Teraherz detectors for astronomy

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Introduction

Sub-mm astronomy

Astronomy at sub-mm wavelengths

Between FIR and millimetre

No strict definition: usually from ~ 200 µm to ~ few mm

CSO and JCMT, Mauna Kea, Hawaii

Why do sub-mm astronomy?

It lets us see cold things - peak in a 10 K blackbody is at 300 µm

Cold things are interesting: usually objects in formation (galaxies, stars, planets…)

• Sub-mm emission usually "optically thin"; so we see the interior rather than just the surface of objects

Example: sub-mm (850 µm) contours overlaid (SCUBA)

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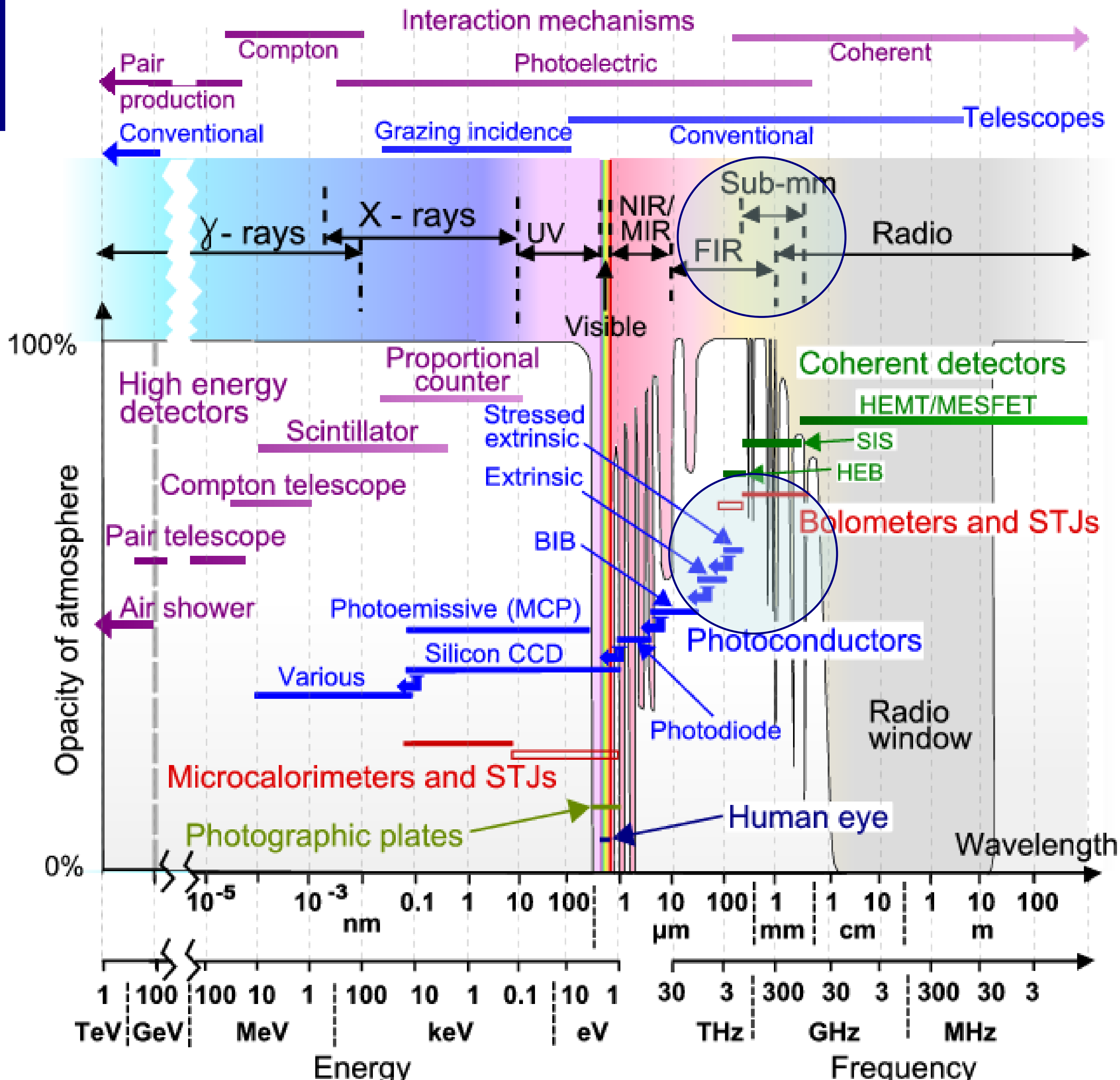


Interaction mechanisms
Pair production
Compton
Photoelectric
Coherent
Conventional
Grazing incidence
Conventional
Telescopes
γ - rays
X - rays
UV
NIR/ MIR
Visible
FIR
Sub-mm
Radio
100%
0%
Opacity of atmosphere
High energy detectors
Proportional counter
Scintillator
Compton telescope
Pair telescope
Air shower
Stressed extrinsic
Extrinsic
BIB
Photoemissive (MCP)
Silicon CCD
Various
Photodiode
Photoconductors
Microcalorimeters and STJs
Photographic plates
Human eye
Coherent detectors
HEMT/MESFET
SIS
HEB
Bolometers and STJs
Radio window
Wavelength
10⁻⁵ 10⁻³ 0.1 1 10 100 nm
1 10 100 µm
1 mm
1 10 cm
1 10 100 m
1 TeV 100 GeV 100 10 1 MeV 100 10 1 0.1 keV 10 1 eV
Energy
30 3 THz 300 30 3 GHz 300 30 3 MHz
Frequency

Sub-mm/FIR astronomy

- Astronomers have very strict requirements on sensitivity and noise
- Detectors operate on extremely expensive telescopes (particularly if in space)
- Every photon counts!
- Ideally background (photon noise limited) performance
    - If not, than the lowest that can possibly be achieved
- So detector types that are useful for other applications aren’t considered in astronomy (e.g. room temperature bolometers in the infrared)
- Similar requirements in biological measurements – too many photons destroy the sample

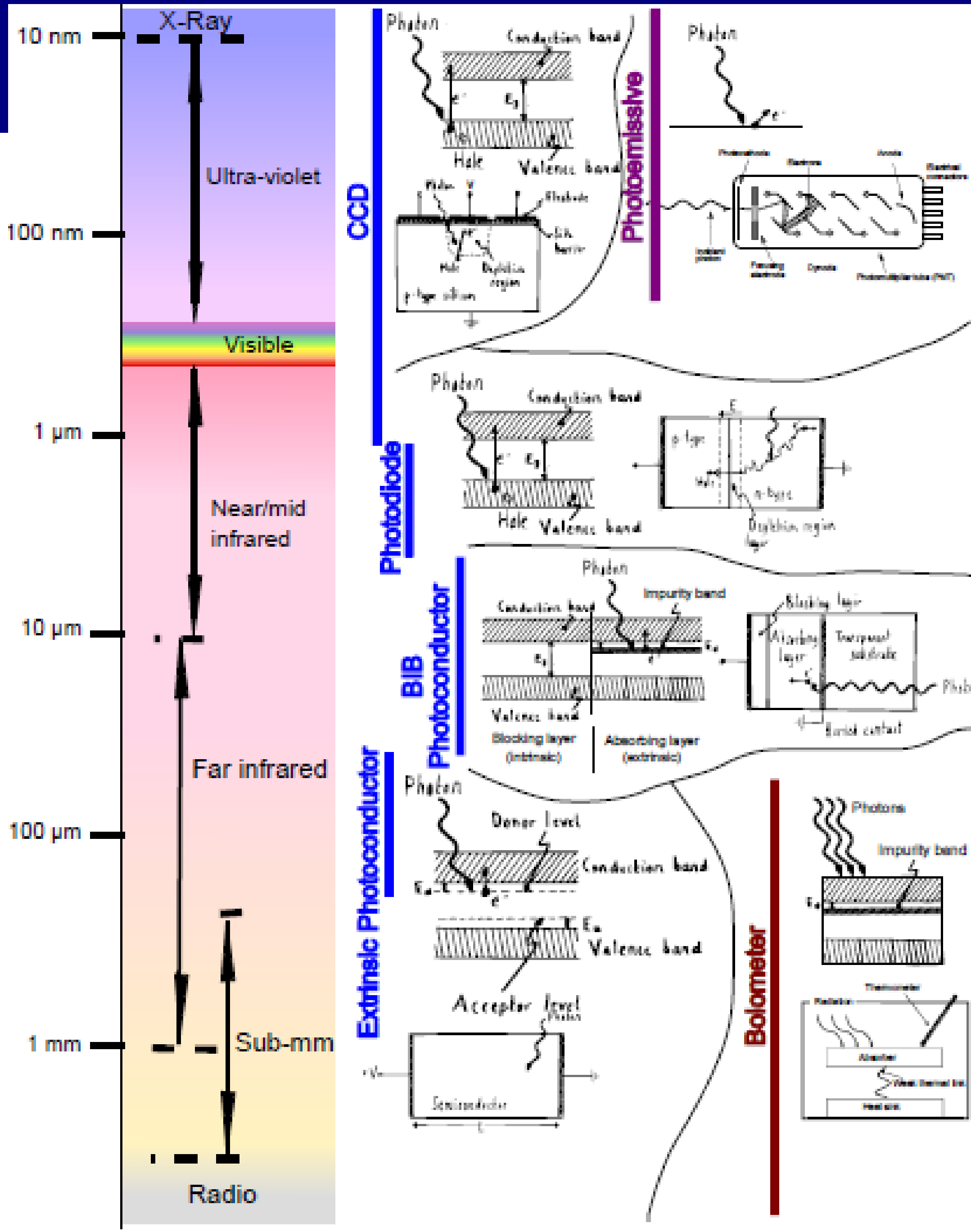
Applications

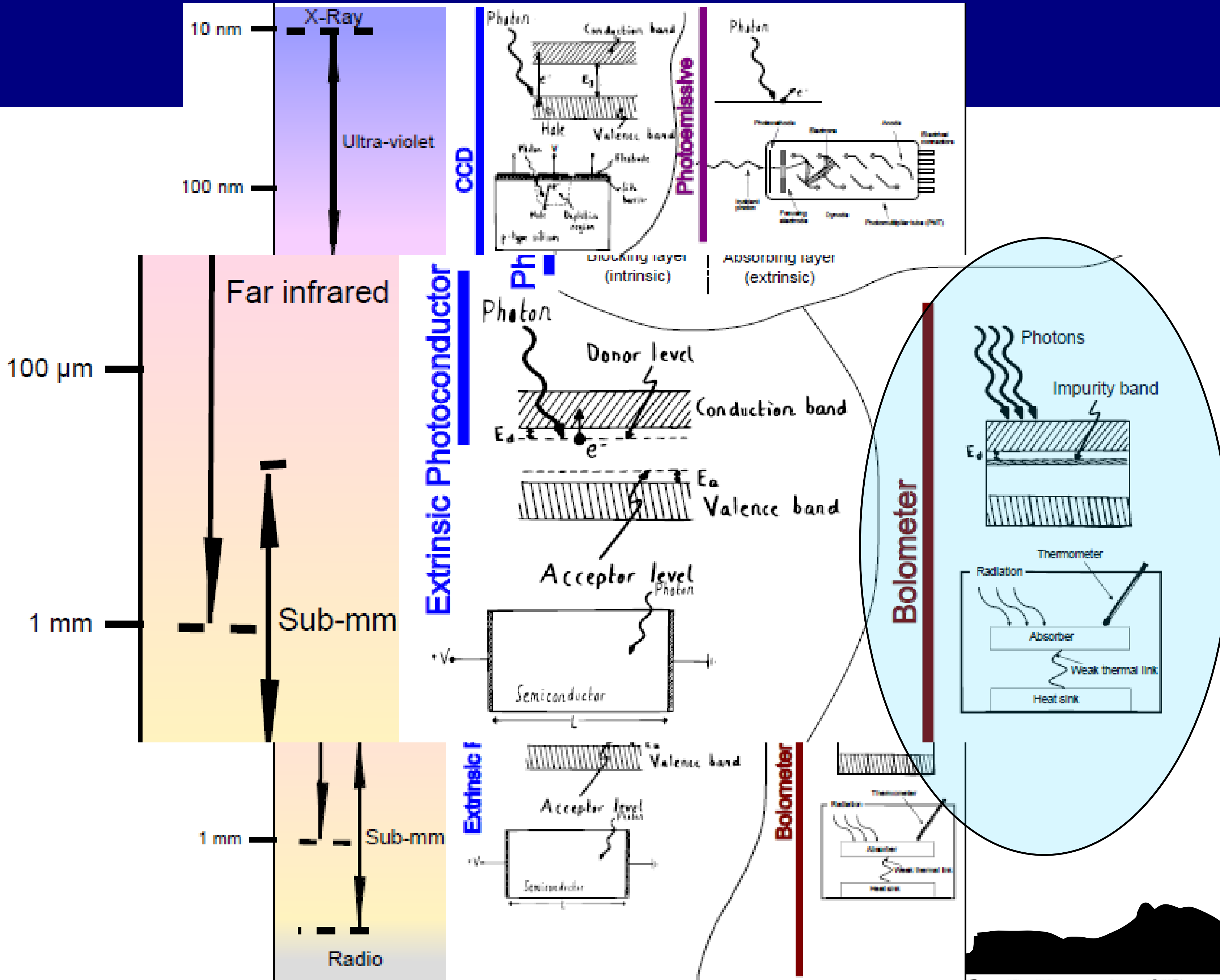
Unlike at optical and NIR wavelengths, historically few commercial and military applications in sub-mm

Development largely in universities and government labs rather than industry

Cost $2000/pixel c.f. $0.12 for infrared, $0.01 for optical

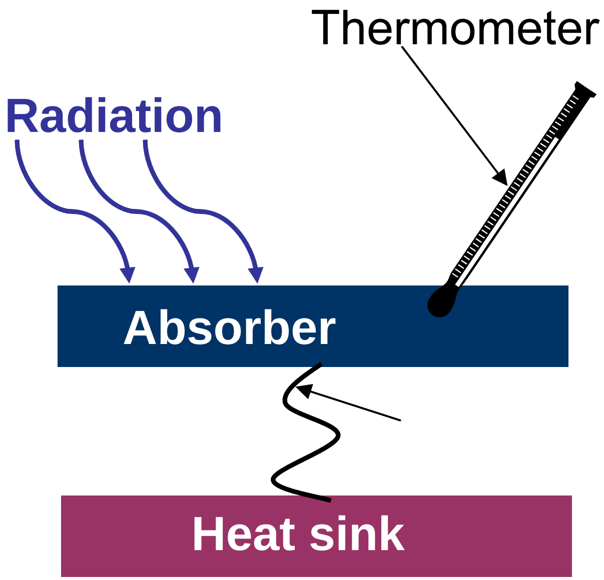
Semiconducting detectors


10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
X-Ray
Ultra-violet
Visible
Near/mid
infrared
Far infrared
Sub-mm
Radio
CCD
Photoemissive
Photodiode
BIB
Photoconductor
Extrinsic Photoconductor
Bolometer
Photon
Conduction band
Valence band
Hole
Impurity band
Blocking layer
(intrinsic)
Absorbing layer
(extrinsic)
Donor level
Acceptor level
Photons


X-Ray
10 nm
Ultra-violet
100 nm
CCD
Photon
Conduction band
Hole
Valence band
Photoemissive
Photon
Blocking layer
(intrinsic)
Absorbing layer
(extrinsic)
Far infrared
100 µm
1 mm
Sub-mm
Extrinsic Photoconductor
Photon
Donor level
Conduction band
E_d
e^-
E_a
Valence band
Acceptor level
Photon
+V
Semiconductor
L
Bolometer
Photons
Impurity band
E_d
Thermometer
Radiation
Absorber
Weak thermal link
Heat sink
1 mm
Sub-mm
Radio
Valence band
Acceptor level
Semiconductor

Cryogenic bolometers

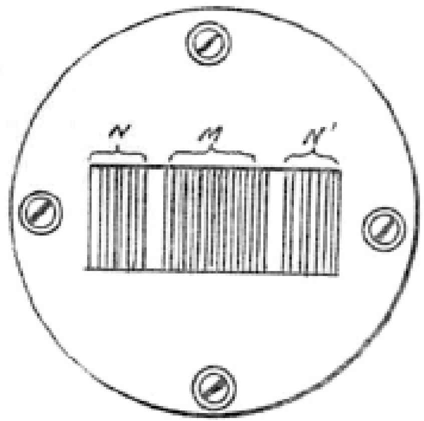
Currently the detector of choice for photometry in the sub-mm (above 200 µm)



The first bolometer

Bolometer invented by S. P. Langley in 1880 for infra-red astronomy (and luminous insects)

FIG. 1.



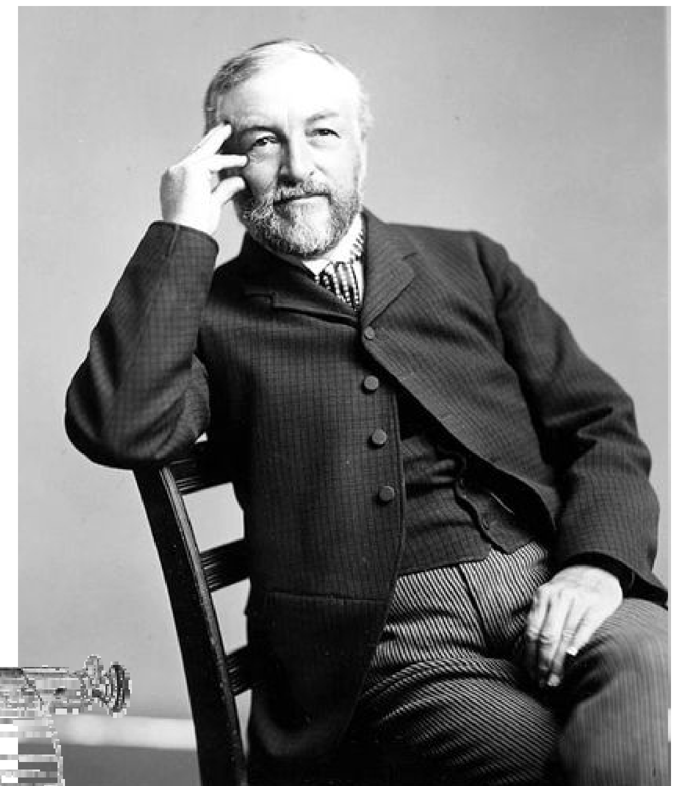
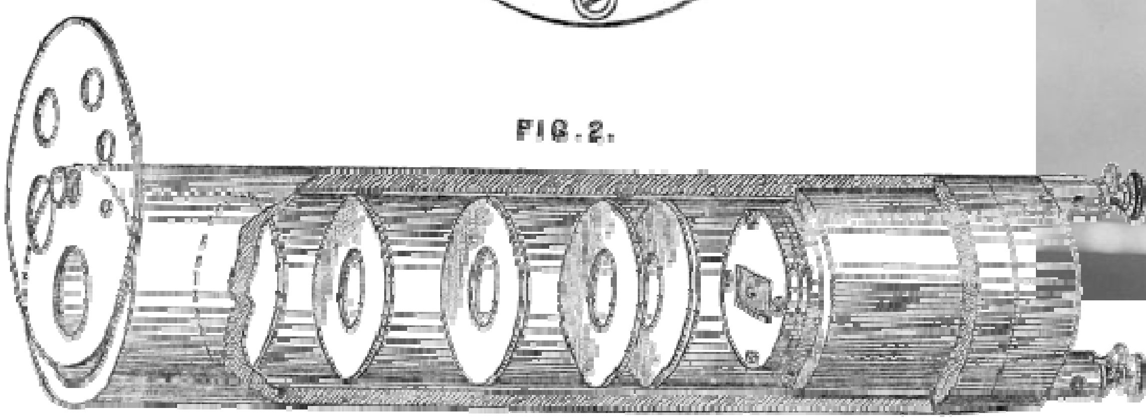


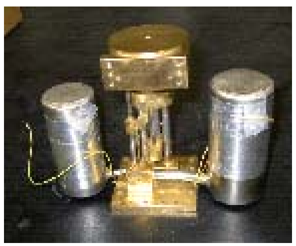
FIG. 2.

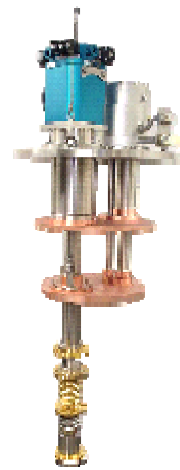


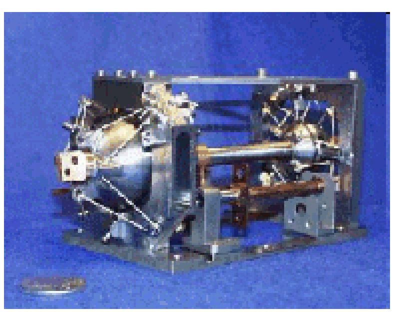
Cryogenic bolometers

To get sufficiently good performance, now operate at 300 mK or lower

- Makes instruments complex (and expensive)
- Much lower than needed in most areas of astronomy



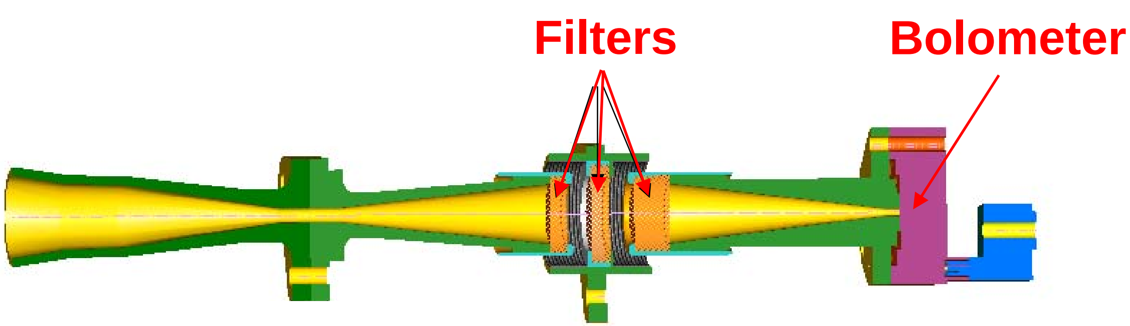




Cryogenic bolometers

Bolometers are broad-band devices: they respond equally to all absorbed wavelengths

- Have to filter out unwanted wavelengths
- Inductive/capacitative metal mesh filters can be produced with well defined bandpasses



Metamaterials offer the possibility of improved filters

- These are currently being researched at Heriot-Watt

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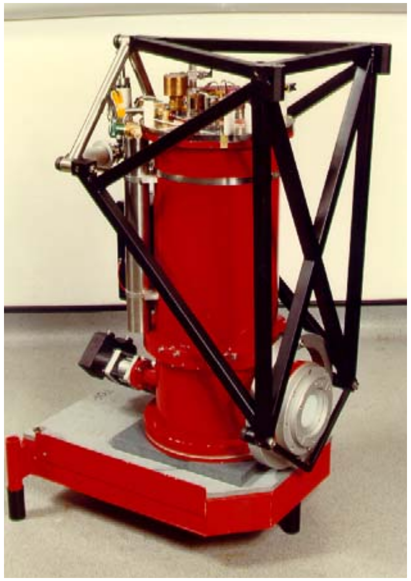
Cryogenic bolometers

- Early sub-mm instruments contained a single pixel
- Thermistor usually small block of Ge:Ga



UKT14 (ROE, Edinburgh)

Bolometer arrays

Arrays appeared in the 1980’s, making better use of telescopes

SCUBA (ROE, Edinburgh)

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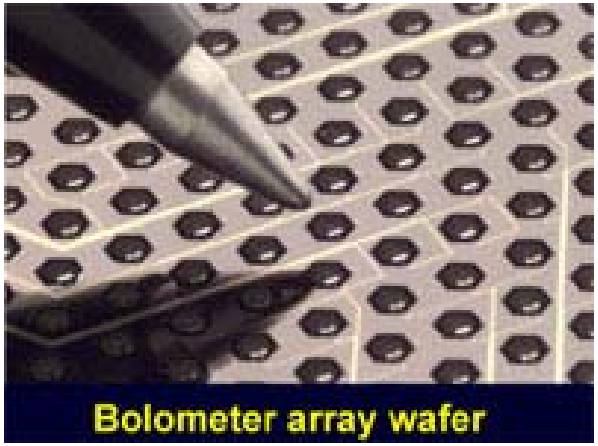
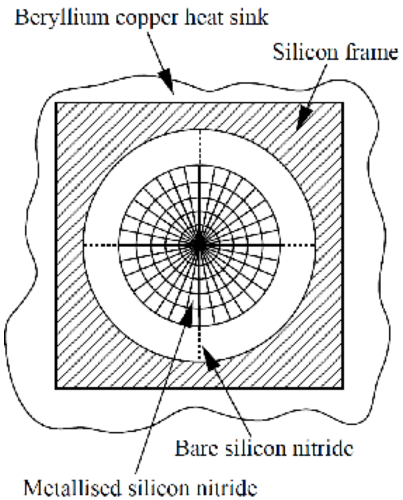
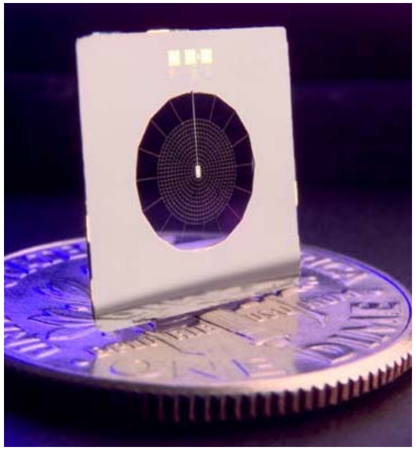
Modern bolometers

Later bolometers built by micromachining

- Silicon nitride deposited on silicon wafer
- Silicon etched to form SiN membranes
- Form absorber and supports
- Metallisation defines absorber and weak thermal link
- “Spiderweb” shape reduces heat capacity and exposure to ionizing radiation





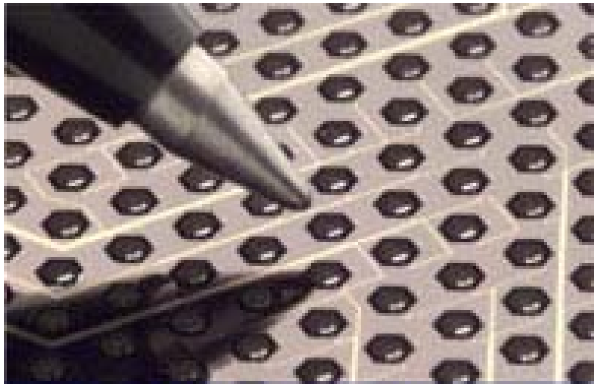


JPL spiderweb bolometers

Modern bolometers

Either break out into individual detectors, or leave to form an array

HFI bolometers (JPL/Cardiff)



Spiderweb array wafer (JPL)

But still have to stick germanium chips individually on each pixel

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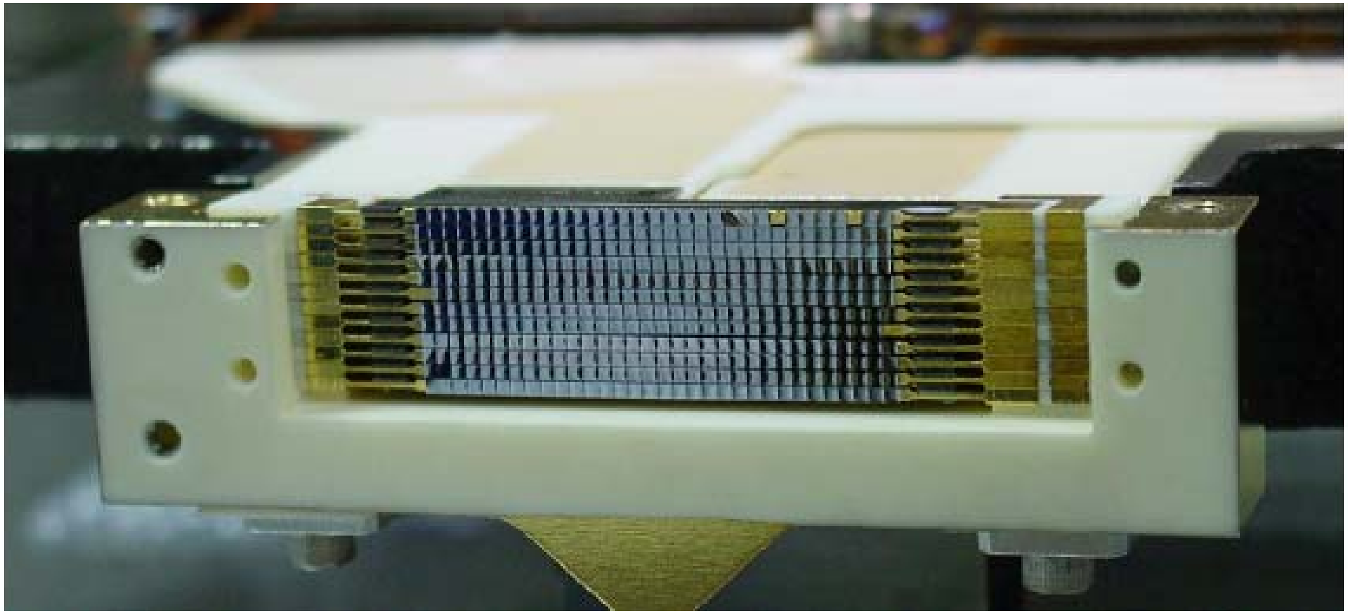
Modern bolometers

Alternative: make thermistors from the silicon itself by ion implantation

- Initial problems with excess noise, but recently discovered it could be removed by using thicker implants



SHARC-II (GSFC/Caltech)

Limitations

Difficult to multiplex germanium or silicon bolometers without introducing too much noise

- Limits array sizes
- "CCD-like" CMOS multiplexed silicon arrays have been produced using very high thermistor resistances to increase signals to partially overcome multiplexer noise

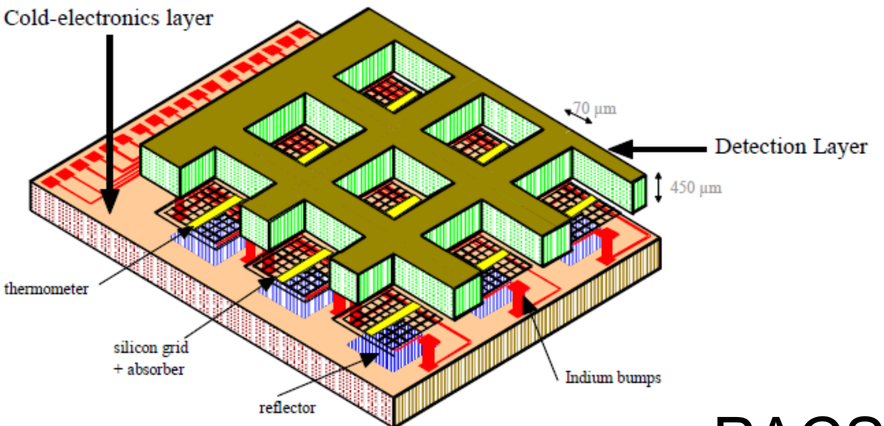


Figure 4: schematic drawing of the PACS bolometer array

PACS arrays (CEA/LETI)

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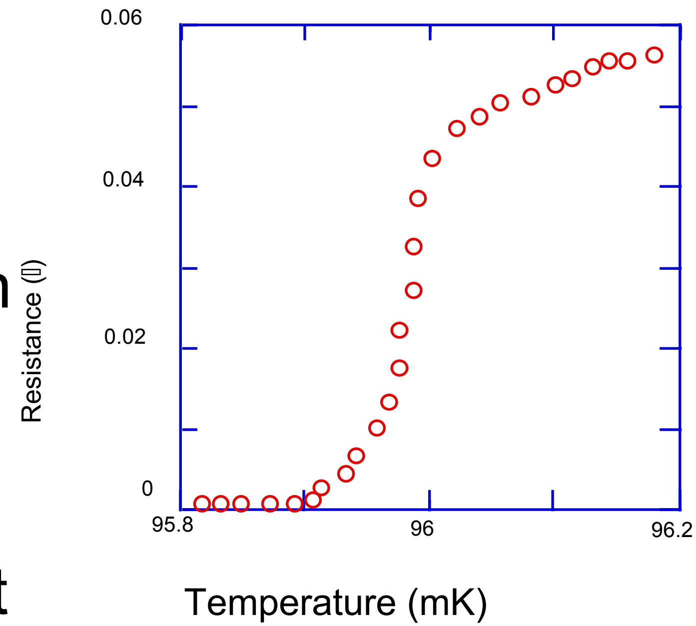
Superconducting bolometers

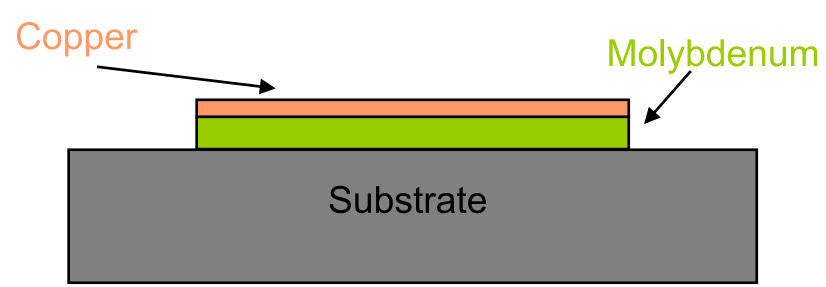
Superconducting bolometers

Even without multiplexing, fundamental noise limits reached

Solution: superconductors (transition edge sensor; TES)

- Very large dR/dT at transition
- But have to keep on transition
- Key to use in astronomy was realisation (K. Irwin, 1995) that voltage bias keeps them automatically on transition





Superconducting bolometers

Has taken ~ 10 years to find and eliminate excess noise sources to make TES arrays practical

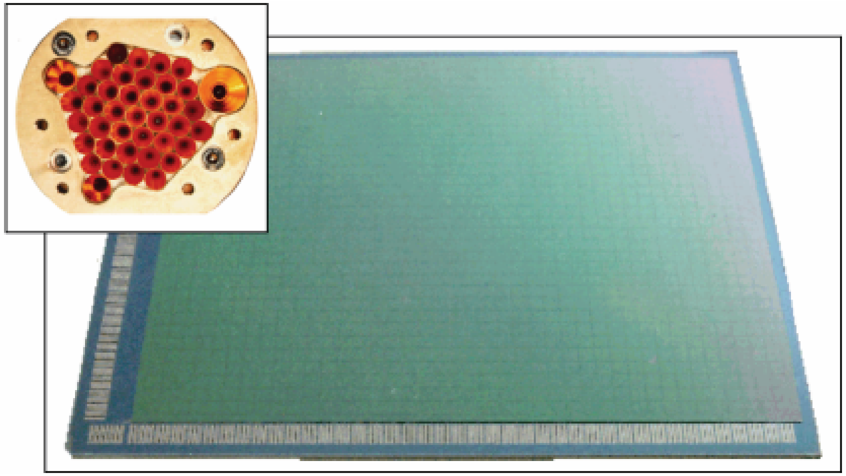
Advantages:

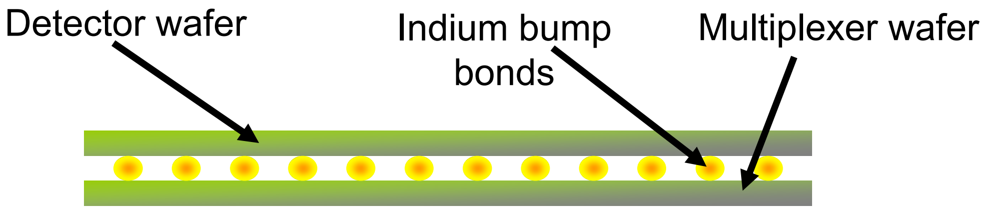
- Low fundamental noise limits
- Can be constructed on an array scale by thin-film deposition and lithography
- Can be multiplexed with minimal noise penalty by superconducting electronics

New generation of instruments using TES arrays now in construction and on telescopes

SCUBA-2

- Most ambitious TES instrument to date is SCUBA-2
- Eight arrays; 1280 pixels each
- Constructed from detector and multiplexer silicon wafer, indium bump bonded together like an infrared array



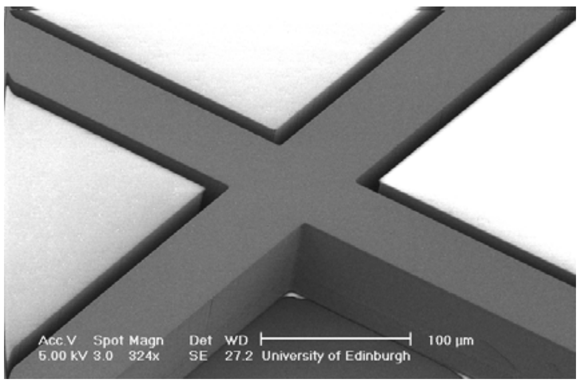


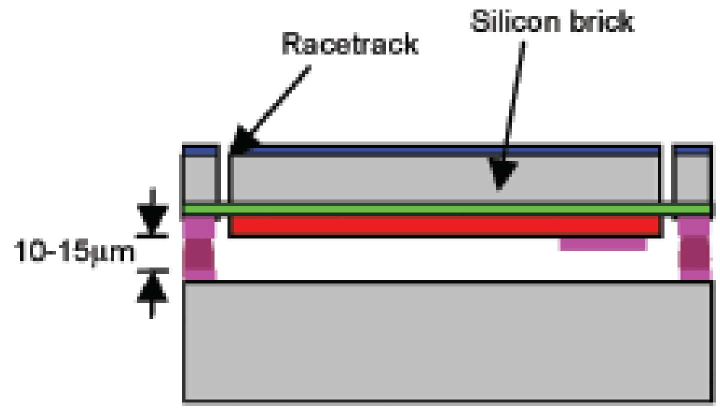
SCUBA-2

Large collaboration, led by ATC

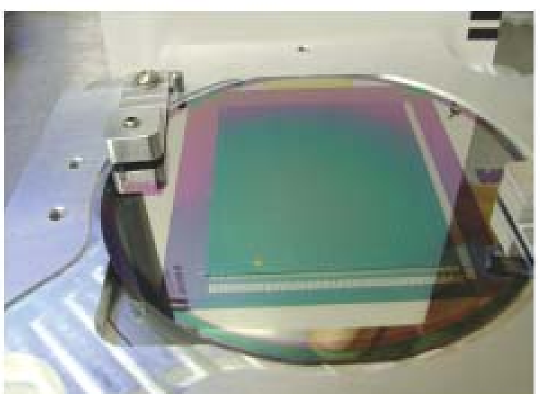
Partners include

- Edinburgh University (SMC): Array micromachining





- Heriot-Watt: Laser dicing of silicon wafers



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In-focal plane multiplexing

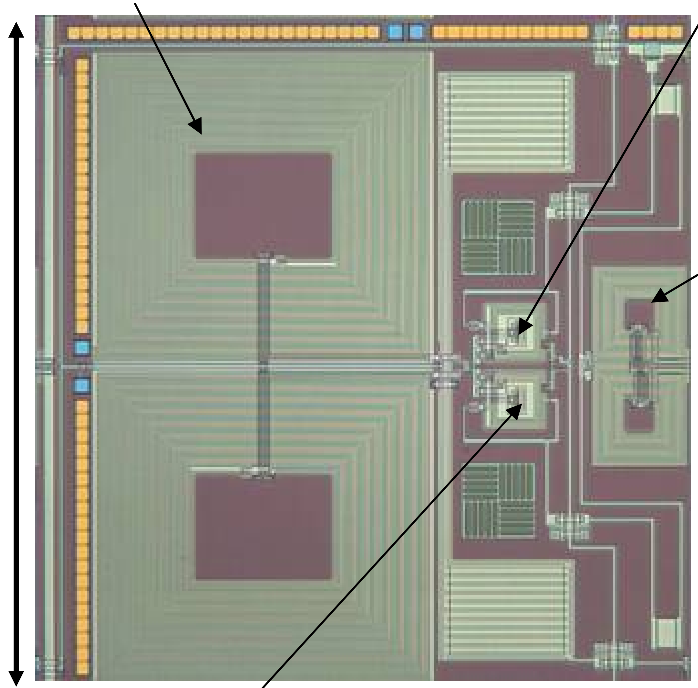
Large array possible only by in-plane multiplexing

Input transformer

Active SQUID

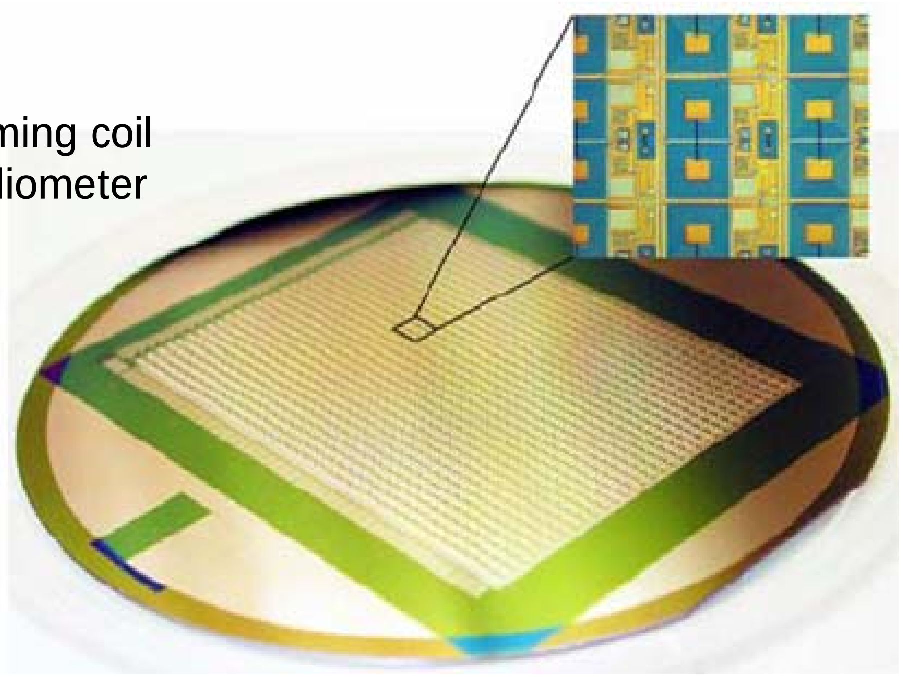
Summing coil gradiometer

~1mm



Dummy SQUID

Pixel scale



Array scale

NIST National Institute of Standards and Technology

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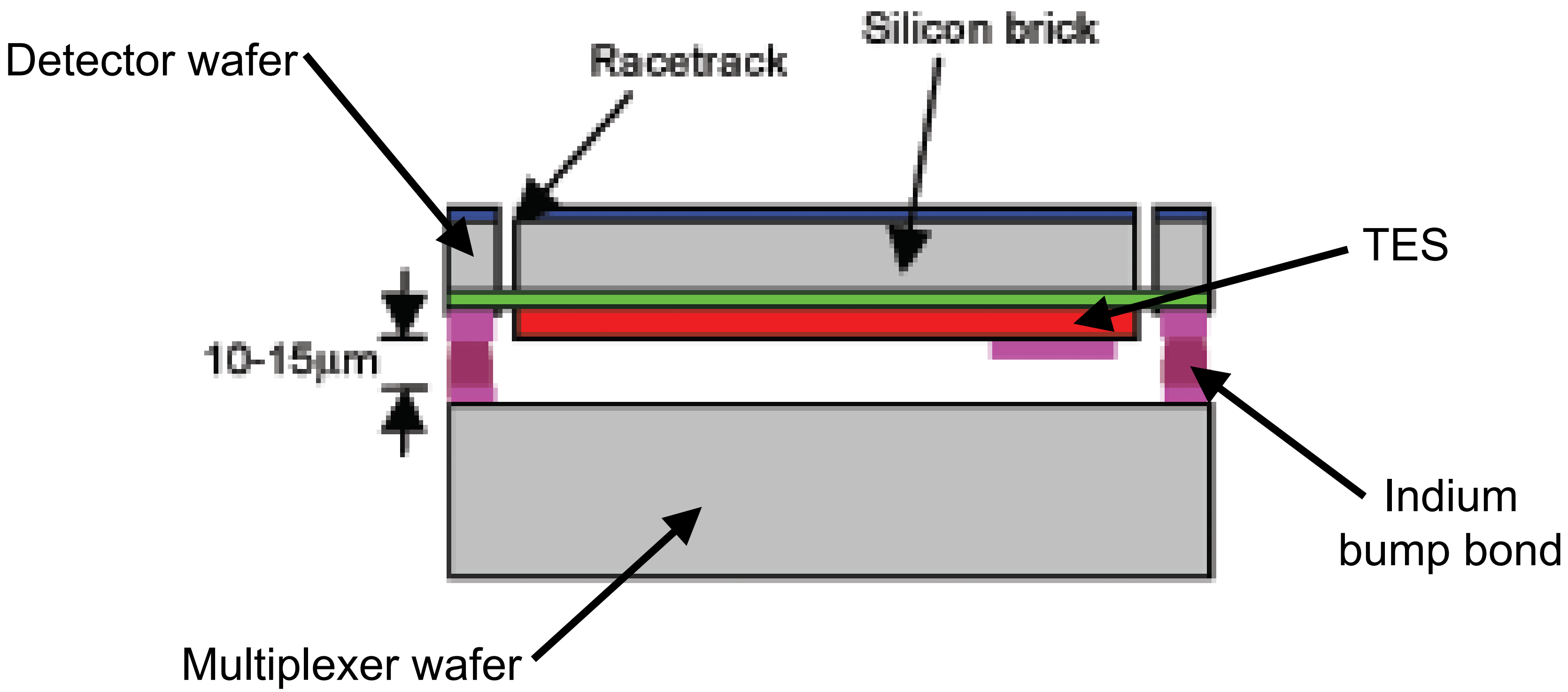
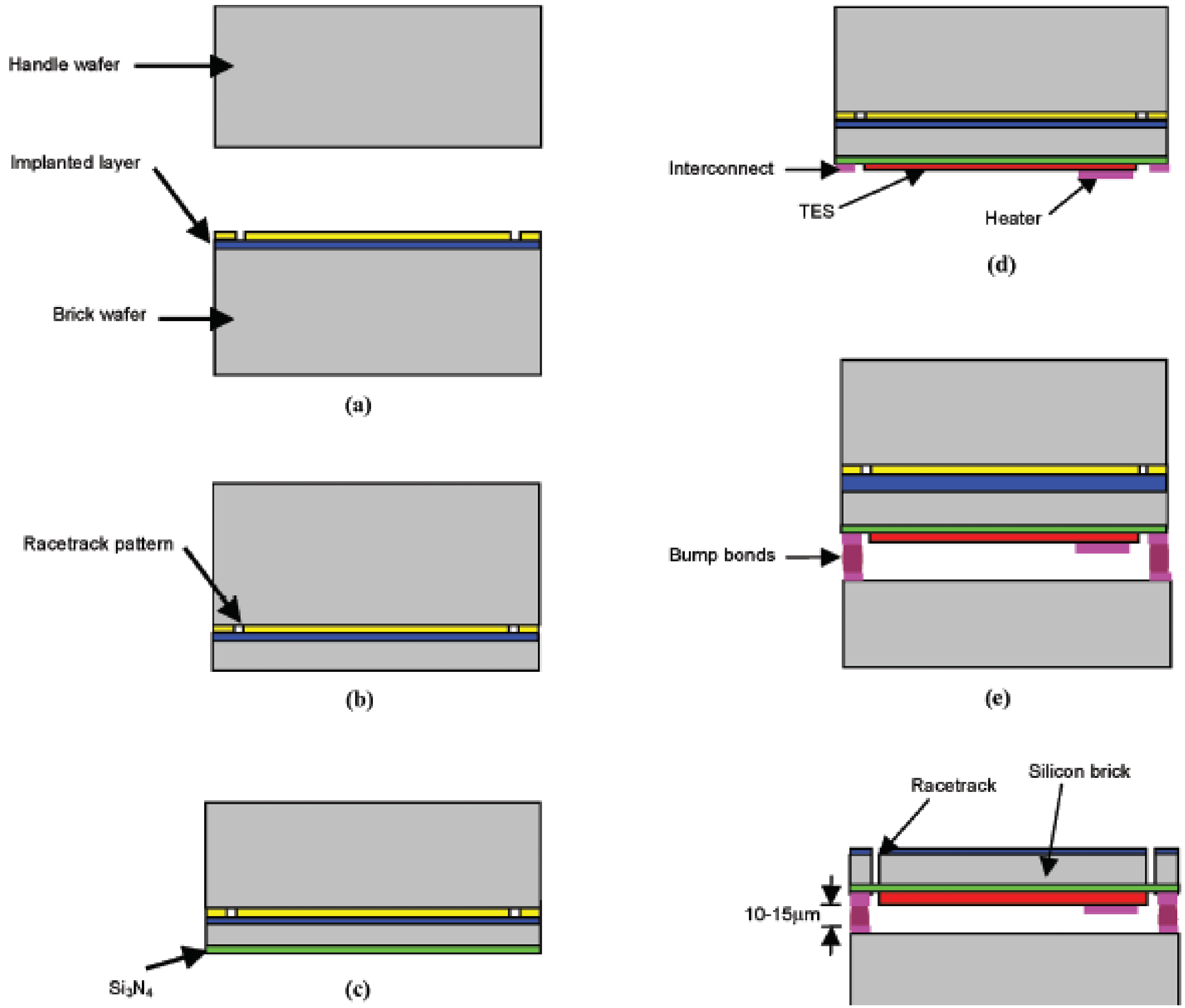
Silicon micro-machining



Silicon micro-machining



Micromachining at the SMC

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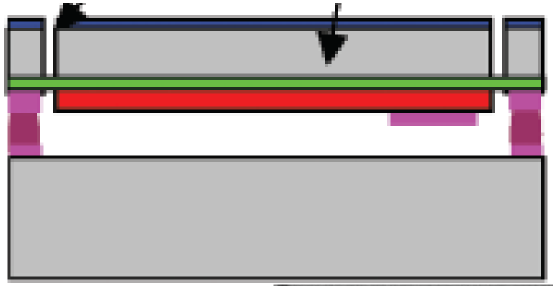
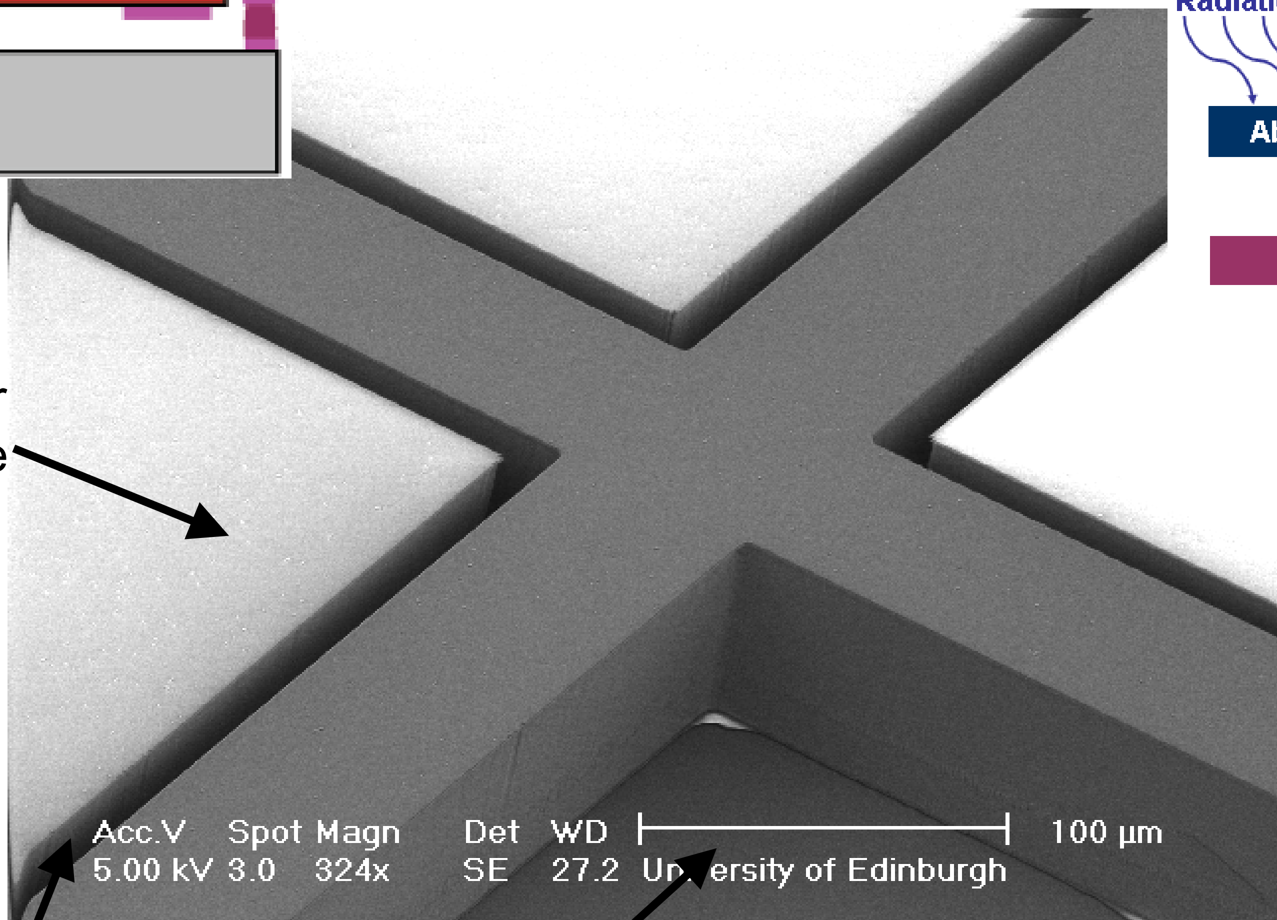
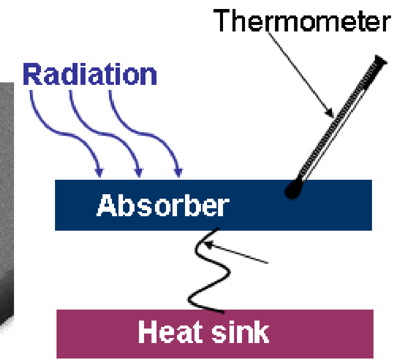
Silicon micro-machining







Lighter colour due to charge build up

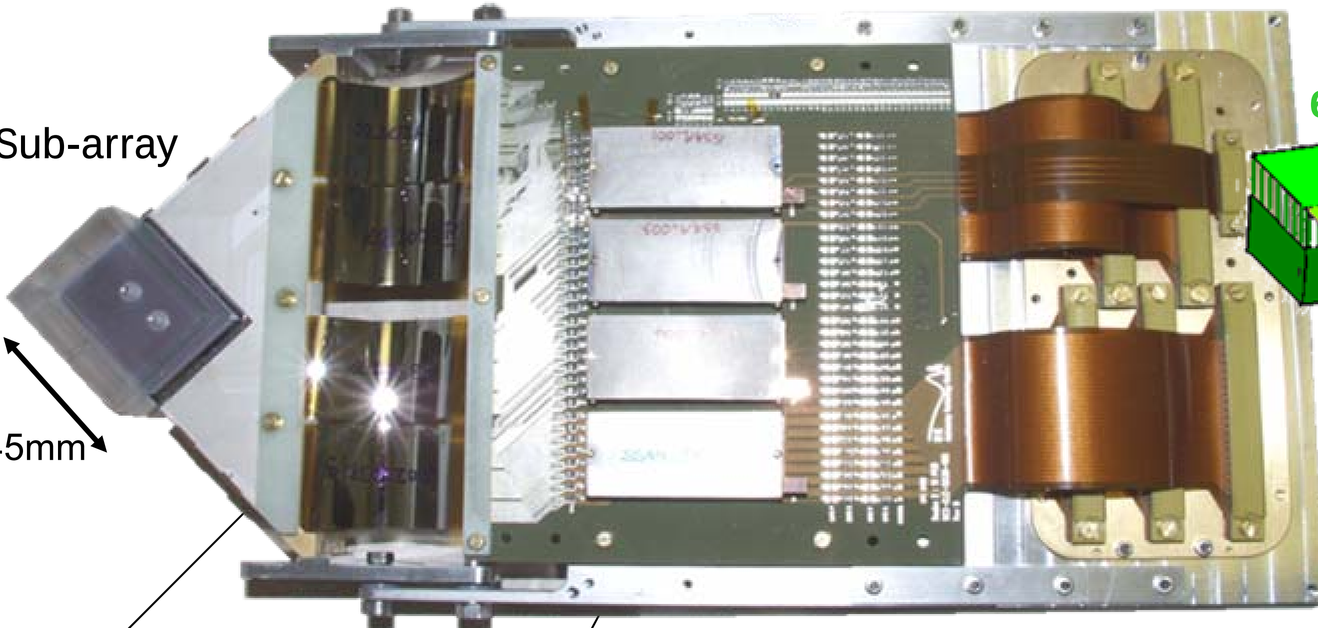
"Trench" for thermal isolation

Missing brick

Sub-array module

Sub-array

45mm

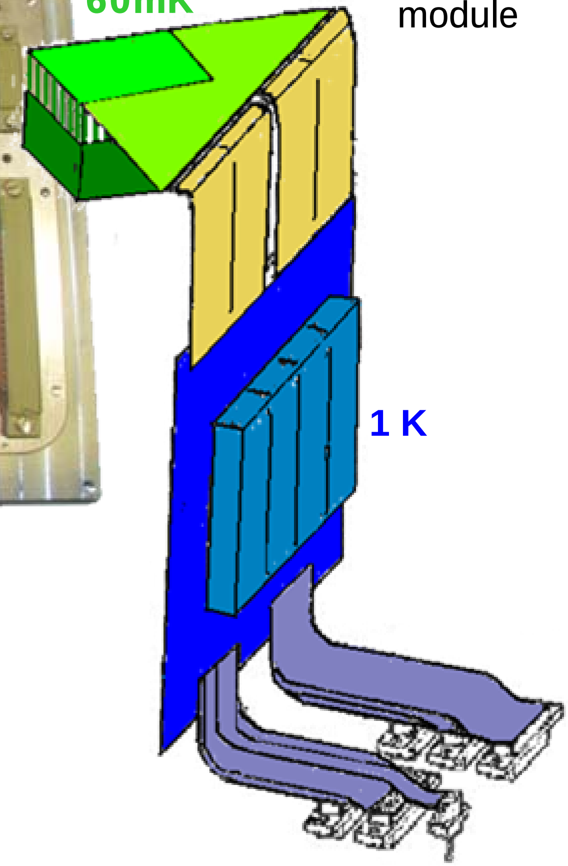


Niobium flex cables

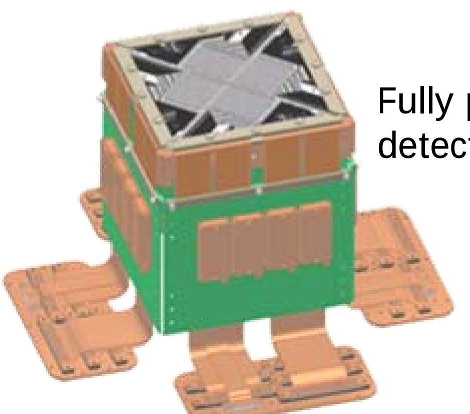
Shielded SQUID Series arrays

Folded sub-array module

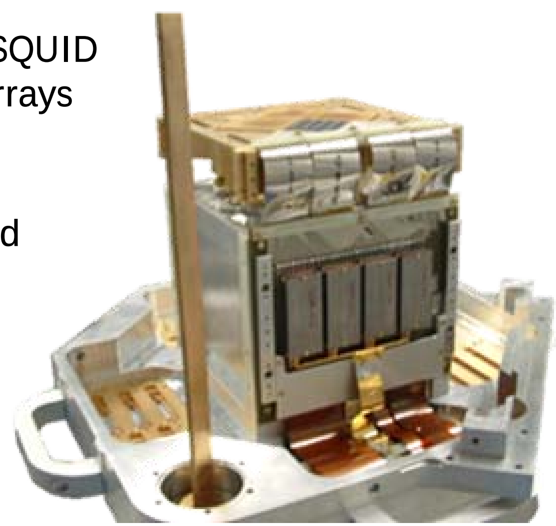
60mK



1 K



Fully populated detector unit



Detector unit with one prototype array installed

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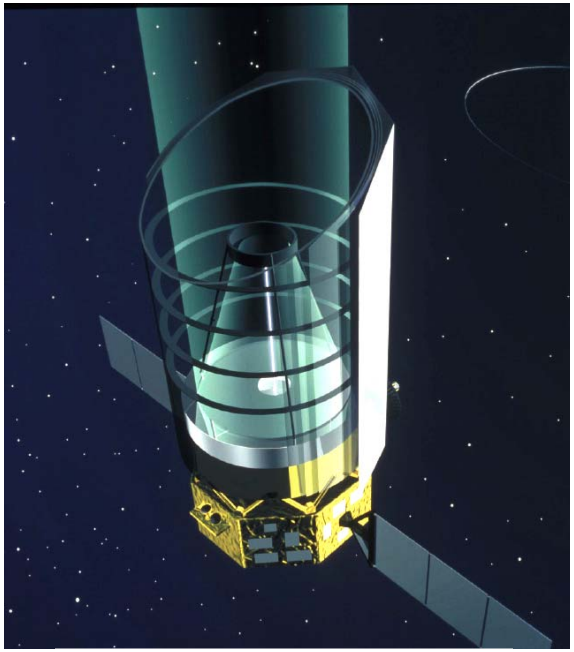
Problems

- Multiplexer fabrication is complex, especially for large arrays
- High wire count; large heat leak to low temperature stage
- Increasing array sizes further will be very difficult
- Too much power sends detector above transition; no response
  - Worrying for a space mission where background unknown, and can't fix problems
  - Semiconductor bolometers work in high background with reduced sensitivity

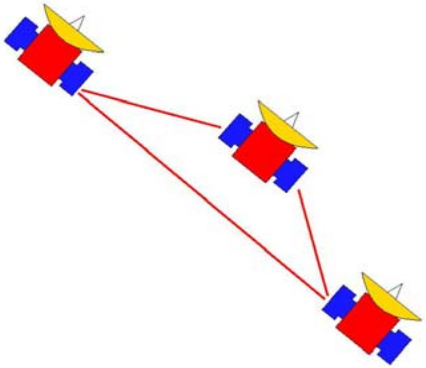
Problems



• New generation of space missions (e.g. SAFARI, FIRI) planned with cryogenically cooled primary mirrors

• Reduced photon noise from cool mirrors means need higher sensitivity than current detectors

- For a bolometer need very low thermal conductivity
- Hard to get good enough mechanical support
- Run into fundamental physical limits on thermal isolation



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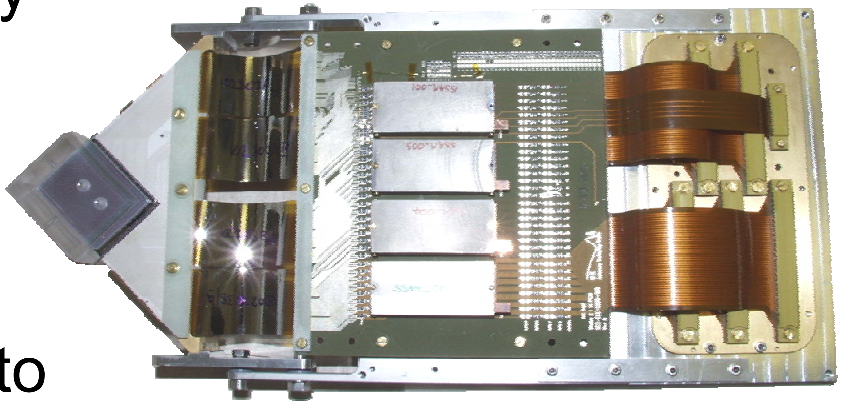
Where do we go now?

Bolometers

- Push to lower noise
  - Understand SiN conductivity
- Improve multiplexing
  - TFM vs FDM
  - RF FDM?
  - Move multiplexing circuitry to cold electronics?
- Can we simplify TES bolometer/MUX fabrication?
- Can noise in CMOS multiplexed Si bolometers be reduced further?



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Replacing bolometers: KIDs

Alternative technology: Kinetic Inductance Device

- Use superconductor *below* transition
- Radiation breaks Cooper pairs
  - like electron-hole pair creation in semiconductor, but with smaller energy gap
- Detect by change in AC inductance
- Advantage: can read out many devices with single coax
  - Simple detector fabrication
  - No complex multiplexer to make
- Still need ultra low temperatures though
- Looks very promising

Prototype KID camera (Caltech/JPL)

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Readouts

- KIDS push complexity to room temperature electronics
  - A good thing, but still not straightforward

- Much development work required
  - Need to generate frequency comb (1000? 10 000? channels), then measure response for each frequency
  - FPGA based
  - Readouts also applicable to other technologies (RF SQUID readouts for TES detectors, RF-SET…)
  - Can we do all this in space?
  - Possible future work between ATC and U of E

Other technologies

STJ with RF-SET multiplexer

Cold Electron Bolometers + quasiparticle amplifier

SQPT photoconductor

QWIPs (quantum wells)

Quantum dot devices

Superconducting nanowires

Superconducting nanowires

Work at HW in this area (Robert Hadfield)

- Currently used in optical/IR
    - Single photon counting, high time resolution

- Applications include
    - Biological imaging
    - Quantum cryptography
- Potential to operate up to mm region

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More

Another area being developed is antenna coupled detectors

- Radiation detected by planar antenna
- Transmitted to detector by waveguide
- Can filter wavelengths *electrically* rather than optically
- One antenna can feed several pixels for different wavelengths

Homeland security – “THz” currently of great interest

Conclusions

Conclusions

The next few years will be very interesting:

- Many new instruments coming on line
- Not clear which technologies will dominate for the next generation of instruments

Producing detectors for a space mission with a cold (5 K) mirror is a big challenge

- Will have to be considerably more sensitive than current detectors
- Different groups developing TES, KID, CMOS multiplexed silicon arrays and many more…

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