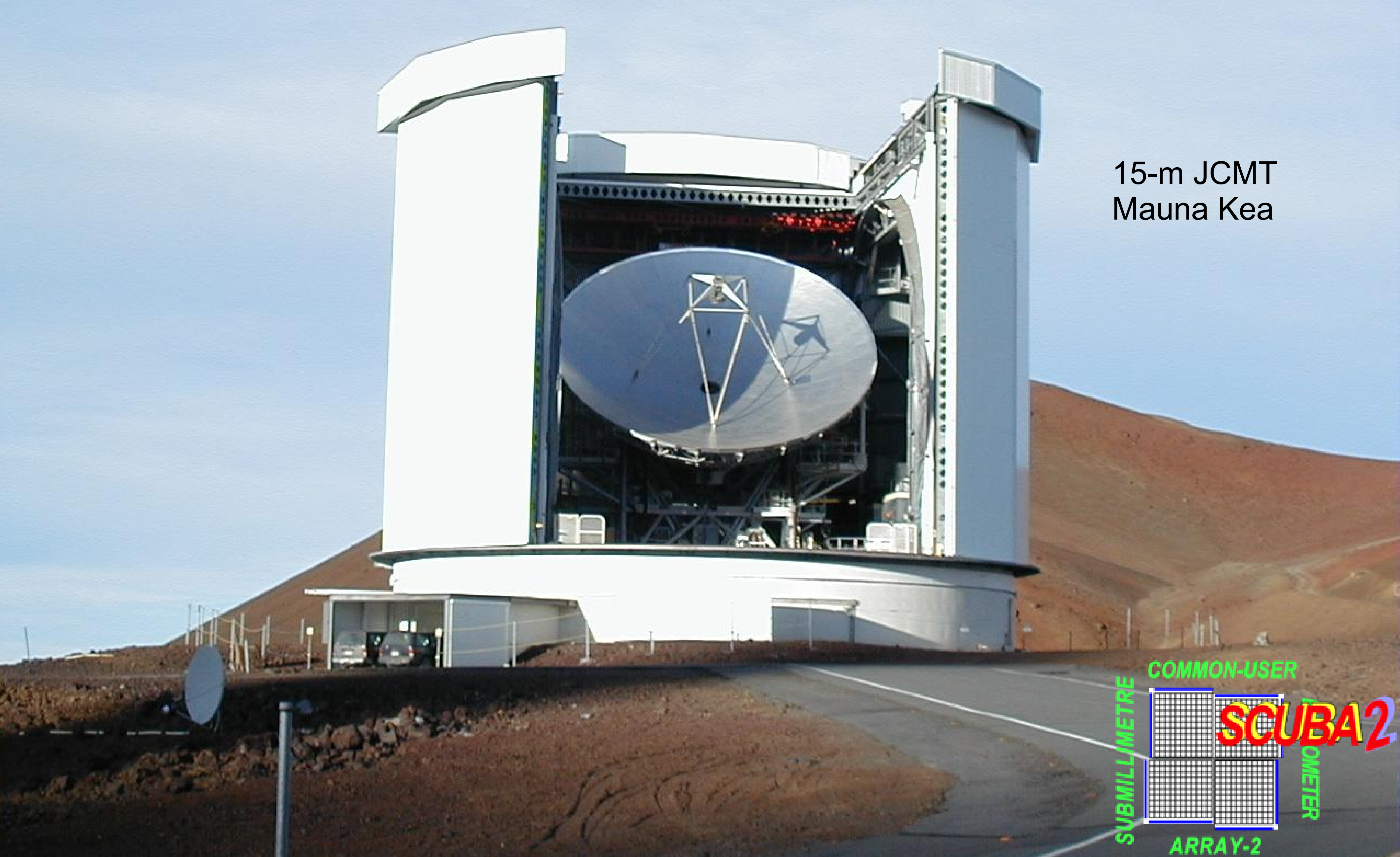
First generation map-making for SCUBA-2

Ed Chapin (XMM SOC, ESAC, Madrid)

Herschel PACS and SPIRE map-making workshop, January 31, 2013 ESAC



Overview

- intro to SCUBA-2 and data properties
- iterative map-making with SMURF
- use of priors / maps of extended structure
- optimal filtering of faint point-source (cosmology) maps
- combining SCUBA-2 and SPIRE data

SCUBA-2: The largest submm camera in the world

Development started ~1999 to replace SCUBA

All JCMT partners (Canada, UK, Netherlands)

10,000 bolometers

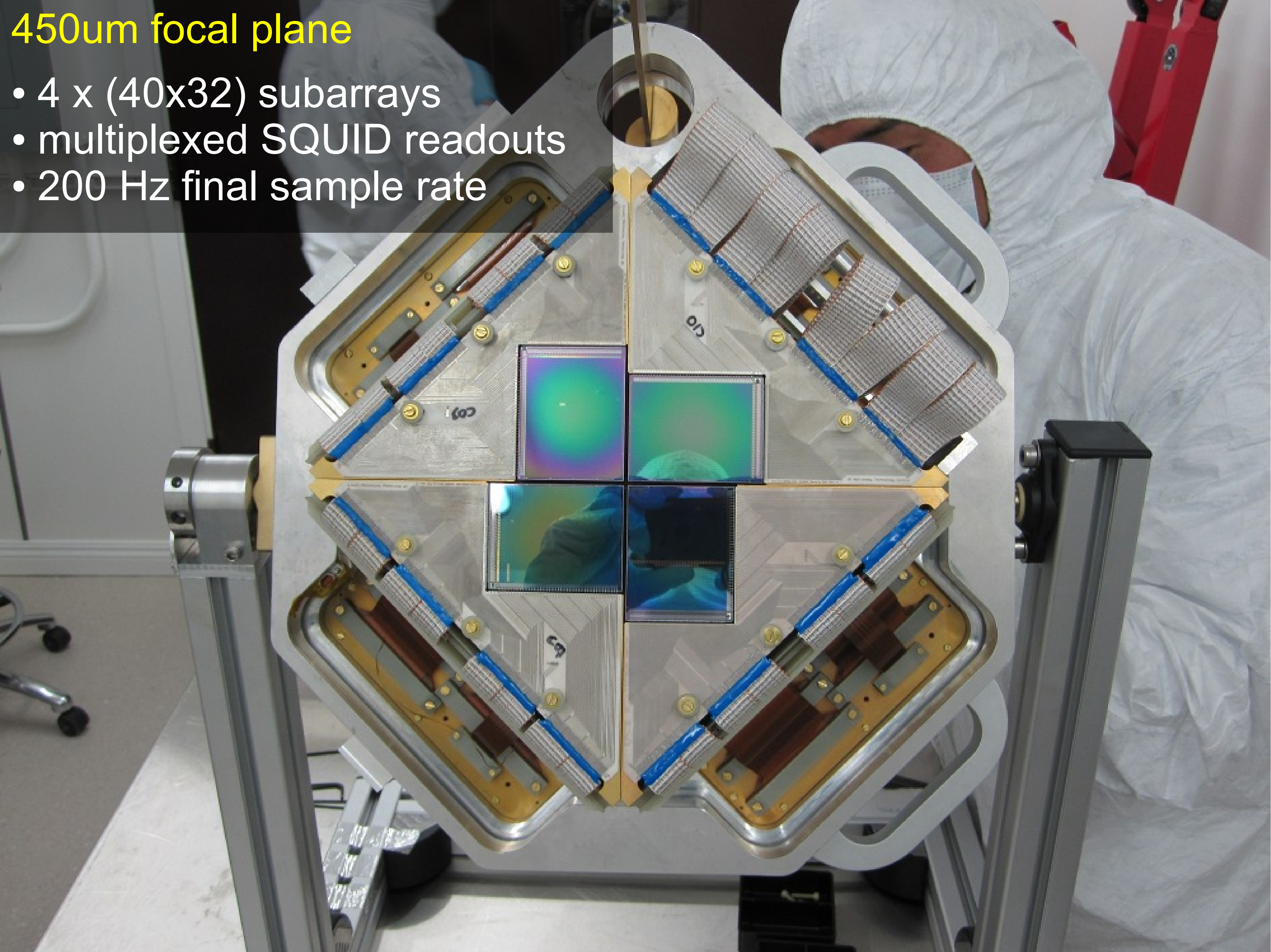
NIST TES arrays

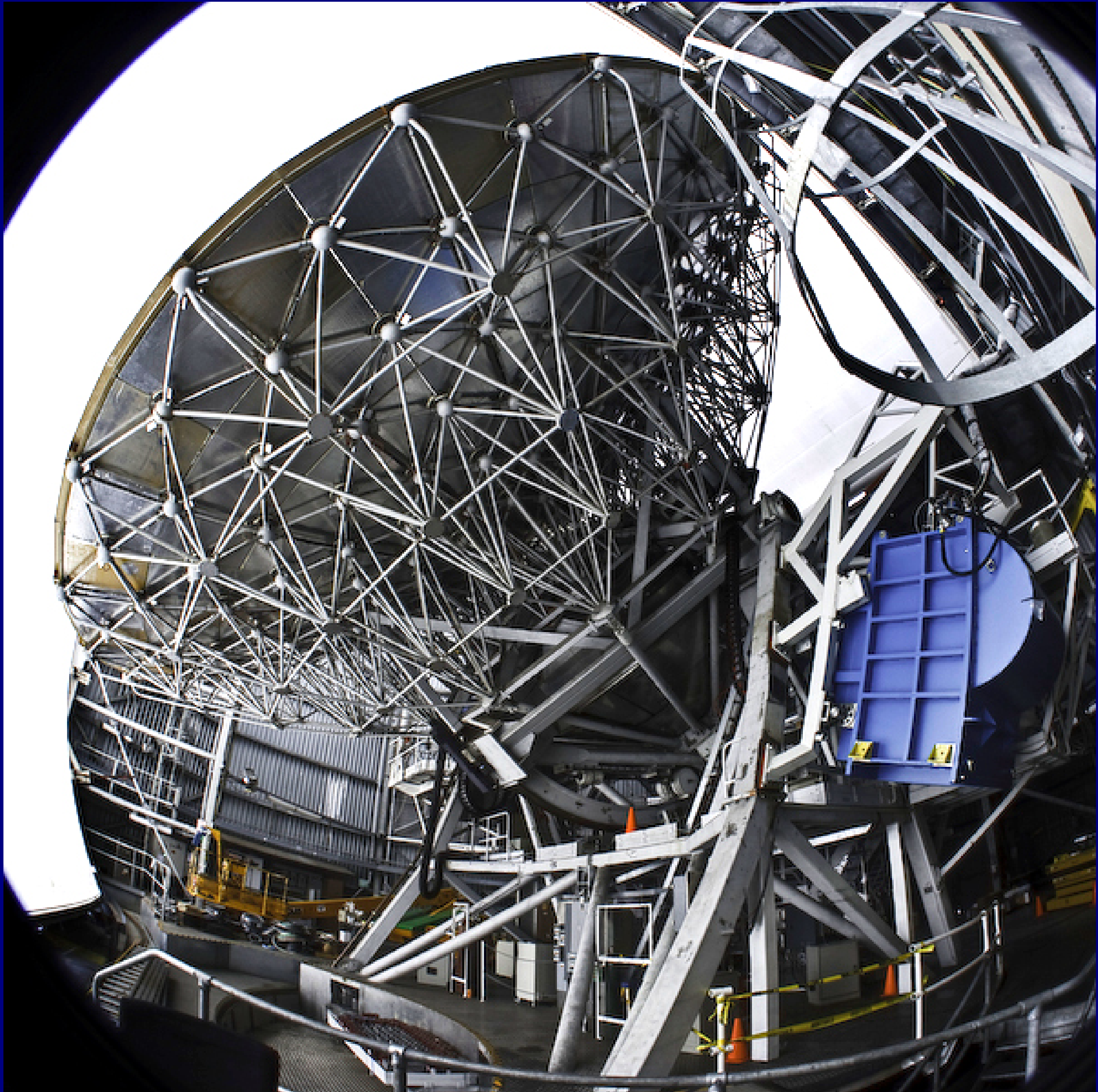
450 / 850 um imaging

FTS + Polarimeter (Canada)

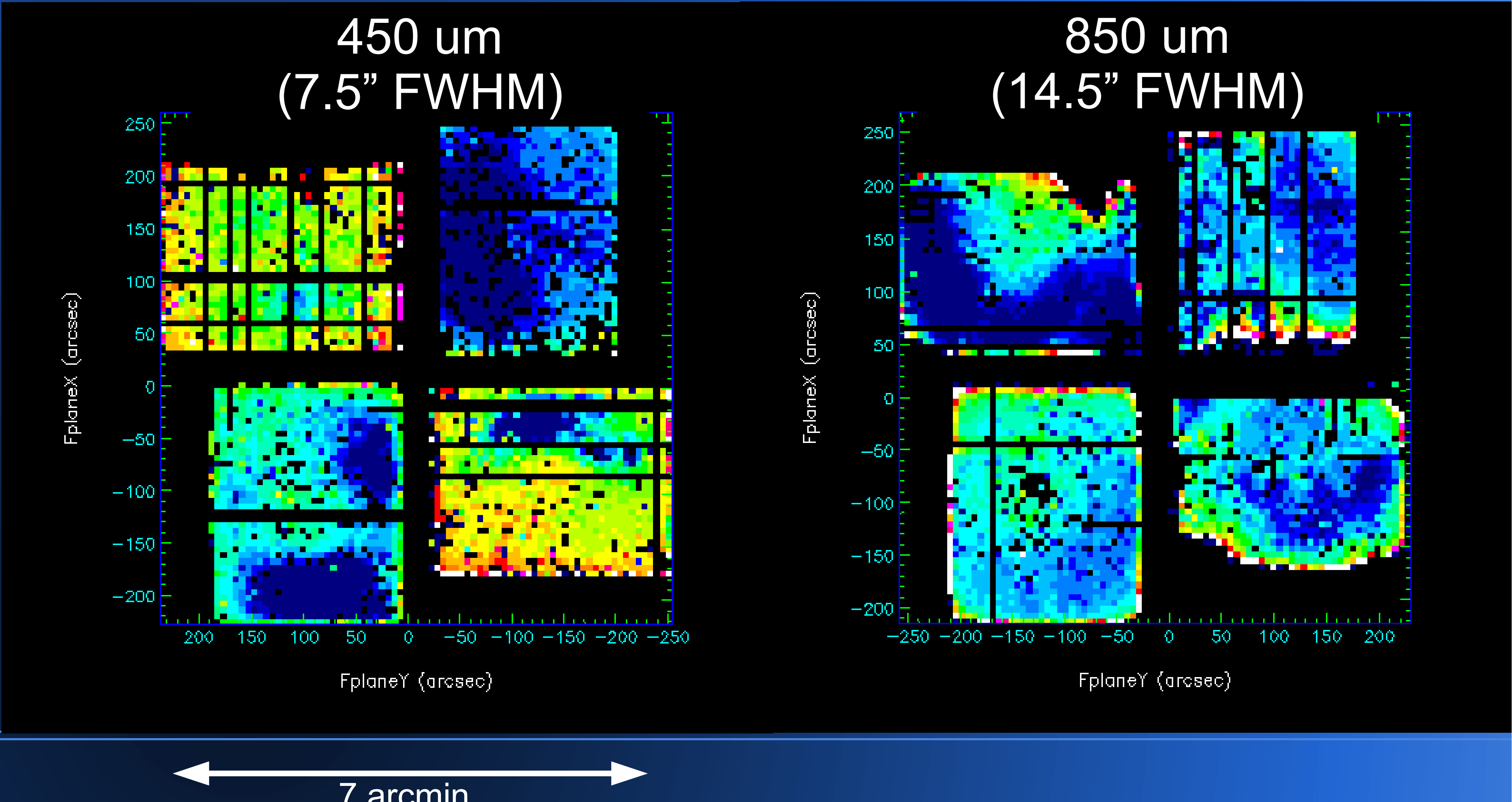
450um focal plane

- 4 x (40x32) subarrays
- multiplexed SQUID readouts
- 200 Hz final sample rate





Filled focal-plane (7000 bolos, ~70% yield)



Mapping Speeds

Table 3. Detection limits in mJy for the SCUBA-2 observing modes. These have been calculated based on τ_{225} values of 0.04 and 0.065 at 450 and 850 µm, respectively, and assuming a source with average airmass of 1.2. The number associated with the PONG refers to the demand diameter of the map in arcsec.

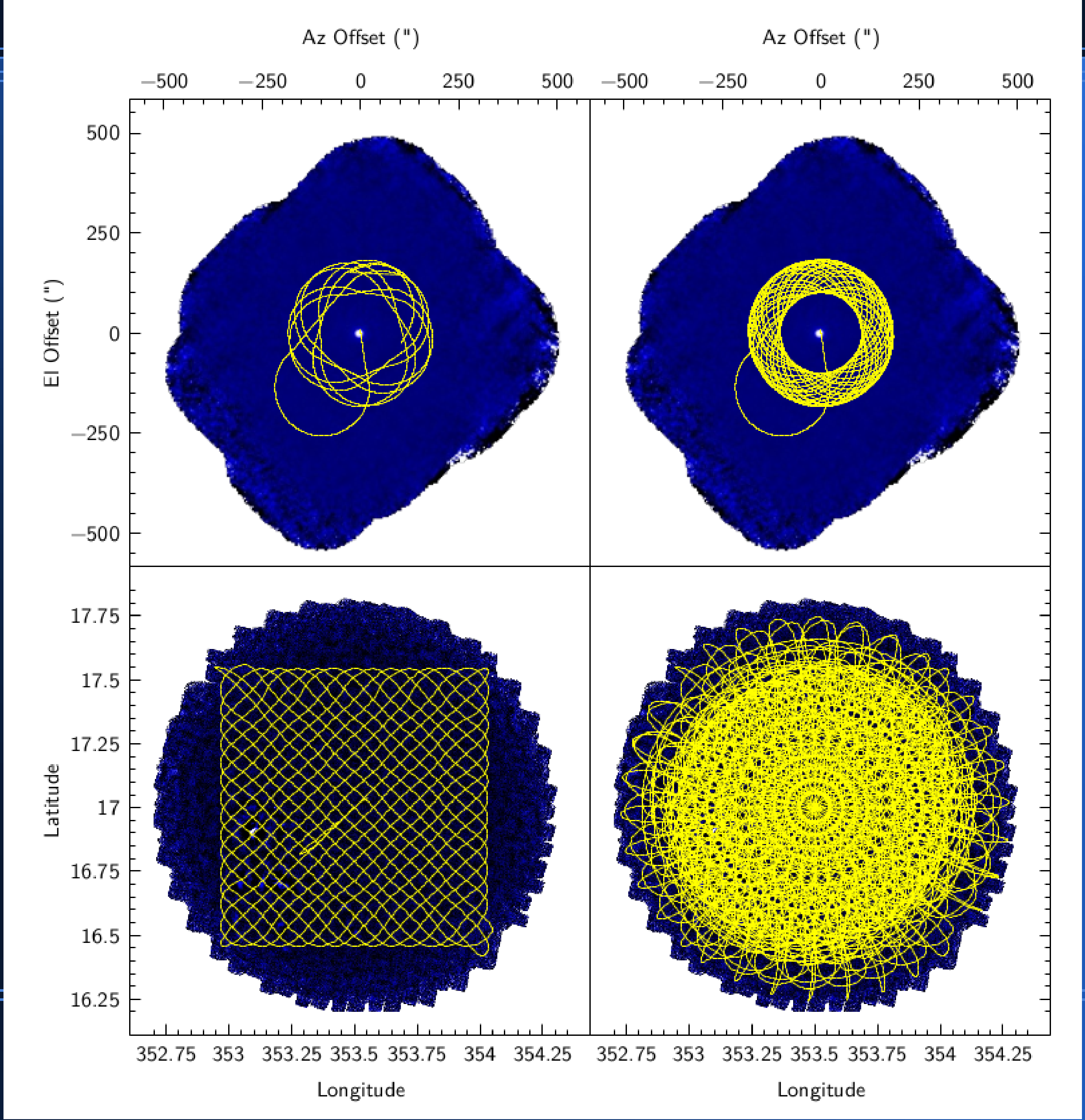
Observing mode		450 µm (mJy)	850 µm (mJy)
DAISY	(3σ,1 hr)	39	5.6
	(5σ,10 hr)	21	2.9
PONG900	(3σ,1 hr)	85	11.9
	(5σ,10 hr)	44	6.3
PONG1800	(3σ,1 hr)	166	23
	(5σ,10 hr)	87	12.2
PONG3600	(3σ,1 hr)	361	49
	(5σ,10 hr)	189	26
PONG7200	(3σ,1 hr)	732	98
	(5σ,10 hr)	384	51

1σ for mapping 1 square degree
for
1 Hour

135 mJy at 450 microns
18 mJy at 850 microns

Holland et al. 2013

Scan modes



CV Daisy

PONG

Holland et al. 2013

Approved JCMT legacy surveys

http://www.jach.hawaii.edu/JCMT/surveys/SurveyAllocations.html

The total awards are shown in the following table.

(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

The number of hours awarded within each weather band are shown in the following table.

	Hours awarded in CSO weather bands			
Survey	Band 1	Band 2	Band 3	Band 4
SASSy				480
S2CLS	629	695	454	
NGLS		100		
JPS			450	
GBS	70	342		
SONS		135	135	
TOTALS	699 (20.0%)	1272 (36.4%)	1039 (29.7%)	480 (13.8%)

59% surveys
31% PI
10% UH

Until
Sept 2014

Instrument team papers to appear in MNRAS

SCUBA-2: The 10000 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], H. S. Thomas[3]

arXiv:1301.3650

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]†, Wayne S. Holland[4,5]

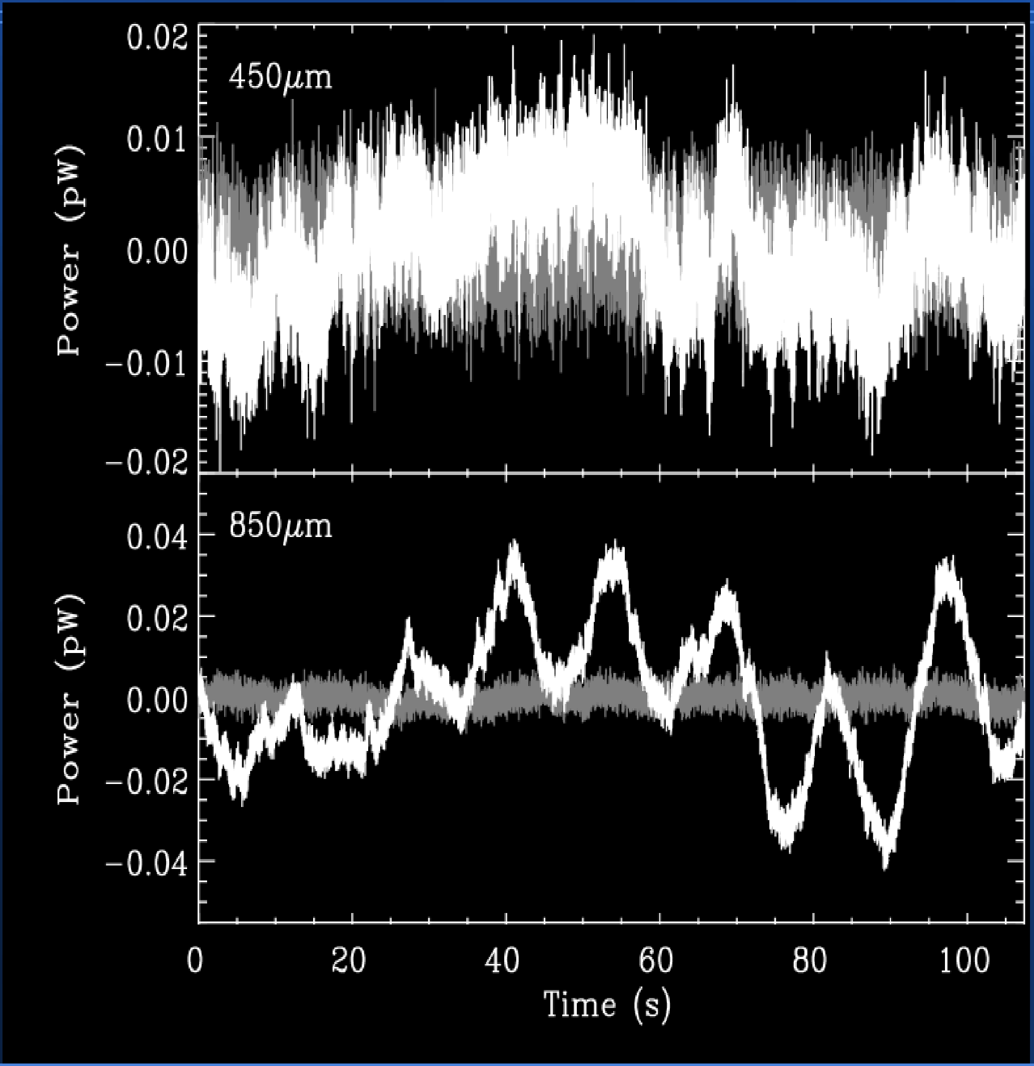
arXiv:1301.3652

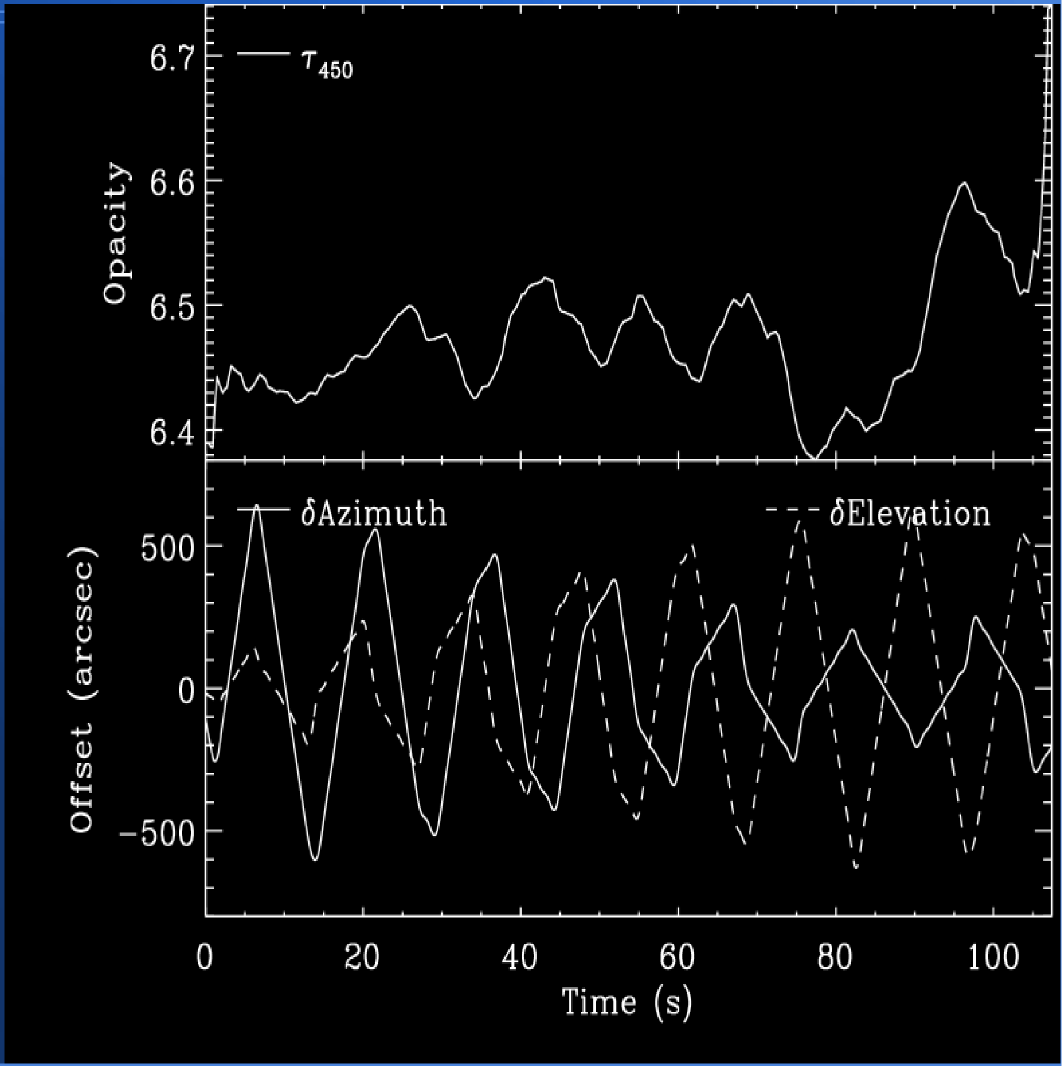
SCUBA-2: on-sky calibration using submillimetre standard sources

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], E. I. Robson[2]

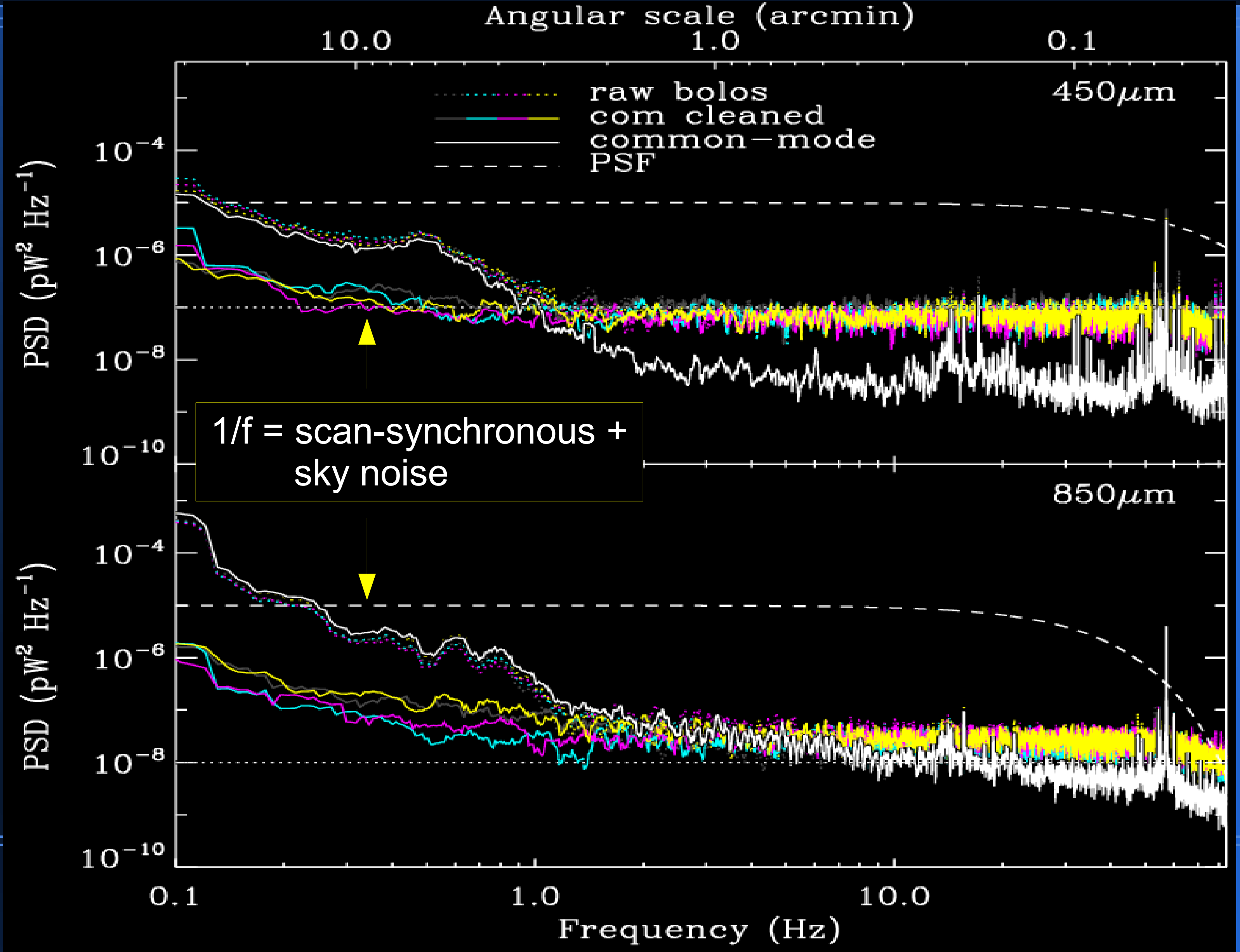
arXiv:1301.3773

Typical bolometer time streams





Typical bolometer power spectra



Software Design Goals

"Gosh,

*200 Hz * 5000 bolos (per wavelength) = a lot of data..."*

- real-time processing on summit computers (not a cluster!)

  (~4—12 cores, ~32—96 GB RAM)
- Hands-off so that it can run in a pipeline
- Possibly not *optimal* map-maker, but good enough to do science

SubMillimetre User Reduction Facility

- Iterative map-maker: less memory/computationally intensive
- Methodology borrows from many previous instruments:
  COBE, MAXIMA, SCUBA, BOLOCAM, SHARC-II, AzTEC...
- Very flexible, many different knobs (common-mode removal, whitening filters FFT filters, map prior constraints, PCA cleaning, map-based de-spiking...)
- Written in C: multi-threaded, uses Starlink libraries
- **Can reduce data faster than observing time on single desktop computer**
- ORACDR pipeline:
  - Run in real-time at telescope / Reduced data products at CADC
  - Cloud computing: Canadian Advanced Network For Astronomical Research

Basic Algorithm: pre-processing

- Apply flatfield (response to heater ramps: convert amps -> Watts)
- Fix steps (SCUBA-2 data are riddled with them ...)
- Remove mean, or higher-order polynomial baselines
- Measure power spectra, flag noisiest outlier detectors

Basic Algorithm: map-making

$$b(t) = f^*[e(t)a(t) + n(t)]$$

$b(t) \equiv$ bolometer signal

$f \equiv$ responsivity / DAC constant

$e(t) \equiv$ time-varying atmospheric extinction

$a(t) \equiv$ astronomical signal

$n(t) \equiv$ noise

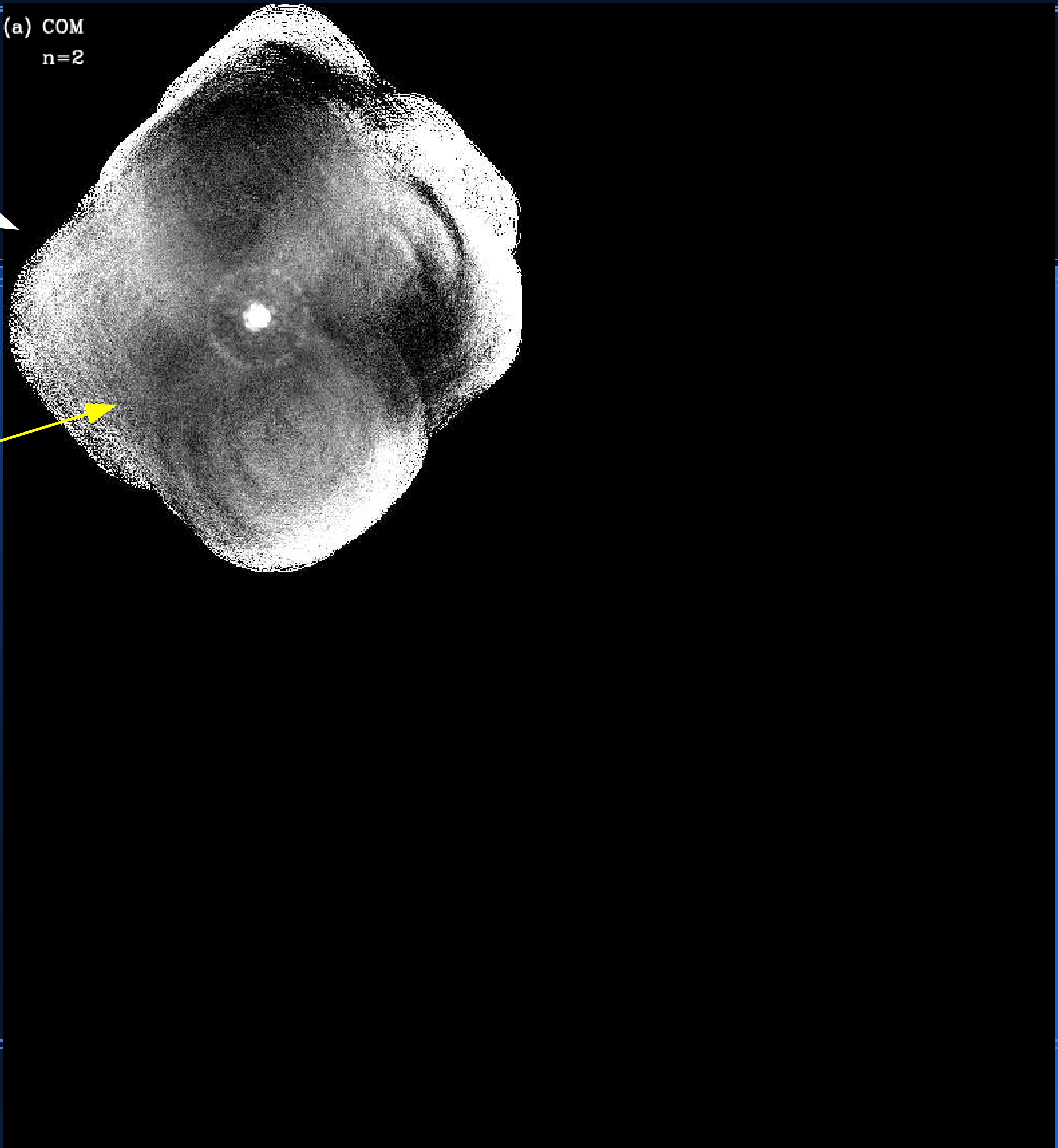
Basic Algorithm: map-making

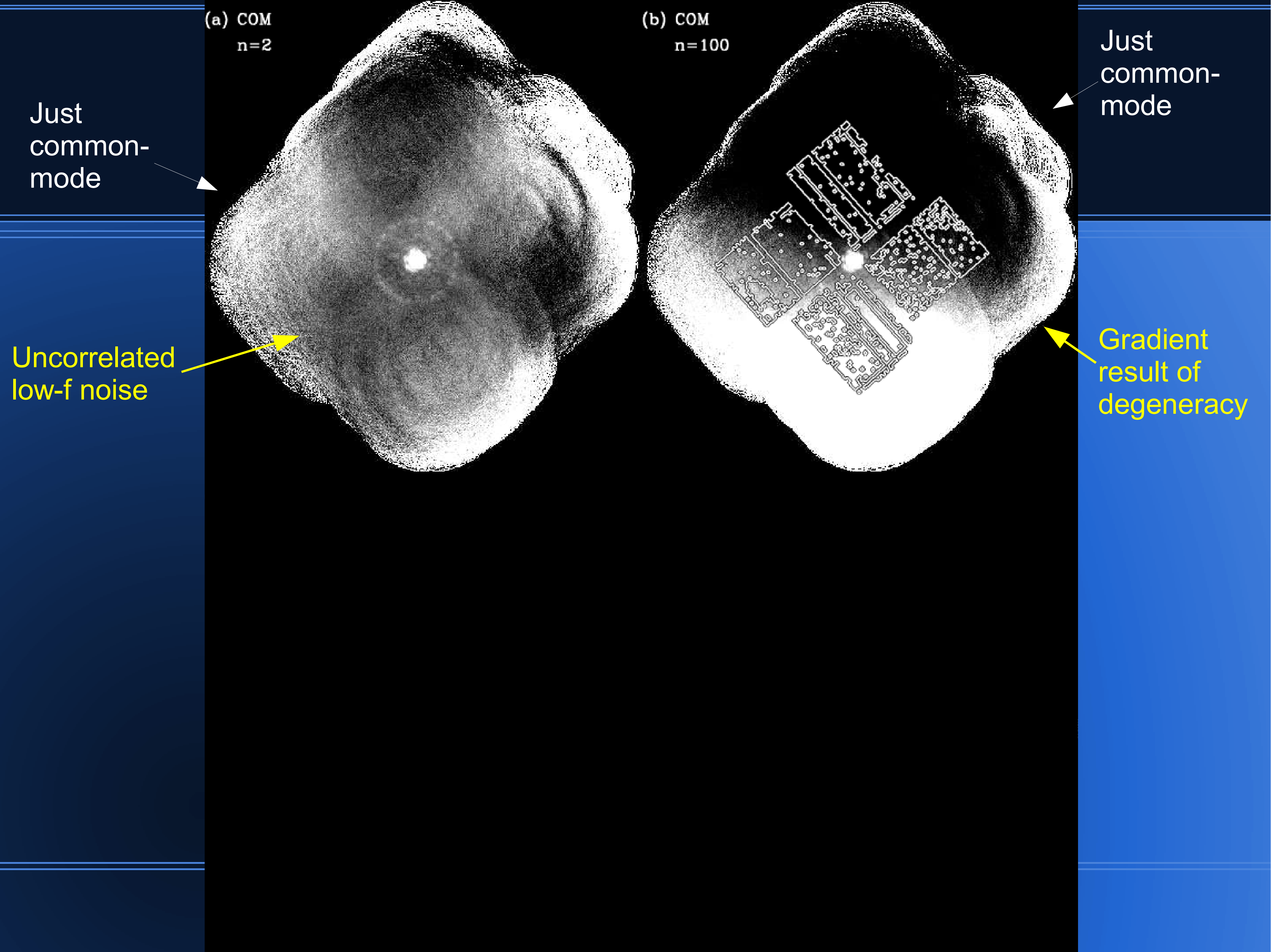
$$b(t) = f^*[e(t)a(t) + n(t)]$$

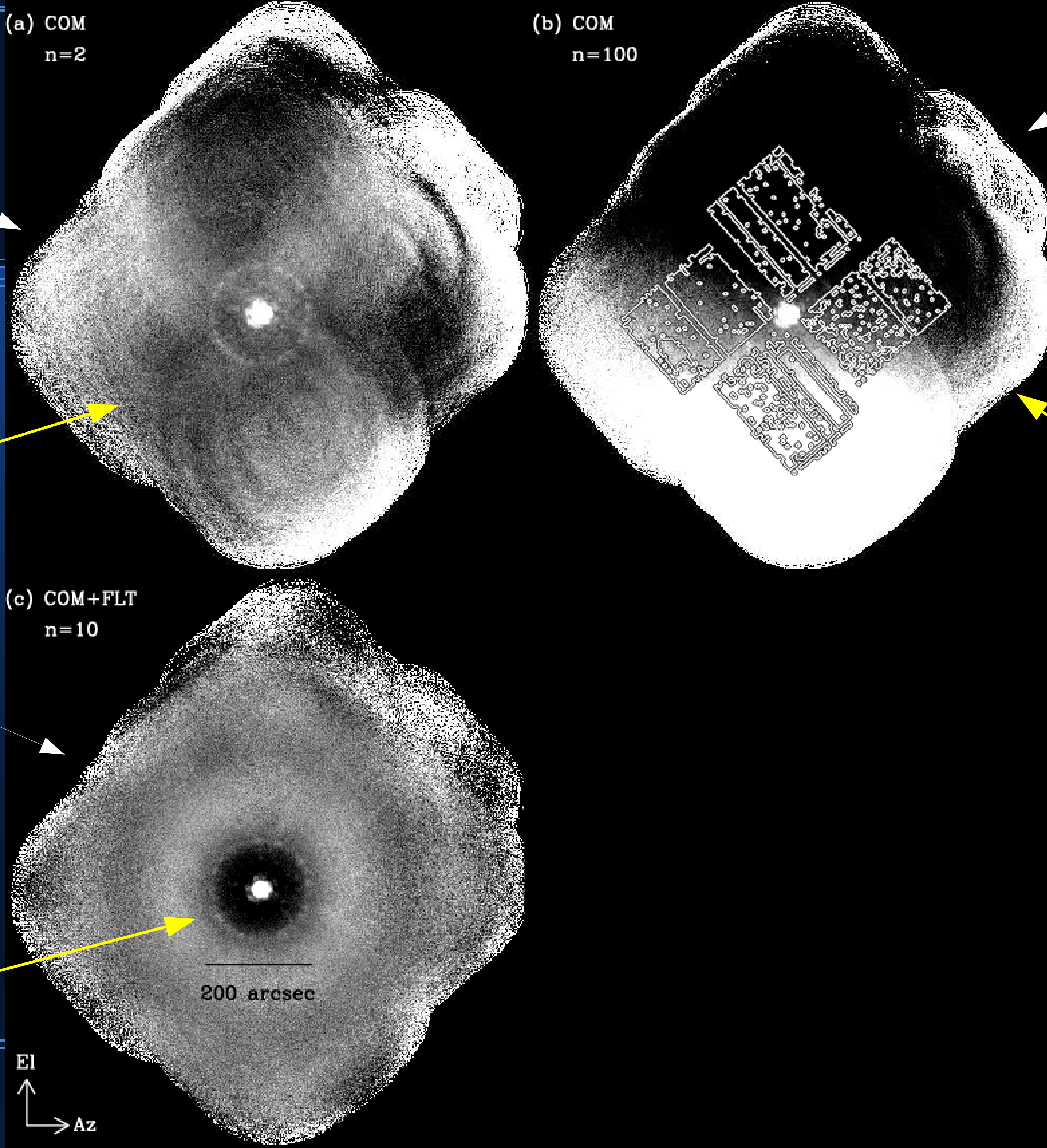
$b(t) \equiv$ bolometer signal
$f \equiv$ responsivity / DAC constant
$e(t) \equiv$ time-varying atmospheric extinction
$a(t) \equiv$ astronomical signal
$n(t) \equiv$ noise

- Divide $b(t)$ by f *(fixed quantity)*
- Remove most of $n(t)$ with common-mode subtraction
- Divide by $e(t)$ (noisy measurement from WVM)
- Remove remainder of low-f noise in $n(t)$ with high-pass filter
- Regrid ($a(t)$ + ~white noise) to estimate map (noise map from scatter)
- Remove back-projected signal from time streams (measure noise weights from 2—10 Hz power spectra of residuals)

Astronomical sources cause ringing - So iterate!


(a) COM
n=2
Just common-mode
Uncorrelated low-f noise


(a) COM
n=2
(b) COM
n=100
Just common-mode
Just common-mode
Uncorrelated low-f noise
Gradient result of degeneracy



Just common-mode

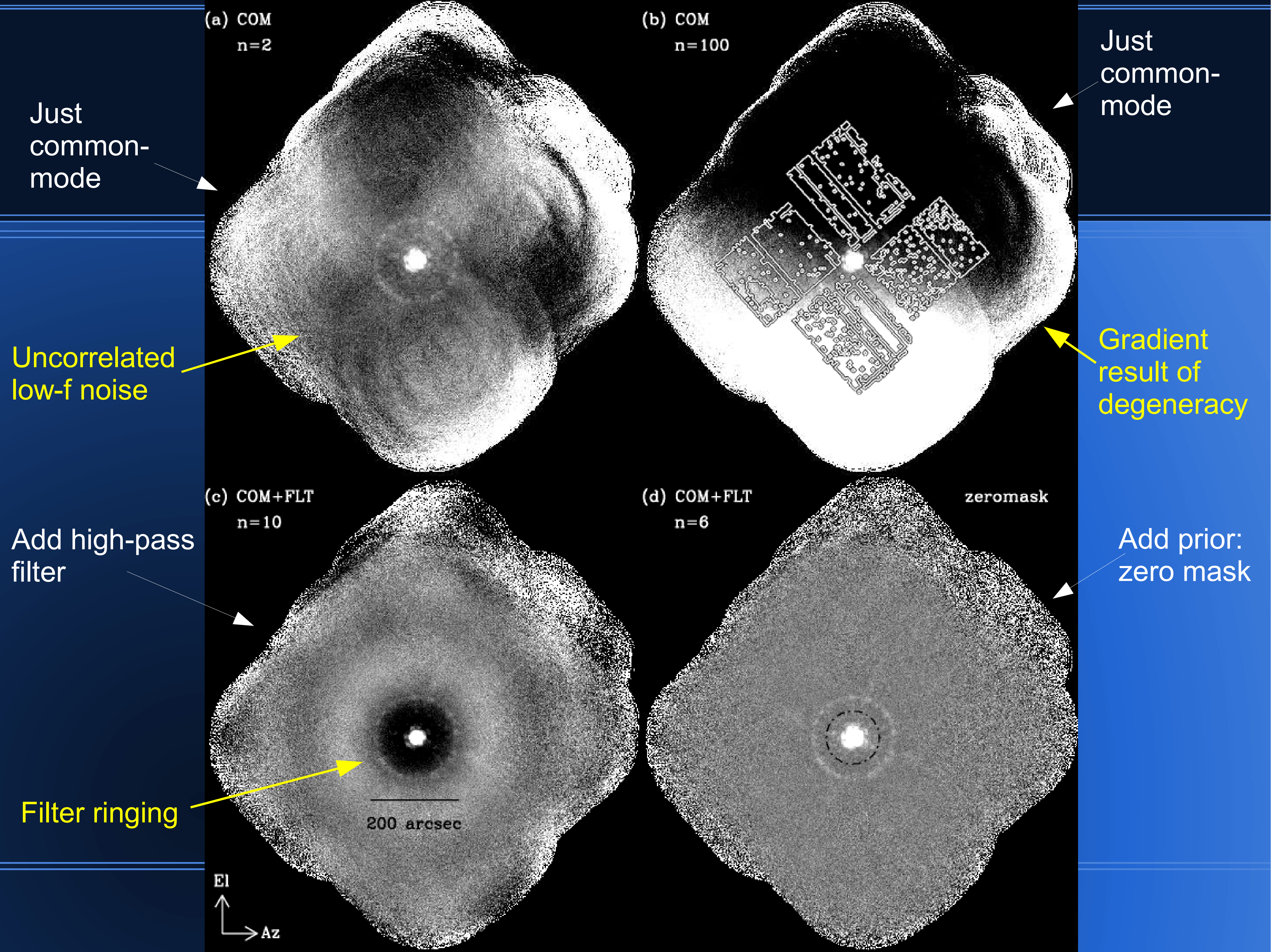
Uncorrelated low-f noise

Just common-mode

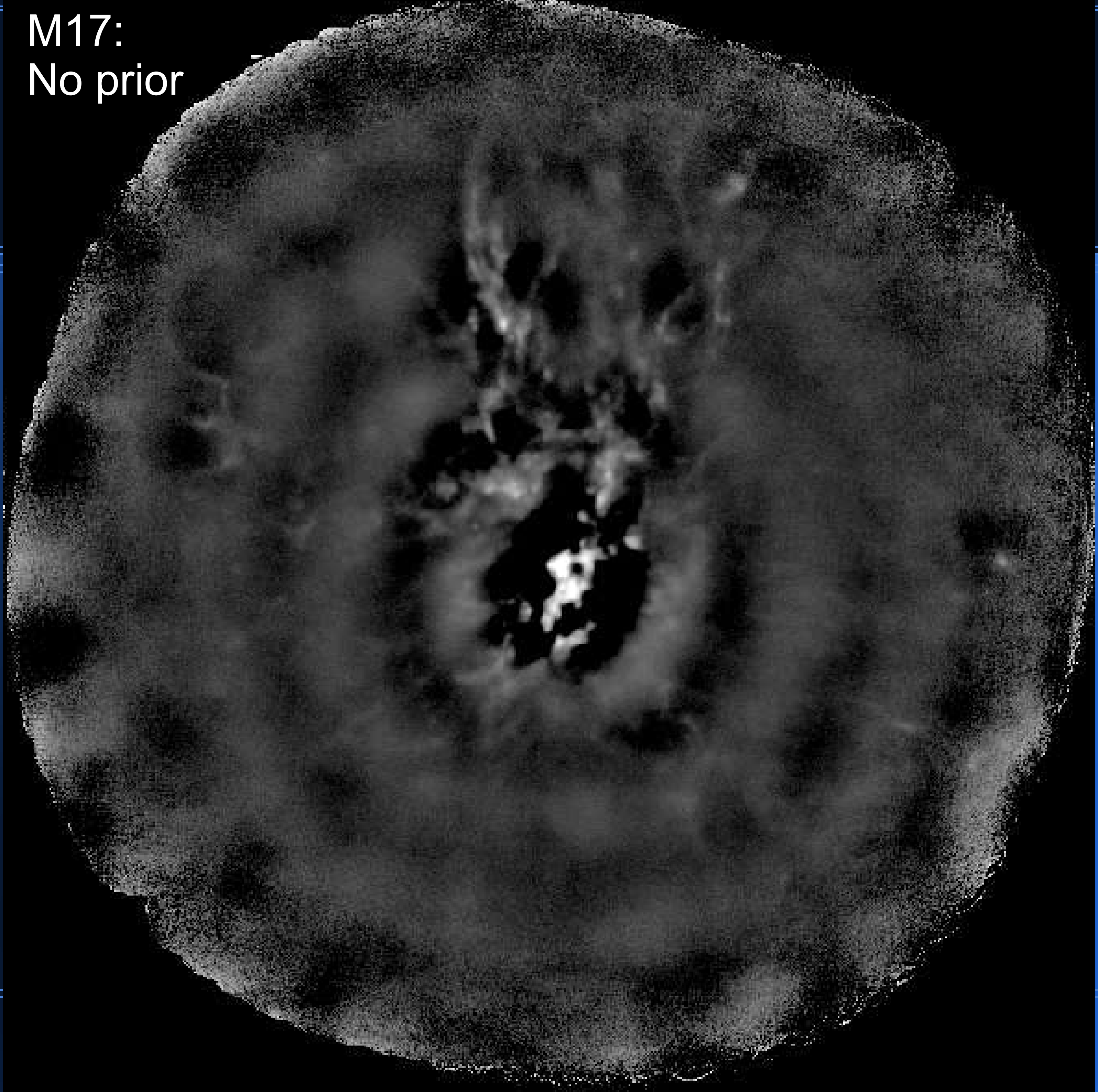
Gradient result of degeneracy

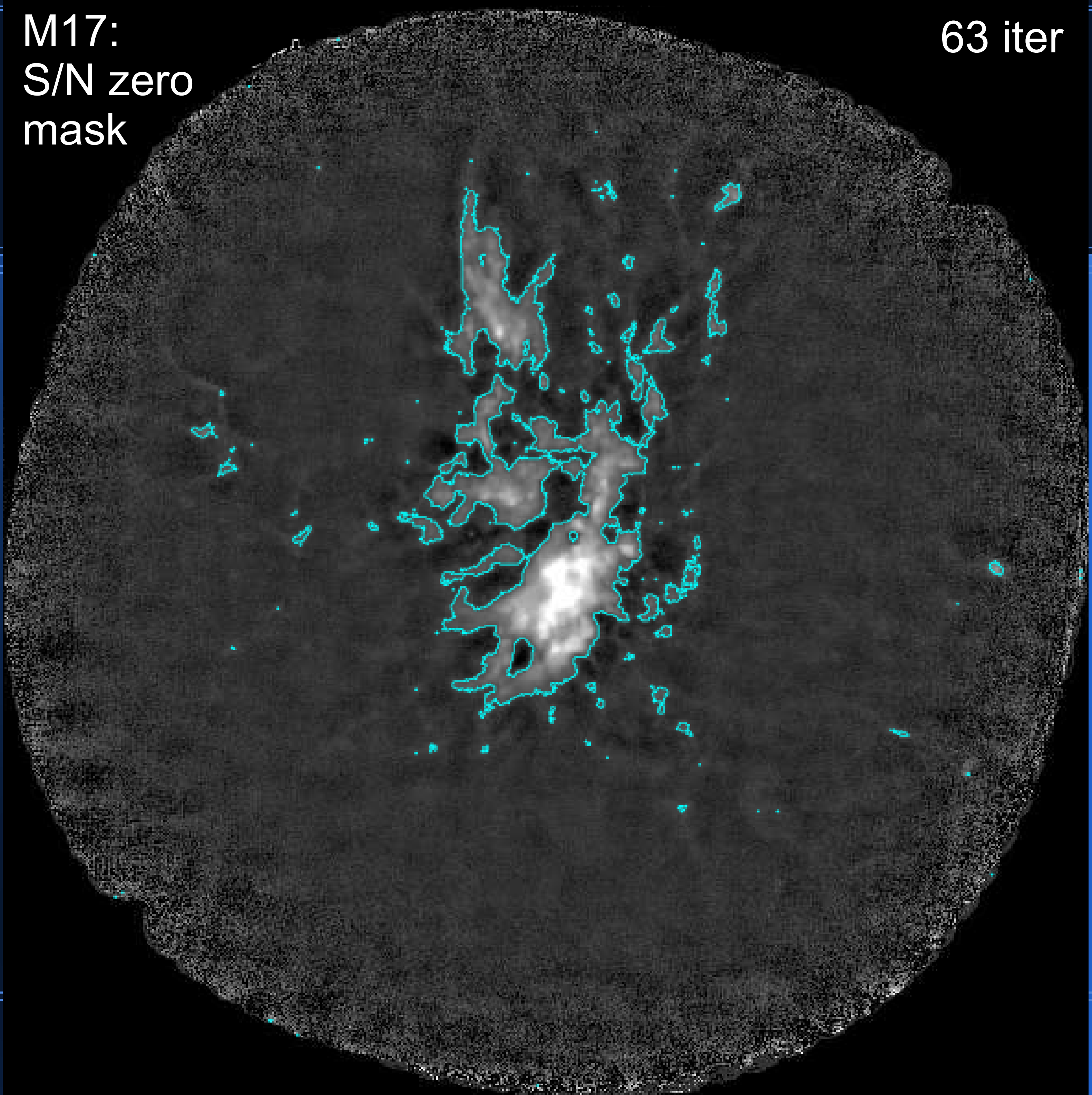
Add high-pass filter

Filter ringing

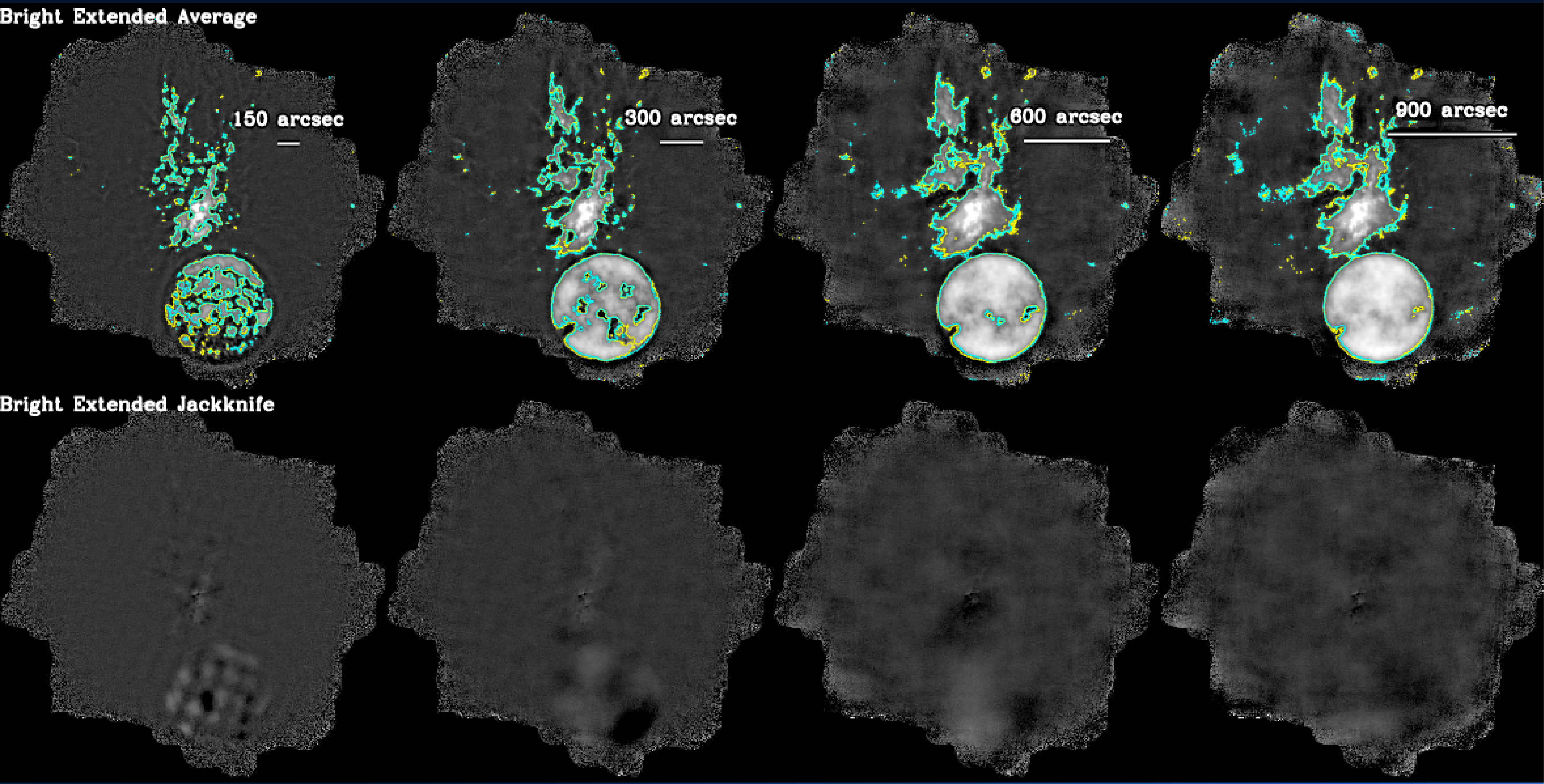


(a) COM
n=2
(b) COM
n=100
(c) COM+FLT
n=10
200 arcsec
(d) COM+FLT
n=6
zeromask
El
Az
Just common-mode
Uncorrelated low-f noise
Just common-mode
Gradient result of degeneracy
Add high-pass filter
Filter ringing
Add prior: zero mask

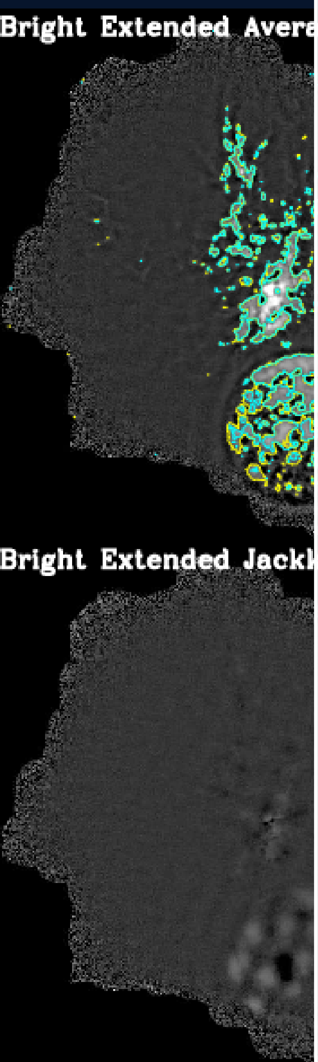

M17:
No prior


M17:
S/N zero
mask
63 iter

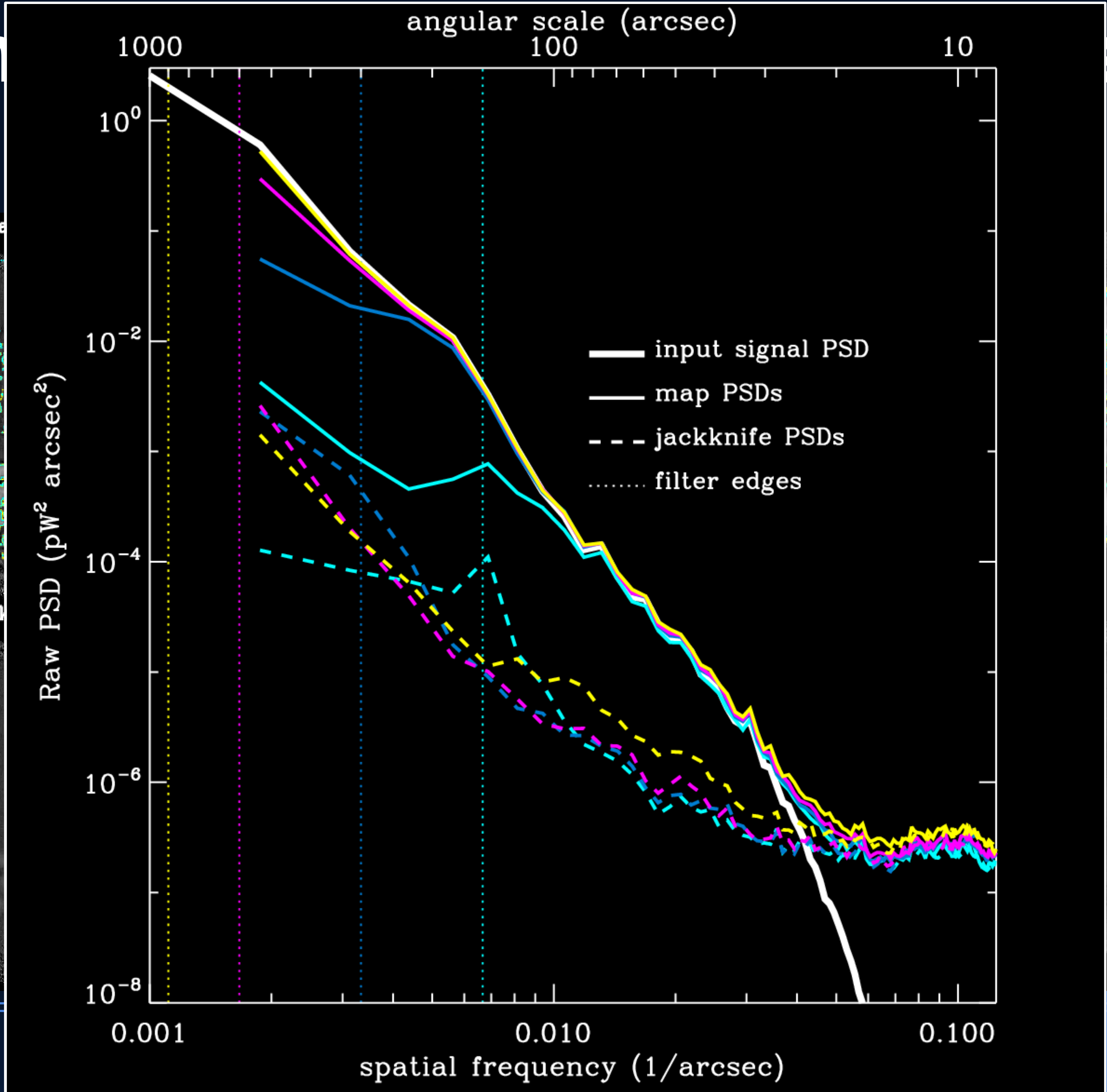
Characterize response/noise as f(filter scale)



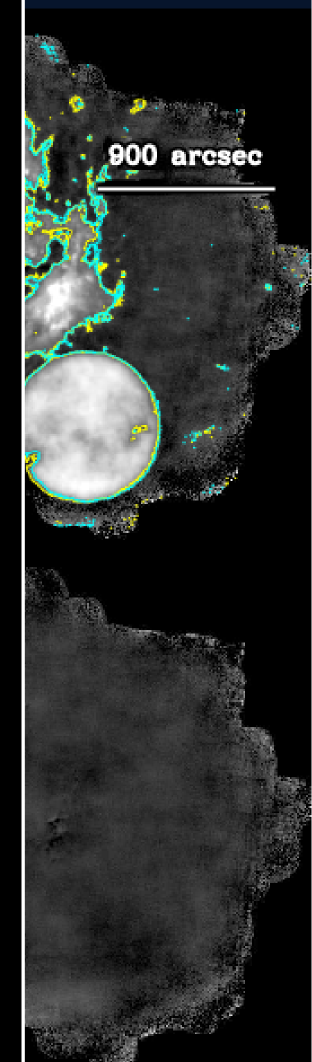
Ch as



Bright Extended Avera
Bright Extended Jackk

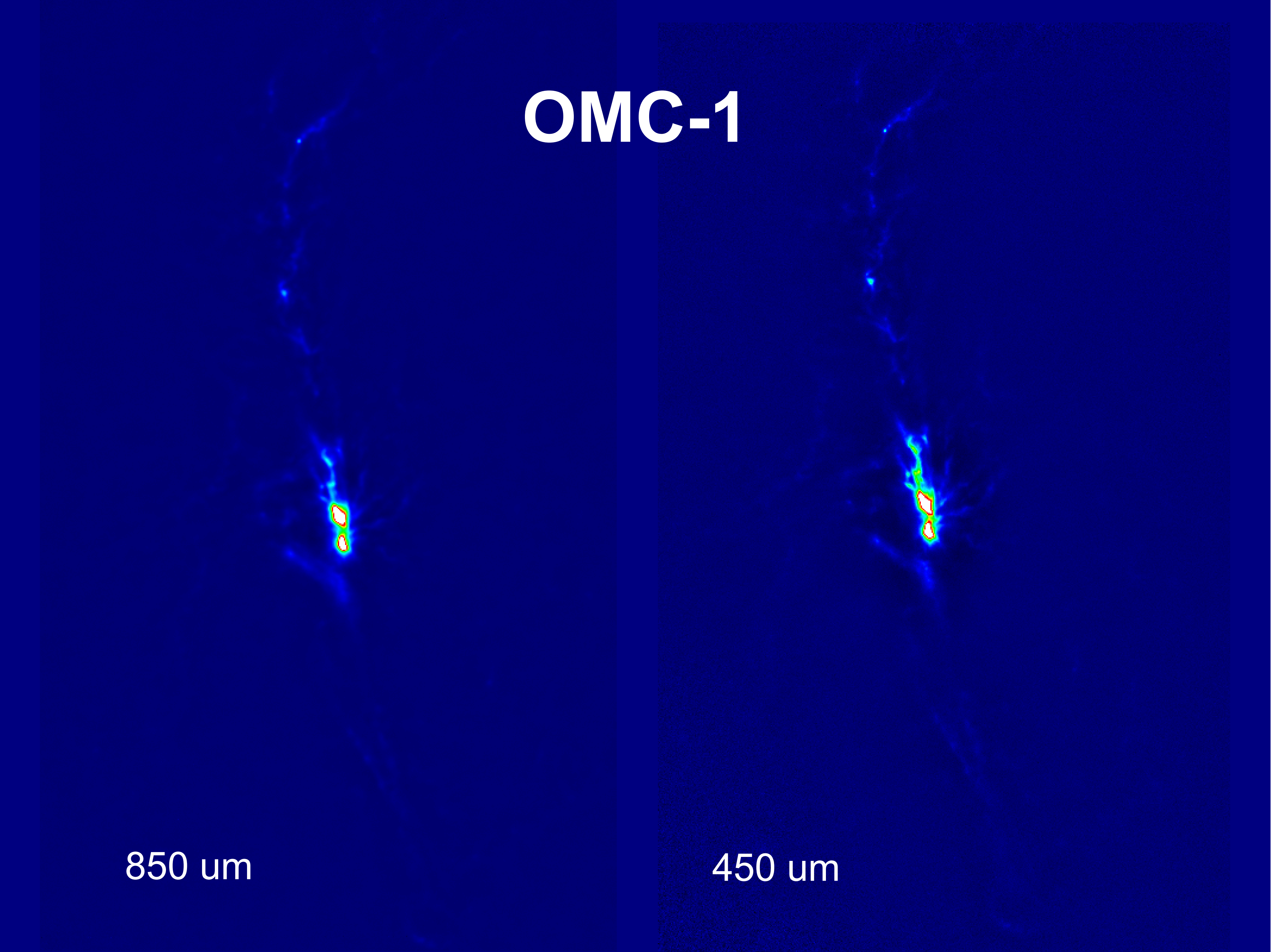


angular scale (arcsec)
1000
100
10
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Raw PSD (pW^2 arcsec^2)
input signal PSD
map PSDs
jackknife PSDs
filter edges
0.001
0.010
0.100
spatial frequency (1/arcsec)

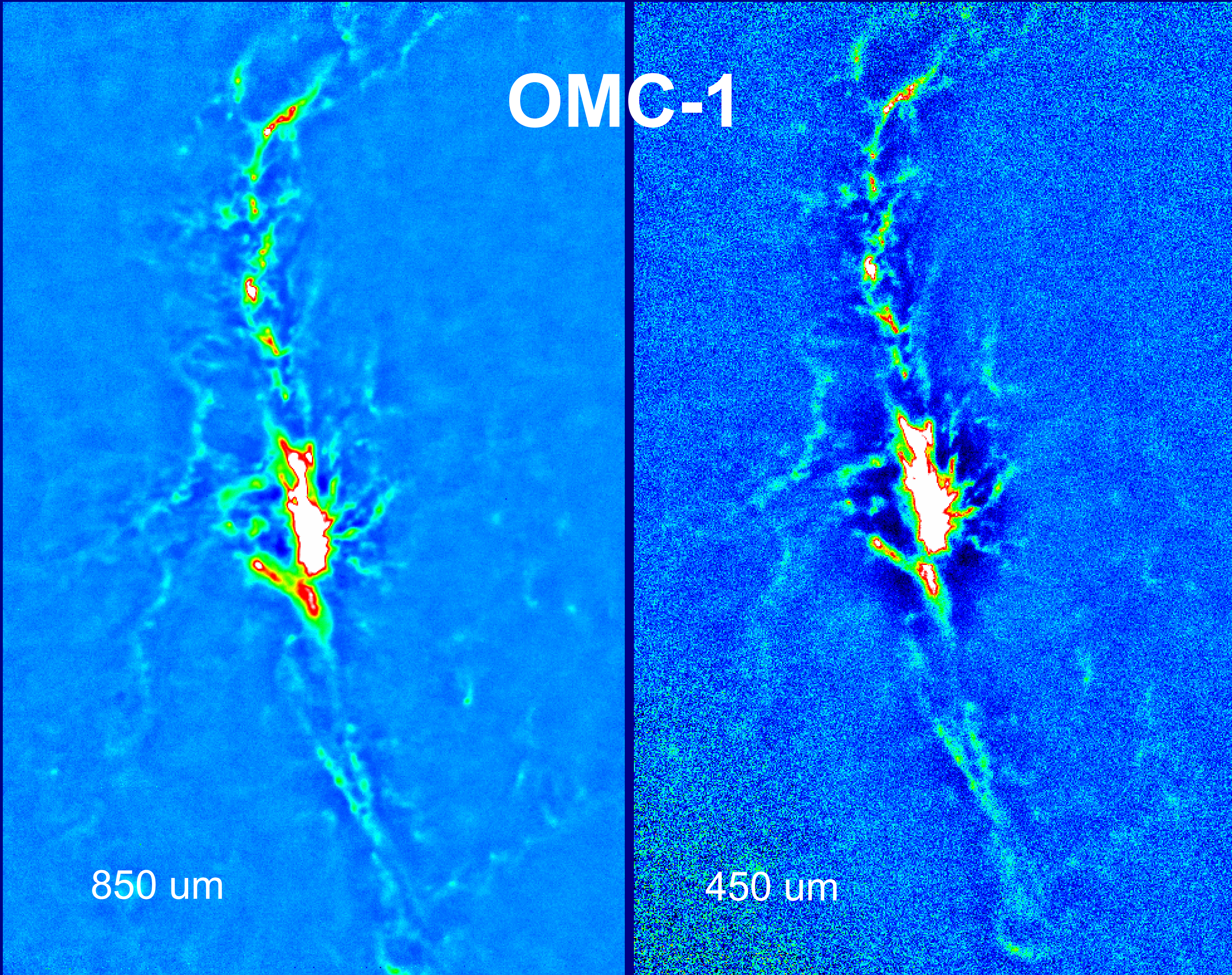


900 arcsec

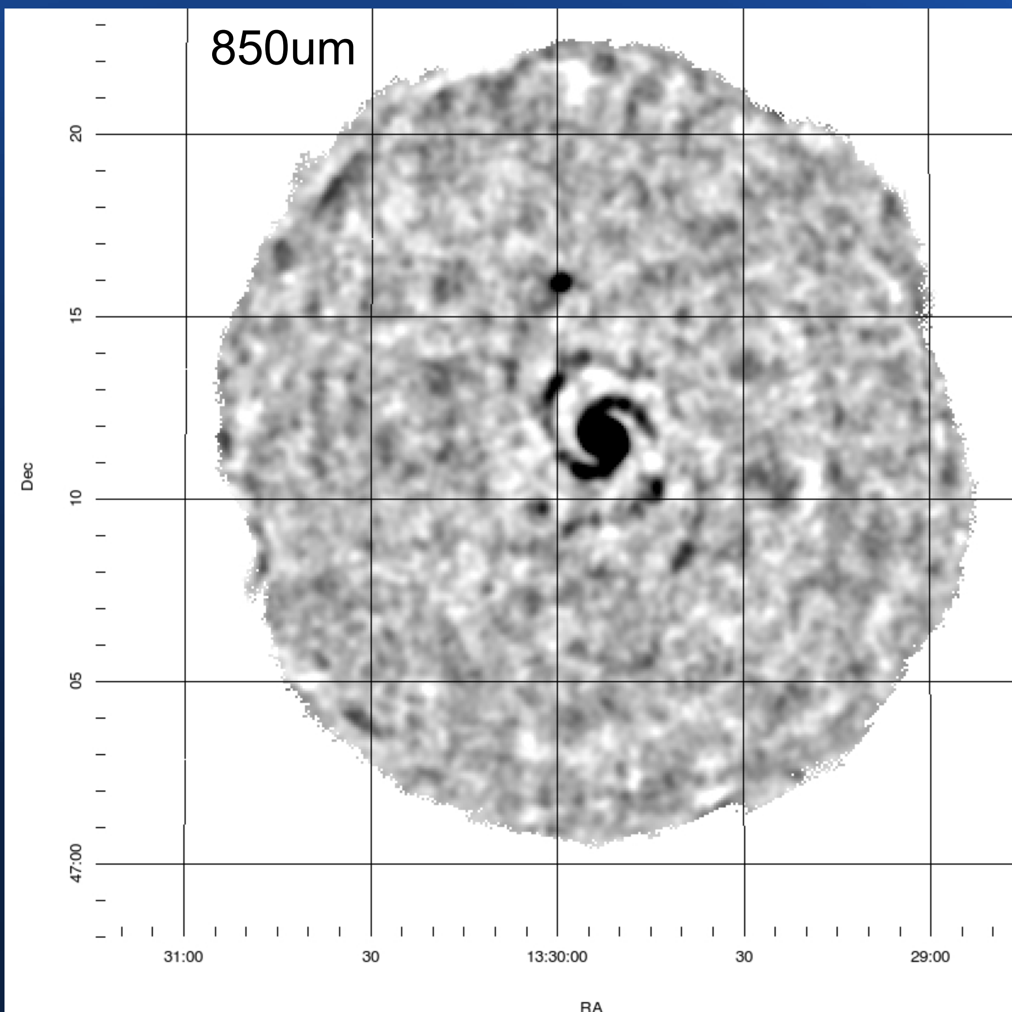
OMC-1

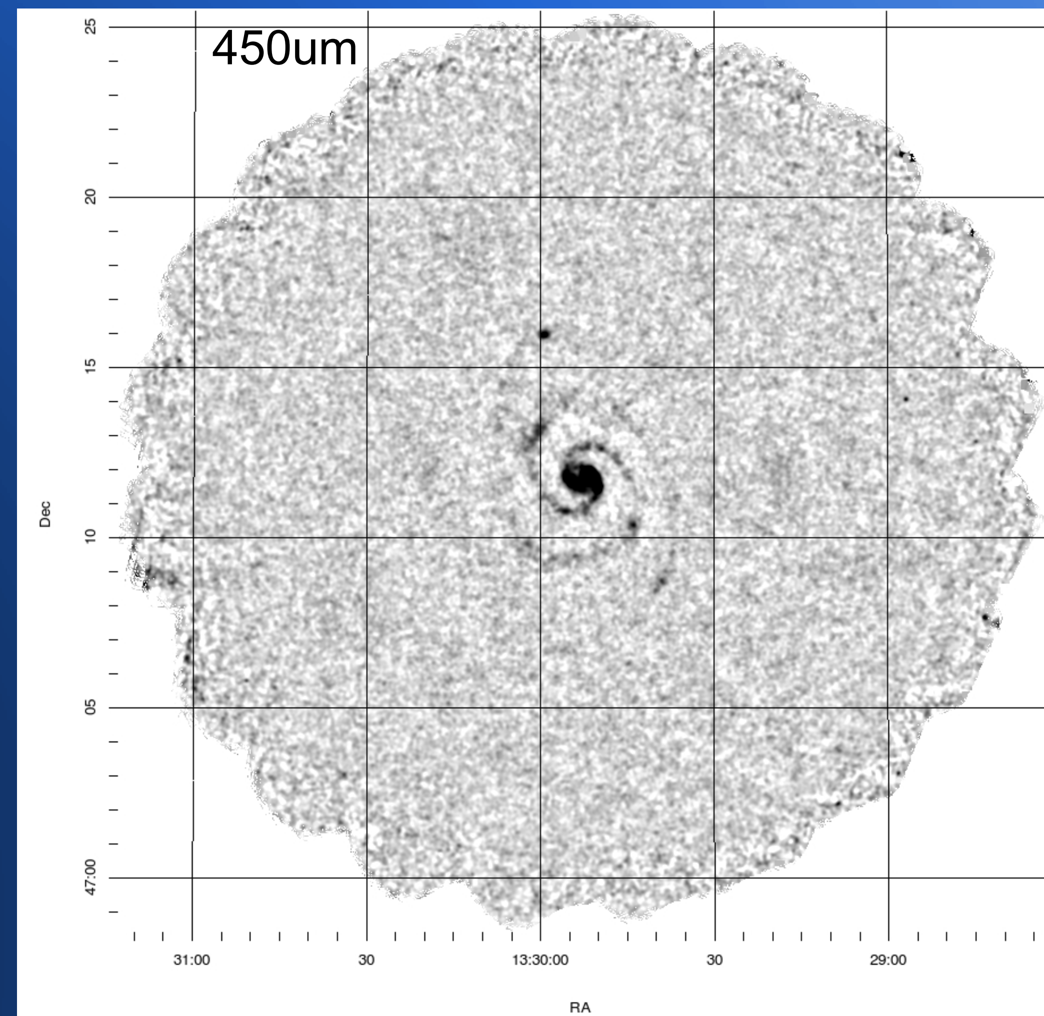


OMC-1



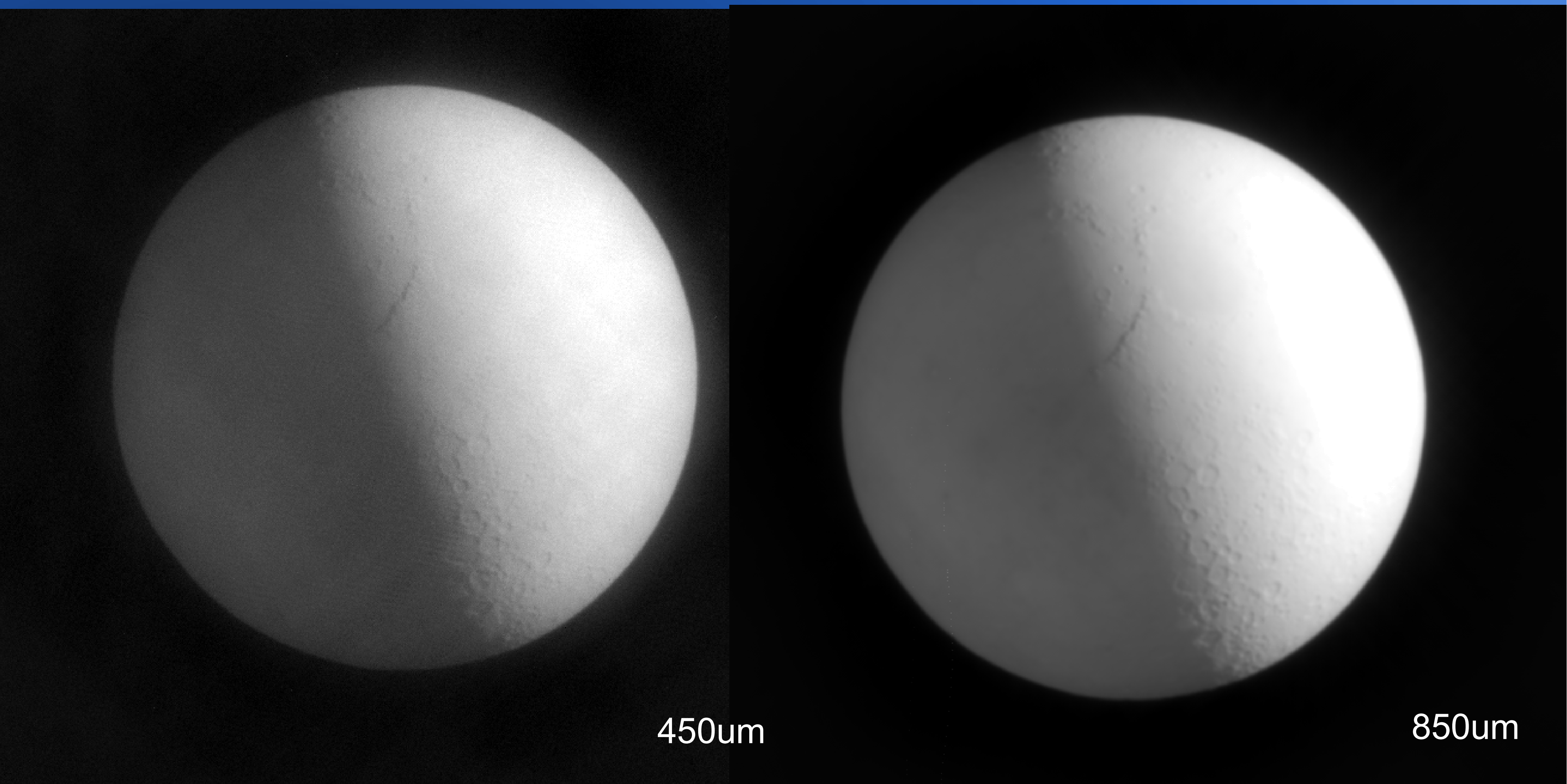
M51



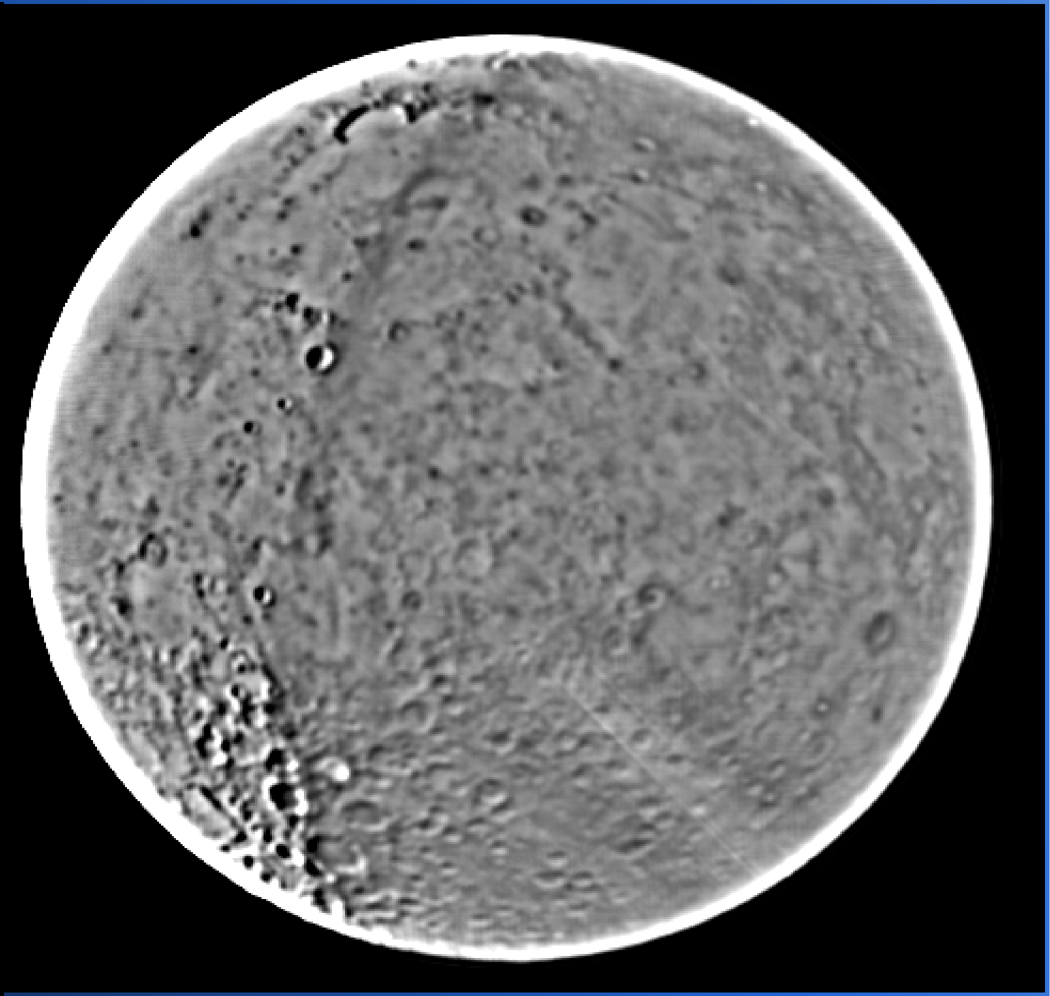


“A pilot study for SASSy” Mackenzie et al., 2011, MNRAS, 415, 1950

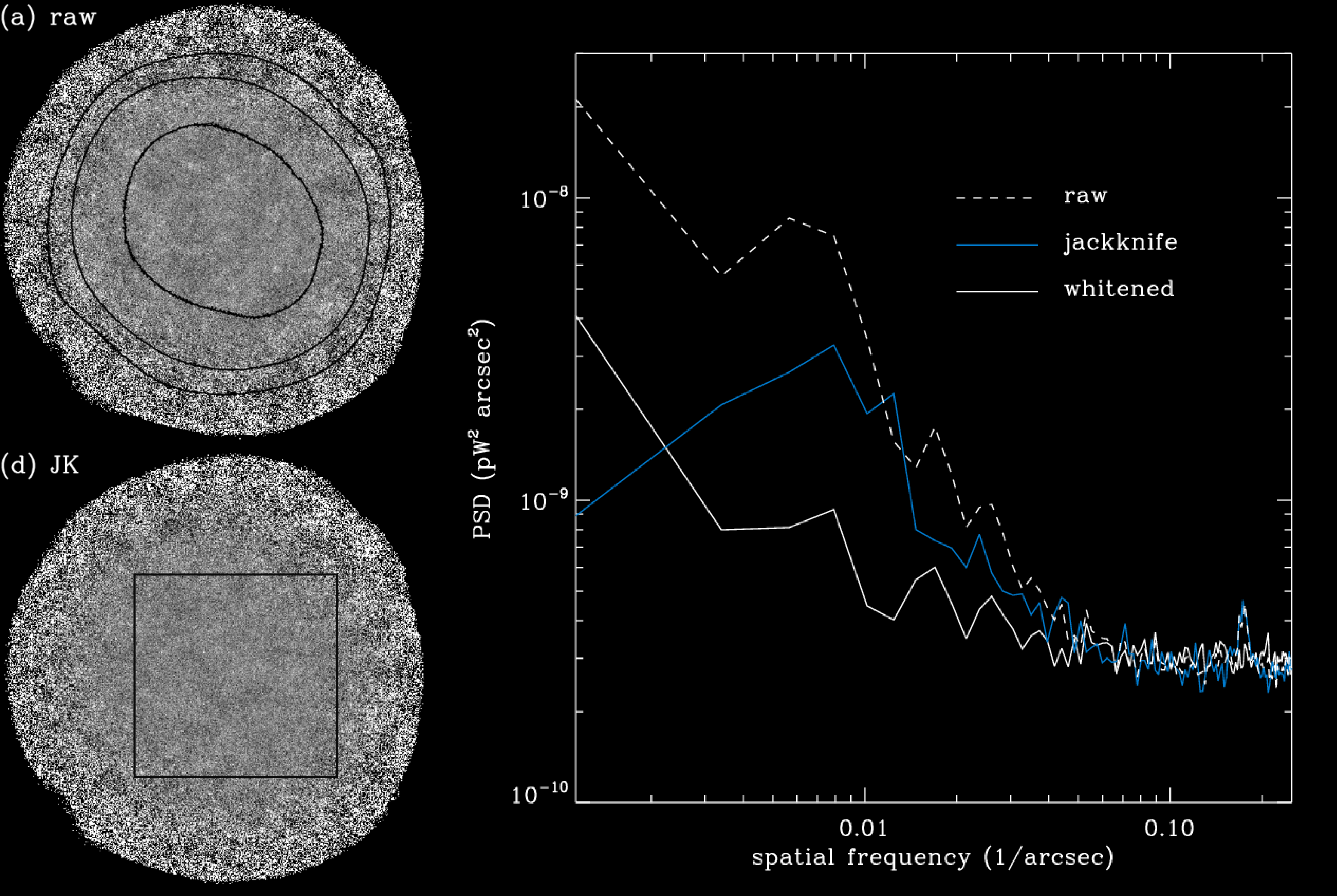
The moon...



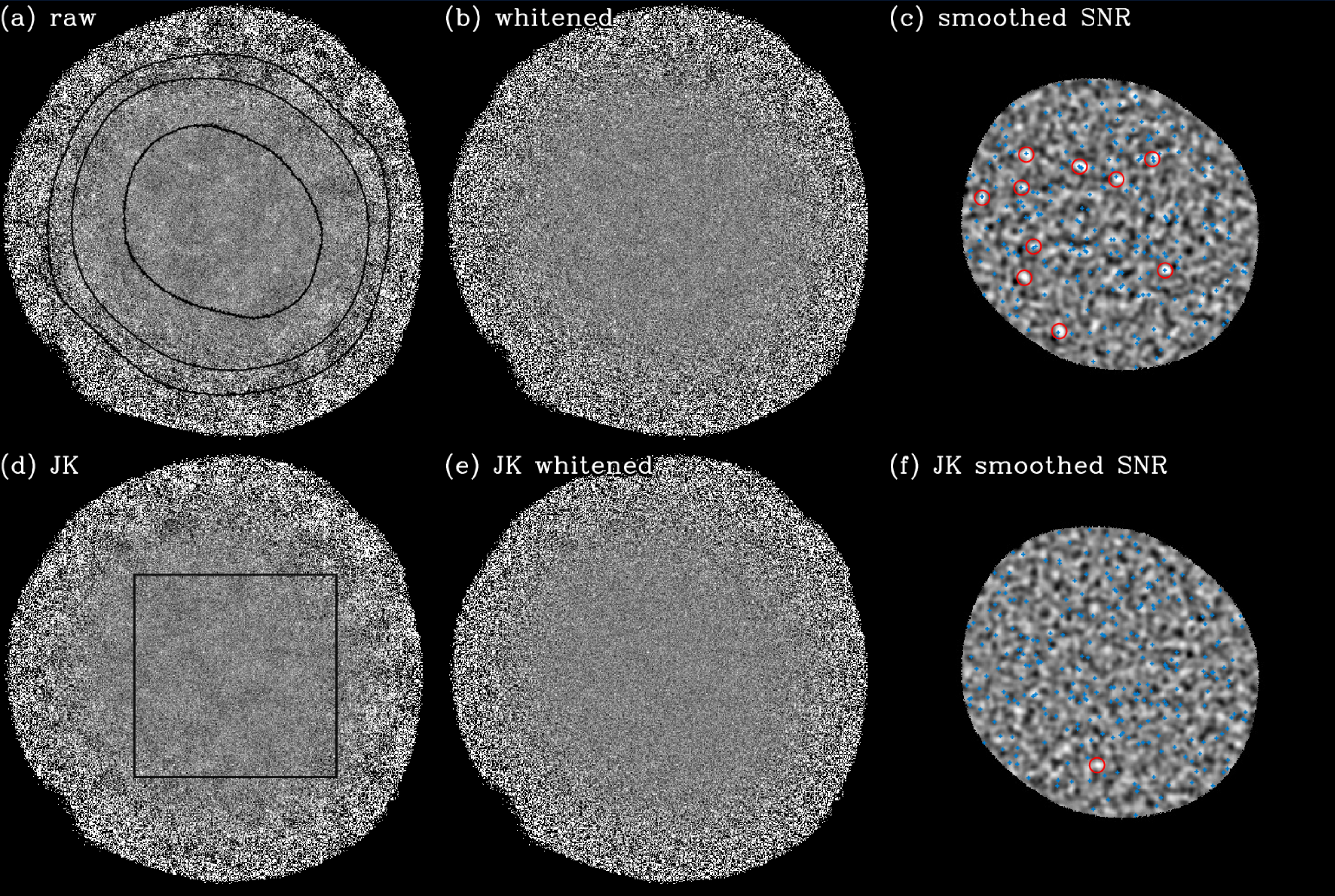
The moon...



Cosmology Fields: No prior, no iterative filtering



Cosmology Fields: No prior, no iterative filtering



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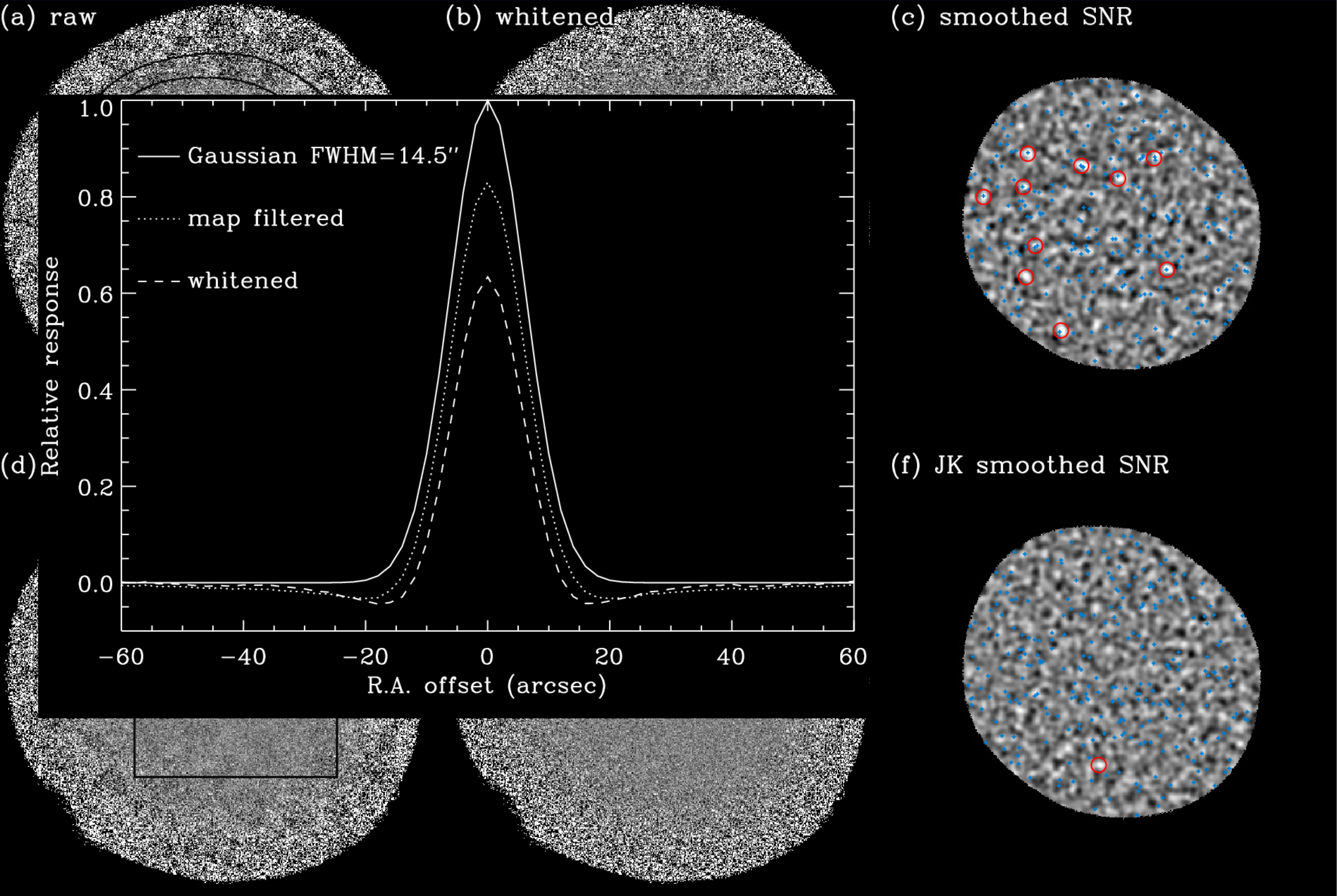
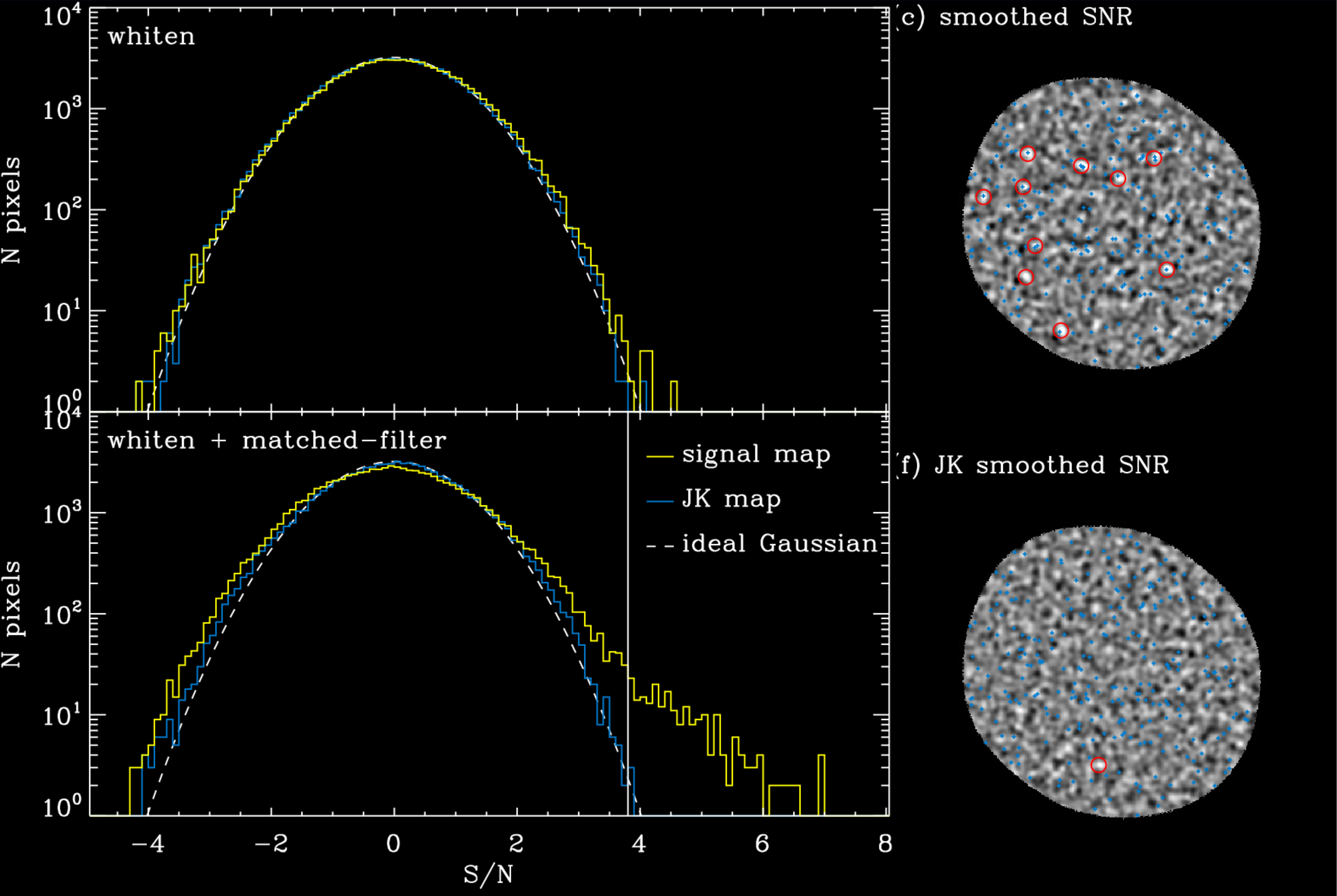
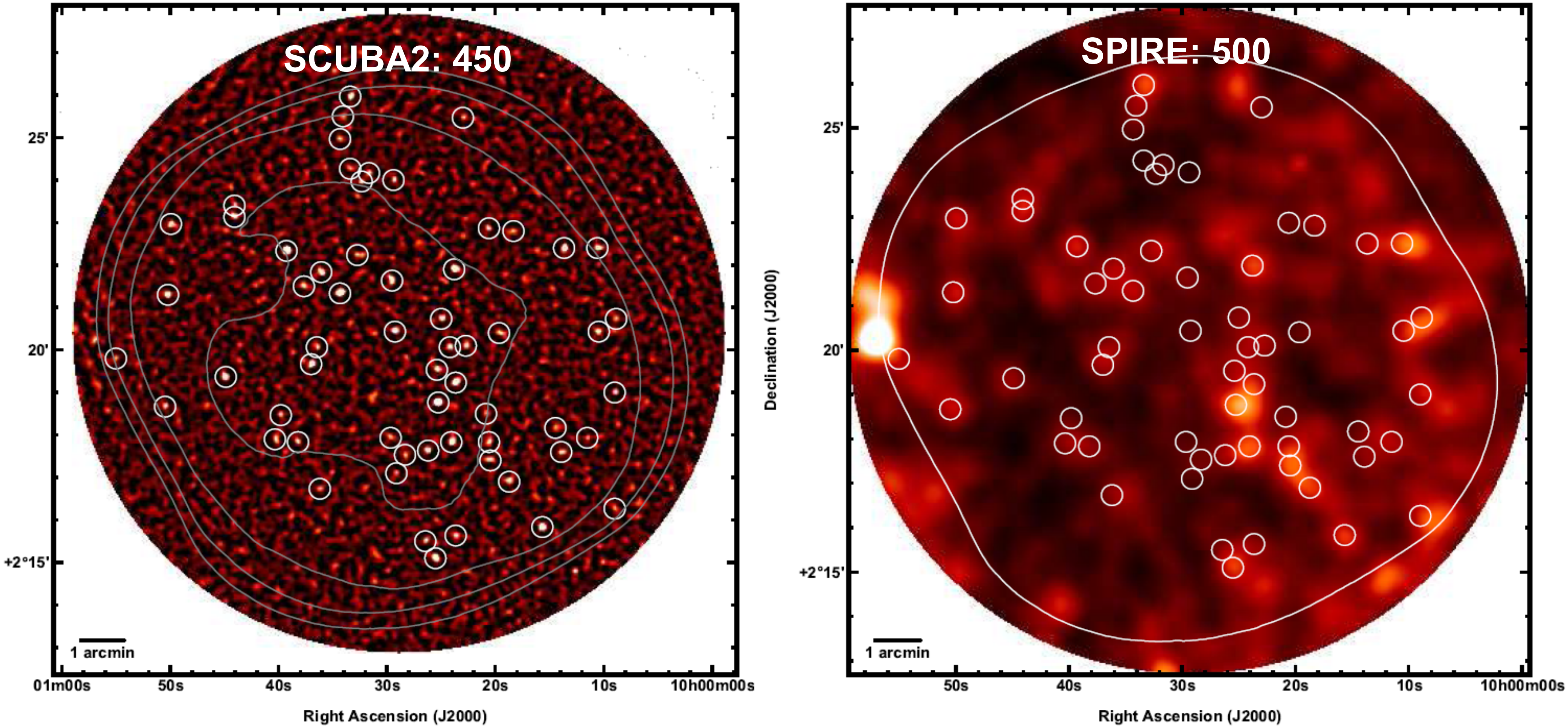


Cosmology Fields: No prior, no iterative filtering



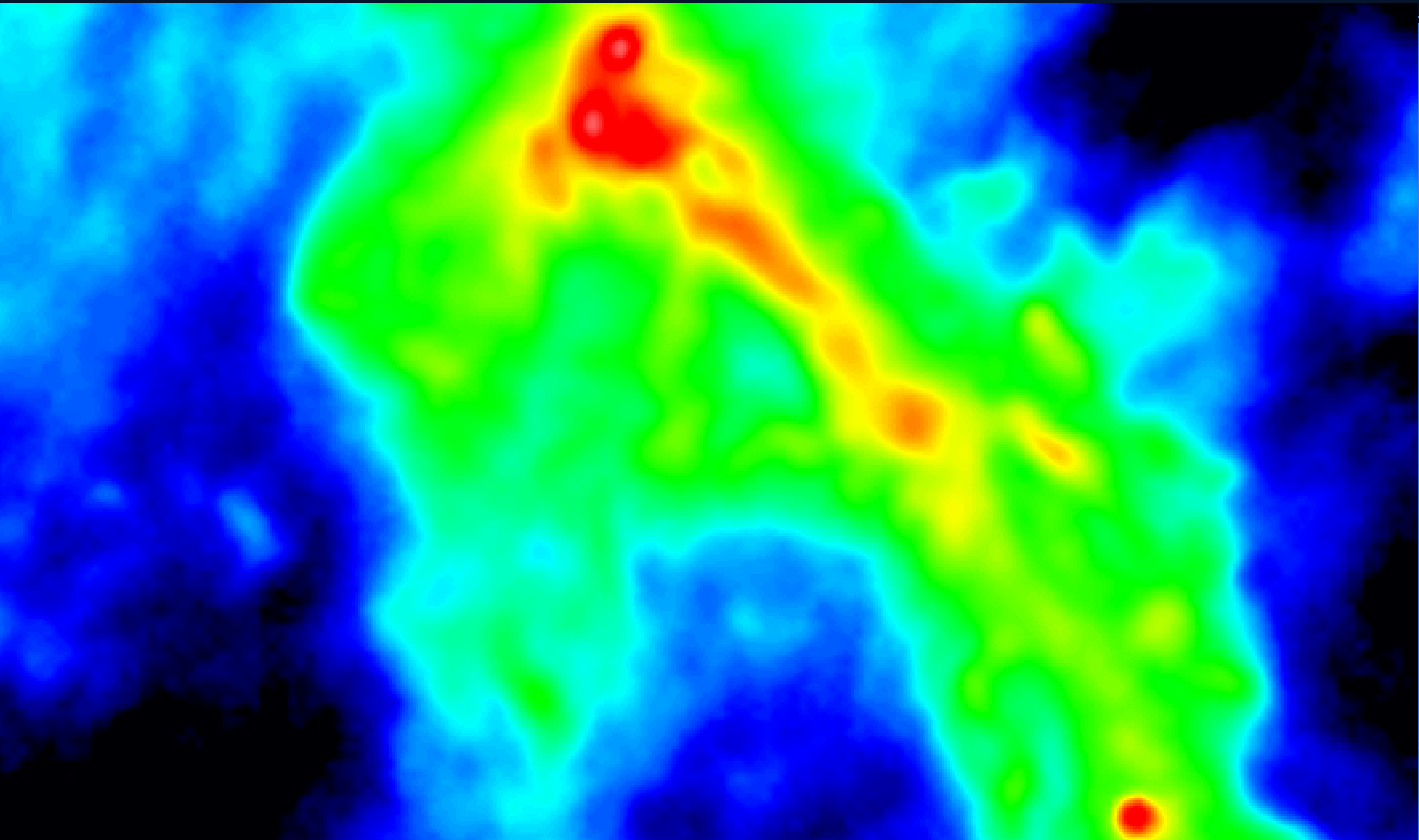
COSMOS-CANDELS



Geach et al. 2012
arXiv:1211.6668

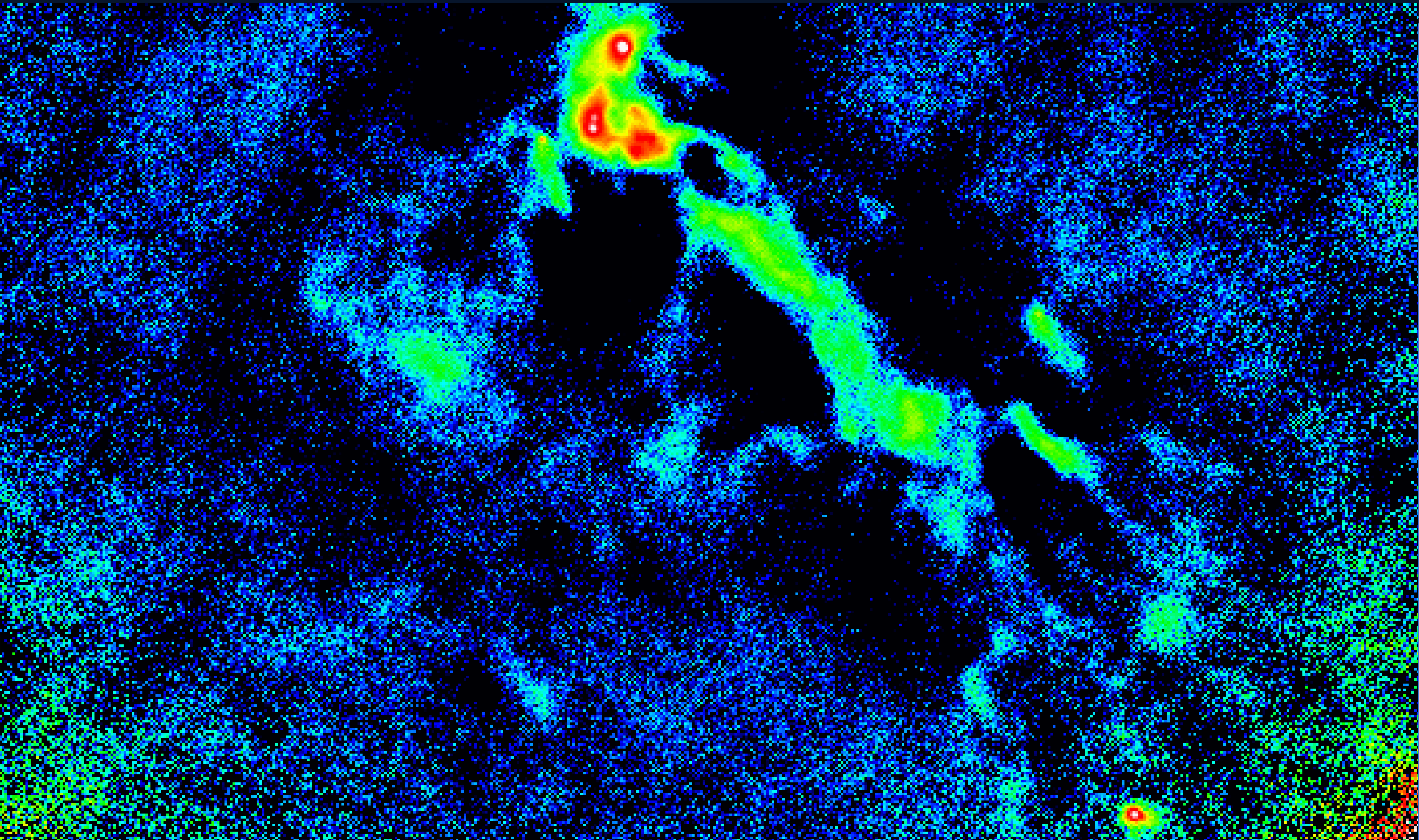
Perseus B1: SPIRE @ 500um

Courtesy Doug Johnstone / Gould Belt Survey



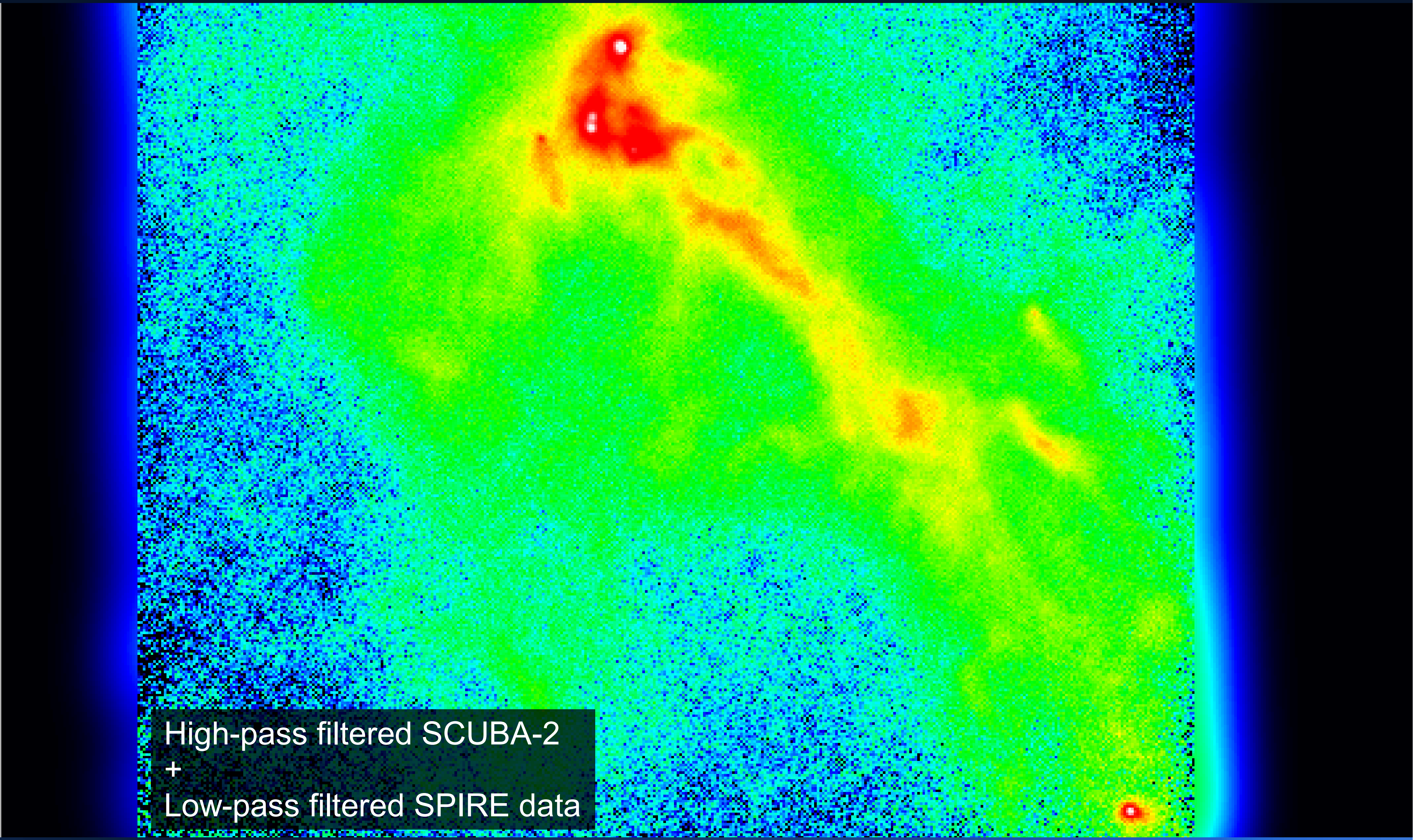
Perseus B1: SCUBA-2 @ 450um

Courtesy Doug Johnstone / Gould Belt Survey



Perseus B1: SPIRE + SCUBA2

Courtesy Doug Johnstone / Gould Belt Survey



Summary

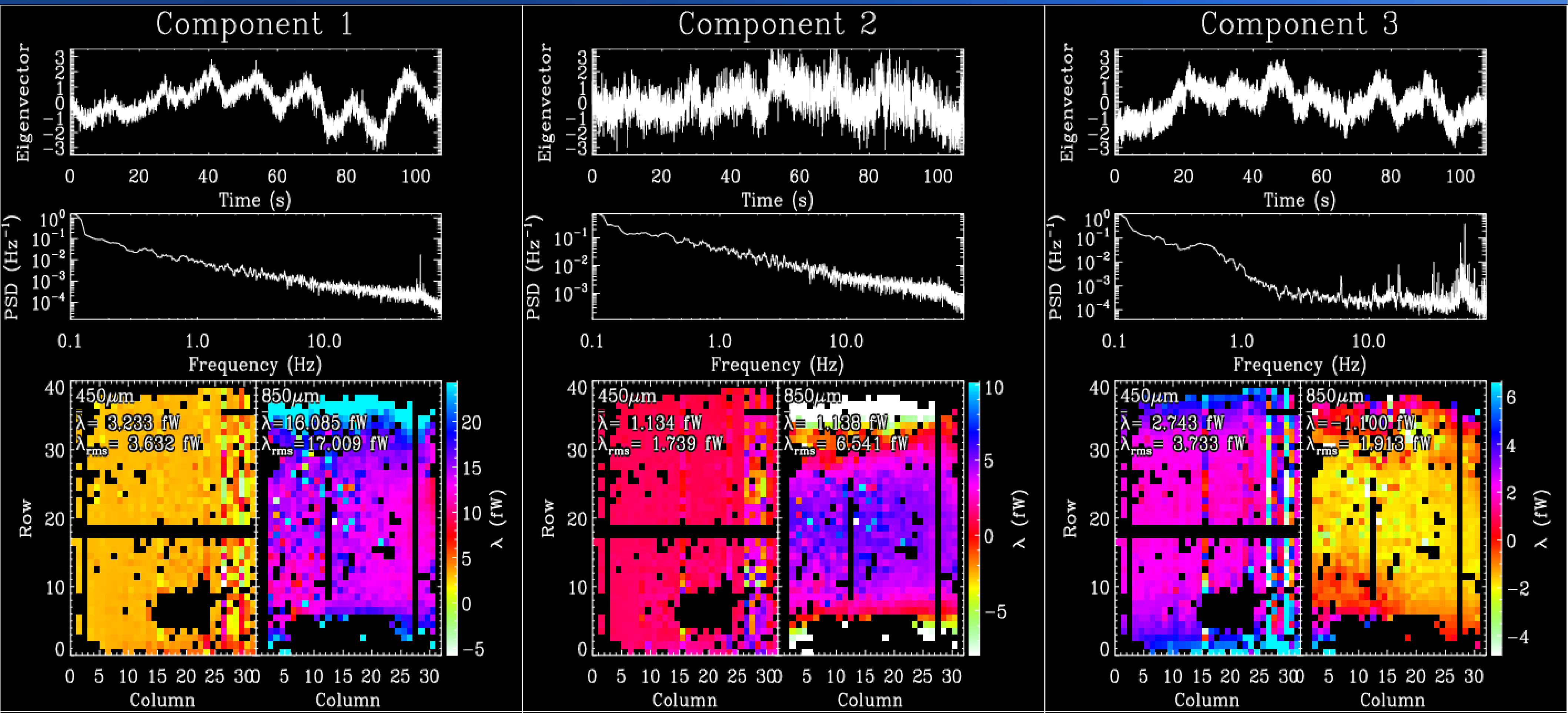
Achieved stated goals:

- SMURF can reach the theoretical white-noise limit for studies of unresolved sources
- Can accurately recover large-scale information up to ~7 arcmin (the array footprint)
- Does not require a cluster to reduce data in reasonable amount of time
- A few canned algorithms do the job without user interaction

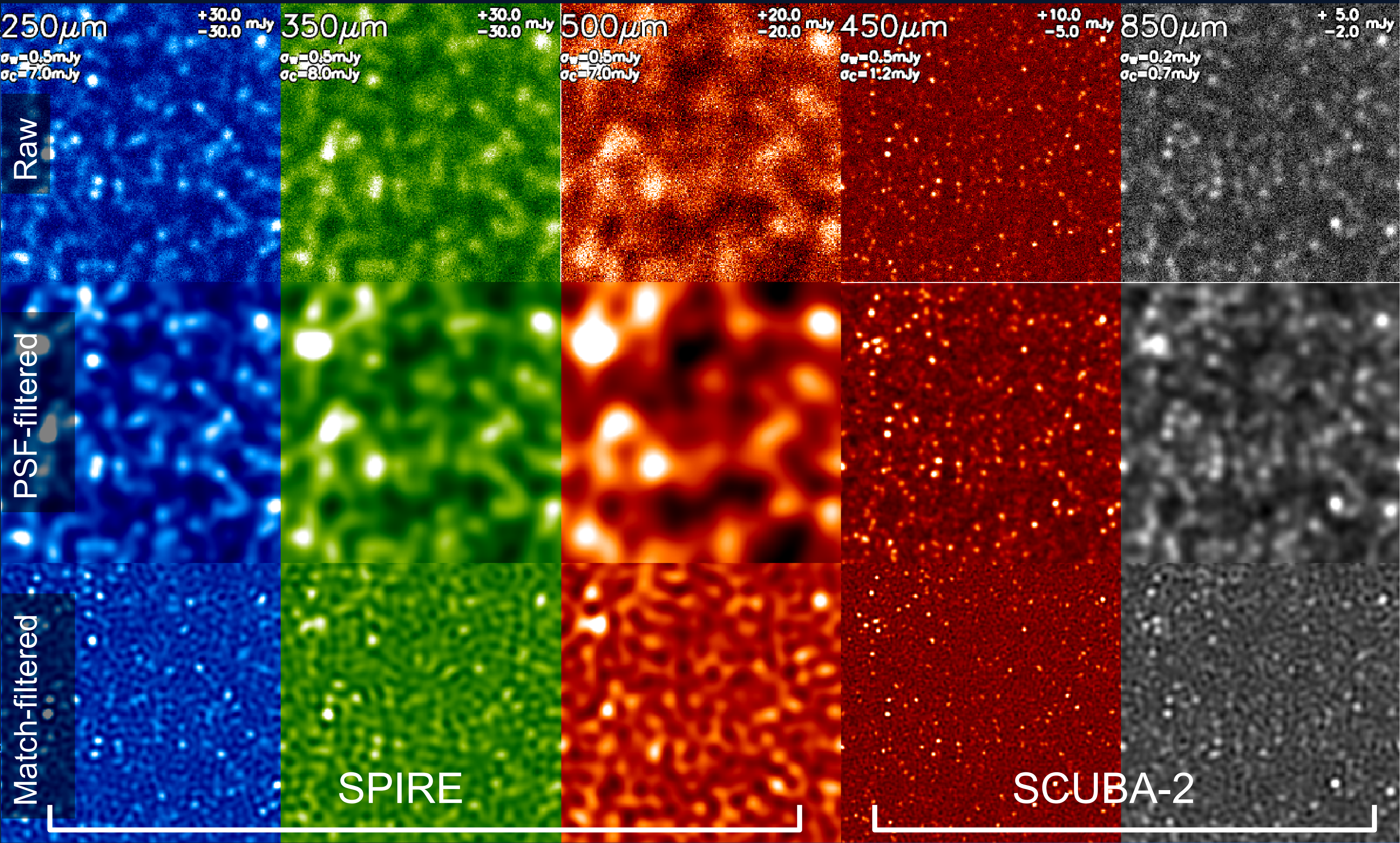
Future:

- Even better map-maker? (maximum-likelihood, e.g. SANEPIC)
- Overlap with surveys that provide large angular scales (*Herschel*, *Planck*?)

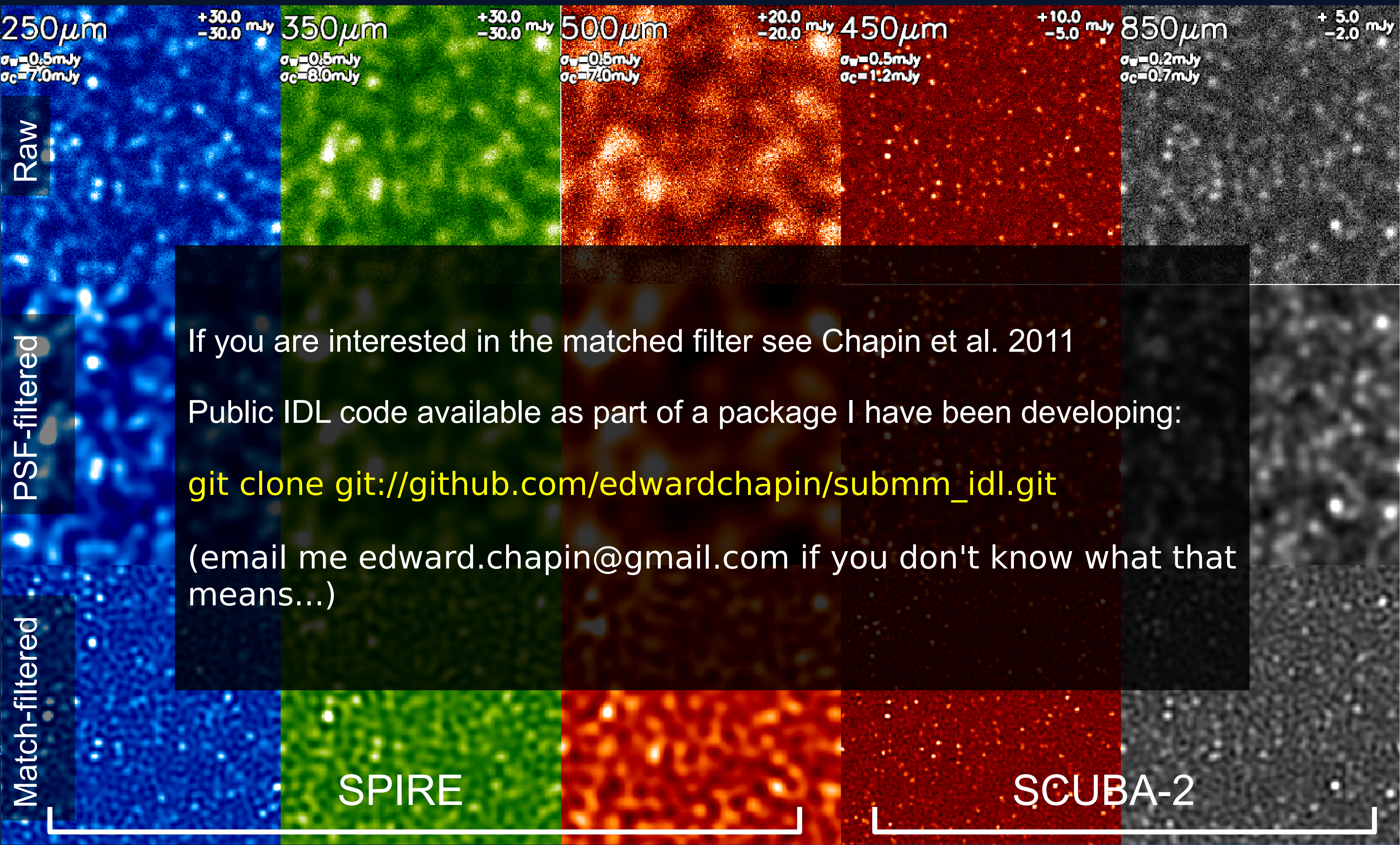
Principal Component Analysis



0.02 deg^2 "450um" CLS fields



0.02 deg^2 "450um" CLS fields

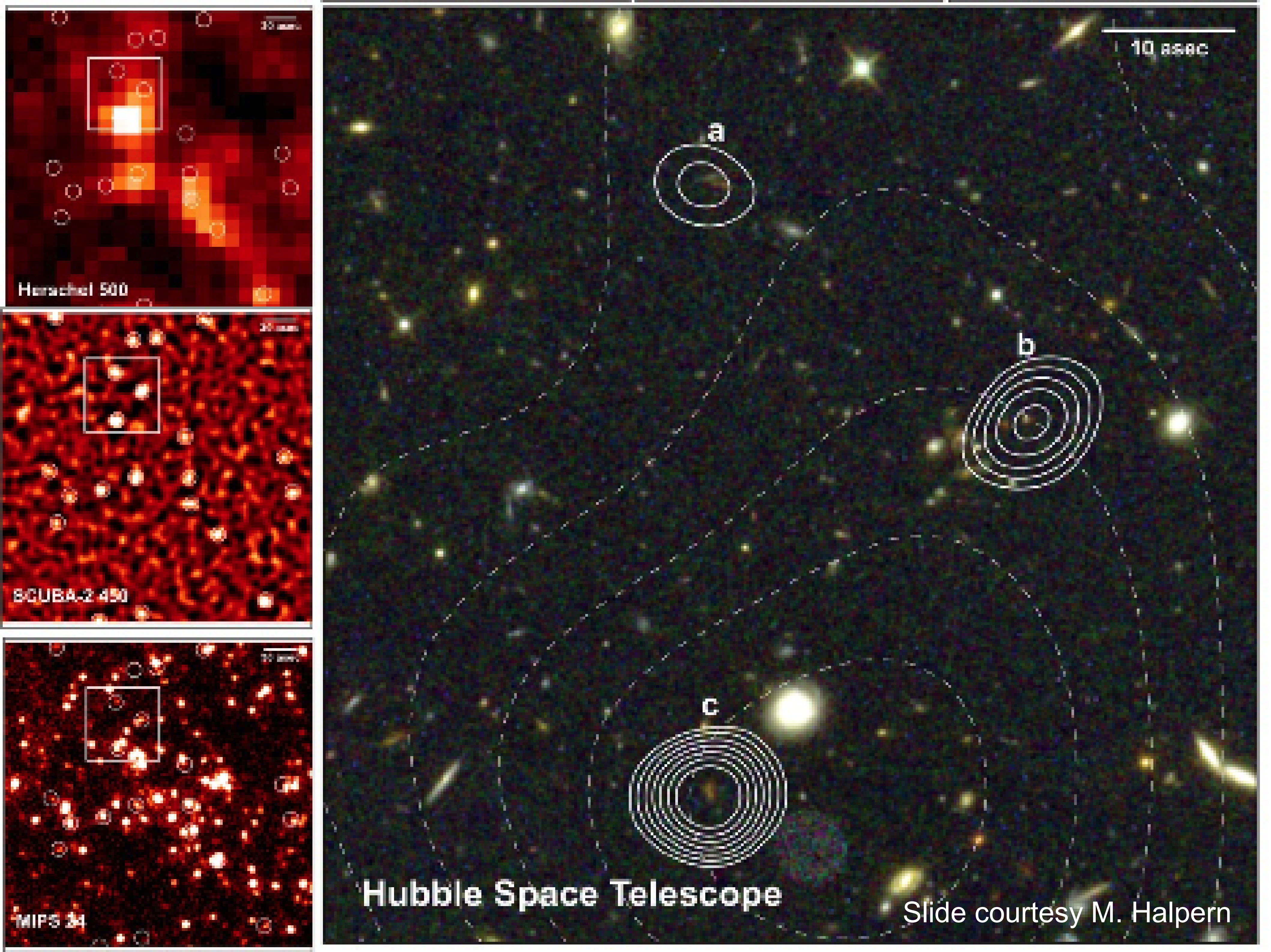


If you are interested in the matched filter see Chapin et al. 2011

Public IDL code available as part of a package I have been developing:

git clone git://github.com/edwardchapin/submm_idl.git

(email me edward.chapin@gmail.com if you don't know what that means...)


Herschel 500
SCUBA-2 450
MIPS 24
10 asec
a
b
c
Hubble Space Telescope
Slide courtesy M. Halpern