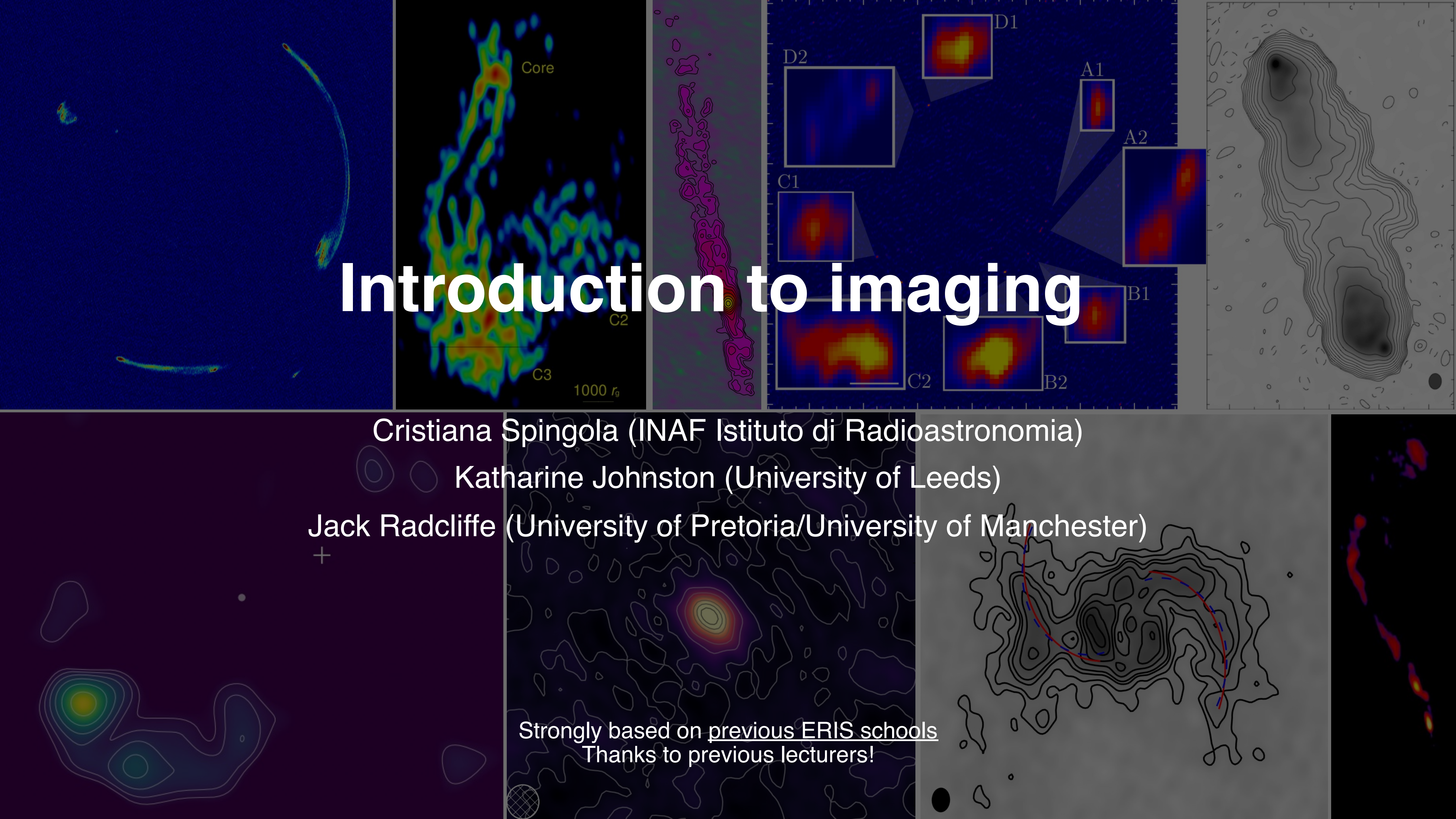


Introduction to imaging

Cristiana Spingola (INAF Istituto di Radioastronomia)
Katharine Johnston (University of Leeds)
Jack Radcliffe (University of Pretoria/University of Manchester)

Strongly based on previous ERIS schools
Thanks to previous lecturers!

#adv conference: save the date

Bologna VLBI: Life begins at 40!

New frontiers and scientific challenges with enhanced frequency/time/space dynamic range

40th anniversary of the start of VLBI operations in Italy

22-26 May 2023 – Bologna, Italy

If you are interested, start booking the hotel now! For further info contact me spingola@ira.inaf.it

Before starting

https://www.jb.man.ac.uk/DARA/ERIS22/imaging.html

You should download
ERIS22_imaging_tutorial.tar.gz

In the folder you are working now, you should have
- 1252+5634.ms – measurement set with visibilities of the target
- 3C277.1_imaging_outline2022.py – script that we will use now
- 3C277.1_imaging_all2022.py – script with spoilers!

Imaging 101

https://www.jb.man.ac.uk/DARA/ERIS22/imaging.html#imaging101

Imaging 101: intro

The output of an interferometer is basically a table of the correlation (amp. & phase) measured on each baseline every few seconds.

To get the final image out of our visibilities the steps are:

Calibration and data editing

Deconvolution (making a CLEANed image)

Refining calibration (self-cal)

Final self-calibrated image

Imaging 101: Fourier Transform imaging and sampling function

S = sampling function
= 1 where there is a measurement in the uv plane
= 0 otherwise

B = Intrinsic source brightness distribution

Convolution

D = dirty beam = point spread function (PSF)

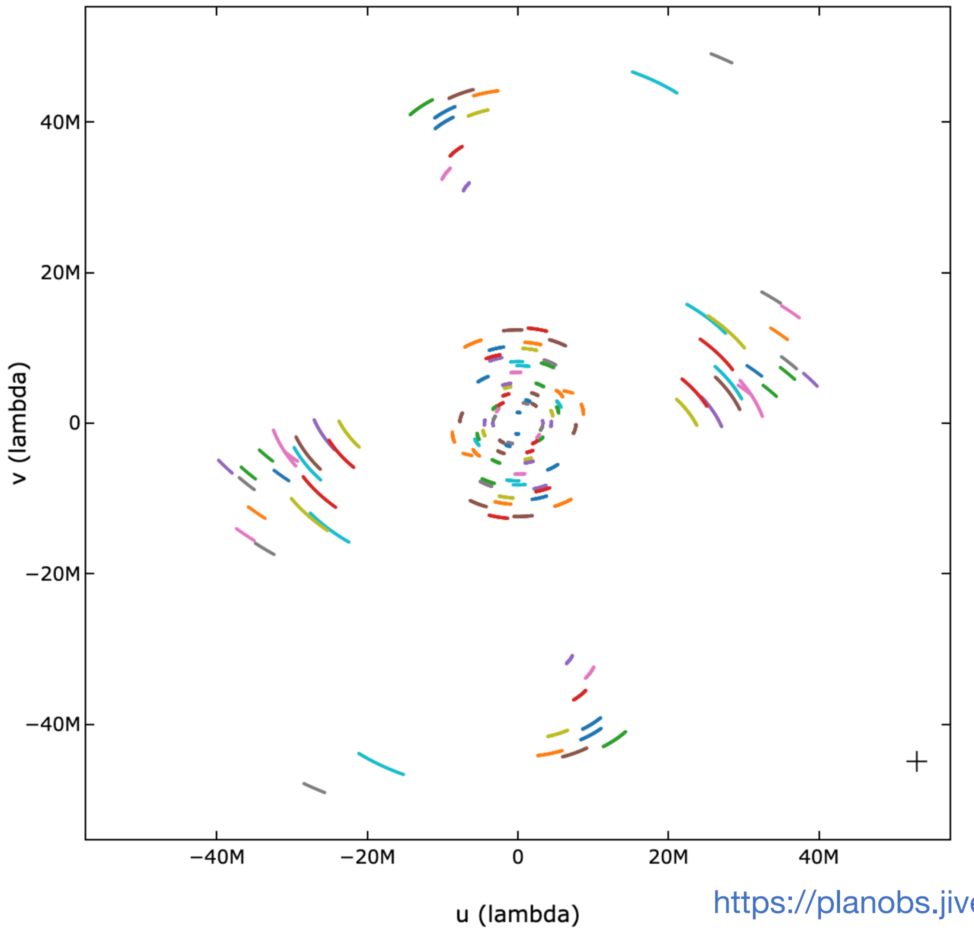
S = Sampling function

Observed visibilities = $$\mathsf{B}(l,m) * \mathsf{D}(l,m) \approx \iint_{uv} \mathsf{S}(u,v)\mathsf{V}(u,v)e^{2\pi i(ul+vm)}dudv$$

$$\mathsf{D}(l,m) = \iint_{uv} \mathsf{S}(u,v)e^{2\pi i(ul+vm)}dudv$$

Dirty beam D(l,m) = Fourier transform of the sampling function
We know D(l,m) !!!

We need to **deconvolve** B(l,m) from the dirty beam D(l,m)



1 h EVN

https://planobs.jive.eu/

Imaging 101: Fourier Transform imaging and sampling function

S = Sampling function

B = Intrinsic source brightness distribution

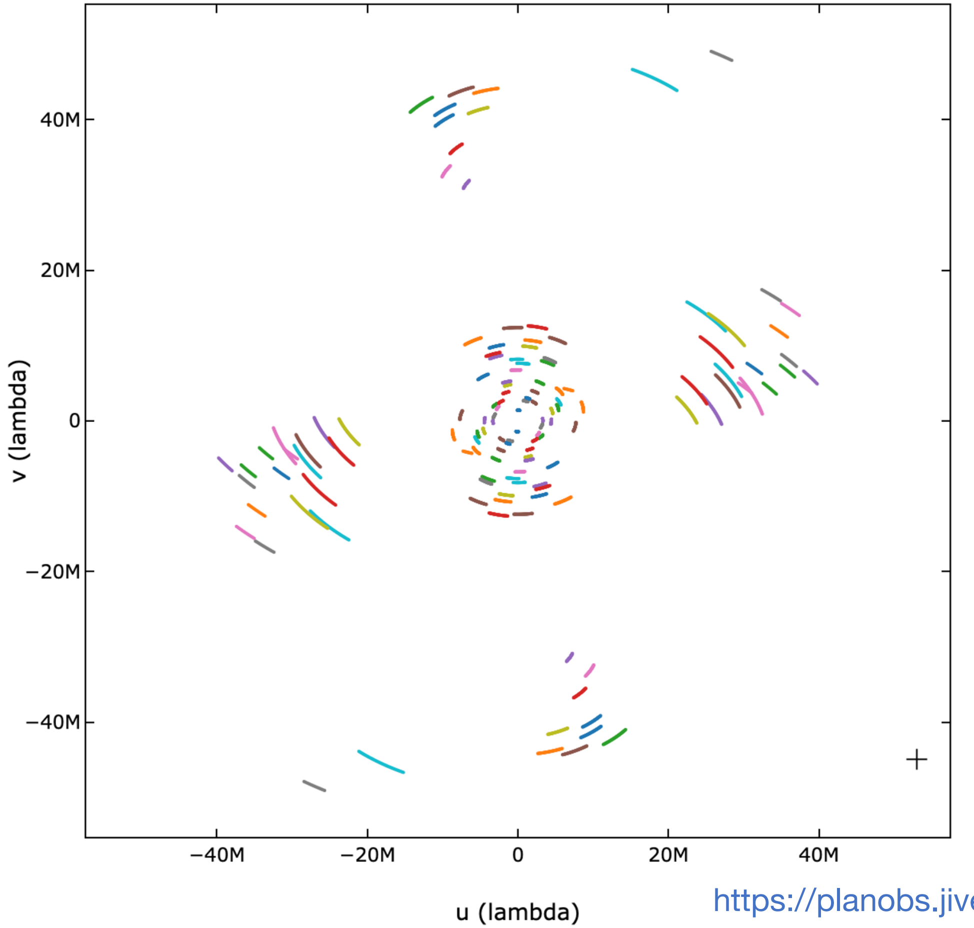
D = dirty beam = point spread function (PSF)

Convolution

$$\text{Observed visibilities} = \mathsf{B}(l,m) * \mathsf{D}(l,m) \approx \iint_{uv} \mathsf{S}(u,v)\mathsf{V}(u,v)e^{2\pi i(ul+vm)}dudv$$

$$\mathsf{D}(l,m) = \iint_{uv} \mathsf{S}(u,v)e^{2\pi i(ul+vm)}dudv$$

S = sampling function
= 1 where there is a measurement in the uv plane
= 0 otherwise



1 h EVN

https://planobs.jive.eu/

An ideal interferometer would deliver
on a regularly highly sampled rectangular grid.
An image of would then be made by simply applying
a Fourier transform

But, arrays provide (poorly) sampled Fourier Transform of the radio brightness region of sky

You need as many V(u,v) points as possible to reconstruct as robustly as possible the surface brightness distribution of the source

Imaging 101: Fourier Transform imaging and sampling function

B = Intrinsic source brightness distribution

Convolution

D = dirty beam = point spread function (PSF)

S = Sampling function

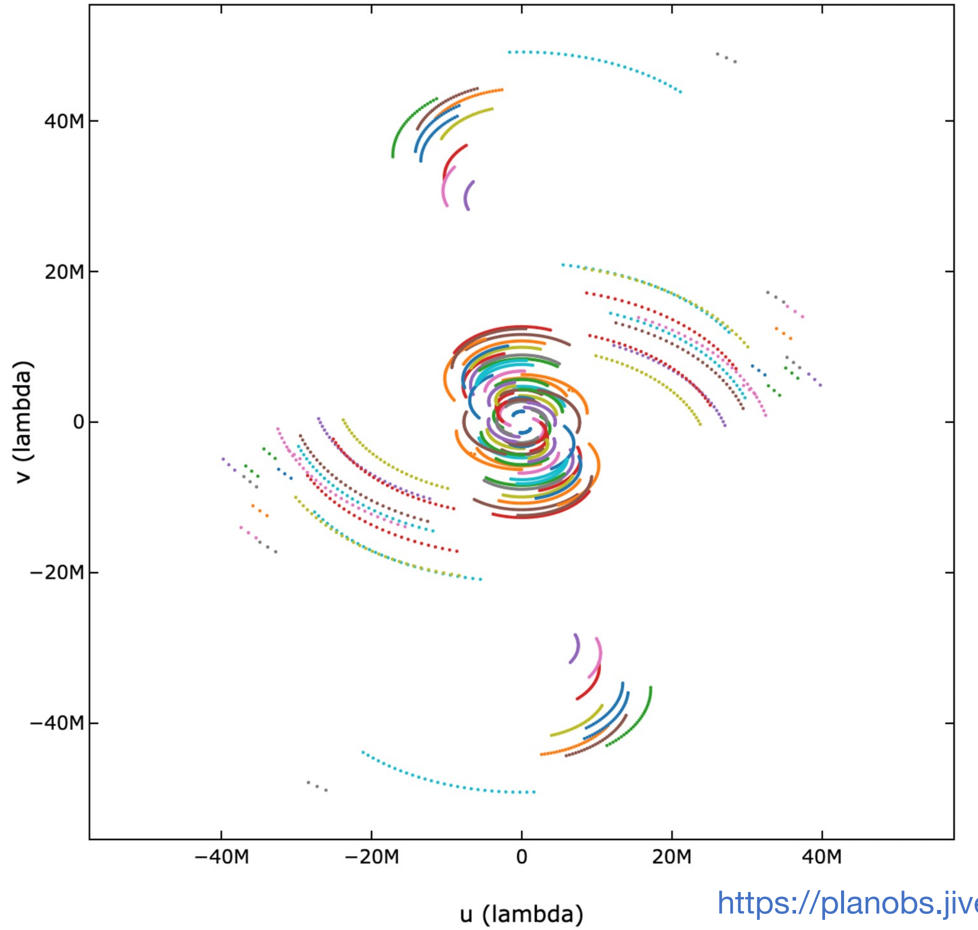
$$\text{Observed visibilities} = B(l,m) * D(l,m) \approx \iint_{uv} S(u,v)V(u,v)e^{2\pi i(ul+vm)}dudv$$

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

S = sampling function

= 1 where there is a measurement in the uv plane

= 0 otherwise



6 h EVN

https://planobs.jive.eu/

An ideal interferometer would deliver on a regularly highly sampled rectangular grid. An image of would then be made by simply applying a Fourier transform

But, arrays provide (poorly) sampled Fourier Transform of the radio brightness region of sky

You need as many V(u,v) points as possible to reconstruct as robustly as possible the surface brightness distribution of the source

Imaging 101: Fourier Transform imaging and sampling function

B = Intrinsic source brightness distribution

S = Sampling function

D = dirty beam = point spread function (PSF)

Convolution

Observed visibilities = $\mathsf{B}(l,m) * \mathsf{D}(l,m) \approx \iint_{uv} \mathsf{S}(u,v)\mathsf{V}(u,v)e^{2\pi i(ul+vm)}dudv$

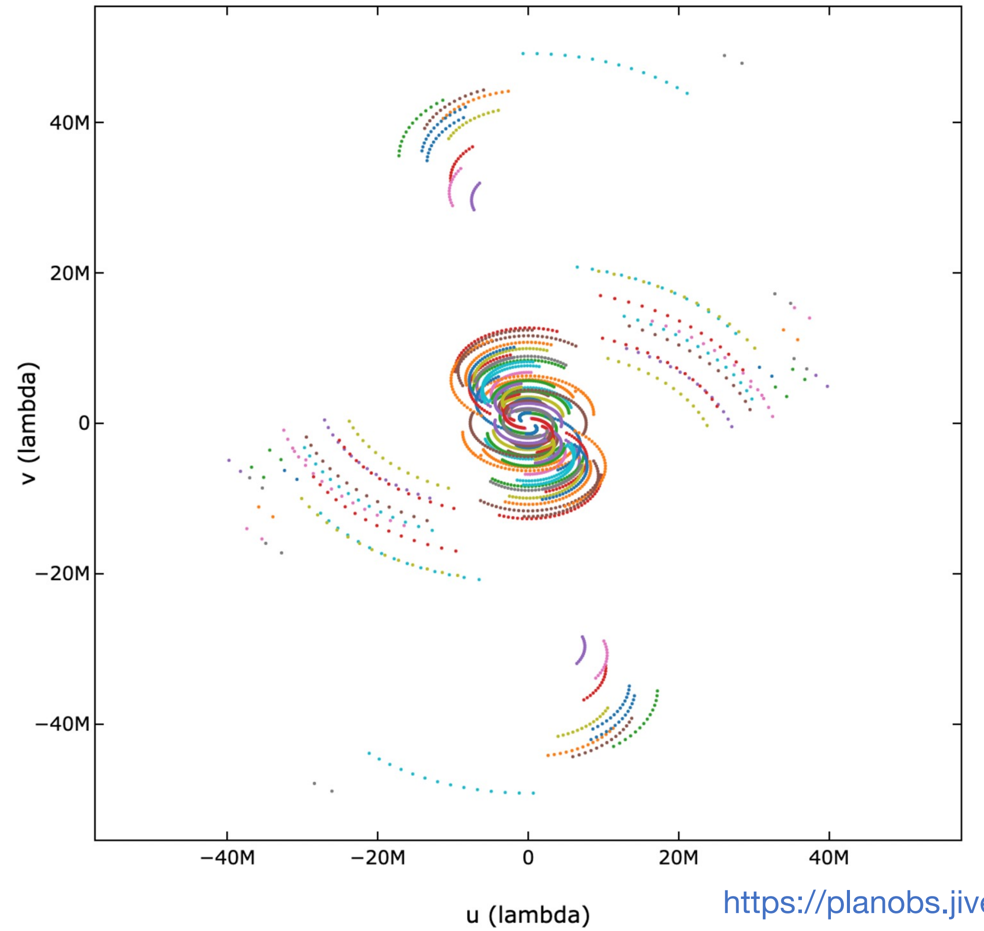
$$\mathsf{D}(l,m) = \iint_{uv} \mathsf{S}(u,v)e^{2\pi i(ul+vm)}dudv$$

An ideal interferometer would deliver
on a regularly highly sampled rectangular grid.
An image of would then be made by simply applying
a Fourier transform

But, arrays provide (poorly) sampled Fourier Transform of the radio brightness region of sky

You need as many V(u,v) points as possible to reconstruct as robustly as possible the surface brightness distribution of the source

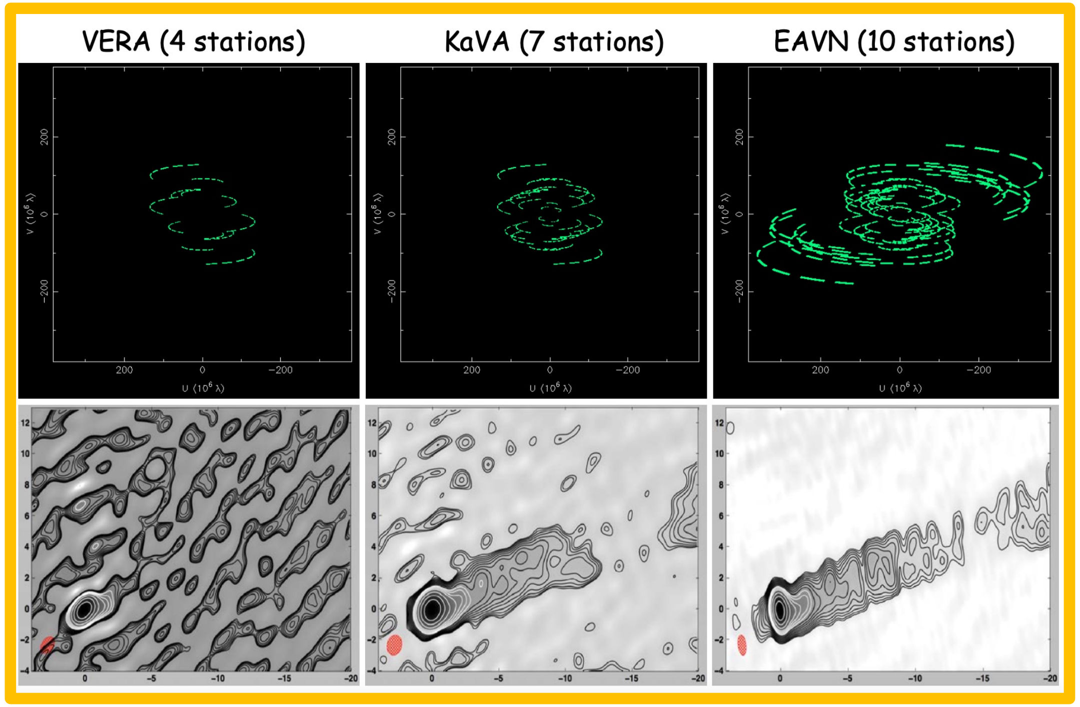
S = sampling function
= 1 where there is a measurement in the uv plane
= 0 otherwise



12 h EVN

https://planobs.jive.eu/

Imaging 101: Fourier Transform imaging and sampling function



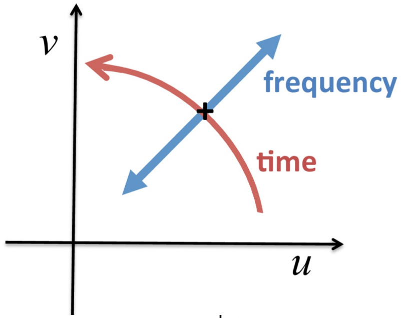
Credits: Prof. Kazuhiro Hada

An ideal interferometer = measurements on a regularly highly sampled rectangular grid.
An image of would then be made by simply applying a Fourier transform

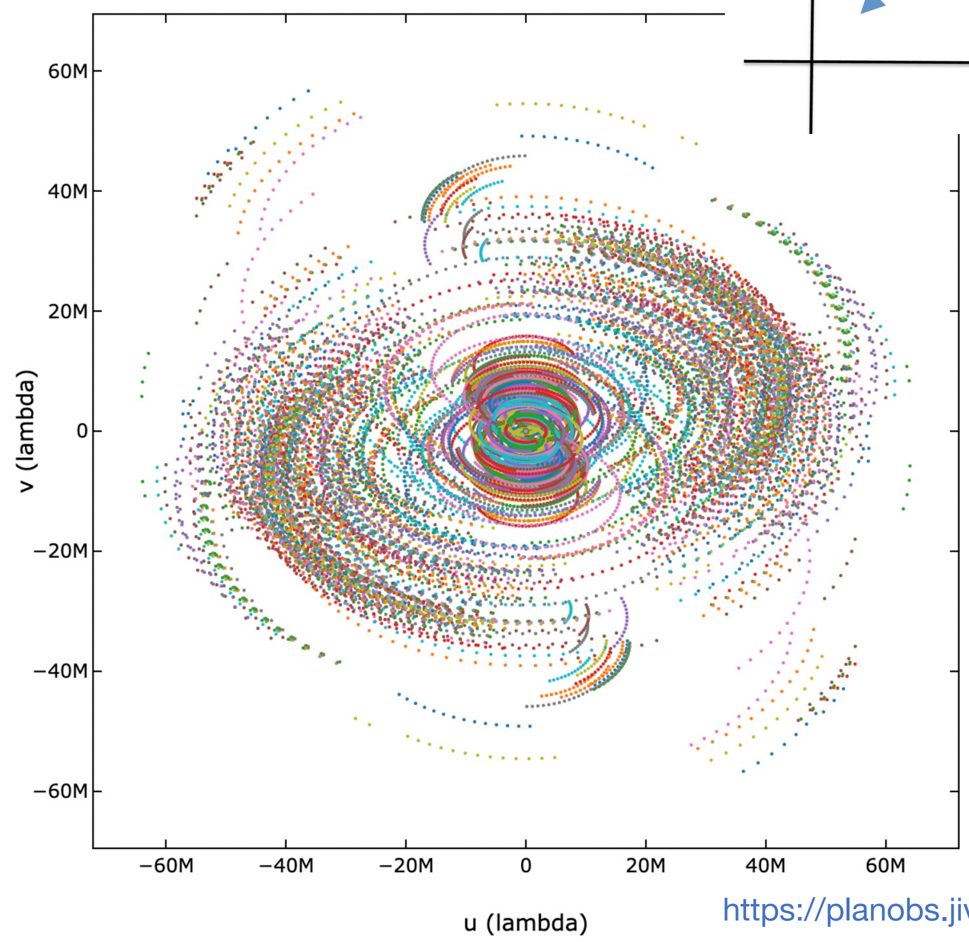
But, arrays provide (poorly) sampled Fourier Transform of the radio brightness region of sky

You need as many V(u,v) points as possible to reconstruct as robustly as possible the surface brightness distribution of the source

S = sampling function
= 1 where there is a measurement in the uv plane
= 0 otherwise



Credits: Prof. Scaife ERIS 2017



12 h
>30 antennas

https://planobs.jive.eu/

Imaging 101: Gridding

But, arrays provide (poorly) sampled Fourier Transform of the radio brightness region of sky
AND
There will always be gaps in the u-v plane!

Two approaches

Direct Fourier Transform (DFT) = FT evaluated at every point of a rectangular grid – $O(N^2)$ operations

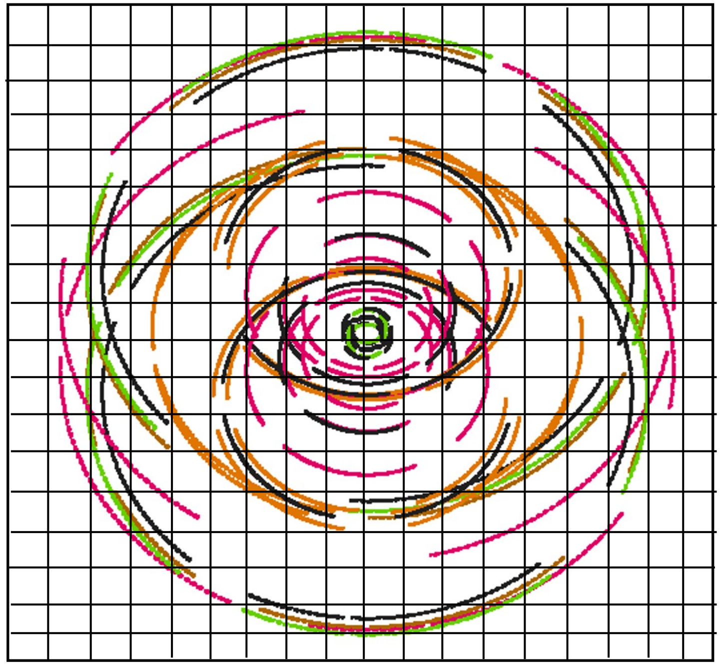
impractical for large number of visibilities

Fast Fourier Transform (FFT) = interpolate the data onto a rectangular grid – O(N log N) operations

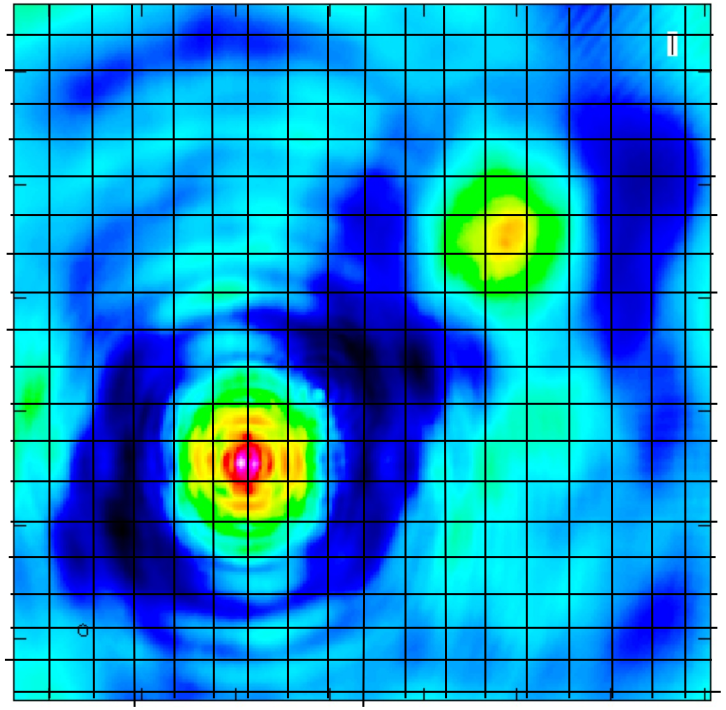
It saves a lot of computing time!!

This FFT method requires the observed visibilities to be interpolated on a regular grid

Usually we define the grid in the image plane, where grid spacing = cell size

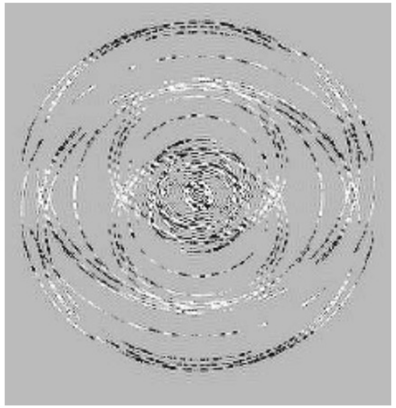


NxN grid



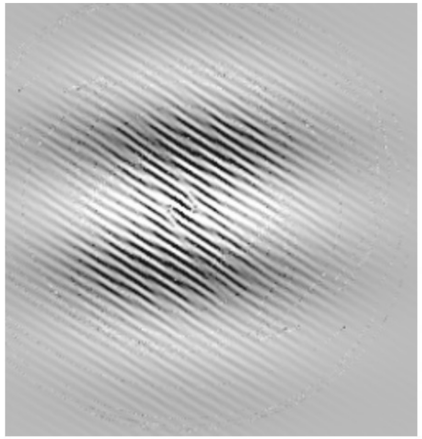
Imaging 101: the need for deconvolution

Sampled visibilities V'(u,v)



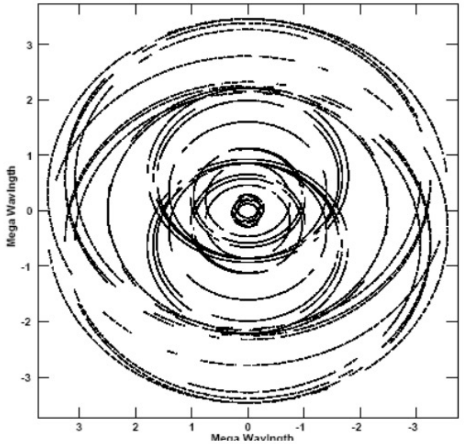
=

True visibilities V(u,v)



X

Sampling function S(u,v)

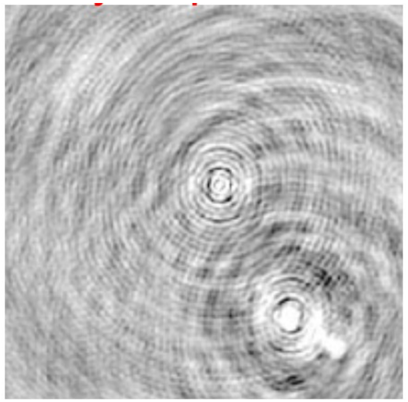


«Visibility domain»

FT

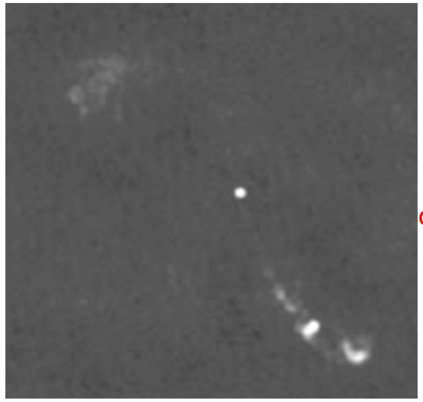
«Image domain»

Dirty image B' (l,m)



=

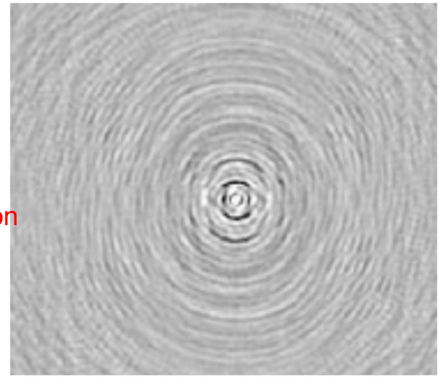
True sky B (l,m)



*

convolution

Dirty beam (l,m)



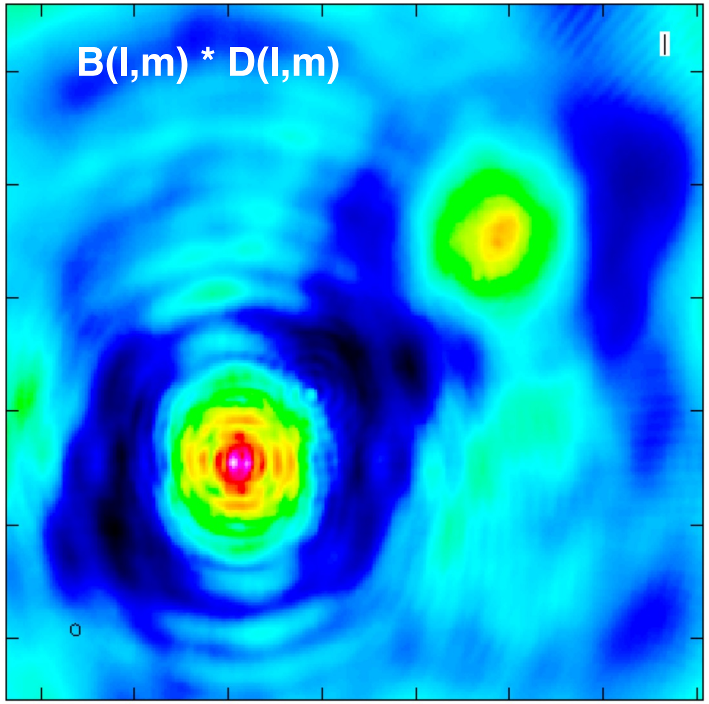
The dirty image is not the true image of the source, since <u>the sampled visibilities are not the true visibilities</u>

Corrections of the effect of Fourier sampling deficiencies on the dirty image = CLEAN algorithms

Original slide from
Prof. Garrington ERIS 2017

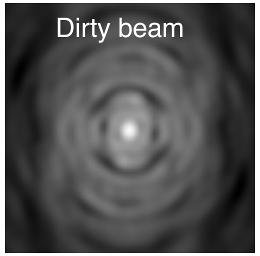
Imaging 101: Deconvolution

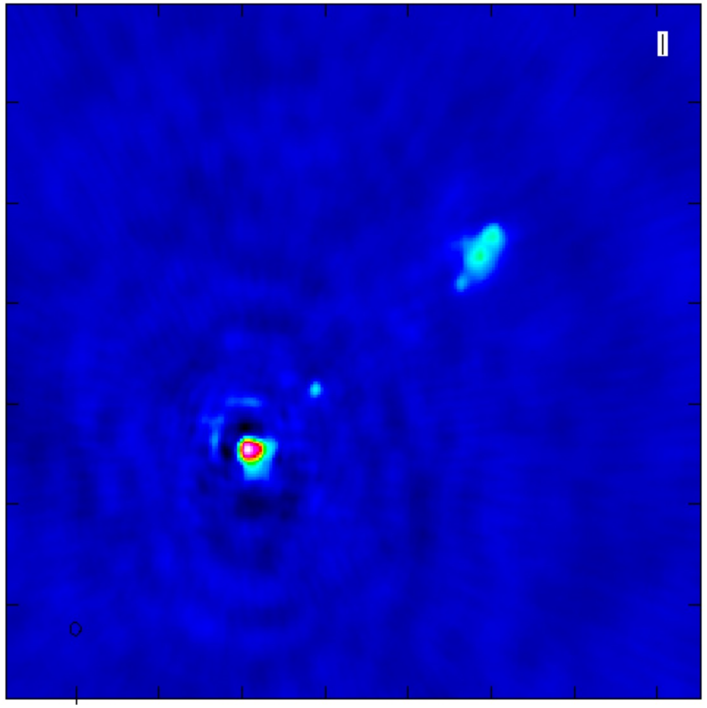
….Why do we need all of this again?



From «dirty image»

Deconvolve the intrinsic source brightness distribution B(l,m) from the **dirty beam** D(l,m)





To «CLEAN image»

Imaging 101: Deconvolution

Since only a finite number of (noisy) samples are measured, to recover B(l,m) we need **some stable non-linear approach** + ***a priori* information**:

- B(l,m) must be positive
- Radio sources do not resemble the dirty beam (i.e. sidelobes-like patterns)
- Sky is basically empty with just a few localised sources

S = Sampling function

B = Intrinsic source brightness distribution

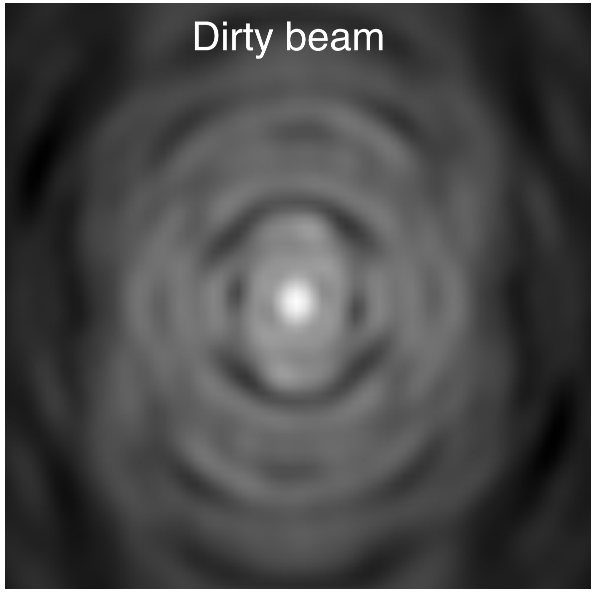
D = dirty beam = point spread function (PSF)

Convolution

$$\mathsf{B}(l,m) * \mathsf{D}(l,m) \approx \iint_{uv} \mathsf{S}(u,v)\mathsf{V}(u,v)e^{2\pi i(ul+vm)}dudv$$

$$\mathsf{D}(l,m) = \iint_{uv} \mathsf{S}(u,v)e^{2\pi i(ul+vm)}dudv$$

We know this!
To recover B we have **“just" to deconvolve** the D(l,m) term



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (first image = dirty image)

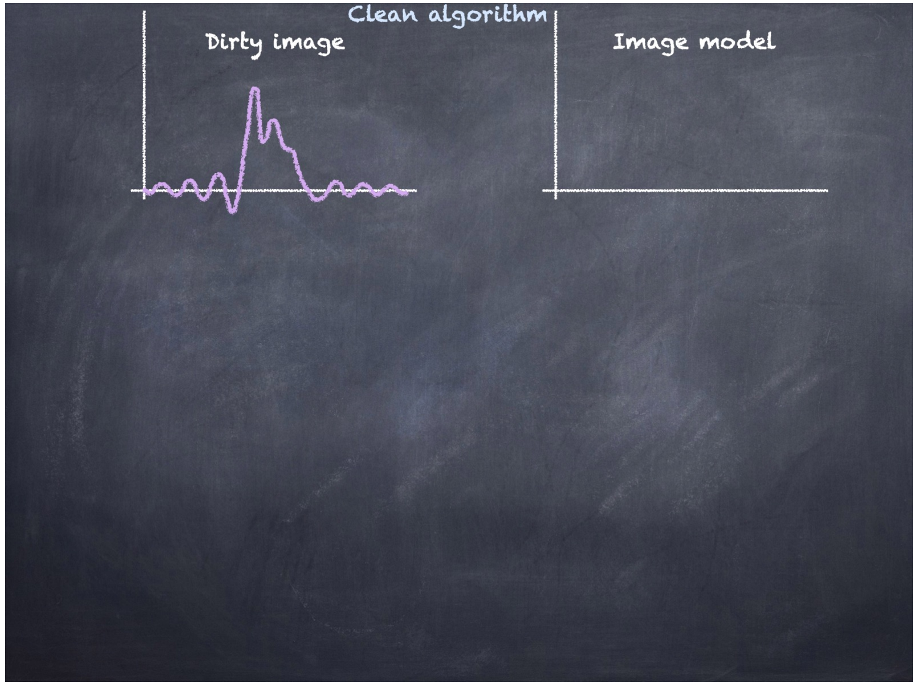
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

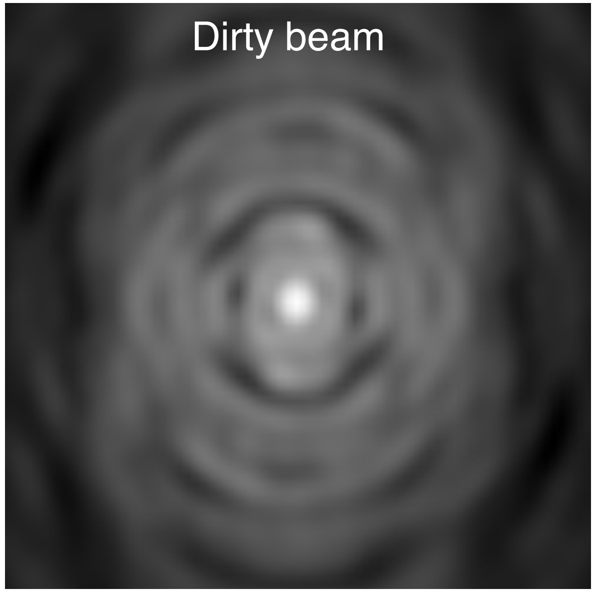
4) Go to 1) unless you reach the stopping criterion

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (first image = dirty image)

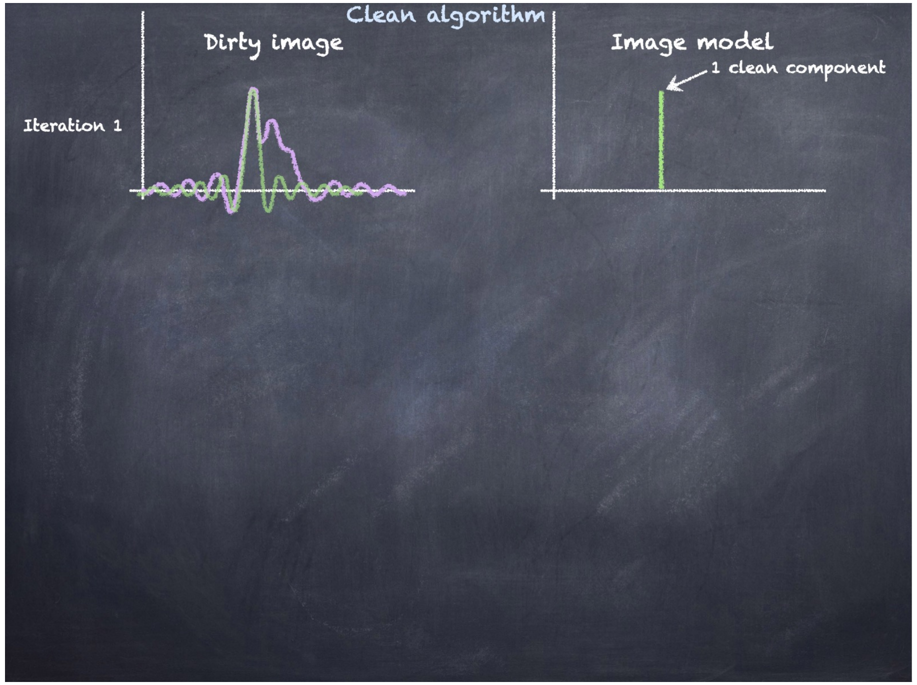
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

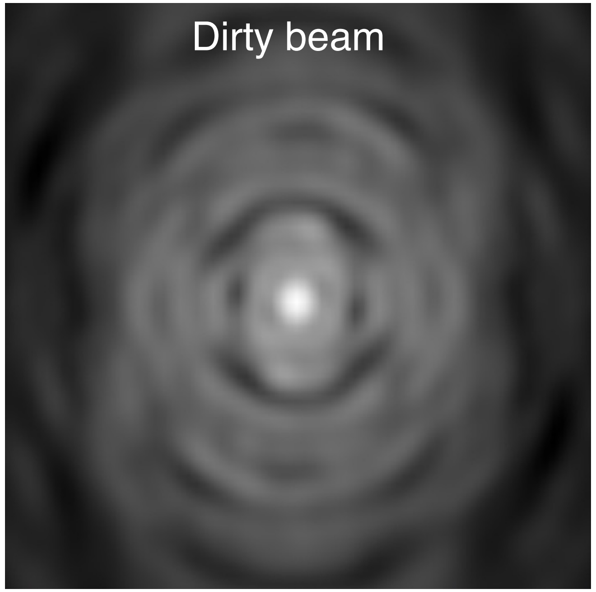
4) Go to 1) unless you reach the stopping criterion

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (first image = dirty image)

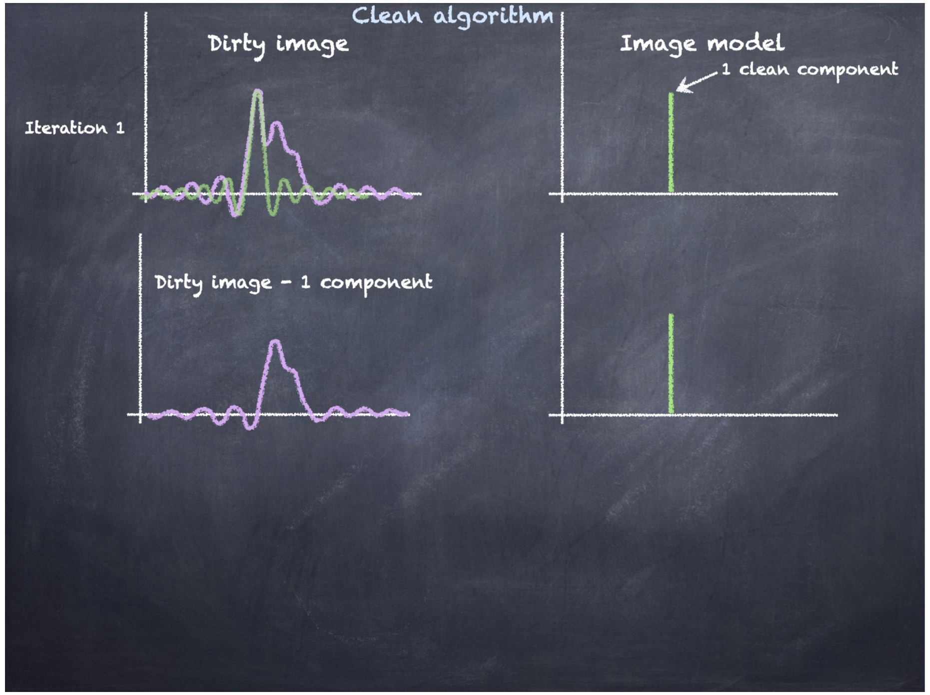
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

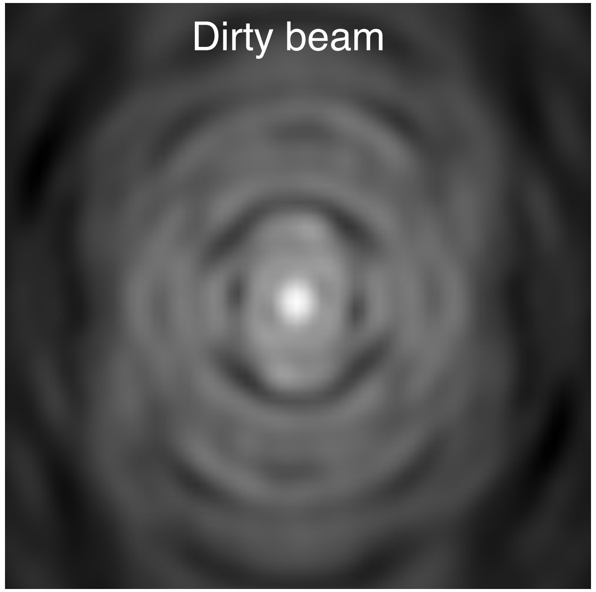
4) Go to 1) unless you reach the stopping criterion

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (first image = dirty image)

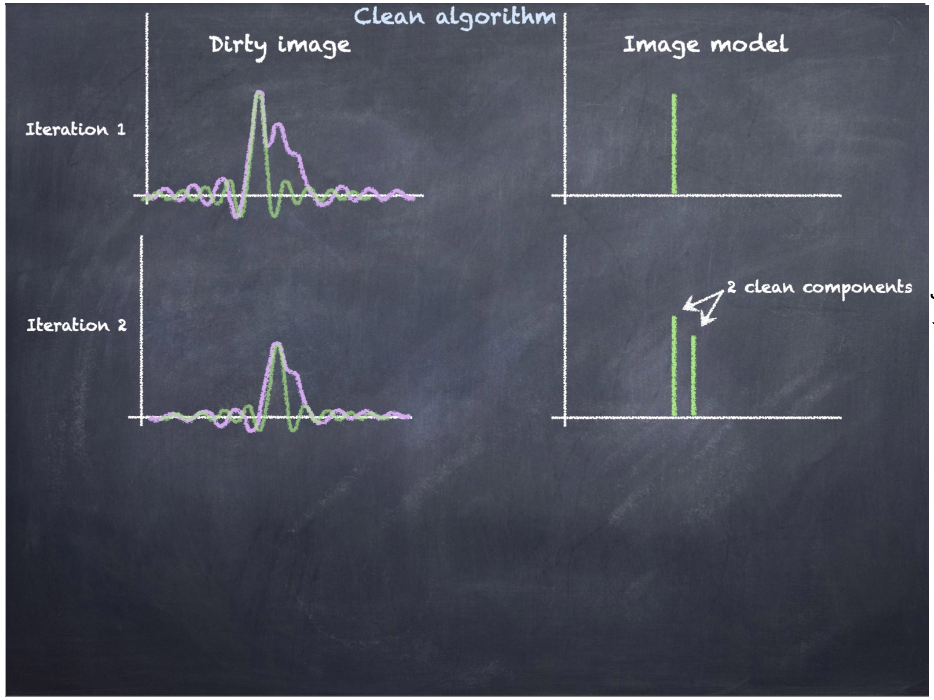
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

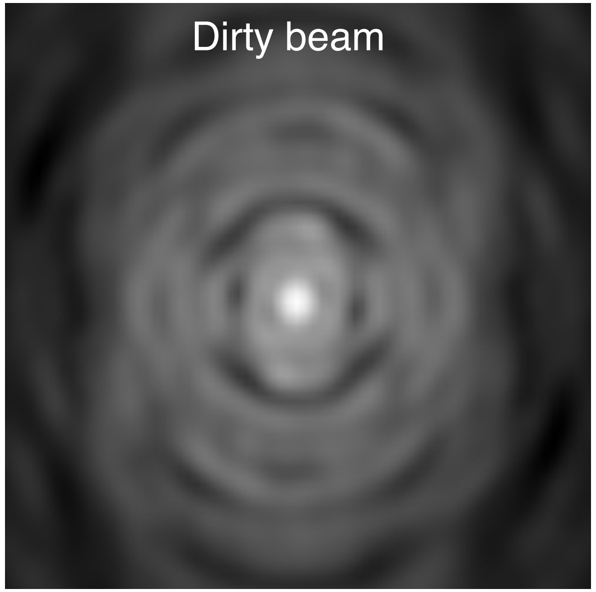
4) Go to 1) unless you reach the stopping criterion

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (data - model)

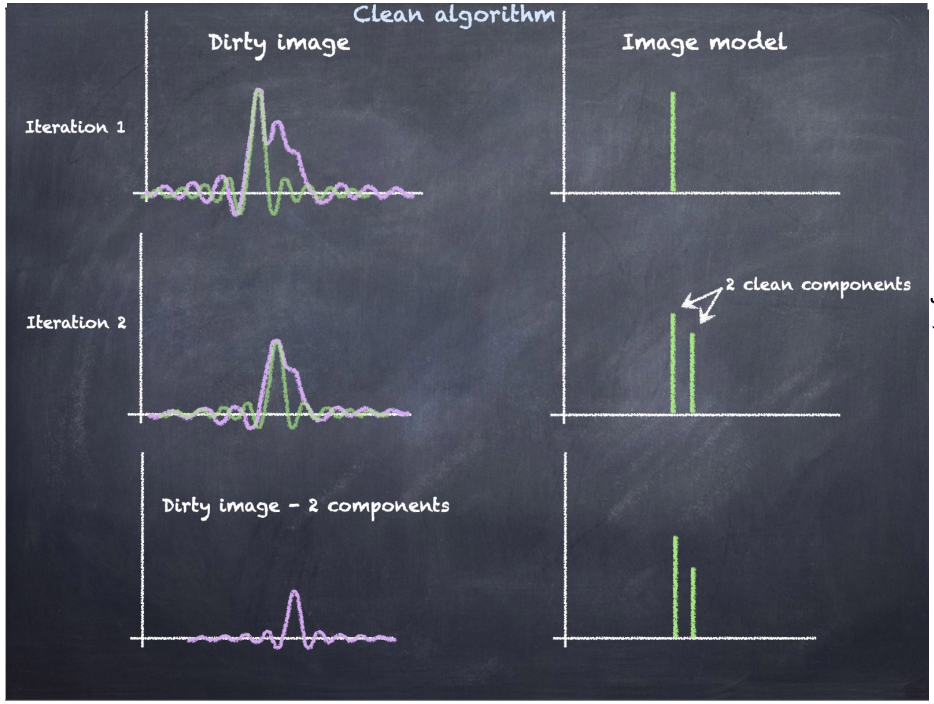
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

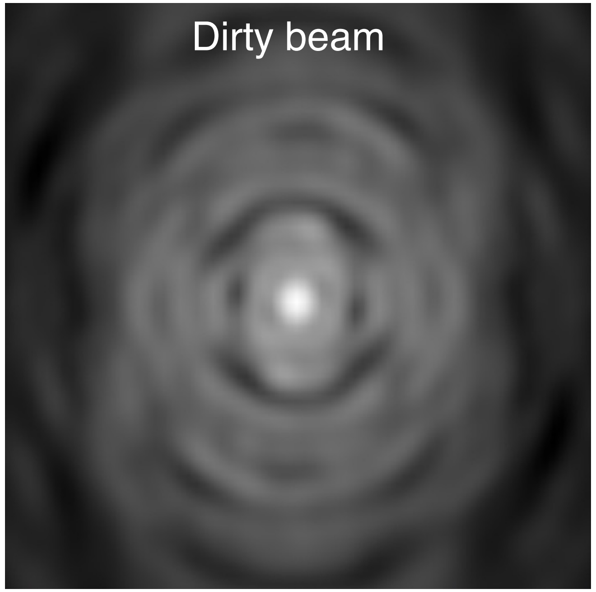
4) Go to 1) unless you reach the stopping criterion

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (first image = dirty image)

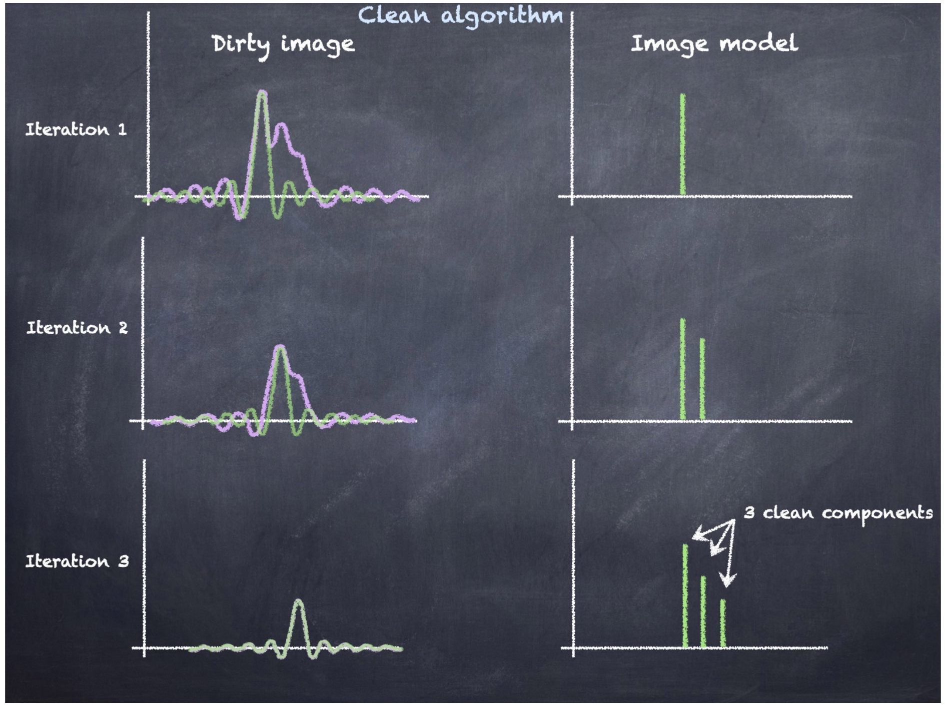
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

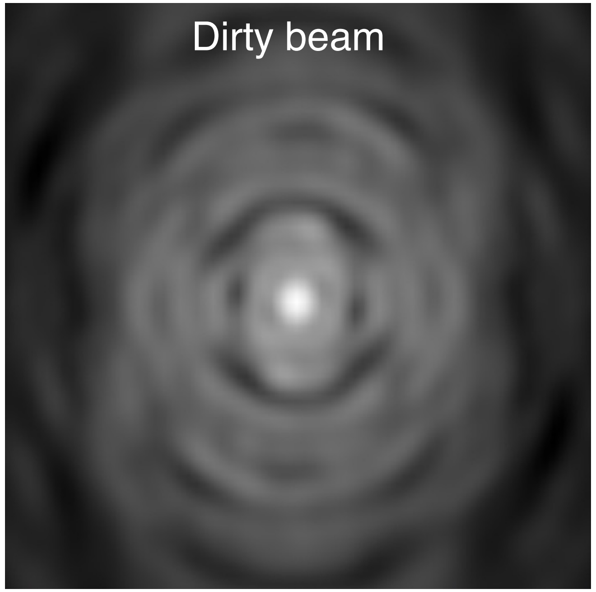
4) Go to 1) unless you reach the stopping criterion

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (first image = dirty image)

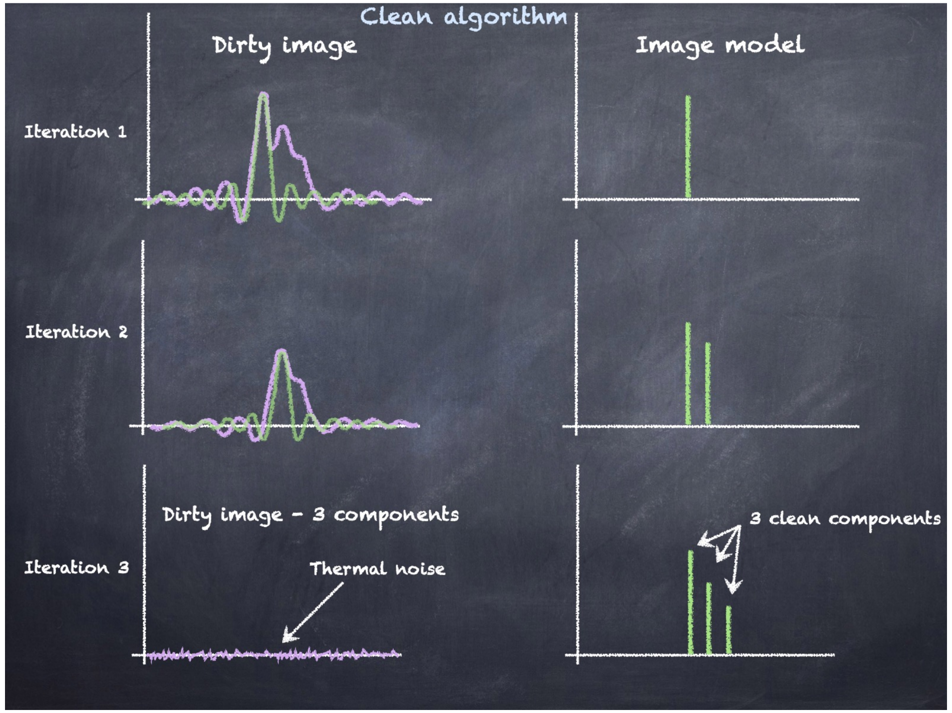
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

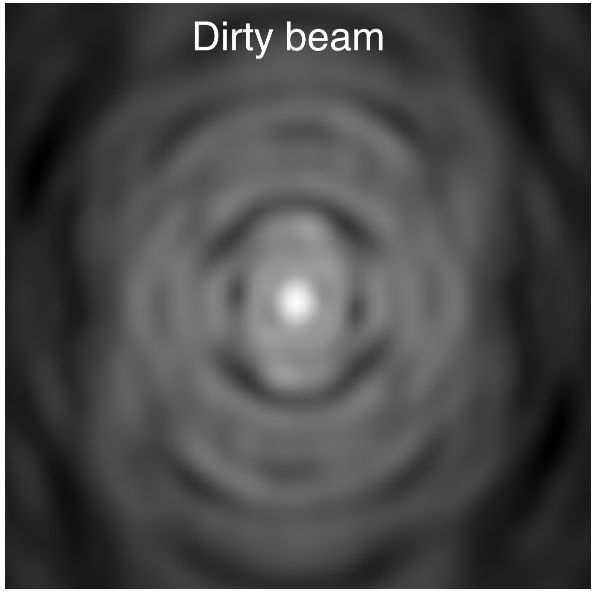
4) Go to 1) unless you reach the **stopping criterion**

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (first image = dirty image)

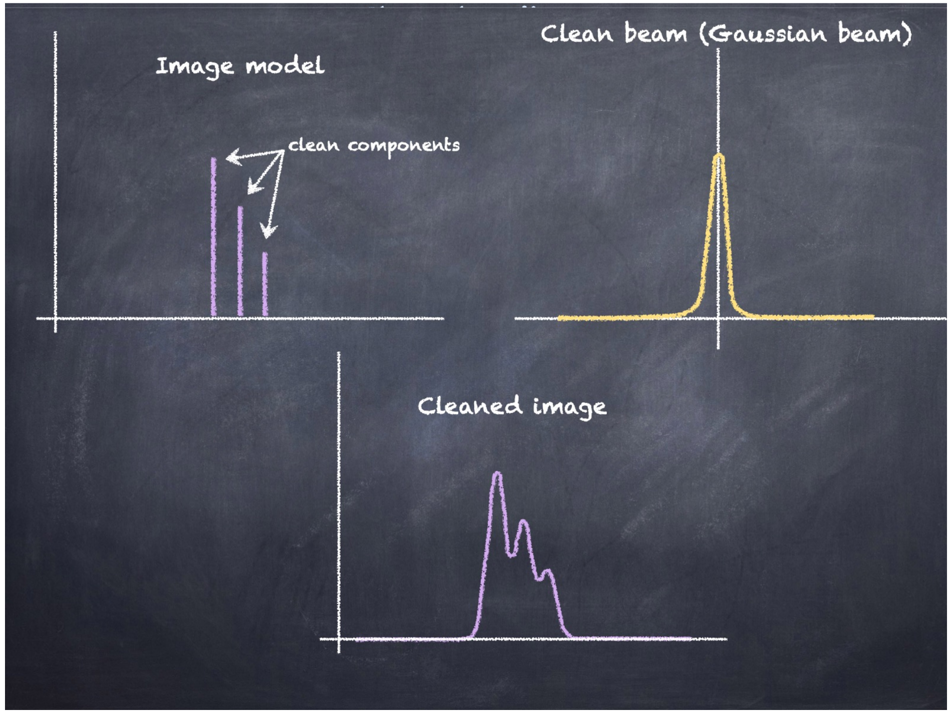
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

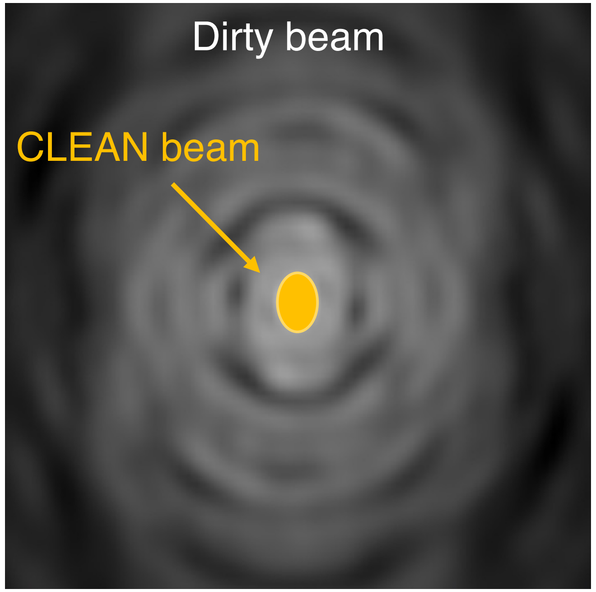
4) Go to 1) unless you reach the stopping criterion

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Imaging 101: Deconvolution

CLEAN method principal steps (Clark's algorithm):

1) Initialize a residual map (first image = dirty image)

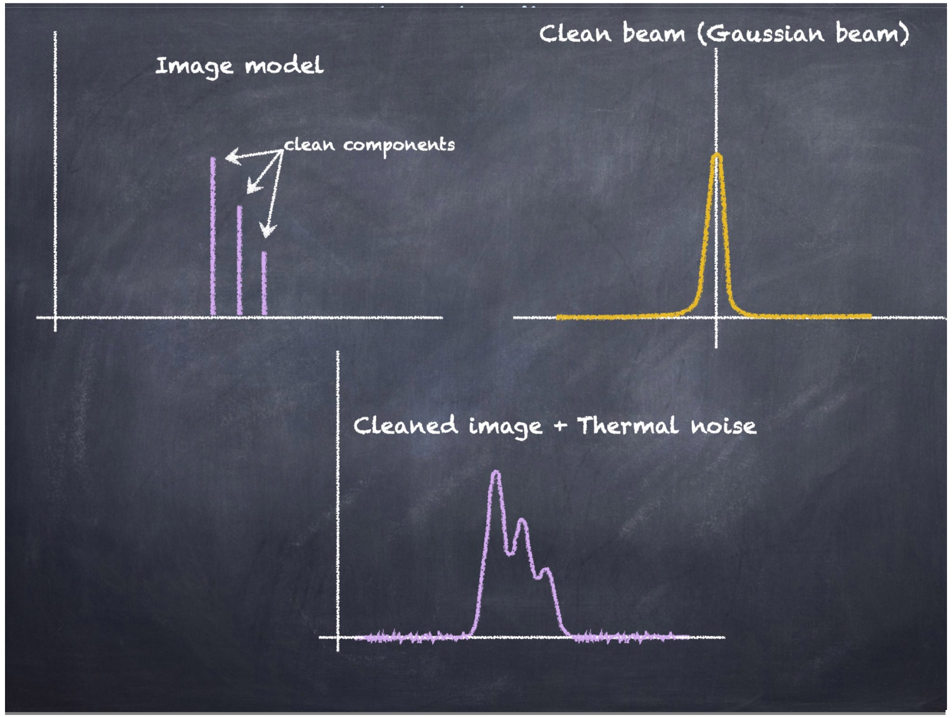
2) Identify strongest peak as a delta component

3) Record the position and magnitude in a model (clean components), subtract it from the dirty image

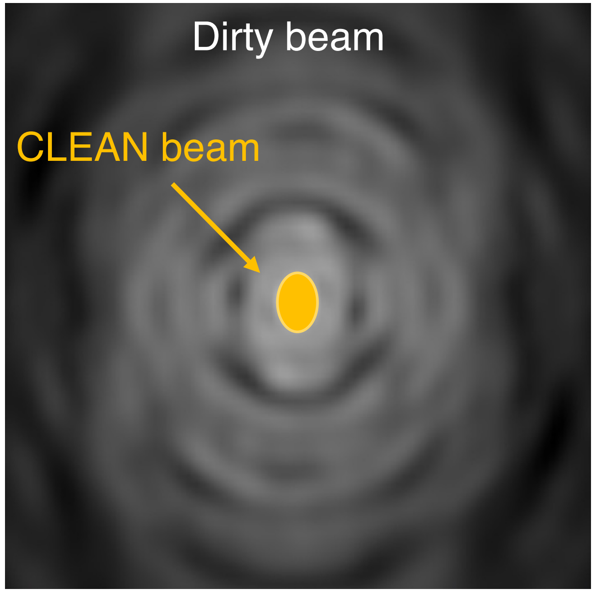
4) Go to 1) unless you reach the stopping criterion

5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)

6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019

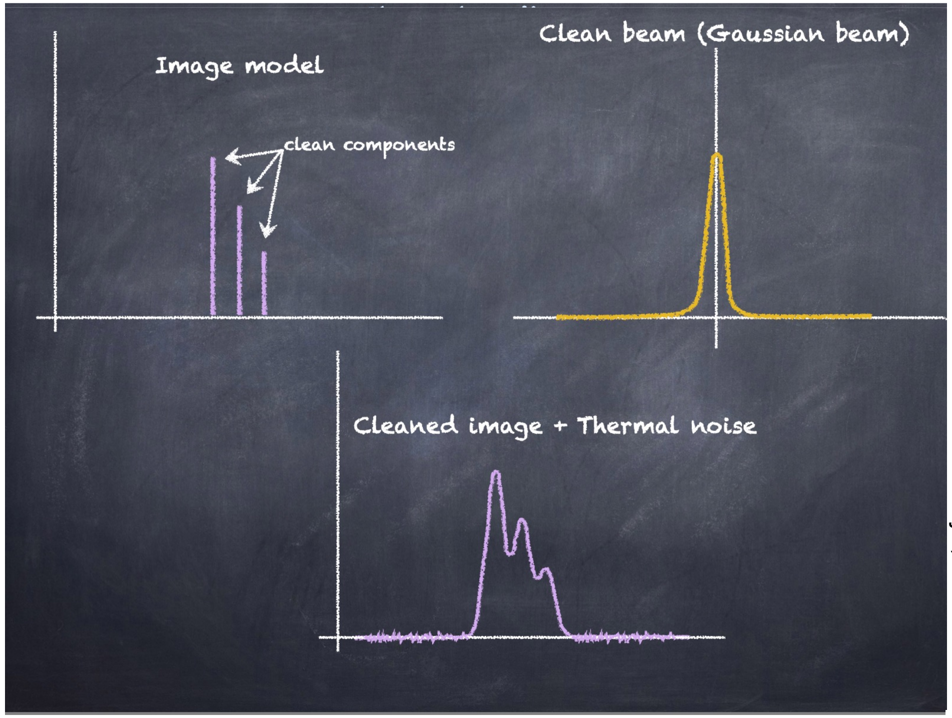


Imaging 101: Deconvolution

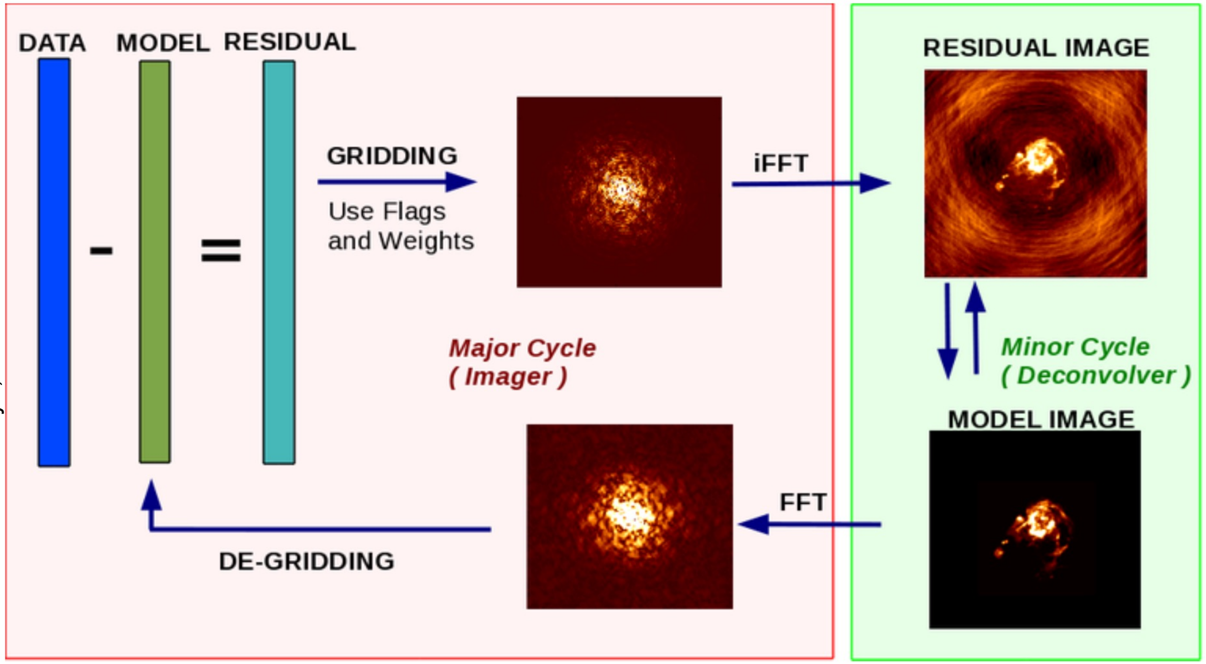
CLEAN method principal steps (Clark's algorithm):

Minor cycle

1) Initialize a residual map (first image = dirty image)
2) Identify strongest peak as a delta component
3) Record the position and magnitude in a model (clean components), subtract it from the dirty image
4) Go to 1) unless you reach the stopping criterion
5) Convolve the model (clean components) with an idealized CLEAN beam (elliptical Gaussian fit of the main lobe of the dirty beam)
6) Add the residual of the dirty image to the CLEAN image



Credits: Daniel Tafoya, ERIS 2019



Credits: Daniel Tafoya, ERIS 2019

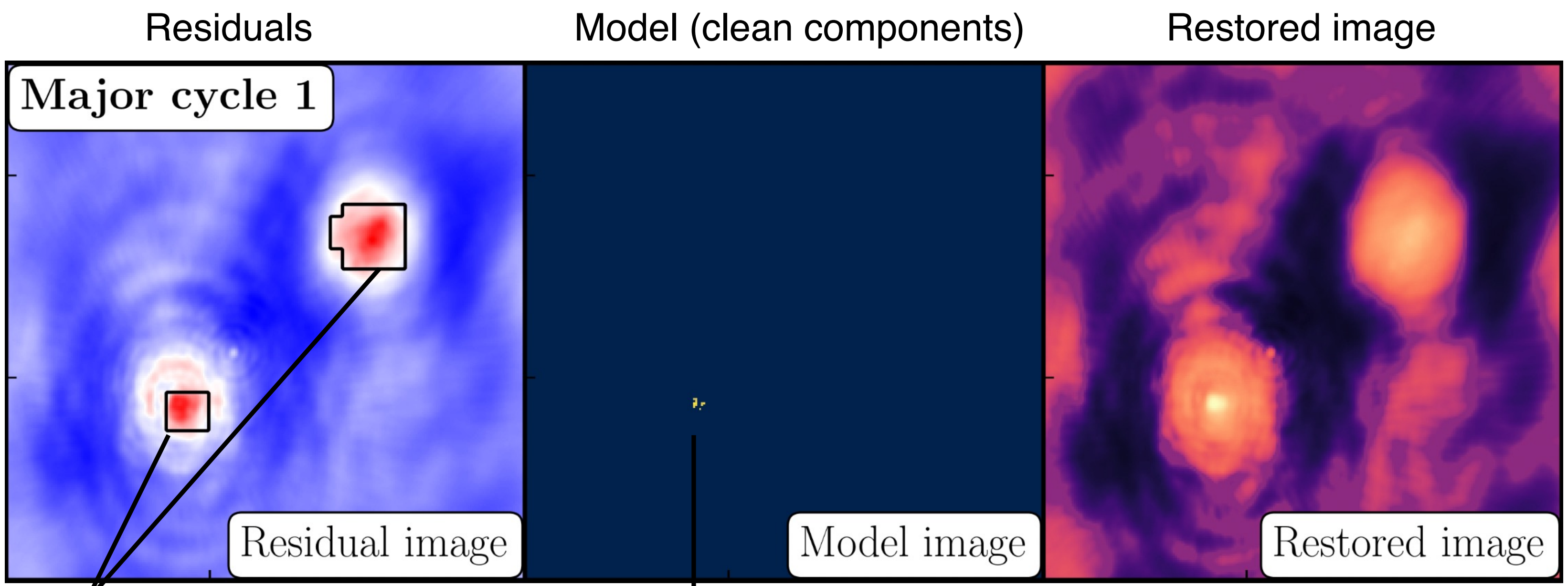
The major cycle implements FT between the data and image domains

The minor cycle operates purely in the image domain

(The 2-cycles approach makes the deconvolution faster)

Imaging 101: Deconvolution

CLEAN in action



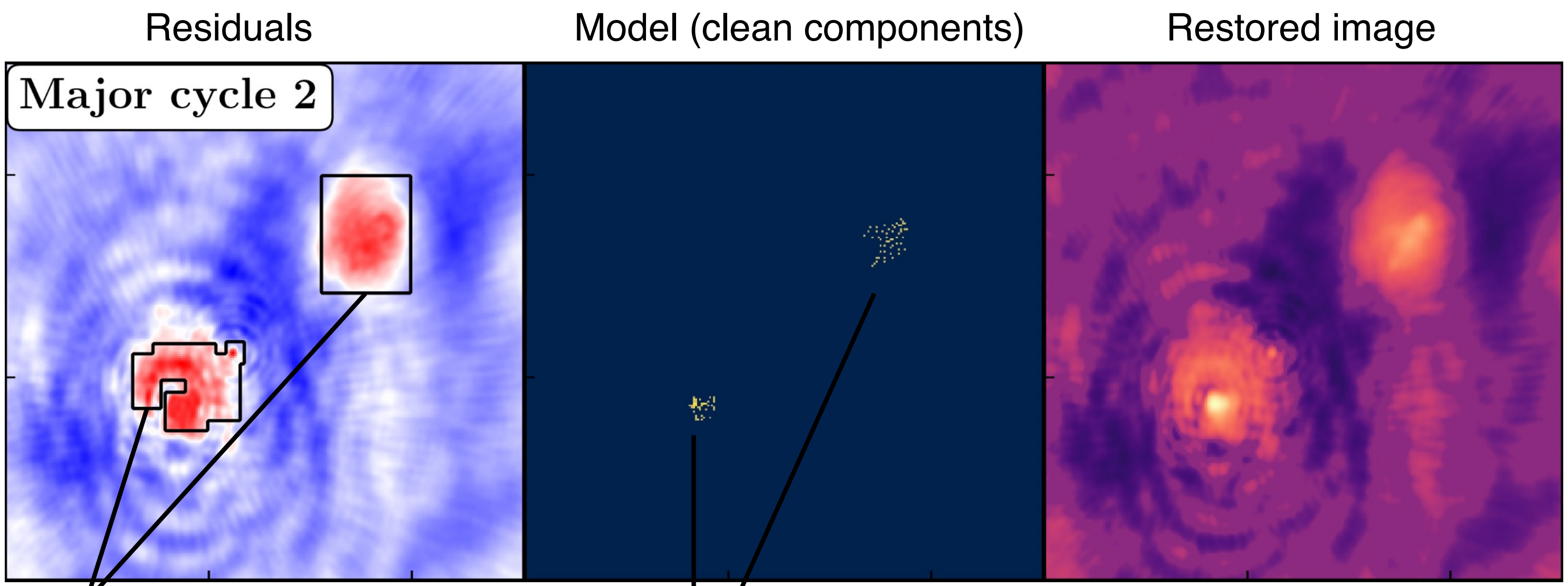
To make this process converge faster
we use the so-called CLEAN boxes (mask)

Also useful to not let CLEAN go to sidelobes
(see next slides)

CLEAN components obtained
during several minor cycles

Imaging 101: Deconvolution

CLEAN in action

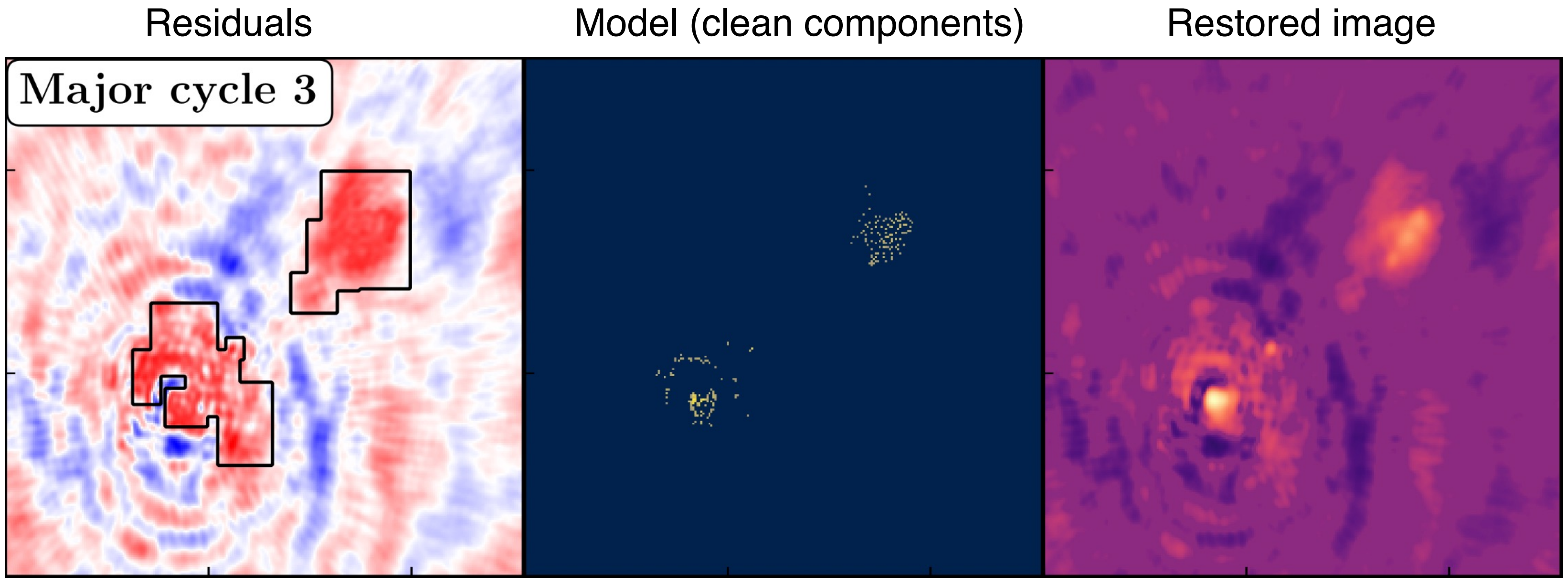


The residual image now shows fainter emission: we enlarge the CLEAN boxes to cover this

New CLEAN components added to the previous ones

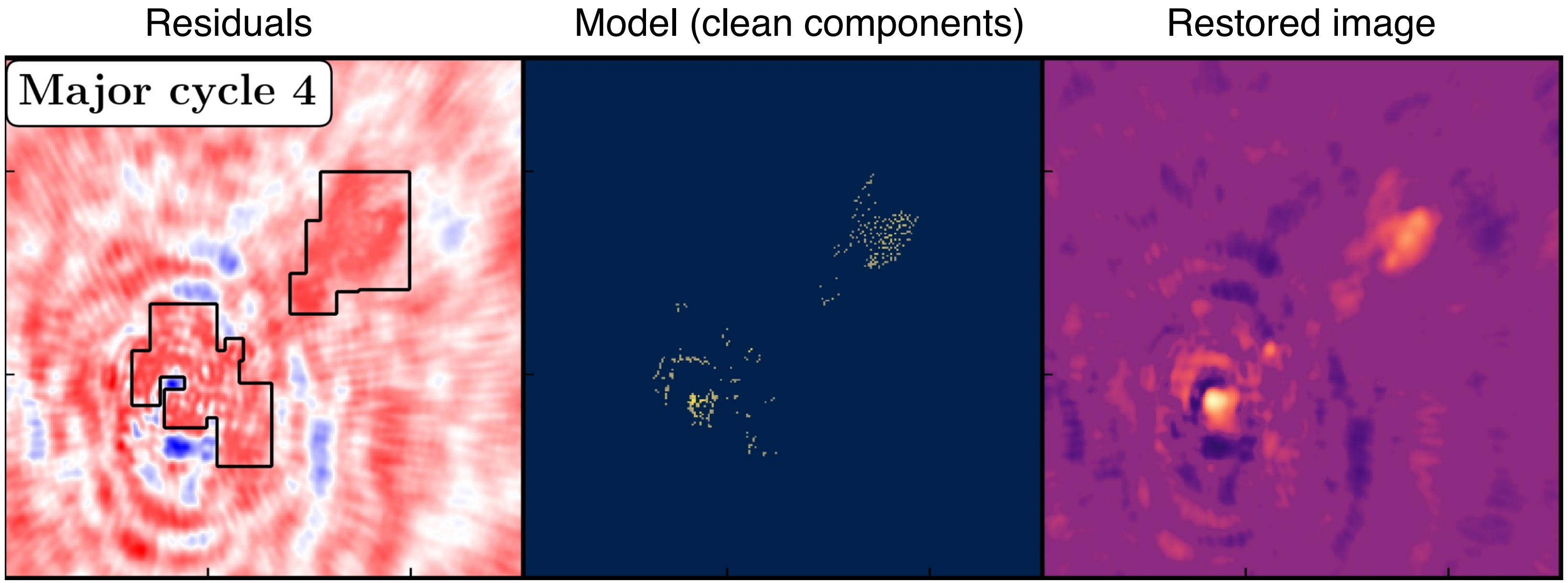
Imaging 101: Deconvolution

CLEAN in action



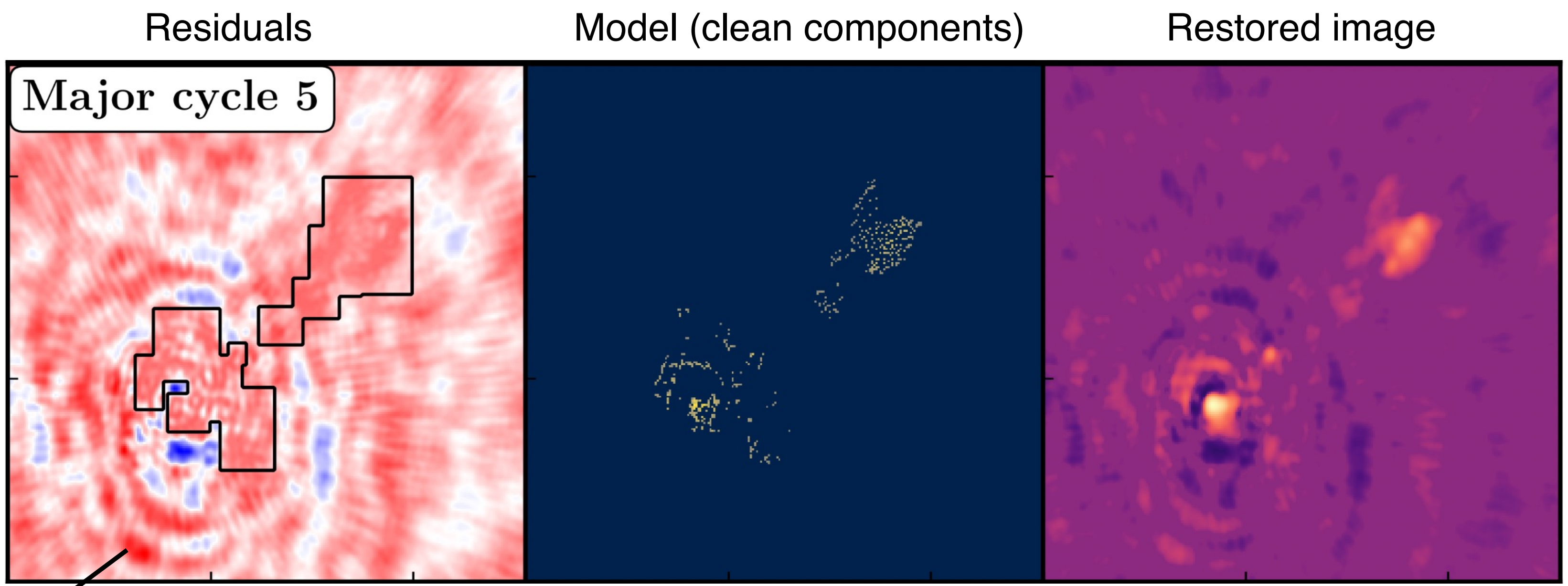
Imaging 101: Deconvolution

CLEAN in action



Imaging 101: Deconvolution

CLEAN in action



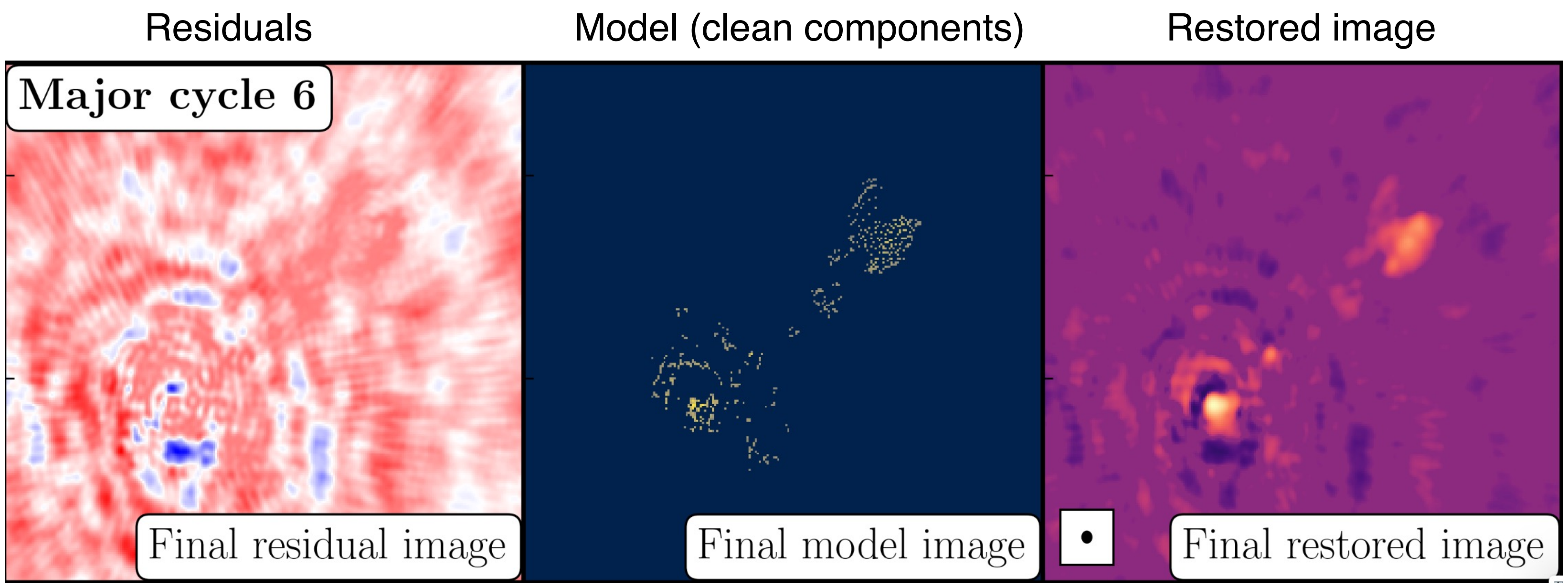
This emission is brighter BUT it's due to sidelobes!

It's always a good idea take a look at the dirty beam before starting cleaning

+ CLEAN boxes prevent the CLEANing of sidelobes

Imaging 101: Deconvolution

CLEAN in action



Residual image should look like «only noise»

Imaging 101: CLEANing stopping criteria

- **Visually**, when your residuals contain only noise – this means that you cleaned all the flux density of the source

- **Convergence**: Check the logger for max-min (possibily symmetrical), total flux density should increase while cleaning (if not, stop), noise level should decrese (if it does not change anymore, stop → overcleaning)

- **Negative peak identified** (negatives can indicate that CLEAN is now working on sidelobes/noise, but it can also indicate that CLEAN is trying to fix earlier mistakes)

- **Smallest peak identified below a threshold** – which can be noise-based (e.g. 3 x theoretical noise estimated with exposure calculator)

- **Number of iterations** (not the best criterion, as you may end up doing too much or too little cleaning)

Imaging 101: CLEANing issues and recognizing errors

CLEANING-related

- Interpolation of **unsampled (u,v) spacings** (in particular short spacings) : reconstruction of largest spatial scales is always an extrapolation (CLEAN boxes help)

- Assumption of **point-sources for extended structure** is not great (see Radcliffe's lecture tomorrow on imaging!)

- **Under- and over-cleaning** are often an issue
(over-cleaning: rms in logger does not change anymore)

- **Computationally expensive**, as it requires iterative,
non-linear fitting process (CLEAN boxes help this too)

Calibration and data-handling related

- **Bandwidth and time smearing**

- **Amplitude/phase errors** from previous calibration and/or unflagged data **(symmetric/antisymmetric artefacts)**

Source-related

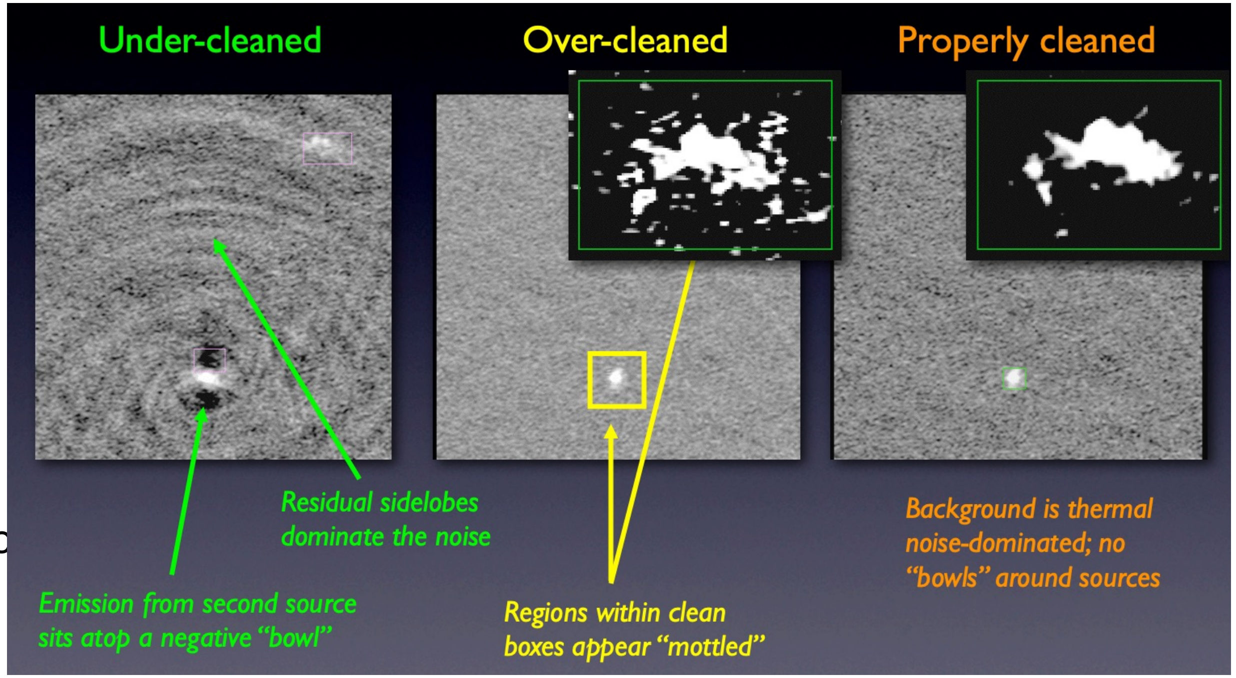
- **Variability** of the source

- **Spectral variations of the source** – multi frequency synthesis
(gridding different frequencies on the same (u,v) grid is now standard)
see Radcliffe's lecture tomorrow on imaging!

Imaging 101: CLEANing issues and recognizing errors

CLEANING-related

- Interpolation of **unsampled (u,v) spacings** (in particular short spacings) : reconstruction of largest spatial scales is always an extrapolation (CLEAN boxes help)
- Assumption of **point-sources for extended structure** is not great (see Radcliffe's lecture tomorrow on imaging!)
- **Under- and over-cleaning** are often an issue (over-cleaning: rms in logger does not change anymore)
- **Computationally expensive**, as it requires iterative, non-linear fitting process (CLEAN boxes help this too)



Credits: Michael Wise UVA lectures

Calibration and data-handling related

- **Bandwidth and time smearing**
- **Amplitude/phase errors** from previous calibration and/o **(symmetric/antisymmetric artefacts)**

Source-related

- **Variability** of the source
- **Spectral variations of the source** – multi frequency synthesis (gridding different frequencies on the same (u,v) grid is now standard) see Radcliffe's lecture tomorrow on imaging!

Imaging 101: CLEANing issues and recognizing errors

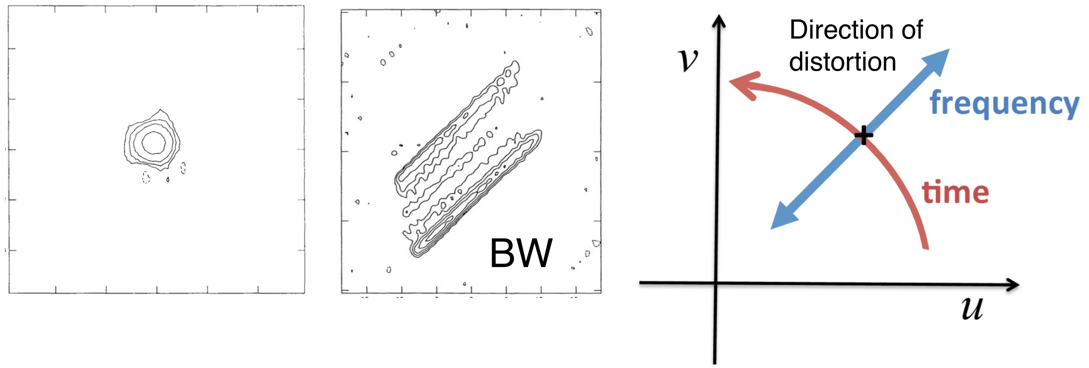
CLEANING-related

- Interpolation of **unsampled (u,v) spacings** (in particular short spacings) : reconstruction of largest spatial scales is always an extrapolation (CLEAN boxes help)

- Assumption of **point-sources for extended structure** is not great (see Radcliffe's lecture tomorrow on imaging!)

- **Under- and over-cleaning** are often an issue (over-cleaning: rms in logger does not change anymore)

- **Computationally expensive**, as it requires iterative, non-linear fitting process (CLEAN boxes help this too)



Cotton 1989

Calibration and data-handling related

- **Bandwidth and time smearing**

- **Amplitude/phase errors** from previous calibration and/or unflagged data **(symmetric/antisymmetric artefacts)**

Source-related

- **Variability** of the source

- **Spectral variations of the source** – multi frequency synthesis (gridding different frequencies on the same (u,v) grid is now standard) see Radcliffe's lecture tomorrow on imaging!

Imaging 101: CLEANing issues and recognizing errors

CLEANING-related

- Interpolation of **unsampled (u,v) spacings** (in particular short spacings) : reconstruction of largest spatial scales is always an extrapolation (CLEAN boxes help)

- Assumption of **point-sources for extended structure** is not great (see Radcliffe's lecture tomorrow on imaging!)

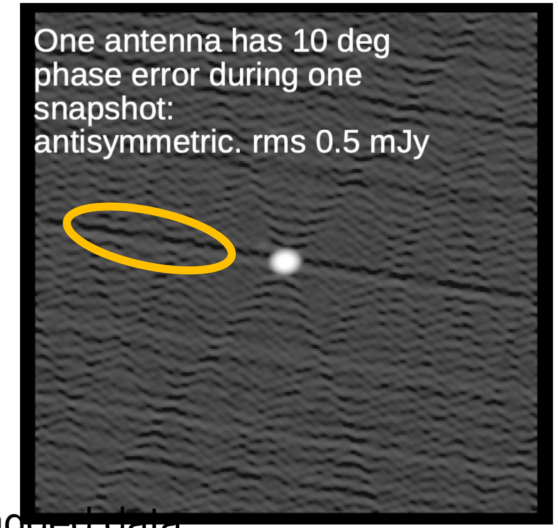
- **Under- and over-cleaning** are often an issue
(over-cleaning: rms in logger does not change anymore)

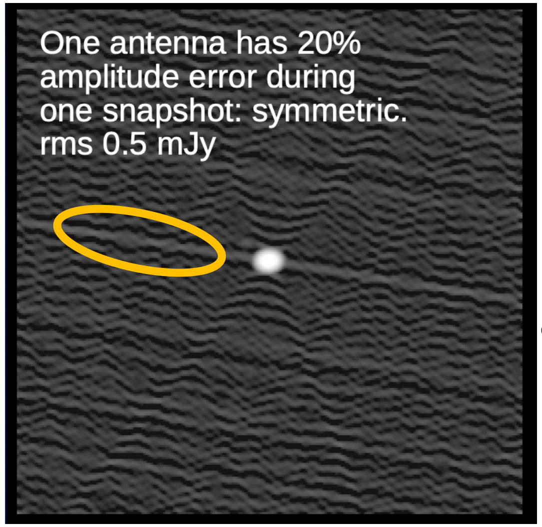
- **Computationally expensive**, as it requires iterative, non-linear fitting process (CLEAN boxes help this too)

Calibration and data-handling related

- **Bandwidth and time smearing**

- **Amplitude/phase errors** from previous calibration and/or unflagged data **(symmetric/antisymmetric artefacts)**





Credits: Laing ERIS 2013

Source-related

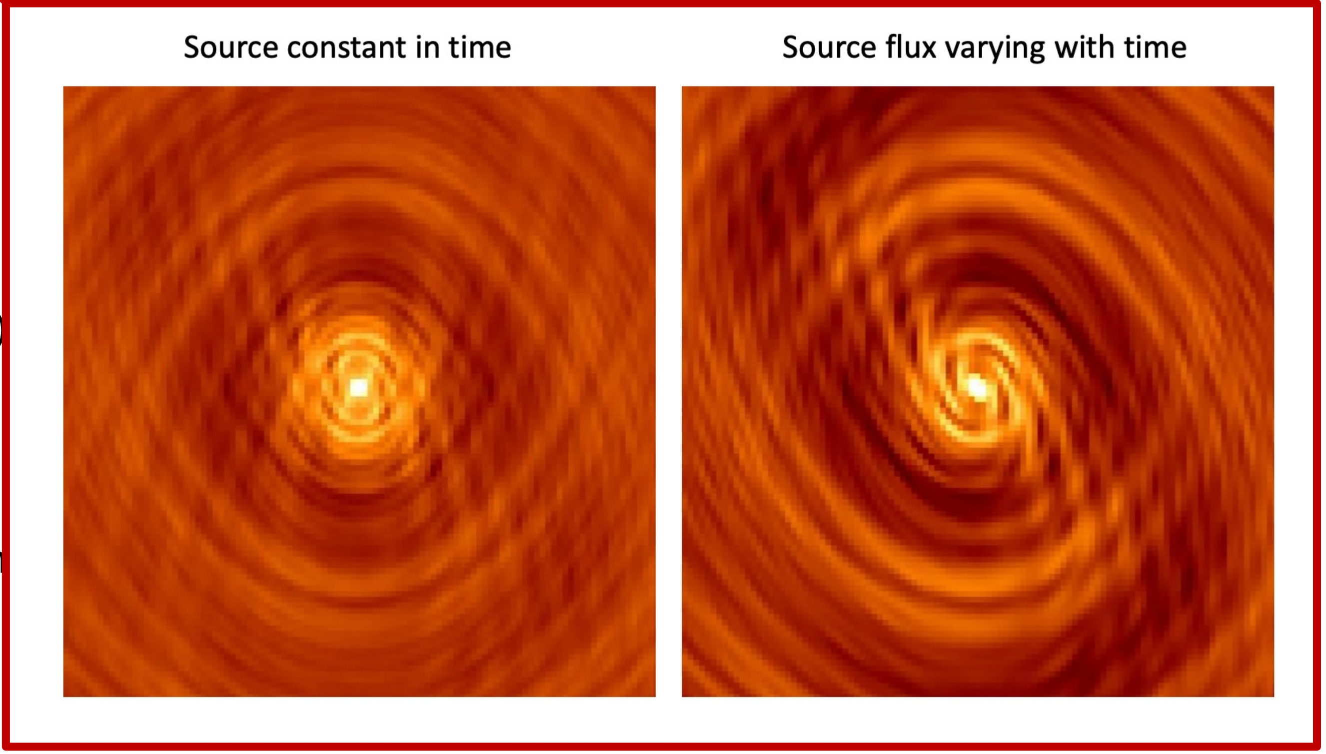
- **Variability** of the source

- **Spectral variations of the source** – multi frequency synthesis
(gridding different frequencies on the same (u,v) grid is now standard)
see Radcliffe's lecture tomorrow on imaging!

Imaging 101: CLEANing issues and recognizing errors

CLEANING-related

- Interpolation of **unsampled (u,v) spacings** (in particular short spacings) : reconstruction of largest spatial scales is always an extrapolation (CLEAN boxes help)
- Assumption of **point-sources for extended structure** is not great (see Radcliffe's lecture tomorrow on imaging!)
- **Under- and over-cleaning** are often an issue (over-cleaning: rms in logger does not change anymo
- **Computationally expensive**, as it requires iterative, non-linear fitting process (CLEAN boxes help this too)



Credits: Stewart 2012 GLOW school

Calibration and data-handling related

- **Bandwidth and time smearing**
- **Amplitude/phase errors** from previous calibration an **(symmetric/antisymmetric artefacts)**

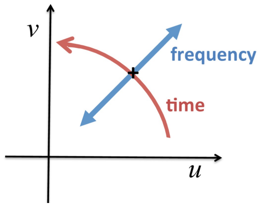
Source-related

- **Variability** of the source
- **Spectral variations of the source** – multi frequency synthesis (gridding different frequencies on the same (u,v) grid is now standard) see Radcliffe's lecture tomorrow on imaging!

Imaging 101: CLEANing issues and recognizing errors

CLEANING-related

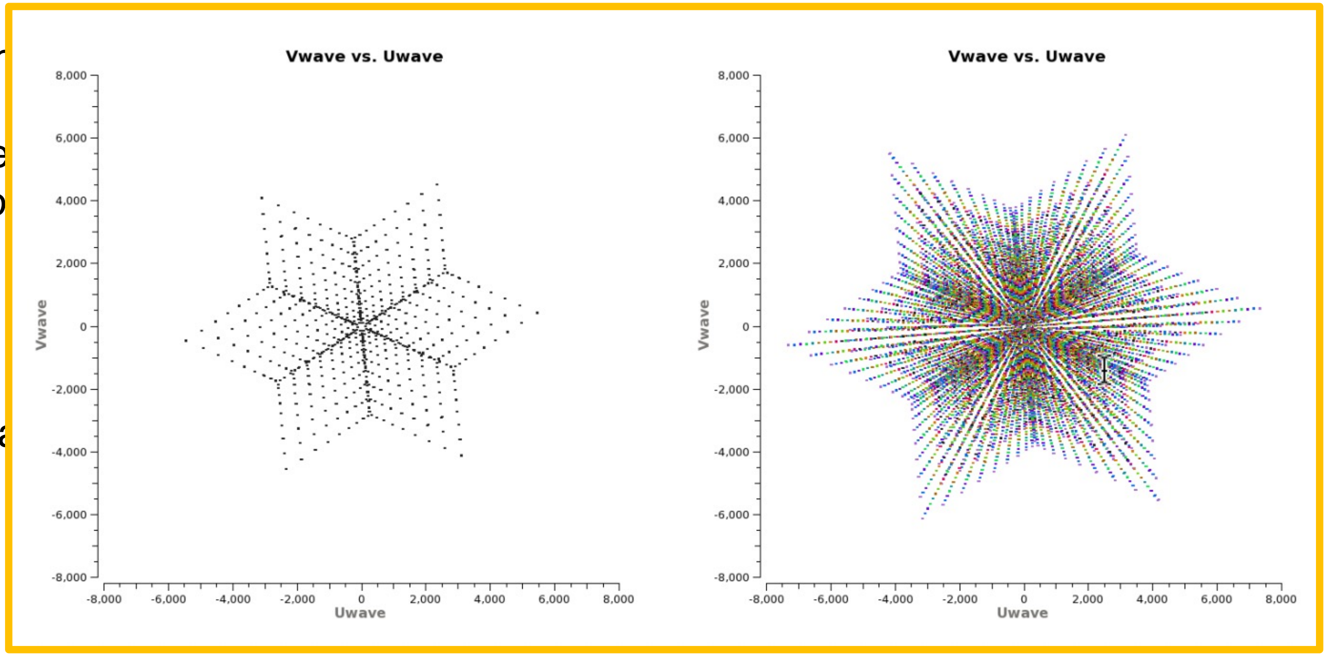
- Interpolation of **unsampled (u,v) spacings** (in particular short spacings) : reconstruction of largest spatial scales is always an extrapolation (CLEAN boxes help)



- Assumption of **point-sources for extended structure** is not great (see Radcliffe's lecture tomorrow on imaging!)

- **Under- and over-cleaning** are often an issue (over-cleaning: rms in logger does not change anym

- **Computationally expensive**, as it requires iterative non-linear fitting process (CLEAN boxes help this to



Credits: Michael Wise UVA lectures

Calibration and data-handling related

- **Bandwidth and time smearing**

- **Amplitude/phase errors** from previous calibration a **(symmetric/antisymmetric artefacts)**

Source-related

- **Variability** of the source

- **Spectral variations of the source** – multi frequency synthesis (gridding different frequencies on the same (u,v) grid is now standard) see Radcliffe's lecture tomorrow on imaging!

Determining imaging parameters

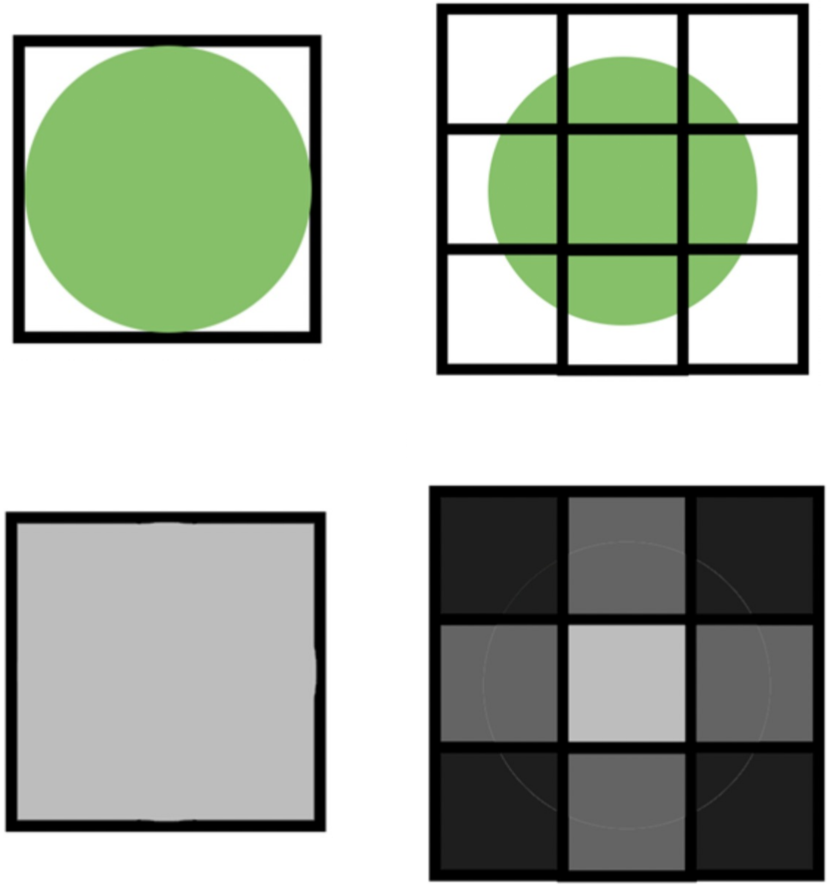
https://www.jb.man.ac.uk/DARA/ERIS22/imaging.html#determining

Imaging parameters: pixel size

Nyquist sampling theorem in astronomical terms
The FWHM of the PSF should be sampled by at least two pixels

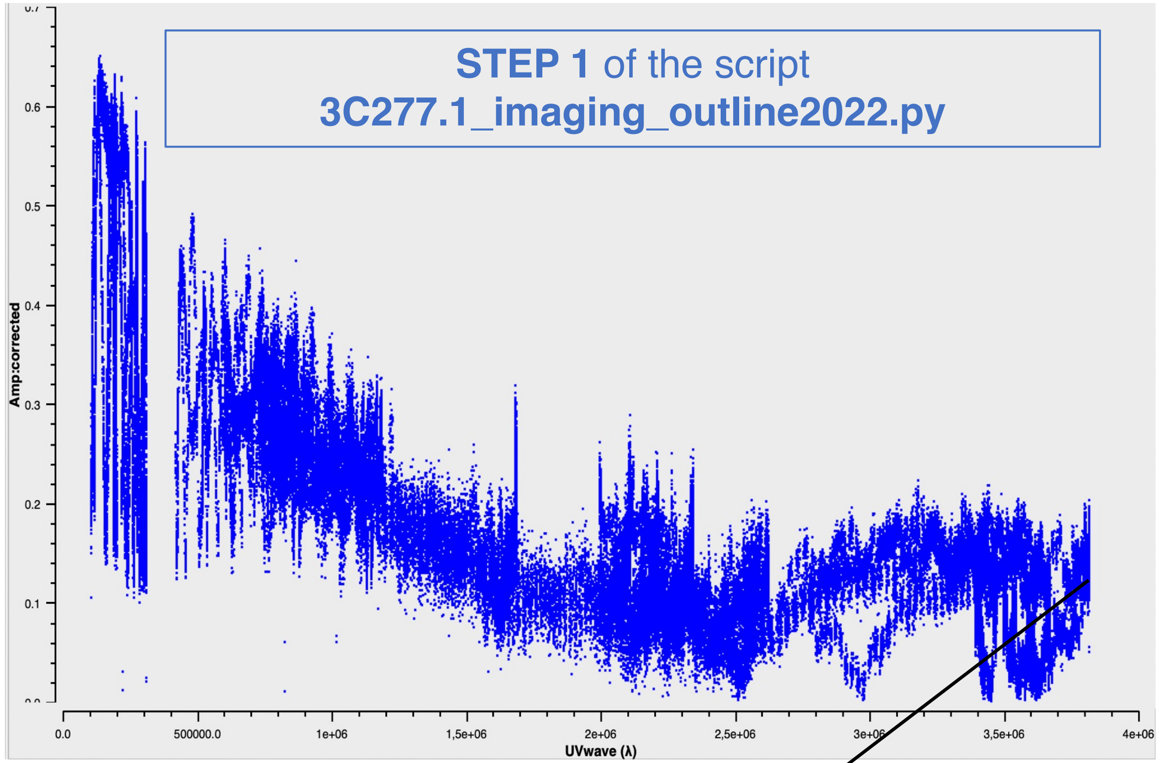
PSF relative to pixels

Output pixels (image)



Credits: HySpex

Nyquist sampling theorem in ***radioastronomical*** *terms*



$$\text{cell} \approx \frac{180}{\pi N_s} \times \frac{1}{D_{\max}\,[\lambda]}\ [\text{deg}]$$

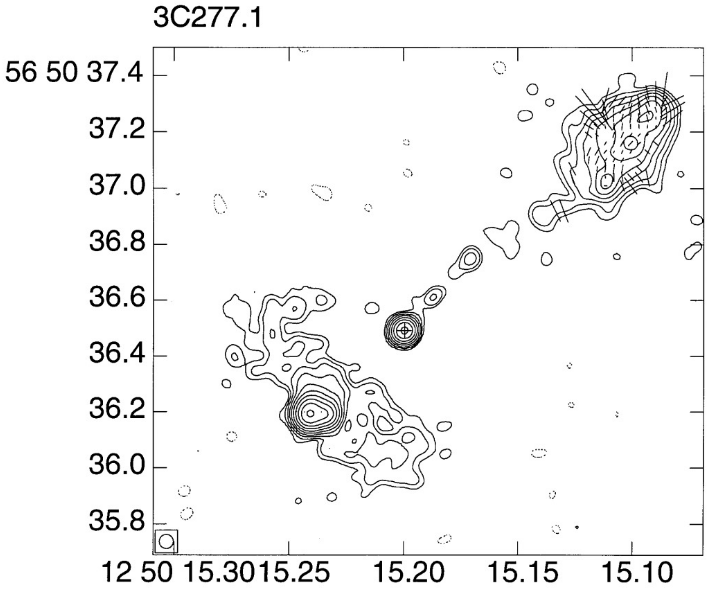
N_s at least 2

Imaging parameters: field of view and image size

The source size is typically much smaller than the entire Field-of-View (FoV), which corresponds approximately to the single-dish beam $\approx \lambda/D$ (homogeneous array)

But it is also limited by time and bandwidth smearing: a typical FoV for VLBI is of the order of a few arcseconds

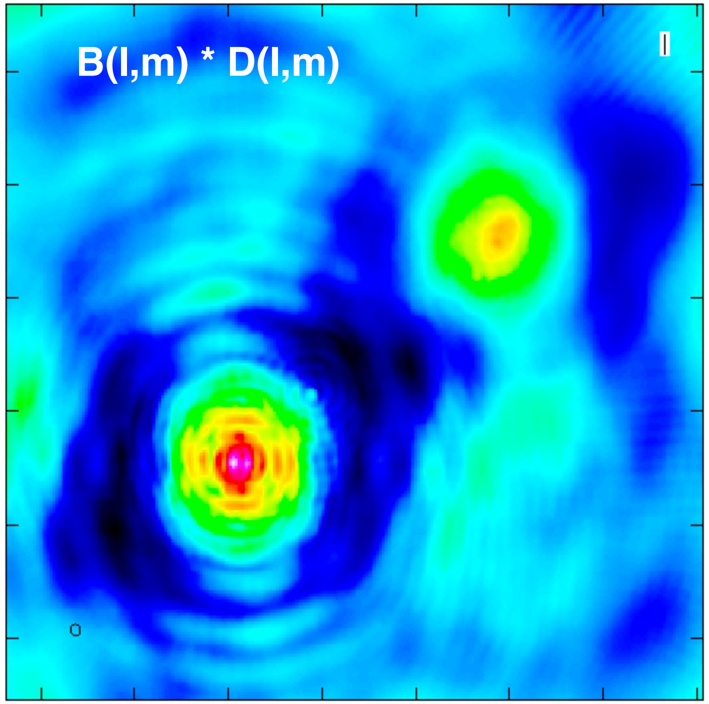
Also: it's always good to check what is already known about your target! For 3C277.1 check Lüdke+1998 (MNRAS, 299, 467–478)



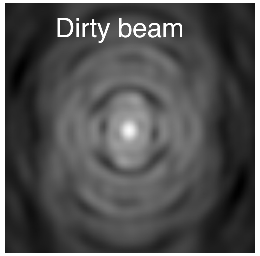
Lüdke+1998

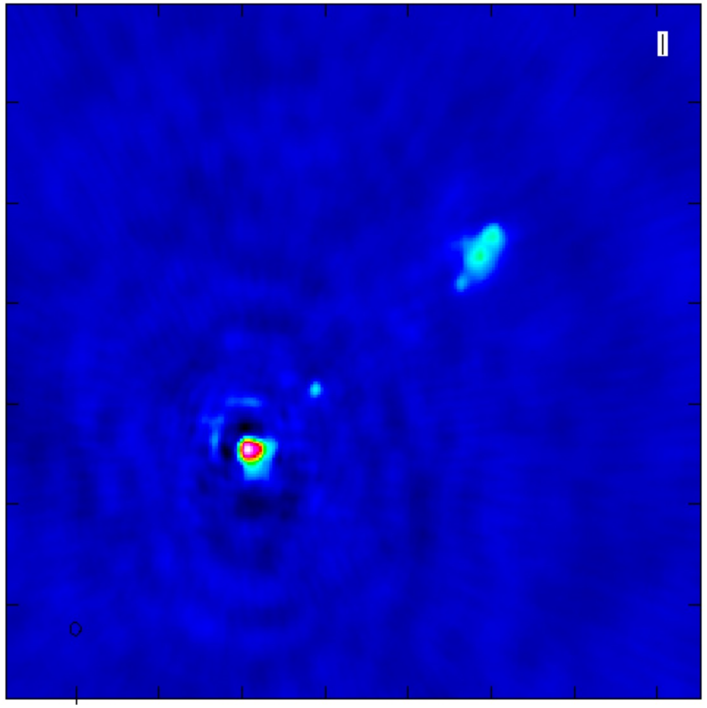
Let’s create a CLEAN image of 3C277.1!

https://www.jb.man.ac.uk/DARA/ERIS22/imaging.html#first_image



Deconvolve the intrinsic source brightness distribution B(l,m) from the **dirty beam** D(l,m)





From dirty image

To CLEAN image

STEP 2 of the script
3C277.1_imaging_outline2022.py

First image of 3C277.1

https://www.jb.man.ac.uk/DARA/ERIS22/imaging.html#first_image

Imaging parameters in CASA: tclean

If you don't know what a parameter means, its units…
just type
`help tclean`

`imagename`

`field`

`cell`

`imsize`

`deconvolver`

`niter`

`weighting`

Imaging parameters in CASA: tclean

If you don't know what a parameter means, its units… just type **`help tclean`**

`imagename` this is up to you

`field` Name of the field (source) that you would like to image

`cell`

`imsize`

`deconvolver`

`niter`

`weighting`

Imaging parameters in CASA: tclean

If you don't know what a parameter means, its units… just type **`help tclean`**

`imagename` this is up to you

`field` Name of the field (source) that you would like to image

`cell` Angular size of your pixel

`imsize`

`deconvolver`

`niter`

`weighting`

Imaging parameters in CASA: tclean

If you don't know what a parameter means, its units…
just type
help tclean

`imagename` this is up to you

`field` Name of the field (source) that you would like to image

`cell` Angular size of your pixel

`imsize` Size of image in pixels – typically power of two 2^n (128x128, 256x256, 512x512 etc.)

`deconvolver`

`niter`

`weighting`

Imaging parameters in CASA: tclean

If you don't know what a parameter means, its units… just type **`help tclean`**

`imagename` this is up to you

`field` Name of the field (source) that you would like to image

`cell` Angular size of your pixel

`imsize` Size of image in pixels – typically power of two 2^n (128x128, 256x256, 512x512 etc.)

`deconvolver` CLEAN algorithm -- Clark's algorithm is fine for now!

`niter`

`weighting`

Imaging parameters in CASA: tclean

If you don't know what a parameter means, its units… just type
`help tclean`

`imagename` this is up to you

`field` Name of the field (source) that you would like to image

`cell` Angular size of your pixel

`imsize` Size of image in pixels – typically power of two 2^n (128x128, 256x256, 512x512 etc.)

`deconvolver` CLEAN algorithm -- Clark's algorithm is fine for now!

`niter` If = 0 computes the dirty image; if > 0 runs major and minor cycles (sub-parameter *'cycleniter'*)

`weighting`

Imaging parameters in CASA: tclean

If you don't know what a parameter means, its units… just type
`help tclean`

`imagename` this is up to you

`field` Name of the field (source) that you would like to image

`cell` Angular size of your pixel

`imsize` Size of image in pixels – typically power of two 2^n (128x128, 256x256, 512x512 etc.)

`deconvolver` CLEAN algorithm -- Clark's algorithm is fine for now!

`niter` If = 0 computes the dirty image; if > 0 runs major and minor cycles (sub-parameter *'cycleniter'*)

`weighting` $V_{obs}(l,m) = V_{true}(u,v)\ S(u,v)$

S(u,v) is 1 if there's a measurement and 0 elsewhere
so-called **natural weights**

Imaging parameters in CASA: a slide about weights

`weighting`

$V_k \rightarrow$ AMP(a_k) PHASE(ϕ_k) NOISE(σ_k) WEIGHT (w_k)

Better rms, worse beam

Natural

$w_k = 1 / \sigma_k^2$

«more weights on short baselines», best sensitivity (important for more extended structures) but poor beam shape with overemphasized sidelobes

Robust
(Briggs 1995)

$w_k = 1 / (S^2 + \sigma_k^2)$

$$S^2 = \frac{(5 \times 10^{-R})^2}{\overline{w}}$$

R = robustness (or robust factor) and it goes from -2 to 2

Average variance weighting factor over the grid cell in the image

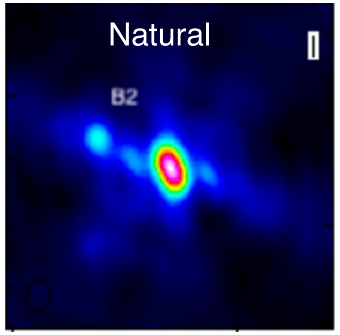
Uniform

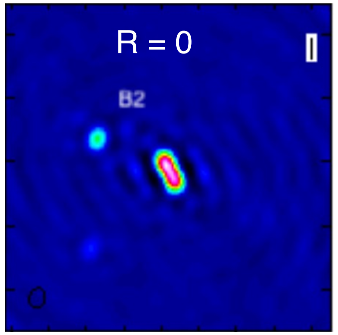
Sampling density function

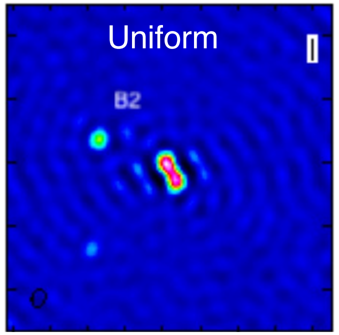
$w_k = 1 / \varrho (u_k, v_k)$

«more weights on long baselines», better resolution (tighter main lobe) and lower sidelobes

Better beam, worse rms



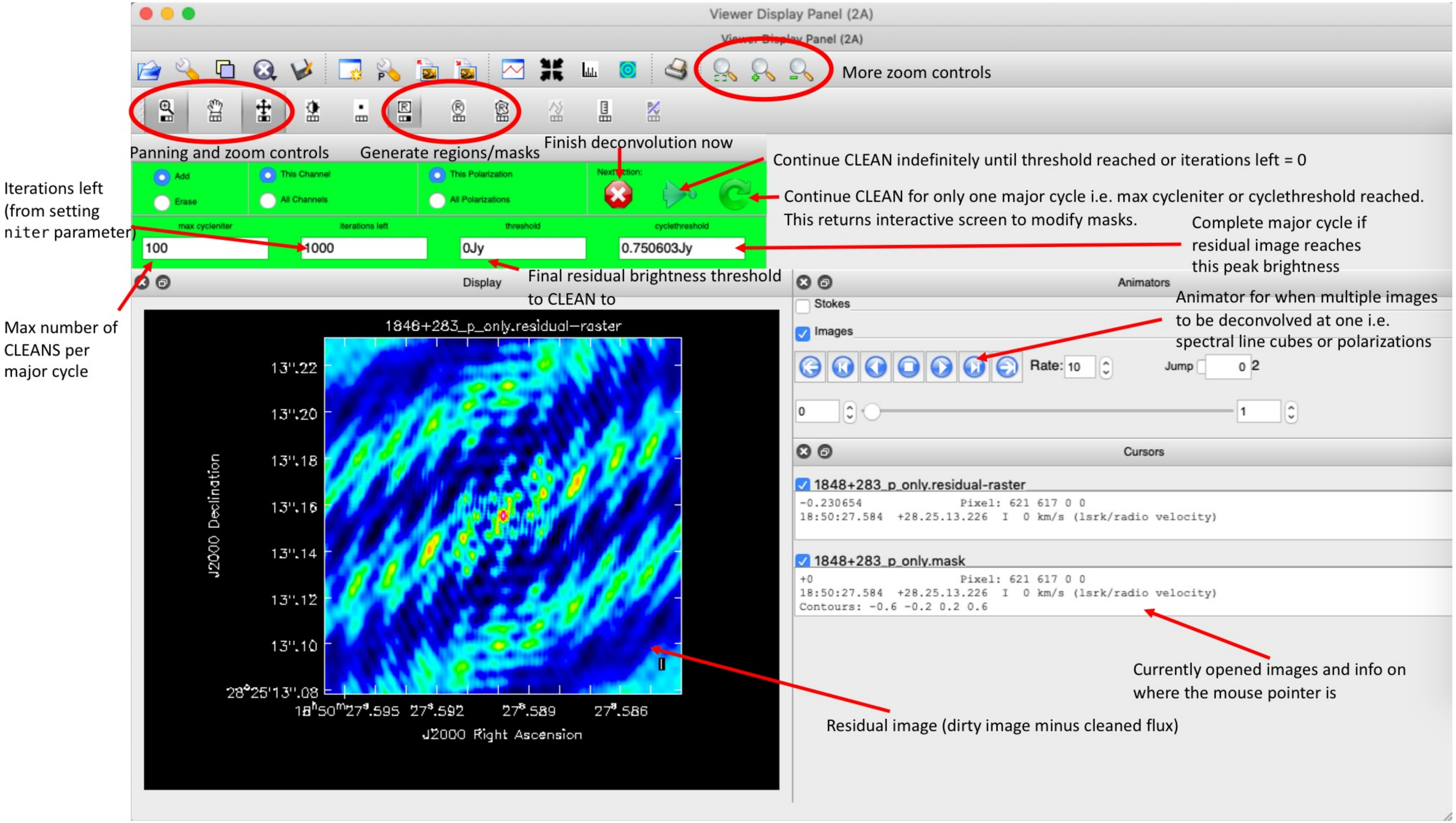




Imaging in CASA: interactive cleaning

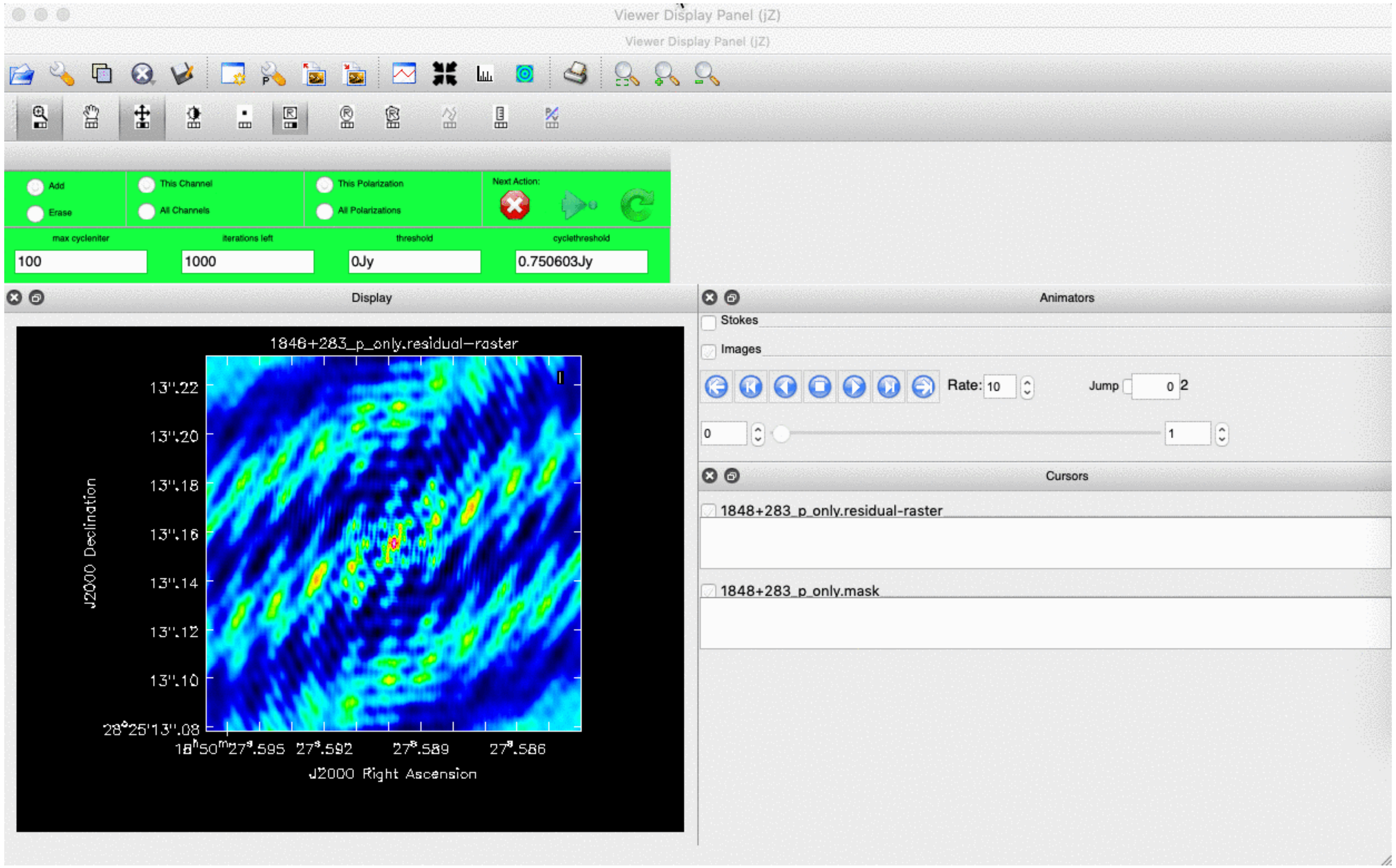
```
Cell = ['13.5mas']
Imsize = [256,256]
```

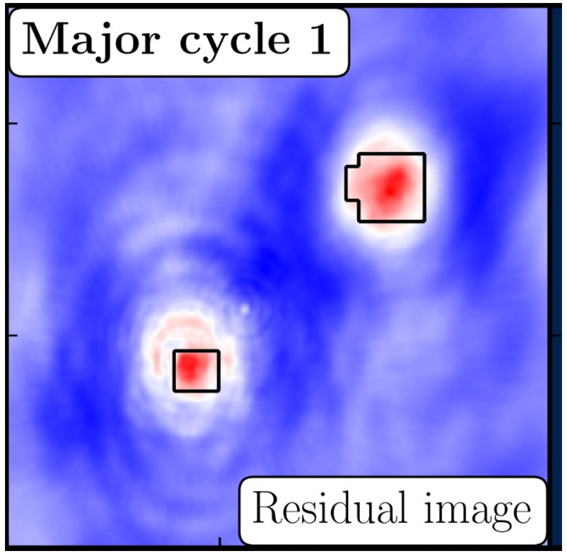
Once you are happy with the choice of parameters … `go tclean`



Imaging in CASA: interactive cleaning

Create the mask (CLEAN boxes)



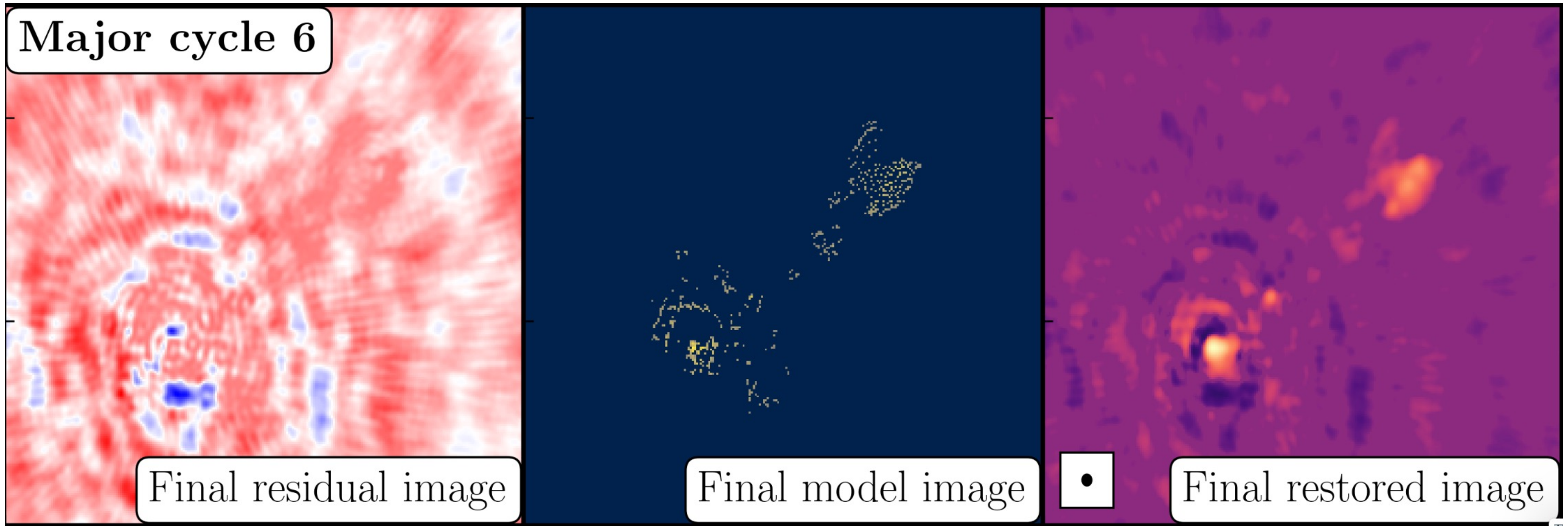


Put the boxes around the brightest emission first

It's an iterative process, you will be able to enlarge the boxes at later cycles

Imaging in CASA: interactive cleaning

Continue the cleaning process unitl your image looks like noise



ALWAYS take a look at the logger!

E.g., Flux density in the model should increase

```
Major Cycle 1    model=0->0.177024,
Major Cycle 2    model=0.177024->0.381401,
Major Cycle 3    model=0.381401->0.504565
```

If it keeps decreasing: STOP CLEANING!

```
model=0.686961->0.683864
```

Imaging in CASA: output of tclean

.tt0, .tt1 … → Suffix to indicate Taylor terms for multi-term wideband imaging

.alpha and .alpha.error → spectral index and its error map

.mask → mask used (clean boxes)

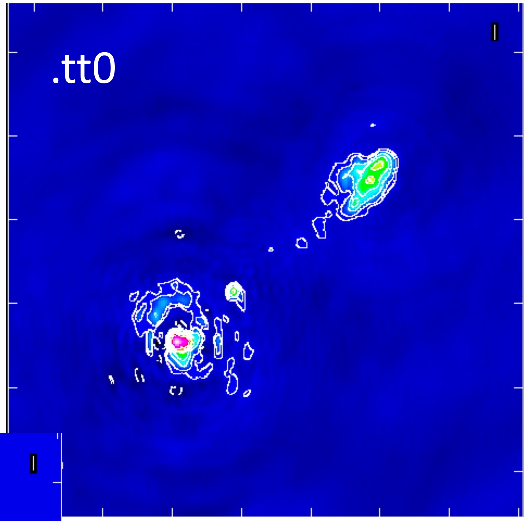
.psf (for tt0, tt1,...) → dirty beam

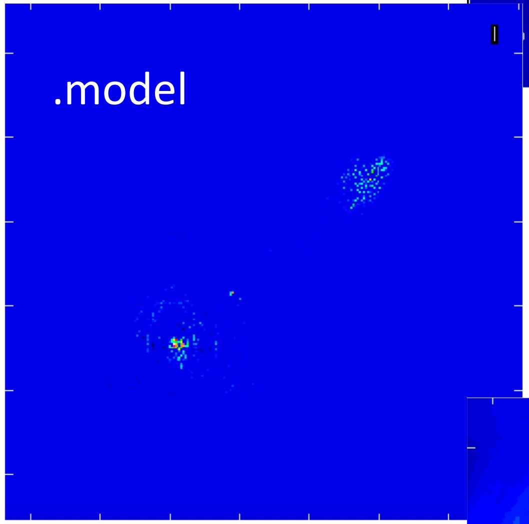
.pb → primary beam

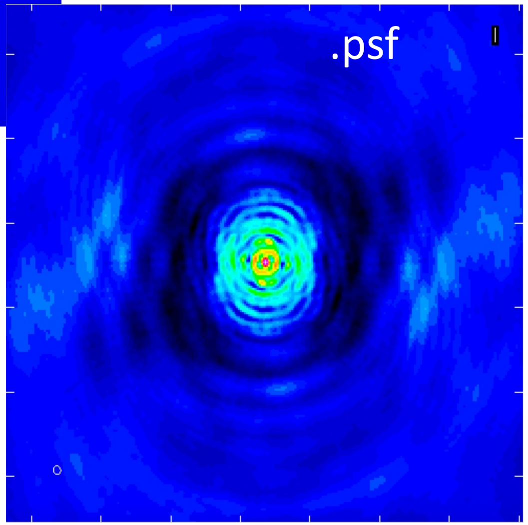
.residual → residual image (data – model)

.sumwt → sum of the weights

Other details can be found here
https://casa.nrao.edu/docs/taskref/tclean-task.html







Measuring image properties

https://www.jb.man.ac.uk/DARA/ERIS22/imaging.html#image_properties

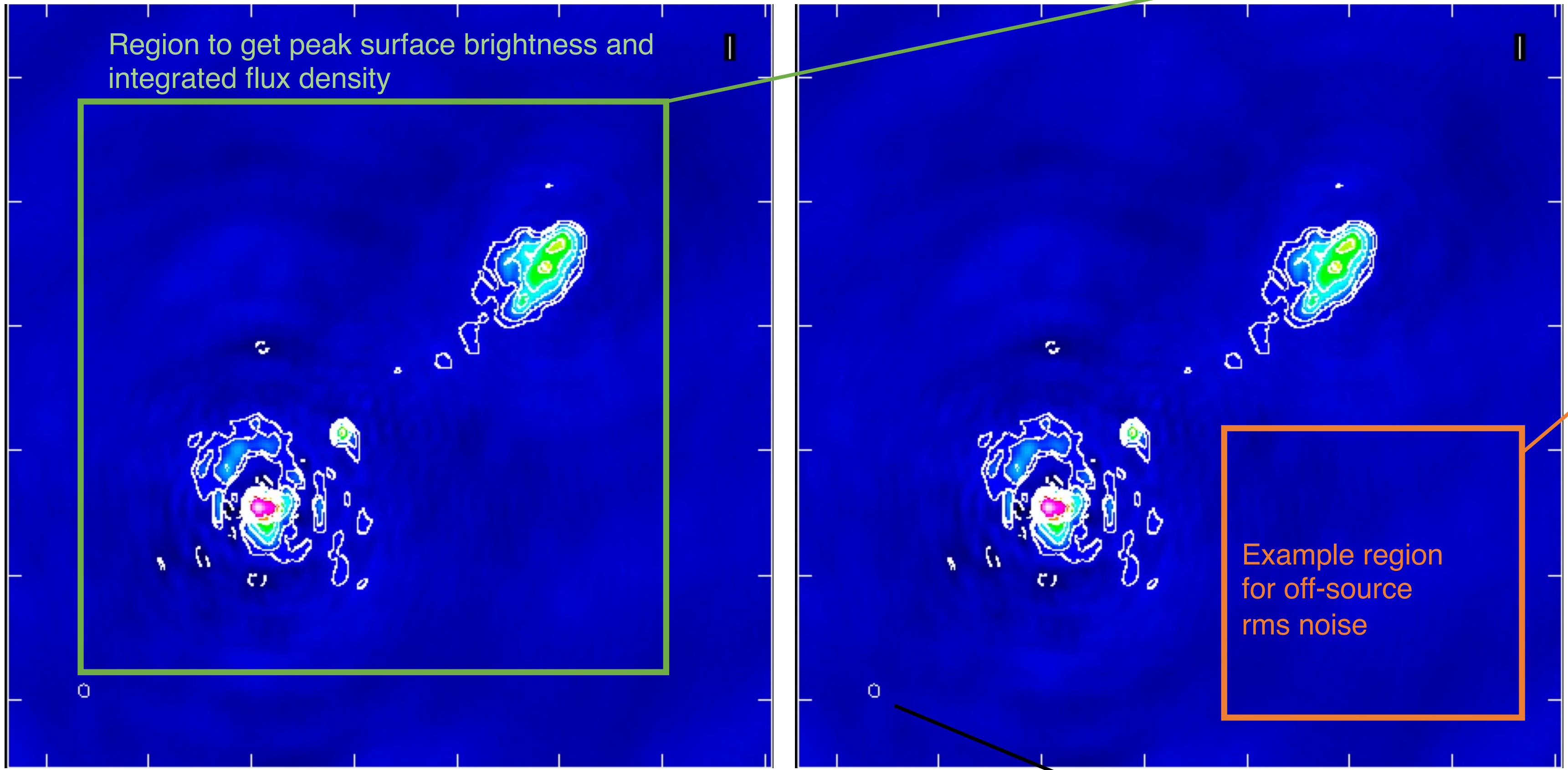
Imaging in CASA: measuring image properties

https://www.jb.man.ac.uk/DARA/ERIS22/imaging.html#image_properties

Task `imstat`
Step 3 of the script

The peak s.b. is in Jy /beam

While the integrated flux density is in **Jy**



The rms of the image is in Jy / beam

Restoring beam (CLEAN beam)

What is the dynamic range (peak / off-source rms) of your image ???

Imaging in CASA: measuring image quality

- **Off-source rms** noise close to theoretical noise

- **Dynamic range** (peak / off-source rms) -- tipycal (good) values 10^2- 10^6

- **«Fidelity»** – difference with an input model (need *a priori* info)

- Off-source rms **noise structure quite uniform**, close to a Gaussian random field («no stripes»): check for any phase and amplitude errors (see previous slides)
  any «weird» structure might be a symptom that something went wrong (at the deconvolution stage and/or during calibration)

References

Chapters 7 and 8 of «Synthesis imaging in radio astronomy II» (Edited by Taylor Carilli and Perley)

Campbell 2019 http://old.evlbi.org/user_guide/fov/fovSFXC.pdf

Interferometry and Synthesis in radio imaging (Thompson, Moran and Swenson) https://link.springer.com/book/10.1007/978-3-319-44431-4

Previous ERIS imaging lectures can be found here https://www.astron.nl/events/eris-2022/

Lecture on imaging by Michael Wise https://www.astron.nl/astrowiki/lib/exe/fetch.php?media=ra_uva:ra_uva_lecture8.pdf

Images in the first slide: Spingola+2018, Giovannini+2018(NatAs), Boccardi+2016, Hartley+2019, McKean+2011, Giroletti+2020, Radcliffe+2016, Johnston+2020, Kellermann+2007

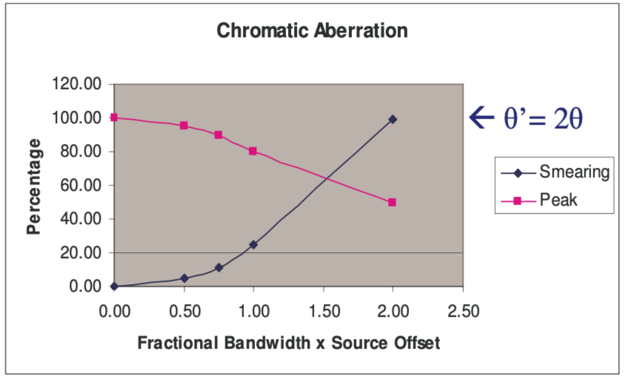
Extra slide: bandwidth and time smearing

Bandwidth smearing

•Bandwidth smearing (chromatic aberration) will produce radial smearing and reduction in source peak

•Parameterized by the product of the fractional bandwidth and the source offset in synthesised beamwidths

$$\boxed{\delta\upsilon / \upsilon_0 \;\; x \;\; \theta/\theta_{HPBW}}$$



•Can be alleviated by observing and imaging in spectral line mode with many narrow frequency channels gridded separately prior to Fourier inversion – reduces $\delta\upsilon$

•Detailed form of response depends on individual channel bandpass shapes.

Time smearing

•Time-average smearing (de-correlation) will produce tangential smearing

•In general cannot be easily parameterized. At Declination=+90° a simple case exists where the effects can be parameterized by the equivalent product:

$$\boxed{\omega_e \delta t_{int} \;\; x \;\; \theta/\theta_{HPBW}}$$

Where ω_e is the Earth's angular rotation rate and δt_{int} is the integration time interval in the dataset

•For other Declinations the effects are more complicated. However they can be alleviated by ensuring that δt_{int} is small enough such that there at least 4 samples per turn assuming a maximum rate of θ/θ_{HPBW} turns in 6 hours