Lessons learned from SCUBA-2 for future cryogenic instrumentation in space

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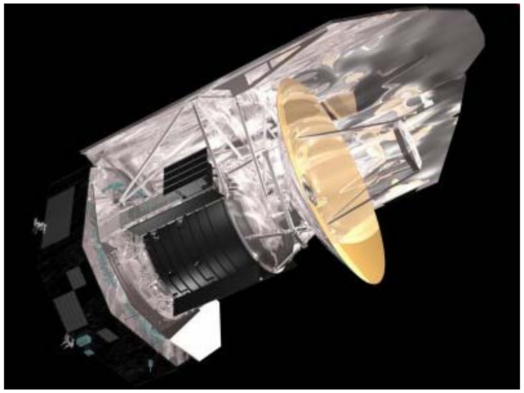
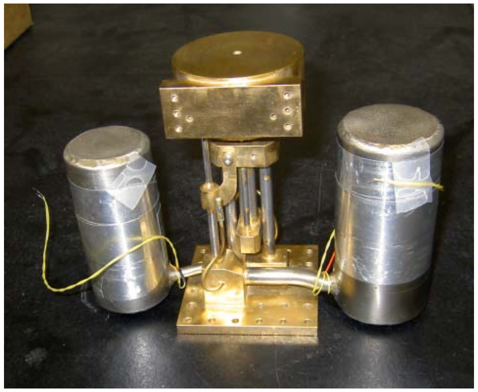
Background

- Building good sub-Kelvin (< 1 K) instruments is hard
  - Building good instruments for space is hard
    - Doing both at once is very hard!





Background

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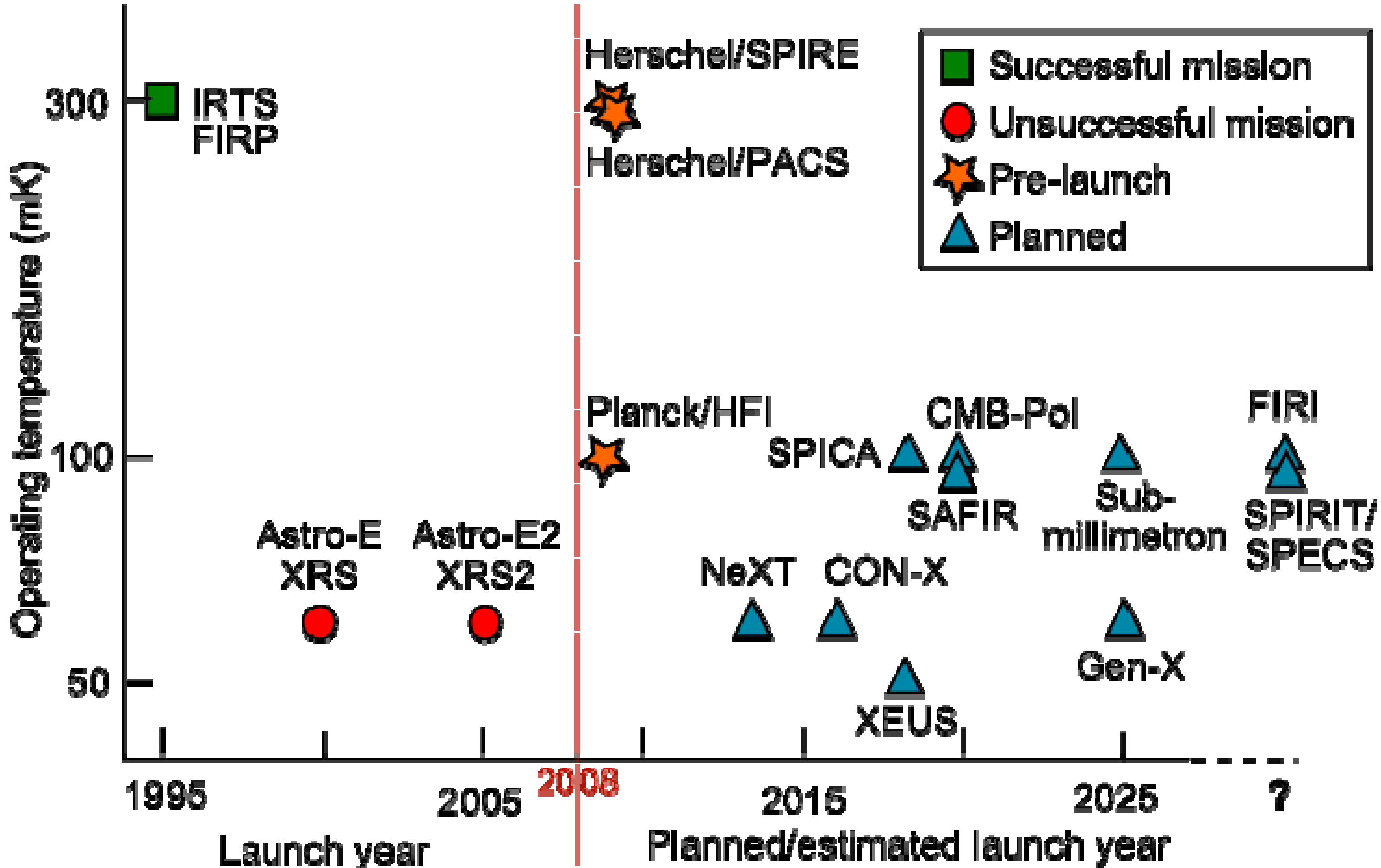
- But there are many planned missions which will require this



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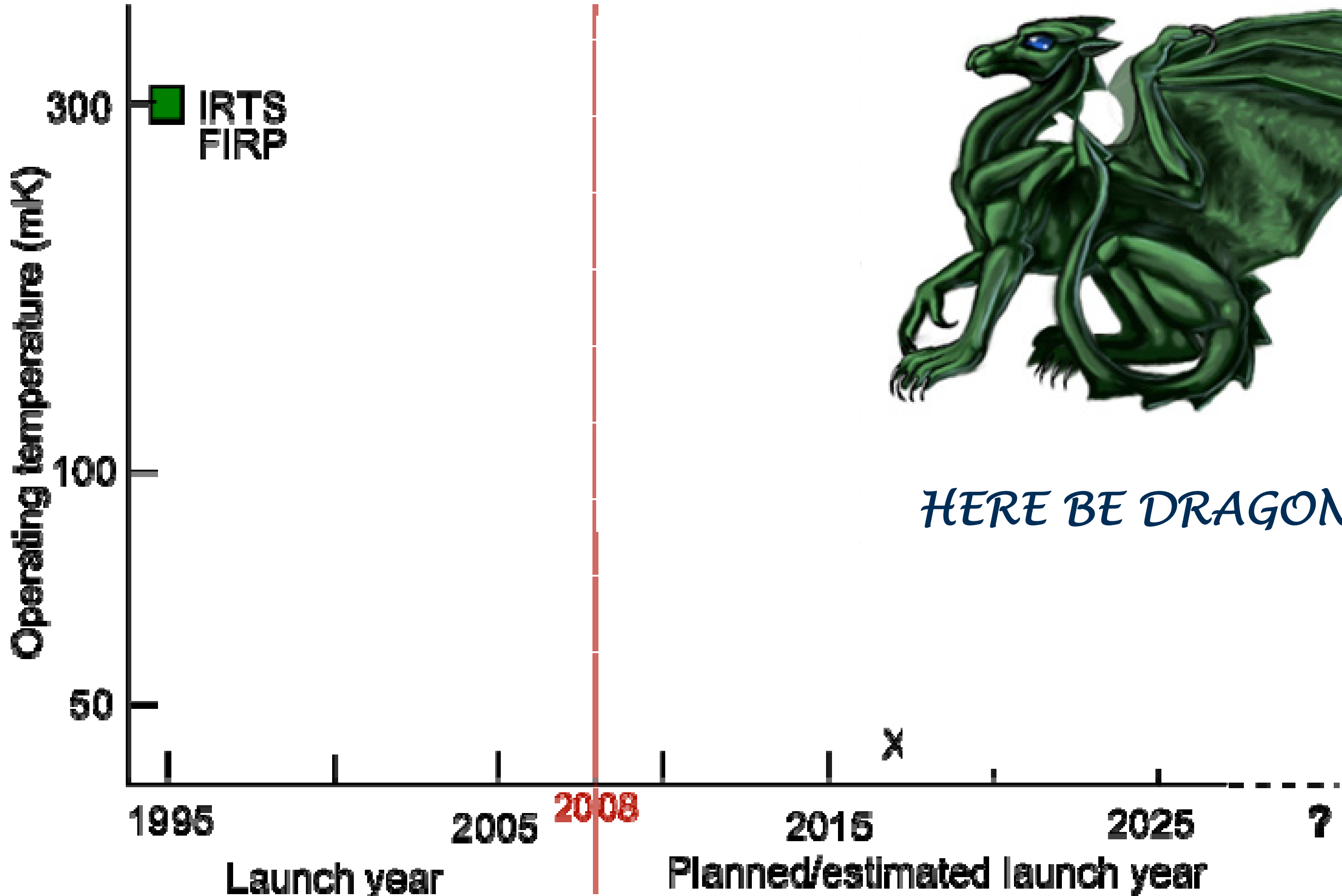
Background

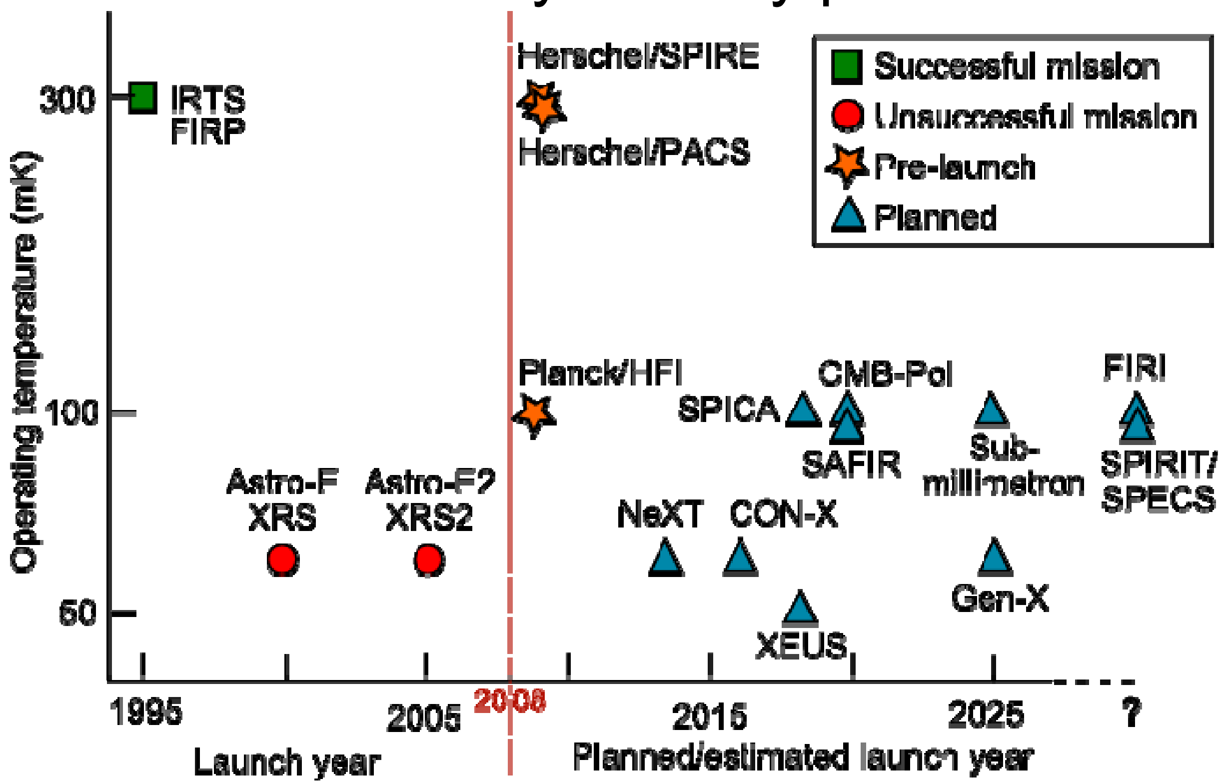
- Current experience is somewhat limited



HERE BE DRAGONS

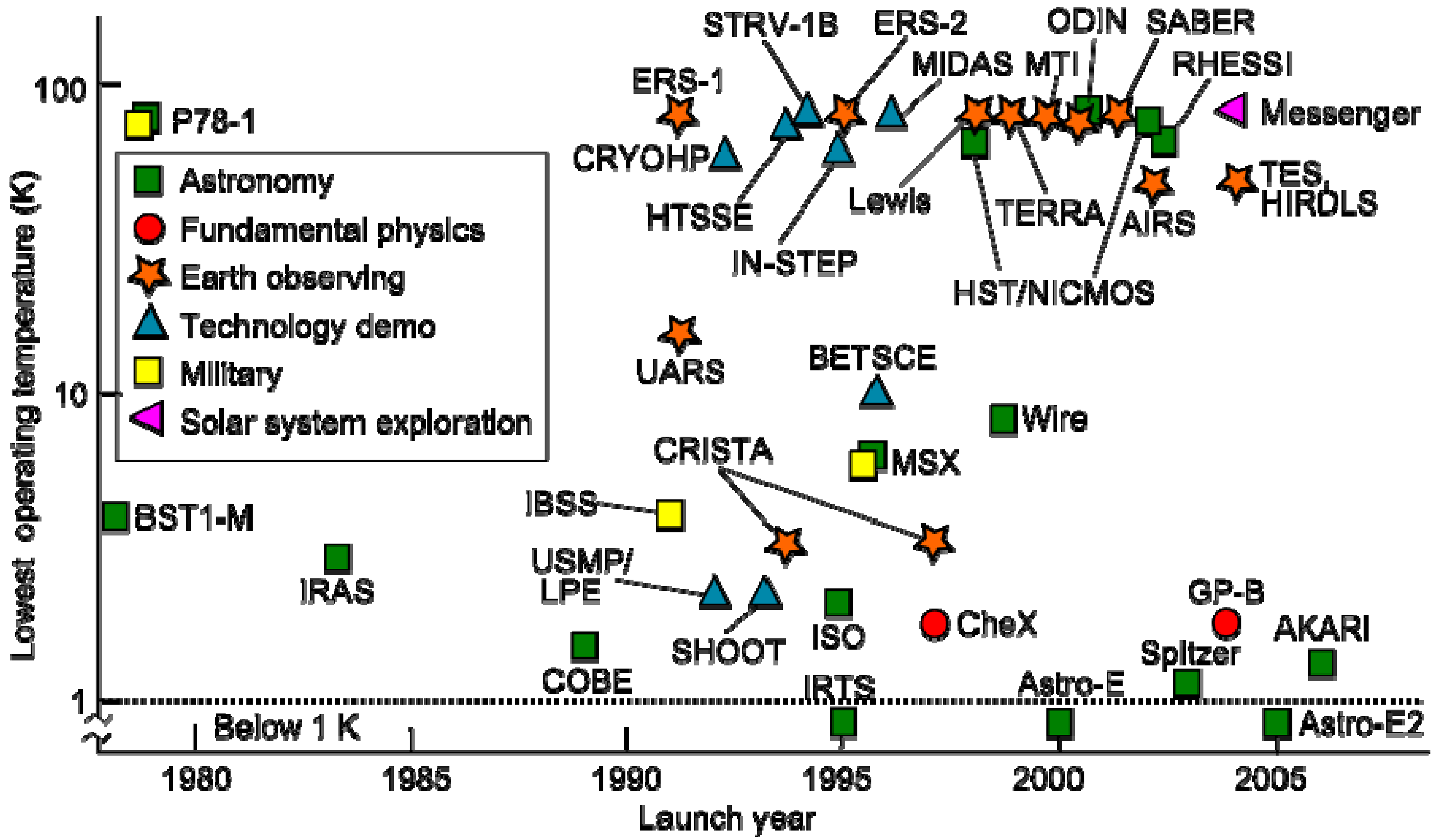
Background

- Probably not all of these will fly
  - But (barring breakthrough in technology), future FIR/Sub-mm and X-ray missions will need ULT detectors
  - Some missions already in study phase



Background

- ULT systems require full cooling chain
  - Experience at higher temperatures extensive



Background

- BUT:
  - Future ULT missions likely to be more demanding than those already built
  - Need to look to experience on the ground

- SCUBA-2: most complex ULT astronomical instrument ever built?
  - Future space missions likely to have similar complexity but with severe mass, power, volume etc. constraints
  - Even as a ground-based instrument, SCUBA-2 was not straightforward
  - So what did we learn from SCUBA-2?

SCUBA-2

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- A wide-field imaging camera with up to 1000× the mapping capability of SCUBA
- Capable of carrying out large-scale surveys of the submillimeter sky
- Ultra-deep imaging to the (extragalactic) confusion limit
- Polarimetry and medium resolution spectroscopy also available

SCUBA-2

SCUBA-2

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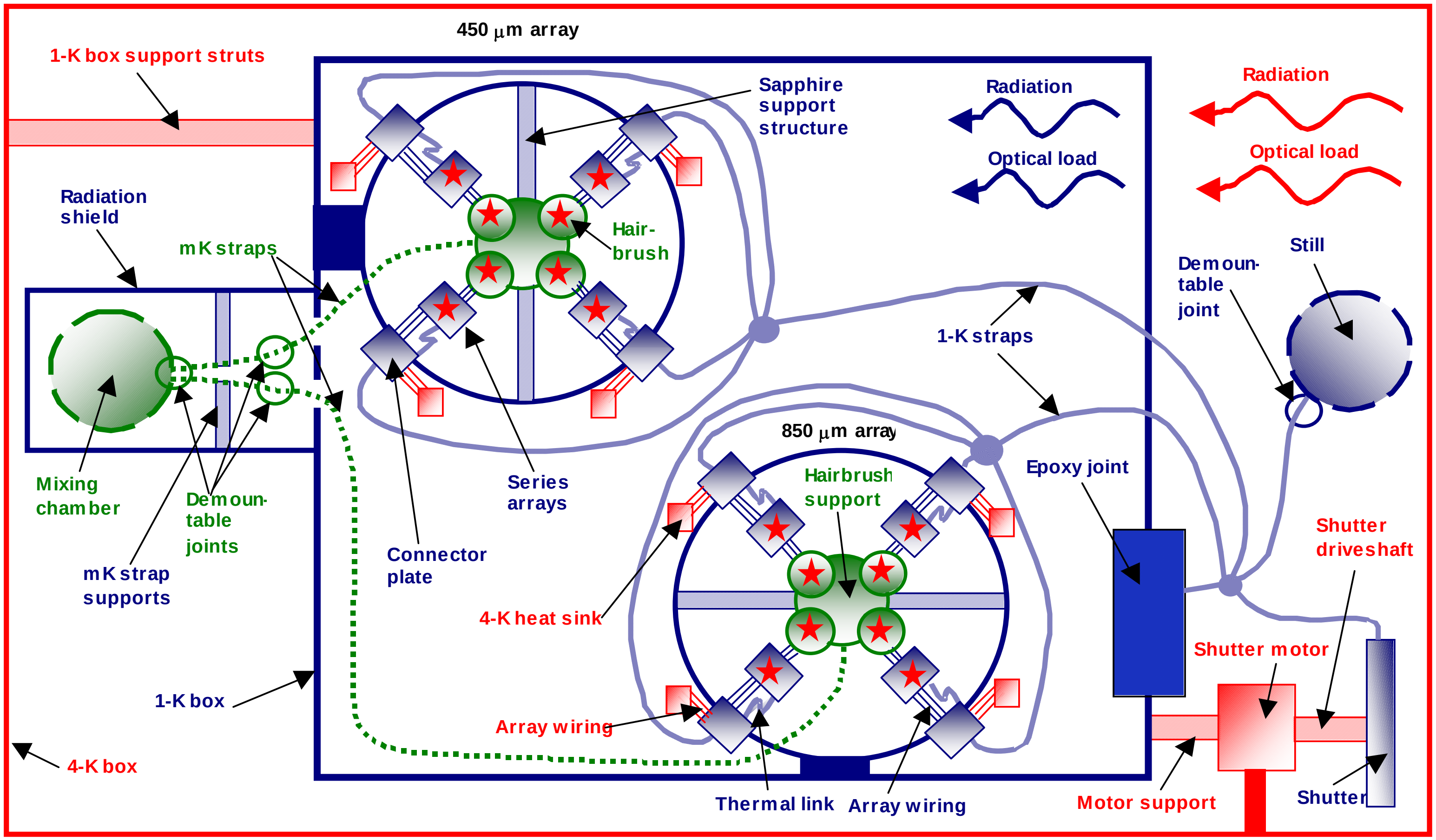
- SCUBA-2
  - Two focal planes each made from 4 subarrays massing ~ 10 kg each
  - Operate from heat sink < 50 mK, ~ 1 m from cooling source (dilution fridge)
  - Arrays have to be individually removable
  - Have to support arrays rigidly with low heat leak onto mK stage
  - Cryocooler operation

SCUBA-2 - 1-K box

Most challenging part of the thermal design



SCUBA-2 - 1-K box

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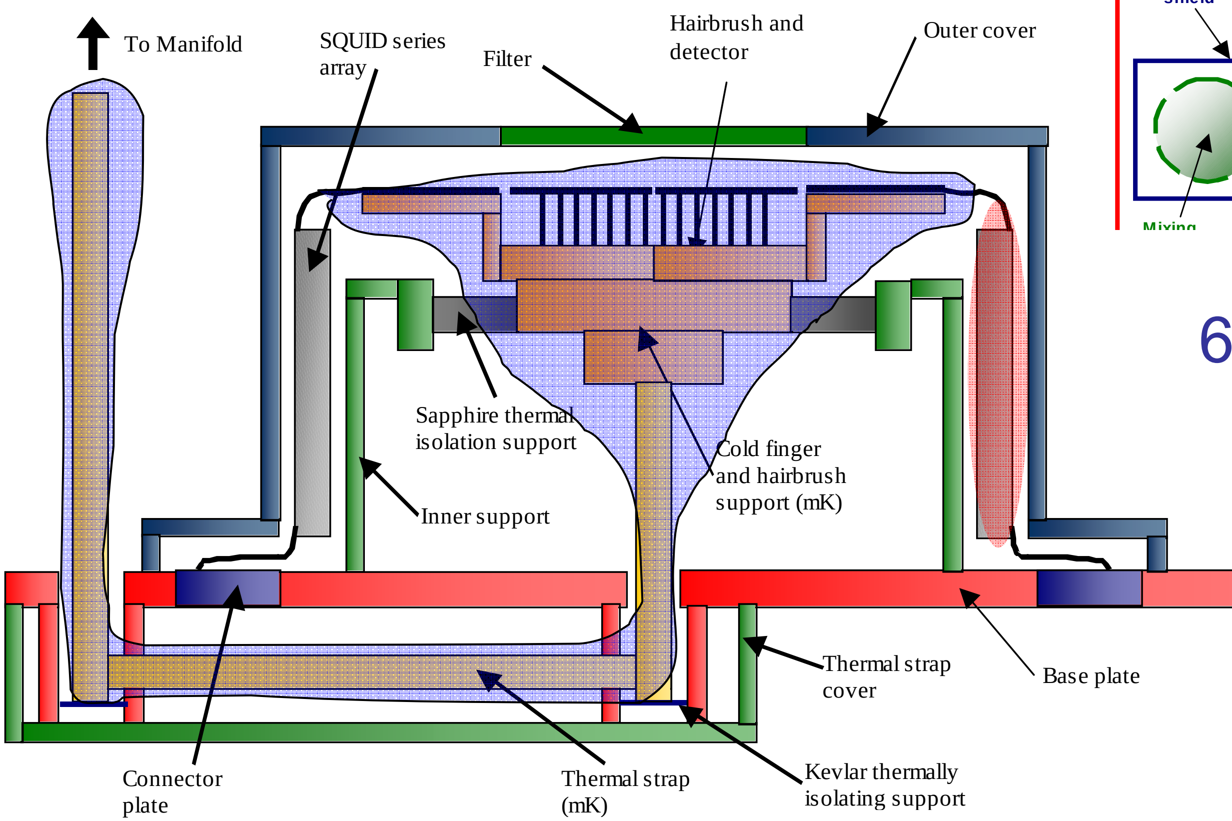
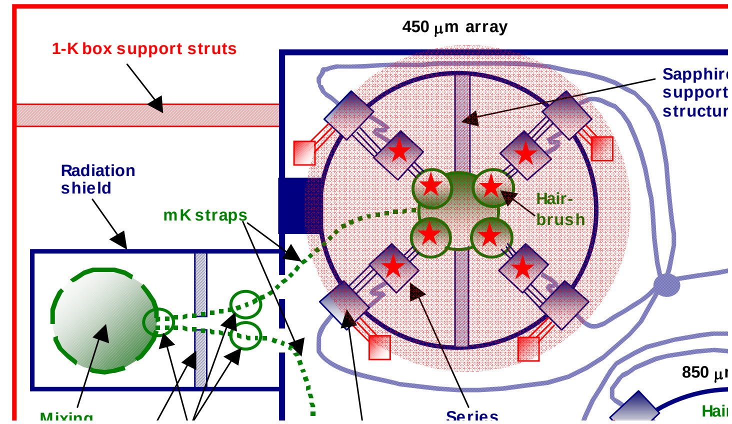
Detector unit





60 mK

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SCUBA-2 – 1-K box

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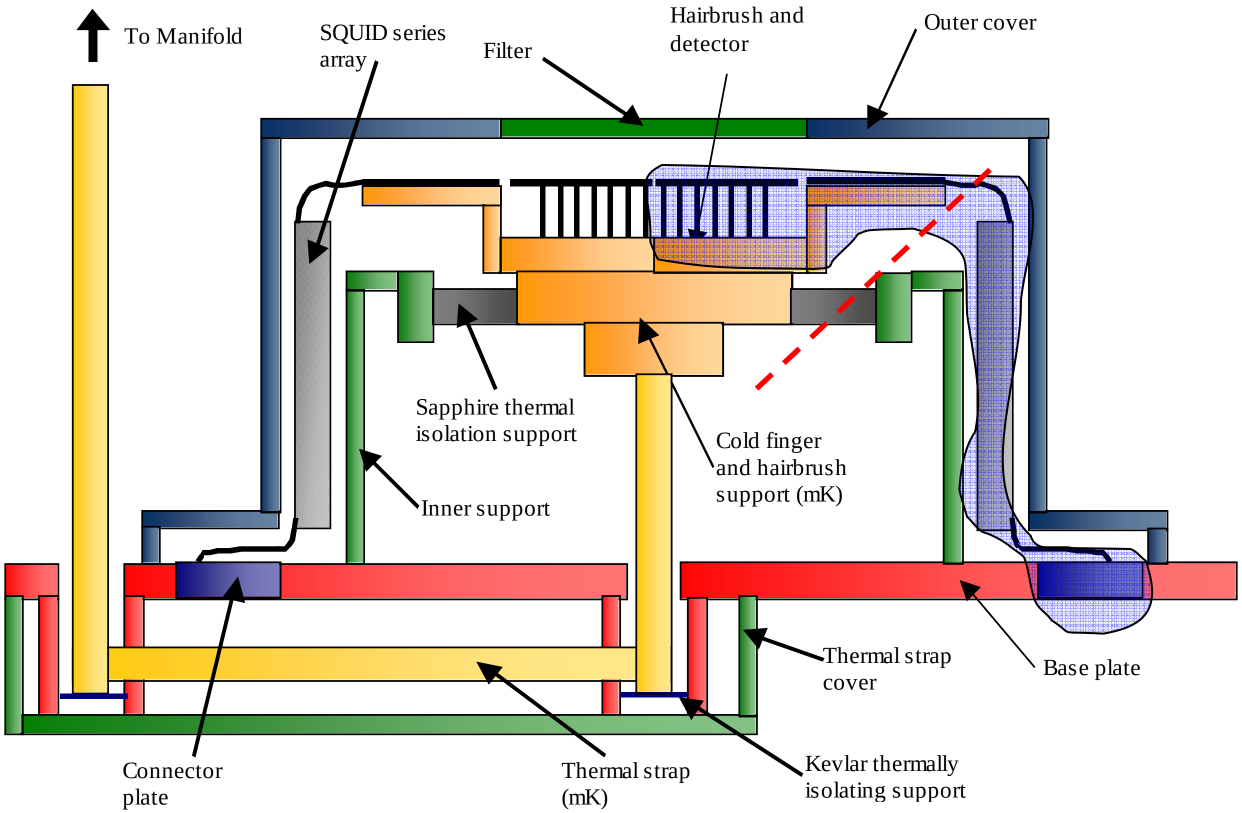
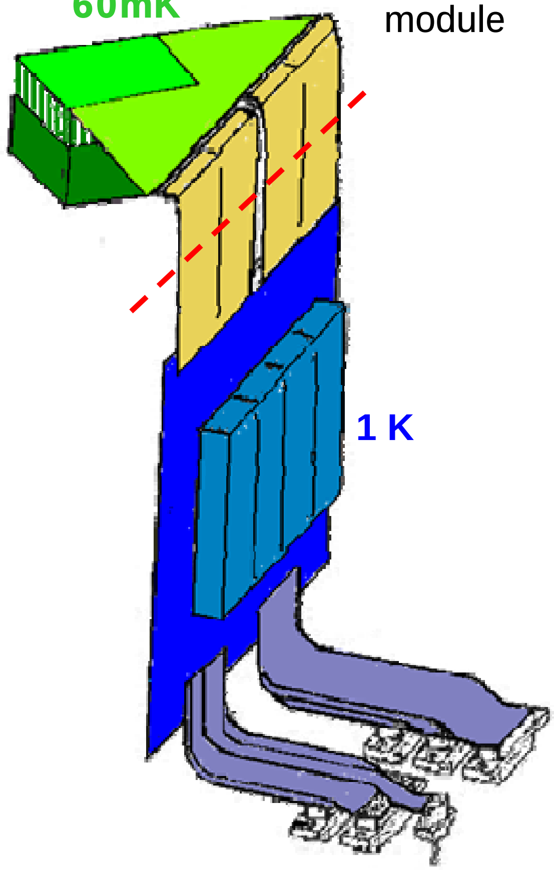
Sub-array module





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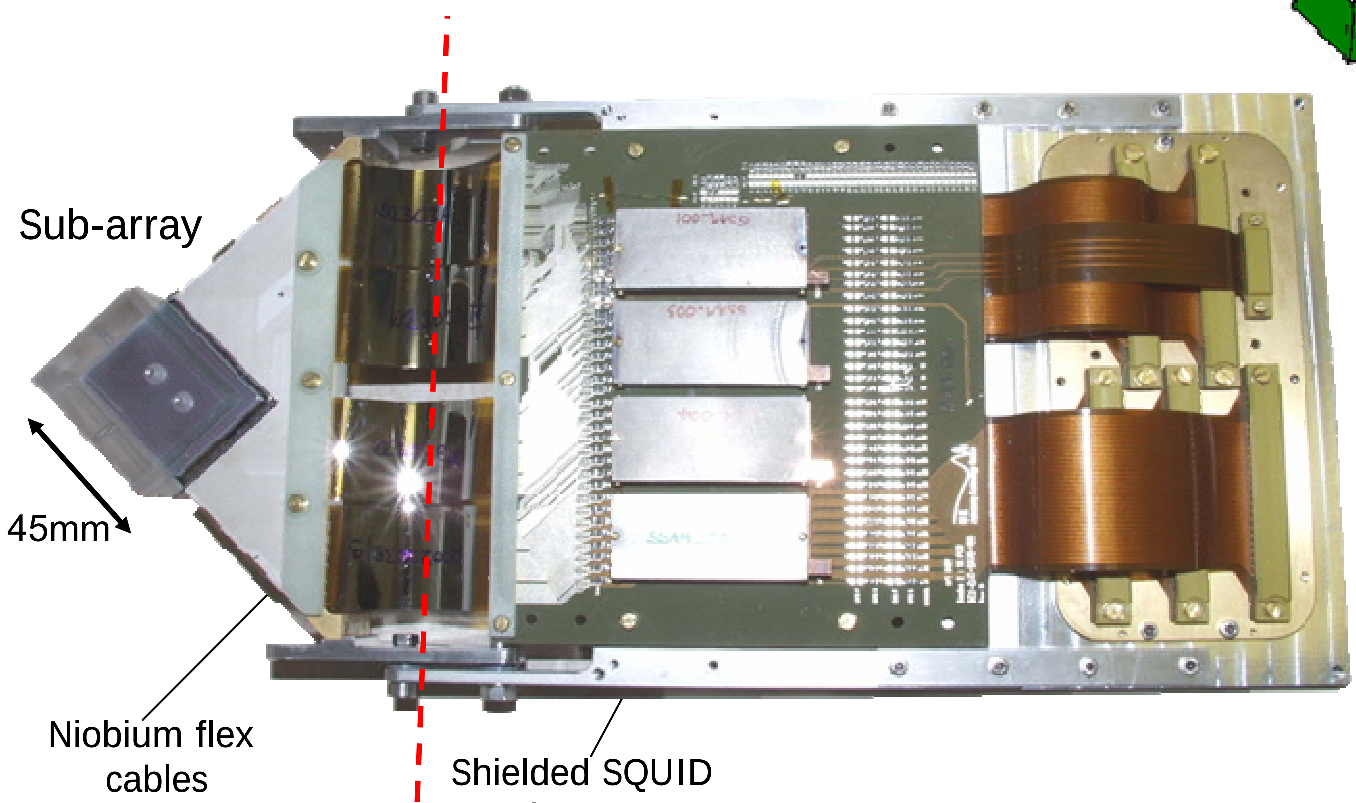
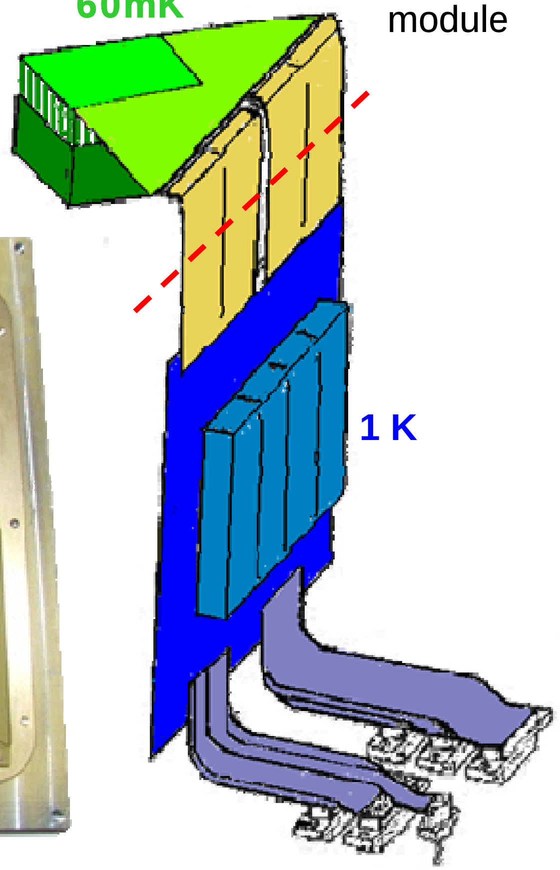
Sub-array module





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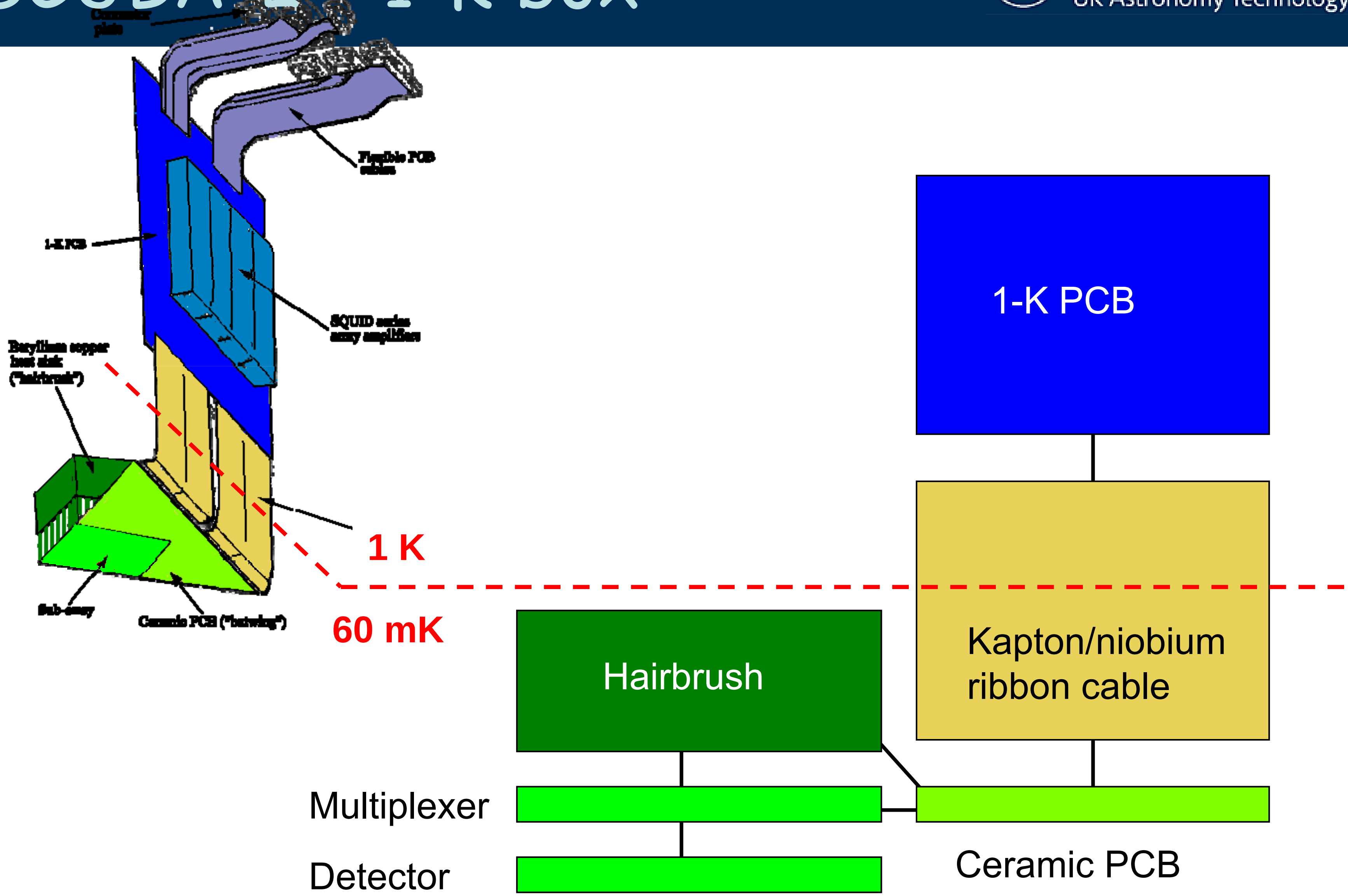
SCUBA-2 – 1-K box



SCUBA-2 - hairbrush

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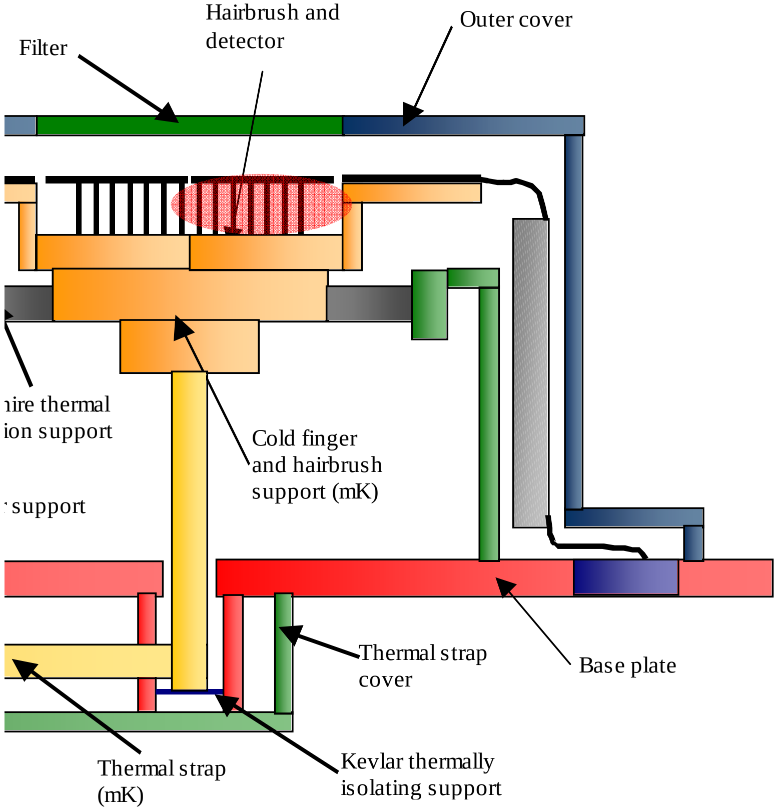
Provides heat sinking and mechanical support to detectors without breaking them due to differential thermal contraction

Made from high conductivity beryllium copper alloy



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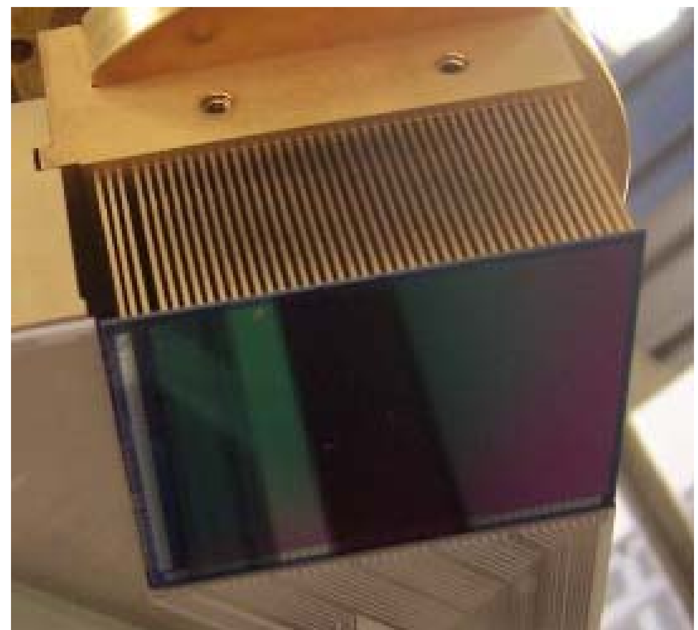
SCUBA-2 - hairbrush

- 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
- Haven't lost an array yet!

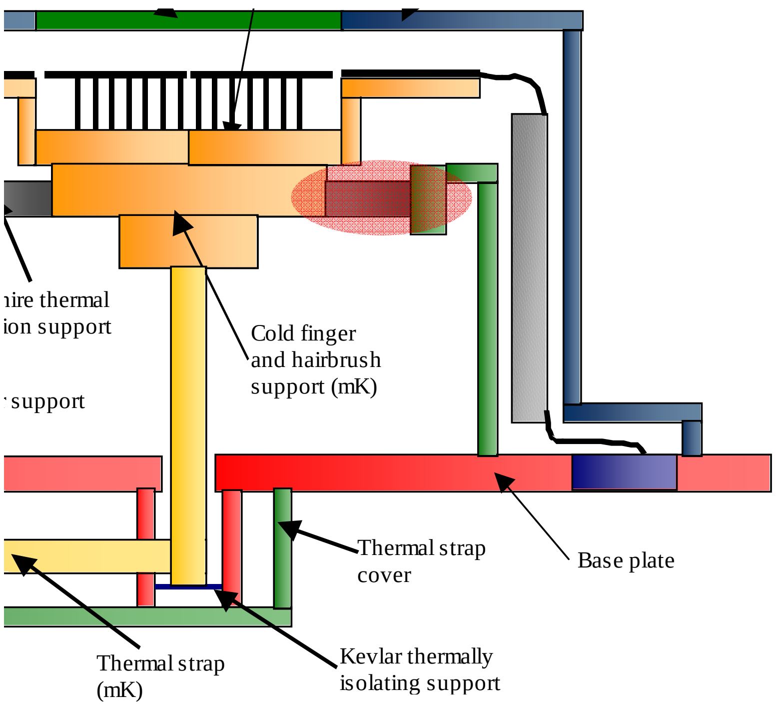


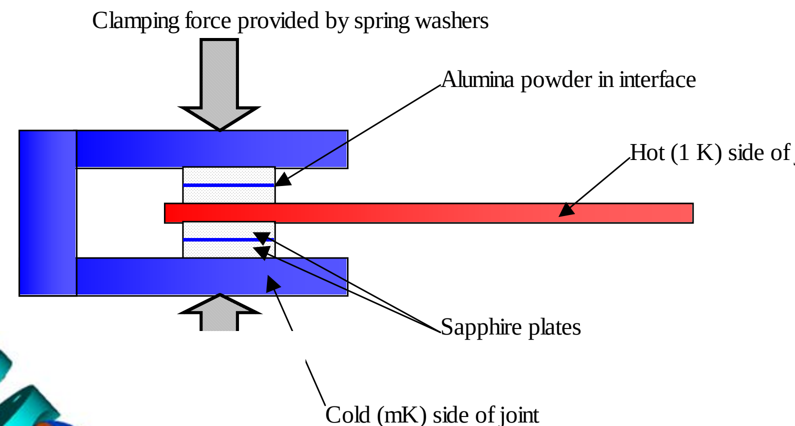
SCUBA-2 - sapphire support

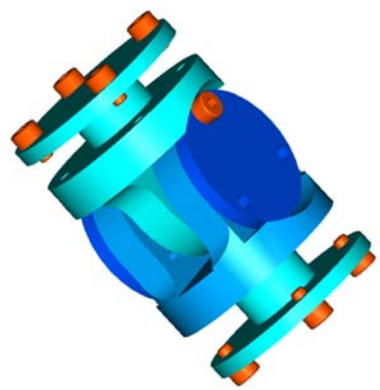
Need to support arrays rigidly with low heat leak

Wanted to avoid Kevlar (creep and catastrophic failure possible)

Solution: “sapphire interface” support: 2.5 μW heat leak from 1 K to 100 mK - sapphire discs with alumina powder between







SCUBA-2 - sapphire support

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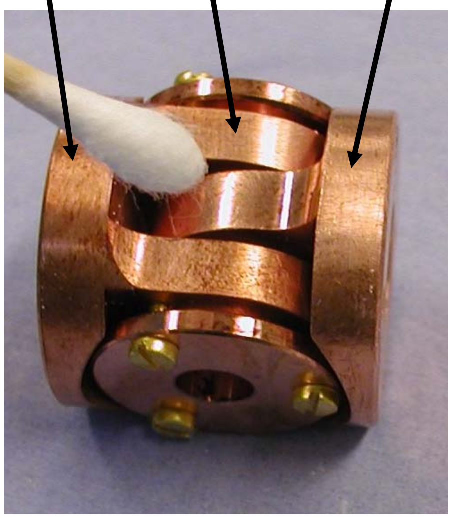
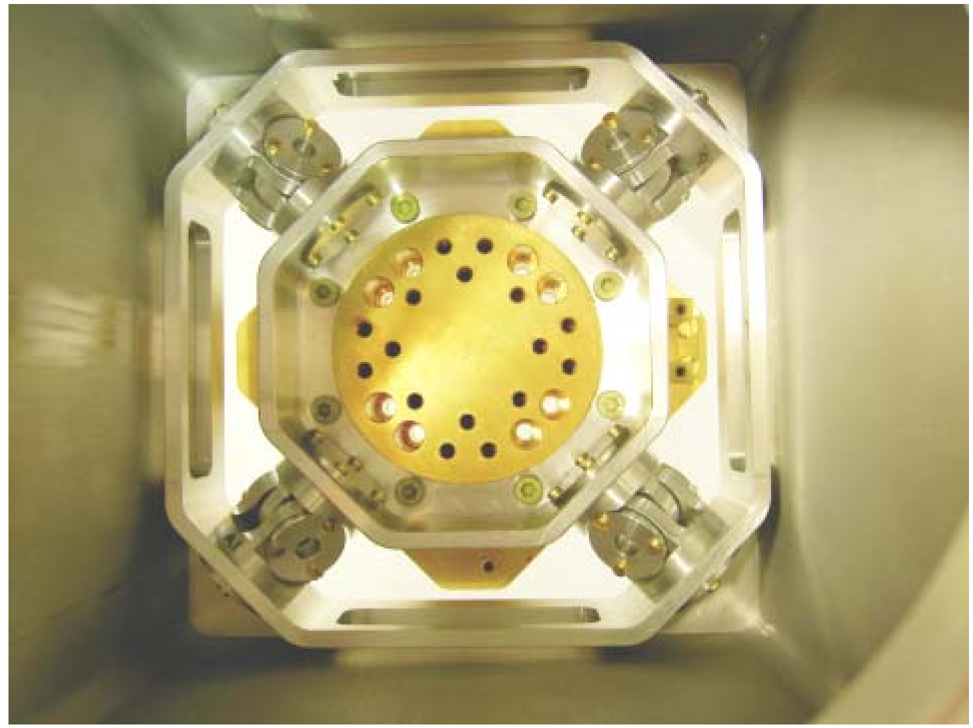
Test joint:

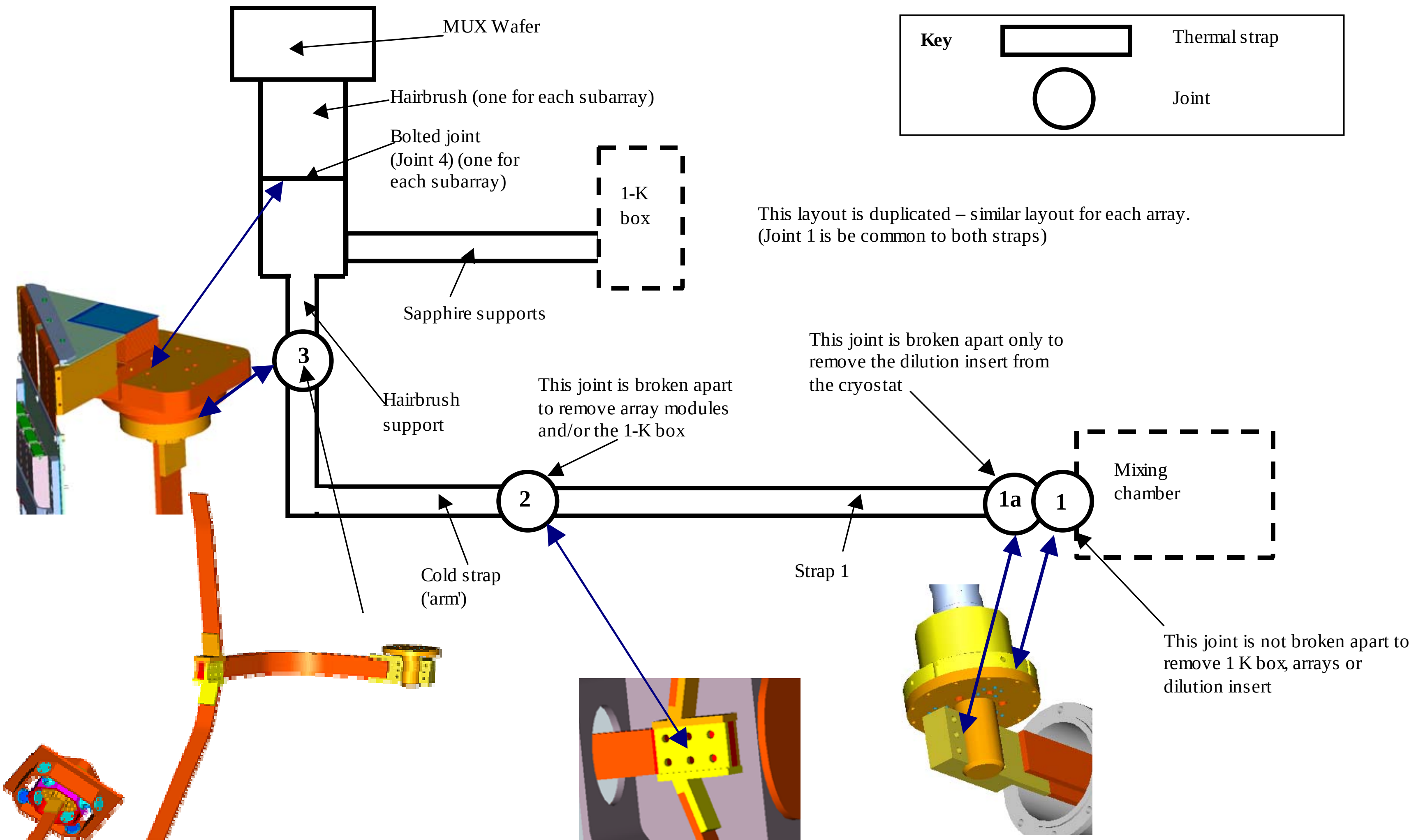


Finished isolation support



2.5 µW heat leak from 1 K to 100 mK
Used in Clover

Strap system



- Stacks of foils for compliance

Material properties

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- Lack of information on material properties was a problem
  - Not unique to SCUBA-2, but more serious issue than for small instruments
  - Couldn't always use tried and tested materials
    - Had to carry out tests
  - Even with well known materials, have to worry about sample variation

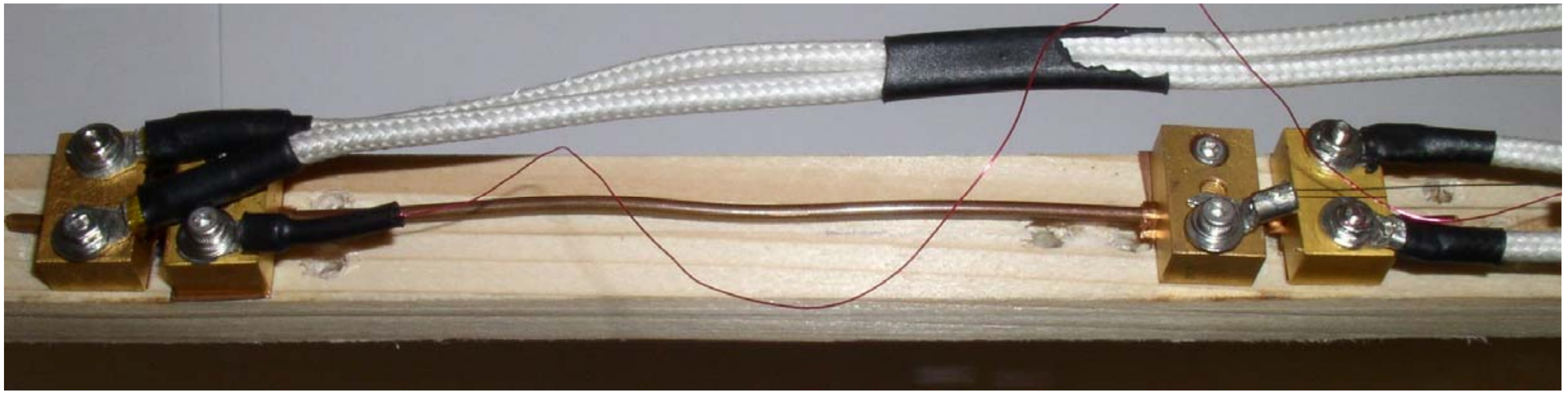
Worse, G10 is a specification on *electrical* properties, not thermal or mechanical, or even the composition!
Using G10 is therefore risky

Material properties

It is *essential* to test conductivity of same materials that will be used, with the same treatement (e.g. annealing)

SCUBA-2 required considerable test campaign

Fortunately, this can be done electrically (Wiedemann-Franz law) for metals



Material properties

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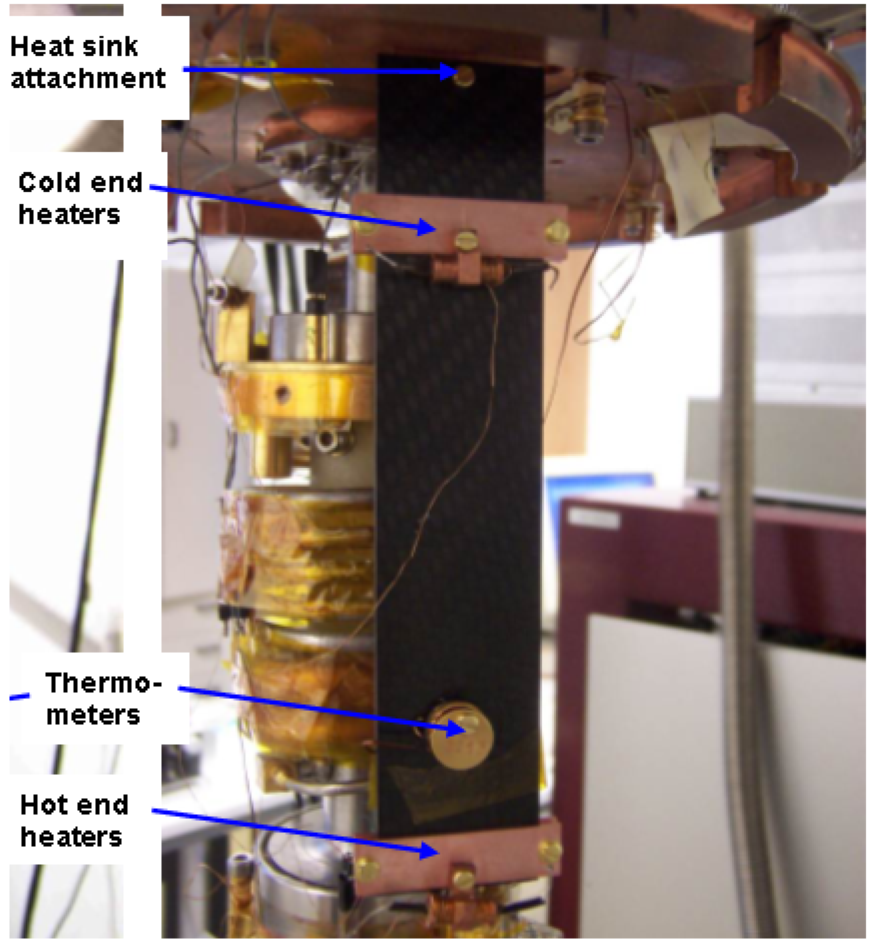
- The 1-K box is supported from the 4-K shield with CFRP
- Properties are somewhat variable depending on the exact composition, and possibly from lot to lot
- We therefore measured the conductivity of samples from the material used



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Joints

- Joints are even harder than getting the straps right
- Fixed joints can be made by electron beam welding, giving near bulk properties
    - IF the welding is done properly…

Joints

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Removable joints are the hardest. Not very well understood.

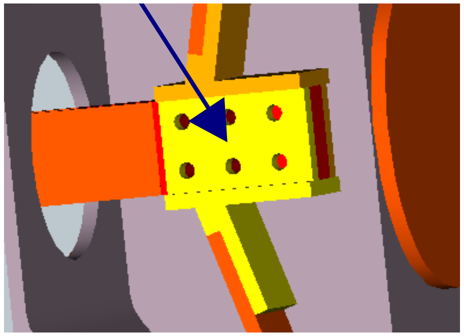
Little data to enable accurate modelling; depends on many variables.

Gold plating required to avoid oxide layer

Need to use high pressure (multiple bolts, high torque). Do **NOT** use grease!

Performance not necessarily repeatable

Again, electrical tests are very useful



Every joint must perform sufficiently well! A single poor joint can destroy the usefullness of the entire cooling chain

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SCUBA-2 – 1-K box

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

This gives us two problems:

1) The thermal conductivity of aluminium alloys is relatively poor

2) It is hard to make good contact to aluminium because of the tenacious oxide layer
   - Gold plating aluminium is difficult, and would be even harder for such a large structure

SCUBA-2 – 1-K box

A system of 1-K straps ensures good heat sinking to components

Straps are similar, and have similar issues, to mK straps

- Requirements are less demanding
- But we have rather more straps and contacts

SCUBA-2 – 1-K box

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We still need to make good thermal contact to the box itself to cool it and maintain its temperature

- Requirement: temperature < 1.5 K to minimize radiation
- Wiring heat sinks must be < 1.1 K to minimize heat leaks
- Hot end of sapphire supports must also be < 1.1 K

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

- Trade large microscopic contact area for poorly conducting intermediate layer
- Worked well on SPIRE

SCUBA-2 – 1-K box

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

So we did something right!

What did we do right?

- **More generally….**
- Thermal design treated as integral; large amount of effort (not something you bolt on afterwards)
- Project team *experienced*, and *at this temperature range* (100 mK is not 2 K!)
  - Thermal design not always treated as seriously as it should be?
- Experience from outside astronomy on review boards
- Detailed thermal model updated in parallel with mechanical design
- Subsystems tested before finalising design where possible; otherwise large margins used

Subsystems

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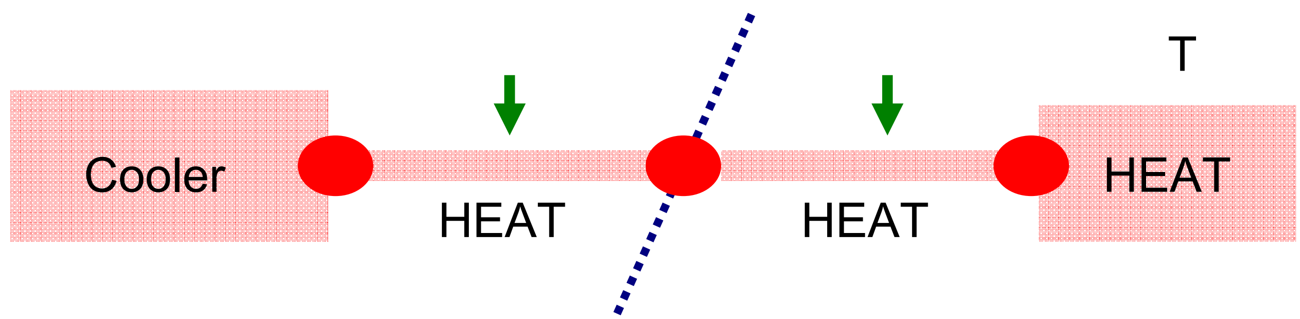
- Problems with splitting cryogenic systems into separate subsystems
  - Example: far end has maximum tolerable T
  - Must divide into contribution from each subsystem
  - Each subsystem needs power budget. Cooler temperature depends on power
  - BUT we have to set these budgets *before* detailed design, yet we don't know appropriate values at this point
  - We've now turned a simple system with one requirement (T) into something much more complex



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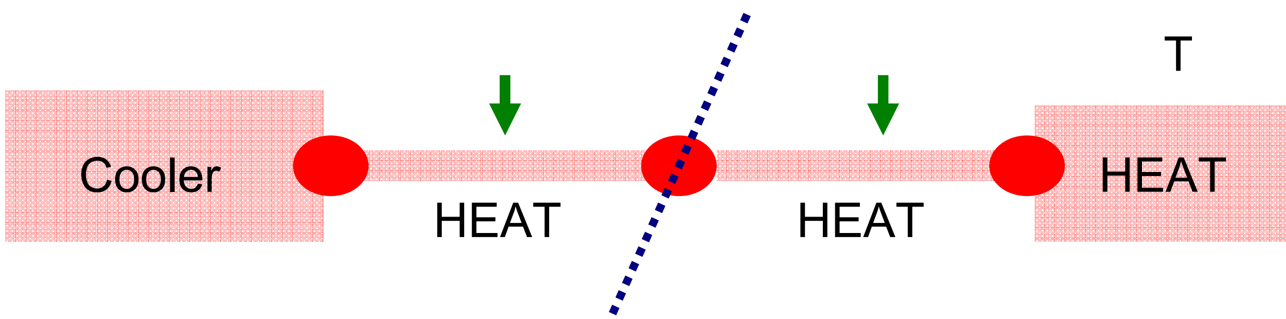
Subsystems

- Probably can't avoid splitting into subsystems. But can:
  - Define carefully, basing not entirely on mechanical considerations
  - Have strong oversight of overall thermal design
  - Be ready to adjust requirements where necessary



Subsystems

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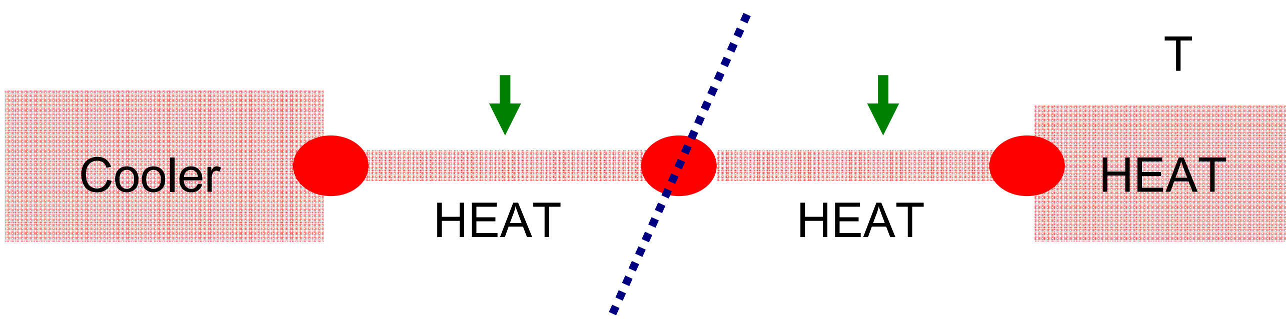
From a mechanical point of view, a bolted joint in a strap is an obvious interface

- But from a thermal point of view this is a subsystem, which should be designed and tested in one piece
- (And whose thermal budget does the temperature drop across the interface come out of?)



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What did we do wrong?

- Decoupled thermal and mechanical design too much after initial design
  – Elegant thermal design was corrupted piece by piece to meet mechanical requirements

- Didn't have time to test all sub-components
  – Had to overengineer
  – Unlikely to be an option for ULT space missions!

What did we *have* to do wrong?

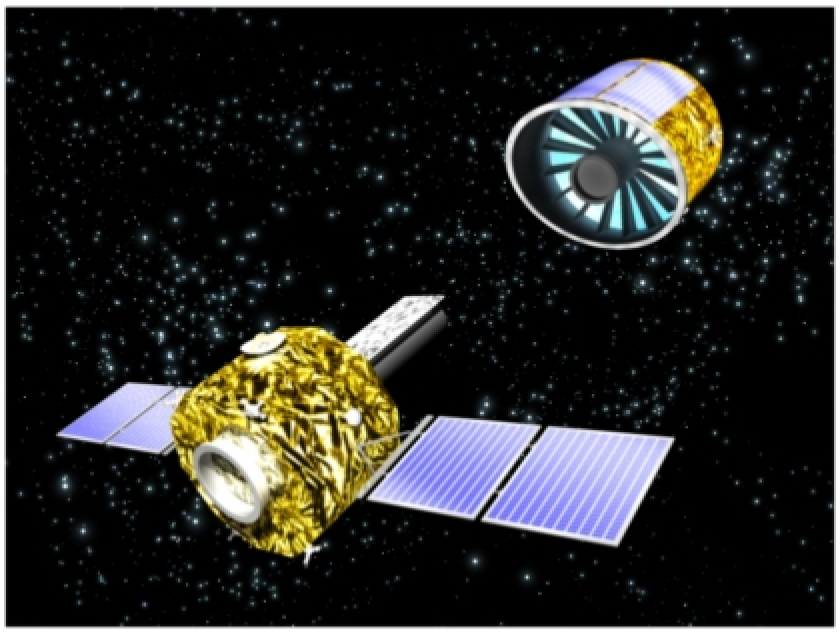
- Limited design by concentrating on materials which have already been measured

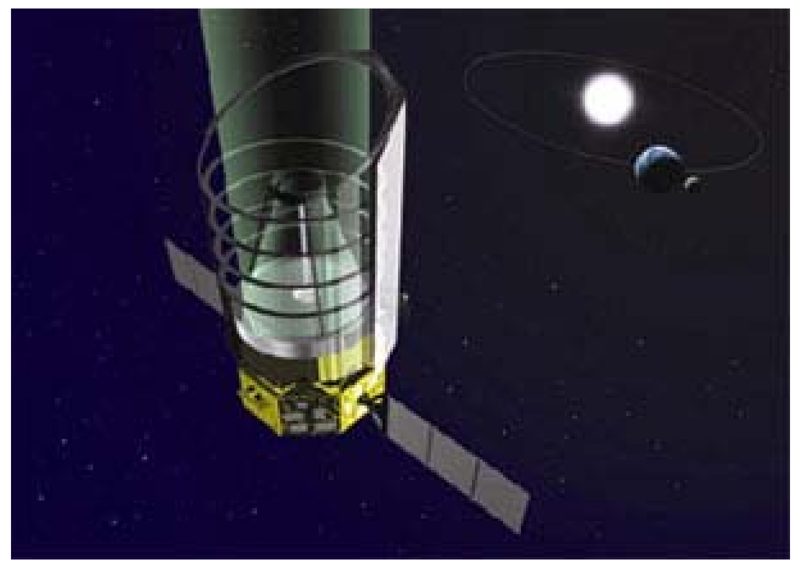
- Stopped tests as soon as we had a good enough solution for SCUBA-2
  - With further testing could have developed more generic solutions and more understanding of principles

- These are near universal problems
  - Something needs to be done!

Conclusions

- There will be great challenges ahead for ultra-low temperature cryogenic space missions
- We *must* learn from experience (good and bad) with current ground and space instruments!





Summary

- “A little knowledge is a dangerous thing”

- “It's not what we don't know that's the problem, it's what we know that ain't so”