Synthesis imaging using CASA

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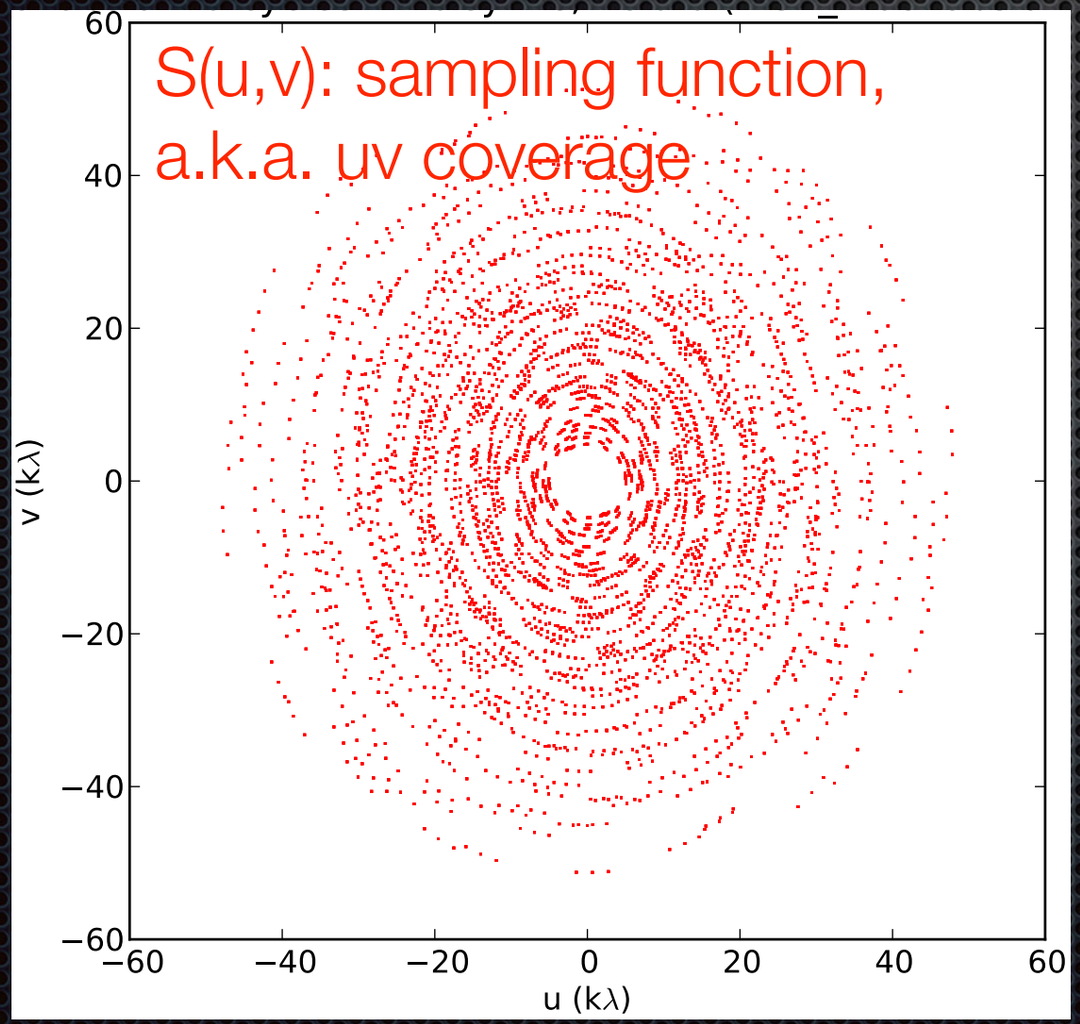
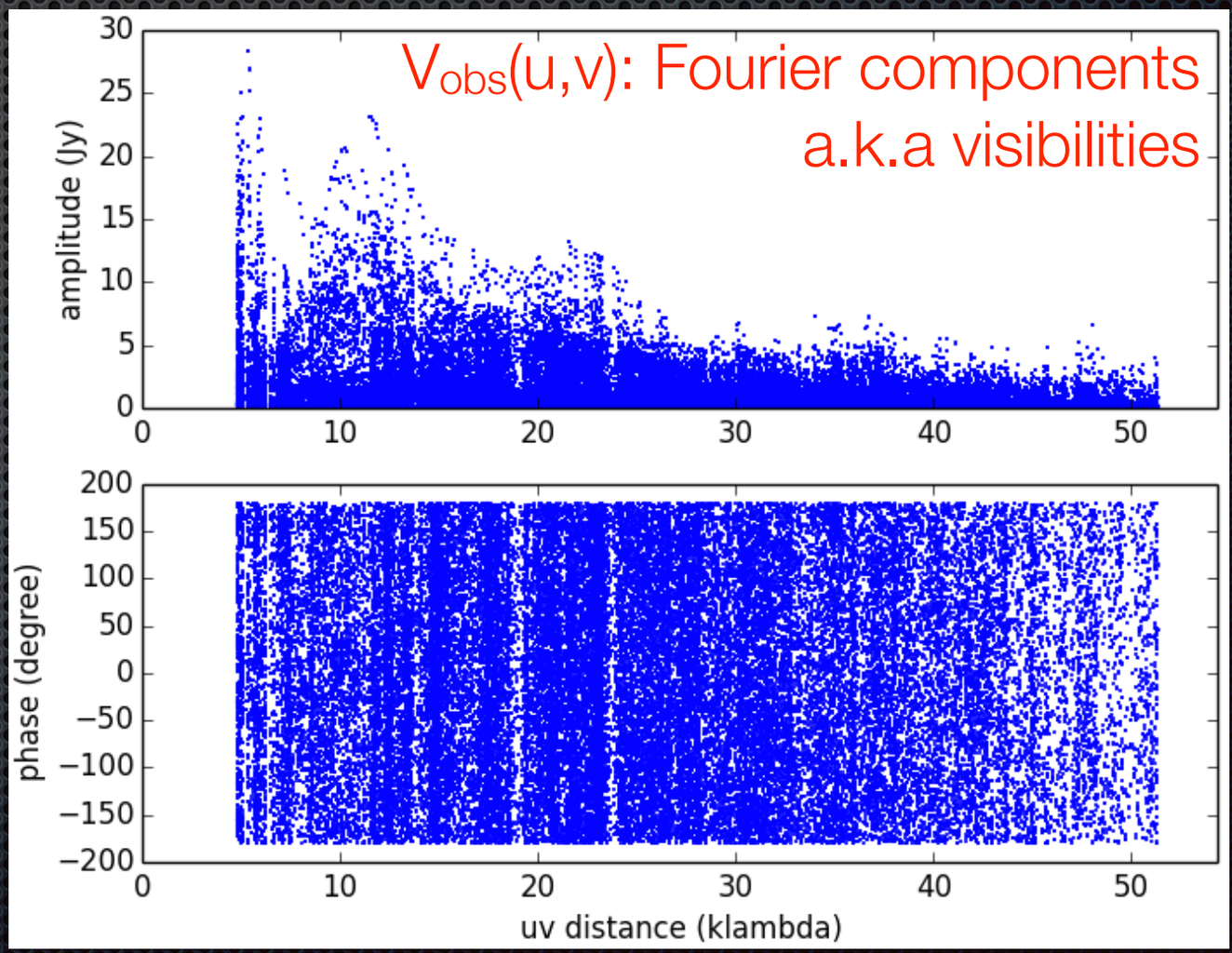
Recap

Radio interferometric observations

- The products from the array are Visibilities (Fourier domain, u-v), not images (physical domain, x-y).

$$V_{\rm obs}(u,v) = S(u,v) \iint I_{\rm true}(x,y) e^{-2\pi i(ux+vy)} dx dy$$





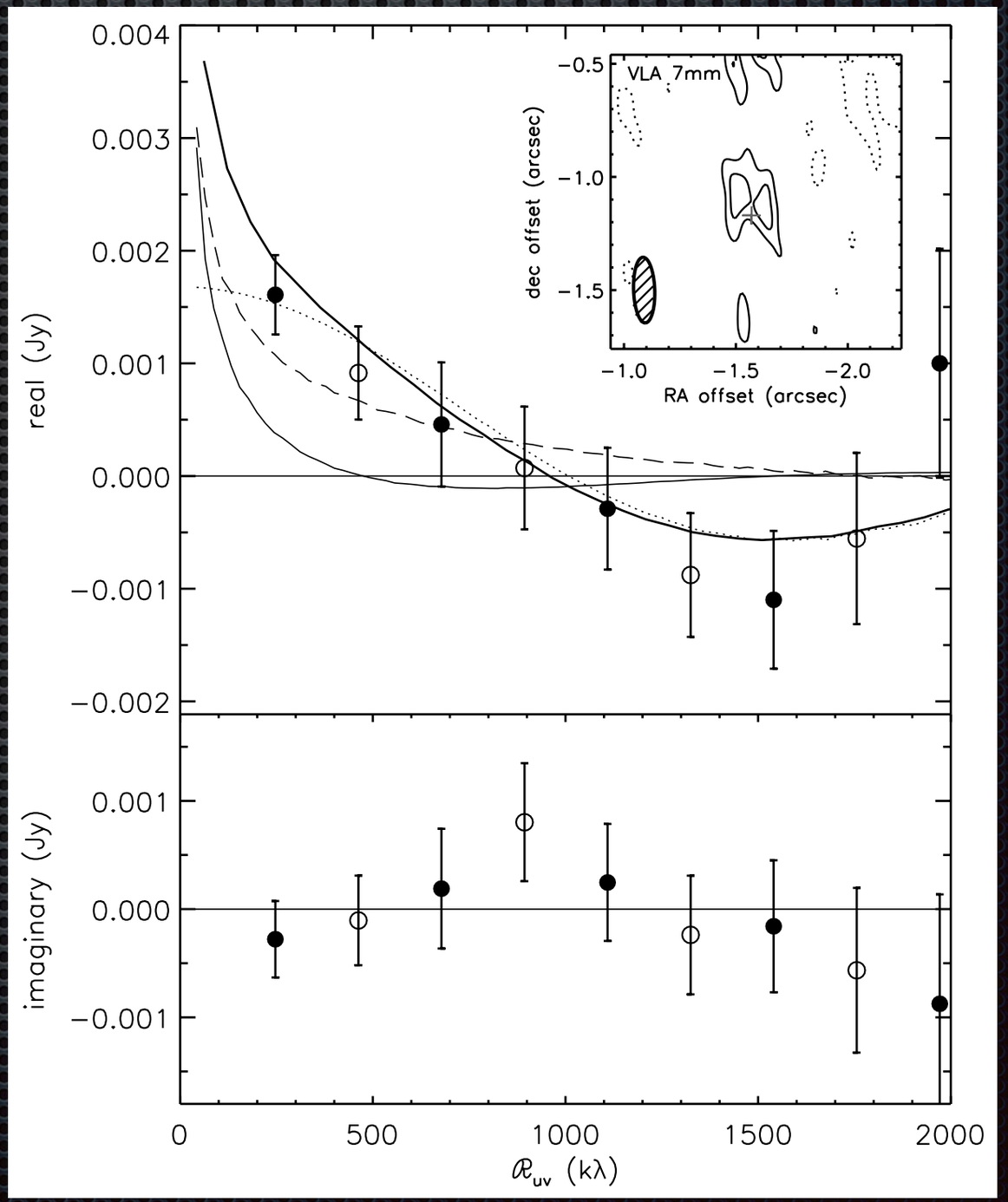
What to do with visibilities[calibrated]?

- Stay in the uv-domain and perform your analysis in the Fourier domain (works for simple source geometry)
- Reconstruct a model sky brightness distribution, then perform your analysis in the physical domain

$$V_{\rm obs}(u,v) \xrightarrow{\text{FT}^{-1}} I^{\rm dirty}_{\rm model}(x,y)$$

"CLEAN"

$$I^{\rm clean}_{\rm model}(x,y) \sim I_{\rm true}(x,y)$$



TW Hya 7mm cont. (Hughes et al. 2007)

CLEAN: concepts

Nomenclature

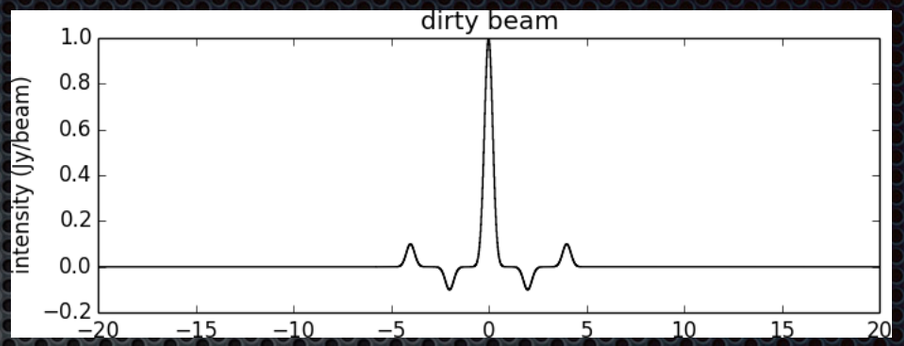
- Dirty beam (synthesized beam): point-source response (point spread fn.), FT of uv-coverage and normalize the peak to unity [Jy/beam]
- Dirty map: FT^{-1} of visibilities [Jy/beam]
- Clean beam: (usually) a 2D Gaussian approximation of the main lobe of the dirty beam [Jy/beam]
- Clean map: the sum of clean component map convoluted with clean beam and the residual map [Jy/beam]
- Clean component map: an assumable of point sources determined from CLEAN algorithms [Jy/pixel]
- Residual map: a dirty map with clean components (convolved with dirty beam) removed, usually noise-like [Jy/beam]

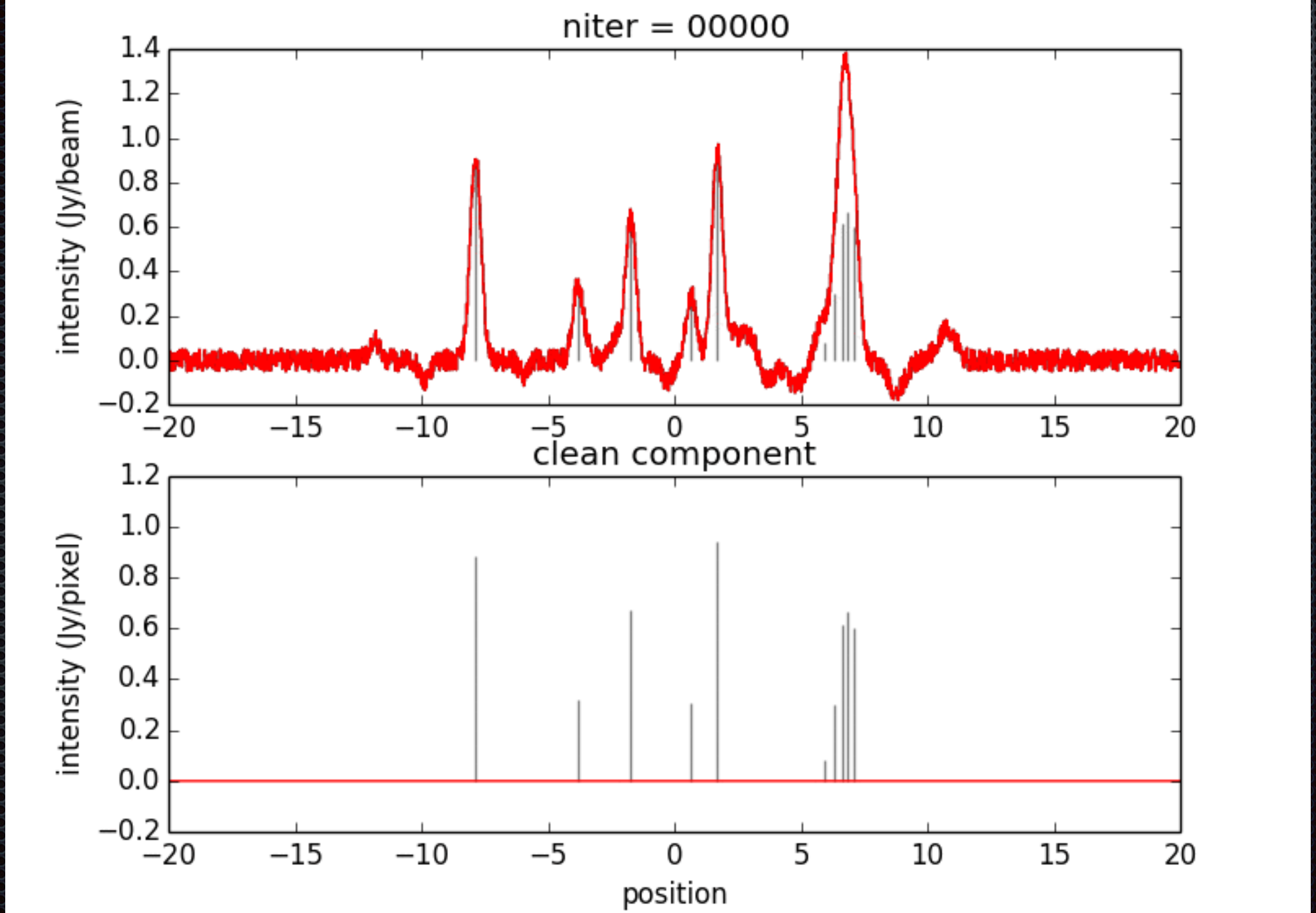
CLEAN (Högbom 1974)

recommended to read

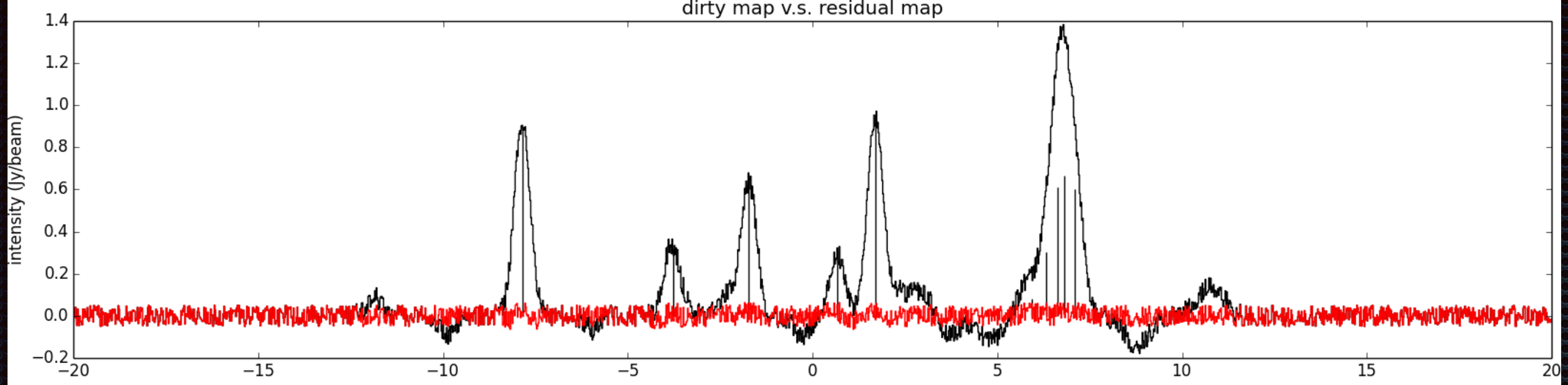
- An (iterative) algorithm proposed/summarized by J. A. Högbom
  - I: compute dirty beam and dirty map
  - II: subtract over the whole dirty map with a dirty beam pattern (multiplied by a factor, e.g., 0.1) which is centred at the point where the dirty map has its maximum of absolute value of intensity
  - III: Repeat step II, each time replacing the dirty map by the remaining map (i.e., residual map) from the previous iteration
  - IV: once the iteration is satisfied, generate the clean map by adding the final residual map with the clean component map convolved with the clean beam

1D example

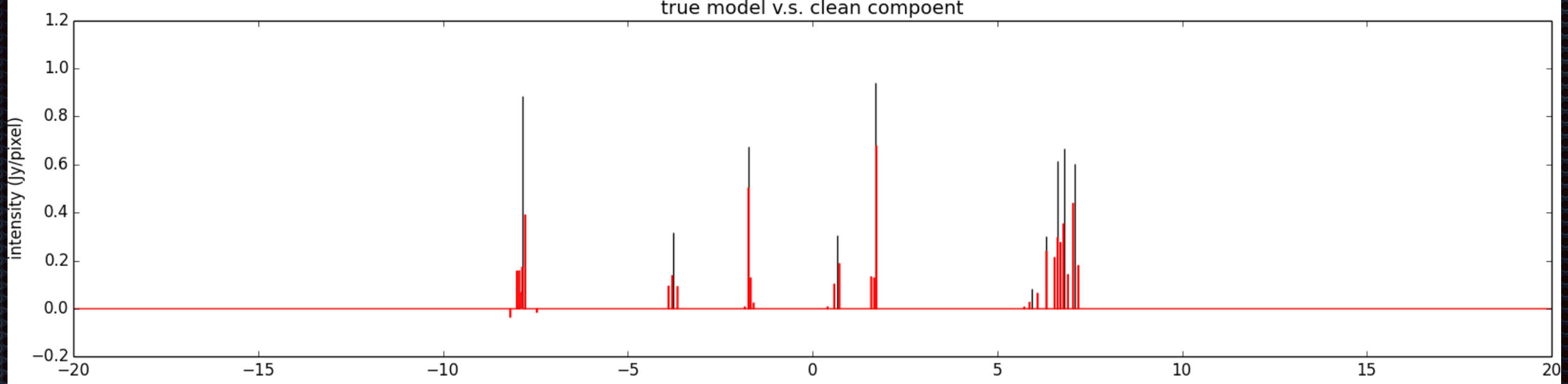

dirty beam
intensity (Jy/beam)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−20
−15
−10
−5
0
5
10
15
20


niter = 00000
intensity (Jy/beam)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−20
−15
−10
−5
0
5
10
15
20
clean component
intensity (Jy/pixel)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−20
−15
−10
−5
0
5
10
15
20
position

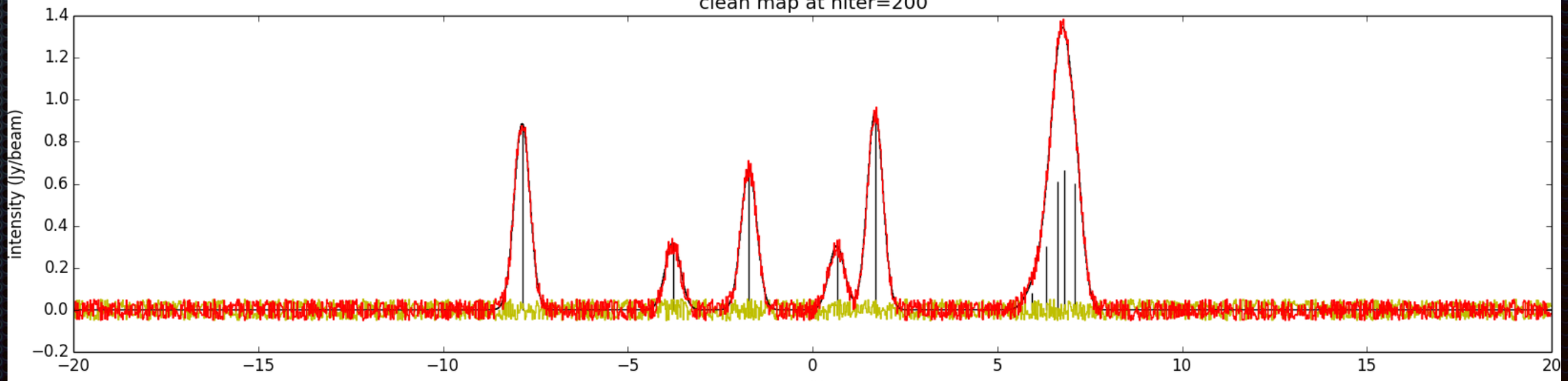
dirty map v.s. residual map



true model v.s. clean compoent



clean map at niter=200



dirty map v.s. residual map

intensity (Jy/beam)

$I_{\text{model}}^{\text{dirty}}$

I_{true}

$I_{\text{model}}^{\text{residual}}$

true model v.s. clean compoent

intensity (Jy/pixel)

I_{true}

$I_{\text{model}}^{\text{clean\_component}}$

clean map at niter=200

intensity (Jy/beam)

$I_{\text{model}}^{\text{clean}}$

I_{true}

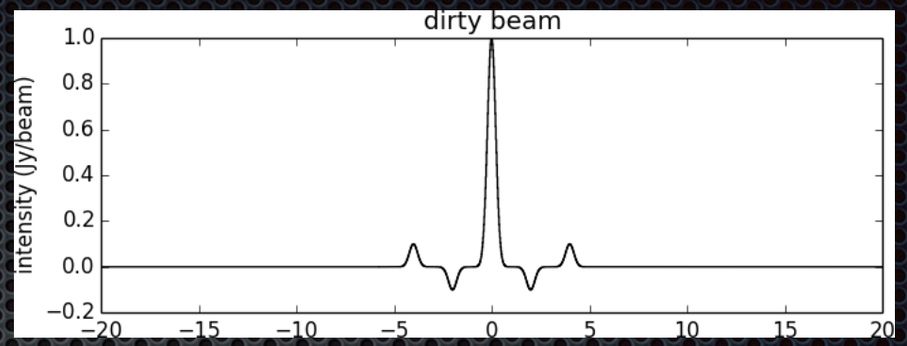
$I_{\text{true}} * \text{clean\_beam} - I_{\text{model}}^{\text{clean}}$

position

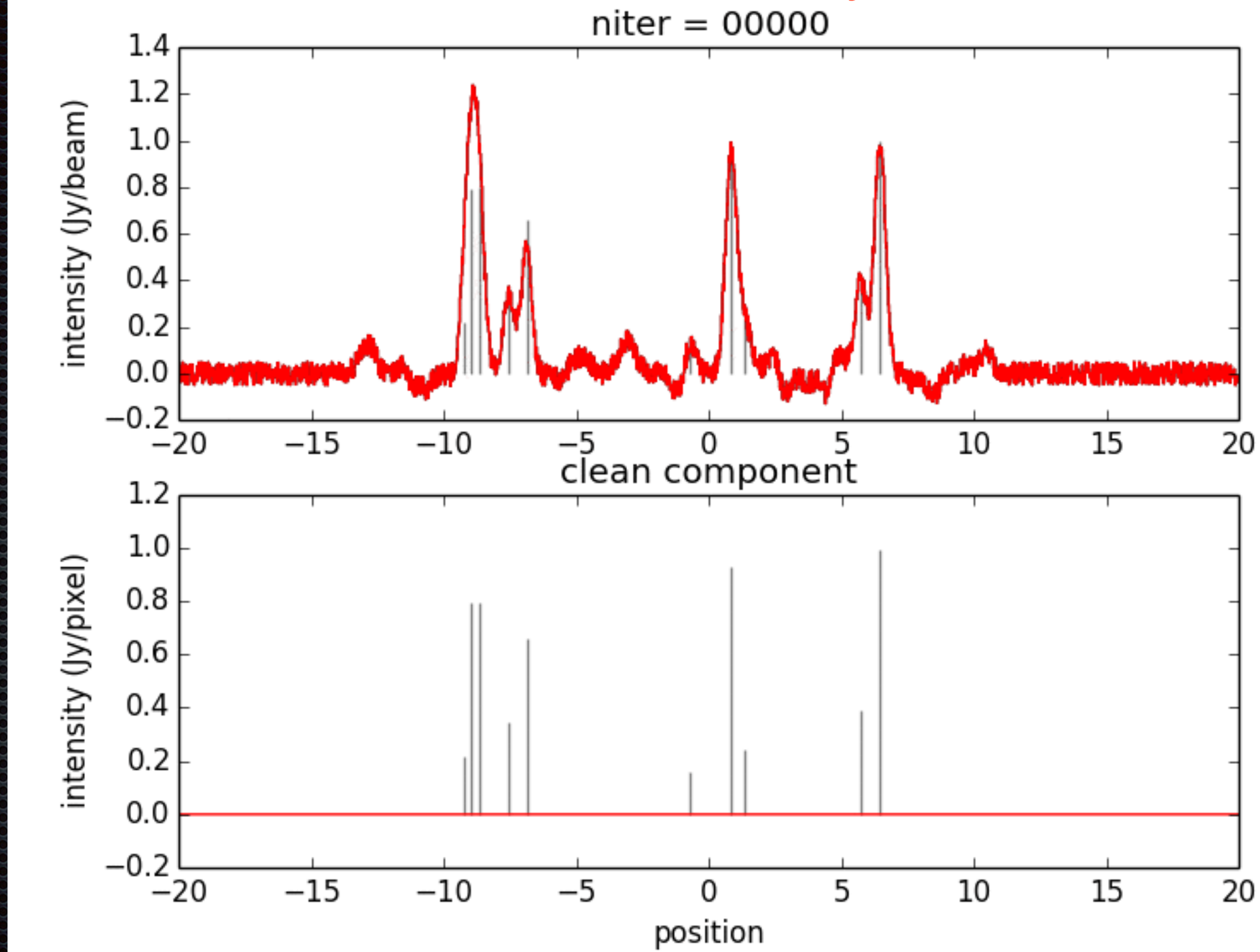
What if…

- I iterate the CLEAN process too many times?
- the strength of sidelobes is similar to the main lobe? (i.e., dirty map is really “dirty”)

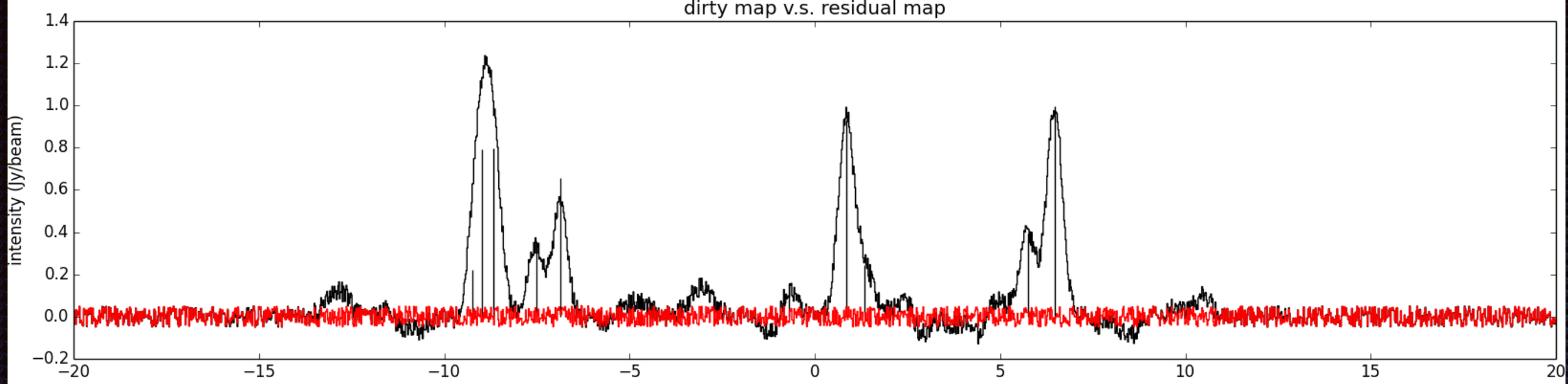
1D example 2



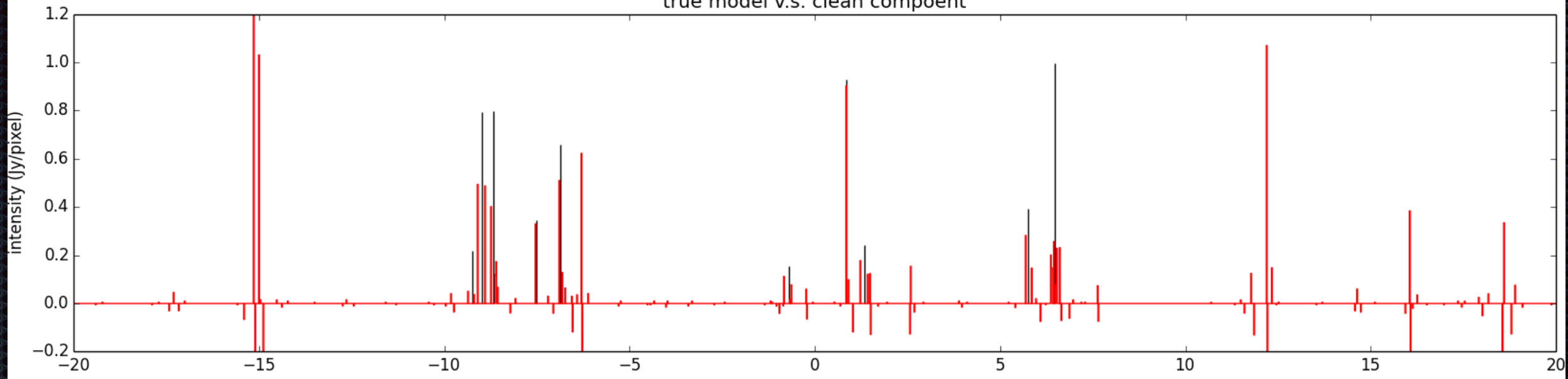
small sidelobes, too many iterations



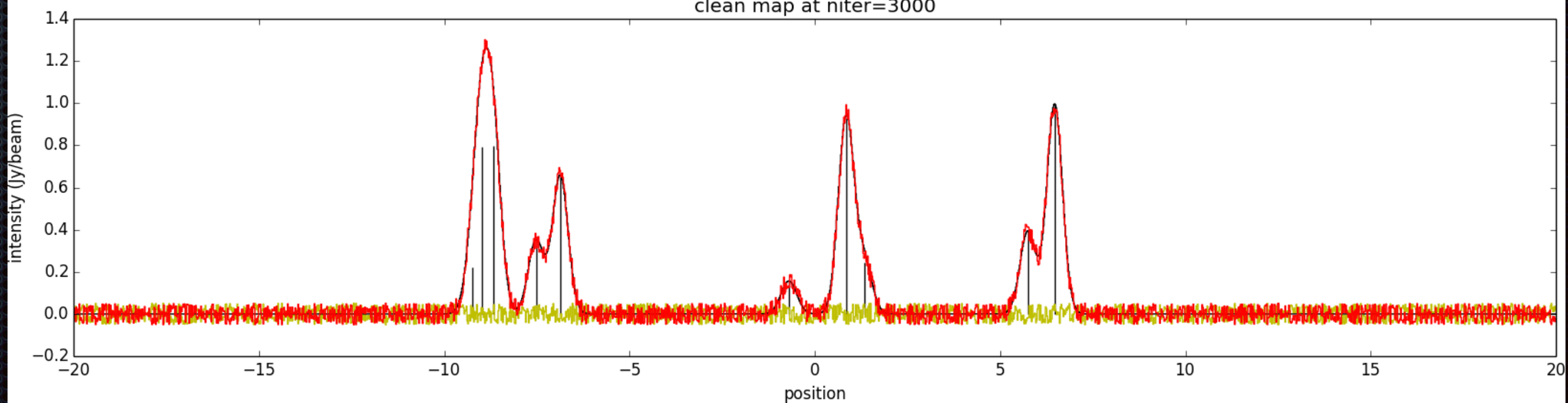
dirty map v.s. residual map



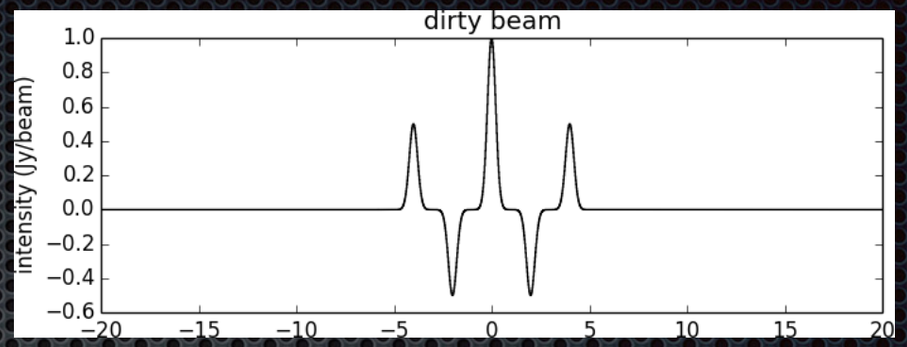
true model v.s. clean compoent



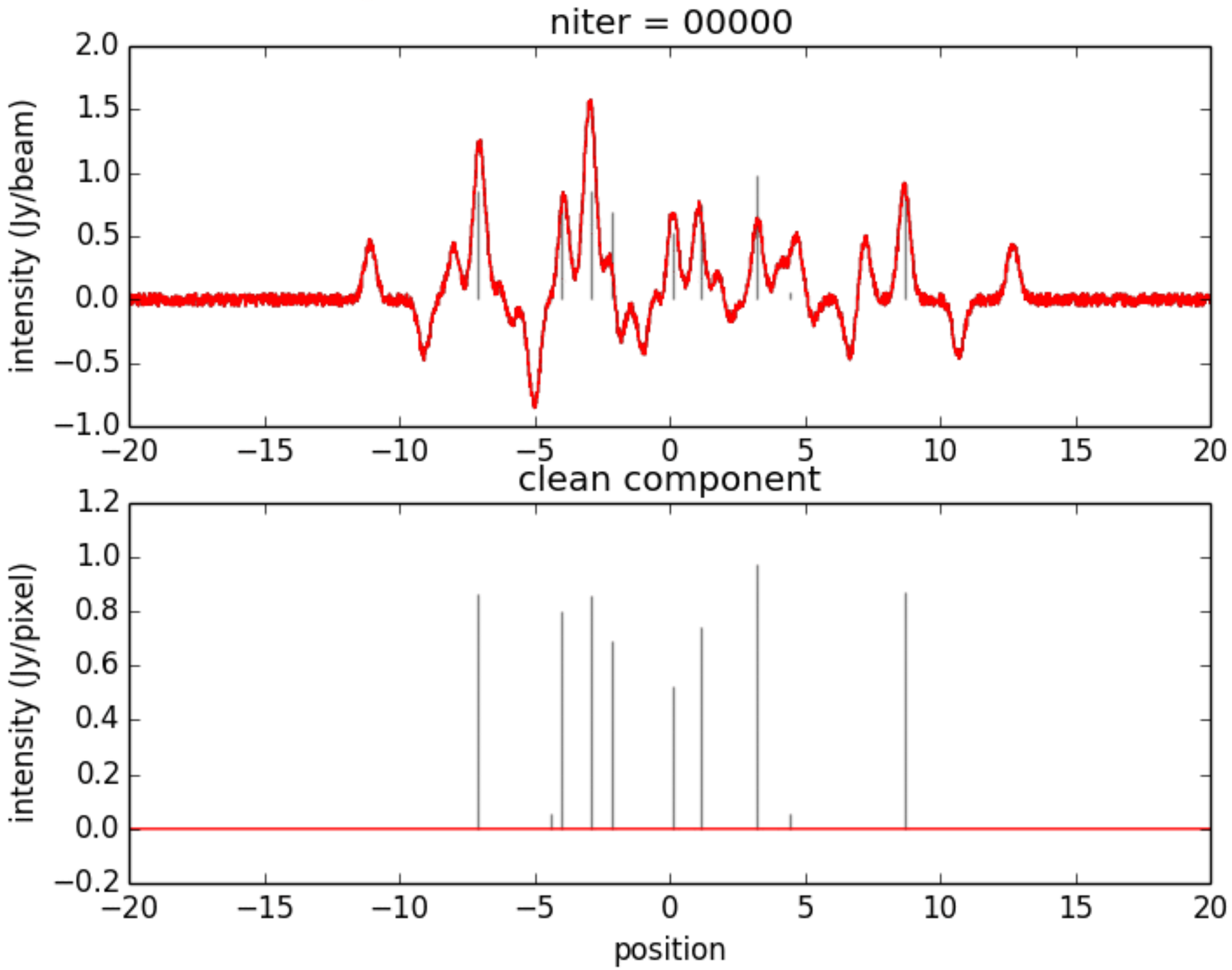
clean map at niter=3000



1D example 3



large sidelobes, a few iterations



dirty map v.s. residual map

intensity (Jy/beam)

true model v.s. clean compoent

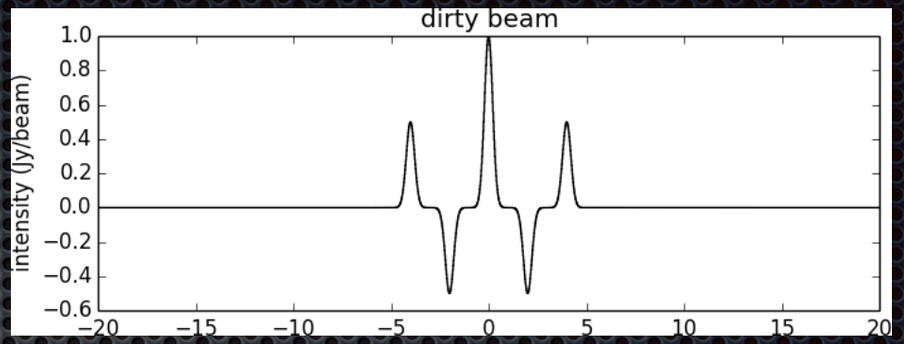
intensity (Jy/pixel)

clean map at niter=200

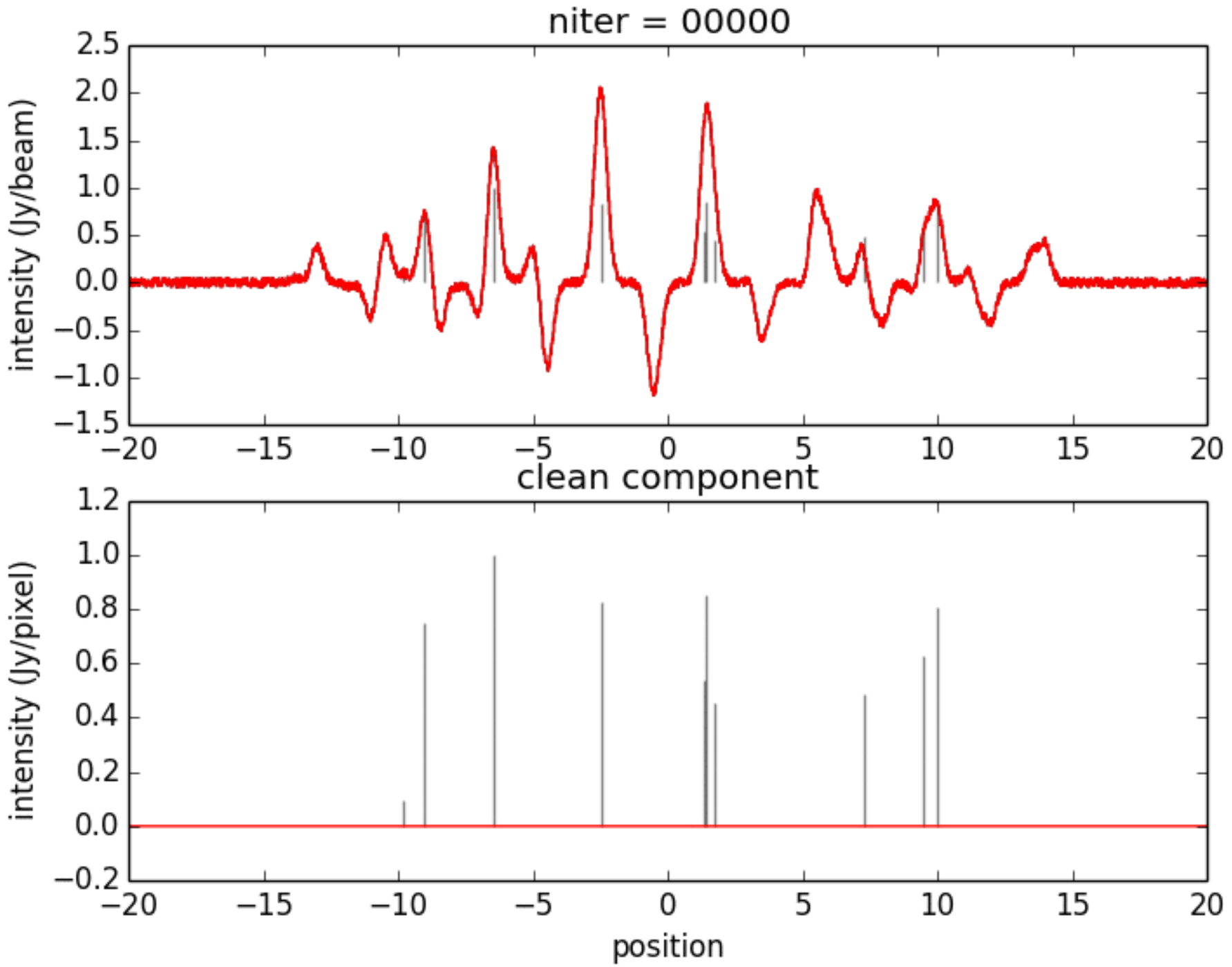
intensity (Jy/beam)

position

1D example 4



large sidelobes, too many iterations



dirty map v.s. residual map

intensity (Jy/beam)

true model v.s. clean compoent

intensity (Jy/pixel)

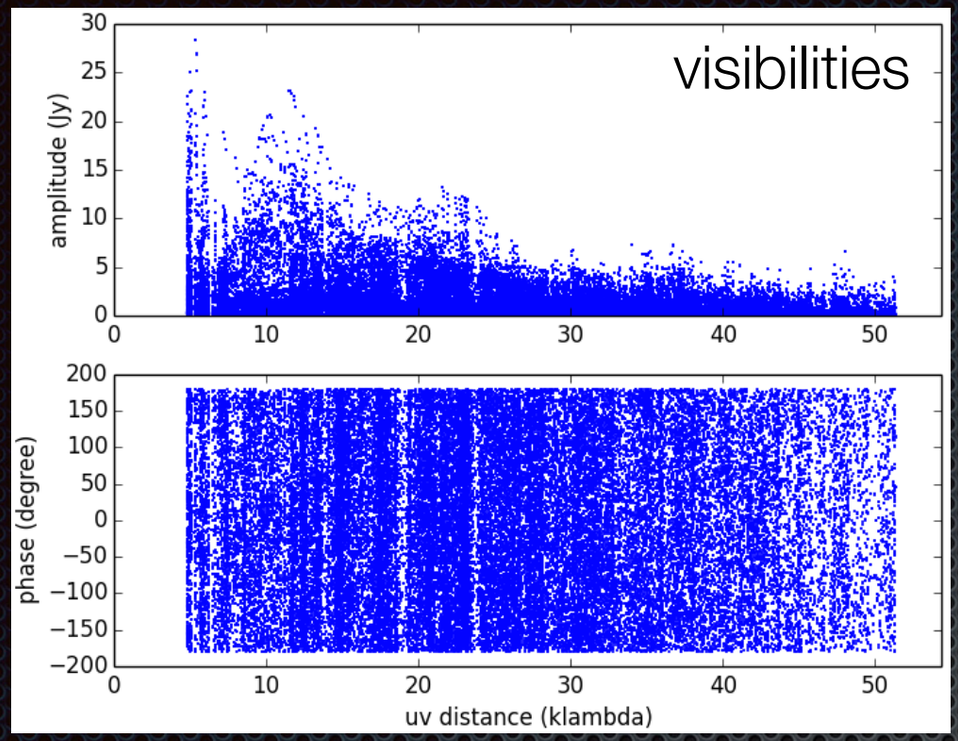
clean map at niter=3000

intensity (Jy/beam)

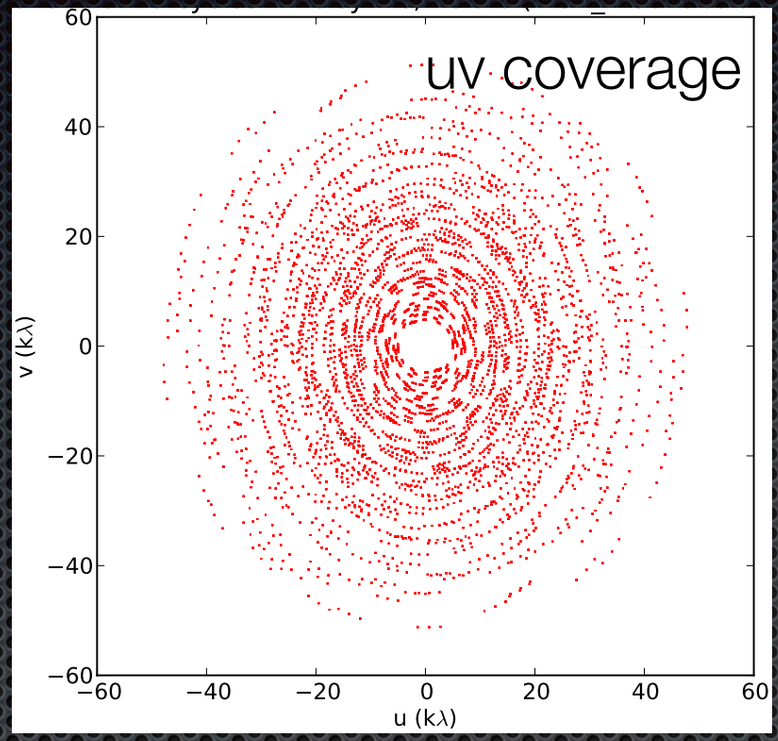
position

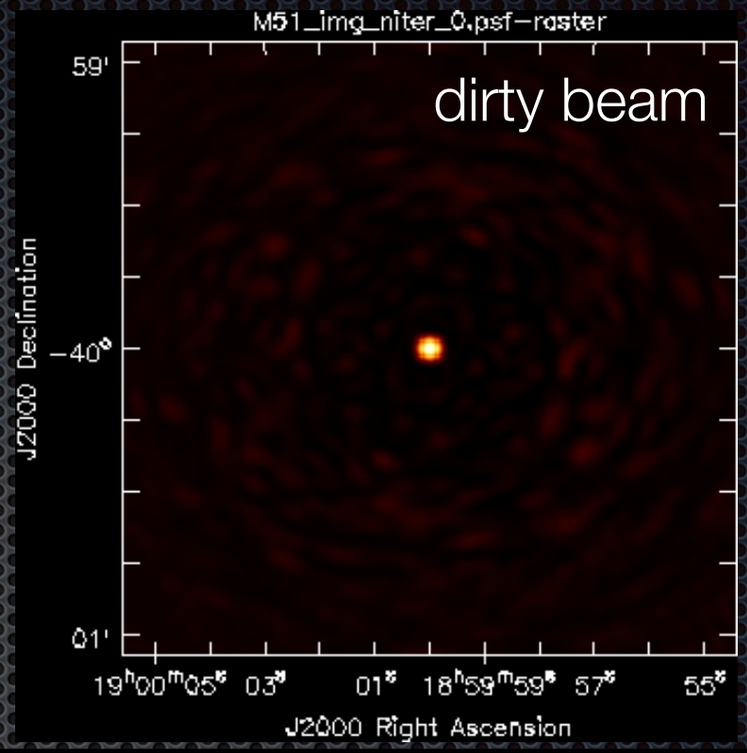
Real data: a face-on spiral galaxy

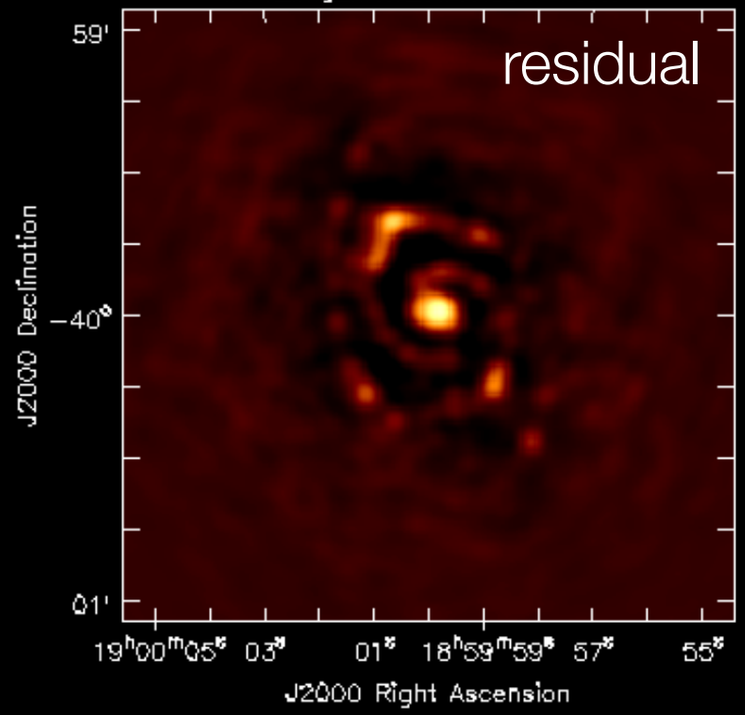
visibilities

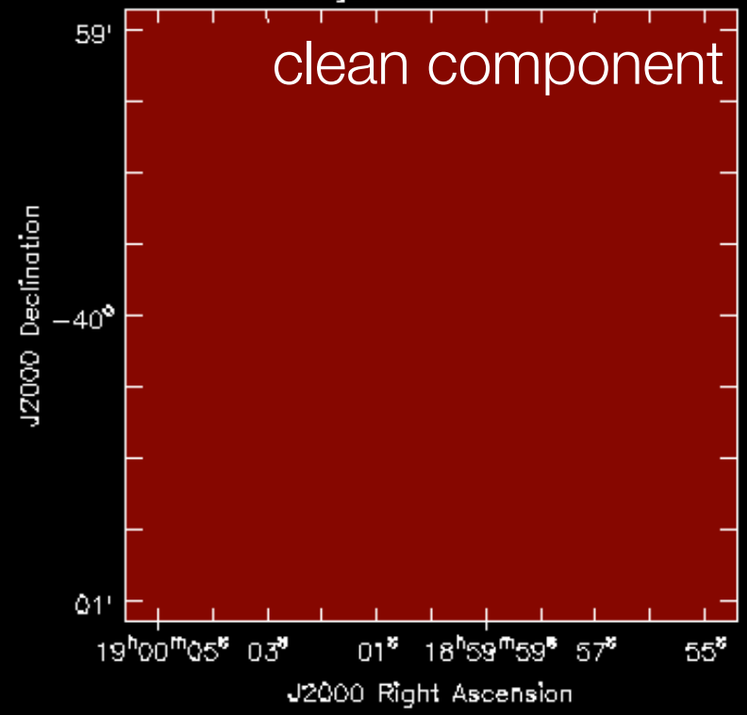


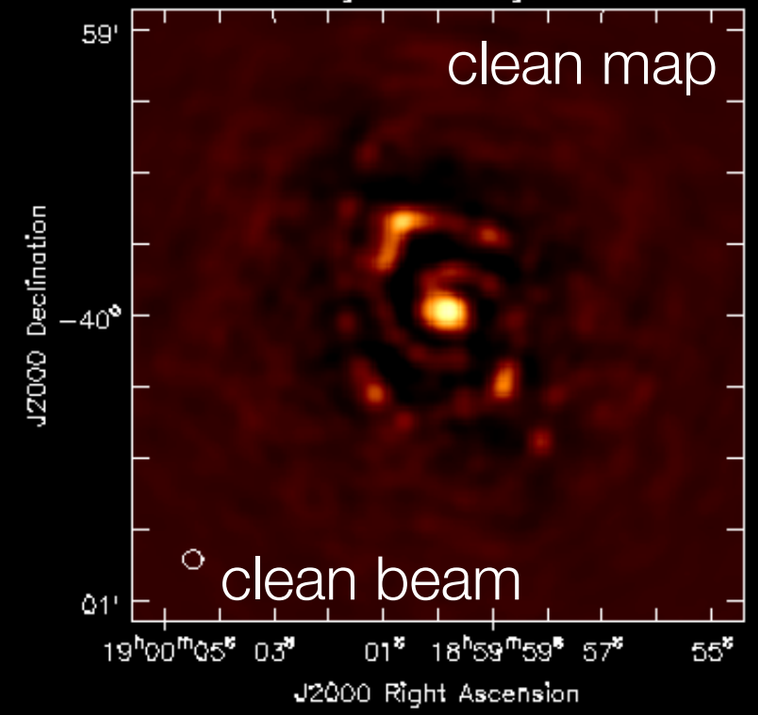
uv coverage











CLEAN: CASA setup

CLEAN with CASA

- CASA 4.7.2 (https://casa.nrao.edu/casa_obtaining.shtml)
- > casapy
- > inp clean
- > clean?

```
#  clean :: Invert and deconvolve images with selected algorithm
vis                 =         ''            #  Name of input visibility file
imagename           =         ''            #  Pre-name of output images
outlierfile         =         ''            #  Text file with image names, sizes,
                                            #   centers for outliers
field               =         ''            #  Field Name or id
spw                 =         ''            #  Spectral windows e.g. '0~3', '' is
                                            #   all
selectdata          =       True            #  Other data selection parameters
     timerange      =         ''            #  Range of time to select from data
     uvrange        =         ''            #  Select data within uvrange
     antenna        =         ''            #  Select data based on antenna/basel
     scan           =         ''            #  Scan number range
     observation    =         ''            #  Observation ID range
     intent         =         ''            #  Scan Intent(s)

mode                =      'mfs'            #  Spectral gridding type (mfs, chann
                                            #   velocity, frequency)
     nterms         =          1            #  Number of Taylor coefficients to
                                            #   model the sky frequency dependenc
     reffreq        =         ''            #  Reference frequency (nterms > 1),'
                                            #   uses central data-frequency
```

Important keywords

- vis

The value of the vis parameter is either the name of a single MS, or a list of strings containing the names of multiple MSs, that should be processed to produce the image. For example,

vis = 'ngc5921.ms'

set a single input MS, while

vis = ['ngc5921_day1.ms', 'ngc5921_day2.ms']

points to two separate measurement sets that will be gridded together to form the image.

Important keywords

- field

The field parameter selects the field indexes or names to be used in imaging. Unless you are making a mosaic, this is usually a single index or name:

```
field = '0' #   First field (index 0)
field = 'NGC1234' #  source name
field = '0~10' # 11 pointings to mosaic
```

Important keywords

- spw

The spw parameter selects the spectral windows that will be used to form the image, and possibly a subset of channels within these windows.
The spw parameter is a string with an integer, list of integers, or a range, e.g.

```
spw = '1' #  select spw 1
spw = '0,1,2,3' #  select spw 0,1,2,3
spw = '0~3' #  same thing using ranges
spw = '1:10~30' # select channels 10-30 of spw 1
spw = '0:5~55,3:5;6;7' # chans 5-55 of spw 0 and 5,6,7 of spw 3
```

Important keywords

- imagename

The clean task will produce a number of output images based on the root name given in imagename. These include:

<imagename>.image # the restored image
<imagename>.flux # the effective response (e.g. for pbcor)
<imagename>.flux.pbcoverage # the PB coverage
(ftmachine='mosaic' only)
<imagename>.model # the model image
<imagename>.residual # the residual image
<imagename>.psf # the synthesized (dirty) beam

Important keywords

- imagename

  WARNING: If an image with that name already exists, it will in general be overwritten. Beware using names of existing images. However, if the clean is run using an imagename where <imagename>.residual and <imagename>.model already exist then clean will continue starting from these (effectively restarting from the end of the previous clean). Thus, if multiple runs of clean are run consecutively with the same imagename, then the cleaning is incremental.

Important keywords

- cell

The cell parameter defines the pixel size in the x and y axes for the output image. If given as floats or integers, this is the cell size in arc seconds, e.g.

cell=[0.5,0.5]

make 0.5′′ pixels. You can also give the cell size in quantities, e.g.

cell=[’1arcmin’, ’1arcmin’]

If a single value is given, then square pixels of that size are assumed.

Usually cell = 1/5 of the minor axis of the clean beam

Important keywords

- imsize

  The image size in numbers of pixels on the x and y axes is set by imsize. For example,

  imsize = [640, 640]

  makes a square image 640 pixels on a side.
  In general, the best performance is obtained with image sizes that are even and factorizable to 2,3,5,7 only. An easy rule of thumb would be 2n × 10 where n is an integer number, like 160, 320, 640, 1280, 2560, etc.

  Usually imsize= FOV (1.22λ/D) or mosaic area+half FOV each side

Important keywords

- phasecenter

The phasecenter parameter indicates which of the field IDs should be used to define the phase center of the mosaic image, or what that phase center is in RA and Dec. The default action is to use the first one given in the field list.
For example:

phasecenter=’5’ # field 5
phasecenter=’J2000 19h30m00 -40d00m00’ # specified position

Important keywords

- mode (expandable)

The mode parameter defines how the frequency channels in the synthesis MS are mapped onto the image. The allowed values are:

mfs # multi-frequency-synthesis, for continuum imaging

channel # image the specified channels

velocity # for line imaging

frequency # grid in frequency

e.g. LSRK, BARY

```
mode                =  'velocity'        #  Spectral gr
                                         #   velocity,
nchan               =            -1      #  Number of c
                                         #   image; -1
start               =            ''      #  Velocity of
                                         #   '0.0km/s'(
                                         #   SpW of MS)
width               =            ''      #  Channel wid
                                         #   (''=width
                                         #   SpW of MS)
interpolation       =     'linear'       #  Spectral in
                                         #   linear, cu
resmooth            =         False      #  Re-restore
                                         #   beam when
chaniter            =         False      #  Clean each
                                         #   (True), or
                                         #   (False)
outframe            =            ''      #  spectral re
                                         #   image; ''
veltype             =      'radio'       #  Velocity de
```

Important keywords

- imagermode

This choose the mode of operation of clean, either as single-field deconvolution using image-plane major and minor cycles only (imagermode=’ ’), single-field deconvolution using Cotton-Schwab (CS) residual visibilities for major cycles (imagermode=’csclean’), or multi-field mosaics using CS major cycles (imagermode=’mosaic’).

In the CS mode, cleaning is split into minor and major cycles. For each field, a minor cycle is performed using the PSF algorithm specified in psfmode. At major-cycle breakpoints, the points thus found are subtracted from the original visibilities.

Important keywords

- psfmode

The psfmode parameter chooses the “algorithm” that will be used to calculate the synthesized beam for use during the minor cycles in the image plane. The value types are strings. Allowed choices are ’clark’ (default) and ’hogbom’.

Important keywords

- gain

The gain parameter sets the fraction of the flux density in the residual image that is removed and placed into the clean model at each minor cycle iteration. The default value is gain = 0.1 and is suitable for a wide-range of imaging problems. Setting it to a smaller gain per cycle, such as gain = 0.05, can sometimes help when cleaning images with lots of diffuse emission.

Important keywords

- threshold

The threshold parameter instructs clean to terminate when the maximum absolute residual reaches this level or below. Note that it may not reach this residual level due to the value of the niter parameter which may cause it to terminate early.

threshold = ‘0.1mJy’

- niter

The niter parameter sets the maximum total number of minor-cycle CLEAN iterations to be performed during this run of clean.

niter = 2000

Important keywords

- weighting

To determine how we weight the visibilities.
For weighting='natural', visibilities are weighted only by the data weights, which are calculated during filling and calibration and should be equal to the inverse noise variance on that visibility. It gives best signal-to-noise ratio, worst angular resolution.

For weighting = 'uniform', the data weights are calculated as in 'natural' weighting. The data is then gridded to a number of cells in the uv-plane, and after all data is gridded the uv-cells are re-weighted to have "uniform" imaging weights. It gives best angular resolution, worst signal-to-noise ratio.

The weighting = 'briggs' mode is an implementation of the flexible weighting scheme. The robust keyword takes value between –2.0 (close to uniform weighting) to 2.0 (close to natural).

Important keywords

- restfreq

The value of the restfreq parameter, if set, will overwrite the rest frequency in the header of the first input ms to define the velocity frame of the output image. For example:

restfreq='115.2712GHz',

will set the rest frequency to that of the CO 1-0 line.

ALERT: Setting restfreq explicitly here in clean is good practice, and may be necessary if your ms has been concatenated from different files for different spectral windows

Important keywords

- mask

To limit the clean algorithm where to look for clean components. Default is the full image plane. Putting a mask is sometimes useful for poor dirty beam and for somehow known source structure. Check manual for more detail.

- pbcor

The pbcor parameter (True or False) controls whether the final .image is scaled to correct for the Primary Beam of the array or not. Check the task impbcor as well.

Important keywords

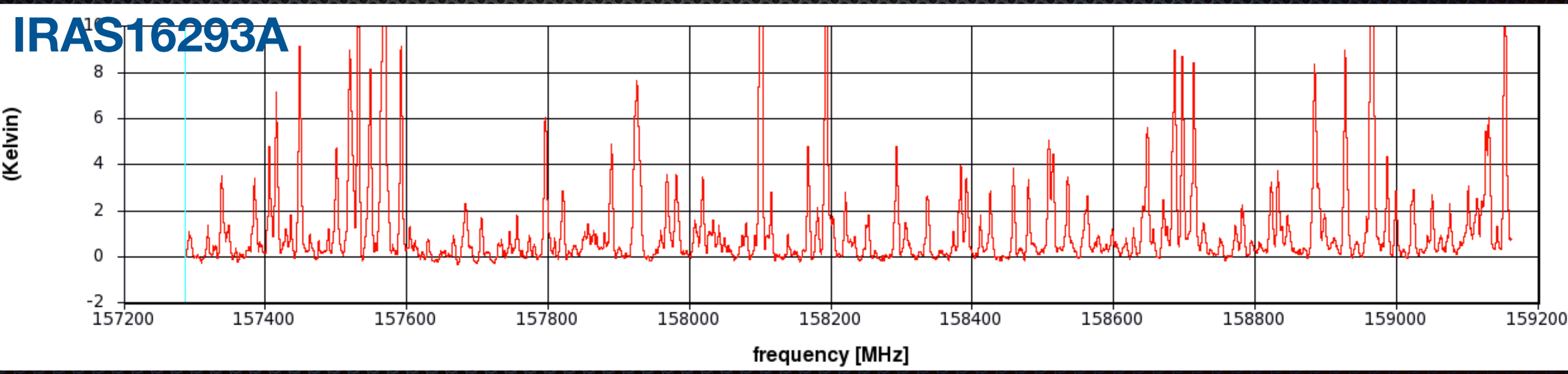
check manual or type “clean?” for more information

CLEAN: hands-on

Before we start

- Demo dataset: “continuum.ms” and “molecular_line.ms”, both come from the IRAS16293-2422 Band4 science verification (SV) dataset (https://almascience.nao.ac.jp/almadata/sciver/IRAS16293Band4/)

- IRAS16293-2422: a low-mass protostellar binary system with a rich amount of molecular line emission



The contents of a MS: listobs

```
CASA <2>: listobs vis='continuum.ms'
```

- With “listobs”, figure out
  - How many fields are observed?
  - How many spectral windows (spw)in the ms?
    - Center frequency?
    - Bandwidth?
    - Number of channels?
    - Channel width?
  - How many antennae in the array?

CASA <2>: listobs vis='continuum.ms'

Log Messages (:/Users/kswang/Documents/synthesis_imaging_tutorial2016/demo_dataset/casapy-20160818-021652.log)

Search Message: Filter: Time

Message

```
CASA Version 4.6.0-REL (r36590)
  Tagged on: 2016-04-01 11:11:00 -0400 (Fri, 01 Apr 2016)

##########################################
##### Begin Task: listobs             #####
listobs(vis="continuum.ms",selectdata=True,spw="",field="",antenna="",
        uvrange="",timerange="",correlation="",scan="",intent="",
        feed="",array="",observation="",verbose=True,listfile="",
        listunfl=False,cachesize=50,overwrite=False)
================================================================================
           MeasurementSet Name:  /Users/kswang/Documents/synthesis_imaging_tutorial2016/demo_dataset/continuum.ms      MS Version 2
================================================================================
   Observer: satoko     Project: uid://A002/X8666bf/Xc
Observation: ALMA
Data records: 166980       Total elapsed time = 4550.98 seconds
   Observed from   11-Jul-2014/04:11:36.5   to   11-Jul-2014/05:27:27.5 (UTC)
Compute subscan properties

   ObservationID = 0         ArrayID = 0
  Date        Timerange (UTC)          Scan  FldId FieldName             nRows     SpwIds   Average Interval(s)    ScanIntent
  11-Jul-2014/04:11:36.5 - 04:17:56.8     9      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              04:18:56.3 - 04:25:16.6    11      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              04:26:37.0 - 04:32:57.2    14      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              04:34:03.9 - 04:40:24.2    16      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              04:41:46.9 - 04:48:07.2    19      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              04:49:06.5 - 04:55:26.7    21      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              04:56:45.0 - 05:03:05.3    24      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              05:04:12.9 - 05:10:33.2    26      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              05:11:57.0 - 05:18:17.2    29      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              05:19:17.2 - 05:25:37.4    31      0 IRAS16293-2422          16560  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
              05:26:57.3 - 05:27:27.5    34      0 IRAS16293-2422           1380  [0]   [6.05] [OBSERVE_TARGET#ON_SOURCE]
          (nRows = Total number of rows per scan)
Fields: 1
  ID   Code Name                RA               Decl           Epoch   SrcId      nRows
  0    none IRAS16293-2422      16:32:22.735600 -24.28.32.50000 J2000   0         166980
Spectral Windows:  (1 unique spectral windows and 1 unique polarization setups)
  SpwID  Name                           #Chans   Frame   Ch0(MHz)  ChanWid(kHz)  TotBW(kHz) CtrFreq(MHz) BBC Num  Corrs
  0      ALMA_RB_04#BB_4#SW-01#FULL_RES    192   TOPO  146977.222     -9765.625   1875000.0 146044.6047        4  XX  YY
Sources: 1
  ID   Name               SpwId RestFreq(MHz)  SysVel(km/s)
  0    IRAS16293-2422     0     146050         3
Antennas: 23:
```

The contents of ms: listobs

```
CASA <2>: listobs vis='continuum.ms'
```

command line mode, scripting style

- With “listobs”, figure out
  - How many fields are observed? [one, ID = 0]
    - How many spectral windows (spw)in the ms? [one, ID = 0]
      - Center frequency? [146044.6047 MHz TOPO frame]
      - Bandwidth? [1.875 GHz]
      - Number of channels? [192]
      - Channel width? [-9.765625 MHz]
- How many antennae in the array? [23]

Set up “CLEAN”

`CASA <14>: clean?`

full user guide for help

`CASA <9>: inp clean` *interactive mode*

```
#  clean :: Invert and deconvolve images with selected algorithm
vis                 =         ''            #  Name of input visibility file
imagename           =         ''            #  Pre-name of output images
outlierfile         =         ''            #  Text file with image names, sizes,
                                            #   centers for outliers
field               =         ''            #  Field Name or id
spw                 =         ''            #  Spectral windows e.g. '0~3', '' is
                                            #   all
selectdata          =       True            #  Other data selection parameters
     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)

mode                =      'mfs'            #  Spectral gridding type (mfs, channel,
                                            #   velocity, frequency)
     nterms         =          1            #  Number of Taylor coefficients to
                                            #   model the sky frequency dependence
     reffreq        =         ''            #  Reference frequency (nterms > 1),''
                                            #   uses central data-frequency

gridmode            =         ''            #  Gridding kernel for FFT-based
                                            #   transforms, default='' None
niter               =        500            #  Maximum number of iterations
gain                =        0.1            #  Loop gain for cleaning
```

Set up “CLEAN” (continuum imaging)

```
CASA <9>: inp clean
```

- Essential (necessary) keywords
  - vis = ‘continuum.ms’
  - imagename = ‘I16293_cont’
  - field = ‘0’
  - spw = ‘0’
  - mode = ‘mfs’ # mfs means multi-frequency synthesis. We use this mode for continuum imaging.
  - niter = 3000
  - gain = 0.1 # this is the default, usually a good number
  - threshold = ‘0.9mJy’

Set up “CLEAN” (continuum imaging)

- Essential (necessary) keywords
  - psfmode = ‘clark’
  - imagermode = ‘csclean’
  - cell = [‘0.15arcsec’,’0.15arcsec’]
  - imsize = [256,256]
  - weighting = ‘natural’ / weighting = ‘uniform’
  - pbcor = False
  - when you are ready, type ‘go’

Image visualization

`CASA <9>: viewer`

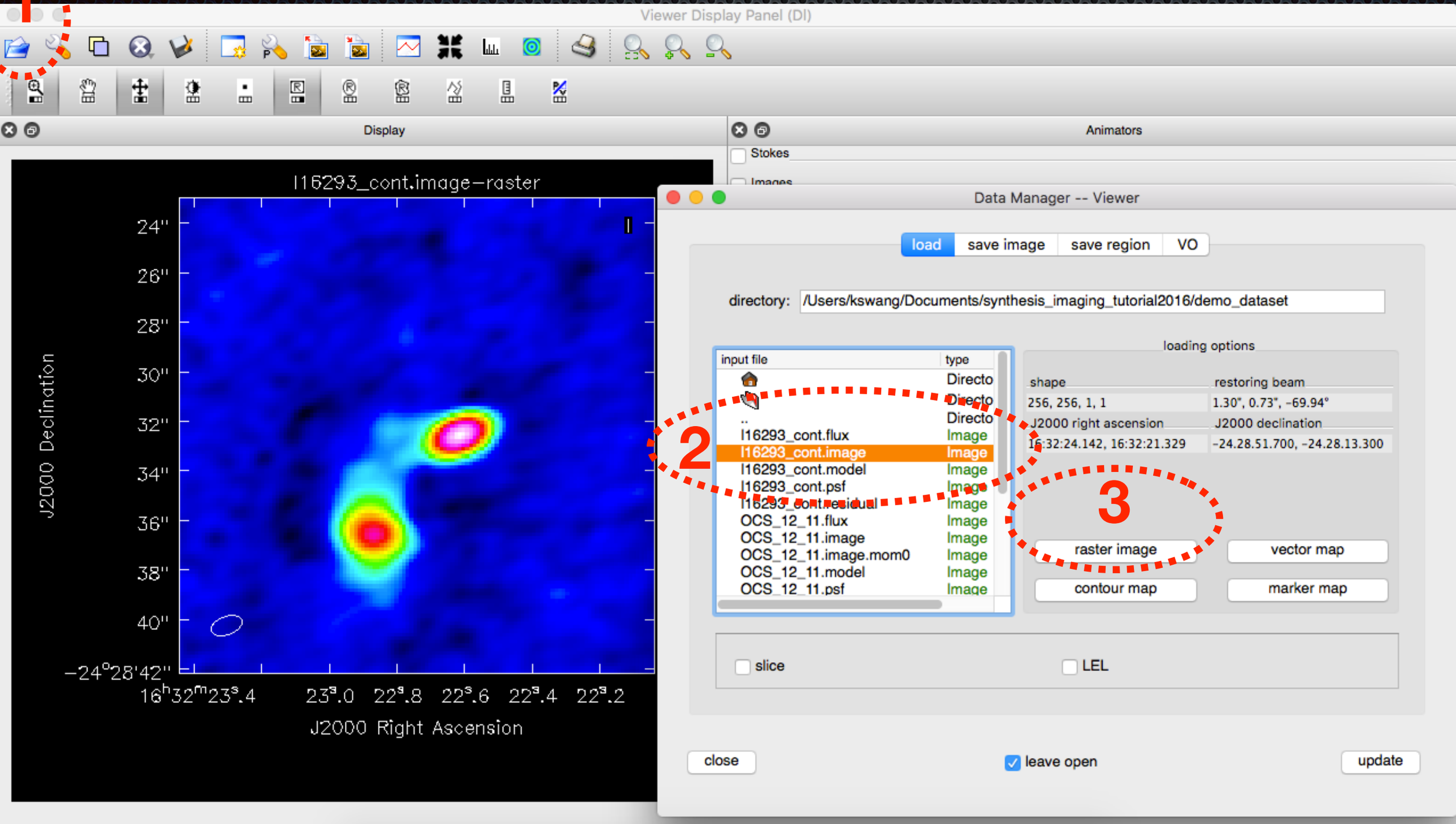
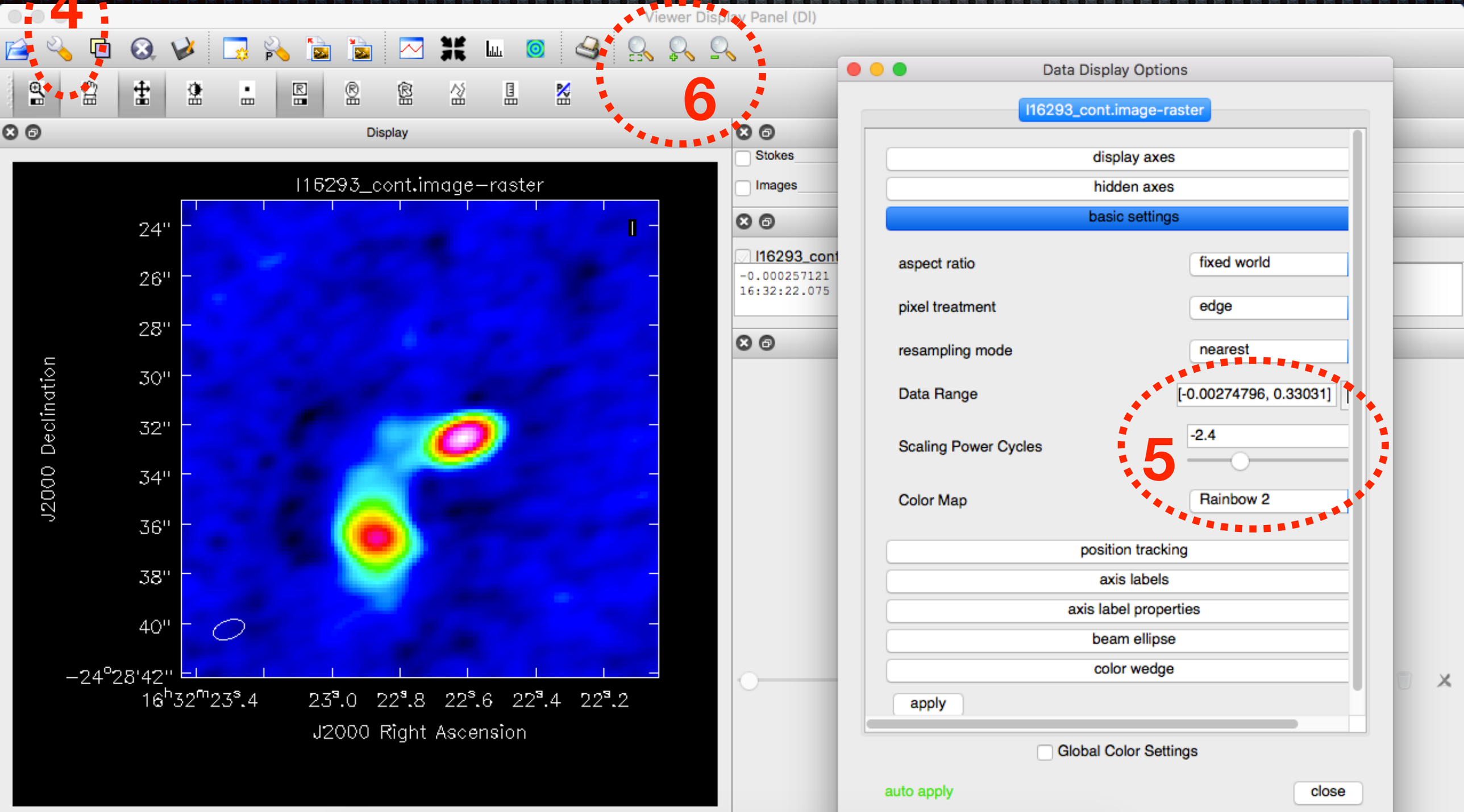
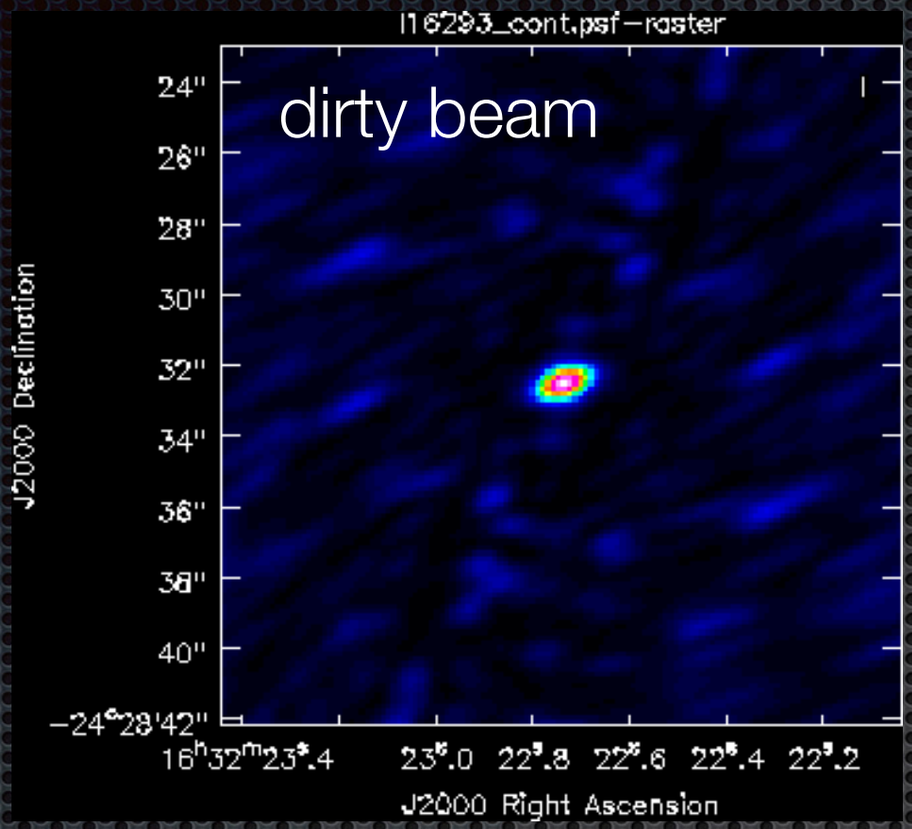


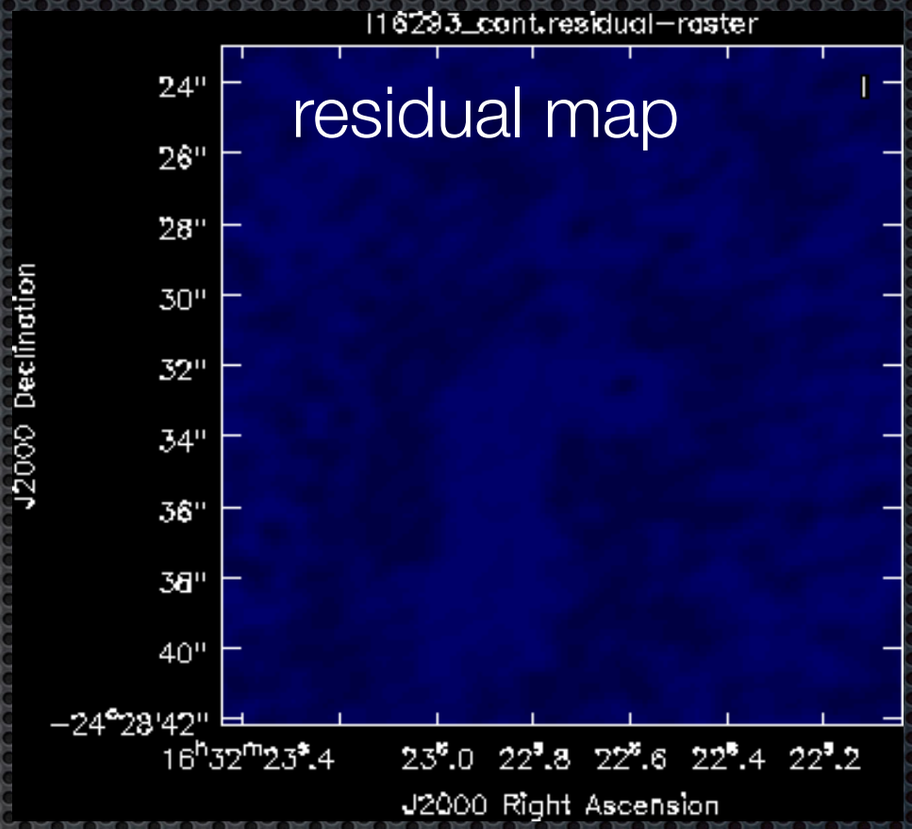
Image visualization

`CASA <9>: viewer`



IRAS 16293-2422 Continuum





Set up “CLEAN” (line imaging)

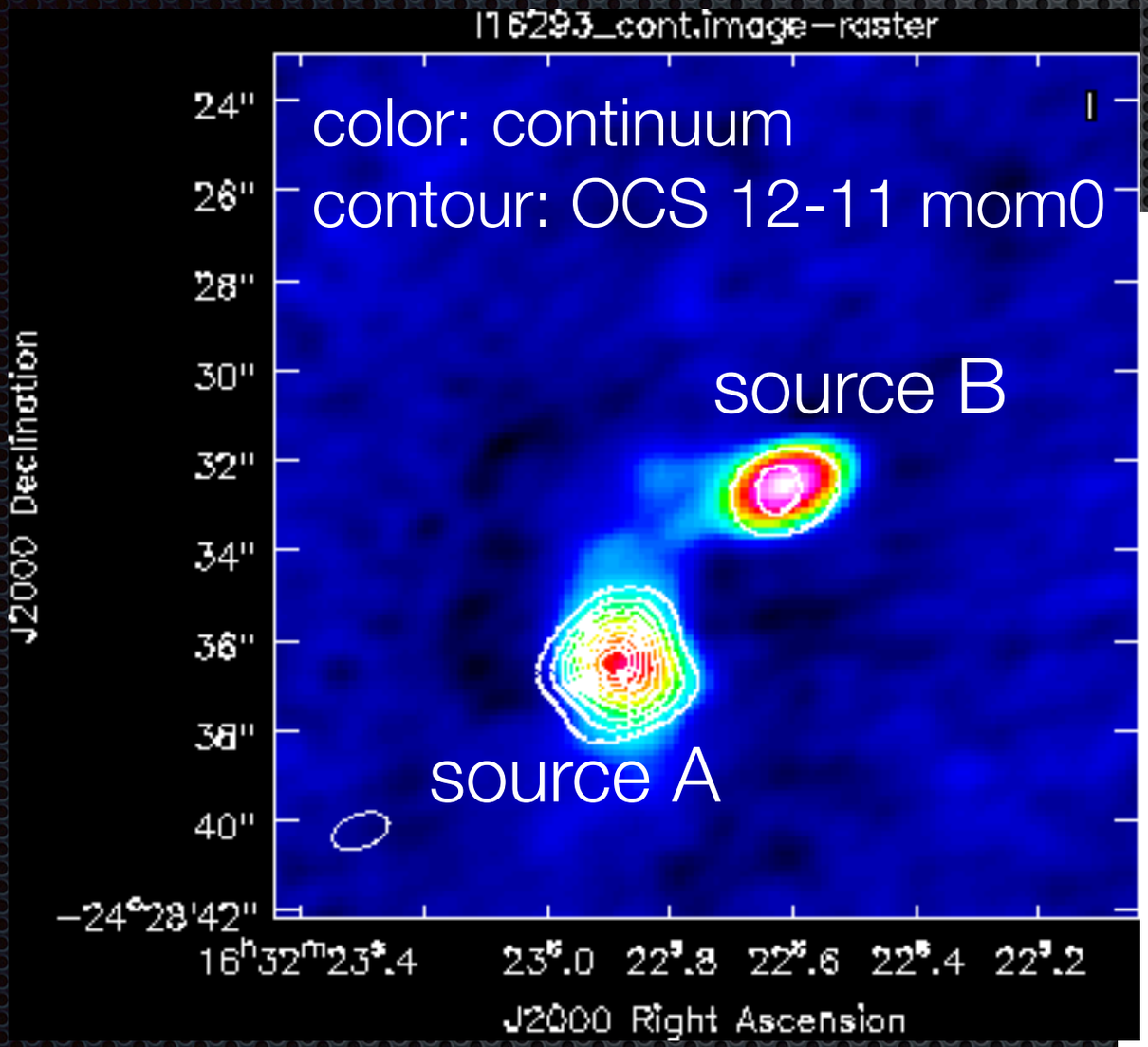
```
CASA <8>: listobs vis='molecular_line.ms'
CASA <9>: inp clean
```

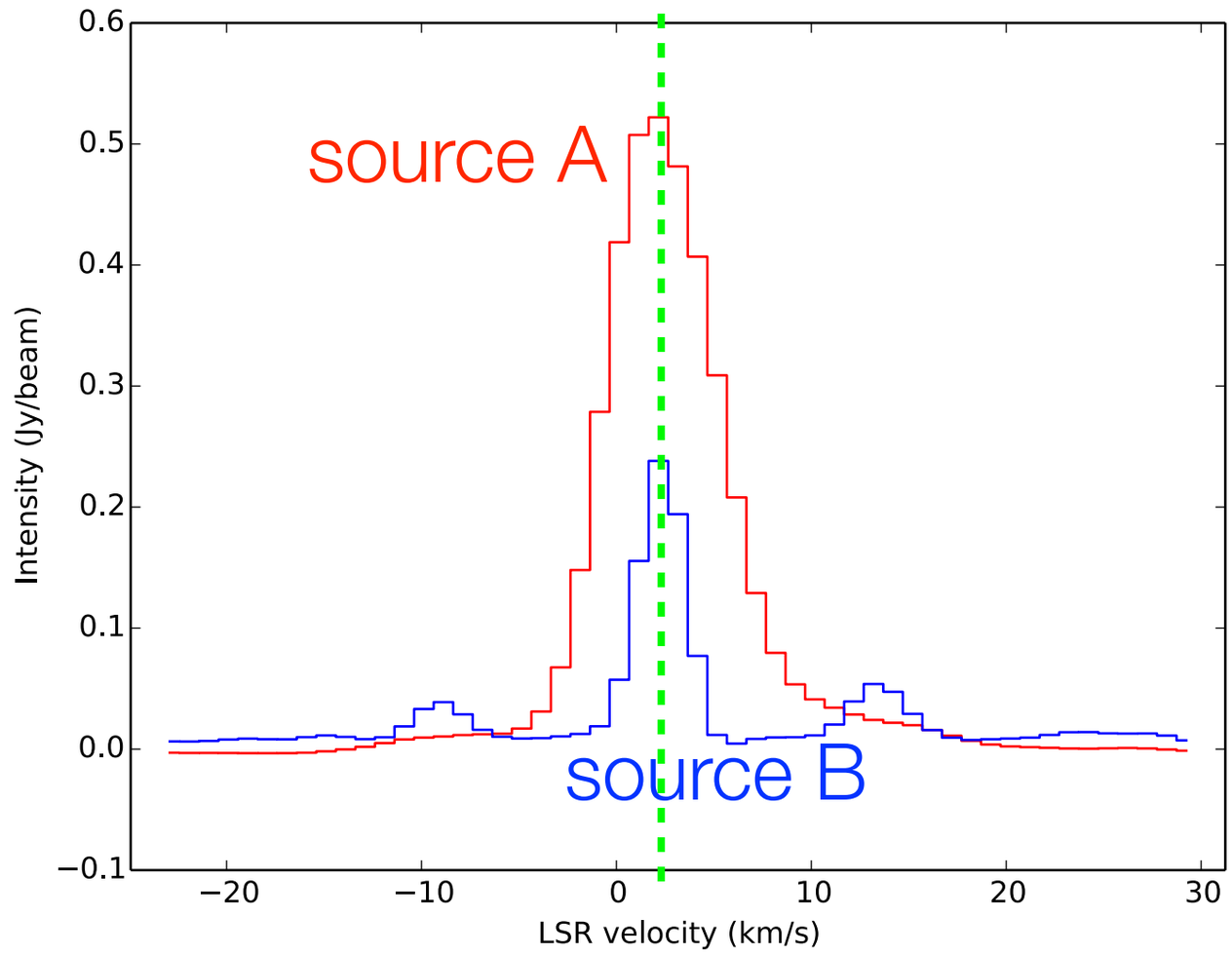
- Essential (necessary) keywords
  - vis = ‘molecular_line.ms’
  - imagename = ‘OCS_12_11’
  - field = ‘0’
  - spw = ‘0’
  - mode = ‘velocity’
  - niter = 3000
  - gain = 0.1
  - threshold = ‘5mJy’

Set up “CLEAN” (line imaging)

- Essential (necessary) keywords
  - psfmode = ‘clark’
  - imagermode = ‘csclean’
  - outframe = ‘LSRK’
  - restfreq = ‘145946.815MHz’
  - cell = [‘0.15arcsec’,’0.15arcsec’]
  - imsize = [256,256]
  - weighting = ‘natural’ / weighting = ‘uniform’
  - pbcor = False
  - when you are ready, type ‘go’

IRAS 16293-2422 OCS 12-11





Excellent reference to read

- CASA cookbook, Chapter 5 (https://casa.nrao.edu/casa_cookbook.pdf)
- “CLEAN” algorithm (Högbom 1974; http://adsabs.harvard.edu/abs/1974A%26AS...15..417H)
- “Bible”
  - Interferometry and Synthesis in Radio Astronomy (http://as.wiley.com/WileyCDA/WileyTitle/productCd-0471254924.html)
  - Synthesis Imaging in Radio Astronomy II (http://www.aspbooks.org/a/volumes/table_of_contents/?book_id=292)

Quiz

- How to generate dirty image with CLEAN?
- Try to image “m51_mockObs.ms”
  - input hints
    - field=‘0~22’
    - imsize=[512,512]
    - cell = [‘0.5arcsec’,’0.5arcsec’]
    - phasecenter = ‘11’