Imaging

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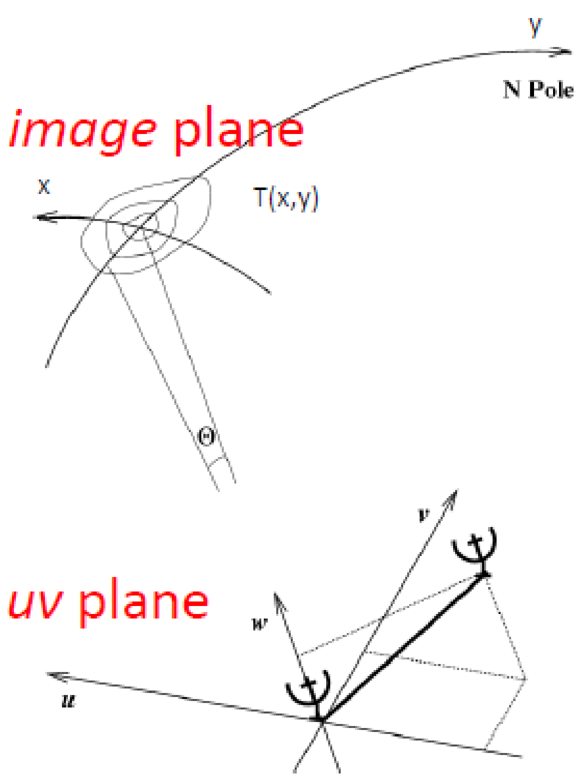
What to do with calibrated visibilities

- **Analyze them in the visibility domain (uv plane)**
  good for simple structures, e.g. point sources, symmetric disks
  Model fitting algorithms available (in CASA uvfit)

- **Recover the image from the visibilities and analyze the results in the image plane**

  - basics of the imaging process
  - the clean algorithm
  - fundamental parameters in clean
  - continuum imaging
  - spectral line imaging

In the interferometer the signals from two antennas are cross-correlated
each baseline measures one *visibility* (per int, per chan, per pol)



(van Cittert-Zernike theorem)

Fourier space/domain

$$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dx dy$$

$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$$

Image space/domain

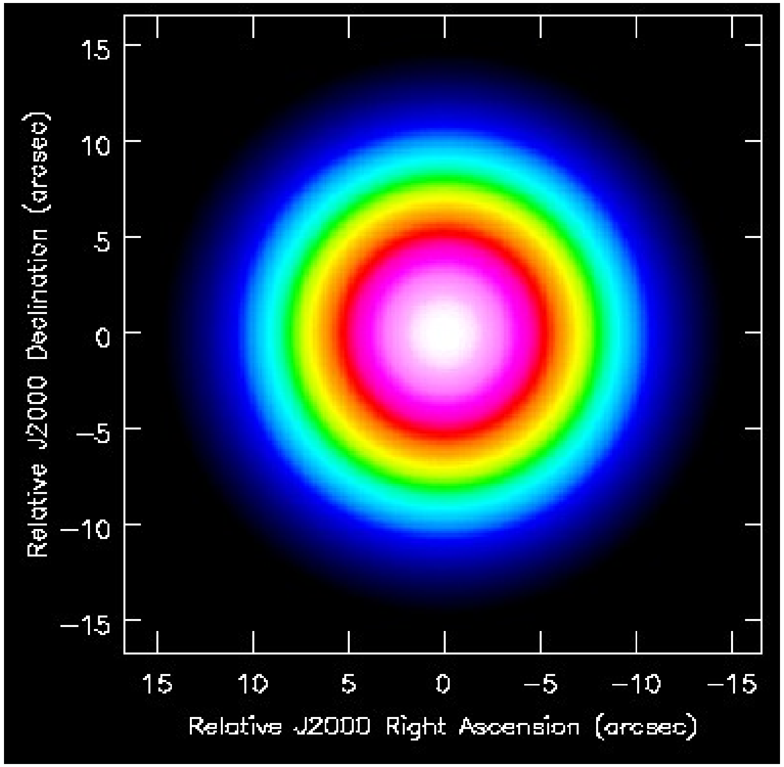
$$V(u,v) = FT\ T(x,y)$$

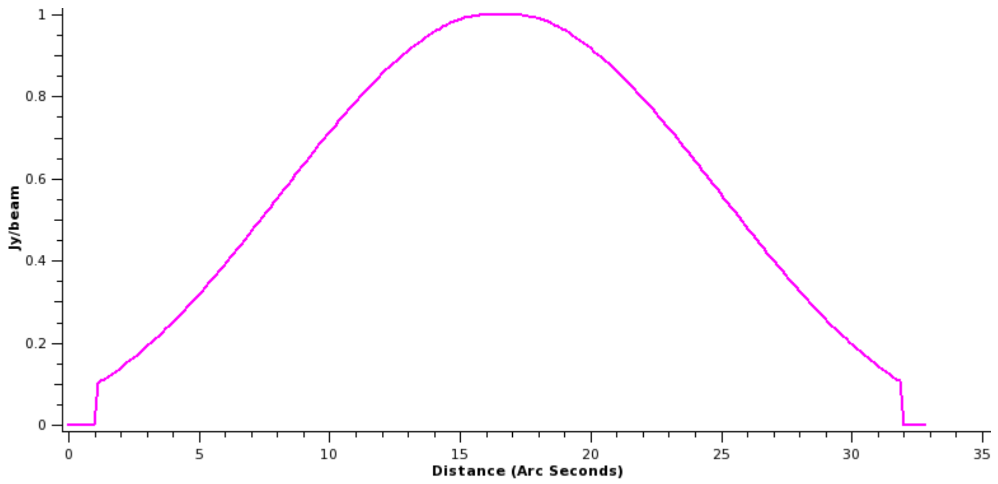
We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

But

Interferometer elements are sensible to direction of arrival of the radiation

- **Primary beam effect** $\rightarrow$ $T(x,y) = A(x,y)\, T'(x,y)$





The response of the antennas in the array must be corrected for during imaging to get accurate intensities for source outside the core of the beam.

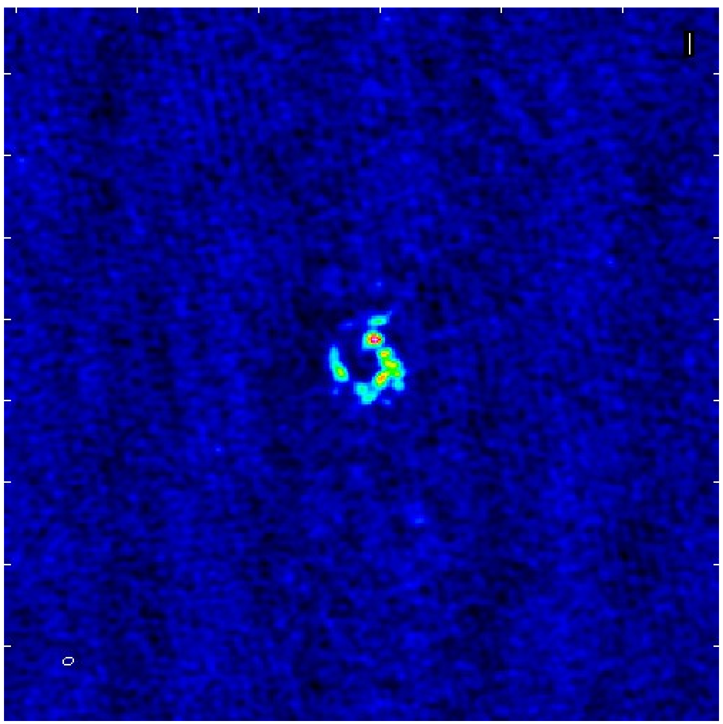
PB corrected images are usually available in the archive

We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

But

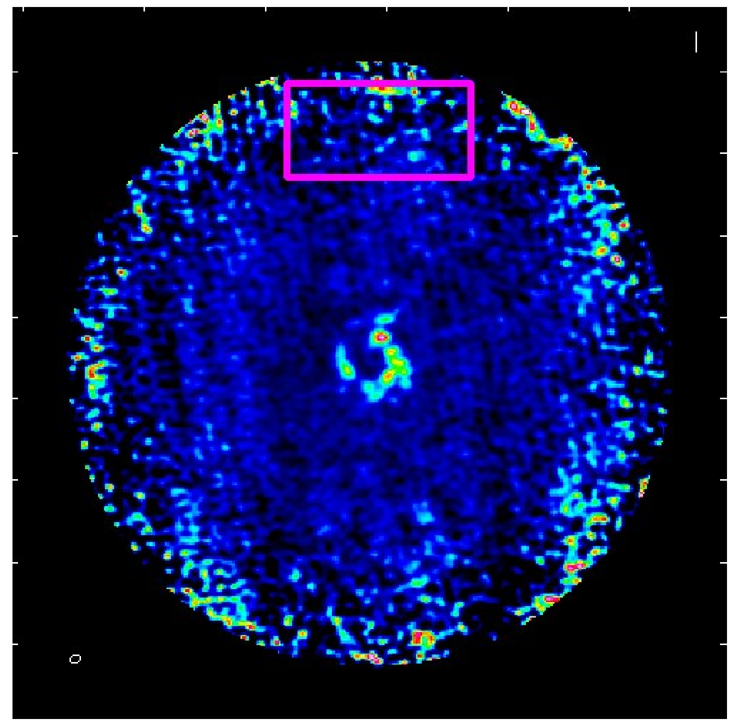
- **Primary beam effect** $\rightarrow$ $T(x,y) = A(x,y)\, T'(x,y)$

$T(x,y)$



rms 8e-4

$T'(x,y)$



rms 3e-3

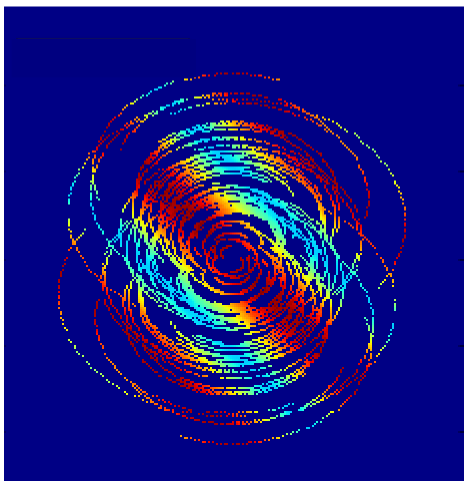
PB corrected images are usually available in the archive

We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

But

we actually sample the Fourier domain at discrete points

$V_{meas}(u,v) = C(u,v) \cdot V_{true}(u,v)$



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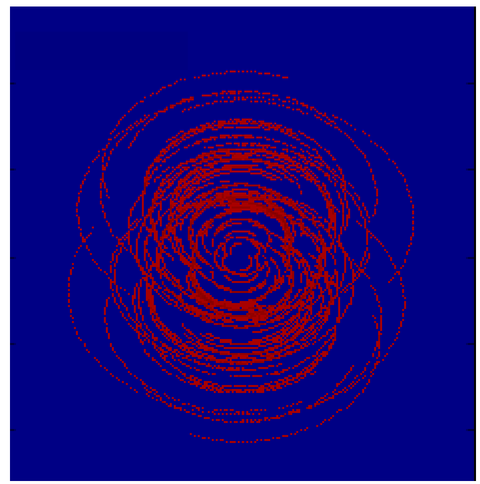

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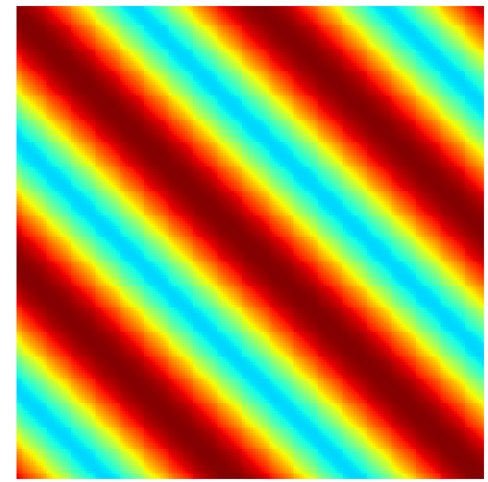


where C(u,v) is the sampling function

C= 1 at points where visibilities are measured

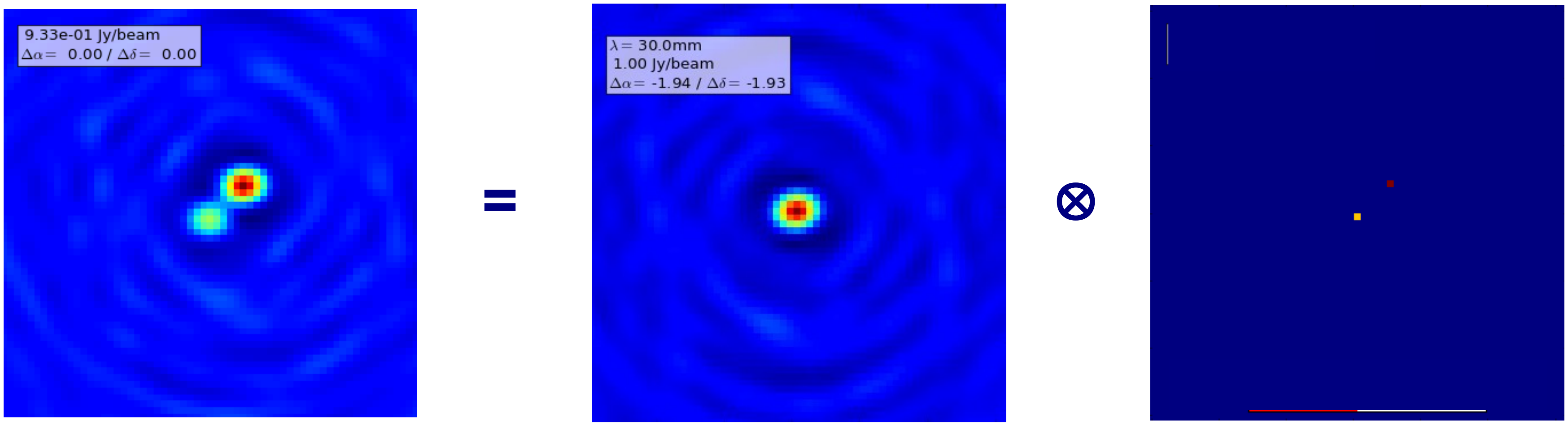
and C = 0 elsewhere

* Yesterday's example with 2 point-like sources with APSYNSIM (I. Marti-Vidal)

We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

Applying the convolution theorem:

$$FT\,(V_{meas}) \;=\; FT\,(C) \;\otimes\; FT\,(V_{True})$$



The Fourier transform FT of the sampled visibilities gives the true sky brightness convolved with the Fourier transform of the sampling function (called **dirty beam**).

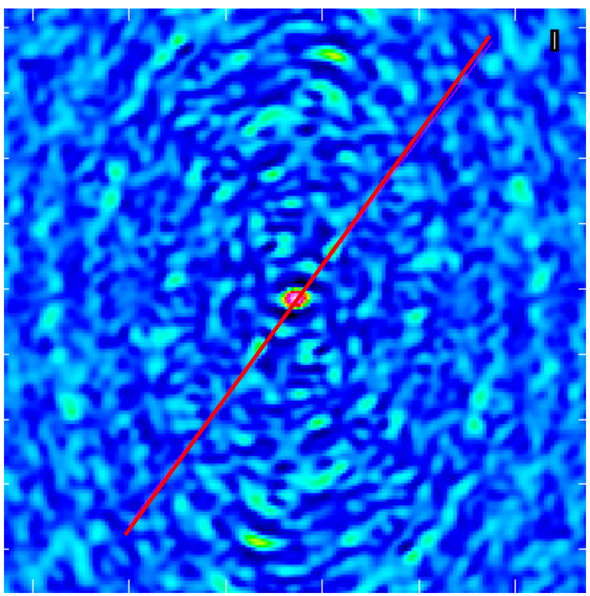
$$T^D(x,y) \;=\; D(x,y) \;\otimes\; T\,(x,y)$$

To get a useful image from interferometric data we need to Fourier transform sampled visibilities, and **deconvolve for the dirty beam** → **clean**

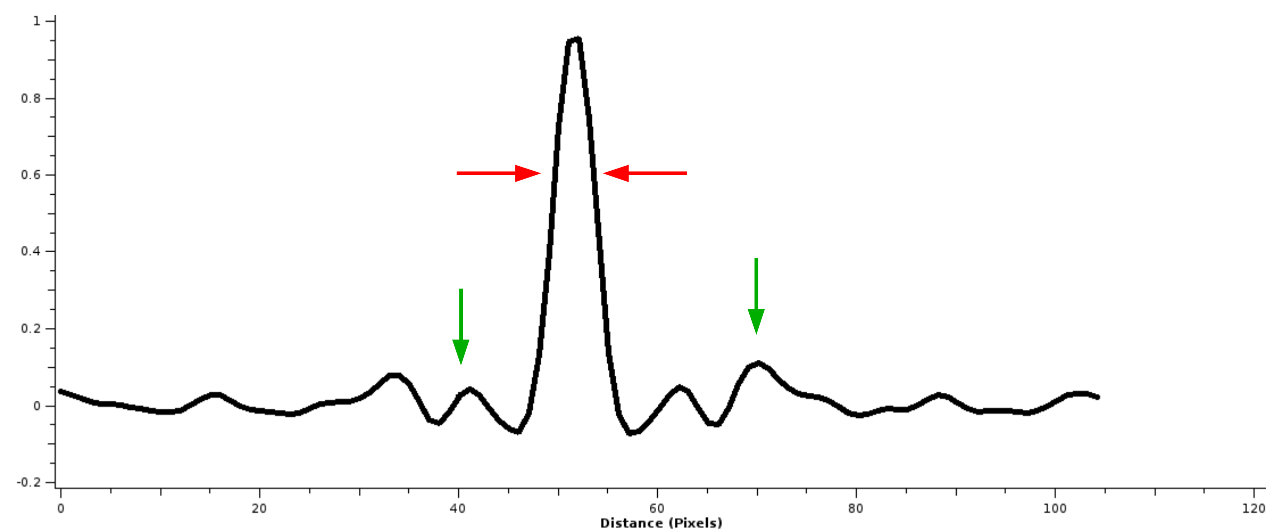
Imperfect reconstruction of the sky

- **Incomplete sampling of uv plane → sidelobes**

$D(x, y)$



- Central maximum has width $1/(u_{max})$ in x and $1/(v_{max})$ in y
- Has ripples (sidelobes) due to gaps in uv coverage

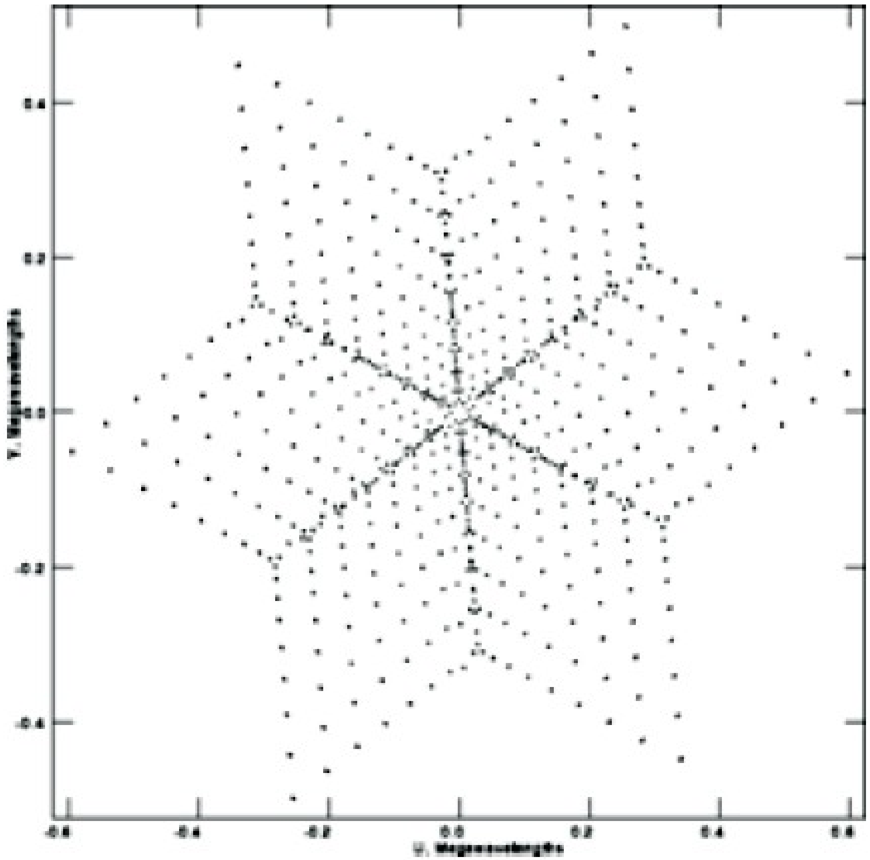


deconvolution → sidelobes removal

We need to get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$

But

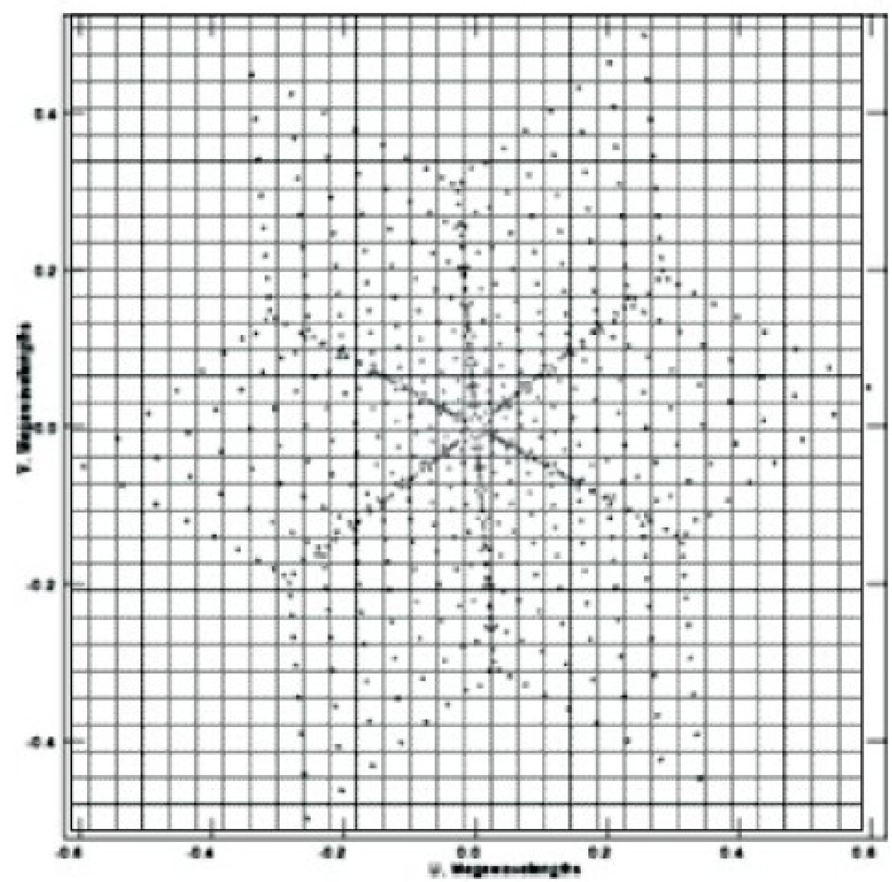
The efficient Fast Fourier Transform needs the data on a regular grid.



We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

But

The efficient Fast Fourier Transform needs the data on a regular grid → **Gridding**



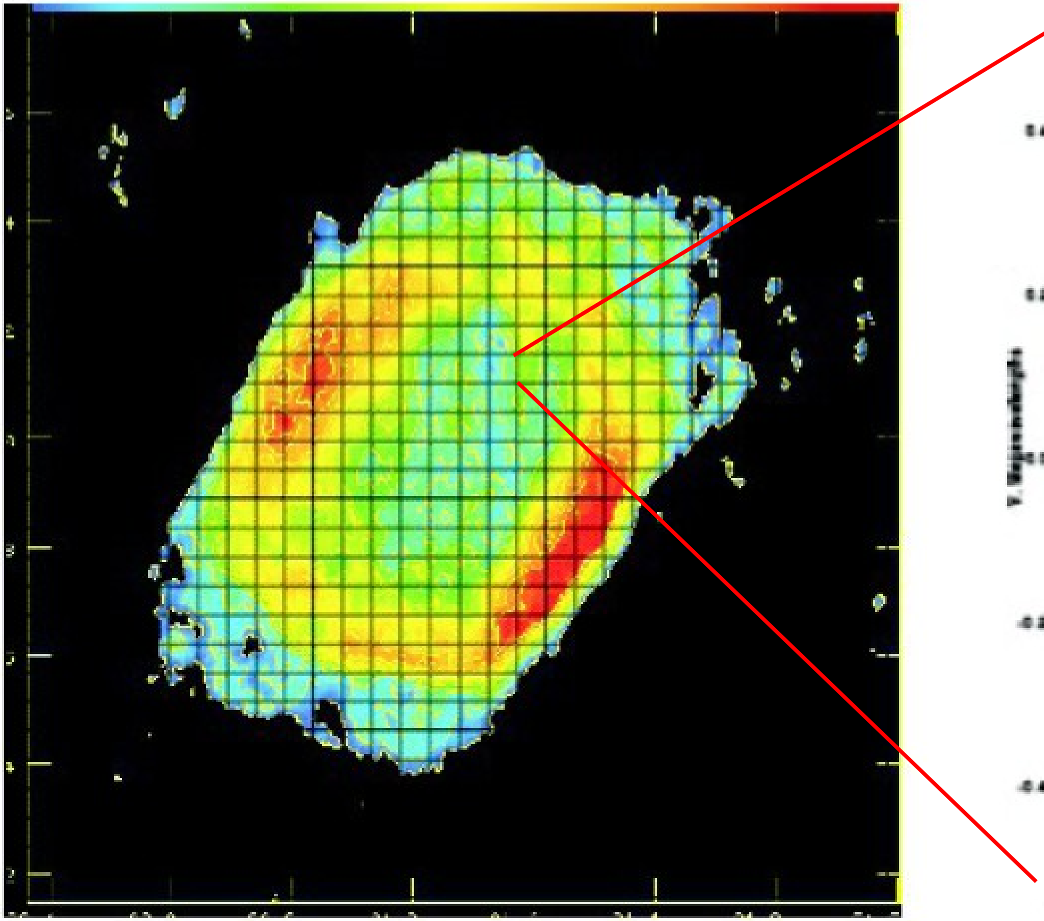
UV plane

Grid spacing: Δu

Size: u_{max}

We need to get $T(x, y) = \int\int V(u, v) e^{-2\pi i(ux+vy)} du dv$

Gridding



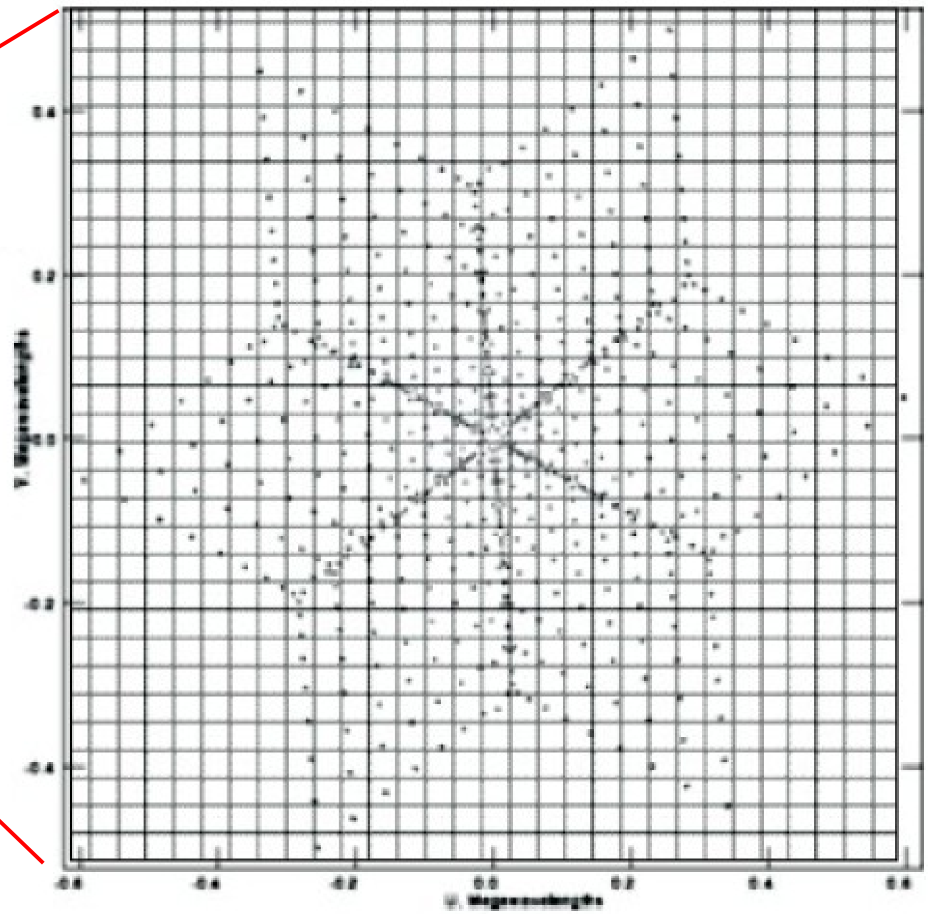
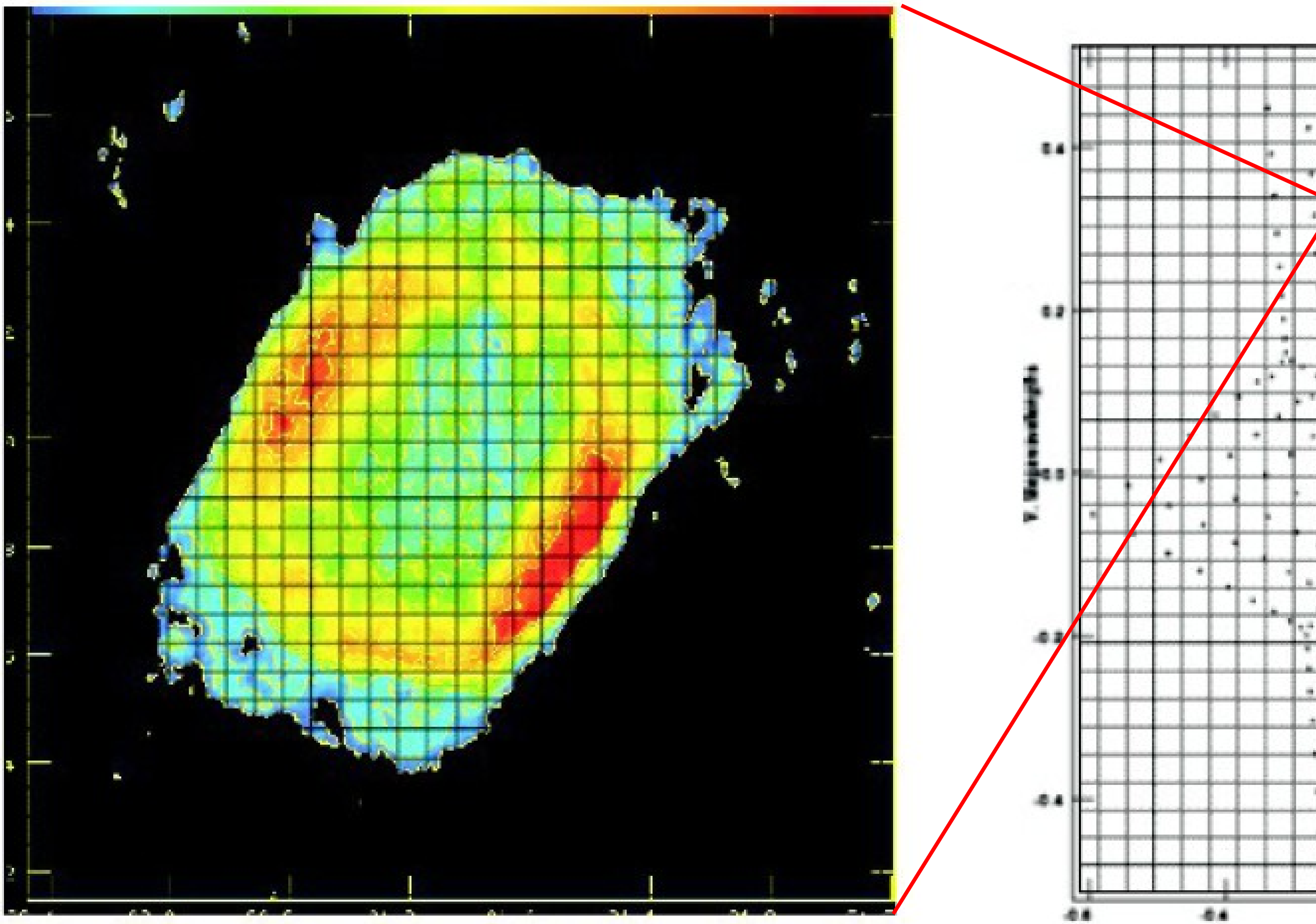


Image plane
Grid spacing: $1/(u_{max})$

UV plane
Grid spacing: Δu
Size: u_{max}

Gridding

We need to get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$



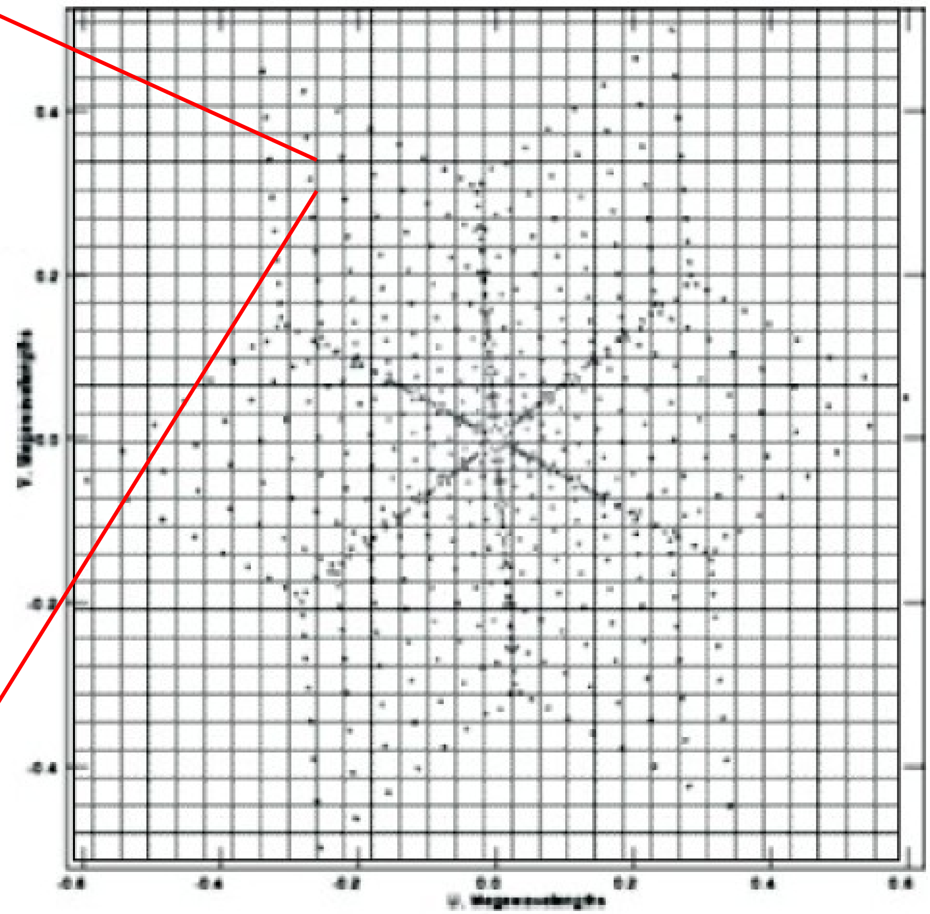


Image plane
Grid spacing: $1/(u_{max})$
Size: $1/\Delta u$

UV plane
Grid spacing: Δu
Size: u_{max}

We need to get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$

In practice

Need to choose:

Image pixel size (cellsize)

Make the cell size small enough for Nyquist sample of the longest baseline ($\Delta x < 1 / 2\ u_{max}$; $\Delta y < 1 / 2\ v_{max}$)

Usually 1/4 or 1/5 of the synthesized beam to easy deconvolution

Image size (imsize)

The natural resolution in the uv plane samples the primary beam

At least twice the field of view for the Nyquist sampling

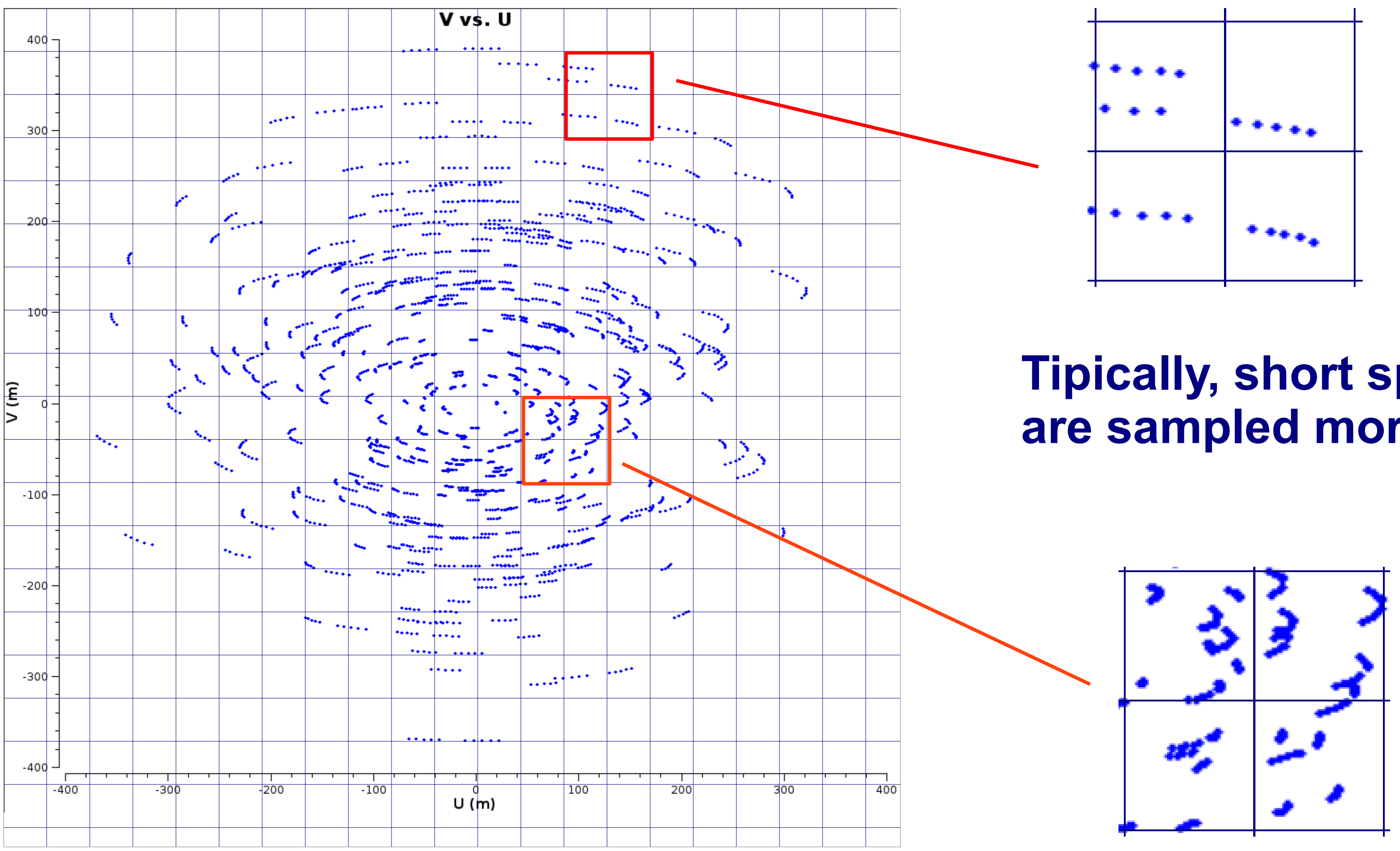
Larger if there are bright sources in the sidelobes of the primary beam (they would be aliased in the image)

We need to get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$

But

measured visibilities actually contain noise and some uv ranges are sampled more than others

- **Gridded visibilities are →** $V(u,v) = W(u,v)\, V'(u,v)$



Tipically, short spacing are sampled more than long

We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

- **Natural weighting** $W(u,v) = 1/\sigma^2(u,v)$

σ is the noise variance of the visibilities

- **Uniform weighting** $W(u,v) = 1/\delta_s(u,v)$

δ_s is the density of (u,v) points in a symmetric region of the uv plane

Unfortunately, in reality, the weighting which produces the best resolution **(uniform)** will often utilize the data very irregularly resulting in poor sensitivity → compromises

- **Briggs weighting**

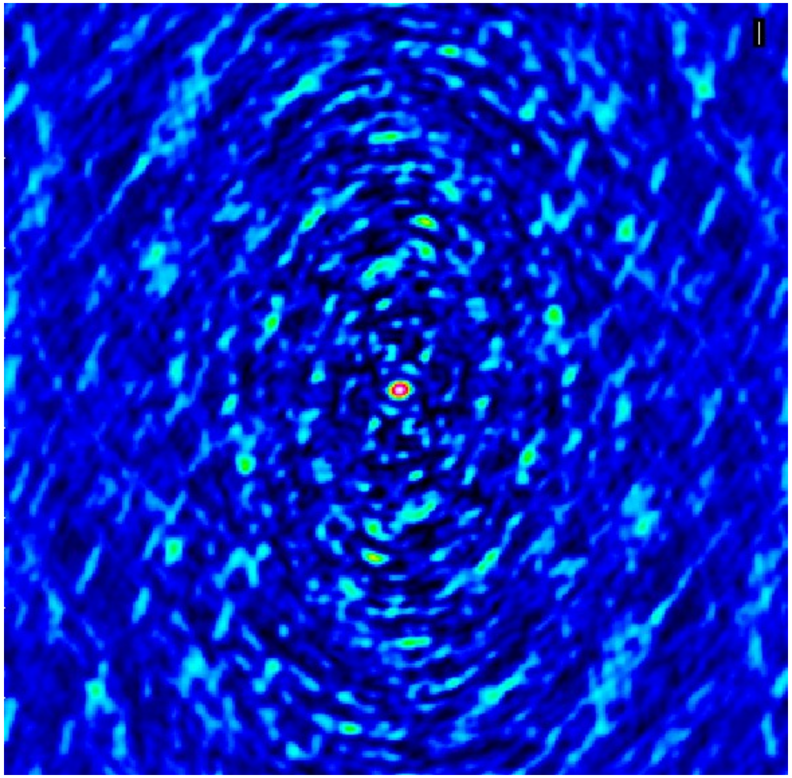
combines inverse density and noise weighting.
An adjustable parameter "robust " allows for continuous variation between natural (robust=+2) to uniform (robust=-2)

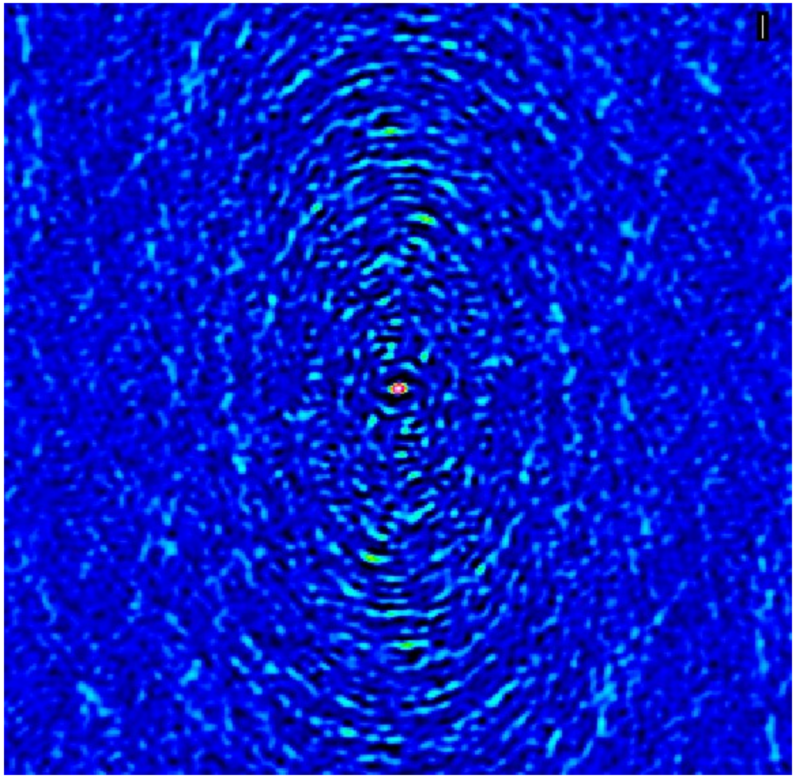
We need to get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$

✯ Weighting effects on the Dirty beam

Natural
0.29" x 0.23"
Best sensitivity

Uniform
0.24"x0.17"
Best angular resolution



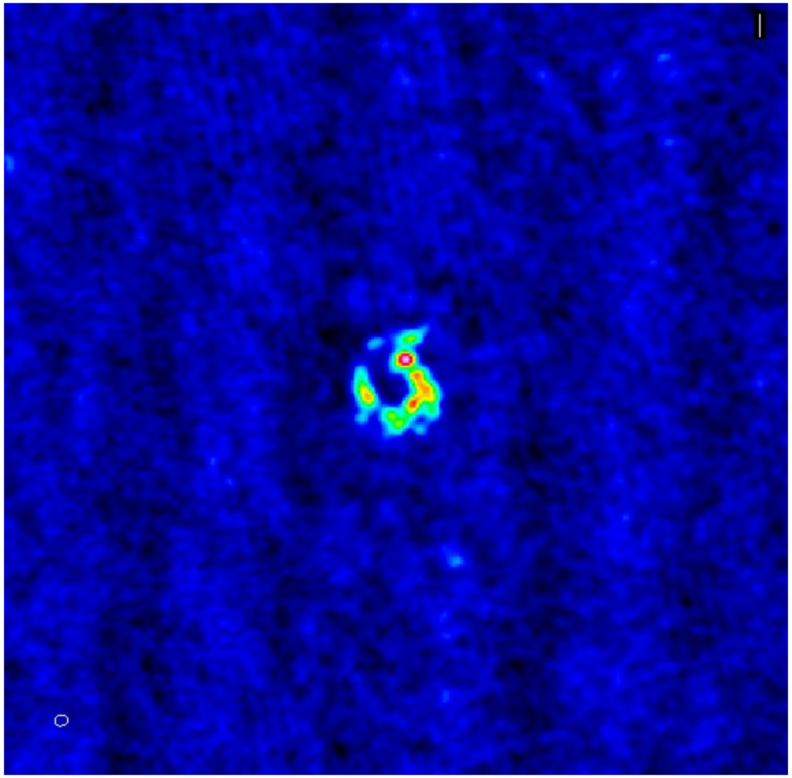


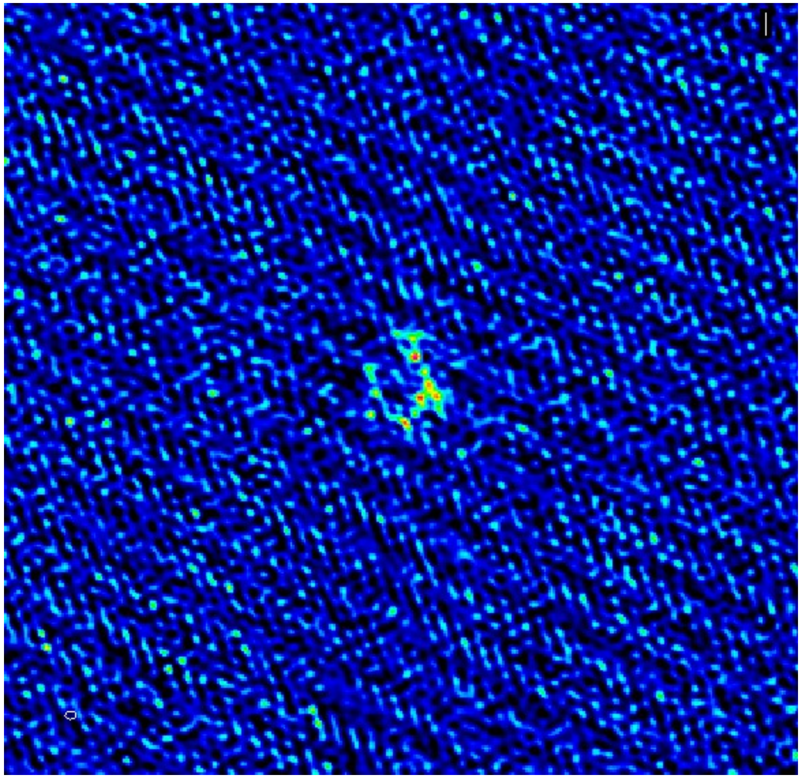
We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

Weighting effects on the image

Natural
res = 0.29" x 0.23"
rms = 0.8 mJy/beam

Uniform
res = 0.24"x0.17"
rms = 3 mJy/beam

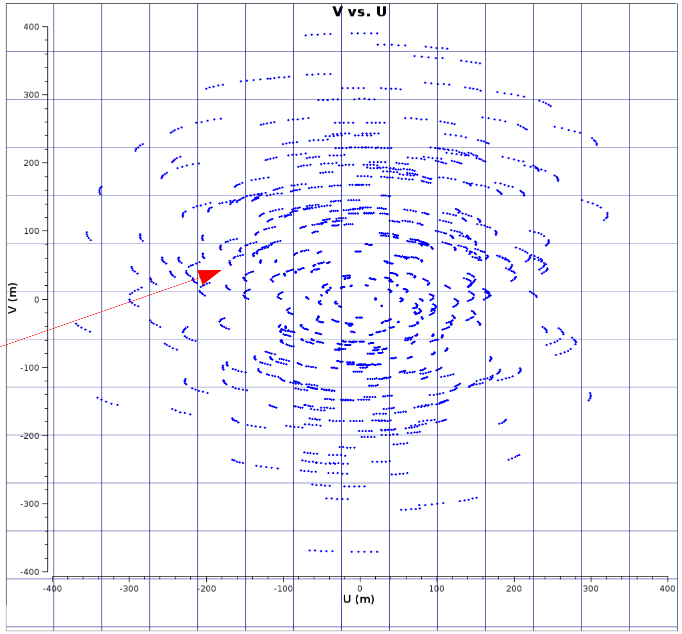




To get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$

we need to Fourier transform sampled visibilities and deconvolve from the dirty beam

$$T^D(x,y) = D(x,y) \otimes T(x,y)$$



∃ an infinite number of T(x,*y*) compatible with sampled V(u,v), since we have unsampled (u,v) regions

Deconvolution

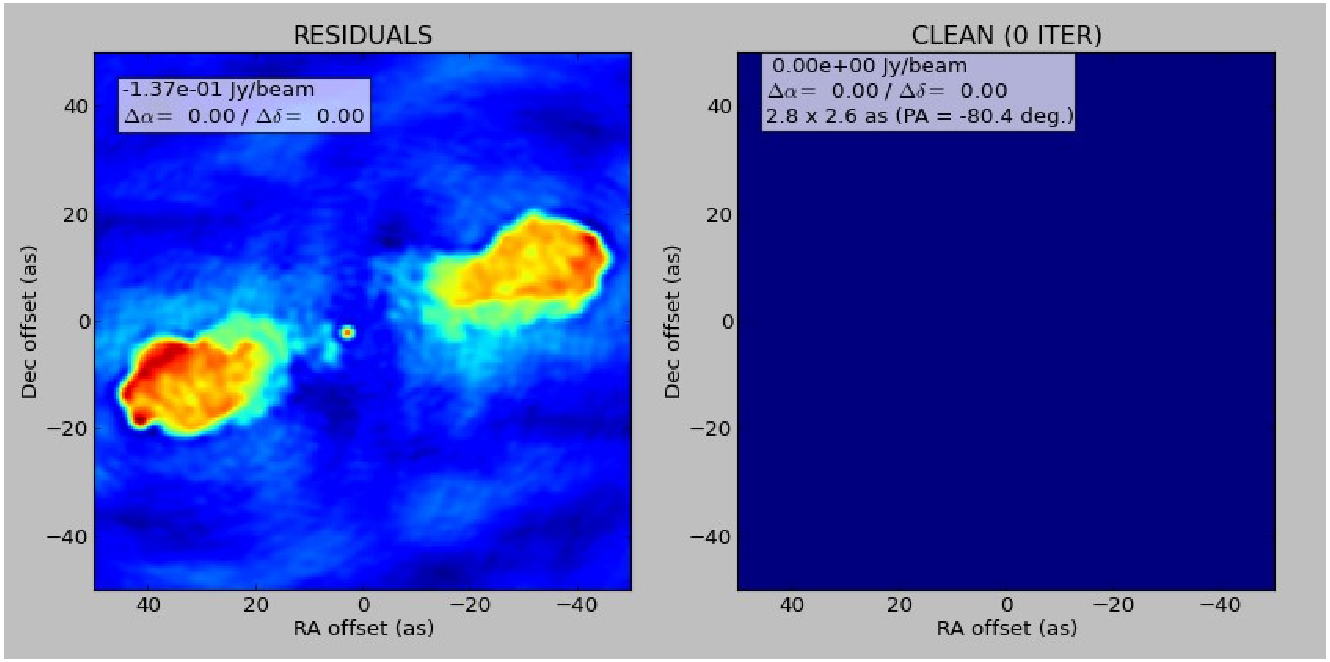
- uses non-linear techniques effectively interpolate/extrapolate samples of V(u,v) into actually unsampled regions
- Aims to find a reasonable model of I(l,m) compatible with the data
- Requires a priori assumptions about I(l,m):
  (e.g. sky intensity is positive, point-like compact structure, smooth extended emission)
- Iteratively fits a sky-model to the observed visibilities

Deconvolution - Classic CLEAN

Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

Basic assumption: each source is a collection of point sources

1) Initializes the residual map to the dirty map and the Clean component list to an empty value

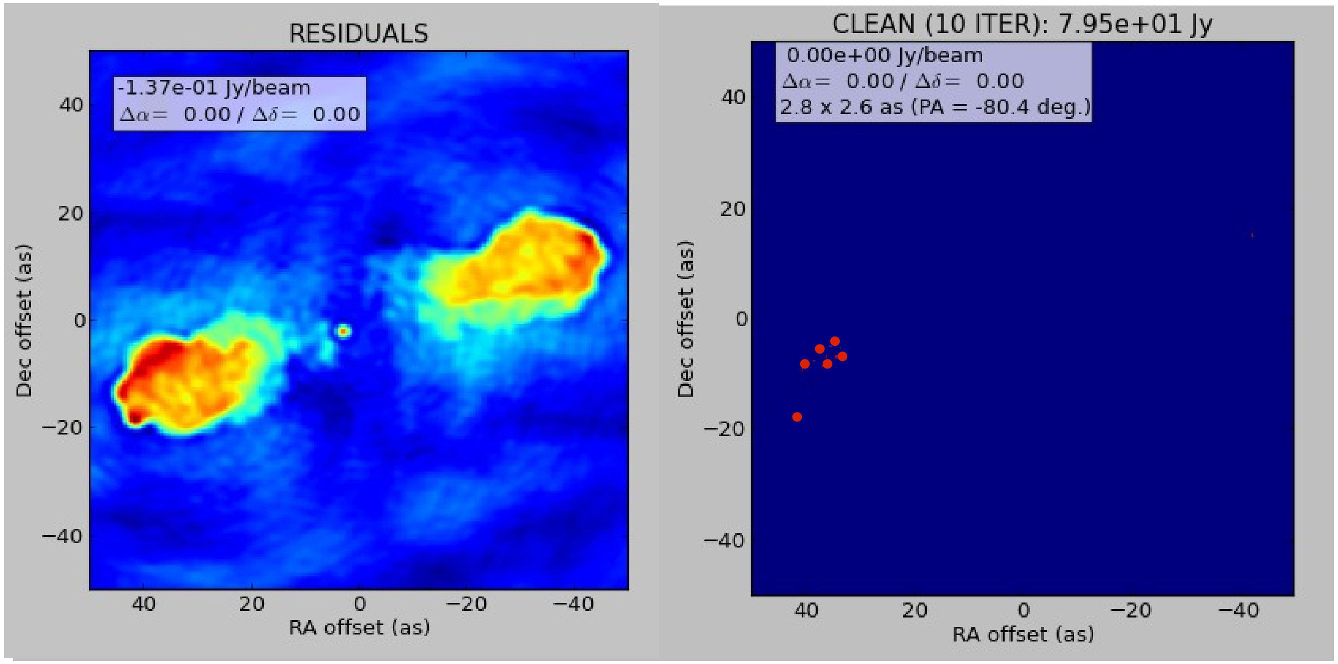


Deconvolution - Classic CLEAN

Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

Basic assumption: each source is a collection of point sources

2) Identifies the pixel with the peak of intensity (I_{max})in the residual map and adds to the clean component list a fraction of I_{max} = γI_{max}



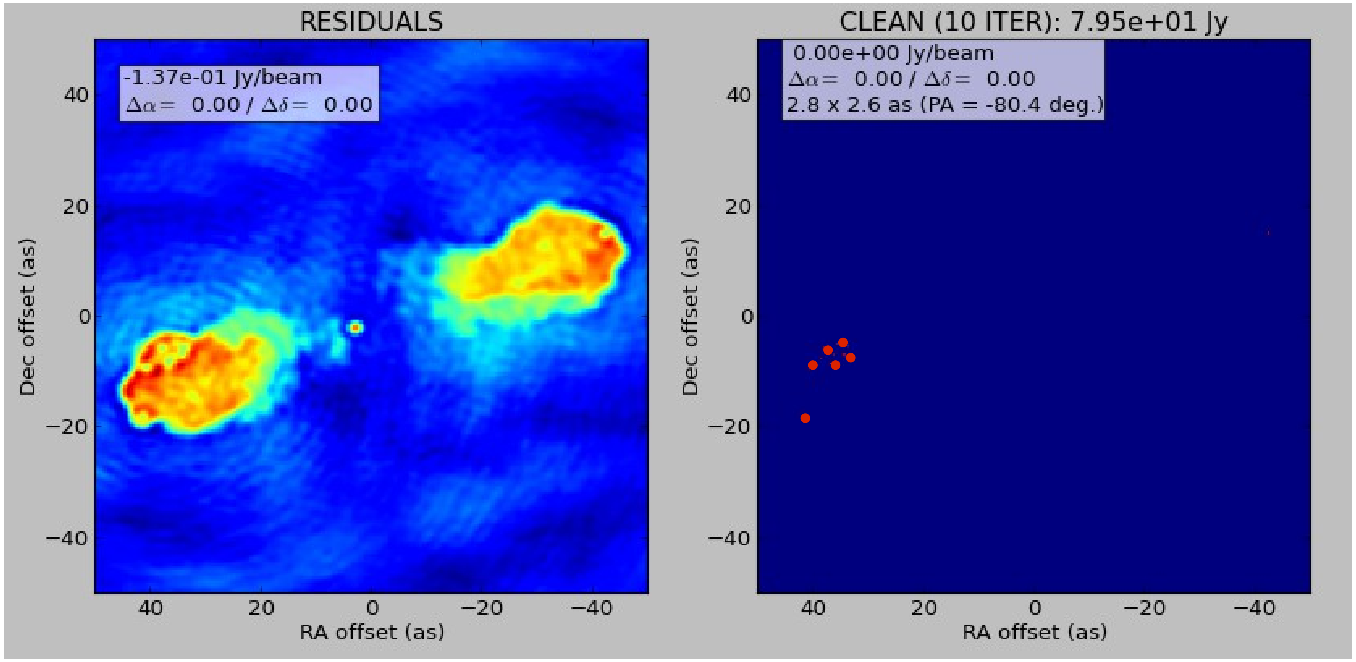
Loop gain

typically
$\gamma \sim 0.1 - 0.3$

Deconvolution - Classic CLEAN
Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

Basic assumption: each source is a collection of point sources

3) Multipies the clean component by the dirty beam and subtract it to the residual

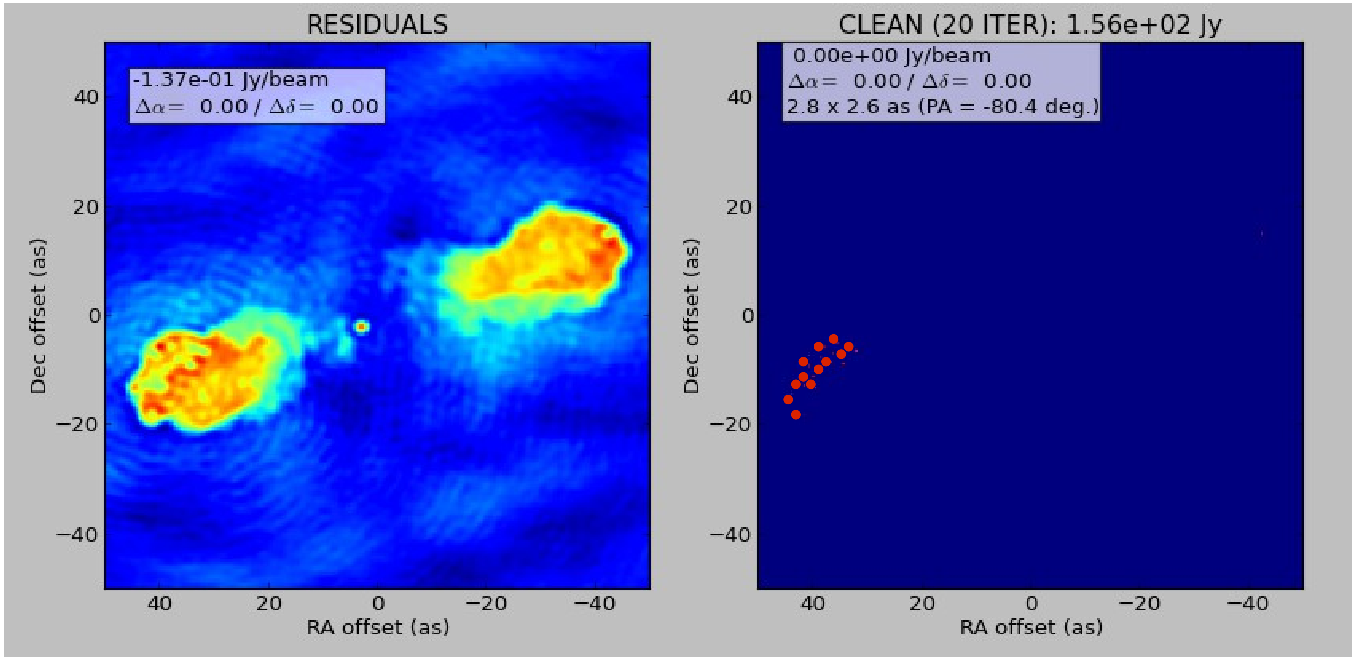


Deconvolution - Classic CLEAN

Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

Basic assumption: each source is a collection of point sources

4) Iterates until stopping creteria are reached



Stopping criteria

$|I_{max}|$ < multiple of the rms (when rms limited)

$|I_{max}|$ < fraction of the brightest source flux (when dynamic range limited)

Deconvolution - Classic CLEAN
Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

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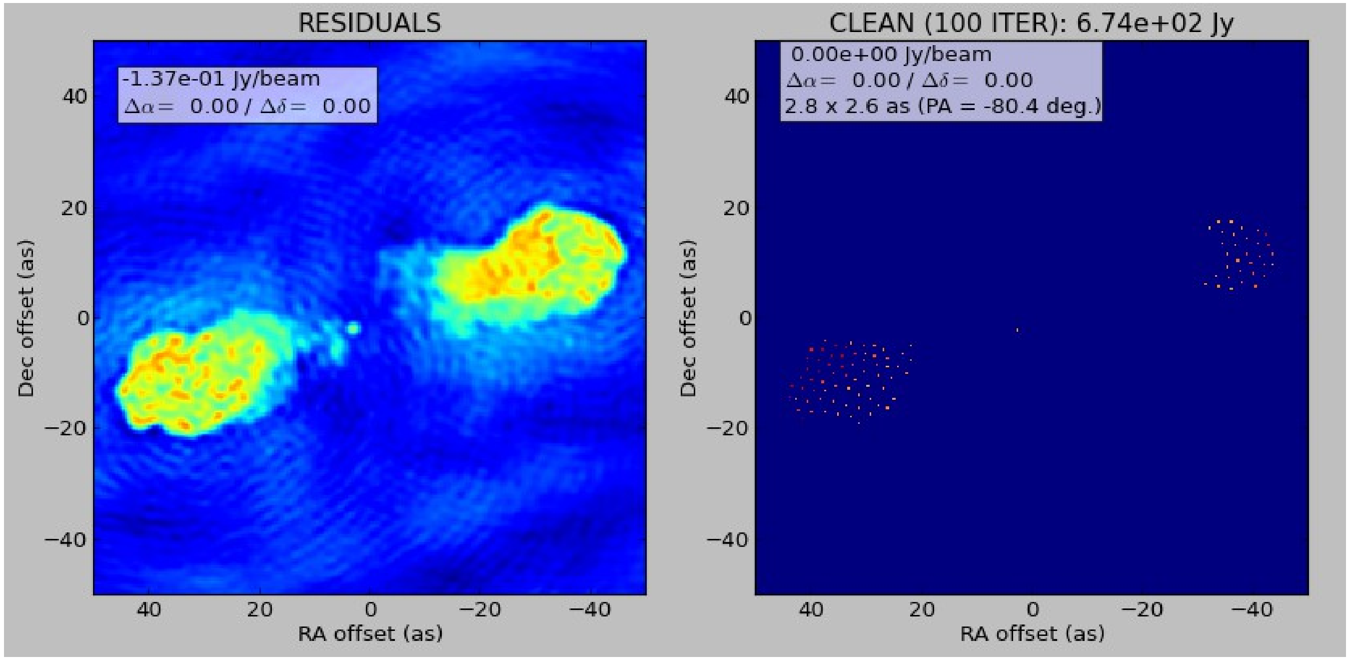

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Deconvolution - Classic CLEAN

Hogbom 1974, Clark 1980, Cotton-Schwab 1984

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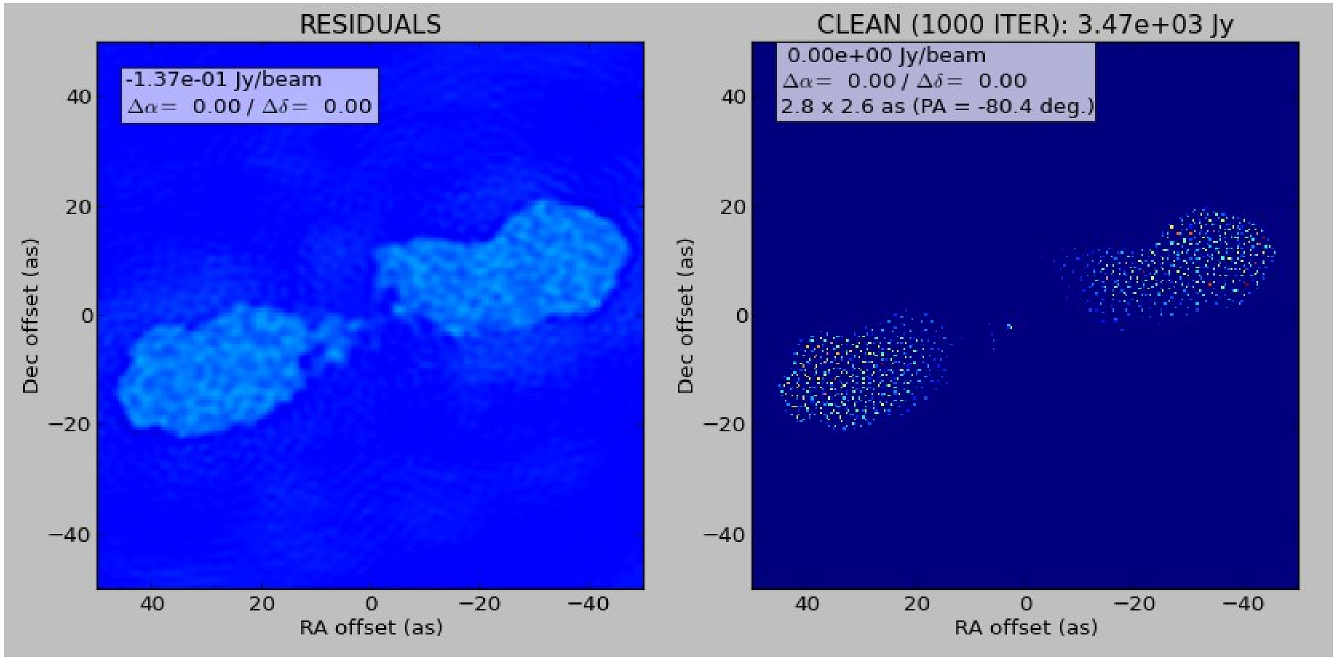

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Deconvolution - Classic CLEAN

Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

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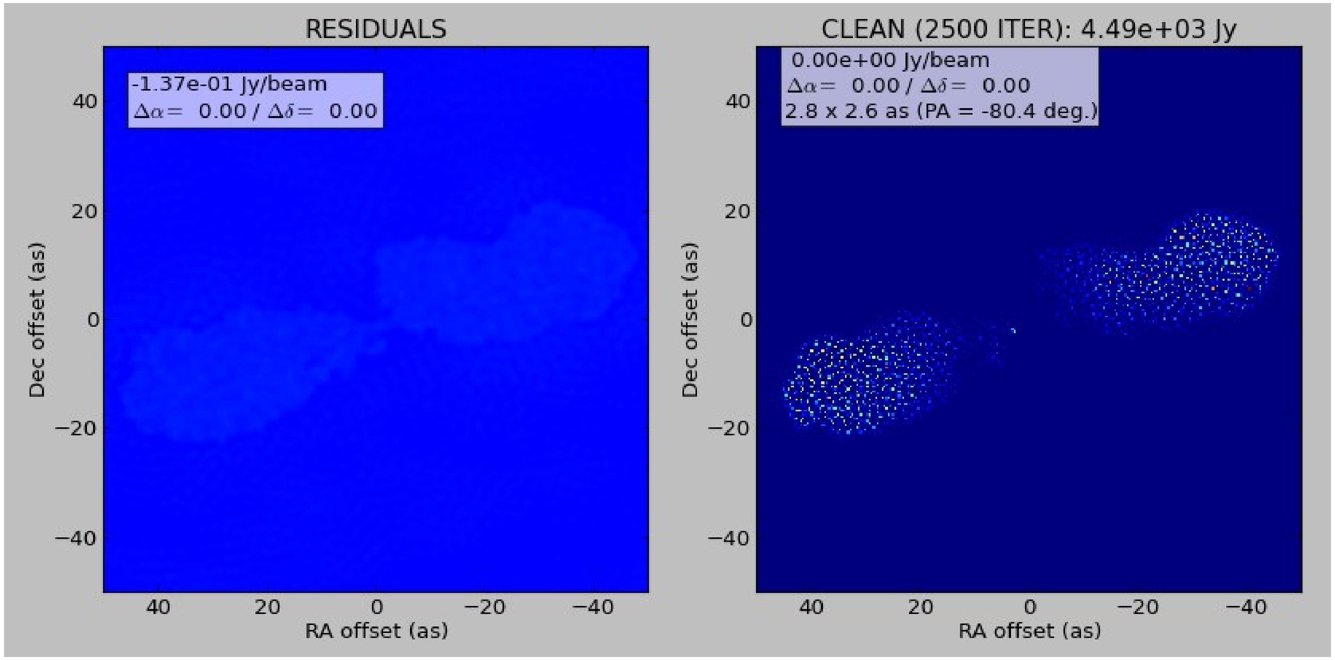


Stopping criteria

$|I_{max}|$ < multiple of the rms (when rms limited)

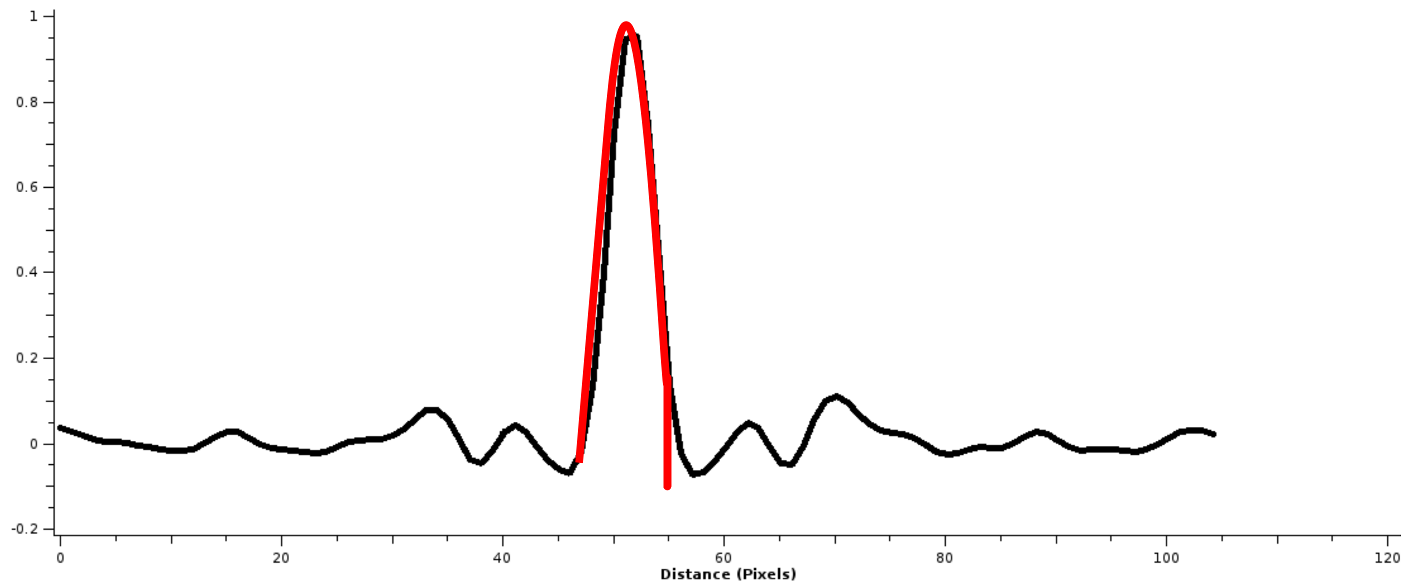
$|I_{max}|$ < fraction of the brightest source flux (when dynamic range limited)

Deconvolution - Classic CLEAN

Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

Basic assumption: each source is a collection of point sources

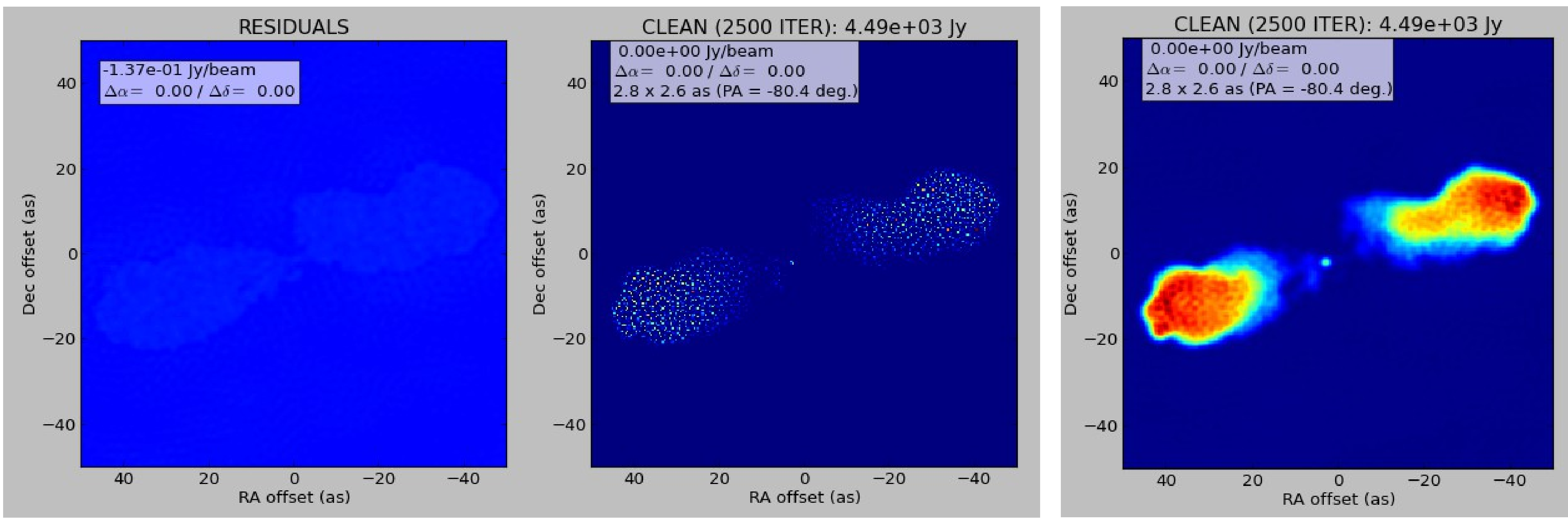
5) Multipies the clean components by **the clean beam**
an elliptical gaussian fitting the central region of the dirty beam
→ **restoring**



Deconvolution - Classic CLEAN
Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

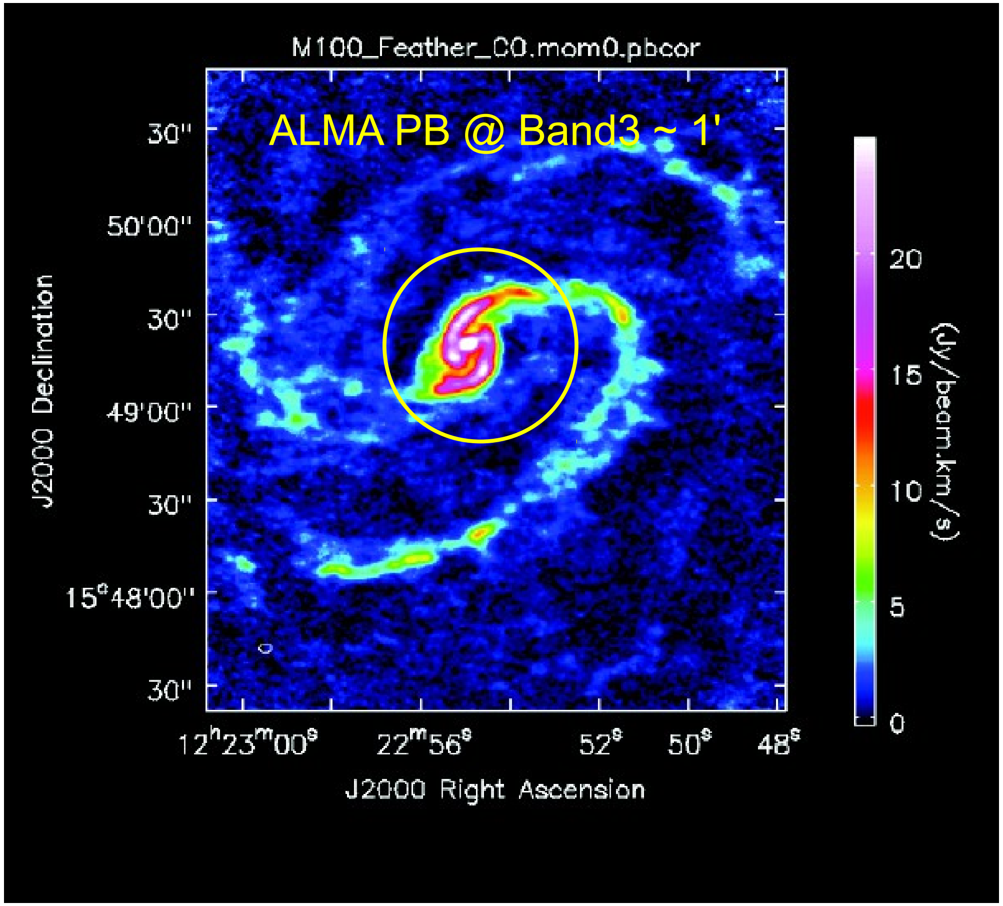
Basic assumption: each source is a collection of point sources

5) Multipies the clean components by the clean beam (**restore**) and add it back to the residual



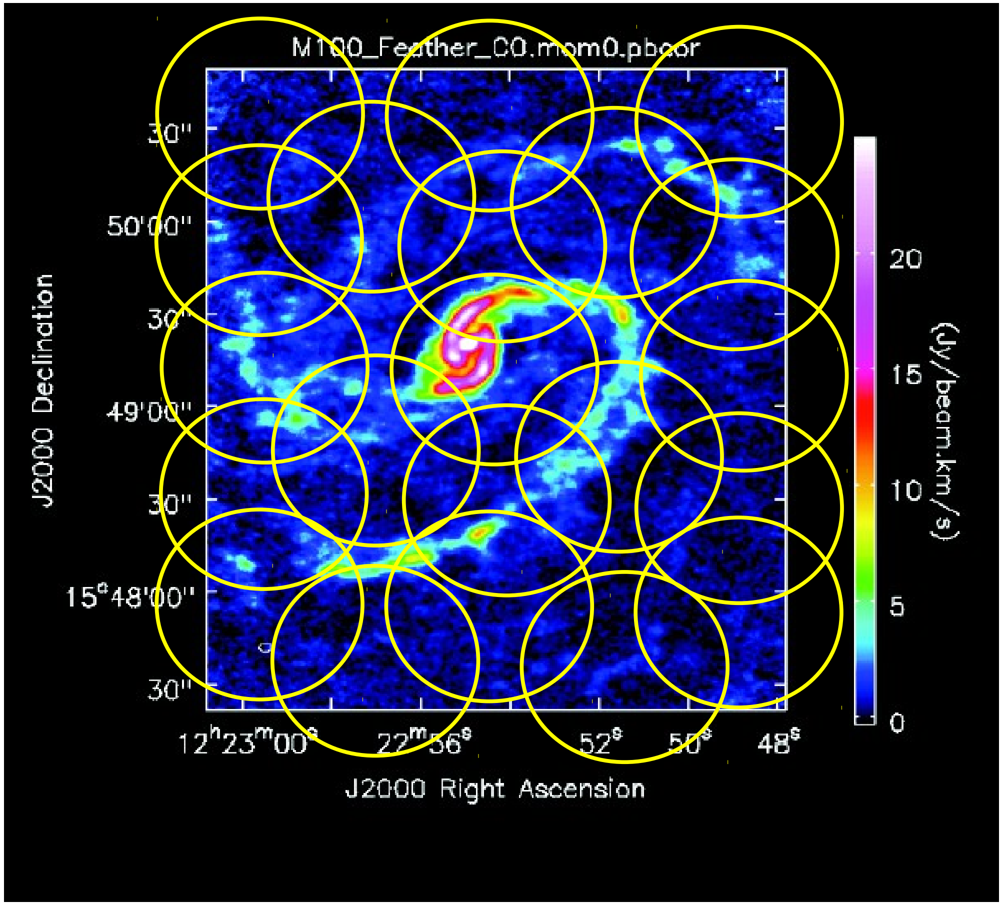
Resulting image pixel have units of Jy per clean beam

If the region of interest is larger than the primary beam



If the region of interest is larger than the primary beam

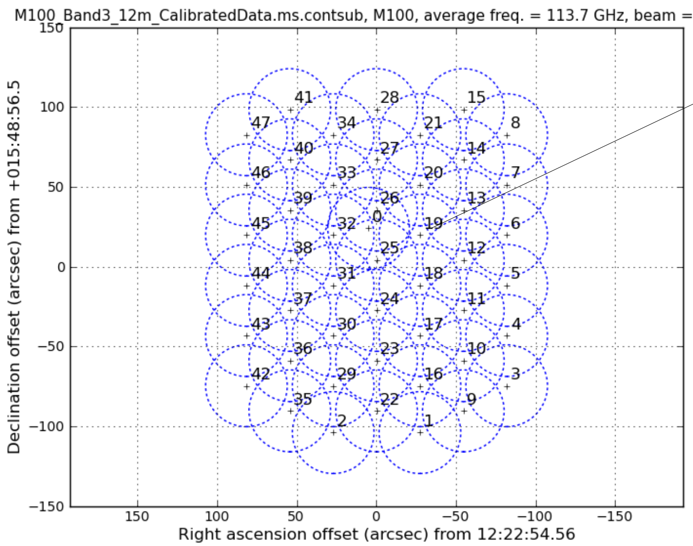
need to mosaic many interferometric pointings

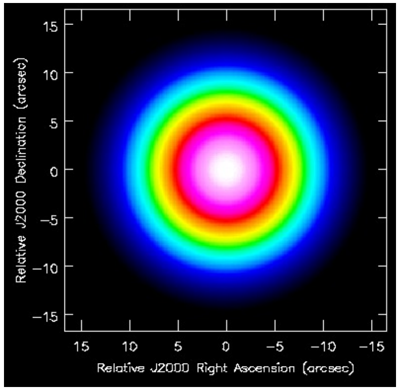


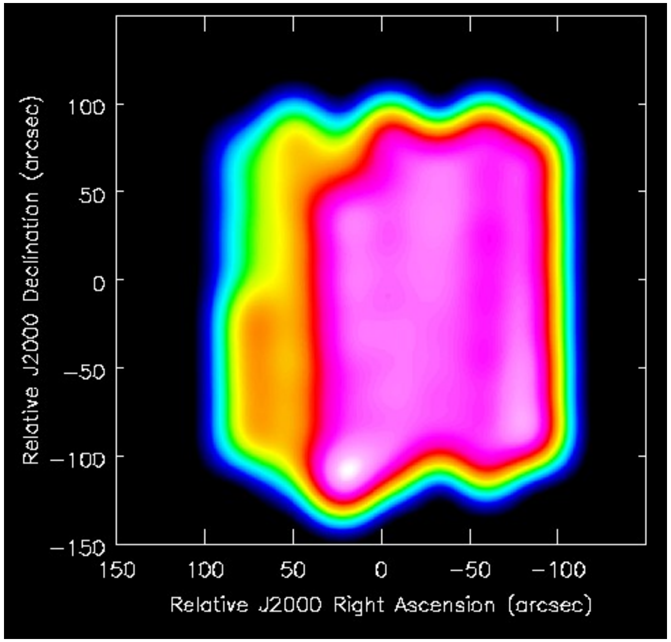
Clean is basically the same →
need to specify the central pointing (phasecenter)
the image size = full mosaic area
and the mode 'mosaic' (imagermode and ftmachine)

M100 example: 12 m array

ALMA Band 3 observations (FOV~51”)
47 12m pointings are needed
to cover ~200” square area
ToS ~ 124 min







The mosaic primary beam response pattern is the convolution of individual HPBW of the different pointings

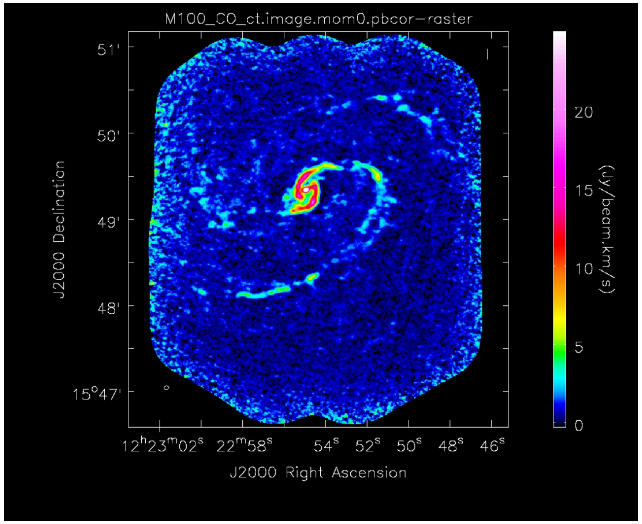


Image with 12 m data

The largest structures > $\theta_{MRS} \approx \frac{\lambda}{B_{min}}$

are not recovered

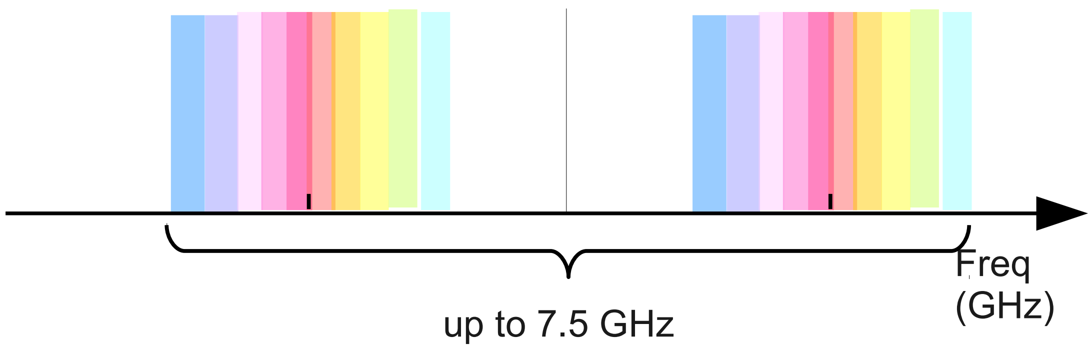
→ **need ACA and possibly Total Power**

Continuum images

- **Multi-Frequency synthesis (MFS)**

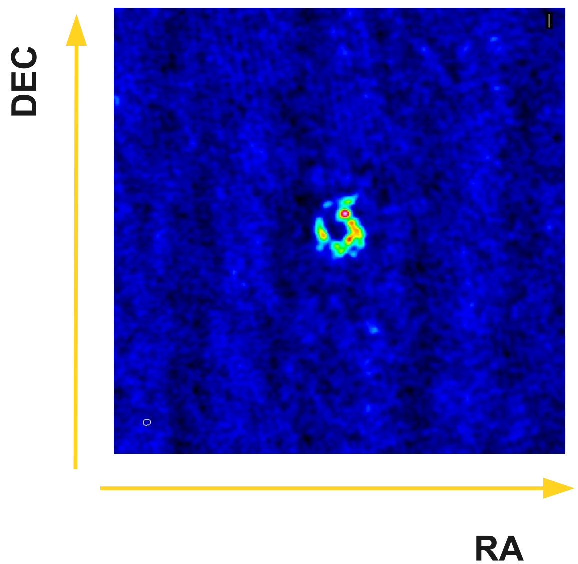
- Wide bandwidths allow higher sensitivity to continuum emission

$$\sigma = \frac{2k}{\eta} \frac{T_{\mathrm{sys}}}{\sqrt{\Delta t \Delta \nu}\sqrt{N_{\mathrm{ant}}(N_{\mathrm{ant}}-1)A}}$$



MFS
combines all channels

the result is a single image



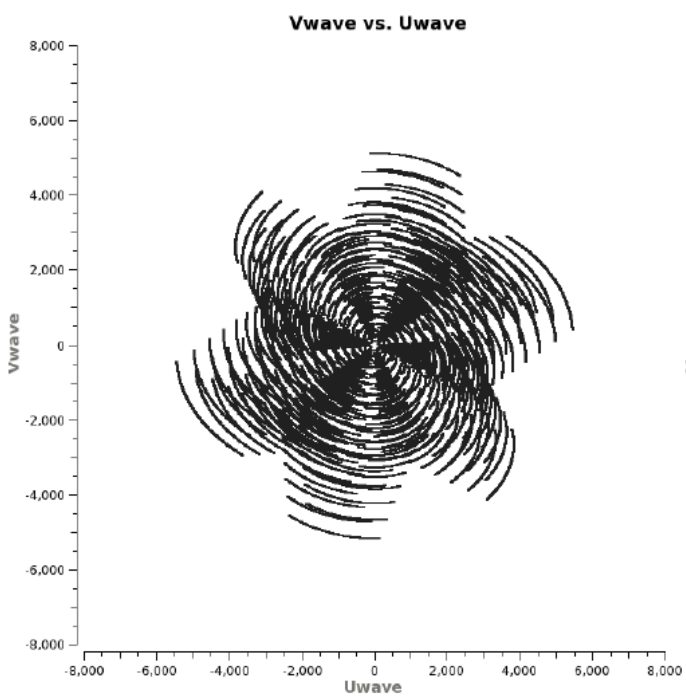
Continuum images

- **Multi-Frequency synthesis (MFS)**

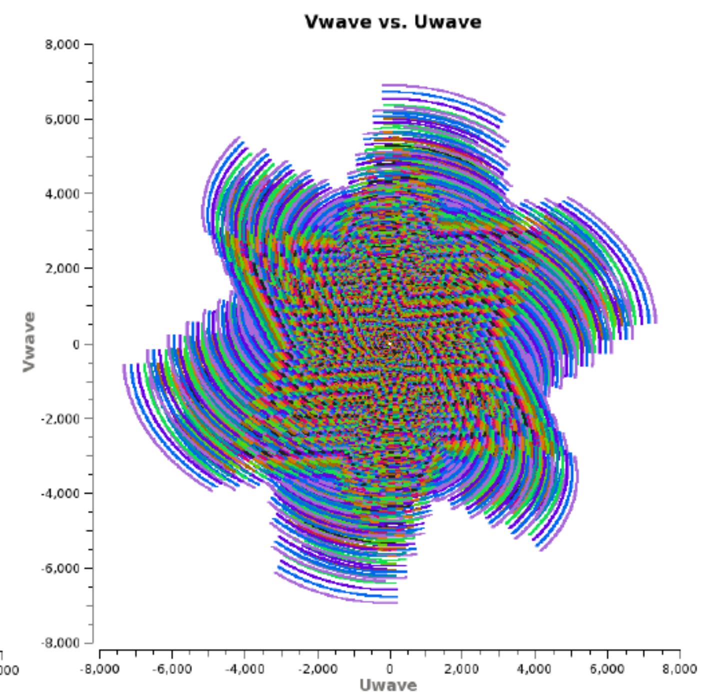
- Wide bandwidths allow higher sensitivity to continuum emission but also **uv coverage is improved**

$$\sigma = \frac{2k}{\eta} \frac{T_{\text{sys}}}{\sqrt{\Delta t \Delta \nu}\sqrt{N_{\text{ant}}(N_{\text{ant}}-1)}A}$$

- Distance in the uv-plane is proportional to b/λ so observing a large range in wavelengths changes points in the uv-plane into lines.



1.5 GHz



1 – 2 GHz

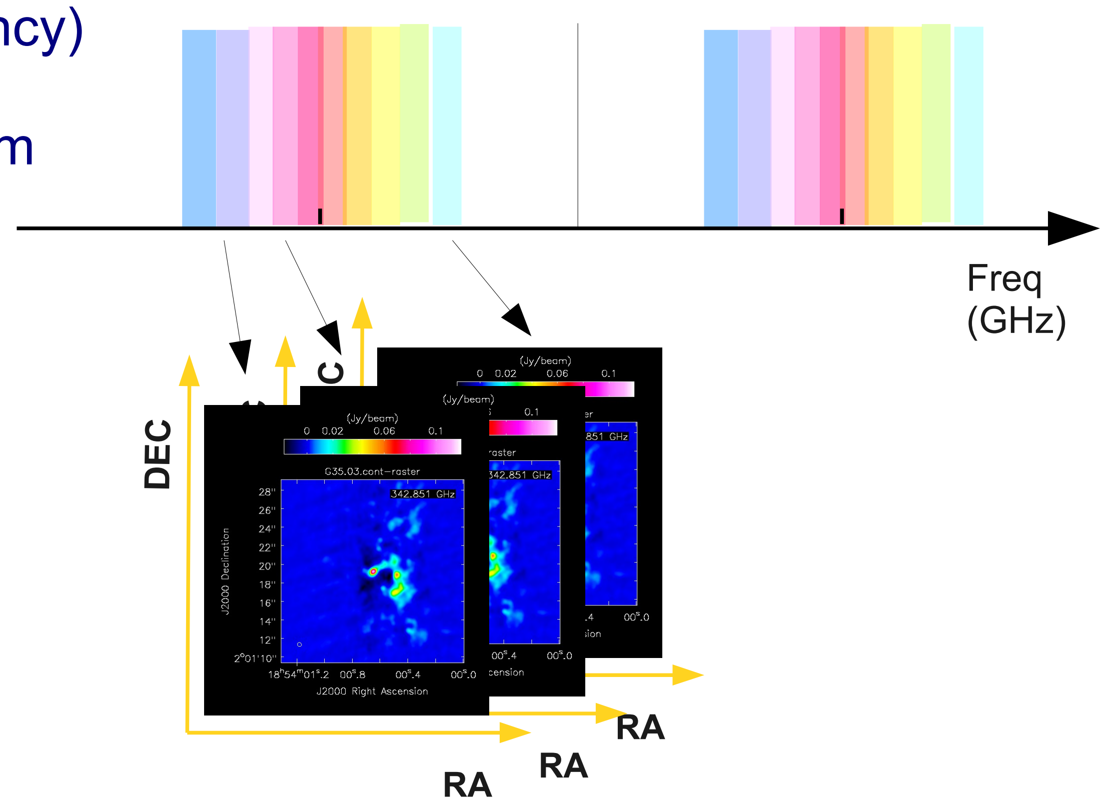
Spectral line observations

$$\sigma = \frac{2k}{\eta} \frac{T_{\mathrm{sys}}}{\sqrt{\Delta t \Delta \nu} \sqrt{N_{\mathrm{ant}}(N_{\mathrm{ant}} - 1) A}}$$

- The imaging process is the same as for a continuum map **but** making an image for each channel (a cube with axes RA, DEC and velocity/frequency)

- The rms is larger than for continuum

- While imaging it is possible to average channels if the full spectral resolution is not needed



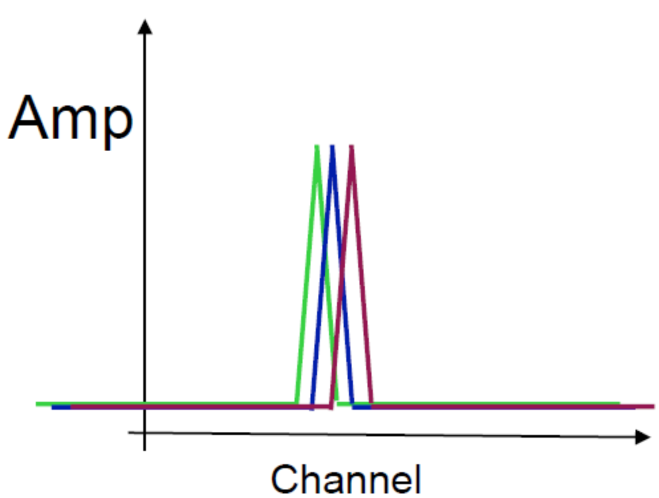
Spectral line

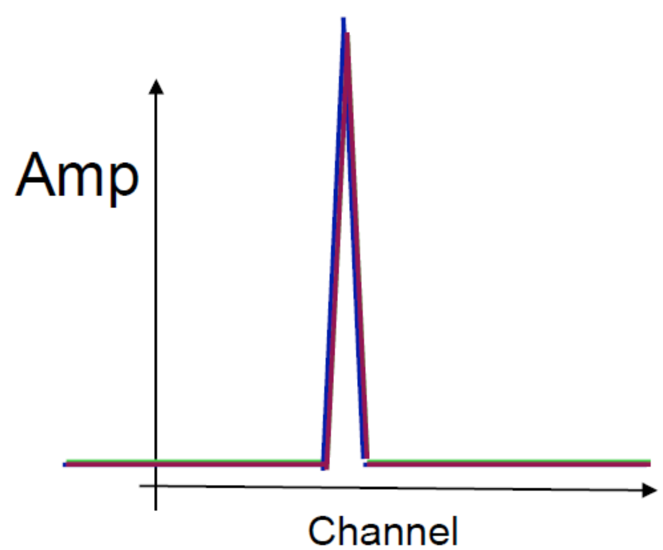
Observing from the Earth, our velocity with respect to the astronomical sources is not constant in time or direction.

- **On-line doppler tracking** would correct automatically in real time during the observations to a given reference frame
  For wide frequency bands (VLA, ALMA) it is not done/recommended

In ALMA

- **Sky** frequency is calculated once at the start: **Doppler setting**
- **No Doppler tracking**
  → needs to be done in post-processing (with cvel or clean)





Spectral line

Velocity frames

ALMA default velocity frame is **Topocentric** rest frame: Telescope
→ No correction applied

Typically

- **galactic data are in LSRK**
- rest frame: center of mass of local stars: corrects for solar motion relative to nearby stars

- **extragalactic data are in BARY**
  rest frame: Earth-Sun center of mass: corrects for motions around the Solar System barycenter

Spectral line observational considerations

Velocity conventions

- $\mathbf{V_{radio} = c\ \Delta\nu\ /\ \nu_0}$
  often used because constant frequency increment channels correspond to constant velocity increment channels

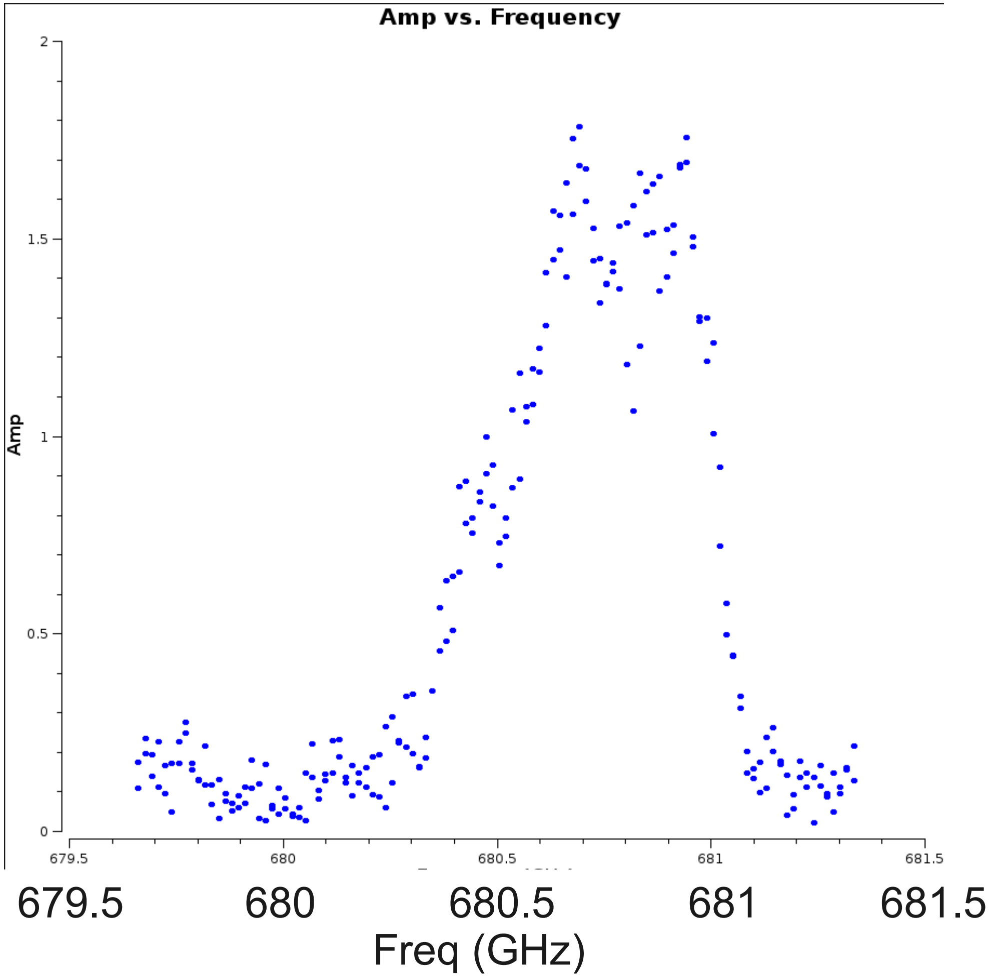
- $\mathbf{V_{optical} = c\ \Delta\lambda\ /\ \lambda_0 = cz}$

  differences become larger as redshift increases

Spectral line observational considerations

Example: data of the hands-on session
CO(5-6) line (rest freq 691.473 GHz) in a source @ 68 Mpc

Frequency is sky frequency



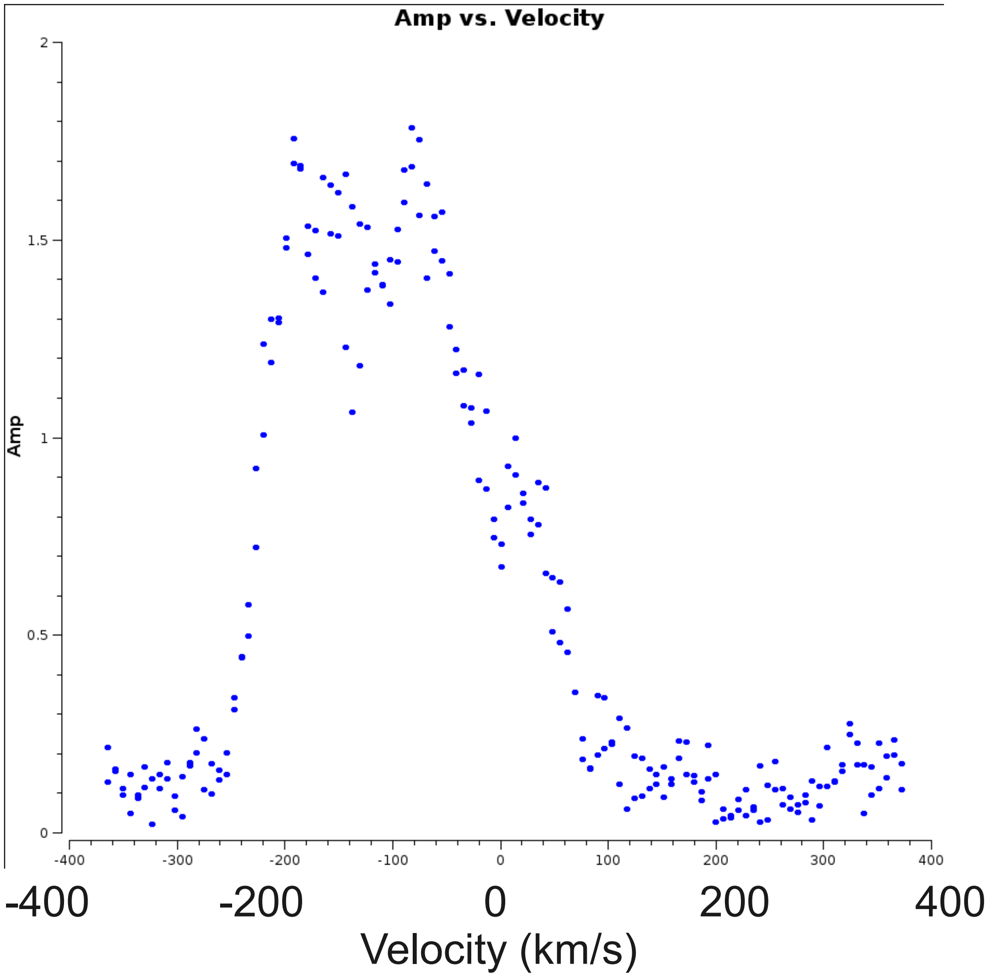
Spectral line observational considerations

Example: data of the hands-on session
CO(5-6) line (rest freq 691.473 GHz) in a source @ 68 Mpc

Radio velocity (the velocity axis does not correspond to the source velocity)

If no restfreq is fixed the velocity is calculated with respect to the freq of the central channel of the spw

$$\frac{\delta\nu}{\nu}=\frac{V}{c}$$



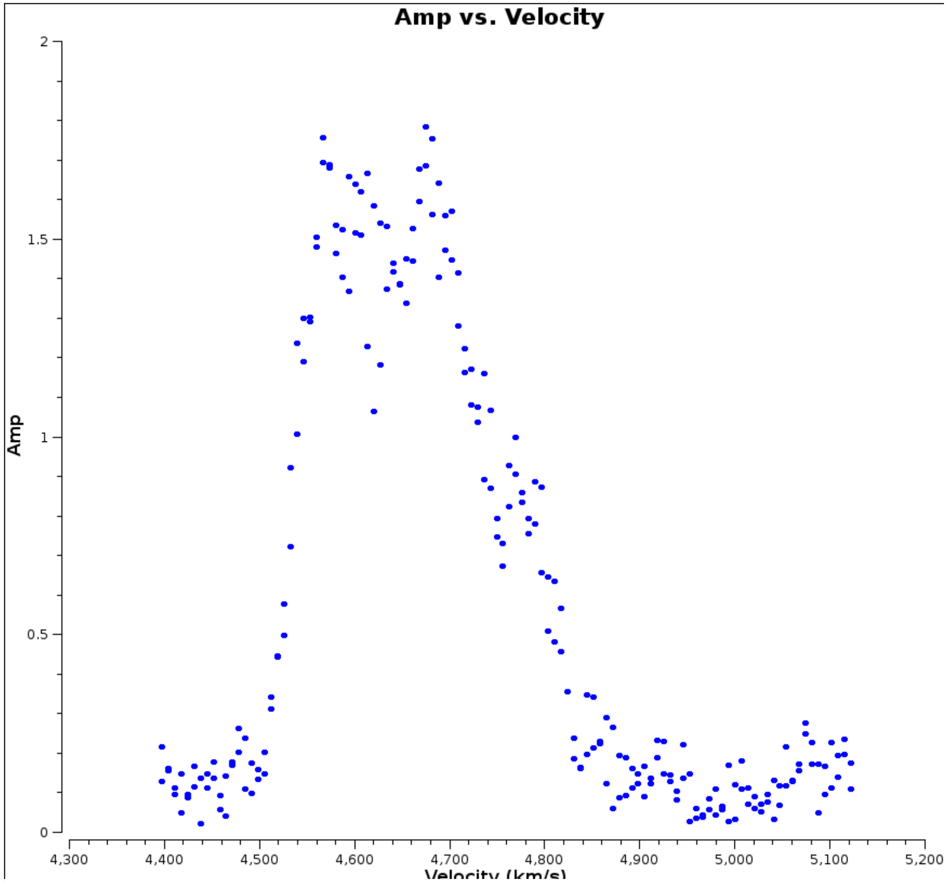
Spectral line observational considerations

Example: data of the hands-on session
CO(5-6) line (rest freq 691.473 GHz) in a source @ 68 Mpc

Need to add the restfreq of the line to visualize the correct velocity

Adding restfreq computes the velocity of each channel with respect to that restfreq.

restfreq 691.473 GHz
we have the velocity of the galaxy with respect to the Earth.



4300 4500 4700 4900 5100
Velocity (km/s)

Spectral line observational considerations

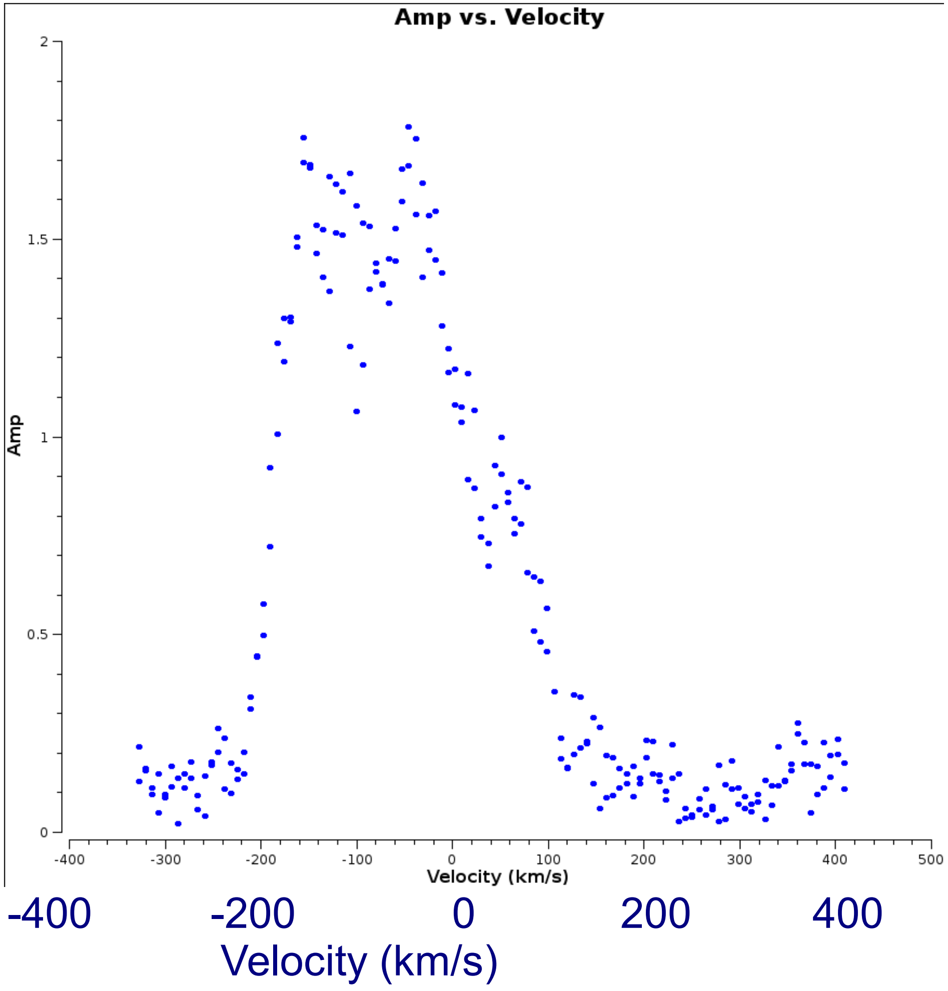
Example: data of the hands-on session
CO(5-6) line (rest freq 691.473 GHz) in a source @ 68 Mpc

Adding restfreq
computes the velocity of each channel with respect to that restfreq.

The systemic velocity is **4723 km/s**
(Xu et al 2015).

Using the redshifted CO(5-6) freq:
restfreq 680.587 GHz

In this case there is a 50 km/s shift with respect to the velocity indicated in the proposal



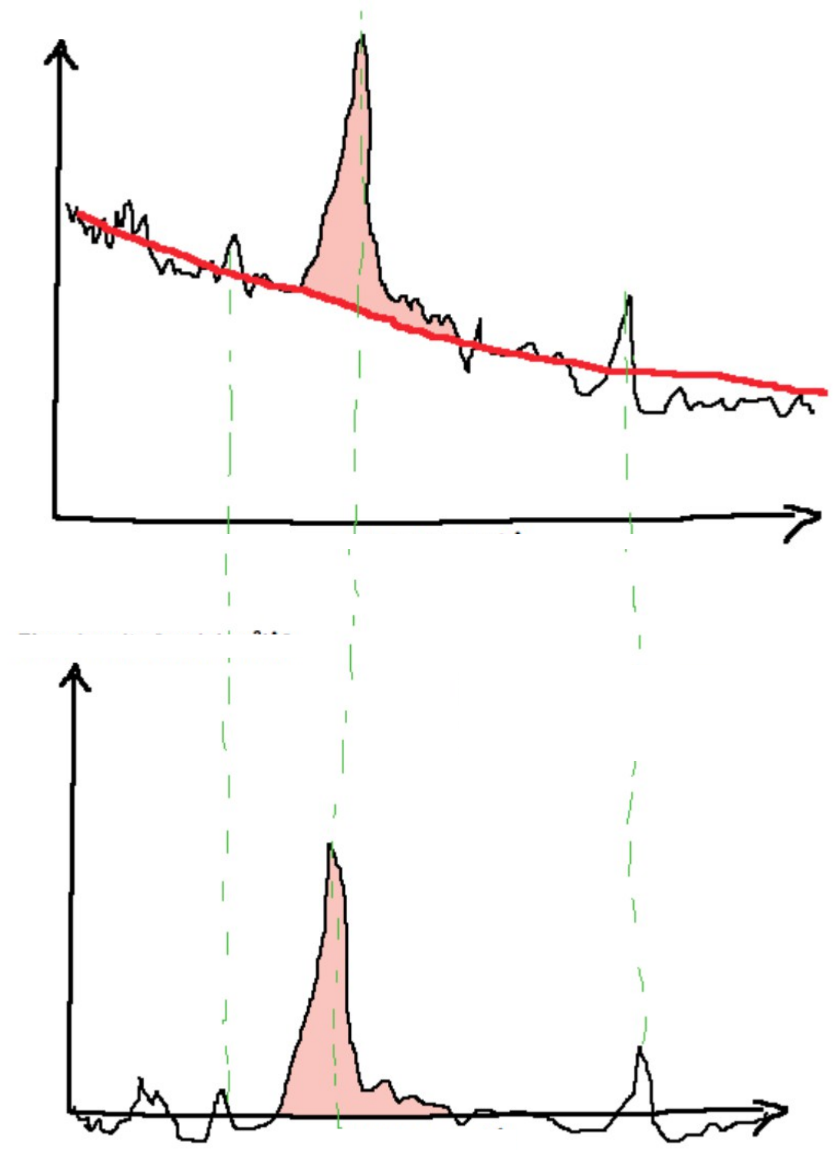
Spectral line observations

- Spectral line data often contains continuum emission from the target which can complicate the detection and analysis of lines

- Model the continuum using channels with no lines: low-order polynomial fit

- Subtract this continuum model from all the channels

- It can be done before imaging
  in the uv plane (uvcontsub)
  or in the image plane (imcontsub)



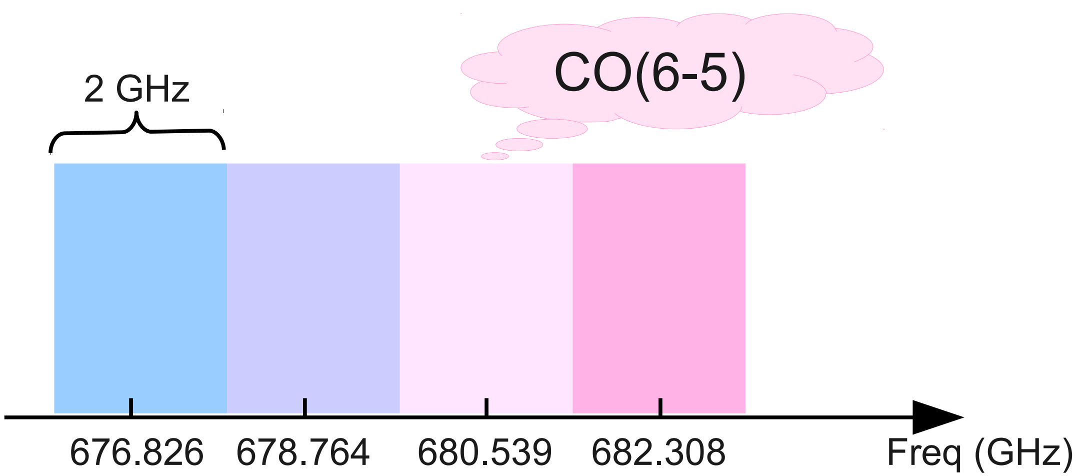
Hands-on dataset 1

ALMA observations of warm dense gas in NGC1614 – Breaking of the star formation law in the central kiloparsec

Xu et al. 2015

Cycle 0
ALMA Band 9 observations (~680 GHz)

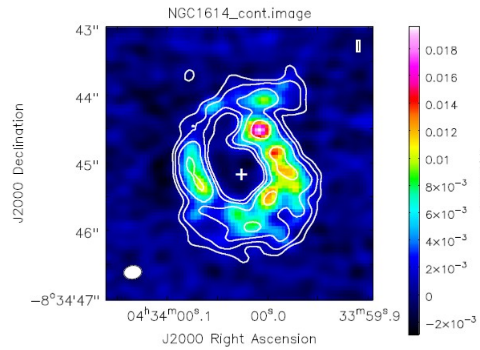
Aim: observations of the central region of the galaxy **NGC1614 (d=68 Mpc)** in CO(6-5) line emission (rest frequency = 691.473 GHz) and 435 μm (689 GHz) dust continuum.



Each spectral window has 128 channels 15 MHz wide providing a velocity resolution of 6.8 Km/s

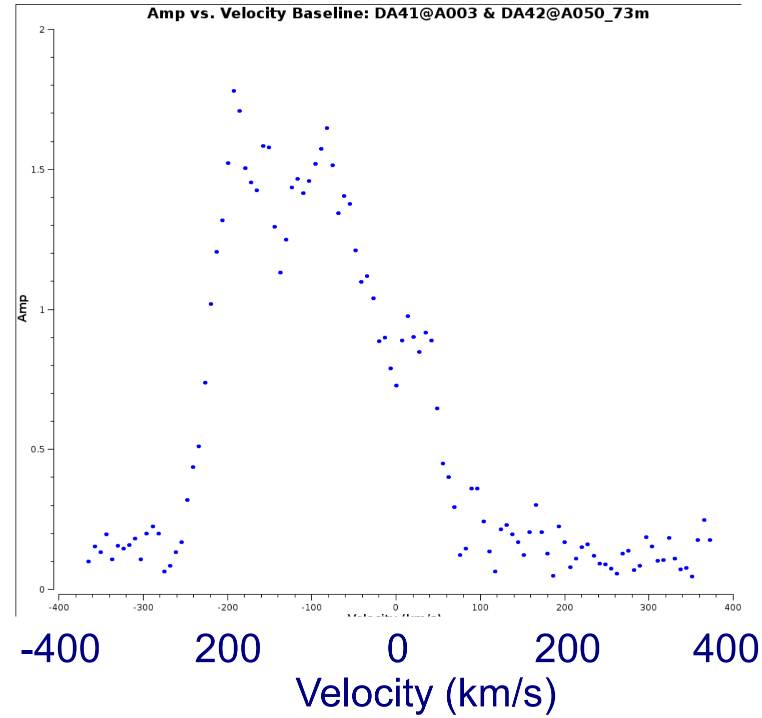
$$\frac{\delta \nu}{\nu} = \frac{\delta V}{c}$$

Hands-on dataset 1



Available in the archive

- Continuum image



- Line image
  non continuum subtracted
  no restfreq added

- Two scripts for Imaging (continuum and line)

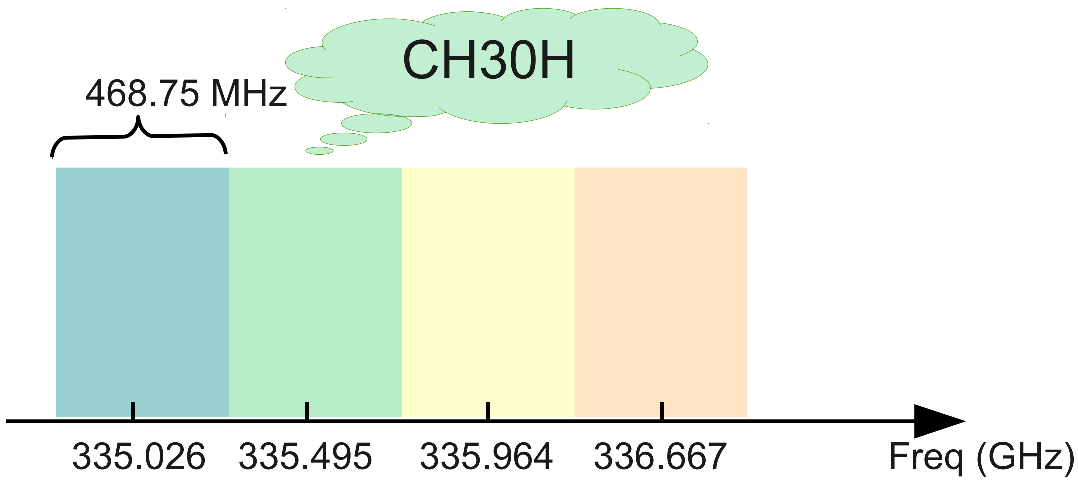
- We are going to modify the imaging scripts to produce
  - continuum images with different weightings
  - line image with correct source velocity

- 2 datasets (EB) Total Time on source 50 min
- N antennas 27
- Expected rms 0.4 mJy

Hands-on dataset 2

Cycle 2
ALMA Band 7 observations (~340 GHz)

Aim: observations of a low mass protostellar source **IRAS 16293-2422** spectral scan.



Each spectral window
has 1920 channels 244.14 KHz wide
providing a velocity resolution
of ~218 m/s

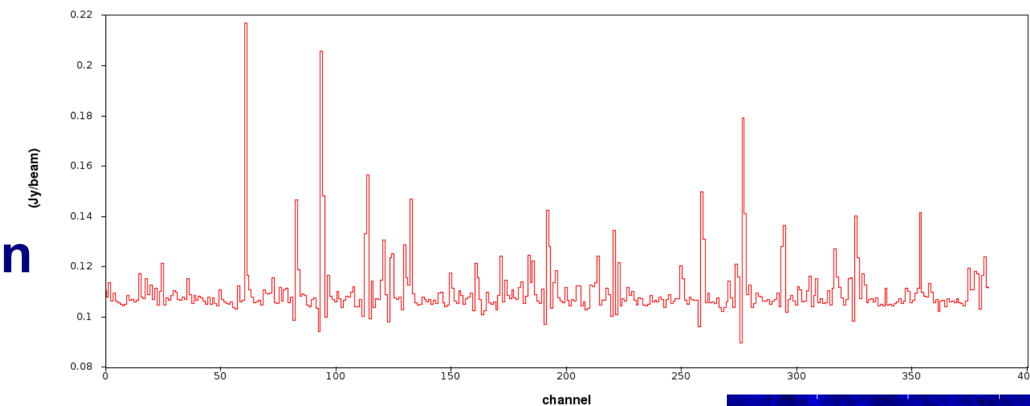
$$\frac{\delta \nu}{\nu} = \frac{\delta V}{c}$$

N ant 36
Time on source 14 min
Max baseline 555 m $\rightarrow$ ~ 0.5 arcsec

Hands-on dataset 2

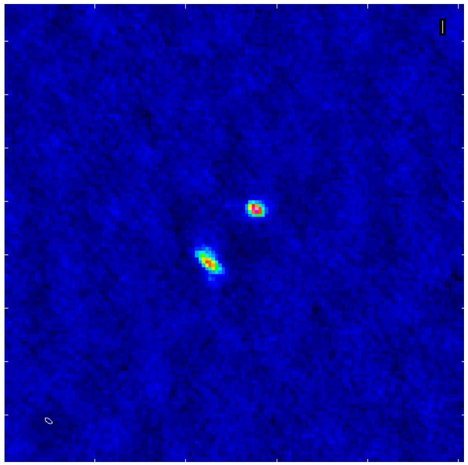
Available in the archive

- PB corrected line images of the four spw
- One script for imaging



- **No continuum subtraction**
  - 5 channels averaged
  (to match the bandwidth
  for sensitivity requested by the PI)

  - cellsize used: 0.25 arcsec
  λ/B_{max} 0.33 arcsec



- We are going to modify the imaging script to produce
  - a continuum subtracted image of CH3OH
  - improving the spatial sampling and the spectral resolution

Concluding remarks

Interferometry samples "partially" the Fourier components of the sky brightness, deconvolution attempts to correct for incomplete sampling

- First be sure that all the spatial scales you are interested in are actually sampled (if necessary require multiple arrays and SD)

- Imaging and deconvolution require care and astronomers judgement try different parameters (e.g weighting) to get the better results for your purposes

- **It is difficult but it is worth the trouble!**

Many more issues not covered in this talk → please see

Book review: **Synthesis Imaging in Radio Astronomy II – The "White Book"**
Astronomical Society of the Pacific Conference Series Volume 180

https://science.nrao.edu/science/meetings/2014/14th-synthesis-imaging-workshop

http://www.iram-institute.org/EN/content-page-248-7-67-248-0-0.html

https://casaguides.nrao.edu