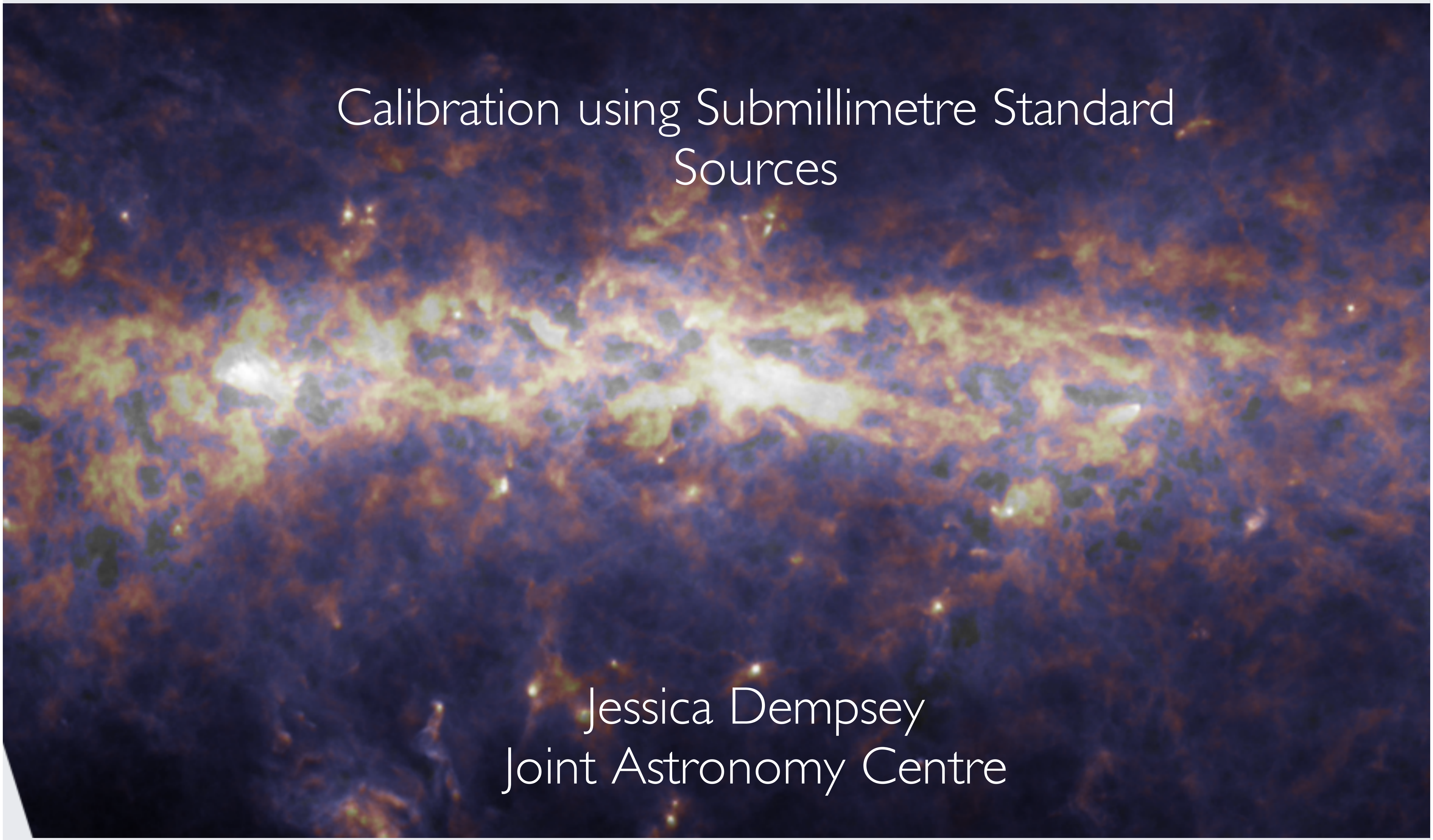
SCUBA-2

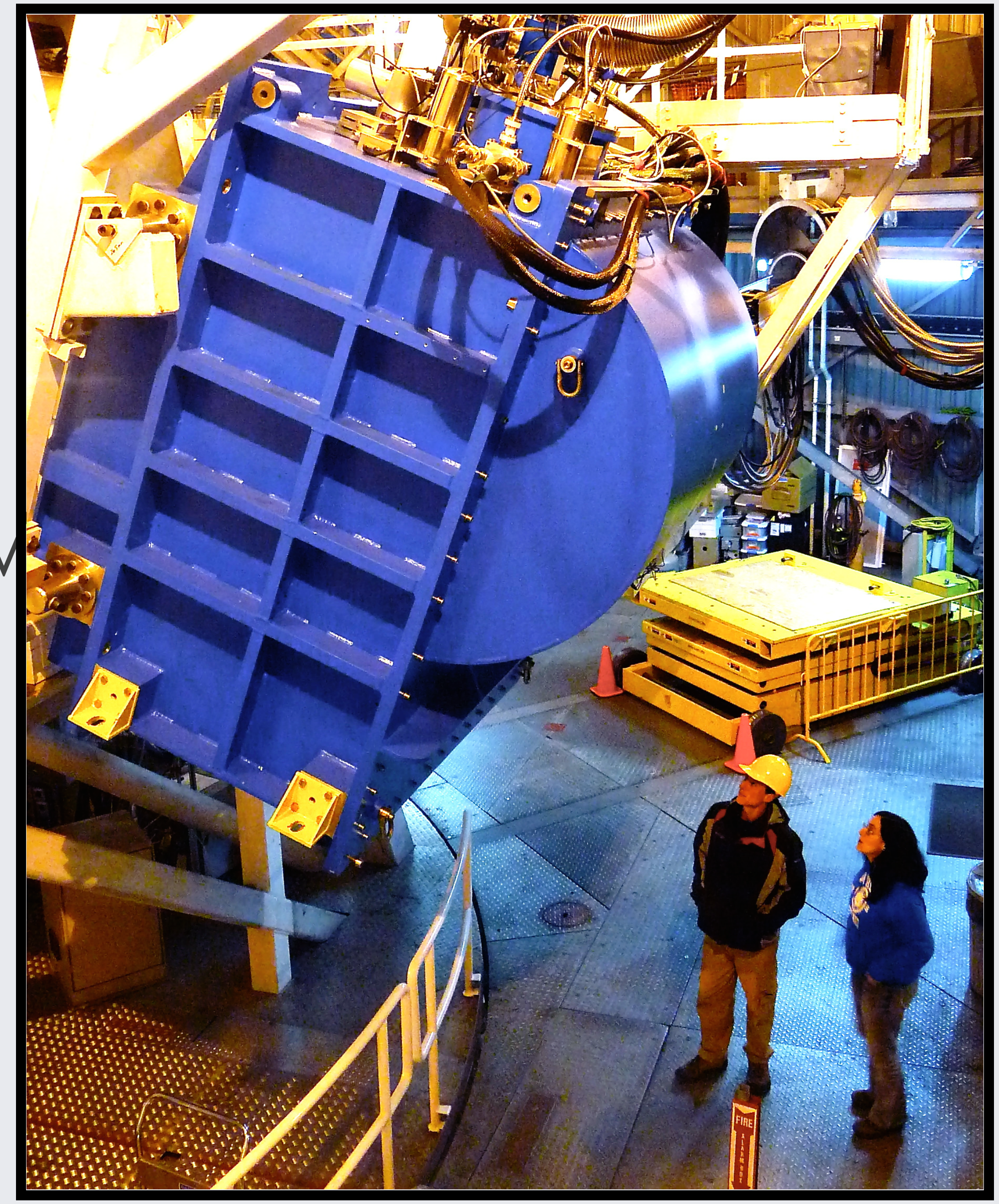


Calibration using Submillimetre Standard Sources

Jessica Dempsey
Joint Astronomy Centre

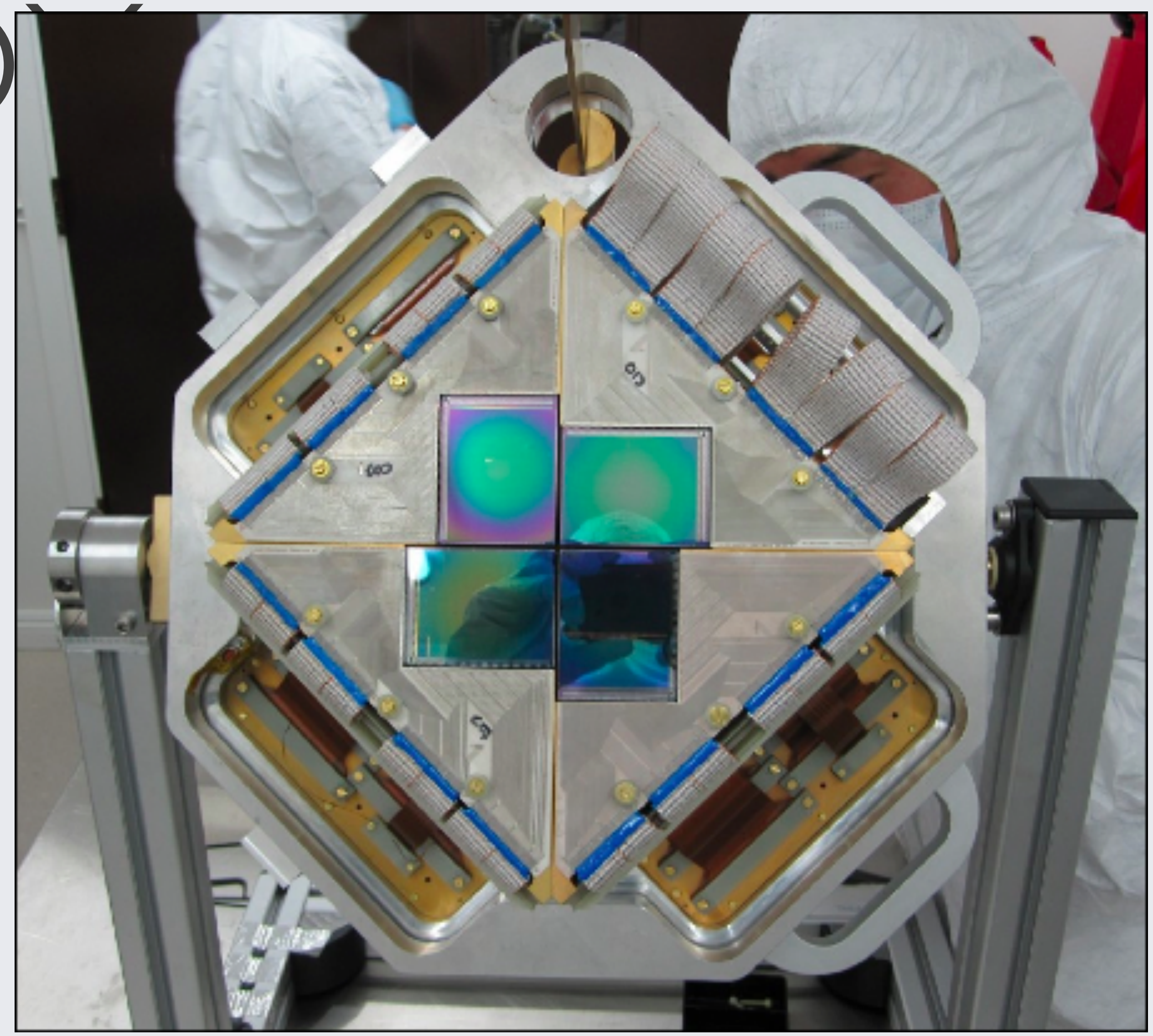
OUTLINE

- SCUBA-2: nuts and bolts
- Observing modes and mapmaking
- Calibrating the detector output
- Discarding skydips: line-of-sight PWV
- Primary calibrators
- Flux conversion factors
- Caveats and complications



SCUBA-2: WHAT'S IN THE BOX

- Two focal planes for observing the 450μm and 850 μm wavebands simultaneously
- 5120 pixels in each focal plane unit
  - made up of 4 sub-arrays of 32x40 bolometers
  - superconducting transition-edge sensors (TES)
- Instantaneous field of view of 43 square-arcmin
  - maximises the JCMT f-o-v available at the Nasmyth focus
  - 850 μm focal plane fully sampled, 450 μm focal plane under-sampled
- Cryostat cooled to sub-Kelvin temperatures
  - operational base temp ~60 mK and focal-plane controlled



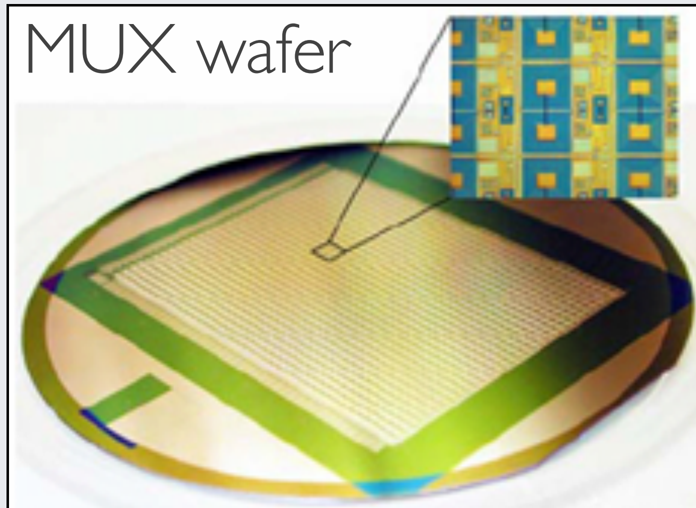
450 μm focal plane unit prior to installation

DETECTOR ARRAYS

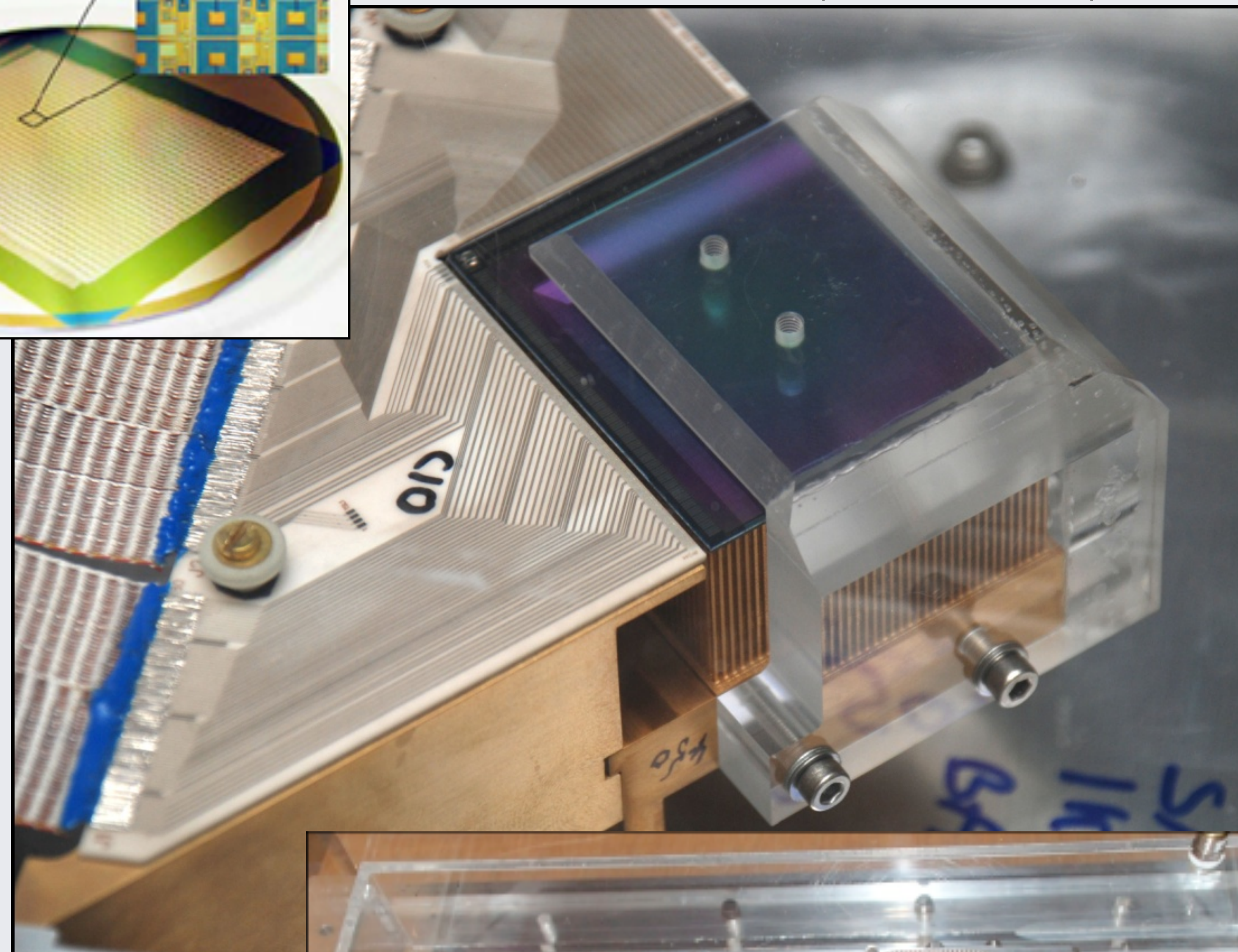
New generation large-format superconducting TES arrays

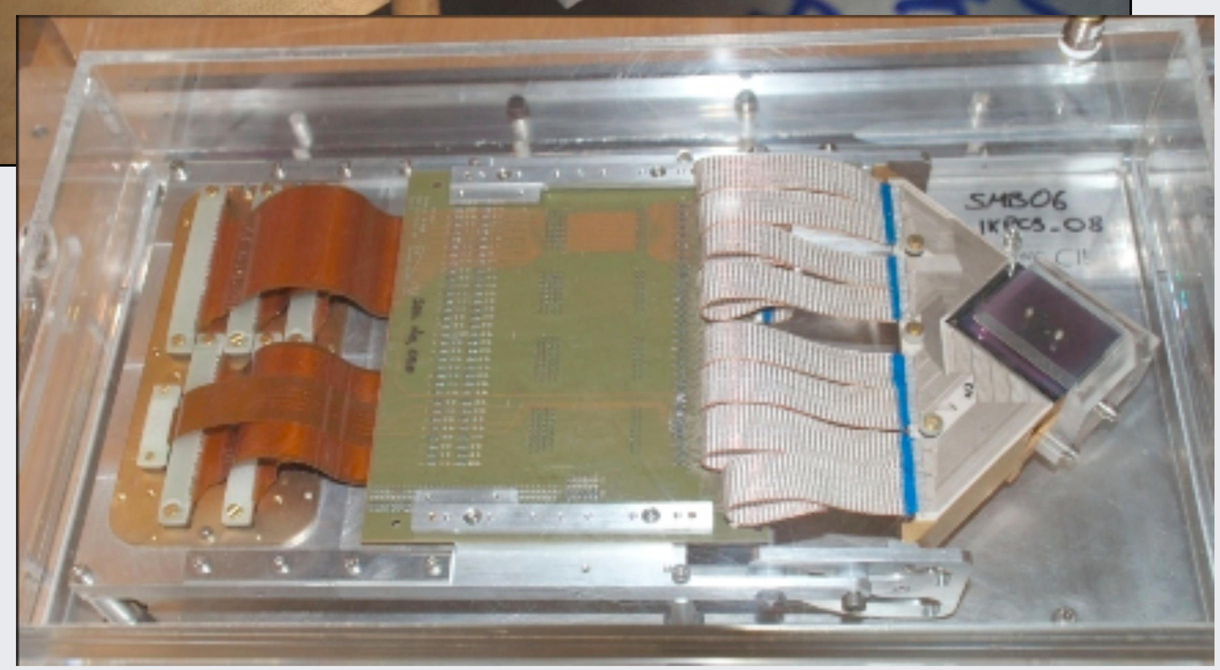
SQUID amplifier based multiplexer to read out the signals

Detectors cooled to 70mK for optimum performance – complex thermal design



1280 pixel sub-array





Array module

SCUBA-2 AND HERSCHEL

Complementary facilities:

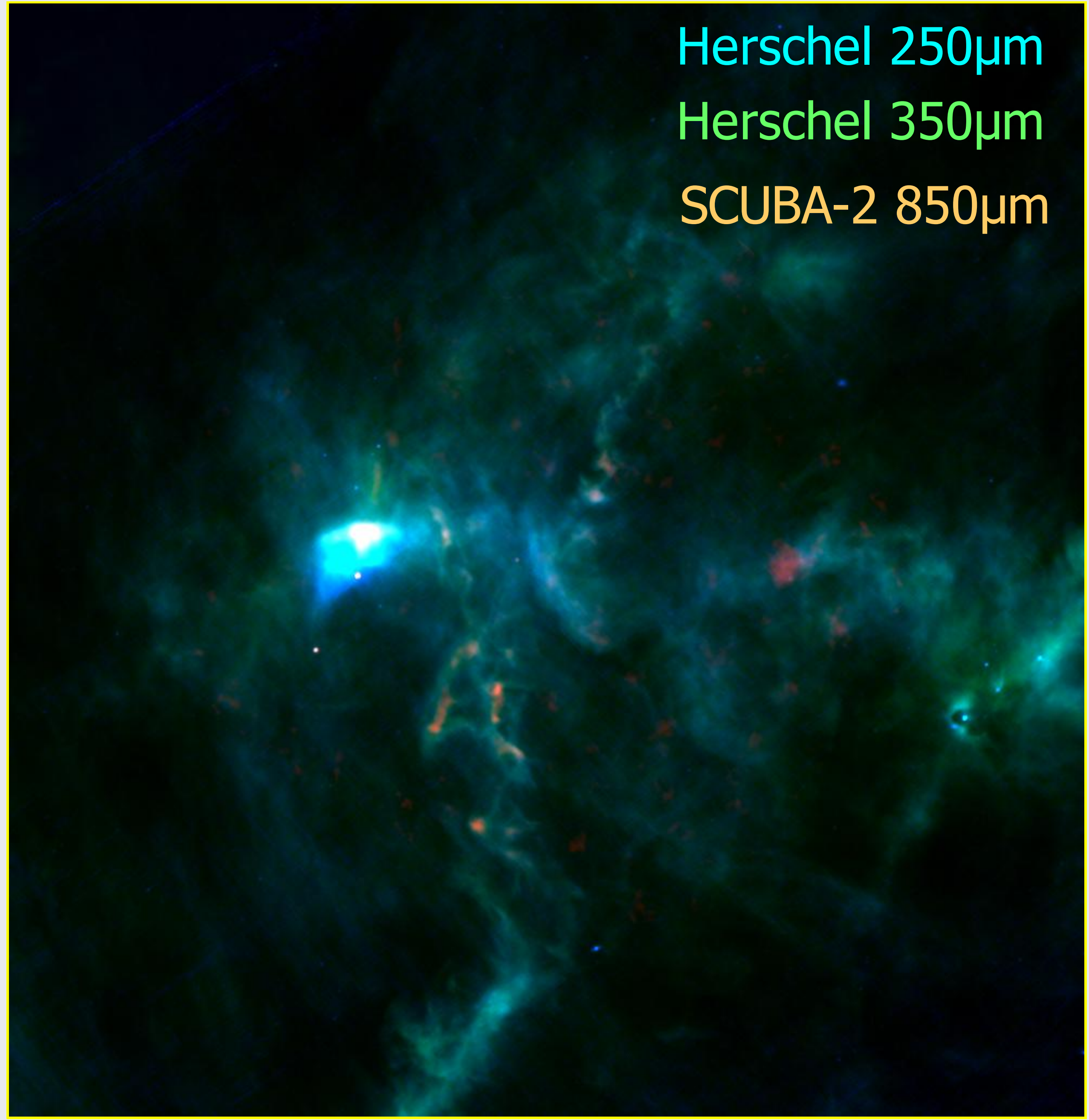
JCMT offers higher angular resolution

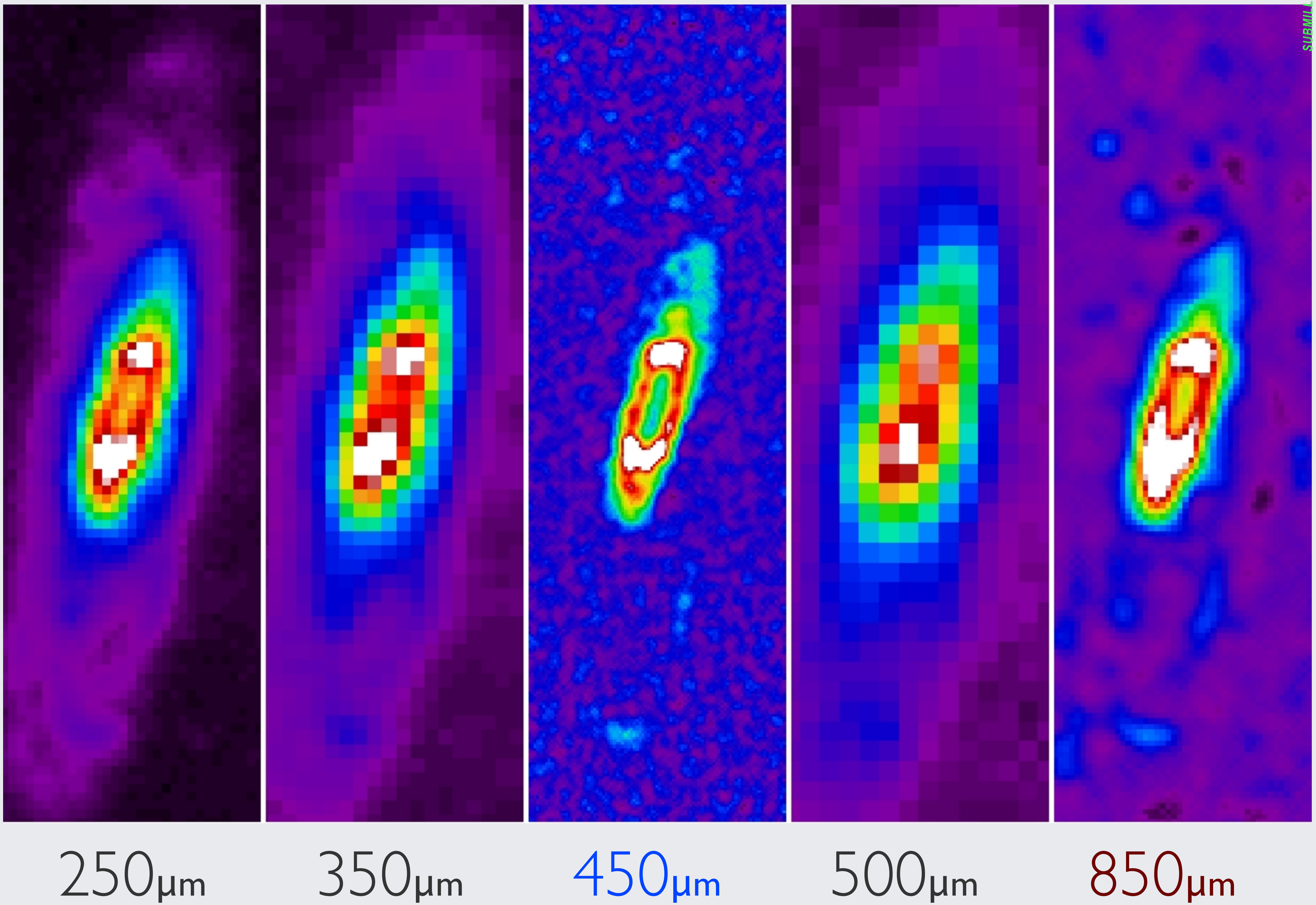
SCUBA-2 offers longer-wavelength data over comparable area

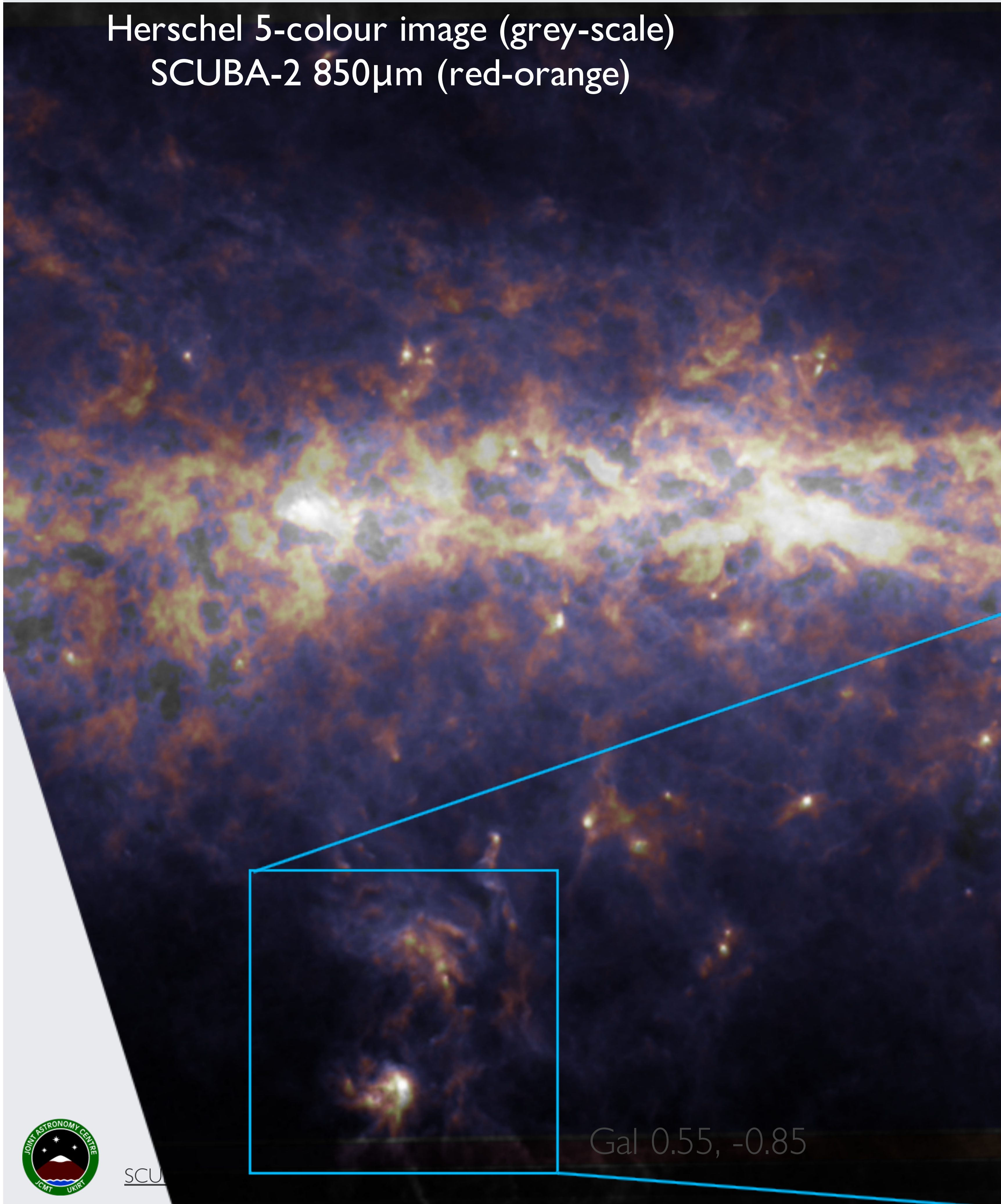
extragalactic: sample different redshift ranges

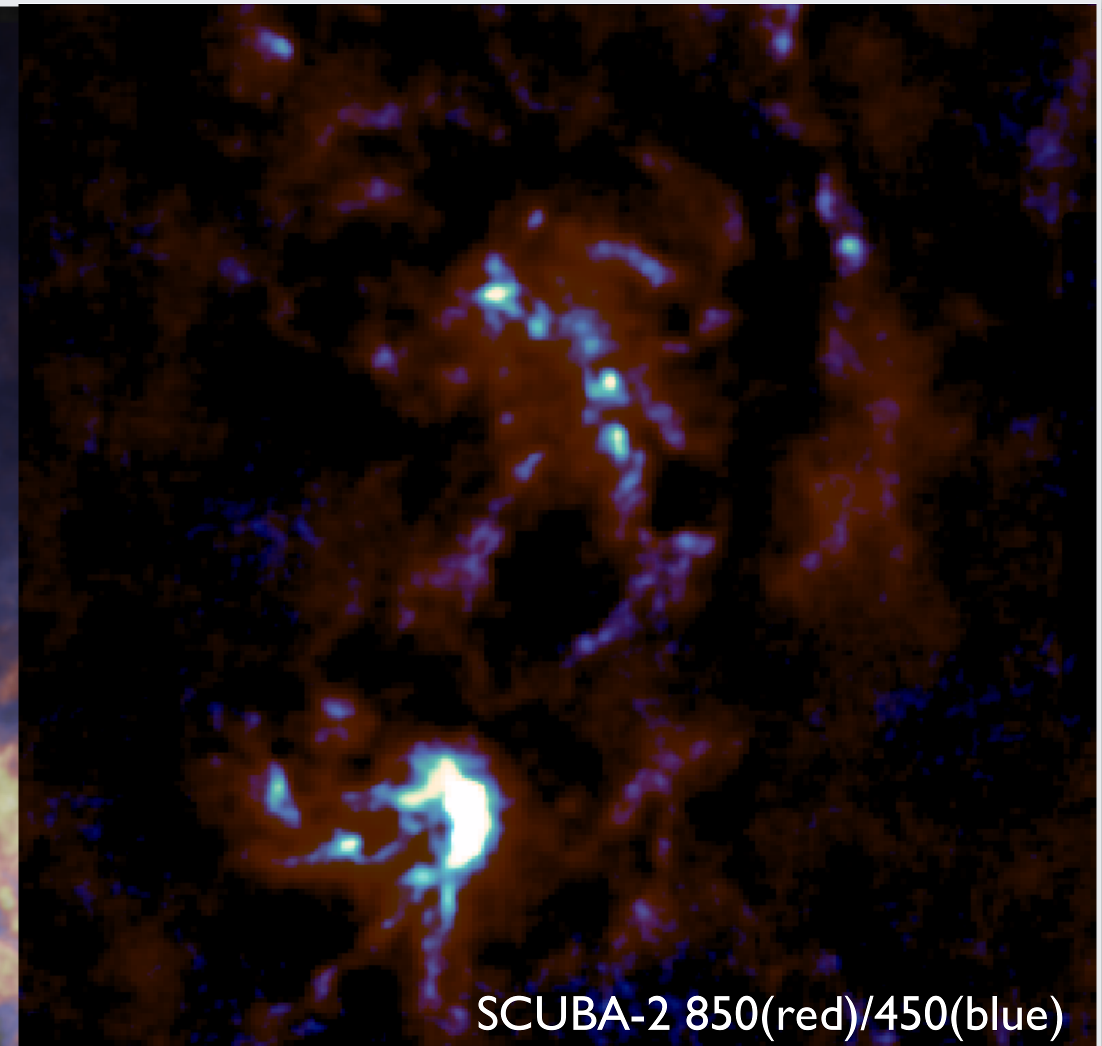
galactic: sample different core temperatures

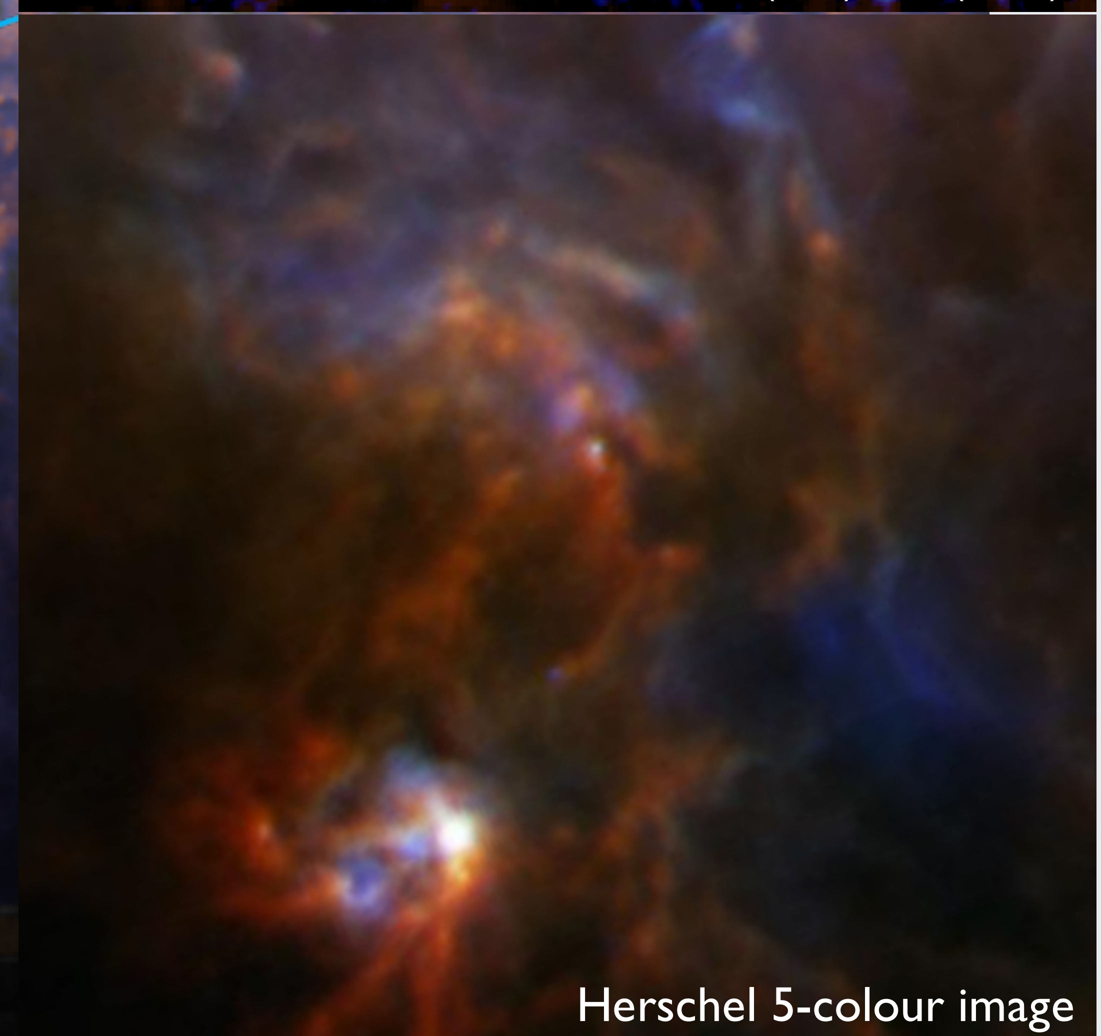
galactic: break degeneracy between dust temperature and emissivity




250μm
350μm
450μm
500μm
850μm


Herschel 5-colour image (grey-scale)
SCUBA-2 850µm (red-orange)
Gal 0.55, -0.85


SCUBA-2 850(red)/450(blue)


Herschel 5-colour image

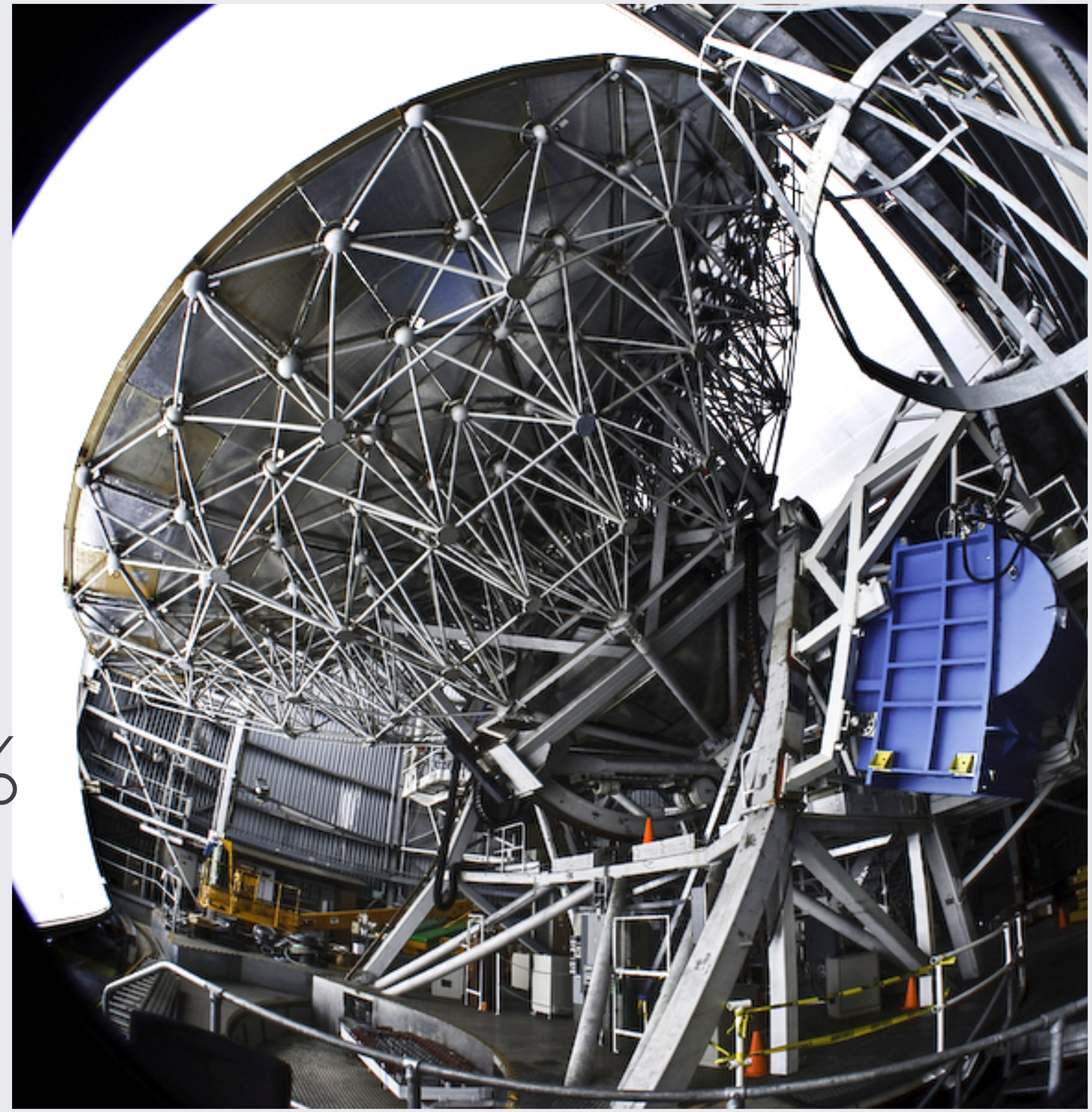
SCU

SCUBA-2 SINCE FIRST LIGHT

Commissioning completed in October 2011

Eighteen months of full science operations

65% Legacy surveys, 35% PI project time

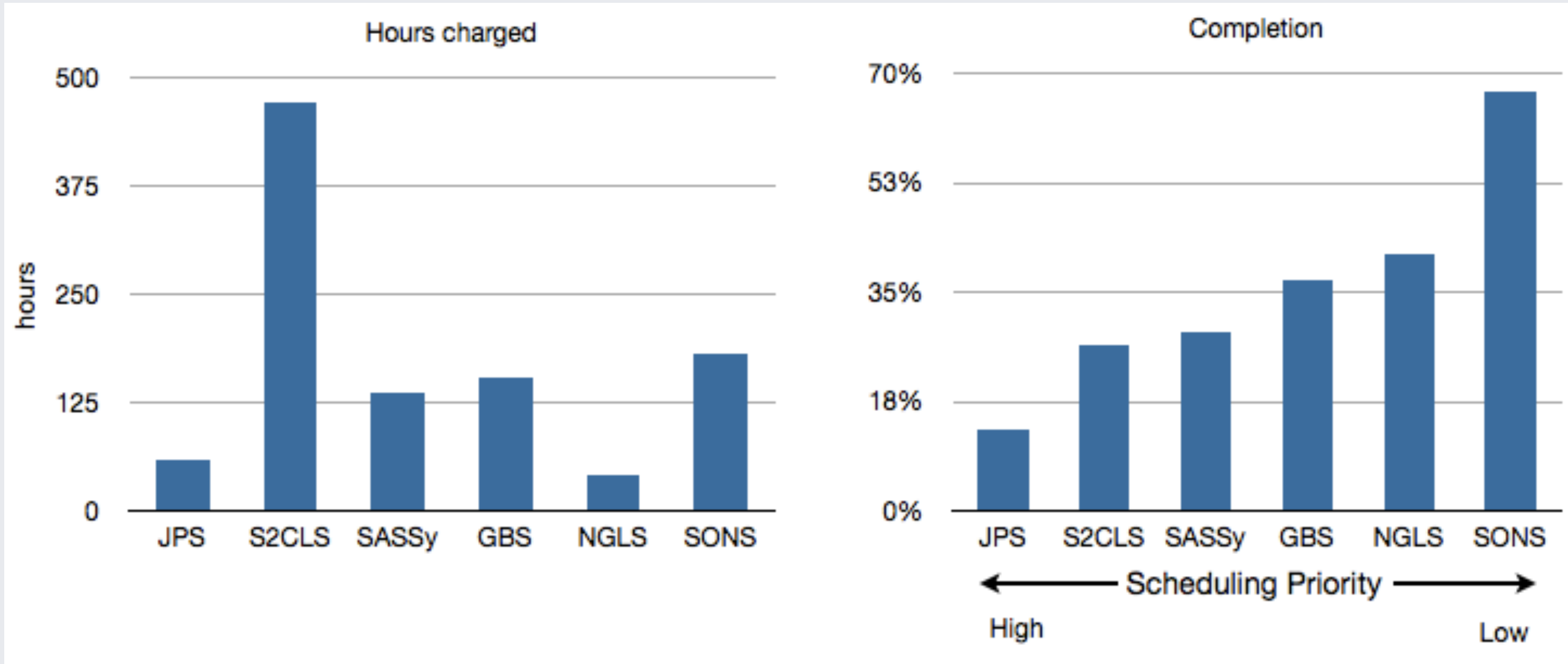


JCMT LEGACY SURVEYS

High complementarity with Herschel key projects

Targeted to maximise impact of SCUBA-2 in a now limited time-frame

(SCUBA-2) Survey	Hours awarded	
SCUBA-2 "All Sky" Survey: SASSy	480	13.8 %
SCUBA-2 Cosmology Legacy Survey: S2CLS	1778	50.9 %
Nearby Galaxies Legacy Survey: NGLS	100	2.9 %
JCMT Galactic Plane Survey: JPS	450	12.9 %
Gould Belt Survey: GBS	412	11.8 %
SCUBA-2 Observations of Nearby Stars: SONS	270	7.7 %
TOTAL	3490	291 nights



REFERENCE PAPERS

MNRAS, VOL 430, ISSUE 4, 2013

SCUBA-2: the 10 000 pixel bolometer camera on the James Clerk Maxwell Telescope

W. S. Holland[1,2,★], D. Bintley[3], E. L. Chapin[3,4,†], A. Chrysostomou[3,‡], G. R. Davis[3], J. T. Dempsey[3], W. D. Duncan[1,5,§], M. Fich[6], P. Friberg[3], M. Halpern[4], K. D. Irwin[5], T. Jenness[3], B. D. Kelly[1], M. J. MacIntosh[1], E. I. Robson[1], D. Scott[4], P. A. R. Ade[7], E. Atad-Ettedgui[1], D. S. Berry[3], S. C. Craig[3,¶], X. Gao[1], A. G. Gibb[4], G. C. Hilton[5], M. I. Hollister[2,||], J. B. Kycia[6], D. W. Lunney[1], H. McGregor[1,★★], D. Montgomery[1], W. Parkes[8], R. P. J. Tilanus[3], J. N. Ullom[5], C. A. Walther[3], A. J. Walton[8], A. L. Woodcraft[7,††], M. Amiri[4], D. Atkinson[1], B. Burger[4], T. Chuter[3], I. M. Coulson[3], W. B. Doriese[5], C. Dunare[8], F. Economou[3,‡‡], M. D. Niemack[5], H. A. L. Parsons[3], C. D. Reintsema[5], B. Sibthorpe[1], I. Smail[9], R. Sudiwala[7] and H. S. Thomas[3]

SCUBA-2: on-sky calibration using submillimetre standard sources

J. T. Dempsey[1,★], P. Friberg[1], T. Jenness[1], R. P. J. Tilanus[1], H. S. Thomas[1], W. S. Holland[2,3], D. Bintley[1], D. S. Berry[1], E. L. Chapin[1,4,†], A. Chrysostomou[1], G. R. Davis[1], A. G. Gibb[4], H. Parsons[1] and E. I. Robson[2]

SCUBA-2: iterative map-making with the Sub-Millimetre User Reduction Facility

Edward L. Chapin[1,2,★,†], David S. Berry[2], Andrew G. Gibb[1], Tim Jenness[2], Douglas Scott[1], Remo P. J. Tilanus[2,3], Frossie Economou[2,‡] and Wayne S. Holland[4,5]

OBSERVING MODES

SCUBA-2 operates in scanning mode

Goal: scan speed high enough to place point-source signal at frequency higher than 1/f noise in bolometer power spectrum

Ideal observing mode must also scan sky on different time and spatial scales to minimise scan-synchronous noise; ‘cross-linking’

Adapt to limitations of telescope and instrument

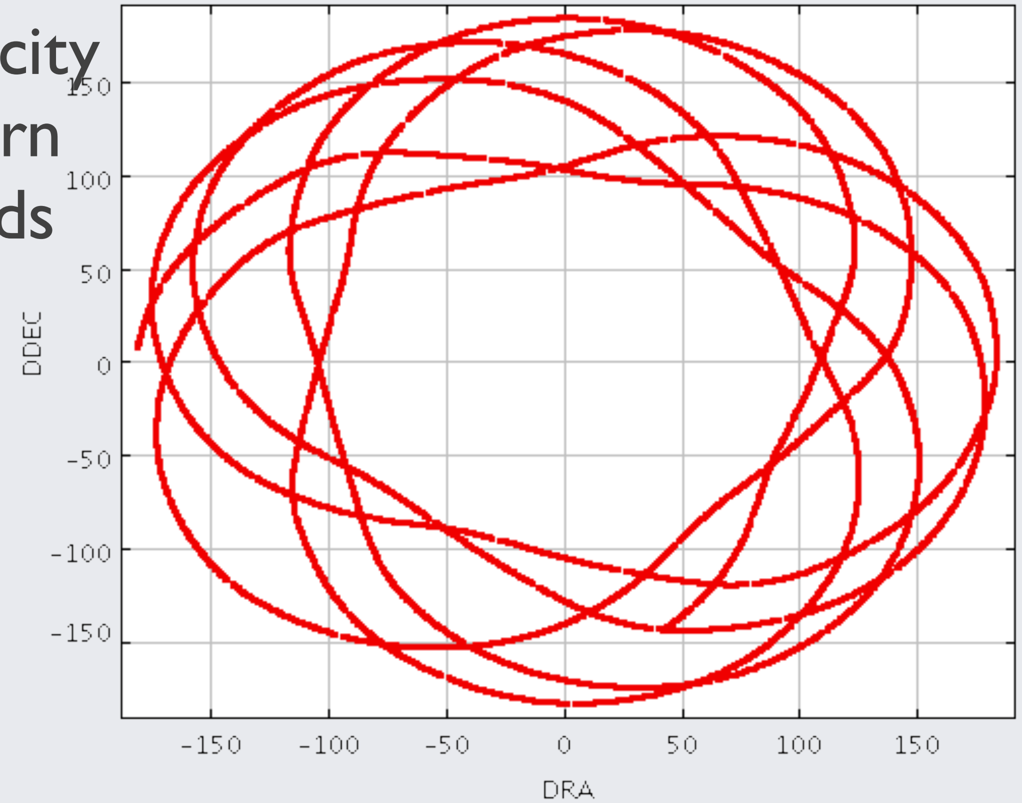
OBSERVING MODES

Get away from sky chopping and telescope nodding

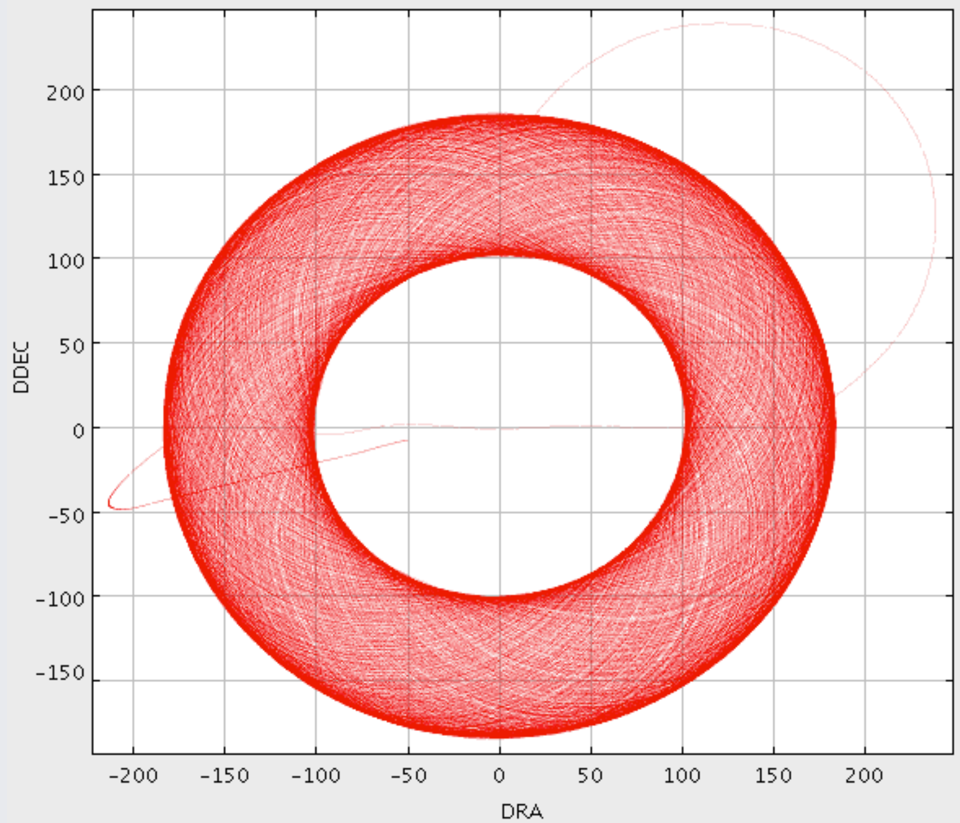
Developed scanning strategies that modulate the sky spatially and temporally

Cover the same region at different position angles and cross link scans

Constant velocity “Daisy” pattern for small fields



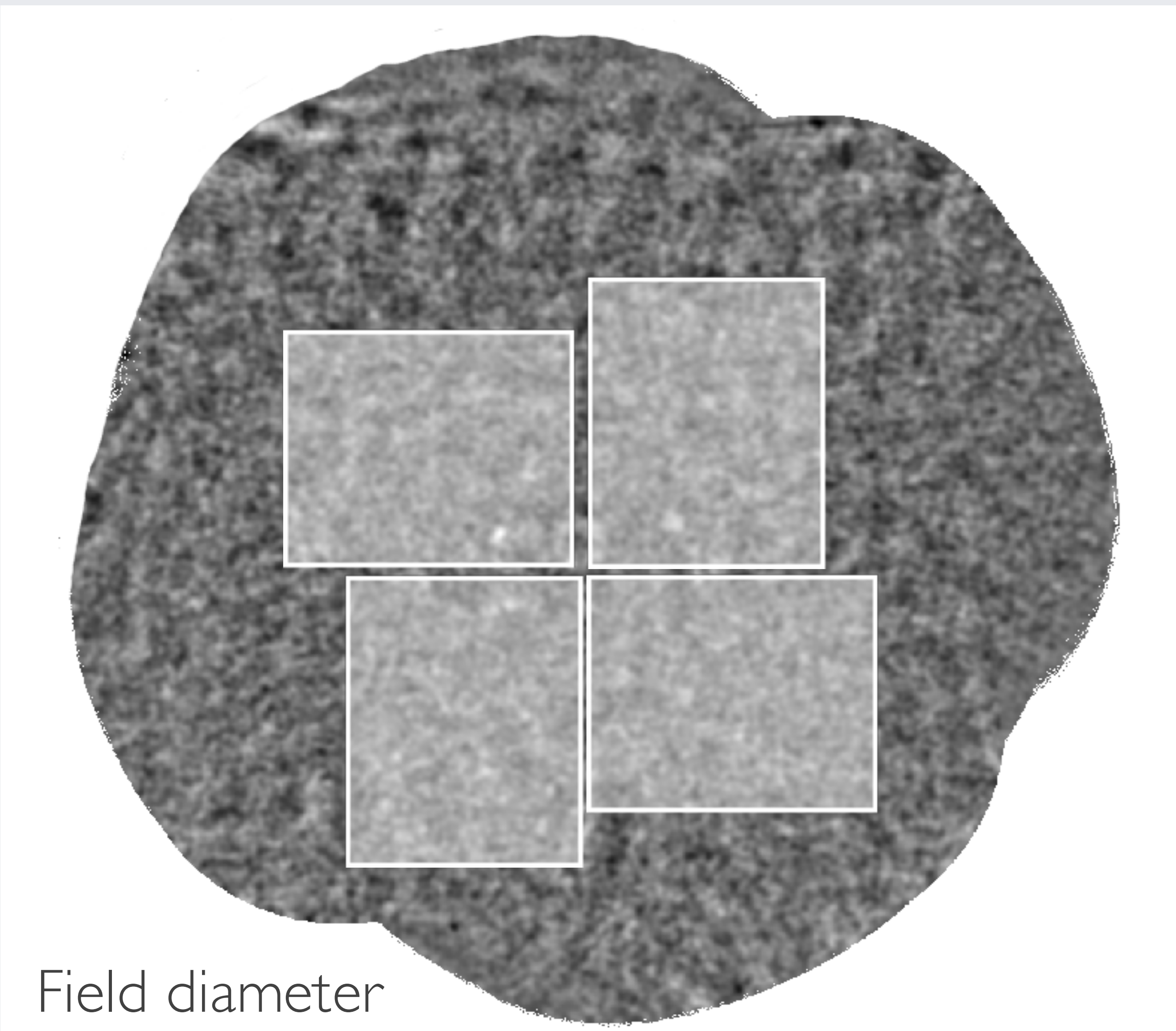
Telescope track from a 30-sec sub-scan



Telescope track from 30-min observation

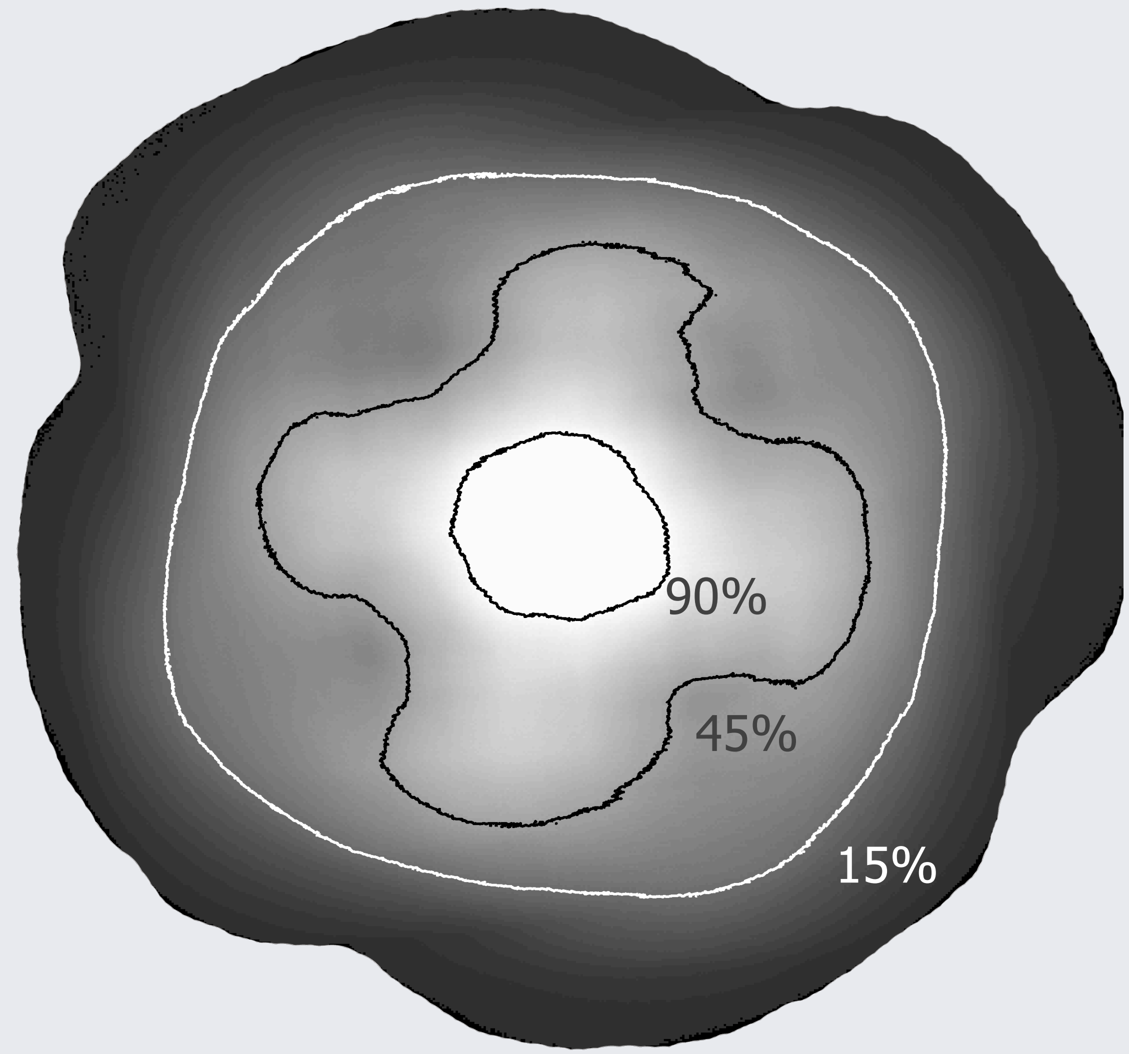
FIELD COVERAGE: DAISY

Maximises the exposure time in the centre of the image, for example:



Field diameter
~13 arcmin

Image plane



Exposure time

For a Nyquist sampled output map, exposure time in central 3’ region ~ 0.25 × elapsed time

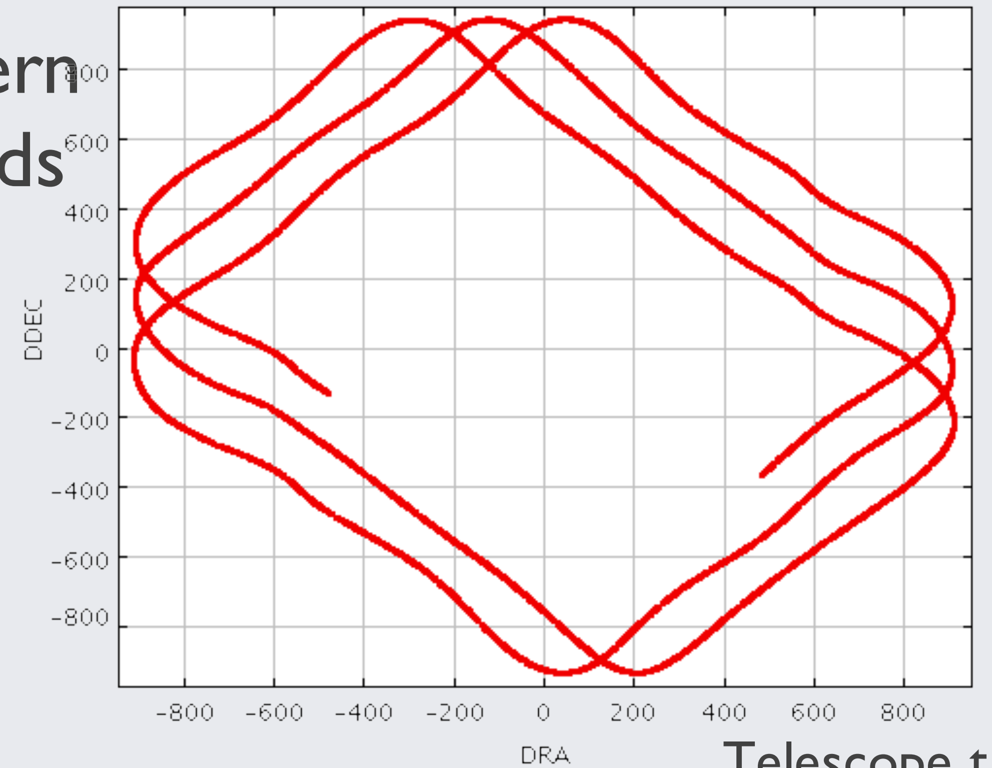
OBSERVING MODES

Get away from sky chopping and telescope nodding

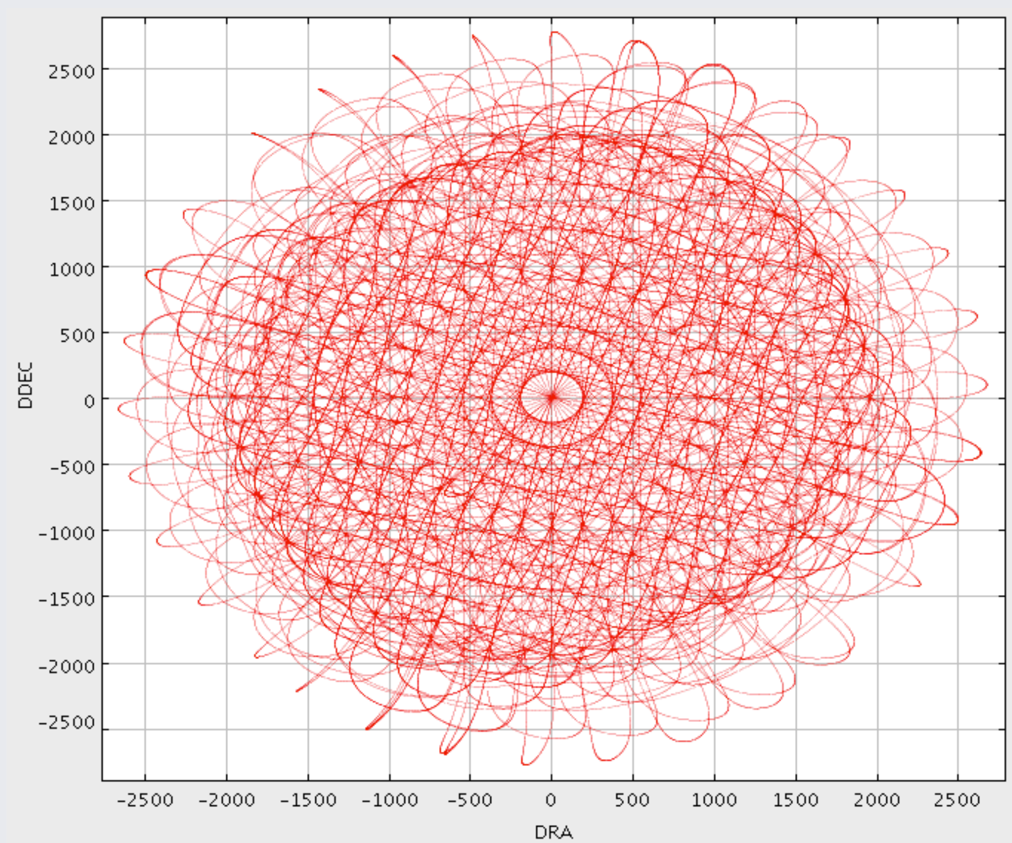
Developed scanning strategies that modulate the sky spatially and temporally

Cover the same region at different position angles and cross link scans

Rotating "Pong" pattern for large fields



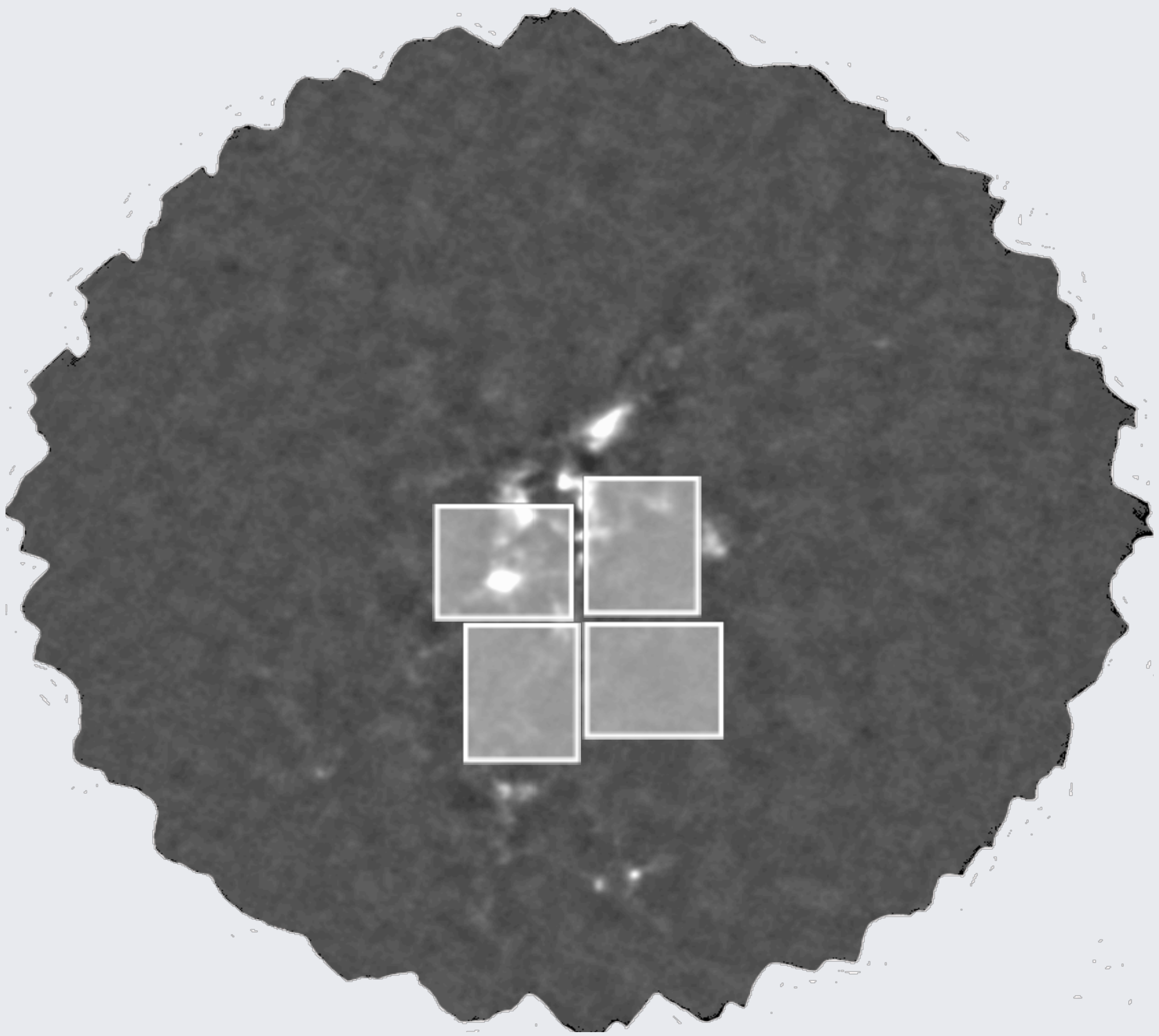
Telescope track from a 30-sec sub-scan



Telescope track from 40-min observation

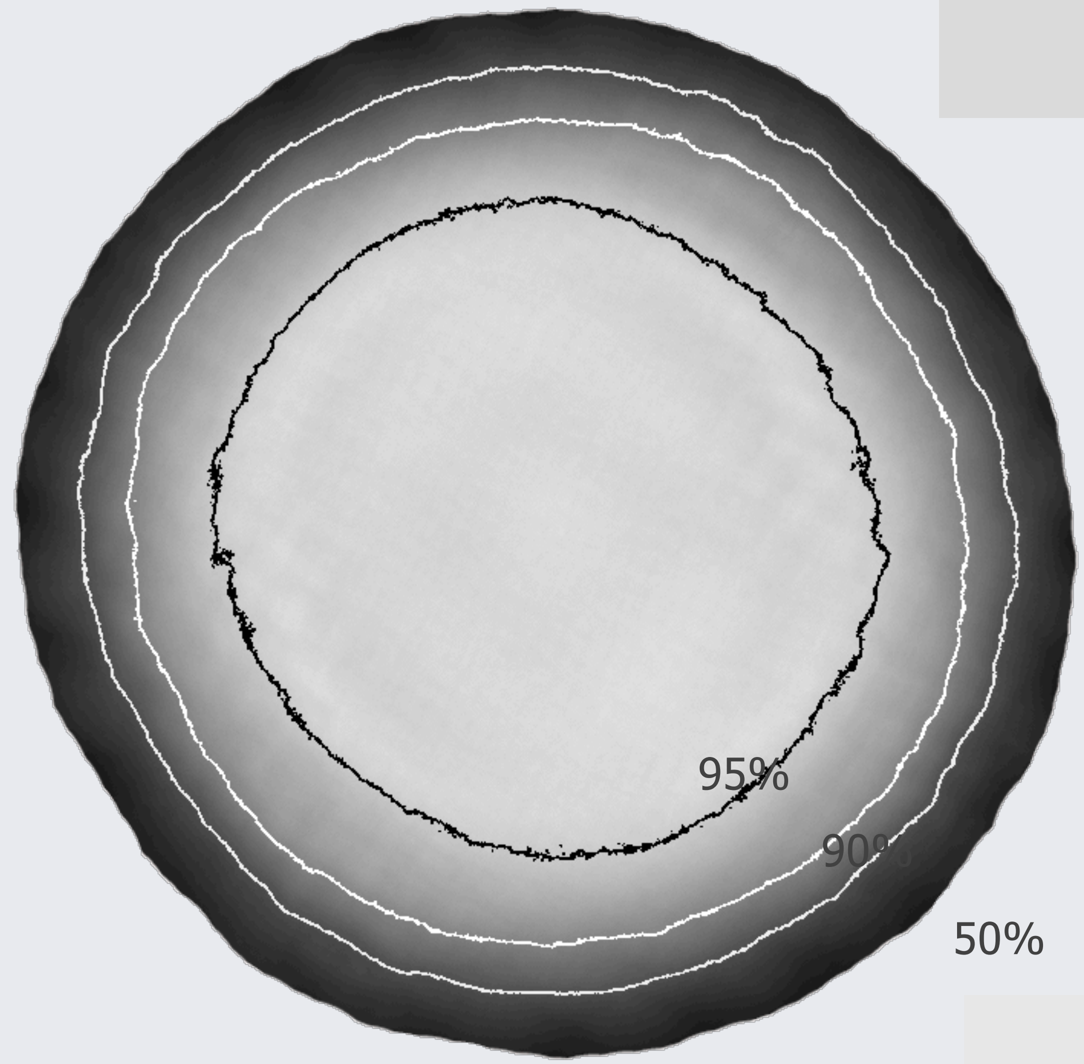
FIELD COVERAGE: PONG

Maximises the field coverage and maintains exposure time uniformity, for example:



Field diameter
30 arcmin

Image plane



Exposure time

For a Nyquist sampled output map, exposure time in central 3' region ~ 0.014 × elapsed time

MAKING MAPS

SMURF software package distributed as part of the Starlink software

Data arrives at 1MB/s from each of the eight subarrays. Data written out in 30 sec chunks

The map-maker:

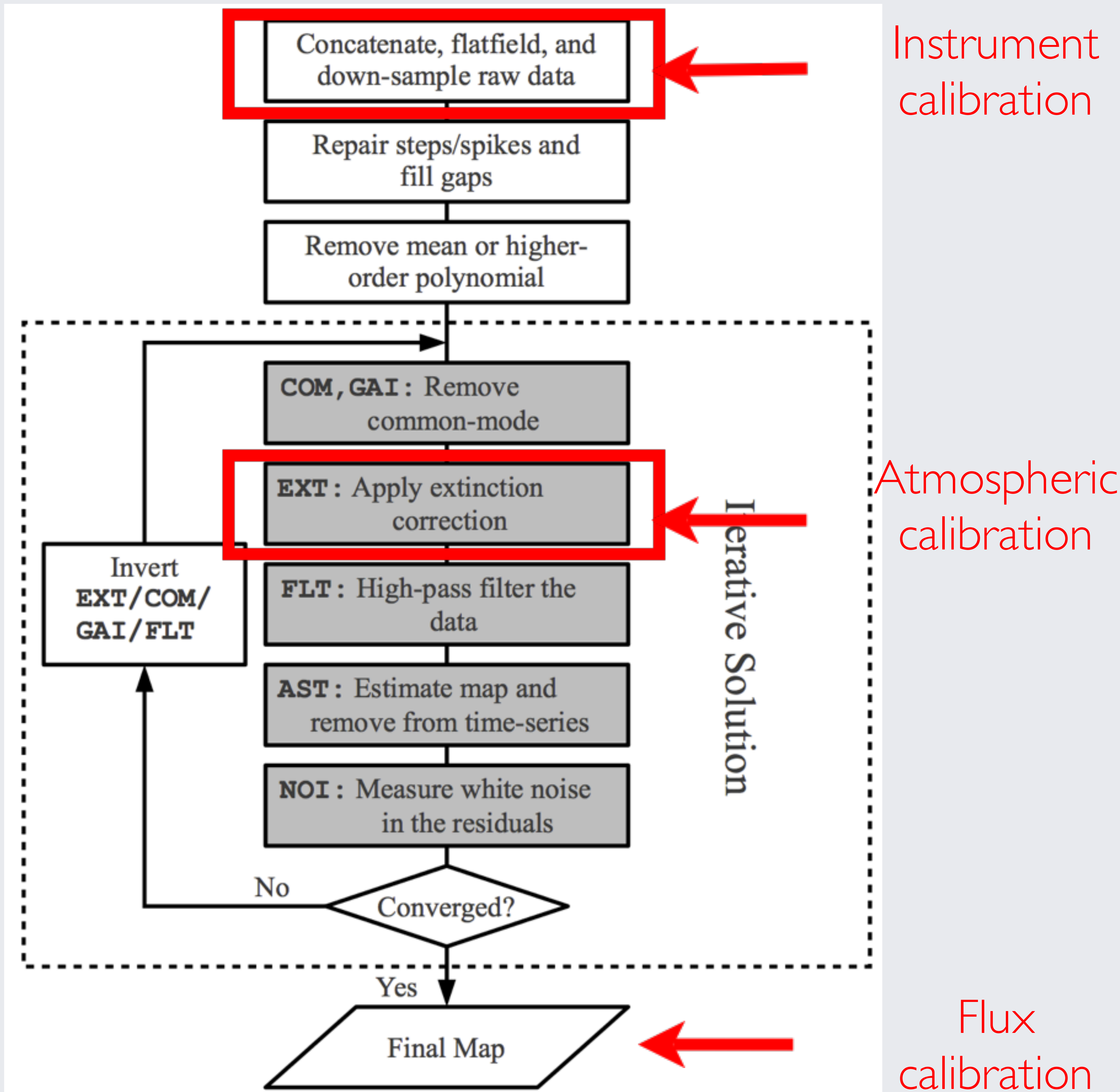
Puts the data together into contiguous time-series

Applies the flatfield solution from the ramps

Cleans the time-series to remove anomalies

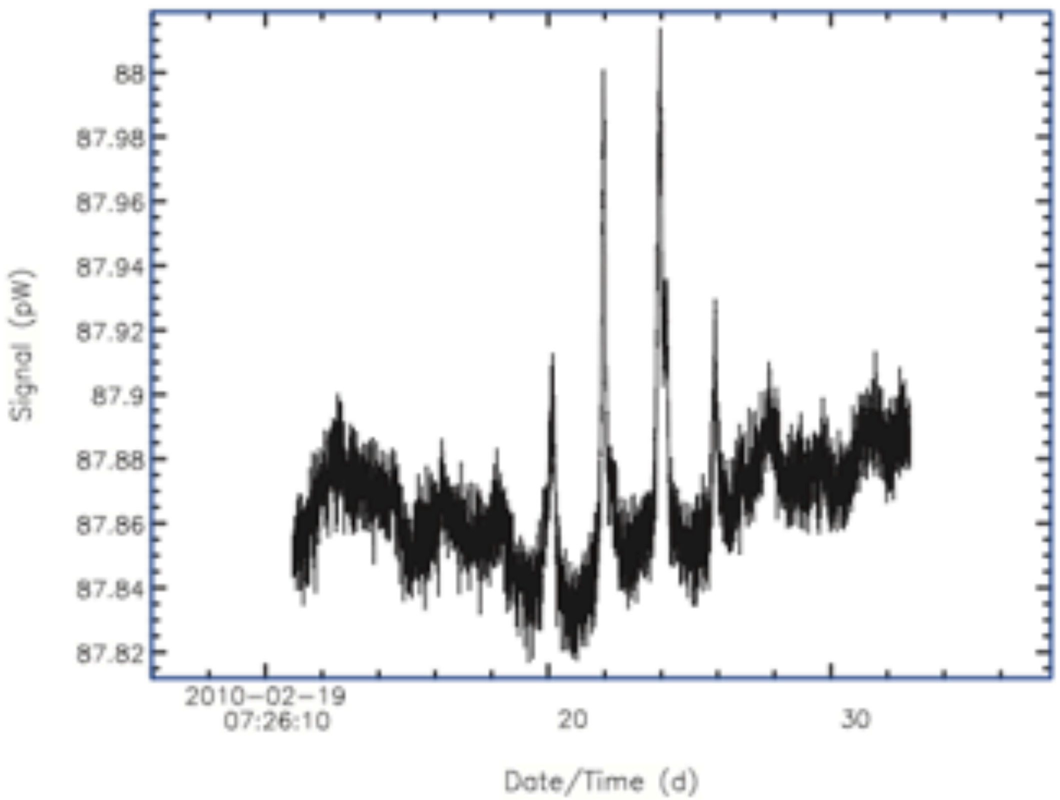
Makes the map using an iterative technique

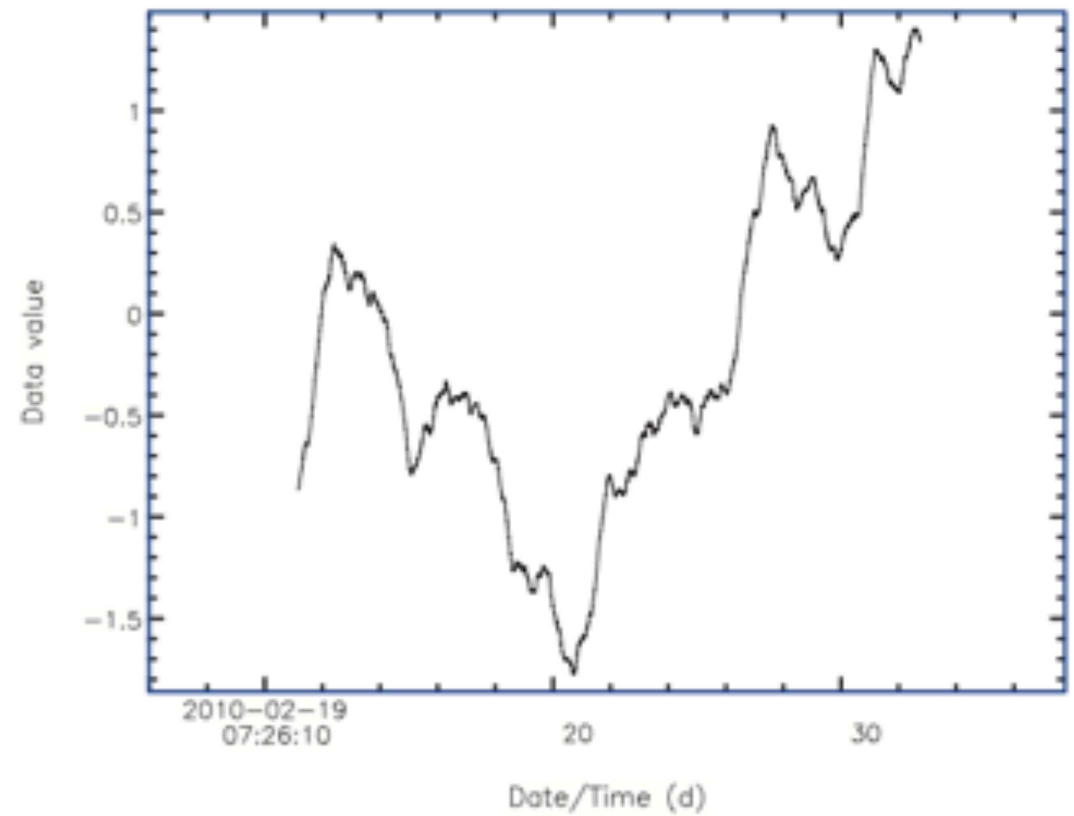
Configuration options for different source types (bright, faint, extended)

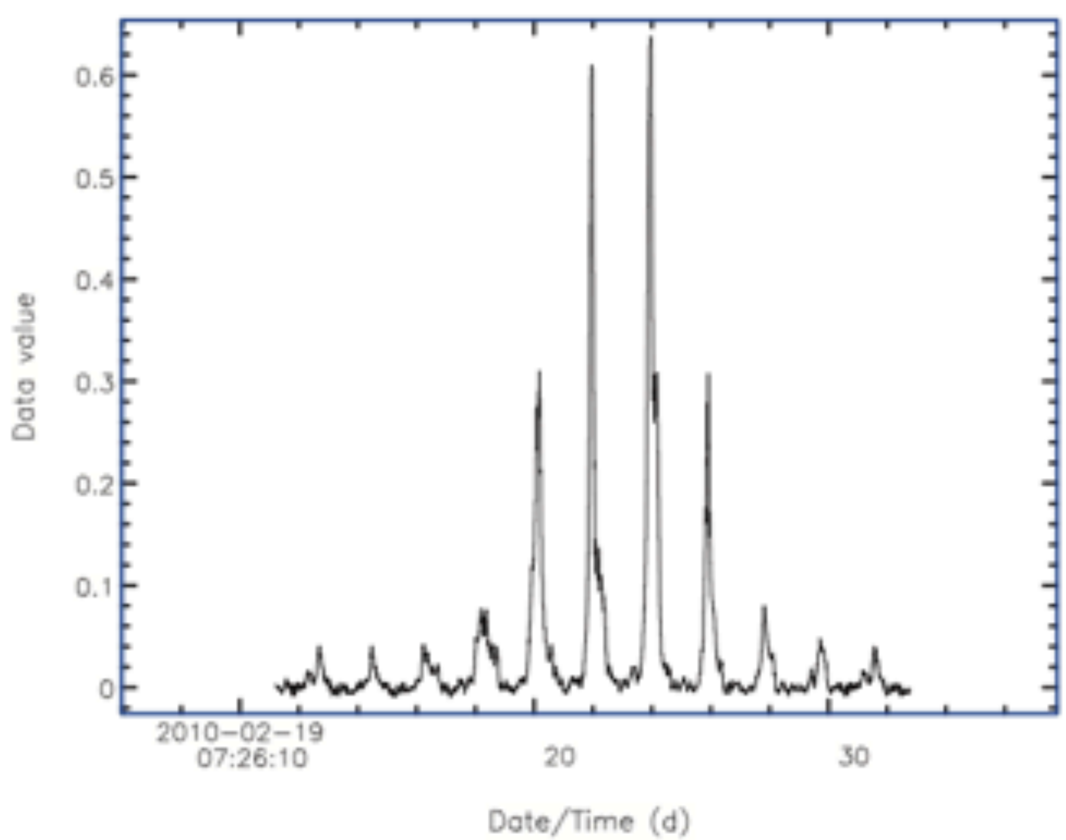


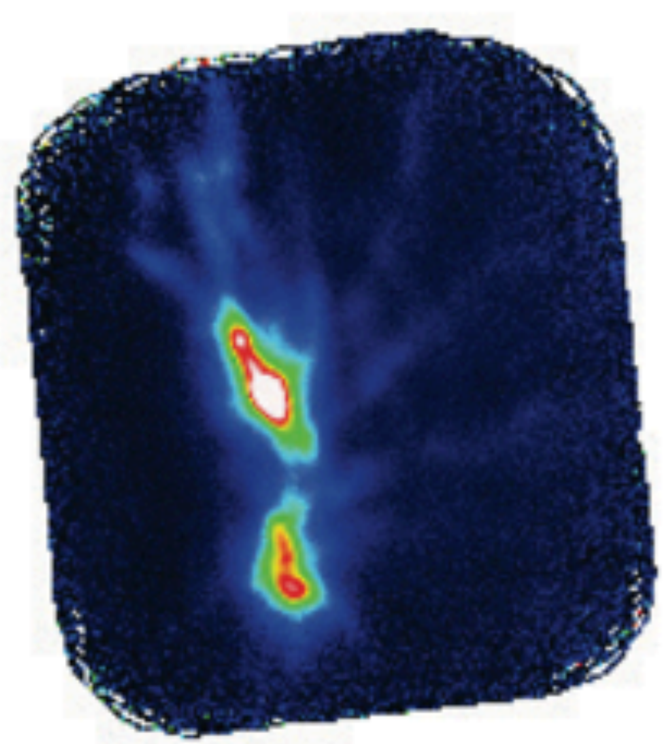
Concatenate, flatfield, and down-sample raw data
Repair steps/spikes and fill gaps
Remove mean or higher-order polynomial
COM,GAI: Remove common-mode
EXT: Apply extinction correction
FLT: High-pass filter the data
AST: Estimate map and remove from time-series
NOI: Measure white noise in the residuals
Converged?
No
Yes
Invert EXT/COM/GAI/FLT
Iterative Solution
Final Map
Instrument calibration
Atmospheric calibration
Flux calibration

MAKING MAPS


Signal (pW)
88
87.98
87.96
87.94
87.92
87.9
87.88
87.86
87.84
87.82
2010−02−19
07:26:10
20
30
Date/Time (d)


Data value
1
0.5
0
−0.5
−1
−1.5
2010−02−19
07:26:10
20
30
Date/Time (d)


Data value
0.6
0.5
0.4
0.3
0.2
0.1
0
2010−02−19
07:26:10
20
30
Date/Time (d)



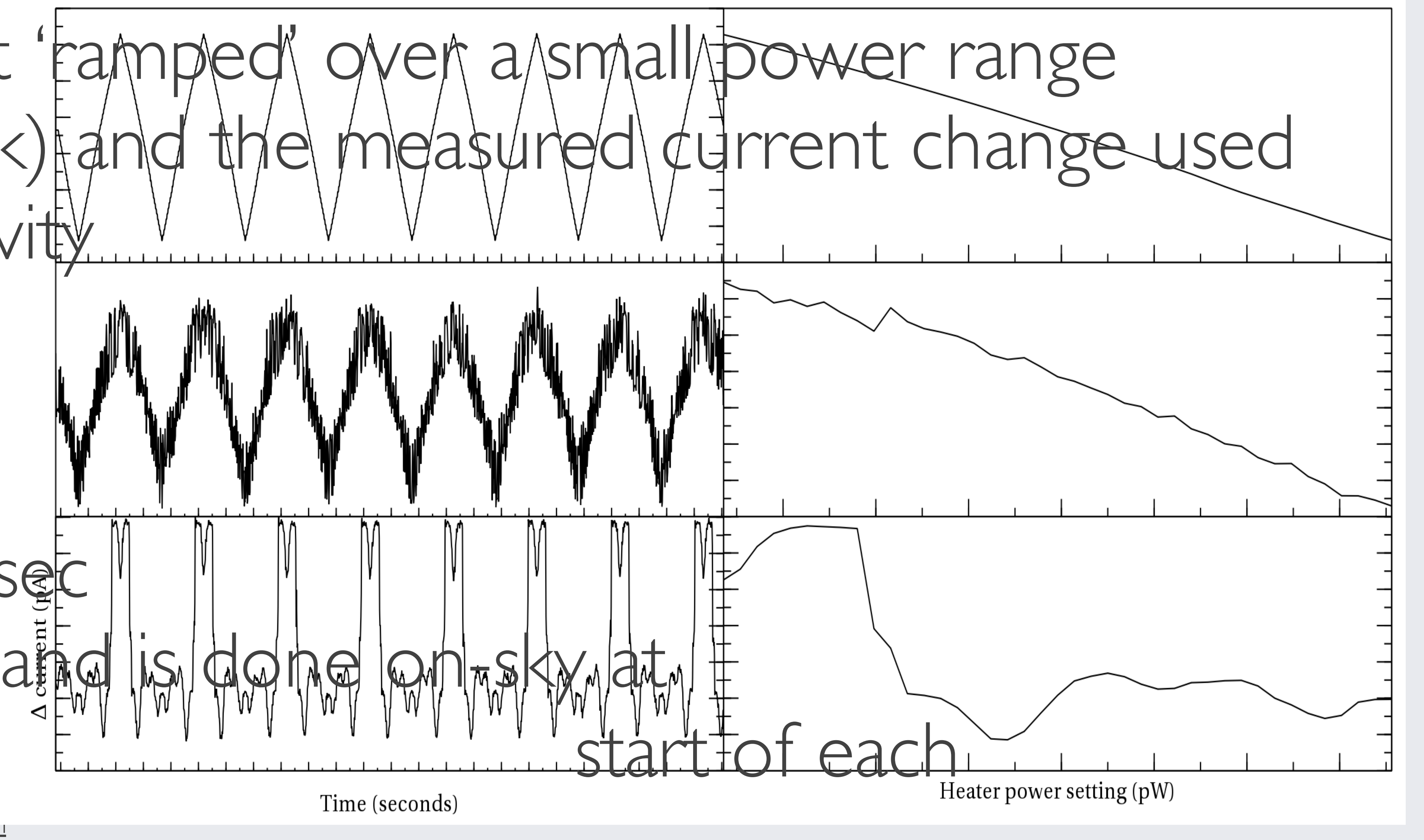
DETERMINING BOLOMETER RESPONSE: FLAT-FIELDING

Individual heaters below each bolometer can be adjusted to account for optical power and keep TES in optimal point in transition

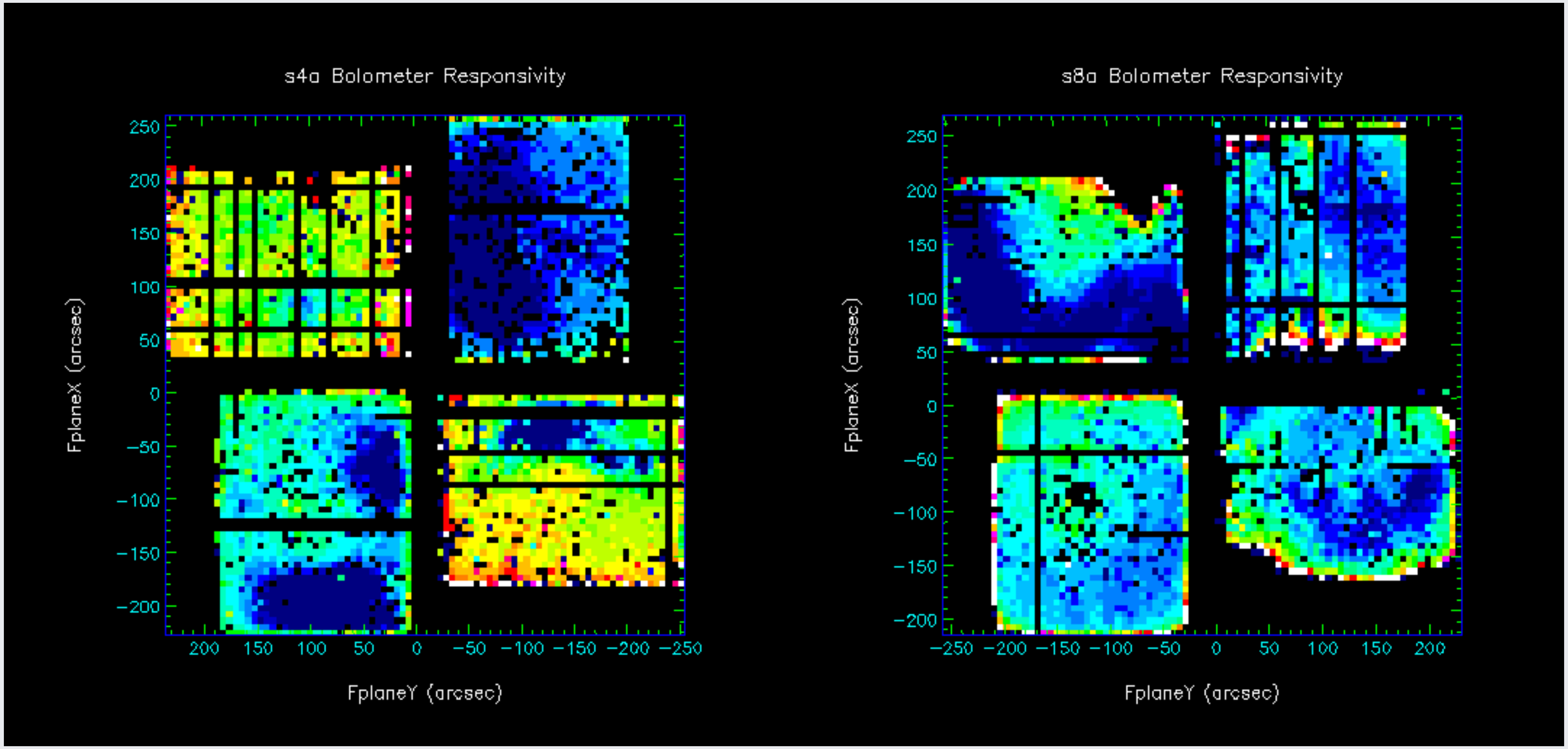
They can also be fast 'ramped' over a small power range (~3pW peak-to-peak) and the measured current change used to calculate responsivity

R = **δ**I/**δ**P (A/W)

Flat-field takes ~10 sec and is done on-sky at start of each observation



ASSESSING THE NOISE PERFORMANCE :NEPS

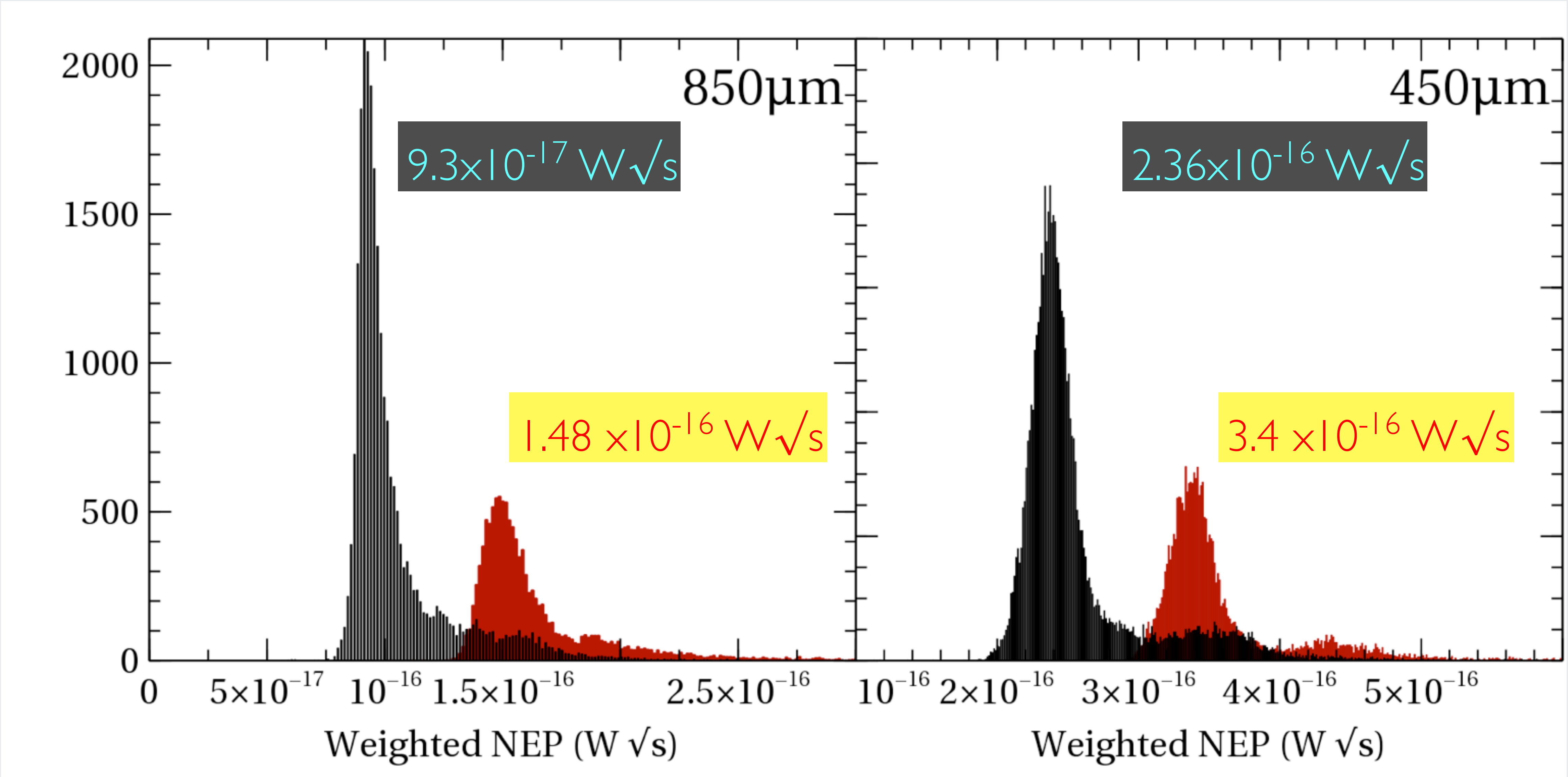


NEP calculated from bolometer power spectrum between 2-10Hz

Optimised to be low, stable, maximum bolometer yield

Aim: to be background limited

NEP distribution repeatable and defined by physical array properties



Dark NEP good stability, <5% higher noise state

Sky NEP wider distribution as they are affected by sky conditions

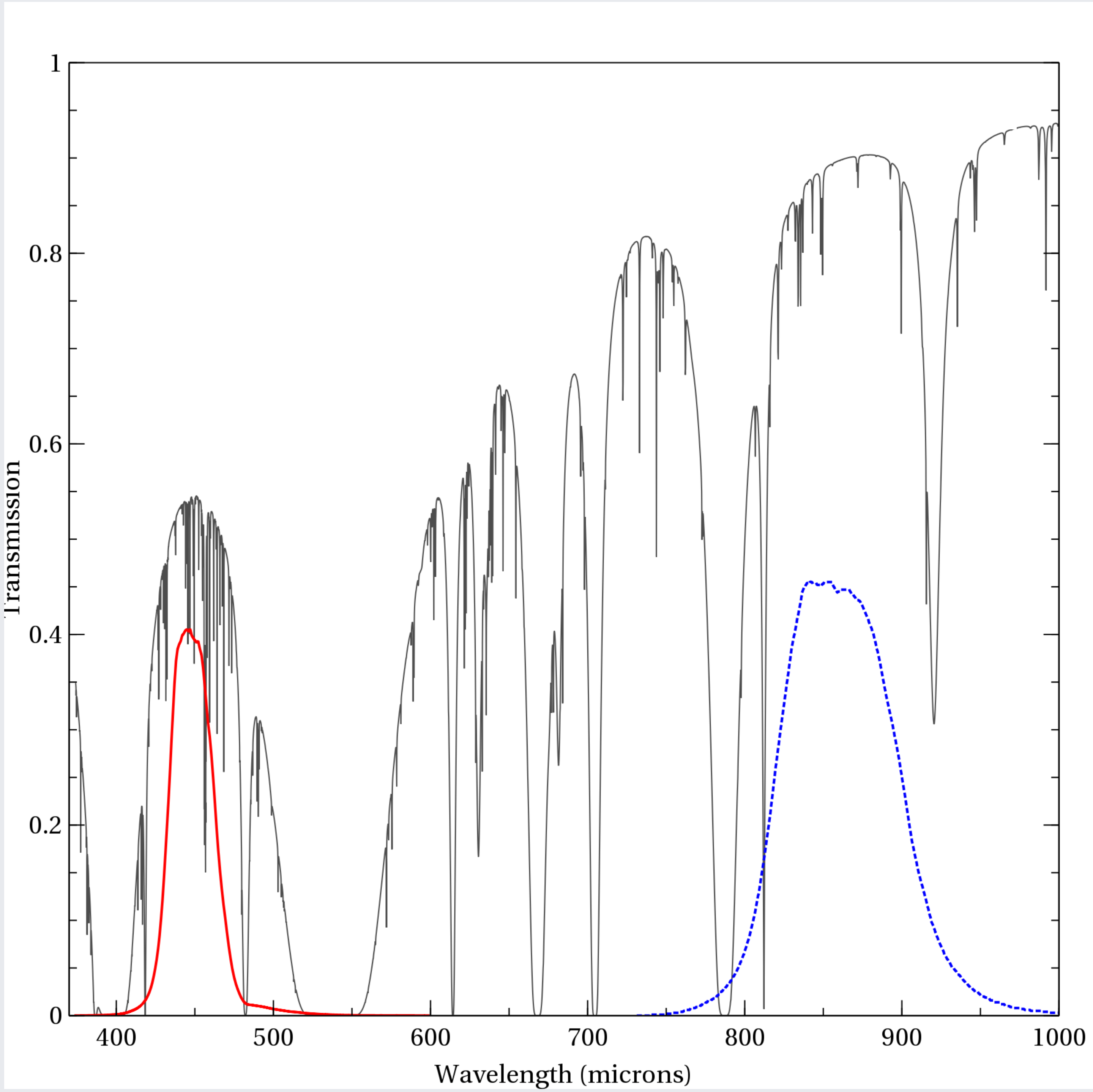
Average yield ~ 3400 bolometers at both wavelengths

EXTINCTION CORRECTION

Extinction coefficients, τ_λ, must be determined for both wavebands

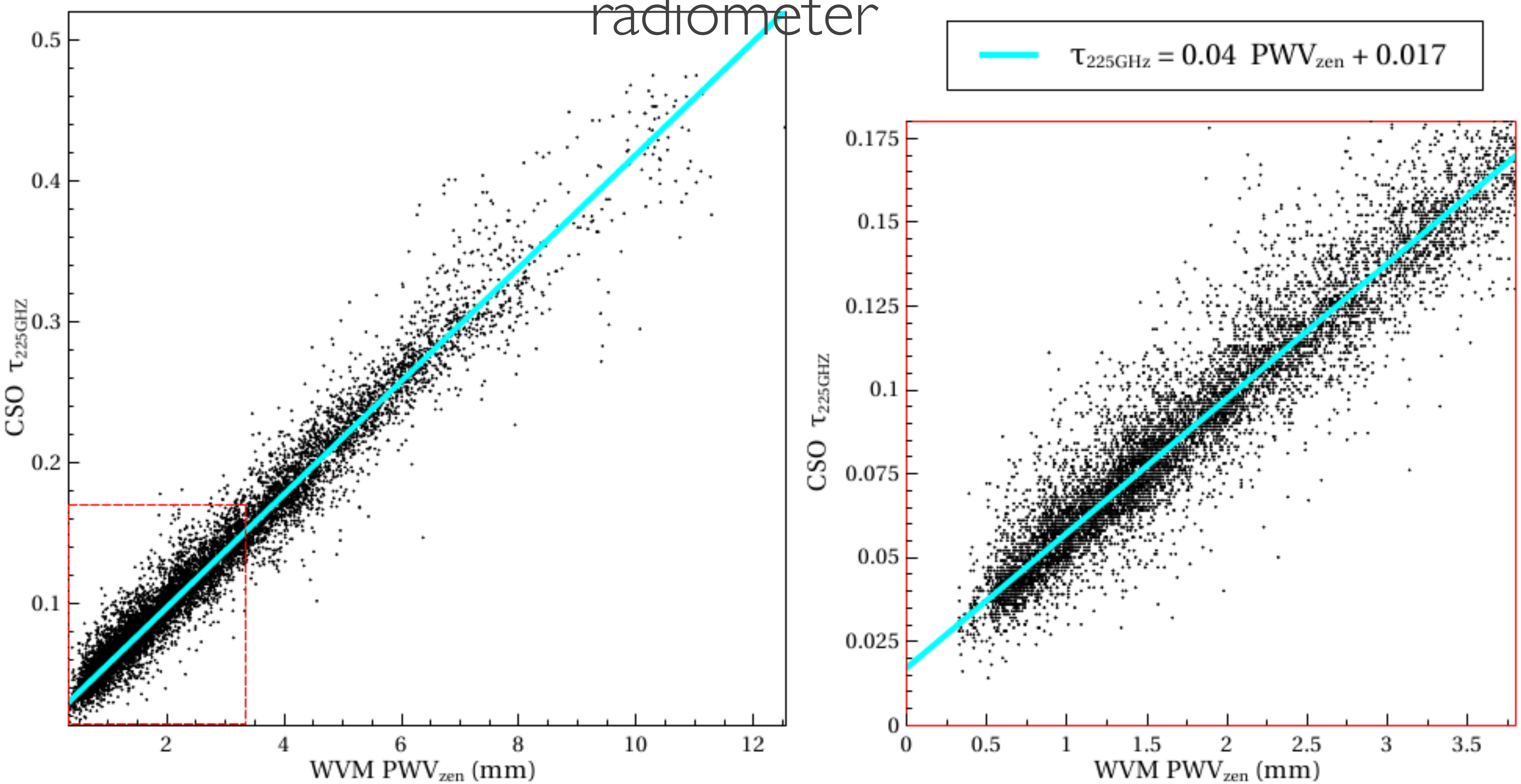
SCUBA used the CSO 225 GHz radiometer and skydips

SCUBA-2 - uses 183 GHz water vapour monitor - measures PWV(mm) along line-of-sight every 1.2 sec



LINE OF SIGHT PWV

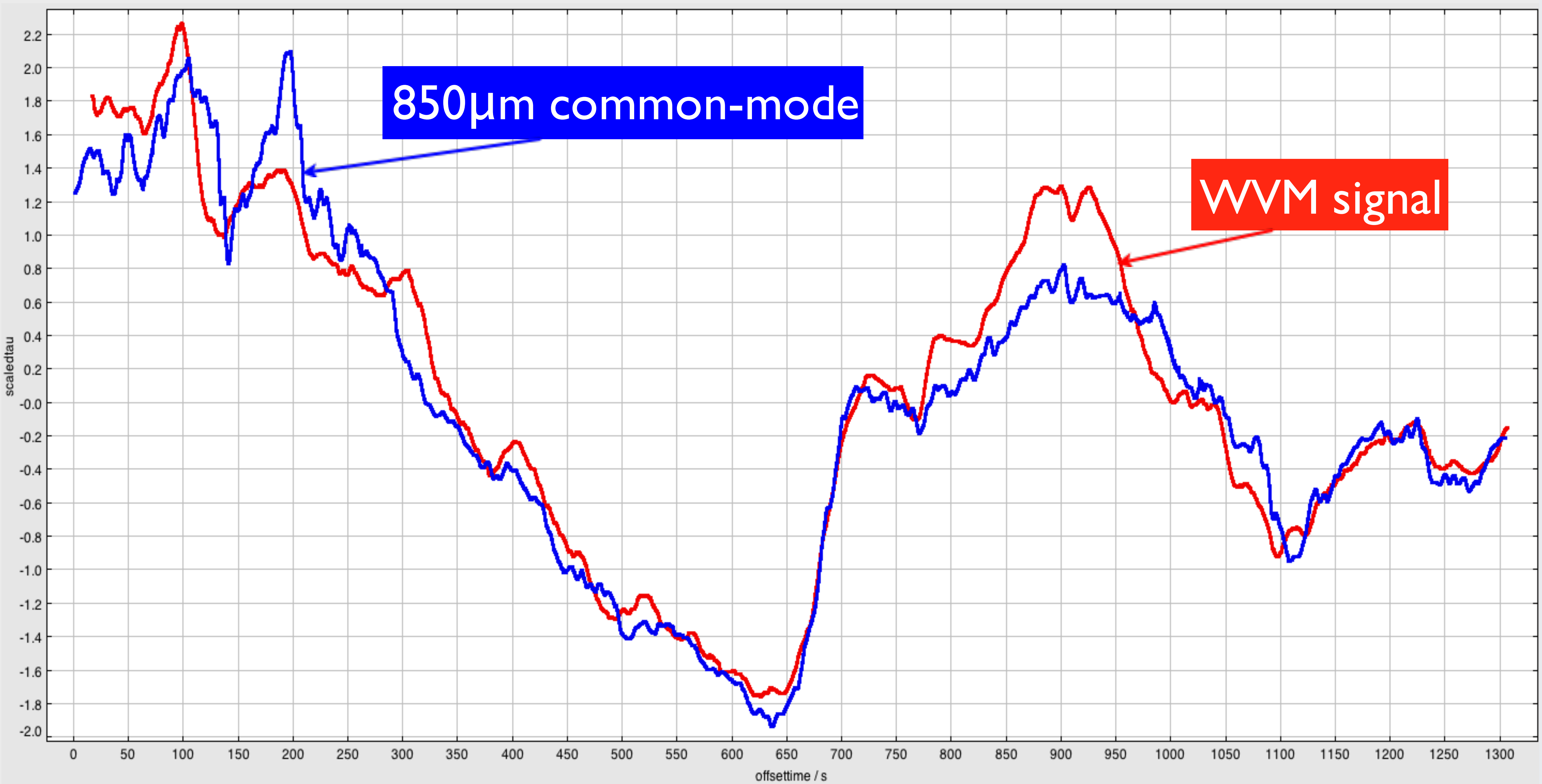
Sanity checking against the CSO 225 GHz radiometer



Transmission is calculated every 1.2 sec, smoothed, and applied to the time series using resulting coefficients

$$\tau_{850} = 0.179 \times (PWV_{los} + 0.337)$$

$$\tau_{450} = 1.014 \times (PWV_{los} + 0.142)$$



PRIMARY CALIBRATORS

Uranus and Mars, when available are used as the primary calibration sources

Uranus model: Moreno, 2010

Mars model: Wright, 1976

Extinction factors were obtained by fitting to the uncorrected flux of these planets as a function of airmass

Independent results agreed to within 2%

STANDARD SOURCES

CRL618 and CRL2688 are our 'go-to' calibrators in addition to Uranus and Mars

During commissioning, a selection of other possible candidate calibrators were also consistently observed

SOURCE	RA (J2000)	Dec. (J2000)	850 [I] (Jy)	450 [I] (Jy)	850 [P] (Jy beam^{-1})	450 [P] (Jy beam^{-1})	ref
CRL618	04:42:53.67	+36:06:53.17	4.73 ± 0.33	12.1 ± 2.2	4.55 ± 0.2	11.5 ± 1.5	d[I],b[P]
CRL2688	21:02:18.27	+36:41:37.00	6.39 ± 0.51	30.9 ± 3.8	5.9 ± 0.2	24.0 ± 2.1	d[I],b[P]
Arp220	15:34:57.27	+23:30:10.48	0.83 ± 0.086	—	0.7*	5.0*	f[I],c[P]
PV Cep	20:45:54.39	+67:57:38.8	1.0 ± 0.02	6.5 ± 0.015	—	—	a
MWC 349	20:32:45.53	+40:39:36.6	2.6 ± 0.007	5 ± 1.1	—	—	a
HD169142	18:24:29.78	-29:46:49.37	0.565 ± 0.01	3.34 ± 0.115	—	—	a
V883 Ori	05:38:19	-07:02:2	1.41 ± 0.022	9.45 ± 0.17	—	—	g
HL Tau	04:31:38.44	+18:13:57.65	2.36 ± 0.24	9.9 ± 2.0	2.3 ± 0.15	10.0 ± 1.2	d[I],b[P]
BVP 1	17:43:10.37	-29:51:44.00	—	—	1.069 ± 0.02	11.318 ± 0.6	e

[I] indicates integrated flux measurements. [P] indicates peak flux measurements. References: (a) Sandell et al. (2011), background-corrected integrated flux. (b) Sandell (2003), peak flux in Jy beam^{-1}. (c) Truch et al. (2008), BLAST primary calibrator. *Peak flux based on fit to SED curve fitted to measurements at other wavelengths.(d) Jenness et al. (2002) integrated flux in a 40 arcsec aperture. (e) Barnard et al. (2004) Peak flux. Denoted as object G6 in that text. (f) Lisenfeld et al. (2000) integrated flux. (g) Sandell & Weintraub (2001), background-corrected integrated flux.

FLUX CONVERSION FACTORS

FCFS are produced in two ways

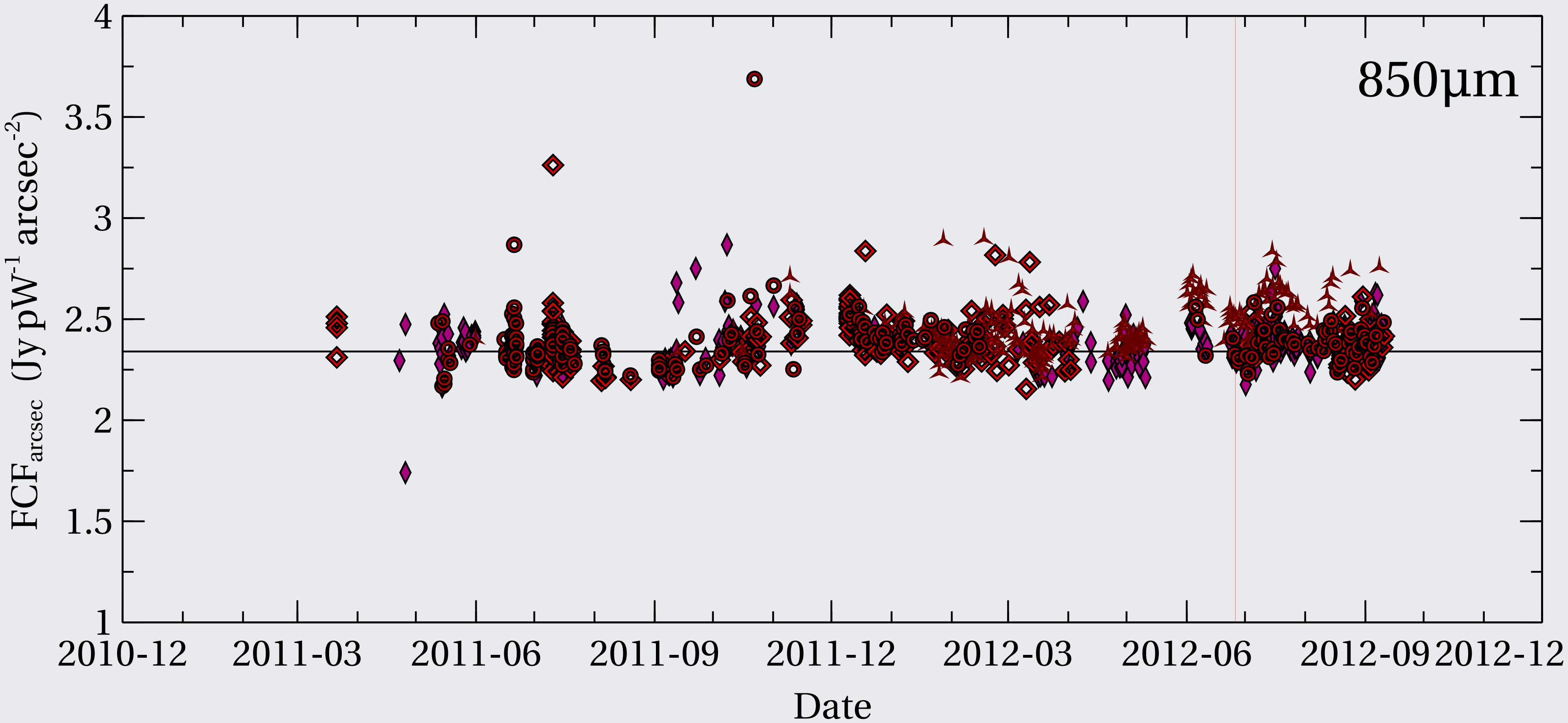
$$\mathrm{FCF}_{\mathrm{arcsec}} = \frac{S_\nu}{I_0\ A} \quad Jy\ pW^{-1}\ arcsec^{-2}$$

$$\mathrm{FCF}_{\mathrm{peak}} = \frac{S_p}{I_p} \quad Jy\ pW^{-1}\ beam^{-1}$$

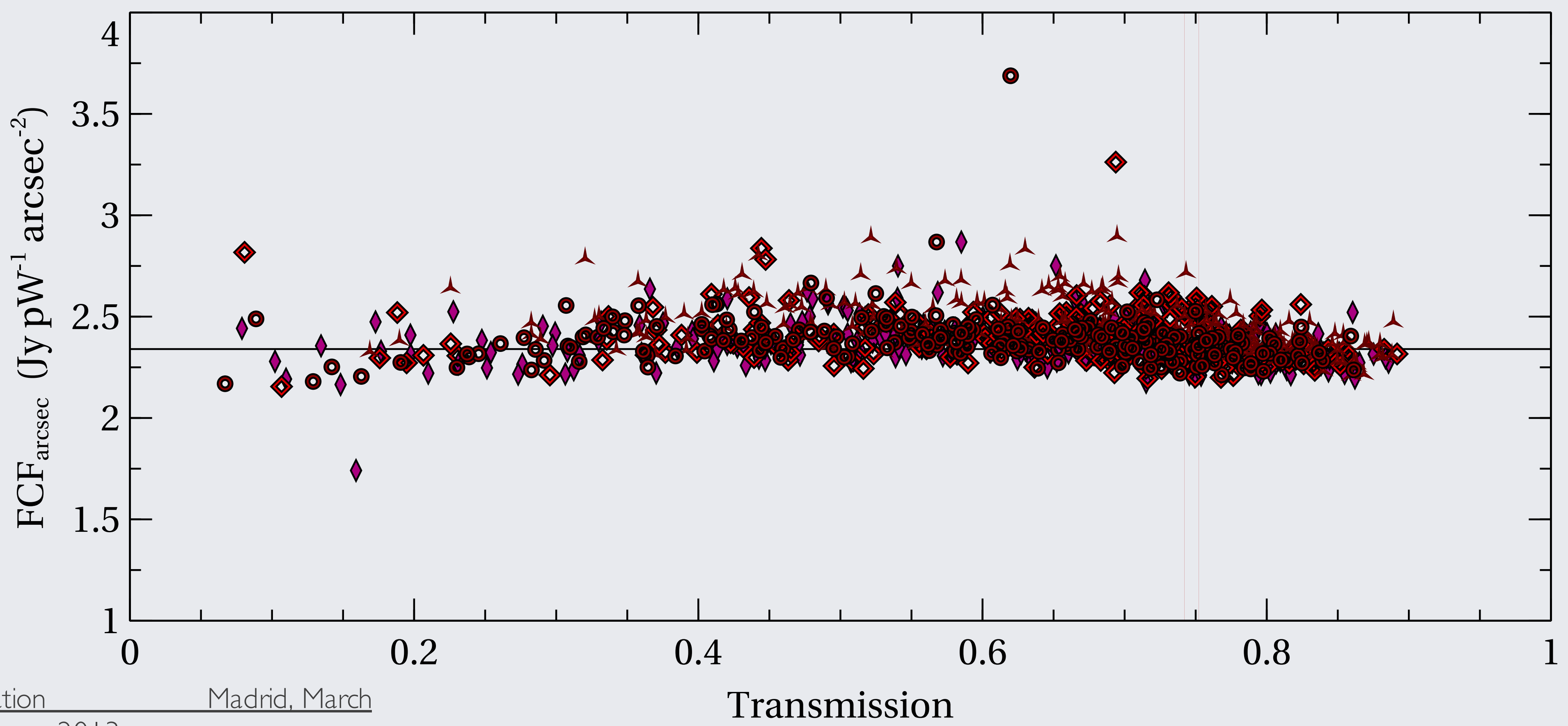
Variation is dominated by thermal effects on the dish and focus

Thus, the $\mathrm{FCF}_{\mathrm{peak}}$ is more susceptible, and more so at 450um

FCF: RESULTS

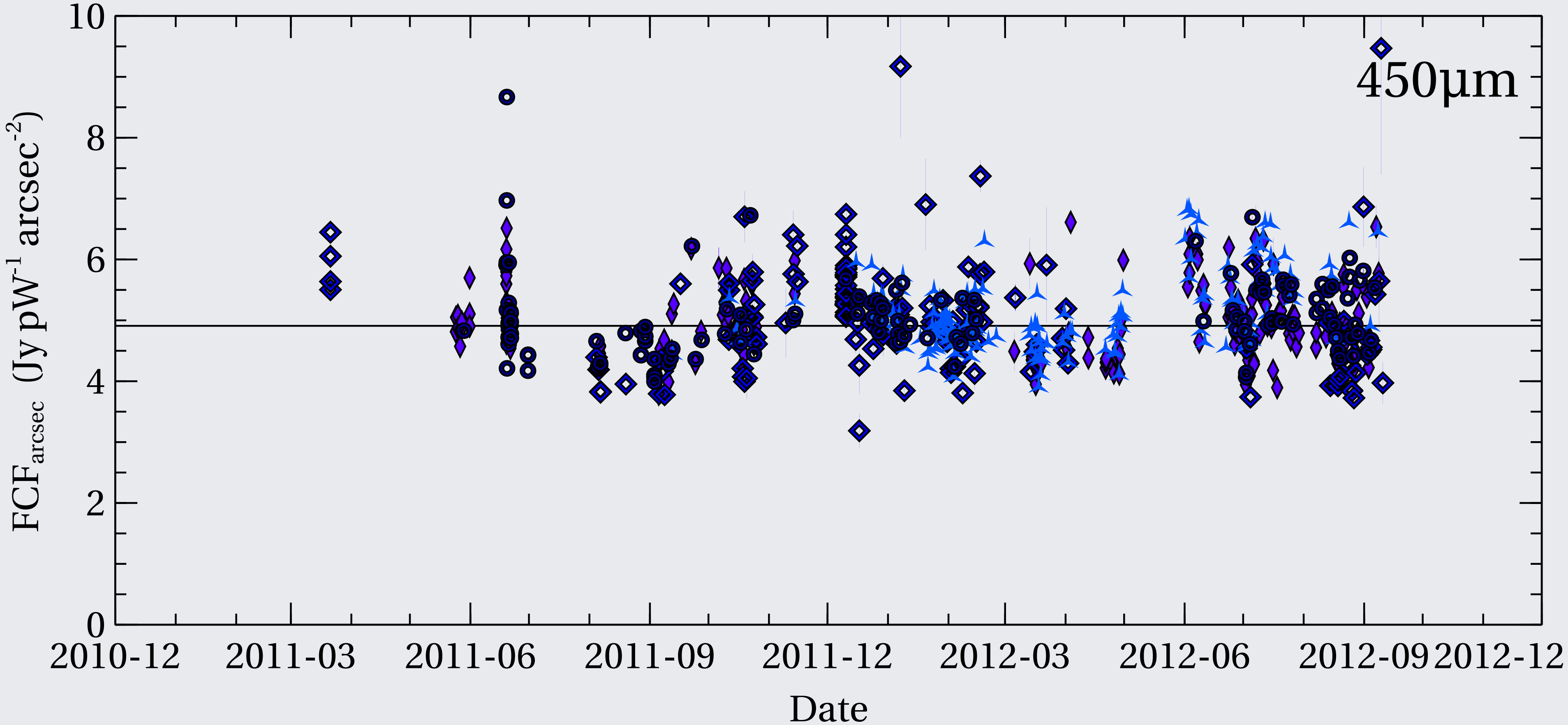


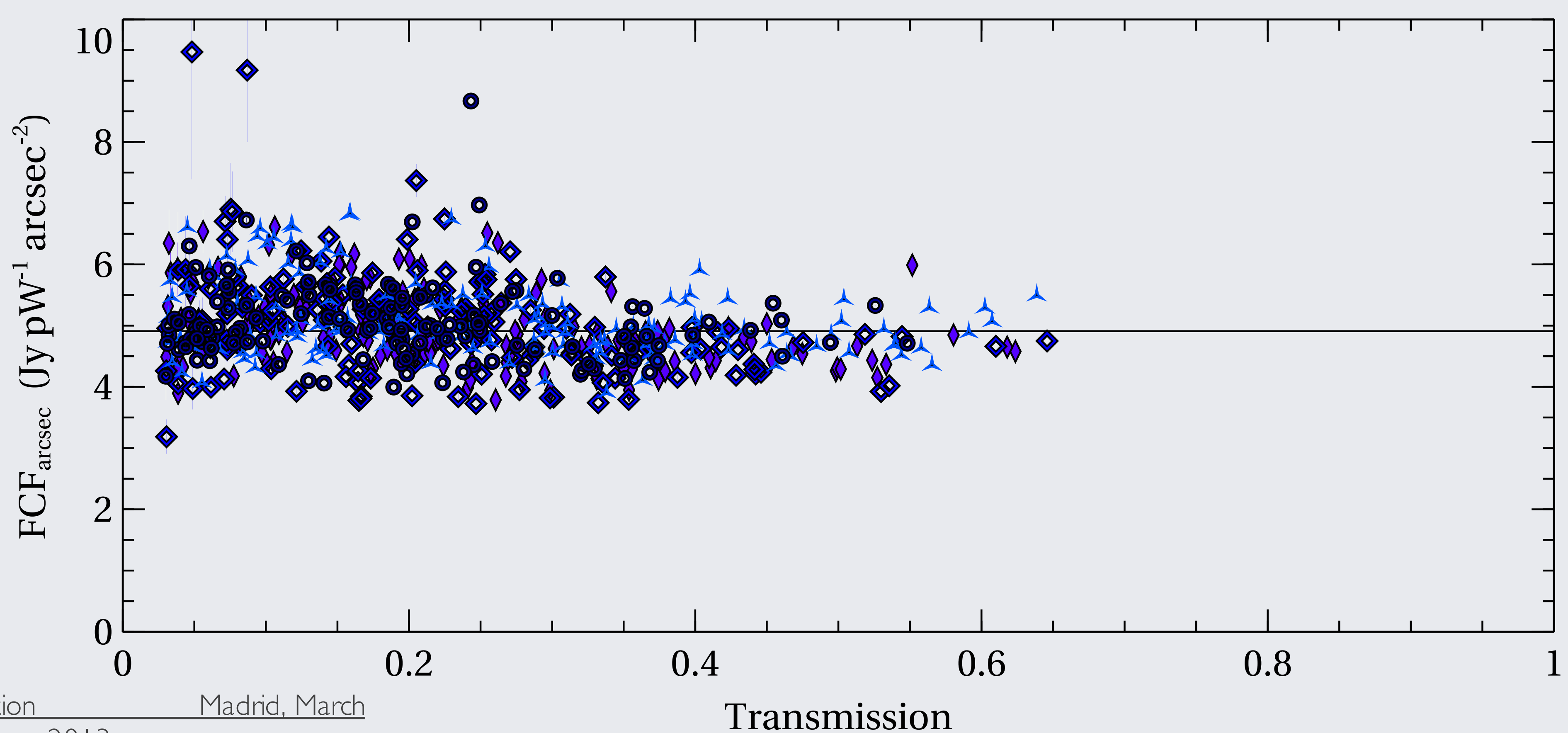
850µm
FCF$_{arcsec}$ (Jy pW^{-1} arcsec^{-2})
4
3.5
3
2.5
2
1.5
1
2010-12
2011-03
2011-06
2011-09
2011-12
2012-03
2012-06
2012-09
2012-12
Date



FCF$_{arcsec}$ (Jy pW^{-1} arcsec^{-2})
4
3.5
3
2.5
2
1.5
1
0
0.2
0.4
0.6
0.8
1
Transmission

FCF: RESULTS


450µm
FCF$_{arcsec}$ (Jy pW^{-1} arcsec^{-2})
0
2
4
6
8
10
2010-12
2011-03
2011-06
2011-09
2011-12
2012-03
2012-06
2012-09
2012-12
Date


FCF$_{arcsec}$ (Jy pW^{-1} arcsec^{-2})
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
Transmission

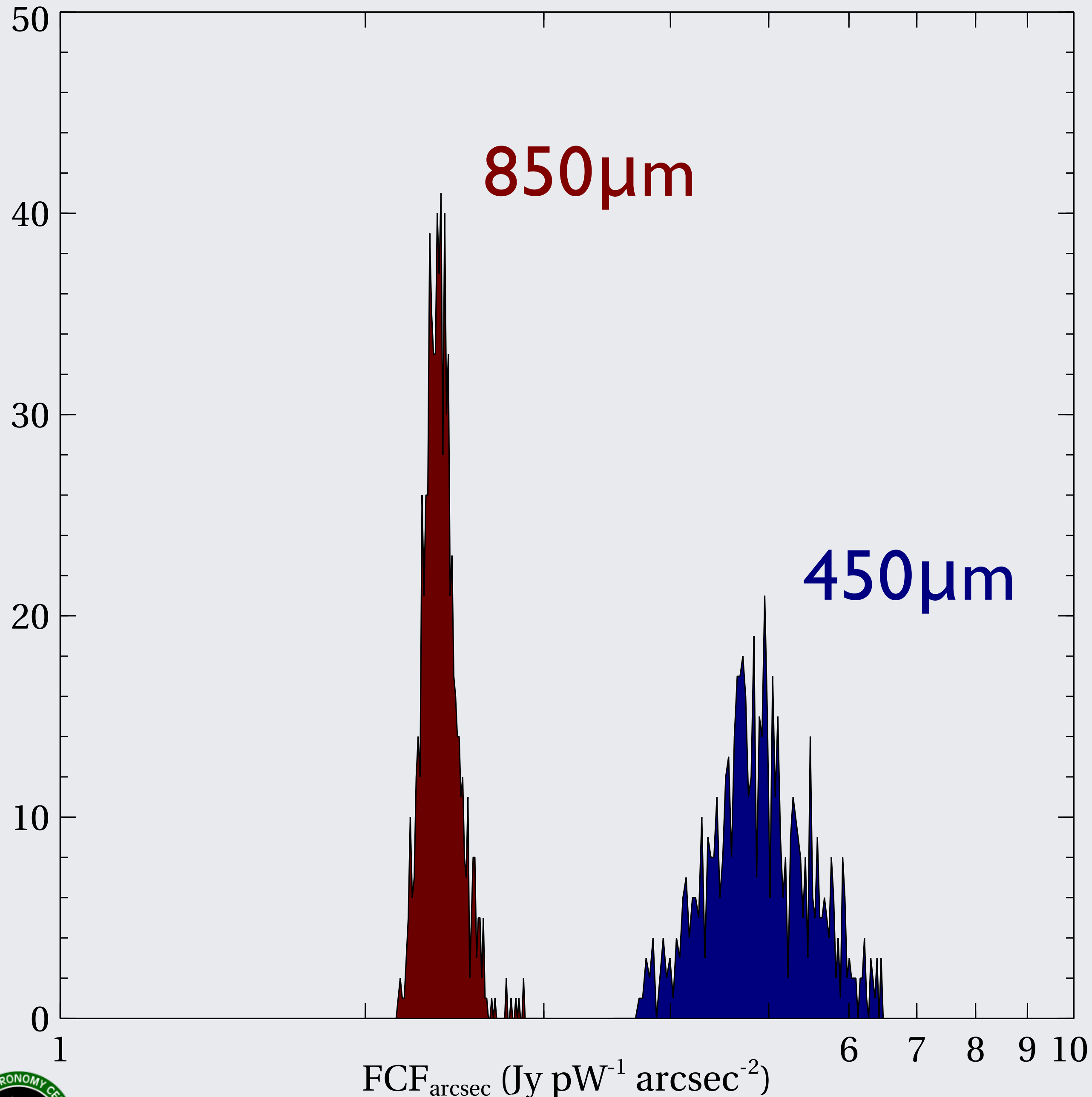
FCF: RESULTS

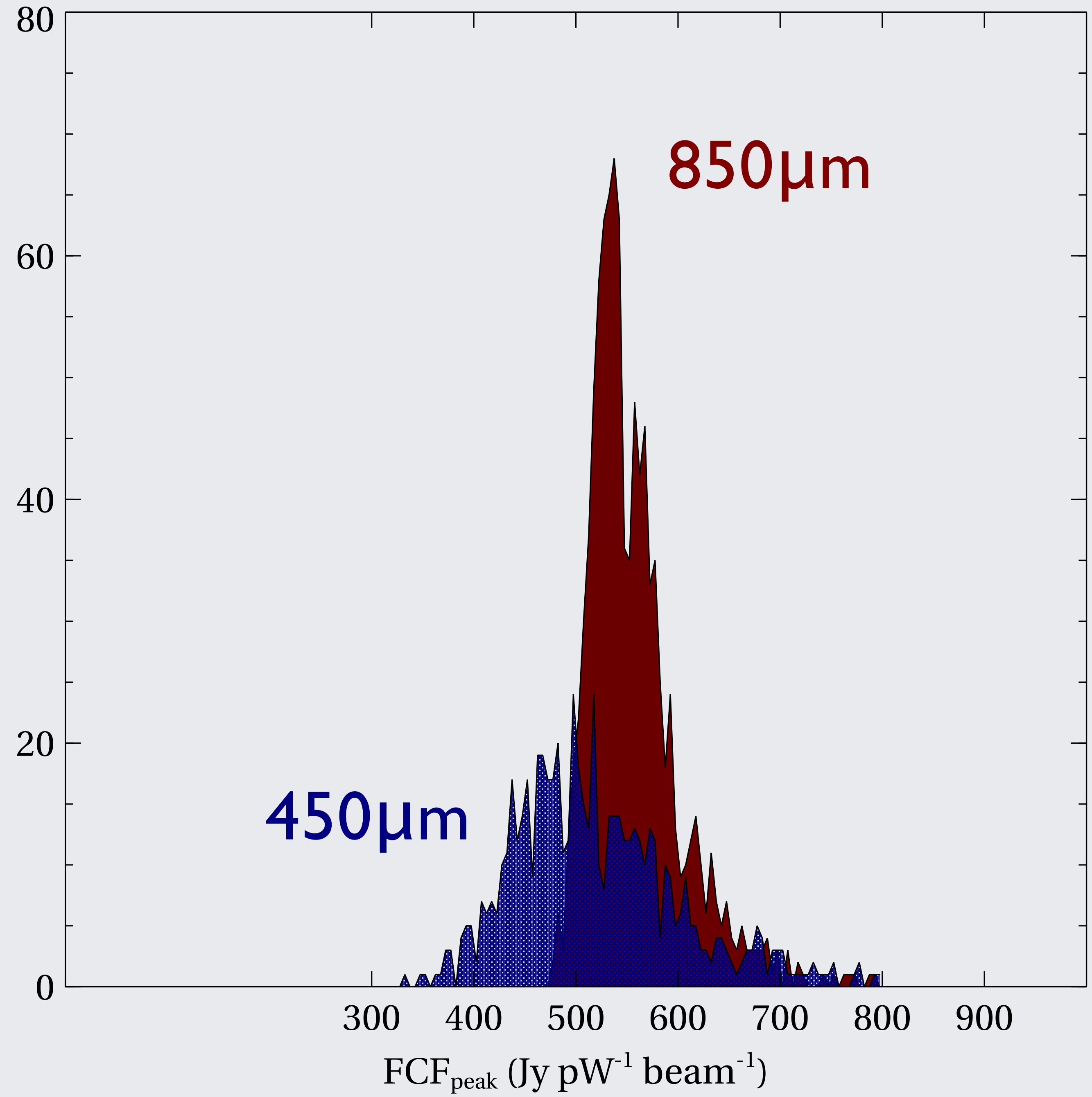
$FCF[850]_{arcsec} = 2.34 \pm 0.08$ *Jy pw^{-1} arcsec^{-2}*

$FCF[850]_{peak} = 537 \pm 26$ *Jy pw^{-1} beam^{-1}*

$FCF[450]_{arcsec} = 4.71 \pm 0.5$ *Jy pw^{-1} arcsec^{-2}*

$FCF[450]_{peak} = 491 \pm 67$ *Jy pw^{-1} beam^{-1}*





CALIBRATION ERRORS

Using the standard deviation on our Uranus and Mars results

Relative calibration errors of

$\sigma(850) = 5\ \%$

$\sigma\ (450) = 10\%$

Taking into account the uncertainties in the planetary models

Absolute calibration errors of

$\sigma\ (850) \simeq 8\%$

$\sigma\ (450) \simeq 15\%$

STANDARD SOURCE RESULTS

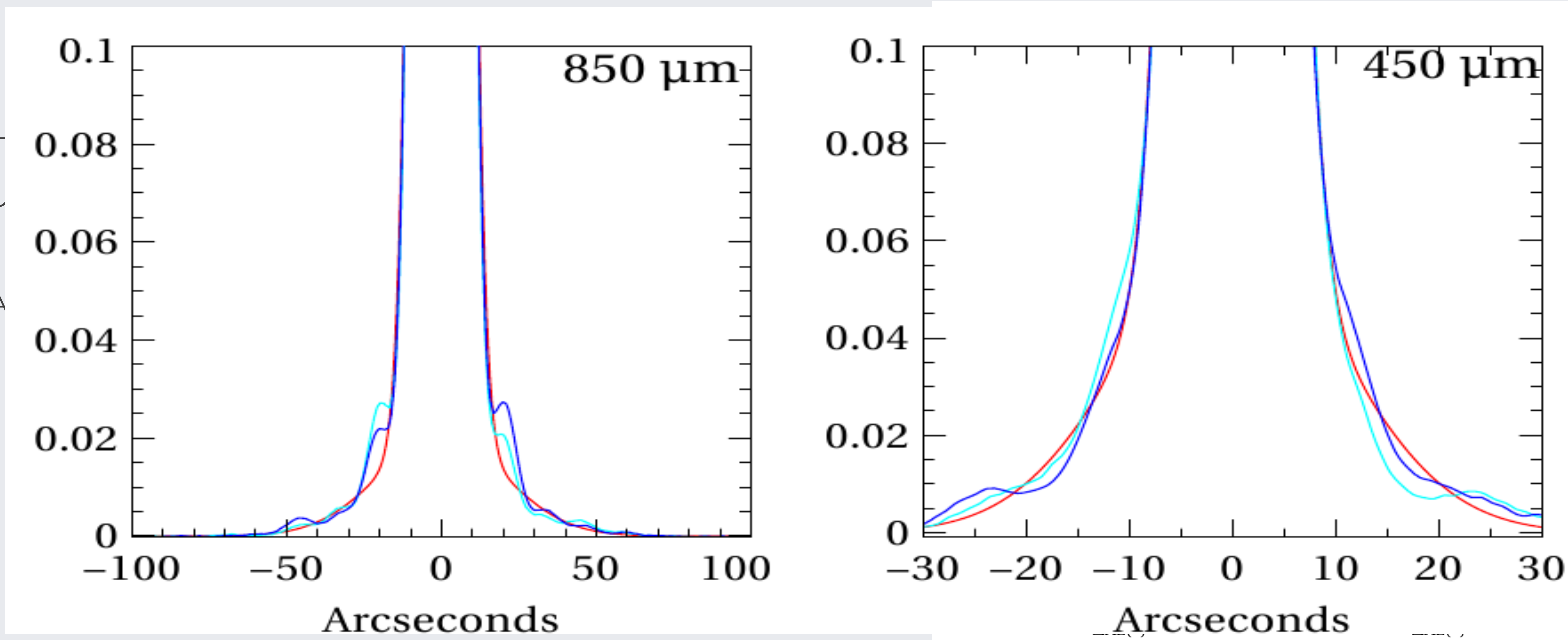
Derived using the standard calculated FCFs

Table 4. Measured fluxes of SCUBA-2 secondary calibrators

SOURCE	RA (J2000)	Dec. (J2000)	N(obs)	850[I] (Jy)	450[I] (Jy)	850[P] (Jy beam^{-1})	450[P] (Jy beam^{-1})	Note
CRL618	04:42:53.67	+36:06:53.17	113	5.0 ± 0.2	12.10 ± 1.05	4.89 ± 0.24	11.50 ± 1.4	y
CRL2688	21:02:18.27	+36:41:37.00	173	6.13 ± 0.211	29.10 ± 2.5	5.64 ± 0.27	24.9 ± 2.9	y,(a)
Arp220	15:34:57.27	+23:30:10.48	20	0.81 ± 0.07	5.4 ± 0.7	0.79 ± 0.9	5.2 ± 0.8	y
PV Cep	20:45:54.39	+67:57:38.8	21	1.35 ± 0.05	10.6 ± 0.86	0.82 ± 0.04	5.7 ± 0.65	n,(a)
MWC 349	20:32:45.53	+40:39:36.6	14	2.19 ± 0.08	3.2 ± 0.25	2.21 ± 0.11	3.4 ± 0.26	n
HD169142	18:24:29.78	-29:46:49.37	12	0.58 ± 0.02	3.41 ± 0.24	0.52 ± 0.03	2.21 ± 0.25	y, (a,b)
V883 Ori	05:38:19	-07:02:2	3	2.00 ± 0.07	10.4 ± 1.0	1.55 ± 0.09	7.8 ± 1.00	y, (b)
HL Tau	04:31:38.44	+ 18:13:57.65	9	2.42 ± 0.08	10.3 ± 0.86	2.32 ± 0.1	8.3 ± 1.03	y, (b)
BVP 1	17:43:10.37	-29:51:44.00	4	1.55 ± 0.05	16.9 ± 0.8	1.37 ± 0.07	11.5 ± 1.5	y,(a,b)

[I] indicates integrated flux measurements. [P] indicates peak flux measurements. Error is quadrature addition of uncertainty in the FCF measurement and the rms noise in the co-added map for each calibrator. Notes: y/n indicates if the source will continue to be observed as a SCUBA-2 calibrator. (a) Extended emission at 450 µm. Col. 4 gives the number of observations taken per source between 2011 July and 2012 May. (b) Low S/N measurement, particularly at 450 µm. Accuracy of these flux densities is uncertain, and further observations are required.

CHARACTERISING THE BEAM



$$G_{\mathrm{total}} = \alpha\, G_{\mathrm{MB}} + \beta\, G_{\mathrm{S}}$$

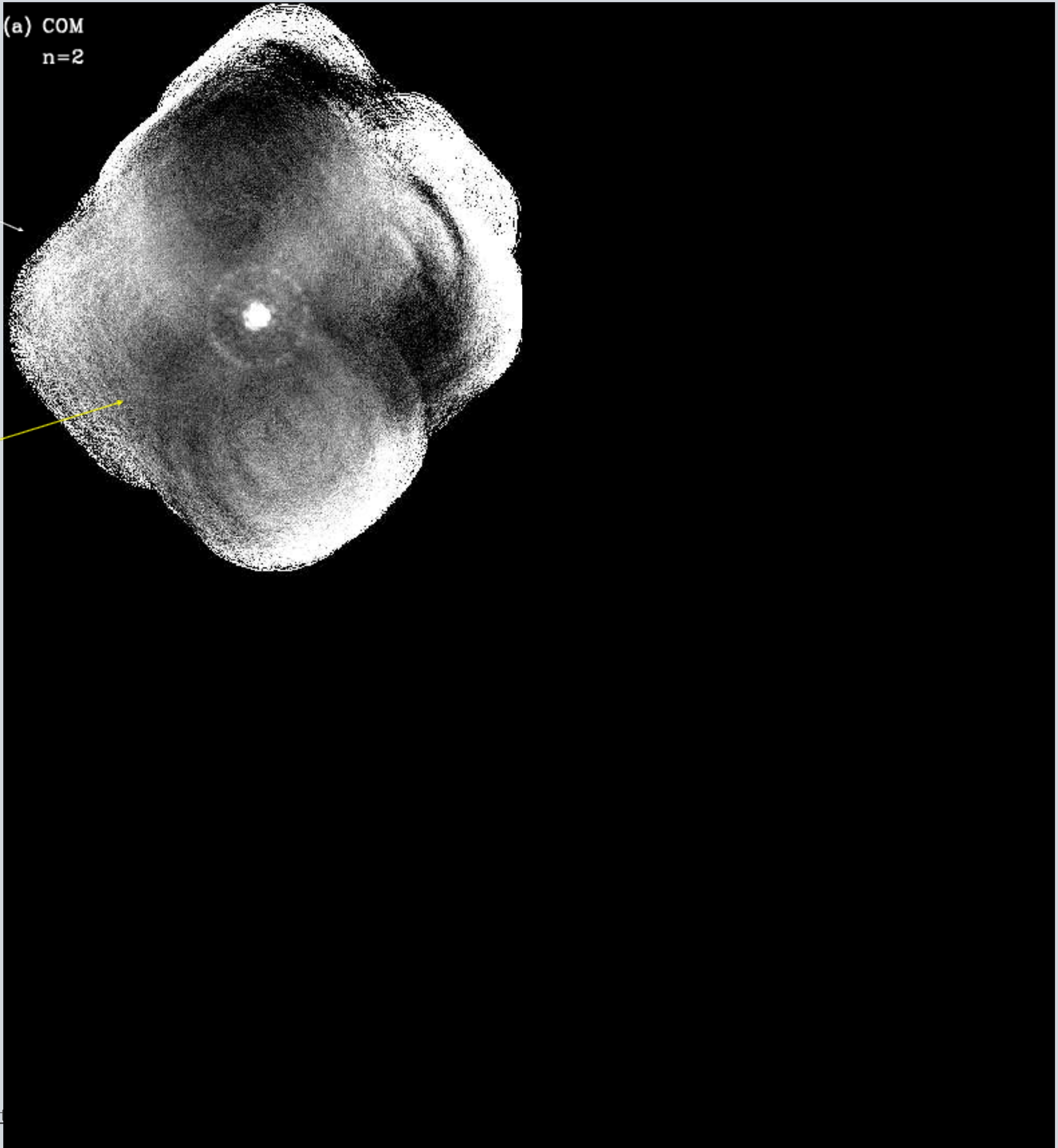
	450	850
FWHM Main beam (θ_{MB})	7.9″	13.0″
FWHM Secondary Comp. (θ_{S})	25″	48″
Rel. Amp. Main Beam (α)	0.94	0.98
Rel. Amp. Secondary Comp (β)	0.06	0.02
Rel. Vol. Main	0.6	0.75
Rel. Vol. Secondary Comp	0.4	0.25

COMPLICATIONS

Recovery of large-scale structure and its relative calibration is less well understood

1/f noise dominates at the frequency scales where large-scale emission is present - requiring a high-pass filter to remove the 1/f ... but this introduces its own problems

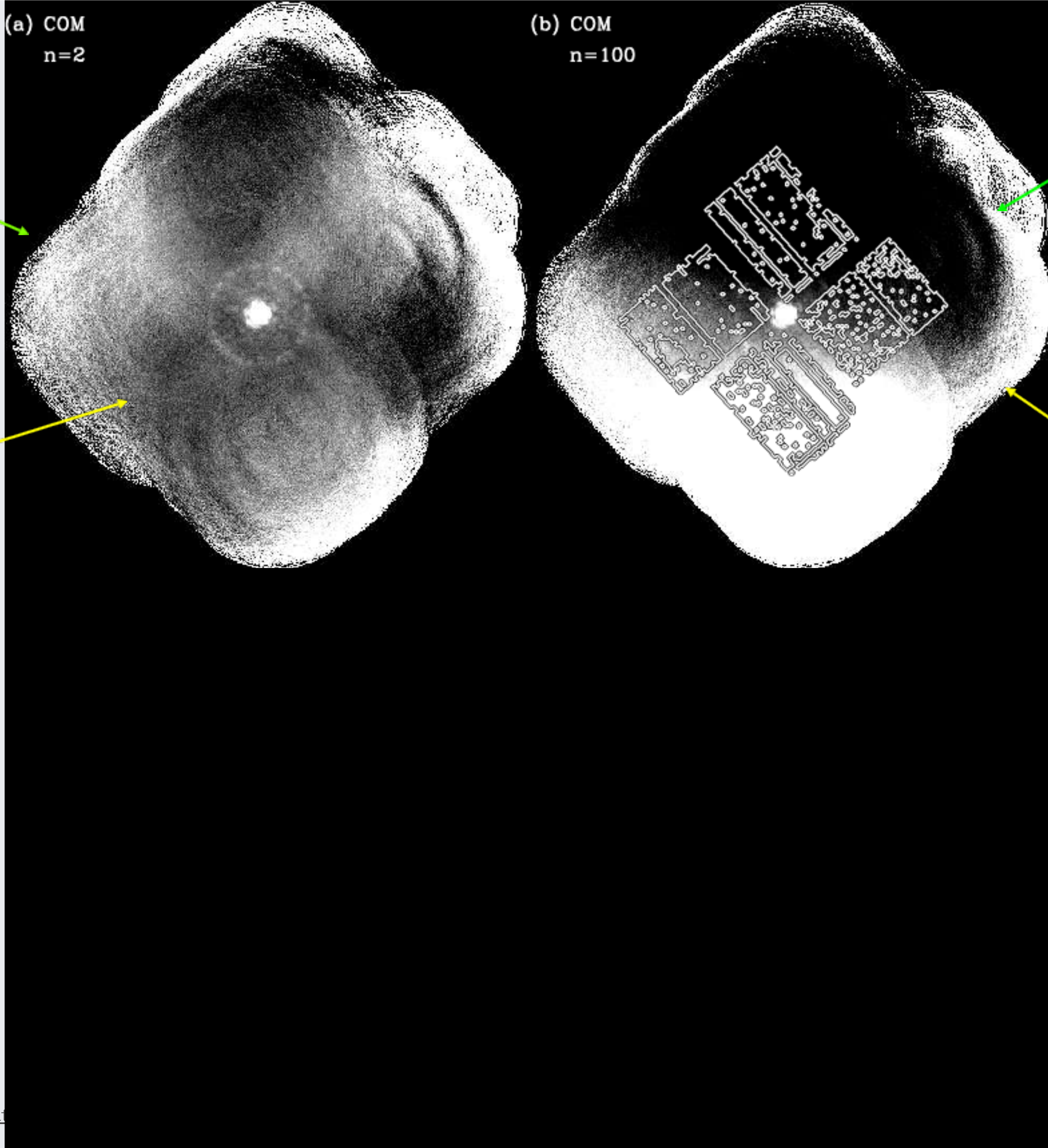
Just common-mode



Uncorrelated low-f noise

Just common-mode

Uncorrelated low-f noise



Just common-mode

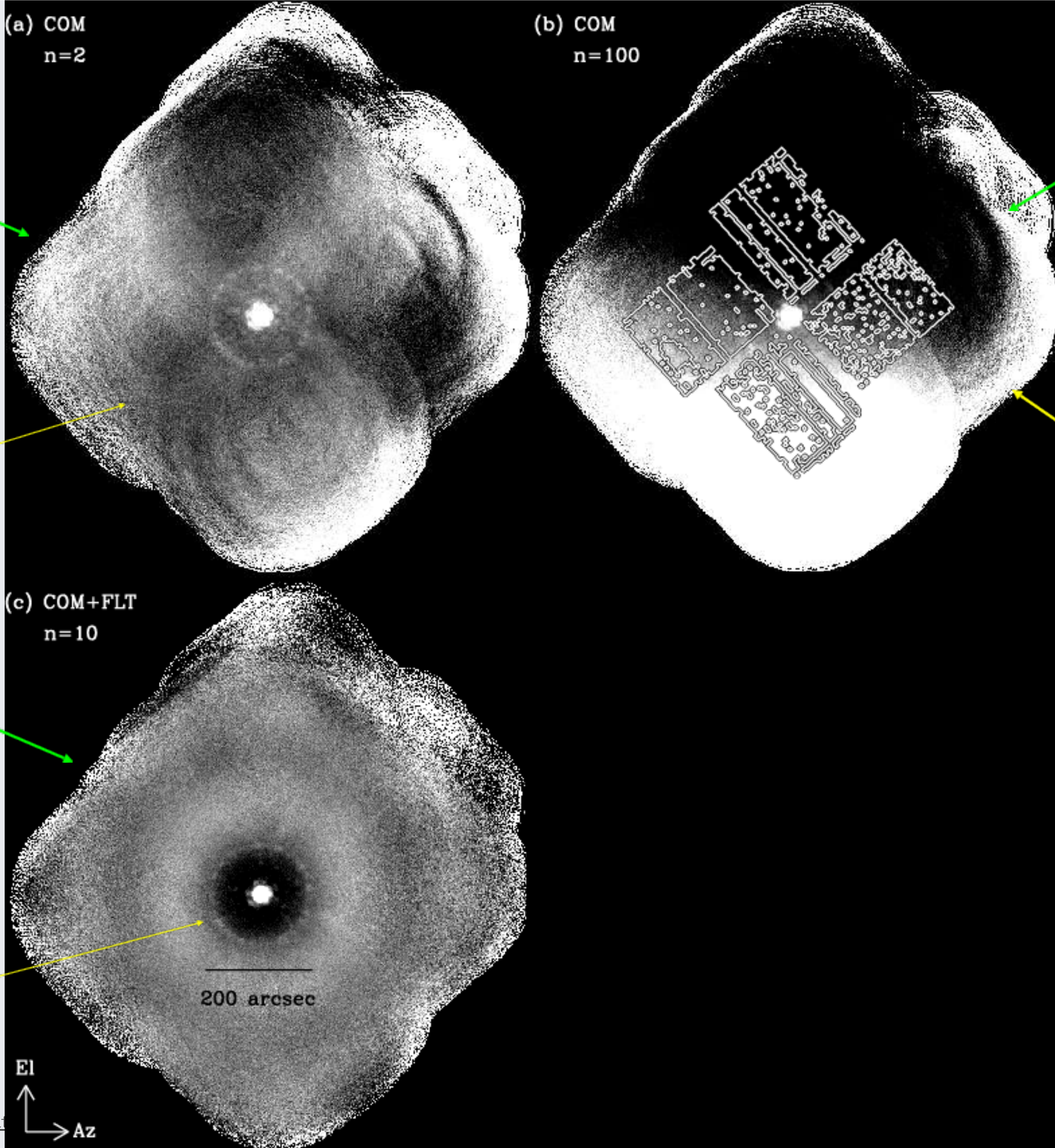
Gradient result of degeneracy

Just common-mode

Uncorrelated low-f noise

Add high-pass filter

Filter ringing



Just common-mode

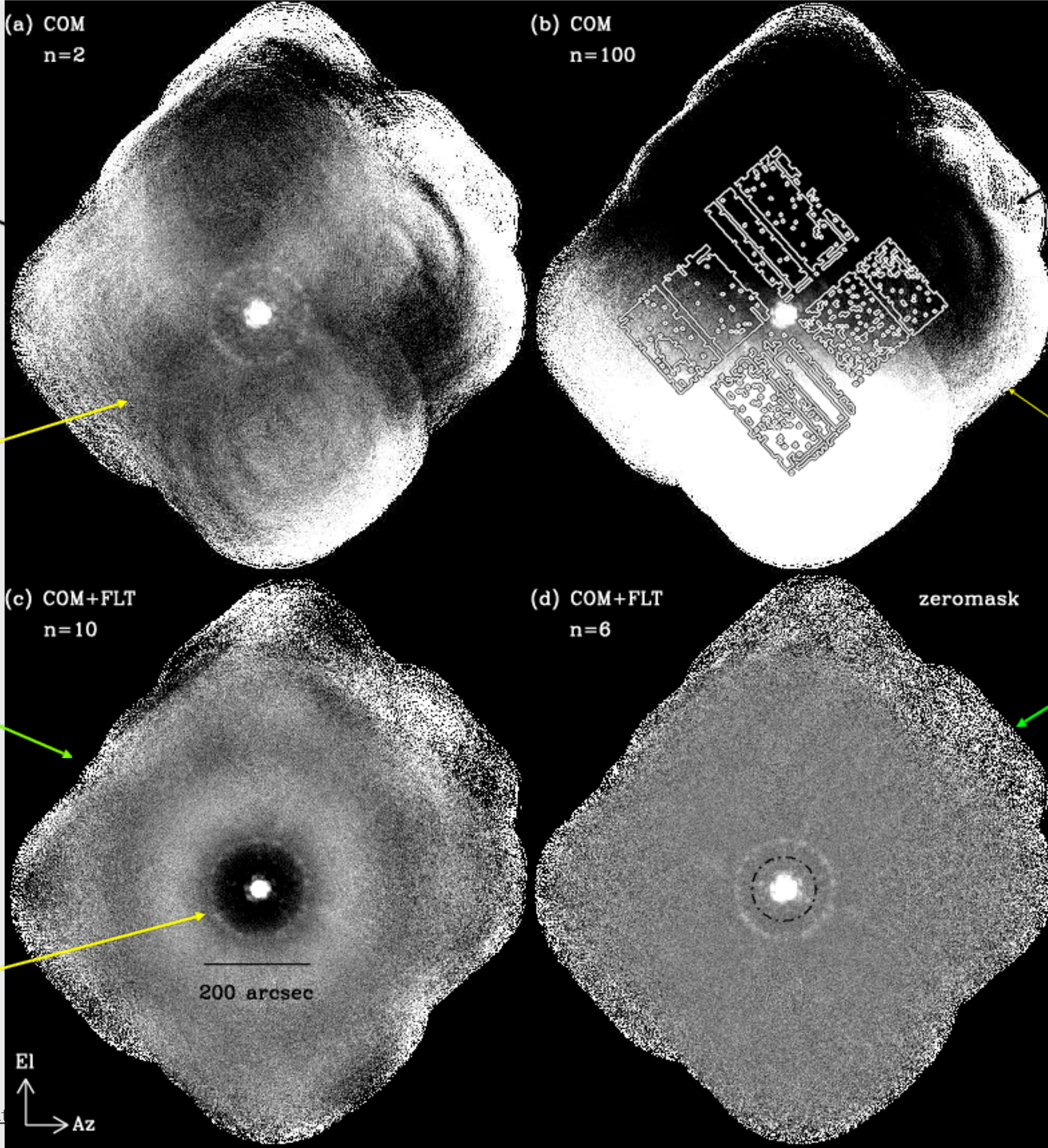
Gradient result of degeneracy

Just common-mode

Uncorrelated low-f noise

Add high-pass filter

Filter ringing

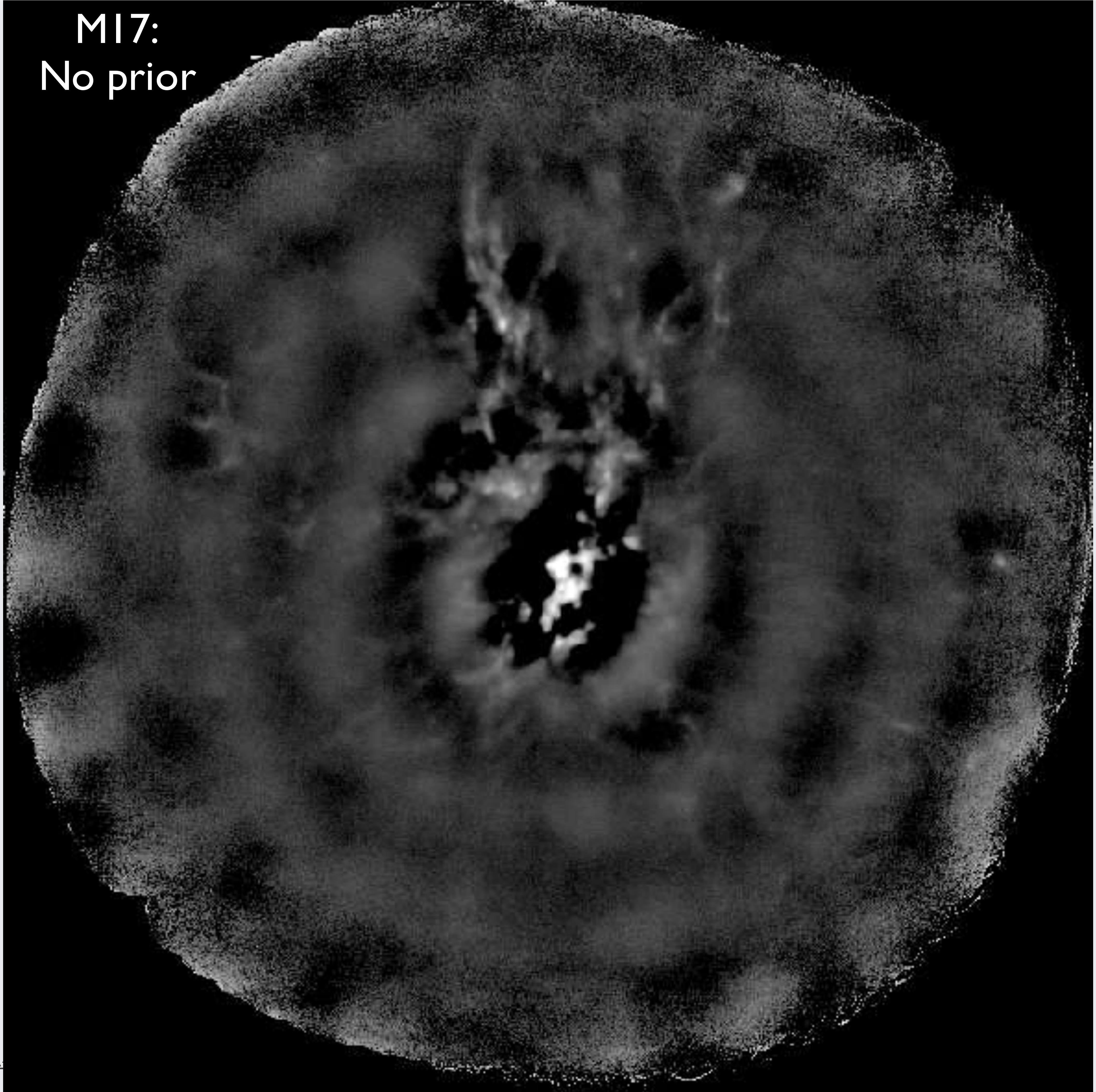


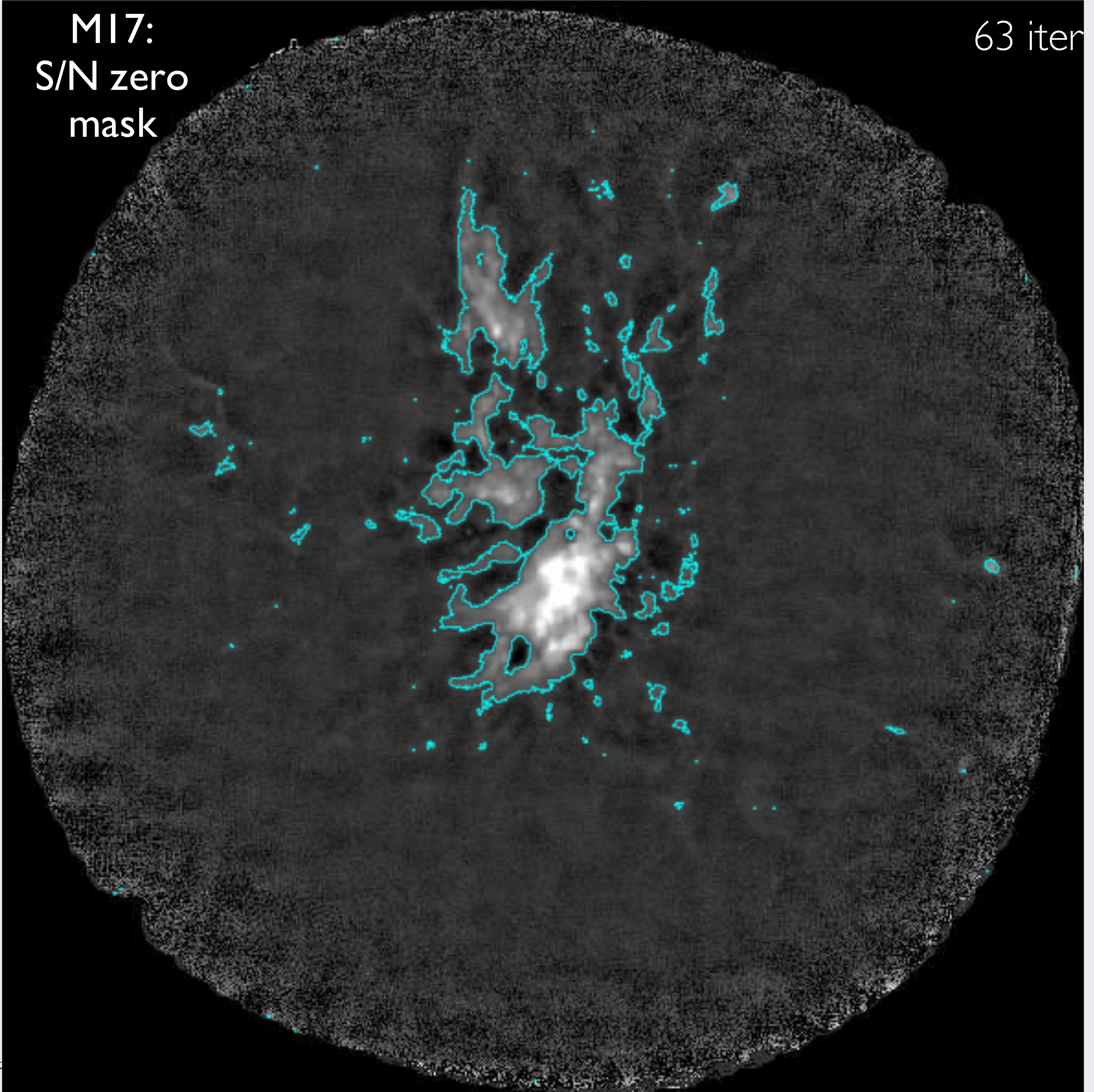
Just common-mode

Gradient result of degeneracy

Add prior: zero mask

M17: No prior




M17:
S/N zero
mask
63 iter

COMMON-USER
SUBMILLIMETRE
SCUBA2
ARRAY-2

COMPLICATIONS

Recovery of large-scale structure and its relative calibration is less well understood

Known, compact sources are well described by the calibration discussed here

There is ongoing investigation into larger-scale emission structures: conservatively, at this time recovery of emission on scales larger than the array footprint is unconstrained

LESSONS LEARNED

Calibration is much easier from space...

Calibration accuracy from the ground is dominated by atmospheric effects so... accurate, high-time-resolution measurements of the line-of-sight opacity should be a high(er) priority

Cross-calibration between Herschel and SCUBA-2:

Point sources can be well-calibrated with our current methodology

We need a thorough investigation of how flux is conserved in our mapmaker at larger angular scales in order to allow for meaningful comparison

THE FUTURE

Against the clock: current shutdown of JCMT scheduled for September 2014

SCUBA-2 calibration database: daily updated reduced products, FCFs, and other useful performance statistics is scheduled to go live in May.

Point source catalogues from ongoing surveys are in the works

Improving the understanding of the mapmaking algorithms will lead to better calibration of large scale emission structures