basic!
introduction to radio/submm interferometry

2014 La Serena School for Data Science
Sebastian Perez @ MAD / Universidad de Chile

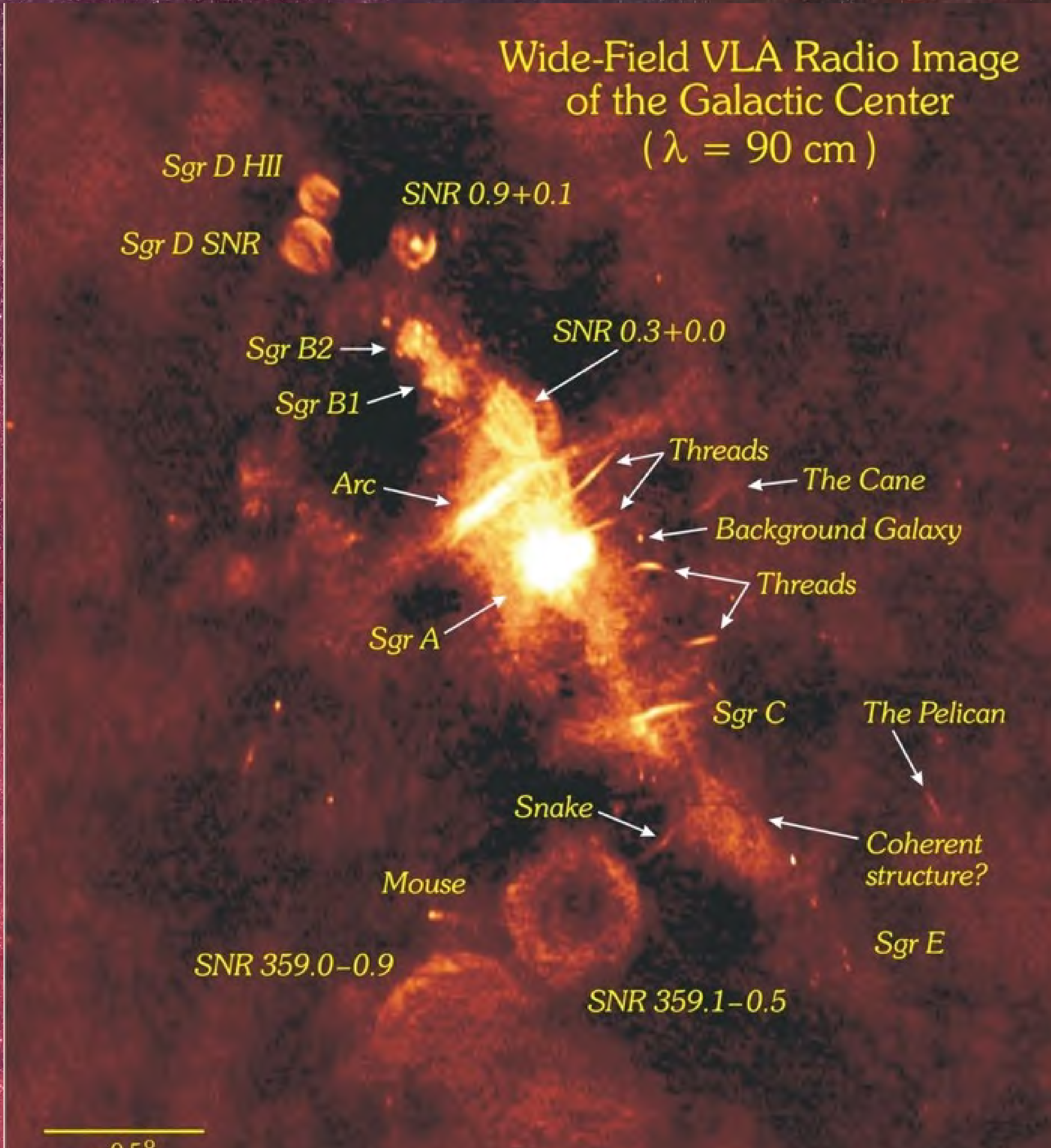
lecture overview

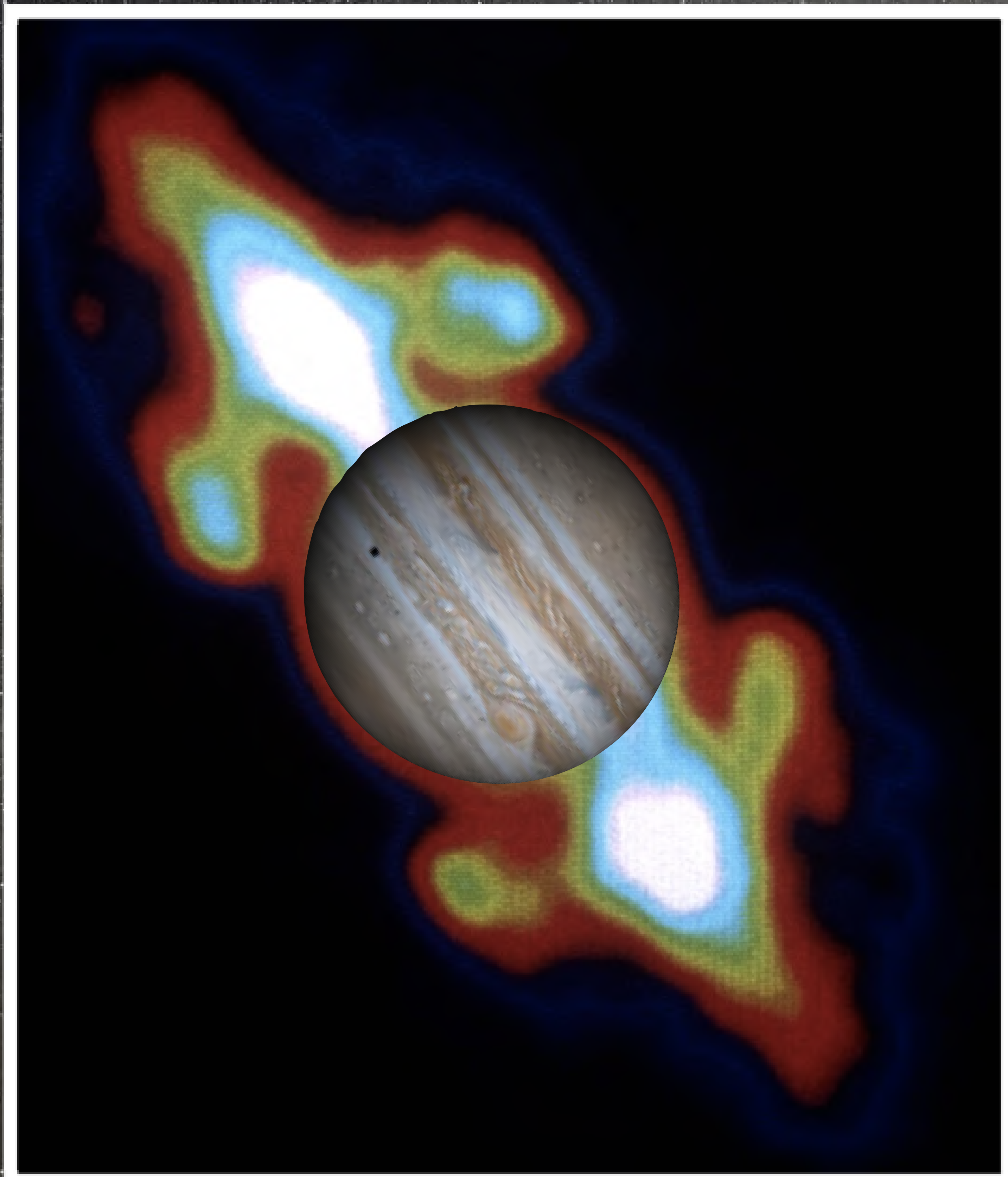
1) a bit of **HISTORY: radio astronomy / interferometry**
2) motivation - **why interferometry?**
3) basics: **interferometers / visibilities / uv-plane**
4) **imaging**
5) **deconvolution**
6) **power of interferometry via 2 cool examples**

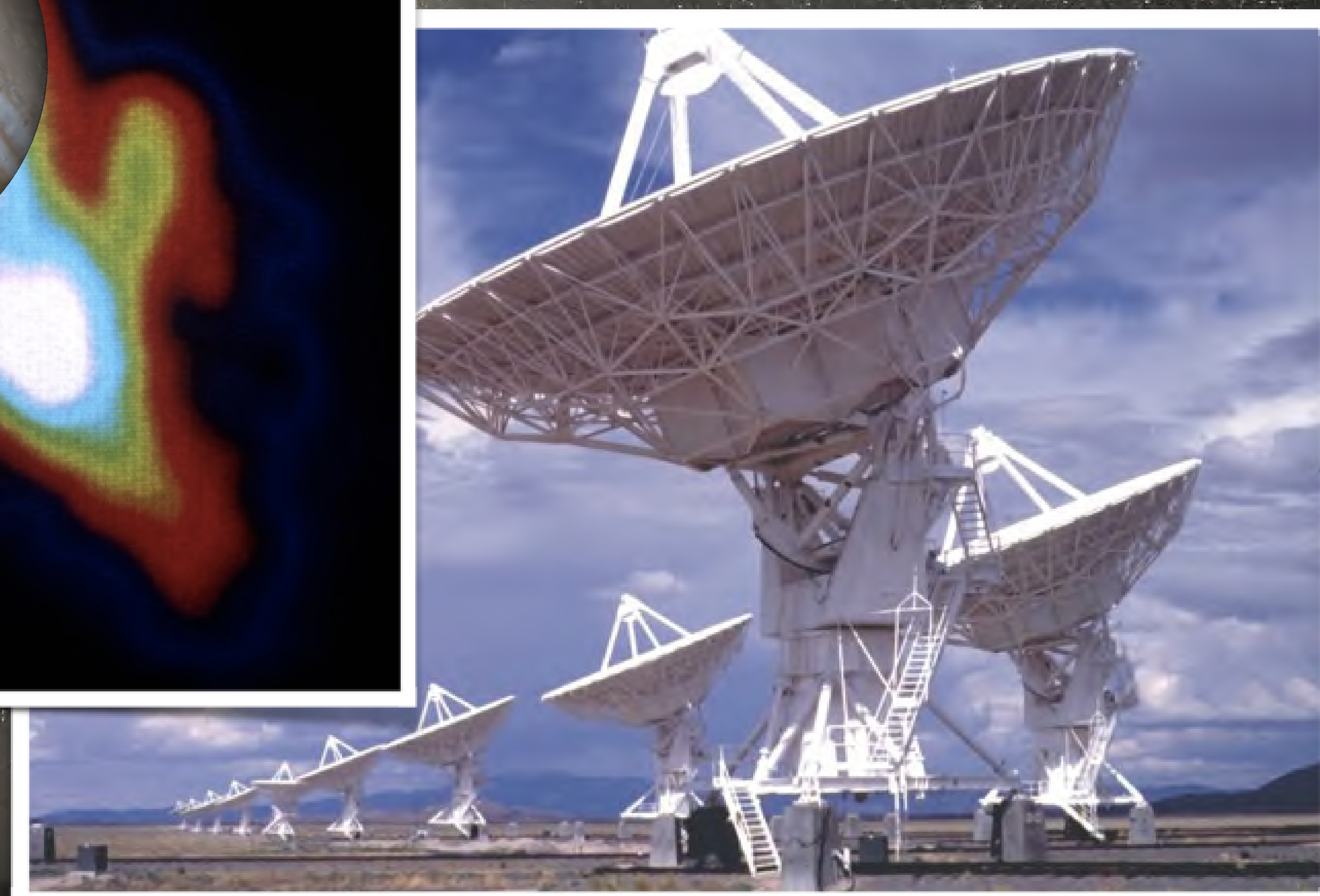
For thousands of years human observation of the Universe was limited to the visible spectrum

Karl Jansky's serendipitous discovery

an engineer of Bell Laboratories, investigating static that interfered with short wave transatlantic voice transmissions. Using a large directional antenna, Jansky noticed that his analog pen-and-paper recording system kept recording a repeating signal of unknown origin. Since the signal peaked about every 24 hours, Jansky originally suspected the source of the interference was the Sun crossing the view of his directional antenna.


Wide-Field VLA Radio Image
of the Galactic Center
(λ = 90 cm)
Sgr D HII
SNR 0.9+0.1
Sgr D SNR
Sgr B2
SNR 0.3+0.0
Sgr B1
Threads
The Cane
Arc
Background Galaxy
Threads
Sgr A
Sgr C
The Pelican
Snake
Coherent
structure?
Mouse
Sgr E
SNR 359.0–0.9
SNR 359.1–0.5



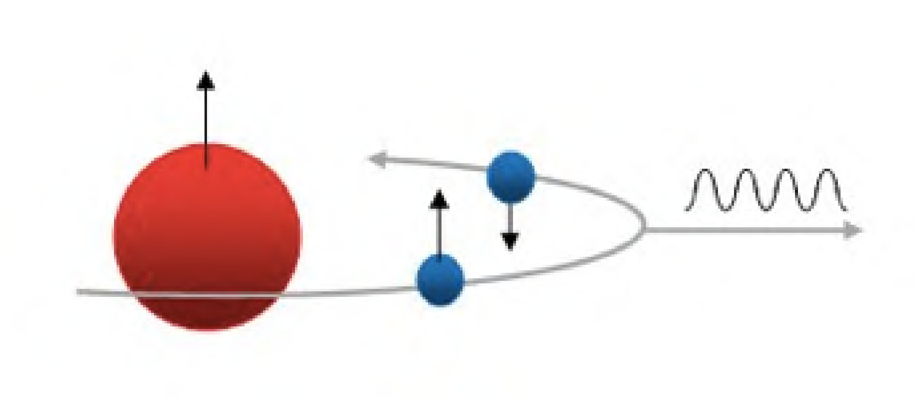


Motivation: why interferometry?

answer: all has to do with **diffraction**
which is the limiting resolution of your telescope.

$$\theta_{\text{ang res}} \approx \frac{\lambda}{D}$$

largest fully steerable radio dish: GBT with 100m dish



```
$theta = (21e-2/100) * 206265 / 60
       = 7.2 arcminutes :(
```

to reach 1 arc sec resolution you need a **42 km aperture!!**

studied radio signals emanating from the Sun

built the first multi-element astronomical radio interferometer in 1946.

production of a number of important radio source catalogues, including the Third Cambridge (3C) Catalogue, which helped lead to the discovery of the first Quasar.

Motivation: why interferometry?

there is a need to develop a better technique than just building larger and larger antennas..

for an interferometer, resolution is given by

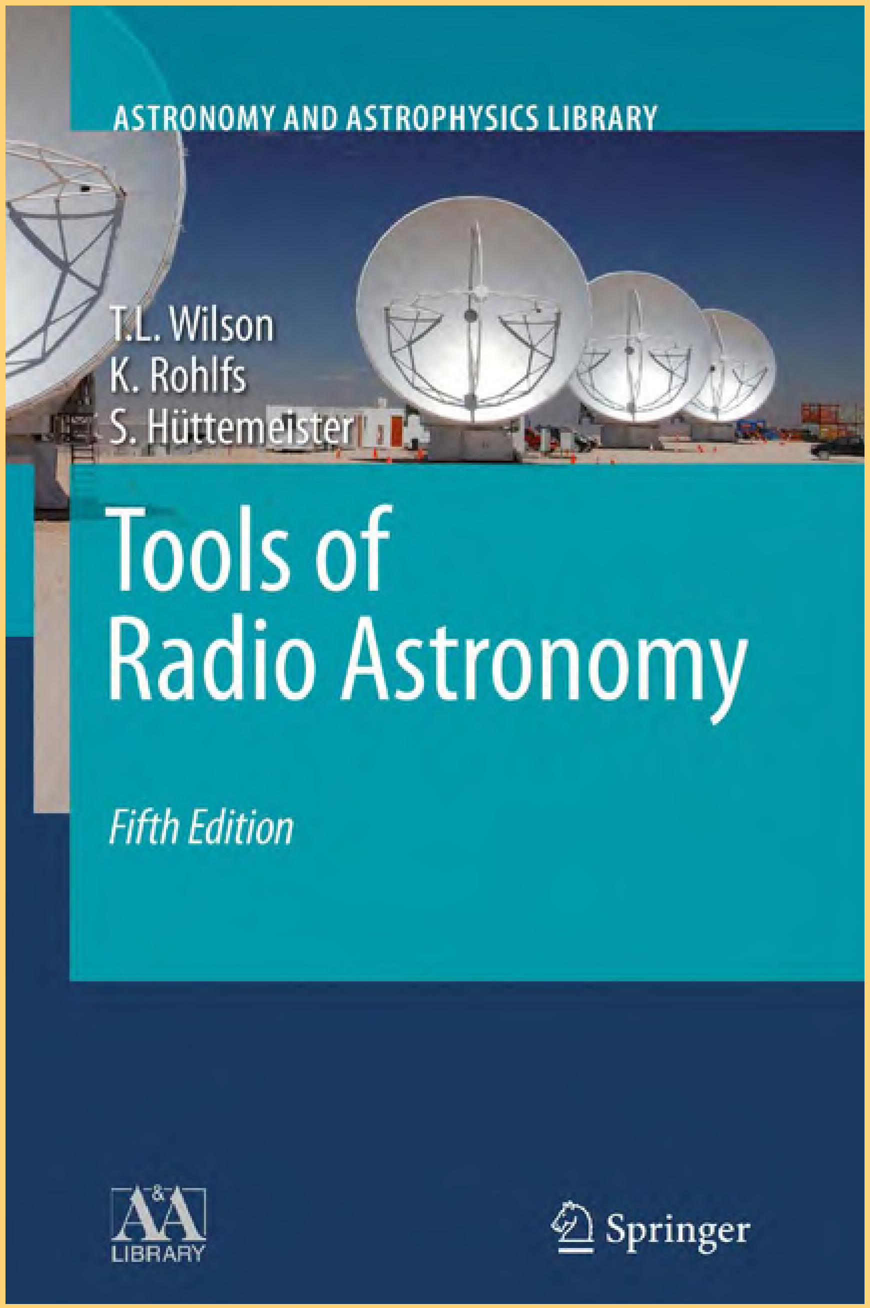
$$\theta_{\mathrm{ang\ \ res}} \approx \frac{\lambda}{B}$$

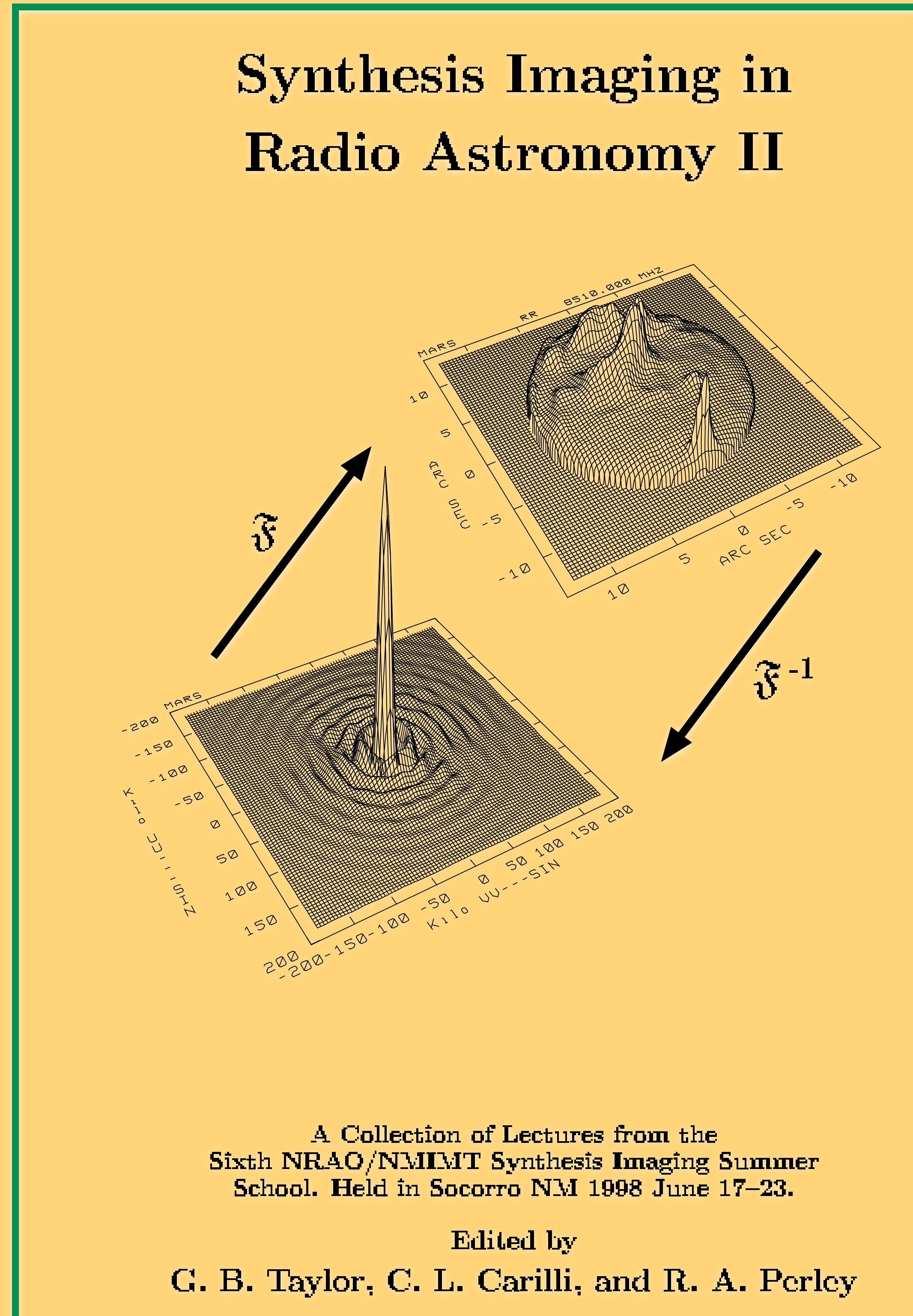
```
$theta = (21e-2/100e3) * 206265
        = 0.4 arcsec   :)
```

Aperture synthesis: methodology of synthesising a continuous aperture through summation of separated pairs of antennas.

The Essential Books

NRAO Synthesis Imaging Workshop
in Socorro (VLA) every two years

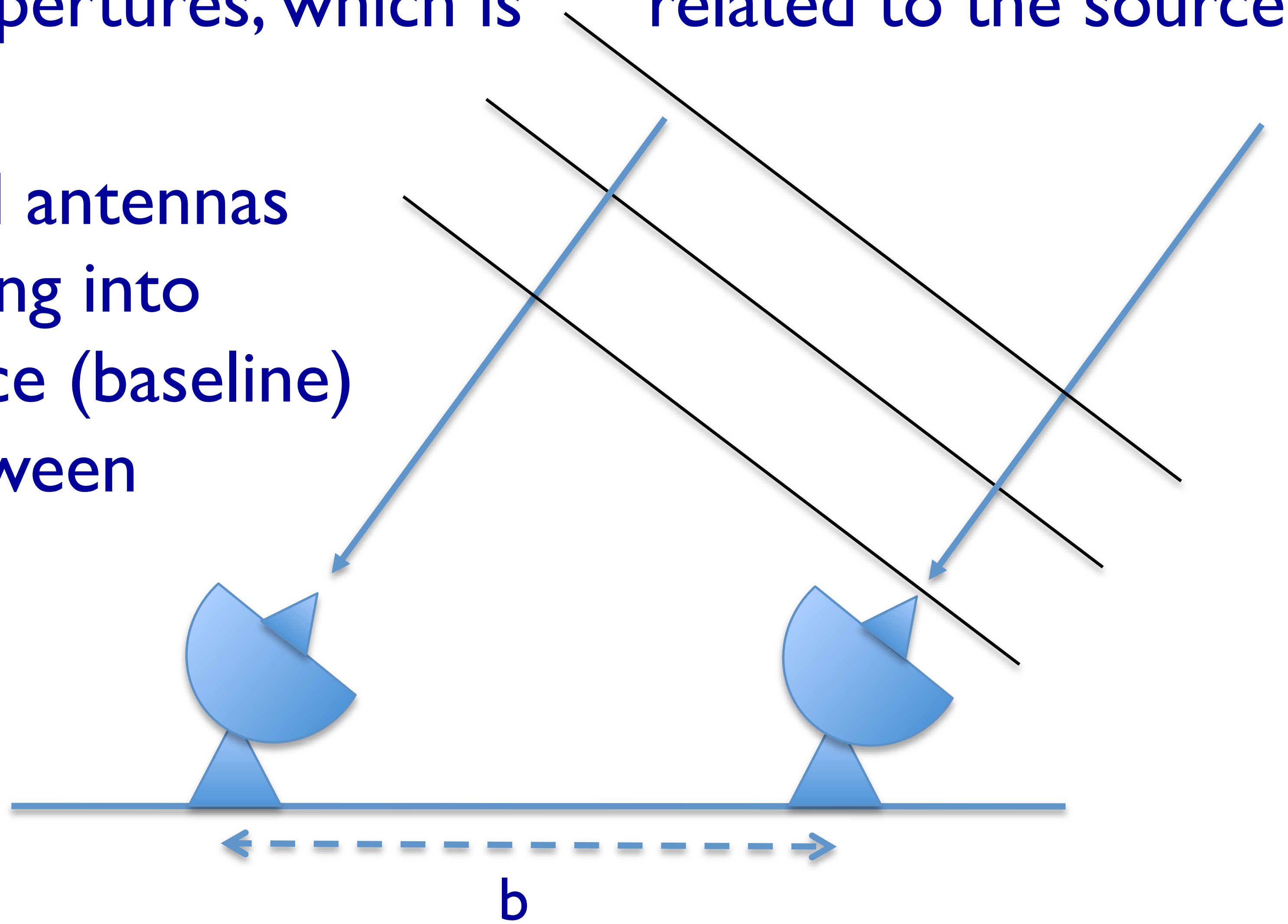




Interferometers: the basics

ALMA

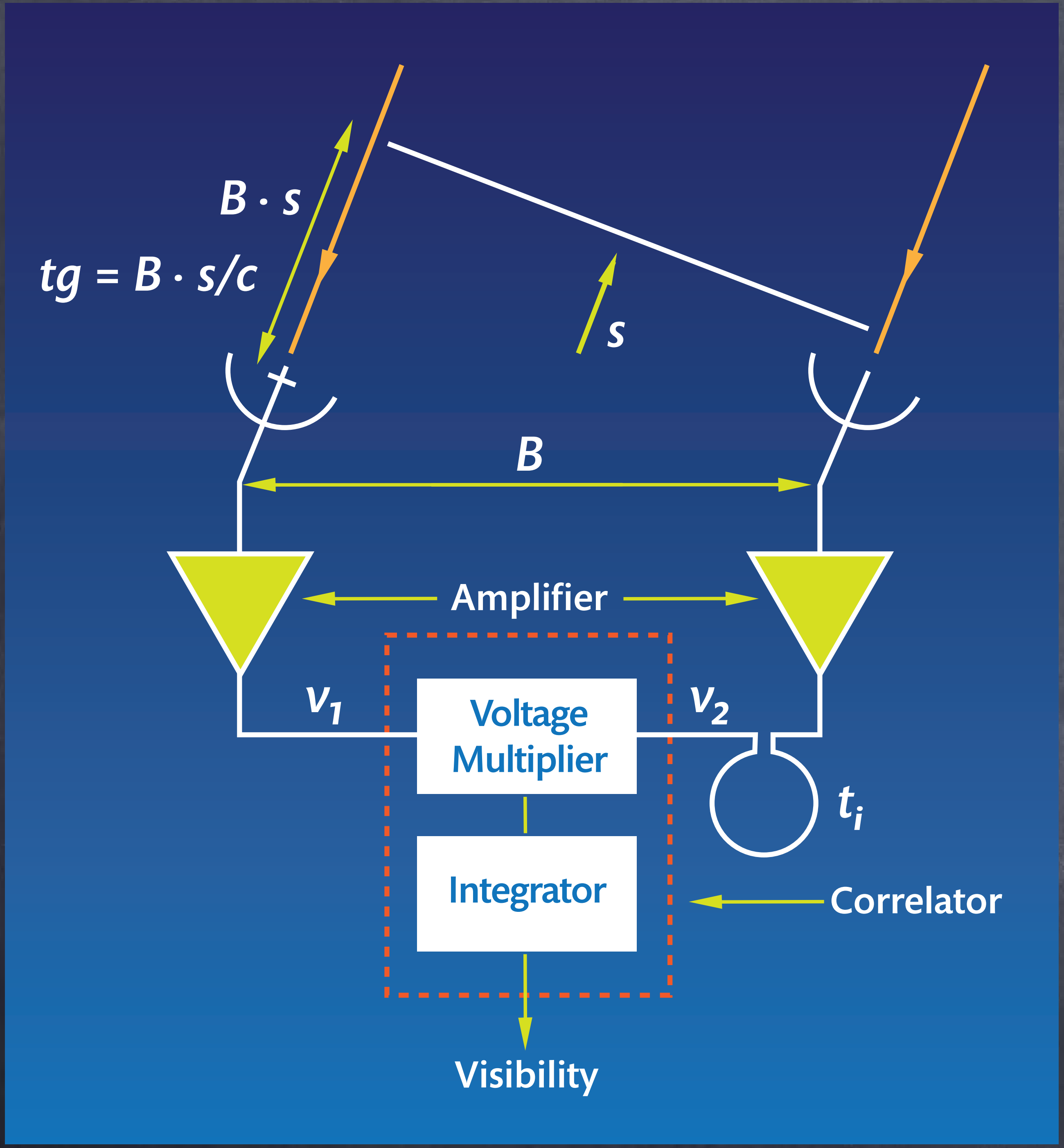
- Interferometry: a method to ‘synthesize’ a large aperture by combining signals collected by separated small apertures
- An Interferometer measures the interference pattern produced by two apertures, which is related to the source brightness.
- The signals from all antennas are correlated, taking into account the distance (baseline) and time delay between pairs of antennas



stolen from: Nuria Marcelino

North American ALMA Science Center

two-element interferometer



the **most basic interferometer** seeks a relation between the the product of the voltages from two separated antennas and the distribution of the brightness of the originating source on the sky

2.Visibility data

$$C_{12}(\nu) = \langle E_\nu(\vec{r}_1) E_\nu(\vec{r}_2) \rangle$$

Calibration

$$V_\nu(\vec{u}) = \iint \frac{dx dy}{\sqrt{1 - x^2 - y^2}} I_\nu(\vec{x}) A_\nu(\vec{x}) \exp\left[-2\pi i (\vec{x} \cdot \vec{u})\right]$$

$\vec{u} = \vec{B}^s_{12}/\lambda$

Sky image

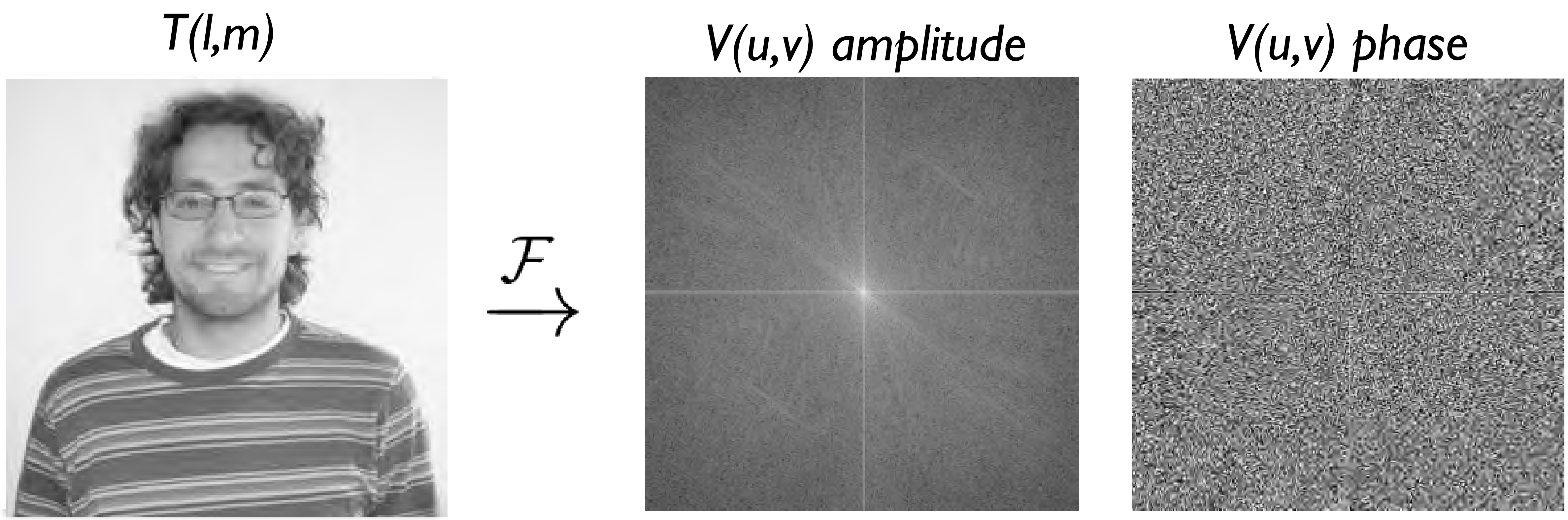
primary beam

from S. Casassus' lecture

Visibilities

- each *V(u,v)* contains information on *T(l,m) everywhere*, not just at a given *(l,m)* coordinate or within a particular subregion

- each *V(u,v)* is a complex quantity
  - expressed as *(real, imaginary)* or *(amplitude, phase)*



Jean Baptiste Joseph Fourier

Fourier transforms are at the heart of interferometry

FT relationships	$f(x) \rightleftharpoons F(s)$
scaling	$f(\alpha x) = \alpha^{-1} F(s/\alpha)$
shifting	$f(x - x_0) = F(s) e^{i2\pi x_0 s}$
convolution/ multiplication	$g(x) = f(x) \otimes h(x); \quad G(s) = F(s)H(s)$

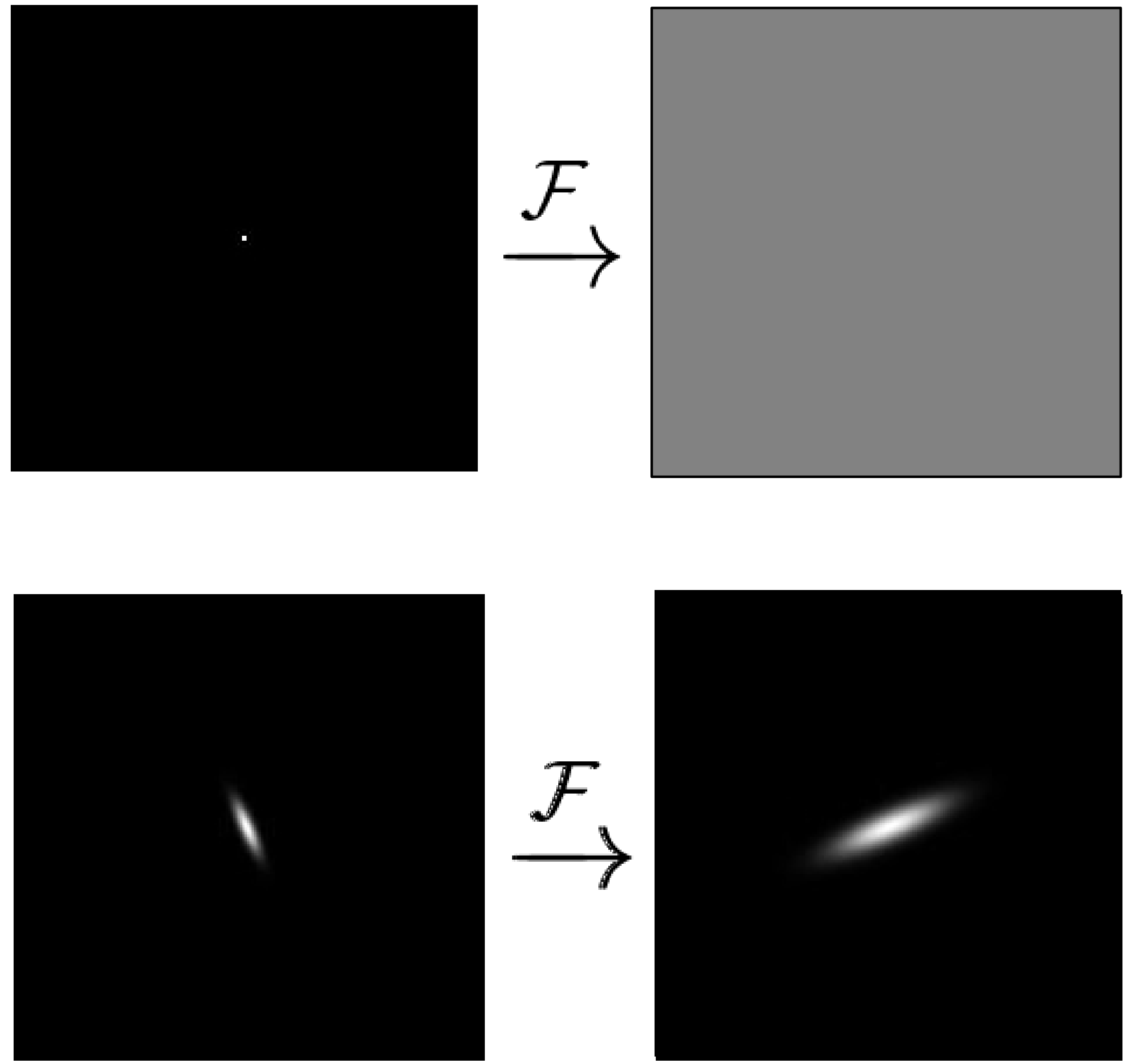
Thompson, Moran & Swenson (2001)

Example 2D Fourier Transforms

T(l,m) — *V(u,v) amplitude*

δ function → constant

elliptical Gaussian → elliptical Gaussian



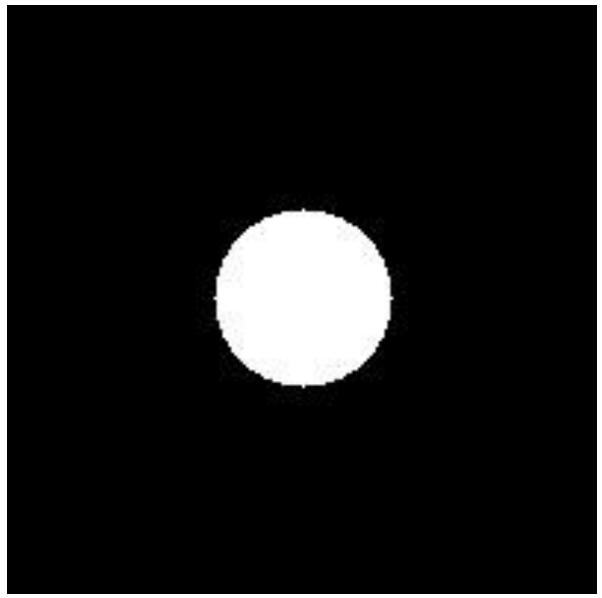
narrow features transform into wide features (and vice-versa)

stolen from: David Wilner

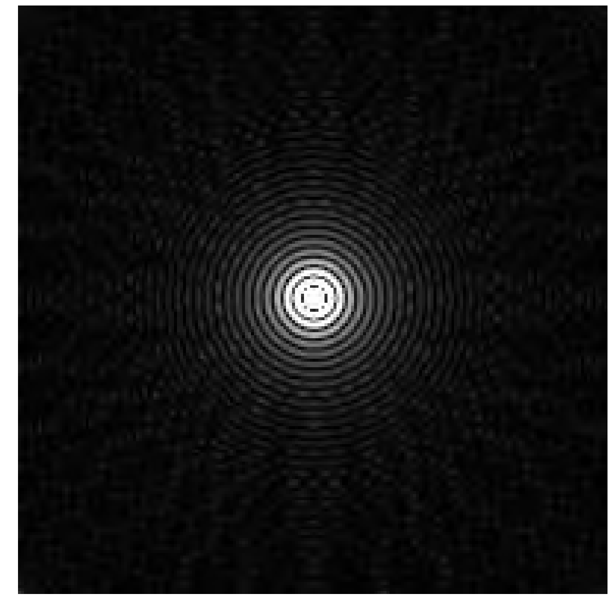
Example 2D Fourier Transforms

T(l,m) | *V(u,v) amplitude*

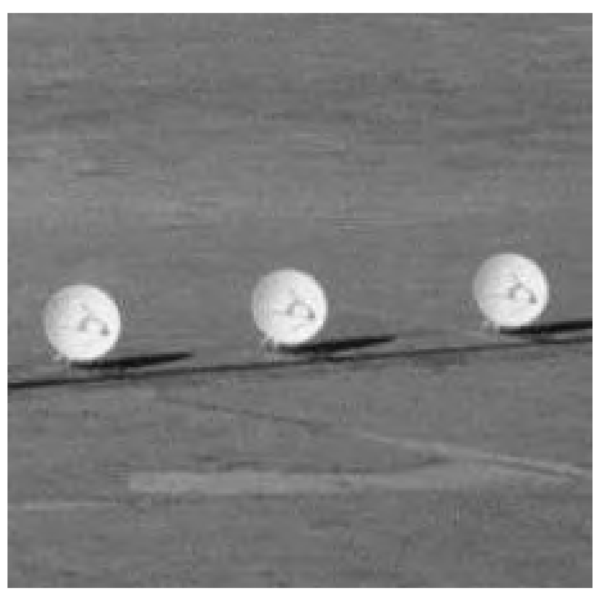
uniform disk



$\xrightarrow{\mathcal{F}}$



Bessel function



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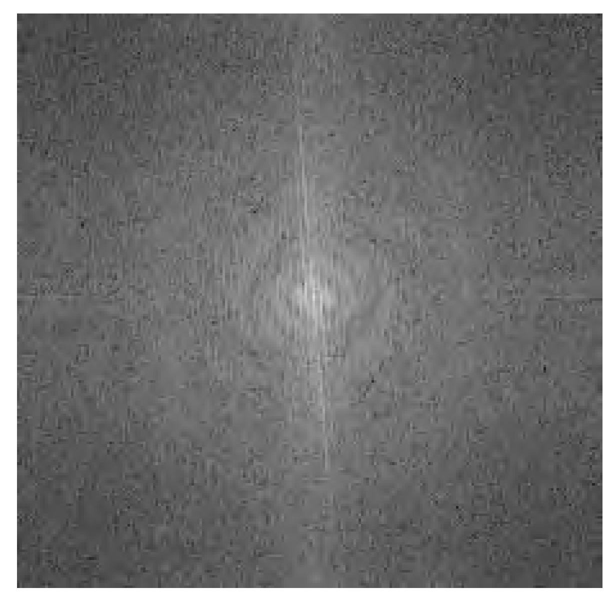

sharp edges result in many high spatial frequencies

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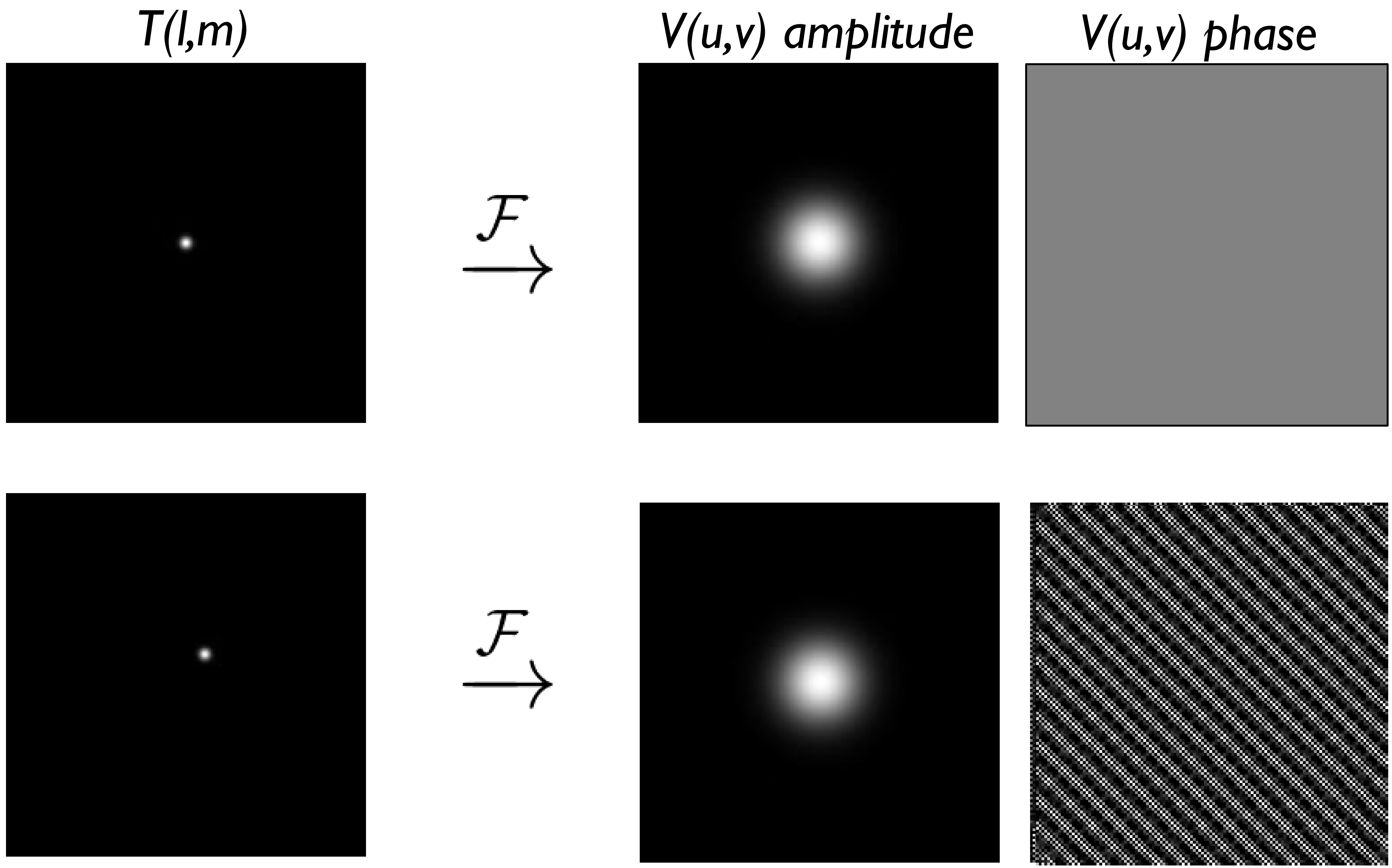
Amplitude and Phase

- amplitude tells “how much” of a certain spatial frequency
- phase tells “where” this spatial frequency component is located



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The Visibility Concept

$$V(u,v) = \int\int T(l,m)e^{-i2\pi(ul+vm)}dldm$$

- 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 *(l,m)*
- *V(u=0,v=0)* is the integral of *T(l,m)dldm* = total flux density
- since *T(l,m)* is real, *V(-u,-v)* = V^**(u,v)*
  – *V(u,v)* is Hermitian
  – get two visibilities for one measurement

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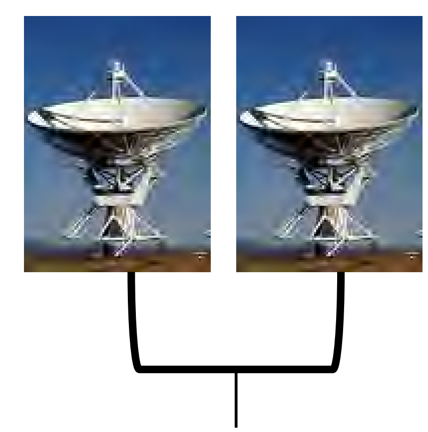

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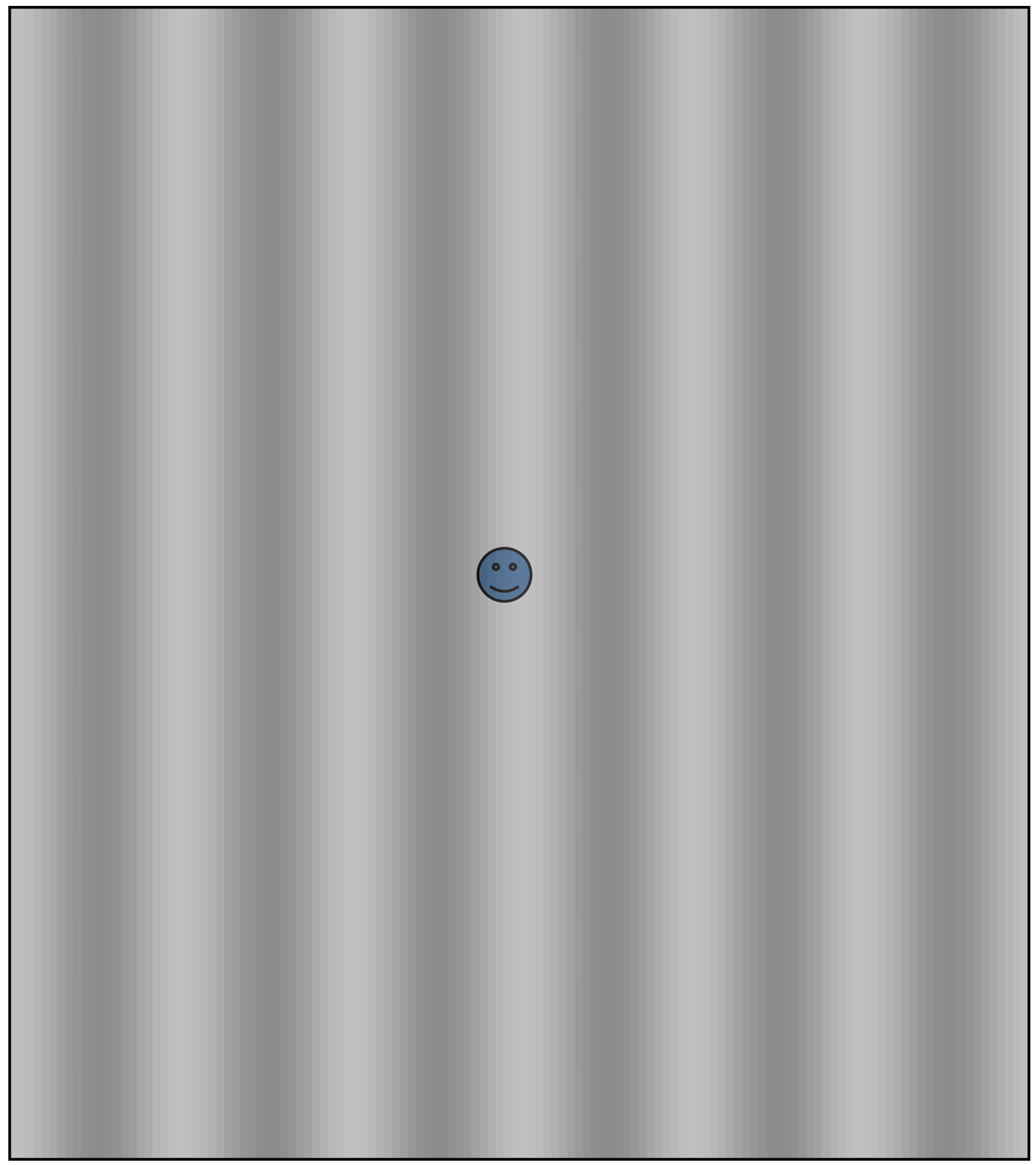

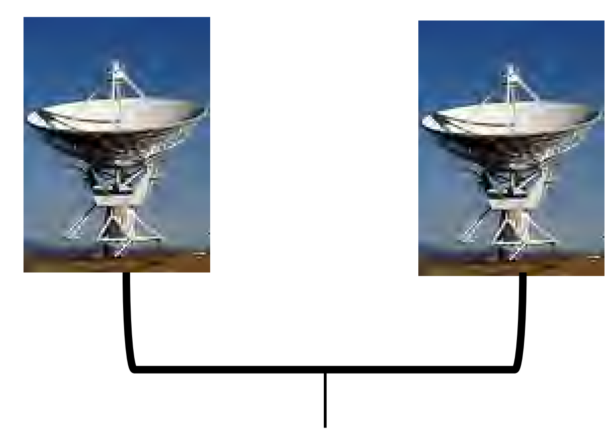

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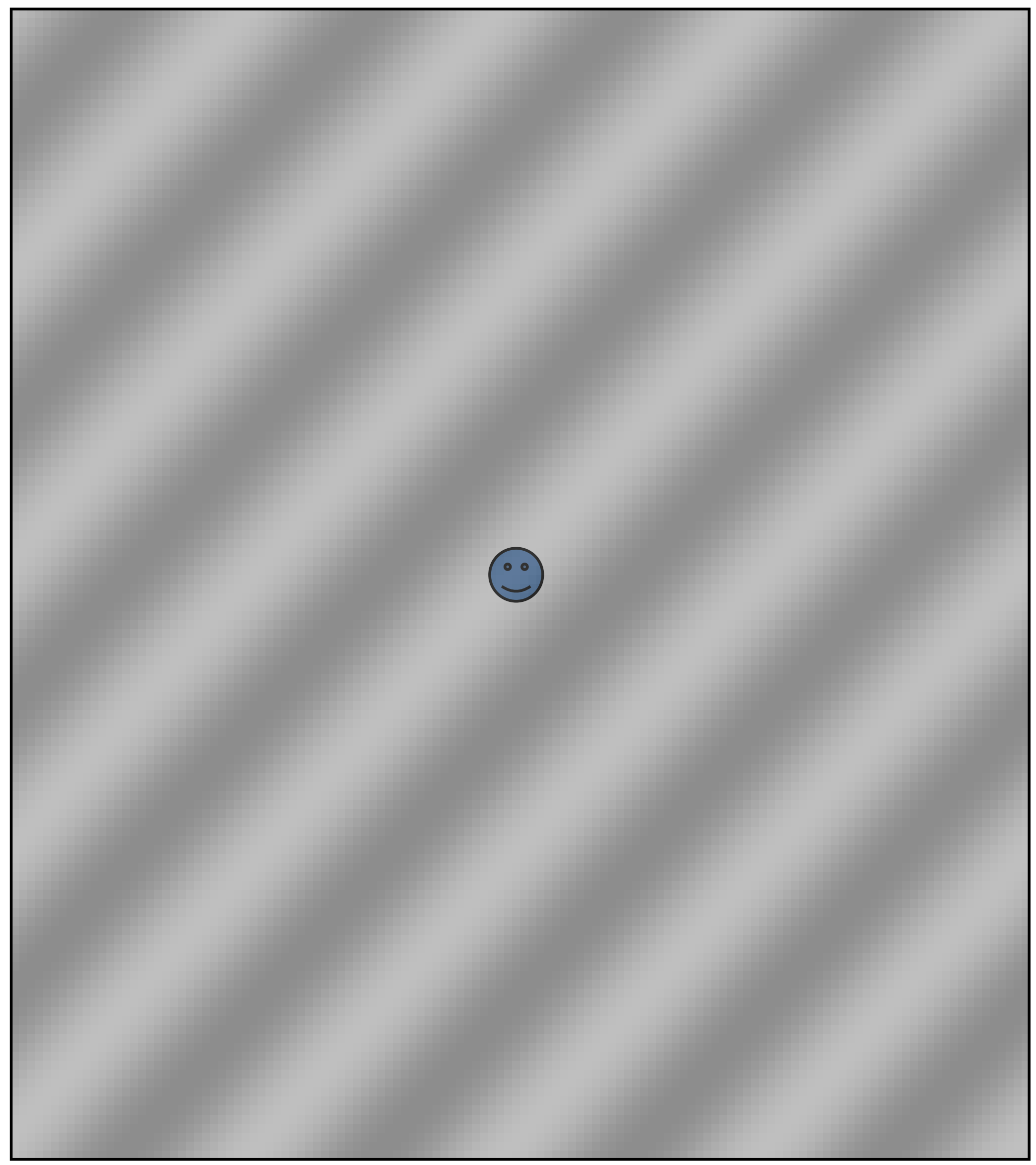

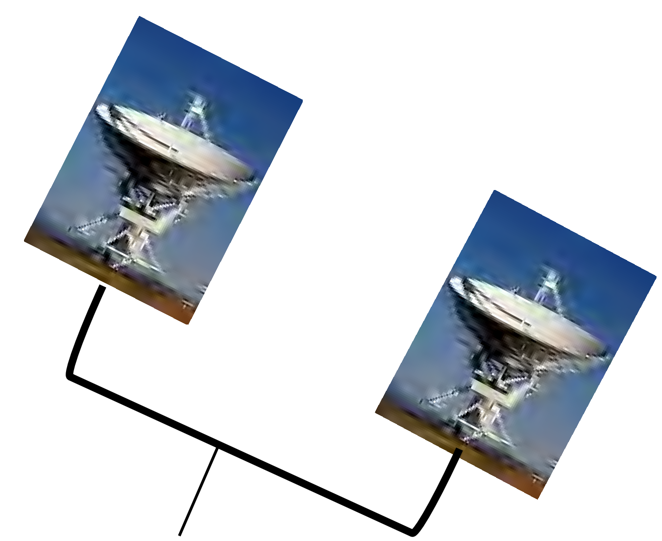

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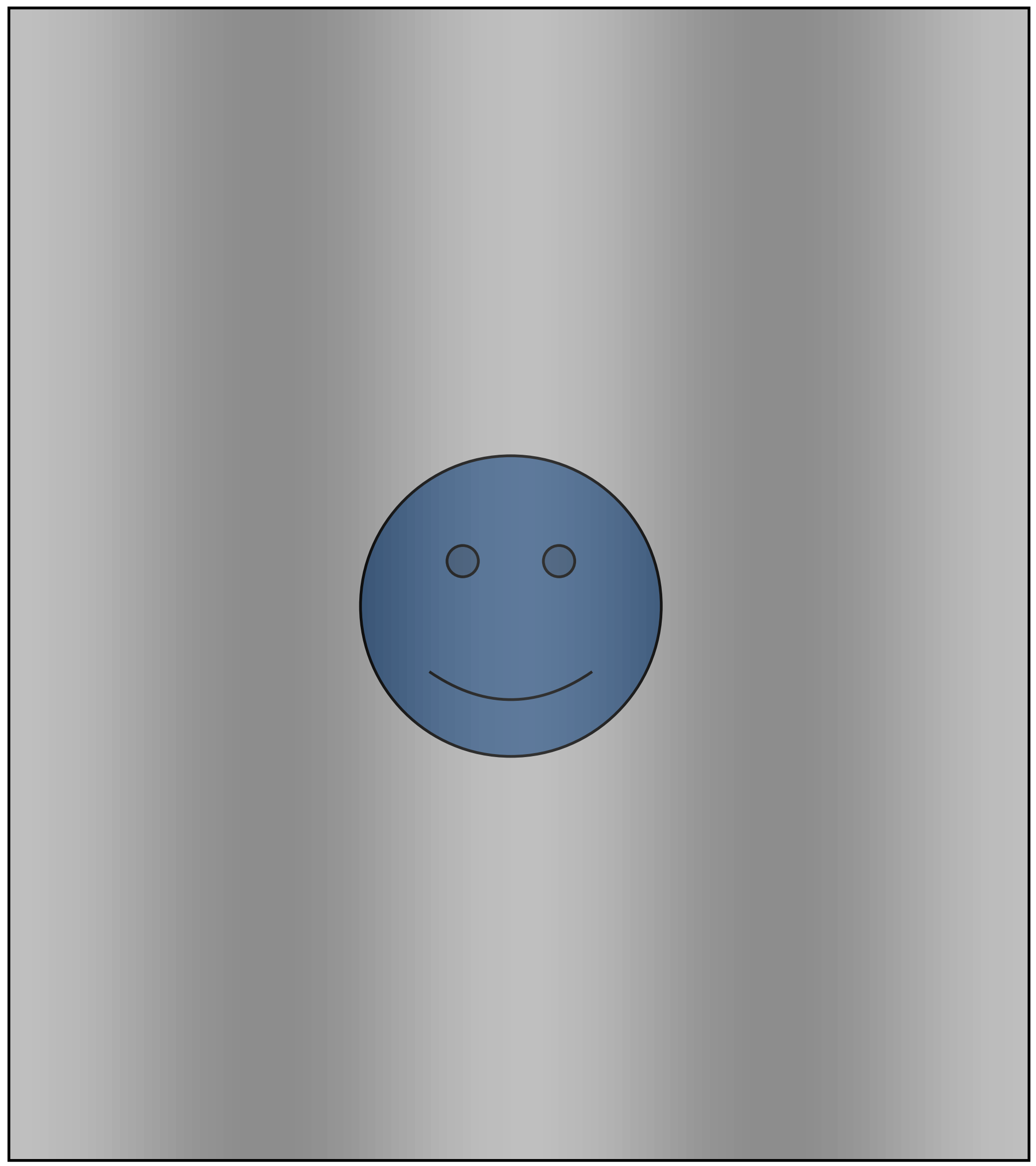

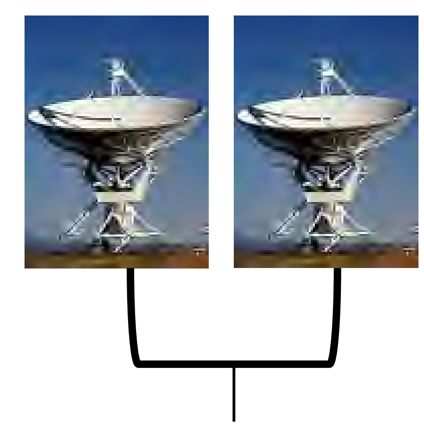

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New Mexico CONSORTIUM

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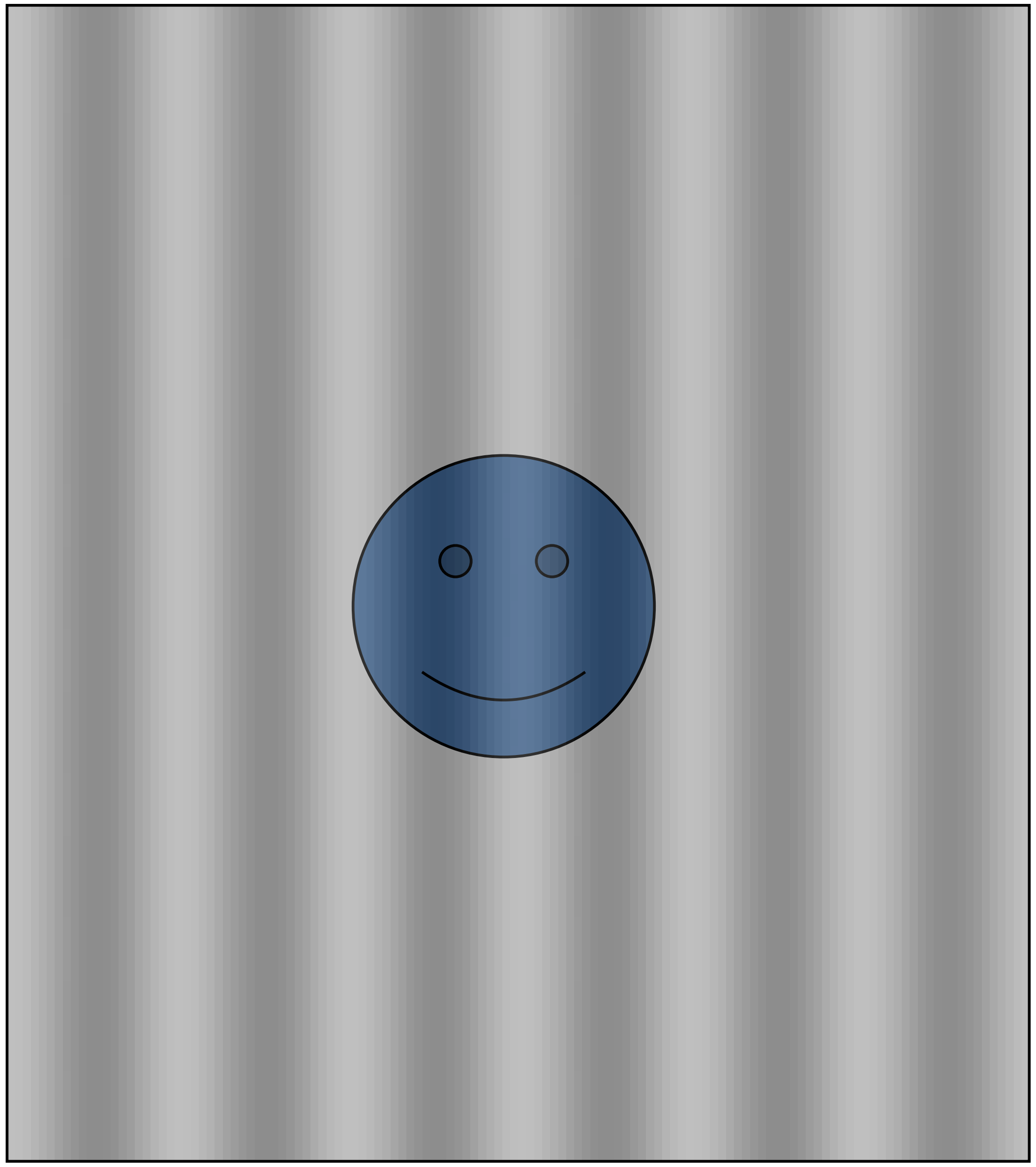

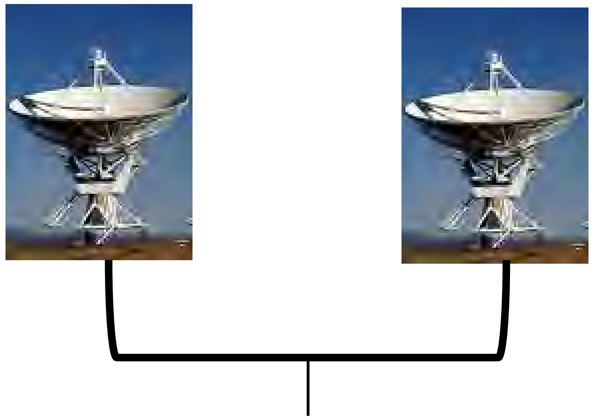

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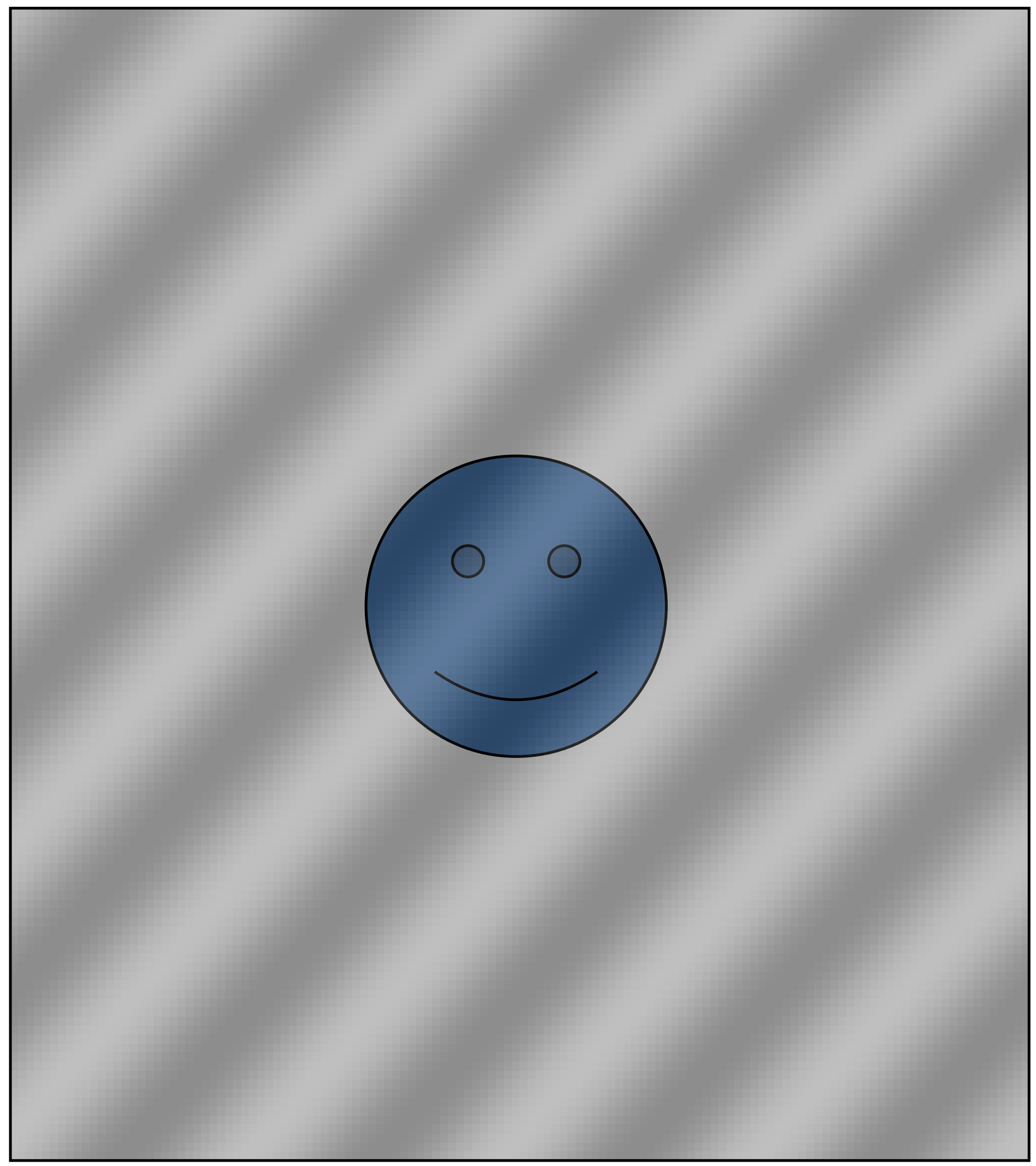
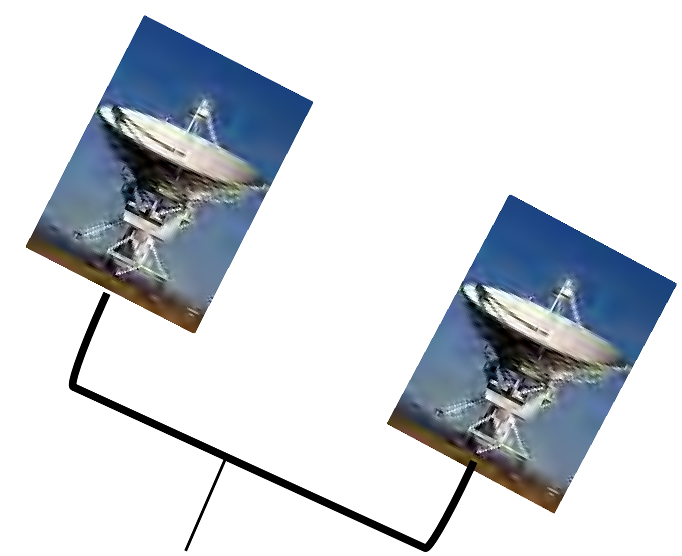
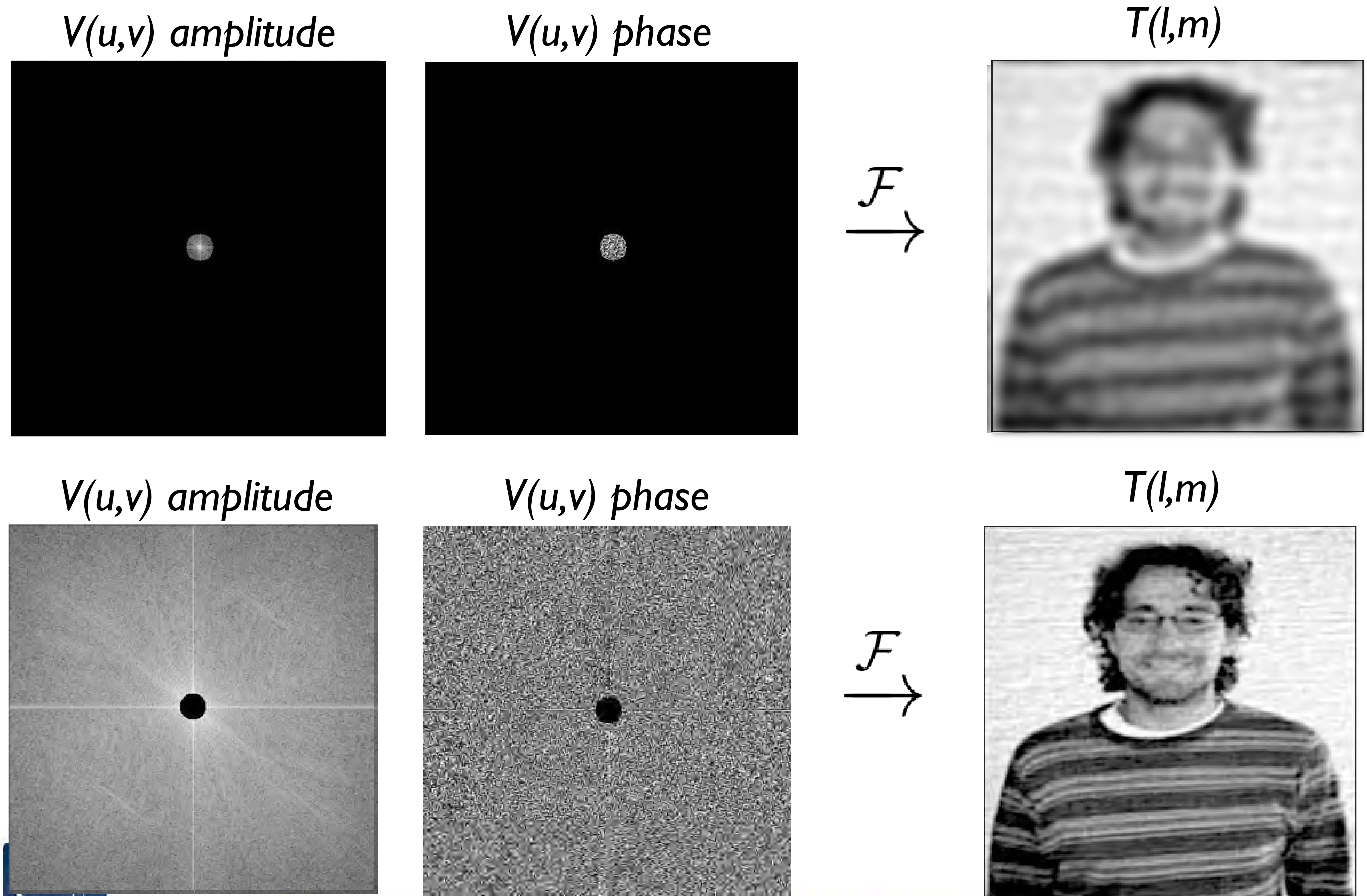




Inner and Outer (u,v) Boundaries



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$\vec{u} = \vec{B}^s_{12}/\lambda$

Sky image

primary beam

from S. Casassus' lecture

Aperture Synthesis Basics

- idea: sample *V(u,v)* at enough *(u,v)* points using distributed small aperture antennas to synthesize a large aperture antenna of size (u_{max}, v_{max})

- one pair of antennas = one baseline
  = two *(u,v)* samples at a time
- N antennas = N(N-1) samples at a time
- use Earth rotation to fill in *(u,v)* plane over time
  (Sir Martin Ryle, 1974 Nobel Prize in Physics)
- reconfigure physical layout of N antennas for more samples
- observe at multiple wavelengths for *(u,v)* plane coverage, for source spectra amenable to simple characterization ("multi-frequency synthesis")

- if source is variable, then be careful

Sir Martin Ryle
1918-1984

Two ingredients to get an interferometric image

You need two things...

1 Fourier Transform

&

2 Deconvolution

(actually, there's a bit more to it than this,
but time is short and so are attention spans)

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Synthesis imaging in a nutshell

The recovered 'dirty' image

The *uv*-plane sampling function

The Fourier Transform of the true sky brightness distribution

$$I^D(x,y) \Leftrightarrow S(u,v) \times I(u,v)$$

Image plane

Fourier plane

A Fourier transform

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Synthesis imaging in a nutshell

The recovered 'dirty' image

FT of the uv-plane sampling function

The true sky brightness distribution (what we want!)

$$I^D(x,y) = Beam \otimes I(x,y)$$

Image plane

What we need to deconvolve

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Examples of Aperture Synthesis Telescopes (for Millimeter Wavelengths)

The separation of the VLA antennas is altered every ~4 months.

Most extended: A   Most compact: D

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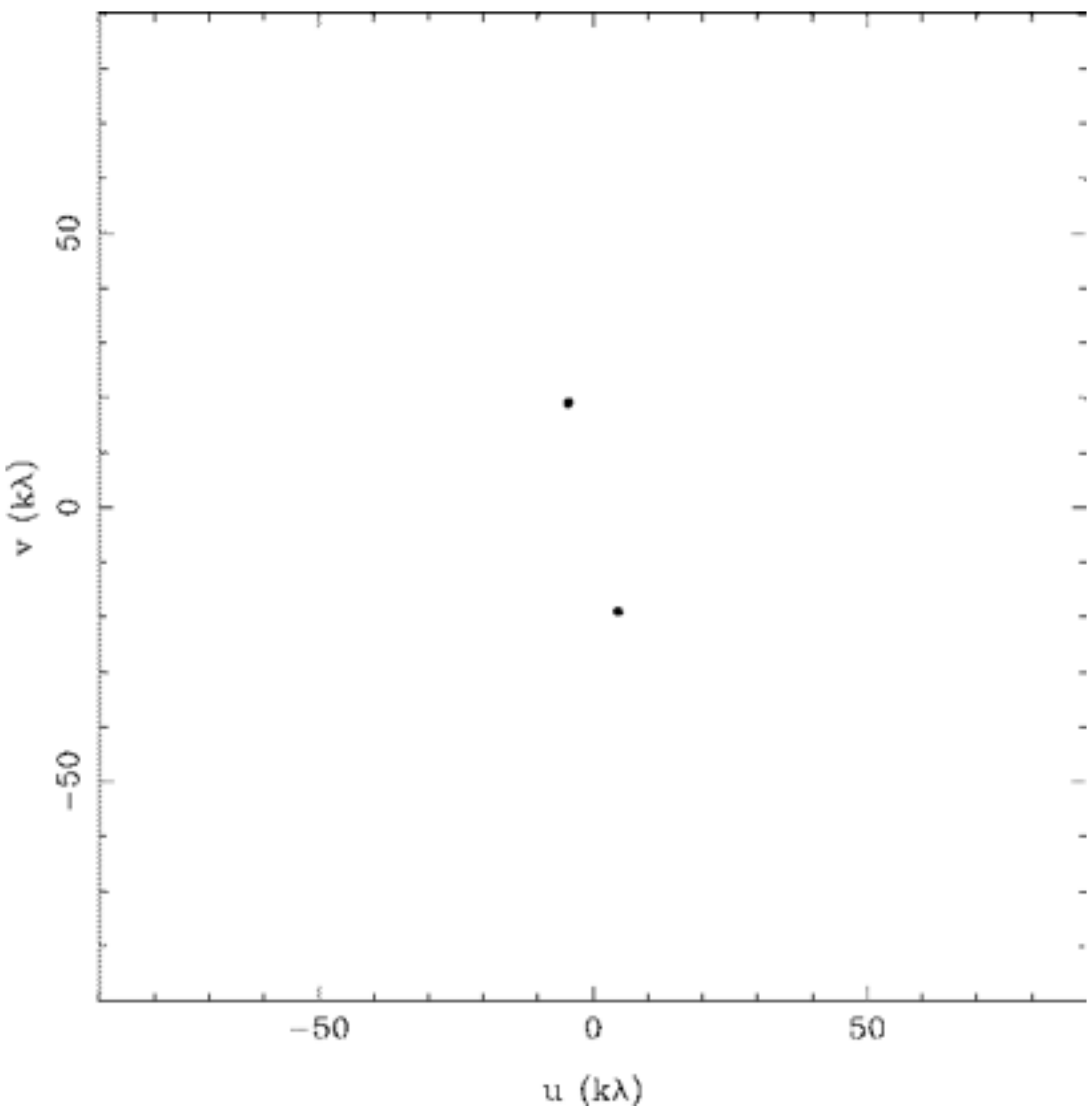
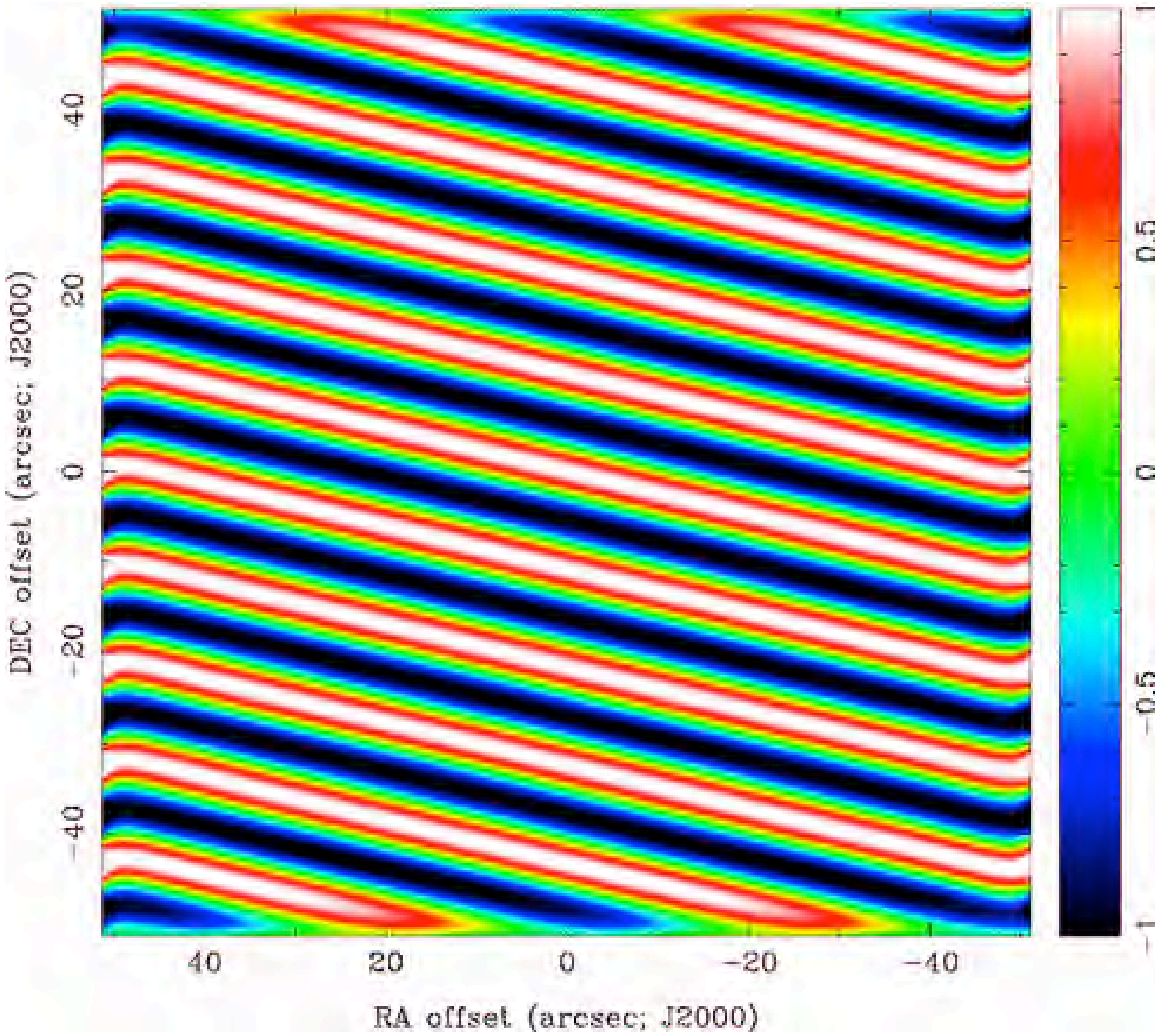
Dirty Beam Shape and N Antennas

2 Antennas





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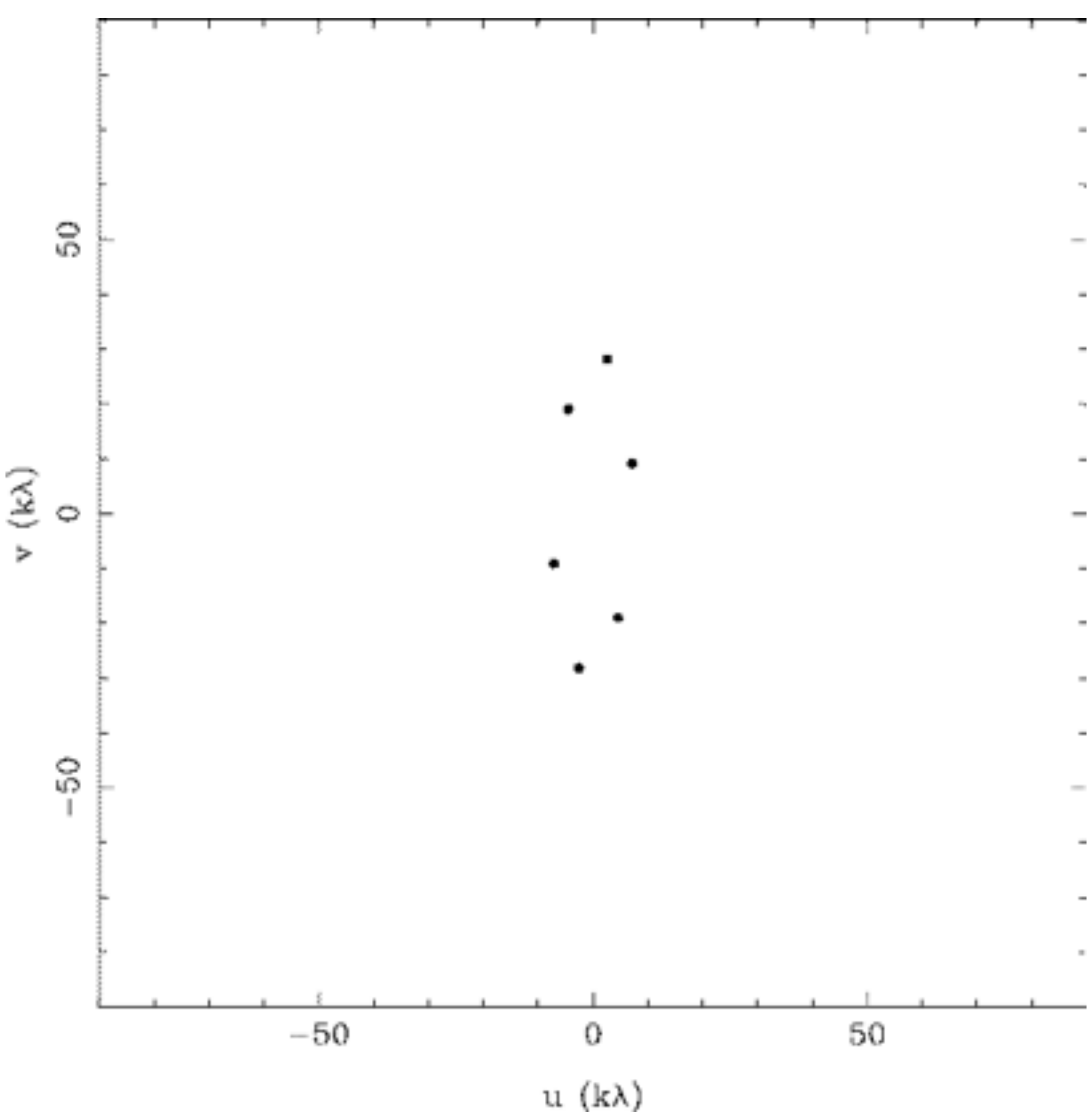
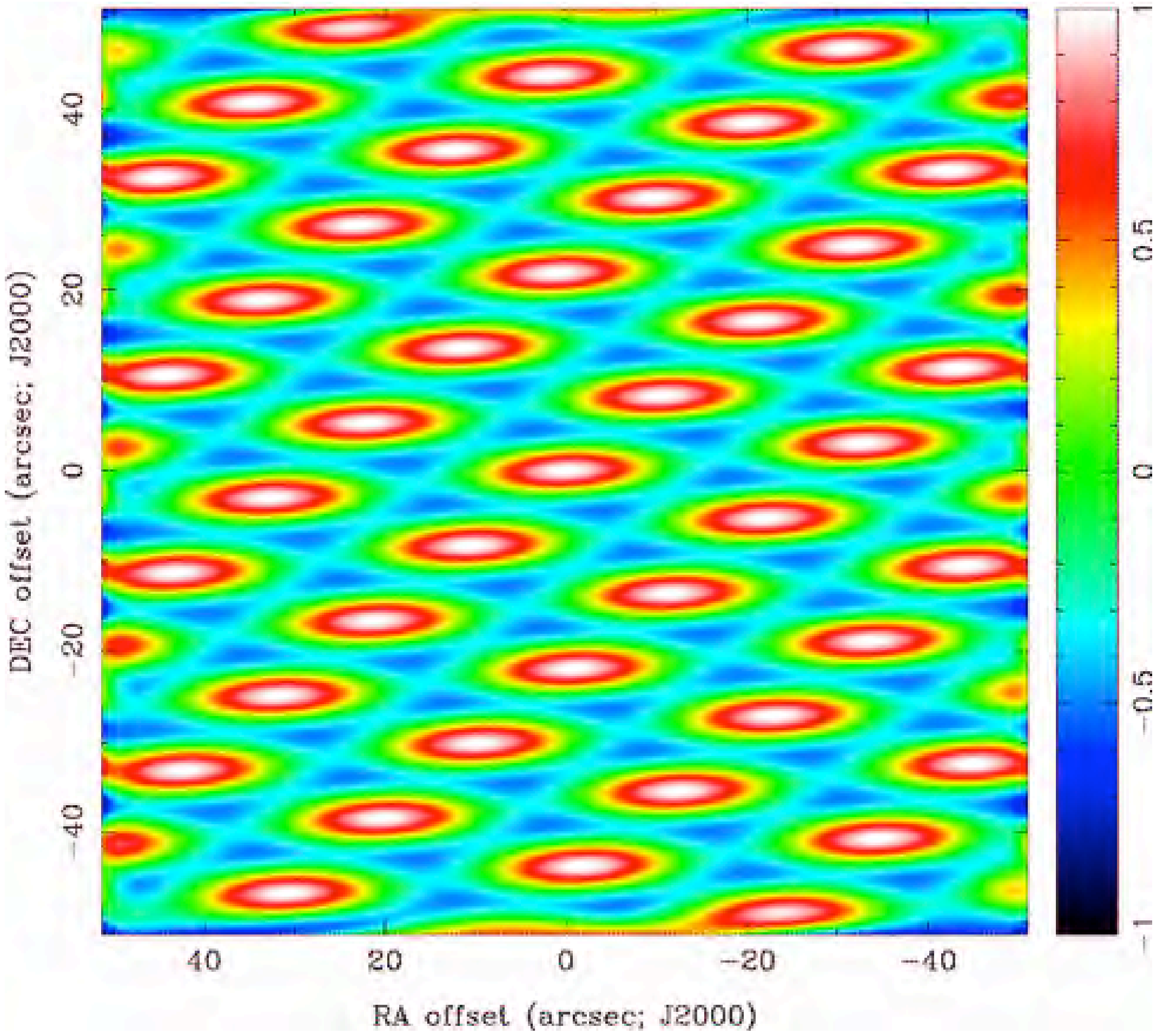
Dirty Beam Shape and N Antennas

3 Antennas





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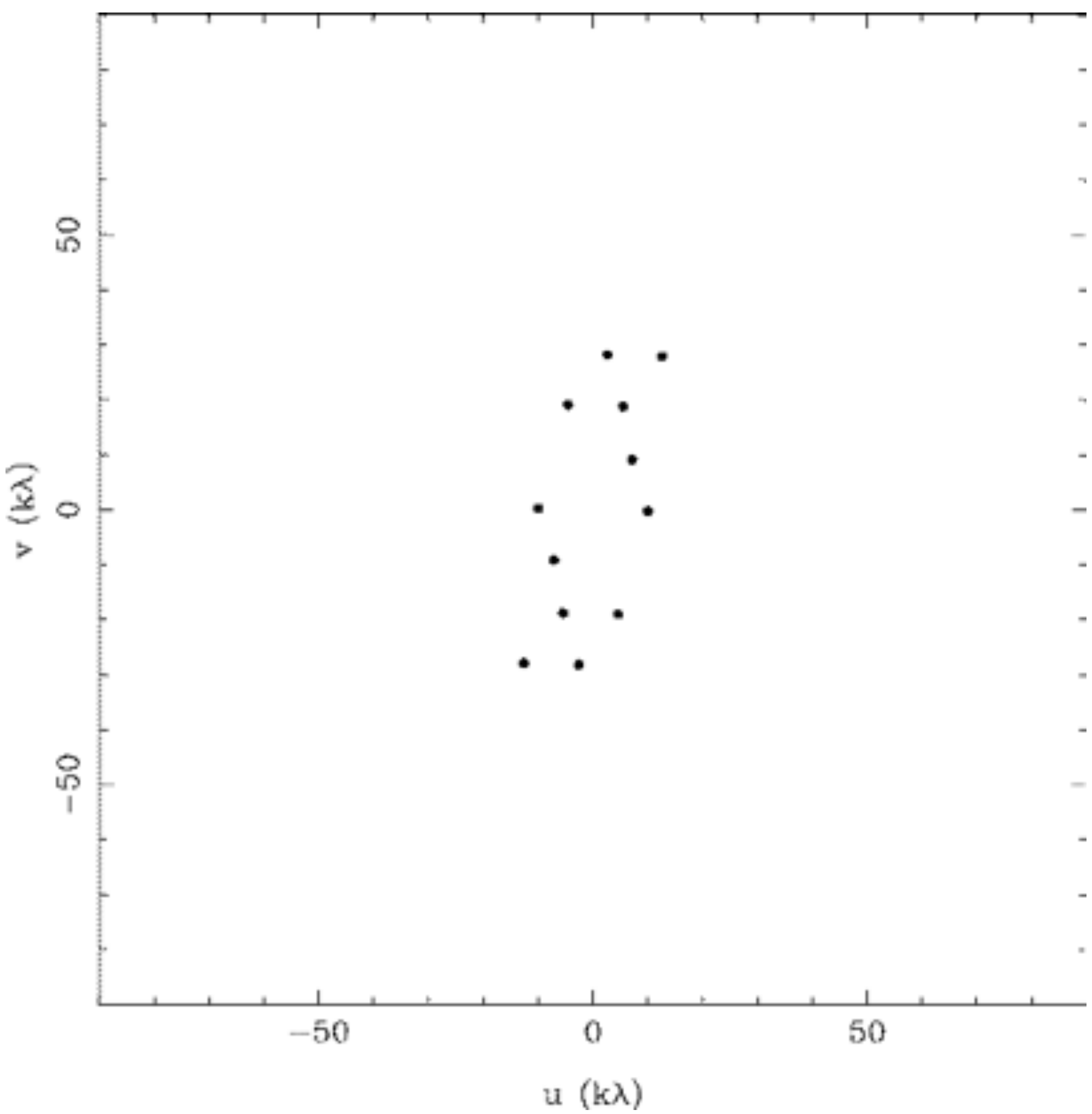
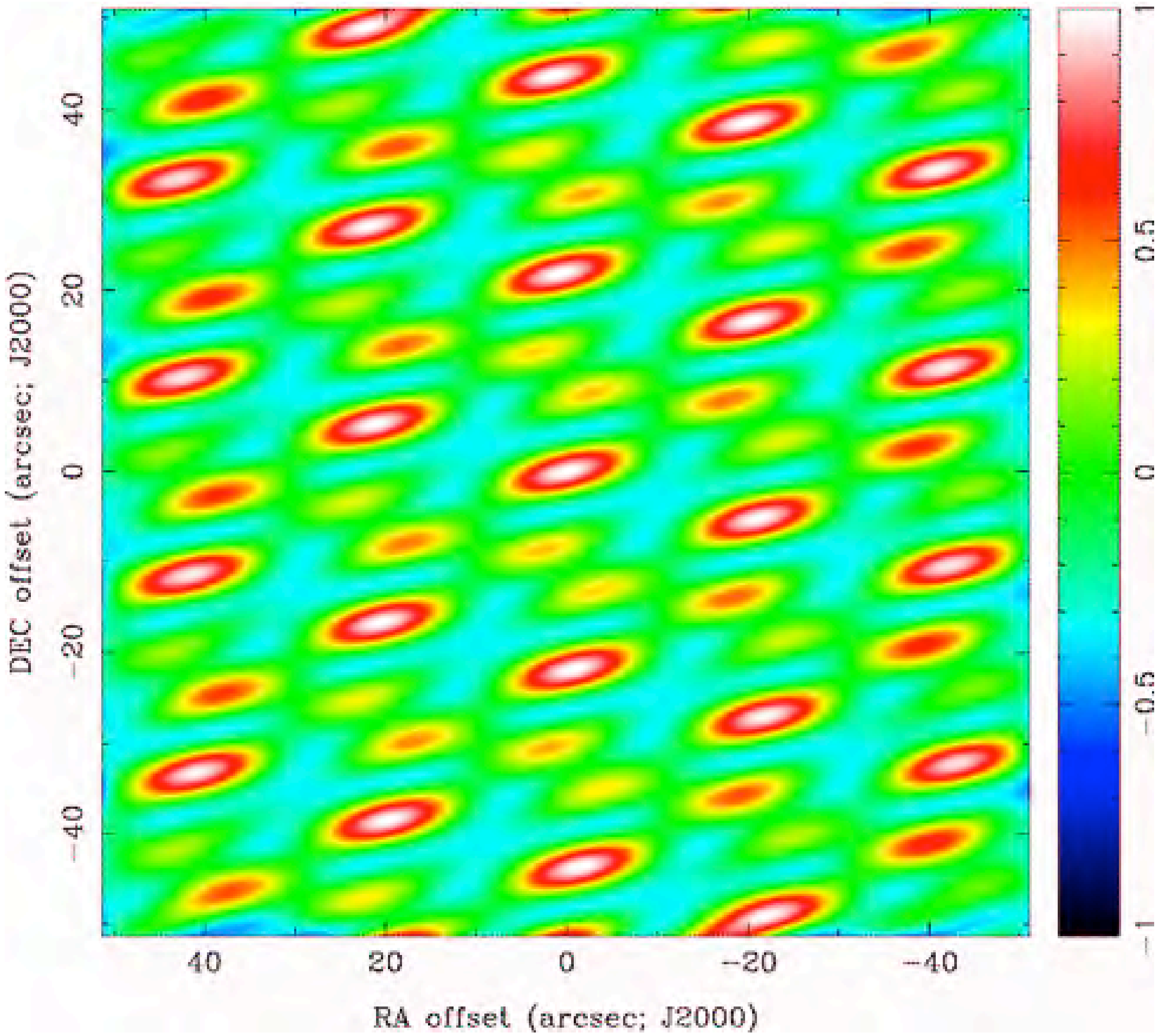
Dirty Beam Shape and N Antennas

4 Antennas





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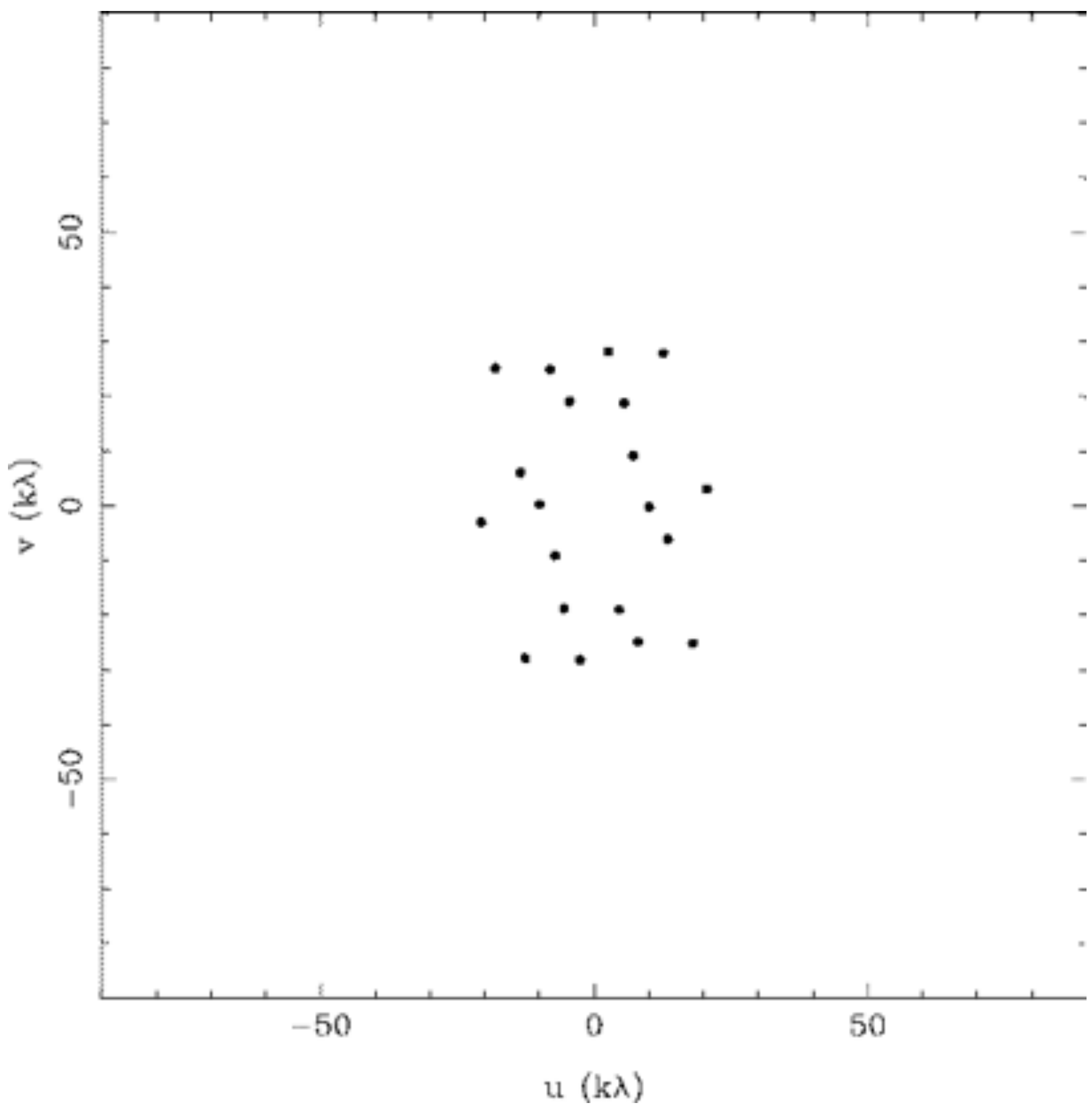
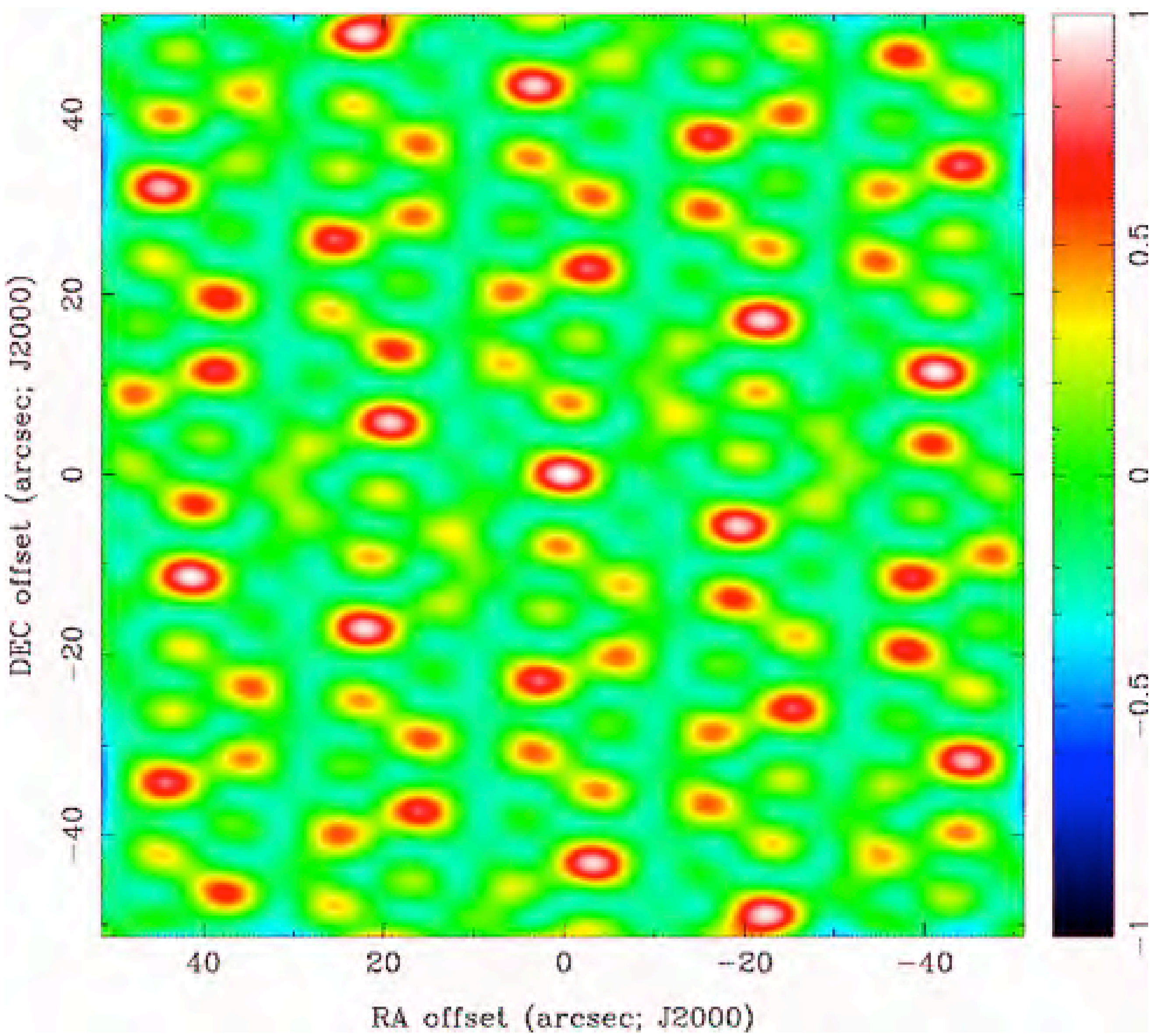
Dirty Beam Shape and N Antennas

5 Antennas





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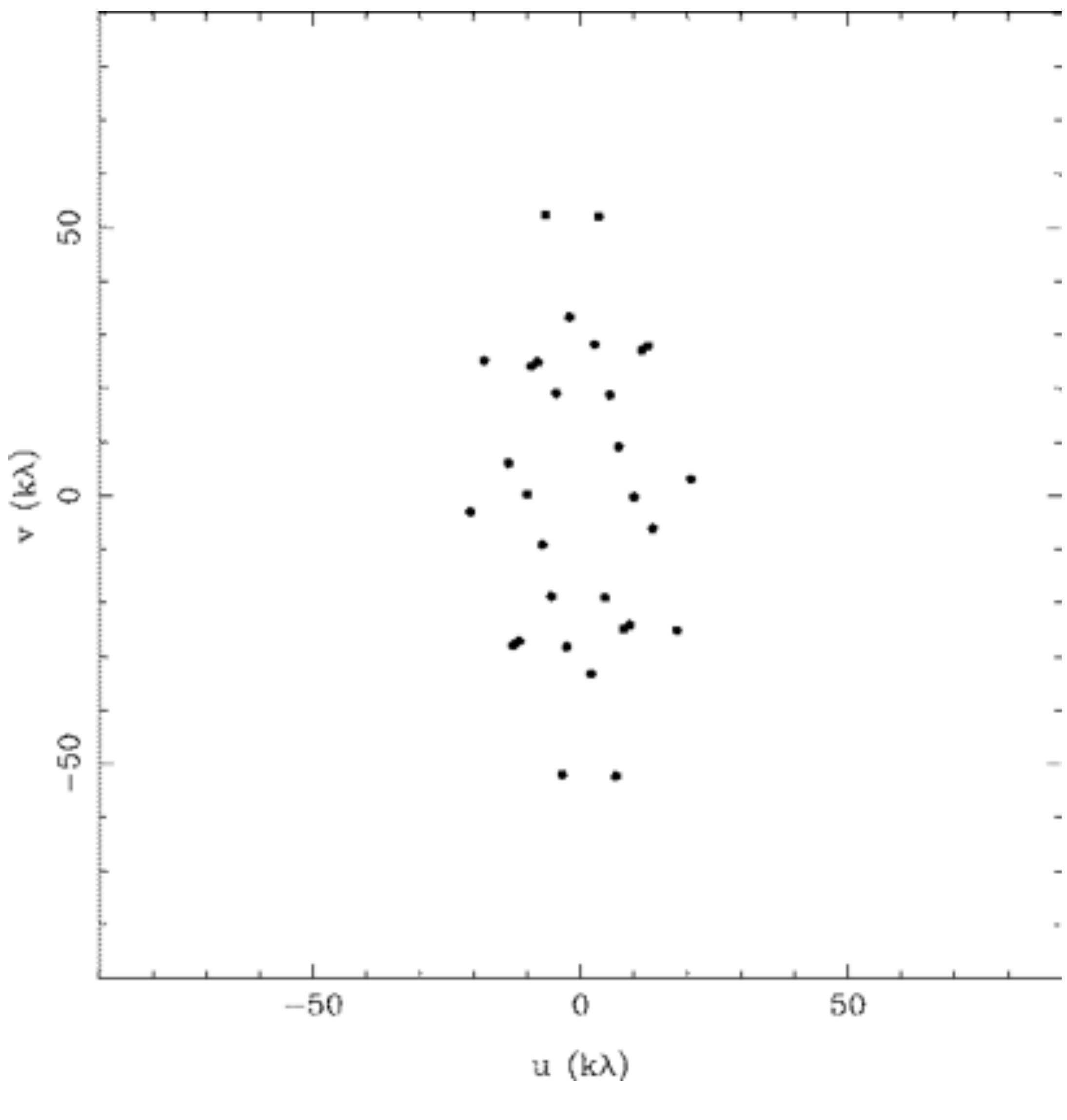
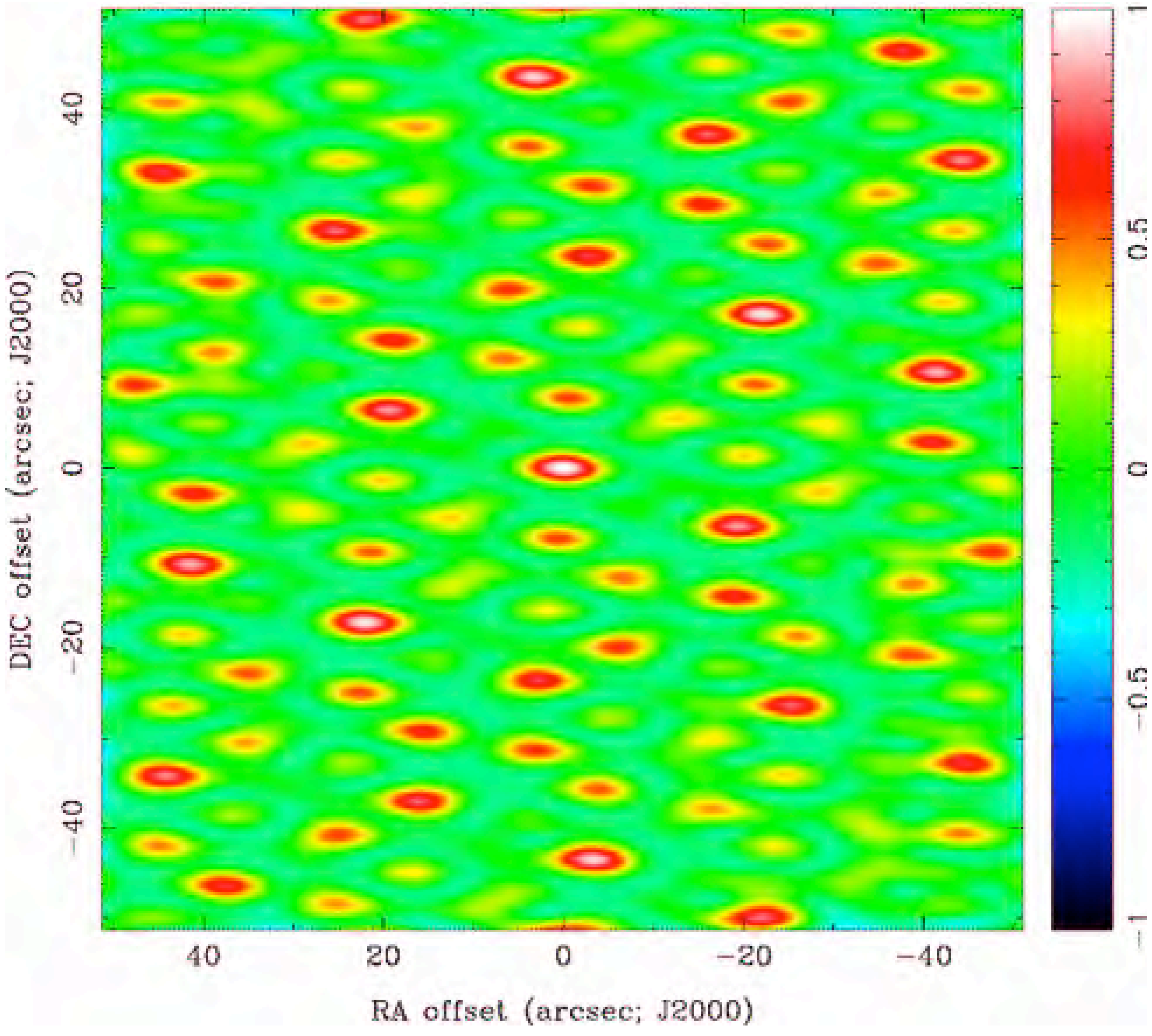
Dirty Beam Shape and N Antennas

6 Antennas





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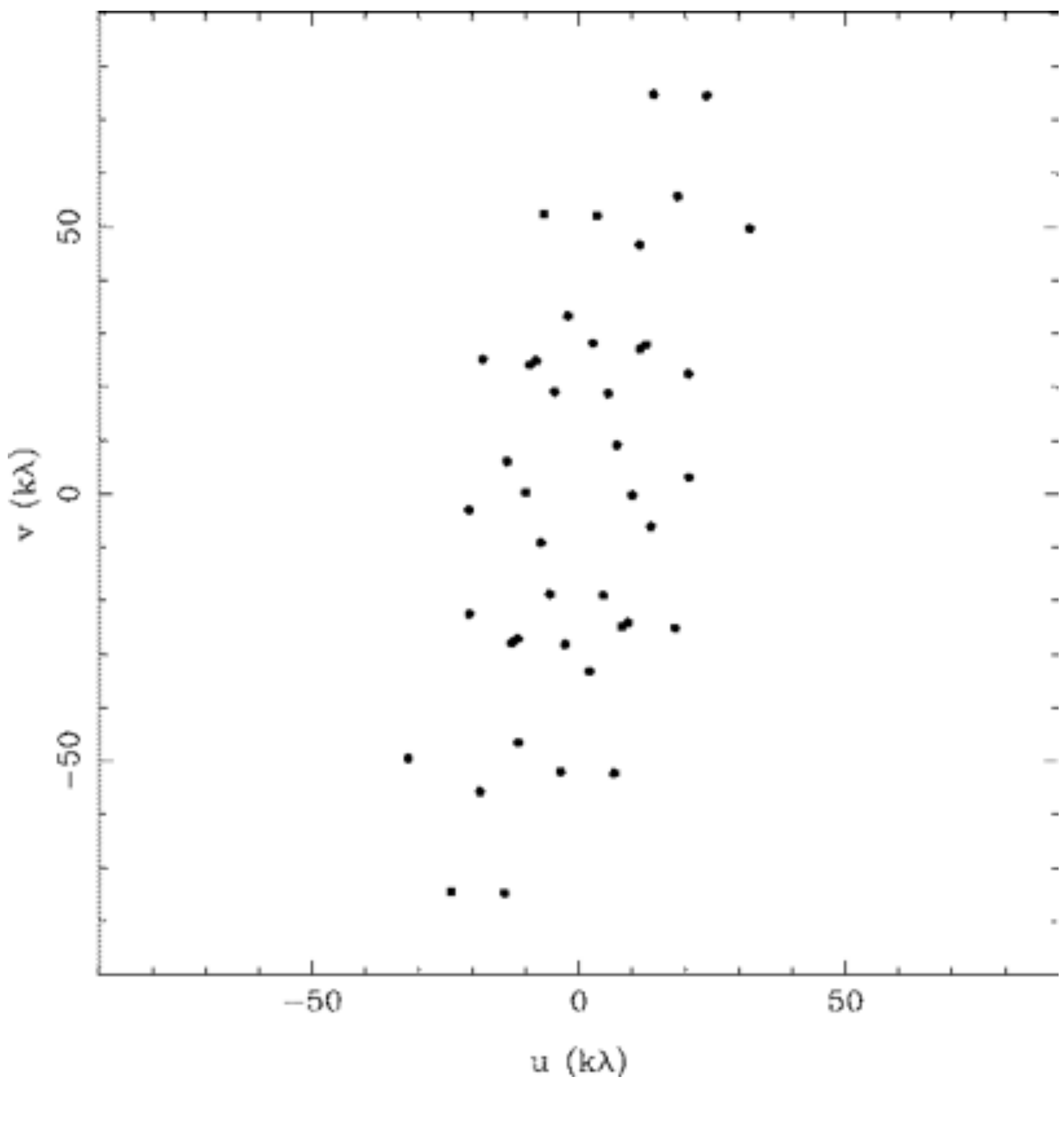
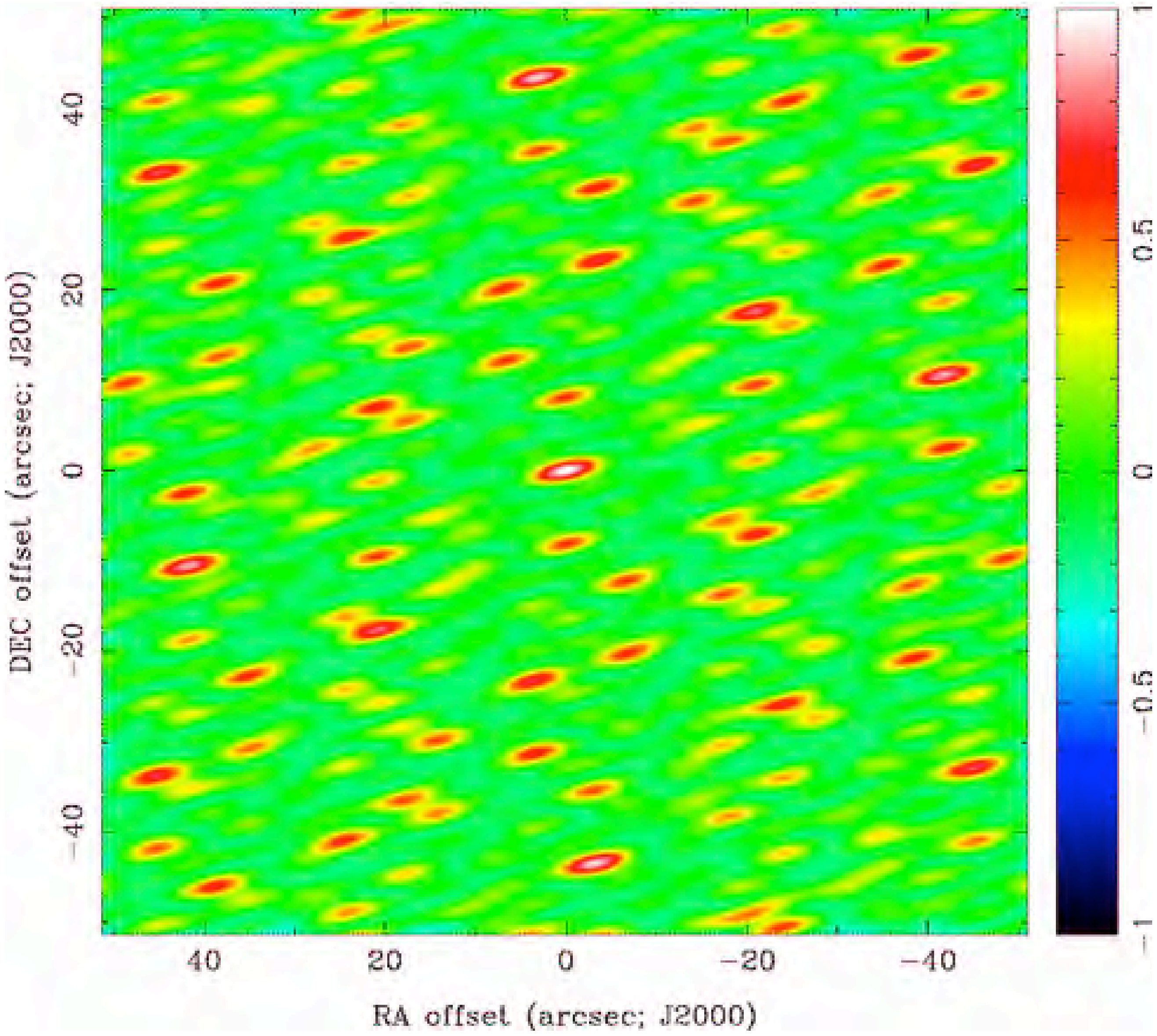
Dirty Beam Shape and N Antennas

7 Antennas





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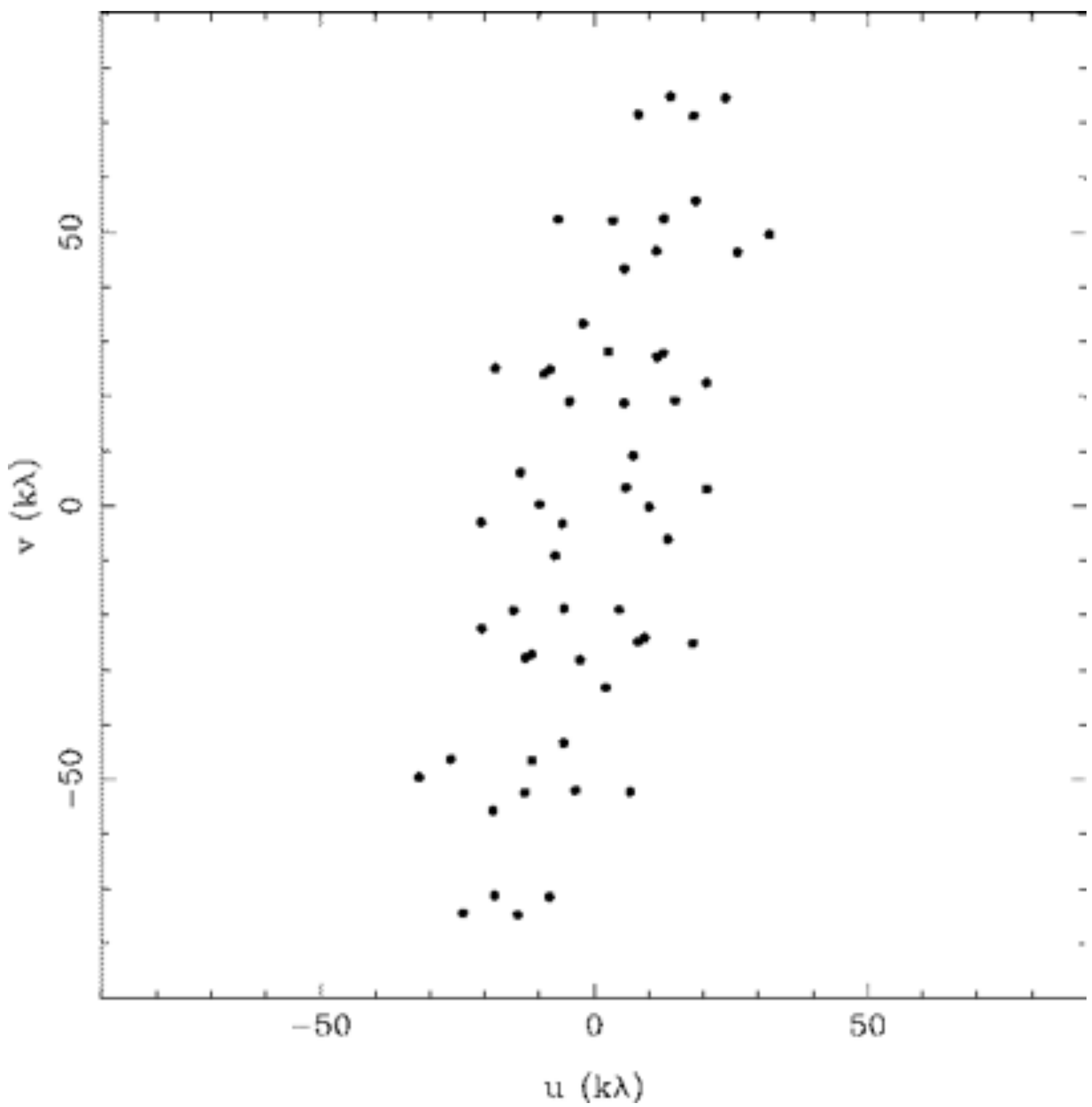
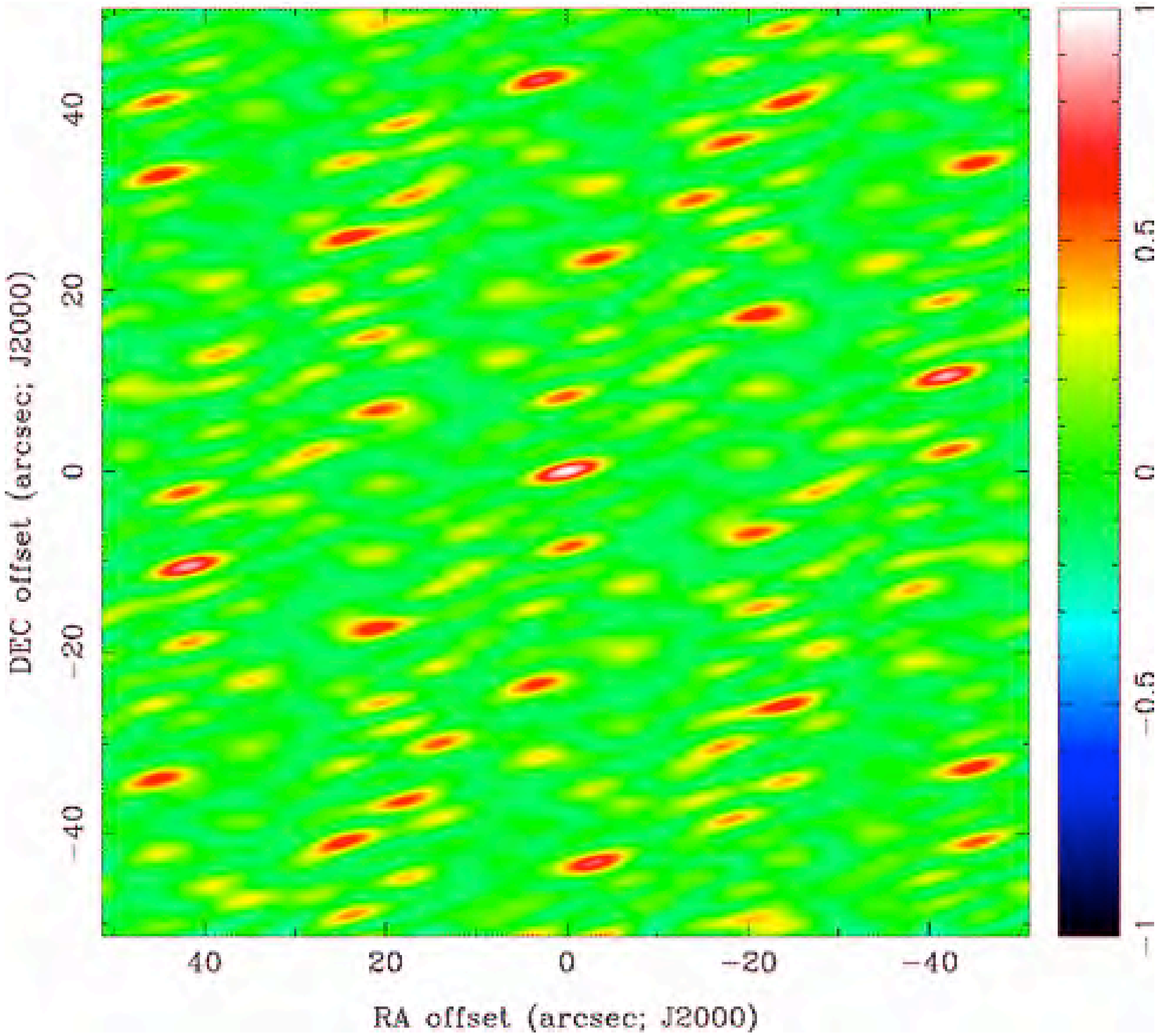
Dirty Beam Shape and N Antennas

8 Antennas





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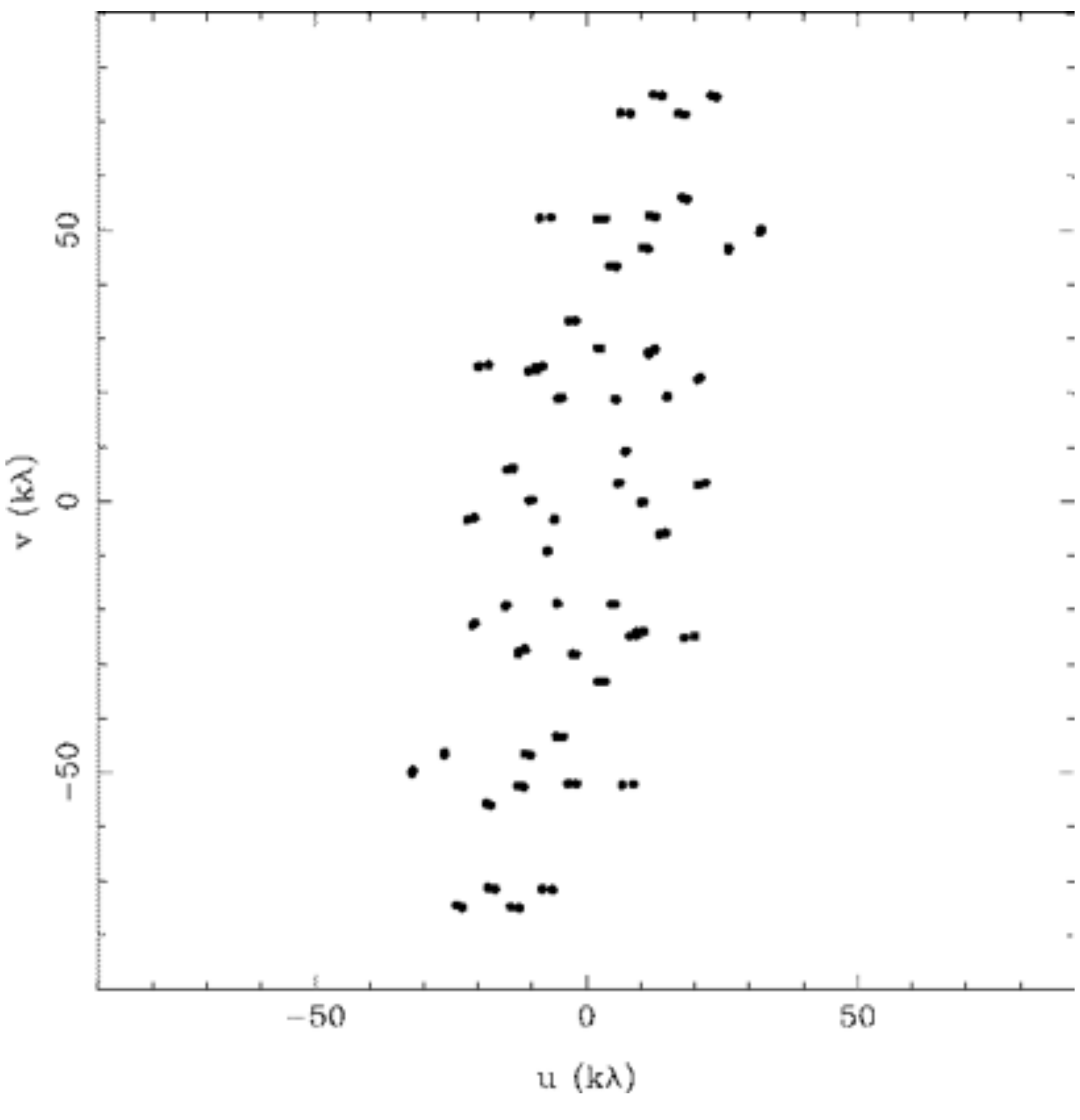
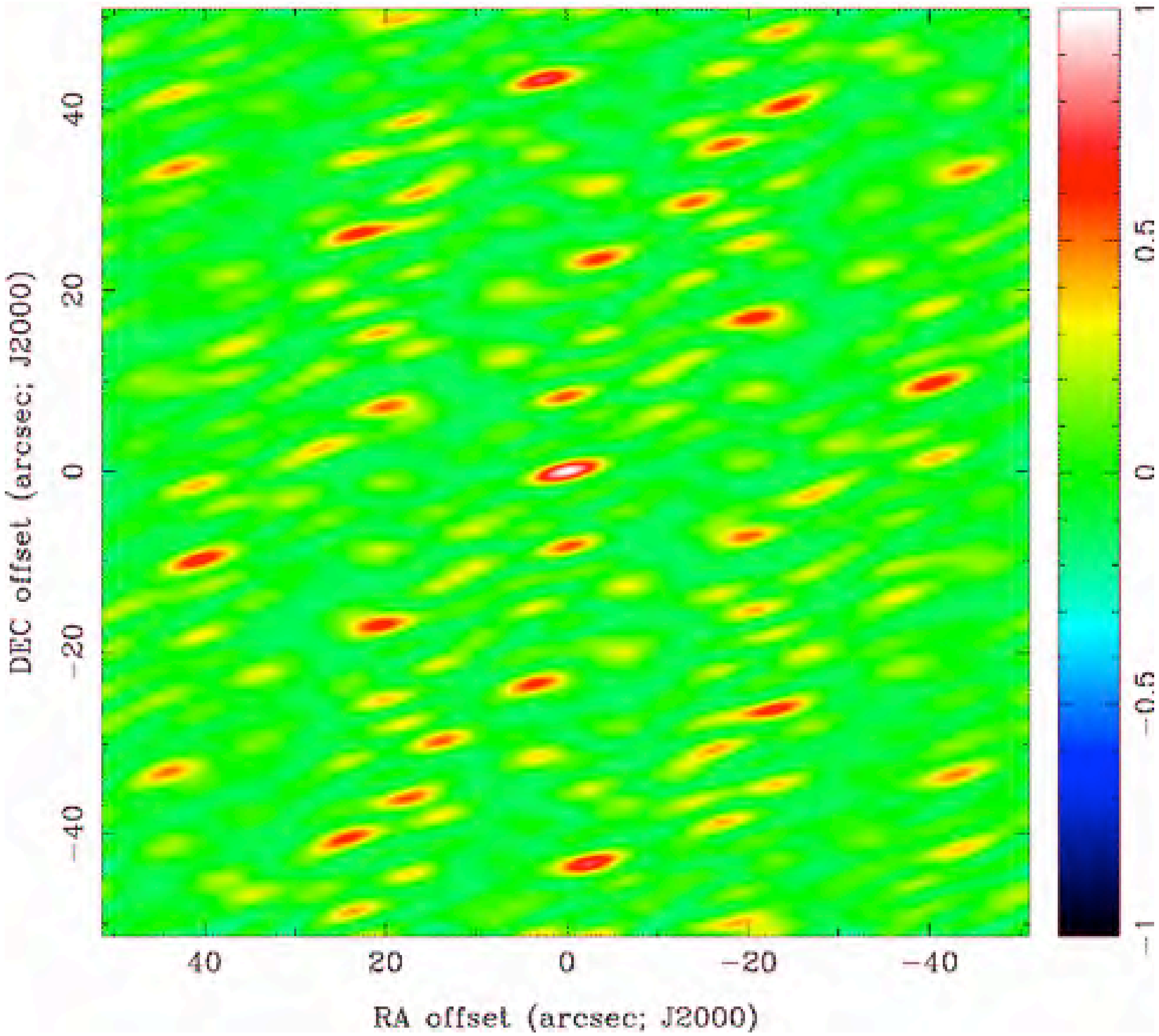
Dirty Beam Shape and Super Synthesis

8 Antennas x 2 samples





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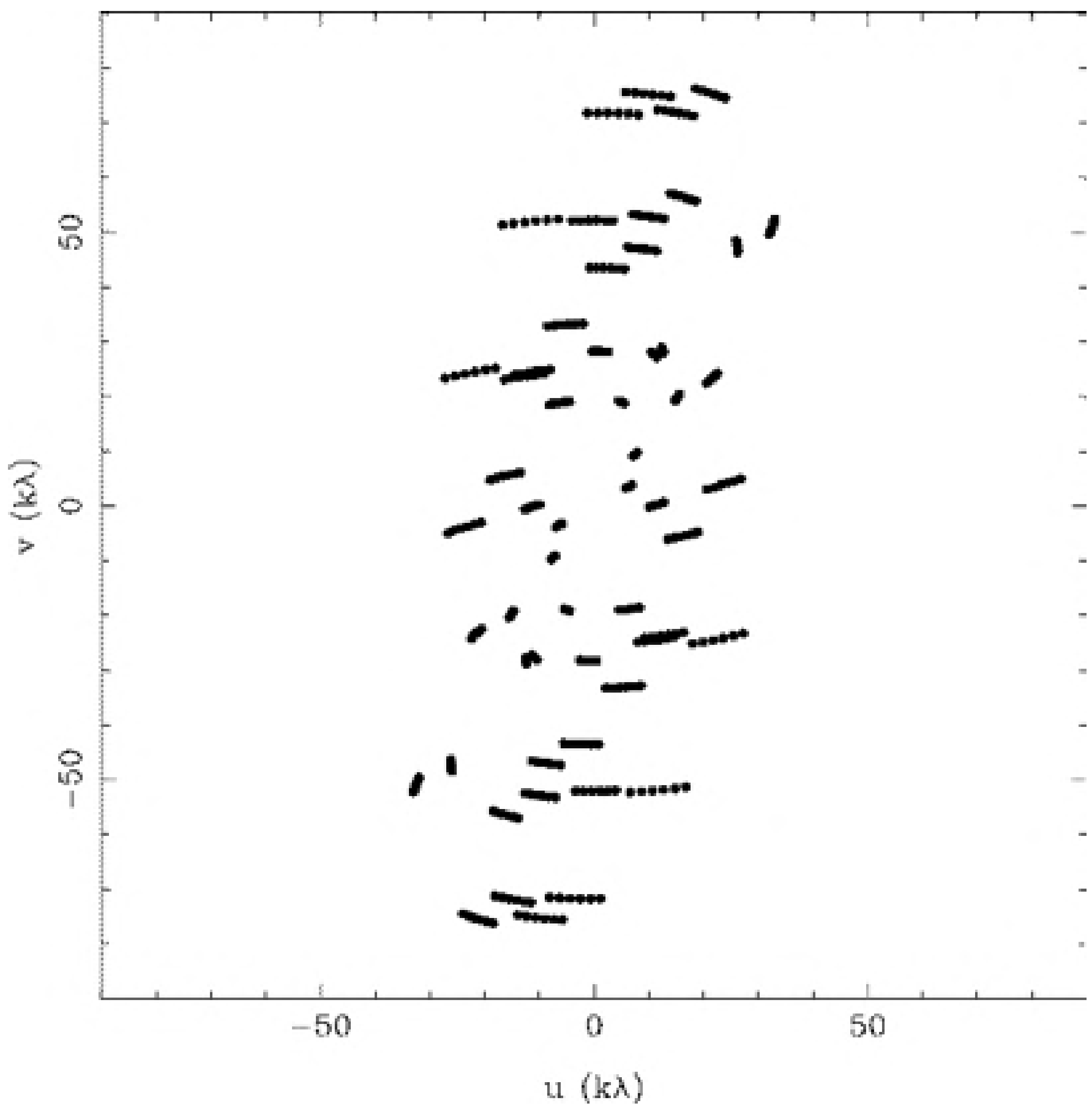
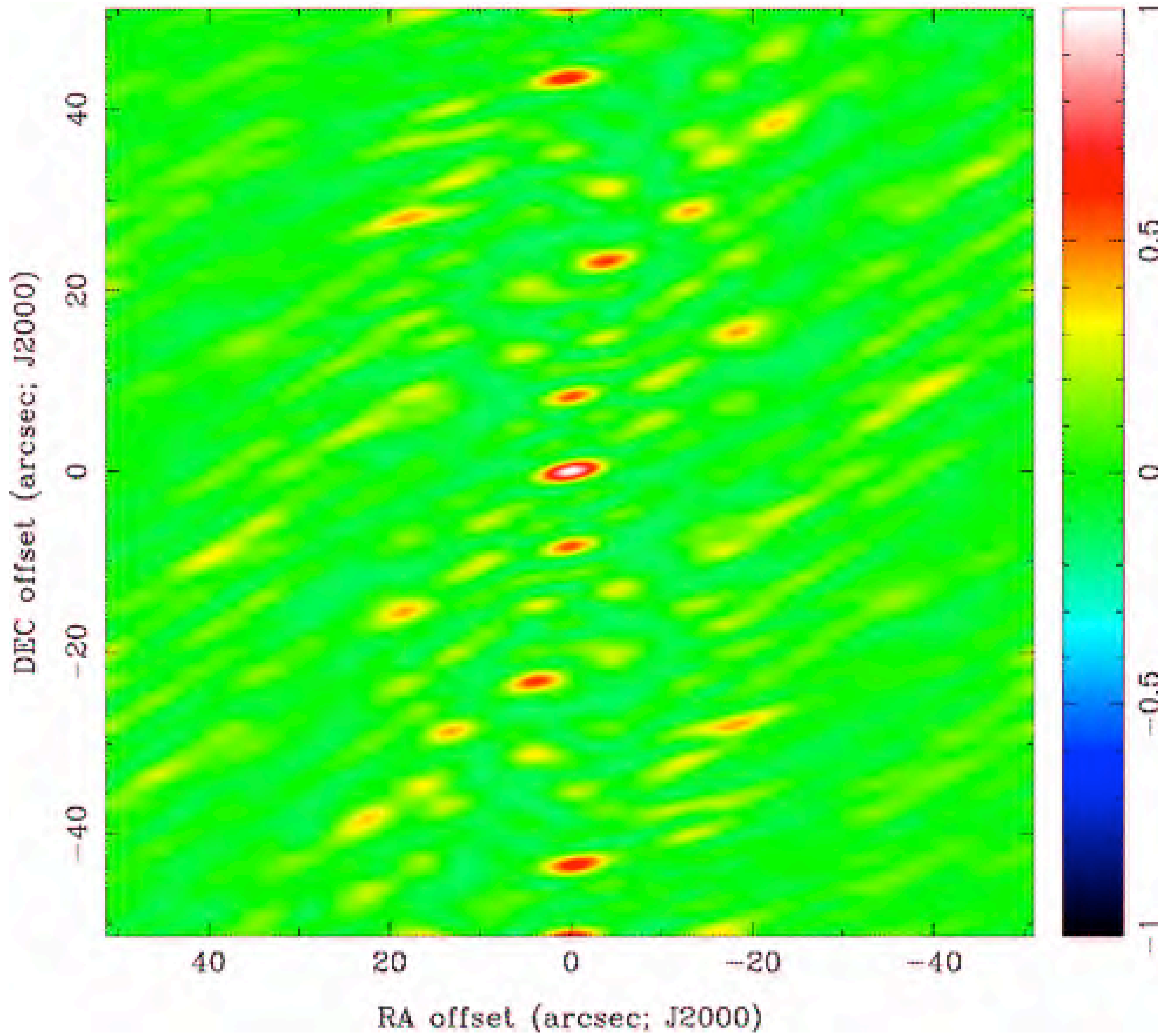
Dirty Beam Shape and Super Synthesis

8 Antennas x 6 samples





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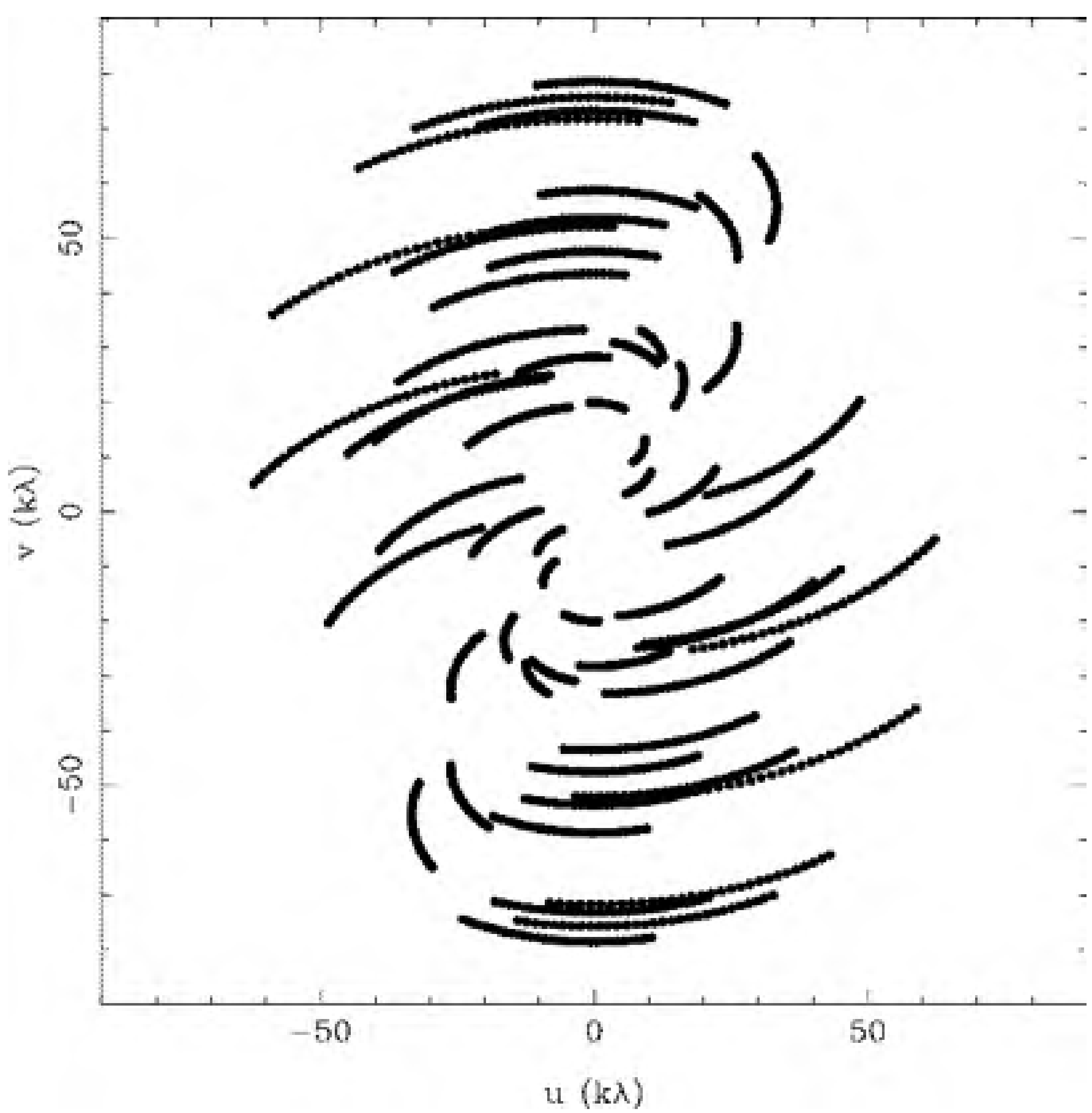
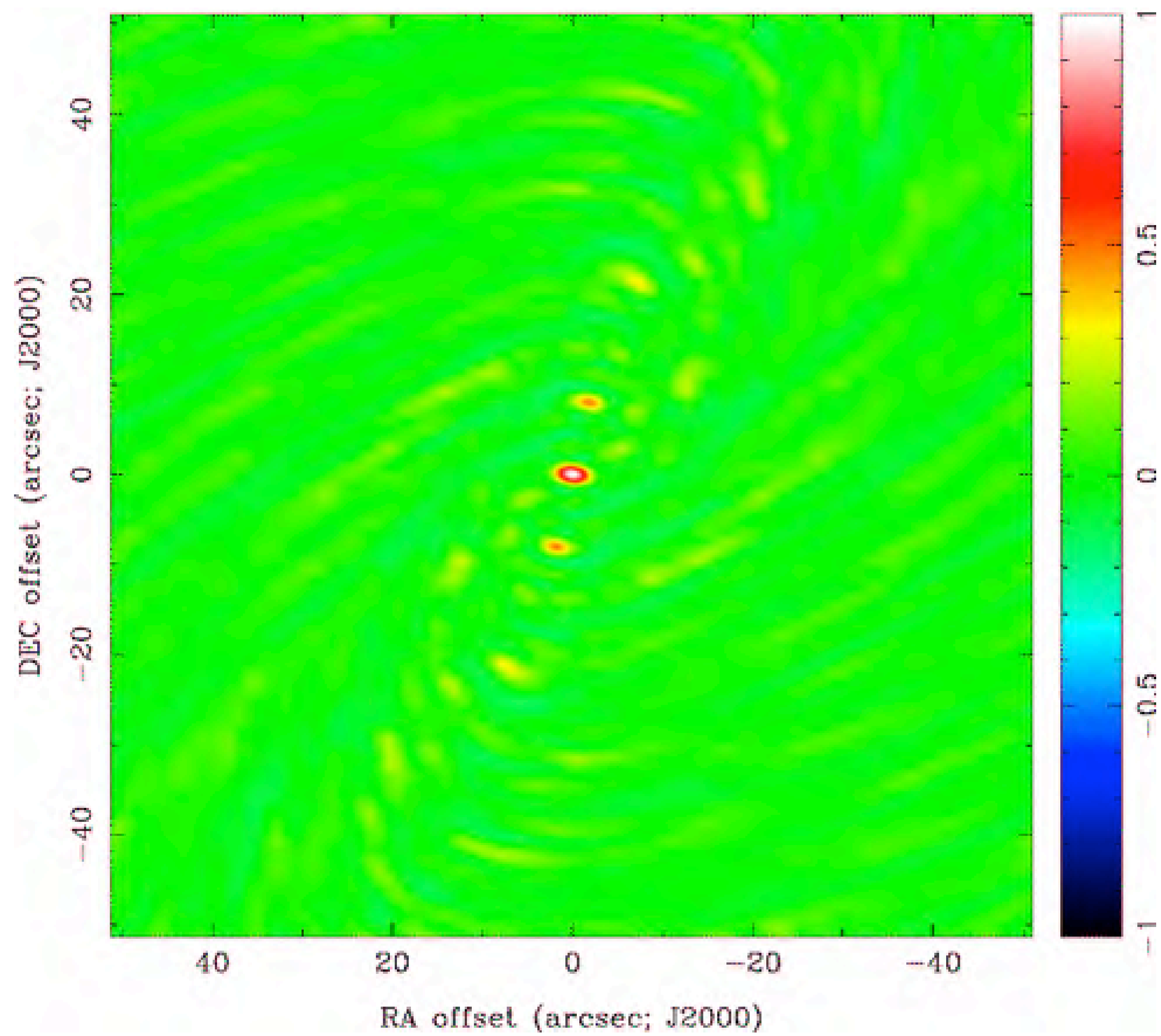
Dirty Beam Shape and Super Synthesis

8 Antennas x 30 samples





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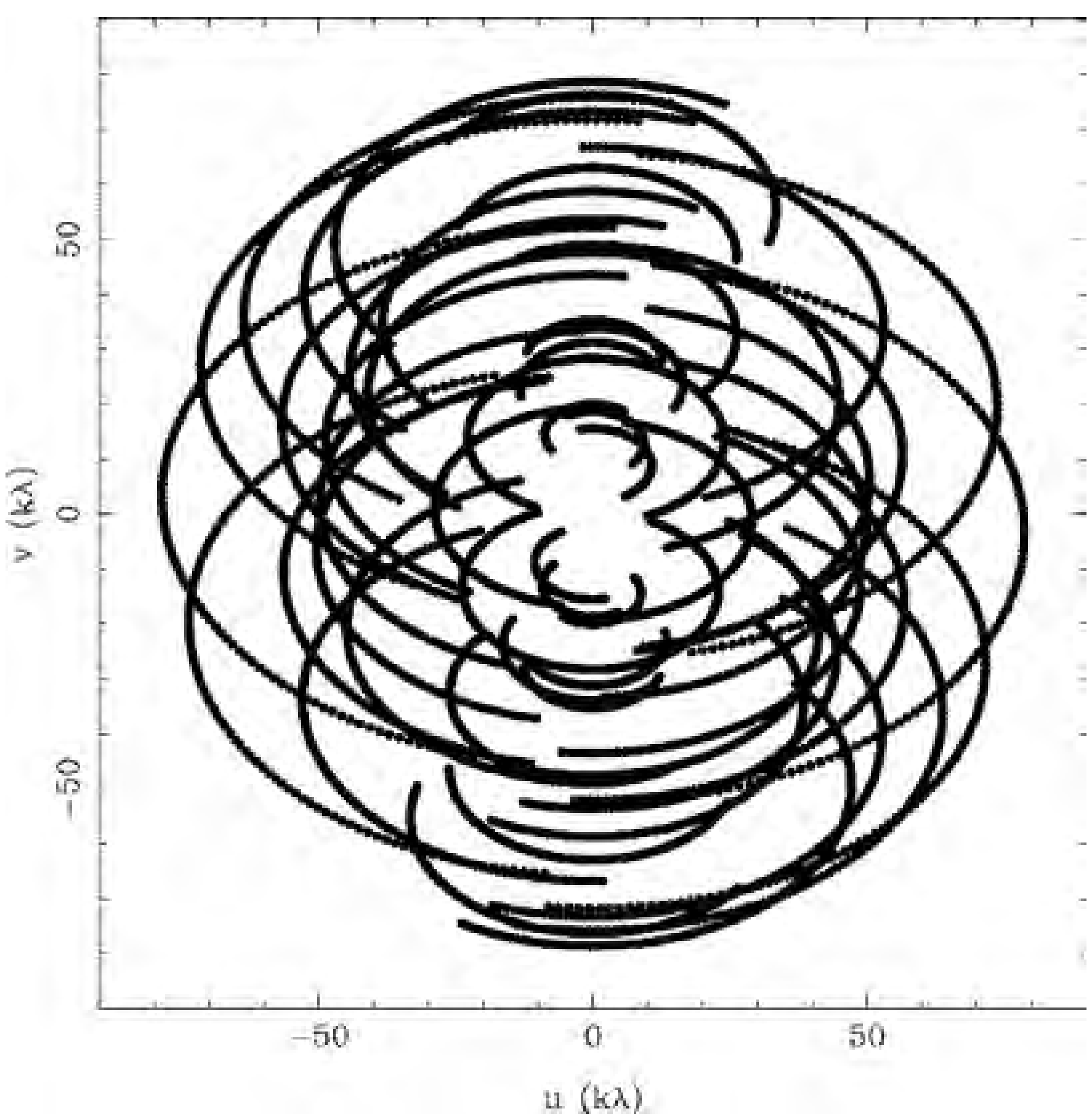
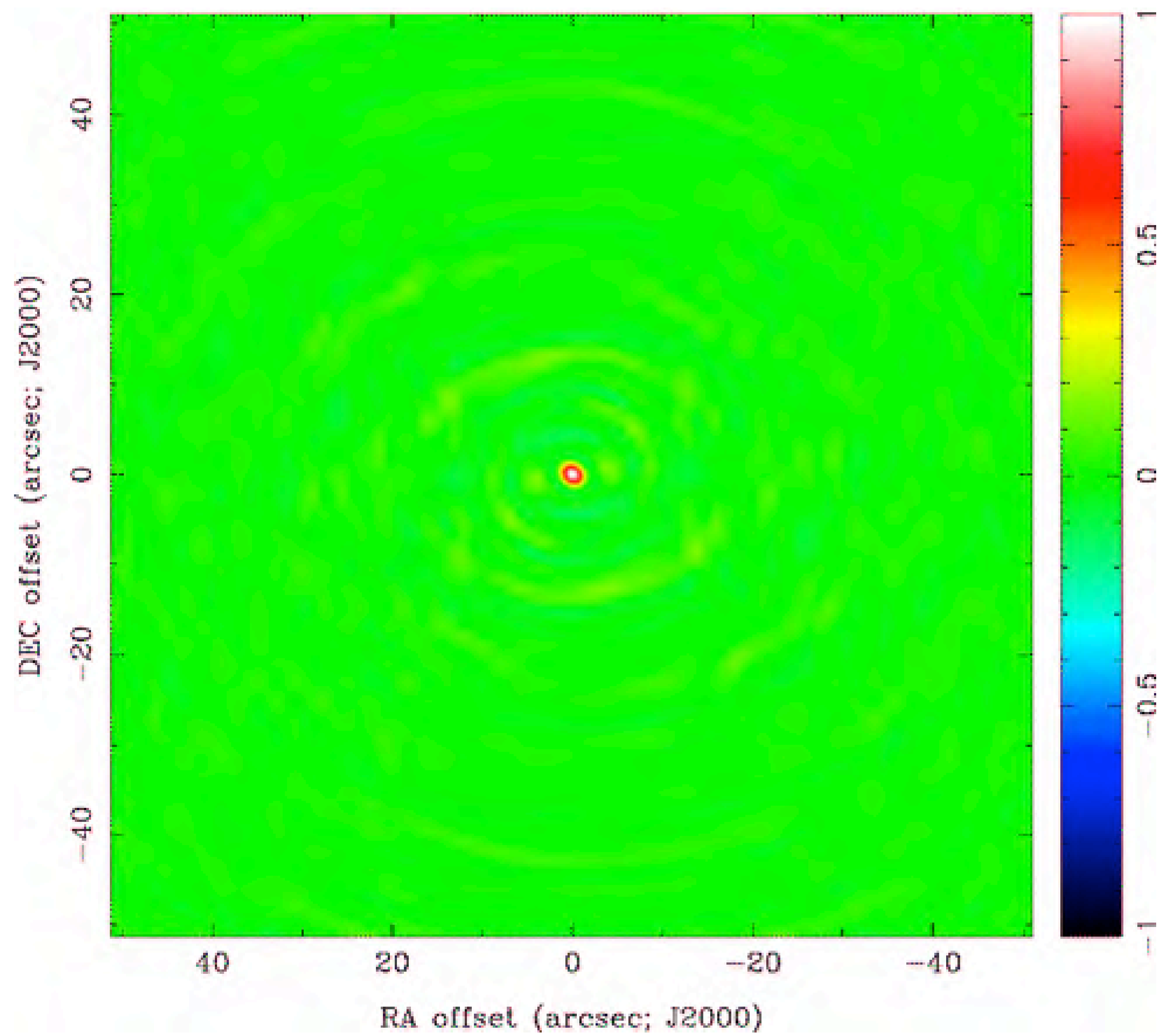
Dirty Beam Shape and Super Synthesis

8 Antennas x 107 samples





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Deconvolution Algorithms

- an active research area, e.g. compressive sensing methods

- clean: dominant deconvolution algorithm in radio astronomy
  - *a priori* assumption: *T(l,m)* is a collection of point sources
  - fit and subtract the synthesized beam iteratively
  - original version by Högbom (1974) purely image based
  - variants developed for higher computational efficiency, model visibility subtraction, to deal better with extended emission structure, etc.

- maximum entropy: a rarely used alternative
  - *a priori* assumption: *T(l,m)* is smooth and positive
  - define "smoothness" via a mathematical expression for entropy, e.g. Gull and Skilling (1983), find smoothest image consistent with data
  - vast literature about the deep meaning of entropy as information content

NRAO

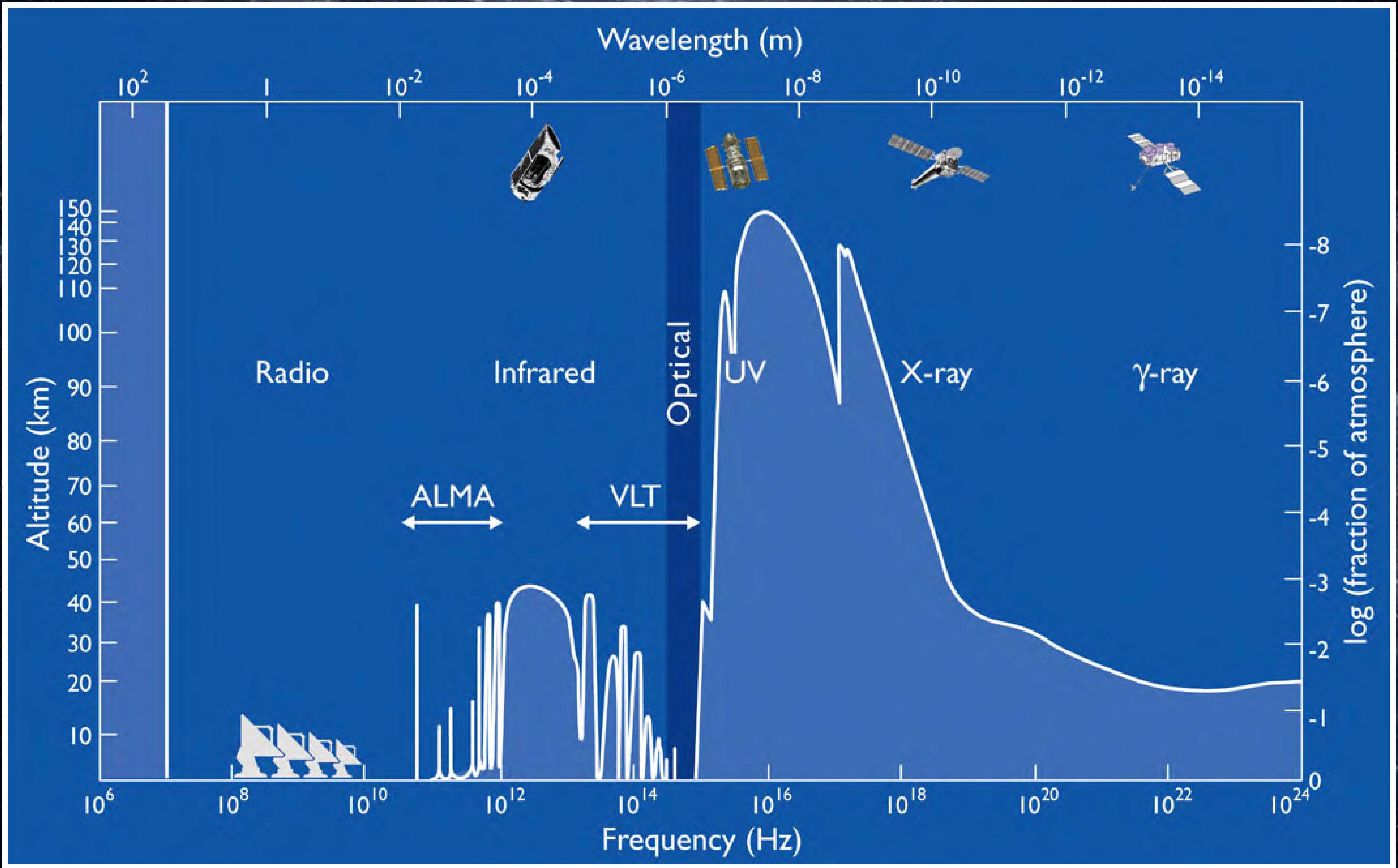
New Mexico CONSORTIUM

Aperture synthesis or synthesis imaging is a type of Interferometry that mixes signals from a collection of telescopes to produce images having the same angular resolution as an instrument the size of the entire collection.

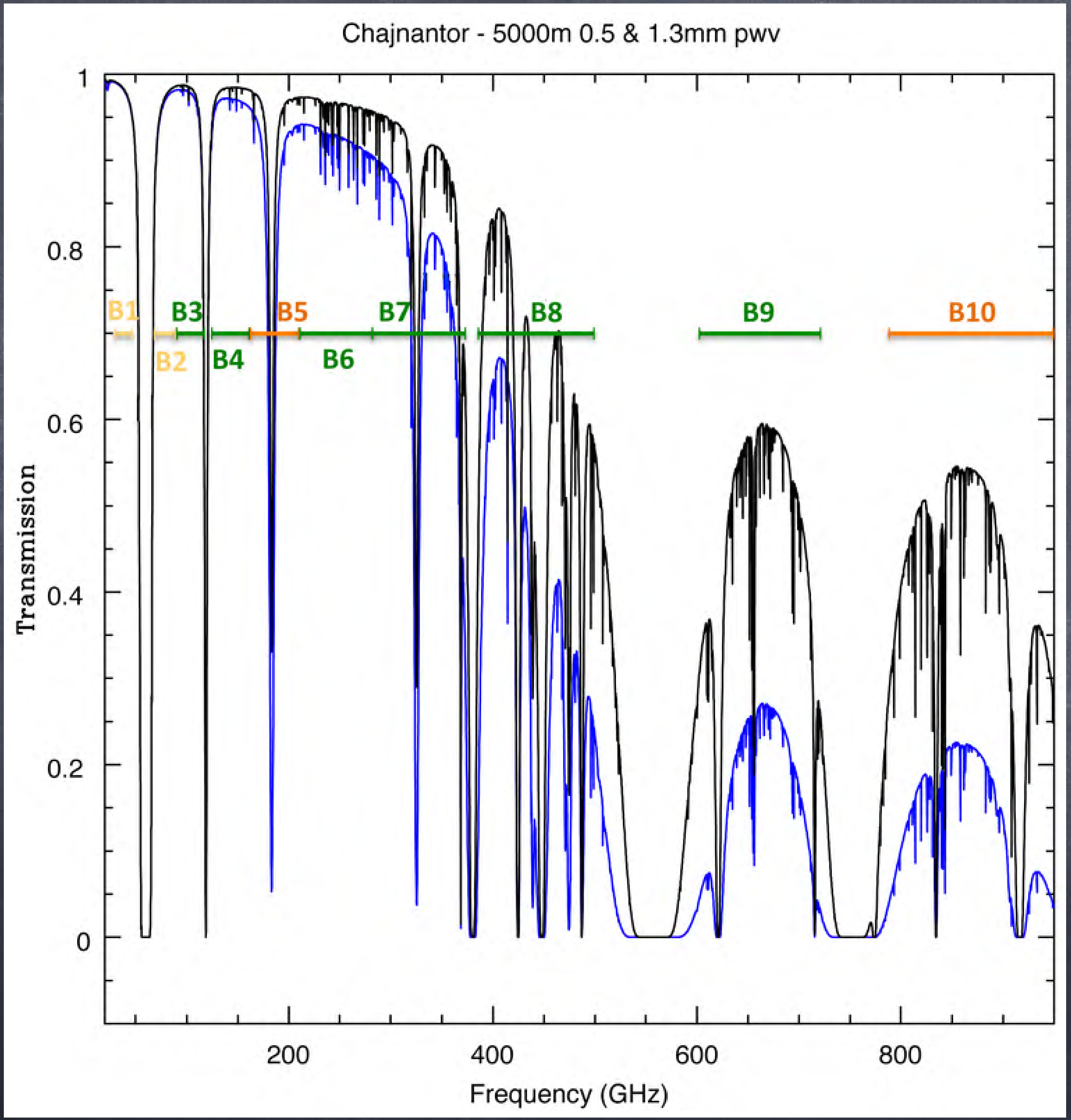
Observations from the Earth's surface are limited to wavelengths that can pass through the atmosphere. At low frequencies, limited by the ionosphere, which reflects waves with frequencies less than its characteristic plasma frequency.

Higher frequencies (eg. sub-mm), water vapor is the limiting factor.

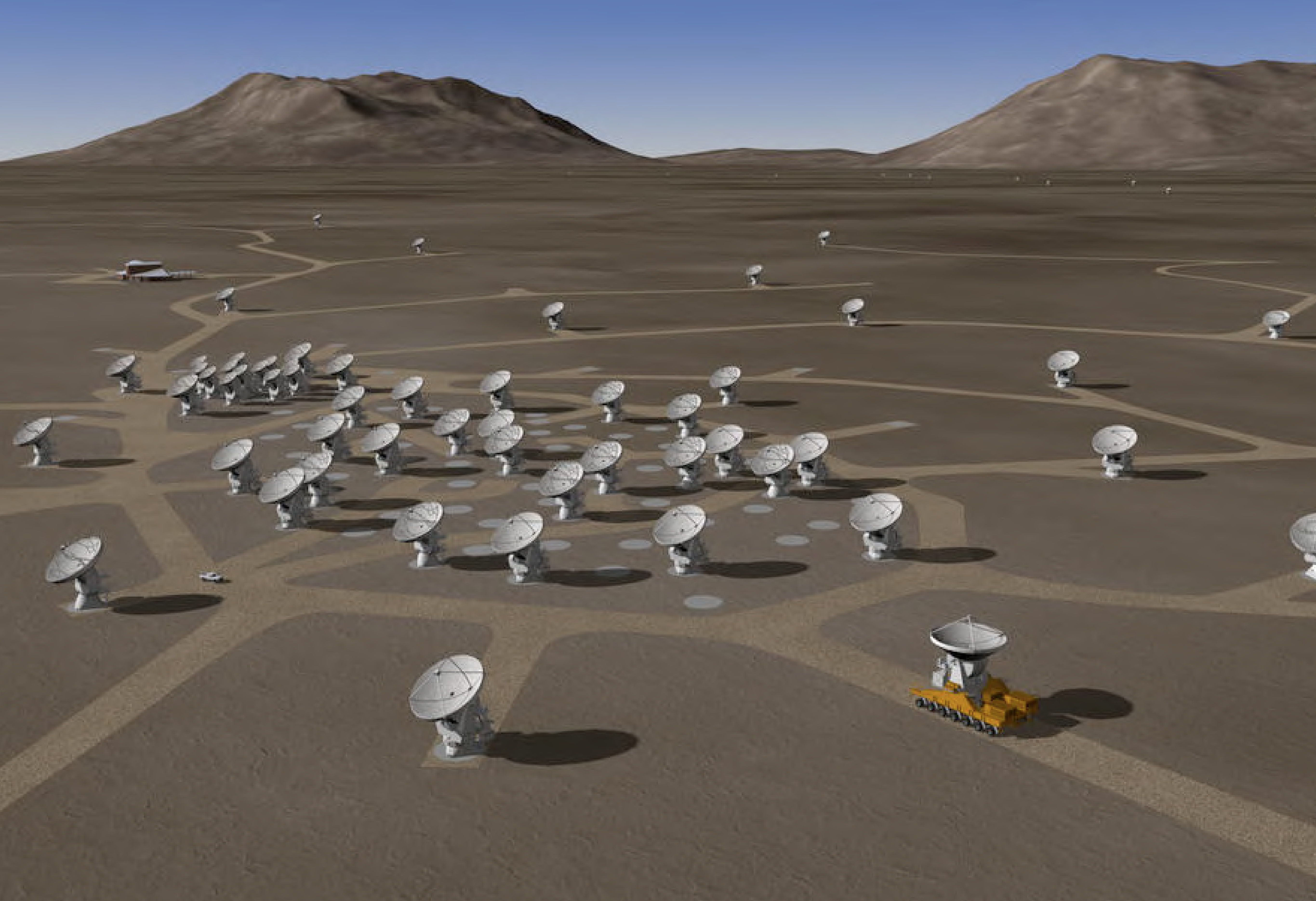
A whole spectrum of radiation!



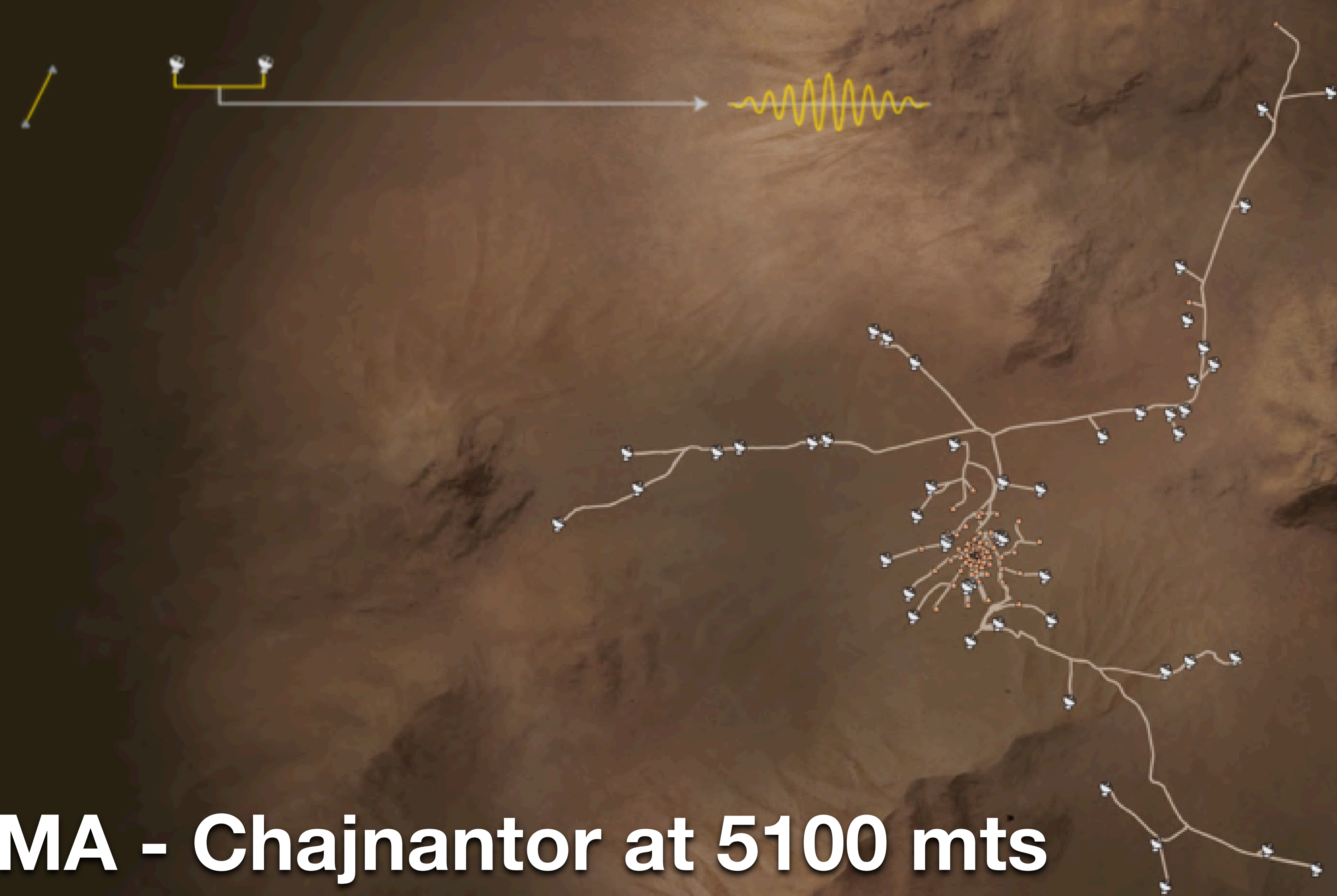
Curves showing the transparency of the atmosphere above the ALMA site as a function of frequency.



ALMA Fiction

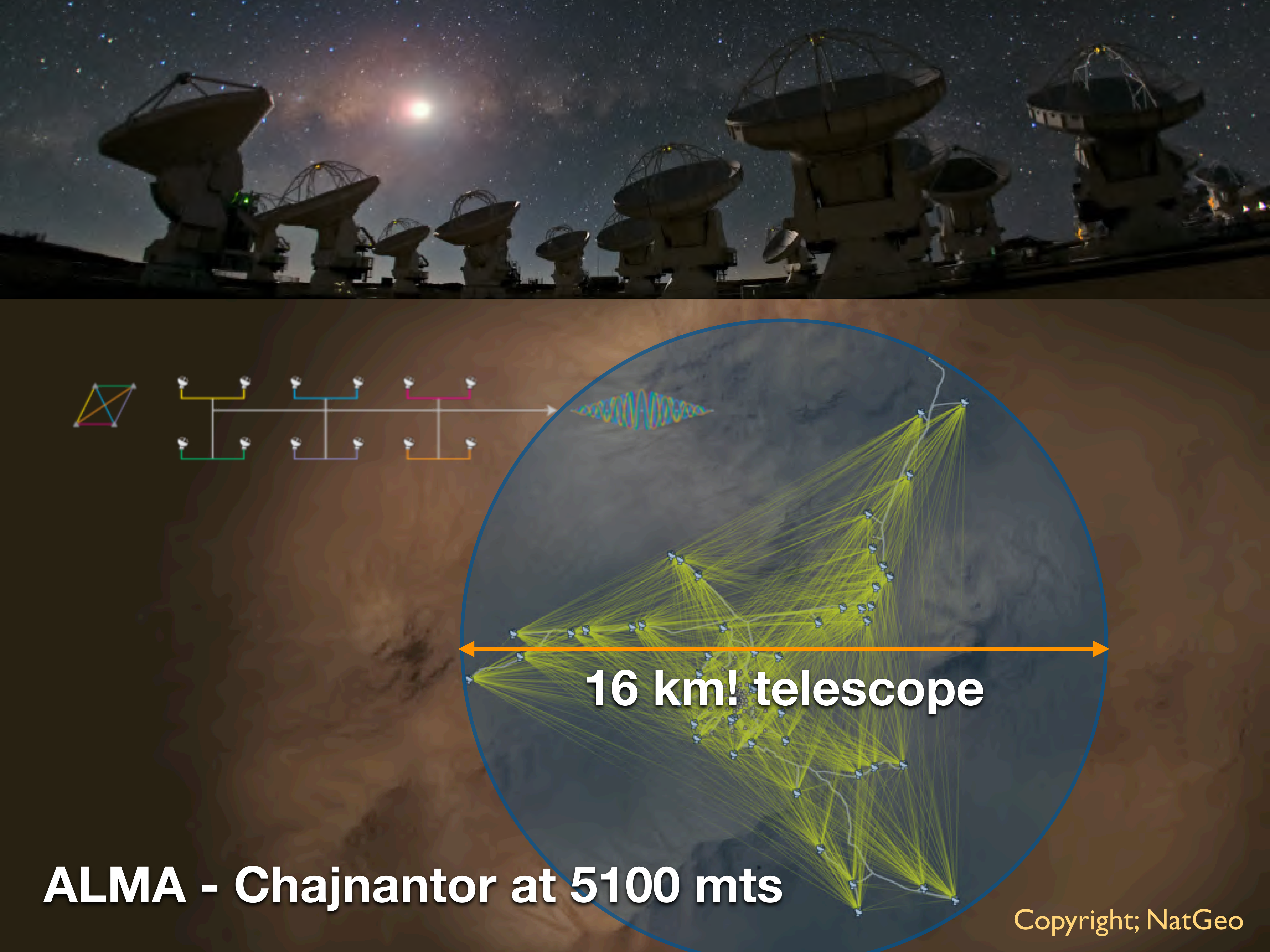


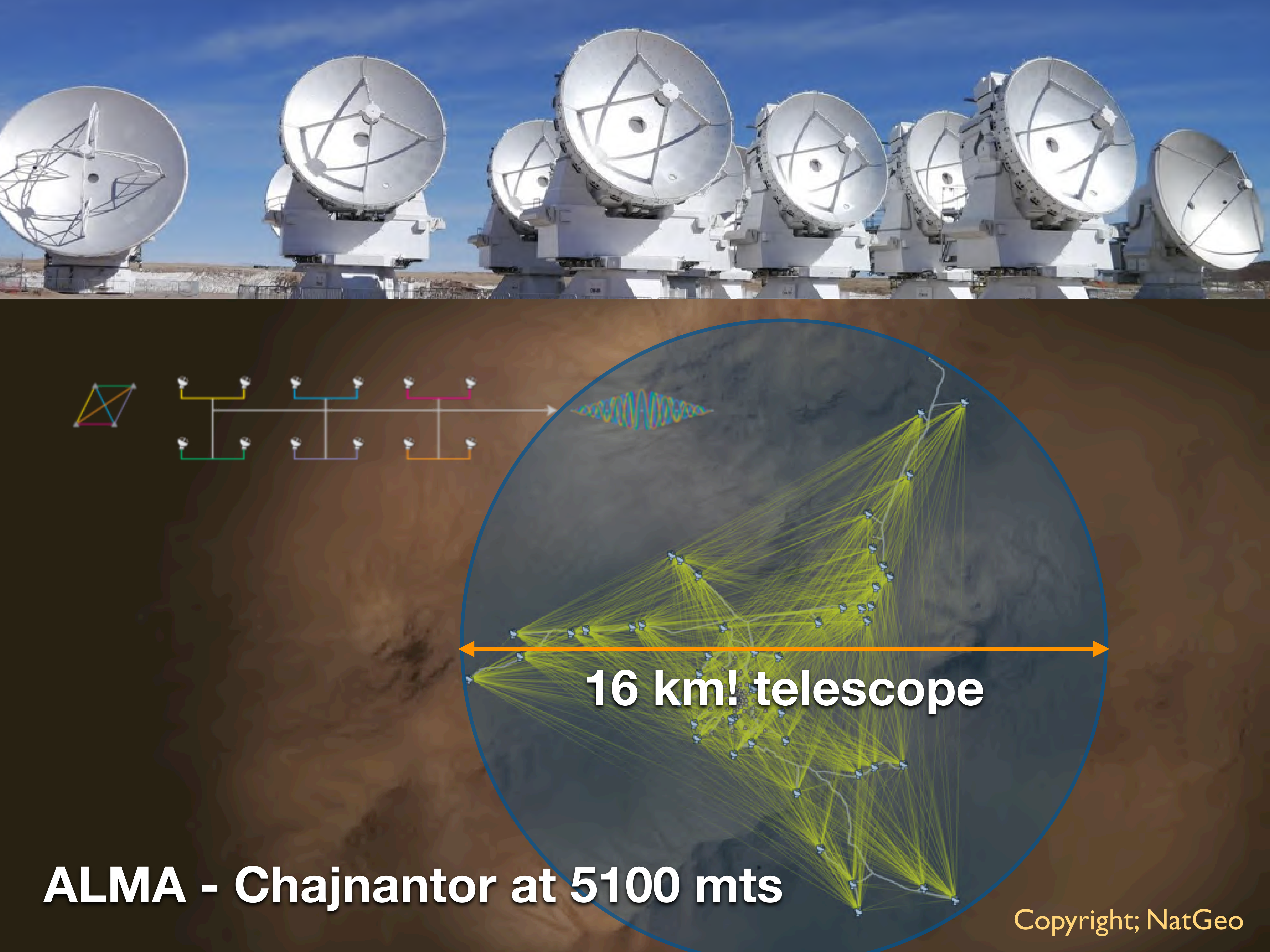
ALMA - FACT / Chajnantor at 5100 mts



ALMA - Chajnantor at 5100 mts

Copyright; NatGeo


16 km! telescope
ALMA - Chajnantor at 5100 mts
Copyright; NatGeo


16 km! telescope
ALMA - Chajnantor at 5100 mts
Copyright; NatGeo

The Correlator, ALMA's central computer, 2009.
Credit: ALMA (ESO/NAOJ/NRAO), S. Argandoña.

The Correlator, ALMA's central computer, is located in ALMA's Operations Center on the Chajnantor Plateau. **It receives, processes and stores the information sent by the *back end*.**

The **Correlator is ALMA's brain.** Here, the data collected by the antennas is processed at a rate of **thousands of millions of times per second.**

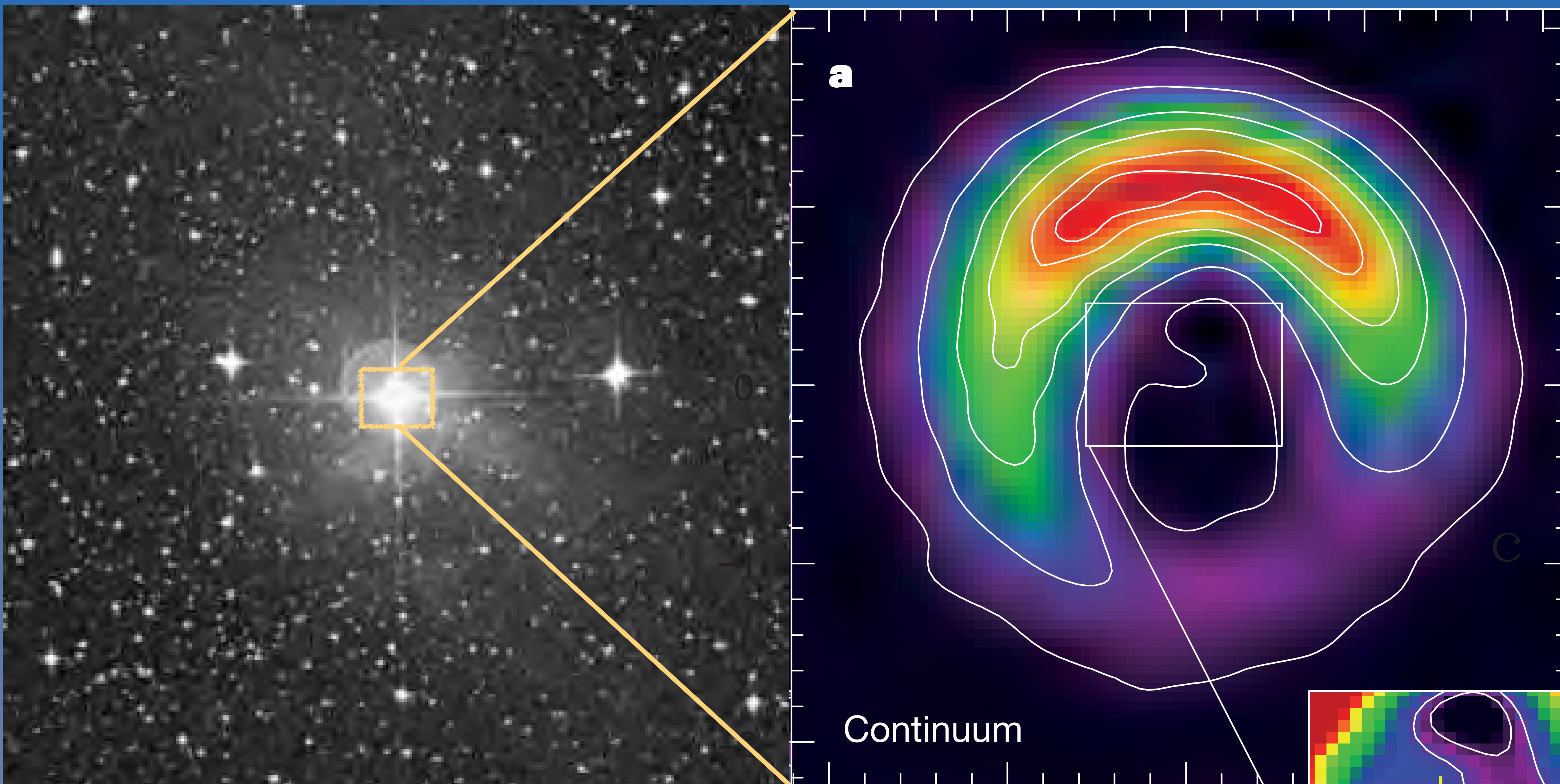
You would need over **3 million laptop computers to carry out the same number of operations** per second.

This colossal machine is the **world's most powerful calculator** and has been designed especially for ALMA.

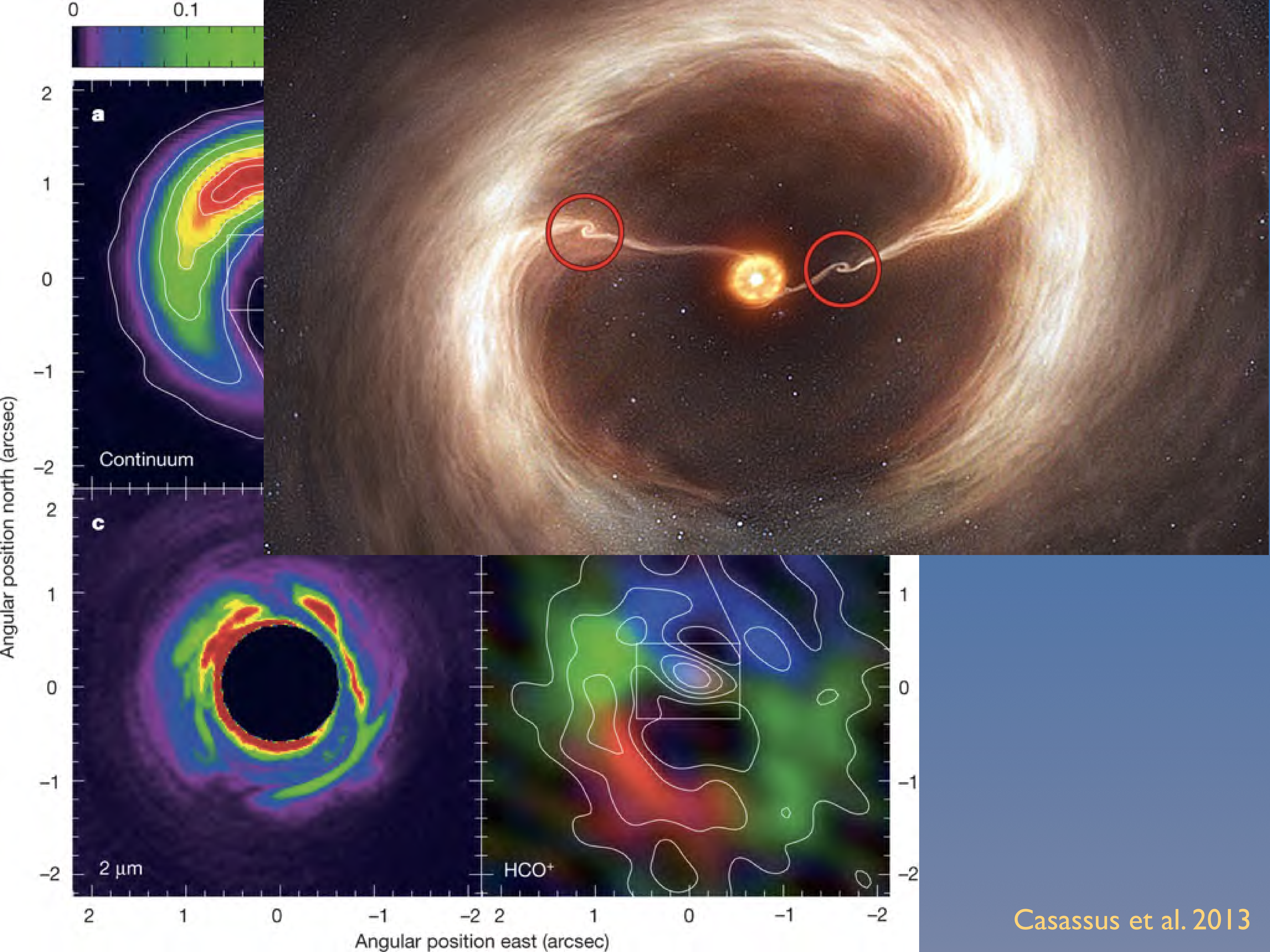
2 cool examples:

HD 142527 - Protoplanetary Disk
SS 433 - Stellar Mass Black Hole (famous)

ALMA's view / HD142527



Casassus et al. 2013



Casassus et al. 2013

SS433

X-ray binary / Microquasar

Companion star: **unknown**

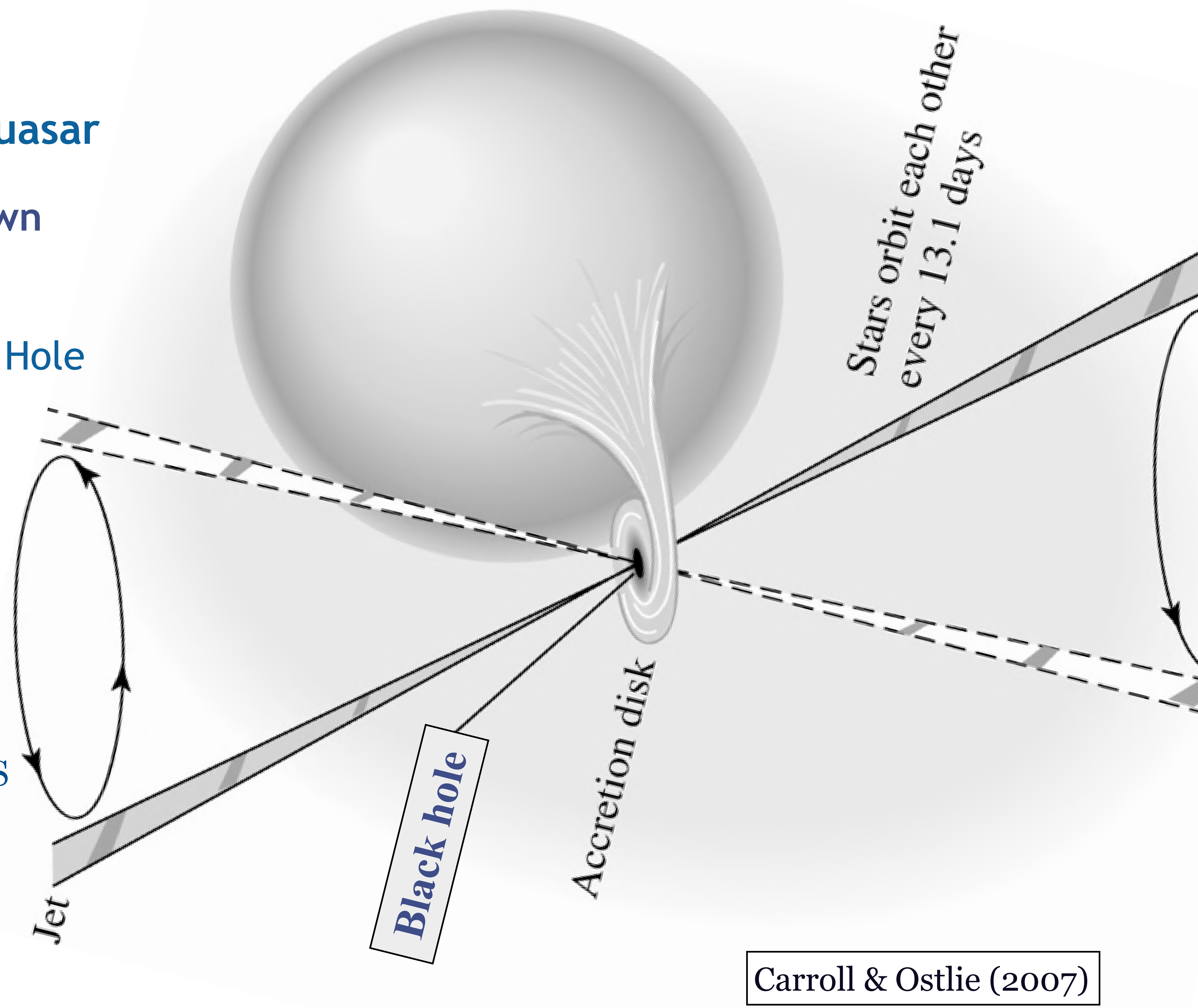
Compact object:
most likely a Black Hole

Accretion disc

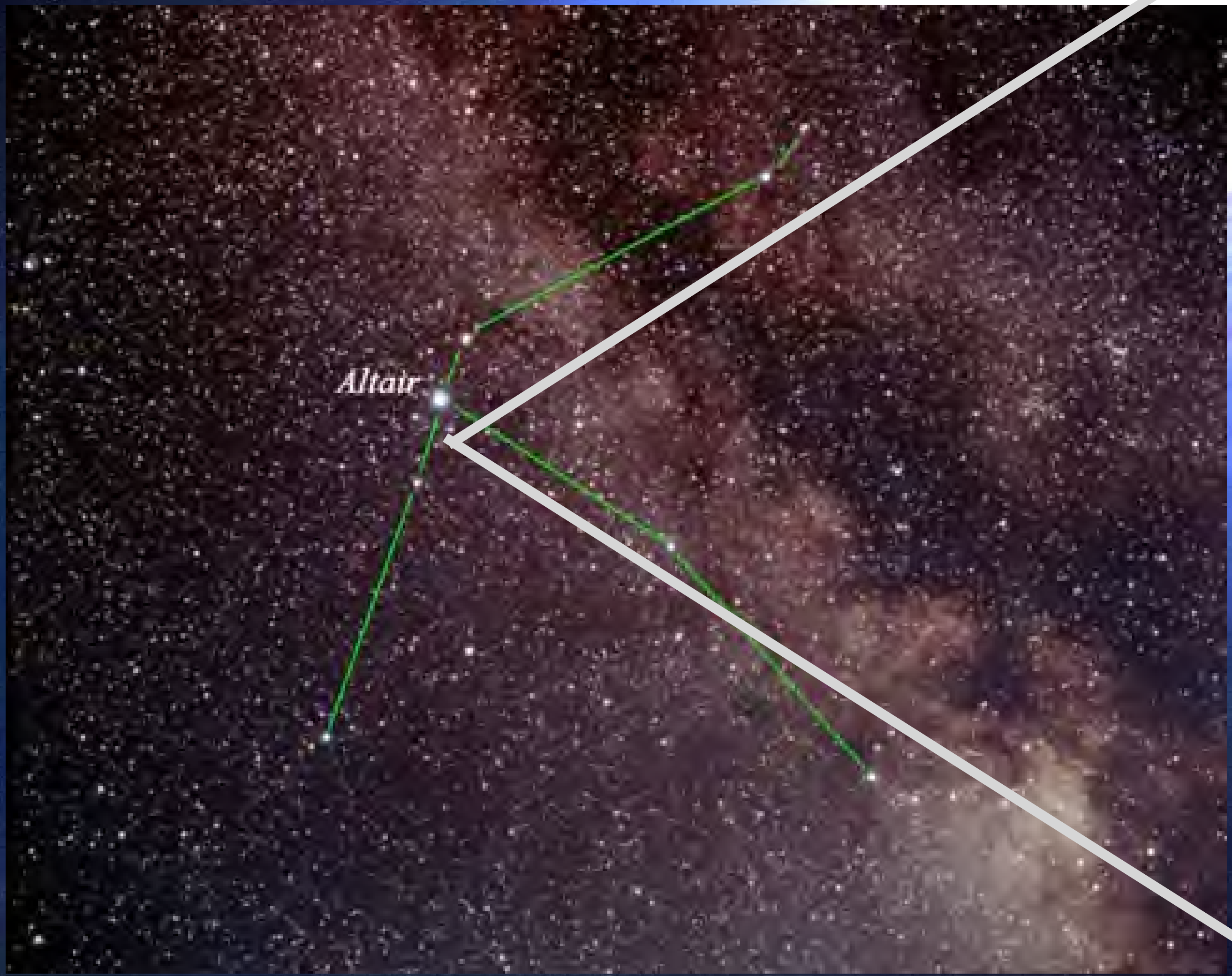
Relativistic jets

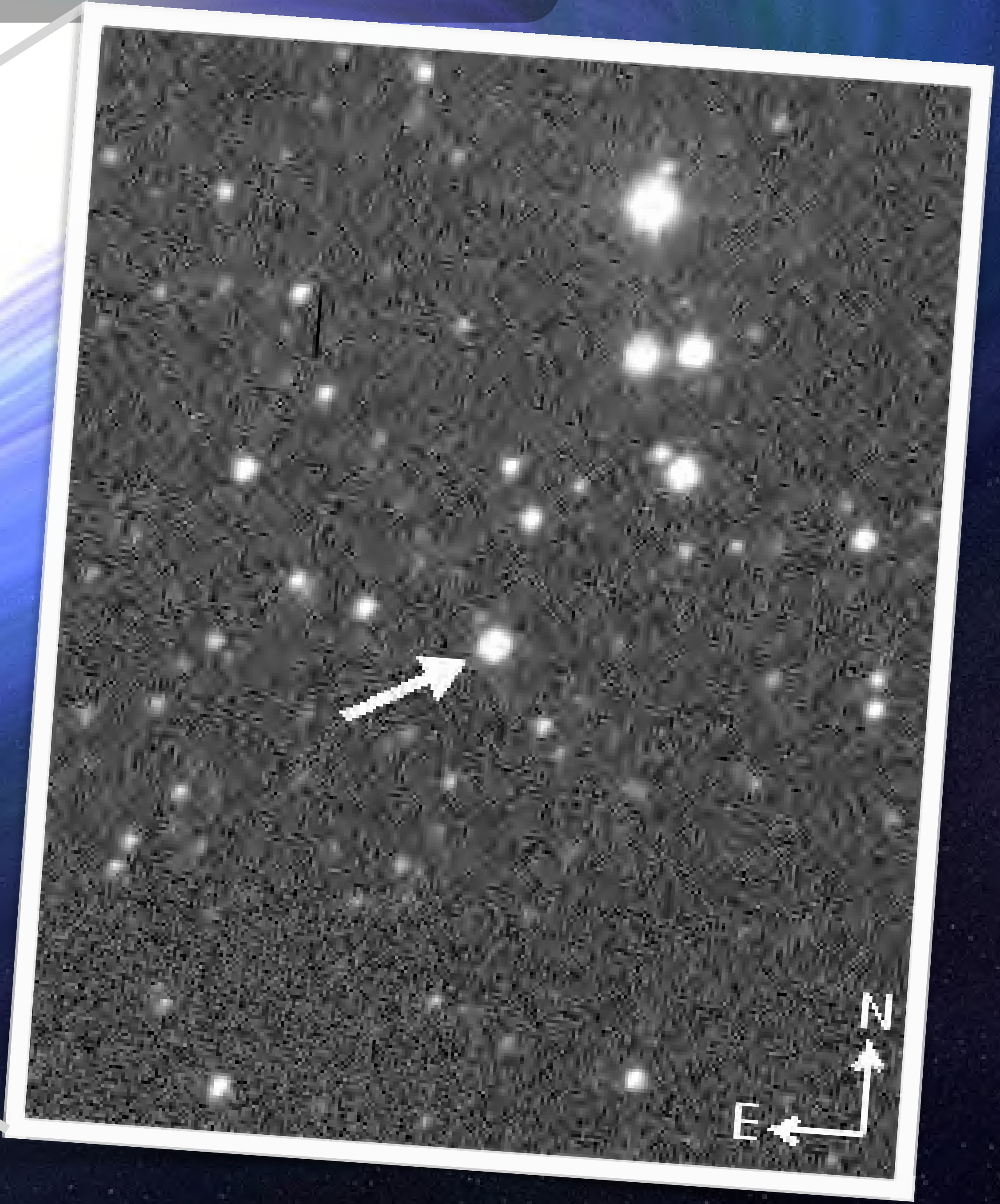
3 main periodicities:

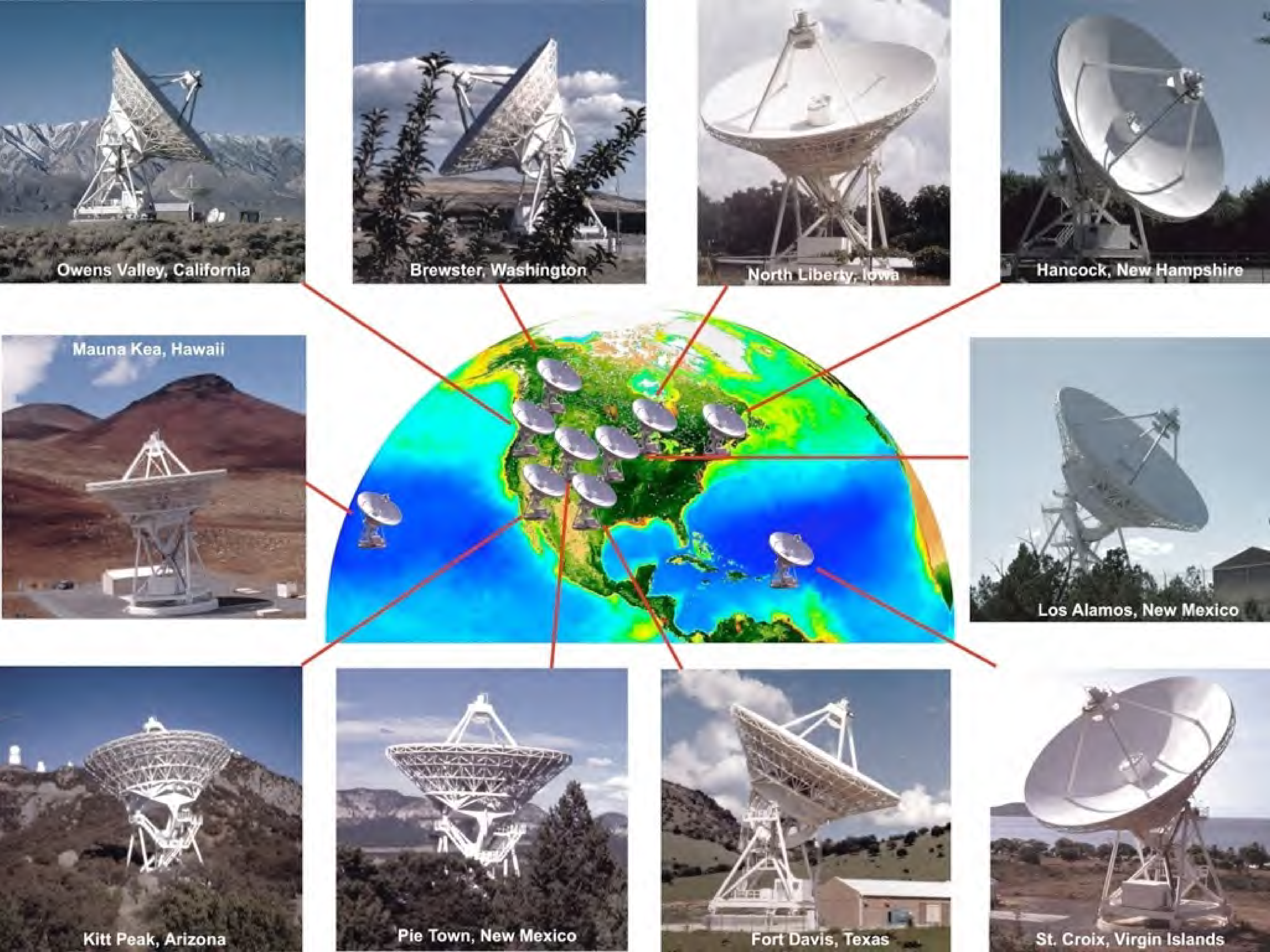
$$P_{\rm orb} = 13.1 \text{ days}$$
$$P_{\rm prec} = 162 \text{ days}$$
$$P_{\rm nut} = 6 \text{ days}$$



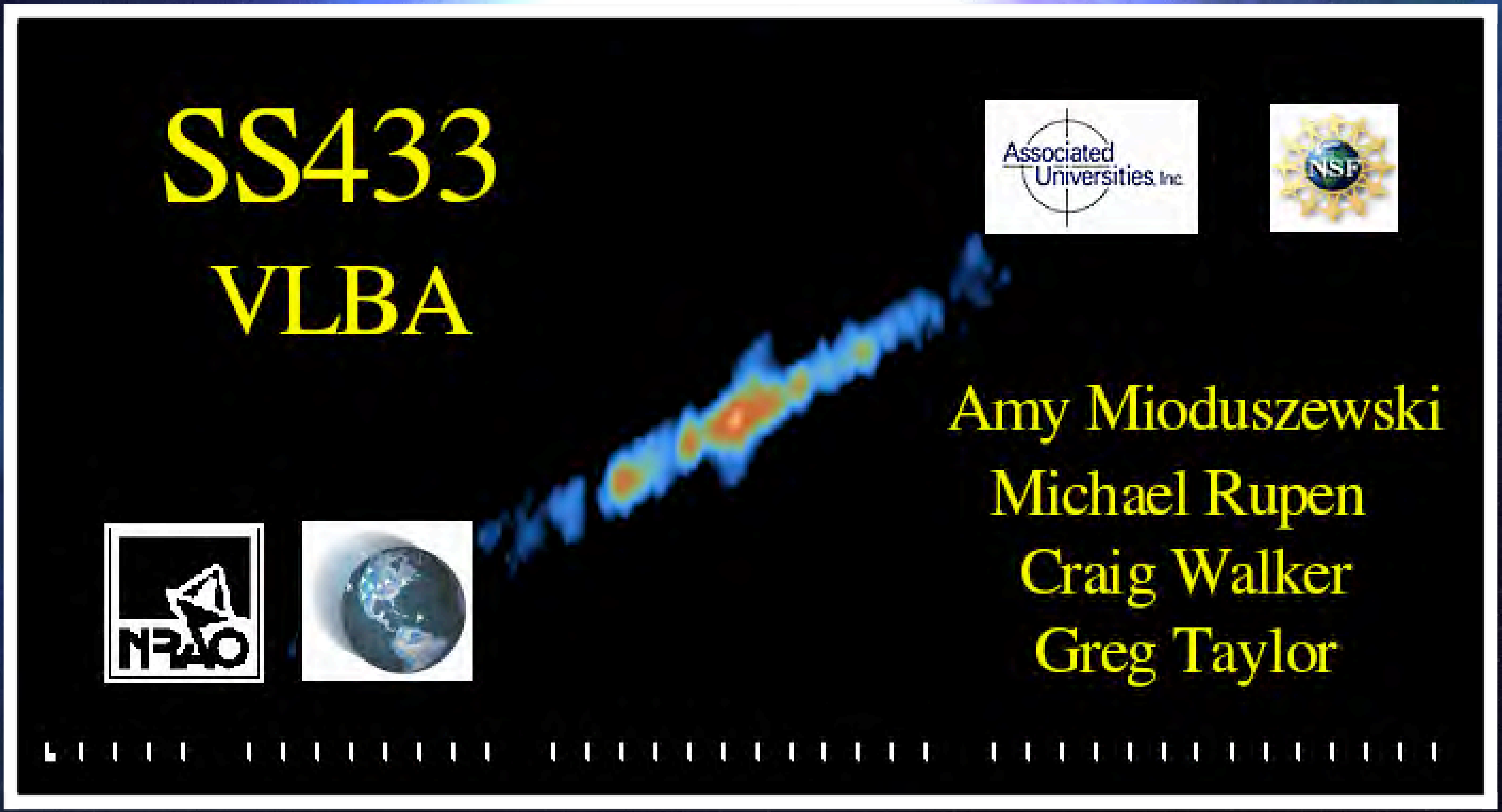
An optical view of a microquasar in the Milky Way



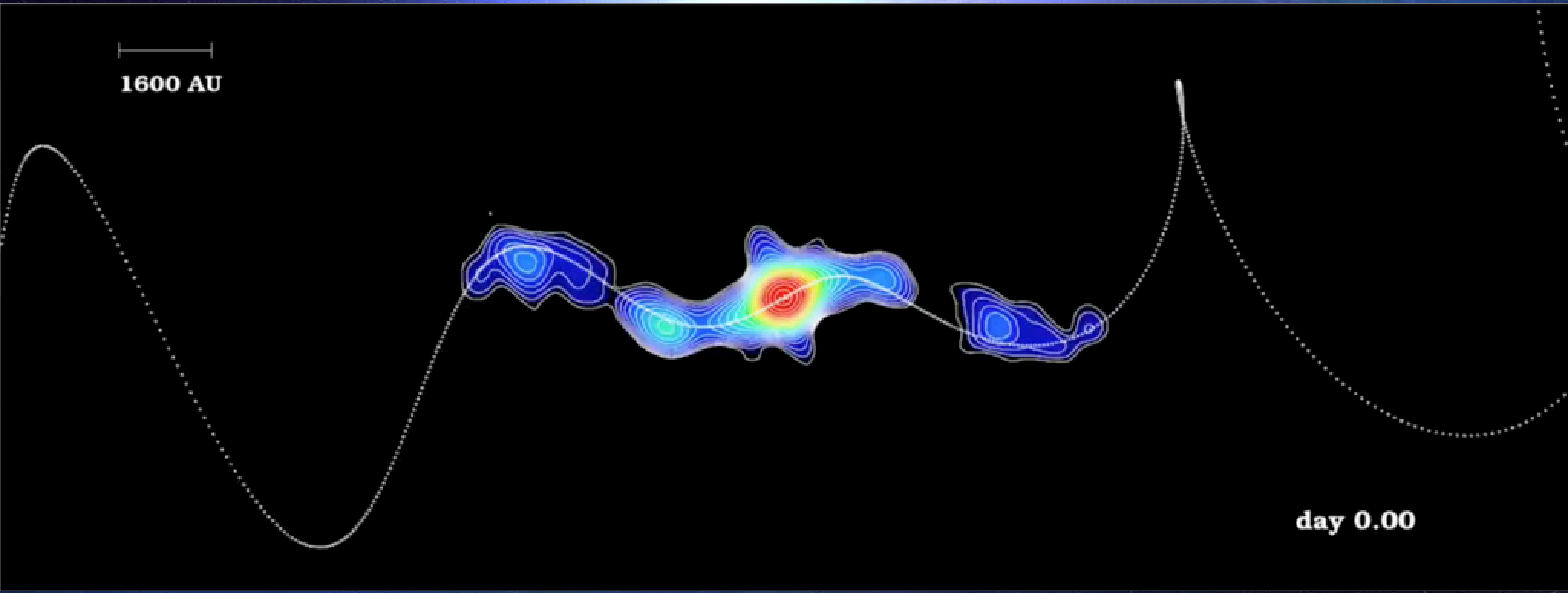



Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands

Why is SS 433 special?



SS 433



fraction of a milli-arcsecond resolution!

(0.12 mas at 0.3 cm)

graphical tool for demonstrating the techniques of radio interferometry:

Pynterferometer

(python based)

written by A. Avison from ALMA UK arc