Image and Non-Imaging Analysis

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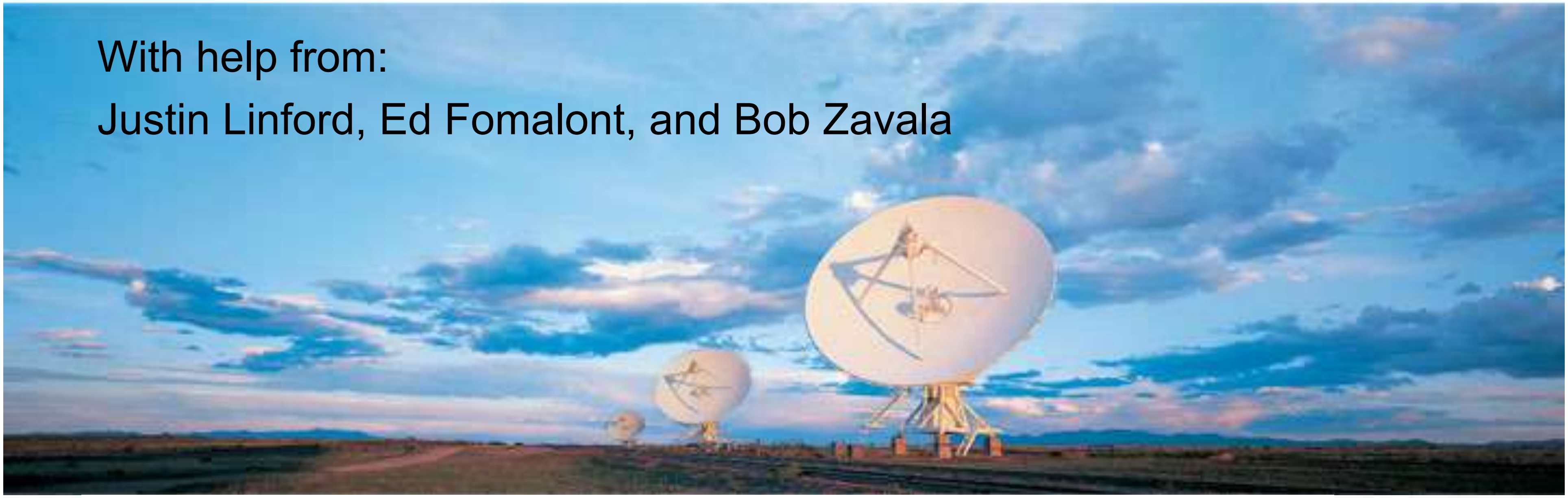

With help from:

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Image and Non-Imaging ANALYSIS

- Input: Well-calibrated data-base producing a high quality image
- Output: Parameterization and interpretation of image or a set of images

This is very open-ended

Depends on source emission complexity

Depends on the scientific goals

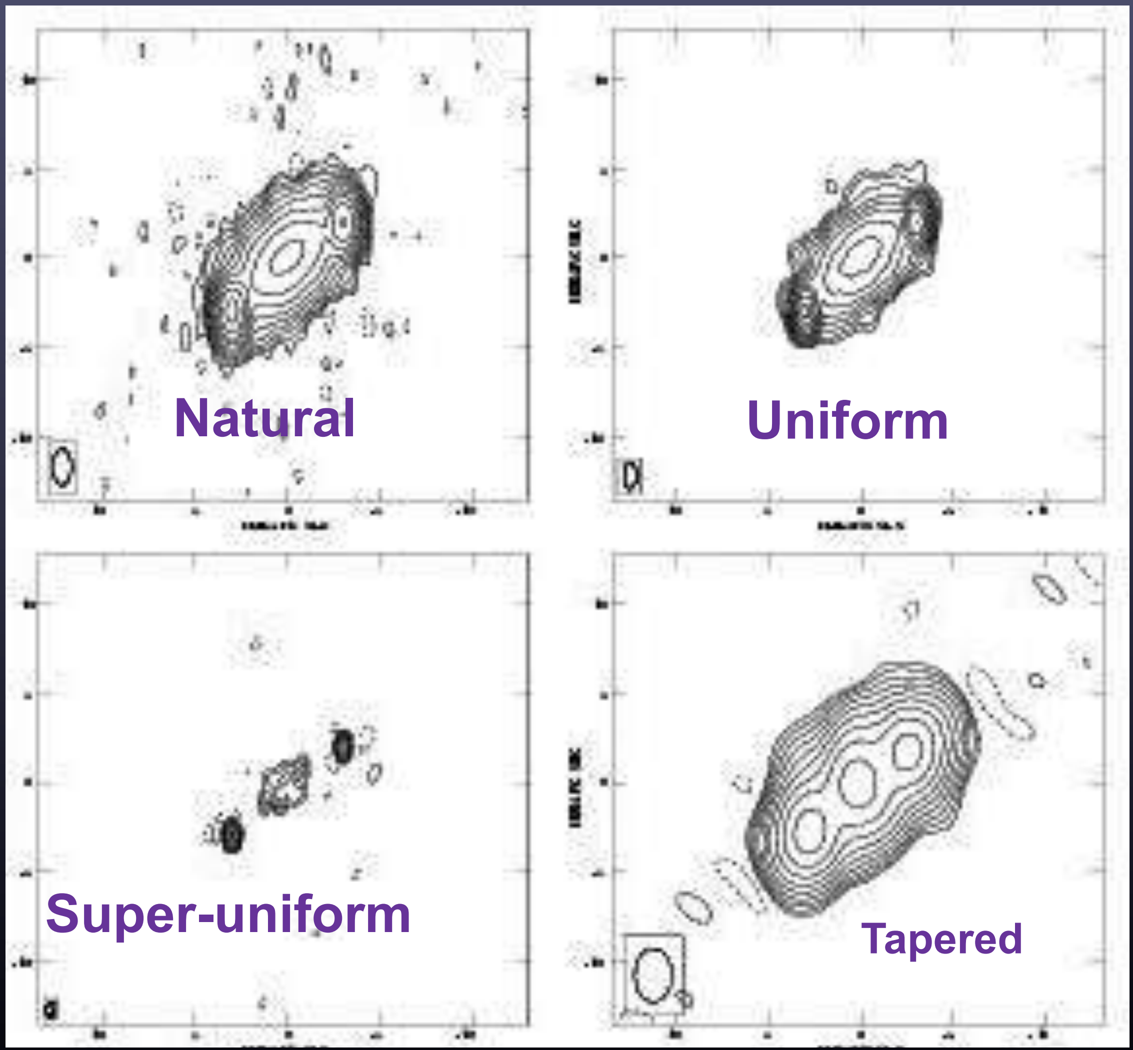
Examples and ideas are given.

Many software packages, besides AIPS and Casa (e.g.. IDL, DS-9) are available.

IMAGE ANALYSIS OUTLINE

- Multi-Resolution analysis of a radio source
- Parameter Estimation of Discrete Components
- Image Comparisons
- Positional Registration

IMAGE AT SEVERAL RESOLUTIONS



Milli-arcsec

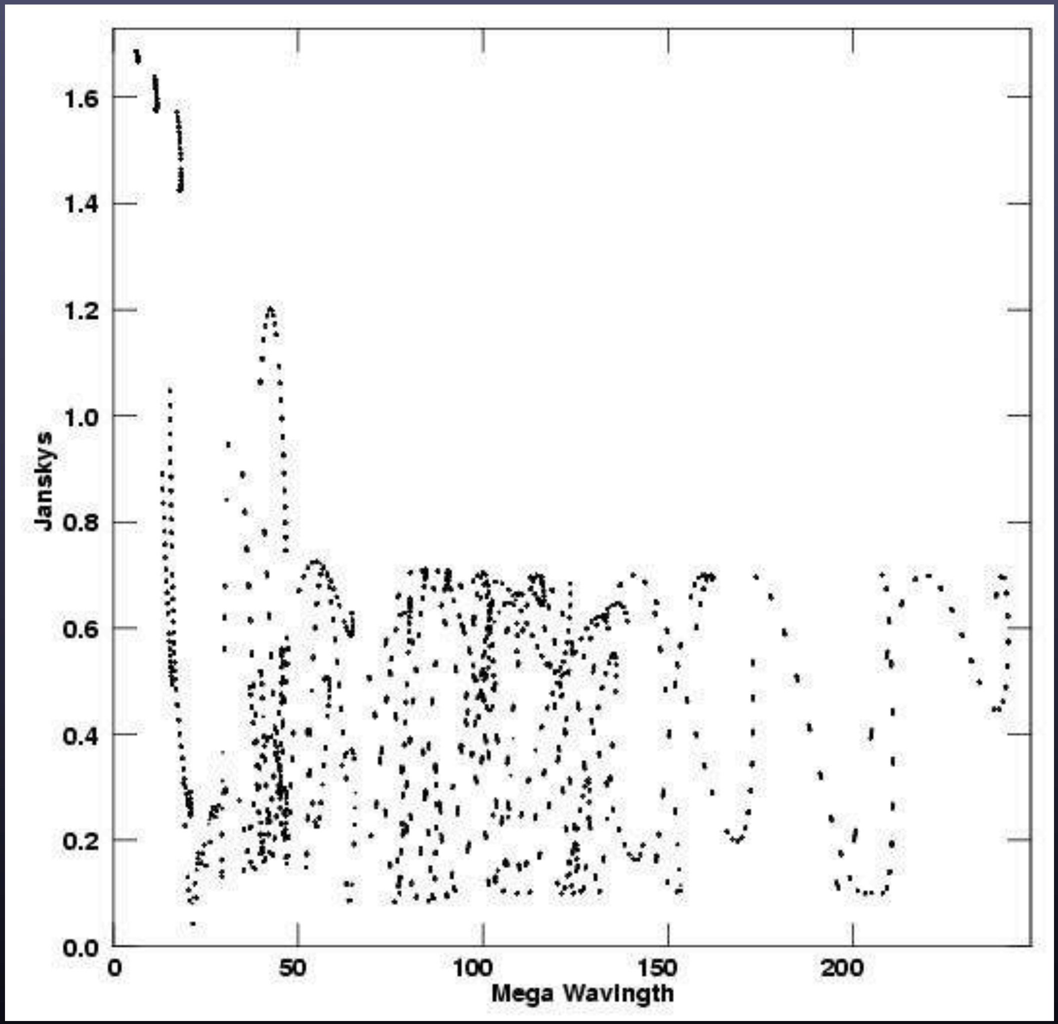
Different aspect of source structure can be see at various resolutions, shown by the ellipse in the lower left corner of each box.

SAME DATA USED FOR ALL IMAGES

For example,
Outer components are small from SU resolution
There is no extended emission from low resolution

Recall - DATA DISPLAYS(2)

Jy



Mega Wavelength

Visibility Amplitude versus Projected (u,v) spacing

General trend of data.

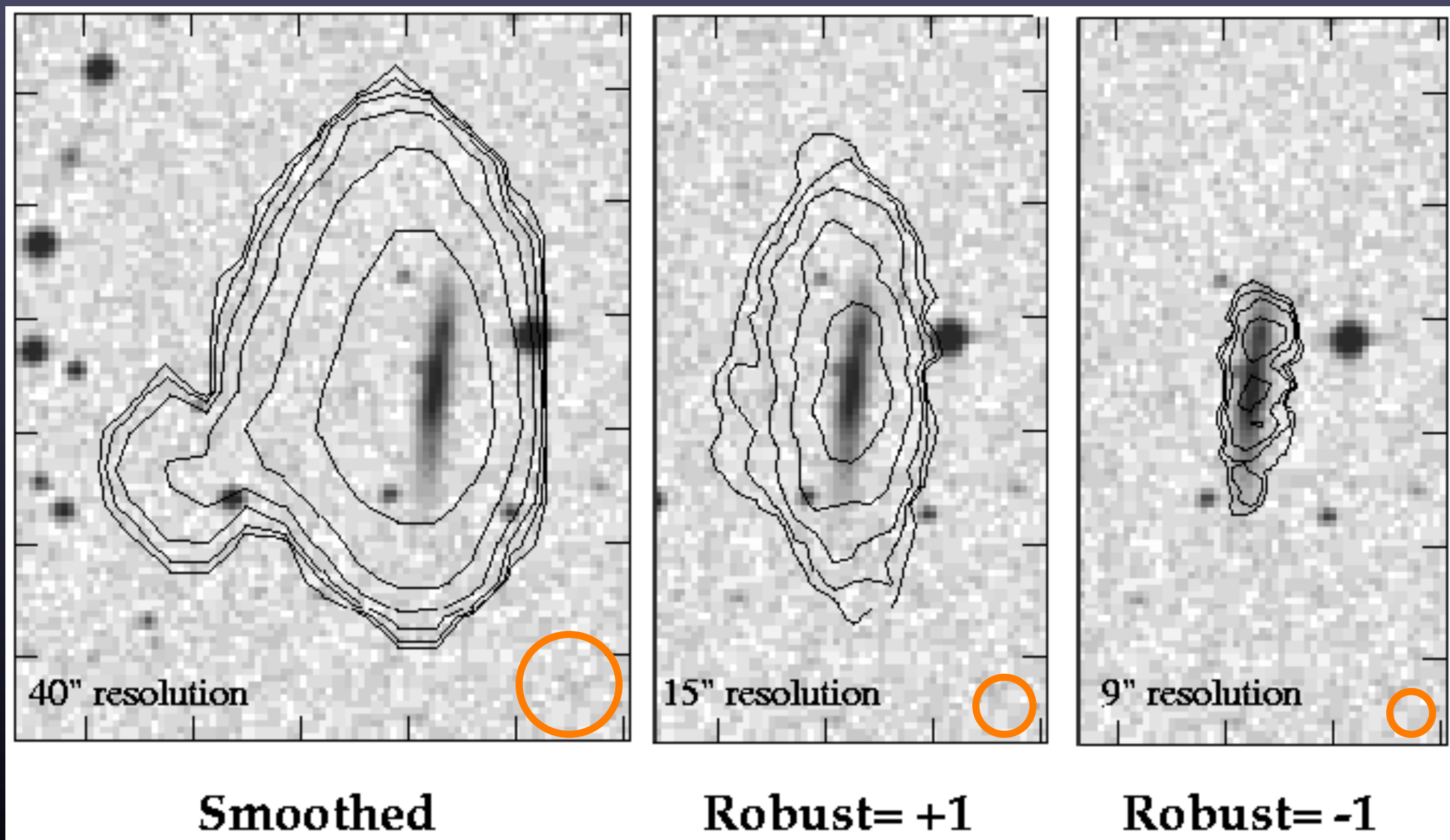
Useful for relatively strong sources.

Triple source model. Large component causes rise at short spacings.

Oscillations at longer spacings suggest close double.

Imaging and Deconvolution of Spectral Line Data:

Type of weighting in imaging



HI contours overlaid on optical images of an edge-on galaxy

PARAMETER ESTIMATION 1

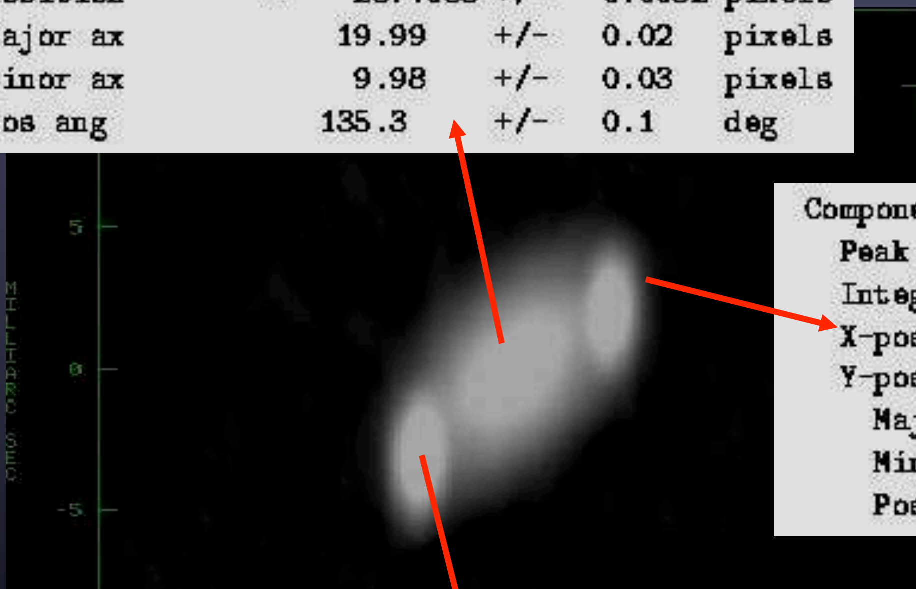
Parameters associated with discrete components

- Fitting in the image plane
  - Assume source components are Gaussian-shaped
  - Deep cleaning restores image intensity with Gaussian-beam
  - True size * Beam size = Image size, if Gaussian-shaped. Hence, estimate of true size is relatively simple.

IMAGE FITTING

Component 2-Gaussian

Peak intensity	= 0.104	+/-	0.005	JY/BEAM
Integral intensity	= 0.998	+/-	9,47	JANSKYS
X-position	= 255.986	+/-	0.0029	pixels
Y-position	= 257.033	+/-	0.0032	pixels
Major ax	19.99	+/-	0.02	pixels
Minor ax	9.98	+/-	0.03	pixels
Pos ang	135.3	+/-	0.1	deg



Component 1-Gaussian

Peak intensity	= 0.300	+/-	0.005	JY/BEAM
Integral intensity	= 0.302	+/-	0.008	JANSKYS
X-position	= 270.991	+/-	0.001	pixels
Y-position	= 267.018	+/-	0.001	pixels
Major ax	0.53	+/-	0.01	pixels
Minor ax	0.00	+/-	0.05	pixels
Pos ang	21.6	+/-	1.1	deg

Component 3-Gaussian

Peak intensity	= 0.393	+/-	0.004	JY/BEAM
Integral intensity	= 0.403	+/-	0.008	JANSKYS
X-position	= 241.007	+/-	0.001	pixels
Y-position	= 241.988	+/-	0.001	pixels
Major ax	1.54	+/-	0.01	pixels
Minor ax	0.21	+/-	0.01	pixels
Pos ang	3.6	+/-	0.2	deg

AIPS task: JMFIT

Casa tool

imfit

Non-Imaging Analysis

Reasons for model fitting visibility data

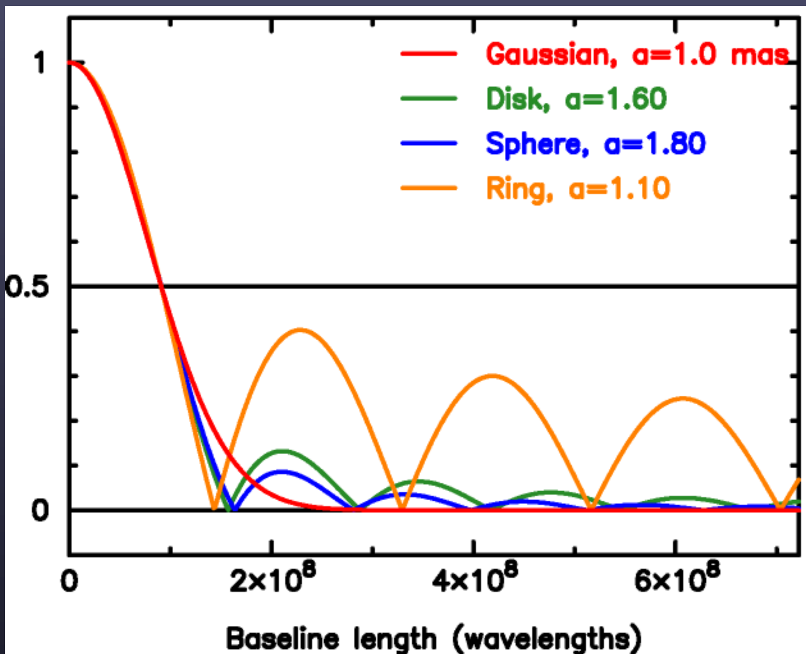
- Insufficient (*u,v*)-plane coverage to make an image
- Inadequate calibration
- Missing data (e.g. no phases)
- Quantitative analysis
- Direct comparison of two data sets
- Error estimation
  - Usually, visibility measurements are independent gaussian variates
  - Systematic errors are usually localized in the (*u,v*) plane
- – Statistical estimation of source parameters

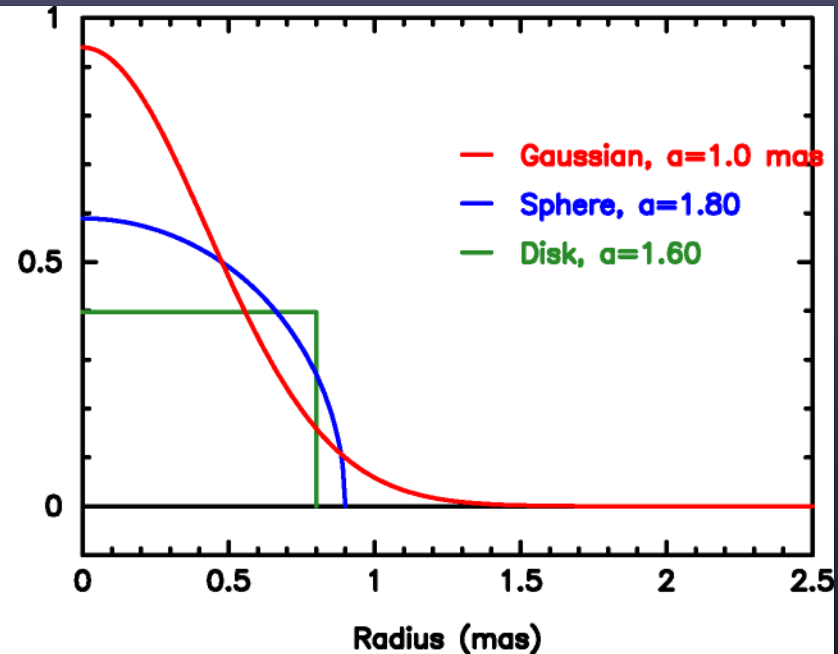
PARAMETER ESTIMATION 2

Fitting in (u,v) plane (aka model-fitting)

- Parameters associated with discrete components
  - Better estimates of parameters for simple sources
  - May be possible even when imaging is not
  - Can fit to more source models (e.g. Gaussian, ring, disk)
- Error estimates of parameters
  - Simple ad-hoc error estimates
  - Estimates from fitting programs
  - Monte Carlo simulations if model-fitting

Simple models



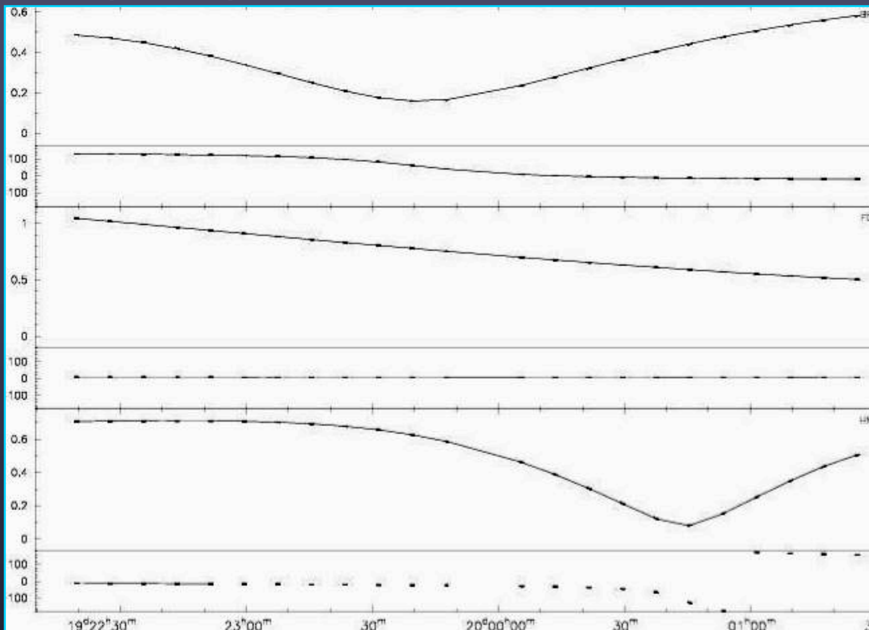


Visibility at short baselines contains little information about the profile of the source.

(u,v) DATA FITTING

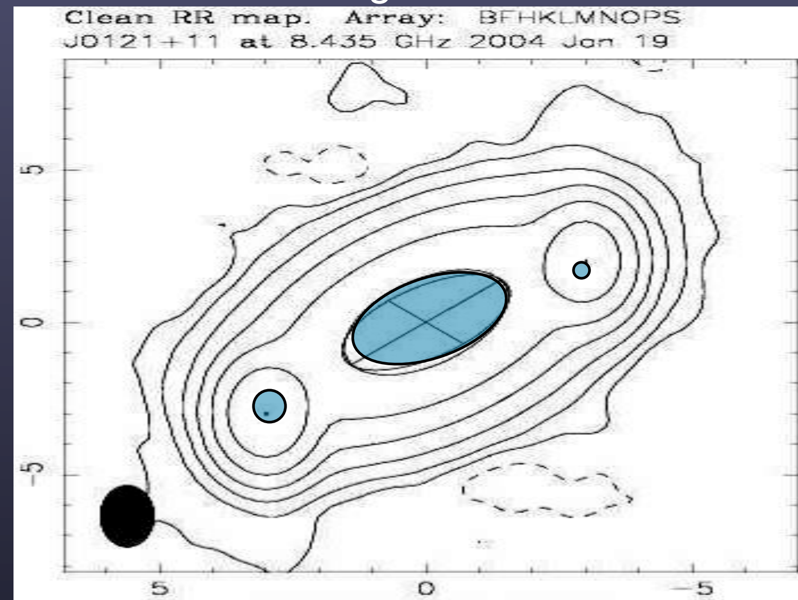
Amp and phase vs. time for three baselines

Jy
Deg
Jy
Deg
Jy
Deg



Time

Contour image with model fits



milliarcsec

milliarcsec

DIFMAP has good (u,v) fitting algorithm

Fit model directly to (u,v) data

Compare model to data

Contour display of image

Ellipses show true component size. (SNR dependent resolution)

Inspecting Visibility Data

- Fourier imaging

$$V(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathcal{A}(l,m) I(l,m) \exp[-2\pi i(ul + vm)]\, dl\, dm$$

- Problems with direct inversion
  - Sampling
    - Poor (*u*,*v*) coverage
  - Missing data
    - e.g., no phases (speckle imaging)
  - Calibration
    - Closure quantities are independent of calibration
  - Non-Fourier imaging
    - e.g., wide-field imaging; time-variable sources (SS433)
  - Noise
    - Noise is uncorrelated in the (*u*,*v*) plane but correlated in the image

Model fitting

Imaging as an Inverse Problem

- In synthesis imaging, we can solve the **forward problem**: given a sky brightness distribution, and knowing the characteristics of the instrument, we can predict the measurements (visibilities), within the limitations imposed by the noise.
- The **inverse problem** is much harder, given limited data and noise: the solution is rarely unique.
- A general approach to inverse problems is **model fitting**. See, e.g., Press et al., *Numerical Recipes*.
    1. Design a model defined by a number of adjustable parameters.
    2. Solve the forward problem to predict the measurements.
    3. Choose **a figure-of-merit** function, e.g., rms deviation between model predictions and measurements.
    4. Adjust the parameters to **minimize the merit function**.
- Goals:
    1. Best-fit values for the parameters.
    2. A measure of the goodness-of-fit of the optimized model.
    3. Estimates of the uncertainty of the best-fit parameters.

Uses of model fitting

Model fitting is most useful when the brightness distribution is simple.

- Checking amplitude calibration
- Starting point for self-calibration
- Estimating parameters of the model (with error estimates)
- In conjunction with CLEAN or MEM
- In astrometry and geodesy

Programs

- AIPS UVFIT
- Difmap (Martin Shepherd)

Parameters

Example

- Component position: (*x,y*) or polar coordinates
- Flux density
- Angular size (e.g., FWHM)
- Axial ratio and orientation (position angle)
  - For a non-circular component
- 6 parameters per component, plus a “shape”

- This is a conventional choice: other choices of parameters may be better!
- (Wavelets; shapelets* [Hermite functions])
  - * Chang & Refregier 2002, ApJ, 570, 447

Limitations of least squares

Assumptions that may be violated

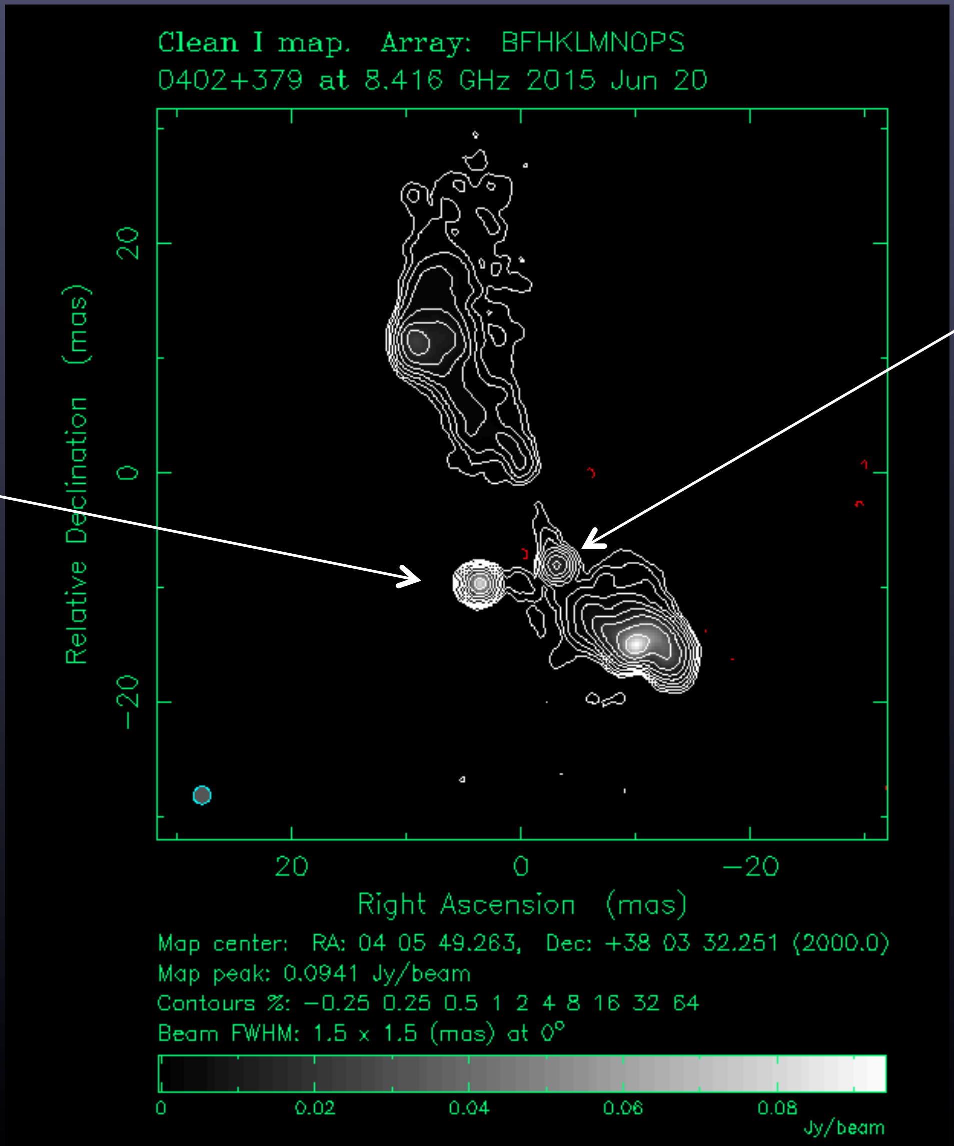
- The model is a good representation of the data
  - Check the fit
- The errors are gaussian
  - True for real and imaginary parts of visibility
  - Not true for amplitudes and phases (except at high SNR)
- The variance of the errors is known
  - Estimate from T_{sys}, rms, etc.
- There are no systematic errors
  - Calibration errors, baseline offsets, etc. must be removed before or during fitting
- The errors are uncorrelated
  - Not true for closure quantities
  - Can be handled with full covariance matrix

Demo!

Supermassive Binary Black Hole Candidate 0402+379

Goal is to measure motion of the jets and the core components C1 and C2

C1

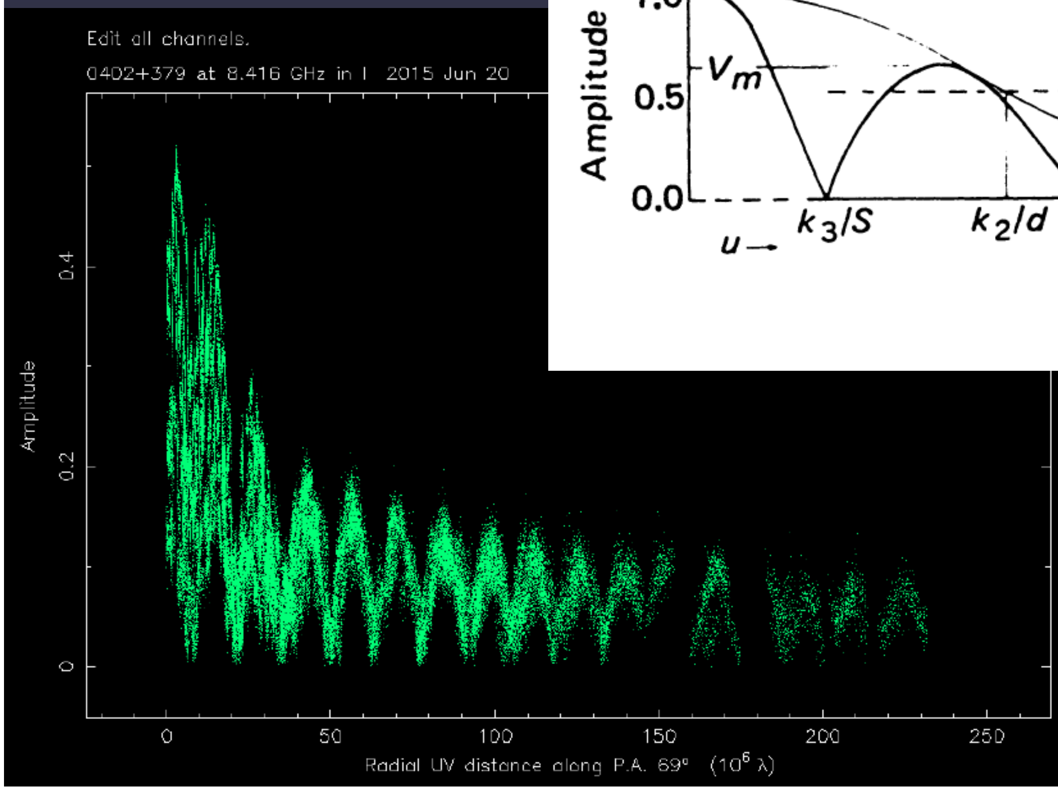


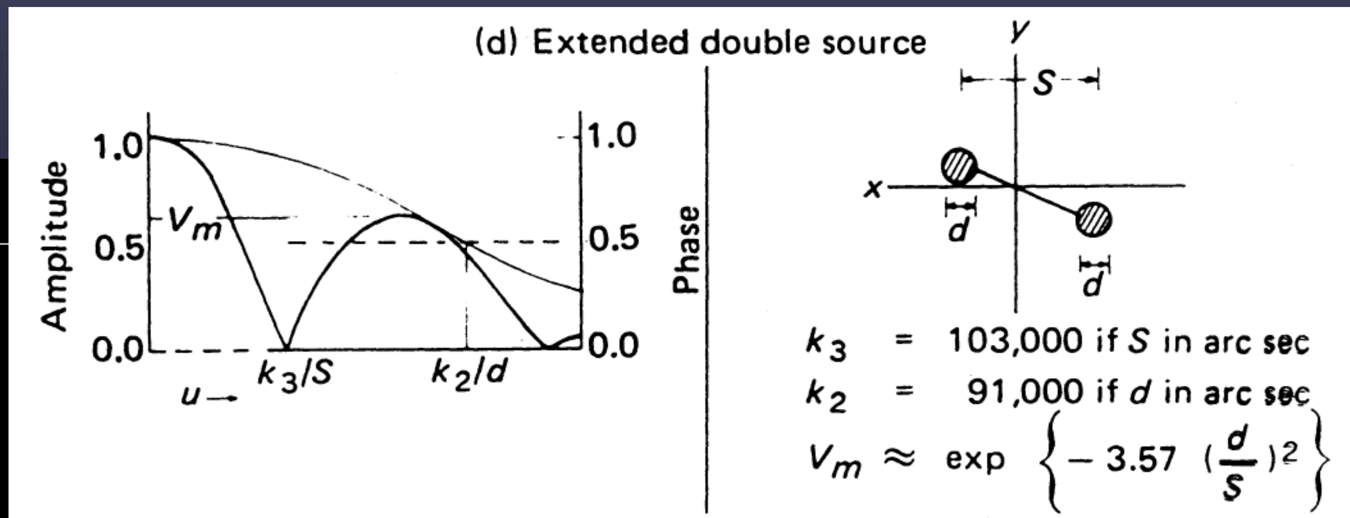
C2

Recall - Trial model

By inspection, we can derive a simple model:

- Two roughly equal components, each 0.1 Jy, separated by about 15 milliarcsec in p.a. 69º, each about 0.5 milliarcsec in diameter (gaussian FWHM)





To be refined now …

COMPONENT ERROR ESTIMATES

$\boldsymbol{P}$ = Component Peak Flux Density

σ = Image rms noise $\qquad$ $\boldsymbol{P/\sigma}$ = signal/noise = $\boldsymbol{S}$

$\boldsymbol{B}$ = Synthesized beam size

θ_ι = Component image size

$\Delta\boldsymbol{P}$ = Peak error = σ

$\Delta\boldsymbol{X}$ = Position error = $\boldsymbol{B / 2S}$

$\Delta\theta_\iota$ = Component image size error = $\boldsymbol{B / 2S}$

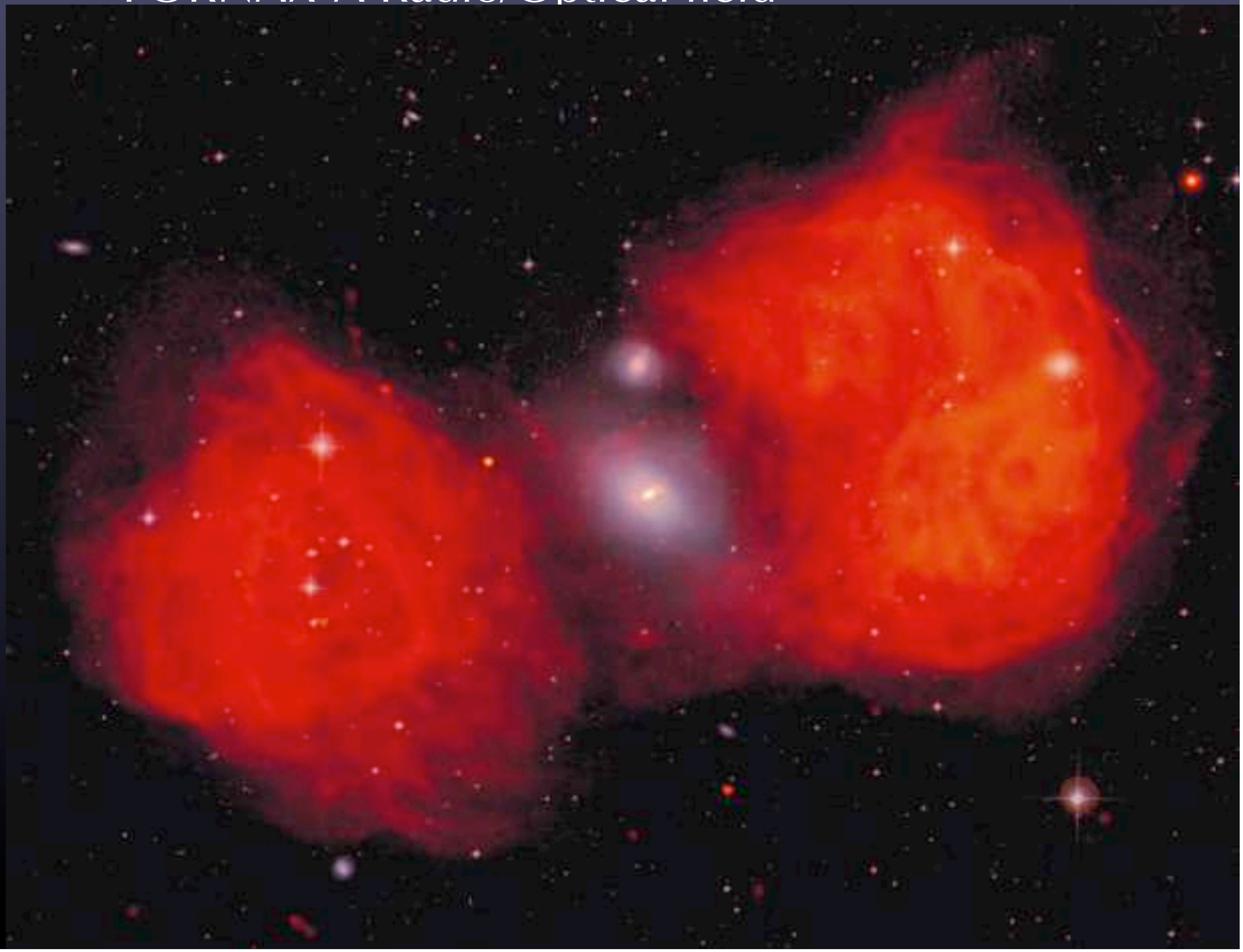
θ_t = True component size = $(\theta_\iota^2 - B^2)^{1/2}$

$\Delta\theta_t$ = Minimum component size = $\boldsymbol{B / S^{1/2}}$

eg. S=100 means can determine size of B/10

Comparison and Combination of Images of Many Types

FORNAX-A Radio/Optical field

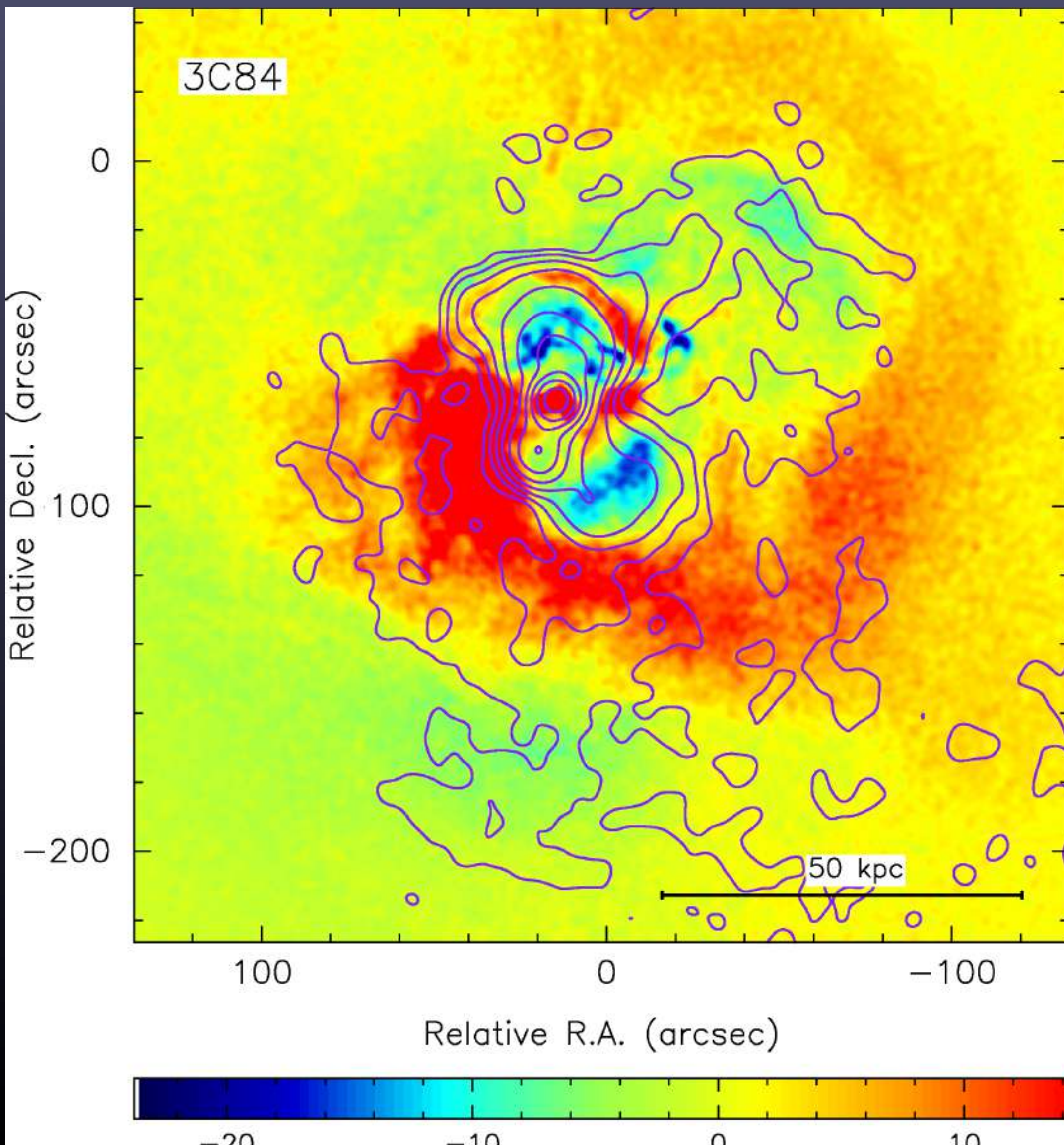


Radio is red
Faint radio core in center of NGC1316

Optical in blue-white

Frame size is 60′ x 40′

COMPARISON OF RADIO/X-RAY IMAGES



Contours of radio intensity at 1.4 GHz

Color intensity represents X-ray intensity smoothed to radio resolution

Expanded Long Wavelength Array (ELWA)

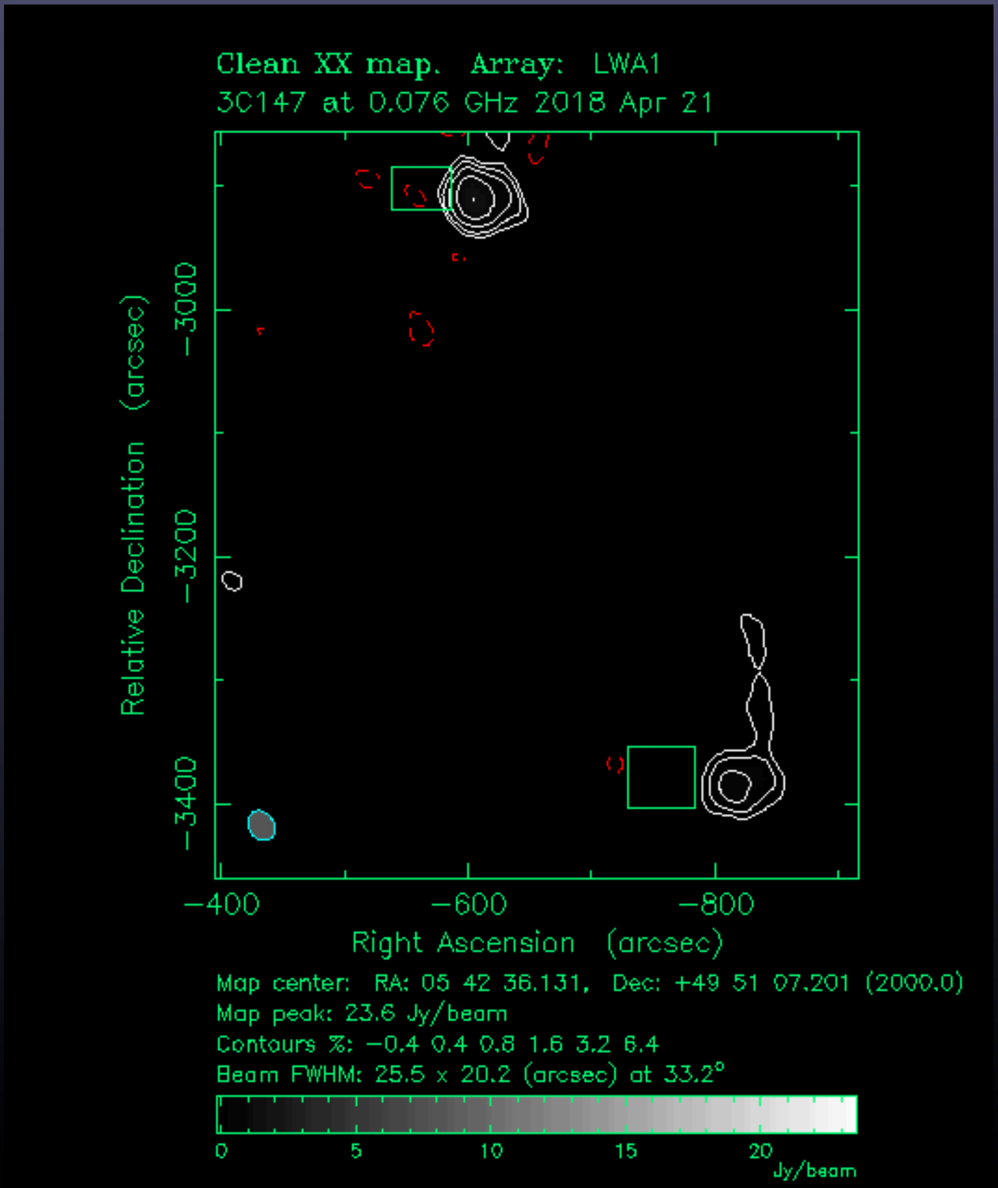
Ionospheric effects:

- Green box = April 20
- Contours = April 21

Offset 50 arcsec

~2% error

Scales with distance from phase center



VLA 50-86 MHz

New 4 band feeds (MJP)
4 meter band: 50-86 MHz
21 installed

All 27 by end of 2018

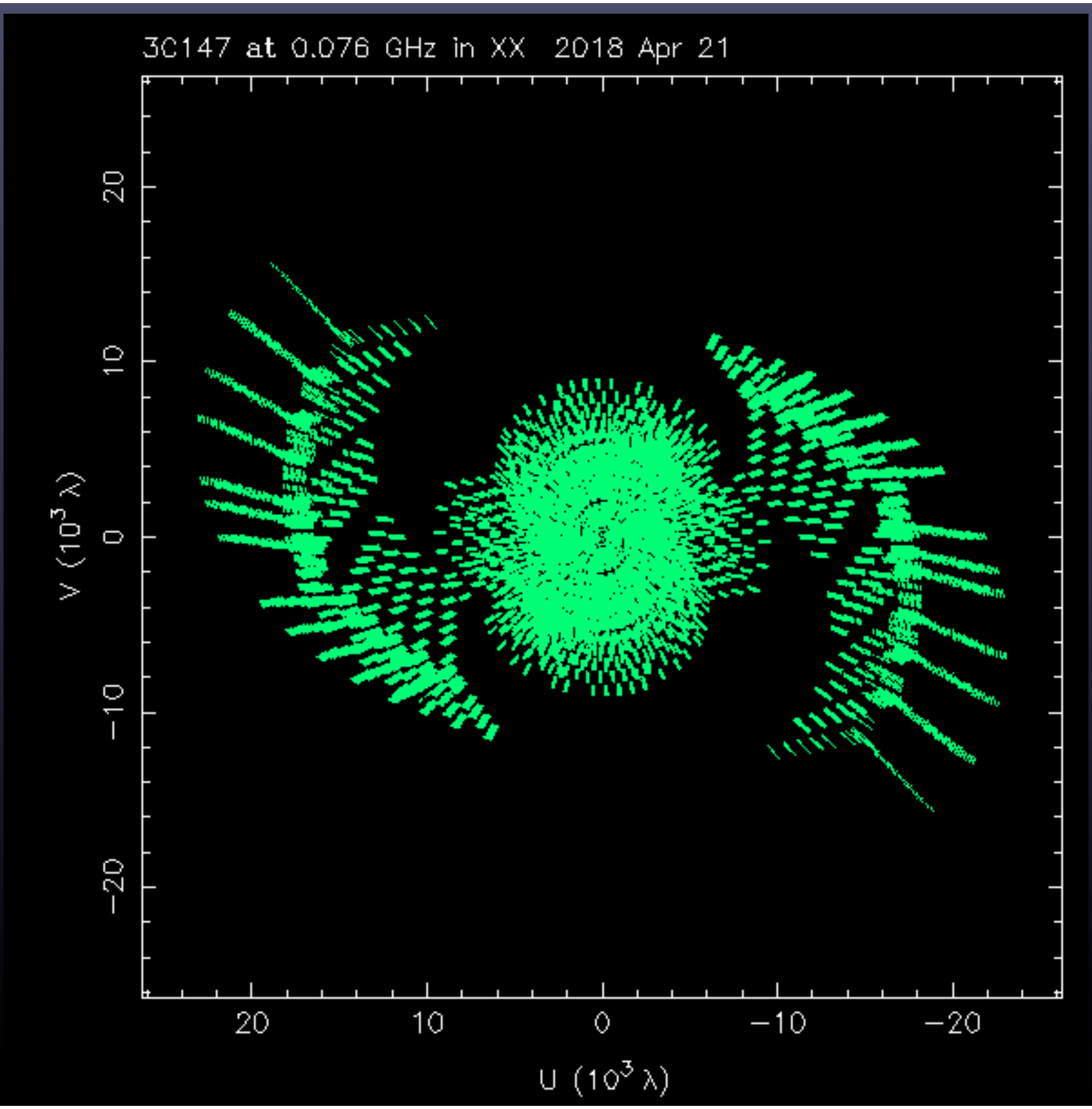
LWA 10-88 MHz

LWA1

LWA-SV

75 km separation

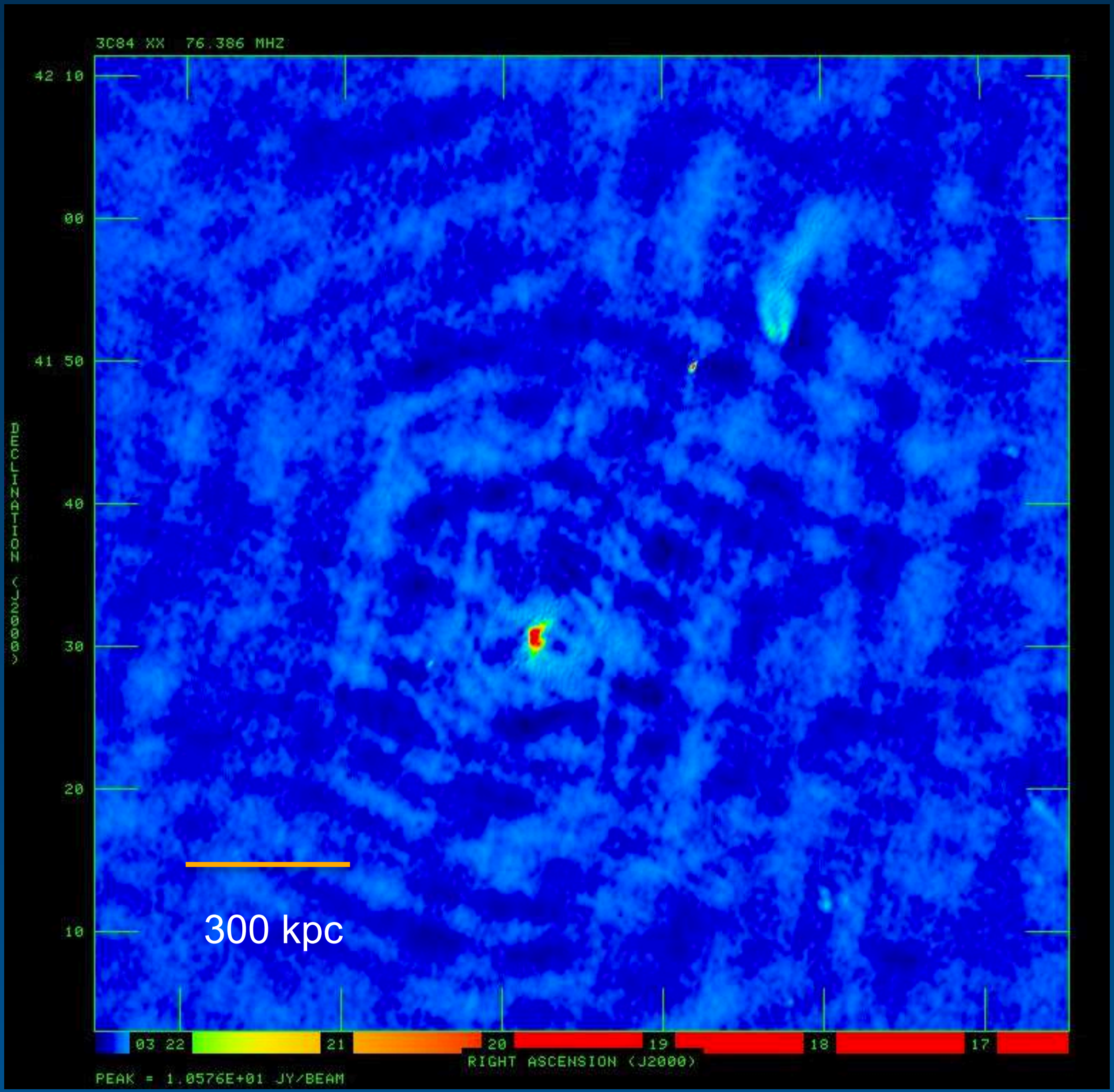
Expanded Long Wavelength Array (ELWA)



ELWA - Demonstration

3C84 at 76 MHz
Apr 21, 2018
LWA1 + LWA-SV
+ 21 VLA

15 mJy noise



ELWA - Demonstration

Hydra A at 76 MHz
Apr 24, 2018
LWA1 + LWA-SV
  + 21 VLA

100 mJy noise
Dynamic range 1000:1

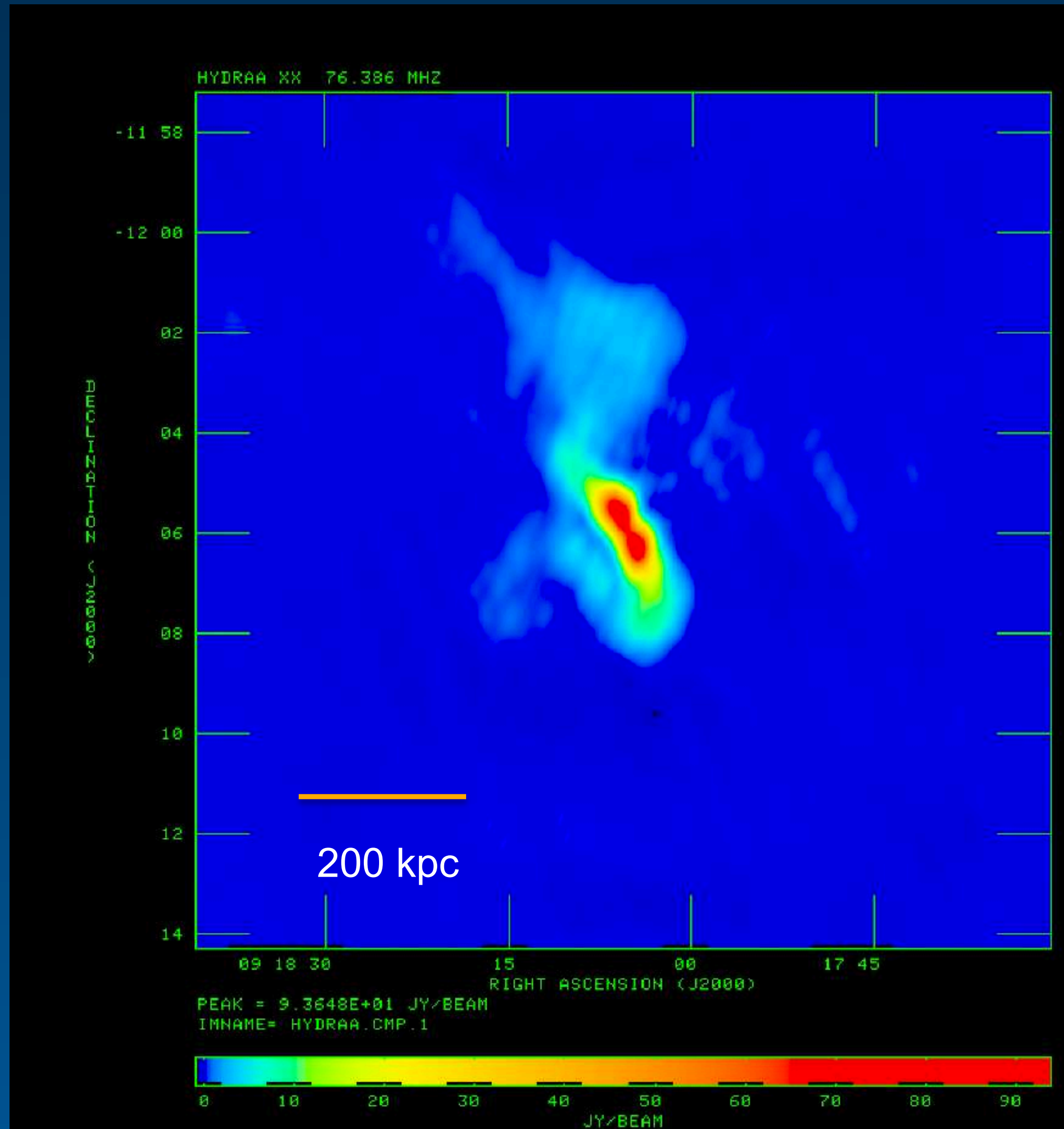


IMAGE REGISTRATION AND ACCURACY

- Separation Accuracy of Components on One Image due to residual phase errors, regardless of signal/noise:

  Limited to 1% of resolution

  Position errors of 1:10000 for wide fields, i.e. 0.1″ over 1.4 GHz PB

- Images at Different Frequencies:

  Multi-frequency. Use same calibrator for all frequencies.
  Watch out at frequencies < 2 GHz when ionosphere can produce displacement. Minimize calibrator-target separation

- Images at Different Times (different configuration):

  Use same calibrator for all observations. Daily troposphere changes can produce position changes up to 25% of the resolution.

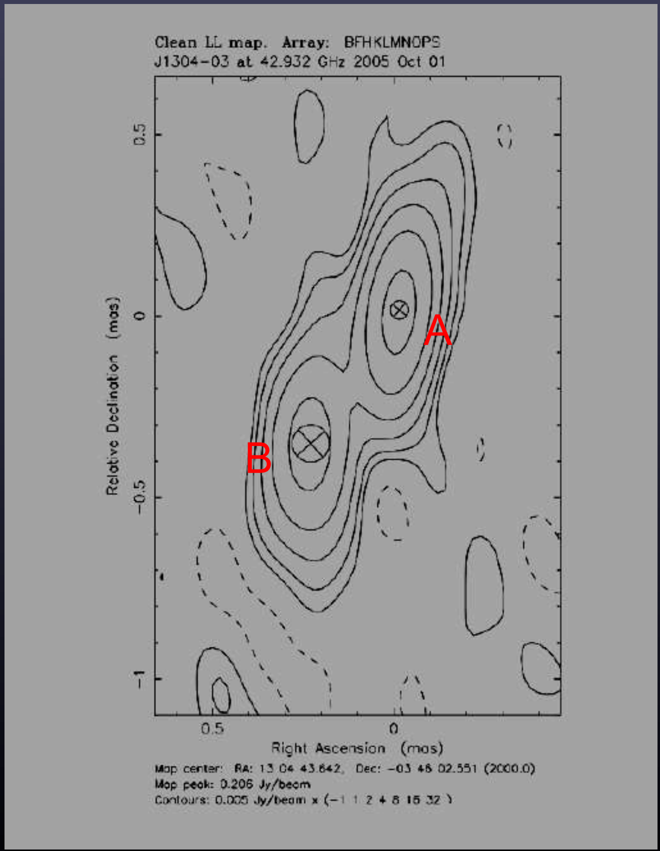
- Radio versus non-Radio Images:

  Header-information of non-radio images often much less accurate than for radio. For accuracy <1″, often have to align using coincident objects.

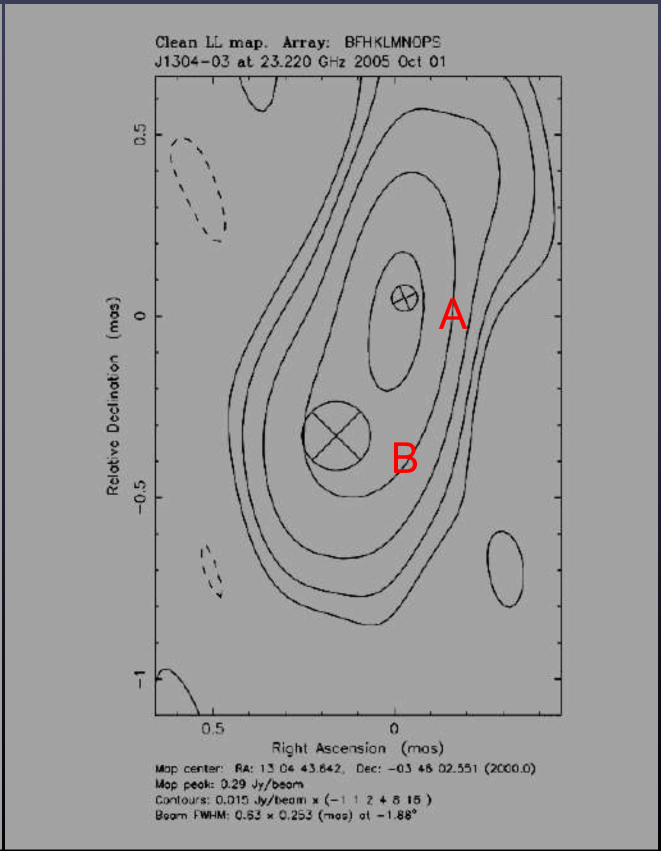
Radio Source Alignment at Different Frequencies

Self-calibration at each frequency aligns maximum at (0,0) point
Frequency-dependent structure causes relative position of maximum to change
Fitting of image with components can often lead to proper registration

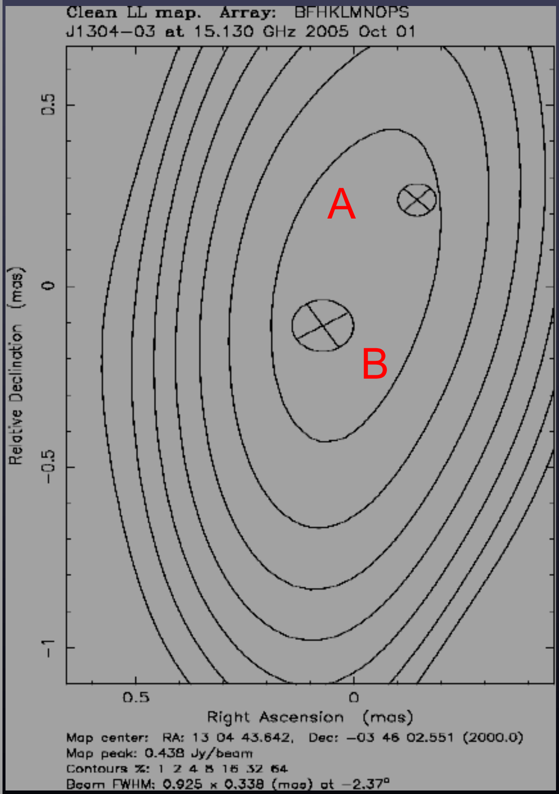
43 GHz: res = 0.3 mas



23 GHz: res = 0.6 mas



15 GHz: res = 0.8 mas



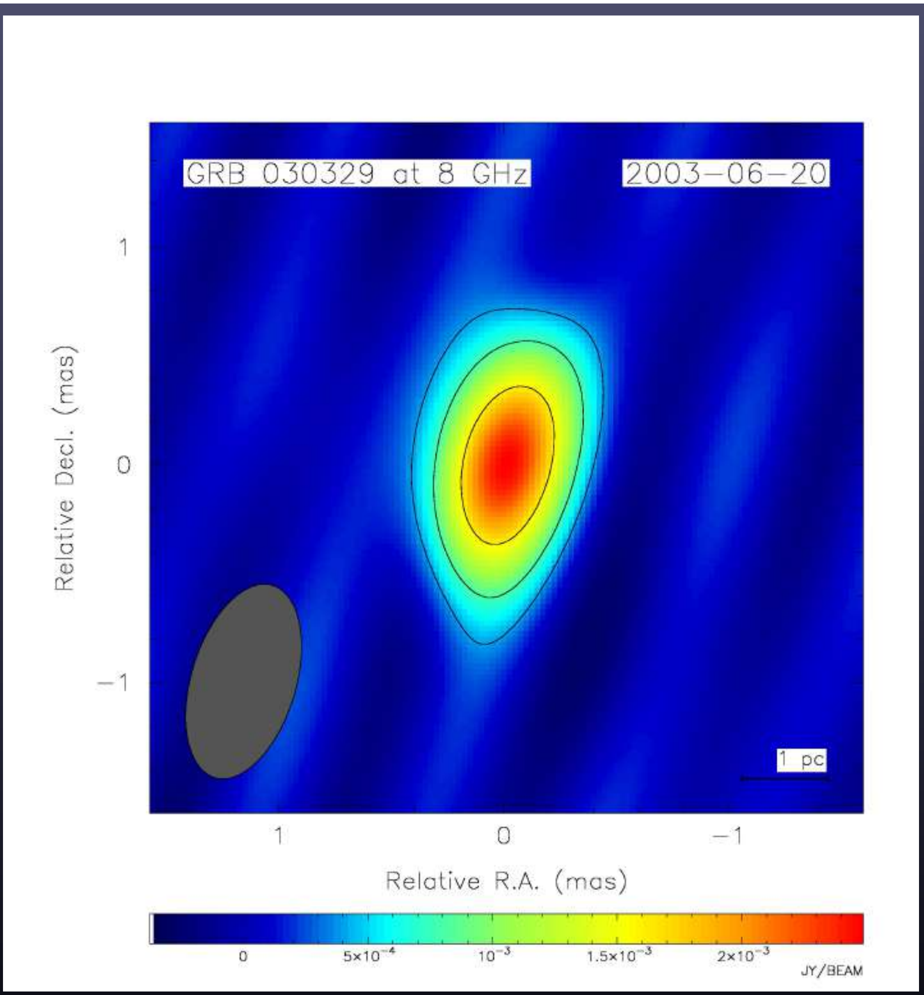
Applications - GRB030329

June 20, 2003

t+83 days

Peak ~ 3 mJy
Size 0.172 +/- 0.043 mas
0.5 +/- 0.1 pc
average velocity = 3c

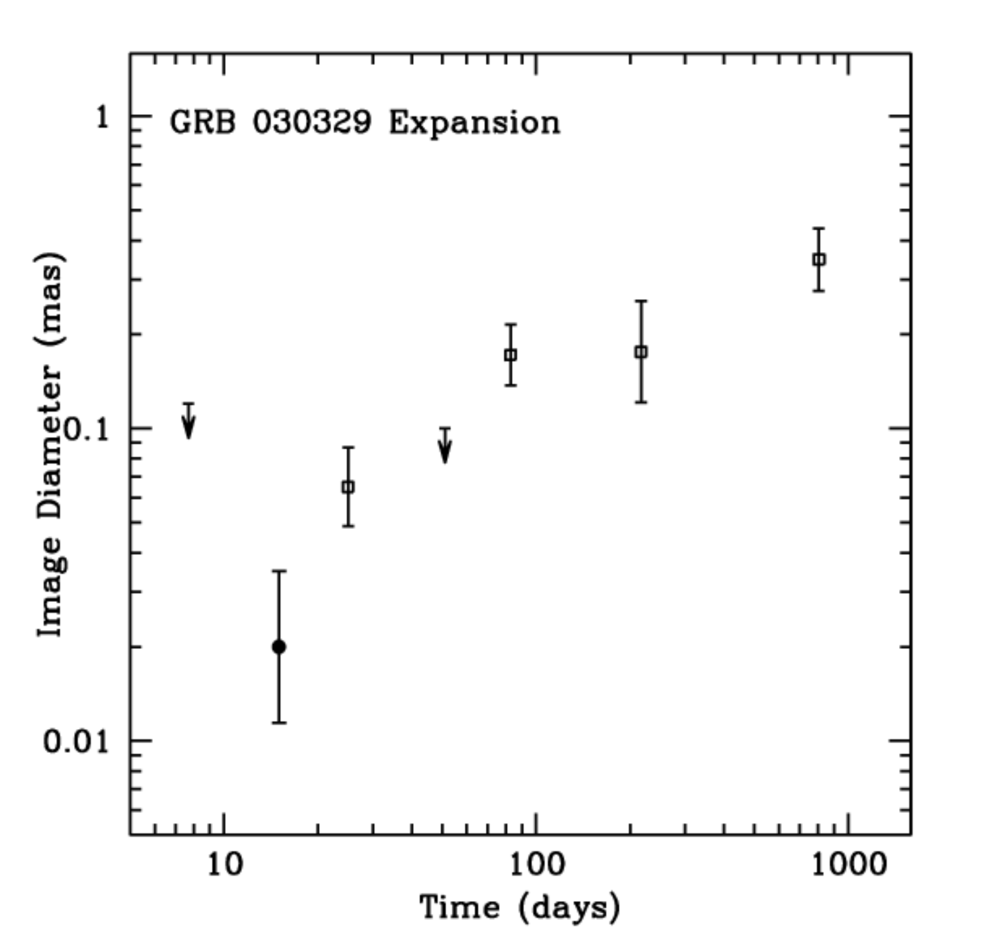
Taylor et al. 2004



GRB 030329

Expansion over 3 years

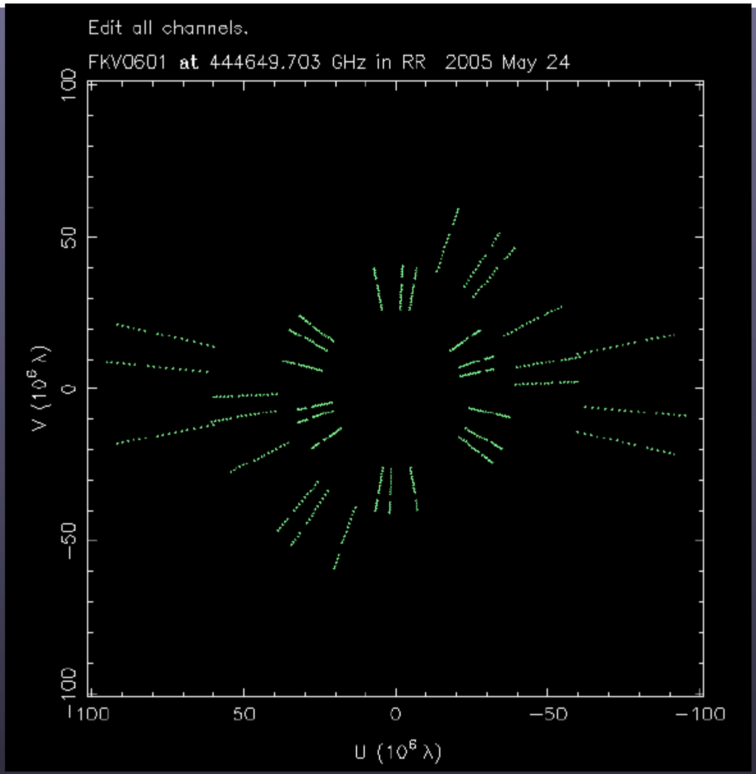
Apparent velocity ranging from
8c at 25 days to
1.2c after 800 days

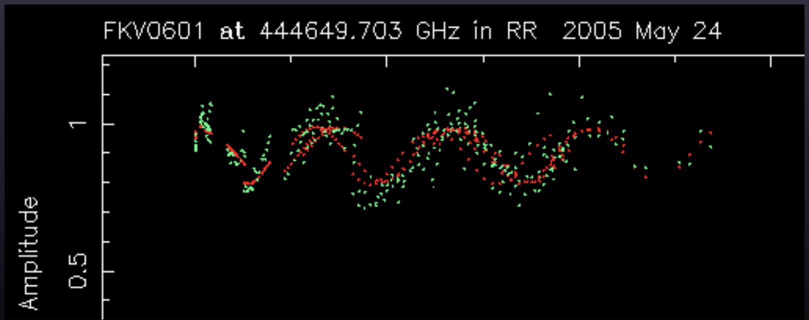


Applications: A Binary Star

- Binary Stars
  - Many stars are in binary systems
  - Orbital parameters can be used to measure stellar masses
  - Astrometry can provide direct distances via parallax and proper motions.
- Application of model fitting
  - Optical interferometry provides sparse visibility coverage
  - Small number of components
  - Need error estimates.
- Example: NPOI observations of Phi Herculis (Zavala et al. 2006)
  - No phase information
  - One epoch shown, multiple observations map out the orbit

NPOI Observations of Phi Her





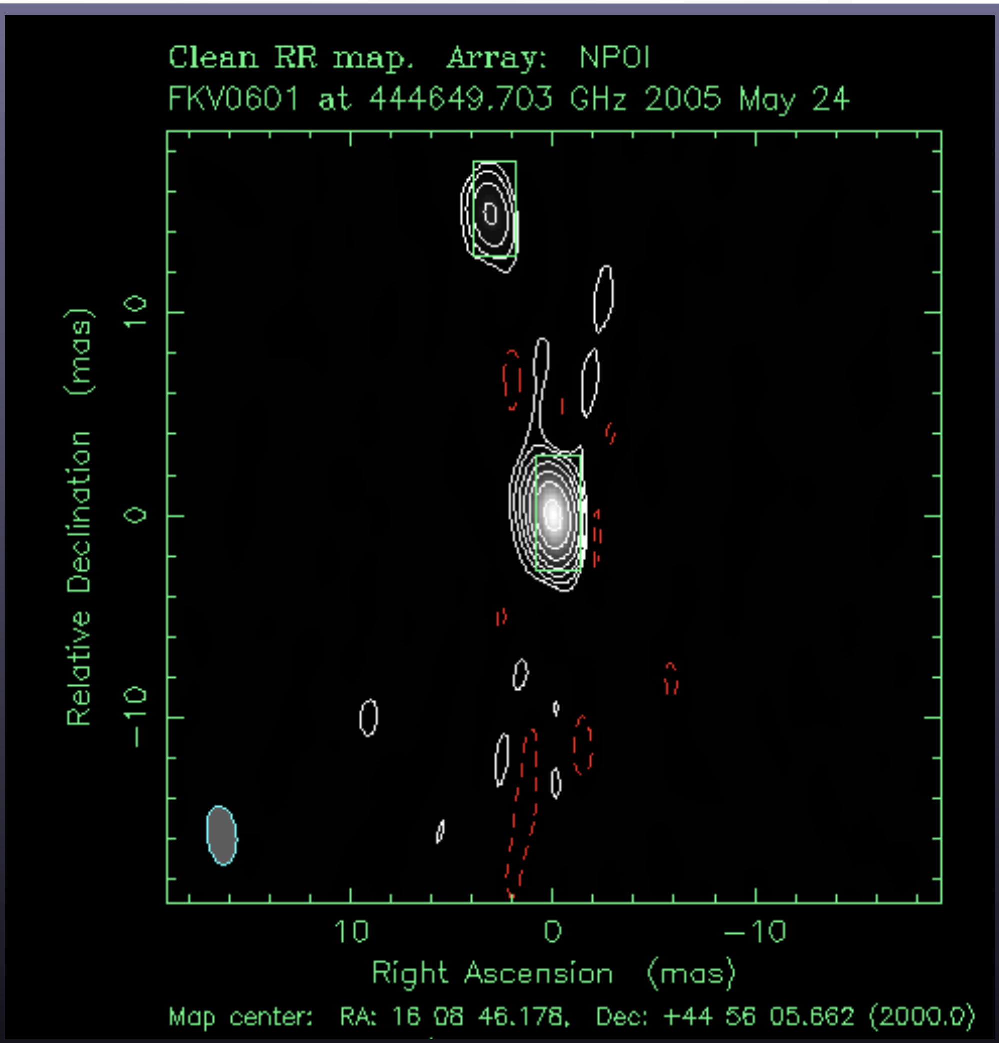


IMAGE ANALYSIS: SUMMARY

- Analyze and display data in several ways
  - Adjust resolution to illuminate desired interpretation, analysis
- Parameter fitting useful, but be careful of error estimates
  - Fitting in (u,v) plane and/or image plane
- Registration of a field at different frequencies or wave-bands can be subtle.
  - Whenever possible use the same calibrator
  - May be able to align using ‘known’ counterparts
- Check spectral index image for artifacts

Model Fitting Summary

- For simple sources observed with high SNR, much can be learned about the source (and observational errors) by inspection of the visibilities.
- Even if the data cannot be calibrated, the **closure quantities** are good observables, and modelfiting can help to interpret them.
- Quantitative data analysis is best regarded as an exercise in **statistical inference**, for which the maximum likelihood method is a general approach.
- For gaussian errors, the ML method is the **method of least squares**.
- Visibility data (usually) have uncorrelated gaussian errors, so analysis is most straightforward in the (u,v) plane.
- Consider visibility analysis when you want a quantitative answer (with error estimates) to a simple question about a source.
- Visibility analysis is inappropriate for large problems (many data points, many parameters, correlated errors); standard imaging methods can be much faster.

Further Reading

- http://www.nrao.edu/whatisra/
- www.nrao.edu

- 2010 Lecture on Non-Imaging Analysis
- Synthesis Imaging in Radio Astronomy
- ASP Vol 180, eds Taylor, Carilli & Perley
- Numerical Recipes, Press et al. 1992