# Imaging

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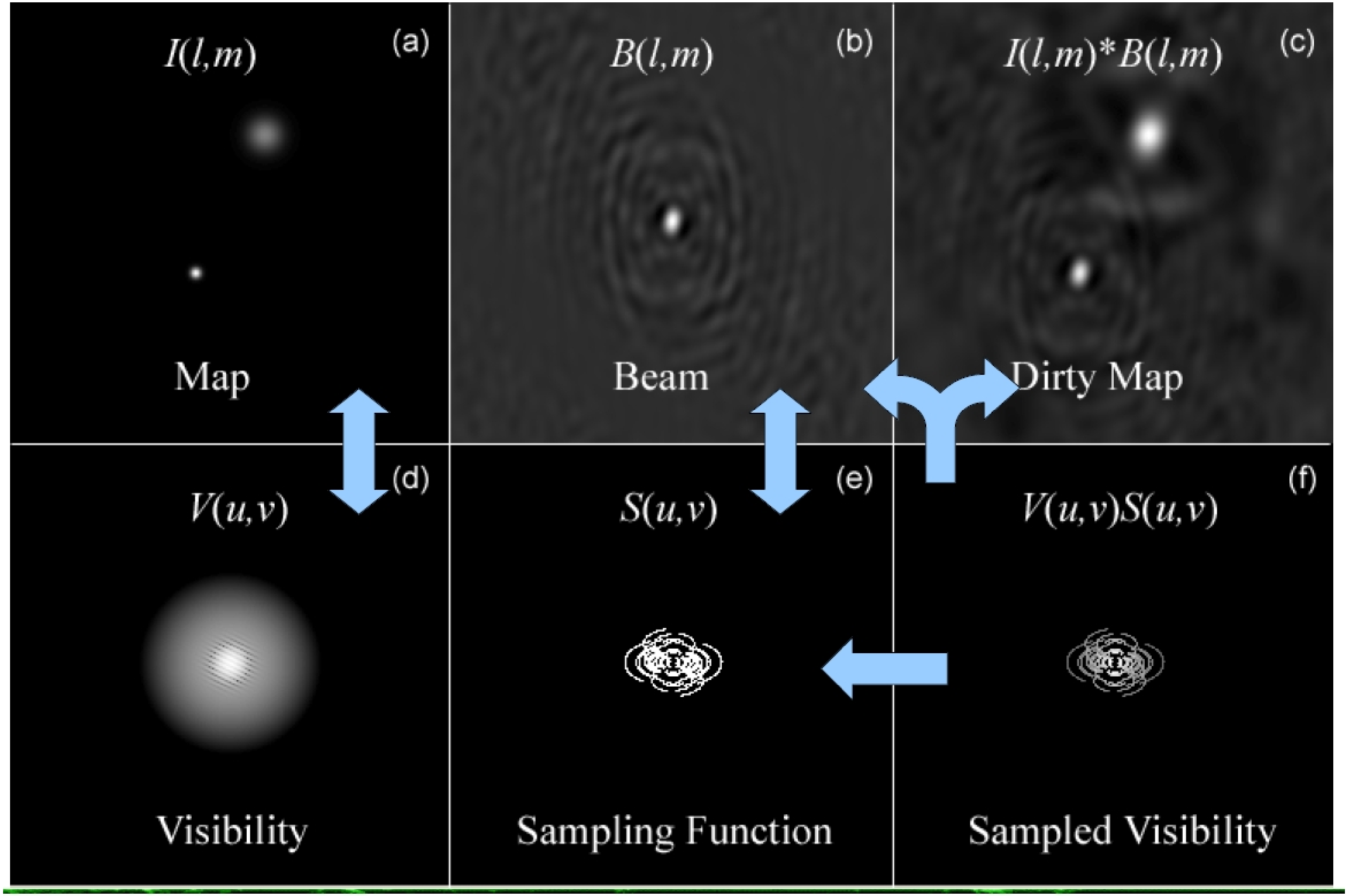
## From lectures:



## From lectures:

Visibilità di Frangia $V'(u_i, v_j)$

$\Downarrow$

INVERSIONE DI FOURIER

$\Downarrow$

Dirty Image $I_d(\theta, \varphi)$ + Dirty Beam $P_n^d(\theta, \varphi)$

$\Downarrow$

Max matrice $|I_d(\theta, \varphi)| = I_m(\theta_m, \varphi_m) \rightarrow I_d = A_i$ $\Leftarrow$

$\Downarrow$

SOTTRAZIONE $I_d(\theta, \varphi) - \gamma \, I_m \, P_n^d(\theta_m, \varphi_m) = I_{resid}(\theta, \varphi)$

$\Downarrow$

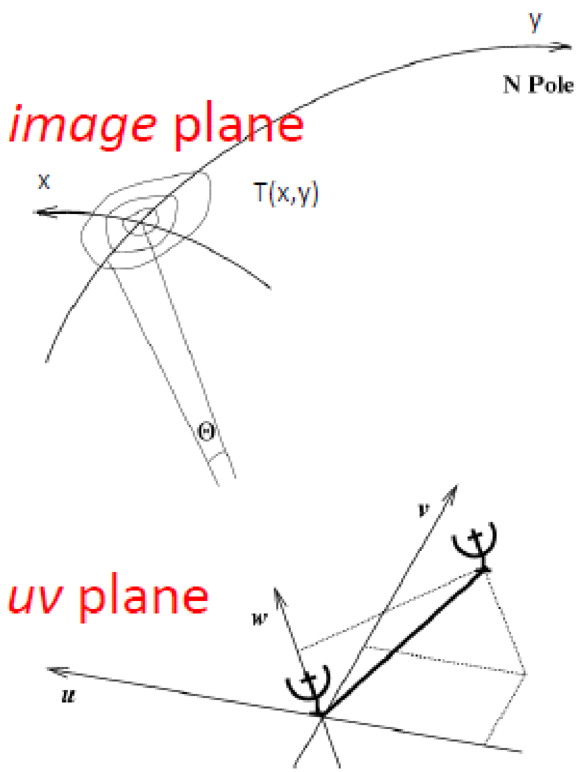
Altre $A_i$? $\Rightarrow$

$\Downarrow$

RESTORE: $I_f^r(\theta, \varphi) = I_{resid}(\theta, \varphi) + \sum_{i=1}^{N} A_i P_n^c(\theta_i, \varphi_i)$

$I_f^r(\theta, \varphi)$ = immagine finale del processo di **cleaning**
$P_n^c(\theta, \varphi)$ = clean beam, avente lobo principale identico al dirty beam, ma **privo di lobi secondari**

**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

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

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

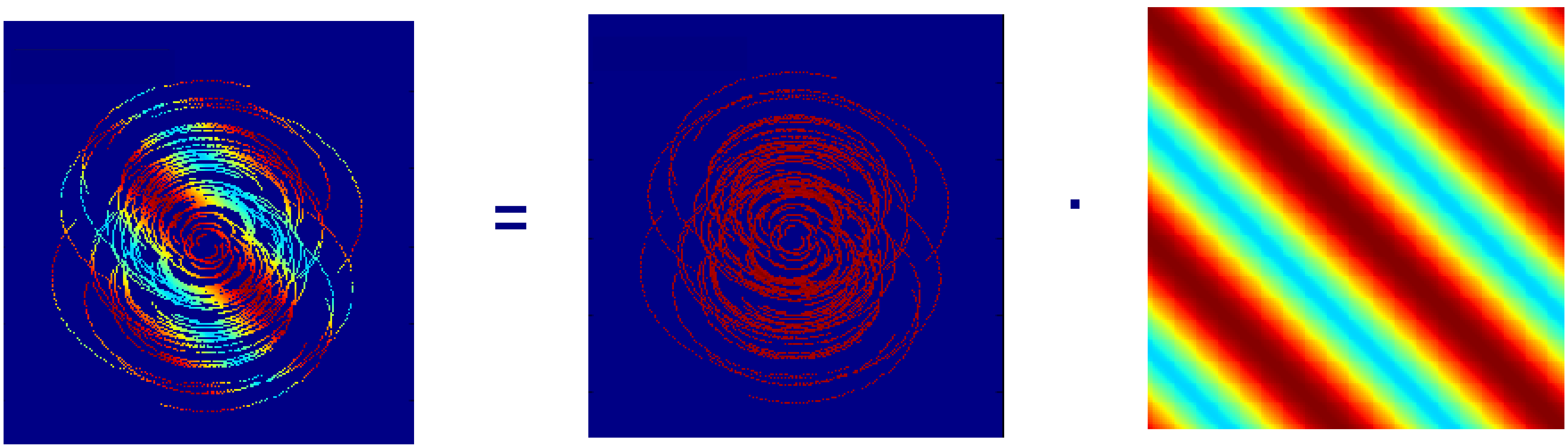
Image space/domain

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

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

**But**
we actually sample the Fourier domain at discrete points

$$V_{cal}(u,v) \quad = \quad S(u,v) \quad \cdot \quad V_{true}(u,v)$$



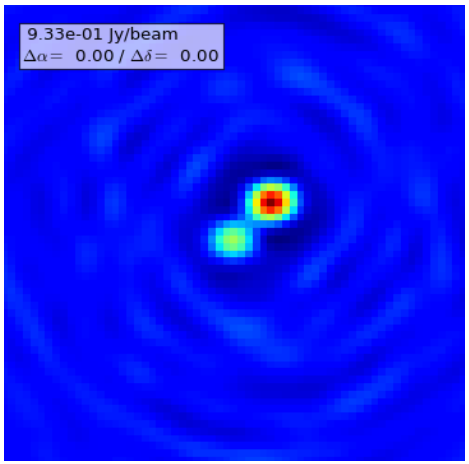
where C(u,v) is the sampling function
C= 1 at points where visibilities are measured
and   C = 0 elsewhere

* 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:

$$FT^{-1}(V_{cal}) = FT^{-1}(S) \otimes FT^{-1}(V_{True})$$

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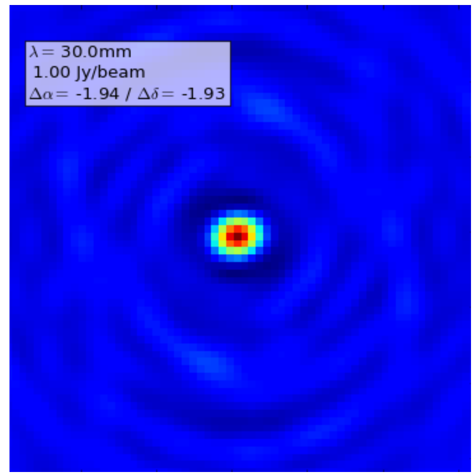


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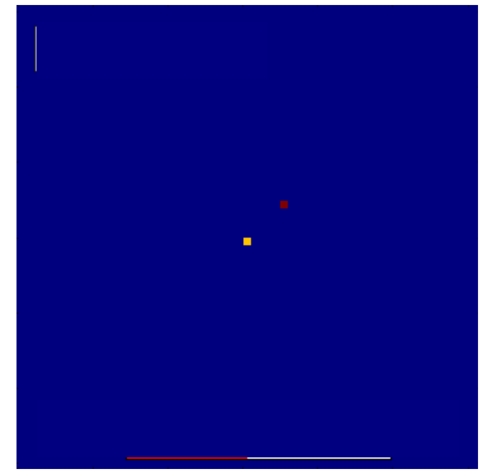


The Fourier transform FT of the sampled visibilities gives the true sky brightness convolved with the Fourier transform of the sampling function (called **dirty beam**).

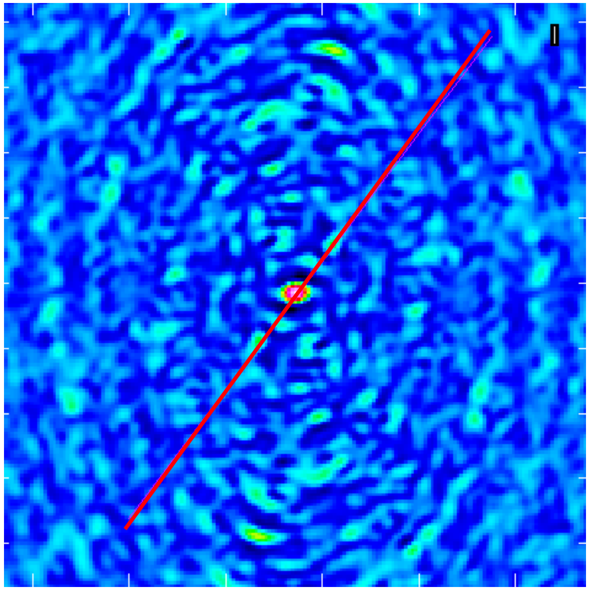
$$I^D(x,y) = B_{dirty}(x,y) \otimes I(x,y)$$

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

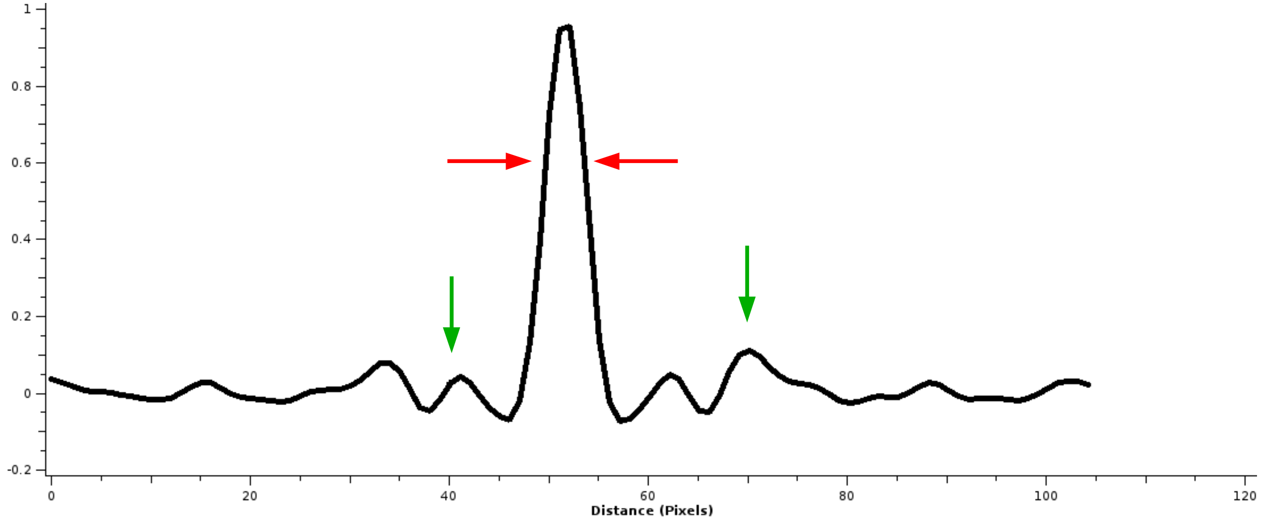
# Imperfect reconstruction of the sky

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

$$B_{dirty}(x, y)$$



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

**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

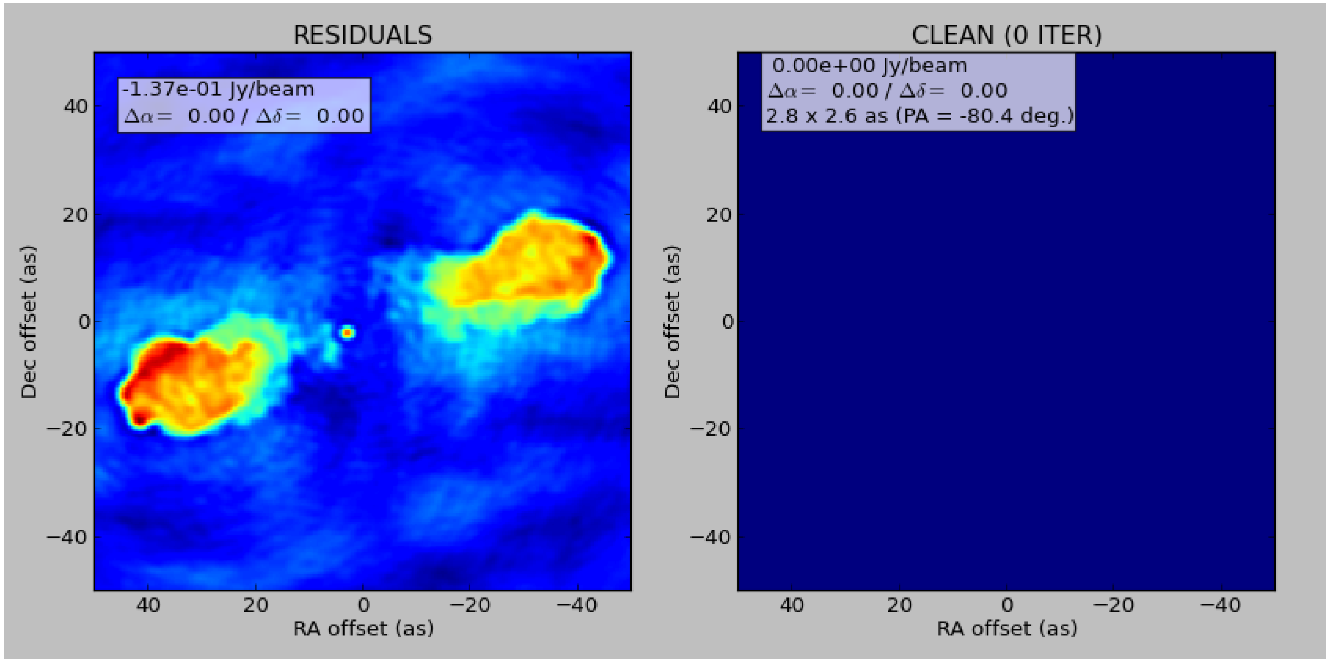
**At least twice the field of view for the Nyquist sampling**

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

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

**Basic assumption:** each source is a collection of point sources

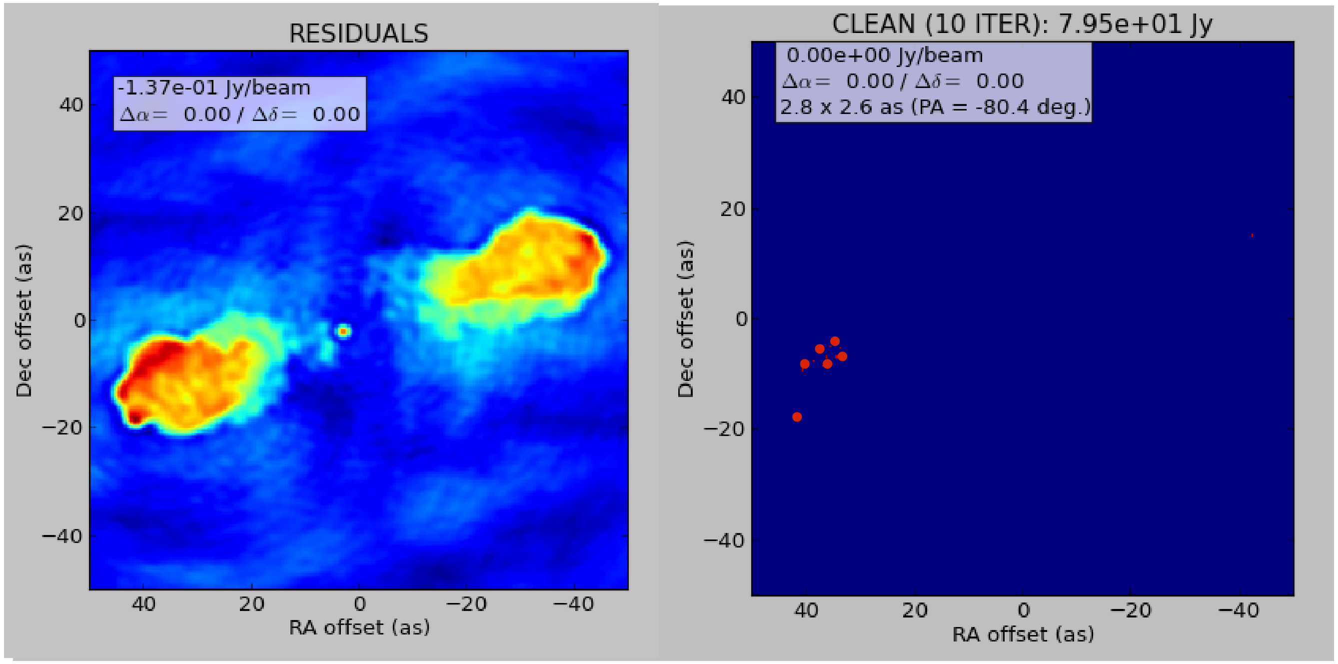
1) Initializes the residual map to the dirty map and the Clean component list to an empty value



**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 $I_{max} = \boldsymbol{\gamma} \mathbf{I_{max}}$




**Loop gain**

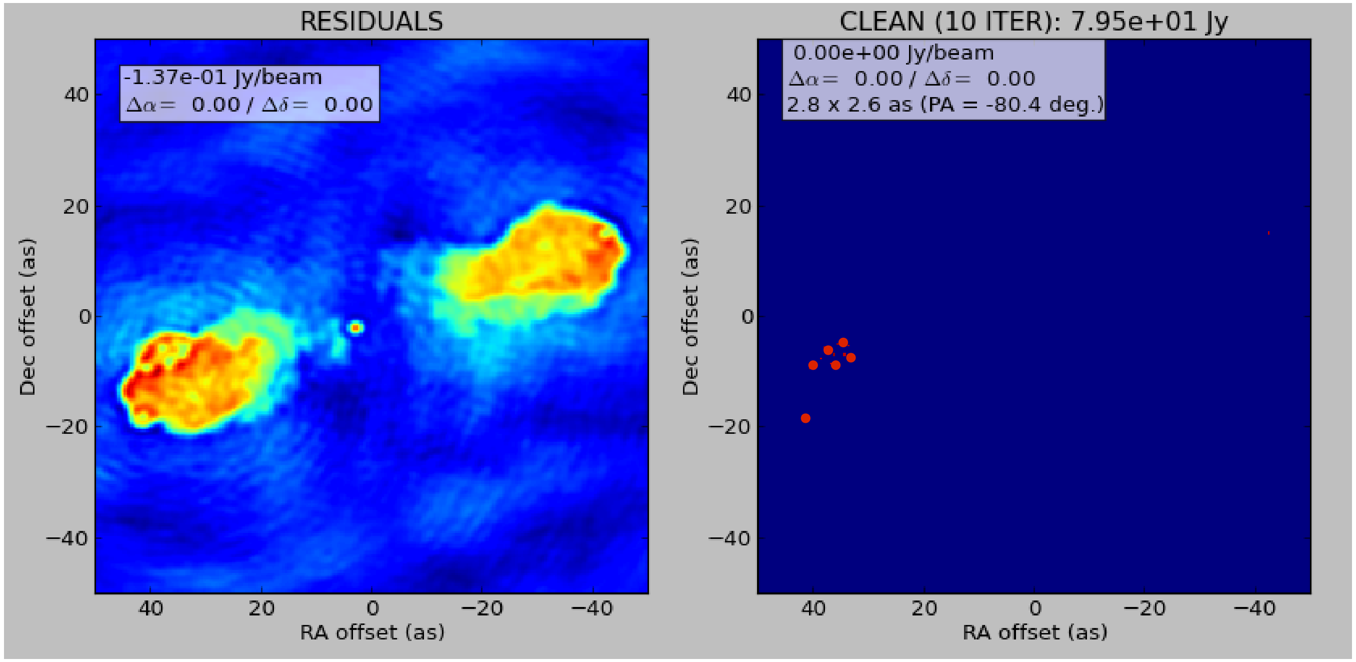
**typically**
$\boldsymbol{\gamma \sim 0.1 - 0.3}$

## 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

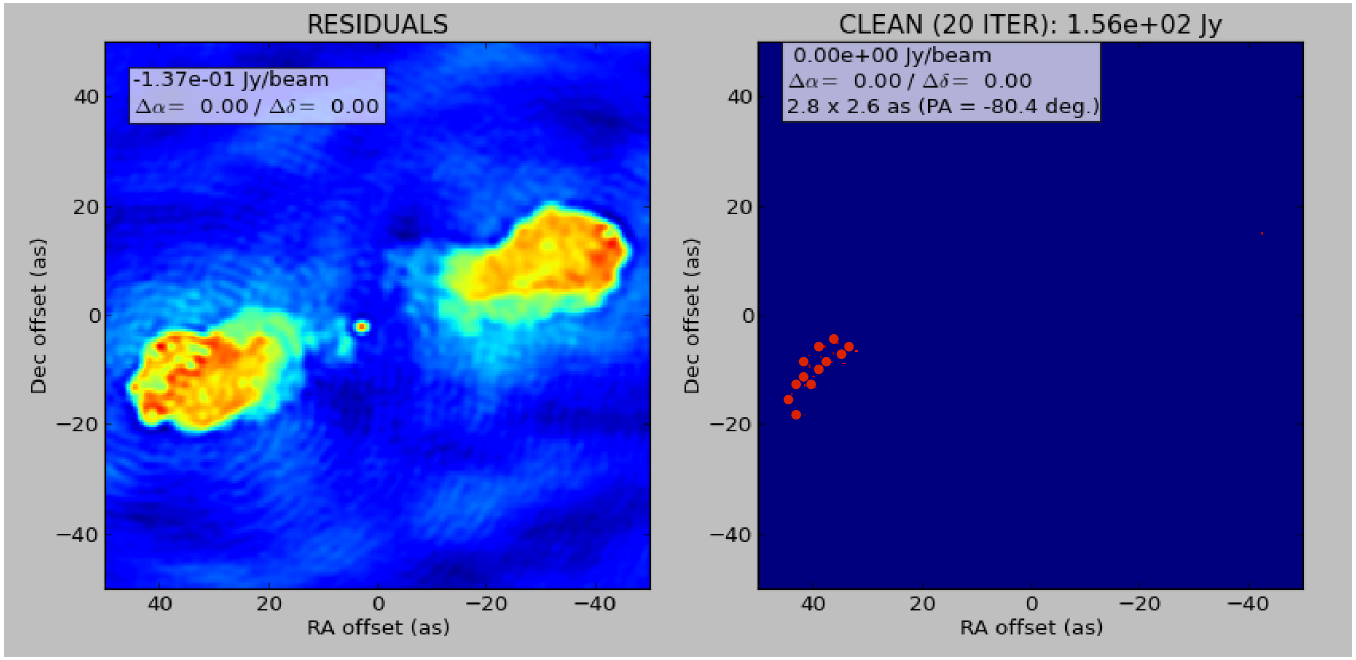


## Deconvolution - Classic CLEAN

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)

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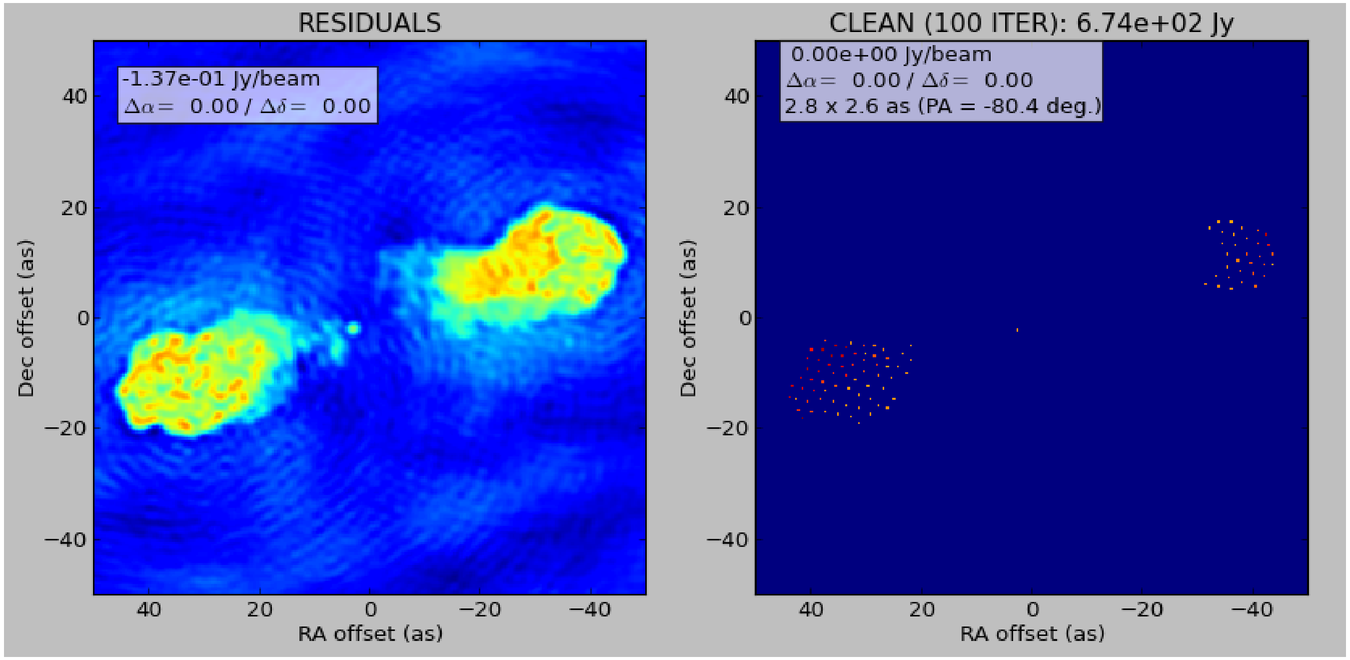


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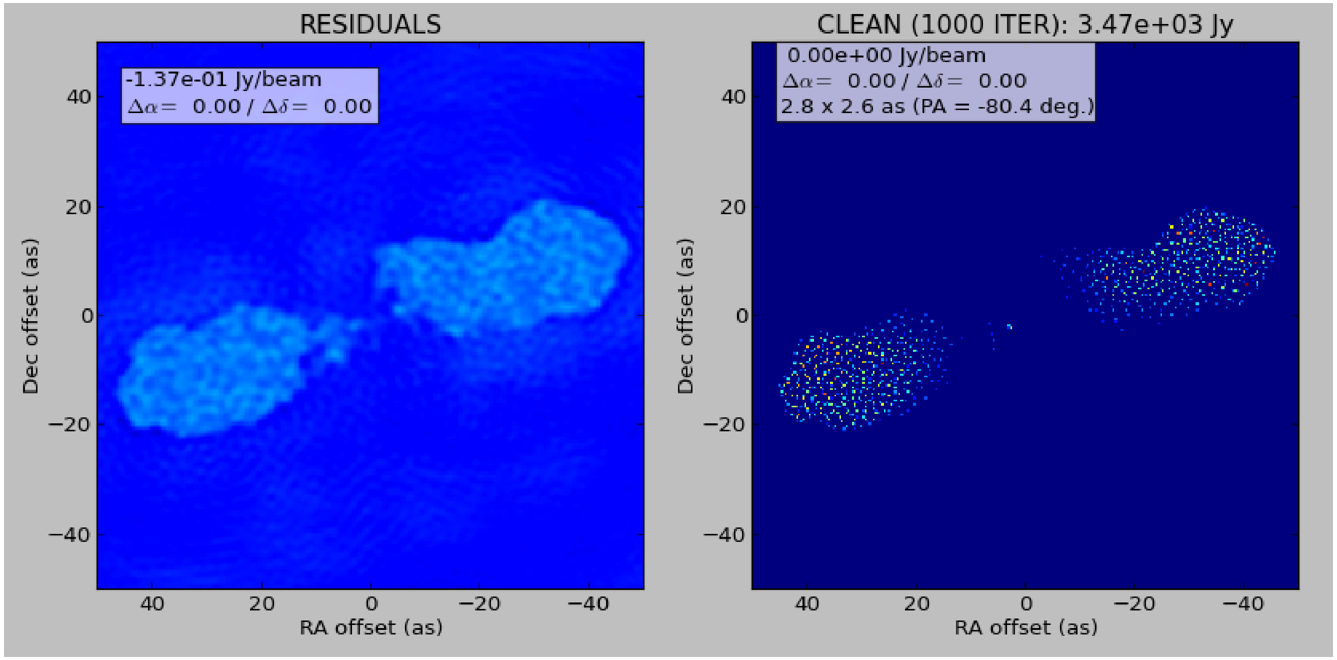


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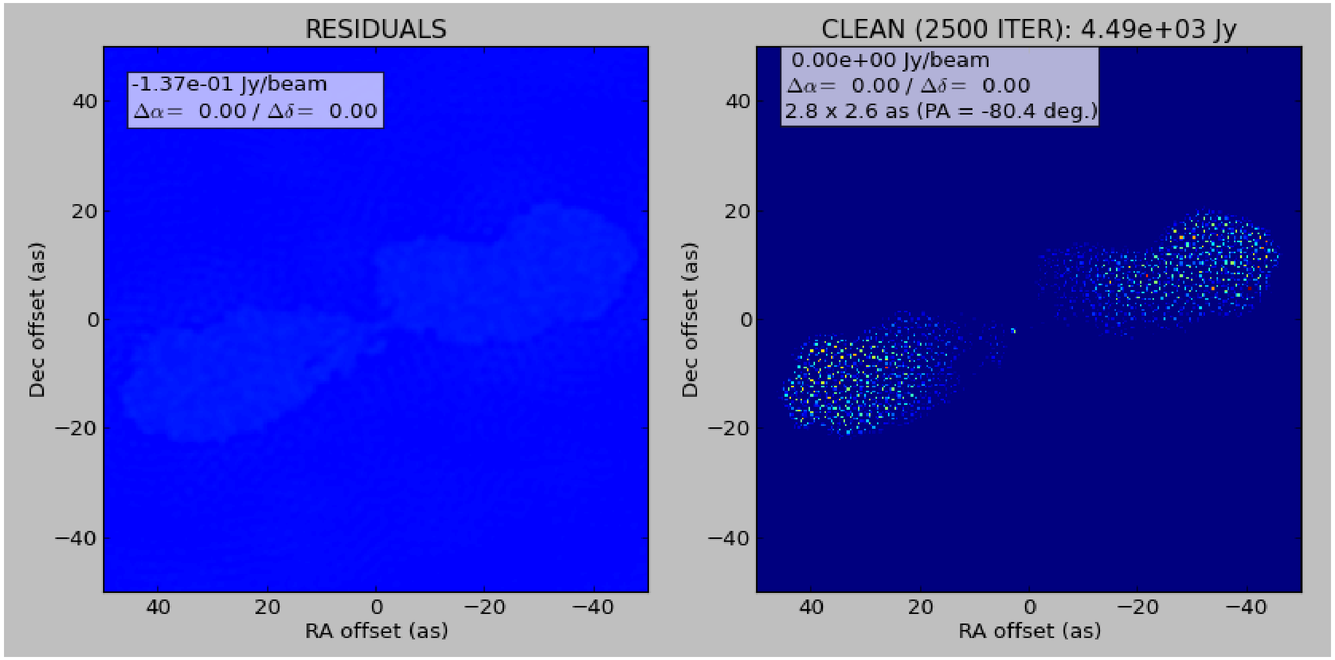


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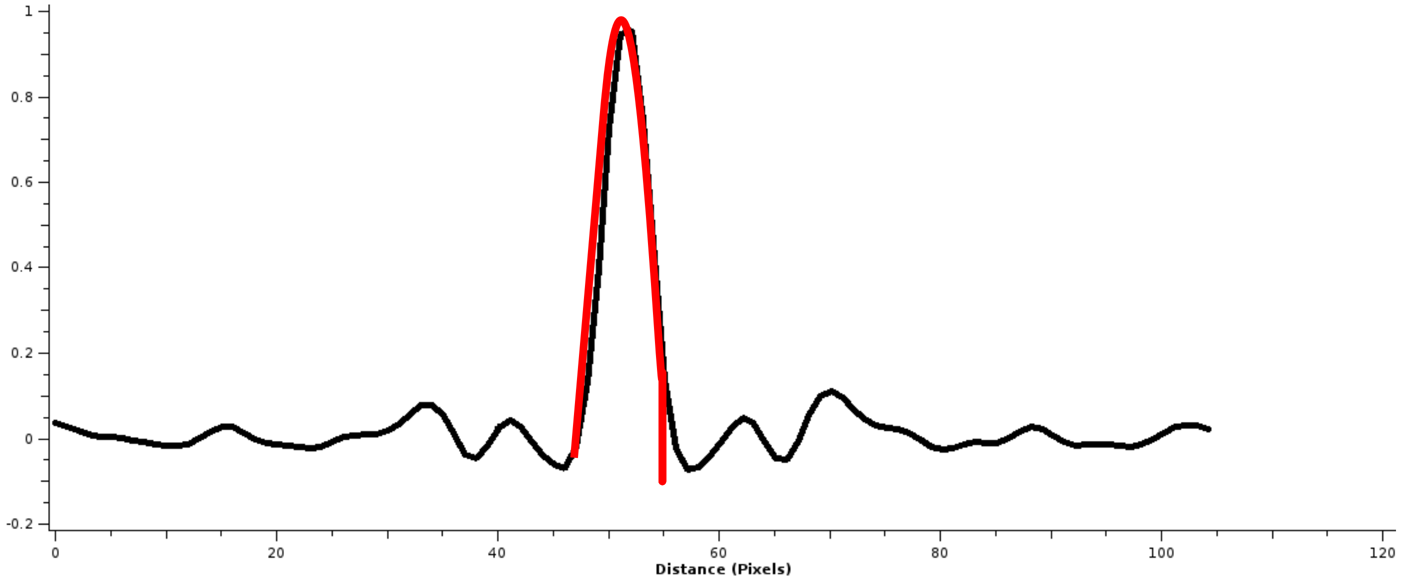
$|I_{max}|$ < fraction of the brightest source flux (when dynamic range limited)

**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**

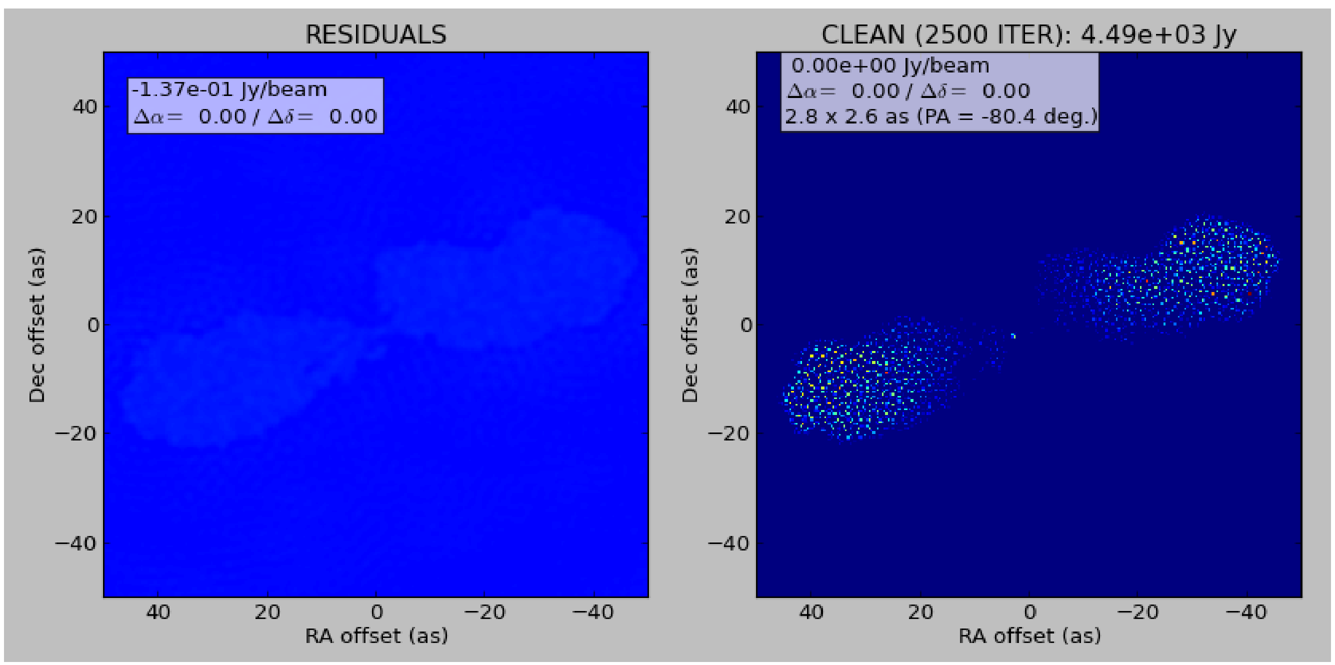


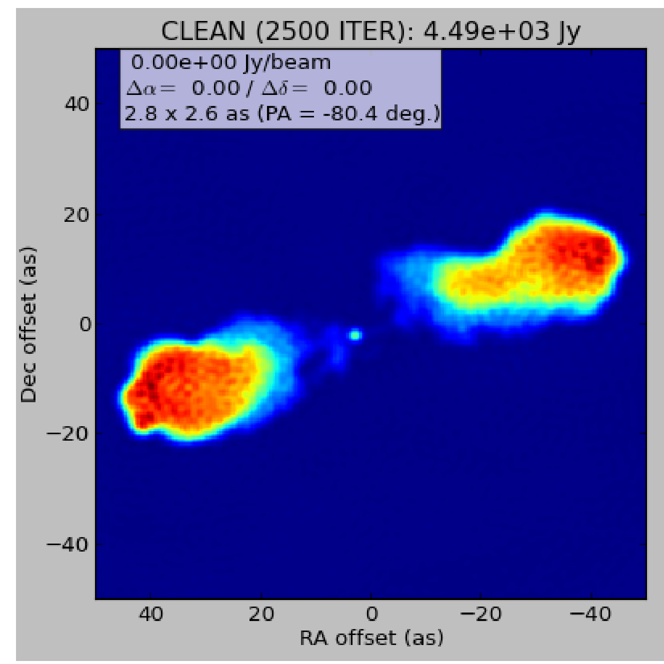
## Deconvolution - Classic CLEAN

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

**Basic assumption:** each source is a collection of point sources

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



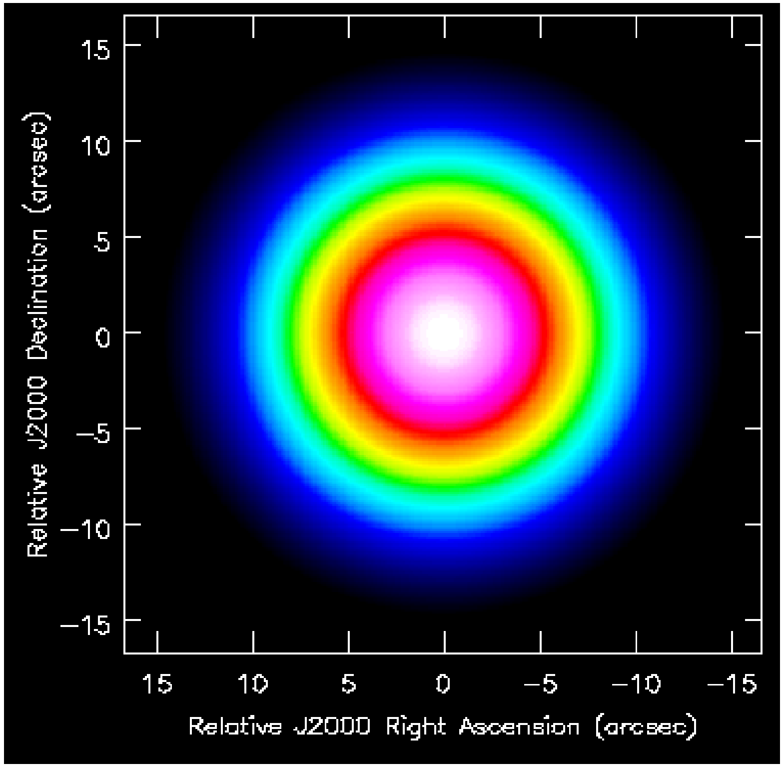

**Resulting image pixel have units of Jy per clean beam**

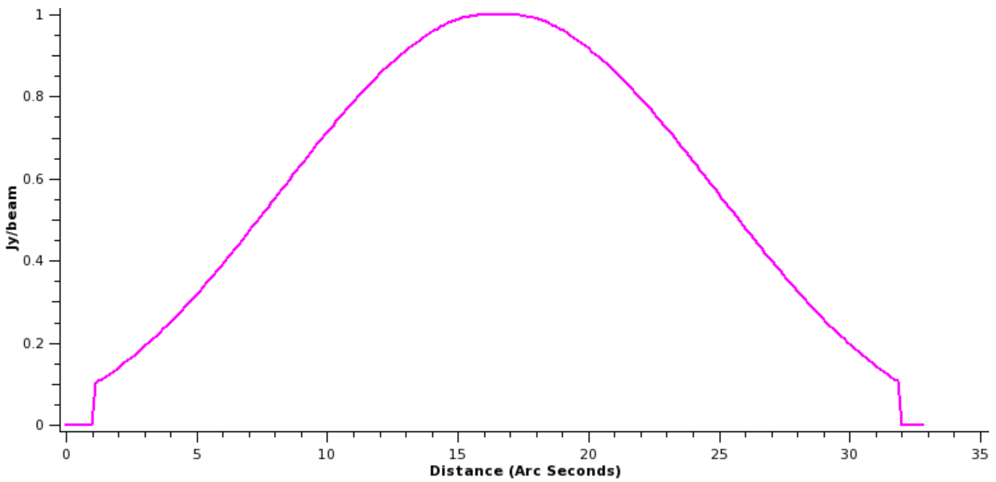
*We need to get* $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

*But*

**Interferometer elements are sensible to direction of arrival of the radiation**

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



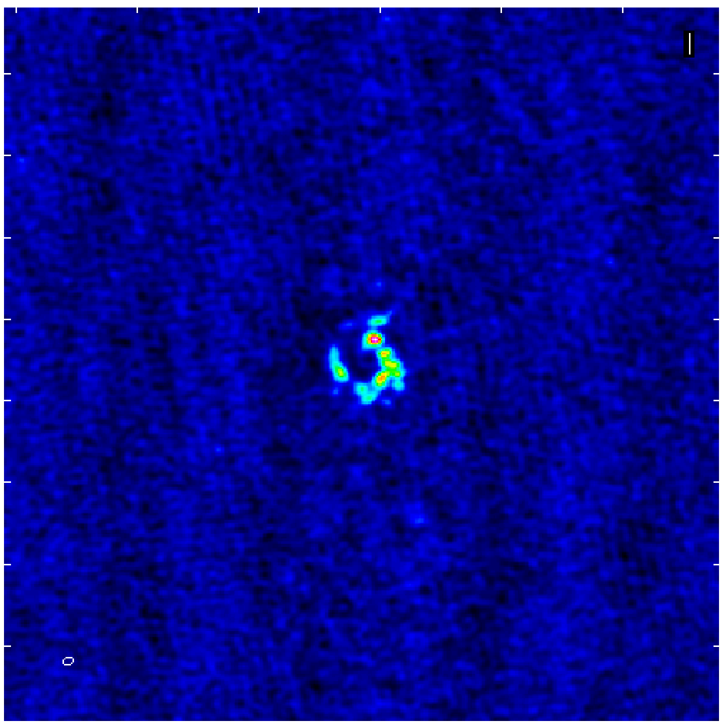

The response of the antennas in the array must be corrected for during imaging to get accurate intensities for source outside the core of the beam.

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

***But***

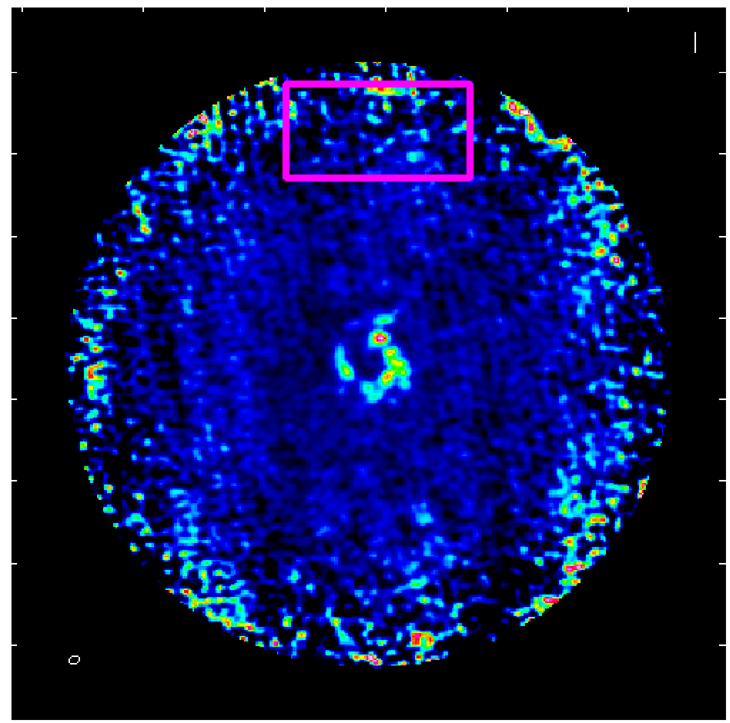
- **Primary beam effect** → $T(x,y) = A(x,y)\, T'(x,y)$

$T(x,y)$



**rms 8e-4**

$T'(x,y)$



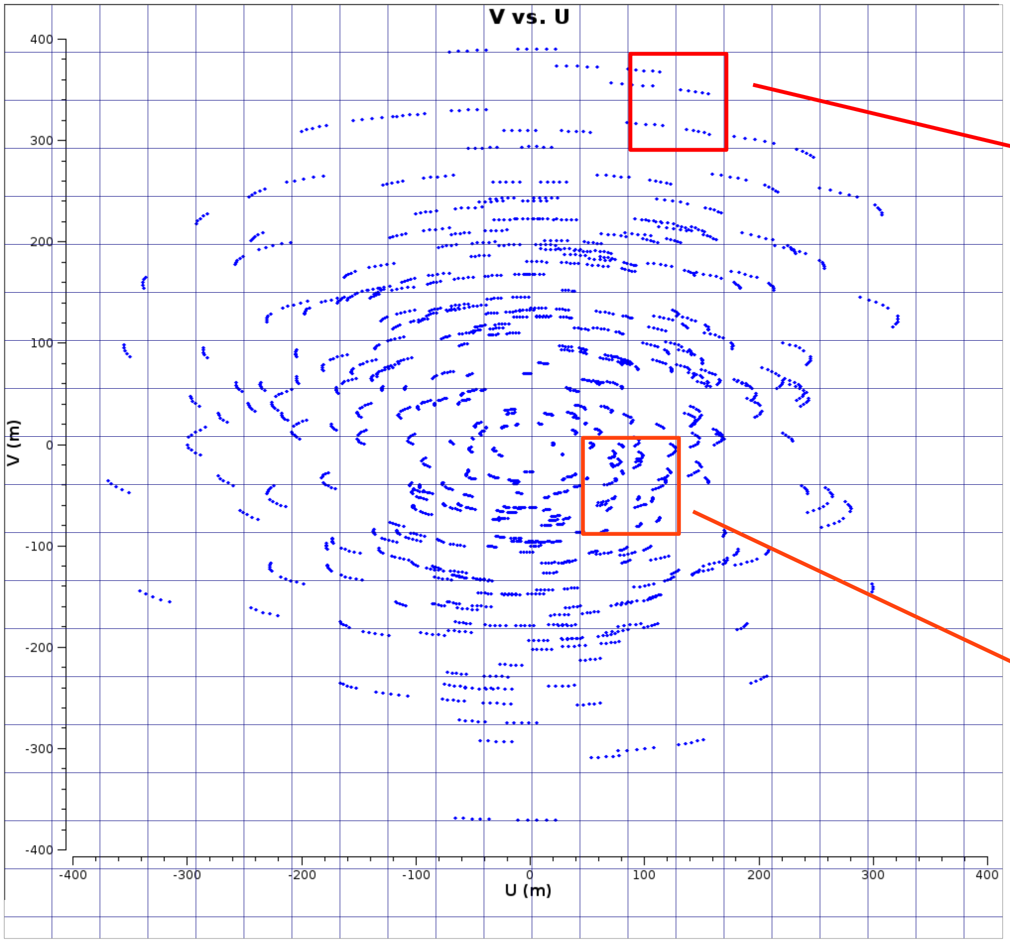
**rms 3e-3**

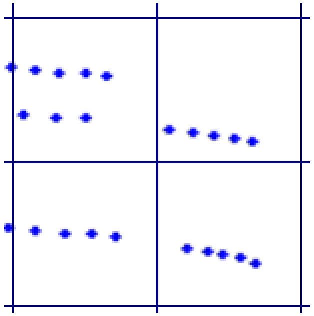
$$\sigma(u,v) \propto \frac{1}{\sqrt{T_{sys1} T_{sys2}}}$$

*But*

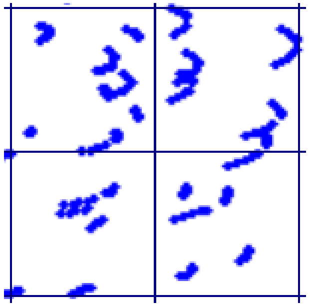
**measured visibilities actually contain noise and some uv ranges are sampled more than others**

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

$\delta_s$ 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

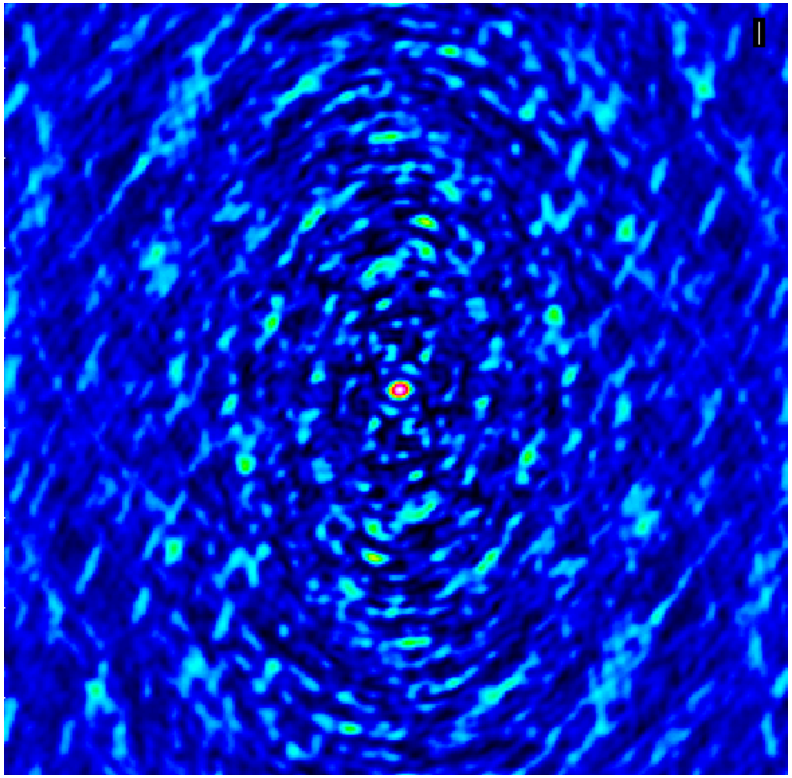
- **Briggs weighting**

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

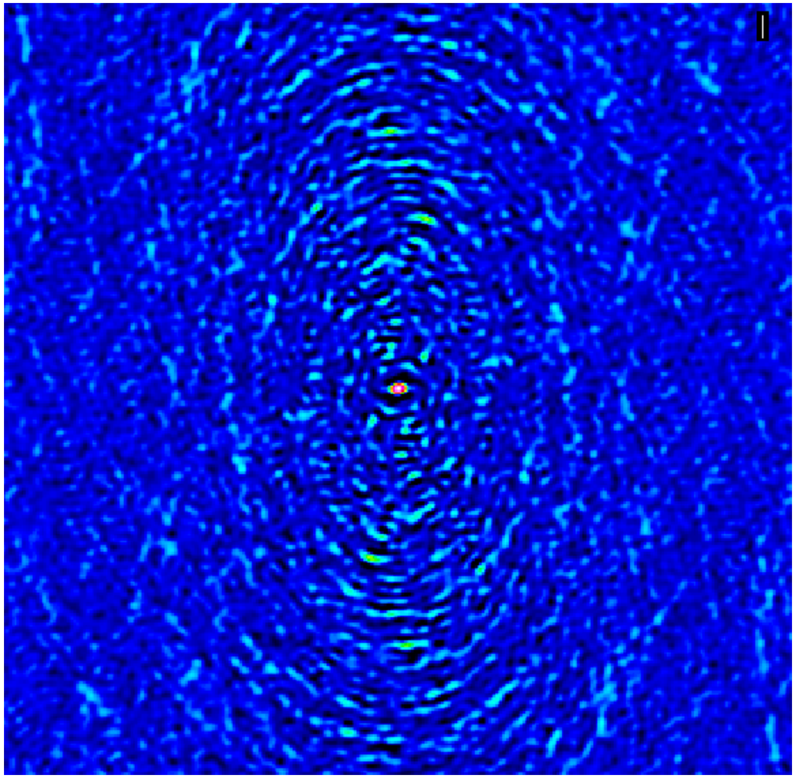
*We need to get* $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

## Weighting effects on the Dirty beam

**Natural**
0.29" x 0.23"
Best sensitivity



**Uniform**
0.24"x0.17"
Best angular resolution

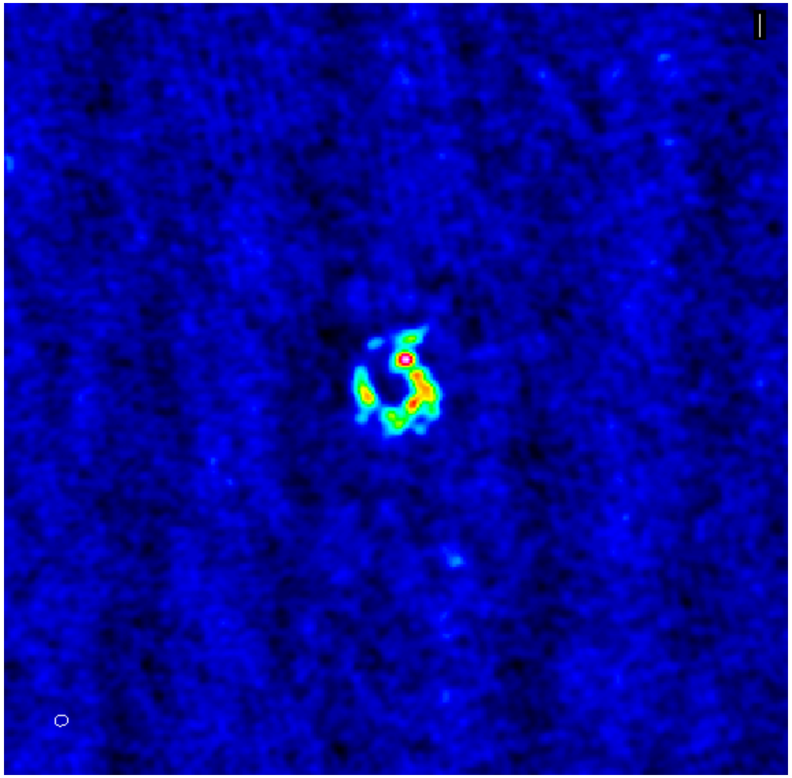


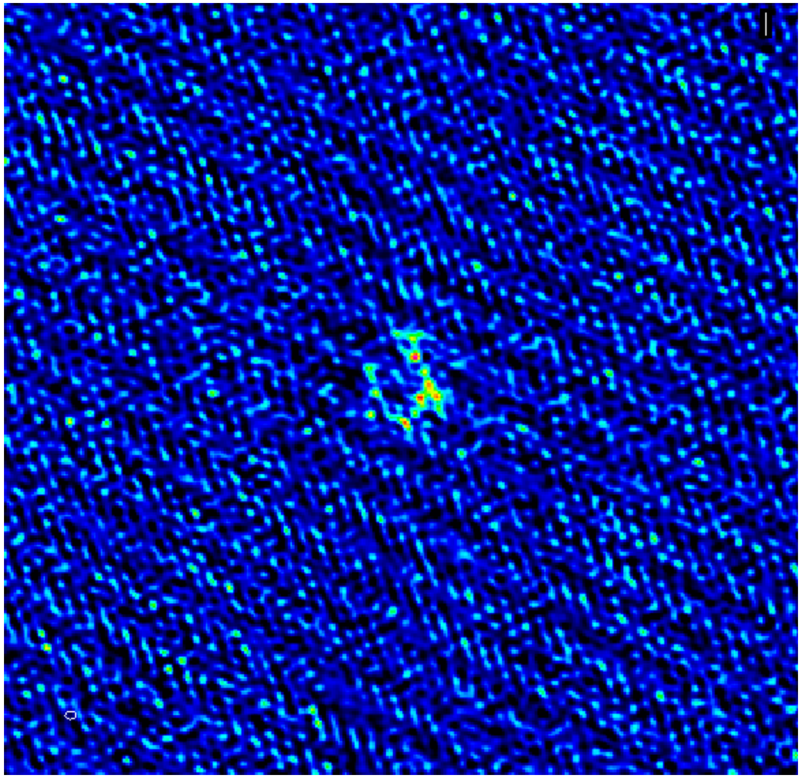
*We need to get* $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

## Weighting effects on the image

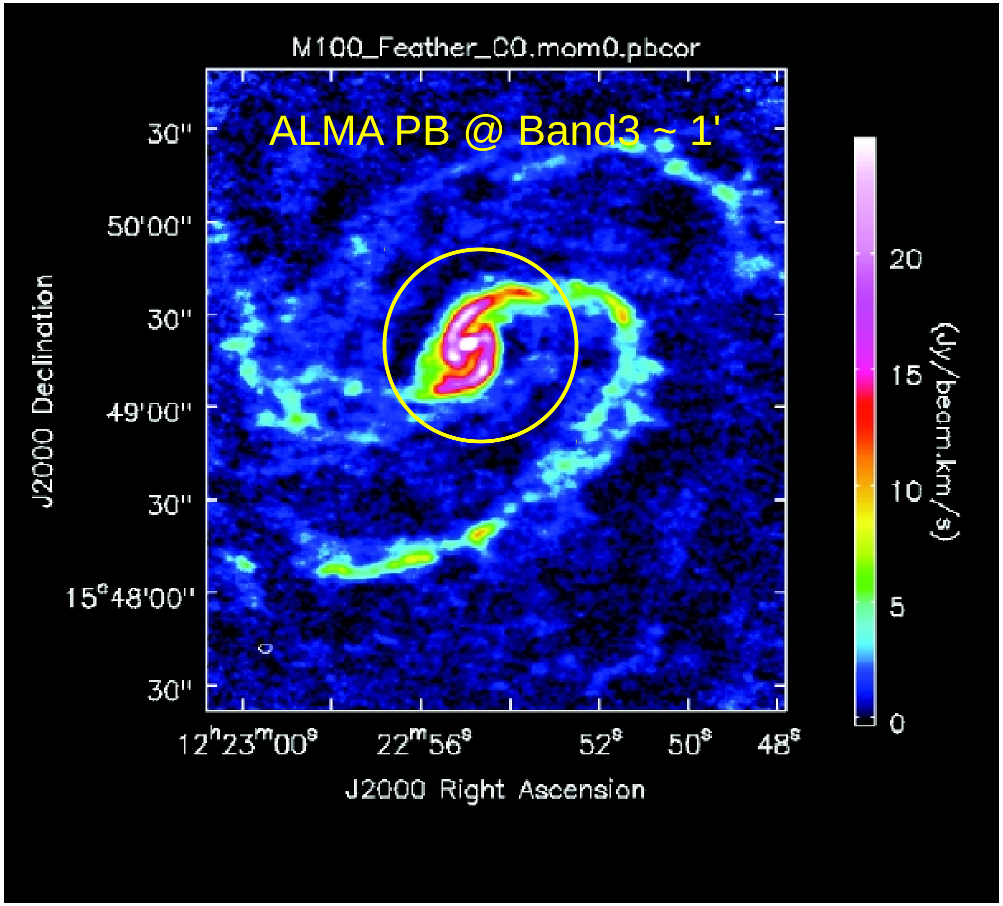
**Natural**
res = 0.29" x 0.23"
rms = 0.8 mJy/beam

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



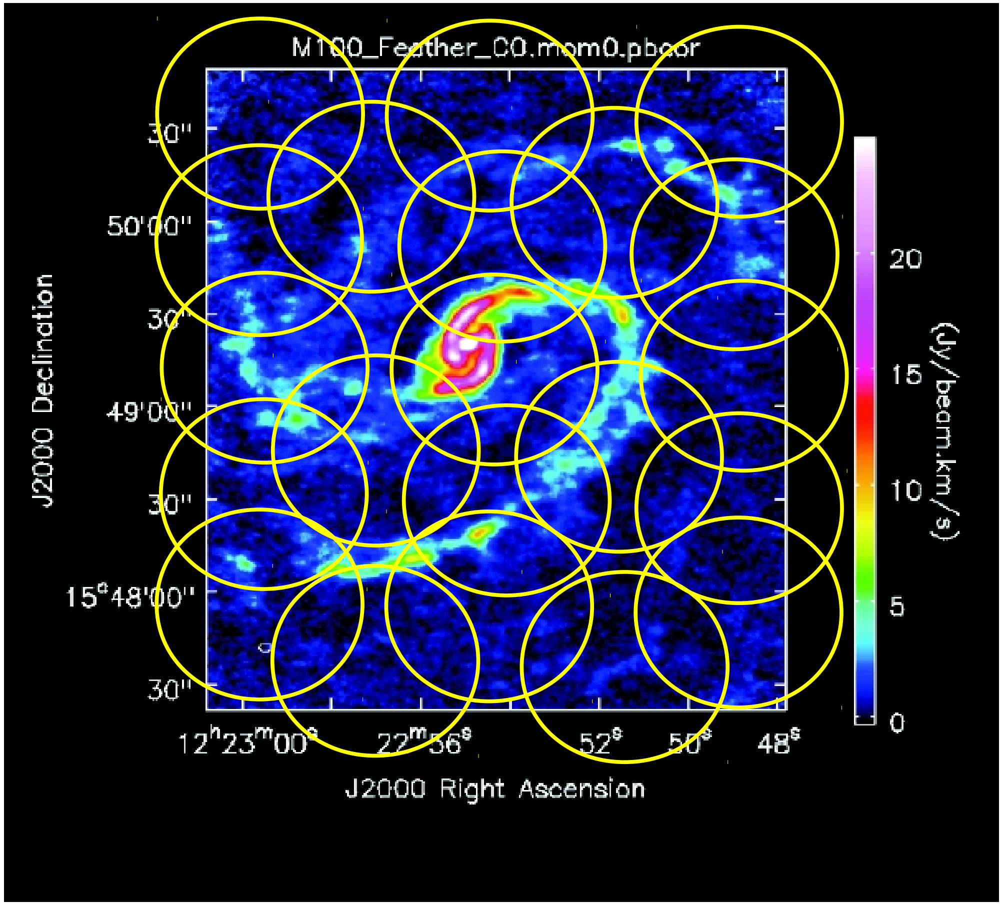


# If the region of interest is larger than the primary beam



**If the region of interest is larger than the primary beam**

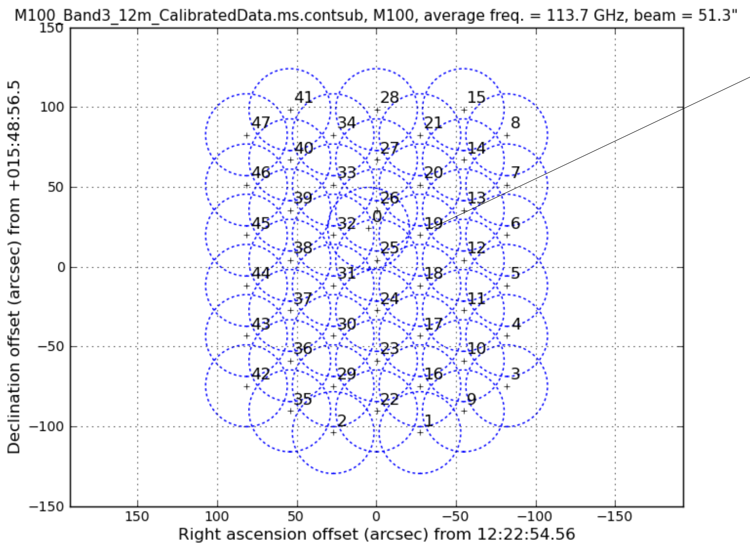
need to mosaic many interferometric pointings

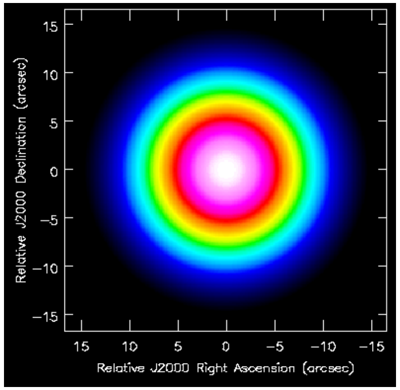


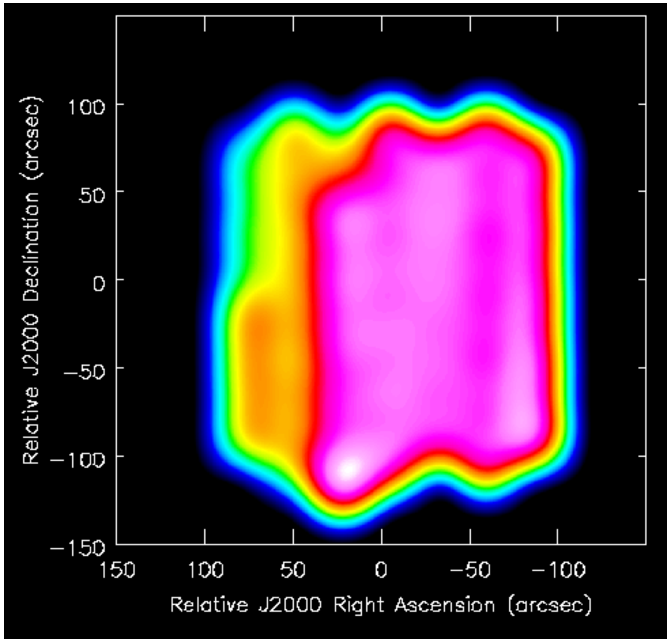

Clean is basically the same →
**need to specify the central pointing** (phasecenter)
**the image size = full mosaic area**
**and the mode 'mosaic'** (imagermode and ftmachine)

# 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

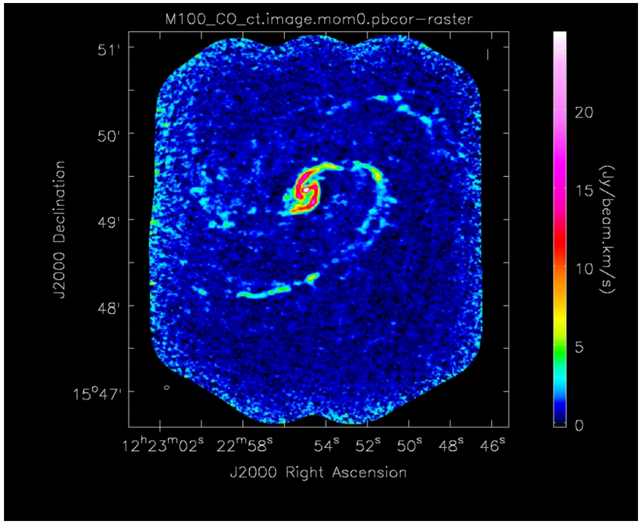



Image with 12 m data

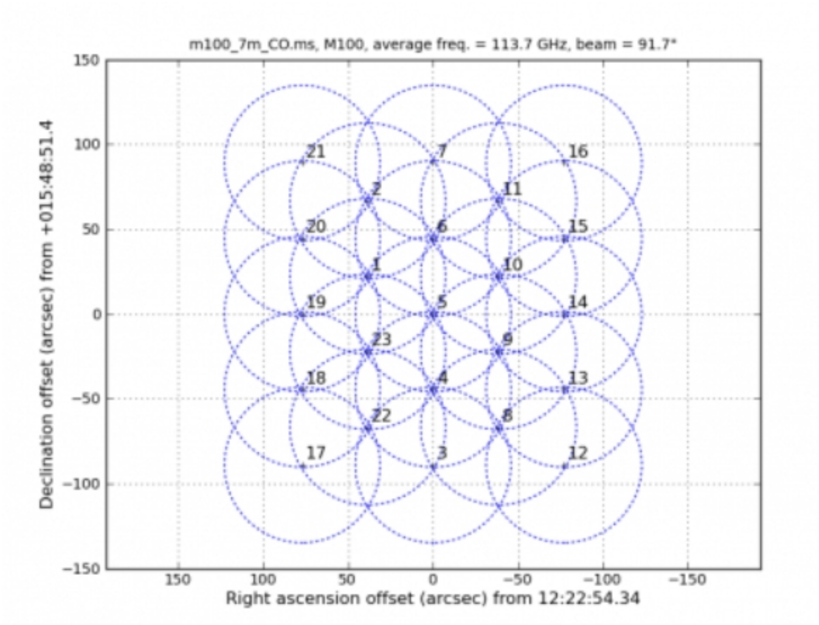
**The largest structures >** $\theta_{MRS} \approx \frac{\lambda}{B_{min}}$

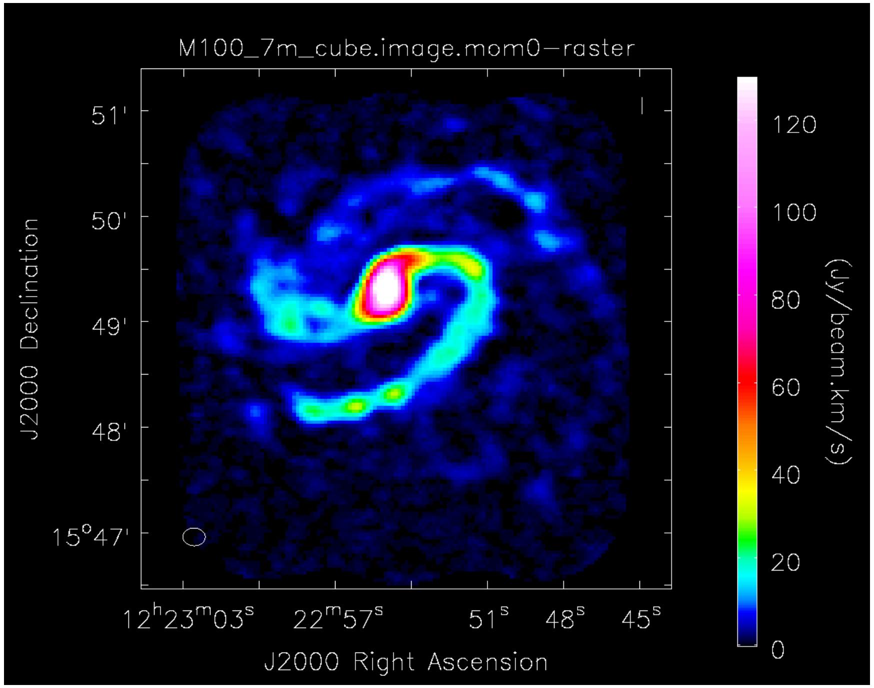
**are not recovered**

→ **need ACA and possibly Total Power**

# M100 example: ACA

23 7m pointings are needed
to cover an area slightly larger than
200” square
ToS 188 min



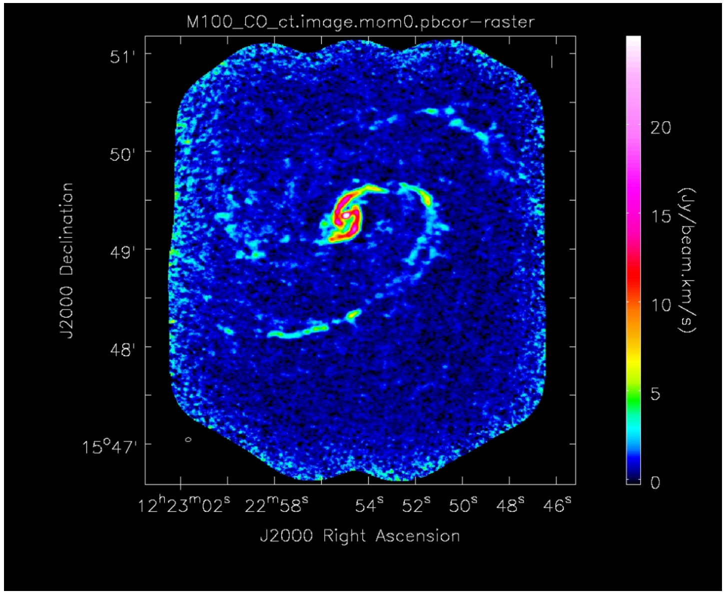



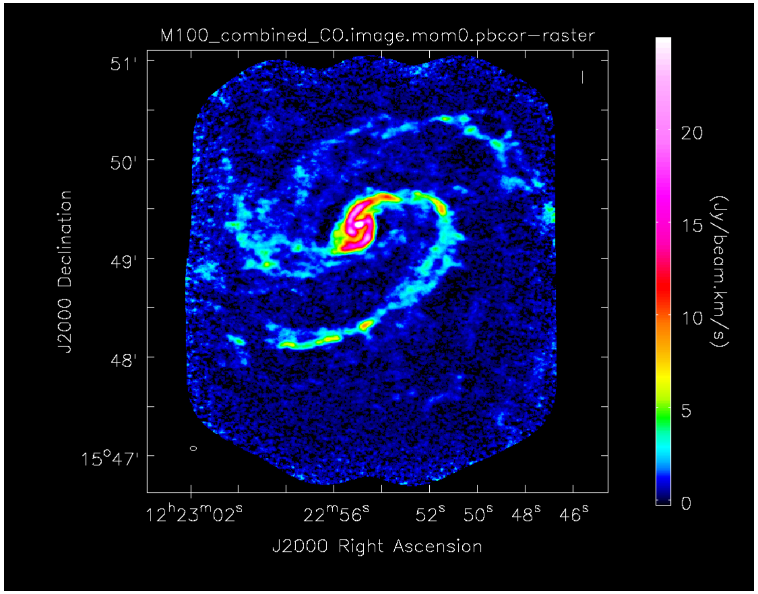

**Moment 0 for 7m data**

**12m and 7 m data are combined in the uv plane**

# M100 example: 12 + 7 m

## 12m and 7 m data are combined in the uv plane



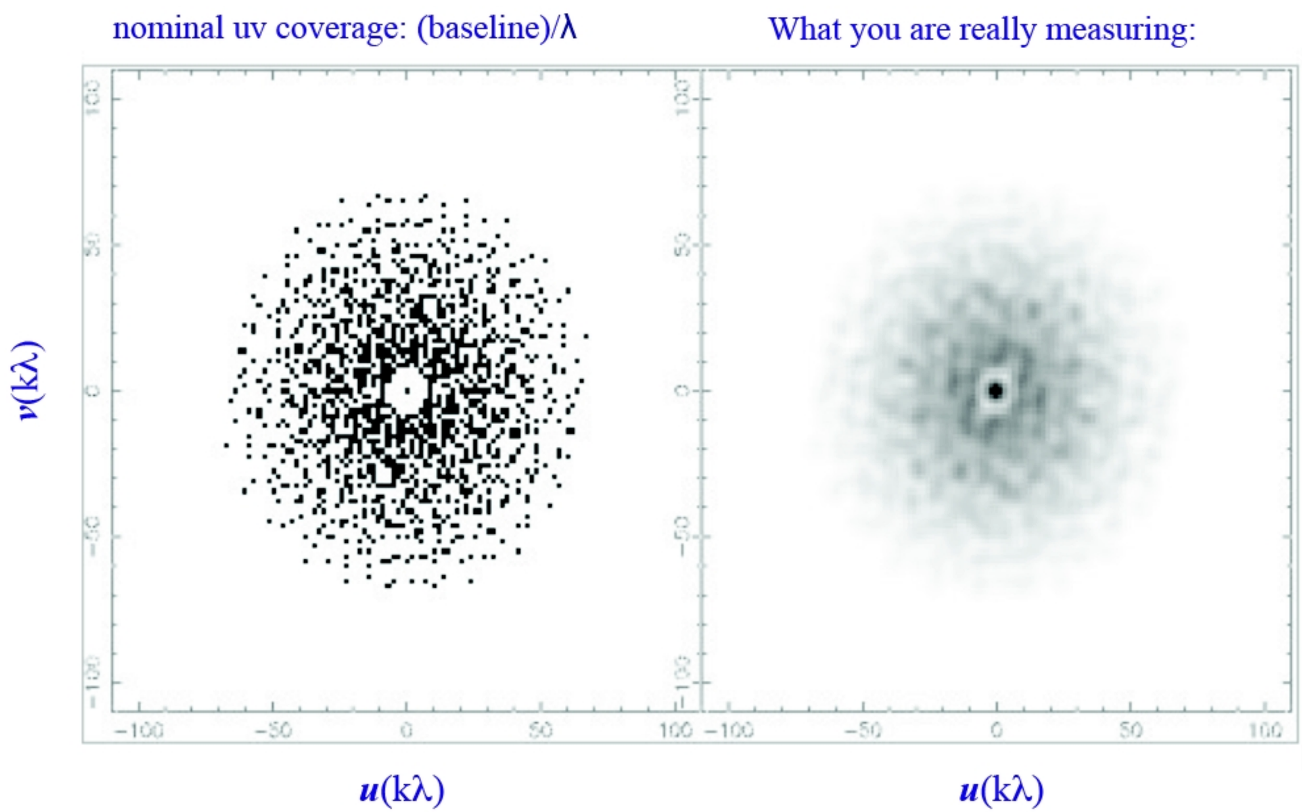

**12m only**

**12 + 7m data**

**If the region of interest is much larger than the**

$$\theta_{LAS} = \frac{1}{2}\frac{\lambda}{B_{min}} \leq \frac{\lambda}{2D}$$

need to image with smaller dishes **and add single dish to recover the total flux (baseline zero)**

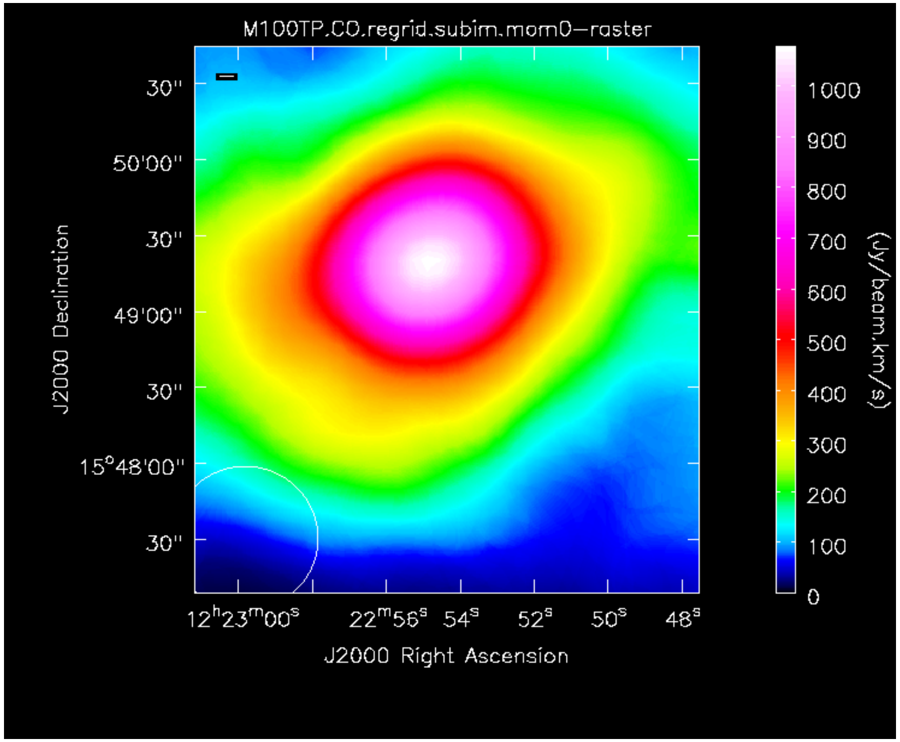



There is still a hole between (0,0) and $B_{min}$

To maximize flux recovery and image quality, it would be needed a single dish of **$D > 1.5 \times B_{min}$**

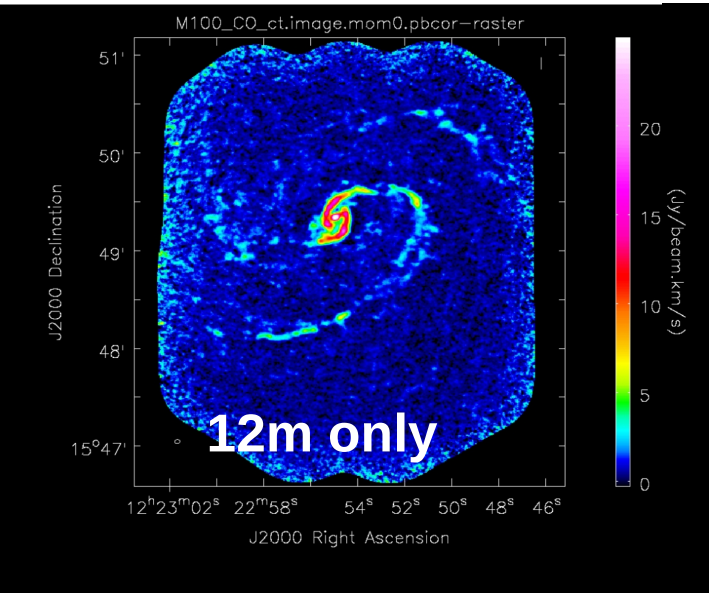
# M100 example: Single dish

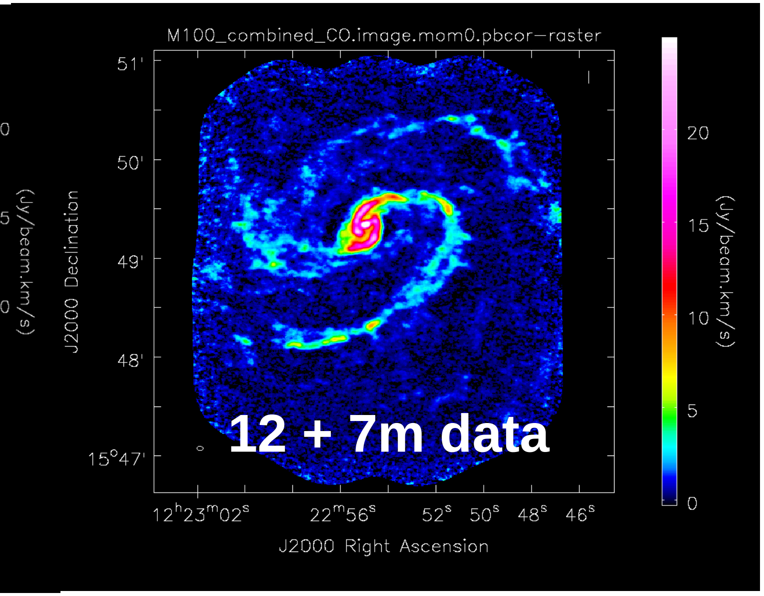
**2 Total power antennas (12 m)**
~ the same field of view ~200” squared covered with on the fly mapping
ToS 172 min




**Moment 0 for SD observaton**

# M100 example: mom0 comparison

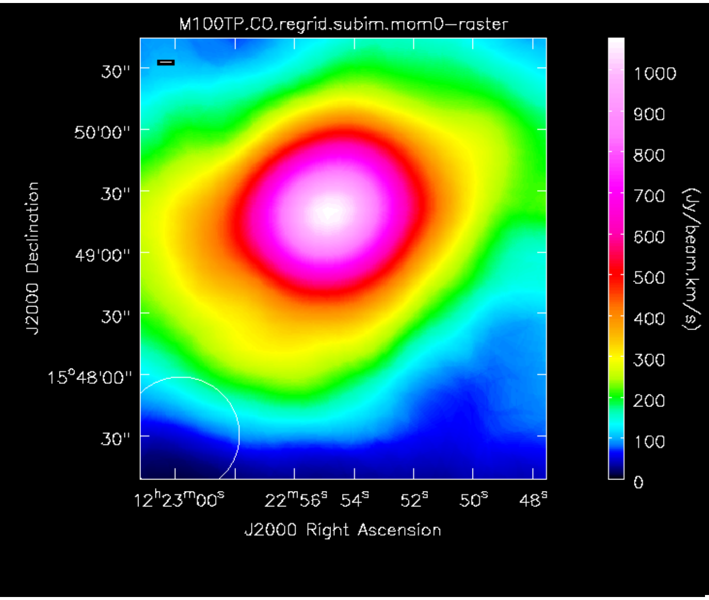


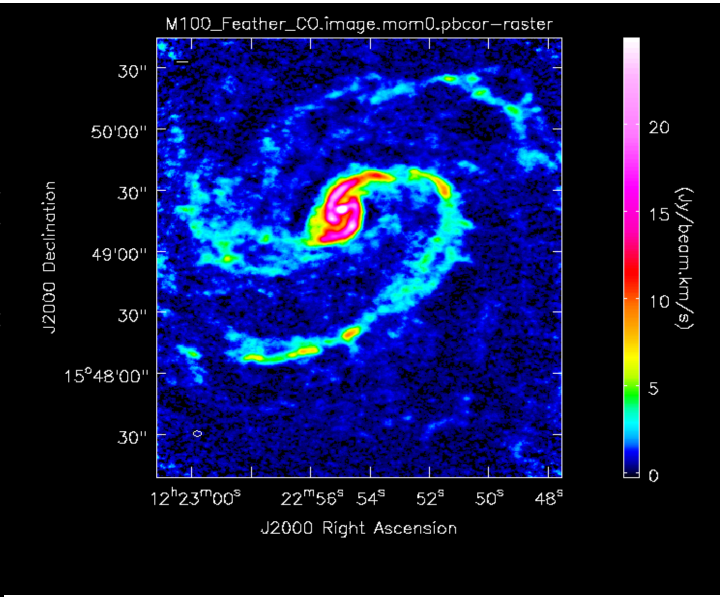




Comparison

Total flux

- **12+7 m = 1418 Jy km/s**
- **TP = 2776 Jy km/s**
- **Combined image = 2776 Jy km/s**




**The combination preserves the flux of the TP data**

**SD only**

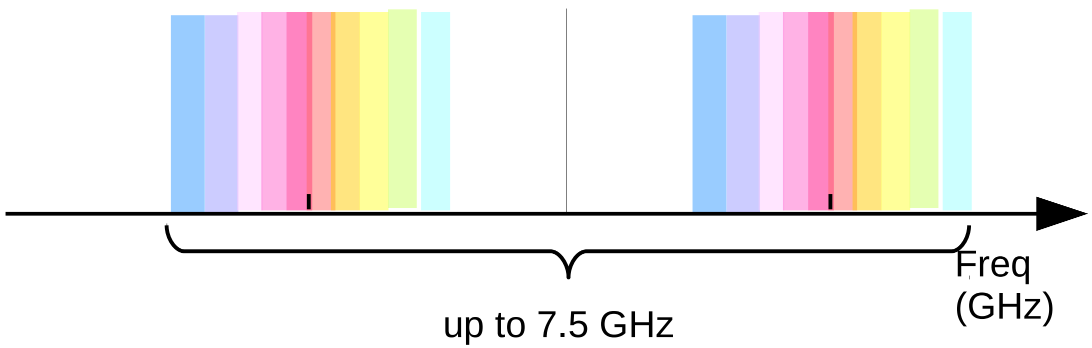
**SD + 12 + 7m**

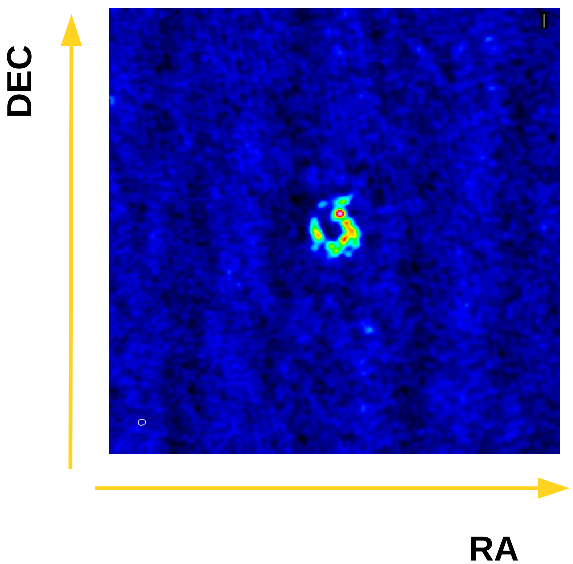
**https://casaguides.nrao.edu/index.php?title=M100_Band3**

## Continuum images

- **Multi-Frequency synthesis (MFS)**
- Wide bandwidths allow higher sensitivity to continuum emission

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




MFS
combines all channels

the result is a single image

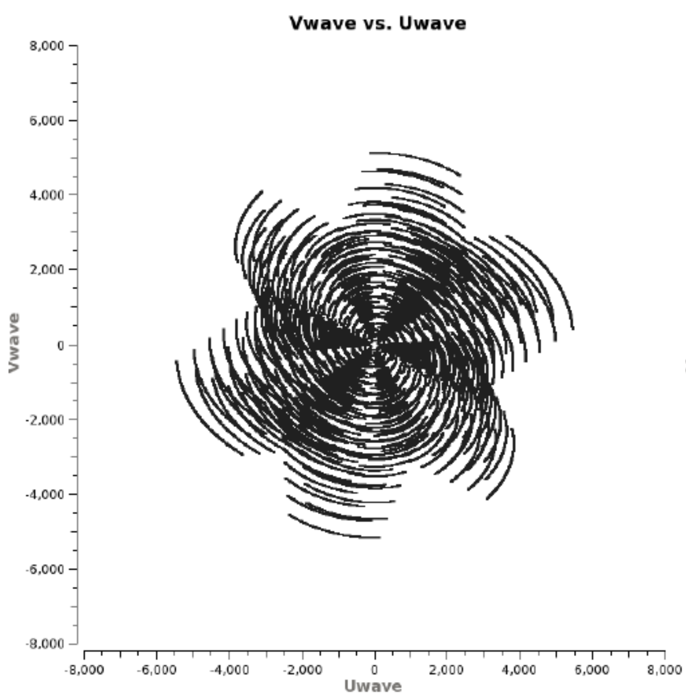
## Continuum images

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

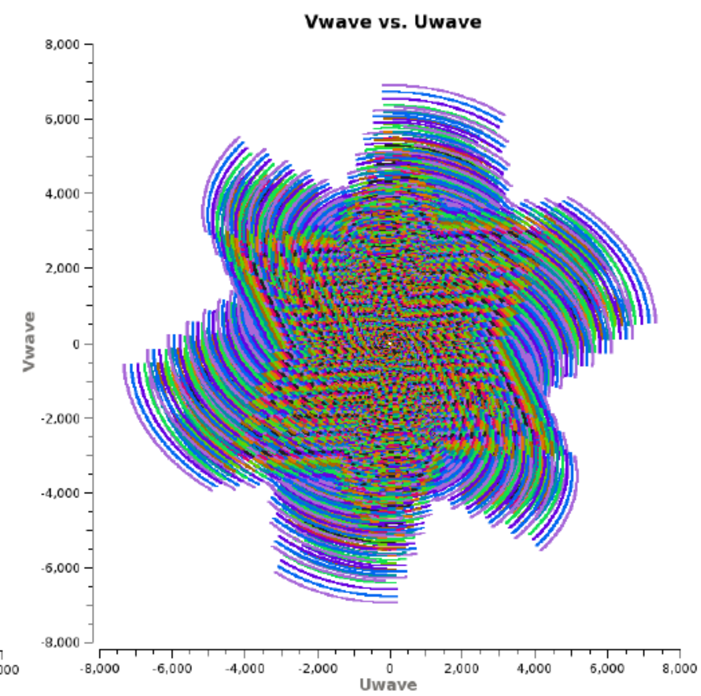
- Wide bandwidths allow higher sensitivity to continuum emission but also **uv coverage is improved**

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

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



1.5 GHz

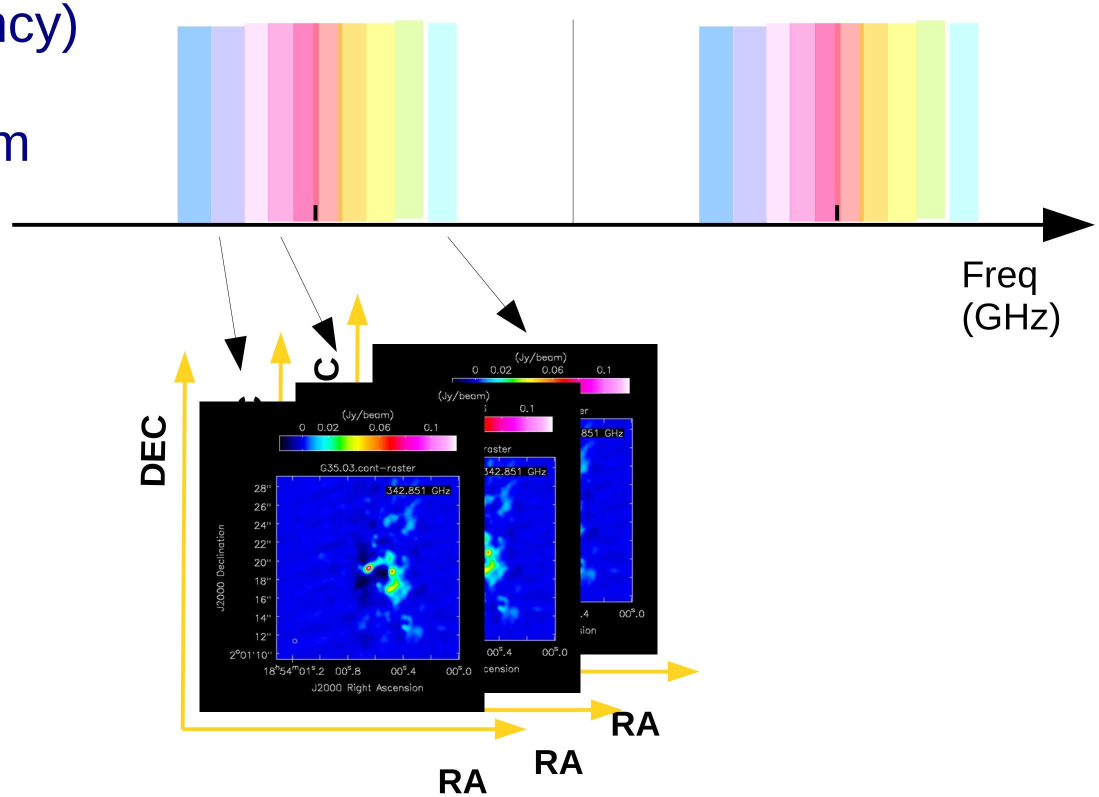


1 – 2 GHz

## Spectral line observations

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

- 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



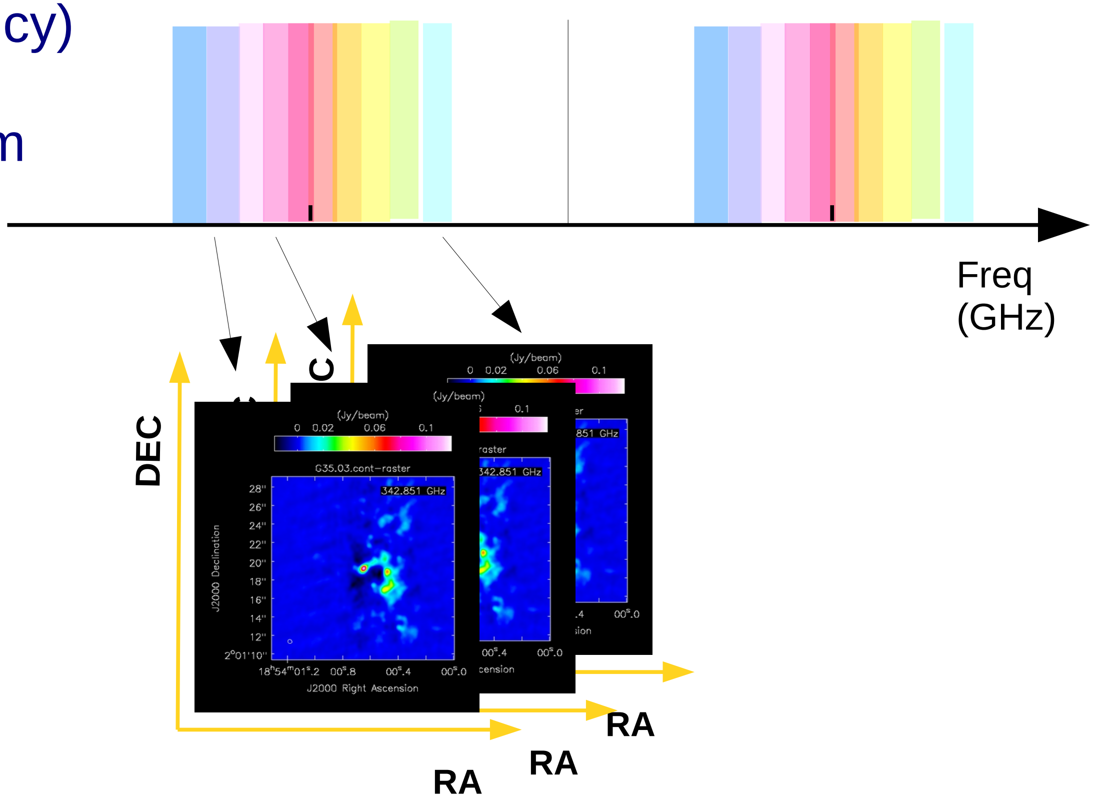
# Spectral line observations

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

- 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)

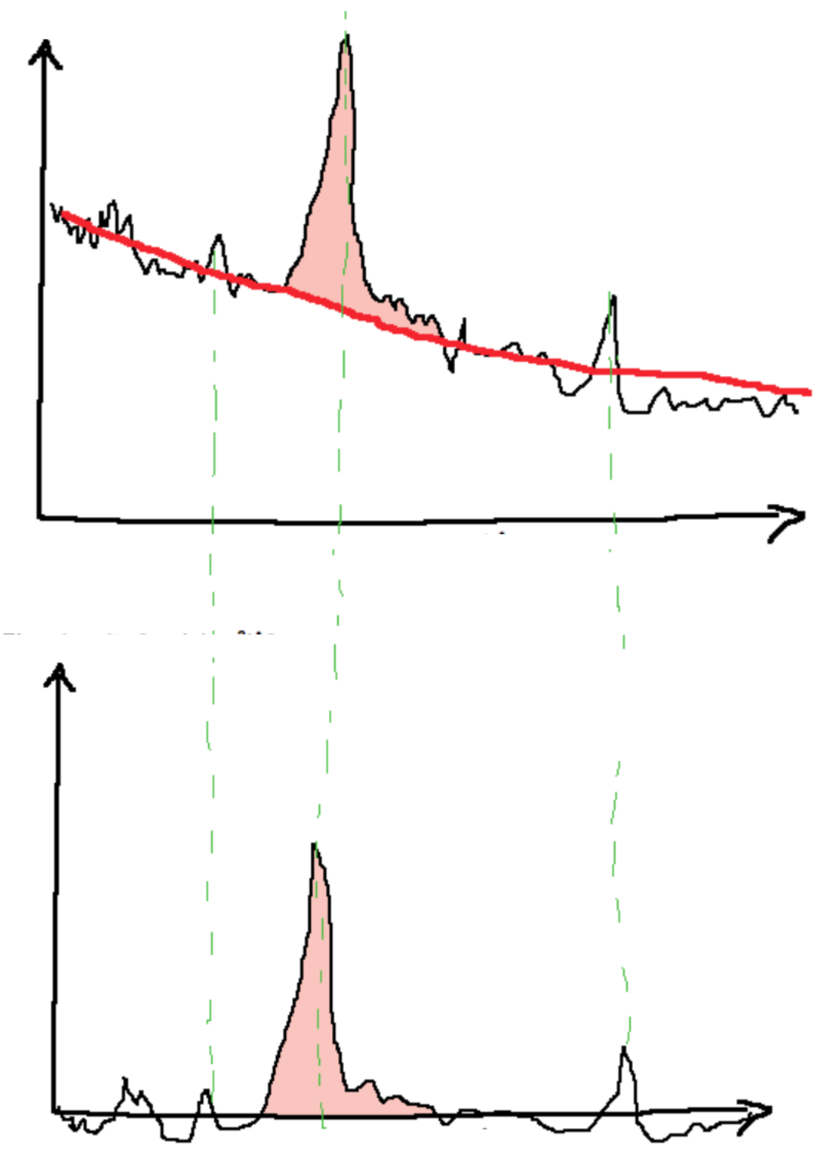
- The rms is larger than for continuum

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



## Spectral line 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)



# 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**