Introduction to Radio Interferometry

Steve Ertel

Includes material from:
Alison Peck, Jim Braatz, Ashley Bemis, Sabrina Stierwalt

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Very Long Baseline Array

NRAO

(1) Introduction to Radio Astronomy

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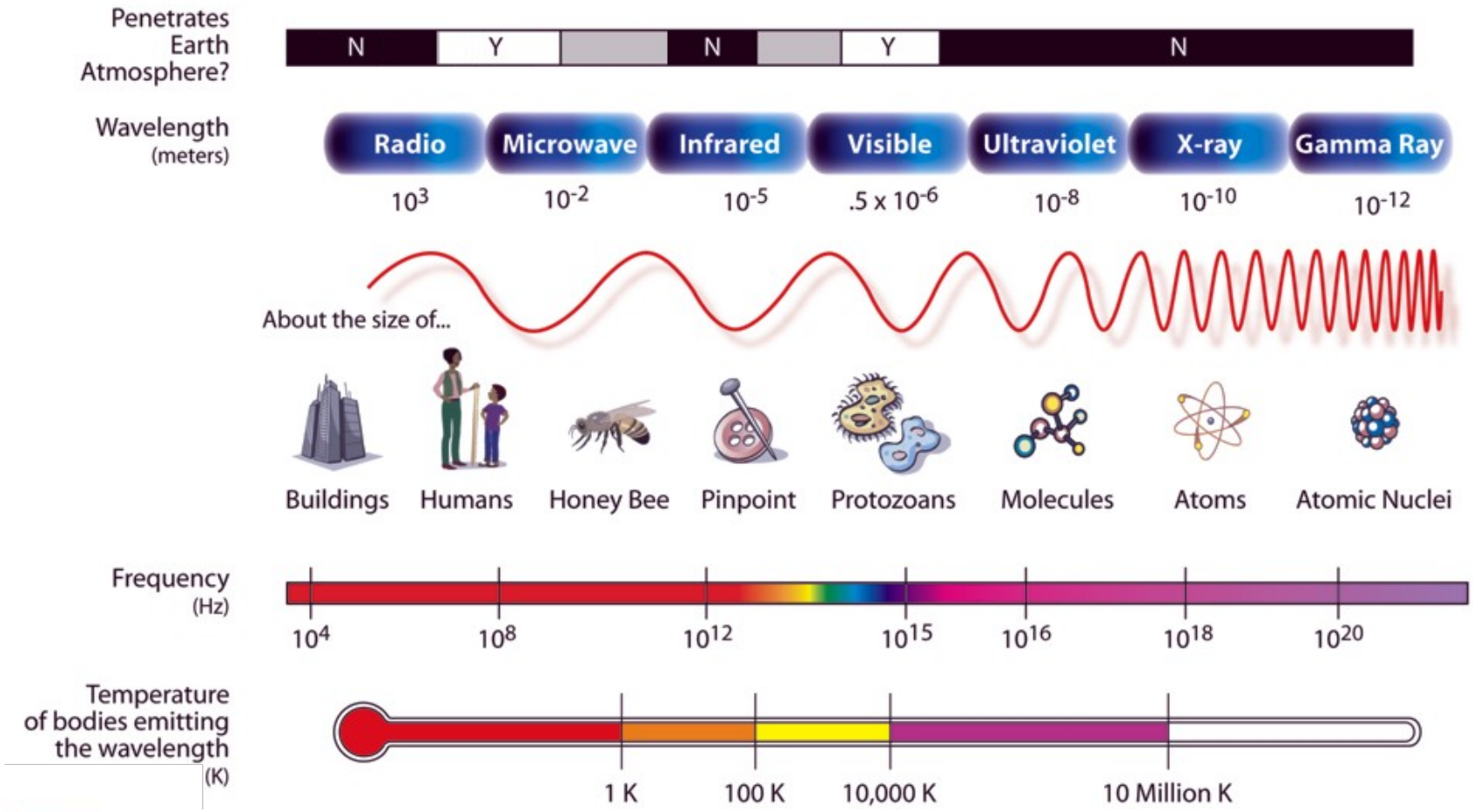
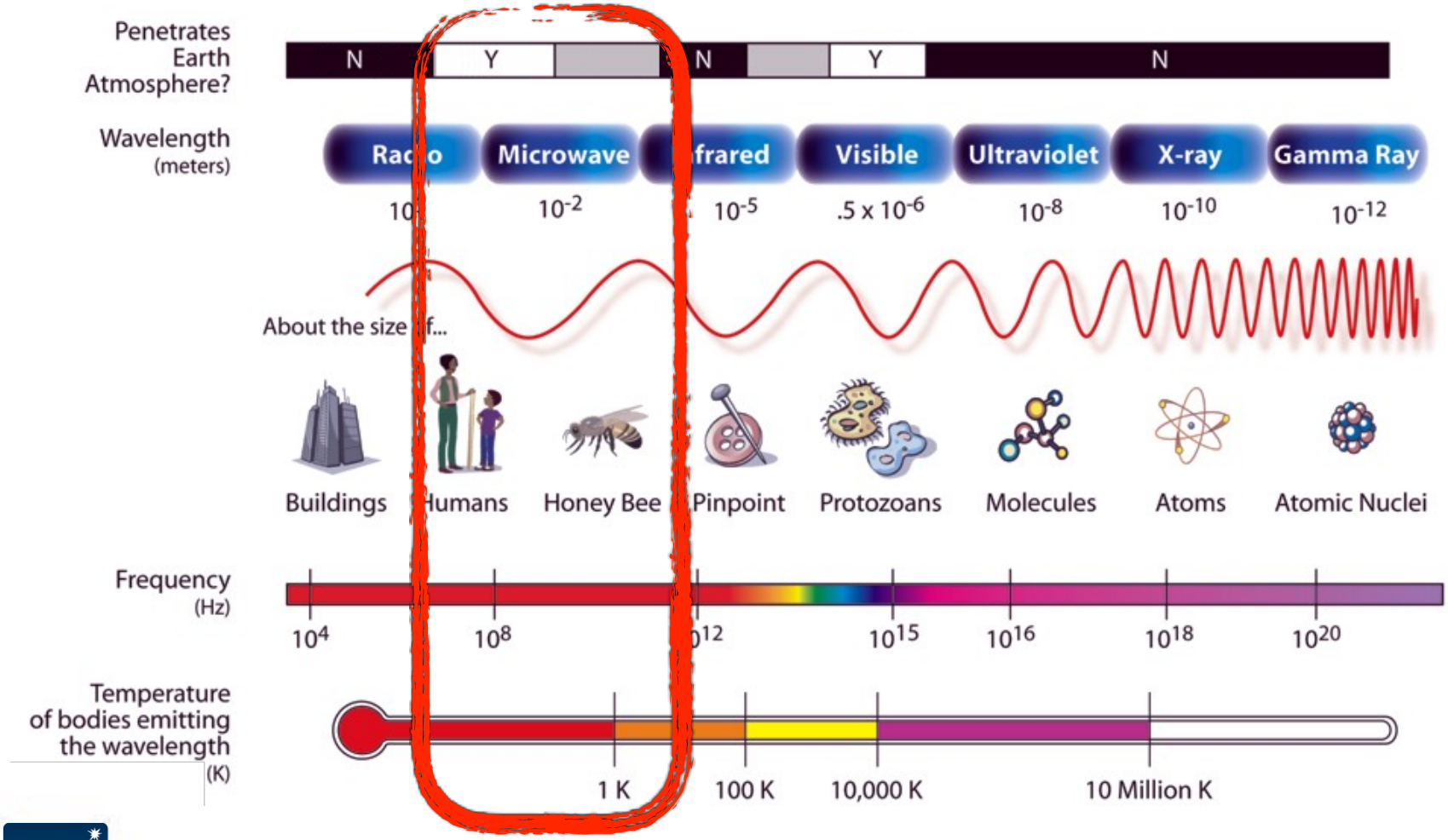
THE ELECTROMAGNETIC SPECTRUM



‘Radio astronomy’ now used for most telescopes using heterodyne technology



What does heterodyne mean?

- Observed sky frequencies are mixed with artificial signal from Local Oscillator, thus converts signal to lower frequency
- Retains original phase and amplitude information
- But signal can then be transmitted, amplified and analyzed more easily

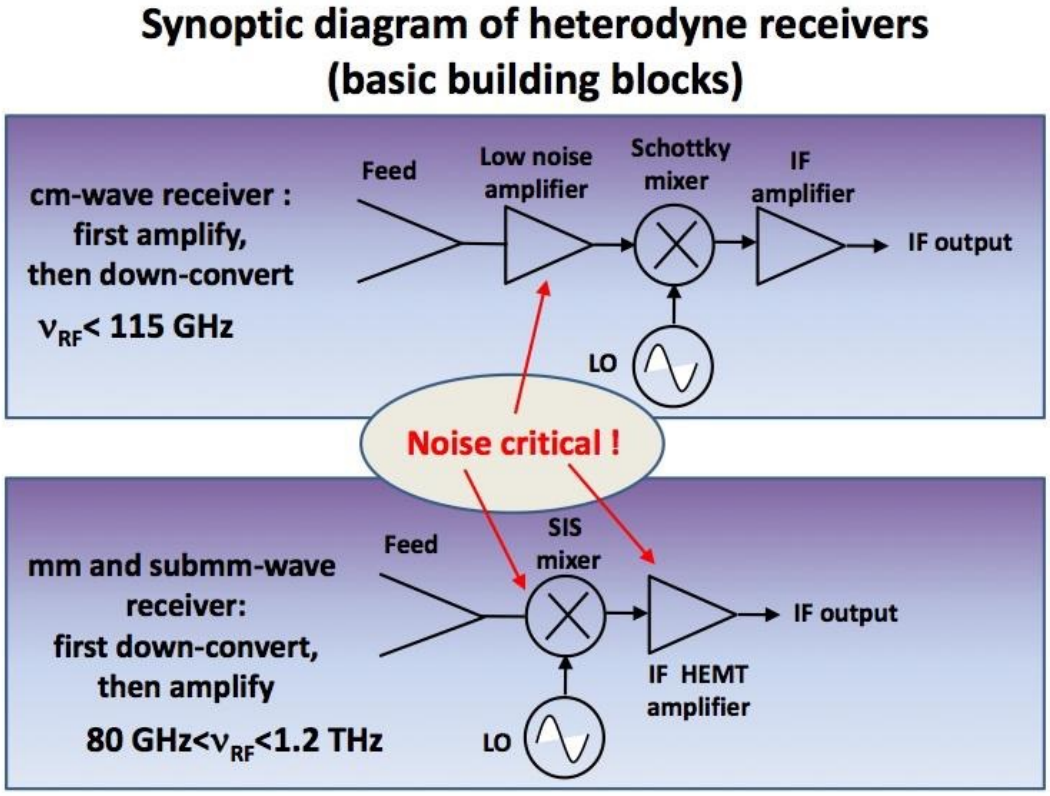


Image from Alessandro Navarrini (IRAM)

Long wavelength means no glass mirrors

What can we observe?

Radiation mechanisms:

- Cold thermal emission (e.g., dust, asteroids)
- Molecular lines
- free-free emission (and absorption)
- synchrotron emission (and absorption)

Soruces:

- AGN, galaxies, quasars
- Stars (& the Sun!), circumstellar material (disks, mass loss)
- Molecular clouds & ISM
- Solar system bodies (planets, rings, moons, asteroids, comets)
- CMBR

Resolution is a problem

Angular resolution for most telescopes is ~ λ/D

- D is the diameter of the telescope
- λ is wavelength of observation

For example, Hubble Space Telescope:

- λ ~ 600nm, D of 2.4m —> resolution ~ 0.05” (50 mas)

Reaching that resolution at λ ~1mm
requires a ~4 km-diameter telescope!

Interferometry allows one to circumvent this problem
by combining many smaller dishes

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(2) Introduction to Interferometry

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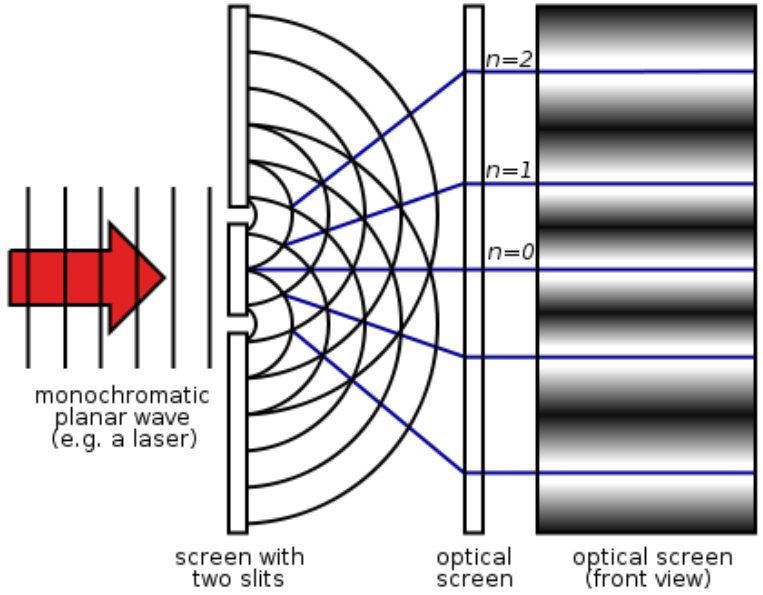
What is an interferometer?

An *interferometer* measures the interference pattern produced by multiple apertures, much like a 2-slit experiment.



*However, the interference patterns measured by radio telescopes are produced by **multiplying** - not adding - the wave signals measured at the different telescopes (i.e. apertures)

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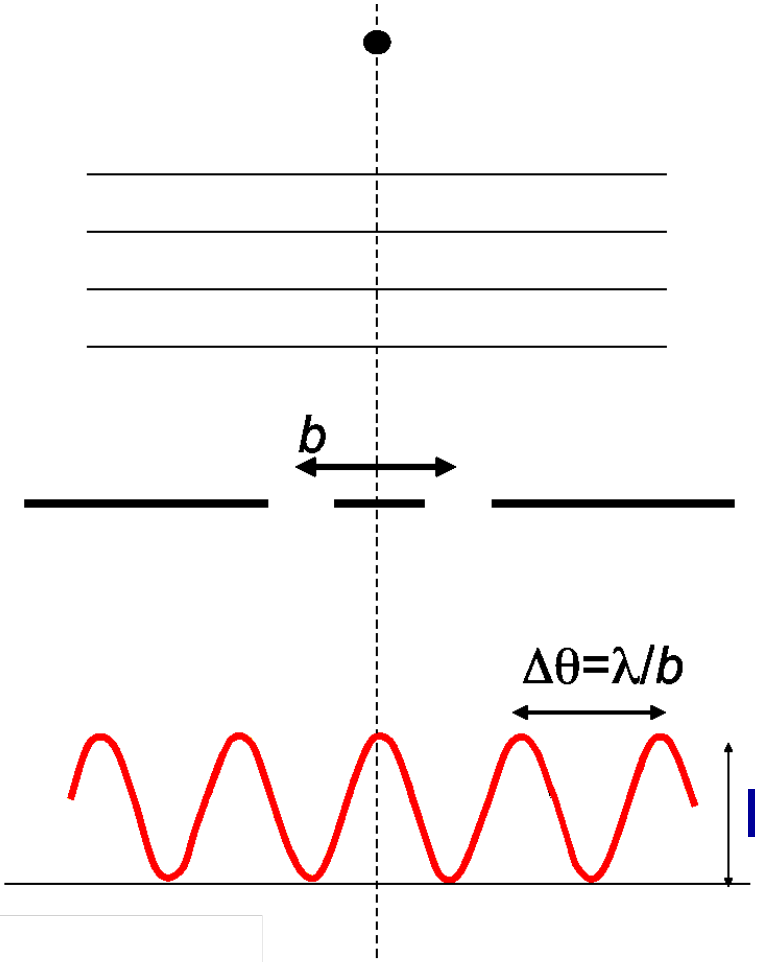
Astronomical interferometry



Visibility value $|V|$:

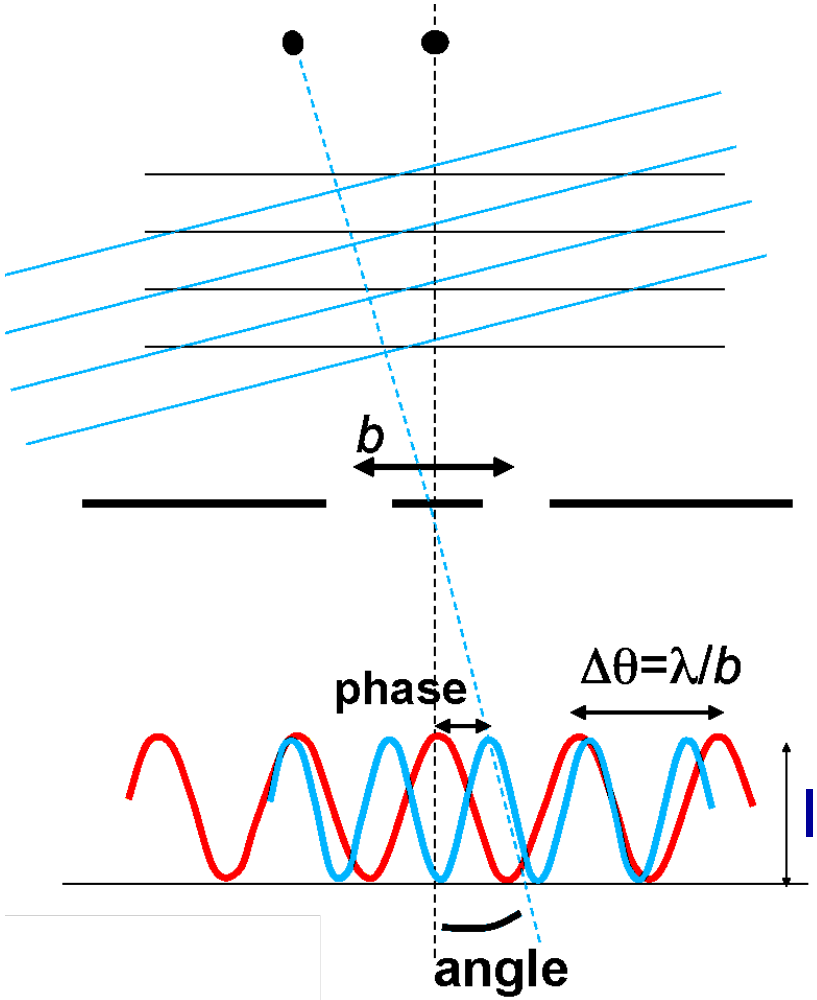
$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

= fringe contrast,

$|V| = [0, 1]$

Interferometry, one point source

Astronomical interferometry



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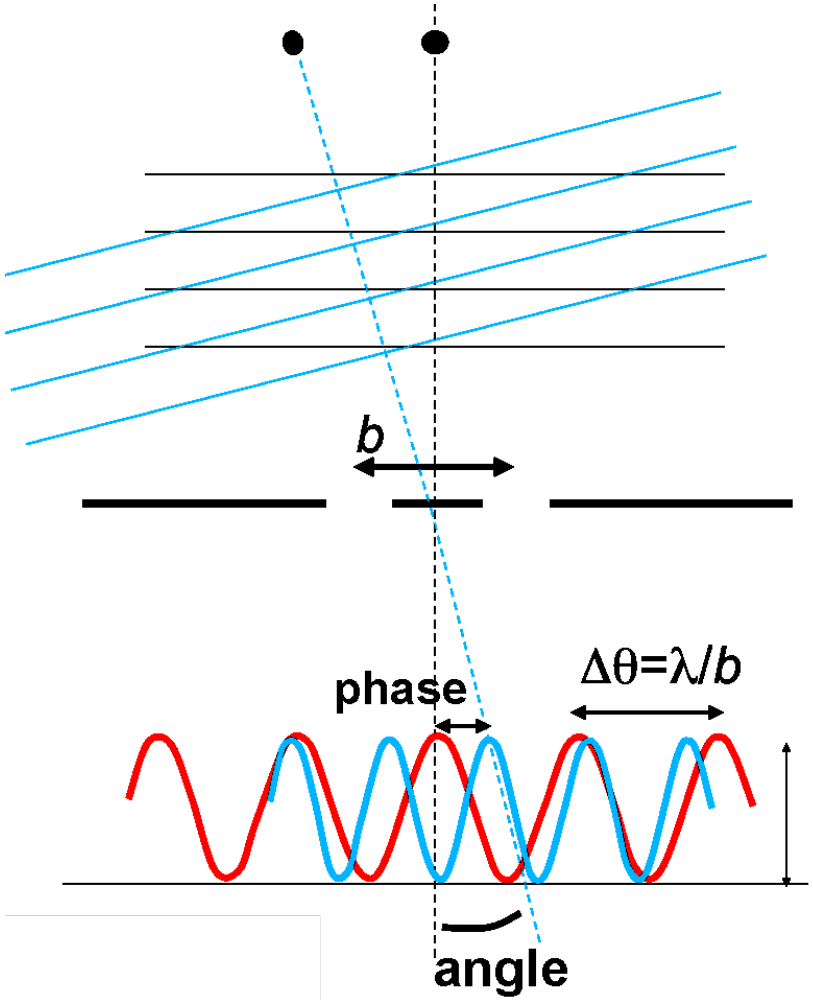
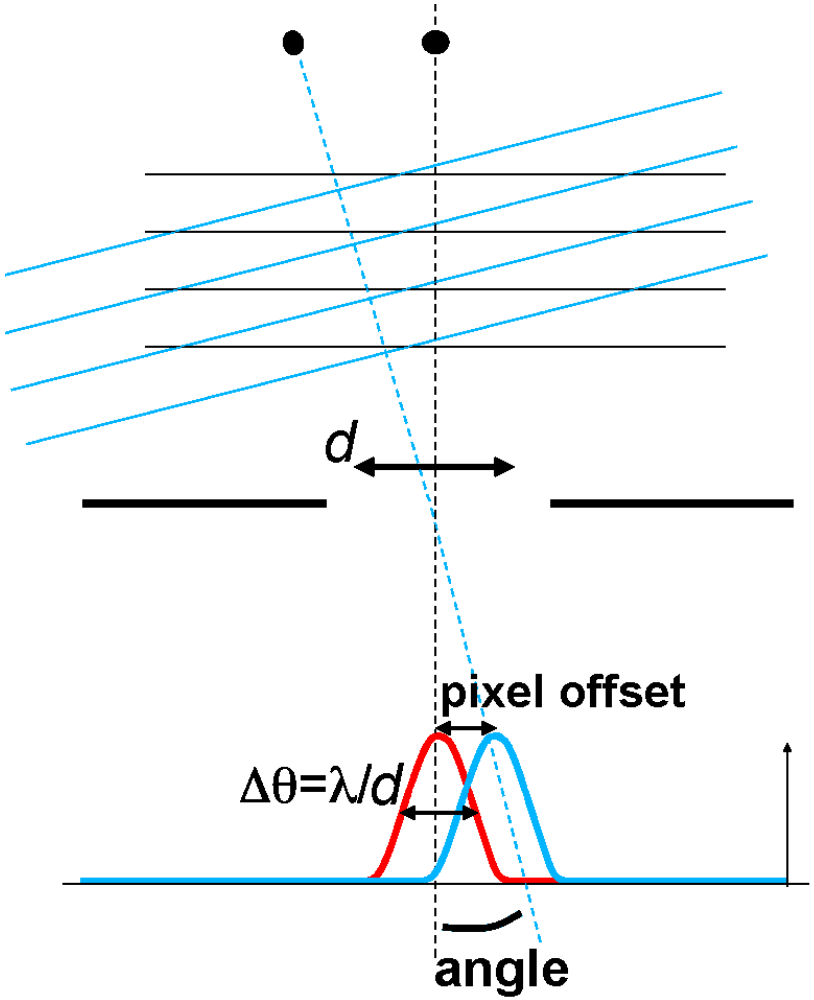
Interferometry, two point sources

Astronomical interferometry



Interferometry, two point sources



Imaging, two point sources

Astronomical interferometry

Two problems:

(1) How to recover flux distribution on sky from visibility measurements at different baselines?

(2) How to deal with consequences of limited baseline sampling?

Astronomical interferometry

Two problems:

(1) How to recover flux distribution on sky from visibility measurements?

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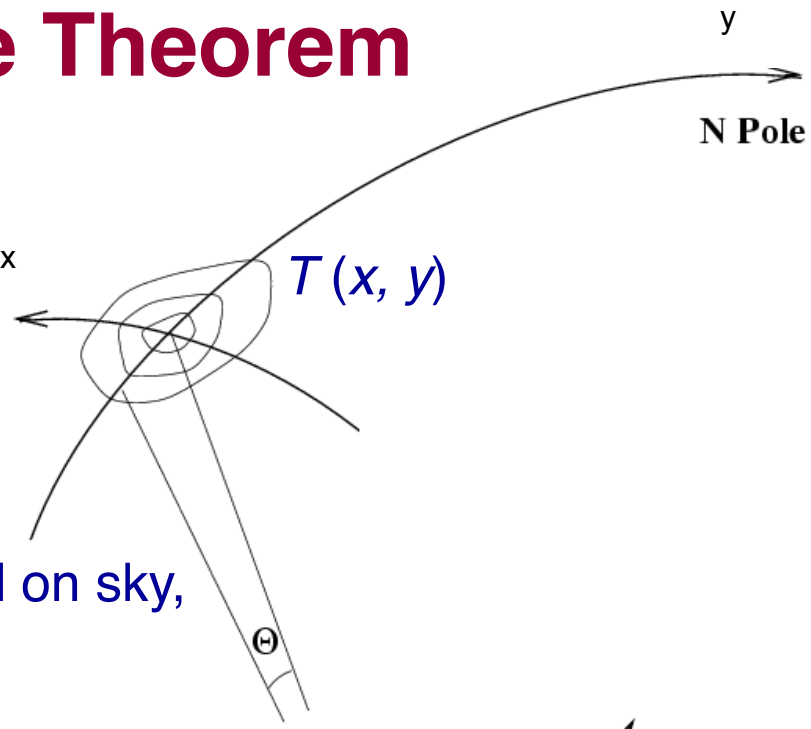
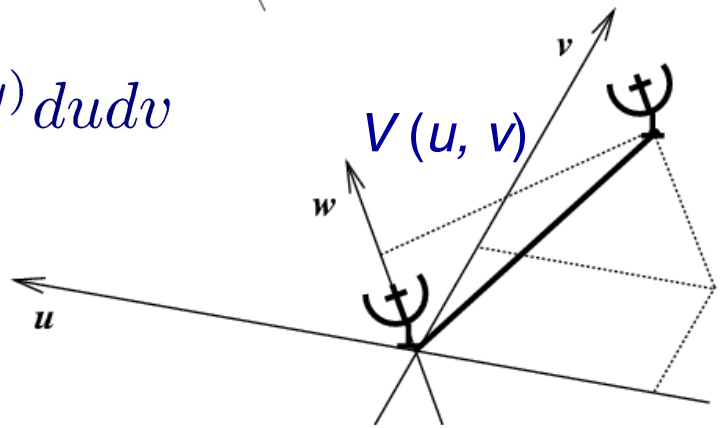
The Van Cittert Zernike Theorem



T (*x, y*): Intensity distribution on sky
('image plane')

V (*u, v*): Visibility distribution between telescopes (baselines projected on sky, '*u-v*-plane')

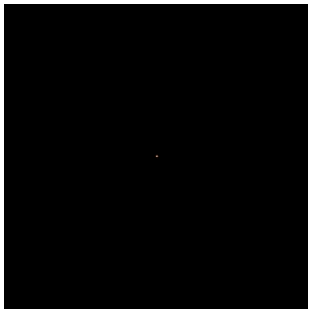
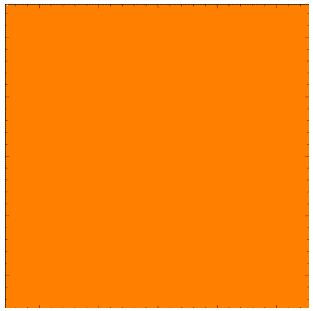
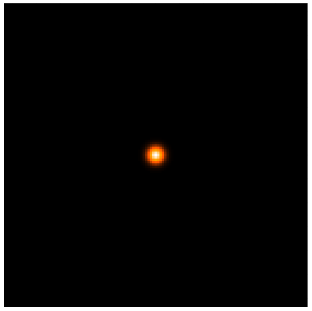
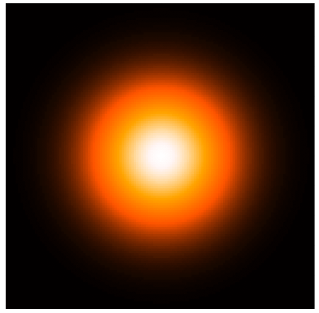
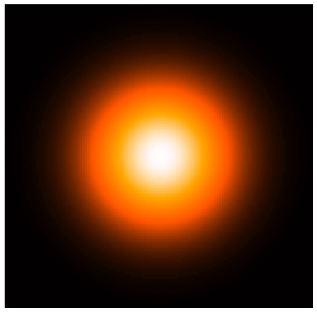
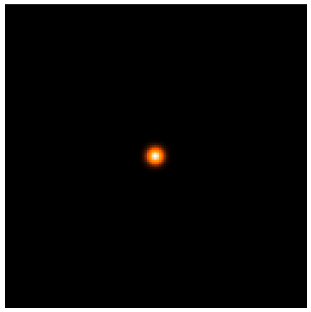
$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$$



Visibility is a complex number!

$V = |V| \exp(i\phi)$

Some 2D Fourier Transform Pairs

$T(x, y)$		$V(u, v)$
δ Function	 ⇌ 	Constant
Gaussian	 ⇌ 	Gaussian
Gaussian	 ⇌ 	Gaussian

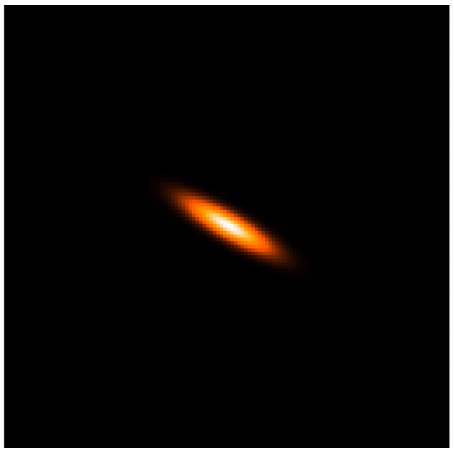
Small spatial scales mean large ‘spatial frequencies’ and vice-versa

2d Fourier transform pairs

$T(x, y)$

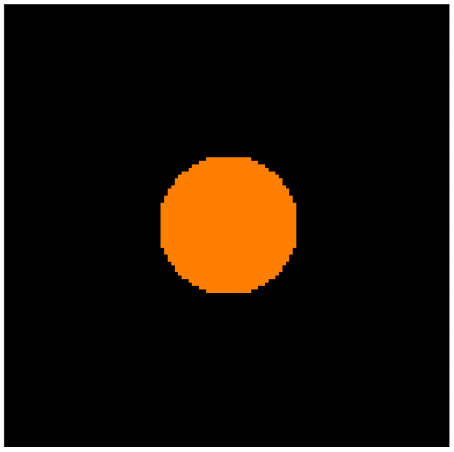
$V(u, v)$

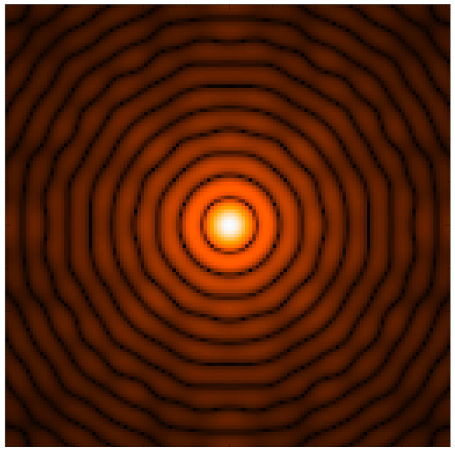
elliptical Gaussian



elliptical Gaussian

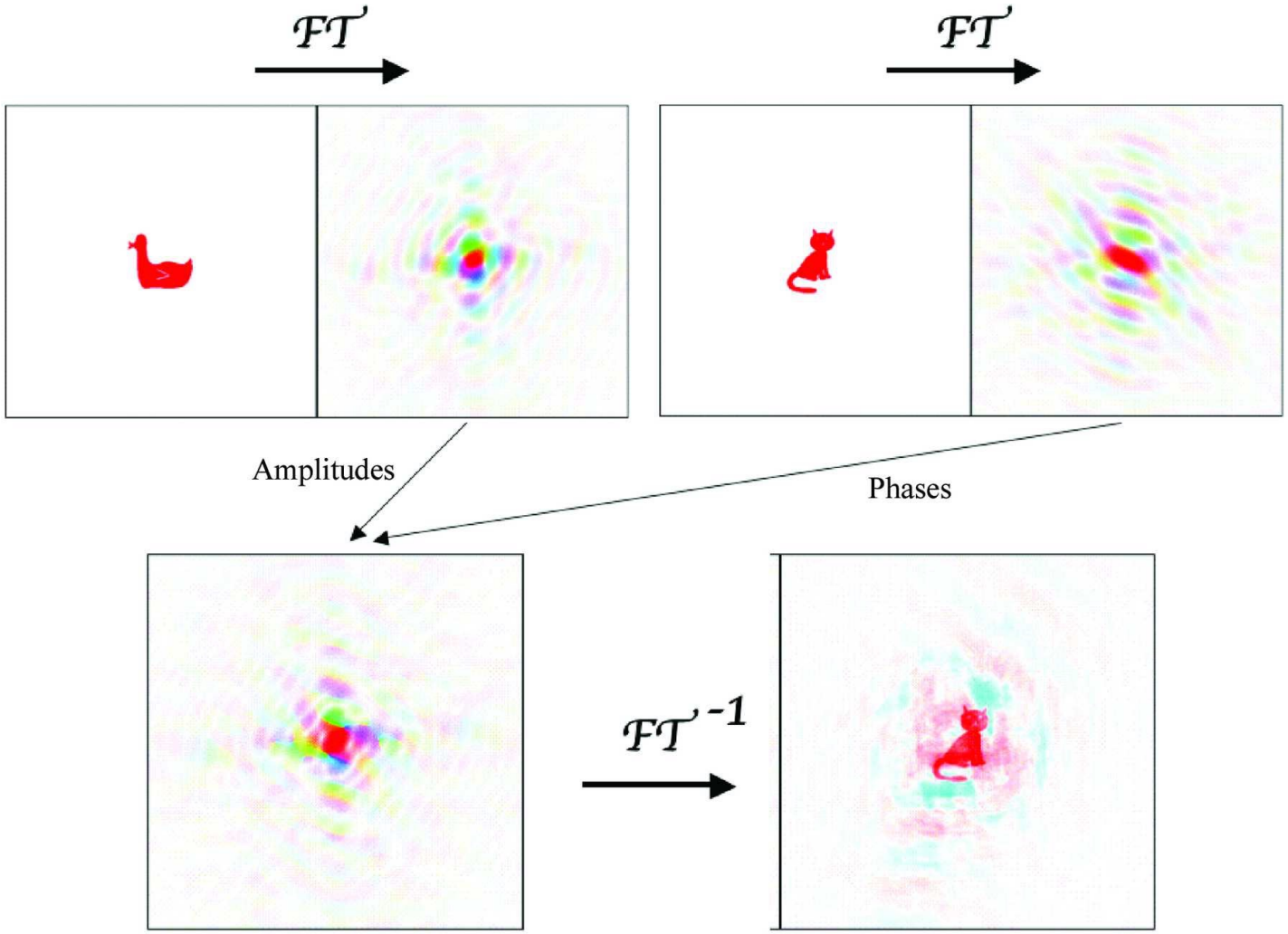
Disk





Bessel

Phase information critical!



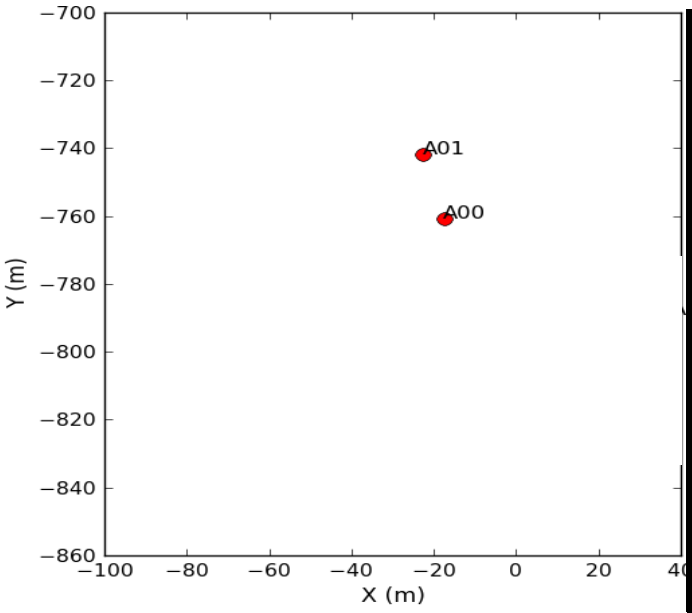
Astronomical interferometry

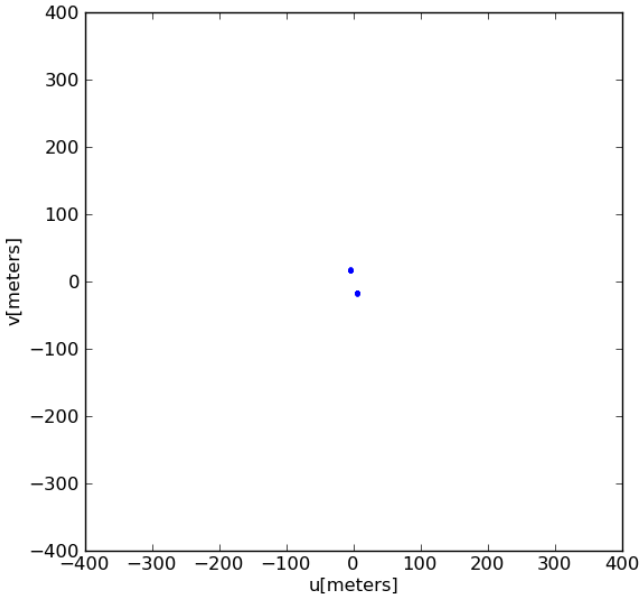
Two problems:

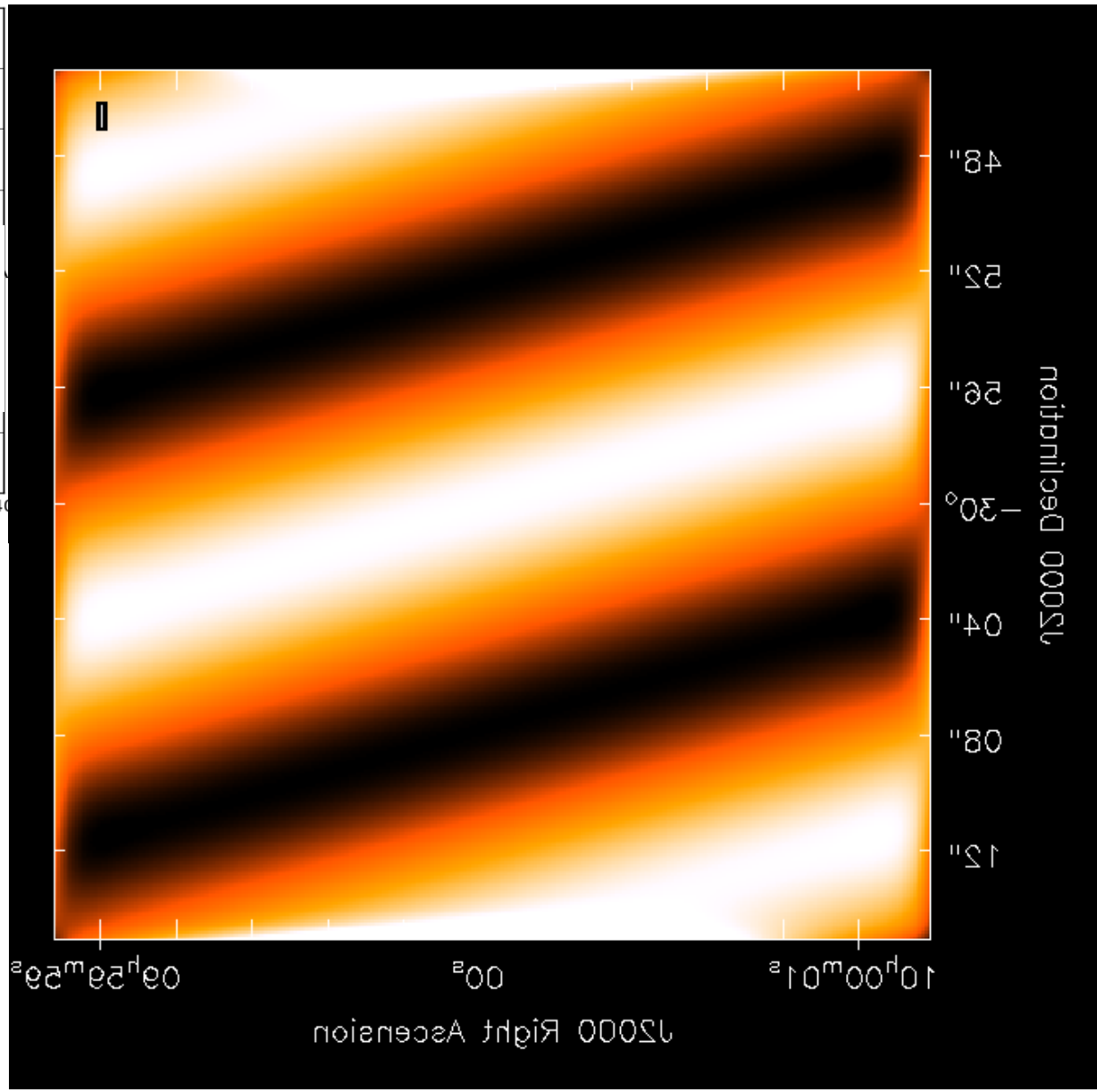
(1) How to recover flux distribution on sky from visibility measurements?

(2) How to deal with consequences of limited baseline sampling?
(specifically for imaging interferometry with a large array)

Limited baseline sampling (e.g., ALMA)







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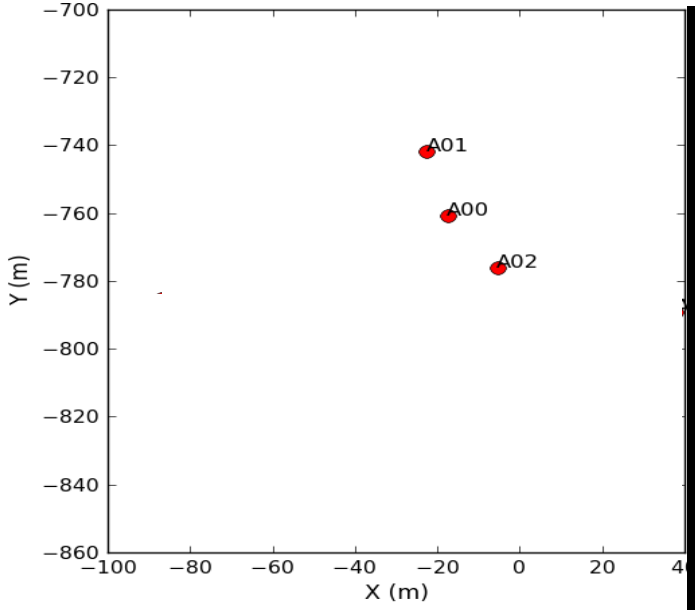

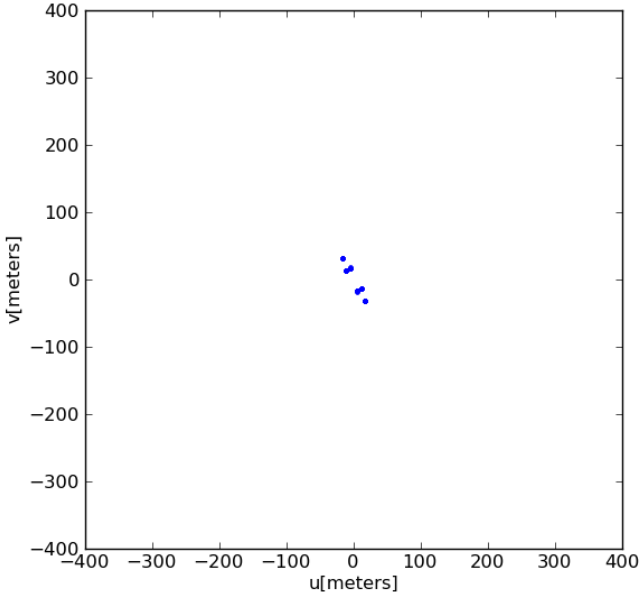

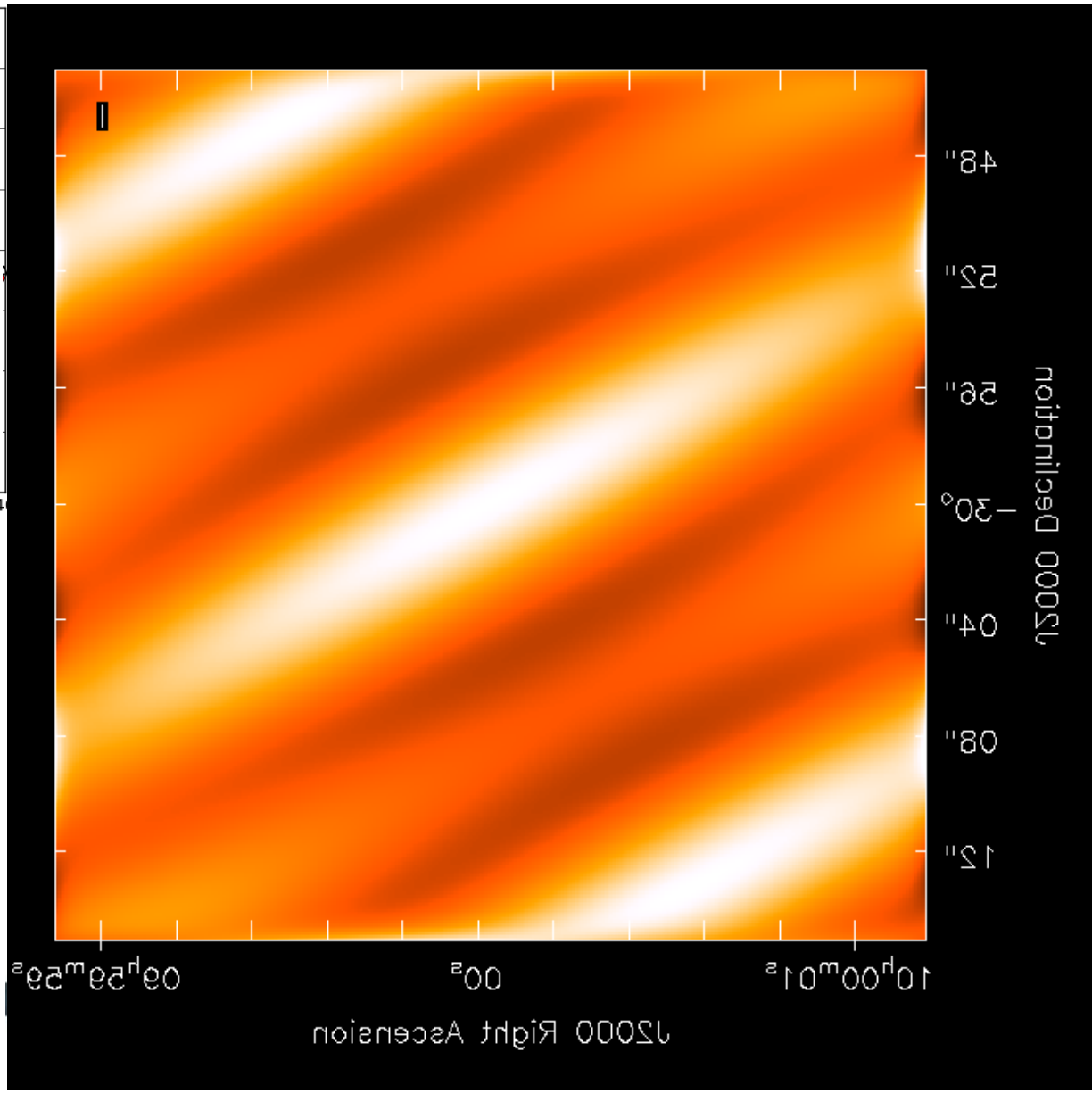

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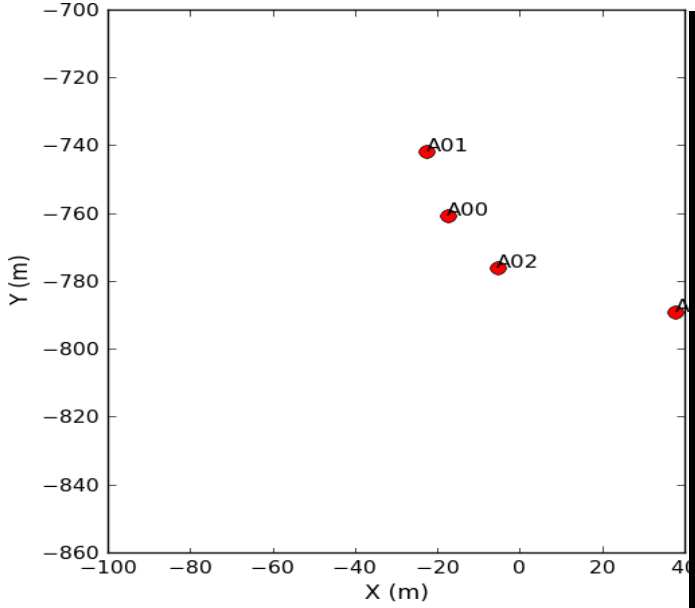

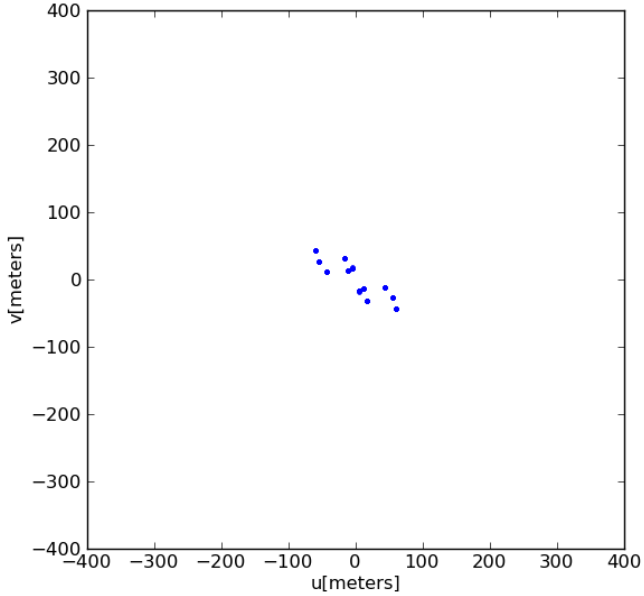

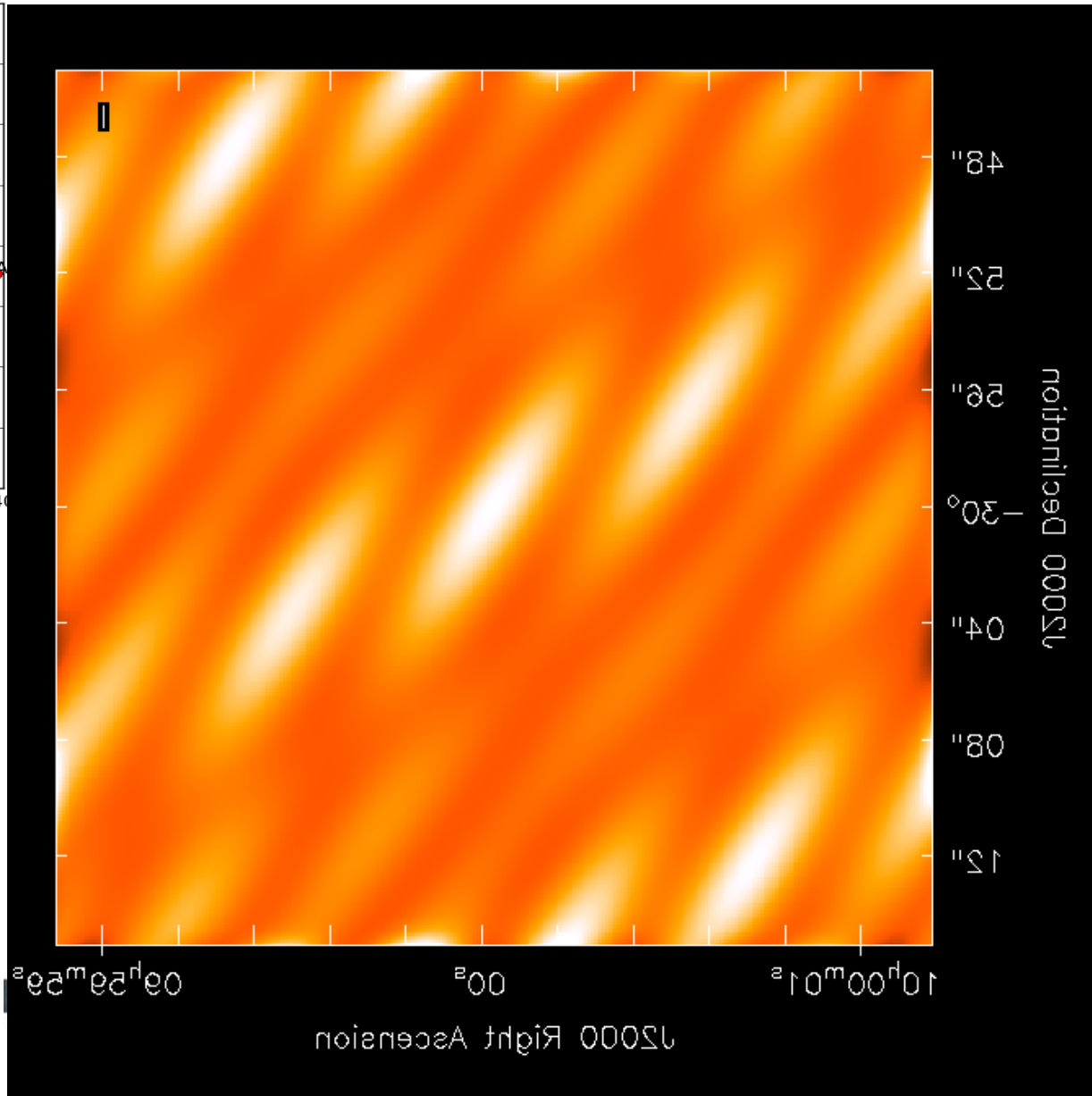

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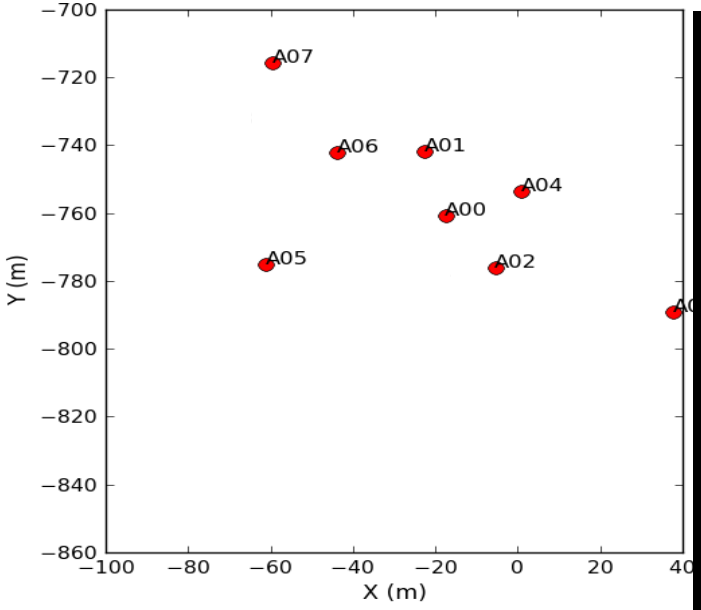

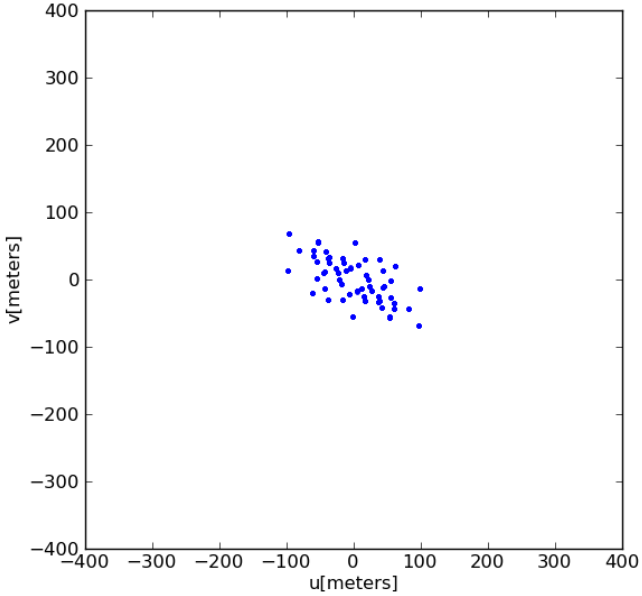

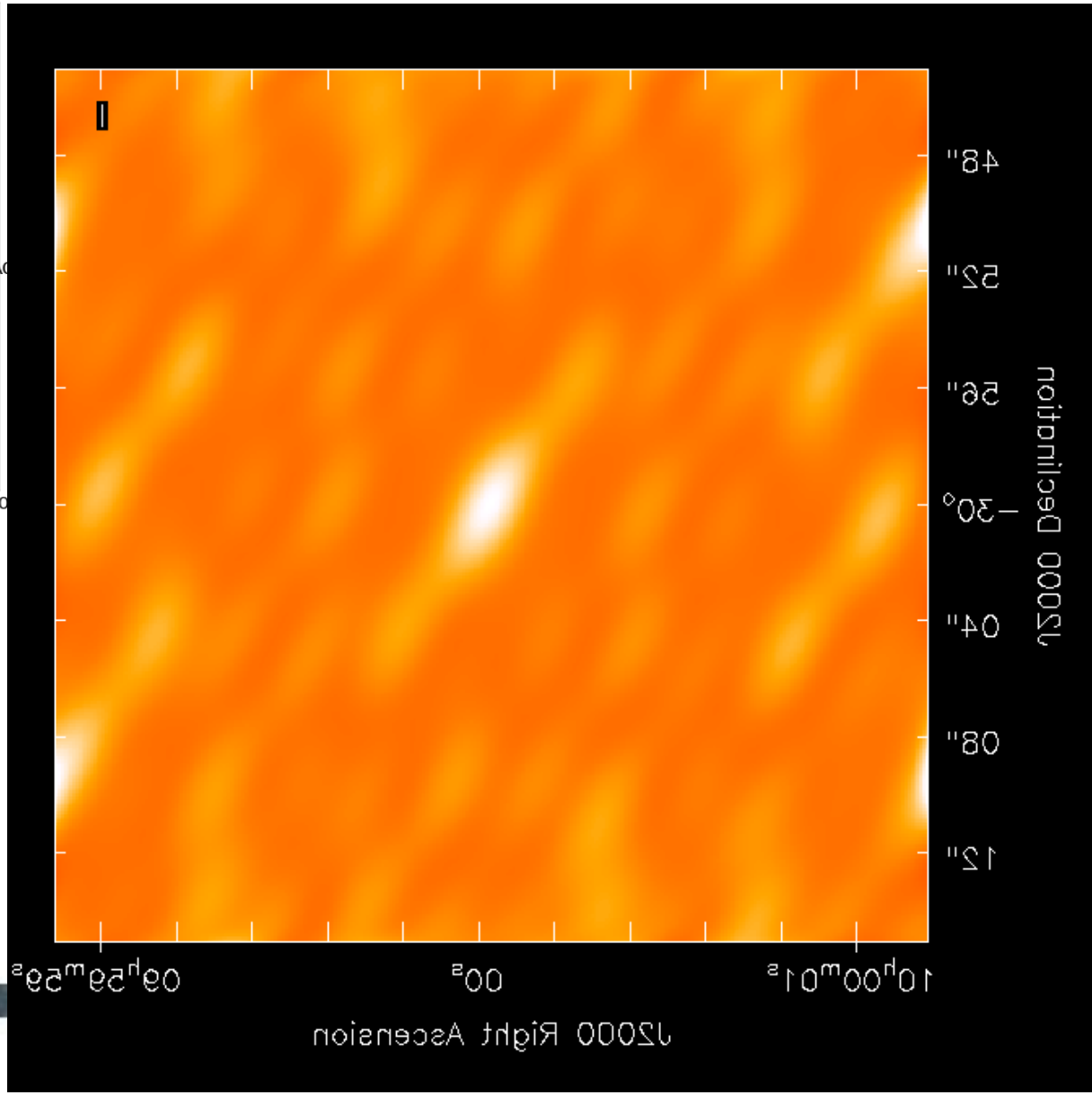

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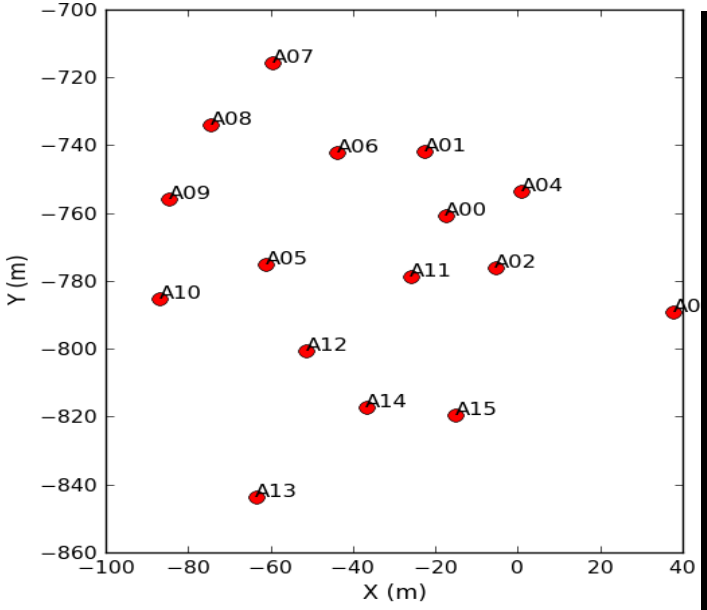

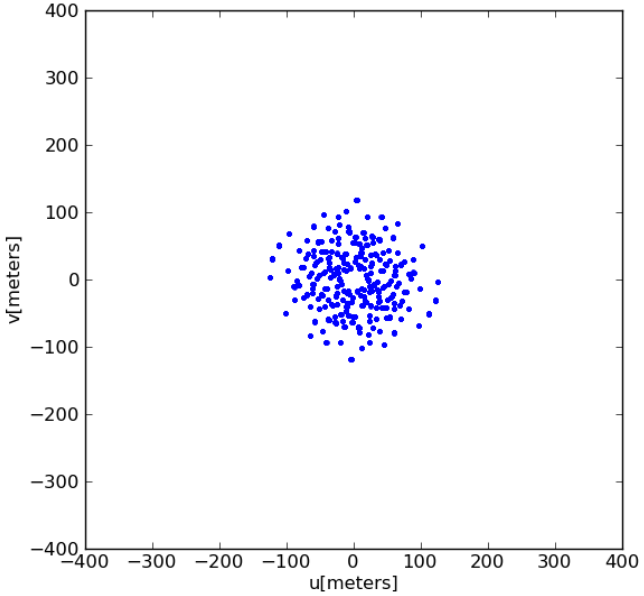

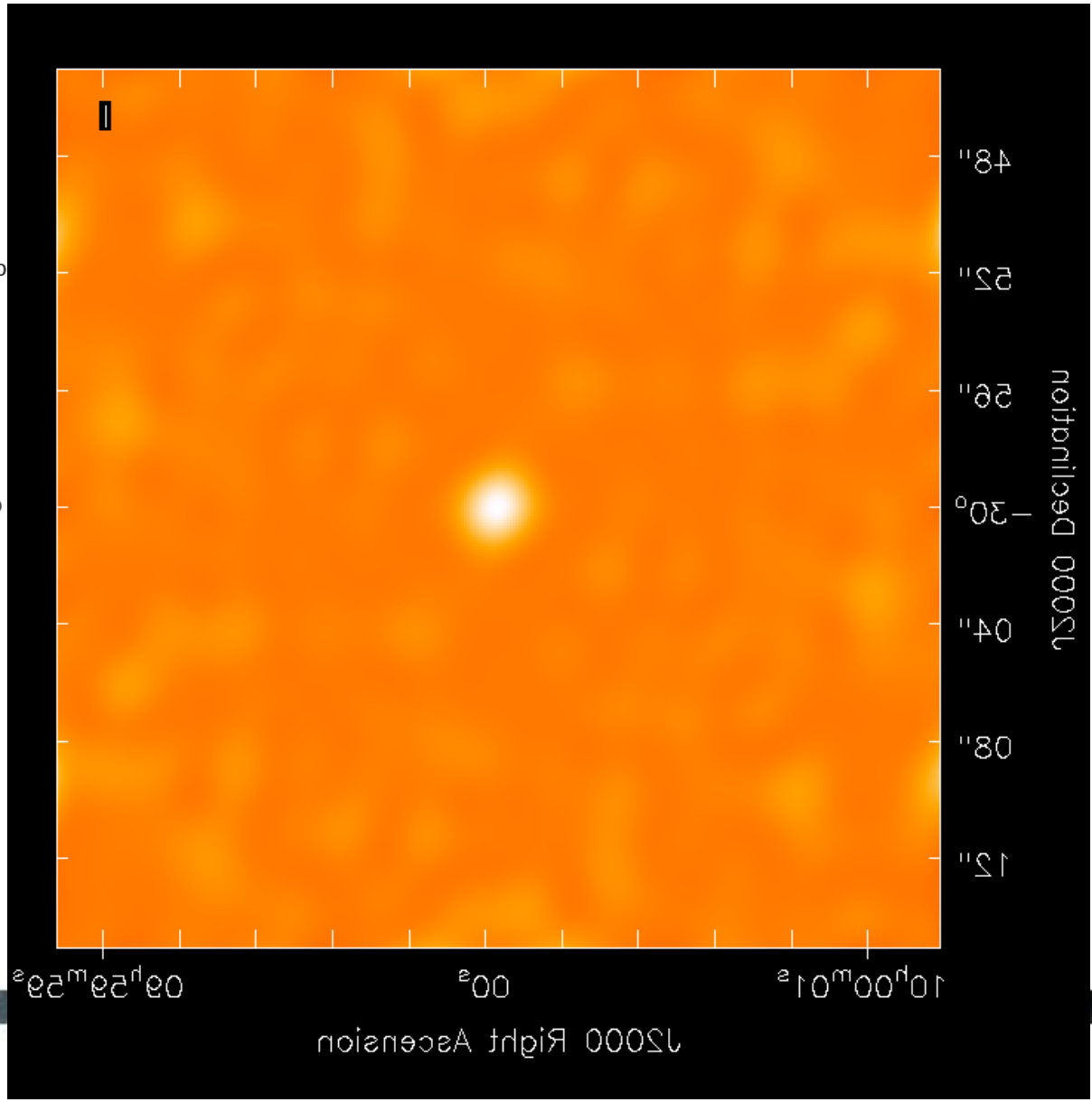

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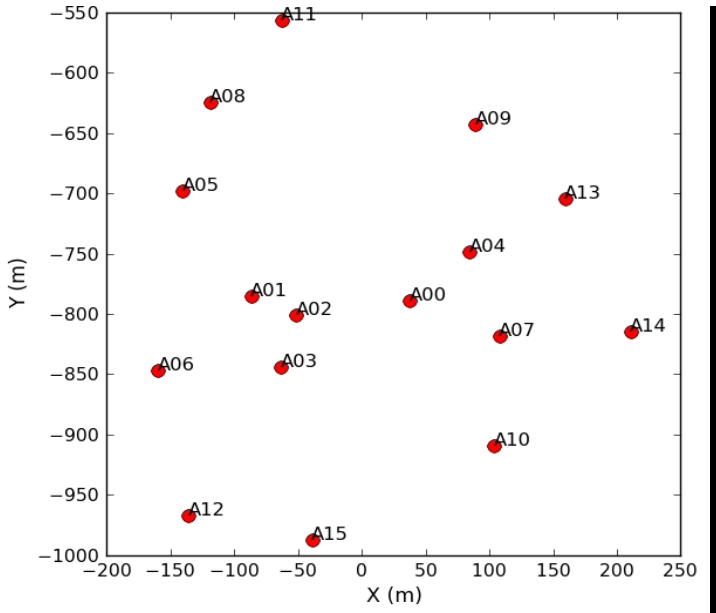

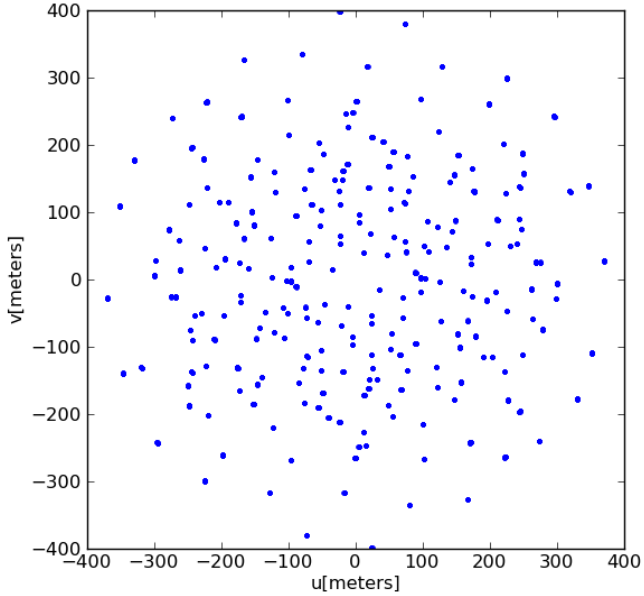

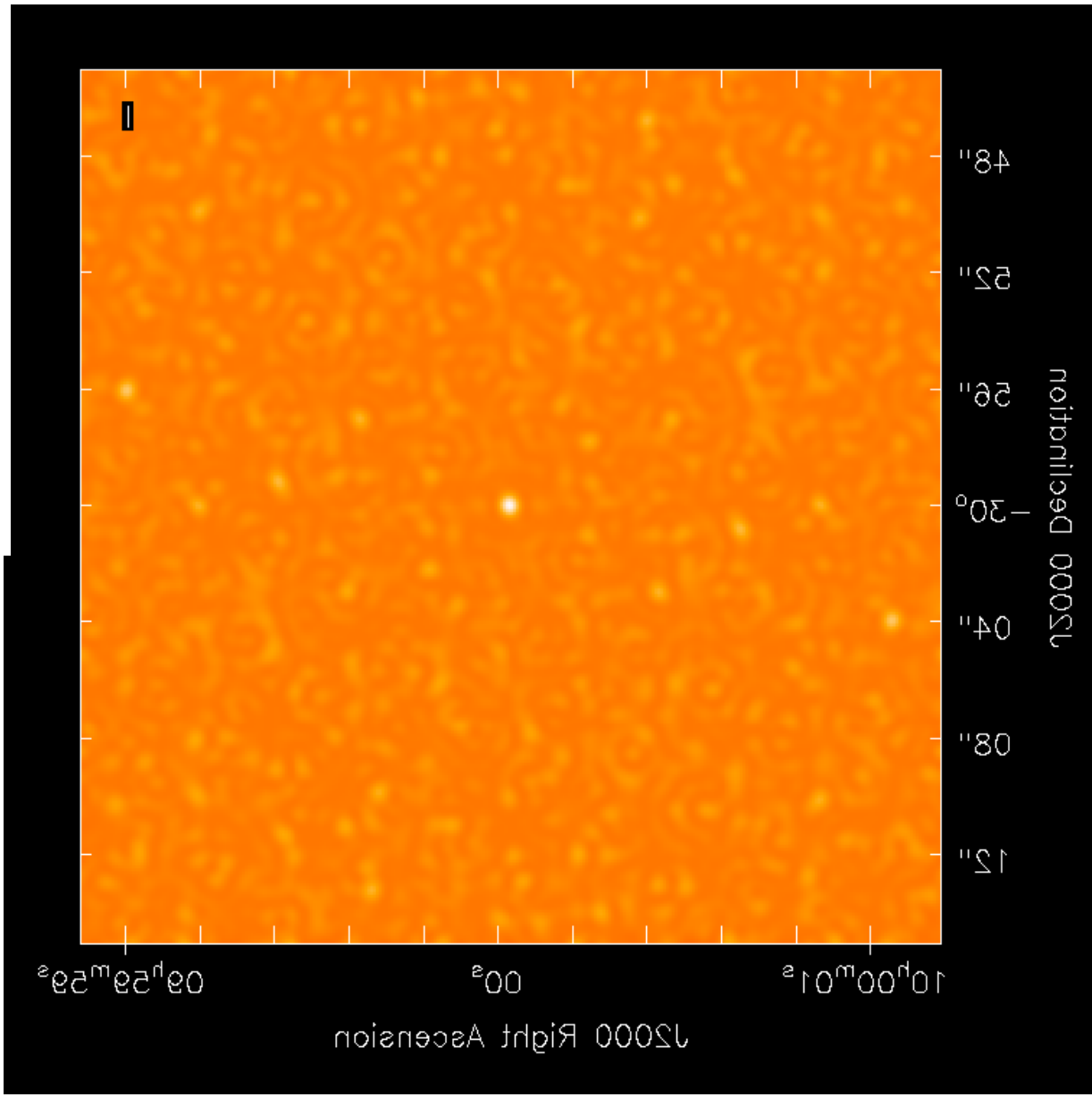

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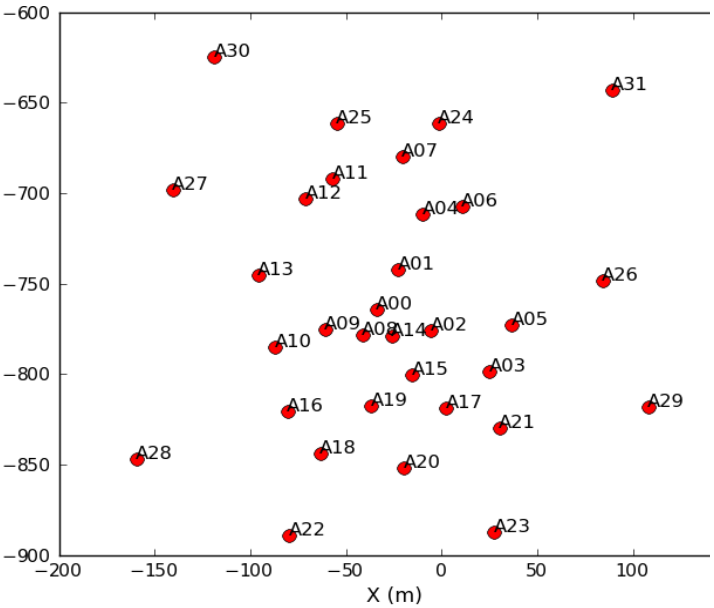

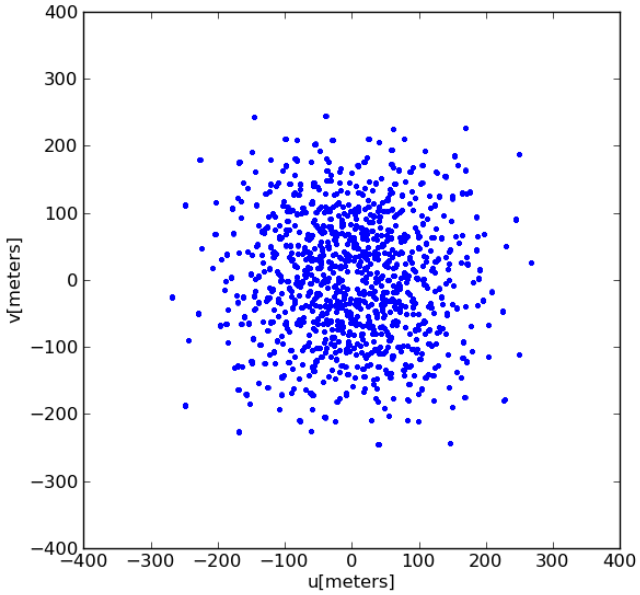

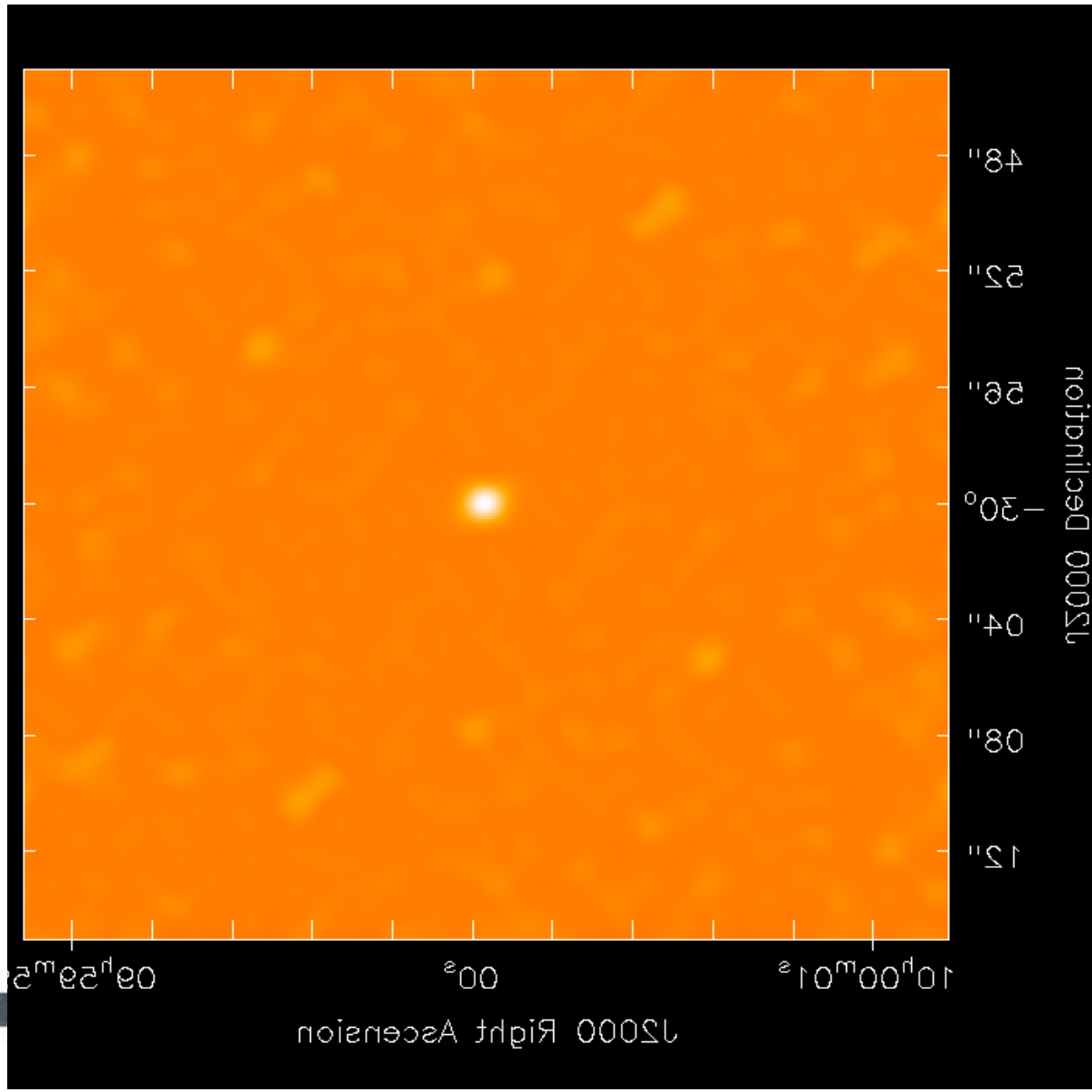

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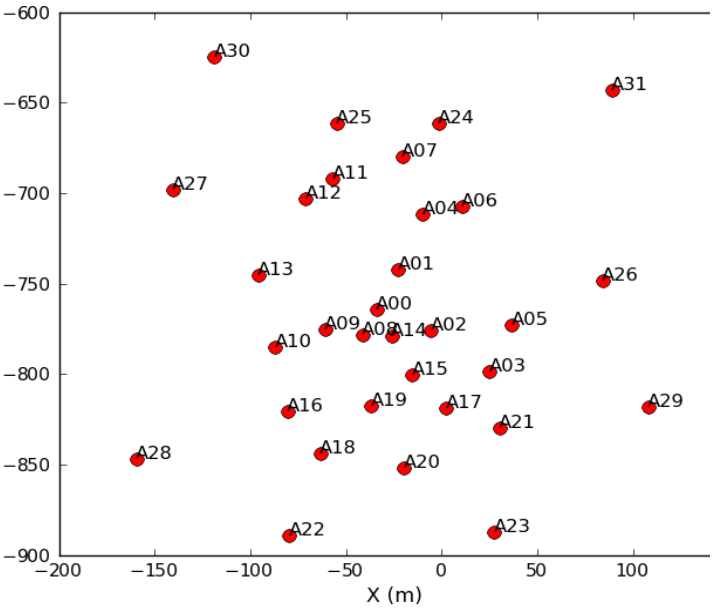

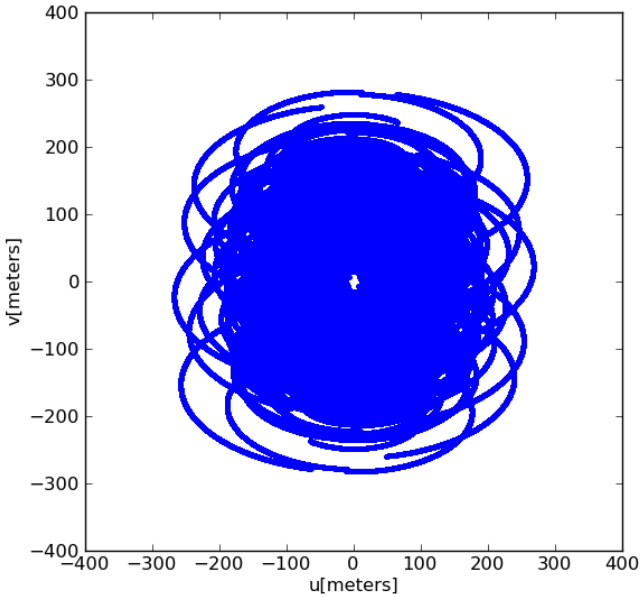

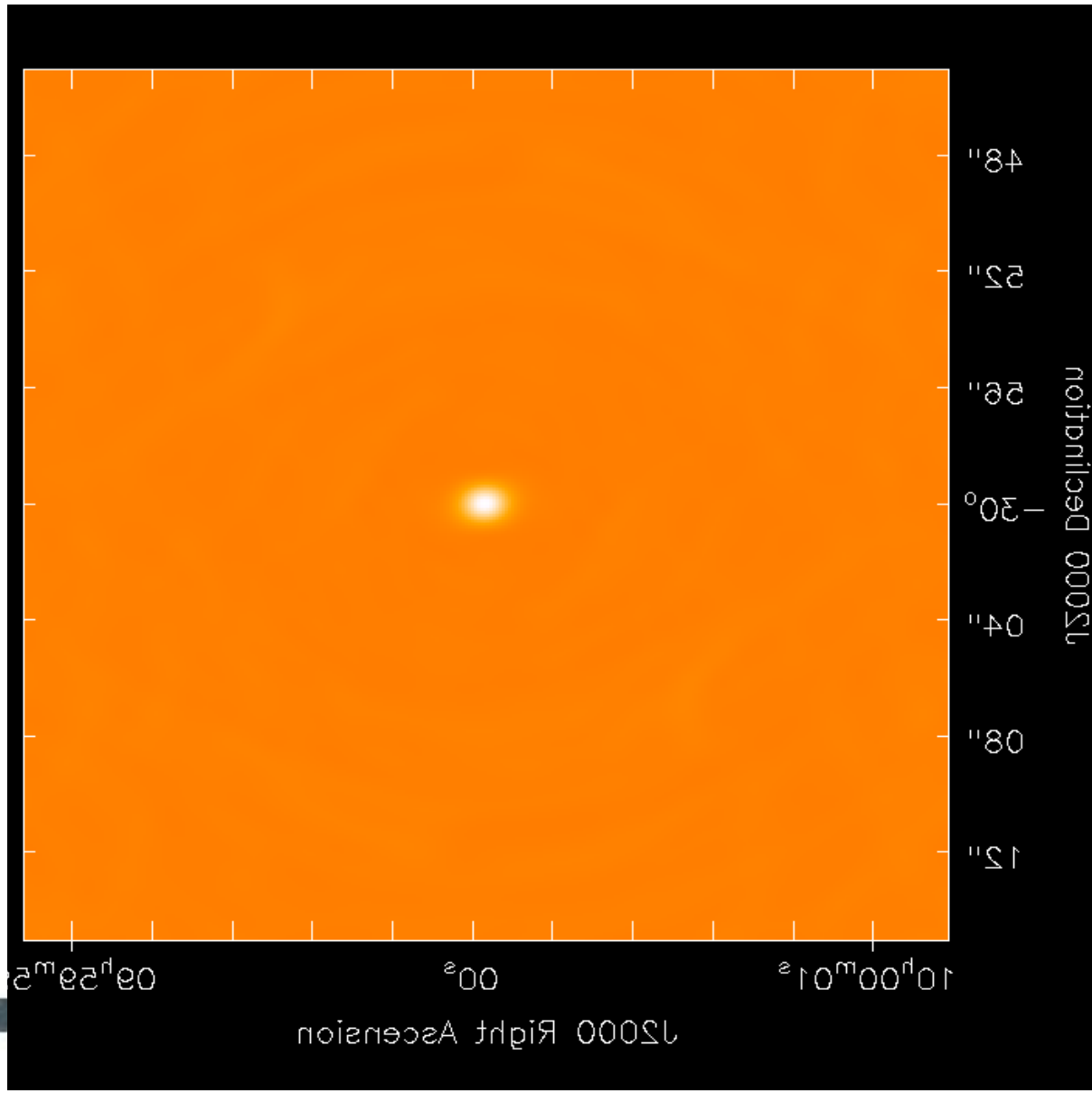

Important constraints: Angular scales!

- The **resolution** is given by the largest distance between antennas (maximum baseline *b*)
  $\boldsymbol{FWHM \sim \lambda / b_{max}}$

- The **field of view** is given by the diameter *d* of a single antenna (the resolution element of a single dish telescope)
  $\boldsymbol{FWHM \sim \lambda / d}$

- The **maximum recoverable scale** that can be imaged is given by the shortest distance between antennas
  $\boldsymbol{MRS \sim \lambda / b_{min}}$

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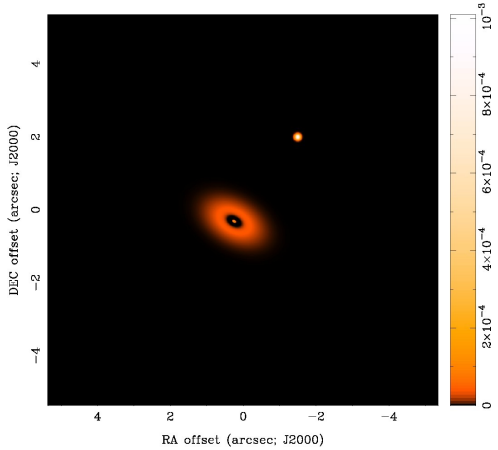
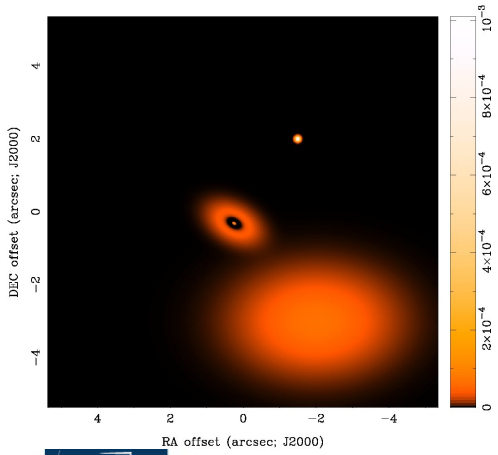
Maximum recoverable scale

Two sky models



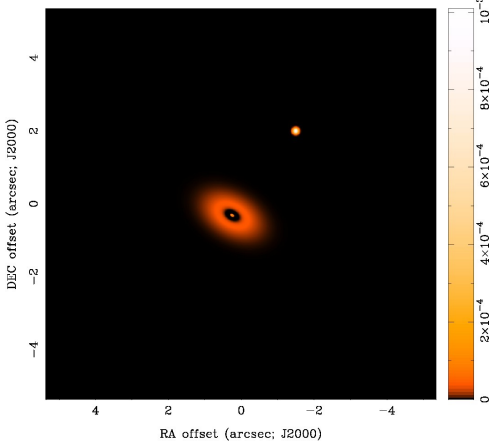


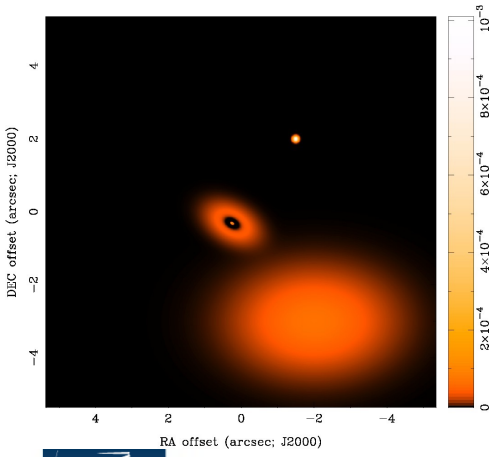
Courtesy D. Wilner

New Mexico CONSORTIUM

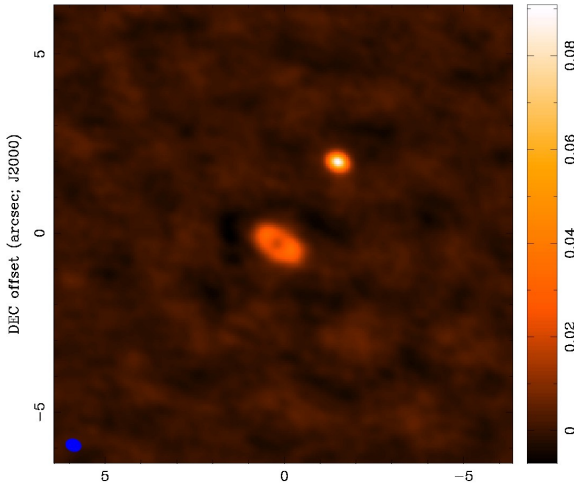
Maximum recoverable scale

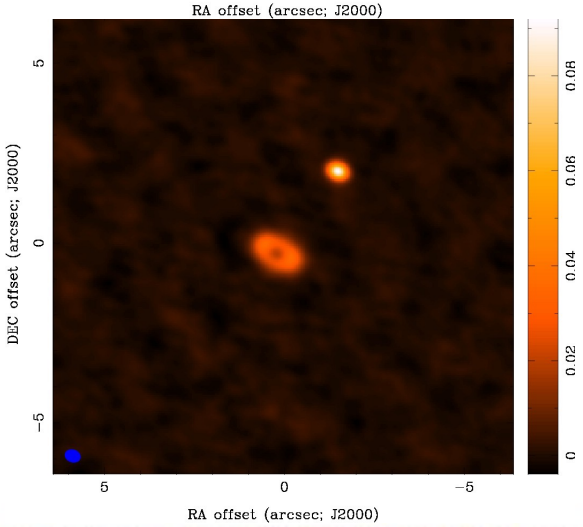
Two sky models





Simulated observation

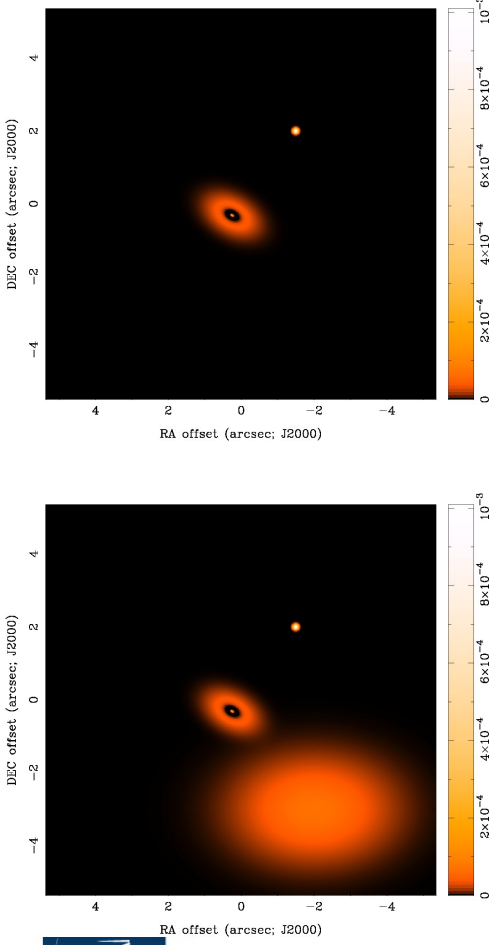




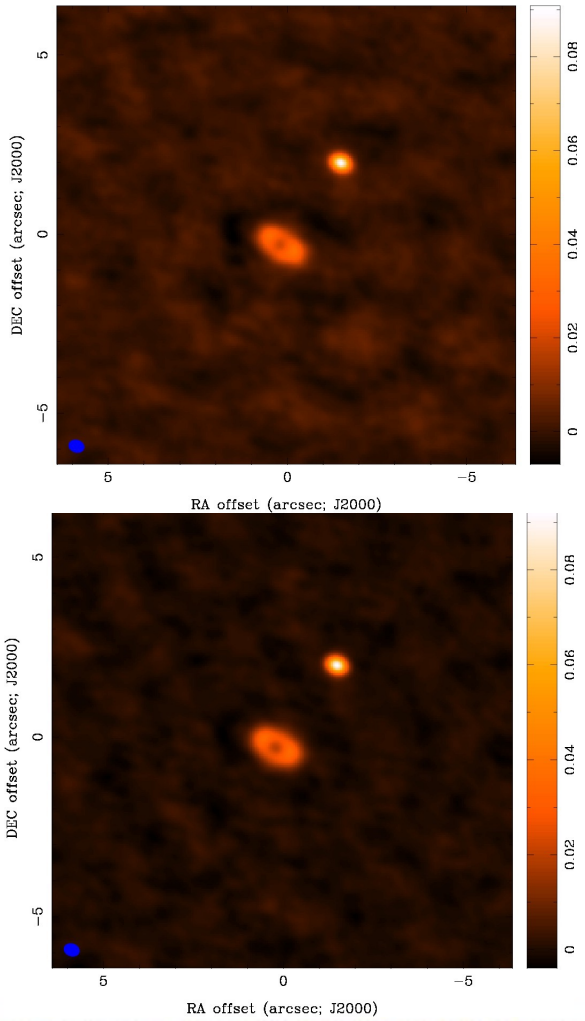
Courtesy D. Wilner

Maximum recoverable scale

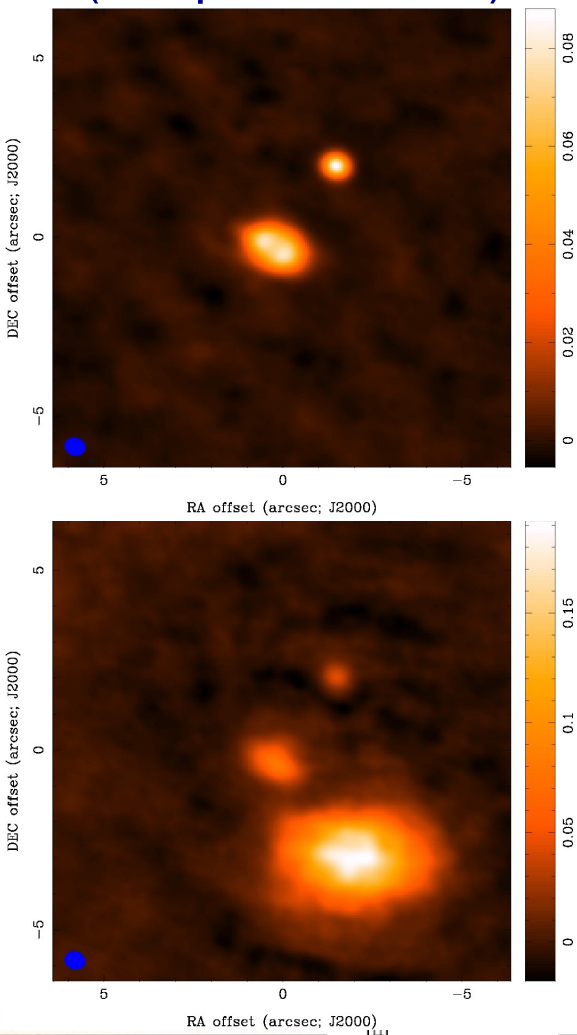
Two sky models



Simulated observation

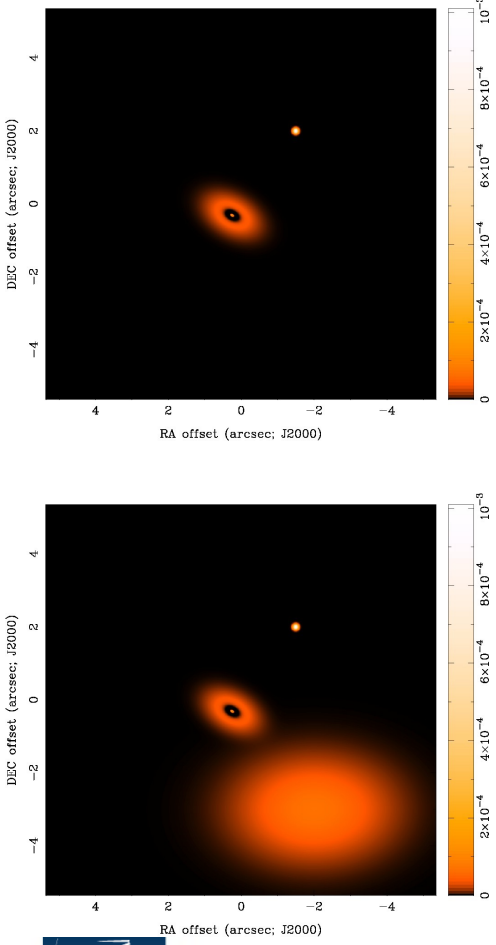


Simulated observation (all spatial scales)

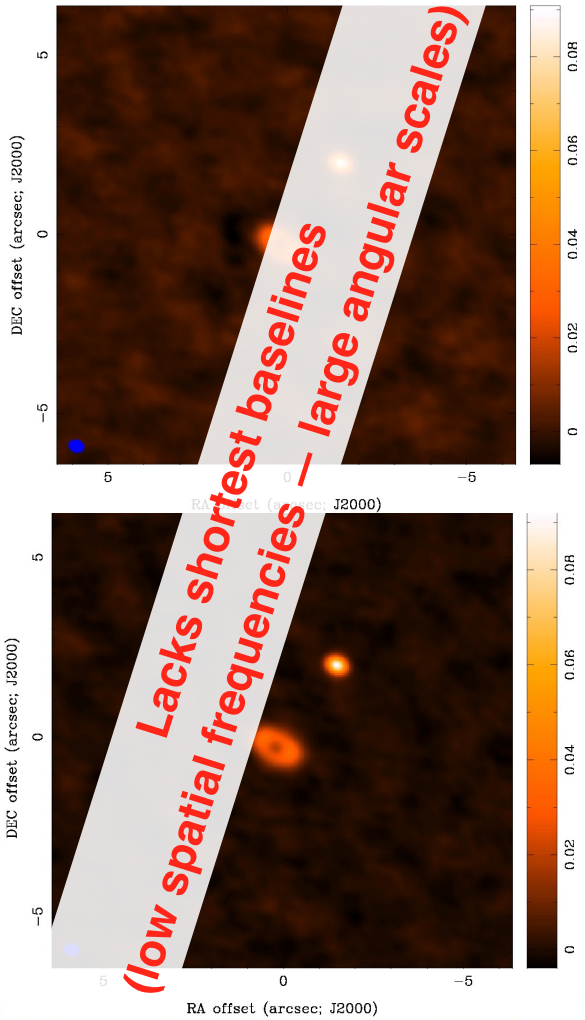


Maximum recoverable scale

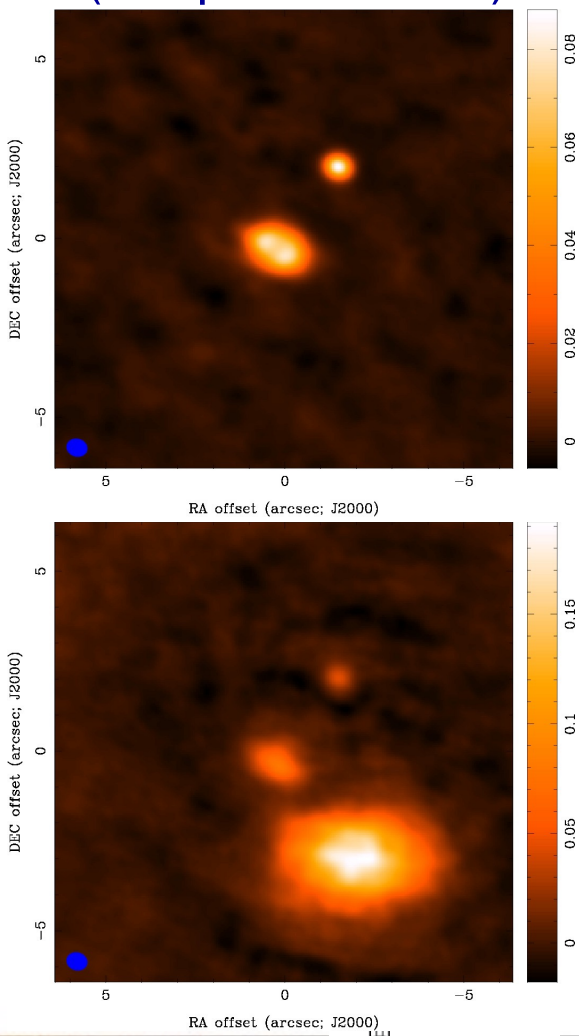
Two sky models



Simulated observation



Simulated observation (all spatial scales)



NRAO

New Mexico CONSORTIUM

(3) Introduction to Radio Interferometry

Steve Ertel

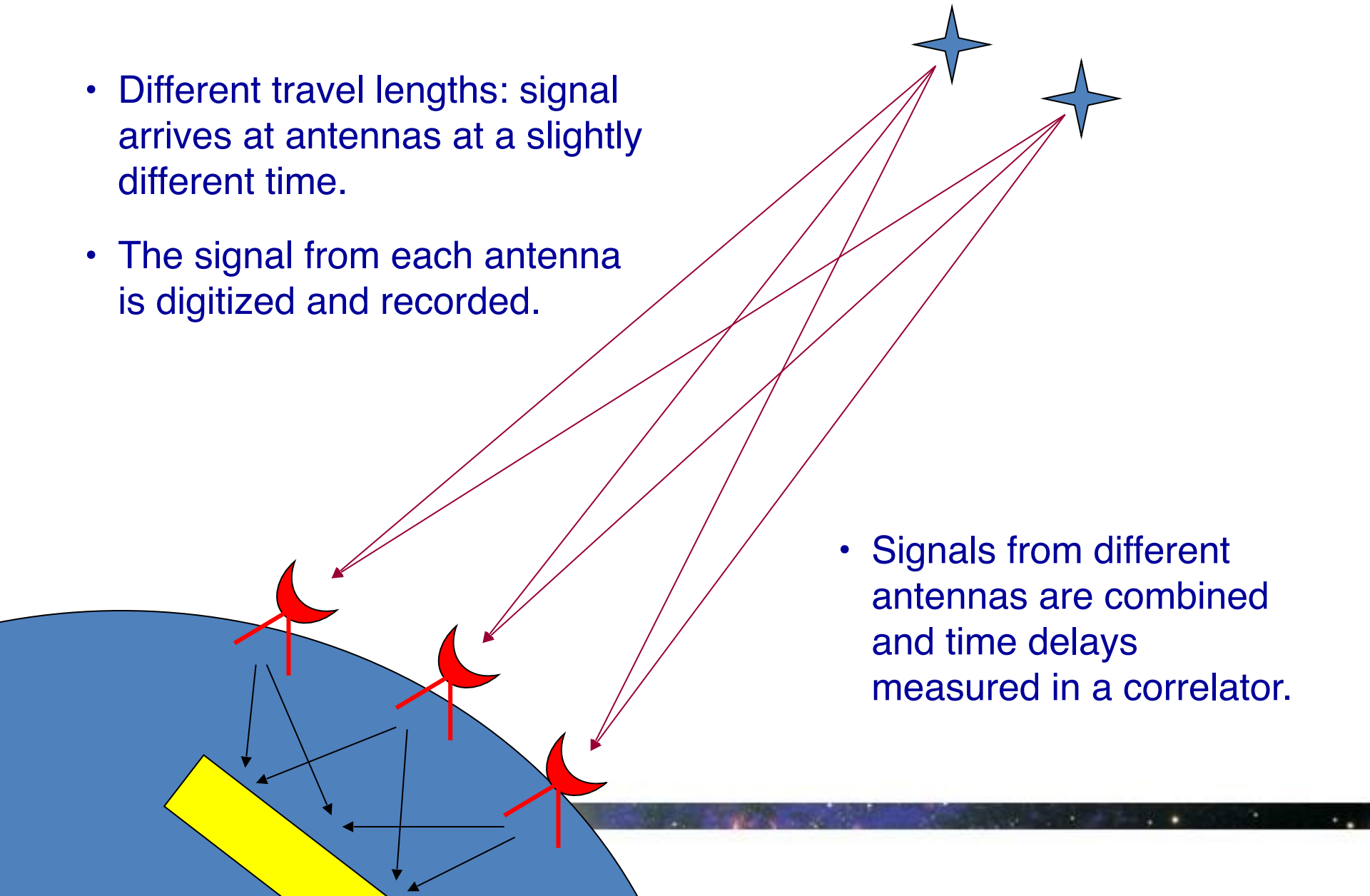
Includes material from:
Alison Peck, Jim Braatz, Ashley Bemis, Sabrina Stierwalt

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Very Long Baseline Array

NRAO

How does ALMA do interferometry?

- Different travel lengths: signal arrives at antennas at a slightly different time.
- The signal from each antenna is digitized and recorded.

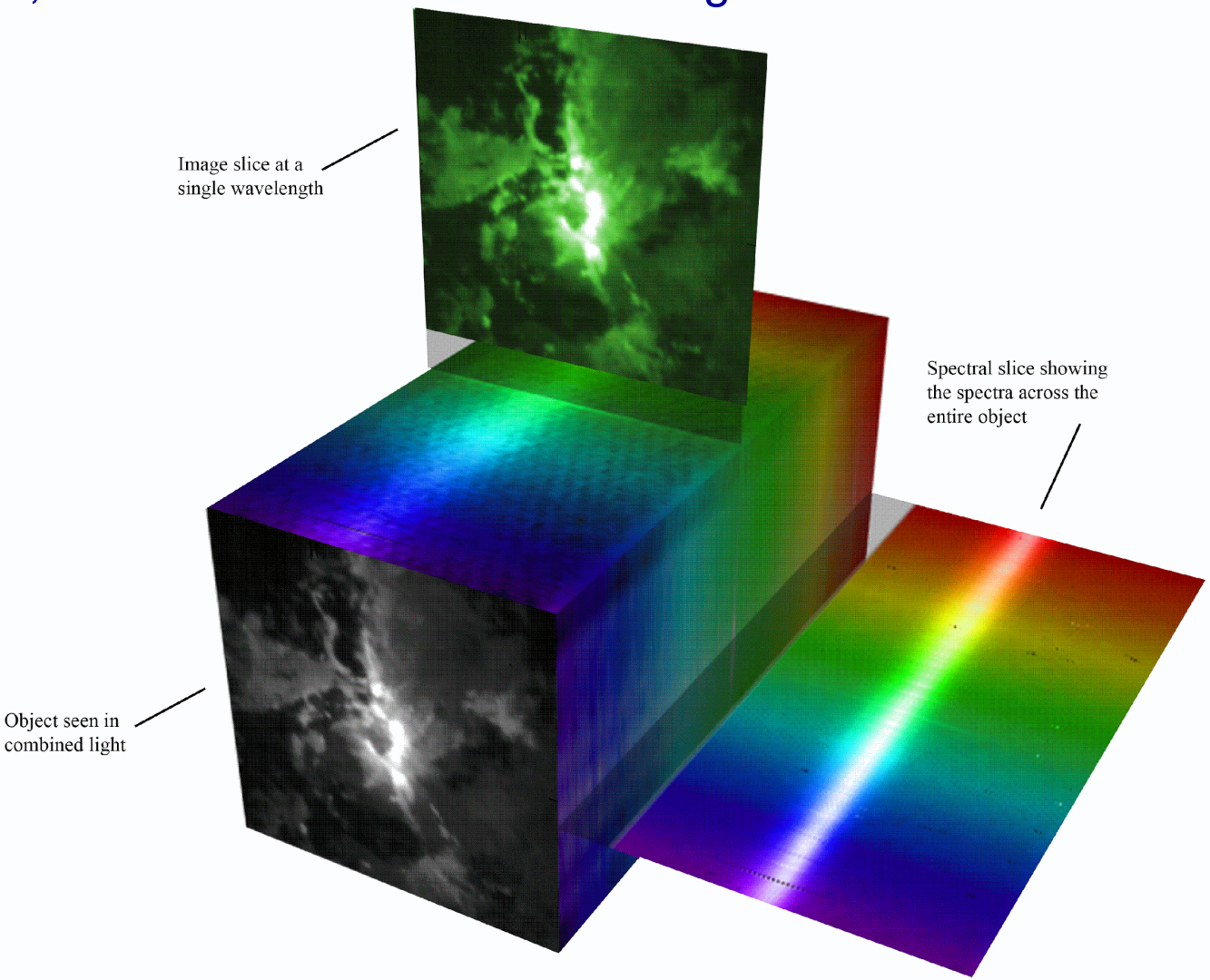


- Signals from different antennas are combined and time delays measured in a correlator.

Heterodyne: frequency information

Final data (typically) have the form of a spectral image cube:

2d images, third dimension is the wavelength!

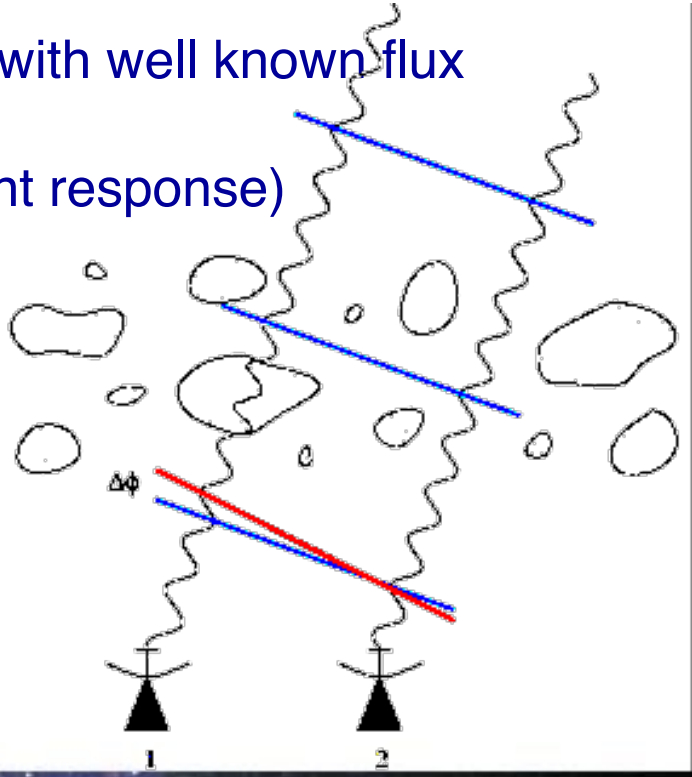


Calibration in radio interferometry

Calibration is handled by the observatory! But here's a summary.

Need to calibrate:

- Absolute flux scale
  - Similar to photometric calibrator
  - Bright Solar system object or quasar with well known flux
- Bandpass (frequency dependent instrument response)
  - Similar to telluric calibrator
  - Bright quasar
- Gain (phase and visibility amplitude)
  - Similar to adaptive optics
  - Bright quasar



Some good references

- Thompson, A.R., Moran, J.M., Swensen, G.W. 2004 “Interferometry and Synthesis in Radio Astronomy”, 2nd edition (Wiley-VCH)
  There’s a 3rd edition of this and it is online for FREE
- Perley, R.A., Schwab, F.R., Bridle, A.H. eds. 1989 ASP Conf. Series 6 “Synthesis Imaging in Radio Astronomy” (San Francisco: ASP)
  –www.aoc.nrao.edu/events/synthesis
- IRAM Interferometry Schoolproceedings
  –www.iram.fr/IRAMFR/IS/IS2008/archive.html