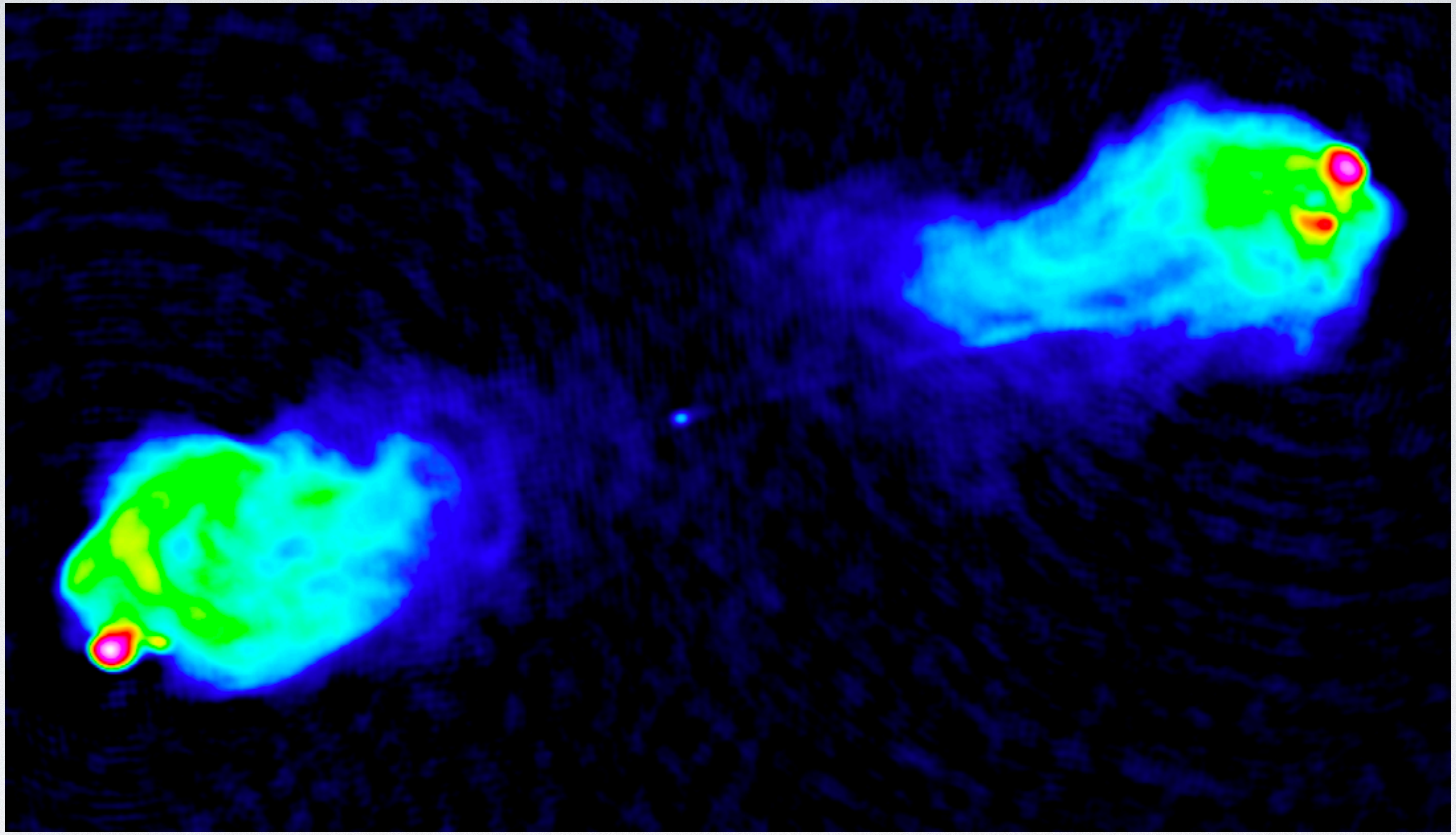


INTRODUCTION TO IMAGING

DARA UNIT 4

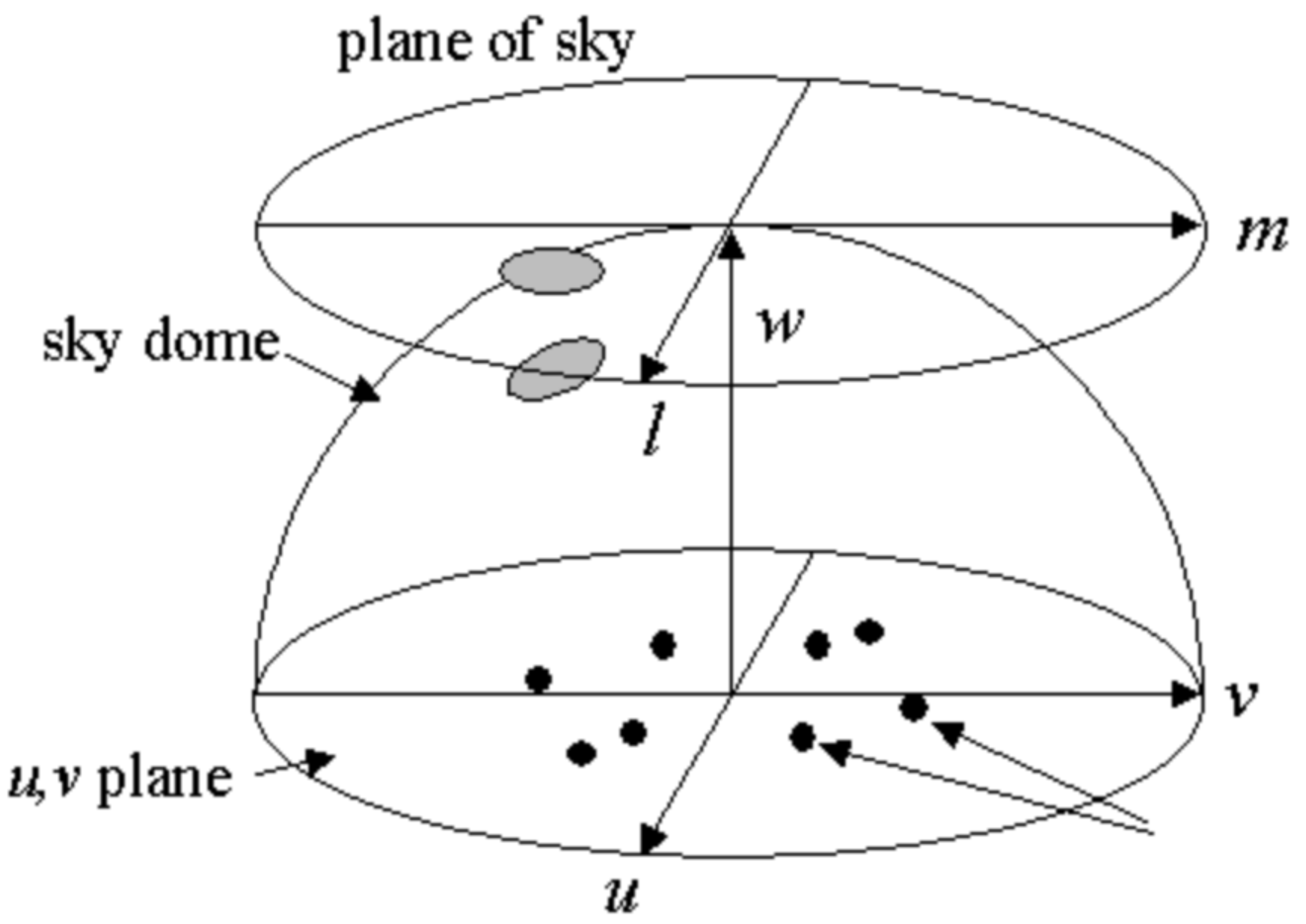
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Katie Hesterly
Cardiff University

DEVELOPMENT IN AFRICA WITH RADIO ASTRONOMY

Visibilities

- The complex visibility function, $V(u, v)$, is the 2D Fourier transform of $T(l, m)$
  - where $T(l, m)$ is the sky brightness distribution (e.g. for small fields of view)



Credit: Prof Dale Gary, NJIT

Mathematically

$$V(u, v) = \int\int T(l, m) e^{-2\pi i(ul + vm)} dl dm$$

$$T(l, m) = \int\int V(u, v) e^{2\pi i(ul + vm)} du dv$$

$$V(u, v) \xrightarrow{F} T(l, m)$$

The Fourier Transform

- The Fourier theory: any well behaved signal (including images) can be expressed as the sum of sinusoids.

- The Fourier transform (FT) is the mathematical tool that allows us to decompose the signal into its sinusoidal components.

    - the FT contains all of the information from the original signal

If you know the the FT you know all of the information about the original signal!

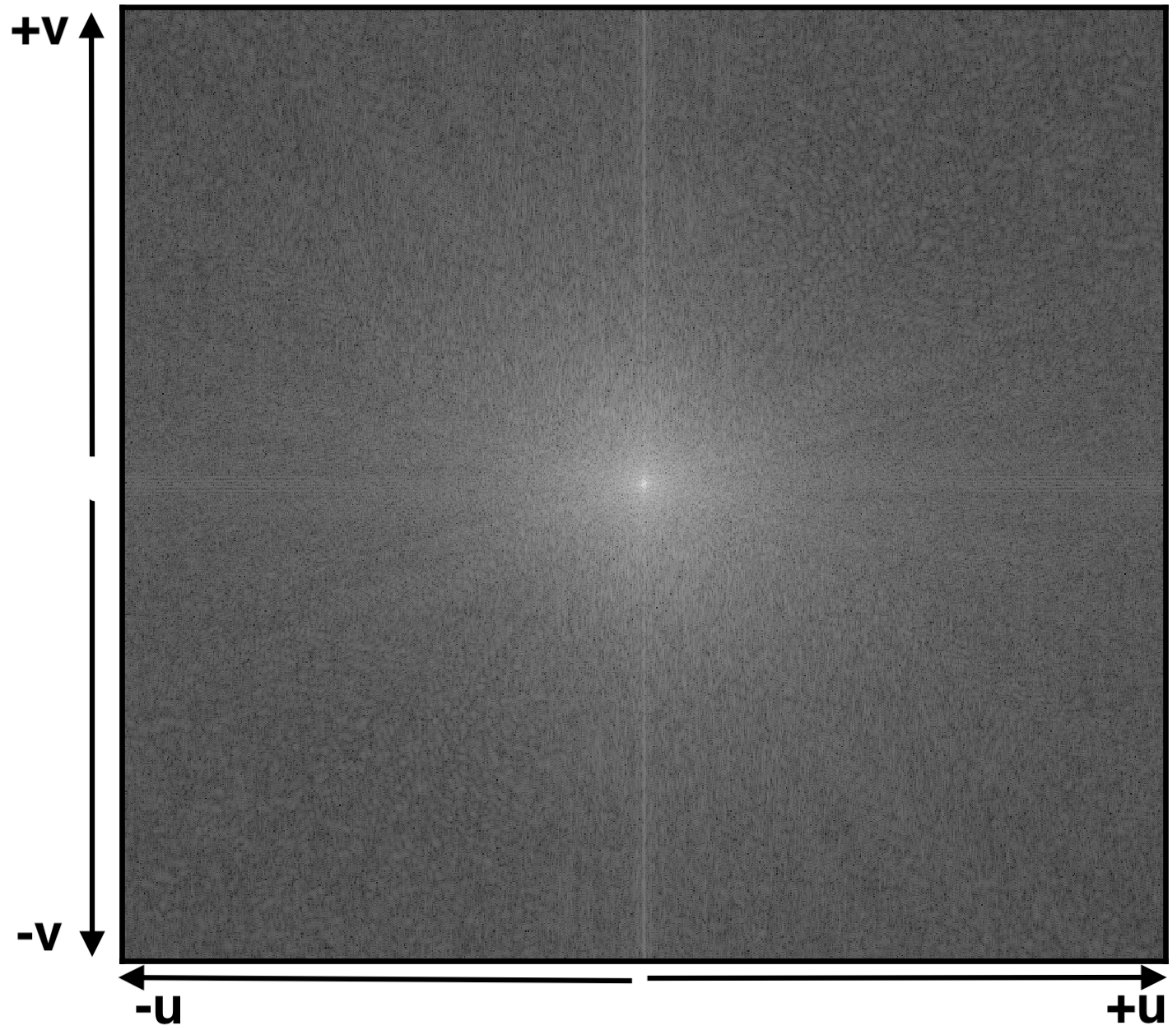
The Fourier Transform

$V(u, v)$ is a complex quantity and can be expressed as (real, imaginary) or (amplitude, phase).

Important: Each $V(u, v)$ contains information on $T(l, m)$ everywhere in the field because of the sinusoidal phase term.

Robin

Fourier robin

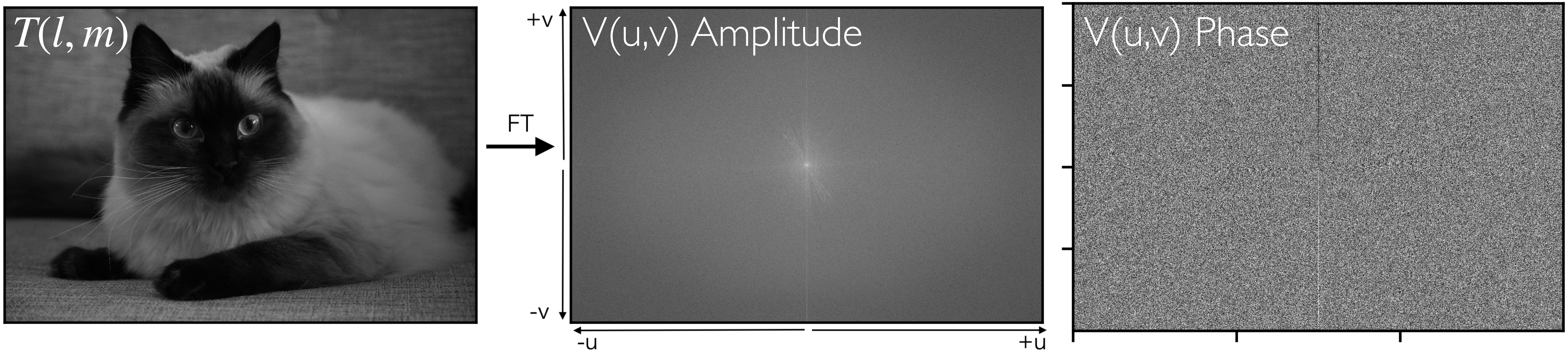


The Fourier Transform

Amplitude tells us how much of a certain spatial frequency there is and phase tells us where the spatial frequency component is located.

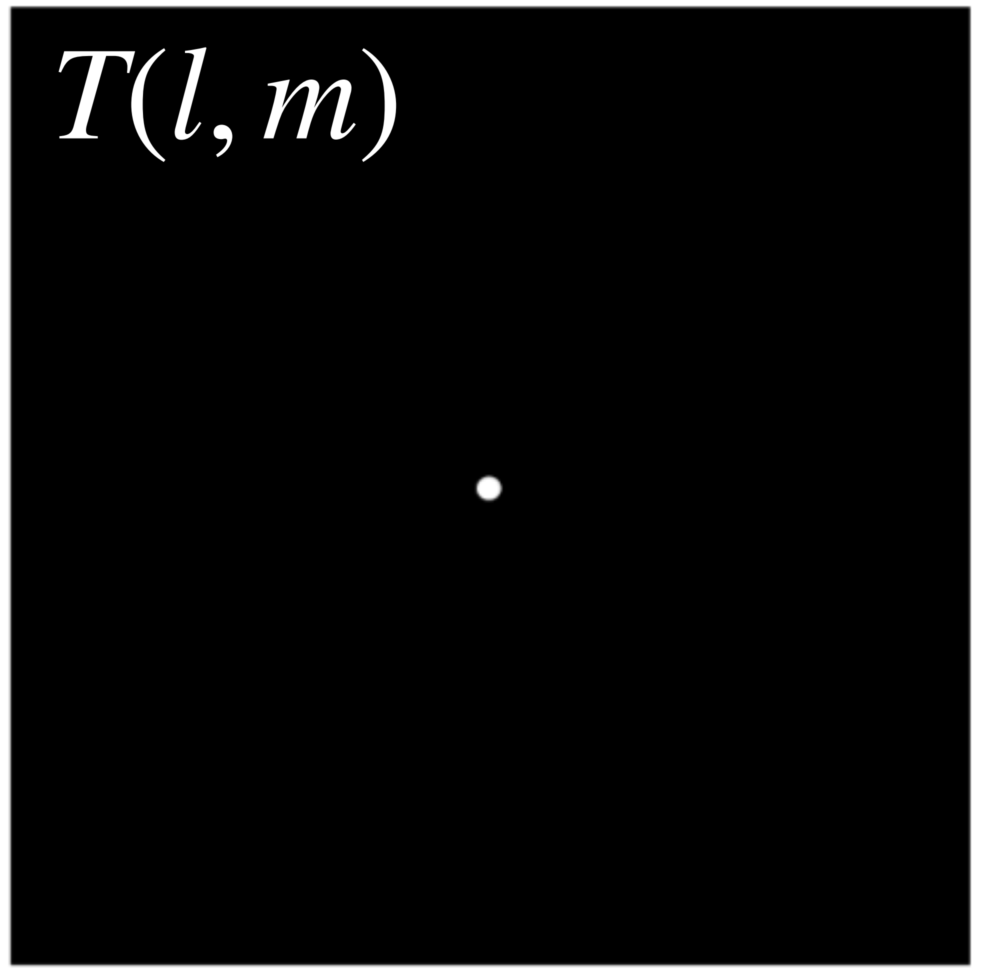
Cat

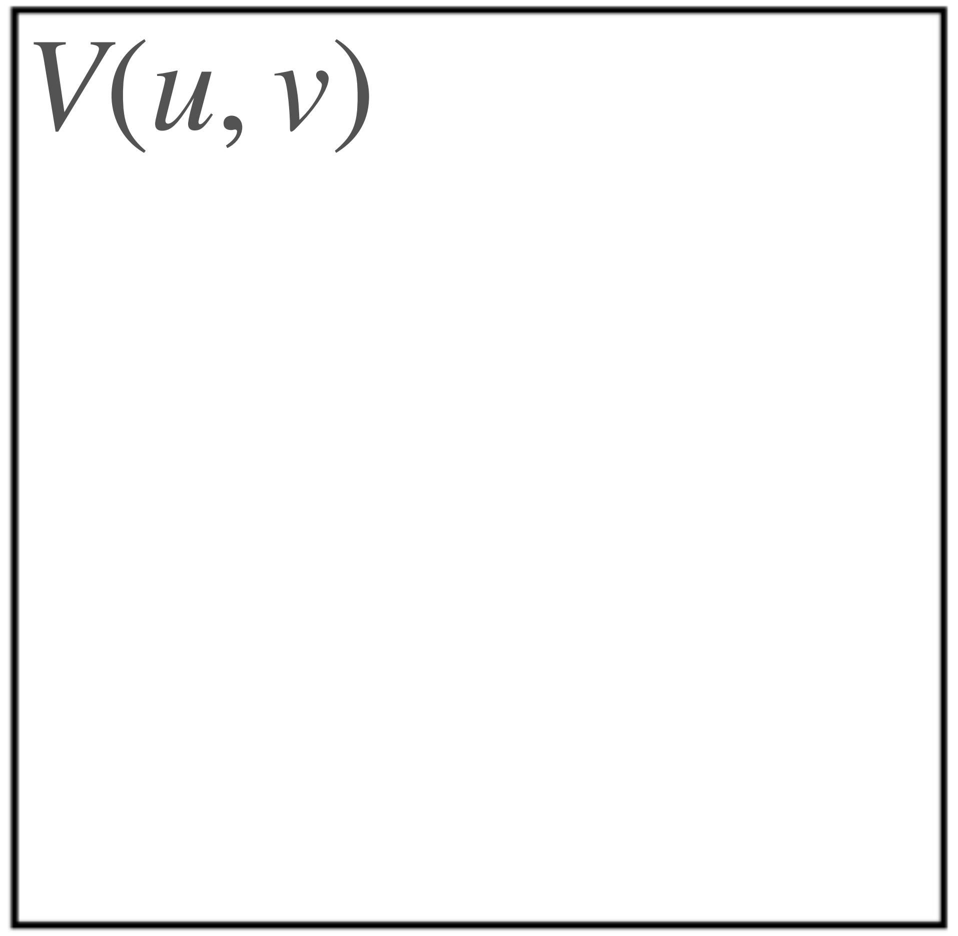
Fourier cat



Examples

$\delta -$ function

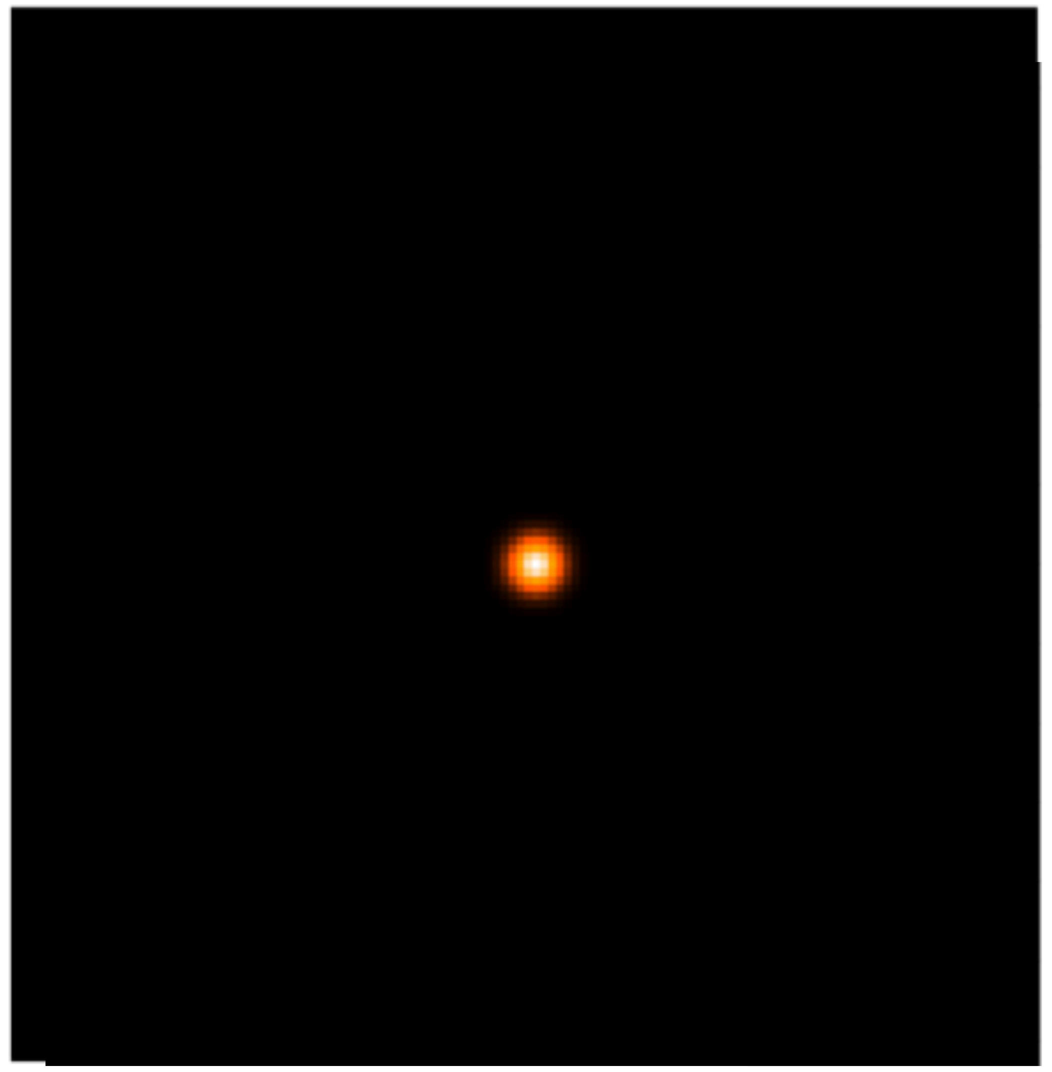


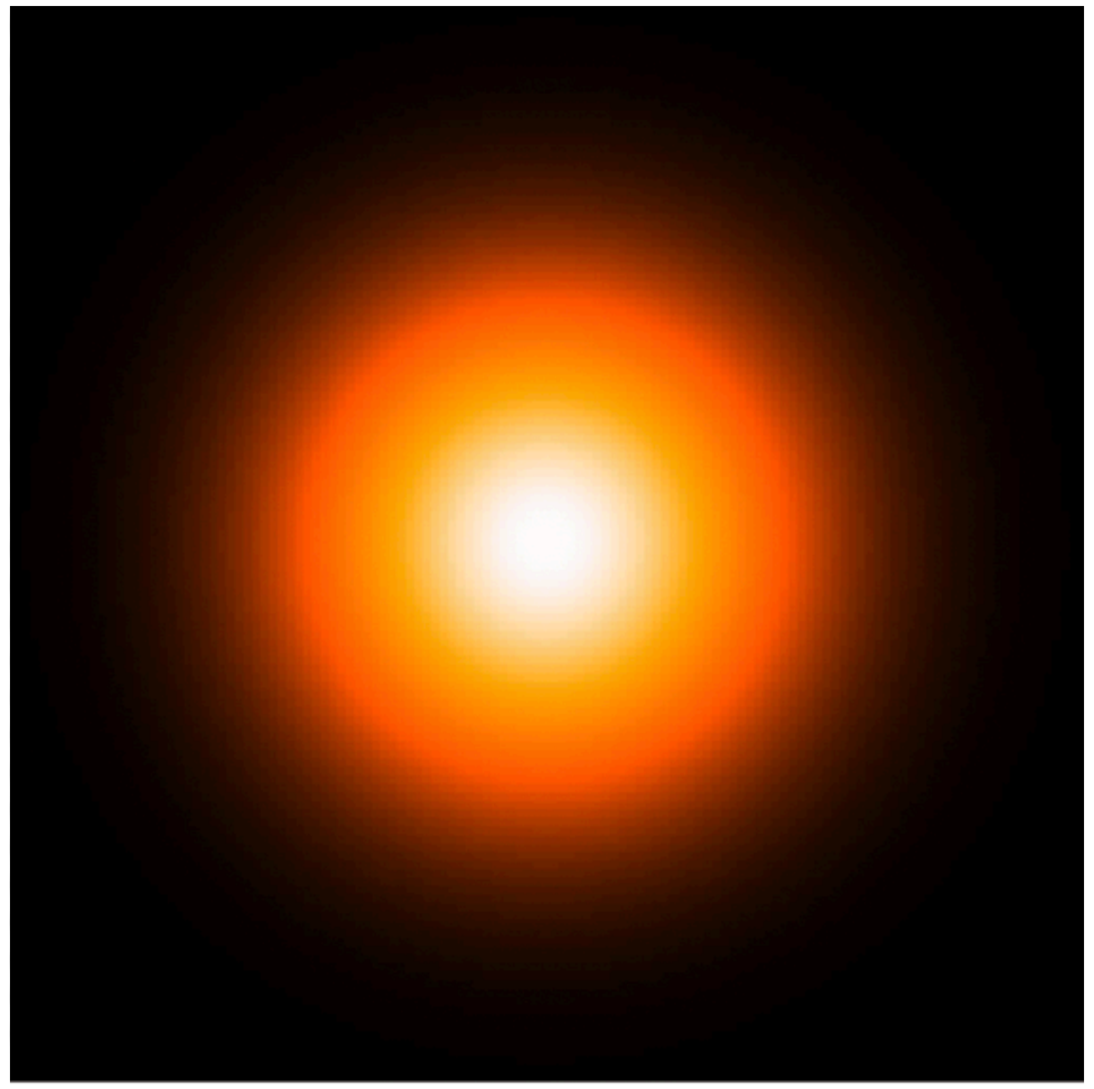


Narrow, bright peak is a constant at every u,v point.

Narrow features transform into a wide features. Wide features transform into narrow features.

Gaussian →

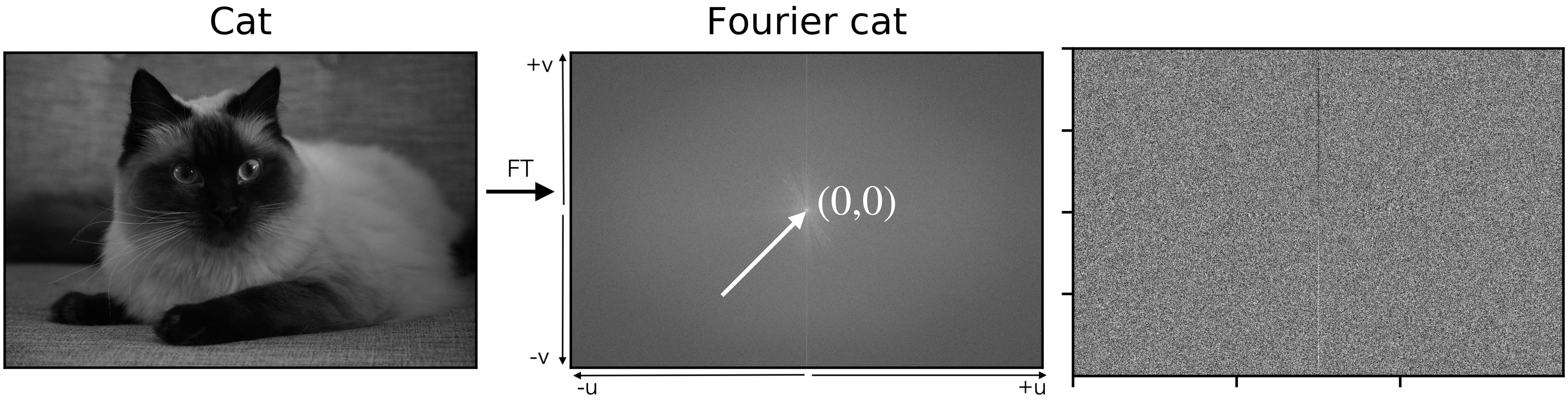




The total flux density is at the origin:

$$V(u=0, v=0) = \iint T(l,m)\,dl\,dm$$

Since the sky brightness is real, $V(-u,-v) = V(u,v)$. We get two visibility points with one measurement.

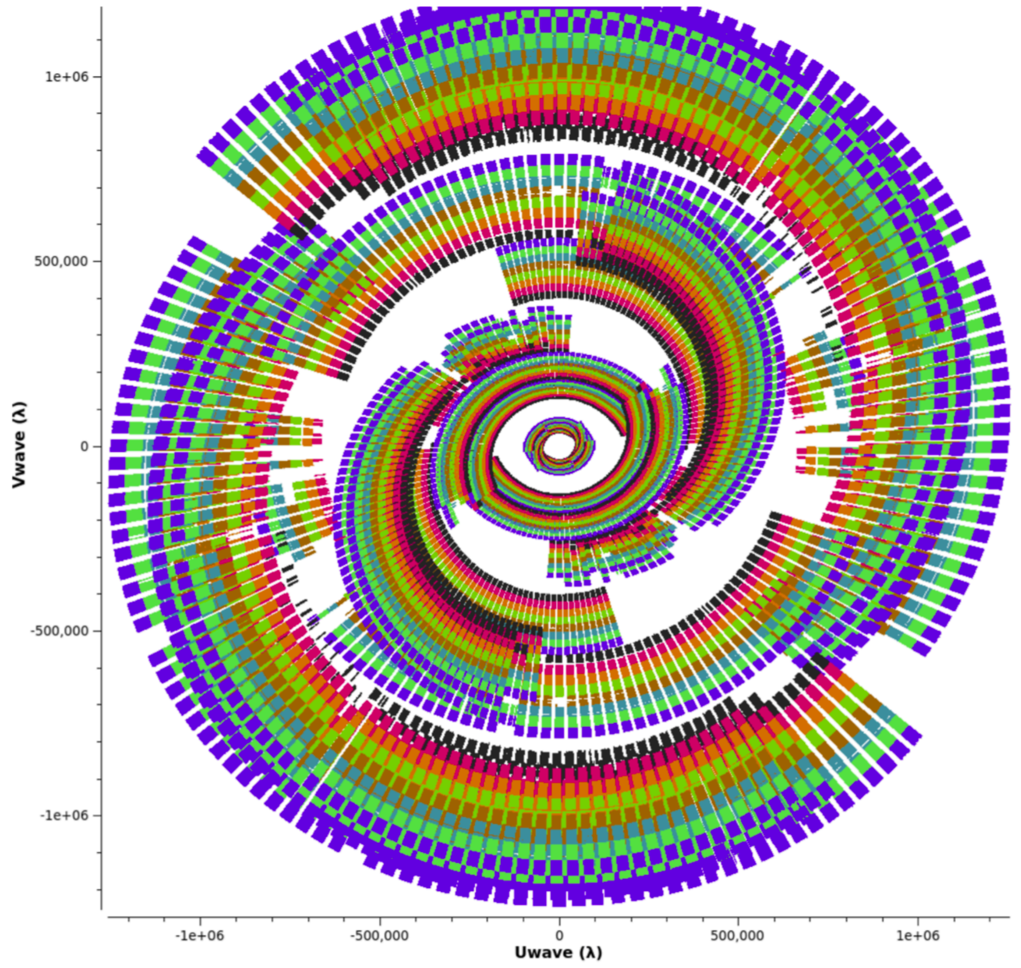


Deconvolution

- $V(l, m)$ is not known everywhere but sampled at particular places on the *uv* plane

- The sampling function can be described by $S(u, v)$ and is equal to 1 when the *uv* plane is sampled and zero otherwise:

$$T^D(l,m) = \iint V(u,v)S(u,v)e^{2\pi i(ul+vm)}dudv$$



Deconvolution

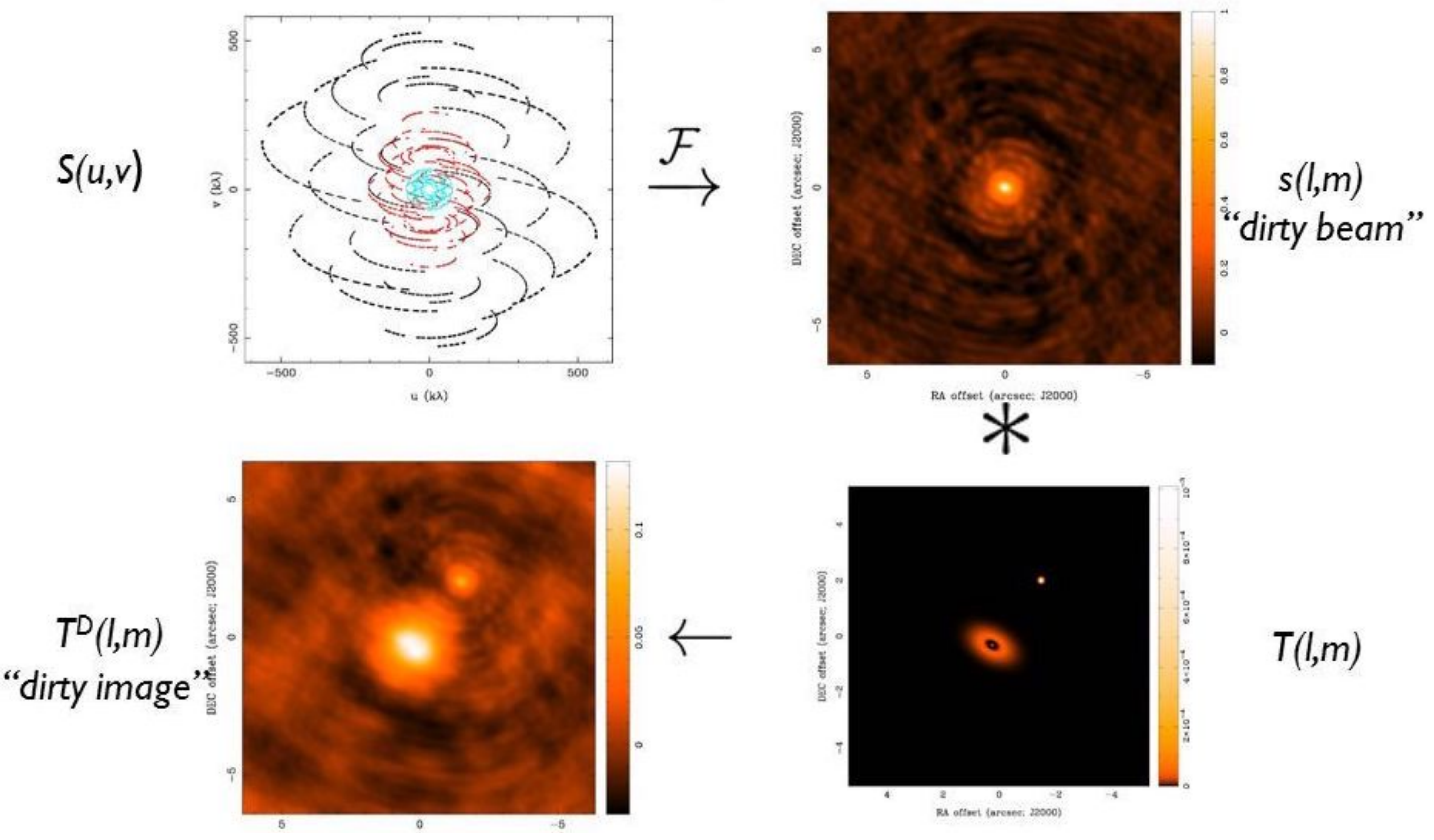
The Fourier transform of the sampled visibilities yields the true sky brightness convolved with the point spread function (psf)

$$T^D(l,m) = T(l,m) * B(l,m)$$

B is the 'dirty beam' or the point spread function.

- B is the FT of the sampling function:

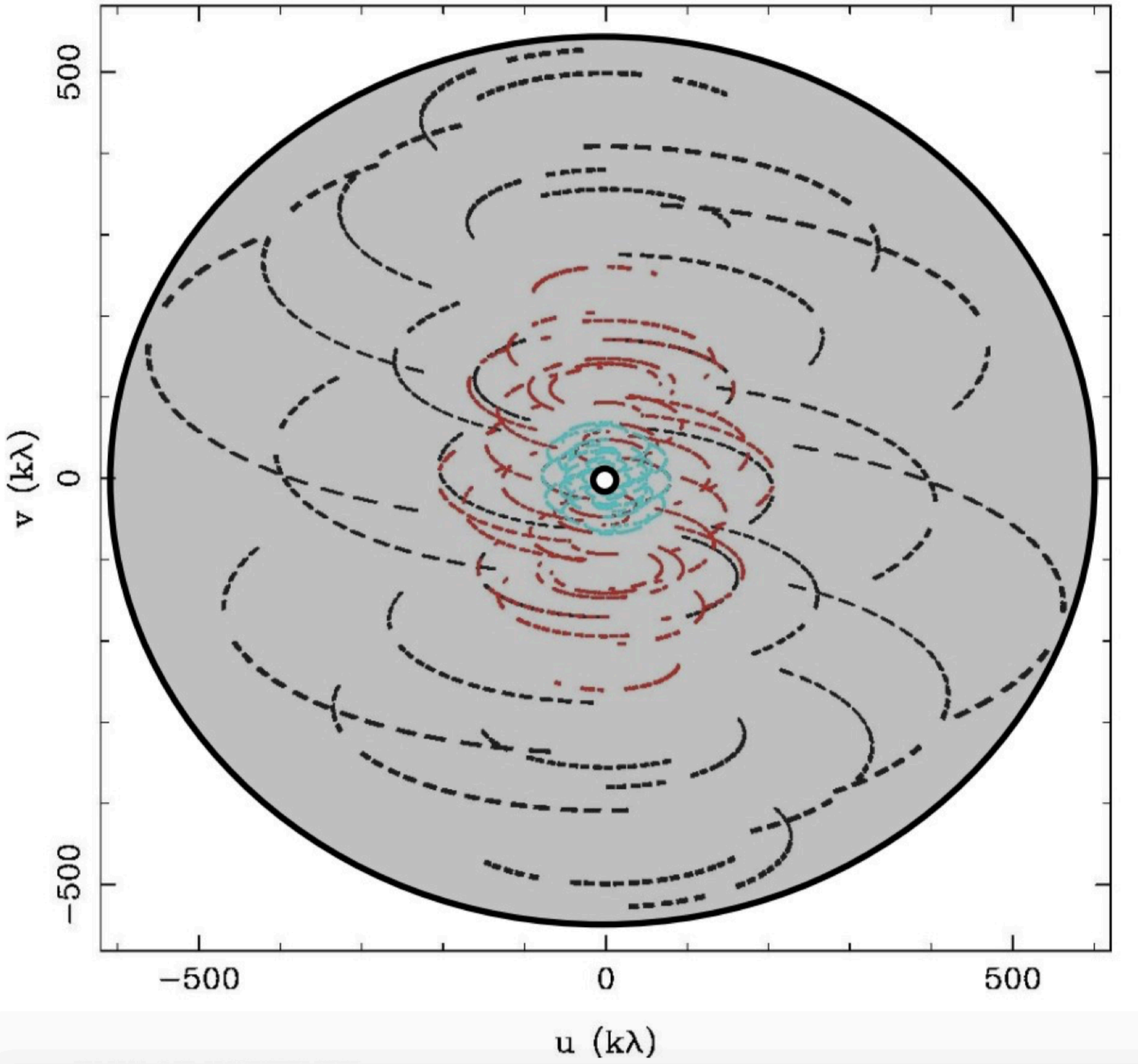
$$B(l,m) = \int\int S(u,v)e^{2\pi i(ul+vm)}dudv$$


S(u,v)
$\mathcal{F}$
s(l,m)
"dirty beam"
*
T(l,m)
$T^D(l,m)$
"dirty image"
u (kλ)
v (kλ)
RA offset (arcsec; J2000)
DEC offset (arcsec; J2000)

Credit: NRAO

Implications of UV Sampling

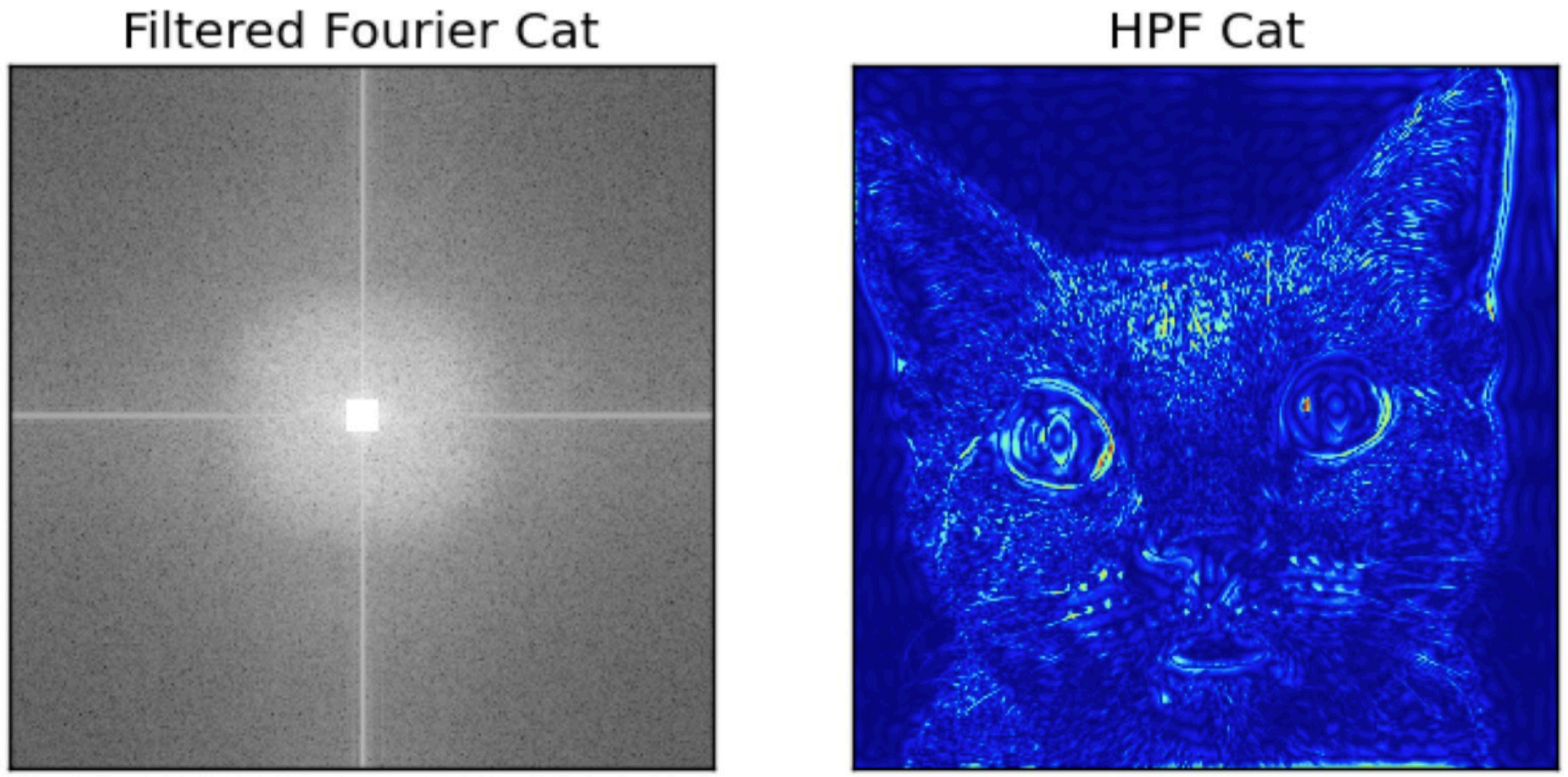
Samples of $V(u, v)$ are limited by the number of antennas and by Earth-sky geometry.



- Outer boundary
  - No information on smaller scales
  - Resolution limit
- Inner hole
  - No information on larger scales
  - Extended structure is visible
- Irregular coverage between boundaries
  - Sampling theorem violated
  - Information missing

Credit: Joe Callingham

Implications of UV Sampling



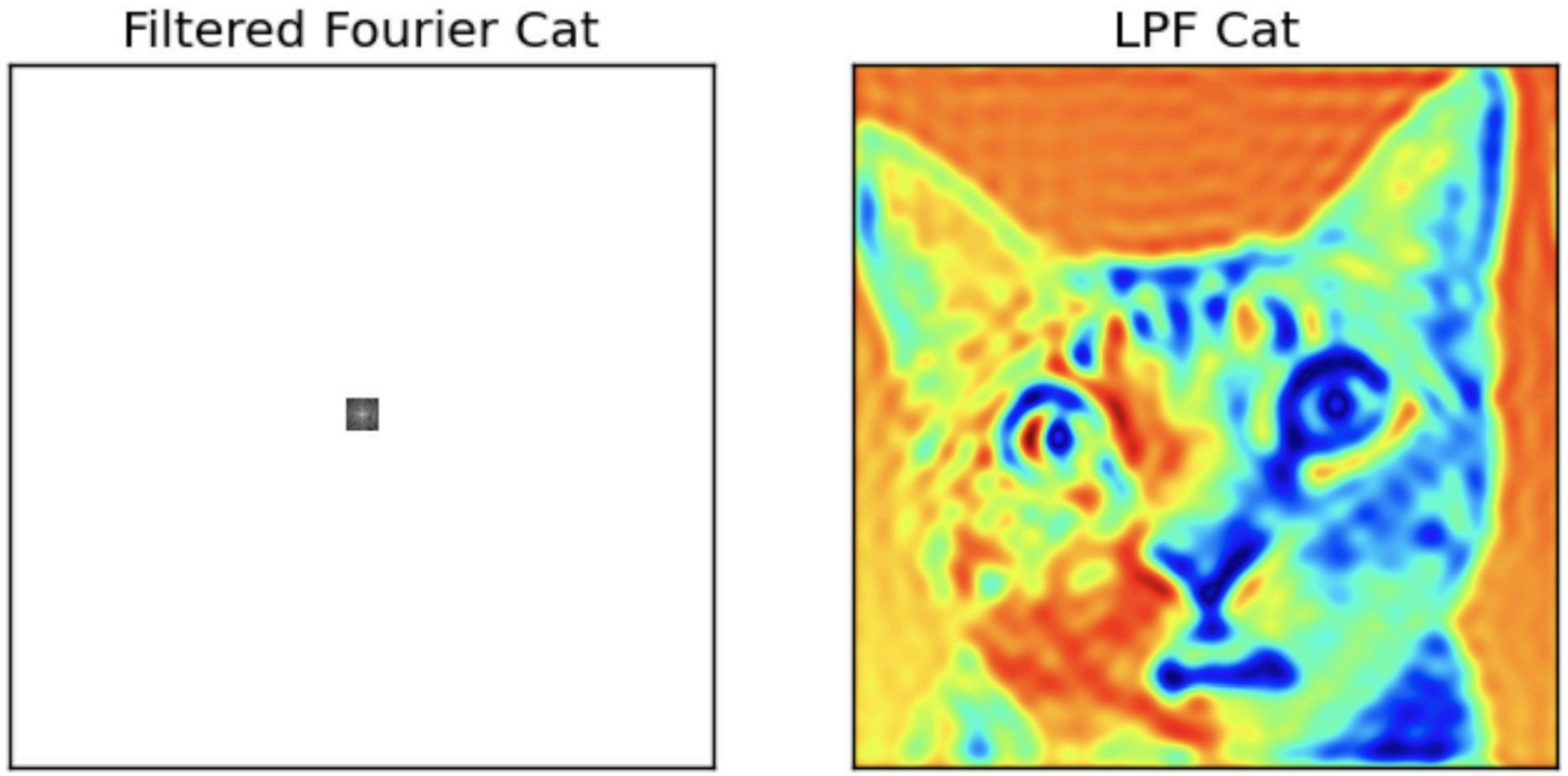
Credit: Joe Callingham

Measure only the low spatial frequencies.

We get a highly spatially filtered image.

Measure only the high spatial frequencies.

We get a blurry cat image.



Credit: Joe Callingham

Fourier Transform and Gridding

- Fourier transform:

— Fast Fourier Transform (FFT) algorithm speeds up the direct Fourier summation.

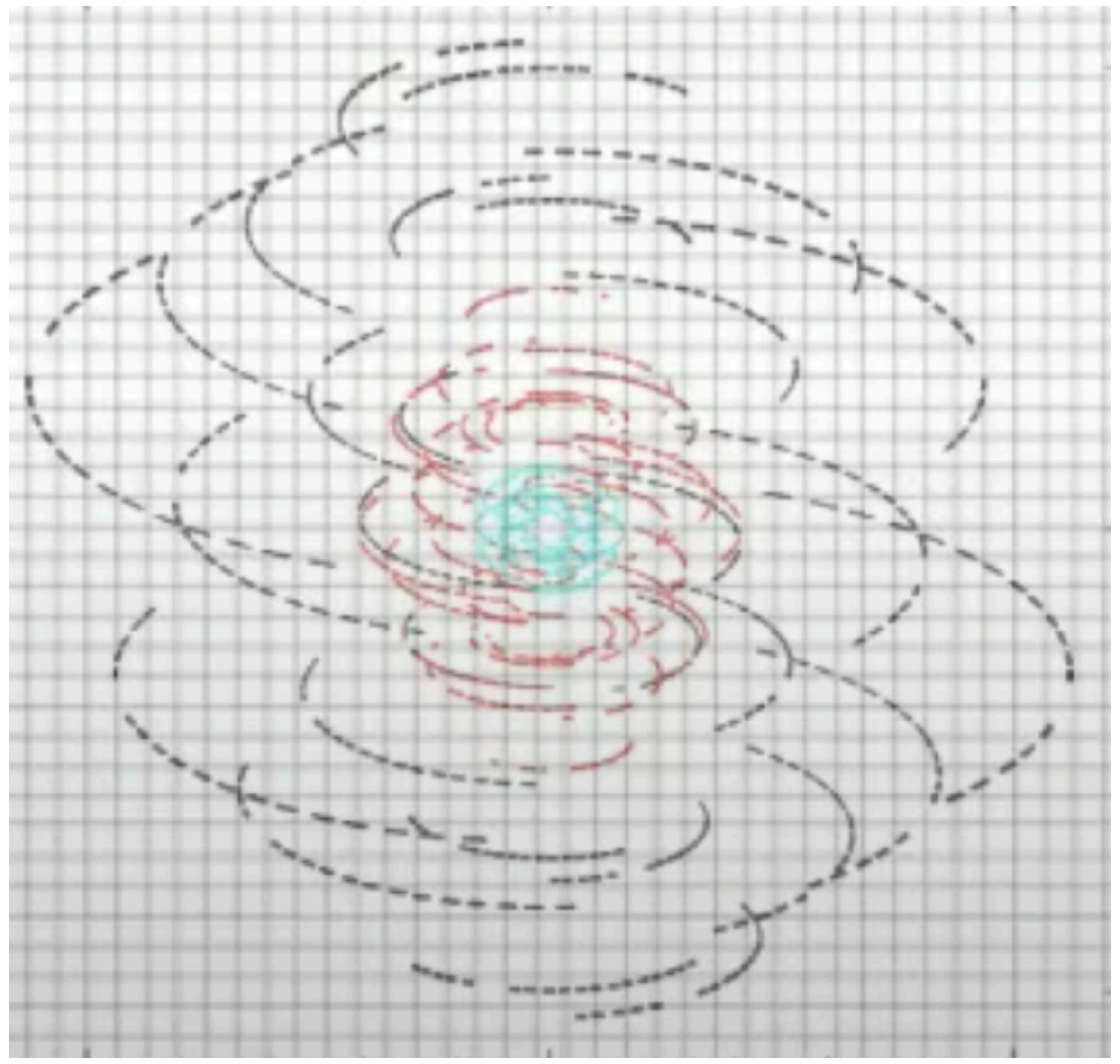
— FFT requires data on a regularly spaced grid (may be in time and frequency but not regularly spaced in u and v)

— Aperture synthesis does not provide V(u,v) on a regularly spaced grid…

- Gridding: resamples V(u,v) for FFT

— customary to use a convolution method

— special ("spheroidal") functions that minimize smoothing and aliasing



$$V^G(u,v) \xrightarrow{F} T^D(l,m)g(l,m)$$

Credit: NRAO

```
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =          ''        #  Name of input visibility file(s)
selectdata          =        True        #  Enable data selection parameters
     field          =          ''        #  field(s) to select
     spw            =          ''        #  spw(s)/channels to select
     timerange      =          ''        #  Range of time to select from data
     uvrange        =          ''        #  Select data within uvrange
     antenna        =          ''        #  Select data based on antenna/baseline
     scan           =          ''        #  Scan number range
     observation    =          ''        #  Observation ID range
     intent         =          ''        #  Scan Intent(s)

datacolumn          = 'corrected'        #  Data column to image(data,corrected)
imagename           =          ''        #  Pre-name of output images
imsize              =       [100]        #  Number of pixels
cell                = ['1arcsec']        #  Cell size
phasecenter         =          ''        #  Phase center of the image
stokes              =         'I'        #  Stokes Planes to make
projection          =       'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =          ''        #  Name of starting model image
specmode            =       'mfs'        #  Spectral definition mode
                                         #   (mfs,cube,cubedata, cubesource)
     reffreq        =          ''        #  Reference frequency

gridder             =  'standard'        #  Gridding options (standard, wproject,
                                         #   widefield, mosaic, awproject)
     vptable        =          ''        #  Name of Voltage Pattern table
     pblimit        =         0.2        #  PB gain level at which to cut off
                                         #   normalizations

deconvolver         =     'hogbom'       #  Minor cycle algorithm (hogbom,clark,multisc
                                         #   ale,mtmfs,mem,clarkstokes)
restoration         =        True        #  Do restoration steps (or not)
     restoringbeam  =          []        #  Restoring beam shape to use. Default is the
                                         #   PSF main lobe
     pbcor          =       False        #  Apply PB correction on the output restored
                                         #   image

outlierfile         =          ''        #  Name of outlier-field image definitions
weighting           =   'natural'        #  Weighting scheme (natural,uniform,briggs,
                                         #   briggsabs[experimental])
     uvtaper        =          []        #  uv-taper on outer baselines in uv-plane

niter               =           0        #  Maximum number of iterations
usemask             =      'user'        #  Type of mask(s) for deconvolution:  user,
                                         #   pb, or auto-multithresh
     mask           =          ''        #  Mask (a list of image name(s) or region
                                         #   file(s) or region string(s) )
     pbmask         =         0.0        #  primary beam mask

fastnoise           =        True        #  True: use the faster (old) noise
                                         #   calculation. False: use the new improved
                                         #   noise calculations
restart             =        True        #  True : Re-use existing images. False :
```

CASA imaging parameters

- CASA imaging tasks: *clean* and *tclean*

- To achieve a basic image, must set:
  - vis - your data name
  - imagename
  - niter - # of CLEAN iterations
  - imsize - the size of the image in pixels (small as possible to reduce computation time)
  - cell - angular extent of each pixel

$$cell \sim \frac{\lambda_f}{3B}$$

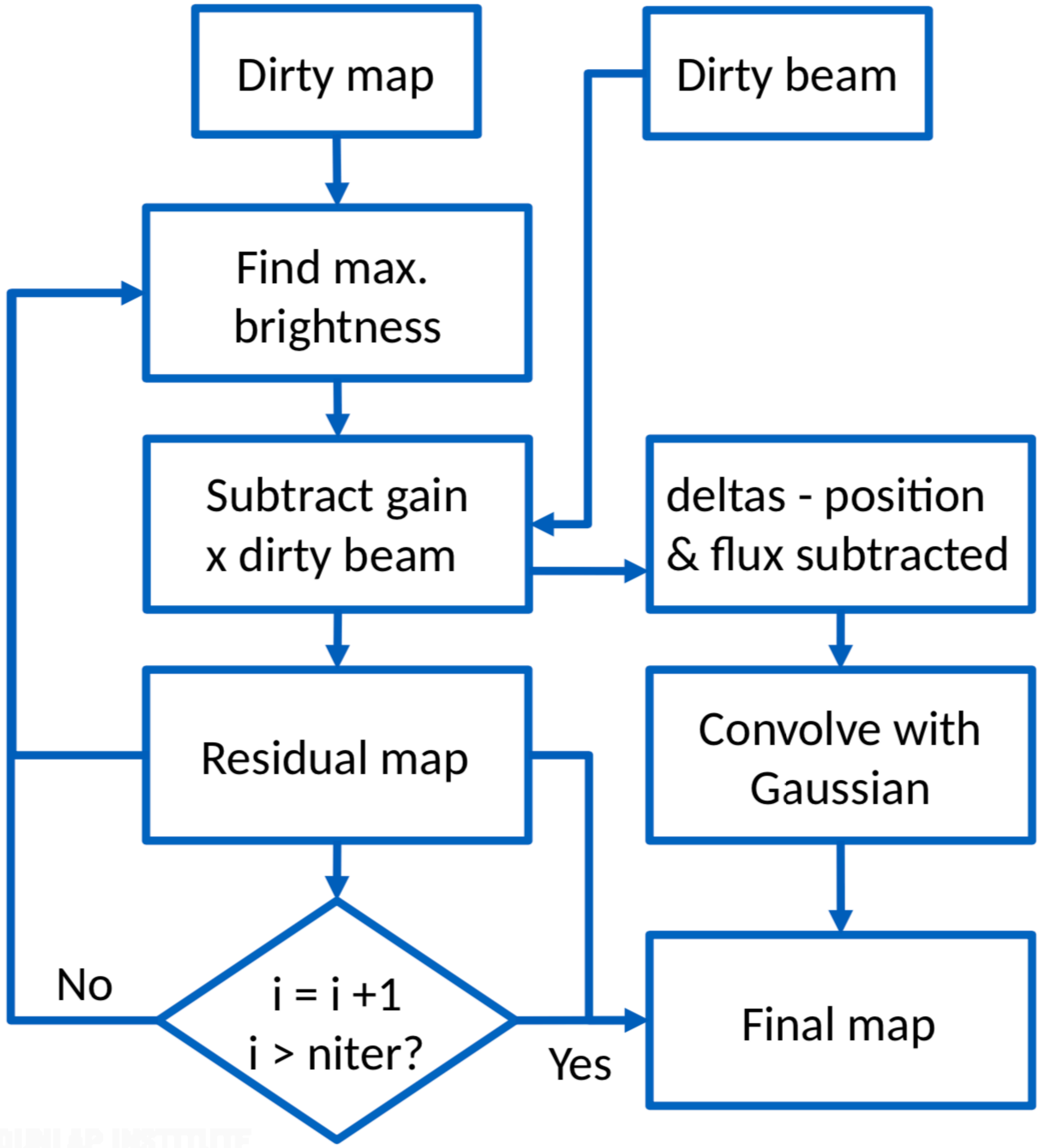
where λ_f = the wavelength of the highest frequency and B is the longest baseline.

Imaging parameters continued…

- In practice, the cell size should be set so that there are 3 to 5 pixels across the main lobe of the dirty beam to help deconvolution.

- Initial image size set to match the primary beam is a good start if you are unsure if there are any additional bright sources in the image. (This can help prevent aliasing.)

Hogbom CLEAN (1974)

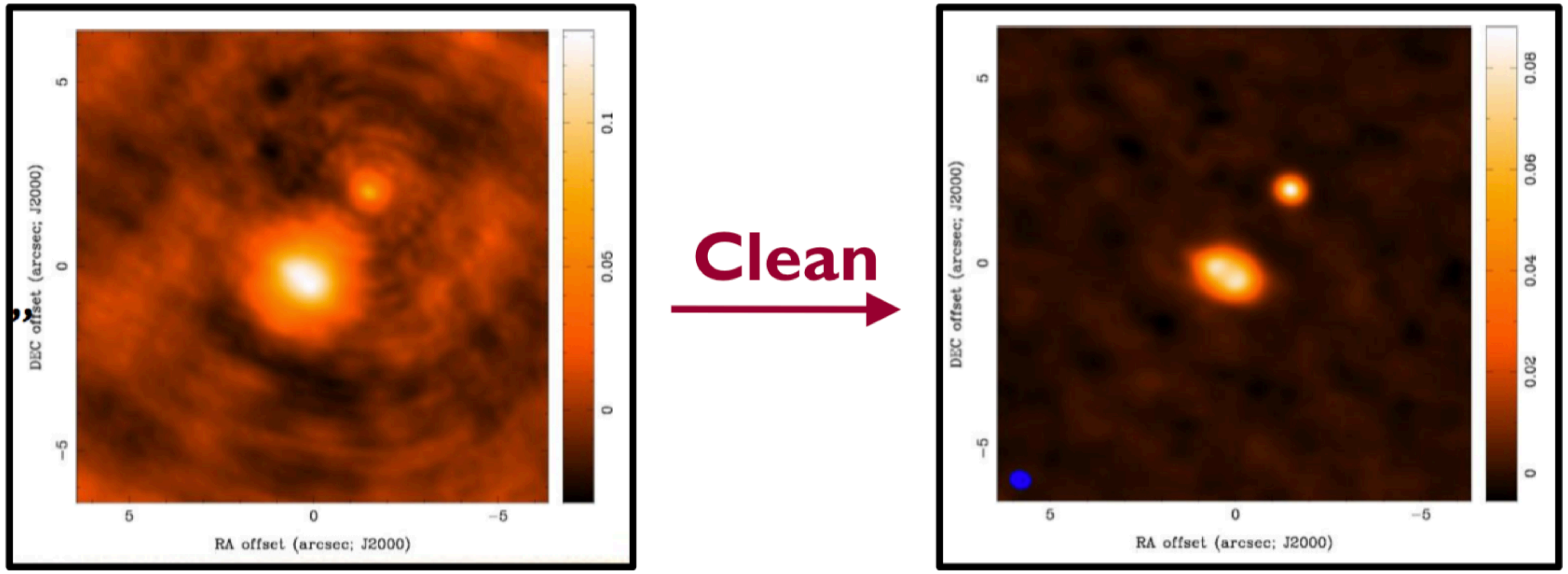


Credit: Joe Callingham

1. Initialize: a residual map to dirty image and empty CLEAN component list
   1. Find the peak in the residual map as a point source.
   2. Subtract beam value multiplied by some gain factor from residual map.
   3. Add the amplitude and location of the point source to the CLEAN component list.
   4. Repeat from step 1 unless the stopping criteria has been reached. (Either number of iterations or max in residual map< multiple rms noise)
2. Convolve CLEAN component (cc) list by an estimate of the main lobe of the dirty beam (this elliptical Gaussian is the "CLEAN beam") and add residual map to make the final "CLEAN"

Imaging result

- A final restored image that is an estimate of the true sky brightness.



$T_D(l,m)$ — Dirty image

$T(l,m)$ — Restored "CLEAN" image

Credit: NRAO

The CLEAN Algorithm

When should I stop?

- Residual map max < multiple of rms (when noise limited)
- Residual map max < fraction of dirty map (dynamic range limited)
- Max number of clean components reached (you've hit the number of iterations you set)

What should the loop gain be?

- typically g ~ 0.1 to 0.3 (usually 0.1 is fine)
- can set g ~ 0.05 for smoother emission (*but if in doubt just use 0.1*)

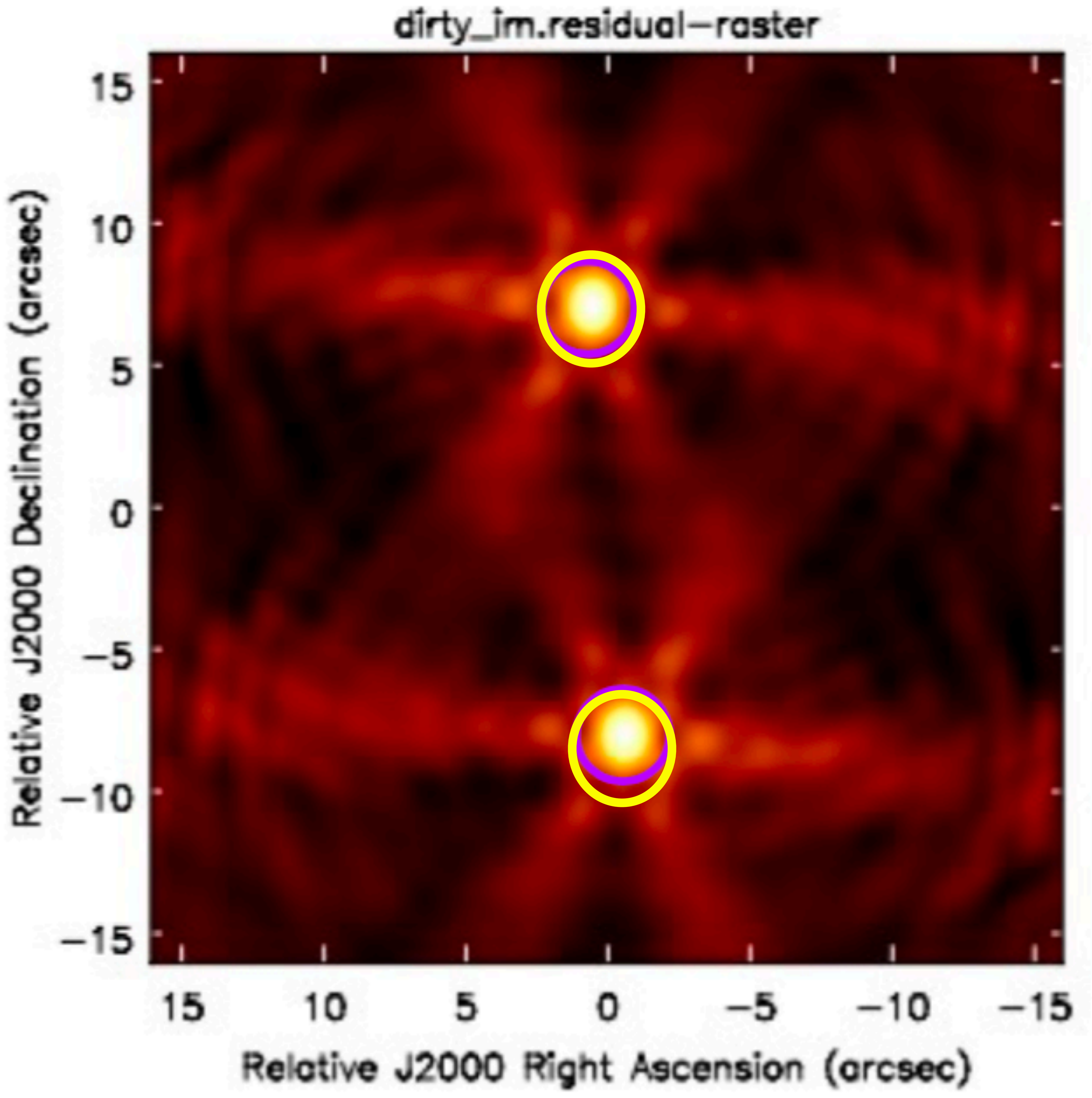
The CLEAN Algorithm

The CLEAN algorithm has two cycles:

1. *Minor cycles* - subtract subimages of the dirty beam

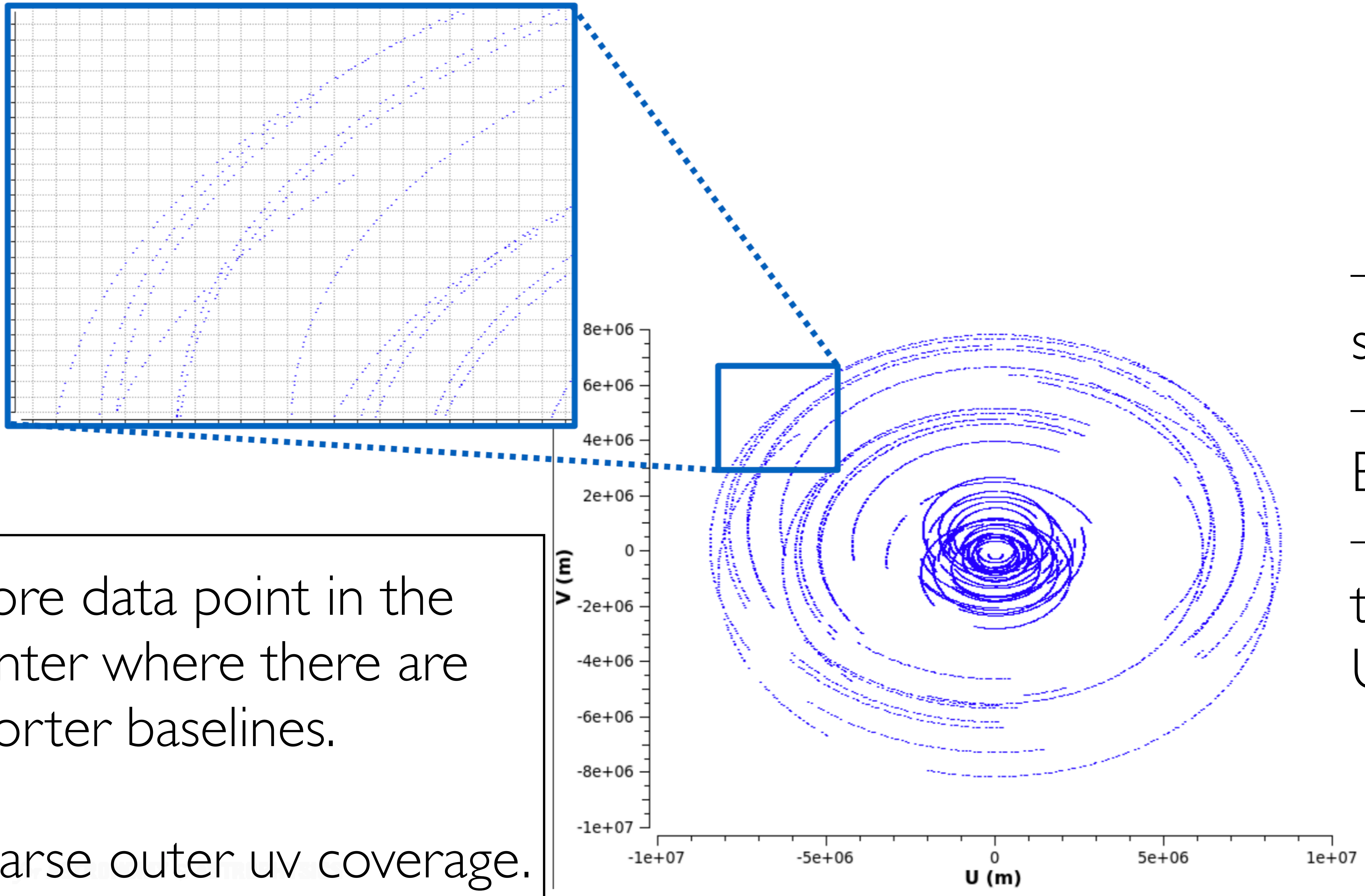
2. *Major cycles* - Fourier transform residual map and subtract

If you know where there is real emission you can set CLEAN boxes to limit the field. Take caution!



Credit: Joe Callingham

Weighting



More data point in the center where there are shorter baselines.

Sparse outer uv coverage.

Credit: Joe Callingham

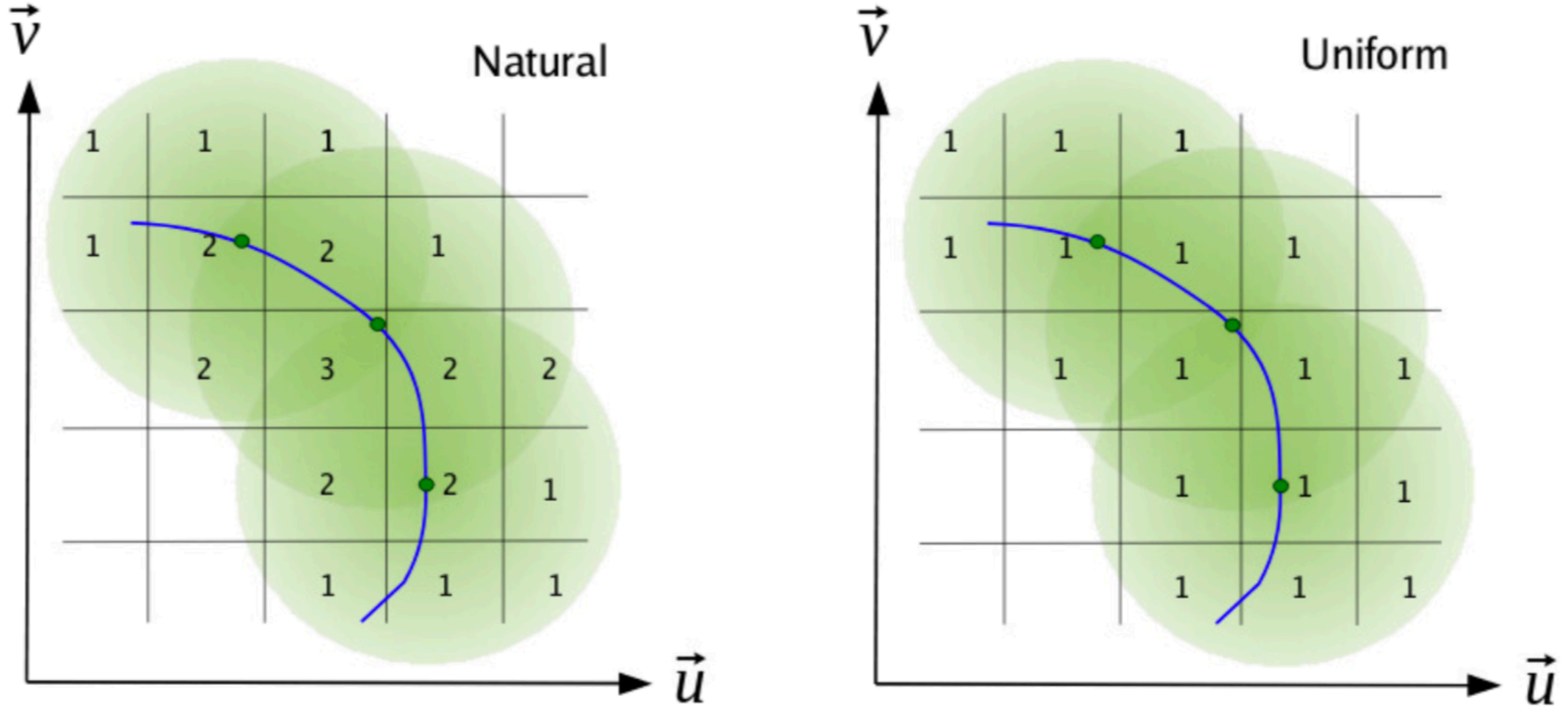
<u>Introduce a weighting function W(u,v)</u>

— Modifies sampling function so that $S(u, v)W(u, v)$

— Changes the dirty beam B(l,m) shape

— Different weighting options to choose from: Natural, Uniform, Briggs…

Weighting cont.



Credit: Australia Telescope National Facility

Weighting cont.

Natural

- Low spatial frequencies are weighted up (due to gridding)
- Con: bad for resolution
- Pro: better S/N

Uniform

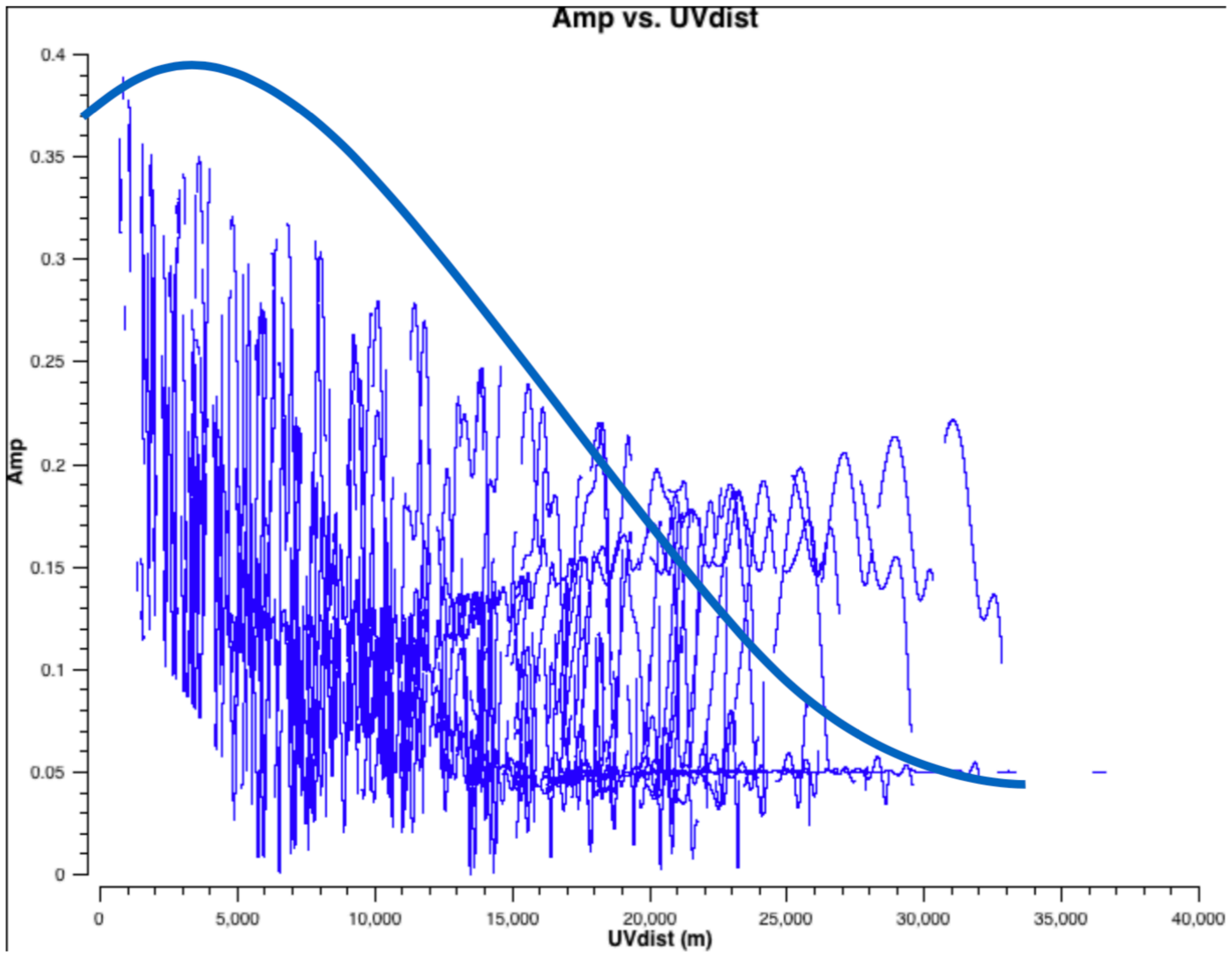
- Low spatial frequencies are weighted down
- Con: Worse S/N
- Pro: Better resolution

Weighting cont.

Briggs Weighting (also known as robust weighting)

- Hybrid between uniform and natural weighting
- Robust adjustable between -2 (fully uniform) and +2 (fully natural). Robust = 0 is right in the middle.
- Avoids giving too much weight to cells low natural weight.
- Can produce images close to uniform weighting but with the noise levels founds in natural weighting

UV tapering



Credit: Joe Callingham

Gaussian uv taper or uv range can smooth the image. Since data are excluded it is at the expense of sensitivity.

— Gives more weight to short baselines (degrades resolution) .

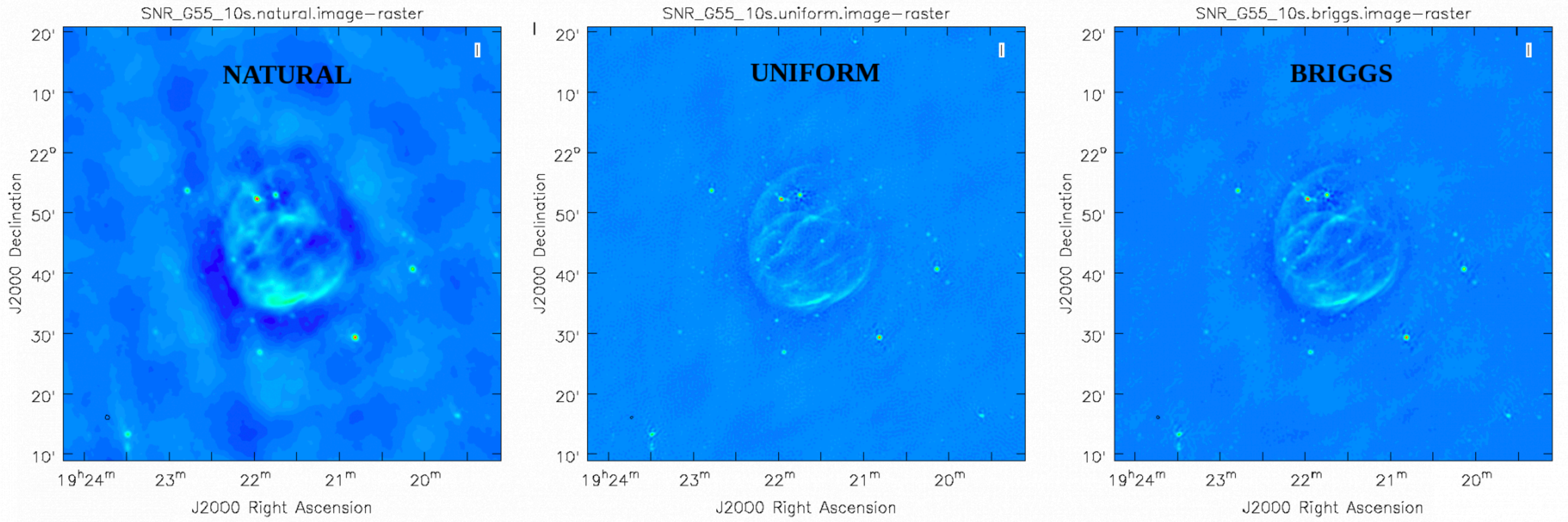
— Downweights some data so point source sensitivity is degraded.

— May improve sensitivity to extended structures though.

Weighting cont.

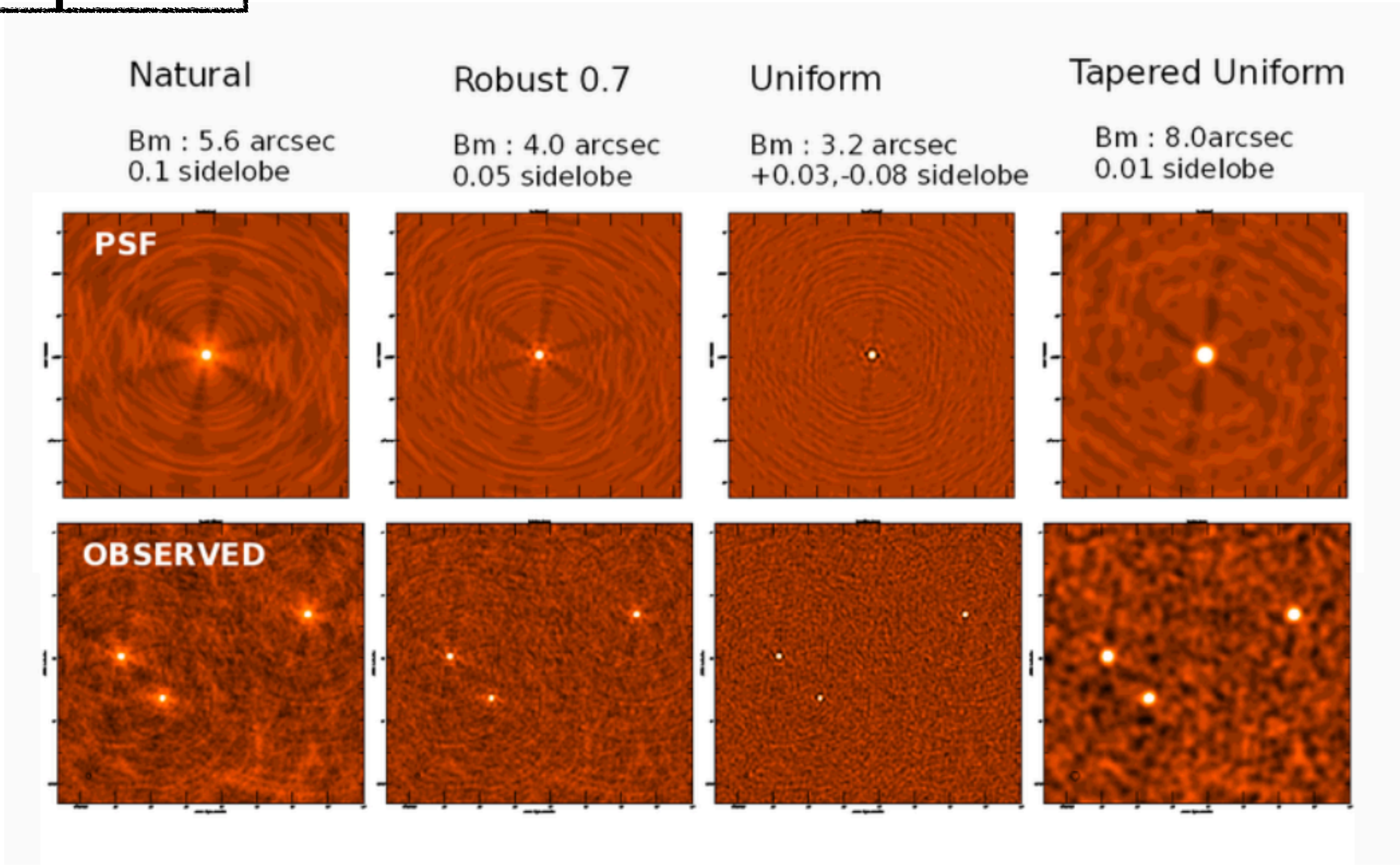
	Natural	Uniform	Briggs	Taper
Resolution	Medium	Higher	Higher	Lower
Point Source Sensitivity	Maximum	Lower	Lower	Lower
Extended Source Sensitivity	Medium	Lower	Lower	Higher
Sidelobes	Higher	Lower	Lower	Depends

Example



Credit: NRAO

Example

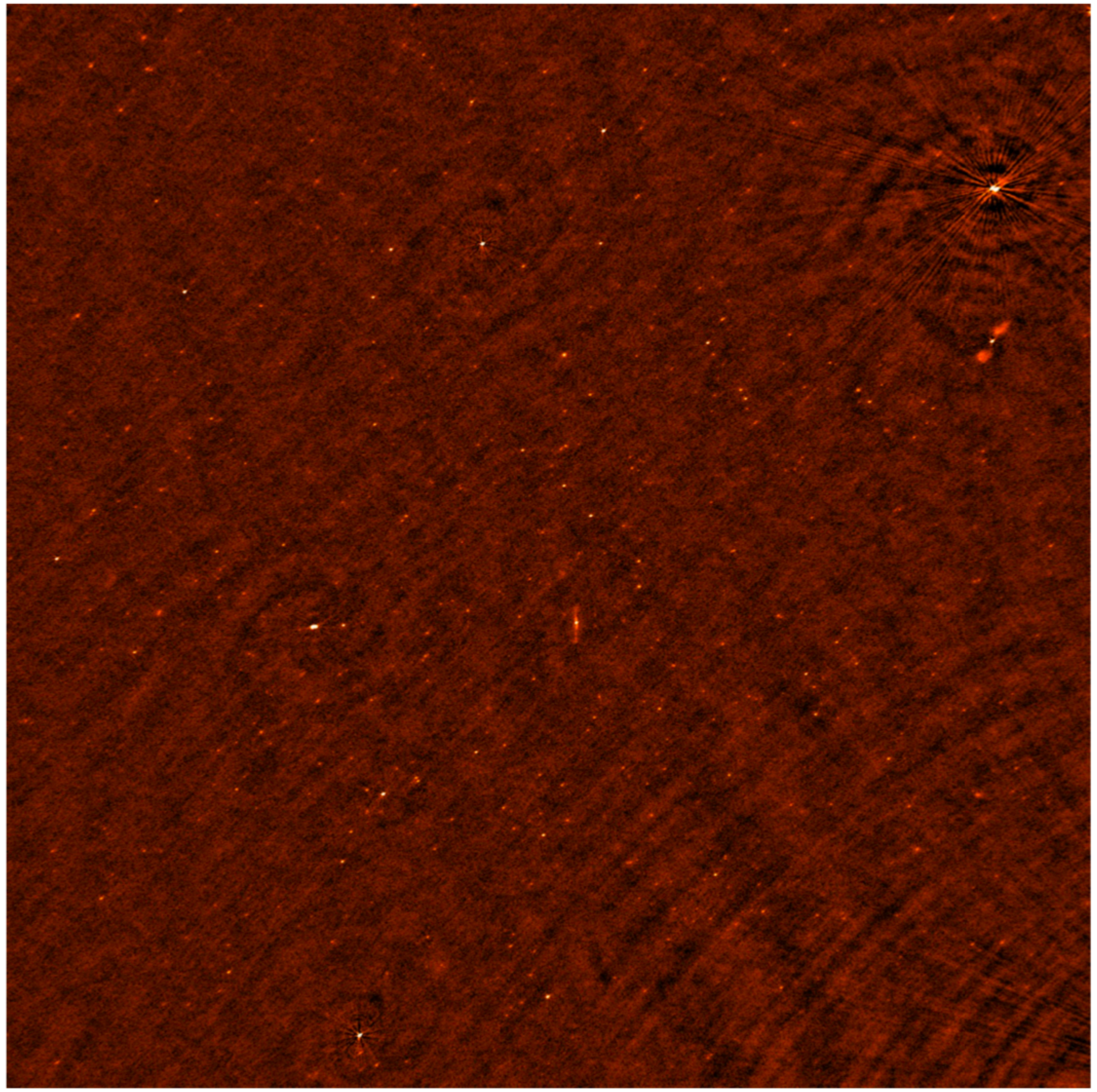


Credit: NRAO

CLEAN files

- <imagename>.image
  - Final clean image (or dirty if niter=0)
- <imagename>.psf
  - point spread function (dirty beam)
- <imagename>.model
  - image of clean components
- <imagename>.residual
  - residual after subtracting clean components (use to decide whether or not to continue to clean)
- <imagename>.flux
  - relative sensitivity on the sky
  - pbcor = True divides .image by .flux

Confusion



JVLA image of GOODS-N showing confusion from a 0.25Jy source to the SE

- Bright radio sources on the edge of the primary beam give rise to ripples in the centre of the field of view.
- The primary beam is spectrally dependent, so image subtraction should include such corrections and be performed in full spectral-line mode.
- Pointing errors introduce gain and phase changes on the edge of the primary beam. If severe, the apparent source structure may change.

Credit: Joe Callingham

Confusion

So how do we deal with these bright sources?

1. Outlier fields (the CASA default option) - deconvolve the confusing source while imaging the field of interest

2. Peeling - self-calibration on confusing source (to remove phase errors), get model & subtract source. Return to original calibration & insert model into visibilities.

3. Direction-dependent calibration -see Advanced Imaging lecture

Confusion

1. Outlier fields

If the source is out of your desired target area, then you can set a small area around the confusing source and deconvolve with the main image.

In CASA, this is achieved by setting multiple images (see right image) or set an outlier file (blue box & example below).

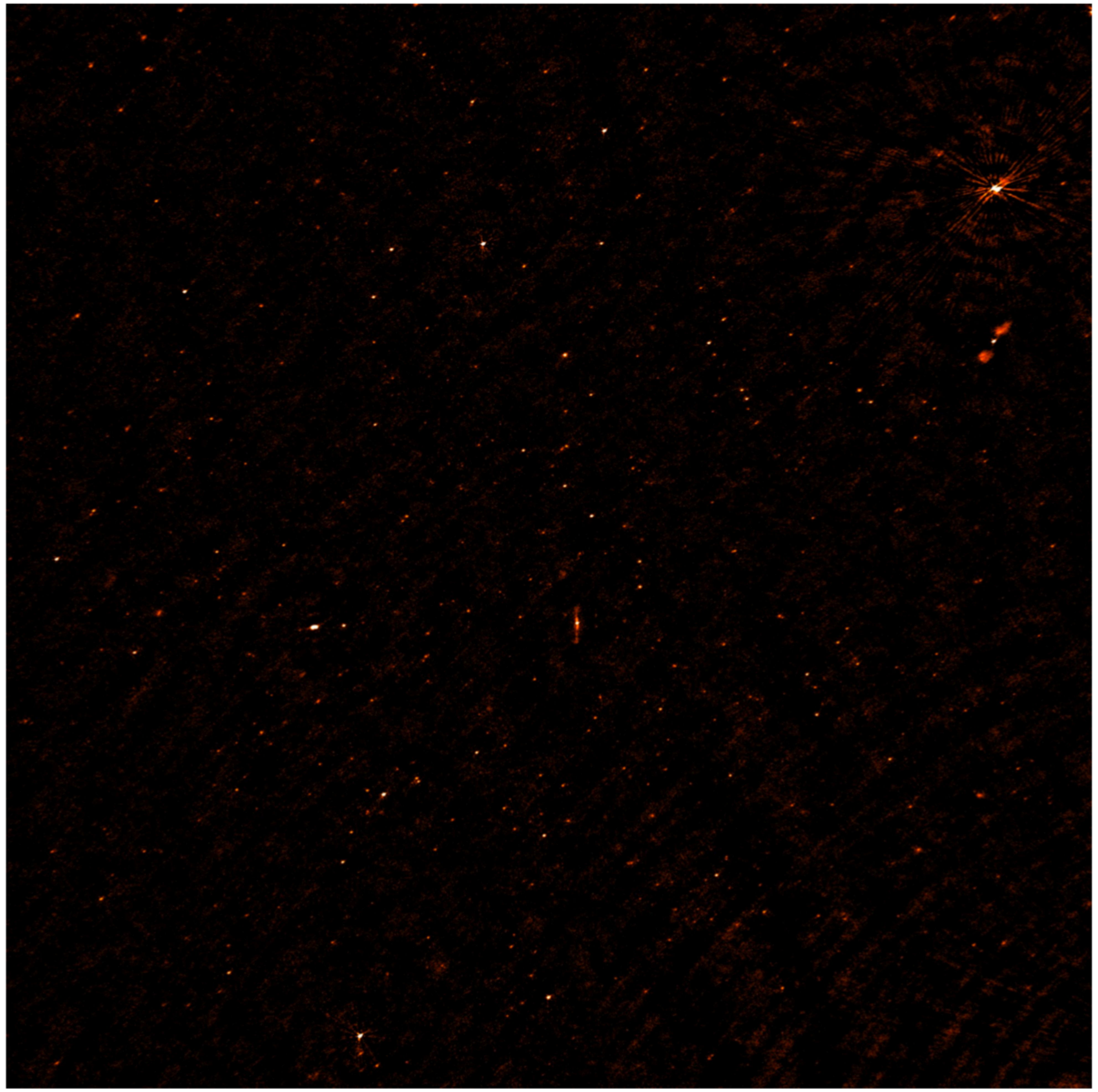
```
#content of outliers.txt
#
#outlier field1
imagename='outlier1'
imsize=[512,512]
phasecenter = 'J2000 12h34m52.2 62d02m34.53'
mask='box[[245pix,245pix],[265pix,265pix]]'
```

```
#  clean :: Invert and deconvolve images with selected algorithm
vis                 = 'JVLA_combined_GOODSN.ms' #  Name of input visibility file
imagename           = ['main', 'outlier'] #  Pre-name of output images
outlierfile         =         ''        #  Text file with image names, sizes, centers for
                                        #   outliers
field               =         ''        #  Field Name or id
spw                 =         ''        #  Spectral windows e.g. '0~3', '' is all
selectdata          =       True        #  Other data selection parameters
     timerange      =         ''        #  Range of time to select from data
     uvrange        =         ''        #  Select data within uvrange
     antenna        =         ''        #  Select data based on antenna/baseline
     scan           =         ''        #  Scan number range
     observation    =         ''        #  Observation ID range
     intent         =         ''        #  Scan Intent(s)

mode                =      'mfs'        #  Spectral gridding type (mfs, channel, velocity,
                                        #   frequency)
     nterms         =          1        #  Number of Taylor coefficients to model the sky
                                        #   frequency dependence
     reffreq        =         ''        #  Reference frequency (nterms > 1),'' uses central
                                        #   data-frequency

gridmode            =         ''        #  Gridding kernel for FFT-based transforms, default=''
                                        #   None
niter               =        500        #  Maximum number of iterations
gain                =        0.1        #  Loop gain for cleaning
threshold           =   '0.0mJy'        #  Flux level to stop cleaning, must include units:
                                        #   '1.0mJy'
psfmode             =    'clark'        #  Method of PSF calculation to use during minor cycles
imagermode          =  'csclean'        #  Options: 'csclean' or 'mosaic', '', uses psfmode
     cyclefactor    =        1.5        #  Controls how often major cycles are done. (e.g. 5
                                        #   for frequently)
     cyclespeedup   =         -1        #  Cycle threshold doubles in this number of iterations

multiscale          =         []        #  Deconvolution scales (pixels); [] = standard clean
interactive         =      False        #  Use interactive clean (with GUI viewer)
mask                =         []        #  Cleanbox(es), mask image(s), region(s), or a level
imsize              = [[8000, 8000], [50, 50]] #  x and y image size in pixels.  Single value:
                                        #   same for both
cell                = ['0.33arcsec']    #  x and y cell size(s). Default unit arcsec.
phasecenter         = ['J2000 12h36m49.4 62d12m58.0', 'J2000 12h34m52.2 62d02m34.53'] #  Image
```

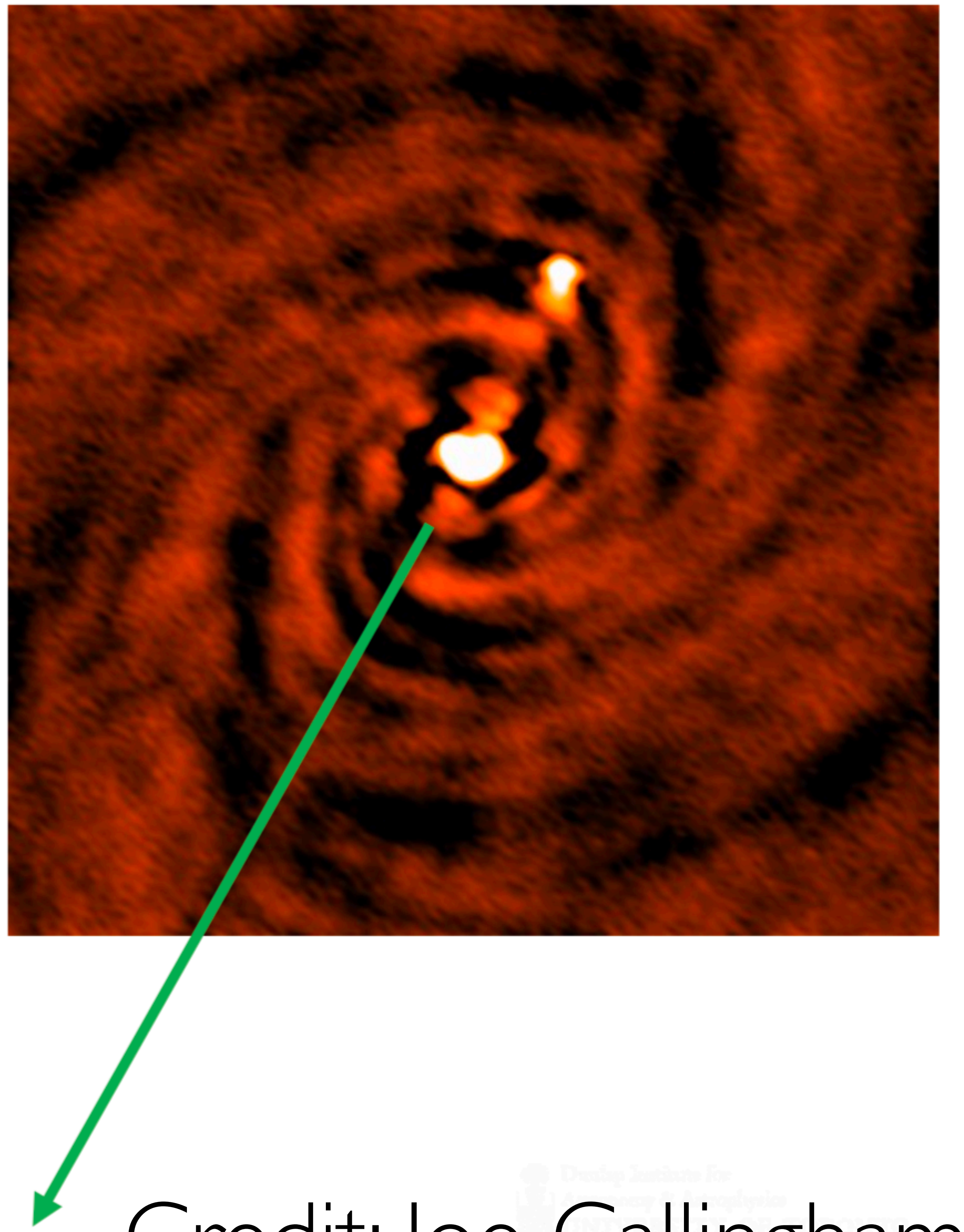
Credit: Joe Callingham

Confusion

1. Outlier fields



0.25 Jy confusing source using outlier field assigned



Credit: Joe Callingham

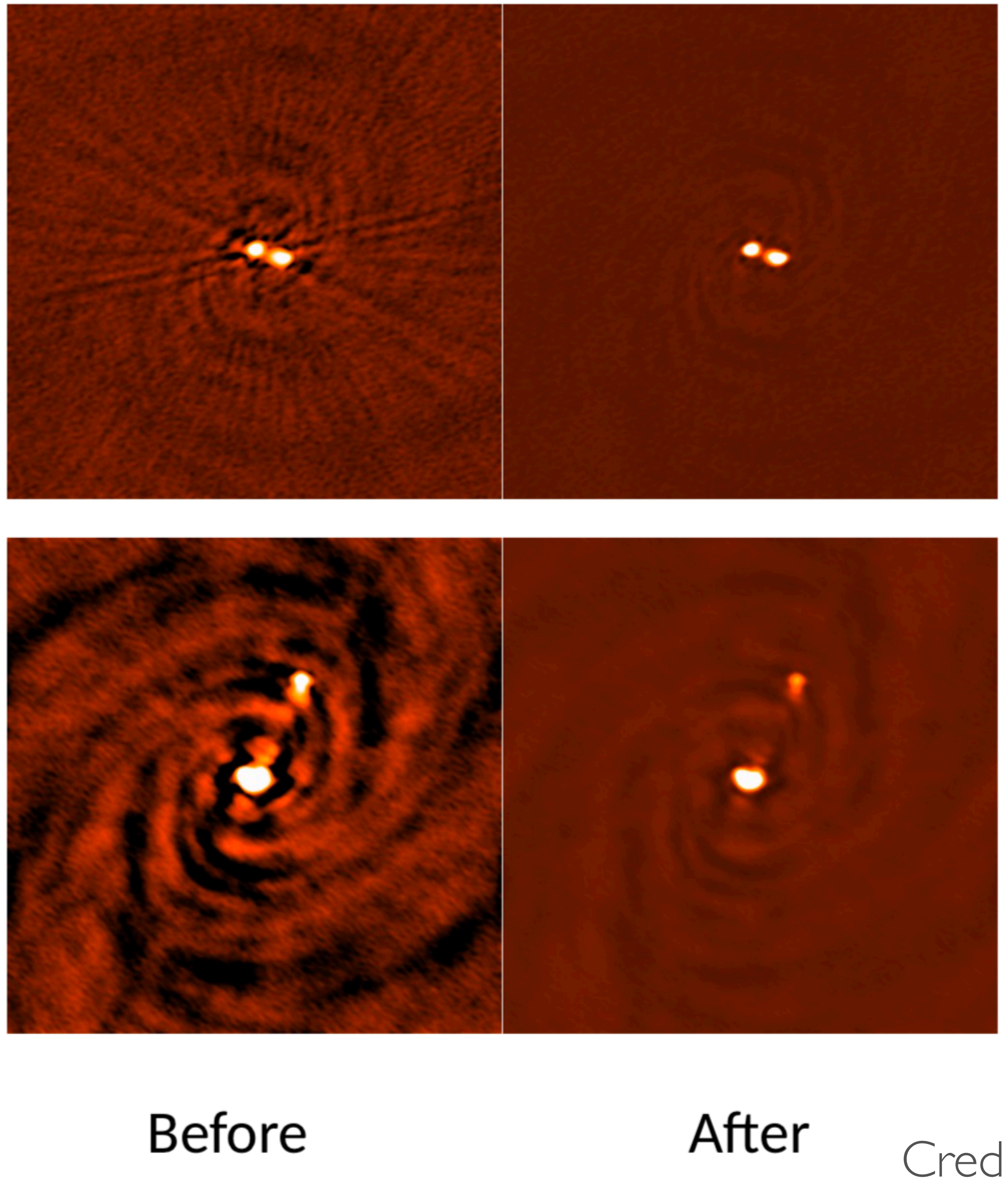
Confusion

2. Peeling — If outlier fields do not solve the problem try peeling!

After phase calibrating the data, perform self-calibration for the brightest confusing source. Subtract source model from visibilities.

Delete phase solutions derived for previous confusing source (1).

Move to the next brightest confusing source and repeat the process until all confusing sources have been subtracted. Delete all self-calibration solutions and image the central regions again.



Credit: Joe Callingham

Signal to Noise

Noise level of a perfect homogeneous interferometer:

$$\text{Noise} = \frac{\sqrt{2} k_B T_{\text{sys}}}{\sqrt{n_b t \Delta\nu A \eta}}$$

where:
- system temperature [K]
- number of baselines
- integration time [s]
- bandwidth [Hz]
- area of apertures [m]
- aperture efficiency

Many factors increase noise level above this value:

— Confusion
— Calibration errors
— Bad data
— Deconvolution artifacts

Conclusion

- Interferometry samples Fourier components of sky brightness
- Make an image by Fourier transforming sampled visibilities
- Deconvolution attempts to correct for incomplete sampling.
- Many different combinations of parameters can be used (weighting changes, outlier fields, etc.) to try and obtain the best image.

There are many more options not discussed in this talk! See upcoming talks and referenes.