Instrumentation for sub-mm astronomy

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Science & Technology Facilities Council
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TEOPS
Technology for Experimental and Observational Physics in Scotland

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Scottish Universities Physics Alliance

Introduction

Sub-mm astronomy

Astronomy at sub-mm wavelengths

Between infrared 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

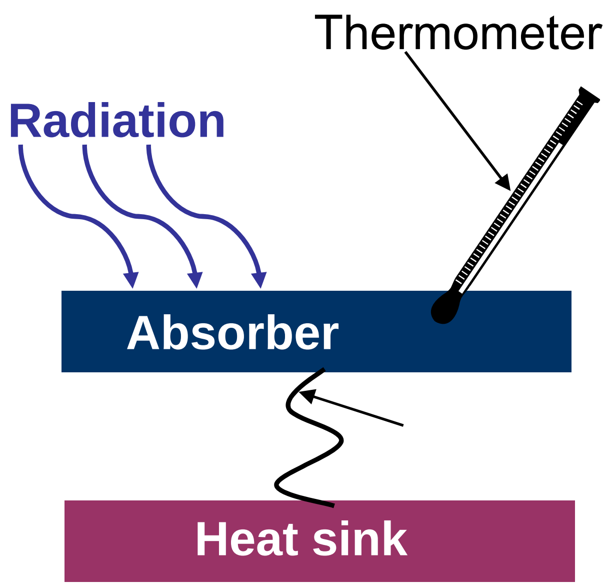
Cold things are interesting: usually objects in formation (galaxies, stars, planets…)

- 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)

Bolometers

Dominant detector type for photometry (as opposed to spectroscopy) is the bolometer



Semiconductor bolometers

The first bolometer

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

FIG. 1.

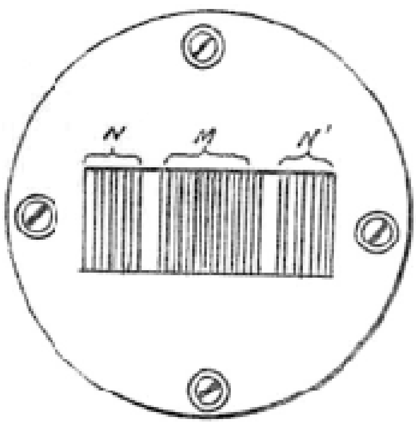
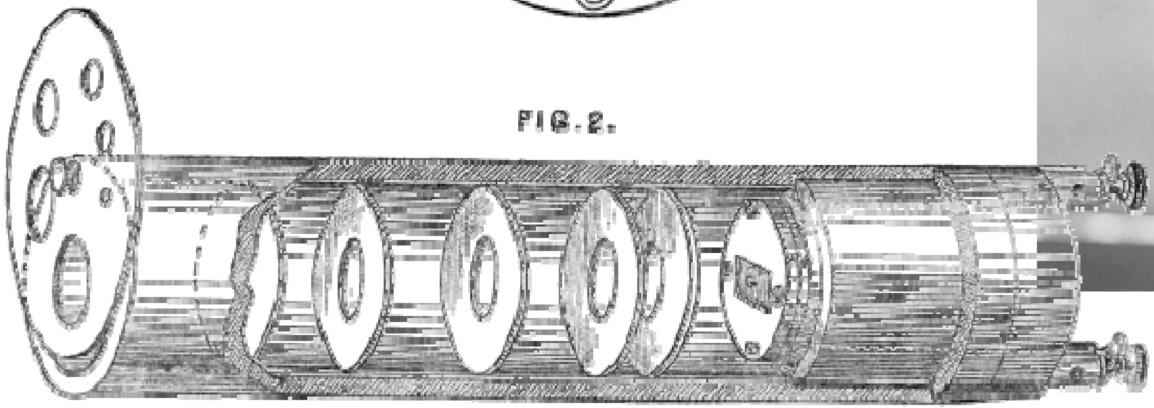
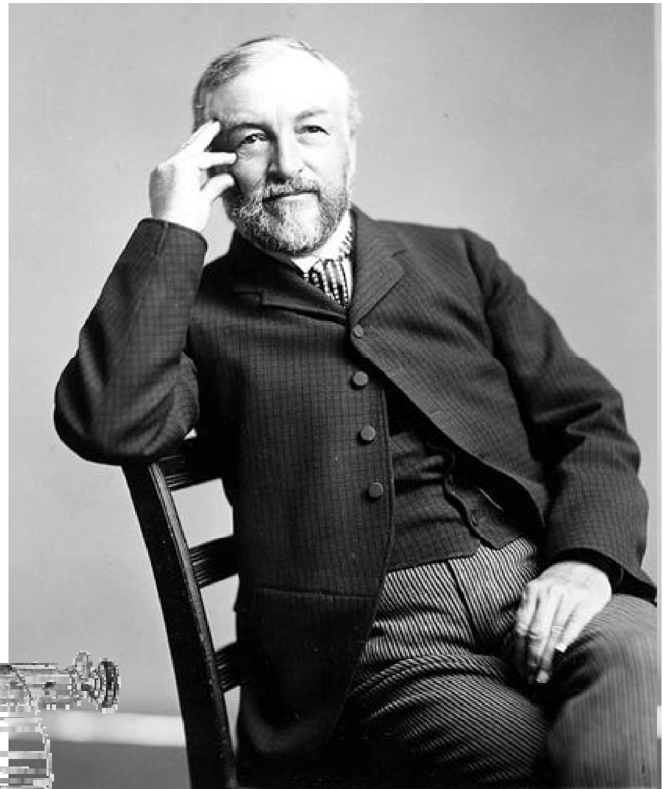


FIG. 2.





Cryogenic bolometers

81 years later, F. Low developed the cryogenic (4 K) bolometer using doped germanium as the thermistor

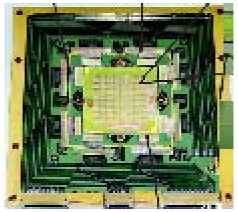
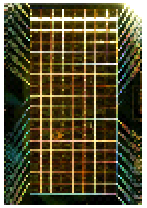
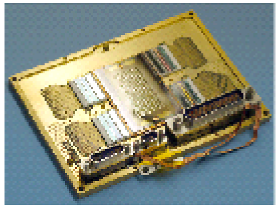
Low temperature operation:

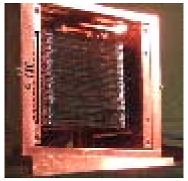
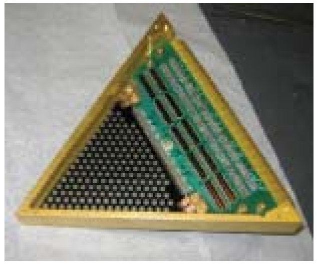
- Reduces blackbody background radiation
- Increases sensitivity:
  - heat capacity is reduced
  - doped semiconductors can have very large dR/dT

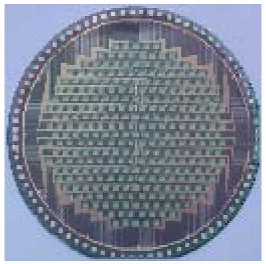
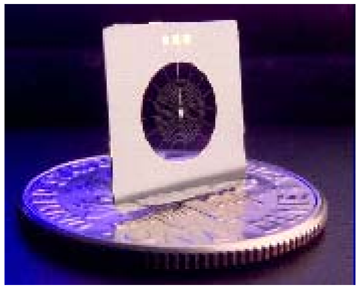
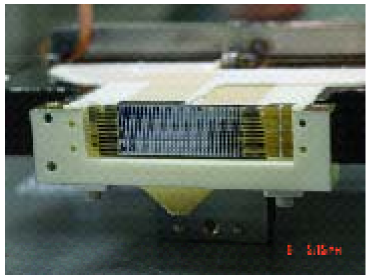
The original application was not astronomy, but soon adopted (along with the inventor) for IR astronomy

Cryogenic bolometers

Now replaced by photodetectors in IR, but the detector of choice for photometry in the sub-mm:

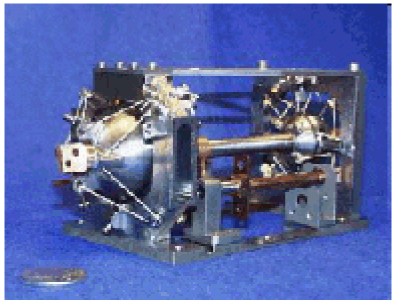



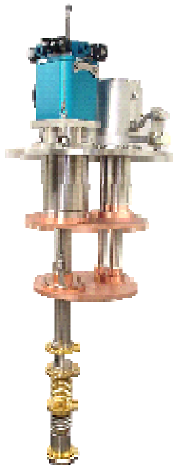





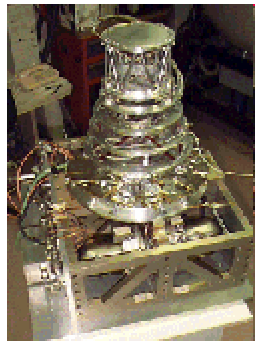
Cryogenic bolometers

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

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



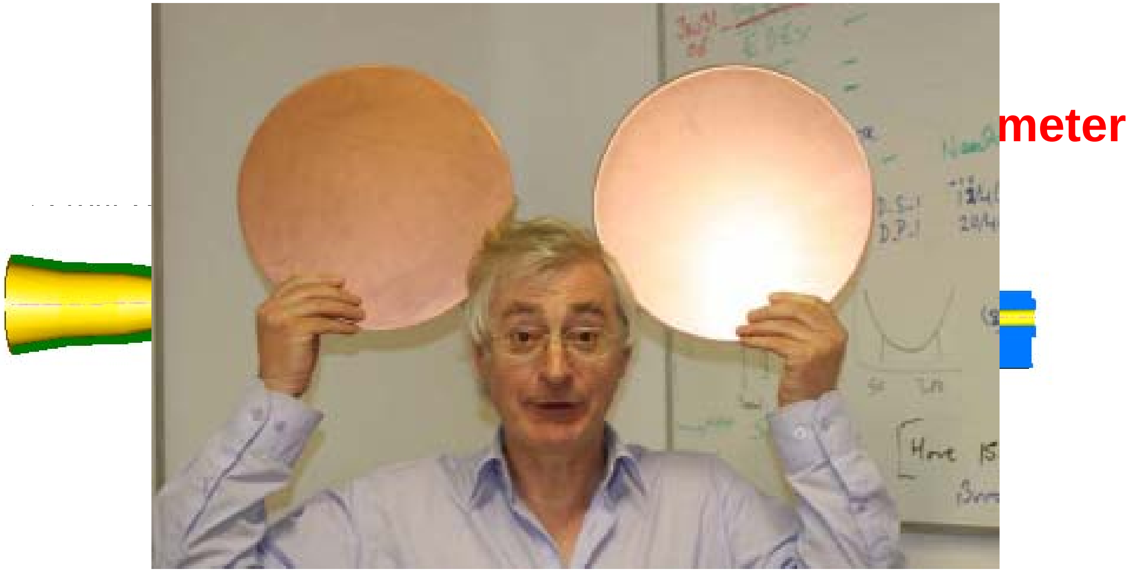




Cryogenic bolometers

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

- Have to filter out unwanted wavelengths
- Metal mesh filters can be produced with precisely defined bandpasses



Cryogenic bolometers

For high resolution spectroscopy, astronomers use coherent (heterodyne) systems, as in radio astronomy

- Outside the scope of this review
- Also operate at low temperatures and challenging to build

Cryogenic bolometers

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

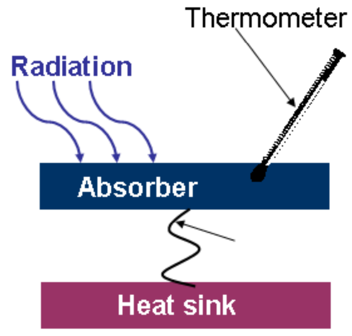
Development largely in universities and government labs rather than industry

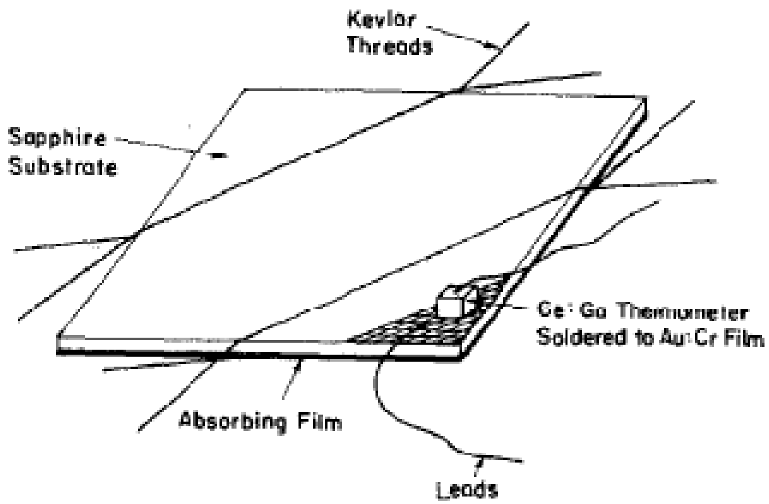
Cost $2000/pixel c.f. $0.12 for infrared, $0.01 for optical

Cryogenic bolometers

Composite bolometers introduced in 1970s

- Reducing thermal conductance increases sensitivity
- But also increases time constant
- Reduce again by reducing heat capacity
- This is the main reason for such low temperatures
- Composite bolometer reduces heat capacity further by separating absorber and thermometer





Cryogenic bolometers

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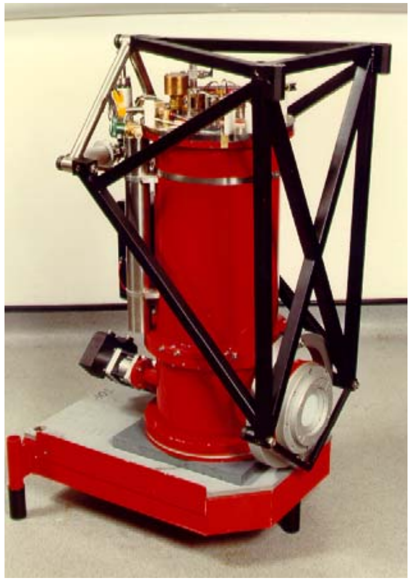
Early instruments contained a single pixel



UKT14 (ROE, Edinburgh)

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Bolometer arrays

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

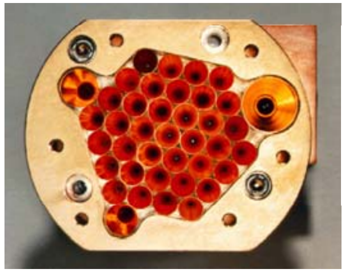
SCUBA (ROE, Edinburgh)

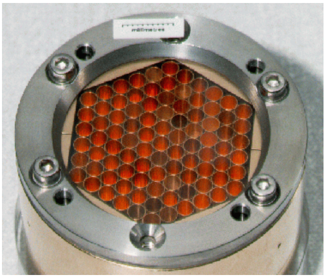
SCUBA

Largest of the early arrays

- 131 pixels
- Composite bolometers (sapphire substrate, brass wire thermal link)
- Hand assembled from individual pixels

- Arrays (and in particular SCUBA) revolutionised the field



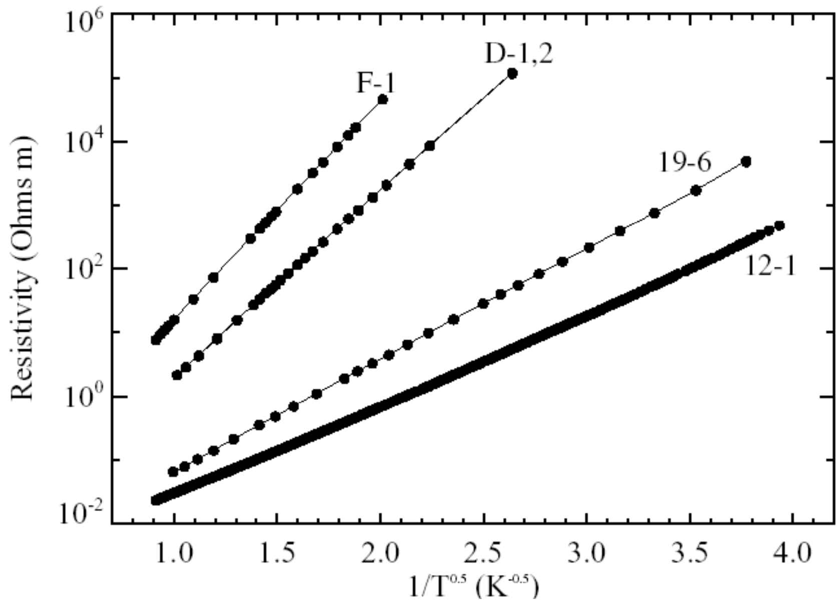


SCUBA individual pixel

NTD germanium

Sensitive and uniform behaviour requires uniform doping

- SCUBA and other modern germanium bolometers use Neutron Transmutation Doping (NTD)
- Converts ^{70}Ge to ^{71}Ga (acceptor) and 74Ge to 75As (donor)
- Since germanium isotopes are uniformly distributed, result is uniform doping and simple behaviour



Early instruments

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Science & Technology Facilities Council

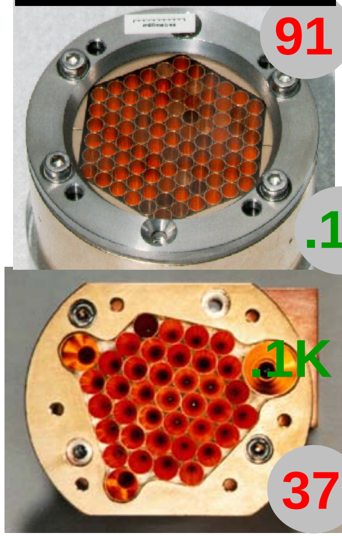
JCMT-UKT14
350µm-2mm

1986-1996

CSO-SHARC
350 µm array

1996-

JCMT-SCUBA
350/450 &
750/850µm



1997-

Also 19 pixel 2 mm array at 0.1 K

IRAM- MPIfR
1.3mm array

1998-

91 Number of pixels

.3K Operating temperature

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Modern bolometers

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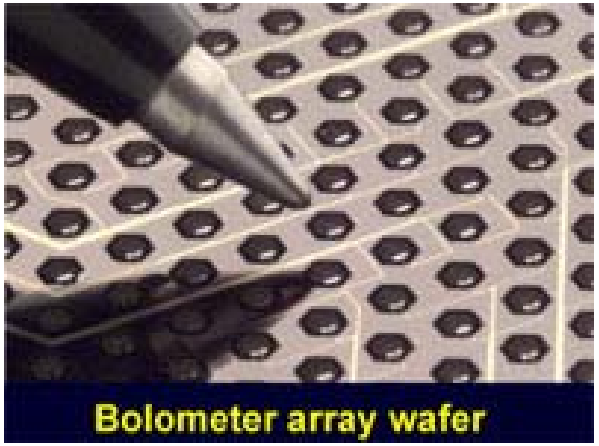
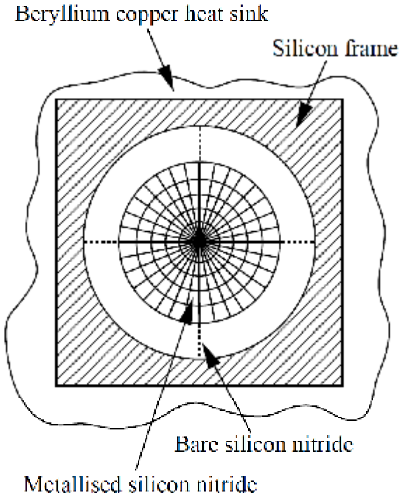
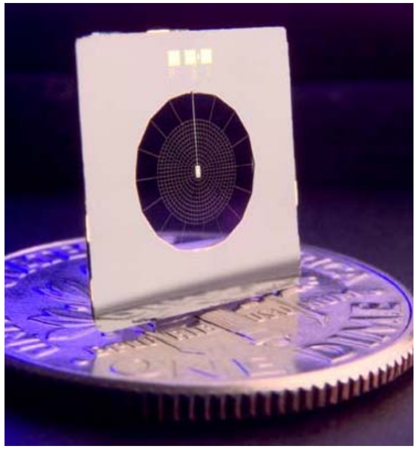
Modern bolometers built by micromachining

- 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

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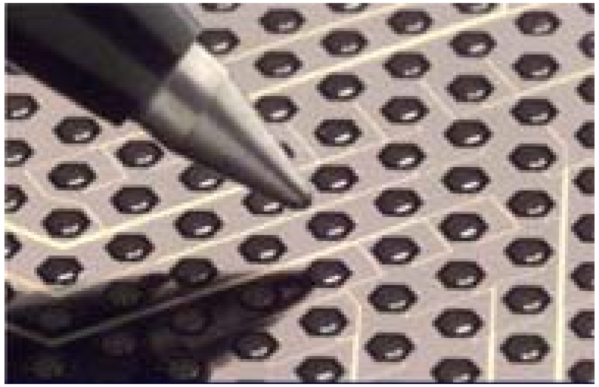
Modern bolometers

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

HFI bolometers (JPL/Cardiff)



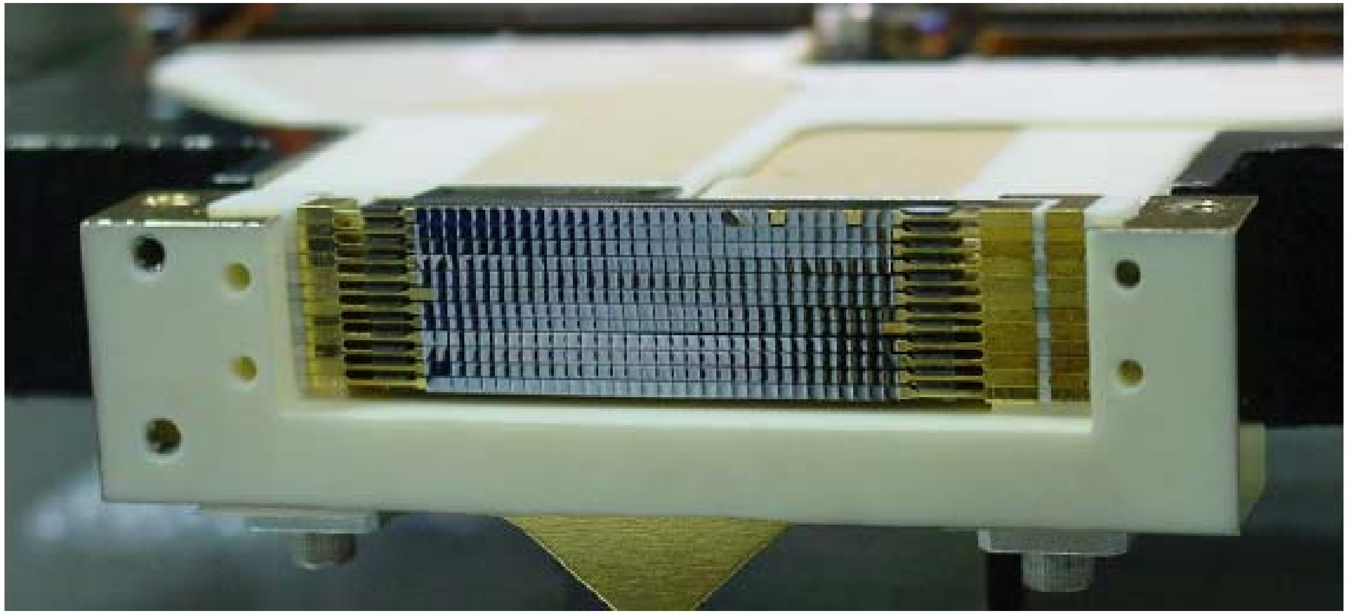
Spiderweb array wafer (JPL)

But still have to stick germanium chips individually on each pixel

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)

Modern bolometers

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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

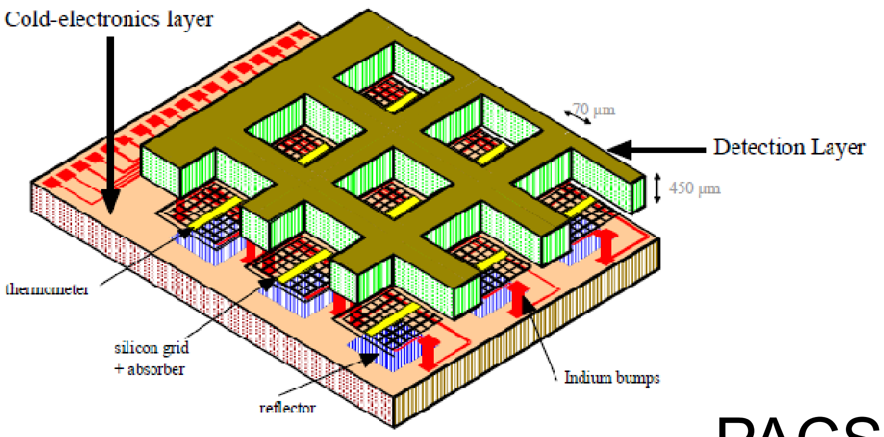


Figure 4: schematic drawing of the PACS bolometer array


PACS arrays (CEA/LETI)

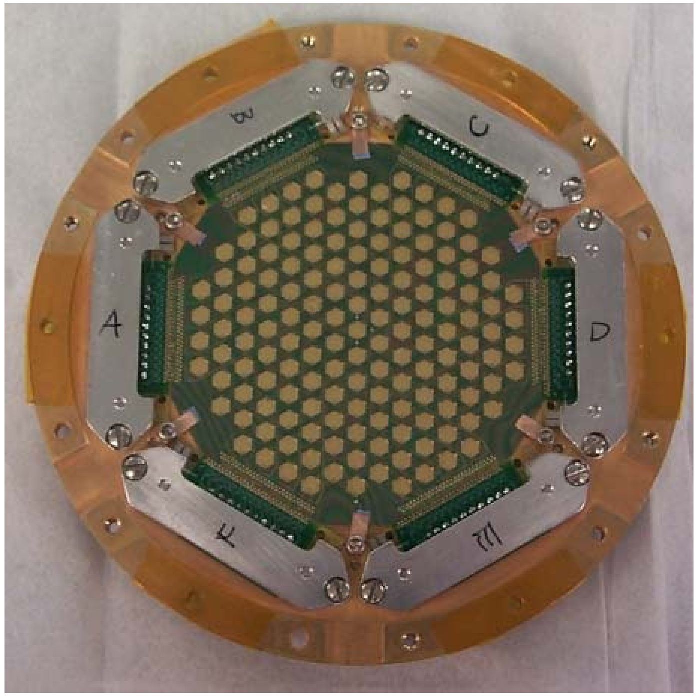
Current instruments

Facility instruments on telescopes now

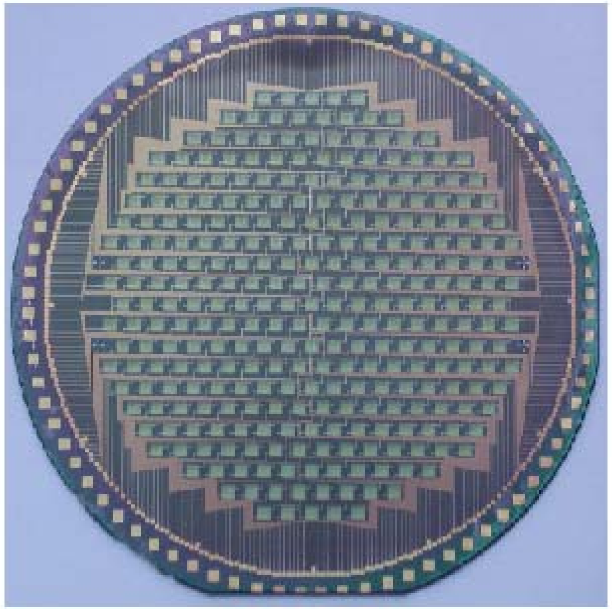
Telescope	Instrument	Wavelength(s)	Pixels	Technology	Temperature	Status
APEX	LABOCA	870 μm	295	NTD Ge	300 mK	
ASTE	AzTEC	1.1 or 2.1 μm	144	NTD Ge	300 mK	
CSO	SHARC-II	350, 450 or 850 μm	384	Ion implanted Si	300 mK	
CSO	Bolocam	1.1 or 2.1 mm	119	NTD Ge	300 mK	
GBT	MUSTANG	3 mm	64	TES	300 mK	In commissioning
Herschel	PACS	60 - 210 μm	2560	Ion implanted Si	300 mK	Awaiting launch (2009)
Herschel	SPIRE	200 - 670 μm	326	NTD Ge	300 mK	Awaiting launch (2009)
IRAM 30 m	MAMBO-2	1.2 mm	117	NTD Ge	300 mK	
JCMT	SCUBA-2	450 and 850 μm	10240	TES	100 mK	In commissioning

Doesn't include dedicated PI instruments or CMB instruments

NTD germanium arrays



AzTEC (JPL)
144 pixels



LABOCA (MPIfR)
295 pixels

Current instruments

Facility instruments on telescopes now

Telescope	Instrument	Wavelength(s)	Pixels	Technology	Temperature	Status
APEX	LABOCA	870 μm	295	NTD Ge	300 mK	
ASTE	AzTEC	1.1 or 2.1 μm	144	NTD Ge	300 mK	
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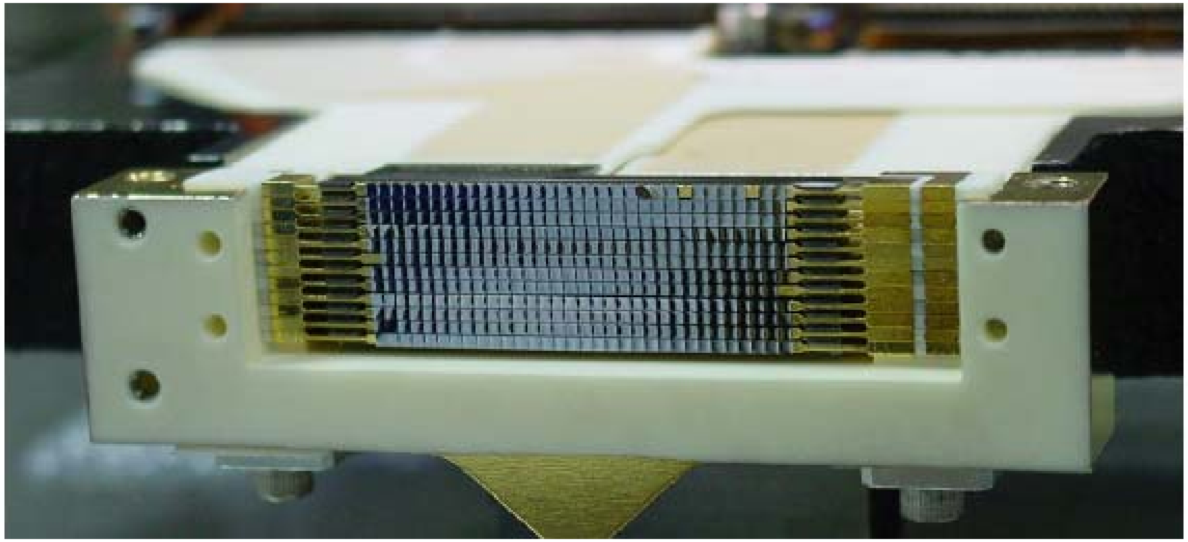
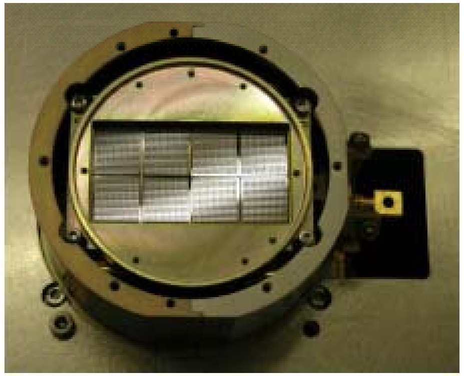
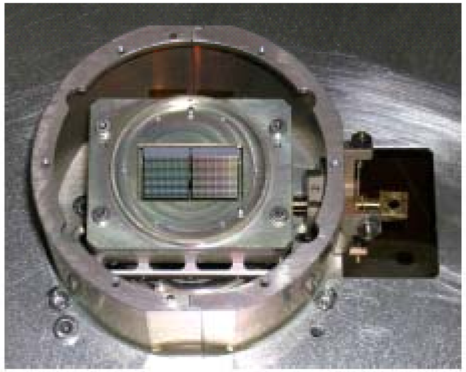
Silicon arrays



SHARC-II
(GSFC/Caltech)
384 pixels

PACS arrays
(CEA/LETI)
2560 pixels



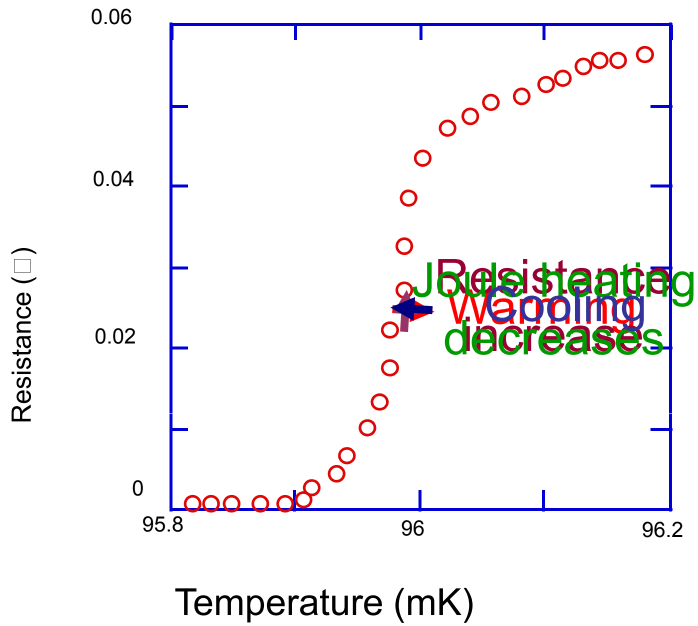


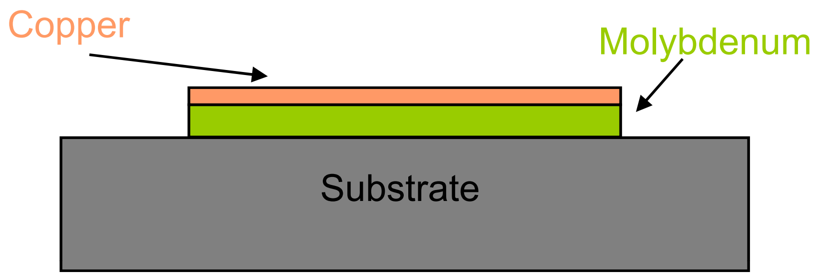
Superconducting bolometers

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:

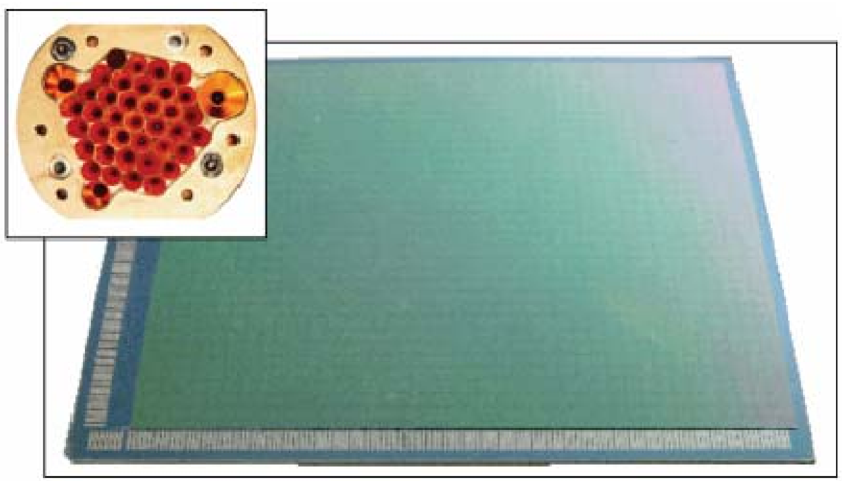
- Low fundamental noise limits
- Can be constructed on an array scale by thin-film deposition and lithography
- Can be multiplexed with minimal noise penalty by superconducting electronics

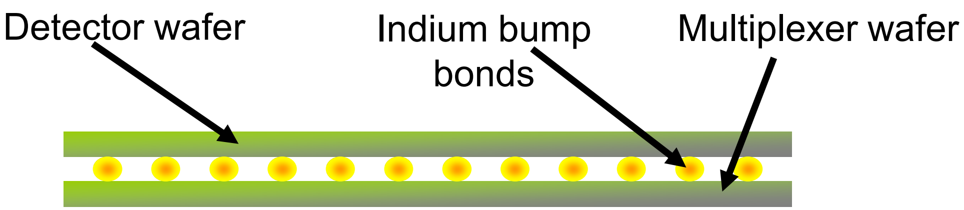
New generation of instruments using TES arrays now in construction and on telescopes

SCUBA-2

- Eight arrays; 1280 pixels each
- Constructed from detector and multiplexer silicon wafer, indium bump bonded together like an infrared array

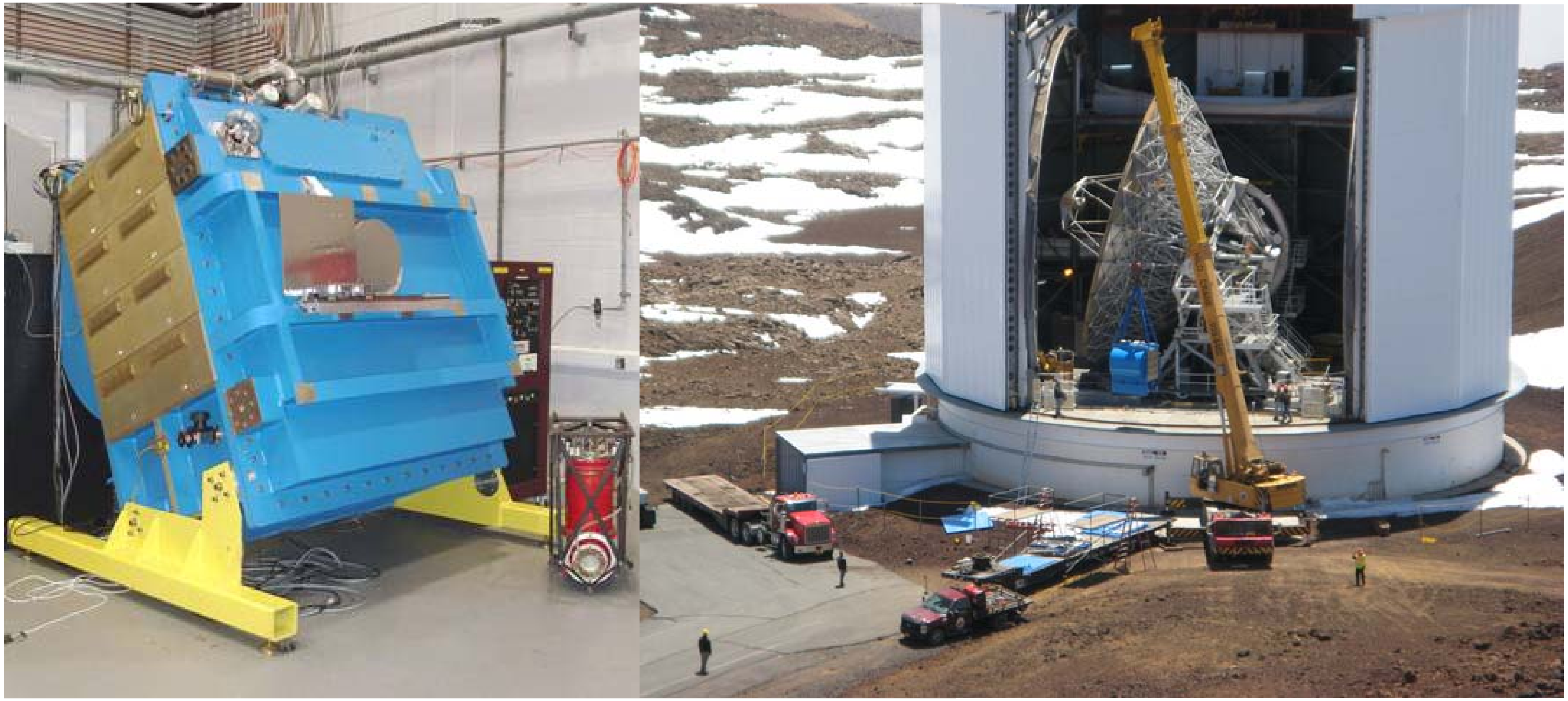
SCUBA-2 sub-array (SCUBA array inset)





SCUBA-2

Somewhat bigger than predecessors



Current instruments

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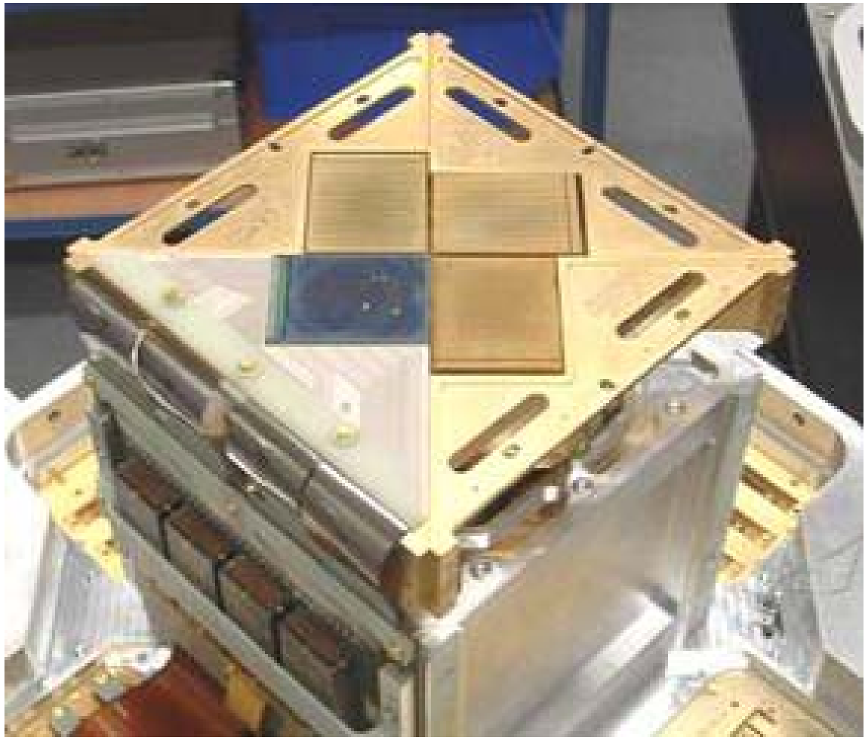
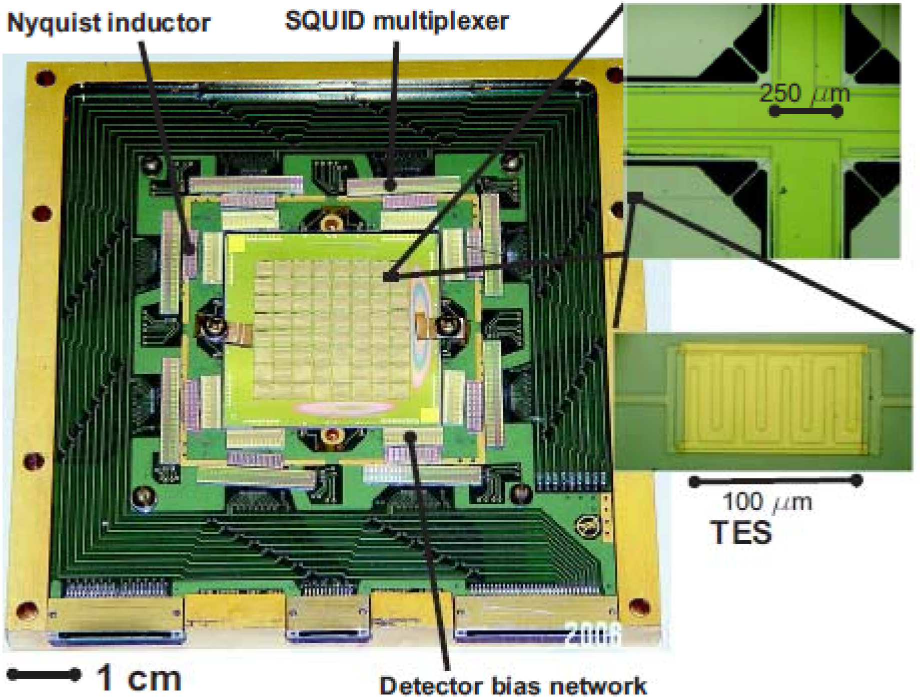
Doesn’t include dedicated PI instruments or CMB instruments

Facility instruments

SCUBA-2

(1280 pixels installed here)





MUSTANG

(64 pixels)

Other arrays

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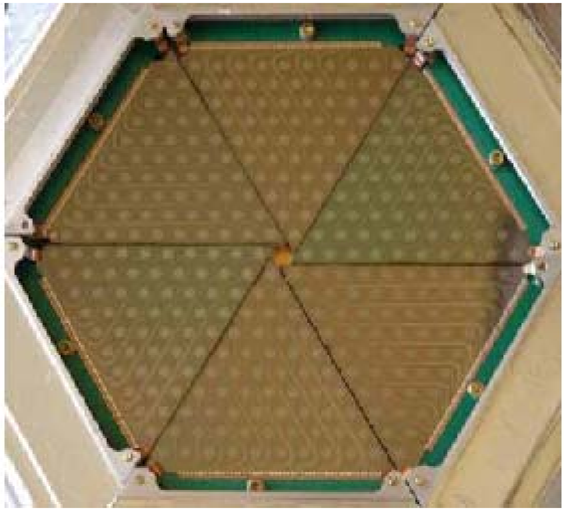
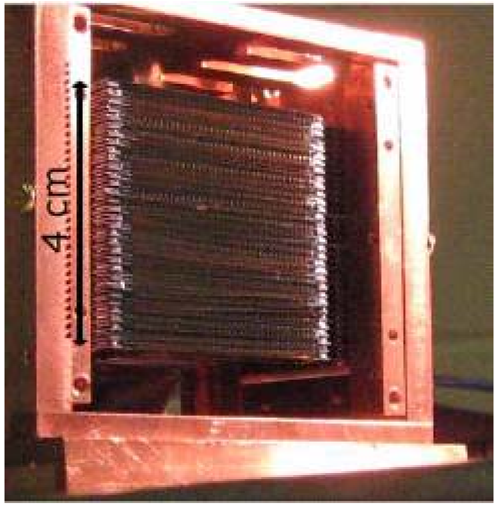
Other arrays already on telescope dedicated to CMB work



APEX-SZ
55 x 6 pixels
(on telescope)



MBAC
1024 pixels
(on telescope)

And many more to come…

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BUT

- Multiplexer fabrication is complex, especially for large arrays
- 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

The future

KIDs

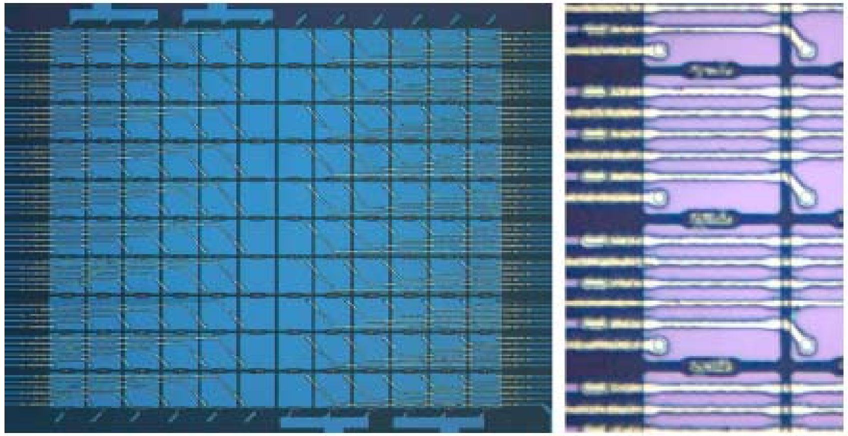
Alternative technology: Kinetic Inductance Device

- 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

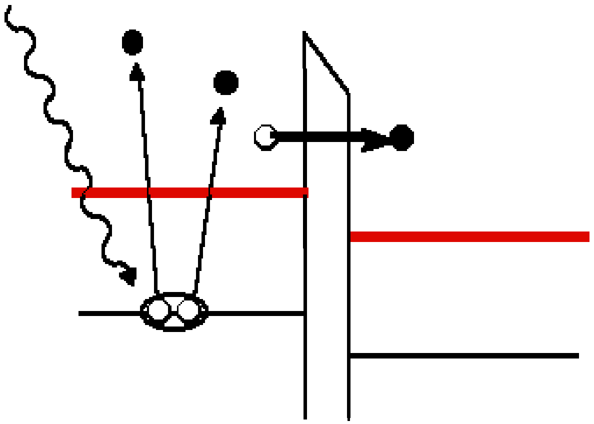
Prototype KID camera (Caltech/JPL)

Superconducting tunnel junctions use similar principle

- Pair breaking detected by current flowing through tunnel junction which blocks Cooper pairs
- Like semiconductor photoconductor
- BUT: currently no practical way to multiplex



STJ array (ESTEC/ESA)



Other technologies

STJ with RF-SET multiplexer

Cold Electron Bolometers + quasiparticle amplifier

SQPT photoconductor

QWIPs (quantum wells)

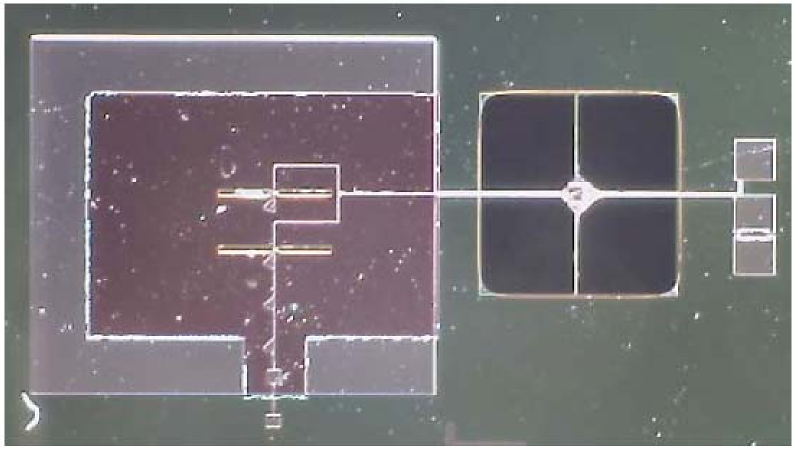
Quantum dot devices

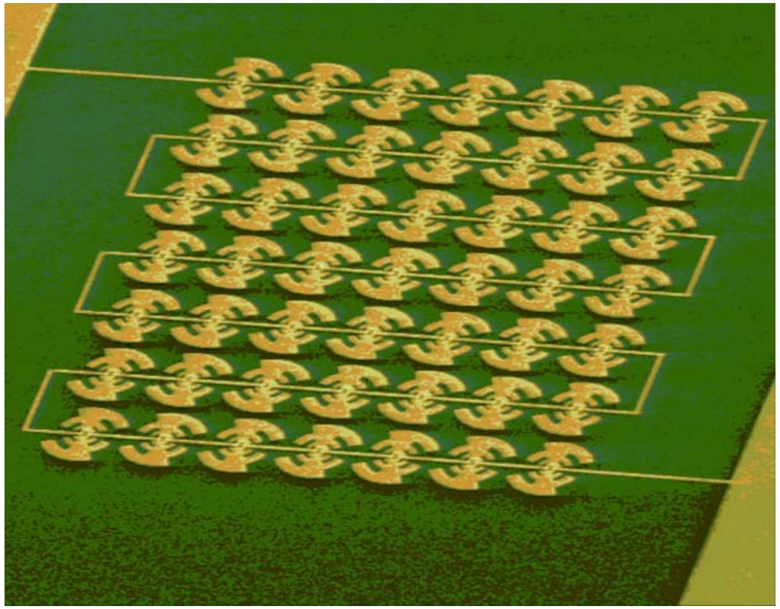
Hot-spot superconducting detectors

Antenna coupling

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





X and gamma detection

All these technologies can also be used to detect X and gamma rays

- Detect energy pulse from individual photons
- Therefore have energy/wavelength resolution
- Appealing for X-ray astronomy (and industrial applications)
  - High resolution and efficiency justify complication of cooling to under 100 mK
- Useful since can share development with sub-mm community

Optical/IR

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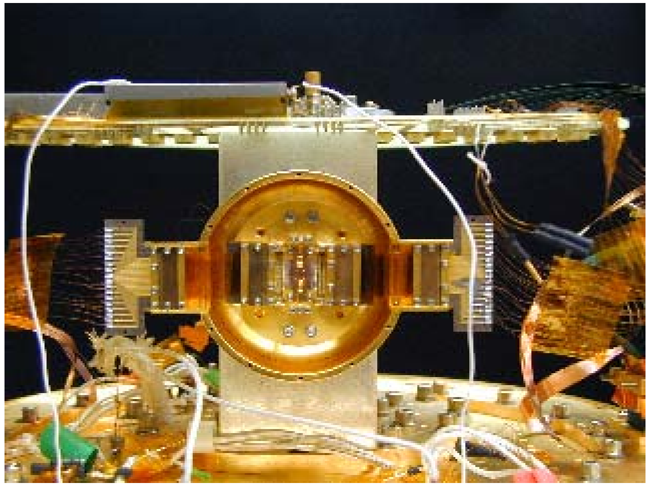
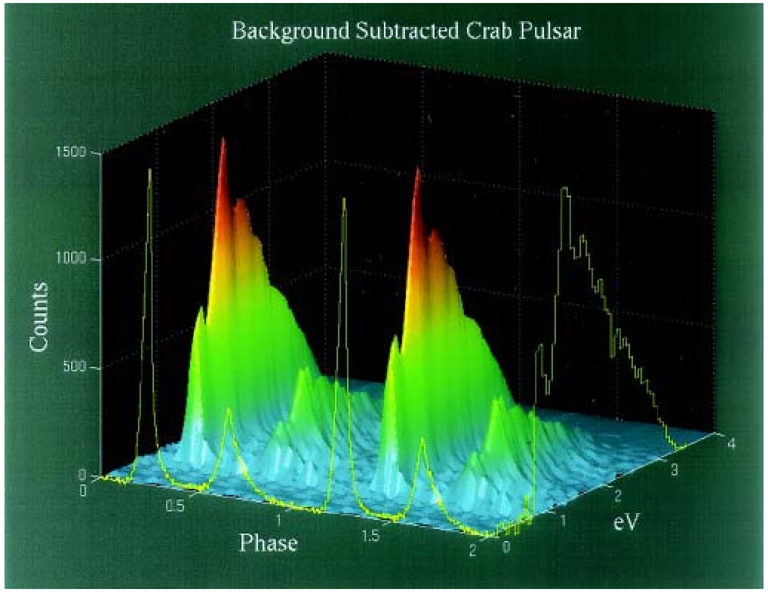
They can even be operated at optical/IR wavelengths

- Detect heat from absorption of single photon, and use to determine wavelength!
- Unique combination of spatial and spectral measurement along with accurate timing information
- Used to measure rapidly varying spectrum e.g. Crab Nebula



Optical TES array (Stanford)



TEOPS Technology for Experimental and Observational Physics in Scotland

SUPA Scottish Universities Physics Alliance

Conclusions

Conclusions

The next few years will be very interesting:

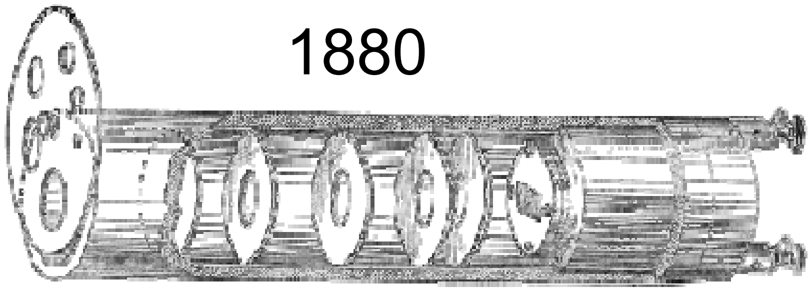
- Many new instruments coming on line
- Not clear which technologies will dominate for the next generation of instruments

One current goal is to produce detectors for a space mission with a cold (5 K) mirror

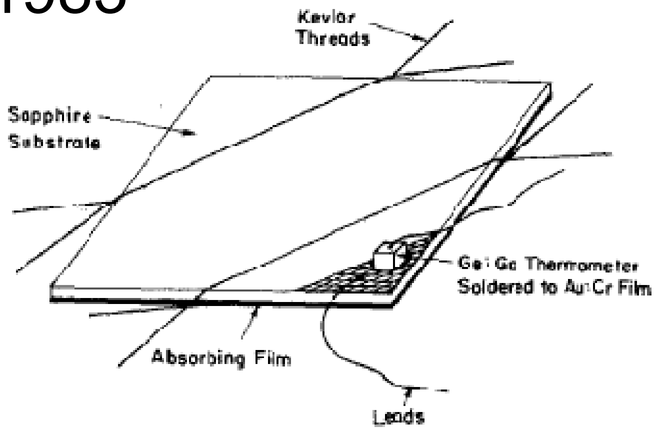
- Will have to be considerably more sensitive than current detectors
- Different groups developing TES, KID, CMOS multiplexed silicon arrays and many more…

The End

1880



1983



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