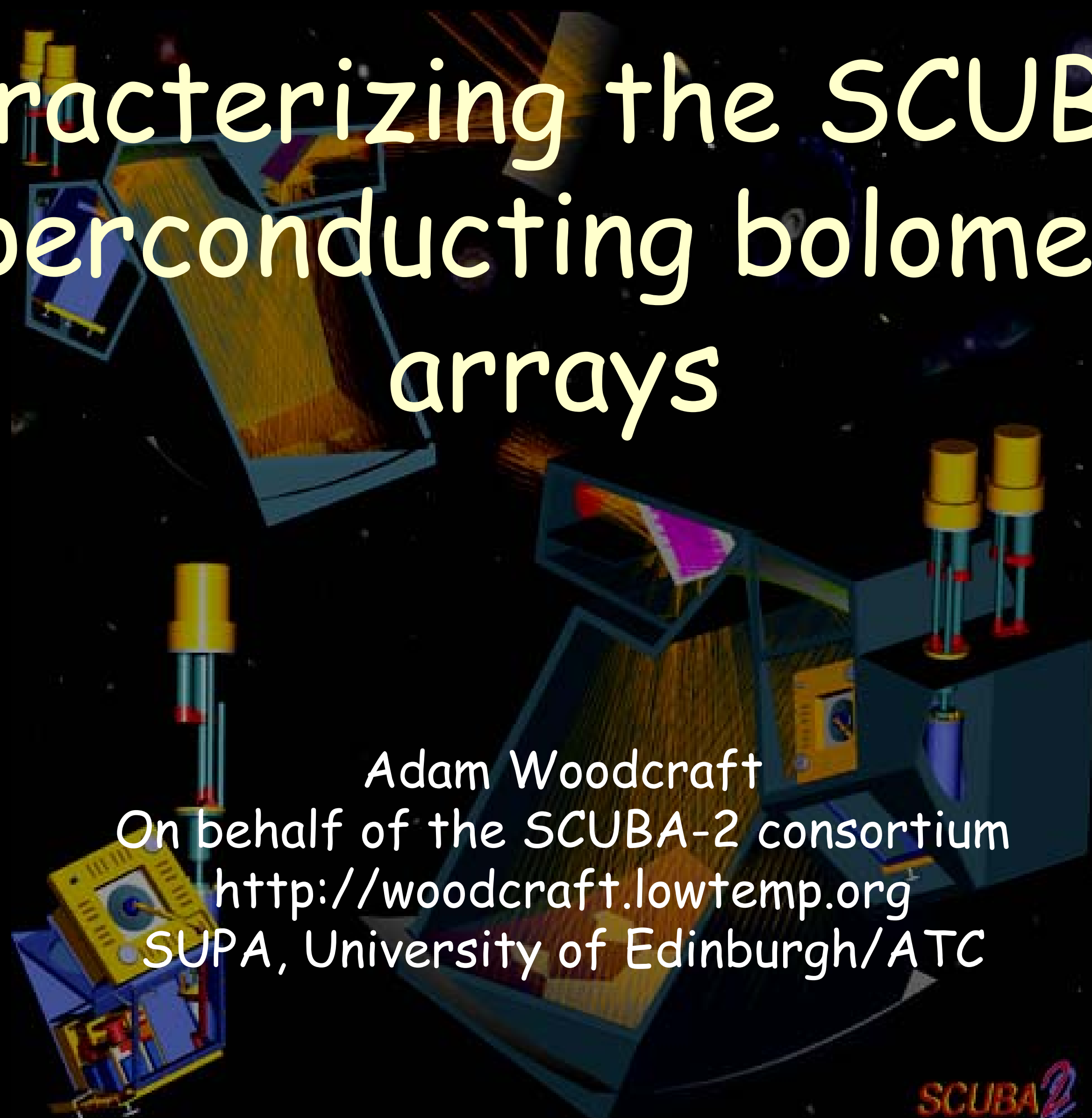
Characterizing the SCUBA-2 superconducting bolometer arrays



Adam Woodcraft
On behalf of the SCUBA-2 consortium
http://woodcraft.lowtemp.org
SUPA, University of Edinburgh/ATC

Science & Technology Facilities Council
UK Astronomy Technology Centre

TEOPS
Technology for Experimental and Observational Physics in Scotland

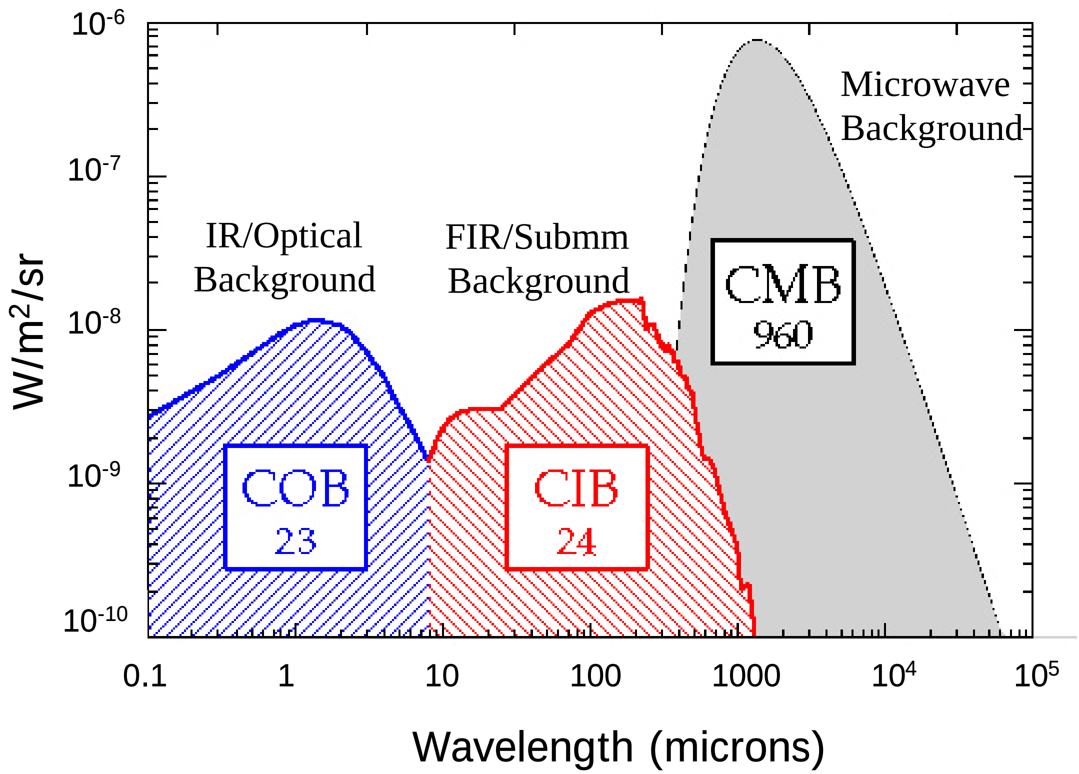
SUPA
Scottish Universities Physics Alliance

Introduction

Background

- Cosmic energy density of the Universe (optical-mm).

- Sub-mm background
  - high-z galaxies
  - young universe



Scientific motivation

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"A unique scientific opportunity"

– Region encompasses the peak of emission from the high-z universe and of the dusty progenitors of stars

– Less than 1% of the far-IR/submm sky has been studied in any detail – it's largely unexplored territory!

– Potentially a huge void between the capabilities of existing facilities and the new generation interferometers

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The Submm Revolution

- Huge revolution over the past decade – very limited access to this region of the spectrum before

- SCUBA on JCMT played a large role:
  - 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

SCUBA on the JCMT

- One of the first imaging “arrays” for the submm
- 128 bolometers in two arrays
- Operated at 350/450 and 750/850µm
- Came into service in 1997
- Made a number of seminal discoveries
- Retired from service in 2005

Beyond SCUBA

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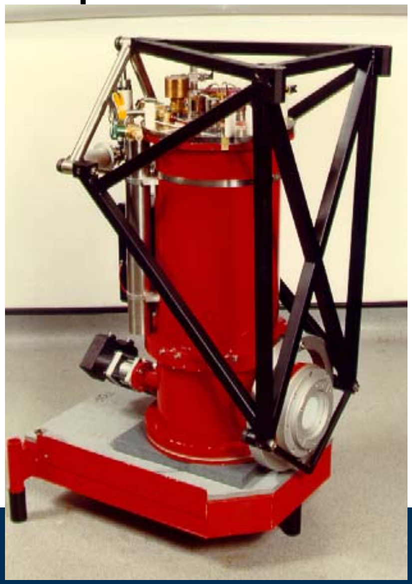
- Instruments limited by small number of pixels
  - Gone from 1 pixel to 100s in a decade – need more!
- Detector development in relative infancy
- No big military or commercial applications (as yet...)
- Detectors not available “off-the-shelf” so have to make your own...

UKT14
1986-1996
1 pixel



SCUBA
1997-2005
128 pixels

SCUBA-2
2008+
10240 pixels

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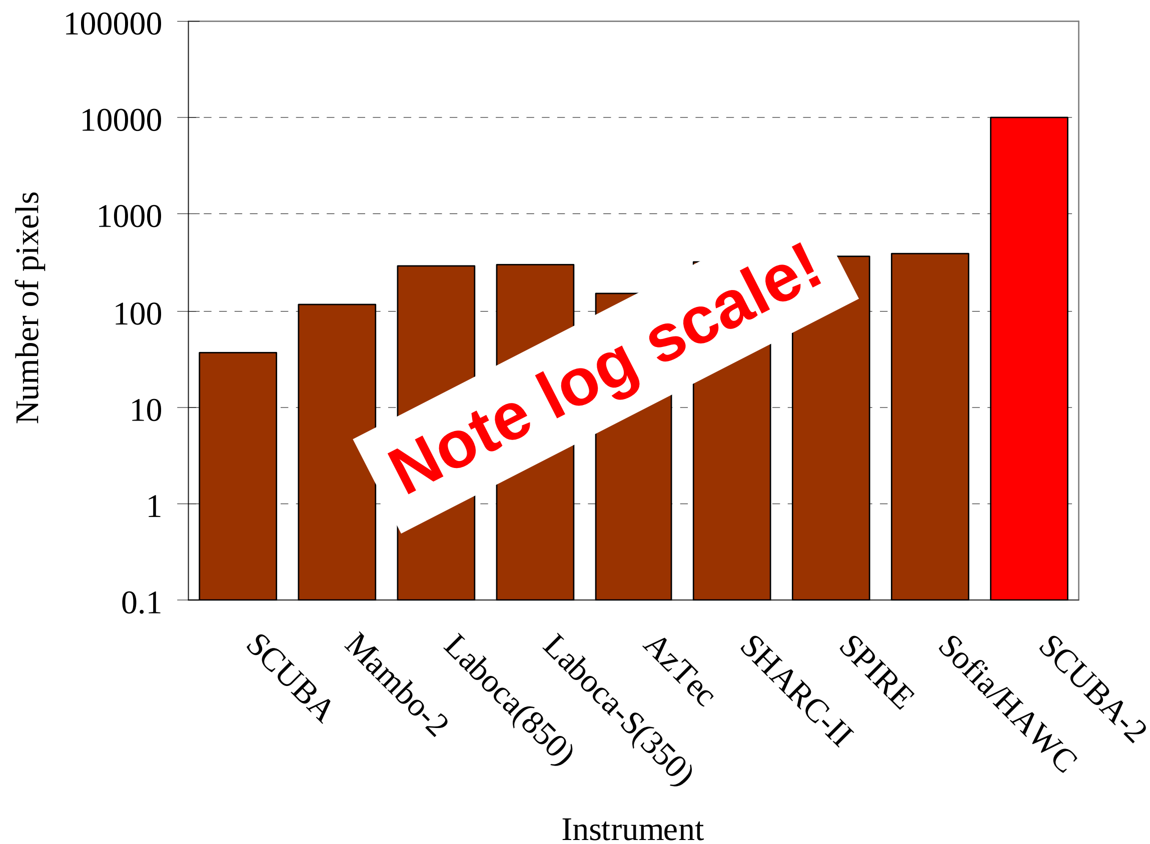
Motivation for SCUBA-2

- Instruments have tended to be limited with only a few hundred pixels at best
- Sensitivity has been poor requiring many tens of hours integration to reach depths of interest



SCUBA-2

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Bolometer instruments on the JCMT – image scaled by number of pixels

UKT14
1986-1996
1 pixel

SCUBA
1997-2005
128 pixels

SCUBA-2
2007+
10240 pixels

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Scientific requirements

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- Maximise the survey potential
  → Large field-of-view
- Deep imaging
  → Improved detector sensitivity
- Improved image fidelity
  → Fully-sampled image planes; no sky chopping
- Imaging at two colours simultaneously
  → Two separate focal planes

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Abilities

- 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

Abilities

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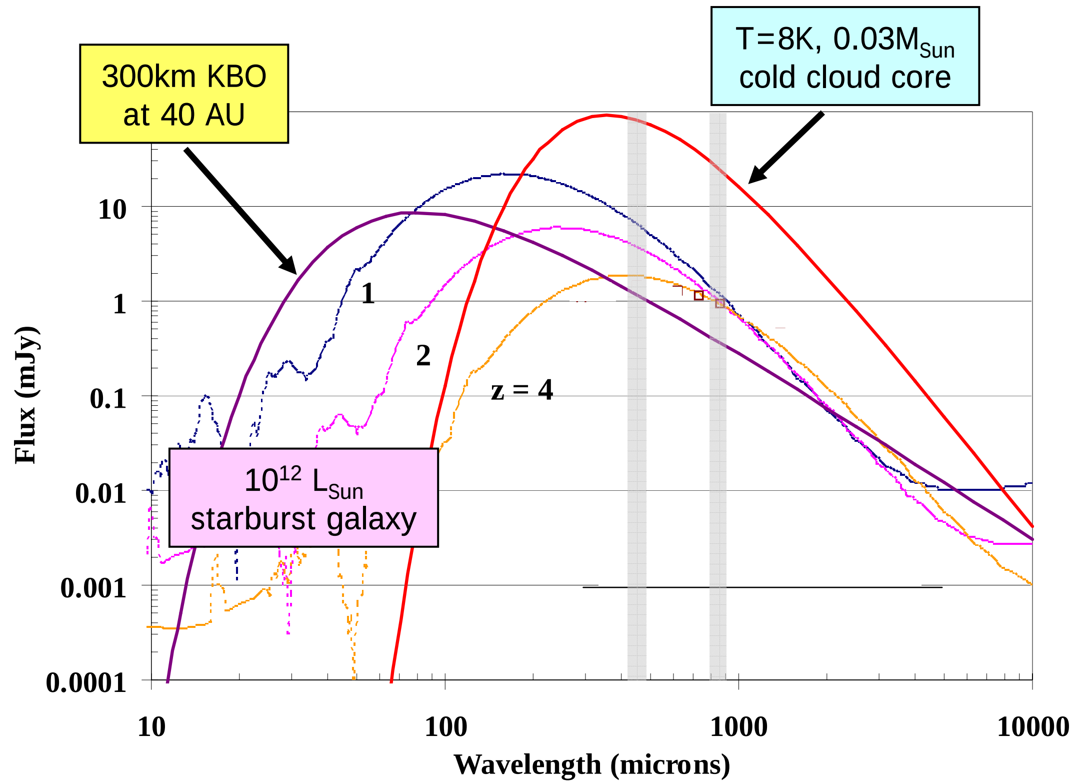
- Ultra-deep imaging and exploiting the higher angular resolution available at shorter submm wavelengths

- Polarimetry and medium resolution spectroscopy also available



Emission from high-z galaxies and cold cloud cores peaks in the far-IR/submm.
SCUBA-2 will have the sensitivity to accurately determine the fluxes of these faint objects.

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Mapping Speed

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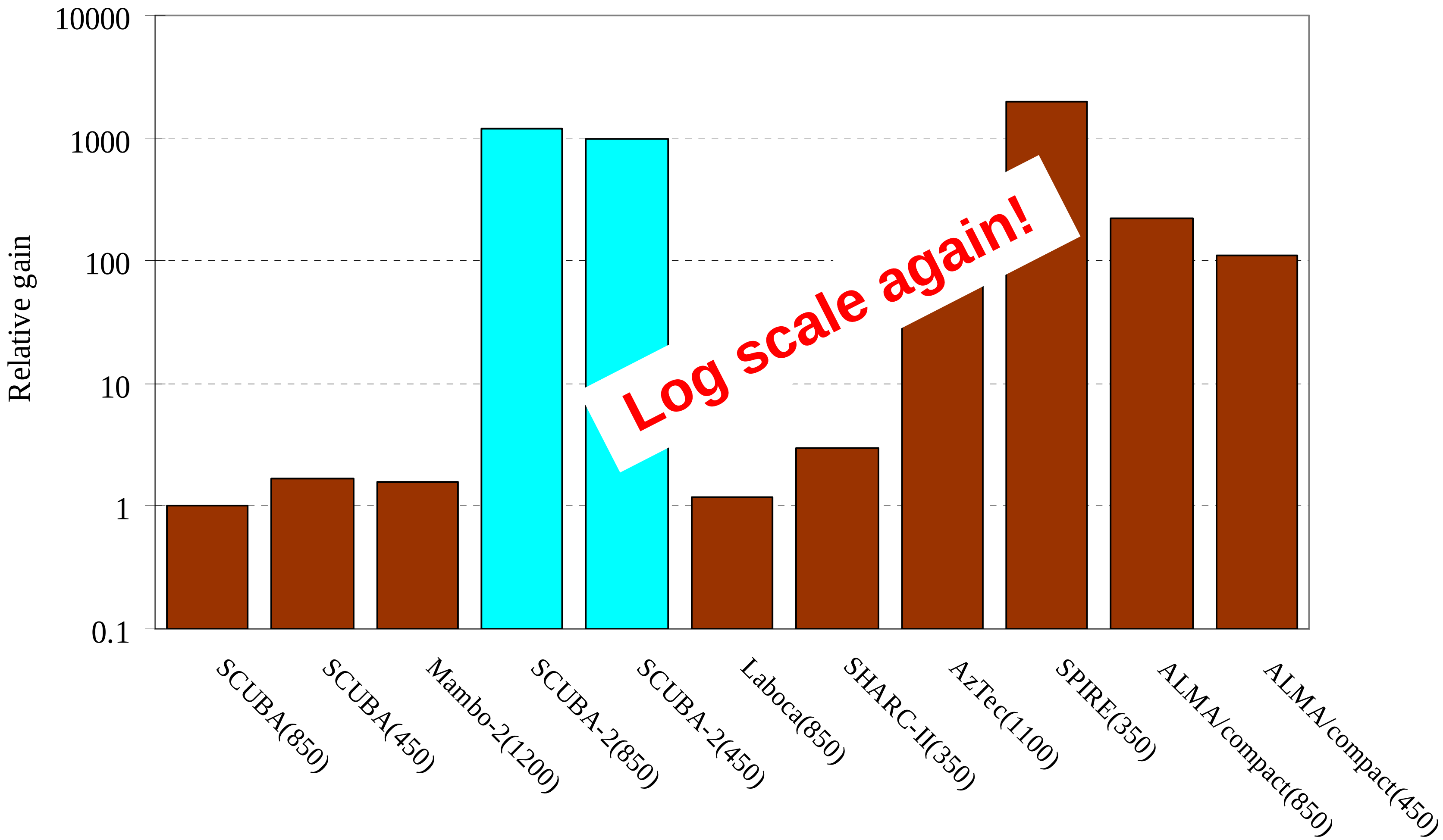
SCUBA-2 wilh fully-populated focal planes and arrays working to minimum spec (80% pixel yield)



Large area mapping speeds assuming a ν^3 dust mass sensitivity (relative to SCUBA 850)

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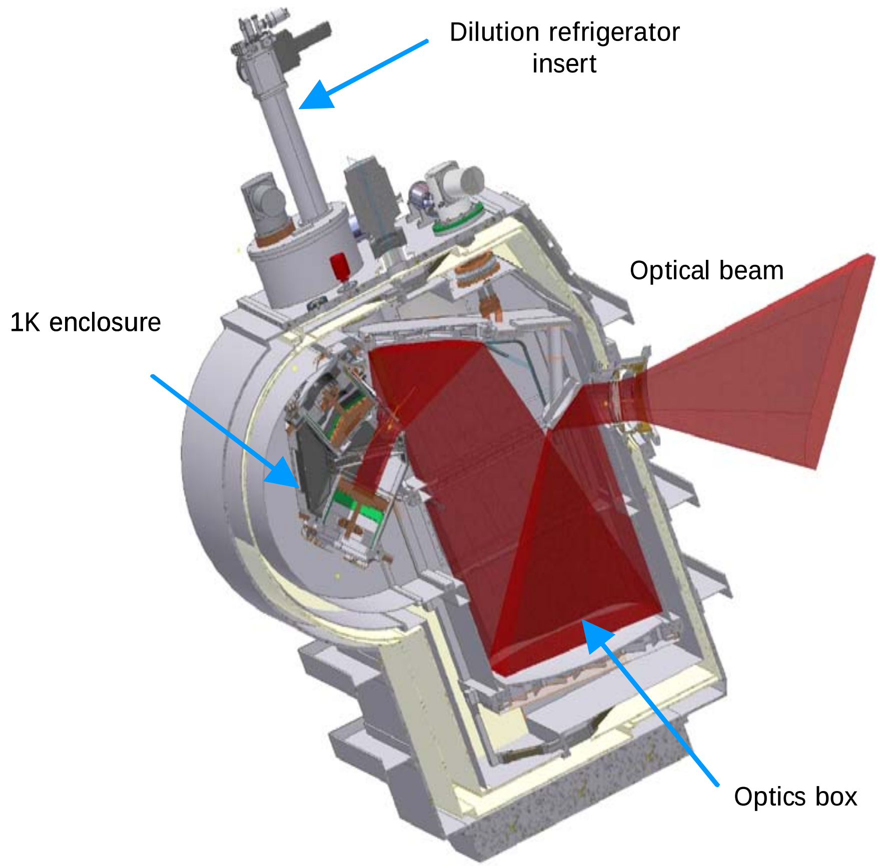
Instrument

Key challenges

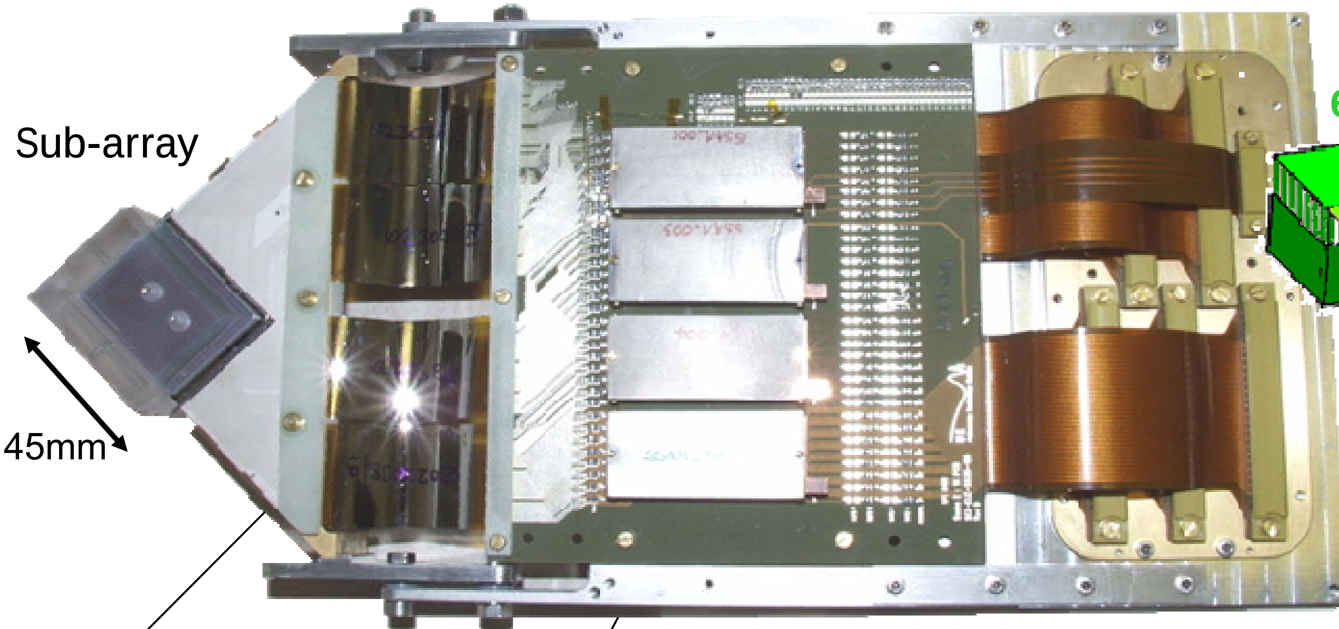
- New format arrays with 1000's of pixels
- Low-temperature thermal design
- Liquid-cryogen free operation
- Stray light control
- Magnetic shielding of readout circuitry
- Cooling 300 kg of optics to 4K
- Large number of signal cables

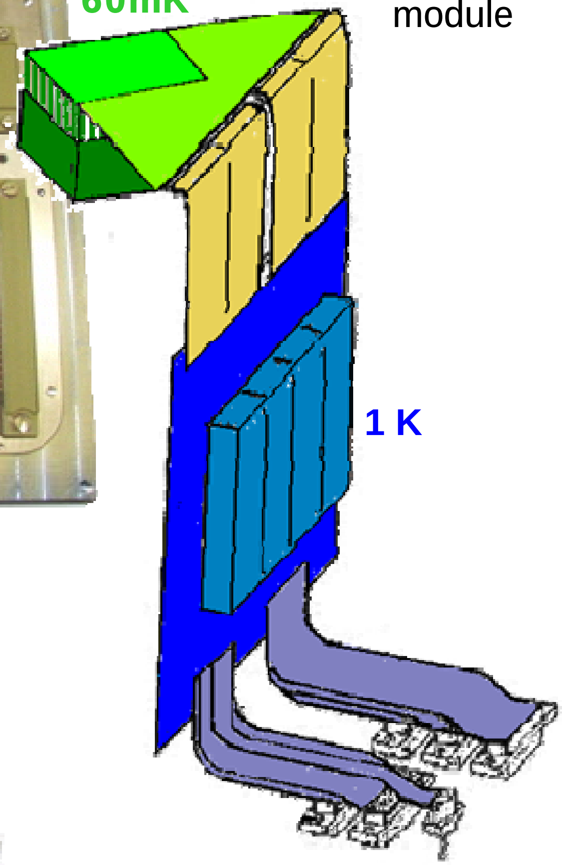


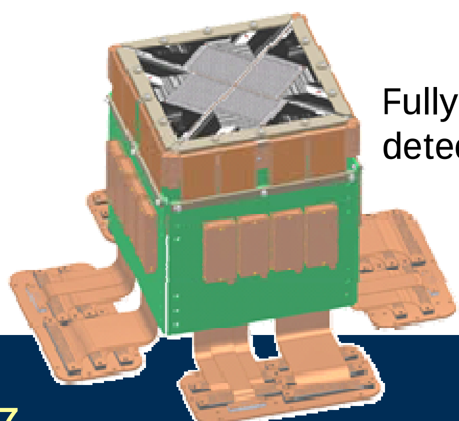
Cryogenic systems

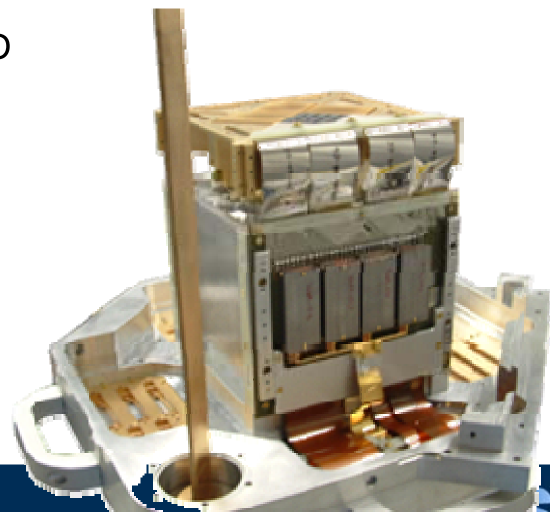
- Novel liquid cryogen-free Leiden Cryogenics dilution refrigerator (first commercial dry DR?)
- Cooling power of ~100μW at 50mK – sufficient (with some margin) to cool all sub-arrays
- Also cools the 100 kg 1K box
- Uses a Cryomech pulse tube cooler and Joule-Thompson heat exchanger
- Two further PTC's keep optics box and radiation shields at temperature

Sub-array module



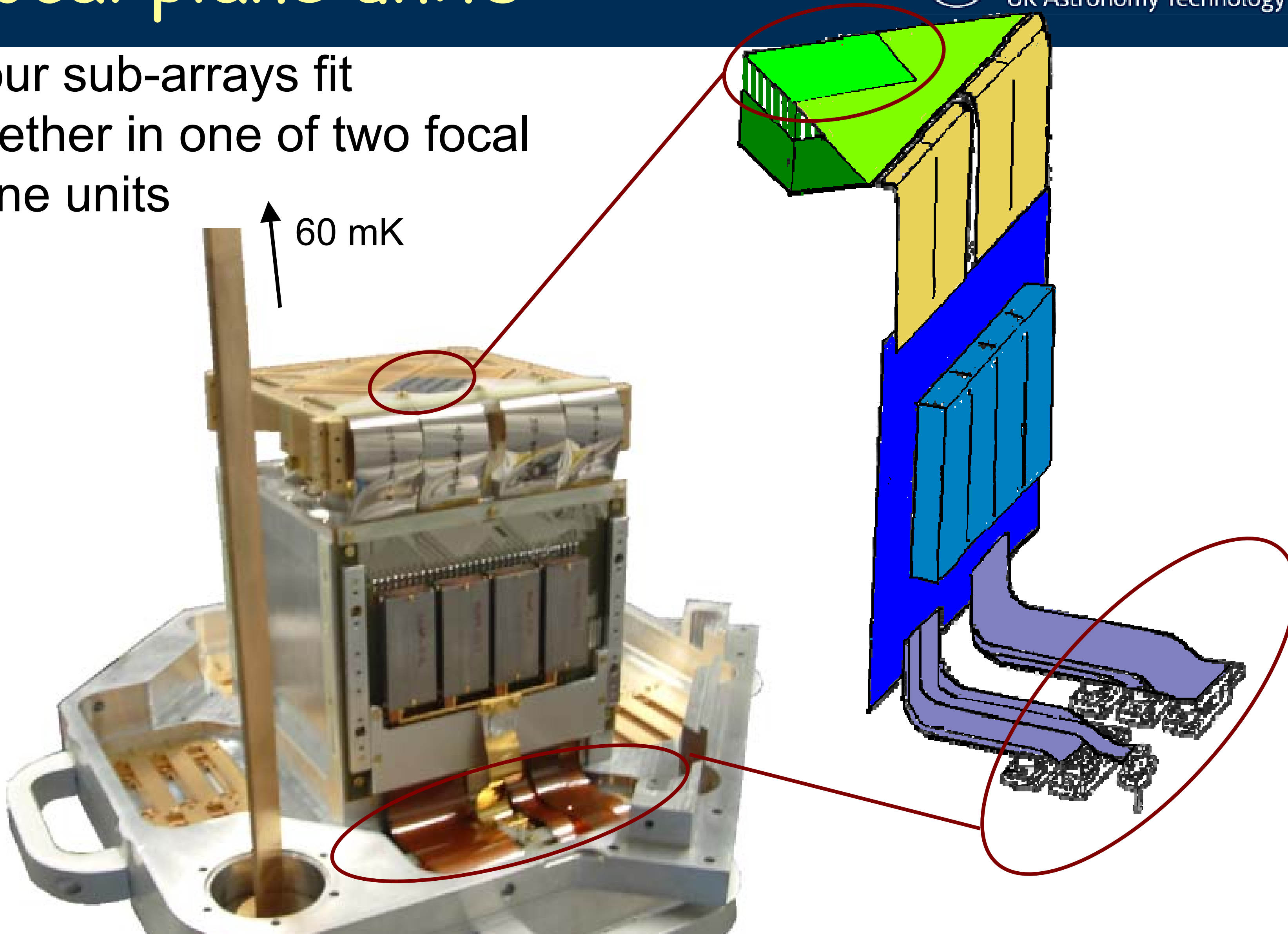




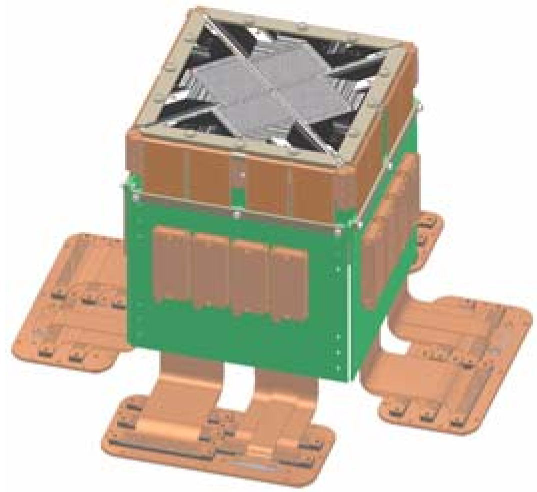


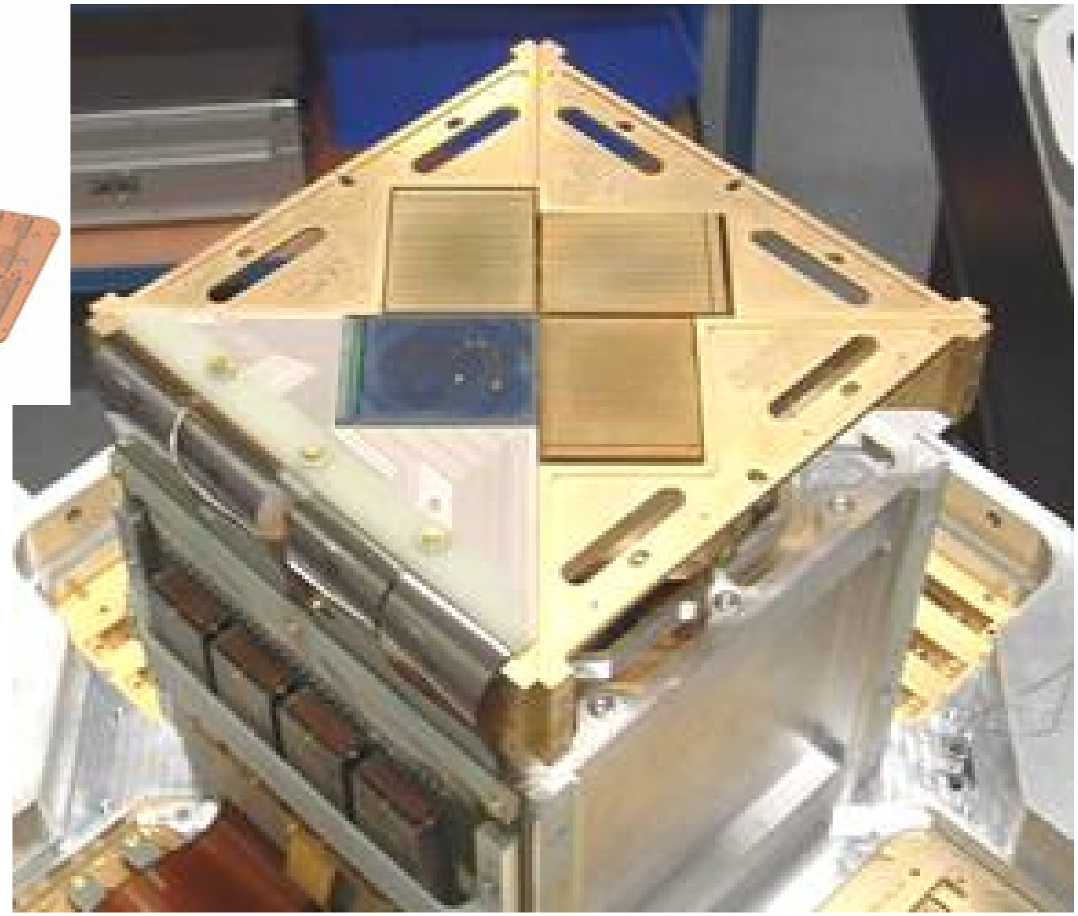
Focal plane units

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



Focal planes





450μm prototype sub-array mounted in focal plane unit

- Two independent focal planes
- 5120 pixels in each focal plane
- Each focal plane consists of 4 sub-arrays of 1280 pixels each

Focal plane layout

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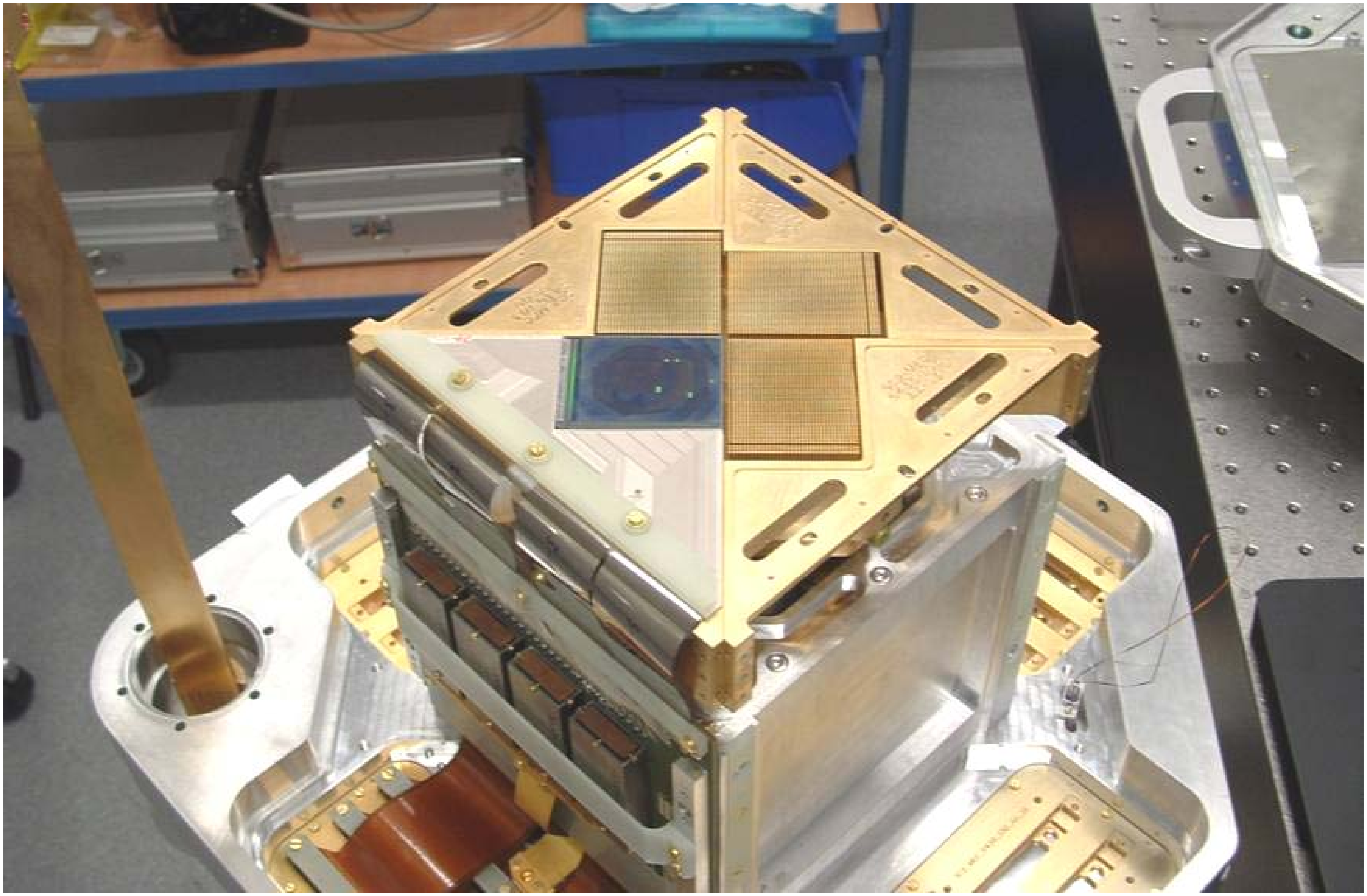

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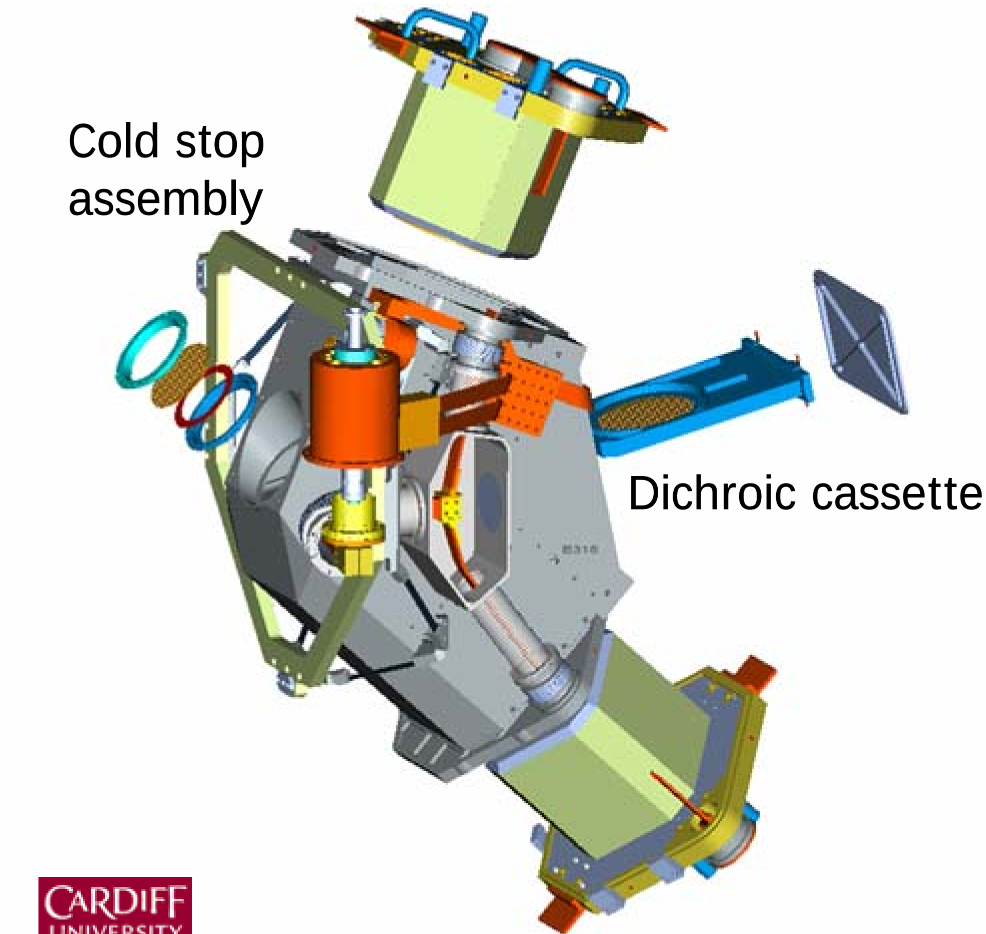
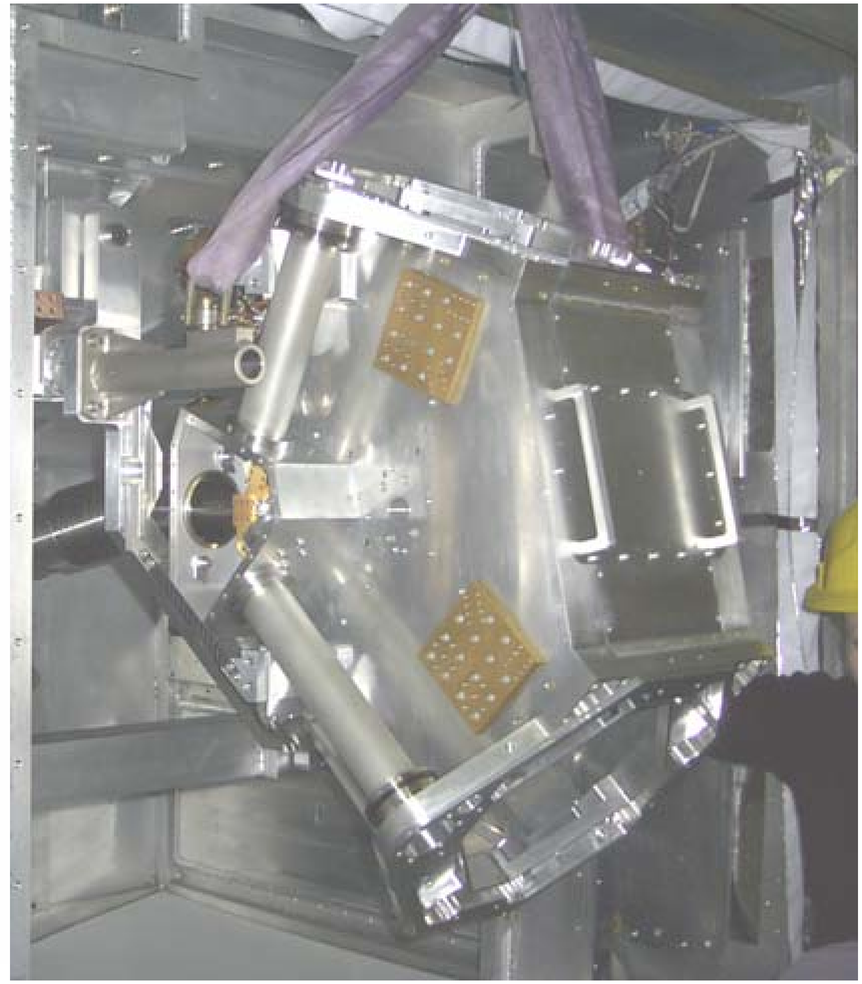
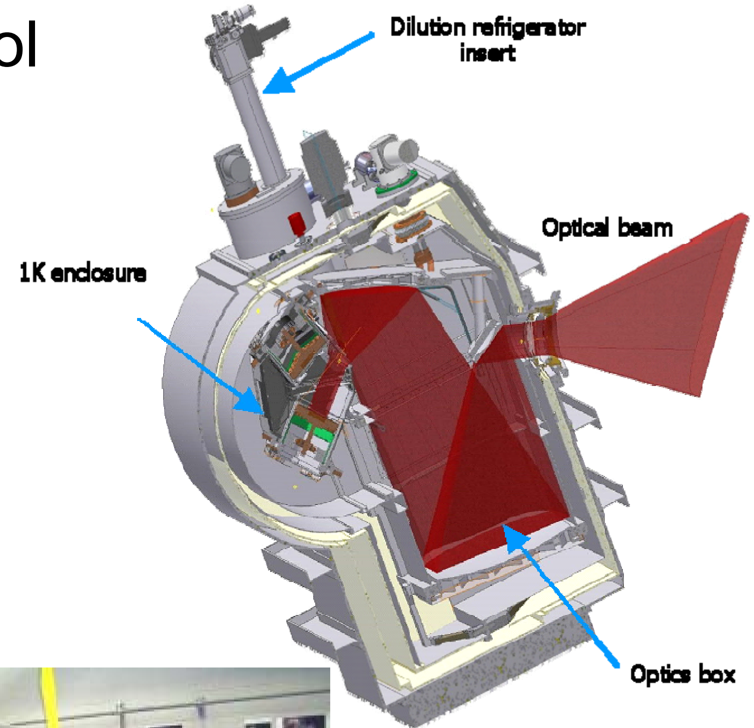
1K enclosure ("1K box")





Size

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



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Installing the mirrors

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Installing the optics box

Radiation shields

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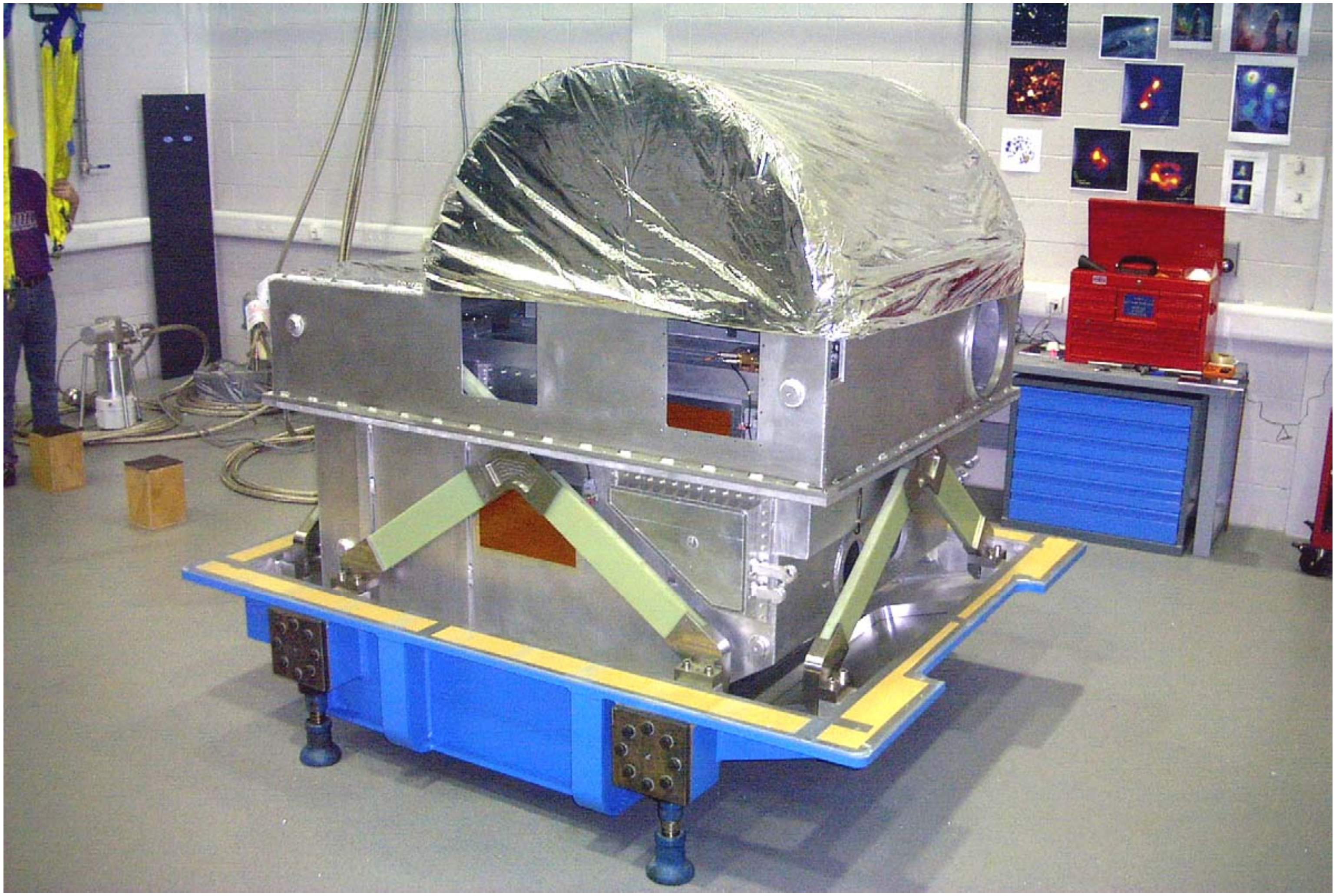

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Vacuum vessel

Packed on a (big) truck…

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From the ROE to the JAC

Onto the telescope…

SCUBA-2 on JCMT

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Status

- Now installed on telescope

- Behaviour similar to in when Edinburgh
  - Survived the air and sea journey
  - Fridge running stably at 58 mK
  - Operates well in telescope environment
    - No interference between SCUBA-2 and other JCMT instrumentation seen

- Currently installed: two “commissioning grade” arrays (one 450 μm, one 850 μm)

Status

- Optical alignment carried out
  - better than 1 mm (double pass from reciever cabin to cryostat and back - 21 m!)
- Interference (noise) between SCUBA-2 arrays seen
  - Removed by running readouts in sync
- First light any day now

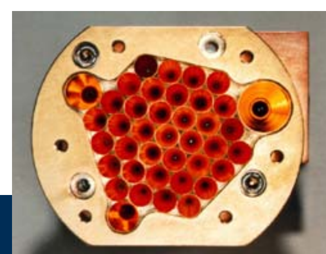
Detectors

Detectors

- Most sensitive detection method is to use bolometers
  - Measure temperature rise due to absorbed radiation
  - Respond to wide wavelength range – define with filters
- Traditionally use NTD germanium thermistors
  - BUT: not background limited for best telescopes
  - Hard to make large arrays:
    - Ge chips have to be individually mounted on each pixel
    - Can't multiplex without prohibitive noise penalty
    - Separate wiring and read-out electronics for each pixel required

SCUBA individual pixel

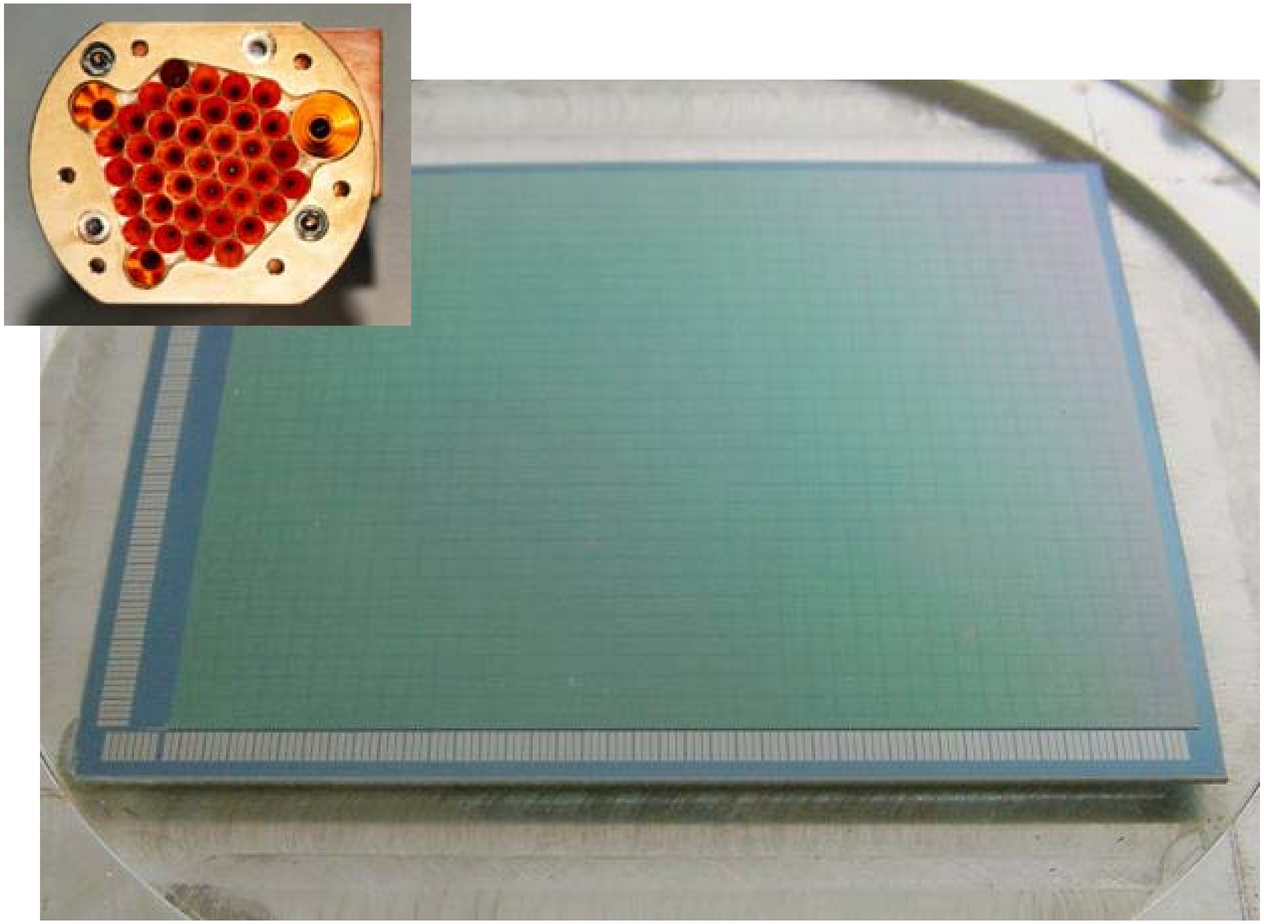
SCUBA focal plane



SPIRE array – multiple pixels on one silicon wafer

Detector arrays

- Superconducting TES detector arrays
- Two independent focal planes
- 5120 pixels in each focal plane
- Detectors cooled to 100mK to make them ultra sensitive
- Construction: NIST/SMC

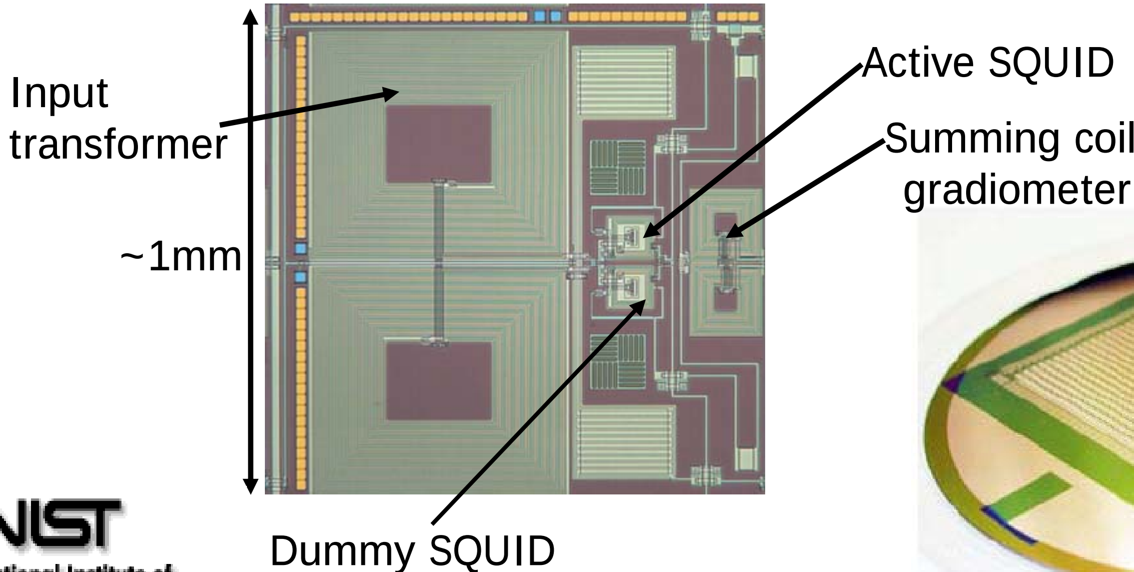


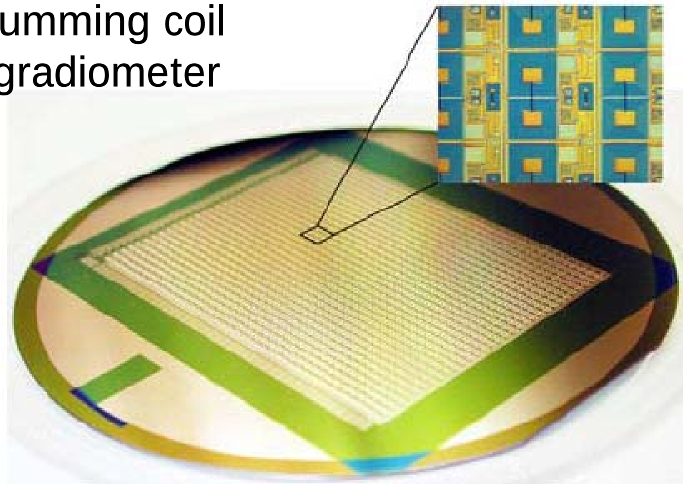
NIST National Institute of Standards and Technology

SMC Scottish Microelectronics 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

In-focal plane multiplexing

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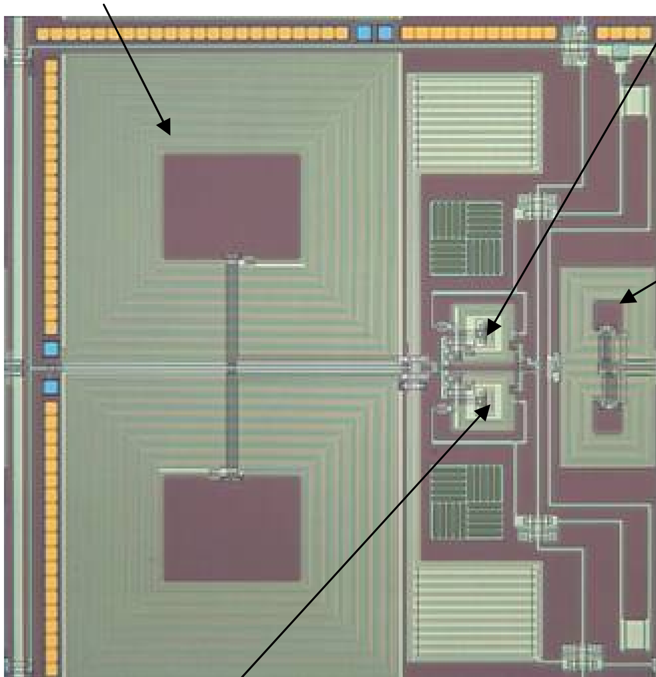
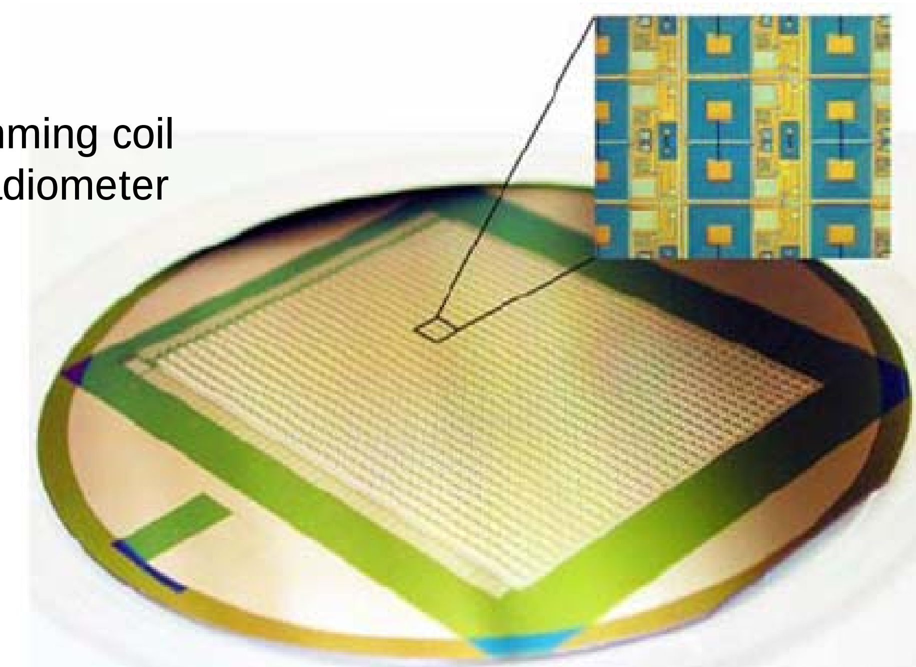


Pixel scale



Array scale

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Measurements

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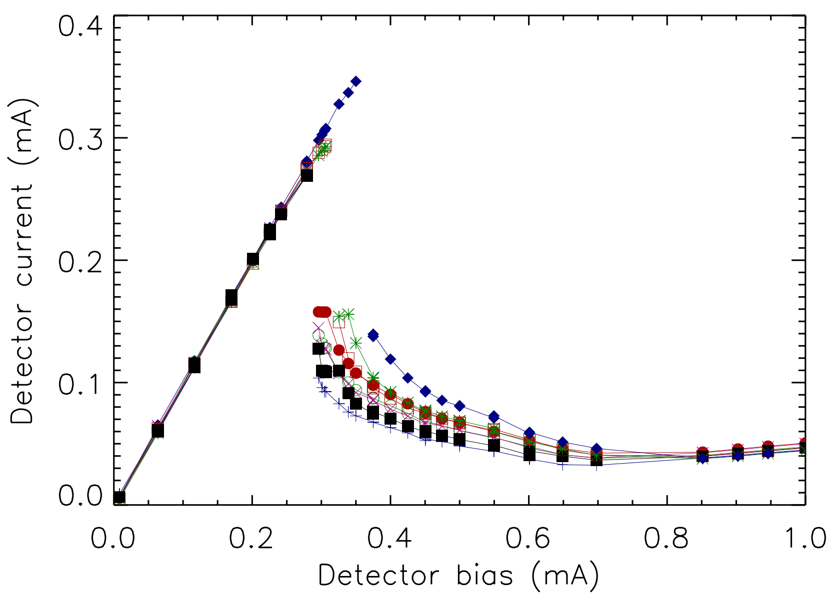
First, a bit of history:

- We started with “engineering” readout system from NIST
  - Locking pixels time consuming
    - (Read through three stage SQUID system)

- Worked with 8-16 pixels at a time on prototype array



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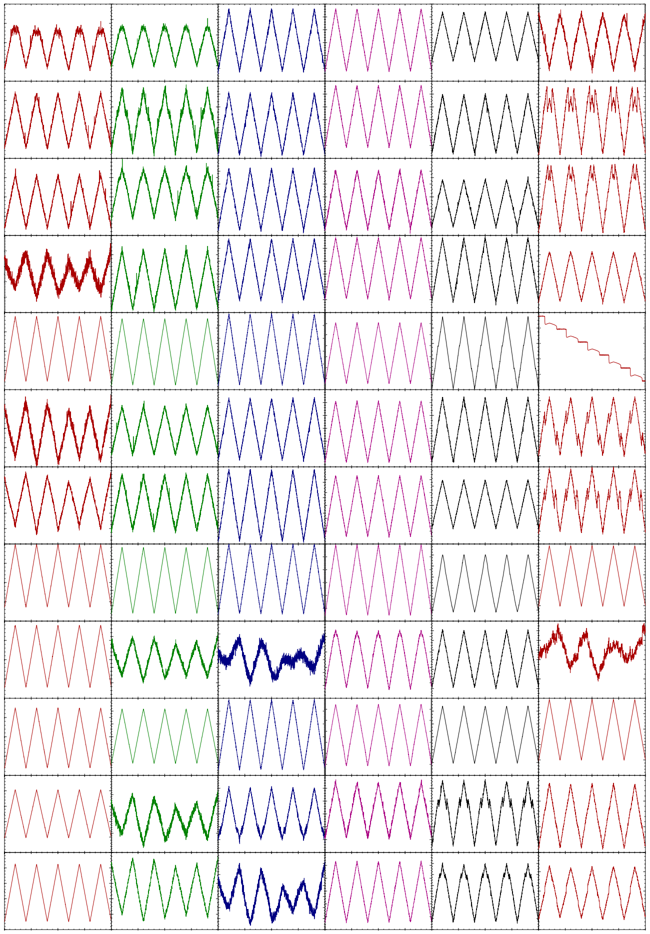
Measurements

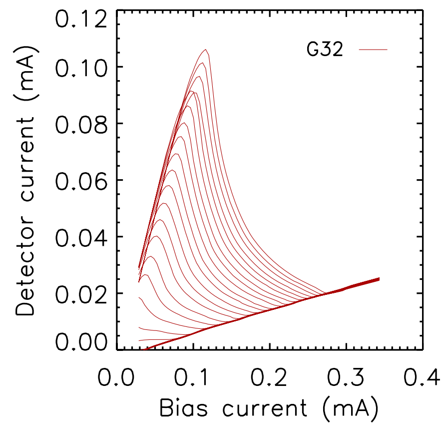
- SPIE 2006 Orlando:
- Commissioning grade array

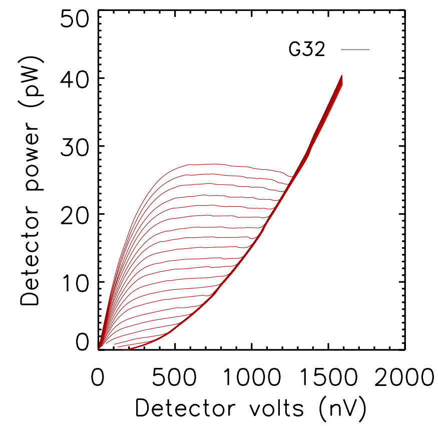
- MCE now available, but no automatic locking
    - All pixels read out simultaneously using multiplexer
    - Shown here responding to modulation of detector bias (6 columns, 12 pixels in each row)

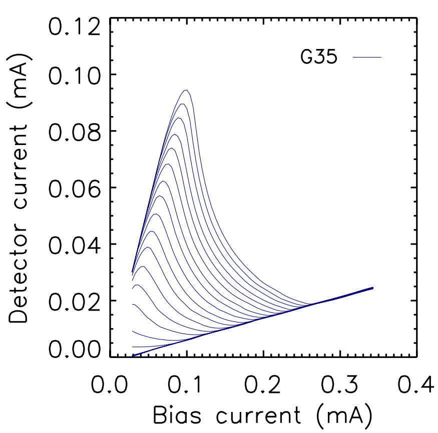


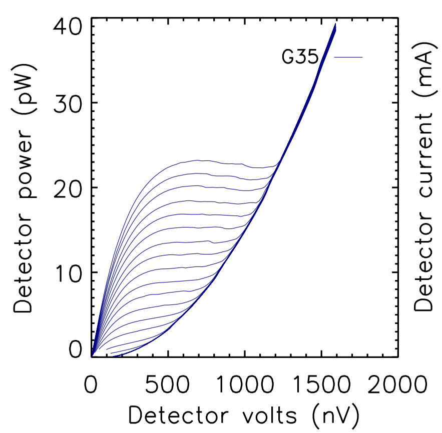
Measurements

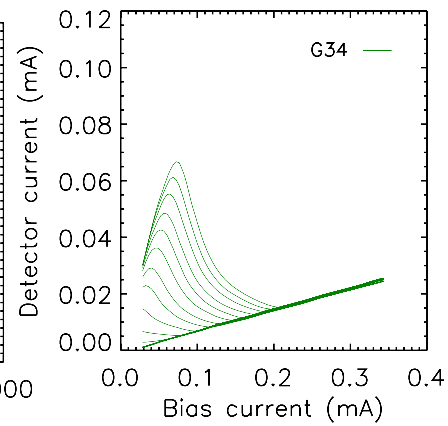
- Load curves
  - Current vs bias
  - Power vs bias

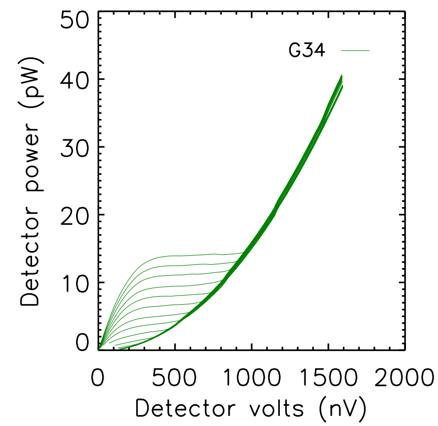




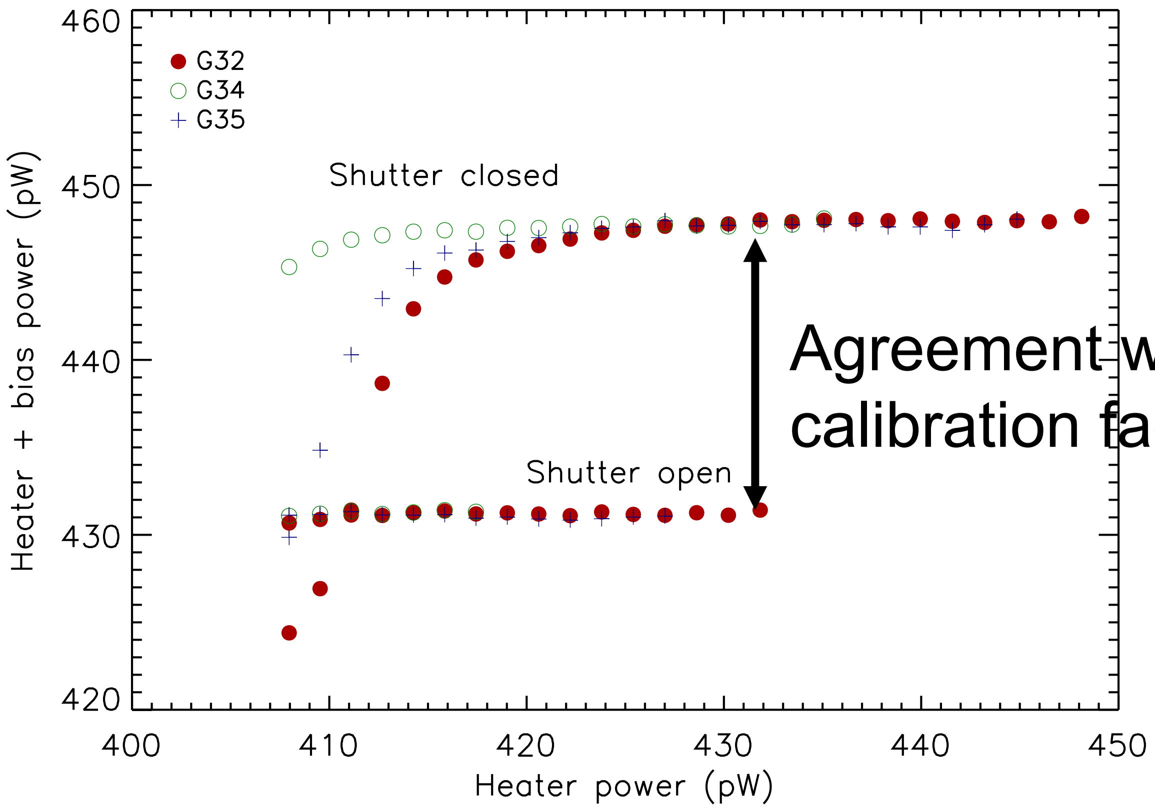








Measurements



Agreement with *no* calibration factor

Data acquisition

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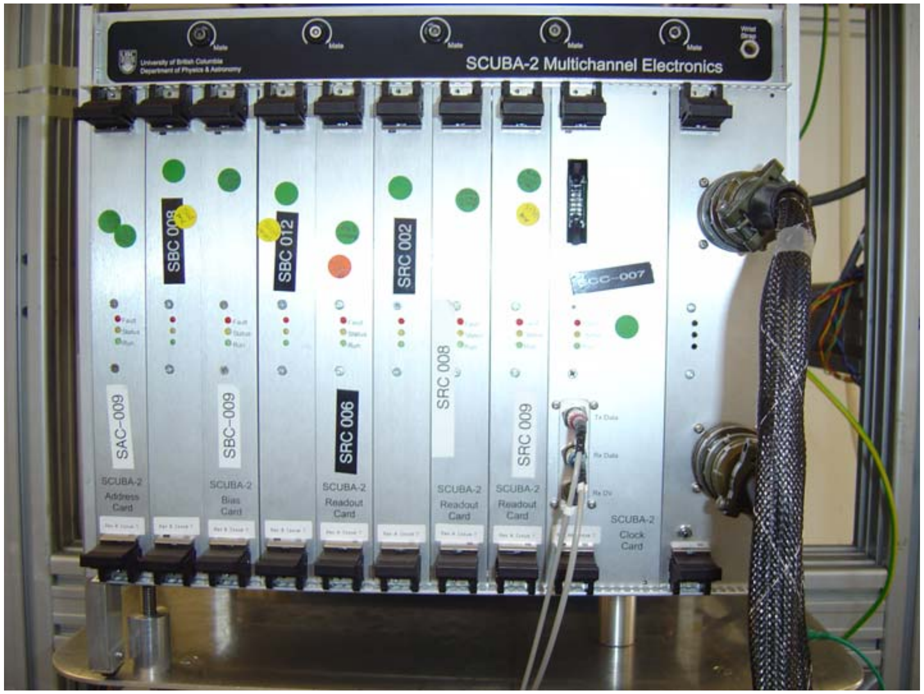
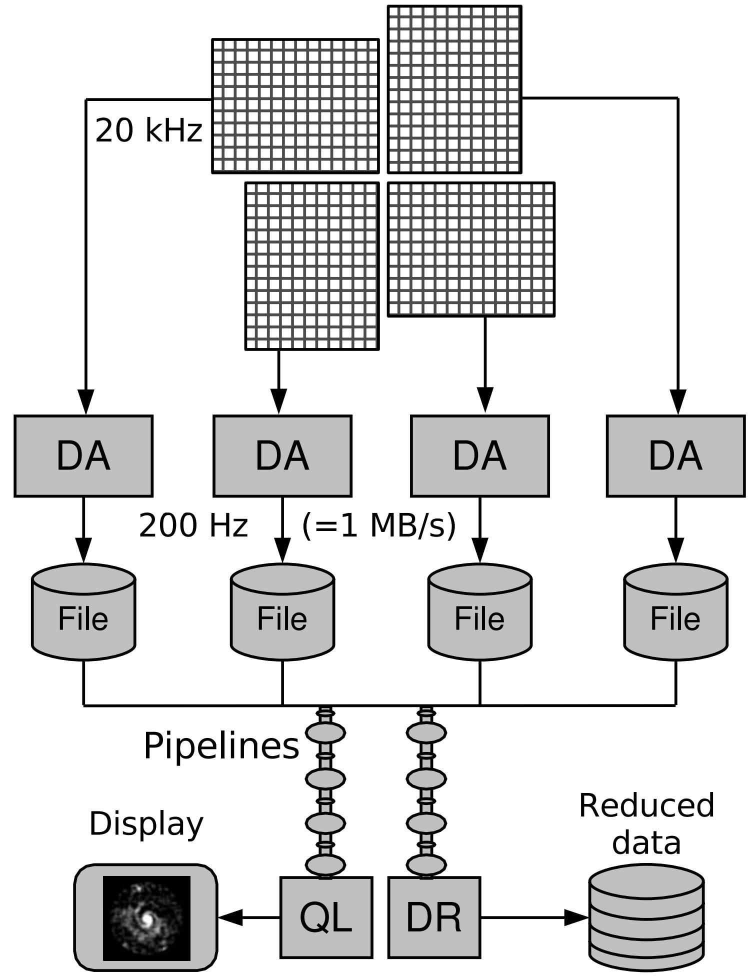


MCE



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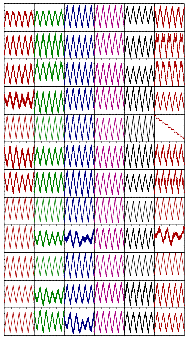
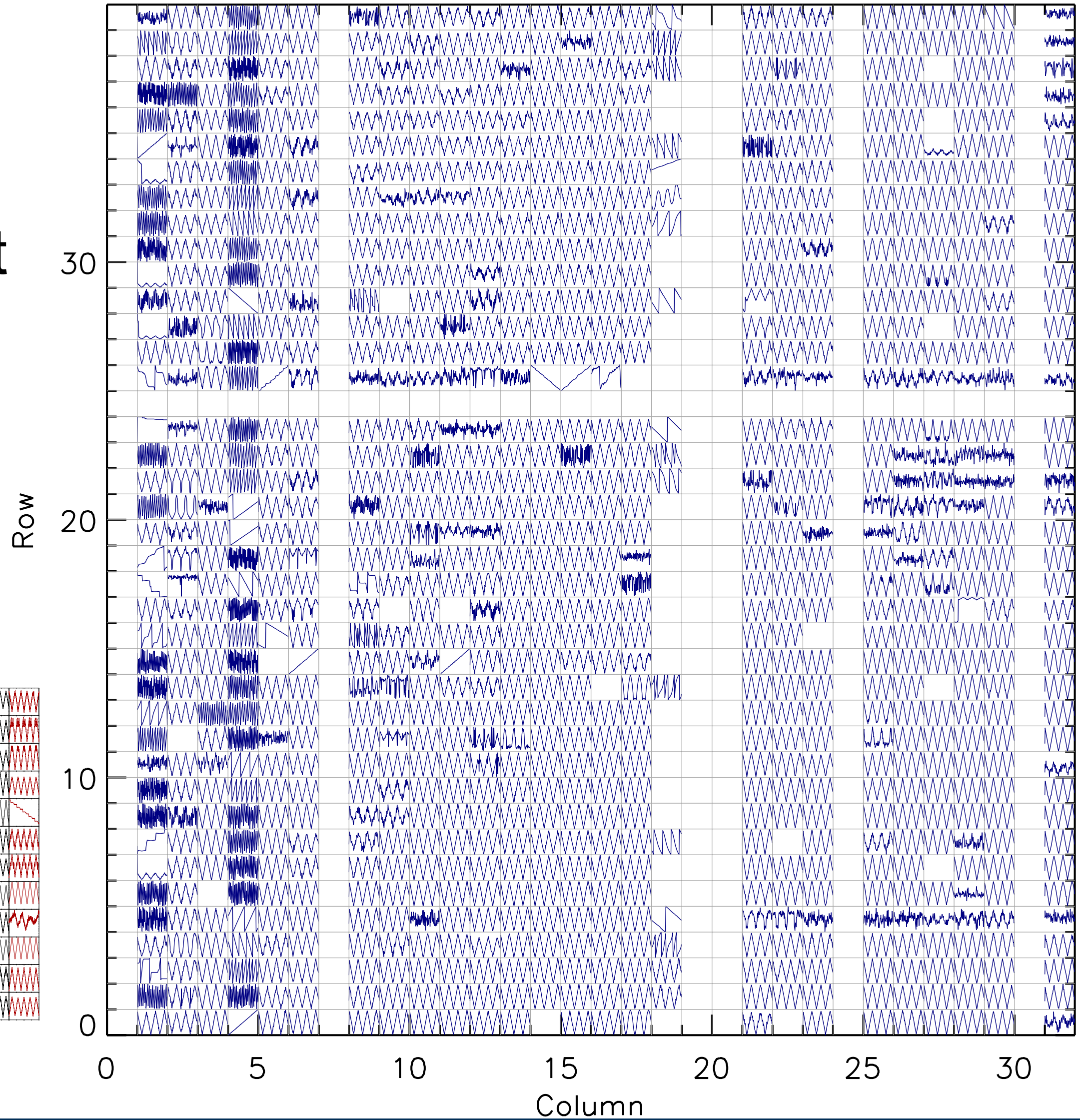
Full array measurements

UK Astronomy Technology Centre

- IRMMW 2007 Cardiff
- Now automatically sets up and reads out whole sub-array of 1280 pixels





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Measurements

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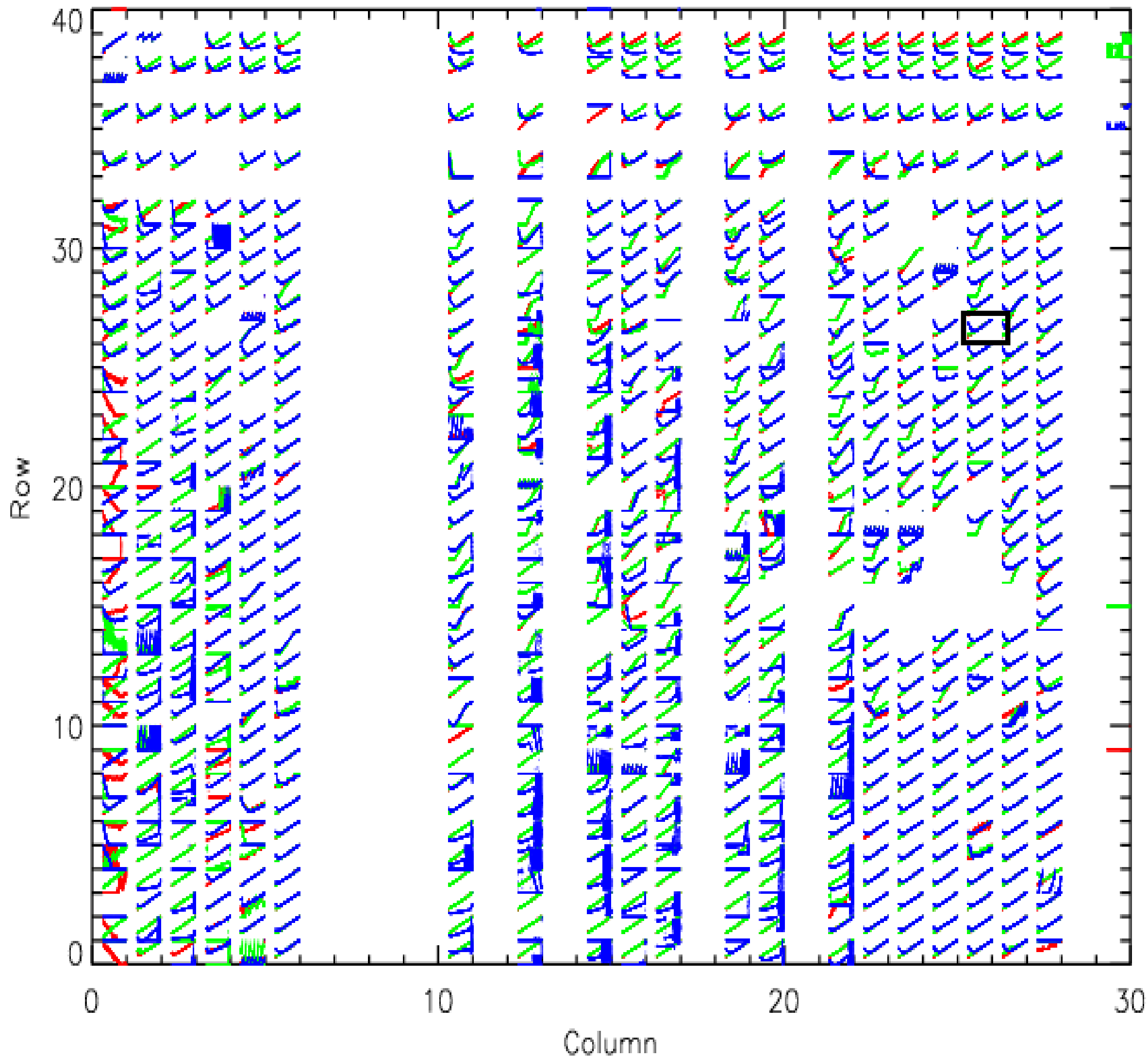
- Now
  - Improved (better behaved) array design
  - Load curves across 850 μm array (taken on telescope)



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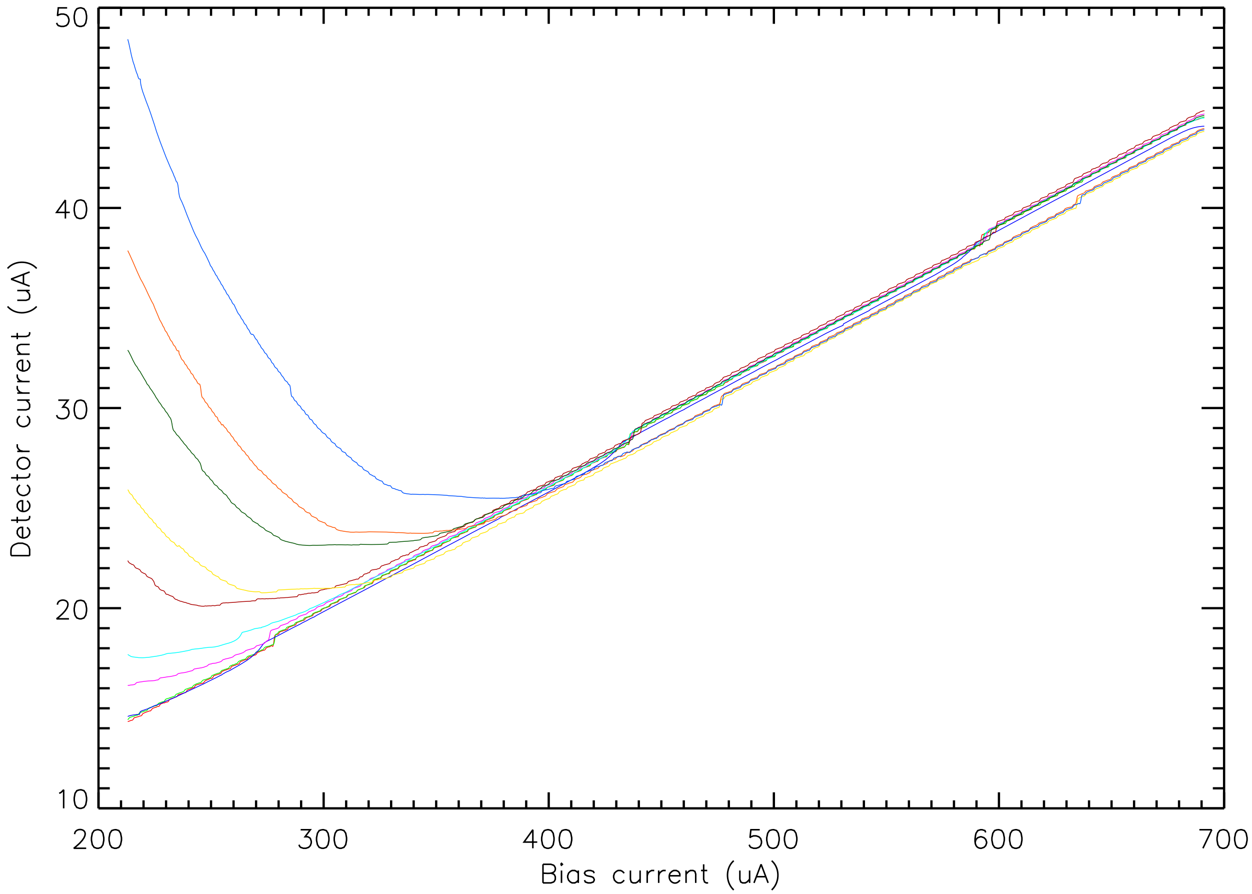
Measurements

Detector current

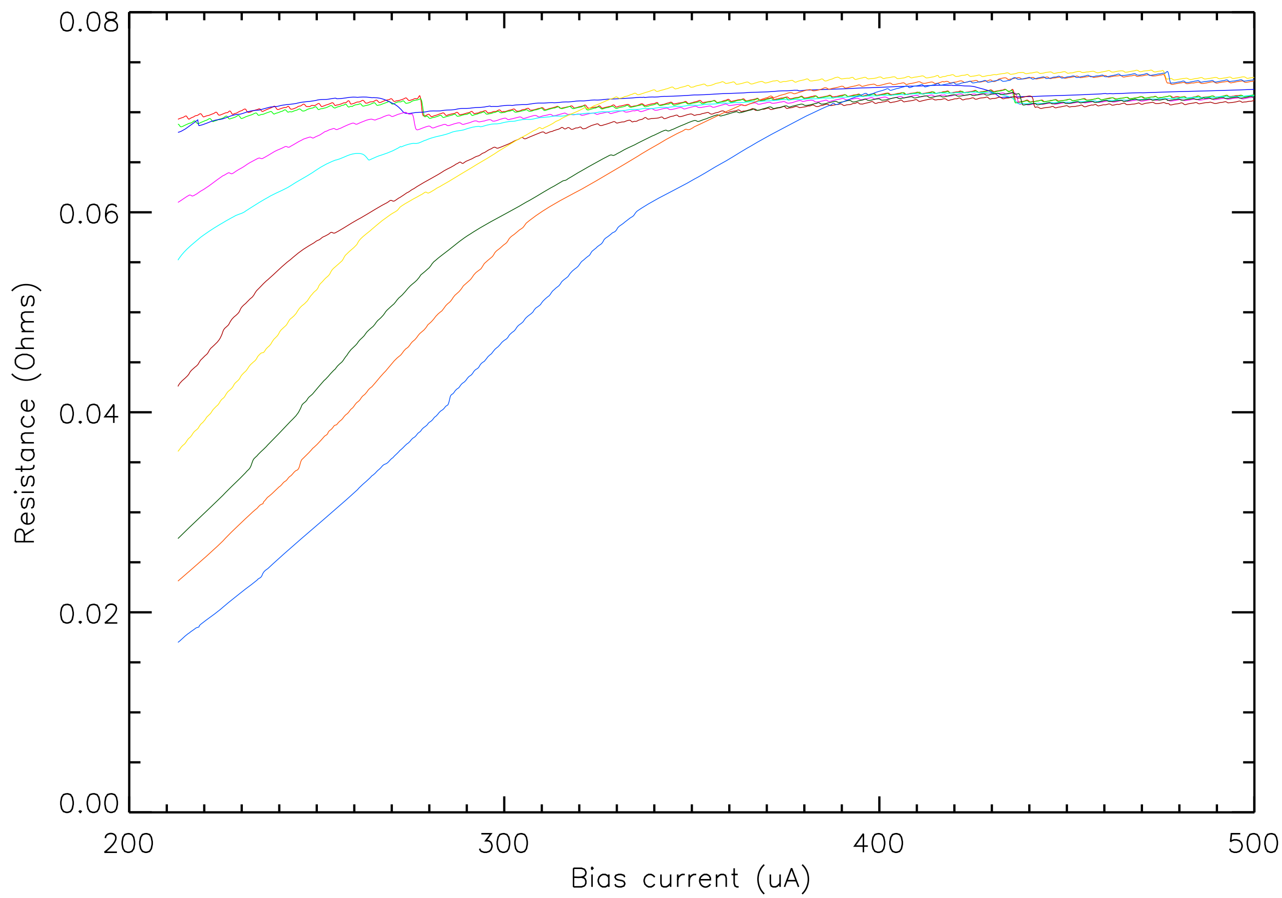


Measurements

UK Astronomy Technology Centre

Science & Technology Facilities Council

Detector resistance



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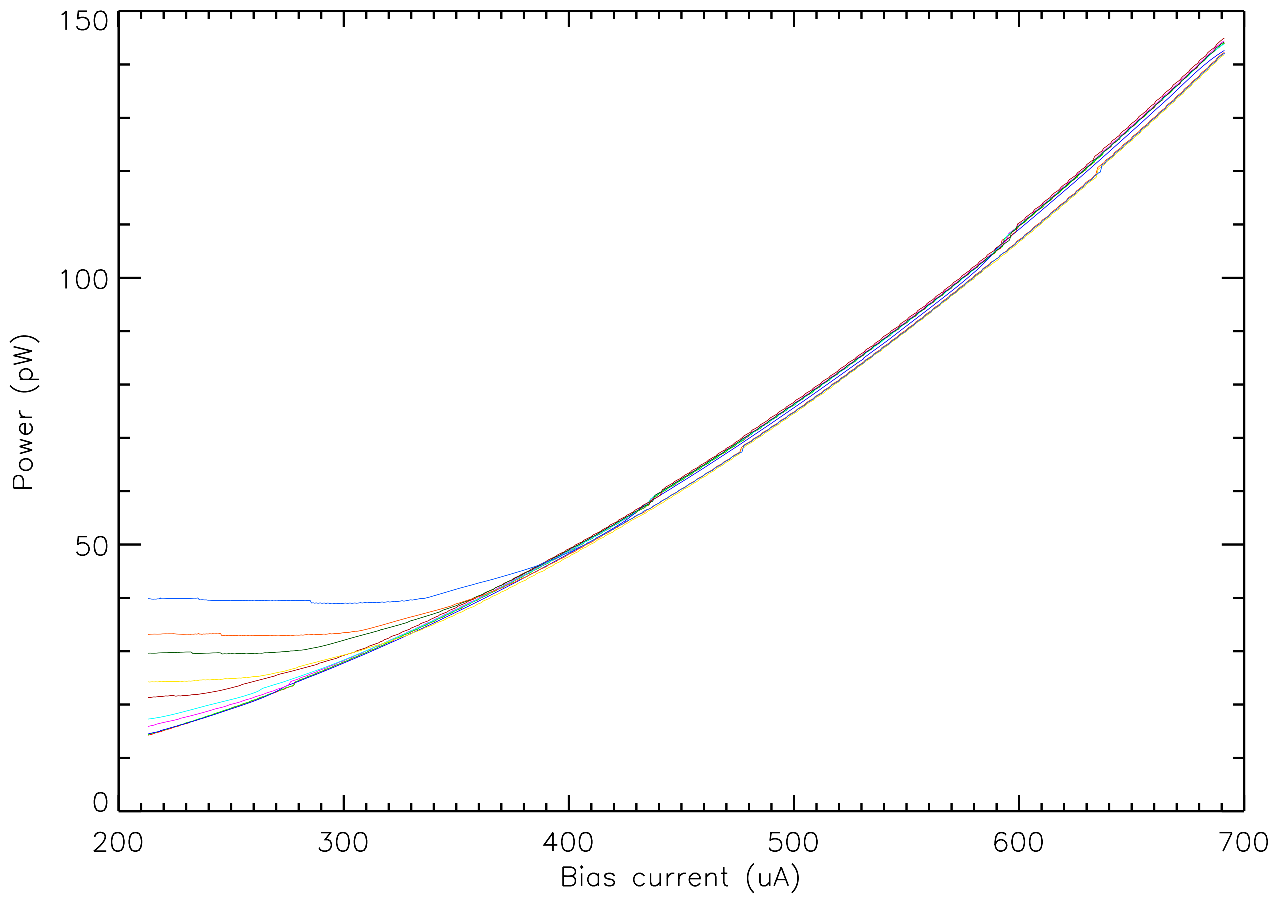
Detector power



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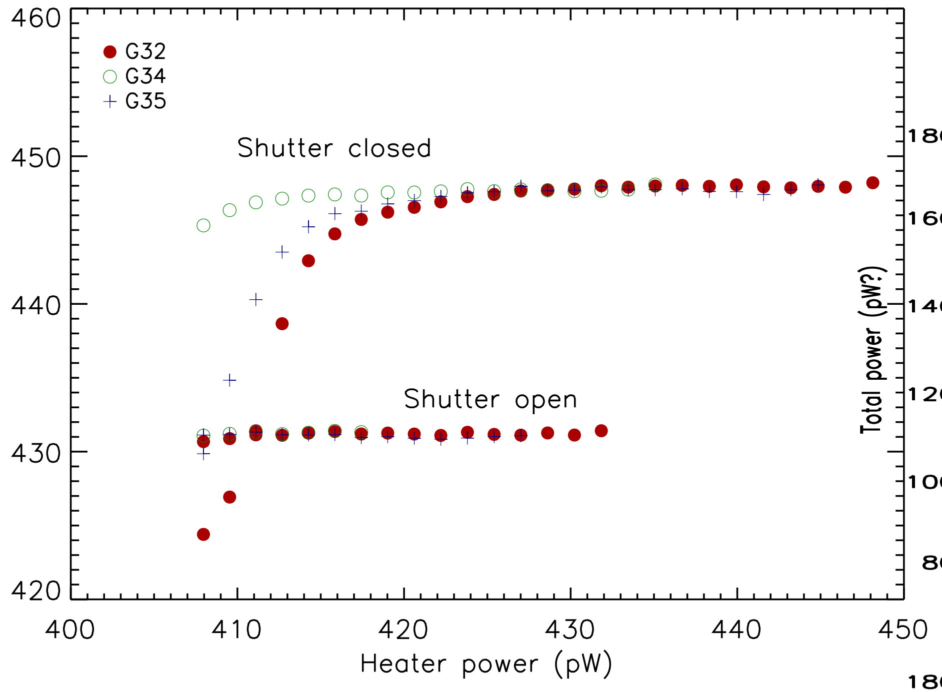

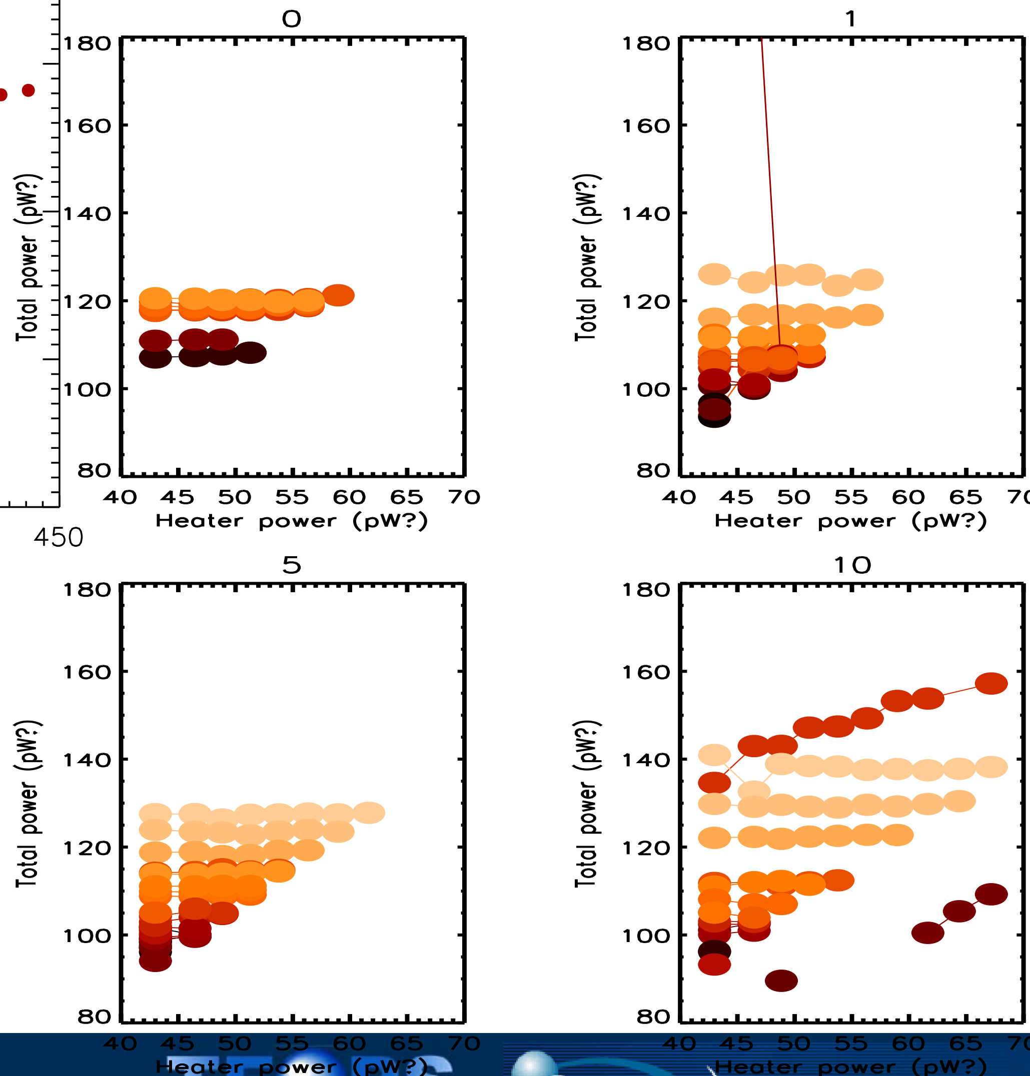

- Constant total power as heater power changed
- Total power varies with Tc (15 mK)

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Measurements

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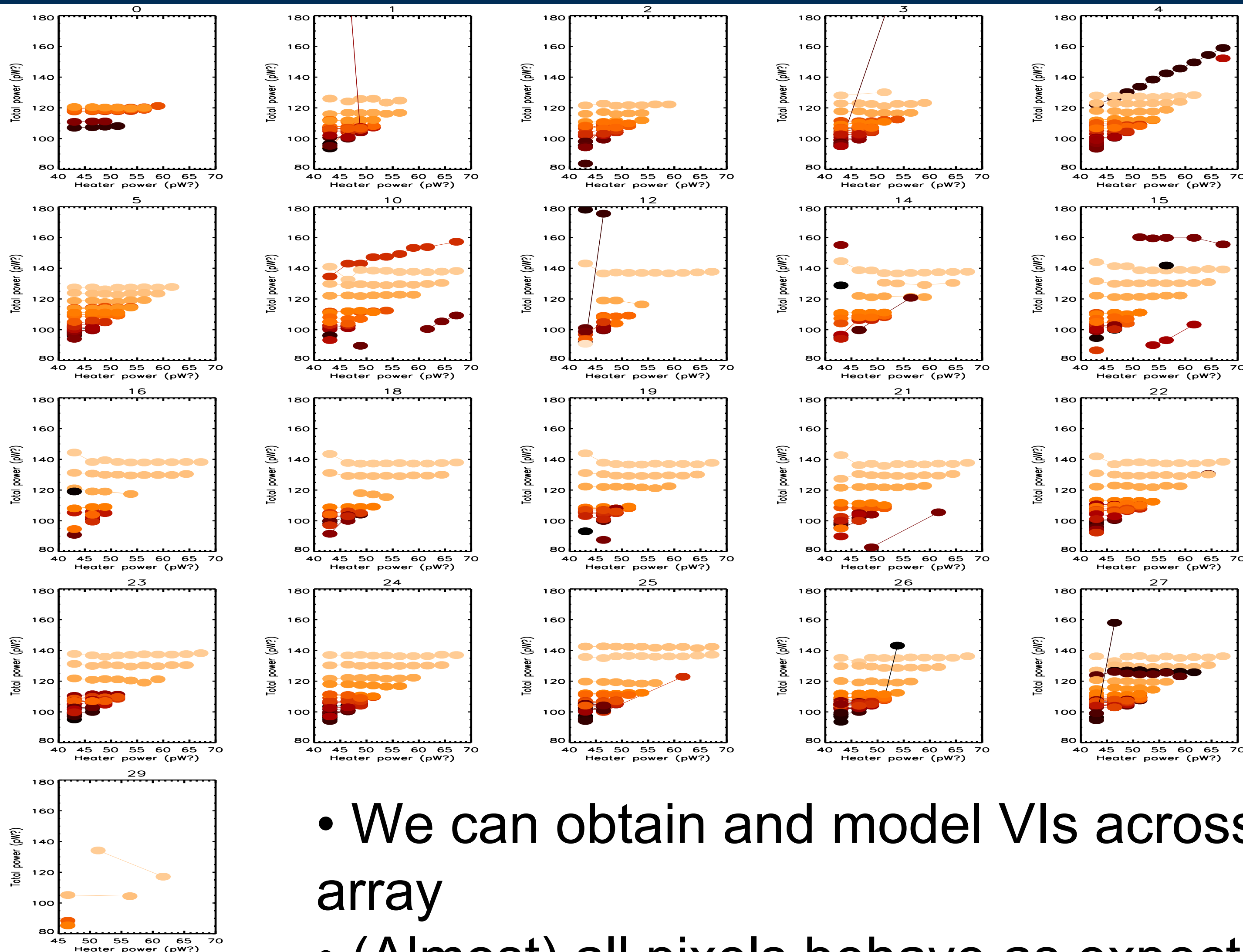

- We can obtain and model VIs across full array
- (Almost) all pixels behave as expected

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Detector status

Array yields

- Currently have 2 commissioning-grade arrays - one for each waveband

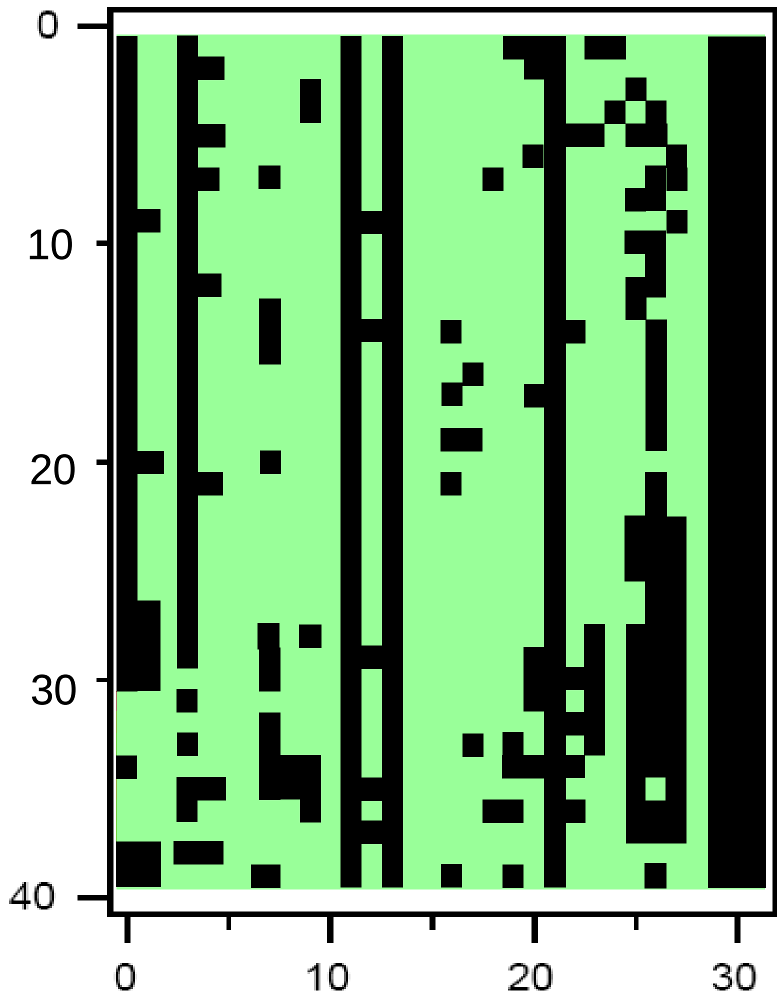
- These are limited in terms of pixel yield, and for the 850, the sensitivity is not background limited

- But good enough to commission the instrument on the telescope

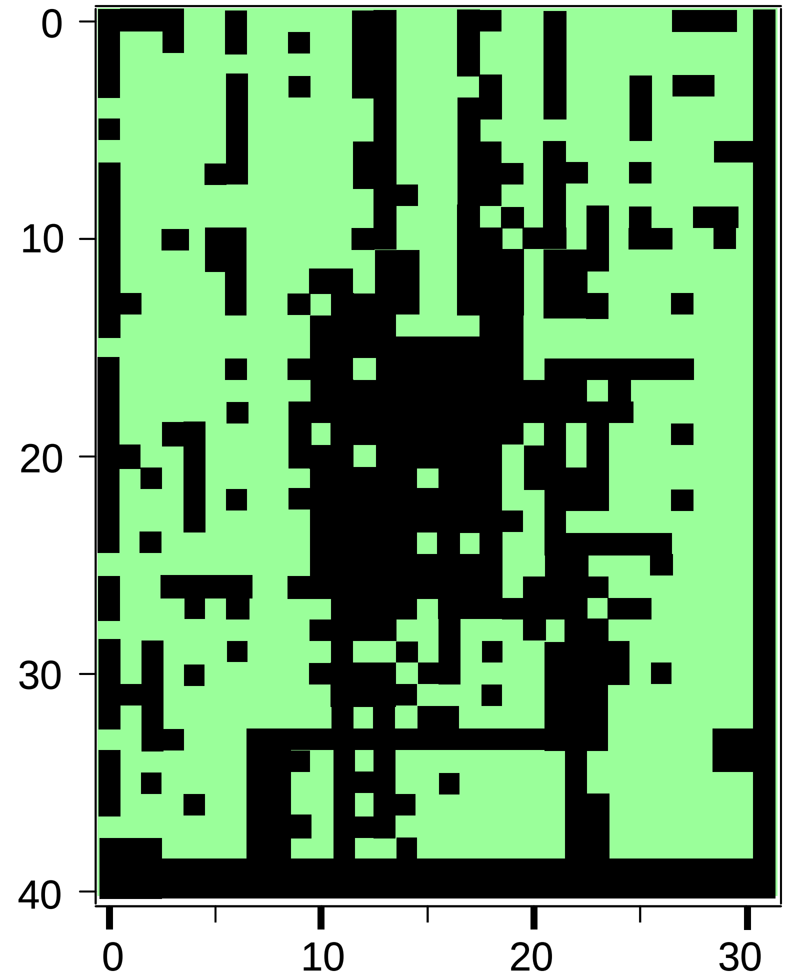
- Instrument will be upgraded with science-grade arrays next year

Array yields

UK Astronomy Technology Centre



450 C-G Array
(~620 pixels working to spec)



850 C-G Array
(~550 pixels working but not to spec)

Array yields

850μm C-G array:

- Fails the sensitivity specification by at least a factor of 2 (Tc and G too high)

- A trade-off has to be made in terms of the number of pixels and their sensitivity

- If adopt a scenario where the cut-off sensitivity is defined as being equivalent to that of SCUBA(-1) then 200 pixels would be useable

Provides mapping speed **~5 times** better than SCUBA

Array yields

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450µm C-G array:

- As measured some 40% of pixels meet the sensitivity (NEP) requirement

- Fails bad pixel distribution criteria (not a S-G array...)

- Should provide mapping speed **~50 times** better than SCUBA (with 40% of pixels)

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Array yield

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Causes of low yield:

- Wire bond failures:
  - Cause loss of entire row or column
- Programme to improve this on the way
- Already seen large improvement over original design

- Failures on MUX
  - All 8 science grade MUXes screened
  - Yield from > 85% to near 100%
    - (One array has *one* bad pixel)

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Array yield

Cause of low yield:

- Excess heating
  - *Small* number of resistive joints in wiring in sub-array module
    - Have to turn off some columns to keep arrays cold enough
  - Alternative cold electronics design being tested

Other issues

- Controlling Tc
  - MUX process control issue
  - Improved process: witness samples show < 2.5 mK variation across array
  - Acceptable for science-grade array

- Controlling G
  - Detector wafer process control issue
  - Work on controlling process in hand to replicate earlier good results

Conclusions

Conclusions

- SCUBA-2 is the first wide-field, ultra-sensitive camera for submm astronomy
- The technology is state-of-the-art and represents a great investment on behalf of the funding agencies
- Now installed on JCMT
  - First light imminent
  - Full complement of science grade arrays early 2009.

We've come a long way…

- There is still work to be done, but we are nearly there!
- Science grade arrays on their way...
- Watch this space!

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Institutions

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*