Multi-bands

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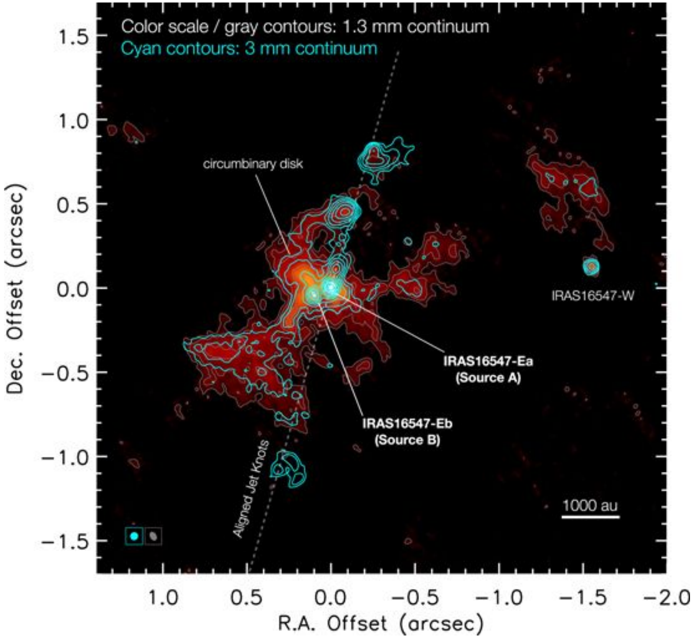
Outline

1. Introduction and ALMA observation
2. Processing raw data from CASA – tclean, convolve, regrid, align the data
3. Spectral index and brightness temperature estimates
4. Spectral cube - convolve, MADCUBA, model fitting, rotational diagram
5. Physical quantities from ALMA bands – column density, dust mass, gas mass

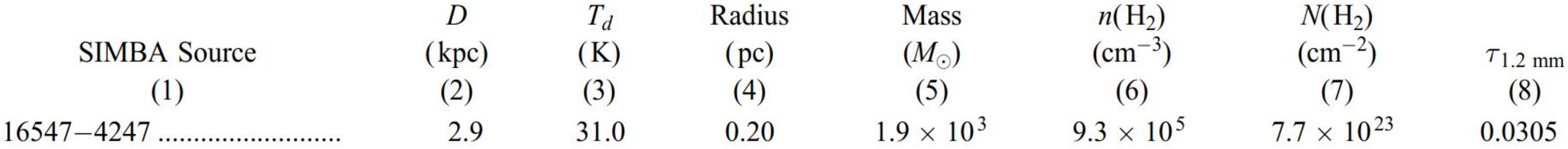
Source: G343.12-0.06 (IRAS 16547-4247)

- High-mass star forming region at 2.9 kpc
- O-type proto-binary system(separation: 300 au)
- Radio Thermal (free–free) Jet:
  spectral index of the lobes suggests a mix of thermal and non-thermal emission (Araudo+2007)
- Methyl cyanide CH3CN: trace the dense core gas

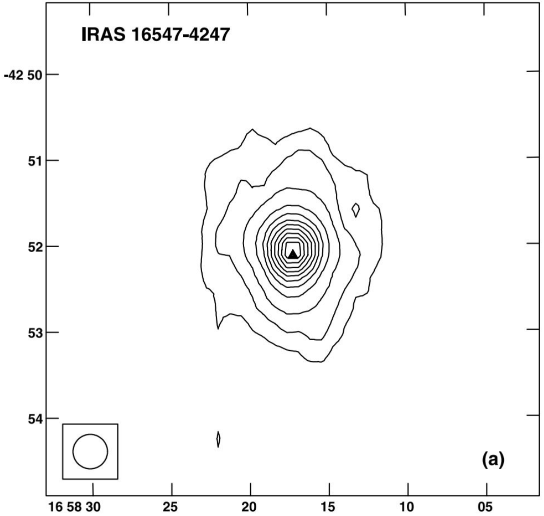


(Tanaka+2020)

Previous Single Dish Studies



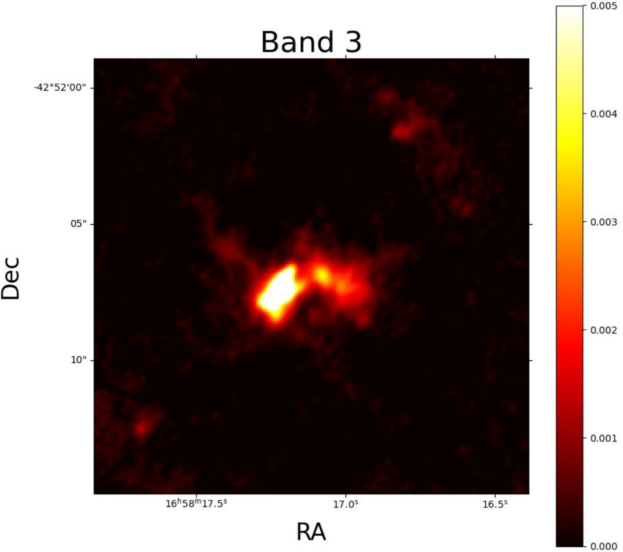
SIMBA Source (1)	D (kpc) (2)	T_d (K) (3)	Radius (pc) (4)	Mass ($M_\odot$) (5)	$n(H_2)$ (cm^{-3}) (6)	$N(H_2)$ (cm^{-2}) (7)	$\tau_{1.2\ mm}$ (8)
16547−4247	2.9	31.0	0.20	1.9×10^3	9.3×10^5	7.7×10^{23}	0.0305



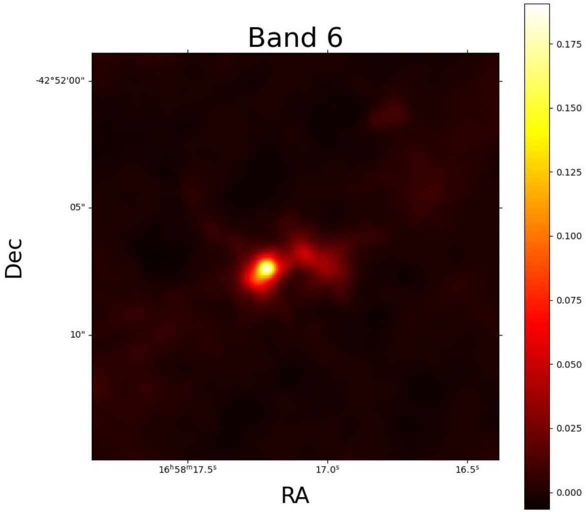
(Garay+2007)

ALMA Observations

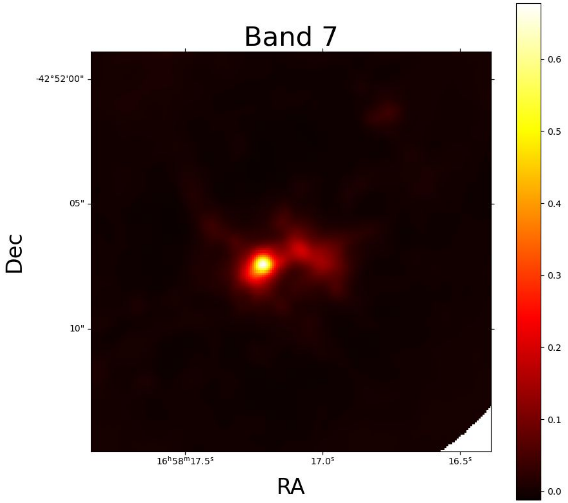
Band 3: 2017.1.00377.S



Band 6: 2017.1.00237.S



Band 7: 2017.1.00377.S



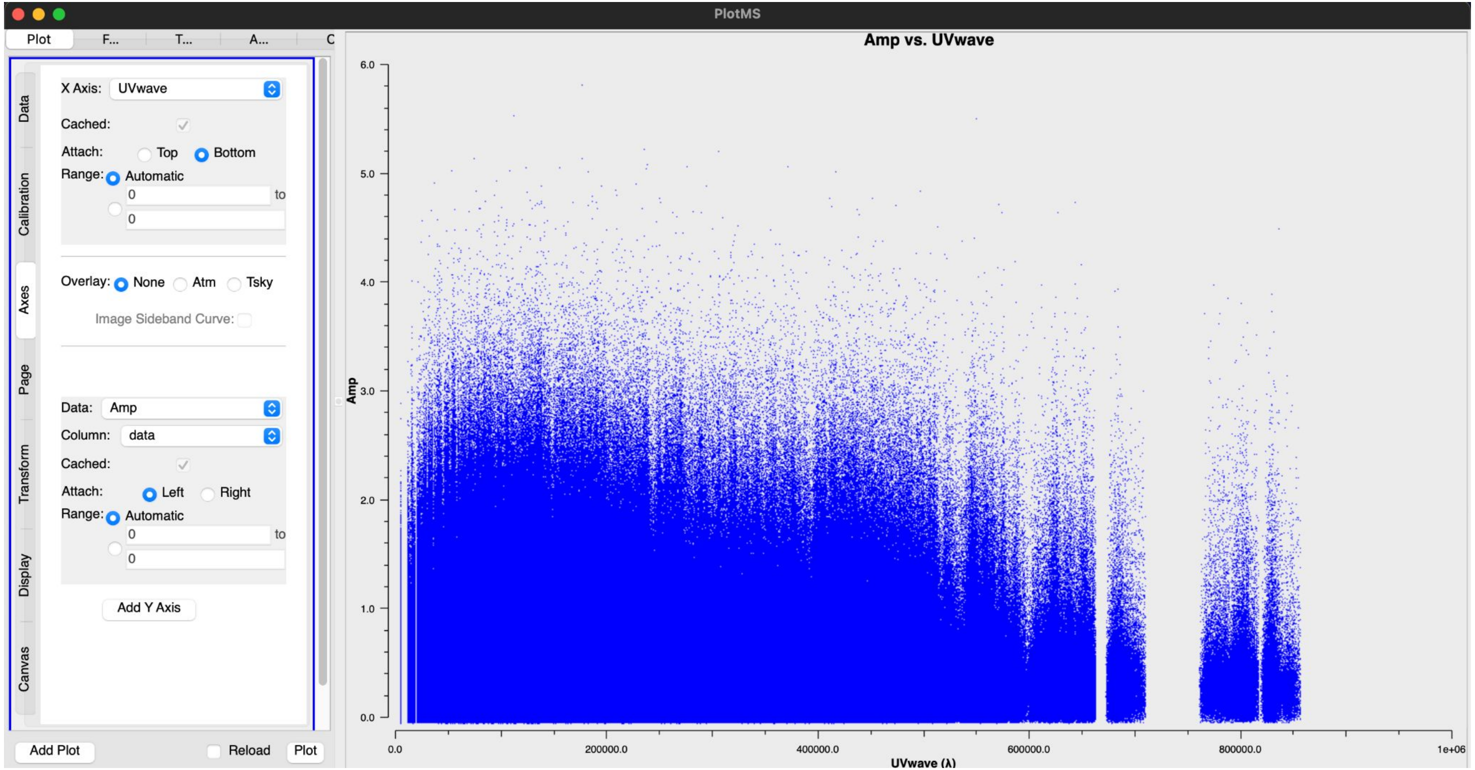
Tools

1. CASA
2. CARTA
3. MADCUBA
4. radio_beam
5. spectral_cube: convolve data

CASA reduction

Homogenizing the data from multiple ALMA bands

- ➔ Select common uv visibility range



X Axis: UVwave

Cached: ☑

Attach: ○ Top ● Bottom

Range: ● Automatic

○ 0 to 0

Overlay: ● None ○ Atm ○ Tsky

Image Sideband Curve: ☐

Data: Amp

Column: data

Cached: ☑

Attach: ● Left ○ Right

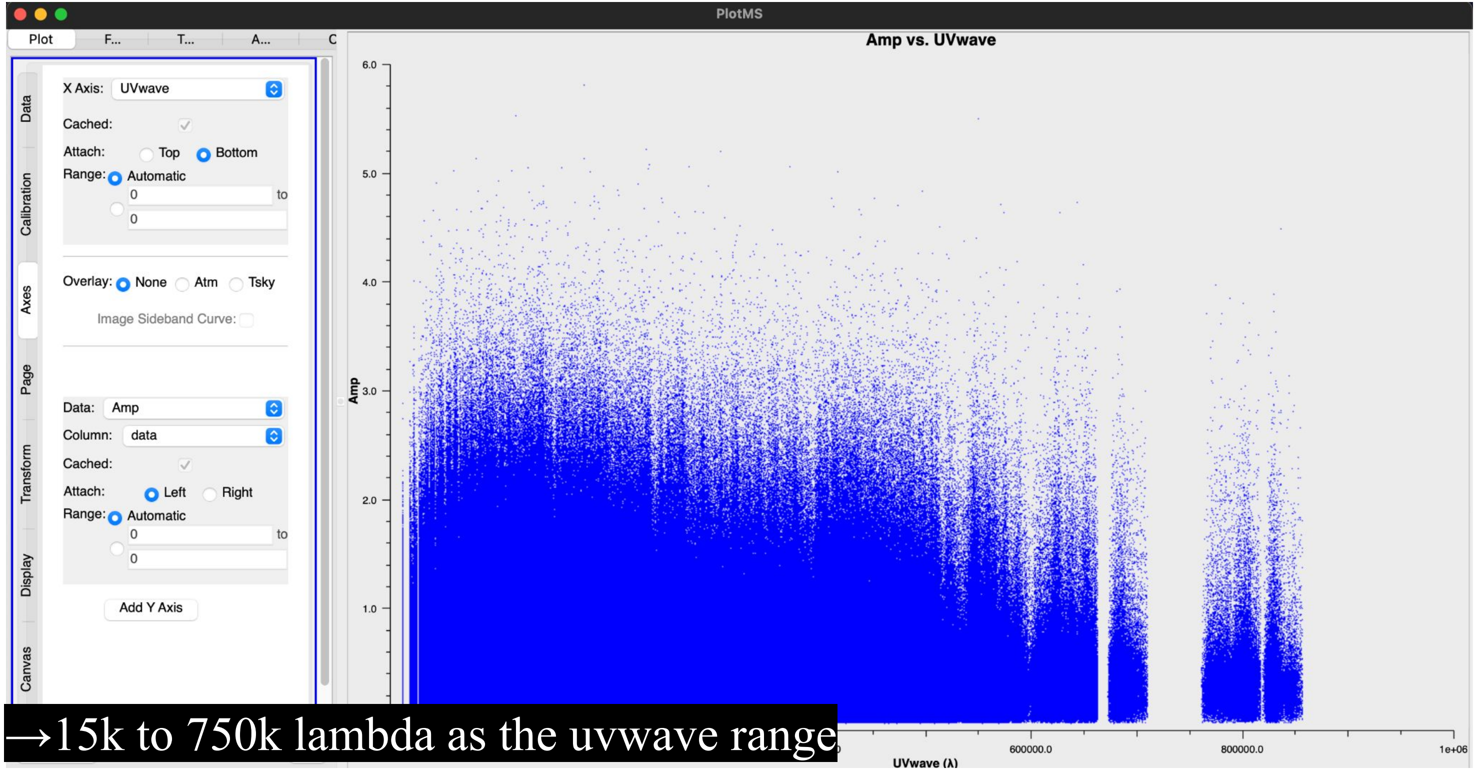
Range: ● Automatic

○ 0 to 0

CASA reduction

Homogenizing the data from multiple ALMA bands

➔ Select common uv visibility range



X Axis: UVwave

Cached: ☑

Attach: ○ Top ● Bottom

Range: ● Automatic ○ 0 to 0

Overlay: ● None ○ Atm ○ Tsky

Image Sideband Curve: ☐

Data: Amp

Column: data

Cached: ☑

Attach: ● Left ○ Right

Range: ● Automatic ○ 0 to 0

→15k to 750k lambda as the uvwave range

CASA reduction

Homogenizing the data from multiple ALMA bands

- ➔ Use ‘tclean’ to create common uv-limited images

```
CASA <2>: tclean(vis='/Users/shridharan/Desktop/Work/EA-ALMA_Workshop/uvdata/G343.13-0.06_band6
     ...: _selfcal_cont.ms',imagename='G343.13-06_band3_selfcal_cont_uvlimited', imsize=960, ce
     ...: ll='0.08arcsec', specmode='mfs', outframe='LSRK', gridder='standard', deconvolver='ho
     ...: gbom', weighting='briggs', uvrange='15~750klambda', robust=0.5,usemask='auto-multithr
     ...: esh',noisethreshold=5,sidelobethreshold=2.0,lownoisethreshold=1.5,minbeamfrac=0.3,neg
     ...: ativethreshold=0,fastnoise=False,niter=0)
```

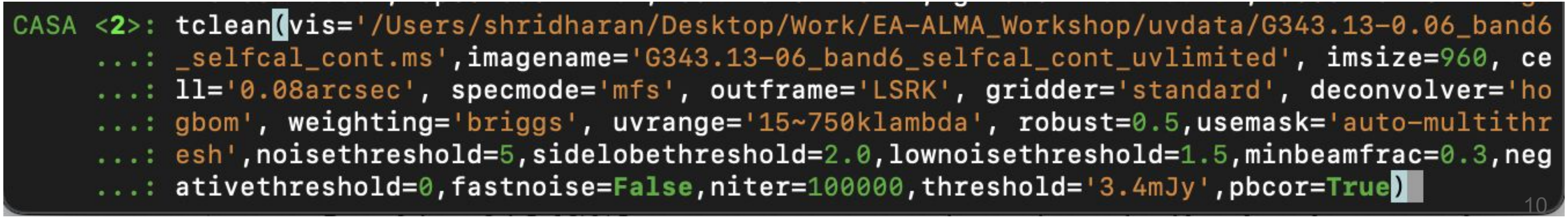
CASA reduction

Homogenizing the data from multiple ALMA bands

- Use ‘tclean’ to create common uv-limited images

```
CASA <2>: tclean(vis='/Users/shridharan/Desktop/Work/EA-ALMA_Workshop/uvdata/G343.13-0.06_band6
   ...: _selfcal_cont.ms',imagename='G343.13-06_band3_selfcal_cont_uvlimited', imsize=960, ce
   ...: ll='0.08arcsec', specmode='mfs', outframe='LSRK', gridder='standard', deconvolver='ho
   ...: gbom', weighting='briggs', uvrange='15~750klambda', robust=0.5,usemask='auto-multithr
   ...: esh',noisethreshold=5,sidelobethreshold=2.0,lownoisethreshold=1.5,minbeamfrac=0.3,neg
   ...: ativethreshold=0,fastnoise=False,niter=0)
```

- Use CARTA or casaviewer to estimate the background rms noise and provide the value to tclean and increase ‘niter’=100000.

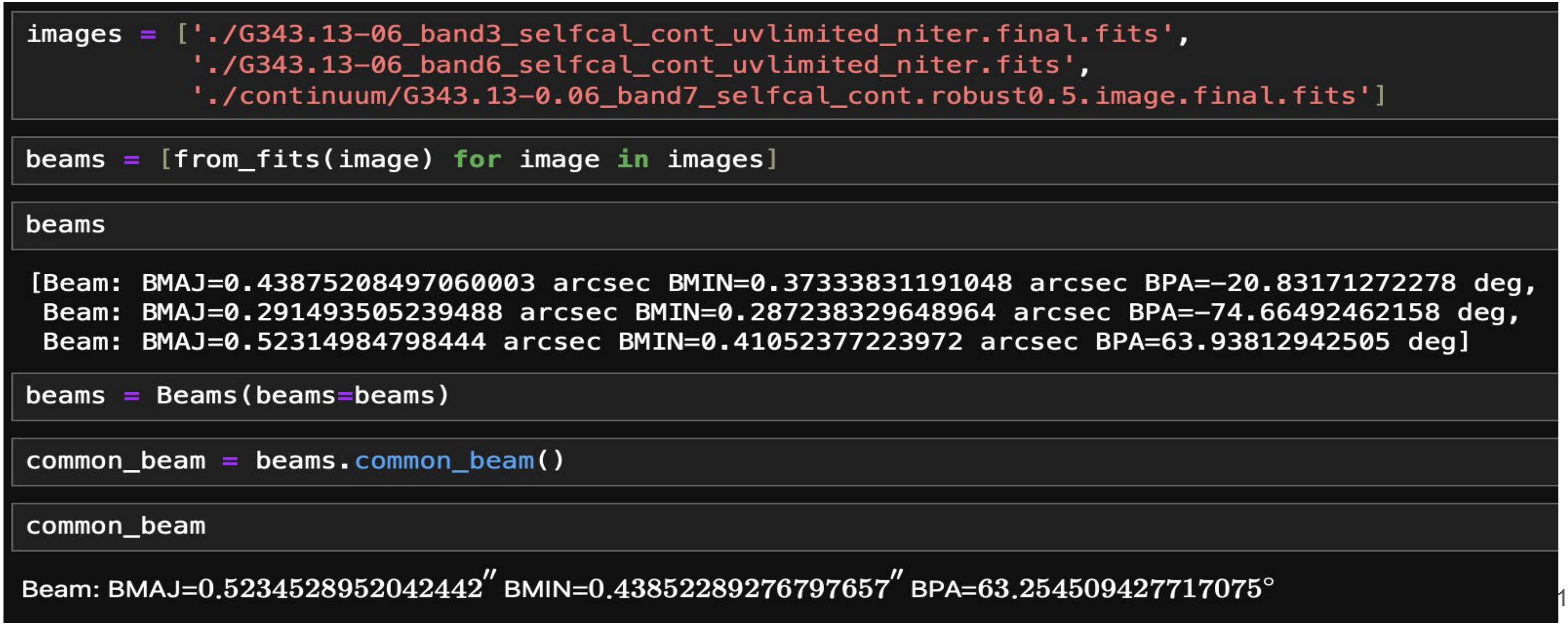


```
CASA <2>: tclean(vis='/Users/shridharan/Desktop/Work/EA-ALMA_Workshop/uvdata/G343.13-0.06_band6
   ...: _selfcal_cont.ms',imagename='G343.13-06_band6_selfcal_cont_uvlimited', imsize=960, ce
   ...: ll='0.08arcsec', specmode='mfs', outframe='LSRK', gridder='standard', deconvolver='ho
   ...: gbom', weighting='briggs', uvrange='15~750klambda', robust=0.5,usemask='auto-multithr
   ...: esh',noisethreshold=5,sidelobethreshold=2.0,lownoisethreshold=1.5,minbeamfrac=0.3,neg
   ...: ativethreshold=0,fastnoise=False,niter=100000,threshold='3.4mJy',pbcor=True)
```

CASA reduction

Homogenizing the data from multiple ALMA bands

➔ Find common beam between the different ALMA bands



```
images = ['./G343.13-06_band3_selfcal_cont_uvlimited_niter.final.fits',
          './G343.13-06_band6_selfcal_cont_uvlimited_niter.fits',
          './continuum/G343.13-0.06_band7_selfcal_cont.robust0.5.image.final.fits']
```

```
beams = [from_fits(image) for image in images]
```

```
beams
```

```
[Beam: BMAJ=0.43875208497060003 arcsec BMIN=0.37333831191048 arcsec BPA=-20.83171272278 deg,
 Beam: BMAJ=0.291493505239488 arcsec BMIN=0.287238329648964 arcsec BPA=-74.6492462158 deg,
 Beam: BMAJ=0.52314984798444 arcsec BMIN=0.41052377223972 arcsec BPA=63.9812942505 deg]
```

```
beams = Beams(beams=beams)
```

```
common_beam = beams.common_beam()
```

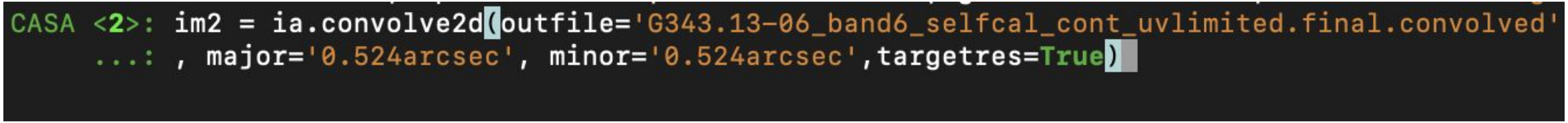
```
common_beam
```

```
Beam: BMAJ=0.5234528952042442″ BMIN=0.43852289276797657″ BPA=63.254509427717075°
```

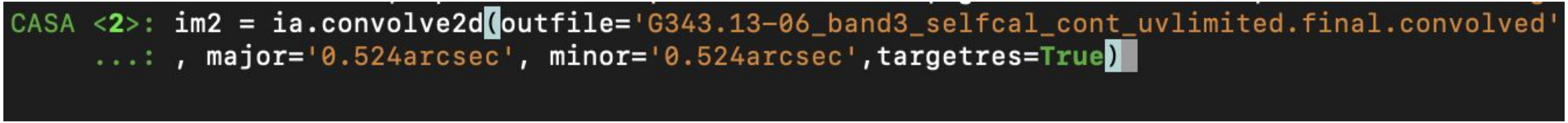
CASA reduction

Homogenizing the data from multiple ALMA bands

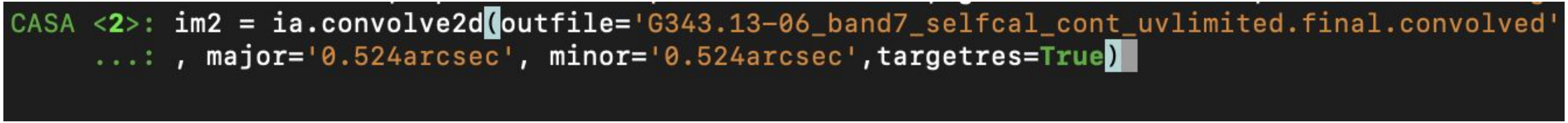
- ➔ Convolve all the bands to similar beam in CASA



```
CASA <2>: im2 = ia.convolve2d(outfile='G343.13-06_band6_selfcal_cont_uvlimited.final.convolved'
     ...: , major='0.524arcsec', minor='0.524arcsec',targetres=True)
```



```
CASA <2>: im2 = ia.convolve2d(outfile='G343.13-06_band3_selfcal_cont_uvlimited.final.convolved'
     ...: , major='0.524arcsec', minor='0.524arcsec',targetres=True)
```



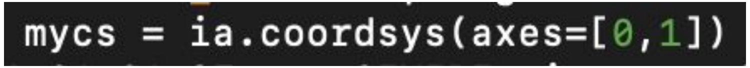
```
CASA <2>: im2 = ia.convolve2d(outfile='G343.13-06_band7_selfcal_cont_uvlimited.final.convolved'
     ...: , major='0.524arcsec', minor='0.524arcsec',targetres=True)
```

CASA reduction

Homogenizing the data from multiple ALMA bands

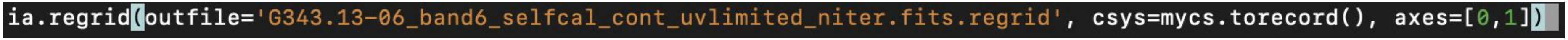
- ➔ Regrid the ALMA bands to have same (x,y) coordinate centers in CASA

Selecting Band 3 as the reference coordinate frame to regrid



```
mycs = ia.coordsys(axes=[0,1])
```

Regrid other bands to ‘mycs’



```
ia.regrid(outfile='G343.13-06_band6_selfcal_cont_uvlimited_niter.fits.regrid', csys=mycs.torecord(), axes=[0,1])
```

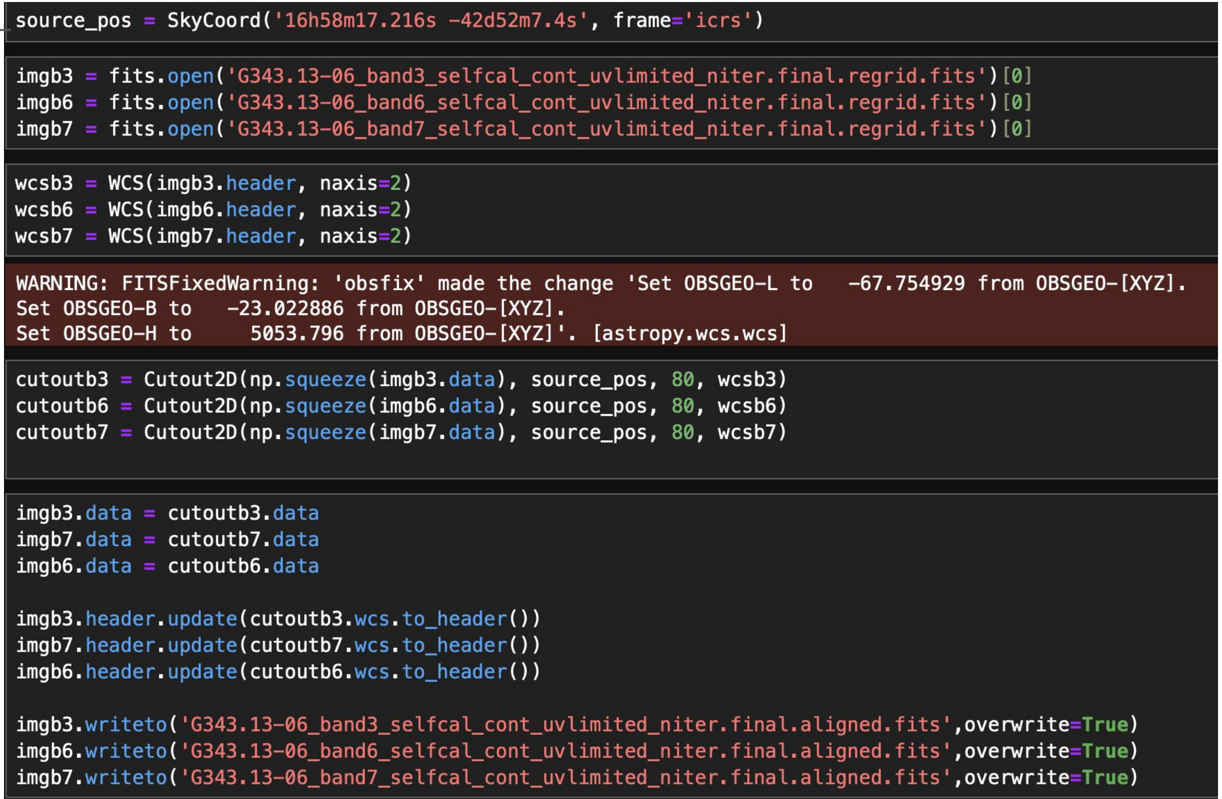
```
ia.regrid(outfile='G343.13-06_band7_selfcal_cont_uvlimited_niter.fits.regrid', csys=mycs.torecord(), axes=[0,1])
```

CASA reduction

Homogenizing the data from multiple ALMA bands

➔ Align the band images with *astropy.nddata.Cutout2D* with source position

Measured with CARTA



```
source_pos = SkyCoord('16h58m17.216s -42d52m7.4s', frame='icrs')
```

```
imgb3 = fits.open('G343.13-06_band3_selfcal_cont_uvlimited_niter.final.regrid.fits')[0]
imgb6 = fits.open('G343.13-06_band6_selfcal_cont_uvlimited_niter.final.regrid.fits')[0]
imgb7 = fits.open('G343.13-06_band7_selfcal_cont_uvlimited_niter.final.regrid.fits')[0]
```

```
wcsb3 = WCS(imgb3.header, naxis=2)
wcsb6 = WCS(imgb6.header, naxis=2)
wcsb7 = WCS(imgb7.header, naxis=2)
```

```
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-L to   -67.754929 from OBSGEO-[XYZ].
Set OBSGEO-B to   -23.022886 from OBSGEO-[XYZ].
Set OBSGEO-H to     5053.796 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
```

```
cutoutb3 = Cutout2D(np.squeeze(imgb3.data), source_pos, 80, wcsb3)
cutoutb6 = Cutout2D(np.squeeze(imgb6.data), source_pos, 80, wcsb6)
cutoutb7 = Cutout2D(np.squeeze(imgb7.data), source_pos, 80, wcsb7)
```

```
imgb3.data = cutoutb3.data
imgb7.data = cutoutb7.data
imgb6.data = cutoutb6.data

imgb3.header.update(cutoutb3.wcs.to_header())
imgb7.header.update(cutoutb7.wcs.to_header())
imgb6.header.update(cutoutb6.wcs.to_header())

imgb3.writeto('G343.13-06_band3_selfcal_cont_uvlimited_niter.final.aligned.fits',overwrite=True)
imgb6.writeto('G343.13-06_band6_selfcal_cont_uvlimited_niter.final.aligned.fits',overwrite=True)
imgb7.writeto('G343.13-06_band7_selfcal_cont_uvlimited_niter.final.aligned.fits',overwrite=True)
```

CASA reduction

Homogenizing the data from multiple ALMA bands

- ➔ Align the band images with *astropy.nddata.Cutout2D* with max peak position

```
path_cont = ['/Users/truonglegiabao/Downloads/continuum/final_result/Band3_final_convolve_regrid.fits',
             '/Users/truonglegiabao/Downloads/continuum/final_result/Band6_final_convolve_regrid.fits',
             '/Users/truonglegiabao/Downloads/continuum/final_result/Band7_final_convolve.fits']
```

```
img1 = fits.open(path_cont[0])[0]
wcs = WCS(img1.header, naxis = 2)
data = np.squeeze(img1.data)
my, mx = np.unravel_index(np.nanargmax(data), data.shape)
cutout = Cutout2D(np.squeeze(img1.data), (mx, my), 130, wcs = wcs)
img1.data = cutout.data
img1.header.update(cutout.wcs.to_header())
img1.writeto('/Users/truonglegiabao/Downloads/continuum/final_result/Band3_final_convolve_regrid_subim.fits', overwr
```

```
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-L to   -67.754929 from OBSGEO-[XYZ].
Set OBSGEO-B to   -23.022886 from OBSGEO-[XYZ].
Set OBSGEO-H to     5053.796 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
```

```
img1 = fits.open(path_cont[1])[0]
wcs = WCS(img1.header, naxis = 2)
data = np.squeeze(img1.data)
my, mx = np.unravel_index(np.nanargmax(data), data.shape)
cutout = Cutout2D(np.squeeze(img1.data), (mx, my), 130, wcs = wcs)
img1.data = cutout.data
img1.header.update(cutout.wcs.to_header())
img1.writeto('/Users/truonglegiabao/Downloads/continuum/final_result/Band6_final_convolve_regrid_subim.fits', overwr
```

```
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-L to   -67.754929 from OBSGEO-[XYZ].
Set OBSGEO-B to   -23.022886 from OBSGEO-[XYZ].
Set OBSGEO-H to     5053.796 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
```

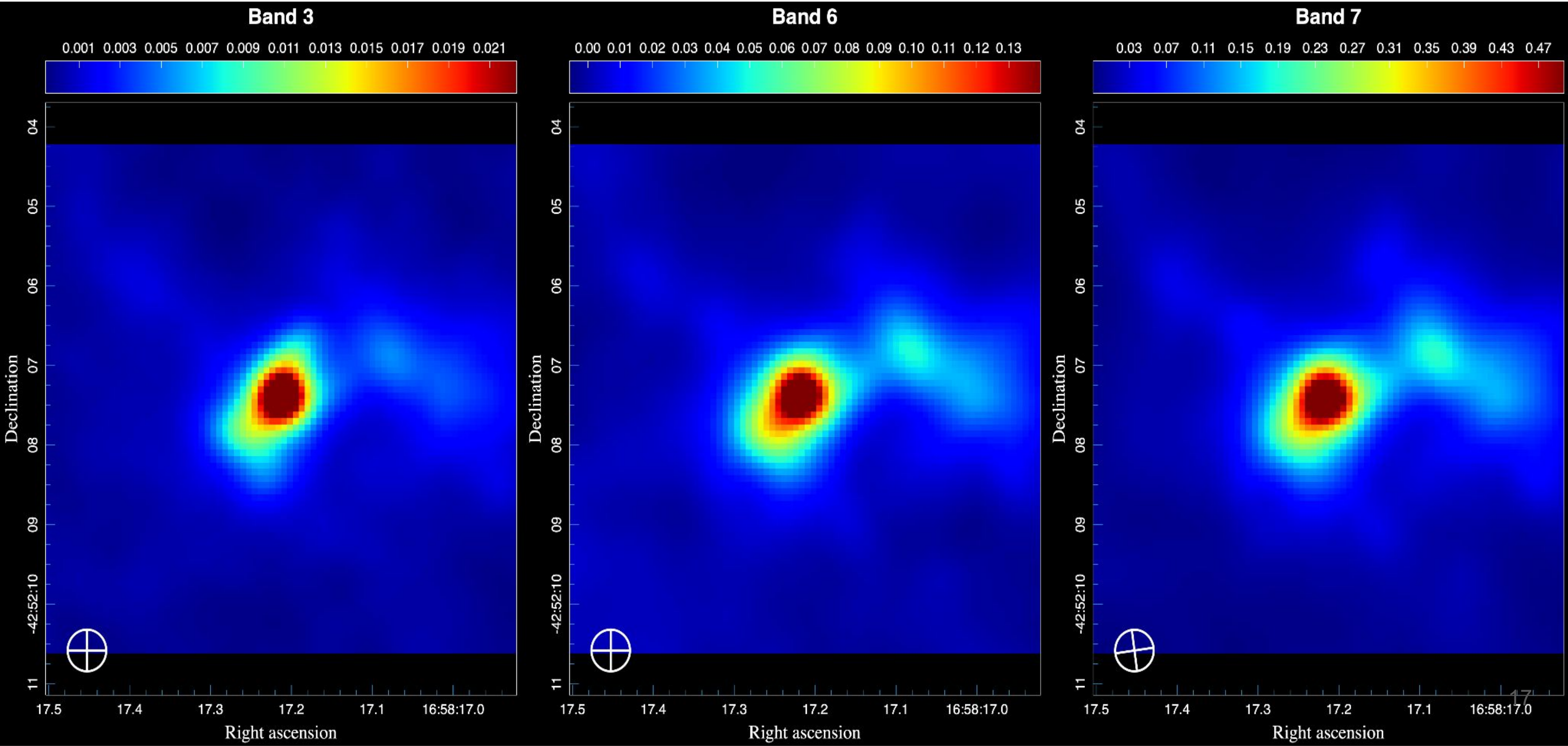
```
img1 = fits.open(path_cont[2])[0]
wcs = WCS(img1.header, naxis = 2)
data = np.squeeze(img1.data)
my, mx = np.unravel_index(np.nanargmax(data), data.shape)
cutout = Cutout2D(np.squeeze(img1.data), (mx, my), 130, wcs = wcs)
img1.data = cutout.data
img1.header.update(cutout.wcs.to_header())
img1.writeto('/Users/truonglegiabao/Downloads/continuum/final_result/Band7_final_convolve_regrid_subim.fits', overwr
```

CASA reduction

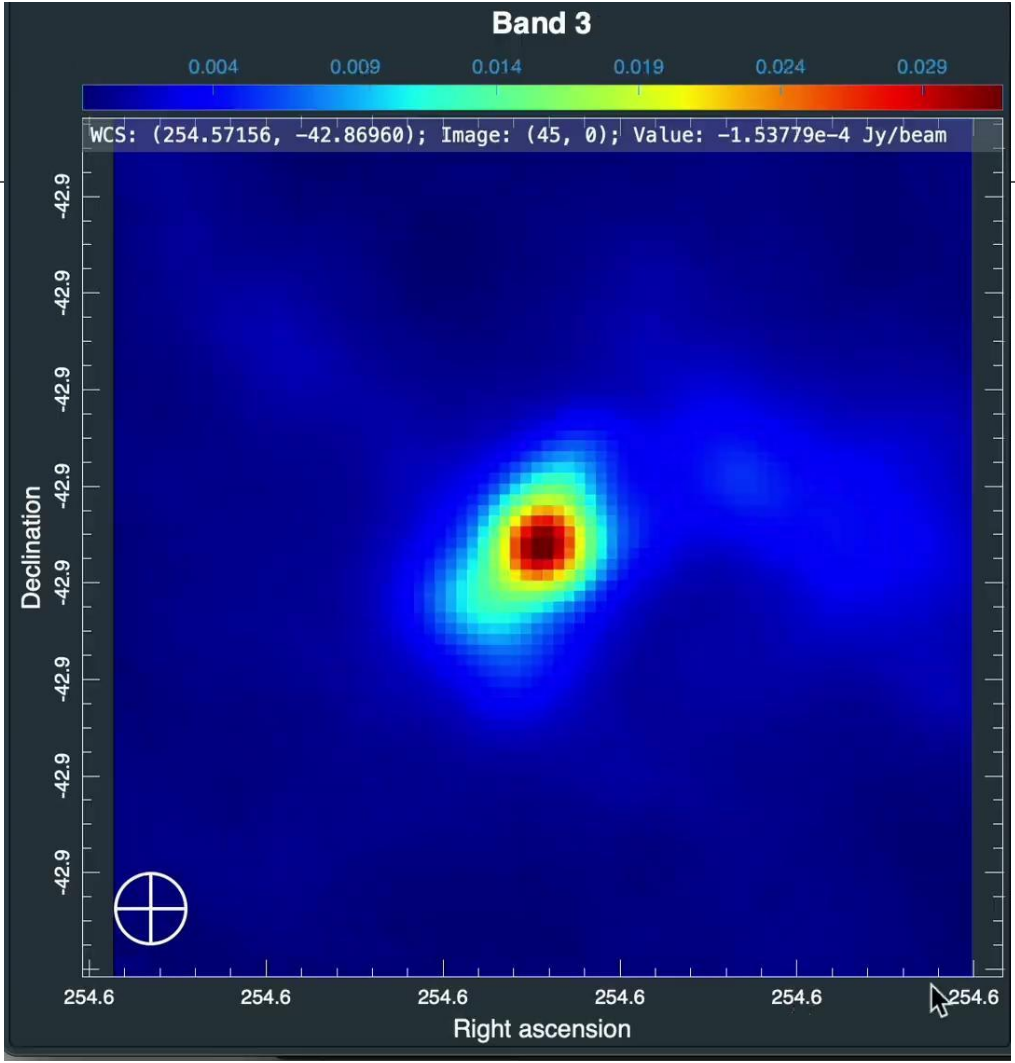
Homogenizing the data from multiple ALMA bands

The multi-band data is
Reduced
Convolved
Regridded
Aligned

CASA reduction

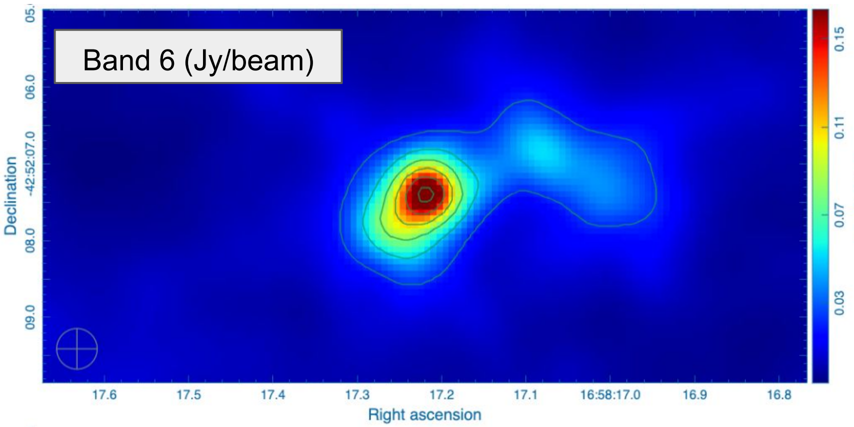


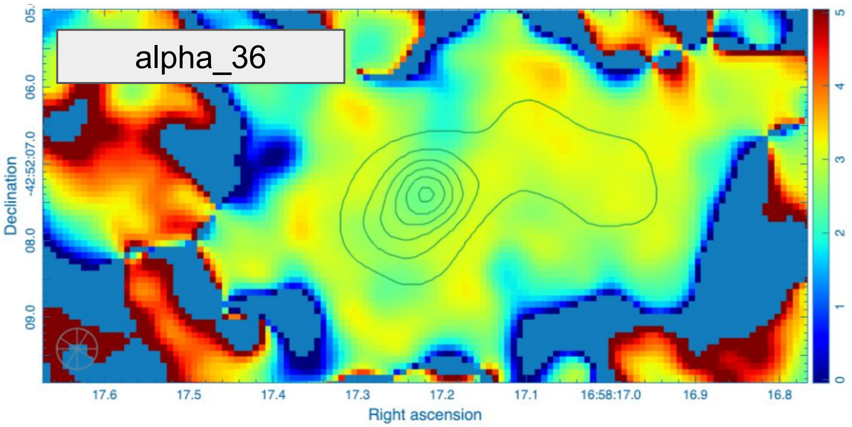
CASA reduction

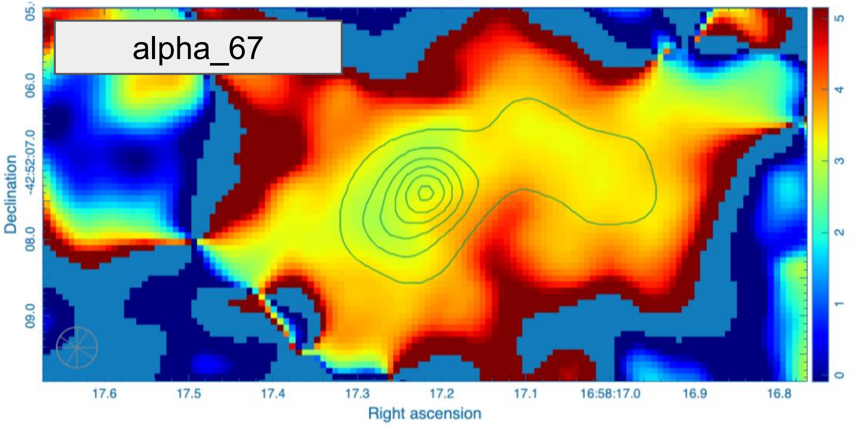


WCS: (254.57156, -42.86960); Image: (45, 0); Value: -1.53779e-4 Jy/beam

Physical quantities - spectral index





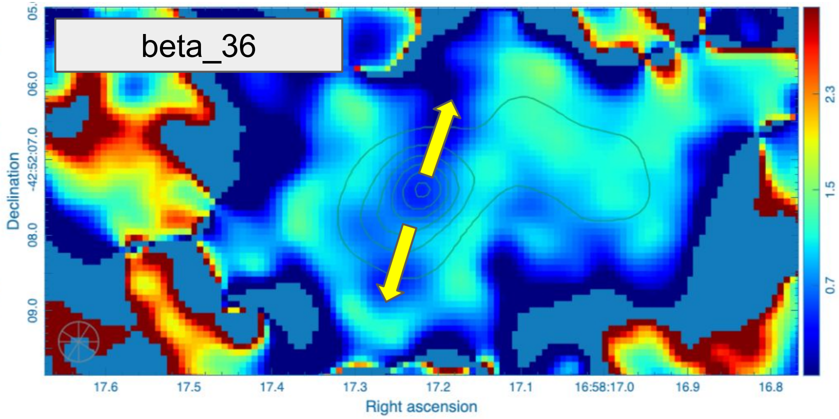


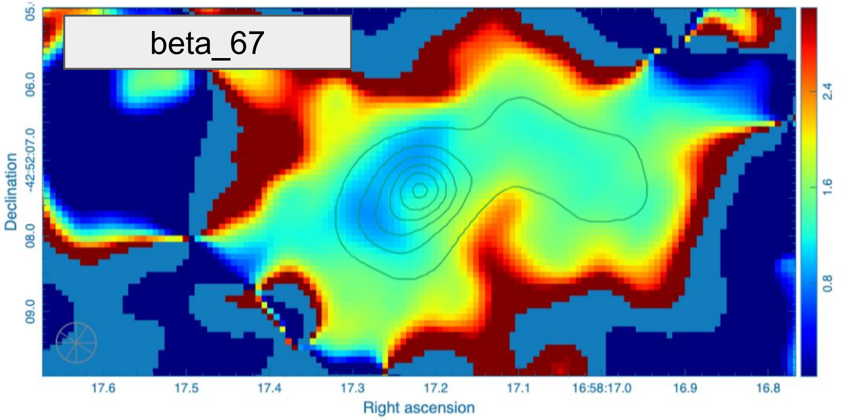
Spectral index:

$$\log(F_{\nu 1}/F_{\nu 2}) = \alpha \log(\nu_1/\nu_2)$$

with $\alpha=\beta+2$

Physical quantities - spectral index



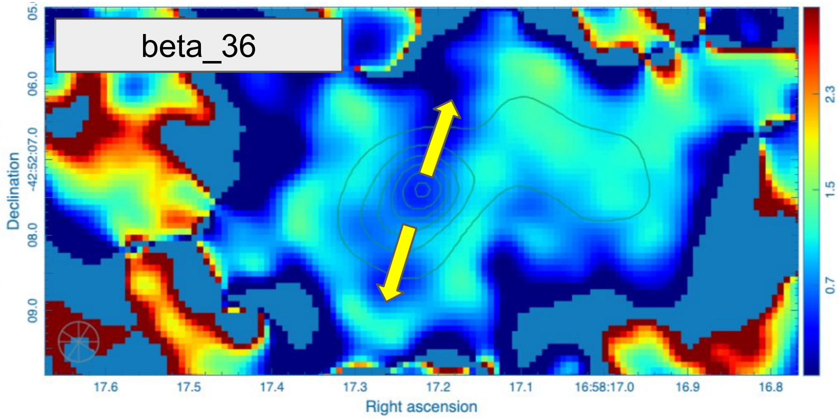


β ~ 0.7-1.5
Outflow: β < 0.7

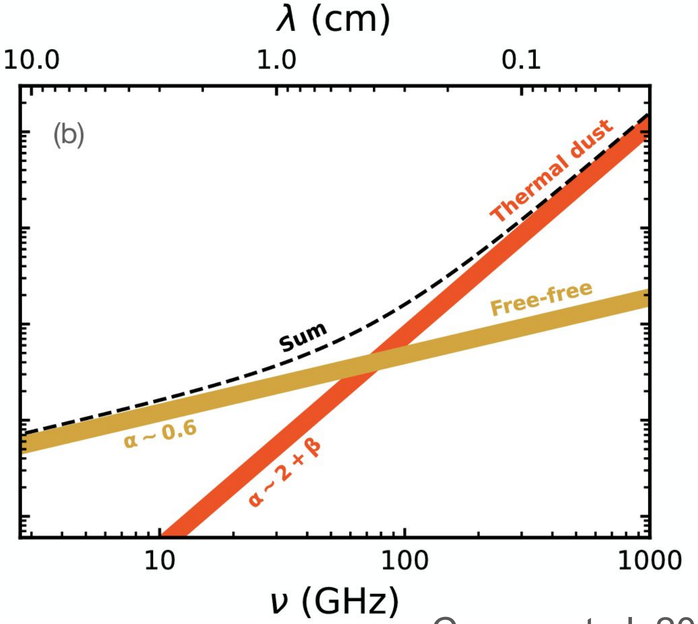
β ~ 1.5-1.8 -> close to β_ISM ~ 1.7
for a = 0.05 - 0.25 um (Draine 2006)

Thermal dust emission + Contamination by free-free emission

Physical quantities - spectral index



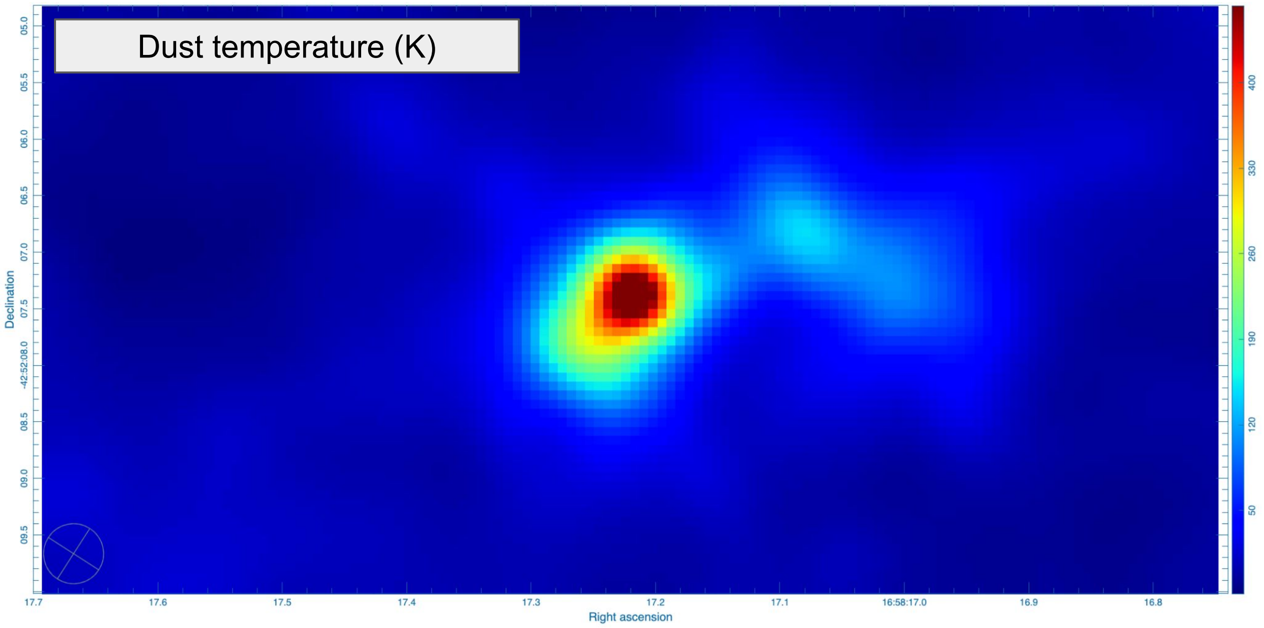
β ~ 0.7-1.5
Outflow: β < 0.7



Curone et al. 2023

Thermal dust emission + Contamination by free-free emission

Physical quantities - dust temperature



Rayleigh-Jeans limit

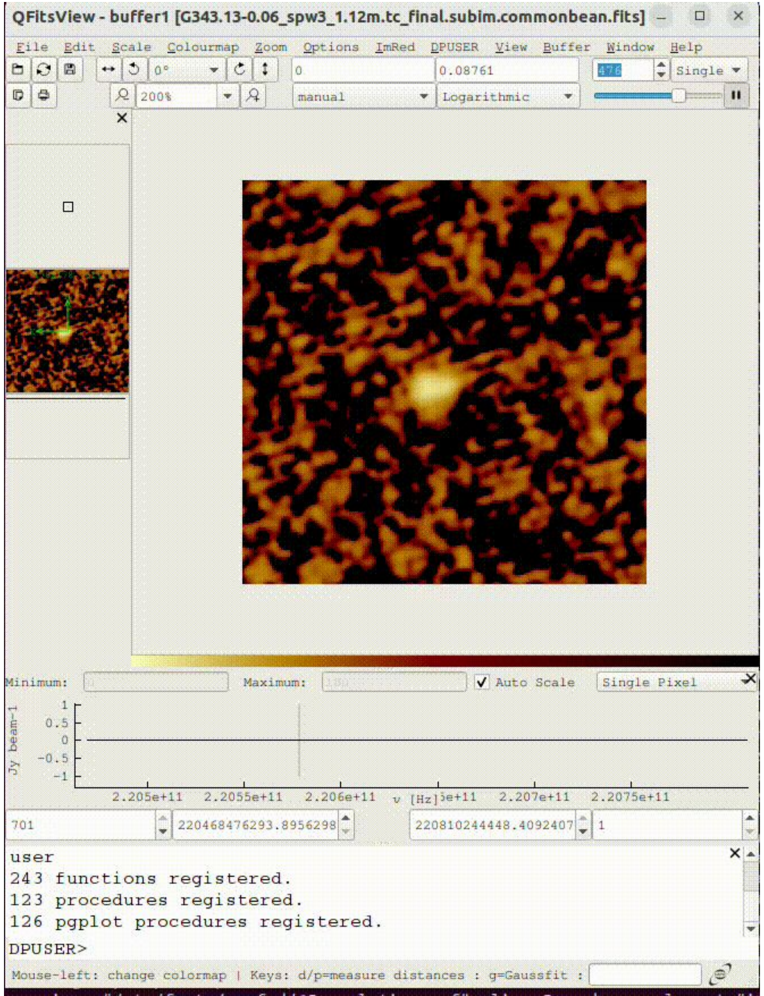
$$B_\nu(T) = \frac{2\nu^2 k_{\rm B} T}{c^2}.$$

$$F_\nu^{\rm c} = \Omega_{\rm c} B_\nu(T_{\rm c})(1 - e^{-(\nu/\nu_0)^\beta}),$$

T = 200 - 500 K

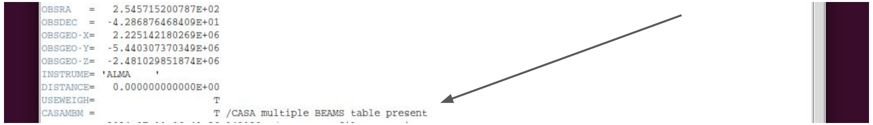
Using Band 6 intensity (less contaminated by free-free emission) -> tau = 0.0305 (Garay et al. 2007)

Cube visualization & cube analysis


QFitsView - buffer1 [G343.13-0.06_spw3_1.12m.tc_final.subim.commonbean.fits]

```
user
243 functions registered.
123 procedures registered.
126 pgplot procedures registered.
DPUSER>
```

- Spectral cube (continuum subtracted)



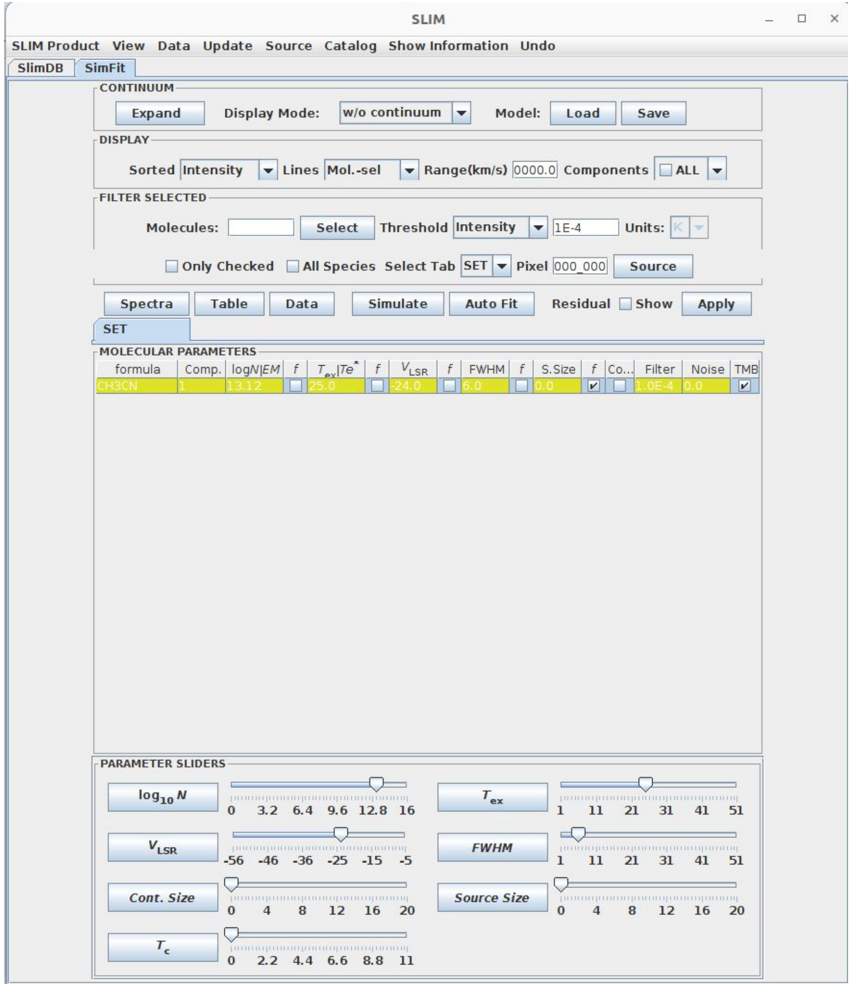
```
OBSRA   =   2.545715200787E+02
OBSDEC  =  -4.286876468409E+01
OBSGEO-X=   2.225142180269E+06
OBSGEO-Y=  -5.440307370349E+06
OBSGEO-Z=  -2.481029851874E+06
INSTRUME= 'ALMA    '
DISTANCE=   0.000000000000E+00
USEWEIGH=                    T
CASAMBM =                    T /CASA multiple BEAMS table present
```

- → convolve channels to same beam:
- Python tools: `SpectralCube`

`Final common beam: BMAJ=0.34 arcsec, BMIN=0.32’’`

- Cube Analysis: MADCUBA

→ model fitting



Display Mode: w/o continuum
Model:

Sorted Intensity
Lines Mol.-sel
Range(km/s) 0000.0
Components ☐ ALL

Molecules:
Threshold Intensity 1E-4
Units: K

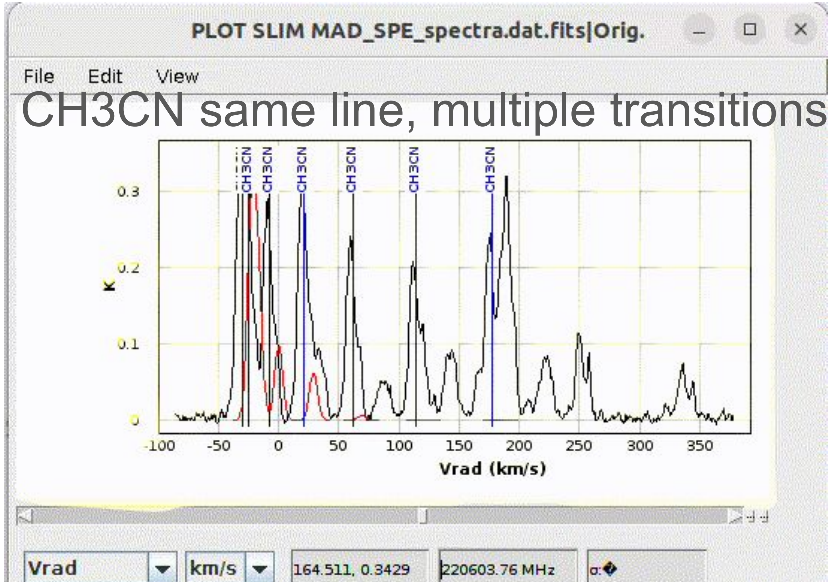
☐ Only Checked
☐ All Species
Select Tab SET
Pixel 000_000

Residual ☐ Show

MOLECULAR PARAMETERS

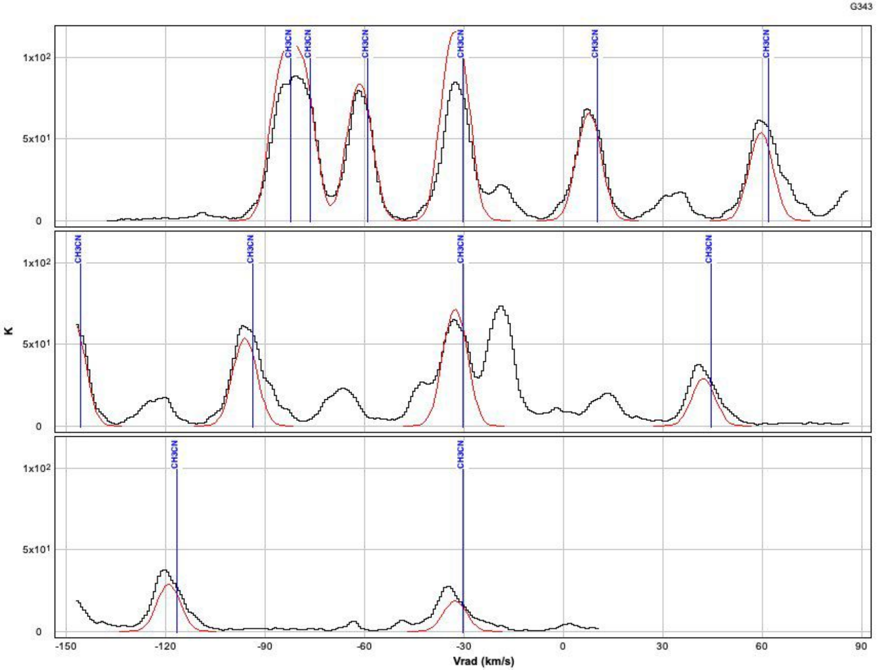
formula	Comp.	log*N*|*EM*	*f*	T_{ex}|Te^*	*f*	V_{LSR}	*f*	FWHM	*f*	S.Size	*f*	Co...	Filter	Noise	TMB
CH3CN	1	13.12	☐	25.0	☐	-24.0	☐	6.0	☐	0.0	☑	☐	1.0E-4	0.0	☑

- Cube Analysis:
- MADCUBA, model fitting of sigle spectrum (CASA)
- Getting physical props: column density, velocity, FWHM, T



CH3CN same line, multiple transitions

Vrad
km/s
164.511, 0.3429
220603.76 MHz

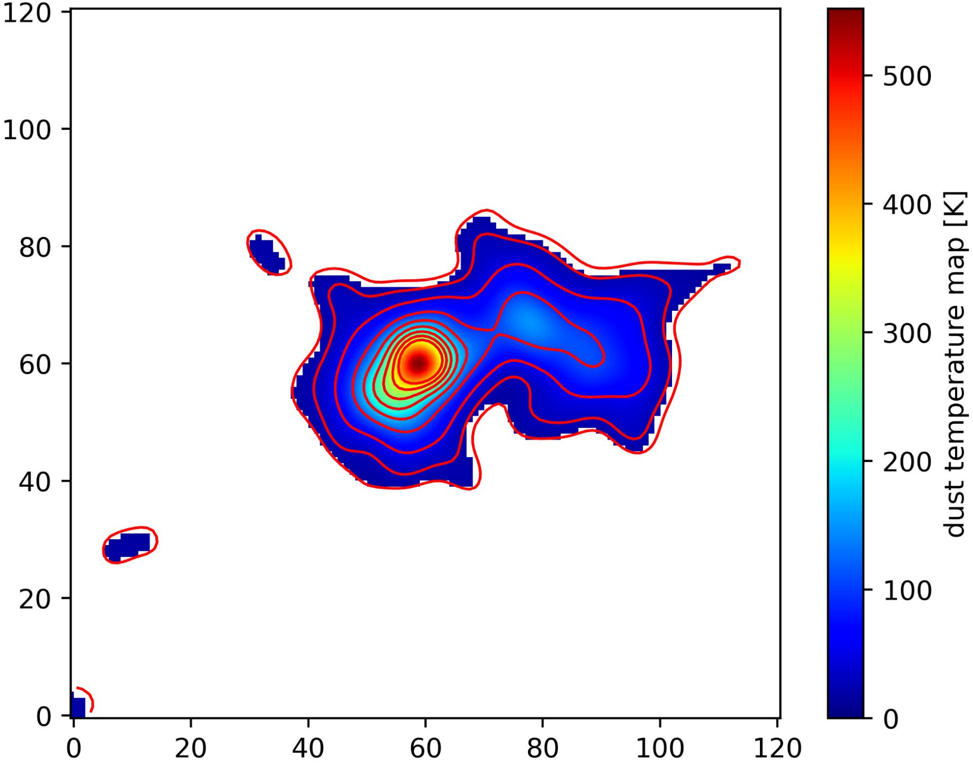


Best fitting model !

9 transitions of CH3CN (J→12-11) K 0-9, same T, VLSR, FWHM

T = 350 K, col. dens = 10^17.4
FWHM = 7 km/s

Physical quantities - column density



The emission above 3 sigma

Td: 73 K

Rgd: 100

d: 2.9 kpc

Kv: 1.2 $cm^2\ g^{-1}$

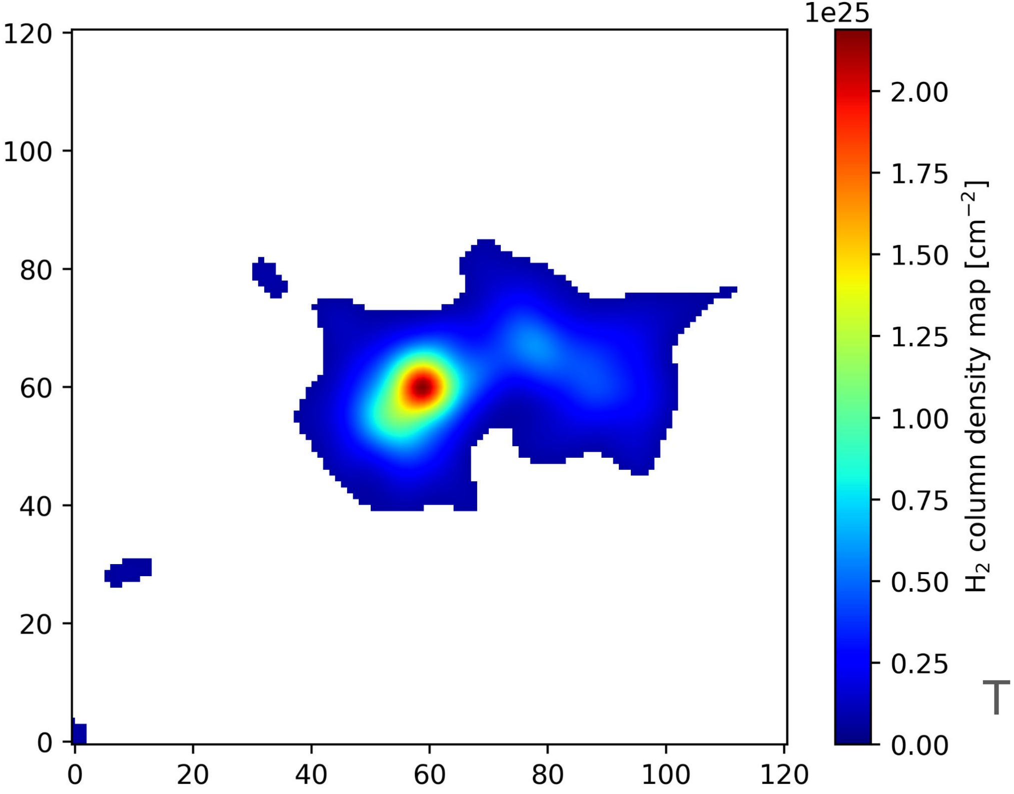
μH2: 2.8

mH: 1.7 x 10-24 g

$$N_{\mathrm{H}_2} = \frac{I_\nu R_{\mathrm{gd}}}{B_\nu(T_d)\kappa_\nu \mu_{\mathrm{H}_2} m_{\mathrm{H}}}$$

$$B_\nu(T) = \frac{2\nu^2 k_{\mathrm{B}} T}{c^2}.$$

Physical quantities - column density



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Rgd: 100

d: 2.9 kpc

Kv: 1.2 cm^2 g^{-1}

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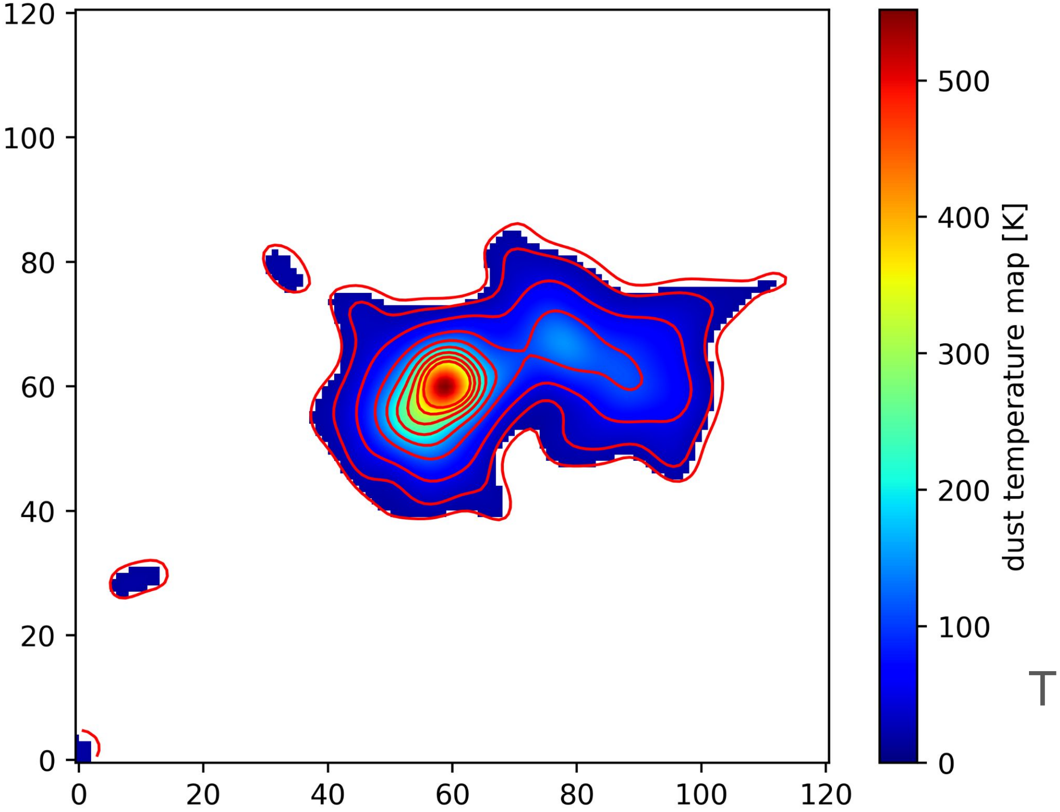
$$N_{\mathrm{H}_2} = \frac{I_\nu R_{\mathrm{gd}}}{B_\nu(T_d)\kappa_\nu \mu_{\mathrm{H}_2} m_{\mathrm{H}}}$$

$$B_\nu(T) = \frac{2\nu^2 k_{\mathrm{B}} T}{c^2}.$$

The mean column density: 2.9 x 10^{24} cm^{-2}

Physical quantities - dust mass



The emission above 3 sigma

Fv: 1.15 Jy

d: 2.9 kpc

Kv: 1.2 cm^2 g^{-1}

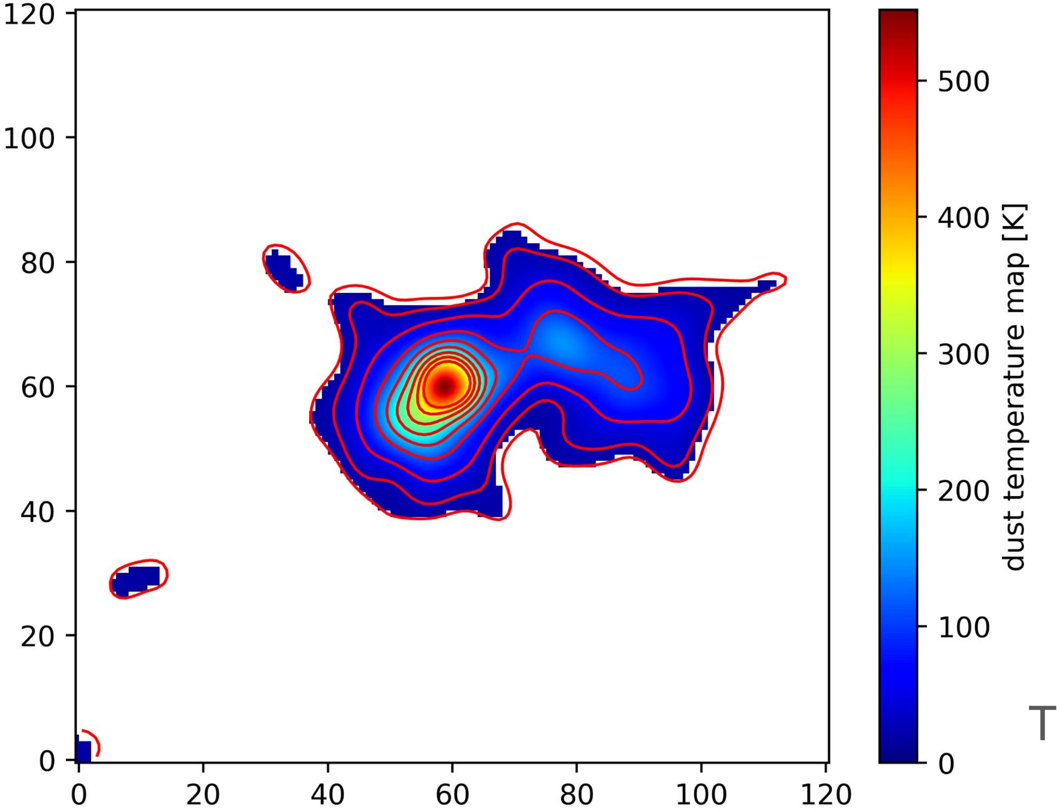
Td: 73 K

$$B_\nu(T) = \frac{2\nu^2 k_\mathrm{B} T}{c^2}.$$

$$M_d = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_d)}$$

The estimated dust mass: 0.34 M$_{\mathrm{sun}}$

Physical quantities - dust + gas mass



The emission above 3 sigma

Fv: 1.15 Jy

d: 2.9 kpc

Kv: 1.2 cm^2 g^{-1}

Td: 73 K

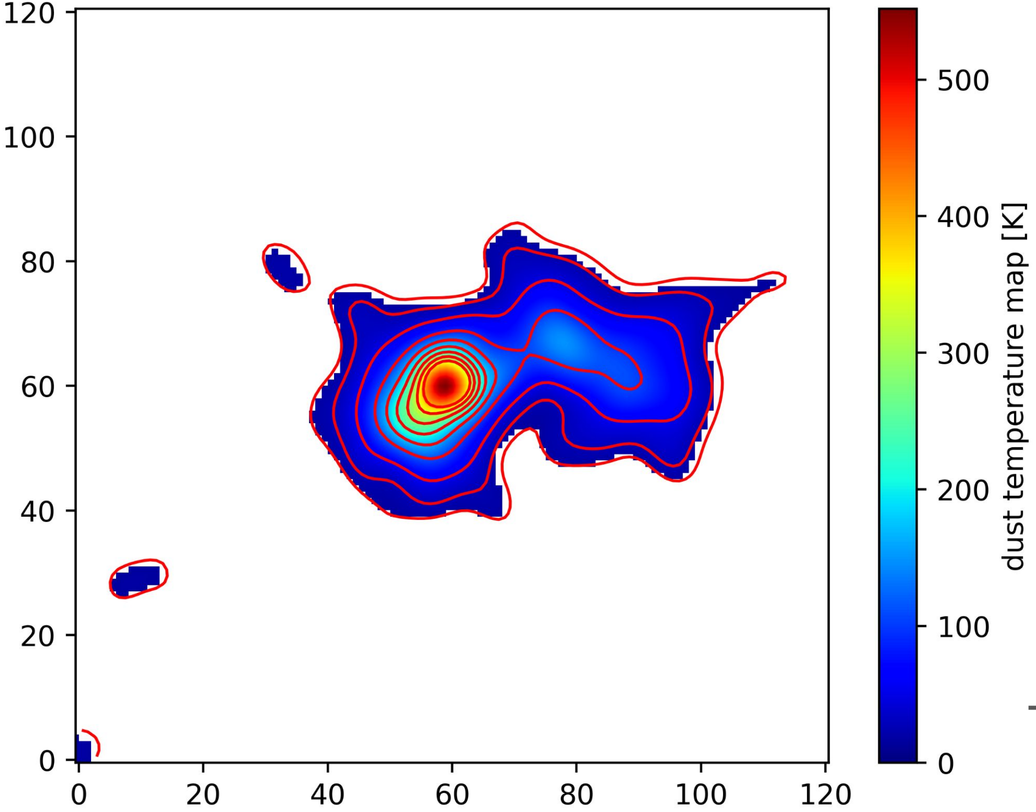
Rgd: 100

$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2}.$$

$$M_d = \frac{F_\nu d^2 R_{gd}}{\kappa_\nu B_\nu(T_d)}$$

The estimated gas mass: 34 M$_{sun}$

Physical quantities - dust + gas mass



	Gas mass
T_d = 10 K	~ 245 M_{sun}
T_d = 73 K	~ 34 M_{sun}
T_d = 100 K	~ 25 M_{sun}
T_d = 500 K	~ 4.9 M_{sun}

Summary

1. Data reduction with casa
2. Generated continuum images of multi-band and compared them
3. Calculated spectral index with two dust continuum data
4. Model fitting to cube data using MADCUBA
5. Estimated temperature, column density and gas mass based on the observed data