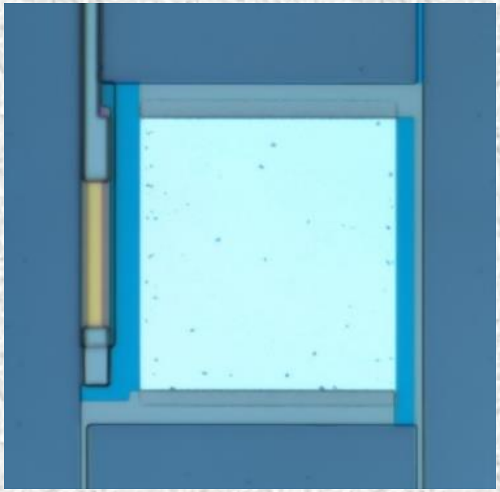
Driven by proximity effect, including lateral proximity effect



Cambridge MoCu – 120 mK (40/106 nm)
Difficult to manufacture
SiO_2 passivation layer to protect Cu



Cambridge MoAu – 150 mK (40/170 nm)
Self passivating - low C
Good inter-diffusion stability



Cambridge TiAl – 550- 650mK (150/40 nm)
Metallurgically stable
Good for Tc ~ 700 mK

SRON TiAu – 120 mK (16/85)
Self passivating
Good inter-diffusion stability

Exploring the performance of thin-film superconducting multilayers as kinetic inductance detectors for low-frequency detection

To cite this article: Songyuan Zhao *et al* 2018 *Supercond. Sci. Technol.* **31** 015007

- Device processing repertoire across a wide range of devices and materials:

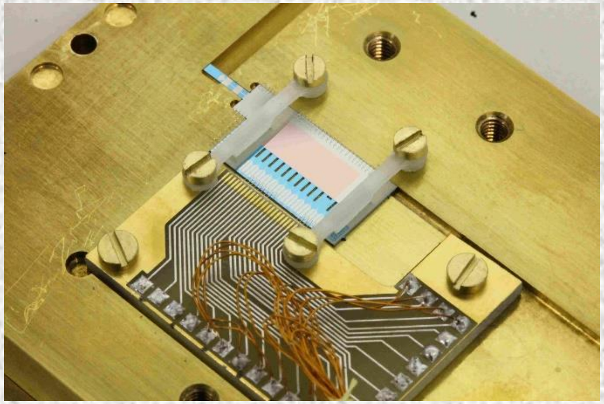
Nb, Ta, β-Ta, Al, NbN, TiN, NbTiN, Mo, Hf, Ir, Cu, Au, AuCu, AuPd, SiO_2 SiO AlOx

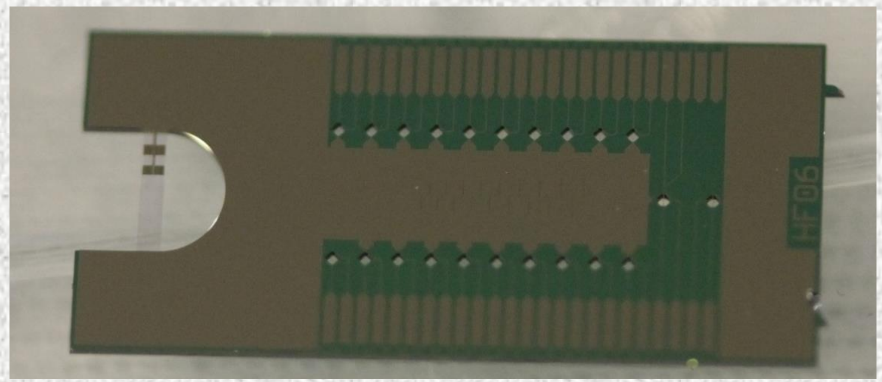
- All on SIN and SoI membranes – 4 UHV deposition systems – sputtering and e-beam

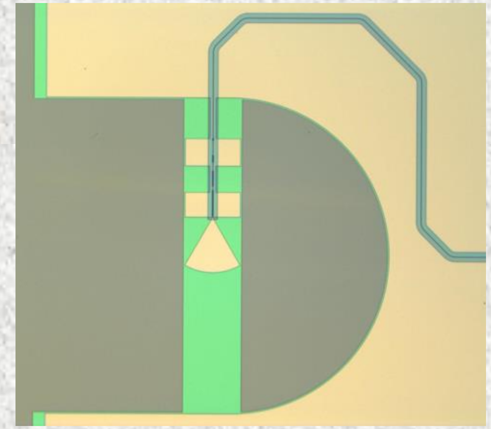
- Bilayers based on proximity effect, and lateral proximity effect, can be used to `engineer' properties of films: MoAu, MoCu, TiAu, TiAl multilayers

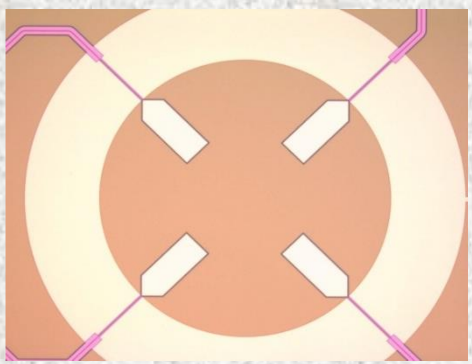
Passive RF components – microstrip to waveguide and cavity couplers: DC- 1.5THz

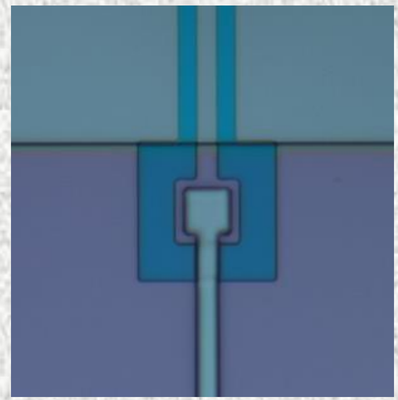
(C.N. Thomas, D.J. Goldie, M Crane, S. Withington)

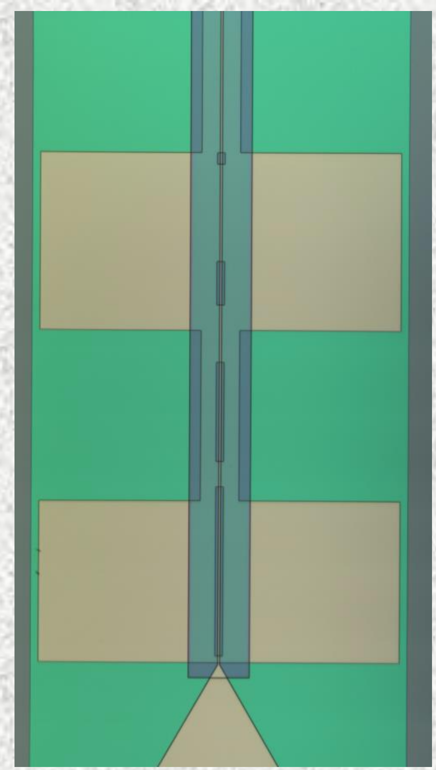


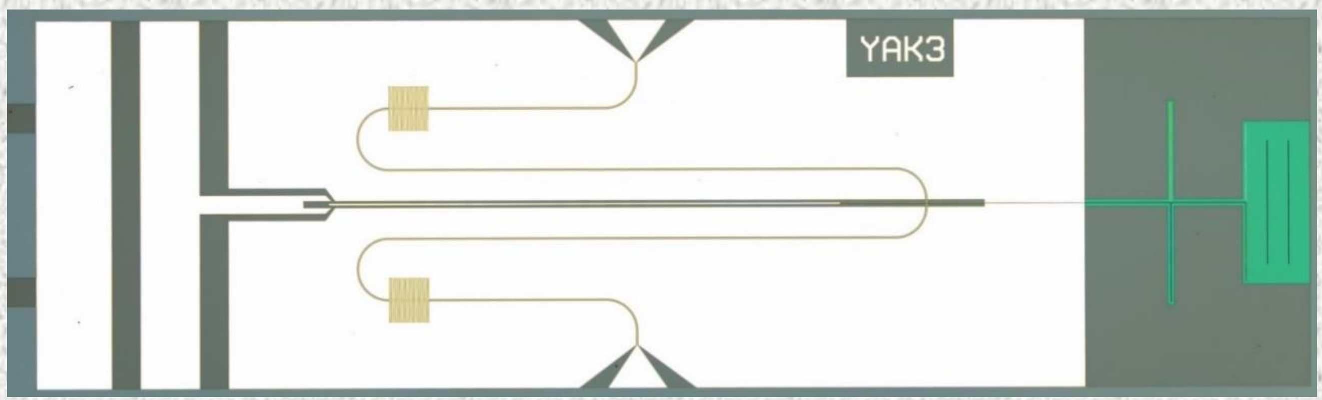




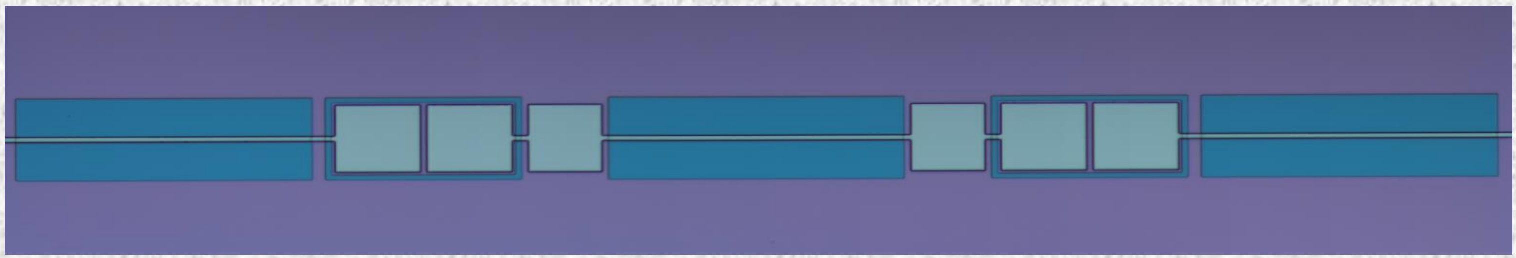


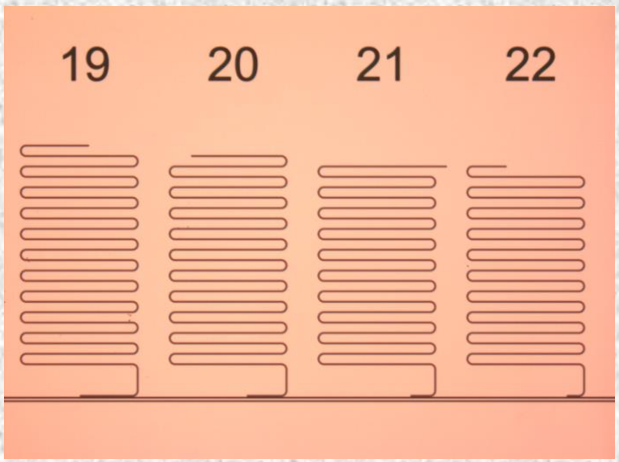


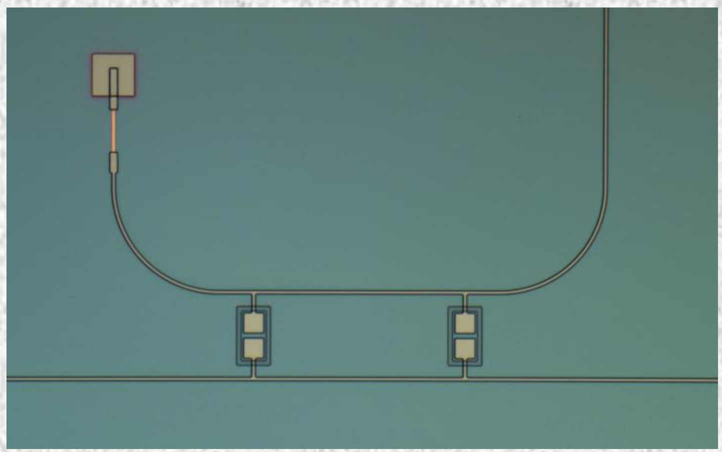


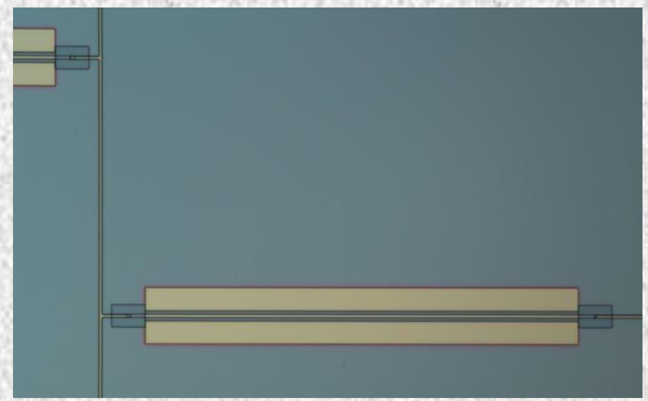


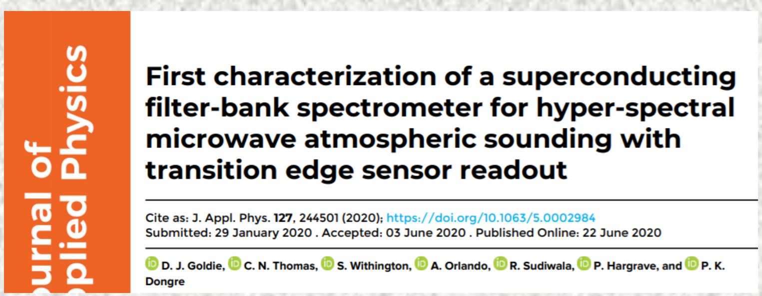
Not only sensors, also passive RF components: filters, directional couplers, resonators: DC-1 THz











First characterization of a superconducting filter-bank spectrometer for hyper-spectral microwave atmospheric sounding with transition edge sensor readout

Cite as: J. Appl. Phys. 127, 244501 (2020); https://doi.org/10.1063/5.0002984
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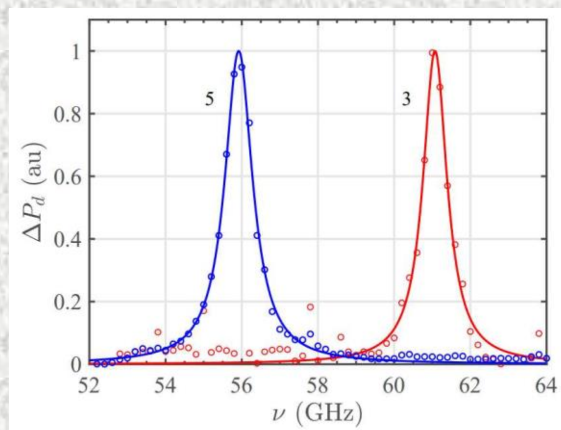
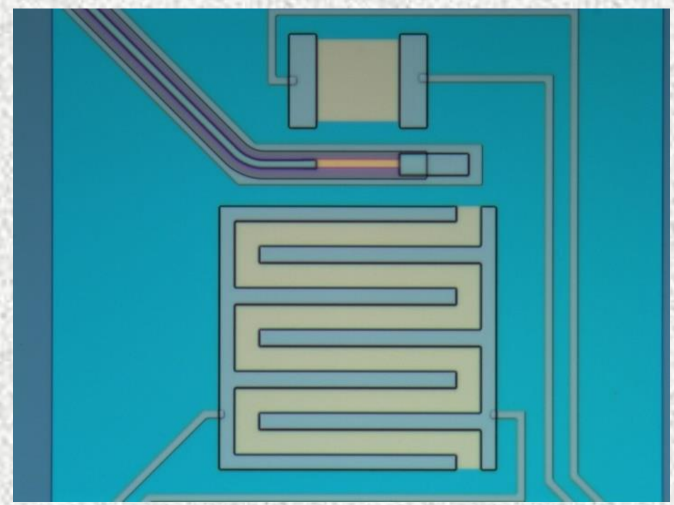
D. J. Goldie, C. N. Thomas, S. Withington, A. Orlando, R. Sudiwala, P. Hargrave, and P. K. Dongre

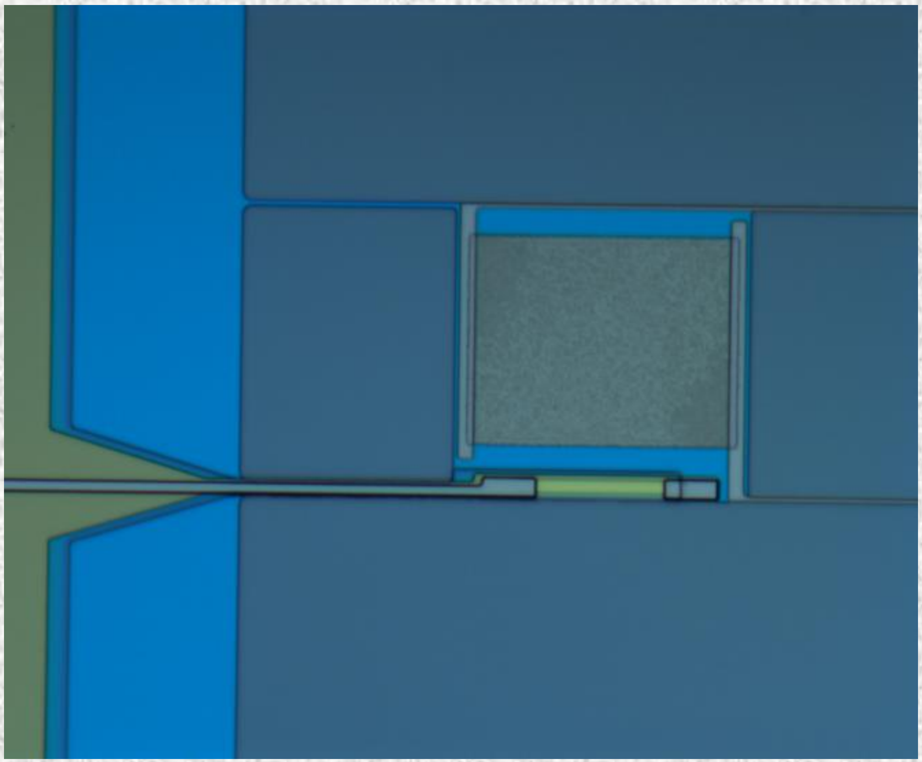


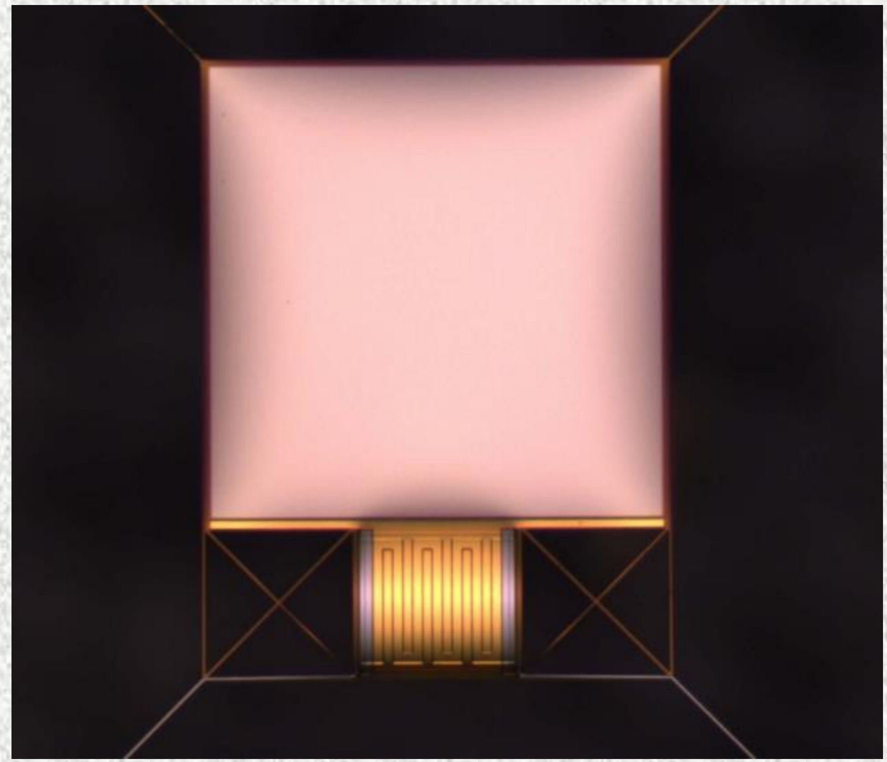


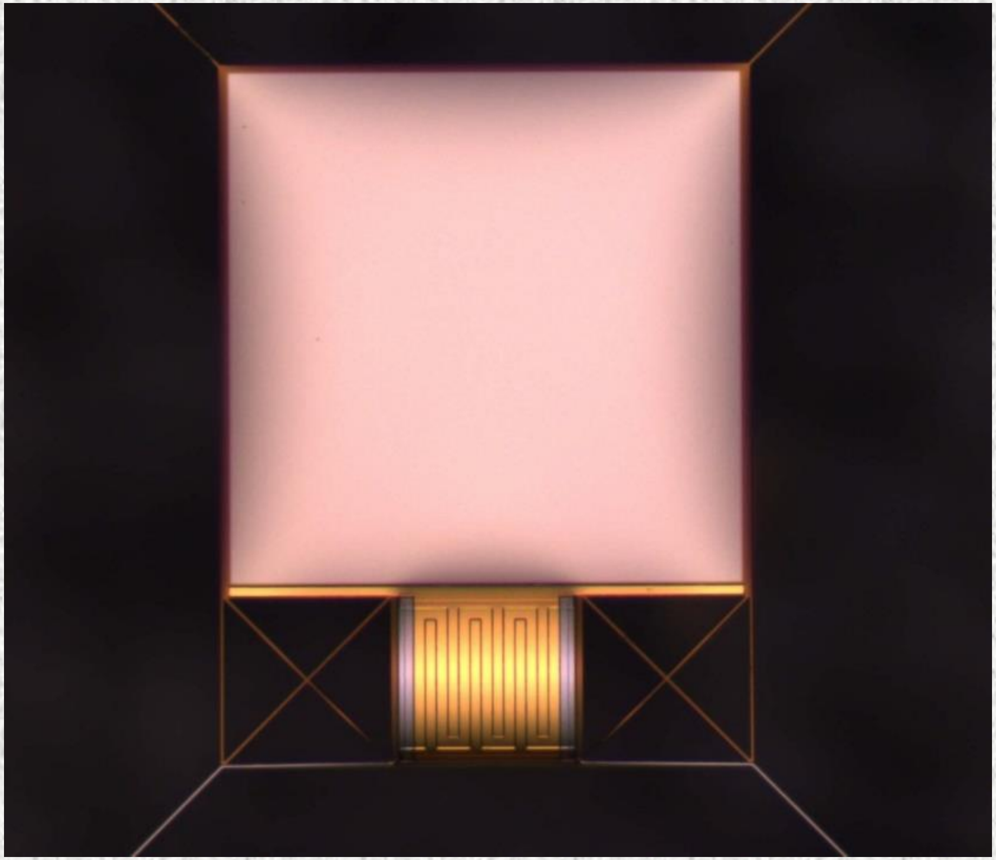
Free-space and *microstrip* coupled TESs

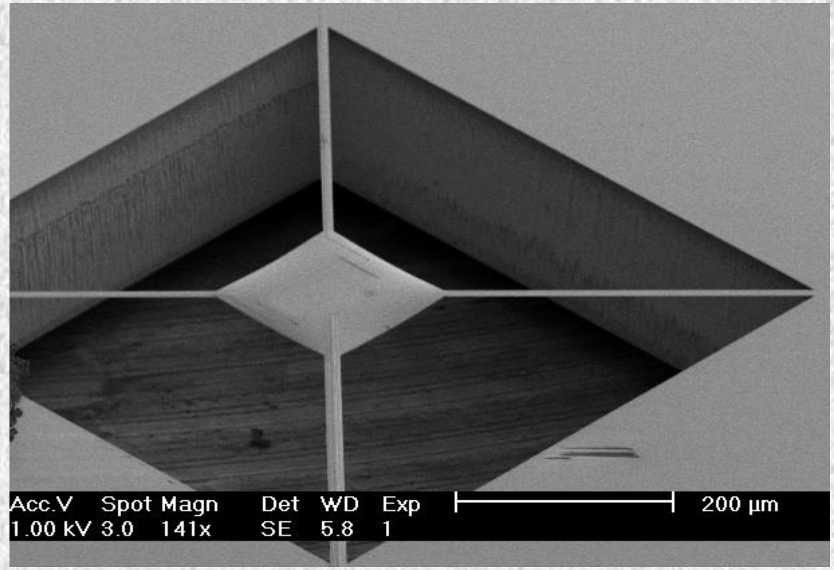
Submillimetre-wave (3mm – 300 µm) to infrared (200-30 µm) applications

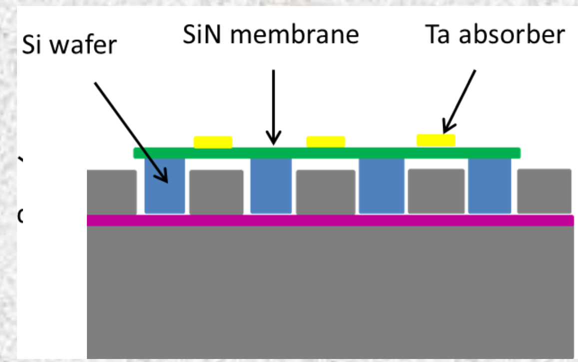
NEPs ~ 10^{-17} - 10^{-20} WHz , Psat ~ 50 pW – 5 fW, T ~ 10 µs – 10 ms



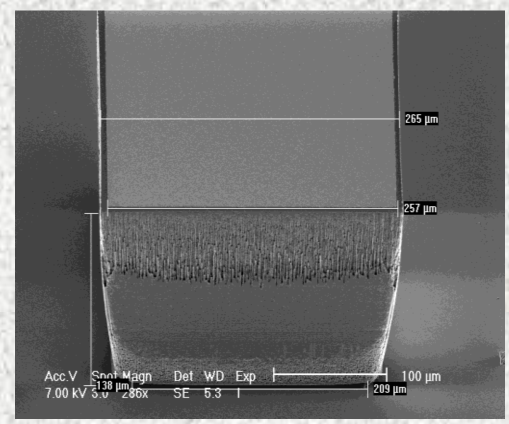


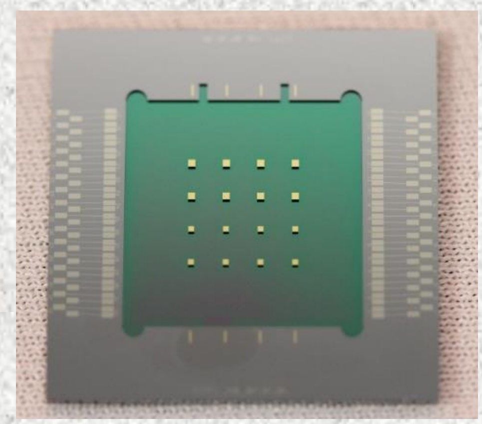


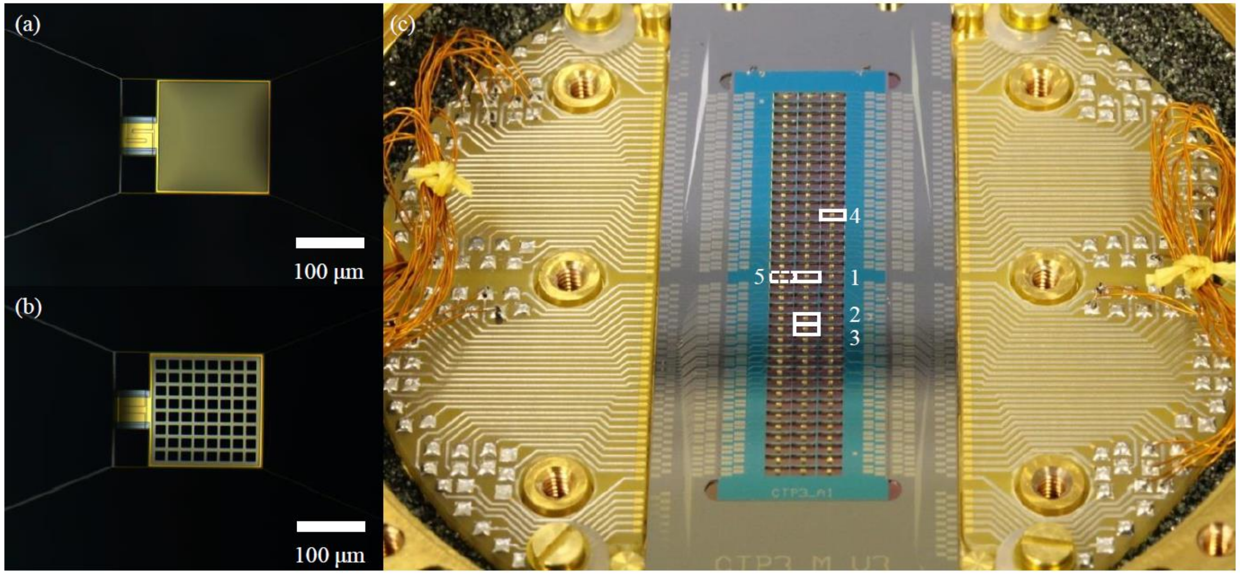


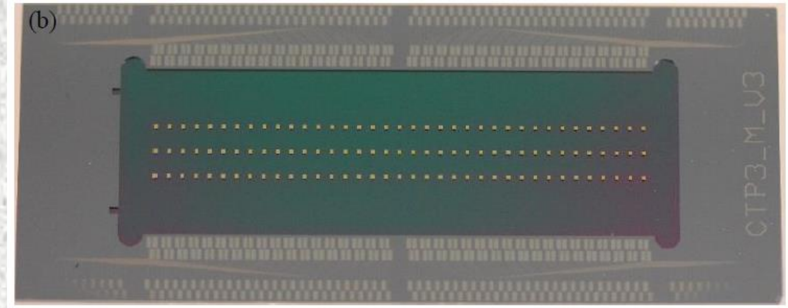


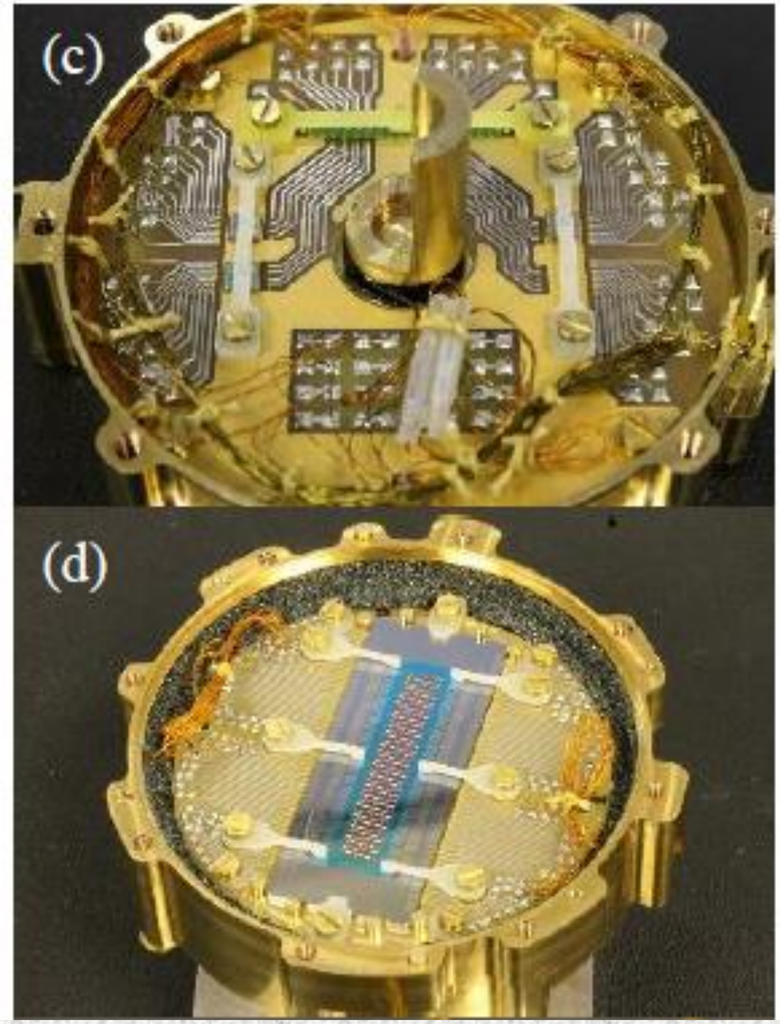
β-phase Ta absorber with Tc of 860 mK
200 nm SiN (high heat capacity due to TLSs)
MoAu bilayers with Tc of 110 mK
G 0.2 pW K^{-1}
NEP 10^{-19} $WHz^{-1/2}$
τ 10mS (on chip integration)
Psat 20 fW







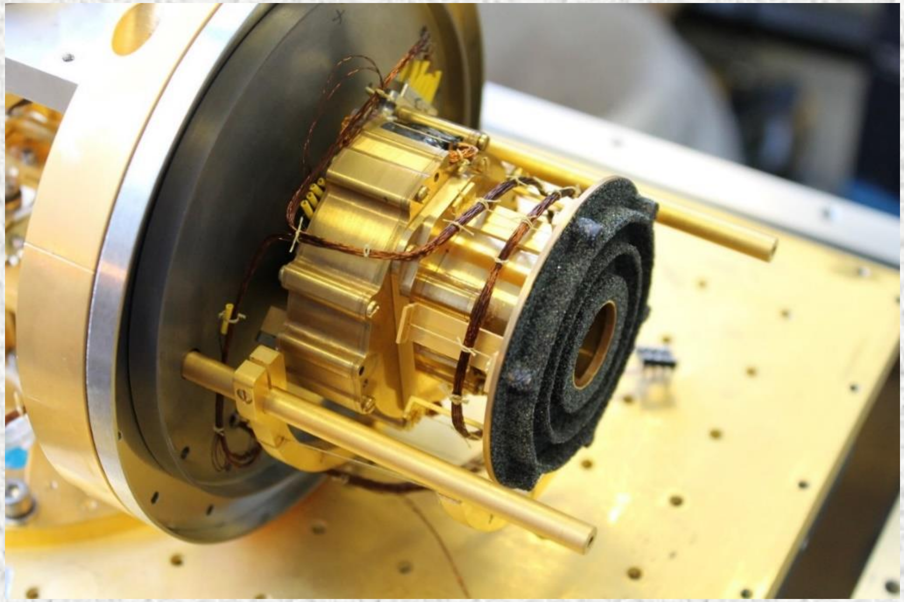


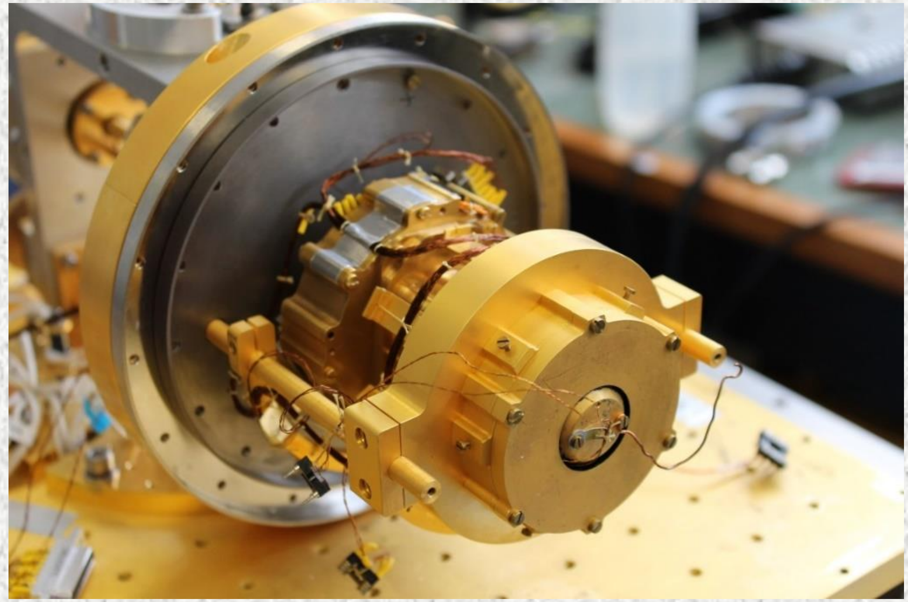


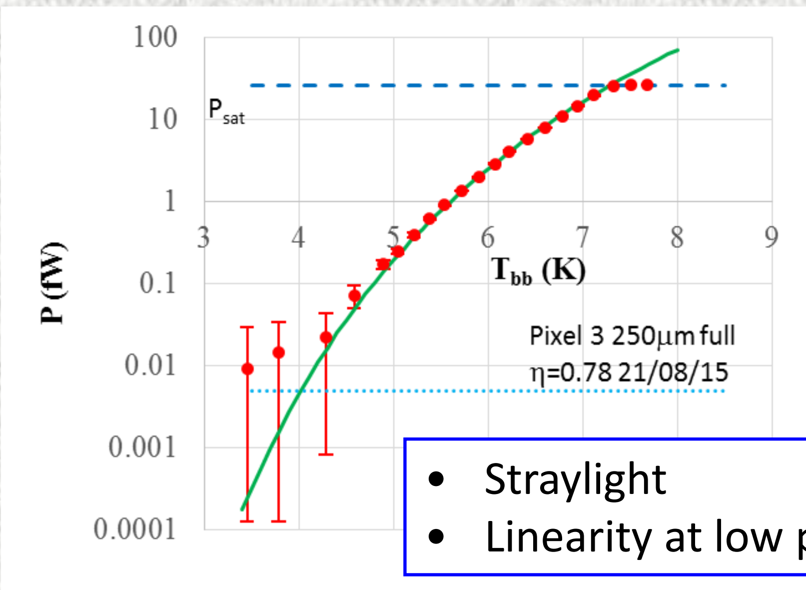
FIR imaging arrays for grating spectrometer readout (SPICA)
(Joint project with University of Cardiff: Ade and Sudiwala)

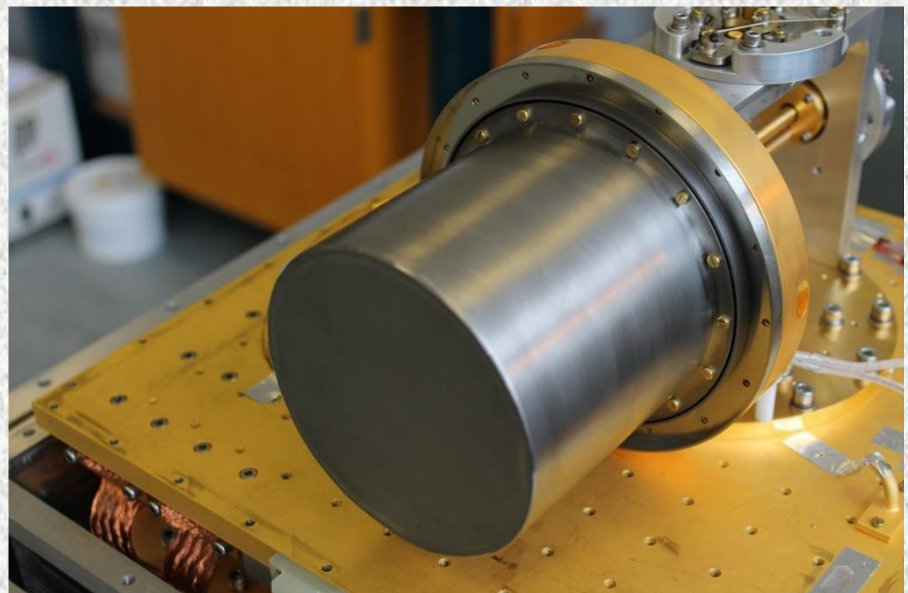
- Micromachined Au coated pillars as reflecting backshorts
- SQUID readout
- Superconducting wiring throughout (0.5 mΩ stray resistance)
- FIR absorber for straylight control
- Noise entirely determine by phonon noise
- NEP ~ 10^{-19} $WHz^{-1/2}$

Development of packaging techniques for superconducting electronics in space with AirBus: suitability for space usage (Emily Williams and Rebecca Harwin, Cambridge)

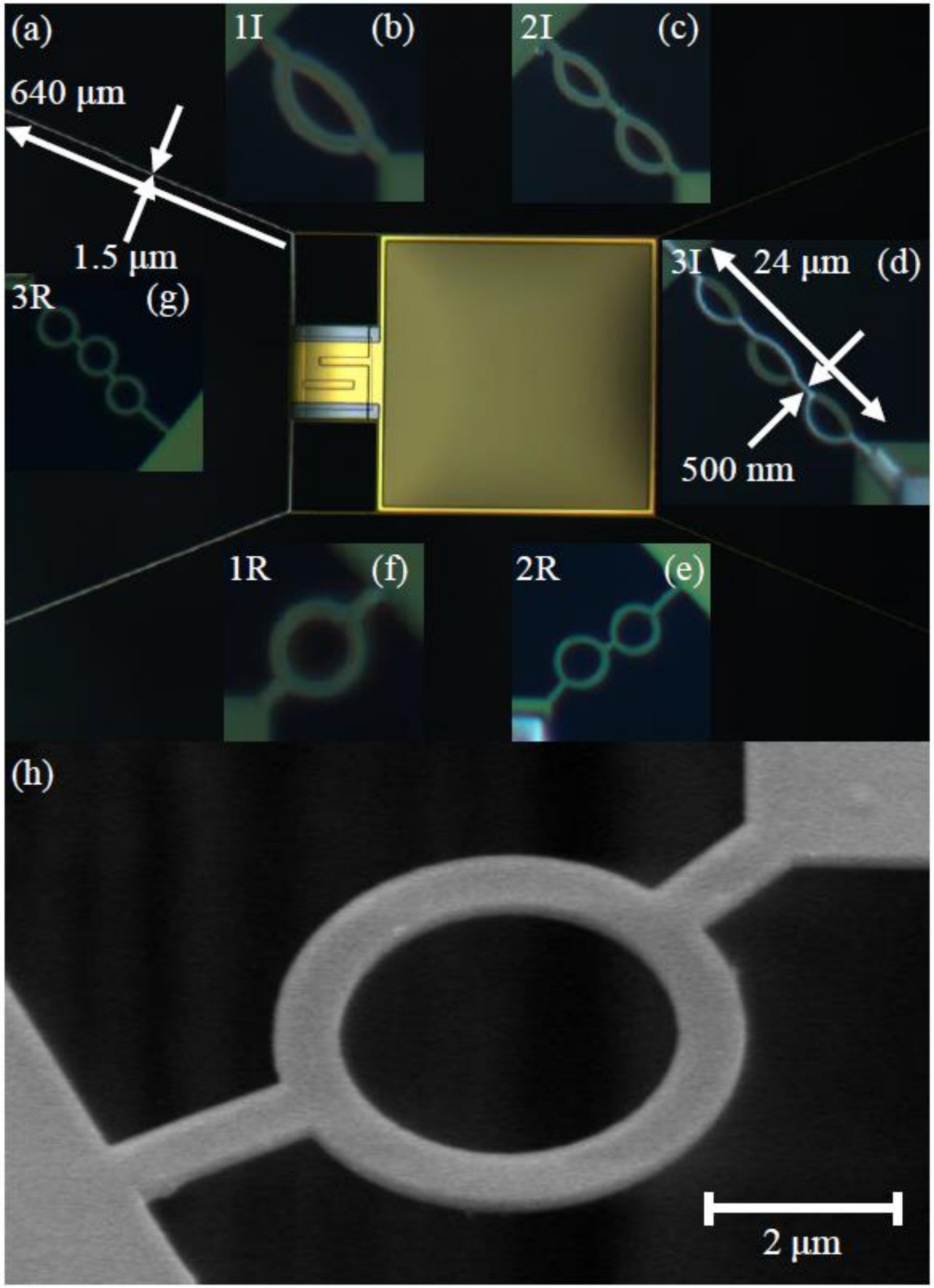




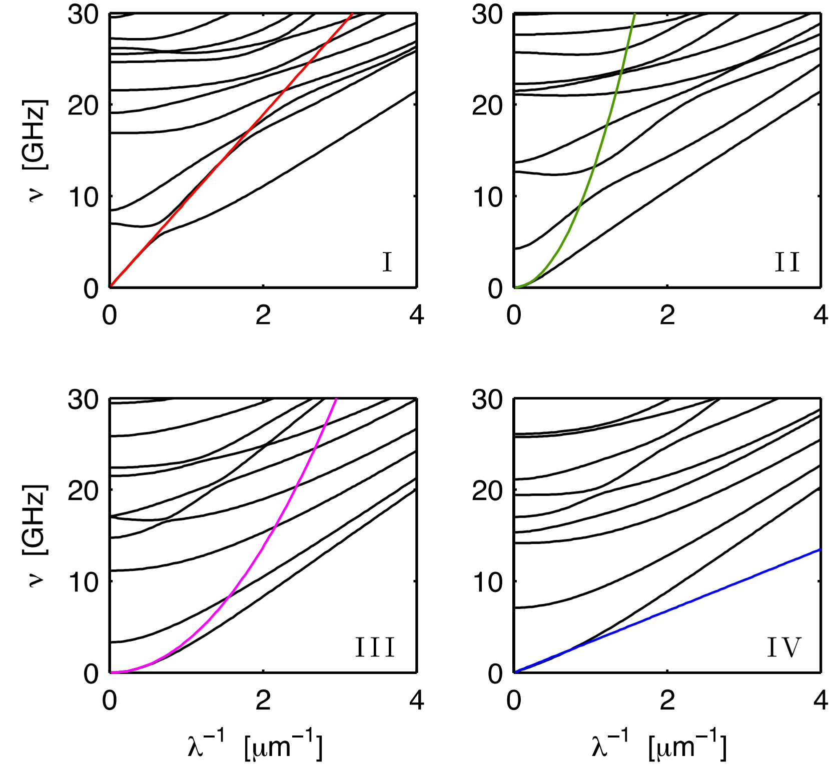




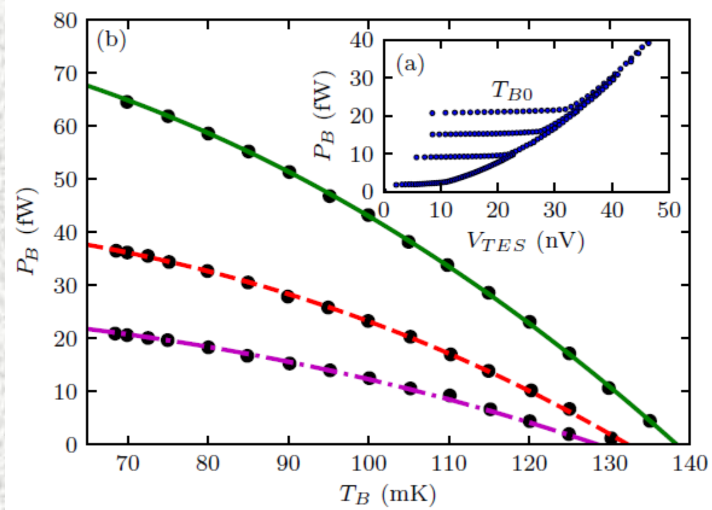
- Straylight
- Linearity at low power



(a)
640 μm
1.5 μm
1I
(b)
2I
(c)
3I
24 μm
(d)
500 nm
3R
(g)
1R
(f)
2R
(e)
(h)
2 μm



ν [GHz]
λ^{-1} [μm^{-1}]
I
II
III
IV



(b)
P_B (fW)
T_B (mK)
(a)
T_{B0}
P_B (fW)
V_{TES} (nV)

Spectroscopy of massive particles using TES:
Xray Photoelectron Spectroscopy (XPS)

(Kunal Patel Univ. Cambridge, Alex Shard NPL)

spectroscopy of low energy electrons (200 eV-1 keV)

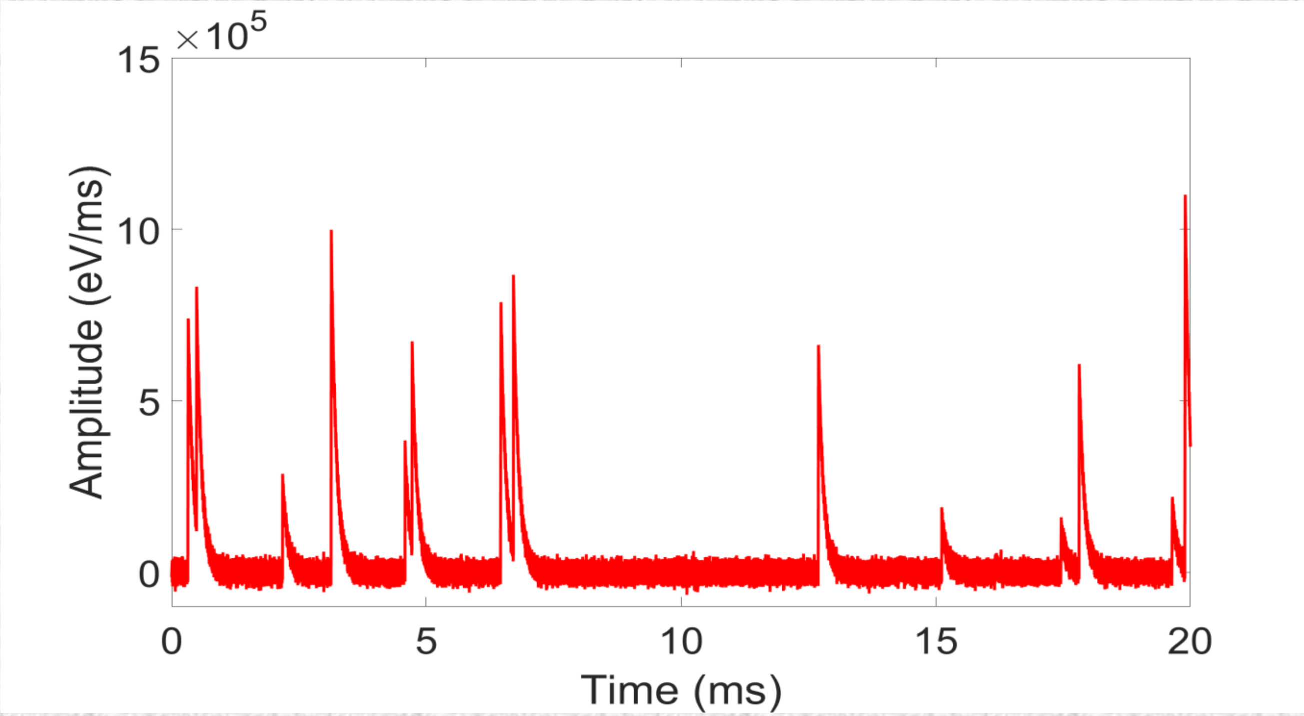
Existing electron spectrometers only measure a narrow electron energy band at a time.

- swept across some total range to build the spectrum.
- energy filtering process discards over 99% of electrons at a time, large and bulky

A TES spectrometer would not discard electrons allowing for a far greater count rate: typical spectrum has ~ 1million events

Comprehensive simulation pipline has been developed (Kunal)

- electrothermal behavior of TES, including phonon and Johnson noise
- stream of pulse on top of the noise floor
- recovery using Bayesian methods
- fundamental limit of energy resolution through Fisher analysis



Simulated TES electron measurement data

⇩

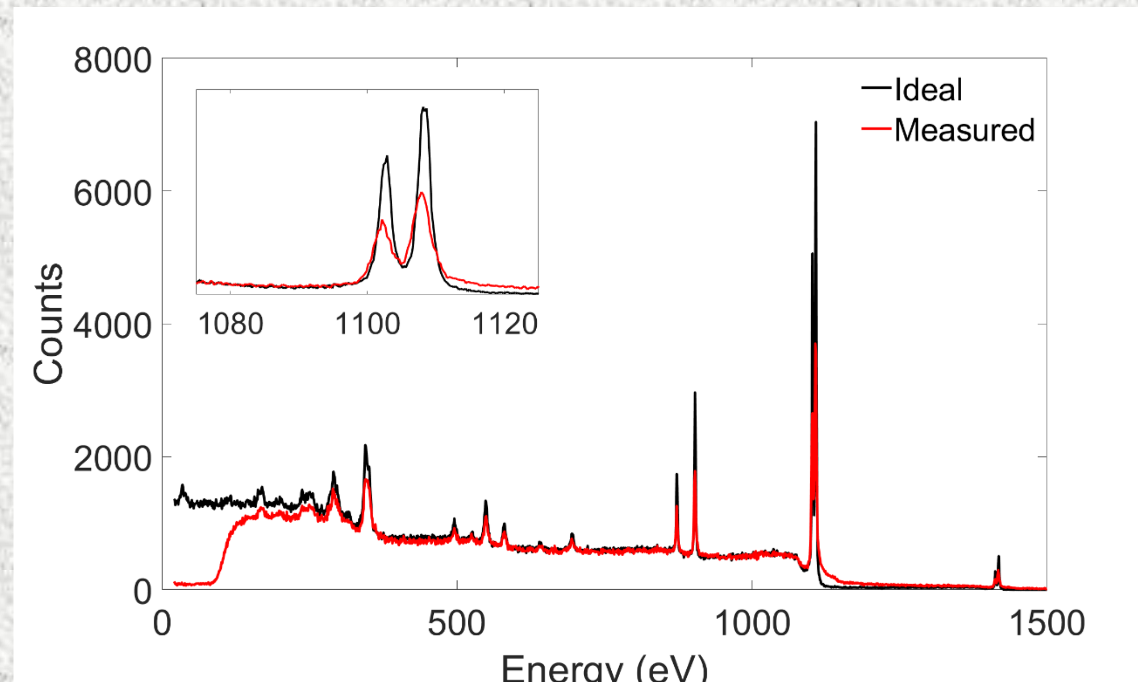
Reconstructed electron spectrum from simulated data

Resolution comparable with current electron spectrometers

~0.5 eV @ 1keV

Array of 100 TESs would improve typical x-ray photoelectron spectroscopy considerably

cf Cyclotron Resonance Emission Spectroscopy



Travelling Wave Parametric Amplifier (TWPA):

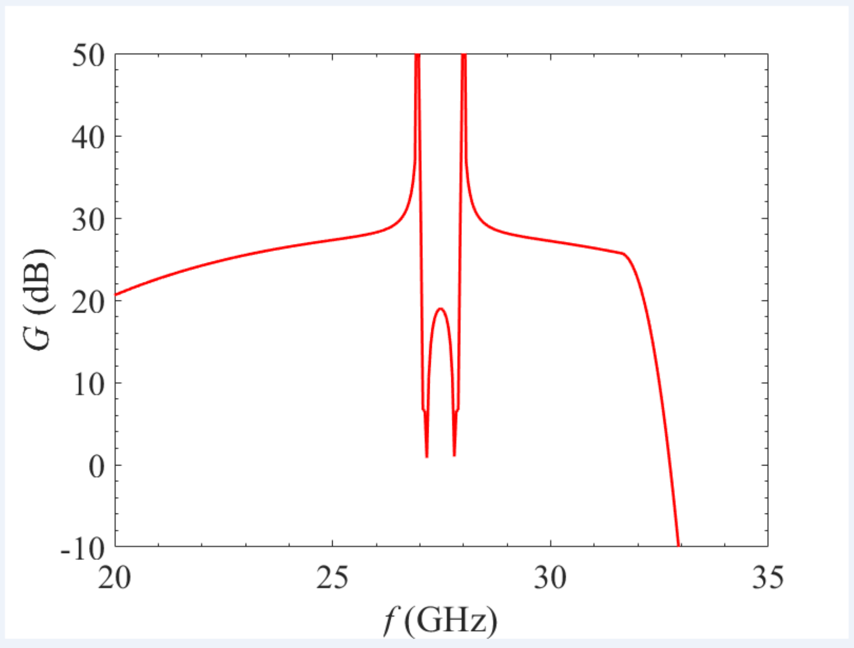
- Microwave demonstrations to date – millimetre-wave entirely feasible
- Near quantum noise limited, high gain ~20 dB, wide bandwidth ~2 GHz
- Production of squeezed vacuum state
- Amplification of squeezed states (to some degree)

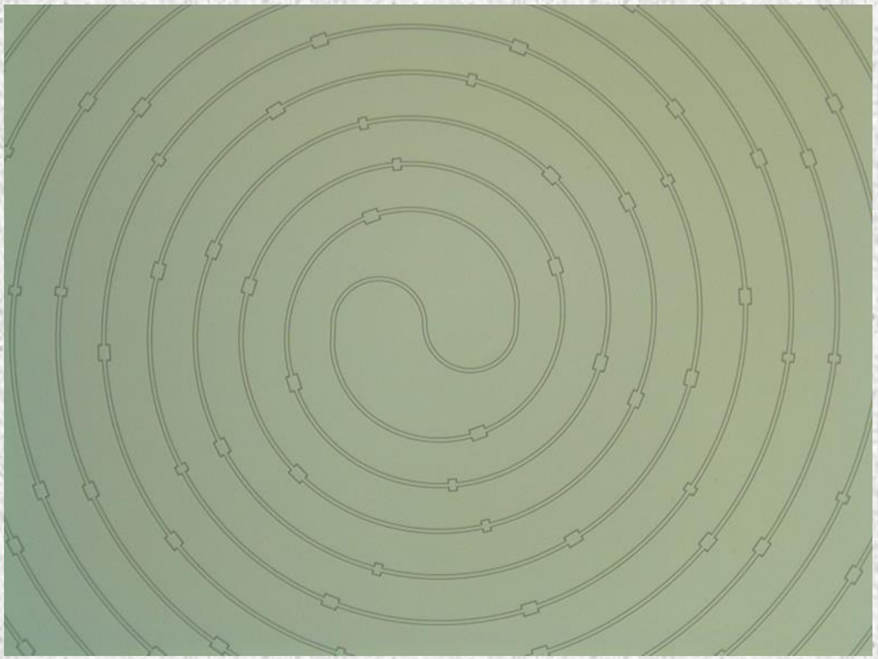
Uses nonlinearity of kinetic inductance effect to achieve non-linear transmission and mixing

- Best operation seen with alloy superconductor (NbTiN)
- In reality exceedingly complex dynamics – dispersion engineering
- Backward propagation not attenuated
- Thermal noise degrades behavior (see upcoming paper by Songyuan Zhao)

Year	Affiliation	Author	Material	Tc
2012	Caltech / JPL	Eom et al.	TiN, NbTiN	4K, 14K
2014	NIST	Bockstiegel et al.	NbTiN	14K
2016	Chalmers / NPL	Adamyan et al.	NbN multilayer	No data 7K-15K ?
2016	Purple Mountain	Shan et al.	NbTiN	No data 14K?
2016	NIST	Vissers et al.	NbTiN	No data 14K?
2017	Caltech / NIST	Chaudhuri et al.	NbTiN	15K
2020	Hebrew Uni of J	Goldstein et al.	WSi	No data 0.5K-5K?

Should operate well into millimetre-wave range





Loss and saturation in superconducting travelling-wave parametric amplifiers

Songyuan Zhao, S Withington, D J Goldie and C N Thomas

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Journal of Physics D: Applied Physics, Volume 52, Number 41

Quantum analysis of second-order effects in superconducting travelling-wave parametric amplifiers

Songyuan Zhao[1,*] and Stafford Withington[1]
[1] *Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 OHE, United Kingdom.*

(Dated: April 9, 2021)

Superconducting device physics is a whole technology, not merely a collection of individual laboratory curiosities:

Material systems

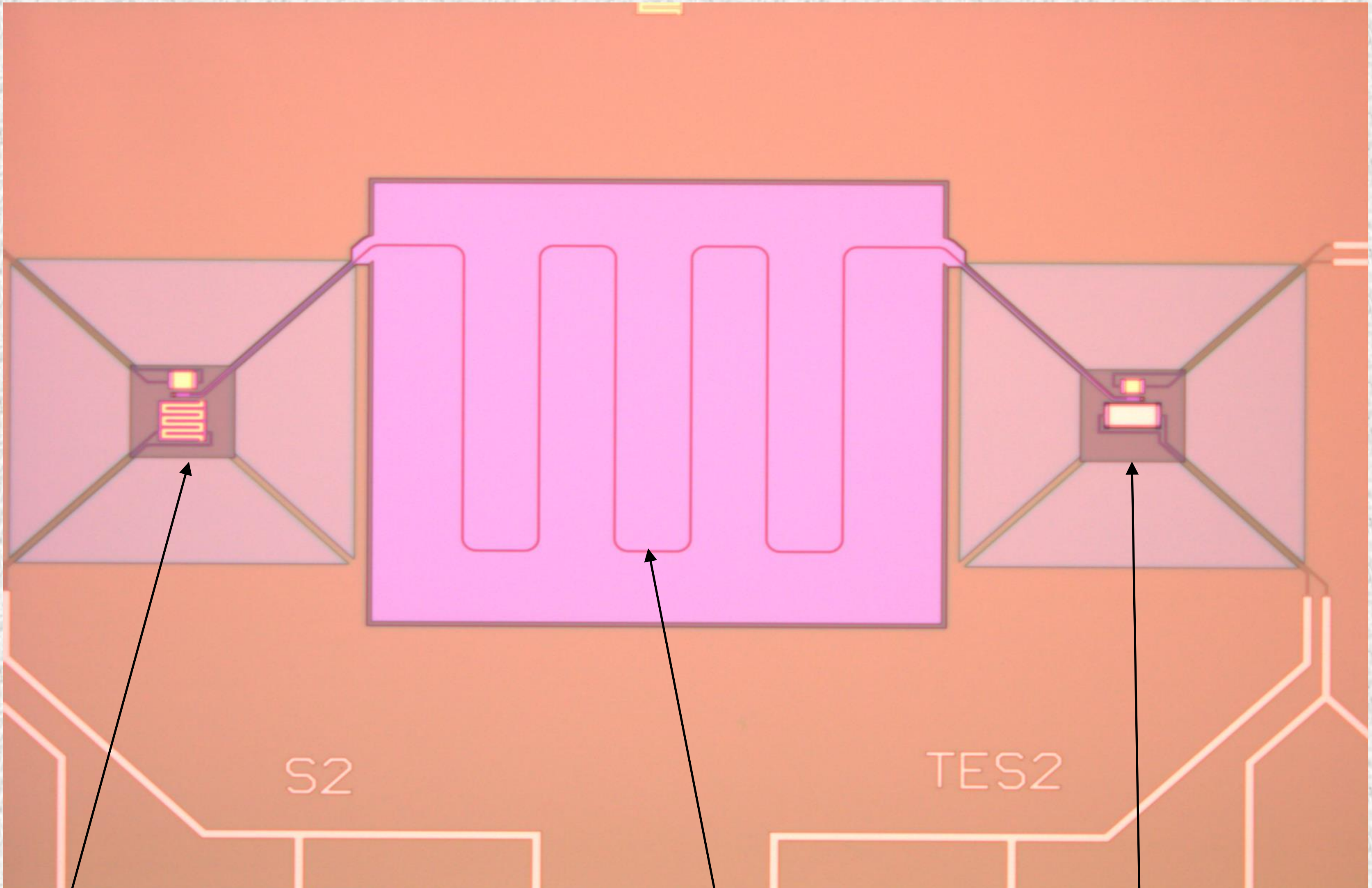
Fundamental device types

All based on thin film deposition techniques and lithographic patterning

Large scale integration with high degree of functionality

Many Thanks

Lab on a chip measurements (low-loss microstrip components to 1 THz)



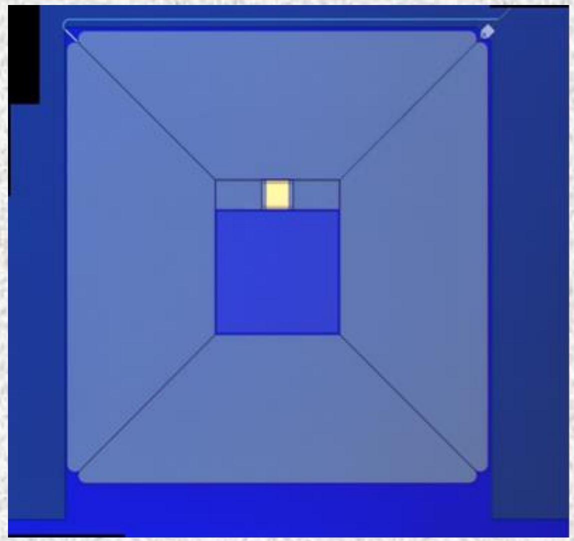
Variable temperature black body load:

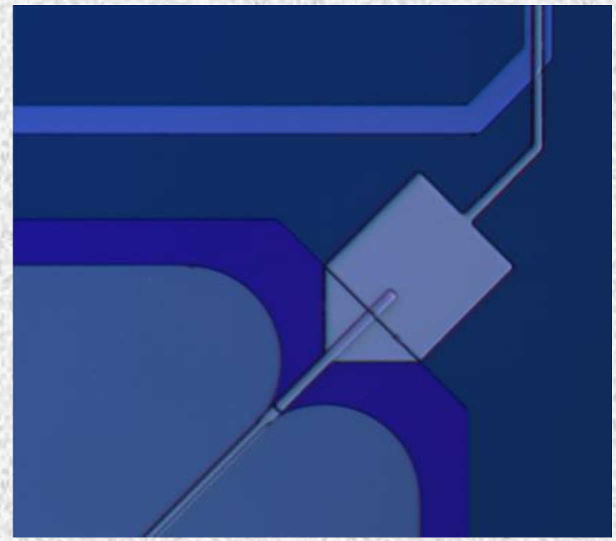
NbN microstrip line

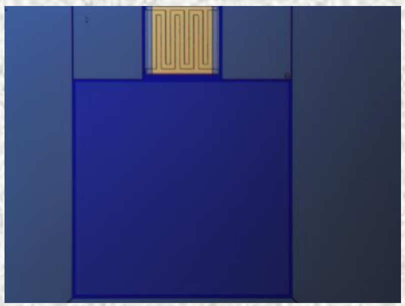
Low-noise TES

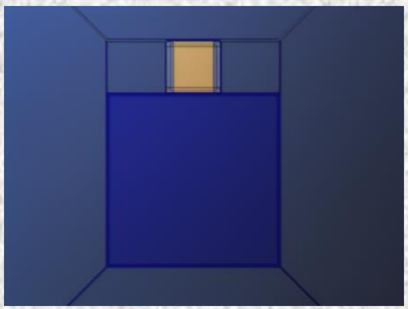
TES array chips:

- Extreme range of leg geometries:
  - 1500µm long and 1.5µm wide
  - 200 µm long and 100µm wide
  - 4um long and 500 nm wide
- Bilayer variations (size, Au bars)
- Absorber variations (meshed)
- Au rim / no rim









Microstrip Nb wiring:

- Fully integrated process $Nb/SiO_2/Nb$
  - track width 2µm
  - space between tracks 2µm
  - 250 tracks/mm density
- Breakout to standard wiring on legs
- Excellent alignment on legs