Sub-mm astronomy at millikelvin temperatures:
from 1 to 10 000 pixels in ten years

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http://woodcraft.lowtemp.org/

Seminar given in the Lancaster University Physics Department
11th November 2005

Sub-mm astronomy

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What is sub-mm astronomy?

Astronomy at wavelengths of a few hundred μm

Typically around 450 and 850 μm

Also often used to describe measurements at wavelengths of a few mm – use same detection techniques

Started in the early 70's

> Looking at sun, moon and planets
> (First proper observations? QMW, using Pic du Midi; French Pyrenees)

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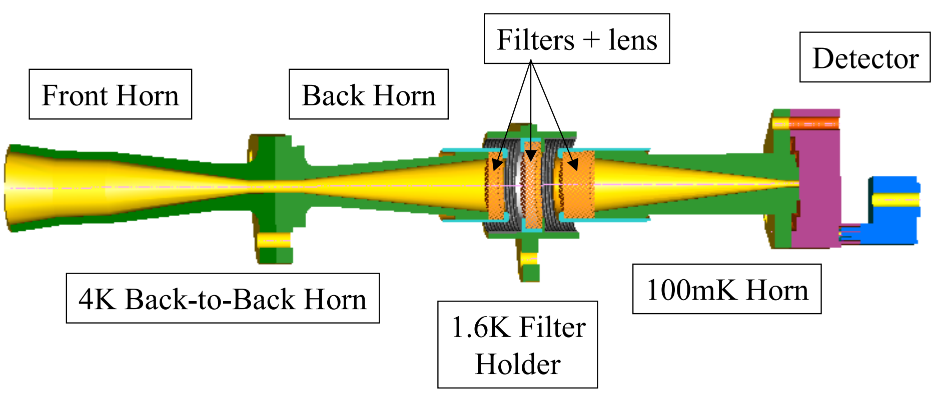
Detecting sub-mm radiation

Sub-mm radiation is at the interface between the optical and radio regions

Use techniques from both:
e.g. radio: waveguides, feedhorns, antennae
optical: filters, mirrors and lenses

Sometimes in the same optical system:



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 (stars, planets…)

Also lets us see far away (red shifted) warmer objects: peak in 40 K blackbody at Z=3 is at 300 μm

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

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Why do sub-mm astronomy?

Electromagnetic content of the universe dominated by:

Microwave Infrared/optical }	well mapped across the whole sky
Sub-mm	mapped in detail only over about an area about the size of the moon!

Unexplored territory... There is still much to be discovered!

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Why NOT to do sub-mm astronomy

It's hard!

Atmosphere is almost totally opaque
"Windows" partially open up only at high and dry enough sites e.g. Mauna Kea, Hawai'i (4200 m altitude)

James Clerk Maxwell Telescope, Mauna Kea, Hawaii

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Why NOT to do sub-mm astronomy

Also, detector development is still in its infancy

No big military applications (unlike infra-red)

So detectors are not commercially available

Need millikelvin temperatures (fun but hard)

On the other hand, it's for these reasons that there are such gains to be made...

Detecting sub-mm radiation

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Detector types

Two main classes of detector used in sub-mm

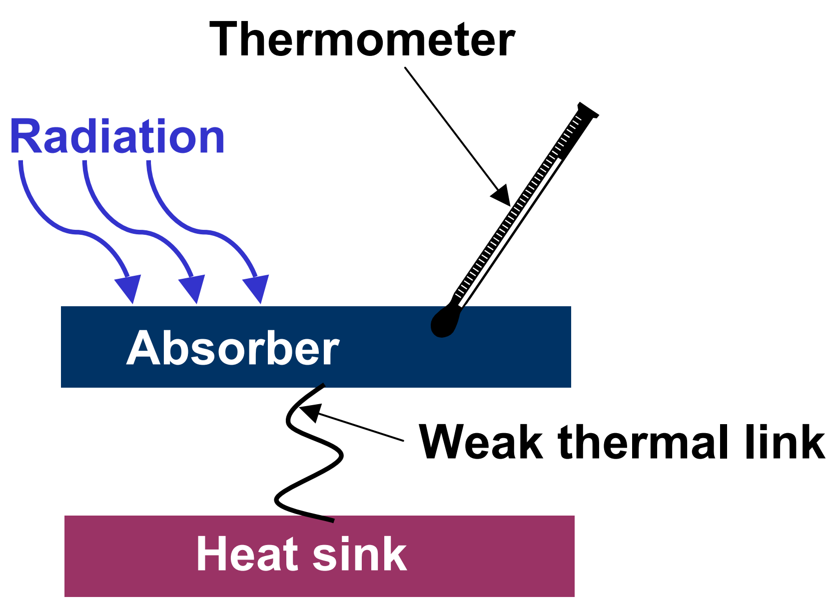
Heterodyne detectors (radio receivers, as used in radio astronomy). Detect narrow band of wavelengths

Continuum (or direct detectors). Detect broad band of wavelengths

In the sub-mm, we use *bolometers* for continuum measurements

Bolometers

A bolometer is conceptually very simple



Nearly flat spectral response over wide bandwidth:
  can define bandwidth using filters/waveguides

Can use simple read-out scheme

High sensitivity; best noise performance

Practical to calibrate

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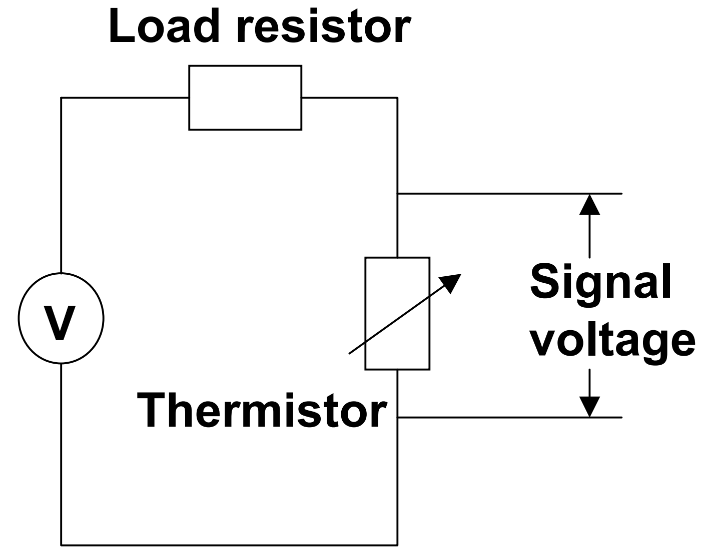
Bolometers

"Classical" design for sub-mm:
Metal-coated dielectric as absorber
Semiconductor resistance thermometer

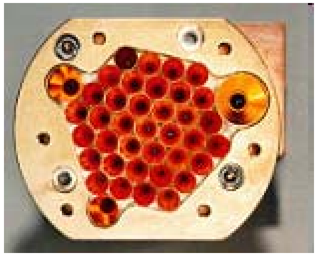
Each pixel illuminated by a feedhorn

Build up focal plane by stacking individual pixels together, each with independent readout



Readout circuit

More information in Woodcraft et al Int. J. Inf. Mill. Waves 23 (4) 575-595 (2002)
http://reference.lowtemp.org/woodcraft_bolometers.pdf



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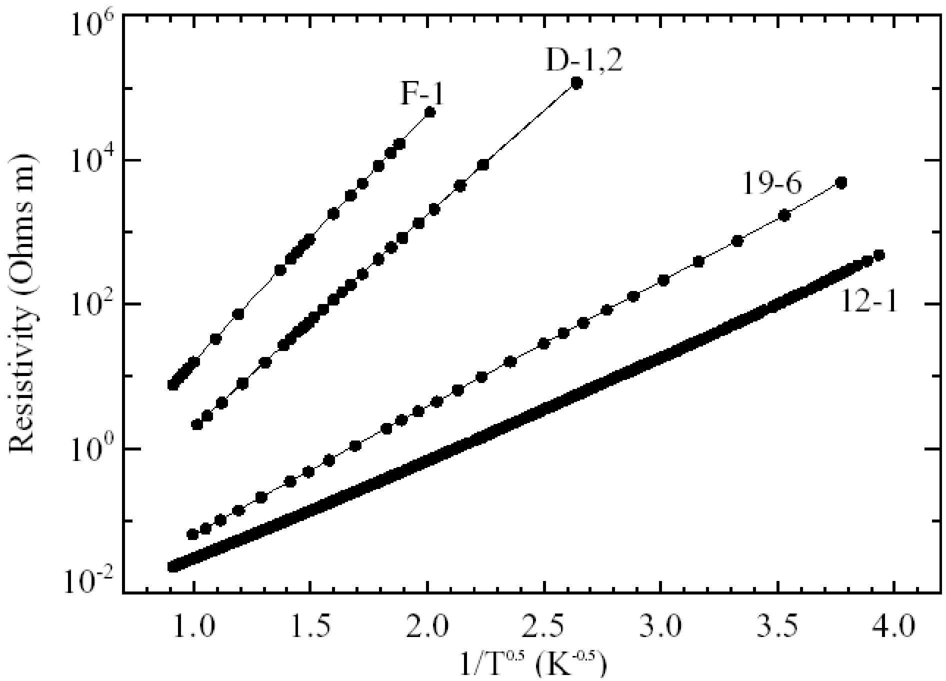
NTD Germanium

Need extremely uniform doping for reproducible behaviour
Neutron transmutation doping converts ^{70}Ge to ^{71}Ga (acceptor) and ^{74}Ge to ^{75}As (donor).
Since isotope distribution is homogenous, doping is uniform
Doping levels can be controlled by altering isotope ratios



More information in http://reference.lowtemp.org/woodcraft_npl05.pdf

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A little history

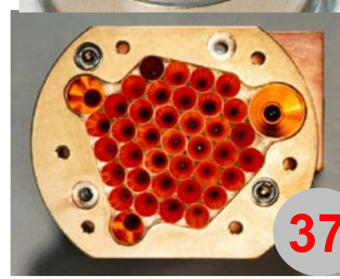
JCMT-UKT14
350μm-2mm

1986-1996

CSO-SHARC
350 μm array

1996-

JCMT-SCUBA
350/450 &
750/850μm



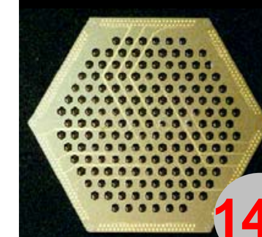
1997-

Also 19 pixel 2 mm array at 0.1 K

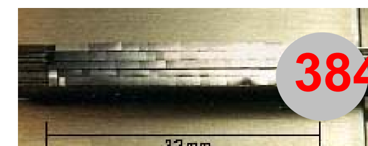
IRAM- MPIfR
1.3mm array

1998-

LMT-BOLOCAM
1.1mm



2001-



CSO-SHARC-II
350/450

2004-

91 Number of pixels

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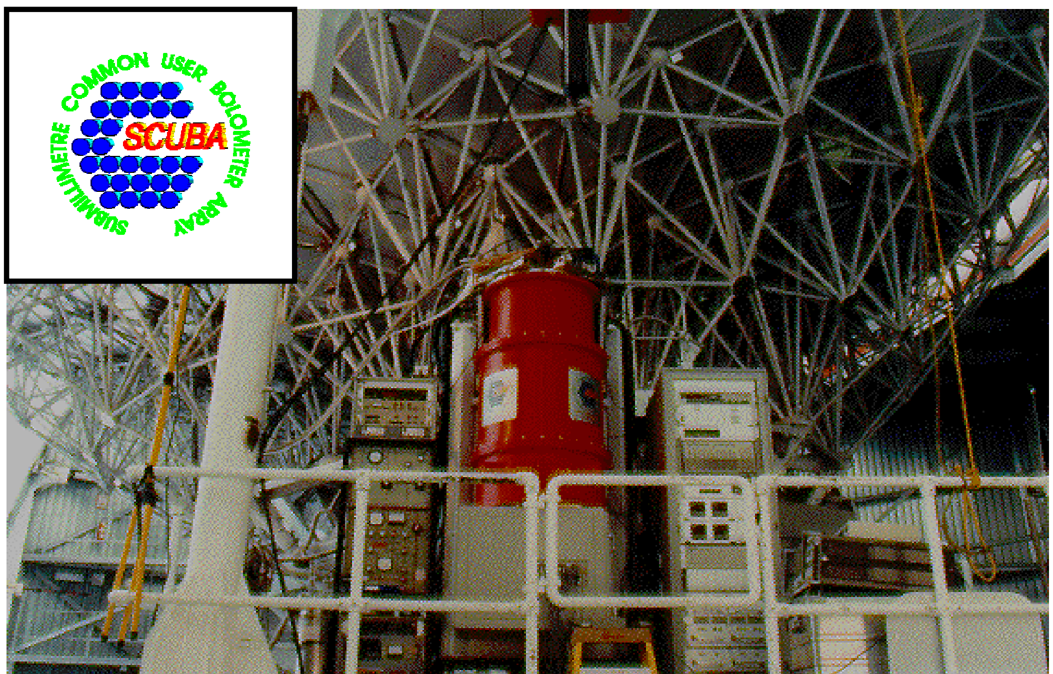
Despite this…

Huge revolution in last decade
Largely down to one instrument – SCUBA on the JCMT in Hawai'i (instrument led by ATC)
Citation rate rivals Hubble, only instrument better known than the telescope it's on?



A little history

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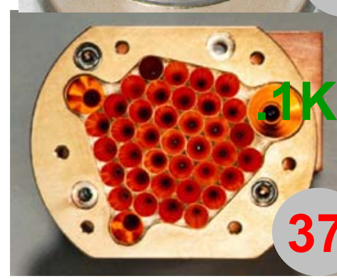

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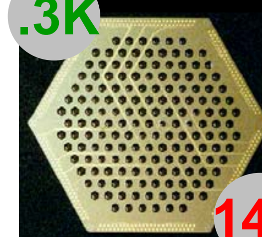

2001-

CSO-SHARC-II
350/450

2004-

91 Number of pixels

.3K Operating temperature

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Why so cold?

Need to avoid blackbody radiation that would swamp the signal you are trying to detect

Need to reduce noise in the detectors – noise sources generally decrease as temperature is decreased

For bolometers, need to reduce heat capacity to increase sensitivity – the lower the heat capacity, the larger the temperature rise for a given (modulated) power input

- Reducing thermal conductance has same effect, but the time constant increases

Refrigeration

Most sub-mm bolometer arrays run at 300 mK
Cooling is often provided by self-contained sorption fridges, using separate ^{3}He and ^{4}He stages.

Refrigeration

Some applications require 100 mK
To date, instruments have used conventional DRs

As instruments become larger, these require complex systems of thermal links to bring cooling to the detectors

A small, self contained dilution fridge would mean cooling can be provided at the detectors rather than some distance away, as is possible with a 300 mK self contained sorption fridge

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Refrigeration

An entirely self-contained sorption DR fridge has been developed in Cardiff

Separate $^{3}He/^{4}He$ fridge cools cryopump to 400 mK

^{3}He gas liquifies in cryopump, then returns to mixing chamber under gravity

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Refrigeration

Adiabatic demagnetisation refrigerators very popular in labs

Used on sounding rockets

Non in use at telescopes?

Two launched into space, but not useable due to launcher and cryogenic problems

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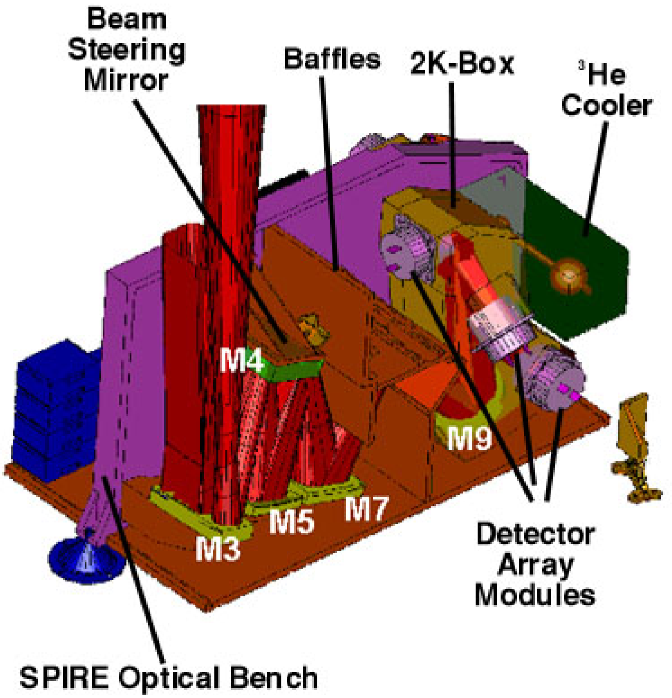
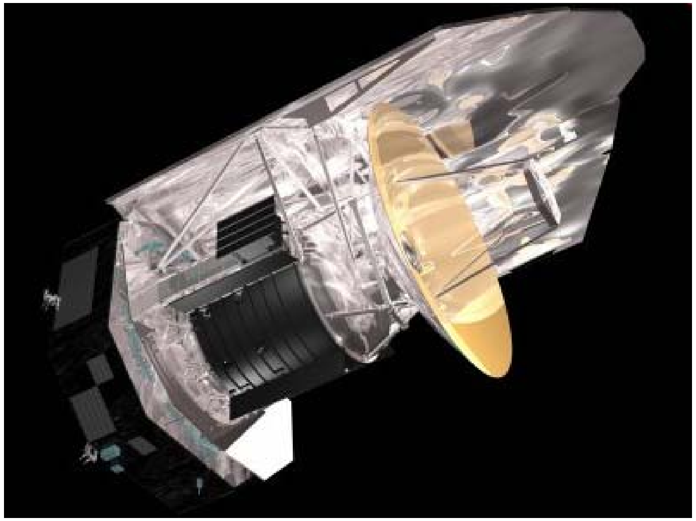
Some examples

Herschel/SPIRE

Sub-mm observatory





Pixels in each array fabricated on single wafer
Separate read-outs
State of the art for Ge detectors.

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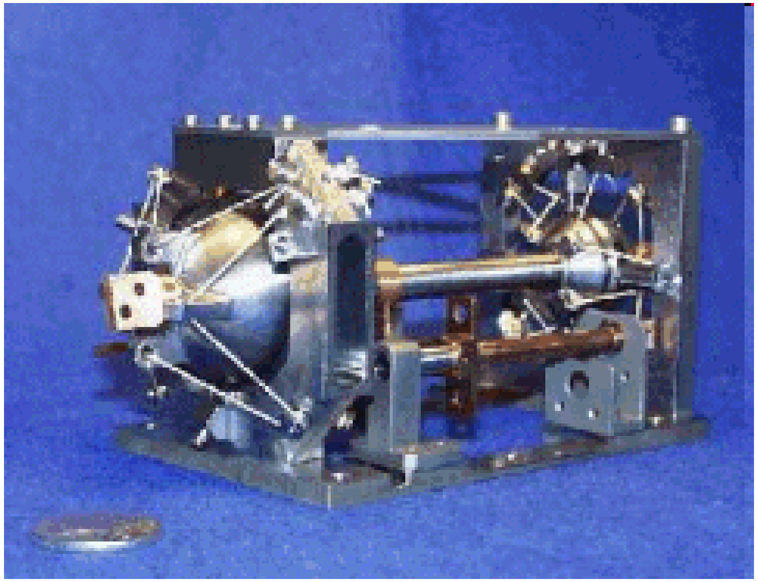
SPIRE refrigeration

Space-borne sorption cooler (CEA, France)
Only minor modifications required to usual concept for operation in microgravity (and surviving launch)



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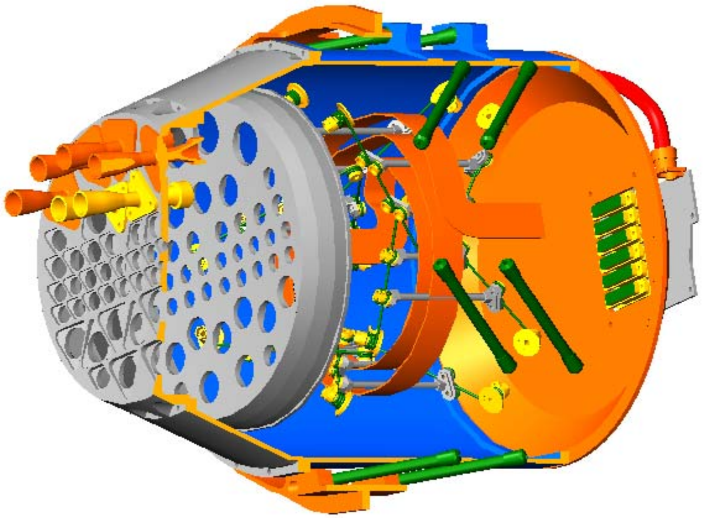
Planck/HFI

Cosmic microwave background experiment (successor to COBE and WMAP)



Each pixel (bolometer and optical chain) independent

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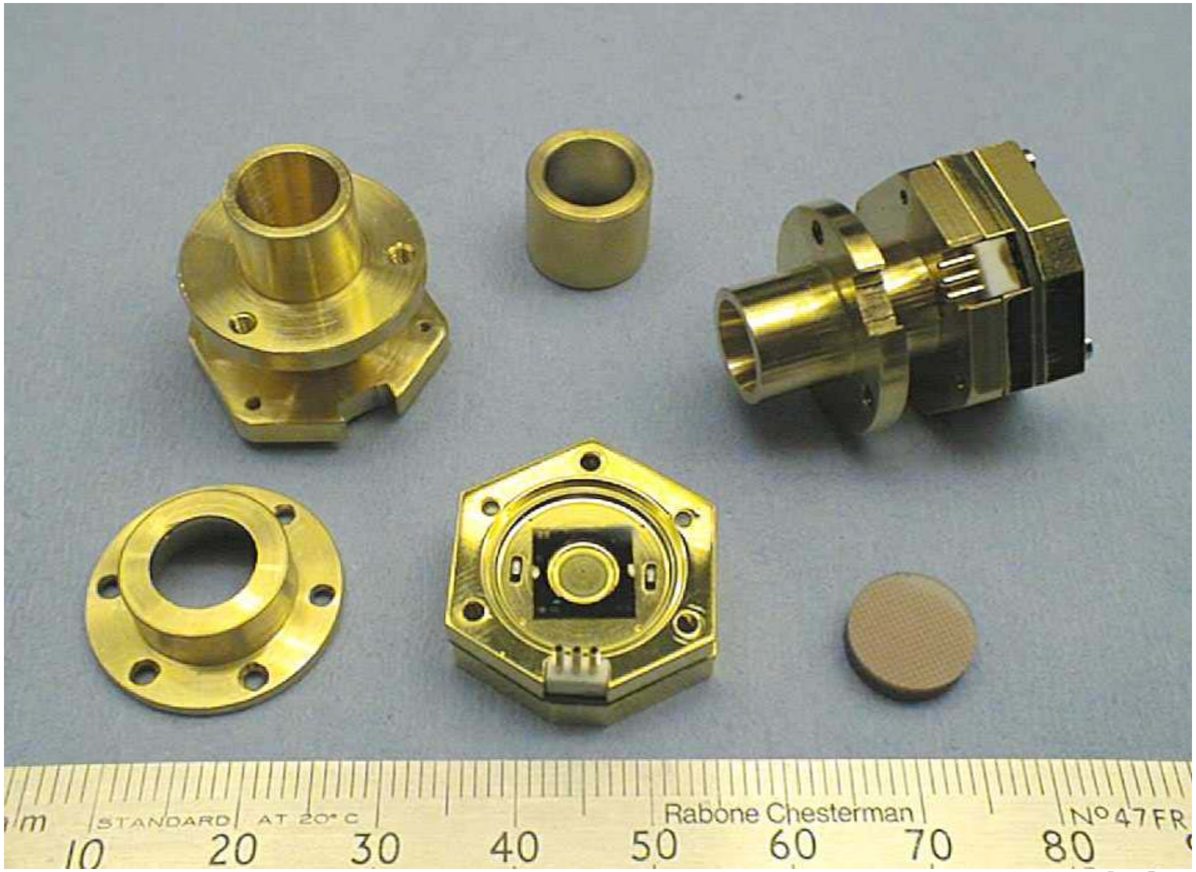
Planck/HFI

JPL NTD germanium spiderweb bolometer module with Cardiff feedhorn and metal mesh filter



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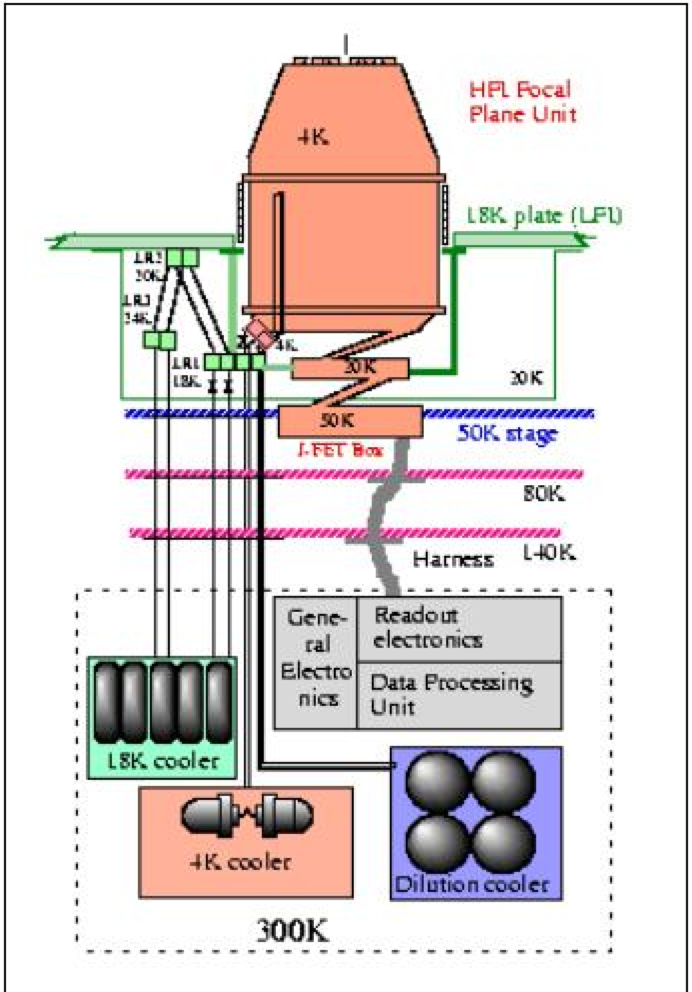
Planck cooling chain



50K Stage: Passive Radiative Cooling
Radiation to free space, effective for L2 orbit

↓

18K Stage: Sorption Cooling
Closed cycle cooler using Joule-Thomson expansion of hydrogen and sorption compressors

↓

4K Stage: Joule Thomson Mechanical Cooler
Mechanically compressed J-T expansion of Helium

↓

1.6K Stage: J-T expansion of mixed helium

↓

0.1K Stage: ^{4}He ^{3}He Dilution Cooler

Cryogenic "tricks"

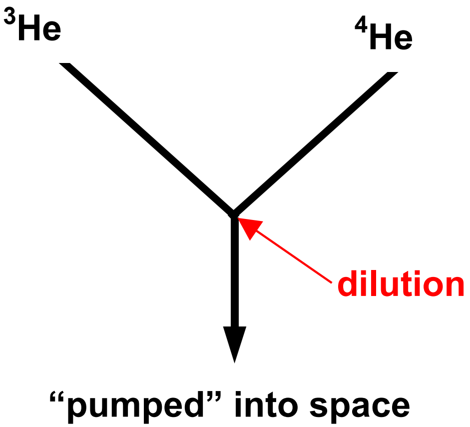
"Memory metal" locks hold structures in place for launch
In flight, instrument cools down and launch locks open

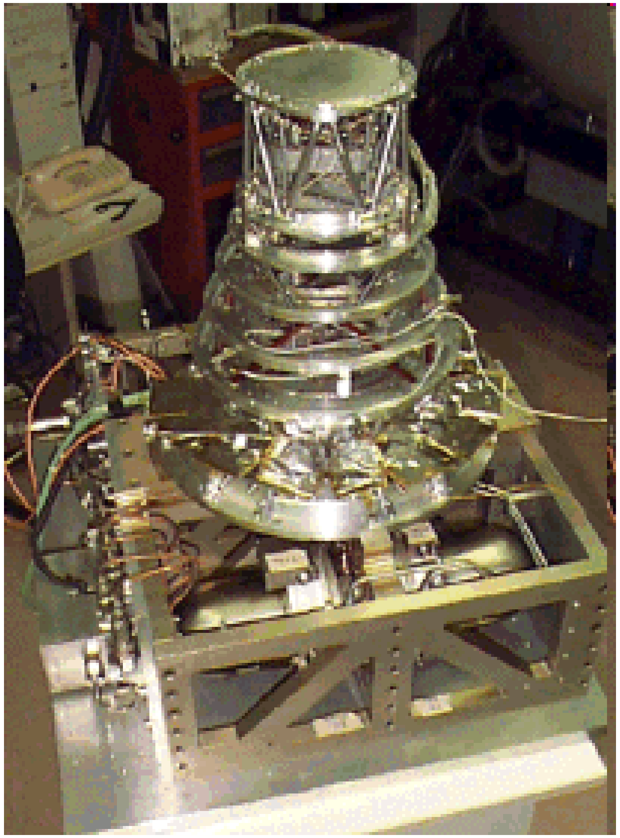
Holmium-yttrium provides high heat capacity to stabilise temperature at 100 mK (alternative of liquid helium "bomb" not felt suitable for space use)

Heat leak down 100 mK stage supports and wiring minimized by using cooling from dilution fridge exhaust gas

Planck/HFI dilution fridge

Space-borne dilution refrigerator (CRTBT, France)
200 nW cooling power at 100 mK
(Invented A Benoit and S Pujol)





Planck/HFI dilution fridge

Advantages:

Continuous cooling power

Provides its own 1.6K stage (Joule-Thompson expansion of exhaust gas)

4K stage can be provided by closed-cycle systems - helium bath is not required

Gravity independent

(Relatively) simple and compact design

Tested in ground and balloon applications

Disadvantages:

Plumbing system must stay leak tight, must not plug

Untried in orbit

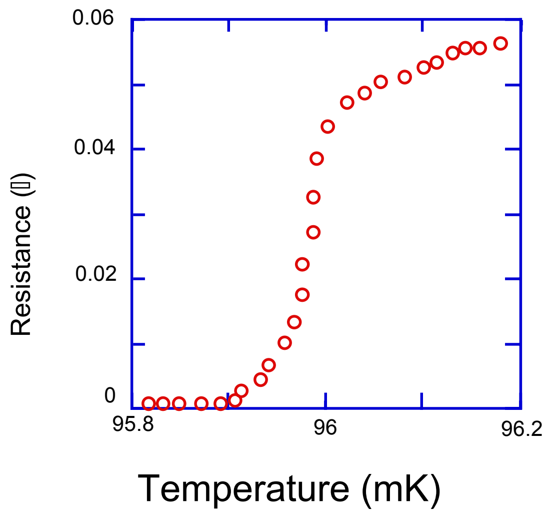
Low cooling power (200nW at 100mK!)

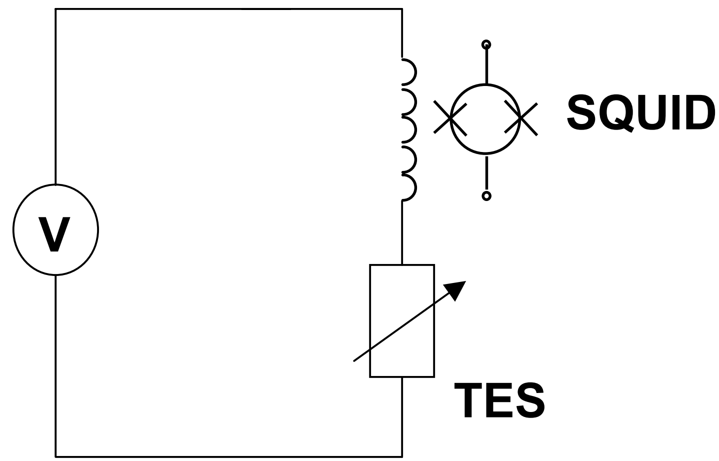
Uses 21600 STP litres ^4He and 4876 STP litres ^3He

Superconducting bolometers

Superconducting bolometers

Alternative design: Transition Edge Sensor (TES)
Obtain large sensitivity from the rapid change in resistance across superconducting transition





Readout circuit

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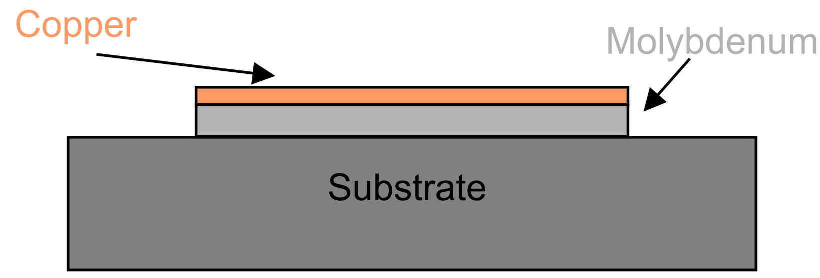
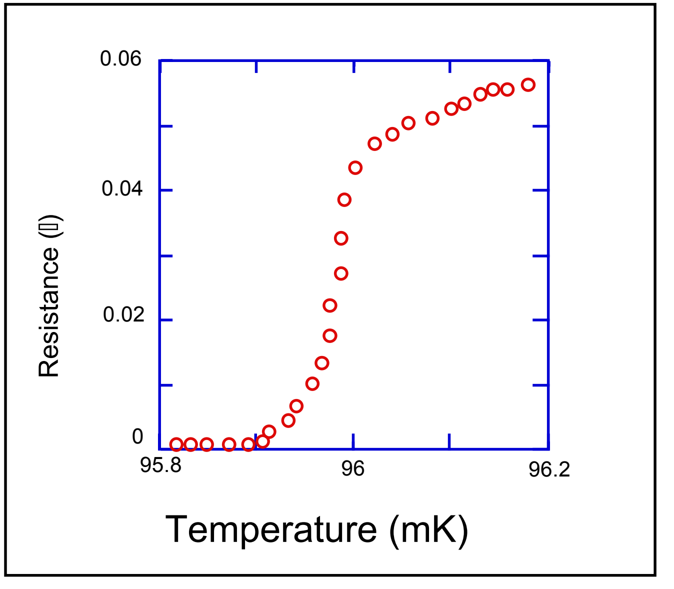
Mo/Cu bilayer

Bilayer of thin superconducting and normal metal films acts as single superconductor with tunable T_c (proximity effect)



Molybdenum/copper:
Robust.
Transition is:
- sharp (<~5 mK)
- stable
- reproducible



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NIST Boulder Colorado

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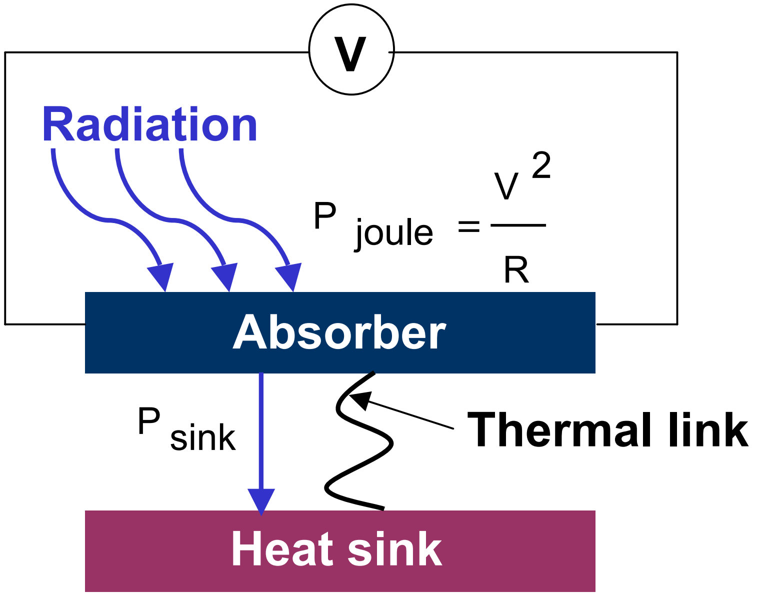
Operation

As the film cools, resistance decreases and Joule heating increases – self-regulation

Holds bolometer in the narrow transition

Reduces Johnson noise

Reduces time constant



TES's are ideal for constructing large arrays

Can fabricate many TES pixels on a single silicon wafer

Can use multiplexed read-out

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SCUBA-2

Current/planned instruments

Instrument	Telescope	Year	No. of pixels
UKT14	UKIRT/JCMT	1986-1996	1
SHARC	CSO	1996	24
SCUBA	**JCMT**	**1997**	**131**
MAMBO	IRAM	2000	117
SHARC-II	CSO	2004	384
HAWC	SOFIA	2005	384
LABOCA	APEX	2005	295
SCUBA-2	**JCMT**	**2006**	**10240**
SPIRE	Herschel	2007	280

Massive advantages to increasing pixel count in sub-mm

SCUBA-2 is clearly a huge leap forward

Brings CCD-like imaging to the sub-mm for the first time

Will map the sky ~ 1000 times faster than SCUBA

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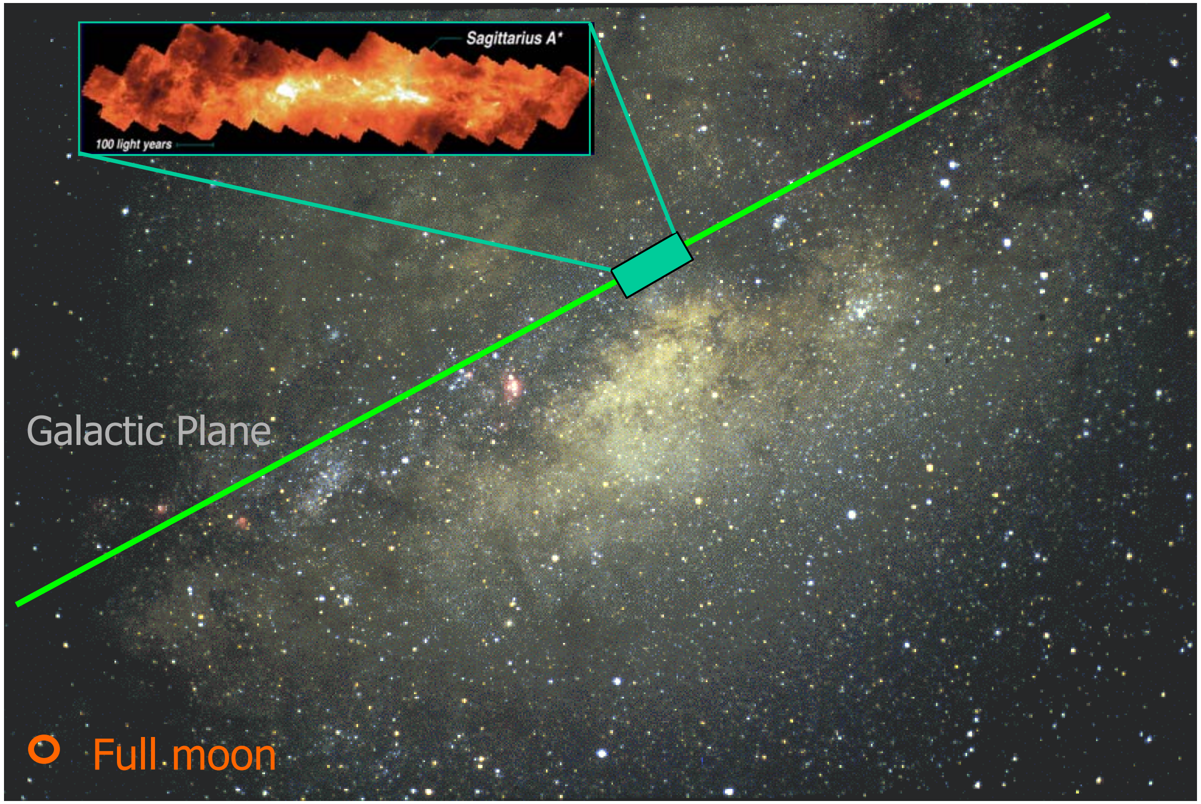
Performance



SCUBA Galactic Centre Survey

~120 hrs over 2 years of excellent weather telescope time

SCUBA-2 could map the ENTIRE AREA shown above in just a couple of hours to the same S/N...

SCUBA-2

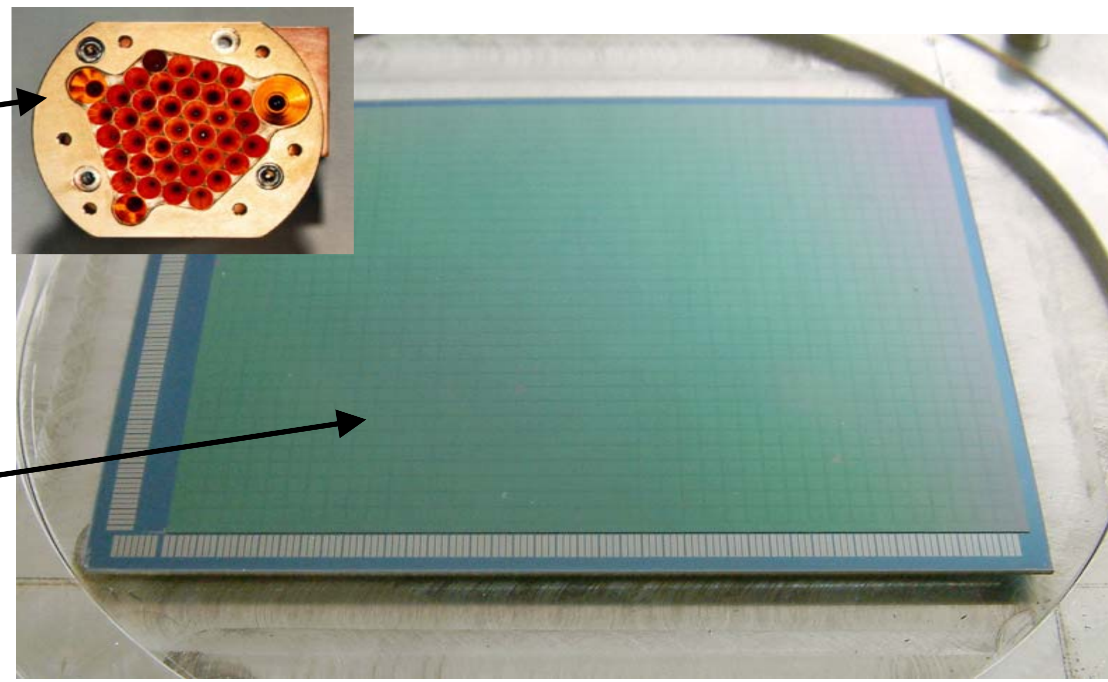
Over 10 000 pixels in total

Two colour operation - 450 µm and 850 µm

Detector and instrument development/build in parallel

SCUBA 850µm array (feedhorns)

Completed 40 × 32 (1280) pixel prototype SCUBA-2 array (bare pixels)



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UK Astronomy Technology Centre

The University of Edinburgh

Joint Astronomy Centre

NIST National Institute of Standards and Technology

UBC

University of Waterloo

Institutions

Instrument design, construction, testing, commissioning: *ATC, Edinburgh*

Multiplexer and TES devices: *NIST, Boulder*

Detector support structure micromachining: *University of Edinburgh*

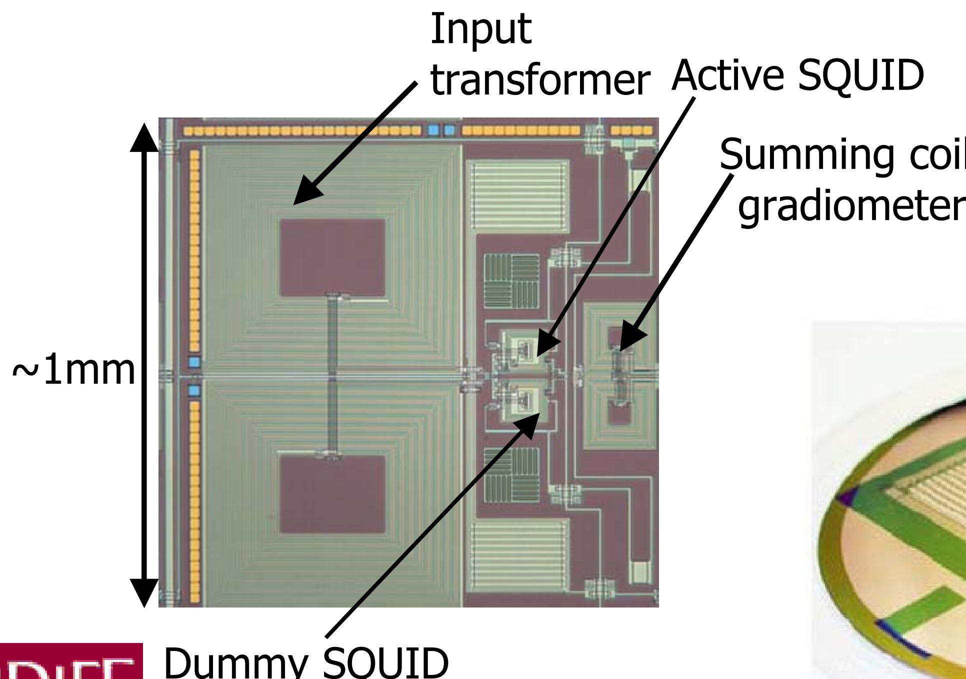
"1-K box" design and construction, detector test programme, filters/dichroic: *Cardiff University*

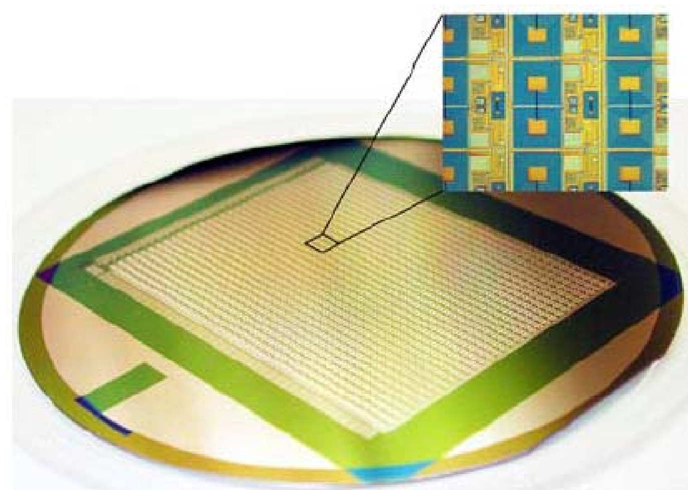
Warm electronics: *University of British Columbia*

Multiplexer

Uses “in-focal-plane” multiplexer - never been done before!

Alternative designs would take up too much space and require too many wires between detectors and multiplexer





A full-sized (40 × 32 pixel) multiplexer wafer

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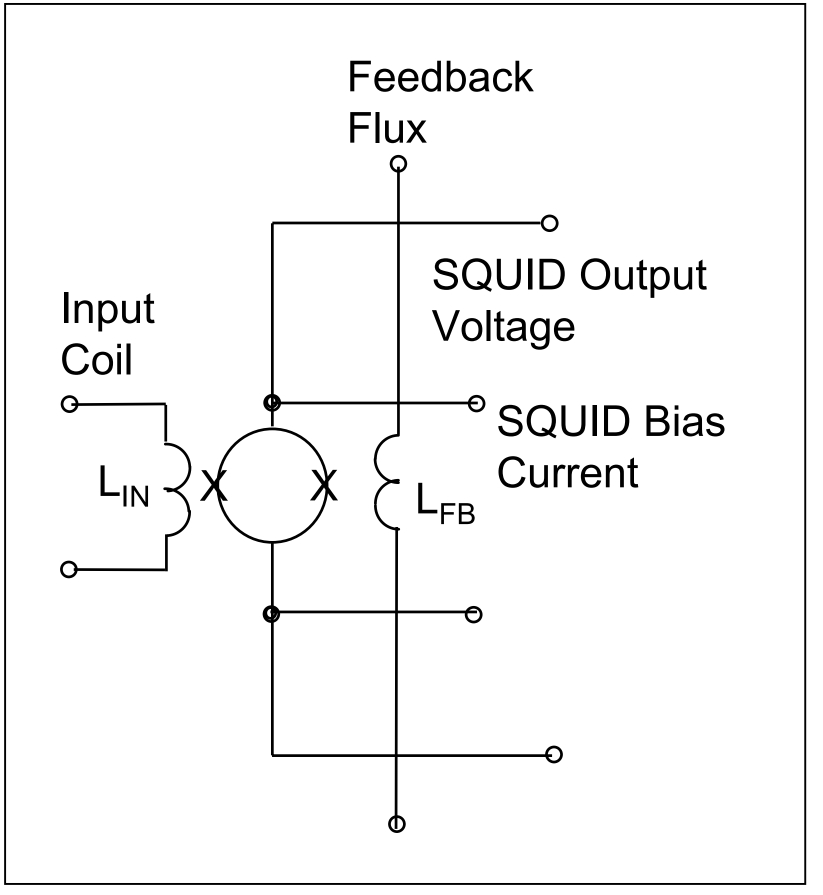
Multiplexer

Each pixel requires 6 wires

76 800 wires for SCUBA-2 (and 12 800 SQUID readout systems with flux locked loop)

This is not terribly practical!



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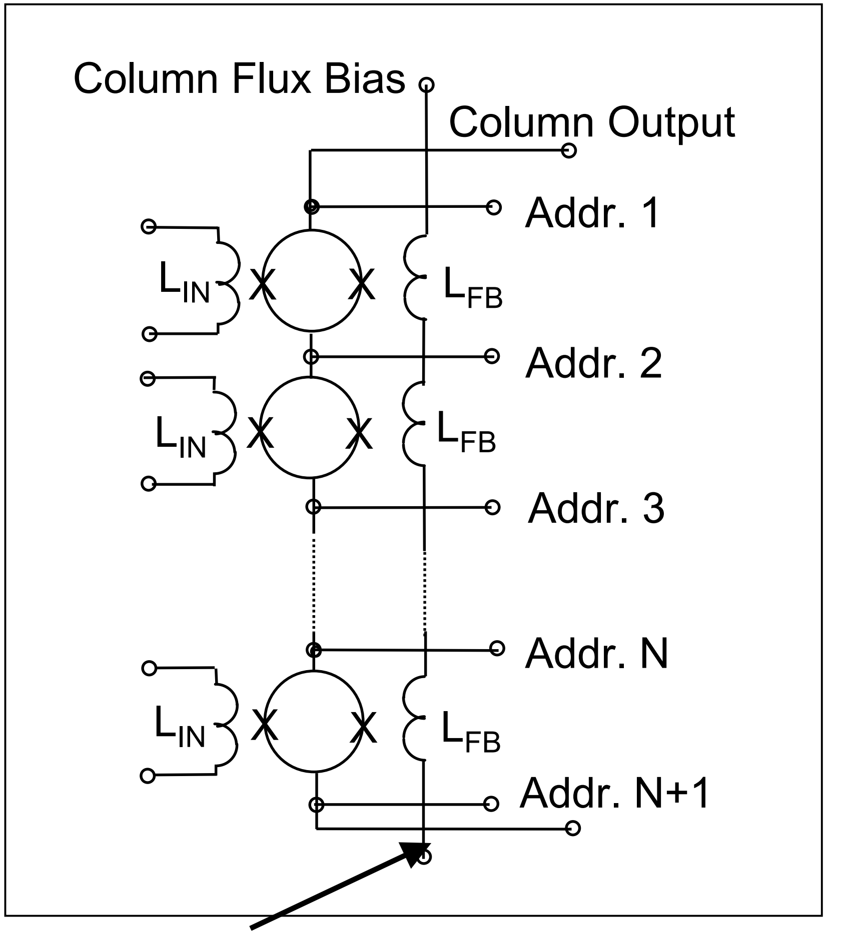
Multiplexer

So we connect a set of SQUIDS in series (NIST development)

We bias each SQUID in turn (time division multiplexing); the unbiased SQUIDS do not contribute signal

Likewise, we can put the feedback coils in series.

Now we have 2 and a bit wires per pixel



Price of TDM with SQUIDs: must use smart digital
feedback which remembers last feedback setting to zero flux

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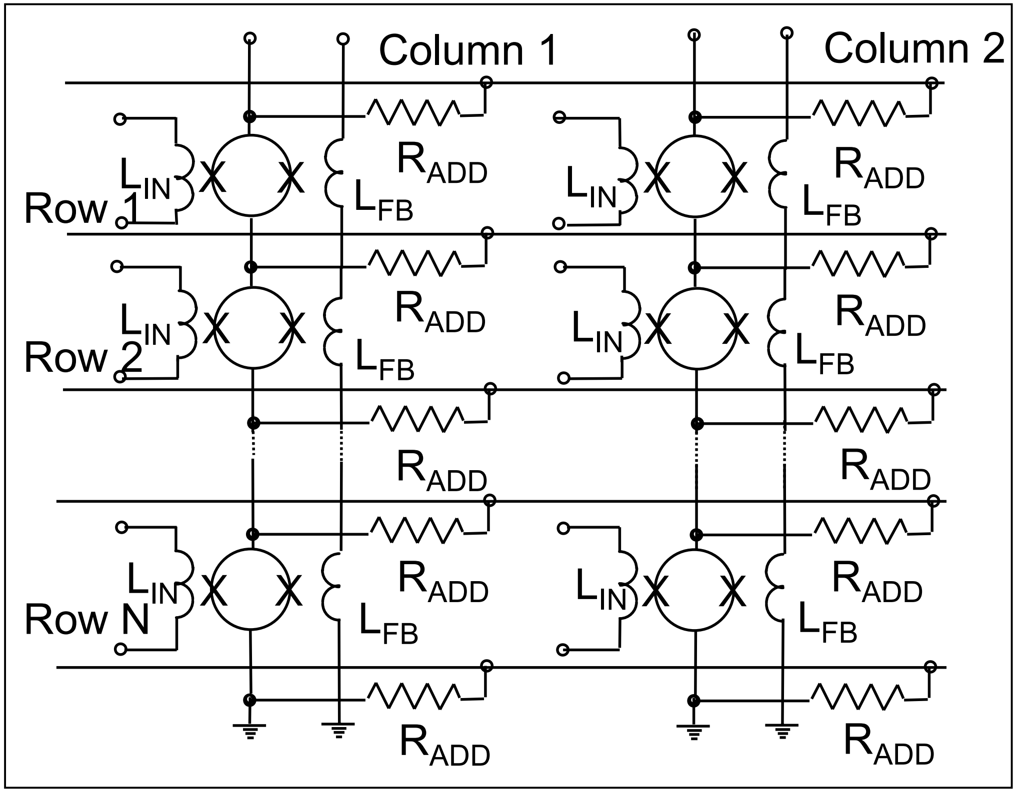
Multiplexer

We can do even better if we have many series SQUID arrays, since we can use the same address lines for each 'column'

Only need a few hundred wires for the whole instrument!

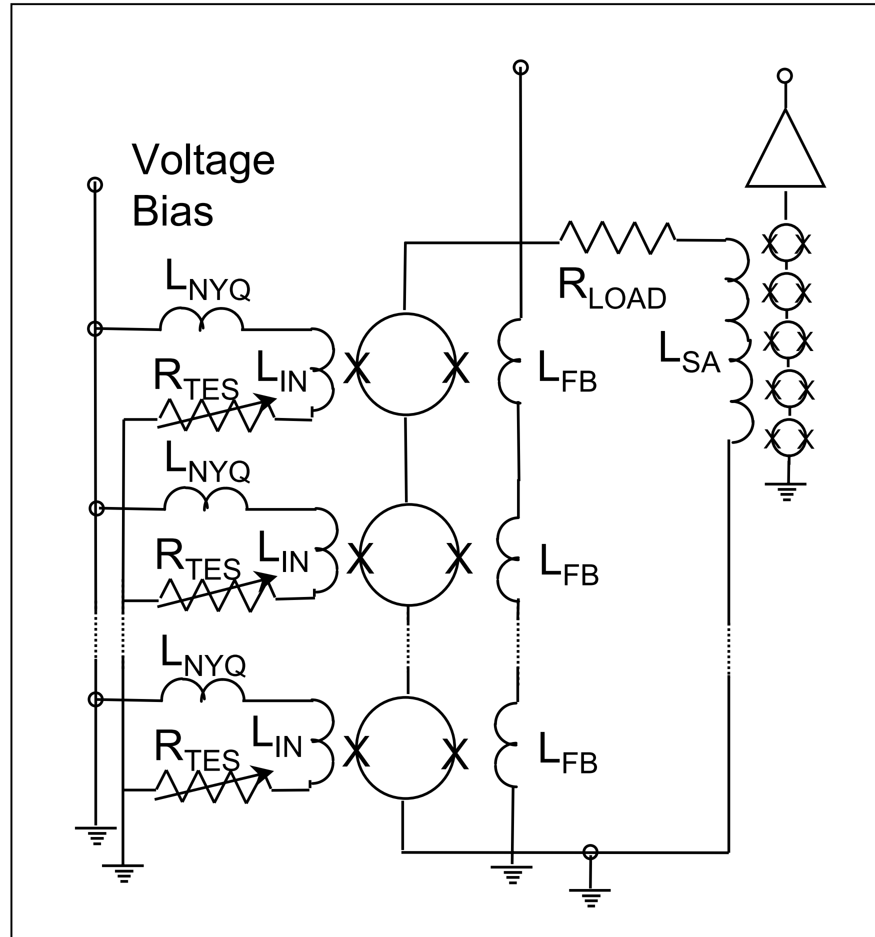


Multiplexer

Conventional SQUIDS have too low impedance
(required for high bandwidth and high dynamic range for switching feedback)

Use series array of 100 SQUIDS (NIST invention) - output in mV

Make SQUIDS *much* easier to handle (though still need paranoia with respect to magnetic shielding)



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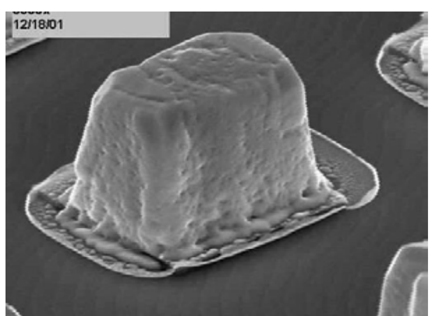
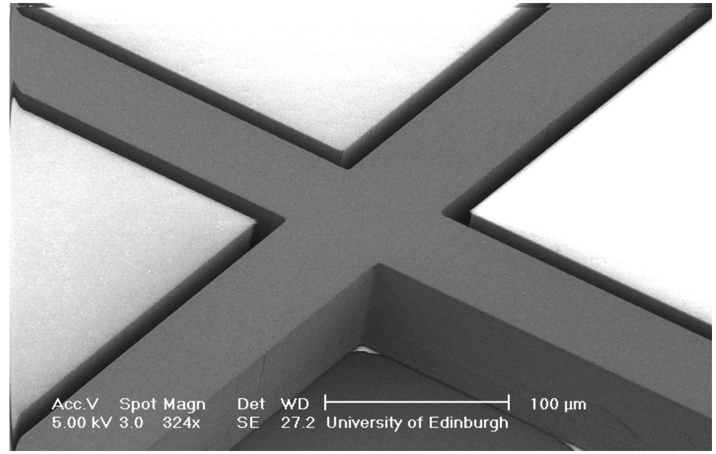
Array production

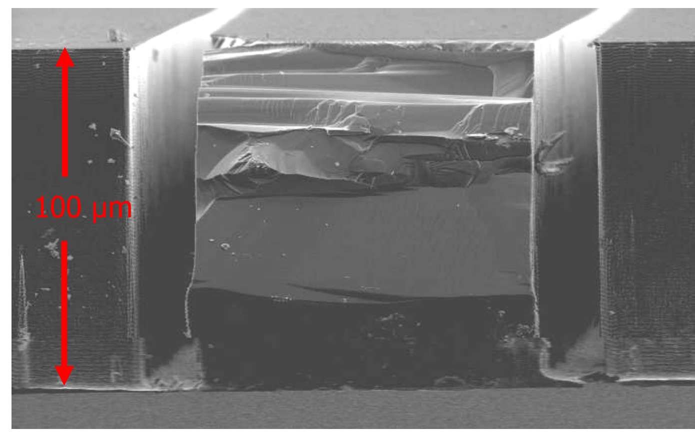
Raytheon

Vision Systems

Bump bonding MUX to detector







Deep etching to isolate detector pixels

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Size

SCUBA-2 is big

Optical system contains table sized mirrors cooled to 4 K

4-K box at ATC

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SCUBA-2 low temperature thermal design

Dilution fridge

Leiden Cryogenics has developed a “dry” dilution fridge cooled with a pulse tube cooler rather than a helium bath

Specification: 500 μW at 120 mK

Large reduction in operating costs at telescope

Many other applications: turnkey cooling down to mK temperatures

Passed acceptance test – now being commissioned

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Leiden Cryogenics BV

Leader in LT Techniques

Thermal design

The detectors require a heat sink at a temperature of 60 mK

Achieving this is an overriding requirement for the design of the entire instrument

Cardiff is responsible for the design of the "1-K box"; an enclosure containing the arrays and the dichroic, maintained at a temperature of approximately 1 K. This has the most demanding thermal requirements.

People: Julian House, Fred Gannaway

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Thermal design

Few instruments have been built on the scale of SCUBA-2 – needed to find novel solutions to various problems

Information on properties often hard or impossible to find – need to extrapolate or measure test samples

Several components required detailed test programmes

Very important to get it right first time; cost and schedule impact of initial failure to cool instrument is large!

Lots of paperwork also required!

More information in Woodcraft et al Proc SPIE 5498, 446-454 (2004)

http://reference.lowtemp.org/woodcraft_scuba2thermal.pdf

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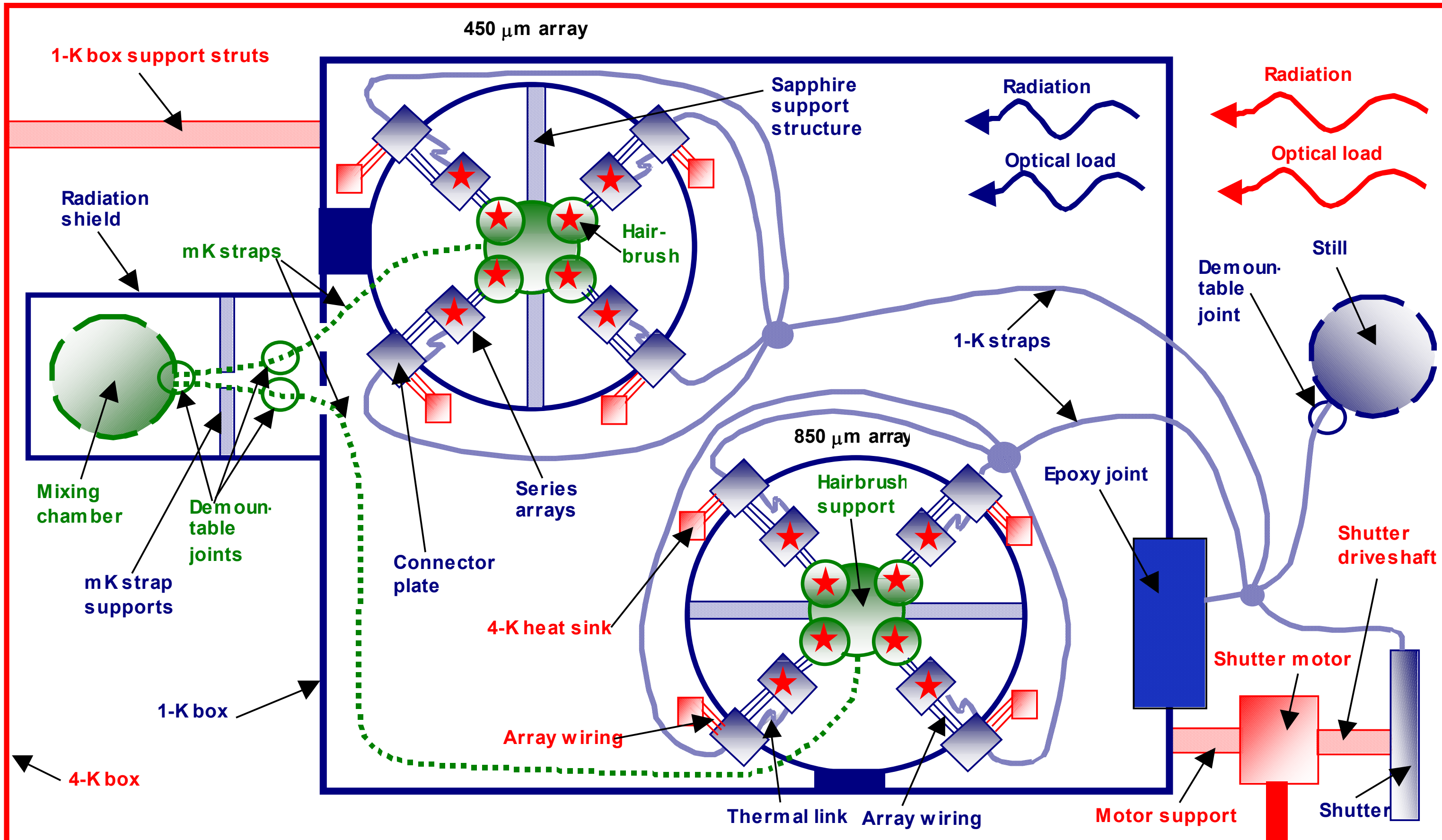
Thermal design

Thermal paths (mK and 1-K) are somewhat complex!



Contact to aluminium

The 1-K radiation shield is made from an aluminium alloy to reduce weight

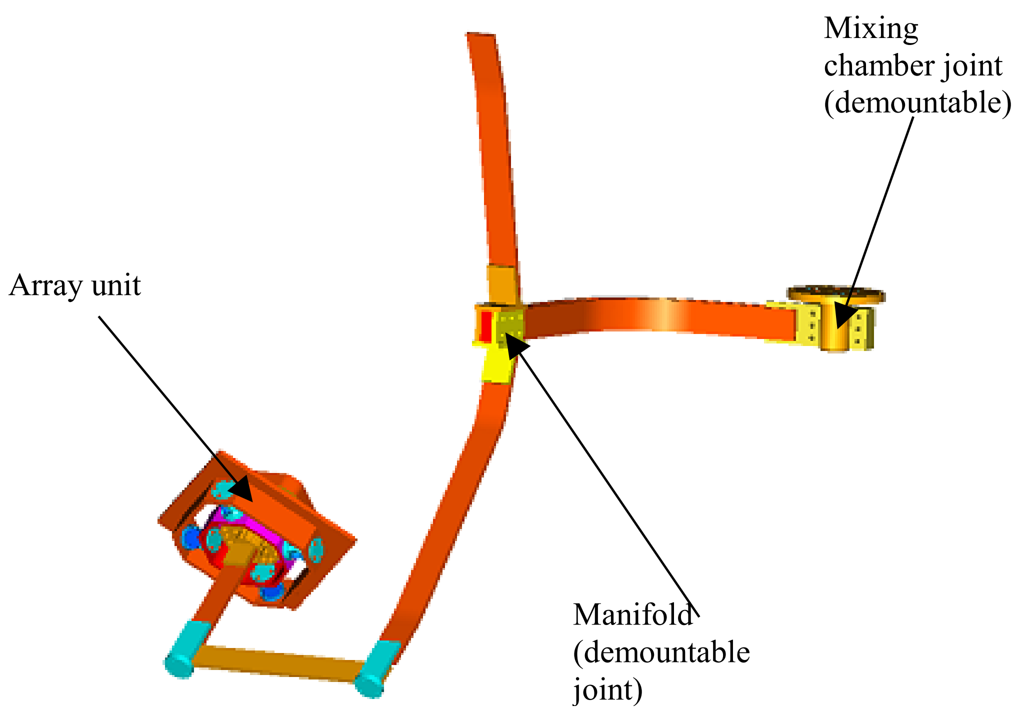
It is important to make good thermal contact to the box to cool it and maintain its temperature

To avoid poor conductance due to the oxide layer on aluminium, we forego metal to metal contact and use a large area epoxy joint to a copper plate. A bolted joint can then be made to this plate

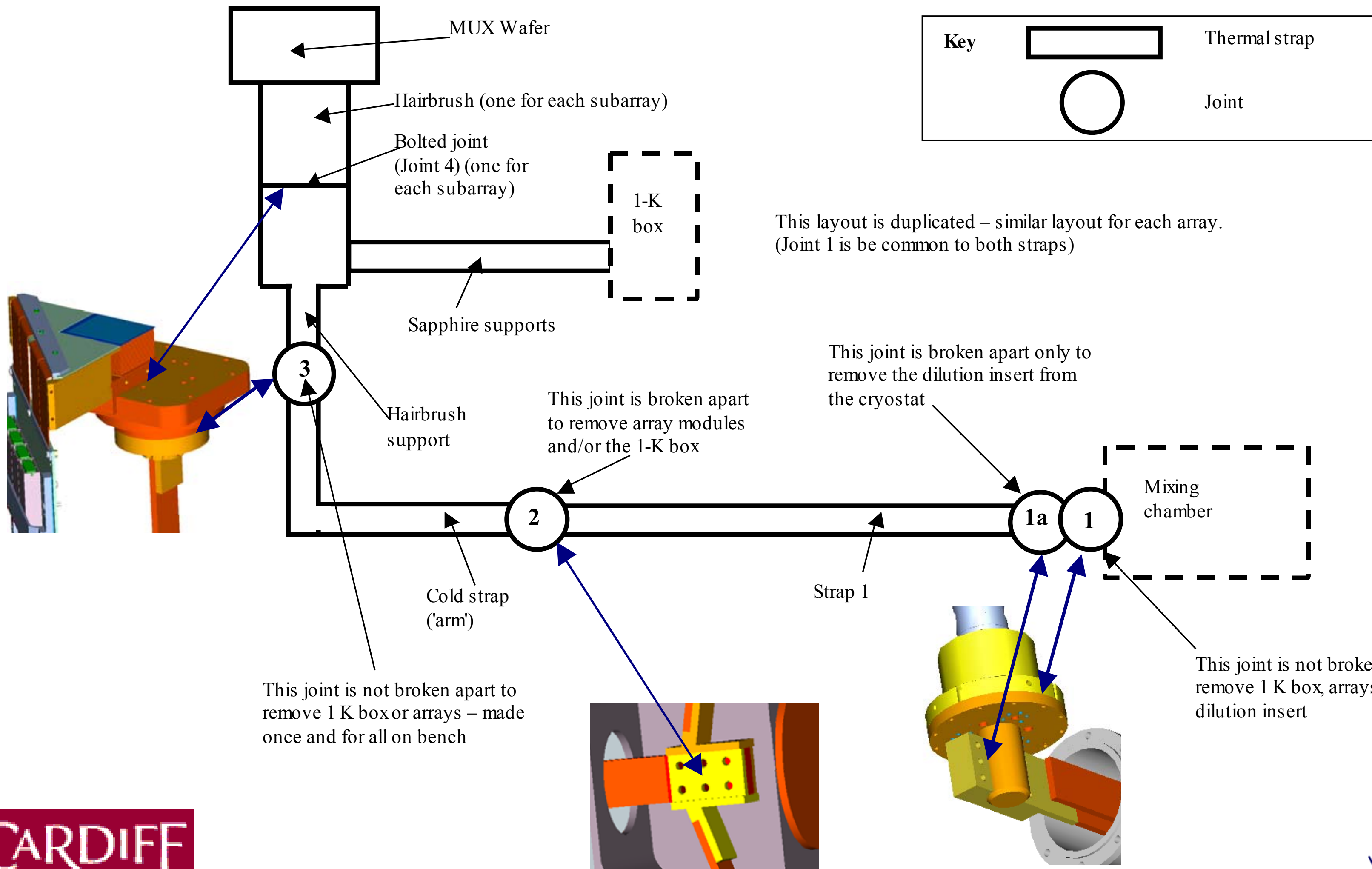
This concept has been tried on SPIRE, and improved thermal contact to radiation shields immensely

Millikelvin strap system

Transfers heat from the arrays to the dilution fridge (~ 1 m)



Strap system



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"Hairbrush"

Provides heat sinking and mechanical support to detectors without breaking them due to differential thermal contraction

Made from high conductivity beryllium copper alloy

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Glueing the hairbrush to the array

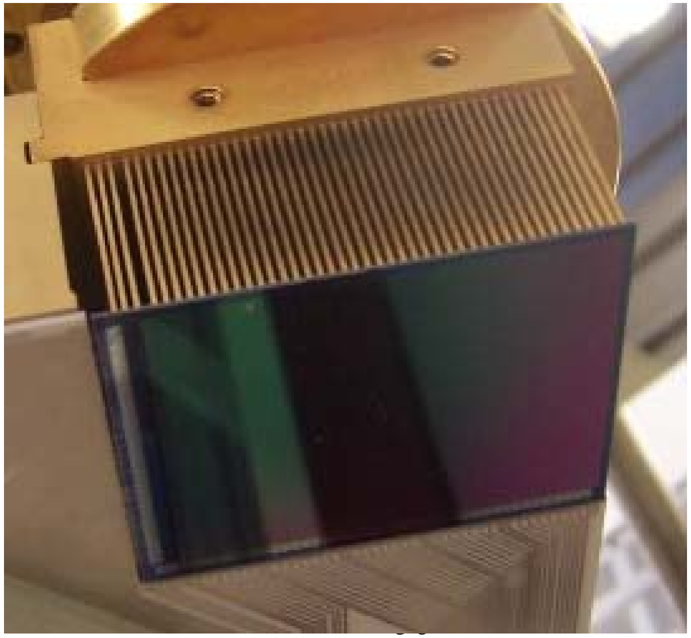
Glueing has to be uniform, musn't bridge the tines

Thermal conduction has to be good enough

Have to get it right first time – detector arrays are very valuable

Lengthy test programme, making and testing samples

Solution: desktop robot deposits metered blob of epoxy on each tine



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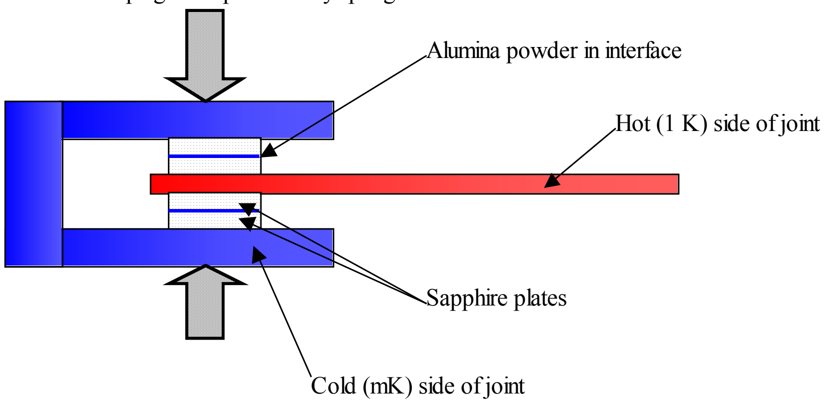
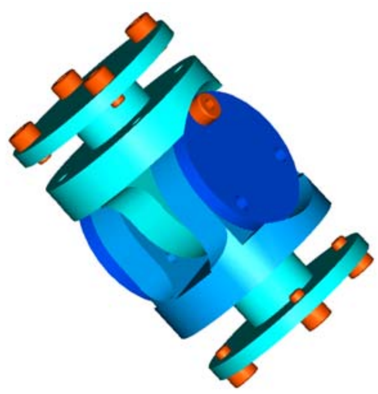
Thermally isolating support

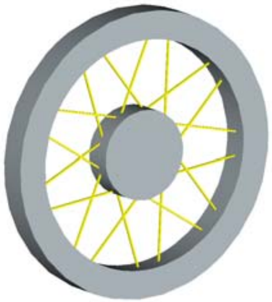
Need to support arrays rigidly with low heat leak

Solution: “sapphire interface” support: 2.5 μW heat leak from 1 K to 100 mK

Uses sapphire discs with alumina powder between







Straps supported by kevlar “wheel”

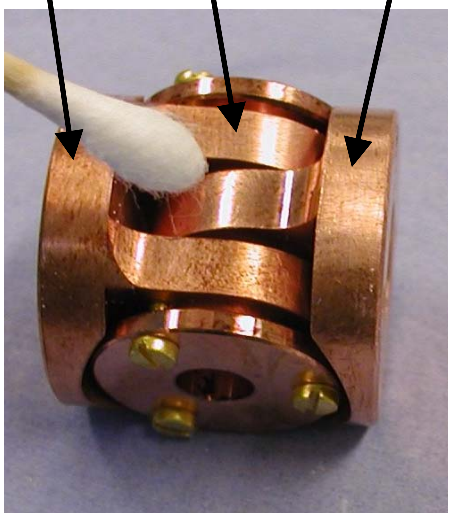
Thermally isolating support

Test joint:

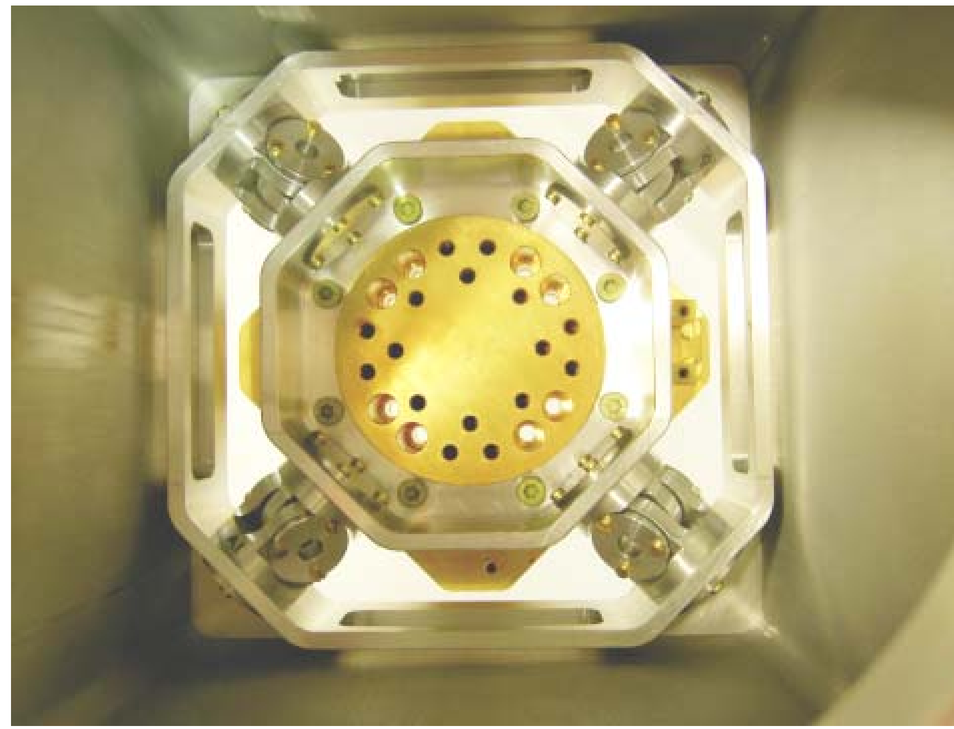
Thermal isolation

Cold side

Warm side



Finished isolation support



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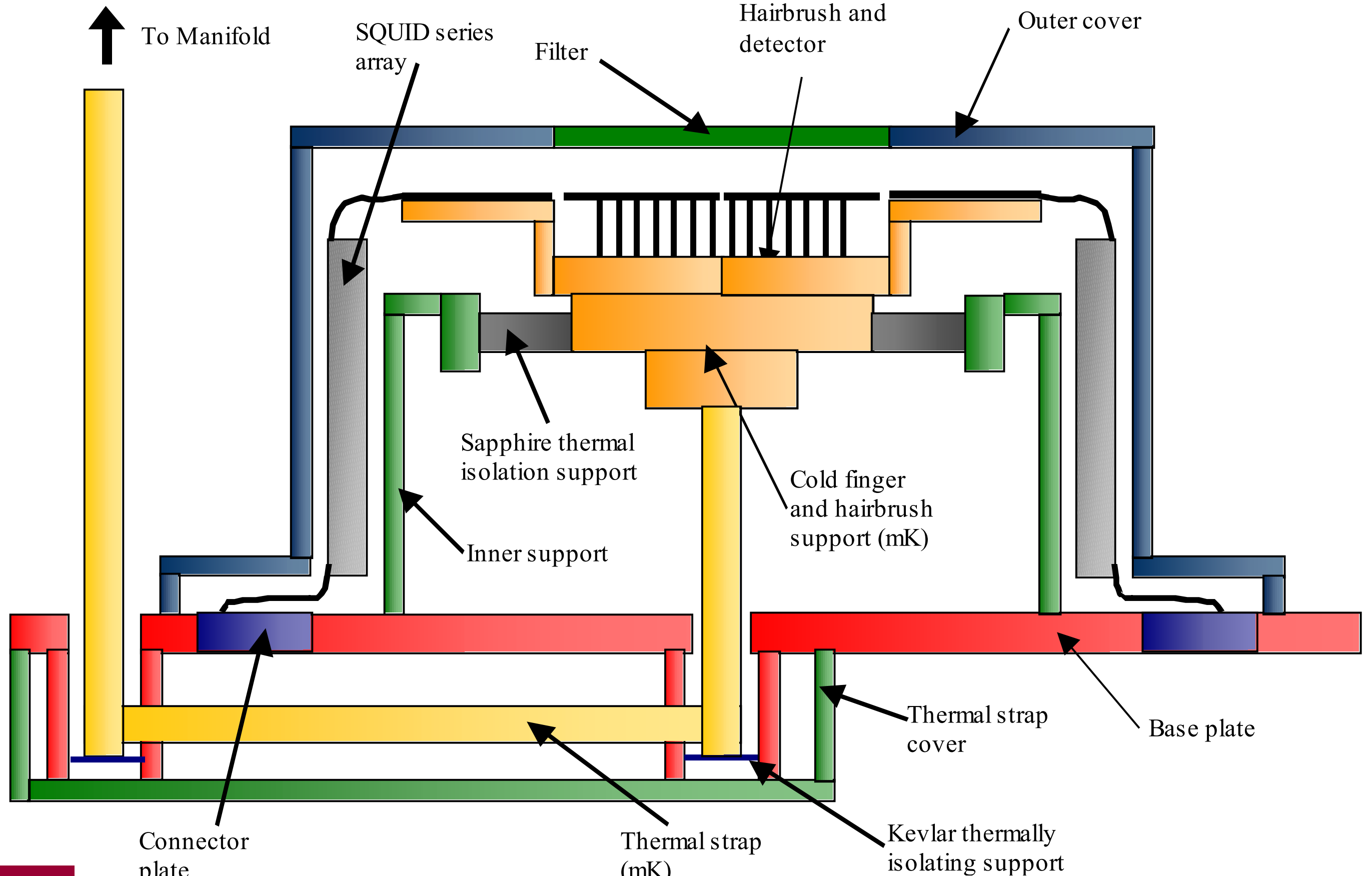
Assembly



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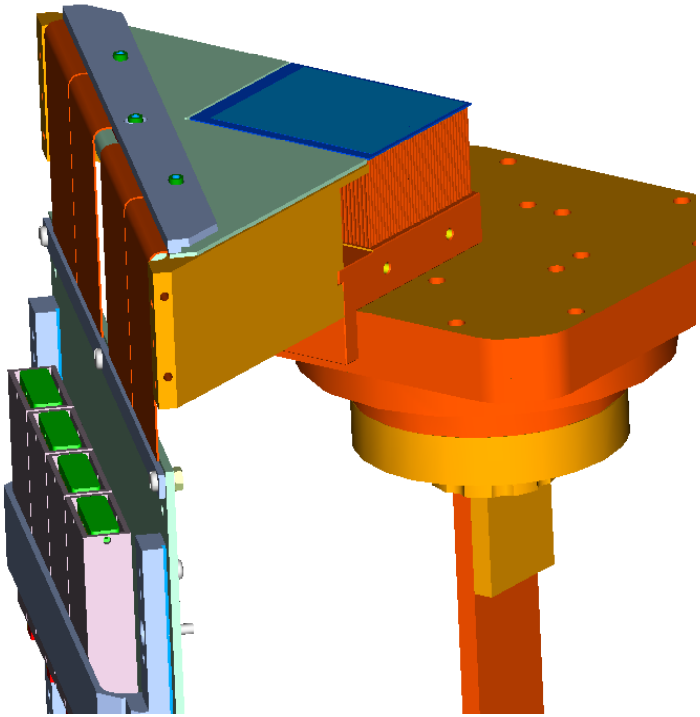
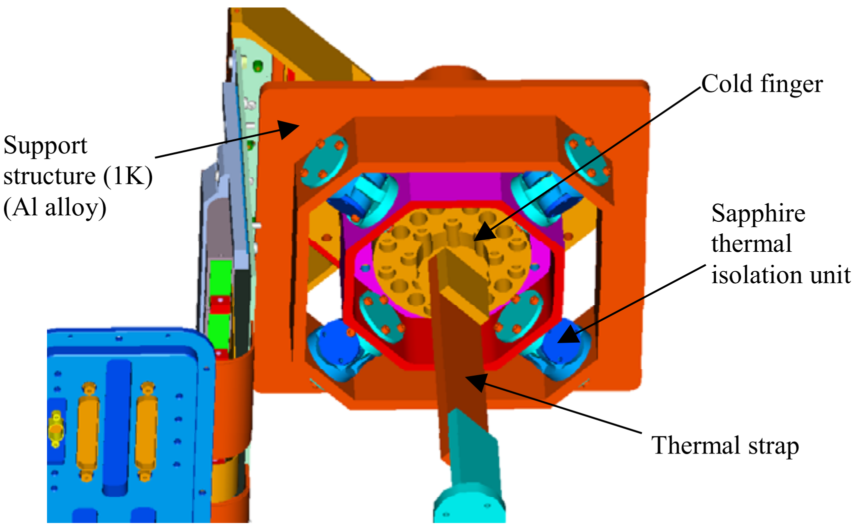
Assembly




Support
structure (1K)
(Al alloy)
Cold finger
Sapphire
thermal
isolation unit
Thermal strap

Thermal design

Critical components have all been tested on their own

System not been tested yet as a unit, but rest of instrument was designed along similar principles, and has exceeded requirements for cool-down time and temperature.

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SCUBA-2 test programme

Test programme

Requires custom testbed facility – mimics instrument

TES arrays of this size have never been tested before

Characterization not straightforward – pixels optimized for use at telescope not characterization

Need to learn as we go along to find out what tests are the most useful and how to carry them out

Also learning how we will use the detectors at the telescope

People: Dan Bintley, Rashmi Sudiwala, Peter Ade, Cynthia Hunt

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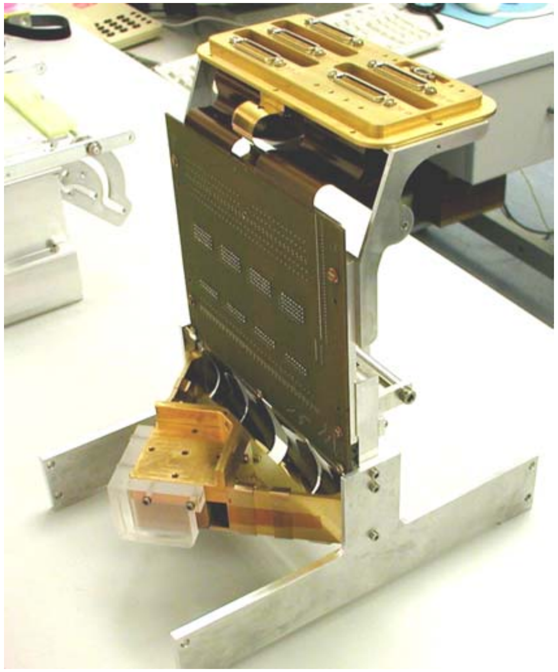
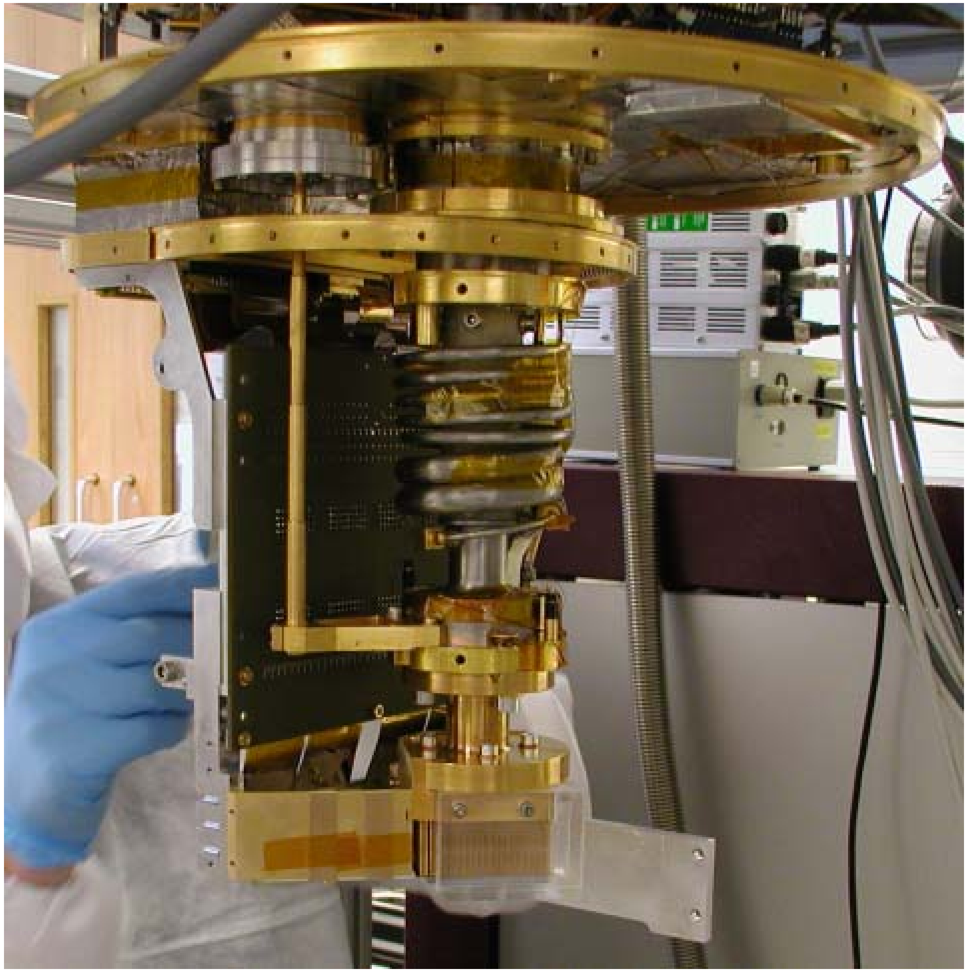
Testbed setup

Test programme



Array unit folded and ready for installation



Installed in Cardiff test facility

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Test programme

Installed in clean-room conditions

Several dummy runs; produce detailed integration document

Also need unintegration (disintegration?) document

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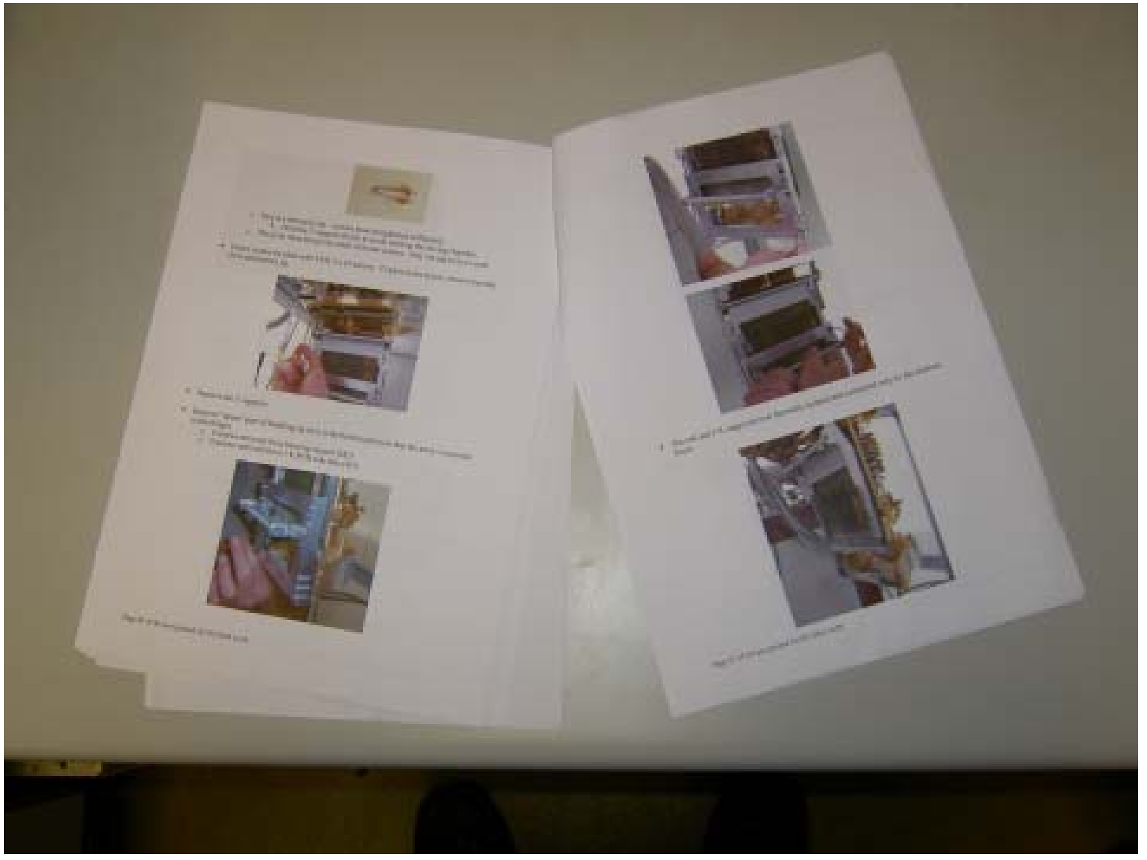
Integration document

Can’t afford to make any mistakes getting the array into the testbed!



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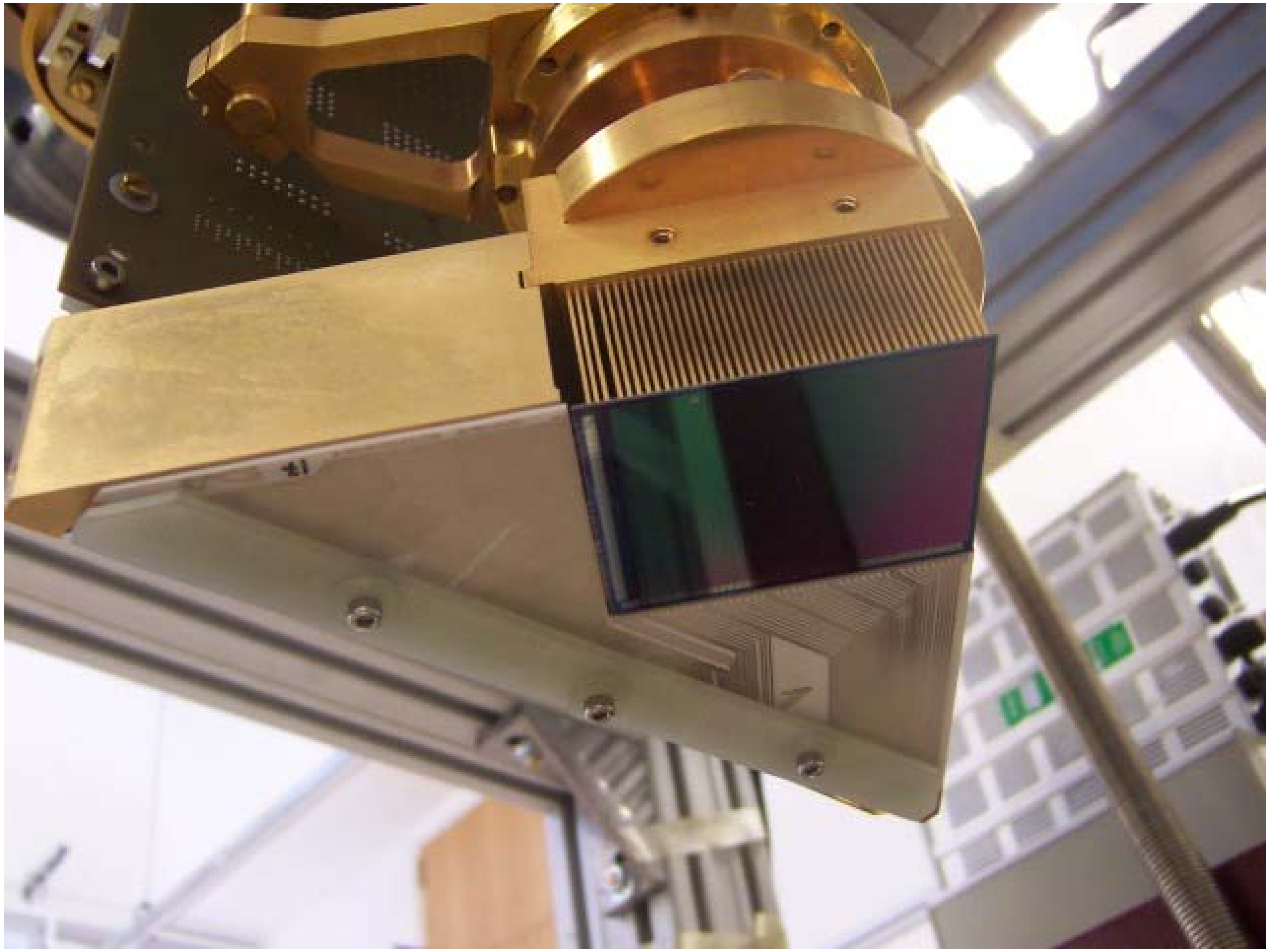
Ready to go…



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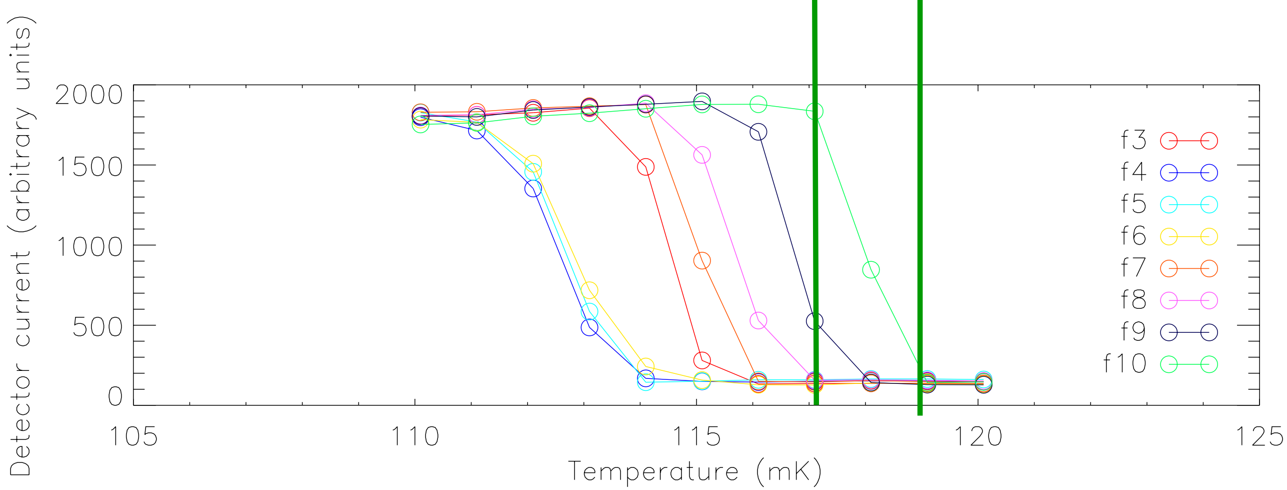
Superconducting transition

Transition width ~ 2 mK

Scatter in T_c < 10 mK



Detector resistance (in arbitrary units) as a function of heat sink temperature

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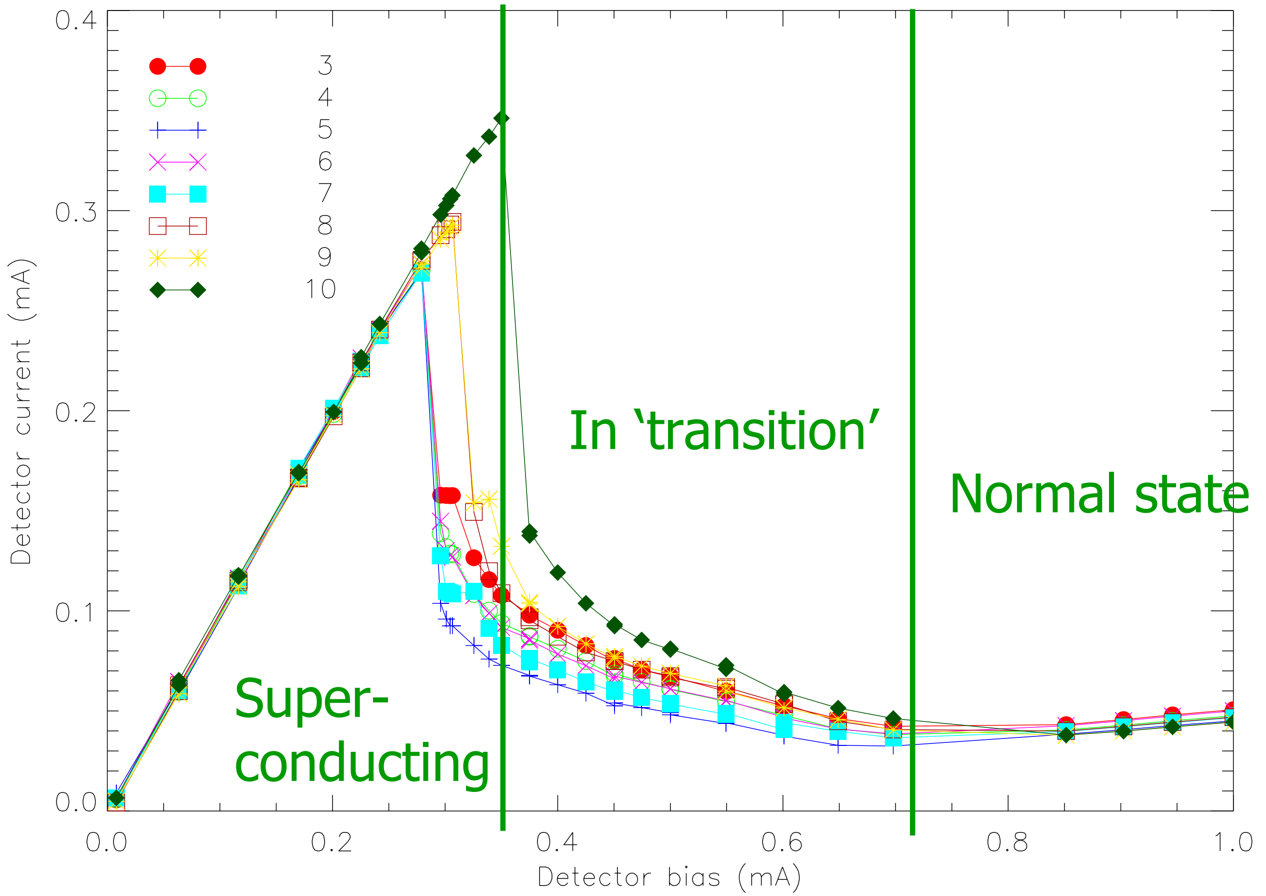
Load curves



Detector current as a function of bias ("load curve")

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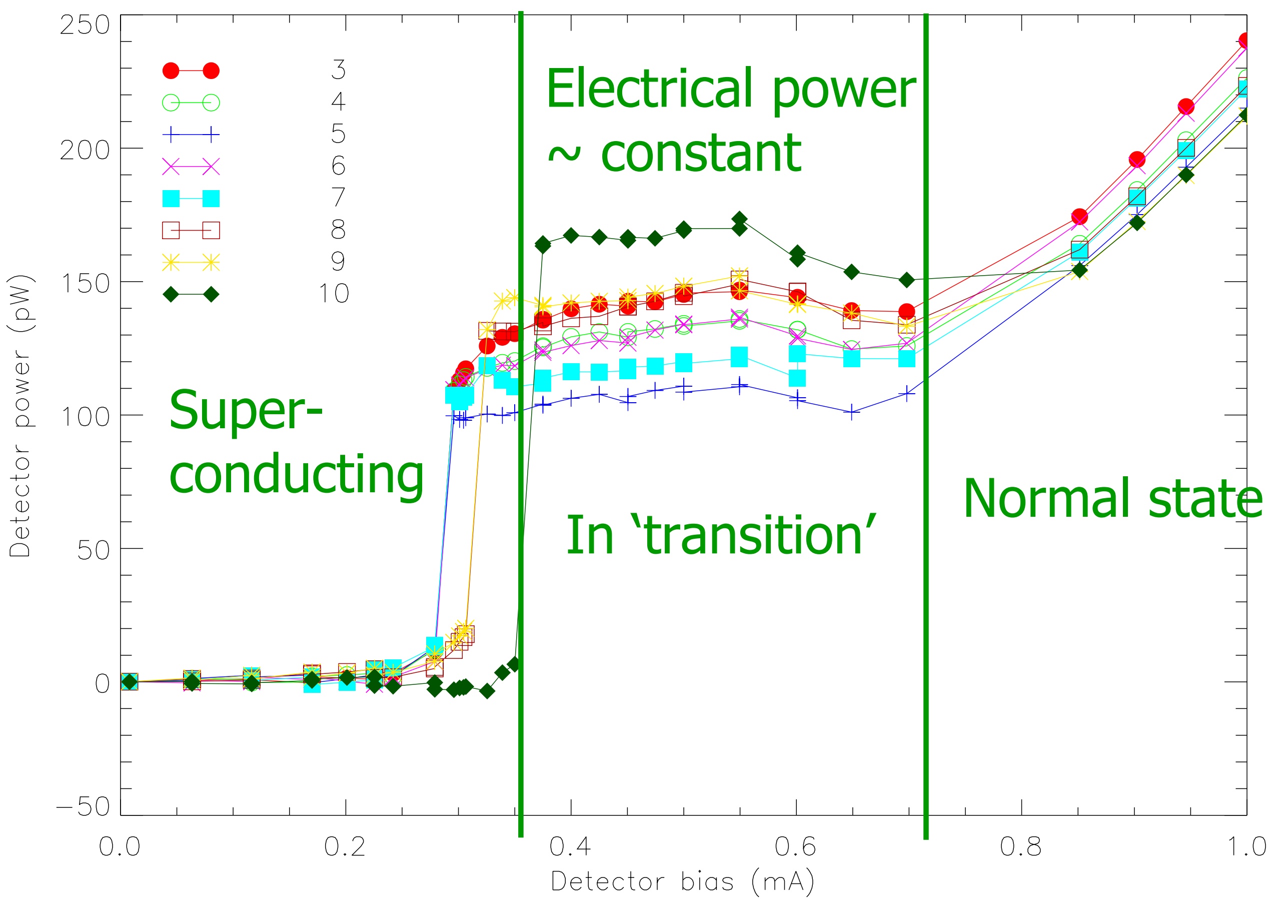
Detector power



Detector power as a function of bias

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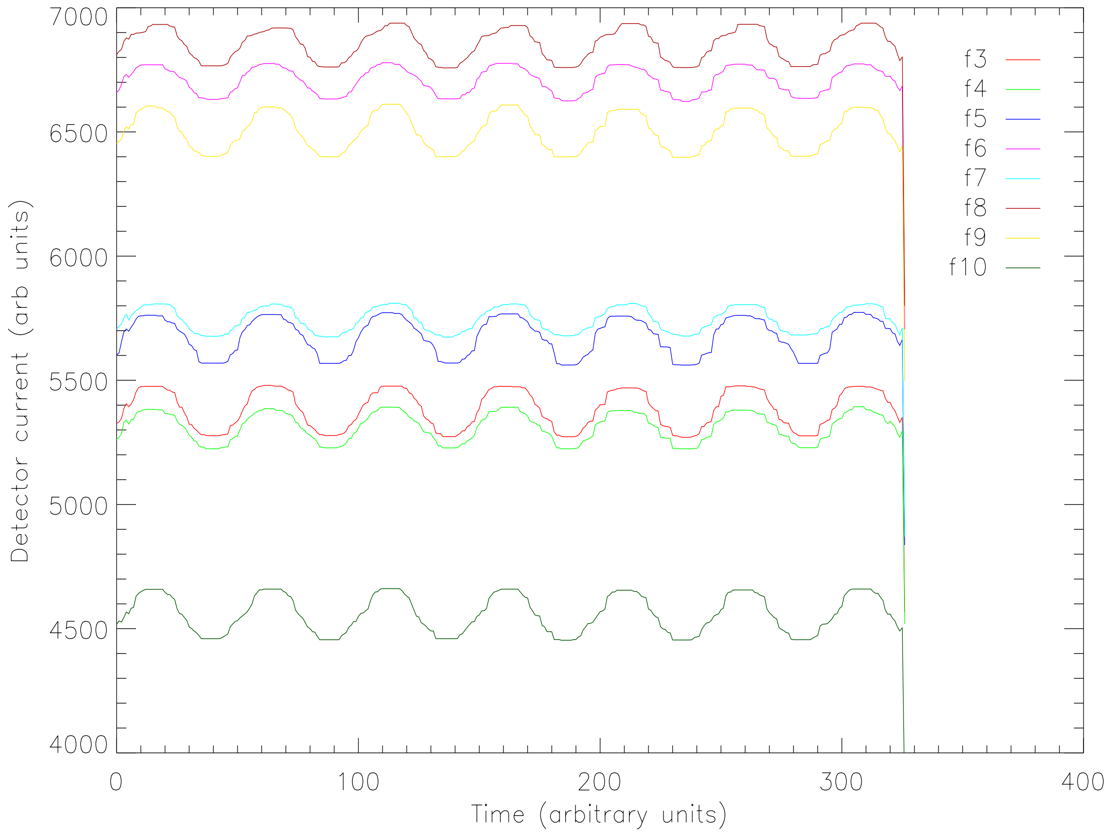
Detector power



Eight pixels responding to modulated sub-mm illumination

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Results

Tested 850 μm and 450 μm prototype arrays
Tests show that arrays function well
Pixel uniformity good (and within spec)
In-plane multiplexer works in a stable fashion
Noise specifications met (NEP ~ 2.5 x 10^{-17}; within spec)
SCUBA – NEP ~ 1 x 10^{-16} at 15 Hz (c.f. ~ kHz for SCUBA2)

Have enabled the start of production of "science grade" arrays that will be used at the telescope

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Spin-offs

Applications outside astronomy:

Semiconductor industry: measuring surface contamination to enable increased miniaturisation

Biomedical: mass spectrometers for drug development, pharmaceutical quality control, forensic studies and possibly even faster DNA sequencing

Techniques for constructing large instruments operating at ultra-low temperatures

Conclusions

Cryogenics is very important for sub-mm astronomy

As instruments become larger, getting the cryogenic design right is increasingly difficult but also increasingly important

The field has gained from decades of low temperature physics work, but is now driving advances in cryogenics (e.g. self-contained dilution fridges, cryogen free dilution fridges, ADRs, ultra-precise thermometry)

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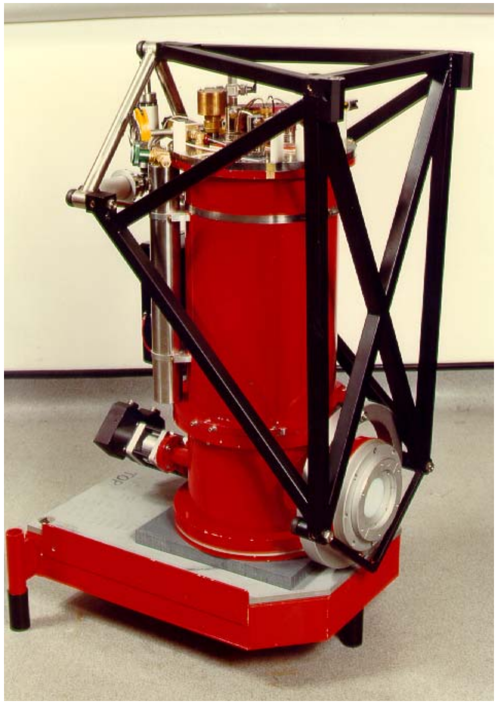
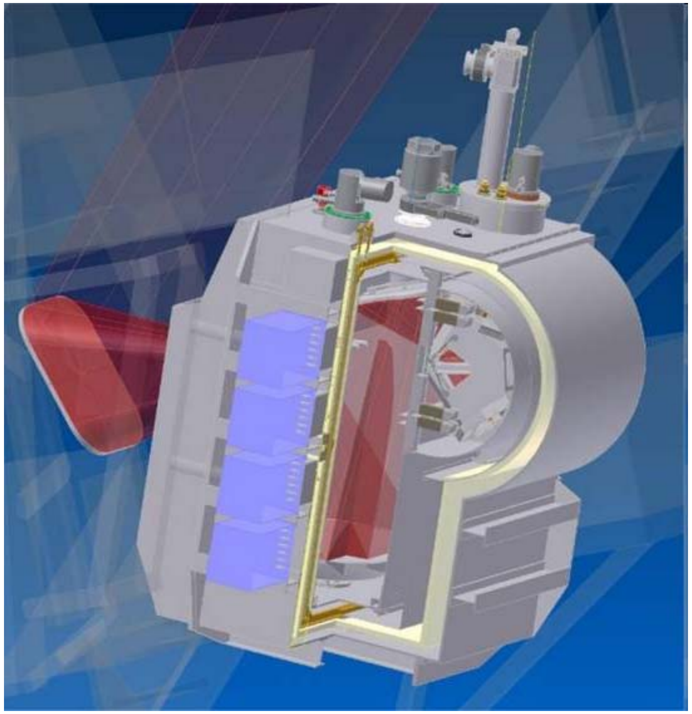
Conclusions

Sub-mm astronomy has come a long way in 10 years!

1996: UKT14 - 1 pixel





2006: SCUBA-2 - 10 000 pixels

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Any questions?