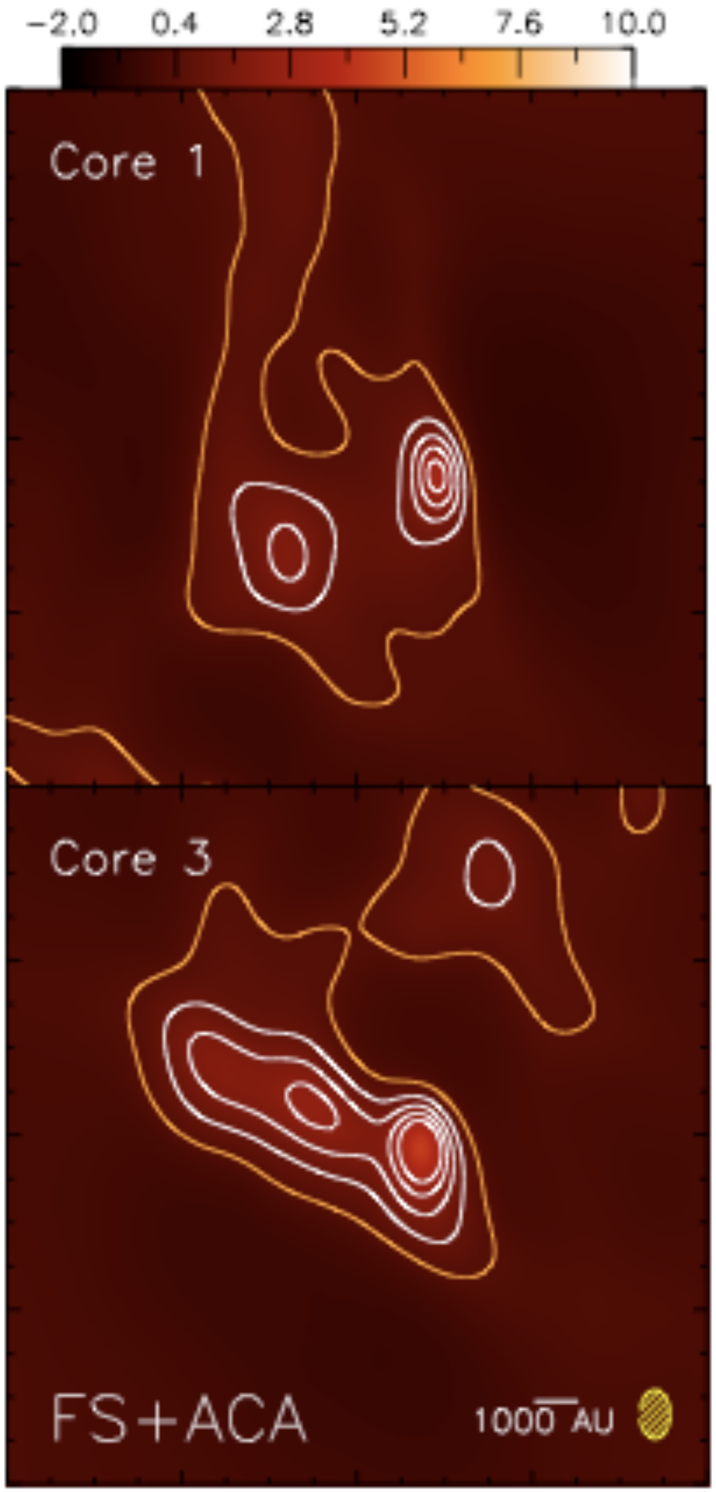


Offner ea 2012

Performing Synthetic Interferometric Observations with CASA

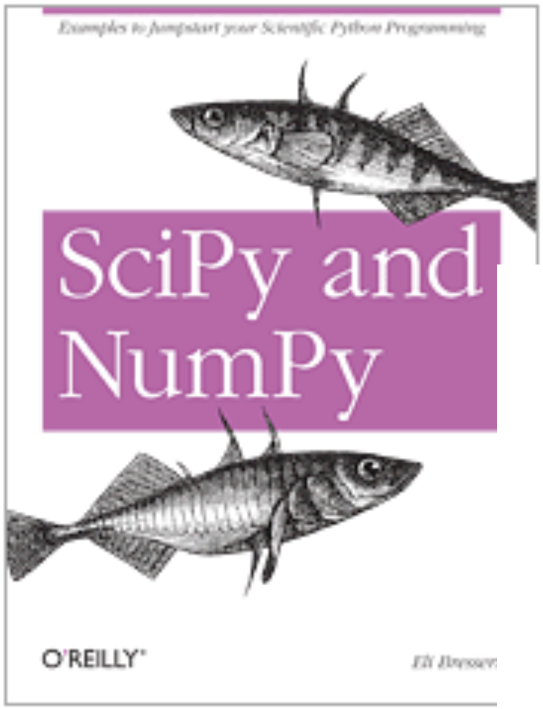
Stella Offner
UC-HiPACC

Aug. 7 2013

CASA
Common Astronomy Software Applications

Python Aside

Browse Contents



Google Preview

Larger Cov

SciPy and NumPy

Examples to Jumpstart your Scientific Python Programming

By Eli Bressert

Publisher: O'Reilly Media
Released: November 2012
Pages: 82

Eli Bressert

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Areas of Expertise:

- Python
- data visualization
- scientific programming
- consulting
- speaking
- programming
- training

Outline

- Why model interferometry?
- Interferometry for Theorists
- CASA
- Project

Outline

- Why model interferometry?
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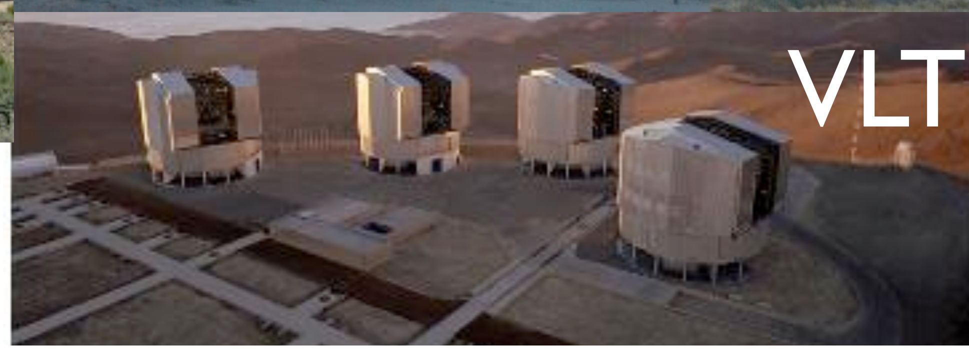
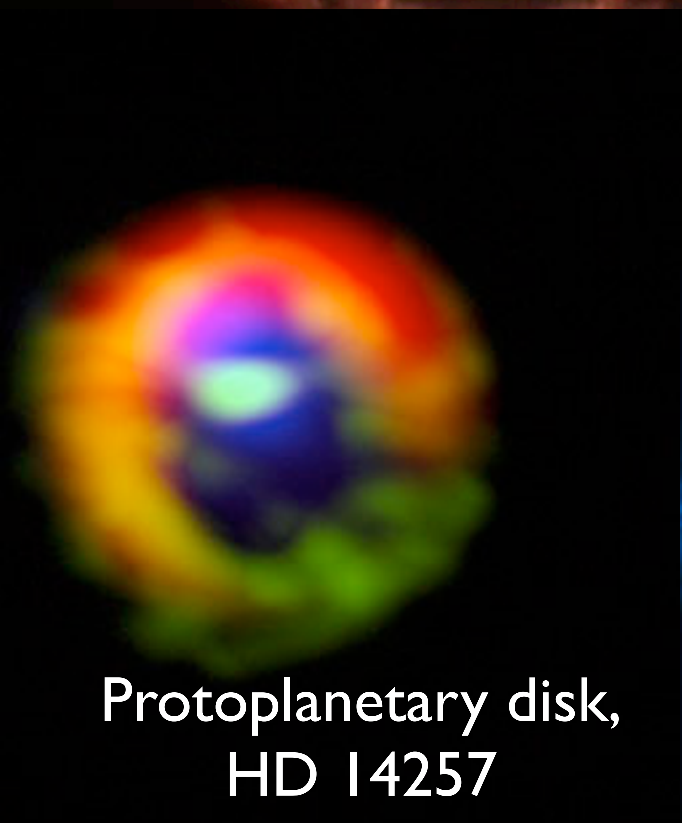
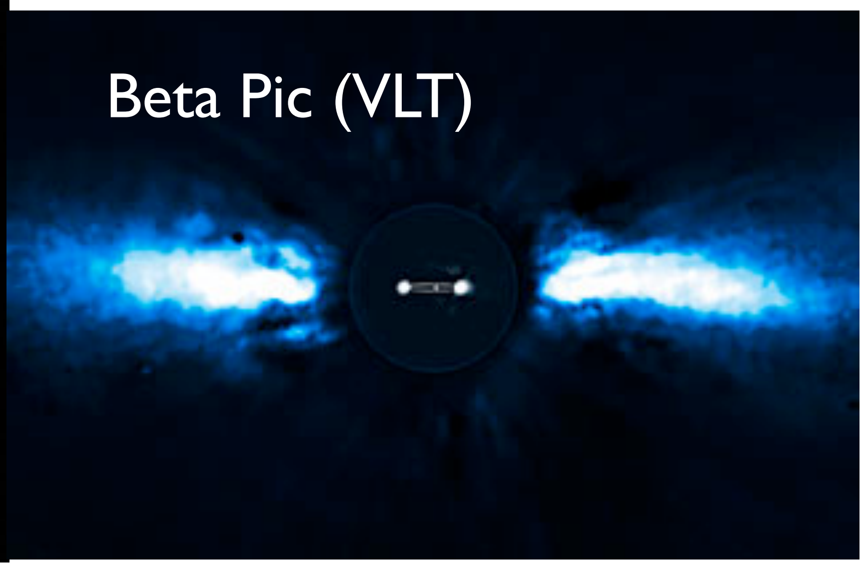
Why model interferometry?



Why model interferometry?

This not that:





Why model interferometry?

- Shell+spiral structure around red giant star
- Created by an unseen companion?

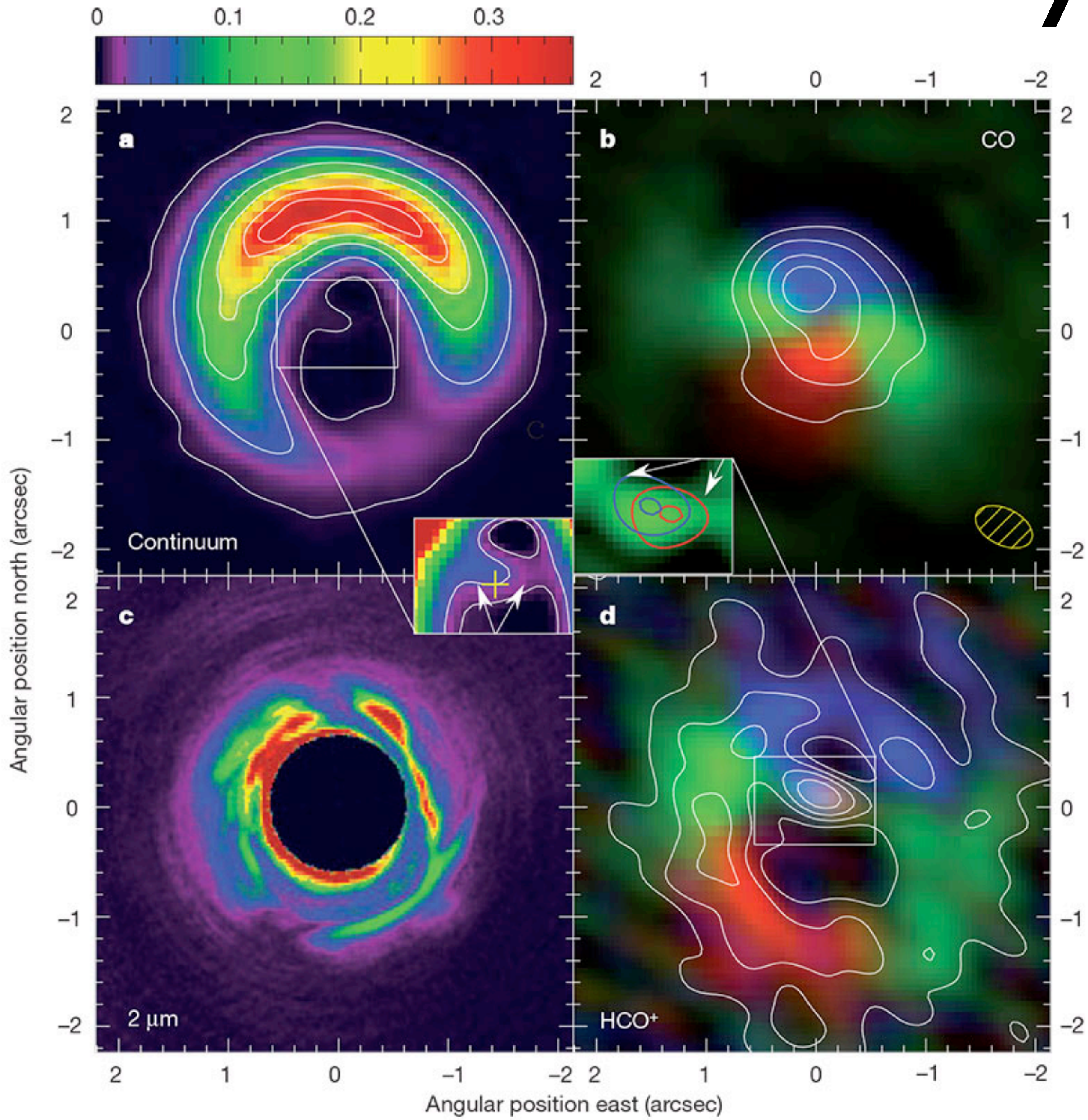
Scan through velocity channels

R Sculptoris
2012

ALMA (ESO/NAOJ/NRAO)/M. Maercker et al./L. Calçada (ESO)

Why model interferometry?

- Protoplanetary disk with gap between 10-140 AU
- Result of a planet orbiting at 90AU?



HD 142527

Casassus et al. 2013, Nature

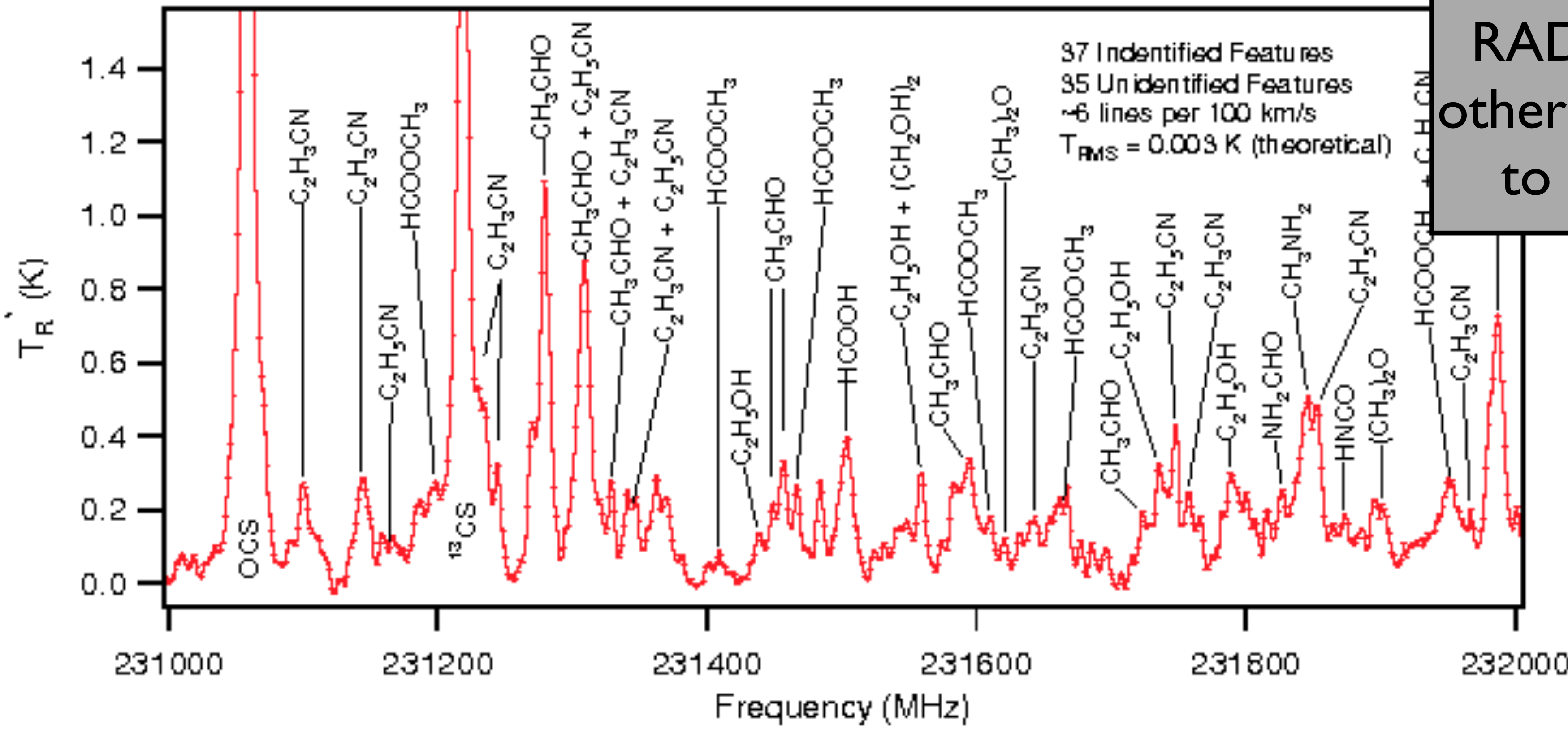
ALMA Early Science: 345 GHz, CO (3-2), HCO+ (4-3)

Why model interferometry?

Found 24796 lines in ALMA Band 3 (84-116 GHz), showing 1 - 500 Next >
Click on the chemical formula below for more information about that species.

	Species	Chemical Name	Ordered Freq (GHz) (rest frame, redshifted)	Resolved QNs	CD Int
1	CH_2CHCN $v_{11}=1$	Vinyl Cyanide	84.00110, 84.00110	16(1,15)-16(0,16)	-5.
2	HCCCHO	2-Propynal	84.00149, 84.00149	9(5, 5)- 8(5, 4)	0.0
3	HCCCHO	2-Propynal	84.00149, 84.00149	9(5, 4)- 8(5, 3)	0.0
4	CH_3OCHO v=0	Methyl Formate	84.00162, 84.00162	25(8,17)-24(9,16) A	-6.
5	$(CH_3)_2CO$ v=0	Acetone	84.00289, 84.00289	36(24,12)-36(23,13) AA	-6.
6	CH_3C_5N	Methylcyanodiacetylene	84.00567, 84.00567	54(6)-53(6), F=54-53	-3.
7	CH_3C_5N	Methylcyanodiacetylene	84.00567, 84.00567	54(6)-53(6), F=53-52	-3.
8	CH_3C_5N	Methylcyanodiacetylene	84.00567, 84.00567	54(6)-53(6), F=55-54	-3.
9	CH_3C_6H	Methyltriacetylene	84.00575, 84.00575	54(9)-53(9)	-4.
10	$(CH_3)_2CO$ v=0	Acetone	84.00852, 84.00852	21(12,10)-21(11,11) EA	-6.
11	c-HCCCD	Cyclopropenylidene	84.00986, 84.00986	23(14,10)-22(17, 5)	-7.
12	$(CH_3)_2CO$ v=0	Acetone	84.01081, 84.01081	21(12,10)-21(11,11) AE	-6.
13	CH_3C_5N	Methylcyanodiacetylene	84.01090, 84.01090	54(5)-53(5), F=54-53	-3.
14	CH_3C_5N	Methylcyanodiacetylene	84.01090, 84.01090	54(5)-53(5), F=53-52	-3.
15	CH_3C_5N	Methylcyanodiacetylene	84.01090, 84.01090	54(5)-53(5), F=55-54	-3.
16	CH_3C_6H	Methyltriacetylene	84.01390, 84.01390	54(8)-53(8)	-4.
17	CH_3C_5N	Methylcyanodiacetylene	84.01518, 84.01518	54(4)-53(4), F=54-53	-3.
18	CH_3C_5N	Methylcyanodiacetylene	84.01518, 84.01518	54(4)-53(4), F=53-52	-3.
19	CH_3C_5N	Methylcyanodiacetylene	84.01518, 84.01518	54(4)-53(4), F=55-54	-3.
20	g-CH_3CH_2OH	gauche-Ethanol	84.01692, 84.01692	77(8,69)-77(9,69), v_t= 1- 0	-8.
21	CH_3C_5N	Methylcyanodiacetylene	84.01850, 84.01850	54(3)-53(3), F=54-53	-3.

ALMA Spectrum



Also need RADMC or other RT code to model

- Dense cloud core SgrB2(N) (Apponi, Ziurys et al.)
- Band 6 at 232 GHz

Outline

- Why model interferometry?
- Interferometry for Theorists
- CASA
- Project

Interferometry for ~~Dummies~~ Theorists

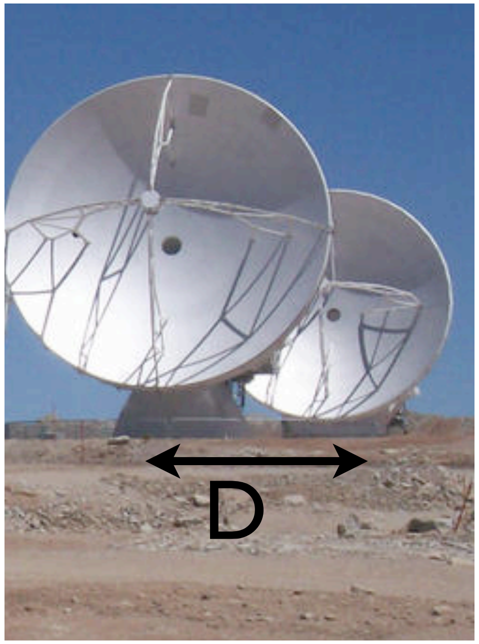
Caveat:
I am not an expert in "real" interferometric observations

Help with this lecture was provided by Scott Schnee, Todd Hunter and Dave Wilner

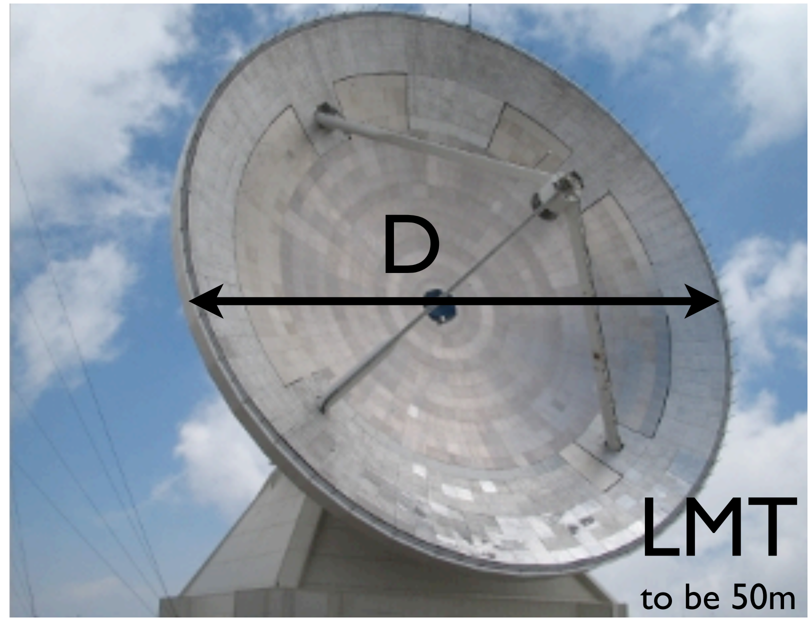
In a nutshell:

The sum of images from many little antennas is almost but not quite equal to an image from one giant antenna

Single vs. Multiple



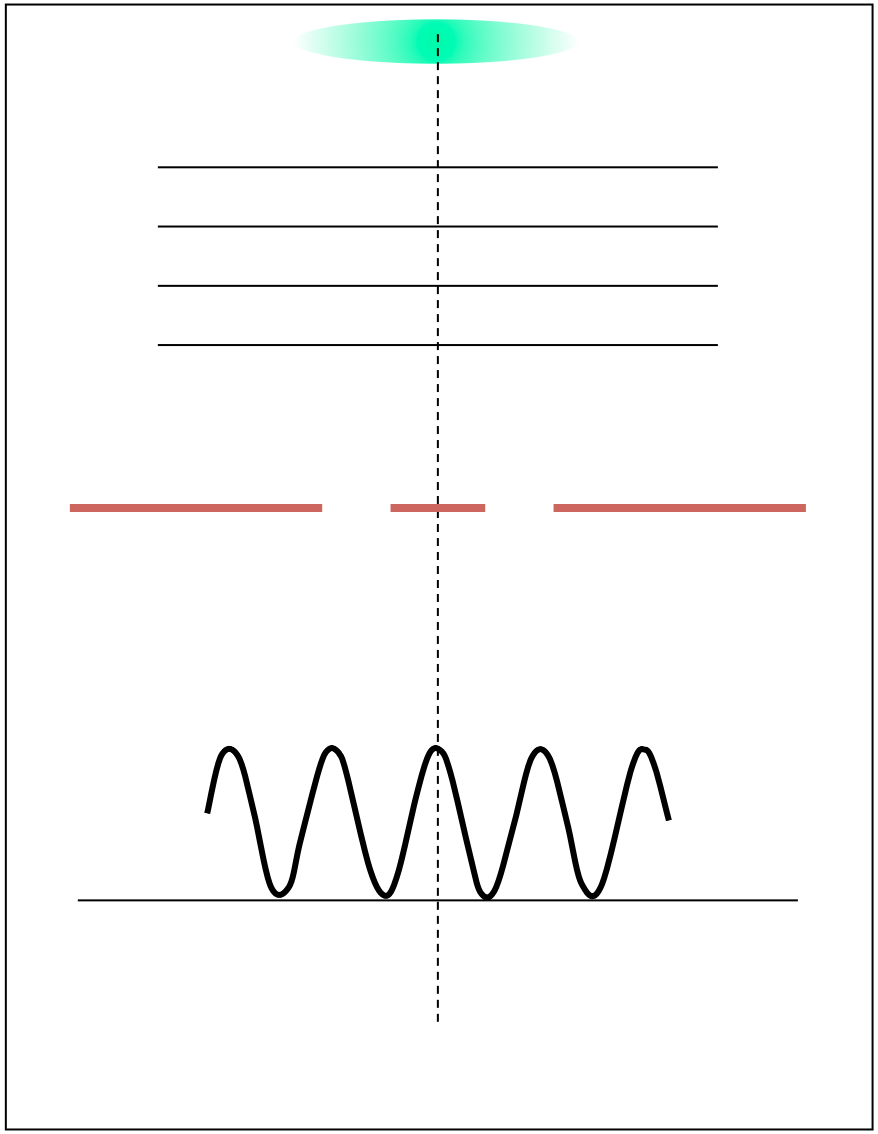
vs.

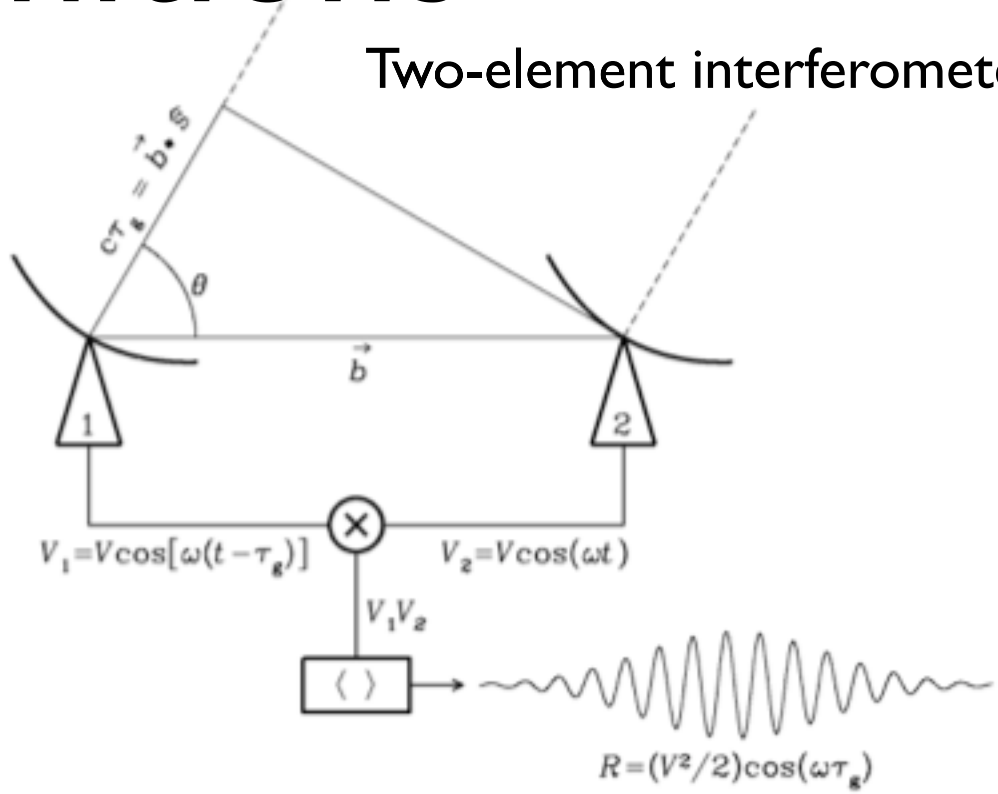


- Resolution of two antennas separated by a distance D is comparable to a single antenna with diameter D
- The angular resolution of the antennas is $\sim \lambda/D$
- Resolution is limited by possible physical separations

Definitions

Two-element interferometer



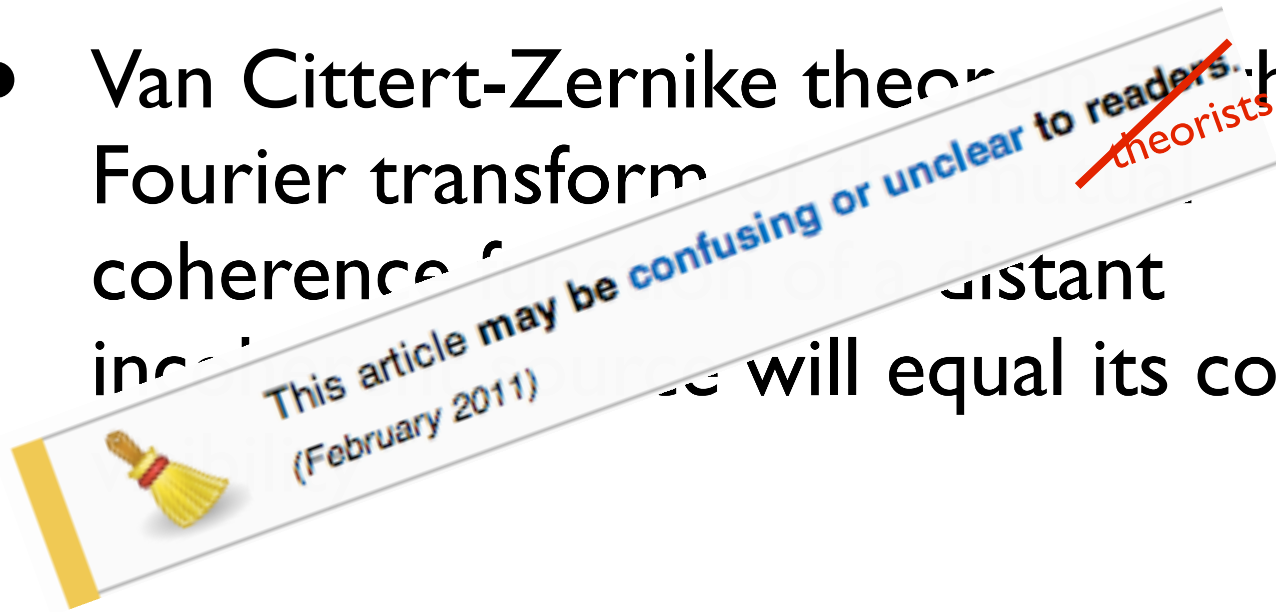


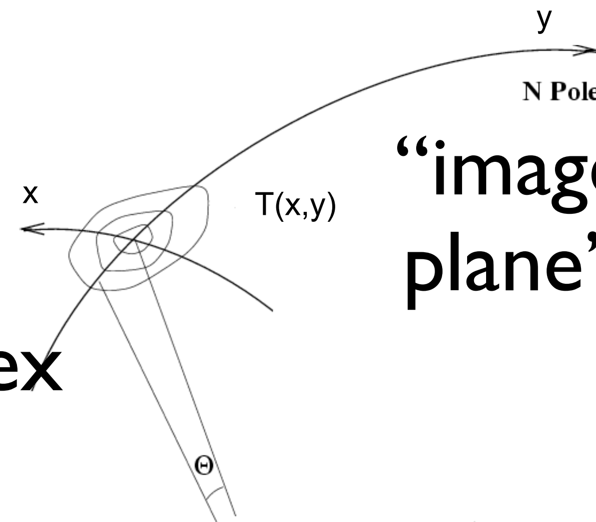
$$|V| = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{Fringe\ Amplitude}{Average\ Intensity}$$

The visibility is a complex quantity:
- amplitude tells "how much" of a certain frequency component
- phase tells "where" this component is located

Definitions

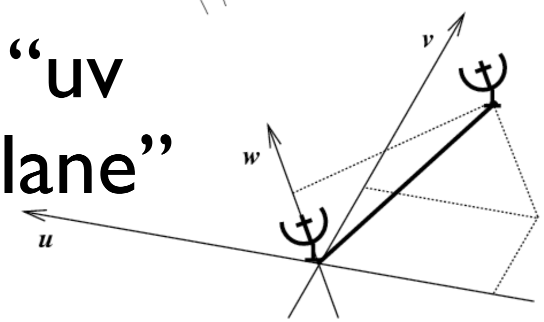
- Brightness on the sky, T(x,y) = actual "real" brightness
- Complex visibility, V(u,v) = the inverse 2D Fourier transform of T(x,y), quantifies interference
- Van Cittert-Zernike theor[...]he Fourier transform[...] coherence [...]distant in[...] will equal its complex





"image plane"

"uv plane"

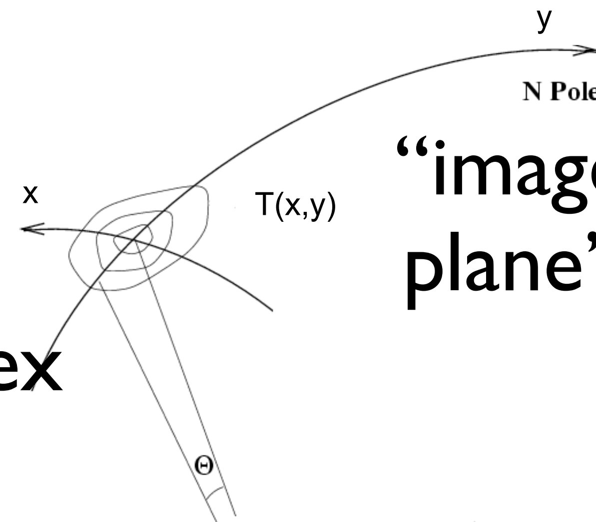


$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$$

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

Definitions

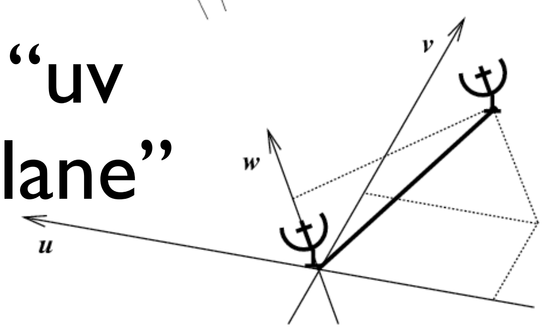
- Brightness on the sky, T(x,y) = actual "real" brightness
- Complex visibility, V(u,v) = the 2D Fourier transform of T(x,y), quantifies interference
- Van Cittert-Zernike theorem = the Fourier transform of the mutual coherence function of a distant incoherent source will equal its complex visibility



"image plane"

By measuring the degree of coherence at different points (visibility function), observers can reconstruct the source's brightness distribution/a 2D map of the source

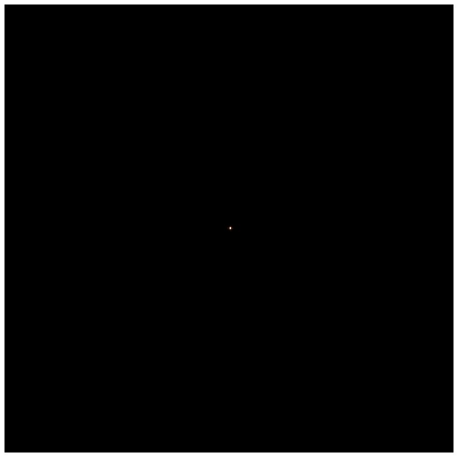
"uv plane"



2D Fourier Transform Pairs

T(x,y) | |V(u,v)|

δ Function



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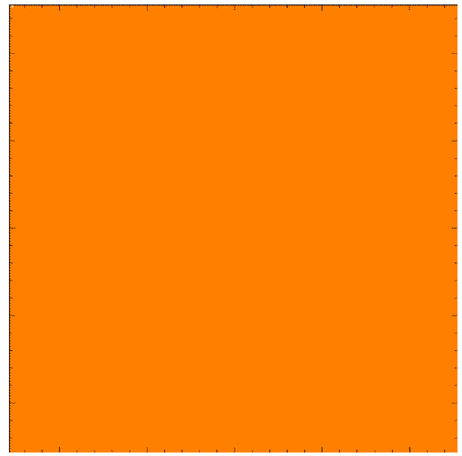
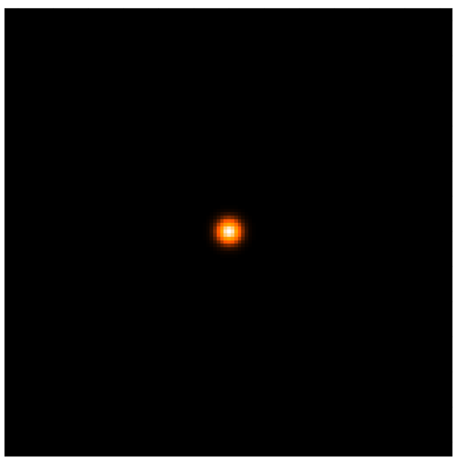


Constant

Gaussian



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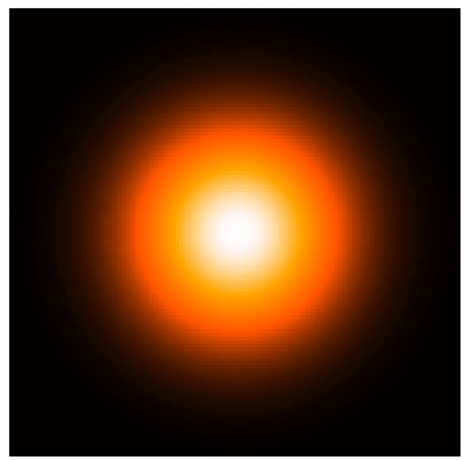
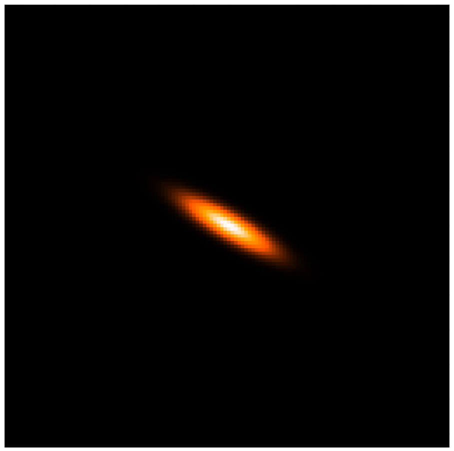


Gaussian

2D Fourier Transform Pairs

T(x,y) | |V(u,v)|

elliptical Gaussian

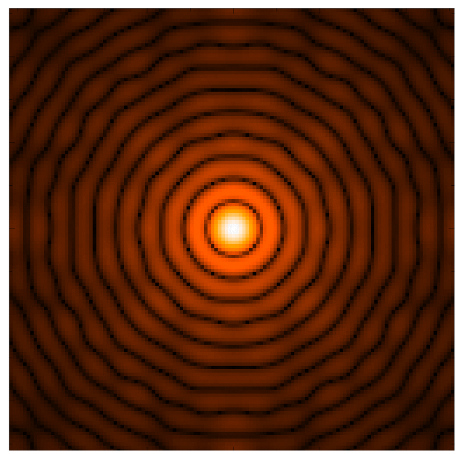


↔

elliptical Gaussian

Disk

↔



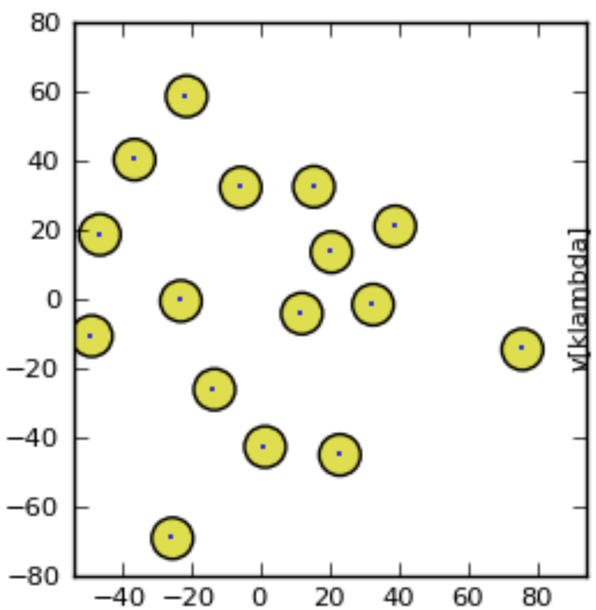
Bessel

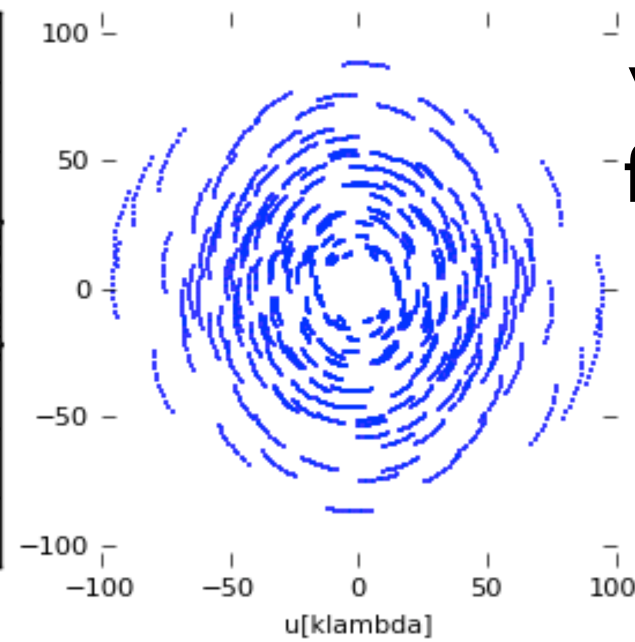
sharp edges result in many high spatial frequencies

Aperture Synthesis

(combining signals from a set of antennas to produce images with the same angular resolution as an antenna the size of the whole set)

- V(u,v) measured at discrete points
- Need good uv coverage to get a good image (many antennas, many different baselines, use earth's rotation)





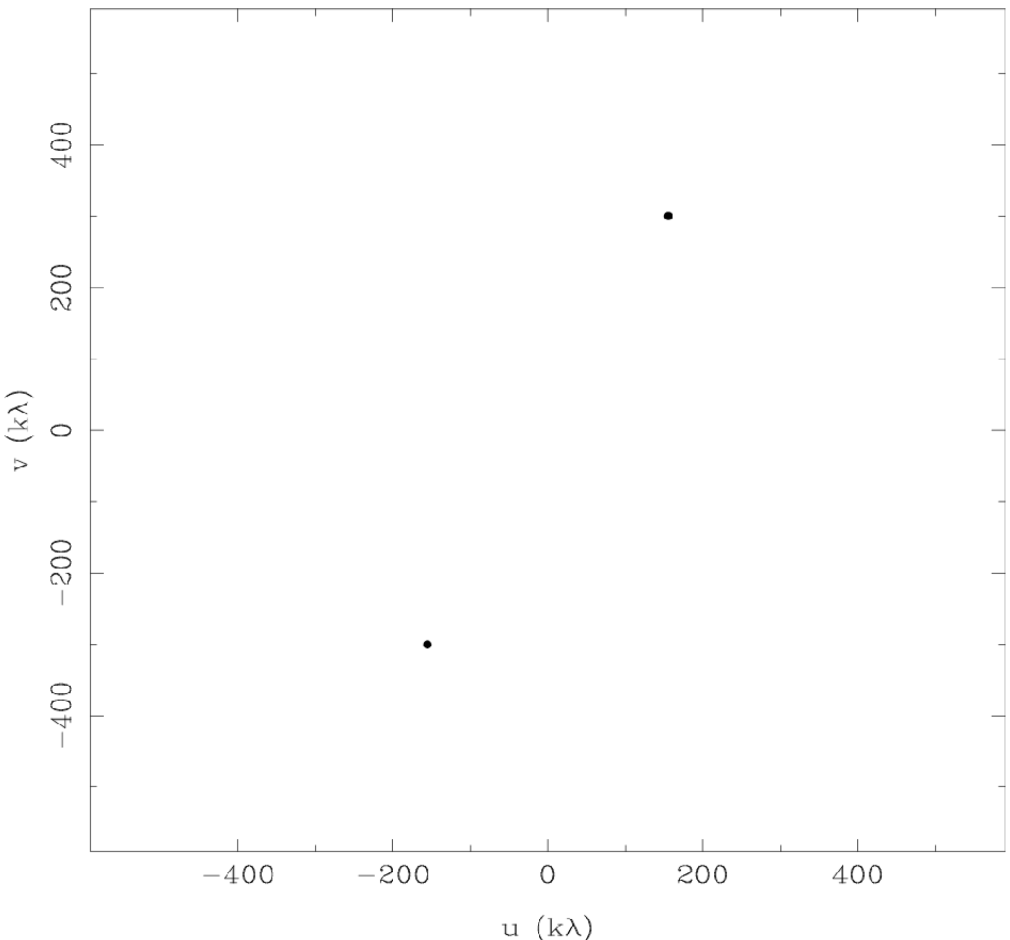
visibility function

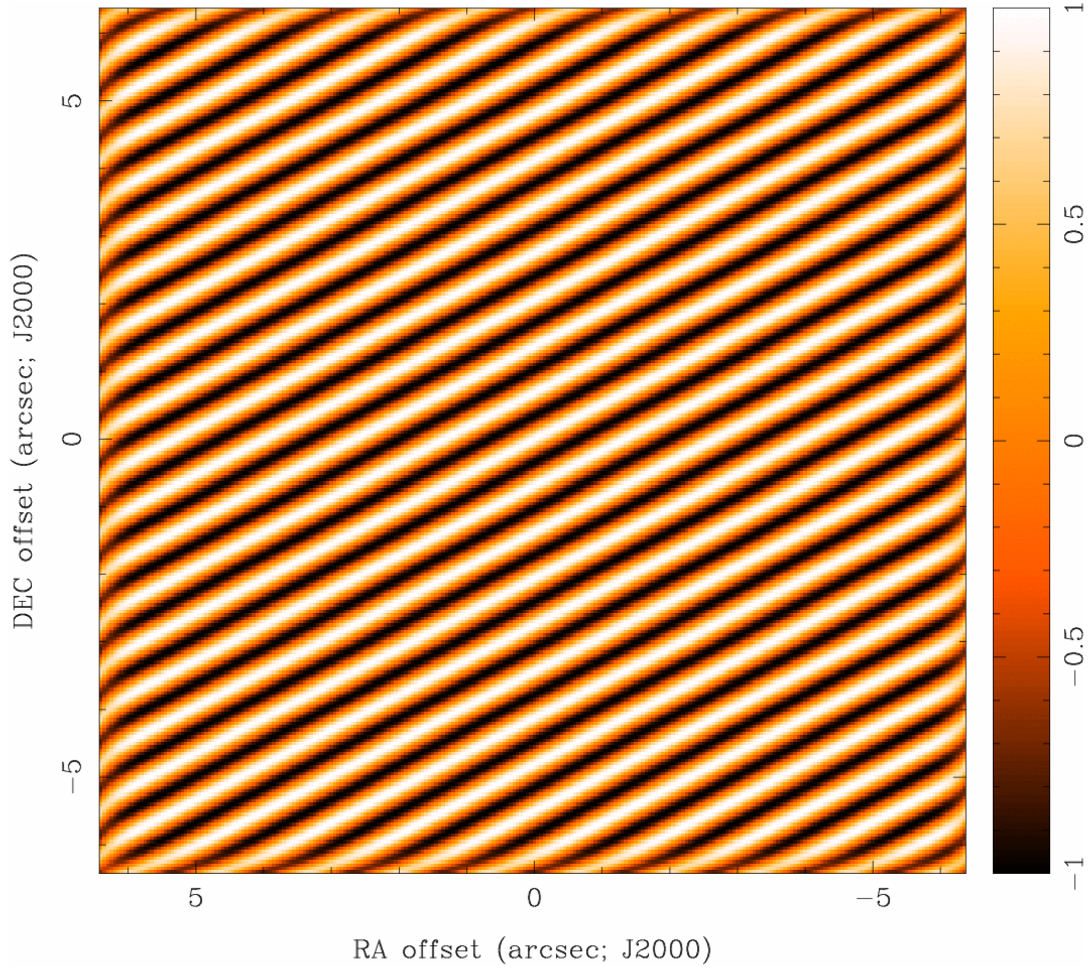
"Dirty Beam Shape" = Point Spread Function

When taking Fourier transform it is convolved everywhere with the PSF; it must be deconvolved or "cleaned" to remove beam artifacts

2 Antennas

(Image sequence taken from Summer School lecture by D. Wilner)





NRAO

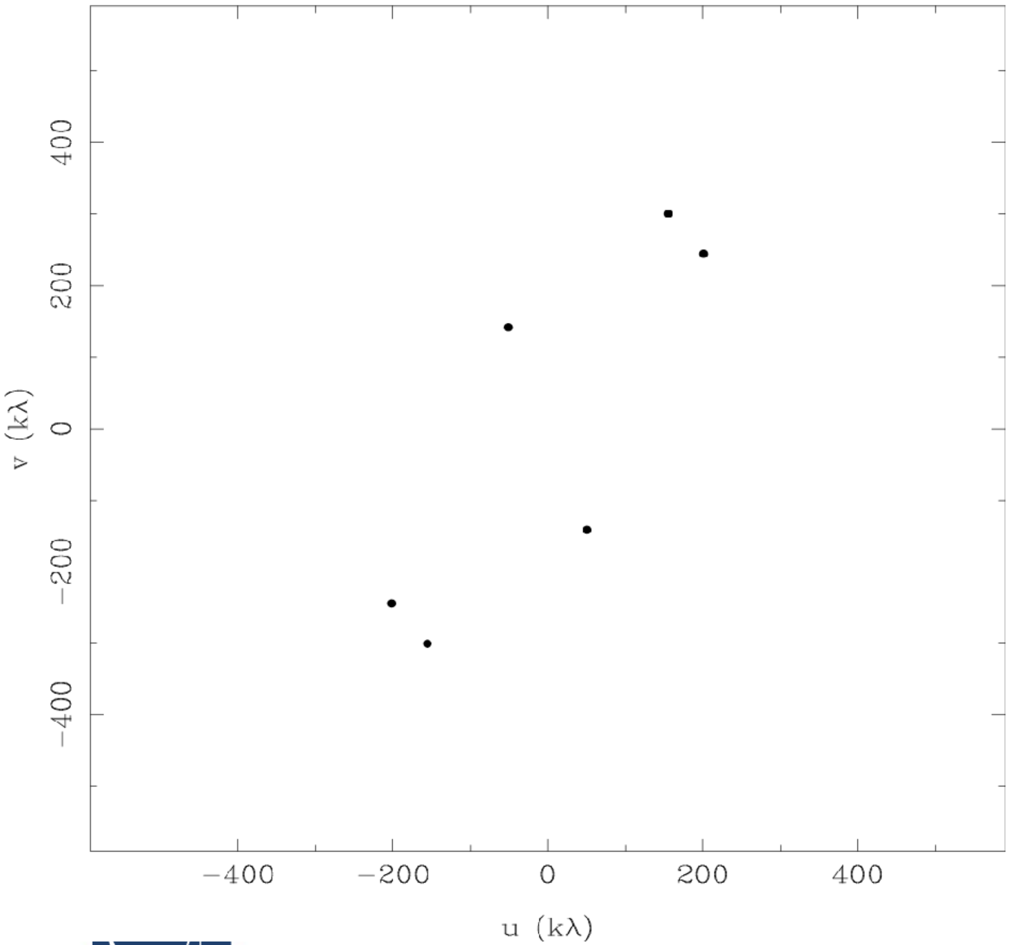
Visibility Function

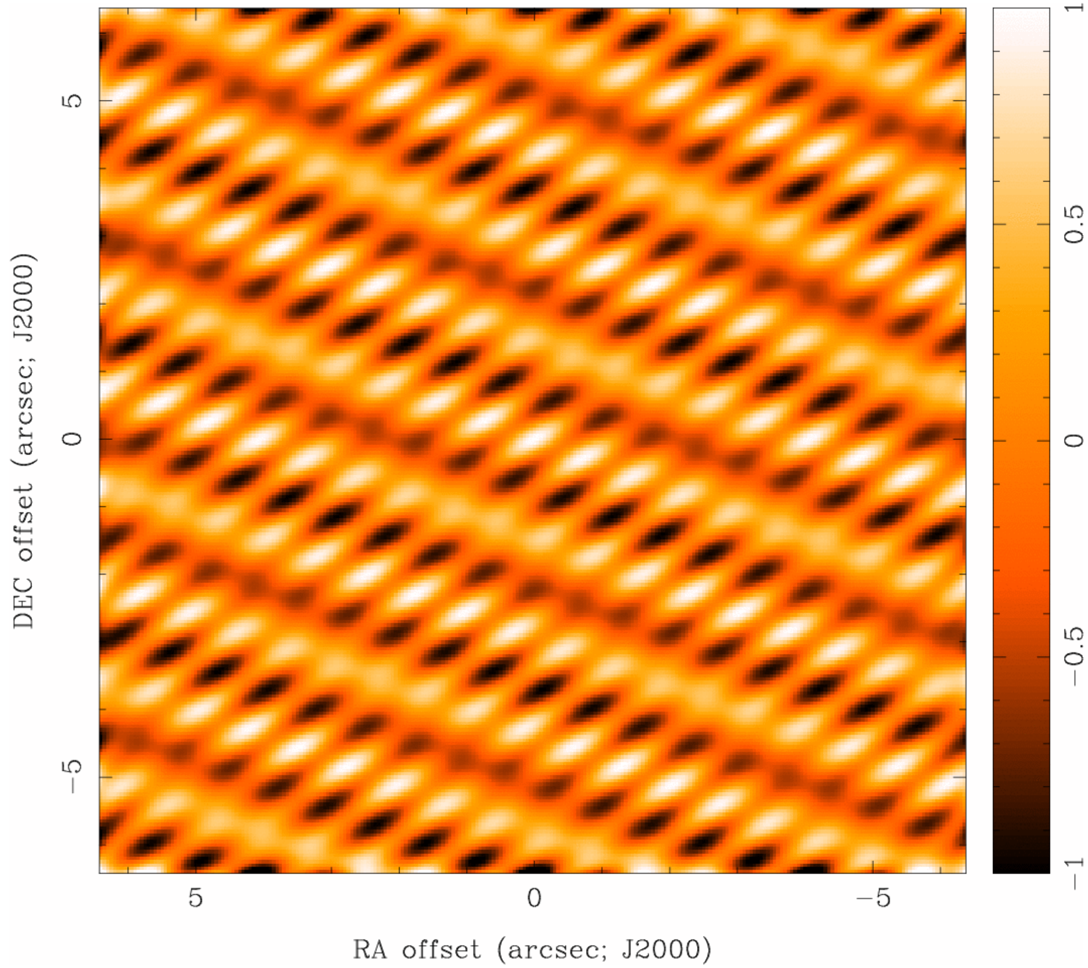
Synthetic Beam

"Dirty Beam Shape" = Point Spread Function

ALMA

3 Antennas

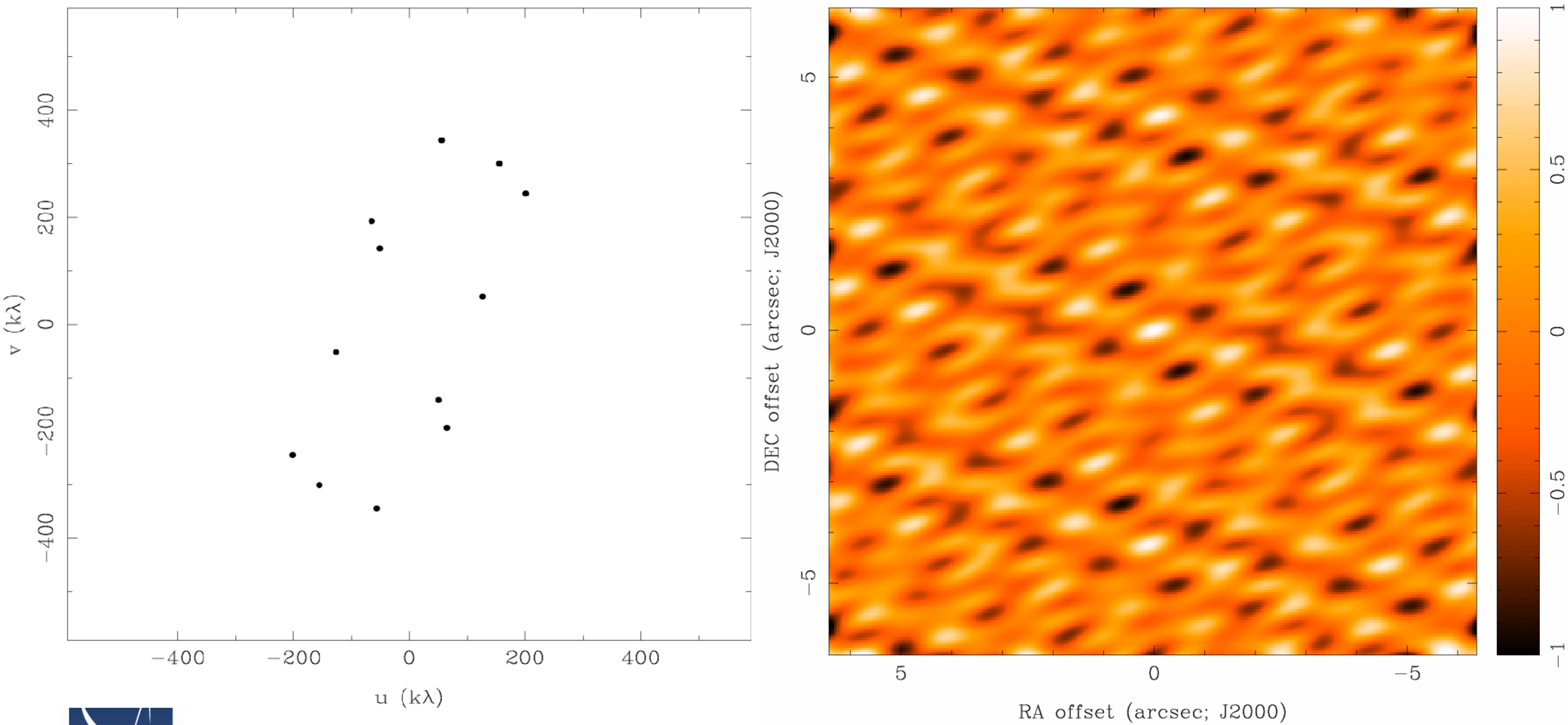




NRAO

“Dirty Beam Shape” = Point Spread Function

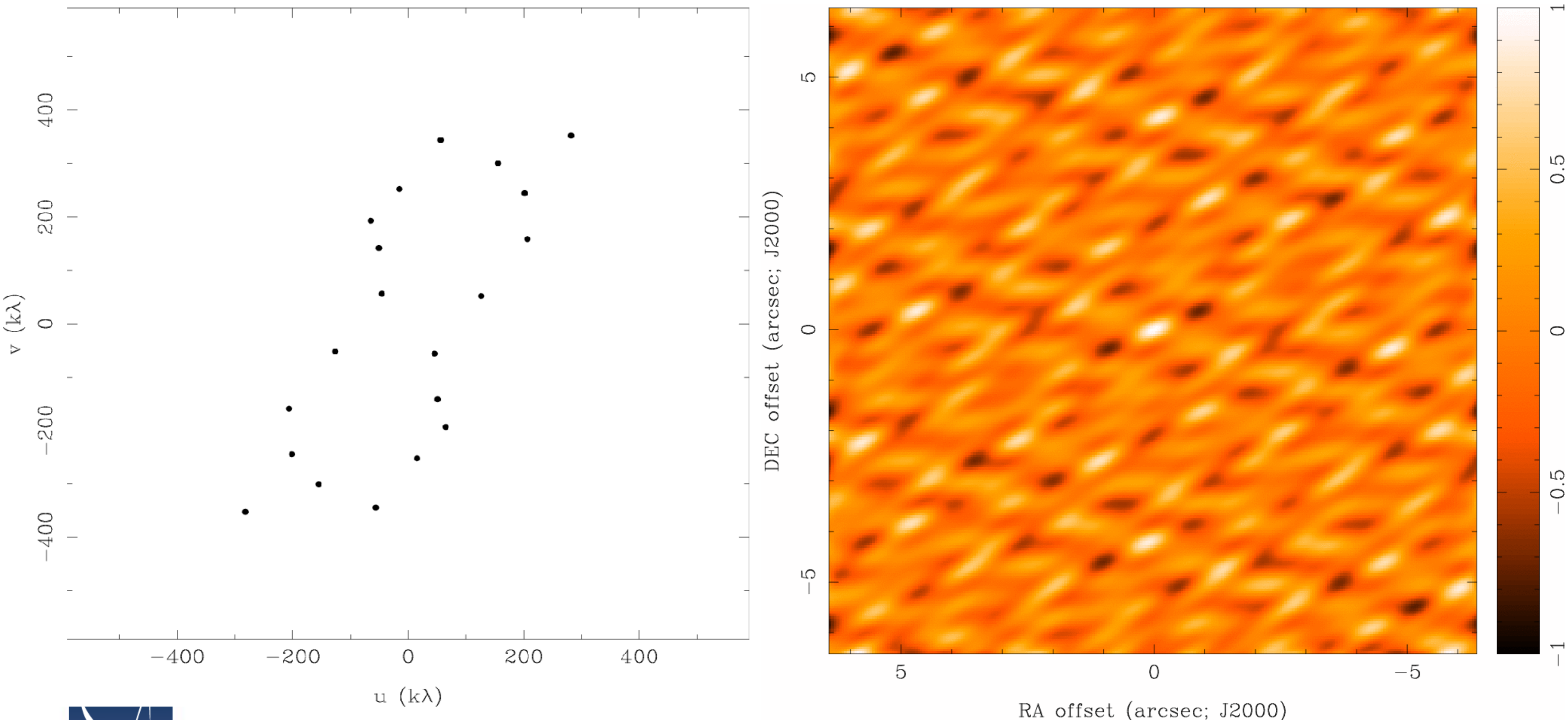
4 Antennas



“Dirty Beam Shape” = Point Spread Function

ALMA

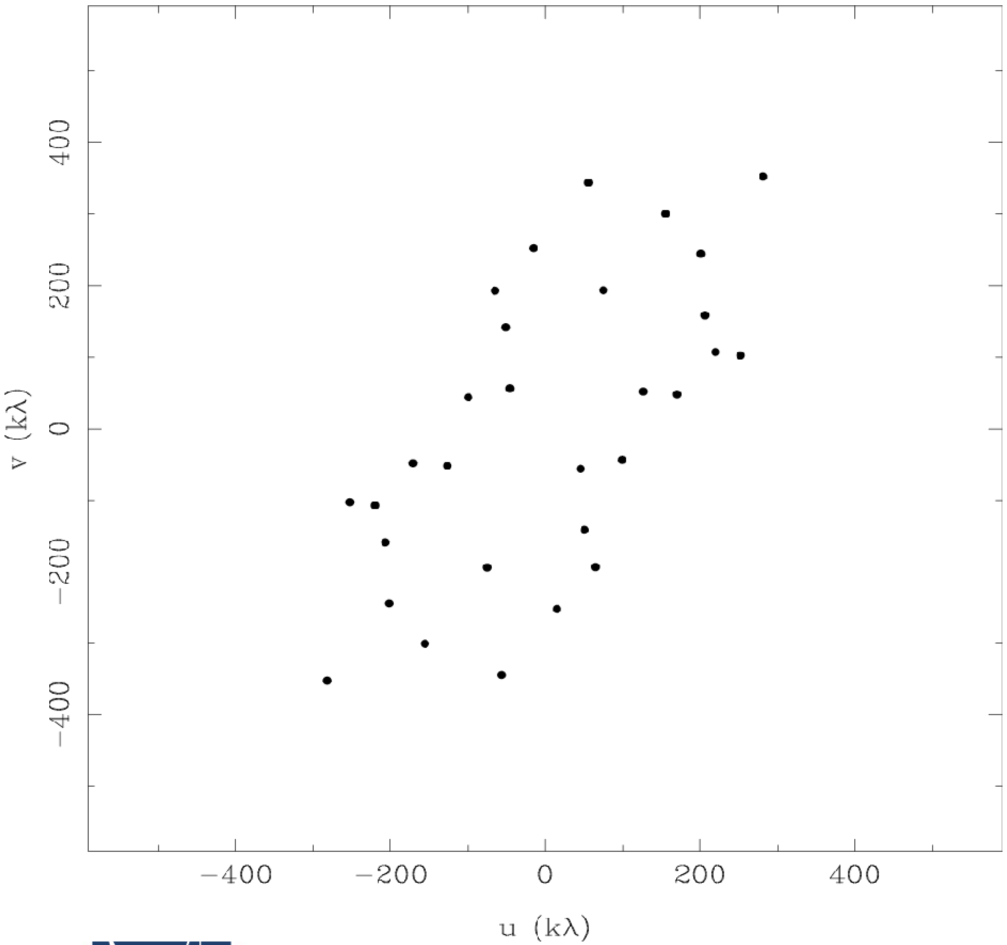
5 Antennas

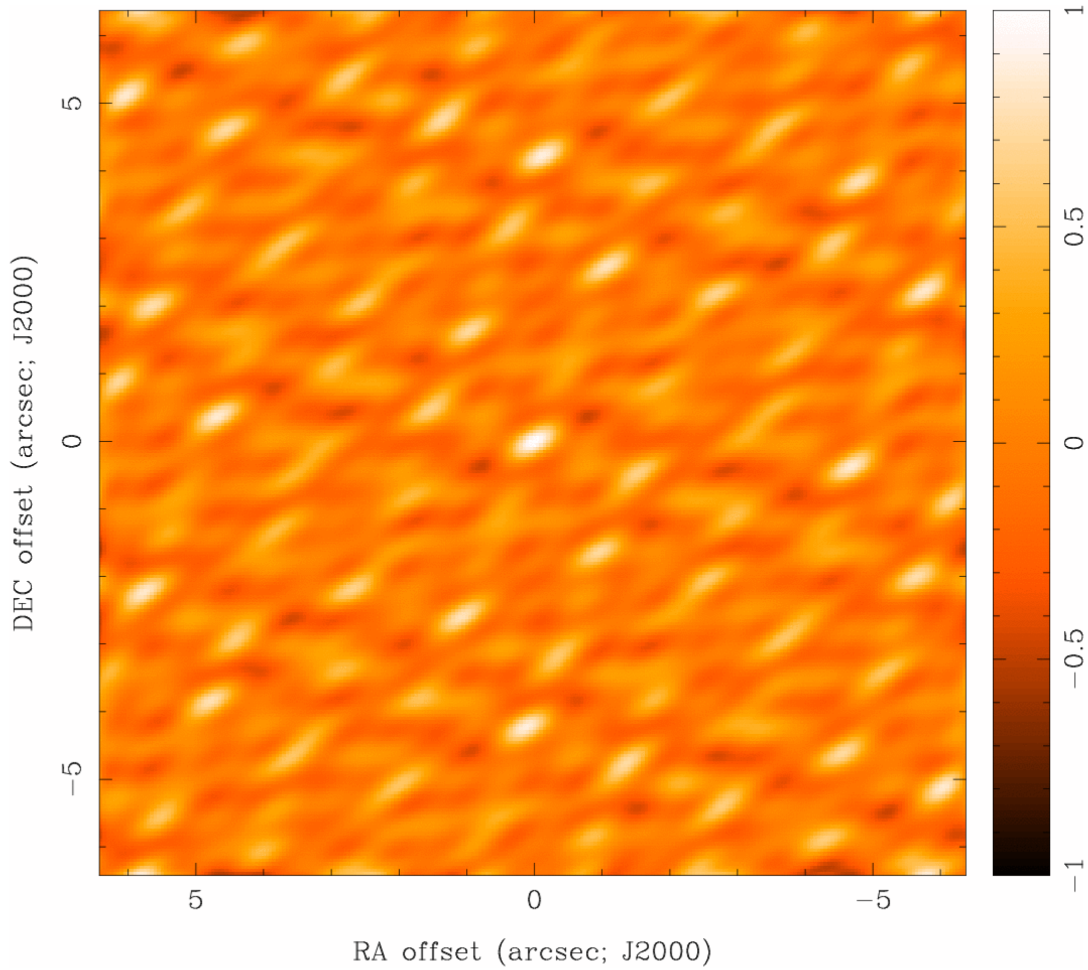


NRAO

“Dirty Beam Shape” = Point Spread Function

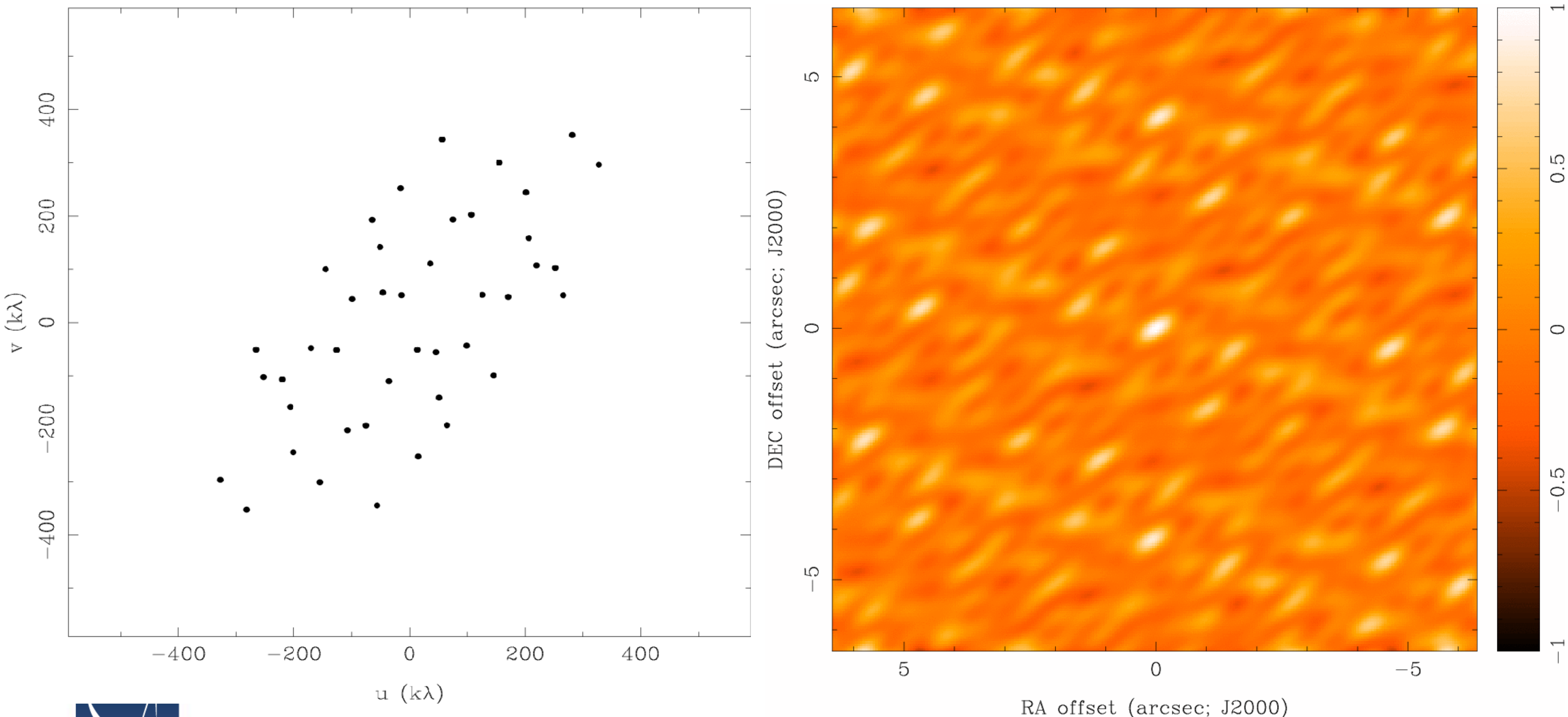
6 Antennas





“Dirty Beam Shape” = Point Spread Function

7 Antennas

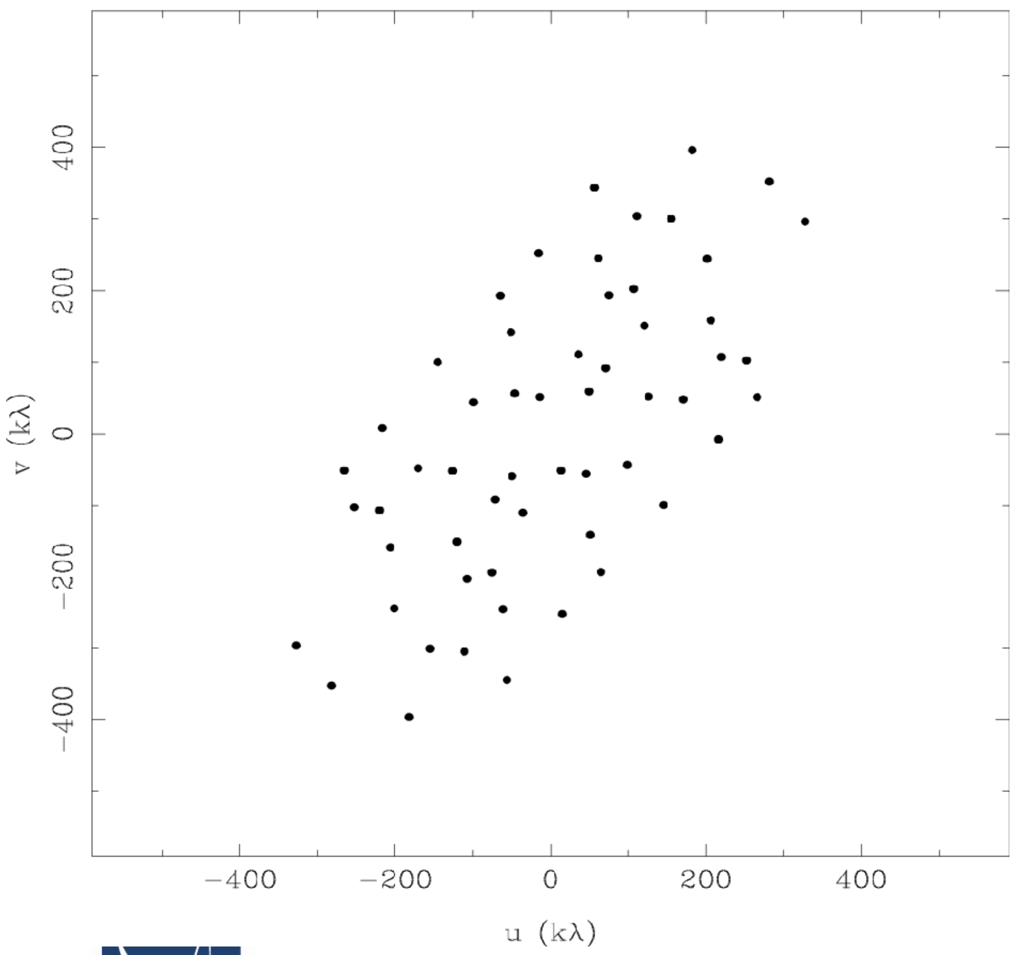


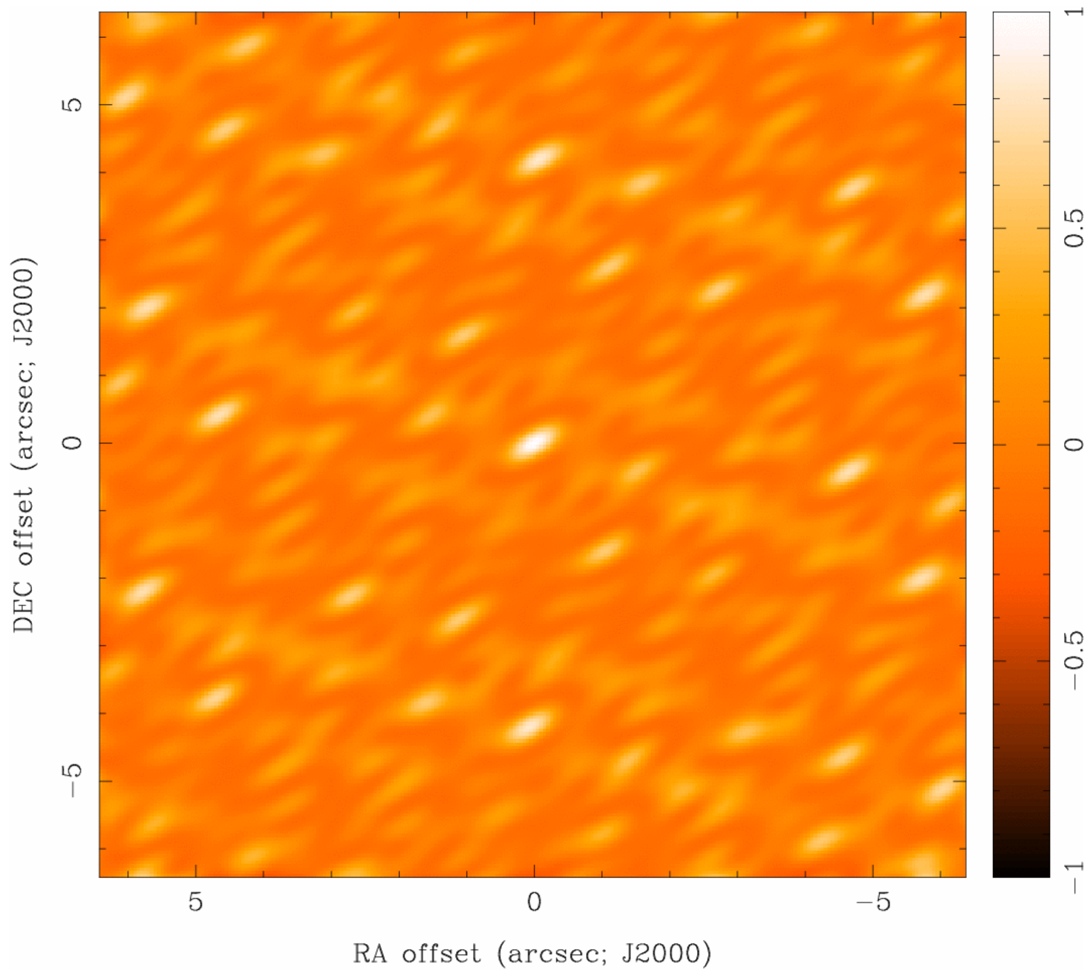
Wednesday, August 7, 13

“Dirty Beam Shape” = Point Spread Function

ALMA

8 Antennas



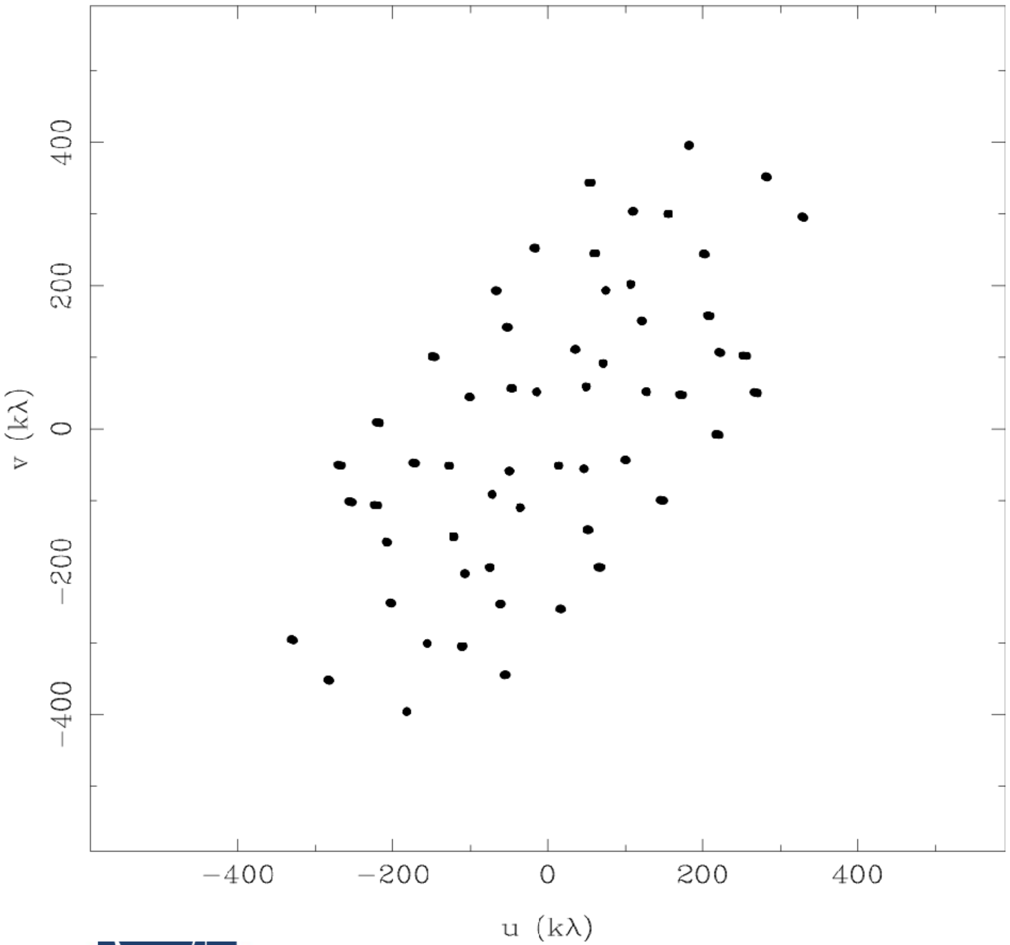


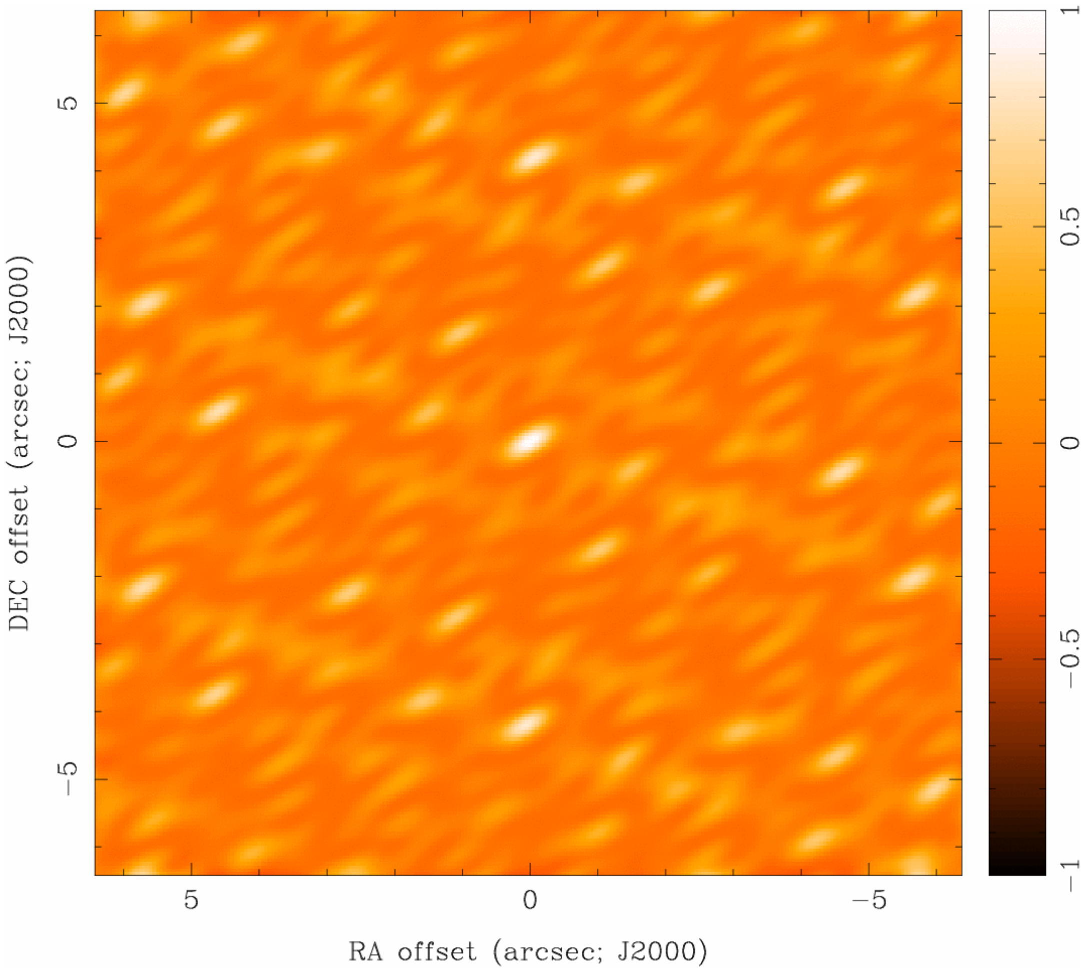
NRAO

“Dirty Beam Shape” = Point Spread Function

ALMA

8 Antennas x 6 Samples



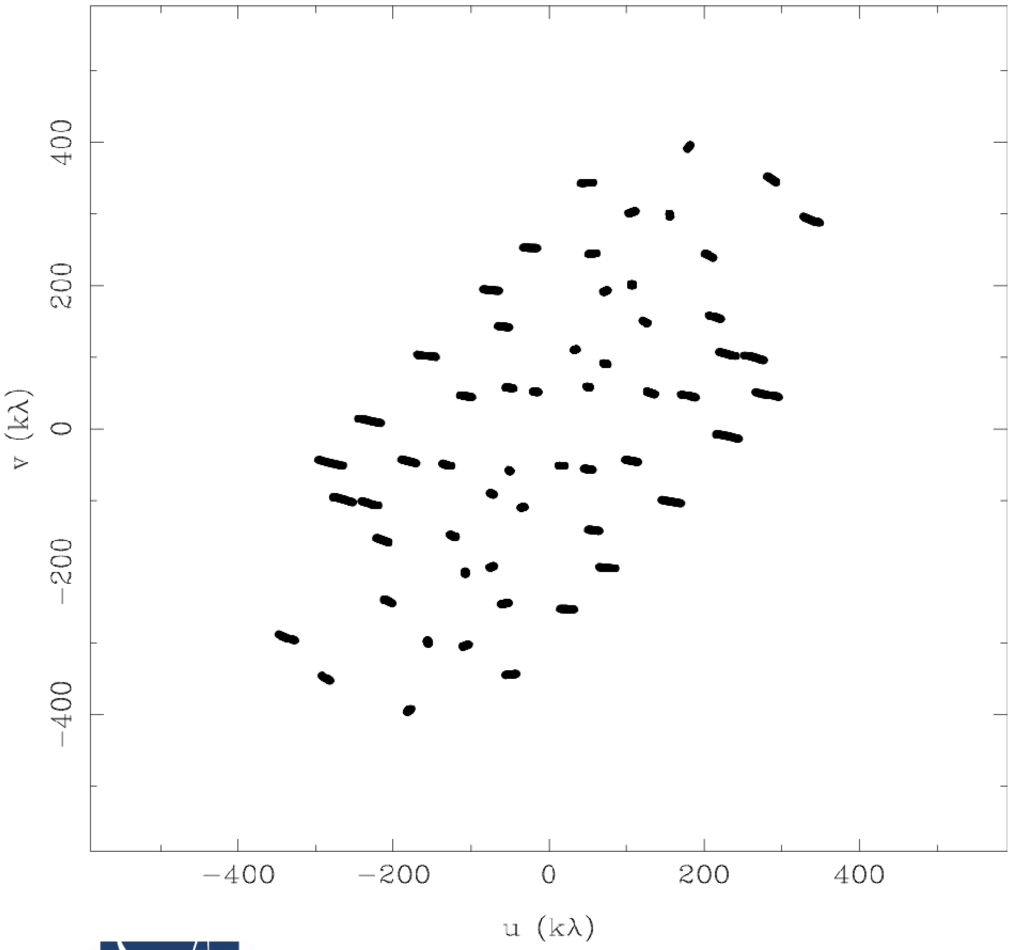


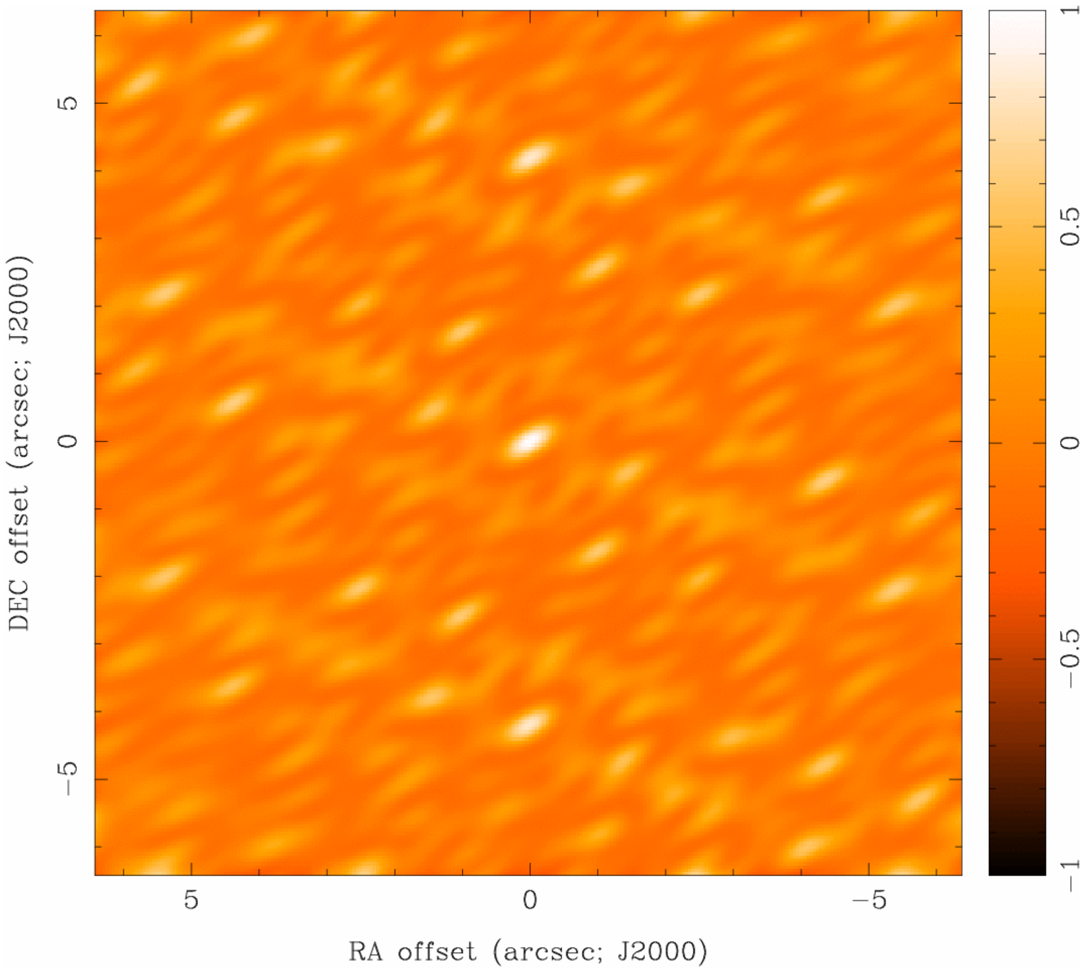
NRAO

Wednesday, August 7, 13

“Dirty Beam Shape” = Point Spread Function

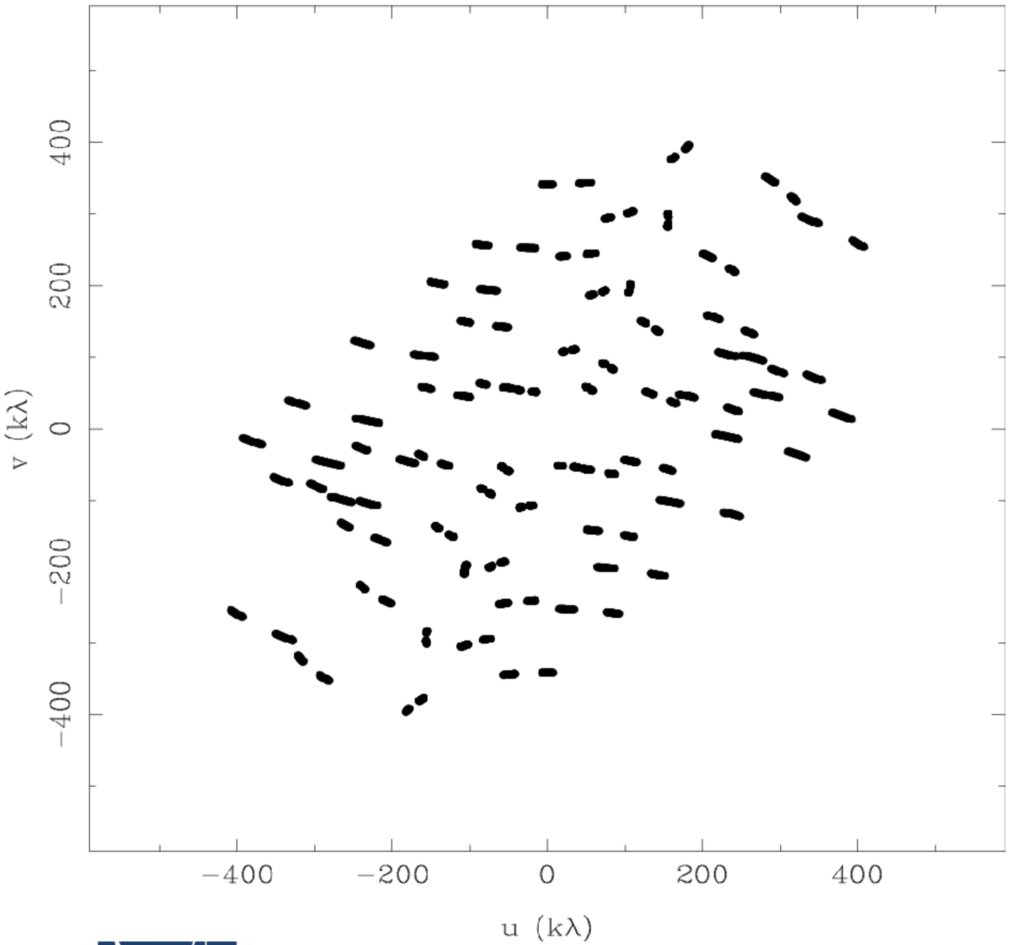
8 Antennas x 30 Samples

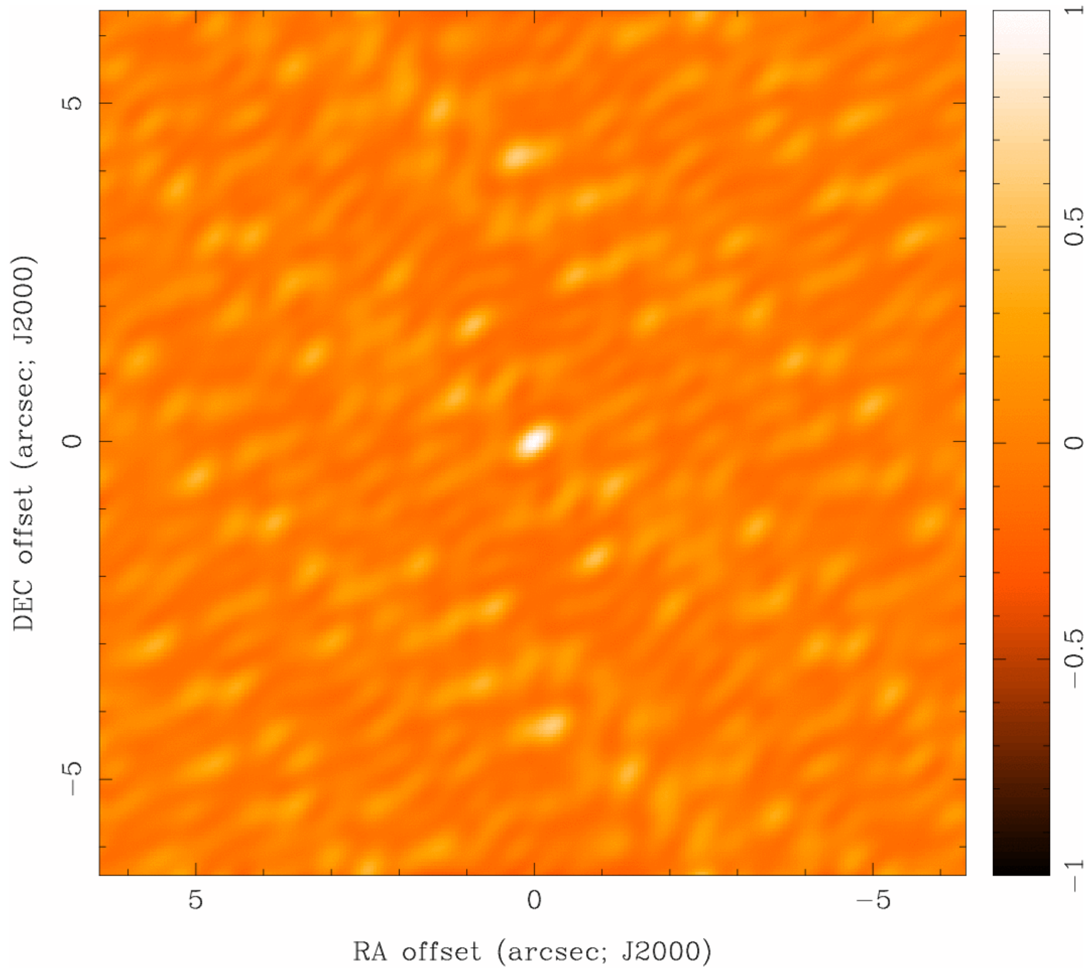




"Dirty Beam Shape" = Point Spread Function

8 Antennas x 60 Samples

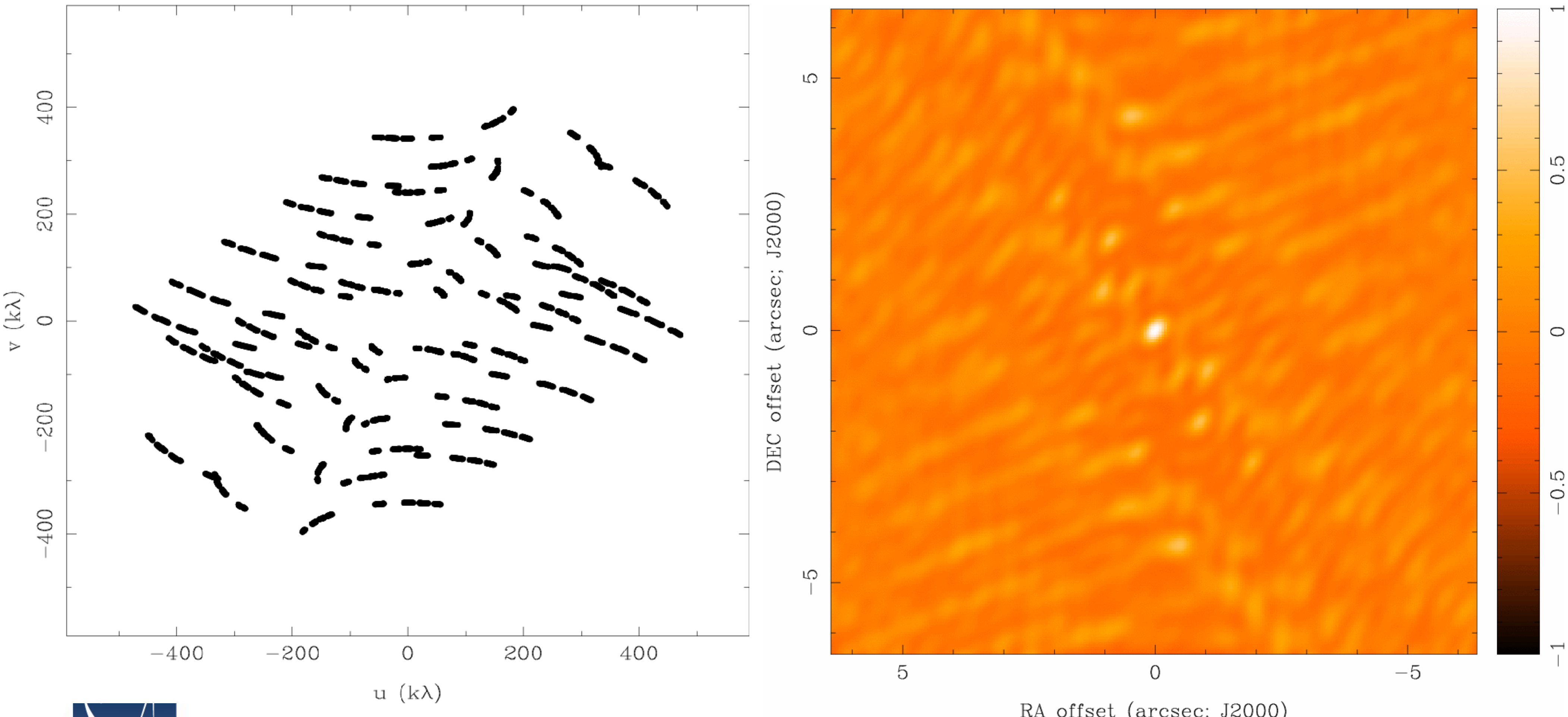




"Dirty Beam Shape" = Point Spread Function

ALMA

8 Antennas x 120 Samples



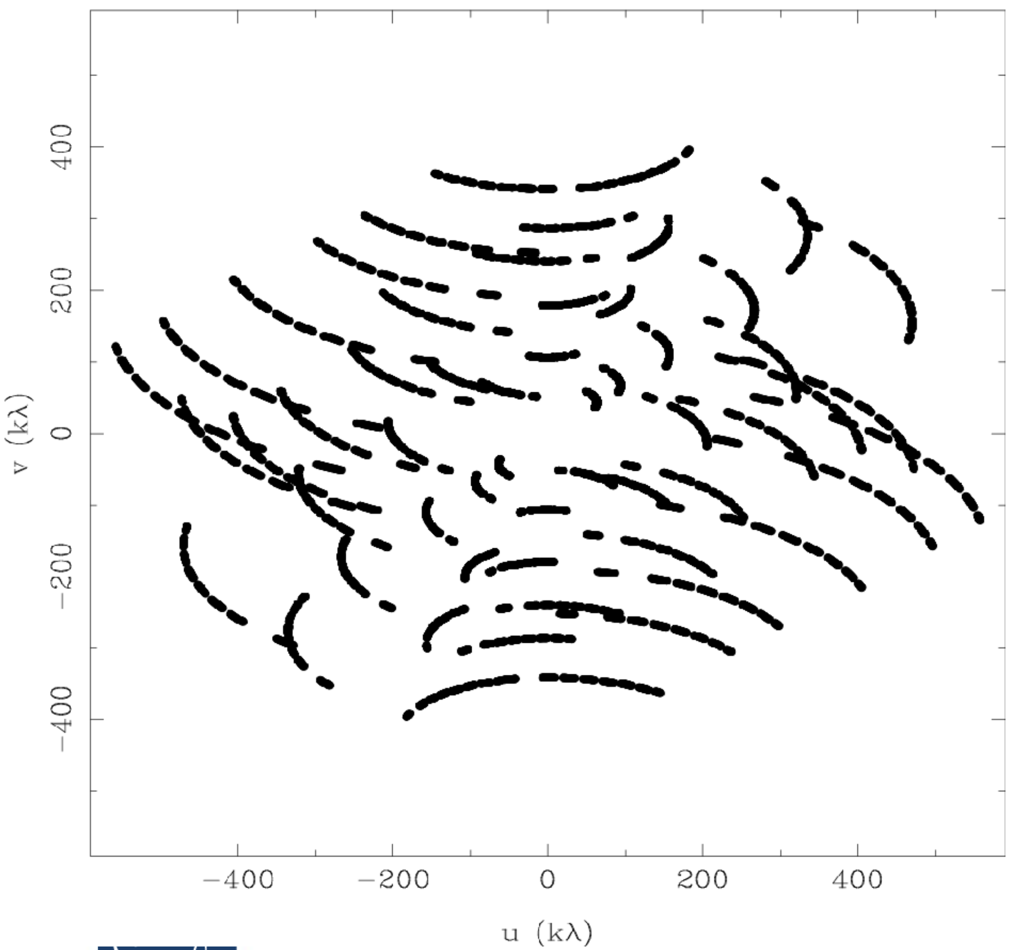
NRAO

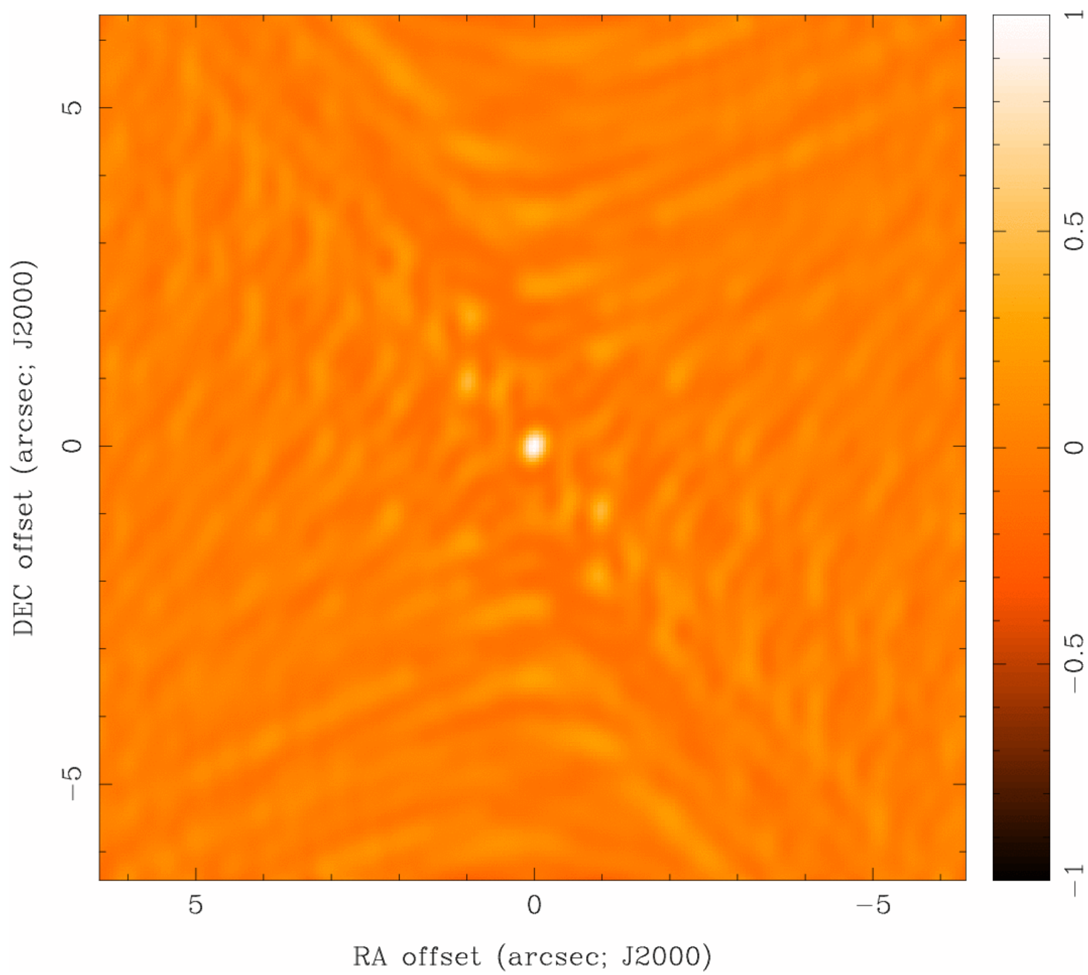
Wednesday, August 7, 13

“Dirty Beam Shape” = Point Spread Function

ALMA

8 Antennas x 240 Samples

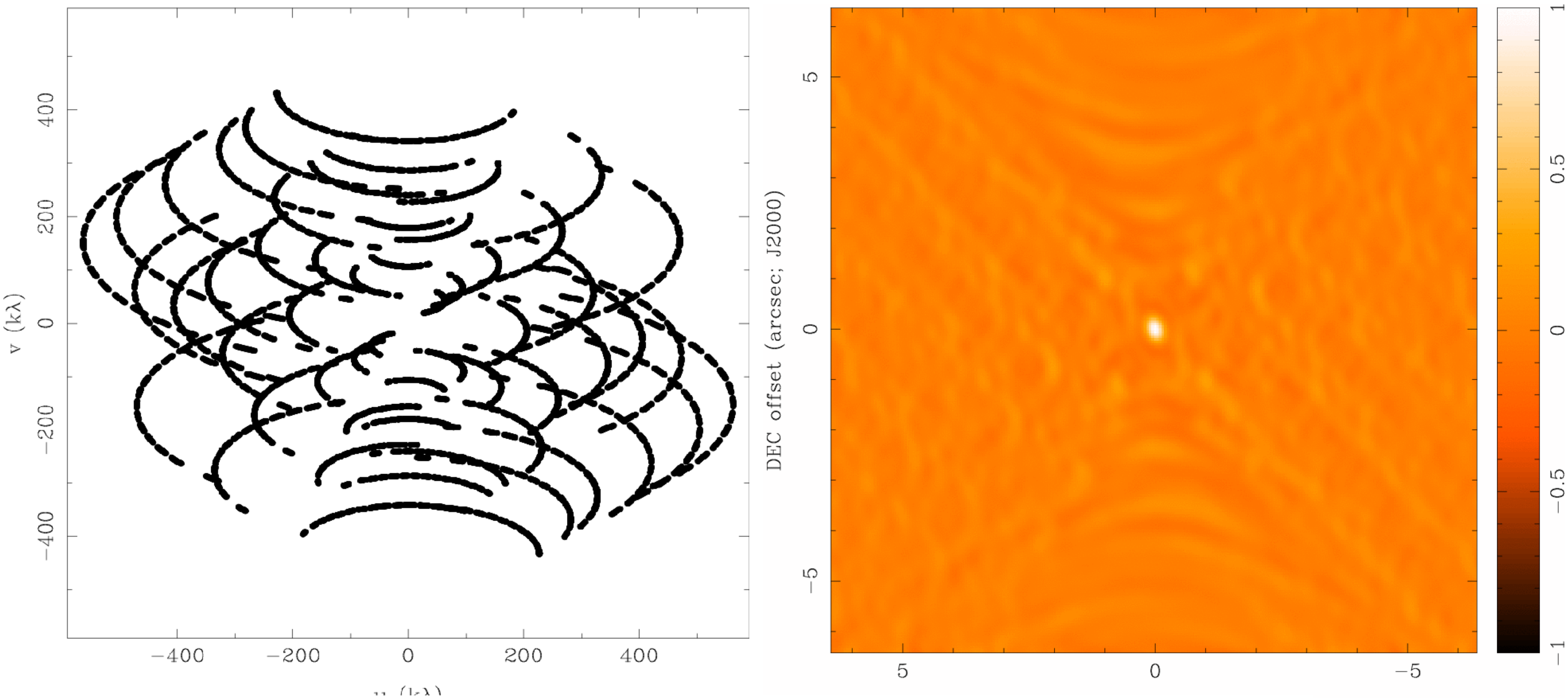




NRAO

“Dirty Beam Shape” = Point Spread Function

8 Antennas x 480 Samples

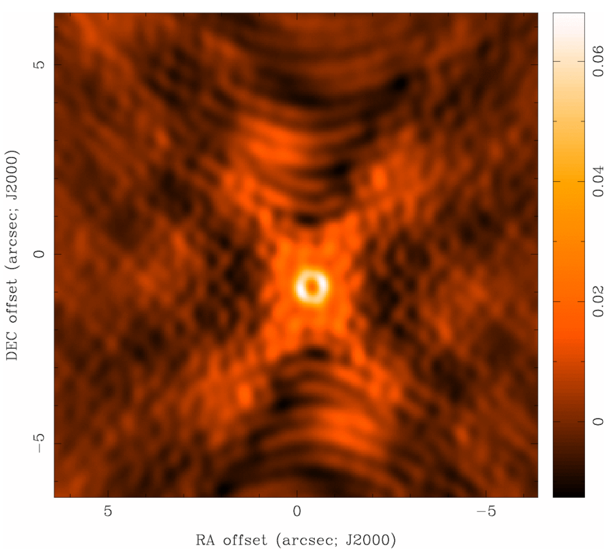


Beam approaches a Gaussian, which can be described by its full width half max (FWHM).

"Cleaning"

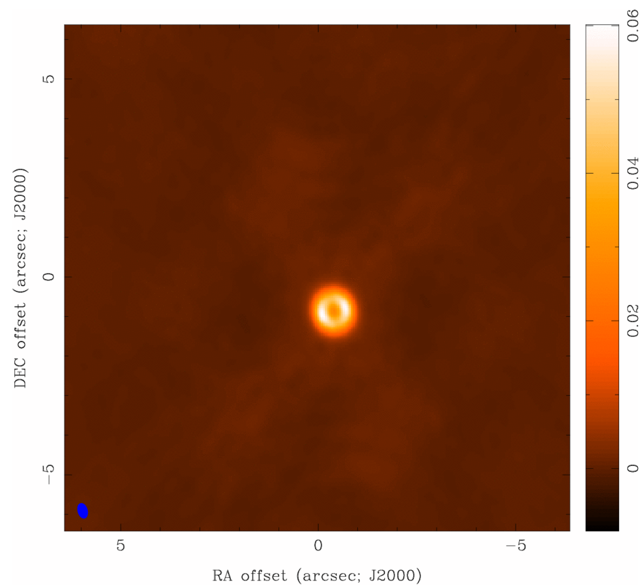
- Deconvolve or "clean" to get rid of beam side lobes
- Basically gives reasonable values in uv areas with no signal to have a nice Gaussian beam

"Dirty" image



Deconvolve

"Clean" image



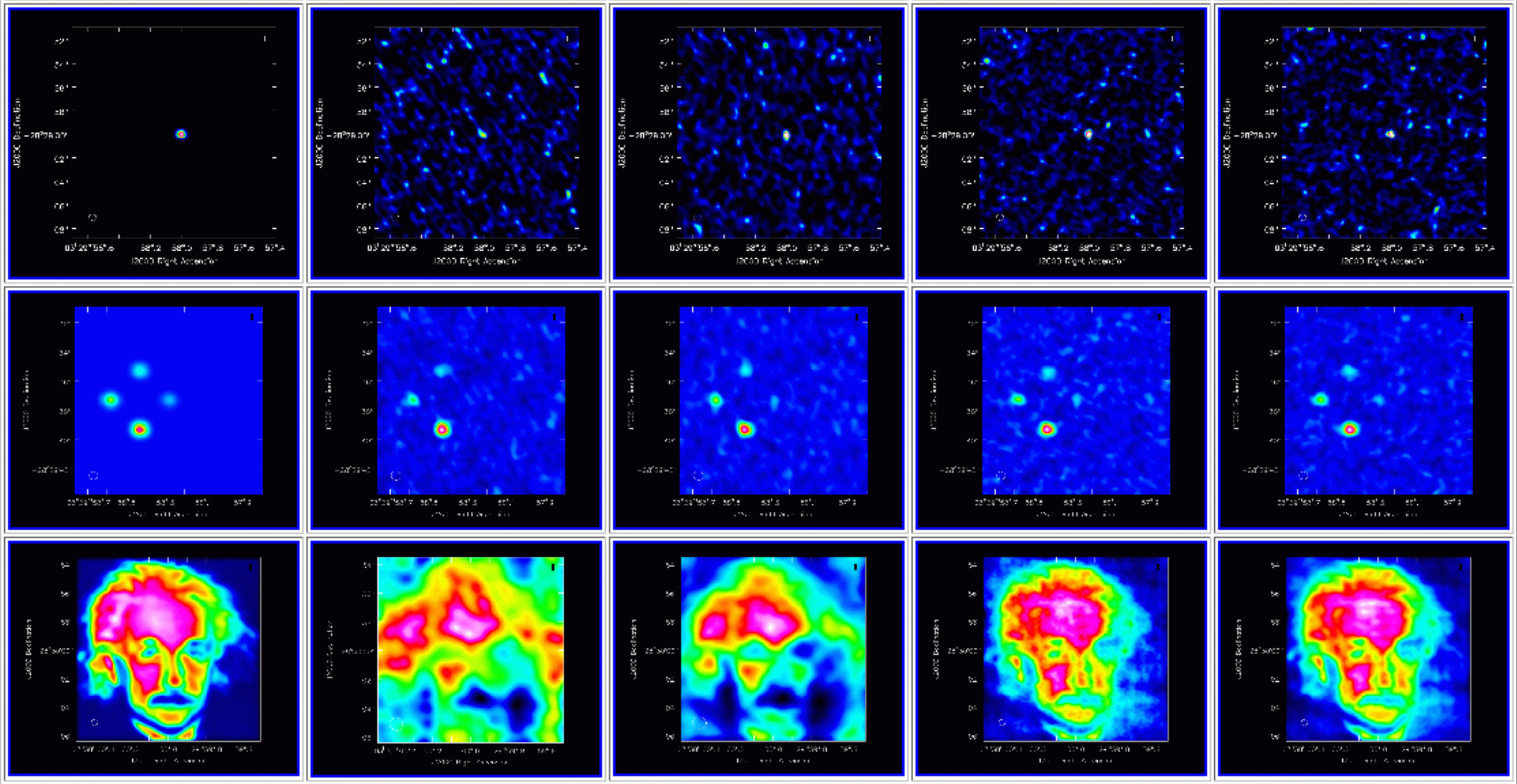
Effects of UV Coverage

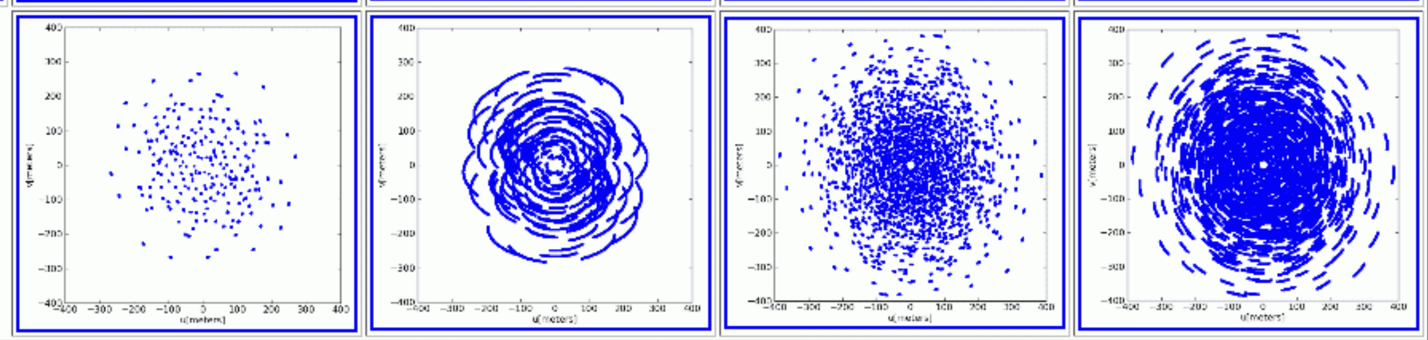
ALMA

Convolved source models	Early Science (16 antennas)		Full Science (50 antennas)	
	10 minutes (0.47 mJy rms)	4 hours (0.091 mJy rms)	10 minutes (0.14 mJy rms)	1 hour (0.057 mJy rms)

5σ

5σ
10σ
15σ
20σ



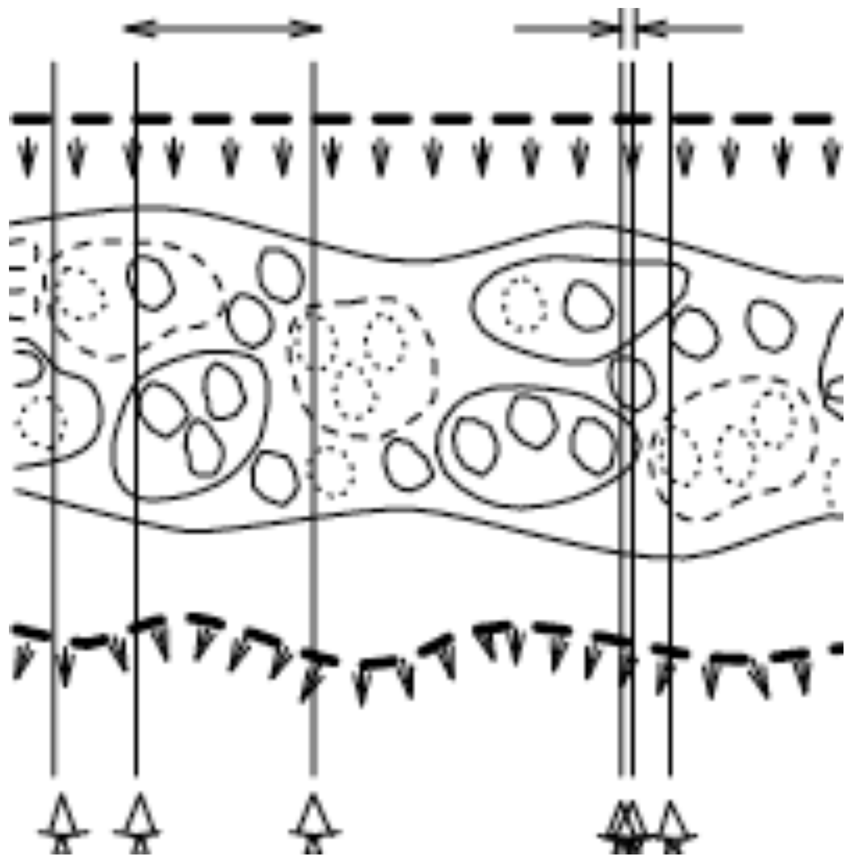


Note improved uv-coverage with time for same config.

Atmospheric phase fluctuations

ALMA

- Variations in the amount of precipitable water vapor (PWV) cause phase fluctuations, which are worse at shorter wavelengths (higher frequencies), and result in
  - Low coherence (loss of sensitivity)
  - Radio “seeing”, typically 1″ at 1 mm
  - Anomalous pointing offsets
  - Anomalous delay offsets



Patches of air with different water vapor content (and hence index of refraction) affect the incoming wave front differently.

> You can observe in apparently excellent submm weather (in terms of transparency) and still have terrible “seeing” i.e. phase stability.

NRAO

Outline

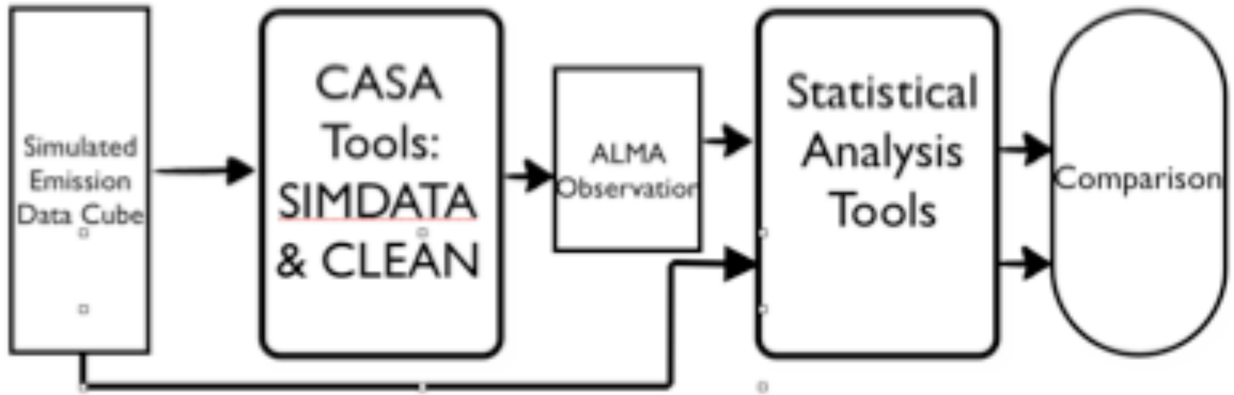
- Why model interferometry?
- Interferometry for Theorists
- CASA
- Project

CASA

- Python-based software package to calibrate, image, and analyze radioastronomical data from interferometers
- CASA Guide: http://casaguides.nrao.edu
- Specifically for simulating observations: http://casaguides.nrao.edu/index.php?title=Simulating_Observations_in_CASA_4.1

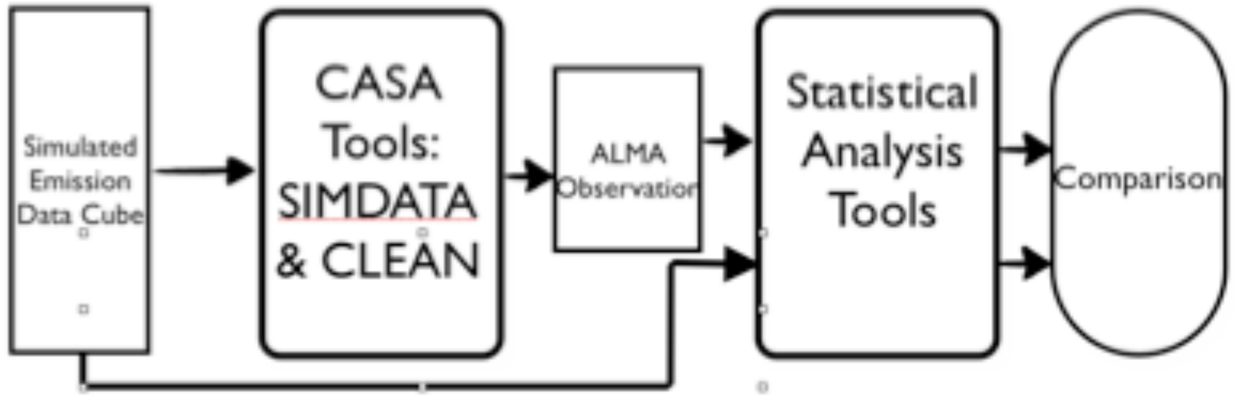
Example

Gilberto Lopez astro thesis
with: C. Cyganoski, C. Beaumont, S. Offner & A. Goodman

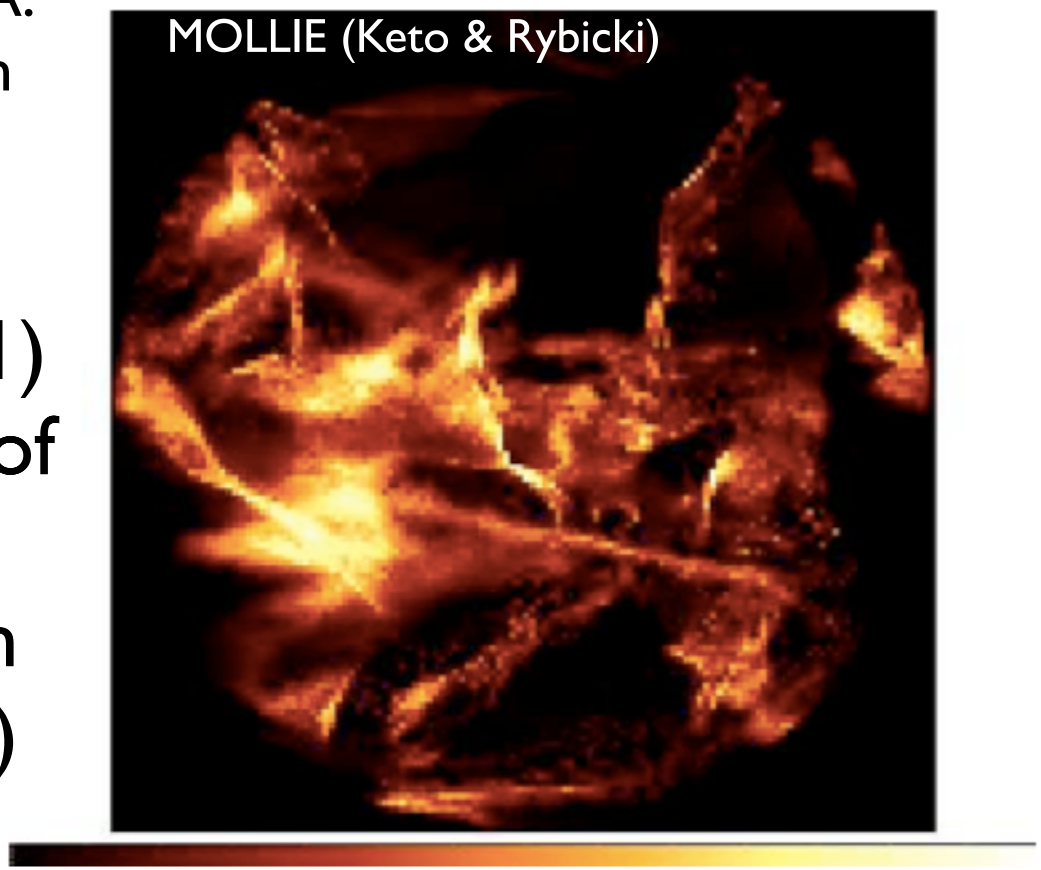


Example

Gilberto Lopez astro thesis
with: C. Cyganoski, C. Beaumont, S. Offner & A. Goodman

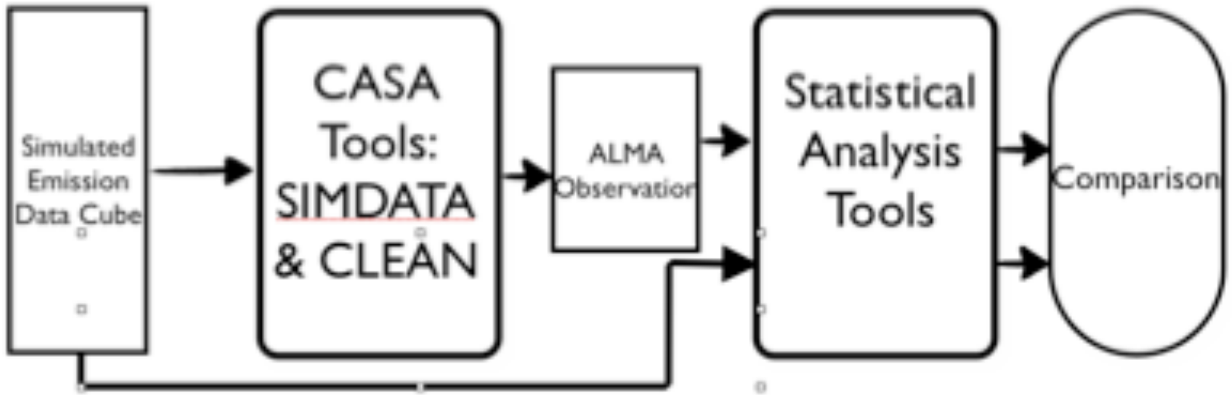


Synthetic 13CO (2-1) data cube of Orion simulation (no noise)

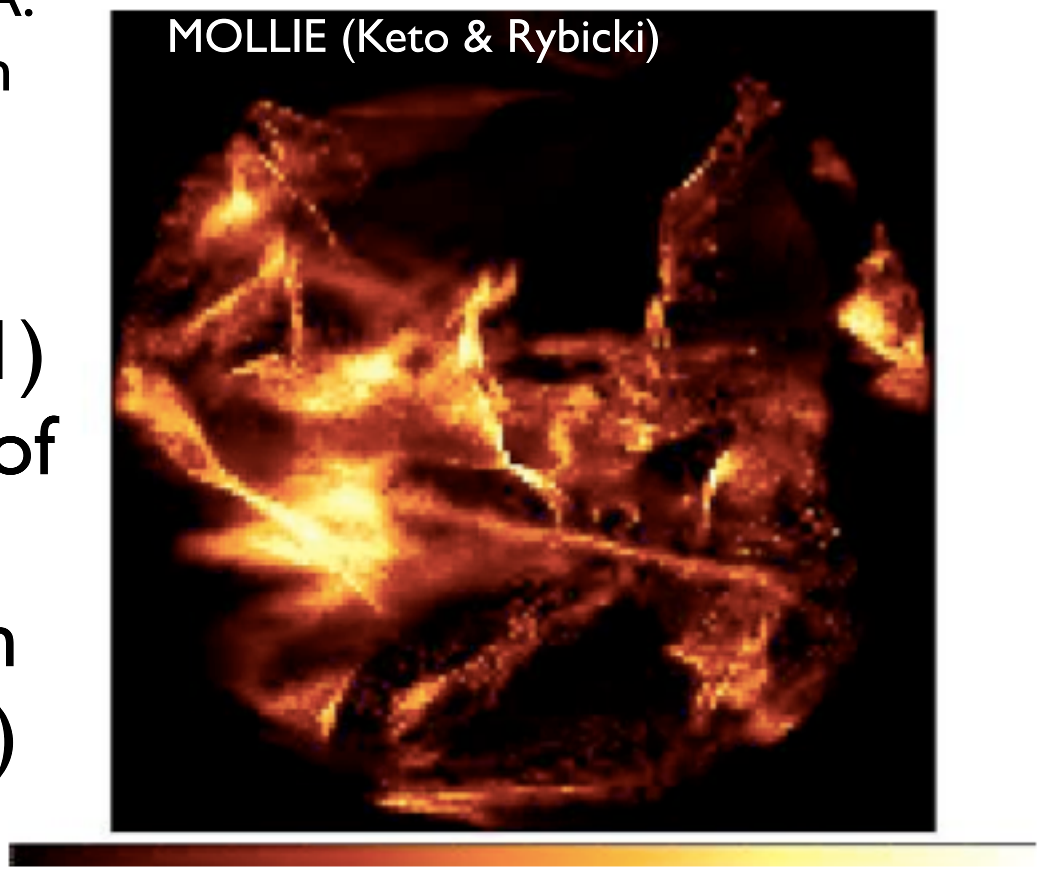


Example

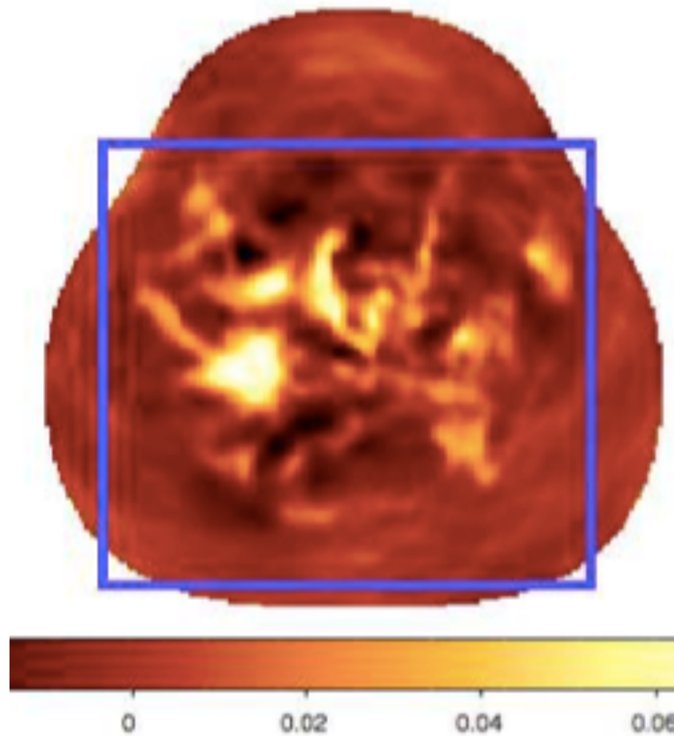
Gilberto Lopez astro thesis with: C. Cyganoski, C. Beaumont, S. Offner & A. Goodman



Synthetic 13CO (2-1) data cube of Orion simulation (no noise)

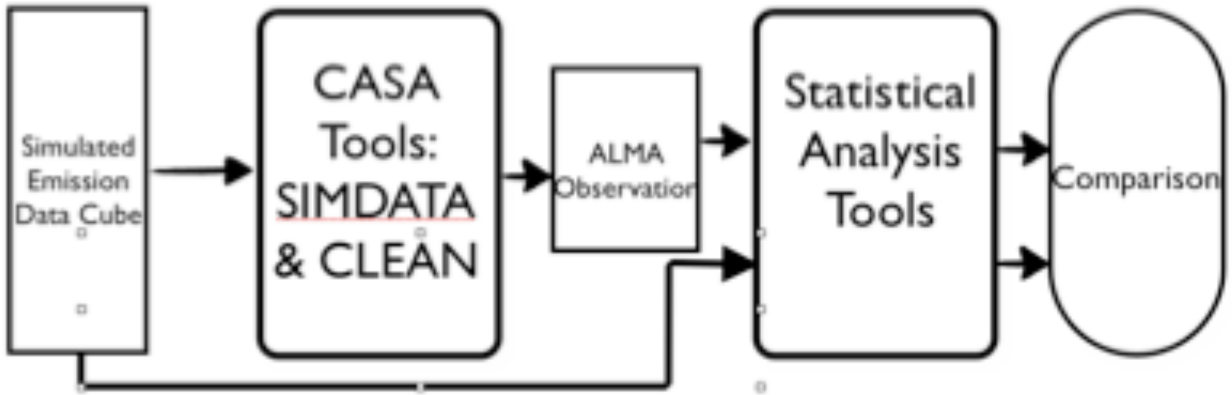


1Hr, No Noise

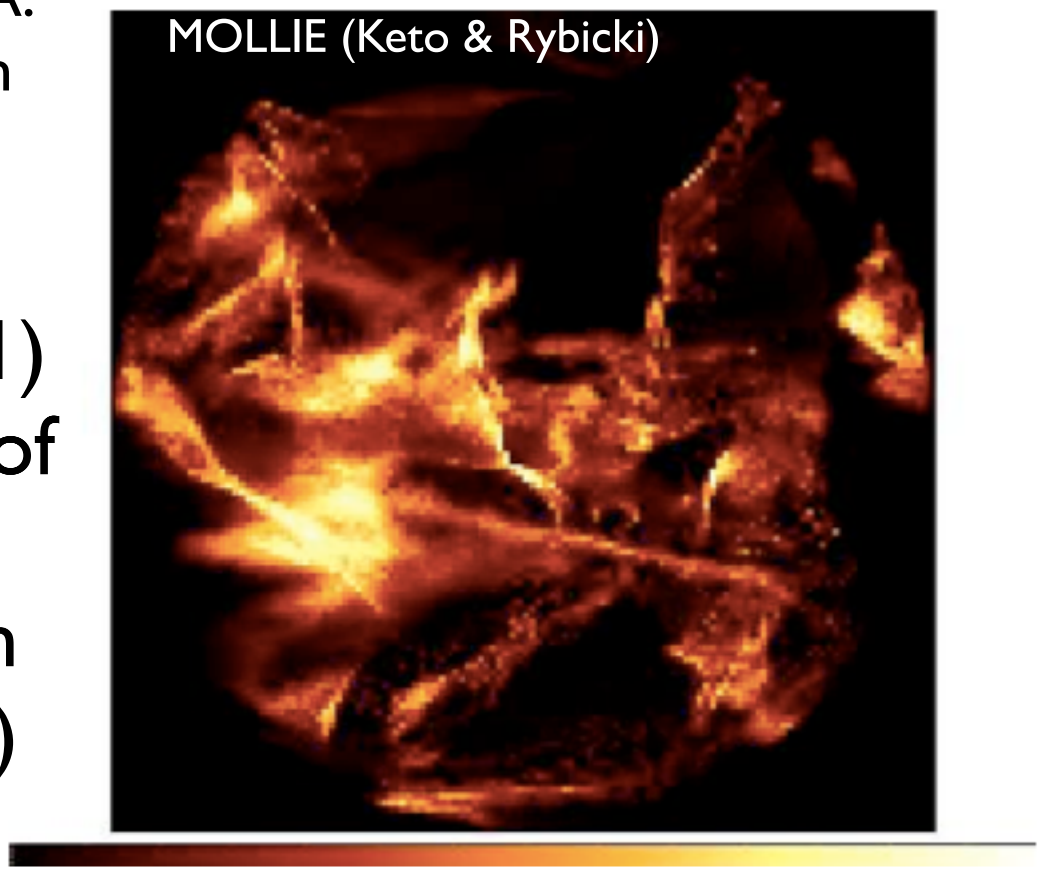


Example

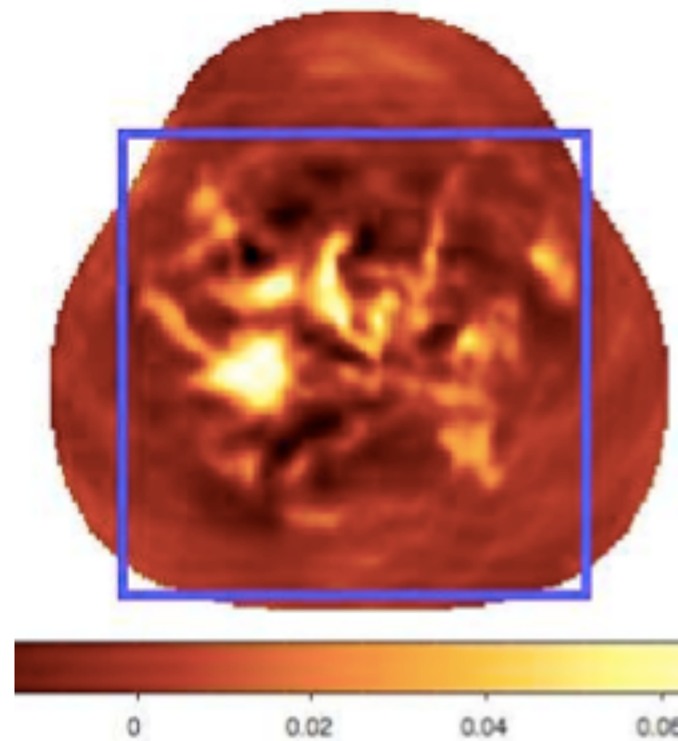
Gilberto Lopez astro thesis
with: C. Cyganoski, C. Beaumont, S. Offner & A. Goodman



Synthetic 13CO (2-1) data cube of Orion simulation (no noise)

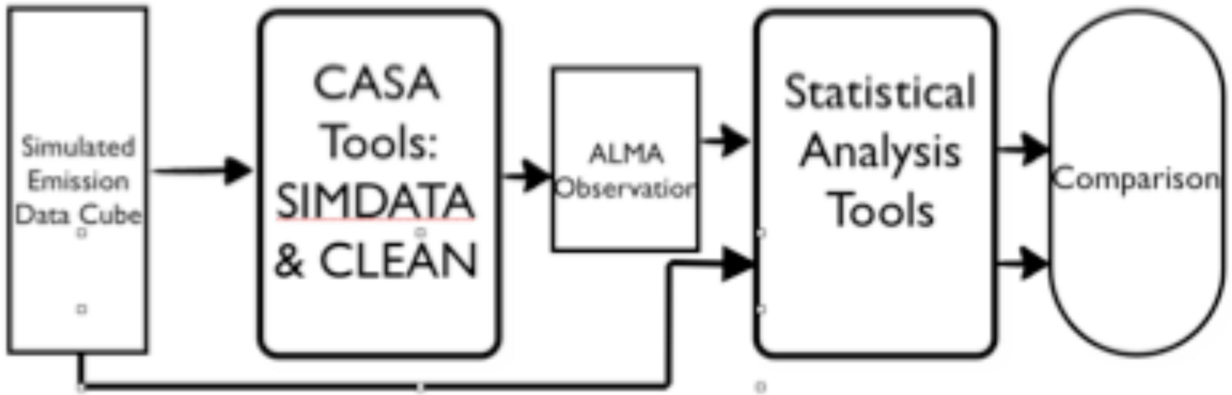


4Hr, No Noise

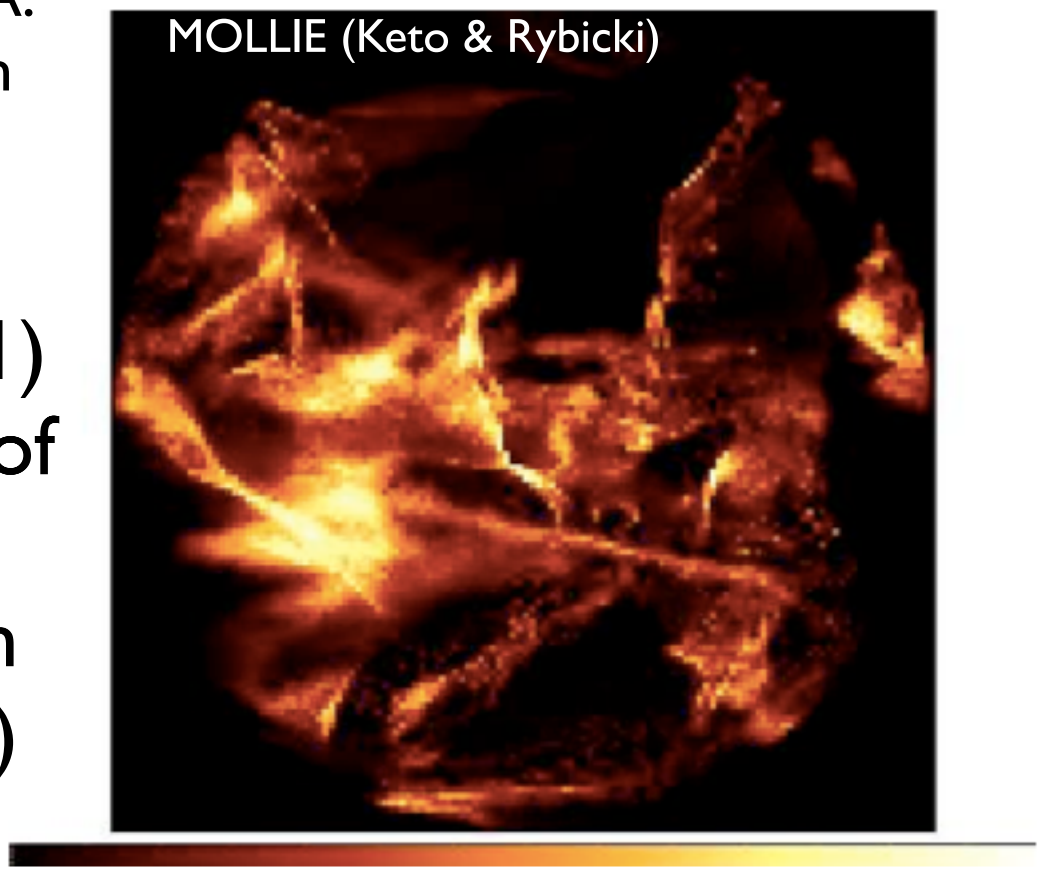


Example

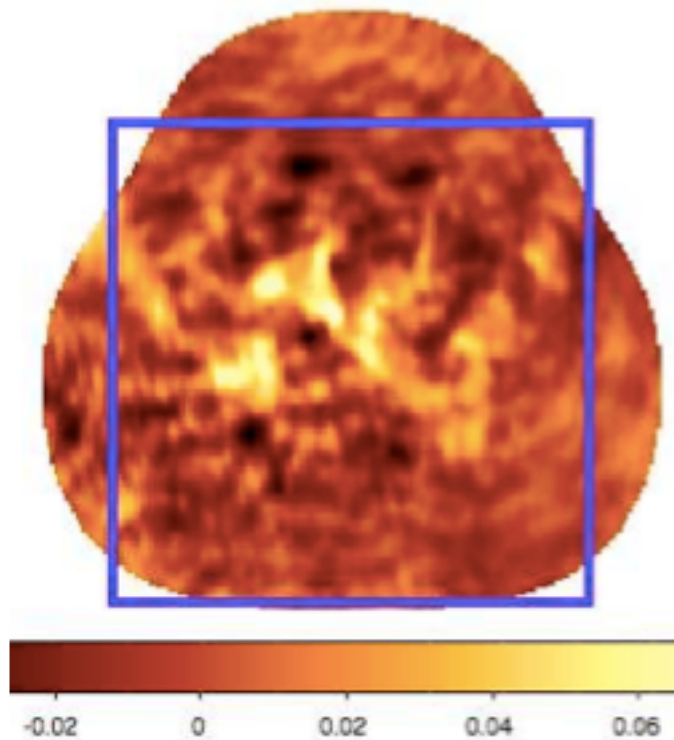
Gilberto Lopez astro thesis with: C. Cyganoski, C. Beaumont, S. Offner & A. Goodman



Synthetic 13CO (2-1) data cube of Orion simulation (no noise)



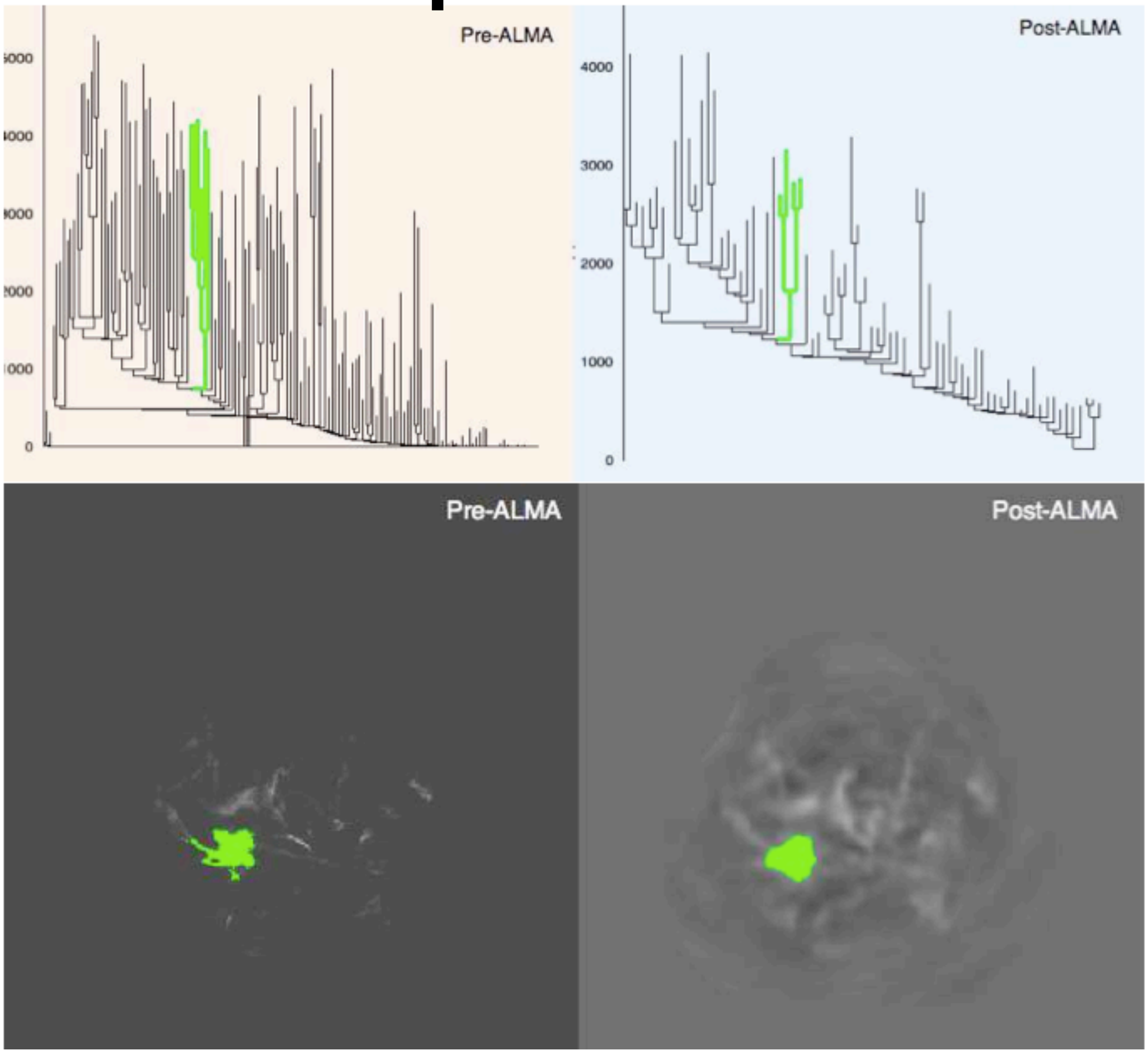
4Hr, with Noise



Example

Gilberto Lopez astro thesis

with: C. Cyganoski, C. Beaumont, S. Offner & A. Goodman



CASA

- Two main tools:
- simobserve
    - Given a brightness map or cube, generates visibilities as would be observed with a specific configuration
    - Uses an atmospheric model to simulate realistic atmospheric conditions and noise
- simanalyze
    - Produce a "cleaned" image
    - Can also difference input/output data to calculate the image fidelity

Example Script:

The People Who Stare at Code III

default = 10s

```
default("simobserve")
#  sim_observe :: mosaic simulation task:
project            =        'sim'          #  root prefix for output file names
skymodel           = '30dor.fits'          #  model image to observe
     inbright      = '0.06mJy/pixel'       #  scale surface brightness of brightest pixel e.g. "1.2Jy/pixel"
     indirection   = 'J2000 10h00m00 -40d00m00' #  set new direction e.g. "J2000 19h00m00 -40d00m00"
     incell        = '0.15arcsec'          #  set new cell/pixel size e.g. "0.1arcsec"
     incenter      =   '230GHz'            #  set new frequency of center channel e.g. "89GHz" (required even for 2D
                                           #   model)
     inwidth       =      '2GHz'           #  set new channel width e.g. "10MHz" (required even for 2D model)

complist           =          ''           #  componentlist to observe
setpointings       =        True
     integration   =      '600s'           #  integration (sampling) time
     direction     =          ''           #  "J2000 19h00m00 -40d00m00" or "" to center on model
     mapsize       =    ['', '']           #  angular size of map or "" to cover model
     maptype       =    'square'           #  hexagonal, square, etc


observe            =        True           #  calculate visibilites using ptgfile
     antennalist   = '/usr/lib64/casapy/test/data/alma/simmos/alma.cycle0.compact.cfg' #  antenna position file
                                           #   or "" for no interferometric MS
     refdate       = '2012/05/21'          #  date of observation - not critical unless concatting simulations
     hourangle     =  'transit'            #  hour angle of observation center e.g. -3:00:00, or "transit"
     totaltime     =    '7200s'            #  total time of observation or number of repetitions


     sdantlist     =          ''           #  single dish antenna position file or "" for no total power MS
     sdant         =           0           #  single dish antenna index in file

thermalnoise       =          ''           #  add thermal noise: [tsys-atm|tsys-manual|""]
leakage            =         0.0           #  cross polarization
graphics           =      'both'           #  display graphics at each stage to [screen|file|both|none]
verbose            =       False
overwrite          =        True           #  overwrite files starting with $project
simobserve()
```

Example Script:

The People Who Stare at Code III

```
default ("simanalyze")
project                 = "sim"
indirection             = 'J2000 10h00m00 -40d00m00'
imsize                  = [150,150]                  # Image size in pixel number
analyze                 = True
showconvolved           = True                       # Plot convolved image
showdifference          = True                       # Plot difference image
showpsf                 = True                       # Plot dirty beam
showclean               = True                       # Plot synthesized image
niter                   = 1                          # Number of iterations for cleaning
simanalyze()
```

>casapy

>help simanalyze ⟵ get help with syntax and parameters

>execfile('my_script.py')

Antenna configuration files:

/home/soffner/casapy-stable-42.0.25430-001-64b/data/alma/simmos/

Outline

- Why model interferometry?
- Interferometry for Theorists
- CASA
- Project

Project

- Compute a synthetic interferometric observation of a mm dust map (see Helpful Formulas); compare fidelity for two different integration times
- Inputs: column density (converted to mm flux), average gas temperature (can vary spatially)
- Outputs: convolved image, fidelity
- Extra credit: use dust emission as computed by Hyperion at 1.1mm as the input

Helpful Formulas

- Flux at a given frequency: $$S_\nu = \Sigma B_\nu(T_D)\kappa_\lambda\Omega_b,$$
- Planck Function: $$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/(k_B T)} - 1}$$
- Beam solid angle: $$\Omega_b = 2.665 \times 10^{-11}\text{sr}\left(\frac{\theta_{\text{HPBW}}}{\text{arcsec}}\right)^2,$$
- Angular size of a pixel at distance, d: $$\theta_{\text{px}} = \left(\frac{\Delta x}{\text{pc}}\right)\frac{360 \times 60 \times 60}{2\pi d_{\text{pc}}}\ [\text{arcsec}],$$

1.1 mm dust opacity[a]	$\kappa_{1.1}$	0.0114 $\text{cm}^2\ \text{g}^{-1}$
3 mm dust opacity [a]	κ_3	0.00169 $\text{cm}^2\ \text{g}^{-1}$
^{12}CO (1-0) transition frequency[b]	$\nu_{12\text{CO},10}$	115.2712018 GHz
^{13}CO (1-0) transition frequency[b]	$\nu_{13\text{CO},10}$	110.2013542798 GHz
cgs flux unit	1 Jy	10^{-23} erg s^{-1} cm^{-2} Hz^{-1}
molecular weight per hydrogen molecule	μ_{H_2}	2.8 (m_p)
mean molecular weight per particle	μ_p	2.33 (m_p)
arcsec	1"	4.85 $\times 10^{-6}$ rad

Useful References

- Online course on radio astronomy (J. Condon & S. Ransom): http://www.cv.nrao.edu/course/astr534/ERA.shtml
- CASA user manual: http://casa.nrao.edu/docs/UserMan/UserMan.html
- http://help.nrao.edu