Quantum Sensors Programme at Cambridge

Stafford Withington

Quantum Sensors Group, University Cambridge

UNIVERSITY OF CAMBRIDGE

- Physics of extreme measurement, tackling demanding problems in *ultra-low-noise measurement for fundamental science*
- Essentially a solid-state physics group with strong emphasis on low-noise physics and superconducting devices.
- Grew out of a group developing superconducting technology and instruments for submillimetre-wave astronomy (100 GHz – 1 THz)
- About 15 years ago, major transfer of equipment and IP from Oxford Instruments
- Since then worked on detectors at millimetre, far-infrared, optical and x-ray wavelengths: ground-based and space-based applications
- Develop and deploy both research-grade and science grade technologies
- Performance uniformity, durability of operation, process control and traceability
- Must understand the device and materials science in detail: will it work in space!

- We use superconducting devices because of their extraordinary properties and capabilities
- Major areas of experimental astrophysics and cosmology (CMB, high-redshift galaxies, molecular-line astronomy, high-energy astrophysics) would not exist if it were not for superconducting devices of many different kinds: mm-wave to x-ray
- Is this true for laboratory based fundamental physics?
- Superconductors have several fundamental properties:
  - Energy gap of a few meV: devices can work on the basis of breaking pairs or not breaking pairs (loss and noise)
  - Exceedingly low dissipation < 1 THz (but subgap photon streams do break pairs)
  - Large-scale macroscopic quantum state (SQUID, copper pair boxes)
  - Quantum noise limited performance, and below?
  - Meissner effect (microscopic as well as macroscopic scales)

- The superconducting state is a coherent state, but most devices use `second order' superconducting device physics to describe their primary and secondary behaviour (such as pair breaking, noise, coherence times, etc.)
- Do have to tackle non-equilibrium superconductivity to understand devices; quasiparticle generation and recombination processes, and two-level-systems for example – many papers on this topic
- Photon and phonon absorption process are intricate, and need special attention
- Extensive modelling of device physics at many levels
- Superconducting sensors represent a whole technology, not just a single device type
- Numerous combinations of fabrication processes, materials and technologies are available leading to quantum noise limited systems, imaging arrays and high single-chip functionality
- Numerous opportunities for innovation exploiting UK infrastructure

- Thin-film superconducting materials *science and device processing, wide repertoire:*

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

- Stress physics, interface physics, defect states.
- Bilayers based on proximity effect can be used to `engineer' properties of films:

    MoAu, MoCu, TiAu, TiAu multilayers

- Tc, diffusion rates, quasiparticle-phonon decoupling, quasiparticle traps
- *Lateral proximity effect can also be used through patterning*
- Extensive SiN and SoI micromachining for membrane-based sensors
- MM-wave, FIR, optical and x-ray devices:

    TESs, KIDs, SIS mixers, SQUIDs, HEBs, CEBs

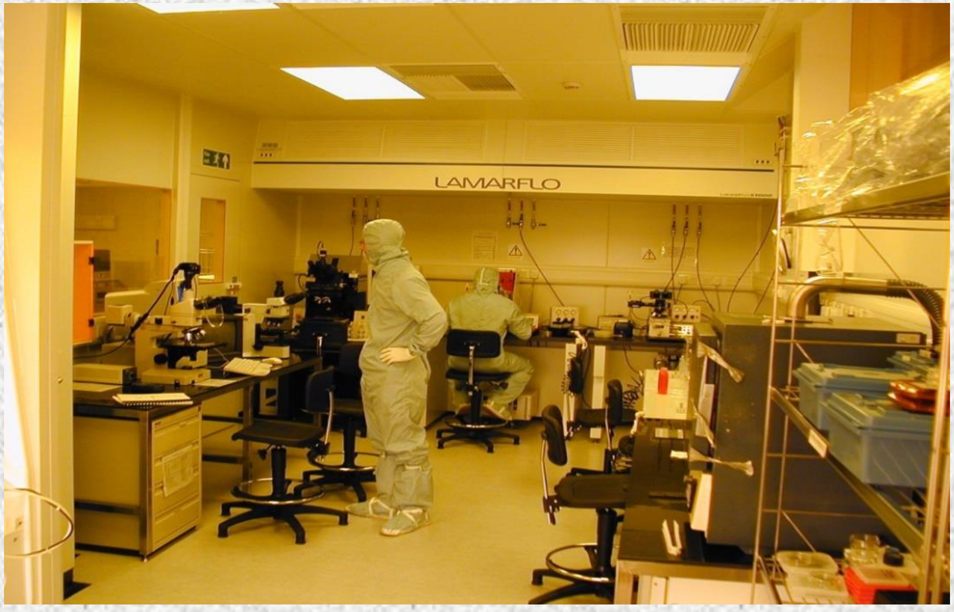
    Lab-on-a-chip type devices – conductance and heat capacity

    Optical and x-ray time-resolved optical photon counting

    High functionality - single chip submillimetre-wave spectrometers

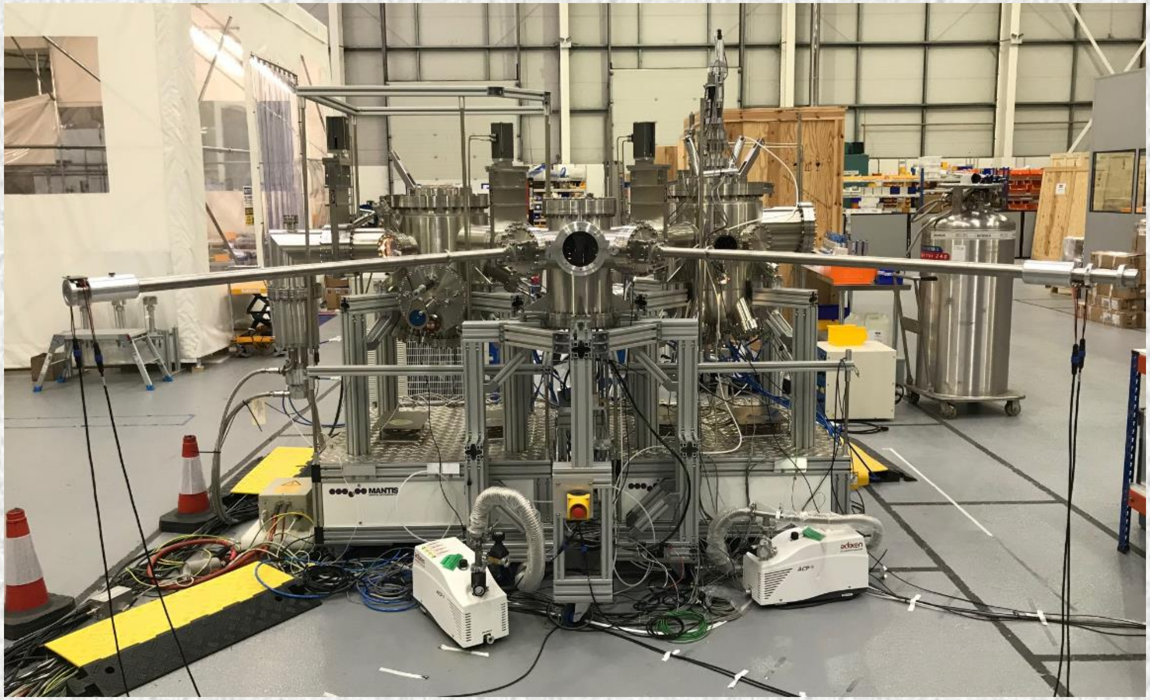
- *Moving into quantum technologies*

Facilities in the Cavendish Laboratory

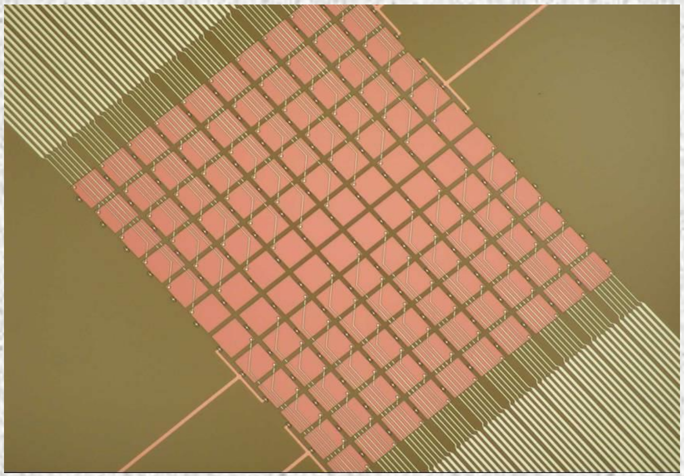


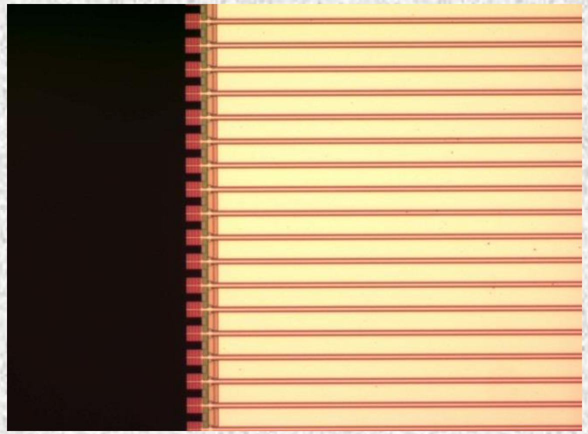
Large investment in infrastructure through quantum technologies – expensive items, requiring expertise and care to maintain (like children)

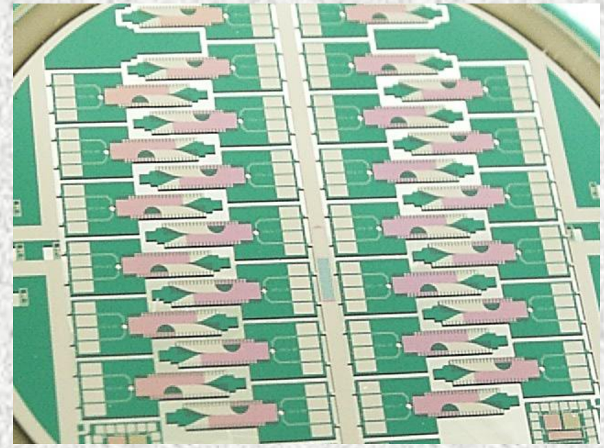
- Two chamber UHV sputtering, <10-10 Torr
- Al, Nb, Mo, etc. plus reactive materials (NbN), controlled oxidation
- Electron beam deposition
- Heating to 1000C, cooling to 77K
- Rotating substrates and angled deposition for tunnel junctions

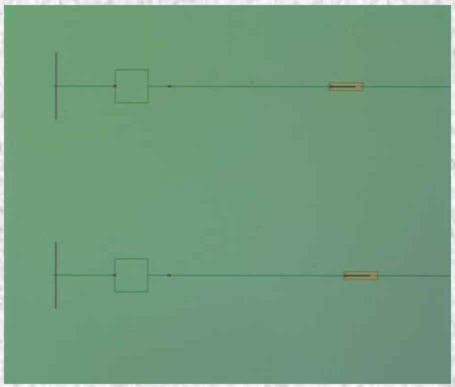


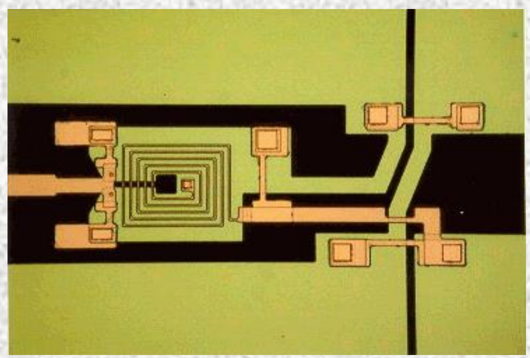
Wide variety of devices for many projects:

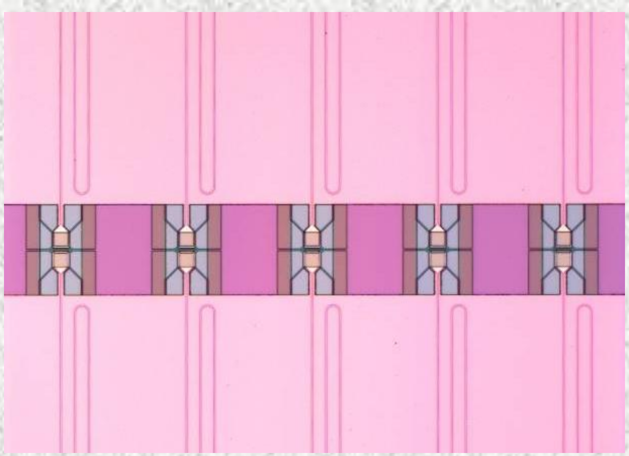


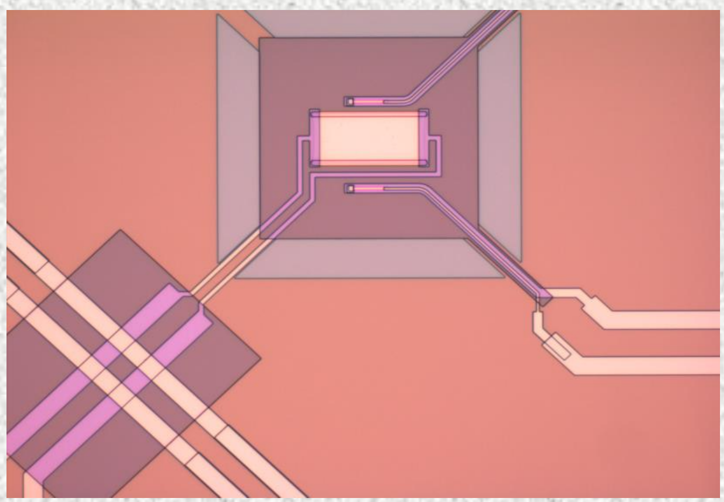


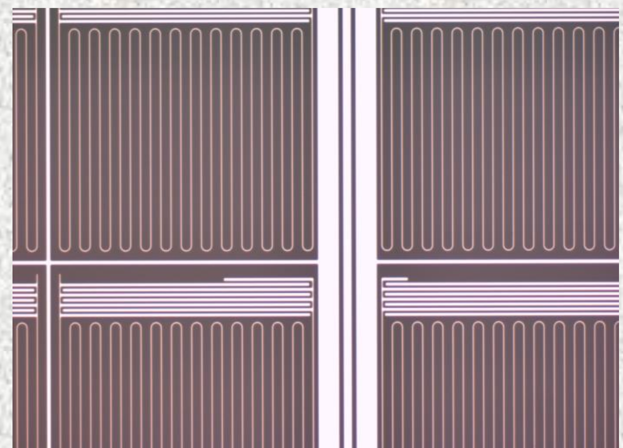








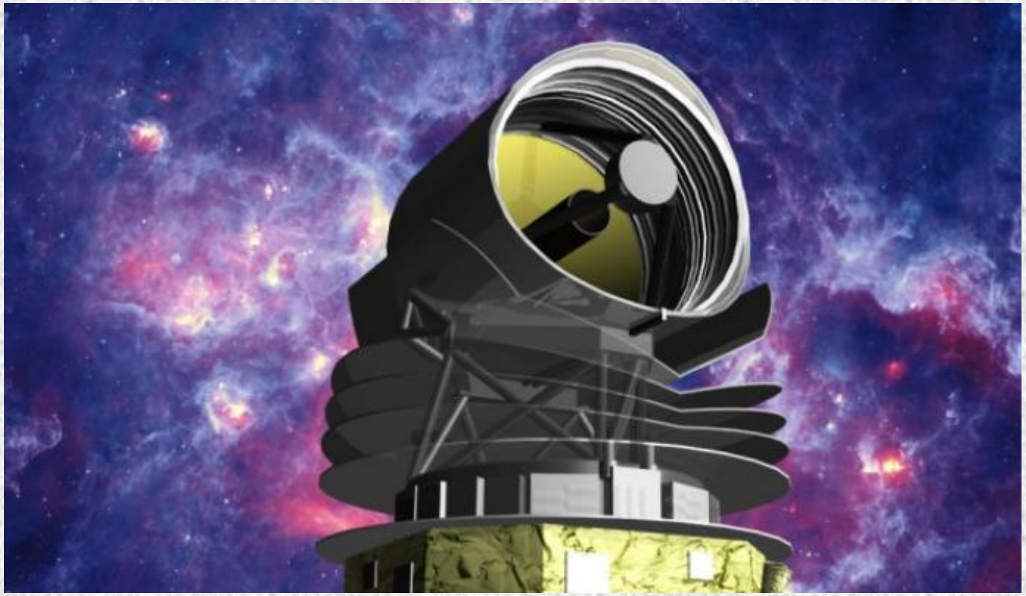


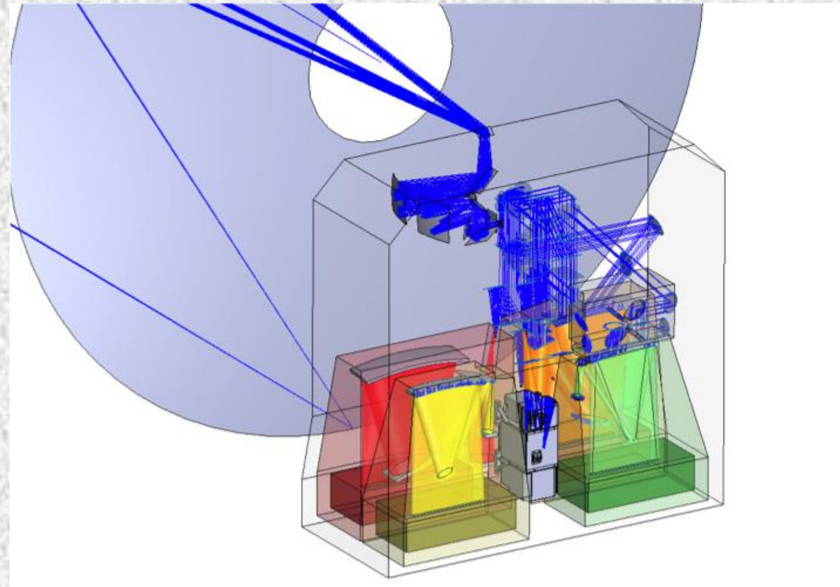


SPICA

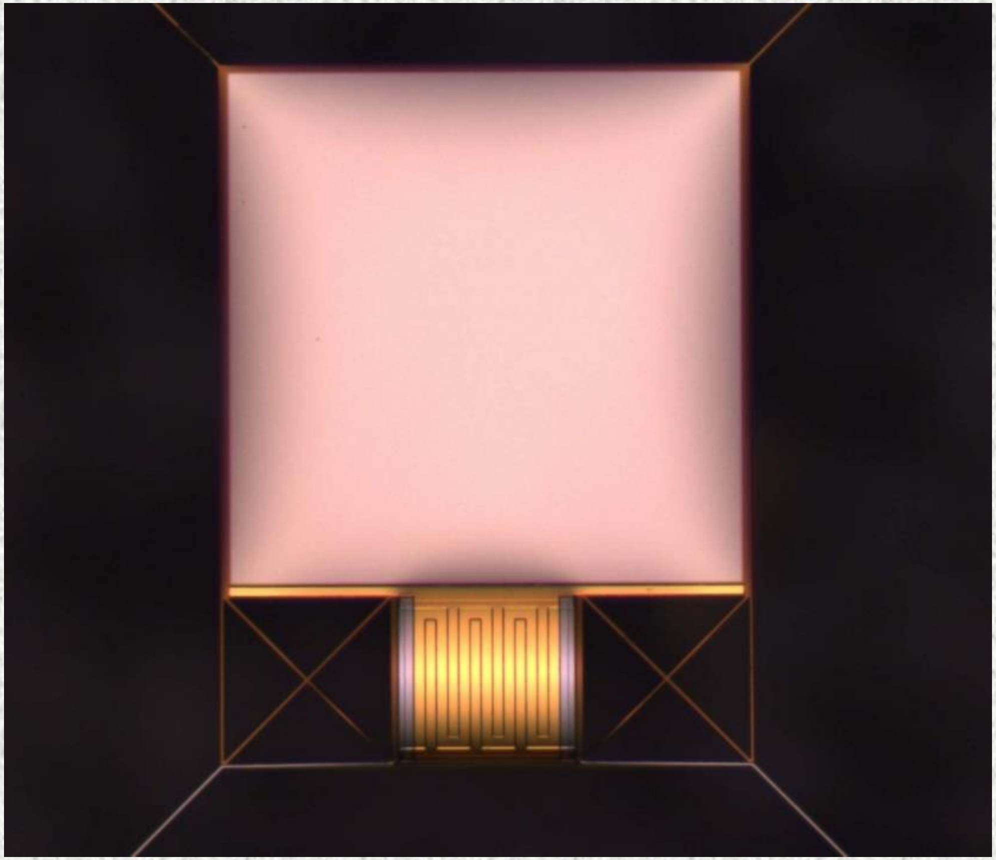
Space Infrared Telescope for Cosmology and Astrophysics

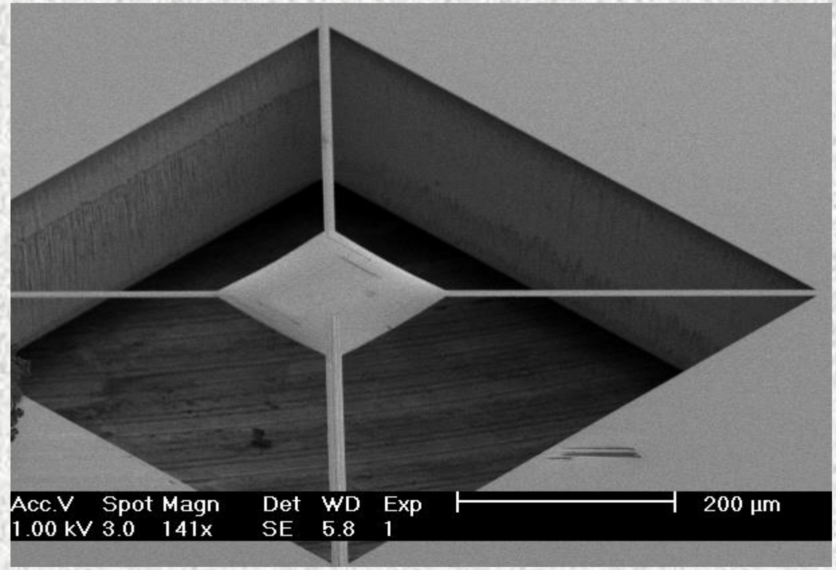
- Supercunducting sensors in fundamental physics: an example

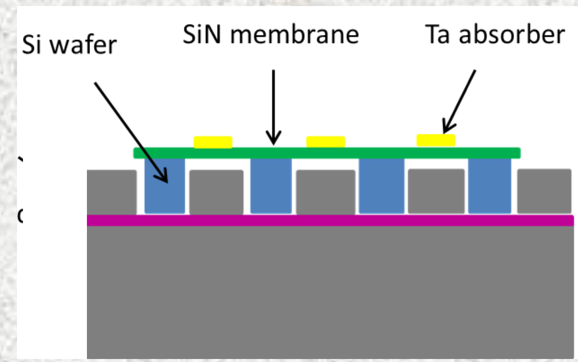




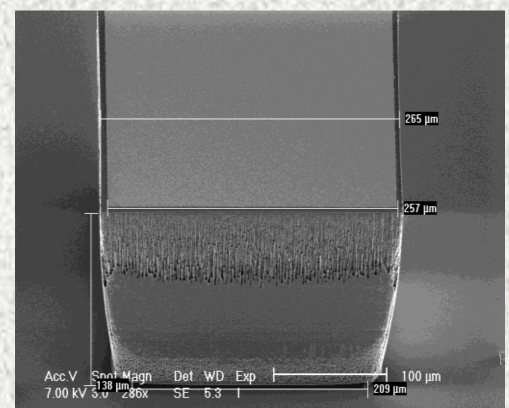
- SPICA: ESA-JAXA mission operating at Lagrange Point L2 (recently down selected)
- Cooled 3.5m telescope (<8K) to eliminate thermal radiation from mirror
- SAFARI grating / Fourier-transform spectrometers
- L-band 210-110 µm, M-band 110-60 µm, S-band 60-34 µm spectrometer arrays
- 3500 superconducting Transition Edge sensors operating at 50 mK, NEP ~2 x 10^{-19} $WHz^{-1/2}$, linearity at aW powers, Psat ~20 fW
- Readout electronics and multiplexer based entirely on superconducting electronics
- UK played a leading role in developing technology (Cambridge and Cardiff)

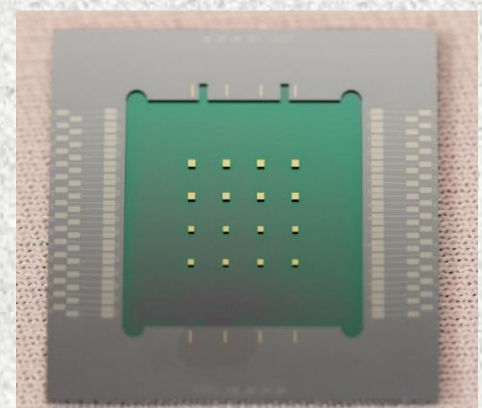






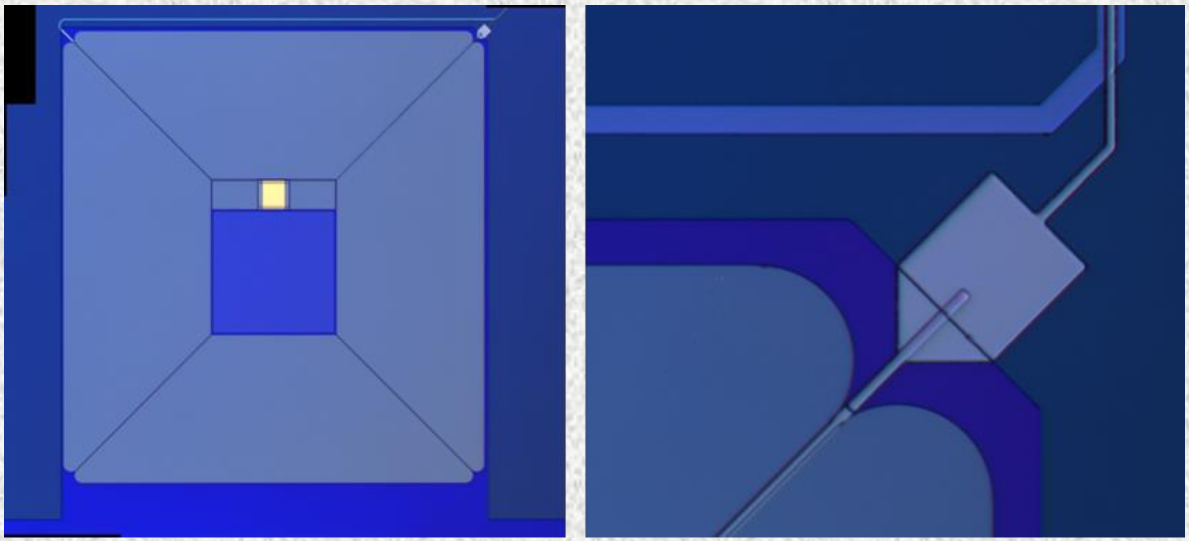
β-phase Ta absorber with Tc of 860 mK
200 nm SiN (high heat capacity due to TLSs)
MoAu bilayers with Tc of 110 mK
G 0.2 pW K^{-1}
NEP 4 x 10^{-19} $WHz^{-1/2}$
τ 10mS (on chip integration)
Psat 20 fW

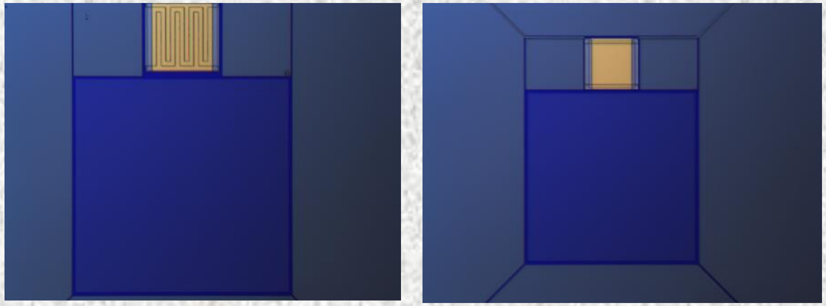


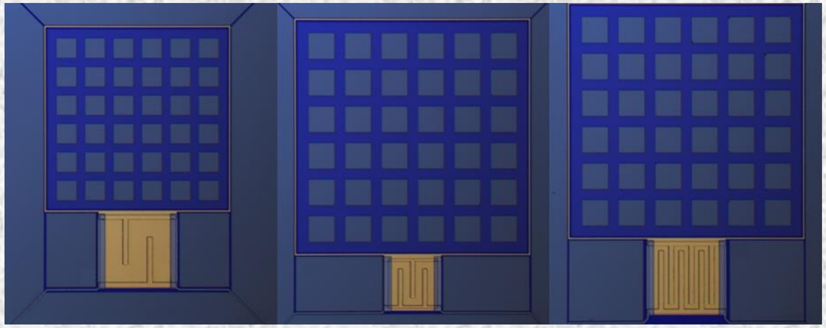


TES array chips:

- 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

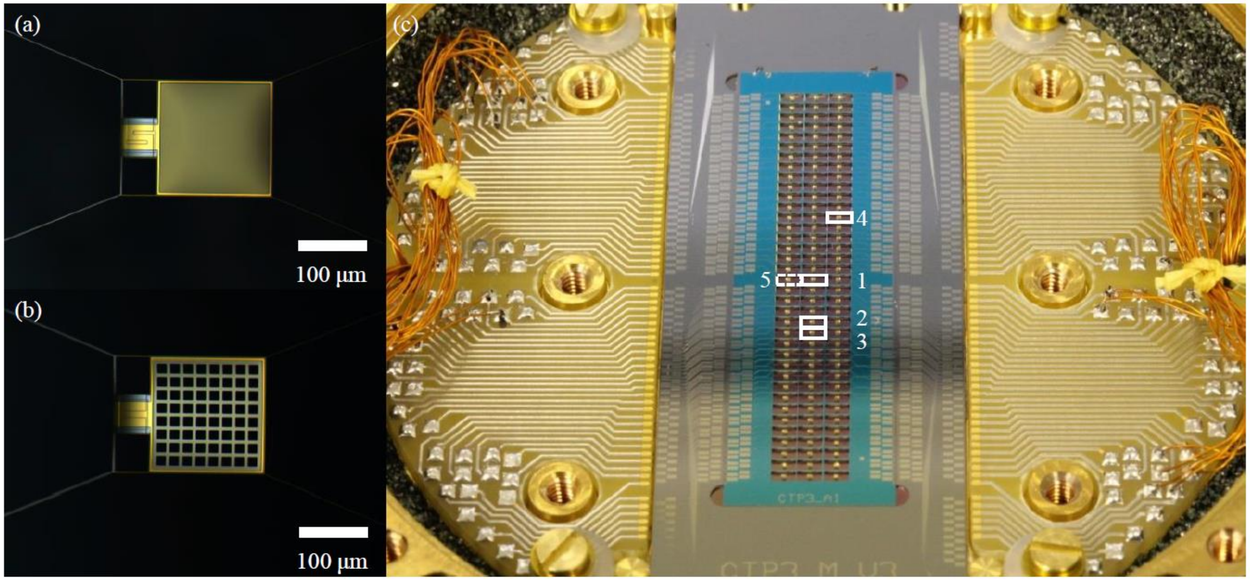


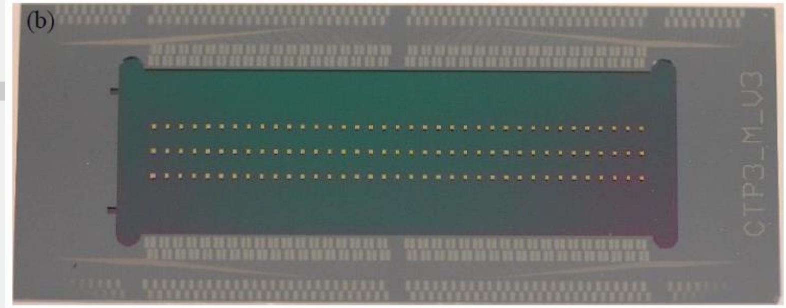


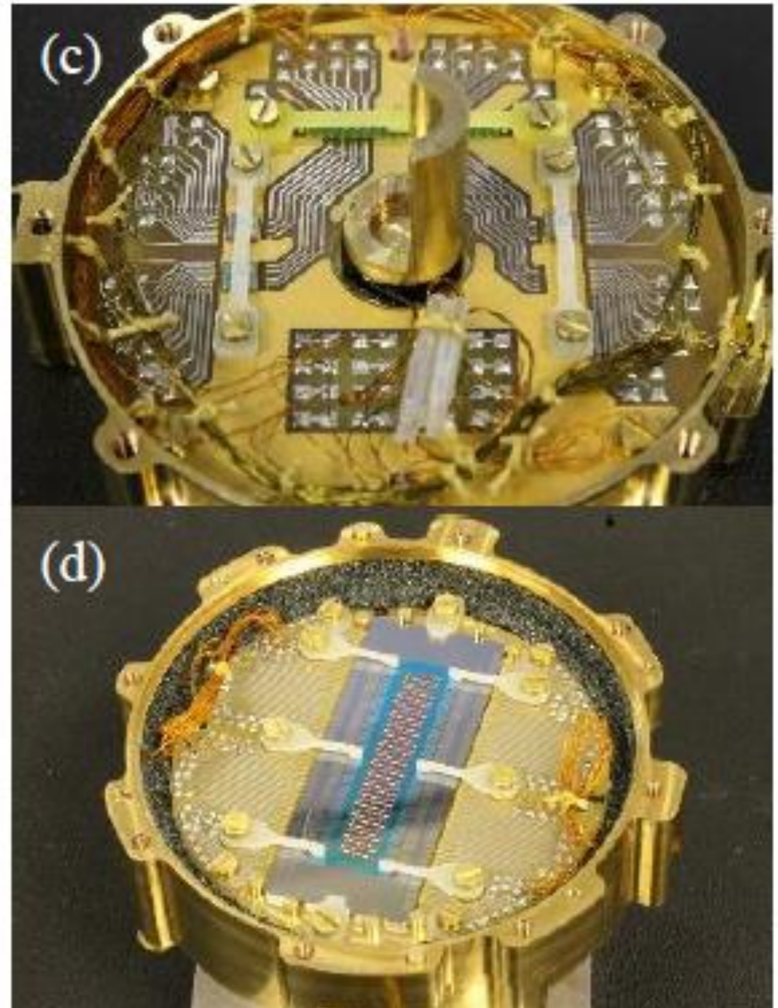


Microstrip Nb wiring:

- 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

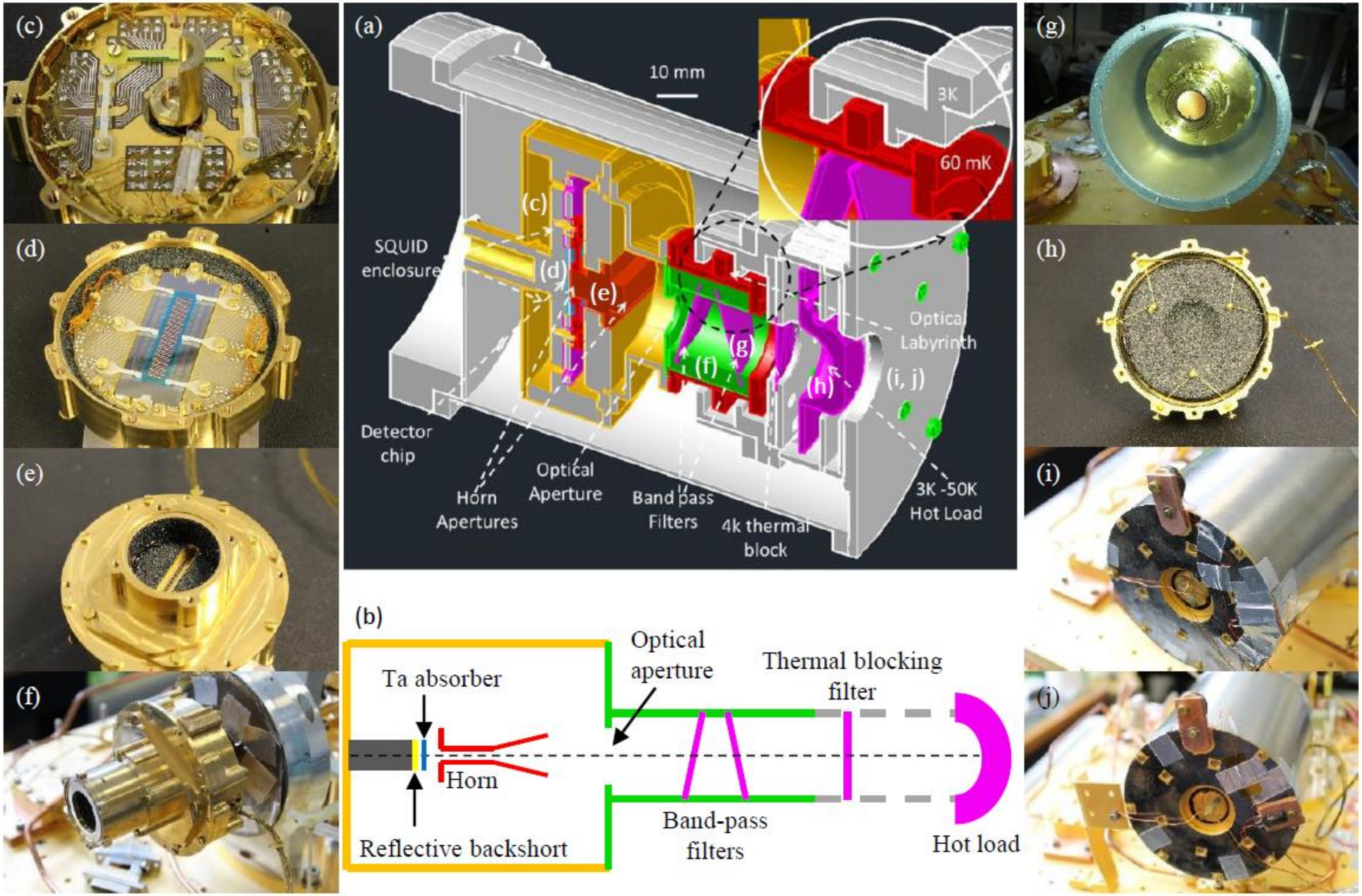




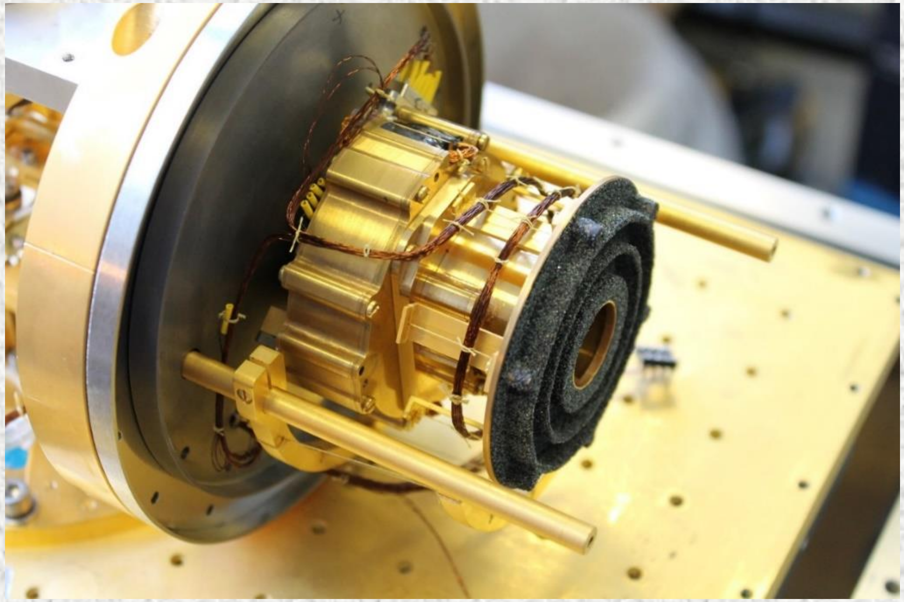


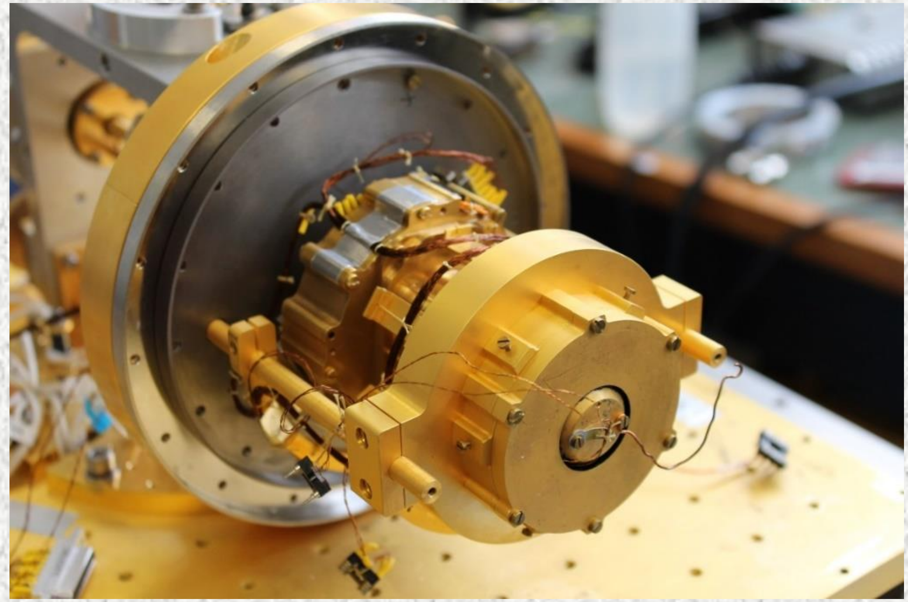
- Prototype linear array for grating spectrometer readout
- 30 – 200 µm, NEP 10^{-19} $WHz^{-1/2}$
- Micromachined Au coated pillars provide reflecting backshorts
- SQUID readout
- Superconducting wiring throughout (0.5 mΩ stray resistance)
- FIR absorber for straylight control

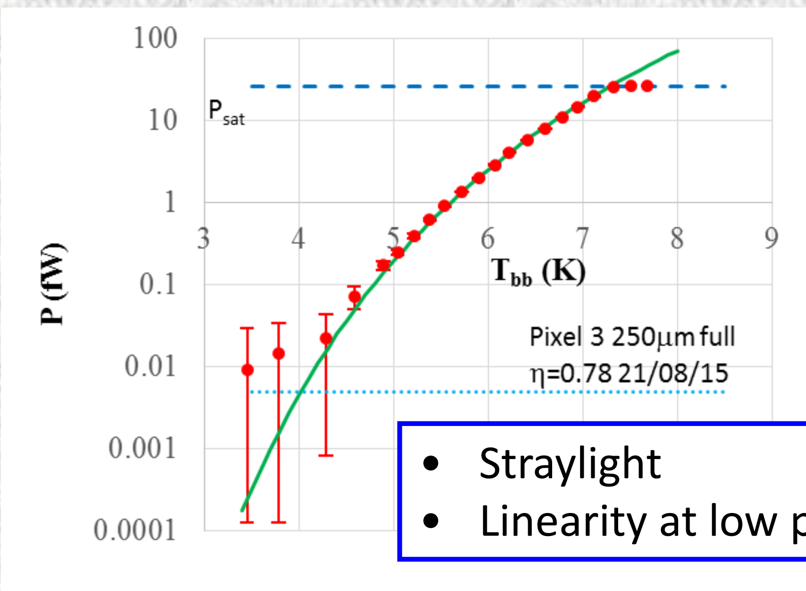
Measure optical performance using broadband blackbody source
Illuminate detectors using same optical modes in same proportions as the instrument itself



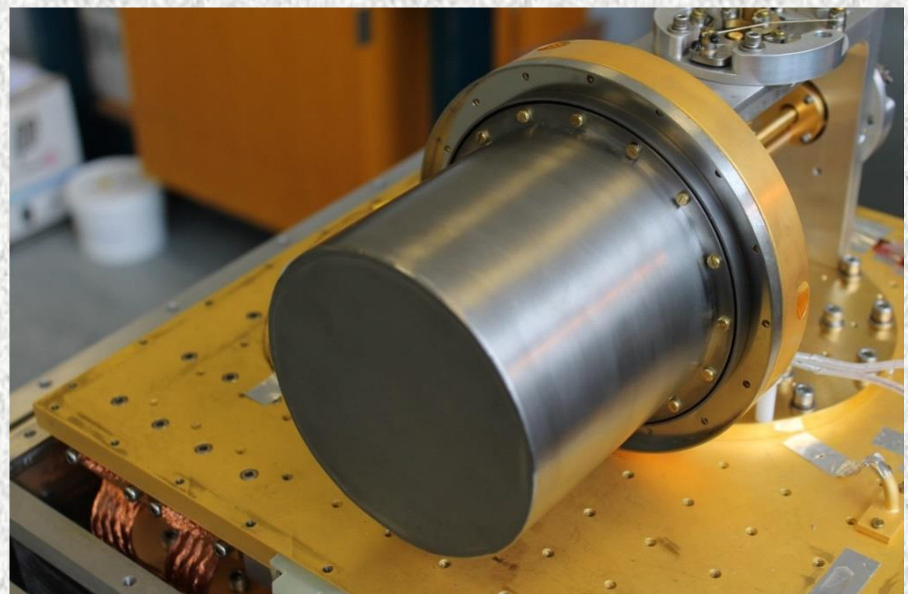
Development of packaging techniques for superconducting electronics in space with AirBus: suitability for space usage (magnetic fields, secondary cosmic electrons, straylight, etc)



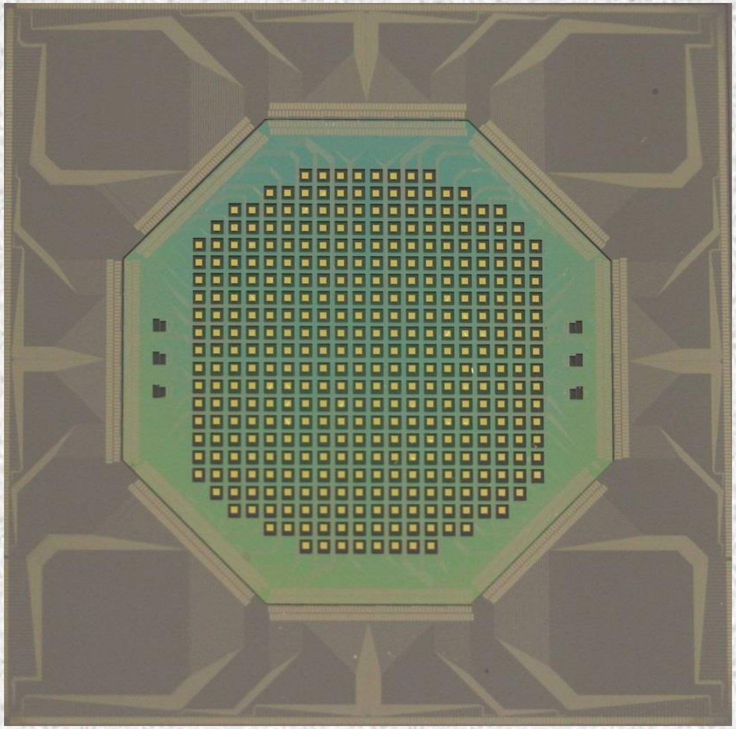


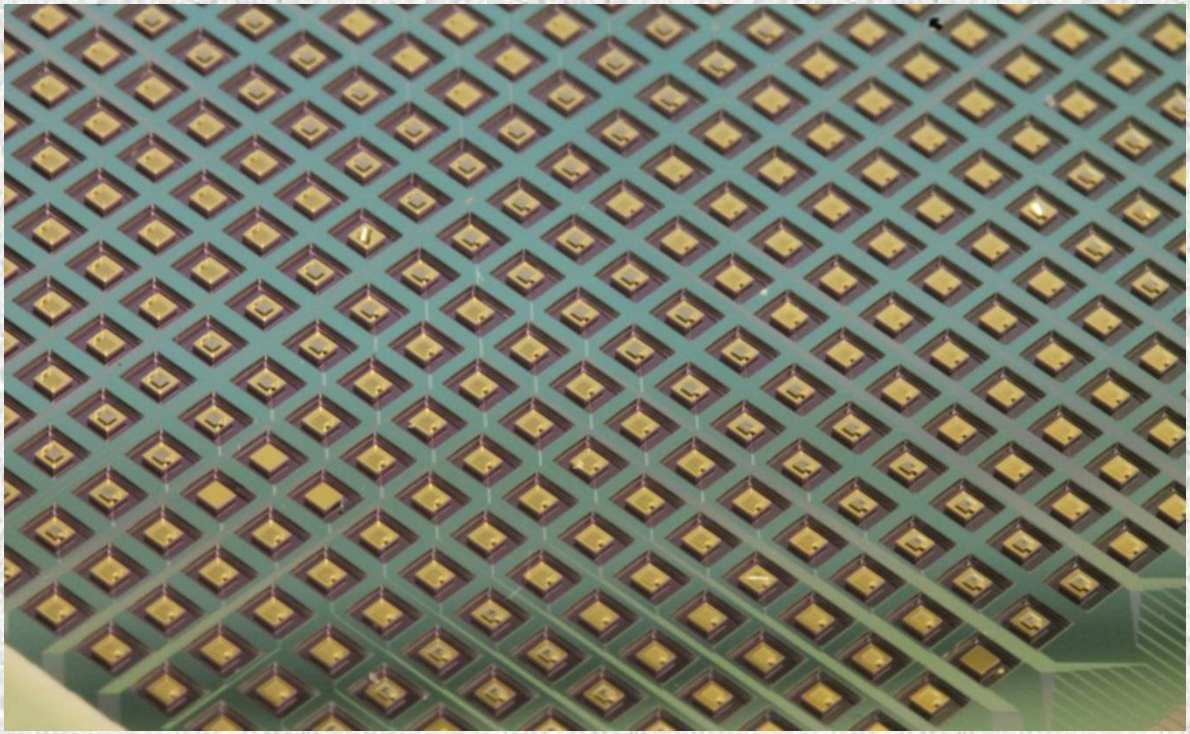


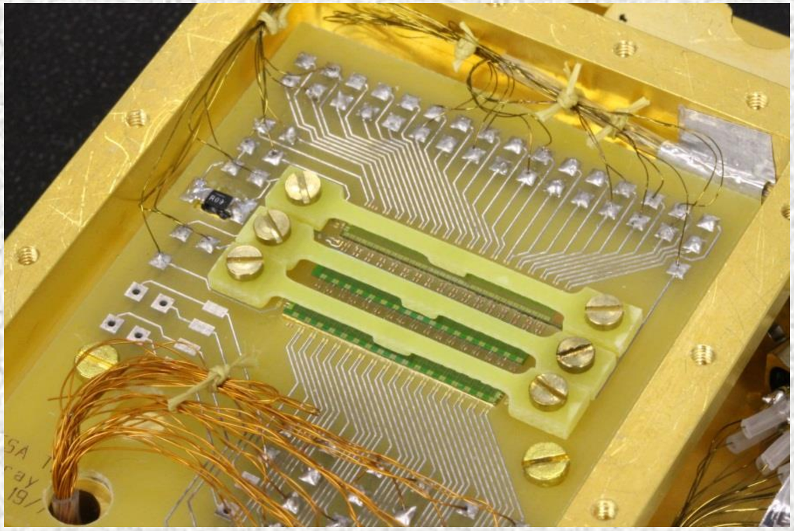
- Straylight
- Linearity at low power

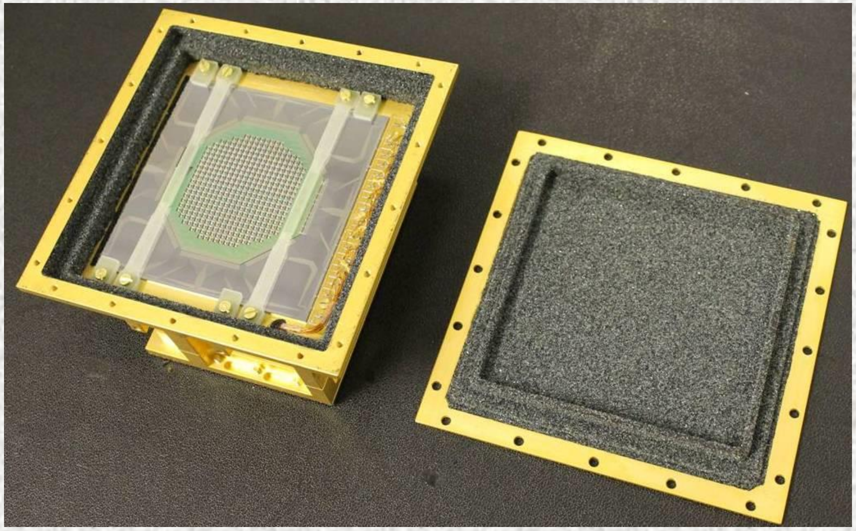


225 µm TES wafer, 670µm carrier wafer, 170µm recess: reflector at 55±1µm

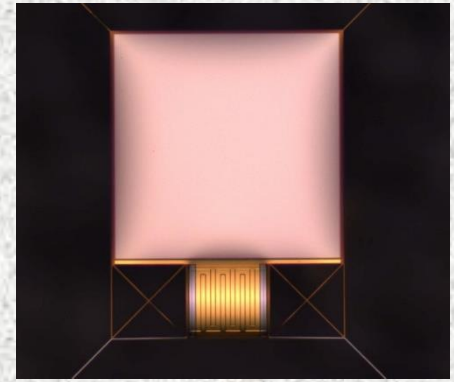


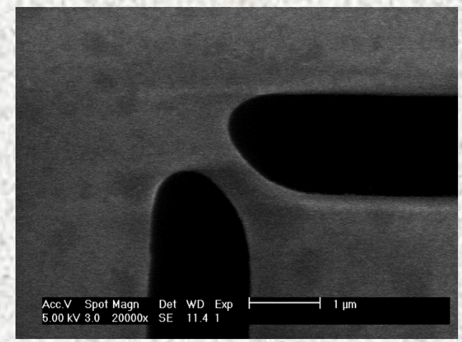






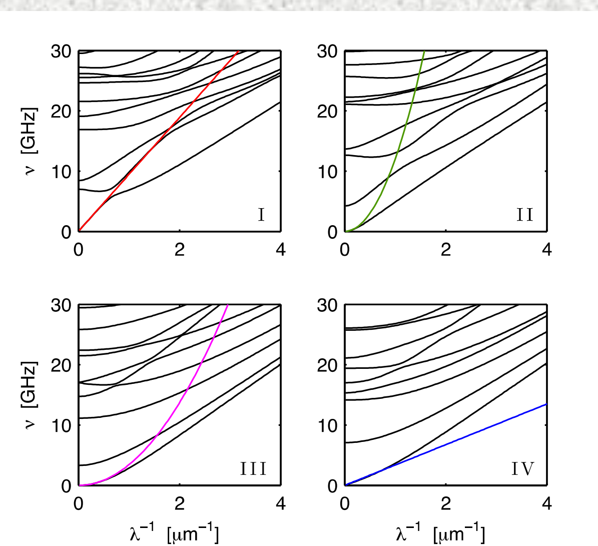
- Thermal fluctuation noise in the legs determines behaviour of whole telescope
- Amorphous materials show localised transport at low temperatures
- Manufacture TESs with few-mode legs working in the ballistic limit

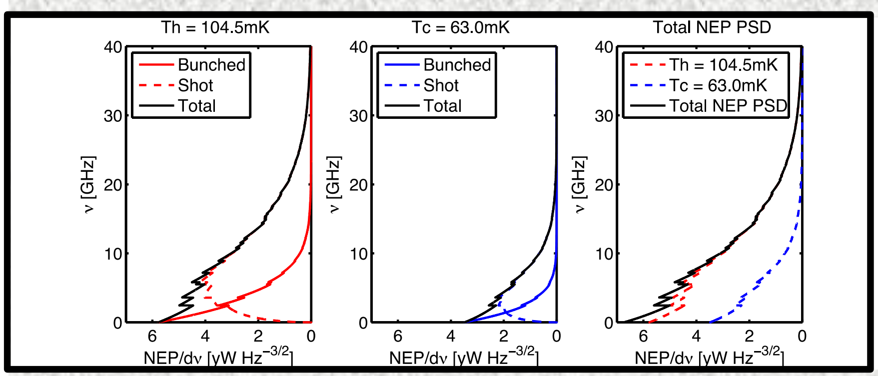


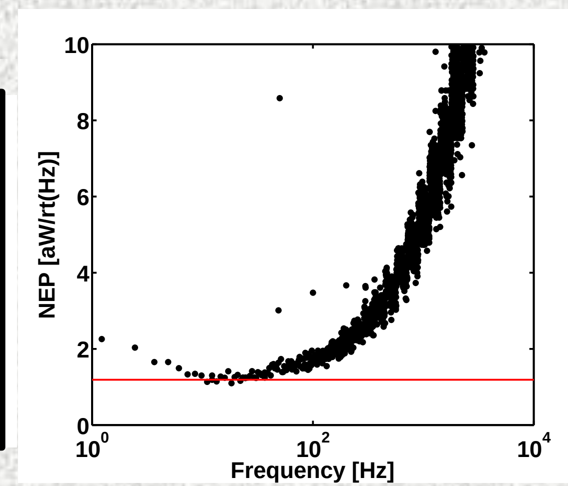


Coherence few-mode ballistic heat transport:

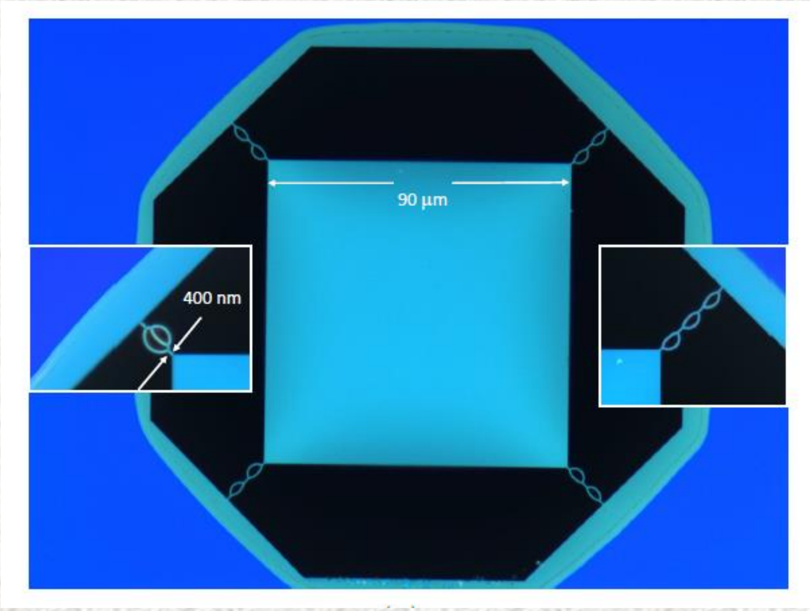
- 1 to 4 µm long, 200 nm thick, 750 nm wide
- Model based on bulk elastic constants only
- Reproduces flux and noise
- No free parameters
- Power carried by 5 modes

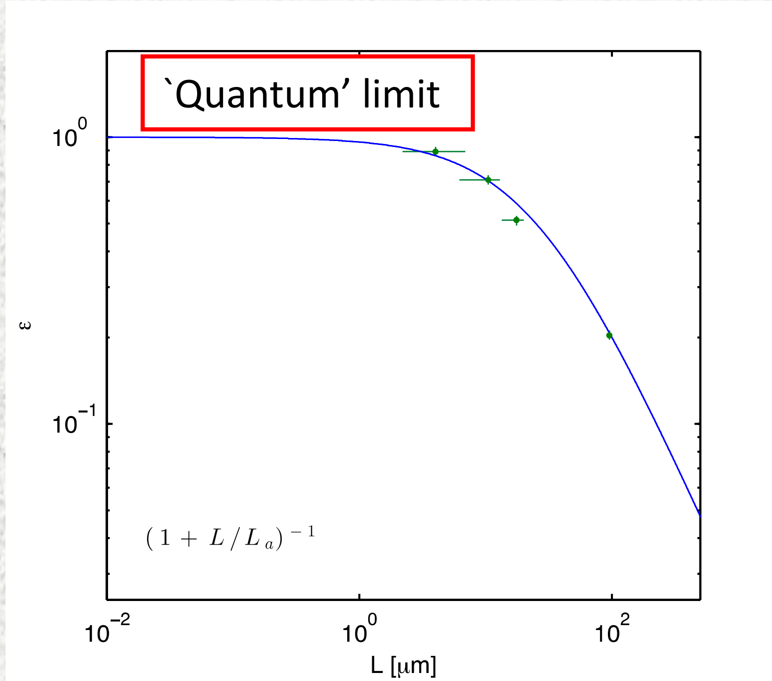


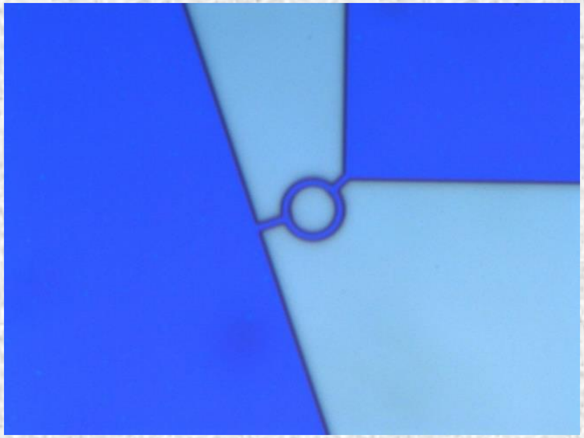


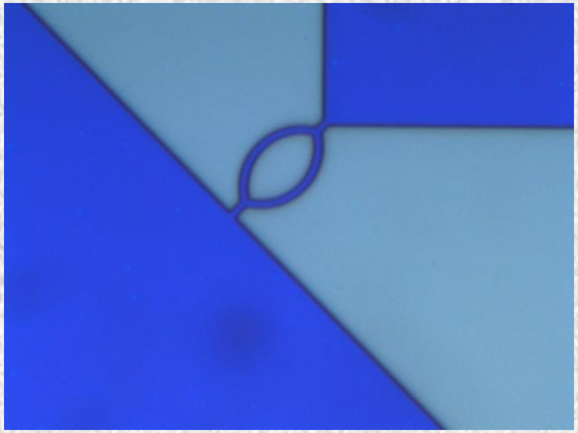


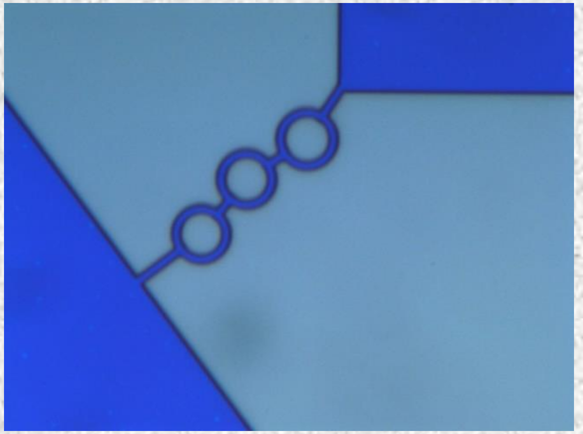
- But, need scattering to lower conductance
- Measured phonon coherence length to be 22 μm
- phononic few mode phononic filters

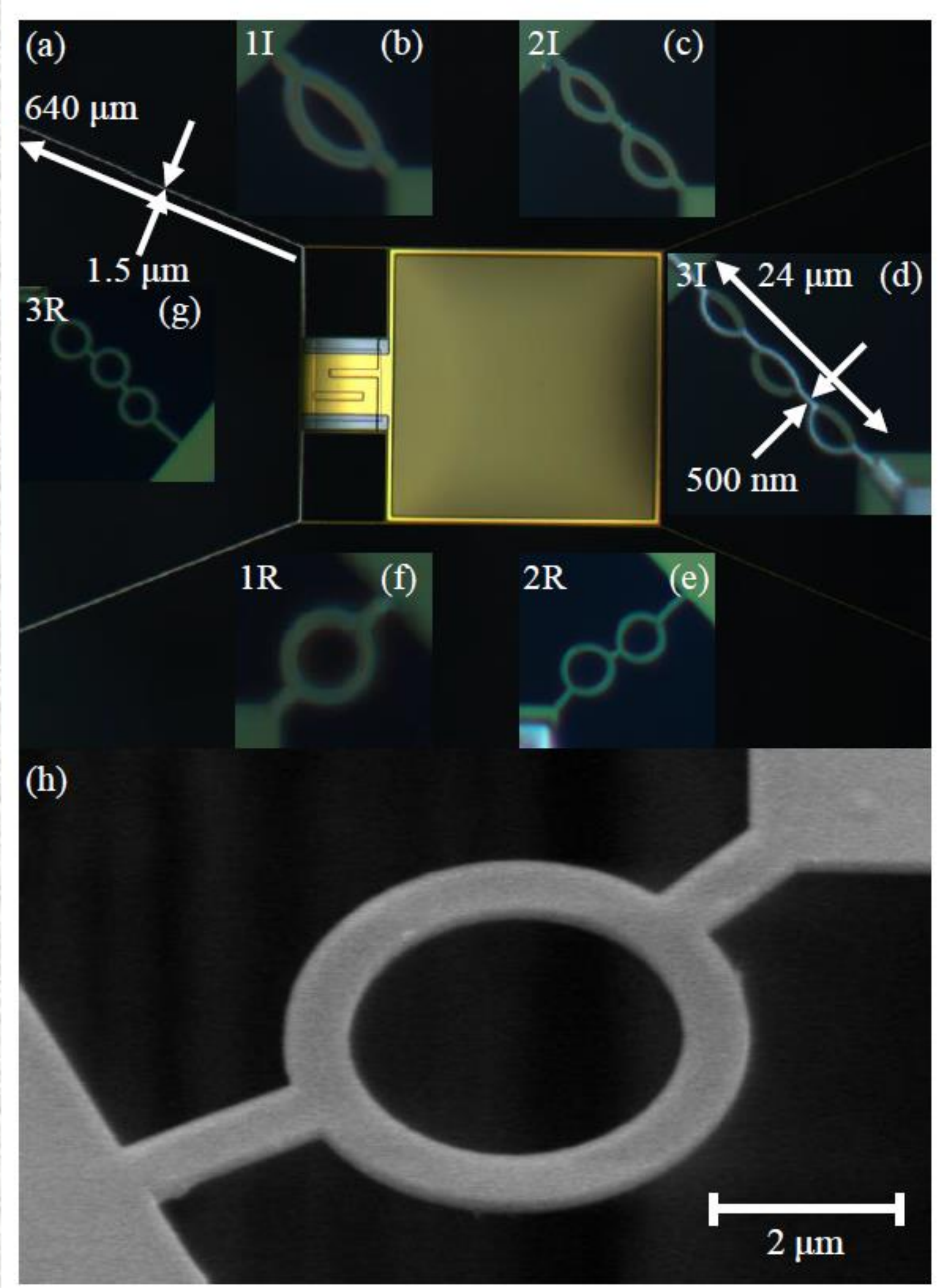


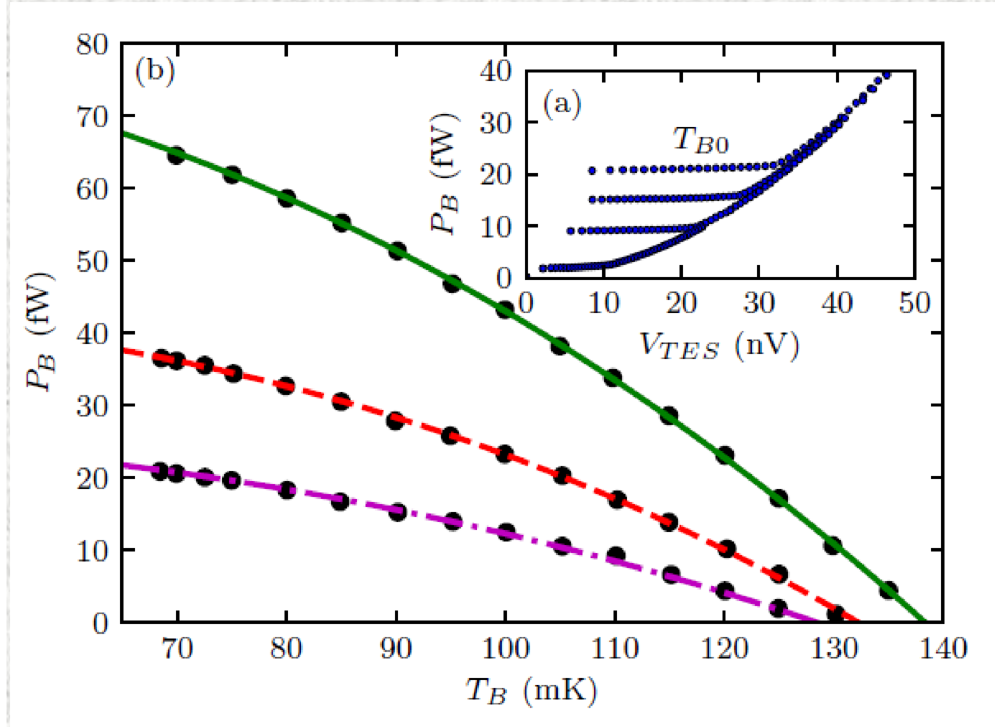


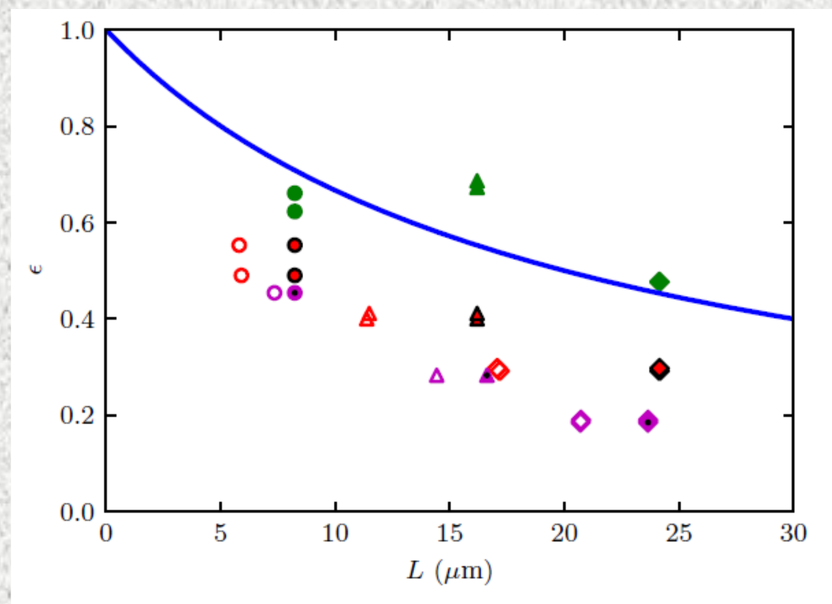




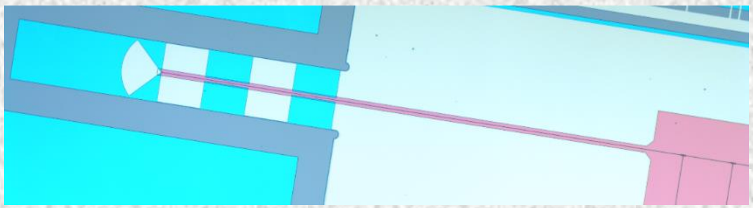


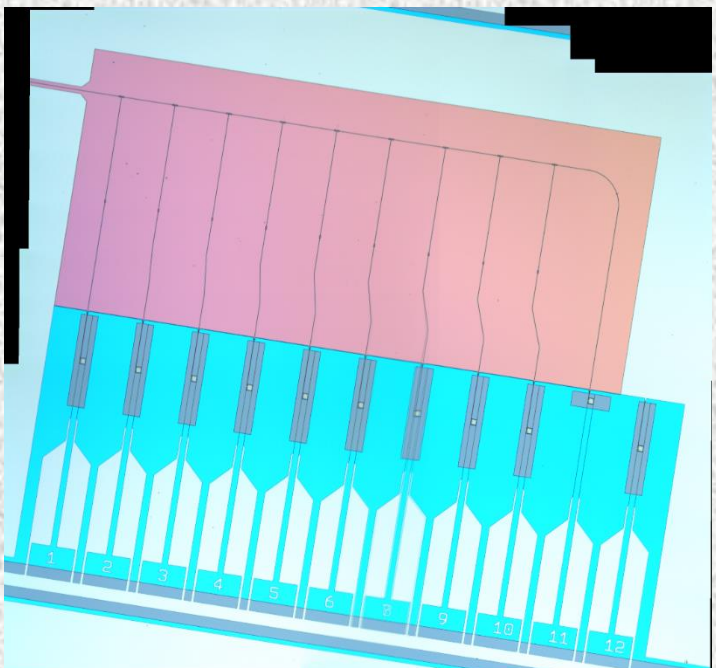

(a)
1I
(b)
2I
(c)
640 μm
1.5 μm
3R
(g)
3I
24 μm
(d)
500 nm
1R
(f)
2R
(e)
(h)
2 μm

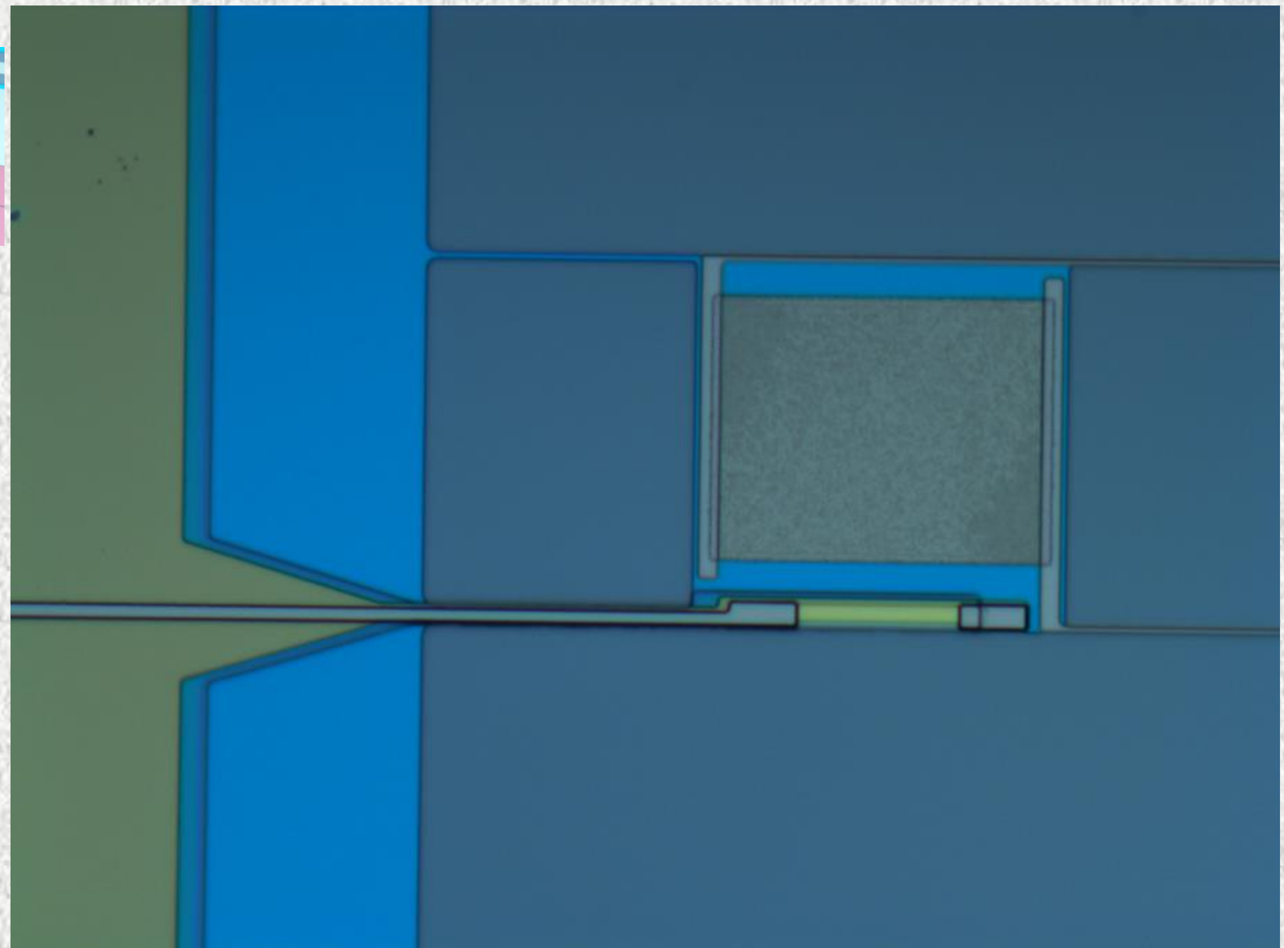

(b)
(a)
T_{B0}
P_B (fW)
V_{TES} (nV)
P_B (fW)
T_B (mK)


ϵ
L (μm)

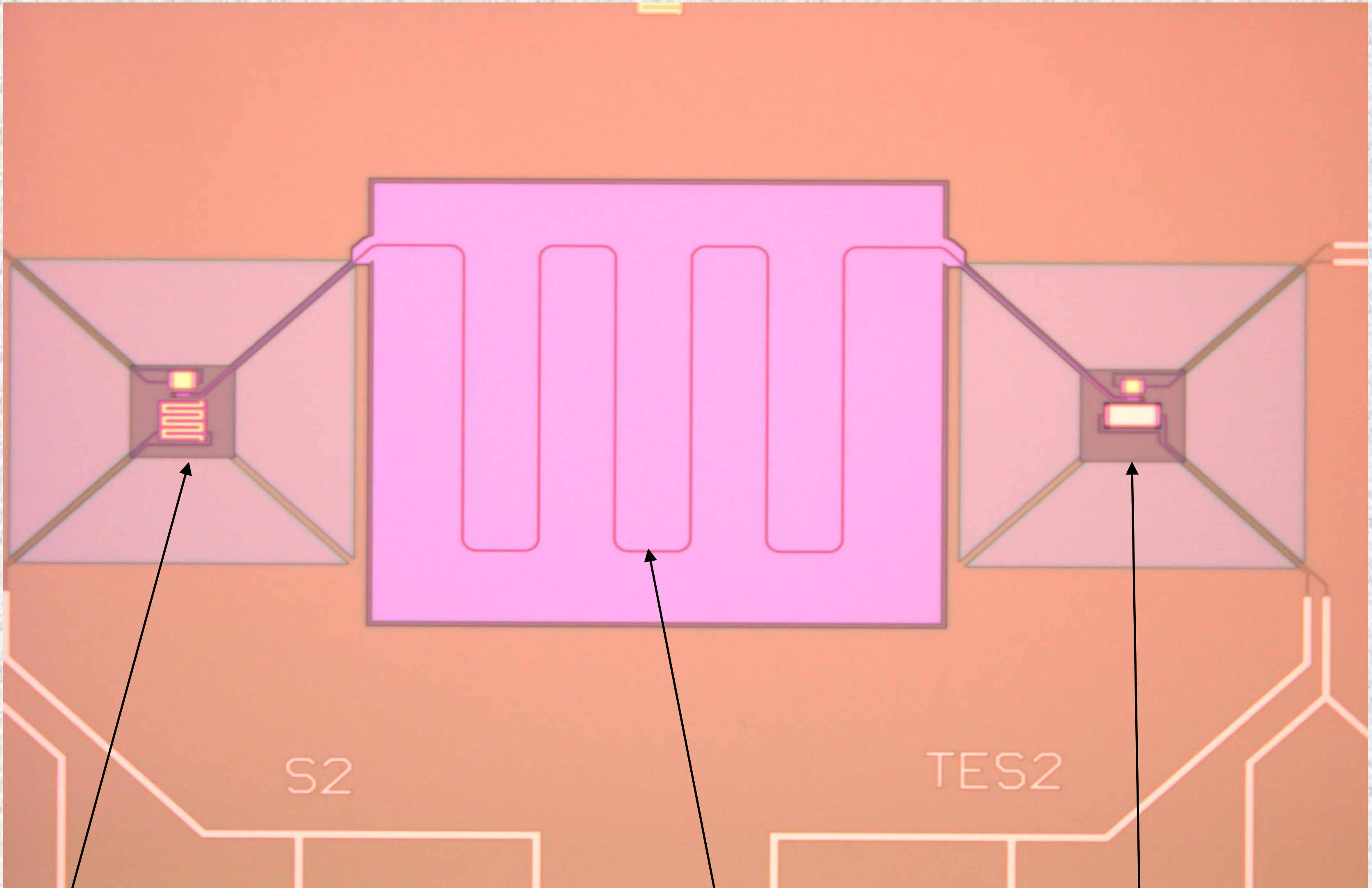
- Filterbank chip spectrometer for space-based Earth observation HYMAS (joint with Cardiff Univ.)
- Microstrip coupled Transition Edge Sensors
- Superconducting microstrip on 1um wide 200nm thick leg and 20Ω load
- Waveguide probe fed at 60 to 90 GHz
- TiAl bilayers having NEP 10 -17 WHz -1/2







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



Variable temperature black body load:

Microstrip line

Low-noise TES

Key points:

- Superconducting electronics offers numerous opportunities for
- laboratory based fundamental physics

- Substantial opportunity for innovation in ultra-low-noise science

- Large area of science developing superconducting nano-mechanical and opto-mechanical quantum, entangled, state devices

- The UK has facilities and expertise to deliver on this innovation

Special thanks for some of the work shown to collaborators at the

  - Oxford Instruments for their original insight and generosity
  - University of Cardiff
  - University of Oxford
  - European Space Agency, Airbus, and many others

Many papers of superconducting sensors available on request....