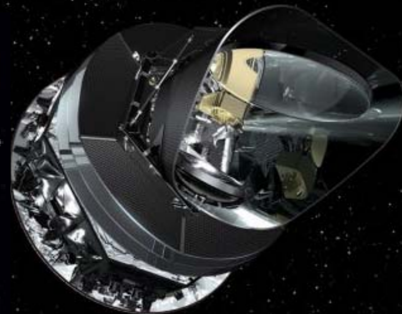
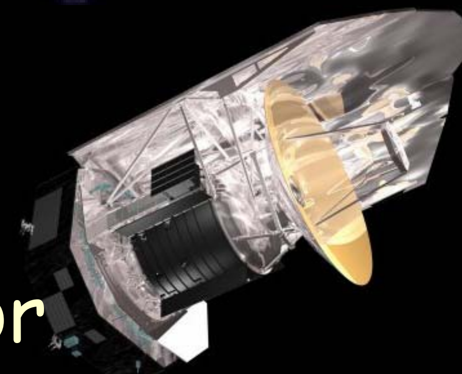




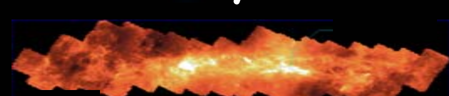
SCUBA-2 and Planck Surveyor

How to get 36 000 SQUIDS into a cryostat and put a dilution fridge into space

Seminar given at the Physics Department of the University of Milan – Bicocca, 13th September 2007

Adam Woodcraft
http://woodcraft.lowtemp.org
SUPA, University of Edinburgh

Science & Technology Facilities Council
UK Astronomy Technology Centre



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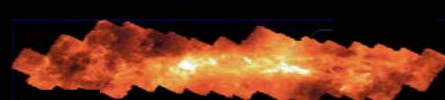
Sub-mm astronomy



SCUBA2

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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 when they use same detection techniques

Started in the early 70's

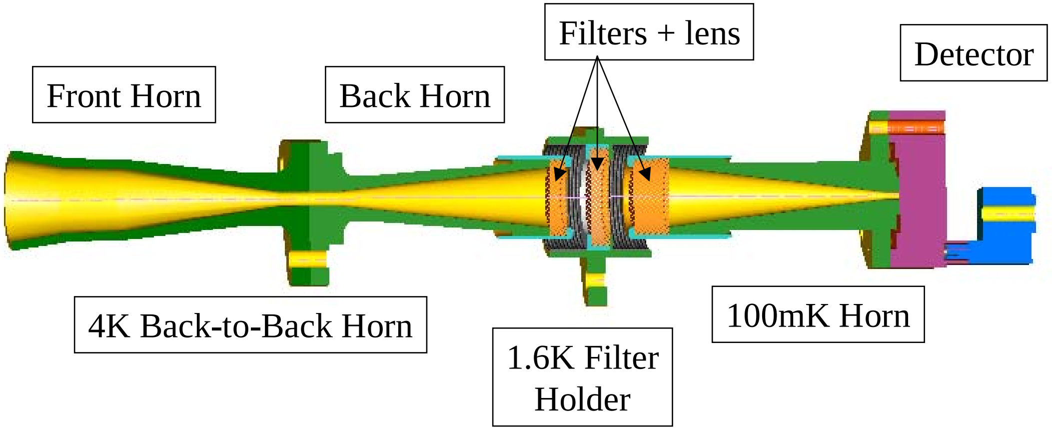
Looking at sun, moon and planets
(First proper observations? Queen Mary and Westfield college, United Kingdom, using Pic du Midi; French Pyrenees)

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?

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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…)

Also lets us see far away (red shifted) warmer objects: peak in 40 K blackbody at Z=3 is at 300 μm – e.g. formation of distant galaxies
- exploration of the early universe

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

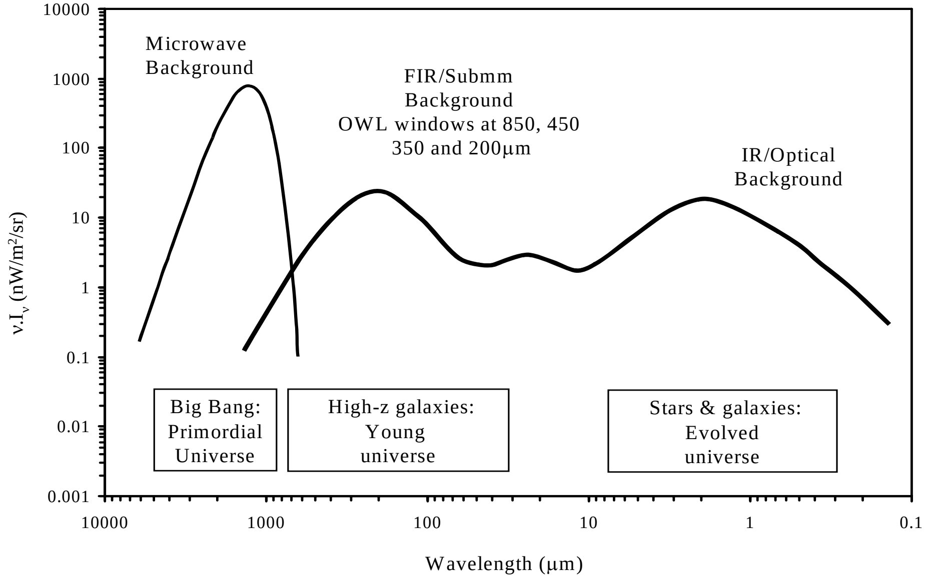
Why do sub-mm astronomy?

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!



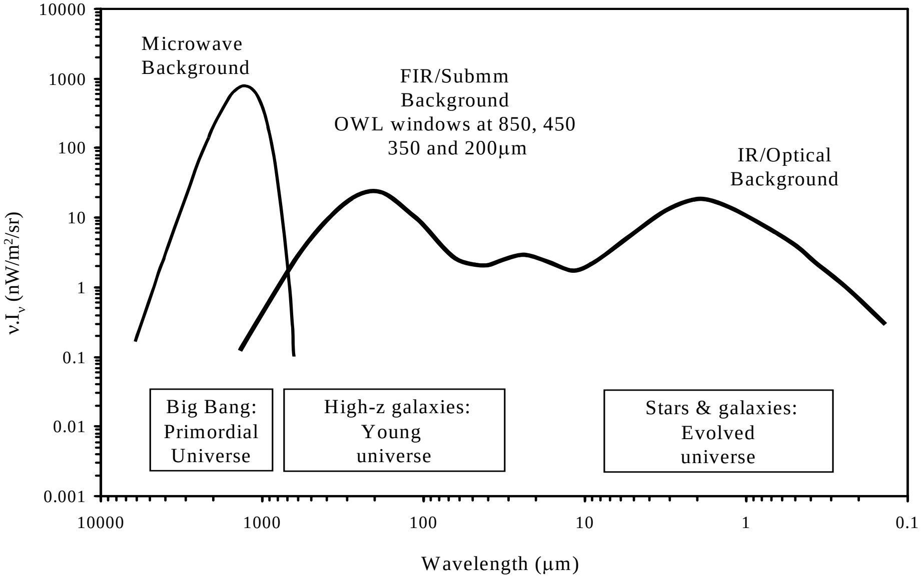
Why do sub-mm astronomy?

Also: cosmic microwave background (CMB) peaks at ~2 mm

- anisotropies in CMB provide information on structure of universe

- scope for considerable improvement on existing measurements

- need measurements in the sub-mm to categorise foregrounds that CMB photons pass through



Why do sub-mm astronomy?

Also: cosmic microwave background (CMB) peaks at ~2 mm

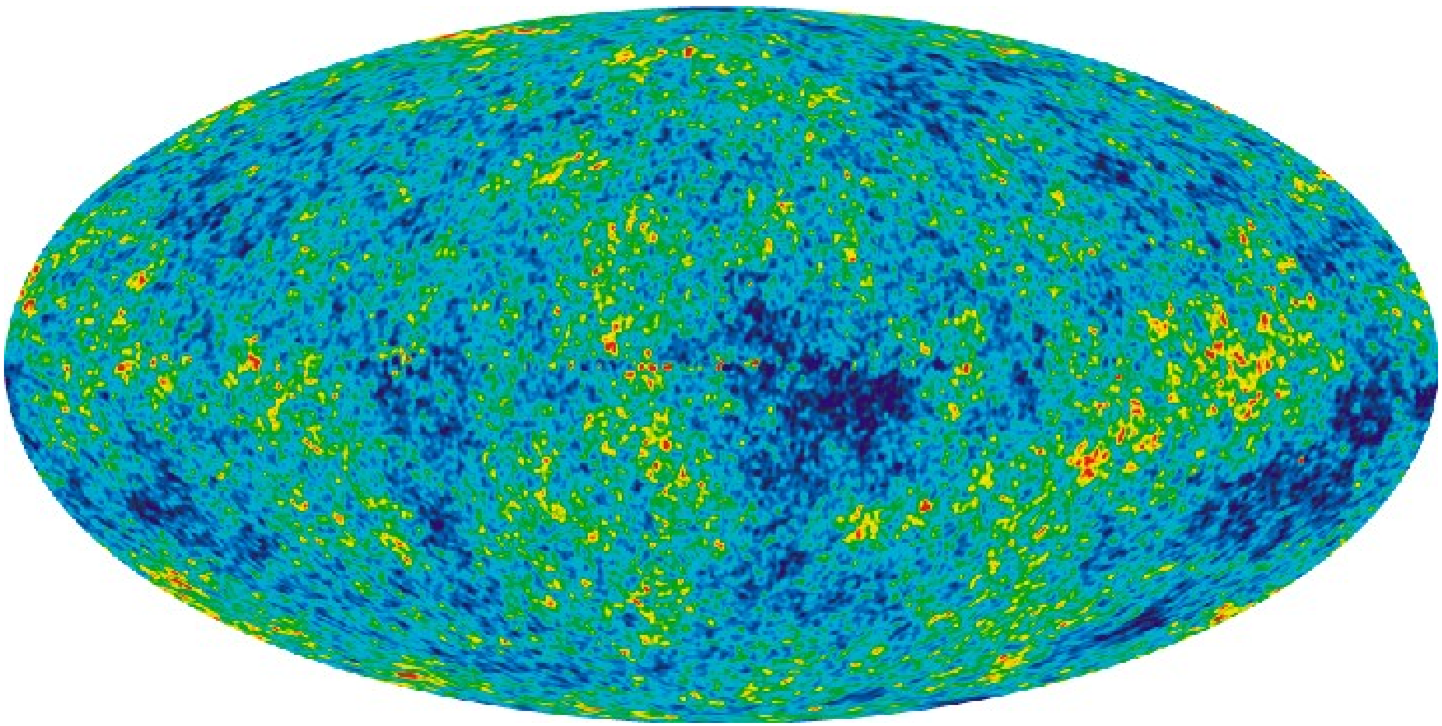


Image: NASA/WMAP Science Team

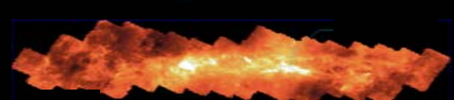
Why NOT to do sub-mm astronomy

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)
- Need mountain-top observatories, balloons, or space missions (coming soon…)

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

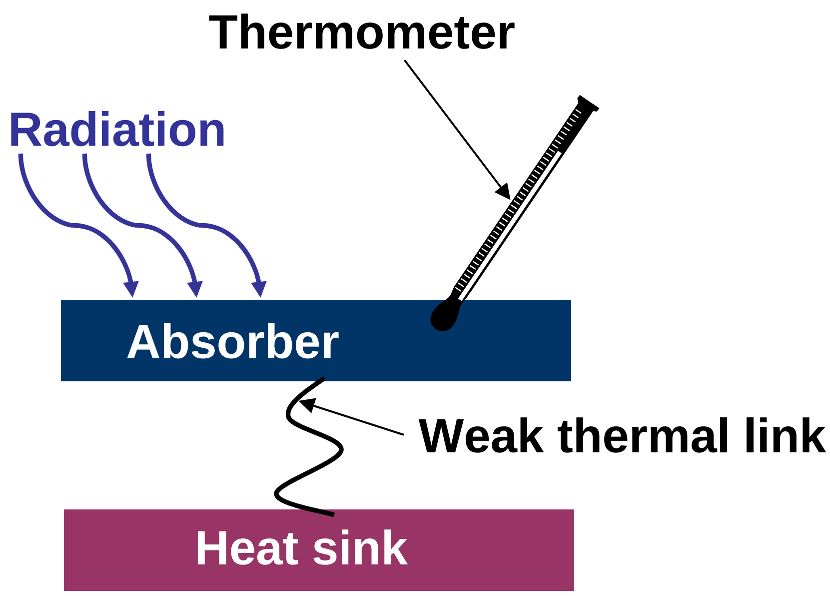
Heterodyne detectors (radio receivers, as used in radio astronomy). Detect narrow band of wavelengths

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

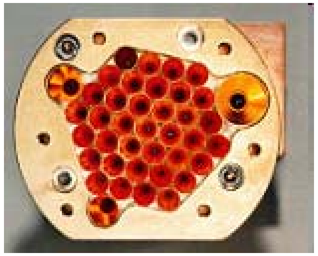
Practical to calibrate

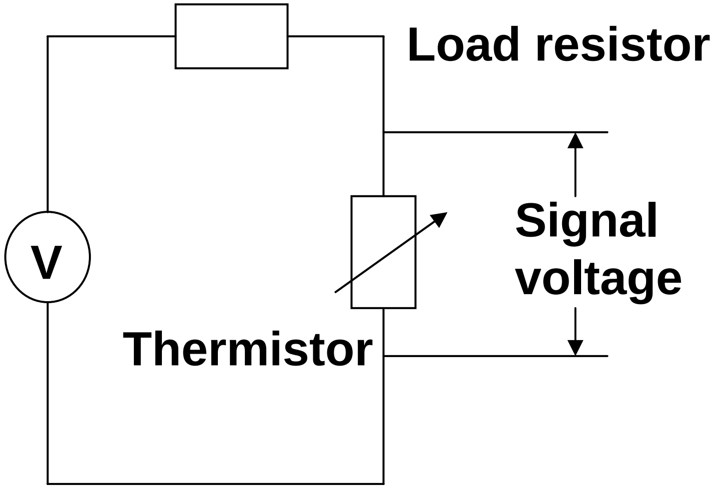
Bolometers

"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





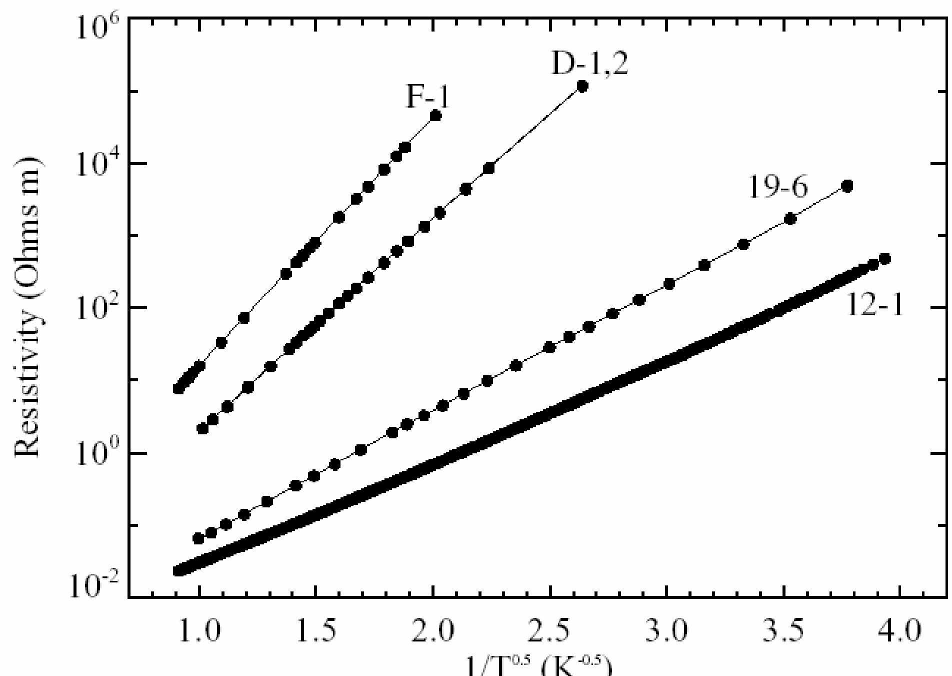
Readout circuit

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

Also see "An introduction to semiconductor bolometer modelling" http://reference.lowtemp.org/woodcraft/bologuide.pdf

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

A little history

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JCMT-UKT14
350μm-2mm

.3K 1

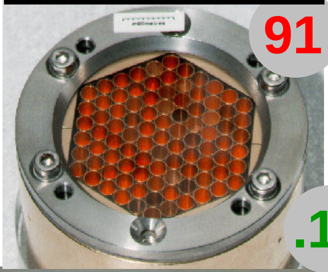
1986-1996

CSO-SHARC
350 μm array

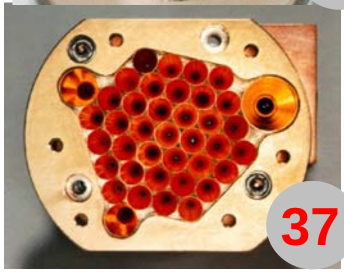
.3K 20

1996-

JCMT-SCUBA
350/450 &
750/850μm



91 .1K



37

1997-

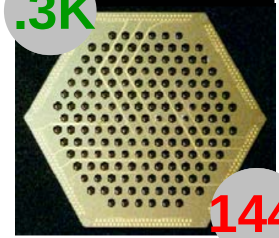
Also 19 pixel 2 mm array at 0.1 K

IRAM- MPIfR
1.3mm array

.3K 37

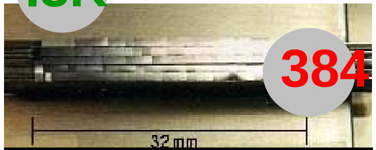
1998-

LMT-BOLOCAM
1.1mm



.3K 144

2001-



.3K 384

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

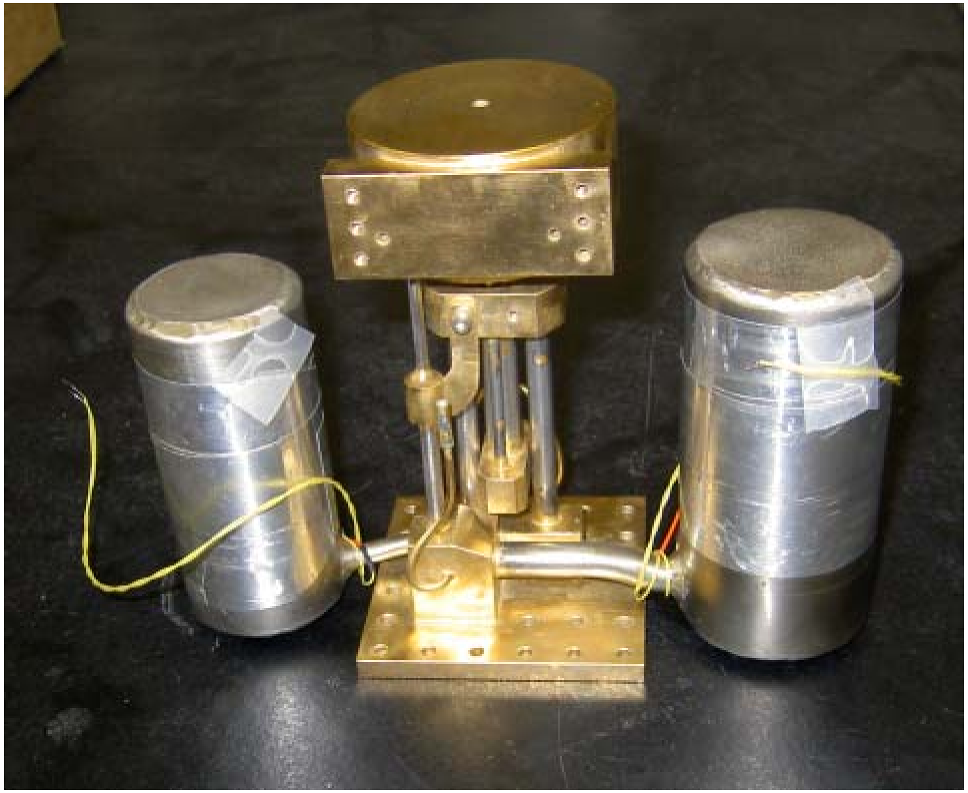
For bolometers, need to reduce heat capacity to increase sensitivity – the lower the heat capacity, the larger the temperature rise for a given (modulated) power input

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

Refrigeration

Most sub-mm bolometer arrays run at 300 mK
- Lowest temperature that can be reached “easily”

Cooling is often provided by self-contained sorption fridges, using separate ^3He and ^4He stages.



Refrigeration

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

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

Refrigeration

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

Possible alternative: self contained dilution fridge to provide cooling at the detectors as is possible with a 300 mK self contained sorption fridge

Self-contained sorption DR fridge has been developed in Cardiff
- Separate $^3He/^4He$ fridge cools cryopump to 400 mK
- ^3He gas liquifies in cryopump, then returns to mixing chamber under gravity

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Some examples - sub-mm astronomy in space

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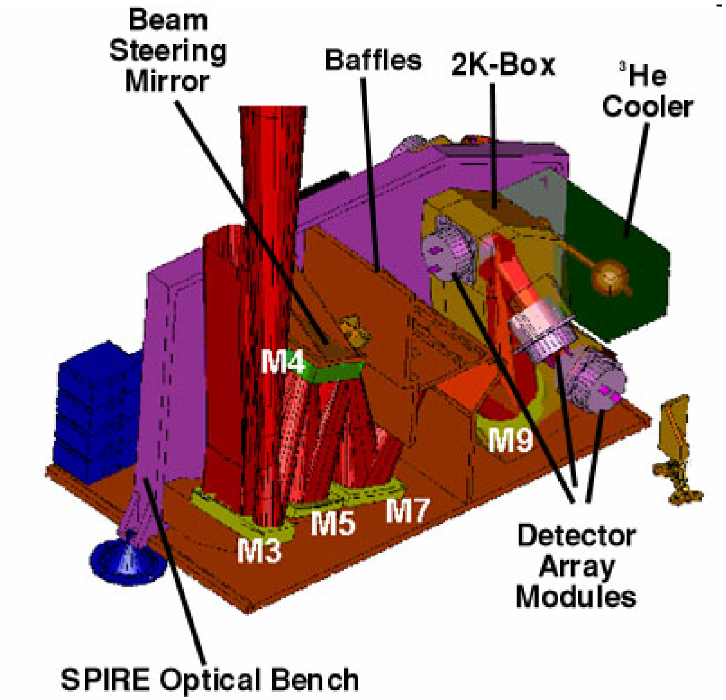
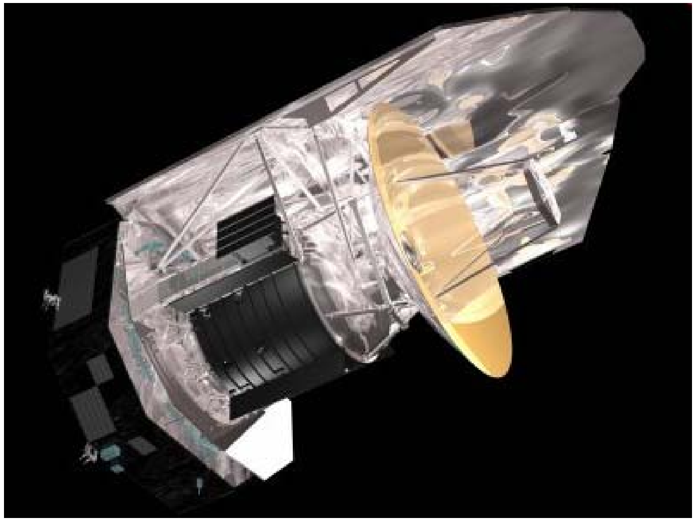
Herschel/SPIRE

Sub-mm observatory

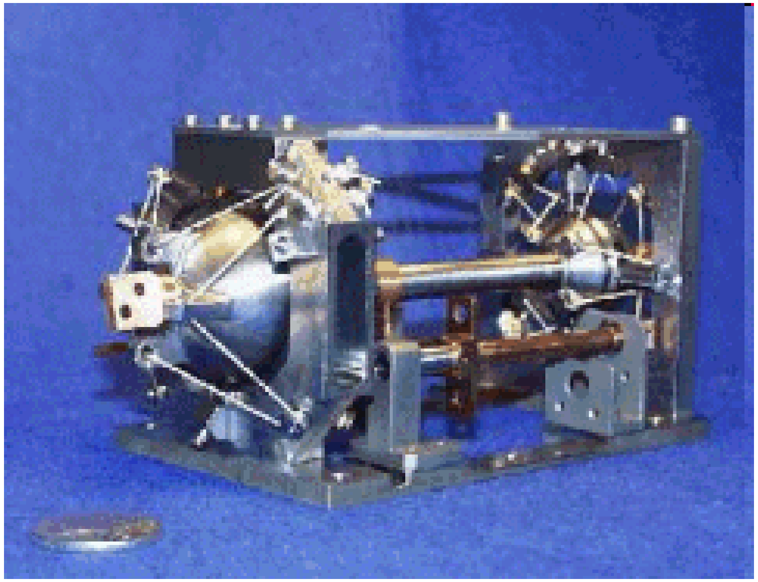




Pixels in each array fabricated on single wafer
Separate read-outs
State of the art for NTD Ge detectors.

SPIRE refrigeration

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



Thermal design

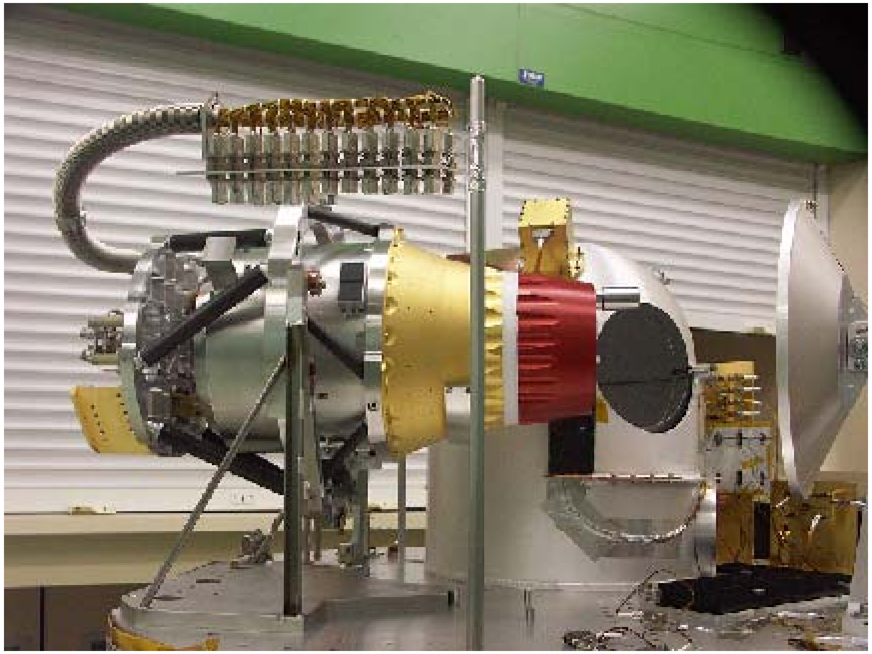
Complex system of thermal straps at 300 mK and ~2 K
- Required considerable R&D on copper conductivity and copper joint conductance

Aluminium radiation shields require good thermal contact to copper straps
- Difficult because of oxide layer on aluminium
- Solution: large area contact using Stycast 2850 FT epoxy
- Trade large microscopic contact area for poorly conducting intermediate layer

Thermal isolation via Kevlar threads
- Requires great care in design to survive launch

Planck/HFI

Cosmic microwave background experiment (successor to COBE and WMAP)



Each pixel (bolometer and optical chain) independent

Planck/HFI

SUPA Scottish Universities Physics Alliance

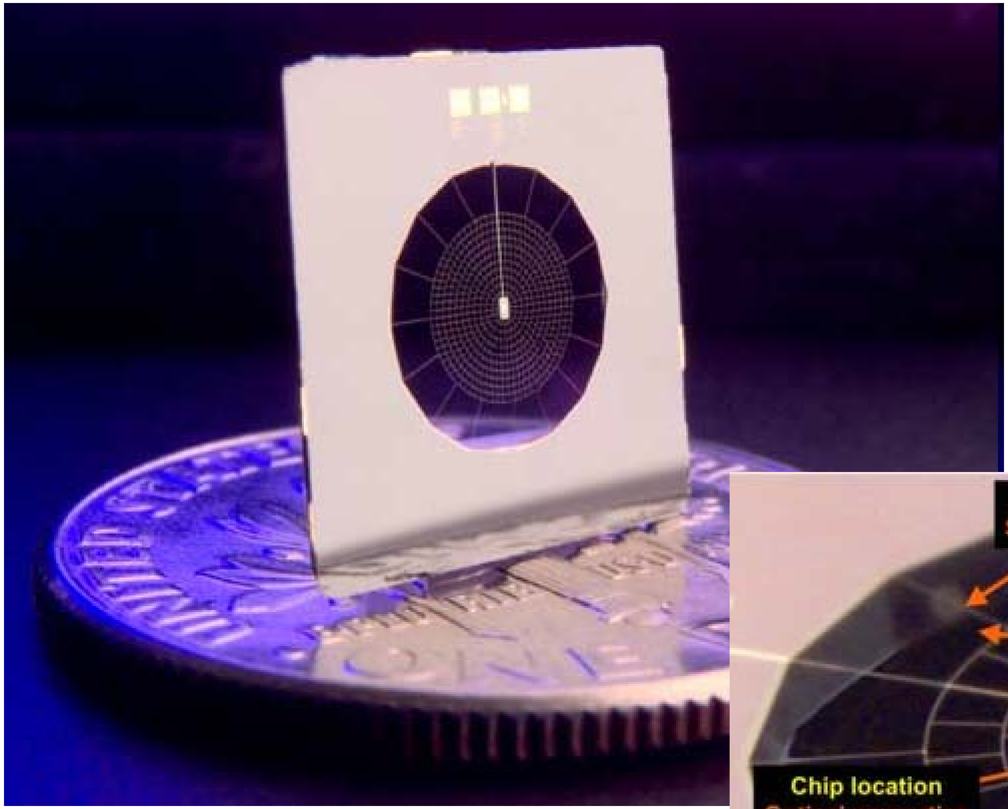
JPL NTD germanium spiderweb bolometer module with Cardiff feedhorn and metal mesh filter

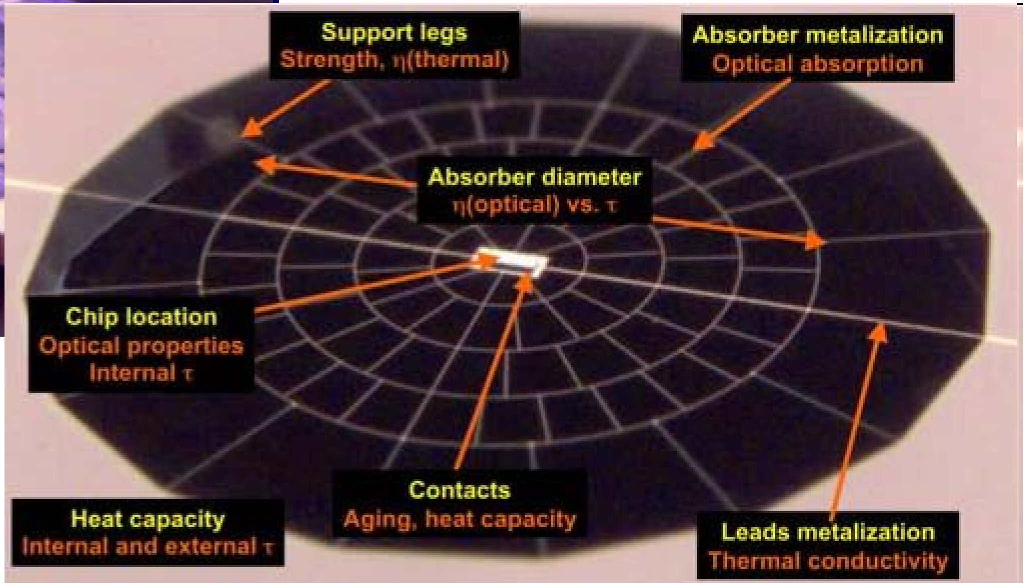
JPL

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Science & Technology Facilities Council UK Astronomy Technology Centre

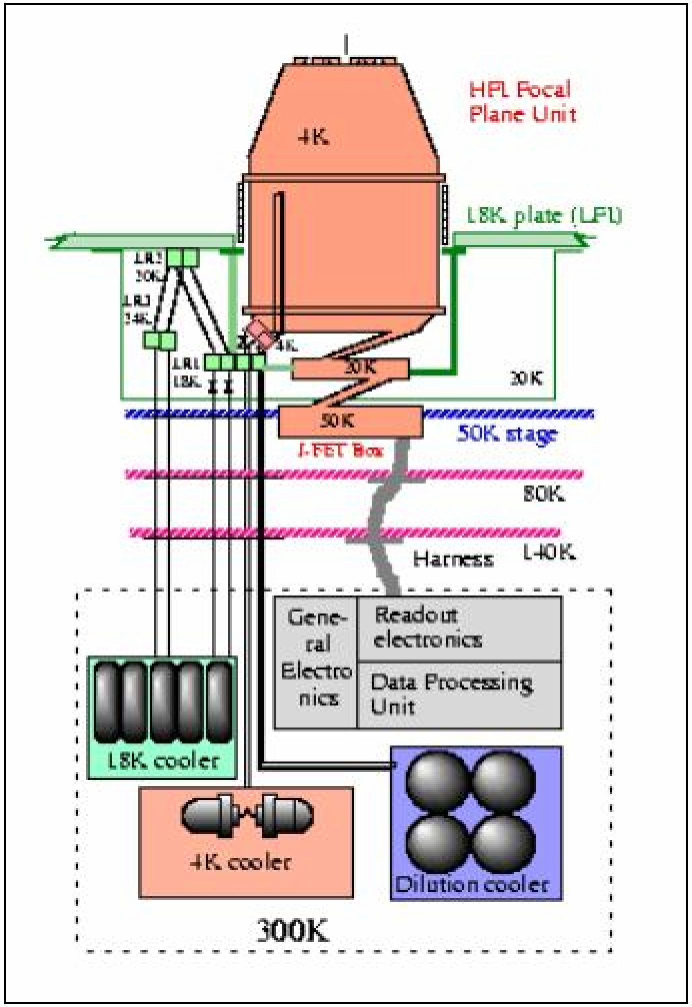
Planck/HFI





Images: JPL

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”

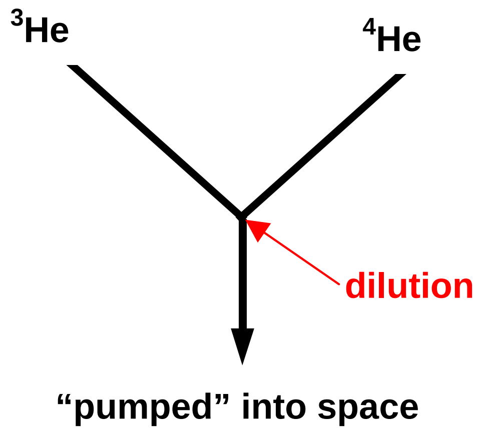
“Memory metal” locks hold structures in place for launch
In flight, instrument cools down and launch locks open

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

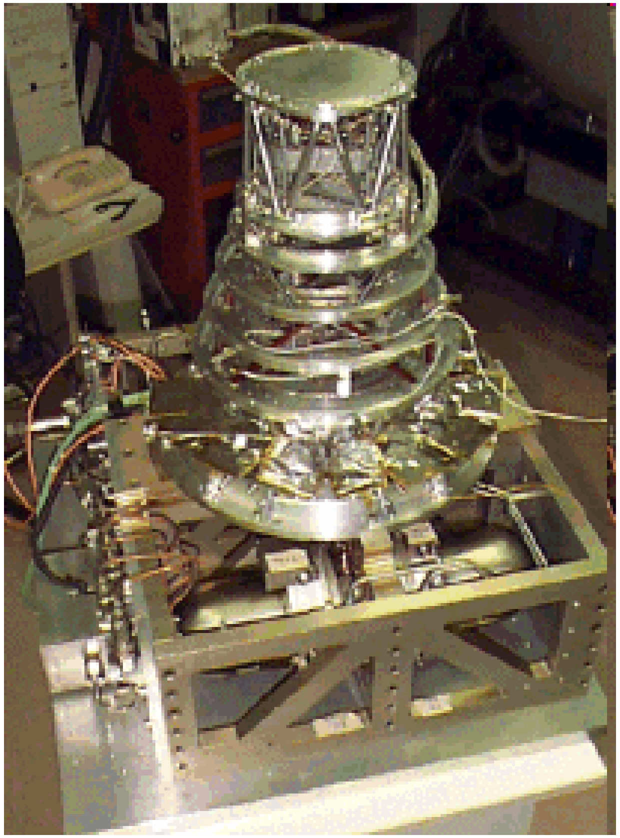
Heat leak down 100 mK stage supports and wiring minimized by using cooling from dilution fridge exhaust gas

Planck/HFI dilution fridge

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



Into space



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 ^{4}He and 4876 STP litres ^{3}He

Superconducting bolometers

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Superconducting bolometers

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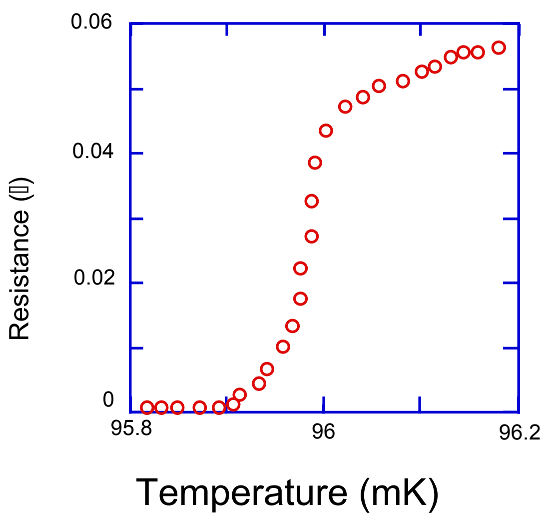
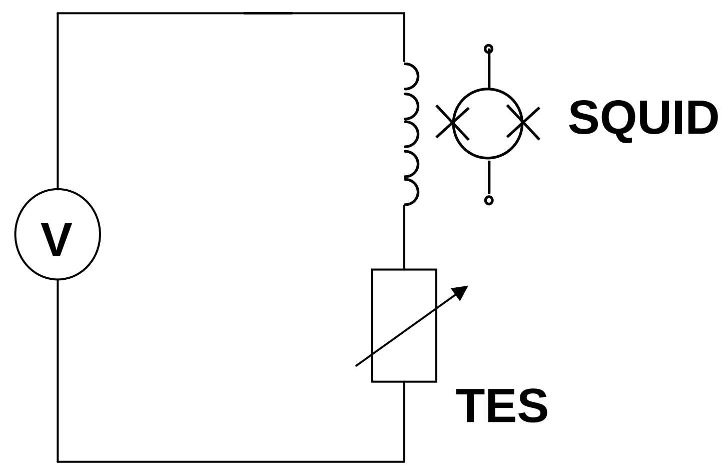
Alternative to “traditional” semiconductor bolometers:
Transition Edge Sensor (TES)
Obtain large sensitivity from the rapid change in resistance across superconducting transition

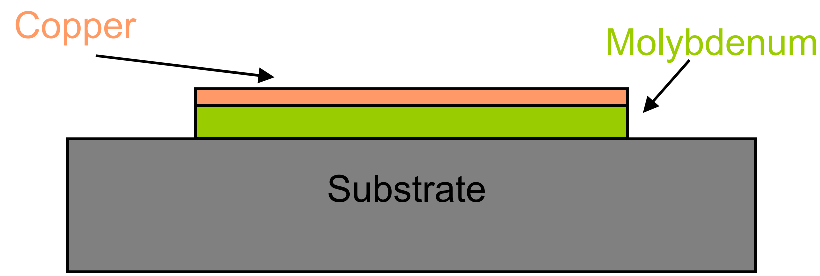




Readout circuit

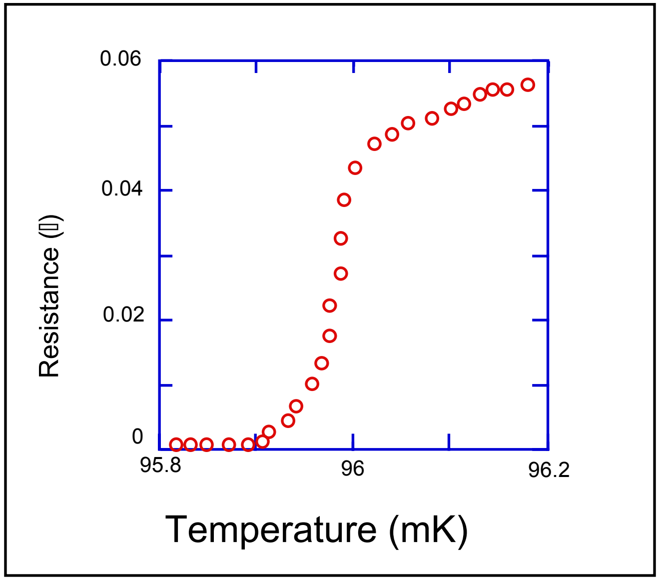
Mo/Cu bilayer

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



NIST Boulder Colorado

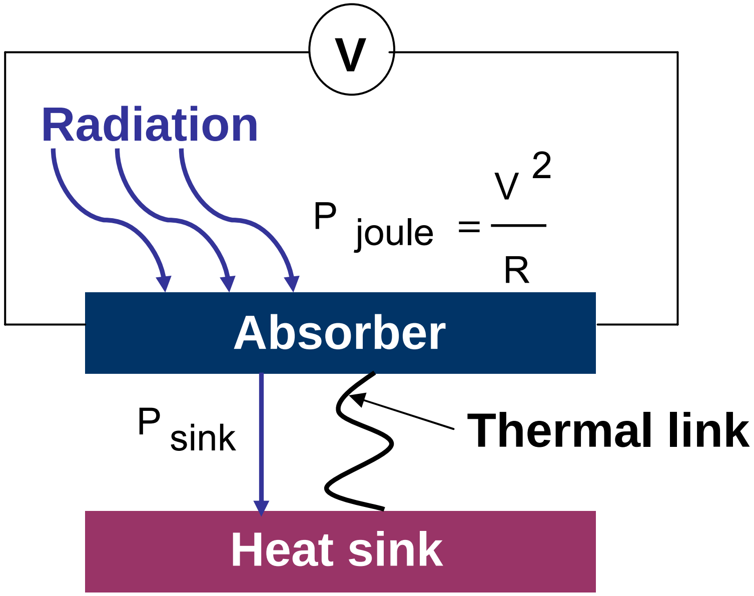
Self-biasing

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

Holds bolometer in the narrow transition

Reduces Johnson noise

Reduces time constant



SCUBA-2

SCUBA2

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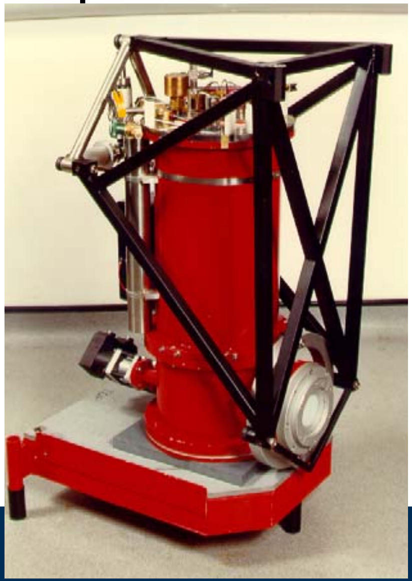
SCUBA-2

Scottish Universities Physics Alliance

- Instruments limited by small number of pixels
  - Gone from 1 pixel to 100s in a decade – need more!
  - Less than 1% of the FIR/submm sky studied in any detail
- BUT: Detector development in relative infancy
- No big military or commercial applications (as yet…)
- Detectors not available commercially

UKT14
1986-1996
1 pixel



SCUBA
1997-2005
128 pixels

SCUBA-2
2007+
10240 pixels

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SCUBA-2 detectors

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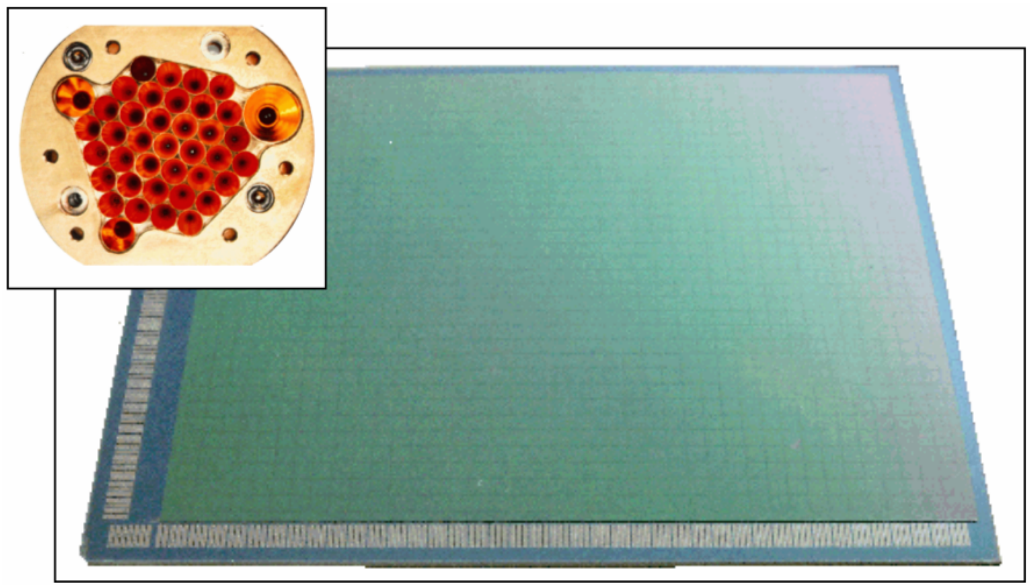
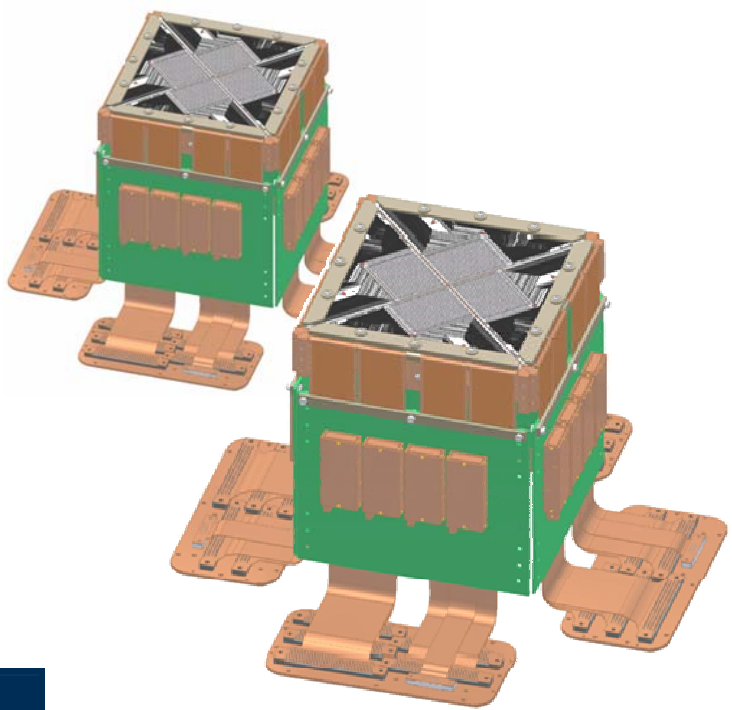
- Simultaneous dual colour imaging (450 and 850 μm)
- Each focal plane made up of four 1280 pixel sub-arrays
- Pixels use Mo/Cu bi-layer superconductors
    - Weak thermal link provided by silicon nitride membrane

SCUBA-2 sub-array (SCUBA array inset)





SCUBA-2 detector units

SMC SCOTTISH MICROELECTRONICS CENTRE

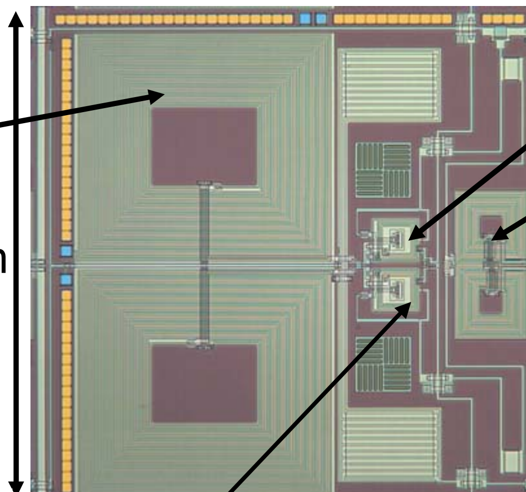
NIST National Institute of Standards and Technology

Science & Technology Facilities Council UK Astronomy Technology Centre

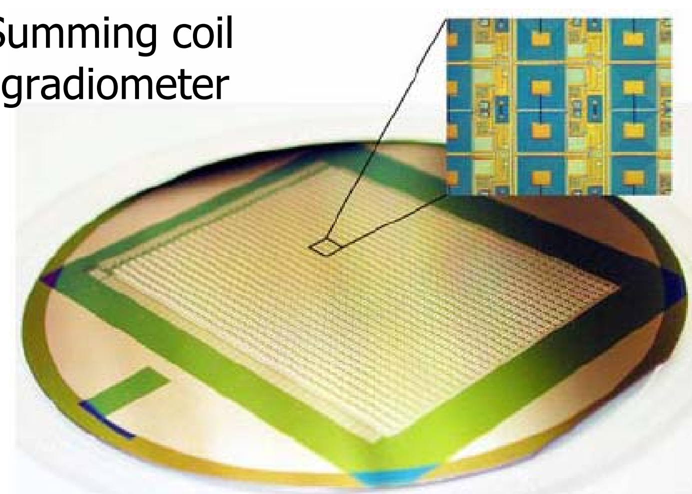
Science & Technology Facilities Council UK Astronomy Technology Centre

Multiplexing

- Previous (much smaller) TES arrays have had separate detector and SQUID multiplexer chips
- Instead, use new compact configuration: in-focal-plane (TDM) multiplexer
  - MUX wafer is bonded to detector wafer
  - Indium bump bonds provide electrical connections



NIST National Institute of Standards and Technology



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

Cryostat design

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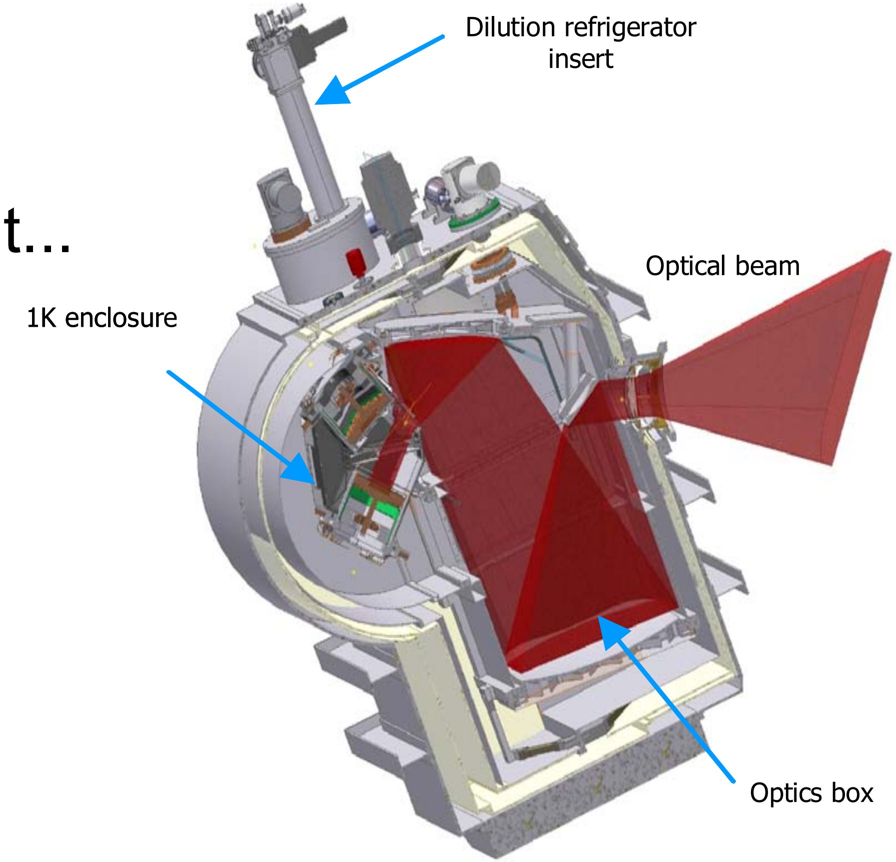
Key challenges:

- Cooling 300 kg of optics to 4K
- Getting all the signal cables out...
- Stray light control
- Magnetic shielding of SQUID circuitry in the multiplexer
- Liquid-cryo free operation



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Cryogenics

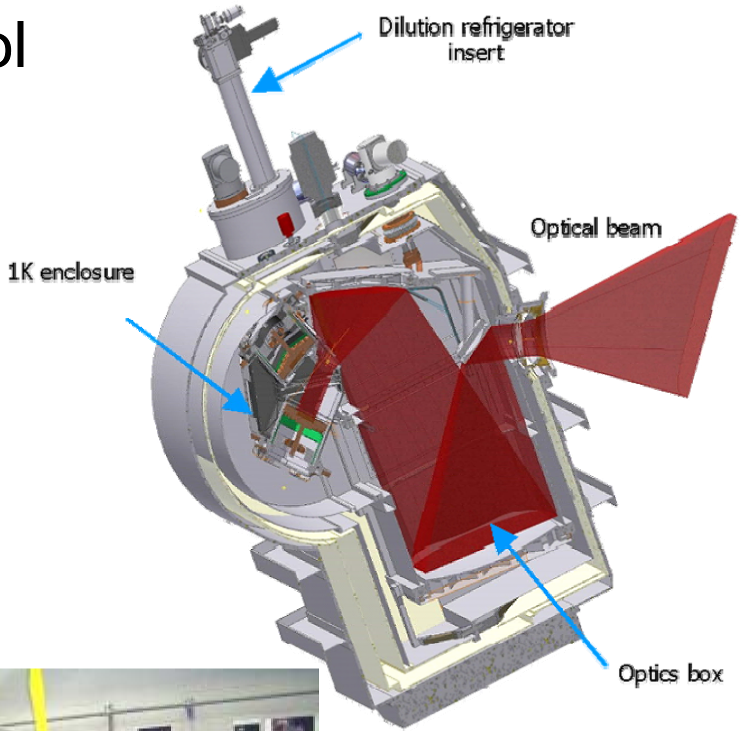
- Arrays must be operated from heat sink at 0.06 K
  - Cooling provided by dilution refrigerator (Leiden Cryogenics)
  - Operates from temperature of 4 K
    - Traditionally provided by bath of liquid helium
    - Instead use mechanical (pulse tube) cooler to reduce running costs
    - First commercial “dry” dilution refrigerator(?)
- Two more pulse tube coolers used for rest of instrument

Leiden Cryogenics BV
Leader in LT Techniques

Dilution refrigerator insert

Size

- Instrument size driven by need to cool large mirrors to below 10 K (to reduce thermal background on arrays)



Installing the mirrors

Installing the optics box

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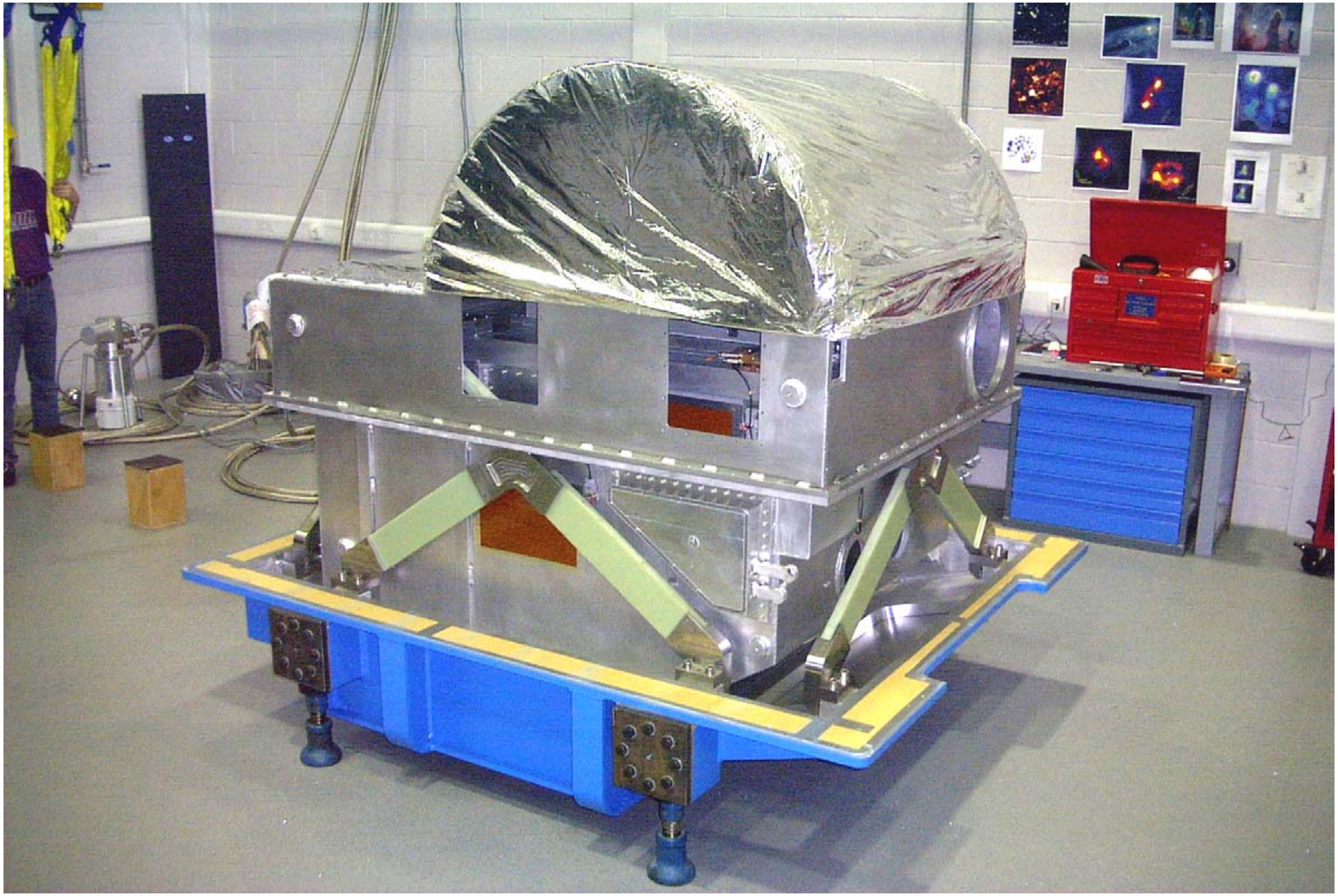
Radiation shields



Vacuum vessel

Onto the telescope…

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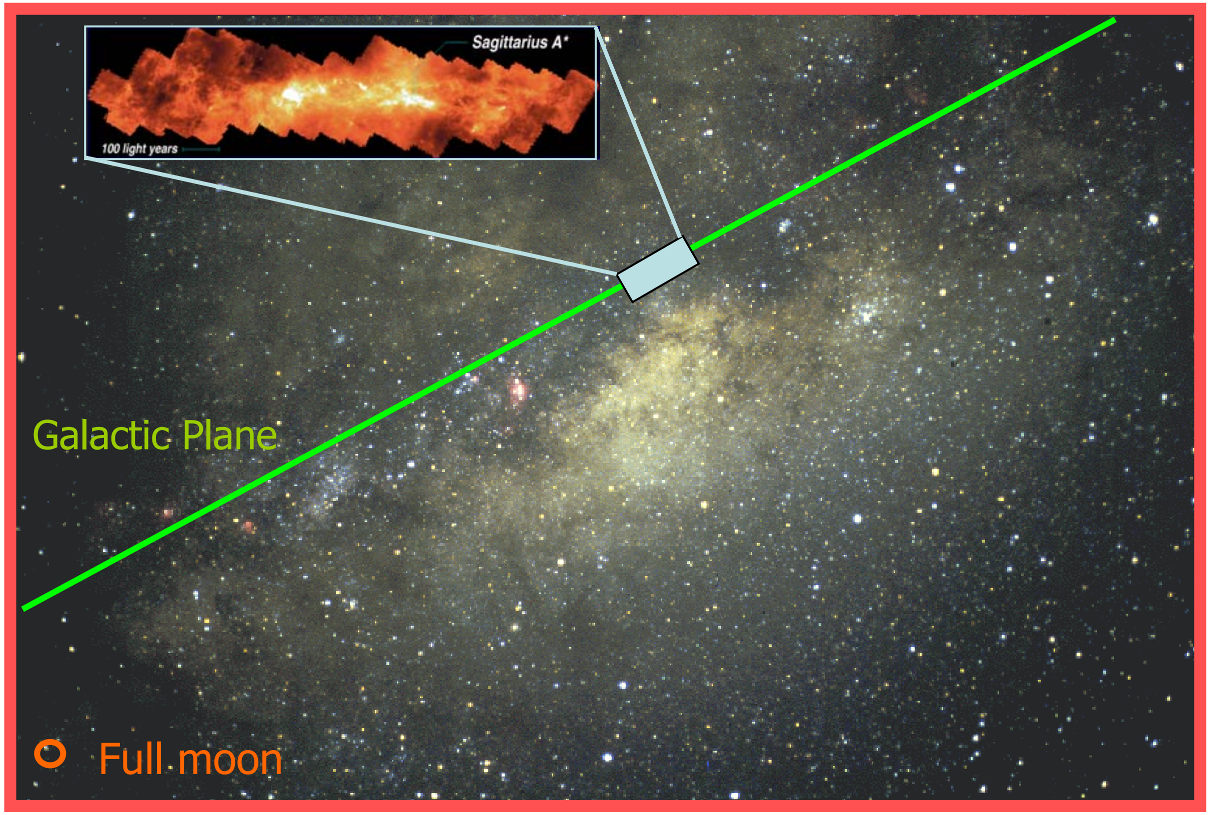
Survey potential



SCUBA Galactic Centre Survey

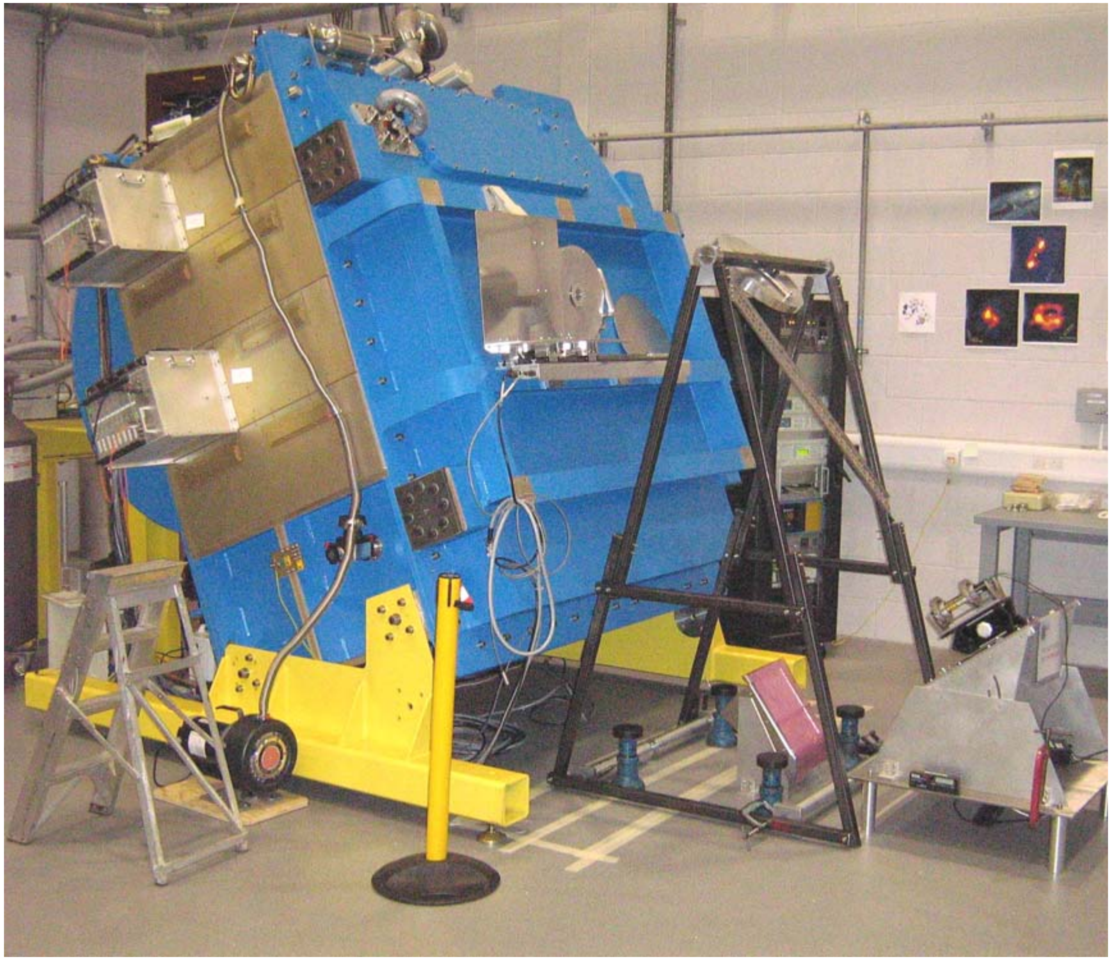
~15 shifts (or 120 hrs) over 2 years

of excellent weather telescope time

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

Current status

- Instrument is now essentially complete – nearing delivery standard
- Instrument verification is now underway; optical tests, operational modes etc.



SCUBA-2 low temperature design (1 K and below)

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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

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

Thermal design

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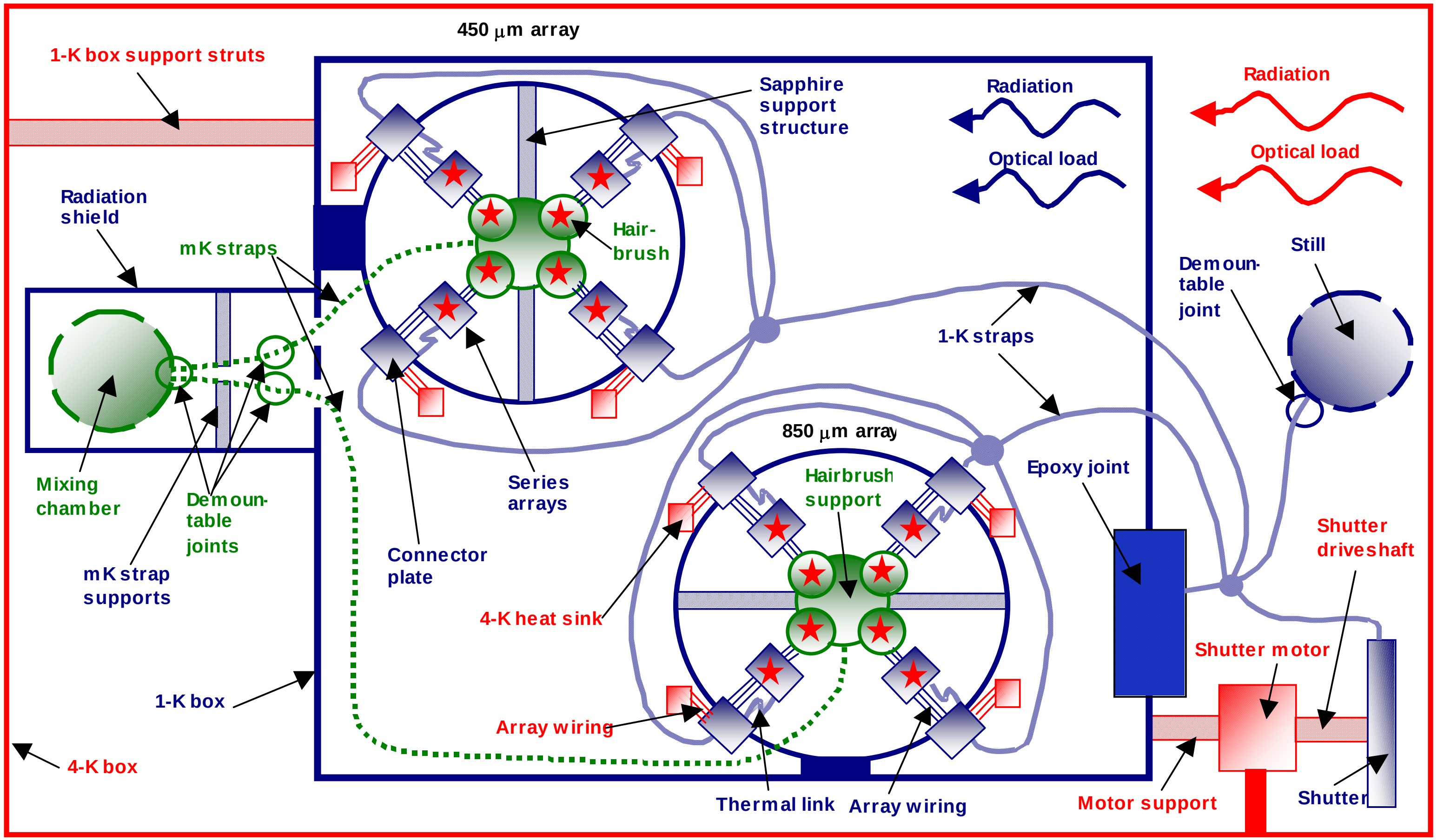
Thermal paths (mK and 1-K) are somewhat complex!



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Contact to aluminium

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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

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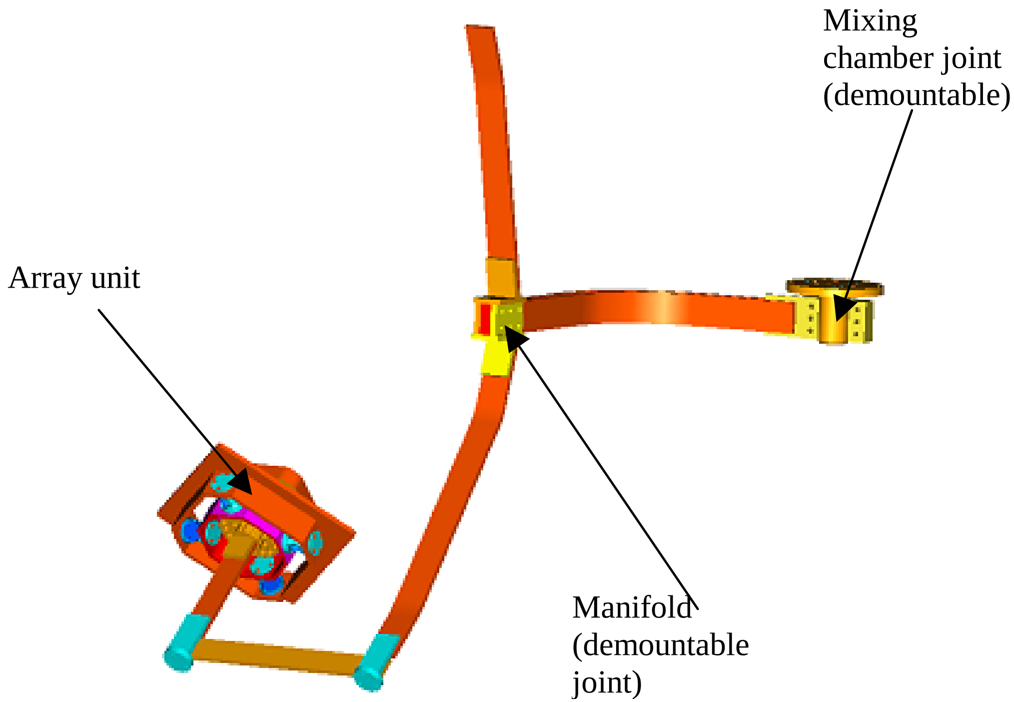
Transfers heat from the arrays to the dilution fridge (~ 1 m)



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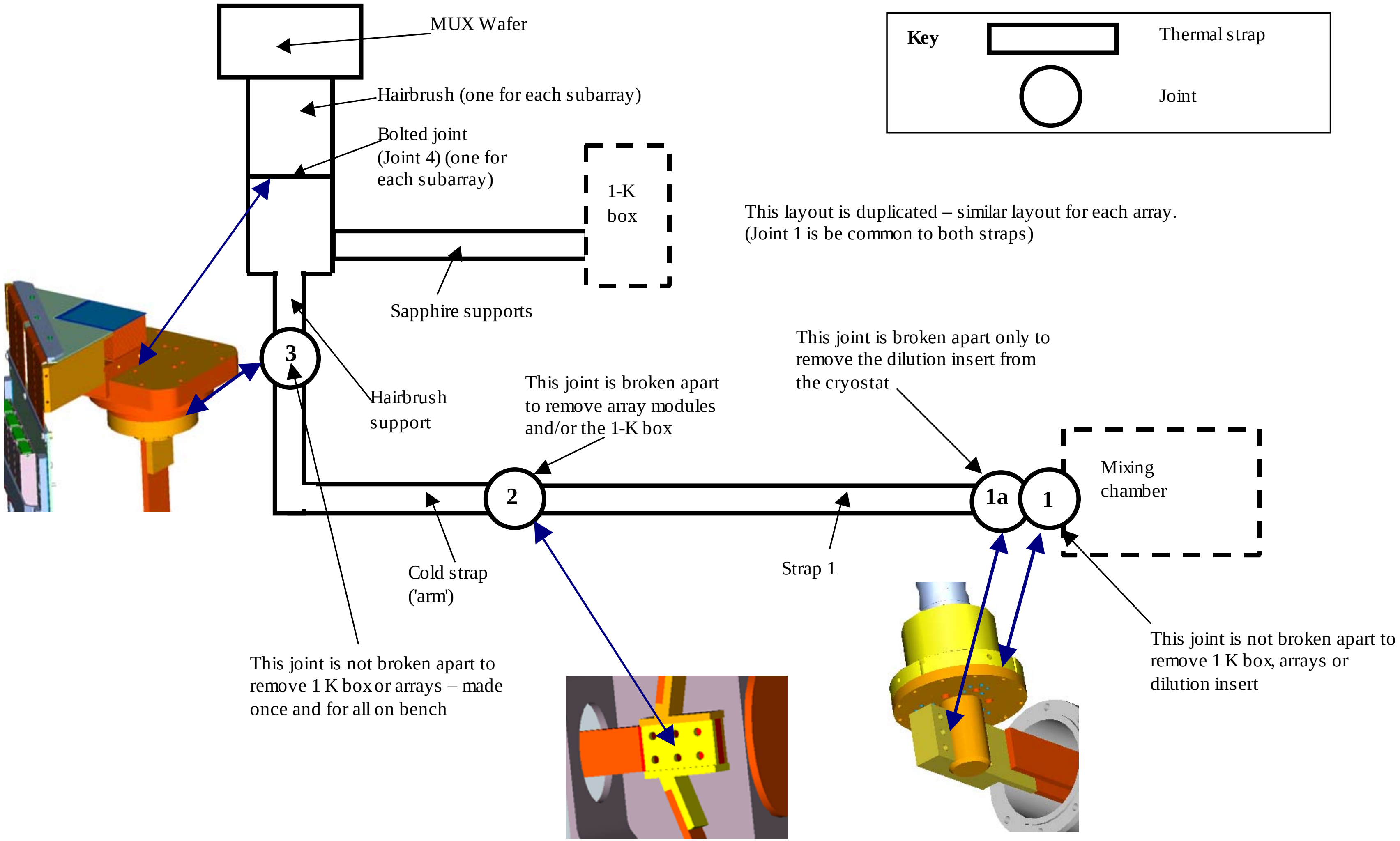
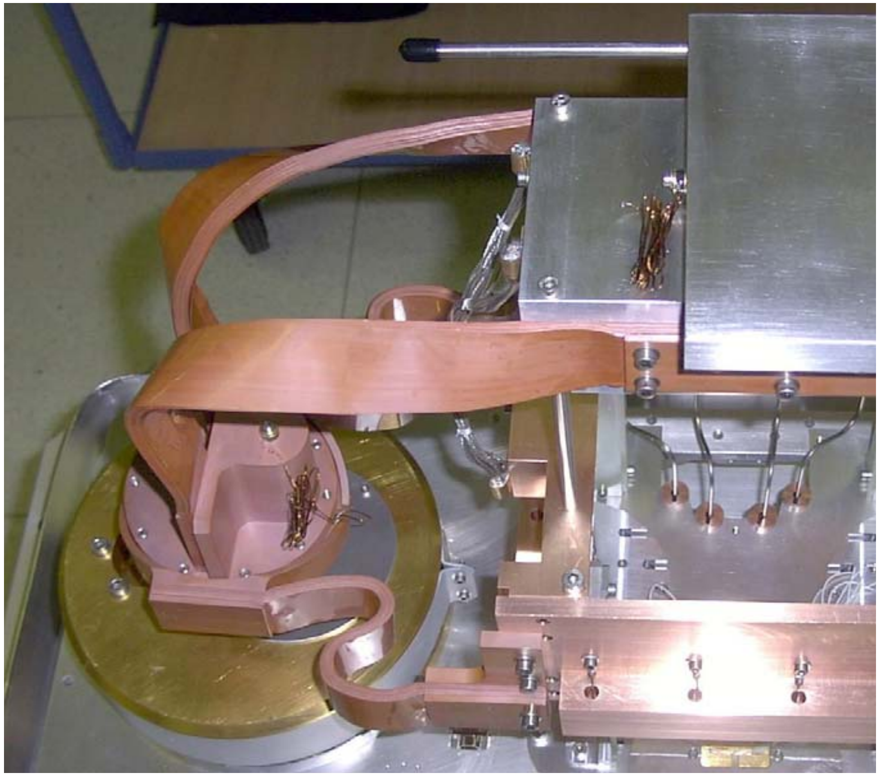
Strap system



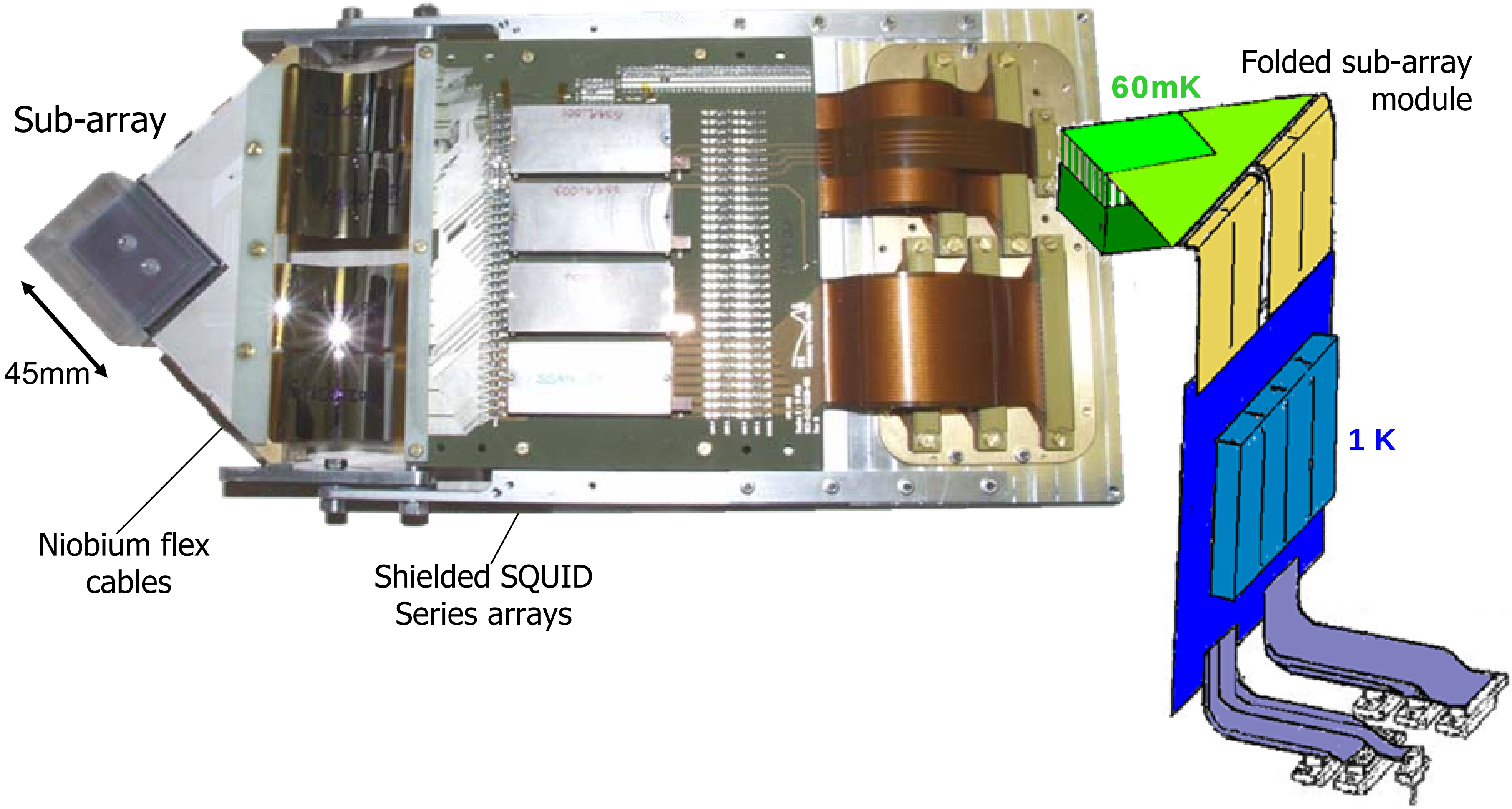
Strap system

Straps made from layers of copper foils to give compliance

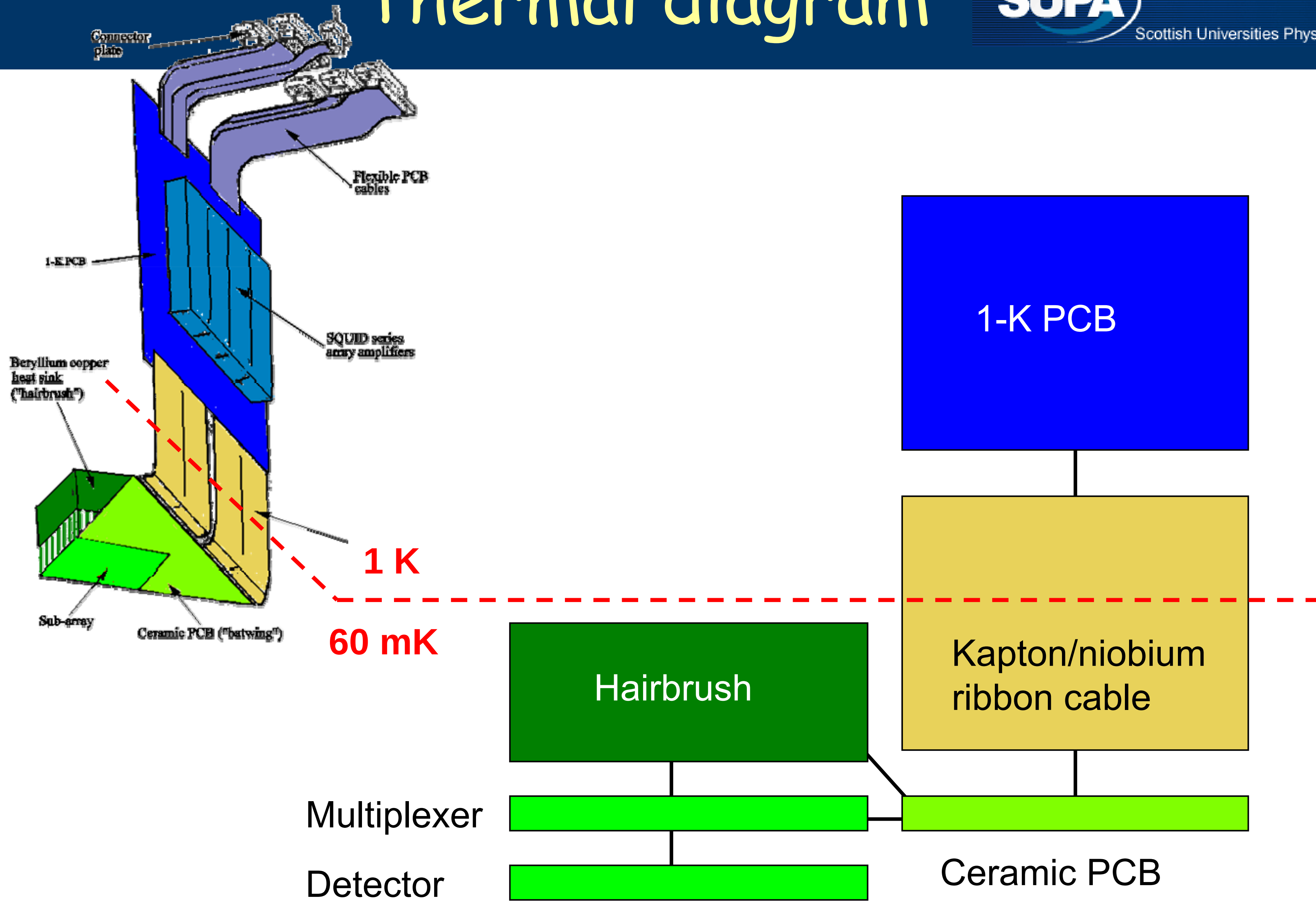
Image of system using similar straps SCUBA-2 interfaces are gold plated!



Sub-array module



Thermal diagram



“Hairbrush”

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

Made from high conductivity beryllium copper alloy

Glueing the hairbrush to the array

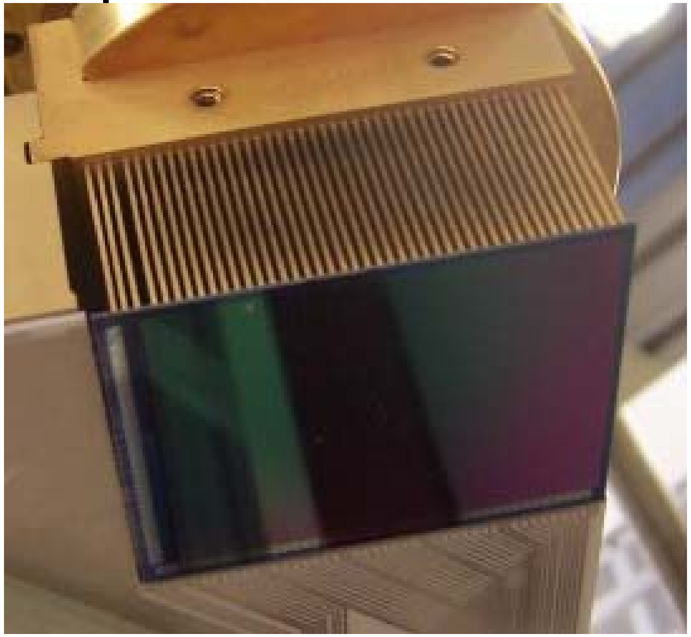
Glueing has to be uniform, musn't bridge the tines

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

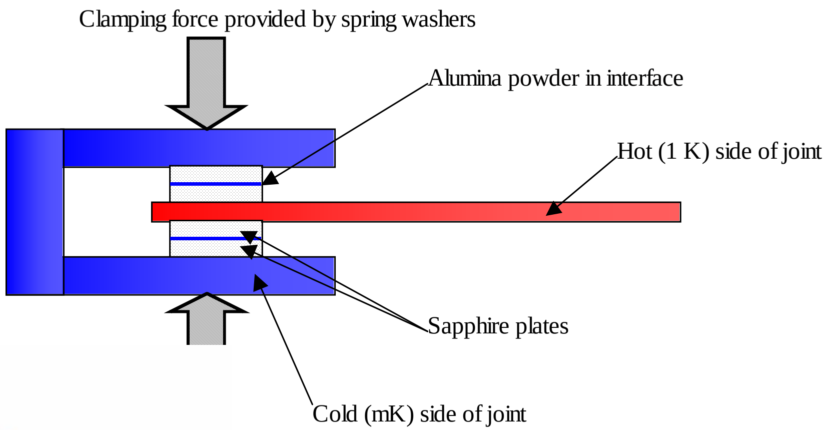


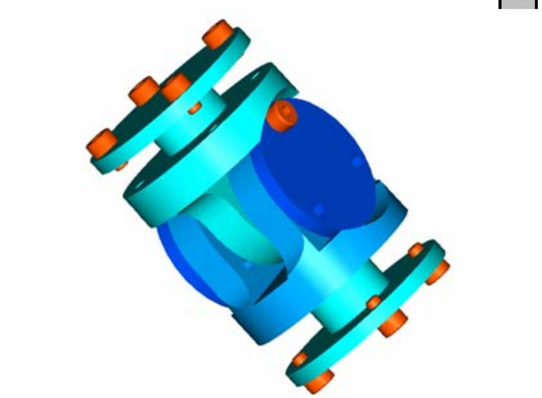
Thermally isolating support

Need to support arrays rigidly with low heat leak

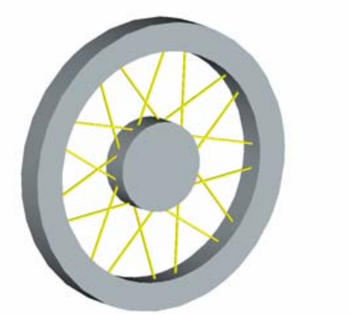
Solution: “sapphire interface” support: 2.5 μW heat leak from 1 K to 100 mK

Uses sapphire discs with alumina powder between





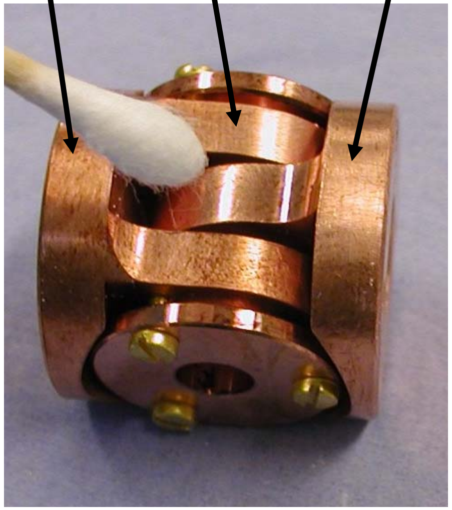
Straps supported by kevlar “wheel”



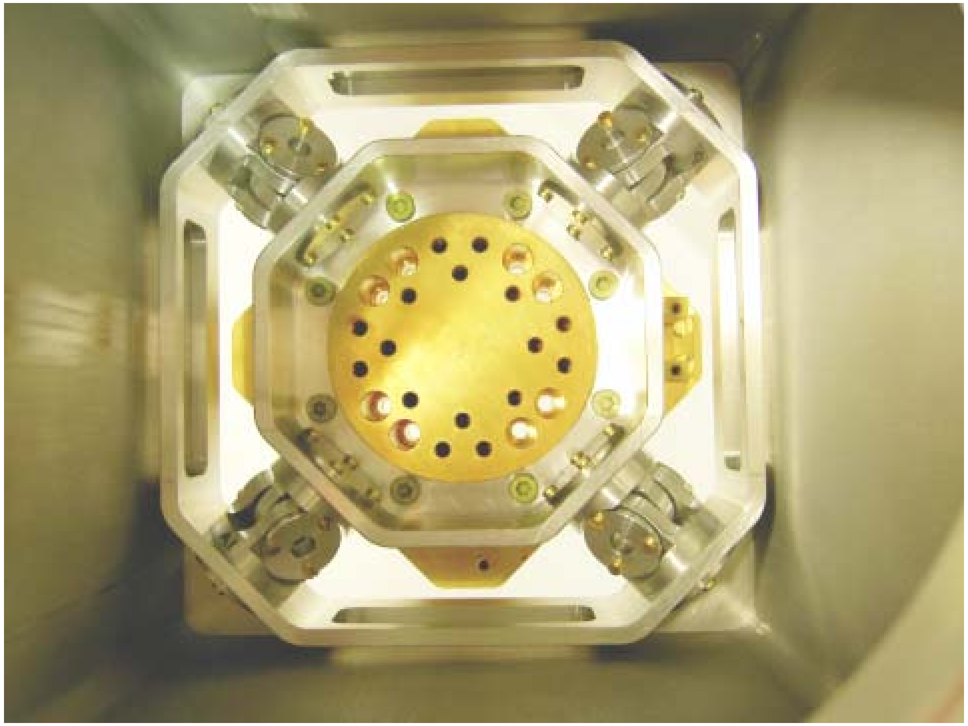
More information in Bintley et al Cryogenics, 47(5-6):333-342 (2007) http://reference.lowtemp.org/woodcraft_sapphire_and_copper.pdf

Thermally isolating support

Test joint:

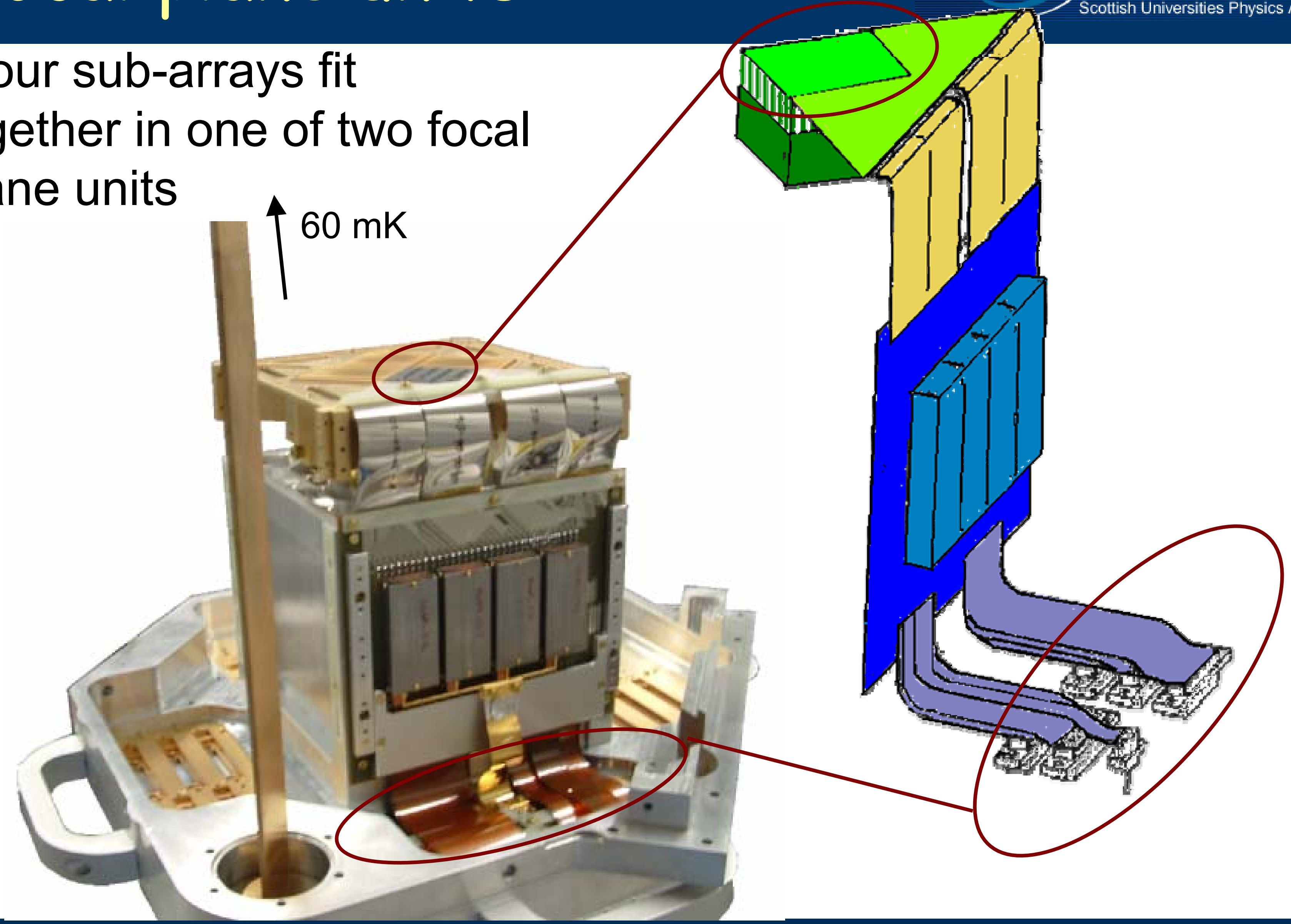


Finished isolation support

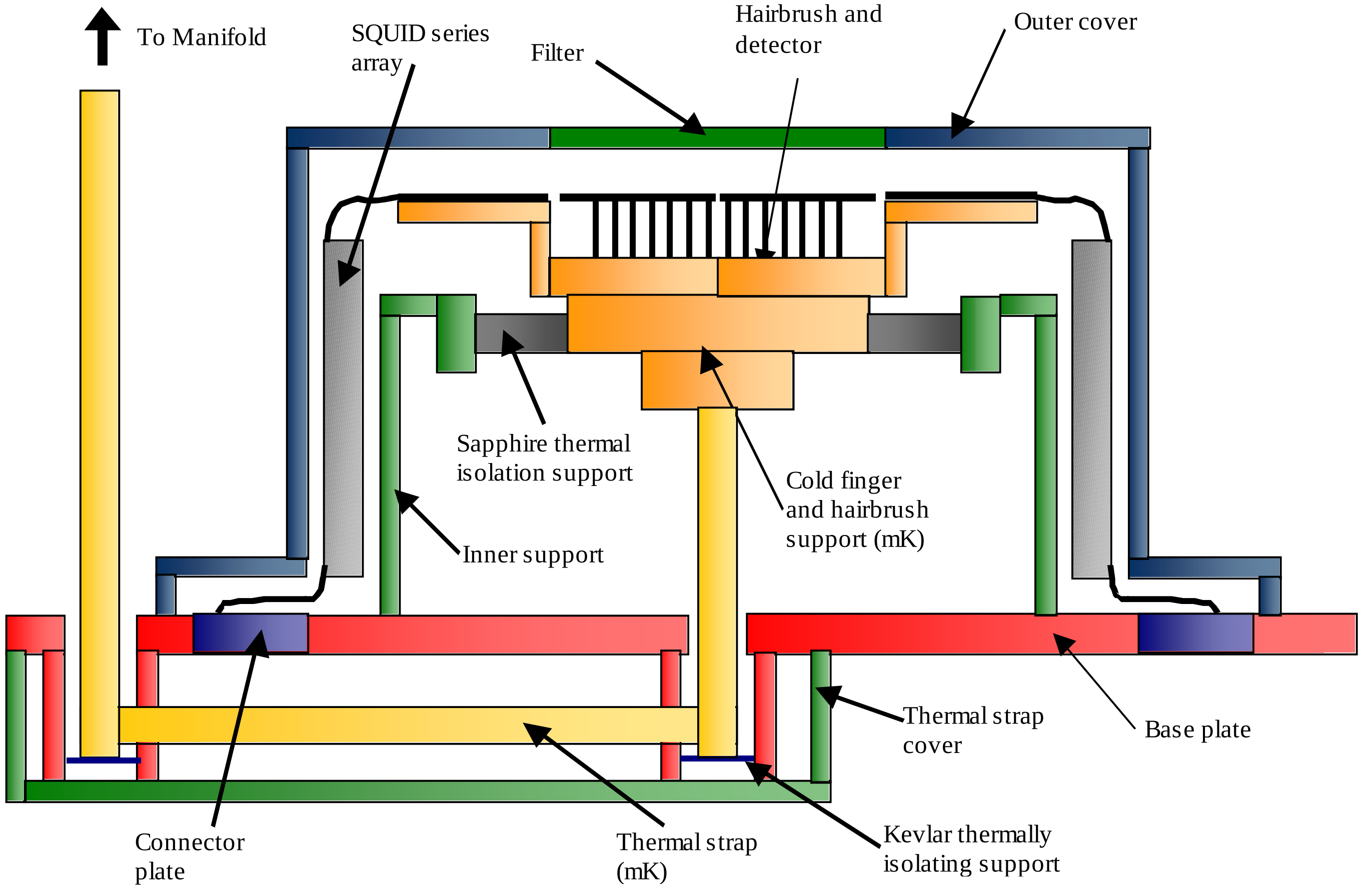


Focal plane units

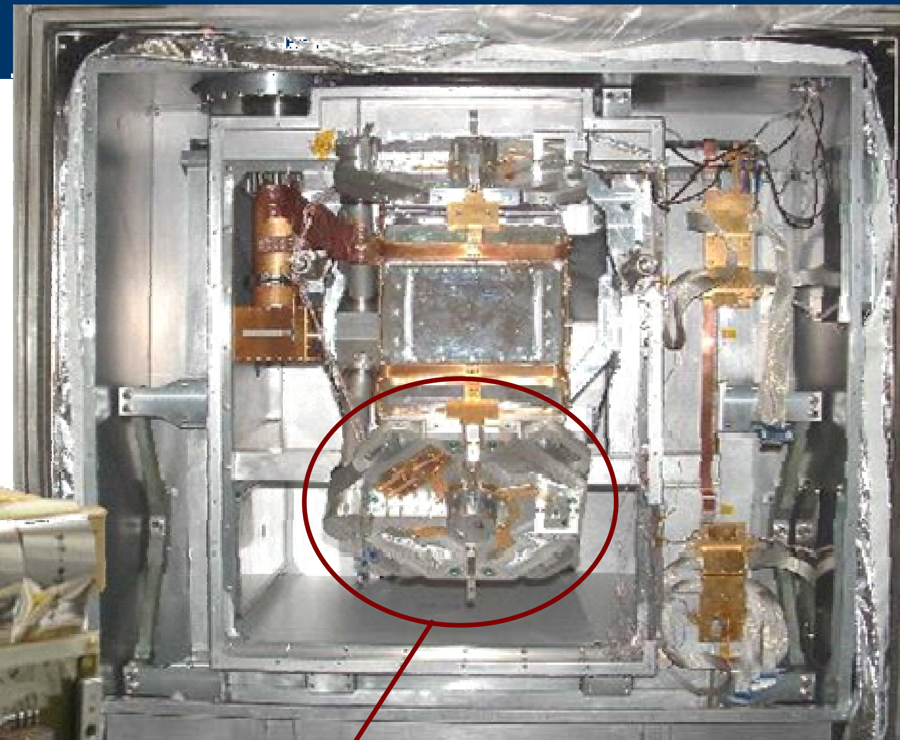
- Four sub-arrays fit together in one of two focal plane units

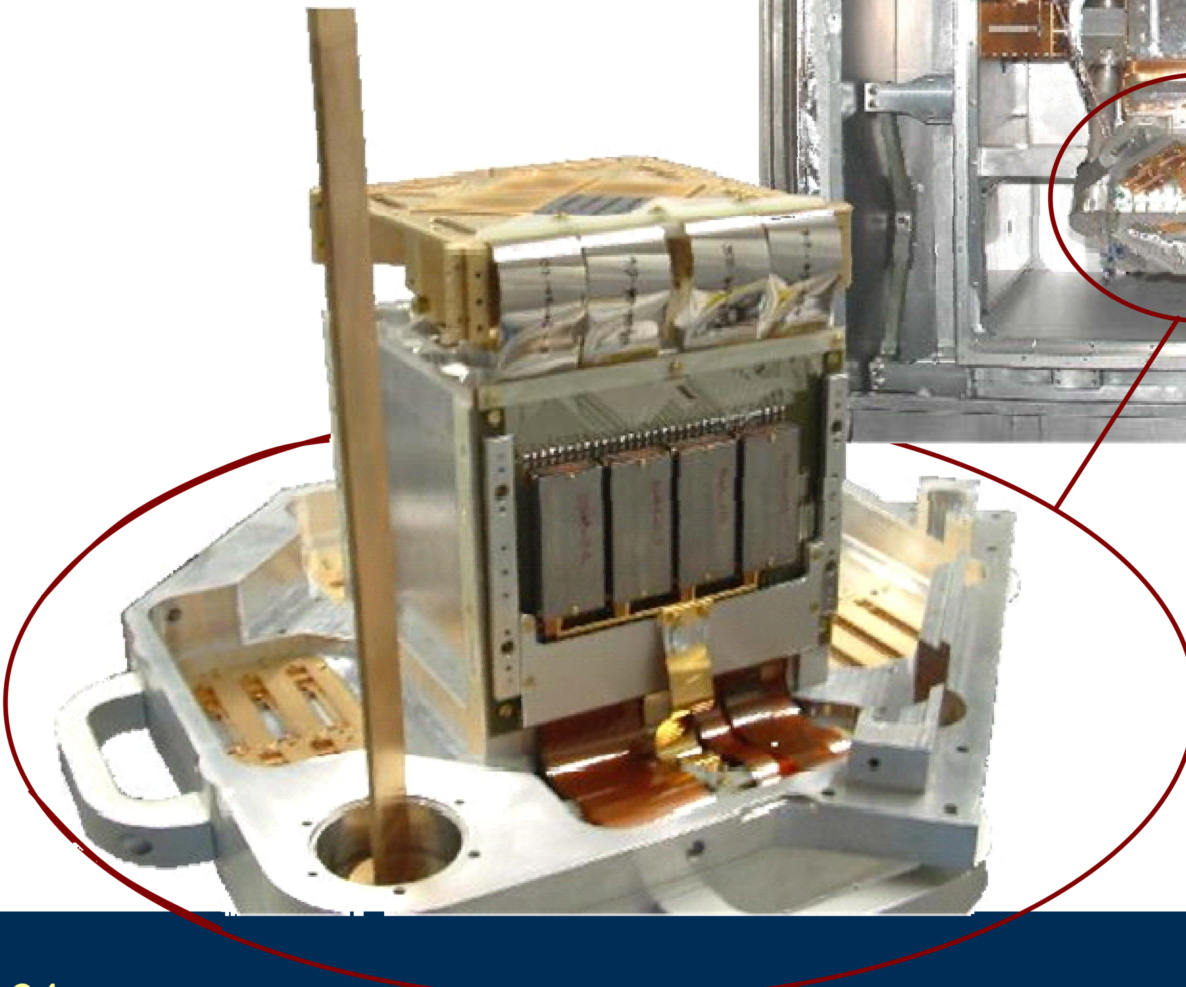


Assembly

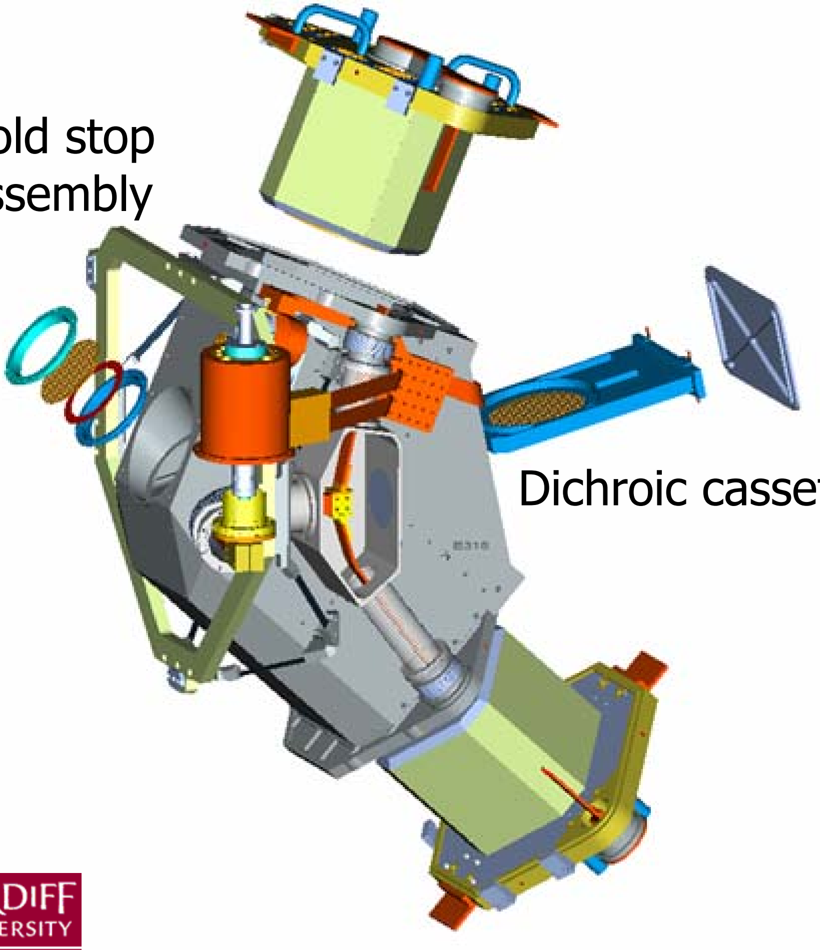

To Manifold
SQUID series array
Filter
Hairbrush and detector
Outer cover
Sapphire thermal isolation support
Cold finger and hairbrush support (mK)
Inner support
Thermal strap cover
Base plate
Connector plate
Thermal strap (mK)
Kevlar thermally isolating support

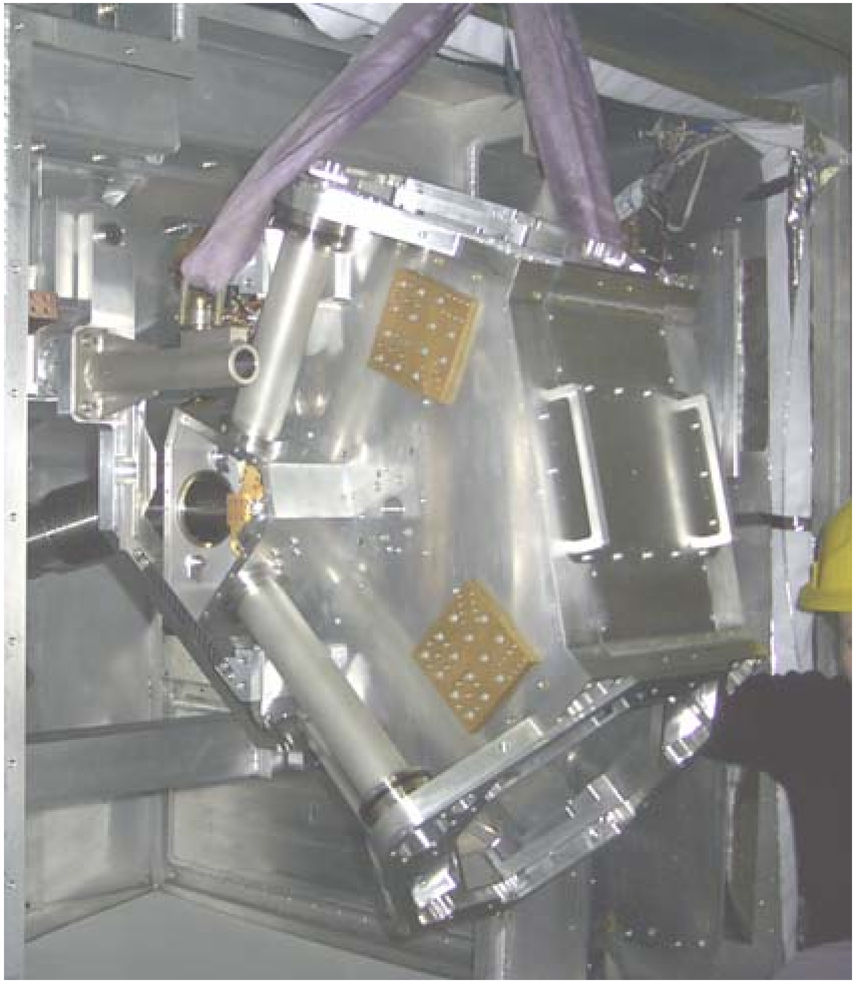
Assembly





1K enclosure ("1K box")





Thermal design

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Critical components have all been tested on their own

In first test, instrument cooled down below required temperature, and more quickly than required!

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The Big Problem

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The need for data

- Good engineering requires reliable data
- This is mostly missing at cryogenic temperatures
- Making measurements:
  - is much harder (and expensive) than at room temperature
  - Need cryostat
    - no access to experiment when cold to alter/repair
    - warm-up and cool-down time-consuming
    - can’t see what’s going on
    - need to get things right first time
    - experiment might as well be in orbit…

The need for data

- Sample to sample variation often much larger than at room temperature
    - Partly down to physics of materials
    - But also because most materials (e.g. alloys) aren't designed to be used at low temperatures - lack of reproducibility at 1 K is not considered a problem

    - Therefore measuring one sample is often insufficient

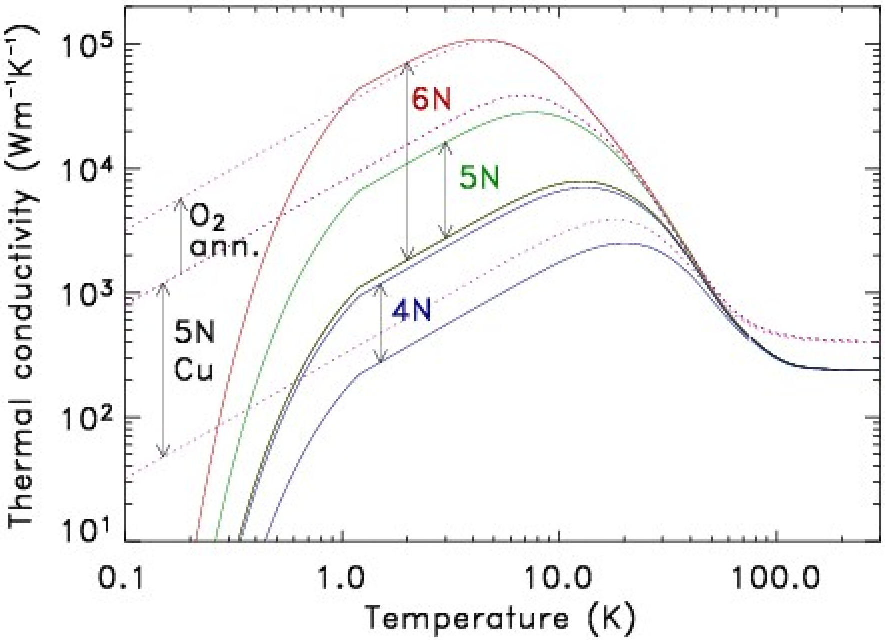
Material data

- Cryogenic instruments and experiments have been constructed and used for decades

- Still a lack of important material property data…
  - Often measured on an ad-hoc basis during instrument development
  - Adds risk:
    - May take longer than expected to make measurements
    - Chosen material may be found to be unsuitable, forcing further unscheduled research
    - Often time is too short to do a good measurement
    - Inexperience and lack of appropriate facilities often leads to poor measurements and false conclusions

Example

- A (nameless) group wanted to choose between pure aluminium and copper for a thermal link
- One sample each of 5N purity Al and Cu was measured
- But there is a huge sample to sample variation!
  - This wasn't a good way to choose between the materials



Thermal conductivity ranges for aluminium of different purities

Figure from Woodcraft, Cryogenics, 45(9):626-636 (2005) http://reference.lowtemp.org/woodcraft_alpaper.pdf

Example

The information they needed did exist, but not in an accessible form (i.e. a critical evaluation)

- A good material property database would have avoided this error.
- Also, measurements are often seriously in error, sometimes in ways that would be obvious with appropriate experience
- Material property measurements need to be decoupled from instrument development!

Astronomy (SCUBA-2)

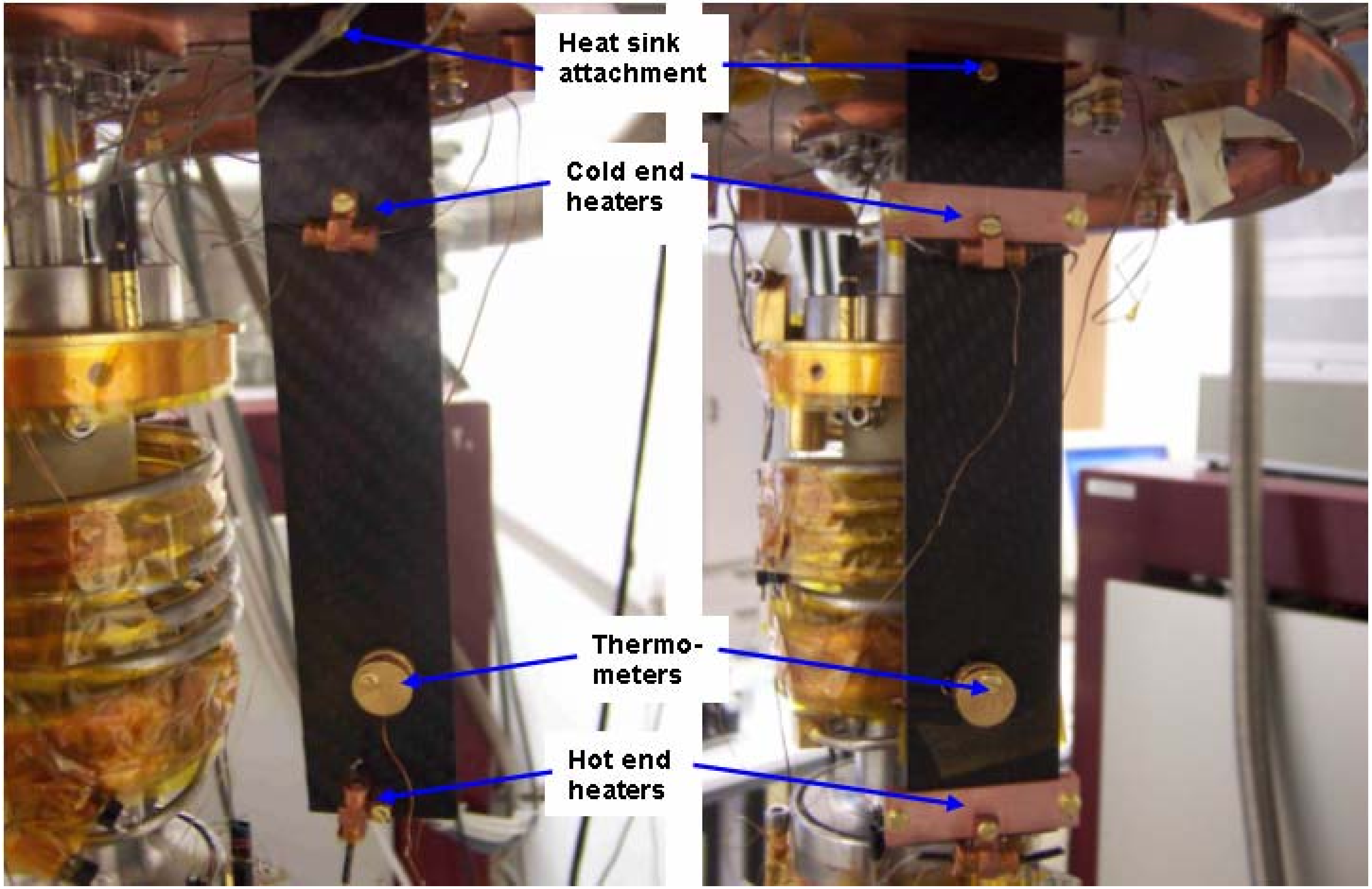
- SCUBA-2:
- Had to measure thermal conductivity of:
    - CFRP supports
    - Welds between various types of aluminium
    - Pure copper for thermal straps
    - Bolted thermal joints

- Insufficient time to measure *all* materials used; had to rely on extrapolation and large safety margins in some cases.

- Design also compromised by need to use well characterised materials despite better choices *probably* being available (who knows?)
- Better information would have led to cheaper and faster construction

CFRP supports

- Measured in detector development testbed



Predictions

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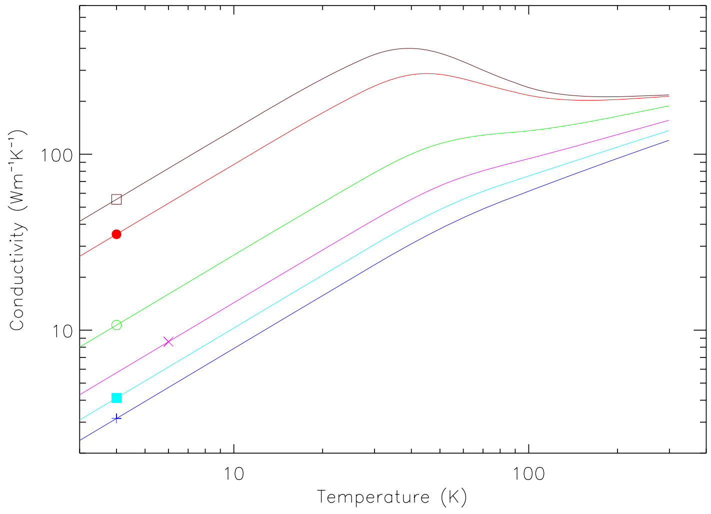
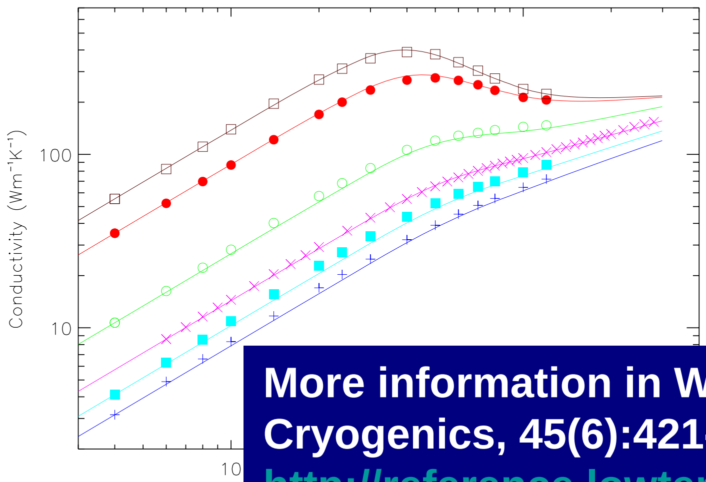
- Method to predict aluminum alloy conductivity from a measurement at a single temperature
- Work I carried out for instruments under development

- Much of the data I used was obtained in the 60's!

Predict from single point…



Remaining measurements agree



More information in Woodcraft, Cryogenics, 45(6):421-432, (2005)
http://reference.lowtemp.org/woodcraft_alalloy.pdf

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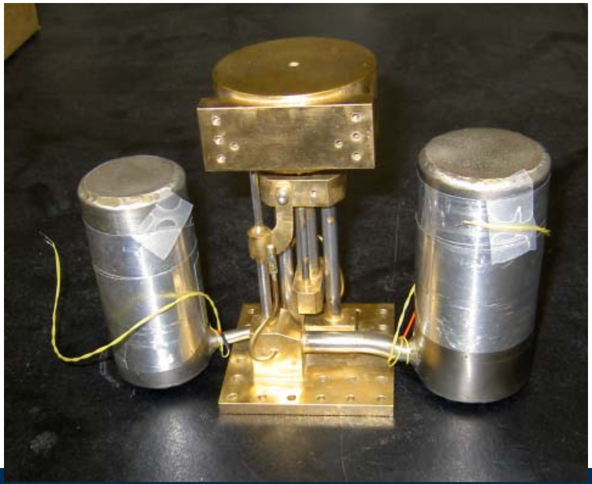
Timeliness

- Instruments requiring cryogenic temperatures are moving out of the lab

- Traditionally the need for frequent helium transfers has limited the use of cryogenics outside the lab
    - Only used in very limited cases e.g. MRI scanners

Timeliness

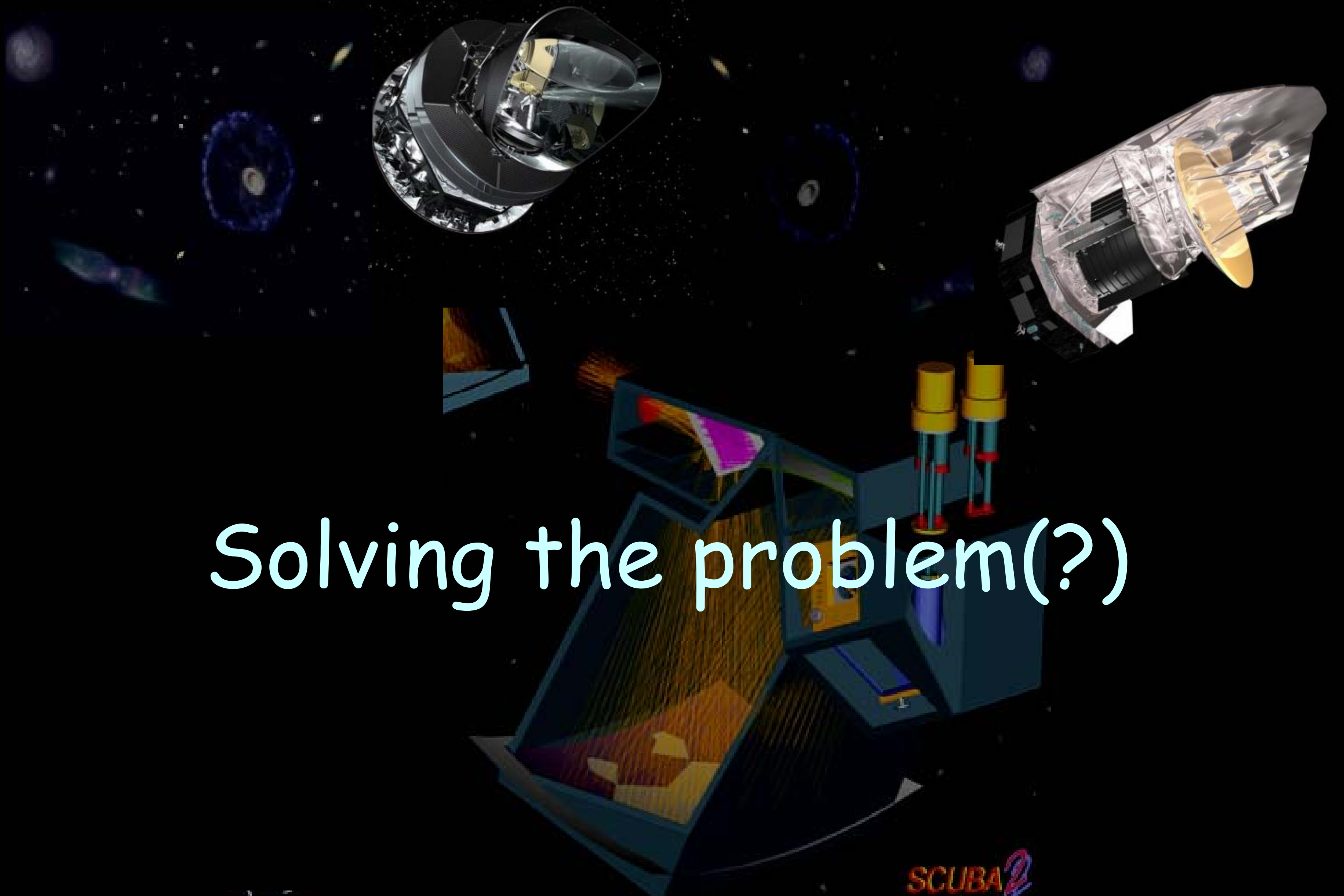
- Pulse tube coolers make ‘turn-key’ operation below 4 K possible without need for helium transfers or experience in cryogenics
    - Closed cycle ^{3}He fridges, dilution fridges and continuous ADRs make temperatures down to 100 mK and below possible in a similar manner



Timeliness

- Examples:
  - Superconducting electronics for mobile phone base stations
  - Passive Terahertz detectors for security applications
  - X-ray microcalorimeter for materials analysis (e.g. semiconductor industry)
  - Superconducting computers
  - Things we haven't even though of yet…
- But reliable engineering data is needed!
- What can we do?

Solving the problem(?)



SCUBA2

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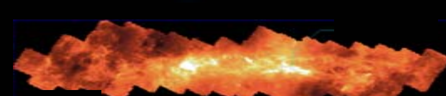

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SUPA cryogenic testbed

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- Located in lab space at the ATC, Edinburgh

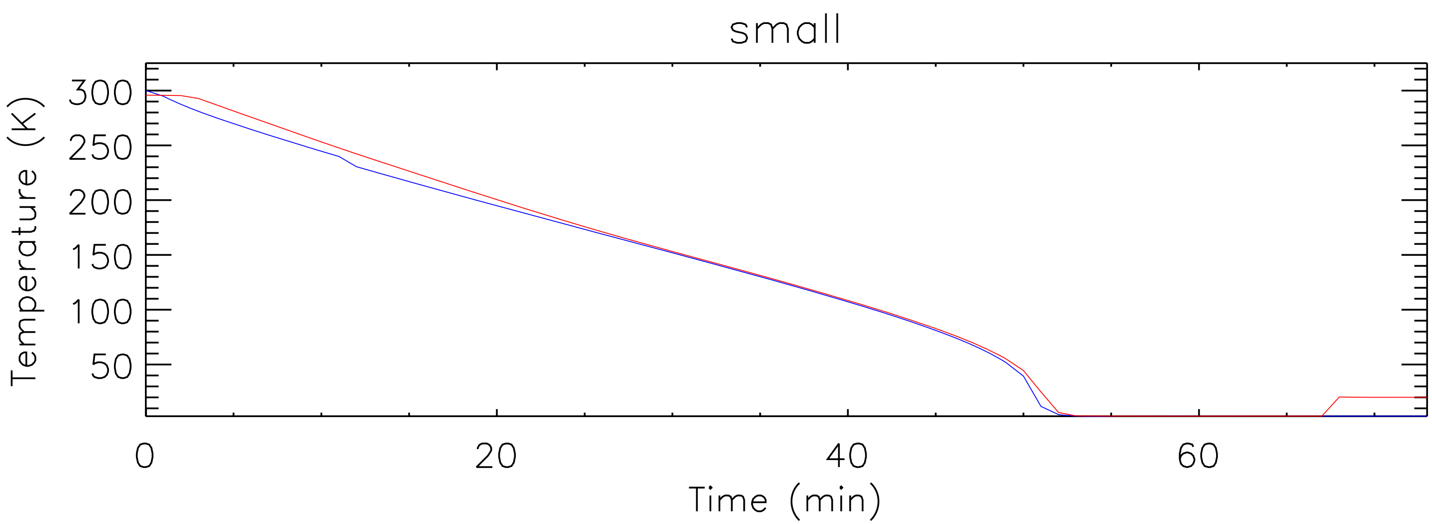
- Primarily available for work relating to TEOPS partners:
    - ATC UK
    - Institute for Gravitational Research, Glasgow
    - Experimental Particle Physics group, Glasgow

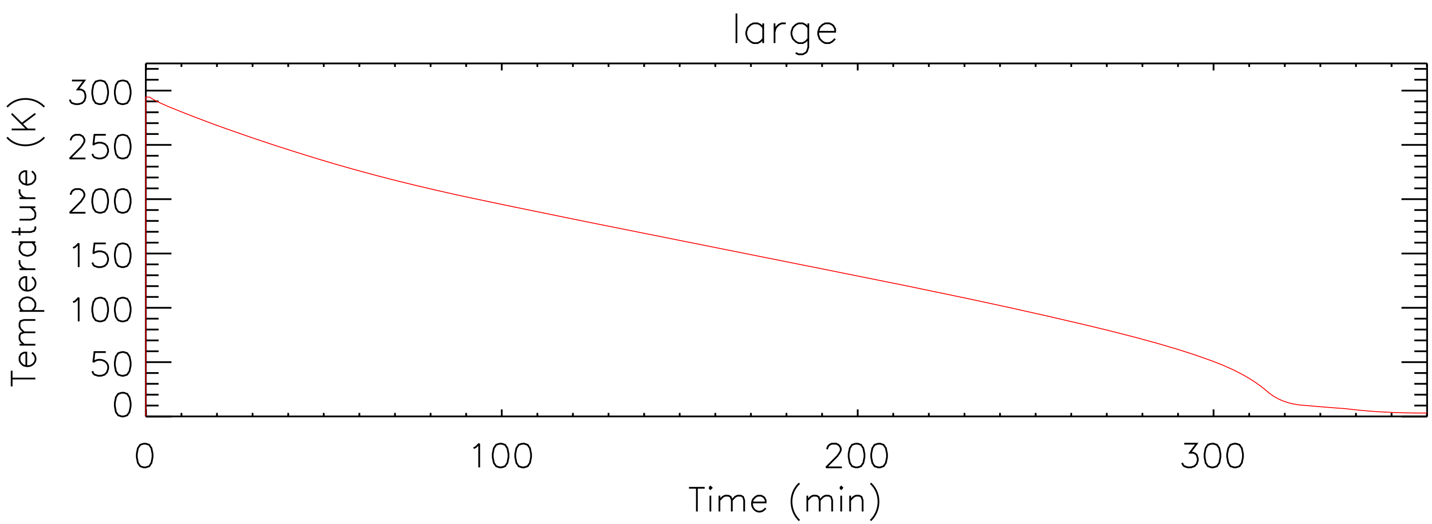
- “Dry” cryostat – liquid cryogens not required for operation

Design

- Two configurations
  - Small: sample space: few cm diameter and height
    - Cool-down time < 1 hr (300 K to < 4 K)
  - Large: sample space 20 cm diameter, 40 cm height
    - Cool-down time ~ 6 hours (300 K to < 4 K)
  - Optical access (4 windows) possible in both configurations
  - Fast switching between configurations
  - Operates at any temperature between < 4 K and 300 K
  - 300 mK operation also possible in large configuration with restricted sample space and cooling power

Cool-down measurements





Initial capabilities

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- Initial planned measurements
  - Thermal conductivity
  - Heat capacity
  - Electrical resistivity

- Future possibilities
  - Thermal expansion coefficient
  - Optical properties (e.g. refractive index)
  - Cold mechanism testing (with possibility of viewing mechanism through windows)

Beyond this

- The number of measurements one group can do is limited
- Wouldn't it be nice to set up a co-ordinated network of institutions to carry out and critically examine the results of material property measurements?
    - Perhaps a network of groups with overlapping specialities, so measurements can be confirmed by independent measurements

- But how do you fund it?
    - European (Framework 7) funding sounds appropriate…
    - But this doesn't seem to fit into any of their categories.

    - ANY IDEAS?