Imaging

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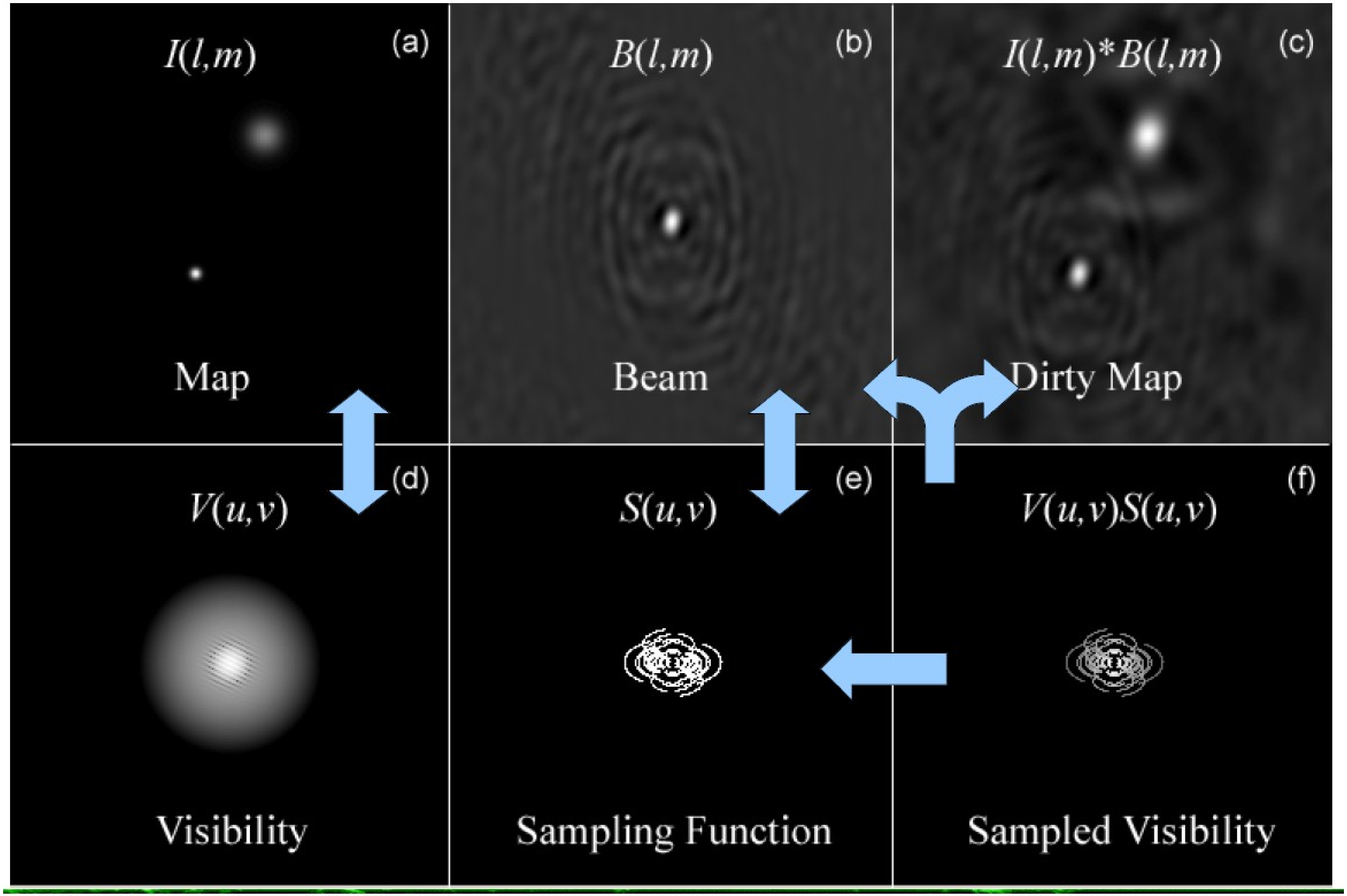
From lectures:



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

$\Downarrow$

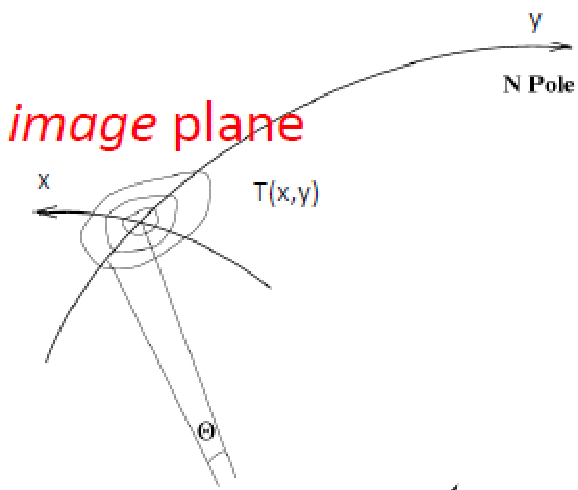
Altre A_i? $\Rightarrow$

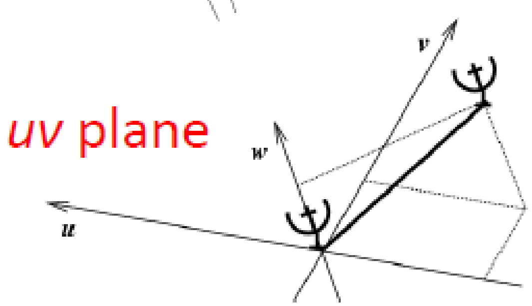
$\Downarrow$

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

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

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

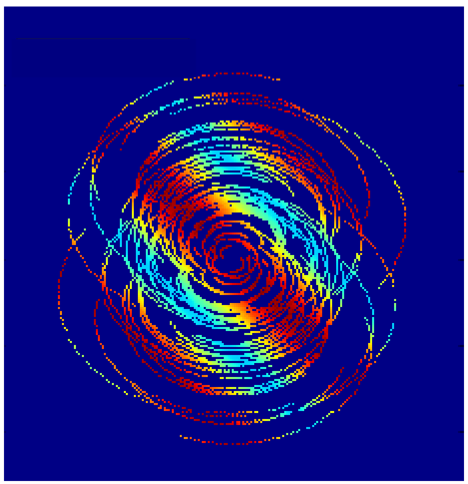
Image space/domain

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

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

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



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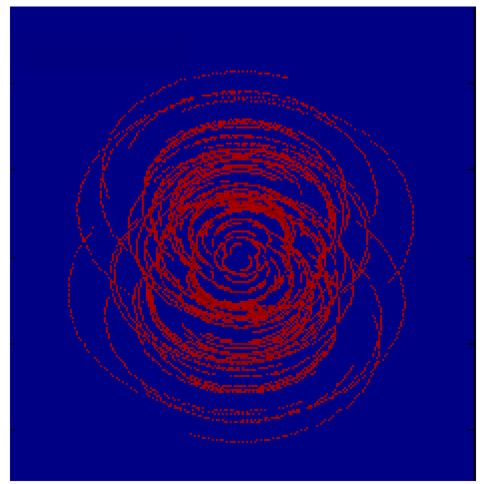

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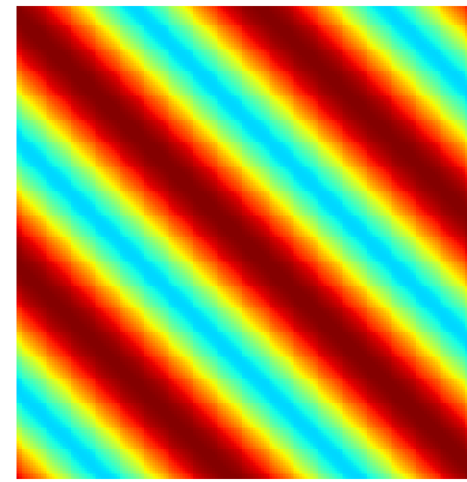


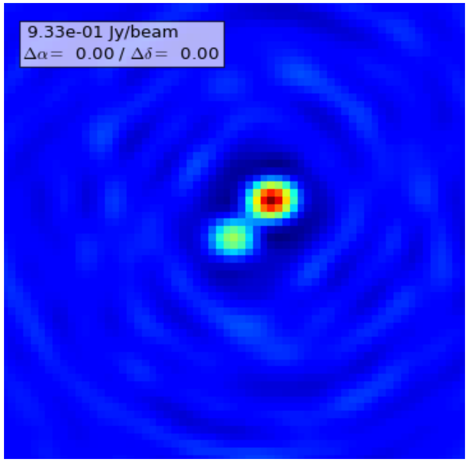
where C(u,v) is the sampling function
C= 1 at points where visibilities are measured
and C = 0 elsewhere

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

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

Applying the convolution theorem:

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



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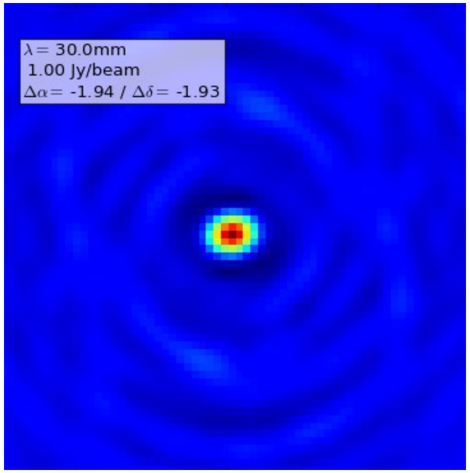

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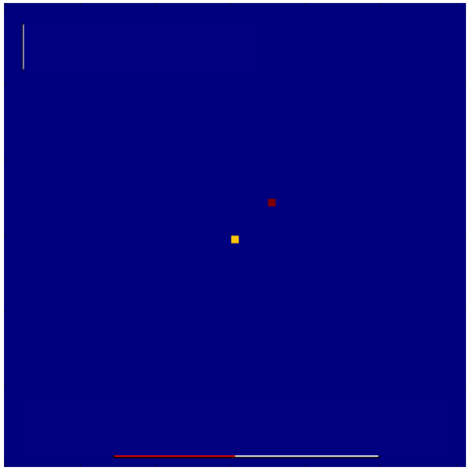


The Fourier transform FT of the sampled visibilities gives the true sky brightness convolved with the Fourier transform of the sampling function (called **dirty beam**).

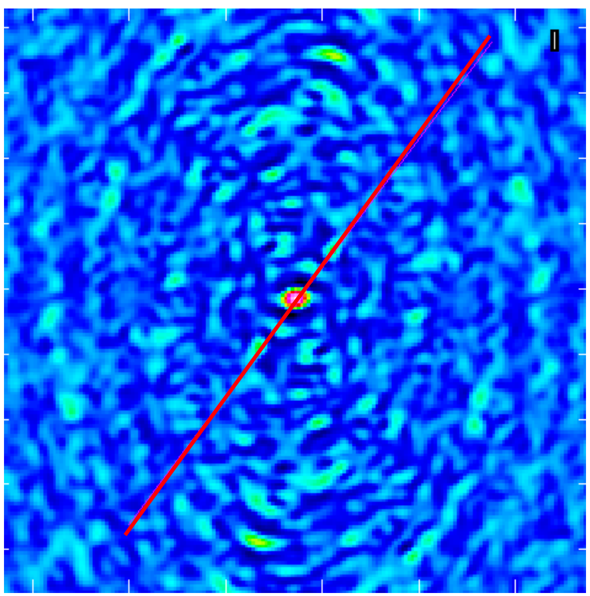
$$I^D(x,y) = B_{dirty}(x,y) \otimes I(x,y)$$

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

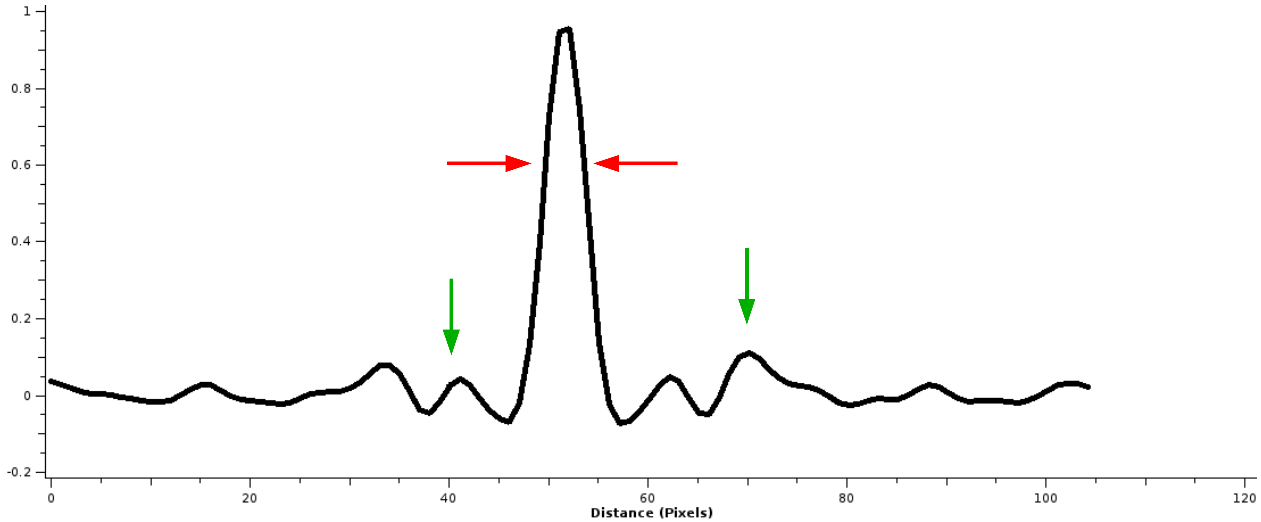
Imperfect reconstruction of the sky

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

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

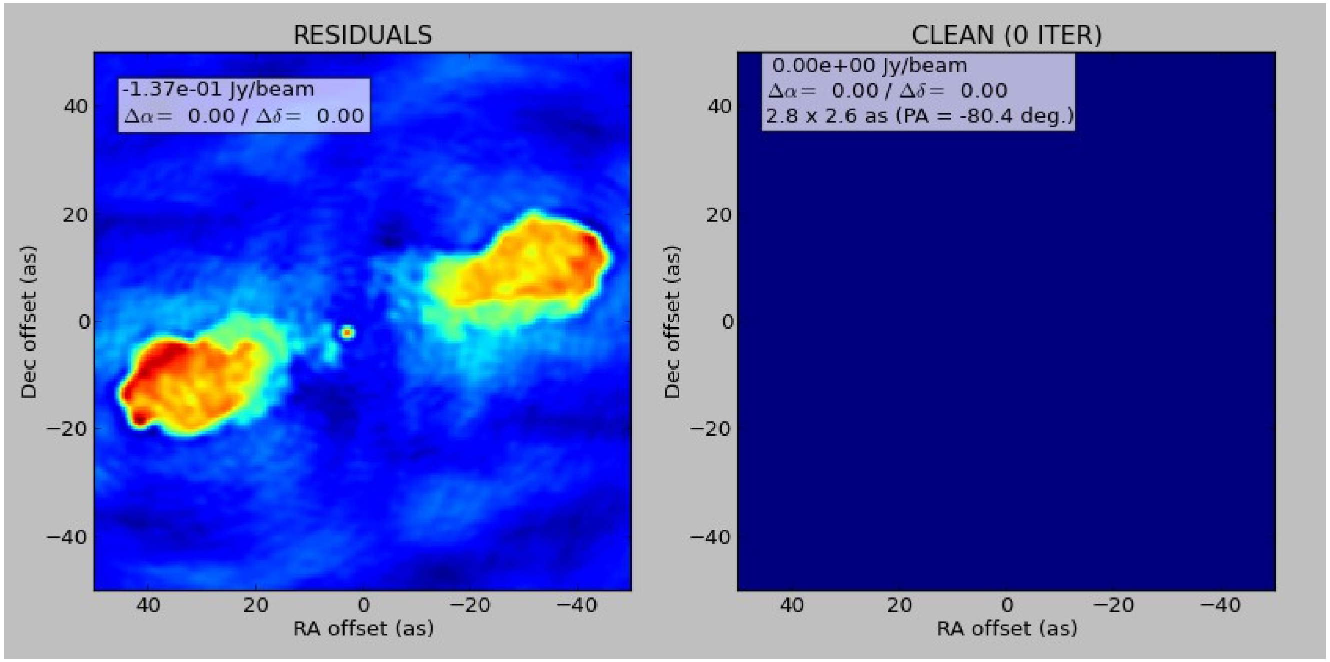
Larger if there are bright sources in the sidelobes of the primary beam (they would be aliased in the image)

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

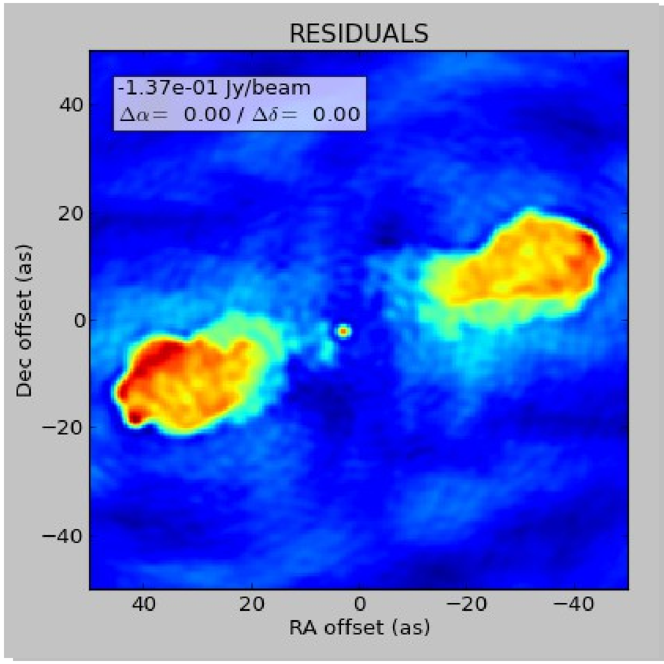


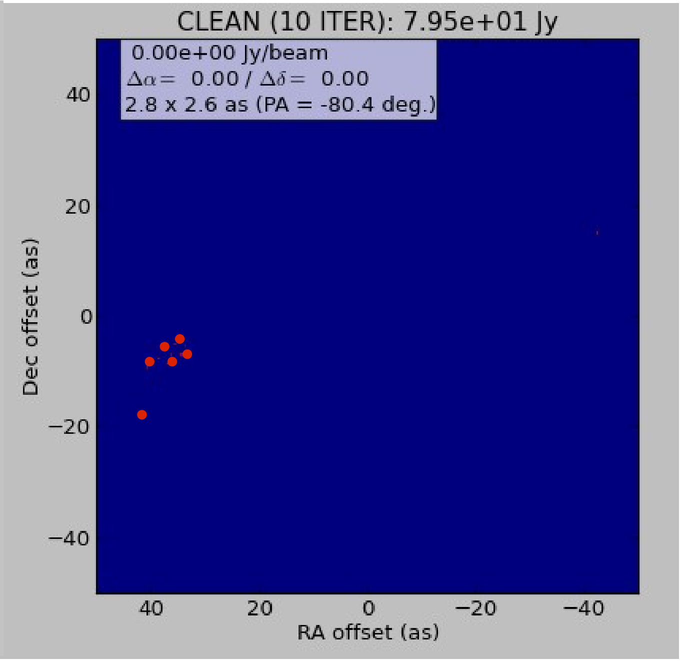
Deconvolution - Classic CLEAN

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 $I_{max} = \gamma\, \mathbf{I_{max}}$





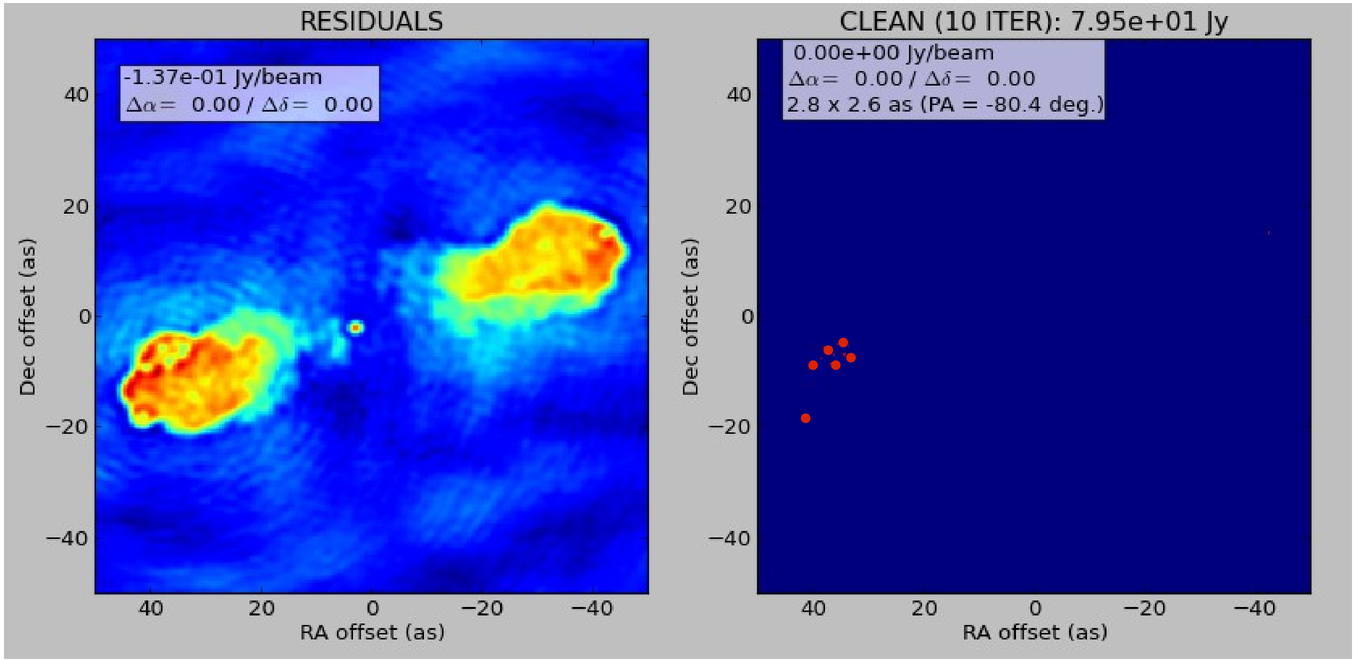
Loop gain

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

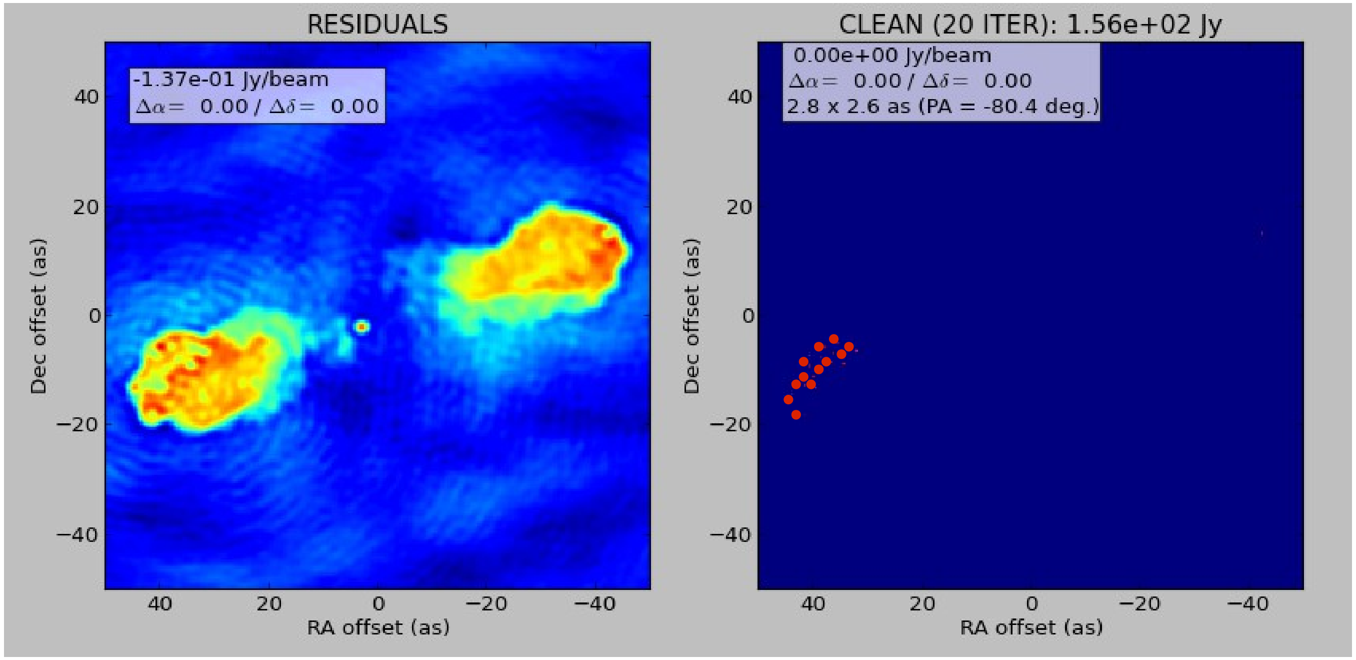
3) Multipies the clean component by the dirty beam and subtract it to the residual



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
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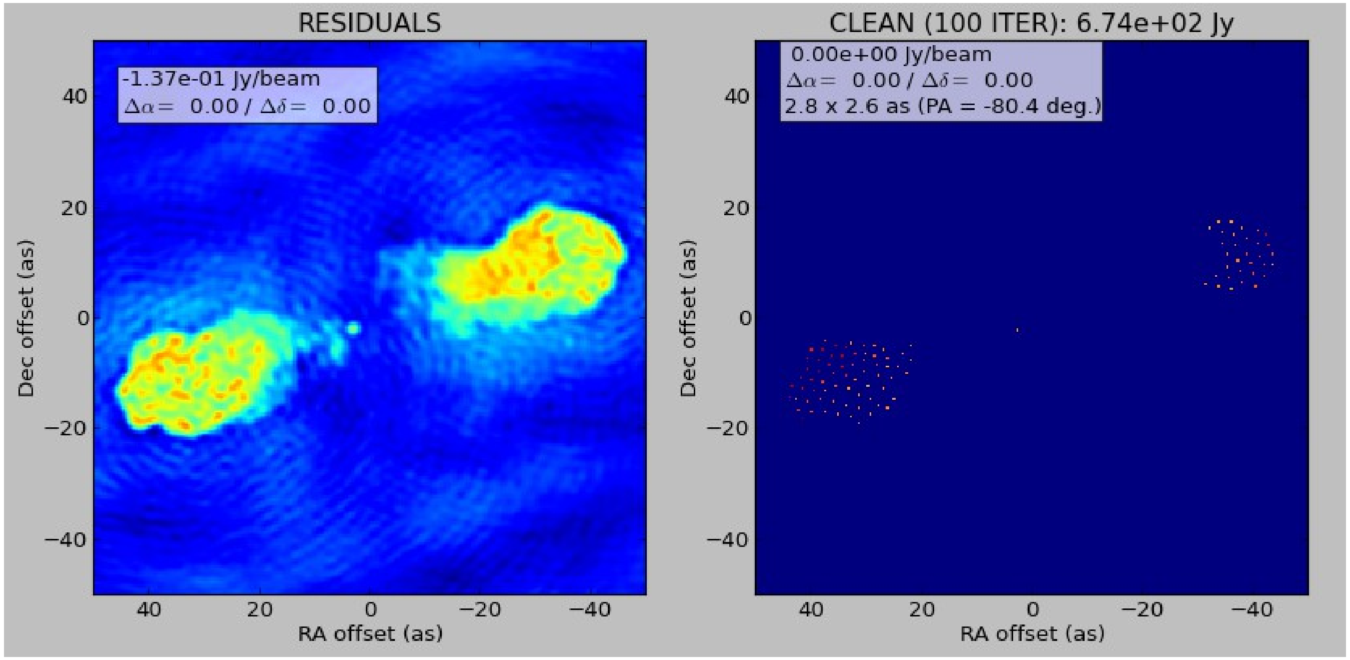

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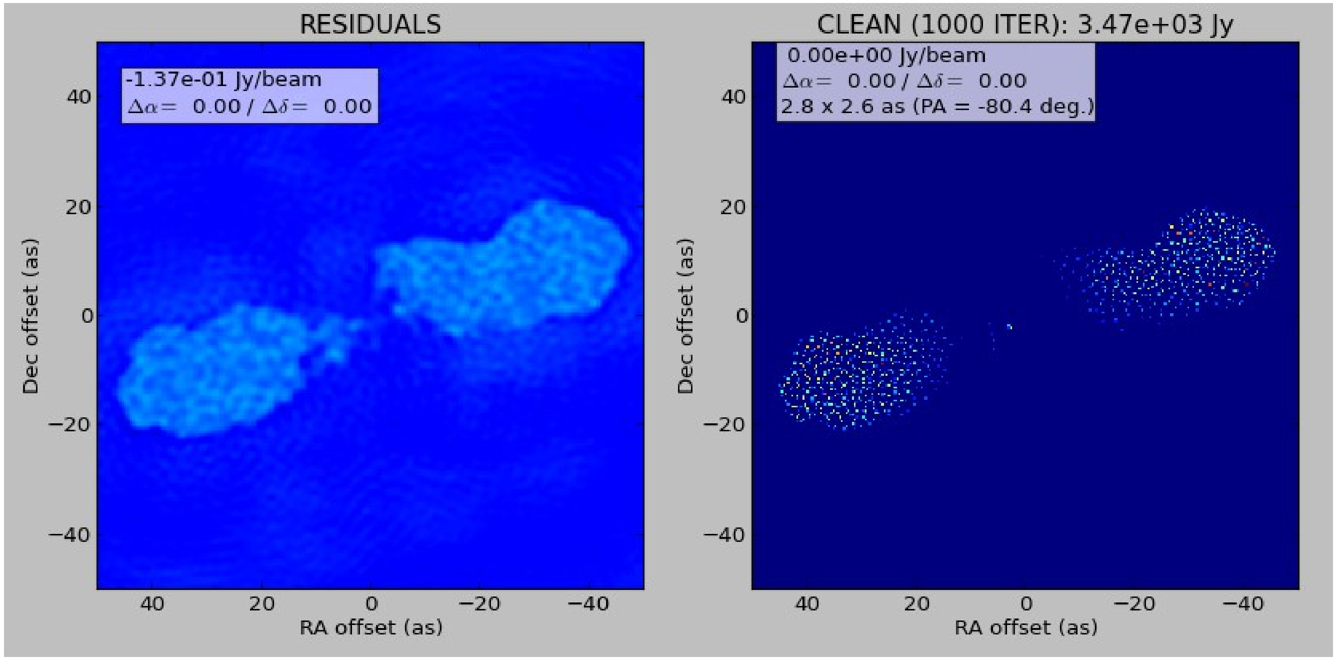

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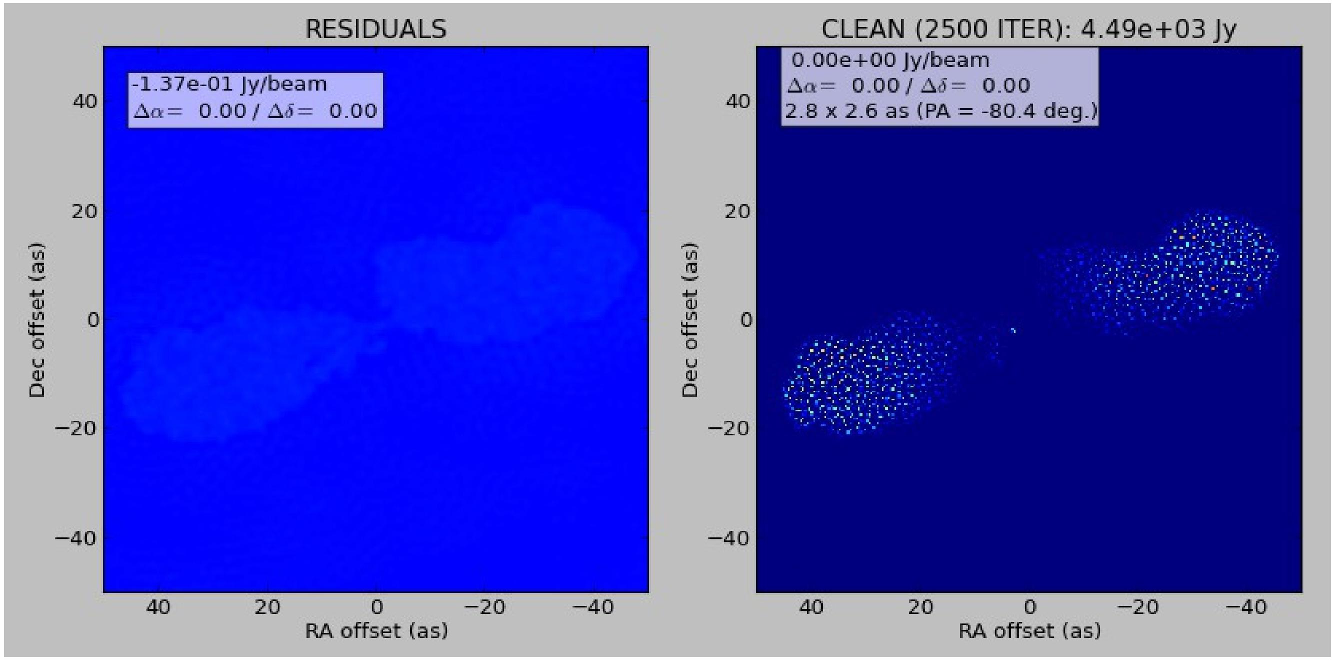

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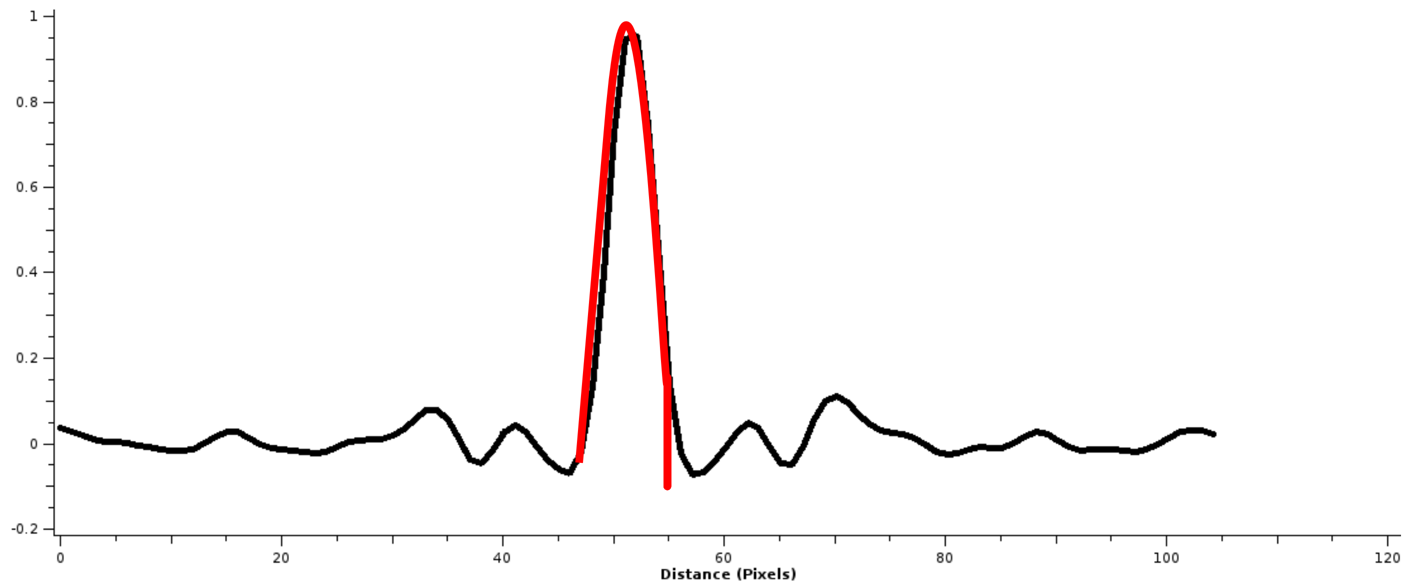
Deconvolution - Classic CLEAN
Hogbom 1974, Clark 1980, **Cotton-Schwab 1984**

Basic assumption: each source is a collection of point sources

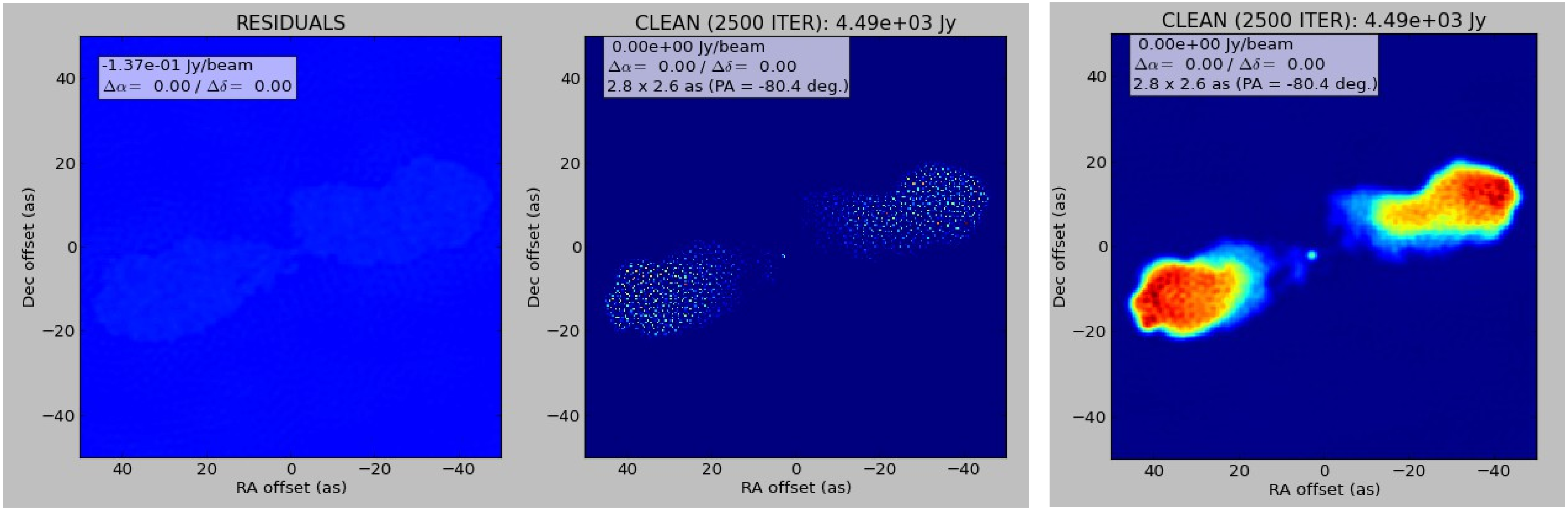
5) Multipies the clean components by **the clean beam**
an elliptical gaussian fitting the central region of the dirty beam
→ **restoring**



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



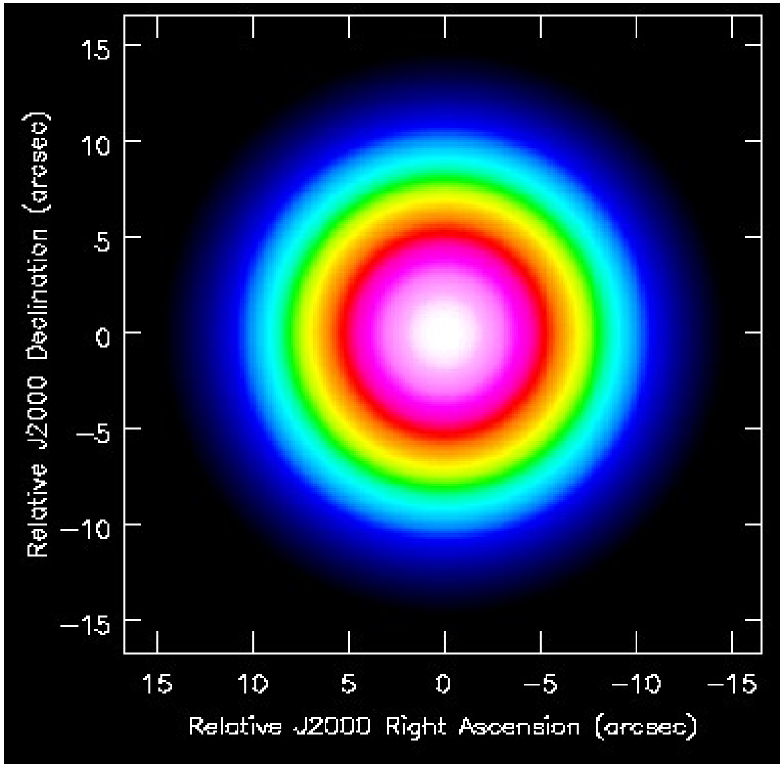
Resulting image pixel have units of Jy per clean beam

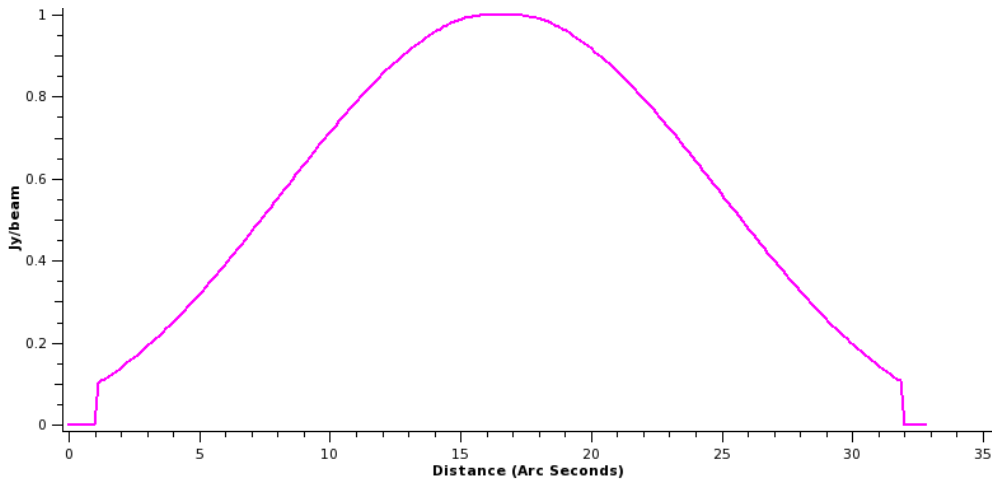
We need to get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$

But

Interferometer elements are sensible to direction of arrival of the radiation

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





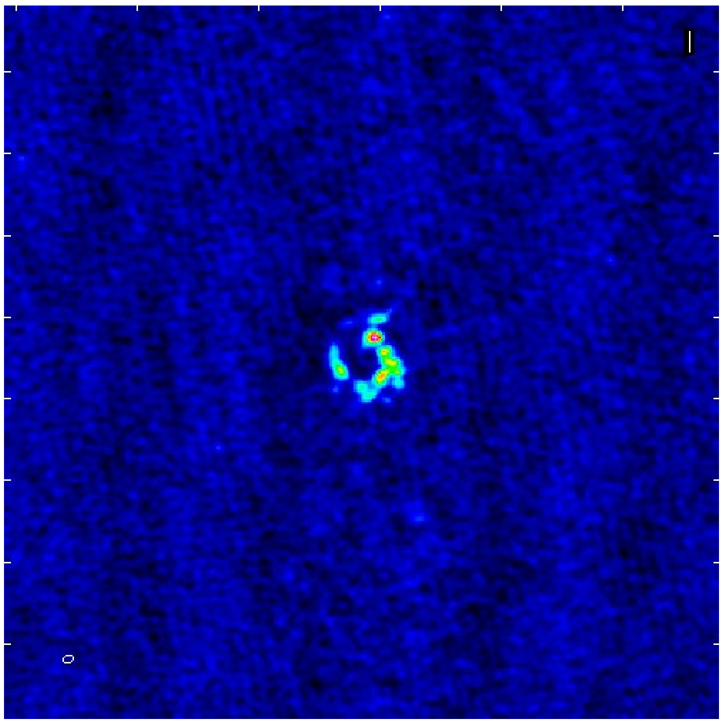
The response of the antennas in the array must be corrected for during imaging to get accurate intensities for source outside the core of the beam.

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

But

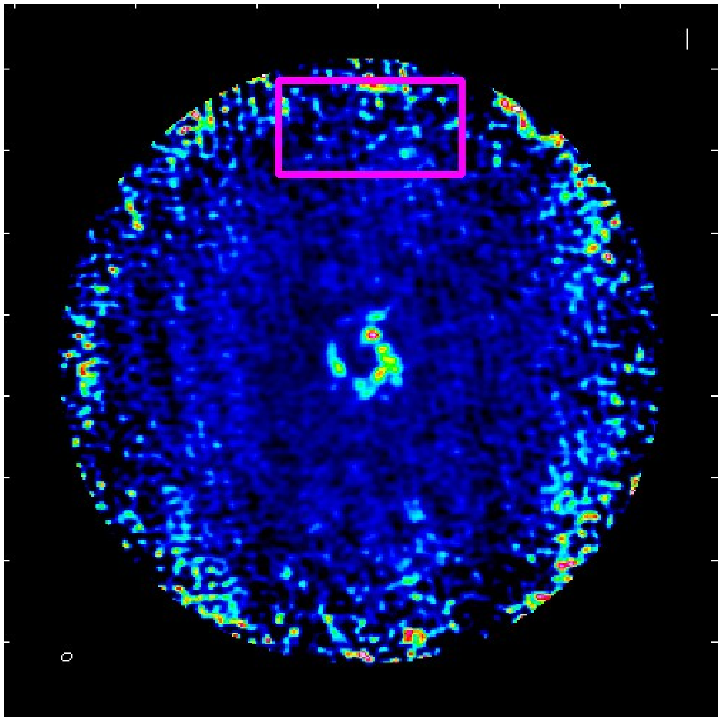
- **Primary beam effect** $\rightarrow$ $T(x,y) = A(x,y)\,T'(x,y)$

$T(x,y)$



rms 8e-4

$T'(x,y)$



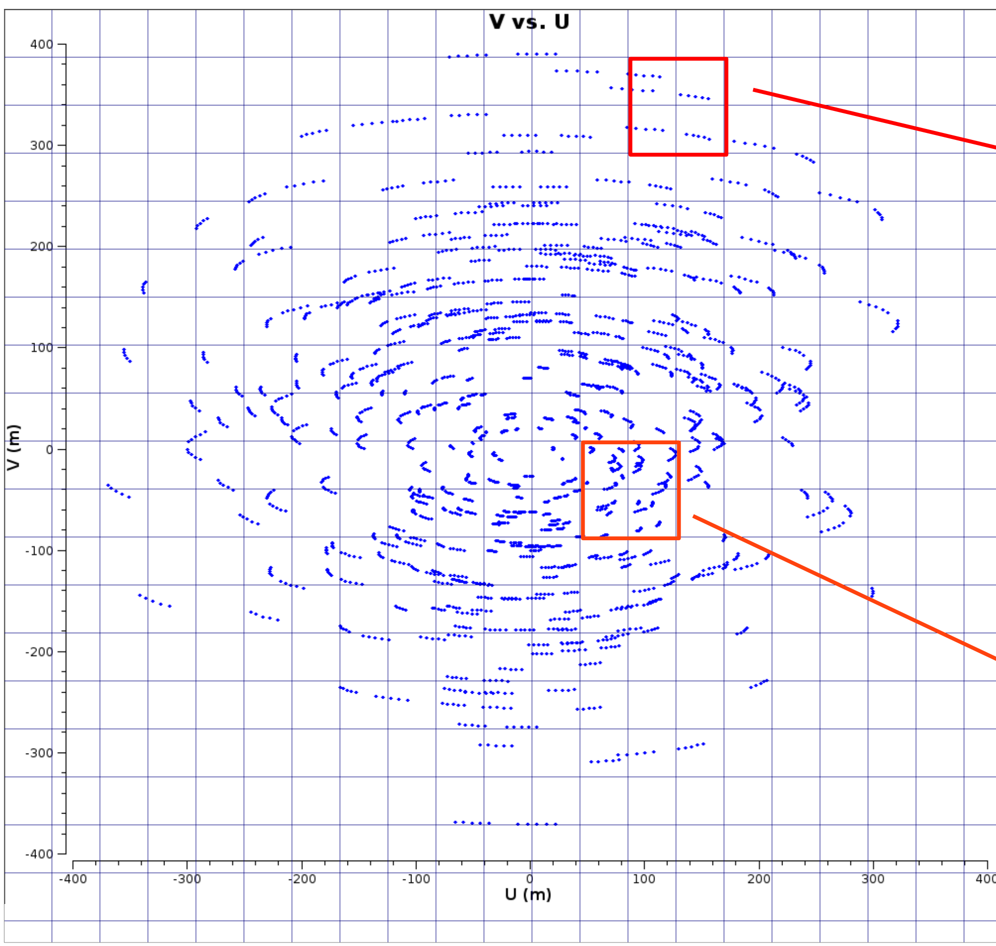
rms 3e-3

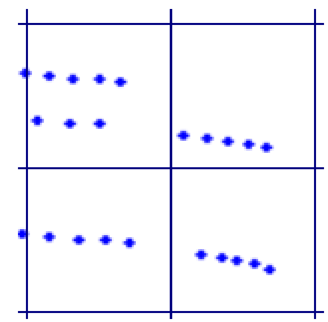
$$\sigma(u,v) \propto \frac{1}{\sqrt{T_{sys1} T_{sys2}}}$$

But

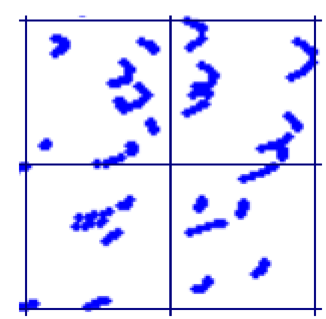
measured visibilities actually contain noise
and some uv ranges are sampled more than others

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





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

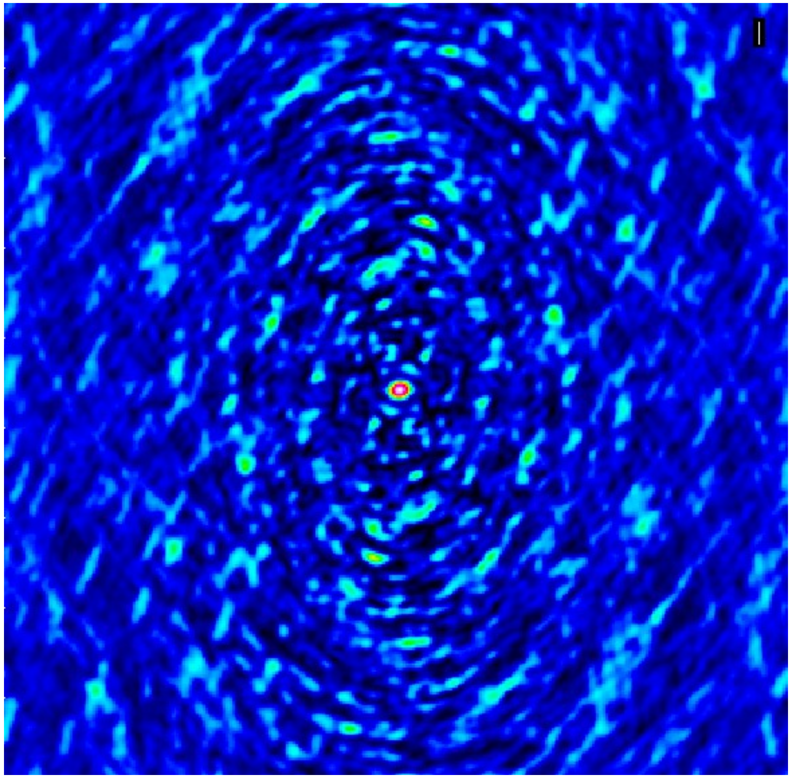
Unfortunately, in reality, the weighting which produces the best resolution **(uniform)** will often utilize the data very irregularly resulting in poor sensitivity → compromises

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

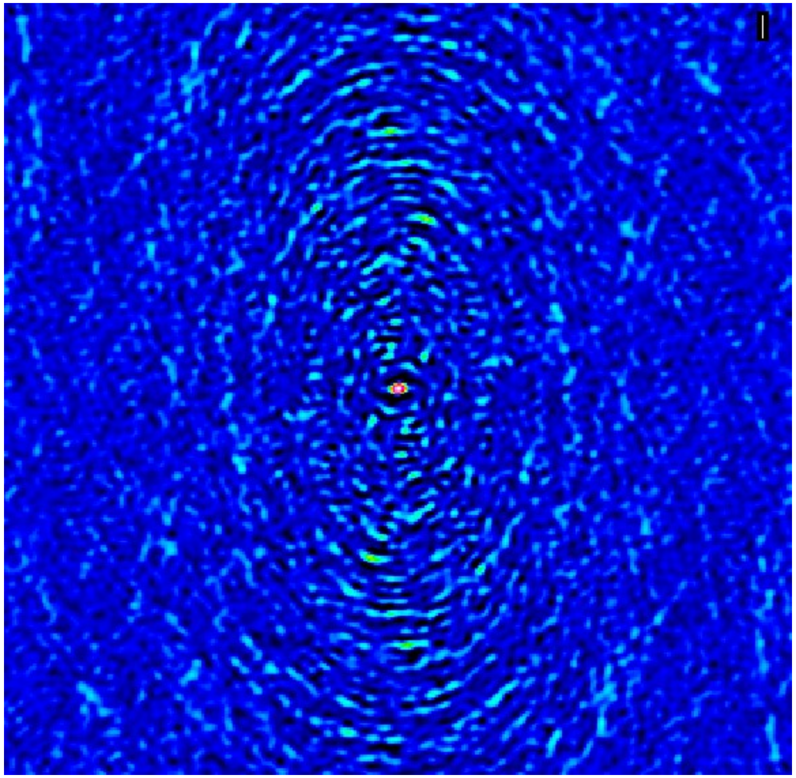
We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

✭ Weighting effects on the Dirty beam

Natural
0.29" x 0.23"
Best sensitivity



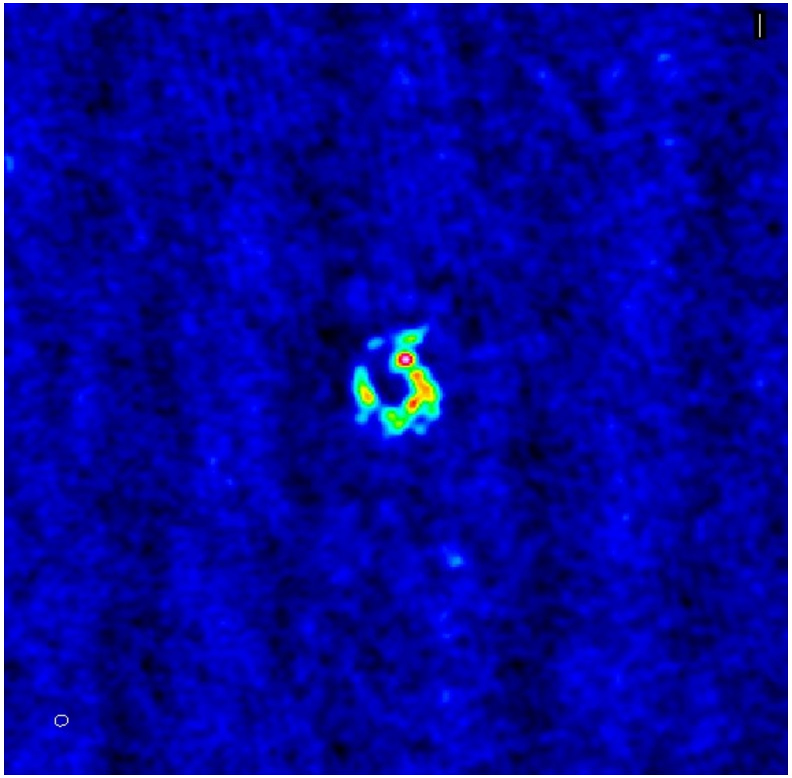
Uniform
0.24"x0.17"
Best angular resolution



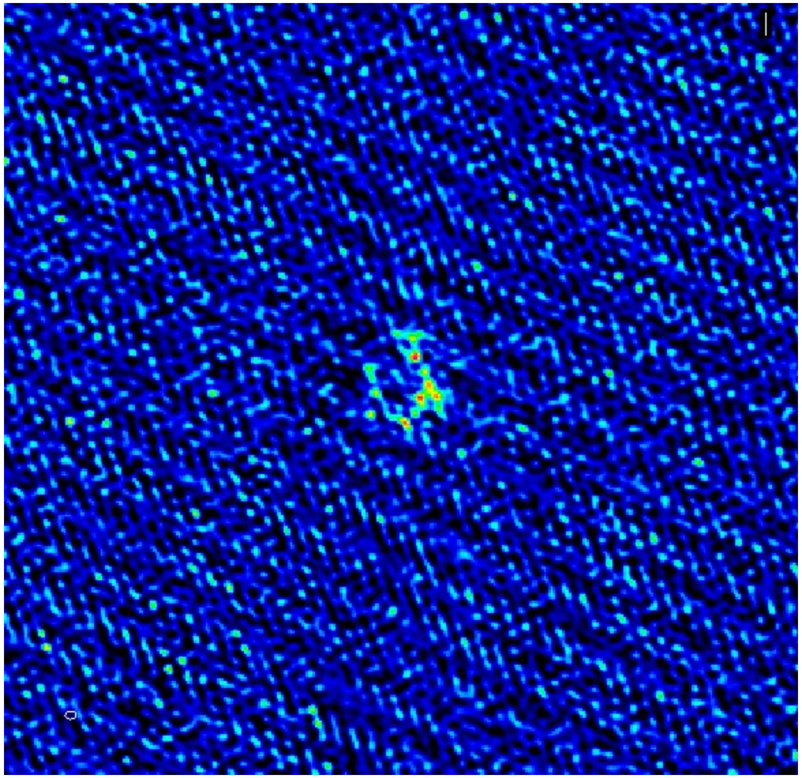
We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

Weighting effects on the image

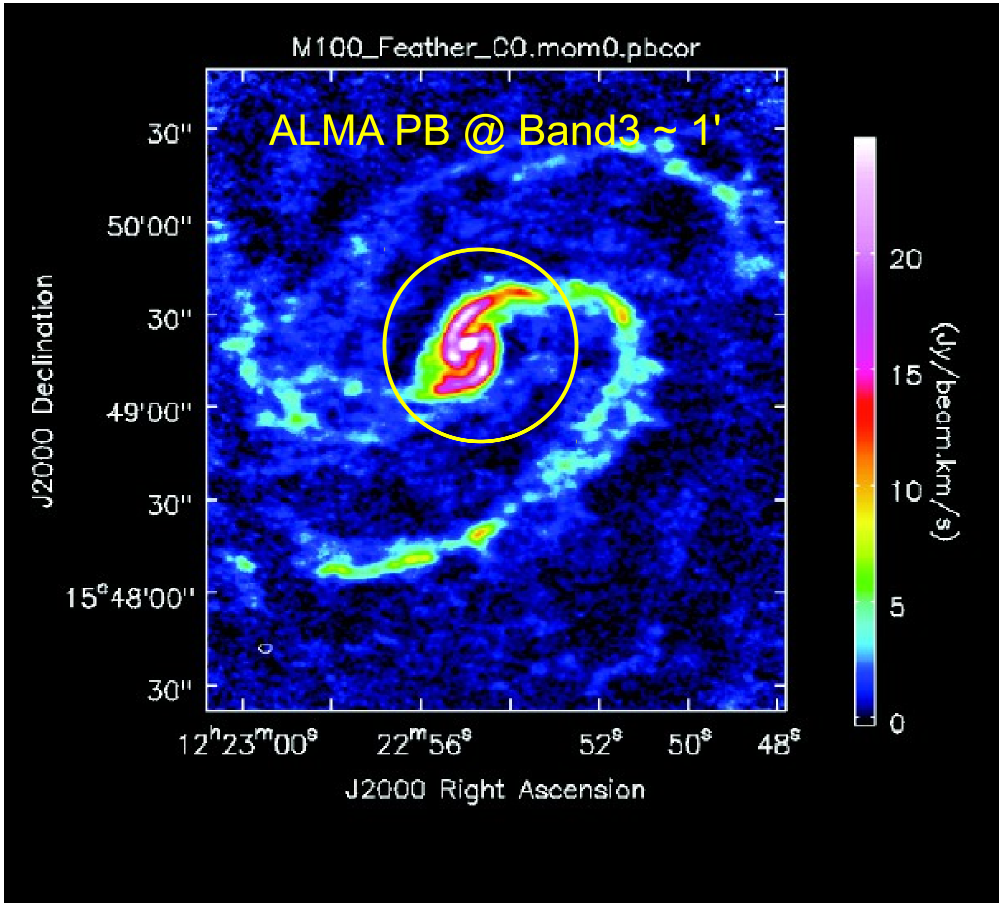
Natural
res = 0.29" x 0.23"
rms = 0.8 mJy/beam



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

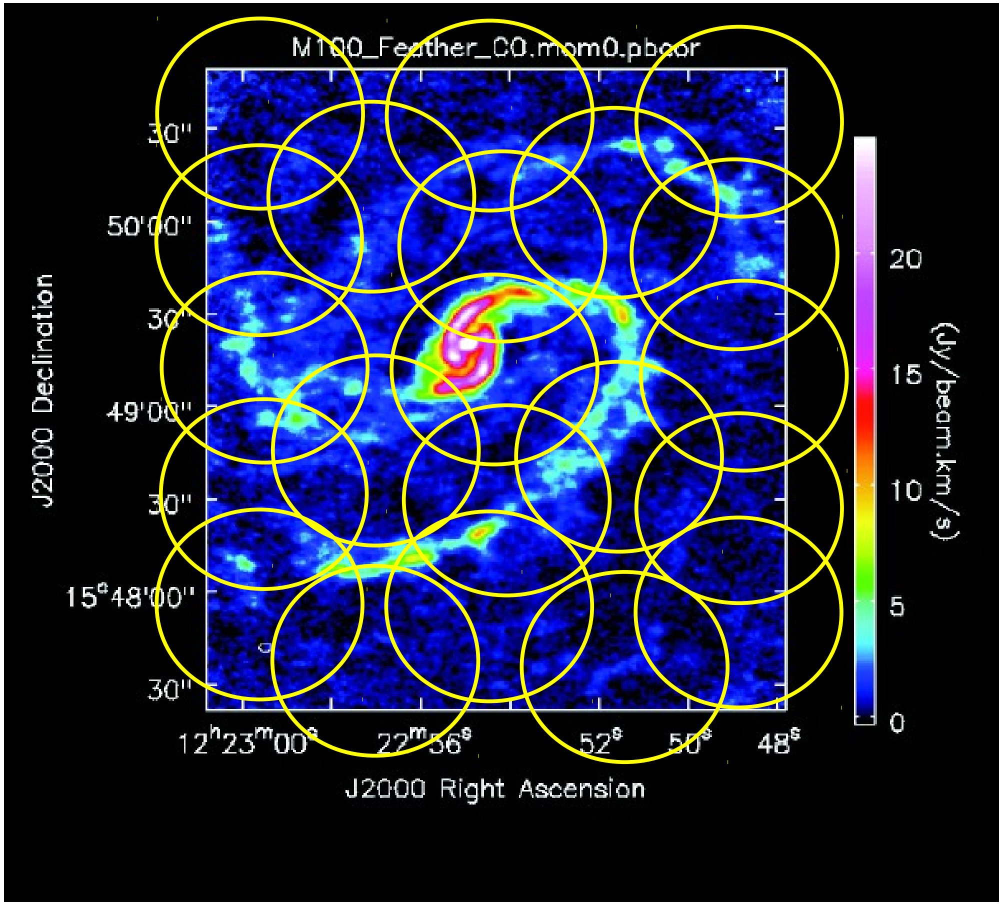


If the region of interest is larger than the primary beam



If the region of interest is larger than the primary beam

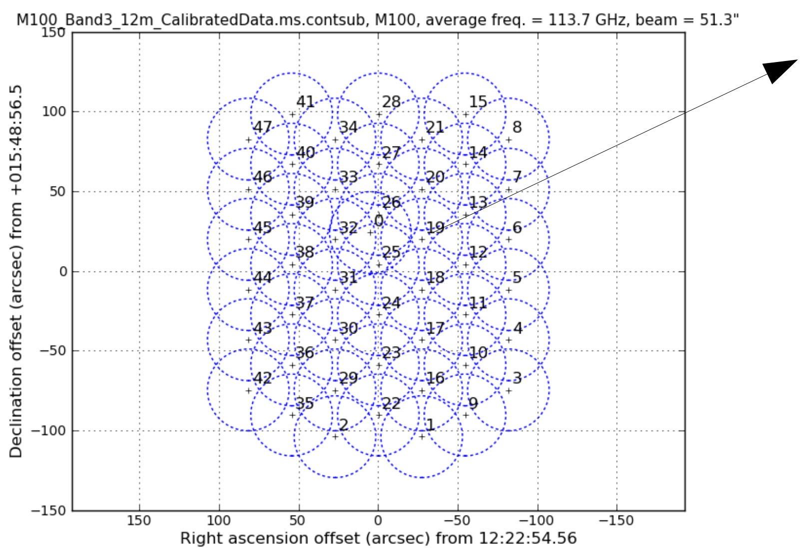
need to mosaic many interferometric pointings

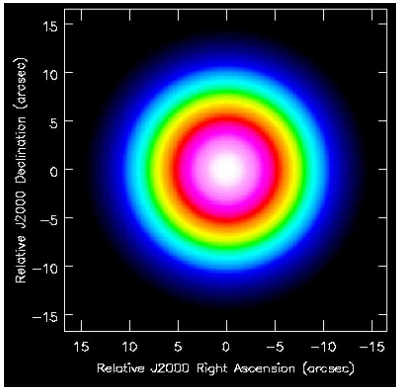


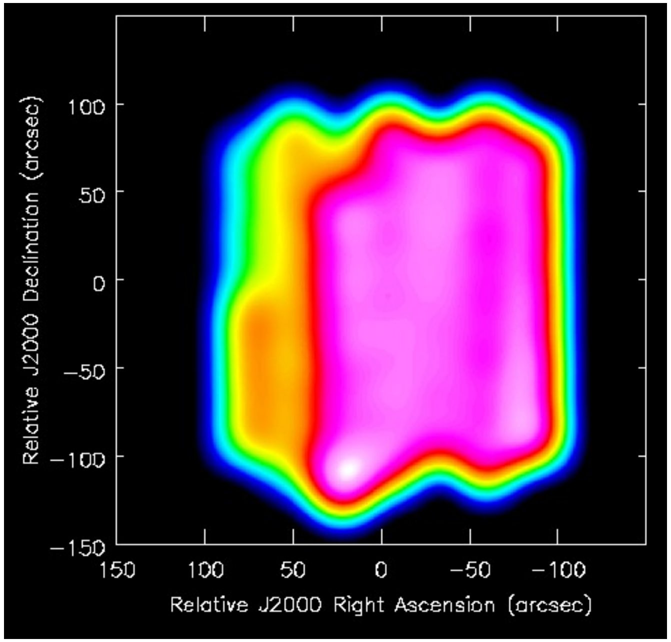
Clean is basically the same →
need to specify the central pointing (phasecenter)
the image size = full mosaic area
and the mode 'mosaic' (imagermode and ftmachine)

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

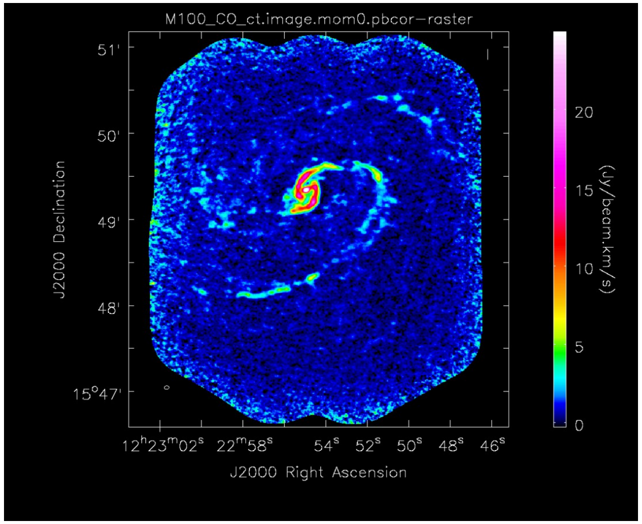


Image with 12 m data

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

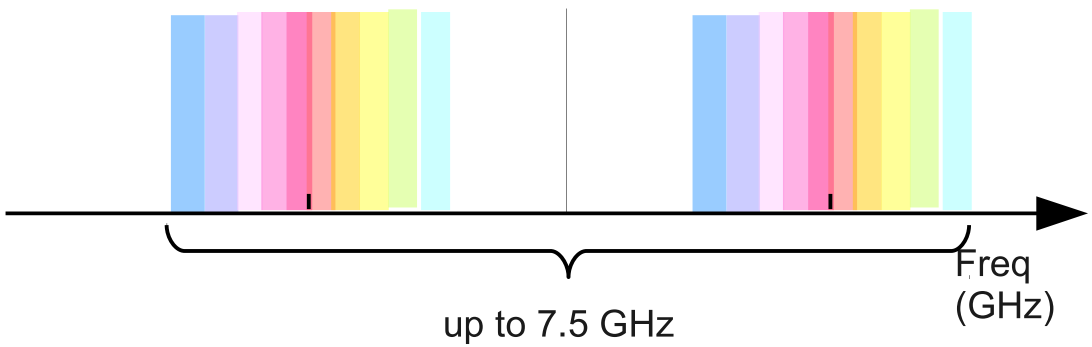
are not recovered

→ **need ACA and possibly Total Power**

Continuum images

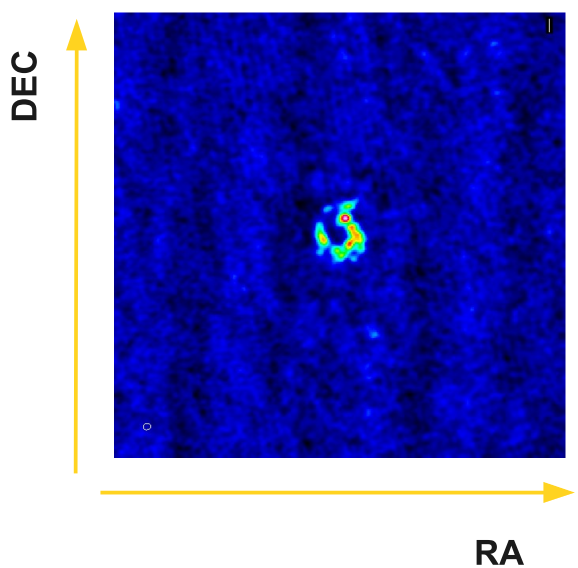
- **Multi-Frequency synthesis (MFS)**
- Wide bandwidths allow higher sensitivity to continuum emission

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



MFS
combines all channels

the result is a single image



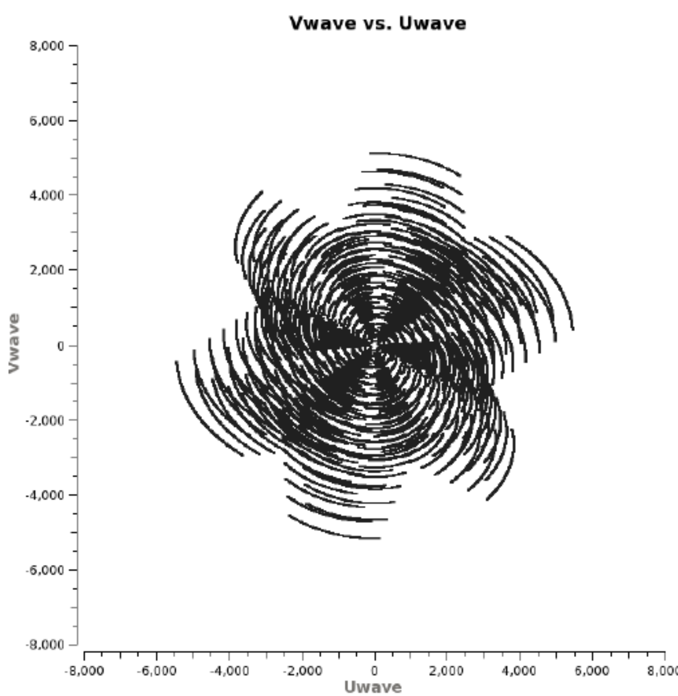
Continuum images

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

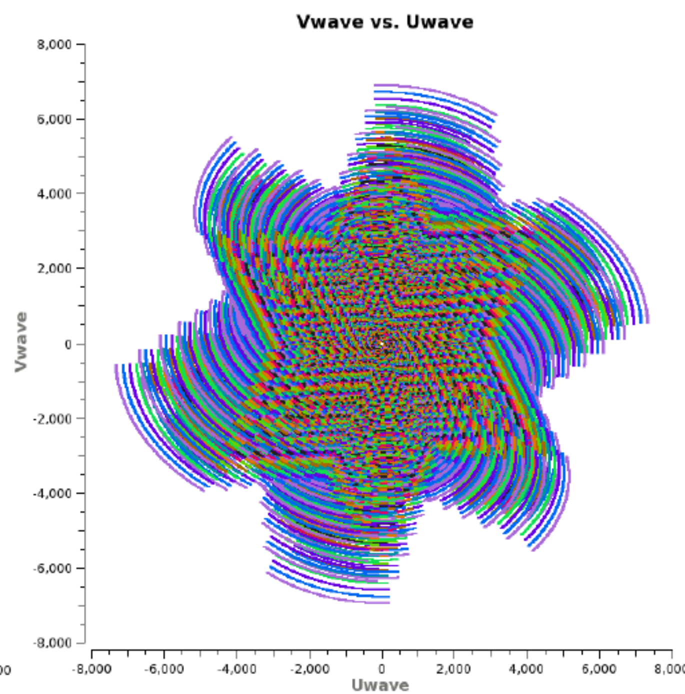
- Wide bandwidths allow higher sensitivity to continuum emission but also **uv coverage is improved**

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

- 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

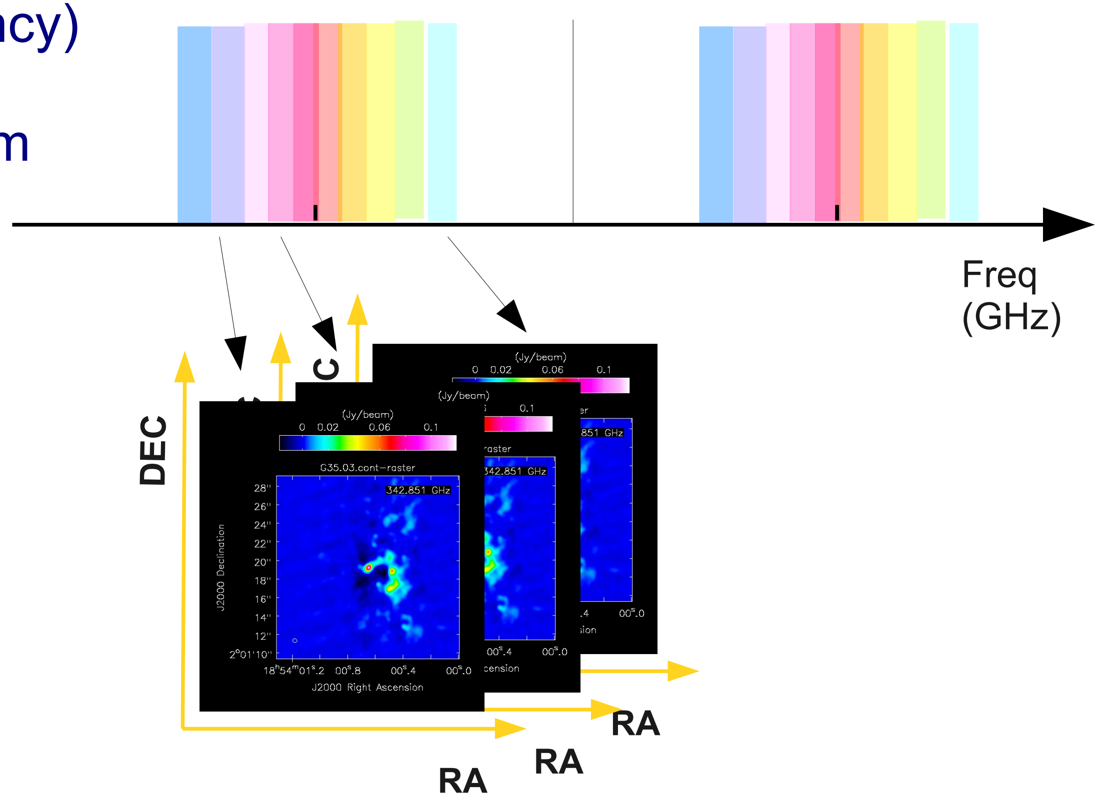


1 – 2 GHz

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 observations

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

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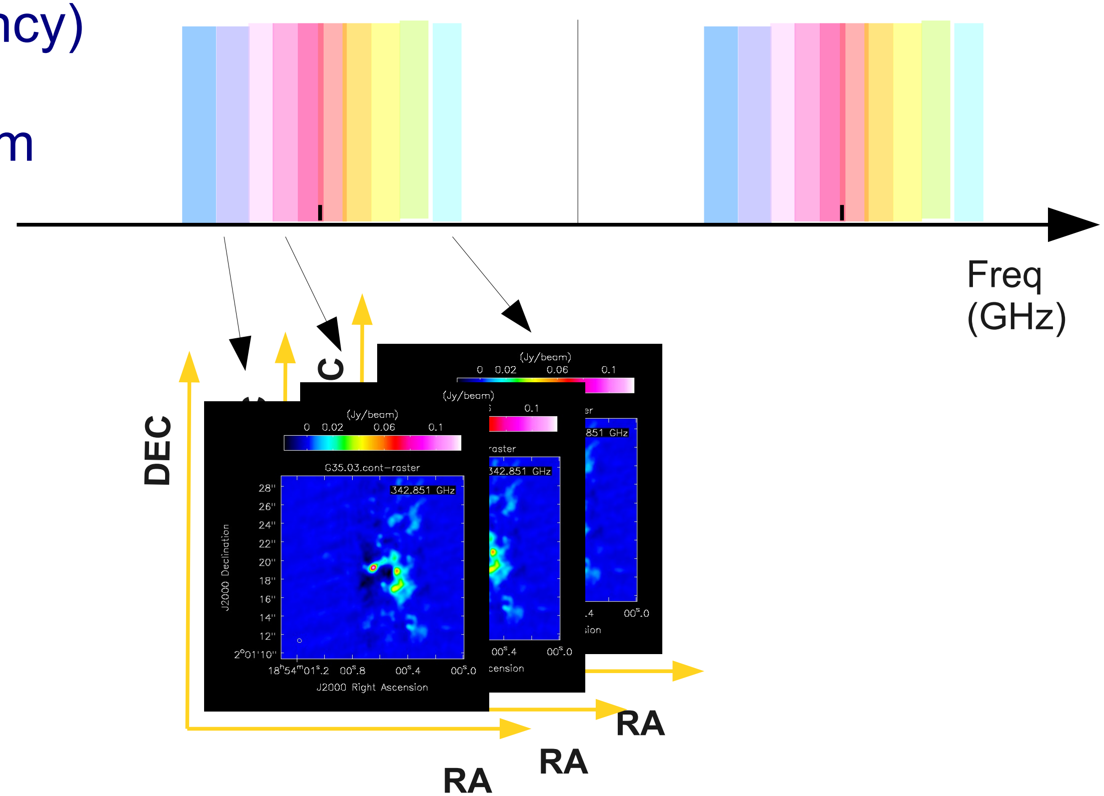


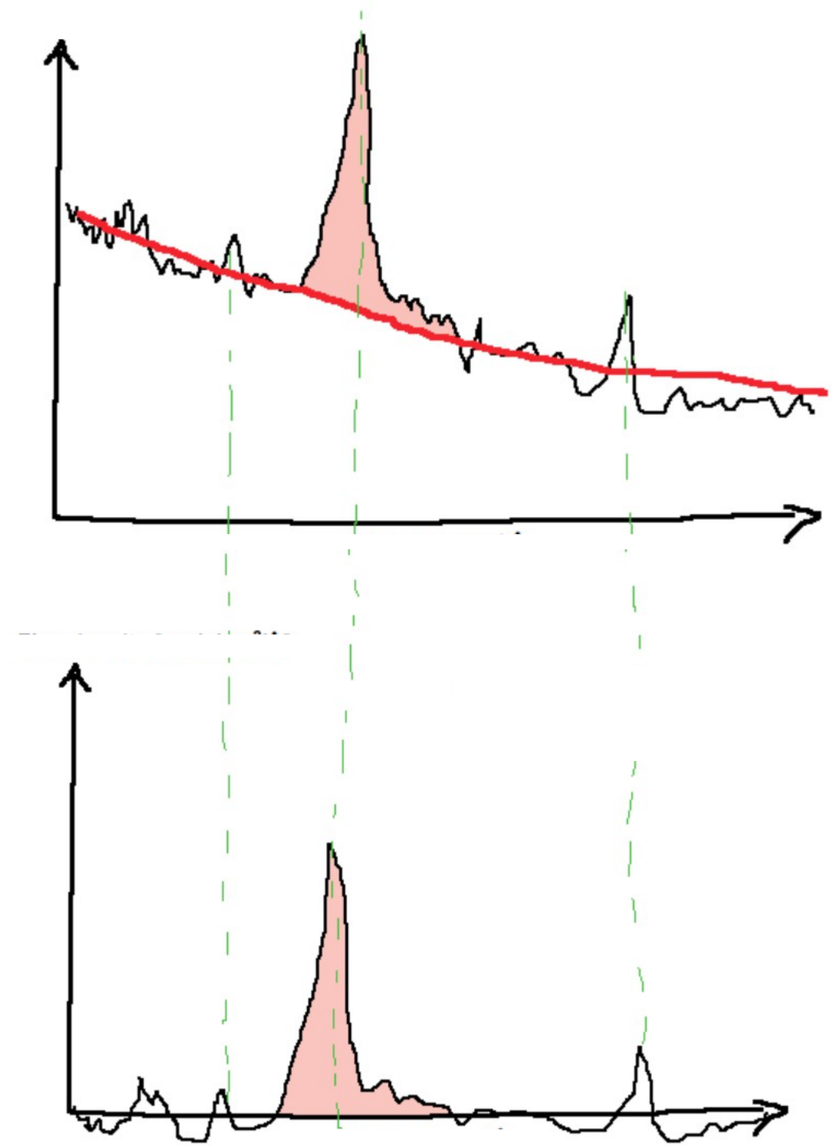
Spectral line observations

- 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