From the birth of stars to measuring the neutrino mass:

Applied condensed matter physics in space, on mountains, and under them

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

Seminar at Birmingham University, 23rd April 2009

Science & Technology Facilities Council
UK Astronomy Technology Centre

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Outline

Science & Technology Facilities Council
UK Astronomy Technology Centre

- Sub-mm astronomy and SCUBA-2
  - SCUBA-2 cryogenics
- SPIRE
- The future
- Beyond astronomy
- Conclusions

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Sub-mm astronomy and SCUBA-2

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…)

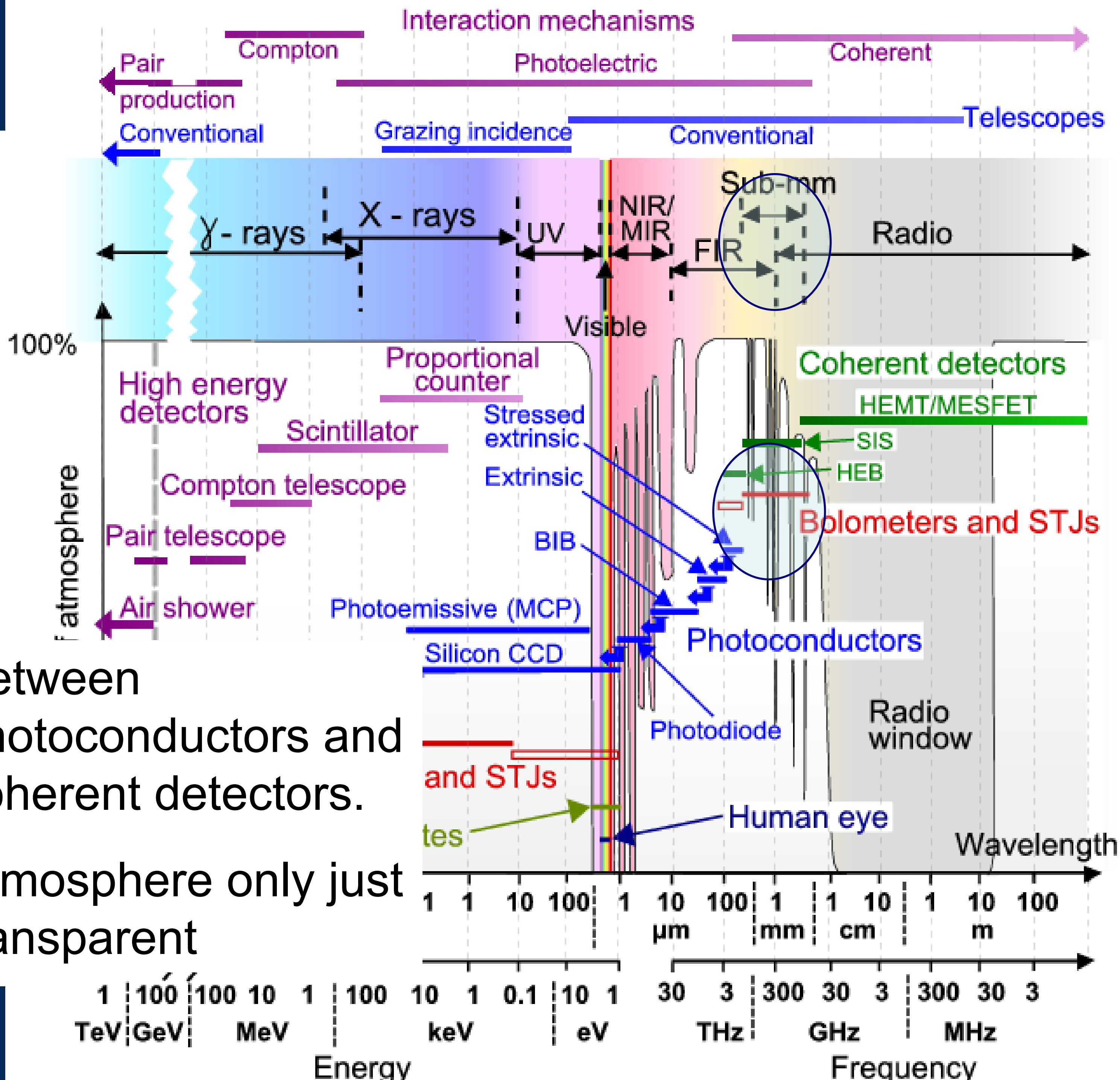
- Sub-mm emission usually "optically thin"; so we see the interior rather than just the surface of objects

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

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…)



Between photoconductors and coherent detectors.

Atmosphere only just transparent

Applications

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

Development largely in universities and government labs rather than industry

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

The Submm Revolution

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- Huge revolution in sub-mm astronomy over the past decade – very limited access to this region of the spectrum before
- SCUBA on JCMT has been largely responsible for this:
  - Built at UK ATC in Edinburgh
  - Produced similar advances that occurred in IR astronomy in the 1980's
  - At the peak of its productivity had a citation rate to rival that of the Hubble Space Telescope

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SCUBA on the JCMT

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- One of the first imaging "arrays" for the submm
- 128 pixels in two arrays
- Detectors cooled to 100 mK with dilution refrigerator (highest DR in the world?)
- Came into service in 1997
- Made a number of seminal discoveries
- Retired from service in 2005
    - DR broke

SUBMILLIMETRE COMMON USER BOLOMETER ARRAY
SCUBA

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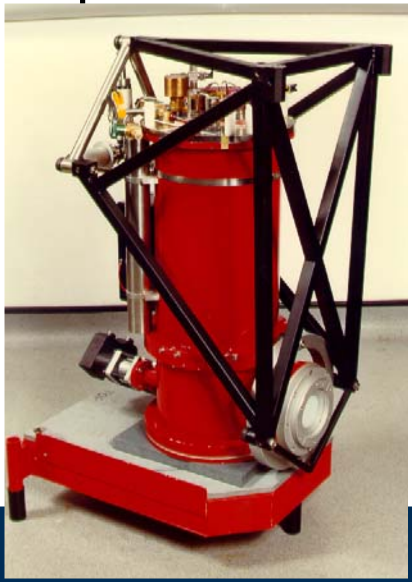
SCUBA-2

- Instruments limited by small number of pixels
    - Gone from 1 pixel to 100s in a decade – need more!
- Detector development in relative infancy

UKT14
1986-1996
1 pixel

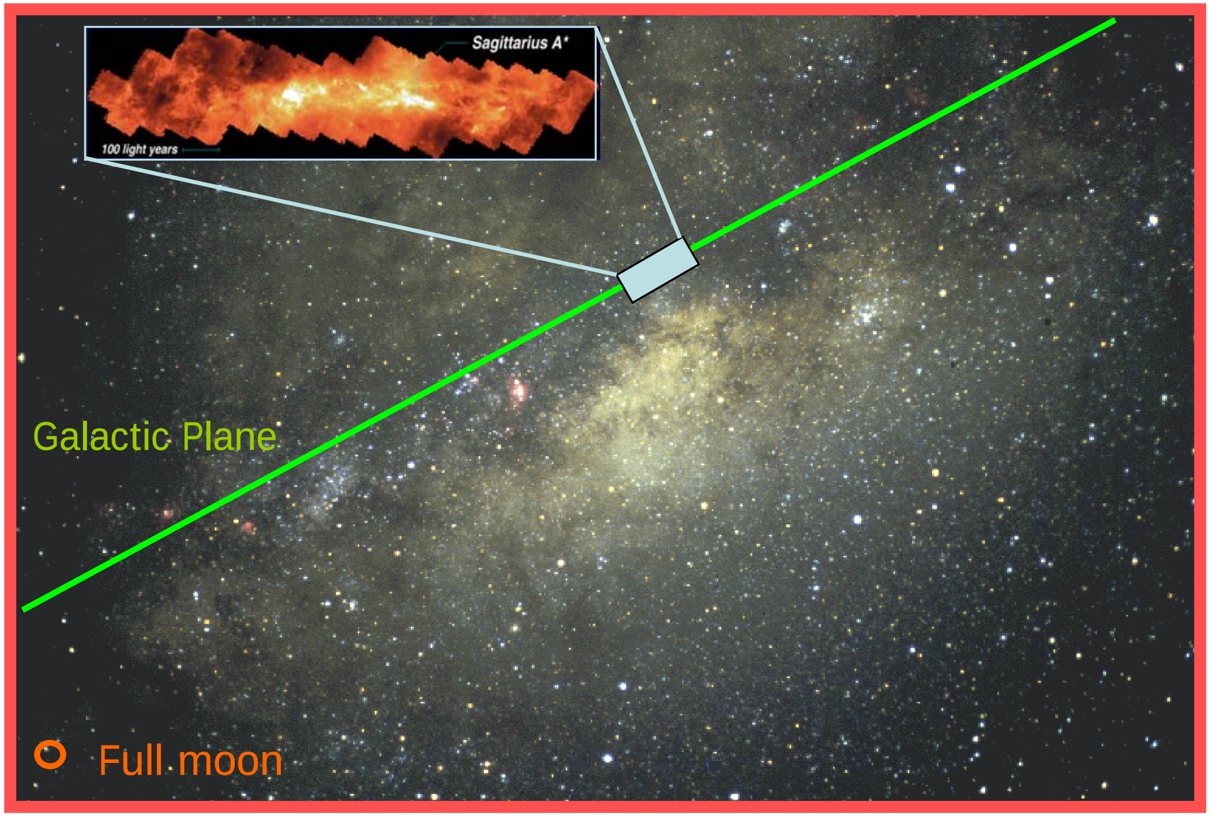


SCUBA
1997-2005
128 pixels

SCUBA-2
2009+
10240 pixels

SCUBA-2

Survey potential



SCUBA Galactic Centre Survey

⇩

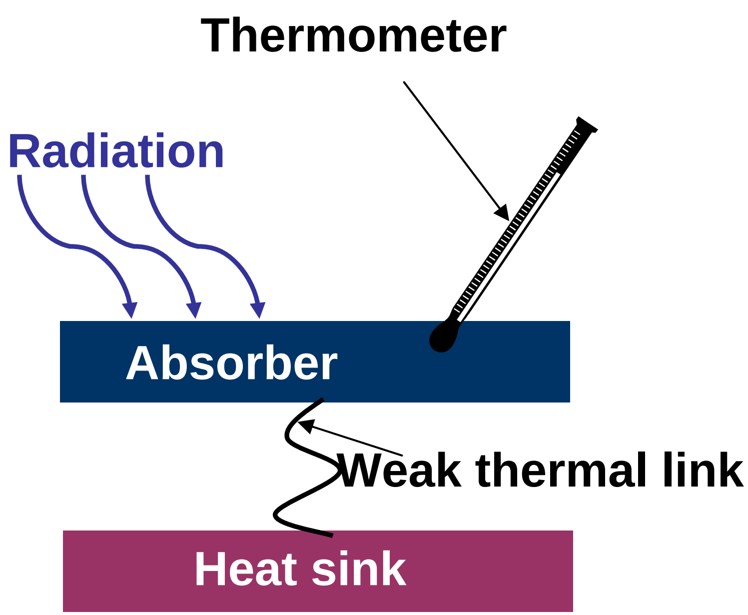
~15 shifts (or 120 hrs) over 2 years

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...

Can do large scale surveys for the first time (currently only area similar to a few full moons explored in any depth)

Bolometer schematic



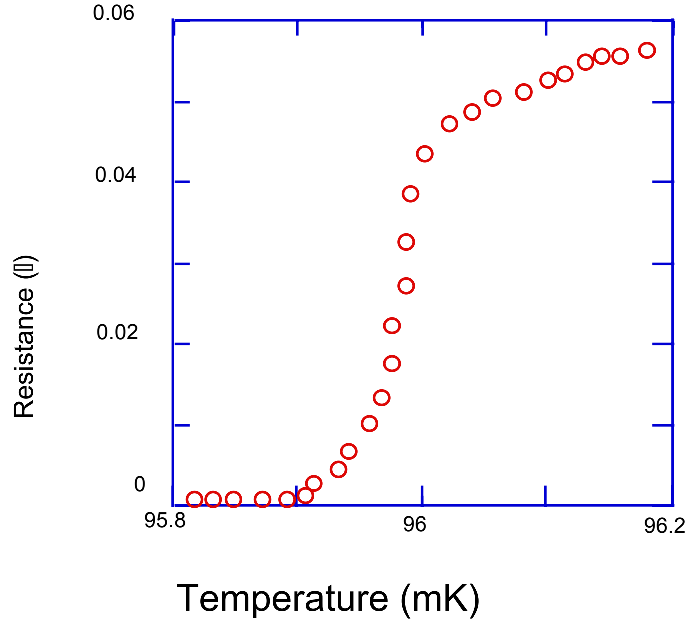
Superconducting bolometers

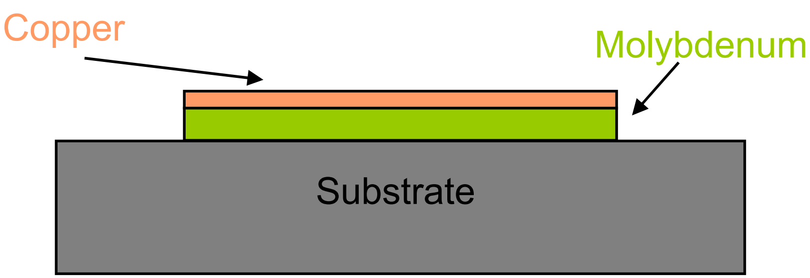
Superconducting detectors (transition edge sensor; TES)

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

Bilayer to tune Tc through proximity effect

Responsivity 1/V





Superconducting bolometers

Advantages:

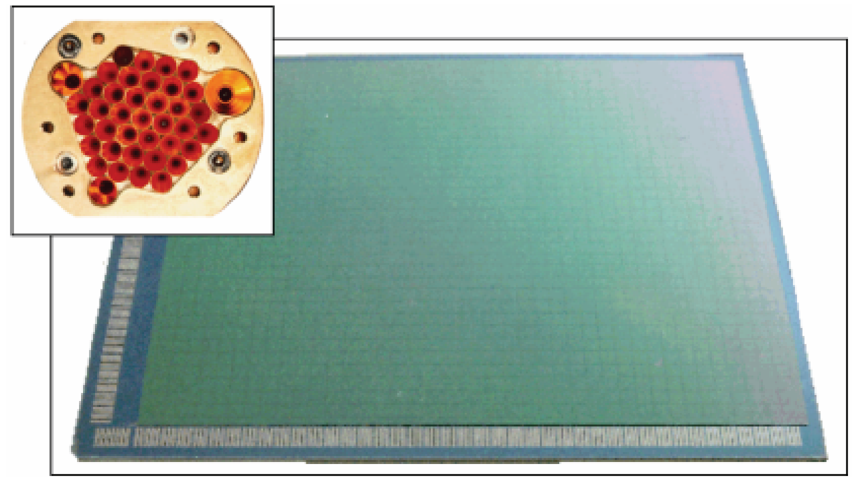
- High sensitivity
- Low fundamental noise limits
- Can be constructed on an array scale by thin-film deposition and lithography
- Can be multiplexed with minimal noise penalty by superconducting electronics

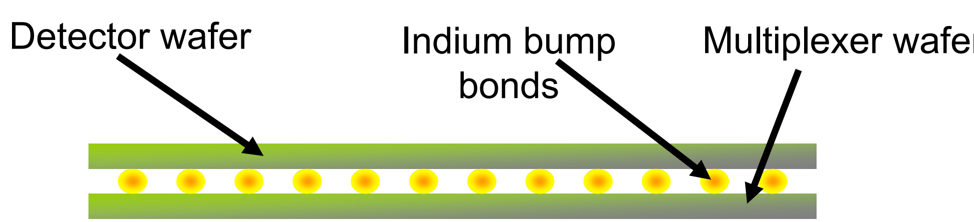
Has taken ~ 10 years to find and eliminate excess noise sources to make TES arrays practical

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

SCUBA-2

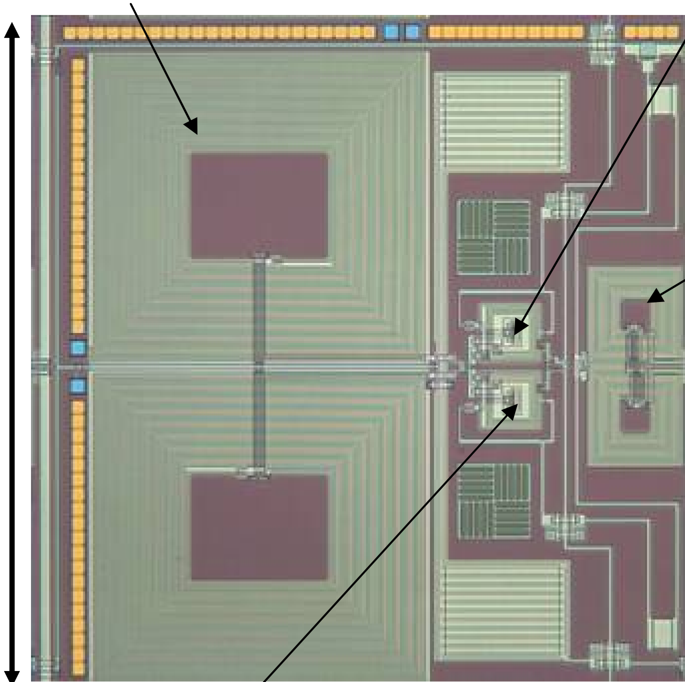
- Most ambitious TES instrument to date is SCUBA-2
- Eight arrays; 1280 pixels each
- Constructed from detector and multiplexer silicon wafer, indium bump bonded together like an infrared array

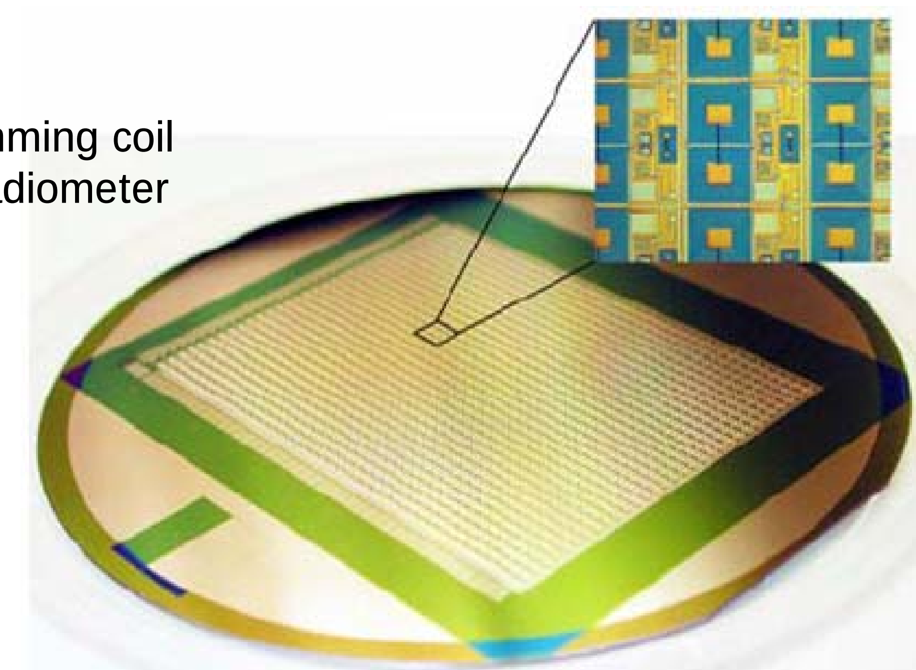




In-focal plane multiplexing

Large array possible only by in-plane multiplexing

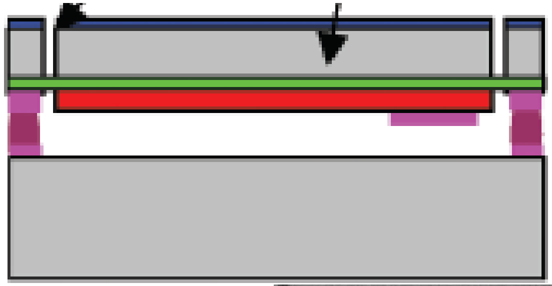


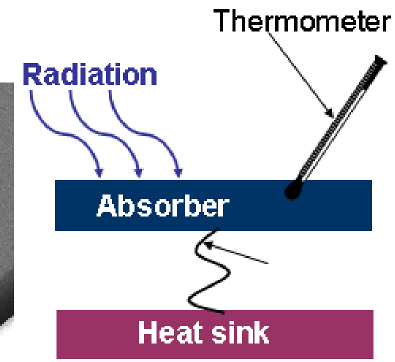


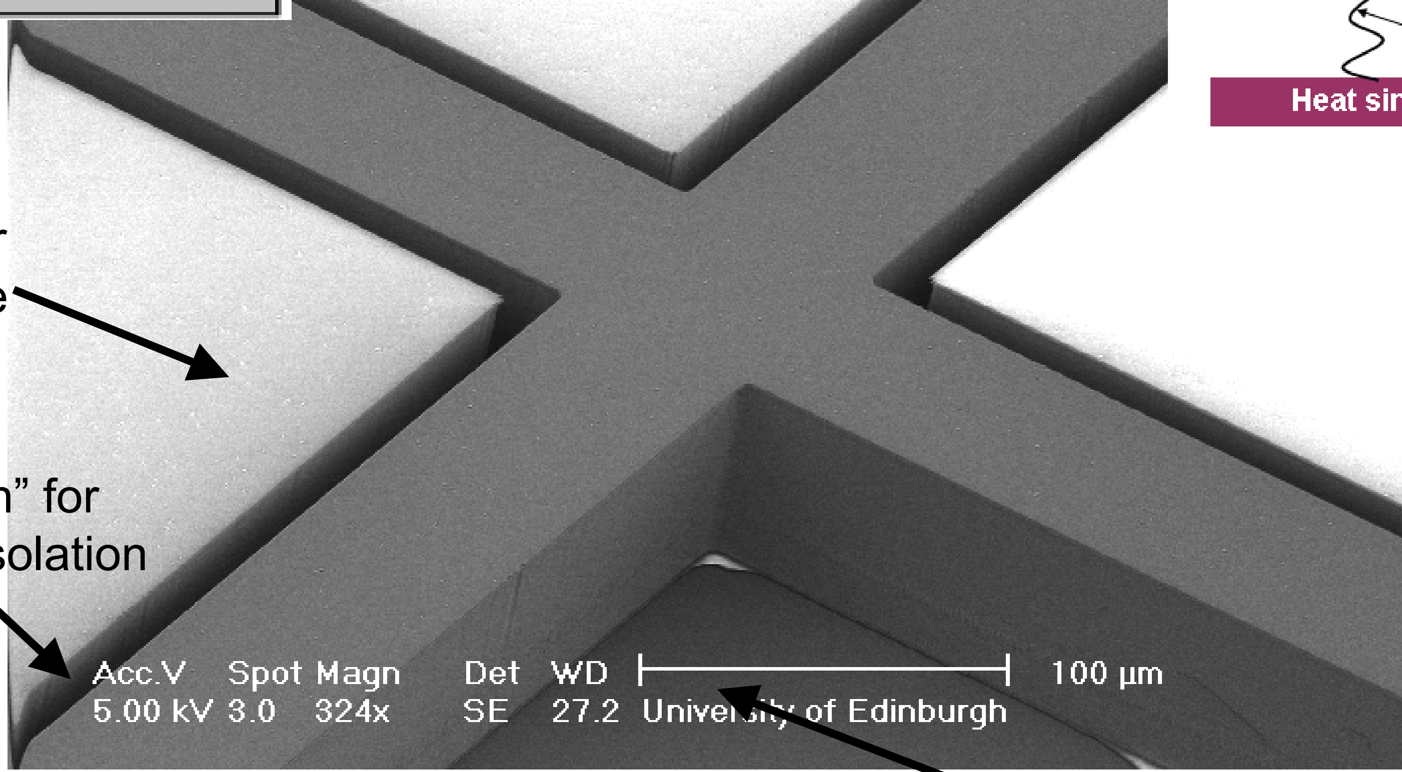
Array scale

NIST
National Institute of Standards and Technology

Silicon micro-machining







Lighter colour due to charge build up

“Trench” for thermal isolation

Missing brick

Institutions

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

Multiplexer and TES devices: *NIST, Boulder*

Detector micromachining: *University of Edinburgh*

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

Warm electronics: *University of British Columbia,* MUX testing, *University of Waterloo*

Telescope infrastructure: *Joint Astronomy Centre, Hawaii*

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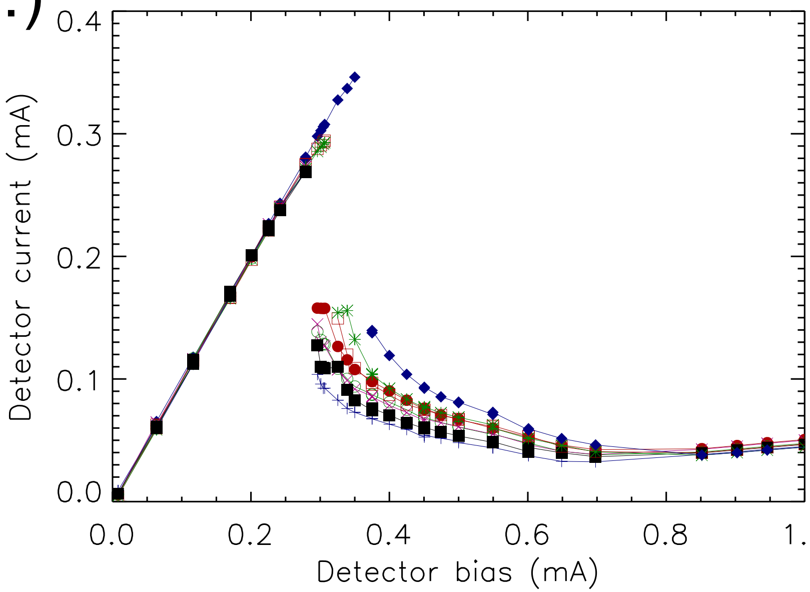
SCUBA-2

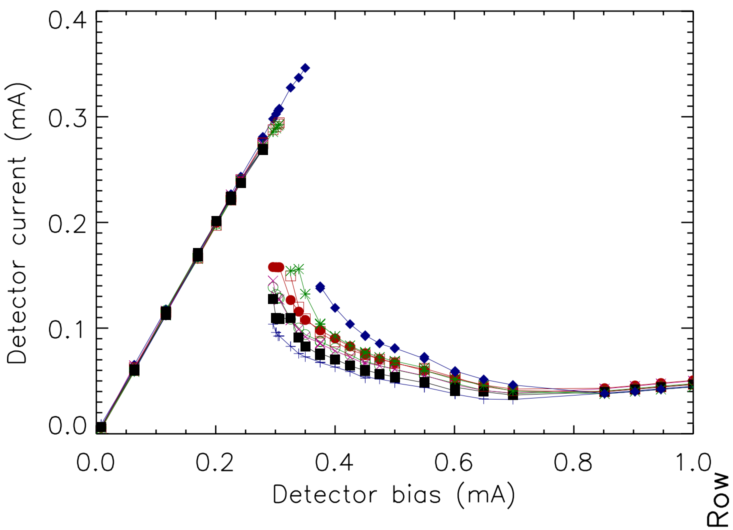
- “SCUBA -2 has been one of the most challenging projects ever undertaken by UK astronomy in that completely new technologies have been needed to realise the ambitious science goals”
- “almost certainly one of the most complex projects that UK astronomers have ever attempted”
- “most sensitive thermal detectors ever built” (measure ~ pW of power)

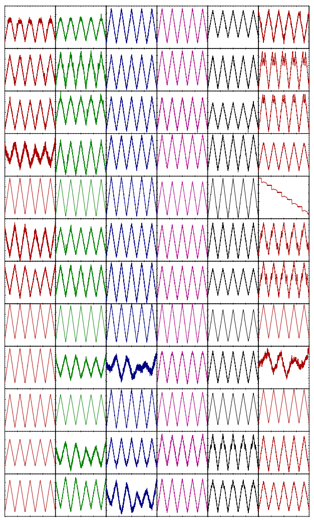
Measurements

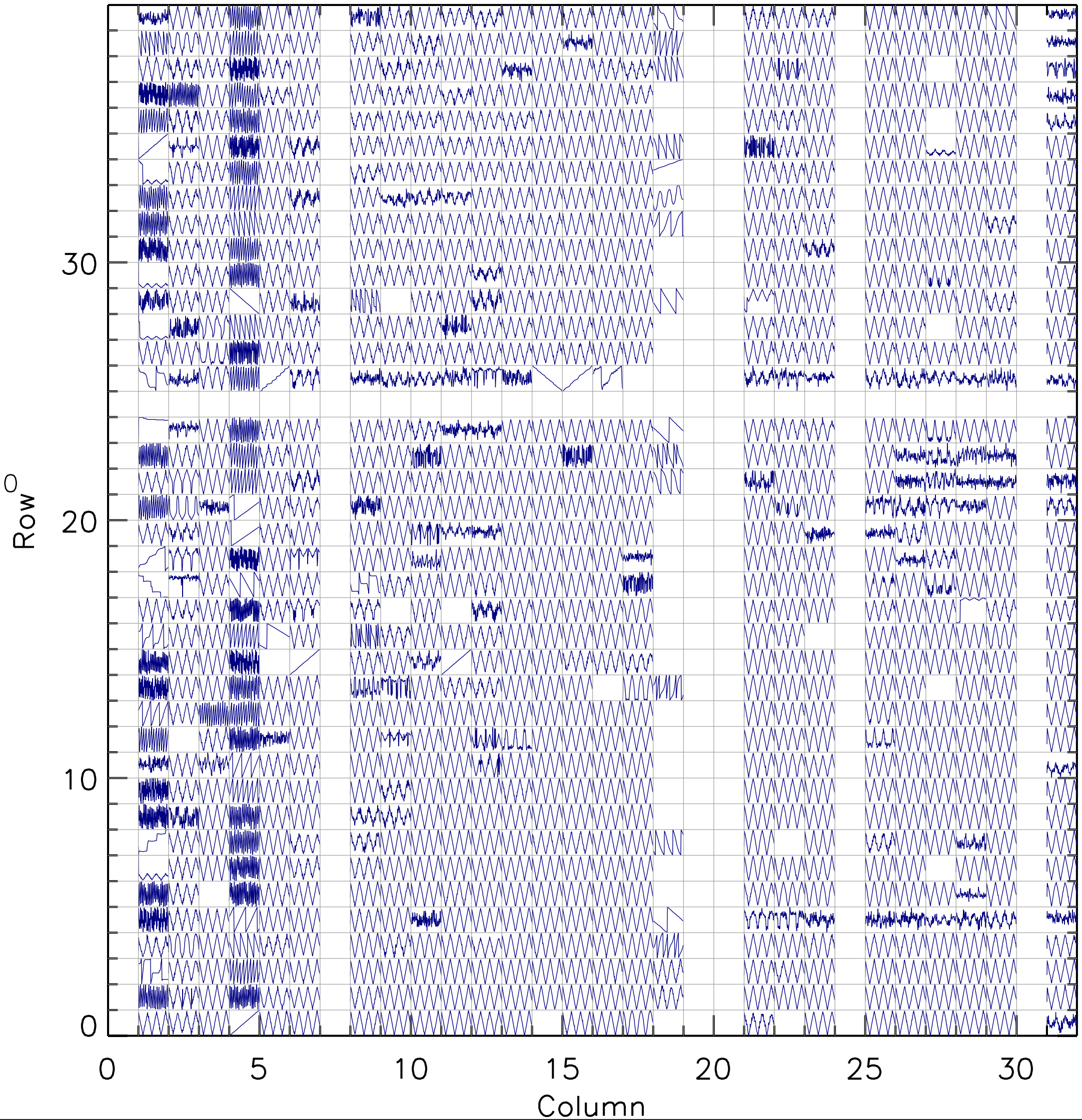
- In-plane MUX changes detector behaviour significantly
- Novel pixel design straight from 1 pixel to full sub-array
- NIST do not have facilities to test such large arrays
- Done by team in Cardiff
- Modelling detectors to determine basic parameters (e.g. Tc, normal state resistance, load resistance, thermal conductance mutual inductances…)
- Information fed back to NIST for next generation
- Detector development carried out in parallel with instrument design and build



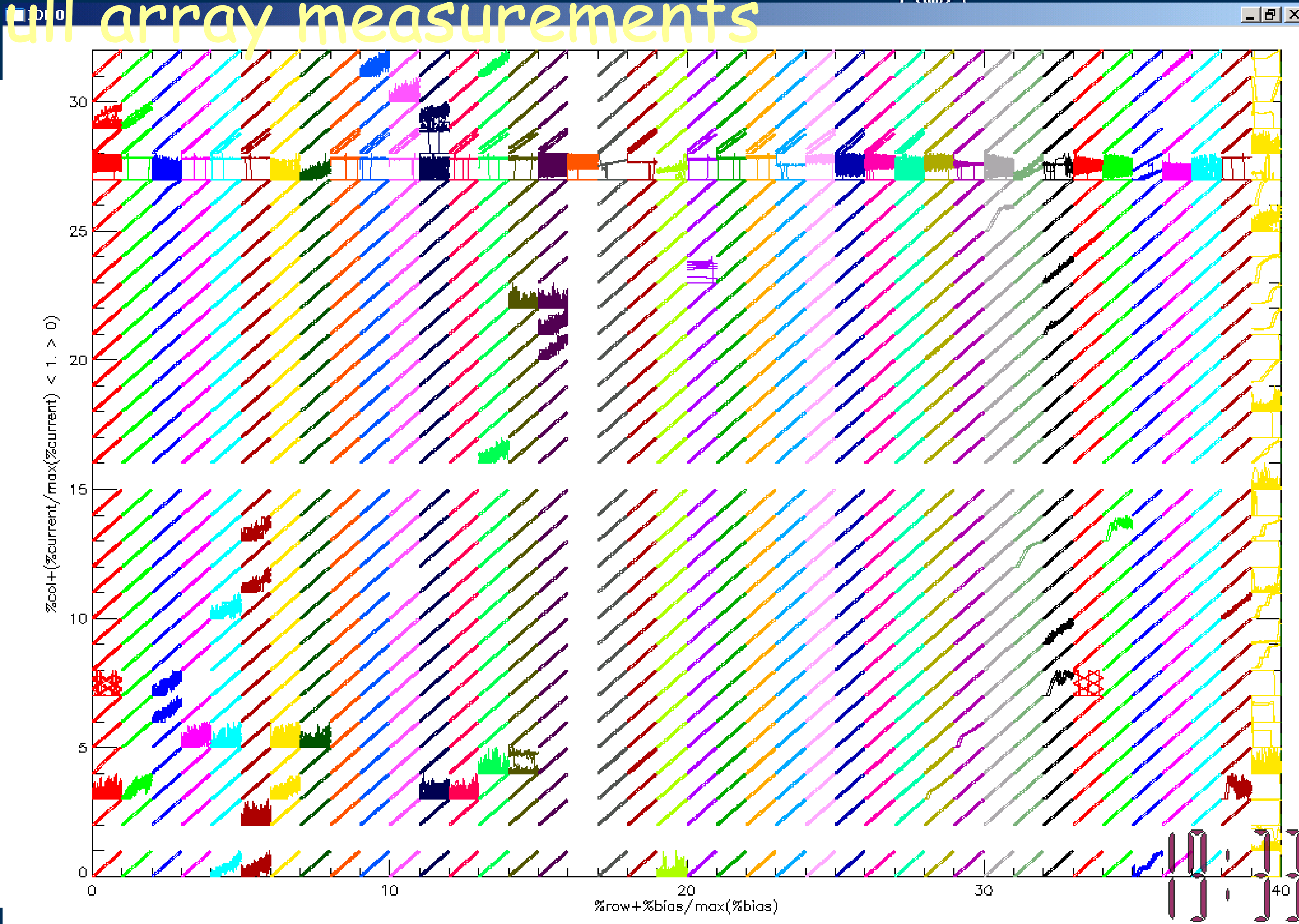
Full array measurements







Full array measurements



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SCUBA-2 croyogenics

Sub-array module

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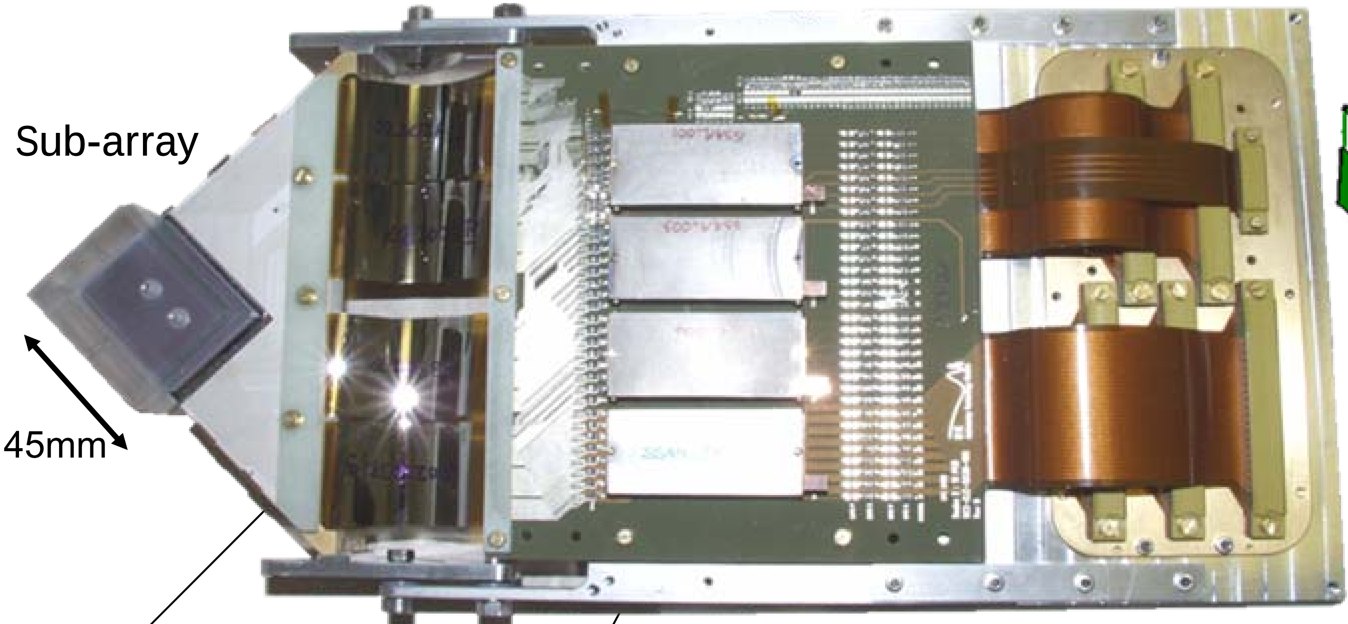
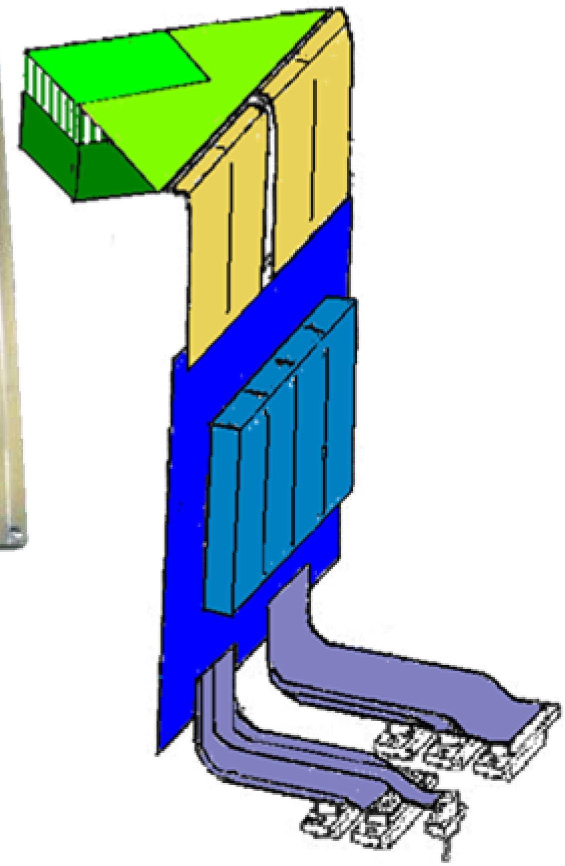
Cryogenics dominates instrument design. Need detectors ~ 100 mK

Sub-array

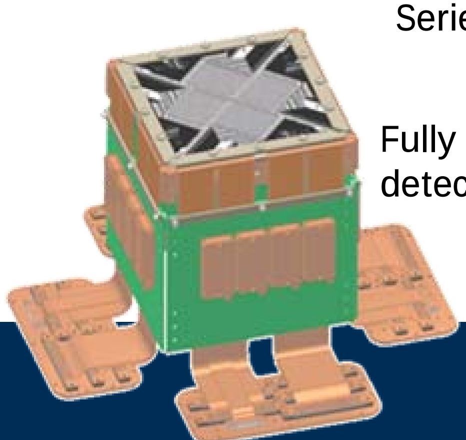
45mm



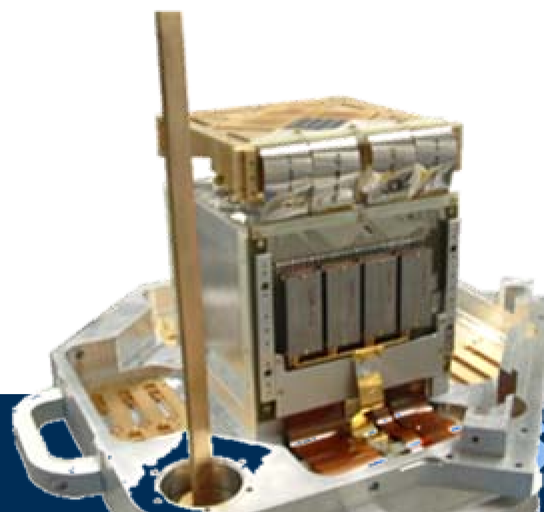


Niobium flex cables

Shielded SQUID Series arrays



Fully populated detector unit



Detector unit with one prototype array installed

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Focal plane layout

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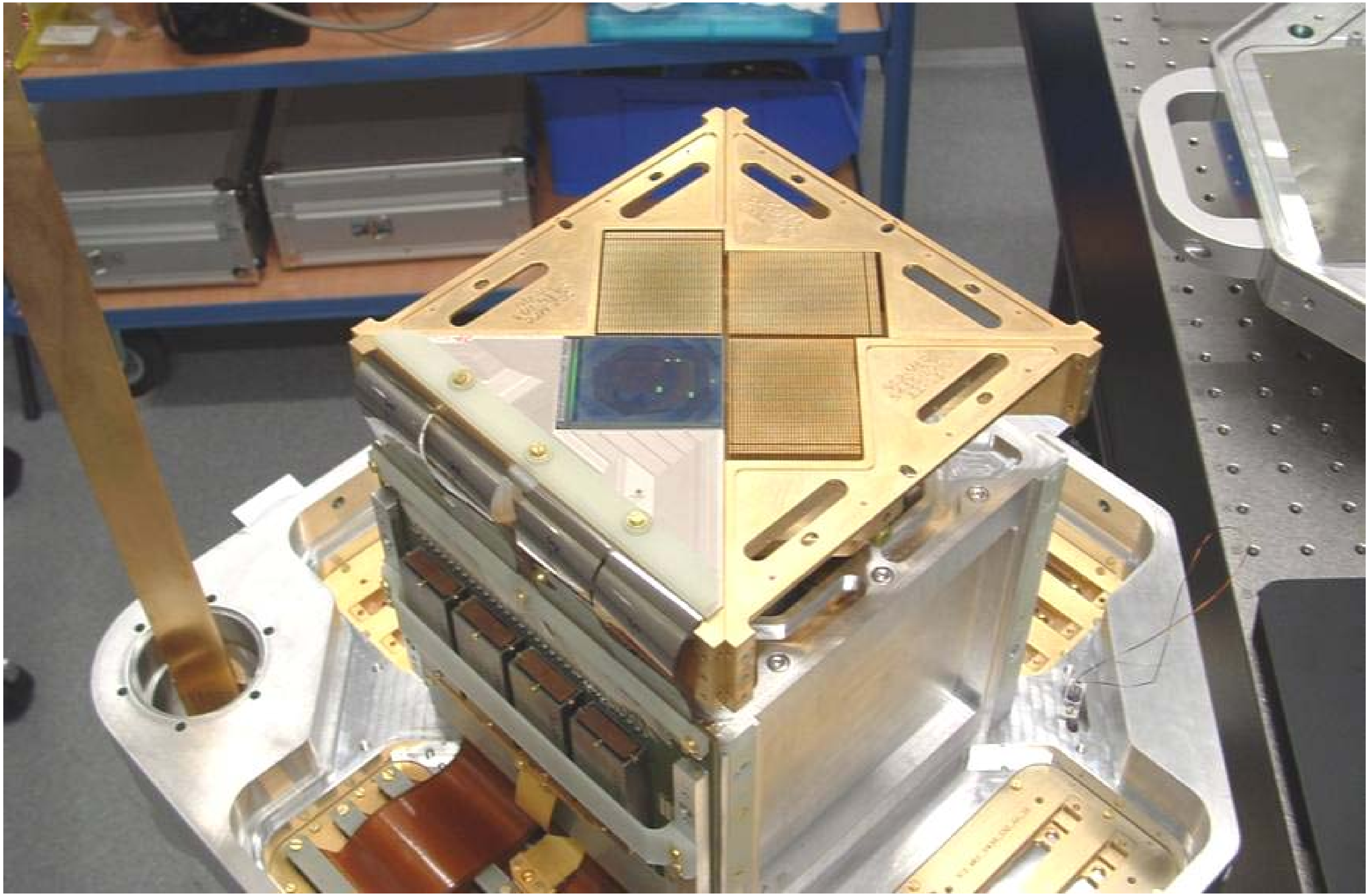

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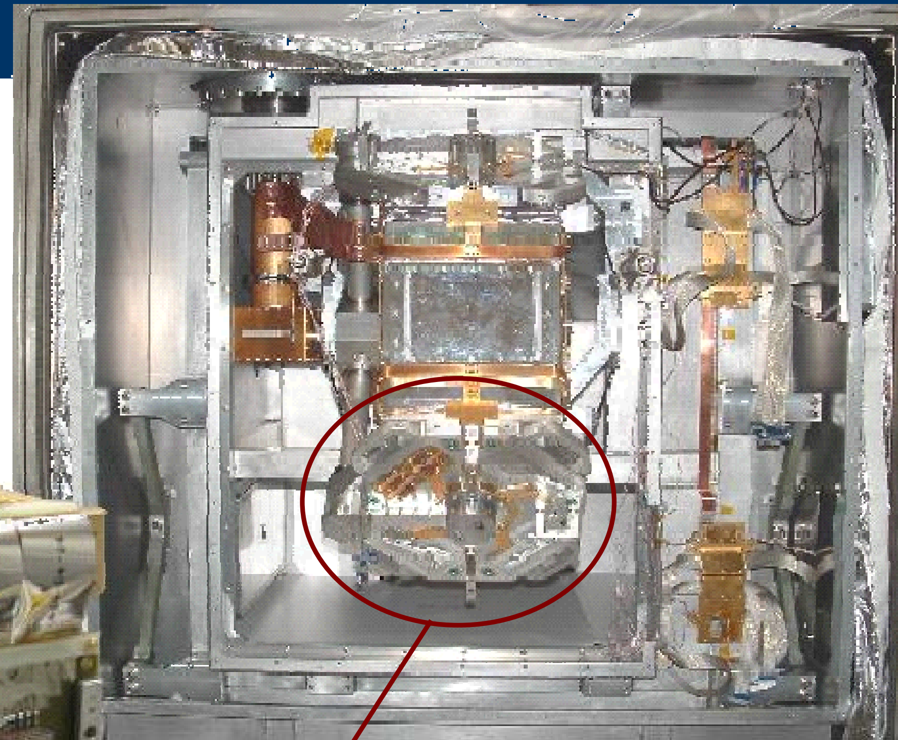
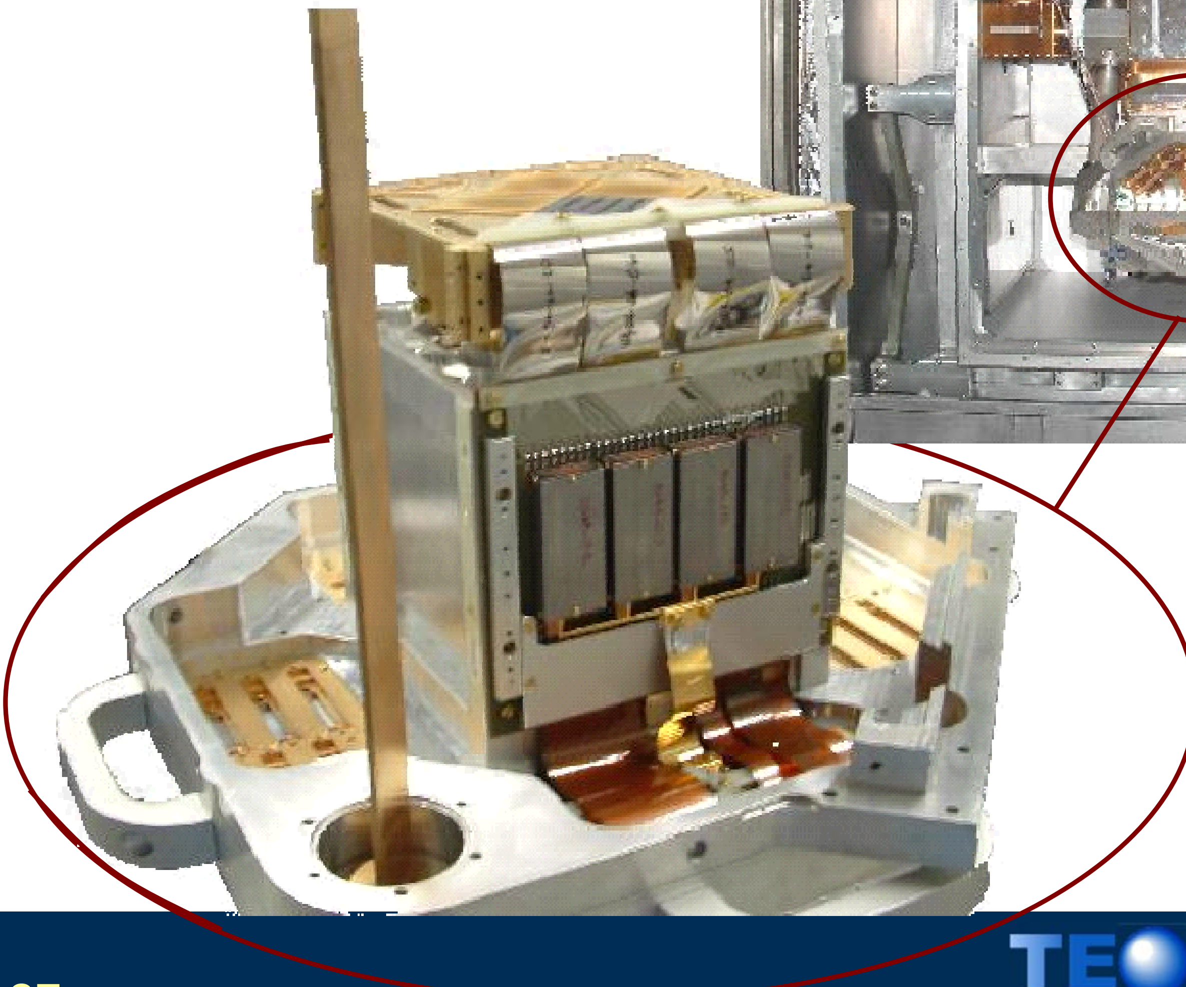
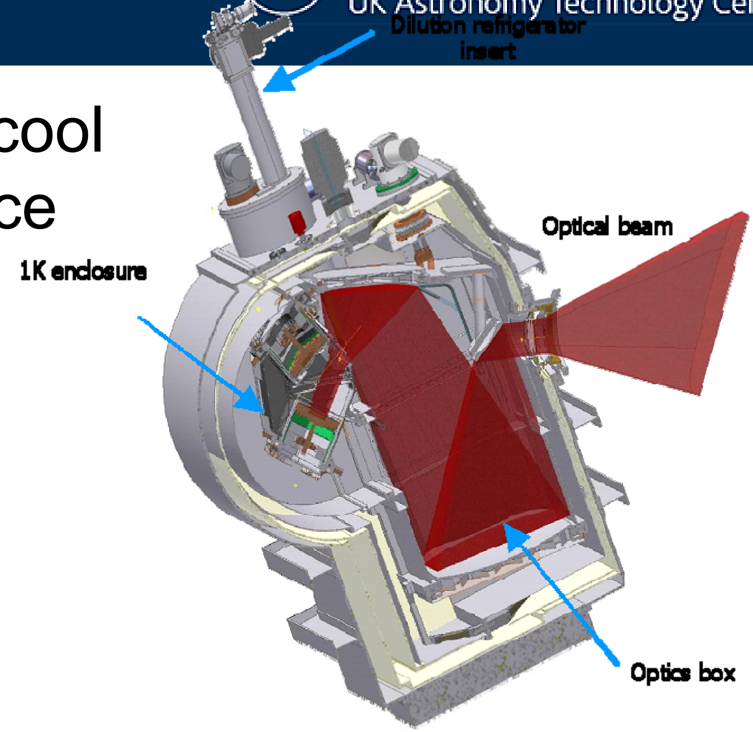
Assembly





Size

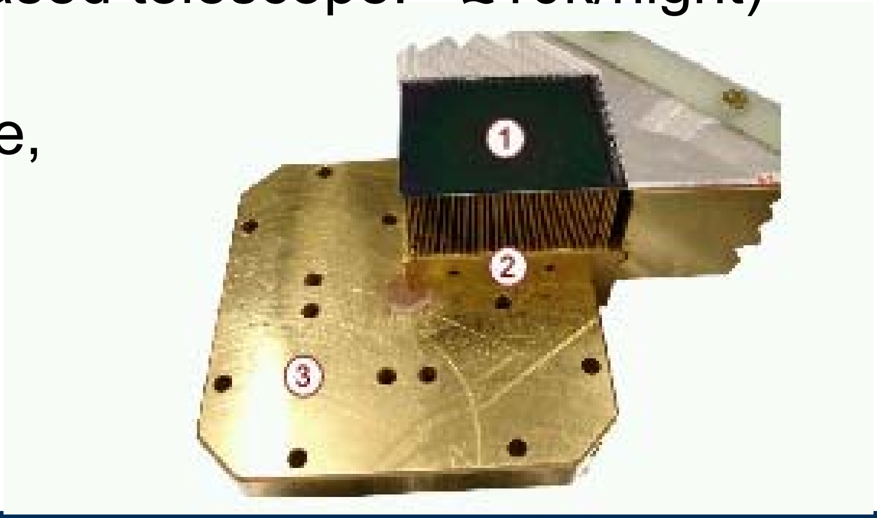
- Instrument size driven by need to cool large mirrors to below 10 K (to reduce thermal background on arrays)



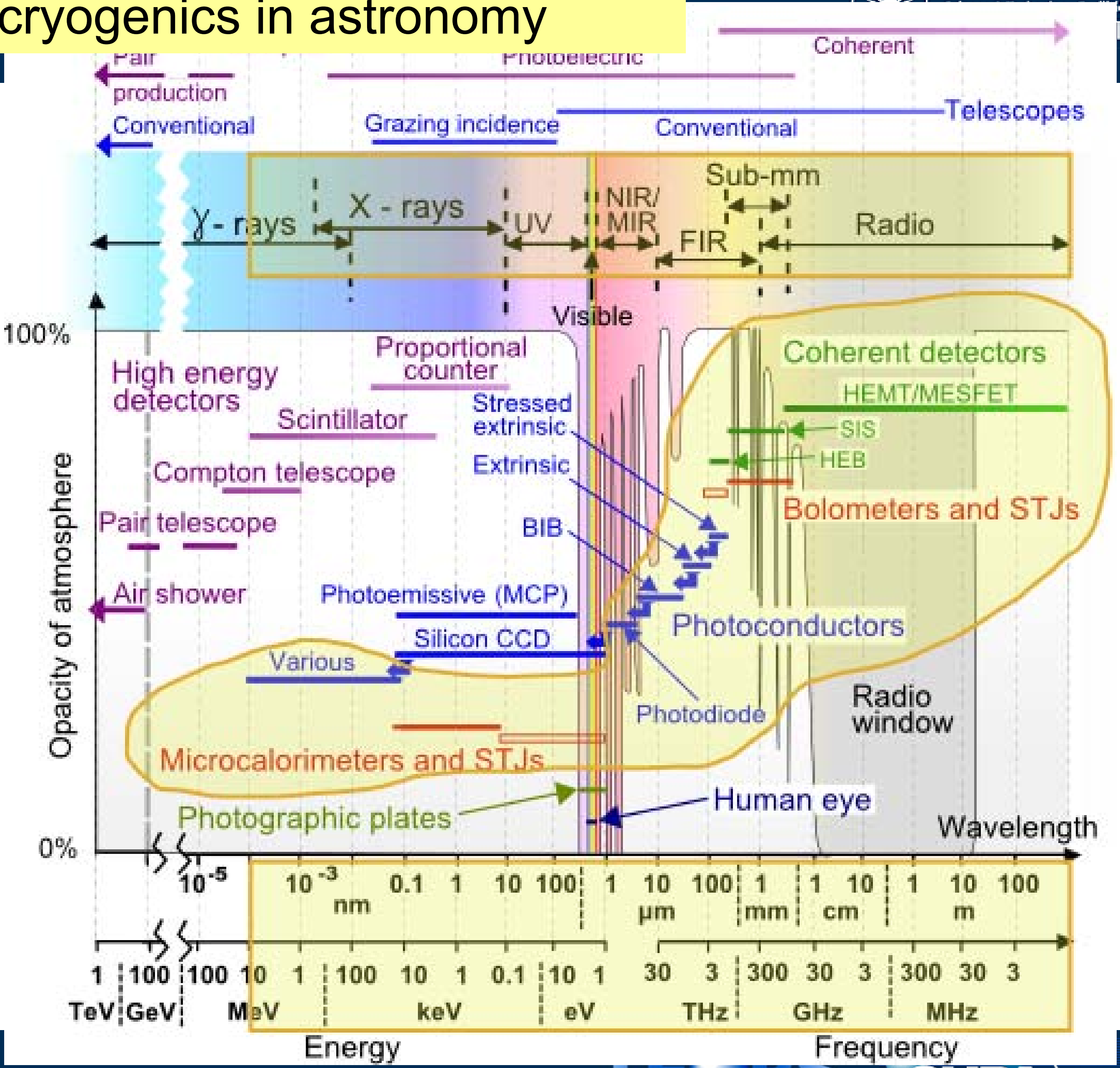
Thermal design

- Few ULT instruments have been built on this scale
    - Unlike most cryogenic experiments, can't rely on tried and tested materials and techniques
- Lack of material property information a big problem (will come back to this later)
- So lots of development required, and some new ideas
- Has to be work in a harsh environment
    - MUST be reliable (ground based telescope: ~£10k/night)

- SCUBA-2 is an extreme example, but cryogenics widespread in astronomy

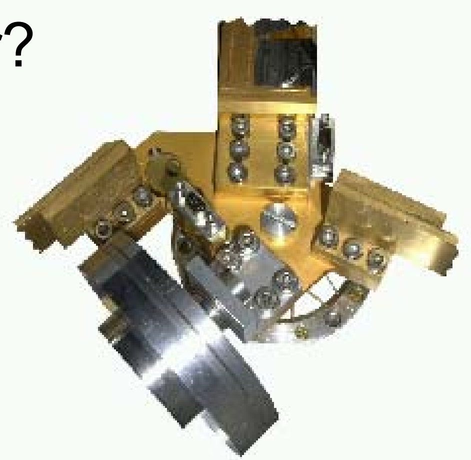


Use of cryogenics in astronomy

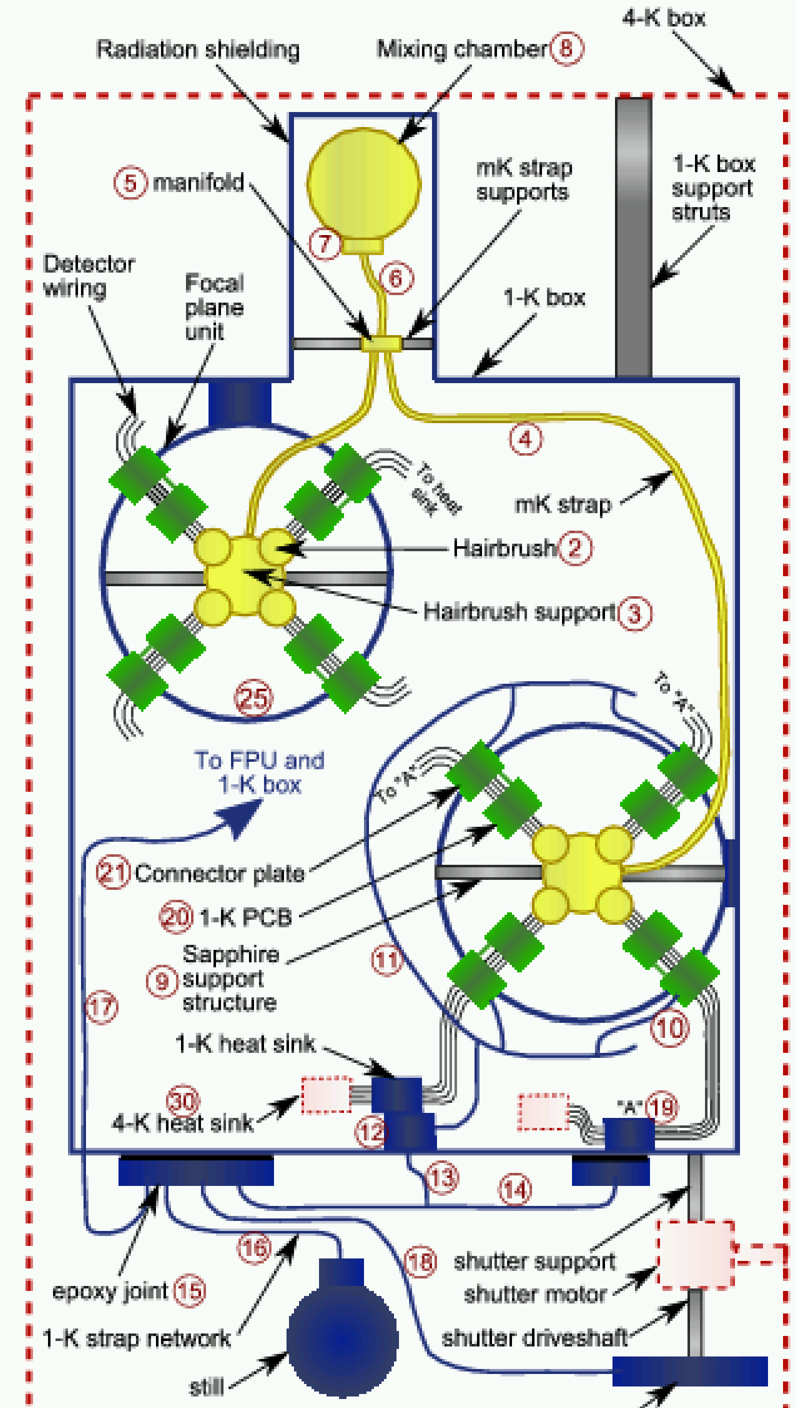


Thermal design

- Large instrument; changes are expensive and time consuming
- Long cooldown-warmup cycle
- So need to get it right!
- Most complex mK instrument ever?



- Two examples…



SCUBA-2 - sapphire support

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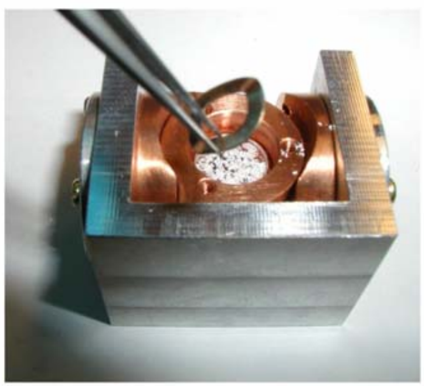
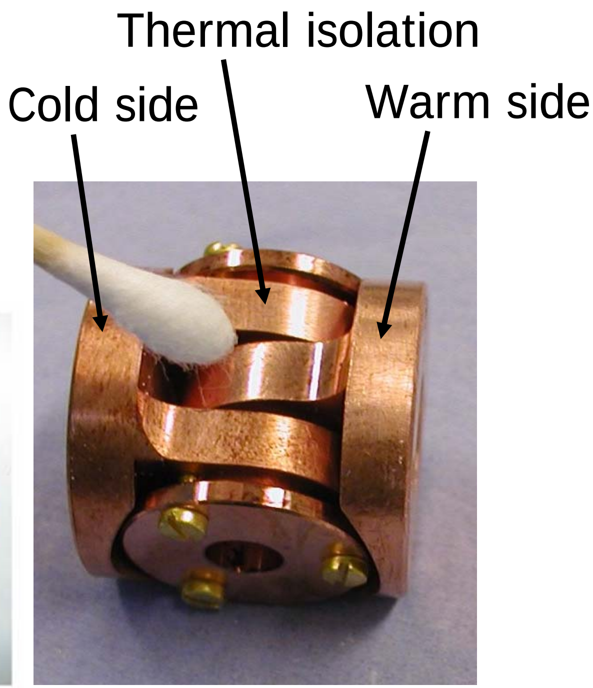
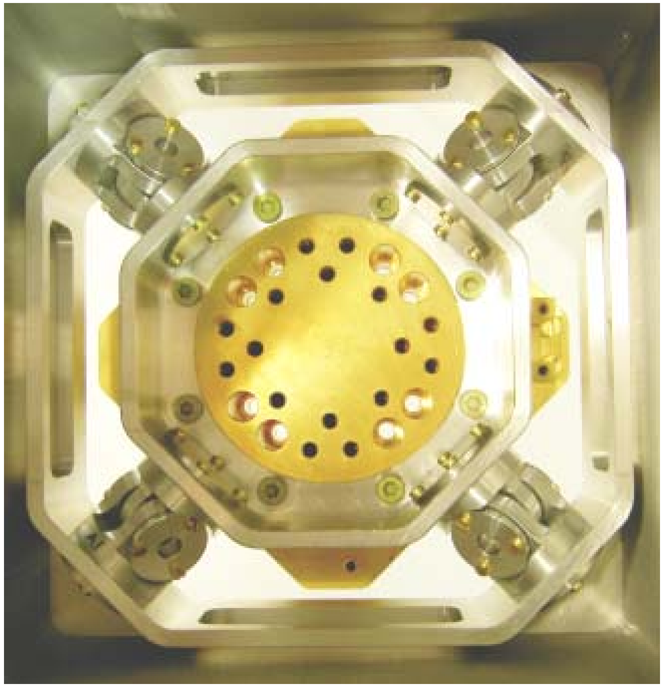
Sapphire thermal boundary isolation supports instead of Kevlar







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

SCUBA-2 - sapphire support

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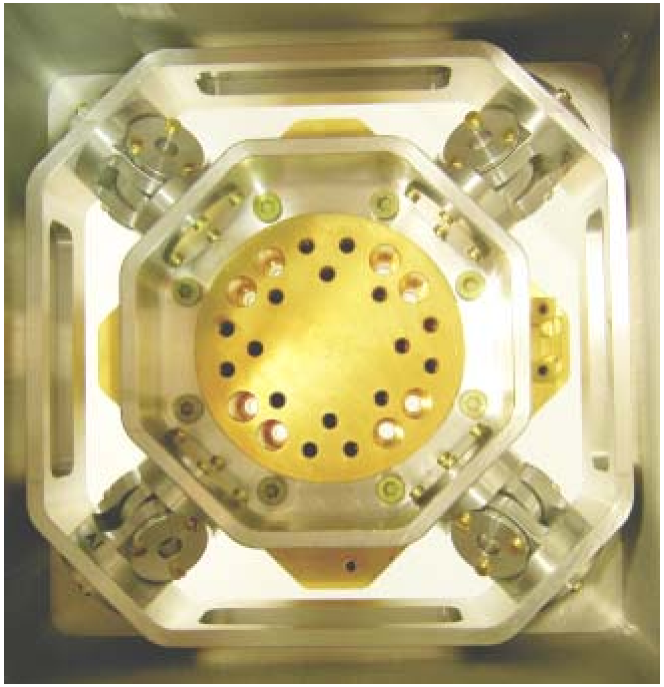
Mechanically extremely robust



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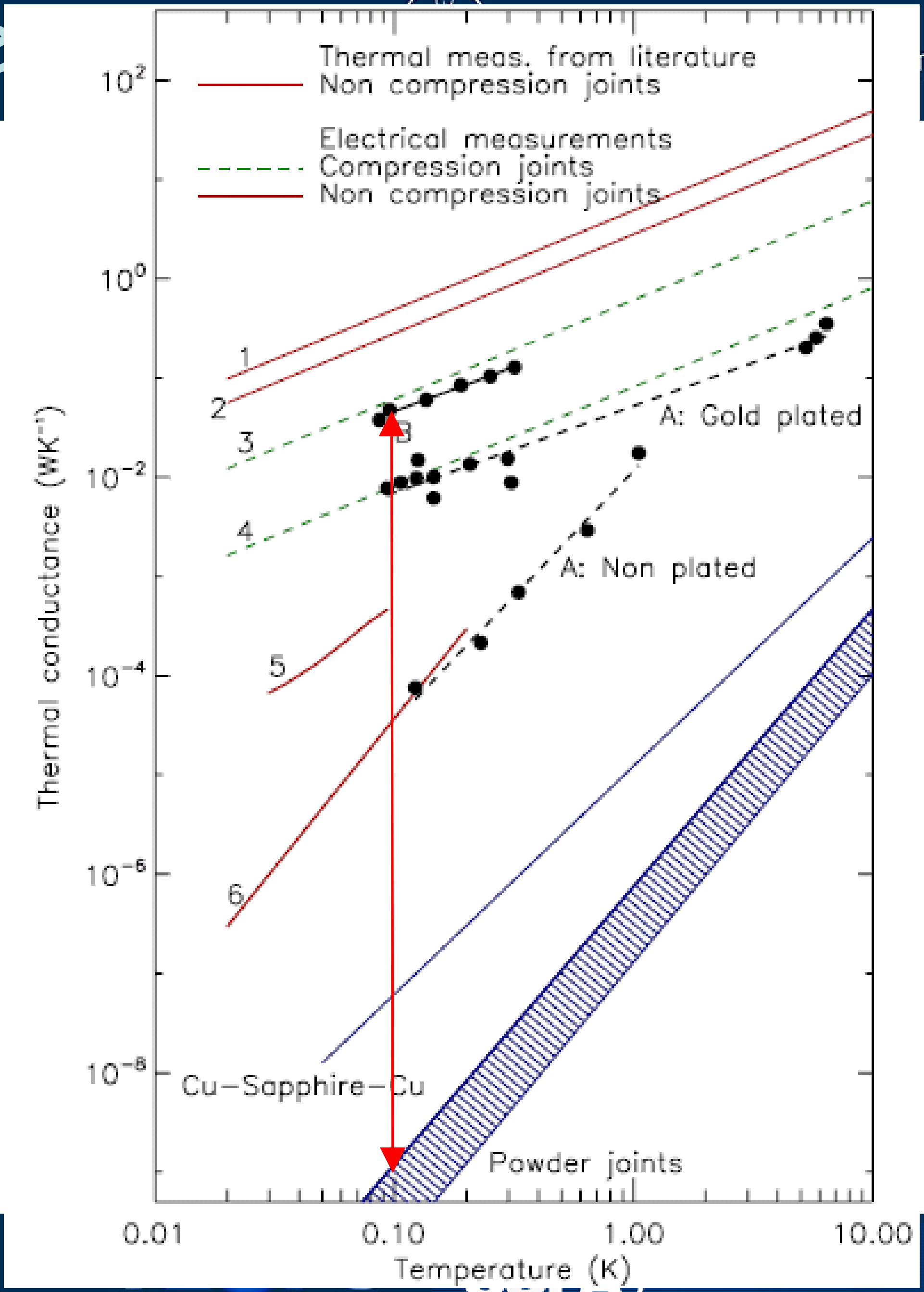
SCUBA-2 - sapphire

- Over 7 orders of magnitude between sapphire joints and bolted conducting joints at 100 mK
    - Highest and lowest direct conductance measurements in literature



"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

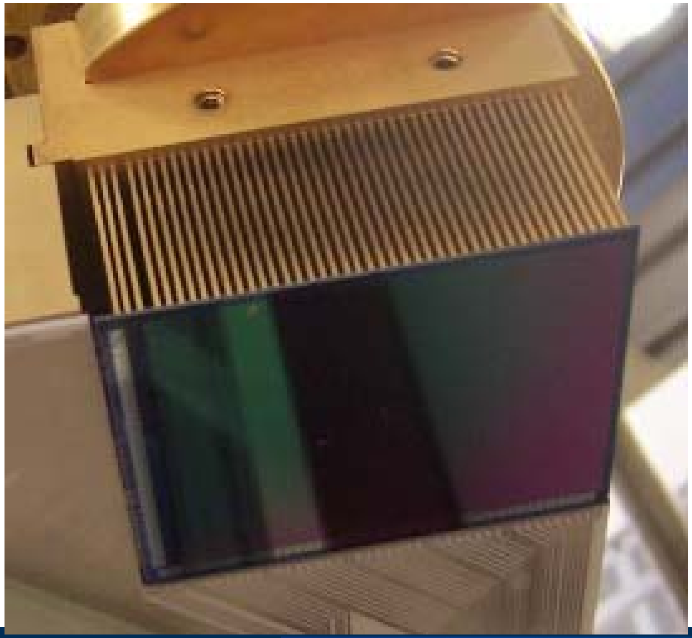
Glueing has to be uniform, musn't bridge the tines

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



Thermal design

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

Packed on a (big) truck...

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Onto the telescope...

SCUBA-2 on JCMT

SPIRE

Herschel

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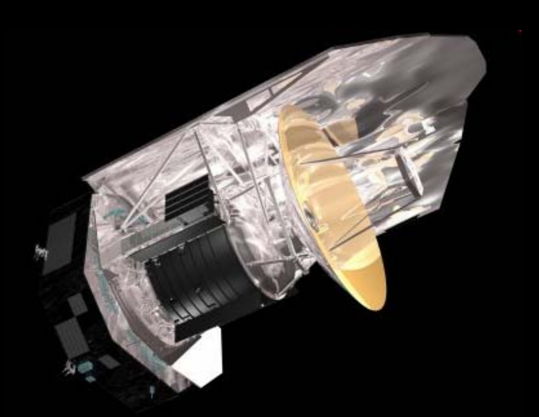
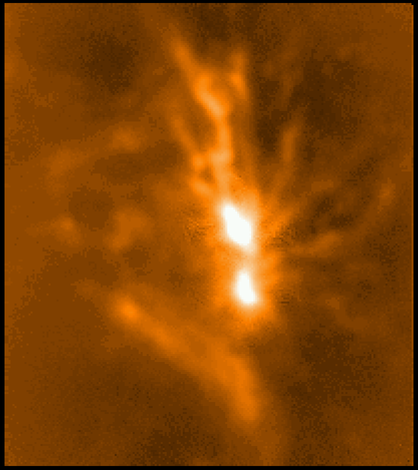
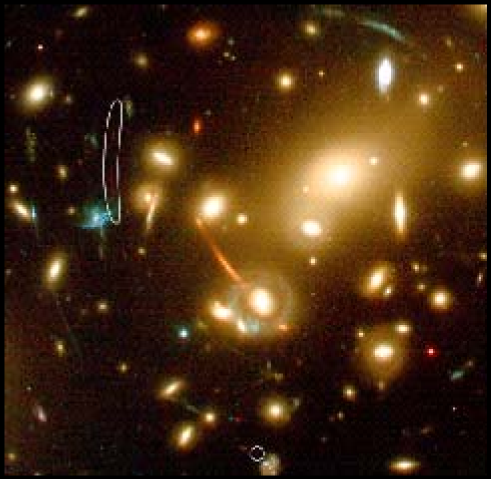
- Study the formation of galaxies in the early universe and their subsequent evolution
- Investigate the creation of stars and their interaction with the interstellar medium
- Observe the chemical composition of the atmospheres and surfaces of comets, planets and satellites







Launch May 2009

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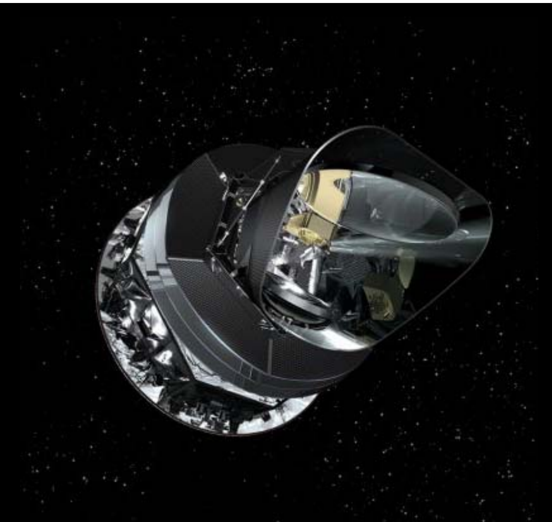
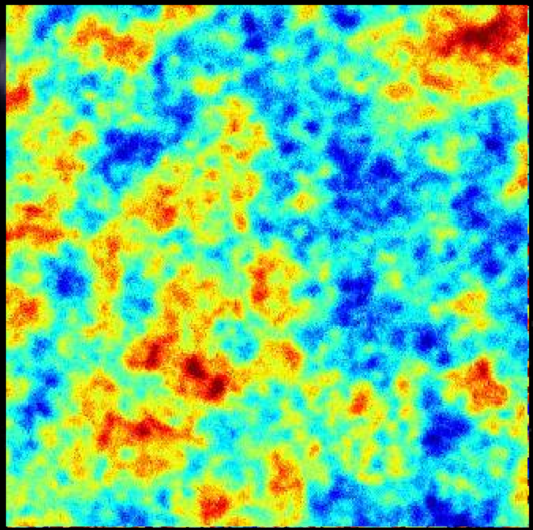
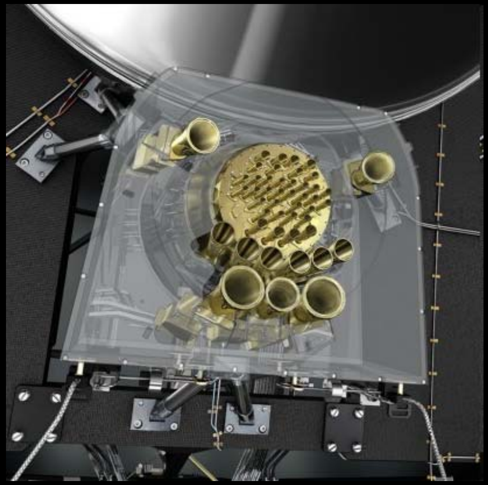
Planck Surveyor

- What are the (more precise) values of fundamental cosmological parameters such as the Hubble constant?
- Can it be shown conclusively that the early Universe passed through an inflationary phase?
- What is the nature of the dark matter that dominates the present Universe?

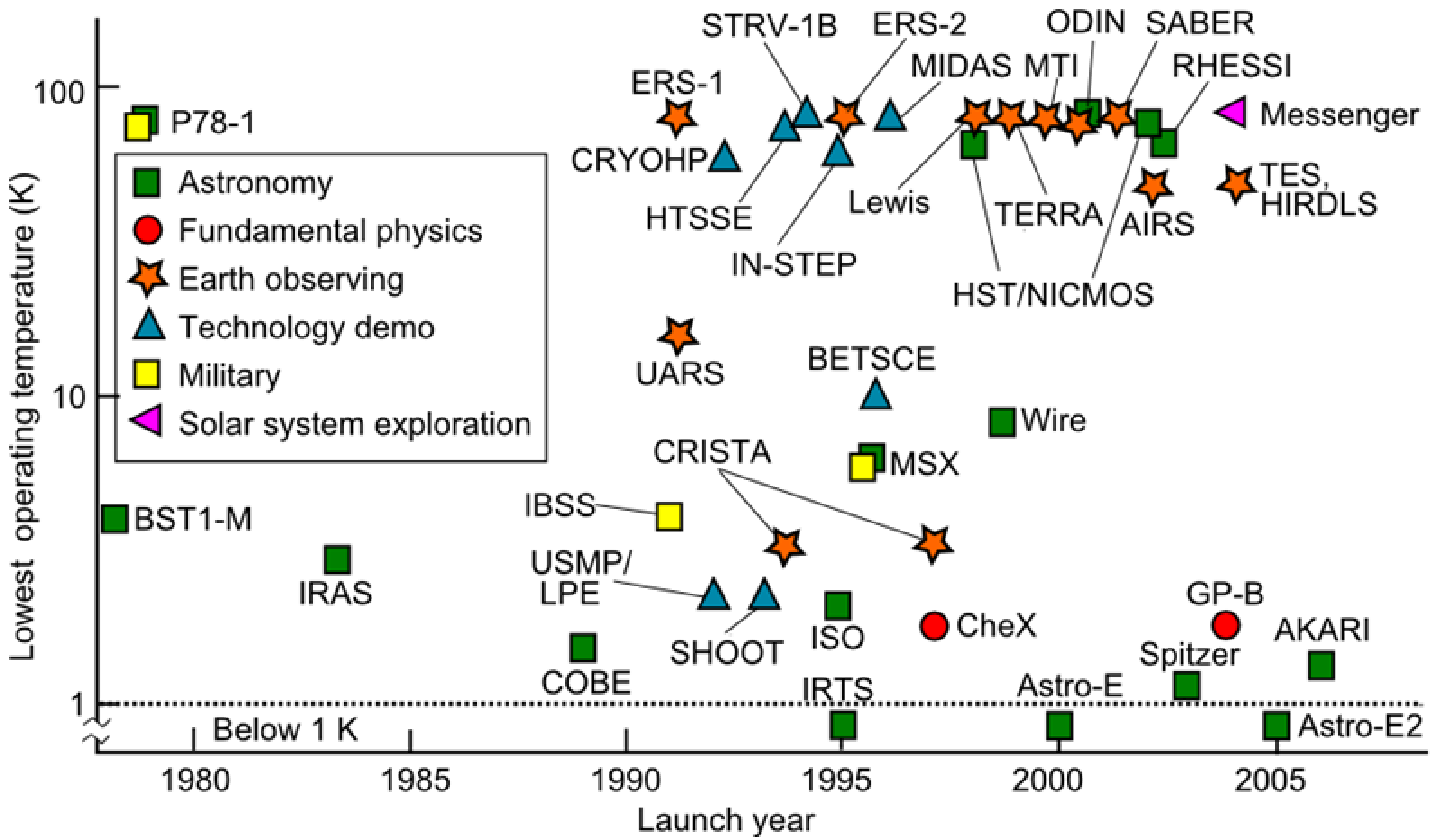






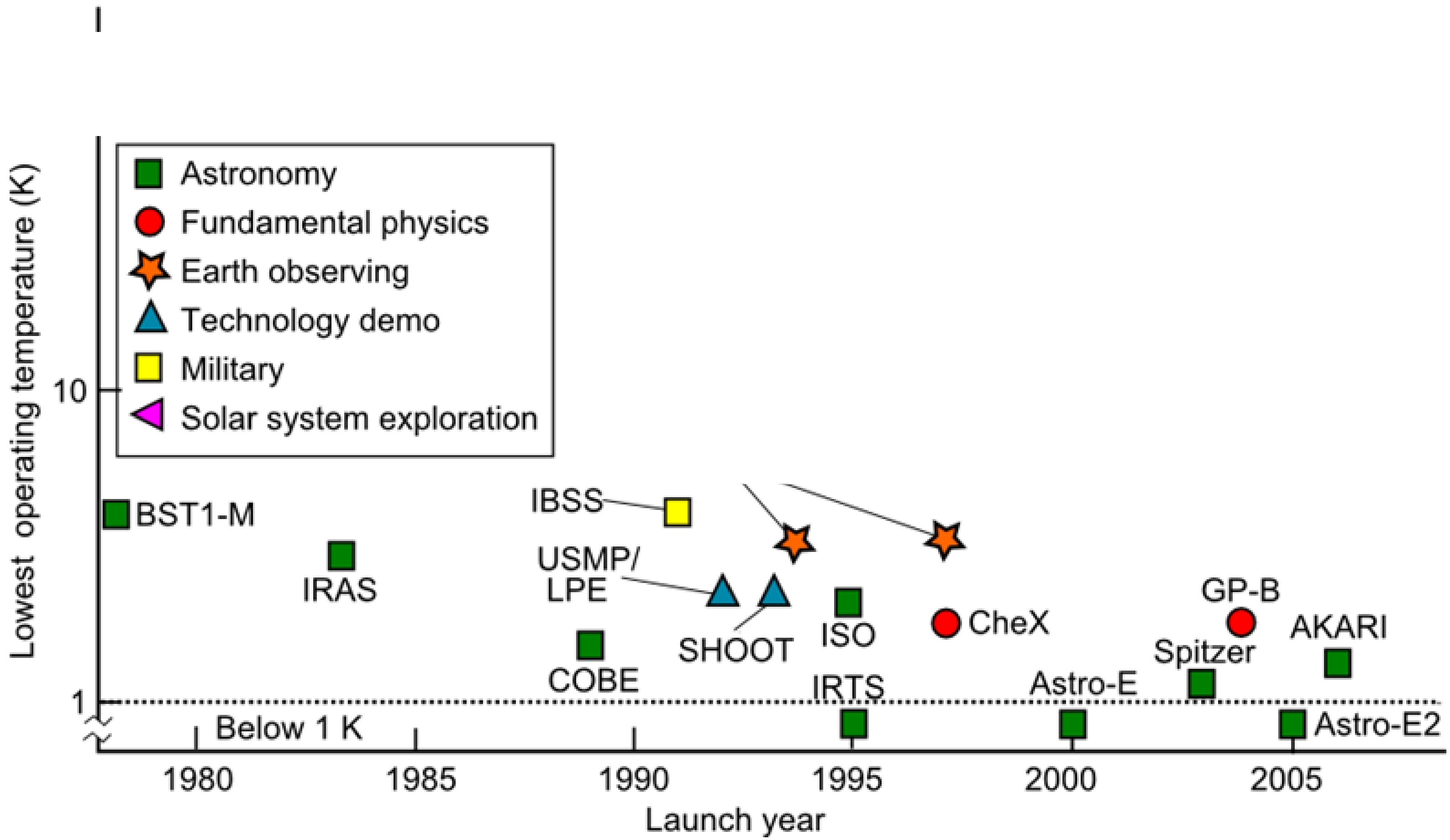
Background

- Fair amount of experience with cryogenics in space > 1 K



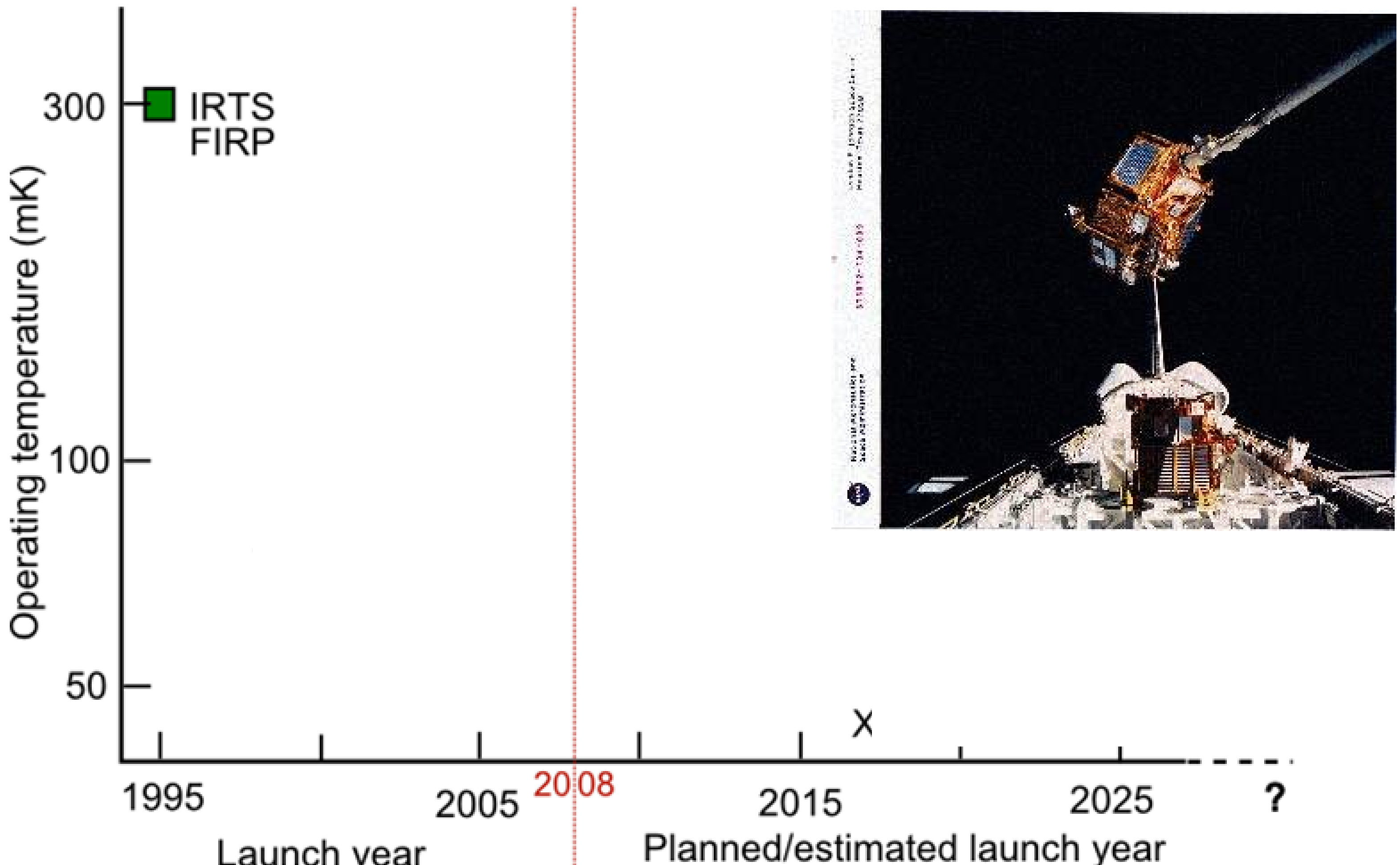
Background

- But experience around 4 K more limited

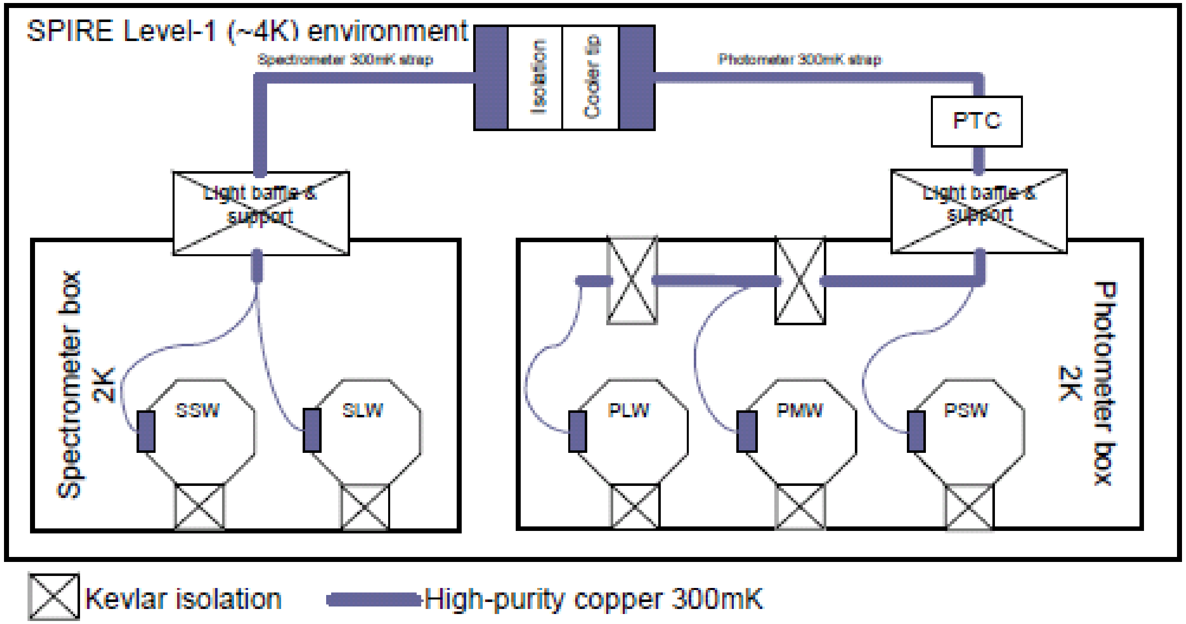


Background

- Even less experience below 1 K

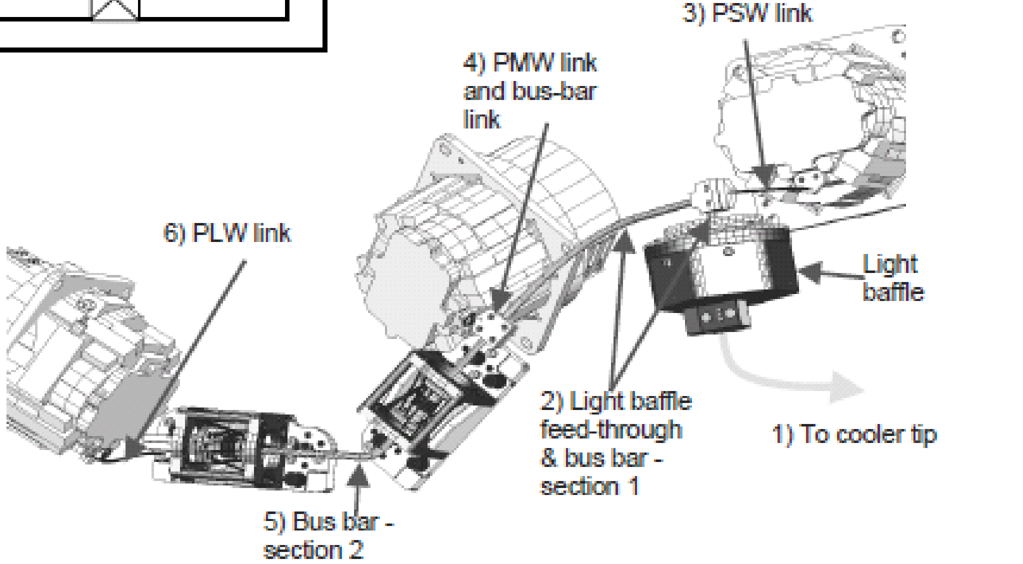


SPIRE thermal design



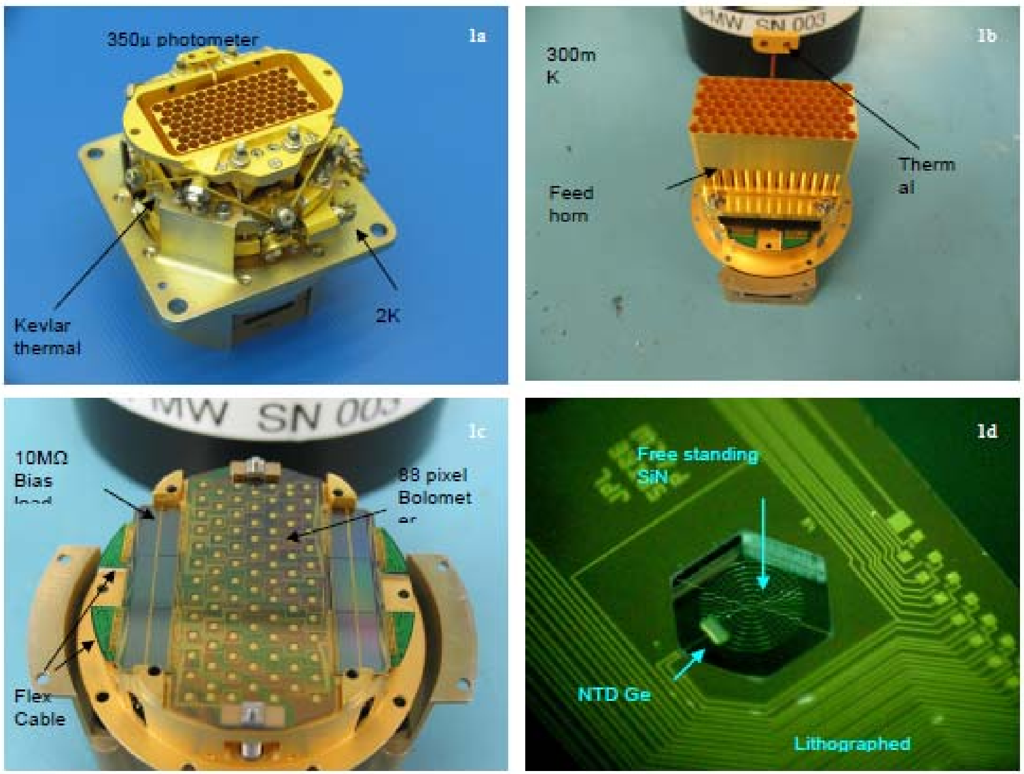
- Similar issues to SCUBA-2
- A bit warmer though (300 mK)

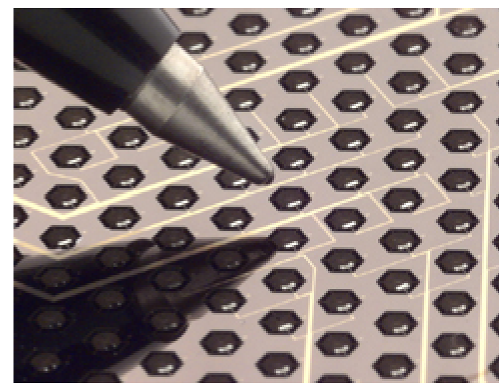
•Tricky areas included:
  - Light baffles
  - Kevlar supports
  - Electrical isolation



SPIRE detectors

- Arrays: semiconductor bolometers
  - more traditional than SCUBA-2, no multiplexing
  - made in USA (again, but UK now building detectors)





Photos: JPL

The future

Results

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- Results from SCUBA-2, SPIRE and HFI:

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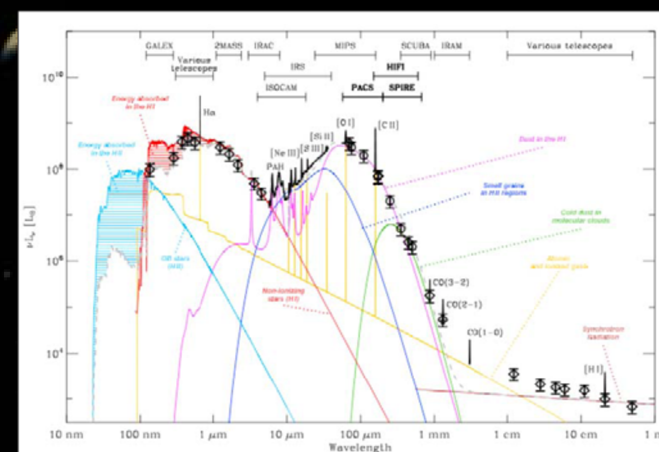
- Breakthrough in sensitivity in mid infra-red
  - Formation and evolution of galaxies
  - Imaging and spectroscopy of extrasolar young massive planets
  - Chemistry of asteroids and comets
- Selected as Cosmic Vision candidate



Launch 2017 ??????????????????

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SPICA and beyond

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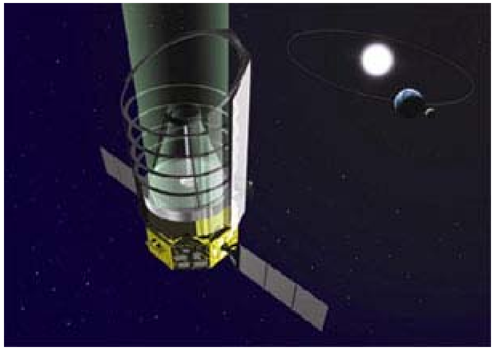
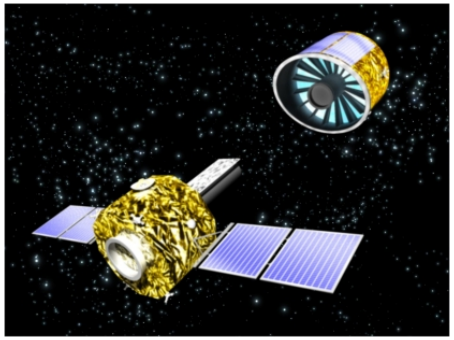


- Longer term missions being planned, e.g. FIRI, IXO
- Major risk areas
    - Cryogenics and refrigerators
        - Need material property measurements, new techniques, optimal cryogenic design
    - Detectors
        - European detectors being developed with large UK contribution



TEOPS Technology for Experimental and Observational Physics in Scotland

SUPA Scottish Universities Physics Alliance

Beyond astronomy

CUORE

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- CUORE
  - Use bolometers to measure heat pulse due to double beta decay in tellurium
  - Absorber is the tellurium crystal itself (source=detector)

  - Requirements:
  - Very low temperature operation (~ 10 mK)
    - Higher masses and lower temperature than astronomy
  - Low background radiation
    - Radiopure materials
    - 6 tons of Roman lead (no ^{210}Pb) at 4 K
      - 2.7 tons at 10 mK!
  - Large crystal mass

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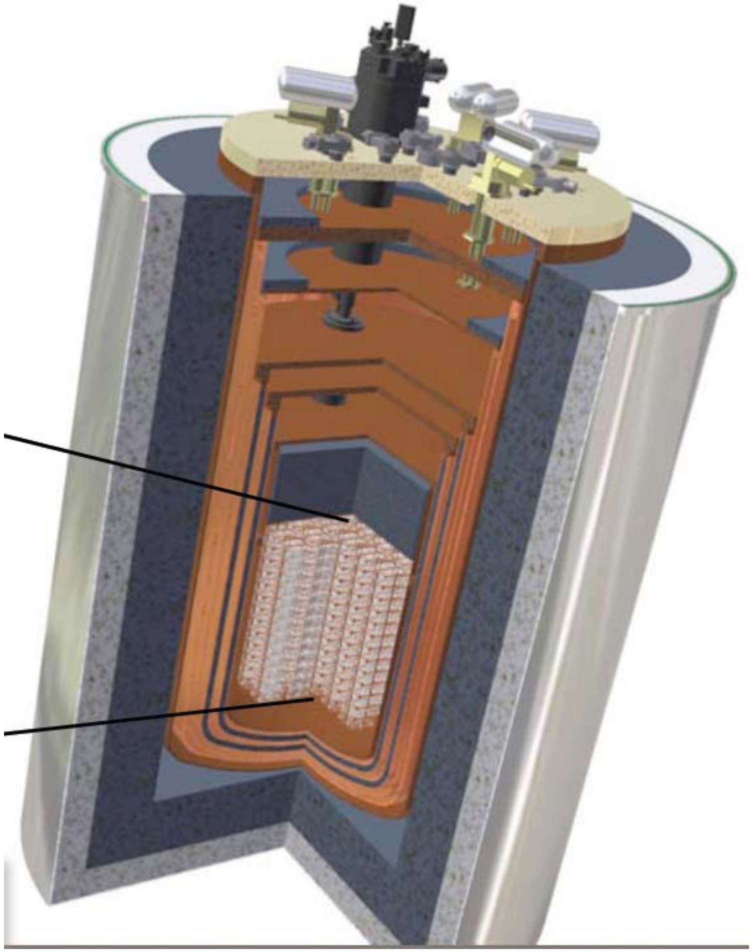
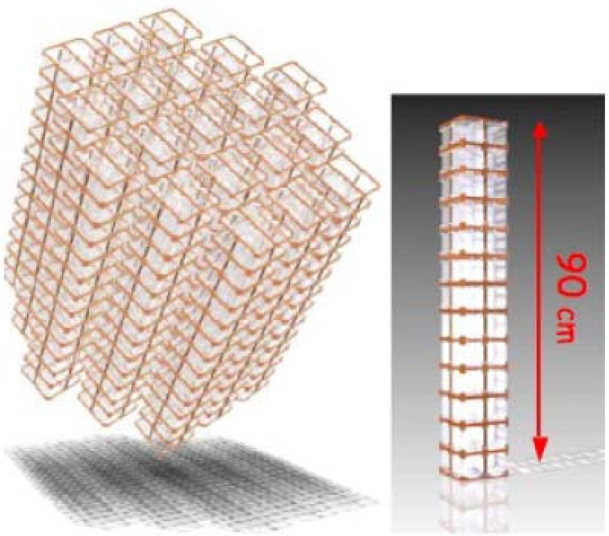
CUORE





TEOPS

- Research pooling: TEOPS
  - Technology in Experimental and Observational Physics in Scotland

- Groups
  - ATC, Royal Observatory, Edinburgh
  - Glasgow University:
  - Institute for Gravitational Research
  - Experimental Particle Physics group

TEOPS examples

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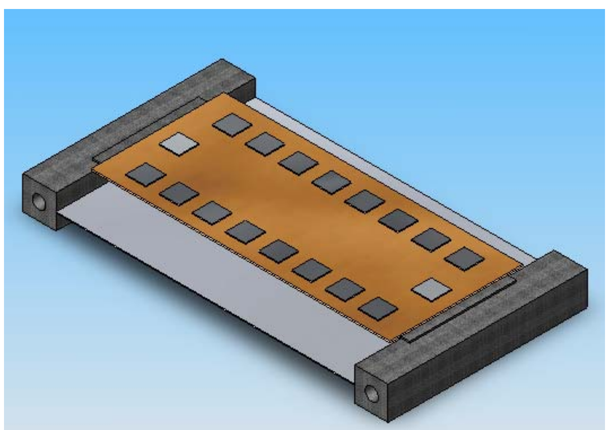
- Next generation gravitational wave detectors expected to operate at cryogenic temperatures to reduce thermal noise
  - Major source of thermal noise comes from optical coatings
  - Glasgow carrying out mechanical dissipation (Q) measurements on coated silicon samples

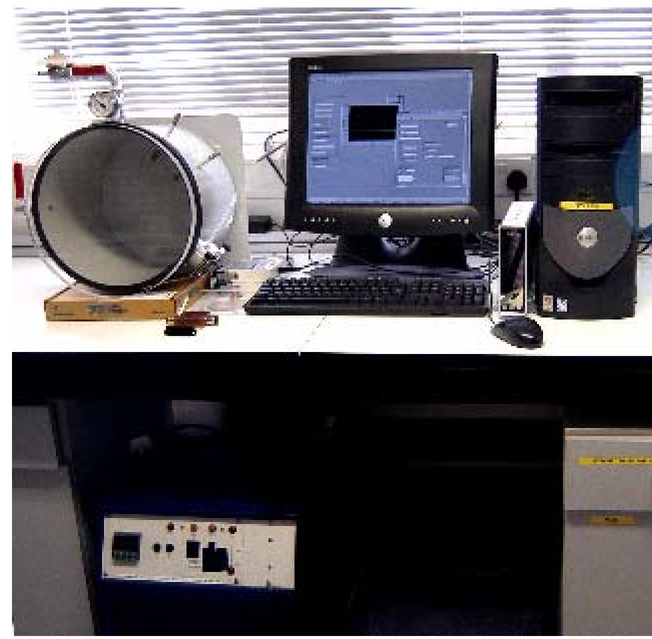
- Using experience from Edinburgh in experimental design and operation

- Other direction:
  - Silicate bonding experience used for deformable mirrors in astronomy

TEOPS examples

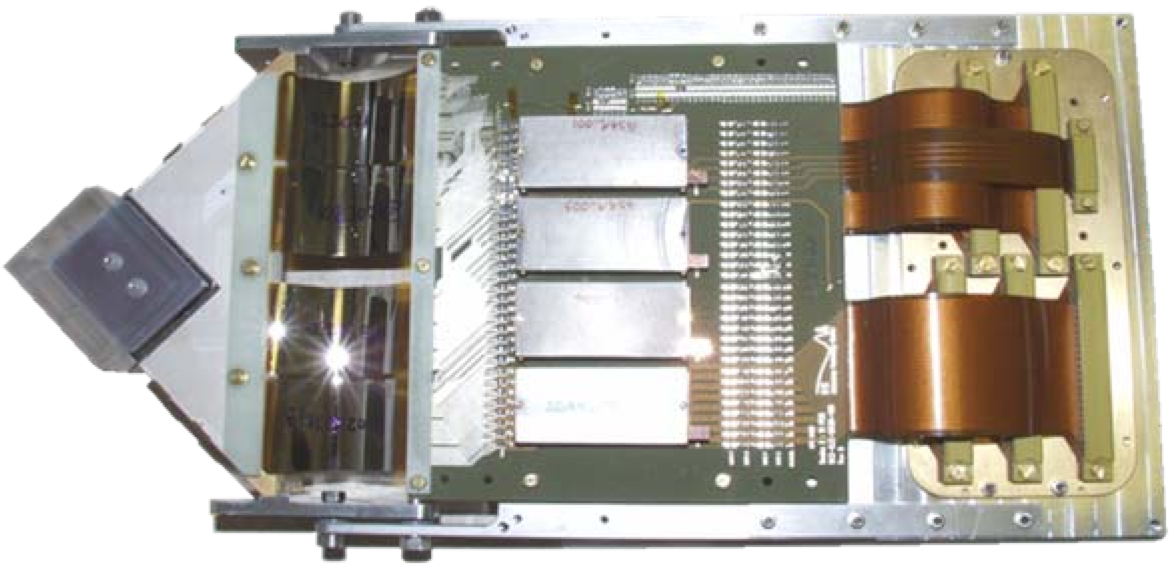
- ATLAS
  - Looking at new materials for thermal management in detectors
  - Plan to operate at lower temperatures in future (-40 C?)
  - Benefit from Edinburgh experience in measuring thermal conductivity





TEOPS examples

- SCUBA-2 detectors wire-bonded using ATLAS equipment in Glasgow after problems with original set-up



TEOPS cryostat

- Testbed for thermal and electrical conductivity measurements
    - Better understanding of cryogenic material properties very important!
    - TEOPS facility; available for all groups (+ external STFC)
    - Supporting existing work at ATC, Edinburgh and Glasgow university
    - Doing more speculative measurements
    - Effort: one PhD student + some of my time

TEOPS cryostat

- Measurements so far for
  - SCUBA-2
  - MIRI (on JWST)
- Near future:
  - Conductivity of silicate bonded samples for IGR
  - Conductivity of materials for ATLAS (reach lower temperatures than in their setup)

- Conductivity of various materials for future astronomical instruments

STFC work

- Part of CfI bid to improve cryogenic knowledge across STFC

Conclusions

Conclusions

- Exciting results expected in the near future from
  - SCUBA-2
  - Herschel
  - Planck
  - CUORE etc.

- R&D for these programmes has produced a large amount of information and experience for future similar (and dissimilar) instruments
  - There is a lot of “science” in designing (and calibrating) these instruments

- Research pooling can work very well

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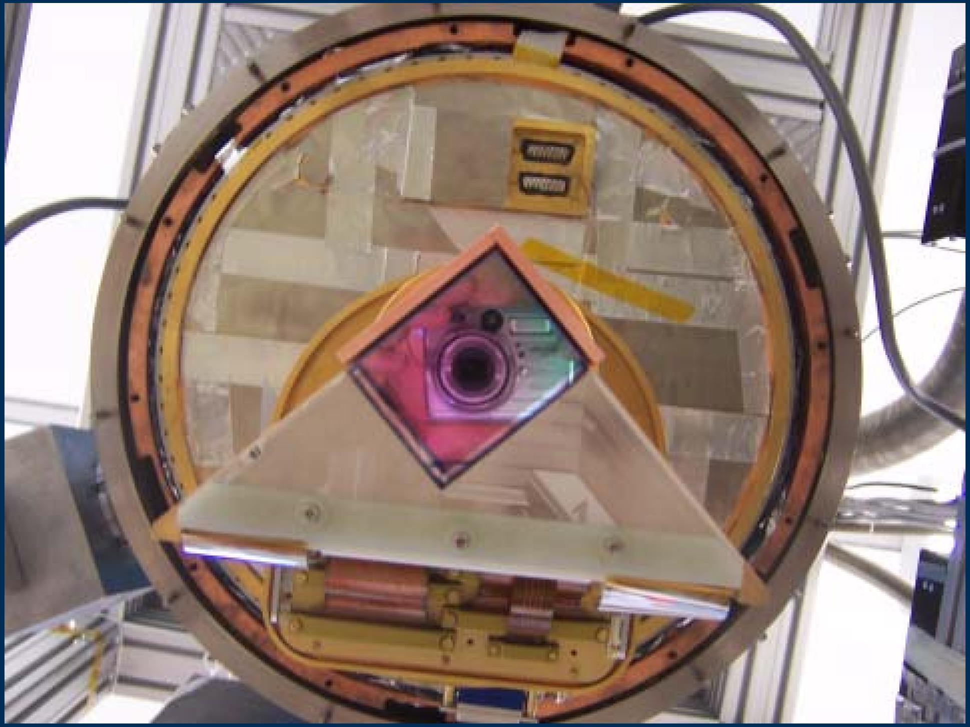

THE END

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