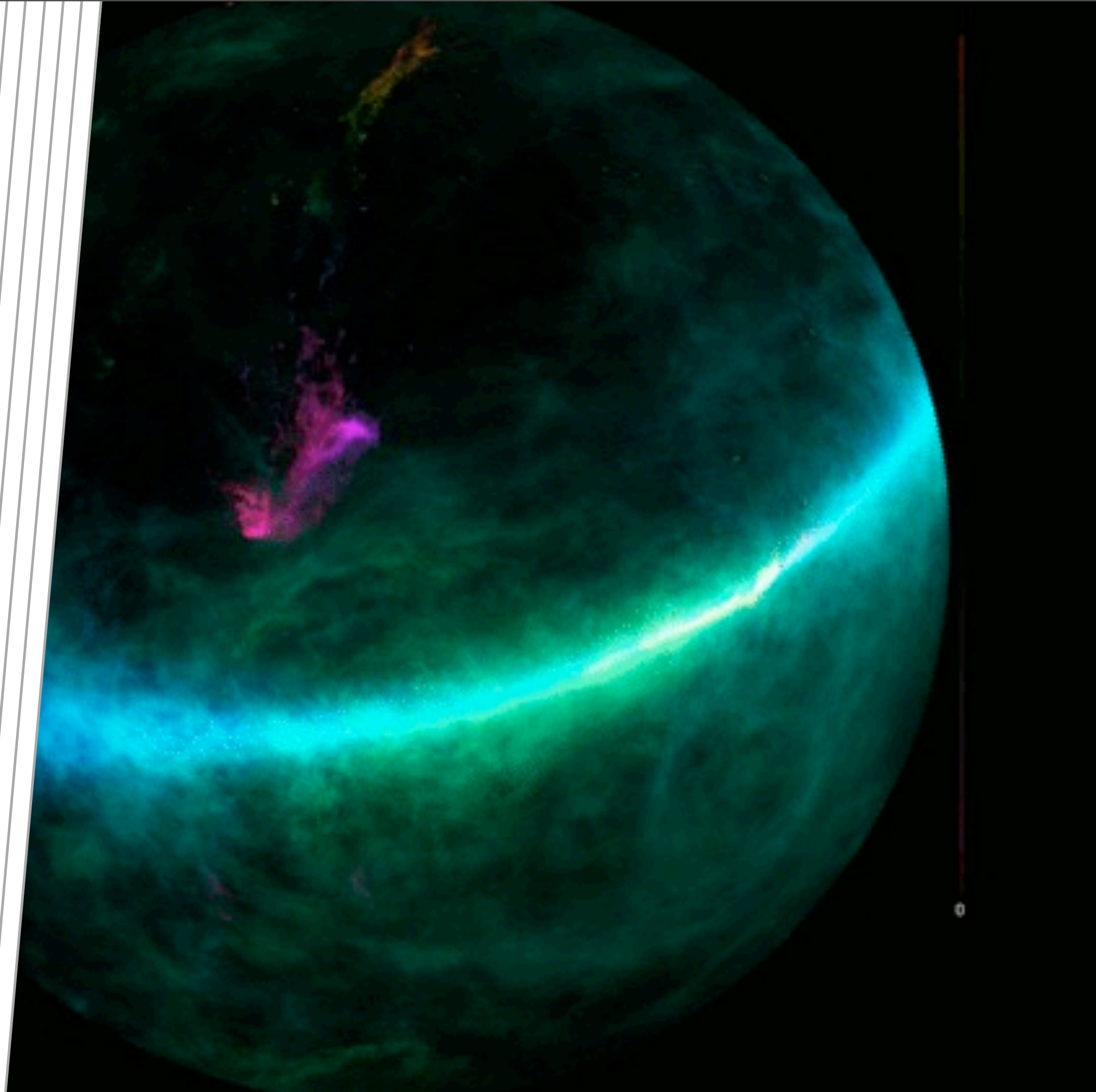


www.csiro.au

Data Analysis

"I have got some data, so what now?"

Naomi McClure-Griffiths
Australia Telescope National Facility
CSIRO Astronomy & Space Science
29 Sep 2010

CSIRO

Outline

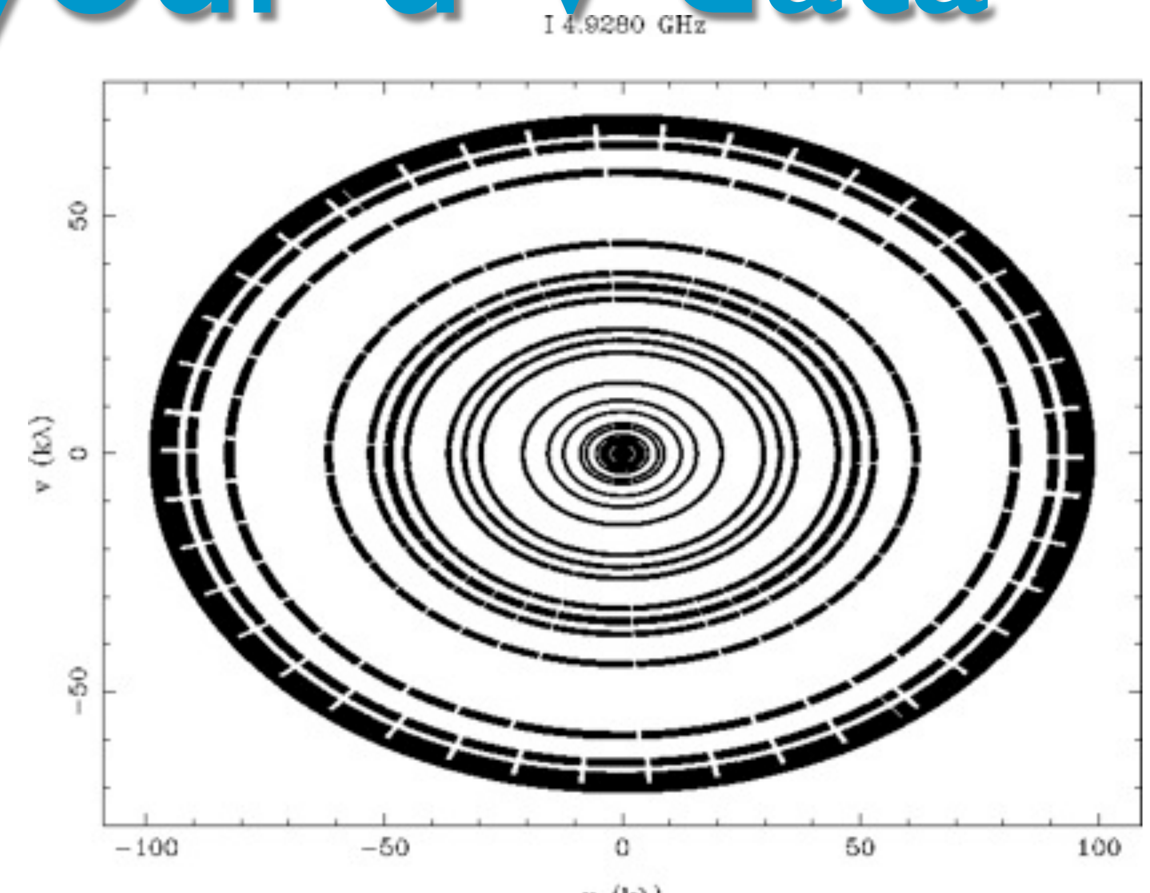
- Non-imaging analysis
- Parameter estimation
  - Point source fluxes, positions
  - Extended source flux
- Image combination
  - Spectral index
  - Polarization - see McConnell and Perley talks
- Visualisation
- 3-D datasets
  - Moments
- Understanding the limitations of your data

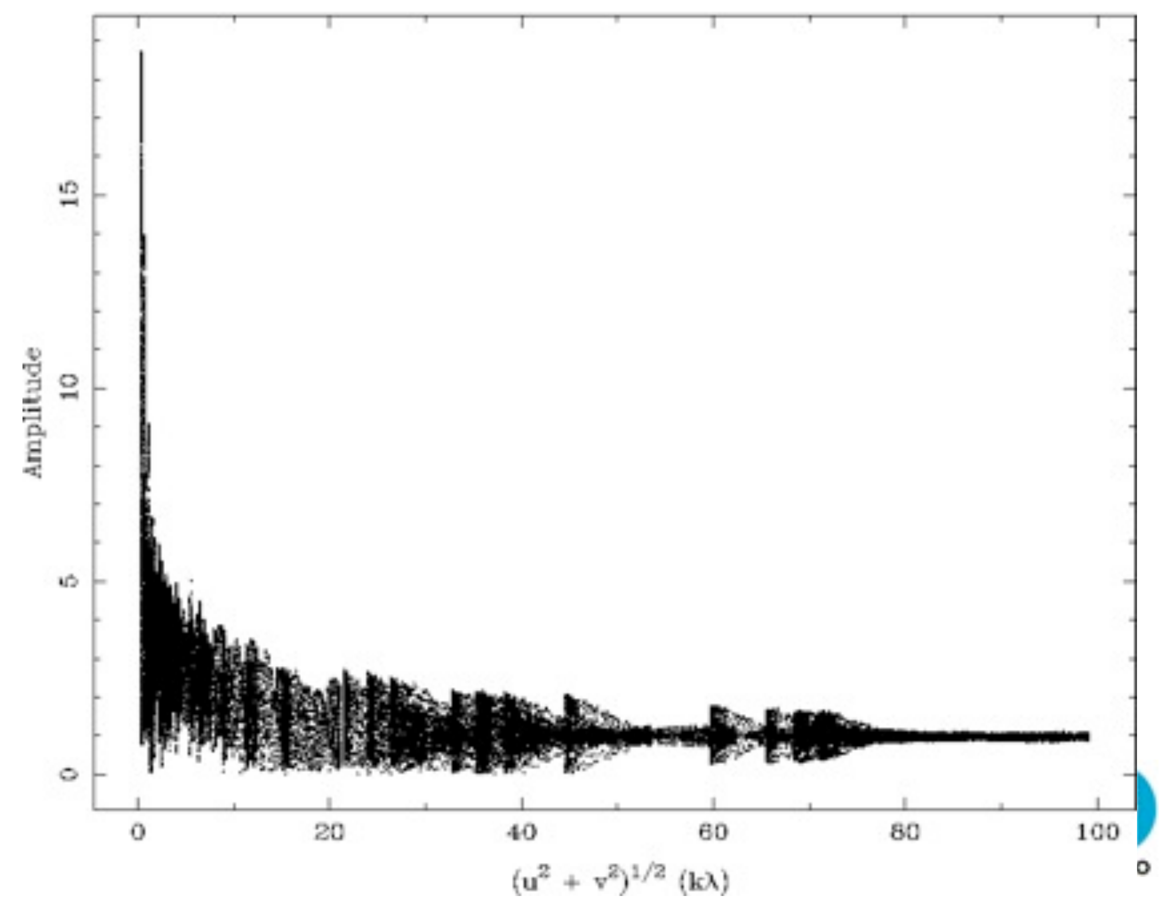
Step 1: What do you want to know from your observations?

- Variability with time?
  - u-v amplitude vs time
- Source position/flux/extent?
  - Characterising a source
  - Model fitting
  - Extend source flux
- Source morphology?
  - data visualisation
- Spectral line velocity, intensity, width?
  - Gaussian fitting
  - Moment analysis
- Emission mechanism?
  - Spectral index
- Magnetic field properties?
  - Polarization angle & intensity, rotation measure

Step 2: Look at your u-v data

- You can tell a lot without even making an image:
  - Amplitude vs. time
  - Amplitude vs. u-v distance
- At times this may be the only way to get something from your data, particularly if:
  - You have poor u-v coverage
  - You are only interested in variability





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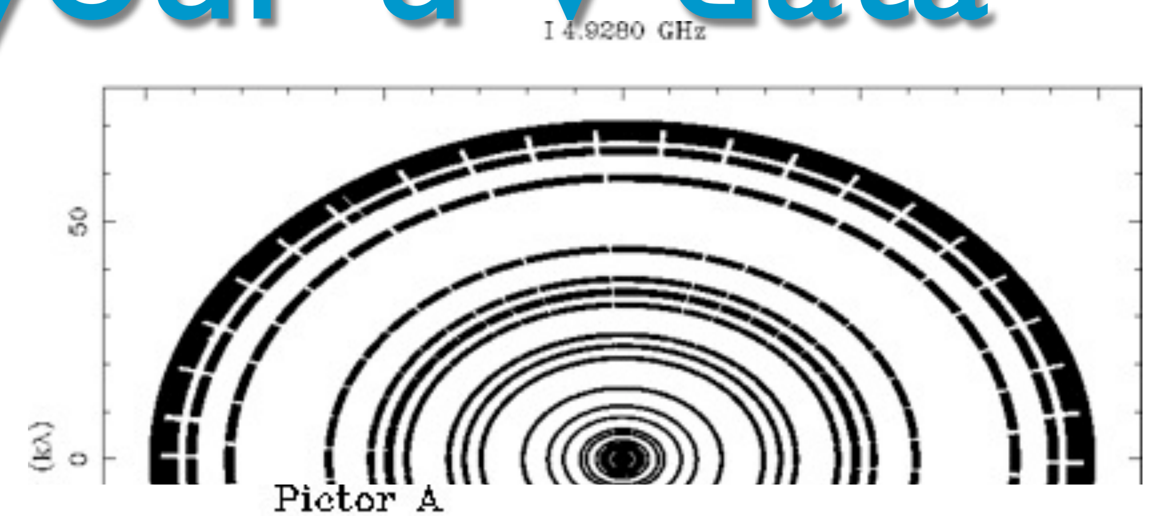
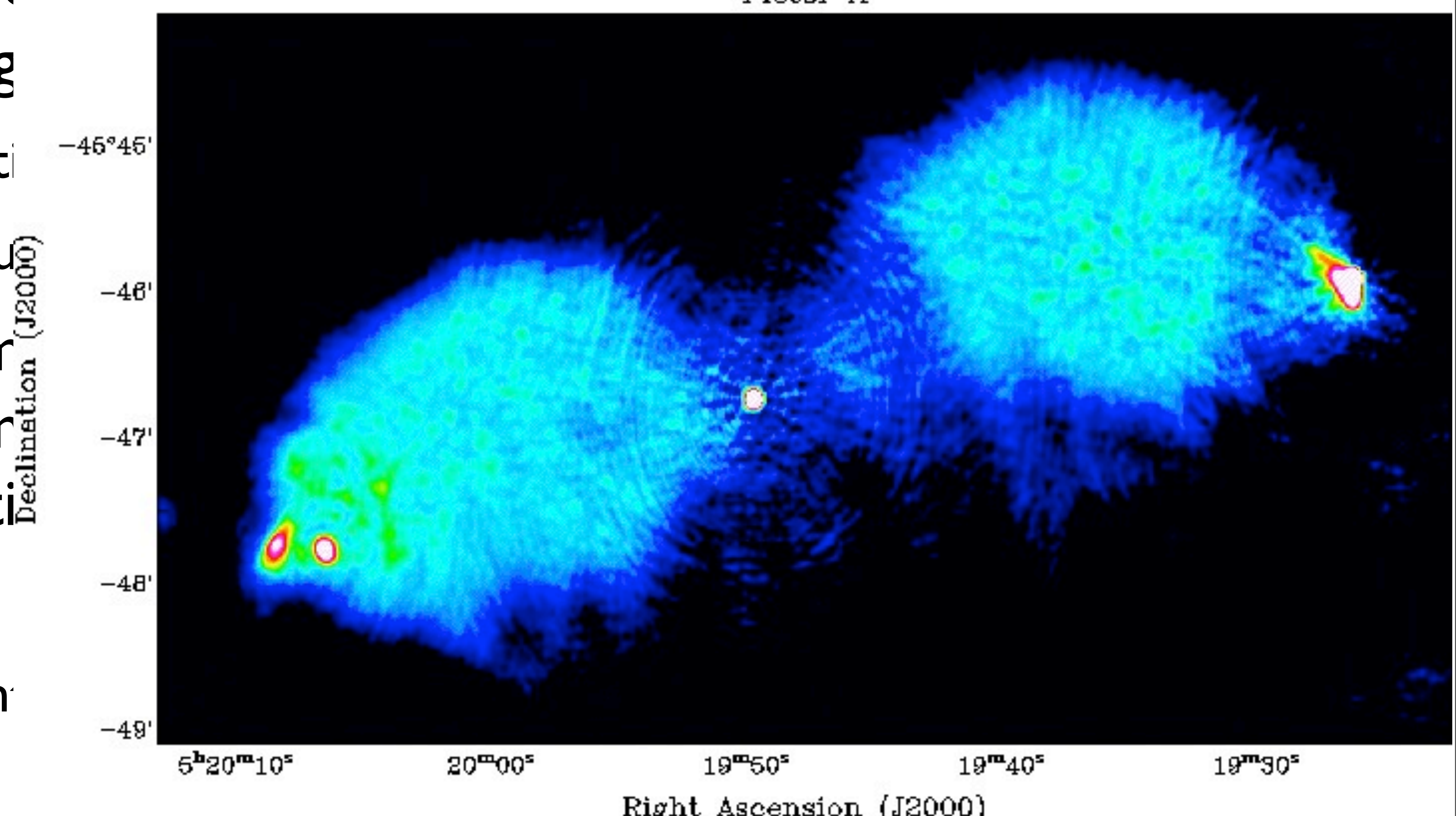
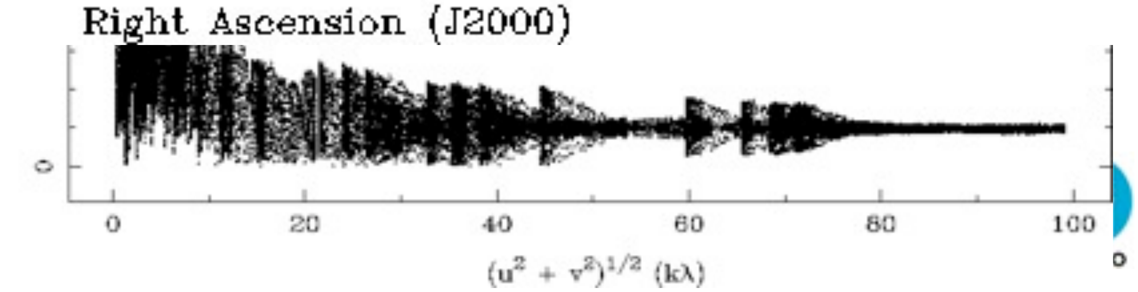






Non-imaging Analysis

- Synthesis imaging is an inverse-problem:
  - We have limited data, a known instrument and we try to infer the sky distribution
- The forward problem is much simpler:
  - Given a known sky distribution, *F*, and a known instrument we can predict the visibilities, *V*:

$$V(u,v) = F(u,v;a_1,...,a_m) + \text{noise}$$

- Advantage: operates in the observational domain, pre-Fourier transform, errors more predictable
- Disadvantage: limited to simple models

Non-Imaging Analysis

- Given a relatively simple source you can fit a model:
    - Define a parametric model for the sky distribution
    - Predict the visibilities for your telescope
    - Adjust the parameters of the model to fit your visibilities
- Useful if you have lots of data or poorly sampled data:
    - Examples:
        - CABB spectropolarimetric observations - just want I, Q, U,V vs. freq for dozens of sources
        - Snapshots of time variable sources

Model Fitting

- The model, *F*, should fit the data, *V*

$$V(u,v) = F(u,v;a_1,...,a_m) + \text{noise}$$

- The likelihood is (for Gaussian errors)

$$L \propto \prod_{i=1}^{n} \left\{ \exp\left[-\frac{1}{2} \left(\frac{V_i - F(u_i,v_i;a_1,...,a_m)}{\sigma_i} \right)^2 \right] \right\}$$

- Minimise -Log(*L*) or minimise the chi-squared for the model fit

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{V_i - F(u_i,v_i;a_1,...,a_m)}{\sigma_i} \right)^2$$

Model Fitting

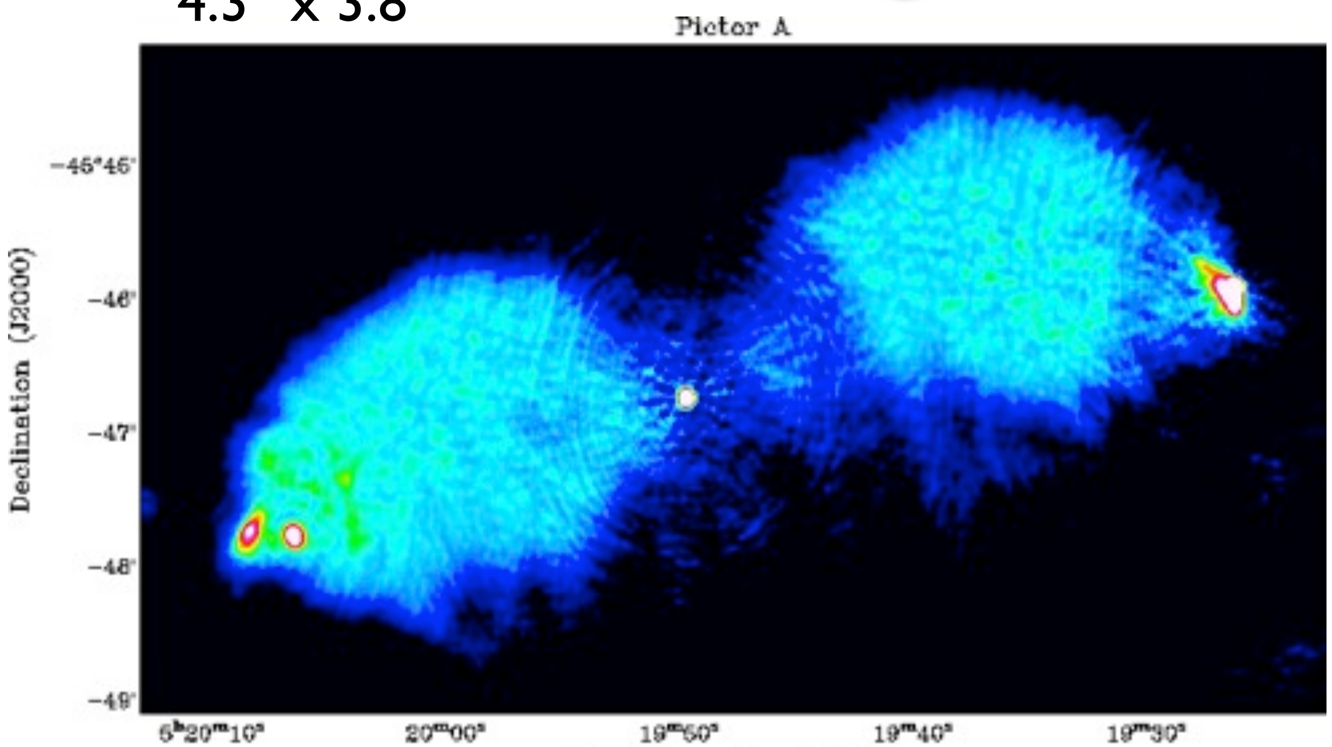
- Works best for sky brightness distributions that can be represented by a simple model with few parameters, eg.
  - Checking your calibrator - is it a point source?
  - Finding positions and fluxes for a few point sources
    - Estimates found this way often are more reliable than estimates from a deconvolved image because the errors are more predictable
  - Modelling and subtracting a bright source before imaging and deconvolution can give a better deconvolution
- Some programs that do model fitting are:
  - miriad *uvflux*: fits a simple point source
  - miriad *uvfit*: fits point sources, gaussians, disks, etc.
  - CASA, but currently limited to one source in model fitting

Step 3: Image your data appropriately

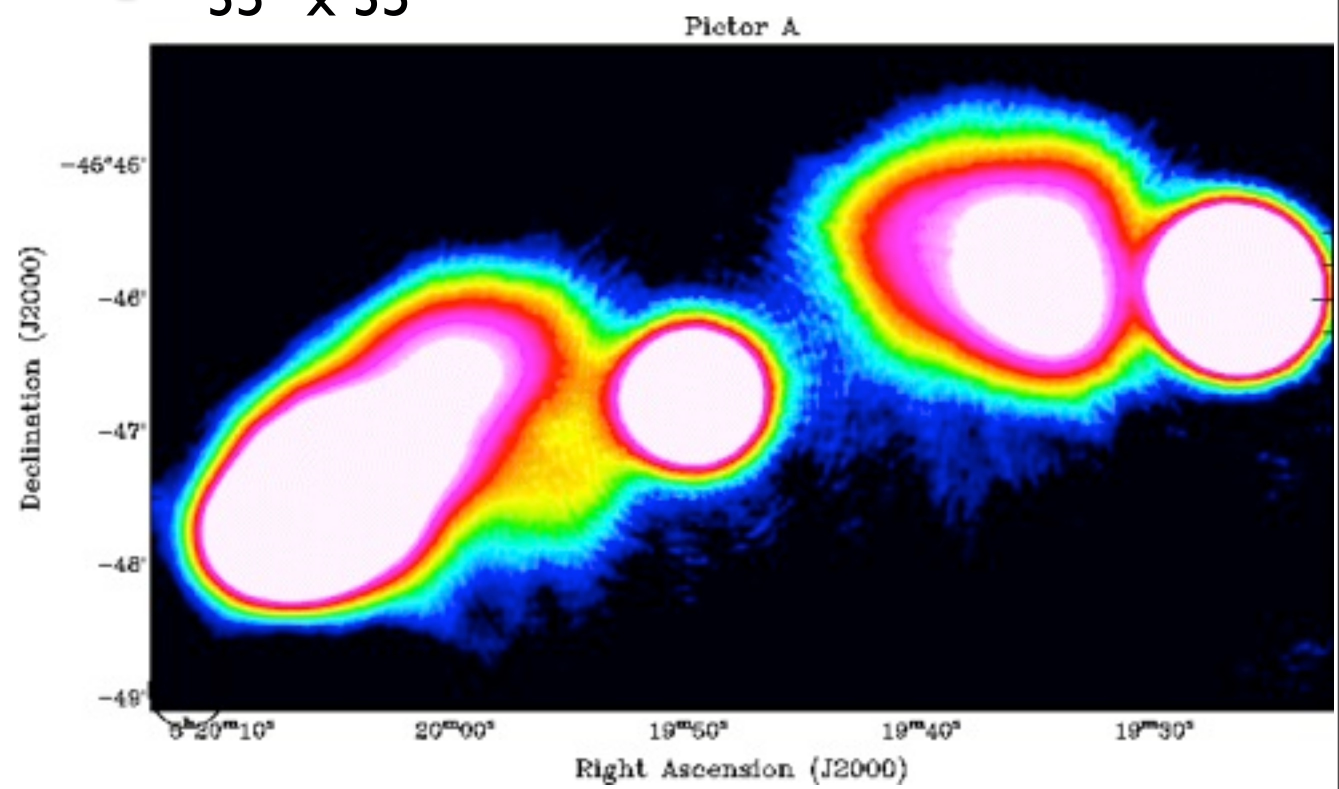
- Do you want to know the position of a source?
  - Image with as small a beam as possible
- Do you want to know the total flux?
  - Image with as large a beam as possible
- Do you want to know the peak flux?
  - Image with a small beam, run a high-pass filter over the image
- Do you want to look for low level emission?
  - Smooth the image

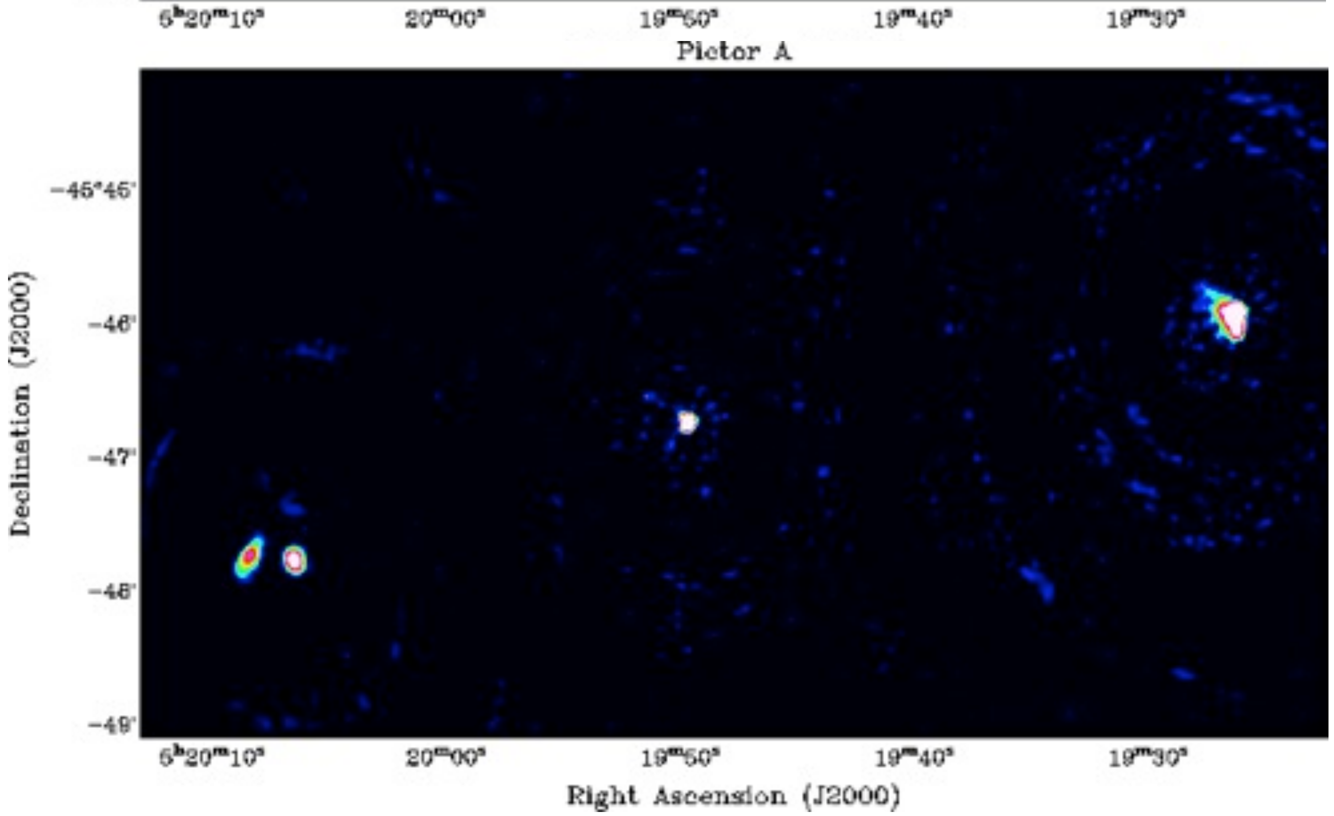
Image Manipulation

4.3" x 3.8"



35" x 35"



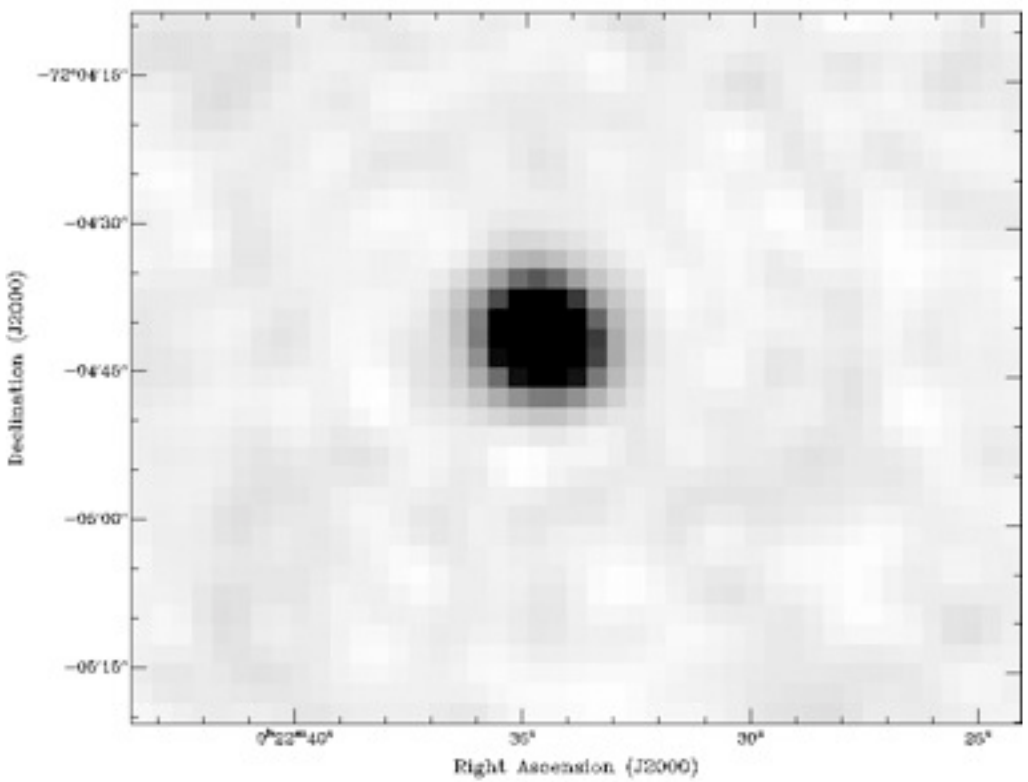


4.3" x 3.8" high-pass filter

Each image emphasises a different aspect of the data:

- Hot spots plus large scale emission
- Total flux
- Peak intensities

Simple source parameters

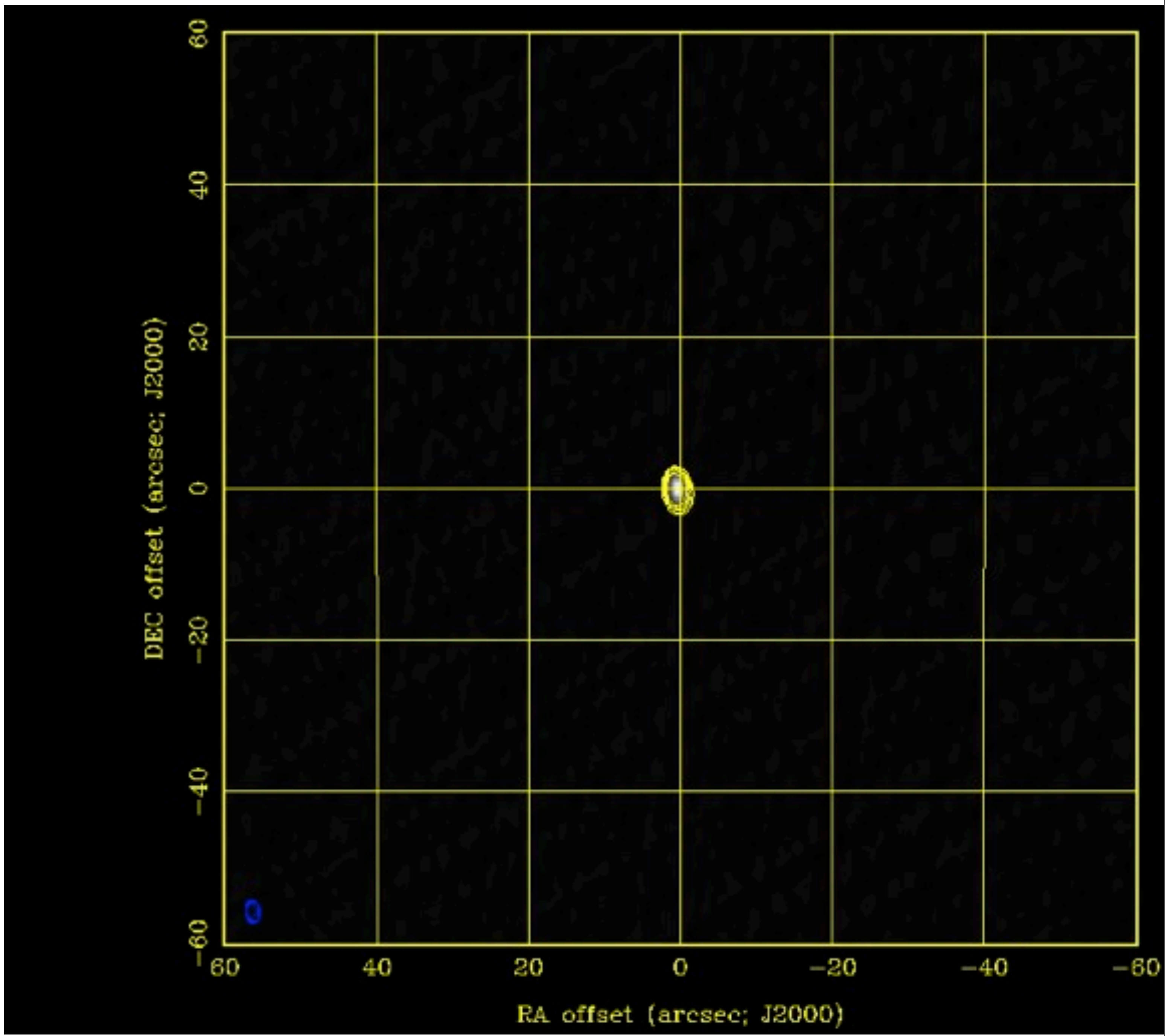


- If you want to know the flux and position of a simple source you have options:
  - Estimate from *kvis* peak value
  - miriad's *maxfit & imfit*
  - CASA *imfit*

```
imfit% inp
  Task:   imfit
  in        = 47tuc_sub.mir
  region    = boxes(219,333,263,368)
  clip      =
  object    = gaussian
  spar      =
  fix       =
  out       =
  options   =
imfit% go

imfit: Revision 1.5, 2010/04/30 08:23:28 UTC

------------------------------------------------
RMS residual is 1.27E-05

Using the following beam parameters when
deconvolving and converting to integrated flux
  Beam Major, minor axes (arcsec):     8.92     8.42
  Beam Position angle (degrees):      44.4

Scaling error estimates by  4.6 to account for
noise correlation between pixels

Source  1, Object type: gaussian
  Peak value:                 9.5209E-04 +/-  2.4637E-05
  Total integrated flux:      9.9578E-04
  Offset Position (arcsec):    -418.425    11.647
  Positional errors (arcsec):     0.100     0.097
  Right Ascension:                0:22:34.634
  Declination:                  -72:04:41.067
  Major axis (arcsec):          9.266 +/-   0.243
  Minor axis (arcsec):          8.472 +/-   0.222
  Position angle (degrees):     55.72 +/-      11.85
  Deconvolved Major, minor axes (arcsec):    2.670    0.380
  Deconvolved Position angle (degrees):      69.8
------------------------------------------------
```

Source size u-v domain

- Source when imaged appears unresolved
  - beam: 2.9” x 1.7”
- U-V amplitude with distance not quite flat
  - Constrains source to 0.4” x 0.2”



credit: PMN, D McConnell

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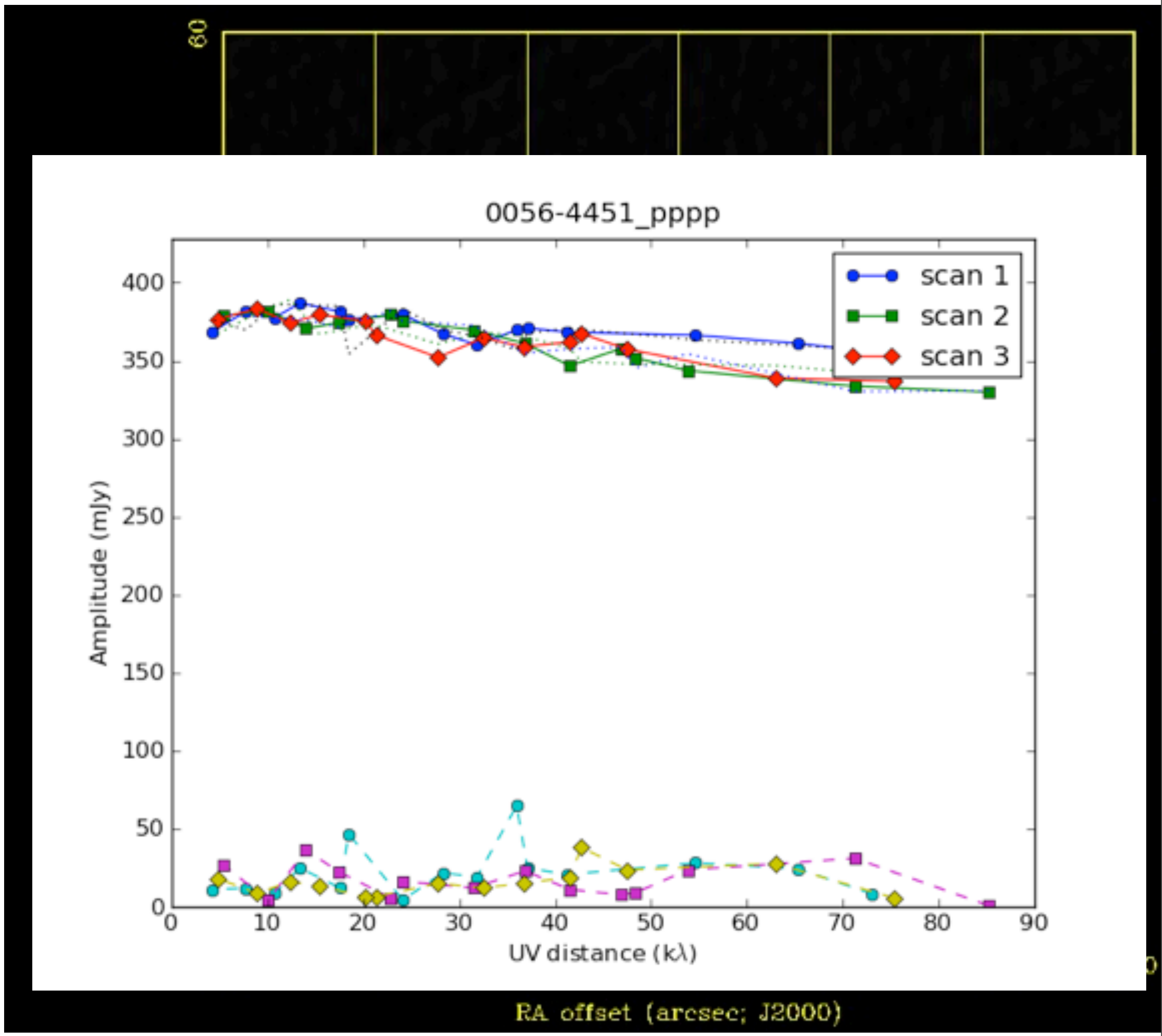

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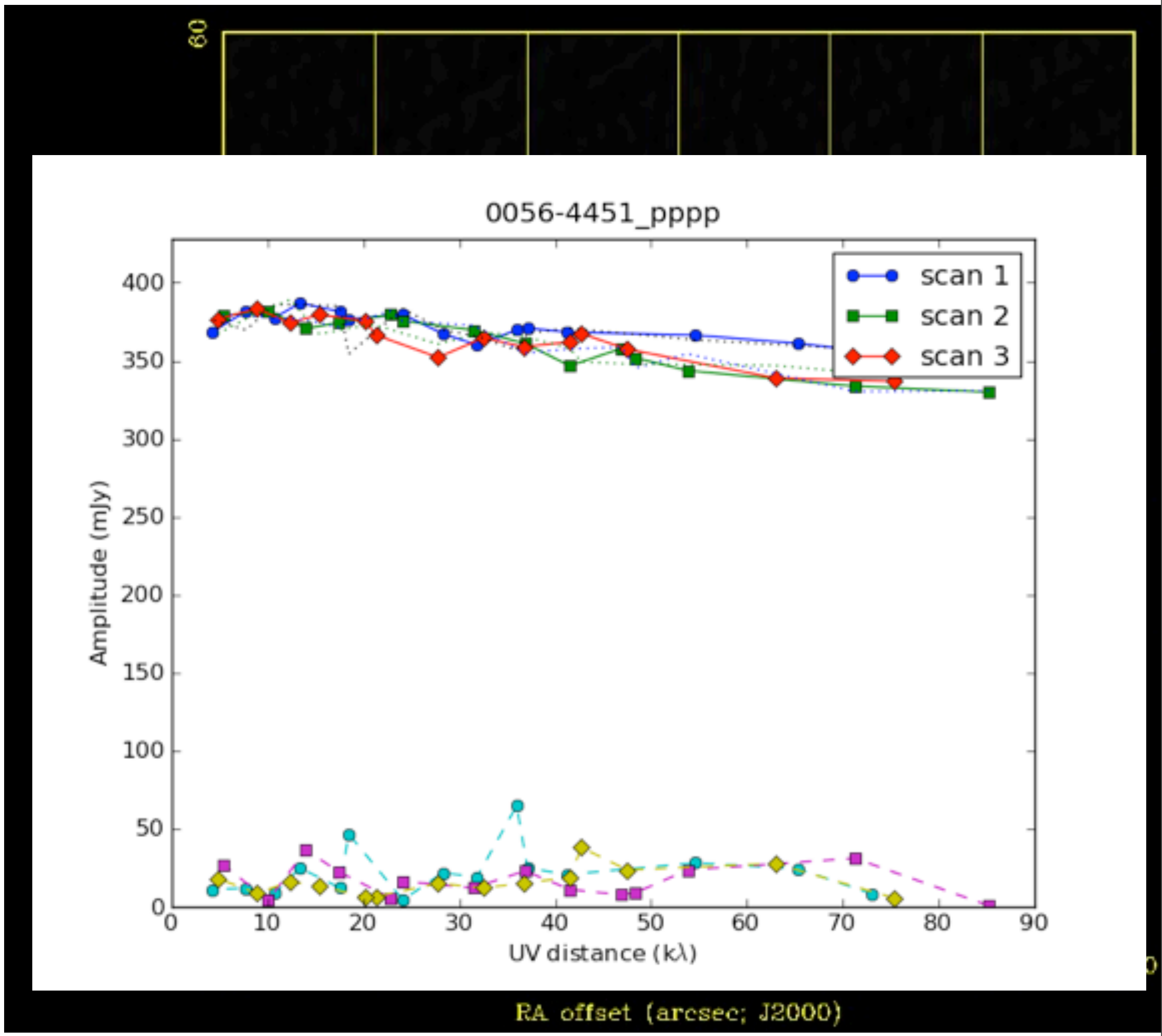
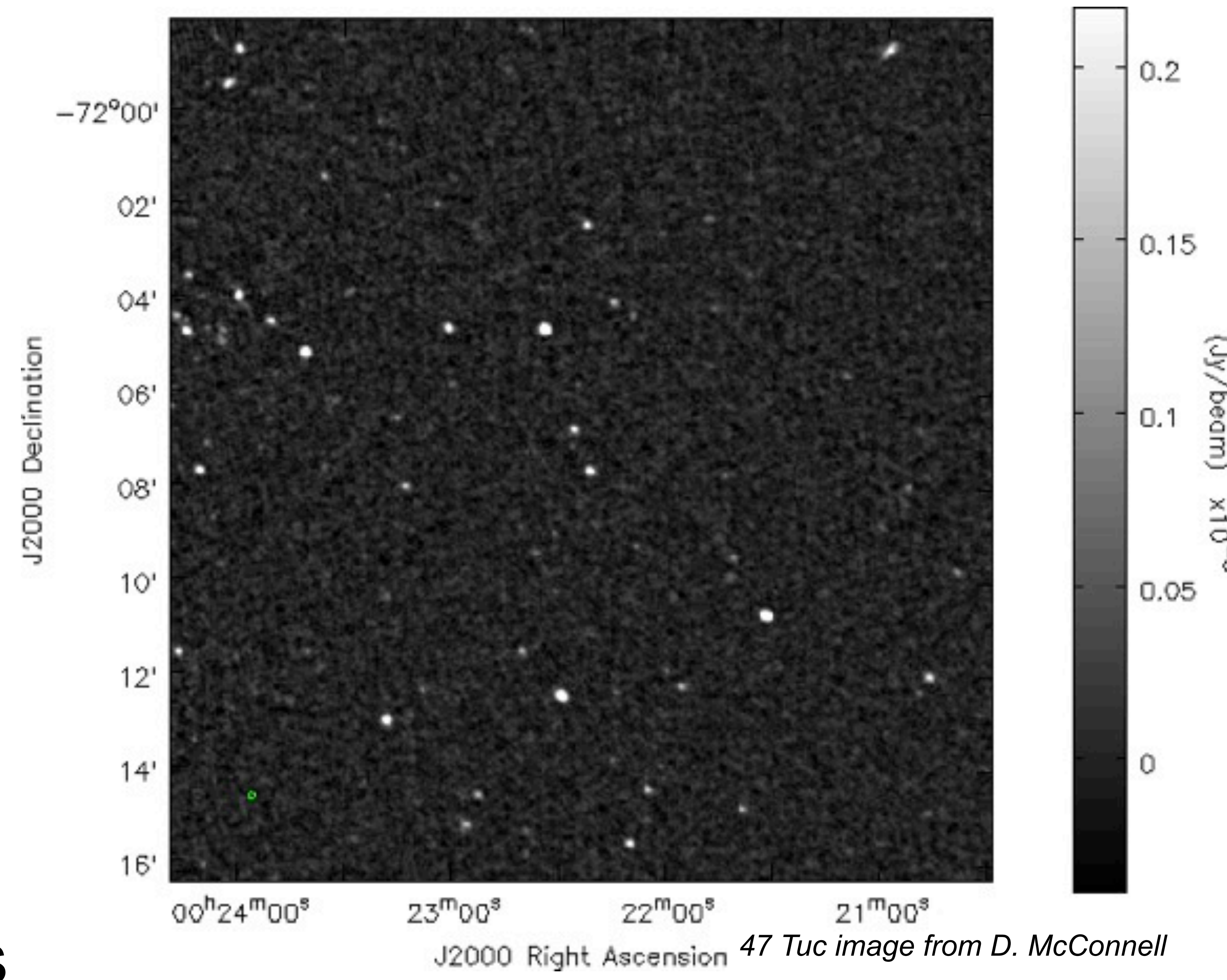


credit: PMN, D McConnell

Source Finding & Characterisation

- There are a number of tools for automated source finding and cataloging:
  - miriad: *imsad*
  - CASA: *findsources* & *fitsky*
  - *Duchamp, etc.*
- Limitations when images have artefacts or sources are extended



47 Tuc image from D. McConnell

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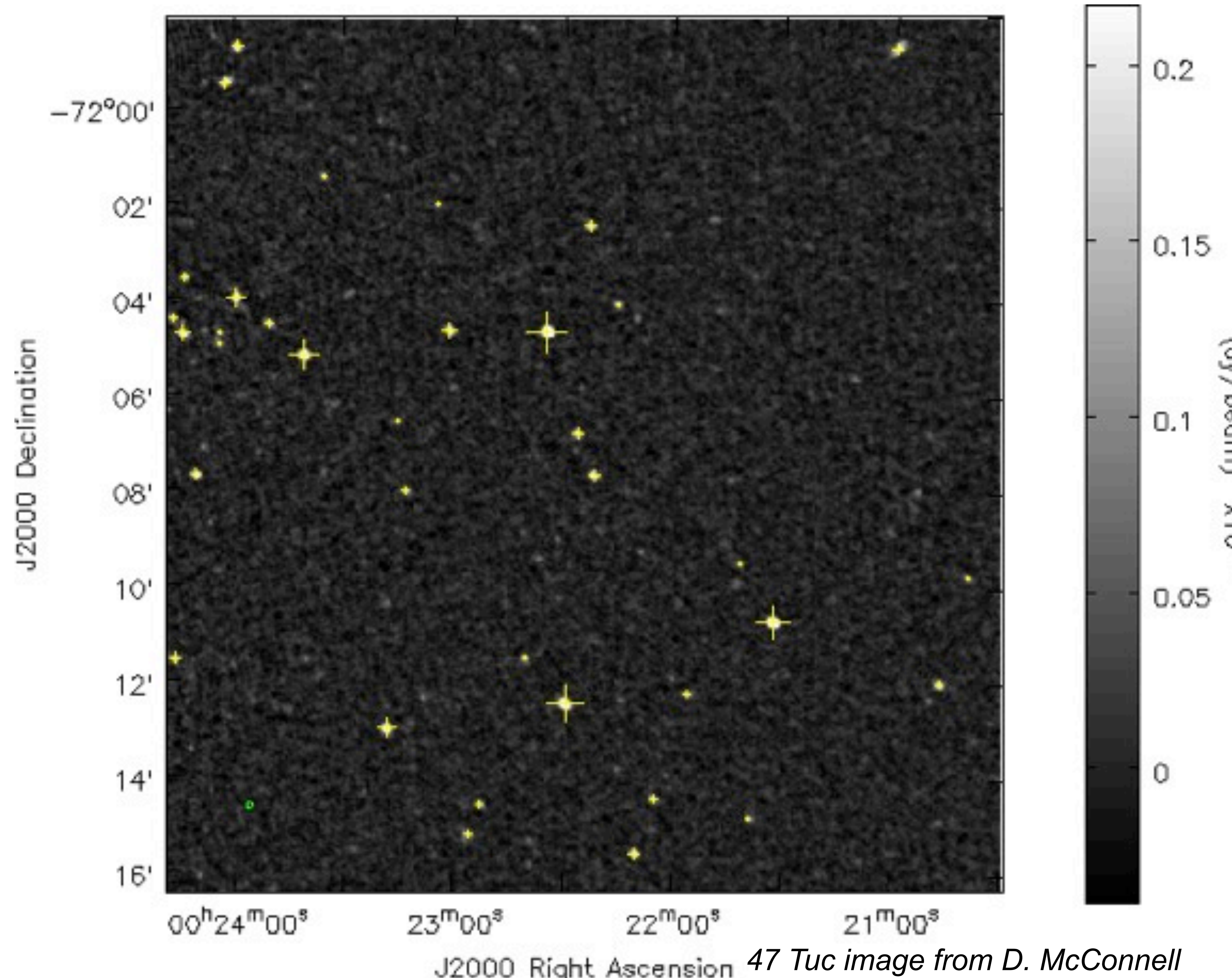
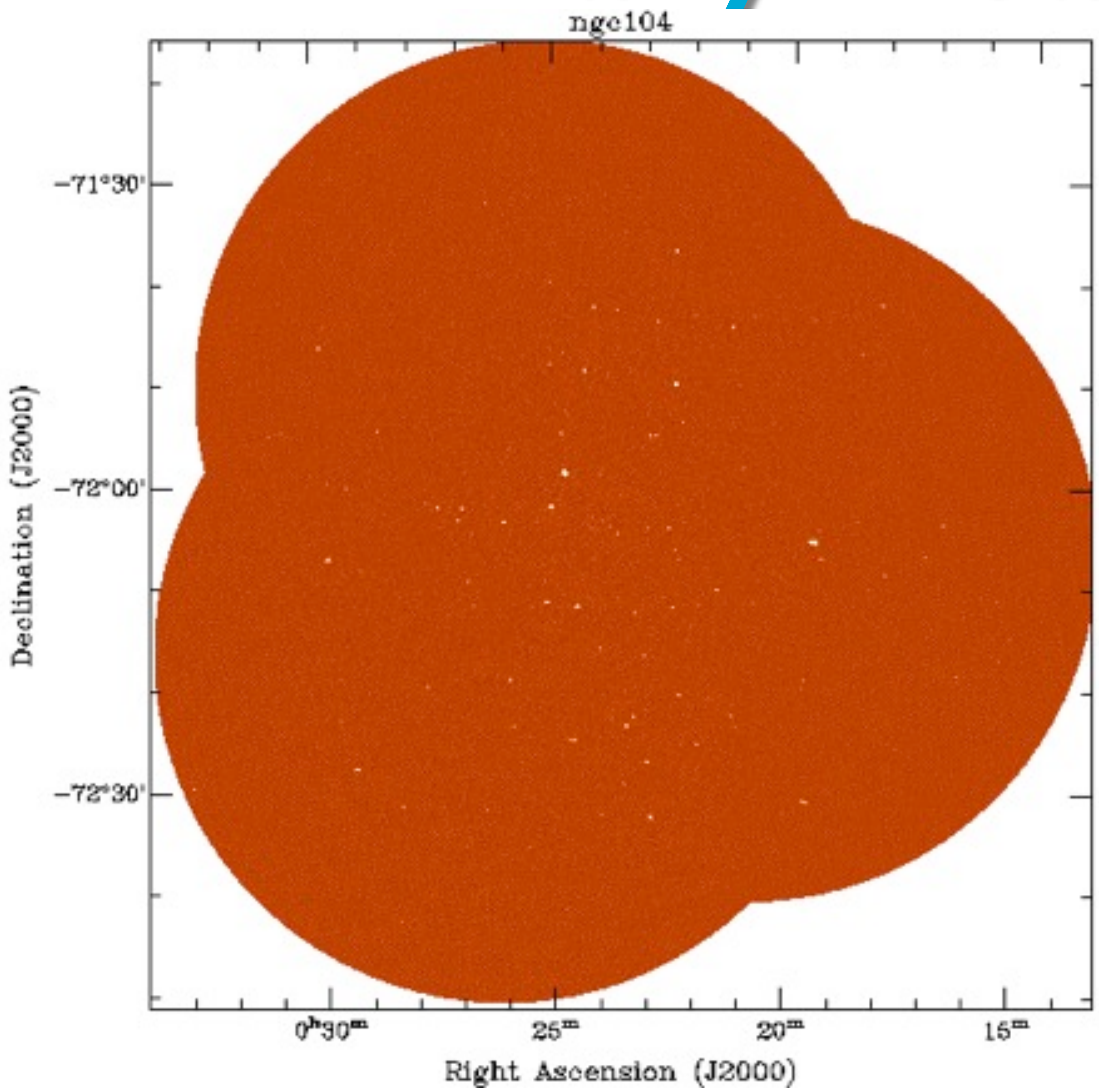


47 Tuc image from D. McConnell

Example from casapy *findsources*:

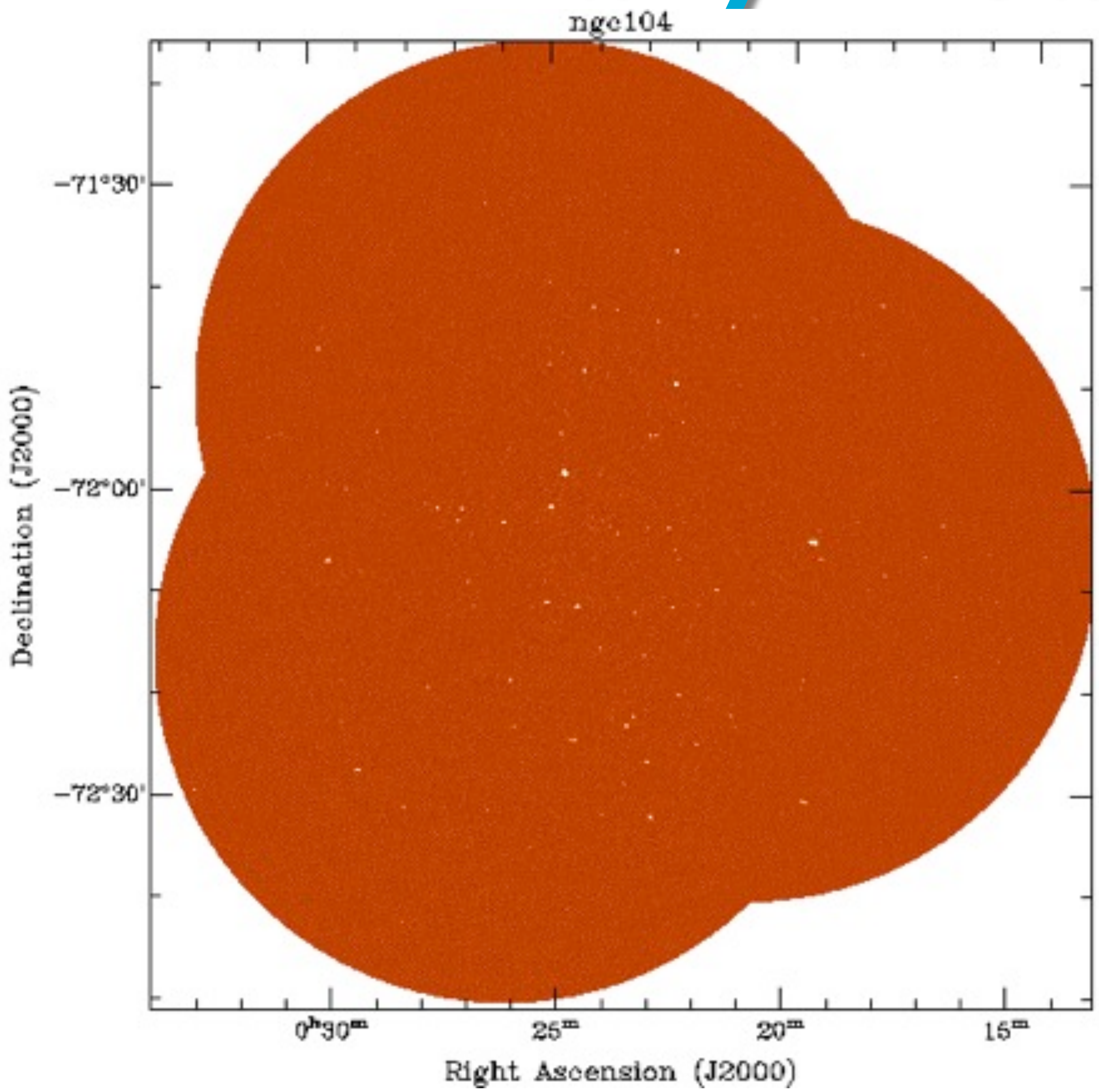
```
ia.open("47tuc.sub.img")
cl=ia.findsources(nmax=100,cutoff=0.1)
```

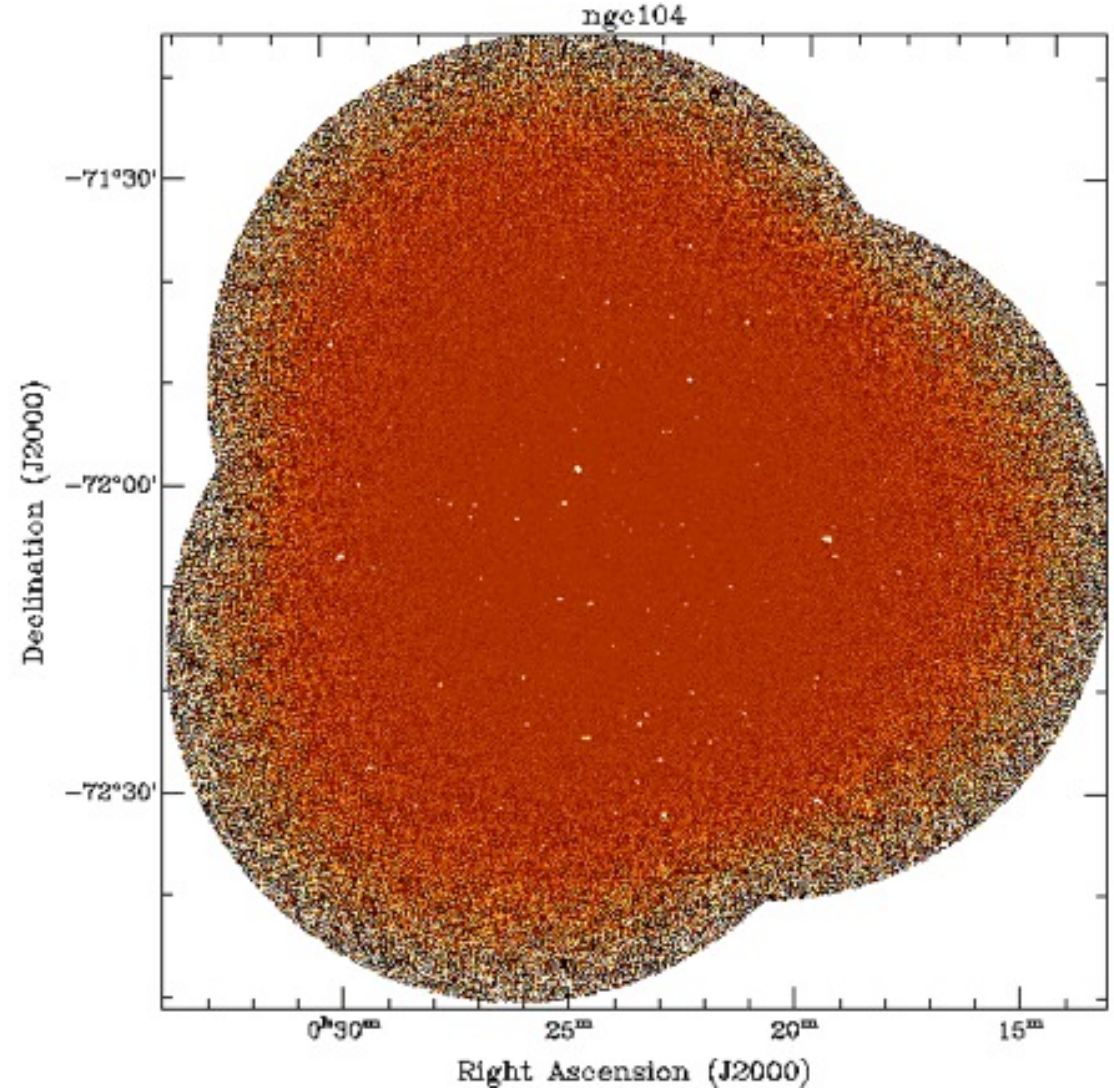
Primary Beam Correction



- Beware the limitations of your image
  - Your image is weighted by the primary beam sensitivity
  - Divide by the primary beam to restore sources to their expected brightness increases the noise at the edge of the image

Primary Beam Correction





Primary beam corrected

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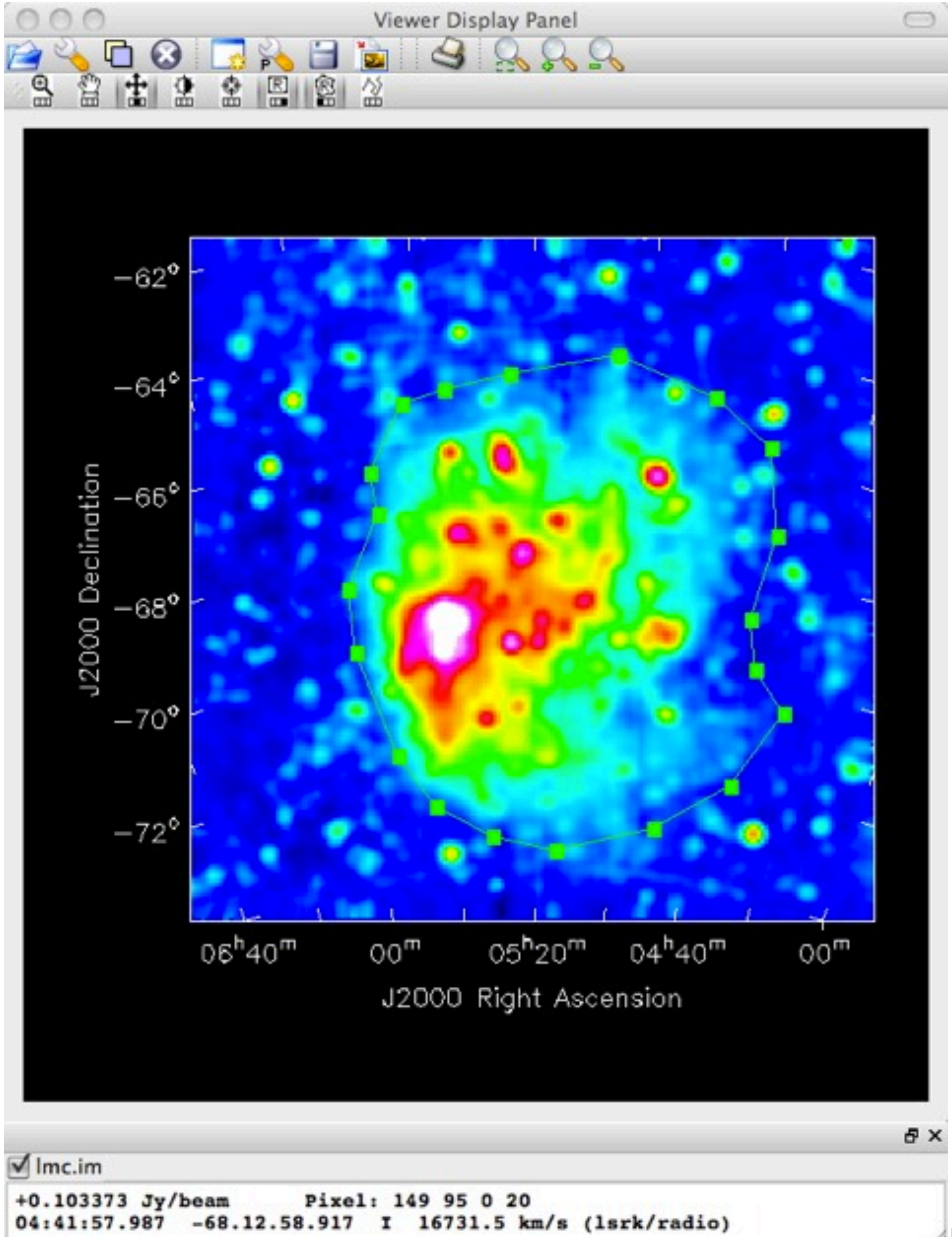
Extended Source Flux



- To estimate the flux for extended sources, integrate over the whole source:

$$S_\nu[\mathrm{Jy}] = \frac{\int I_\nu[\mathrm{Jy\ bm}^{-1}]d\Omega}{\int d\Omega}$$

- If the source is on a background you may need to estimate its contribution and subtract
- For simple sources you can model the source to find the flux

Extended Source Flux

- To estimate the flux for
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$$\ldots n^{-1}]d\Omega$$
$$\ldots \Omega$$

n a
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subtract

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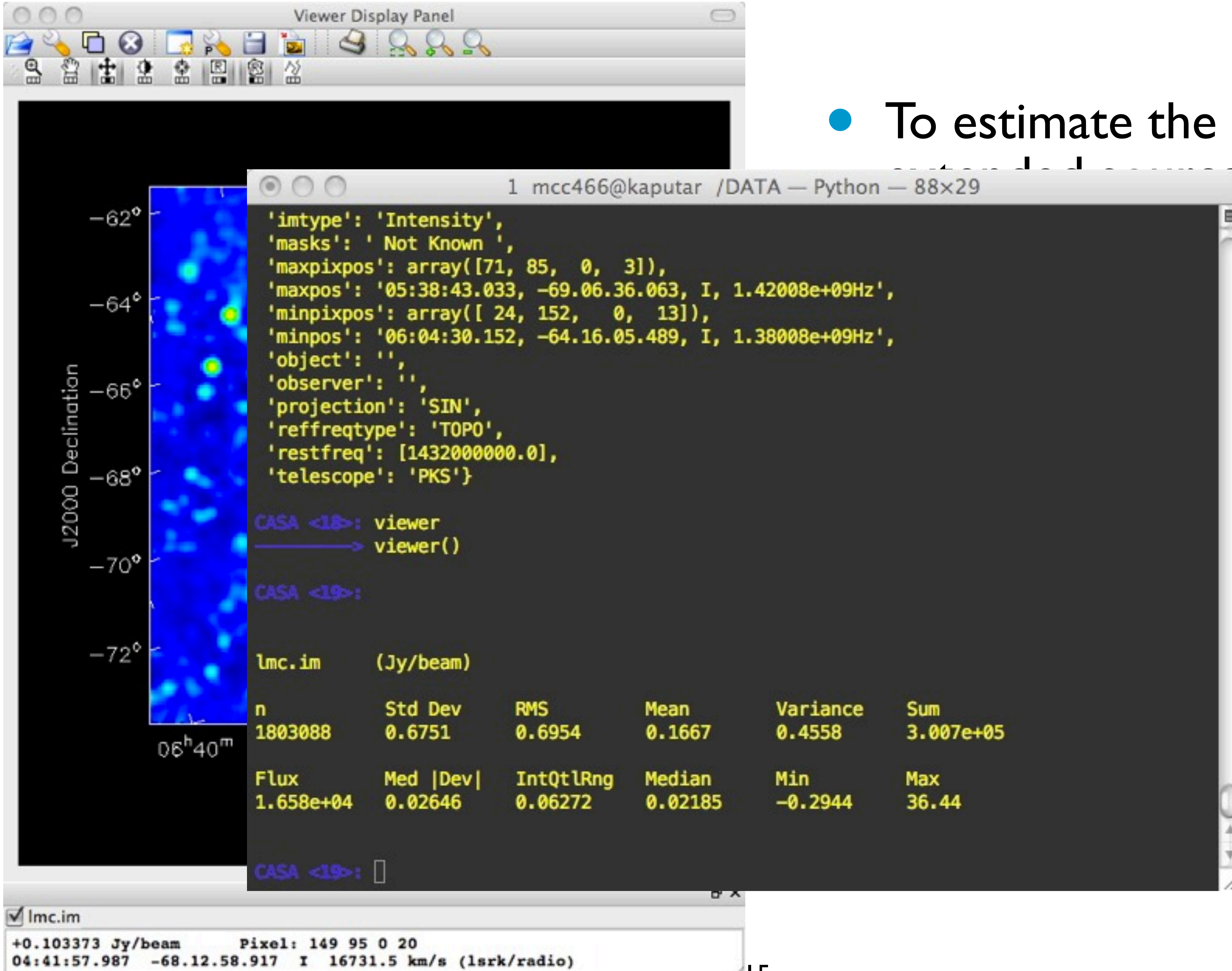
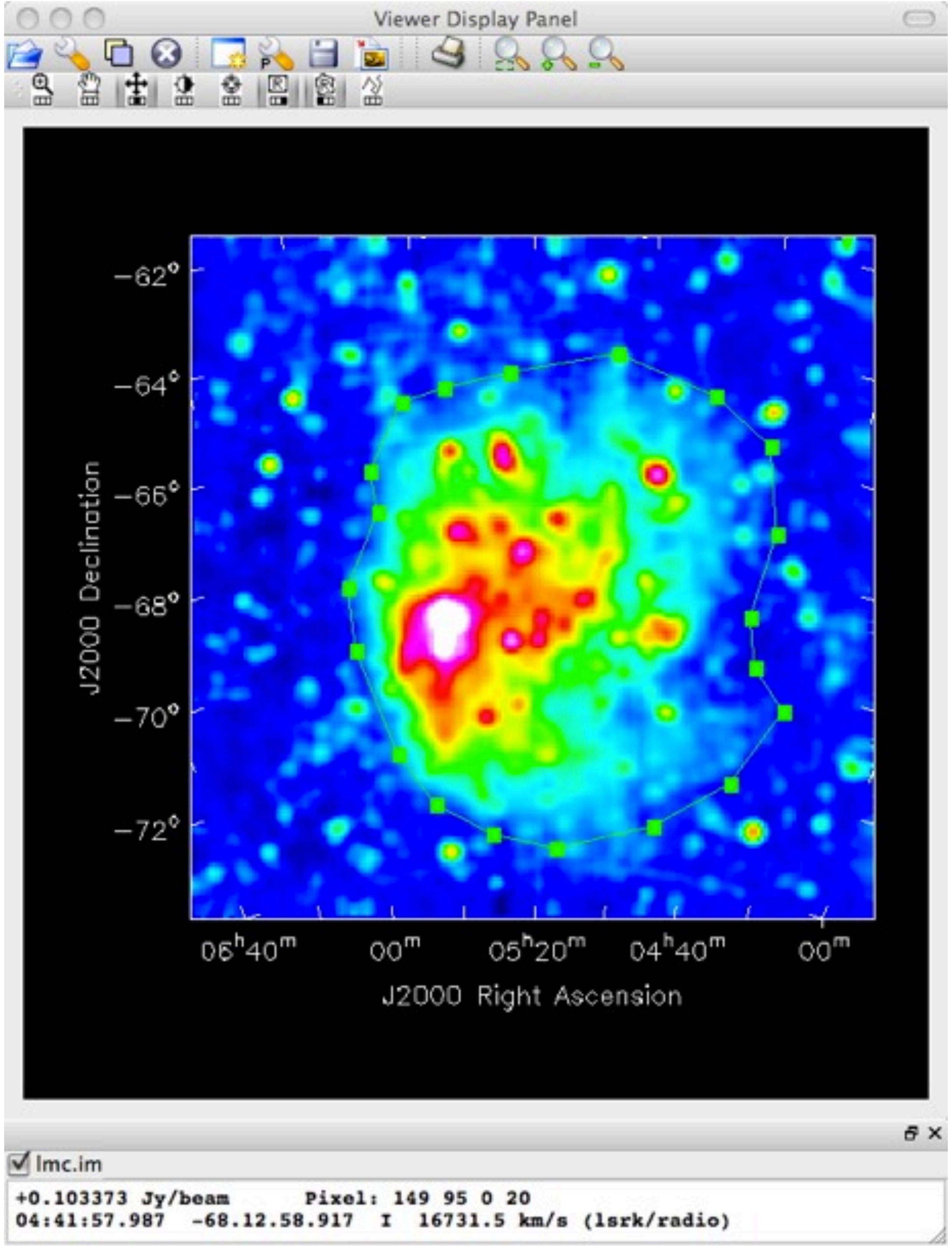


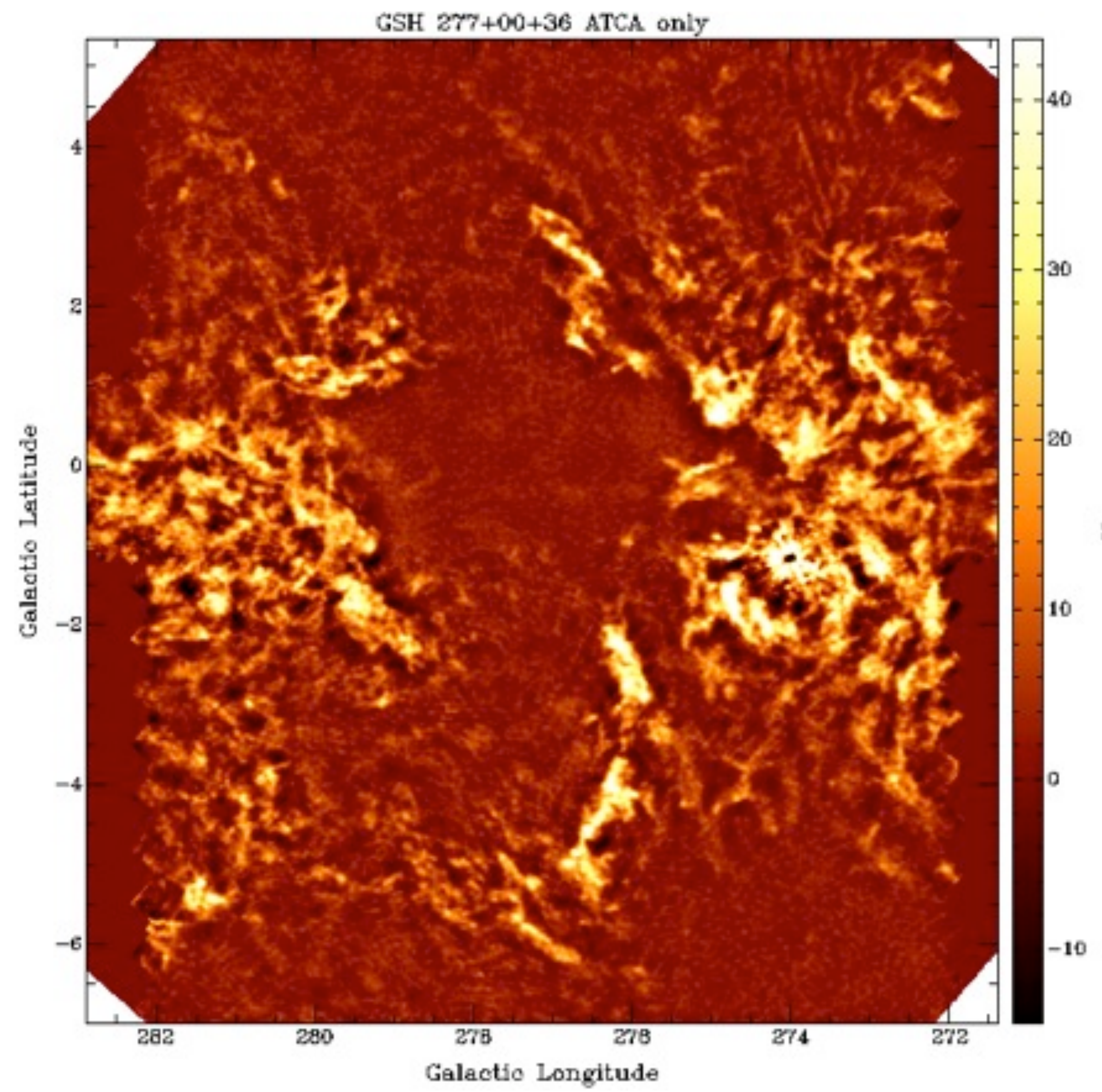
Errors on extended source flux estimates

- Error in flux determined by:
  - estimation of the background level
  - the region you choose to integrate over
  - beam dilution/resolution of image
  - Lack of missing short spacings:
    - total flux measurements will be lower limits



Combining single dish & interferometer data

- To measure total flux or to study extended source morphology you may need to combine your interferometer data with single dish images
    - Necessary if your source size is larger than λ/d_{min}
- Methods:
    - Image, combine, then deconvolve
    - Image, combine during deconvolution
    - Image, deconvolve then combine
- See Stanimirovic 2002, ASP conference series 278



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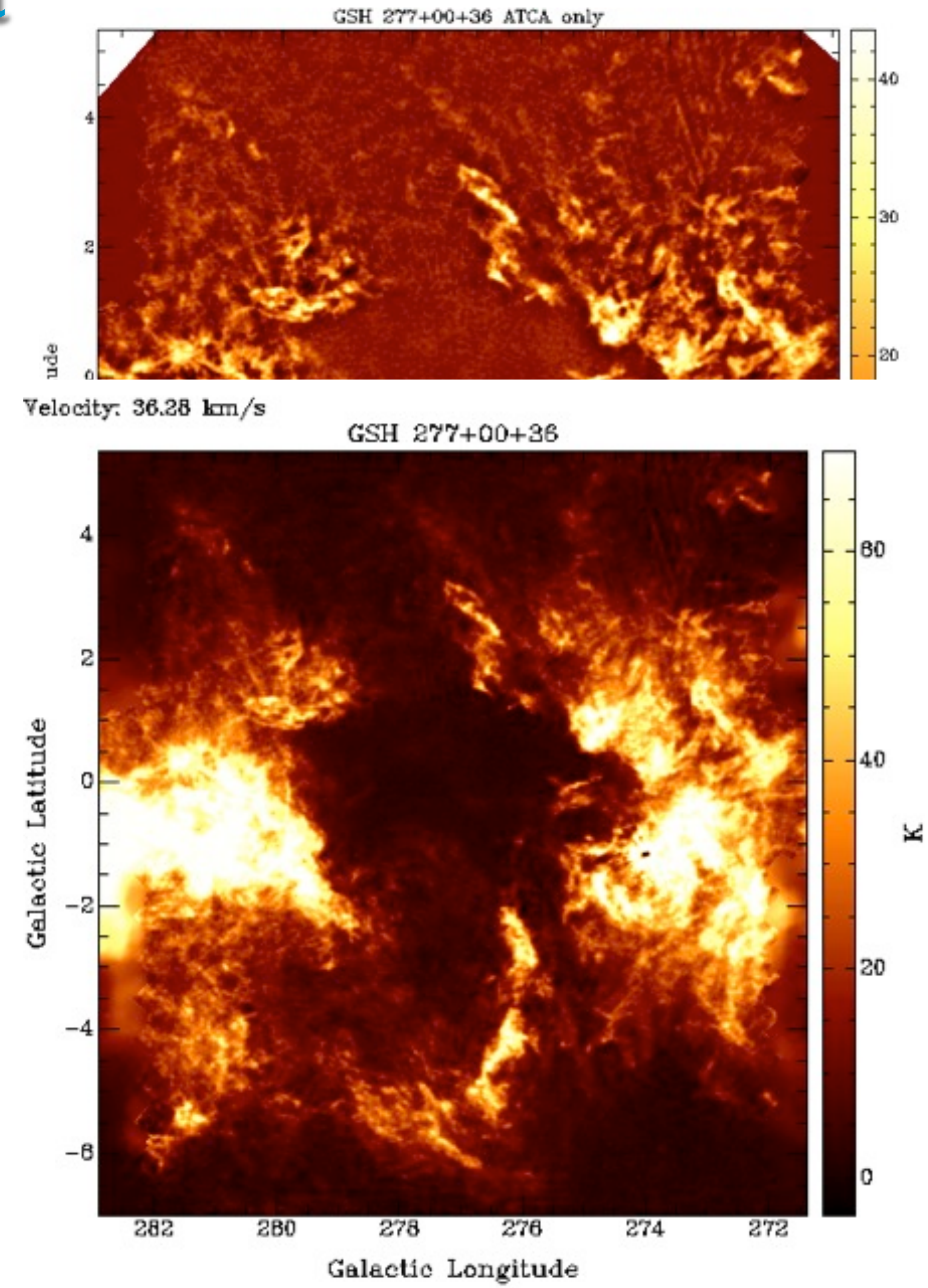


Brightness Temperature

- It is often useful to characterise emission in terms of the brightness temperature, T_b, in Kelvin
  - Temperature of an equivalent blackbody having the intensity, I_ν, in Jy/Bm at a given frequency, ν
- The Rayleigh-Jeans approximation applies so for flux density, S, and synthesised beam, Ω,

$$I_\nu = \frac{S}{\Omega} = \frac{2\nu^2}{c^2} k\, T_b$$

Brightness Temperature II

- The synthesised beam is modelled as a circular Gaussian with FWHM of θ:

$$\Omega = \frac{\pi \theta^2_{\mathrm{HPBW}}}{4 \ln 2}$$

- So the brightness temperature of a feature that fills the beam is:

$$T_b = \frac{2 \ln 2}{\pi} \frac{\lambda^2}{k} \frac{I_\nu}{\theta^2_{\mathrm{HPBW}}}$$

- Or in sensible units:

$$T_b = 1.36 \frac{\lambda[\mathrm{cm}]^2 I_\nu [\mathrm{mJy\ Bm}^{-1}]}{\theta_{\mathrm{HPBW}}[\mathrm{arcsec}]^2}$$

Estimating errors

- Measurements are meaningless without an estimate of the error
- Error estimates need to be made for:
  - Source fluxes
  - Source positions
  - Source sizes
  - Combined images, such as polarization images
- Beware of errors returned from model fits as these are usually formal fitting errors
- Image flux statistics can be estimated from the image itself:
  - miriad: *imstat*
  - kvis: "s" key
  - CASA: polygon region statistics

Position and size errors

- Absolute positional accuracy depends on the quality of your data/ calibration
    - Precision of the position of the phase cal (secondary)
    - Separation of phase cal from source - the closer the better!
    - Weather, phase stability
    - Signal-to-noise
    - Beware of positions after self-cal
- Relative positions and motions
    - Limited by signal to noise
- Source sizes convolve beam and source
    - Source away from phase centre can show effects of bandwidth smearing

Rough Error Estimates:

P = Component Peak Flux Density

σ = Image rms noise

P/σ = signal to noise = S

B = Synthesized beam size

θ_i = Component image size

ΔP = Peak error = σ

ΔX = Position error = $B / 2S$

$\Delta\theta_i$ = Component image size error

$= B / S$

θ_t = True component size

$= (\theta_i^2 - B^2)^{1/2}$

$\Delta\theta_t$ = Minimum component size

$= B / S^{1/2}$

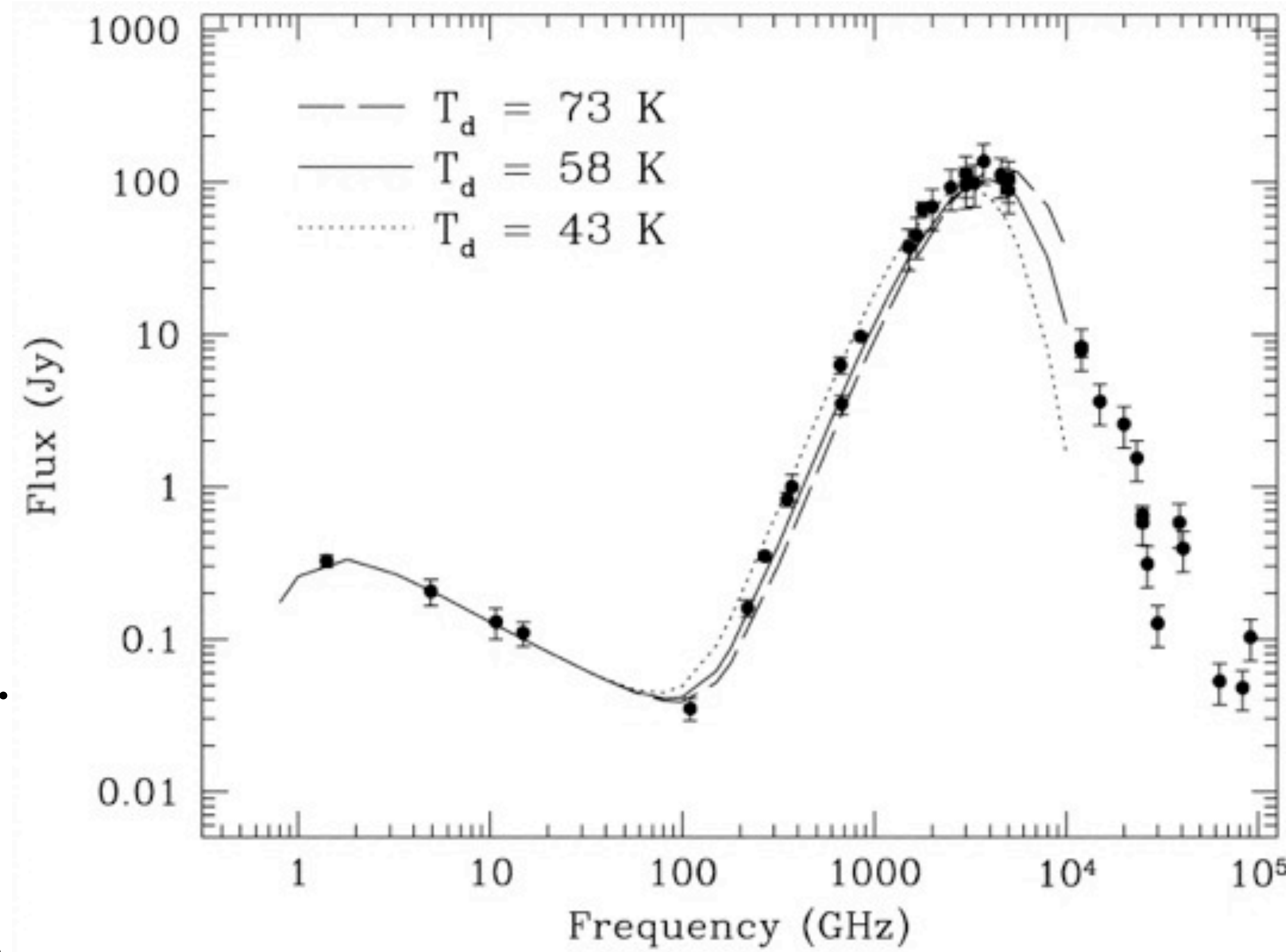
From E. Fomalont

Image combination: spectral index

- Data at multiple frequencies are useful for studying the spectral index:

$$\alpha = \frac{\log(S_{\nu_1}/S_{\nu_2})}{\log(\nu_1/\nu_2)}$$

- Spectral index of emission tells about the emission mechanism, i.e. thermal, synchrotron
- Can tell us about the energy spectrum of the radiating particles



Arp 220 SED: Yun & Carilli (2002)

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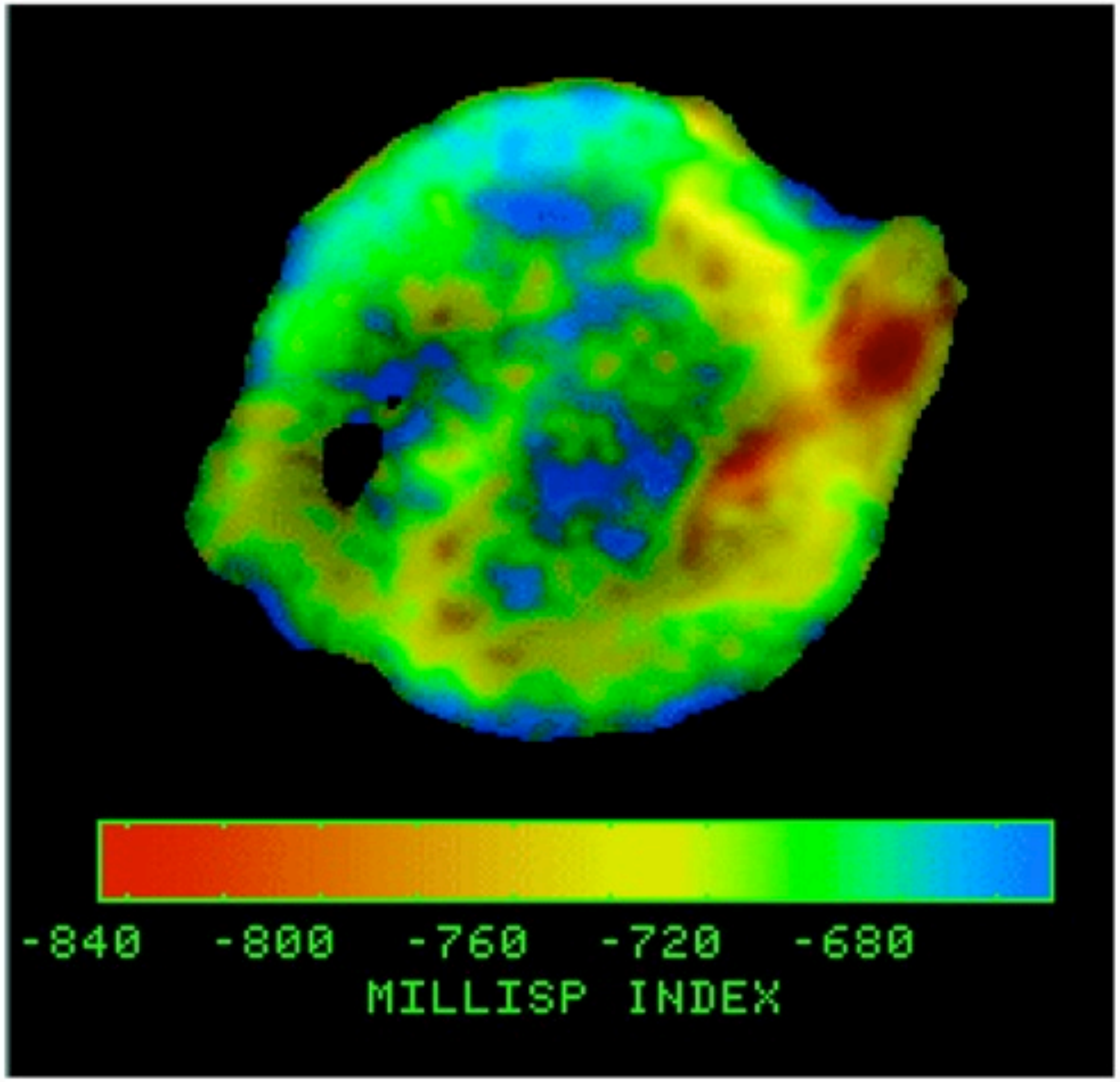
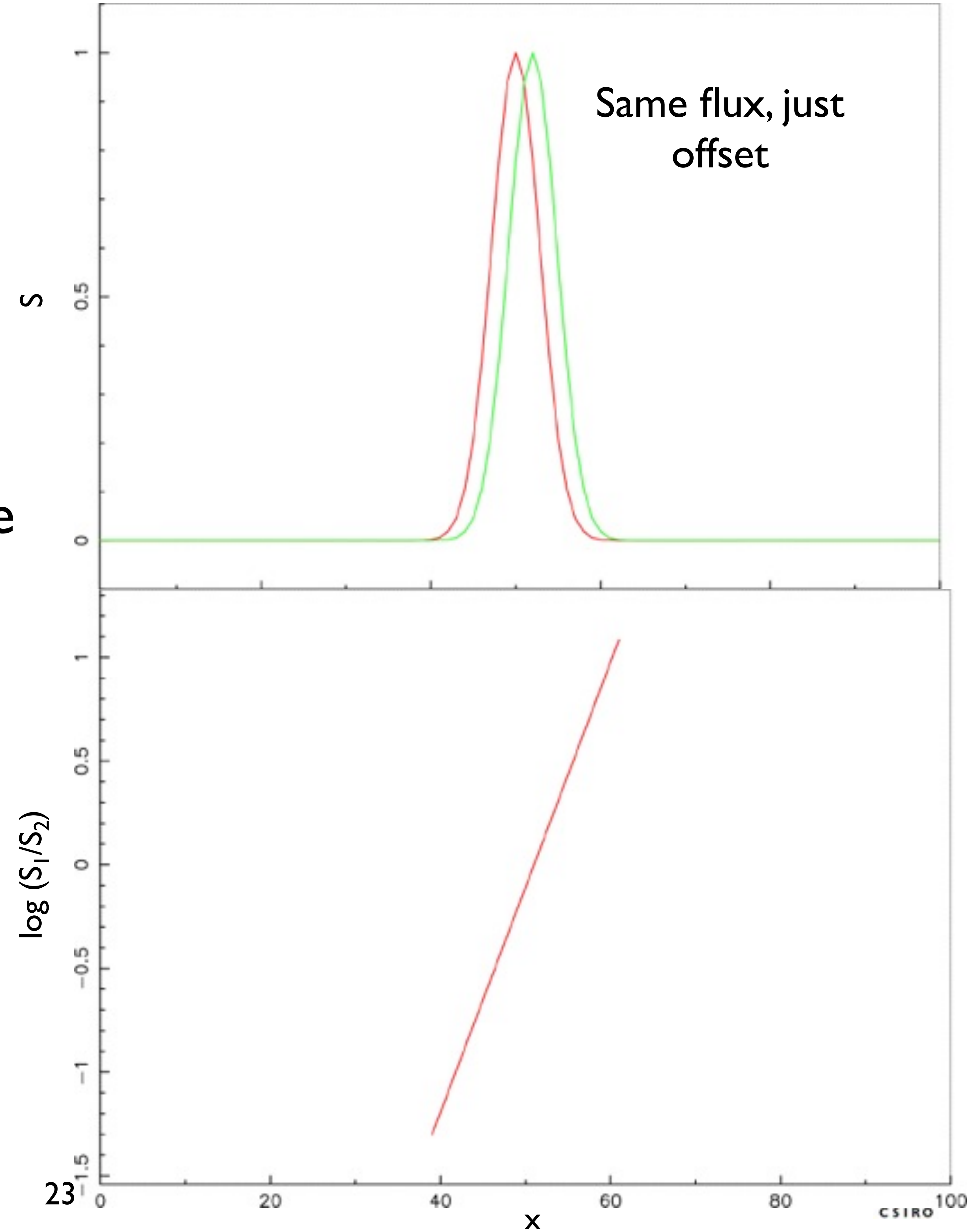


Tycho's SNR
DeLaney et al. (2002)

Spectral Index Pitfalls

- Images must be aligned or you get a false gradient
- It is important to ensure that you have the same size restoring beam for both images
- Spectral index maps of radio emission are dependent on the baselines used



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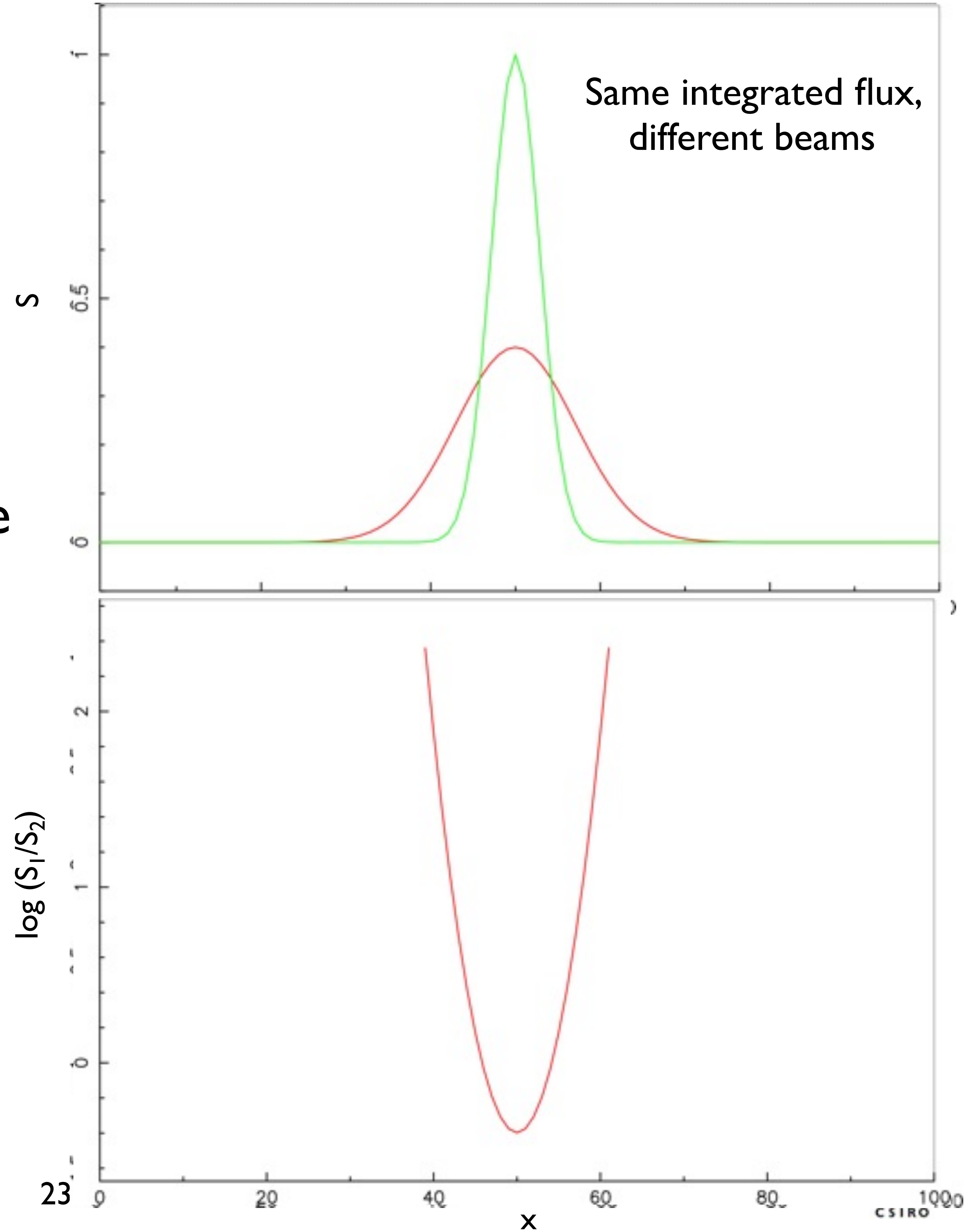

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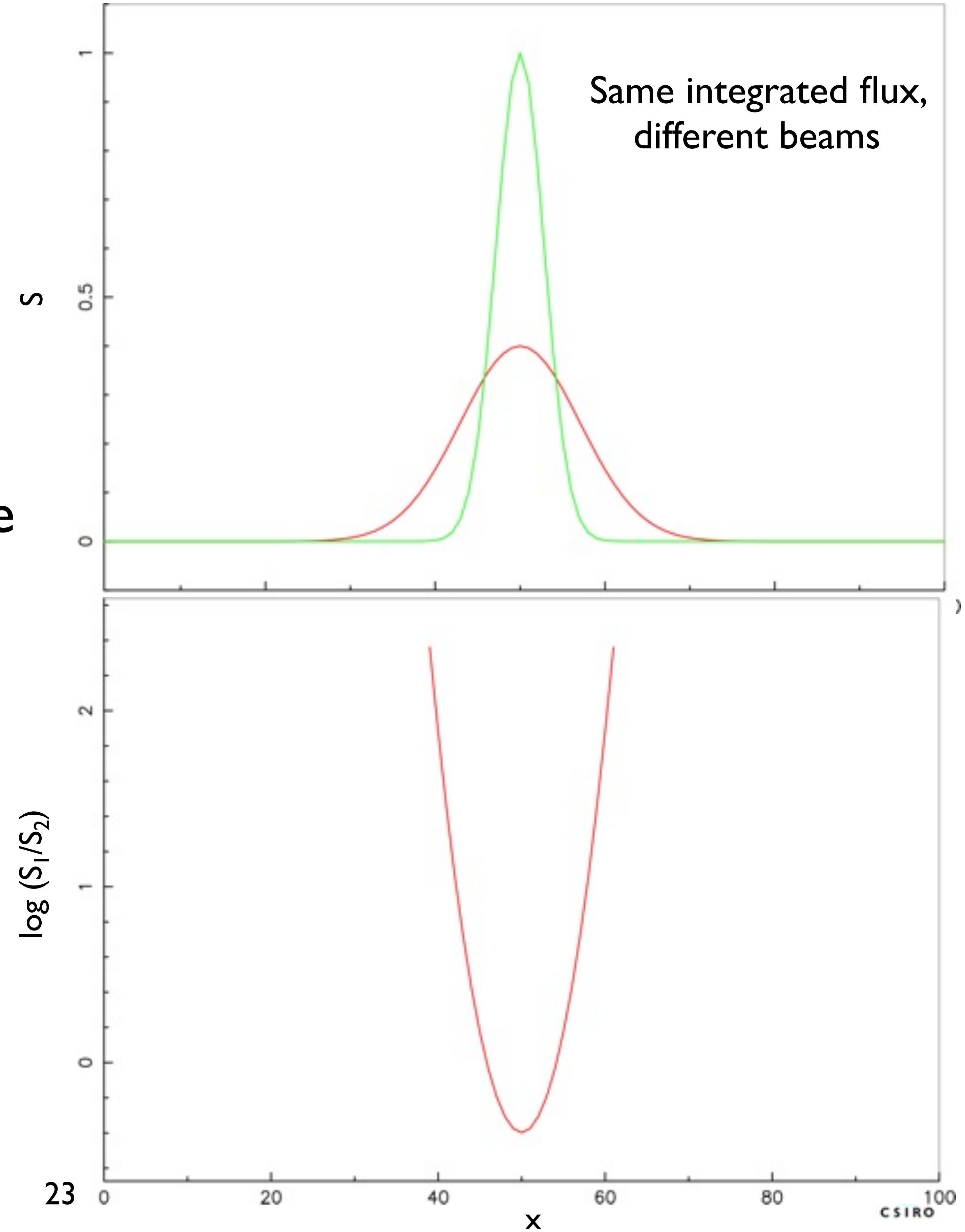


Image combination: Polarization

- Your telescope provides you with images of Stokes parameters I, Q, U, V
- You might want to know the polarized intensity:

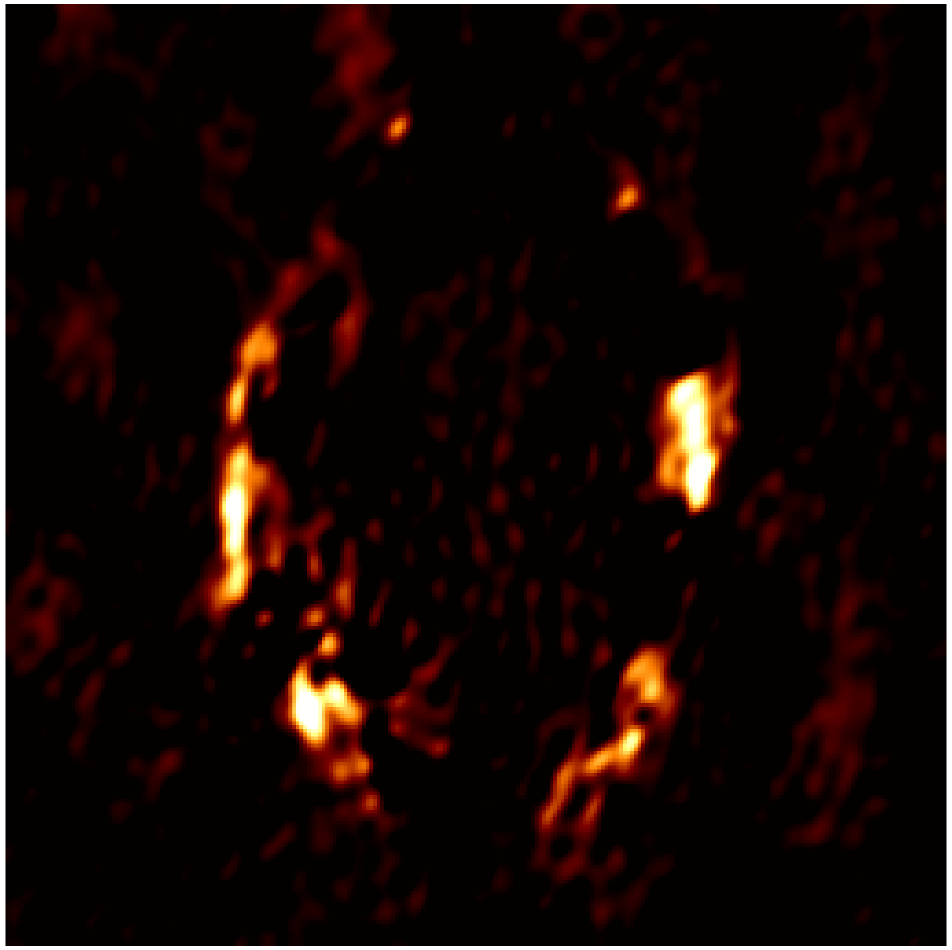
$$PI = \sqrt{Q^2 + U^2}$$

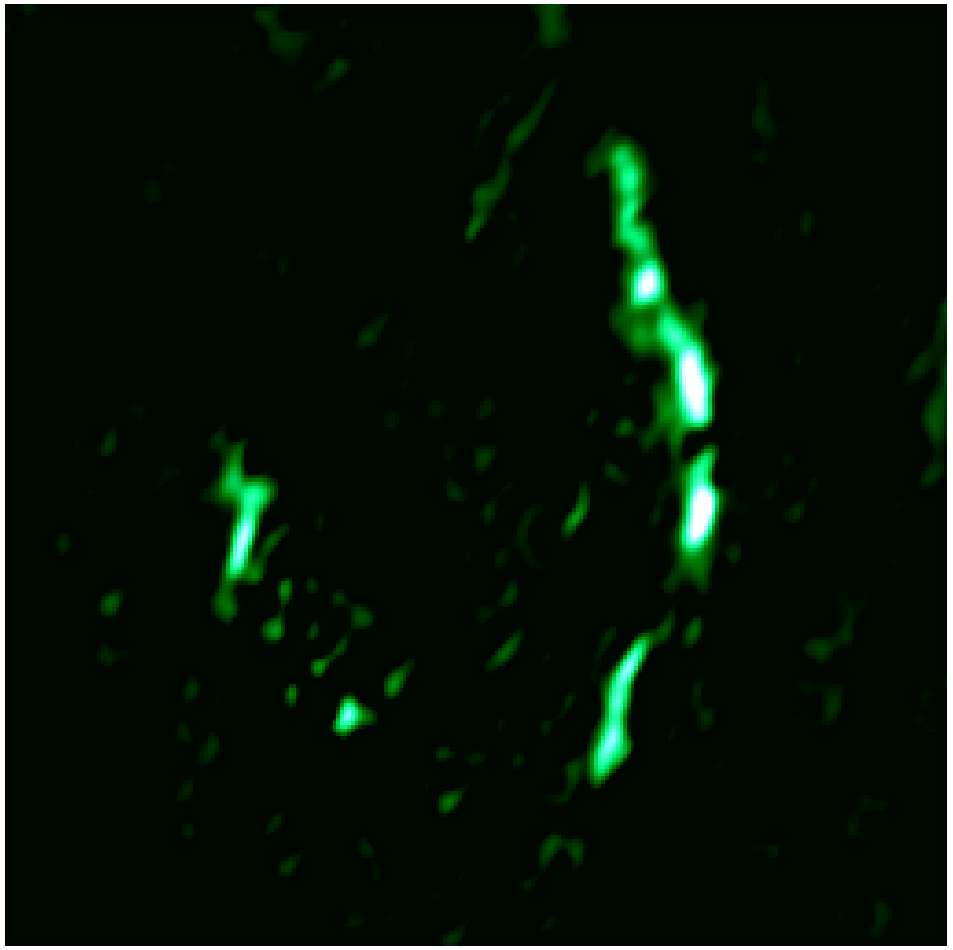
- Polarization angles

$$\chi = 1/2 \tan^{-1}(U/Q)$$

- PI is a positive definite quantity so the noise is no longer Gaussian
  - For low signal-to-noise images to debias
  - Various polarimetric tasks can do this combination for you:
  - e.g. Miriads *impol*

Stokes Q



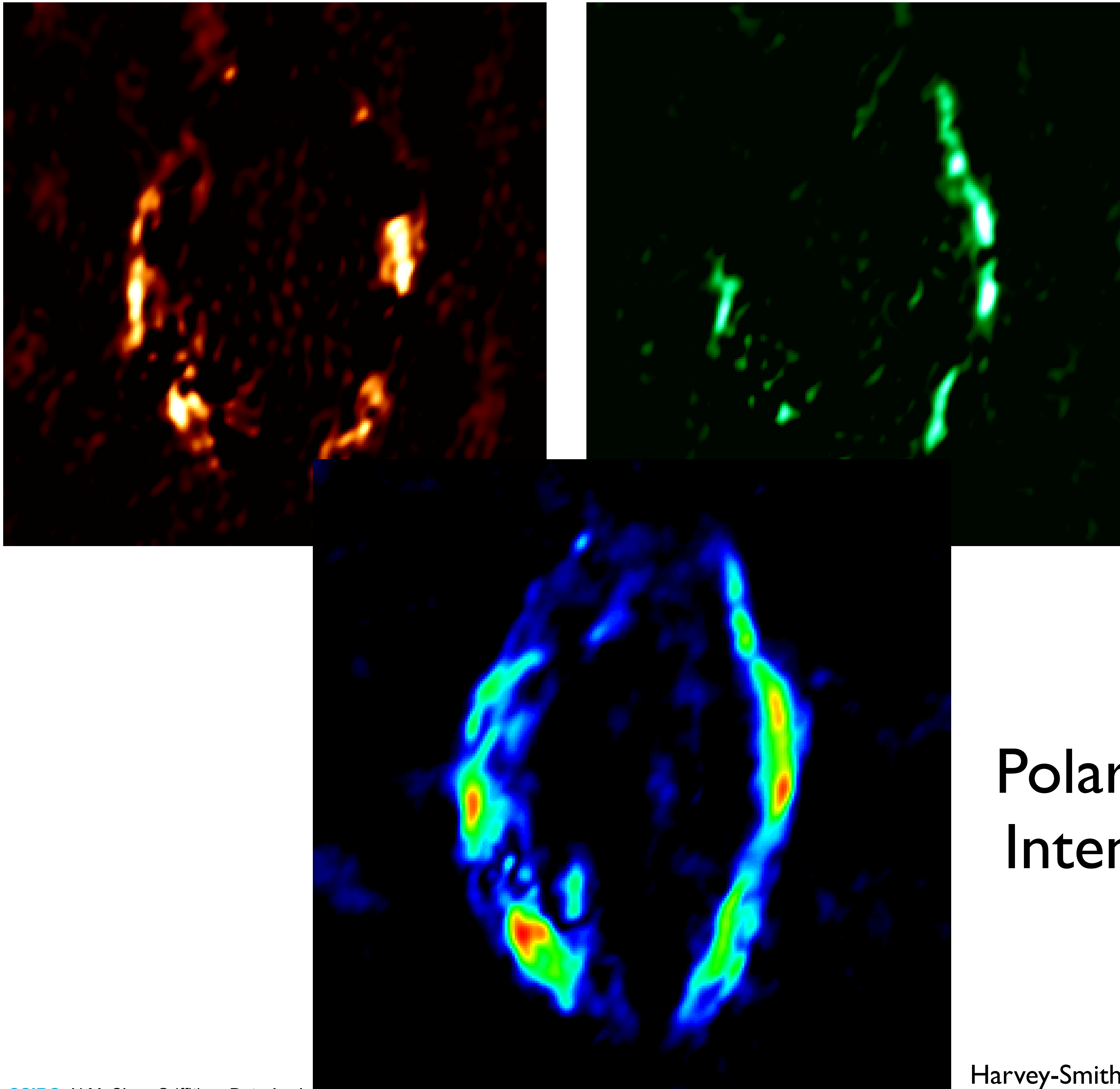


Stokes U

Harvey-Smith et al (2010)

Stokes Q

Stokes U



Polarized Intensity

Harvey-Smith et al (2010)

Polarization Analysis II

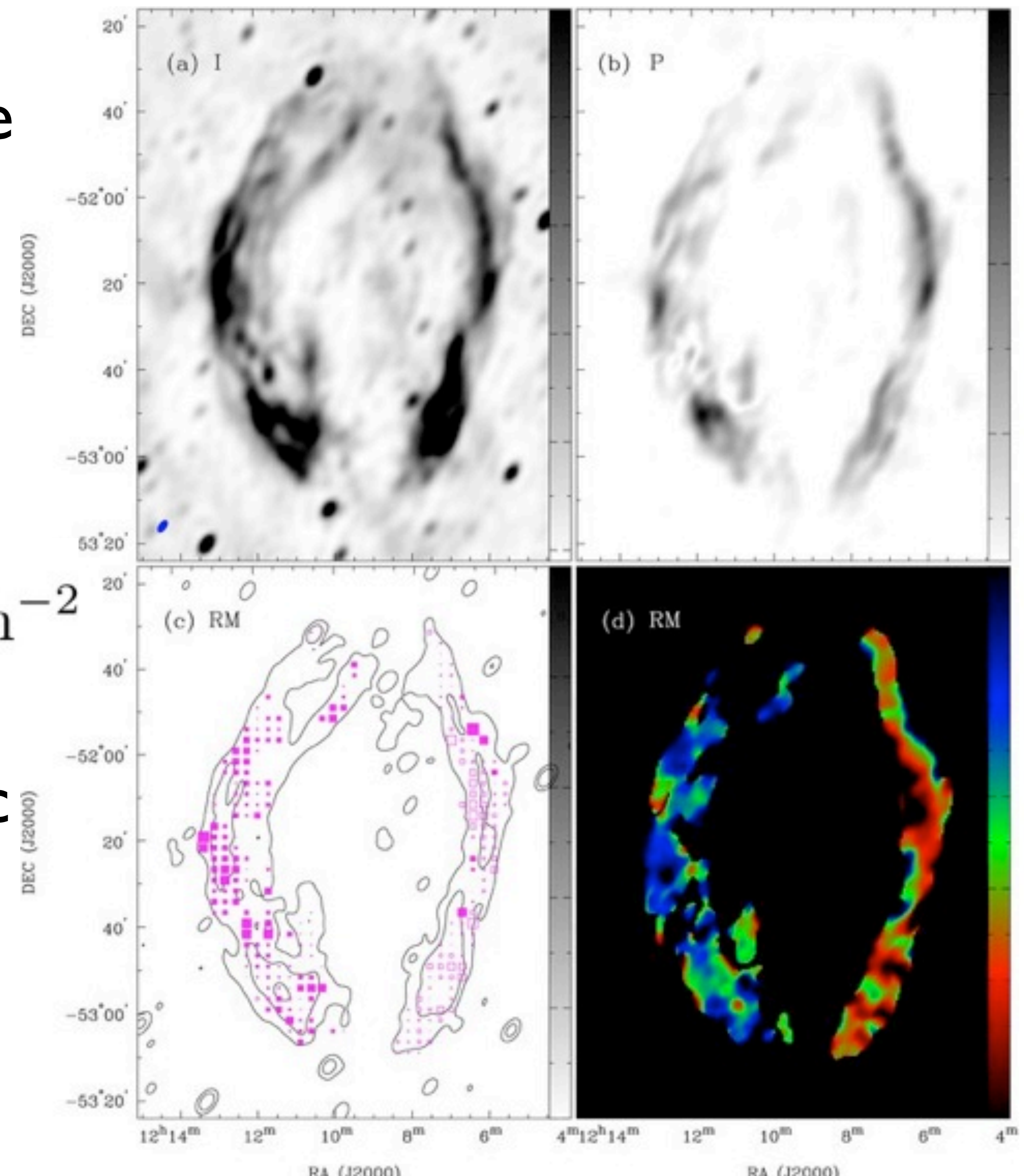
- From the PA at different frequencies we can determine the rotation measure:

$$RM = \frac{d\chi(\lambda^2)}{d\lambda^2}$$

- Where:

$$RM = 0.81 \int_{\mathrm{source}}^{\mathrm{observer}} n_e B_{||} dl \ \mathrm{rad\ m^{-2}}$$

- Gives an estimate of magnetic field strength and direction
- Or estimate the intrinsic position angle:
  - $$\chi = \chi_0 + RM\lambda^2$$

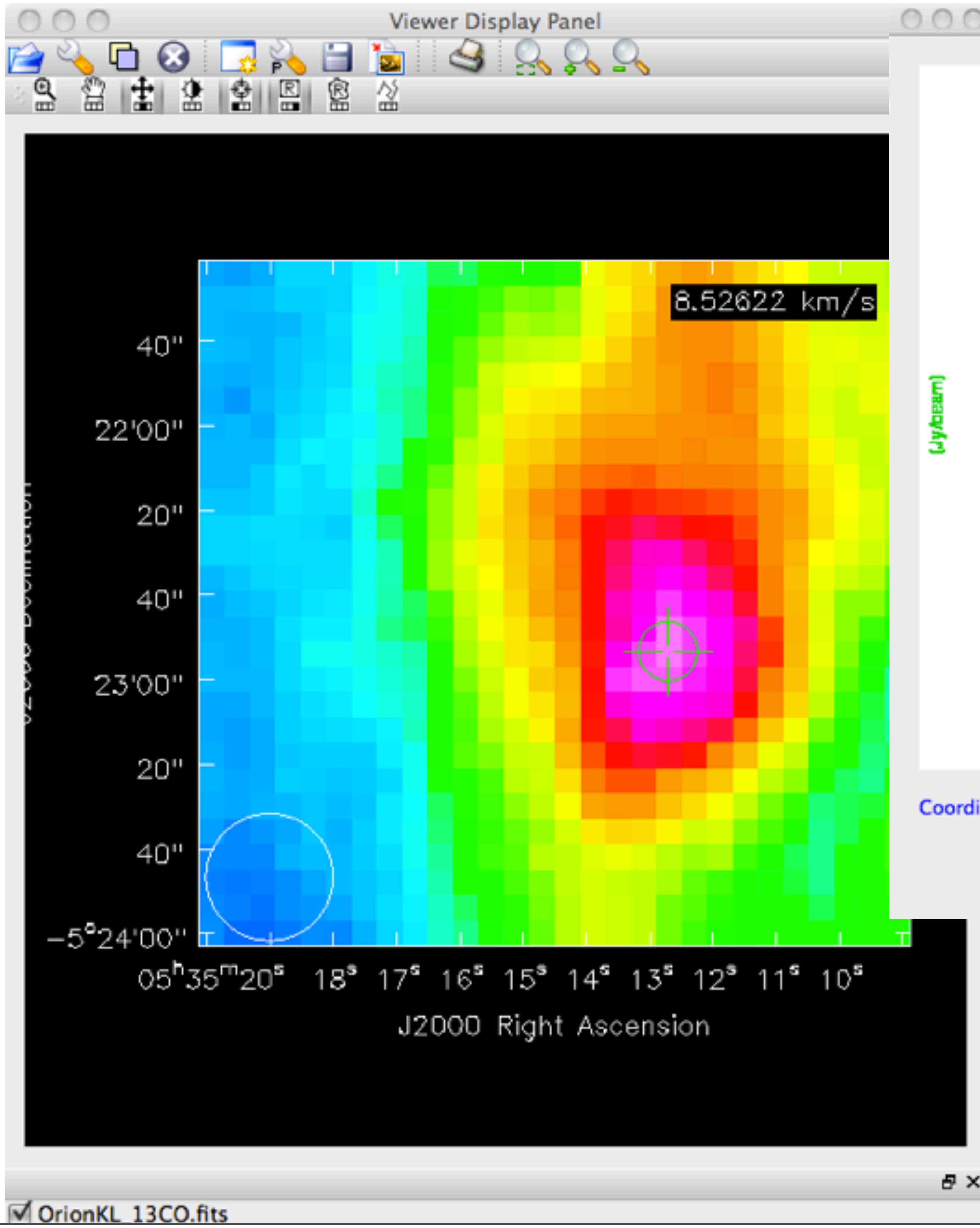


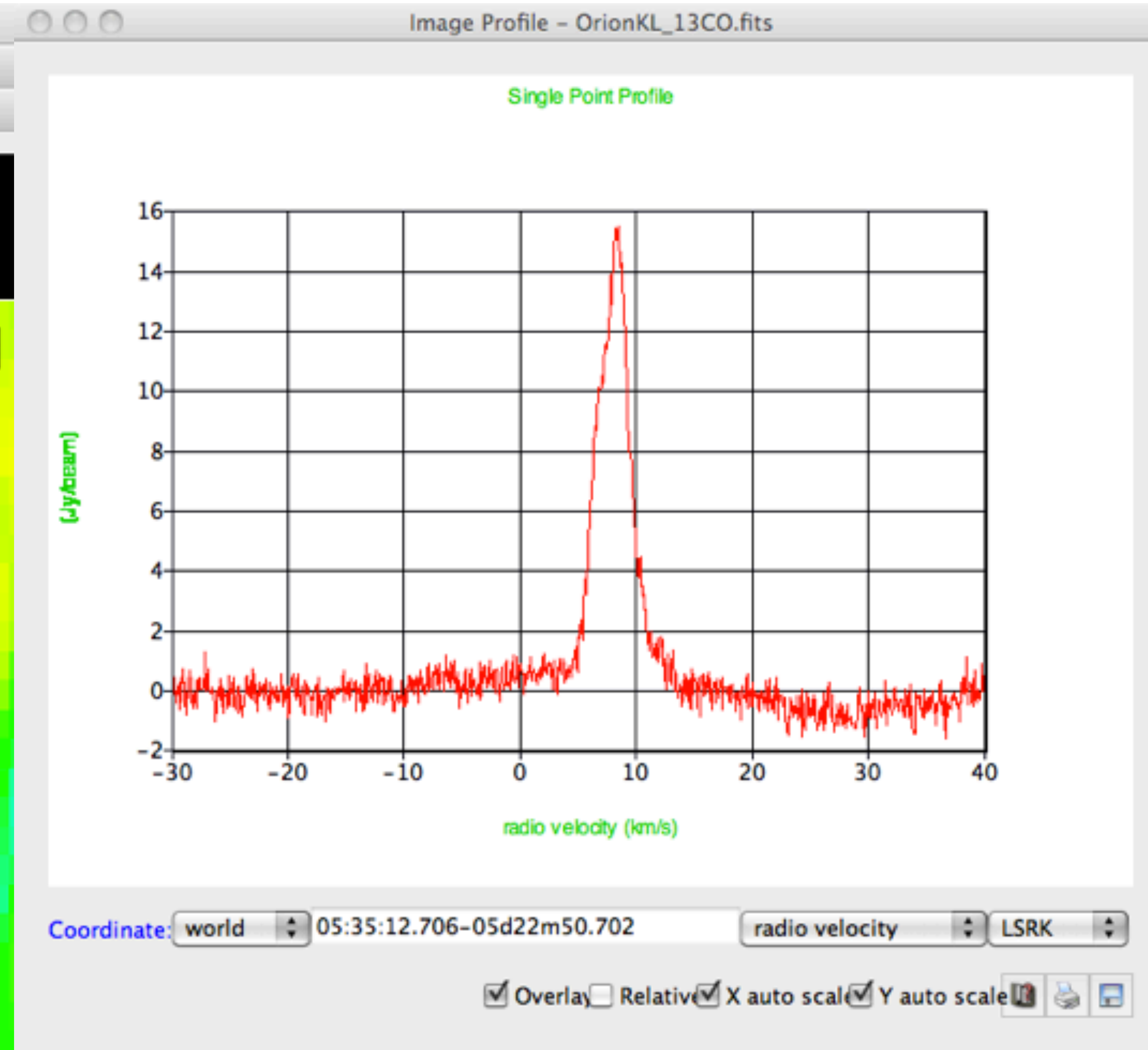
Harvey-Smith et al (2010)

Data Visualisation

- The tools available are extensive:
  - *Miriad cgdisp*: produces good publication quality plots and is scriptable but it's a bit clunky
  - *Kvis*: excellent for quick looks, easy to overlay images and get ballpark estimates of noise, flux, etc. Not as good for publication quality plots and can't handle large areas of sky
  - *CASA viewer*: very good for coordinate systems and some nice analysis tools, not very intuitive
  - *DS9*: aimed mainly at optical/xray images, but it's quite flexible and handles coordinates well

Spectral profiles





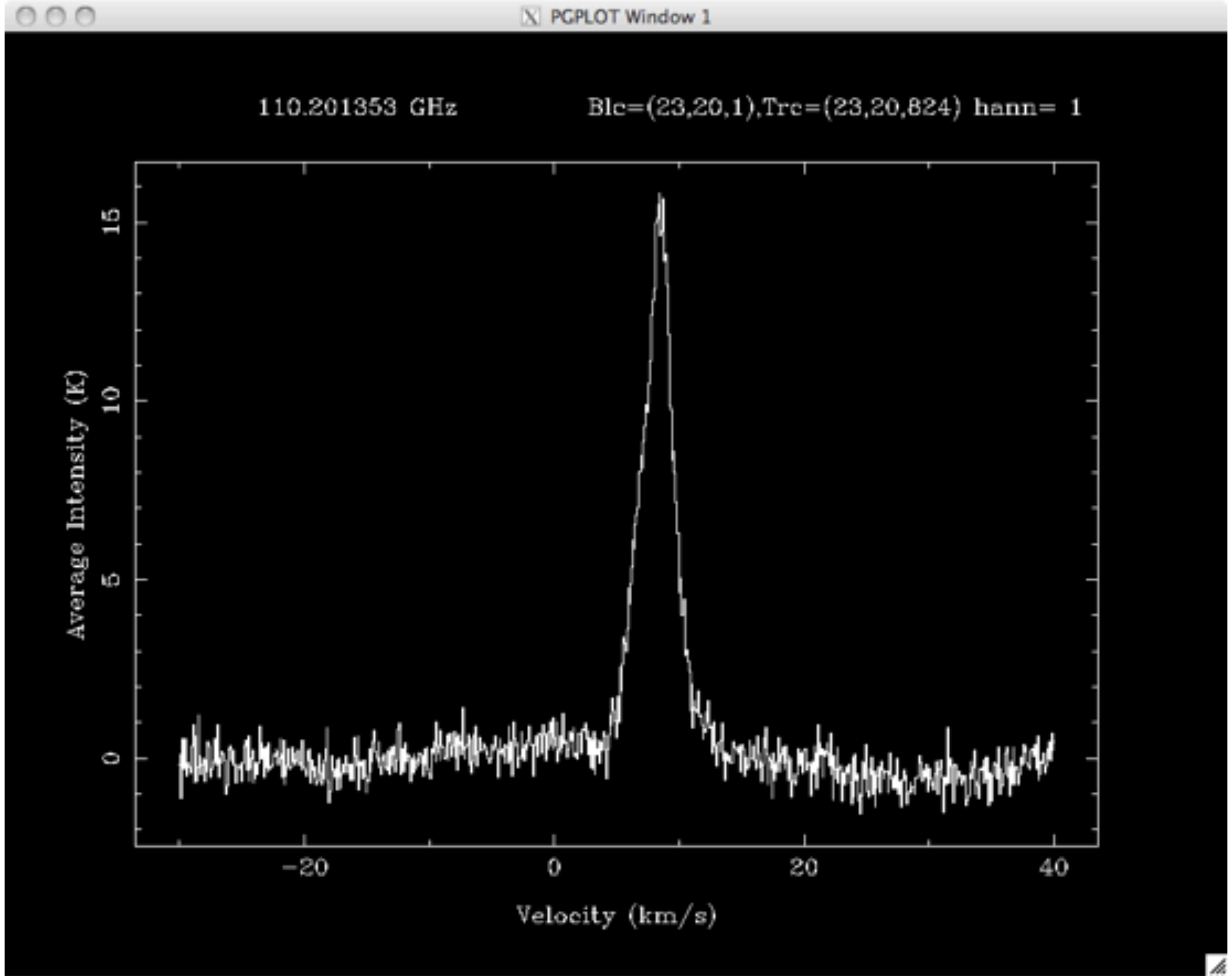
kvis

casa: *viewer*

miriad: *imspec*

Profile Fitting:

- For spectral line analysis it is useful to quantify the strength of a line, its width and its position by fitting a model
- miriad: *gaufit*
  casapy + python



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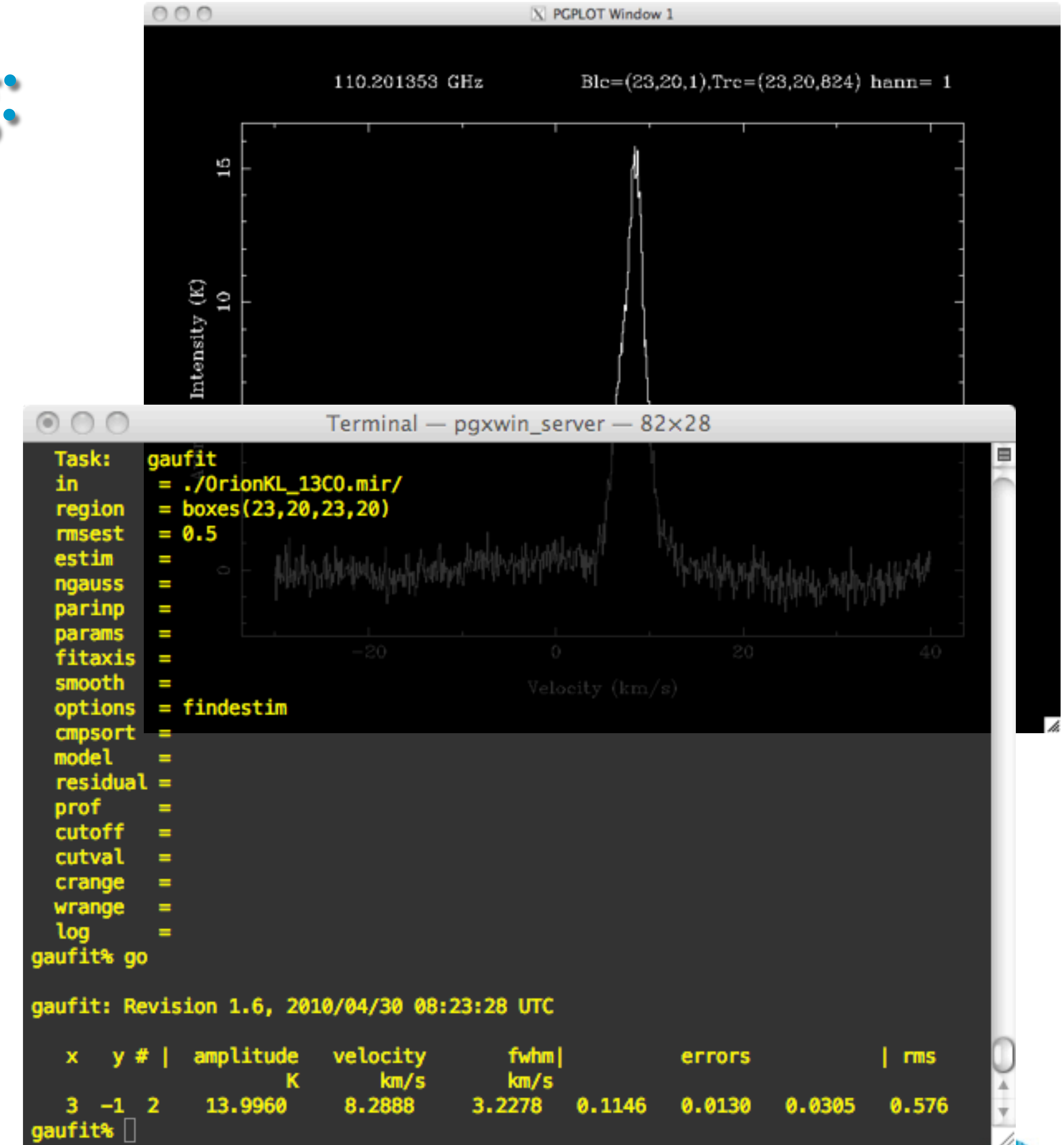
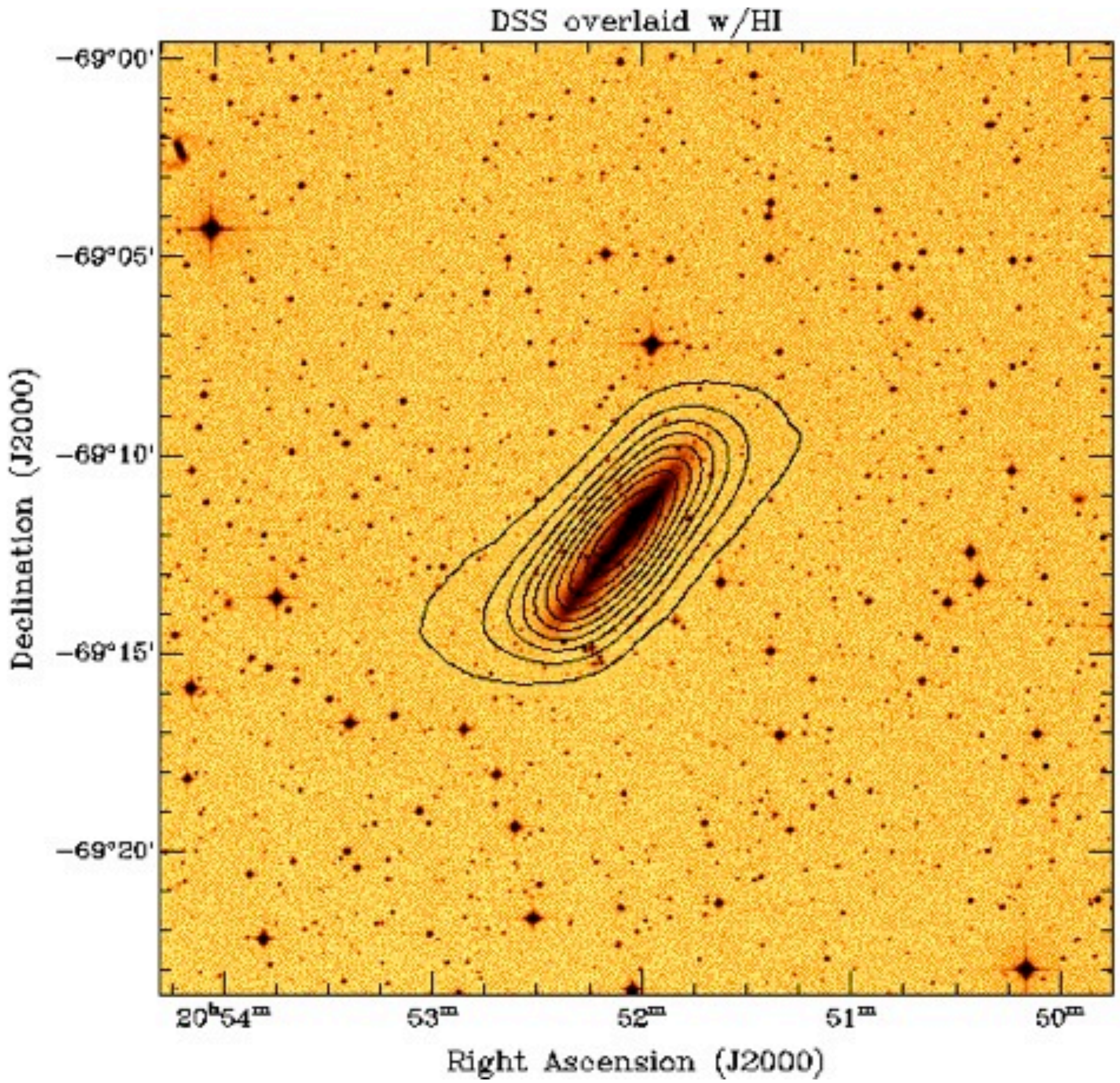
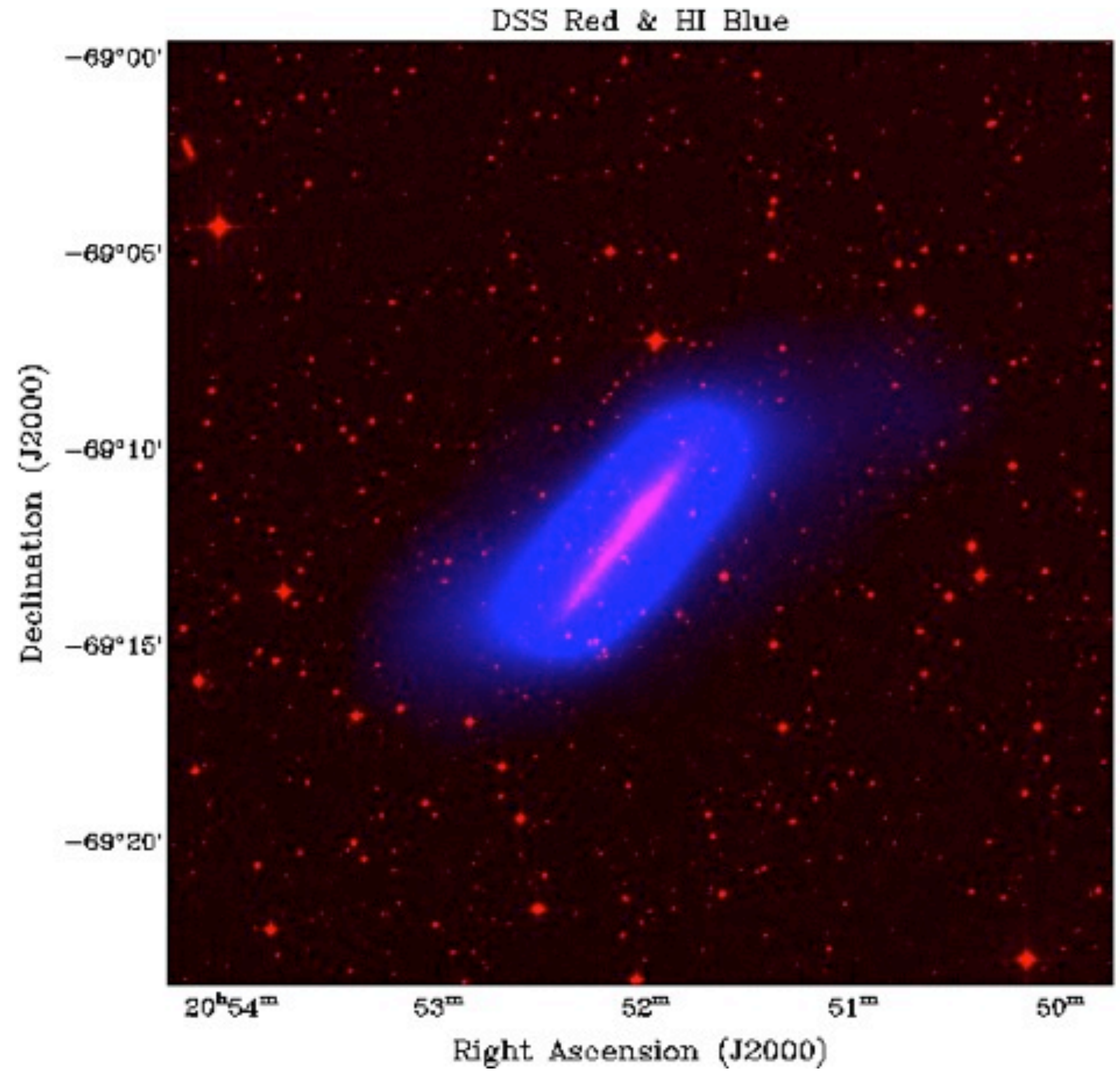
  casapy + python



Data Visualisation



Overlays: DSS Red plate w/ HI total intensity contours



RGB: DSS Red plate with HI total intensity

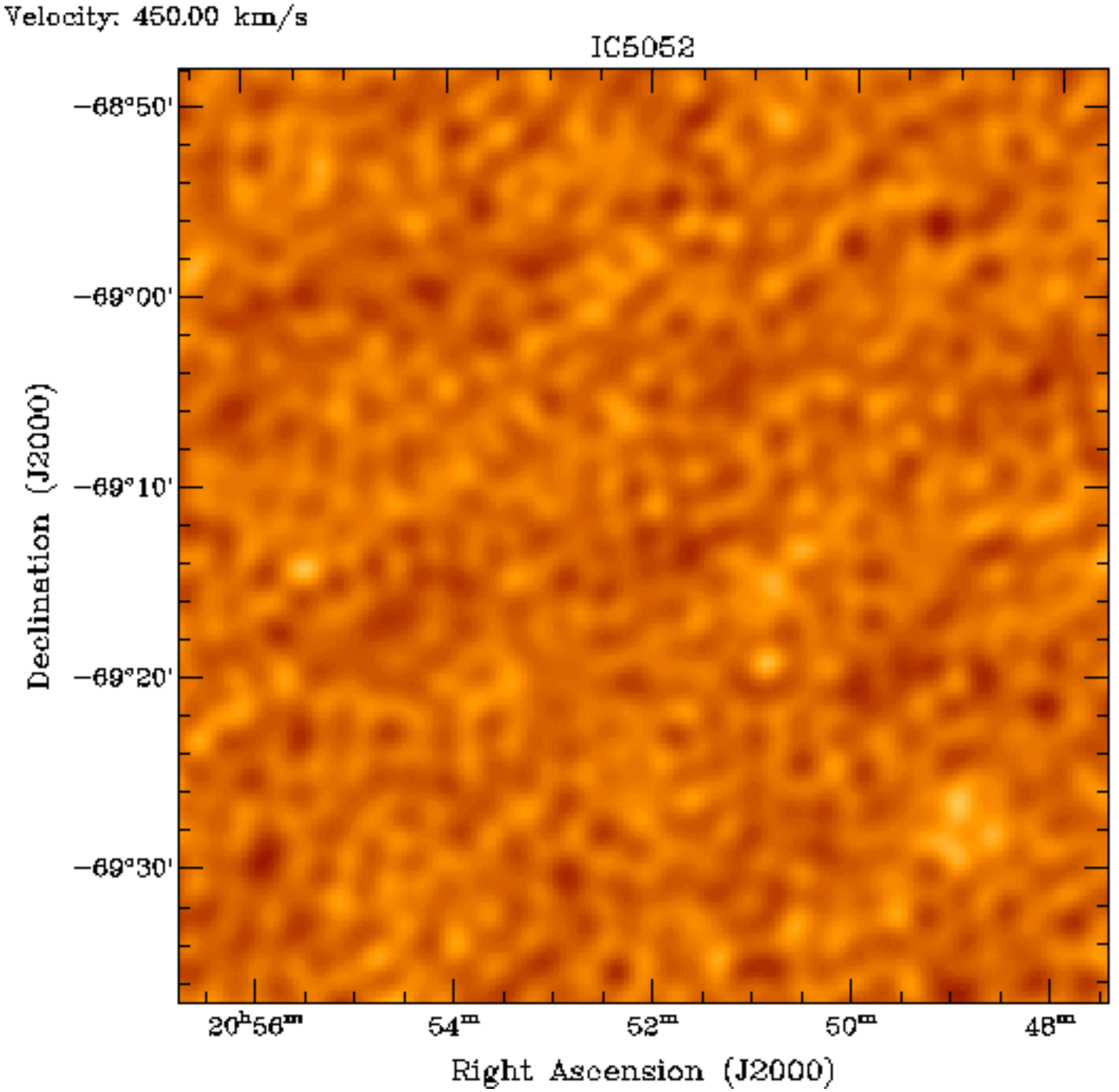
IC 5052 from LVHIS (Koribalski et al. in prep.)

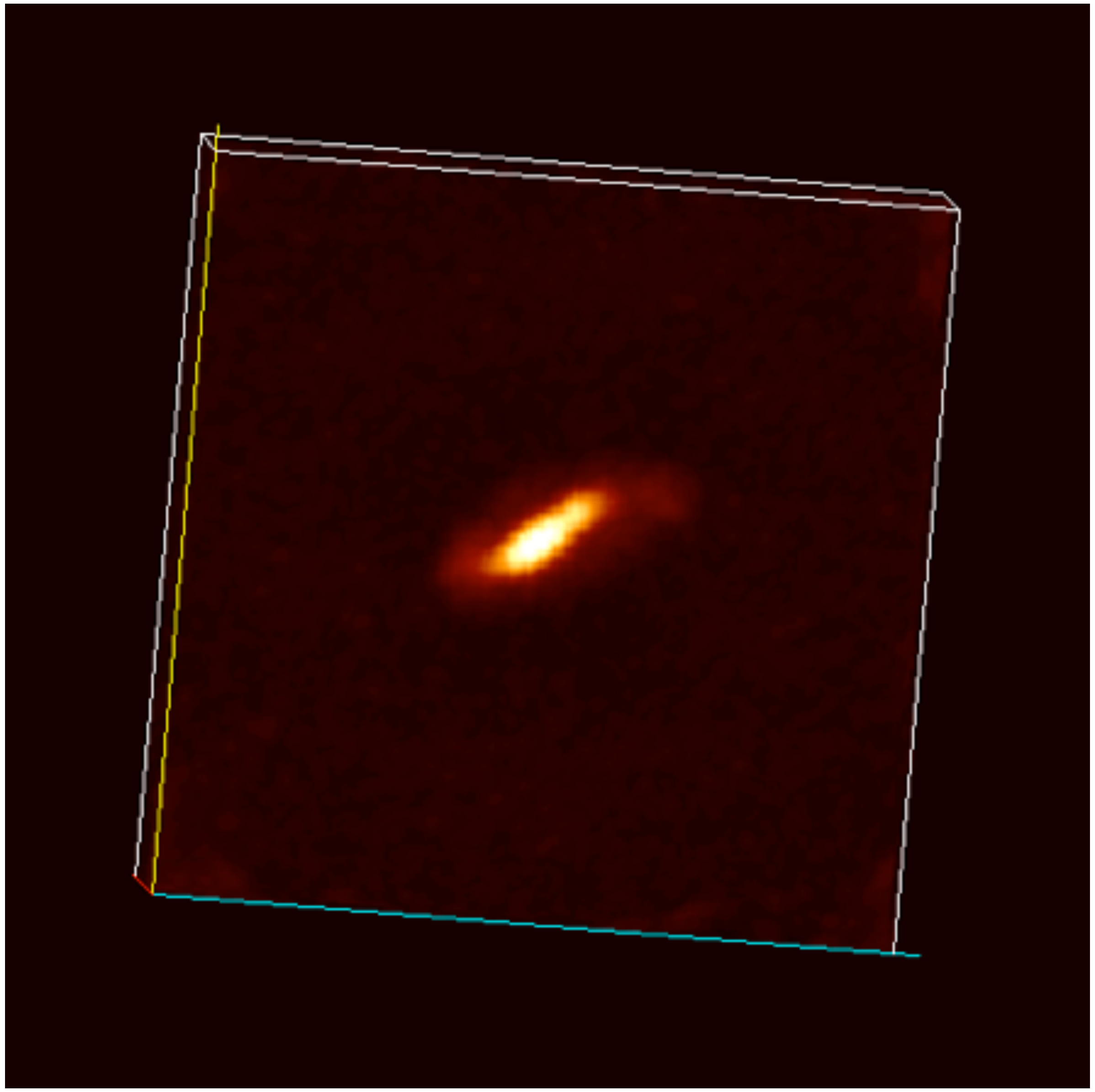
3-d data visualisation

IC 5052 from LVHIS (Koribalski et al. in prep.)

3-d visualisation is tricky, usually use time to probe the 3rd axis - for quantitative analysis need to reduce the dimensionality

3-d data visualisation

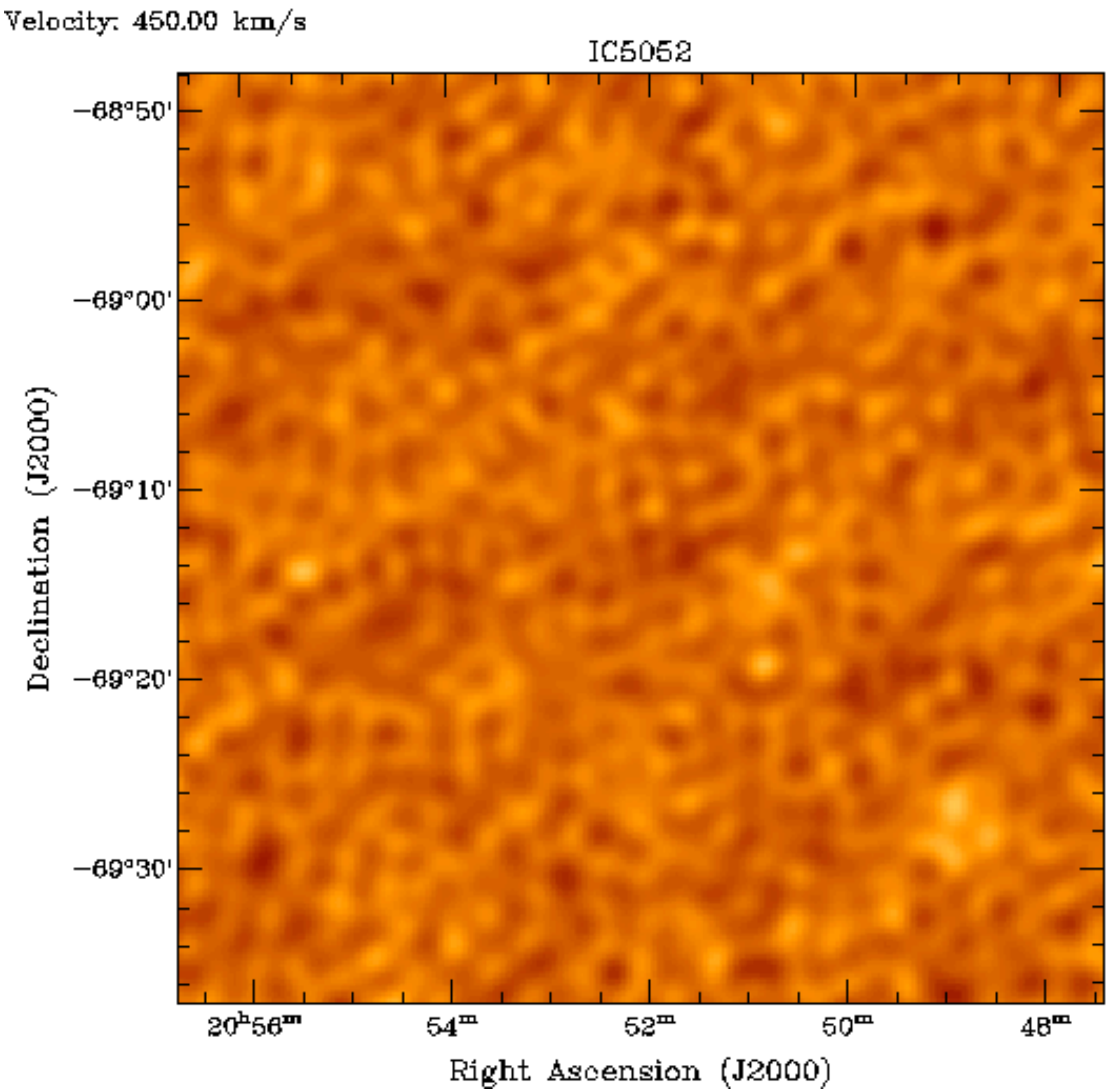


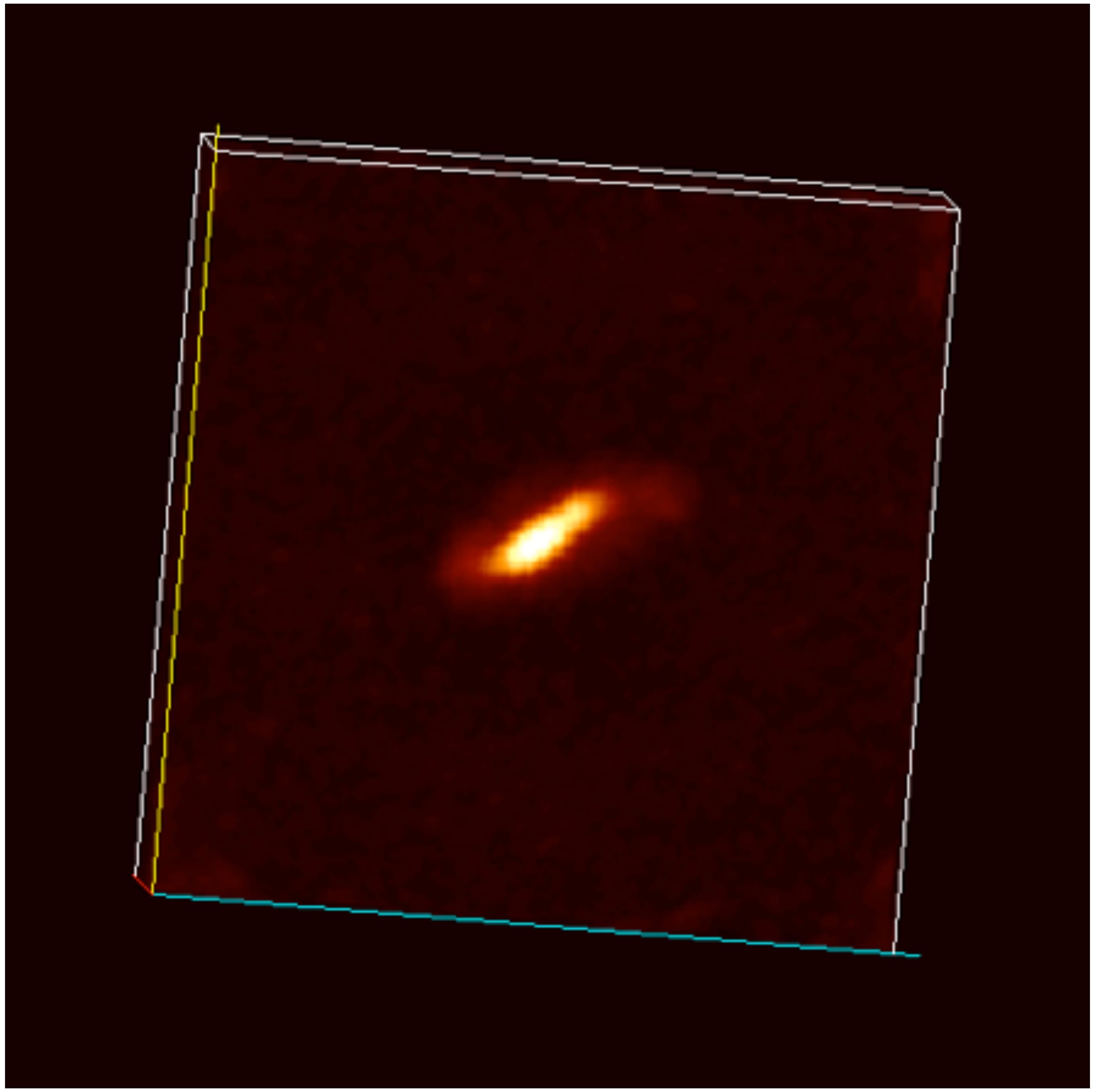


IC 5052 from LVHIS (Koribalski et al. in prep.)

3-d visualisation is tricky, usually use time to probe the 3rd axis - for quantitative analysis need to reduce the dimensionality

3-d data visualisation





IC 5052 from LVHIS (Koribalski et al. in prep.)

3-d visualisation is tricky, usually use time to probe the 3rd axis - for quantitative analysis need to reduce the dimensionality

Reducing the dimensionality: moments

- Zeroth moment - integrated intensity:

$$I_{tot} = \Delta v \sum_{i=1}^{n} I(\alpha, \delta, v_i)$$

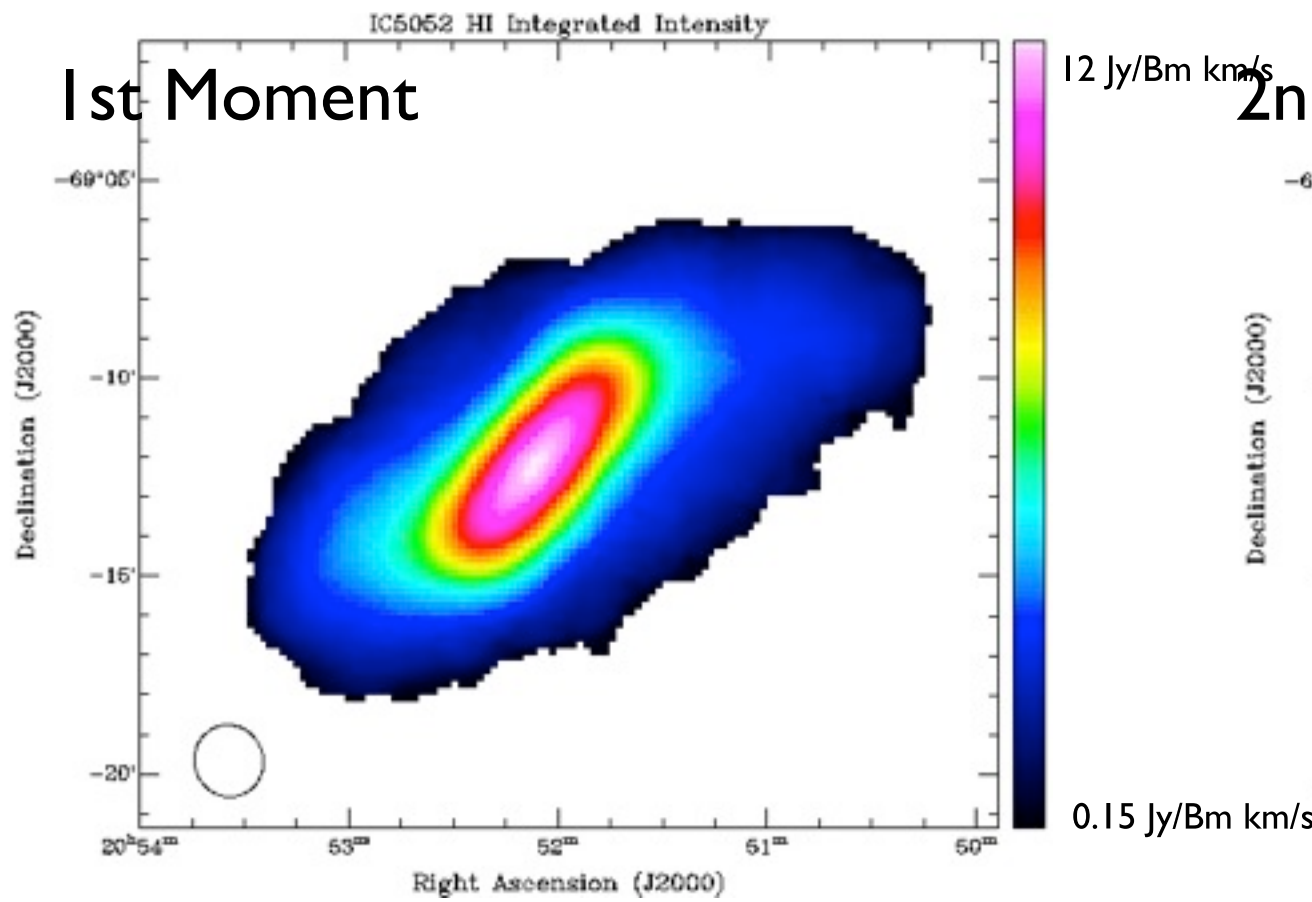
- First moment - intensity weighted coordinate:

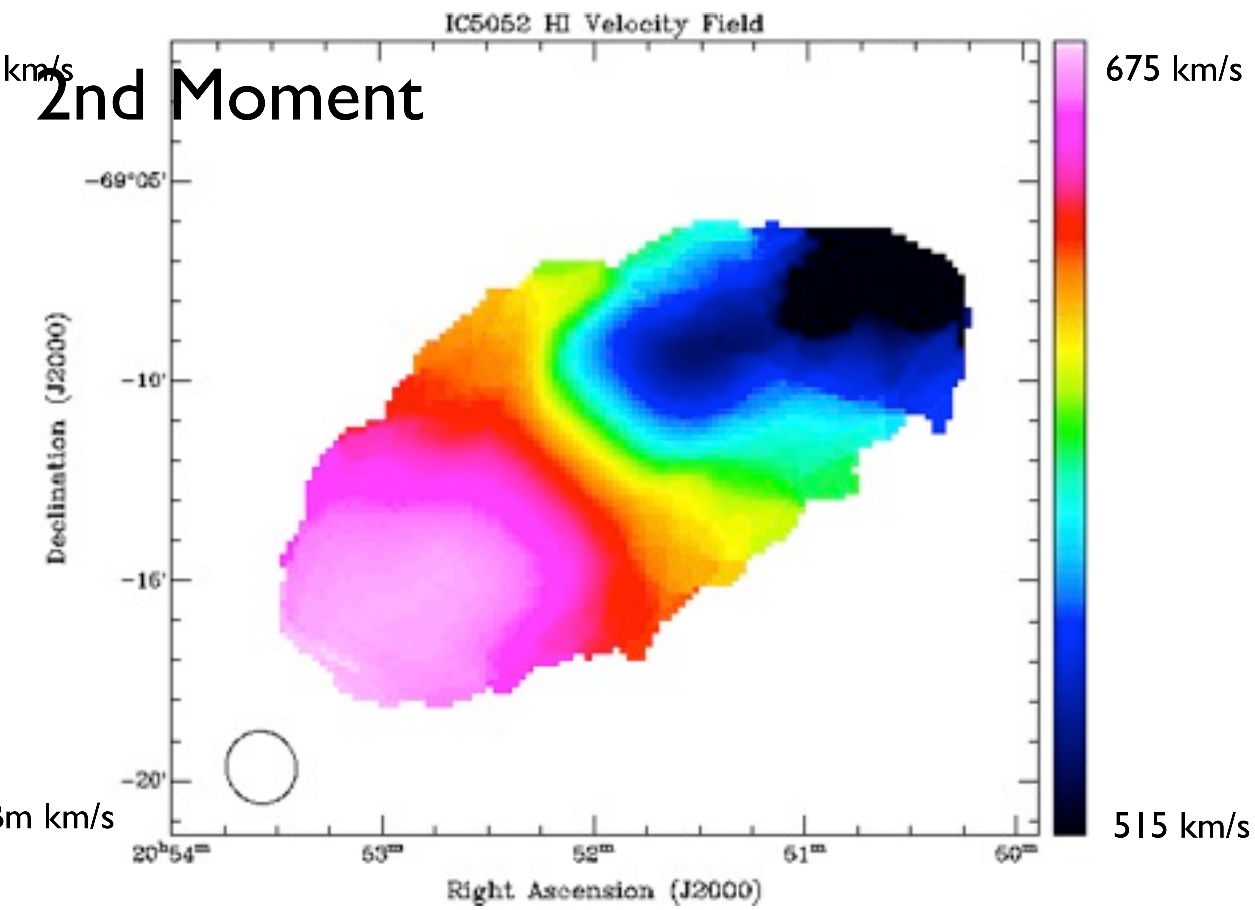
$$\bar{v} = \frac{\sum_{i=1}^{n} v_i I(\alpha, \delta, v_i)}{\sum_{i=1}^{n} I(\alpha, \delta, v_i)}$$

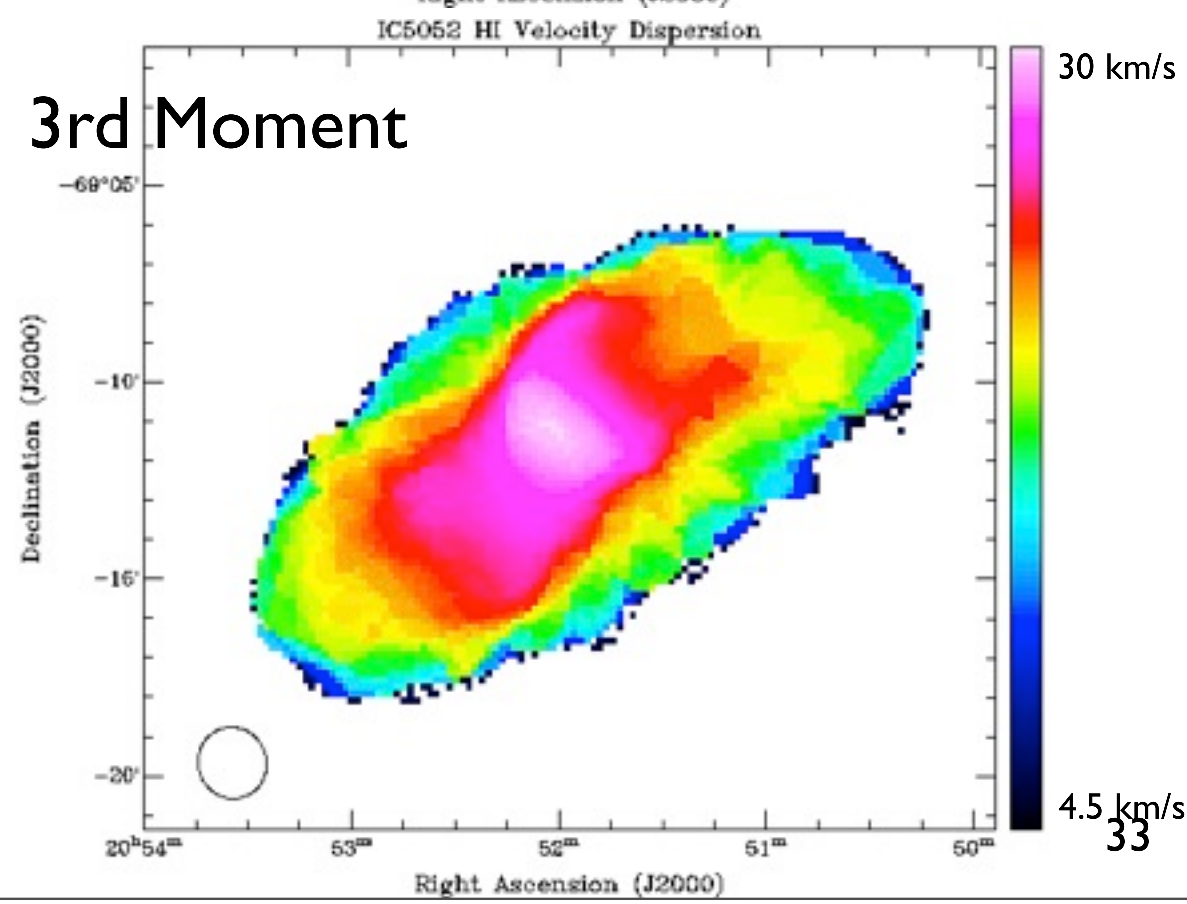
- Second moment - intensity weighted dispersion of coordinate:

$$\sigma_v(\alpha, \delta) = \sqrt{\frac{\sum_{i=1}^{n} I(\alpha, \delta, v_i)(v_i - \bar{v}(\alpha, \delta))^2}{\sum_{i=1}^{n} I(\alpha, \delta, v_i)}}$$

Moments







Moments are used to reduce the dimensionality for quantitative analysis

IC 5052 from LVHIS (Koribalski et al. in prep.)

CSIRO

Summary

- Decide what you want to know before you do anything
  - The question you ask can determine:
    - Whether you image your data
    - How you restore your data
    - How you manipulate your data
- Look at your u-v data
  - Errors and limitations are often easier to spot in the u-v domain
  - It might be useful to work in the u-v domain entirely
- Extended sources may have to be images, but beware of:
  - Backgrounds
  - Missing flux

Summary II

- Many reasons and tools for data combination:
  - Spectral indices
  - Polarization
- Use all of the visualisation tools available to you:
  - Create overlays
  - Look at spectra
  - Look at 3-D data from different perspectives
- For data analysis try to reduce the dimensionality, i.e. take slices, use moments

Summary III

- Make certain you understand your errors:
  - Estimate the rms in your image using kvis or miriad's *imstat*
  - Remember that errors returned by fitting processes are usually formal fitting errors, not the actual error
  - Keep in mind that the signal-to-noise of your image effects the accuracy with which you can determine positions, source sizes
  - Polarization images may need to be de-biased
- There are many techniques so don't be afraid to try a technique from a different field, e.g., use moments in image plane to find source sizes and centroids

Recommended Reading

- Fomalont, E. 1999 in "Synthesis Imaging in Radio Astronomy II, Eds. G. B. Taylor, C. Carilli, R. A. Perley, chapter 14
- Pearson, T. J. 1999 in "Synthesis Imaging in Radio Astronomy II, Eds. G. B. Taylor, C. Carilli, R. A. Perley, Chapter 16
- MIRIAD manual
- CASA cookbook