Imaging & analysis

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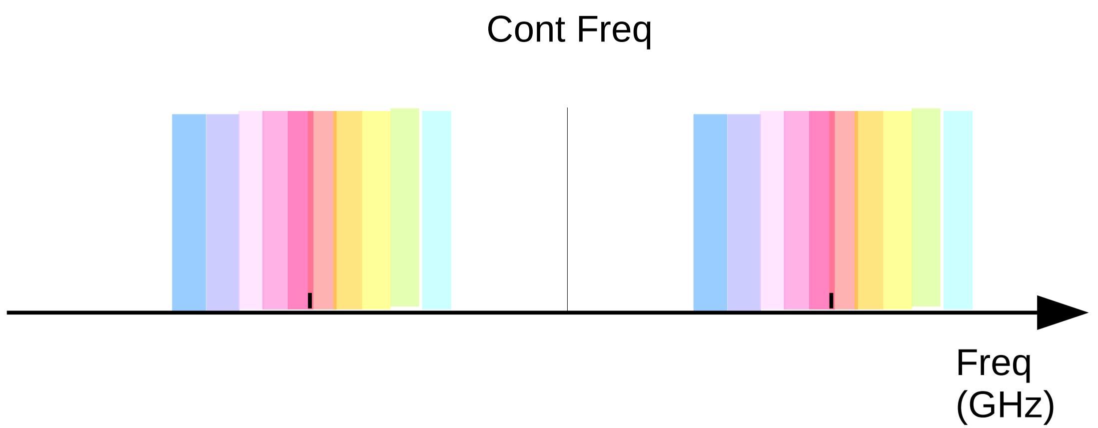
Spectrometers

A spectrometer divides the passband into N adiacent narrow frequency ranges, and simultaneously measures the power in all N channels.

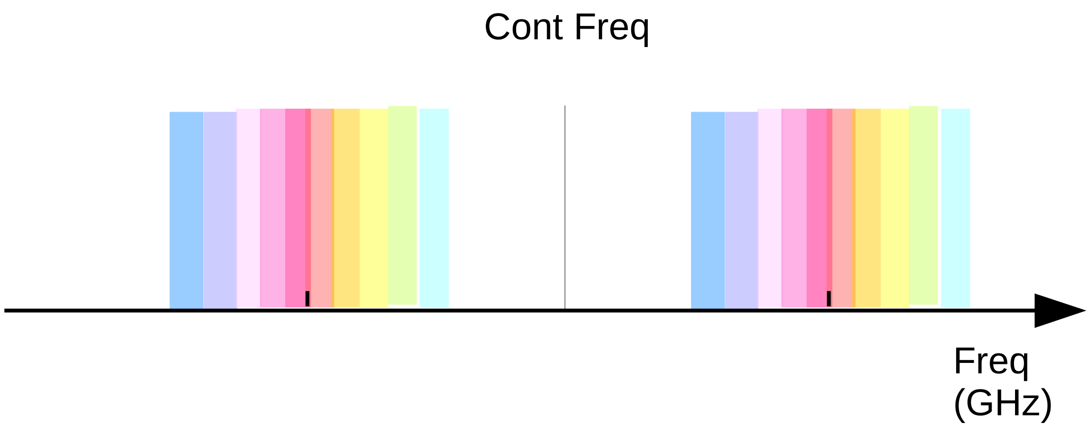


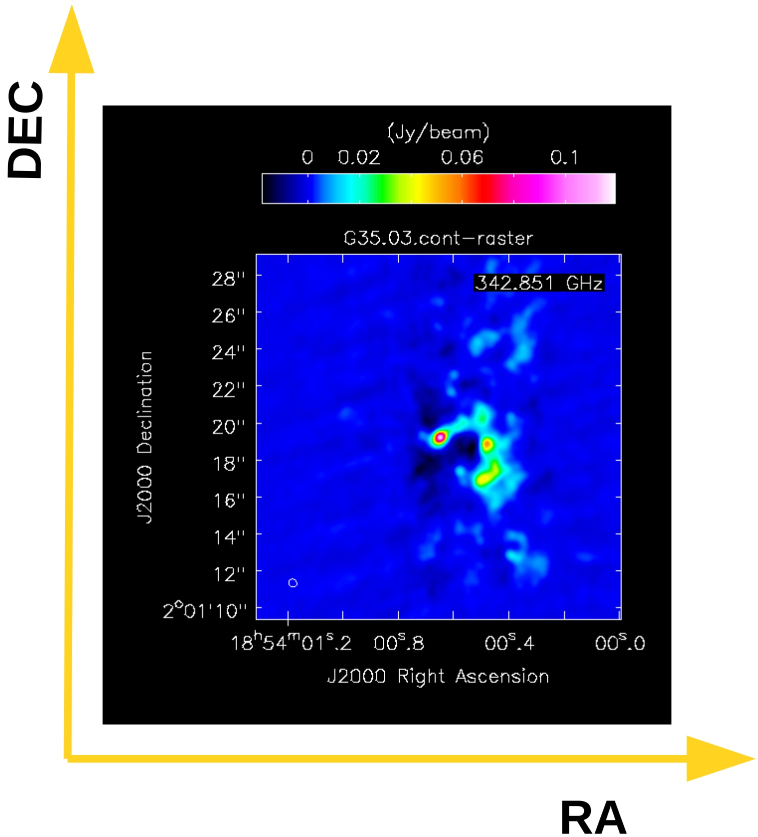
Modern interferometers use large band receivers.
Data are taken in multichannel mode regardless if they are meant for continuum or line observations.

The maximum number of channels in dual polarization mode is
8192 for the VLA
3840 for ALMA

Interferometric data

Continuum images are obtained combining all the (line-free) channels.





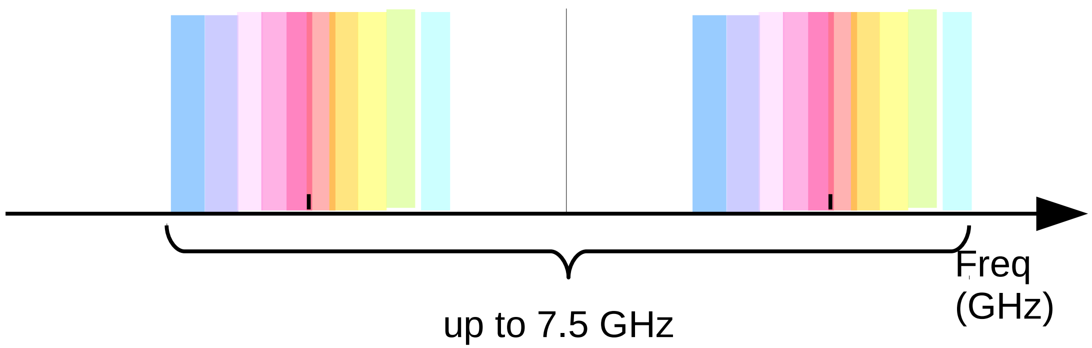
The resulting image is a 2-Dimensional image at the central frequency.

Continuum images

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

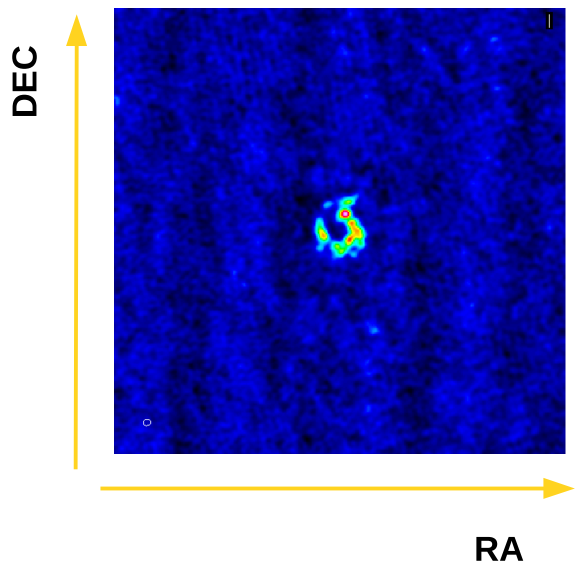
- Wide bandwidths allow higher sensitivity to continuum emission

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



MFS
combines all channels

the result is a single image



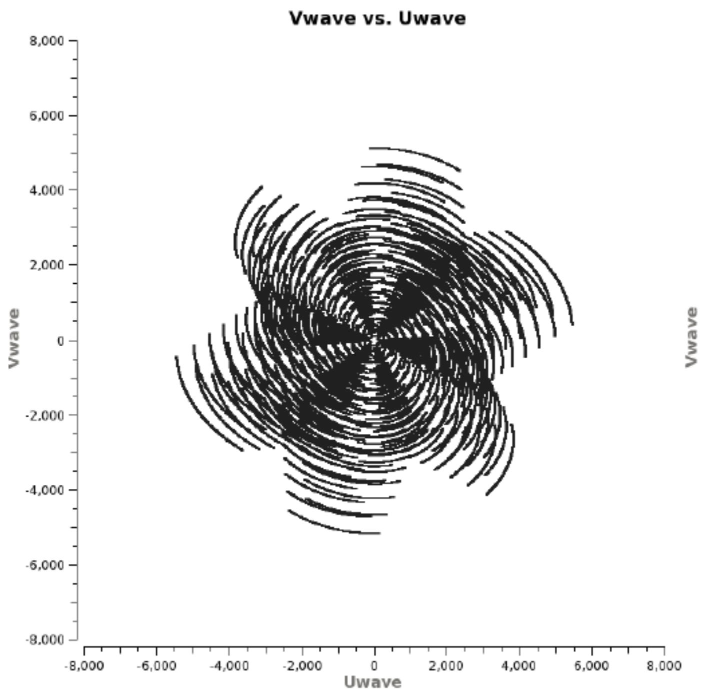
Continuum images

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

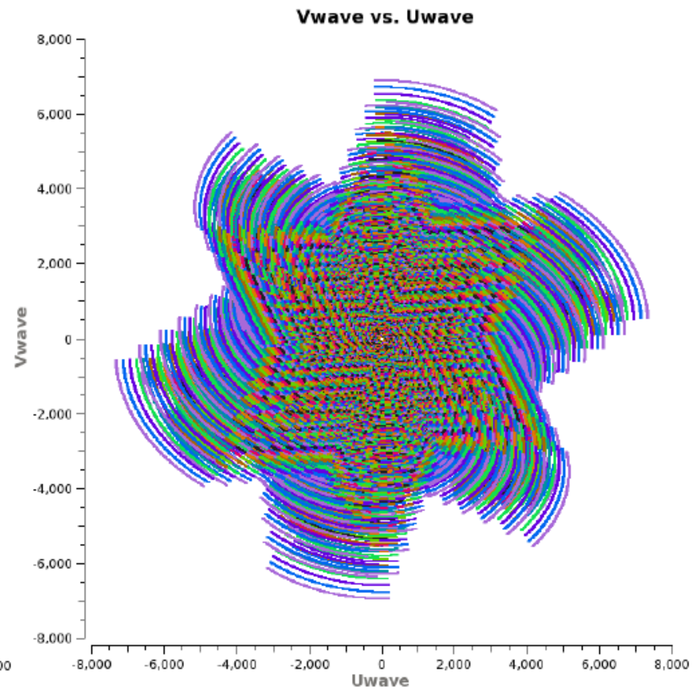
- Wide bandwidths allow higher sensitivity to continuum emission but also **uv coverage is improved**

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

- 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

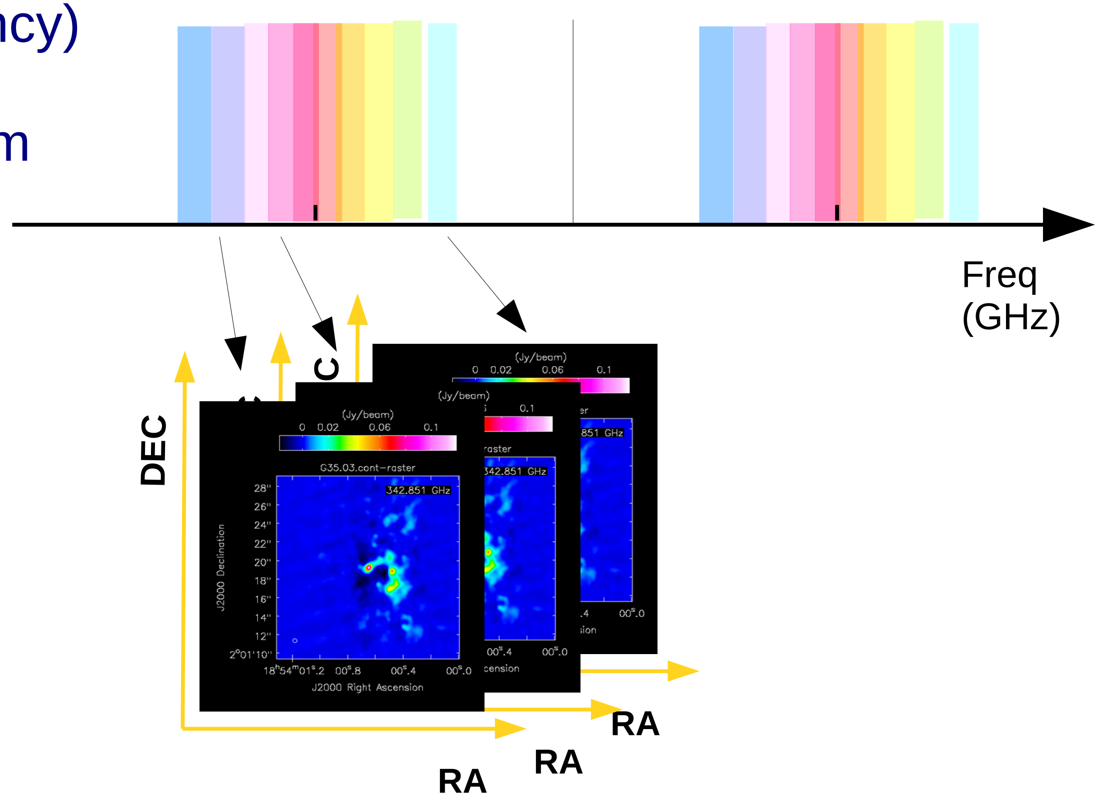


1 – 2 GHz

Spectral line observations

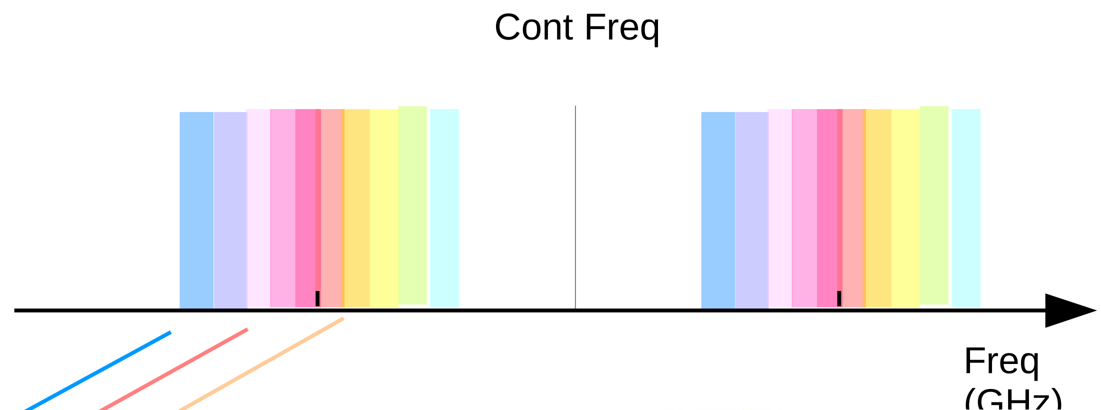
$$\sigma = \frac{2k}{\eta} \frac{T_{\rm sys}}{\sqrt{\Delta t \Delta \nu} \sqrt{N_{\rm ant}(N_{\rm ant}-1)A}}$$

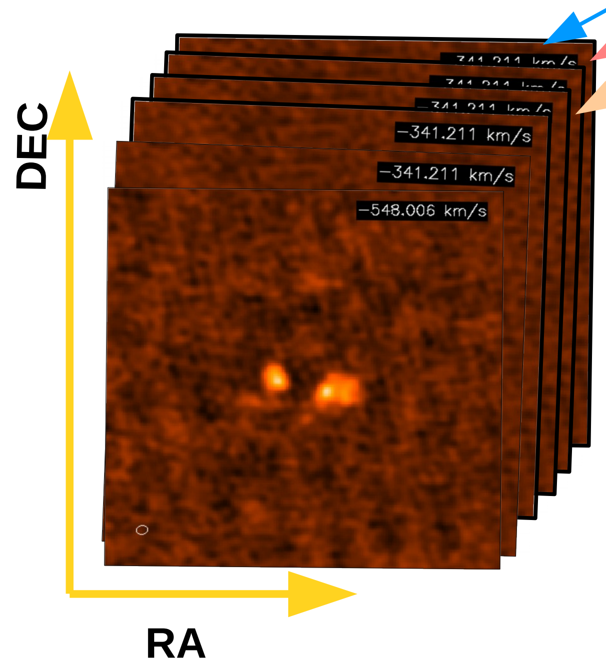
- The imaging process is the same as for a continuum map **but** making an image for each channel (a cube with axes RA, DEC and velocity/frequency)
- The rms is larger than for continuum
- While imaging it is possible to average channels if the full spectral resolution is not needed

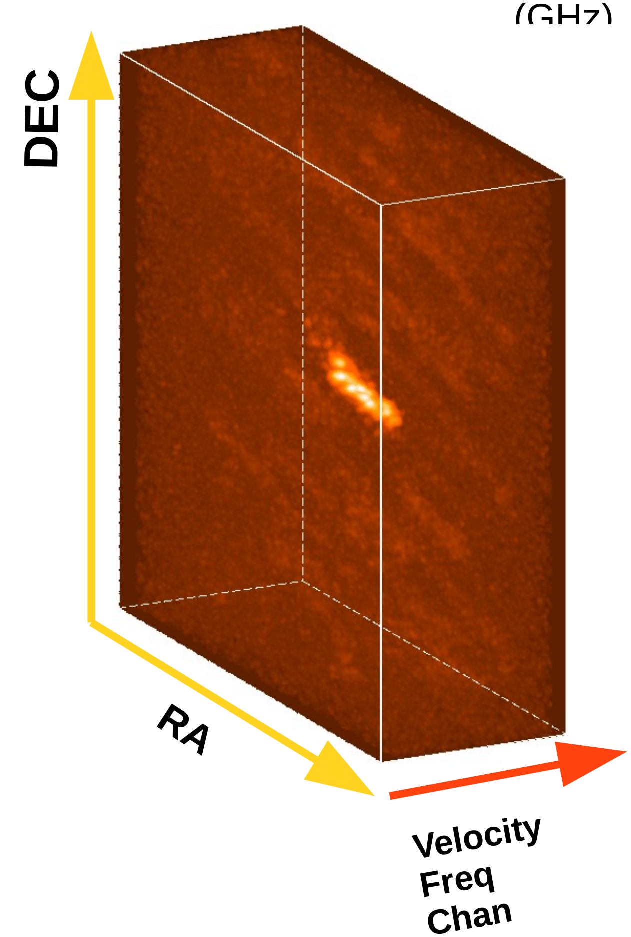


Spectral line images
are 3-dimensional.

One image from each channel







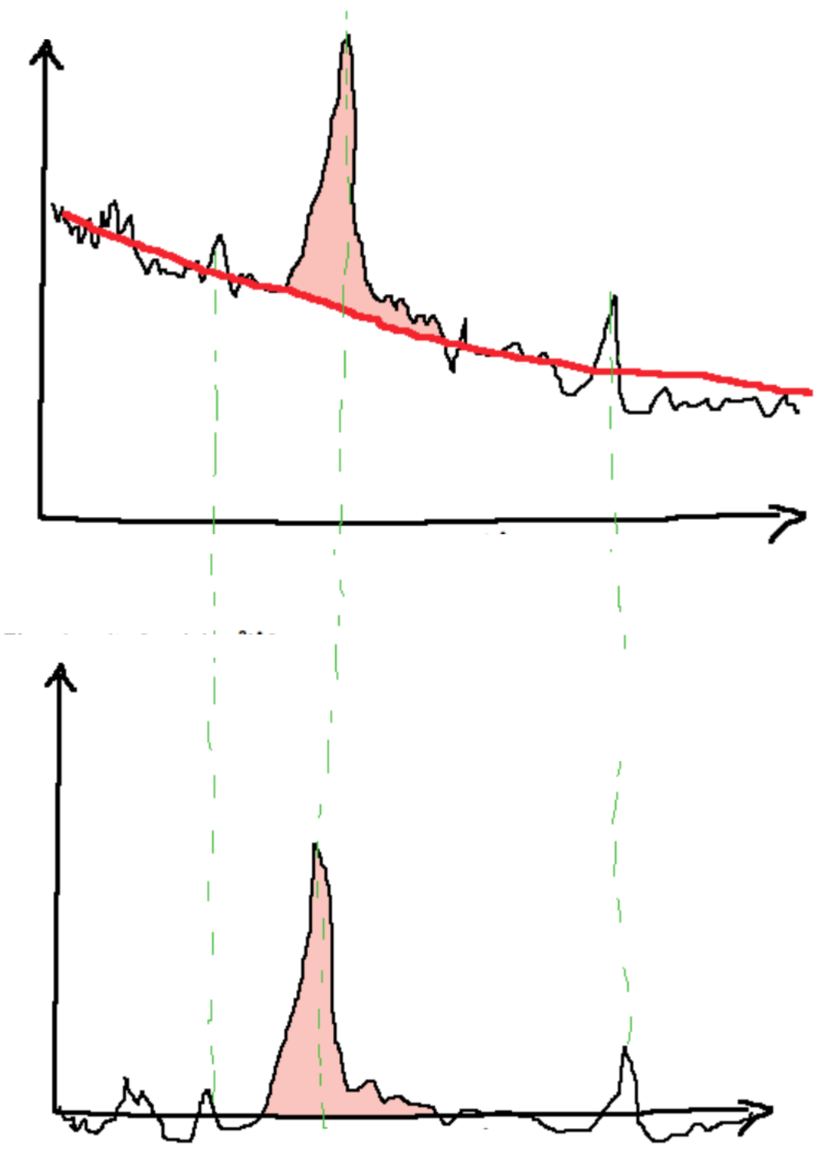
Spectral line observations

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

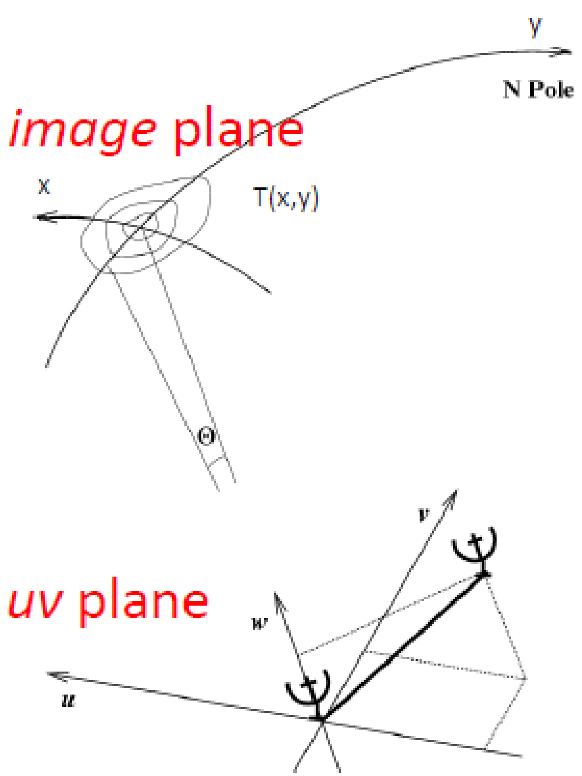
- Model the continuum using channels with no lines: low-order polynomial fit

- Subtract this continuum model from all the channels

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



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

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

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

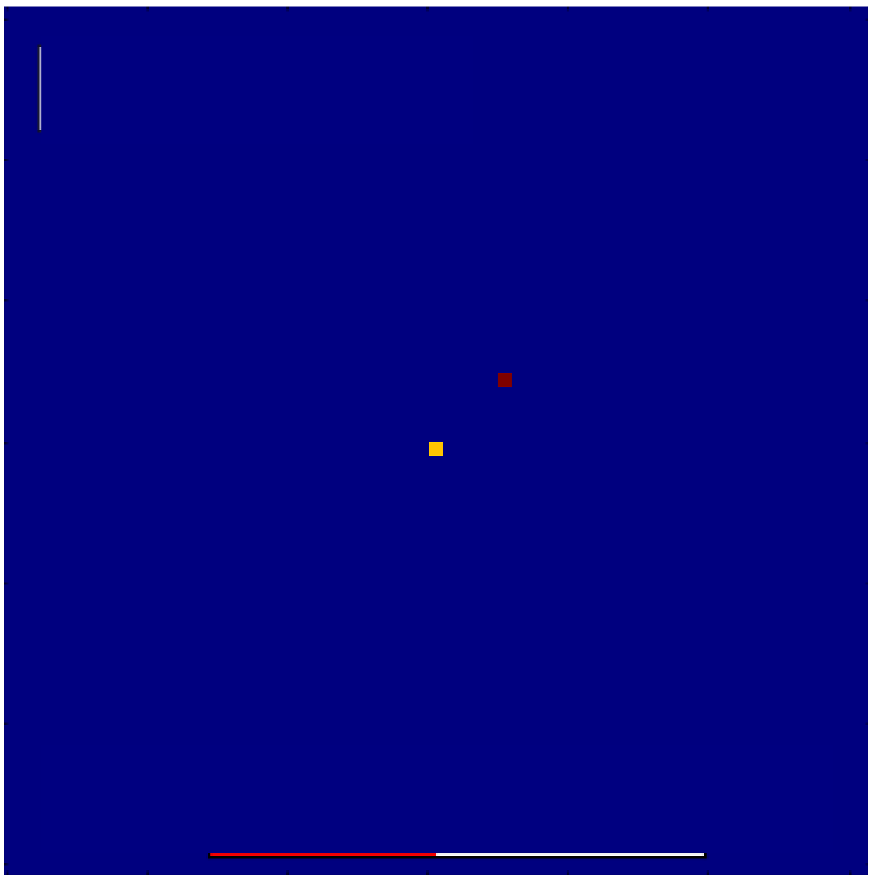
Image space/domain

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

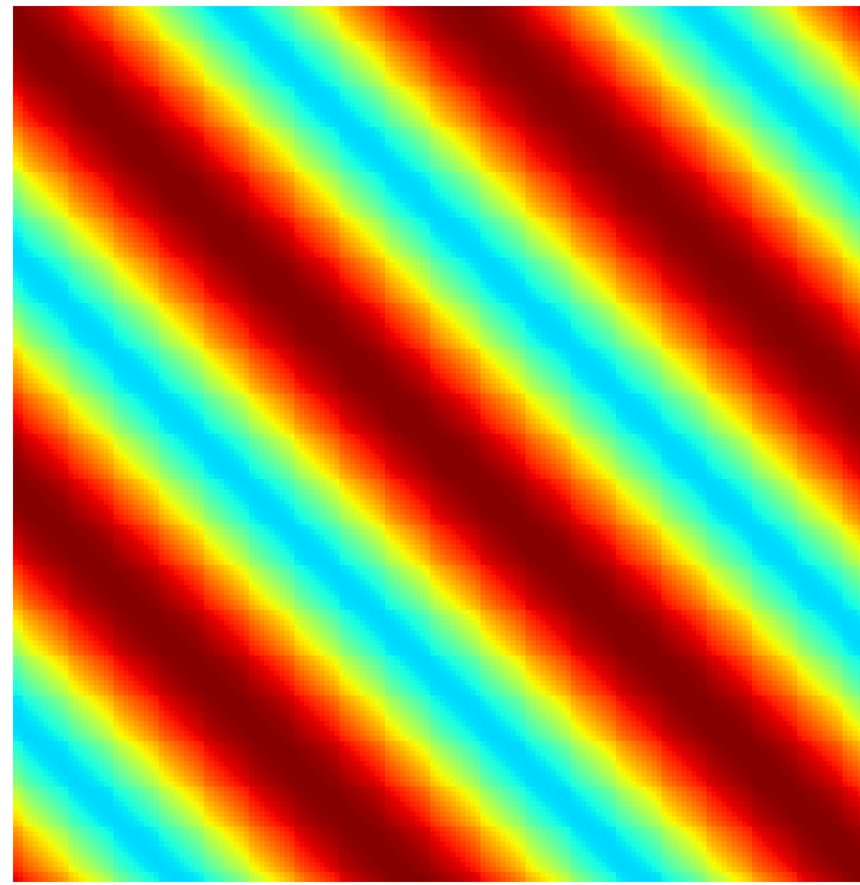
We need to get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$

Consider a two point-like sources as target to observe

I (x, y)



V (u, v)

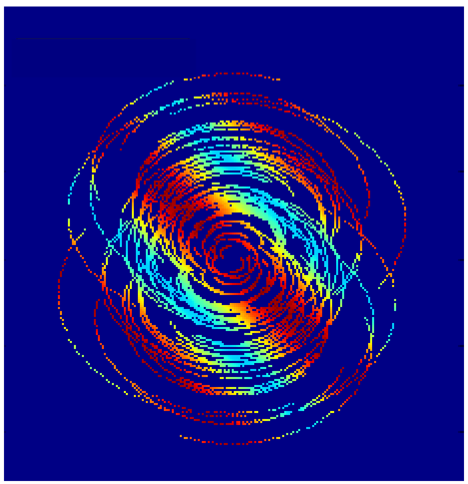


We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

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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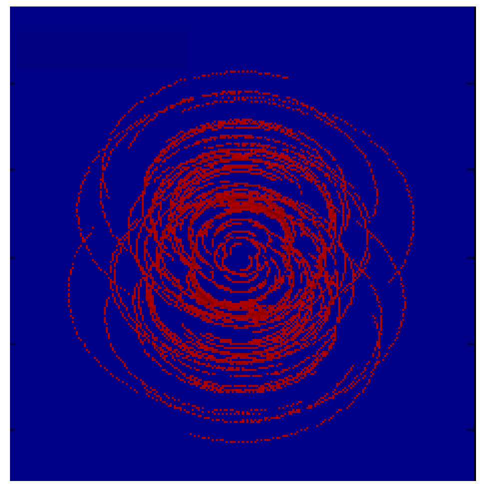

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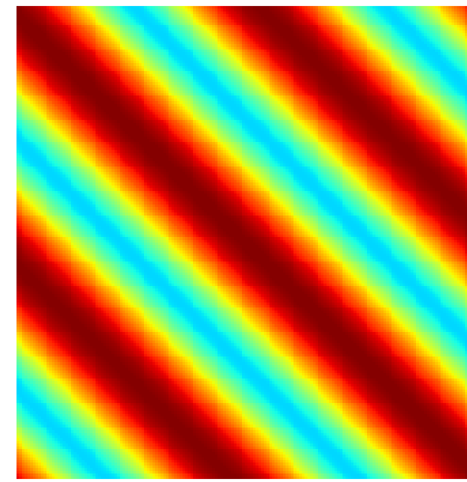


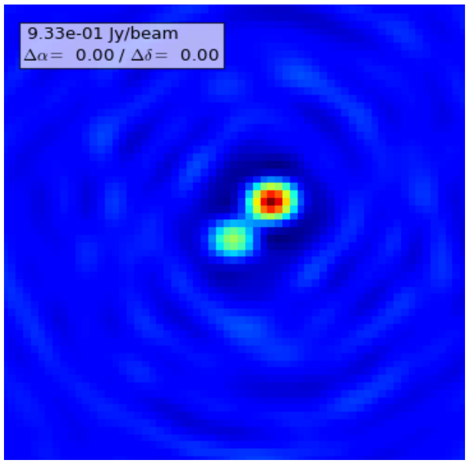
where S(u,v) is the sampling function
S= 1 at points where visibilities are measured
and S = 0 elsewhere

V_{true} is the 2 point-like sources ideal Fourier transform (example from APSYNSIM)

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

Applying the convolution theorem:

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



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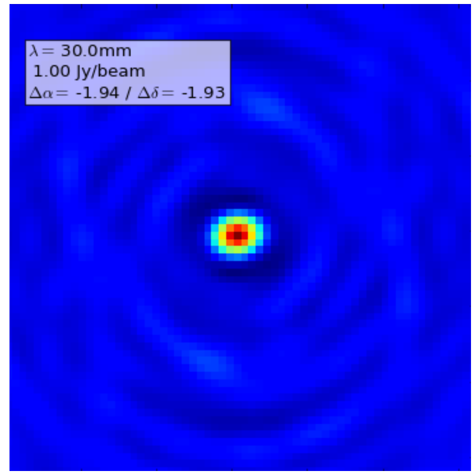

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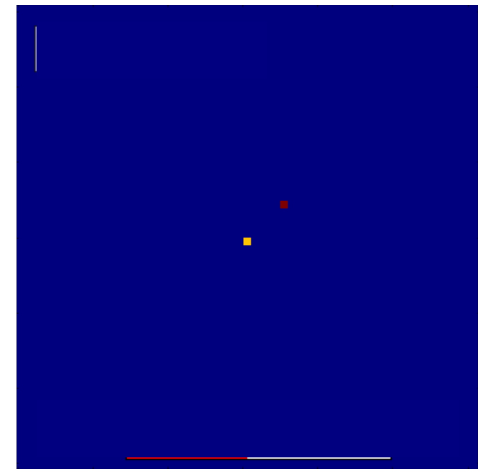


The Fourier transform FT of the sampled visibilities gives the true sky brightness convolved with the Fourier transform of the sampling function (called **dirty beam**).

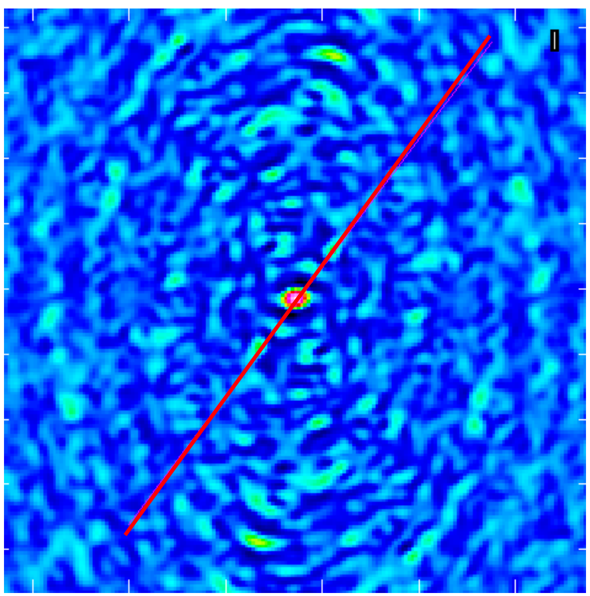
$$I^D(x,y) = B_{dirty}(x,y) \otimes I(x,y)$$

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

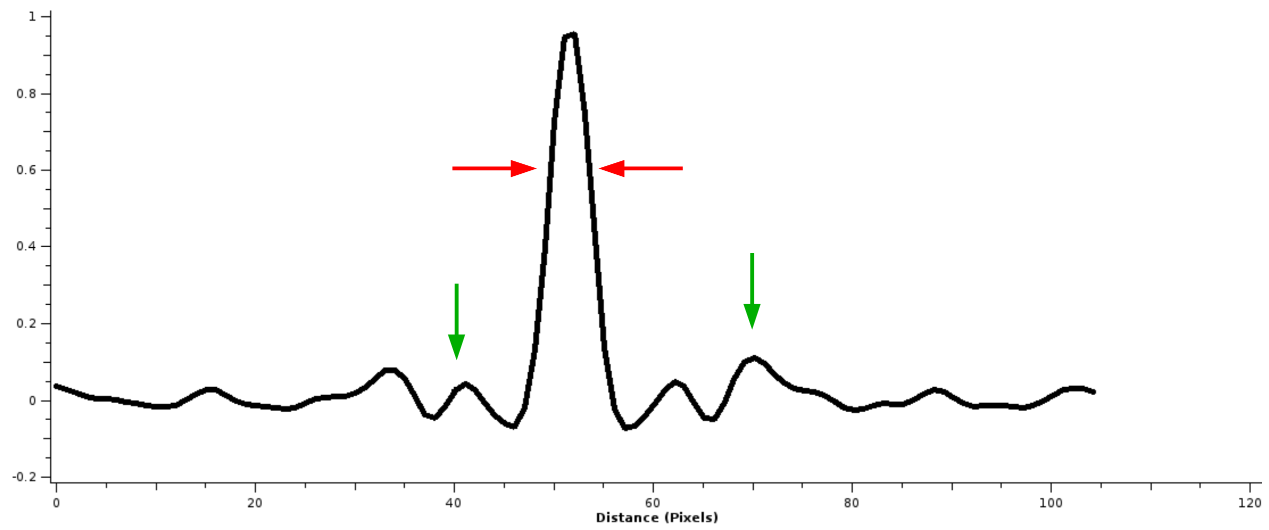
Imperfect reconstruction of the sky

- **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

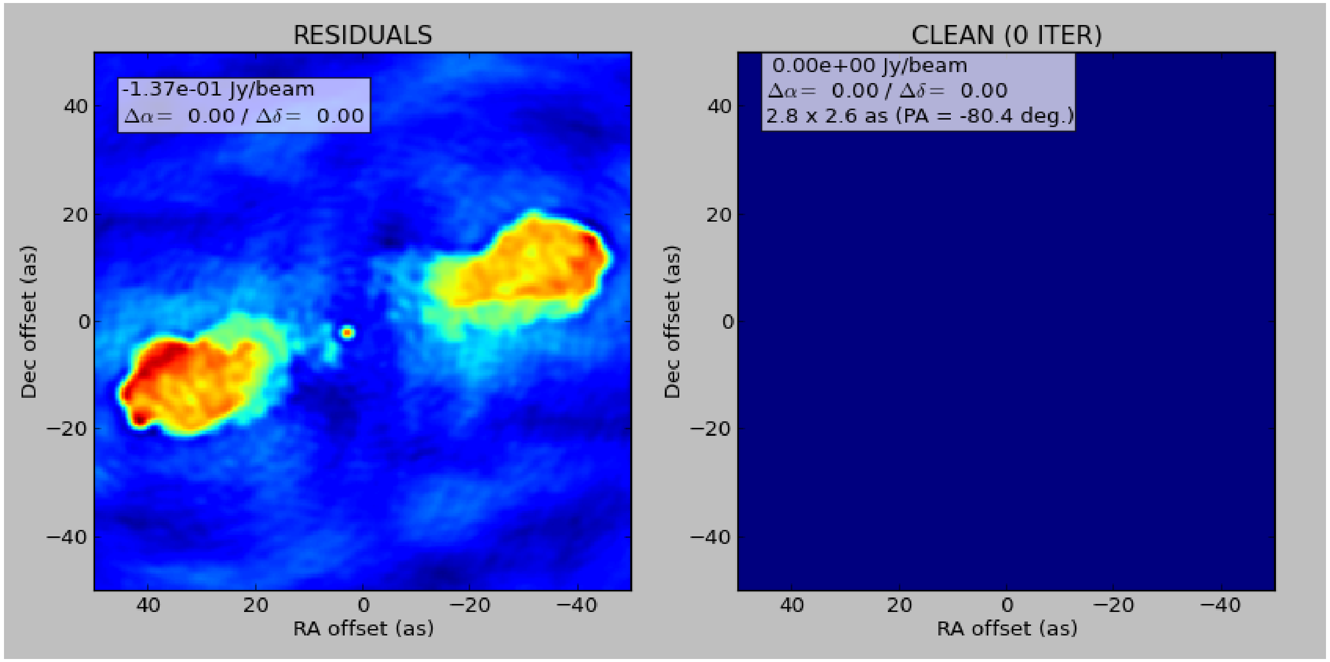
Larger if there are bright sources in the sidelobes of the primary beam (they would be aliased in the image)

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

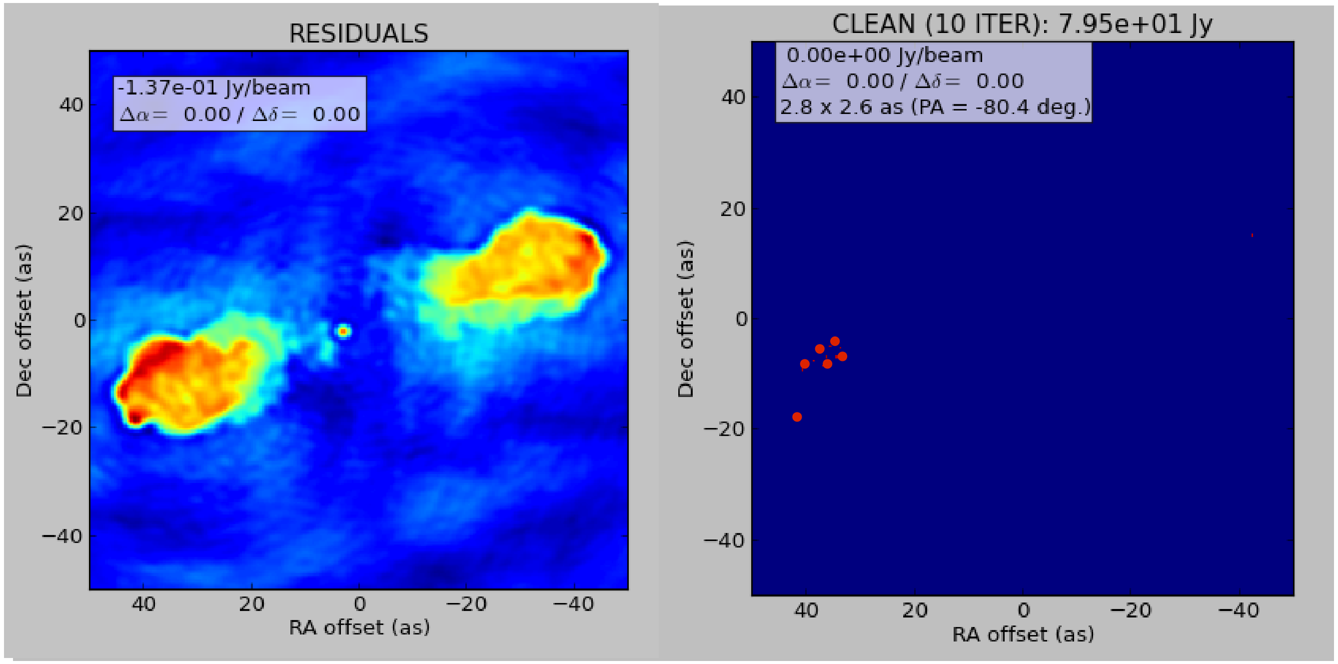


Deconvolution - Classic CLEAN

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



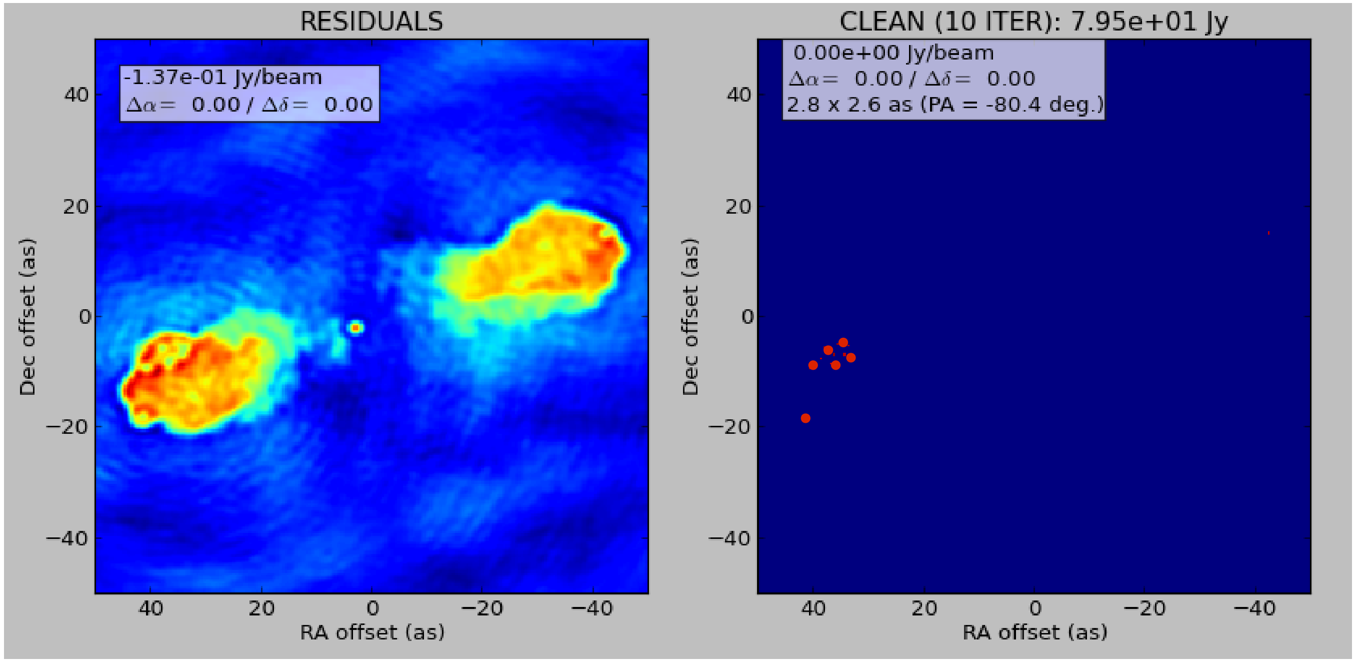
Loop gain

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) Subtracts over the whole map a dirty beam pattern, including the full sidelobes, centered on the position of the peaks saved in the clean component list, and normalized to the γI_{max} at the beam center.

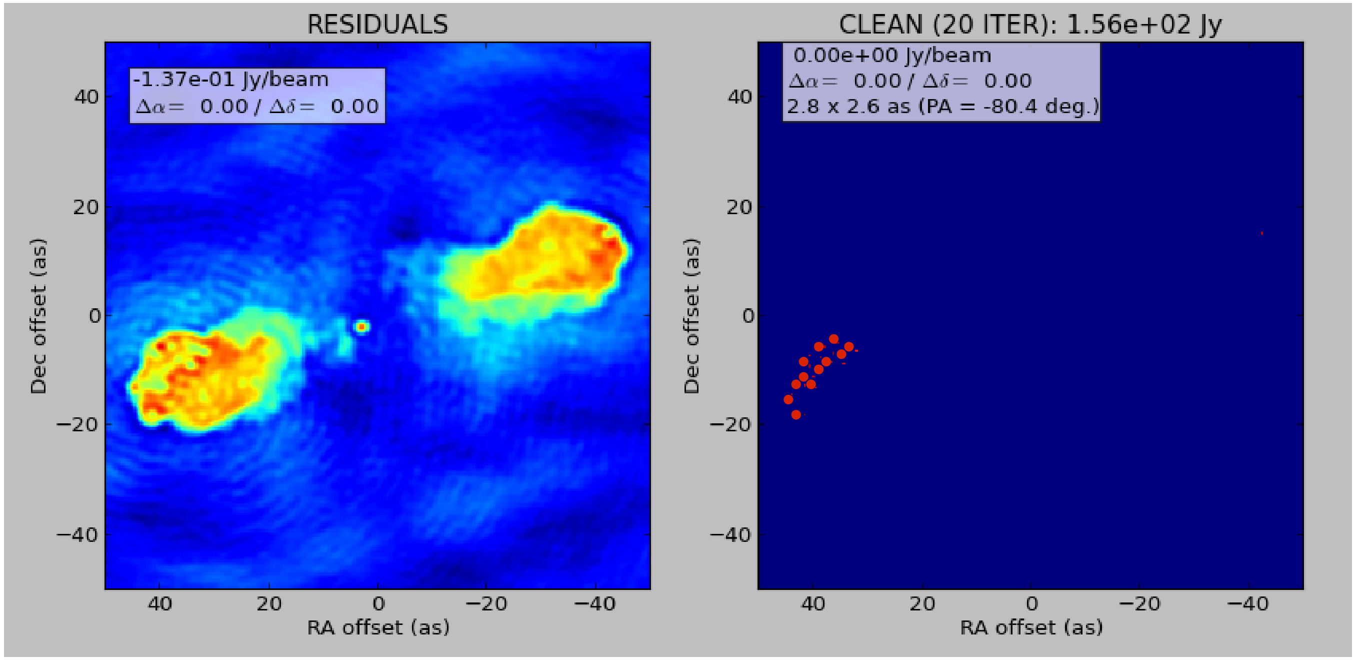


Deconvolution - Classic CLEAN

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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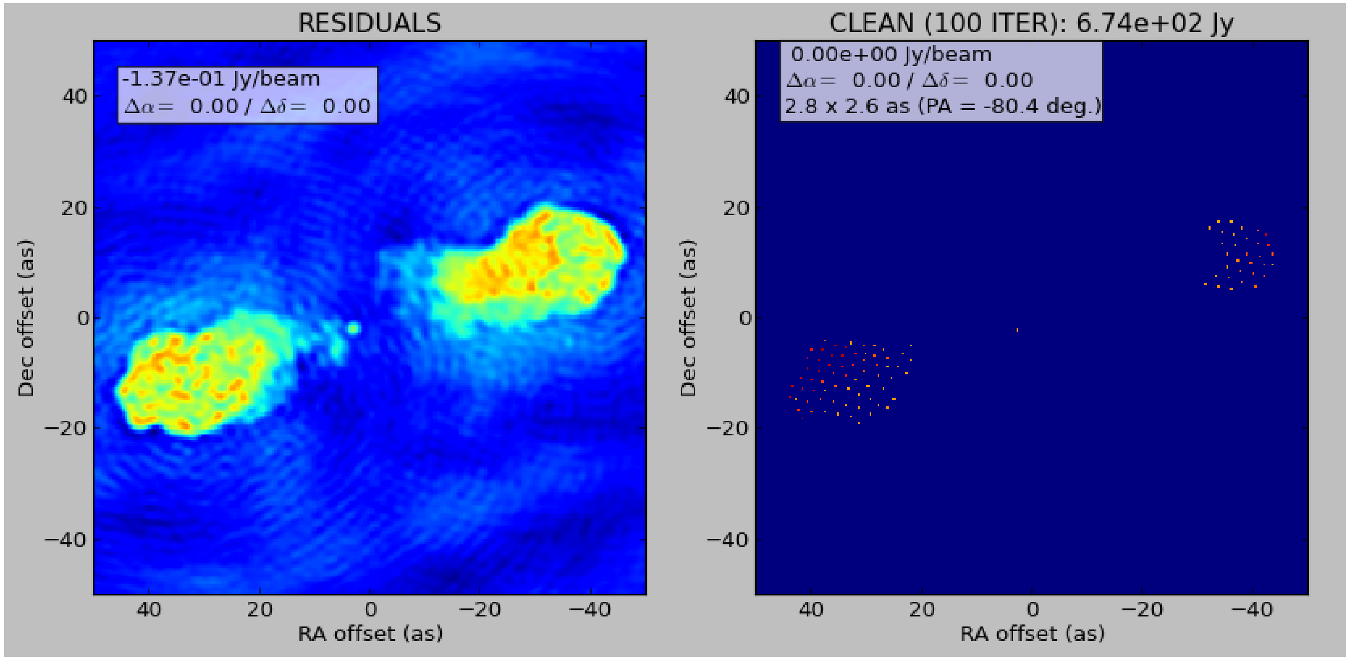

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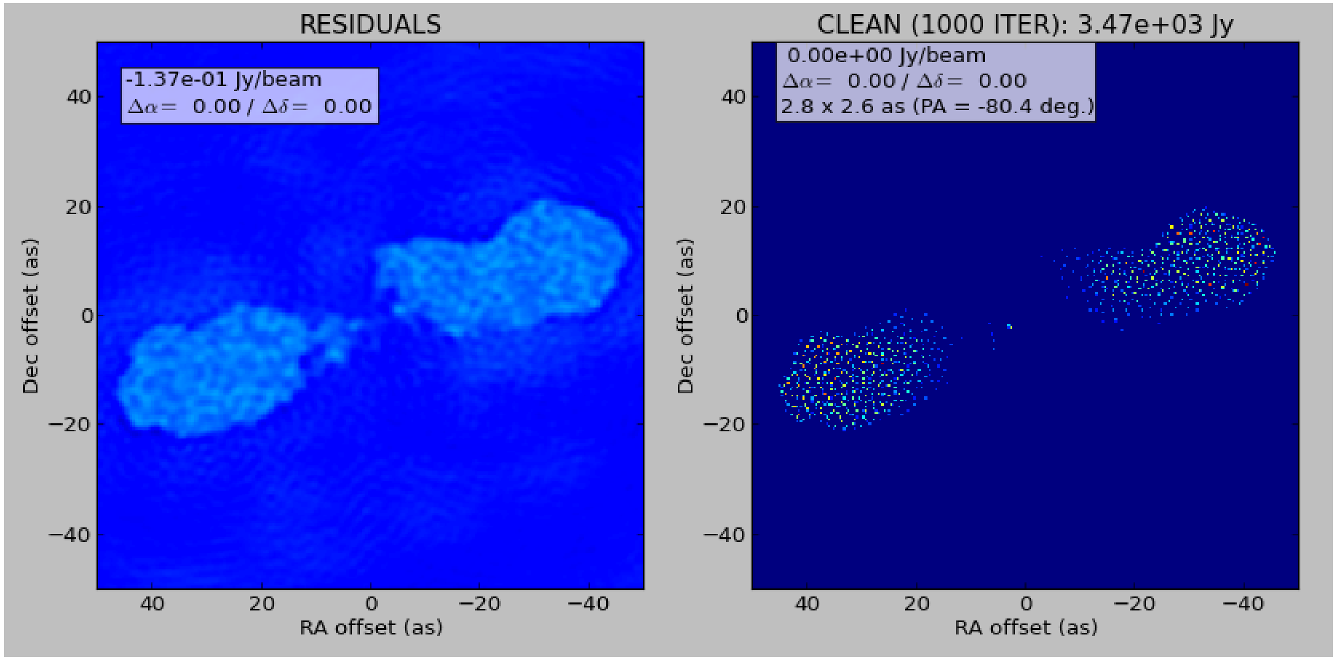

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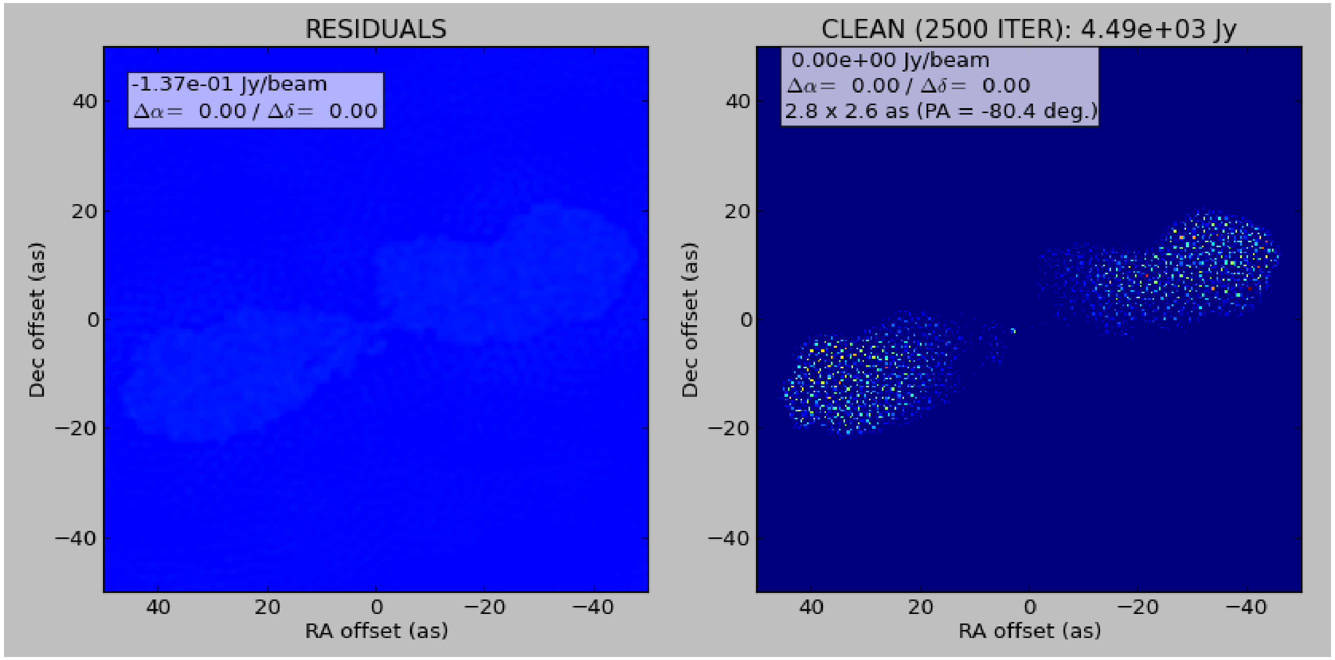

Stopping criteria

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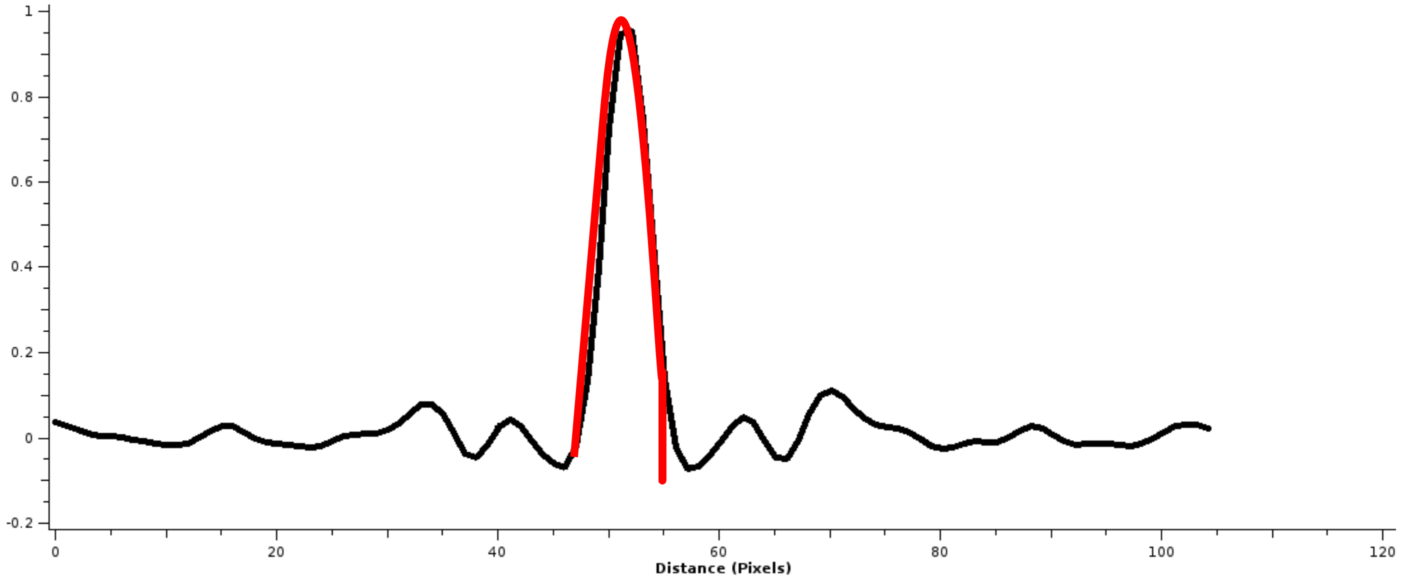
$|I_{max}|$ < fraction of the brightest source flux (when dynamic range limited)

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

Basic assumption: each source is a collection of point sources

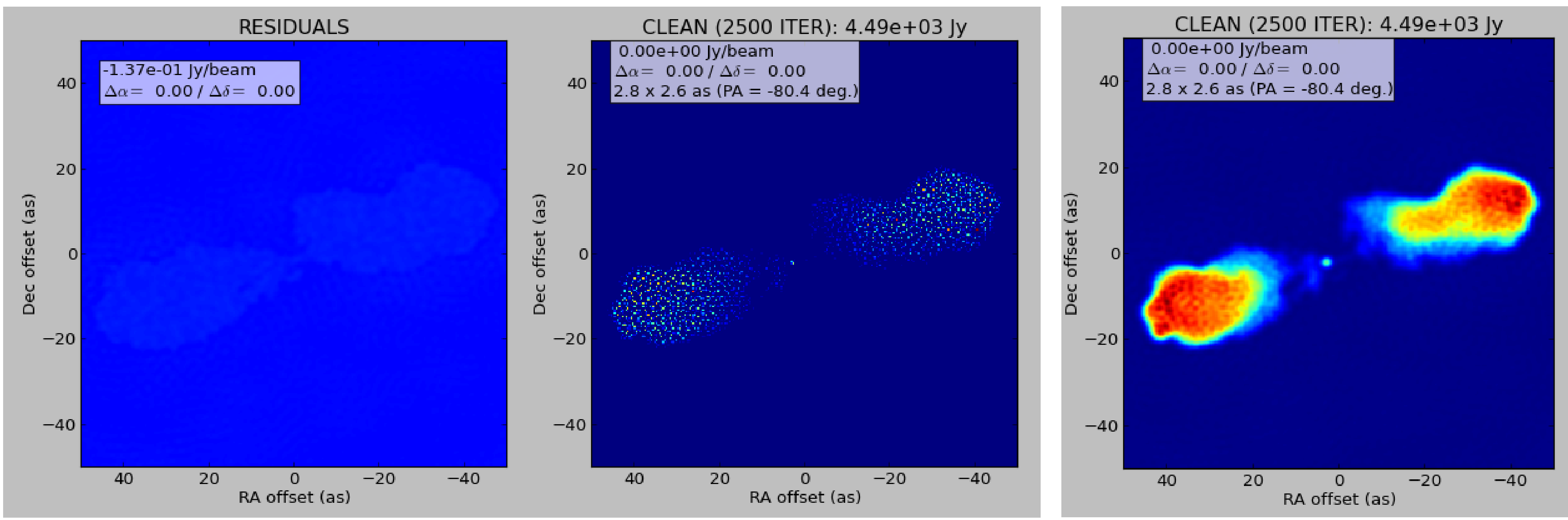
5) Multipies the clean components by **the clean beam**
an elliptical gaussian fitting the central region of the dirty beam
→ **restoring**



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



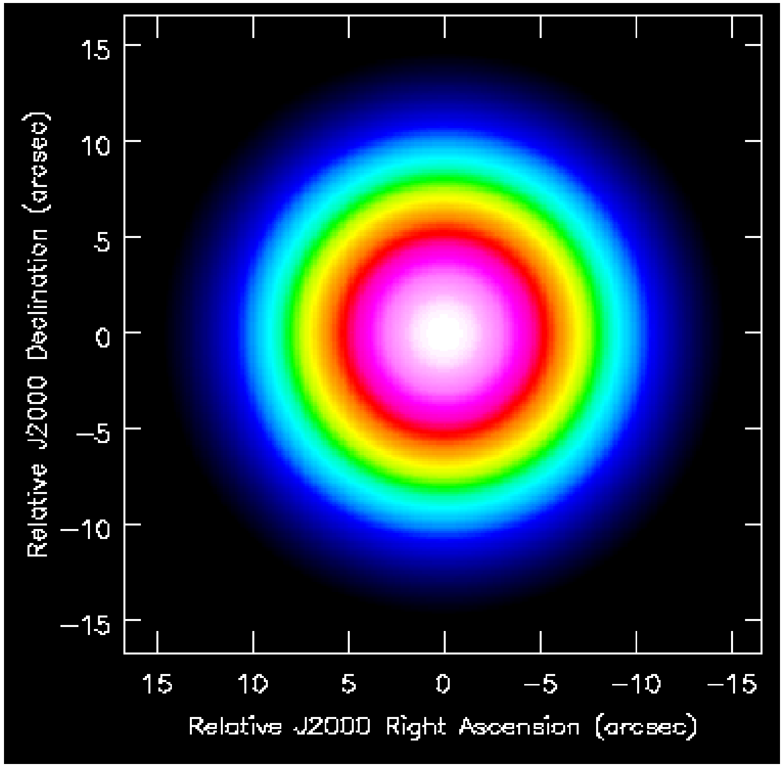
Resulting image pixel have units of Jy per clean beam

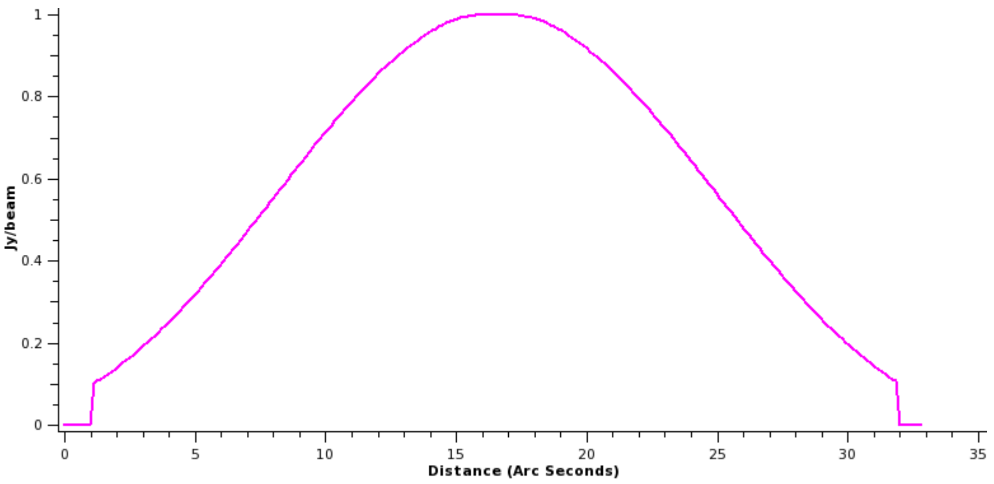
We need to get $T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$

But

Interferometer elements are sensible to direction of arrival of the radiation

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





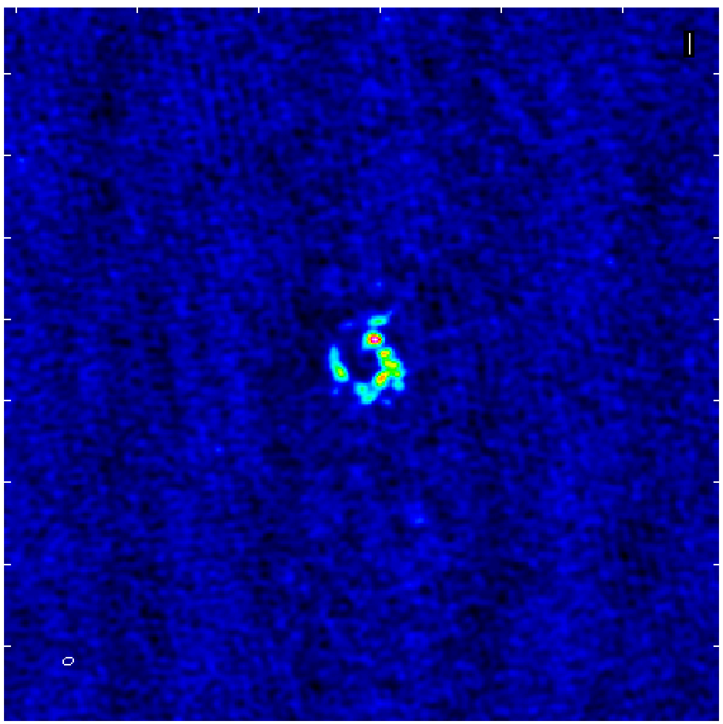
The response of the antennas in the array must be corrected for during imaging to get accurate intensities for source outside the core of the beam.

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

But

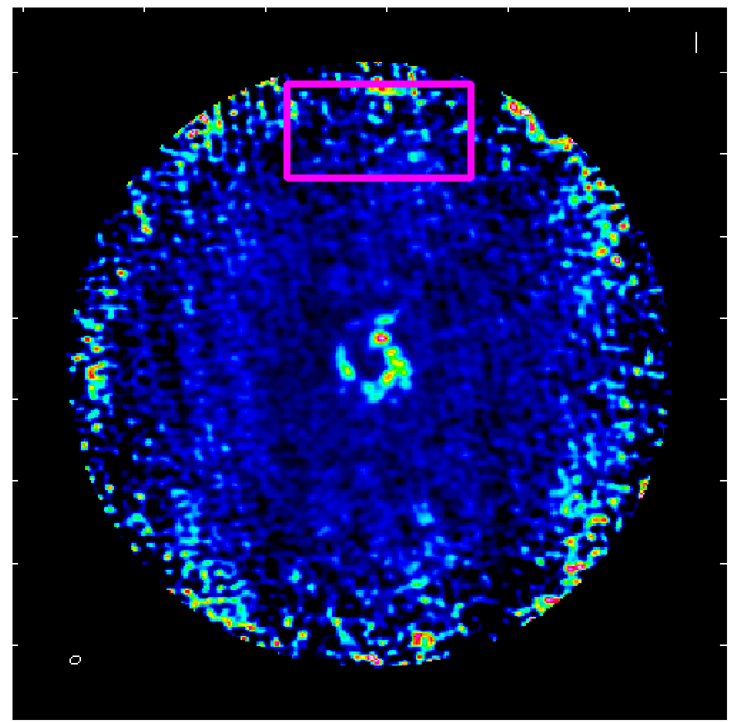
- **Primary beam effect** → $T(x,y) = A(x,y)\, T'(x,y)$

$T(x,y)$



rms 8e-4

$T'(x,y)$



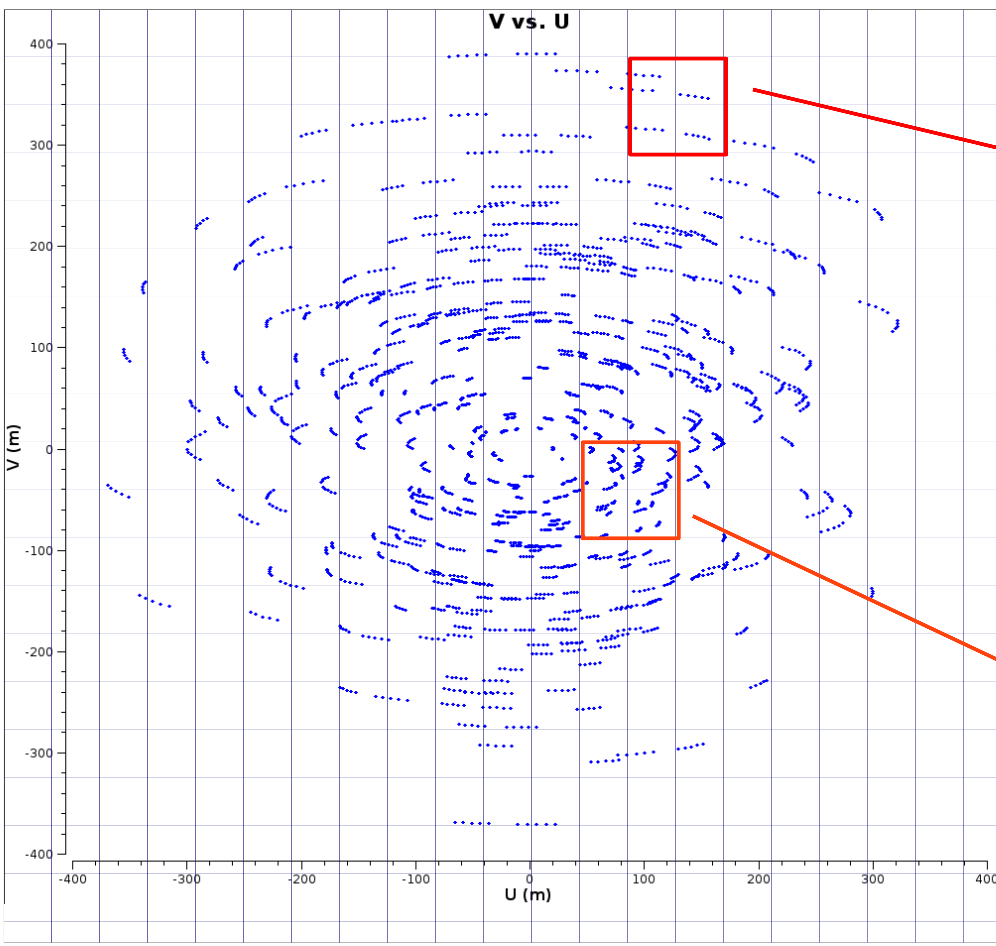
rms 3e-3

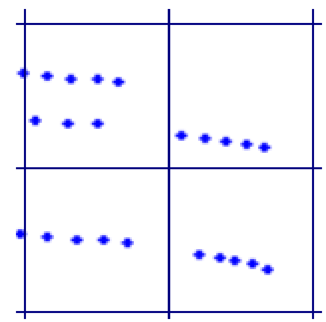
$$\sigma(u,v) \propto \frac{1}{\sqrt{T_{sys1}\,T_{sys2}}}$$

But

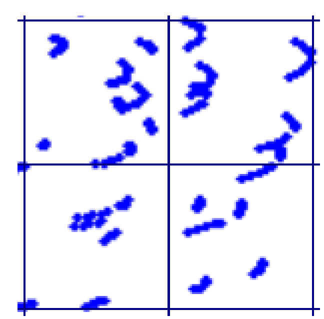
measured visibilities actually contain noise and some uv ranges are sampled more than others

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





Tipically, short spacing are sampled more than long



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

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

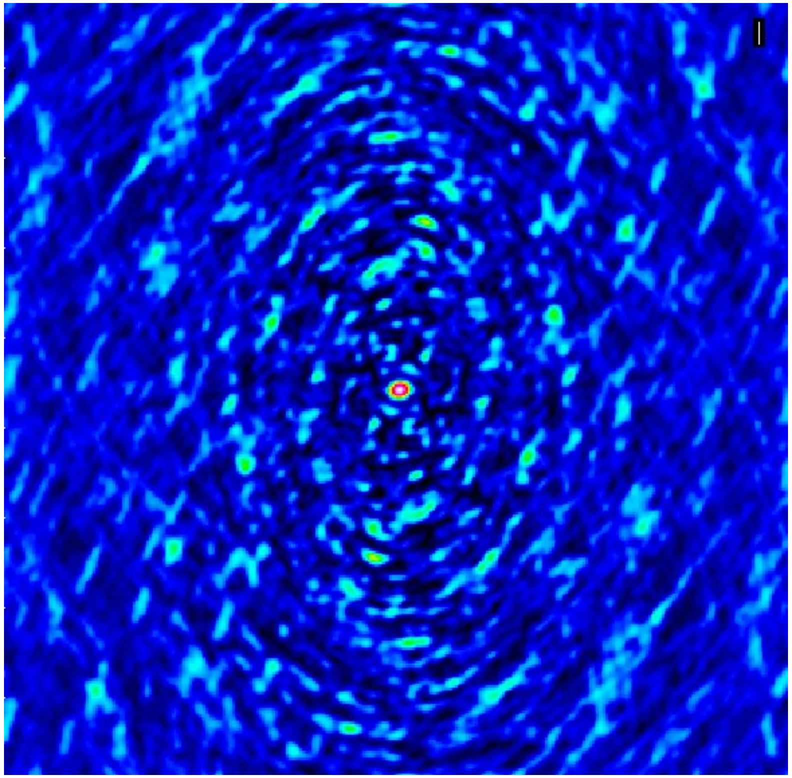
Unfortunately, in reality, the weighting which produces the best resolution **(uniform)** will often utilize the data very irregularly resulting in poor sensitivity → compromises

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

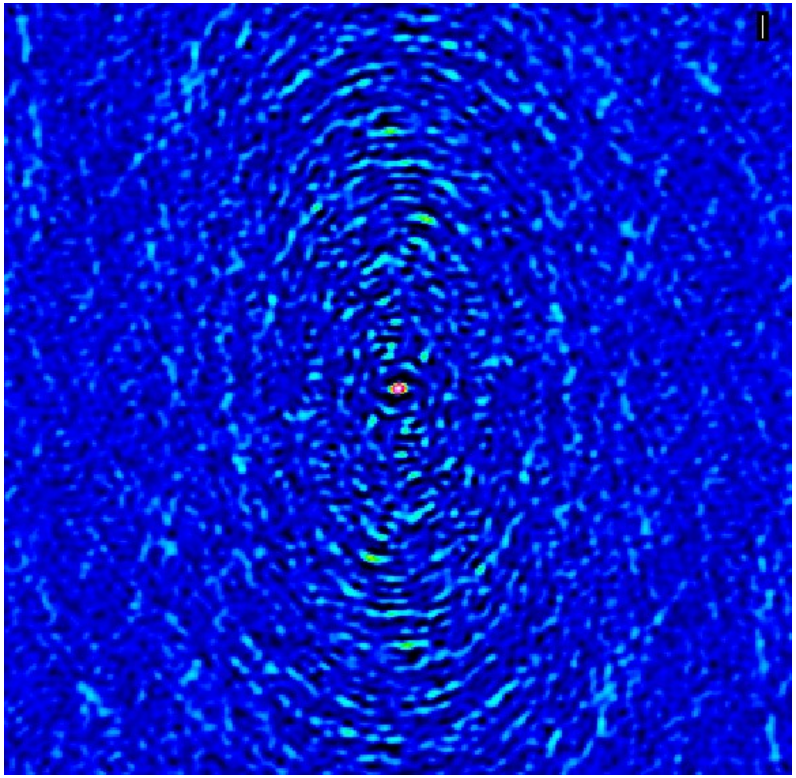
We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

Weighting effects on the Dirty beam

Natural
0.29'' x 0.23''
Best sensitivity



Uniform
0.24''x0.17''
Best angular resolution

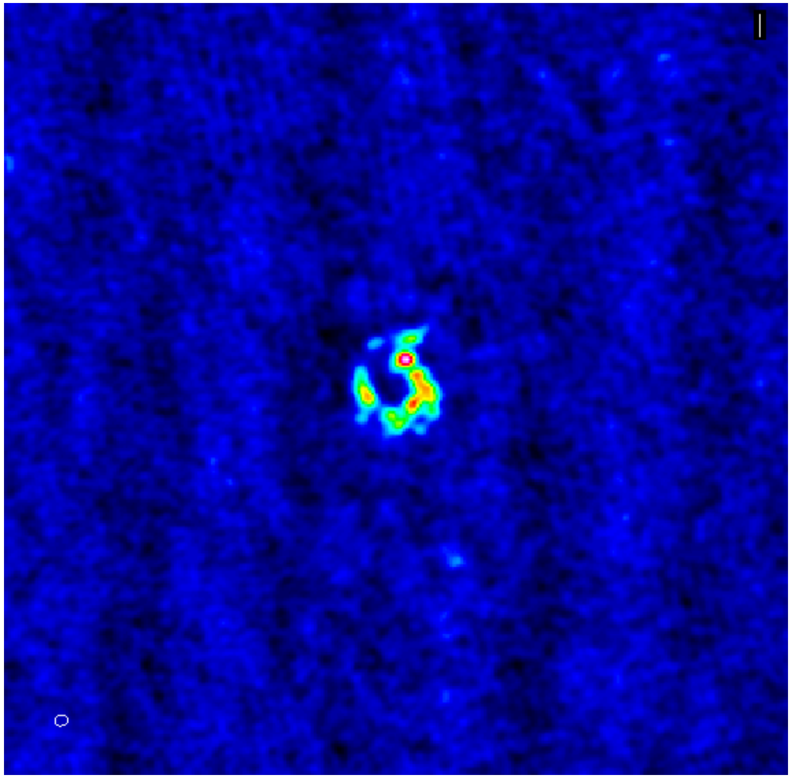


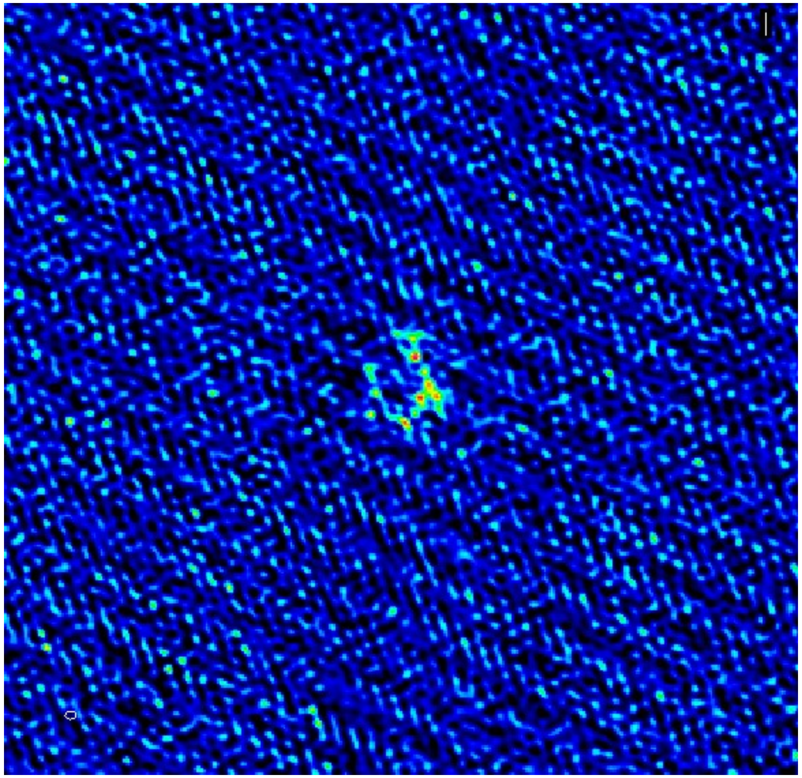
We need to get $T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$

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



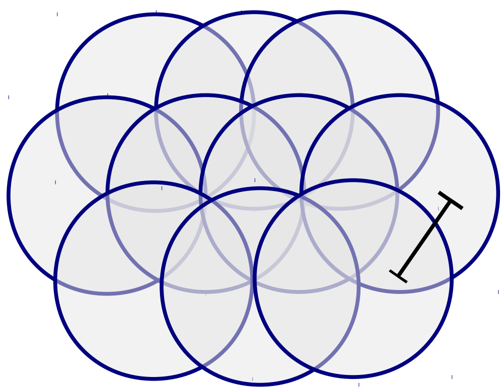


Possible clean iterations stopping criterium

3* expected sensitivity

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

In mosaics the standard pointing strategy



$$\frac{\lambda}{\sqrt{3}\,D}$$

Hexagonal grid

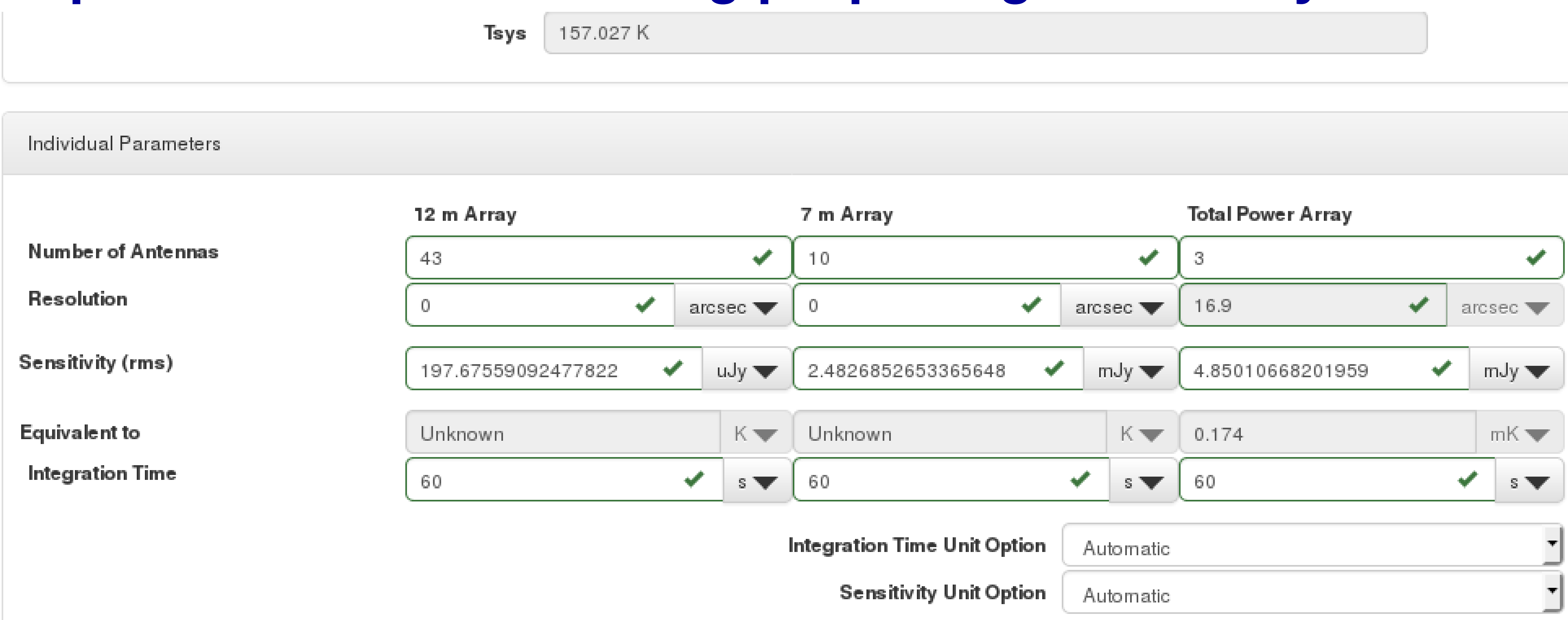
Most efficient coverage with minimal non-uniformity

Sensitivity per pointing improves by a factor 2.5

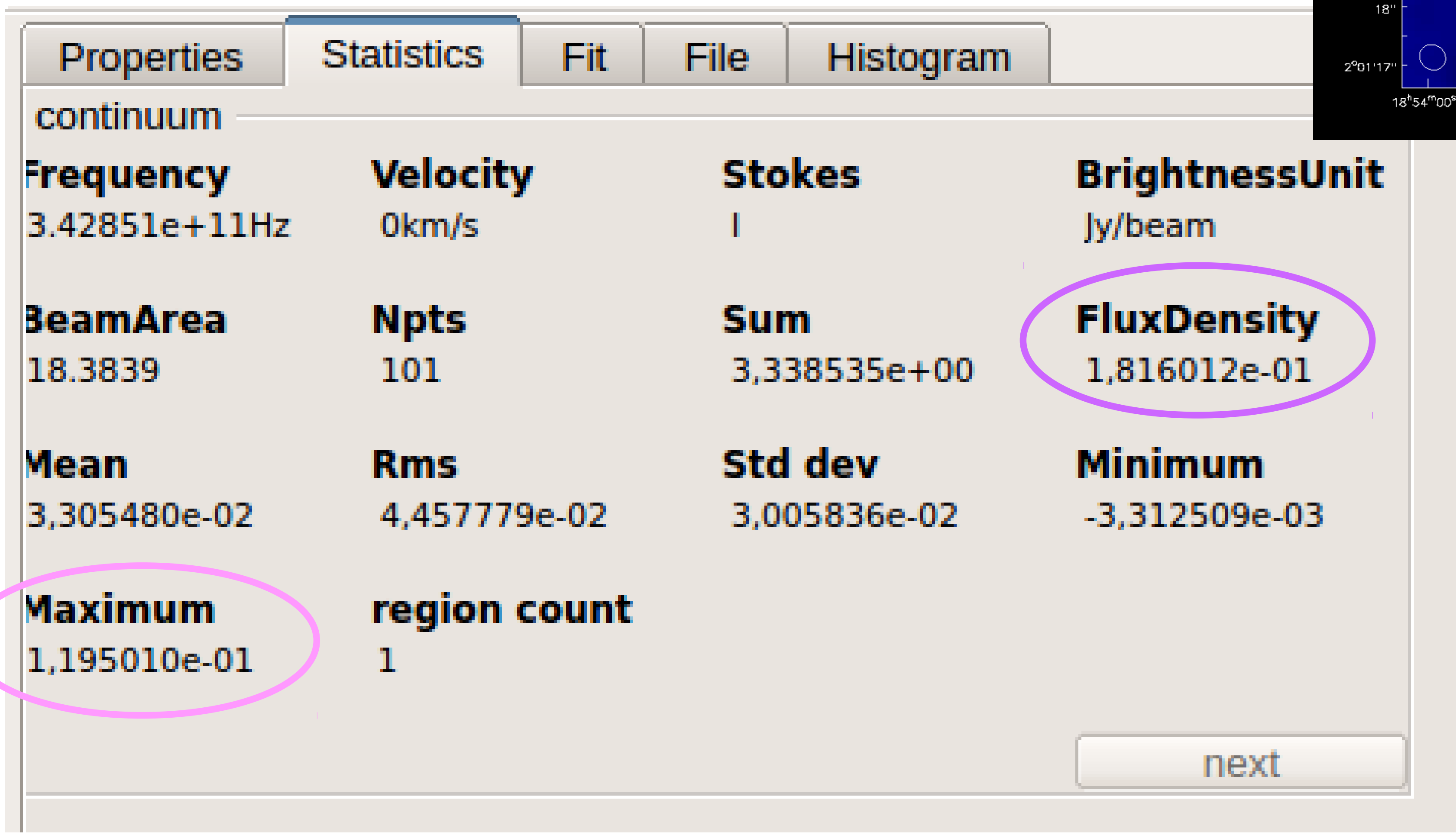
expected sensitivity

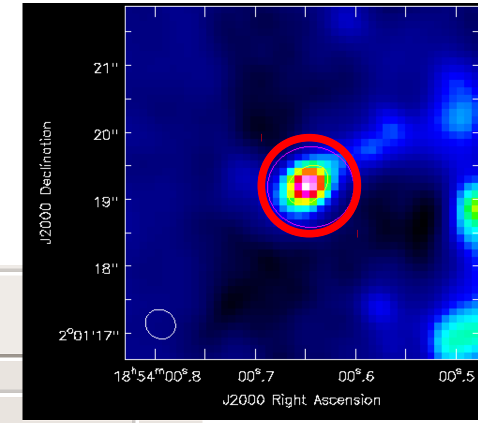
$$\sigma = \frac{2k}{\eta}\frac{T_{\rm sys}}{\sqrt{\Delta t \Delta \nu}\sqrt{N_{\rm ant}(N_{\rm ant}-1)A}}$$

https://almascience.eso.org/proposing/sensitivity-calculator



How to read the results from the viewer:
statistics in a region



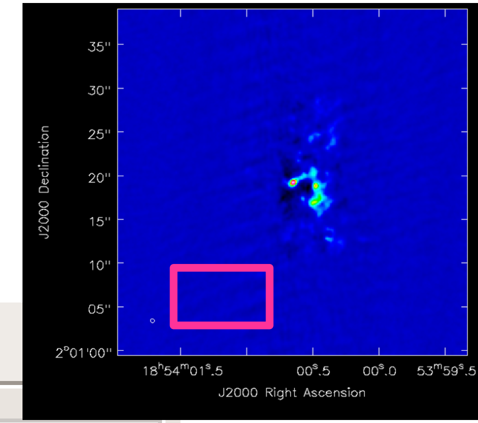


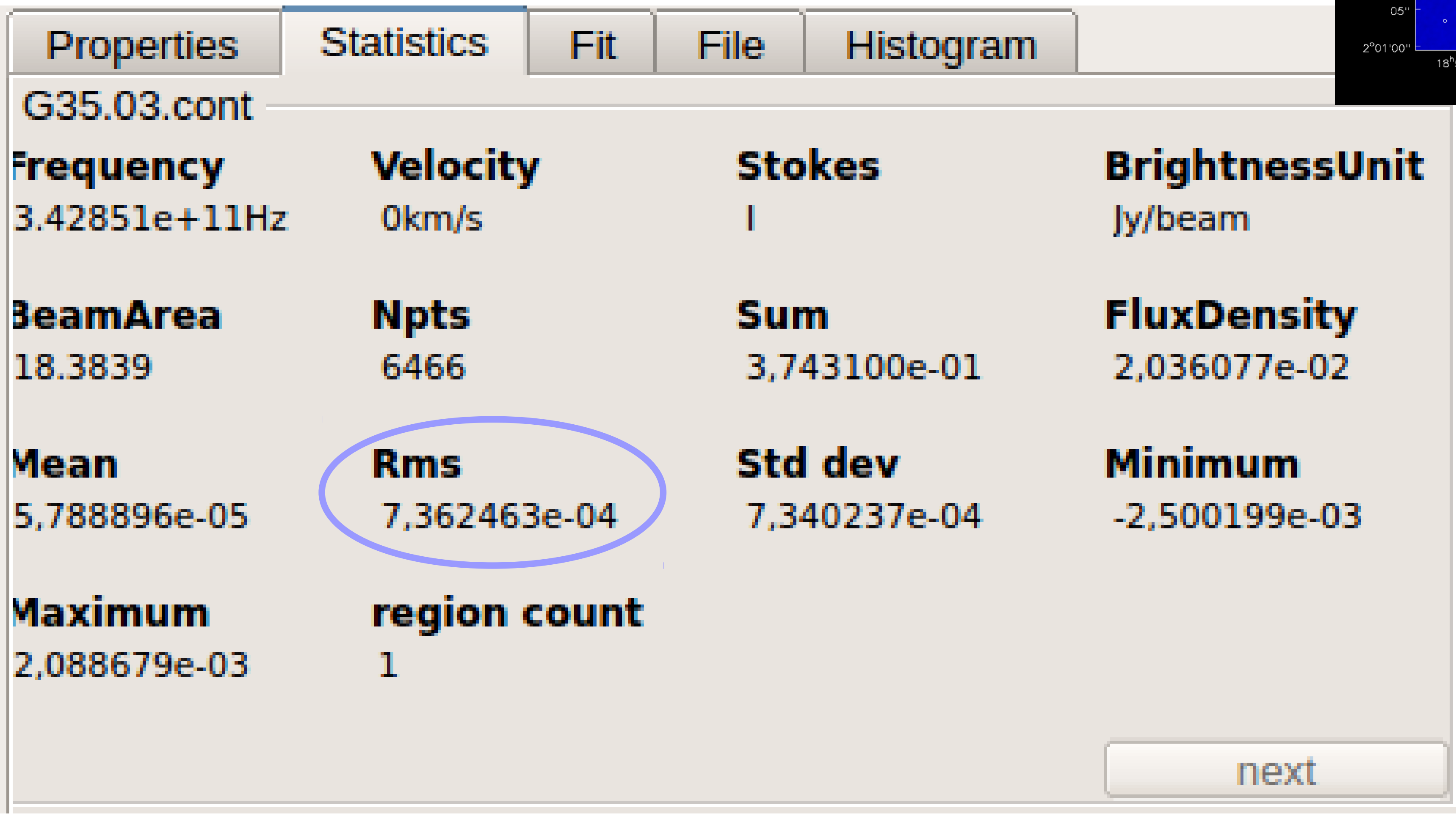
Flux density : the integrated flux density in the region [Jy]

Peak: the maximum pixel value in the region [Jy/beam]

How to read the results from the viewer:

rms in an empty region

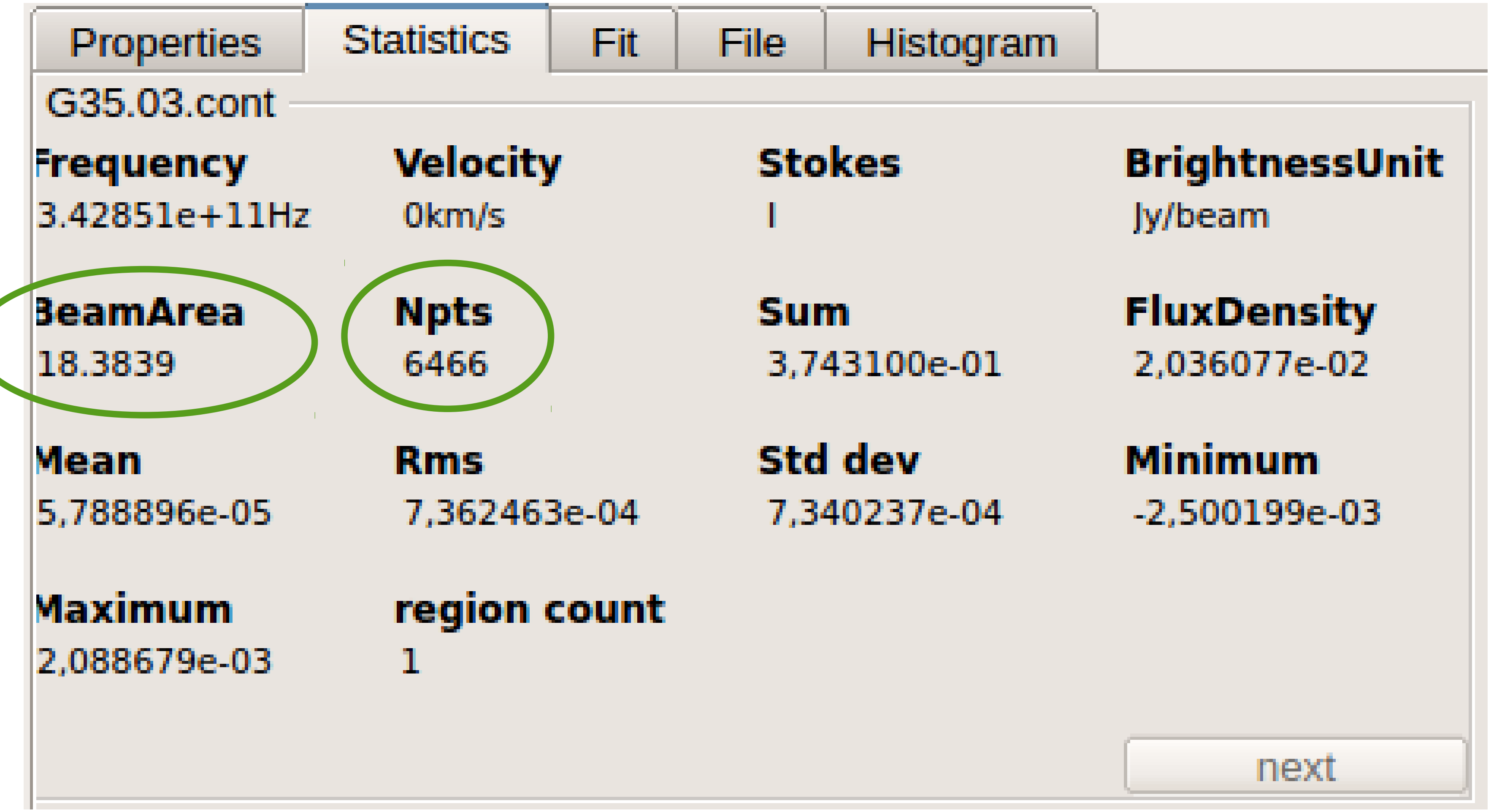




rms: the root mean square of the measures [Jy/beam]

How to read the results from the viewer:

Number of beams in a region



Npts/BeamArea= number of beams in the region

Error on your flux density measurements

The current standard calibration techniques provide a ~10% amplitude calibration accuracy

You measure F

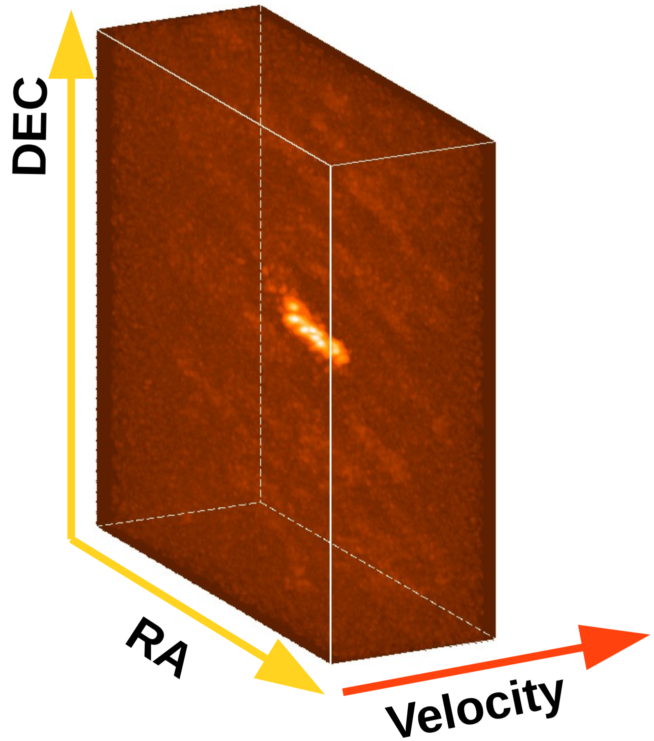
The uncertainty on your measure is

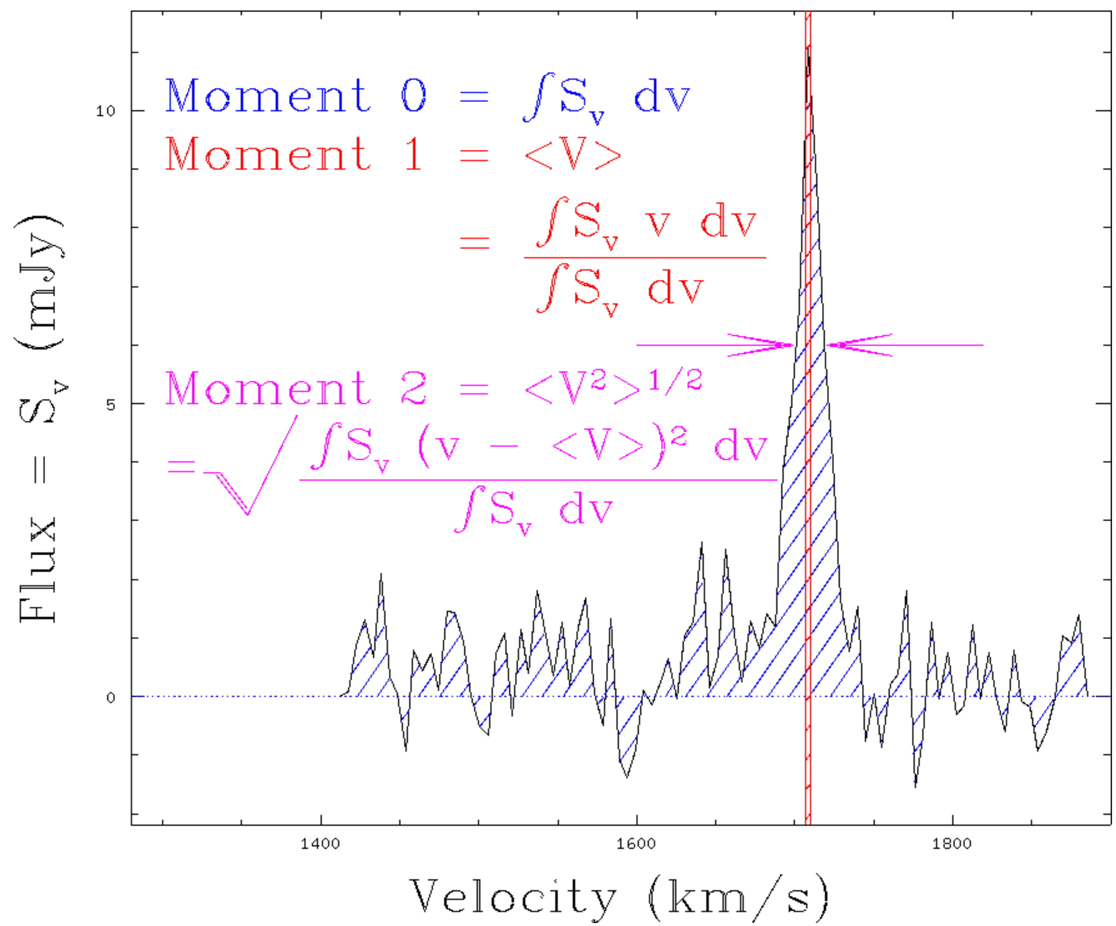
$$\sqrt{\left(rms*\sqrt{N_{beam}}\right)^2+\left(0.10*F\right)^2}$$

where N_{beam} is **Npts/BeamArea**

Moment maps

Integration along the velocity axis





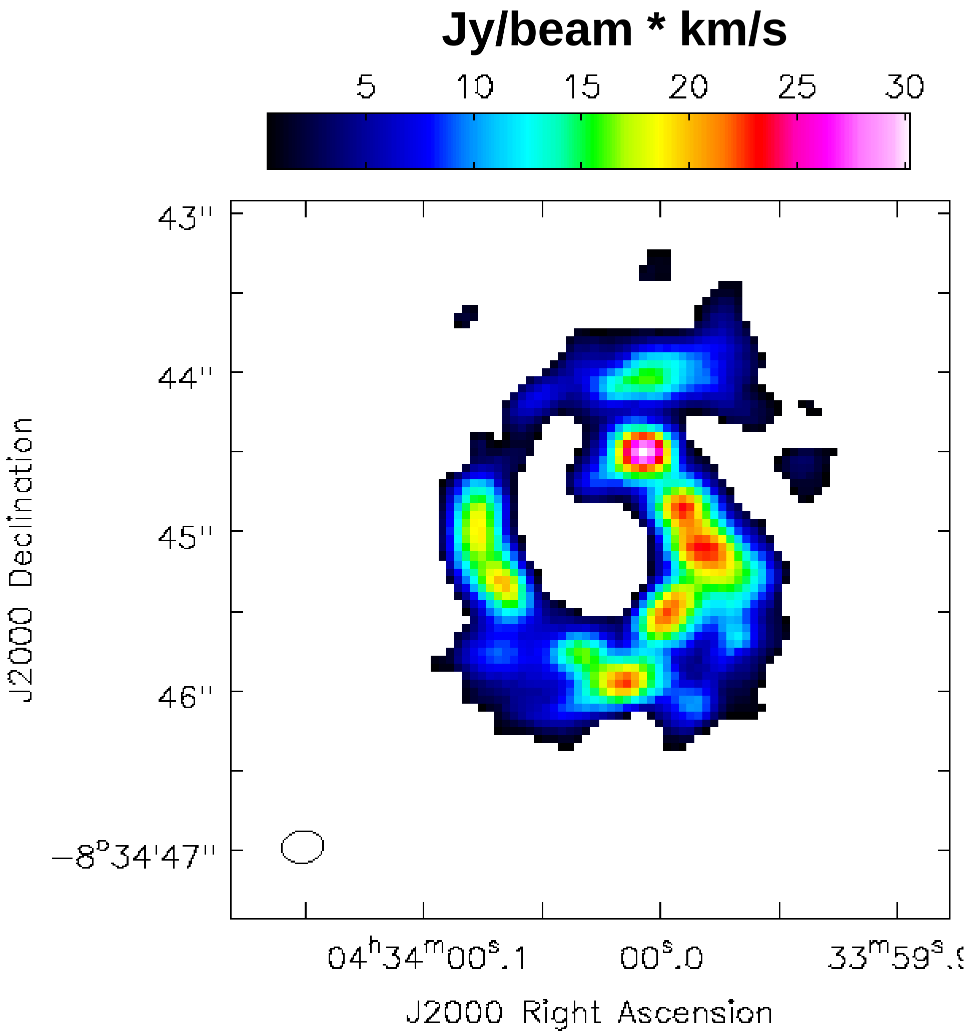
Integrated line intensity
Moment 0

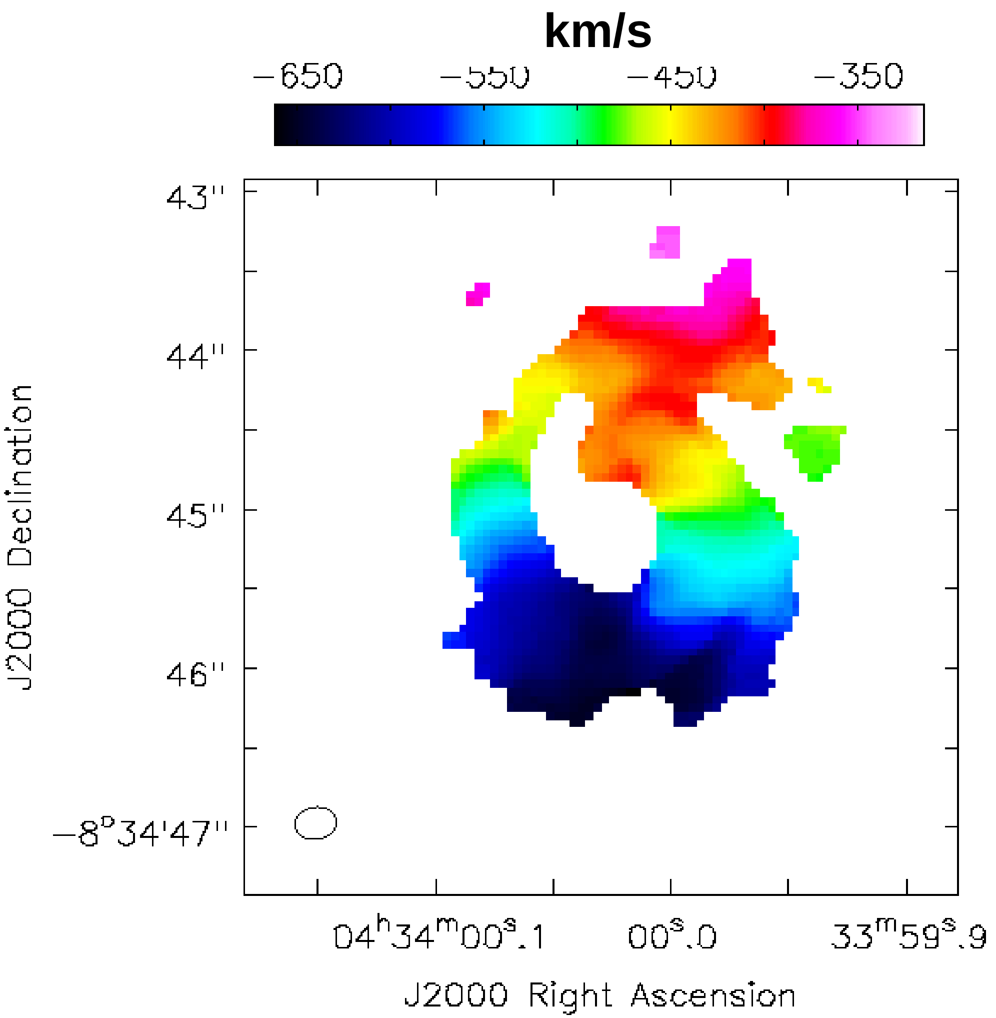
Velocity field
Moment 1

Velocity dispersion
Moment 2

Moment 0 $\int S_v \, dv$

Moment 1 $\dfrac{\int S_v \, v \, dv}{\int S_v \, dv}$

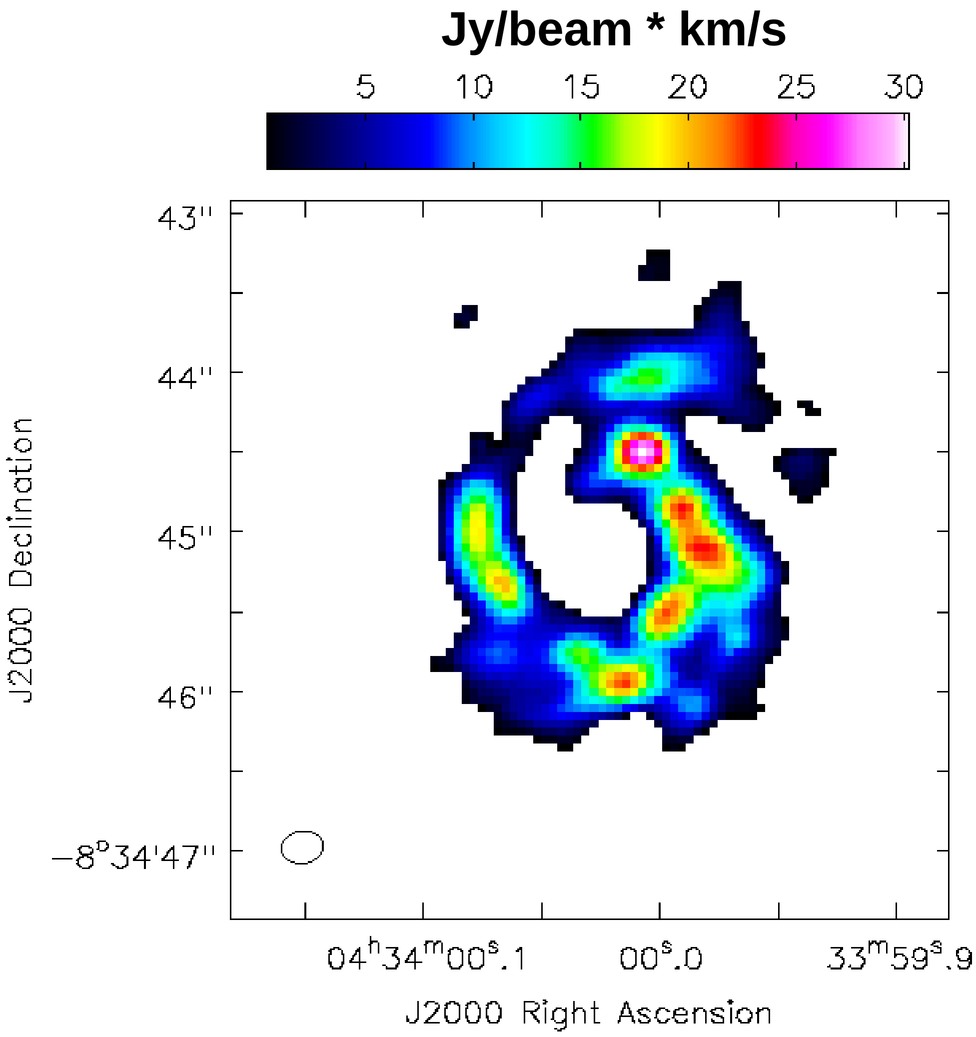




Moment 0 : each pixel shows the integrated intensity over the velocity axis

Moment 1 : each pixel shows the intensity-weighted velocity

Moment 0 $\int S_v \, dv$

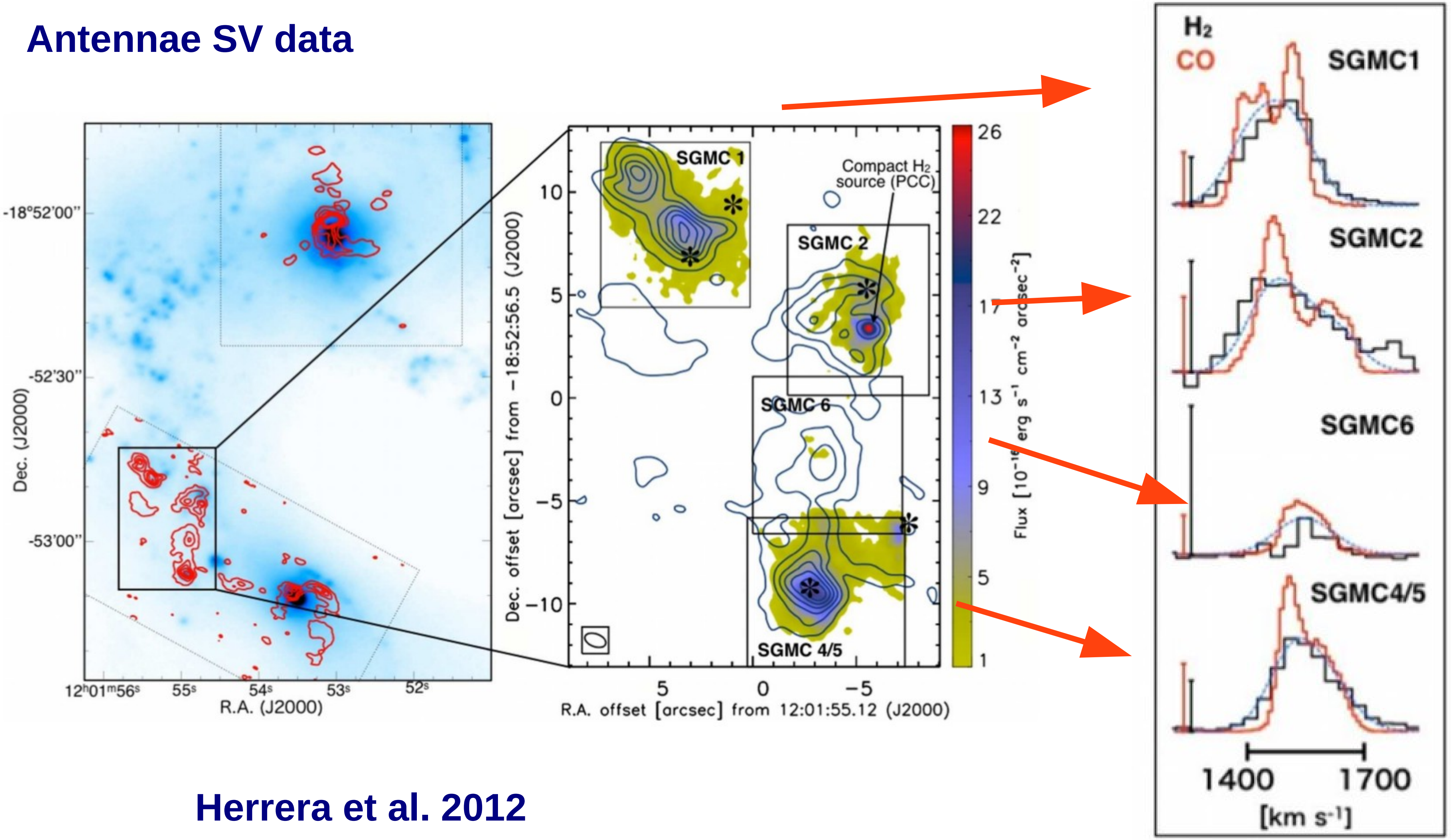


The uncertainty of the mom0 image is

$$rms * \sqrt{N_{chan}} * \delta v$$

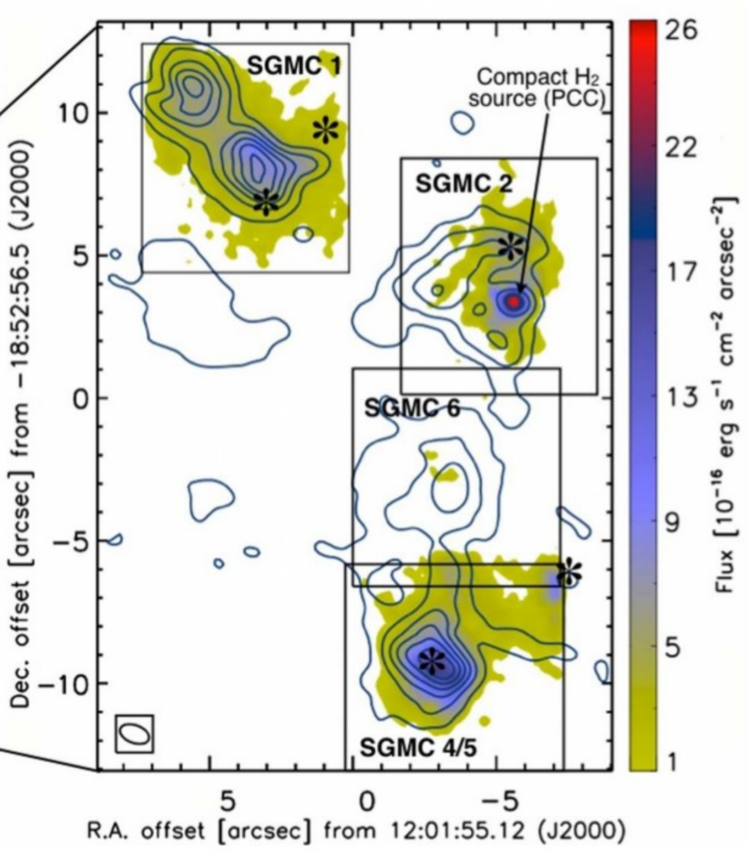
where rms is the rms measured in line-free channels

Antennae SV data

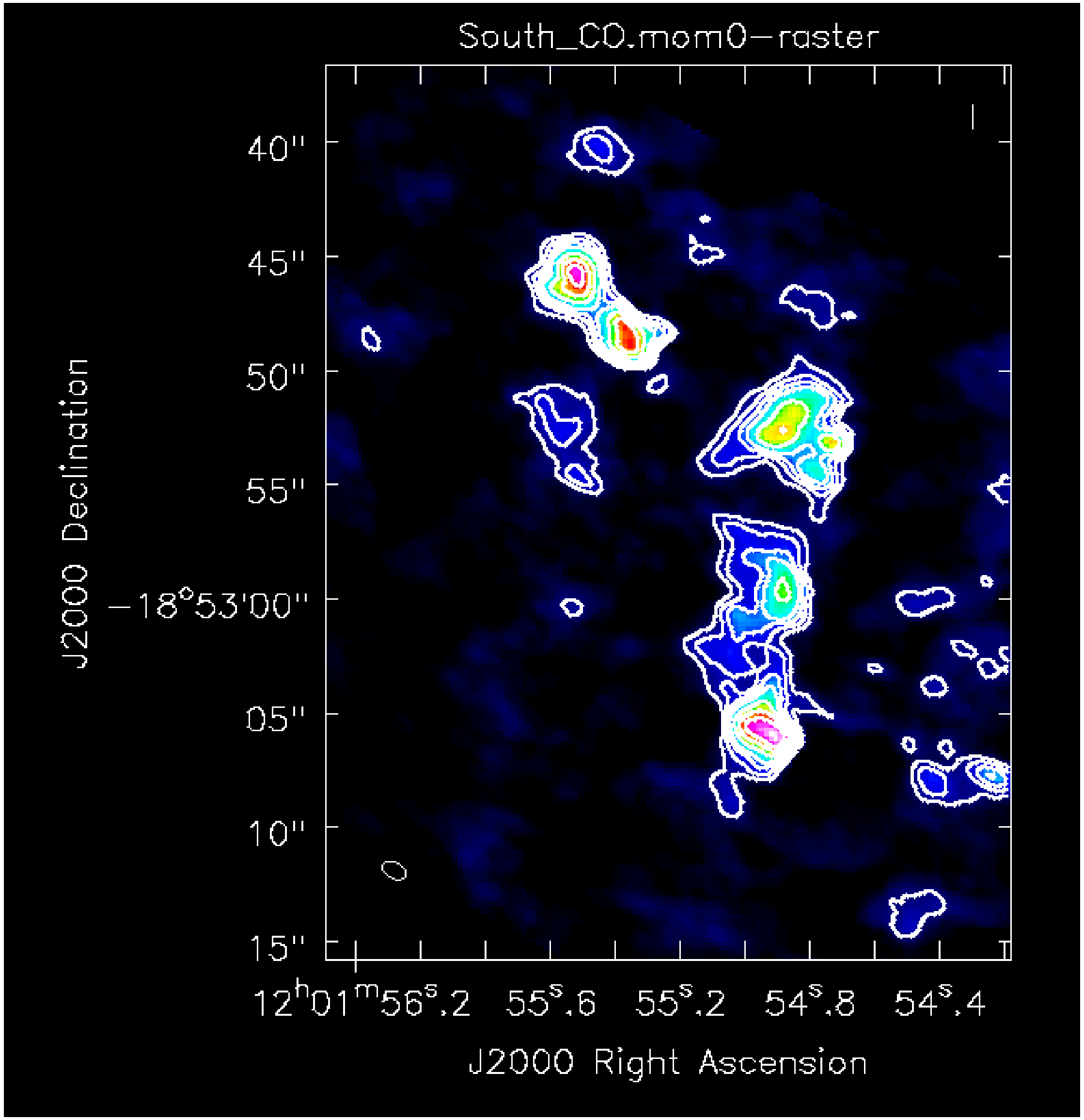


Herrera et al. 2012

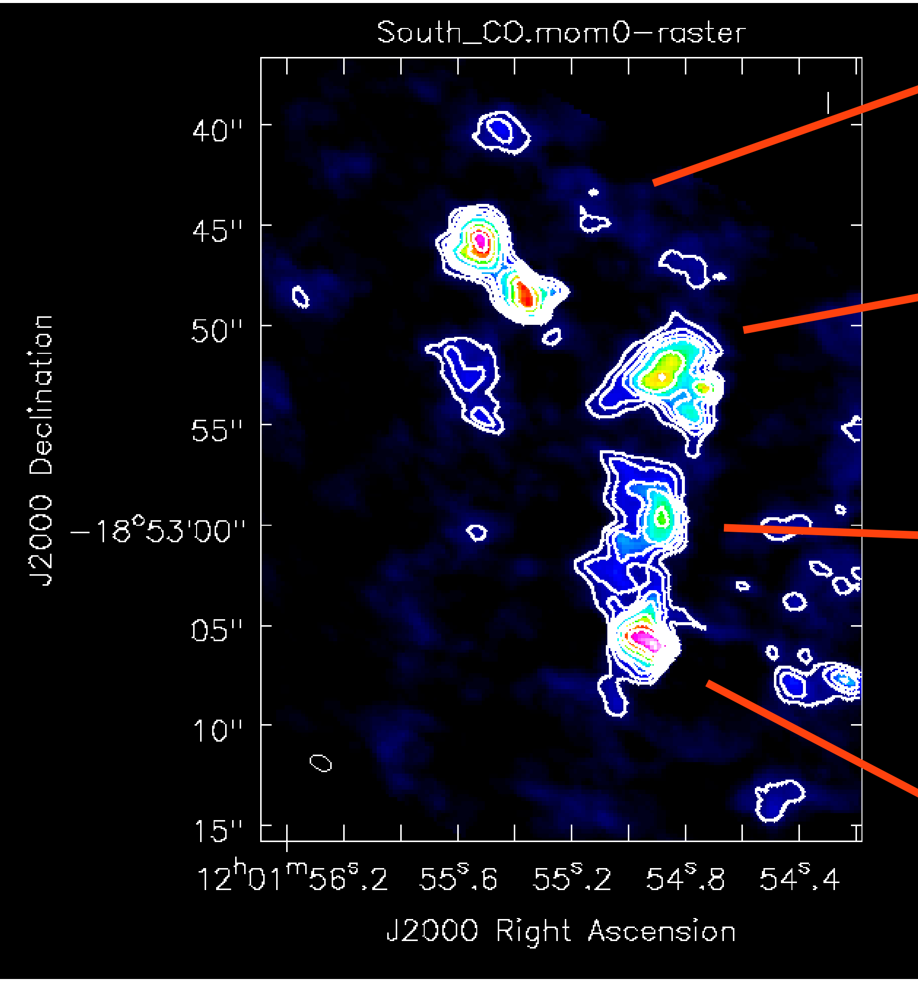
Antennae SV data

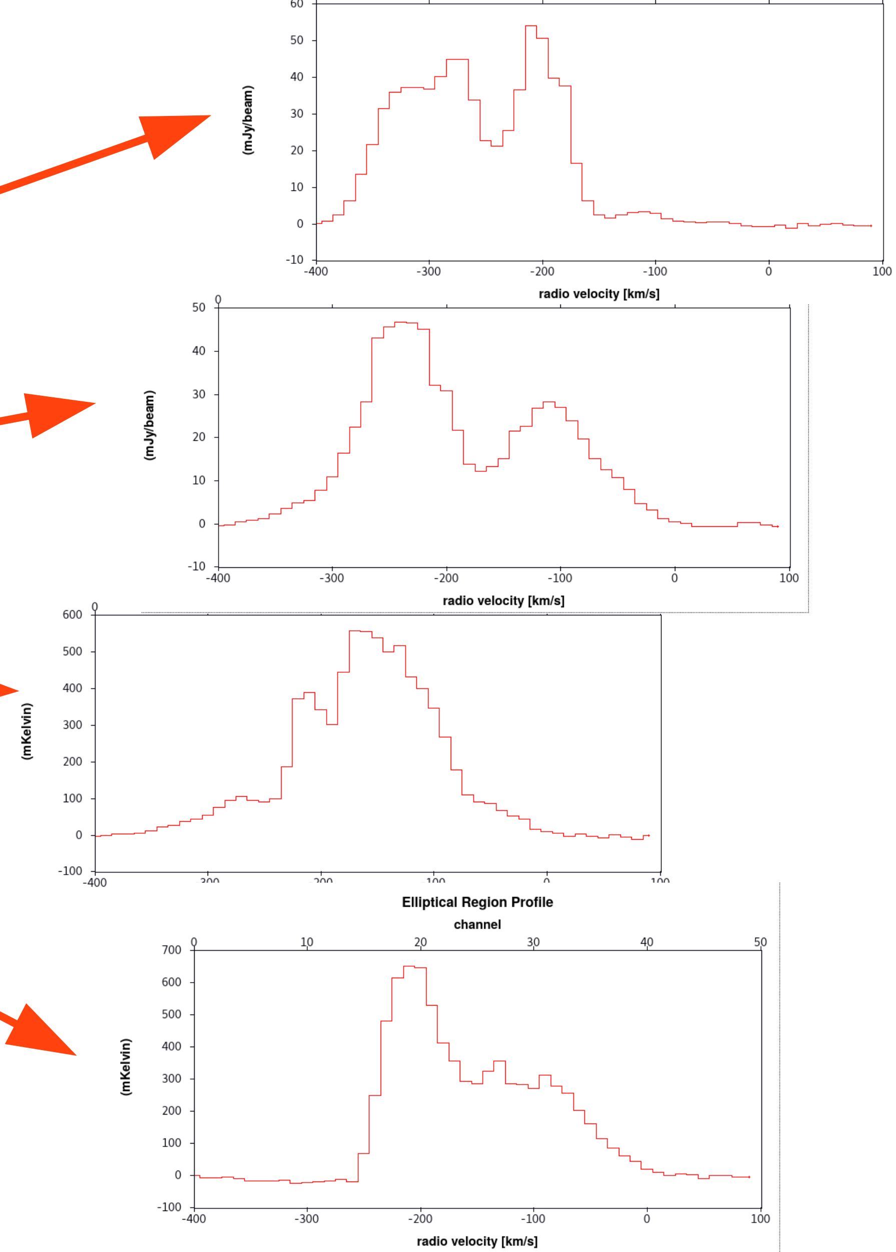


Herrera et al. 2012

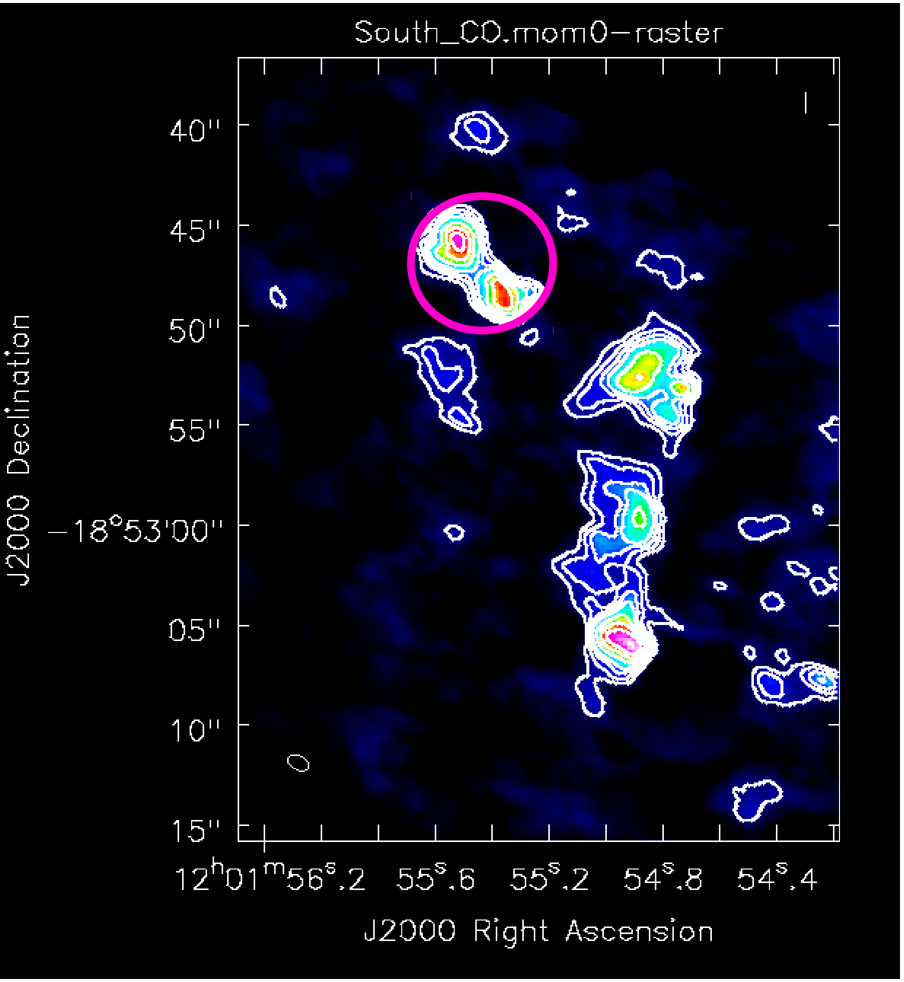


Antennae SV data





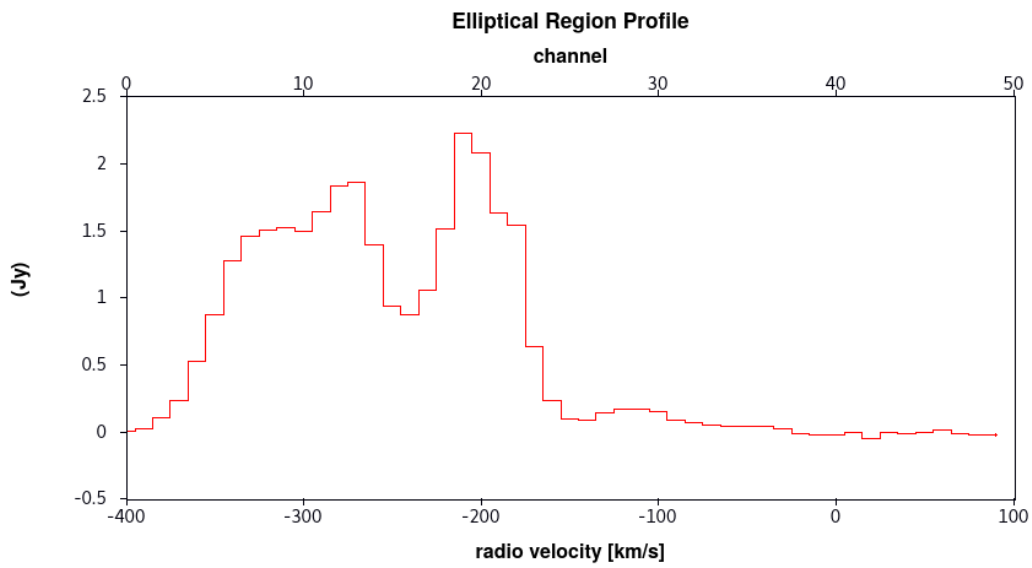
Antennae SV data



From mom0 image
it is possible to measure the
integrated flux density in a region

S_{CO} = 380 ± 11 Jy km/s

it is equivalent to measure the area of the
spectrum extracted from the same region



The CO(1–0) integrated intensity map can be used to calculate the **molecular gas mass** using the CO-to-H_2 conversion factor:

$$X_{CO} = 2 \times 10^{20} \frac{cm^{-2}}{K\, km\, s^{-1}}$$

$$M_{mol} = 1.05 \times 10^{4} \frac{X_{CO}}{2 \times 10^{20} \frac{cm^{-2}}{K\, km\, s^{-1}}} \frac{S_{CO} D_L^2}{(1+z)}$$

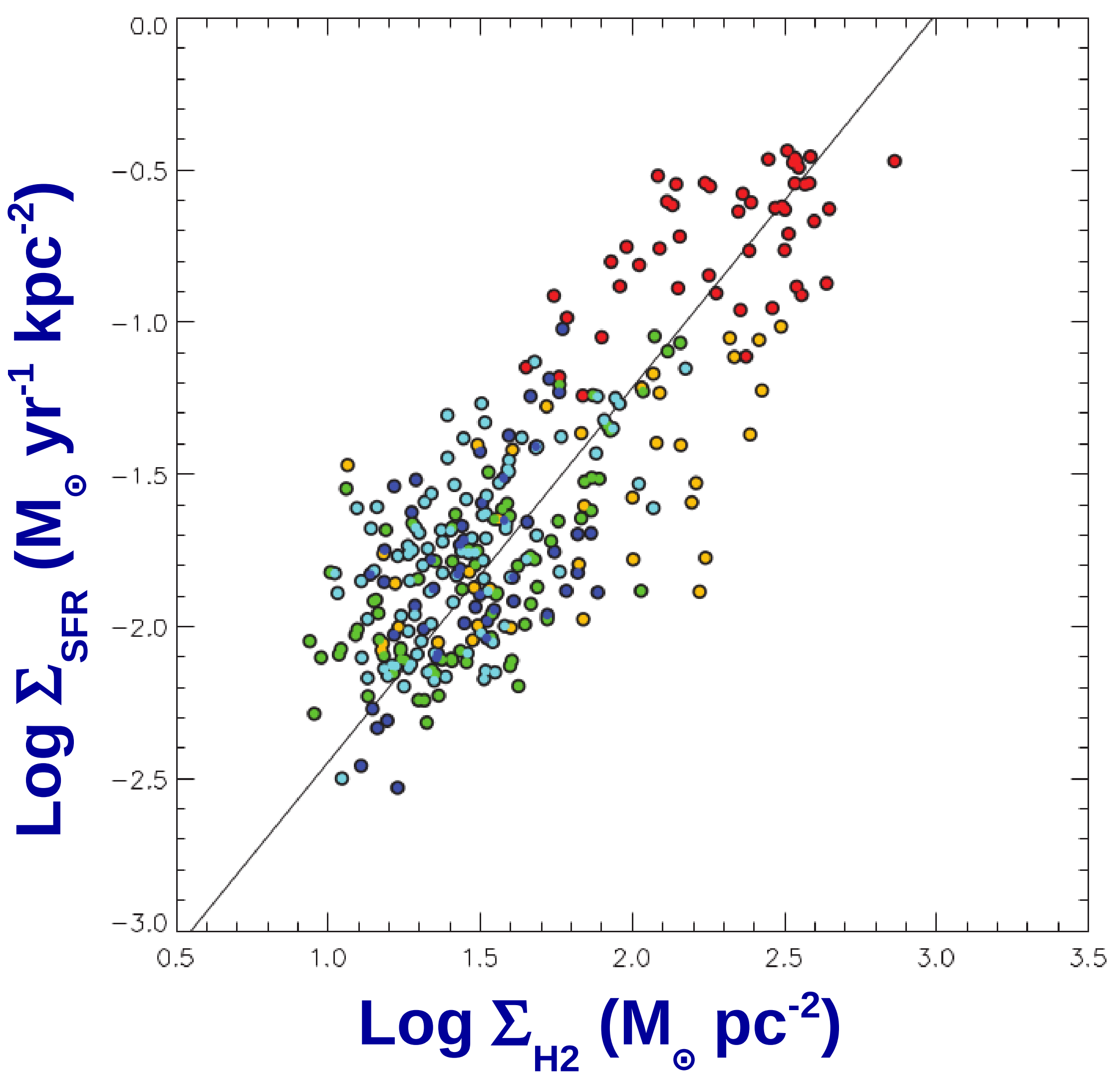
M_{mol} is in Solar masses

S_{CO} is the integrated line flux density in **Jy km/s**

D_L is the luminosity distance in **Mpc**

Bolatto 2013

The Kennicutt-Schmidt law is a relationship between
gas surface density and star formation rate surface density.



The Kennicutt-Schmidt law
for M100.

Points colorized by
galactocentric distance:
fed at the galaxy centre
and blue in the outer spiral arms

Vlahakis 2013