Introduction to Imaging in CASA

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With contributions from Amanda Kepley, Crystal Brogan, David Wilner, Urvashi Rau, and others

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Goals of this talk

- Gain some intuition for interferometric imaging
- Delve into the theory underlying the imaging process.
- Tour of main deconvolution task in CASA: tclean

From Sky Brightness to Visibility

1. An interferometer measures the interference pattern observed by pairs of apertures
2. The interference pattern is directly related to the source brightness. In particular, for small fields of view, the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)

   (van Cittert-Zernike theorem)

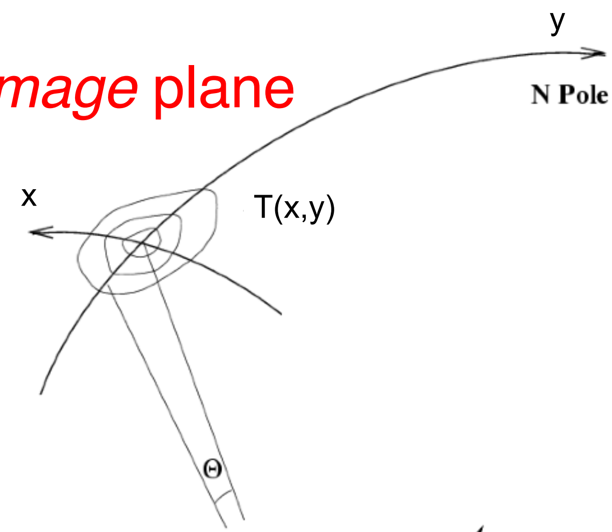
Fourier space/domain

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

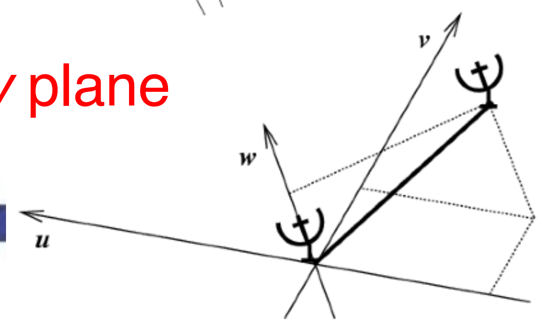
$$T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$$

Image space/domain

image plane



uv plane



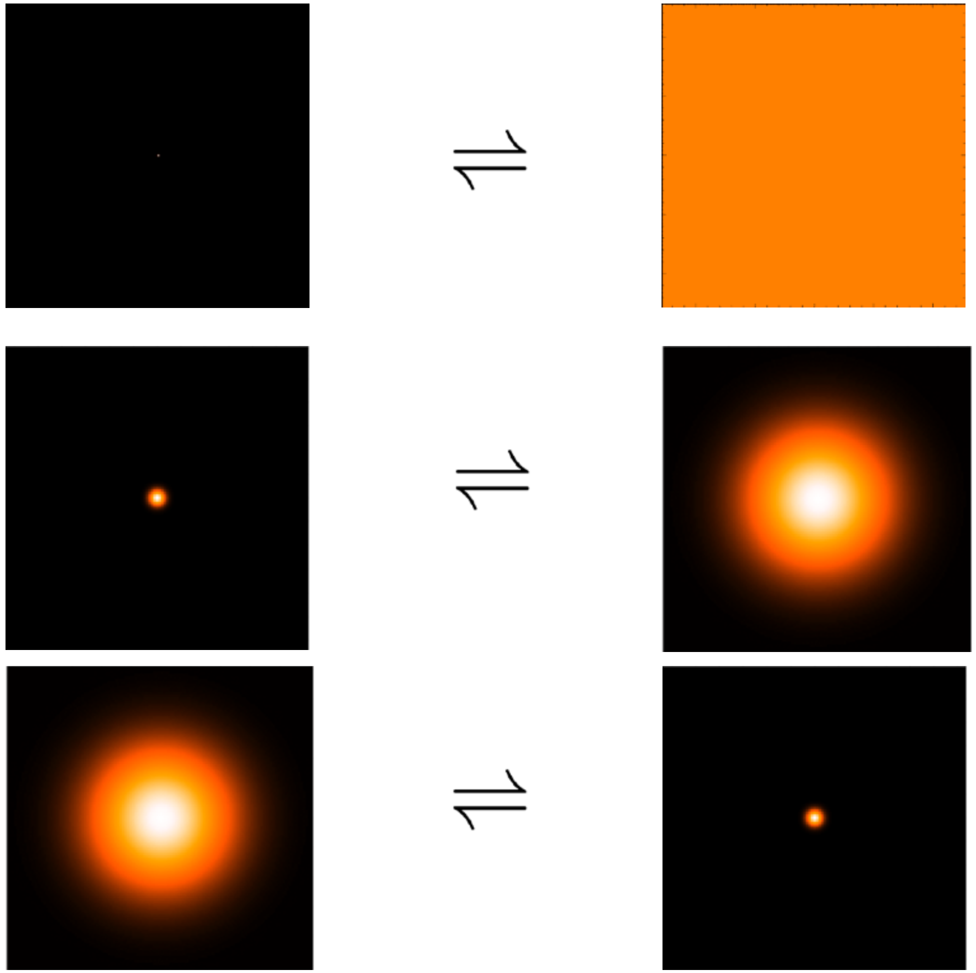
Some 2D Fourier Transform Pairs

T(x,y) | Amp{V(u,v)}

δ Function | Constant

Gaussian | Gaussian

Gaussian | Gaussian

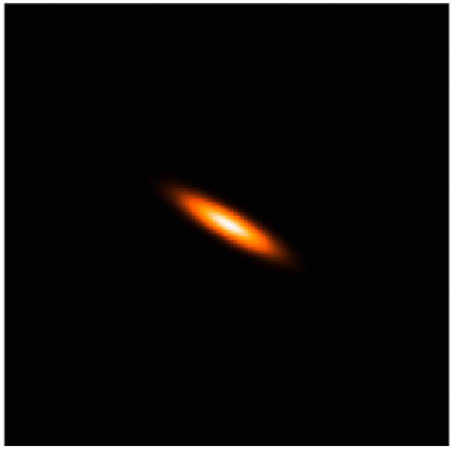


narrow features transform to wide features (and vice-versa)

More 2D Fourier Transform Pairs

T(x,y) | Amp{V(u,v)}

elliptical Gaussian

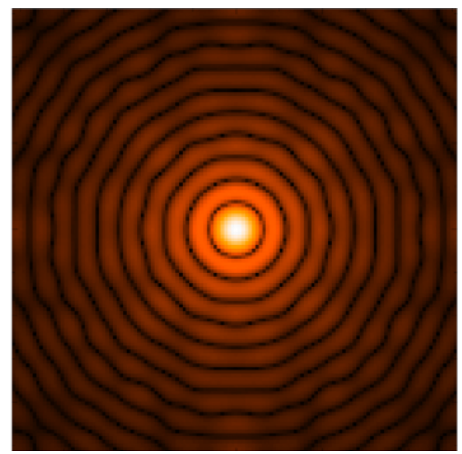


⇌

elliptical Gaussian

Disk

⇌

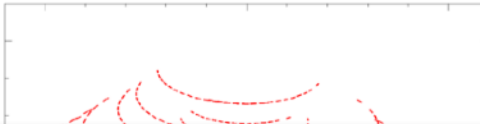


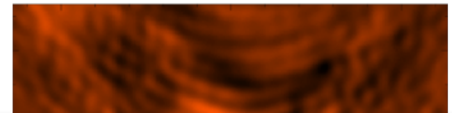
Bessel

sharp edges result in many high spatial frequencies

(sinc function, “ringing”, Gibbs phenomenon)

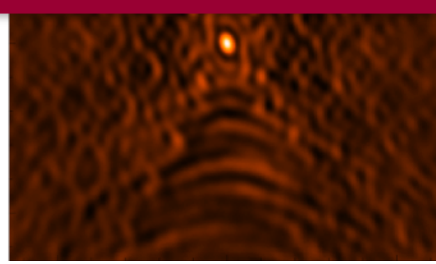
The observed (AKA dirty) image is the true image convolved with the PSF.



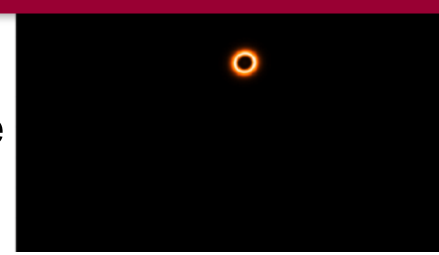


- Fourier transform of sampled visibilities yields the true sky brightness convolved with the point spread function (“dirty beam”).
- You need to deconvolve the PSF from the dirty image to reconstruct the source. A commonly used way to do this is called cleaning.

b(x,y)
(dirty beam or psf)



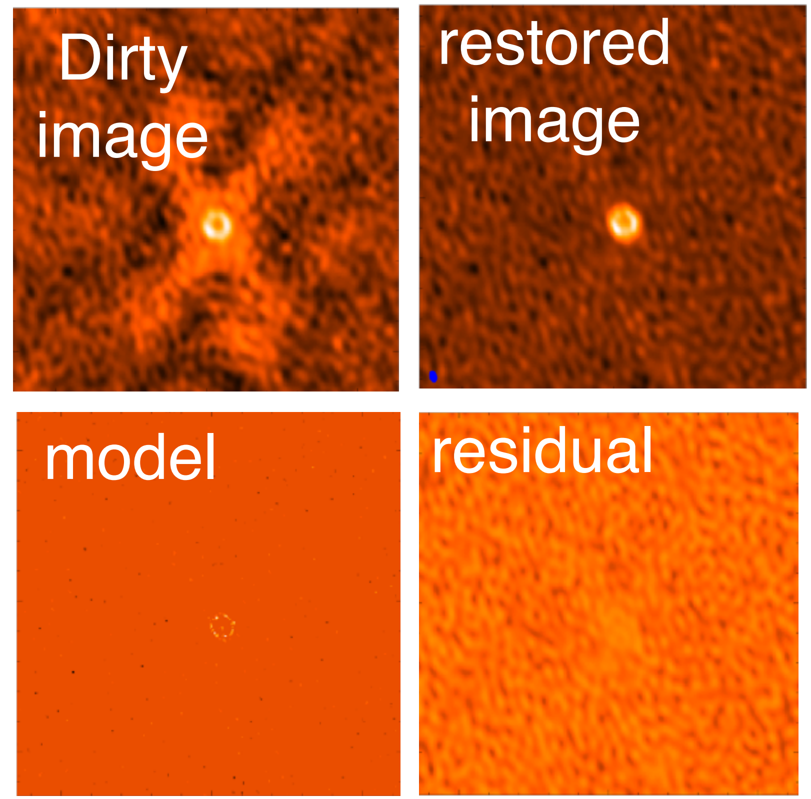
⊗
Convolve



T(x,y)
(True sky brightness)

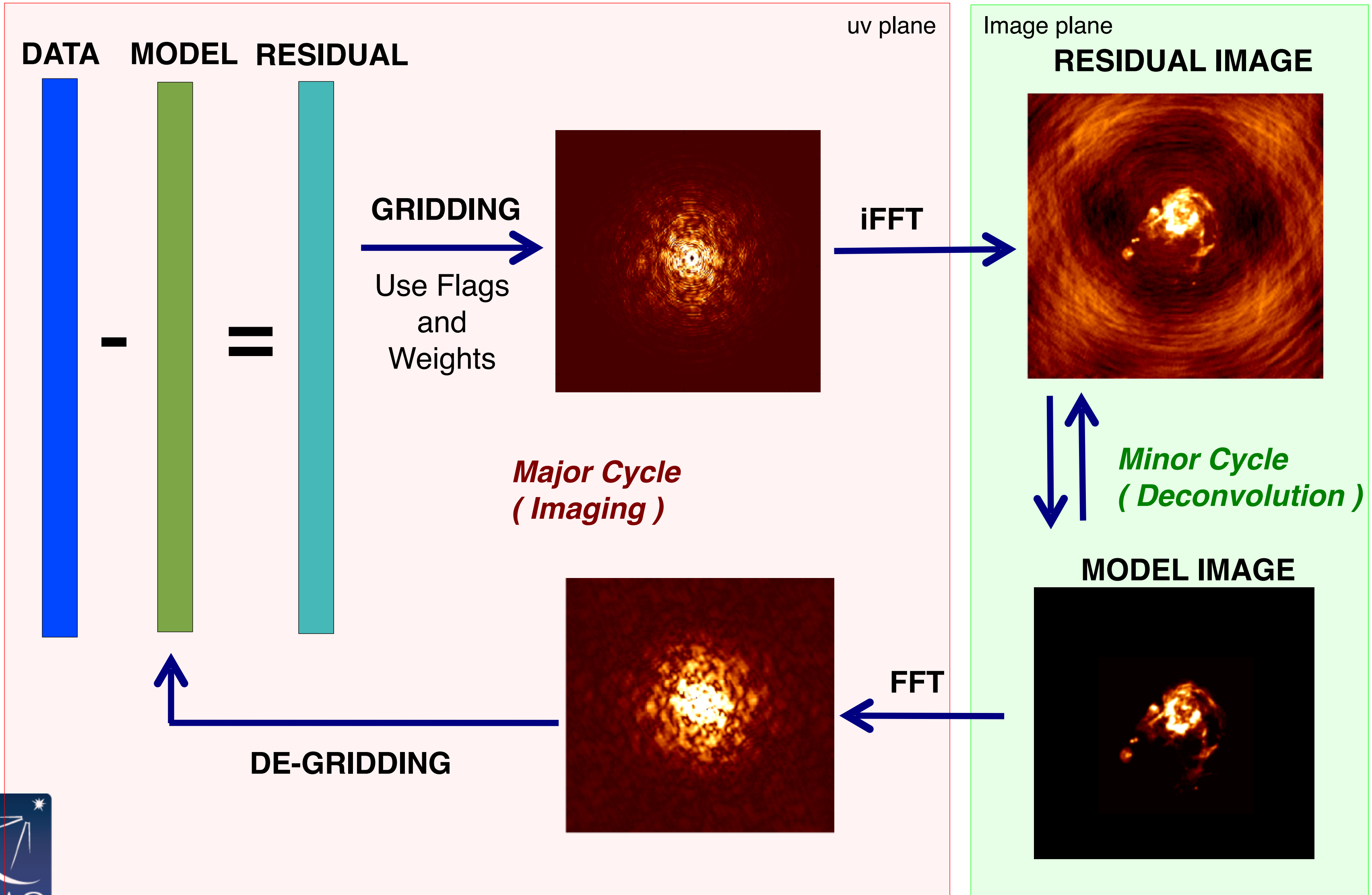
Clean is the most common deconvolution algorithm.

Build up model of data that you convolve with the dirty beam/PSF and add noise to that you compare with the observed data.



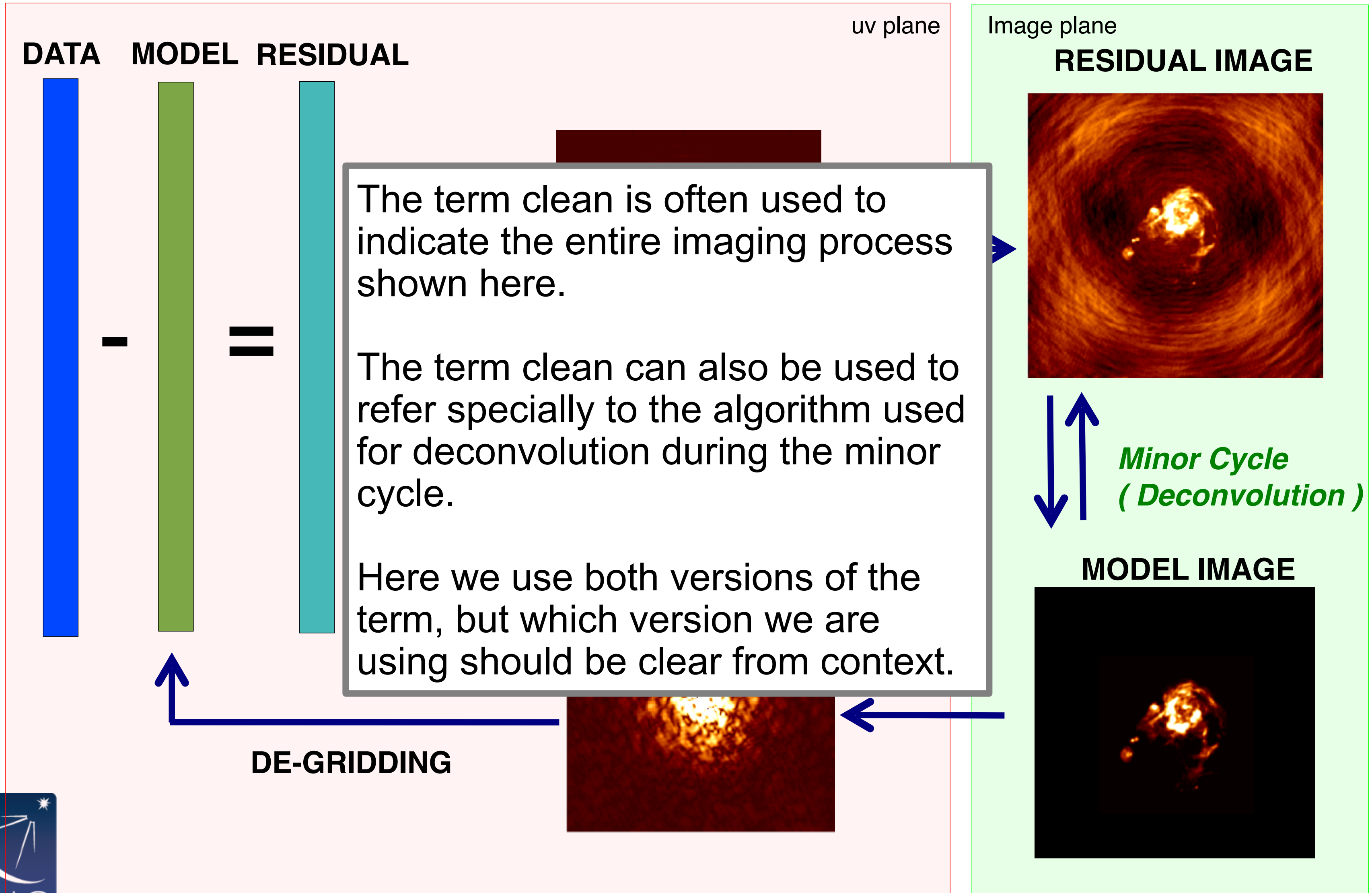
Adapted from slide by Urvashi Rau

This is an iterative process where the data is gridded, deconvolved, and de-gridded.



Slide courtesy Urvashi Rau

A note on terminology

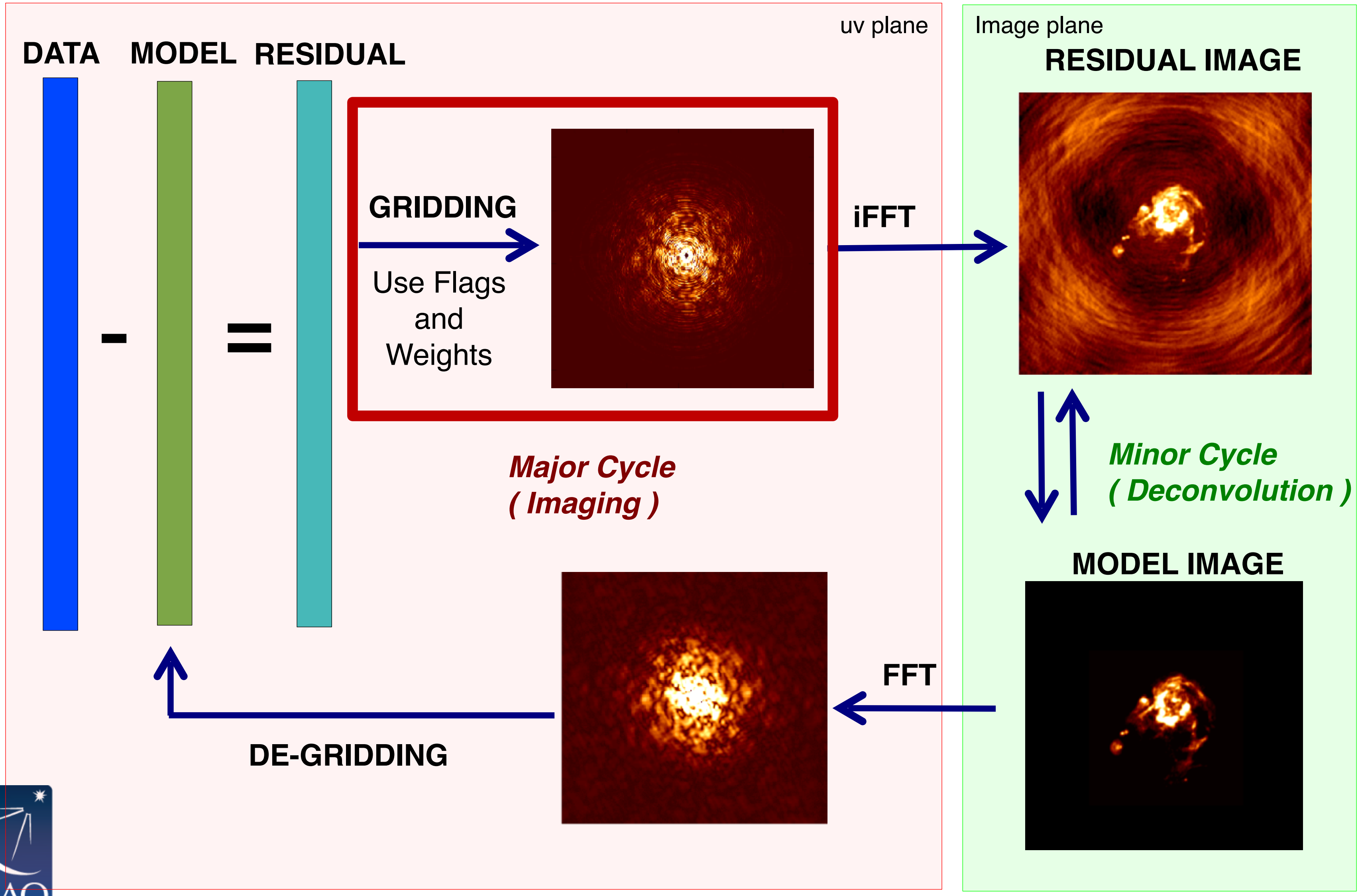


The term clean is often used to indicate the entire imaging process shown here.

The term clean can also be used to refer specially to the algorithm used for deconvolution during the minor cycle.

Here we use both versions of the term, but which version we are using should be clear from context.

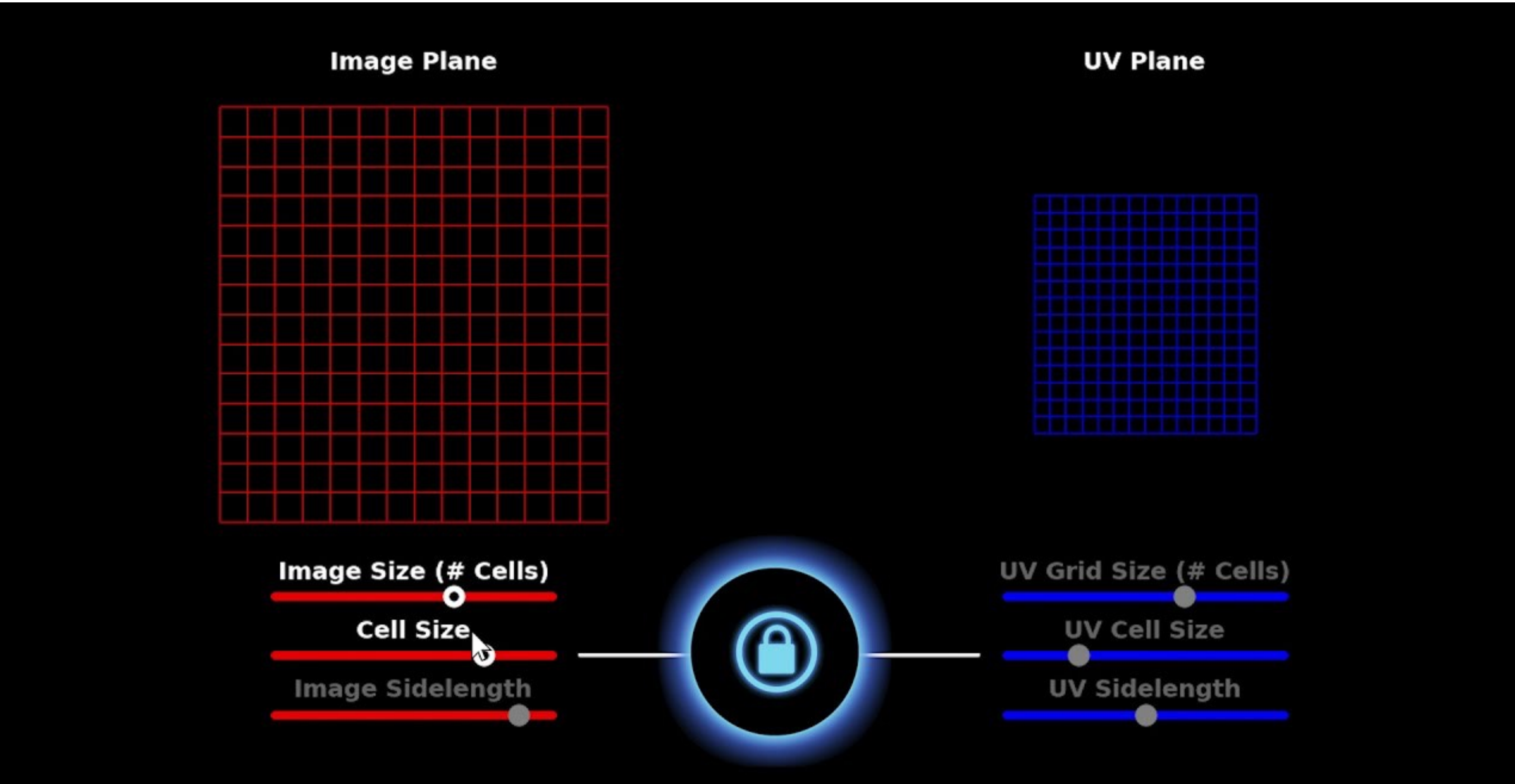
The gridding step requires pixel and image size as well as weighting scheme.



Gridding: Pixel and Image Size

Image size $\propto$ FOV UV plane

FOV image $\propto$ Cell size UV plane



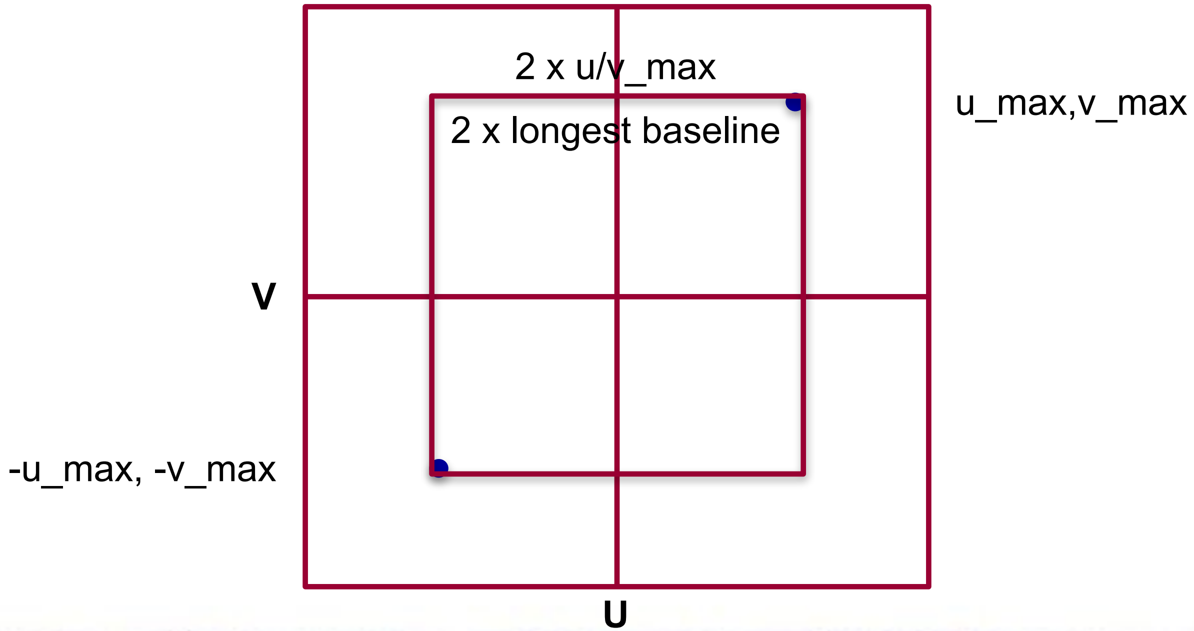
ALMA Primer: https://www.youtube.com/watch?v=hqhZ7g9lJSE

Gridding: Pixel and Image Size

- pixel size: satisfy sampling theorem for longest baselines

$$\Delta l < \frac{1}{2u_{max}} \qquad \Delta m < \frac{1}{2v_{max}}$$

  - in practice, 5 to 8 pixels across dirty beam main lobe to aid deconvolution
  - Beam size [arcsec] = 206265.0/(longest baseline in wavelengths)



Video: https://www.youtube.com/watch?v=OC3IWpRRtEQ&ab_channel=ALMAPrimer

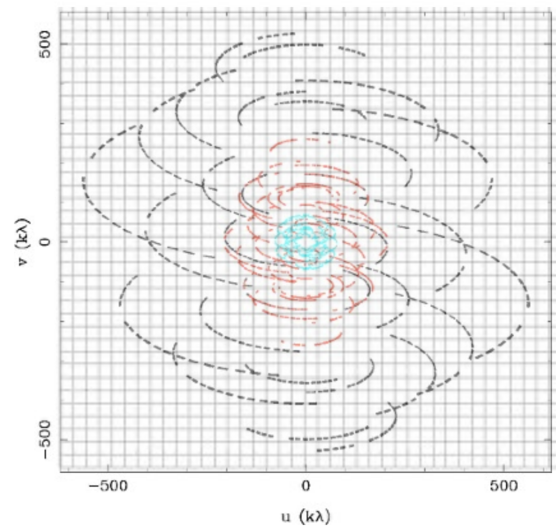
Gridding: Pixel and Image Size

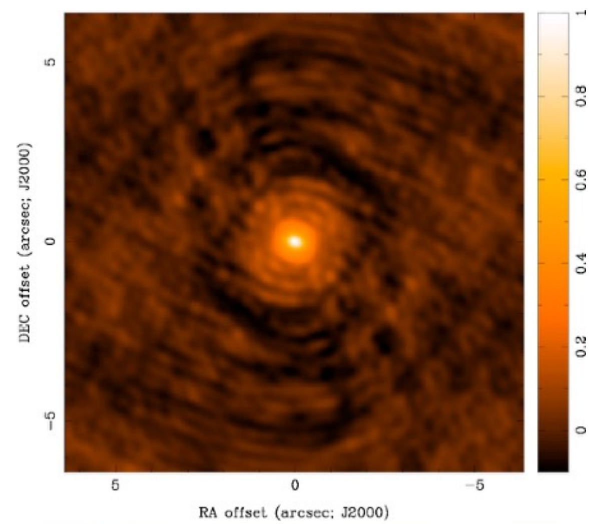
- image size: natural choice often full primary beam *A(l,m)*
  - For single fields:
    - 12m : FOV[arcsec] = 6300 / nu[GHz]
    - 7m: FOV[arcsec] = 10608 / nu[GHz]
    - nu[GHz] is the sky frequency.
  - For mosaics:
    - You can get the imsize from the spatial tab of the OT. The parameters "p length" and "q length” to specify the dimensions of the mosaic. If you're imaging a mosaic, pad the imsize substantially to avoid artifacts.

Gridding: Visibility Weighting

- introduce weighting function *W(u,v)*
  - modifies sampling function
  - $S(u,v) \rightarrow S(u,v)W(u,v)$
  - changes *s(l,m)*, the dirty beam

- "natural" weighting
  - $W(u,v) = 1/\sigma^2$ in occupied cells, where σ^2 is the noise variance
  - maximizes point source sensitivity
  - lowest rms in image
  - generally gives more weight to short baselines, so the angular resolution is degraded

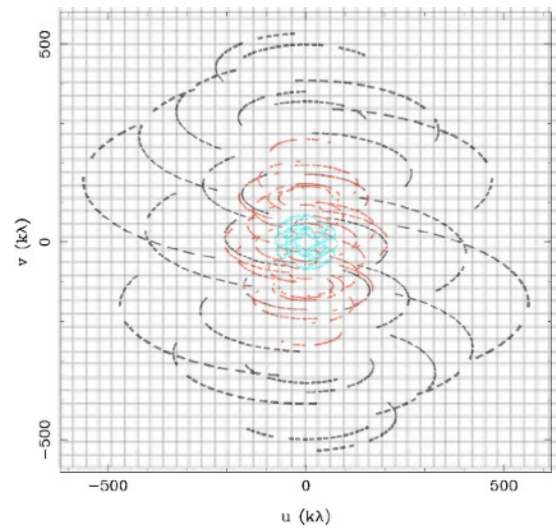


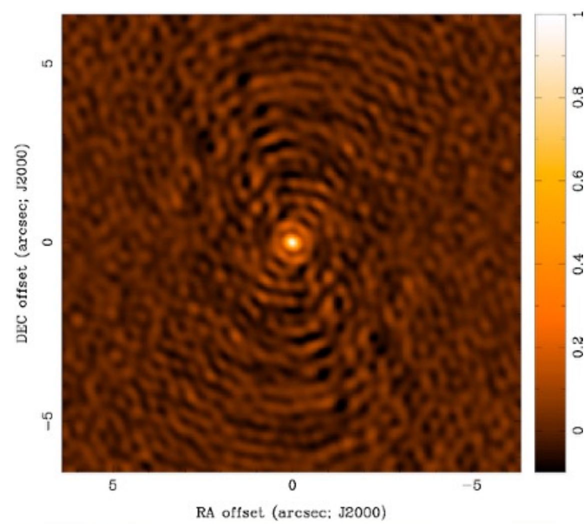


Slide courtesy David Wilner

Gridding: Visibility Weighting

- "uniform" weighting
  - *W(u,v)* inversely proportional to local density of *(u,v)* samples
  - weight for occupied cell = const
  - fills *(u,v)* plane more uniformly and dirty beam sidelobes are lower
  - gives more weight to long baselines, so angular resolution is enhanced
  - downweights some data, so point source sensitivity is degraded
  - can have trouble with sparse *(u,v)* coverage: cells with few samples have same weight as cells with many
  - rarely used in practice because of this.





NRAO

Slide courtesy David Wilner

Gridding: Visibility Weighting

- "robust" (or "Briggs") weighting
  - variant of uniform weighting that avoids giving too much weight to cells with low natural weight
  - software implementations differ
  - e.g. $W(u,v) = \dfrac{1}{\sqrt{1 + S_N^2 / S_{thresh}^2}}$

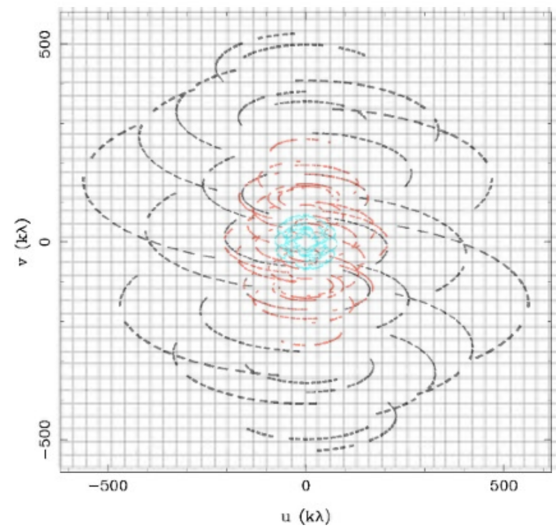
    S_N is cell natural weight

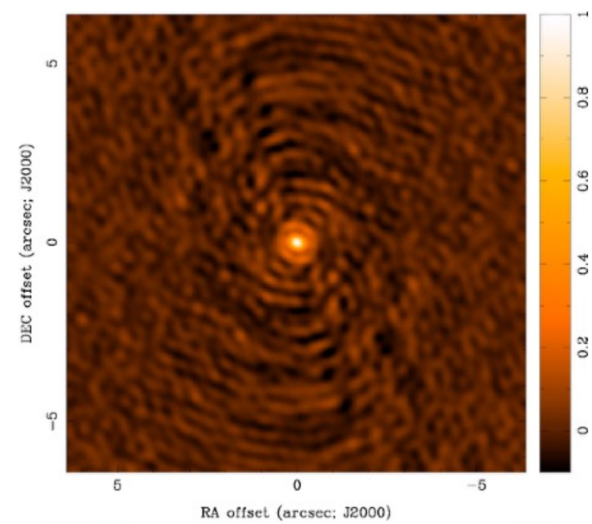
    S_{thresh} is a threshold

    high threshold → natural weight

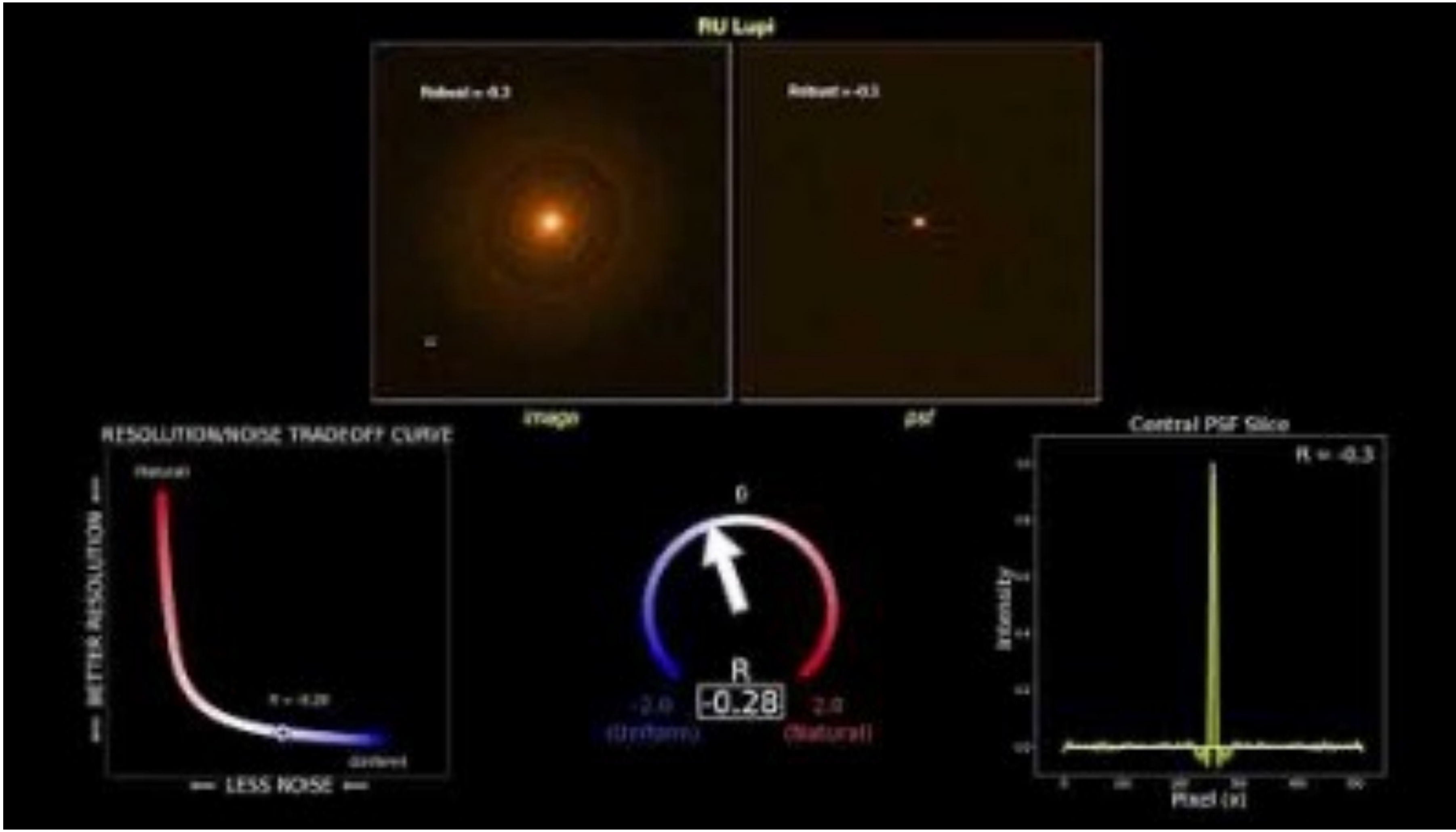
    low threshold → uniform weight

- *an adjustable parameter allows for continuous variation between maximum point source sensitivity and resolution*
- **Use of robust < 0.0 not recommended.**





Weighting Visualization



https://youtu.be/hqhZ7g9IJSE

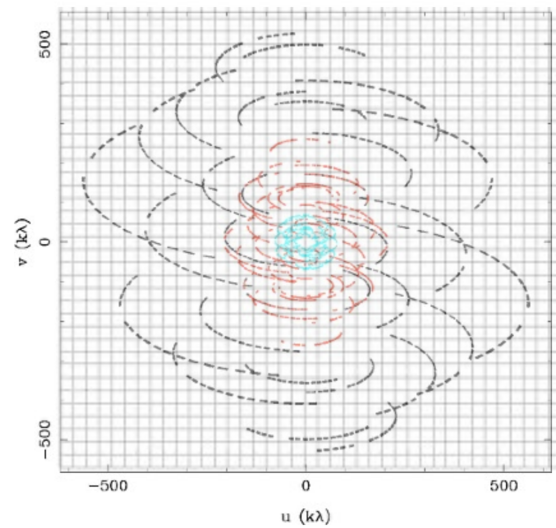
Gridding: Visibility Weighting

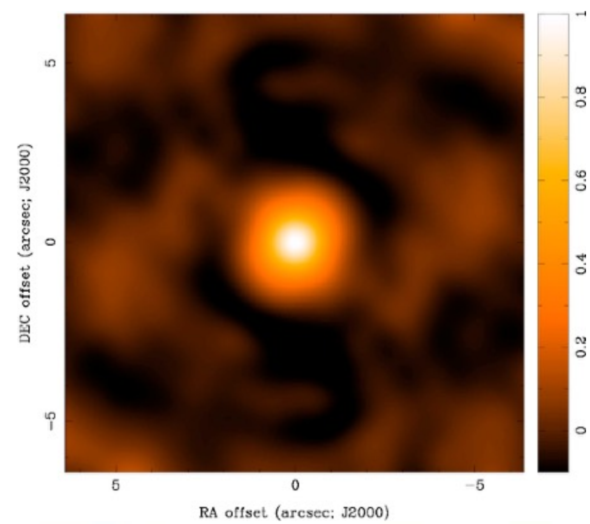
- uvtaper
  - apodize *(u,v)* sampling by a Gaussian

$$W(u,v) = \exp\left(-\frac{(u^2+v^2)}{t^2}\right)$$

  t = adjustable tapering parameter

  - like convolving image by a Gaussian
  - gives more weight to short baselines, degrades angular resolution
  - downweights data at long baselines, so point source sensitivity degraded
  - may improve sensitivity to extended structure sampled by short baselines
  - Not a panacea

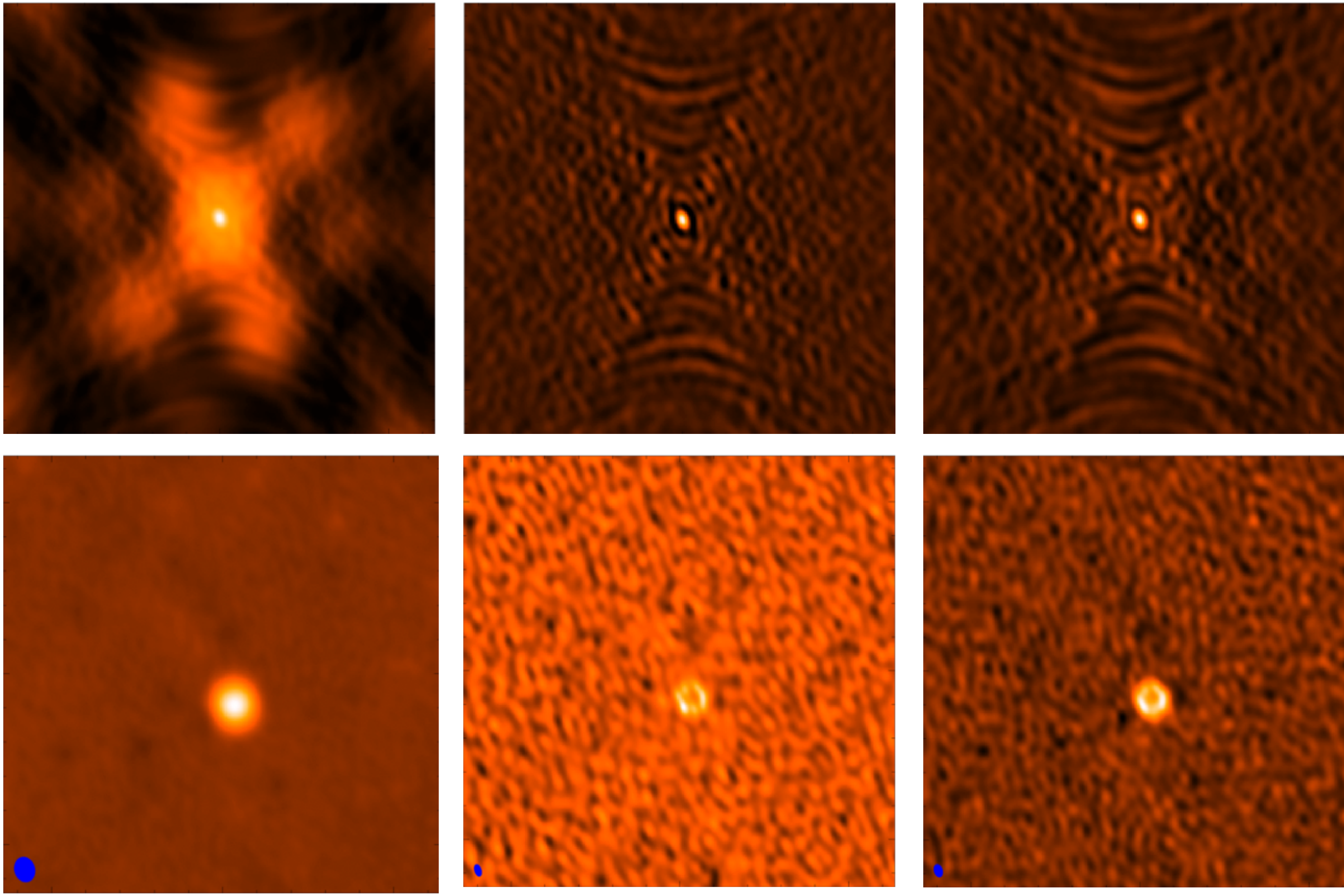




Natural | Uniform | Robust=0

Beam

CLEAN image



The weighting you choose depends on your science goals.

- Good first try is robust=0.5. It's a nice balance between resolution and noise.
- Detection experiment or weak extended source: try **natural** (maybe even with a taper)
- Finer detail of strong sources: try **robust**

	Robust/Uniform	Natural	Taper
resolution	higher	medium	lower
sidelobes	lower	higher	depends
point source sensitivity	lower	maximum	lower
extended source sensitivity	lower	medium	higher

Adapted from slide by David Wilner

For a video overview of these concepts:

https://youtu.be/OC3IWpRRtEQ

https://youtu.be/EVY7000zAD4

- More videos under development!
- **Like and subscribe** to our Youtube channel **ALMA Primer** to get notified when new videos are uploaded.

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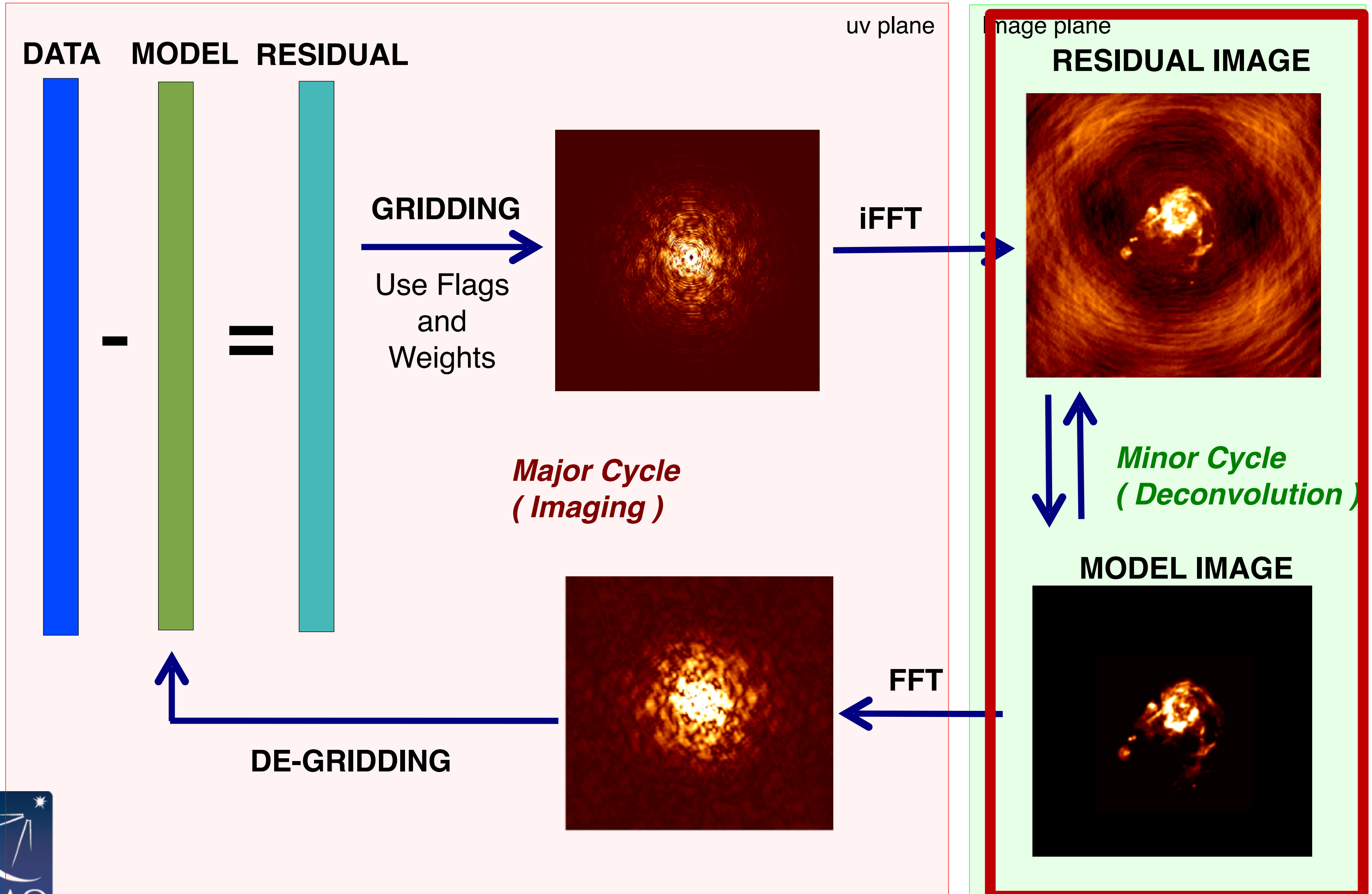
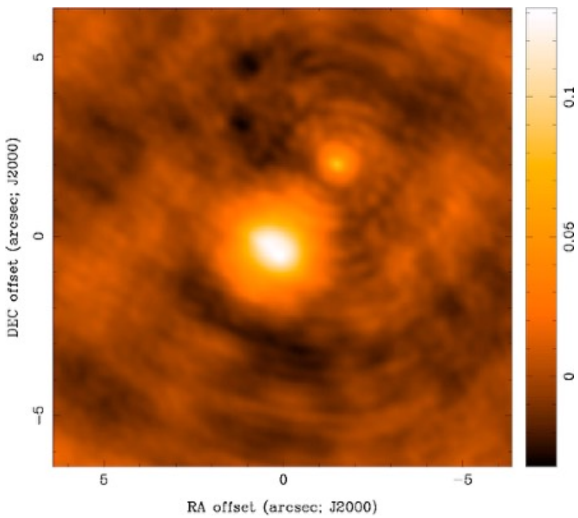
Deconvolution requires specifying how you want to create and subtract the model.



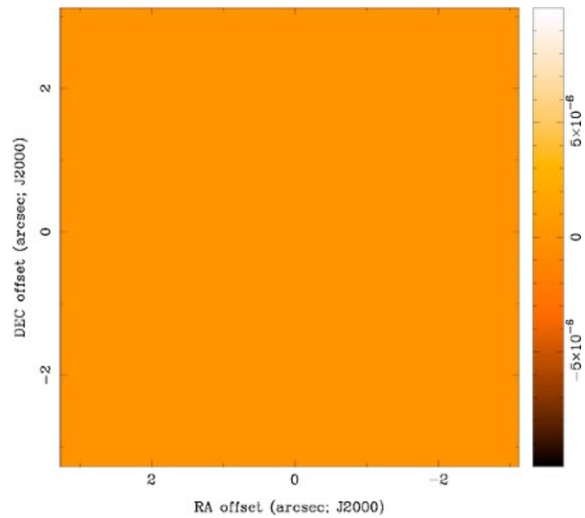
clean example

initialize

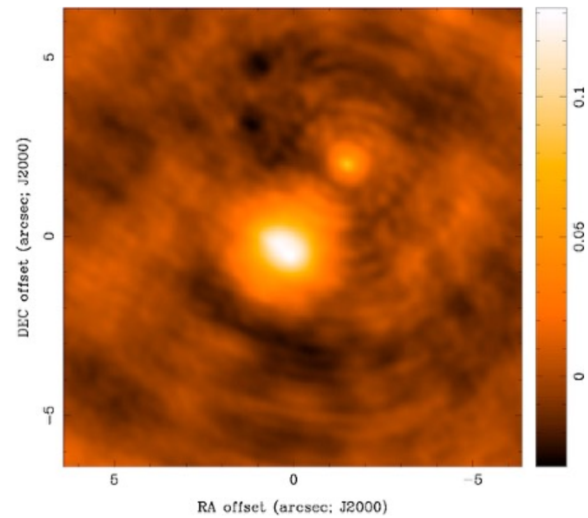
$T^D(l,m)$



0 clean components



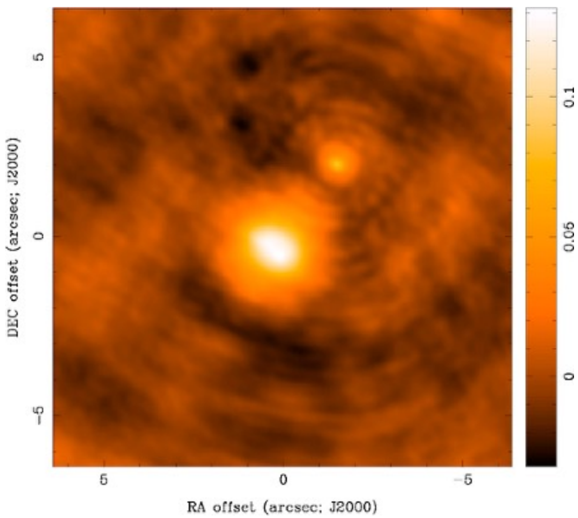
residual map



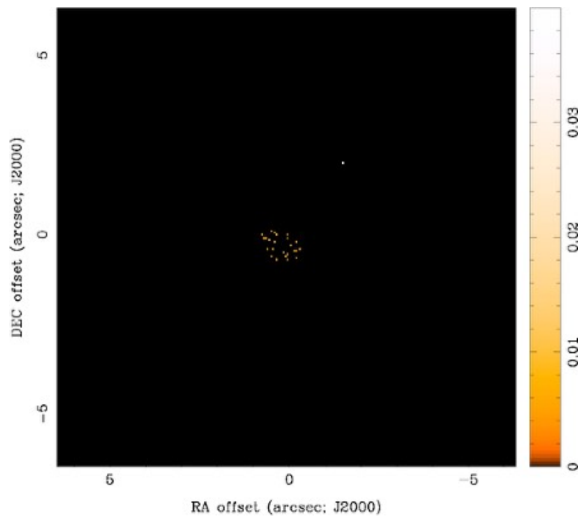
Slide courtesy David Wilner

clean example

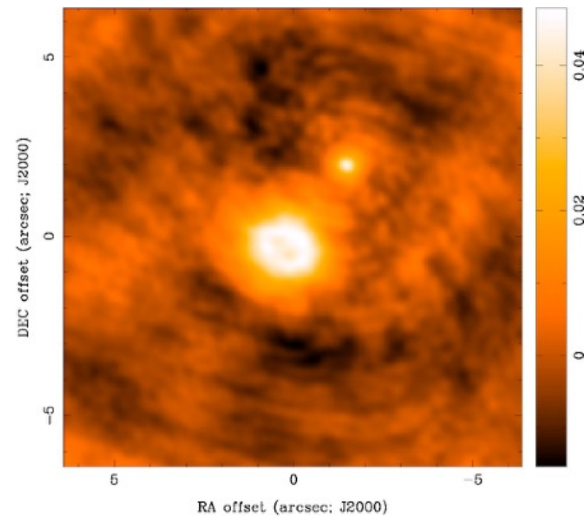
$T^D(l,m)$



30 clean components



residual map

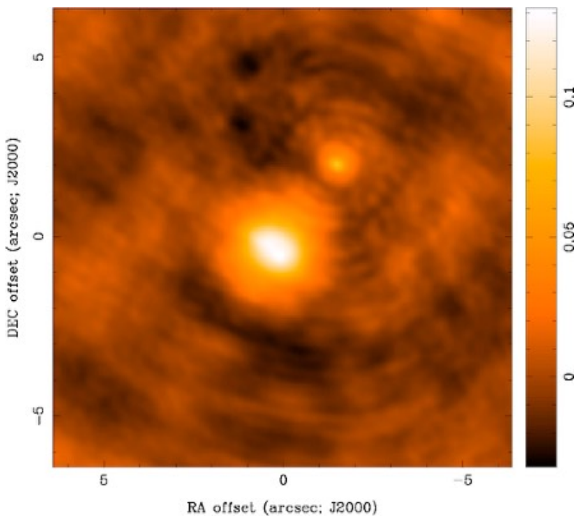


NRAO

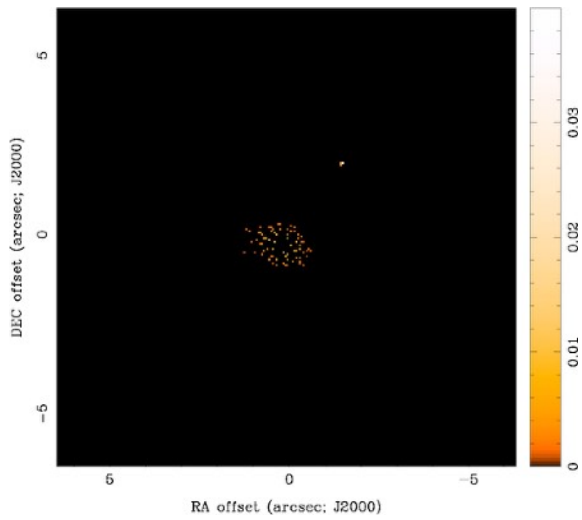
Slide courtesy David Wilner

clean example

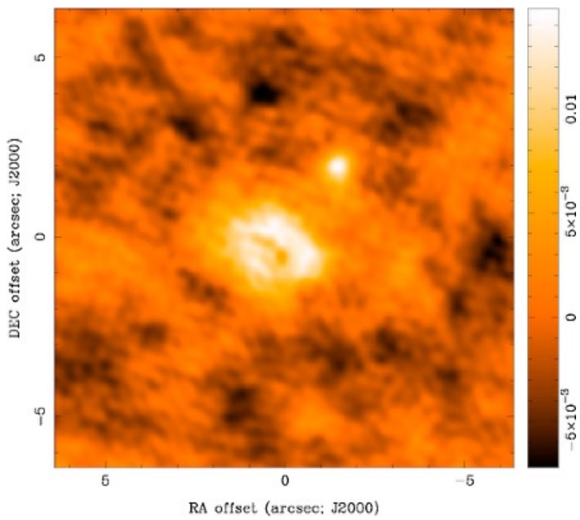
$T^D(l,m)$



100 clean components



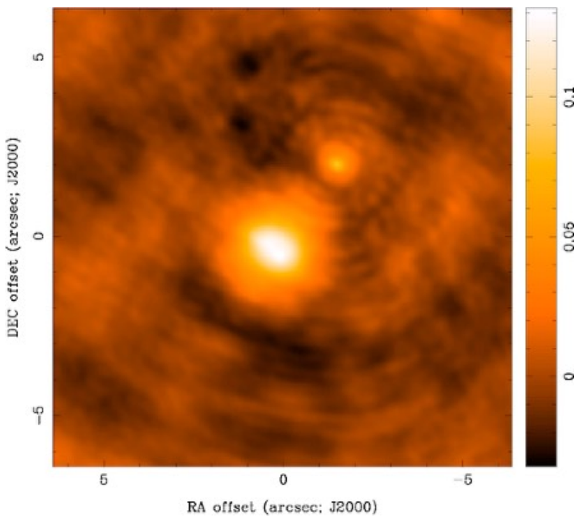
residual map



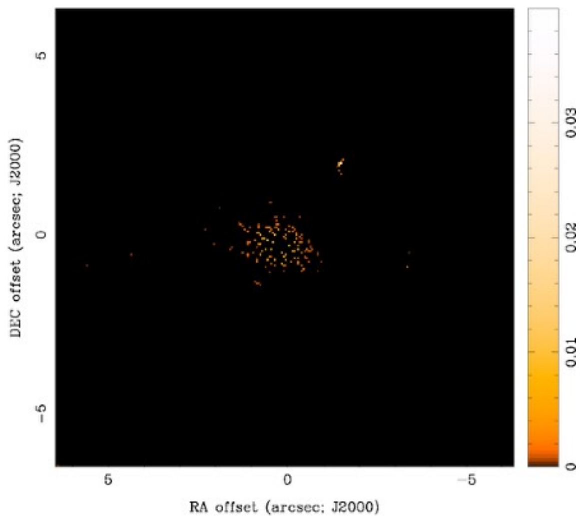
Slide courtesy David Wilner

clean example

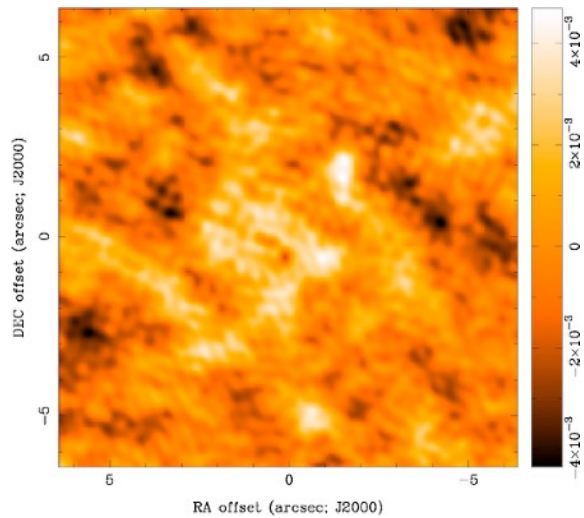
$T^D(l,m)$



300 clean components



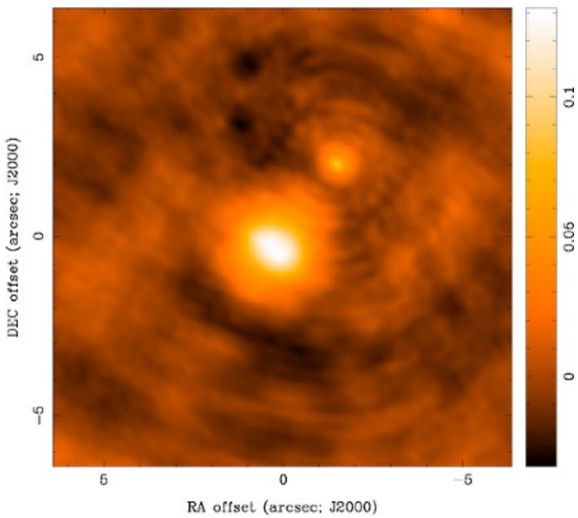
residual map



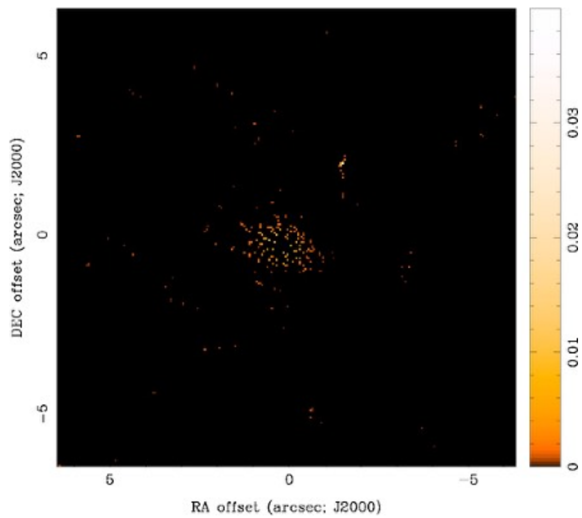
Slide courtesy David Wilner

clean example

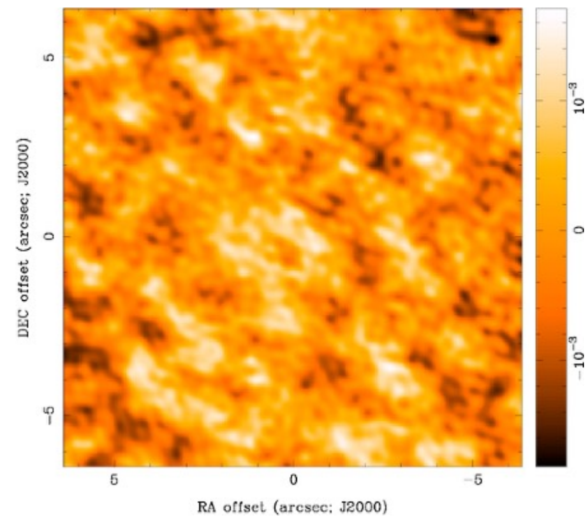
$T^D(l,m)$



583 clean components



residual map

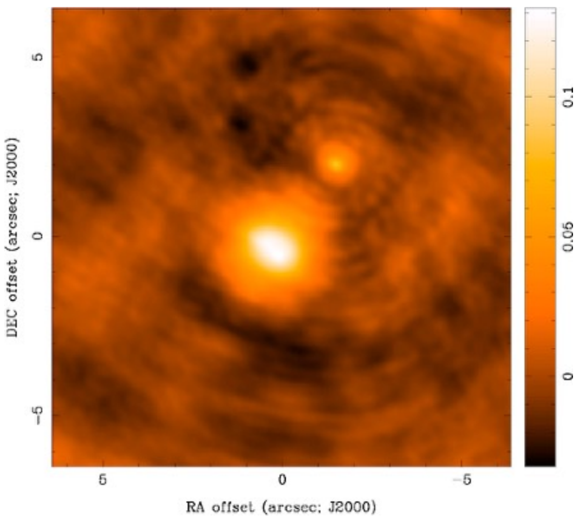


threshold reached

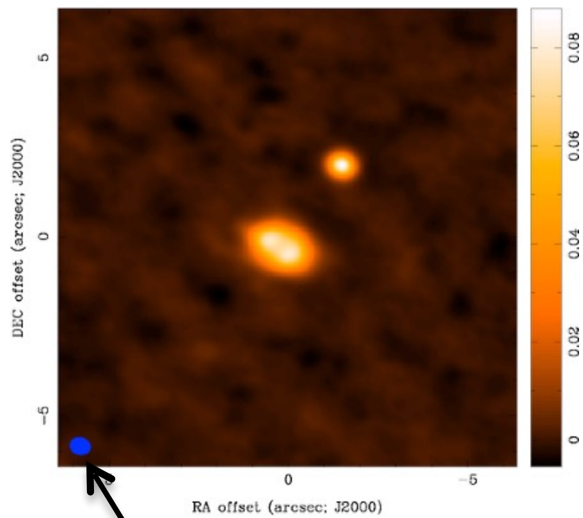
Slide courtesy David Wilner

clean example

$T^D(l,m)$



restored image



ellipse = clean beam fwhm

final image depends on

imaging parameters (pixel size, visibility weighting scheme, gridding) and deconvolution (algorithm, iterations, masks, stopping criteria)

Slide courtesy David Wilner

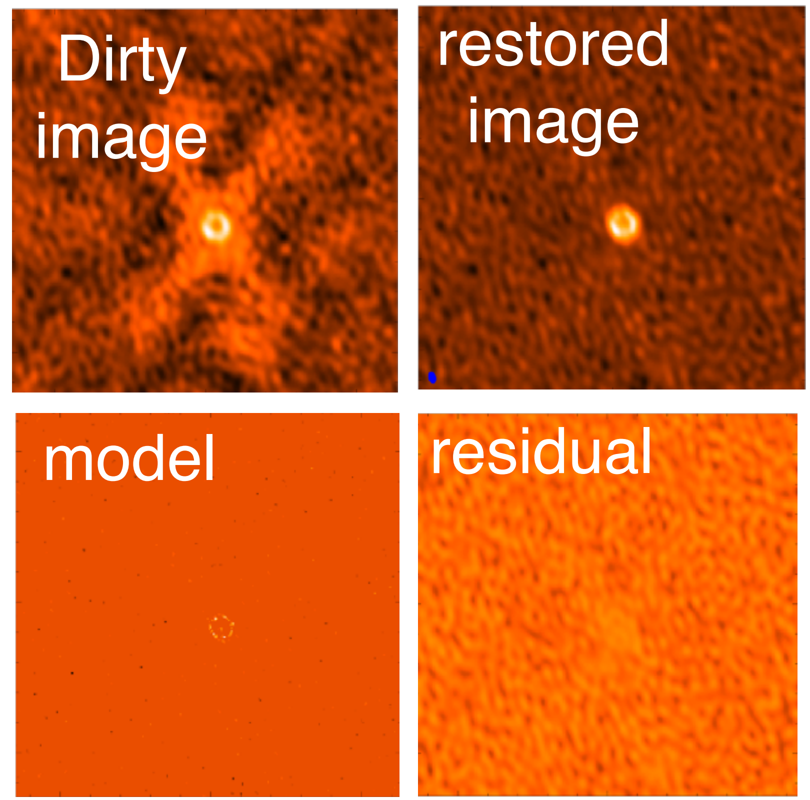
Clean is the most common deconvolution algorithm.

Sky Model : List of delta-functions

(1) Construct the observed (dirty) image and PSF
(2) Search for the location of peak amplitude.
(3) Add a delta-function of this peak/location to the model
(4) Subtract the contribution of this component from the dirty image - a scaled/shifted copy of the PSF

Repeat steps (2), (3), (4) until a stopping criterion is reached.

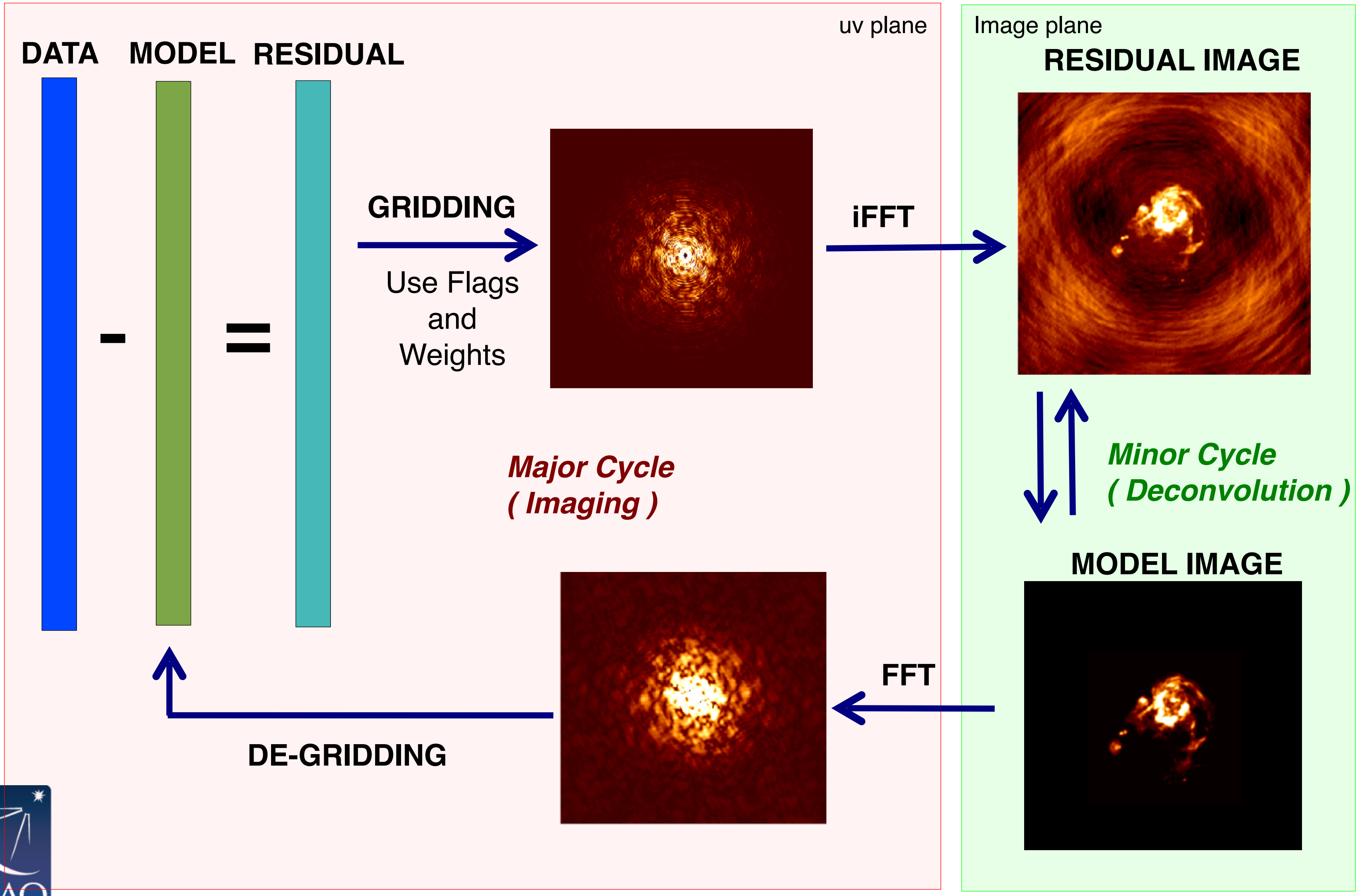
(5) Restore : Smooth the model with a 'clean beam' and add residuals



Choices: what and how much PSF to subtract and when to stop

Adapted from slide by Urvashi Rau

How do we do all this in practice?



Slide courtesy Urvashi Rau

The main imaging task in CASA is tclean.

- Tclean is a refactored version of the original clean task
    - *The original clean task is deprecated and SHOULD NOT BE USED.*
- Tclean task
    - takes the calibrated visibilities
    - grids them on the UV-plane
    - performs the FFT to a dirty image
    - deconvolves the image
    - restores the image from clean table and residual
- Major syntax and usage changes from clean → tclean is summarized here: https://casaguides.nrao.edu/index.php/TCLEAN_and_ALMA

NRAO

TCLEAN in CASA:

There can be an intimidating number of parameters!

Start simple and make it more complicated as you need to.

```
CASA <6>: inp tclean
--------> inp(tclean)
#  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 (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = '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

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

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

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

CASA <7>:
```

TCLEAN in CASA

vis = ms file (can be multiple ms'es)

imagename = whatever you want

```
CASA <6>: inp tclean
---------> inp(tclean)
#  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 (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = '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

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

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

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

CASA <7>:
```

TCLEAN in CASA

imsize = size of image in pixels = typically primary beam (i.e., FOV)

cell = size of pixels in angular units = typically 5-8 pixels across synthesized beam (resolution)

```
CASA <6>: inp tclean
--------> inp(tclean)
#  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 (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = '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

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

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

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

CASA <7>:
```

Key tclean parameters

The **specmode** parameter controls whether you image the continuum or line emission.

The **gridder** option is used to specify what sort of gridding you will be doing (standard, mosaic, widefield, wproject, or awproject). The first two are most common with ALMA. The rest more common with the VLA.

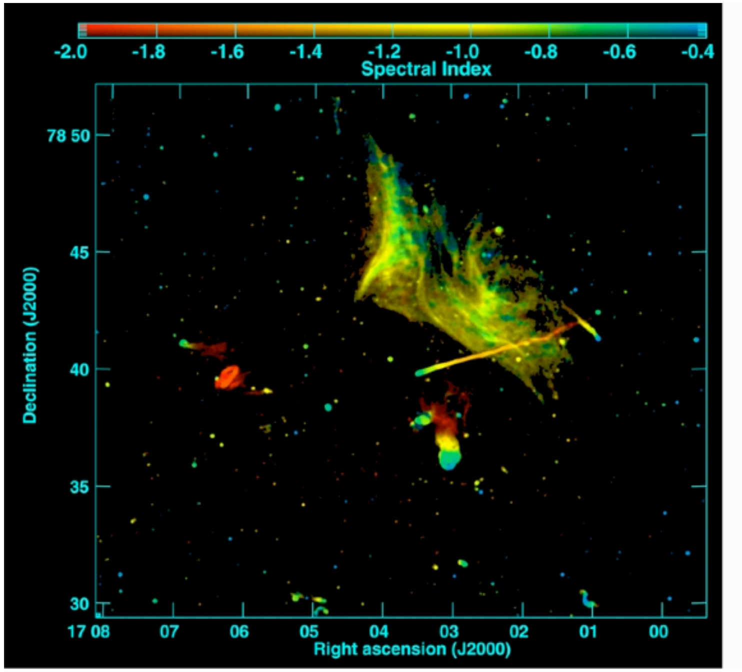
The **deconvolver** options gives you access to different deconvolution options (hogbom, clark, mtmfs, multiscale, clarkstokes)

NRAO

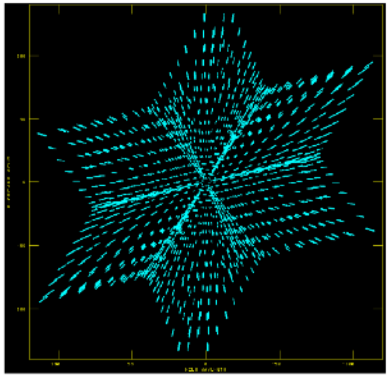
```
CASA <23>: inp
---------> inp()
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =         ''        #  Name of input visibility file(s)
selectdata          =       True        #  Enable data selection parameters
     field          =         ''        #  field(s) to select
     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 (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = '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         =    'mtmfs'        #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
     scales         =         []        #  List of scale sizes (in pixels) for
                                        #   multi-scale algorithms
     nterms         =          2        #  Number of Taylor coefficients in the
                                        #   spectral model

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)
     uvtaper        =         []        #  uv-taper on outer baselines in uv-
                                        #   plane

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

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
```

Specmode options: Continuum Imaging

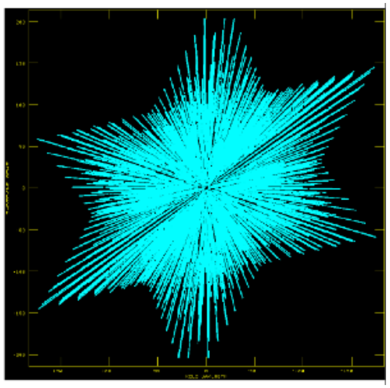
- specmode='mfs' if narrow bandwidth
- add deconvolver='mtmfs' if you have a fractional bandwidth for the aggregate continuum greater than 10% to use multi-term multi-frequency synthesis.
  - Only in ALMA Band 3 and the lower end of Band 4 can have fractional bandwidths of greater than 10% and only when both sidebands are employed.
  - nterm=2 compute spectral index, 3 for curvature etc.
  - tt0 average intensity, tt1 alpha*tt0, alpha images output
  - takes at least nterms longer (image size dependent)



Abell 2256; Owen et al. (2014)



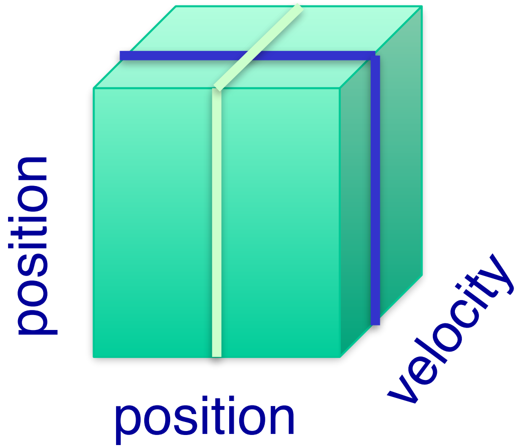
Narrow BW



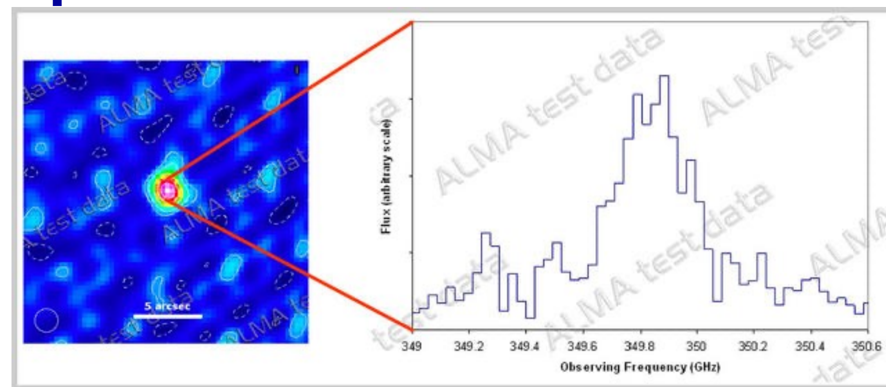
wide BW

(better uv-coverage)

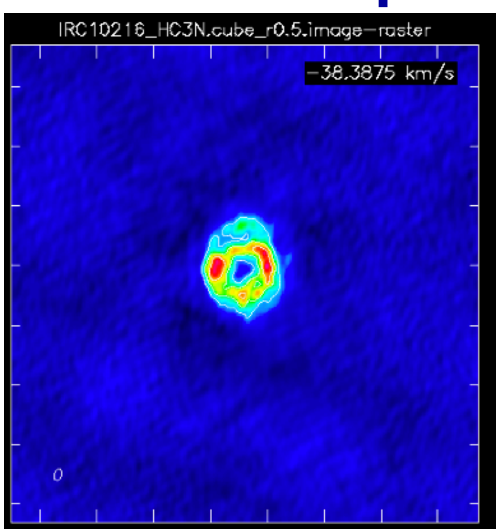
Specmode options: Imaging spectral lines



Spectrum

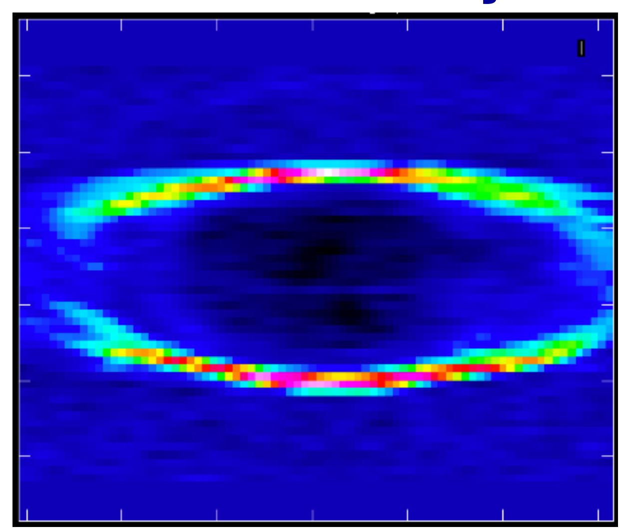


Channel map



Fixed velocity, polarization, etc.

Position-velocity map



One fixed position, polarization, etc.

Specmode options: Imaging spectral lines

specmode='cube'

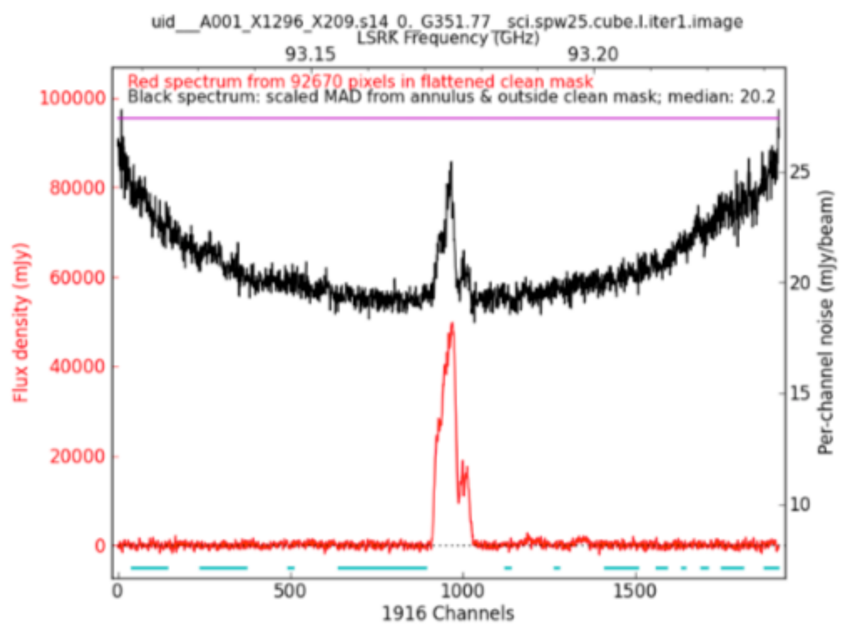
- Set the dimensions of the cube
- Set Rest frequency
- Set Velocity Frame (LSRK, BARY, …)
- Set Doppler definition (optical/radio)
- <CASA 6.2: If imaging large cubes, set chanchunks=-1. Default (1) tries to put entire cube in memory, which can fail for large cubes.
- >=CASA 6.2: chanchunks parameter has no effect
- perchanweightdensity = True weights each channel independently to give flat noise and beams (CASA >=6.2)
- weighting='briggsbwtaper' will give similar beams between cube and mfs. (CASA >=6.2)

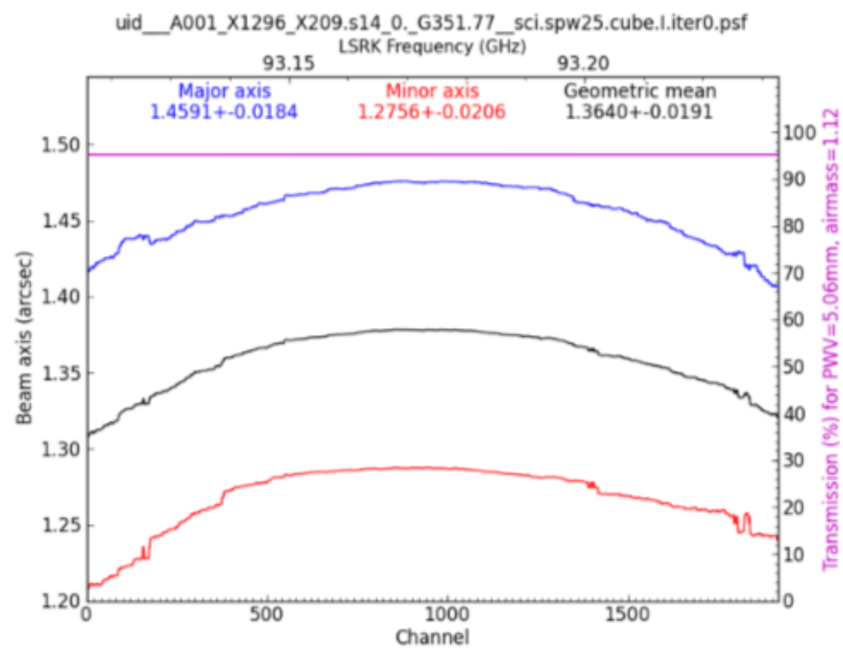
tclean will calculate the Doppler corrections for you! No need to realign beforehand. If needed, **cvel2** will do it for you, e.g. when self-calibrating.

```
CASA <40>: inp tclean
---------> inp(tclean)
#  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 (SIN, HPX)
startmodel          =          ''        #  Name of starting model image
specmode            =      'cube'        #  Spectral definition mode
                                         #   (mfs,cube,cubedata)
     nchan          =         100        #  Number of channels in the output
                                         #   image
     start          =  '100km/s'         #  First channel (e.g. start=3,start='1.
                                         #   1GHz',start='15343km/s')
     width          =   '10km/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       =          []        #  List of rest frequencies
     interpolation  =    'linear'        #  Spectral interpolation
                                         #   (nearest,linear,cubic)
     chanchunks     =          -1        #  Number of channel chunks

gridder             =  '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

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

niter               =           0        #  Maximum number of iterations
usemask             =      'user'        #  Type of mask(s) for deconvolution
                                         #   (user, pb, auto-thresh, auto-
                                         #   thresh2, or auto-multithresh)
     mask           =          ''        #  Mask (a list of image name(s) or
                                         #   region file(s) or region string(s) )
     pbmask         =         0.0        #  primary beam mask

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
```

Perchanweightdensity=False

Introduces curvature in the noise spectrum and beams with frequency.

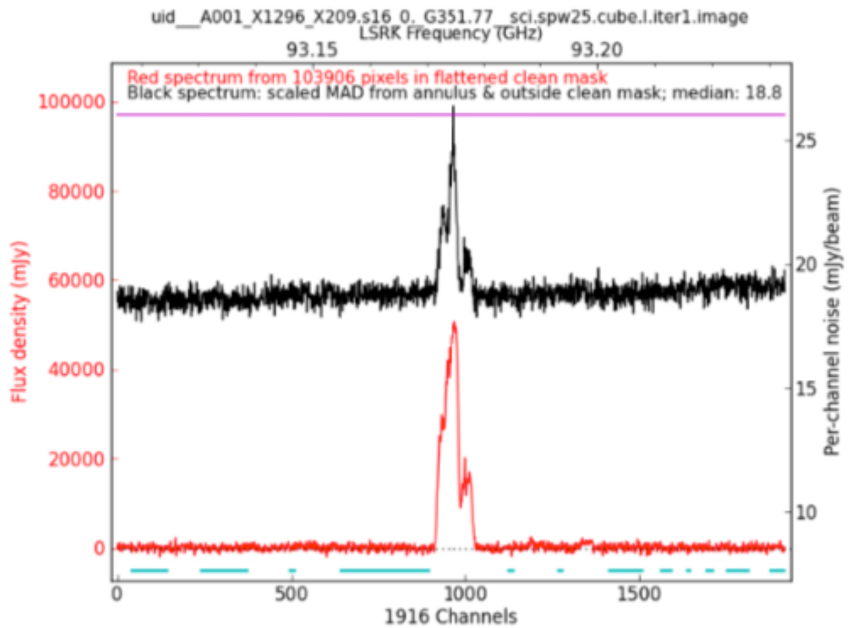


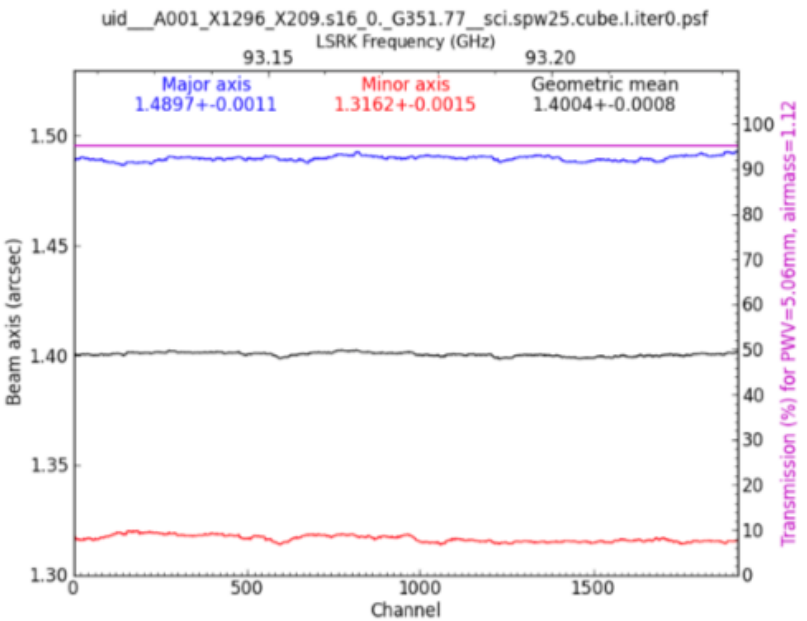


The former is particularly impactful when identifying lines either in the pipeline (findcont and associated heuristics) or using the data for analysis.

Perchanweightdensity=True

Noise spectrum and beams are flat with frequency





But gives cube beams that are larger than mfs beams!

Deconvolver options: PSF sampling choices

- **deconvolver='hogbom'**
  - Subtracts shifted and scaled full PSF from residual image
  - More accurate but can be computationally expensive.
- **deconvolver='clark'**
  - Subtracts small patch of shifted and scaled PSF from residual image
  - Does the major cycle more often to compensate for the above
  - Potentially less accurate, but also less computationally expensive.
- **deconvolver='clarkstokes'**
  - Does the thing as clark, but doing each polarization product separately.

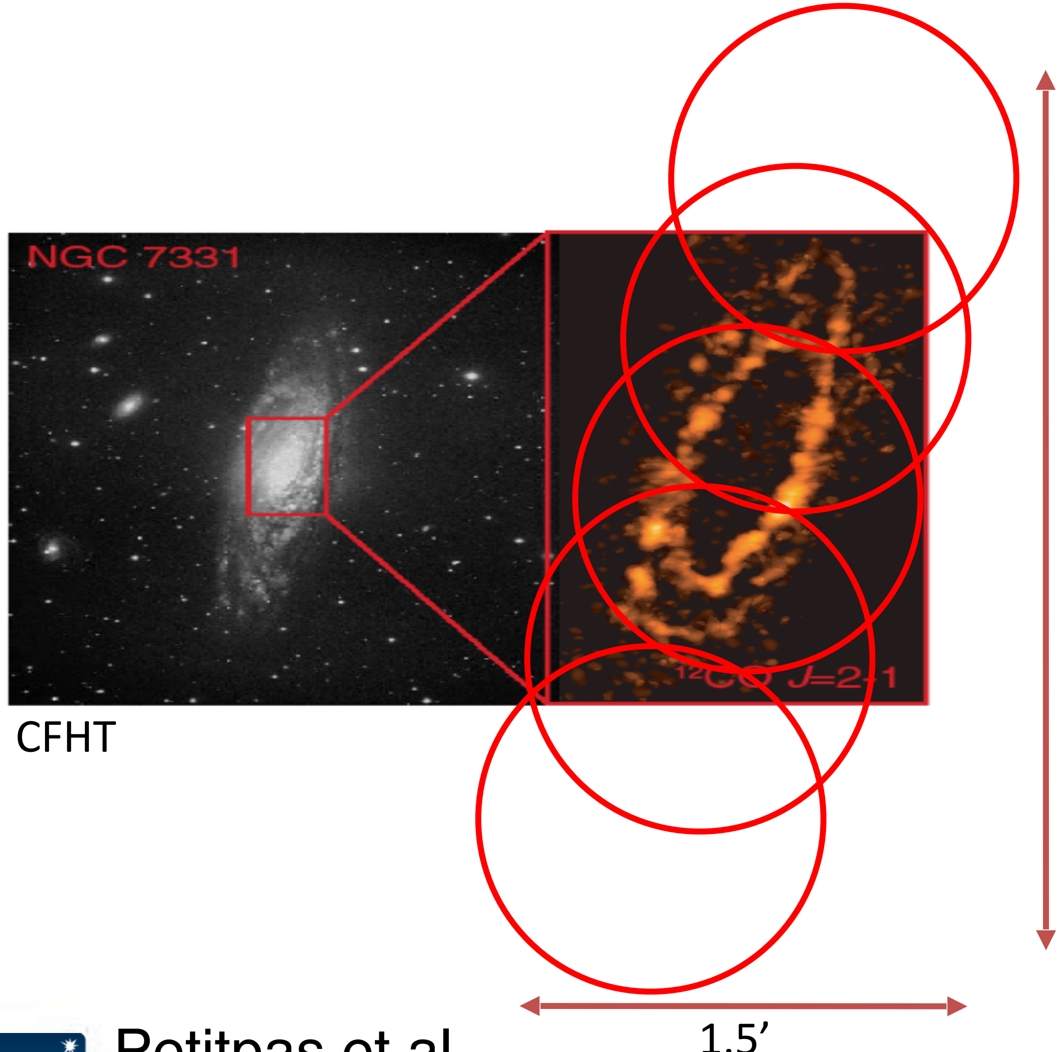
```
CASA <21>: inp
---------> inp()
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =          ''        #  Name of input visibility file(s)
selectdata          =        True        #  Enable data selection parameters
       field        =          ''        #  field(s) to 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 (SIN, HPX)
startmodel          =          ''        #  Name of starting model image
specmode            =       'mfs'        #  Spectral definition mode
                                         #   (mfs,cube,cubedata)
       reffreq      =          ''        #  Reference frequency

gridder             =  '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

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

niter               =           1        #  Maximum number of iterations
       gain         =         0.1        #  Loop gain
       threshold    =         0.0        #  Stopping threshold
       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

usemask             =      'user'        #  Type of mask(s) for deconvolution
                                         #   (user, pb, auto-thresh, auto-
                                         #   thresh2, or auto-multithresh)
       mask         =          ''        #  Mask (a list of image name(s) or
                                         #   region file(s) or region string(s) )
       pbmask       =         0.0        #  primary beam mask

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

CASA <22>:
```

Imaging spectral lines: continuum subtraction

- Generally would like to subtract continuum emission prior to imaging line data.
  - We will see how to identify line-free channels in hands-on session.
- Current best practice is to use `uvcontsub` to do the subtraction in uv plane.

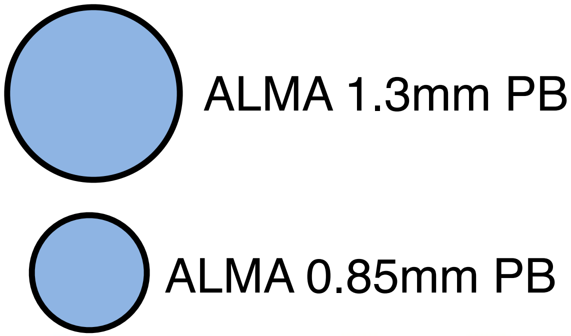
```
CASA <11>: inp
---------> inp()
#  uvcontsub :: Continuum fitting and subtraction in the uv plane
vis                 = 'ngc3256_co.ms'   #  Name of input MS.  Output goes to vis + ".contsub"
field               =         ''        #  Select field(s) using id(s) or name(s)
fitspw              = '0:20~53;71~120'  #  Spectral window:channel selection for fitting the continuum
combine             =         ''        #  Data axes to combine for the continuum estimation (none, or spw and/or scan)
solint              =      'int'        #  Continuum fit timescale (int recommended!)
fitorder            =          0        #  Polynomial order for the fits
spw                 =         ''        #  Spectral window selection for output
want_cont           =      False        #  Create vis + ".cont" to hold the continuum estimate.
async               =      False        #  If true the taskname must be started using uvcontsub(...)
```

Gridder options: mosaics



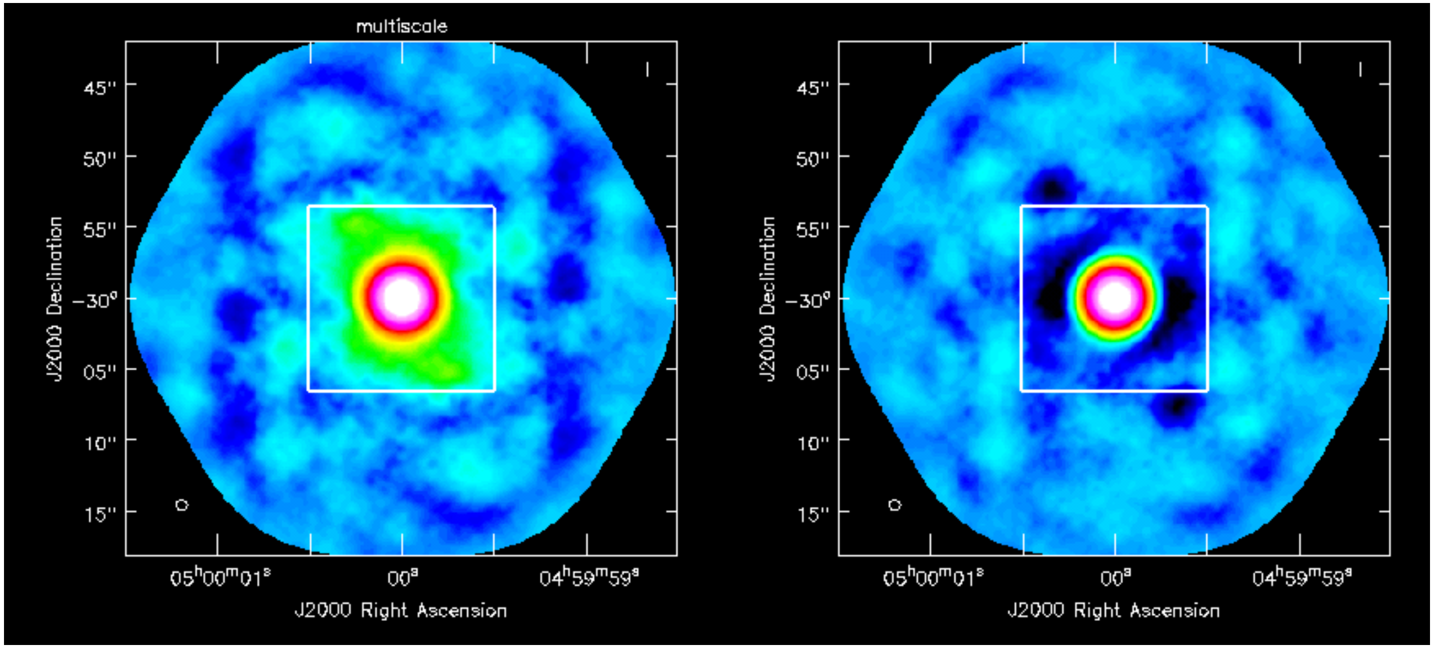
Petitpas et al.

- Mosaics are common with ALMA particularly at high frequencies
- Example: SMA 1.3 mm observations: 5 pointings
  - Primary beam ~1’
  - Resolution ~3”



Deconvolver options: Multi-scale CLEAN

multi-scale "classic" scale



Instead of using delta functions like hogbom or clark, one can use extended clean components to better match emission scales (multiscales, typically paraboloids)

Suggested scale parameter choice : point source, the second the size of the synthesized beam and the third 3-5 times the synthesized beam, etc.

Selecting scales that are close to the size of your source can lead to poor modeling and divergence in clean.

Deconvolver options: Multi-scale CLEAN

deconvolver='multiscale'
- **only do multiscale**
- line or narrow bandwidth continuum

deconvolver='mtmfs'
- **multiscale+multi-terms**
- wide-fractional bandwidth continuum

- For both need to set scales
  - Note that scales is in **pixels**
  - If beam is 5 pixels across, then scales=[0,5,15] is a pretty good choice.

```
#  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 (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = '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         = 'multiscale'      #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
     scales         =         []        #  List of scale sizes (in pixels) for
                                        #   multi-scale algorithms
     smallscalebias =        0.6        #  A bias towards smaller scale sizes

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)
     uvtaper        =         []        #  uv-taper on outer baselines in uv-
                                        #   plane

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

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

CASA <51>:
```

Restoration options: Primary beam correction

pbcor=True

- Correct the output image for the primary beam (i.e., the beam pattern of the telescope)
- You want to measure things from a primary beam corrected image because it includes the response of the telescope.
- The noise will no longer be flat across the image.

For multi-term mfs primary beam corrections (i.e., nterms=2) use the **widebandpbcor** task instead.

```
        :: Radio Interferometric Image Reconstruction
                  =         ''        #  Name of input visibility file(s)
     a            =       True        #  Enable data selection parameters
     d            =         ''        #  field(s) to select
                  =         ''        #  spw(s)/channels to select
     range        =         ''        #  Range of time to select from data
     nge          =         ''        #  Select data within uvrange
     nna          =         ''        #  Select data based on antenna/baseline
                  =         ''        #  Scan number range
     rvation      =         ''        #  Observation ID range
     ntent        =         ''        #  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 (SIN, HPX)
startmodel        =         ''        #  Name of starting model image
specmode          =      'mfs'        #  Spectral definition mode
                                      #   (mfs,cube,cubedata)
     reffreq      =         ''        #  Reference frequency

gridder           = '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       = 'multiscale'      #  Minor cycle algorithm (hogbom,clark,m
                                      #   ultiscale,mtmfs,mem,clarkstokes)
     scales       =         []        #  List of scale sizes (in pixels) for
                                      #   multi-scale algorithms
     smallscalebias =      0.6        #  A bias towards smaller scale sizes

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)
     uvtaper      =         []        #  uv-taper on outer baselines in uv-
                                      #   plane

niter             =          0        #  Maximum number of iterations
usemask           =     'user'        #  Type of mask(s) for deconvolution
                                      #   (user, pb, auto-thresh, auto-
                                      #   thresh2, or auto-multithresh)
     mask         =         ''        #  Mask (a list of image name(s) or
                                      #   region file(s) or region string(s) )
     pbmask       =        0.0        #  primary beam mask

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

CASA <51>:
```

NRAO

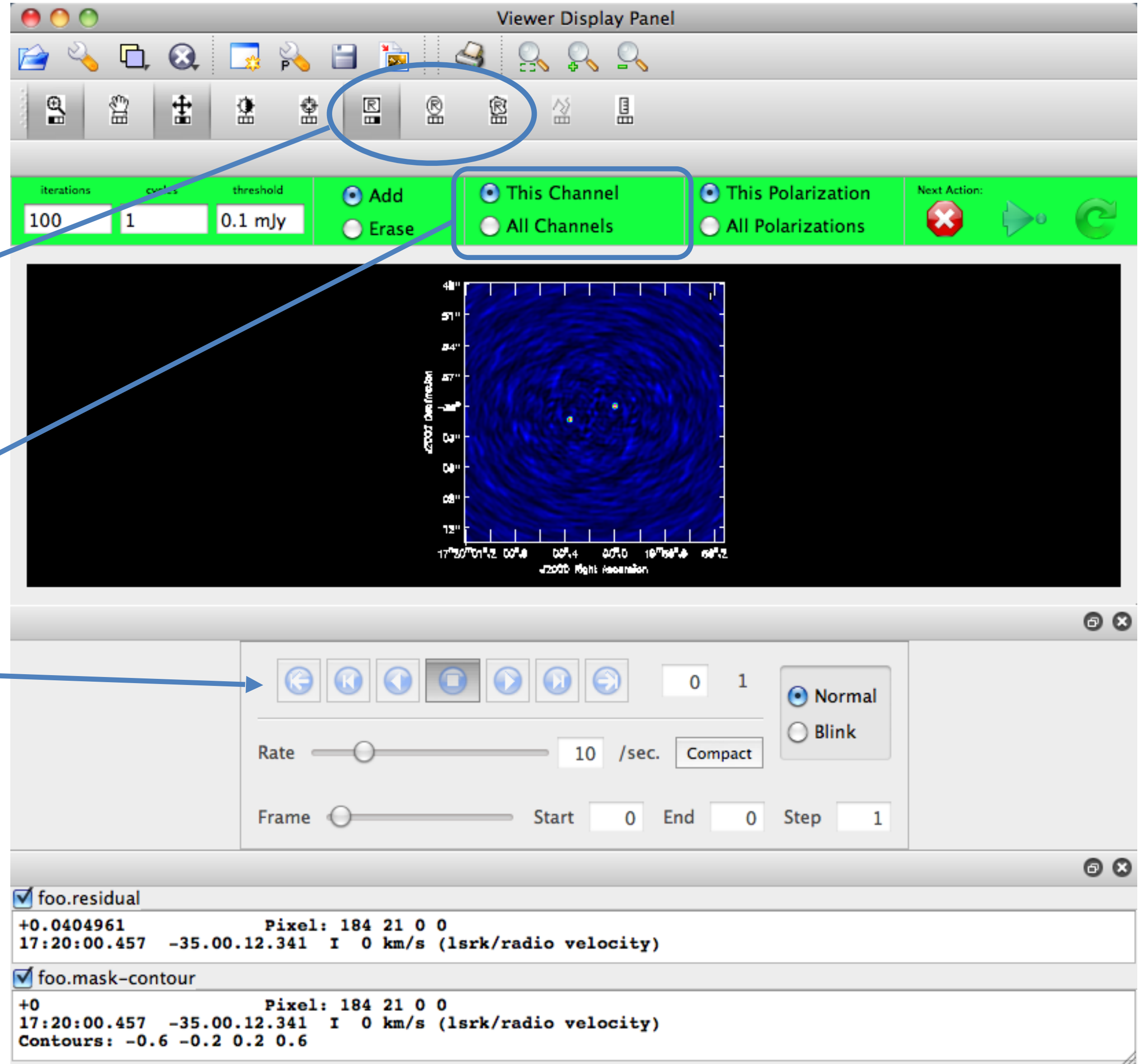
Stopping parameters

- Setting niter>0 exposes stopping parameters
- tclean stops when it completes the maximum number of iterations or when residuals go below the threshold level, whatever comes first.
    - Set niter to a large, but not too large, number
        - 1000 is a decent starting point
        - The more complex your image is the larger niter you will need
    - threshold='3mJy'
        - Usually some multiple of your noise level (1-3 sigma)
- Interactive=True
    - Allows you interactive control of tclean through the viewer
    - Choice of niter and threshold can be controlled through viewer
- Other parameters largely for power users
    - Gain can be useful for cases with extended emission (although see multi-scale clean)
    - cyclefactor, cycleniter,

```
[CASA <21>: inp
---------> inp()
#  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 (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = '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

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

niter               =          1        #  Maximum number of iterations
     gain           =        0.1        #  Loop gain
     threshold      =        0.0        #  Stopping threshold
     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

usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

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
```

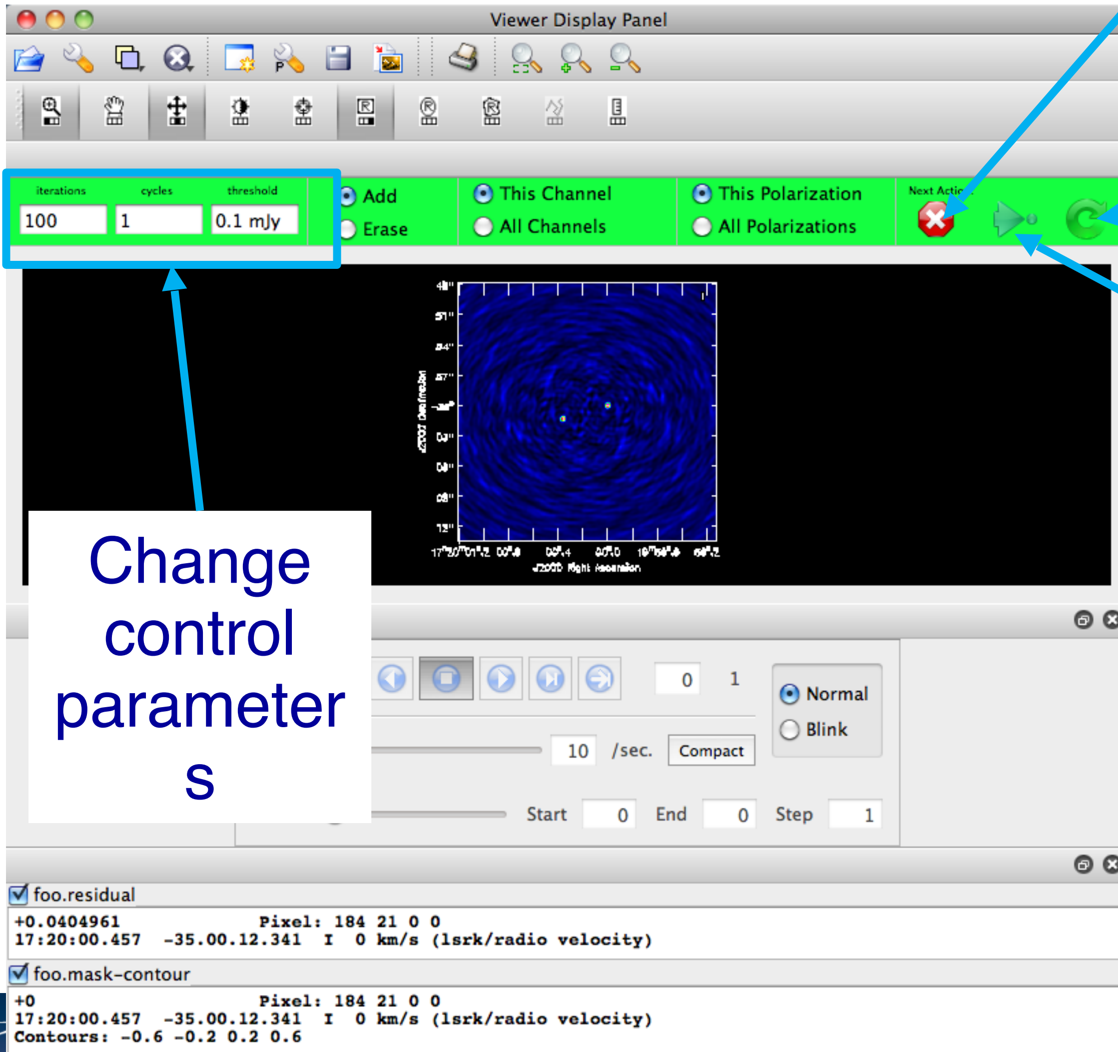
Running TCLEAN interactively

- residual image in viewer
- define a mask with defining a mouse button on shape type
- define the same mask for all channels
- or iterate through the channels with the tape deck and define separate masks



NRAO

Running TCLEAN interactively



Change control parameters

Stop cleaning

Continue for next major cycle and display residual

Exit interactive mode, but continue cleaning. Dangerous if control parameters not set sensibly!! **Using Ctrl+C can corrupt your ms.**

Output of TCLEAN

Minimally:

• my_image.pb	Primary beam model
• **my_image.image**	Cleaned and restored image (Jy/clean bea
• my_image.mask	Clean “boxes”
• my_image.model	Clean components (Jy/pixel)
• my_image.psf	Dirty beam
• my_image.residual	Residual (Jy/dirty beam)
• my_image.sumwt	Sum of weights

Wide-field imaging, multi-term, and parallel imaging will produce additional products.

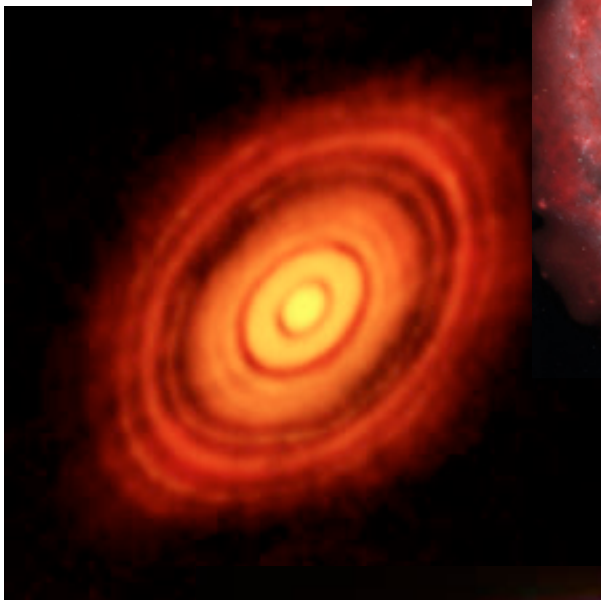
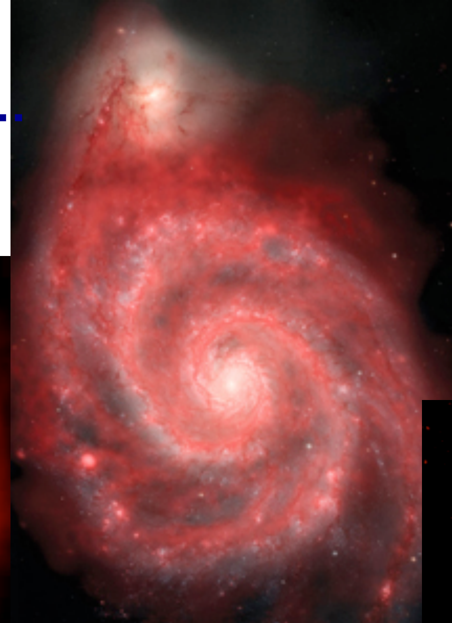
Together images can be used in subsequent tclean runs if necessary. It’s good practice not to delete subsets of images.

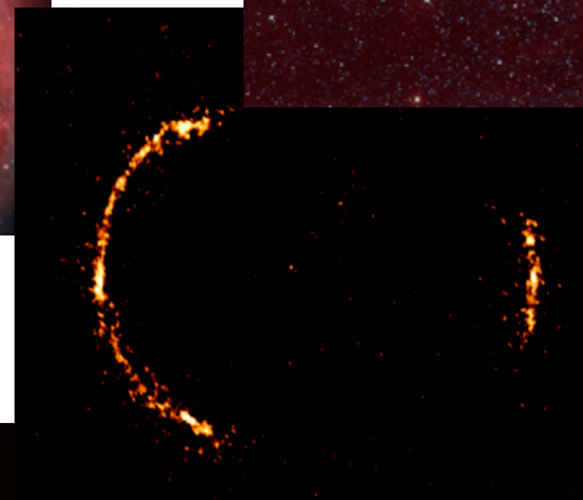
Advanced usage: automasking

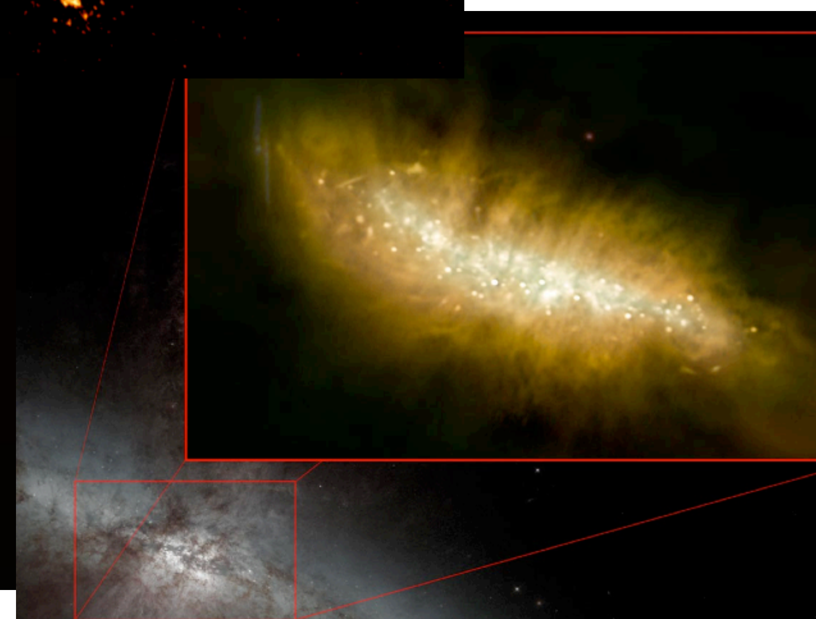
- **usemask=‘auto-multithresh’**
- Used by the ALMA Pipeline starting in Cycle 5. Also available to users as a tclean option.
- Default parameters generally good for ALMA 12m data
- General purpose algorithm so works for ALMA, VLA, ATCA, etc.
- casaguide: https://casaguides.nrao.edu/index.php/Automasking_Guide
- Paper: Kepley et al. 2020, PASP, 132, 1008, 02405

```
CASA <58>: inp
---------> inp()
#  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 (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             =   'mosaic'        #  Gridding options (standard, wproject,
                                        #   widefield, mosaic, awproject)
     normtype       = 'flatnoise'       #  Normalization type (flatnoise,
                                        #   flatsky)
     vptable        =         ''        #  Name of Voltage Pattern table
     pblimit        =        0.2        #  >PB gain level at which to cut off
                                        #   normalizations
     conjbeams      =      False        #  Use conjugate frequency for wideband
                                        #   A-terms

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

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

niter               =          0        #  Maximum number of iterations
usemask             = 'auto-multithresh'#   Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     pbmask         =        0.0        #  primary beam mask
     sidelobethreshold =        3.0     #  sidelobethreshold *  the max sidelobe
                                        #   level
     noisethreshold =        5.0        #  noisethreshold * rms in residual
                                        #   image
     lownoisethreshold =        1.5     #  lownoisethreshold * rms in residual
                                        #   image
     negativethreshold =        0.0     #  negativethreshold * rms in residual
                                        #   image
     smoothfactor   =        1.0        #  smoothing factor in a unit of the
                                        #   beam
     minbeamfrac    =        0.3        #  minimum beam fraction for pruning
     cutthreshold   =       0.01        #  threshold to cut the smoothed mask to
                                        #   create a final mask
     growiterations =         75        #  number of binary dilation iterations
                                        #   for growing the mask
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
```

… some CASA images…





NRAO

More Detailed Help - CASA Guides:
https://casaguides.nrao.edu/index.php?title=ALMAguides

www.nrao.edu
science.nrao.edu

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