

Lecture 2

Interferometry and ALMA

AstroTwin Colombia School 2022
Planet formation and ALMA
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Credits to Logan Francis

Contents

- Introducing ALMA
- Basics interferometry
- ALMA interferometry
- Calibration
- Cleaning/imaging
- Basic CASA inspection
- Continuum vs line
- Detections and non-detections
- Using the ALMA archive

ALMA

ALMA: Atacama Large Millimeter/submillimeter Array



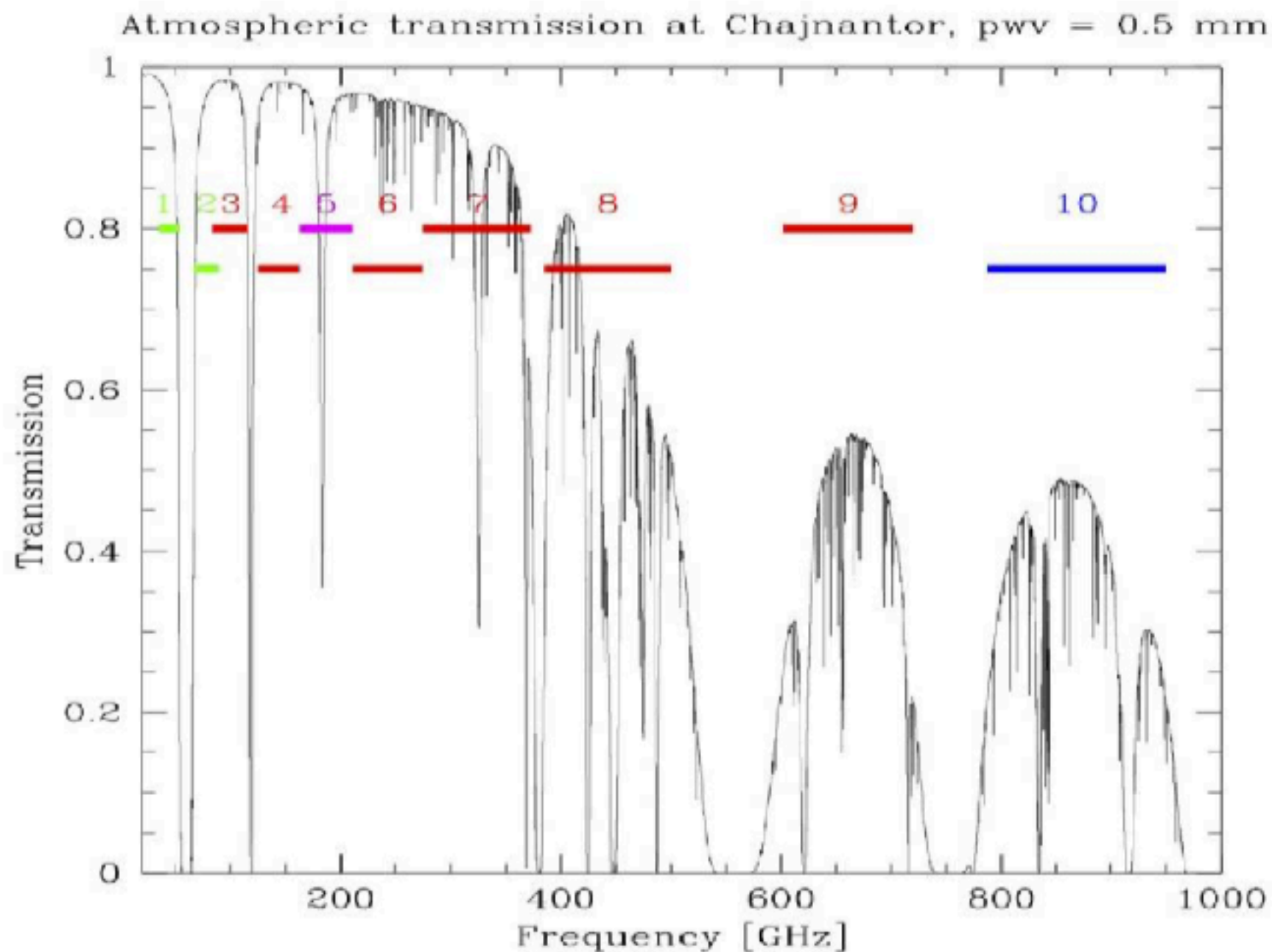
ALMA

- Array of 66 antennas in Atacama desert in Chile at 5100m elevation
- Started operations in 2011
- Global collaboration between Europe, North America, Chile and East Asia
- Budget 1.3 billion \$ for operation of 30 years
- Sensitivity 100 times higher and resolution 200 times better than previous interferometers
- Resolution down to 0.01''!
- ALMA:
 - 12m-array: 50 antennas, 10 possible configurations with baselines <16 km
 - 7m array (ACA): 12 antennas
 - Total power array: 4 antennas



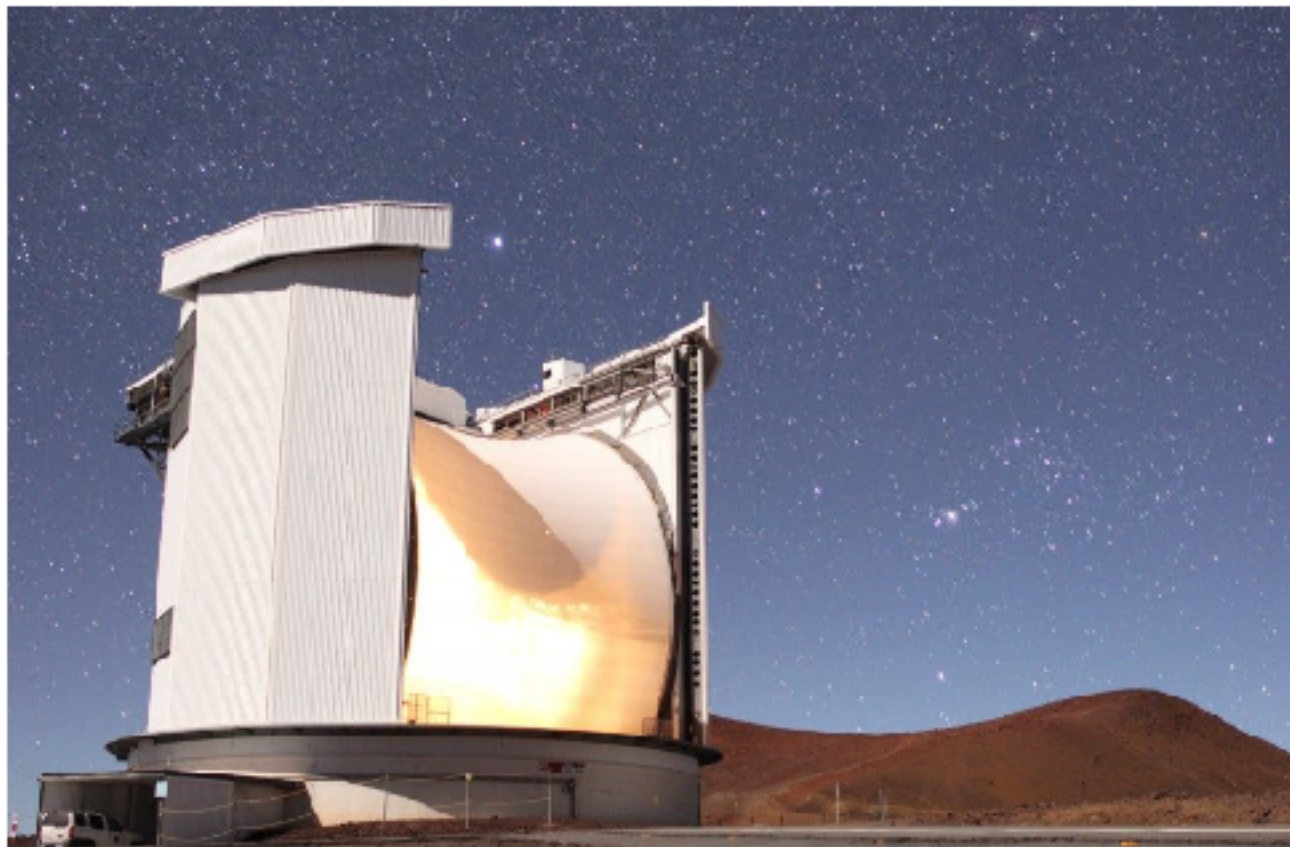
ALMA bands

- ALMA Bands: atmosphere

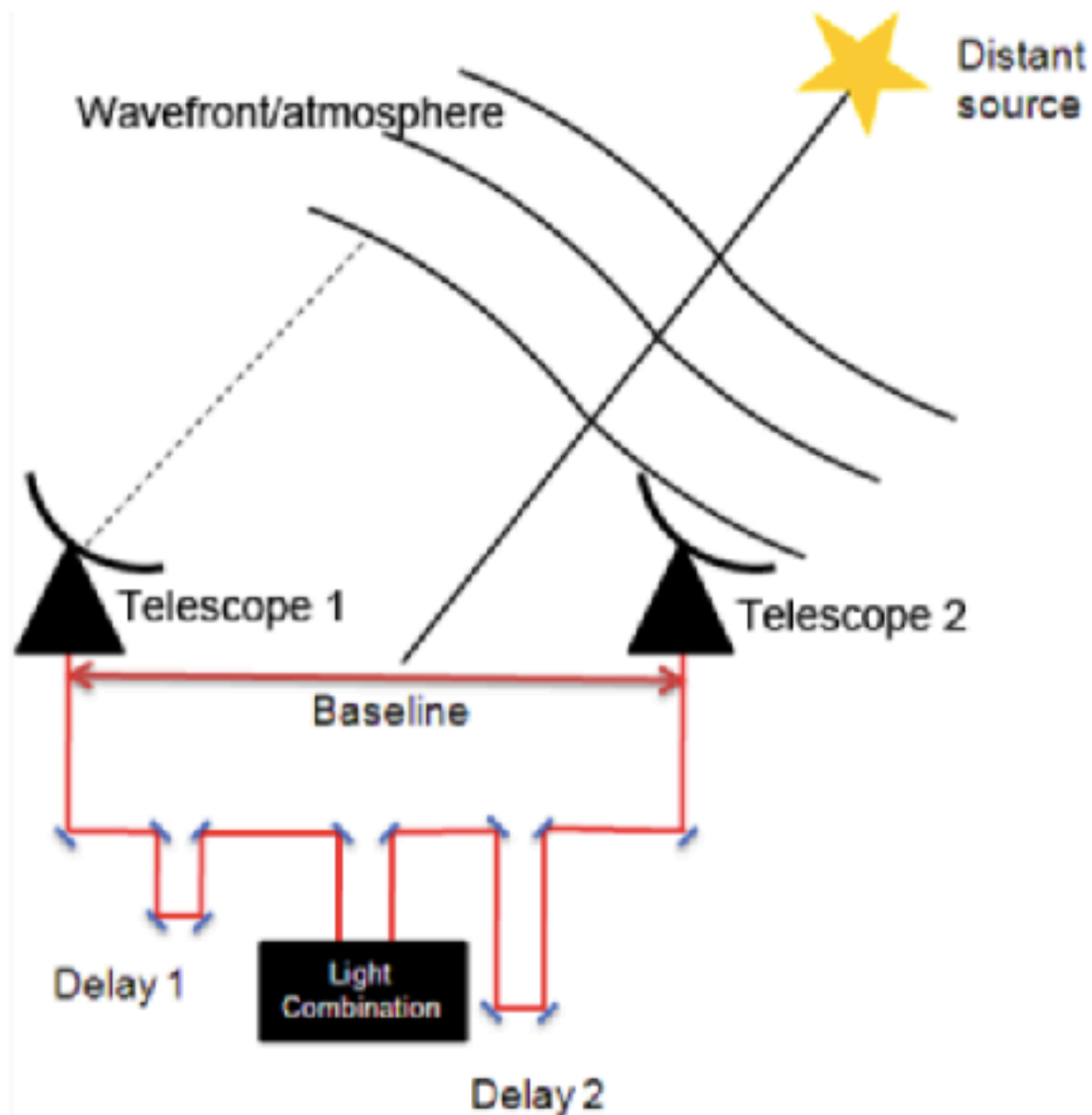


Why interferometry?

JCMT: single dish (15m)



Why interferometry?



Single dish (15m):

$$R \sim \frac{\lambda}{D} \sim 14'' \gg \text{disk size}$$

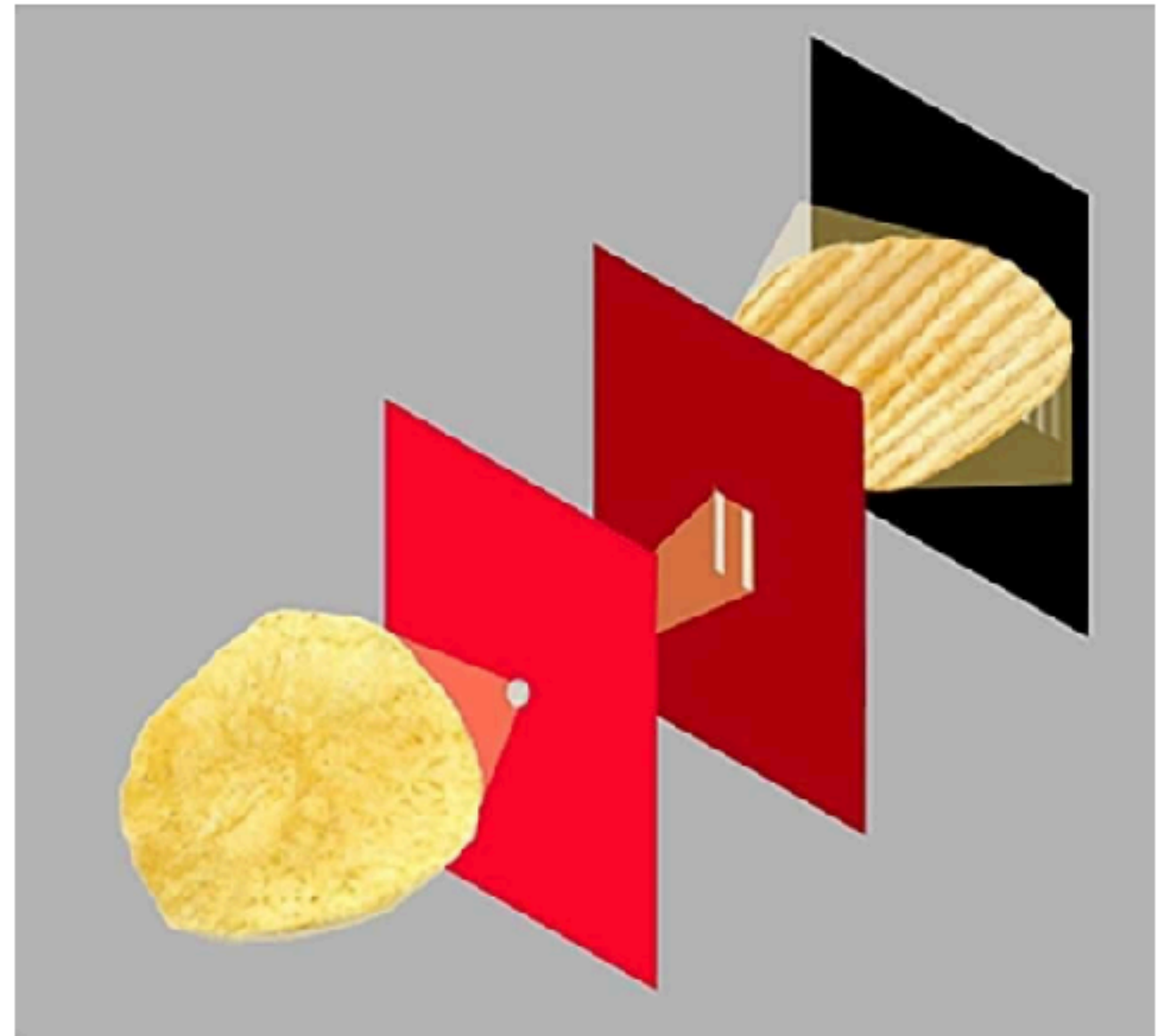
Interferometer:

$$R \sim \frac{\lambda}{B} \sim 0.4'' (B = 500 \text{ m})$$
$$\sim 0.02'' (B = 10 \text{ km})$$

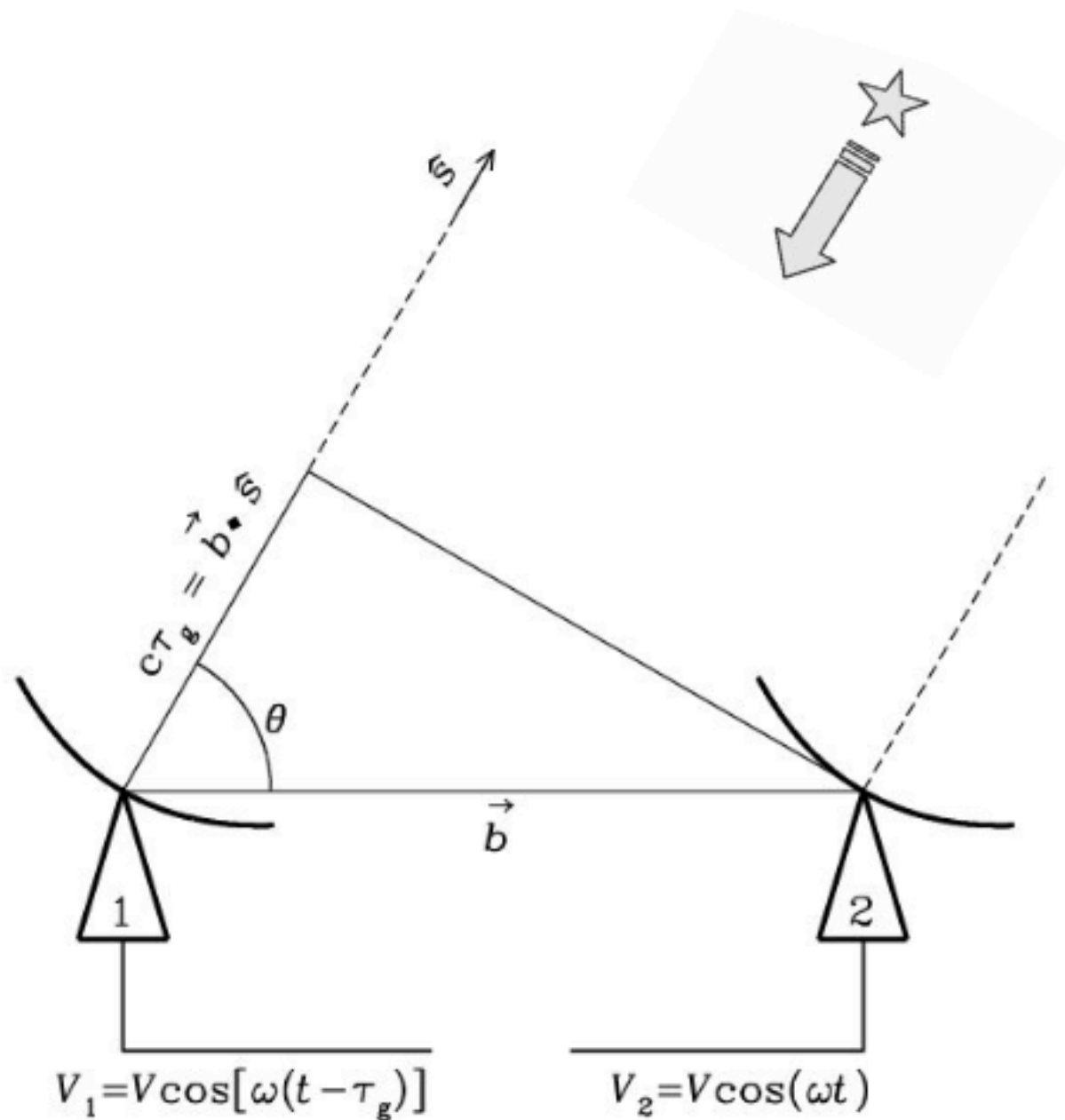
$$\lambda \sim 1 \text{ mm}$$

Interferometry

- Interferometers multiply signals from pairs of antennas to obtain **samples** of a **complex** function called the **Visibility**.
- The Visibility is a **Fourier Transform** of the sky brightness.
- The **samples measured** depend on the antenna separation, orientation, and observing wavelength.
- Imaging require an **inverse** Fourier Transform of the samples and mitigation of sampling sparseness (CLEAN lecture)

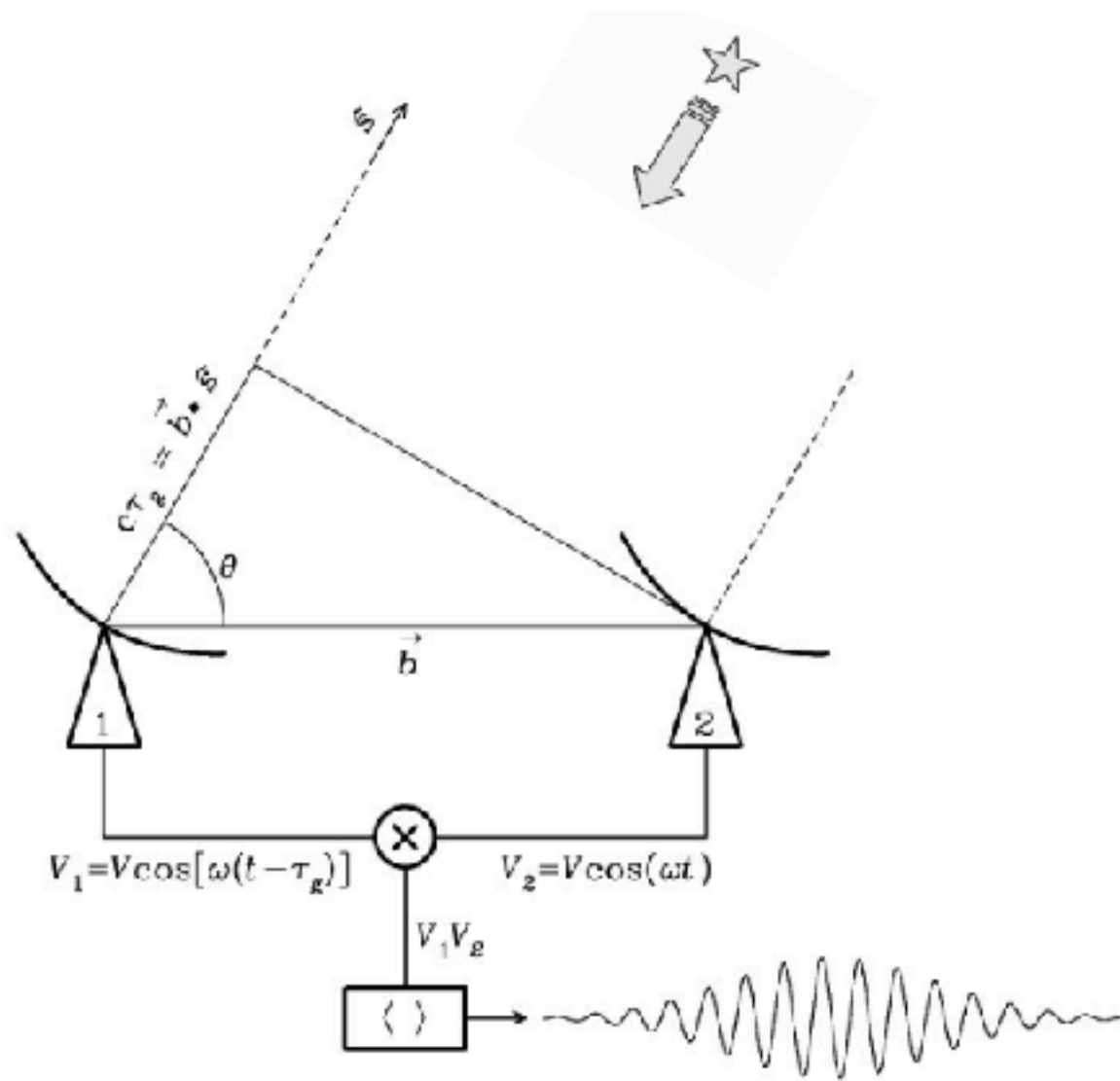


Two-element interferometer



- Let's imagine a pair of antennas separated by baseline distance b observing a source in direction s at frequency ν .
- Each antenna collects and amplifies the signal to measure a voltage V oscillating at $\omega = 2\pi\nu$.
- The same signal reaches both antennas, one sees a delay τ_g .

Two-element interferometer

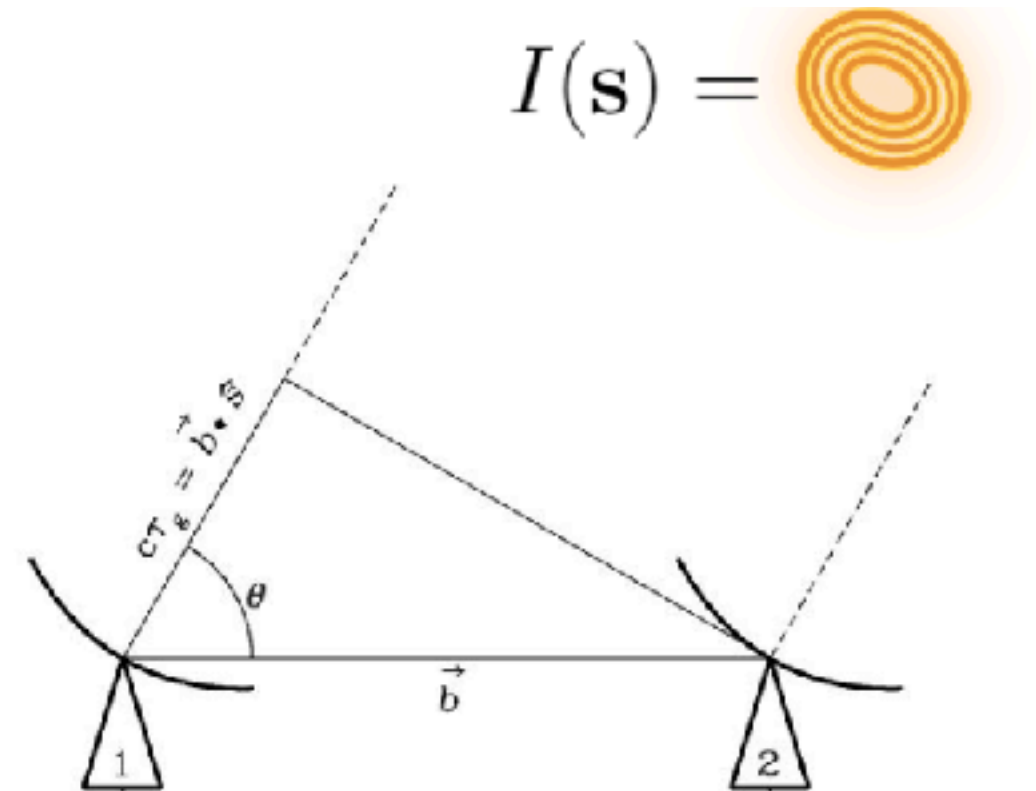


- The signals are digitized, then multiplied and averaged in a correlator to produce fringes with response R_c .
- Fringe amplitude $\propto$ Source brightness.
- Fringe phase is sensitive to source position.

$$R_c = \left(\frac{V^2}{2} \right) \cos(\omega \tau_g)$$

Complex correlator

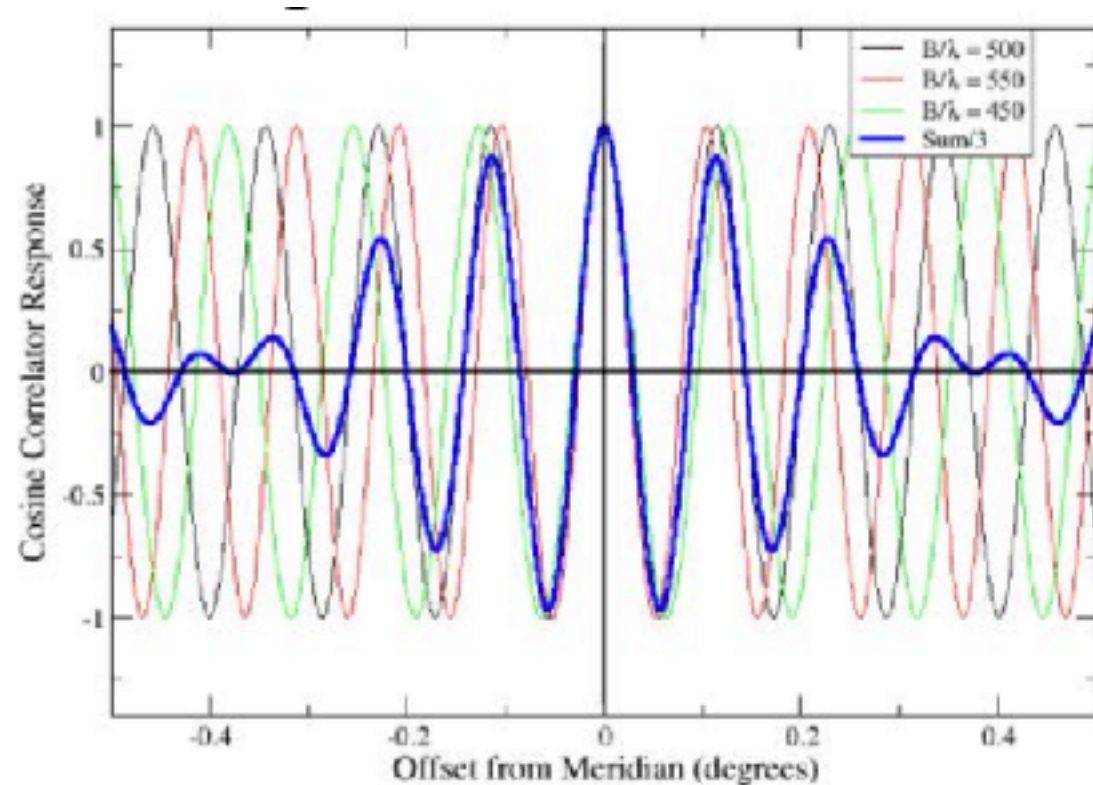
- What if we observe an extended source $I(\mathbf{s})$?
- Cosine correlator is only sensitive to **even** component of extended sources.
- Add 90° delay to make sine correlator and measure **odd** component too.



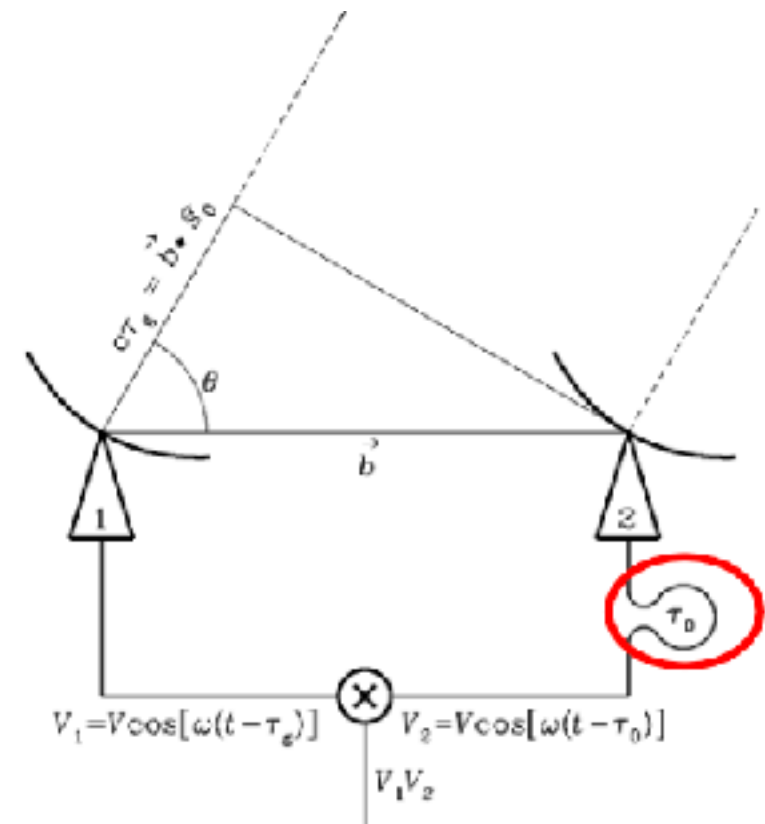
$$R_C = \iint I(\mathbf{s}) \cos(2\pi\nu \vec{b} \cdot \vec{s}/c) d\Omega = \iint I_E(\mathbf{s}) \cos(2\pi\nu \vec{b} \cdot \vec{s}/c) d\Omega$$

$$R_S = \iint I(\mathbf{s}) \sin(2\pi\nu \vec{b} \cdot \vec{s}/c) d\Omega = \iint I_O(\mathbf{s}) \sin(2\pi\nu \vec{b} \cdot \vec{s}/c) d\Omega$$

Bandwidth and fringe tracking



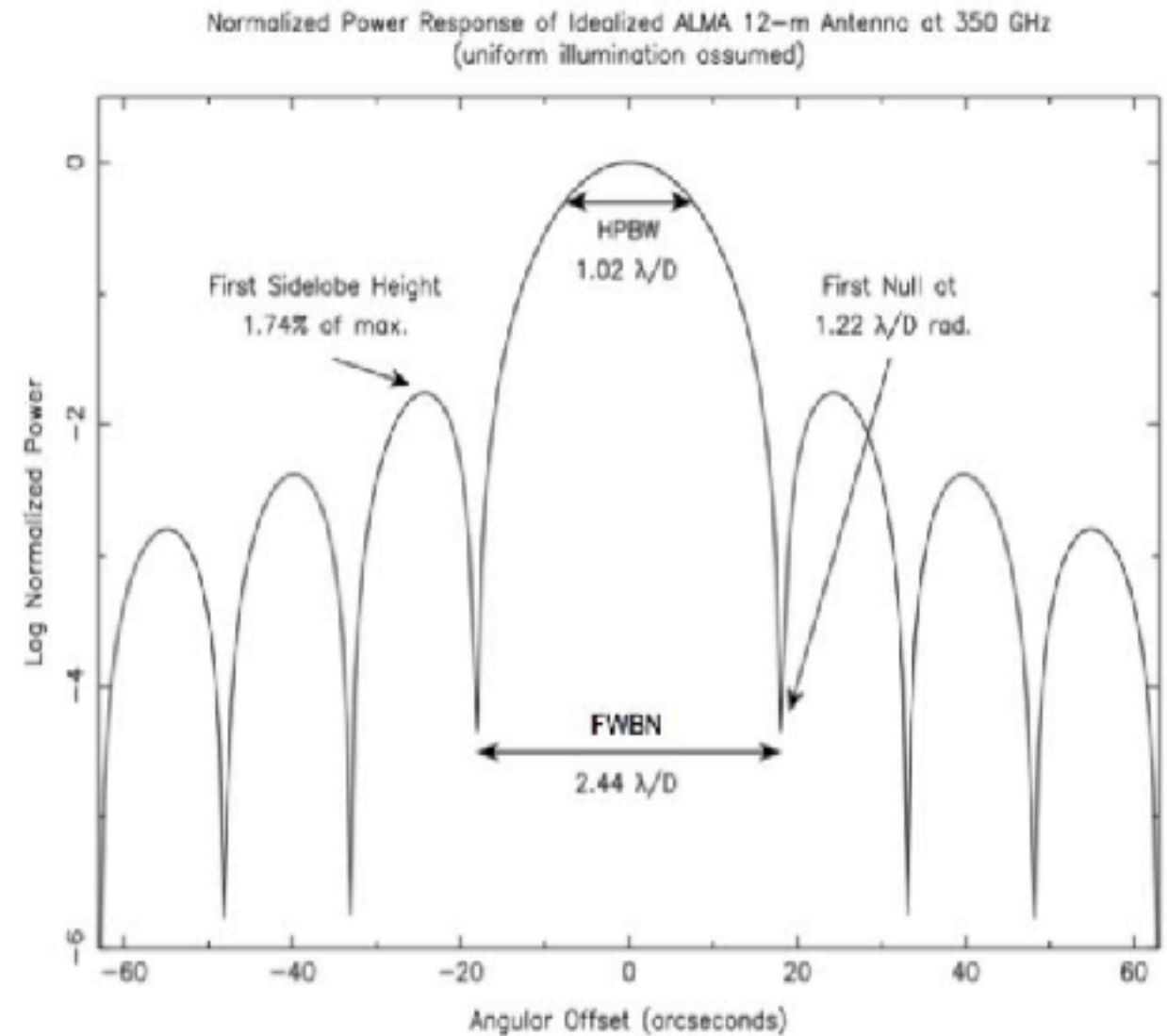
- Finite bandwidth attenuates fringe amplitude away from meridian.
- Earth's rotation moves sources through fringes rapidly.



- Solve both problems by adding extra delay to track a reference "phase center".

Primary beam

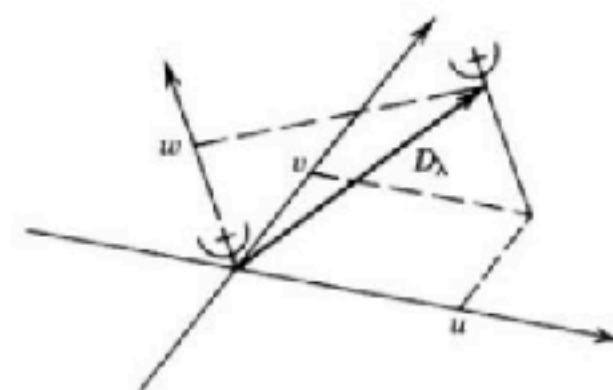
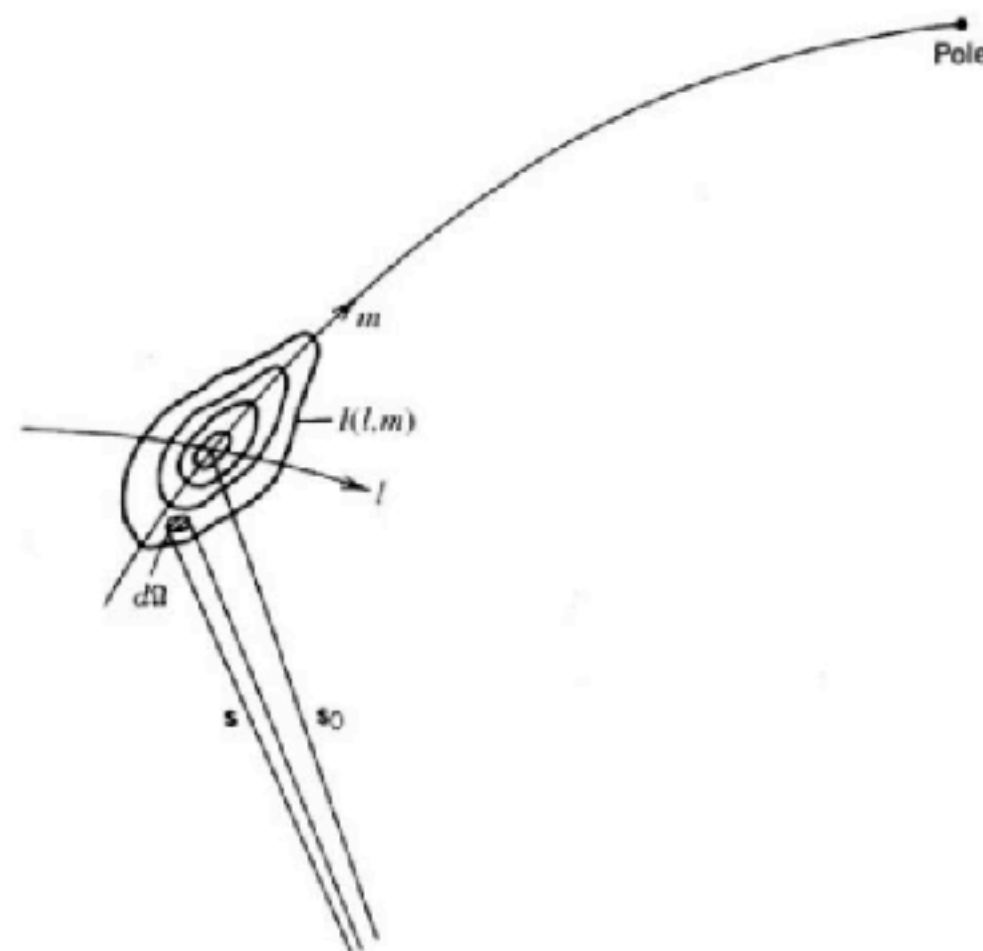
- Parabolic antennas are not uniformly sensitive → emission away from primary beam center attenuated.
- Physically track the motion of the source to compensate.



Coordinates

uv -plane coordinates

- Image plane: l and m are angular separations on sky East/West and North/South, respectively.
- Visibility (uv) plane: u and v are **spatial frequencies** East/West and North/South, respectively.
- u and v are **wavenumbers**, i.e. the length of a baseline in **cycles of the observing wavelength**.



Fourier transform

- The Fourier transform relationship between the image and uv-plane is now:

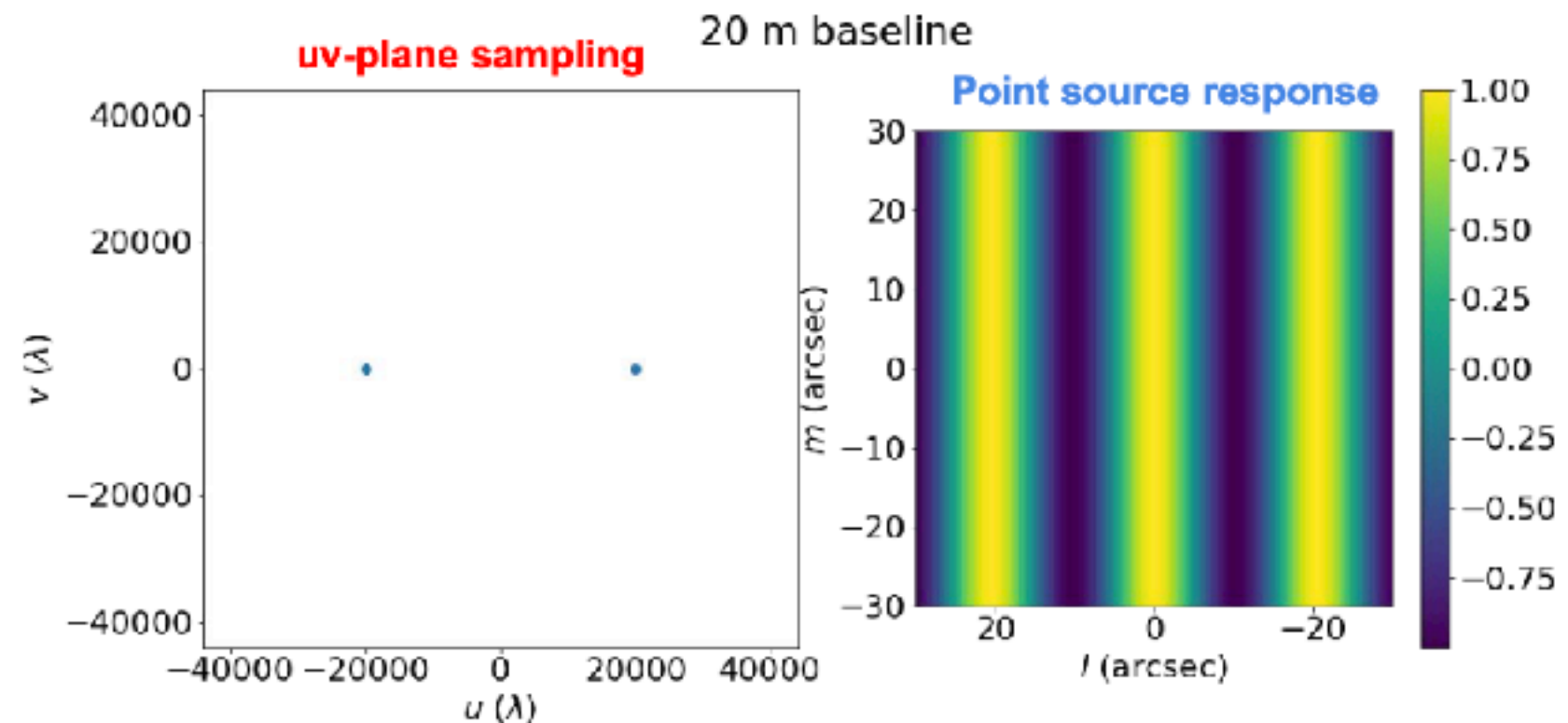
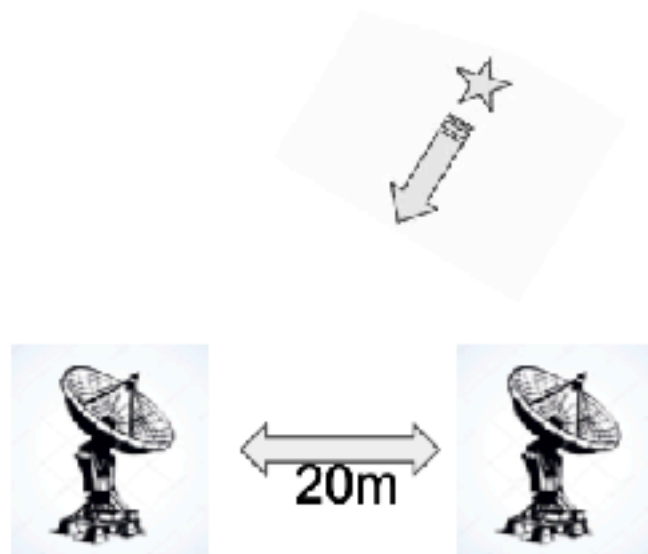
$$V(u, v) = \iint I_\nu(l, m) e^{-2\pi i(ul + vm)} dl dm$$

- **Our goal - measure $I(l, m)$ from our samples of $V(u, v)$.**
- With complete sampling of $V(u, v)$ we could simply apply an inverse Fourier transform to recover $I(l, m)$:

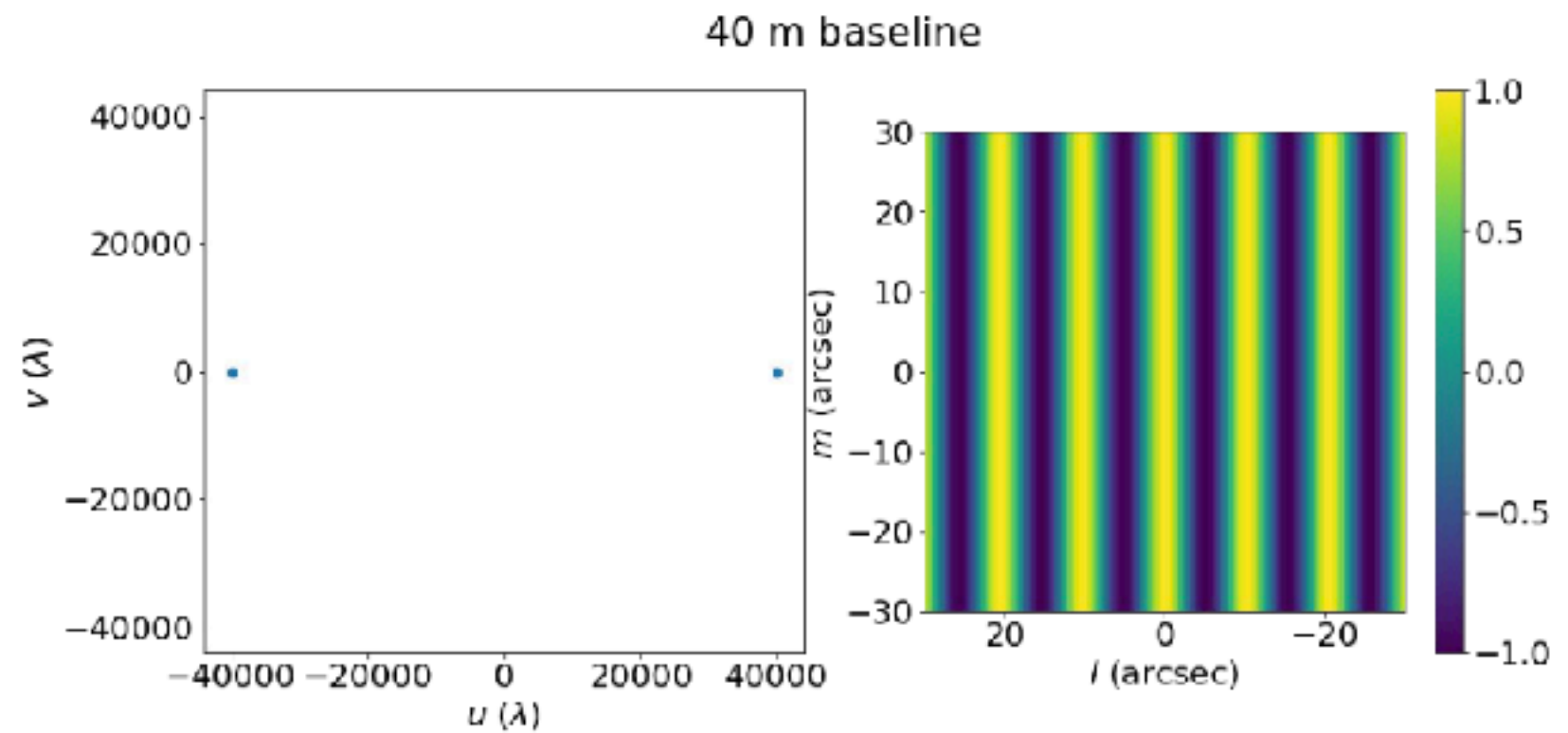
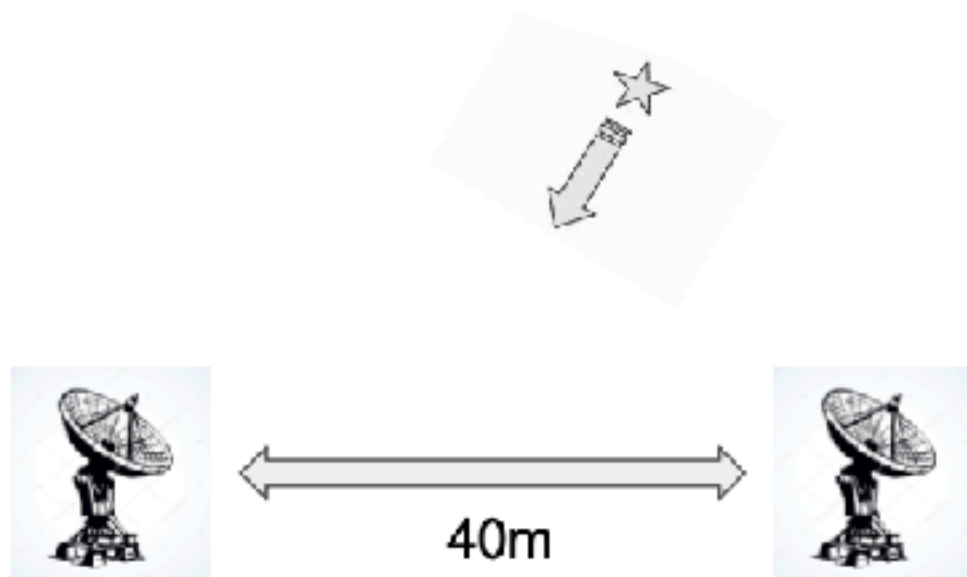
$$I_\nu(l, m) = \iint V(u, v) e^{2\pi i(ul + vm)} du dv$$

Sampling the visibility

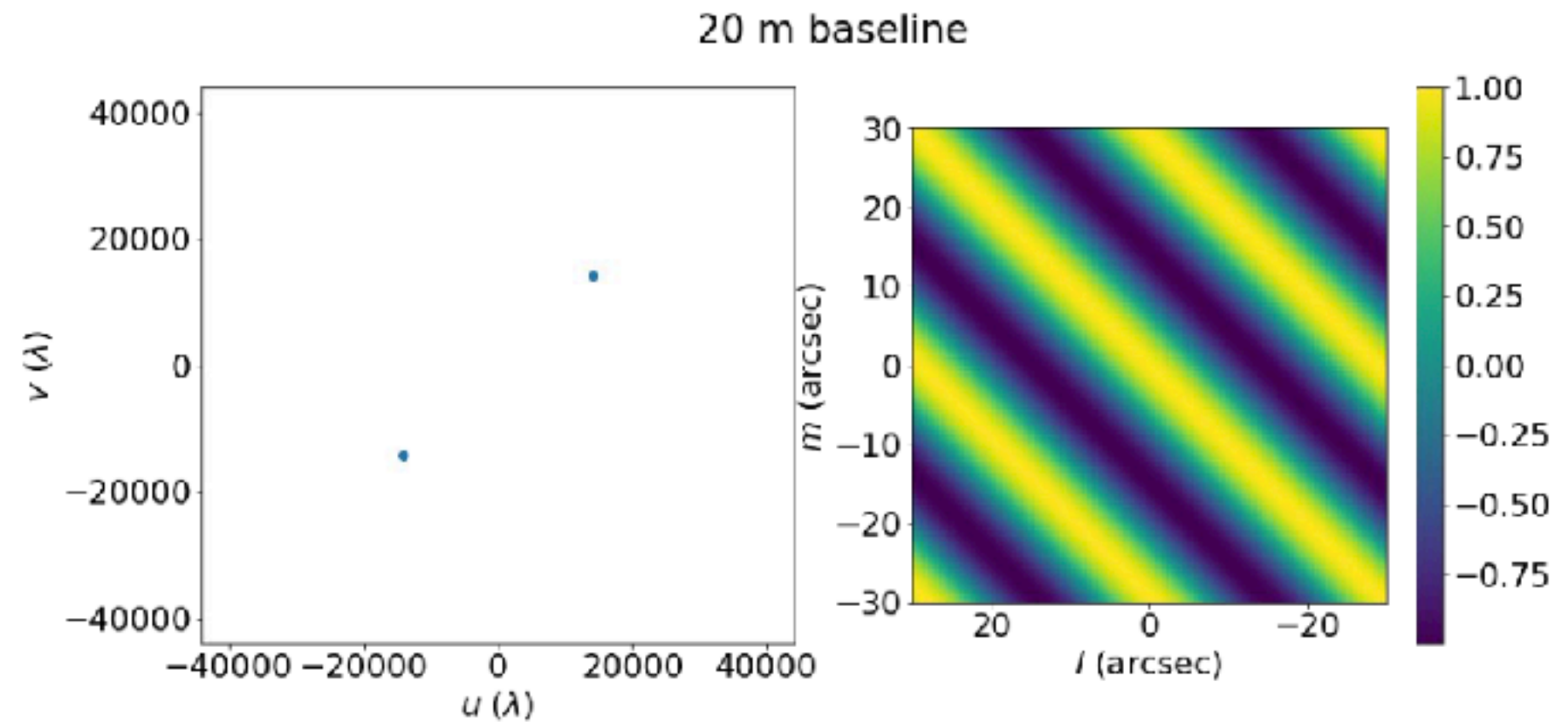
- Each unique baseline vector $\mathbf{b}$ measures a different **spatial frequency** determined by the **projected** baseline length in units of the observing wavelength.
- Assume we observe a point source at a wavelength of 1 mm with a single baseline:



Sampling the visibility

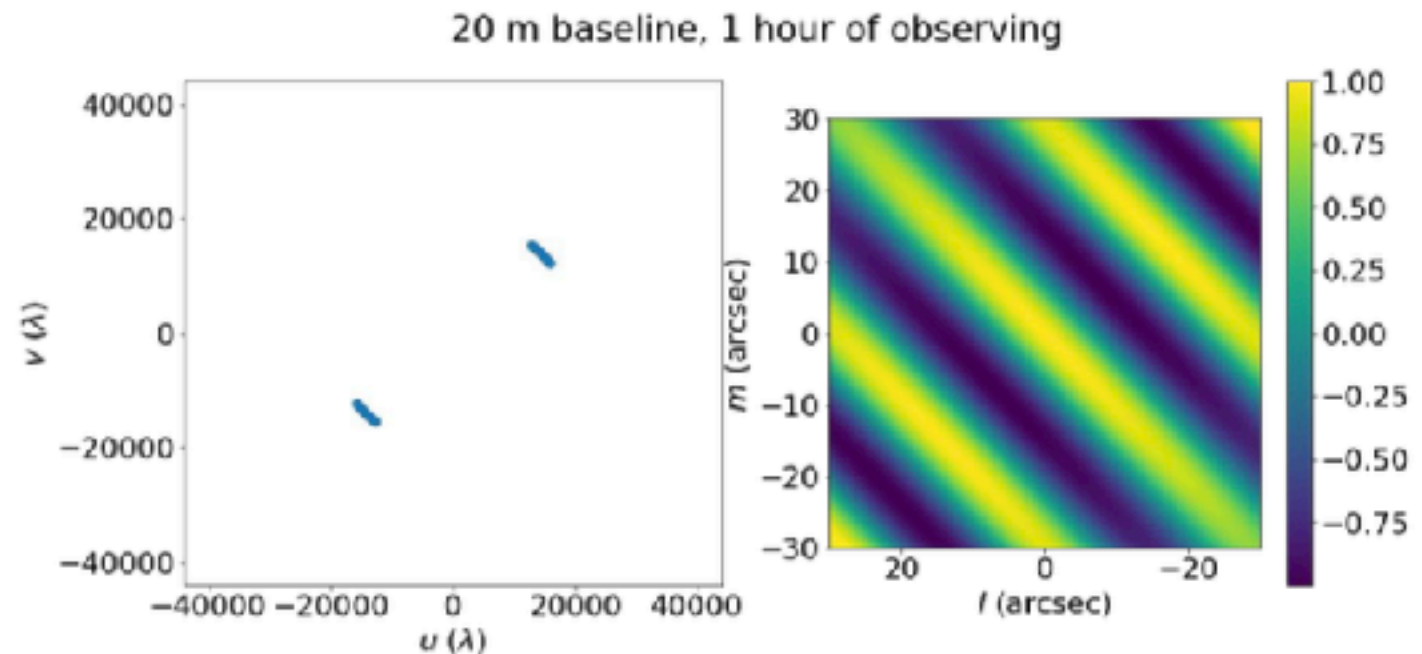
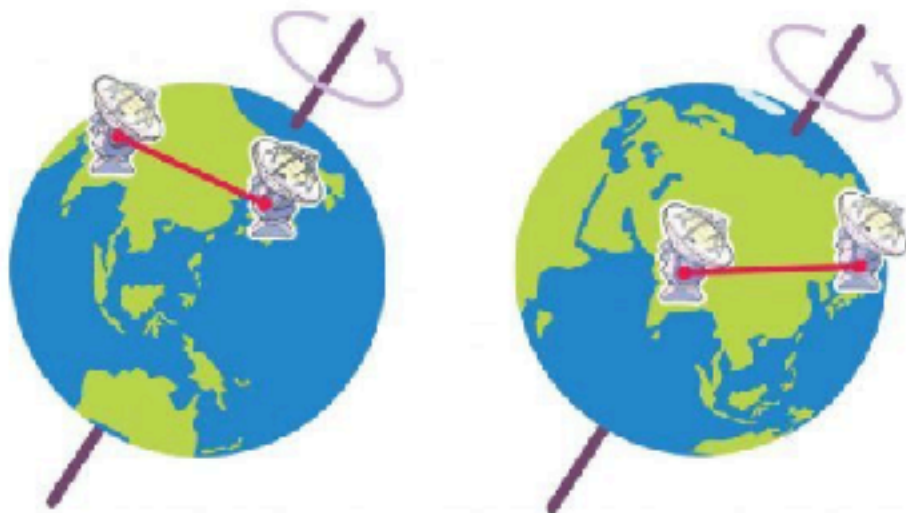


Sampling the visibility



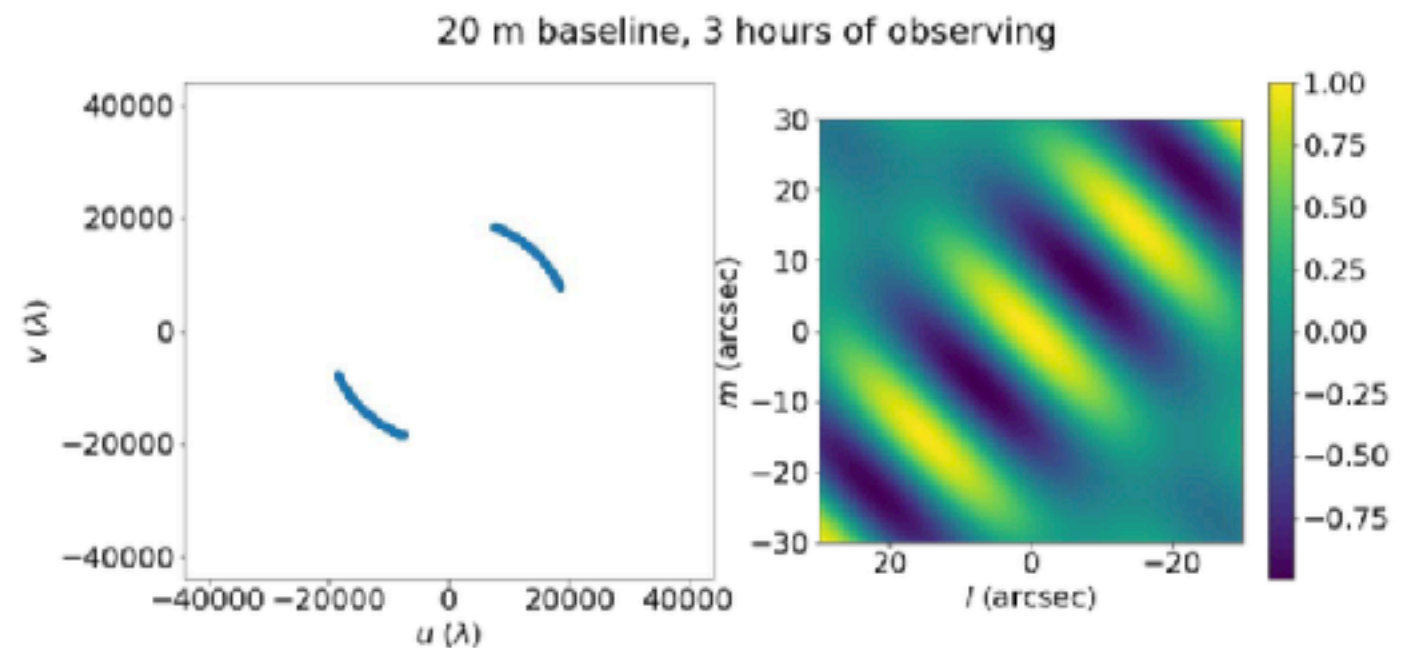
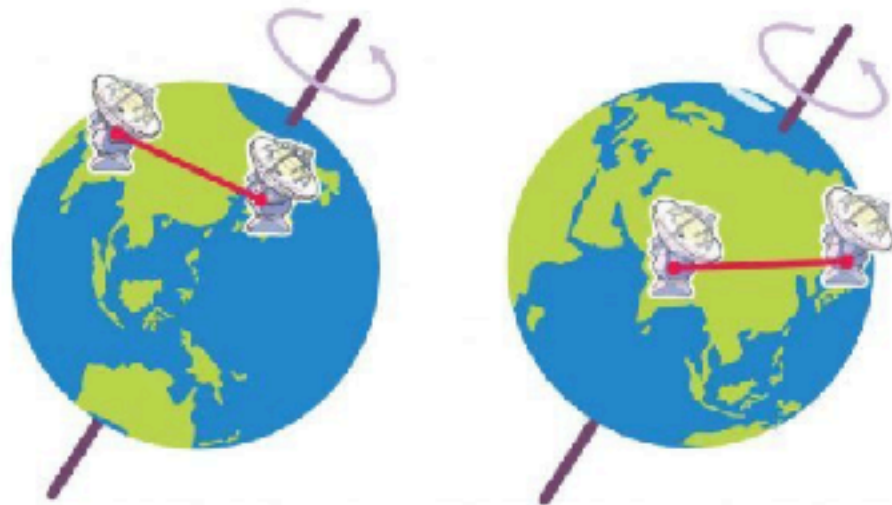
Sampling the visibility

- Baseline projection **changes** as the Earth rotates!
- This allows us to fill in the uv-plane over time.



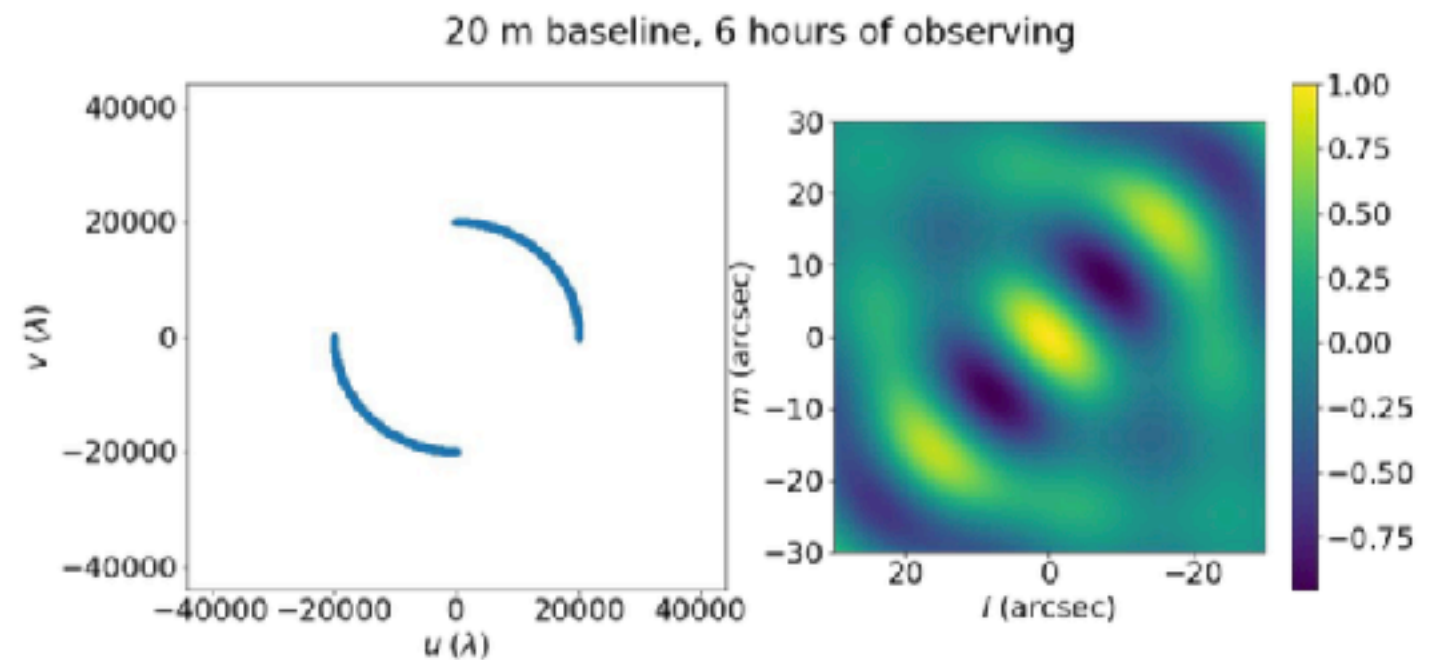
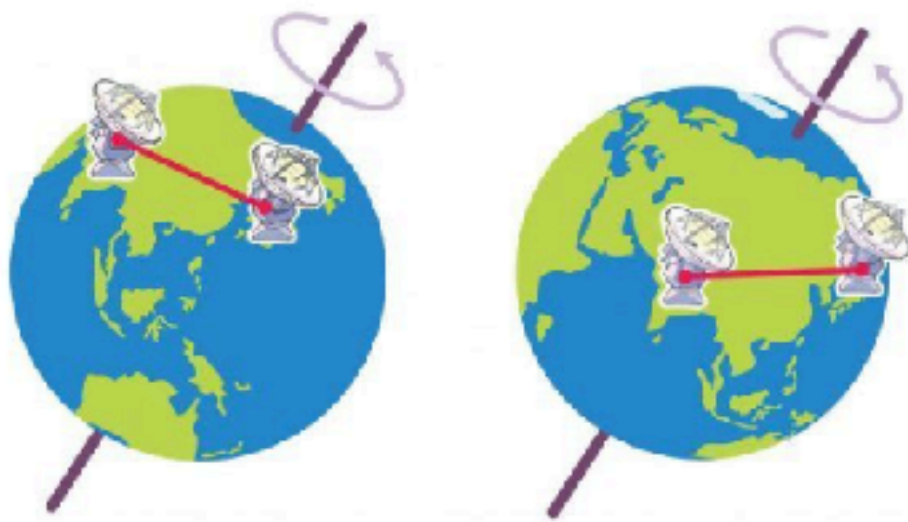
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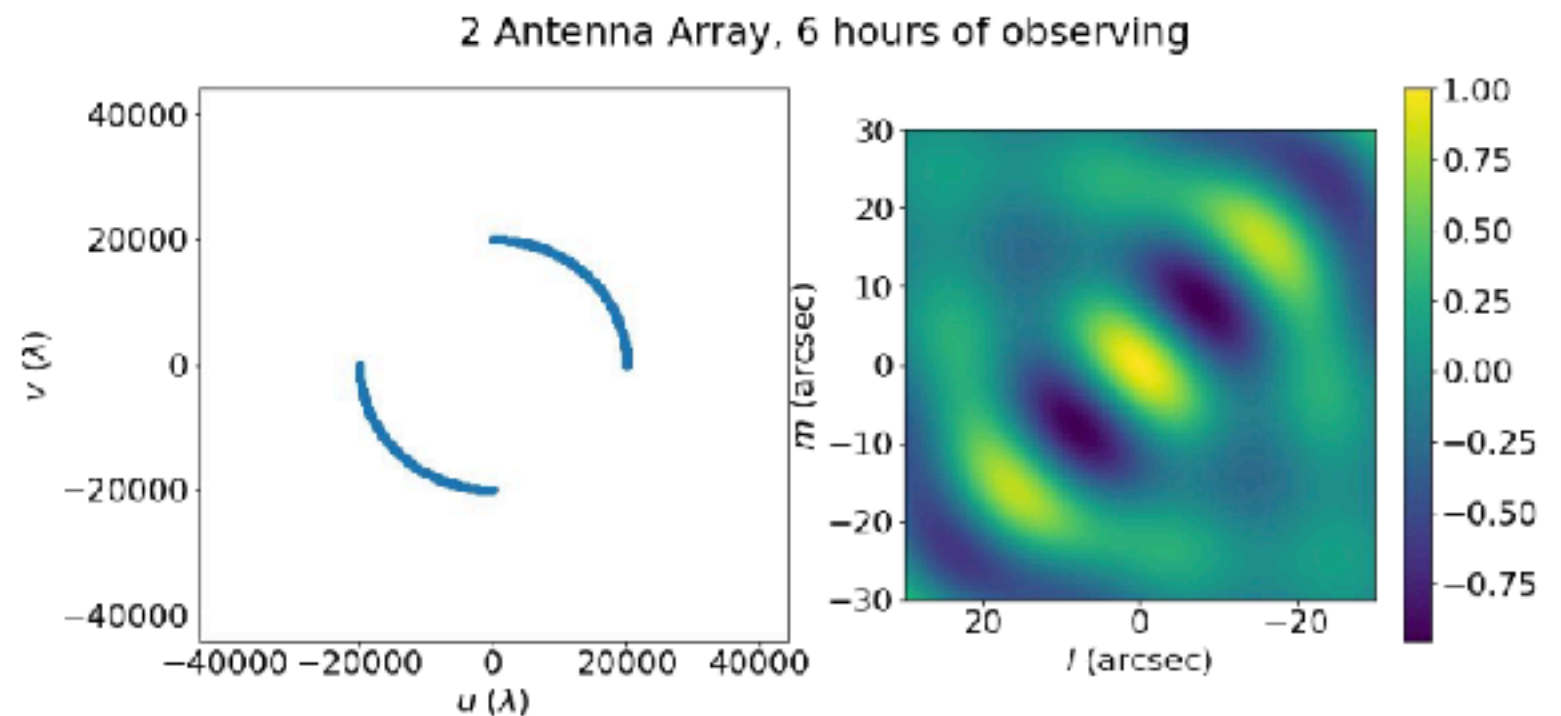
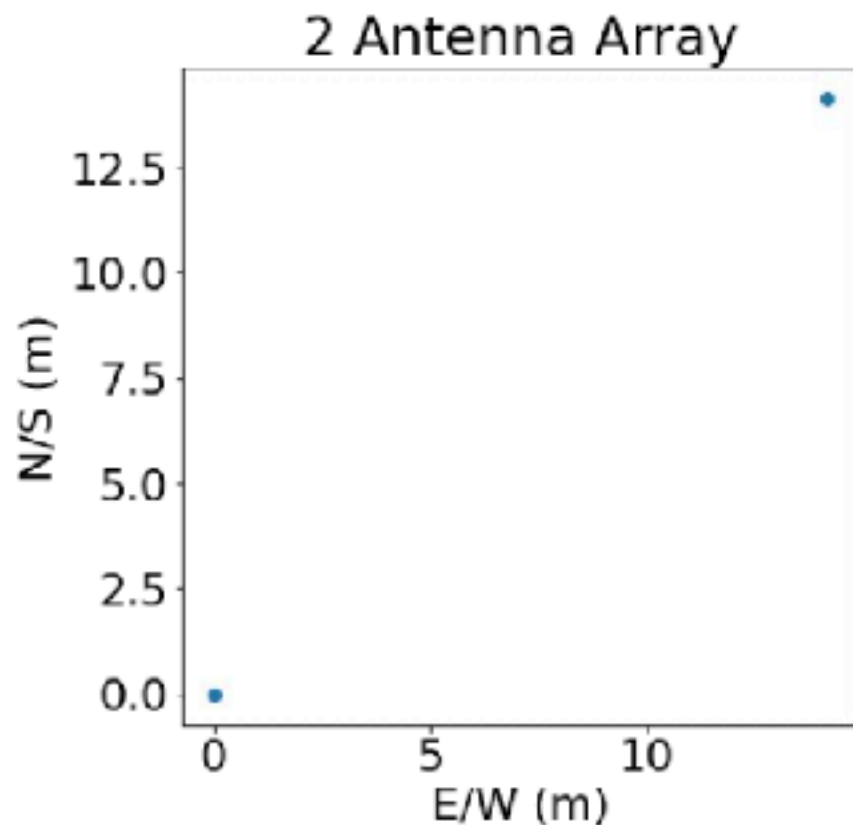
Sampling the visibility

- Baseline projection **changes** as the Earth rotates!
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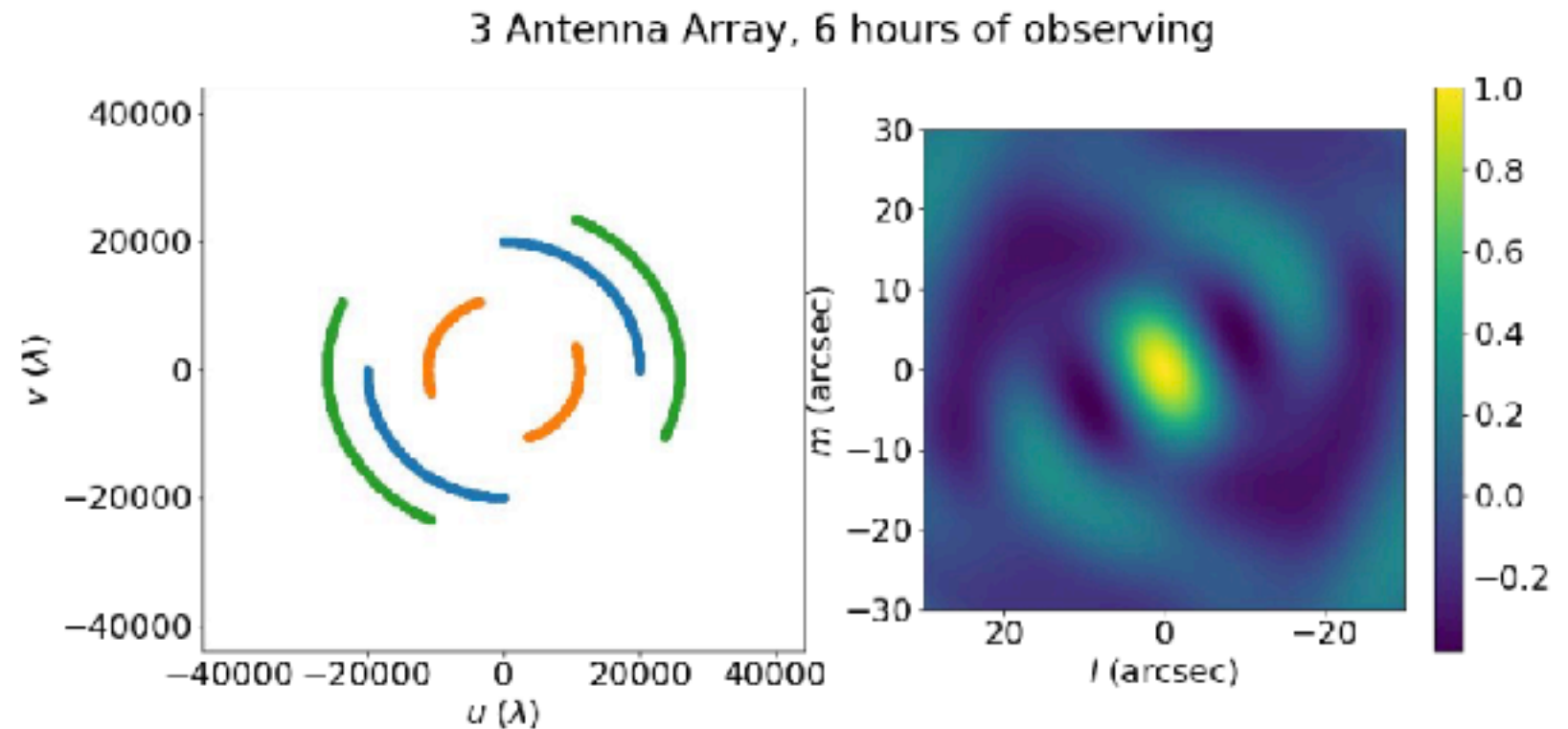
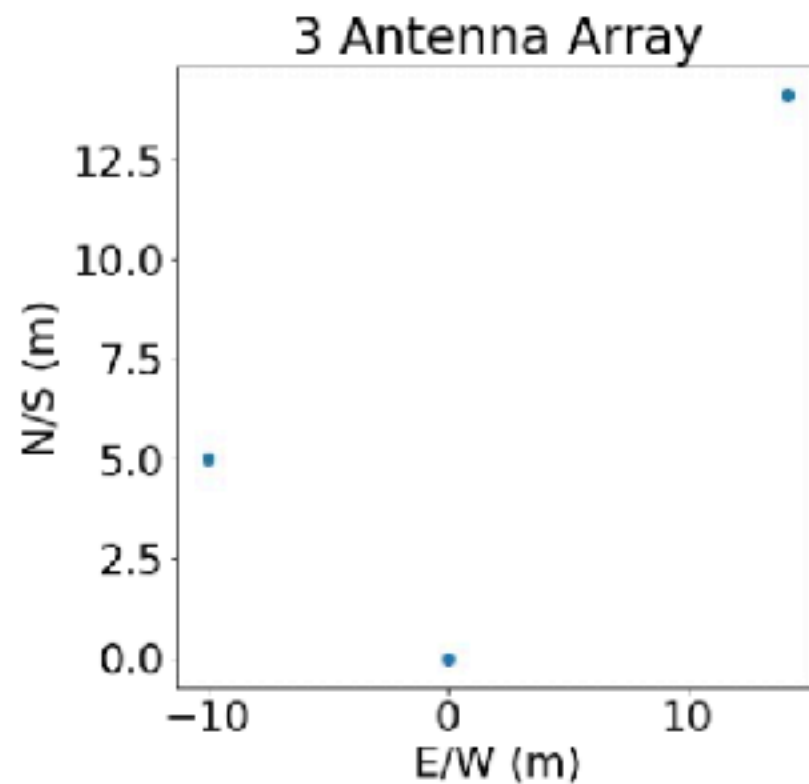
Sampling the visibility

- We also can improve our uv-coverage by adding more antennas with different separations.



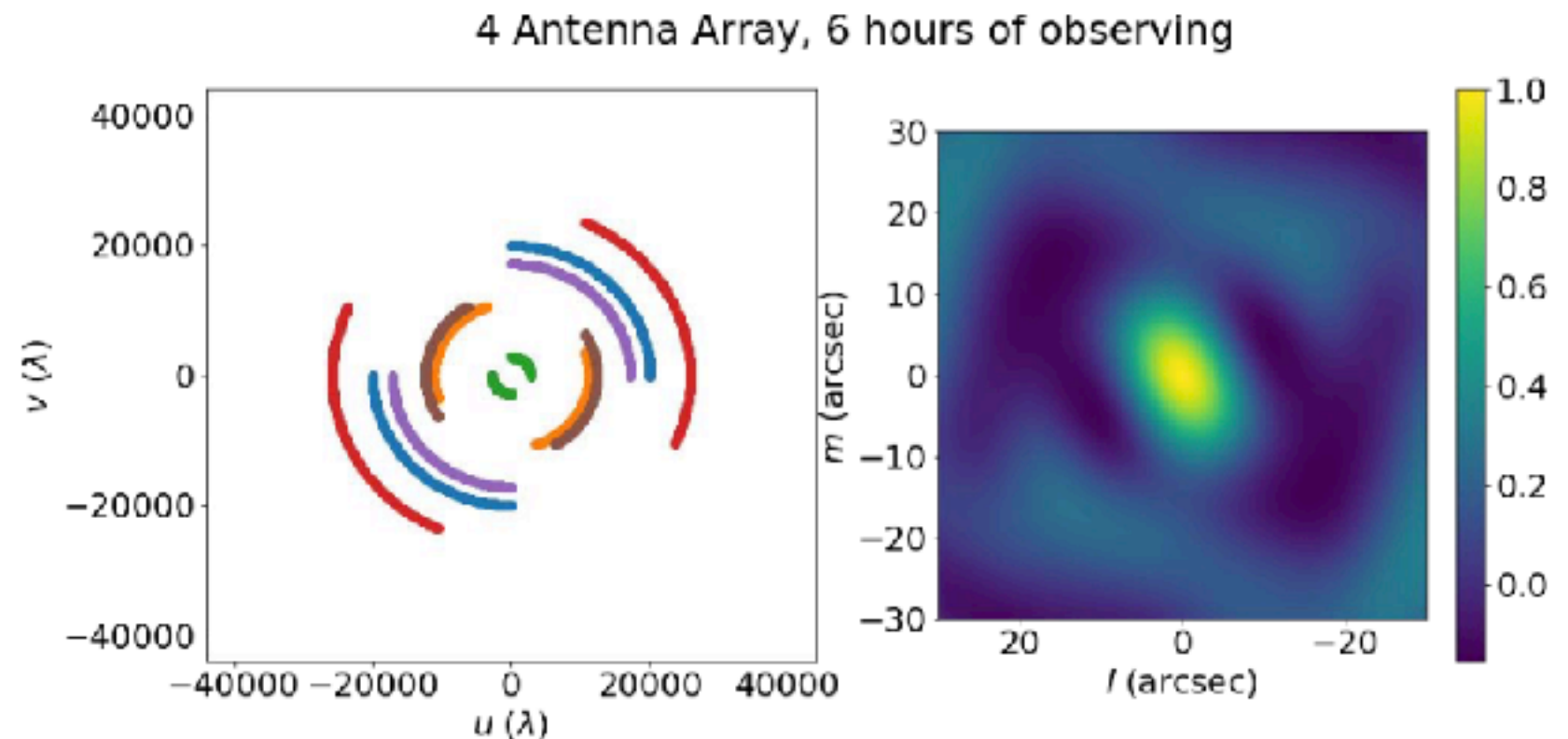
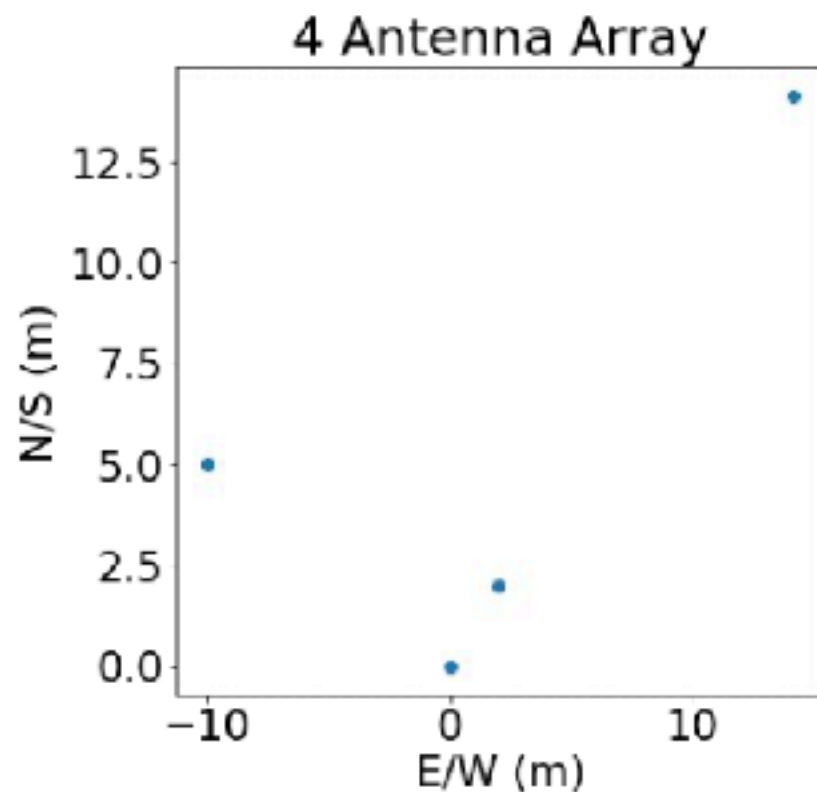
Sampling the visibility

- We also can improve our uv-coverage by adding more antennas with different separations.



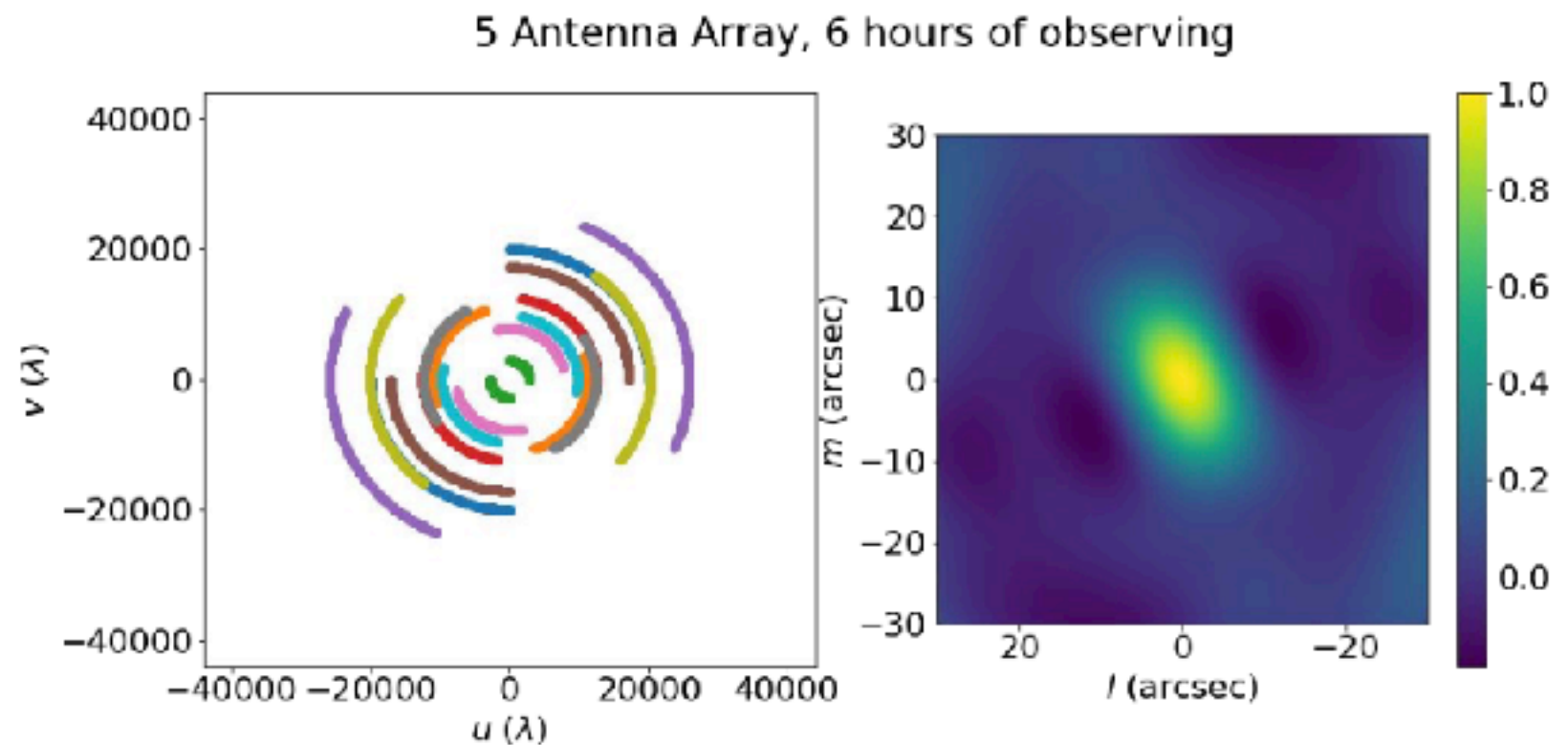
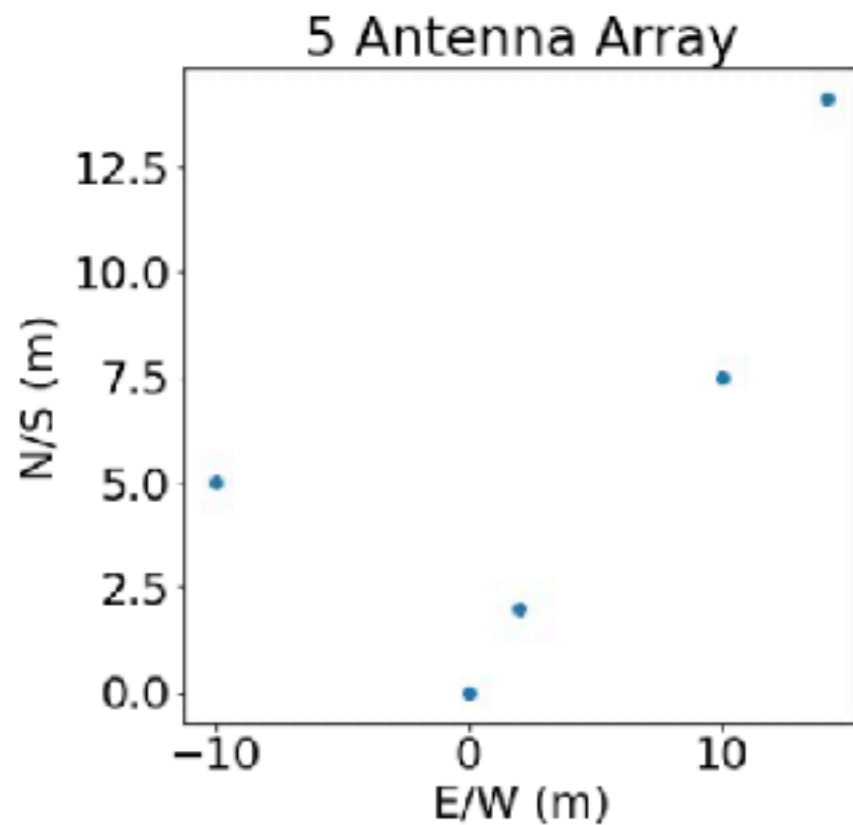
Sampling the visibility

- We also can improve our uv-coverage by adding more antennas with different separations.



Sampling the visibility

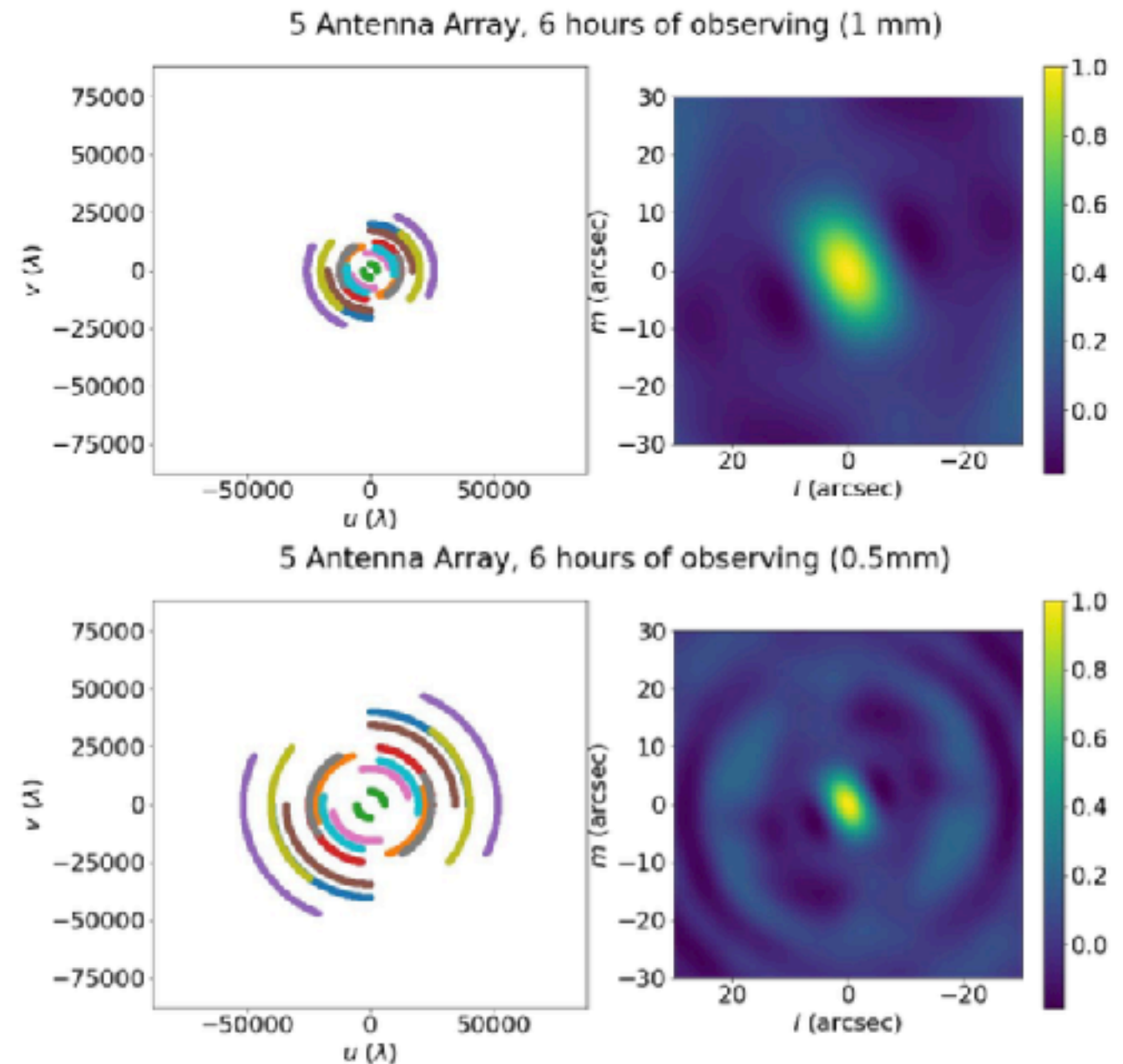
- We also can improve our uv-coverage by adding more antennas with different separations.



Sampling the visibility

Frequency dependence

- The uv-coverage is also dependent on our observing wavelength.
- Better resolution can be obtained at shorter wavelengths (higher frequencies).



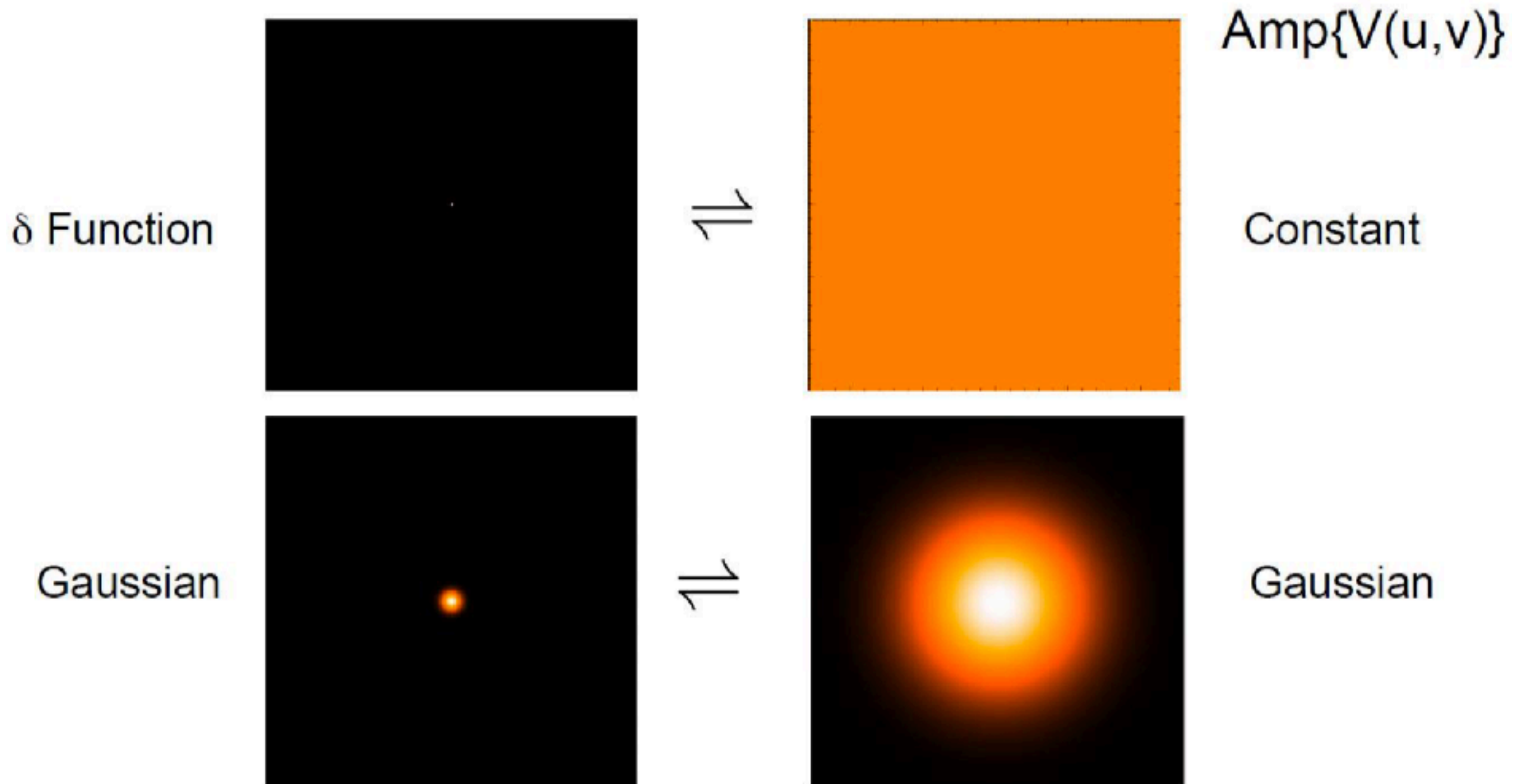


Don't worry! Using data will clarify a lot!

More background

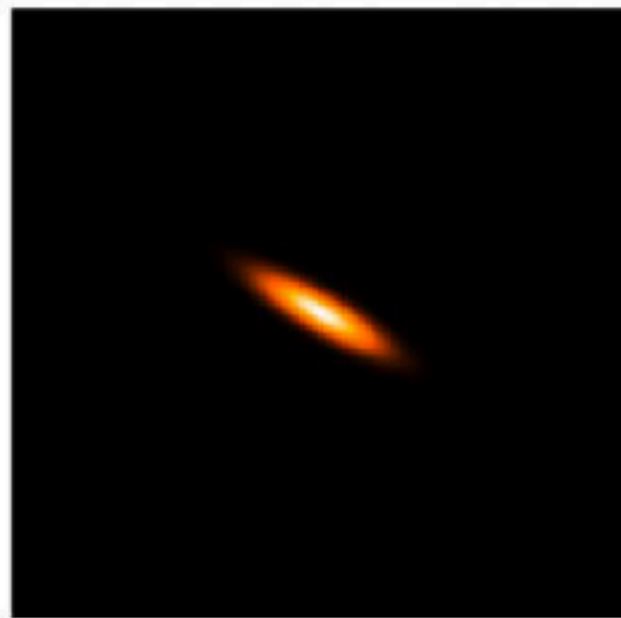
- Interferometry is a deep topic - these will help:
 - NRAO Summer School Lectures - perfect for beginners, has recorded lectures and slides:
<https://science.nrao.edu/science/meetings/2018/16th-synthesis-imaging-workshop/16th-synthesis-imaging-workshop-lectures>
 - Essential Radio Astronomy - beginner textbook
<https://www.cv.nrao.edu/~sransom/web/xxx.html>
 - Interferometry and Synthesis in Radio Astronomy - extremely technical but comprehensive textbook: <https://link.springer.com/book/10.1007/978-3-319-44431-4>
 - ALMA Documentation - See the proposer's guide and primer for easy introduction, and the technical handbook for detailed inquiries.
<https://almascience.eso.org/documents-and-tools/cycle-9-documents>

Fourier transform in practice

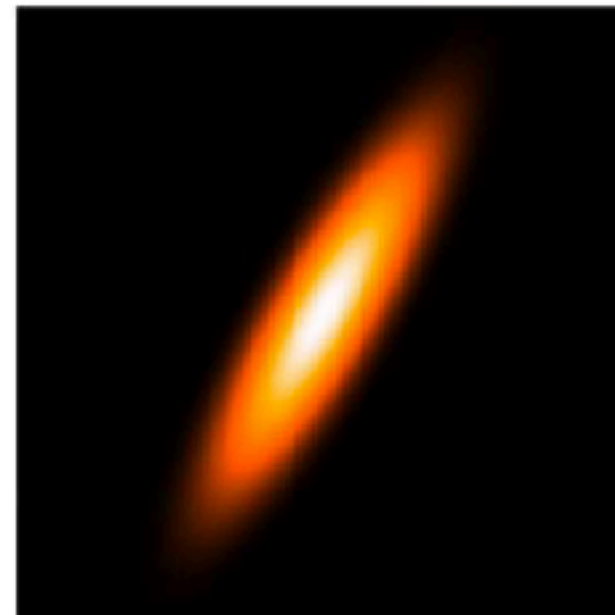


Fourier transform in practice

elliptical
Gaussian



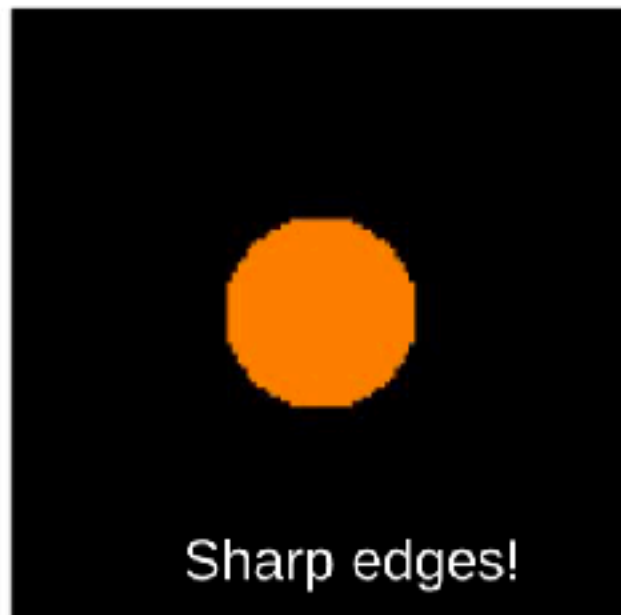
$\mathcal{F}$



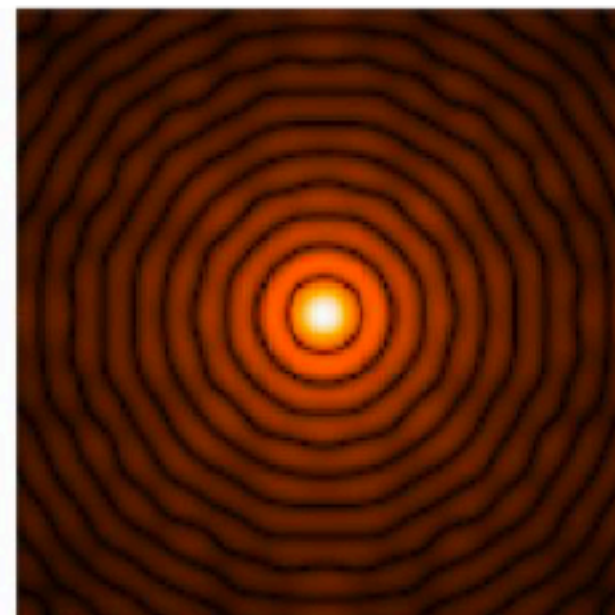
$\text{Amp}\{V(u,v)\}$

elliptical
Gaussian

Disk

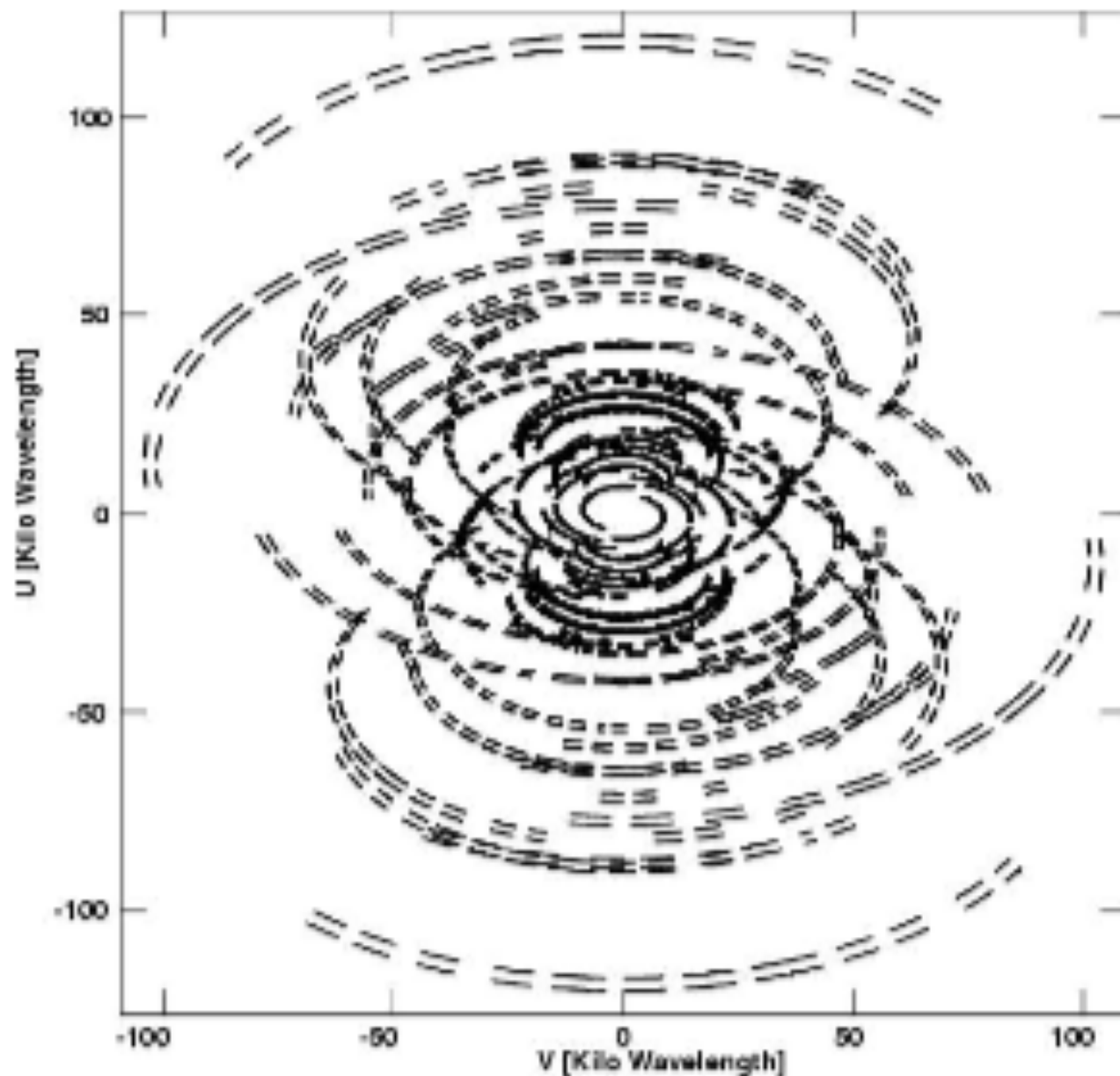


$\mathcal{F}$



Bessel

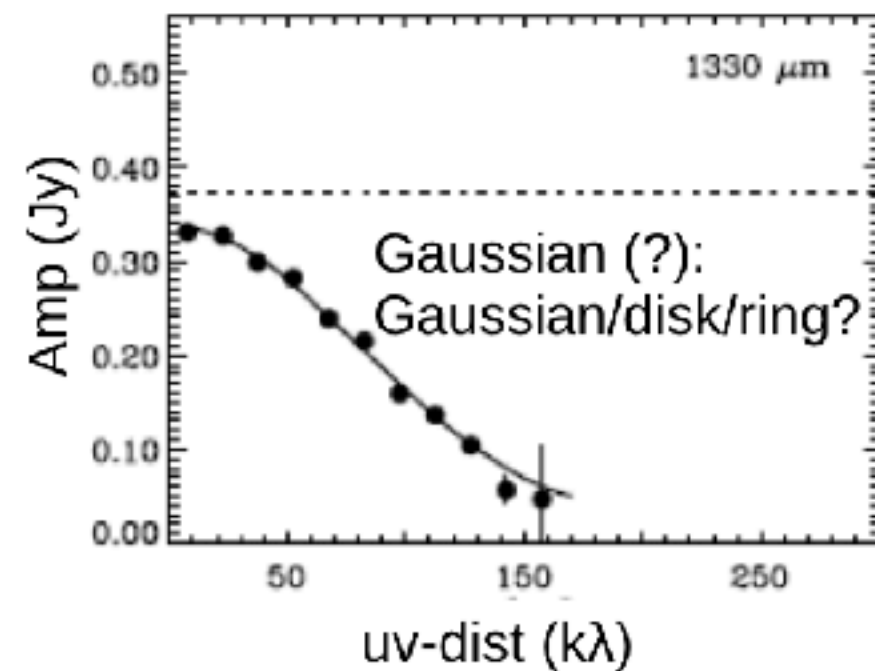
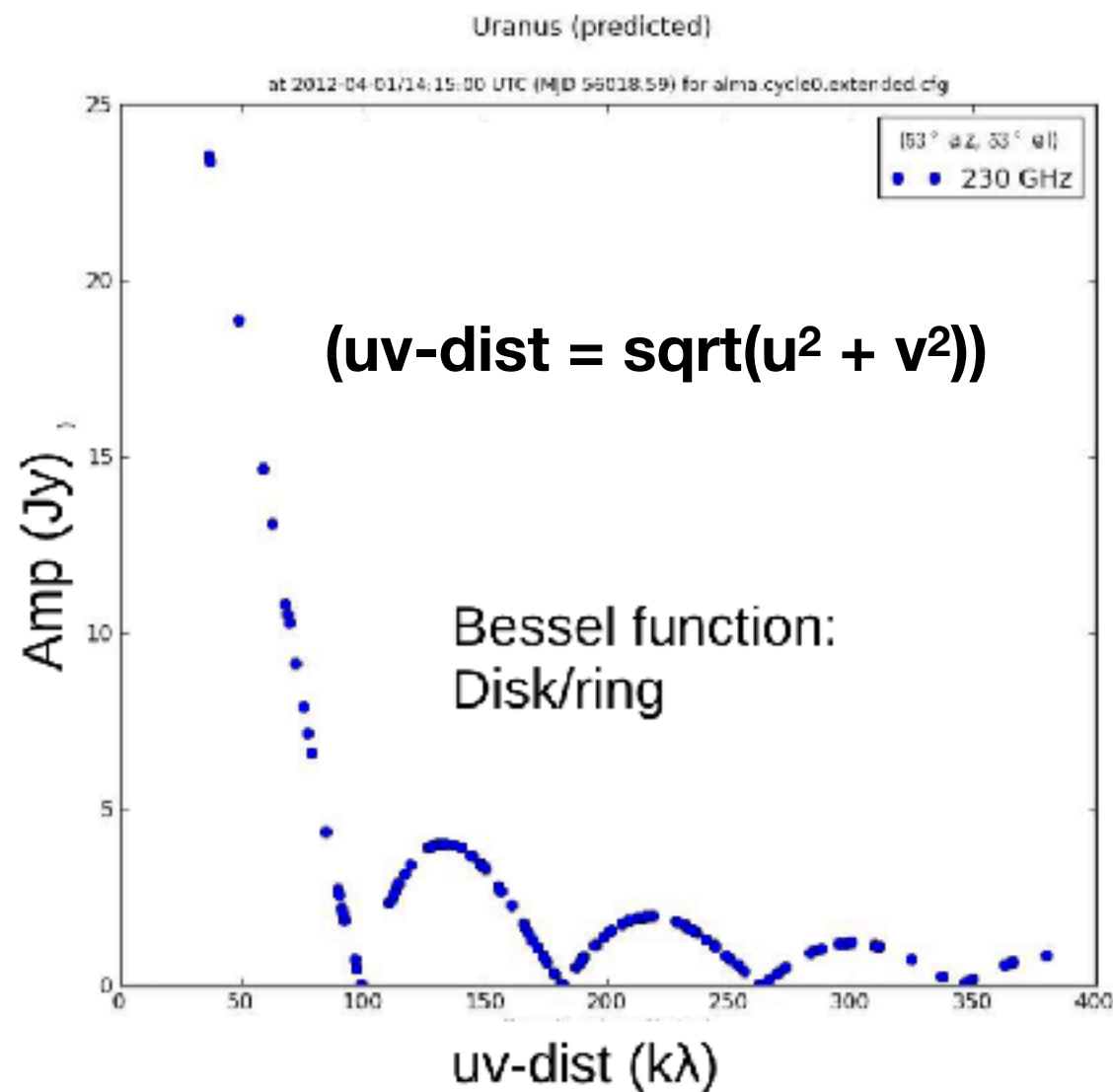
Fourier transform in practice



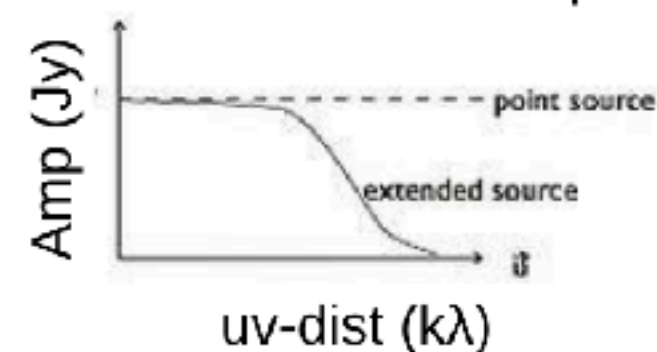
- At each u,v point you measure Real and Imaginary (as function of time and frequency)
- The “Real” represents radial variations
- The “Imag” represents azimuthal variations
- Amplitude = $\sqrt{\text{Real}^2 + \text{Imag}^2}$
- Deprojected baseline = $\sqrt{u^2 + v^2}$

Fourier transform in practice

- Visibility curve: amp vs uv-distance

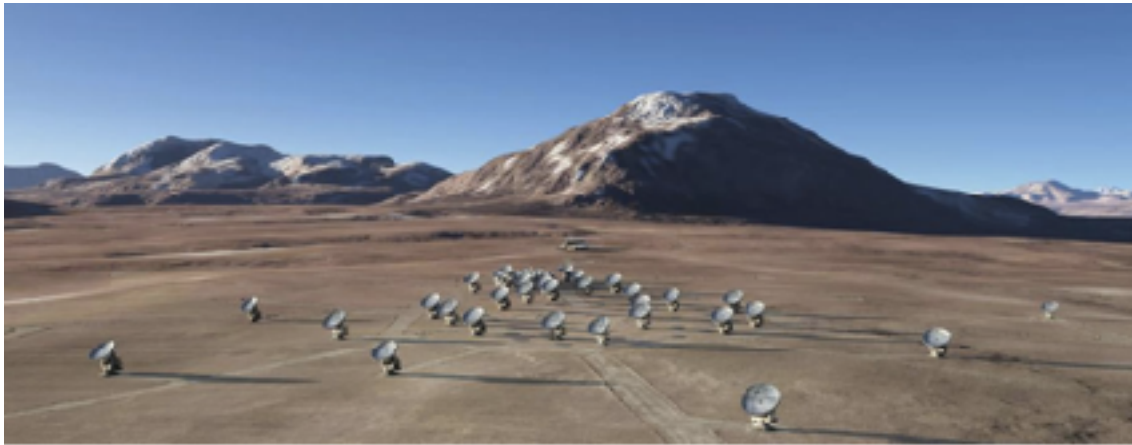


Constant: unresolved point source



**Two major issues when Fourier transforming:
maximum resolvable scale and incomplete PSF**

ALMA interferometry

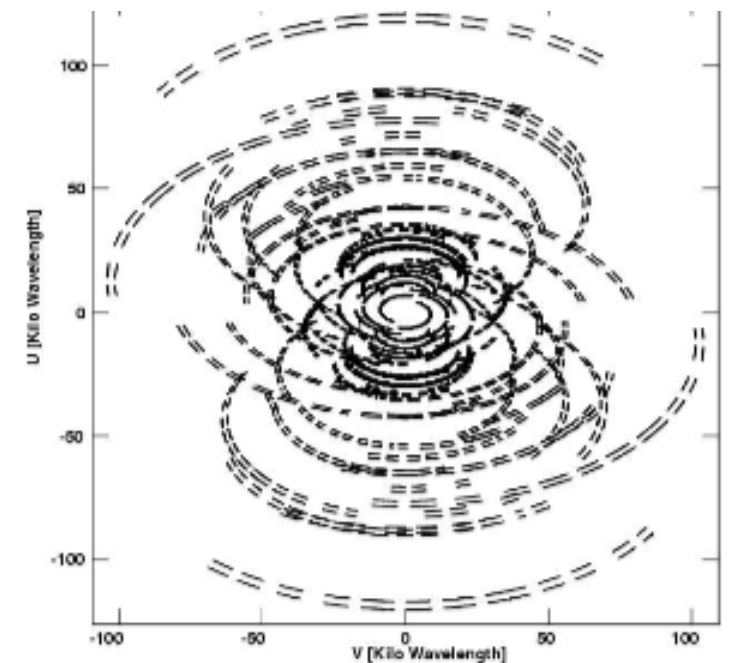


- ALMA:
 - 12m-array: 50 antennas, 10 possible configurations with baselines < 16 km
 - 7m array (ACA): 12 antennas
 - Total power array: 4 antennas
- Every antenna is connected with every antenna (baseline)
- So 3 antennas: 6 baselines, 4 antennas: 24 baselines, etc.
- Each baseline (interference pattern) provides a resolution element or spatial scale λ/B (B = baseline length), which can be described as point in the u,v -plane
- Remember: for observing, you want to 'fill the u,v -plane' as much as possible to cover all possible spatial scales and get a nice clean beam

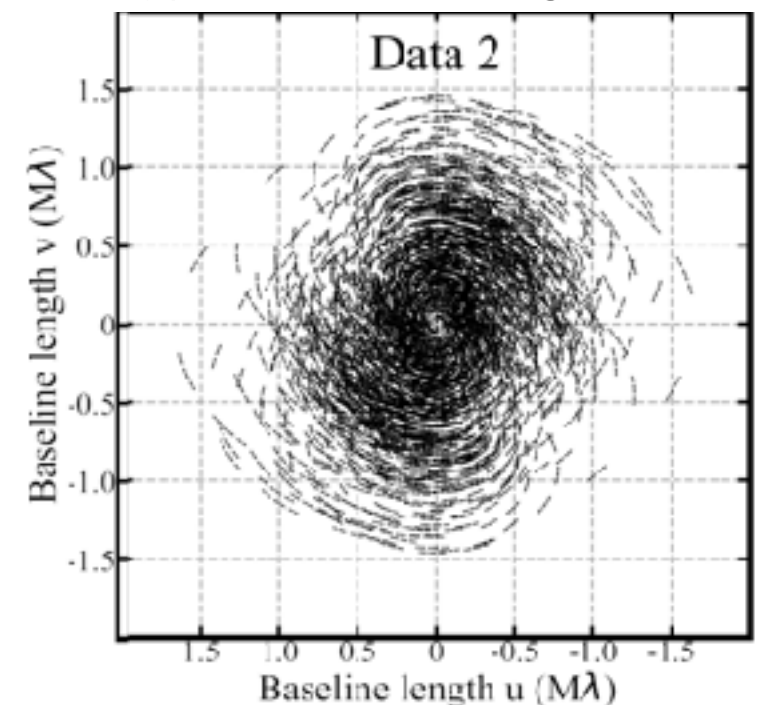
ALMA: uv-plane

- The u,v-plane can be considered the Fourier transform of the x,y-plane: imaging interferometry data means Fourier transforming it
- The u,v-coverage :
 - The sampling of the u,v-plane: the better it is filled, the more accurate your image will be
 - The Fourier transform of the u,v-coverage gives you your beam or PSF: perfect coverage results in a perfect Gaussian beam, imperfect coverage results in a 'dirty beam' with sidelobes
 - Coverage at long baselines means you are sensitive to small spatial scales: coverage at short baselines means you are sensitive to large spatial scales => you usually cannot have both at the same time!

Typical uv-coverage pre-ALMA



Typical uv-coverage ALMA



ALMA interferometry

Table A-1: Angular Resolutions (AR) and Maximum Recoverable Scales (MRS) for the Cycle 7 Array configurations

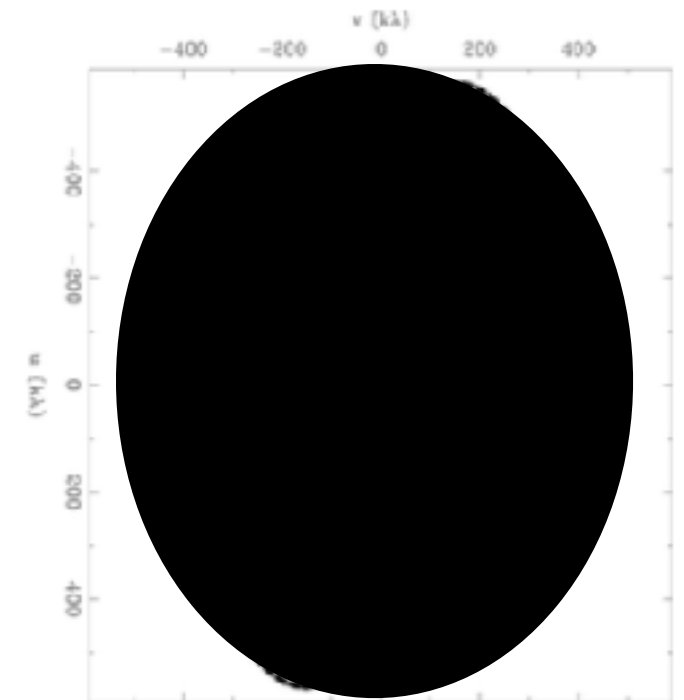
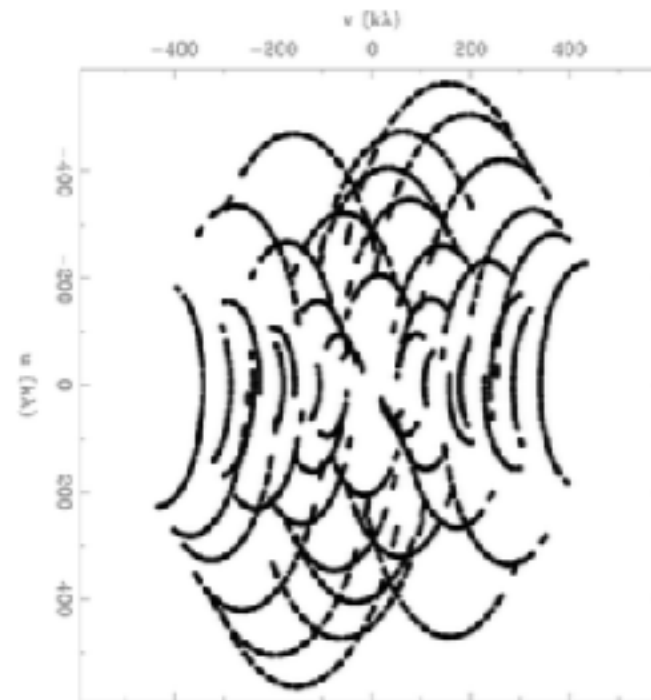
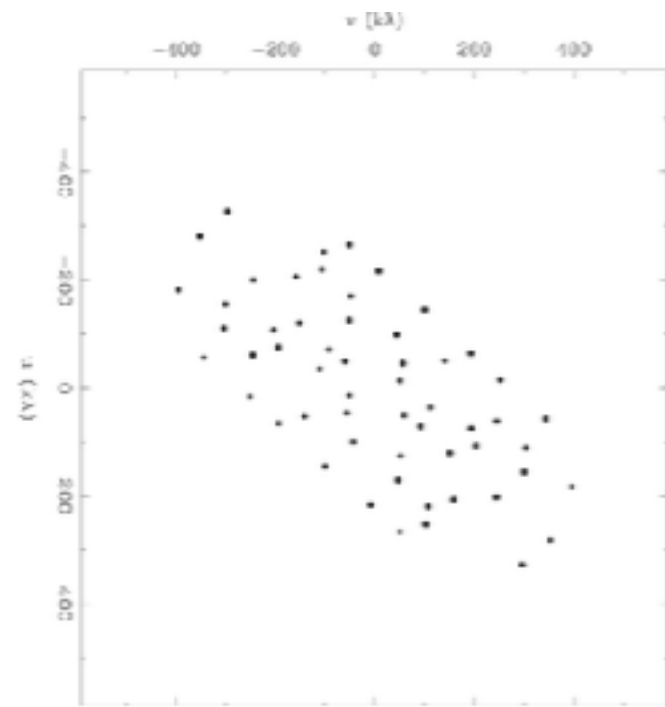
Config	Lmax		Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
	Lmin		100 GHz	150 GHz	183 GHz	230 GHz	345 GHz	460 GHz	650 GHz	870 GHz
C43-1	161 m	AR	3.4"	2.3"	1.8"	1.5"	1.0"	0.74"	0.52"	0.39"
	15 m	MRS	28.5"	19.0"	15.4"	12.4"	8.3"	6.2"	4.4"	3.3"
C43-2	314 m	AR	2.3"	1.5"	1.2"	1.0"	0.67"	0.50"	0.35"	0.26"
	15 m	MRS	22.6"	15.0"	12.2"	9.8"	6.5"	4.9"	3.5"	2.6"
C43-3	500 m	AR	1.4"	0.94"	0.77"	0.62"	0.41"	0.31"	0.22"	0.16"
	15 m	MRS	16.2"	10.8"	8.7"	7.0"	4.7"	3.5"	2.5"	1.9"
C43-4	784 m	AR	0.92"	0.61"	0.50"	0.40"	0.27"	0.20"	0.14"	0.11"
	15 m	MRS	11.2"	7.5"	6.1"	4.9"	3.3"	2.4"	1.7"	1.3"
C43-5	1.4 km	AR	0.54"	0.36"	0.30"	0.24"	0.16"	0.12"	0.084"	0.063"
	15 m	MRS	6.7"	4.5"	3.6"	2.9"	1.9"	1.5"	1.0"	0.77"
C43-6	2.5 km	AR	0.31"	0.20"	0.16"	0.13"	0.089"	0.067"	0.047"	0.035"
	15 m	MRS	4.1"	2.7"	2.2"	1.8"	1.2"	0.89"	0.63"	0.47"

Each configuration has a limited number of baseline lengths, or a limited number of spatial scales you are sensitive to

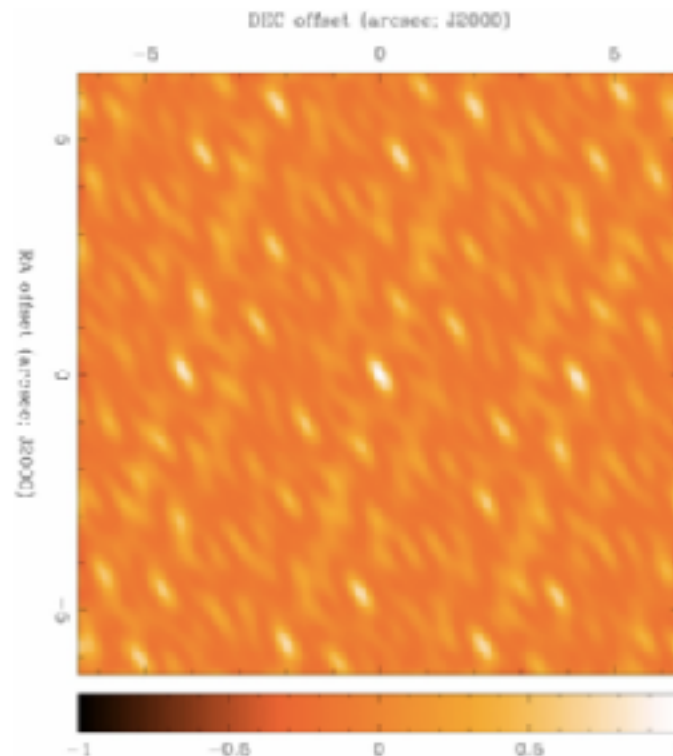
MRS: maximum recoverable scale
AR: angular resolution

Dirty beam

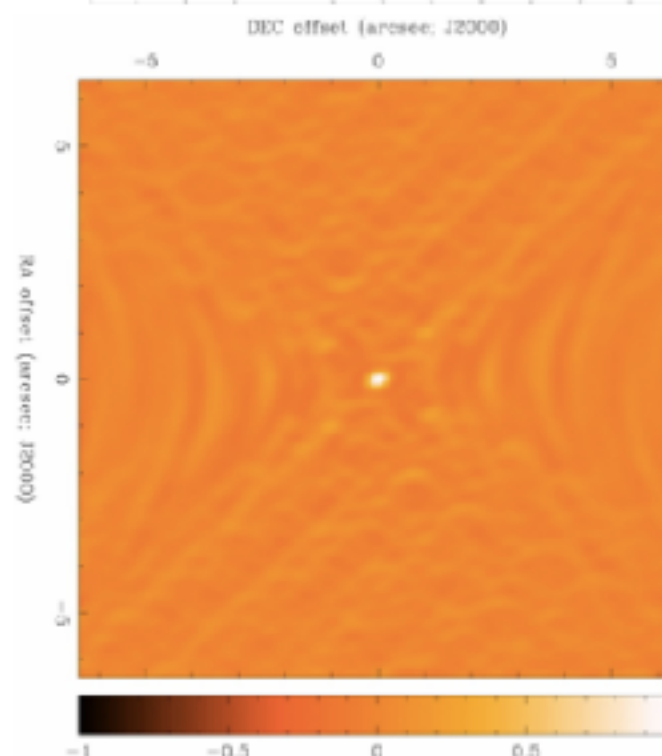
u,v-coverage
(example: SMA
with 8 antennas)



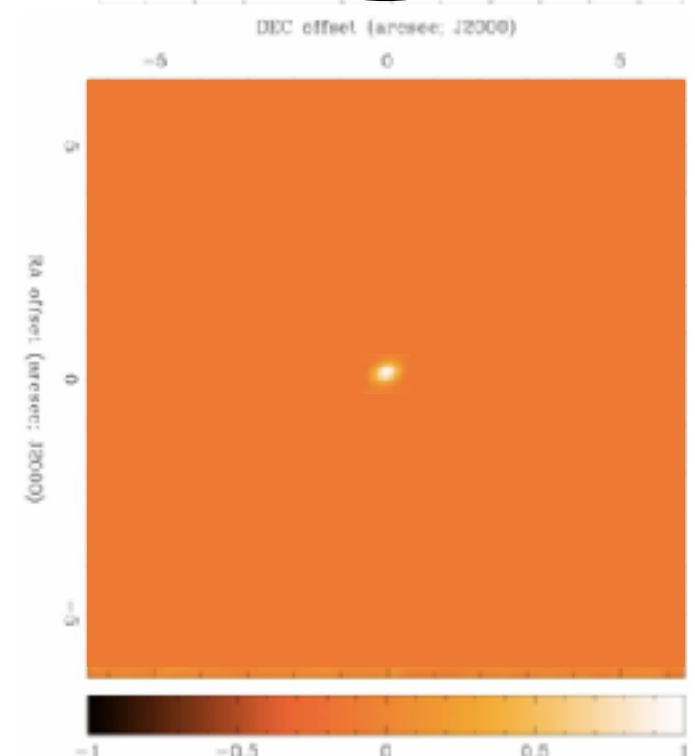
Beam or PSF



Very dirty beam



Dirty beam

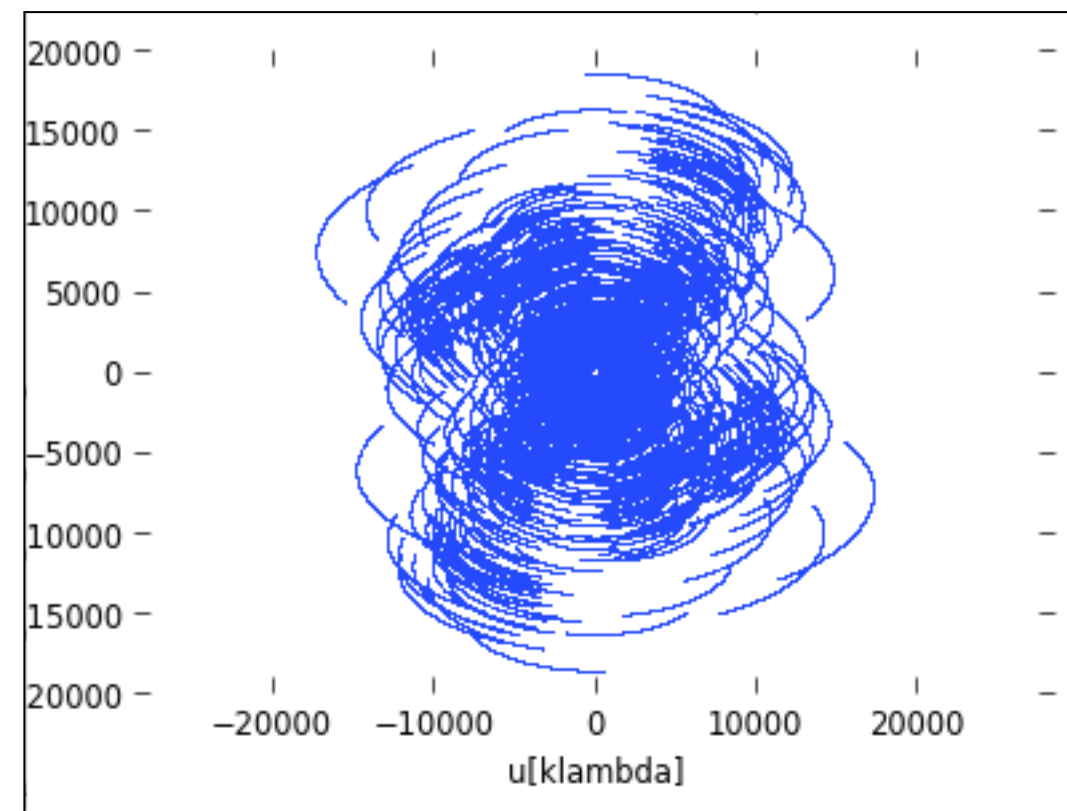


Perfect beam

Demo uv-coverage

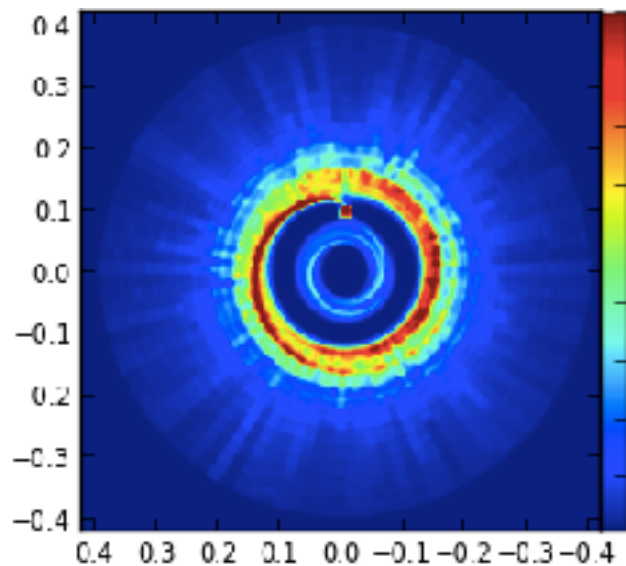
- ALMA simulation in CASA: provide an image and the details of the requested observations (configuration, integration time, declination of source, frequency) and compute how your image *would look like when observed*
- Two main differences between convolution and ALMA simulation: spatial scales + side lobes
- Difference generally gets worse in more extended configurations: less u,v-coverage at long baselines

u,v-coverage
5h ALMA observation



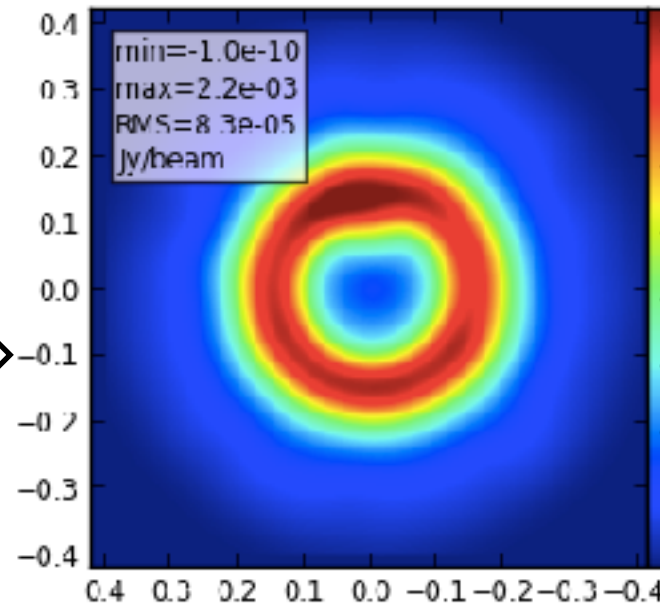
Demo uv-coverage

Model image
(Band9: 672 GHz)

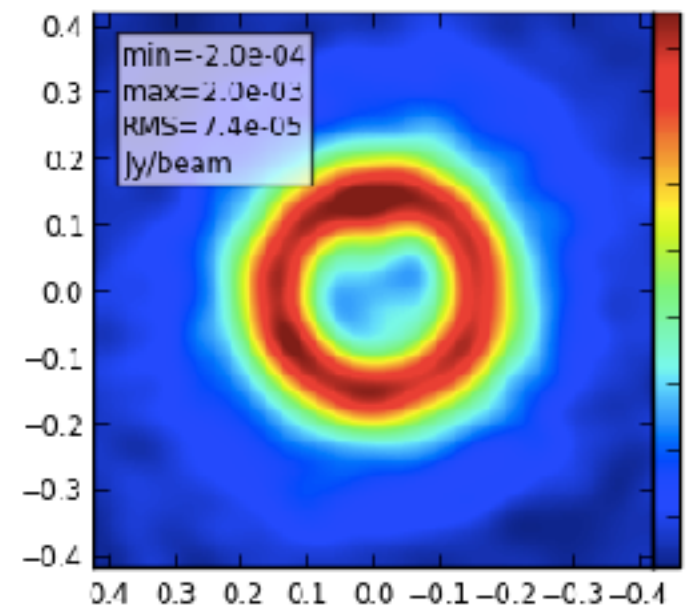


Configuration 5
AR $\sim 0.1''$
MRS $\sim 1.2''$

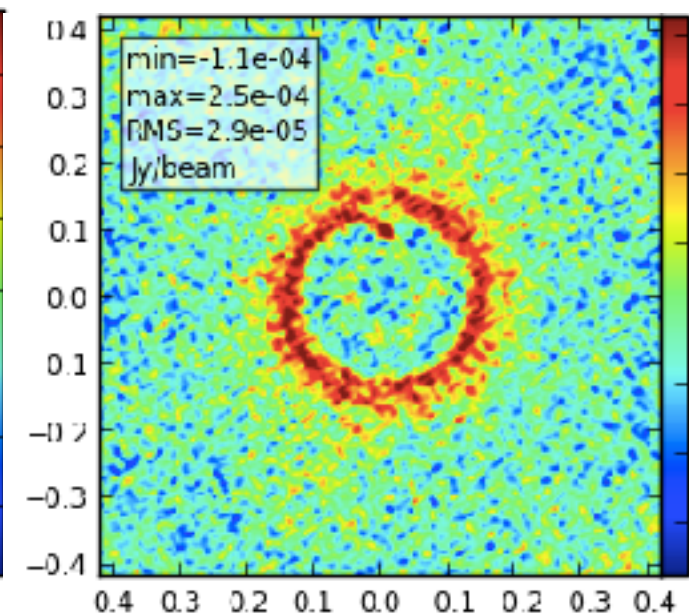
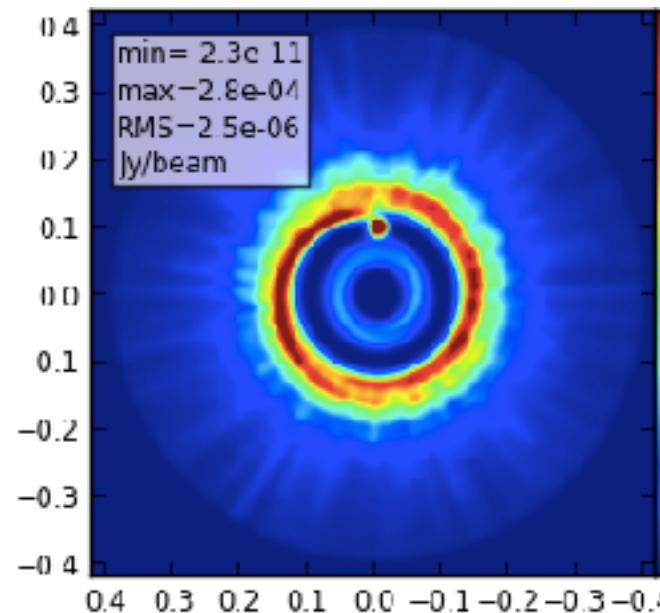
Convolved



Simulated



Configuration 8
AR $\sim 0.02''$
MRS $\sim 0.2''$

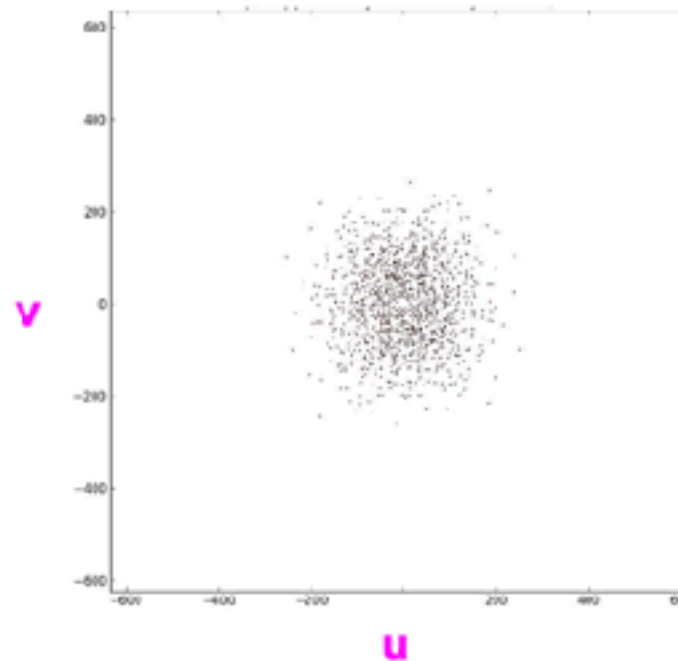


Note that only 2/3 of total flux is recovered in C8

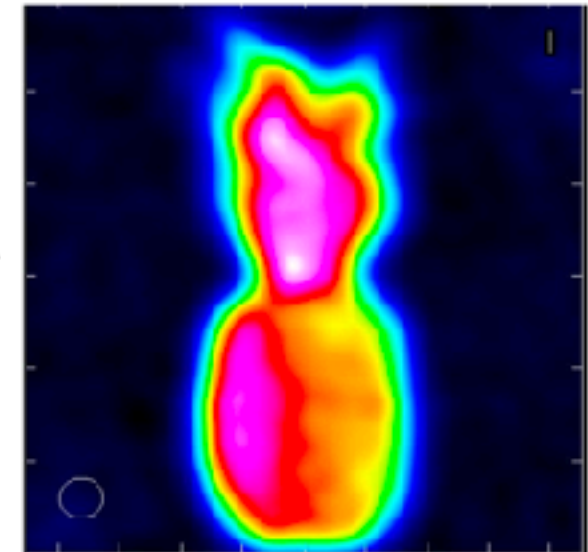
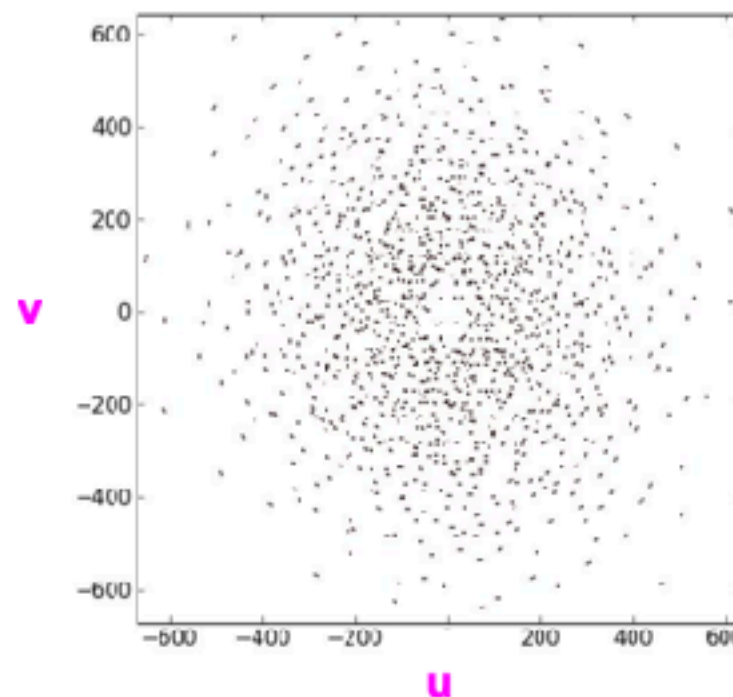
Demo uv-coverage



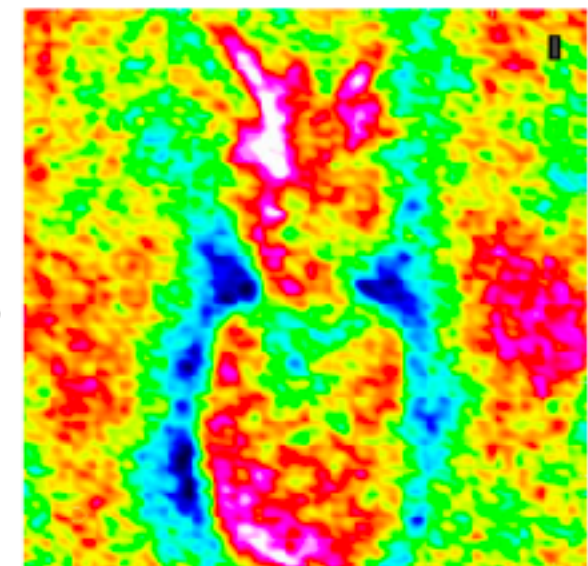
- Interferometers have a **spatial sampling** and **beam shape** determined by their **configuration**.
- **Extended** array configurations (large uv-distances) sample **small scales**.
- **Compact** array configurations (small uv-distances) sample **large scales**.



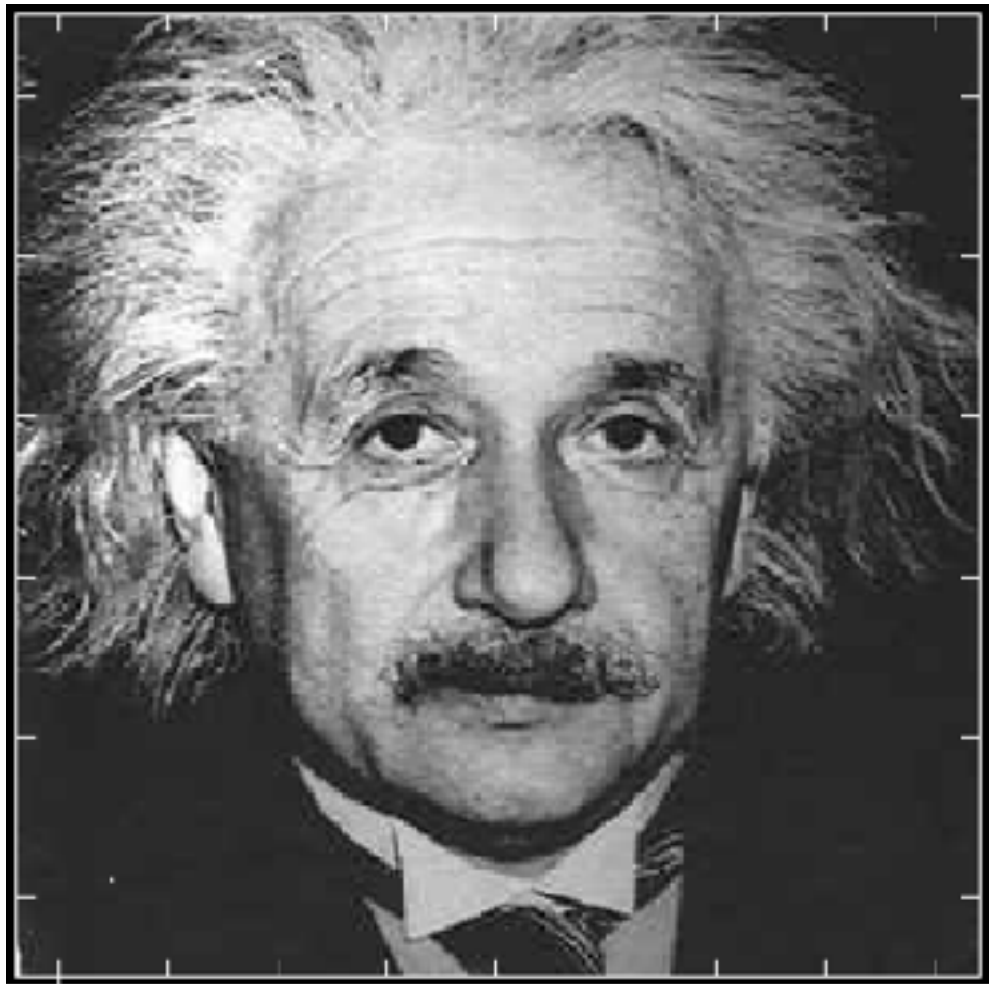
Fourier Domain (uv-plane) Sampling



What ALMA sees:



Demo uv-coverage

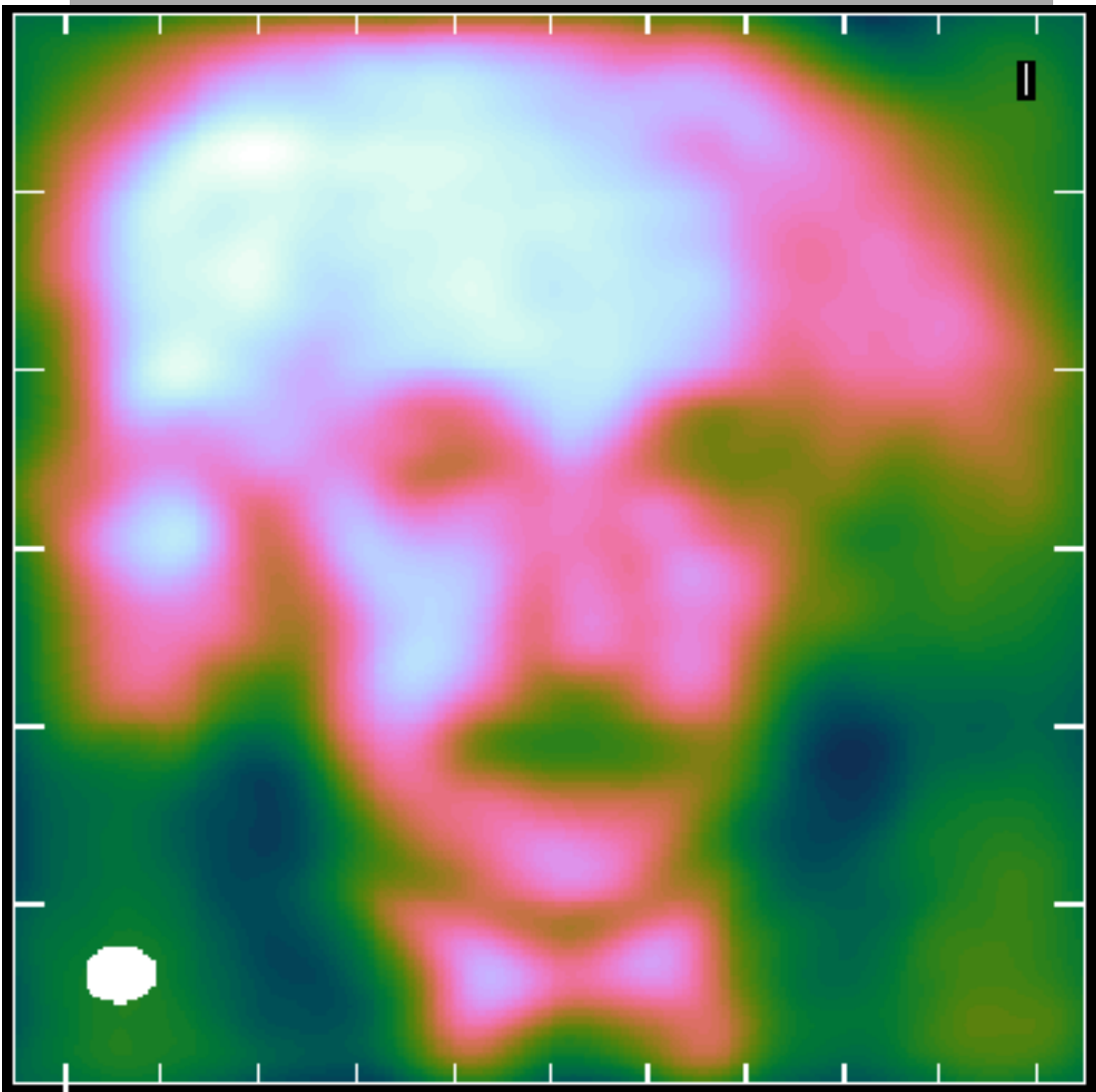


← 1.5" →

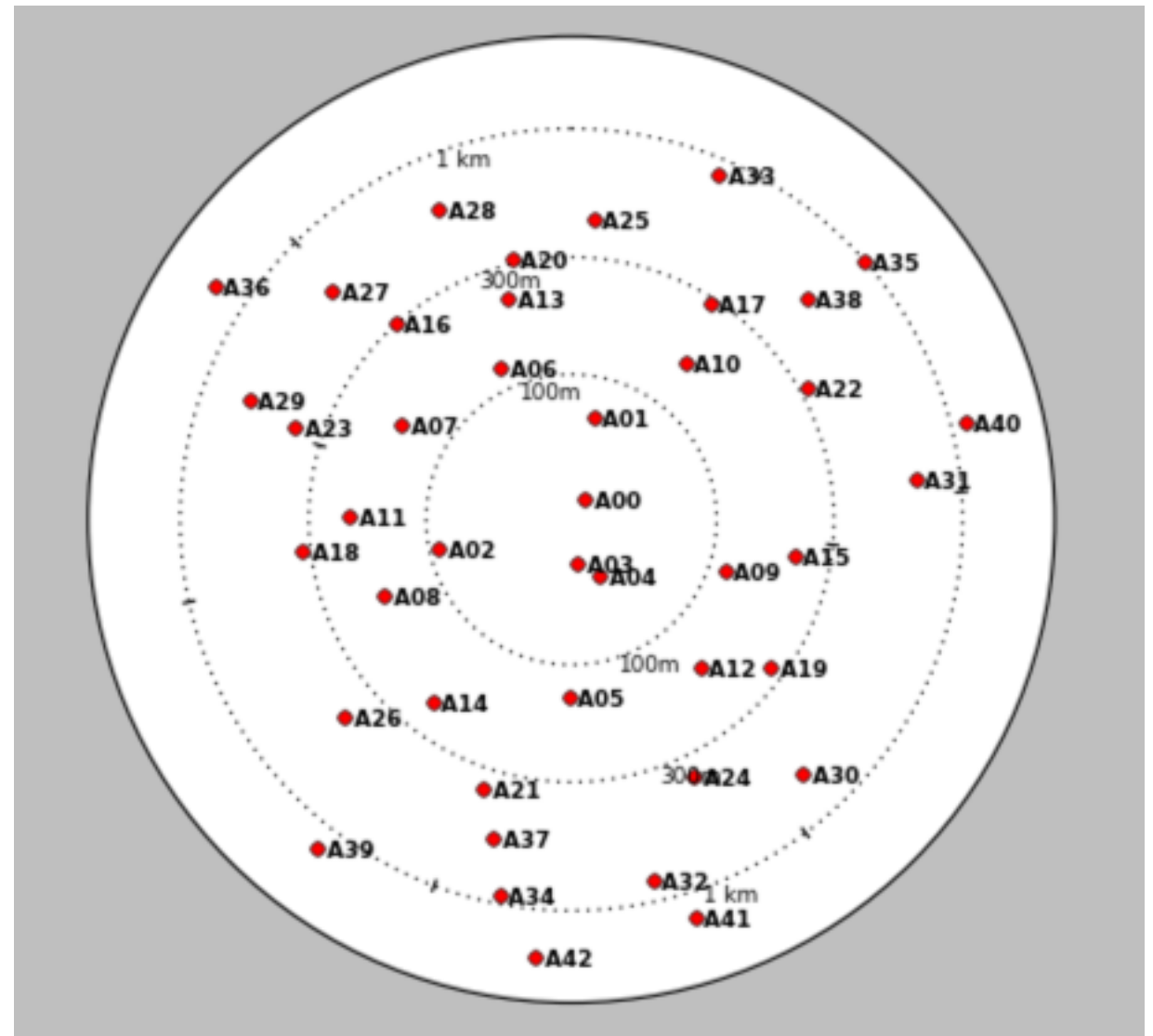
+



Demo uv-coverage

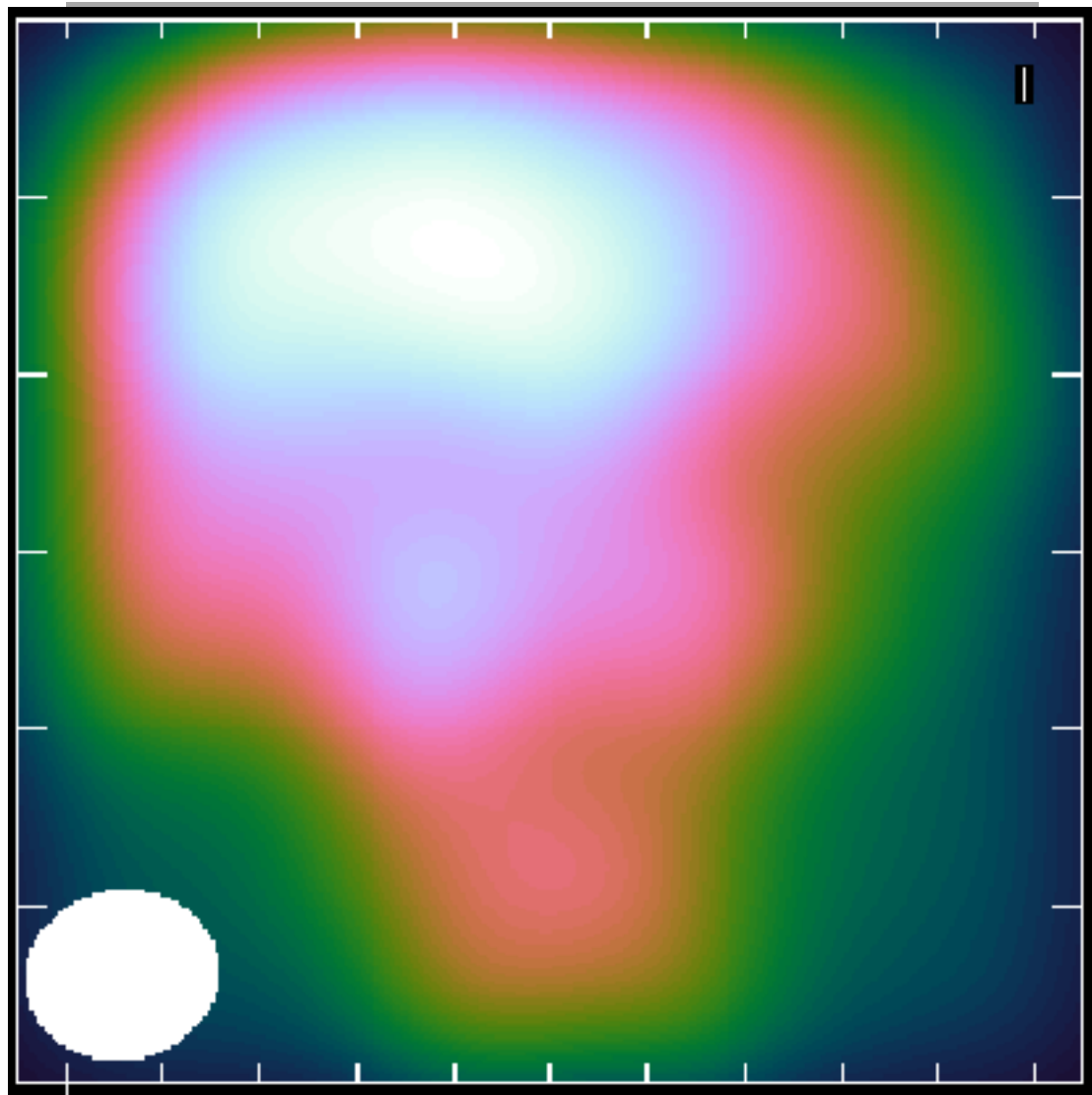


Resolution = $0.2''$

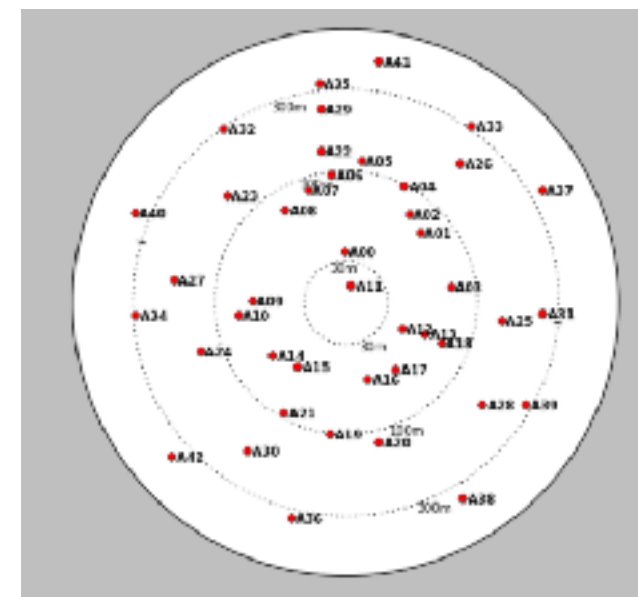


Max baseline = 2 km

Interferometry



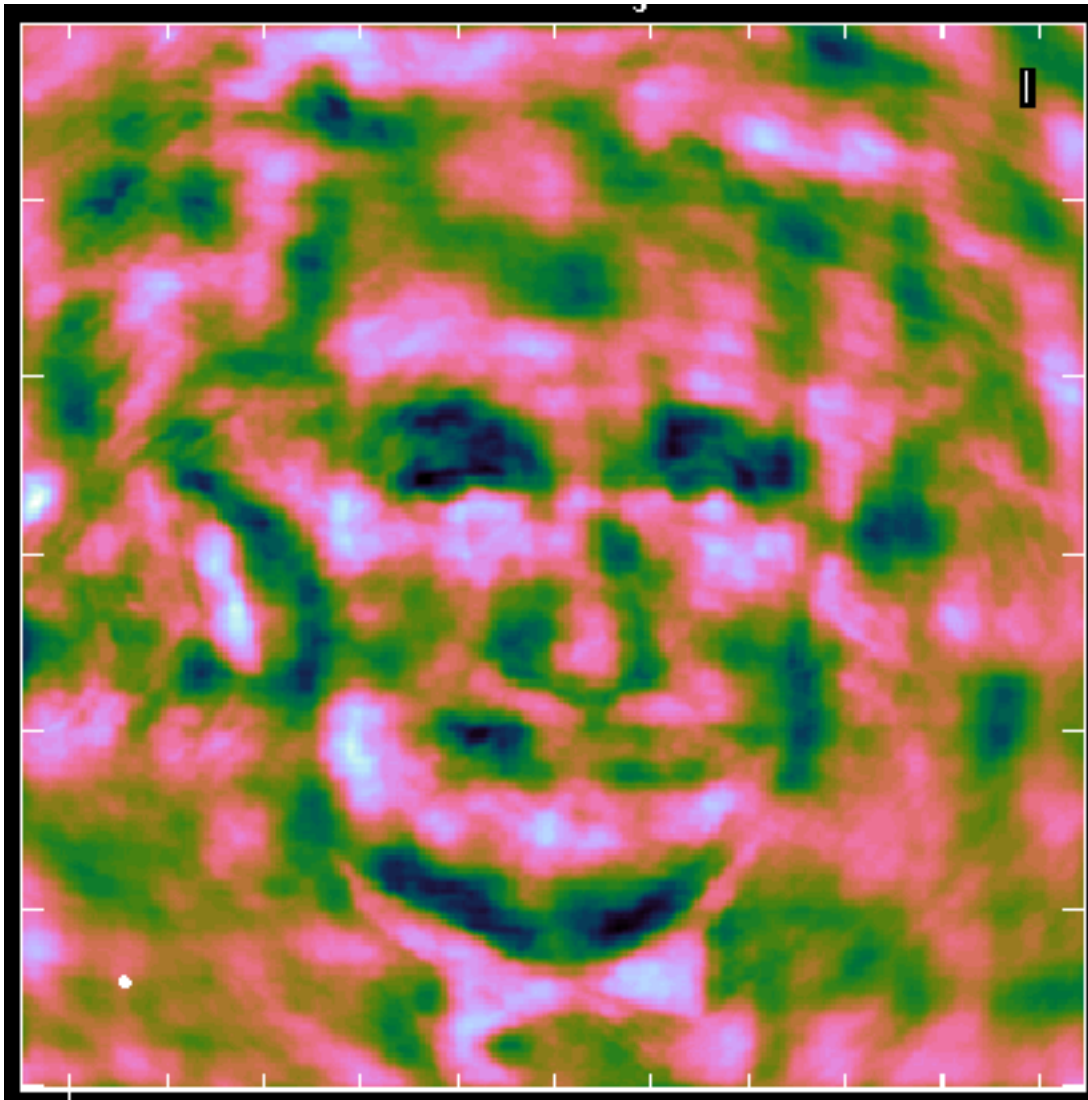
Resolution = $0.6''$



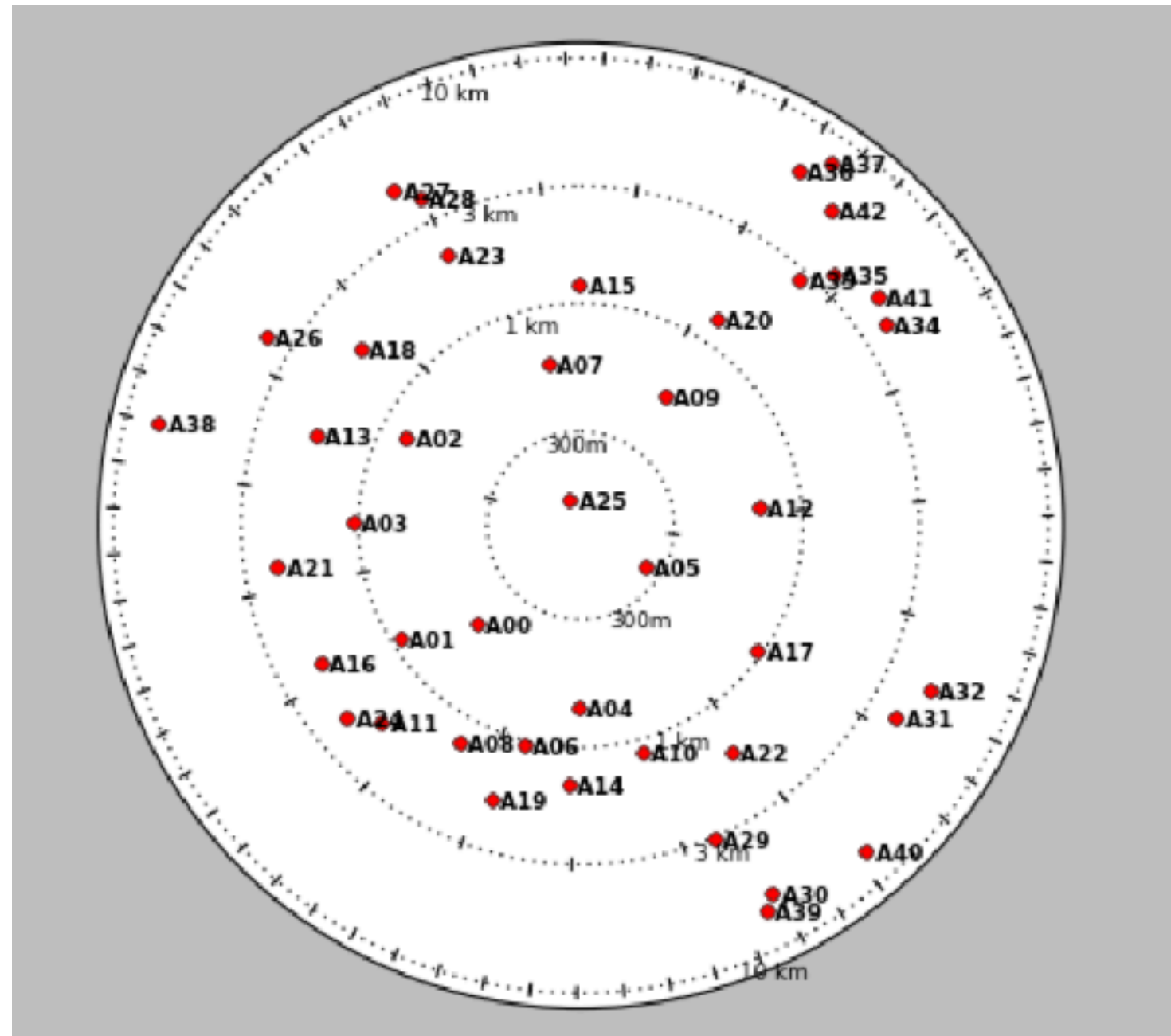
Antenna positions

Max baseline = 600 m

Demo uv-coverage

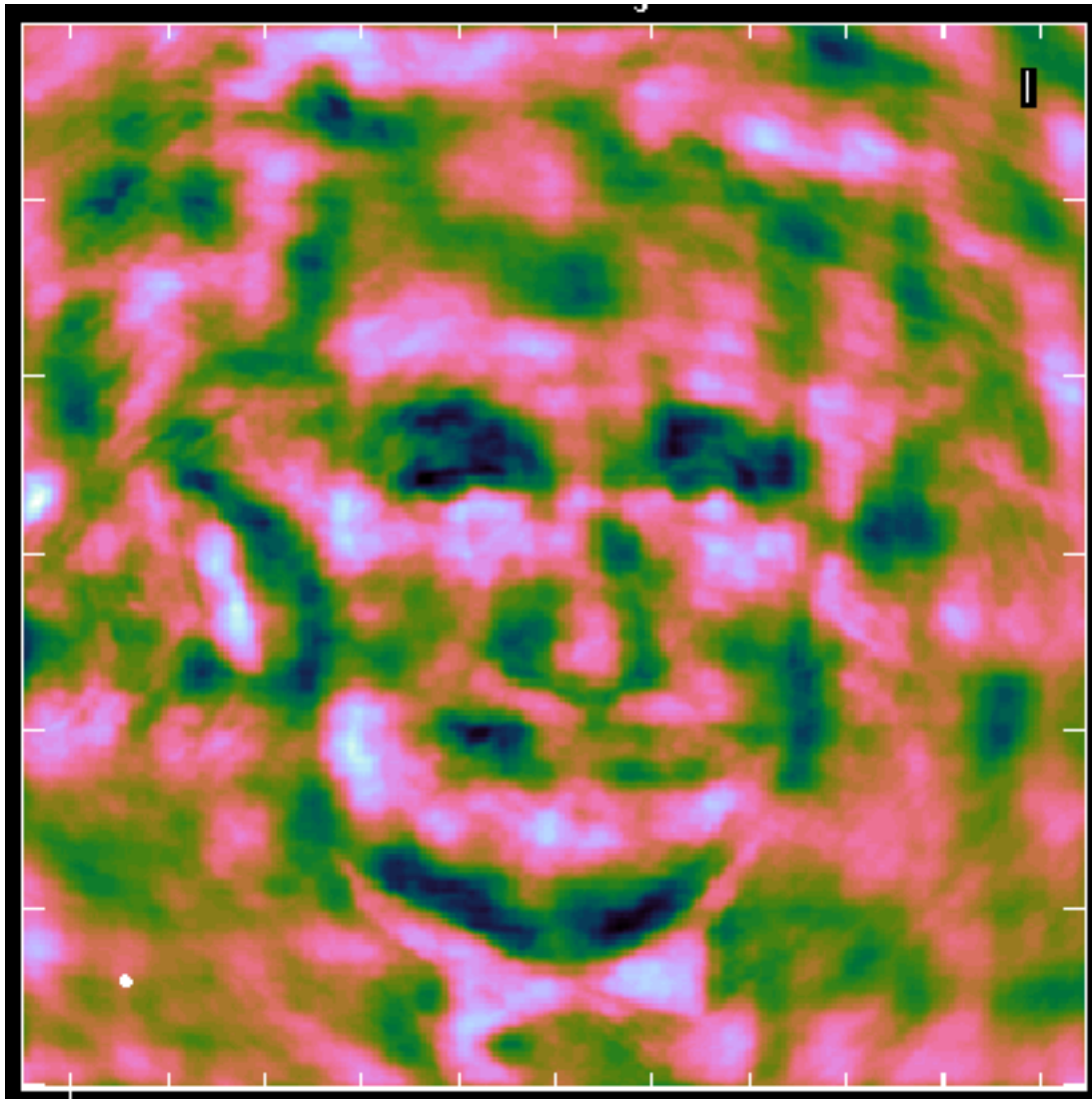


Resolution = $0.03''$

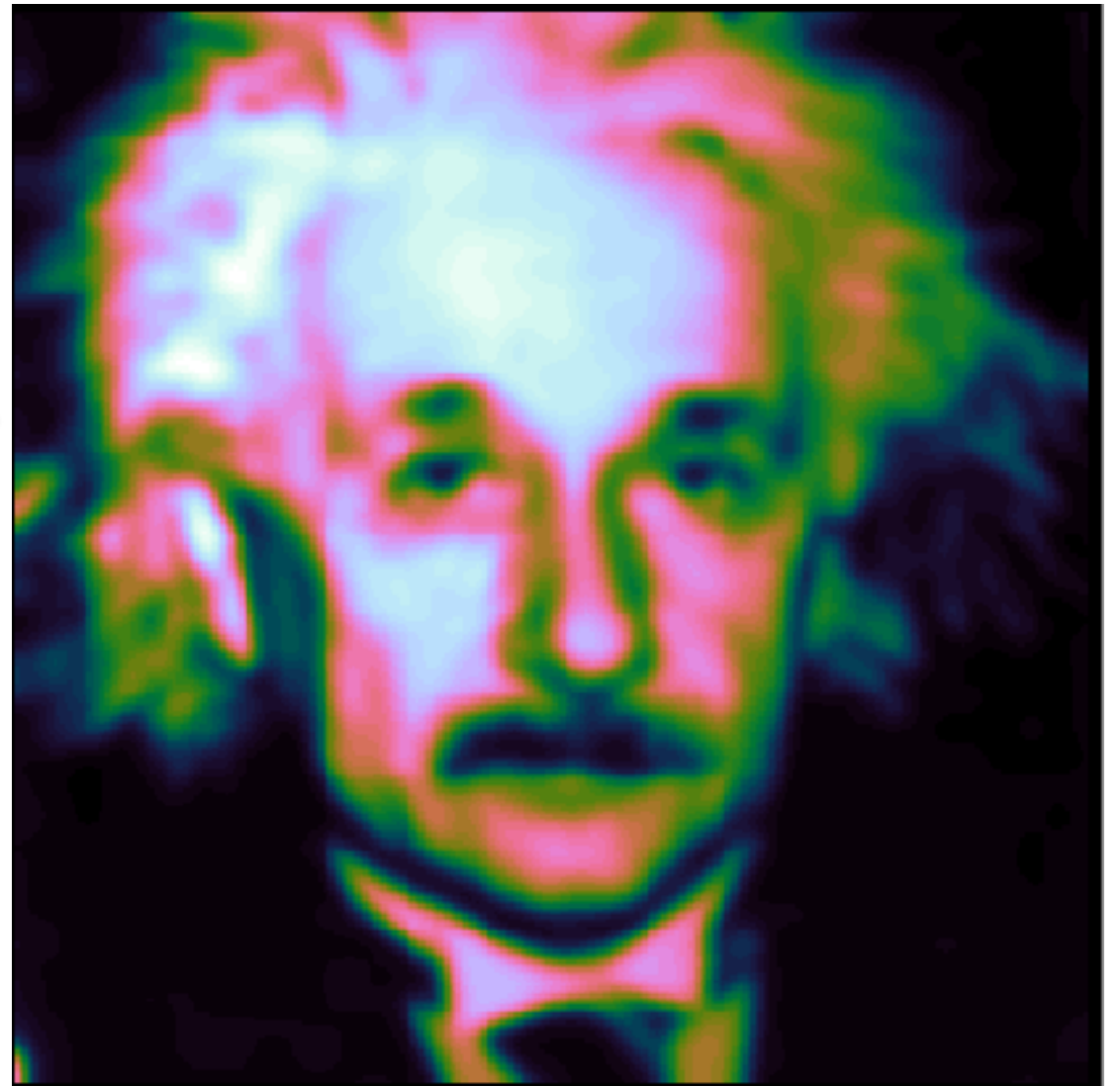


Max baseline = 12 km

Demo uv-coverage



Interferometry

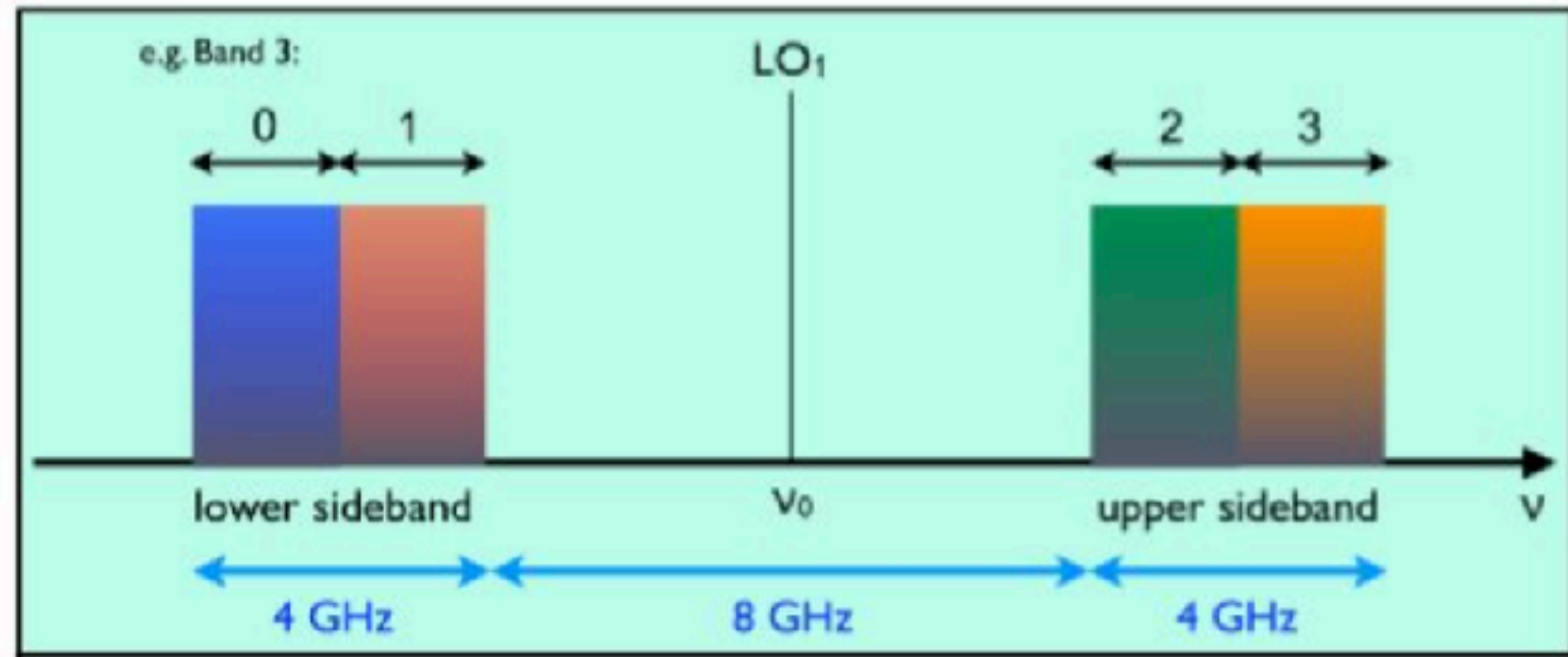


Convolution

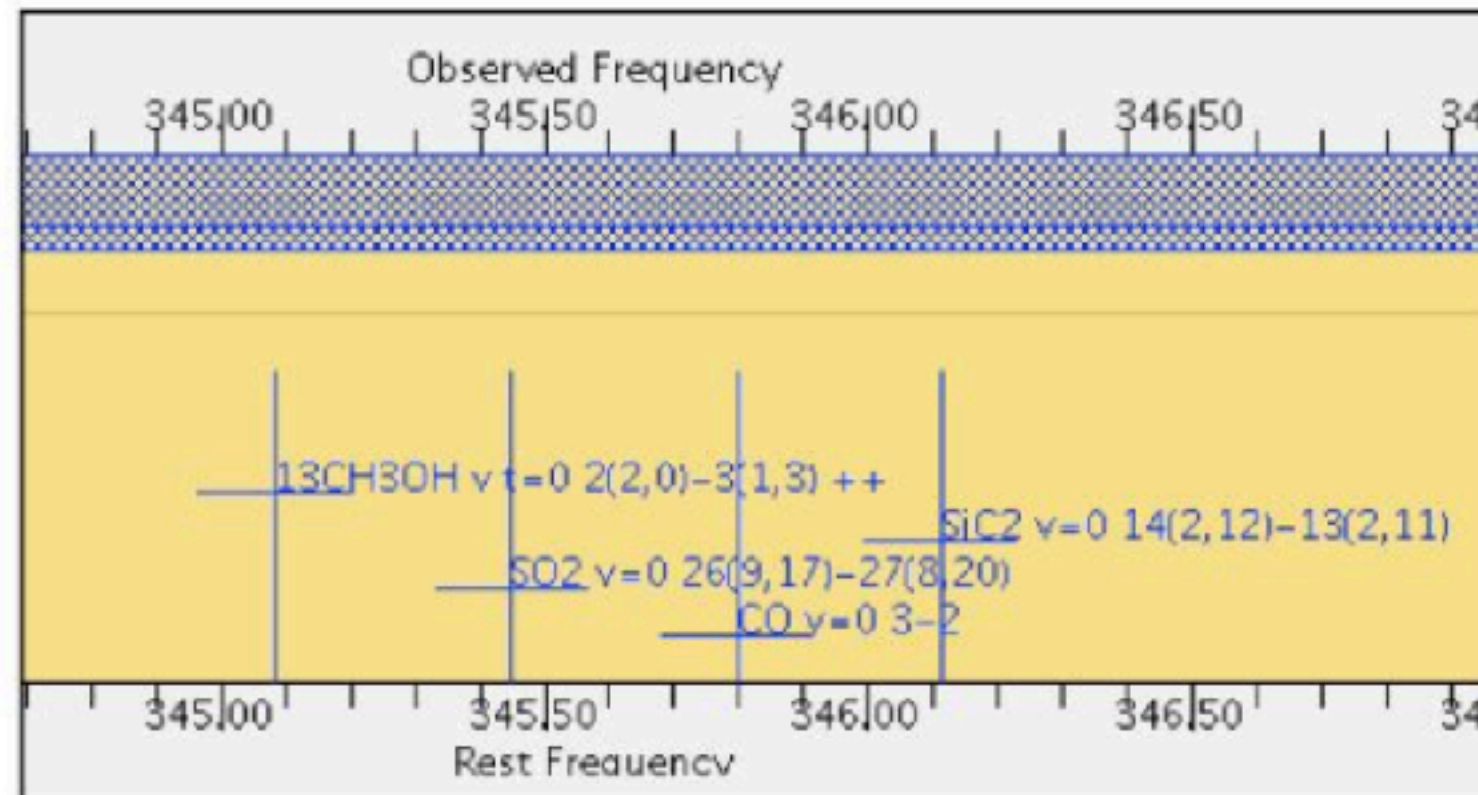
Importance spatial scales

About spectral windows

Lower and upper side band with multiple spectral windows

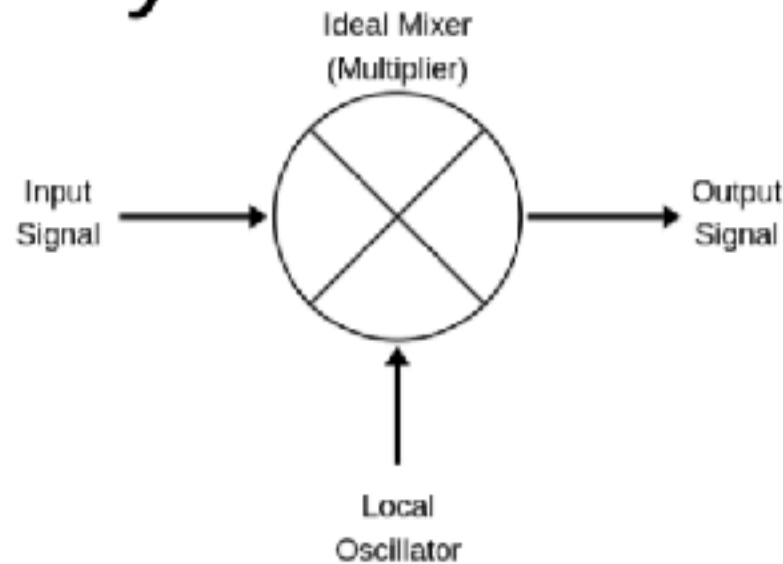


In each spectral window



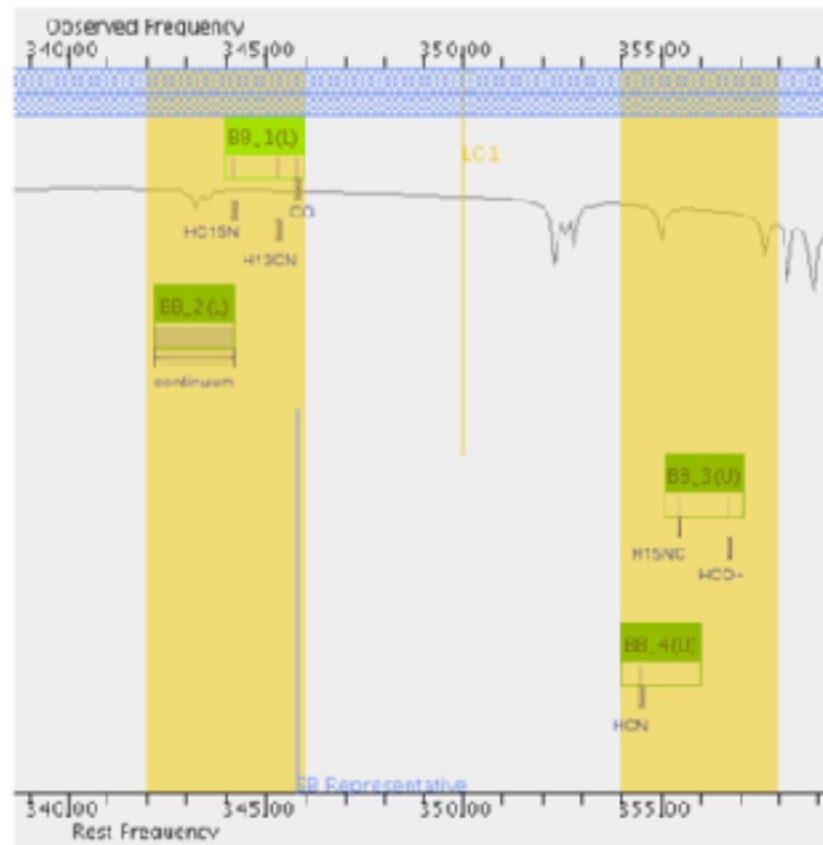
About spectral windows

- Heterodyne receiver: mixing local oscillator

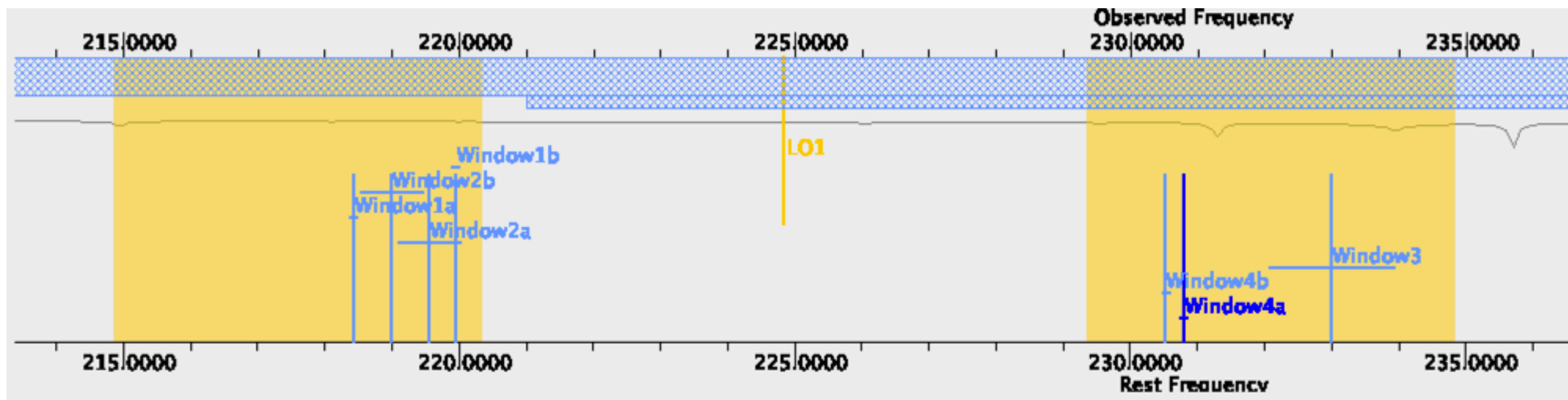


- Frequency spectral windows always within USB and LSB: $LO \pm IF$ ($IF \sim 4-8$ GHz)
- ALMA: B9 double, other bands dual SB: freedom in frequency range

About spectral windows



- Basic setup: 4 basebands of 3840 channels each around LO frequency
- Max 4 spectral windows within each baseband
- Compromise: bandwidth (line width, multi-line coverage, continuum bandwidth) or spectral resolution (velocity resolution)
- Observing frequency: depends on Earth velocity at time of observing, so sometimes multiple spectral windows when observed multiple times



Calibration

- We measure amplitudes and phases of sources
- Time dependent:
 - Weather
 - Atmosphere
 - Antenna response
 - Instrument response
 - Moving antennas
 - Etc.
- So we have to calibrate for **each** antenna **all** the time
- ALMA calibration is done for you (QA2) so basics only now



Observatory calibrations

- These are done rarely, or when antennas are moved.
- For each antenna, calibration measurements are made for:
 - Array Position
 - Focus
 - Pointing/astrometry
 - Surface accuracy
 - Primary beam pattern



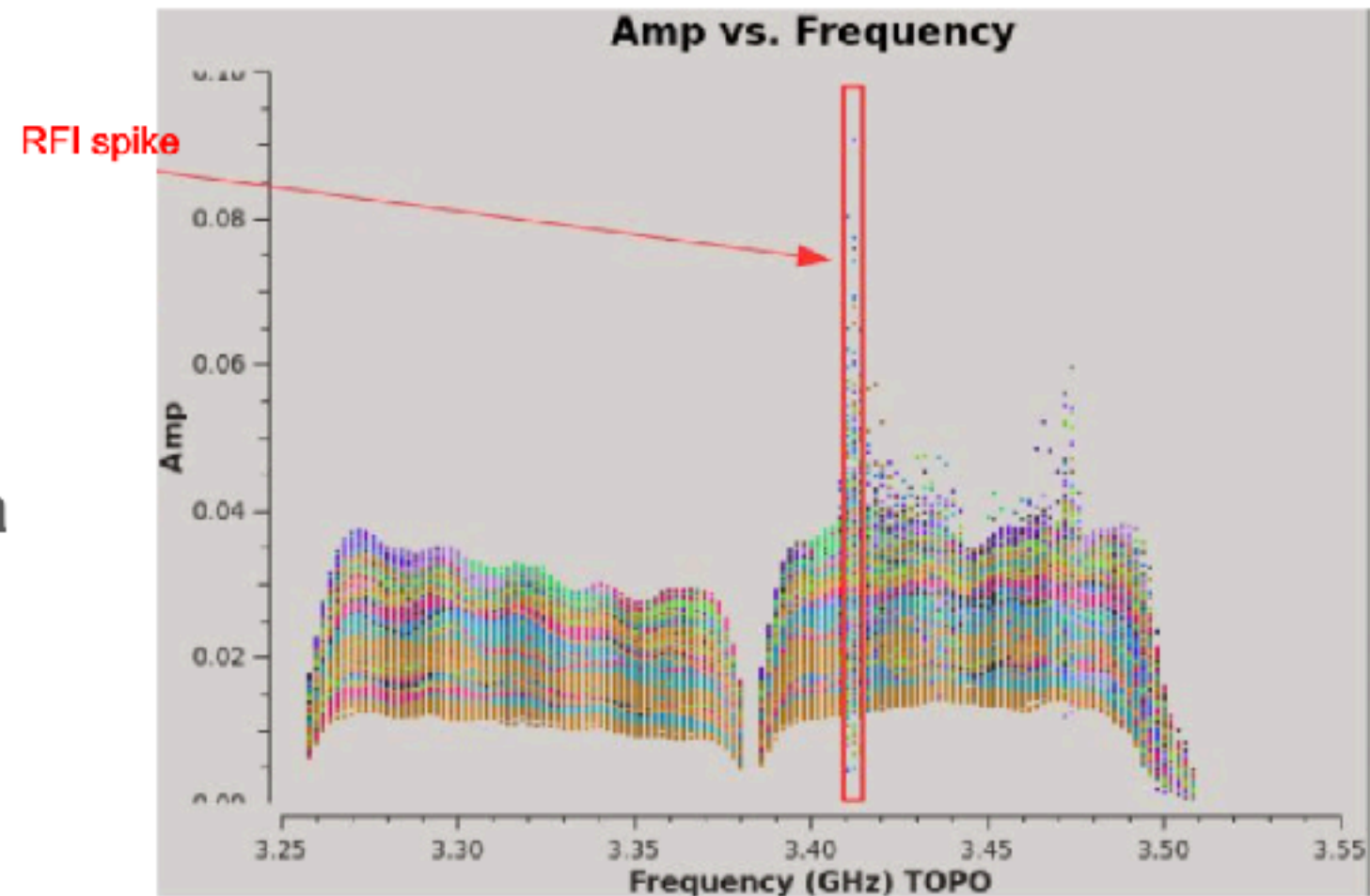
Science observation calibrations

- The following calibrations are done for every ALMA observation:
 - Data Flagging
 - System temperature Measurement
 - Water Vapor Radiometer Corrections
 - Bandpass Calibration
 - Flux Density Scale Calibration
 - Phase (gain) Calibration
 - Check source observations (long-baseline/high frequency only)
 - Polarization Calibrations (polarization observations only)
 - Self-Calibration (ALMA user applied! Friday Workshop :))
 -
- We'll go through (most of them) one at a time.



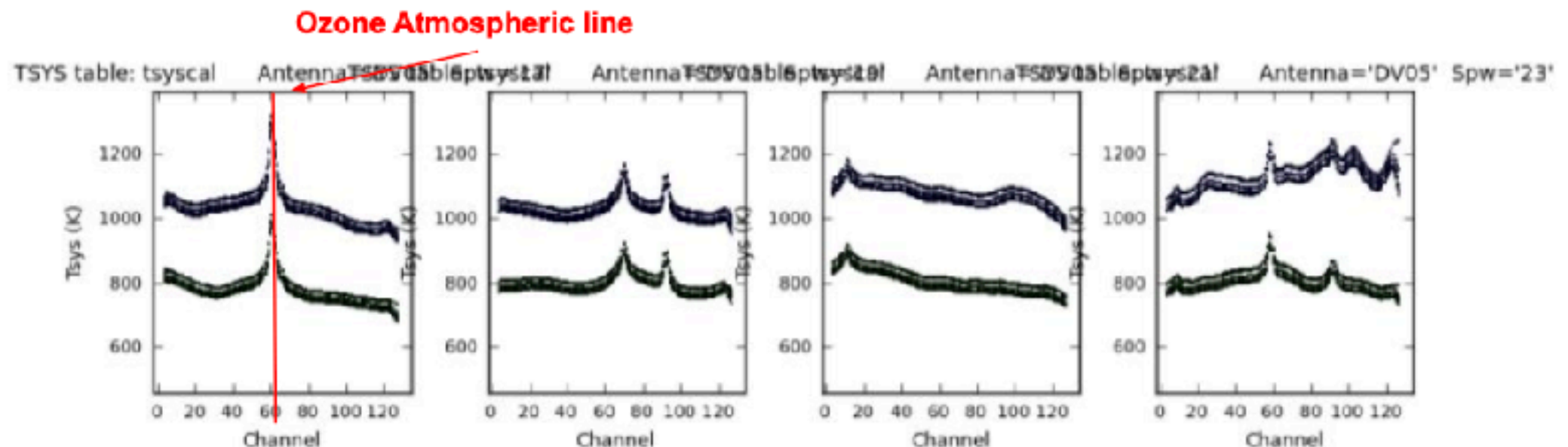
Data flagging

- Some problems can completely ruin data, e.g:
 - Broken antennas
 - Correlator glitches
 - Telescope shadowing
 - Radio Frequency Interference
 - Bad calibration solutions
- When this happens, the bad data is removed or “flagged”.



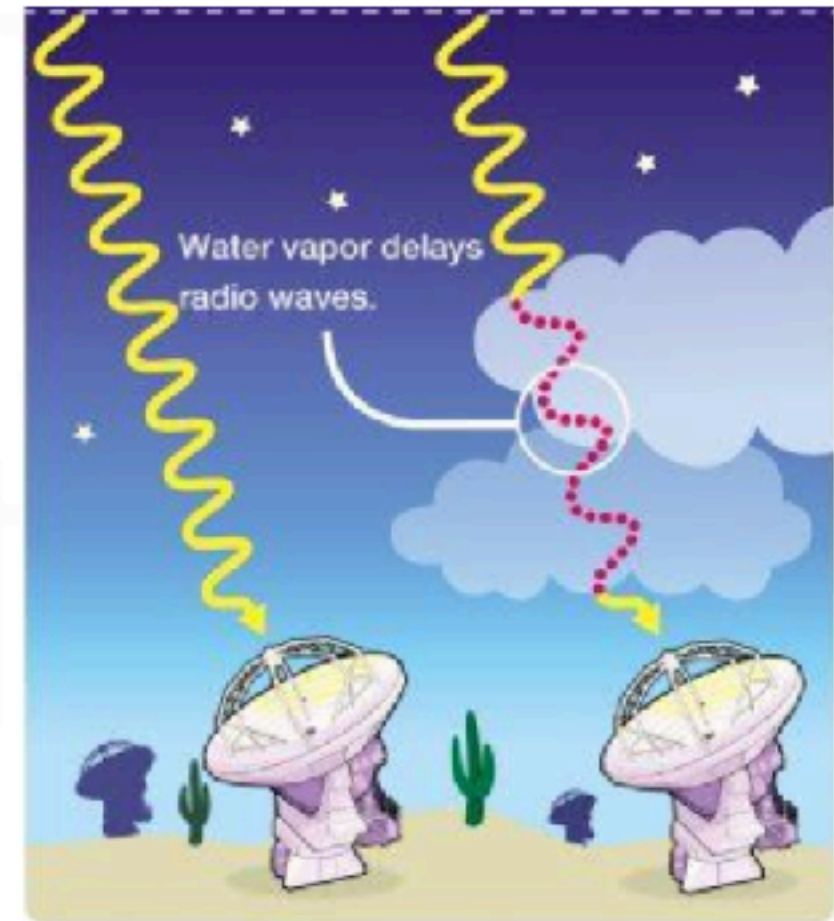
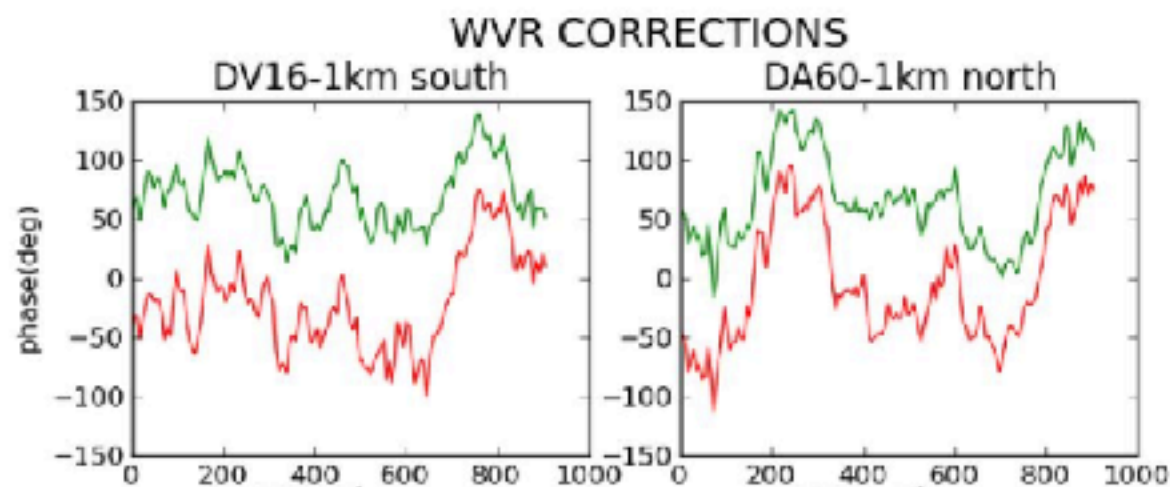
System temperature

- System temperature = noise added to observations.
- $T_{\text{sys}} = T_{\text{bg}} + T_{\text{sky}} + T_{\text{spill}} + T_{\text{loss}} + T_{\text{cal}} + T_{\text{rx}}$, where:
 - T_{bg} = noise contribution from microwave and galactic backgrounds
 - T_{sky} = noise contribution from atmospheric emission
 - T_{spill} = noise contribution due to ground radiation (spillover and scattering)
 - T_{loss} = noise contribution due to losses in feed
 - T_{cal} = noise contribution due to injected noise
 - T_{rx} = receiver noise temperature
- Need to measure T_{sys} **to get correct data weights!**
- Measure calibrator hot/cold “loads” (resistors) and sky contribution.



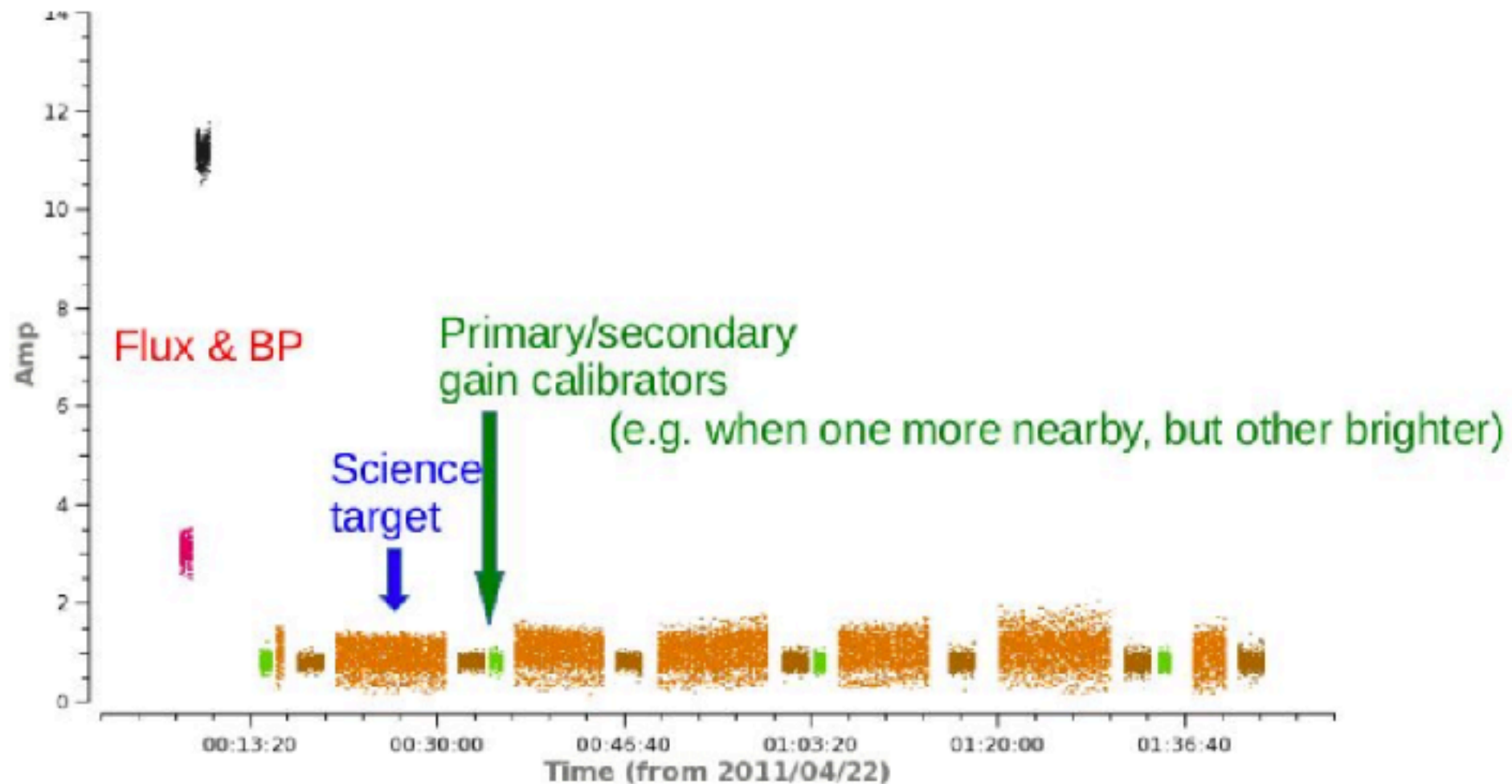
Water vapor

- Variations in water vapor in antenna LOS causes significant phase errors:
- ALMA 12m antennas have radiometers that measure water along LOS every 1.1s to correct for this:



Calibrator source

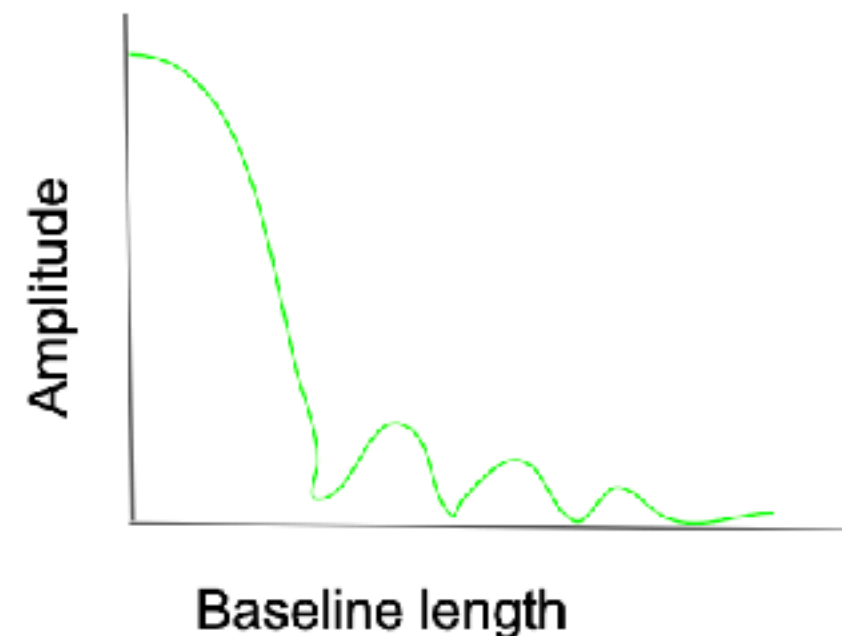
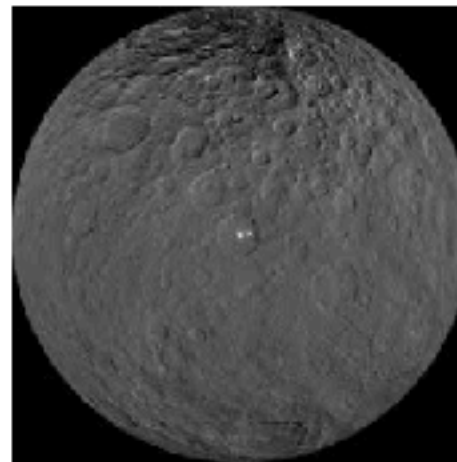
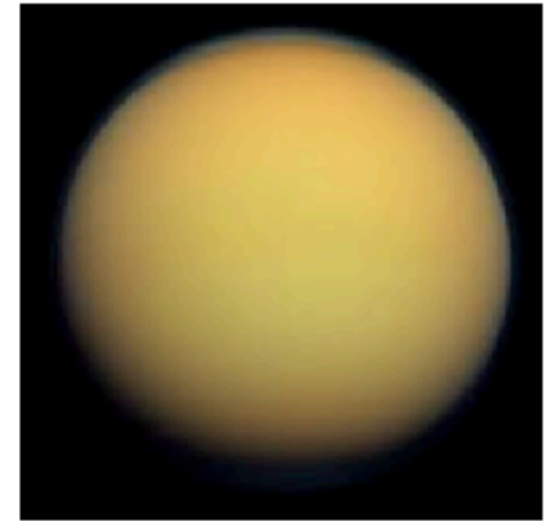
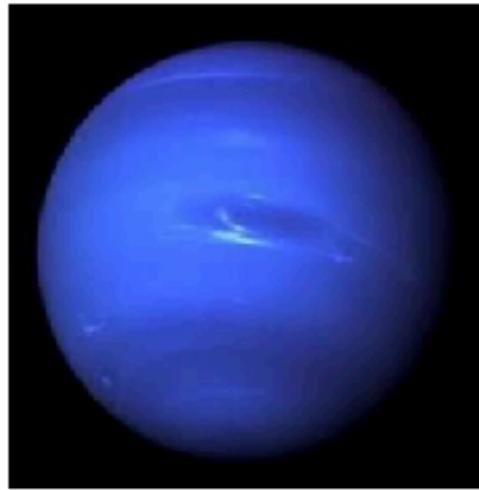
- Flux, bandpass, and phase (gain) calibration vary on short timescales and require observing additional calibrator targets:



Flux calibration

Flux Calibration

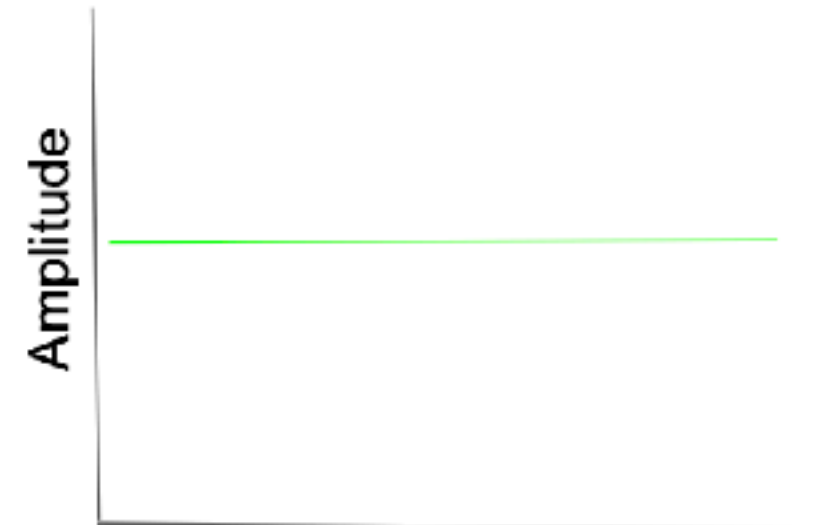
- Ideally: observe a mm source of known brightness and scale our visibility amplitudes.
- Problem: the mm sky has few suitable calibrators!
- Option 1: Solar System bodies
- Pros: bright, flux known to 5%
- Cons: not always observable, low flux on long baselines...



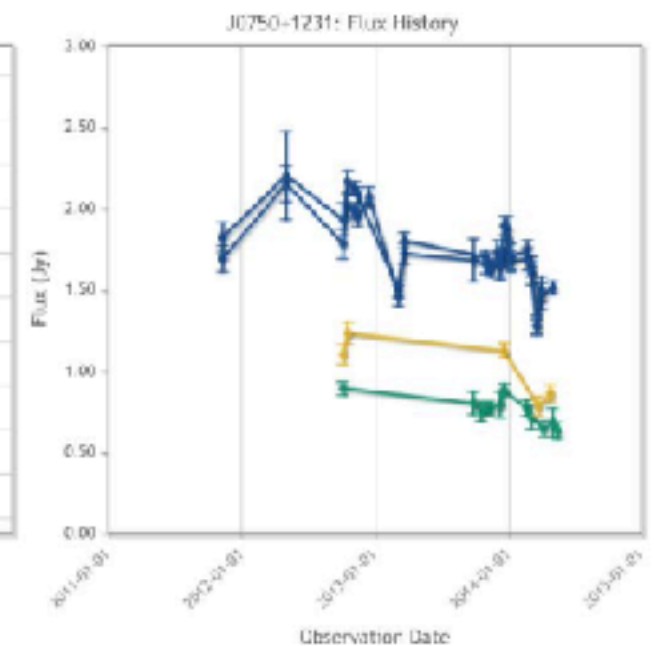
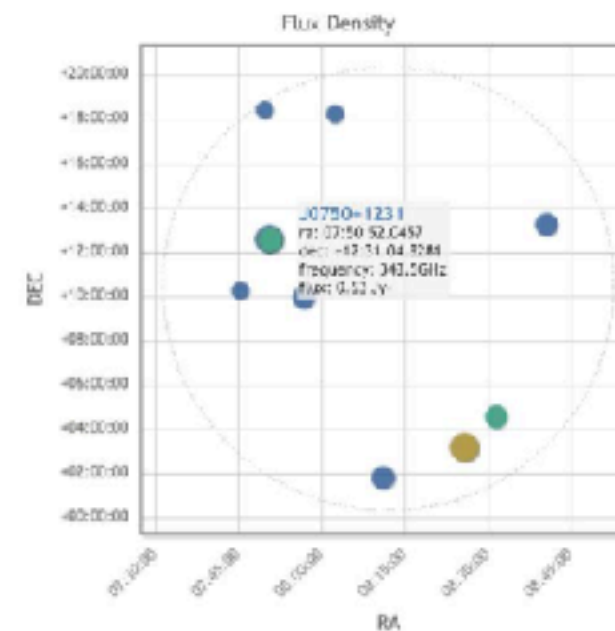
Flux calibration

Flux Calibration

- Option 2: Quasars
- Pros: Bright, point-like, all over the sky
- Cons: **Time variable Flux!**
- ALMA's solution: Observe many quasars regularly with solar system objects in "grid" over the sky.
- Observing an ALMA grid quasar with science targets provides ~10% accuracy at 233 GHz (band 6)

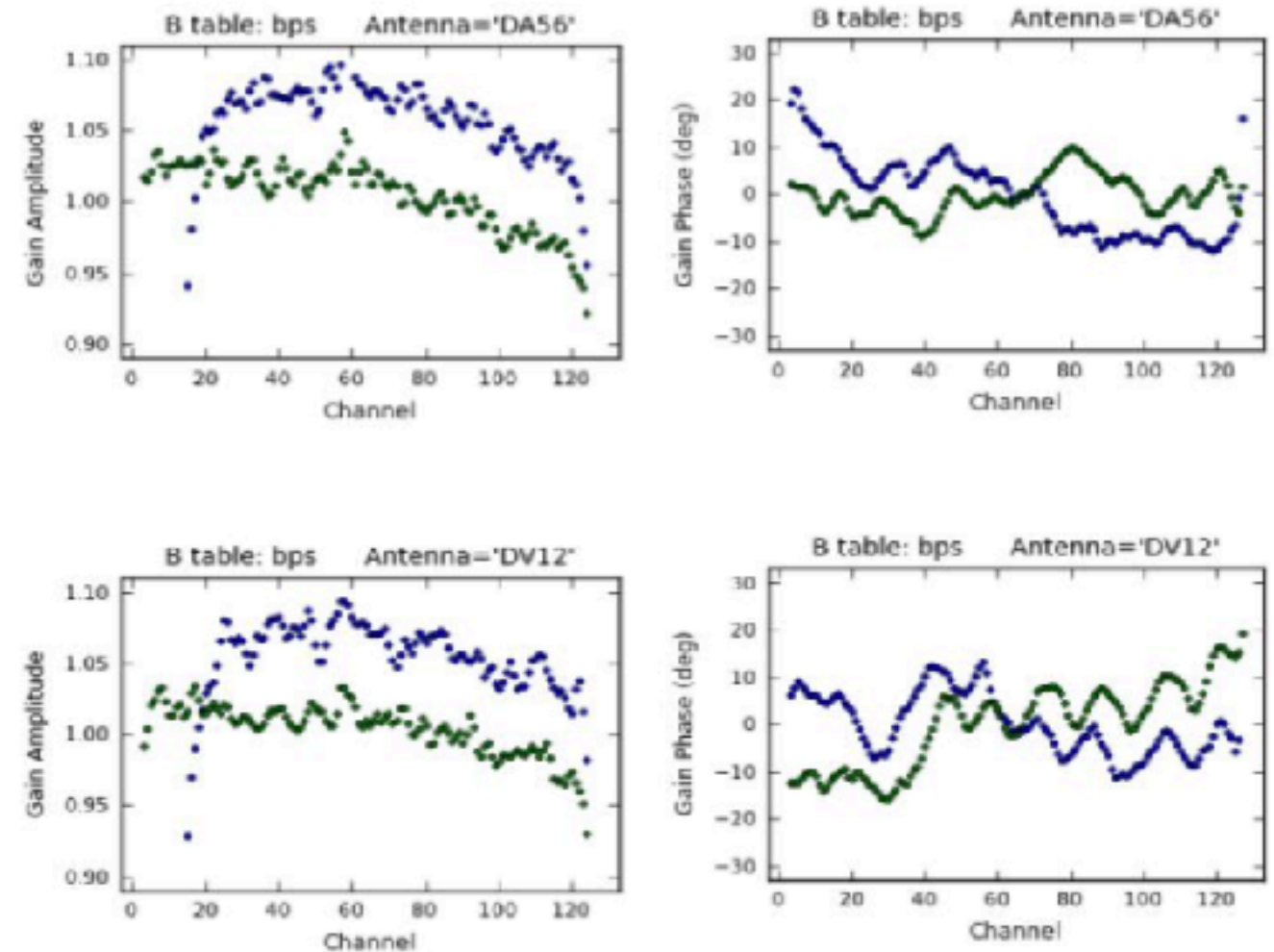


Baseline length



Bandpass calibration

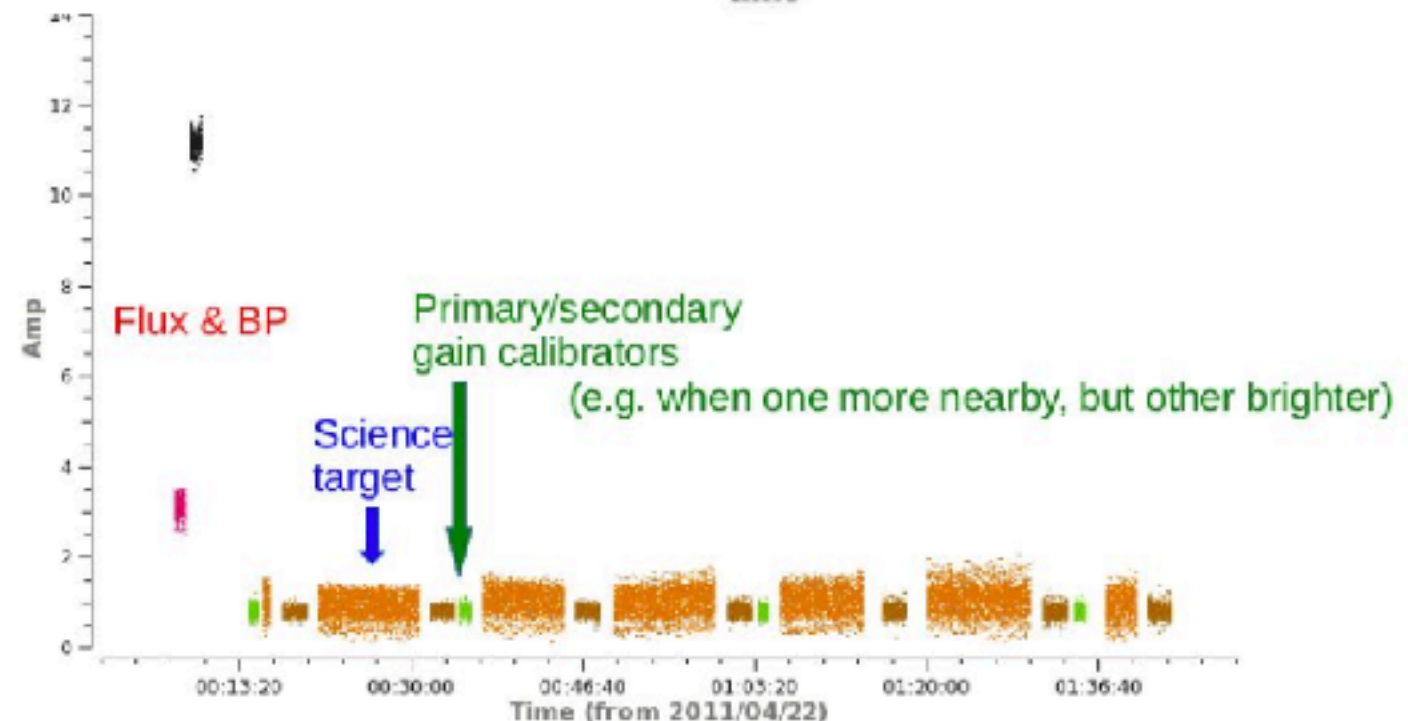
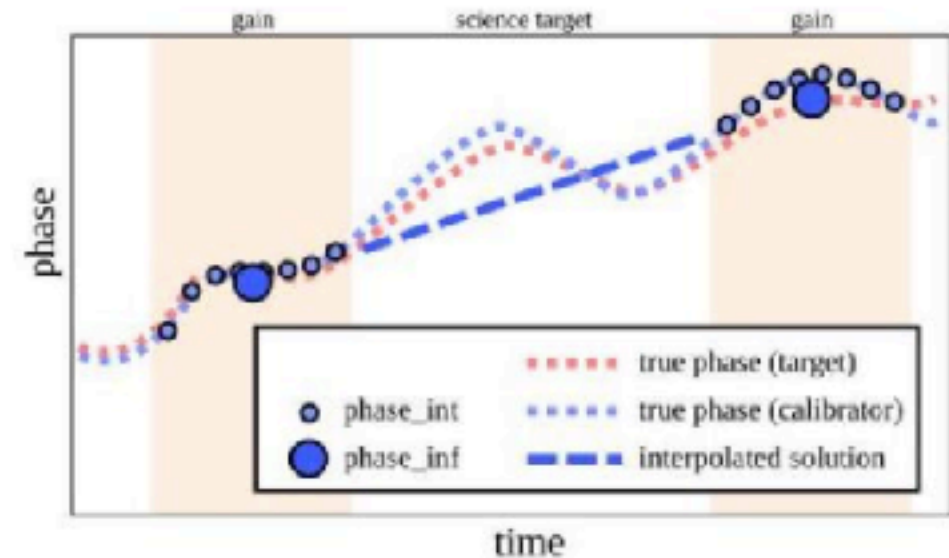
- Correct Amplitude and Phase across bandpass by observing a calibrator.
- Usually done once before/after science target observations.



Phase calibration

Phase (gain) Calibration

- Atmospheric turbulence causes large, time variable phase observations **during** an observation.
- Short science target scans are bracketed by observations of a phase calibrator.
- Calibration solutions are interpolated in time to science observations.



How do we image (‘clean’) visibility data?



Why do we need to clean?

Recall: sampling

Effects of Sampling

- Describe sampling of uv-plane with function $S(u,v)$:

$$V_{\text{obs}} = S(u, v)V(u, v) \quad S(u, v) = \sum_i \delta(u-u_i, v-v_i) + \delta(u+u_i, v+v_i)$$

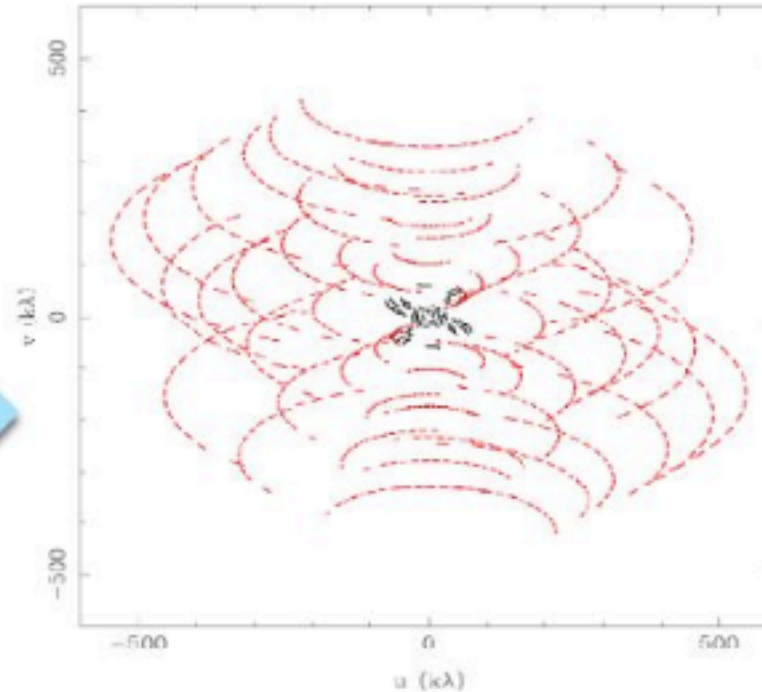
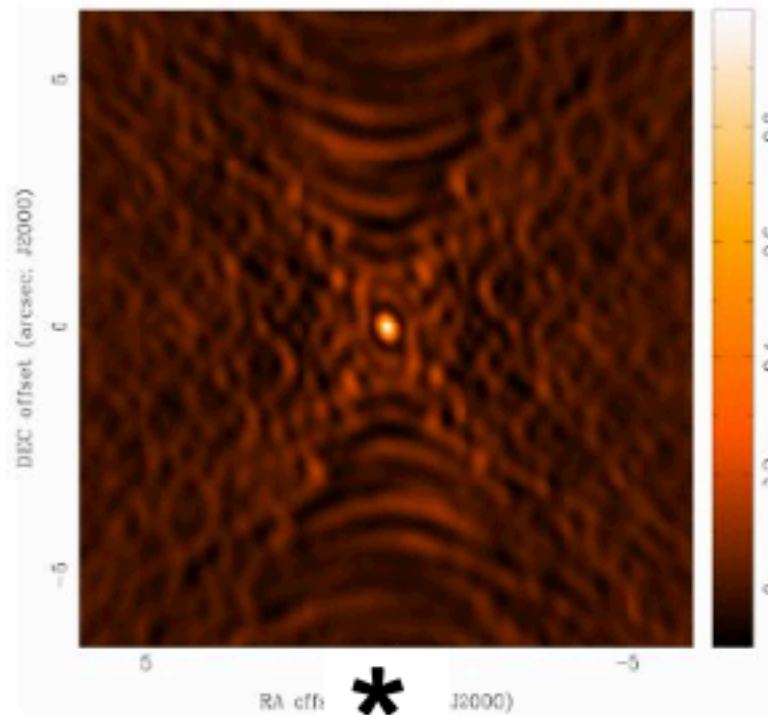
- If we take the Fourier transform of V_{obs} , we obtain the true sky brightness convolved with the Fourier transform of S :

$$B(l, m) = \mathcal{F}\{S(u, v)\} \quad I * B = \mathcal{F}^{-1}\{SV\}$$

- B is known as the “**dirty beam**” or “**synthesized beam**” and is how the array sees a point source. $I*B$ is thus called the “**dirty image**”.

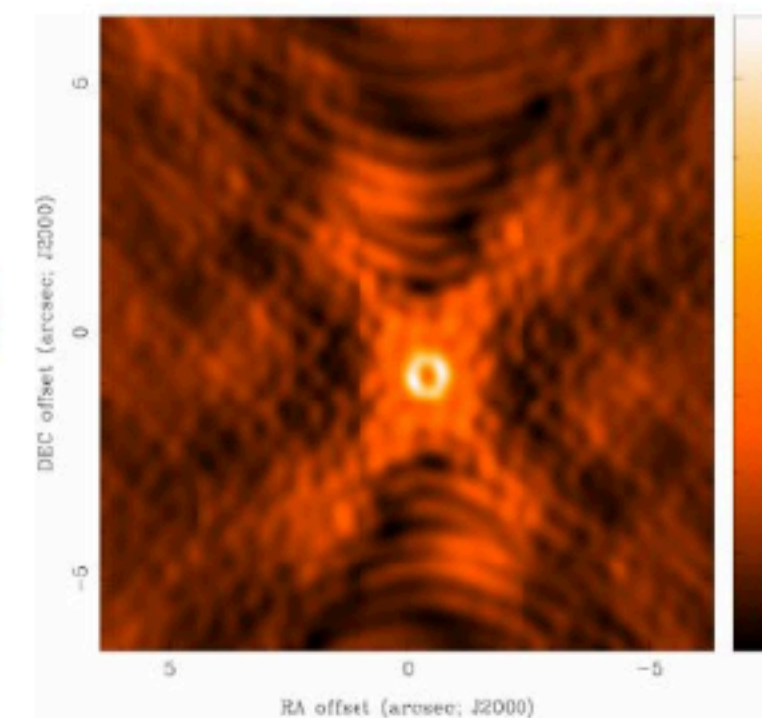
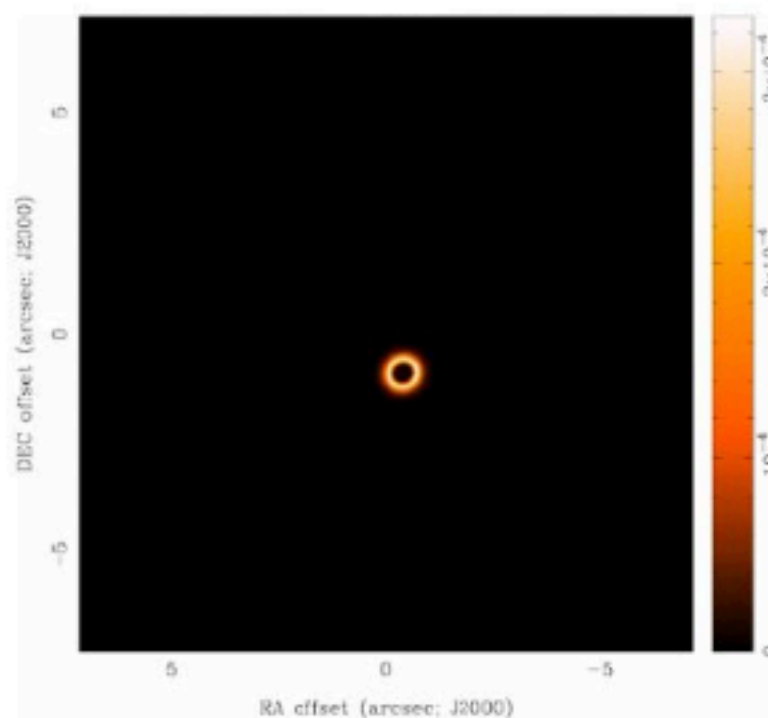
Dirty image

“dirty beam”



$S(u,v)$

“true image”



“dirty image”

Dirty image

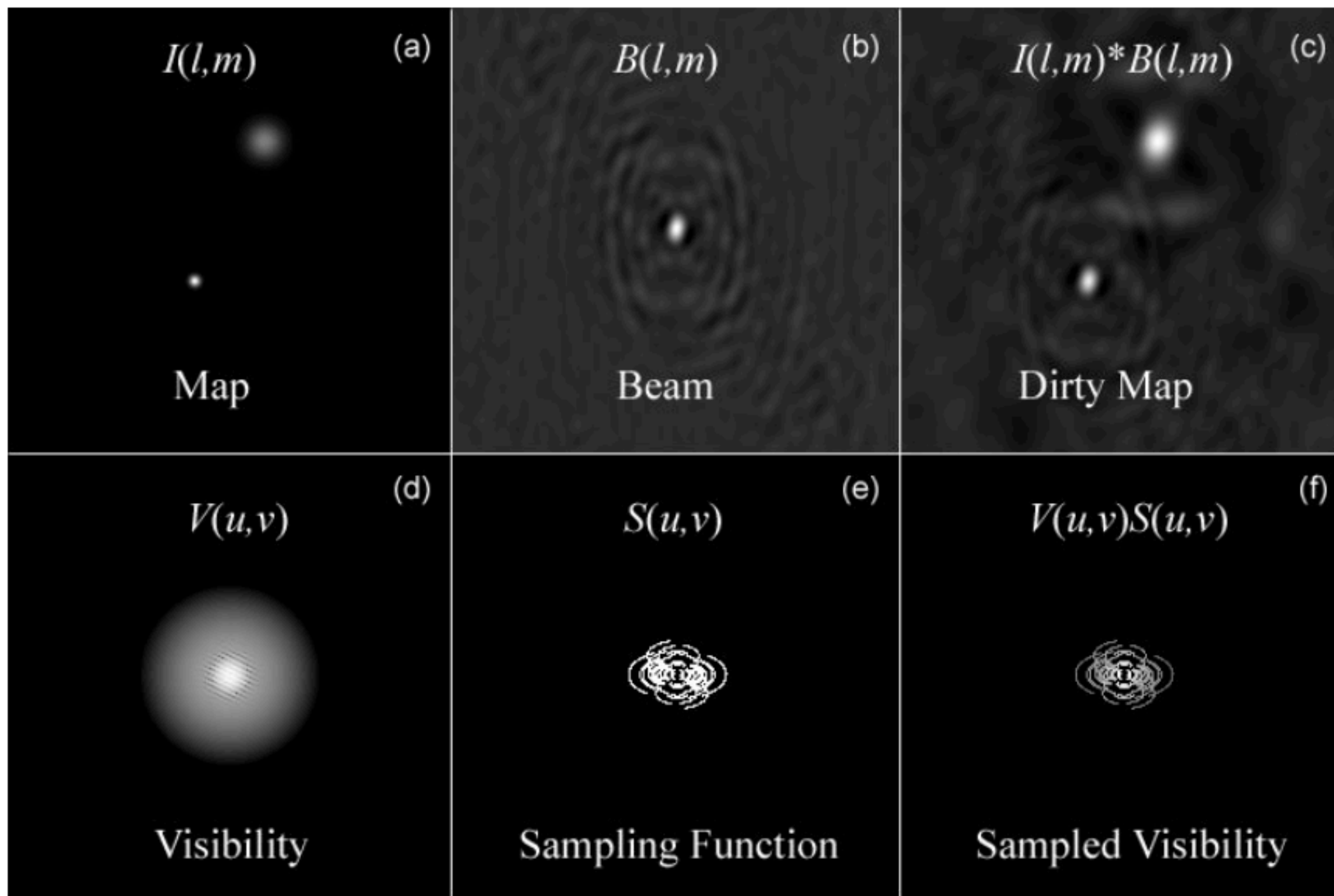
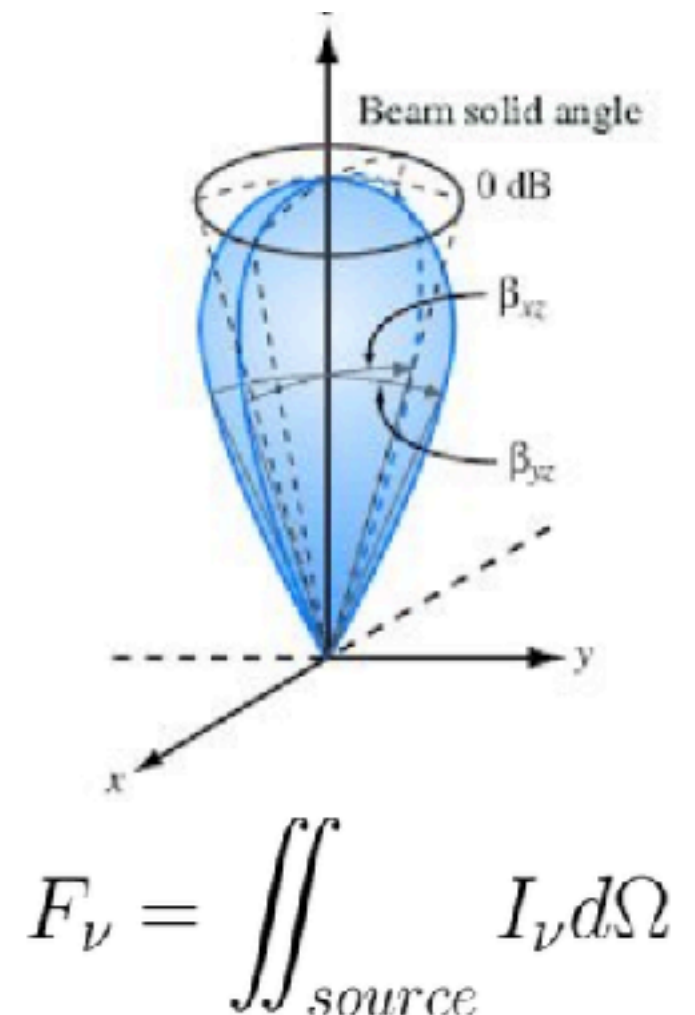


Image units for radio astronomy

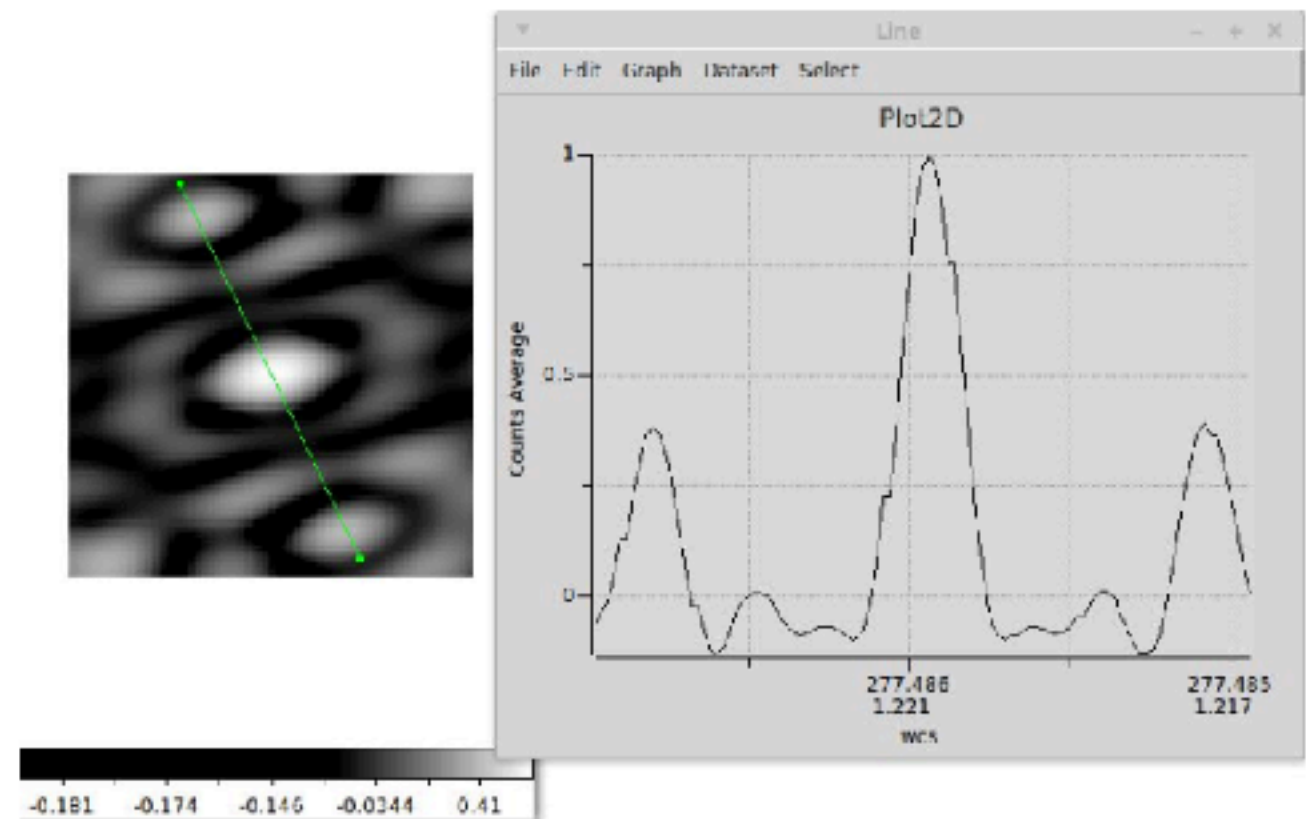
- A Jansky (Jy) is a unit of spectral **flux** density for radio telescopes.
- Image units are often in Jy/**beam**, a unit of spectral **intensity**.
- The **beam** is the solid angle of the telescope point spread function.
- Flux is calculated by integrating the intensity over the angular extent of the source.

$$1 \text{ Jy} = 10^{-26} \frac{\text{W}}{\text{Hz} \cdot \text{m}^2}$$



What is the beam?

- For interferometers, the beam size of the **synthesized beam** main lobe.
- The Full-width at half-maximum (FWHM) of a Gaussian fit to the main lobe is typically used.
- For interferometers, the single dish response is called the **primary beam**.



Weighting schemes

visibilities

(Super-uniform)

- Extreme uniform
- Careful with image quality

Uniform

- Based on uv-coverage
- Smaller beam
- Lower PS sensitivity
- Problems sampling
- Suitable for high S/N

Briggs Robust = +0.5 (-2 ... +2)

- Compromise between resolution and sensitivity
- 'Default'

Natural

- Based on noise-level
- Larger beam
- Higher PS sensitivity
- Suitable for low S/N (weak lines!)

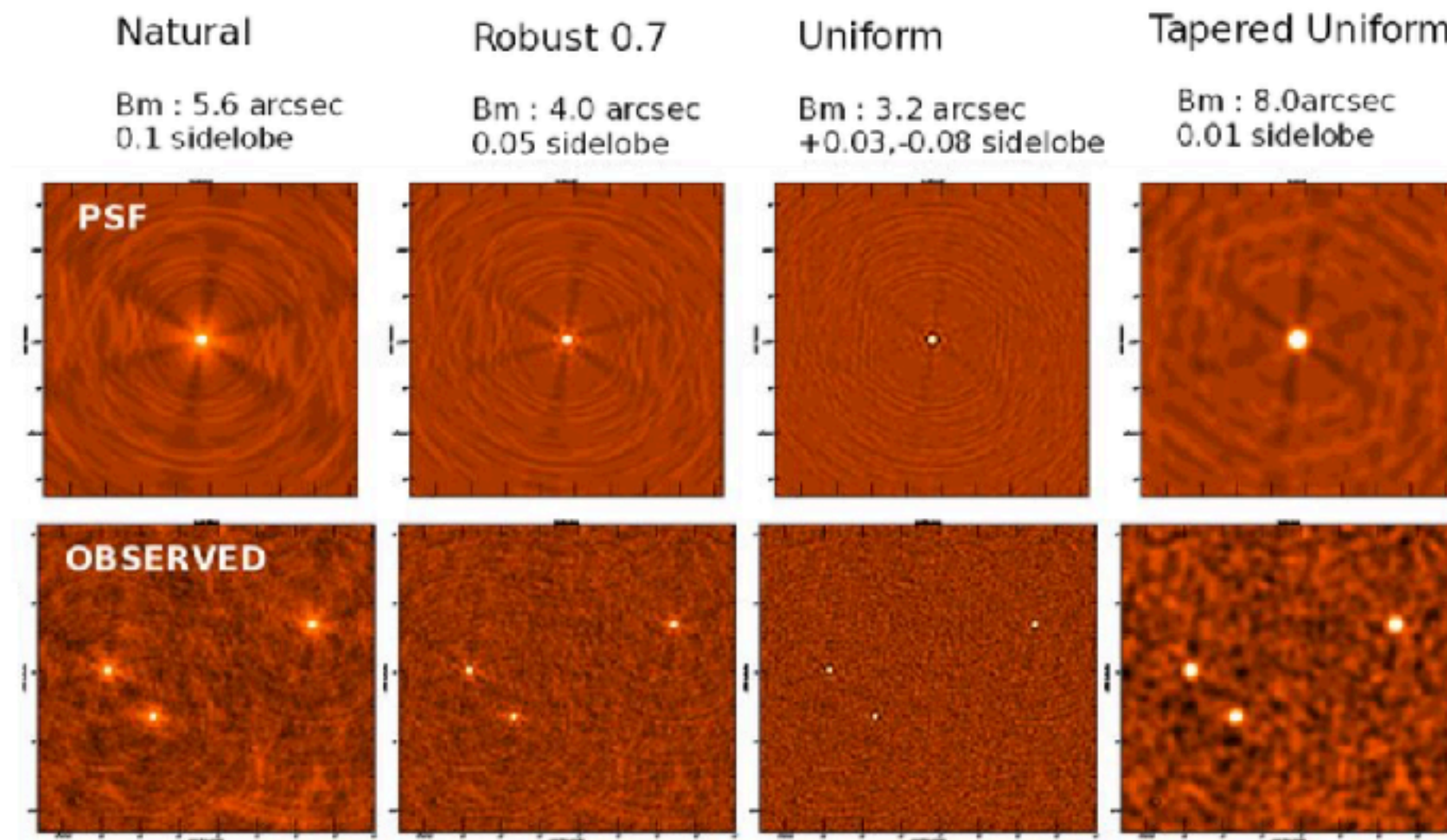
(Tapering)

- Less weight to long baselines: extended structures
- Less relevant in disk studies until $<0.1''$ data

Examples weighting

- We typically include the weights in our expression for the sampling function:

$$S(u, v) = \sum_i w_i (\delta(u - u_i, v - v_i) + \delta(u + u_i, v + v_i))$$



Weighting schemes - natural

- Not all data is created equally - each visibility sample has an uncertainty determined during calibration.
- A “Natural” weighting scheme weights the i 'th according to its uncertainty:

$$w_i = \frac{1}{\sigma_i^2}$$

- Natural weighting provides optimal sensitivity for point source detection.

Weighting schemes - uniform

- The dirty beam has large sidelobes due to the sparseness of uv-plane sampling.
- This can be mitigated by increasing the weight of sparsely sampled regions of the uv-plane:

$$w_i = \left(\frac{1}{\sigma_i^2} \right) / W_k$$

- W_k is the **local density** of data points in the uv-plane, which has been binned into **k** cells of size $2/\text{FOV}$.
- Uniformly weighting data **increases the image noise**.

Weighting schemes - briggs

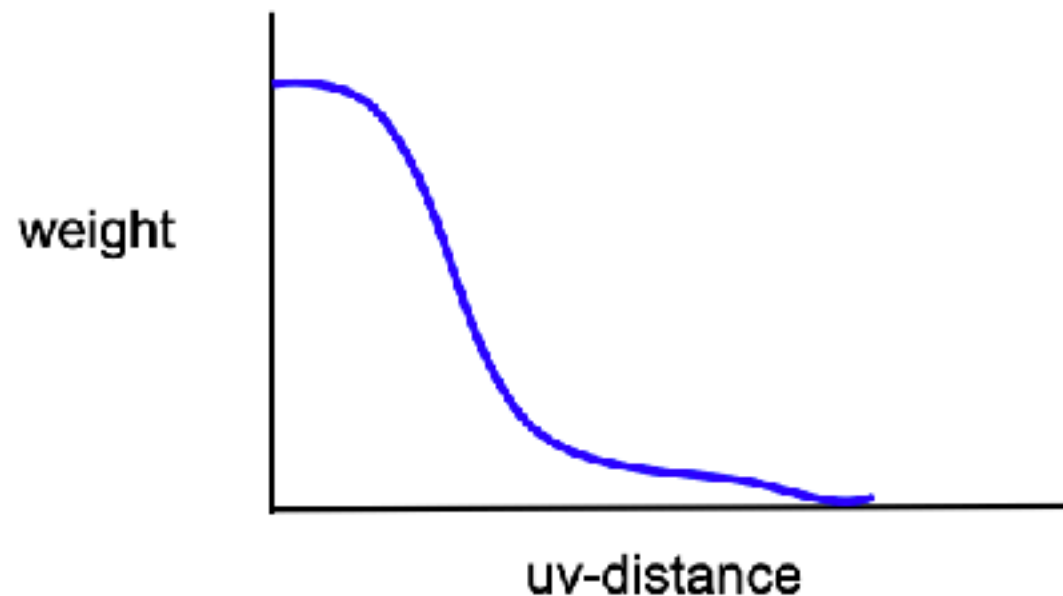
- Brigg's weighting scheme attempts to find a good compromise between uniform and natural weightings.
- The “robustness” parameter **R** takes values between -2 (essentially uniform) and 2 (essentially natural).

$$\omega_i = \frac{1}{\sigma_k^2} \quad w_i = \frac{\omega_i}{1 + W_k f^2} \quad f^2 = \frac{(5 * 10^{-R})^2}{\frac{\sum_k W_k^2}{\sum_i \omega_i}}$$

- R=0.5 provides a good compromise for most ALMA data, but you should experiment and choose what's best for your data!

Weighting schemes - tapering

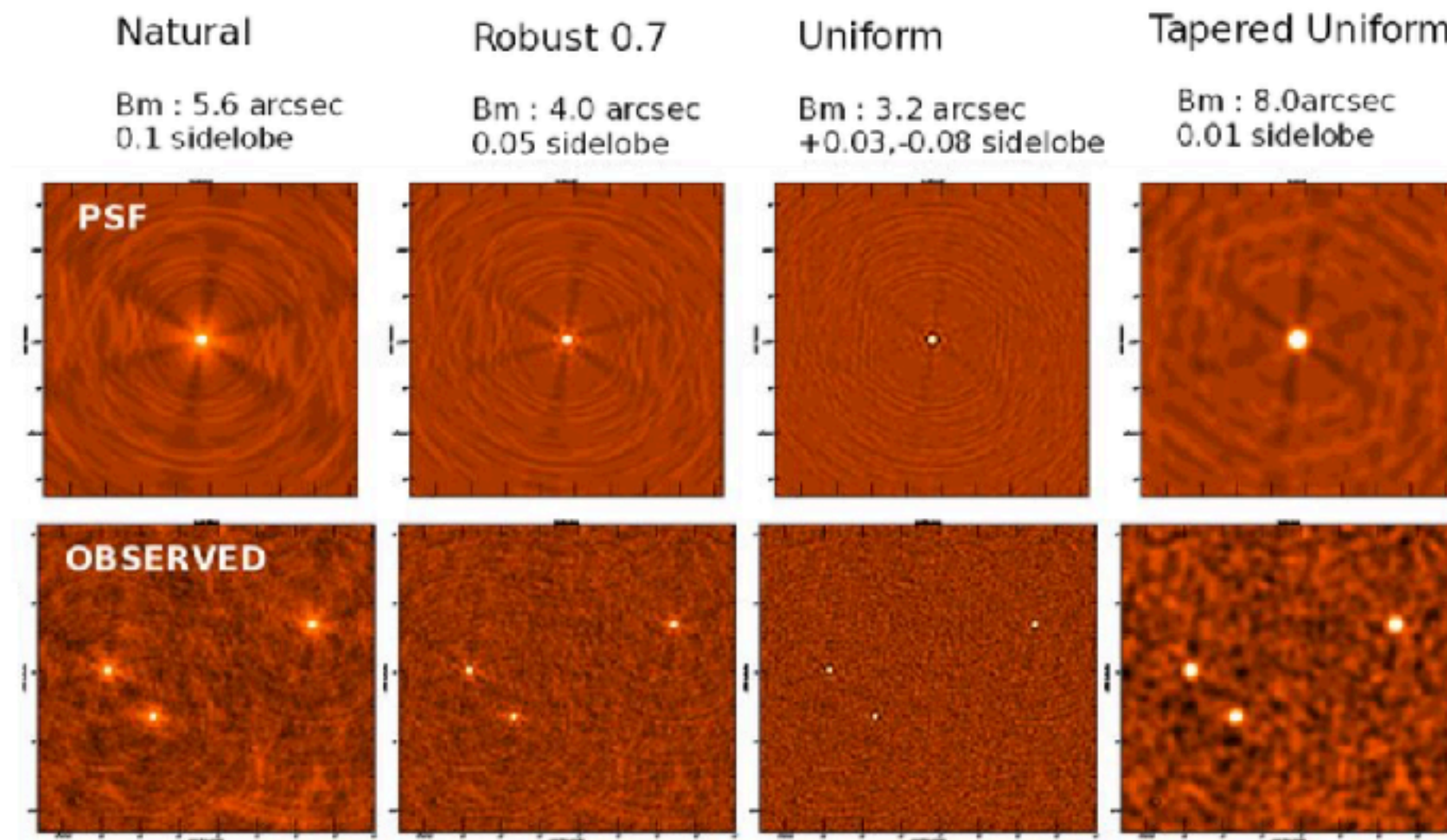
- Long baselines may contribute significantly to high sidelobes in the dirty beam.
- Short baselines recover extended structures which may be of interest.
- We can optimize for this by multiplying our data weights in the uv-plane by a Gaussian, thus “tapering” out the effect of long baselines.
- This **throws away data** and **increases noise!**



Examples weighting

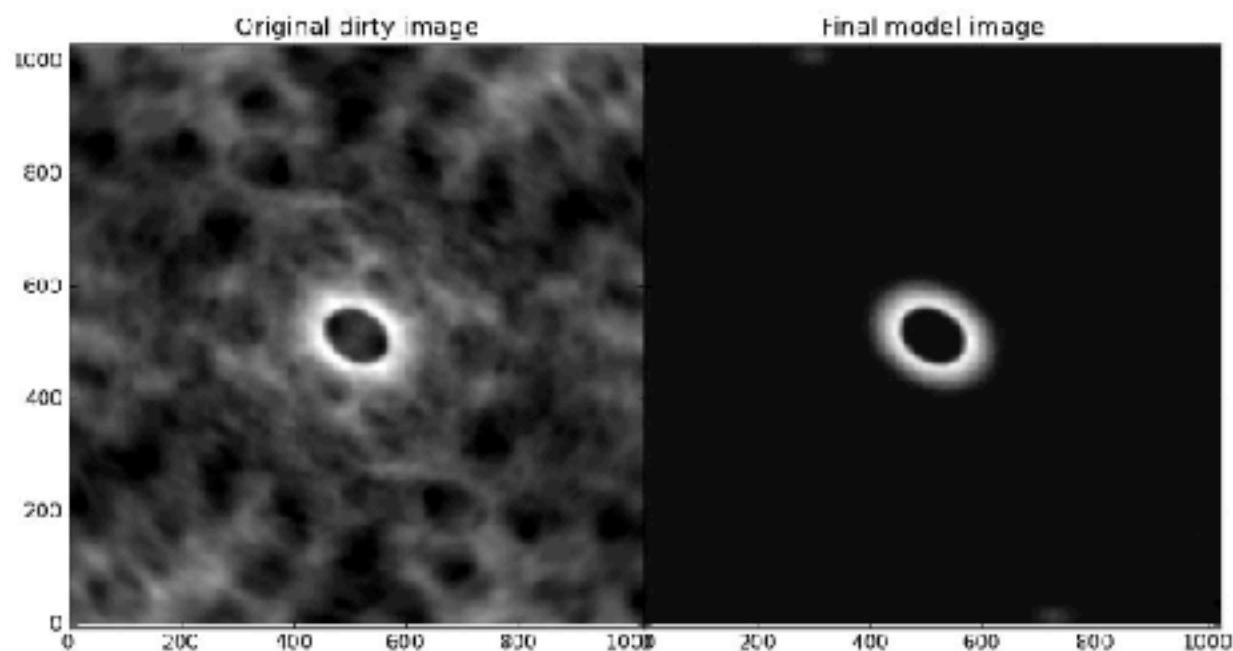
- We typically include the weights in our expression for the sampling function:

$$S(u, v) = \sum_i w_i (\delta(u - u_i, v - v_i) + \delta(u + u_i, v + v_i))$$



The CLEAN algorithm

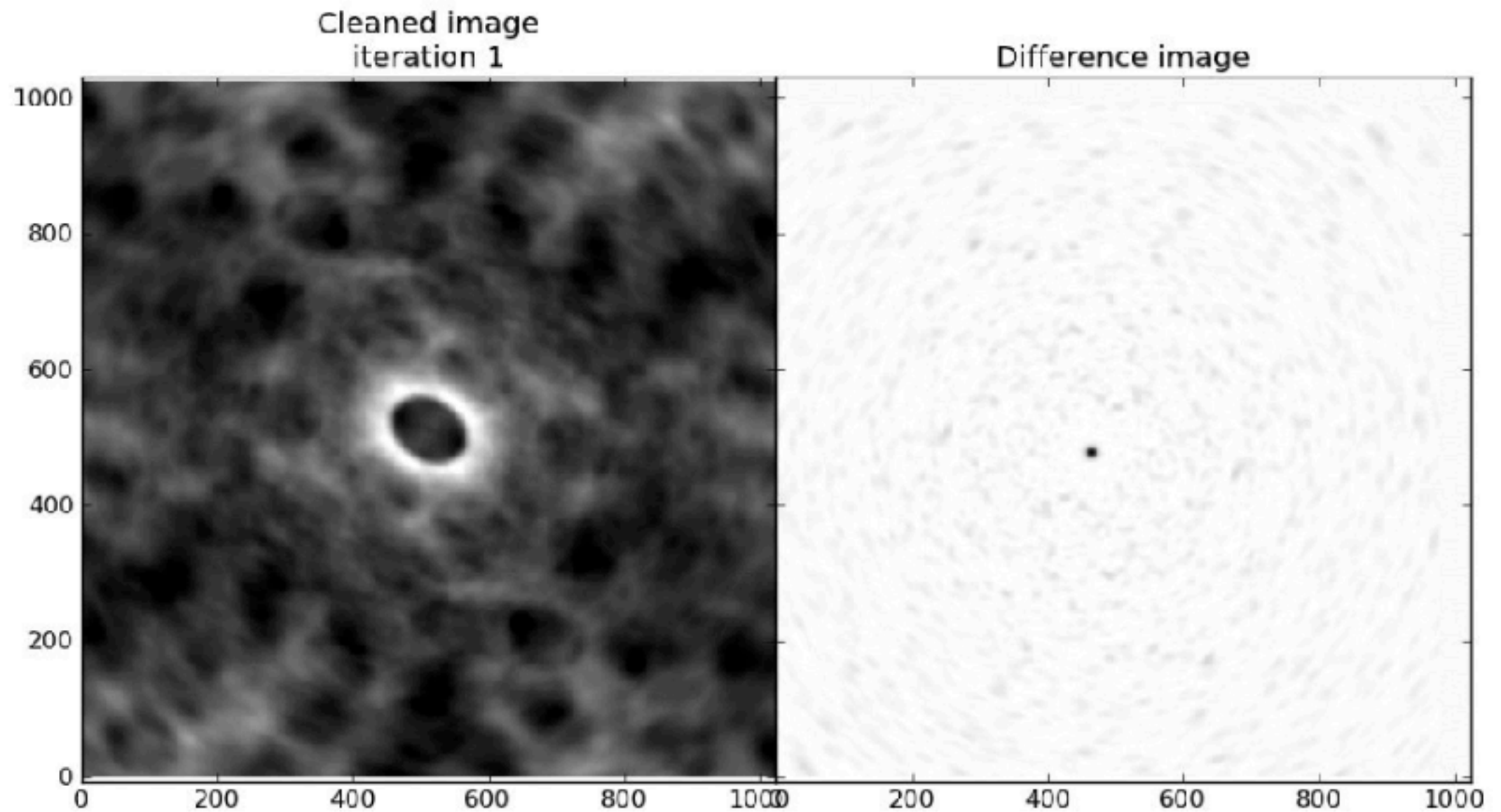
- The CLEAN algorithm (Hogbom 1974) attempts to **deconvolve** the image and remove the effects of the dirty beam.



See <http://nesanders.github.io/glCLEAN/examples.html>

1. Produce an initial dirty image I_D
2. Find brightest point I_0 in I_D
3. Subtract from the image the dirty beam B scaled and shifted to peak at γI_0 , where $\gamma < 1$.
4. Add a point source of brightness γI_0 to “clean” model image.
5. Repeat Steps 2-4, replacing I_D with the subtracted map from the last iteration. Stop when I_0 is comparable to the noise level in the map.
6. Convolve the “clean” model with an ideal “clean” beam, typically a Gaussian fit to the main lobe of the dirty beam.
7. Add dirty image residuals to clean image.

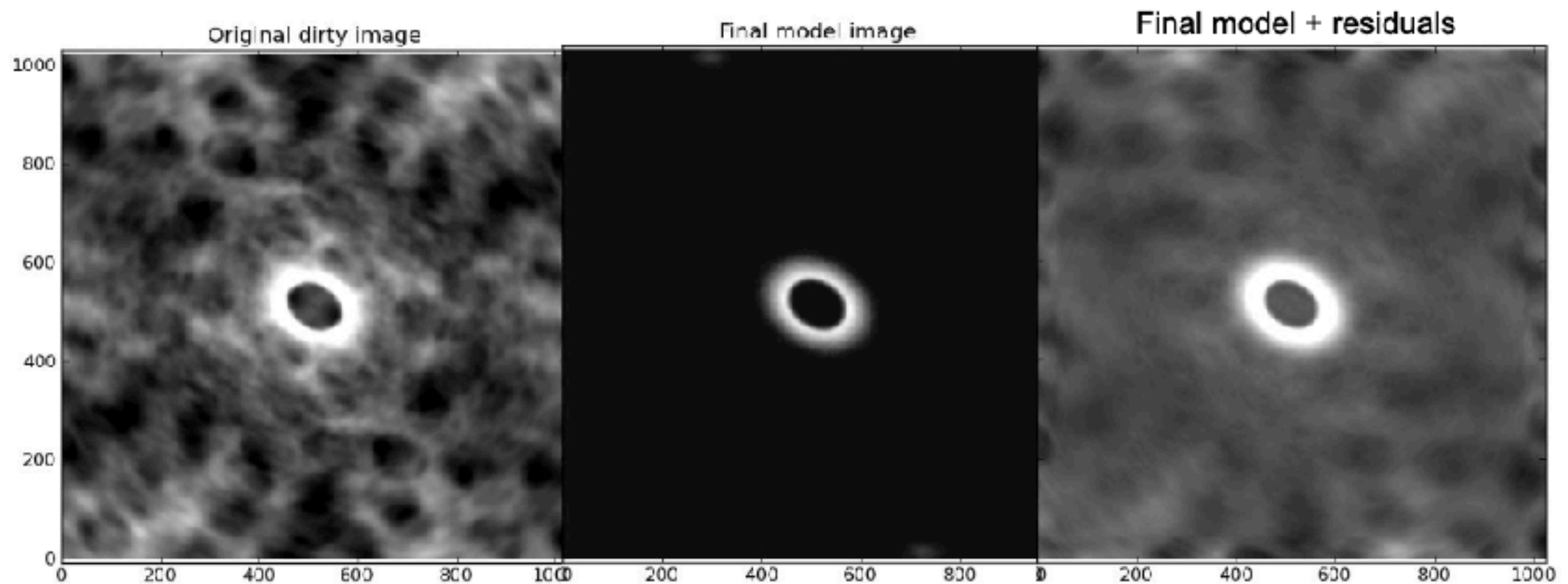
CLEAN in action



- Left: residual image. Right: Removed model x Dirty beam

CLEAN in action

- CLEAN provides an impressive increase in image quality!
- CLEAN works well because we know our images are sparse and mostly empty of emission.



CLEAN and CASA

- Using CLEAN with ALMA data is usually done with the CASA package.
- Set of C++ tools for radio data reduction with python bindings.
- Includes it's own python installation.
- Formerly python 2, new versions will use python 3.
- Documentation:
 - <https://casa.nrao.edu/casadocs/casa-6.1.0>
- CASA Tutorials:
 - https://casaguides.nrao.edu/index.php?title=Main_Page



CASA basics

- Interface provides an ipython interpreter and GUI output logger.
- Radio reduction tools available as “tasks” i.e. python functions.
- Useful commands:
 - **execfile(scriptname)** - execute commands in a script
 - **inp taskname** - check task inputs
 - **help(taskname)** - get task documentation in terminal
 - **doc(taskname)** - get task documentation in web browser
 - **go taskname** - run task with current inputs
 - **tget taskname** - get inputs last used to run task

```
(base) logan@logan-Latitude-7490 ~ $ casa

=====
The start-up time of CASA may vary
depending on whether the shared libraries
are cached or not.
=====

IPython 5.1.0 -- An enhanced Interactive Python.

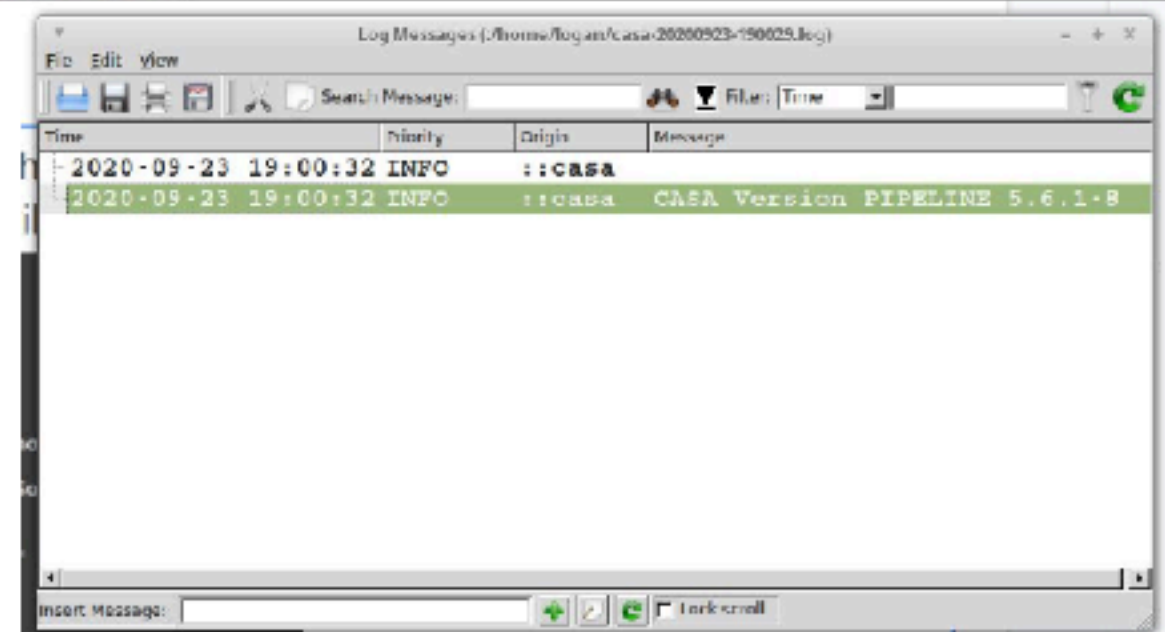
PIPELINE CASA 5.6.1-8 -- Common Astronomy Software Applications

casaVersion = 5.6.1-8
imported casatasks and tools using taskinit *

C++ shared library loaded successfully

--> CrashReporter initialized.
Enter doc('start') for help getting started with CASA...
Using matplotlib backend: TkAgg

CASA <1>:
```



CLEAN in CASA

- CLEAN can be used through task *tclean* in CASA.
- **Huge** number of inputs - but only a handful at a time are needed.

```

clean --help
clean --help=interferometric_image_reconstruction

vis                -          ''          # Name of input visibility file(s)
selectdata         =          True        # Enable data selection parameters
  field            =          ''          # field(s) to select
  spw              =          ''          # spw(s)/channels to select
  timerange        =          ''          # Range of time to select from data
  uvrange          =          ''          # Select data within uvrange
  antenna          =          ''          # Select data based on antenna/baseline
  scan             =          ''          # Scan number range
  observation      =          ''          # Observation ID range
  intent           =          ''          # Scan Intent(s)

datacolumn         = 'corrected'         # Data column to image(data,corrected)
imagenam          =          ''          # Pre-name of output images
imsize            =          [100]       # Number of pixels
cell              = ['1arcsec']          # Cell size
phasecenter       =          ''          # Phase center of the image
stokes            =          'I'         # Stokes Planes to make
projection        =          'SIN'       # Coordinate projection
startmodel        =          ''          # Name of starting model image
specmode          =          'mfs'       # Spectral definition mode
                                          # (mfs,cube,cubedata, cubesource)
  refreq           =          ''          # Reference frequency

gridding           = 'standard'          # Gridding options (standard, wproject,
                                          # widefield, mosaic, awproject)
  vptable          =          ''          # Name of Voltage Pattern table
  pblimit          =          0.2         # PB gain level at which to cut off
                                          # normalizations

deconvolver       =          'hogbom'    # Minor cycle algorithm (hogbom,clark,n
                                          # ultiscale,mtmfs,mem,clarkstokes)
restoration       =          True        # Do restoration steps (or not)
  restoringbeam    =          []         # Restoring beam shape to use. Default
                                          # is the PSF main lobe
  pbcor            =          False      # Apply PB correction on the output
                                          # restored image

outlierfile       =          ''          # Name of outlier-field image
                                          # definitions
weighting         =          'natural'   # Weighting scheme
                                          # (natural,uniform,briggs,
                                          # briggsabs[experimental])
  uvtaper          =          []         # uv-taper on outer baselines in uv-
                                          # plane

niter             =          0           # Maximum number of iterations
usenask           =          'user'      # Type of mask(s) for deconvolution:
                                          # user, pb, or auto-multithresh
  nask             =          ''          # Mask (a list of image name(s) or
                                          # region file(s) or region string(s) )
  pbmask           =          0.0        # primary beam mask

fastnoise         =          True        # True: use the faster (old) noise
                                          # calculation. False: use the new
                                          # improved noise calculations
restart           =          True        # True : Re-use existing images. False
                                          # : Increment imagename
savemodel         =          'none'      # Options to save model visibilities
                                          # (none, virtual, modelcolumn)
calcres           =          True        # Calculate initial residual image
calcpsf           =          True        # Calculate PSF
parallel          =          False       # Run major cycles in parallel

```


Basic tclean parameters

- Most parameters for *tclean* can be left as default.
- Pay attention to datacolumn - 'corrected' contains calibrated data, if present.
- *field* - defaults to select every observed source (a bad idea)
- *spw* - selects all channels/windows by default - fine if there are no spectral lines

```
# tclean :: Radio Interferometric Image Reconstruction
vis = '' # Name of input visibility file(s)
selectdata = True # Enable data selection parameters
field = '' # field(s) to select
spw = '' # spw(s)/channels to select
timerange = '' # Range of time to select from data
uvrange = '' # Select data within uvrange
antenna = '' # Select data based on antenna/baseline
scan = '' # Scan number range
observation = '' # Observation ID range
intent = '' # Scan Intent(s)

datacolumn = 'corrected' # Data column to image(data,corrected)
imagename = '' # Pre-name of output images
imsize = [100] # Number of pixels
cell = ['1arcsec'] # Cell size
phasecenter = '' # Phase center of the image
stokes = 'I' # Stokes Planes to make
projection = 'SIN' # Coordinate projection
startmodel = '' # Name of starting model image
```

Basic tclean parameters

- Specmode:
 - 'mfs' = multifrequency synthesis - used for continuum
 - 'Cube' used to image spectral lines
- *reffreq* - reference frequency of image - defaults to average across selected spw
- *pbcor* - correct for antenna primary beam - important for sources on field edge.

```
specmode = 'mfs' # Spectral definition mode
# (mfs,cube,cubedata, cubesource)
reffreq = '' # Reference frequency

gridding = 'standard' # Gridding options (standard, wproject,
# widefield, mosaic, awproject)
vptable = '' # Name of Voltage Pattern table
pblimit = 0.2 # PB gain level at which to cut off
# normalizations

deconvolver = 'hogbom' # Minor cycle algorithm (hogbom,clark,m
# ultiscale,mtmfs,mem,clarkstokes)
restoration = True # Do restoration steps (or not)
restoringbeam = [] # Restoring beam shape to use. Default
# is the PSF main lobe
pbcor = False # Apply PB correction on the output
# restored image
```

Basic tclean parameters

- *Weighting* - 'natural', 'uniform' and 'briggs' available (and others...).

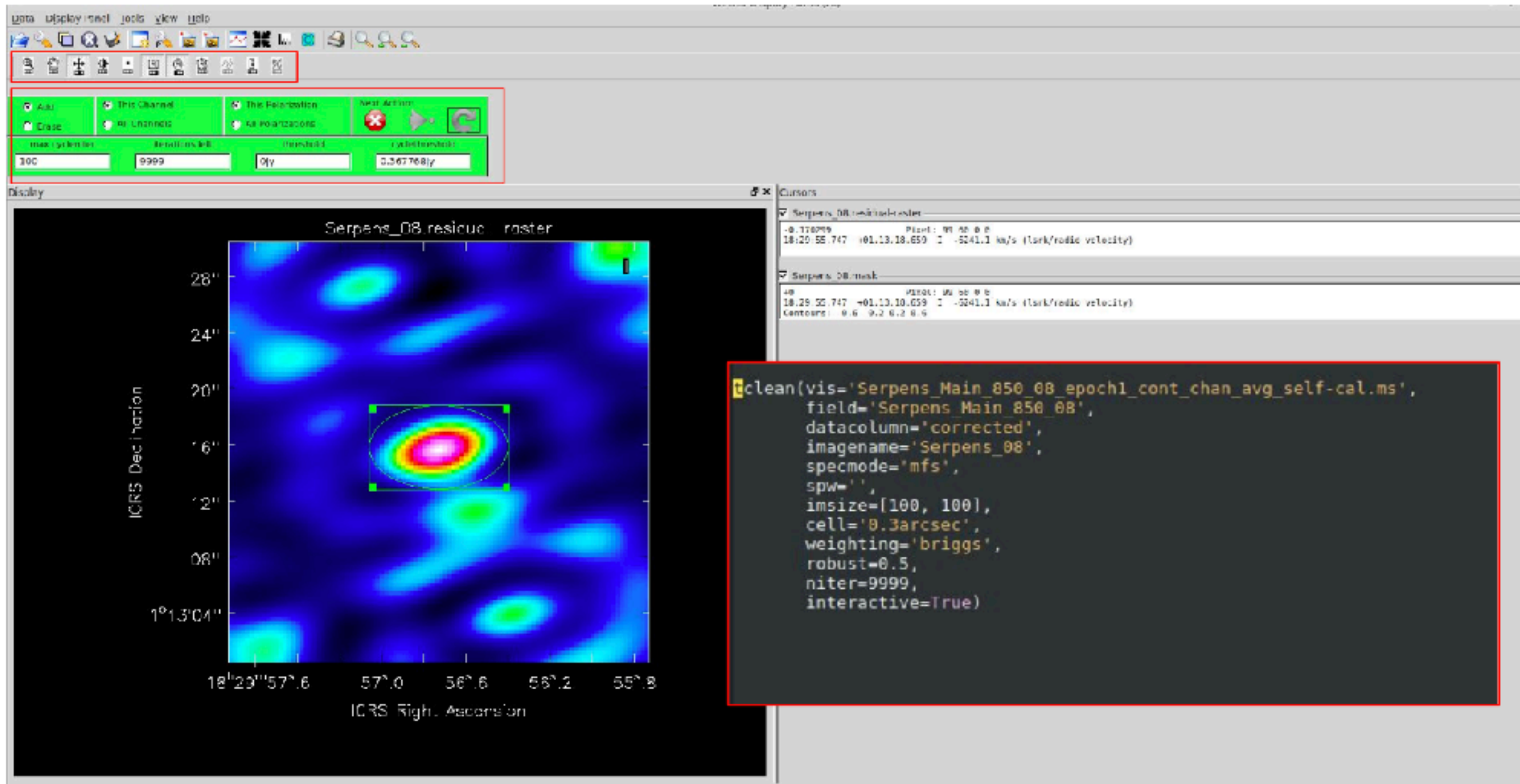
```
weighting = 'briggs' # Weighting scheme
# (natural, uniform, briggs,
# briggsabs[experimental])
robust = 0.5 # Robustness parameter
npixels = 0 # Number of pixels to determine uv-cell
# size
uvtaper = [] # uv-taper on outer baselines in uv-
# plane
```

Basic tclean parameters

- *niter* - just set to some huge number if you don't know what to use
- *threshold* - can be used instead of *niter*, e.g '3 mJy', set to expected noise level in image.
- *Interactive* - Set to "True" to show GUI interface

```
niter = 9999 # Maximum number of iterations
gain = 0.1 # Loop gain
threshold = 0.0 # Stopping threshold
nsigma = 0.0 # Multiplicative factor for rms-based
# threshold stopping
cycleniter = -1 # Maximum number of minor-cycle
# iterations
cyclefactor = 1.0 # Scaling on PSF sidelobe level to
# compute the minor-cycle stopping
# threshold.
minpsffraction = 0.05 # PSF fraction that marks the max depth
# of cleaning in the minor cycle
maxpsffraction = 0.8 # PSF fraction that marks the minimum
# depth of cleaning in the minor cycle
interactive = False # Modify masks and parameters at
# runtime
```


Example

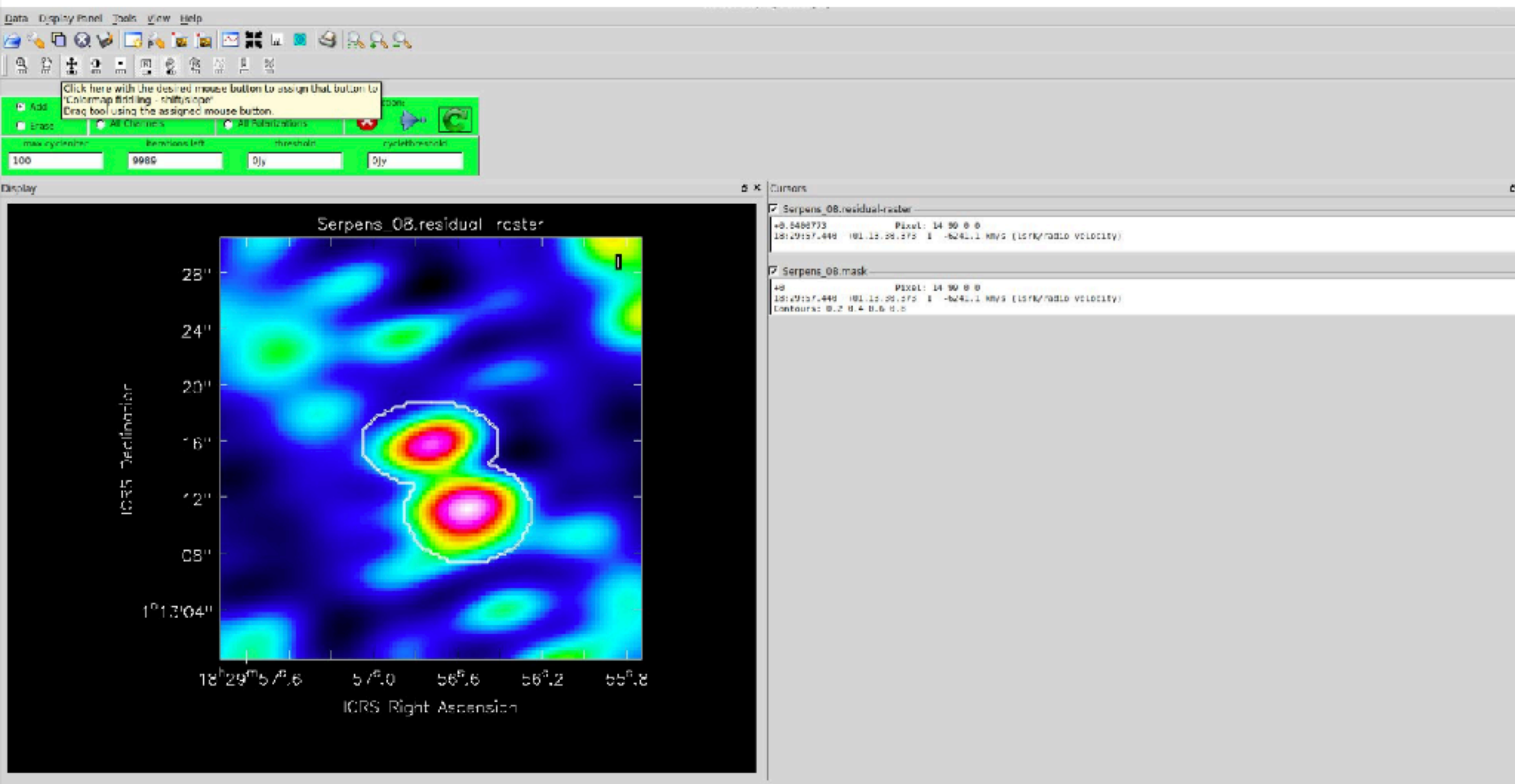


Example

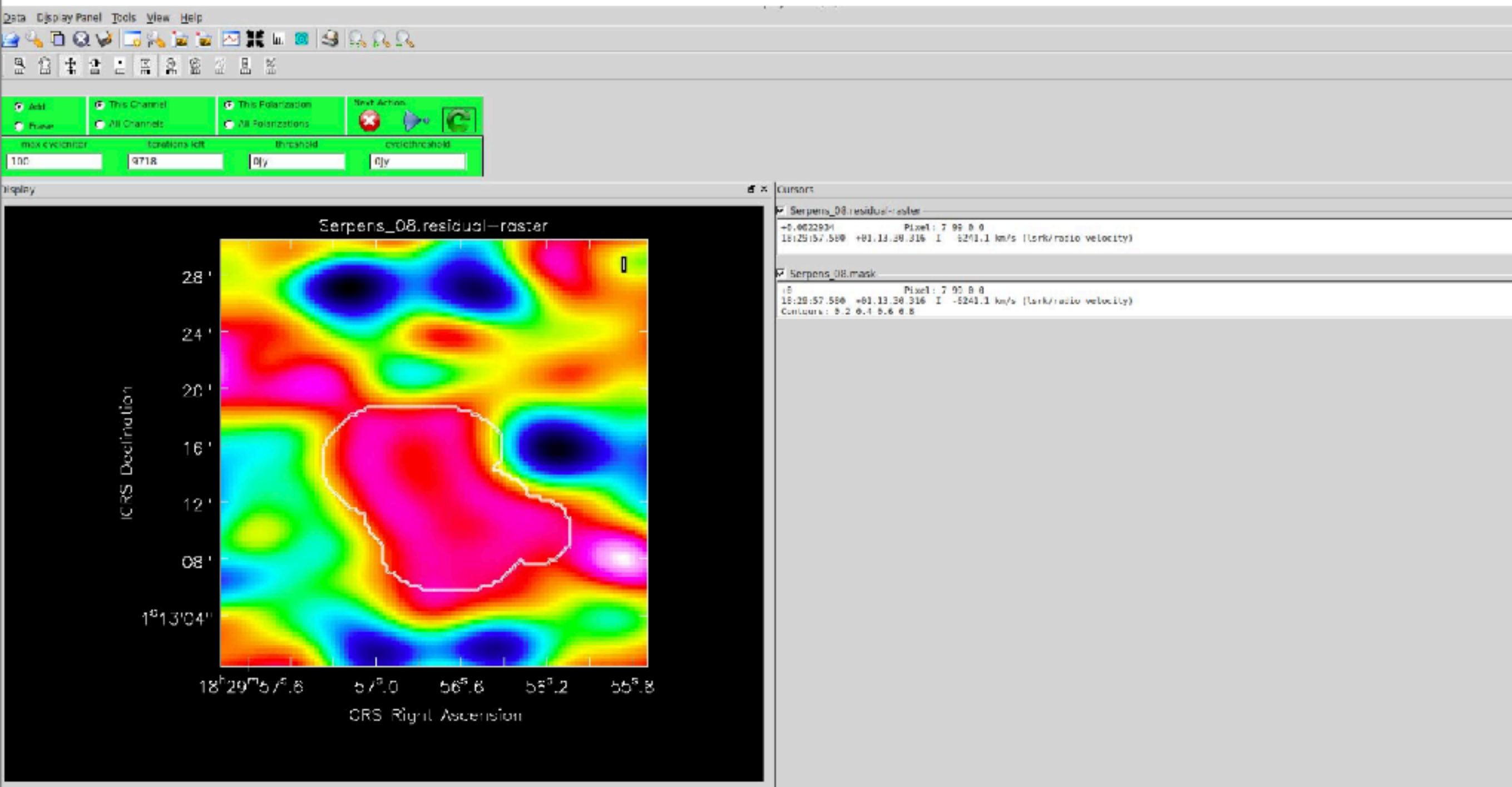
```
INFO      ...fineImage  Impars : start
INFO      ...fineImage  Shape : [100, 100, 1, 1]Spectral : [3.43505e+11] at [0] with increment [1.58443e+10]
INFO      ...fineImage  Set Gridding options for [Serpens_08] with ftmachine : gridft
INFO      ...weight()   Set imaging weights : Briggs weighting: sidelobes will be suppressed over full image
INFO      ...gWeight()  Normal robustness, robust = 0.5
INFO      ...nvolution  Set Deconvolution Options for [Serpens_08] : hogbom
INFO      ...iteration   Set Iteration Control Options
INFO      ...::makePSF   ----- Make PSF -----
INFO      ...nsitivity   [Serpens_08] Theoretical sensitivity (Jy/bm):0.000533952
INFO      ...ntBeamSet   Beam : 5.82657 arcsec, 2.88889 arcsec, -78.1369 deg
INFO      ...imaryBeam   vi2 : Evaluating Primary Beam model onto image grid(s)
INFO      ...ajorCycle   ----- Run Major Cycle 1 -----
INFO      ...mageStats   [Serpens_08] Peak residual (max,min) over full image : (0.94841,-0.264522)
INFO      ...mageStats   [Serpens_08] Total Model Flux : 0
INFO      ...setupMask   [Serpens_08] Initializing new mask to 0.0 for interactive drawing
INFO      ...setupMask   [Serpens_08] Number of pixels in the clean mask : 0 out of a total of 10000 pixels. [ 0 % ]
INFO      ...ctivemask   [Serpens_08.mask] Mask modified from 0 pixels to 510 pixels
INFO      ...teraction   [Serpens_08] Mask changed interactively.
INFO      ...mageStats   [Serpens_08] Peak residual (max,min) within mask : (0.94841,-0.118535) over full image : (0.94841,-0.264522)
INFO      ...mageStats   [Serpens_08] Total Model Flux : 0
INFO      ...minorCycle   ----- Run Minor Cycle Iterations -----
INFO      ...econvolve   [Serpens_08] Run Hogbom minor-cycle | CycleThreshold=0.367768, CycleNiter=100, Gain=0.1
INFO      ...econvolve   [Serpens_08] iters=0->10 [10], model=0->0.61882, peakres=0.94841->0.333689, Reached cyclethreshold.
INFO      ...ionRecord   Completed 10 iterations.
```

In logger

Example

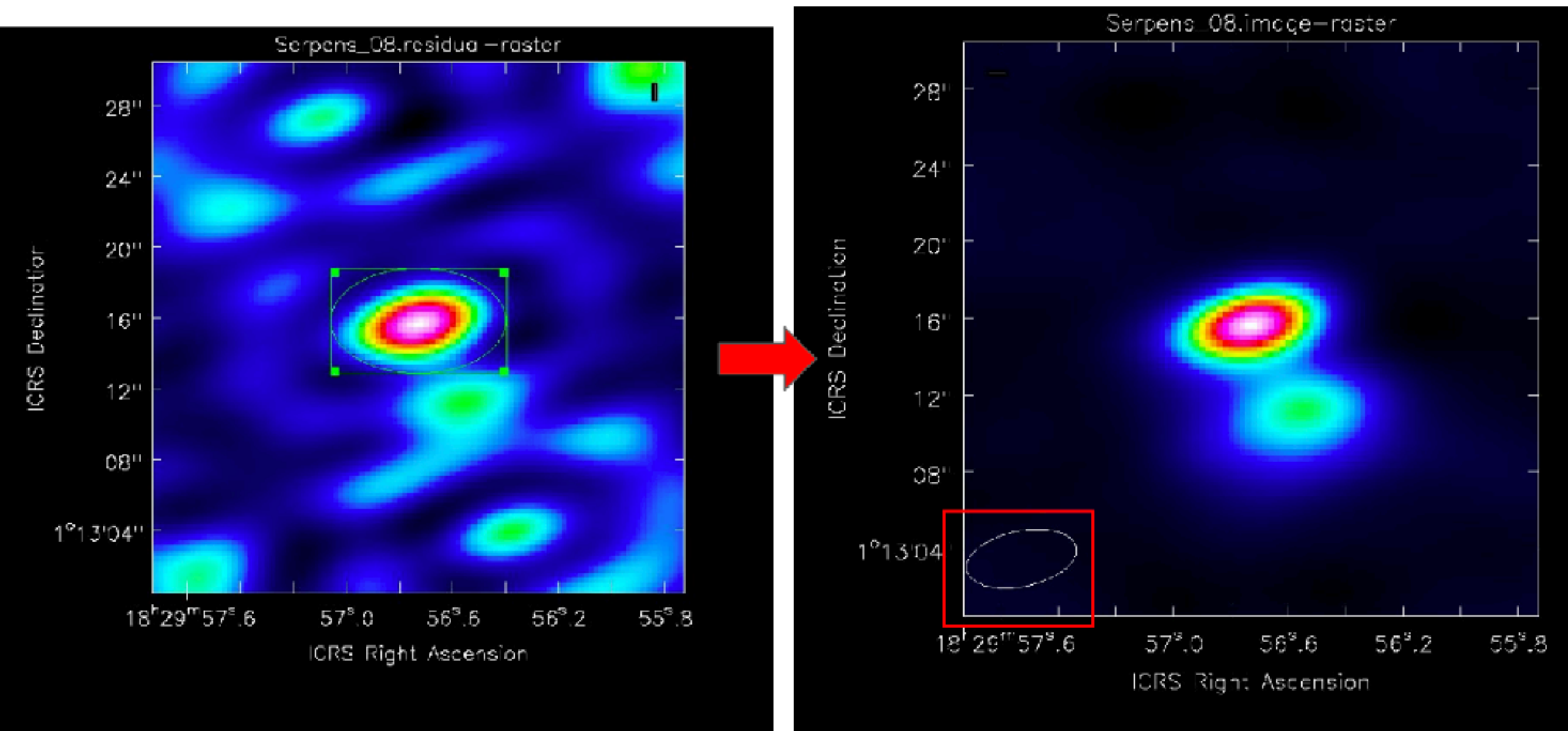


Example



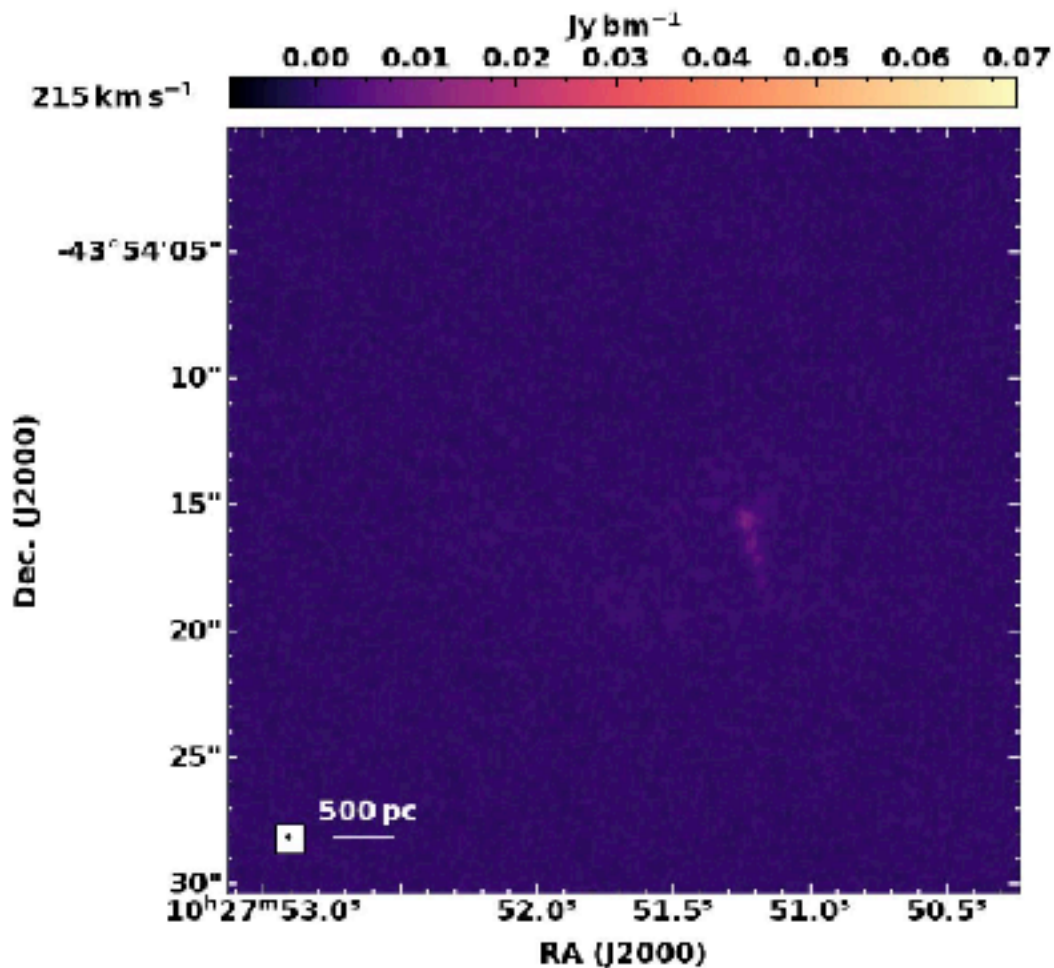
Example

Tclean results



Line cleaning

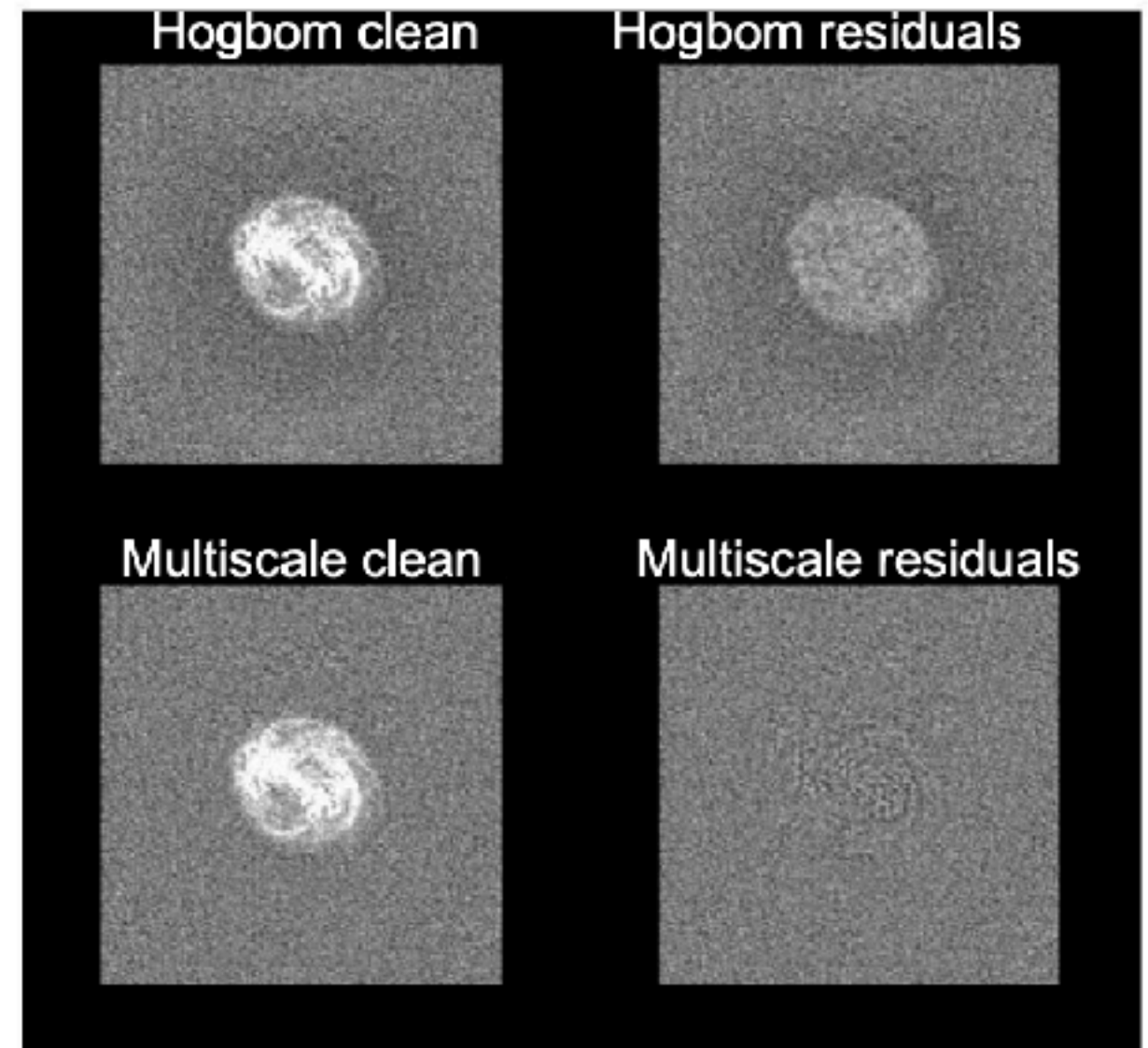
- Use *specmode*='cube' and subparameters to image spectral data



```
specmode = 'cube' # Spectral definition mode
# (mfs,cube,cubedata, cubesource)
nchan = 20 # Number of channels in the output
# image
start = '-20km/s' # First channel (e.g. start=3,start='1.
# 1GHz',start='15343km/s')
width = '2km/s' # Channel width (e.g. width=2,width='0.
# 1MHz',width='10km/s')
outframe = 'LSRK' # Spectral reference frame in which to
# interpret 'start' and 'width'
veltype = 'radio' # Velocity type (radio, z, ratio, beta,
# gamma, optical)
restfreq = '230.538GHz' # List of rest frequencies
interpolation = 'linear' # Spectral interpolation
# (nearest,linear,cubic)
chanchunks = 1 # Number of channel chunks
perchanweightdensity = True # whether to calculate weight density
# per channel in Briggs style
# weighting or not
```

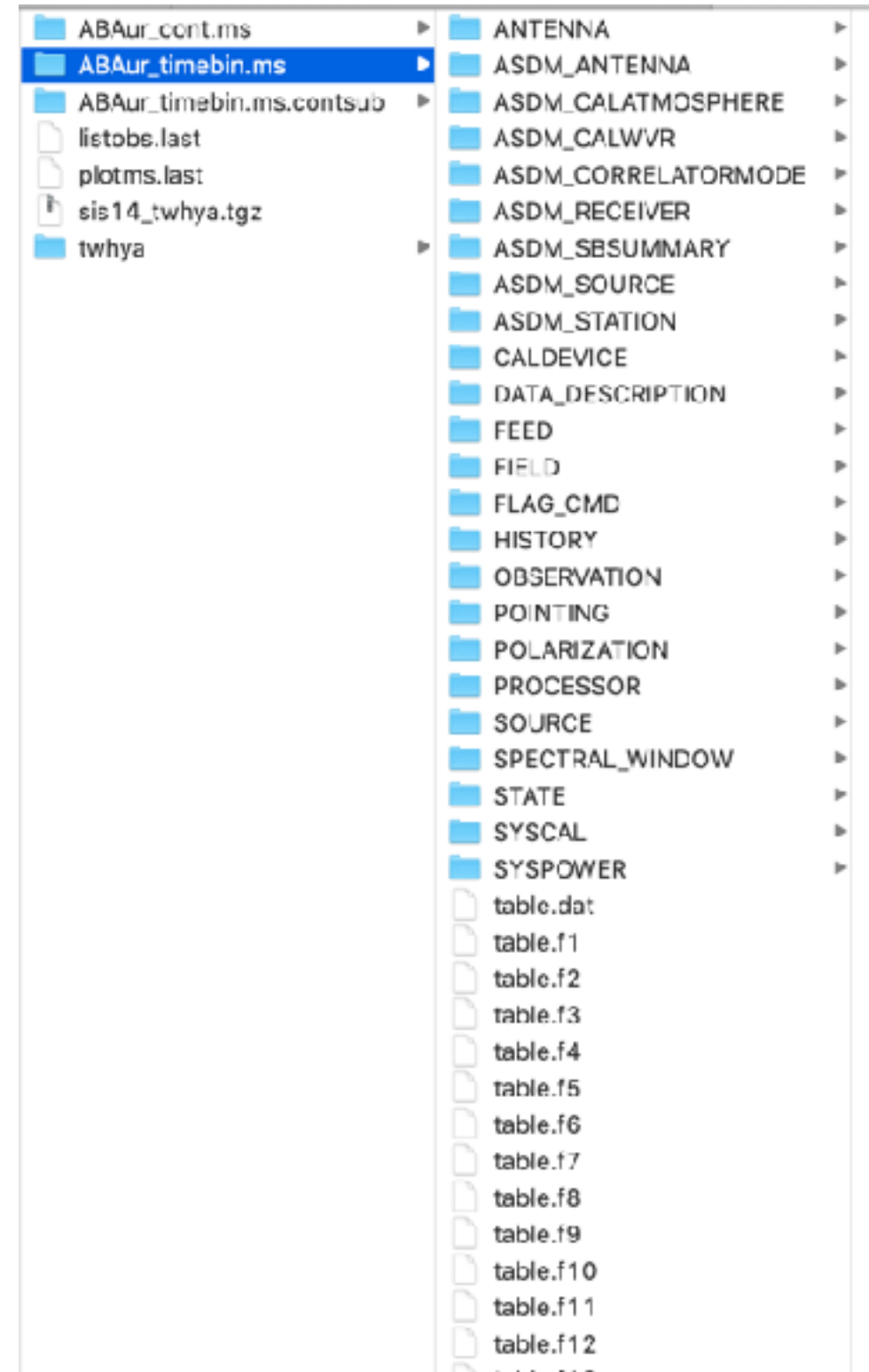

Multiscale

- CLEAN creates models of the sky using collections of point sources.
- This is not optimal for very extended sources.
- Multiscale cleaning allows CLEAN to use extended Gaussian-like functions for creating a model.



CASA inspection

- Measurement set: folder structure which can only be read/edited with CASA!
- Usual extension .ms but can be anything: convenient
- Do NOT change any of data or names inside folder or it becomes unreadable



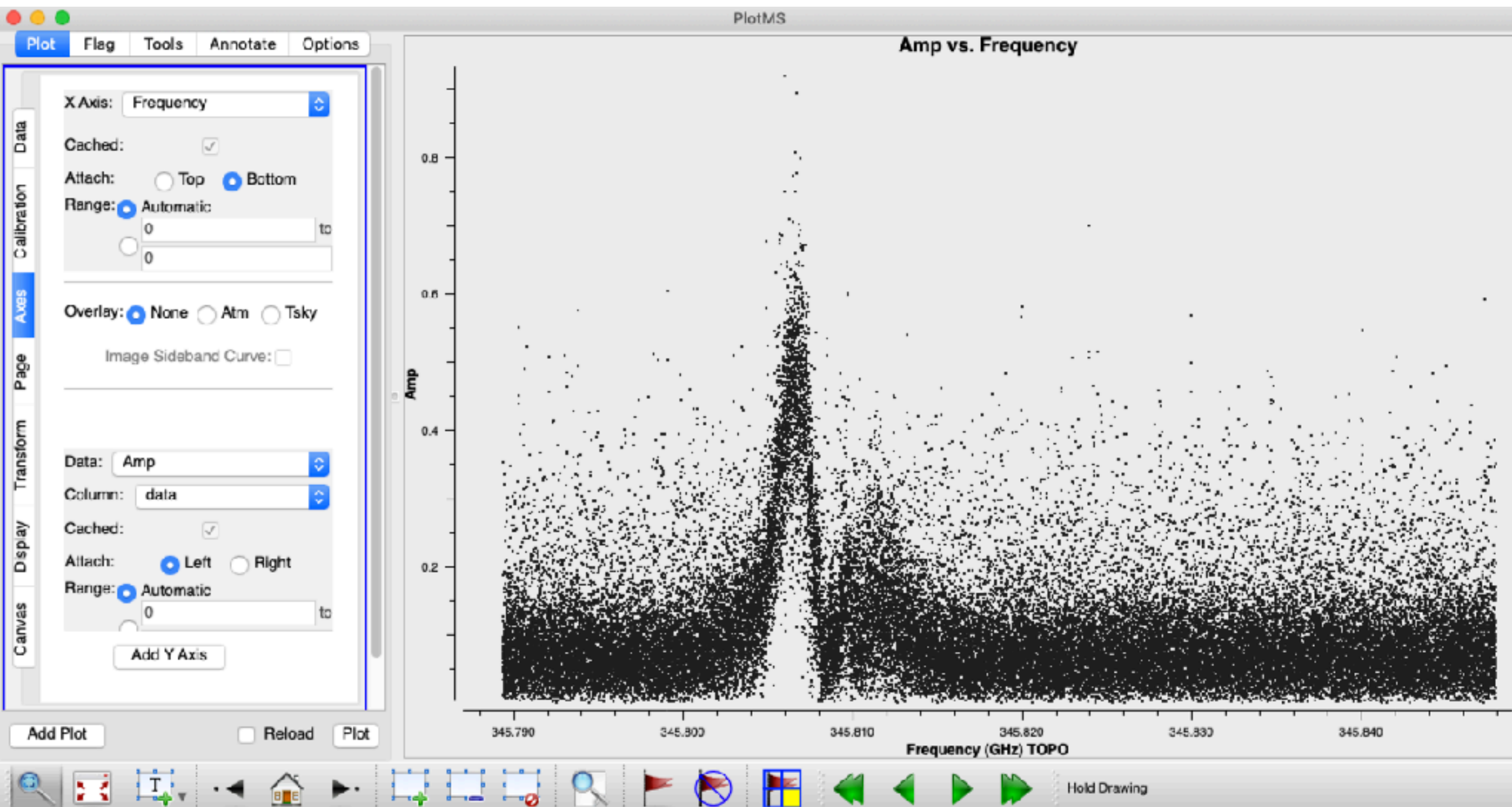
CASA inspection

- listobs(vis='mydata.ms') => basic observational data in logger

Time	Priority	Origin	Message
2020-09-22 23:51:55	INFO	listobs:::	
2020-09-22 23:51:55	INFO	listobs:::+	#####
2020-09-22 23:51:55	INFO	listobs:::+	##### Begin Task: listobs #####
2020-09-22 23:51:55	INFO	listobs:::	listobs(vis="ABRur_timebin.ms",selectdata=True,spw="",field="",antenna="",
2020-09-22 23:51:55	INFO	listobs:::+	uvrange="",timerange="",correlation="",scan="",intent="",
2020-09-22 23:51:55	INFO	listobs:::+	feed="",array="",observation="",verbose=True,listfile="",
2020-09-22 23:51:55	INFO	listobs:::+	listunfl=False,cachesize=50,overwrite=False)
2020-09-22 23:51:55	INFO	..ms::summary	=====
2020-09-22 23:51:55	INFO	..s::summary+	MeasurementSet Name: /Users/nienke/Documents/ALMA/Demo-ABRur/ABRur_timebin.ms MS Version 2
2020-09-22 23:51:55	INFO	..s::summary+	=====
2020-09-22 23:51:55	INFO	..s::summary+	Observer: yuwentang Project: uid://A001/Xa0/X612
2020-09-22 23:51:55	INFO	..s::summary+	Observation: ALMA
2020-09-22 23:51:55	INFO	..s::summary+	
2020-09-22 23:51:55	INFO	..s::summary+	Telescope Observation Date Observer Project
2020-09-22 23:51:55	INFO	..s::summary+	ALMA [4.91456e+09, 4.91456e+09]yuwentang uid://A001/Xa0/X612
2020-09-22 23:51:55	INFO	..s::summary+	ALMA [4.94376e+09, 4.94376e+09]yuwentang uid://A001/Xa0/X612
2020-09-22 23:51:55	INFO	..Properties	Computing scan and subscan properties...
2020-09-22 23:51:55	INFO	..ms::summary	Data records: 130584 Total elapsed time = 2.92084e+07 seconds
2020-09-22 23:51:55	INFO	..s::summary+	Observed from 12-Aug-2014/10:38:53.1 to 16-Jul-2015/12:06:13.4 (UTC)
2020-09-22 23:51:55	INFO	..ms::summary	
2020-09-22 23:51:55	INFO	..s::summary+	ObservationID = 0 ArrayID = 0
2020-09-22 23:51:55	INFO	..s::summary+	Date Timerange (UTC) Scan FldId FieldName nRows SpwIds Average Interval(s) ScanIntent
2020-09-22 23:51:55	INFO	..s::summary+	12-Aug-2014/10:38:53.1 - 10:44:41.1 11 0 ab_aurigae 15120 [0,1,2,3] [56.7, 56.7, 56.7, 56.7] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..s::summary+	10:45:47.0 - 10:52:38.6 13 0 ab_aurigae 17640 [0,1,2,3] [57.5, 57.5, 57.5, 57.5] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..s::summary+	10:56:30.0 - 11:02:18.0 18 0 ab_aurigae 15120 [0,1,2,3] [56.7, 56.7, 56.7, 56.7] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..s::summary+	11:03:24.1 - 11:10:15.7 20 0 ab_aurigae 17640 [0,1,2,3] [57.5, 57.5, 57.5, 57.5] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..s::summary+	11:13:53.3 - 11:19:41.3 25 0 ab_aurigae 15120 [0,1,2,3] [56.7, 56.7, 56.7, 56.7] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..s::summary+	11:20:46.3 - 11:21:48.3 27 0 ab_aurigae 2520 [0,1,2,3] [62, 62, 62, 62] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..ms::summary	
2020-09-22 23:51:55	INFO	..s::summary+	ObservationID = 1 ArrayID = 0
2020-09-22 23:51:55	INFO	..s::summary+	Date Timerange (UTC) Scan FldId FieldName nRows SpwIds Average Interval(s) ScanIntent
2020-09-22 23:51:55	INFO	..s::summary+	16-Jul-2015/11:55:40.0 - 11:50:56.2 28 0 ab_aurigae 11820 [4,5,6,7] [62, 62, 62, 62] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..s::summary+	11:52:02.9 - 11:58:54.4 30 0 ab_aurigae 20748 [4,5,6,7] [57.4, 57.4, 57.4, 57.4] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..s::summary+	12:02:32.5 - 12:06:13.4 35 0 ab_aurigae 11856 [4,5,6,7] [54.1, 54.1, 54.1, 54.1] [OBSERVE_TARGET#ON_SOURCE]
2020-09-22 23:51:55	INFO	..ms::summary	(nRows = Total number of rows per scan)
2020-09-22 23:51:55	INFO	..ms::summary	Fields: 1
2020-09-22 23:51:55	INFO	..s::summary+	ID Code Name RA Decl Epoch SrcId nRows
2020-09-22 23:51:55	INFO	..s::summary+	0 none ab_aurigae 04:55:45.818188 +30.33.03.92532 J2000 0 130584
2020-09-22 23:51:55	INFO	..ms::summary	Spectral Windows: (8 unique spectral windows and 1 unique polarization setups)
2020-09-22 23:51:55	INFO	..s::summary+	SpwID Name #Chans Frame Ch0(MHz) ChanWid(kHz) TotBW(kHz) CtrFreq(MHz) RFC Num Corrs
2020-09-22 23:51:55	INFO	..s::summary+	0 ALMA_RB_07#BB_1#SW-01#FULL_RES 3840 TOPO 345789.363 15.259 58593.8 345818.6522 1 XX YY
2020-09-22 23:51:55	INFO	..s::summary+	1 ALMA_RB_07#BB_2#SW-01#FULL_RES 960 TOPO 342585.556 1953.125 1875000.0 343522.0798 2 XX YY
2020-09-22 23:51:55	INFO	..s::summary+	2 ALMA_RB_07#BB_3#SW-01#FULL_RES 3840 TOPO 330629.728 -15.259 58593.8 330600.4391 3 XX YY
2020-09-22 23:51:55	INFO	..s::summary+	3 ALMA_RB_07#BB_4#SW-01#FULL_RES 128 TOPO 333004.681 -15625.000 2000000.0 332012.4935 4 XX YY
2020-09-22 23:51:55	INFO	..s::summary+	4 ALMA_RB_07#BB_1#SW-01#FULL_RES 3840 TOPO 345770.043 15.259 58593.8 345799.3317 1 XX YY
2020-09-22 23:51:55	INFO	..s::summary+	5 ALMA_RB_07#BB_2#SW-01#FULL_RES 960 TOPO 342575.939 1953.125 1875000.0 343512.4623 2 XX YY
2020-09-22 23:51:55	INFO	..s::summary+	6 ALMA_RB_07#BB_3#SW-01#FULL_RES 3840 TOPO 330620.449 -15.259 58593.8 330591.1593 3 XX YY
2020-09-22 23:51:55	INFO	..s::summary+	7 ALMA_RB_07#BB_4#SW-01#FULL_RES 128 TOPO 332995.386 -15625.000 2000000.0 332003.1993 4 XX YY
2020-09-22 23:51:55	INFO	..ms::summary	Sources: 4

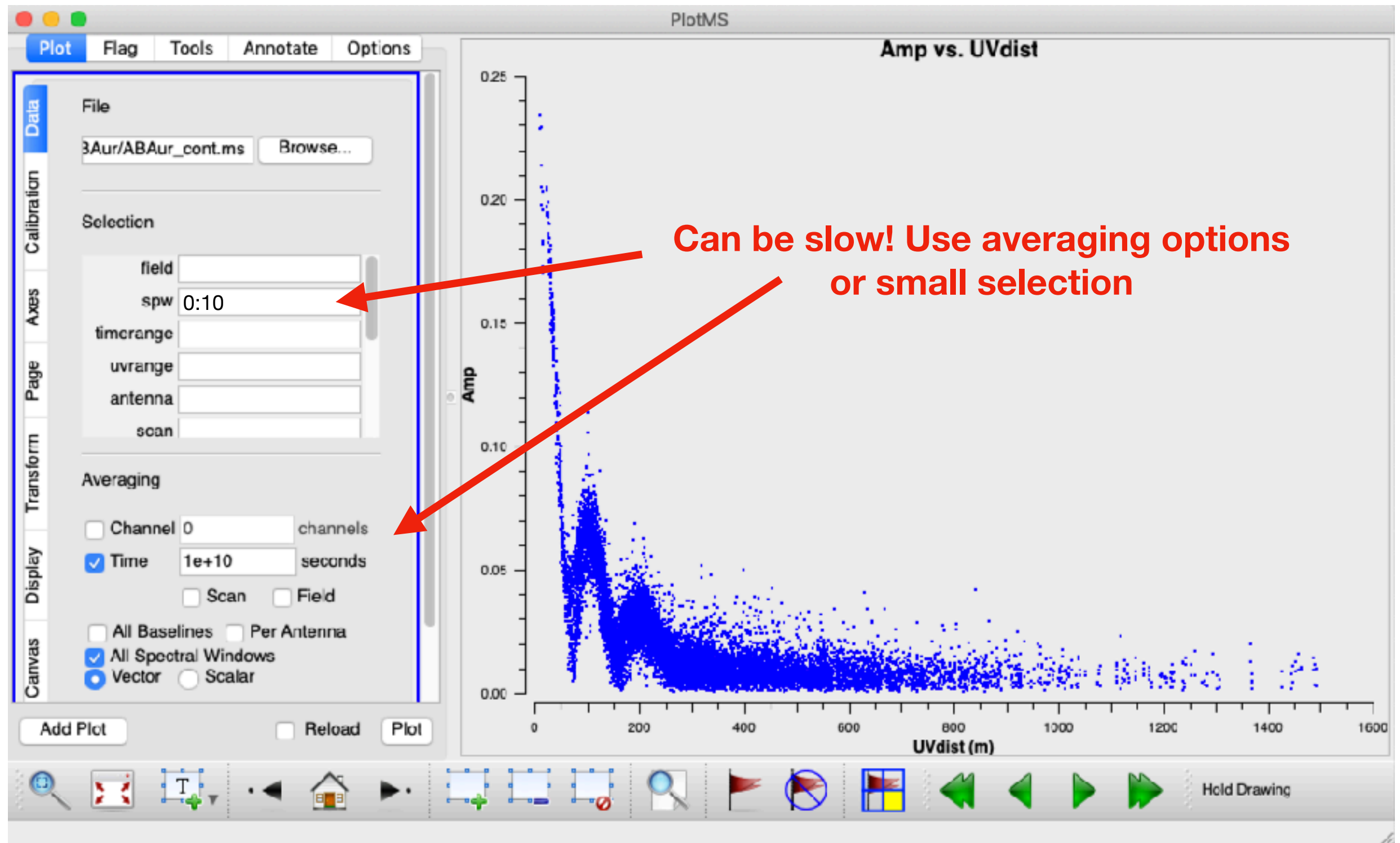
CASA inspection

- `plotms(vis='mydata.ms') => plot visibility data`



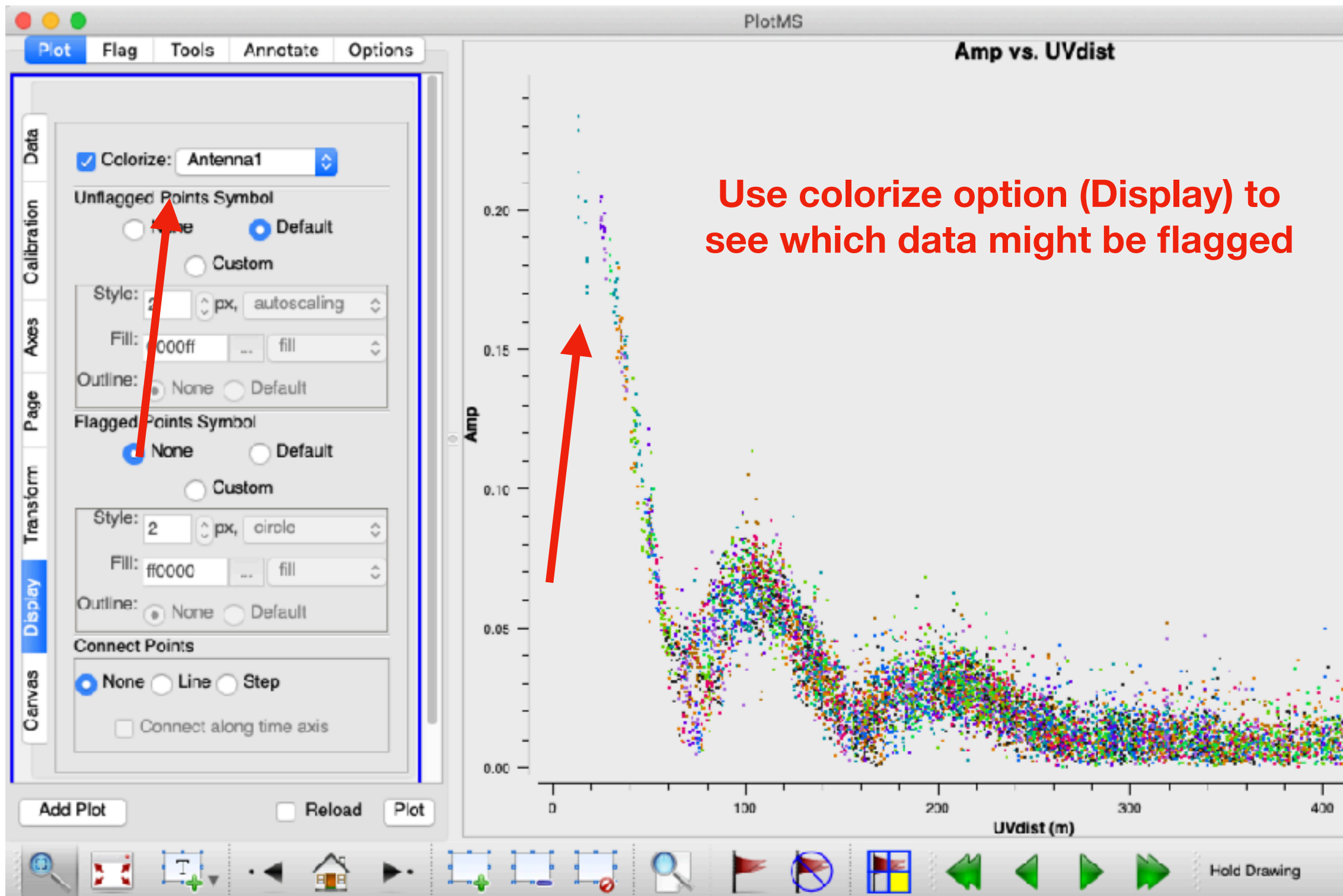
CASA inspection

- `plotms(vis='mydata.ms') =>` plot visibility data

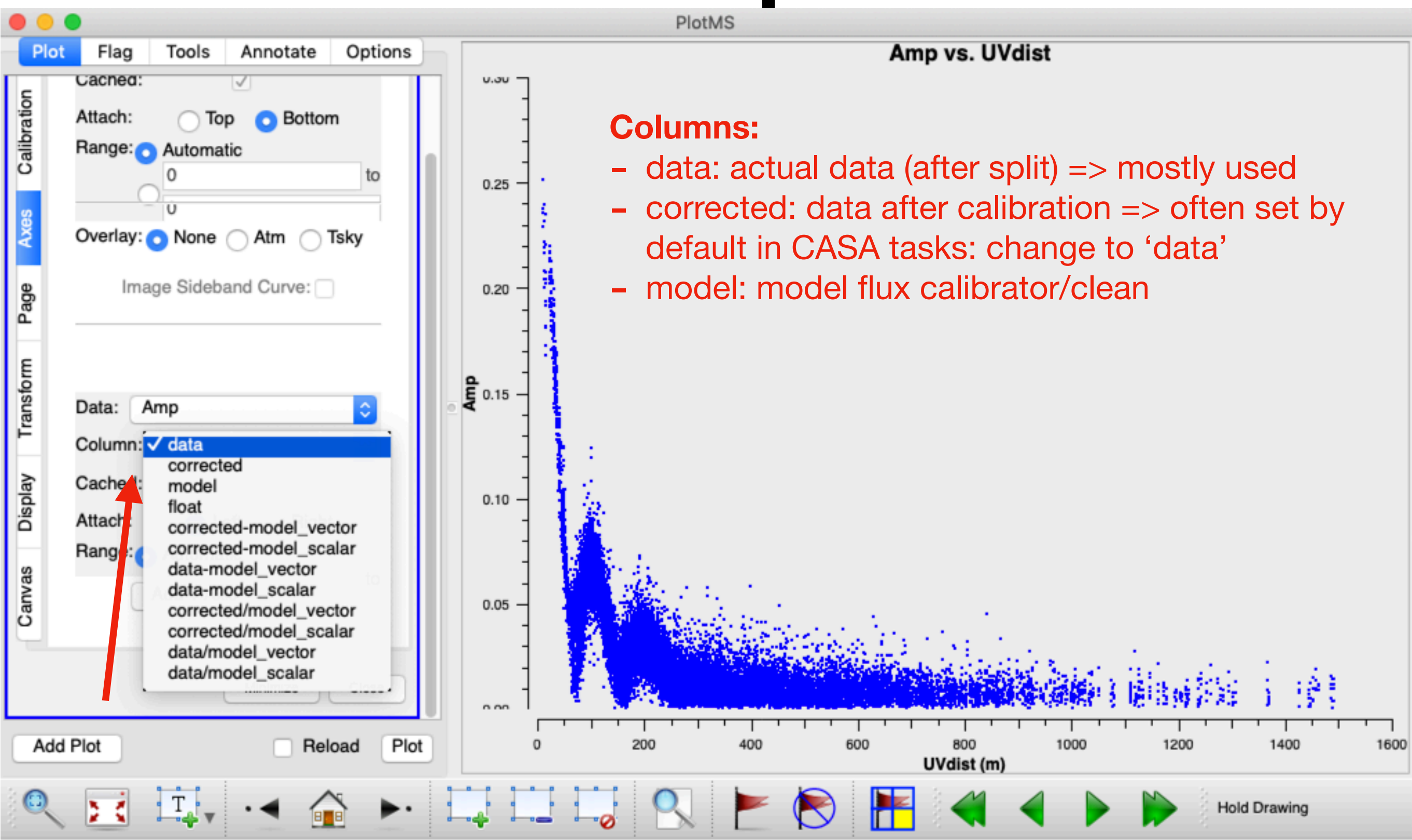


CASA inspection

- `plotms(vis='mydata.ms') =>` plot visibility data



CASA inspection



CASA inspection

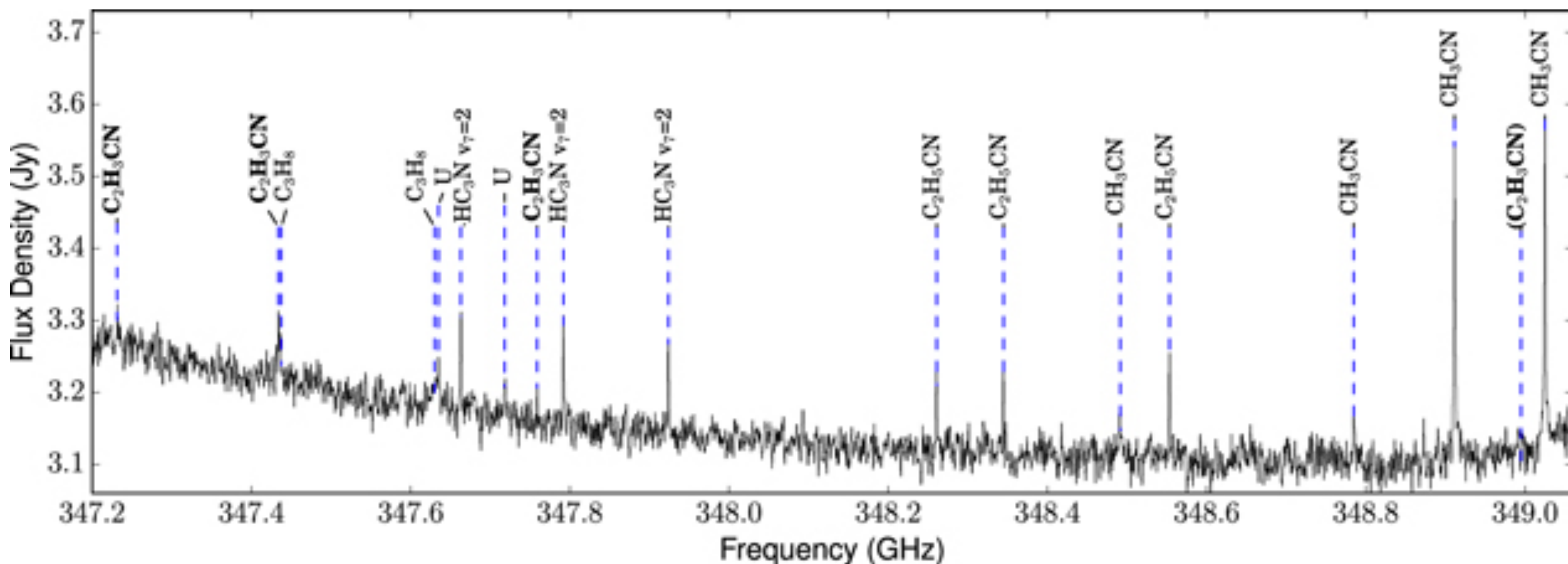
- Datasets can be huge: some tips to reduce (before imaging/plotms)
 - Split out what you need (field, spectral window, channels)
 - Bin in frequency (for continuum)
 - Bin in time domain (if no visibility analysis)

```
[CASA <76>: inp
-----> inp()
# split :: Create a visibility subset from an existing visibility set
vis                = 'AB Aur_timebin.ms' # Name of input visibility file
outputvis          = ''                  # Name of output visibility file
keepmms            = True                 # If the input is a Multi-MS the output
                                         # will also be a Multi-MS.
field              = '3'                 # Select field using field id(s) or
                                         # field name(s)
spw                = '1:100~1000'        # Select spectral window/channels
scan               = ''                  # Scan number range
antenna            = ''                  # Select data based on antenna/baseline
correlation        = ''                  # Select data based on correlation
timerange          = ''                  # Select data based on time range
intent             = ''                  # Select observing intent
array              = ''                  # Select (sub)array(s) by array ID
                                         # number.
uvrange            = ''                  # Select data by baseline length.
observation        = ''                  # Select by observation ID(s)
feed               = ''                  # Multi-feed numbers: Not yet
                                         # implemented.
datacolumn         = 'corrected'         # Which data column(s) to process.
keepflags          = True
width              = 3840                # Number of channels to average to form
                                         # one output channel
timebin            = '30s'               # Bin width for time averaging
combine            = ''                  # Span the timebin across scan, state
                                         # or both
```


Continuum vs line

Example full spectrum

Molecular lines

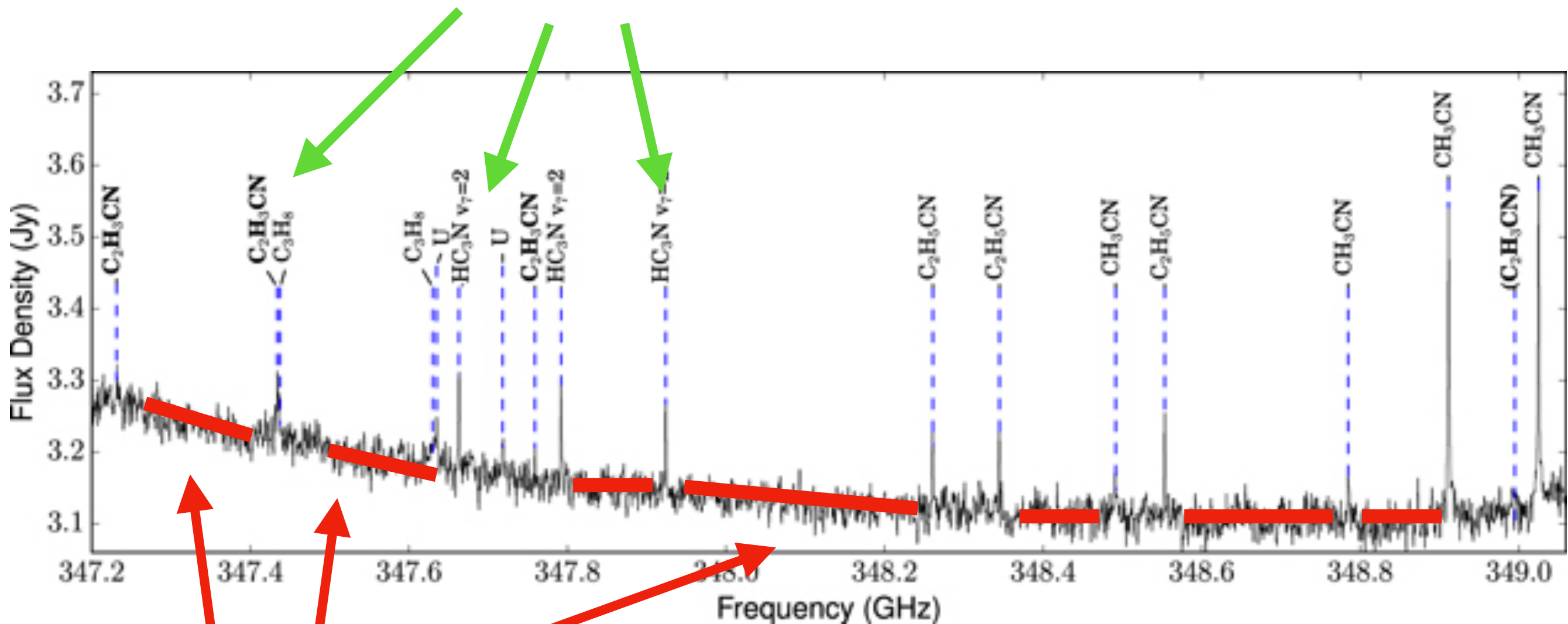


Continuum

Continuum vs line

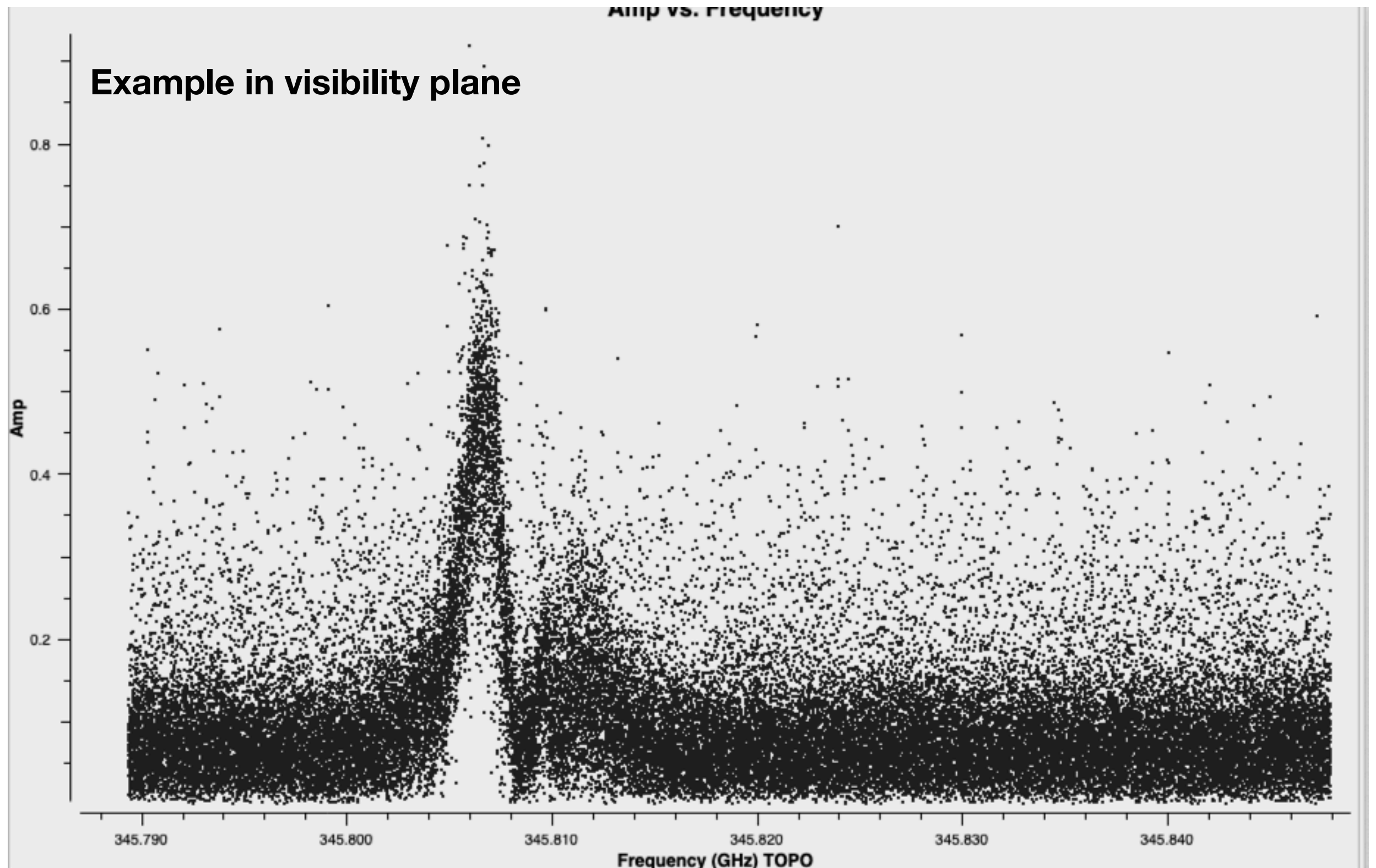
Example full spectrum

Molecular lines



Continuum

Continuum vs line



Continuum vs line

- Continuum

- Thermal dust emission
- Select channels without line emission and average them using `split()` command
- Averaging results in much higher SNR
- Clean using `specmode='mfs'`

- Line

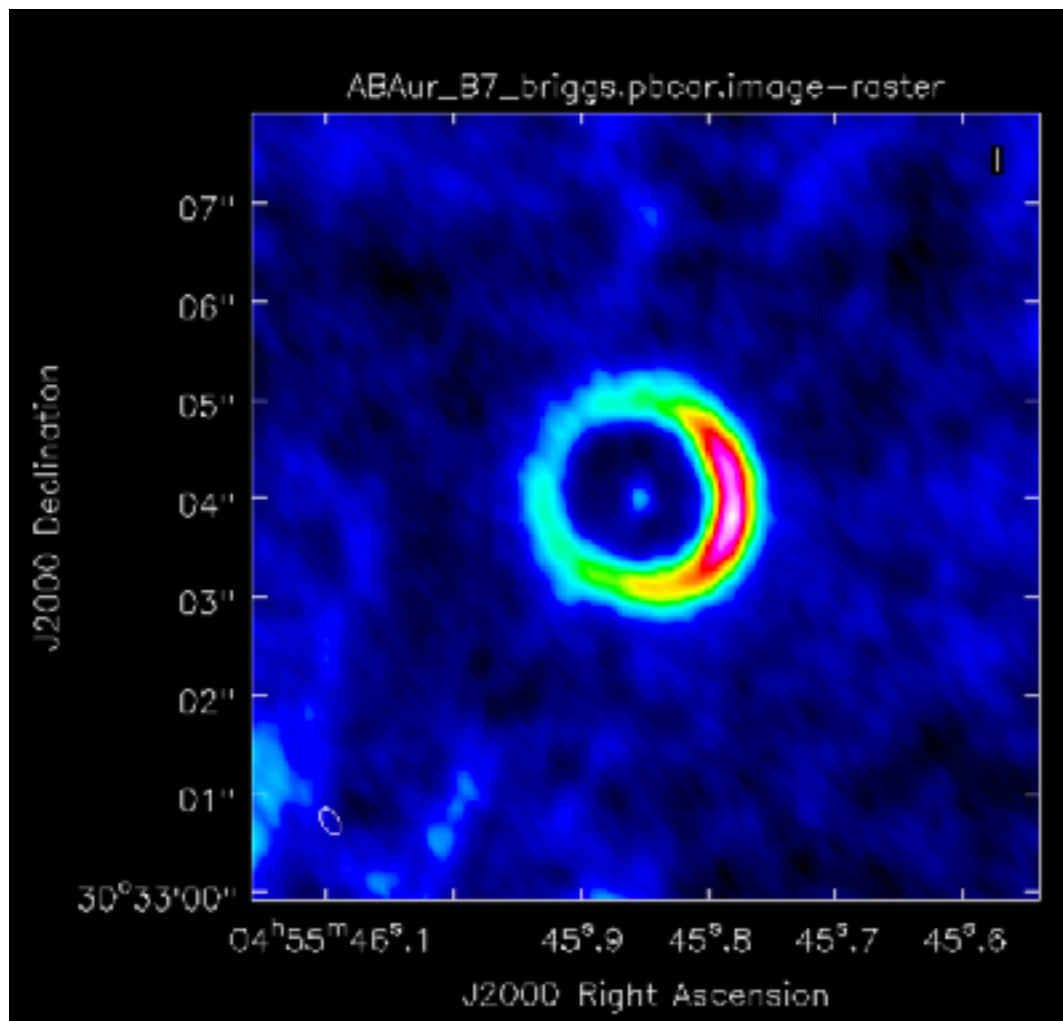
- Molecular line
- Subtract the continuum in the visibility plane using the `uvcontsub()` command, by specifying channels without line emission
- Clean using `specmode='cube'`
- Velocity mode: set `outframe='LSRK'!`
- Set velocity resolution and rest frequency

Molecular lines

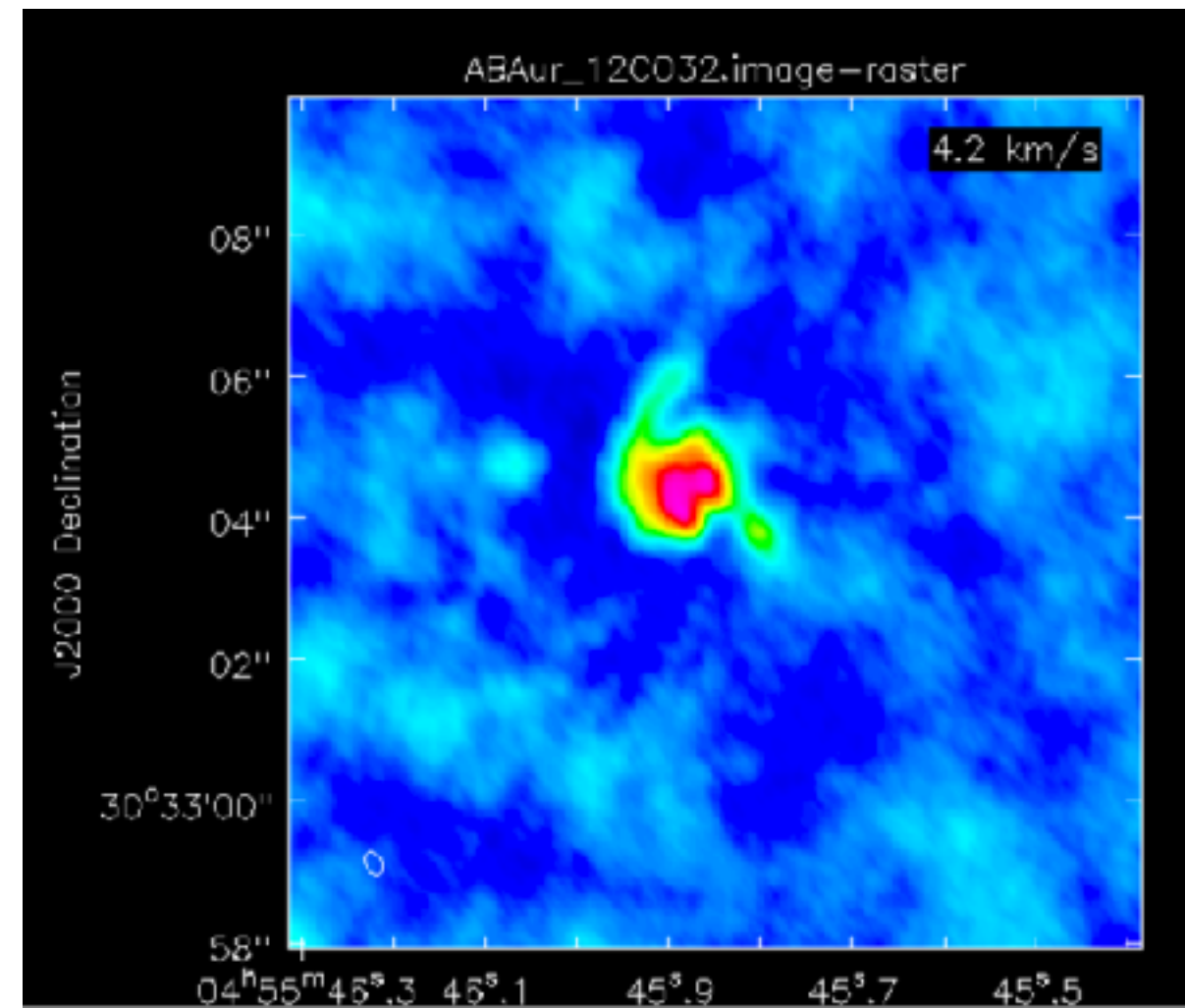
- Molecular line spectroscopy
 - Each molecule emits through a number of transitions, depending on local density and temperature
 - Each transition has a unique frequency (fingerprint): the rest frequency
 - Molecular lines are broadened by kinematics:
 - Shift by source velocity: few km/s for nearby disks
 - Broadened profile by disk rotation
 - Velocity resolution ALMA can be very high (10 m/s)! Depends on user settings (proposal)
 - Rest frequencies and more: <https://splatalogue.online//>

Continuum vs line

Continuum



Cube



(Share screen)

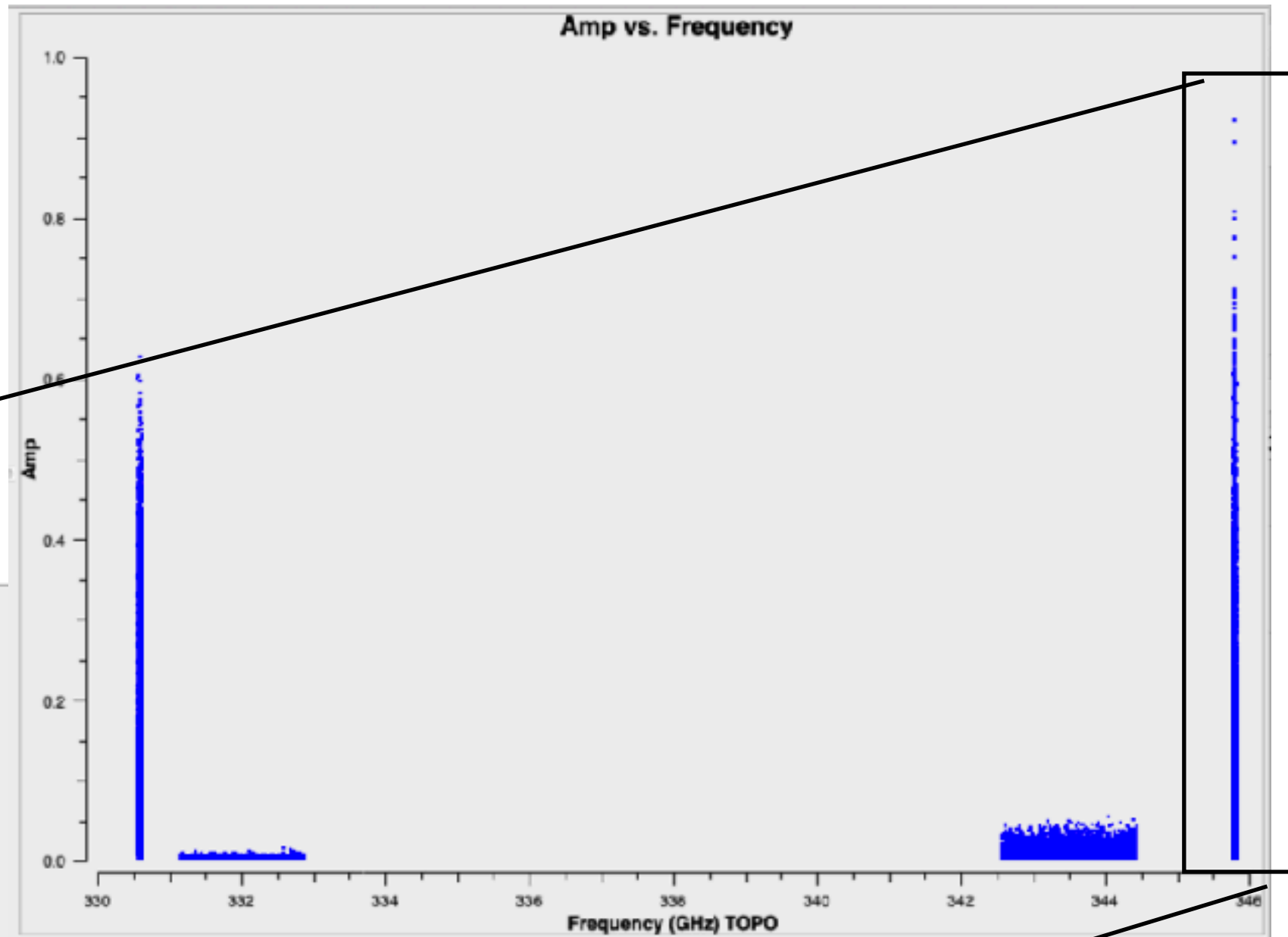
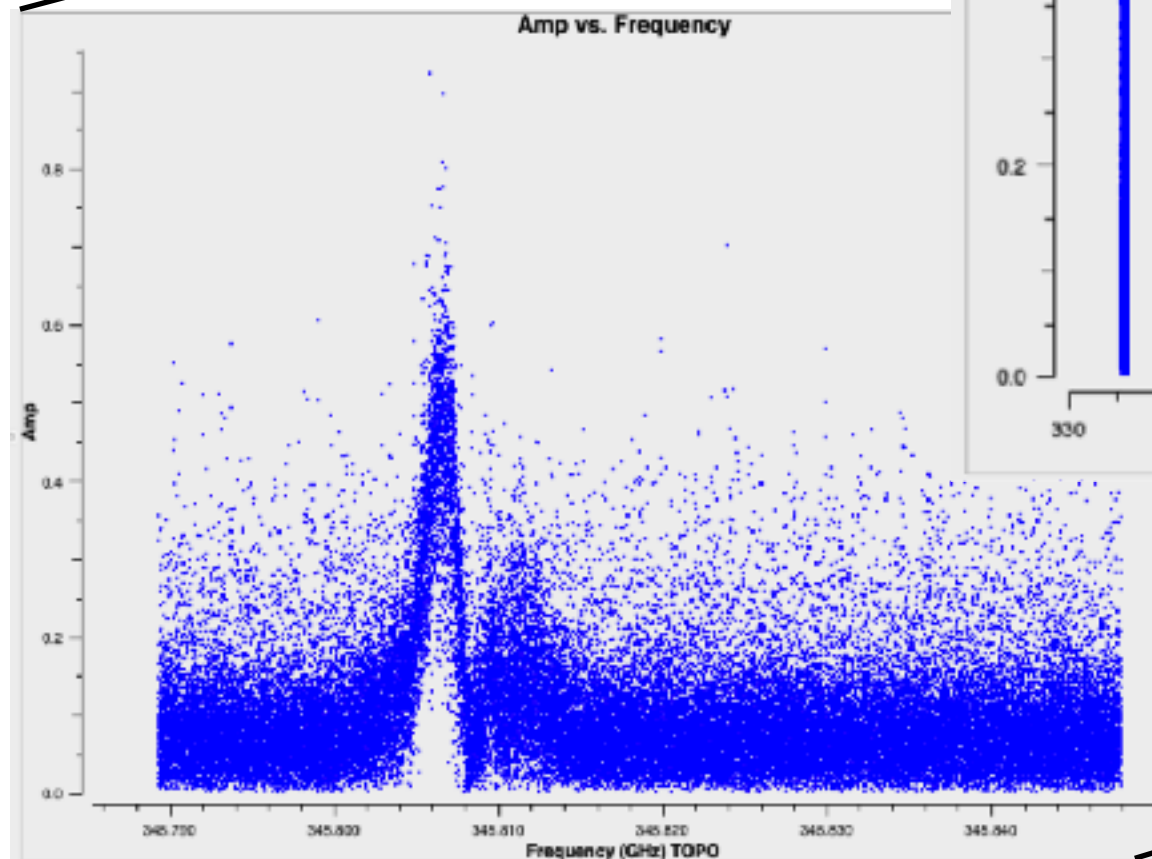
About spectral windows

Practice: output listobs ()

Summary	Spectral Windows: (16 unique spectral windows and 1 unique polarization setups)							
Summary+	SpwID	Name	#Chans	Frame	Ch0(MHz)	ChanWid(kHz)	TotBW(kHz)	CtrFreq(MHz)
Summary+	19	X1135923343#ALMA_RB_06#BB_2#SW-01#FULL_RES	128	TOPO	233201.518	15625.000	2000000.0	234193.7059
Summary+	23	X1135923343#ALMA_RB_06#BB_4#SW-01#FULL_RES	128	TOPO	218493.923	-15625.000	2000000.0	217501.7354
Summary+	25	X1135923343#ALMA_RB_06#BB_1#SW-01#FULL_RES	1920	TOPO	230522.724	976.562	1875000.0	231459.7354
Summary+	27	X1135923343#ALMA_RB_06#BB_3#SW-01#FULL_RES	1920	TOPO	220396.747	-976.562	1875000.0	219459.7354
Summary+	47	X1135923343#ALMA_RB_06#BB_2#SW-01#FULL_RES	128	TOPO	233198.091	15625.000	2000000.0	234190.2783
Summary+	51	X1135923343#ALMA_RB_06#BB_4#SW-01#FULL_RES	128	TOPO	218490.620	-15625.000	2000000.0	217498.4328
Summary+	53	X1135923343#ALMA_RB_06#BB_1#SW-01#FULL_RES	1920	TOPO	230519.421	976.562	1875000.0	231456.4328
Summary+	55	X1135923343#ALMA_RB_06#BB_3#SW-01#FULL_RES	1920	TOPO	220393.445	-976.562	1875000.0	219456.4328
Summary+	75	X1135923343#ALMA_RB_06#BB_2#SW-01#FULL_RES	128	TOPO	233194.079	15625.000	2000000.0	234186.2664
Summary+	79	X1135923343#ALMA_RB_06#BB_4#SW-01#FULL_RES	128	TOPO	218486.755	-15625.000	2000000.0	217494.5673
Summary+	81	X1135923343#ALMA_RB_06#BB_1#SW-01#FULL_RES	1920	TOPO	230515.556	976.562	1875000.0	231452.5673
Summary+	83	X1135923343#ALMA_RB_06#BB_3#SW-01#FULL_RES	1920	TOPO	220389.579	-976.562	1875000.0	219452.5673
Summary+	103	X1135923343#ALMA_RB_06#BB_2#SW-01#FULL_RES	128	TOPO	233193.692	15625.000	2000000.0	234185.8796
Summary+	107	X1135923343#ALMA_RB_06#BB_4#SW-01#FULL_RES	128	TOPO	218486.382	-15625.000	2000000.0	217494.1946
Summary+	109	X1135923343#ALMA_RB_06#BB_1#SW-01#FULL_RES	1920	TOPO	230515.183	976.562	1875000.0	231452.1946
Summary+	111	X1135923343#ALMA_RB_06#BB_3#SW-01#FULL_RES	1920	TOPO	220389.206	-976.562	1875000.0	219452.1946
Summary	Sources: 17							

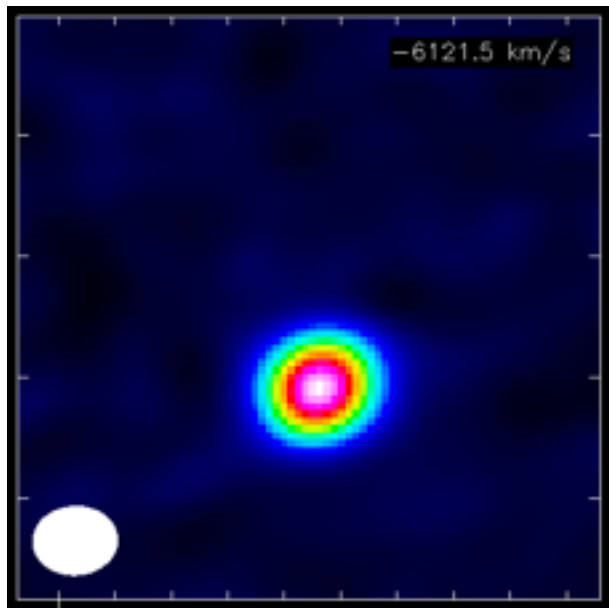
About spectral windows

In practice:
output plots ()

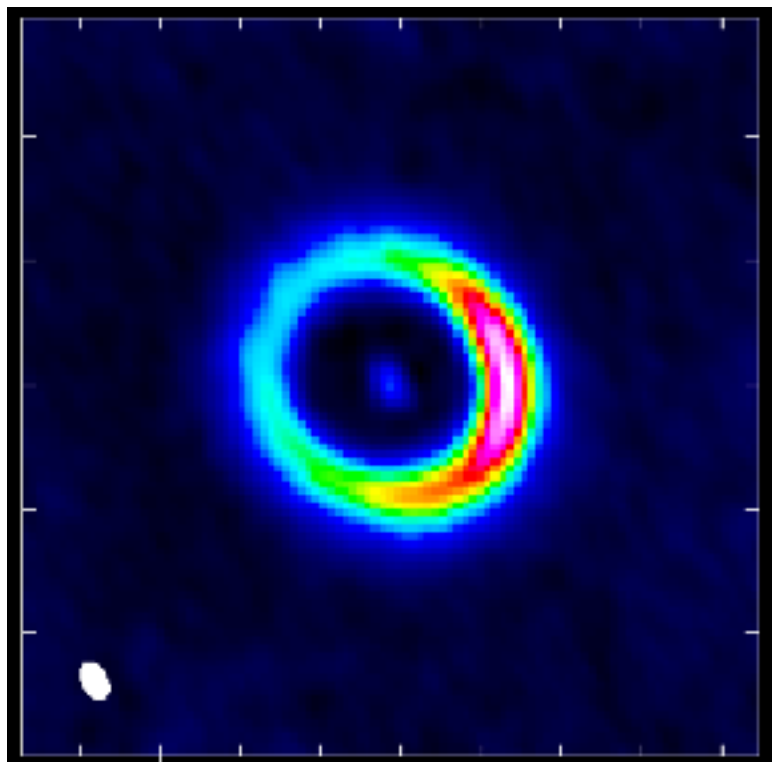


Detections and non-detections

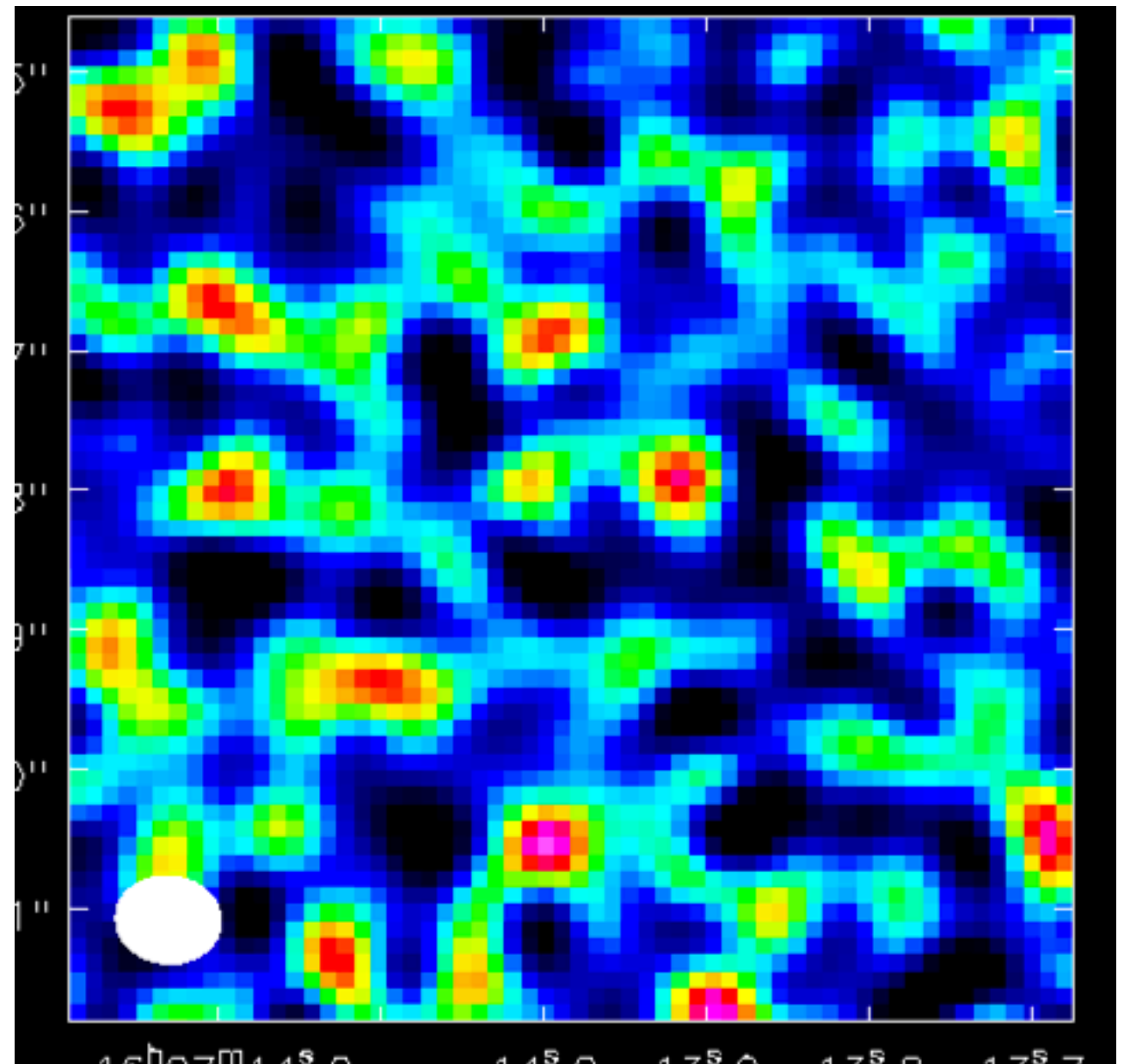
Detection point-source



Detection extended source

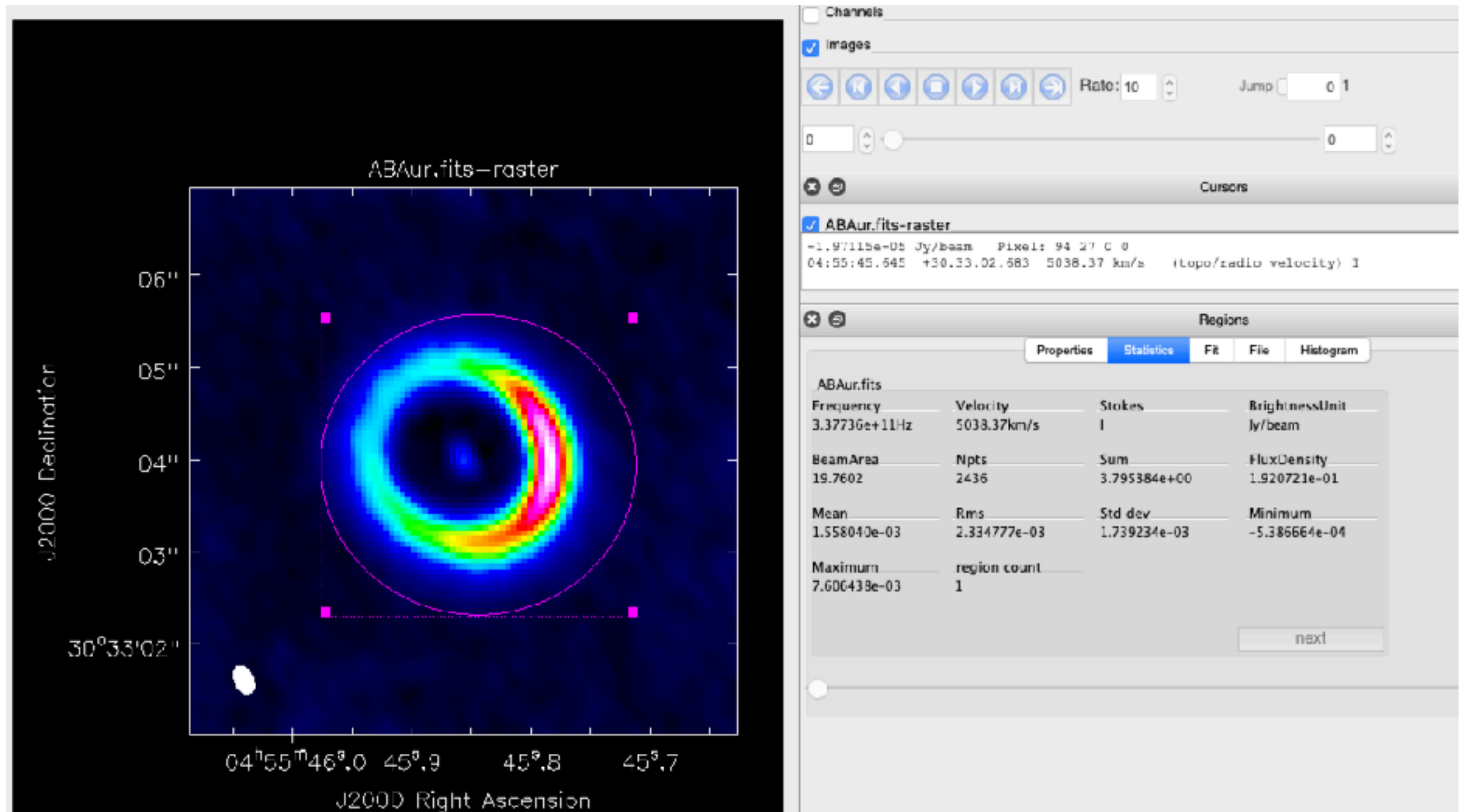


Non-detection

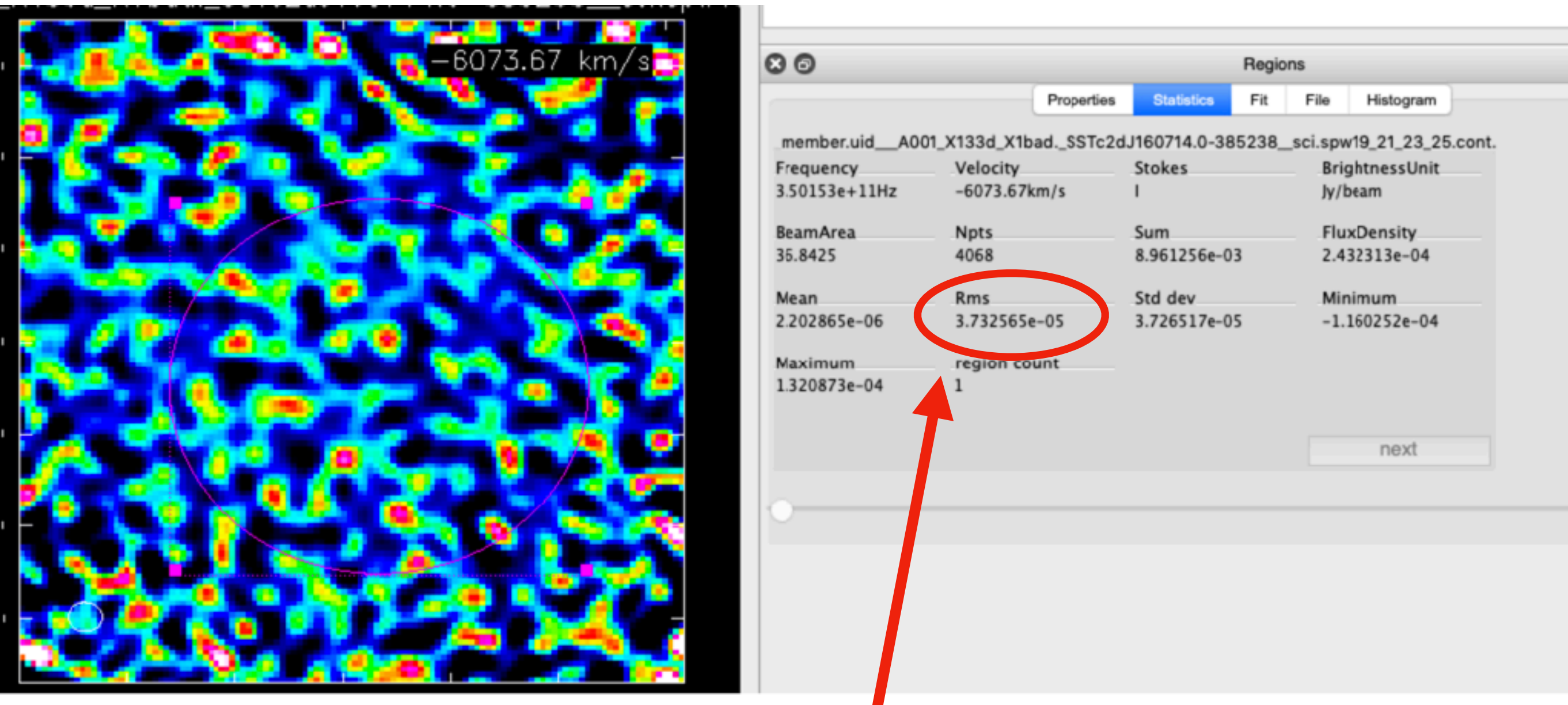


Detections

Get information about flux, size, etc. either with viewer or using `imfit()`



Non-detections/noise



Measure noise in emission-free region

Non-detections/noise

Good practice: compare
with theoretical noise
using ALMA sensitivity
calculator

Common Parameters

Declination	-24:00:00.00
Polarisation	DUAL
Observing Frequency	345
Observing Band	ALMA_RB_07
Bandwidth per Polarization	7.500000
Water Vapour	☒ Automatic Choice ☐ Manual Choice
Column Density	1.262mm (4th Octile)
Trx, tau, Tsky	72 K, 0.211, 47.919 K
Tsys	169.848 K

Individual Parameters

	12 m Array	7 m Array	Total Power Array
Number of Antennas	43 ✓	10 ✓	3
Resolution	0 ✓ arcsec	0 ✓ arcsec	9.6
Sensitivity (rms)	25.62091693992167 ✓ mJy	2.8653846046728888 ✓ mJy	5.246095011230592
Equivalent to	Unknown mK	Unknown mK	0.597
Integration Time	5 ✓ min	60 ✓ s	60

Integration Time Unit Option: Automatic

Sensitivity Unit Option: Automatic

Calculate Integration Time

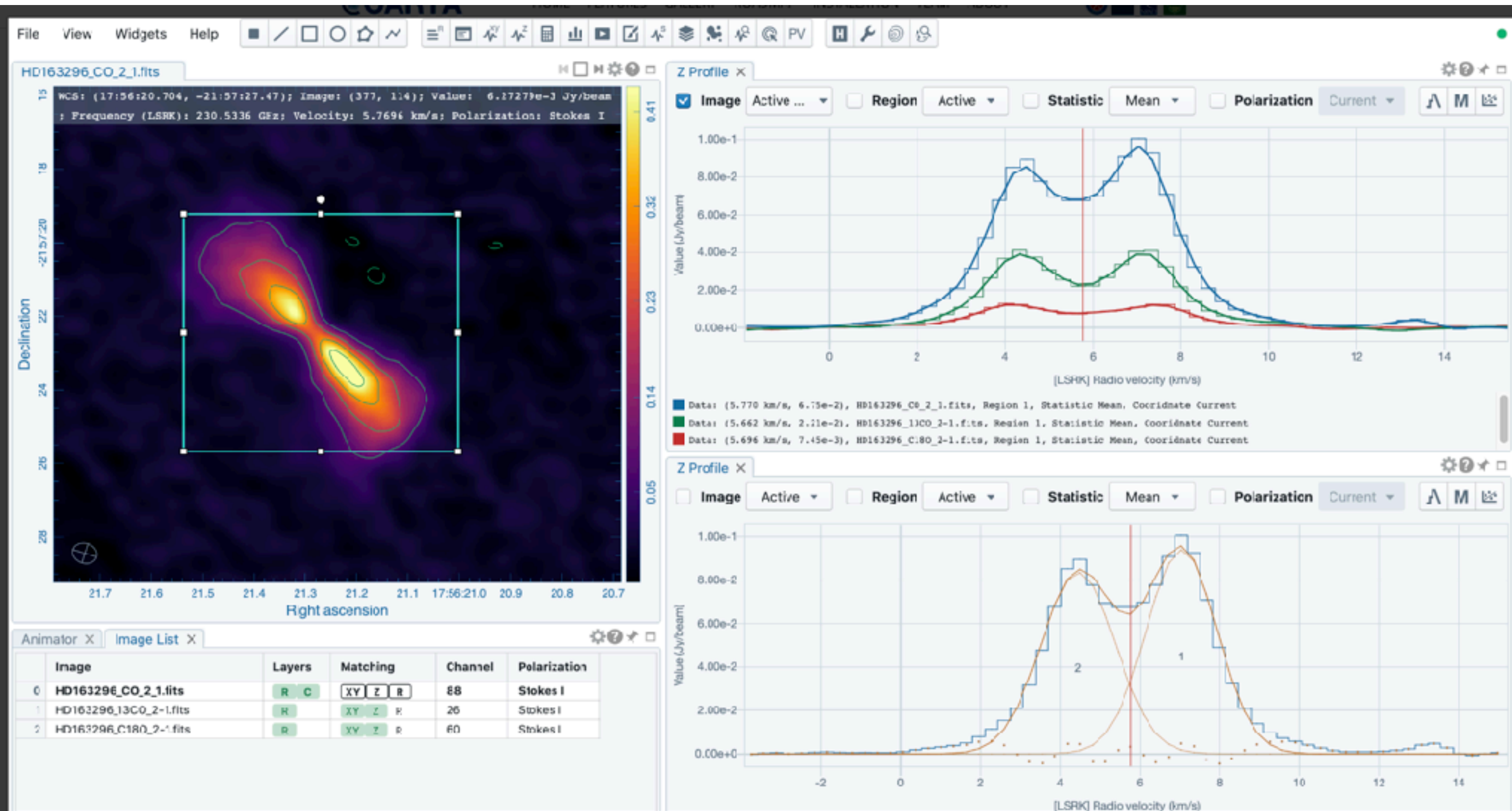
Calculate Sensitivity

<https://asa.alma.cl/SensitivityCalculator/>

Import/export

- For operations outside CASA, export your images to a fitsfile using `exportfits()`
- For most operations in CASA and CASA viewer, import your images to an image file using `importfits()` if not yet in fits format

Another useful tool: CARTAVIS

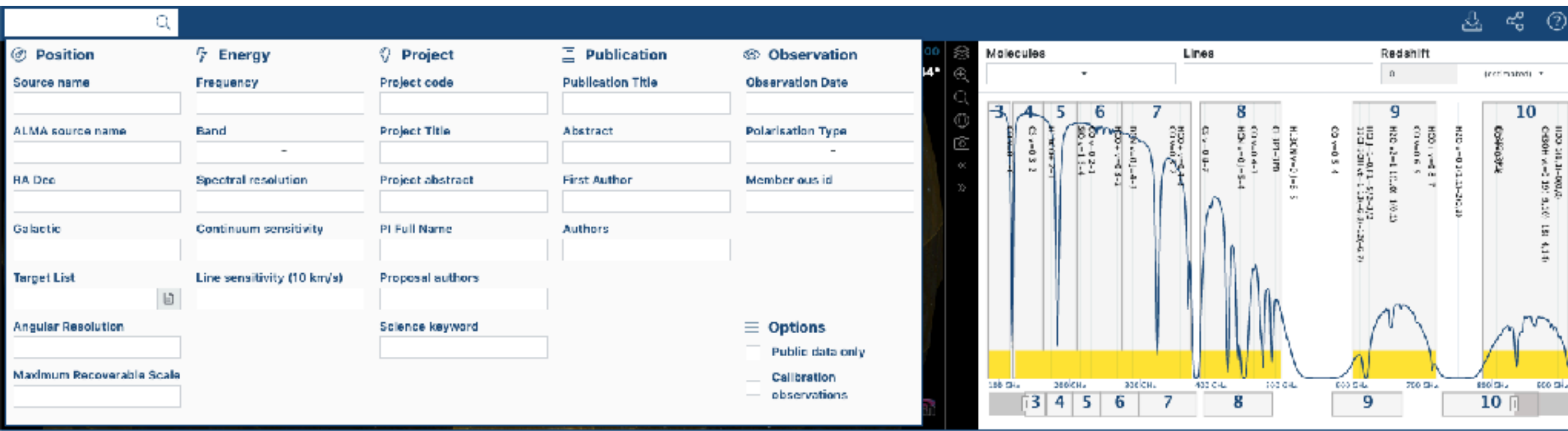


More information

- ALMA proposer's guide:
<https://almascience.nrao.edu/proposing/proposers-guide>
- ALMA CASA tutorials:
<https://casaguides.nrao.edu/index.php/ALMAguides>
- NRAO 17th Synthesis Imaging Workshop 2020:
<http://www.cvent.com/events/virtual-17th-synthesis-imaging-workshop/agenda-0d59eb6cd1474978bce811194b2ff961.aspx>
(online lectures)

ALMA archive

- ALMA data becomes public after 1 year and is provided with reduction script and basic reduced fits files!
- ALMA archive: <https://almascience.nrao.edu/asax/>



Many ways to search...

ALMA archive

- Often many datasets: figure out what you need

Observations (22) Projects (13) Publications (43)																
Project code	ALMA source name	Ra	Dec	Band	Obs. date	Frequency setup	Release date	Publications	Ang. res.	Max. vel. res.	Array	Mosaic	Max. reco. scale	FOV	Scientific category	Science keyword
		hms	dms		mm/dd/yyyy	GHz			arcsec	km/s			arcsec	arcsec		
2011.0.00724.5	LkCa 15	04:39:17.801	+22:21:03.227	9	0.78	884.87..892.37GHz	2014-01-09	12	0.28	0.42	12m	2.39	8.46		Disks and planet forma...	Disks around low-mas...
2013.1.00226.5	LkCa 15	04:39:17.806	+22:21:03.290	6	0.08	241.54..260.55GHz	2015-08-10	26	0.45	0.14	12m	3.97	23.18		ISM and star formation	Low-mass star formati...
2012.1.00170.5	LkCa 15	04:39:17.806	+22:21:03.286	7	0.07	329.21..343.00GHz	2015-11-15	2	0.19	0.11	12m	1.80	17.32		Disks and planet forma...	Disks around low-mas...
2012.1.00811.5	LkCa 15	04:39:17.806	+22:21:03.288	7	0.07	884.07..847.88GHz	2015-12-02	2	0.20	0.11	12m	1.89	17.08		Disks and planet forma...	Disks around low-mas...
2013.1.00226.5	LkCa 15	04:39:17.806	+22:21:03.286	6	0.08	215.08..235.70GHz	2016-08-16	25	0.41	0.16	12m	4.47	25.82		ISM and star formation	Low-mass star formati...
2016.1.00657.5	LkCa 15	04:39:17.807	+22:21:03.268	7	0.03	275.21..280.89GHz	2017-03-14	2	0.88	1.17	12m	8.96	20.57		Disks and planet forma...	Disks around low-mas...
2015.1.00657.5	LkCa 15	04:39:17.807	+22:21:03.266	7	0.04	302.06..317.81GHz	2017-12-29	2	0.53	1.07	12m	5.18	16.78		Disks and planet forma...	Disks around low-mas...
2015.1.00857.5	LkCa 15	04:39:17.807	+22:21:03.266	7	0.03	283.46..299.20GHz	2017-12-29	2	0.58	1.14	12m	5.38	16.99		Disks and planet forma...	Disks around low-mas...
2015.1.00657.5	LkCa 15	04:39:17.807	+22:21:03.266	7	0.05	286.31..314.06GHz	2017-12-30	2	0.60	1.08	12m	6.00	18.02		Disks and planet forma...	Disks around low-mas...

Hover mouse on program number:
Abstract proposal

Hover mouse on Frequency:
Spectral setup

Project title

The origin of transitional disks: grain growth or dynamical clearing by planets?

PI name

Perez, Laura

Proposal abstract

Most young, low-mass stars are surrounded by optically thick accretion disks. A small fraction of these stars show a remarkable depletion of dust in the inner disk regions. These so-called "transition disks" are thought to represent a brief, but extremely important, evolutionary phase between young, optically thick protoplanetary disks and old, optically thin debris disks. A number of mechanisms have been proposed to deplete the inner regions of transition disks, including grain growth, photo-evaporation by the central star, and dynamical clearing by a recently formed planet. Observationally, distinguishing between these mechanisms has been difficult up to now. In this proposal, we request time with ALMA to image a subset of transition disks with large inner holes, large disk masses, and high accretion rates, that likely originate by either grain growth or dynamical clearing by a planetary object. ALMA's exquisite sensitivity and high angular resolution, already available in early Science, can resolve the inner disk and detect

Frequency	Resolution	Sensitivity 10Kms/s	Sensitivity native	Pol. Product	Type
329.21..343.00GHz	122.07kHz	118mJy/beam@10km/s	0.21Jy/beam@native	XX YY	line
330.50..330.74GHz	122.07kHz	150mJy/beam@10km/s	0.33Jy/beam@native	XX YY	line
330.02..341.00GHz	312500kHz	149mJy/beam@10km/s	0.11Jy/beam@native	XX YY	continuum
341.02..343.00GHz	312500kHz	148mJy/beam@10km/s	0.11Jy/beam@native	XX YY	continuum

Or check directly at
publications/projects

ALMA archive

- Download:



- Check what you need

ALMA Request Handler [Login](#)

Anonymous User: Request #1653683601122 ✓
Request Title: click to edit

Download Selected

☒ readme ☒ product ☒ auxiliary ☐ raw ☐ raw (semipass) ☐ external

Project / OUSet / ExecutionBlock	File	Size	Accessible
Request 1653683601122		185 MB	
Project 2017.1.00727.S			
Science Goal OUS uid:/A001/X1296/X66d			
Group OUS uid:/A001/X1296/X66e			
Member OUS uid:/A001/X1296/X66f			
SB LkCa15_a_09_TM1			
☐ readme	member.uid__A001_X1296_X66f_README.txt	3 KB	✗
☐ product	2017.1.00727.S_uid__A001_X1296_X66f_001_of_001.tar	87 GB	✗
☐ auxiliary	2017.1.00727.S_uid__A001_X1296_X66f_auxiliary.tar	1 GB	✗
☐ raw	2017.1.00727.S_uid__A002_Xe03666_X11ca2.asdm.adm.tar	84 GB	✗
☐ raw	2017.1.00727.S_uid__A002_Xe03666_X11ca3.asdm.adm.tar	100 GB	✗
☐ raw (semipass)	2017.1.00727.S_uid__A002_Xe1142b_X0303.asdm.adm.tar	77 GB	✗
Member OUS uid:/A001/X1296/X671			
SB LkCa15_a_09_TM2			
☒ readme	member.uid__A001_X1296_X671_README.txt	269 B	✓
☒ product	2017.1.00727.S_uid__A001_X1296_X671_001_of_001.tar	4 MB	✓
☒ auxiliary	2017.1.00727.S_uid__A001_X1296_X671_auxiliary.tar	181 MB	✓
☐ raw	2017.1.00727.S_uid__A002_Xe169ef_X16c4.asdm.adm.tar	108 GB	✓

ALMA archive

- Select what you need and click Download selected
- Script recommended: easy to continue
- Keep in mind that datasets are huge, 100s of Gb!
Need storage, also for reduction
- Different Cycles: different CASA versions to reduce



Choose one of the following download methods:

Download Script	The downloads are scripted for you. You just need to execute the script from the command line, after making it executable by typing <code>chmod u+x download*.sh</code>
Java Download Manager	ALMA's download manager had to be discontinued due to changes in java. Please use one of the other options instead.
File List	View a text file containing a list of URLs. This is useful for using third-party download manager's such as <i>DownThemAll</i> .

ALMA archive

- Full dataset: folder structure
- README:
comments reduction,
CASA version
- Raw: raw data (ASDM)
- Script: contains main calibration scripts
- QA: quality assessment
- Product: basic reduction: often very large and unnecessary!
- Calibration: calibration tables
- Calibrated: measurement sets (after running script)

Name	Size	Type
▶ calibrated	10 items	Folder
▶ calibration	12 items	Folder
▶ log	7 items	Folder
▶ product	4 items	Folder
▶ qa	24 items	Folder
▶ raw	0 items	Folder
▶ script	8 items	Folder
▶ README	6.3 kB	Text

ALMA archive

- Trick for quick look at product fits files: NAOJ fits archive!
<https://jvo.nao.ac.jp/portal/top-page.do>
- Fill in program number and browse through fits images

ALMA FITS Archive : Project Info

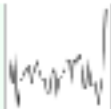
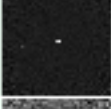
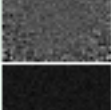
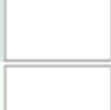
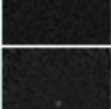
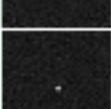
Project Code: 2013.1.00220.5 [ALMA Sci Portal](#)

☐ Show all the data including calibration (*.flux.fits, *.pb.fits, target=J###[+J###]), duplicated, and deprecated data.

Number of data per page : 20

Ordered by dataset_id (desc)

Total number : 78

#	dataset id	☐ all	Download all the checked data	origin ?	image	spect	ra/dec (J2000)	target name	Cube size (XxYxF) ?	Image size (arcmin2)	pixel scale, beam size (arcsec)	band	freq. range (GHz)	freq. scale per pix (MHz)	obs date	release date ?	data type	3rd axis	mem
1	ALMA01024026	☐	Download WebGLv4 VO Search	ALMA official			15h47m50.6 -35d28m35	LupusIII_1002	640 x640 x40 x1	0.32 x0.32	0.030, 0.344 x0.300	Band7	329.304 -- 329.348	1.098	2015- 06-15	2016- 09-05	CUBE	frequency	A001_X12
2	ALMA01024025	☐	Download WebGLv4 VO Search	ALMA official			15h39m27.7 -34d46m17	LupusI_4	640 x640 x1 x1	0.32 x0.32	0.030, 0.325 x0.258	Band7	326.285 -- 343.660	17,375.016	2015- 06-15	2016- 09-05	IMAGE	frequency	A001_X12
3	ALMA01024024	☐	Download WebGLv4 VO Search	ALMA official			15h59m25.2 -42d33m07	LupusV_142	640 x640 x40 x1	0.32 x0.32	0.030, 0.342 x0.314	Band7	329.304 -- 329.348	1.098	2015- 06-15	2016- 09-05	CUBE	frequency	A001_X12
4	ALMA01024023	☐	Download WebGLv4 VO Search	ALMA official			16h00m07.4 -41d49m48	LupusV_146	640 x640 x1 x1	0.32 x0.32	0.030, 0.334 x0.271	Band7	326.285 -- 343.660	17,375.047	2015- 06-15	2016- 09-05	IMAGE	frequency	A001_X12
5	ALMA01024022	☐	Download WebGLv4 VO Search	ALMA official			15h39m27.7 -34d46m17	LupusI_1	640 x640 x1 x1	0.32 x0.32	0.030, 0.325 x0.258	Band7	326.285 -- 343.660	17,375.016	2015- 06-15	2016- 09-05	IMAGE	frequency	A001_X12
6	ALMA01024021	☐	Download WebGLv4 VO Search	ALMA official			15h39m27.7 -34d46m17	LupusI_1	640 x640 x1 x1	0.32 x0.32	0.030, 0.325 x0.258	Band7	326.285 -- 343.660	17,375.016	2015- 06-15	2016- 09-05	IMAGE	frequency	A001_X12
7	ALMA01024018	☐	Download WebGLv4 VO Search	ALMA official			15h58m02.5 -37d36m02	LupusIII_1006	640 x640 x1 x1	0.32 x0.32	0.030, 0.335 x0.280	Band7	326.285 -- 343.660	17,375.028	2015- 06-15	2016- 09-05	IMAGE	frequency	A001_X12

ALMA archive

- ALMA data is quality assessed (checked for noise/beam size proposal: QA1 and QA2) and basic reduced (product fits files) but often room for improvement
- Possible improvements: additional flagging, combination of configurations, self-calibration, imaging (weighting, velocity resolution, etc.)
- Recommended to download raw data, run calibration script and redo imaging for the purpose of your science.
- Very annoying: many different incompatible CASA versions required. Possible solution next year with ARCADE environment.
- Product fits files can be used for initial inspection, but often not science ready

Now it's your turn!



WE WANT YOU!
TO REDUCE ALMA DATA

ALMA reduction

- Today: ALMA CASA tutorial TW Hya
 - Download and install CASA
 - <https://casaguides.nrao.edu/index.php/ALMAguides>
 - [A first look at imaging in CASA 6.4](#): This guide gives a first look at imaging and image analysis in CASA.
 - [A first look at self-calibration in CASA 6.4](#): This guide demonstrates continuum self-cal.
 - [A first look at spectral line imaging in CASA 6.4](#): This guide shows imaging of a spectral line.
 - [A first look at image analysis in CASA 6.4](#): This guide demonstrates moment creation and basic image analysis.
 - Tomorrow: pick your project from an unpublished dataset with many resolved protoplanetary disks (already calibrated and split out science targets: start directly from the measurement set)
- => goal: produce images, analyse them and present on Friday!

Questions?

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<http://www.nienkevandermarel.com>