

ImageAnalysis

Ian Heywood

CSIRO Astronomy & Space Science, Australia

Rhodes University, South Africa

ImageAnalysis

Acknowledgements:

Naomi McClure-Griffiths (ANU)

Robert Laing (ESO)

Ed Fomalont (NRAO)

Paolo Serra (CSIRO)

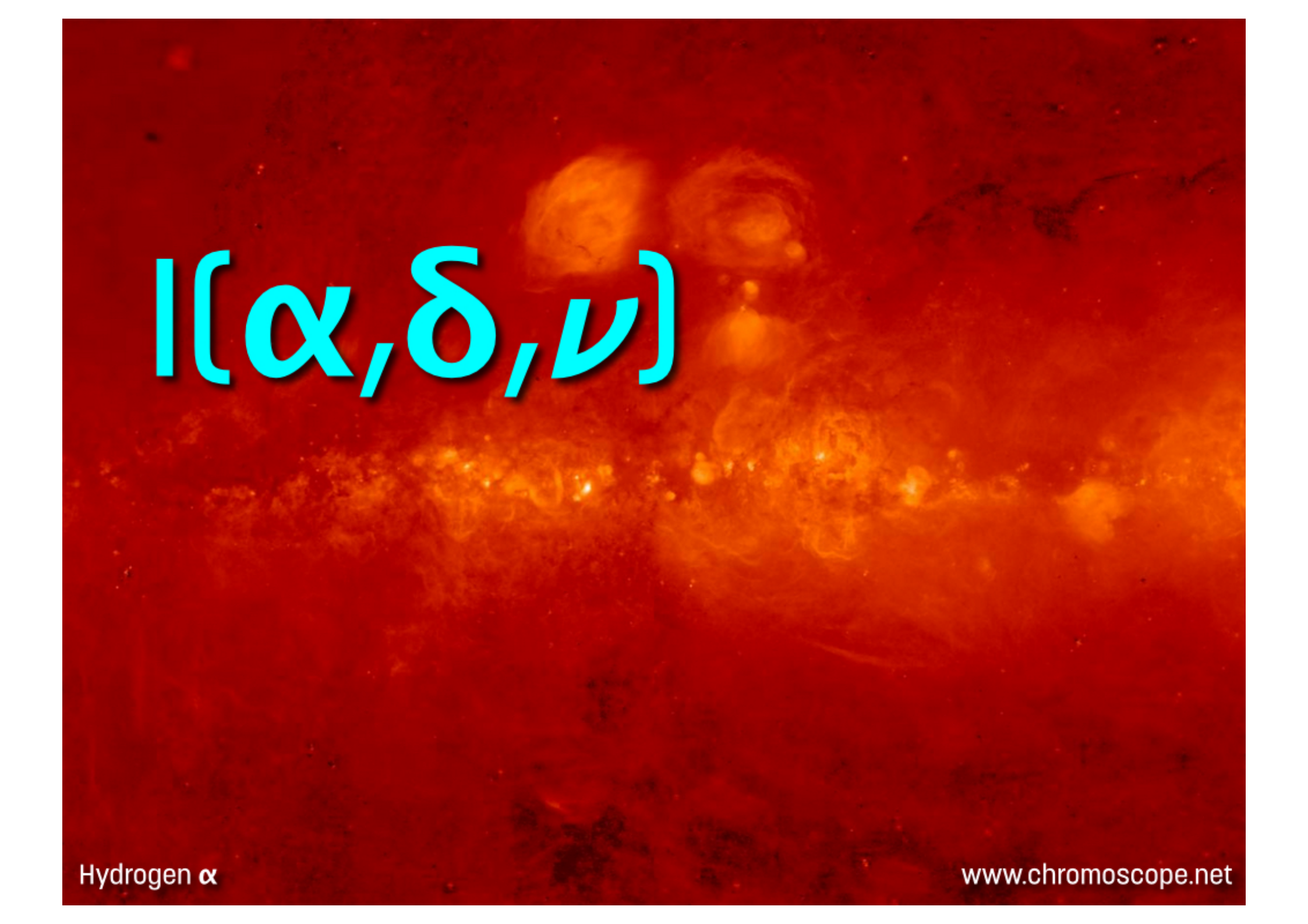
Image?



$I(\alpha, \delta)$

Visible light

www.chromoscope.net



I(α, δ, ν)

A map of the Cosmic Microwave Background (CMB) radiation, showing temperature fluctuations across the sky. The map is color-coded, with a prominent horizontal band of higher temperature (pink/purple) and a darker band of lower temperature (blue/purple) below it. The overall background is a mottled mix of purple, blue, and red.

$I(\alpha, \delta, \nu)$

I(α, δ, ν)

$I(\alpha, \delta, \nu, \rho, t)$

The goal:

Extract scientifically useful measurements from your image

Assumption:

We begin with suitably calibrated data

Interferometers are Fourier Transform machines

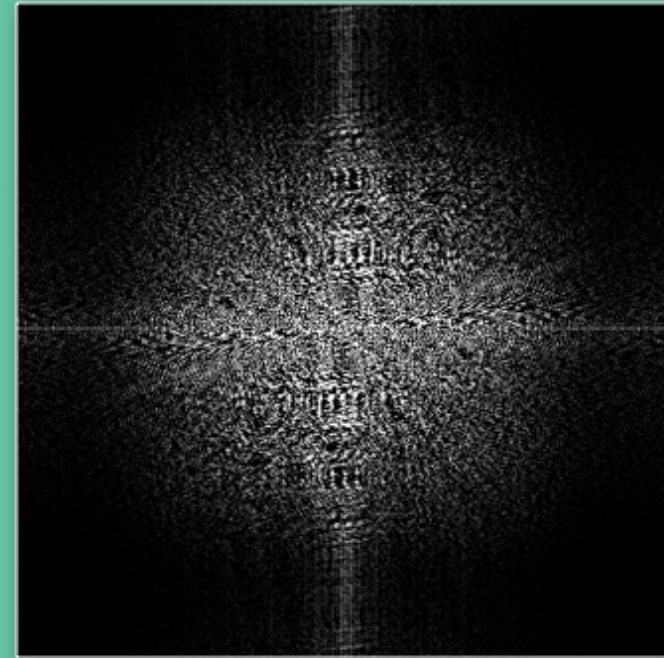
Fourier transform machines

Image domain

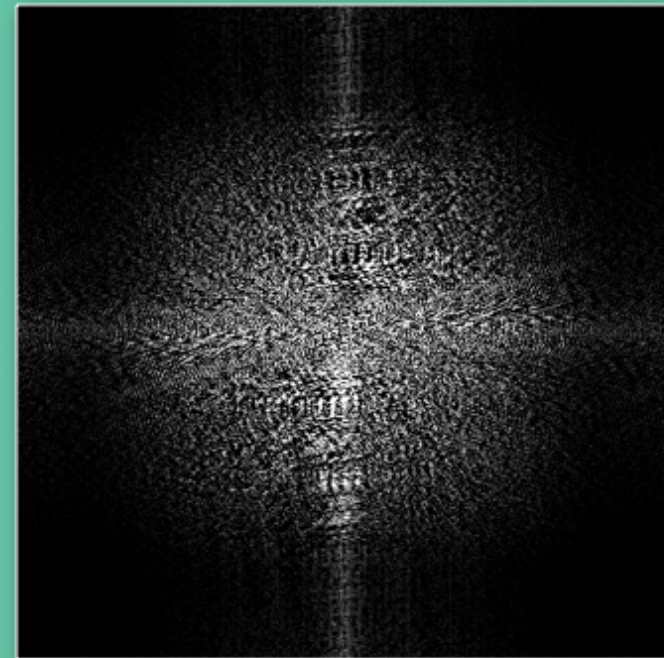


↔
FT

Fourier domain



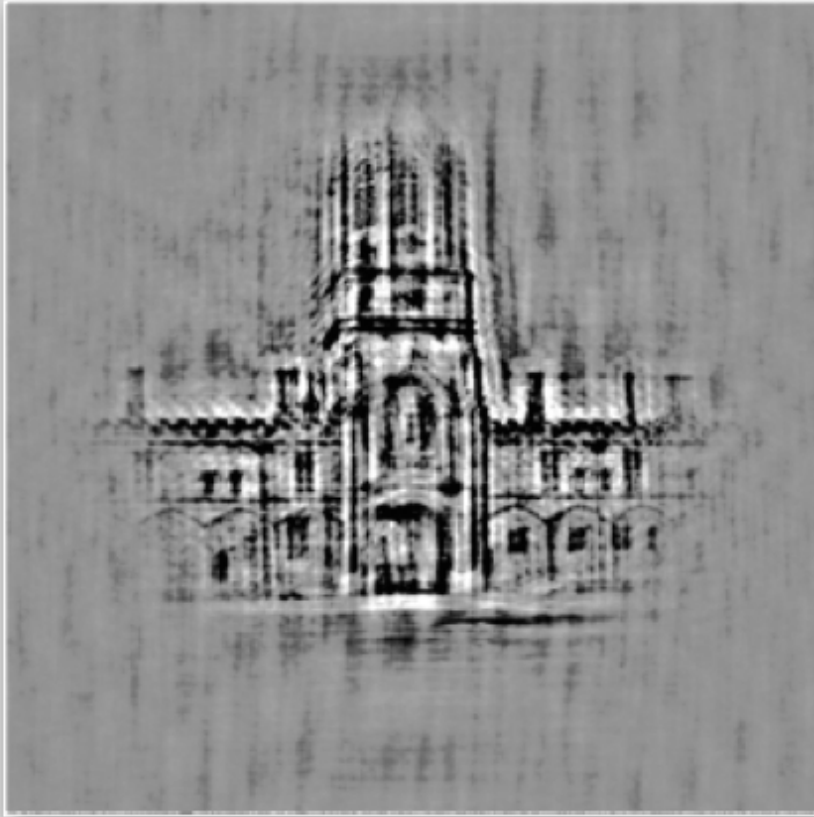
Real



Imag

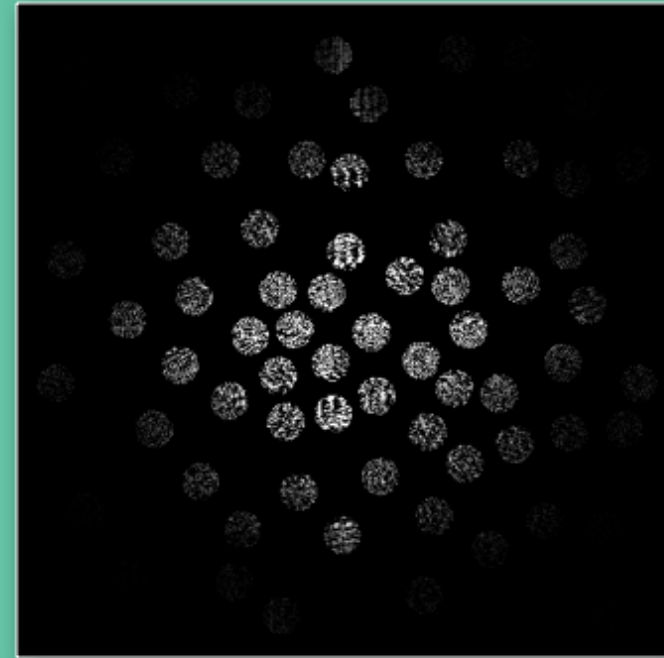
Fourier transform machines

Image domain

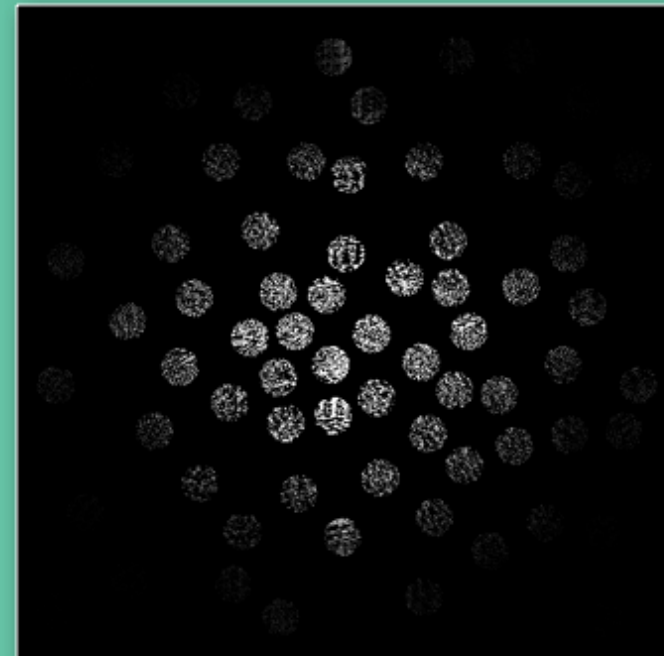


↔
FT

Fourier domain



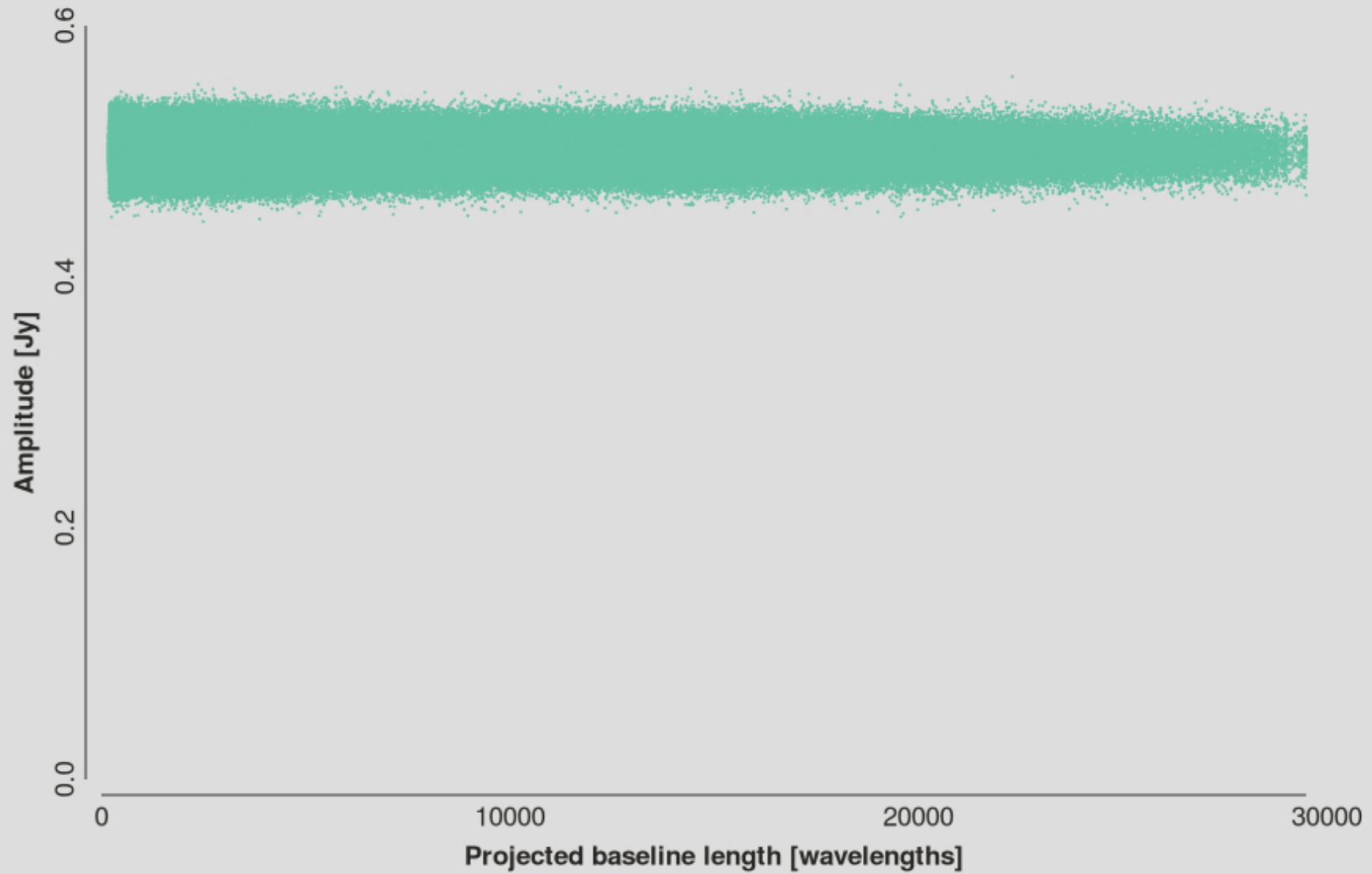
Real



Imag

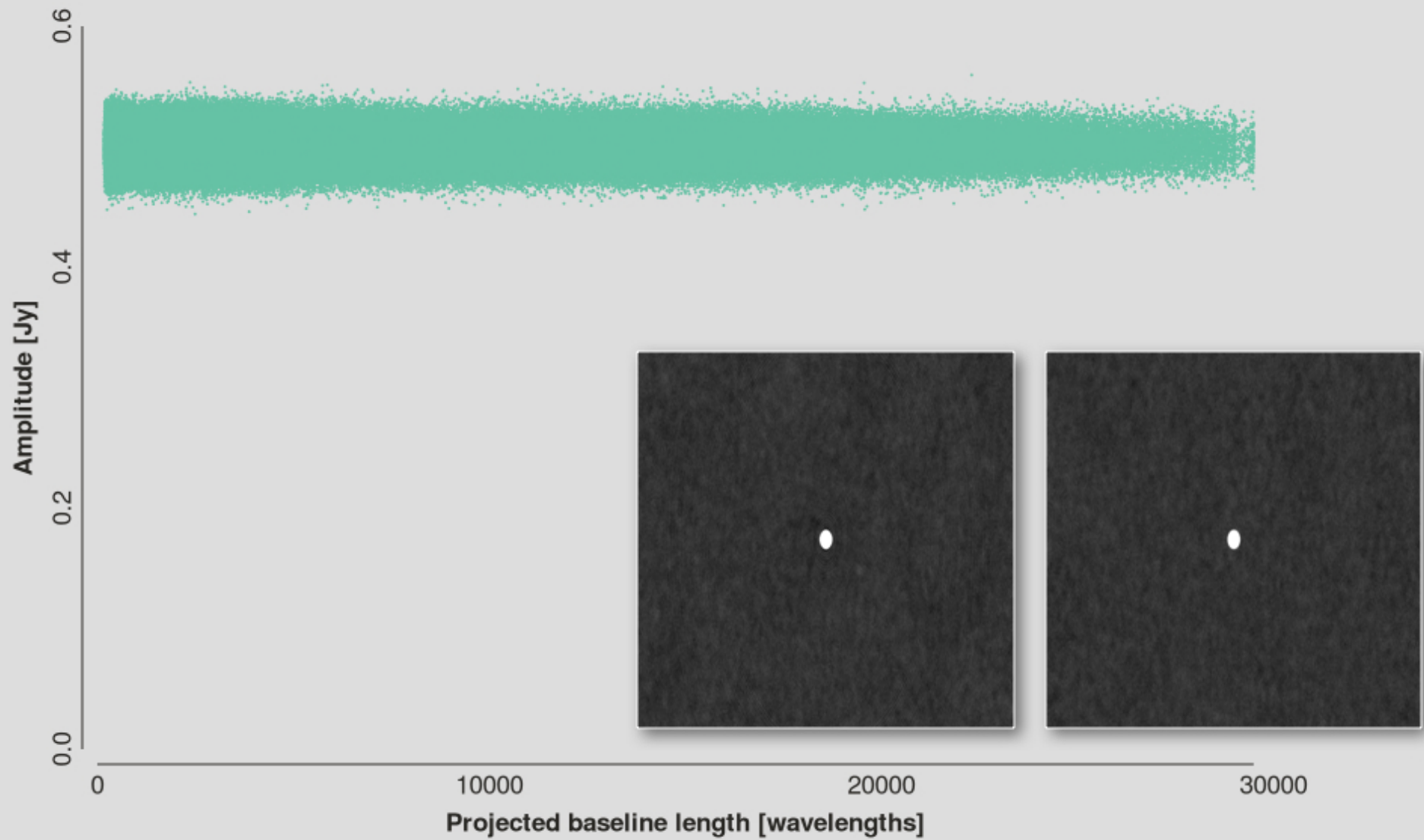
Examining the data in the u, v plane

ATCA simulation • 1.5D config • 12 hour observation
1-2 GHz • 32 × 32 MHz channels • SEFD = 363 Jy



Examining the data in the u, v plane

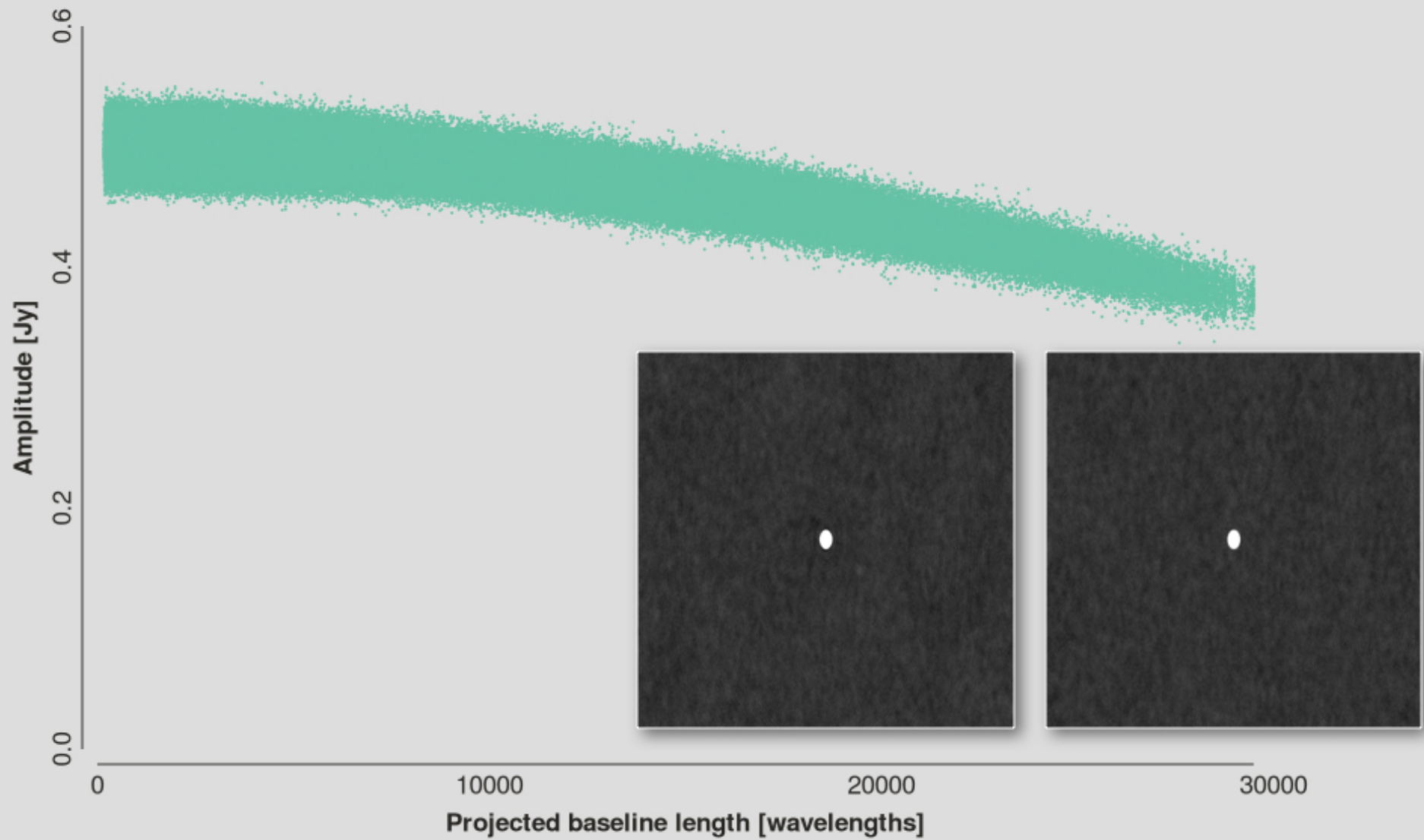
ATCA simulation • 1.5D config • 12 hour observation
1-2 GHz • 32 × 32 MHz channels • SEFD = 363 Jy



500 mJy point source at phase centre

Examining the data in the u,v plane

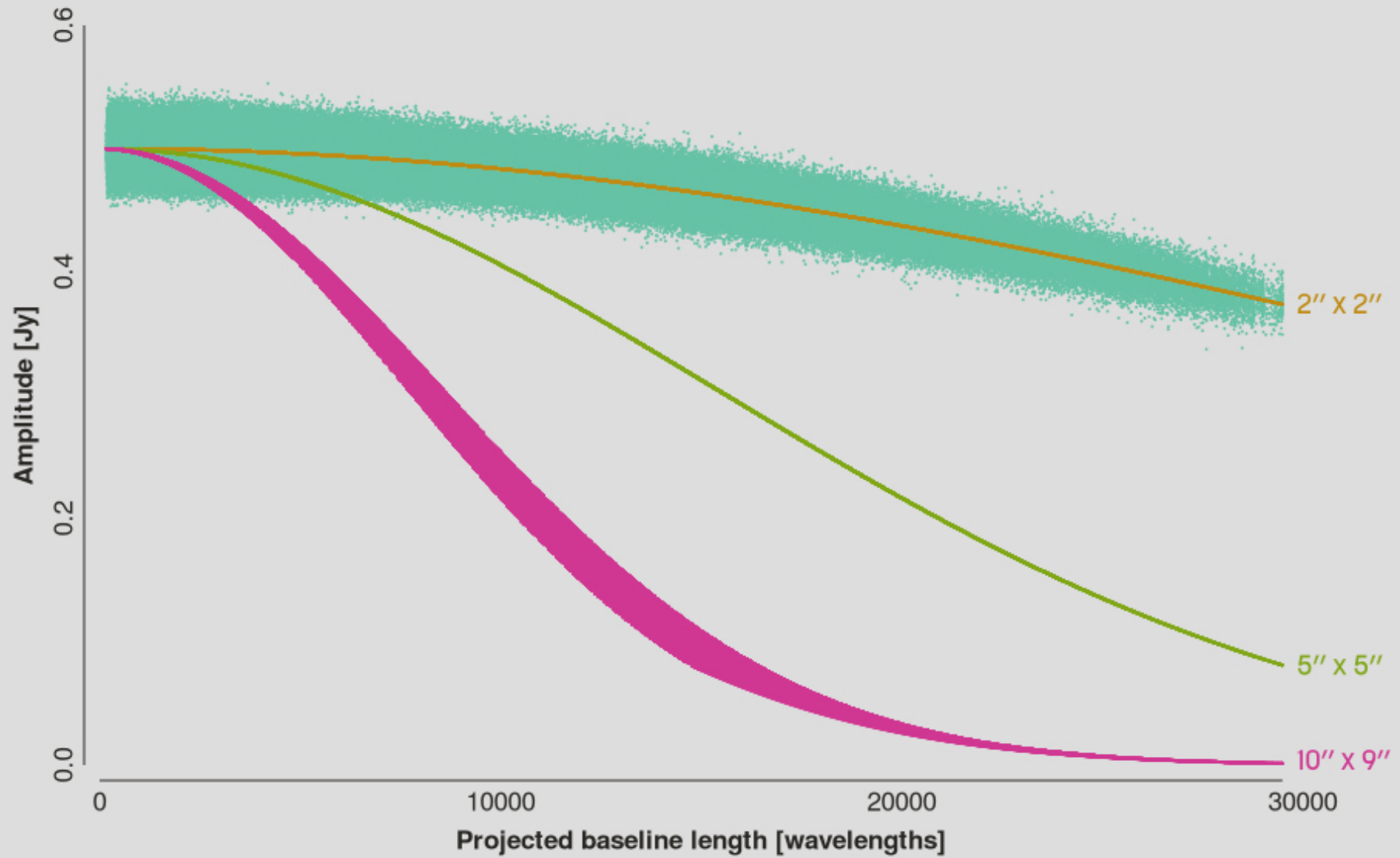
ATCA simulation • 1.5D config • 12 hour observation
1-2 GHz • 32 × 32 MHz channels • SEFD = 363 Jy



500 mJy 2'' x 2'' Gaussian source at phase centre

Examining the data in the u, v plane

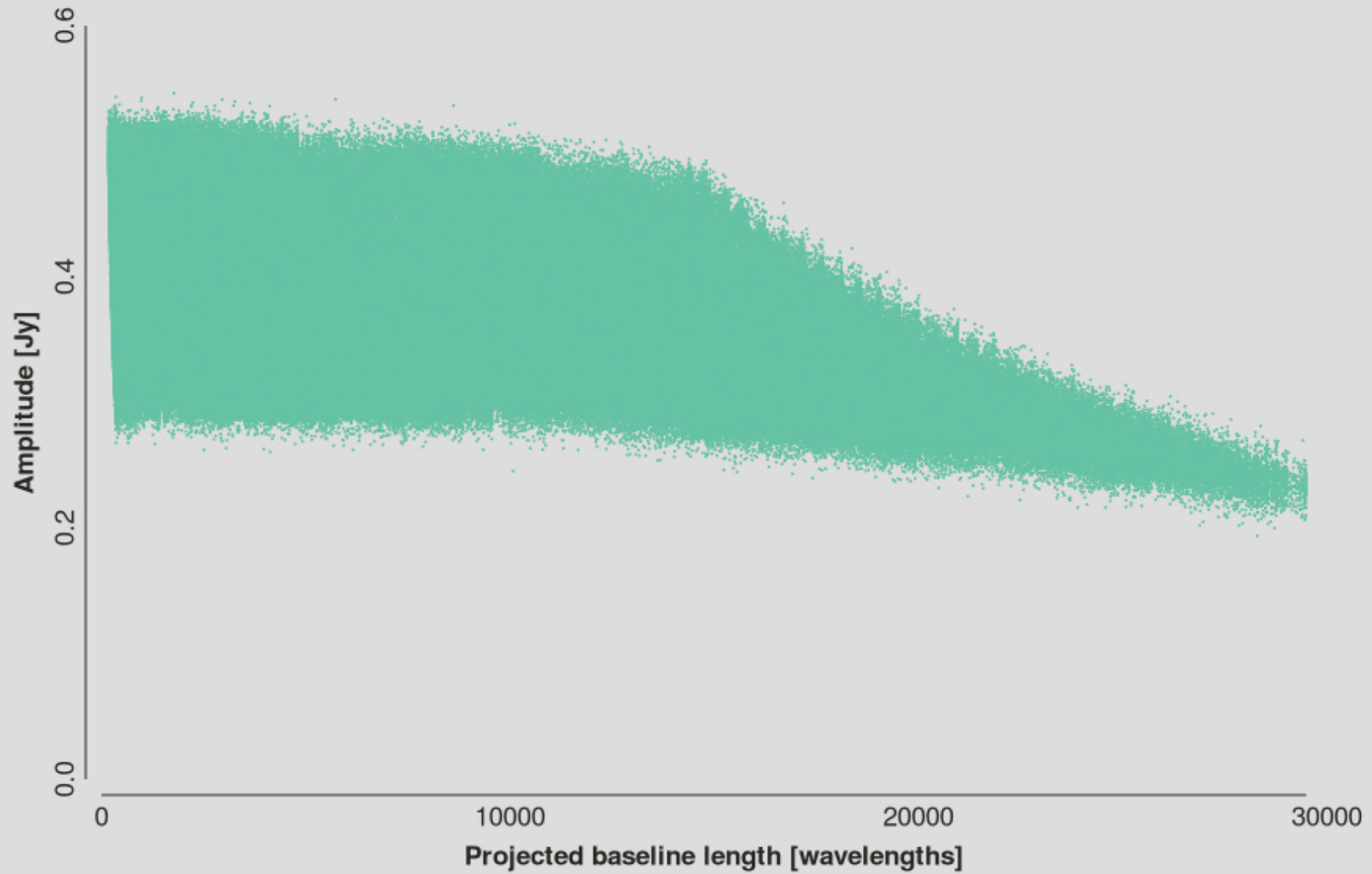
ATCA simulation • 1.5D config • 12 hour observation
1-2 GHz • 32 × 32 MHz channels • SEFD = 363 Jy



500 mJy 2'' x 2'' Gaussian source at phase centre

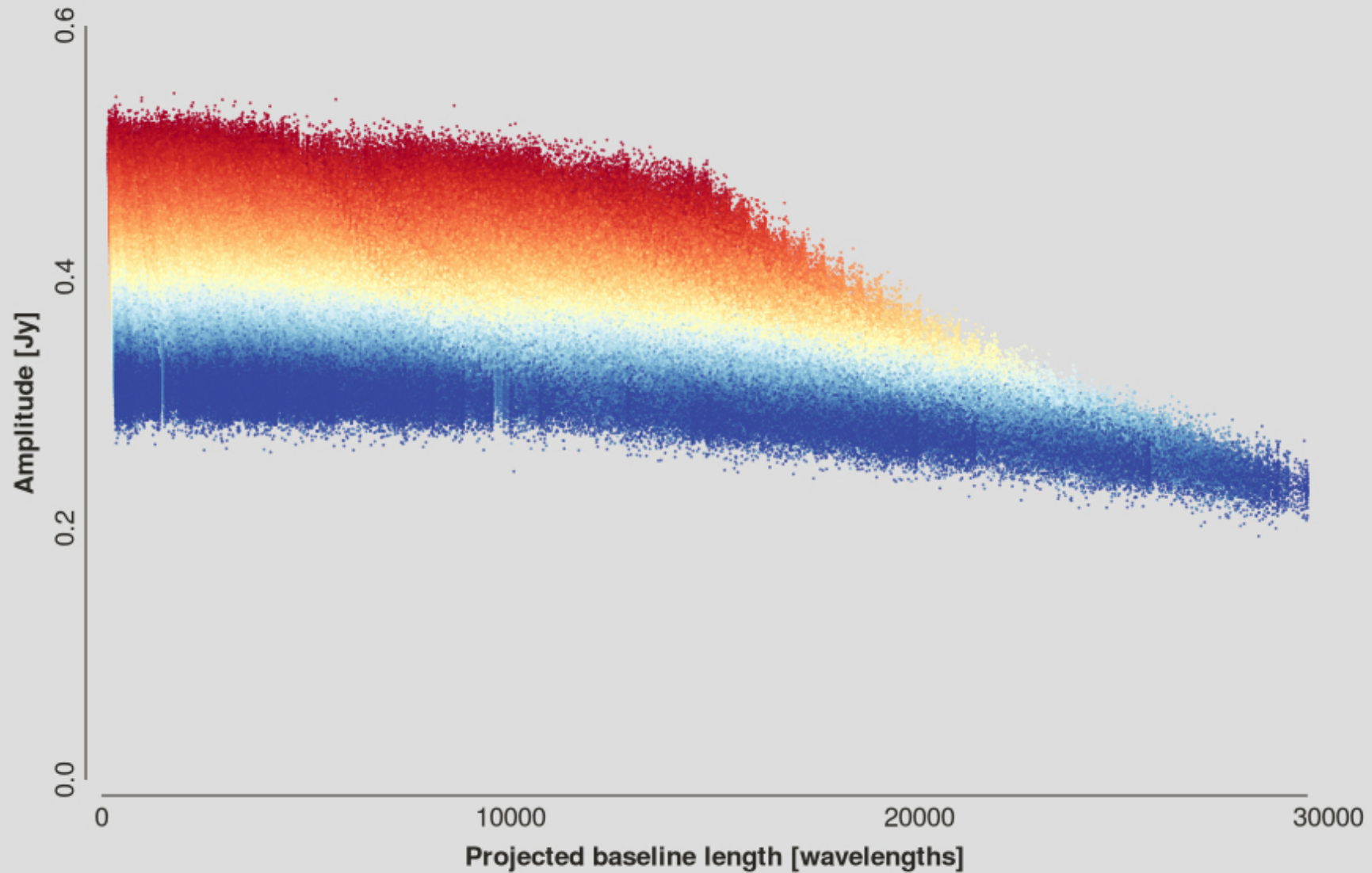
Examining the data in the u, v plane

ATCA simulation • 1.5D config • 12 hour observation
1-2 GHz • 32 × 32 MHz channels • SEFD = 363 Jy



Examining the data in the u, v plane

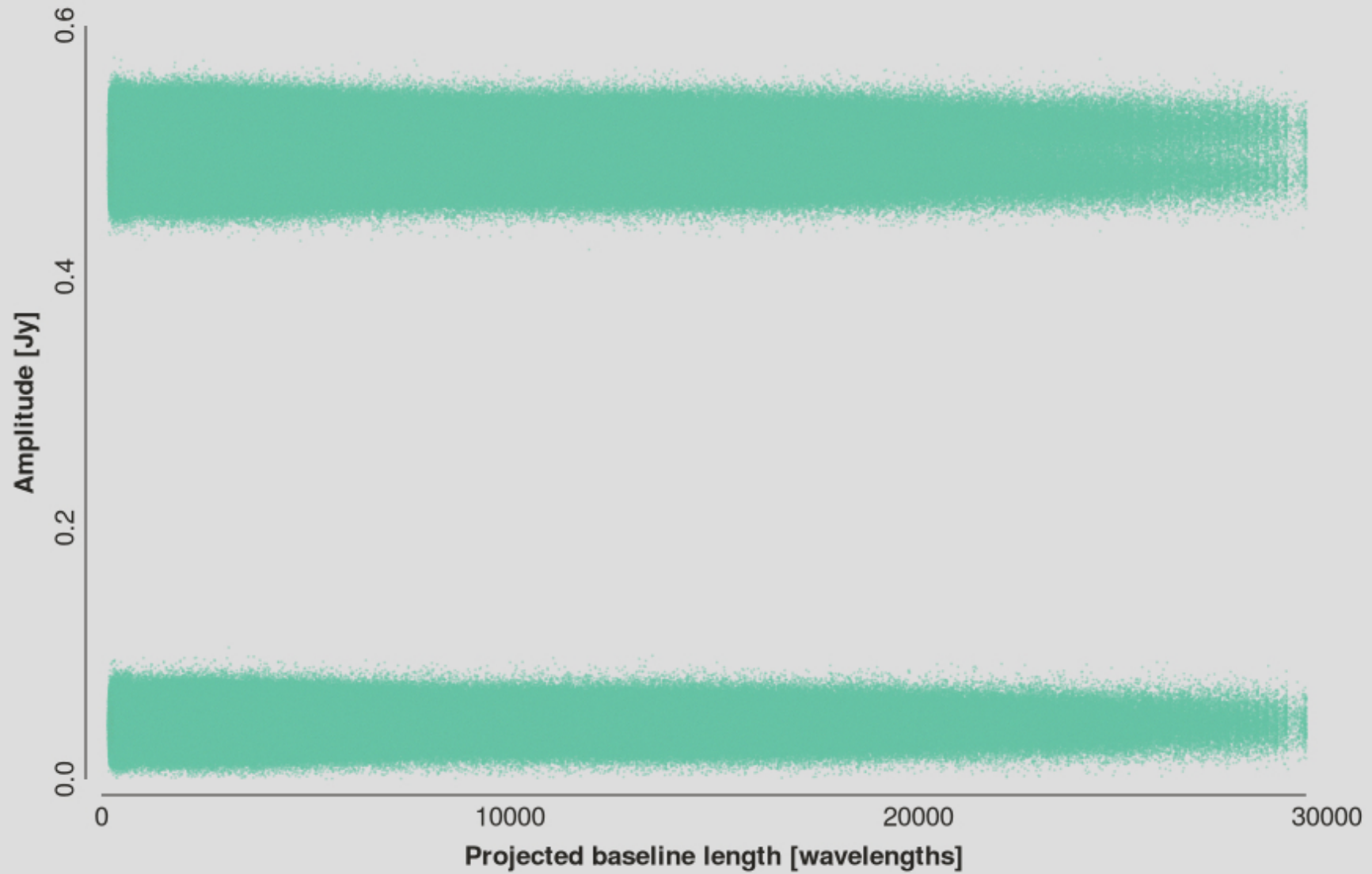
ATCA simulation • 1.5D config • 12 hour observation
1-2 GHz • 32 × 32 MHz channels • SEFD = 363 Jy



500 mJy 2'' x 2'' Gaussian source at phase centre, $\alpha = -0.7$

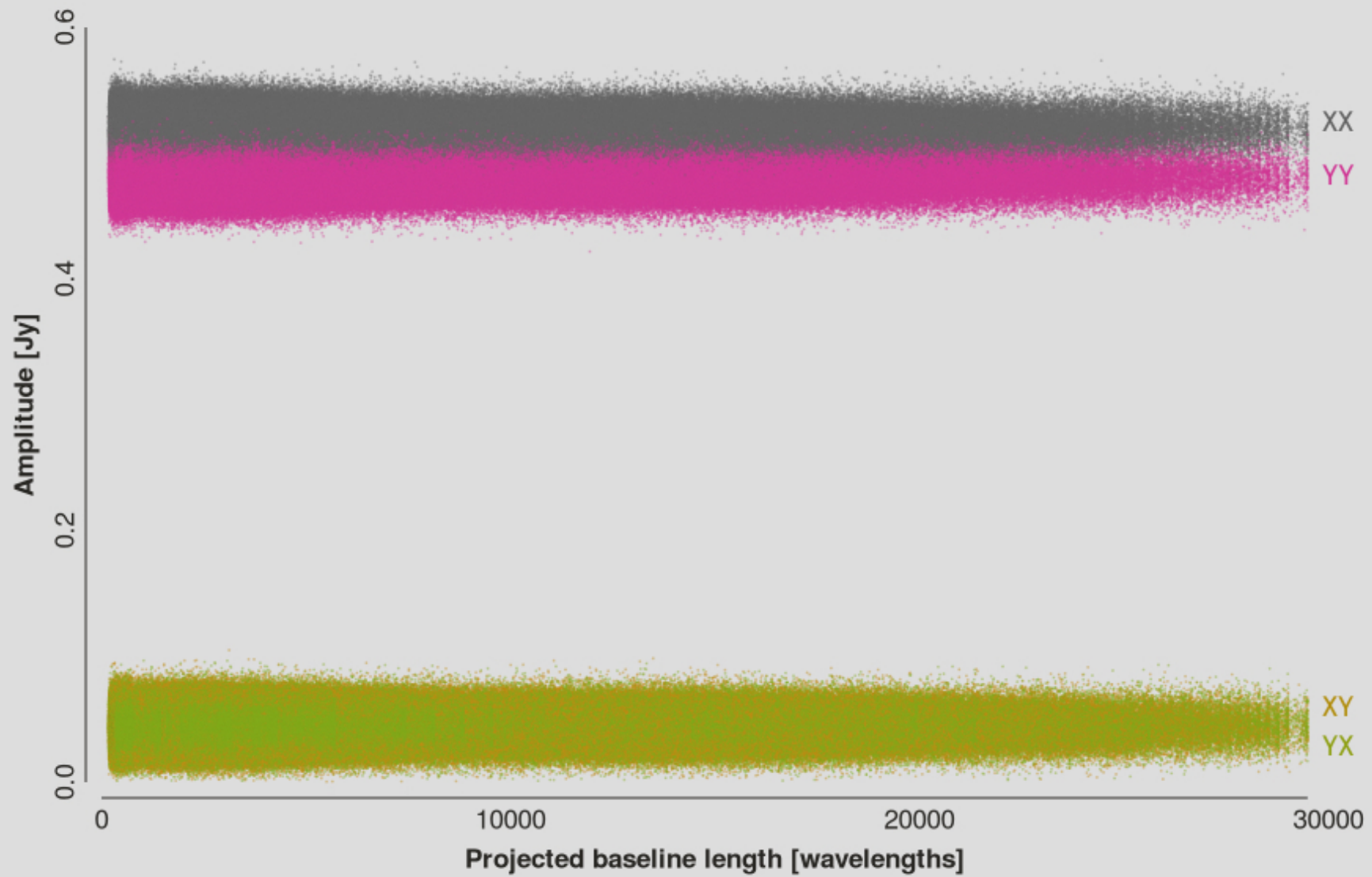
Examining the data in the u, v plane

ATCA simulation • 1.5D config • 12 hour observation
1-2 GHz • 32 × 32 MHz channels • SEFD = 363 Jy



Examining the data in the u, v plane

ATCA simulation • 1.5D config • 12 hour observation
1-2 GHz • 32 × 32 MHz channels • SEFD = 363 Jy



Point source with $I = 500$ mJy; $Q/I = 0.0383$; $U/I = 0.0863$; $V/I = 0$

Examining the data in the u,v plane

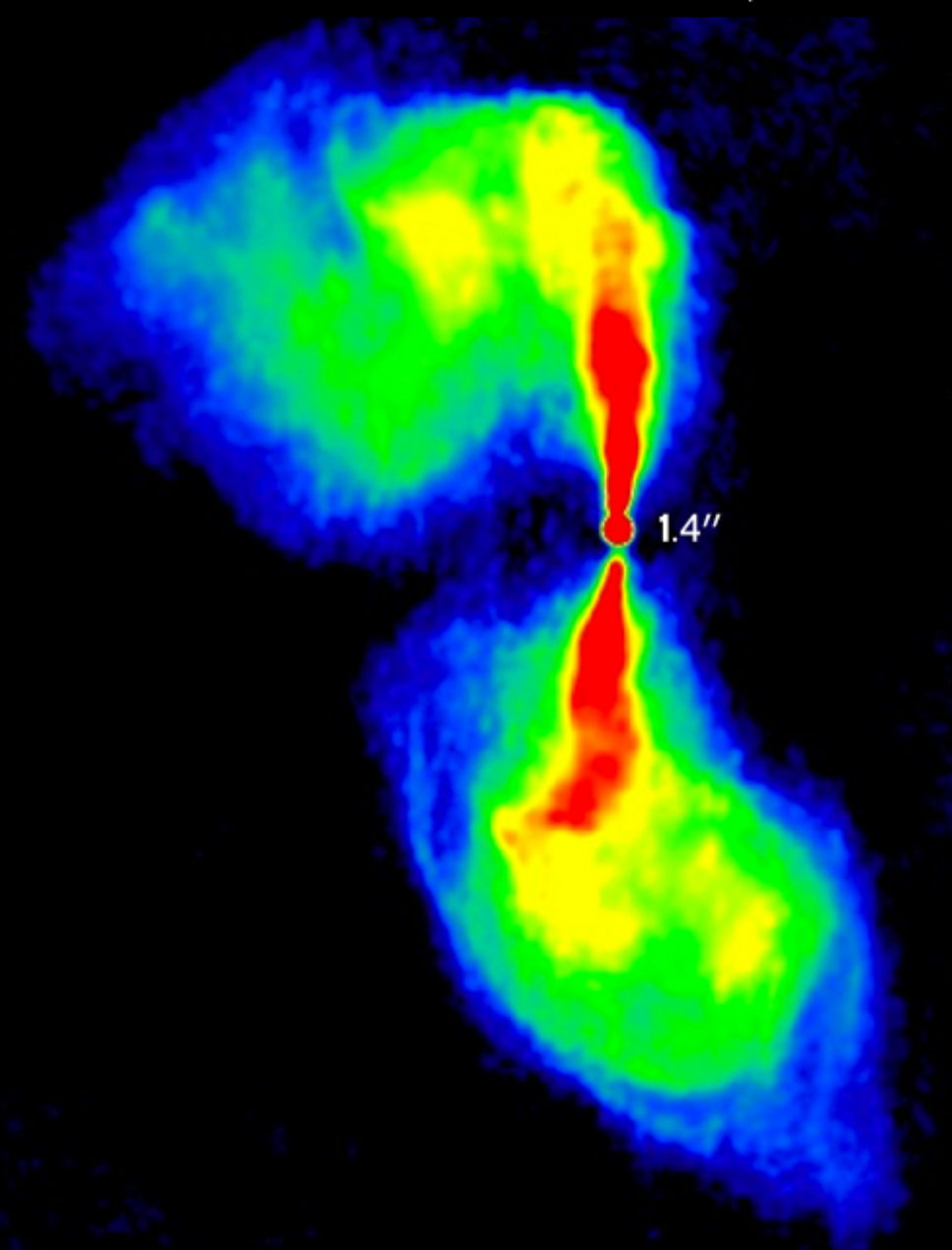
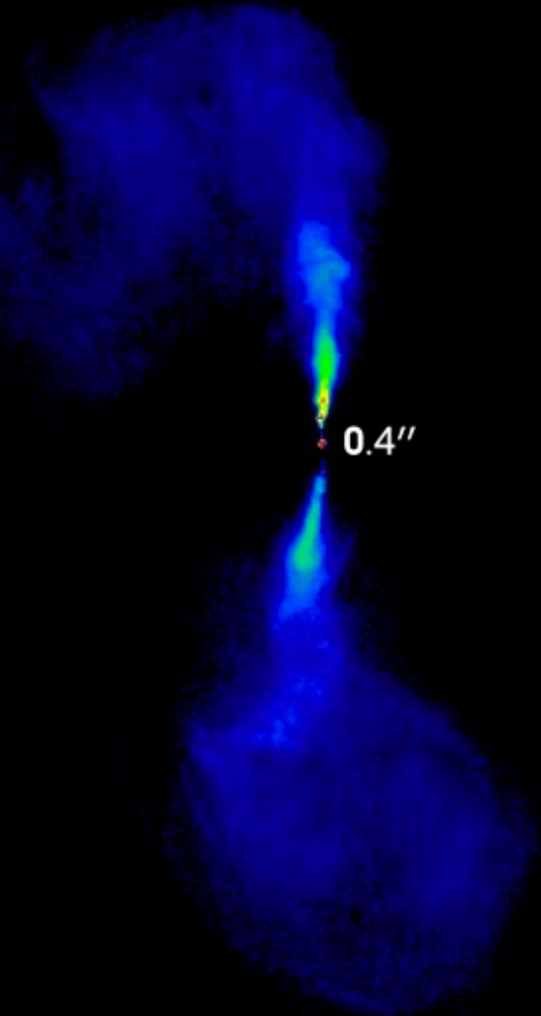
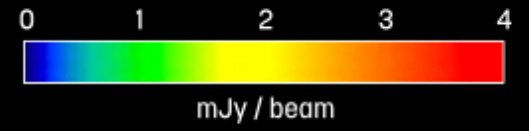
- ▶ You can learn a **lot** about your observations by examining the visibilities:
 - Amplitude vs u,v distance
 - Amplitude vs time
 - Use colours / iterations: frequency channel, baseline, correlation products
- ▶ Tools:
 - Miriad: uvplt
 - AIPS: uvplt, tvflg
 - CASA: plotms, viewer
 - Python packages: pyrap + matplotlib, toyplot, etc.
- ▶ Enjoy it while you can...
 - ATCA: 15 baselines
 - VLA: 351 baselines
 - MeerKAT: 2,016 baselines
 - ASKAP: 630 baselines \times 36 beams = 22,680

Fitting the data in the u,v plane

- ▶ Direct fitting of a visibility model to the data is particularly suited to:
 - Observations with sparse u,v coverage (VLBI, low- N arrays, snapshots, etc.)
 - Fields dominated by a few compact components (minimise the parameters)
 - Variability studies (amplitude vs phase)
- ▶ Direct fitting of a visibility model to the data is difficult for morphologically complex fields
- ▶ Modelling and subtracting a dominant component from the visibilities can often result in improved results when imaging the residuals
- ▶ A non-exhaustive list of tools:
 - Miriad: uvflux, uvfit, uvsfit...
 - AIPS: uvfit
 - CASA: uvmodelfit
 - Difmap
 - MeqTrees: all of it
 - Make your own!

Making an image: match the method to the science goals

Weighting and u,v tapering



3C272.1 (M84)

Same data, same brightness scale, different tapering functions!

Images by Robert Laing

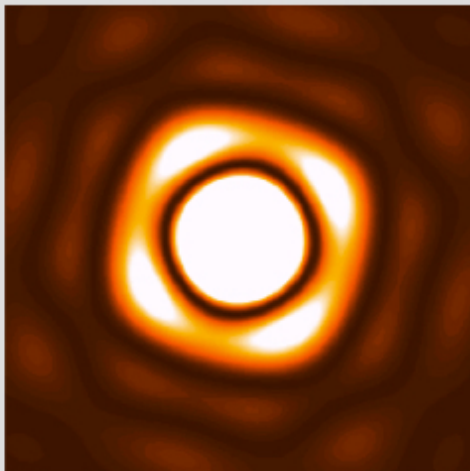
Weighting and u, v tapering

- ▶ Different weighting schemes reveal different aspects of the target
- ▶ Interested in an accurate position measurement?
 - Image with the highest resolution possible
 - Beware of sensitivity loss
- ▶ Interested in the total flux of an extended source?
 - Taper the data to deliver a low resolution image
- ▶ Searching for diffuse, low surface brightness emission?
 - Smooth the image (consider subtraction of compact features, more on that later...)

Beware of the primary beam

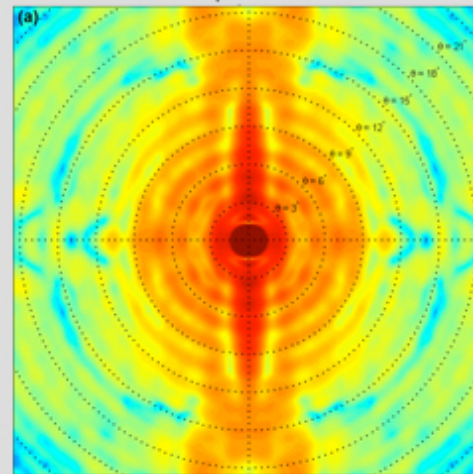
- ▶ The primary beam response of telescope determines sensitivity as a function of direction
 - Sources away from the optical axis (usually the phase centre) are attenuated
 - Usually mitigated by dividing the image by an average primary beam model
 - Off-axis flux densities are corrected, noise is correspondingly raised
- ▶ The more insidious characteristics of the primary beam will be revealed in tomorrow's high dynamic range lecture

VLA (Cassegrain)



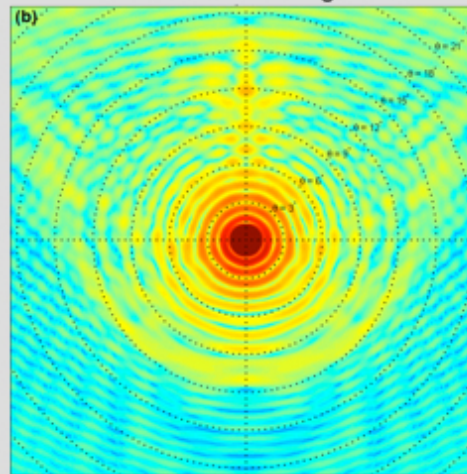
Simulated (Walter Briskin, NRAO)

KAT-7 (prime focus)



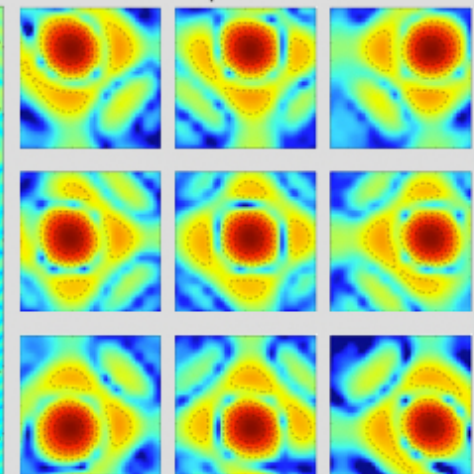
Simulated (Isak Theron, EMSS)

MeerKAT (offset Gregorian)



Simulated (Isak Theron, EMSS)

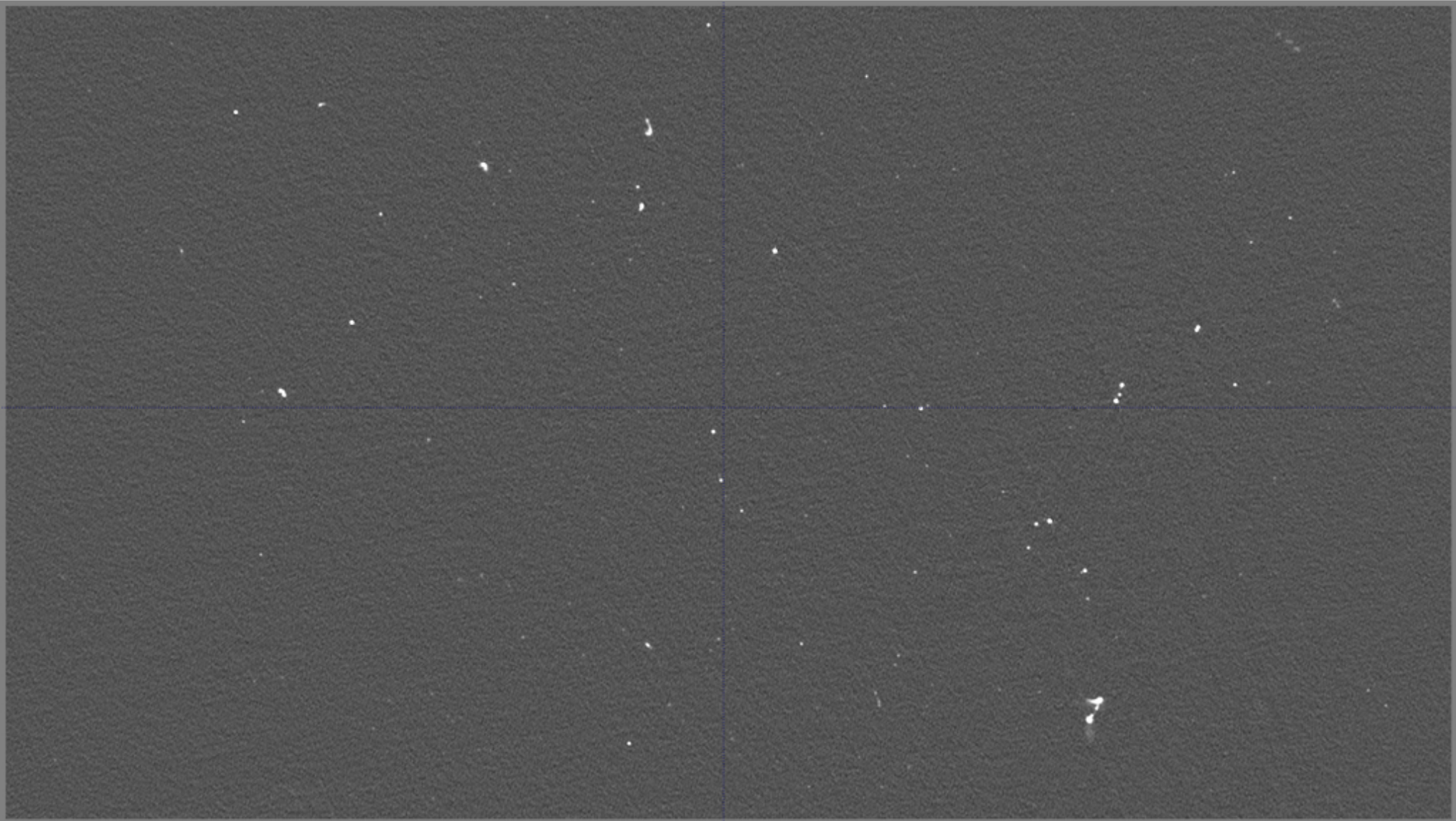
BETA (prime focus)



Measured (Aidan Hotan, CASS)

Primary beam correction

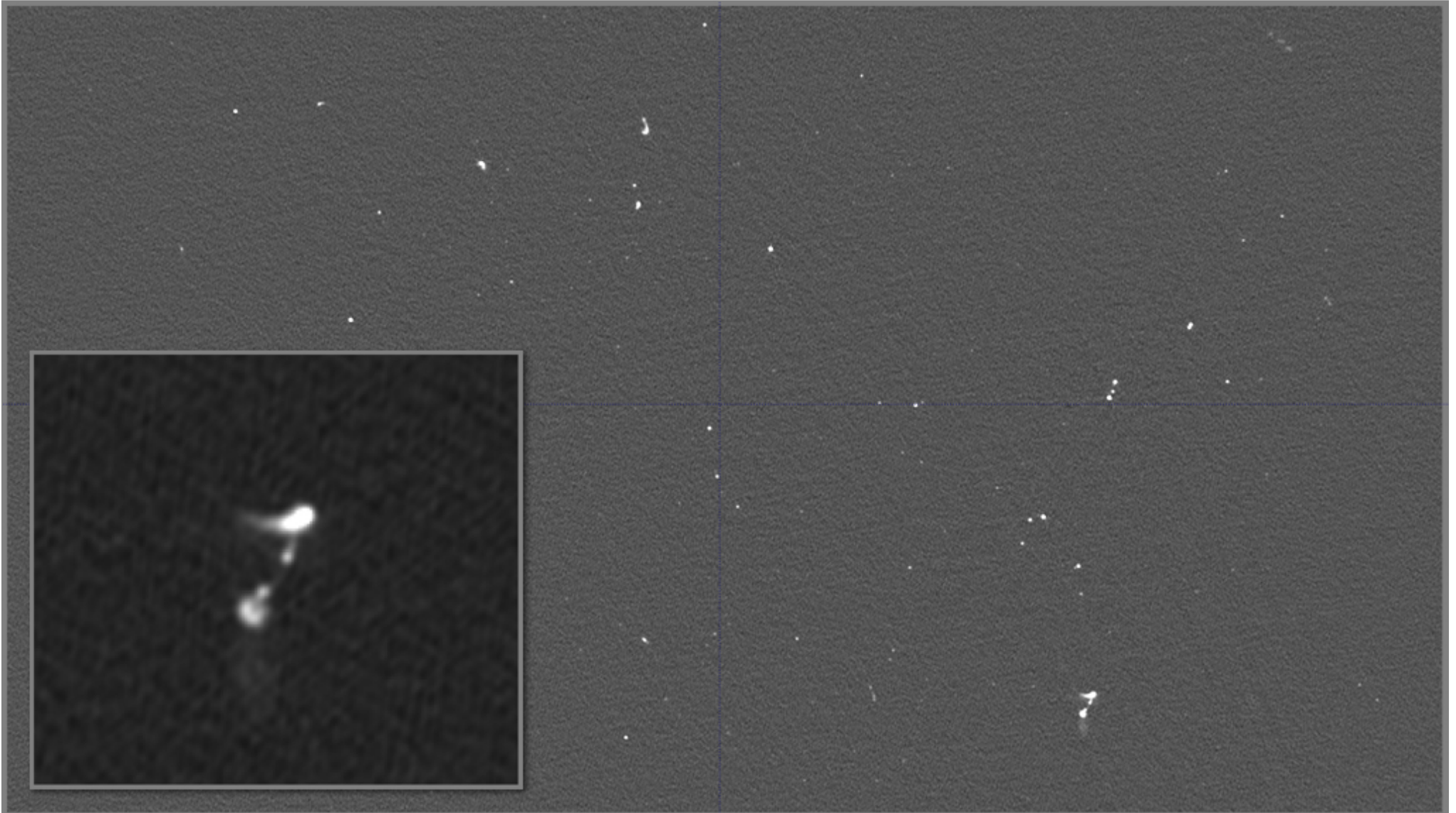
JVLA • B config • 1-2 GHz • 1 hour observation



Deconvolved image

Primary beam correction

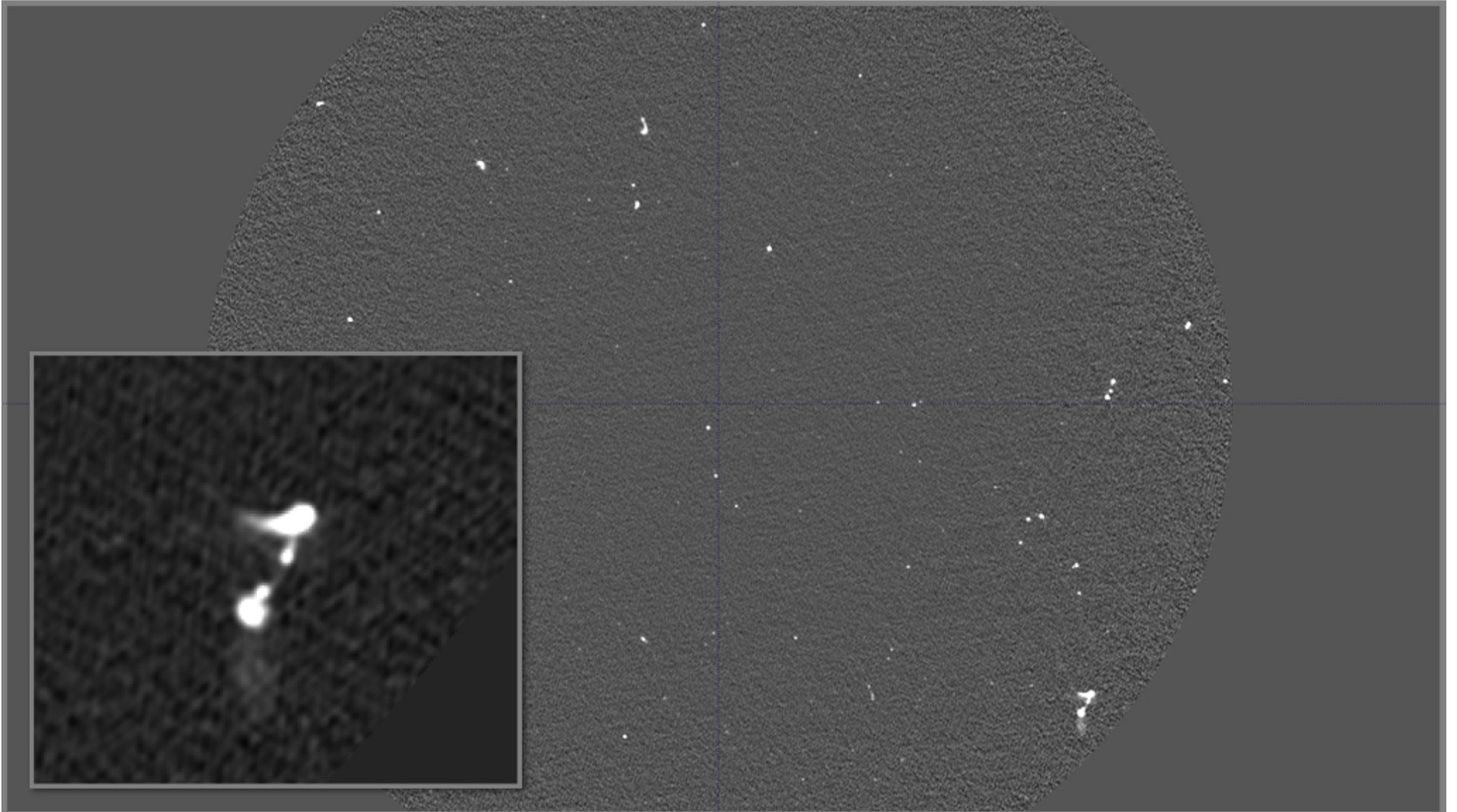
JVLA • B config • 1-2 GHz • 1 hour observation



Deconvolved image

Primary beam correction

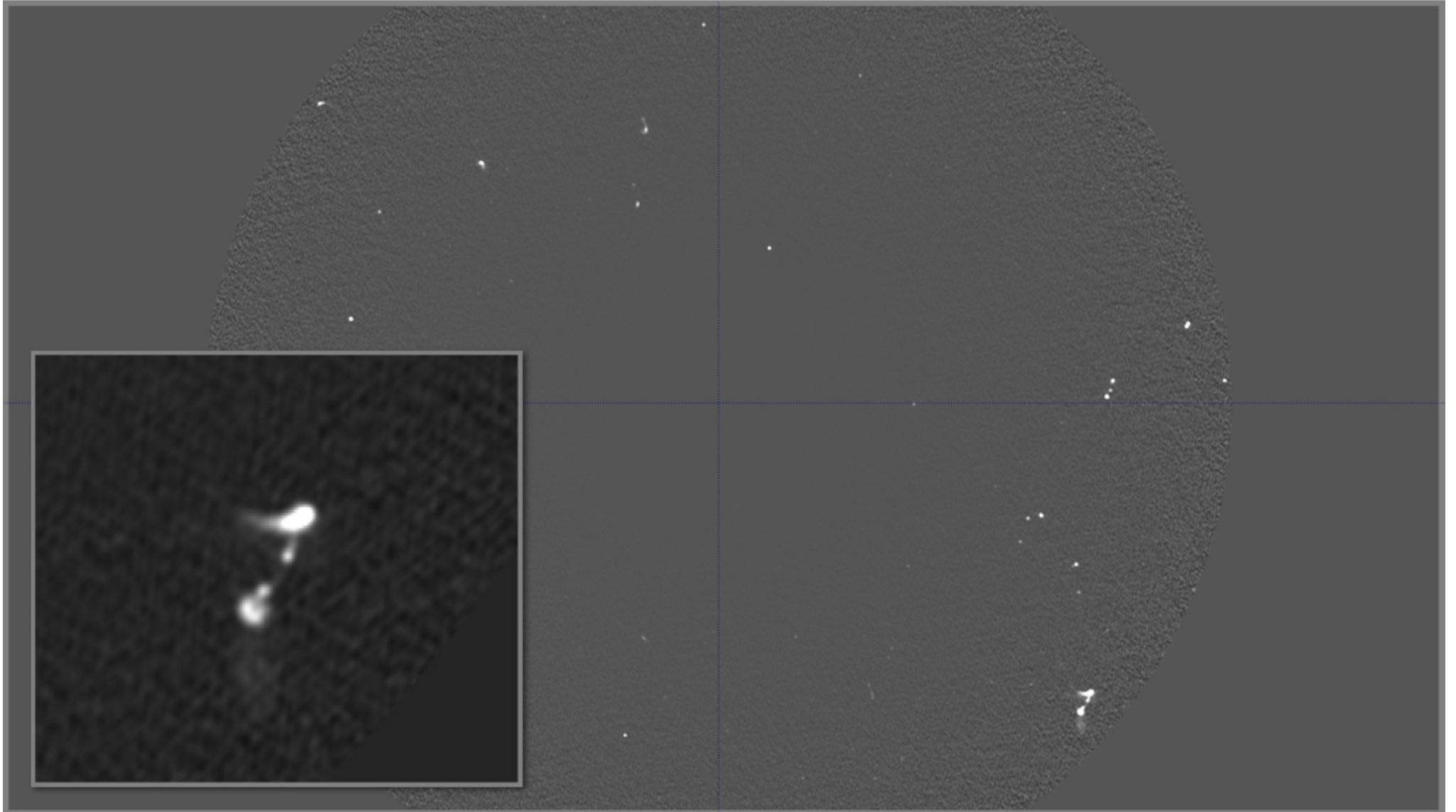
JVLA • B config • 1-2 GHz • 1 hour observation



Primary beam corrected image

Primary beam correction

JVLA • B config • 1-2 GHz • 1 hour observation

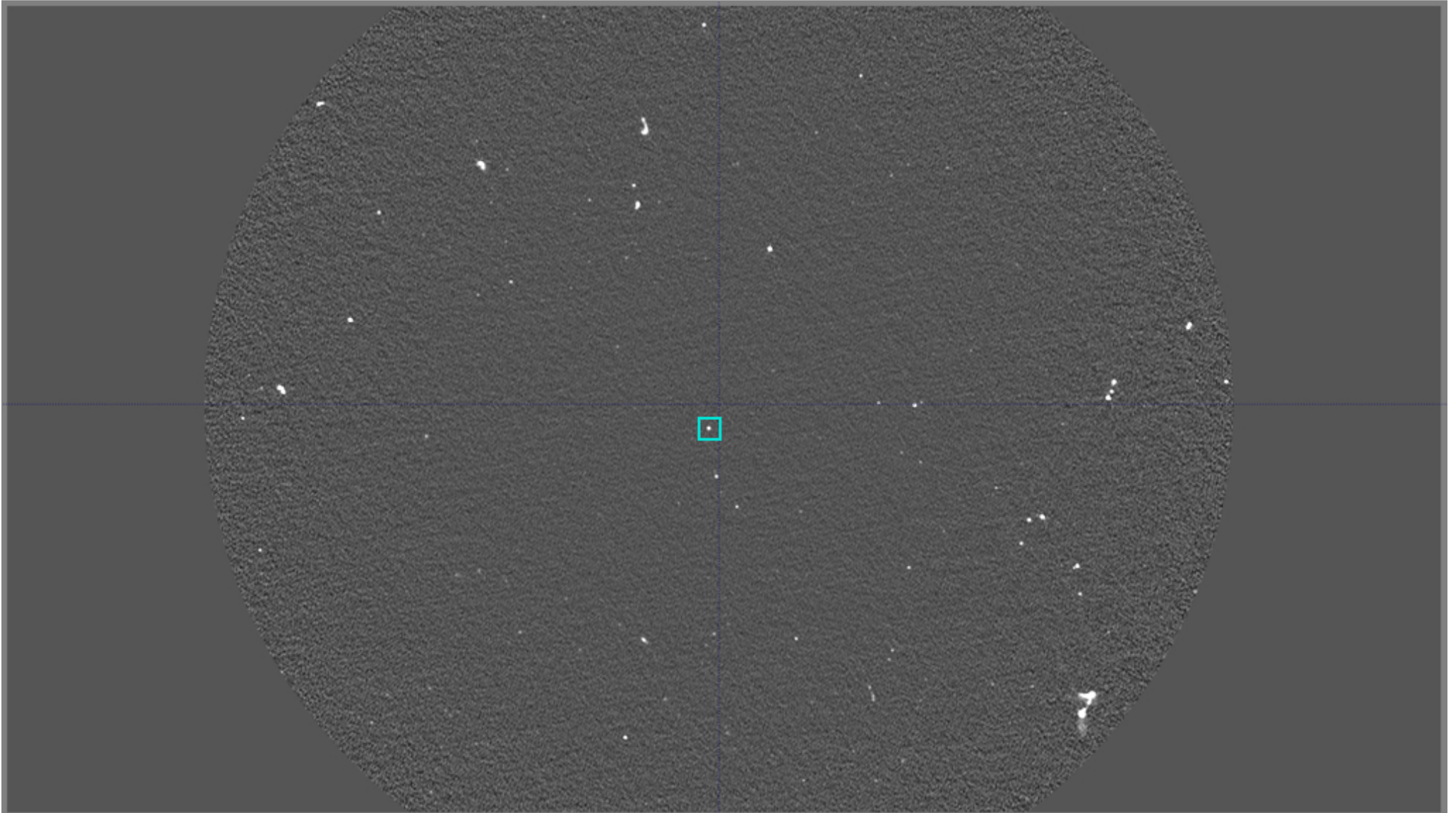


Difference image

Image measurements and source characterisation

Measuring source parameters

JVLA • B config • 1-2 GHz • 1 hour observation





Primary beam corrected image

Measuring source parameters

▶ Quick measurements with a GUI:

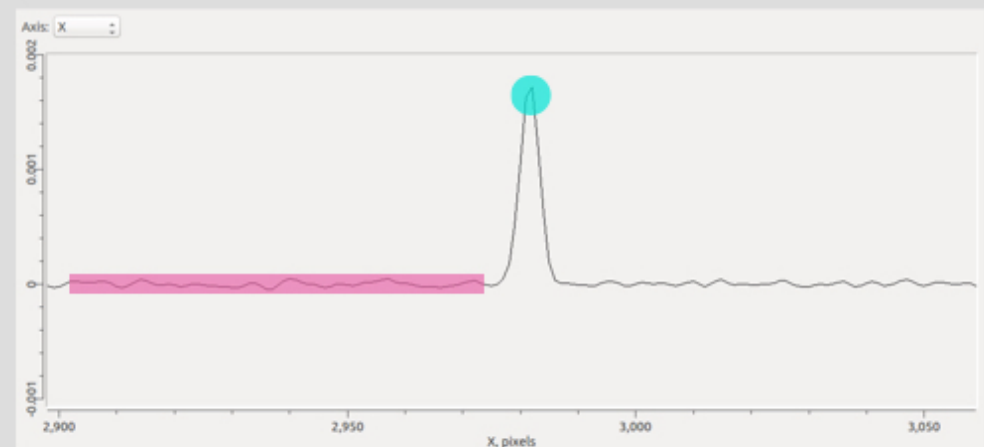
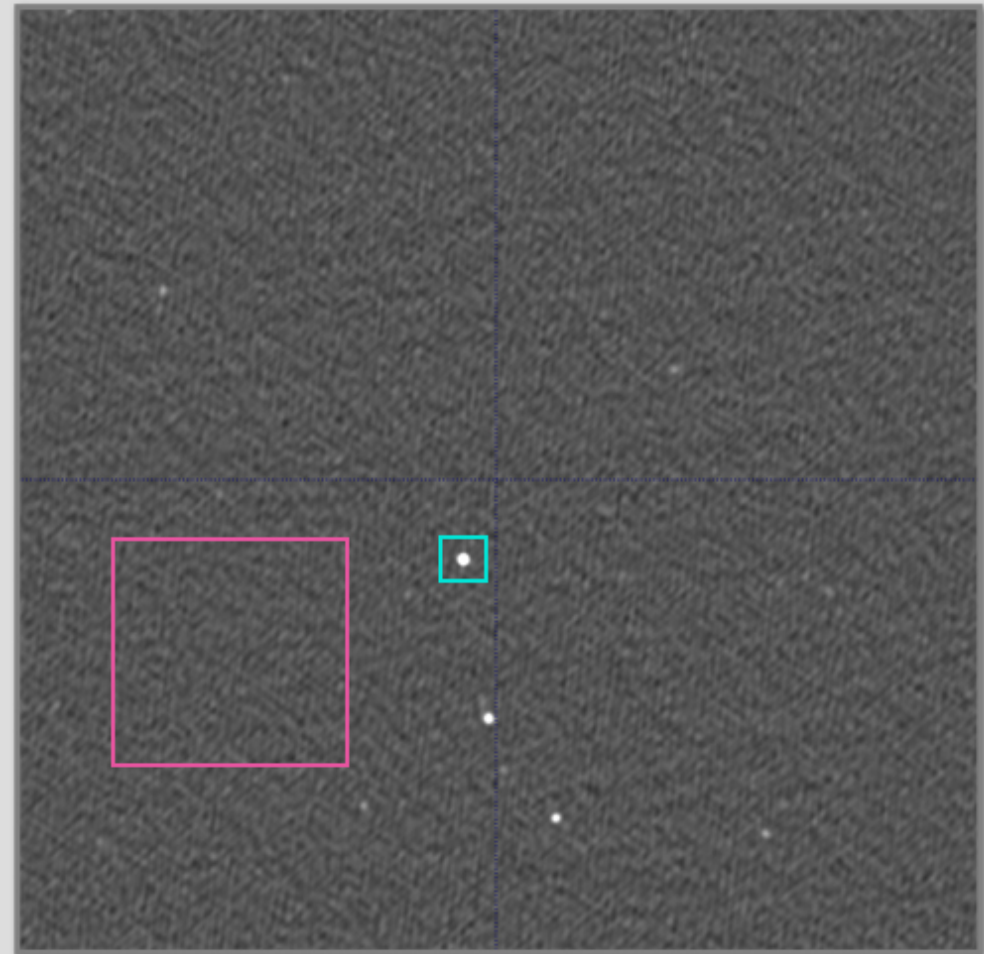
- P = component peak flux density
- σ = RMS background noise
- P/σ = signal to noise ratio

▶ What GUI?

- kvis: drag a box and press 's'
- AIPS: imstat, tvstat
- CASA viewer: define region 
- Tigger: use stats tool 

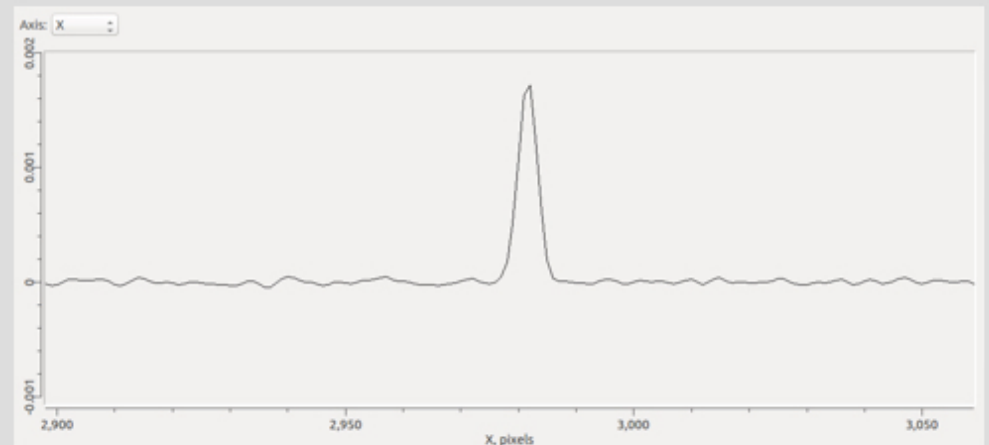
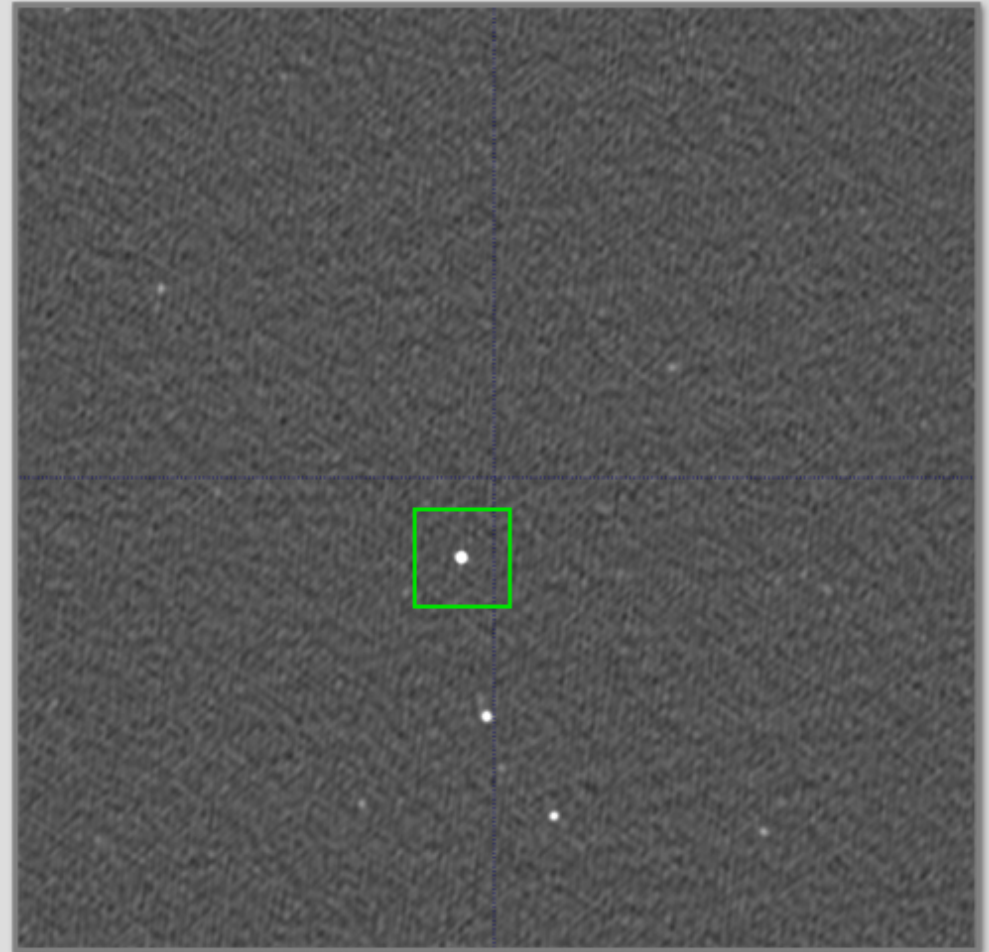
▶ Extended sources

- Sum the flux density over area of source
- Region can be hand drawn
- Use low resolution image



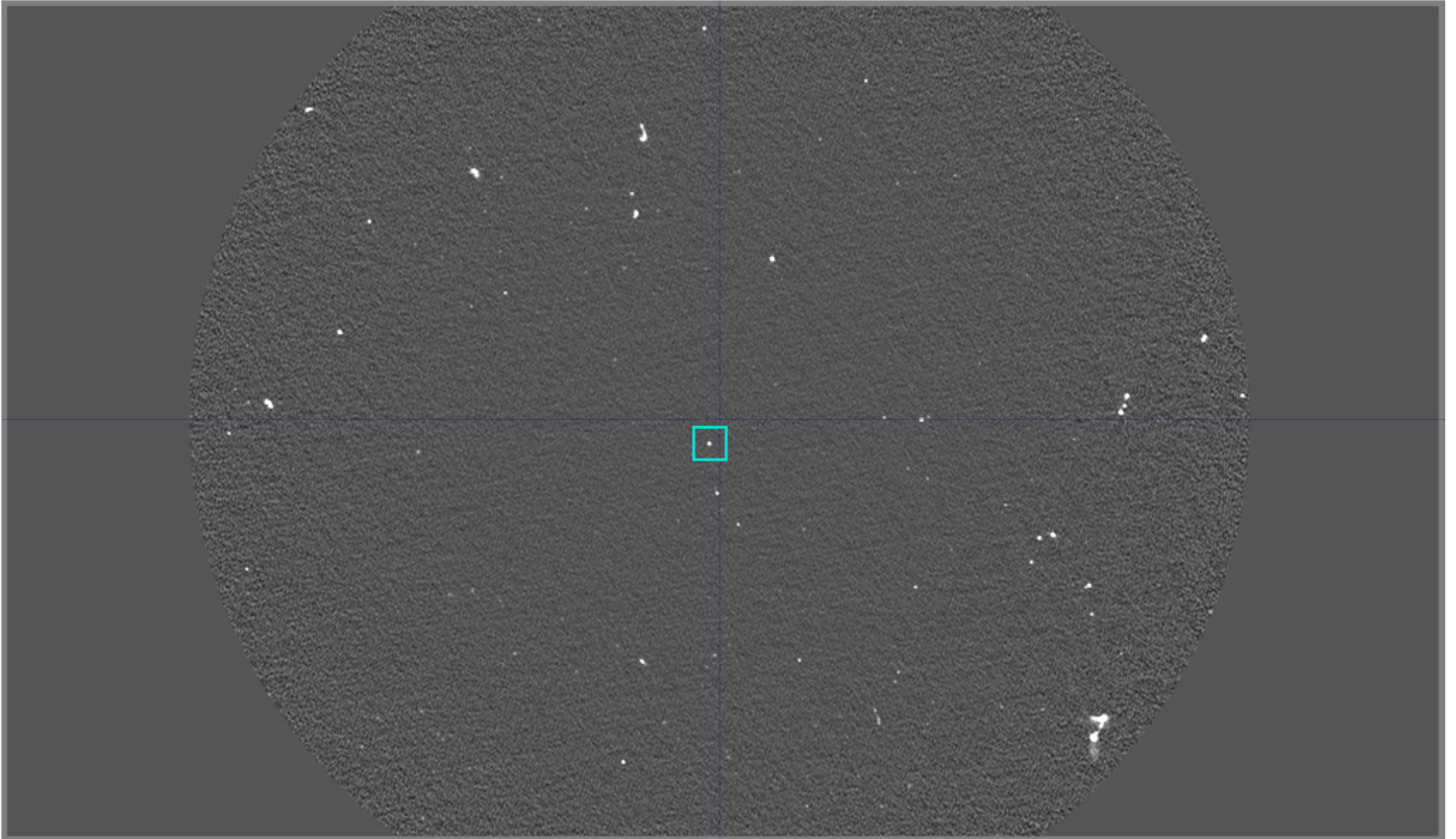
Measuring source parameters

- ▶ Point / Gaussian component fitting:
 - Miriad: imfit
 - AIPS: imfit, jmfitt
 - CASA: imfit
- ▶ Define region to constrain fit
- ▶ Return parameters with error estimates
- ▶ Deconvolve restoring beam to estimate intrinsic source size
- ▶ Generate residual images



Measuring source parameters

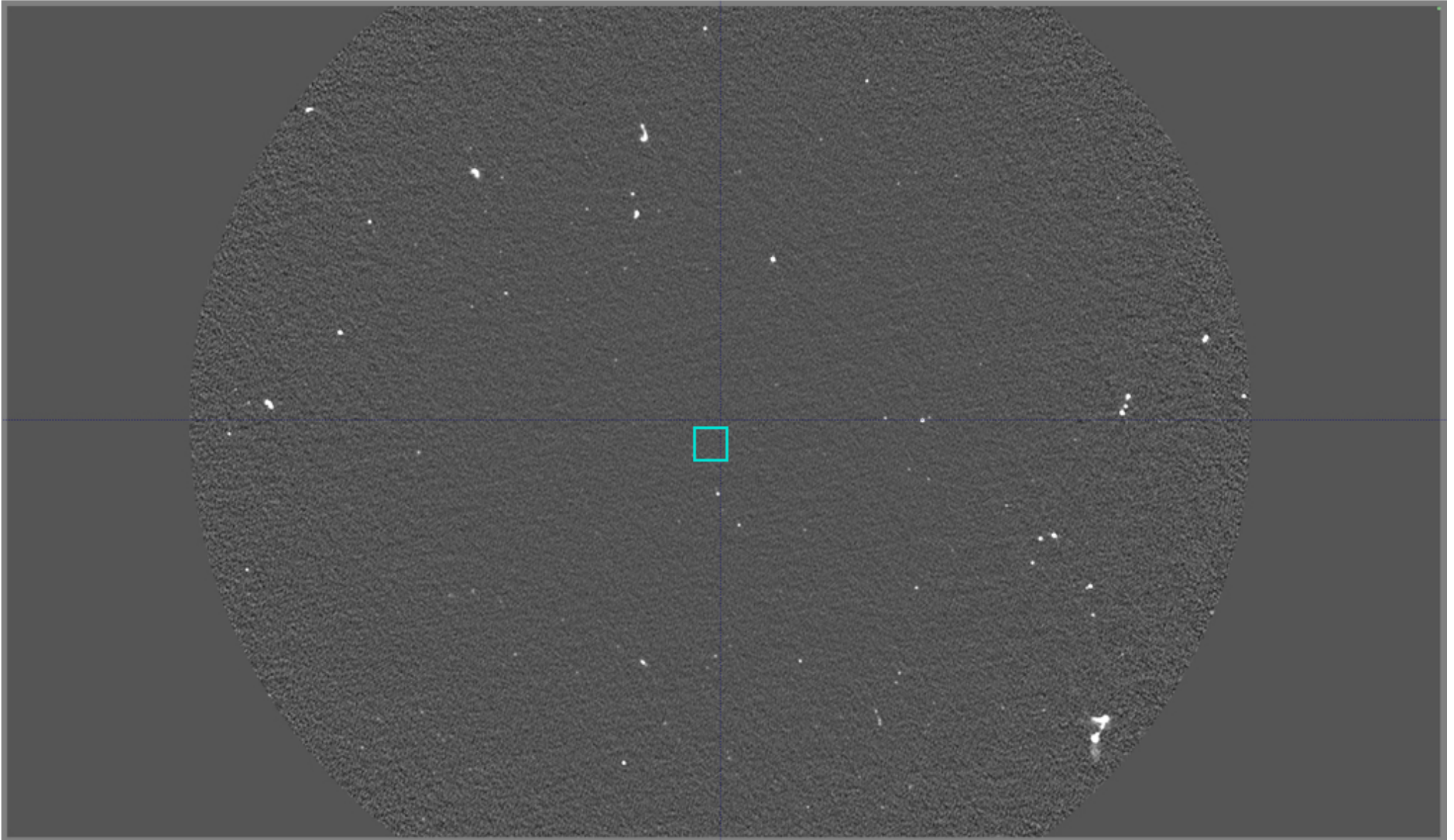
JVLA • B config • 1-2 GHz • 1 hour observation



Example using CASA imfit: input image

Measuring source parameters

JVLA • B config • 1-2 GHz • 1 hour observation



Residual image returned by CASA imfit

Measuring source parameters

JVLA • B config • 1-2 GHz • 1 hour observation

```
***** Fit performed at Wed Sep 23 23:22:44 2015*****
Input parameters ---
  --- imagename:      /home/ianh/Desktop/img_sb26451183_VIDE0_VLA28_9s.ms_main.pbcor.image.tt0.fits
  --- region:
  --- channel:       0
  --- stokes:        I
  --- mask:
  --- include pixel range: []
  --- exclude pixel range: []
*** Details of fit for channel number 0
Number of pixels used in fit: 462
Input and residual image statistics (to be used as a rough guide only as to goodness of fit)
  --- Standard deviation of input image: 0.00027253 Jy
  --- Standard deviation of residual image: 1.87349e-05 Jy
  --- RMS of input image: 0.00028292 Jy
  --- RMS of residual image: 1.87148e-05 Jy

Fit on img_sb26451183_VIDE0_VLA28_9s.ms_main.pbcor.image.tt0.fits component 0
Position ---
  --- ra:    02:20:42.89333 +/- 0.00097 s (0.01456 arcsec along great circle)
  --- dec:  -005.19.32.42999 +/- 0.01505 arcsec
  --- ra:    2981.632 +/- 0.015 pixels
  --- dec:  2954.069 +/- 0.015 pixels

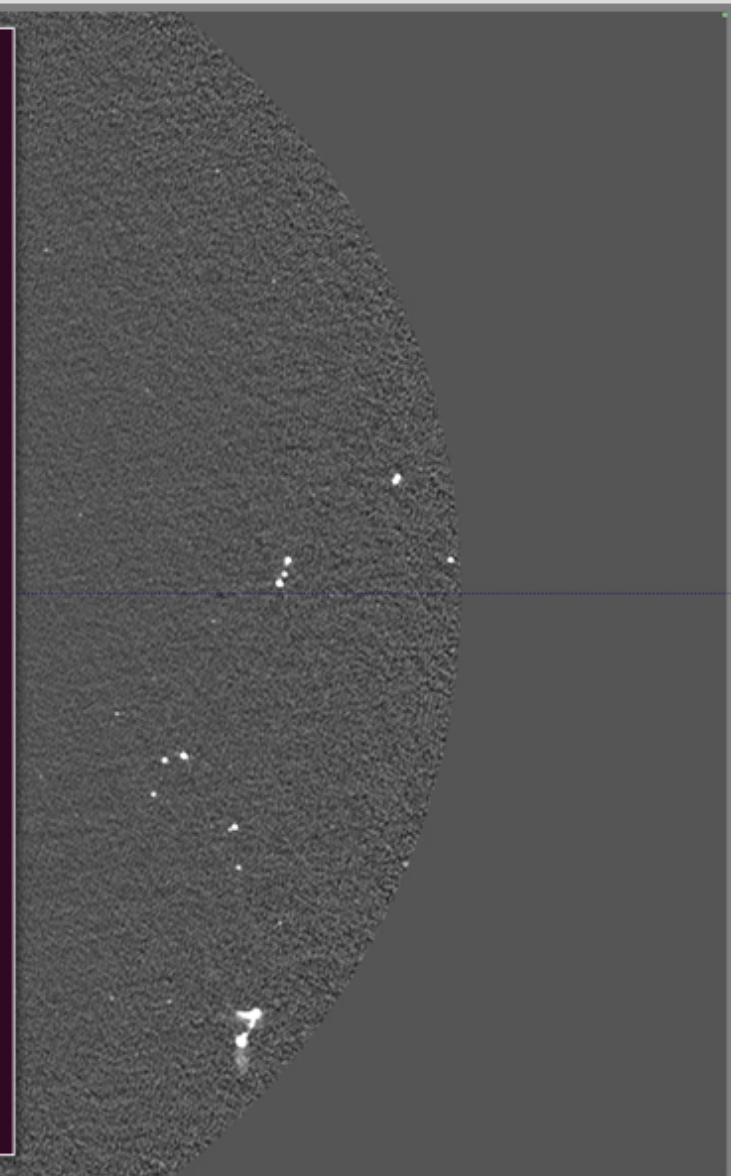
Image component size (convolved with beam) ---
  --- major axis FWHM:    3.944 +/- 0.036 arcsec
  --- minor axis FWHM:    3.856 +/- 0.034 arcsec
  --- position angle: 22 +/- 16 deg

Clean beam size ---
  --- major axis FWHM: 4.00 arcsec
  --- minor axis FWHM: 4.00 arcsec
  --- position angle: 0.00 deg

Image component size (deconvolved from beam) ---
  Component is a point source
  An upper limit on its size cannot be determined

Flux ---
  --- Integrated:  1.965 +/- 0.031 mJy
  --- Peak:        2.067 +/- 0.018 mJy/beam
  --- Polarization: I

Spectrum ---
  --- frequency:    1.499662 GHz (19.99067 cm)
```



Derived parameters from CASA imfit

Parameter error estimation

▶ Given the following measurements:

- P = component peak flux density
- σ = RMS background noise
- $P/\sigma = S$ = signal to noise ratio
- B = synthesised beam size
- θ_i = component size in image
- $\theta_t = [\theta_i^2 - B^2]^{1/2}$ = true component size

▶ Errors are approximately:

- $\Delta P = \sigma$ = peak error
- $\Delta X = B/2S$ = position error
- $\Delta\theta_i = B/2S$ = image component size error
- $\Delta\theta_t = B/S^{1/2}$ = minimum component size

▶ Rigorous treatment of fitting uncertainties:

- Condon 1997, PASP, 109, 166

Publications of the Astronomical Society of the Pacific
109: 166-172, 1997 February

Errors in Elliptical Gaussian Fits

J. J. CONDON
National Radio Astronomy Observatory,¹ 520 Edgemont Road, Charlottesville, Virginia 22903
Electronic mail: jcondon@nrao.edu
Received 1996 May 31; accepted 1996 October 2

ABSTRACT. Elliptical Gaussian fits are used in astronomy for accurate measurements of fundamental source parameters such as central position, peak flux density, and angular size. The full value of a noise-limited image can be realized only if the effects of noise on the fitted parameters are estimated accurately. This paper presents the equations of error propagation for two-dimensional elliptical Gaussian fits in the presence of Gaussian noise plus a new method that simplifies the use of *a priori* size constraints to reduce amplitude errors.

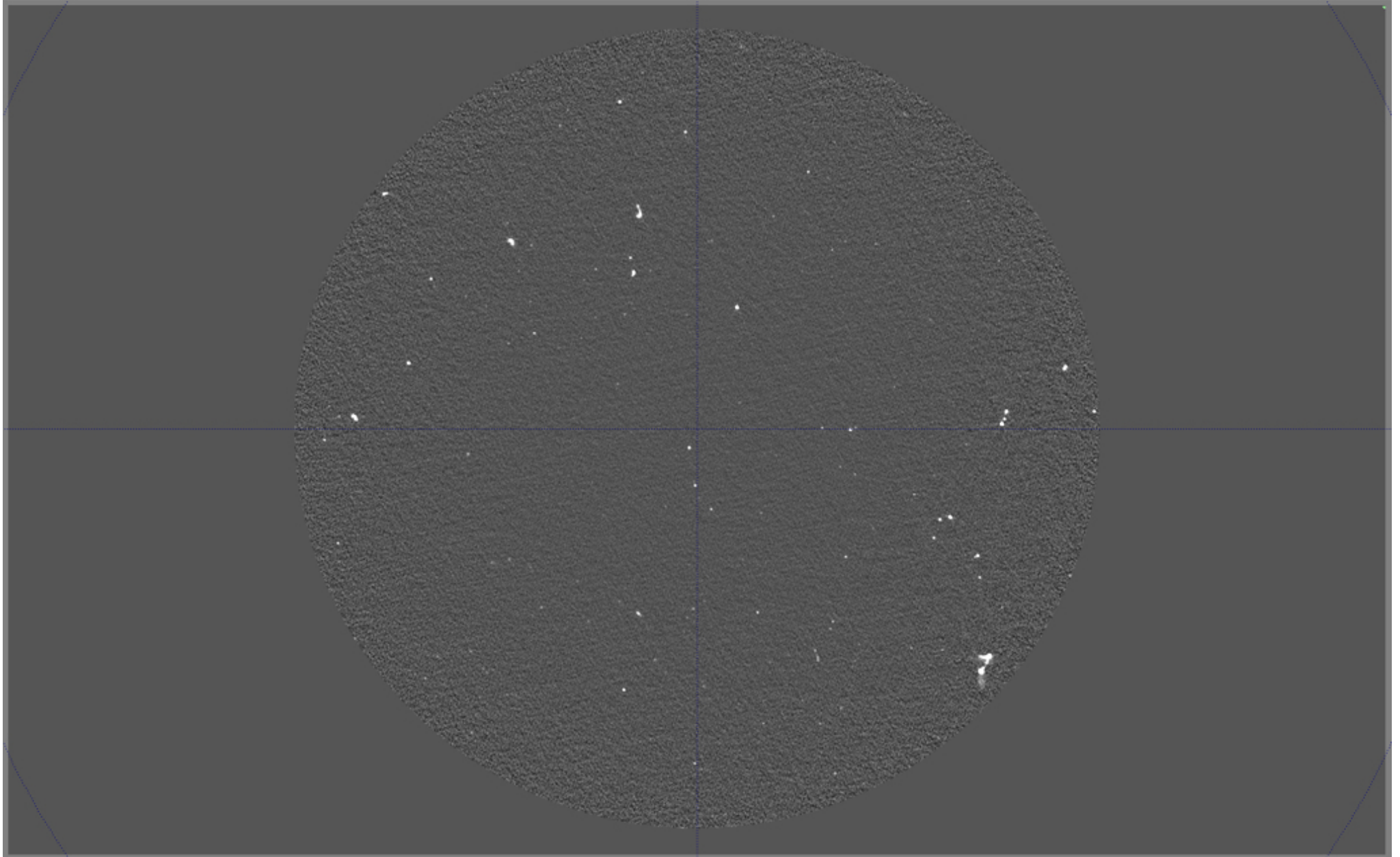
▶ CASA imfit help page also useful:

- <http://casa.nrao.edu/docs/TaskRef/imfit-task.html>

▶ Note that these are *statistical* uncertainties. Errors induced by calibration deficiencies must be estimated separately.

Characterising lots of sources

JVLA • B config • 1-2 GHz • 1 hour observation



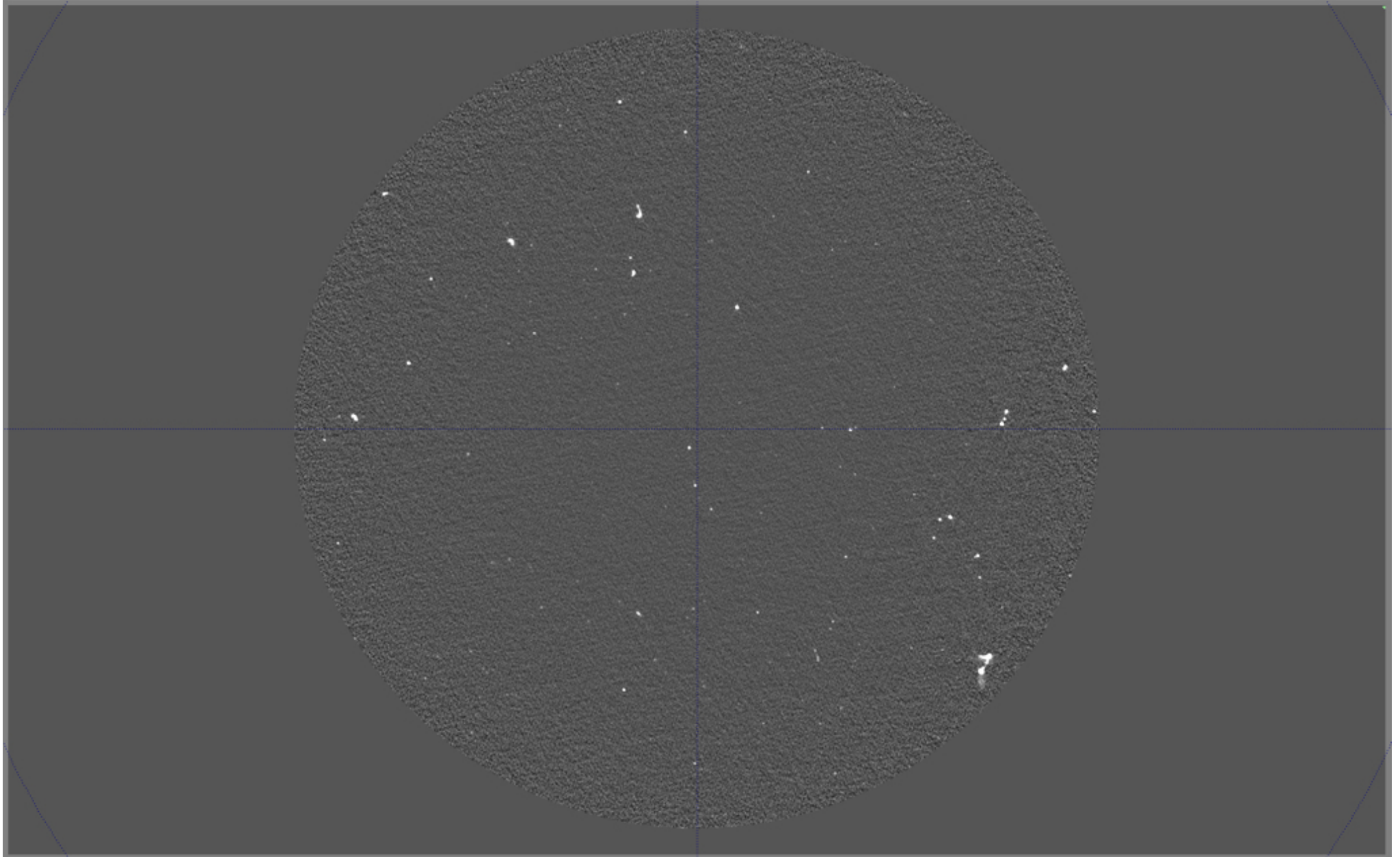
Manually run imfit on all these sources, one by one?

Automated source finding

- ▶ Many software packages available to find sources for you:
 - Miriad: `imsad`, `sfind`
 - AIPS: `sad`
 - CASA: `ia.findsources`
 - Duchamp / Selavy
 - Aegean
 - PyBDSM
 - SoFiA
 - Blobcat
- ▶ Essential for any kind of survey!
- ▶ Algorithms vary: typically an initial thresholded peak search to locate sources, followed by a secondary deeper characterisation method (flood-fill, island component fitting...)
- ▶ Hard or adaptive thresholding available, using estimate of background noise variations
- ▶ Catalogued output, very useful for investigating systematics, statistical uncertainties...

Automated source finding

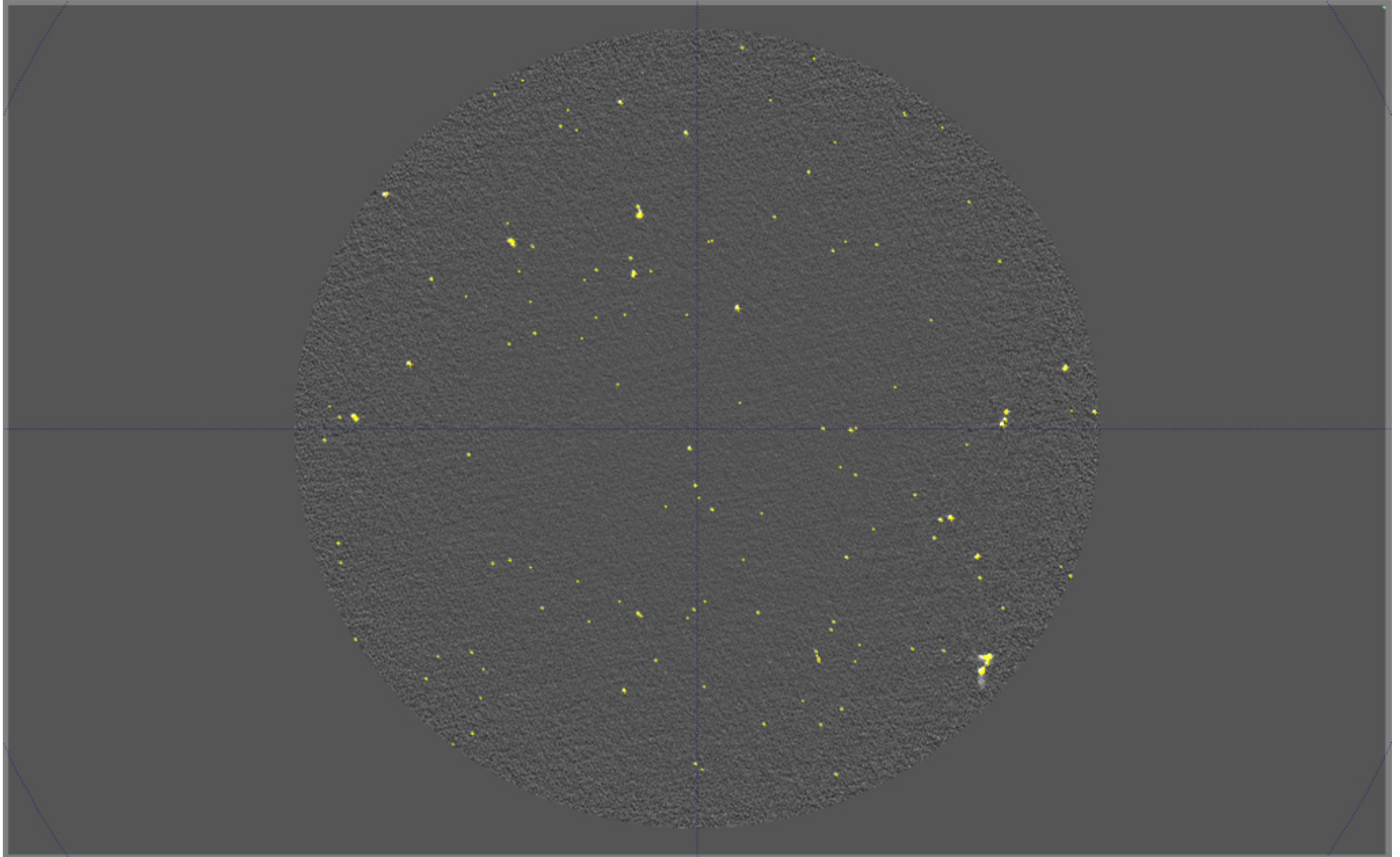
JVLA • B config • 1-2 GHz • 1 hour observation



PyBDSM: 5σ peak threshold, 3σ island threshold

Automated source finding

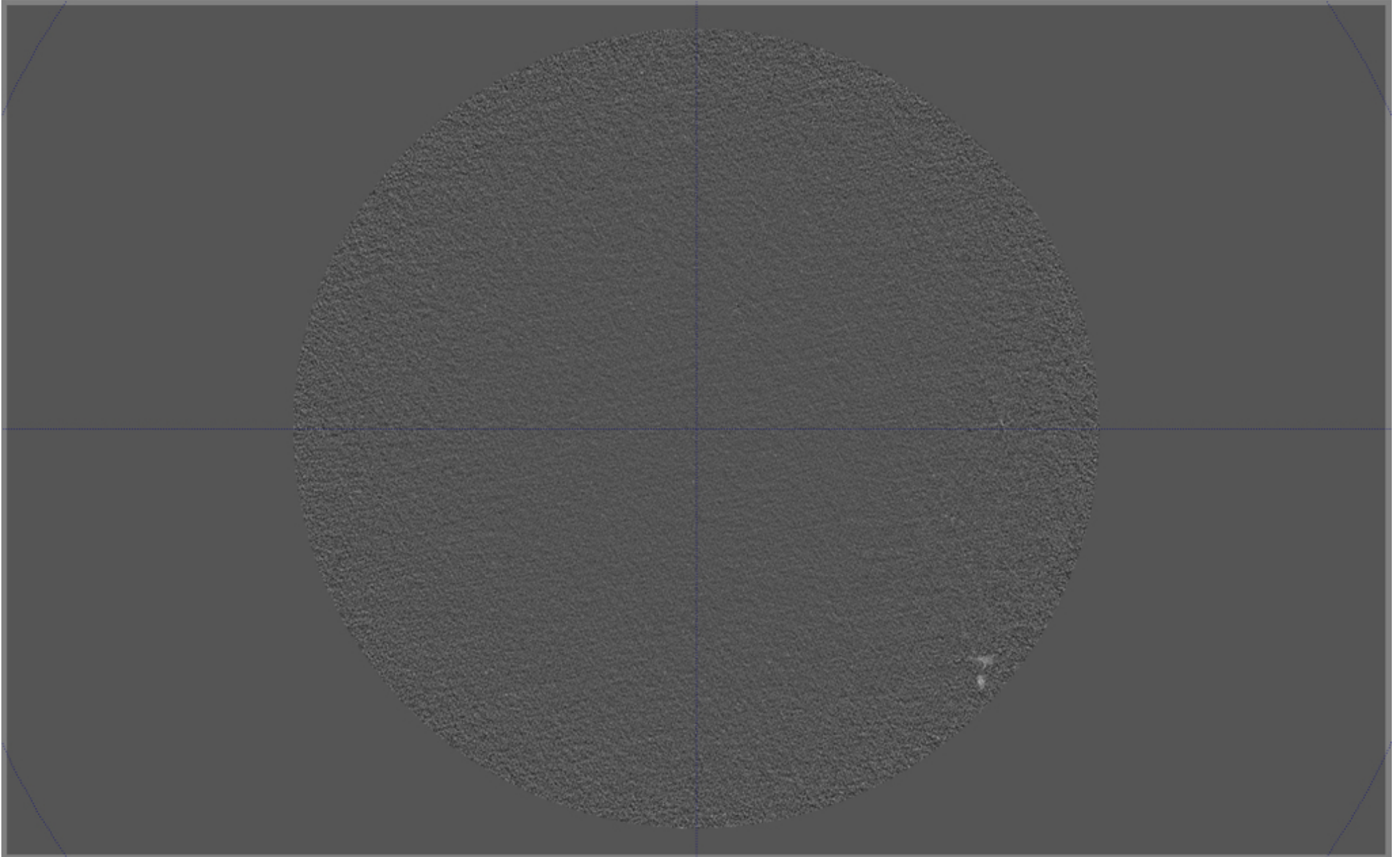
JVLA • B config • 1-2 GHz • 1 hour observation



PyBDSM: 5σ peak threshold, 3σ island threshold

Automated source finding

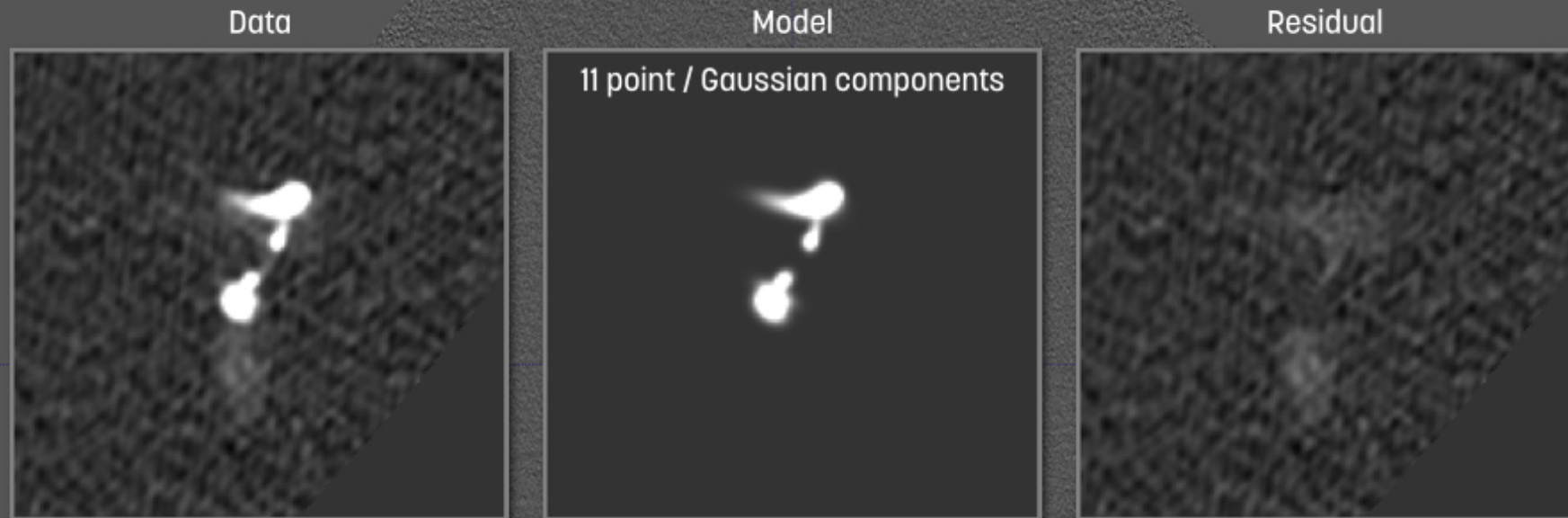
JVLA • B config • 1-2 GHz • 1 hour observation



PyBDSM: 5σ peak threshold, 3σ island threshold (residual image)

Automated source finding

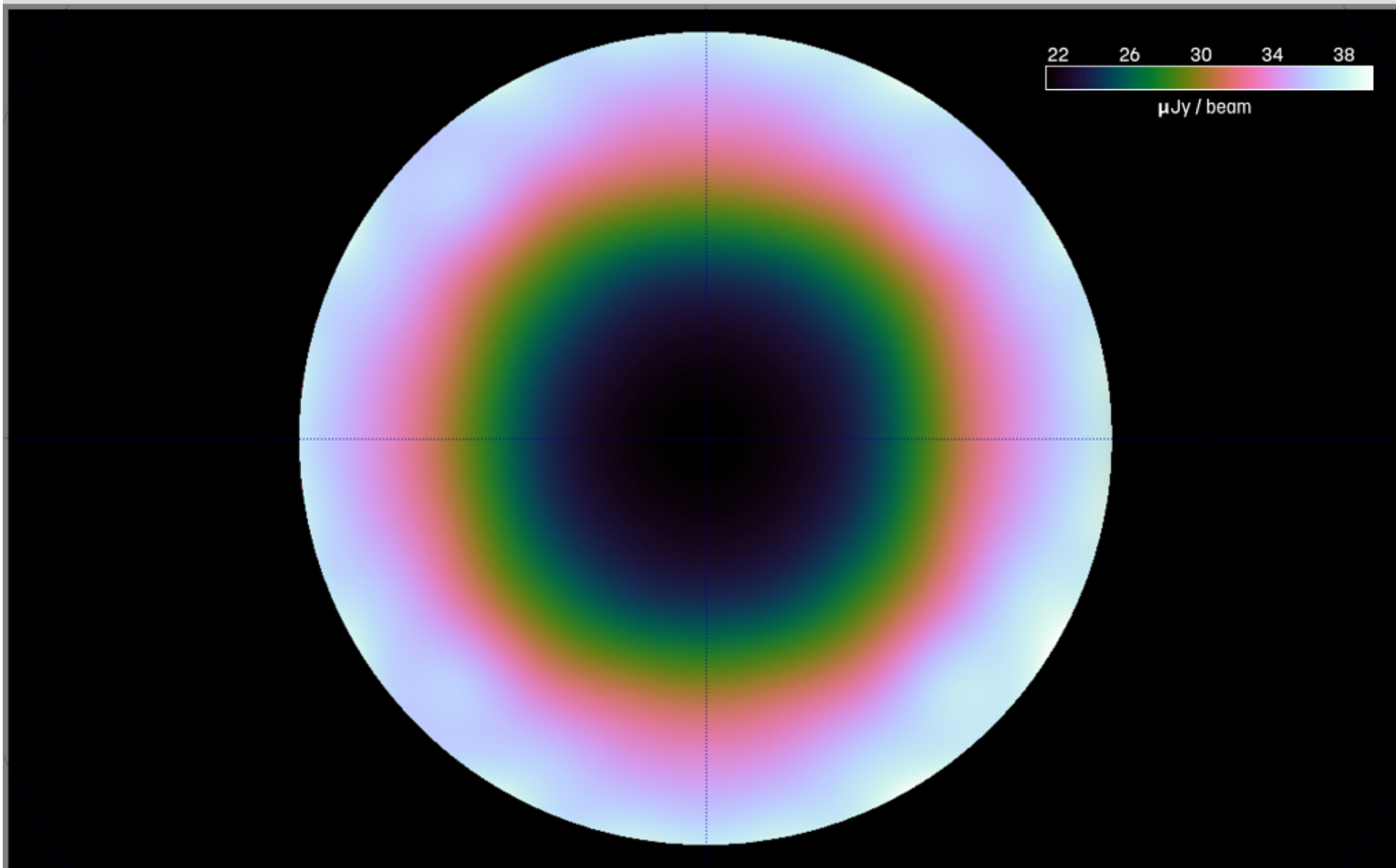
JVLA • B config • 1-2 GHz • 1 hour observation



PyBDSM: 5σ peak threshold, 3σ island threshold (residual image)

Automated source finding

JVLA • B config • 1-2 GHz • 1 hour observation



PyBDSM RMS map

Automated source finding: limitations and pitfalls

- ▶ Faint / diffuse / low surface brightness features are problematic
 - Sum of component fluxes will be an underestimation of the total source flux
- ▶ This cannot be solved by lowering the detection threshold!
 - False detections increase dramatically below 5σ
 - At 5σ expect 6 spurious features in a 10,000 x 10,000 pixel image
 - Eddington bias becomes extremely severe at lower thresholds
- ▶ Relatedly, use source finders with care if you think your map is confusion limited

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The ASKAP/EMU Source Finding Data Challenge

A. M. Hopkins^{1,*}, M. T. Whiting², N. Seymour³, K. E. Chou², R. P. Norris², L. Bonavera⁴, R. Breton⁵, D. Carbone⁶, C. Ferrari⁷, T. M. O. Franzen⁸, H. Garsden⁹, J. González-Nuevo^{9,4}, C. A. Hale^{10,11}, P. J. Hancock^{3,12,13}, G. Heald^{14,15}, D. Herranz⁴, M. Huys¹⁶, R. J. Jurek², M. López-Cariago^{17,4}, M. Massardi¹⁸, N. Mohan¹⁹, S. Molinari²⁰, E. Orr¹⁴, R. Paladino^{20,18}, M. Pestalozzi²⁰, R. Pizzo¹⁴, D. Rafferty²², H. J. A. Röttgering²³, L. Rudnick²⁴, E. Schisano²⁰, A. Skutevski^{14,15}, J. Swinbank^{25,6}, R. Taylor^{26,27}, A. J. van der Horst^{28,6}

- ▶ Source finder showdown paper recently published by Hopkins et al., PASA, arXiv:1509.03931

Image arithmetic

Examples of arithmetic operations on images

- ▶ Primary beam correction

- Divide by primary beam image

- ▶ Make a residual image

- Subtract model image

- ▶ Degree of polarisation

- $p = (Q^2 + U^2)^{1/2} / I$

- ▶ Spectral index

- $\alpha = \frac{\log (S_1 / S_2)}{\log (\nu_1 / \nu_2)}$

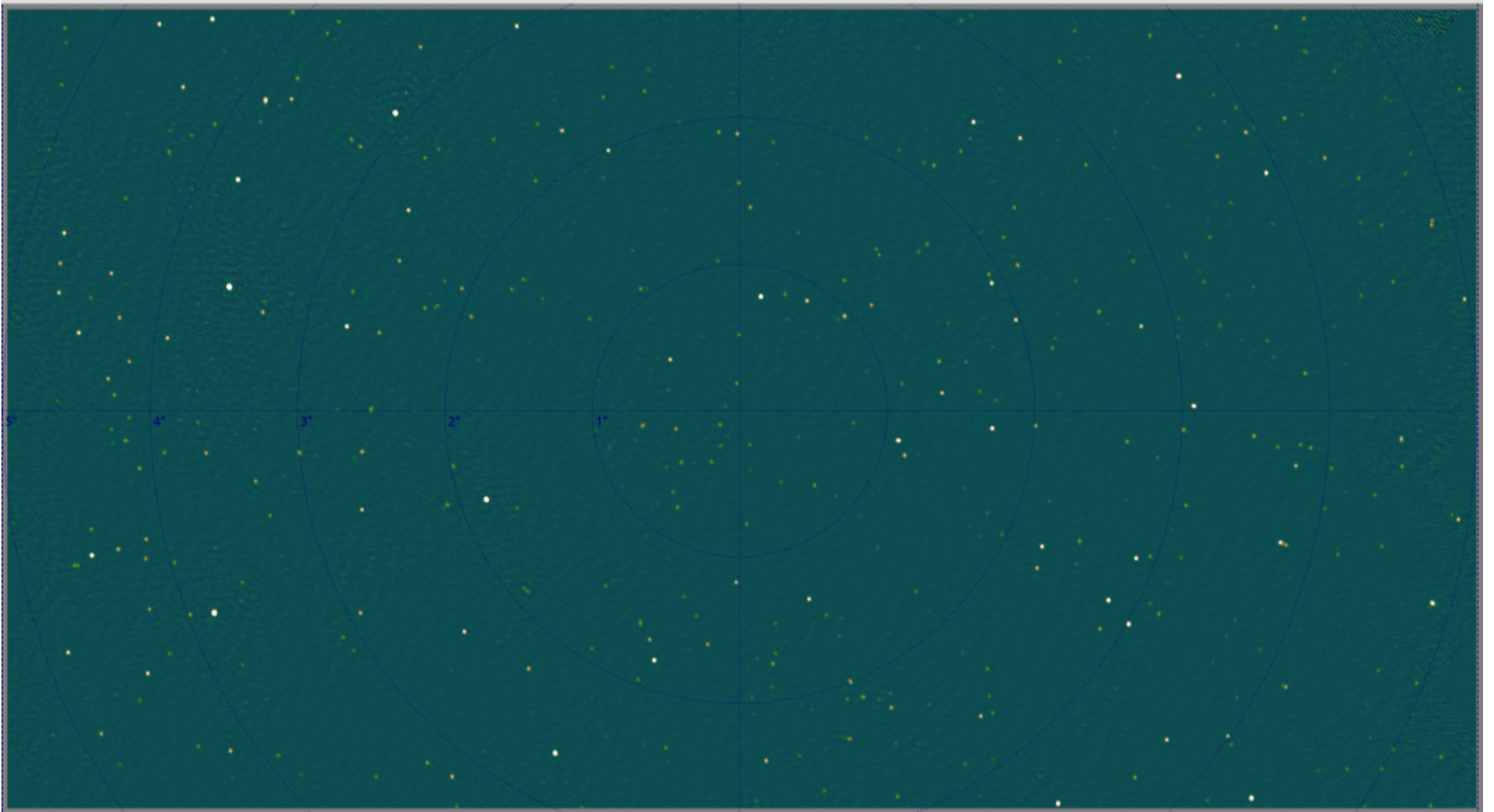
- ▶ Astrometric alignment of input images must be excellent

- ▶ Resolutions must match

- ▶ Convolve, re-grid and interpolate images if necessary

Spectral index measurements

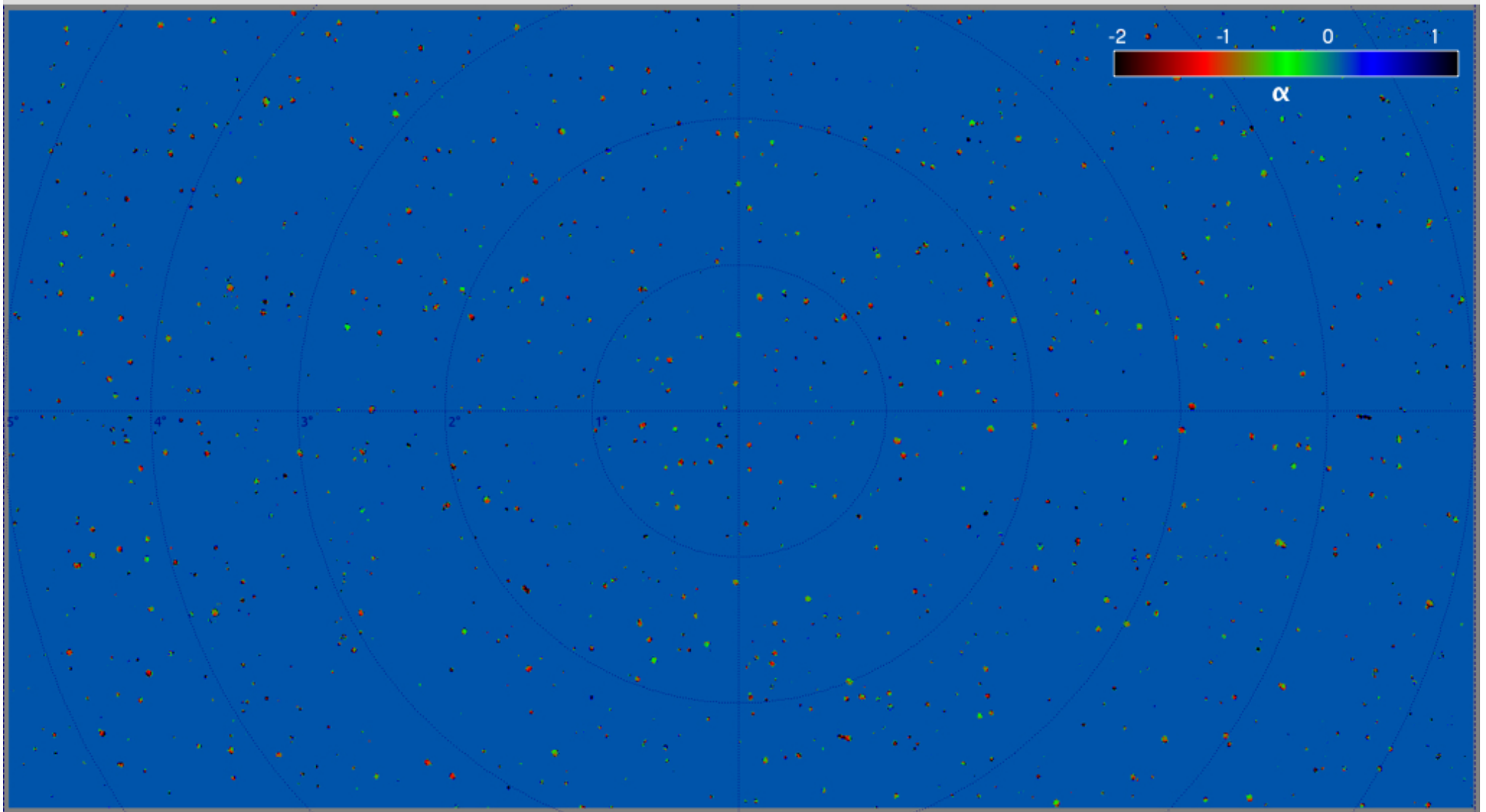
ASKAP / BETA • 711 - 1015 MHz • 3 × 12 hour observations



The 304 MHz band imaged in 4 × 76 MHz chunks

Spectral index measurements

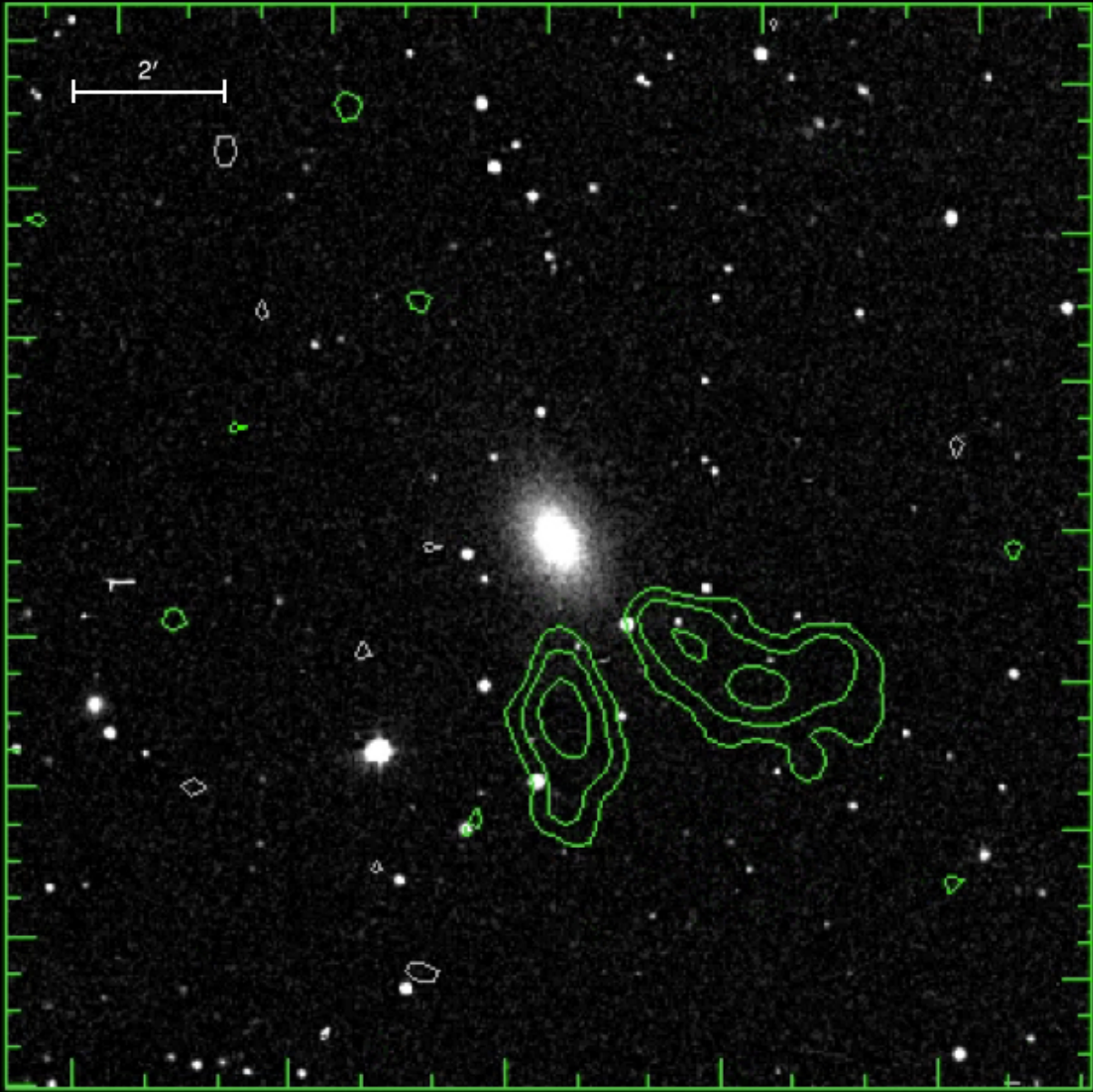
ASKAP / BETA • 711 - 1015 MHz • 3 × 12 hour observations



Pixelwise linear fit to the pixel spectra in log space (gradient = α)

Spectral line cubes

WSRT



Moment images: reduce the dimensionality

▶ Zeroth moment: integrated intensity

$$\bullet I_{tot} = \Delta v \sum_{i=1}^n I(\alpha, \delta, v_i)$$

▶ Computing moment images:

- Miriad: moment
- AIPS: momnt
- CASA: immoments

▶ First moment: intensity weighted velocity (or whatever is the non-spatial coordinate)

$$\bullet \bar{v} = \frac{\sum_{i=1}^n v_i I(\alpha, \delta, v_i)}{\sum_{i=1}^n I(\alpha, \delta, v_i)}$$

▶ Second moment: intensity weighted dispersion of velocity

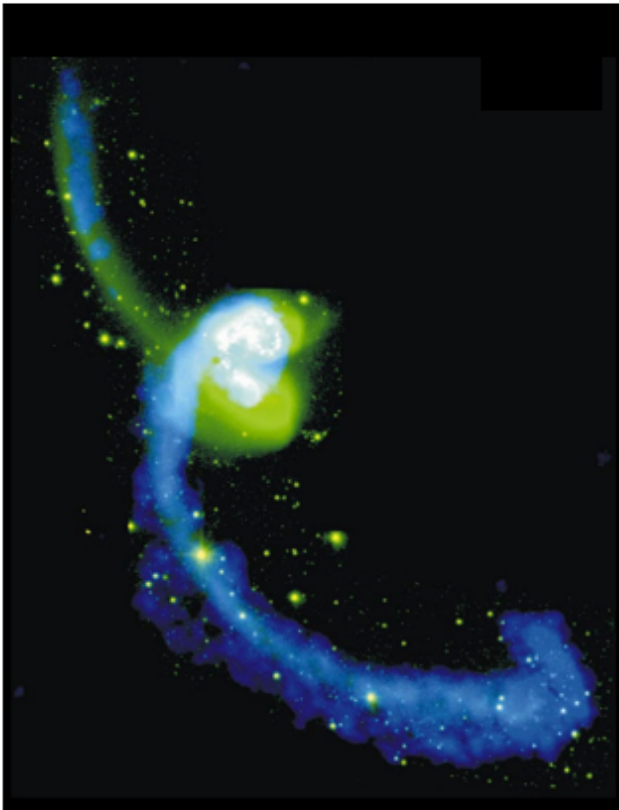
$$\bullet \sigma_v = \sqrt{\frac{\sum_{i=1}^n I(\alpha, \delta, v_i) (v_i - \bar{v}(\alpha, \delta))^2}{\sum_{i=1}^n I(\alpha, \delta, v_i)}}$$

Example moment images

VLA • C+D config • 3.5+8 hours

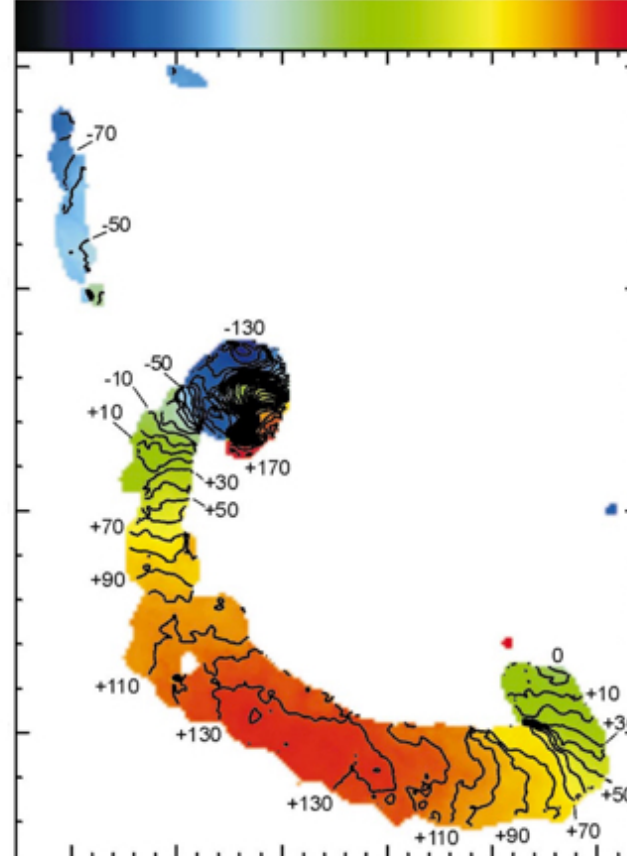
Moment 0

Radio = Blue
Optical = Green / white



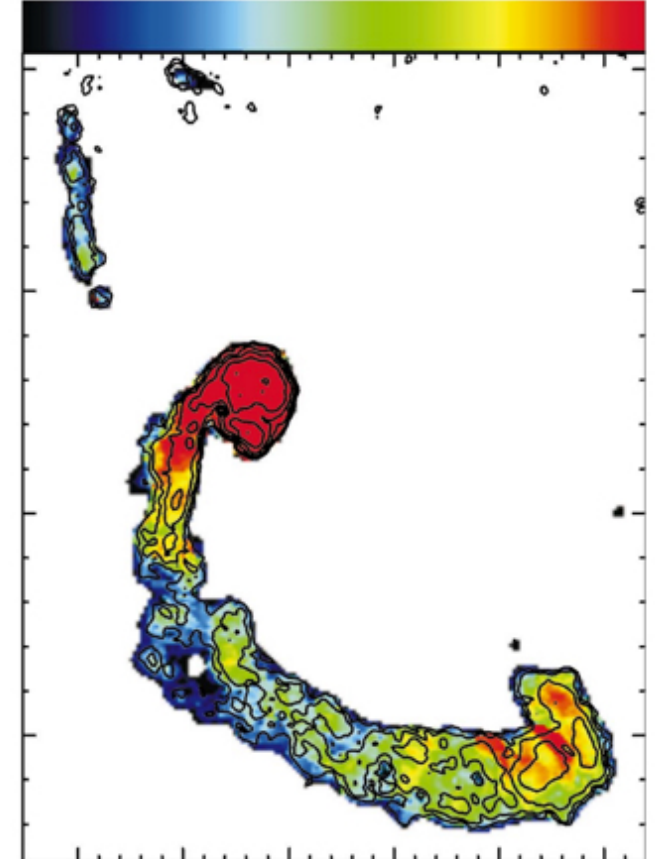
Moment 1

-100 km/s -50 km/s 0 km/s +50 km/s +100 km/s

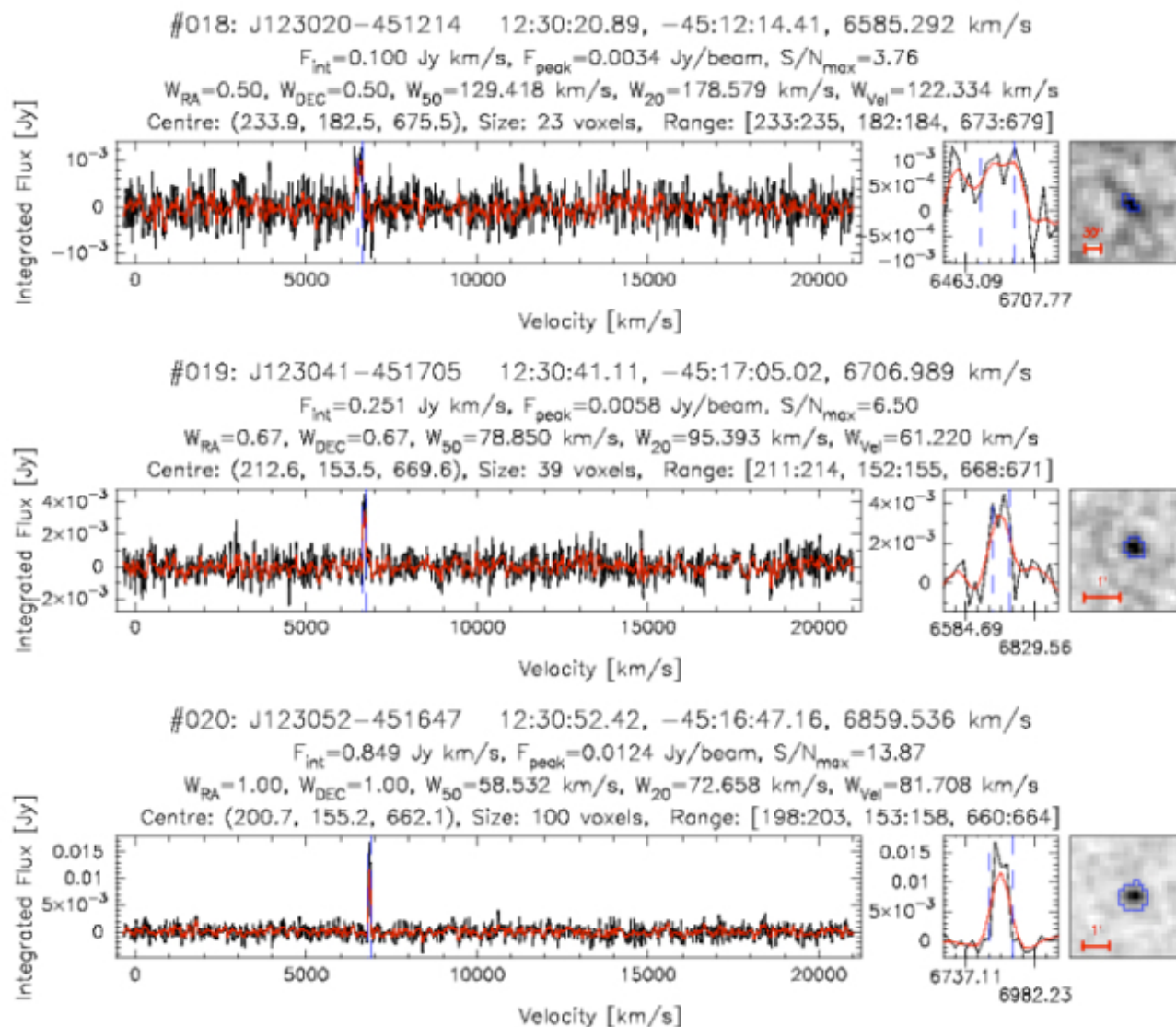


Moment 2

5 km/s 9 km/s 13 km/s



Spectral line source finders



Summary

Adapt your analysis methods to best fit your science goals.

Spend time getting to know your instrument.

The tools are out there, and if they aren't then make your own!