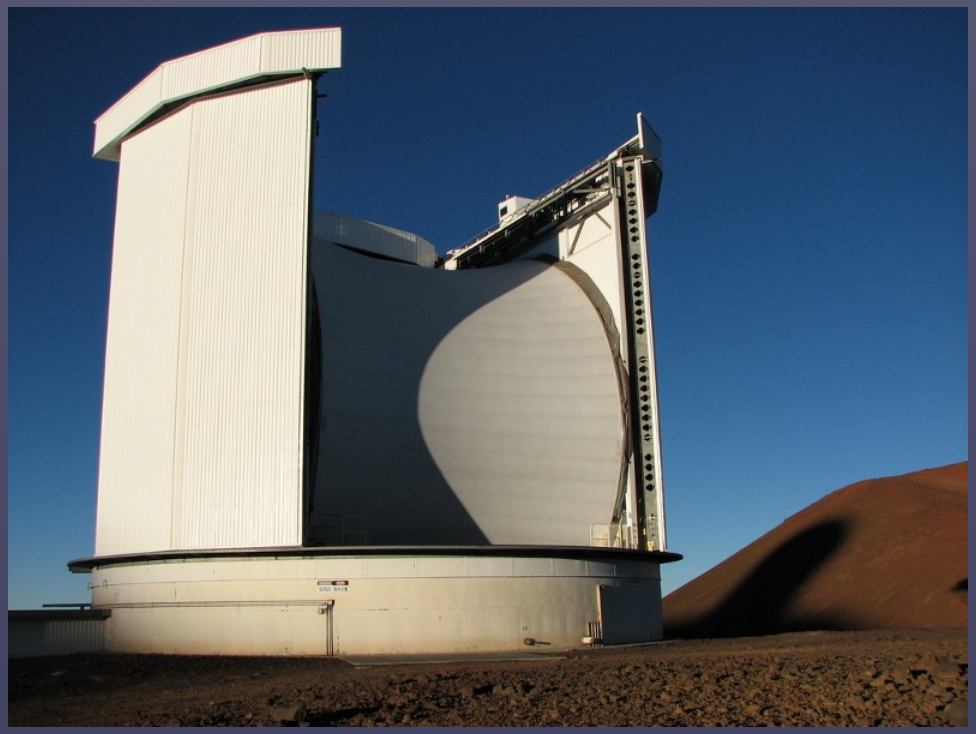
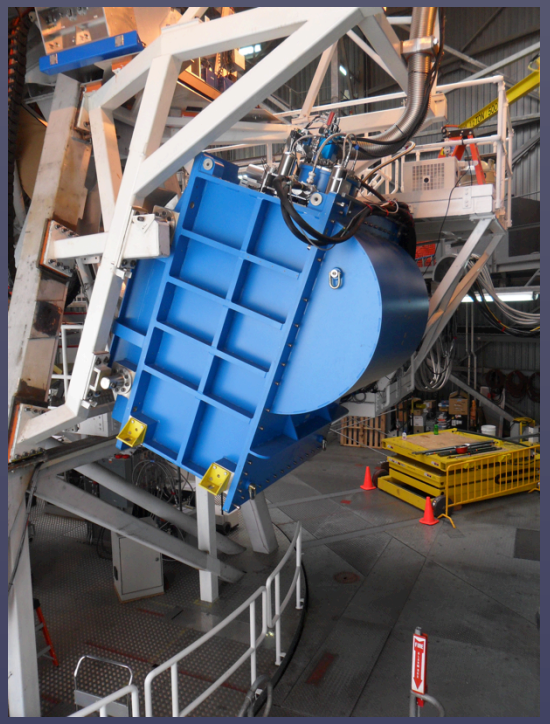
Instrument Performance of SCUBA-2





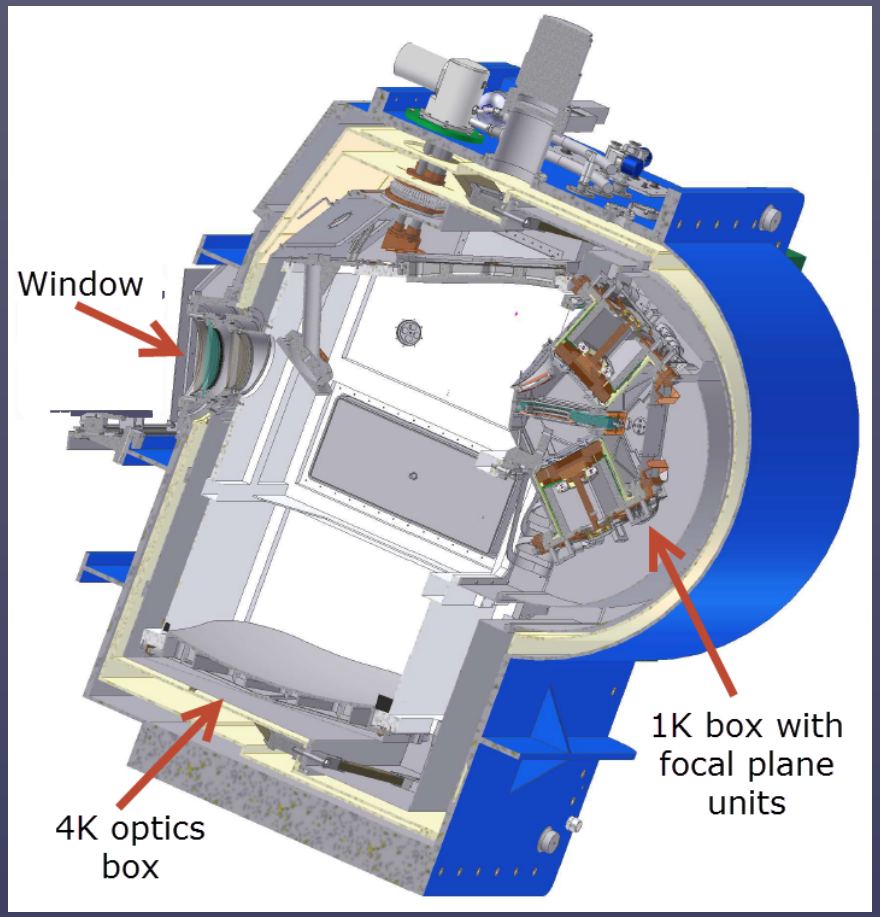
Focus on SCUBA-2

- SCUBA-2 is a 10,000 pixel bolometer camera on the JCMT, operational since October 2011.
- Two focal planes, each with four 32 by 40 MoCu TES sub-arrays with inline 2-D TD SQUID MUX.
- Observes simultaneously at 850μm and 450μm with a 43 sq-arcmin field of view.
- A survey instrument: - a square degree of sky can be mapped to 6mJy/beam at 850μm in less than 7 hours.
- It's working great.

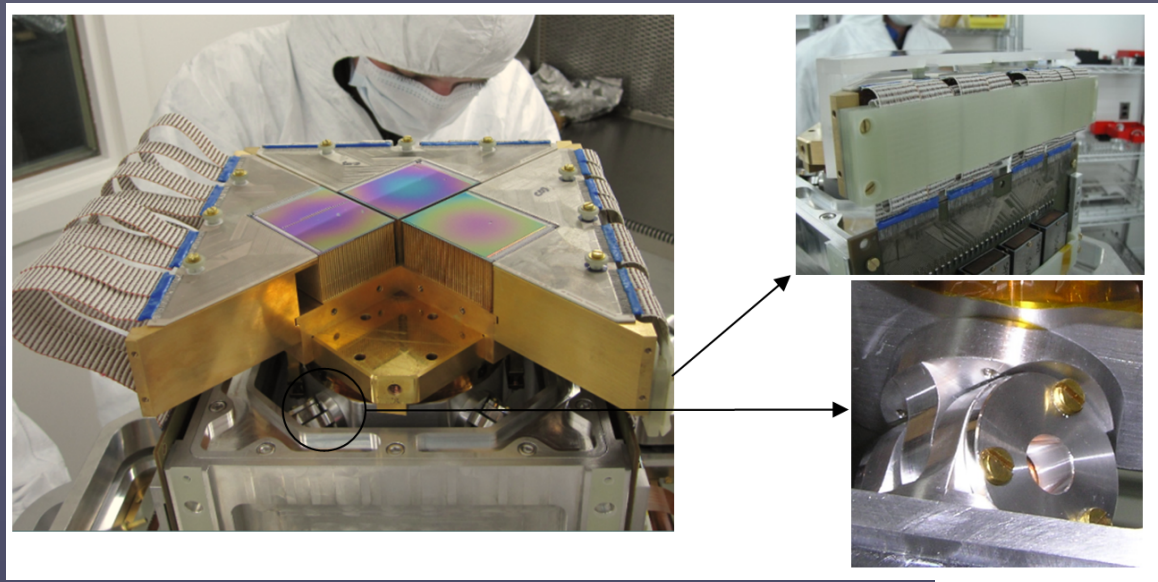
SCUBA-2 Innovation

- Tons on innovation (3.4 Tons to be exact)

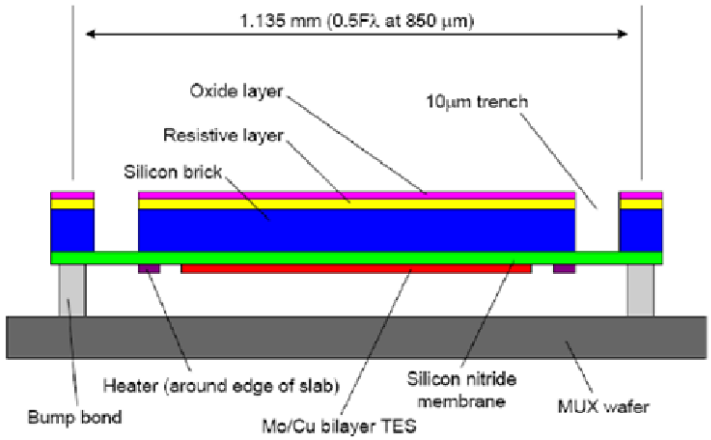
- **(Almost) cryogen free**
- **Worlds first 'dry' dilution fridge**
- **(At the time) Largest low temperature detector arrays**
- **Novel thermal isolation**
- **Novel interconnects at 50mK**
- **Superconducting wiring harness**
- **MCE warm electronics**
- **Data reduction pipeline**



Detector arrays



Assembling the focal plane

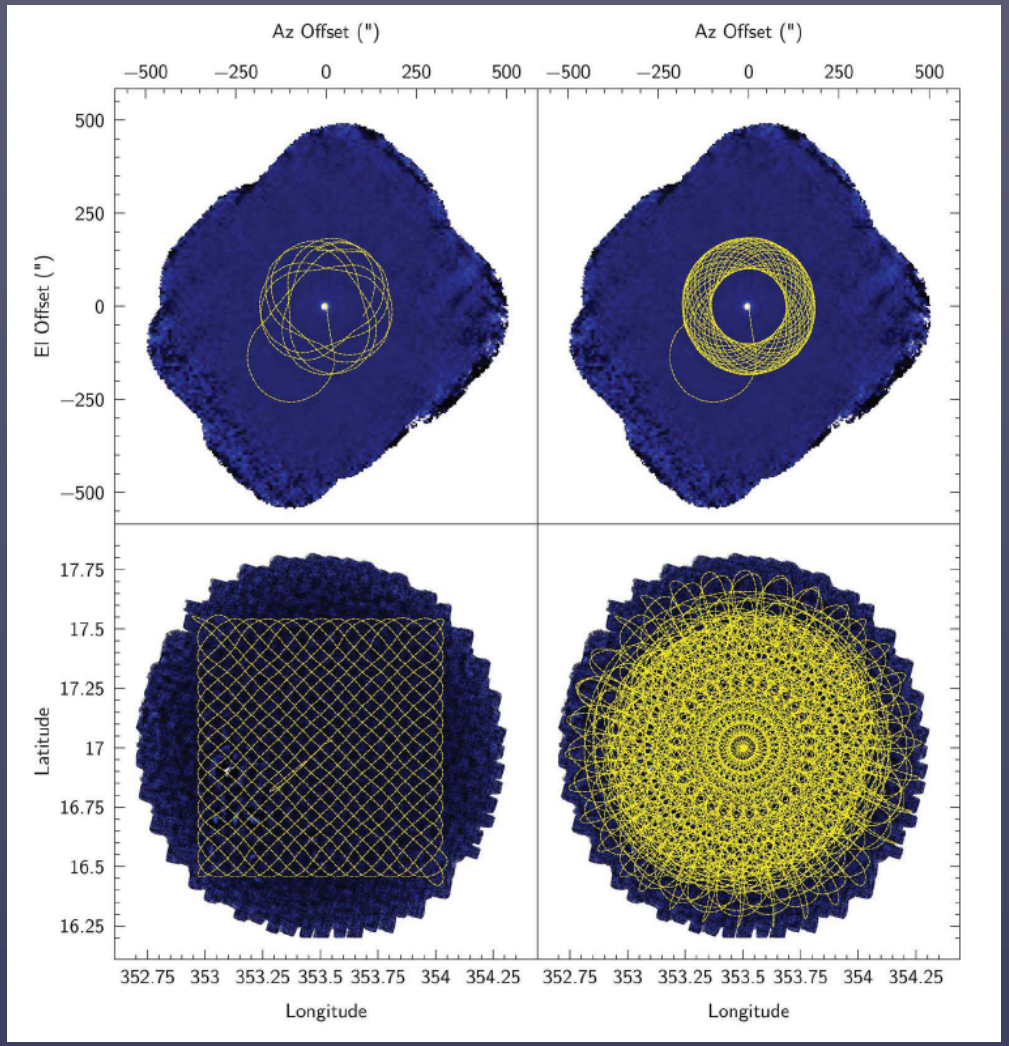


SCUBA-2 detector design

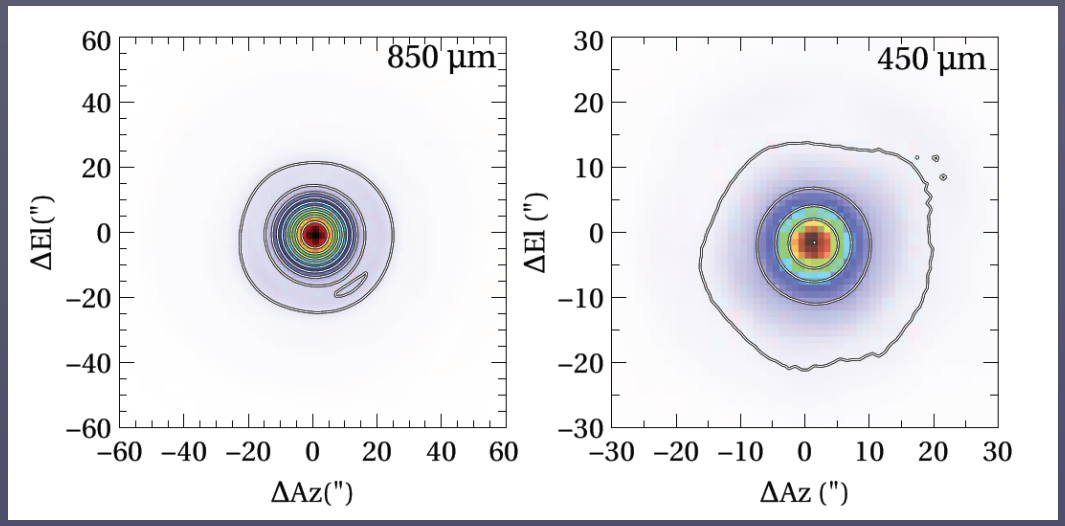
Observing modes

Constant Velocity daisy scans for point or compact sources less than 3 arcmin across

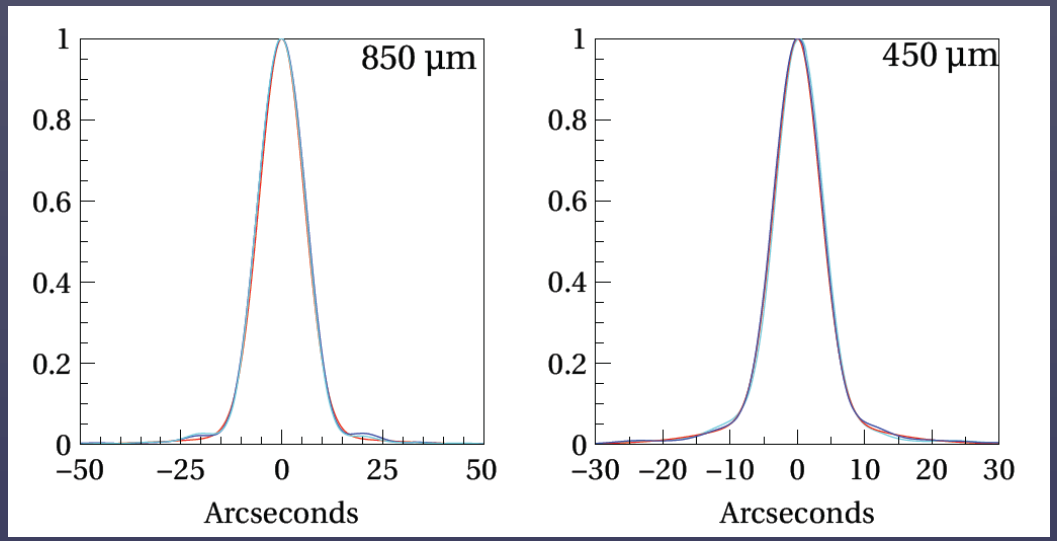
Rotating curvy pong patterns for large-scale mapping



On sky calibration



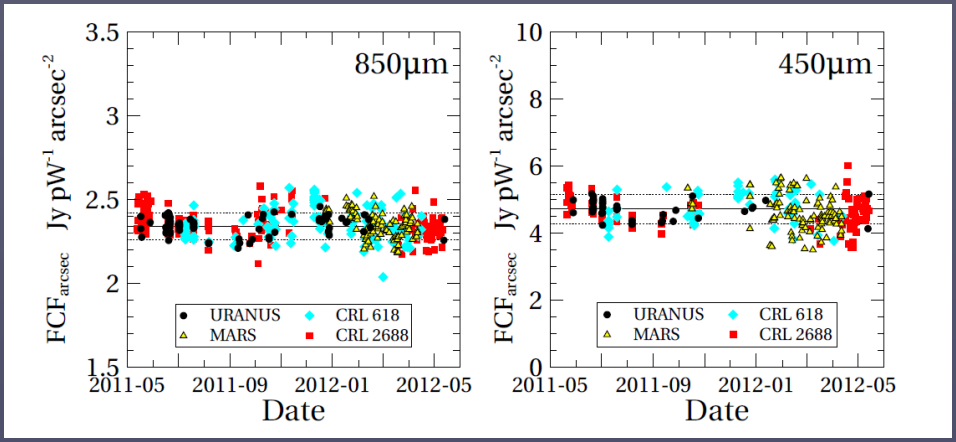
Made over 500 individual observations of primary calibrator sources (Mars, Uranus) and secondary sources (CRL618, CRL2688, plus 7 others).

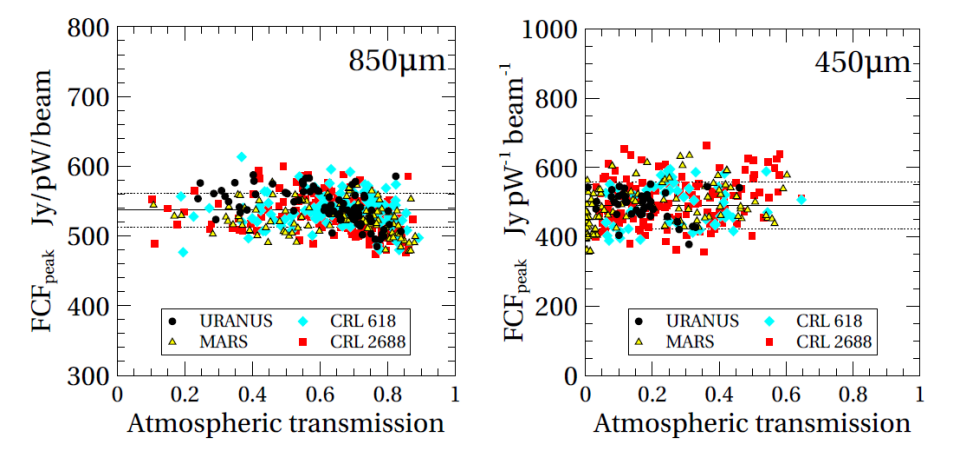


Measured the SCUBA-2 beam shape and focal plane distortion to enable accurate aperture photometry.

Here showing maps of Uranus and the beam and diffraction patterns.

On sky calibration 2





Calculate a Flux Conversion Factor (FCF) from detector units (pW) to astronomical units (Jy).

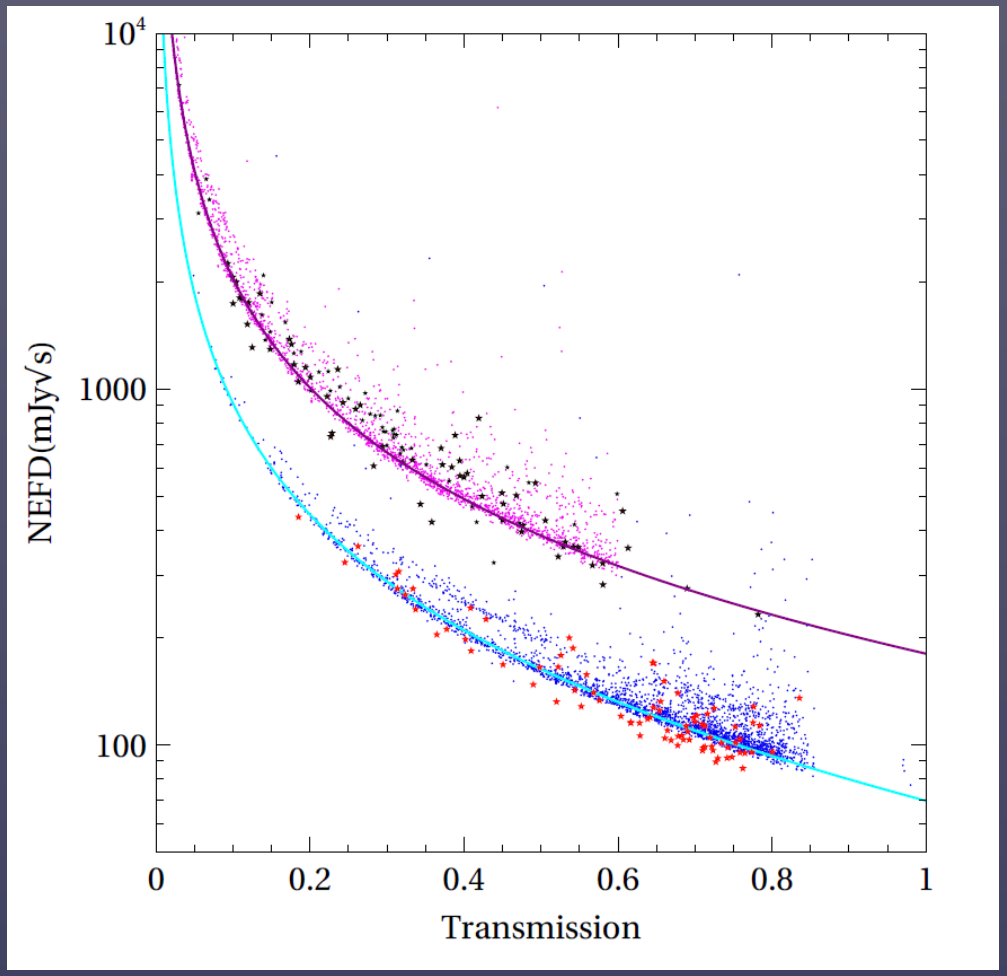
Each night, many calibrators are observed.

The error on the relative flux calibration is less than 5% at 850μm and ~ 10% at 450μm. **A factor of 2 improvement over SCUBA.** Mostly due to the use of a line of sight water vapour meter.

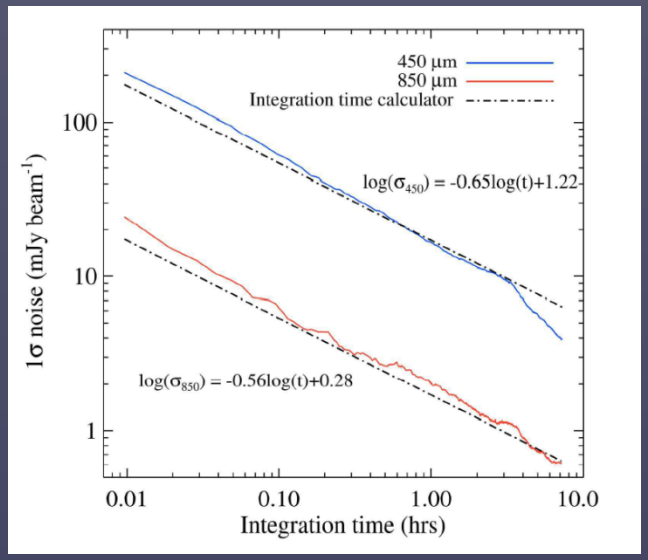
Dempsey 2013

SCUBA-2: on-sky calibration using submillimetre standard sourcesMNRAS (2013) Vol. 430 2534-2544

On sky sensitivity



Measured NEFD for each waveband as a function of fractional sky transmission



Measured RMS noise in 3 arcmin DAISY image vs integration time

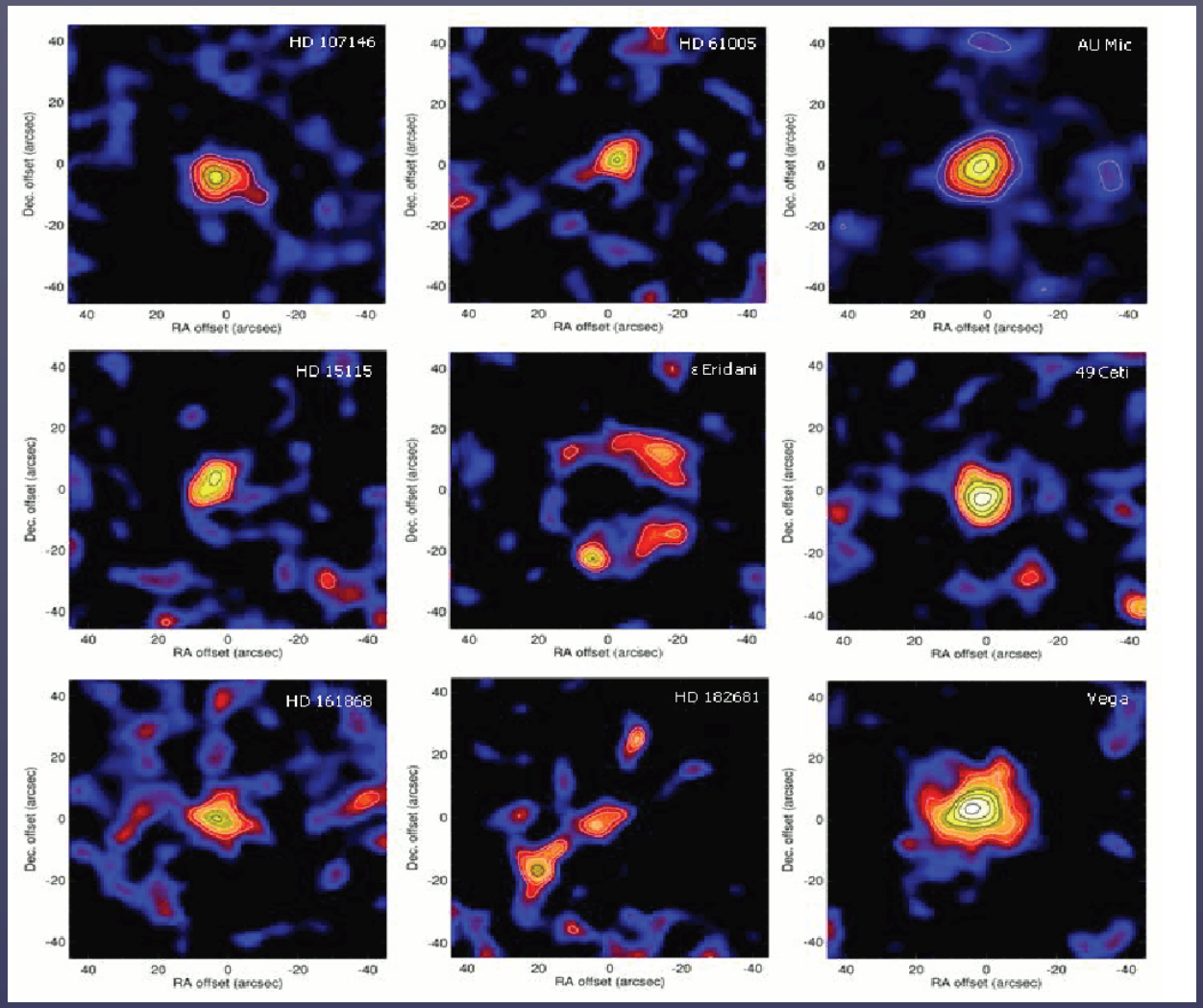
Holland 2013

SCUBA-2: the 10 000 pixel bolometer camera on the James Clerk Maxwell TelescopeMNRAS (April 21, 2013) Vol. 430 2513-2533

Original Scientific Case

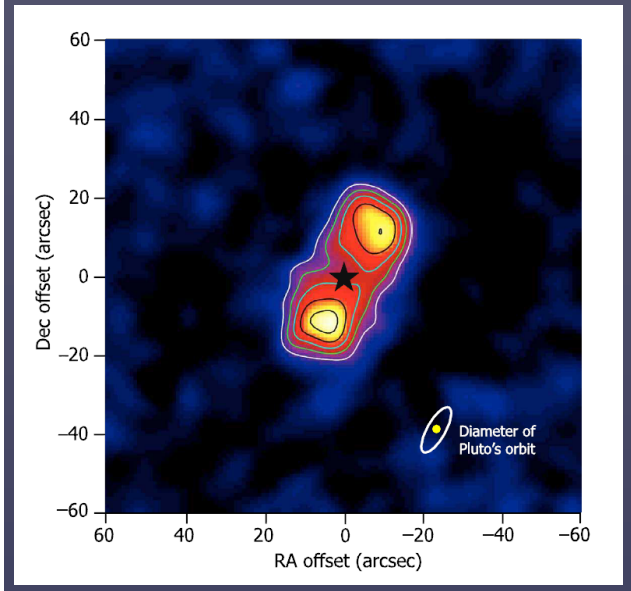
- The original scientific aims for SCUBA-2 spoke of:
  - *"extending capabilities to large-scale projects covering up to tens of degrees of sky, and deep and high fidelity imaging of selected areas. With an estimated mapping speed improvement ≥ 100 times that of SCUBA for an 8-arcmin diameter field-of-view the scientific productivity of the telescope should increase many fold. New kinds of targets and surveys that are currently infeasible with SCUBA will become easily observable with the introduction of SCUBA-2.*
- SCUBA-2 has achieved these goals.
- In good weather, a 3-arcmin diameter field can be mapped by SCUBA-2 to a RMS noise level (in the map) of 1mJy at 850 μ m in 3 hours. For a one-degree diameter field, the RMS noise in the map is below 6mJy in 7 hours. Shallower one-degree maps to 30mJy at 850 μ m take just 15 minutes.

6 JCMT Legacy Surveys



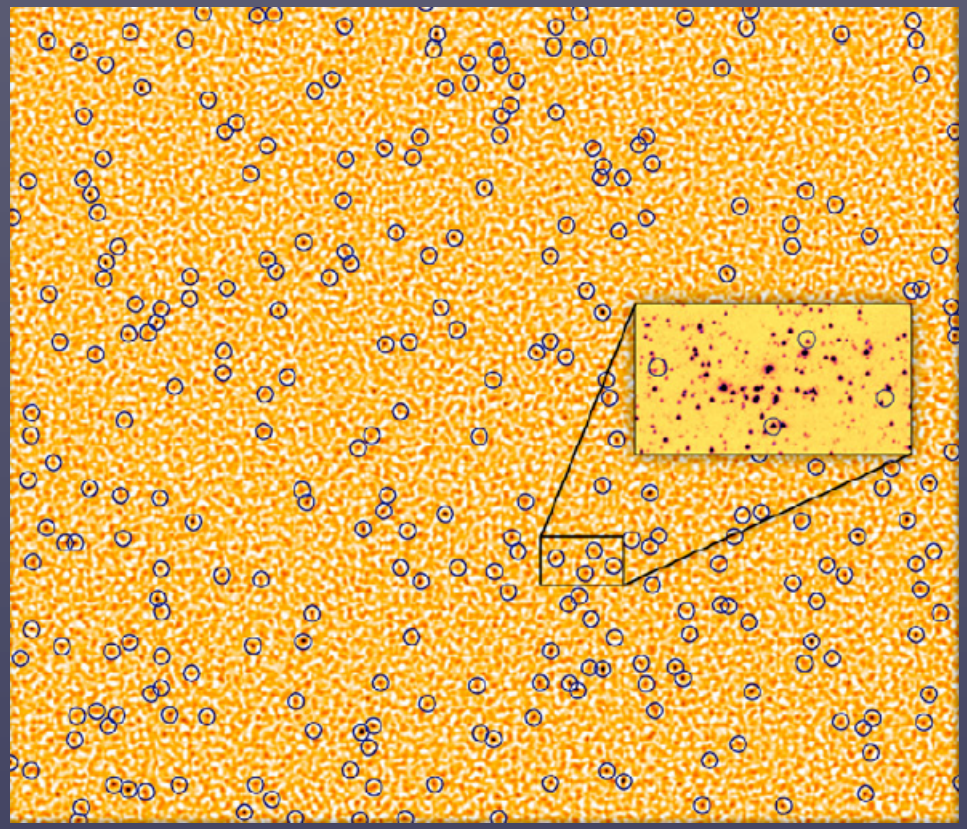
SONS (nearby stars)

Images of debris discs around nearby stars



Images SONS team

JCMT Legacy Surveys



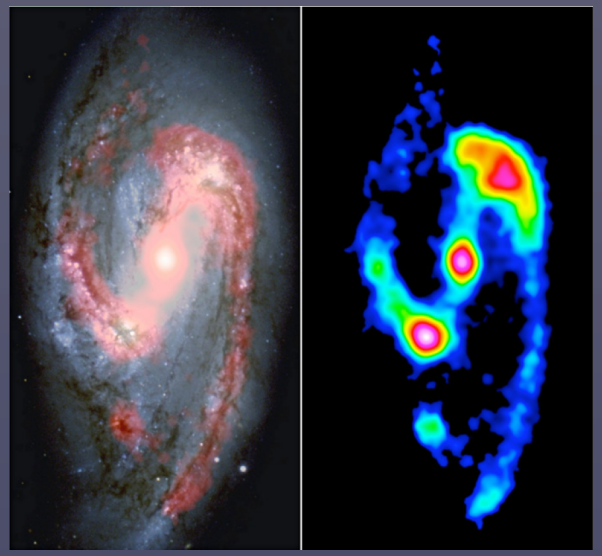
Images CLS team

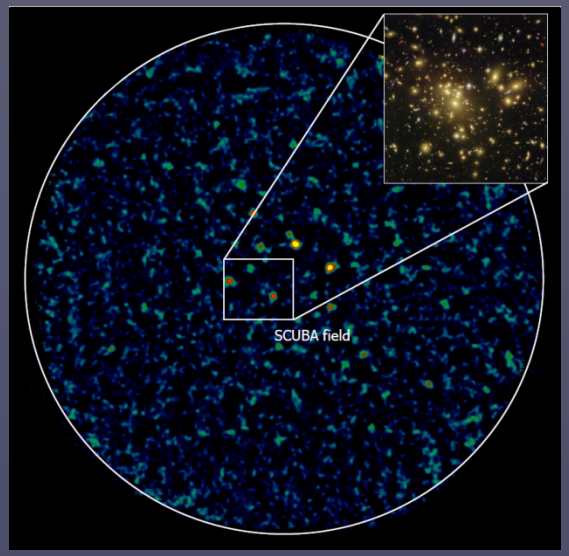
CLS (cosmology)

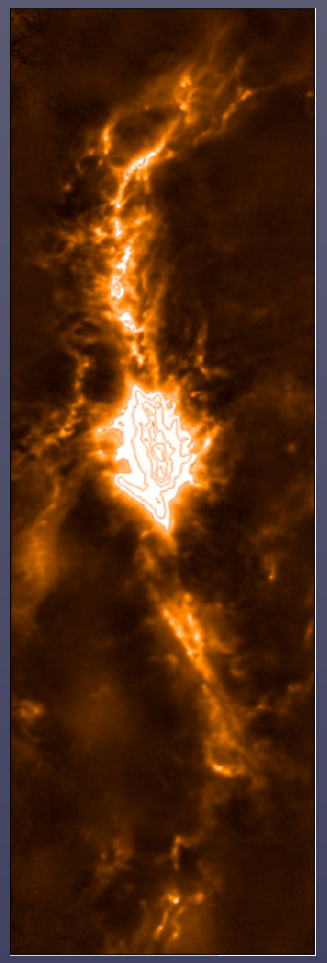
A sq-degree sized 850μm map in the UKIDSS Ultra Deep Survey field. SCUBA-2 detects hundreds of sources; far-infrared galaxies and active galactic nuclei out to z~5 or above.

The insert is a Spitzer image which identifies counterparts to the brighter and low redshift examples.

Other survey team images



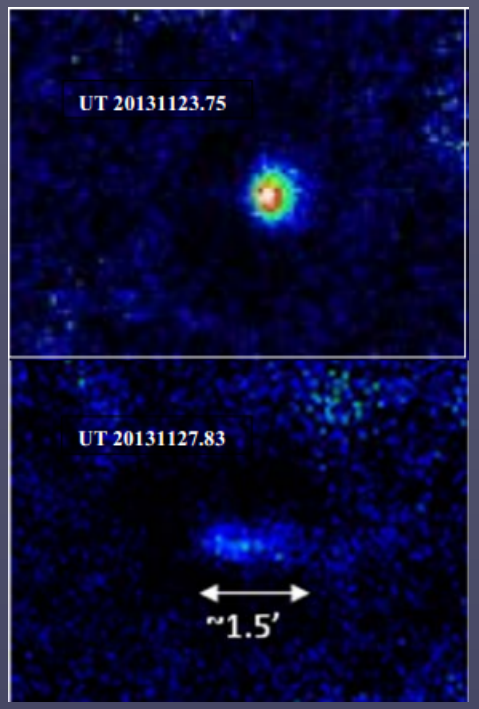




M66 at 850μm (NGS (galaxy) team). **Abell 1689** a massive lensing galaxy cluster (GT team) and 850μm map of **Orien's integral shaped filament** (GBS (Gould Belt) team)

Flexible in operation: Day and Night

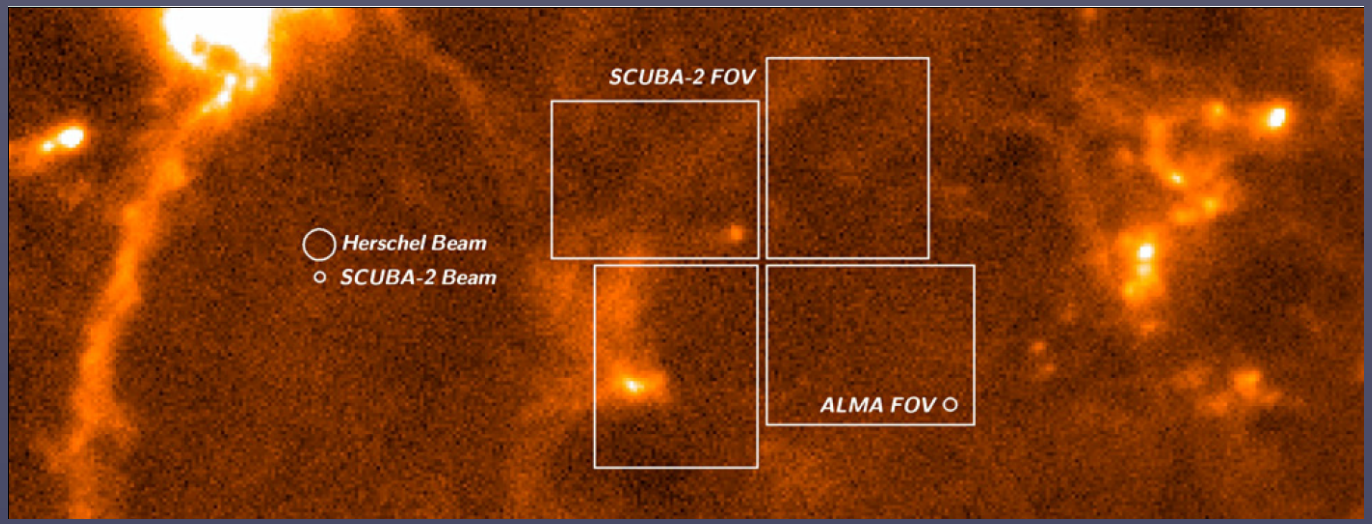
SCUBA-2 was the only ground based instrument to image comet C/2012 S1 (ISON) through perihelion November 28th 2013



850μm images of C/ 2012 S1

Impact of SCUBA-2

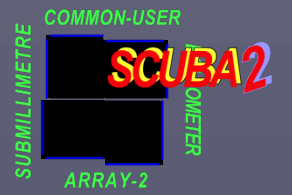
The SCUBA-2 beam size and field of view compared to ALMA (500μm) and SPIRE .



SCUBA in its' lifetime observed 41 square degrees

In the first 3-years, SCUBA-2 surveyed 1778 square degrees

4.5 years of science operations



SCUBA-2 is an excellent facility instrument

- Cryogenics:
  - Major overhall in 2012 – since then cold continuously for up to 16 months at a time – many GHS pump failures along the way.
- Array performance:
  - Consistent and reliable – after warm-ups (to 4K) or months of continuous use.
- Data reduction:
  - Continues to evolve – one of the main issues is recovering extended emission.
  - Clump finding and making source catalogues.
- Cost of operation
  - Cryogenics : $230K (PTC and cold trap) per year ($630 day)

equivalent to 10L He a day

SCUBA-2 array properties and measured performance

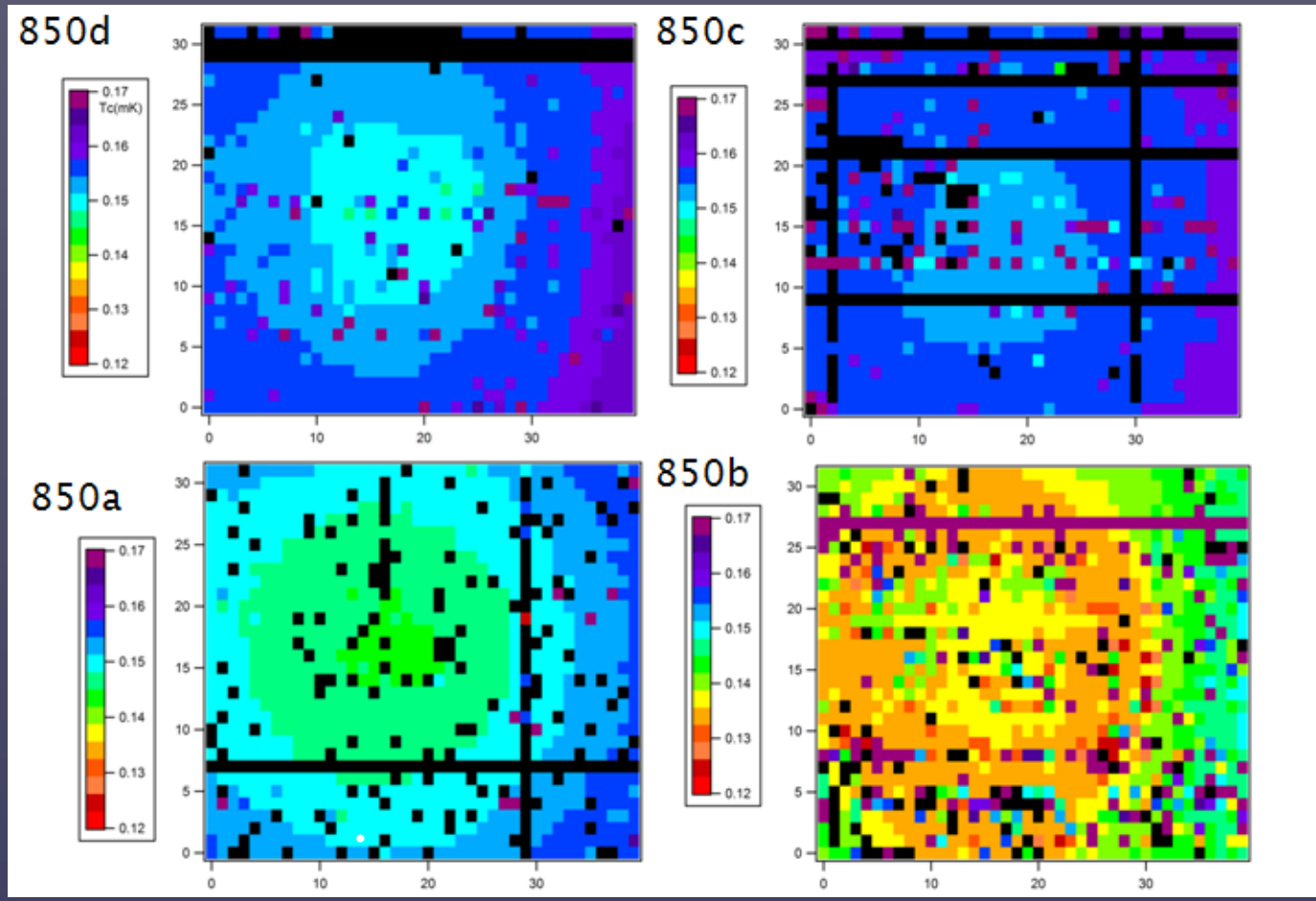
Sub-array	Target/Measured G (nW/K)	Target/Measured Tc (mK)	Phonon limited NEP ($W/Hz^{0.5}$)	Total Power (pW)	Weighted Mean Dark NEP ($W/Hz^{0.5}$)
850a	(1.5) 4.3	(120) 145	7.2×10^{-17}	(60) 162	1.1×10^{-16}
850b	(1.5) 2.8	(120) 130	5.6×10^{-17}	(60) 87	1.5×10^{-16}
850c	(1.5) 3.7	(120) 154	7.0×10^{-17}	(60) 162	1.1×10^{-16}
850d	(1.5) 5.7	(120) 147	8.2×10^{-17}	(60) 238	1.6×10^{-16}
450a	(5.5) 4.9	(190) 212	1.1×10^{-16}	(230) 328	3.2×10^{-16}
450b	(5.5) 6.1	(190) 206	1.2×10^{-16}	(230) 356	2.7×10^{-16}
450c	(5.5) 8.5	(190) 203	1.4×10^{-16}	(230) 541	4.6×10^{-16}
450d	(5.5) 6.1	(190) 198	1.1×10^{-16}	(230) 372	2.7×10^{-16}

SCUBA-2 detector properties

Tc for 850μm focal plane – 10mK variation with radial pattern.

Similar for 450μm focal plane.

Measured G is higher than target values. However we have higher total power handling – which turns out to be useful.



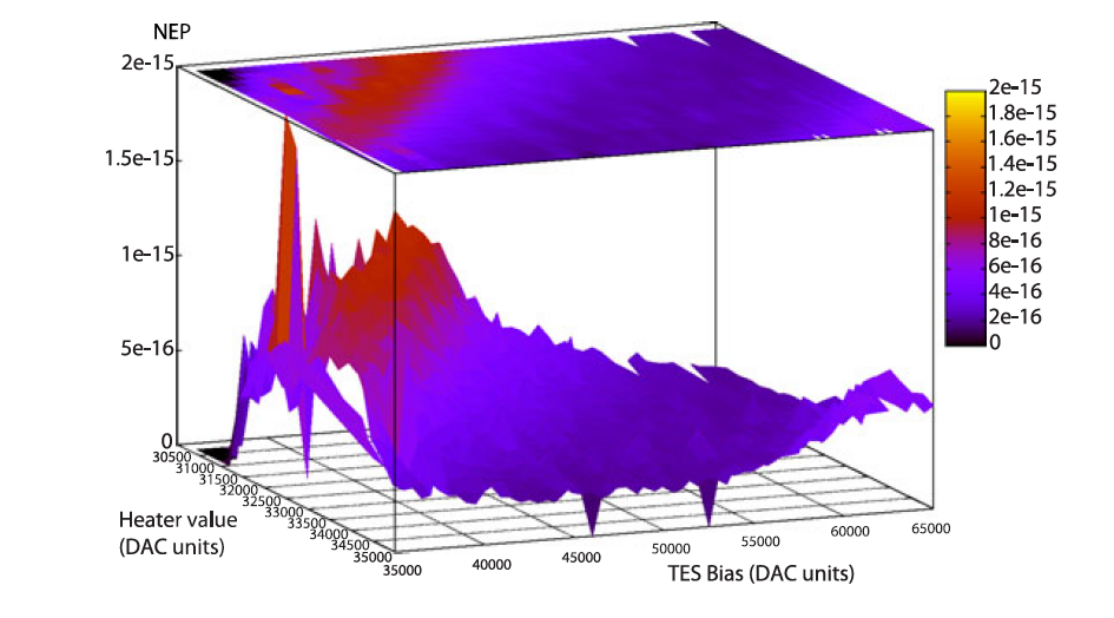
SCUBA-2 optimisation

Each sub-array has a single heater and TES bias setting

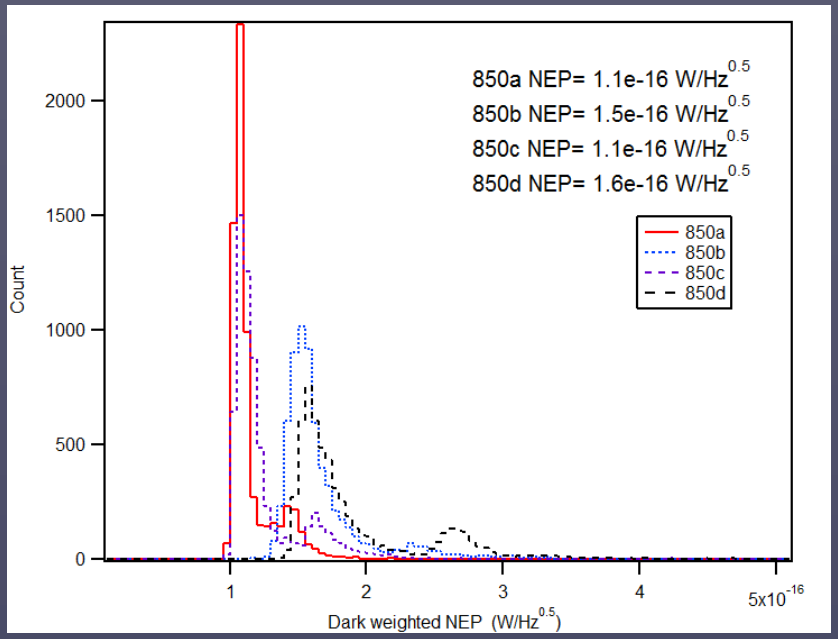
TES bias and heater setting

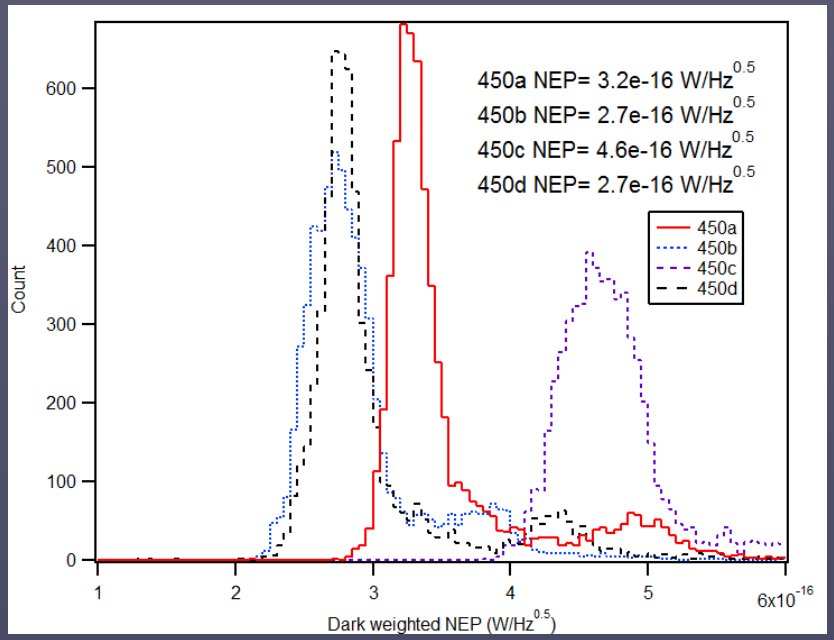
Early on in the commissioning we did a large search of the bias and heater phase space, measuring the dark NEP at each point for all sub-arrays.

From such plots, we selected the optimum settings for TES bias and the heater.



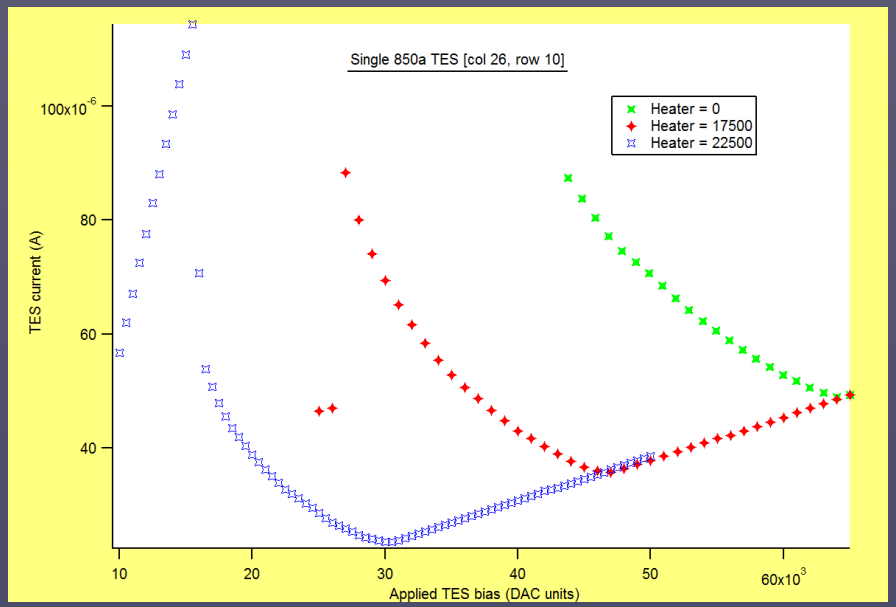
Dark Noise Performance



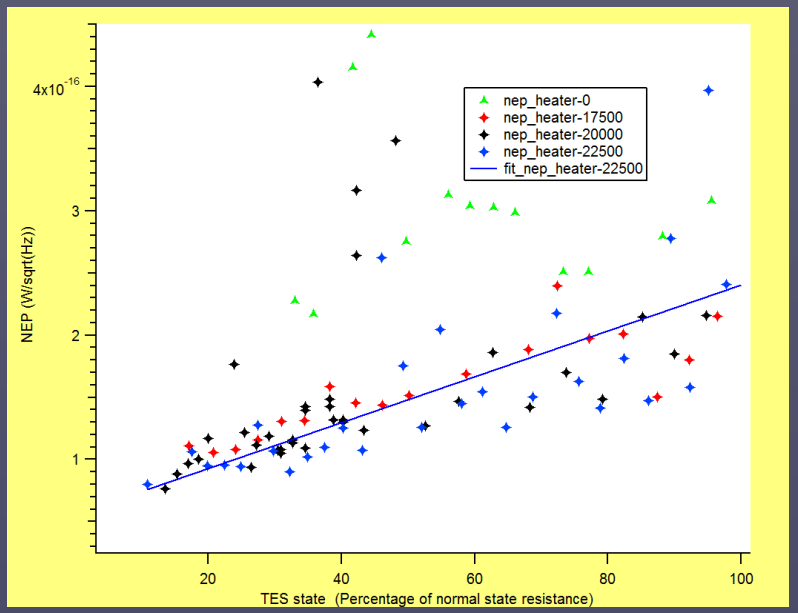


Dark NEP histograms for each sub-array; (right) 850 focal plane (left) 450 focal plane. These comprise all the dark noise observations from Feb 2012 to June 2012: 6,500 NEP measurements in total. **The measured dark NEP is higher than the expected phonon noise limited NEP**.

SCUBA-2 single pixel measurements



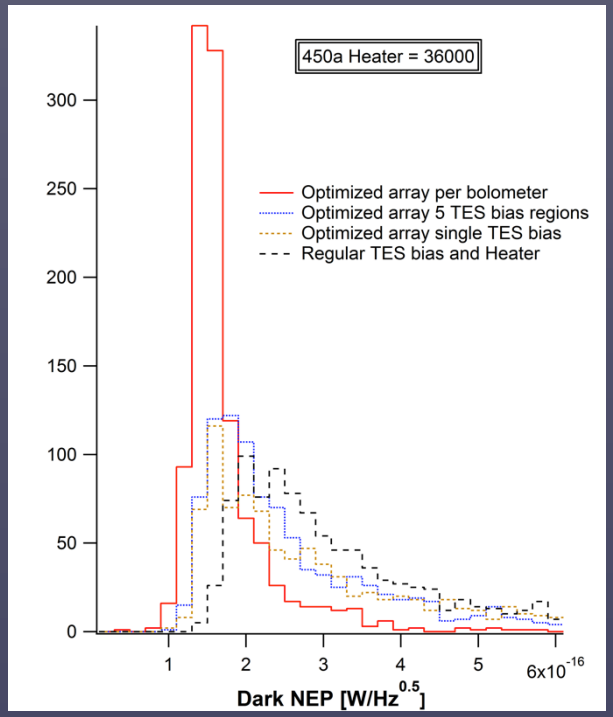
Raw data single pixel IV curves

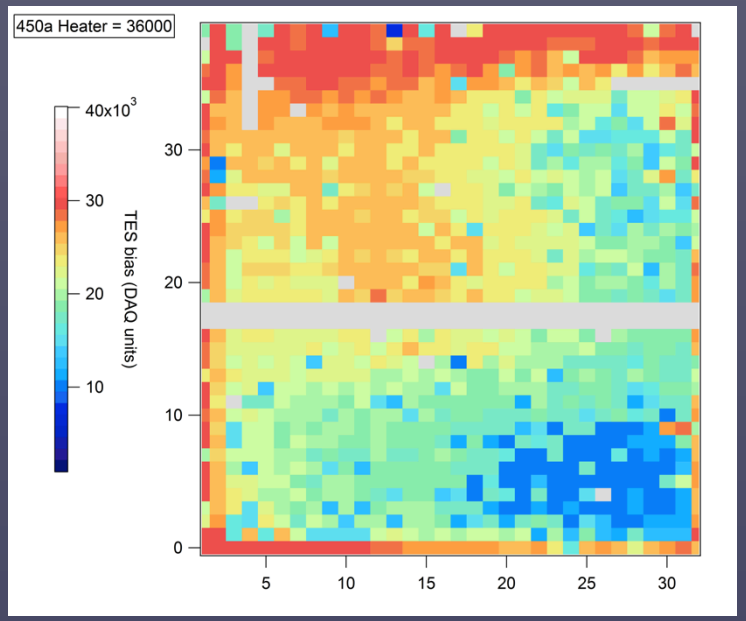


Measured Dark NEP at each point of IV curve

Initially on best sub-array (8a) - measured NEP of individual TES at each point on IV curves, for a range of heater values. At lower TES bias than we bias the whole sub-array, the measured NEP is achieving the expected phonon noise limited value.

Explore – fitting multiple TES bias or heater lines

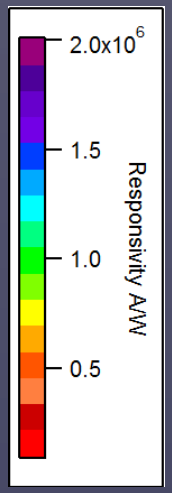


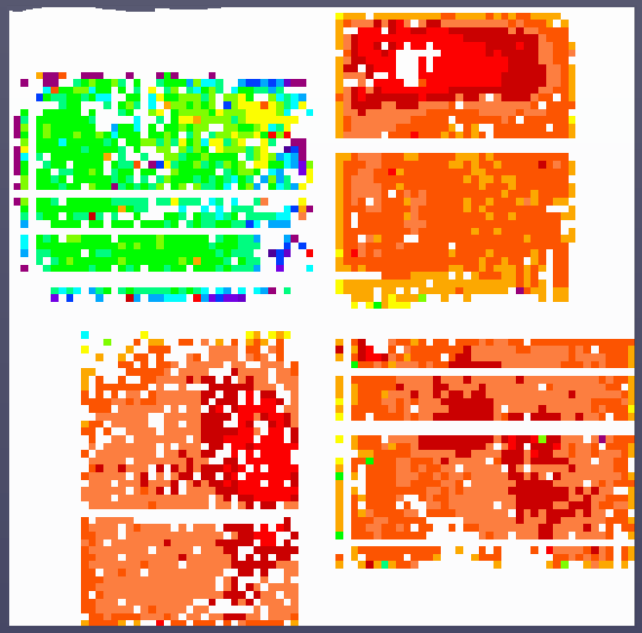


450a sub-array optimal TES bias

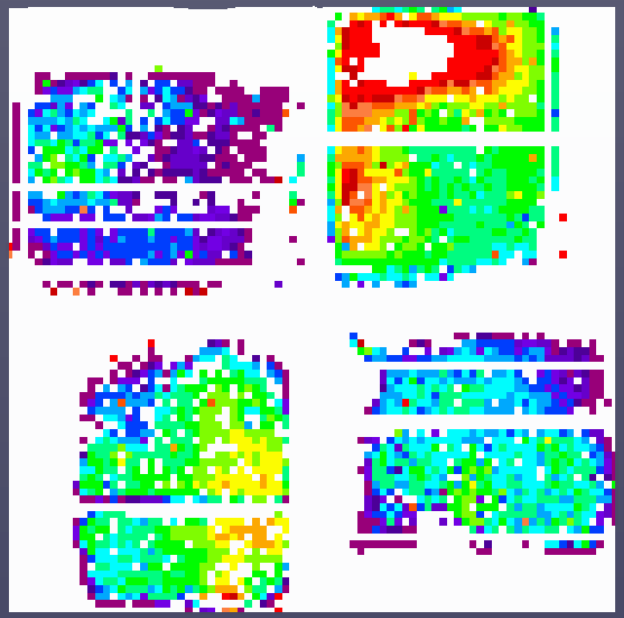
Fewer but better?

- 450 focal plane responsivity





Regular array setup



New lower TES bias setup

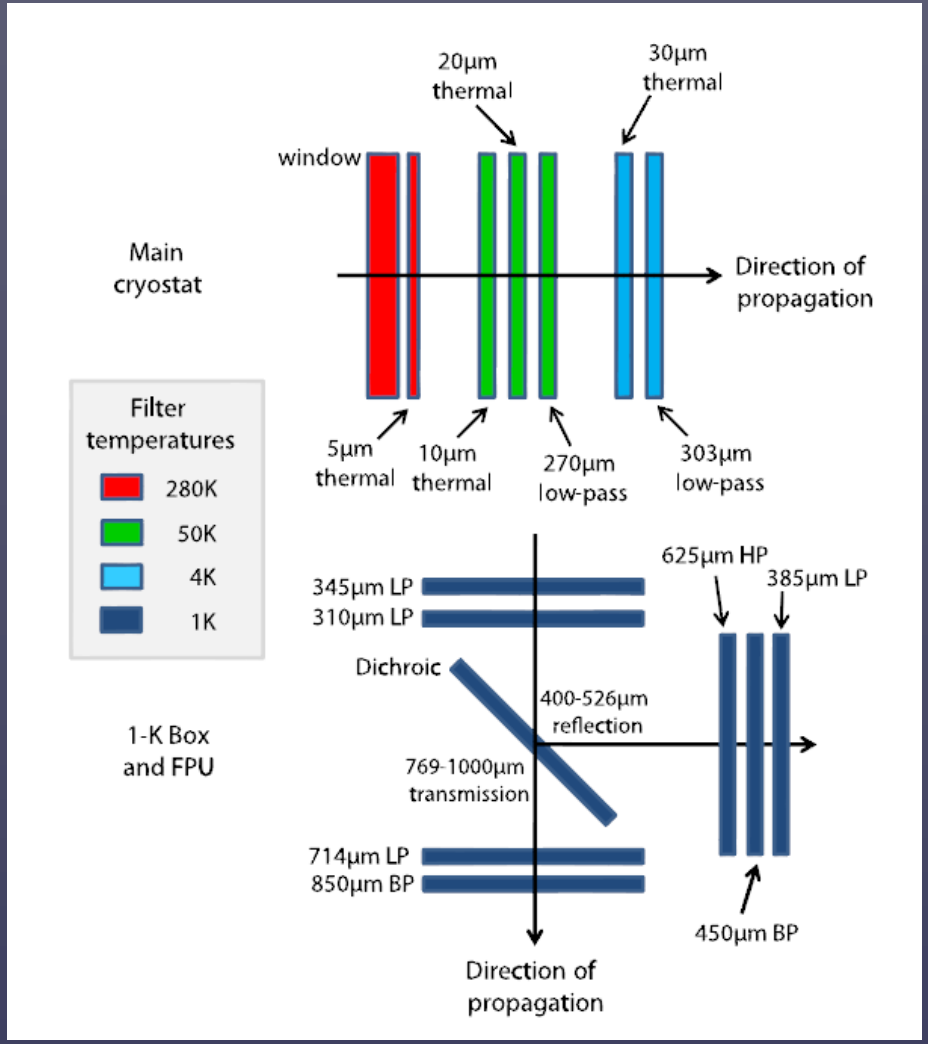
Excess power with shutter open?

Based on detector heater calibration, there is an excess power loading on the 850um focal plane of ~20pW when the shutter is open

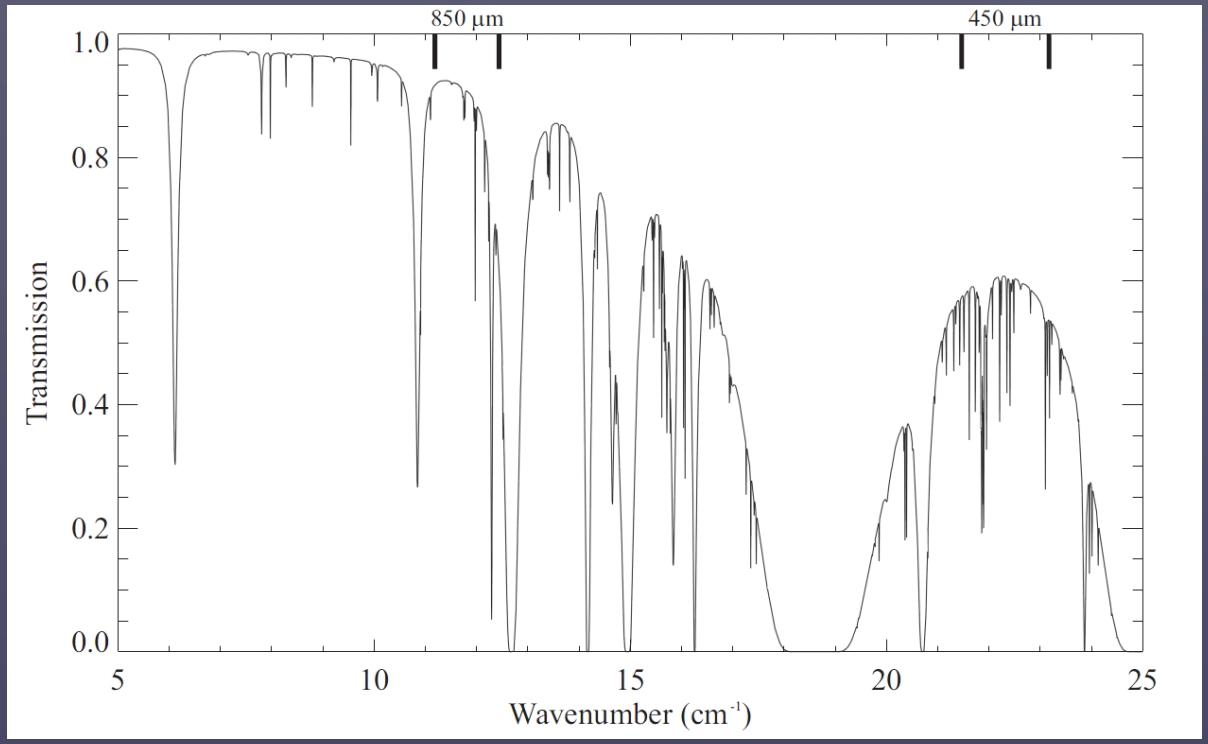
Typical powers measured from heater tracking from shutter closed to sky in good grade 1 (tau < 0.04)

850 ~34pW
450 ~104pW

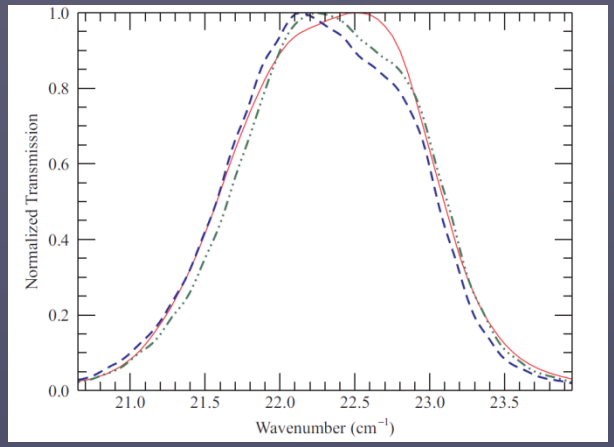
(assuming an effective heater resistance 2Ω)



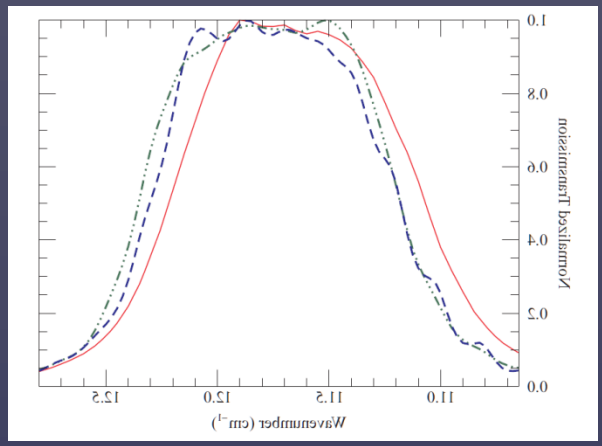
Measured spectral Response



The theoretical atmospheric transmission above Mauna Kea for 0.5 mm water vapor. The thick bars represent the approximate FWHM of the 850 and 450 μm SCUBA-2 filter bands.



450 Spectral response

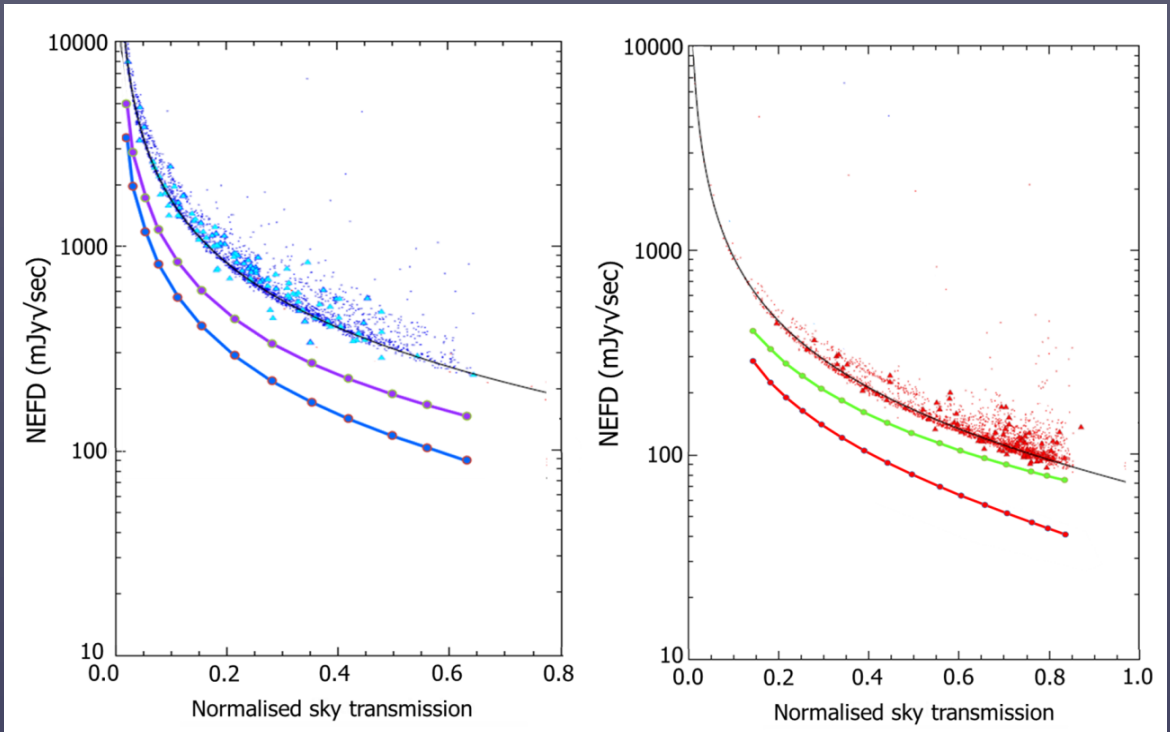


850 Spectral response

On-sky sensitivity

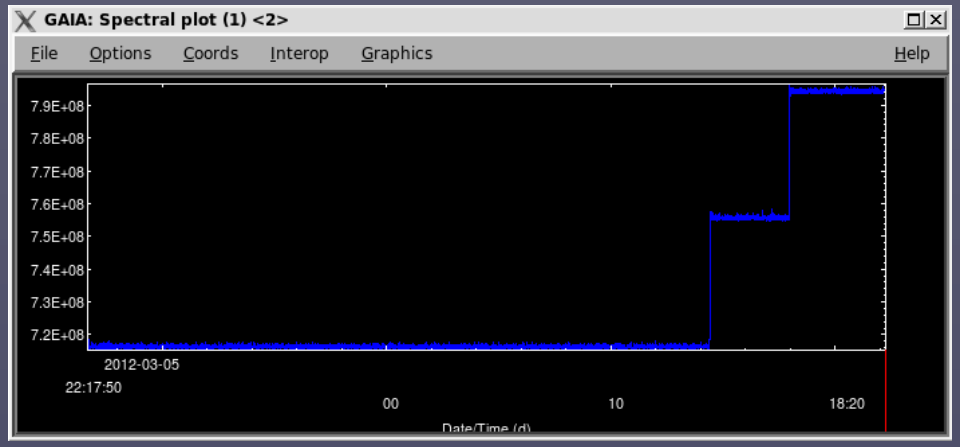
The measured NEFD as a function of normalized sky transmission at 450um (left) and 850um (right).

The blue and red lines are the original target goals for SCUBA-2

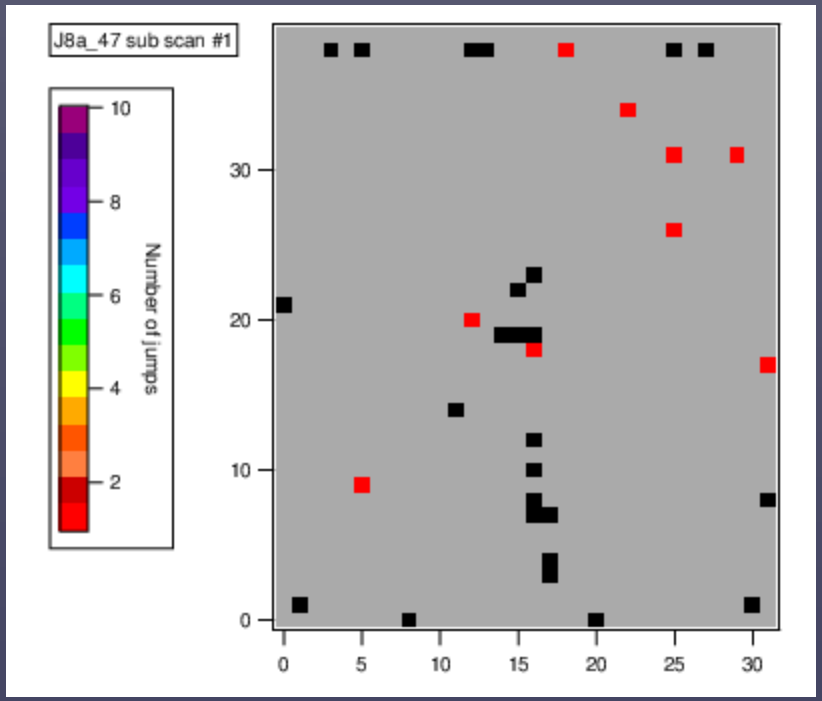


Factor of 3 at 450 and Factor of 2 at 850

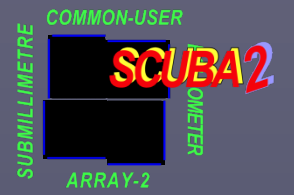
Steps in the detector signal



This is a 30 minute observation. Each colored pixel is a bolometer step (or multiple steps) in a 30s sub-scan



Cryogenic Issues



- There is a large (~mK in the mixing chamber and up to 10mK at the still) 'natural' temperature oscillation within the dilution fridge.
- The residual temperature oscillation of the focal planes, ~30 mK (after temperature control) represents a large (common-mode, but scaled per pixel) signal for the detectors.
- To keep the dilution fridge operating we have added an external 4K cold trap – costing ~ $70,000 per year