Imaging/Image Analysis

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NRAO

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

Imaging: *clean*

After calibration: Make an image!

Task: ***clean***

- Grids the visibilities
- Calculates imaging weights for each cell
- Fourier Transform visibilities to dirty image
- Calculates *dirty* psf/beam from uv-coverage
- Deconvolves (cleans) data (creates a model, a residual, an image=conv. model+residual)
- Calculates *clean* psf/beam
- Applies primary beam correction if requested

Imaging: *clean*

Gridding:

- Regular gridding (spheroidal): single pointing (fov < primary beam)
- Mosaicking: many pointings stitched together in either uv or image plane
- W-projection/faceting: account for wide fields/sky curvature (fov > primary beam)
- Outlier fields: multiple, small sky patches

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Gridding spectral line:

- Grid per channel/velocity/frequency interval
- Specify: number of planes, start frequency/velocity, width of each channel (can be negative)
- For gridding in velocity one also needs rest frequency, velframe (LSRK, BARY, etc.), Doppler (optical, radio) [internal: LSRK, radio]
- *clean* automatically regrids all data to the specified output frame. No cvel is required.
- When $\Delta\nu/\nu$ >5%: CASA will calculate a psf per plane
- CASA analysis tasks can handle such beam variations
- Use imsmooth to bring to common beam if needed

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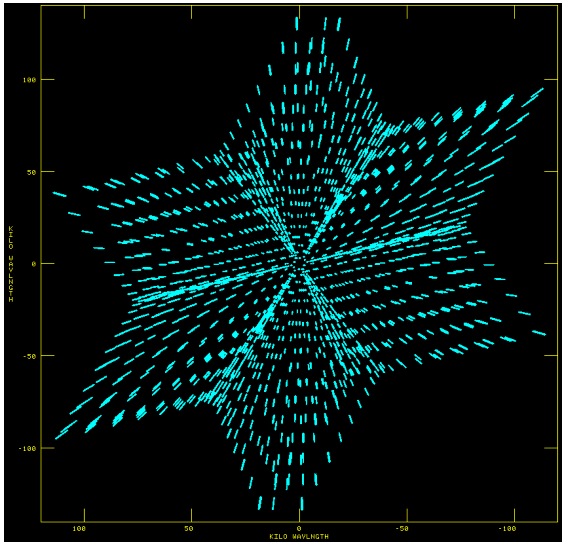
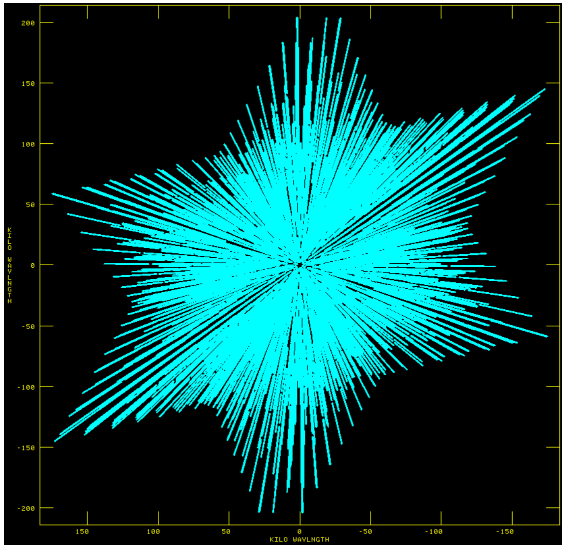
Gridding continuum:

- Multi-frequency synthesis
- Each visibility has a uv-coordinate that depends on the wavelength → wide bands improve uv-coverage and therefore the image quality

Example

64MHz -> 16x64GHZ





Images: E. Momjian

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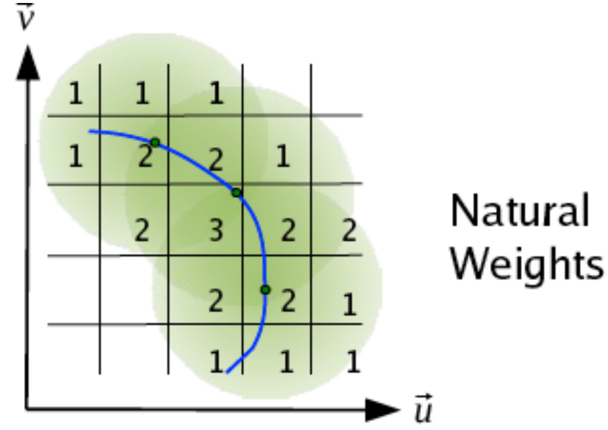
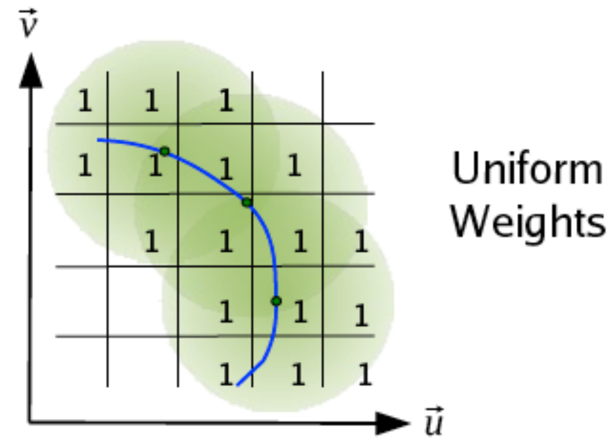
Weighting:

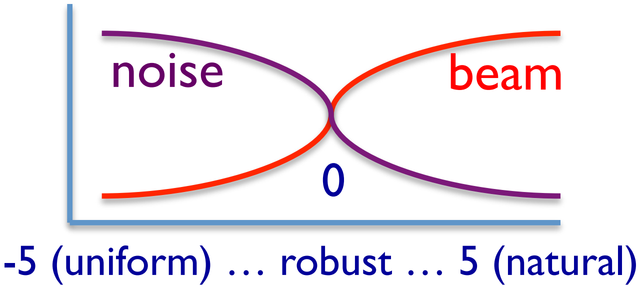
- Will apply weights from visibilities *and also calculate*
- Natural weights (W=1 per *visibility*) creates **largest** psf (lowest resolution) but also **lowest** Jy/beam noise
- Uniform weights (W=1per *cell*): best resolution (**smallest** psf) but **higher** Jy/beam noise
- Briggs (robust) weights is an interpolation between the two extremes

  (typical best compromise: robust=0)
- Taper (Gaussian function of uv-distance)
- Other: super-uniform, radial, briggsabs





Images: U. Rao



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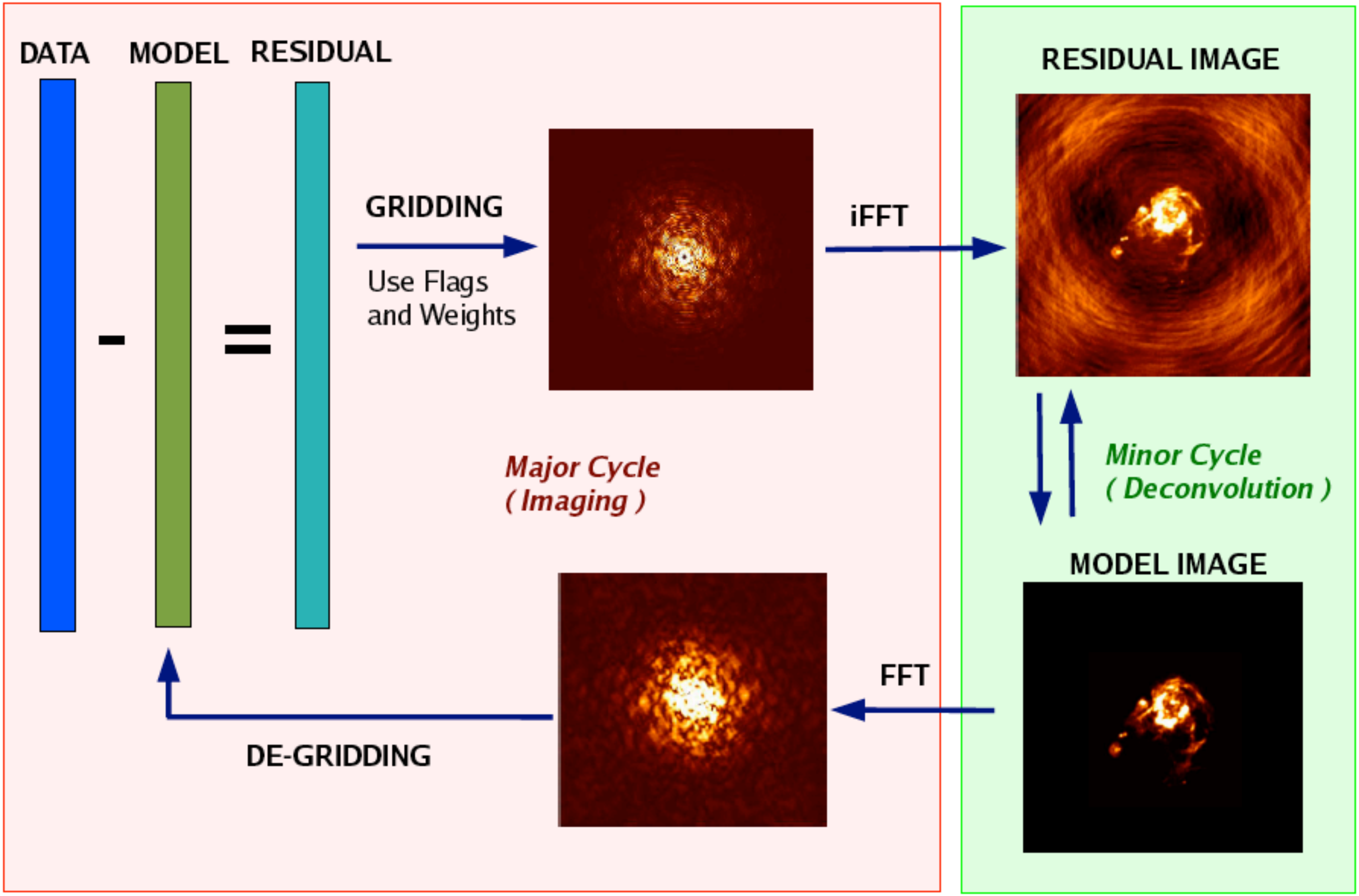
Deconvolution:

imagermode='csclean' performs minor cycles to find components, add to model, go back to visibilities, subtract components, FT into image domain

psfmode:

- Hogbom psf subtraction on full image
- Clark/Clarkstokes uses smaller beam patch for subtraction, improves speed, *clark* searches in combined $I^2+Q^2+U^2+V^2$ for components, *clarkstokes* in each Stokes plane separately

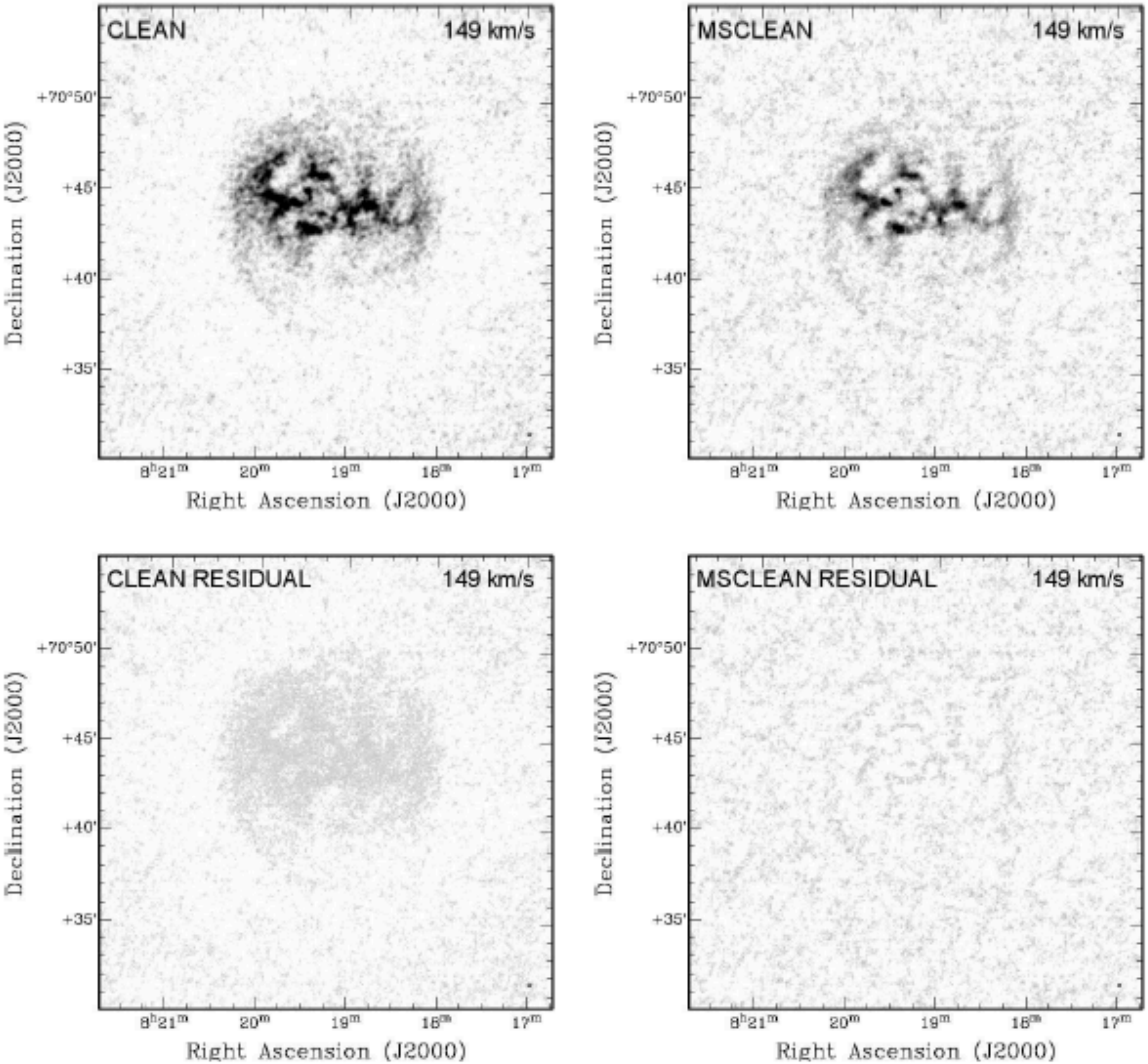

DATA
MODEL
RESIDUAL
-
=
GRIDDING
Use Flags
and Weights
iFFT
RESIDUAL IMAGE
Major Cycle
(Imaging)
Minor Cycle
(Deconvolution)
MODEL IMAGE
FFT
DE-GRIDDING

Images: U. Rao

Imaging: *clean*

Multi-scale cleaning

- Most cleaning algorithms assume that an image is composed of δ-functions
- Flux that is stored in large components will thus be broken up into many small components when they may be better described by fewer but extended components
- multiscale clean allows one to set a range of scales to be cleaned simultaneously
- Appears to reduce 'negative bowl' syndrome of missing short spacings
- Cleans closer to the noise and leaves less flux in the residual image
- Rule of thumb: smallest scale (in units of pixels): 0 (for point sources), largest scale: ~half of the target size, then a few in between (advise: im.setscales)
- Smallscalebias: control the tendency to pick smaller scales



Rich et al. (2008)

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Wideband cleaning MSMFS (multiscale-multi-frequency):

- Fits wideband model to dataset, spatially and spectrally
- Spectral index can be expressed via Taylor-term expansion

$$I_\nu^{\mathrm{sky}} = \sum_t I_t^{\mathrm{sky}} \left(\frac{\nu - \nu_0}{\nu_0} \right)^t$$

- t, the number of terms can be chosen with *nterms* parameter
- The equations can be rewritten to provide
  - Spectral index with *nterms*=2
  - Spectral curvature with *nterms*=3

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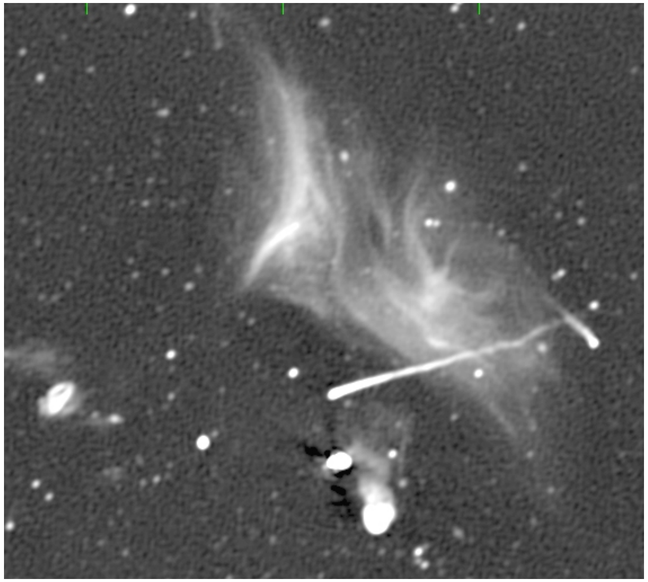
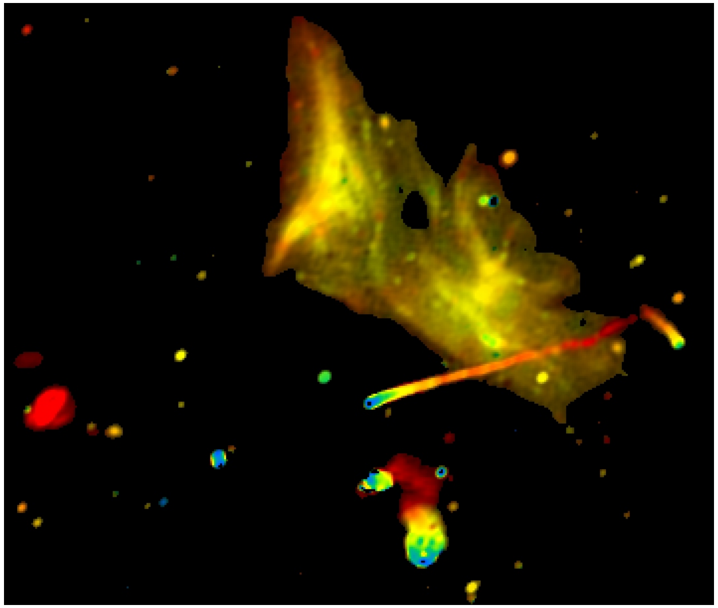
Wideband cleaning MSMFS:

- Example: A2256

Intensity



Spectral Index



Images: F. Owen

Continuum Imaging: *clean*

Wide-band wide-field imaging

- Primary beam also varies with frequency
- Steepening of spectral index towards edge of beam
- widebandpbcorr will apply primary beam correction to Taylor terms (including flux, spectral index, curvature, ..)
- (regular primary beam correction: imbpcor)

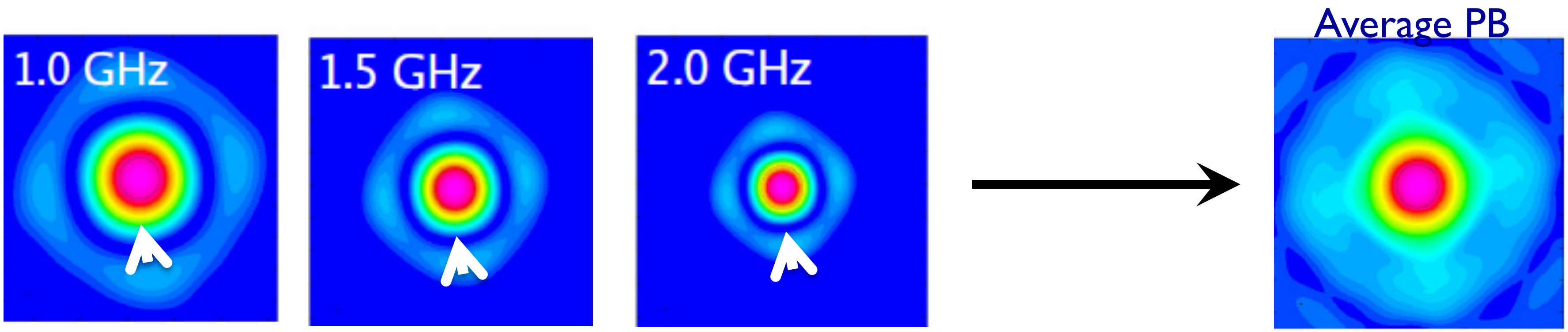
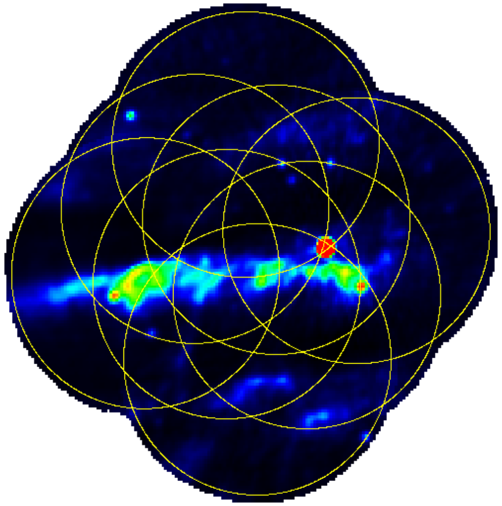


Image credit: U. Rao

Imaging: *clean*



Mosaicking

- Combine multiple pointings on the sky
- 3 basic methods:
  - Image and clean each pointing separately, then combine
  - → linearmosaicking (lm) Tool
  - Image separately, then perform a combined deconvolution (imagermode='mosaic' ftmachine='ft')
  - Combine in uv-domain, FT, clean full mosaic (imagermode='mosaic' ftmachine='mosaic')

  - Images still require primary beam correction (impbcor) using *image.pbcoverage*

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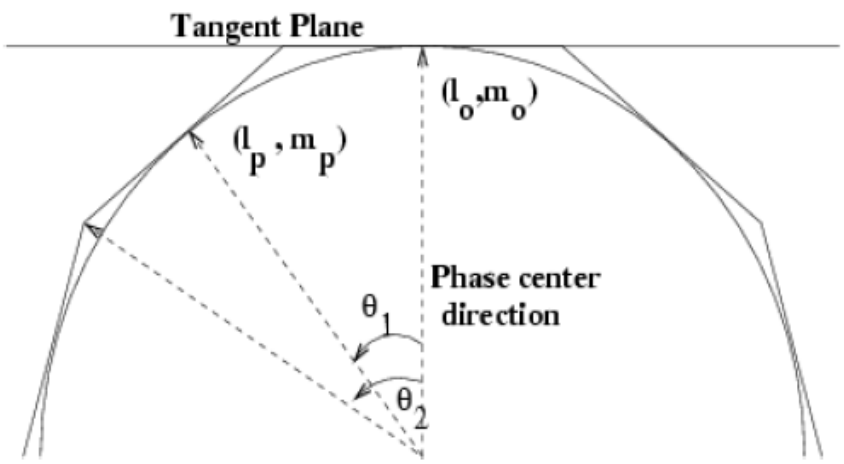
W-projection

- W-projection is a method to correct for non-coplanarity of the sky (regular imaging assumes it is flat)
- Needed for fovs > primary beam or $$\frac{\lambda_{max} B_{max}}{D^2} > 1$$
  (λ: wavelength, B: baseline length, D: dish diameter)
- Faceting: describes the sky curvature by many smaller planes
- Number of facets:

$$N_{poly} \approx 2\theta_{FoV}^2 \frac{B_{max}}{\lambda_{max}} = \frac{2B_{max}\lambda_{max}}{[fD]^2}$$

Example:
VLA A-config
1.0GHz
N>34

f=1 for critical sampling.
f<1 for high dynamic range



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Outlier Fields

- When sources are outside the image but are bright enough to throw sidelobes on the main field, they need to be cleaned
- To be cleaned, they need to be imaged, but the required images could be very large

- Solution: outlier fields
  - User provides positions of those sources (e.g. from all-sky catalogs)
  - Clean will cycle through all fields and subtract the part of the psf that is observed in each field
  - May need to set a large threshold to begin to clean outliers first

Imaging: *clean*

Images produced

- Imagename.model (clean components in Jy/pixel in a cube)
- Imagename.residual (residual image after all components are subtracted; Jy/dirty beam)
- Imagename.image (model x clean beam + residual; expressed in Jy/clean beam)
- Imagename.mask (mask)
- Imagename.flux ([mosaicked] normalized sensitivity map / for single pointing: primary beam response)
- Imagename.pbcoverage (mosaicked primary beams per pointing, use for impbcorr)

- Restarting clean with same imagename will continue cleaning where it left off (if parameters such as image and cell size match)
- To start a new clean remove old files first with rmtables('imagename.*') (rm –rf may keep images in memory)

Imaging: *clean*

Clean tips:

- Clean is writing the model data to the MS. This can be done either as an image (*usescratch=F*) or directly as visibilities (*usescratch=T*)
- Try to avoid CNTRL+C while cleaning. When the model is being written to the MS but interrupted, it can corrupt your MS!
- Some image sizes will compute faster than others, sometimes even larger ones. Rule of thumb for good *imsize* is $10*2^n$ (but clean will suggest good *imsize* when bad numbers are being used)
- Choose a pixel (*cell*) size that is at most ~1/4 the size of the psf minor axis
- dirty image: *niter=0* (*niter=1* if you want a clean beam)
- If you need a model convolved with clean beam, subtract the residual from the combined image

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Imaging: *clean*

Clean tips:

- The CASA logger will report *cleaned and residual peak fluxes*. Good cleaning will increase the cleaned flux and decrease the residual peak. When the numbers oscillate, you may have cleaned into the noise, stop beforehand
- Clean threshold will prevent deep cleaning into the noise (typically used ~2.5σ); use high *niter* so that the threshold limits the cleaning
- An FFT of the image (*ia.fft* tool) can be used to assess how well clean performed. A good clean should interpolate well between measured uv-points
- Mosaicking (Ekers-Rots theorem) and multiscale both help to reduce the missing short spacings issue/negative bowls
- Note that your residual has units of *Jy/[dirty beam]* and your model x Beam *Jy/[clean beam]*. Apply flux corrections if needed (Jörsäter & van Moorsel 1995)

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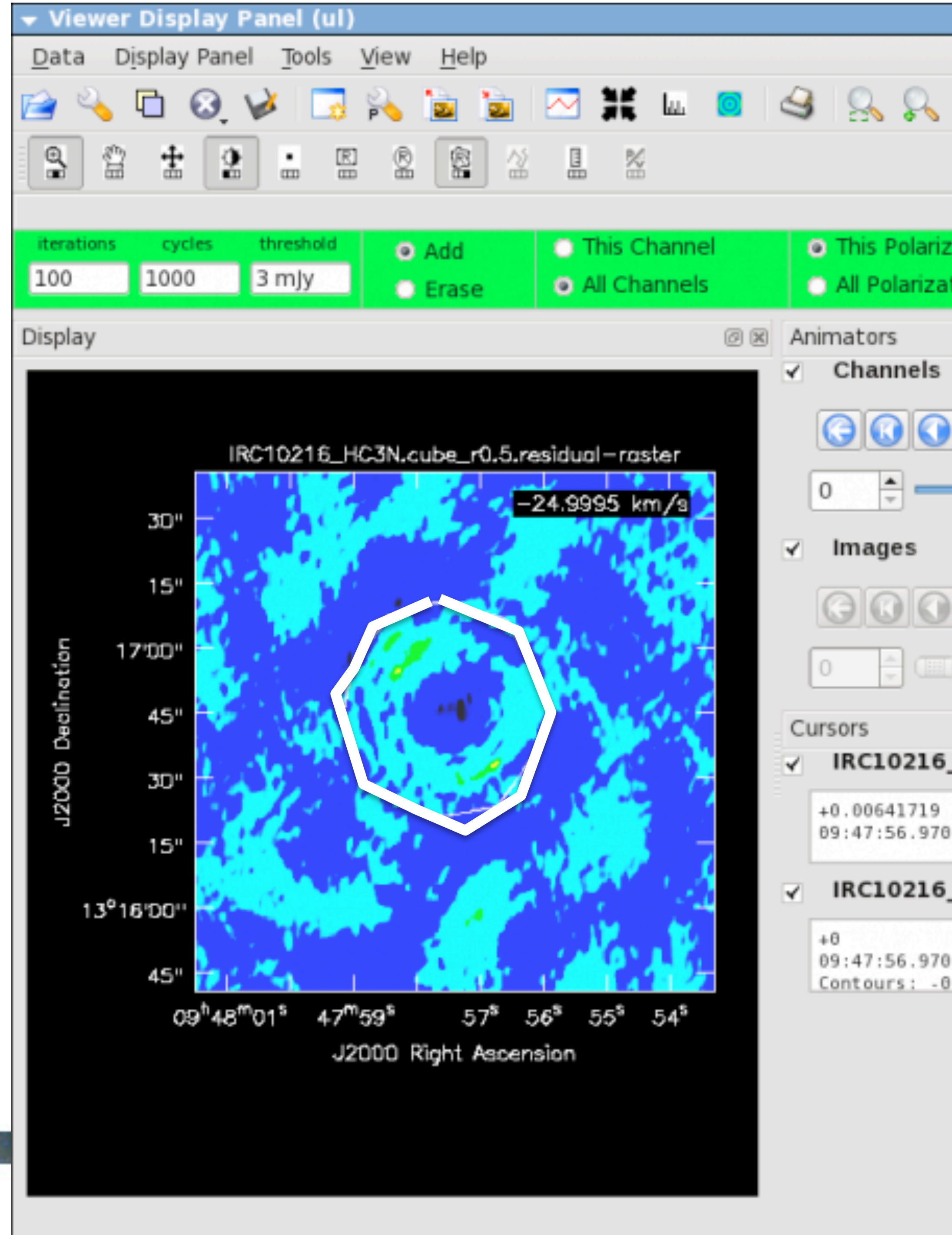
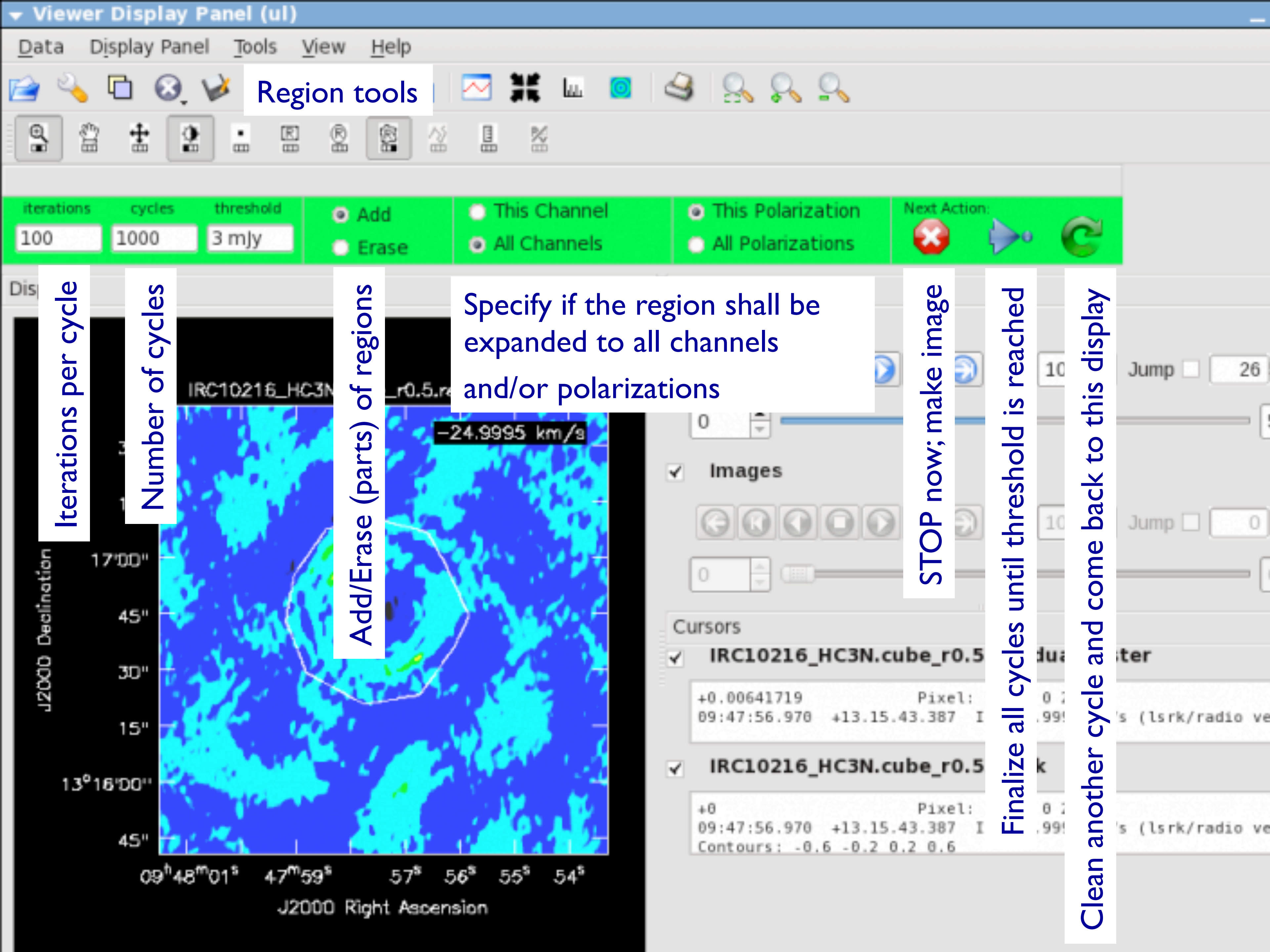
Imaging: *clean*

interactive=T cleaning

- Invokes the viewer with the residual image
- Cleaning regions (masks) can be made for each spectral channel if needed
- If no mask is specified, cleaning is *not* performed (only in interactive mode)




Viewer Display Panel (ul)
Data
Display Panel
Tools
View
Help
Region tools
iterations
cycles
threshold
100
1000
3 mJy
Add
Erase
This Channel
All Channels
This Polarization
All Polarizations
Next Action:
Iterations per cycle
Number of cycles
Add/Erase (parts) of regions
Specify if the region shall be expanded to all channels and/or polarizations
STOP now; make image
Finalize all cycles until threshold is reached
Clean another cycle and come back to this display
-24.9995 km/s
J2000 Declination
J2000 Right Ascension
Images
Cursors
Jump
Contours: -0.6 -0.2 0.2 0.6

Imaging: *tclean*

tclean is an improved *clean* task.

- more logical interface
- additional parameters such as options to write output files
- Parallelization (both continuum and spectral line)
- AW projection: correct for W-term and also for beam rotation on the sky (A-projection)
- *nterms>1* for mosaics
- Hooks for autoboxing algorithms
- Outlier field flexibility (e.g. different gridding,, *nterms*)
- Better output (includes theoretical rms)

Image/Data combination: *clean+feather*

To combine VLA arrays:

- run statwt on each dataset to adjust the weights
- *Clean* the datasets together

To add single dish (make sure the SD header complies, in particular it has to be in units of Jy/beam):

- Use SD image as *modelimage* in *clean* to be a starting model for interferometric data, the model retains short spacings from SD image
- Use feather (or casafeather GUI) to combine a high-resolution image (typically interferometric) with low-resolution image (SD) in the Fourier domain
- SD data will define the total flux of your image and remove negative bowls

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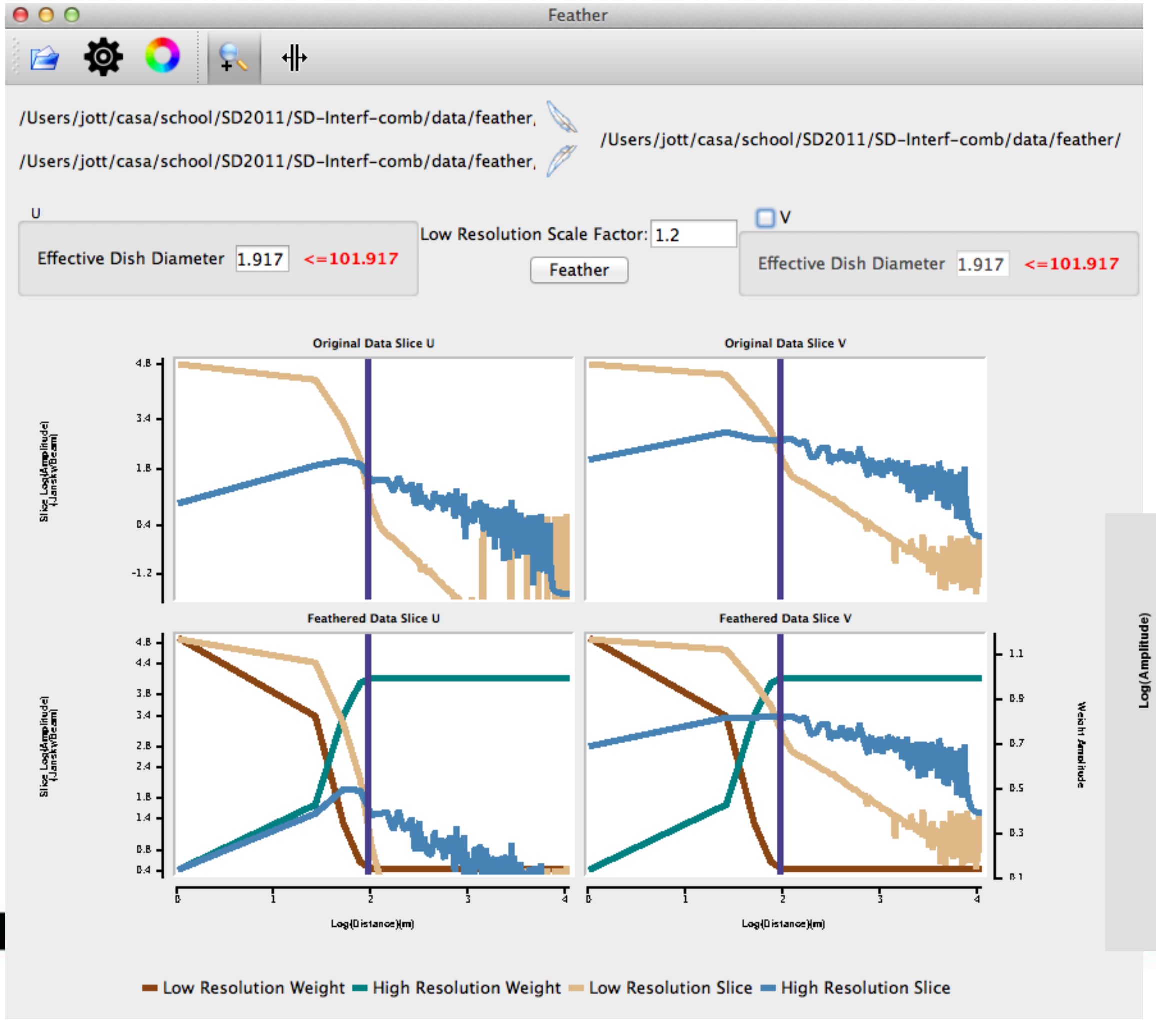
Image/Data combination: *clean+feather*

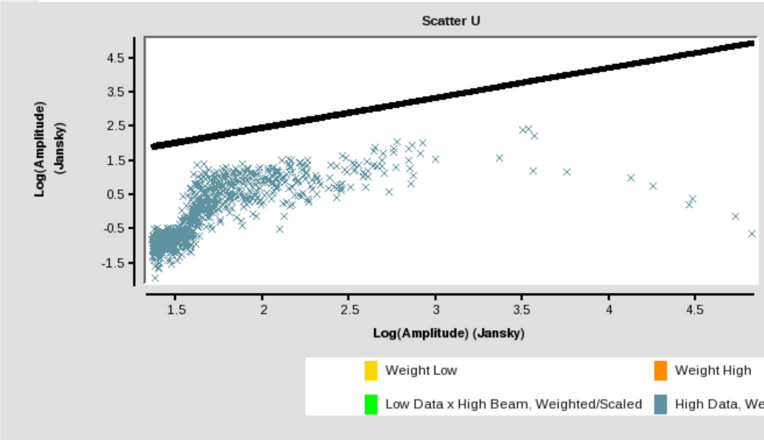
Image combination

Example feather



Works in *Fourier domain*

- FFT SD, apply PB(SD) as weight
- FFT *cleaned* interferometric image, apply 1-PB(SD) as weight
- Adjust calibration differences
- Add
- FFT^{-1}



Image/Data: *clean+feather*

Image combination

Example feather

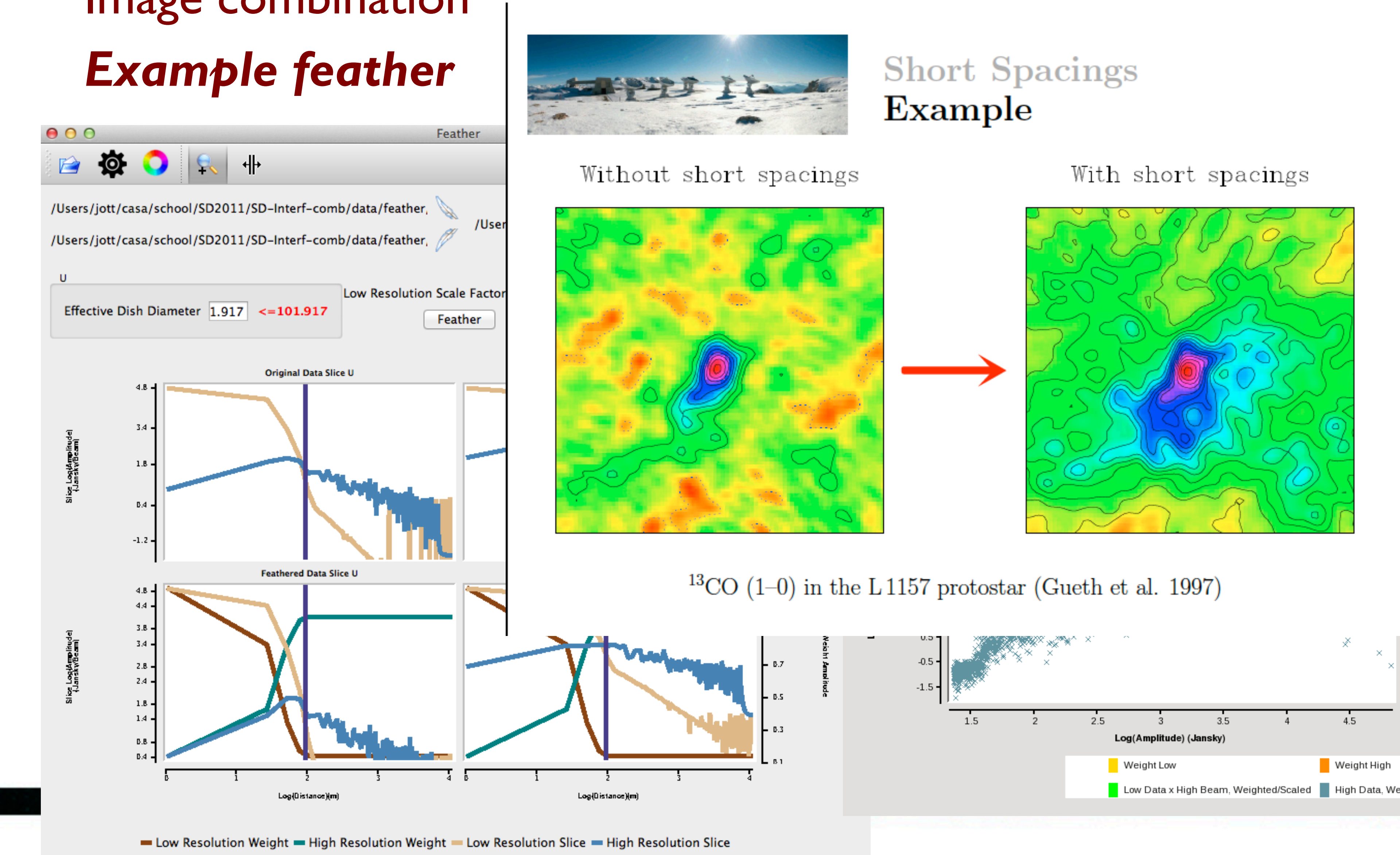


Image Viewer

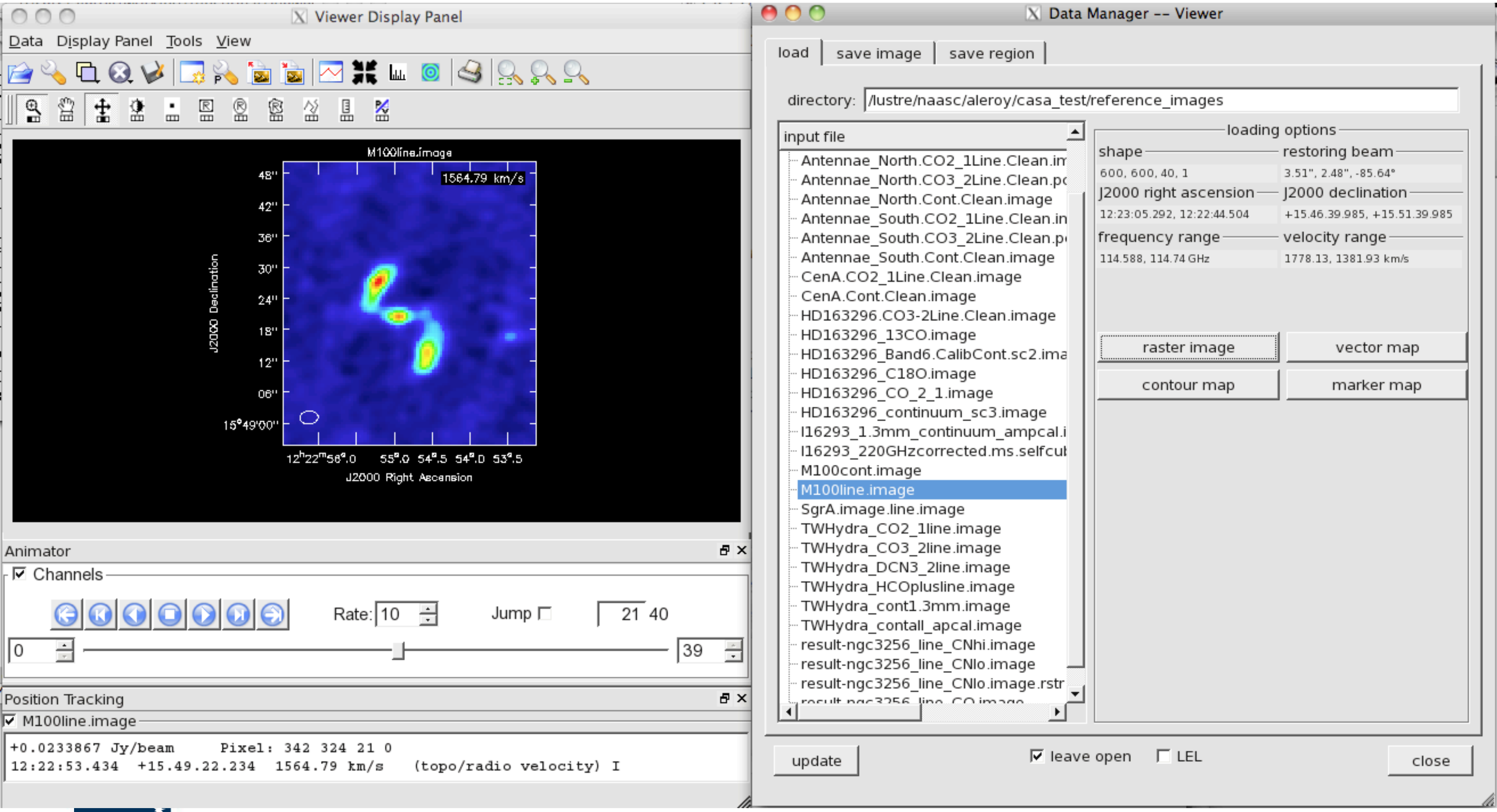


Image Viewer

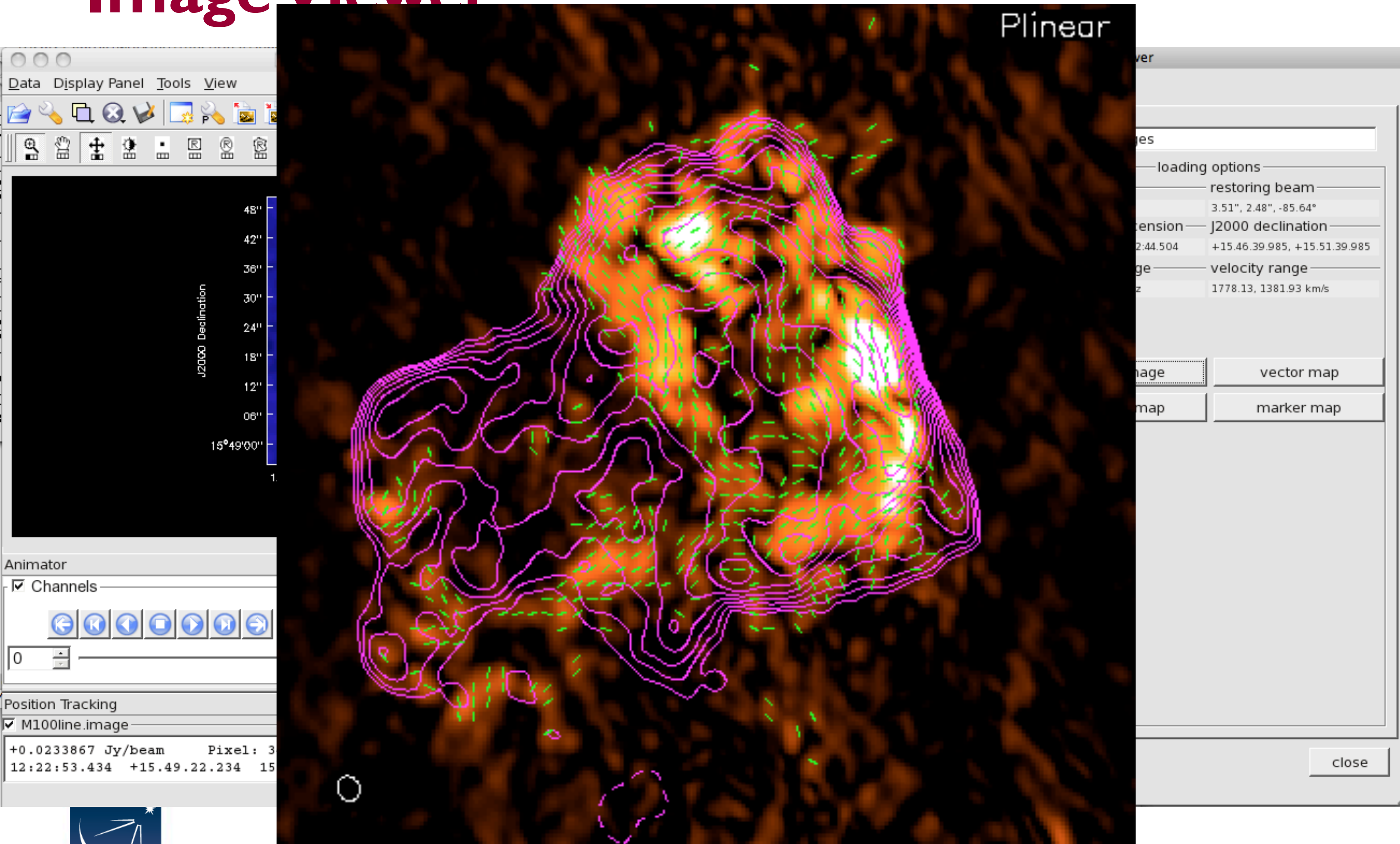
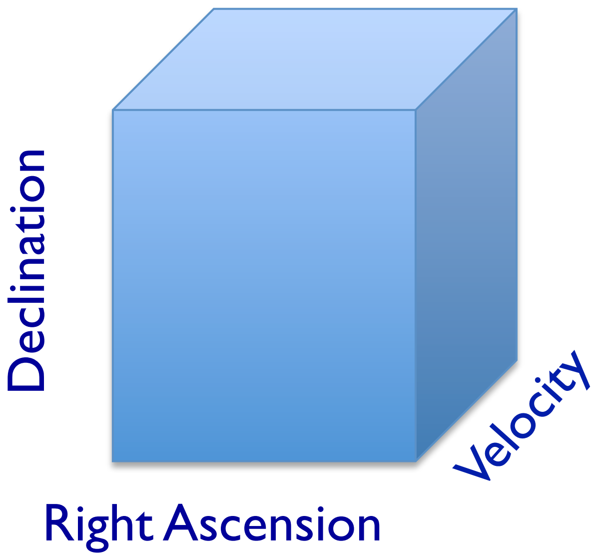


Image Viewer

- Displaying cubes
- Movies
- Channel maps



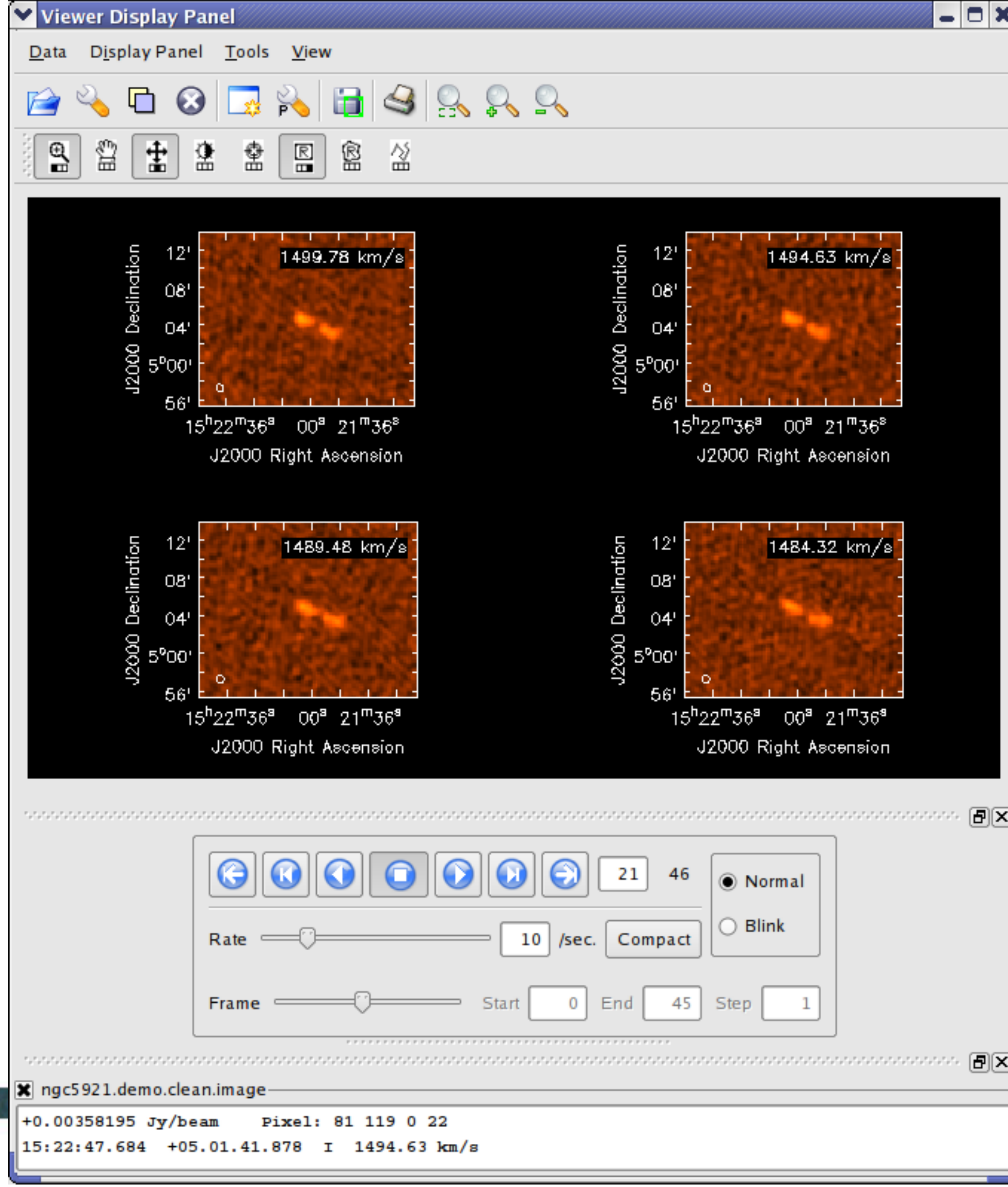


Image Viewer

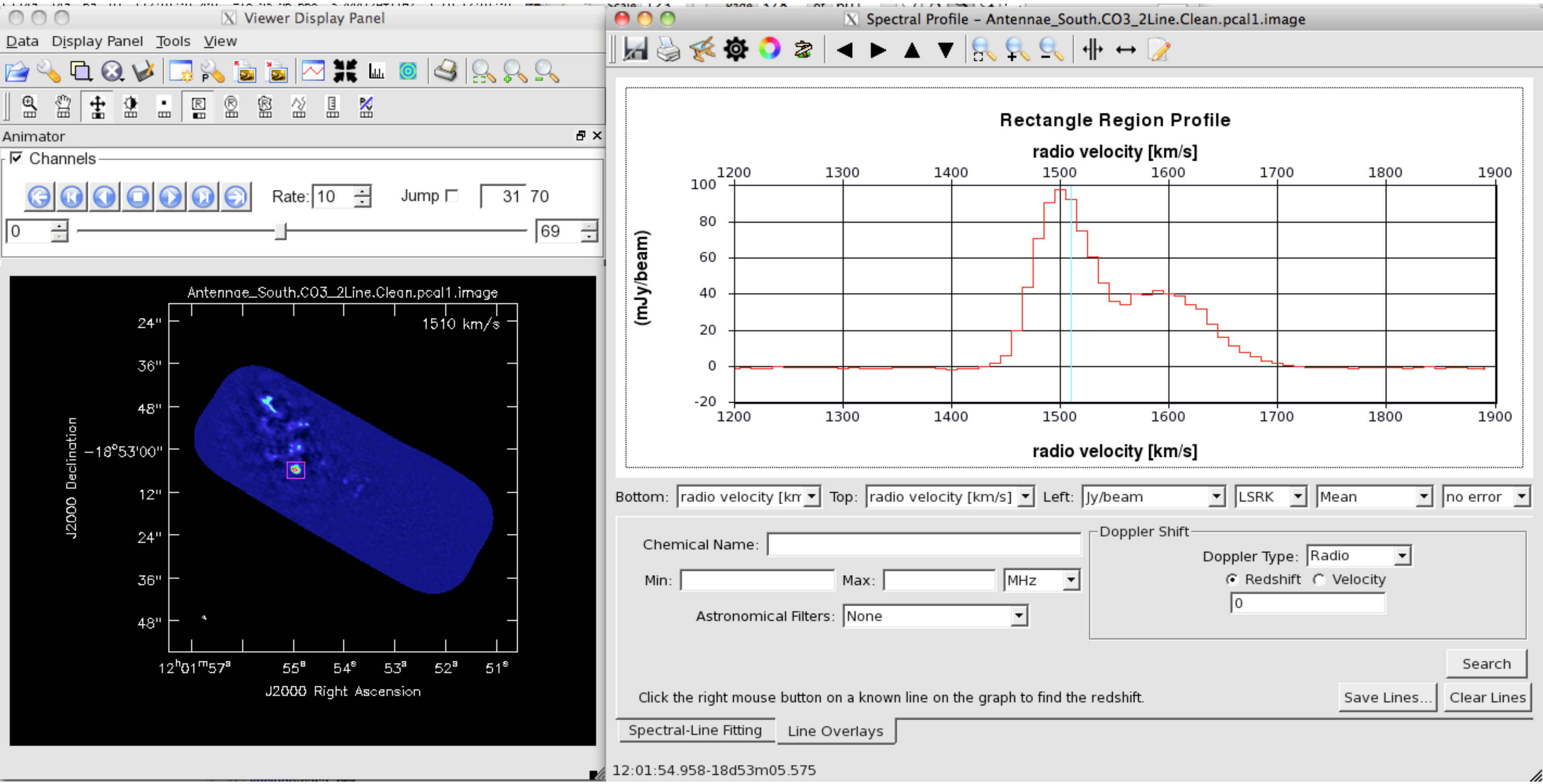


Image analysis

Image analysis tasks can frequently performed in both, a task or in the viewer, these tasks also accept changing psf per plane.

- **immoments**: create moment maps of spectral cubes

  includes:
  - integrated intensity (moment 0)
  - intensity-weighted mean velocity (moment 1)
  - intensity-weighted velocity dispersion (moment 2)
  - plus many other modes like peak intensity map, median, etc (which are mathematically not moments)
  - Can exclude some pixel ranges
  - Can calculate many moments in one execution

Image analysis

- **imcontsub:** image-based continuum subtraction
  - Calculates continuum per pixel through a polynomial
  - Subtracts from image
  - Creates a continuum and a line-only image

- **immath:** mathematical operations on images
  - Calculates any mathematical expression, e.g. IM0+exp(IM1*200)
  - Has modes to calculate spectral index, polarization position angle, polarized intensity images
  - Uses *LEL* language:
    - Mathematical expression on images
    - Also used for thresholds (e.g. 'IM0>0.1Jy')
    - Boolean operators (e.g. 'IM0>0.1Jy && IM1!=0')
    - Conditions (e.g. 'IM0[IM1>0.1Jy] / IM1')
    - Special functions (e.g. SPECTRALINDEX, amp, ..)

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Image analysis

- **impv:** Position Velocity diagrams

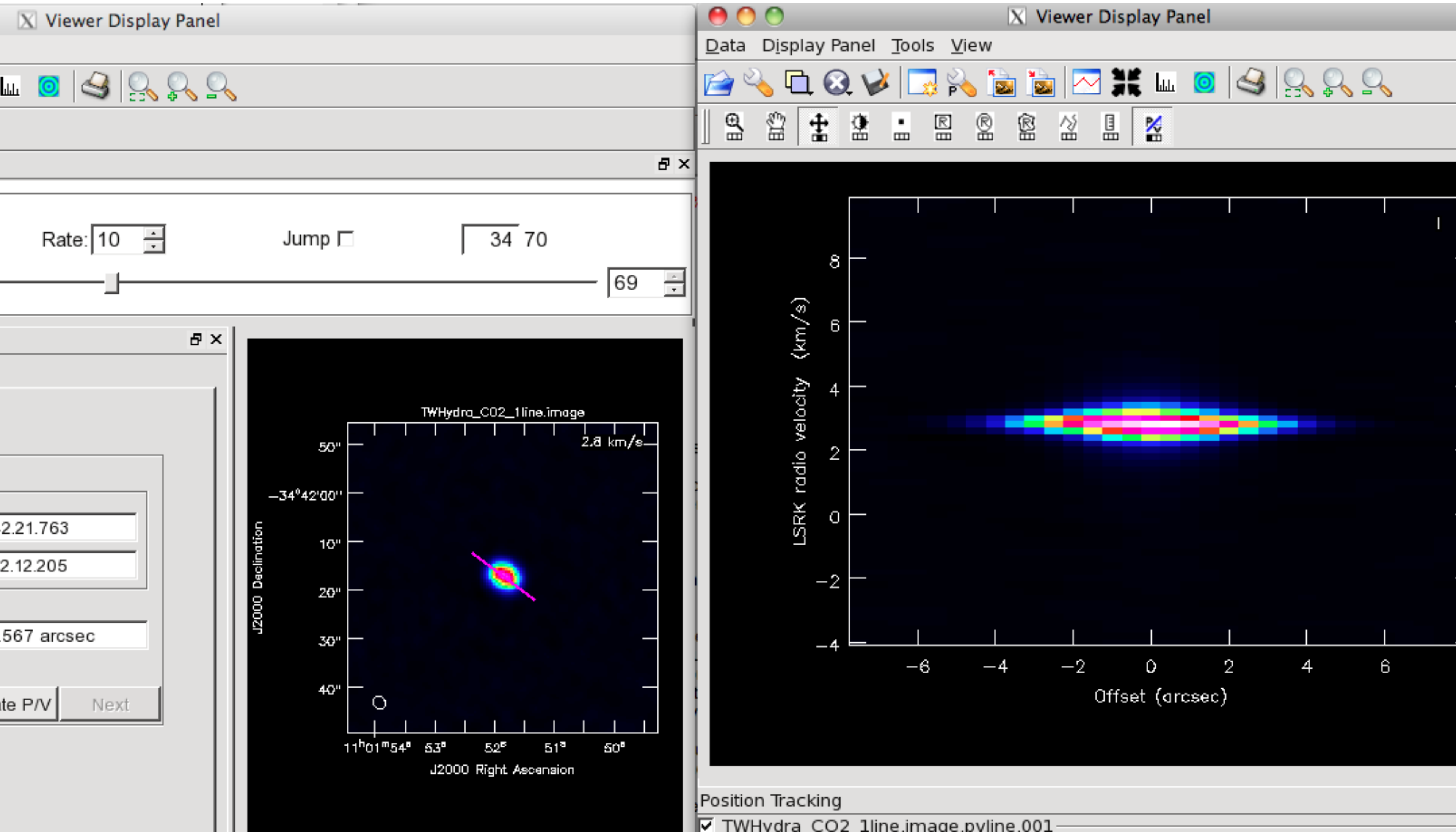

Image analysis

- **specfit**: fits 1-dimensional Gaussians and/or polynomial models to an image or image region, typically along the spectral axis
  - Can fit multiple Gaussian multiplets with constraints
  - Can be per pixel → images of amp, fwhm, center velocity for each Gaussian component

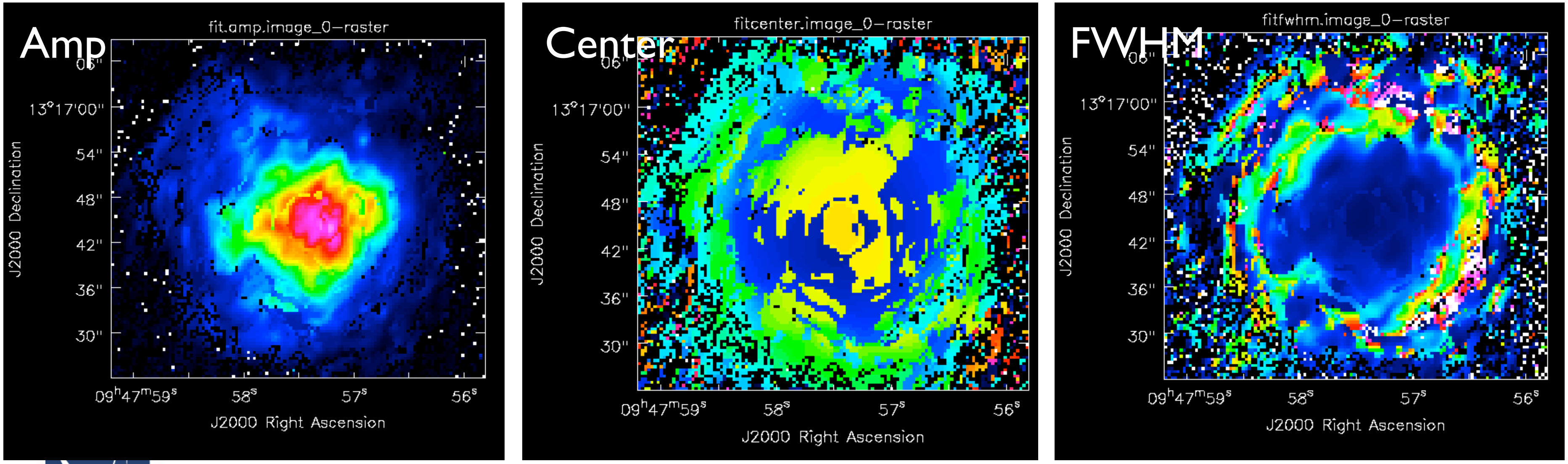

Image analysis

- **imfit**: fit one or more spatial elliptical Gaussian components to sources
  - ia.findsources can be used for source detection
- **imstat**: image statistics, many robust methods are available
- **imregrid, imtrans, imreframe:** transform image coordinates spatially and spectrally
- **imrebin, imsubimage**: change image/pixel size
- **rmfit, spxfit:** calculation of rotation measures and spectral indices
- **imval**: dump out the data into a python dictionary

- Many image analysis tasks return python dictionaries, use as
  - **data=imval('image')** to assign the python dictionary output to a variable (here: 'data')
- Use the power of python! Once the data is available as a python dictionary only the sky (well, the universe..) is the limit of your data analysis!

Images: Golap, Marvil, Maercker, Ott, Owen, Brogan