INTRODUCTION TO INTERFEROMETRY

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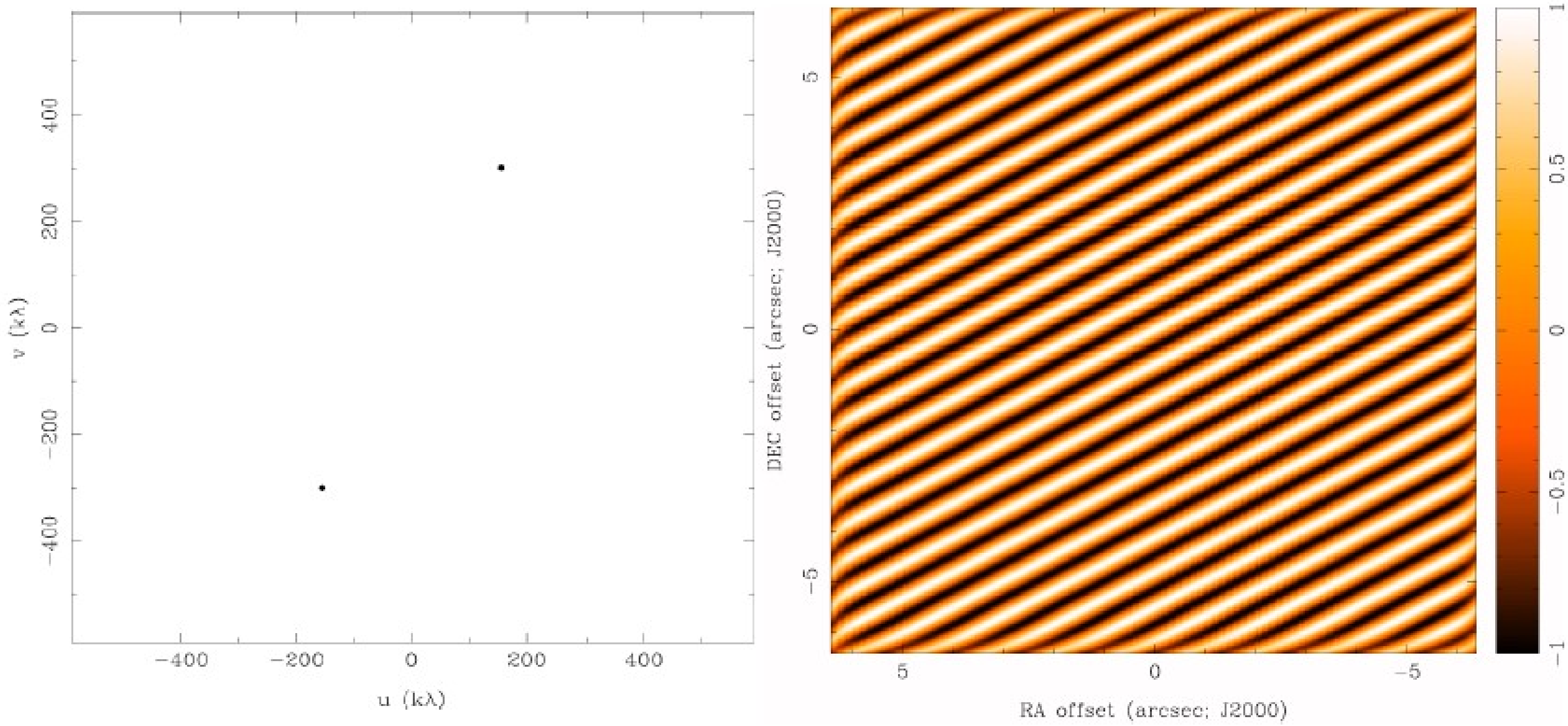
Dirty Beam Shape and N Antennas

2 Antennas



Courtesy David J. Vilner, Harvard-Smithsonian Center for Astrophysics, USA

The Visibility Concept

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

- visibility as a function of baseline coordinates (u,v) is the Fourier transform of the sky brightness distribution as a function of the sky coordinates (x,y)

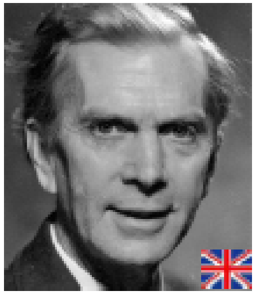
- V(u=0,v=0) is the integral of T(x,y)dxdy = total flux

- since T(x,y) is real, V(u,v) is Hermitian: V(-u,-v) = V*(u,v)
  - get two visibilities for one measurement

Courtesy David J. Vilner, Harvard-Smithsonian Center for Astrophysics, USA

Aperture Synthesis Basics

- idea: sample V(u,v) at *enough* baselines to synthesize a large aperture of size (u_{max}, v_{max})
  - one pair of telescopes = one baseline = one (u,v) sample at a time
  - N telescopes = N(N-1) (u,v) samples at a time
  - use Earth rotation to fill in (u,v) plane with time (Sir Martin Ryle 1974 Physics Nobel Prize)
  - reconfigure physical layout of N antennas for more
  - observe at multiple wavelengths simultaneously, if source spectrum amenable to simple characterization

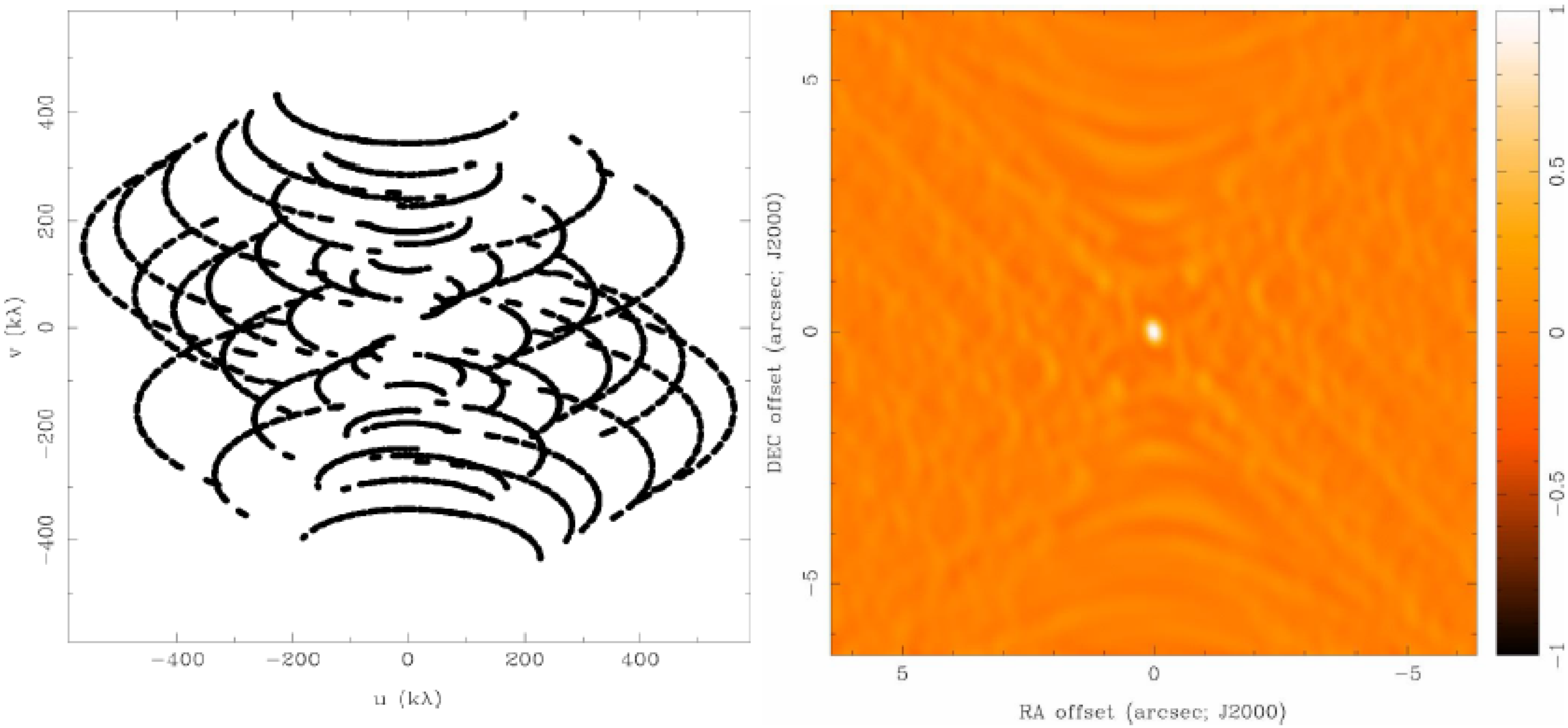


Sir Martin Ryle
1918-1984

Courtesy David J. Vilner, Harvard-Smithsonian Center for Astrophysics, USA

Dirty Beam Shape and N Antennas

8 Antennas x 480 samples



Courtesy David J. Vilner, Harvard-Smithsonian Center for Astrophysics, USA

So what do we finally have?

- $B^S(\theta,\varphi)$ = FT (S(u,v) x V(u,v))
- From convolution theorem

  $B^S(\theta,\varphi) = P(\theta,\varphi) \otimes B(\theta,\varphi)$

  $\otimes$ - convolution

  $P(\theta,\varphi)$ = FT S(u,v); $B(\theta,\varphi)$ = FT V(u,v)

The FT of sampled visibilities gives the True sky Brightness distribution convolved with the Point Spread Function.

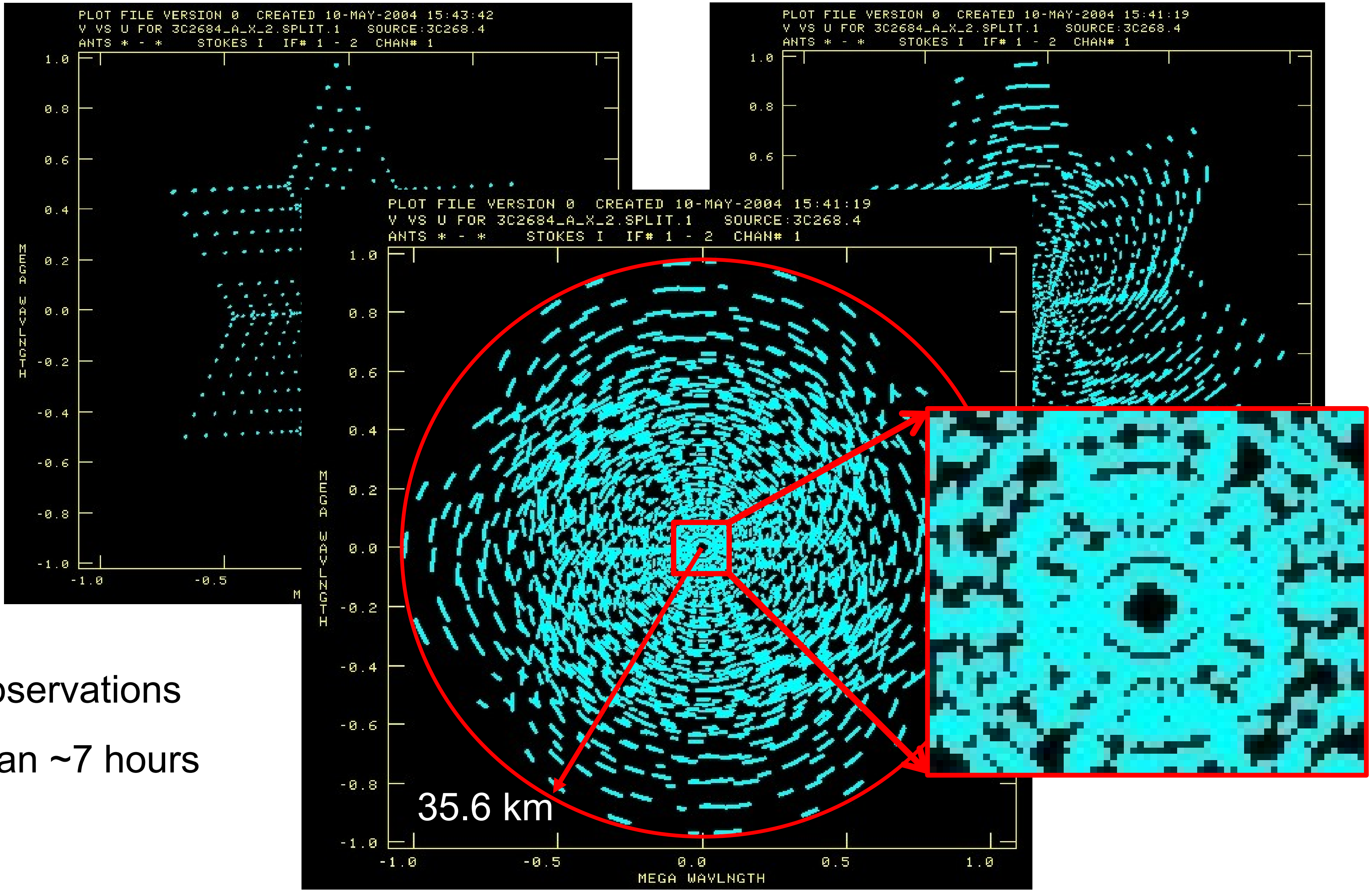
'***Dirty image***' is True image convolved with the '***Dirty beam***'.

A real life example

- The Very Large Array (VLA), NM
- 8.43 GHz (λ = 3.56cm)
- $\Delta\nu$ = 86 MHz
- 3C268.4

- Data courtesy - Colin Lonsdale, MIT Haystack Observatory

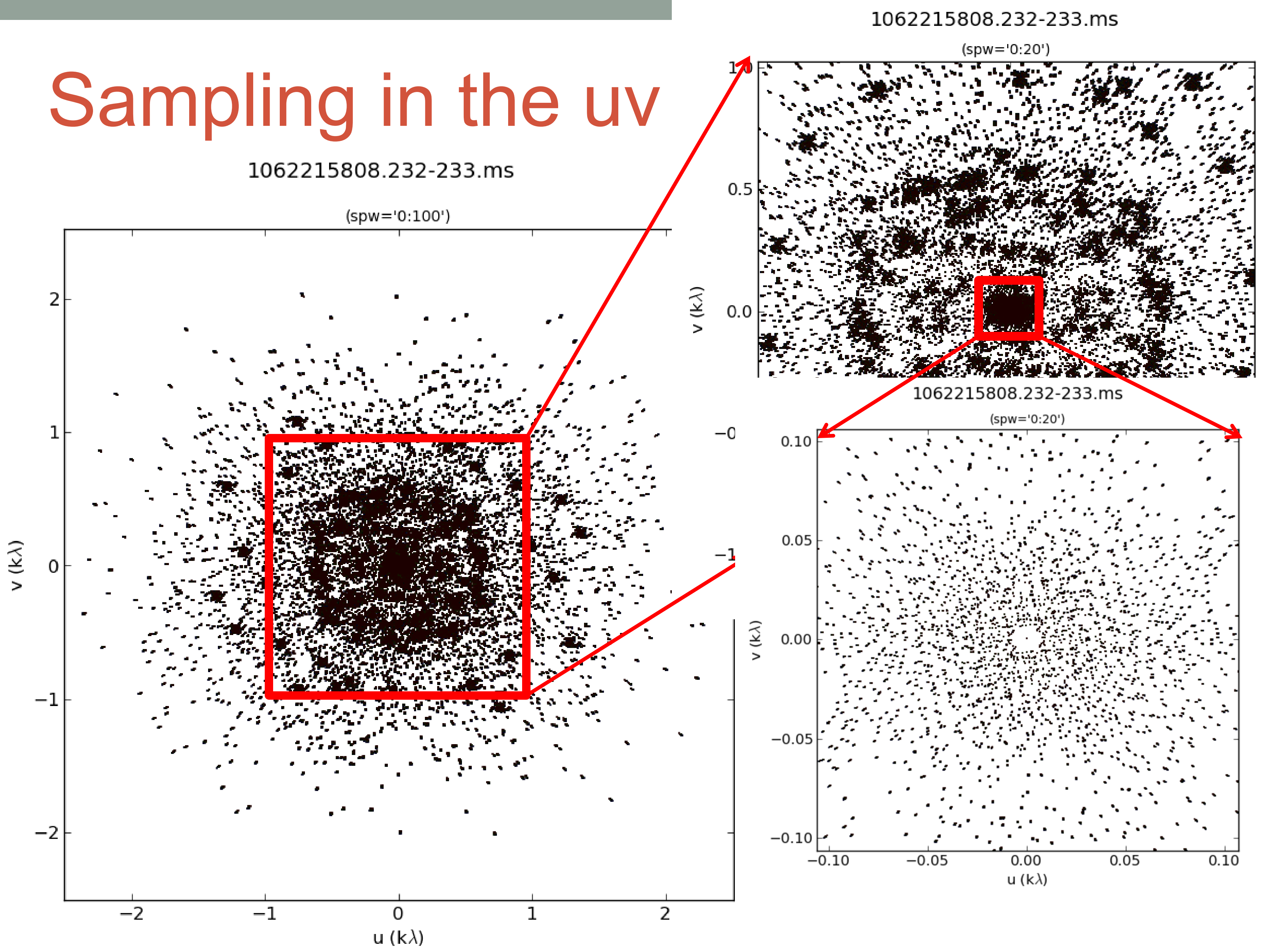
Array configuration and u-v coverage



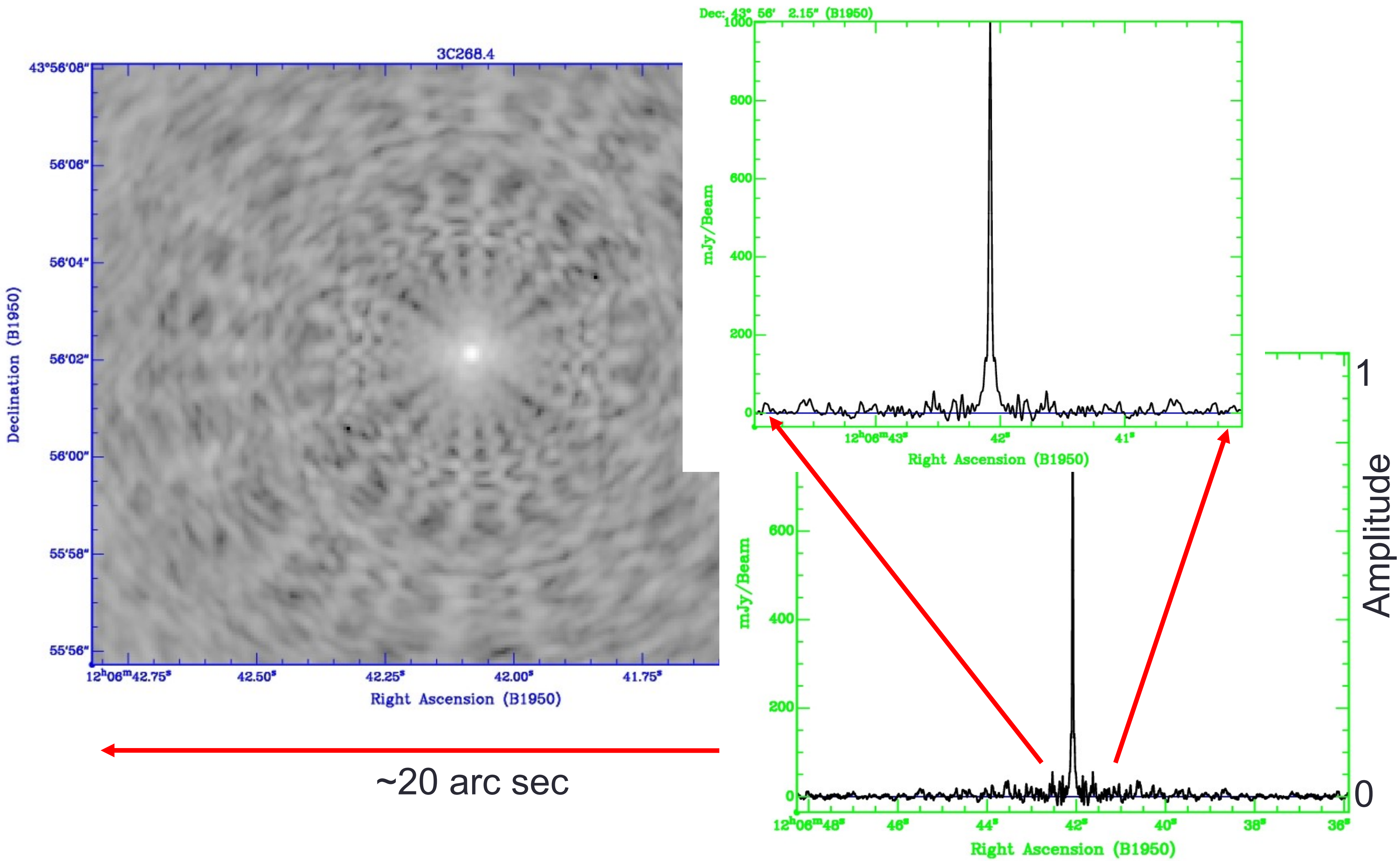
Observations

span ~7 hours

Sampling in the uv



The interferometer response function (Point Spread Function)



The measured cross-correlations

A typical FM radio station ~0.1 W Hz^{-1} placed at the distance of the Sun (1.5×10^8 km)
$\Rightarrow$ ~35 Jy at Earth

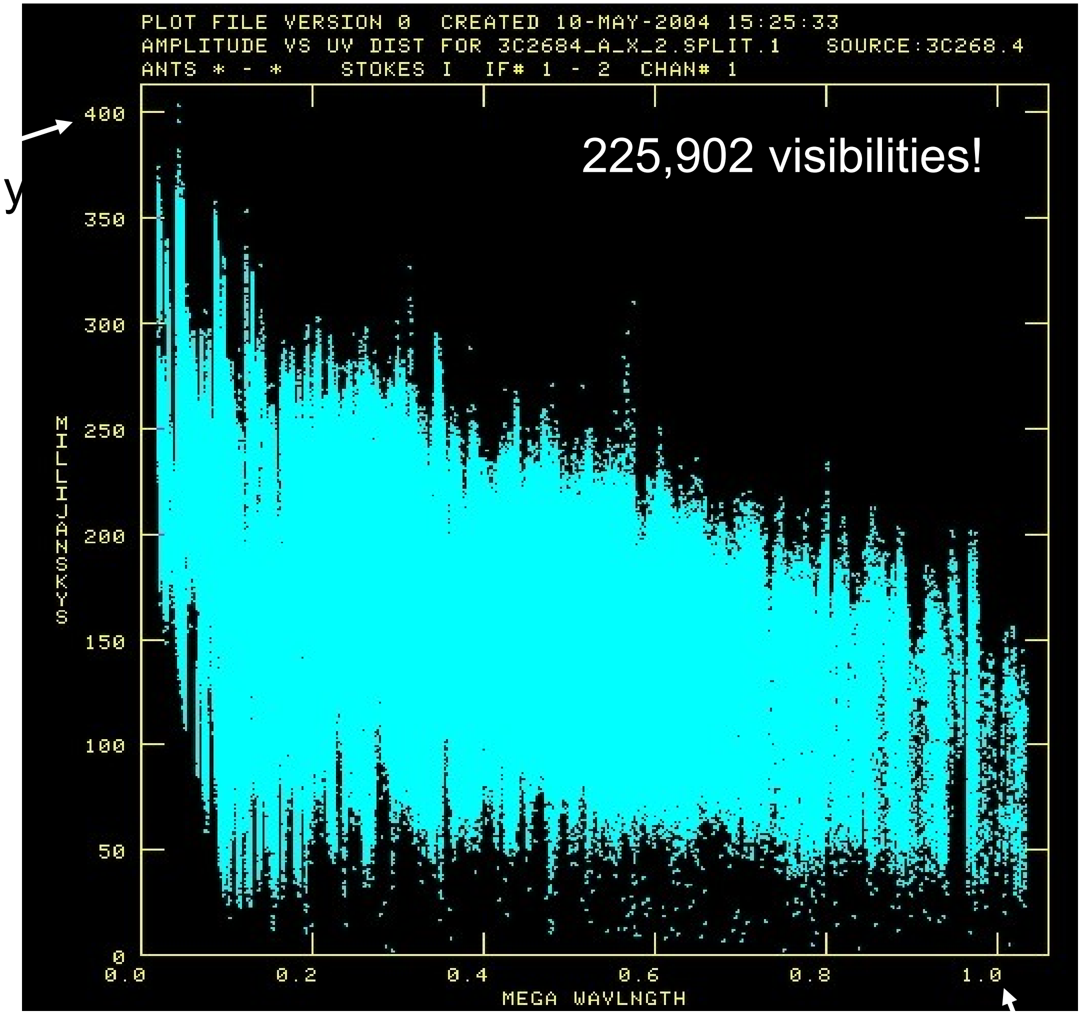
VLA sensitivity at 8 GHz ~45×10^{-6} Jy (10 min, 86 MHz)

In 10 min VLA can detect a source as strong as a typical FM station ~88 AU away!

$1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$

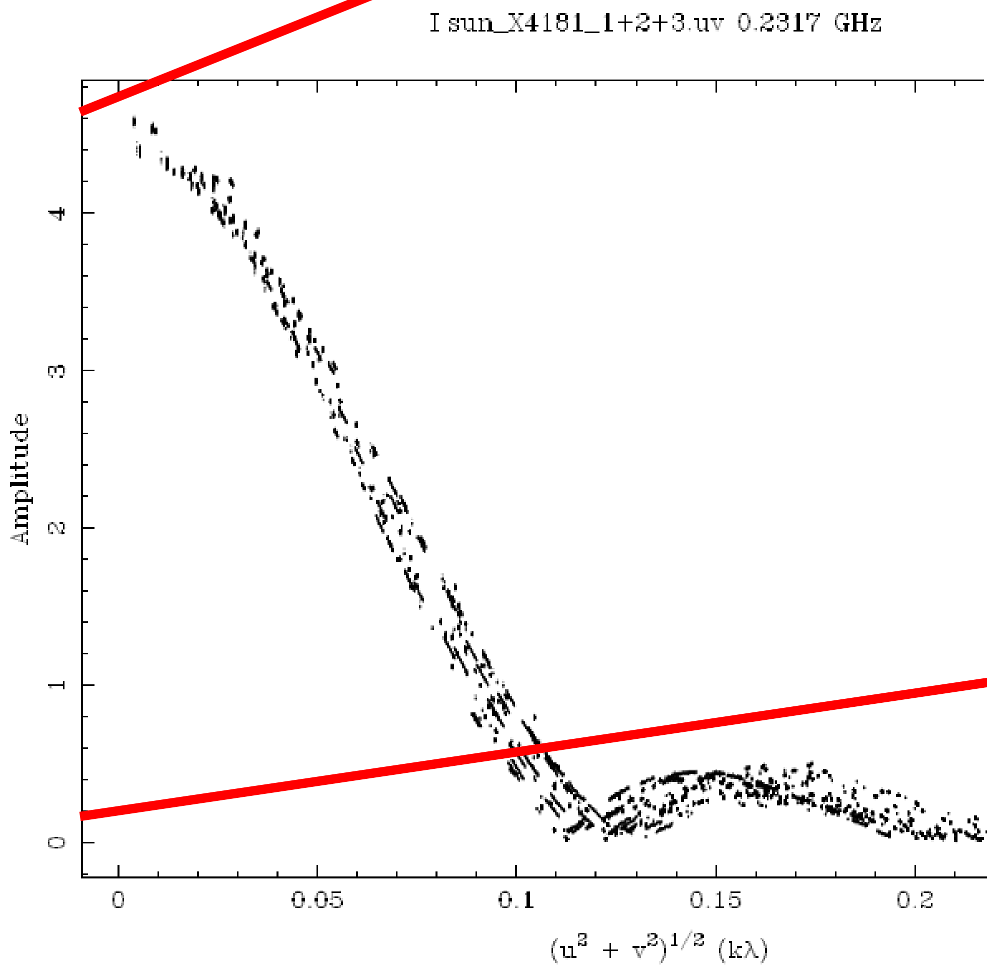
400 mJy

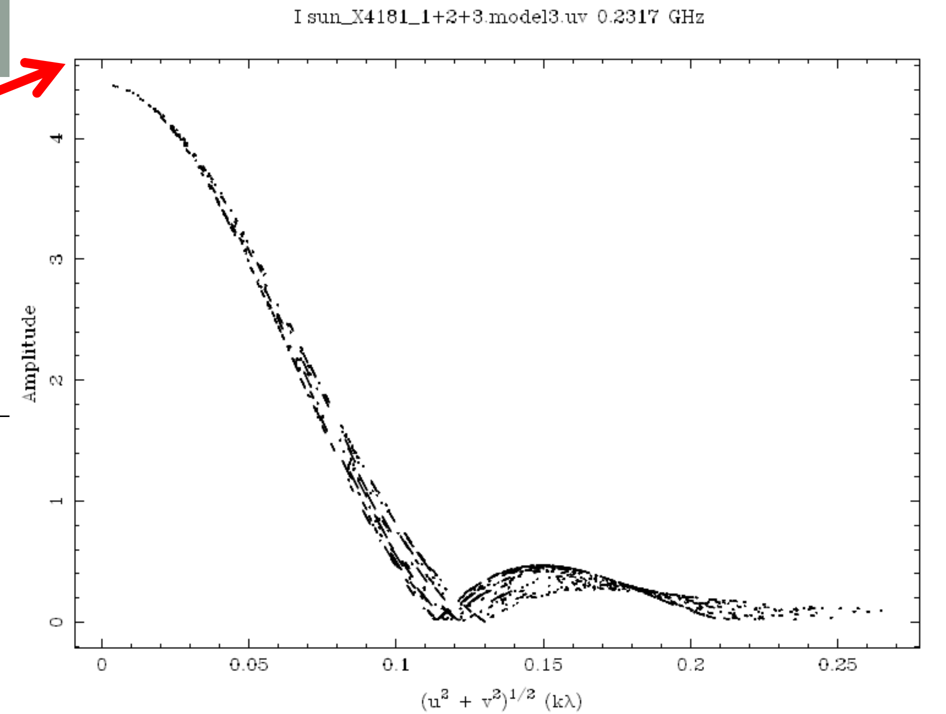
Amplitude (mJy)

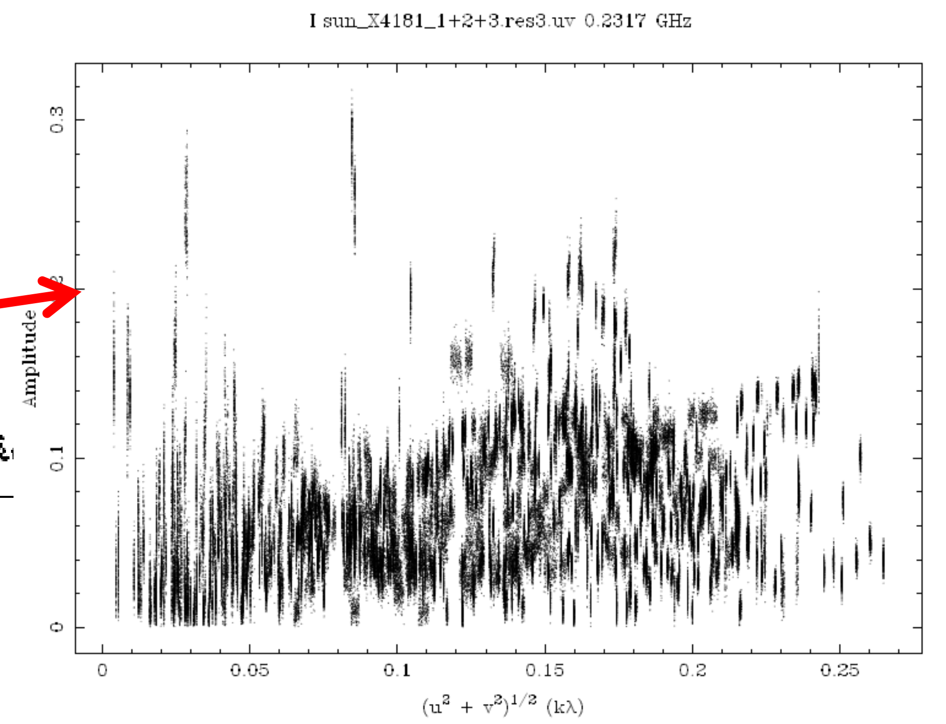


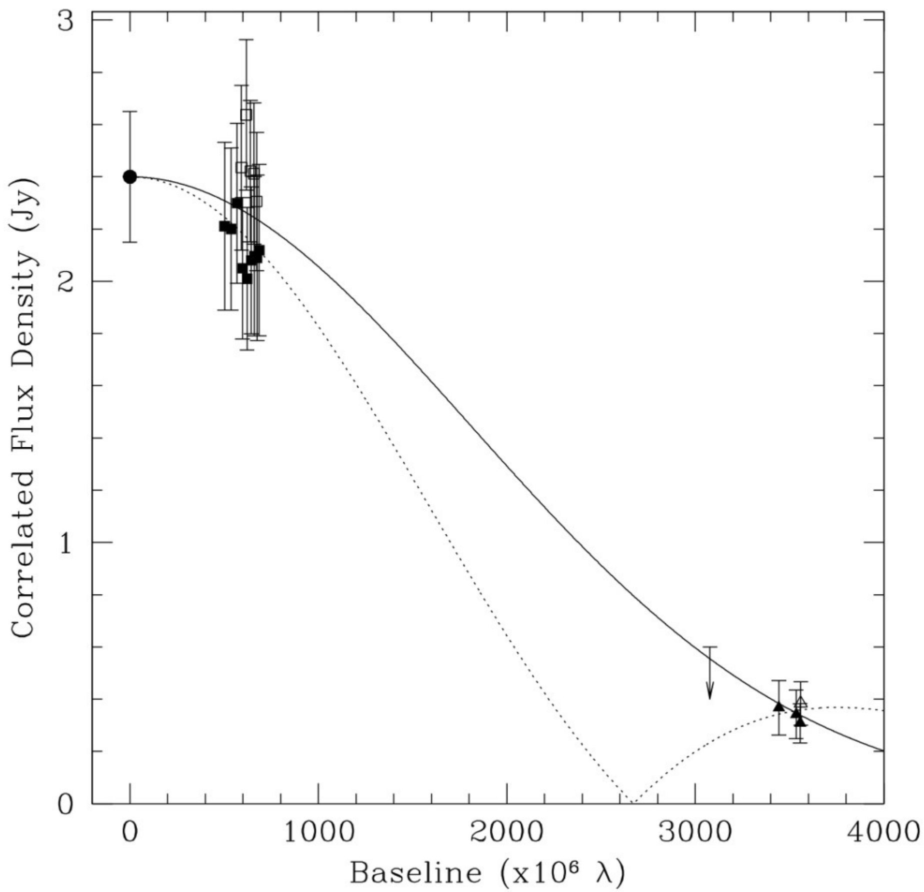
Sqrt($u^2 + v^2$) (λ)

231.7 MHz – Disk





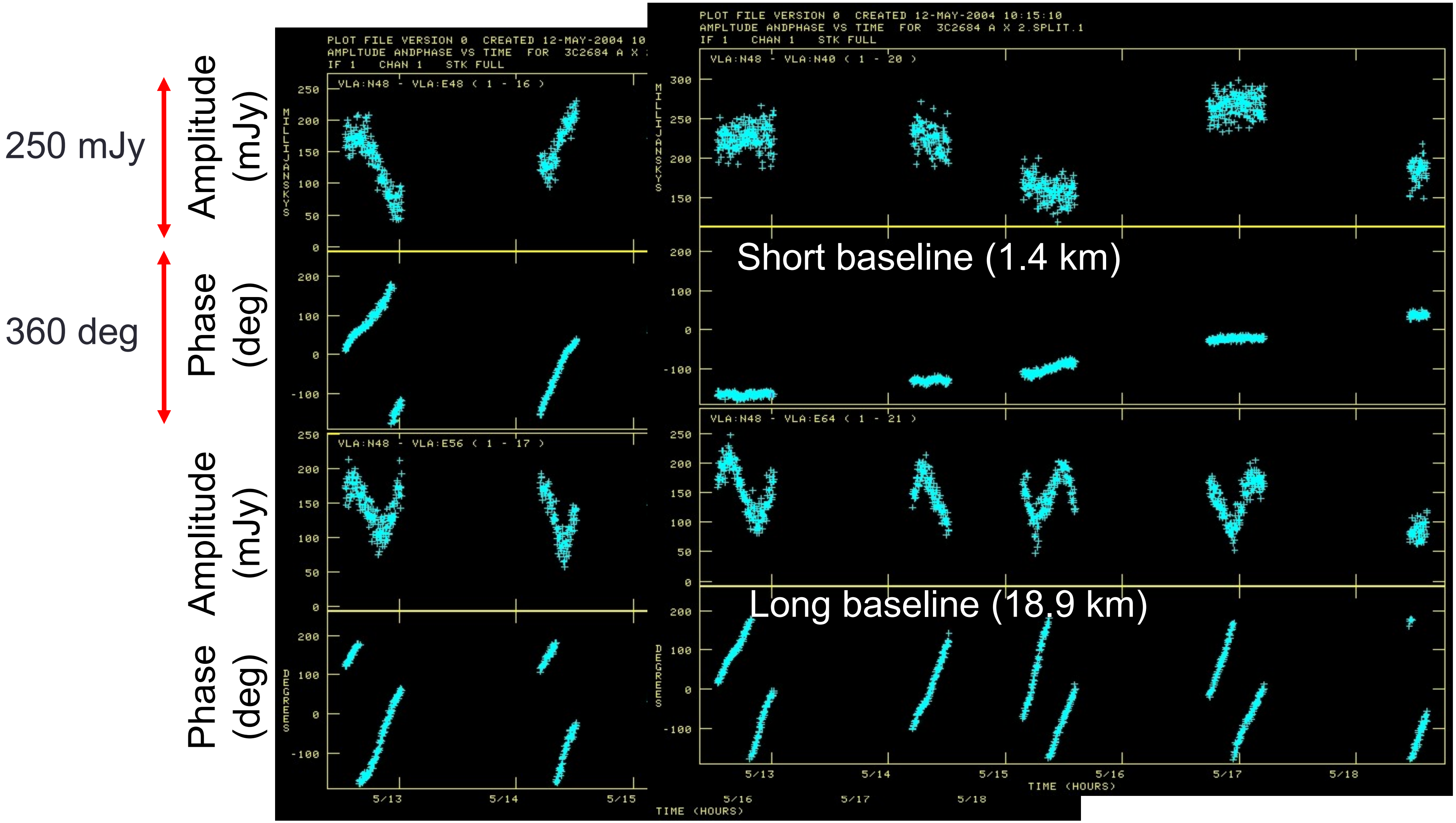




Fitting the size of Sgr A* with 1.3 mm VLBI. A plot of correlated flux density vs. baseline length with squares showing the SMT-CARMA baseline, triangles showing the SMT-JCMT baseline, an an upper limit (arrow) for non-detections on the JCMT-CARMA baseline. Open symbols for April 10, 2007 and filled symbols for April 11. The solid curve is the circular Gaussian fit with FWHM of 43 micro arcseconds. Dashed line is for annular ring model of inner radius 35 micro arcseconds and outer radius of 80 micro arcseconds.

Doeleman, et al; Nature, v 455 pp 78-80 (2008)

The cross-correlations…

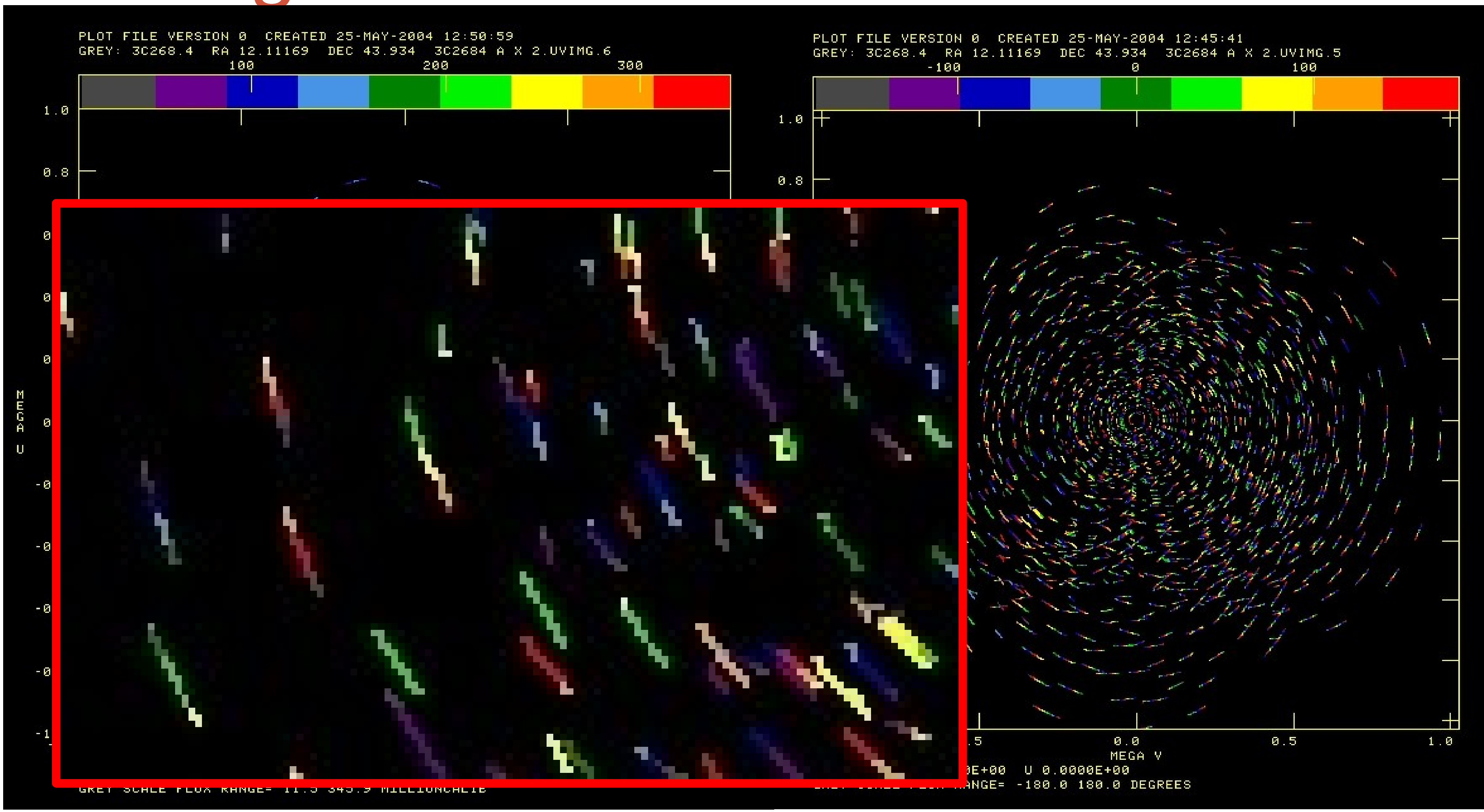


Time (hours) ~7 hrs

Observed visibilities to *gridded* visibilities

- Fast Fourier Transform (FFT)
  - O(N logN) for 2^N x 2^N image
  - Requires data on a regular grid
  - Aperture synthesis does not provide regularly sampled data …
- Gridding – to resample the observed visibilities to a regular grid
  - Implemented via convolution
    - Measured visibilities are noisy samples of an underlying smooth distribution
    - Nearby visibilities are not independent
    - Use a function which falls off quickly in uv plane
- Weighting
  - Modify beamshape and sidelobes match science objectives

The gridded visibilities



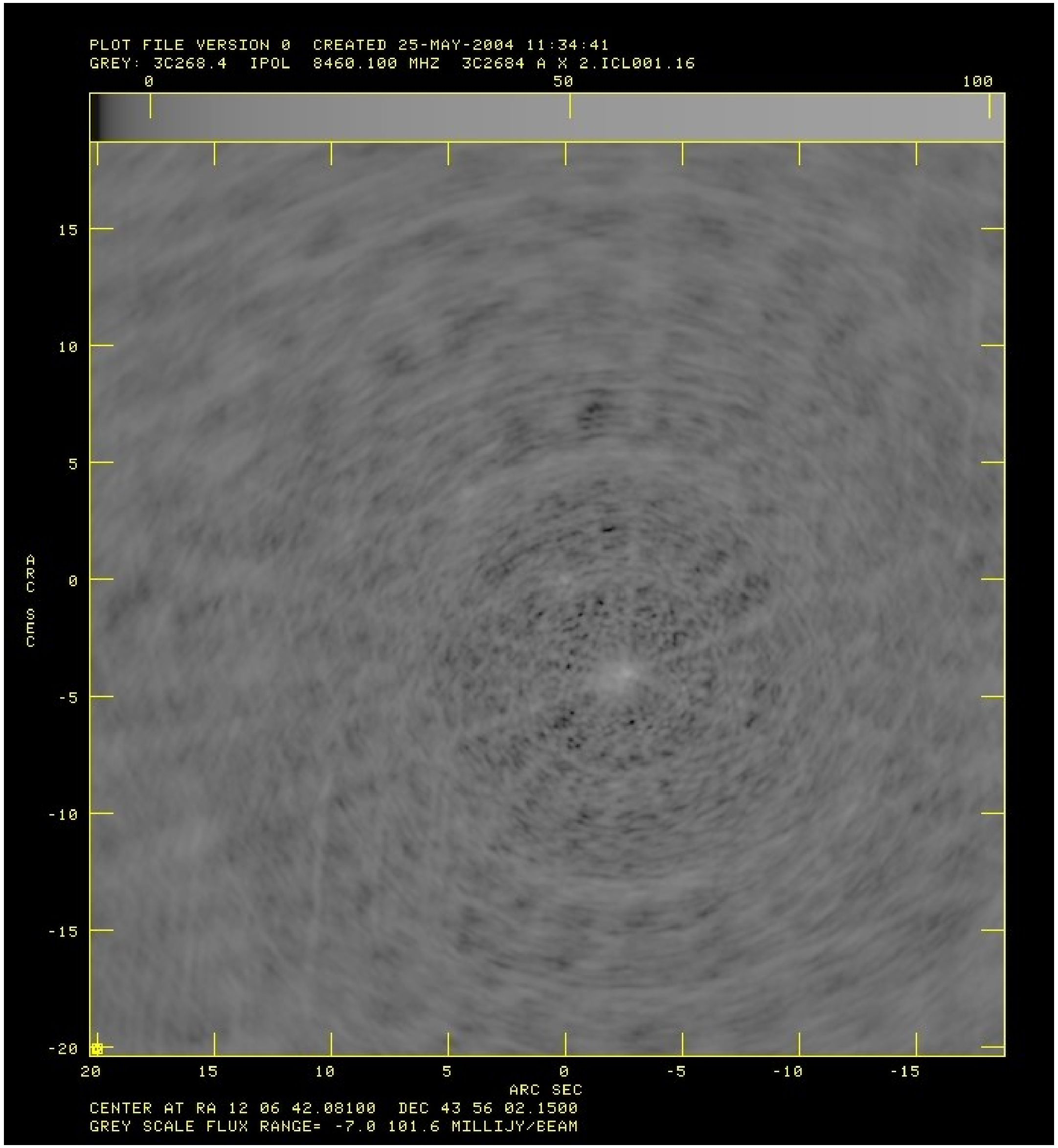
Amplitude

Phase

FT of gridded visibilities

The *dirty* map

Convolution of the PSF with the Brightness distribution



Log scale

The problem of deconvolution

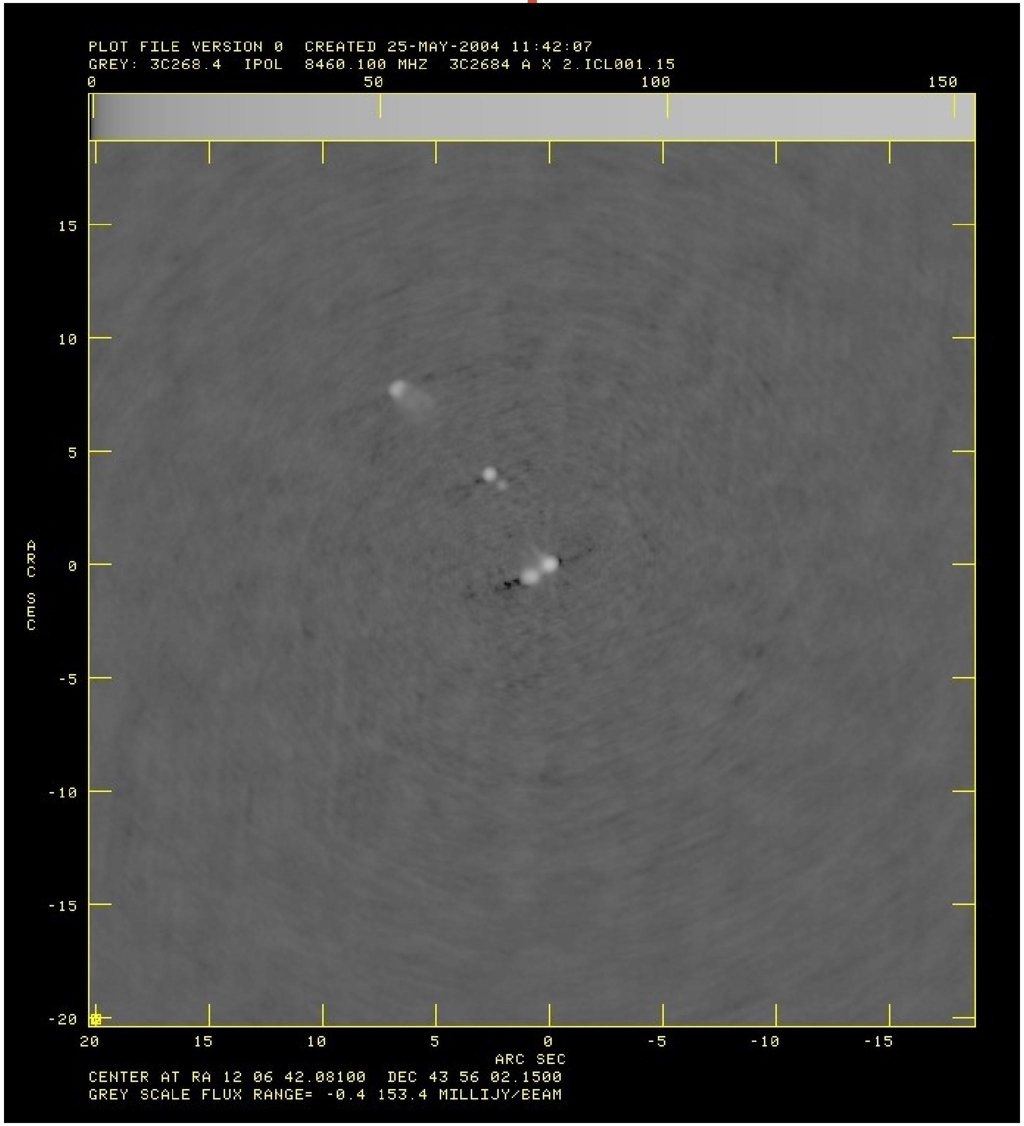
- The measurements from any instrument are really the *convolution* of the *transfer function* of the instrument and the input signal.
- In order to figure out the true input signal, it is necessary to *deconvolve* the *transfer function* from the measurements
- Radio Astronomy solutions
  - CLEAN algorithm(s) – standard workhorse
  - Maximum Entropy Method(s) – limited applications
  - Compressive Sensing Methods – being researched

The CLEAN approach

- Assumption – Astronomical sources can be represented as a sum of discreet point sources
- Essentially fit and subtract PSF iteratively
  - Locate the brightest point in the dirty map
  - Subtract a scaled copy of the PSF centered at this pixel and note down the strength and the location of the PSF subtracted
  - Loop over subtracting sources till the strength of the brightest pixel drops to some pre-determined criteria
  - The final map is the collection of all the point sources which had been subtracted with the residual noise from the dirty map added to it

The *CLEANed* map

Actually, CLEANed and *Self-calibrated* map



~50,000 Clean iterations

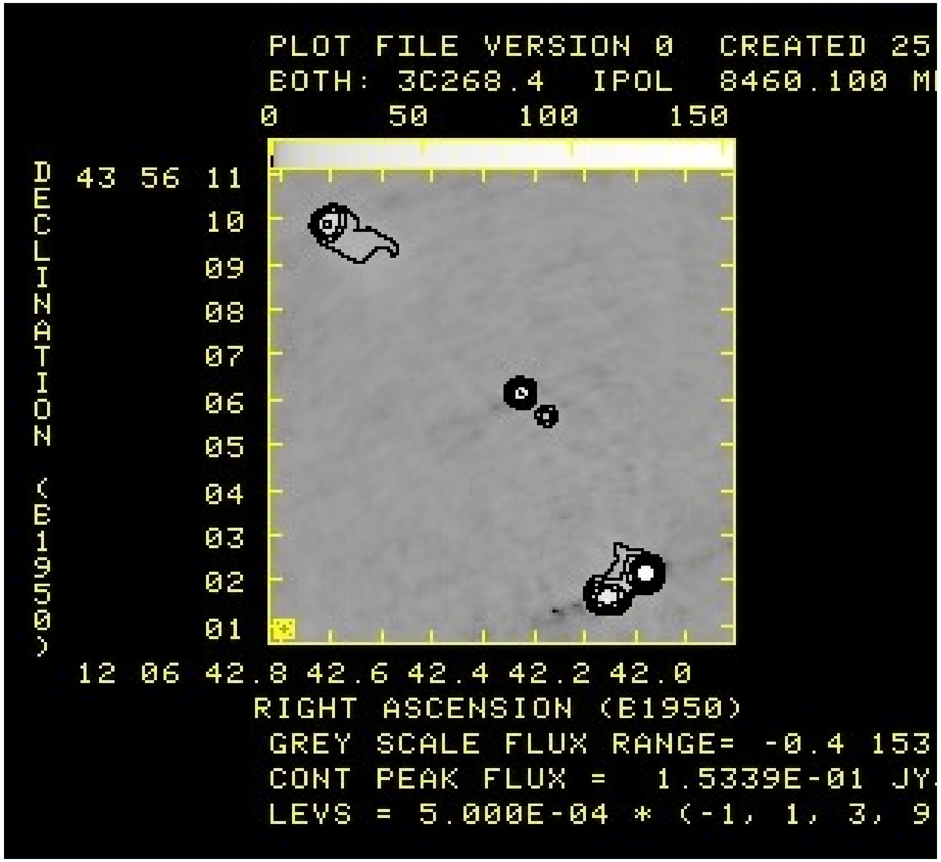
~4000 Clean components

Dynamic range ~5000

Noise ~30 μJy/beam

Log scale

A comparison with other results



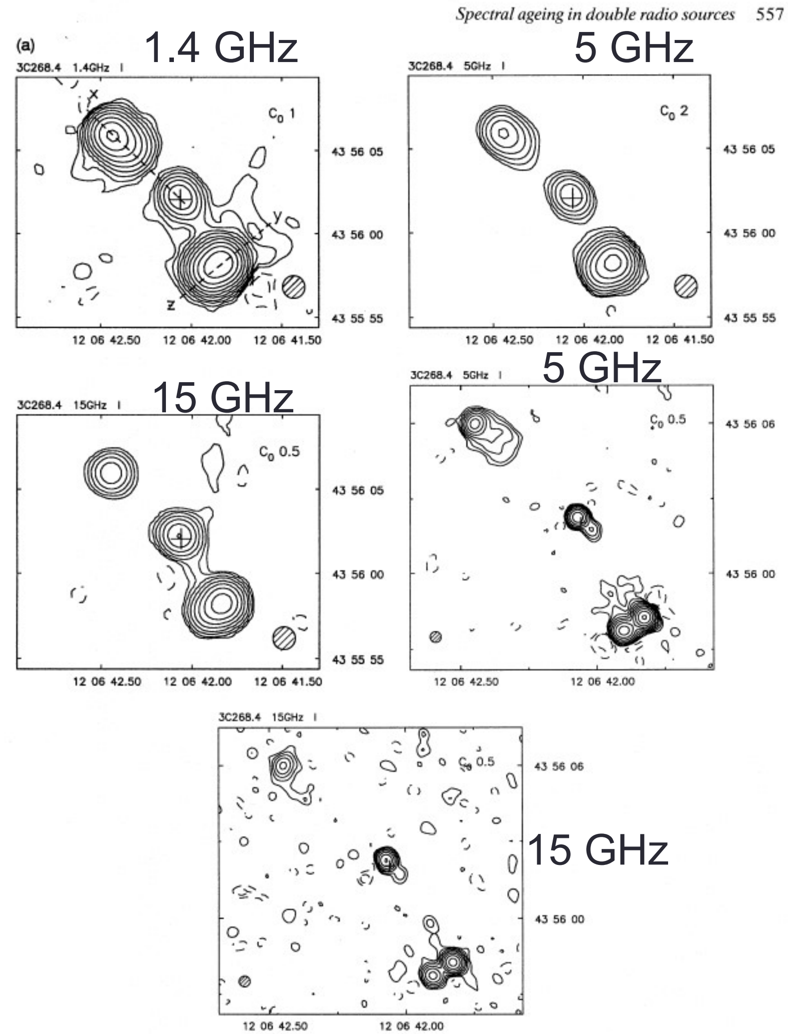
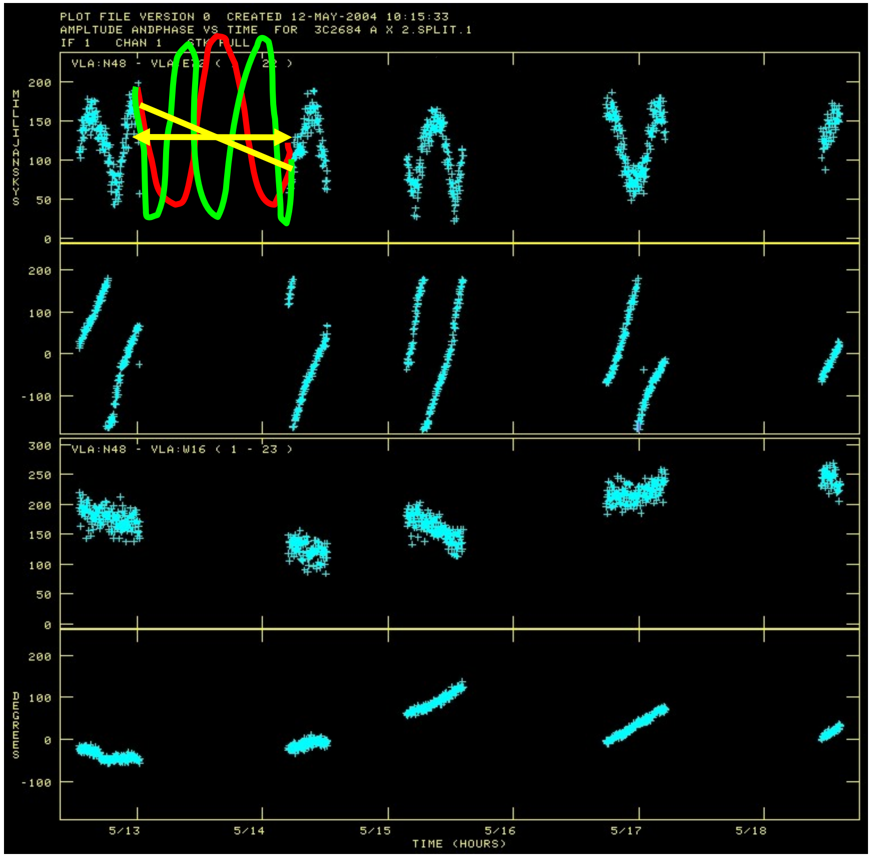


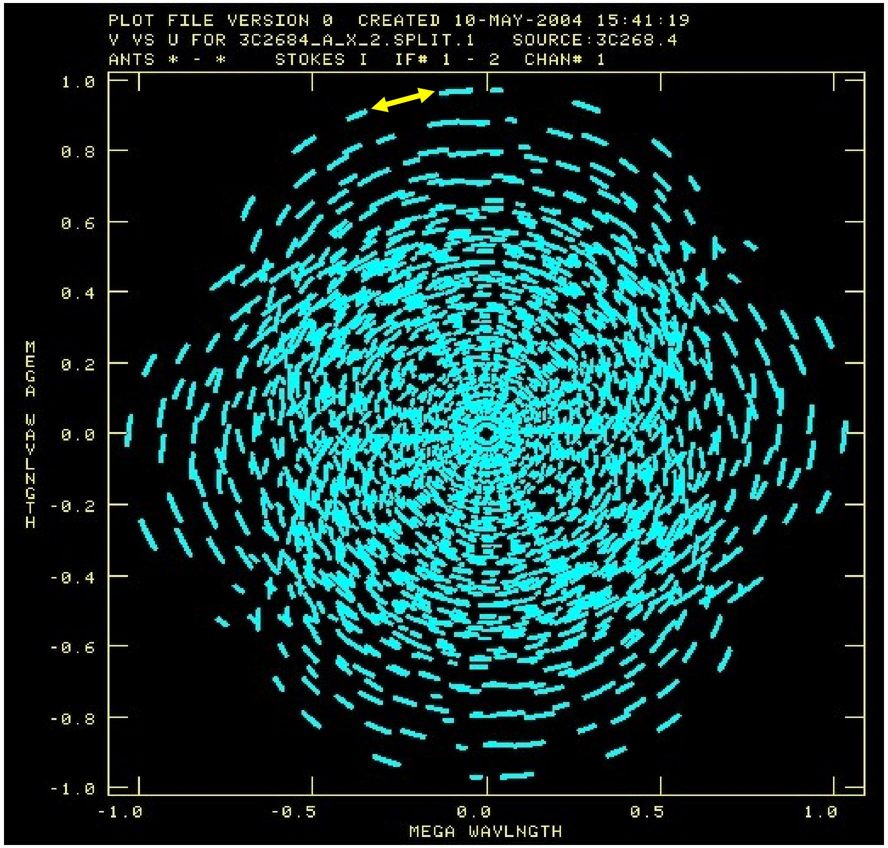
Figure 10. (a) Total intensity maps and (b) strip profiles of total intensity at 1.4 GHz, spectral index and age along the lobe axes indicated by the letters in (a), for 3C268.4. See the caption to Fig. 4 for further details.

Some caveats about radio imaging

- Like optical images, the size of the synthesised aperture (lens, mirror) limits the resolution
- In addition, images are made using an *incompletely filled lens* $\Rightarrow$ some of the information is missing
- The imaging process interpolates or extrapolates to fill in this missing information
- Amounts to fabricating data in absence of measurements!
- Implications
    - Images are consistent with data but not unique
    - Imaging process also might lead to some artifacts in the image (recognisable)

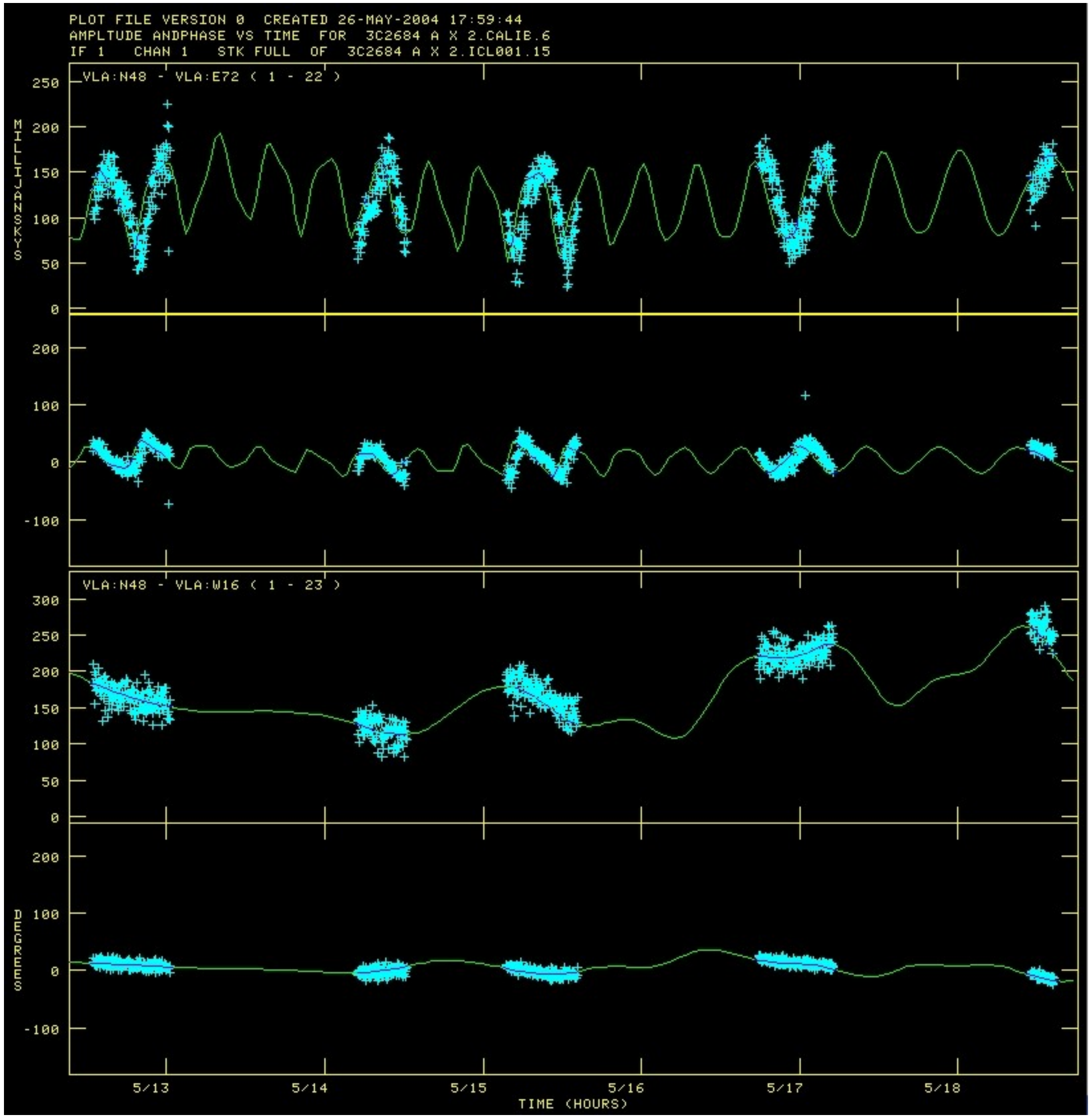
Caveats contd.



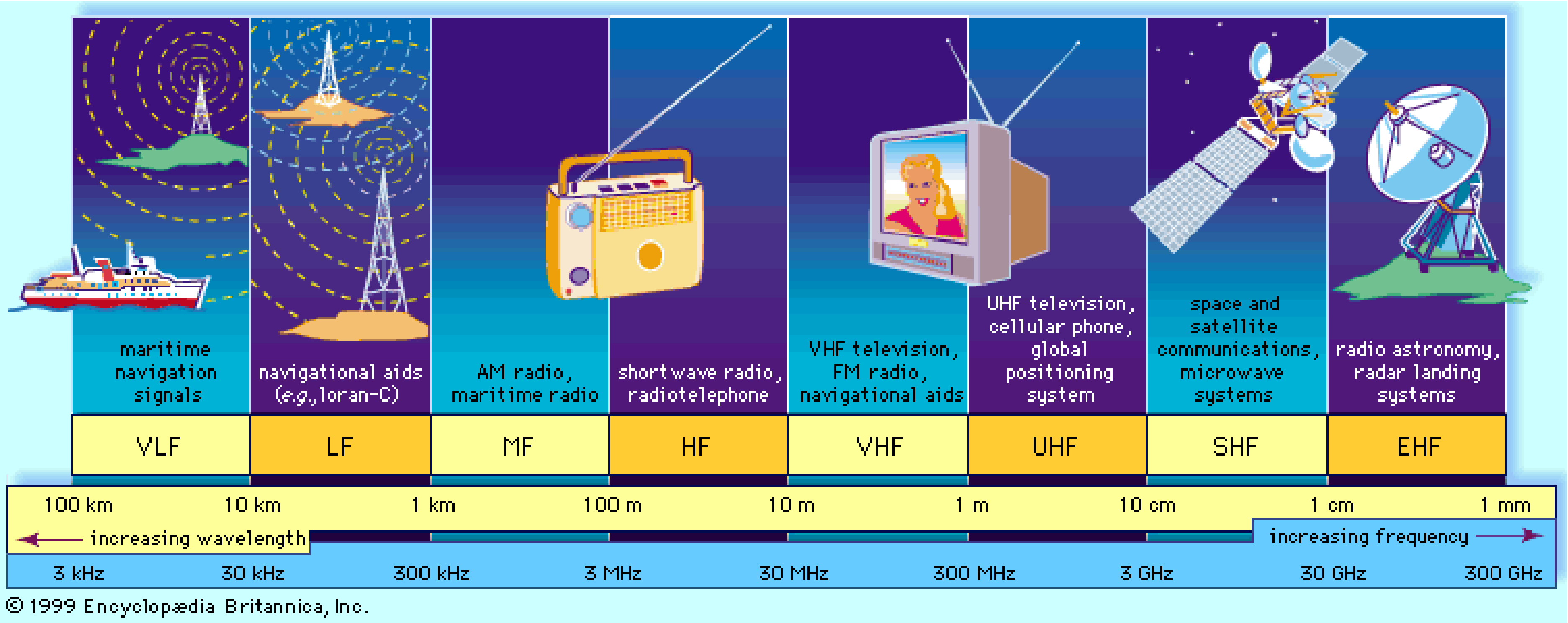


The CLEAN model

Actually, clean + self calibration model



Radio analog of dark-sky problem



Human presence = radio pollution

Cell phones, chord less phones, garage door openers, keyless entry systems, computers, florescent lights, petrol vehicles, mircowave ovens, bluetooth devices, air-traffic-control/police and other wireless coms, satellites, …

The World: Population Density, 2000