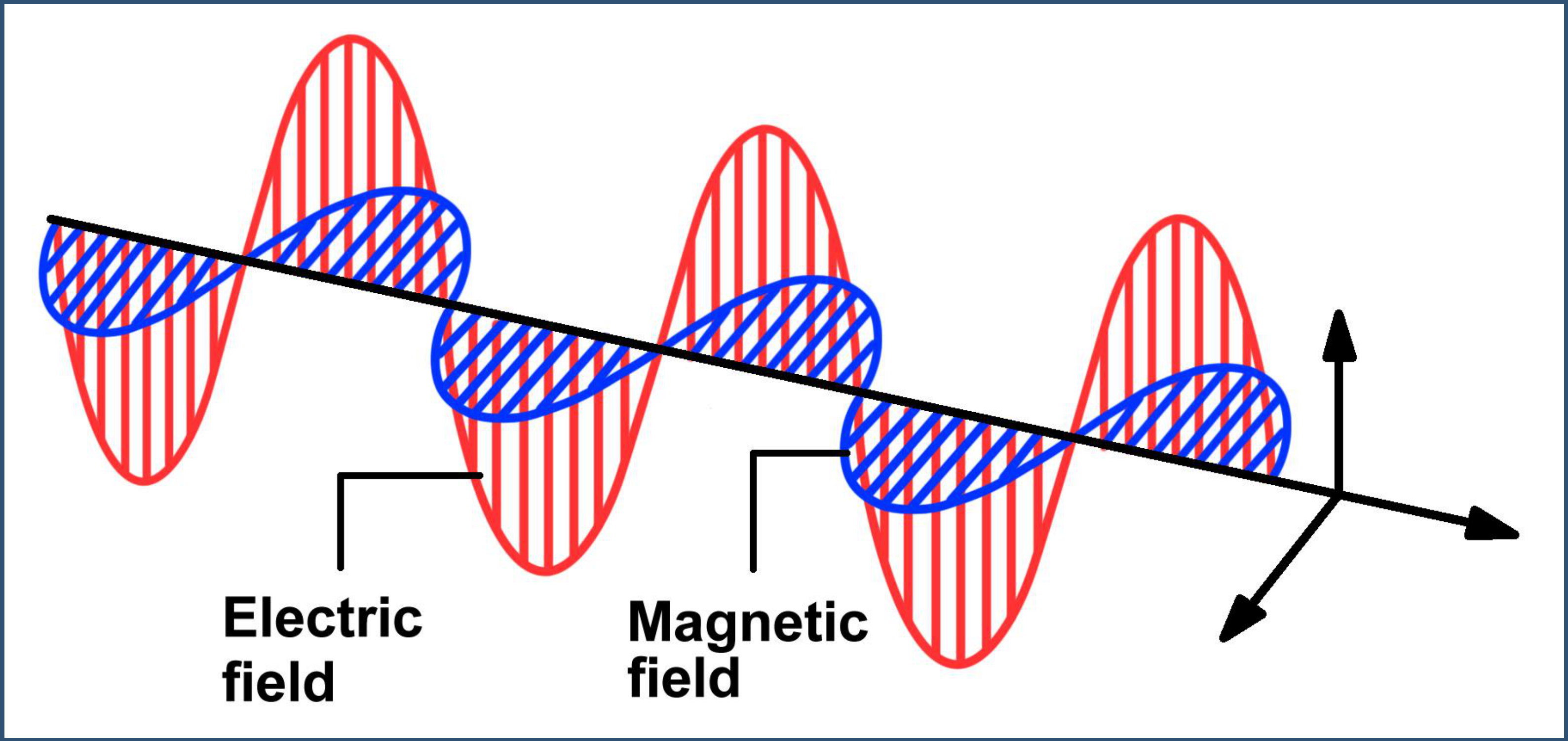
Interferometry

Stephen Muchovej -- Caltech

Outline

I. Quick review of astronomy
II. Brief history of radio astronomy
III. Radio telescopes
IV. Interferometry in words
V. Interferometry in practice
VI. (An) Application of Interferometers
VII. Activities

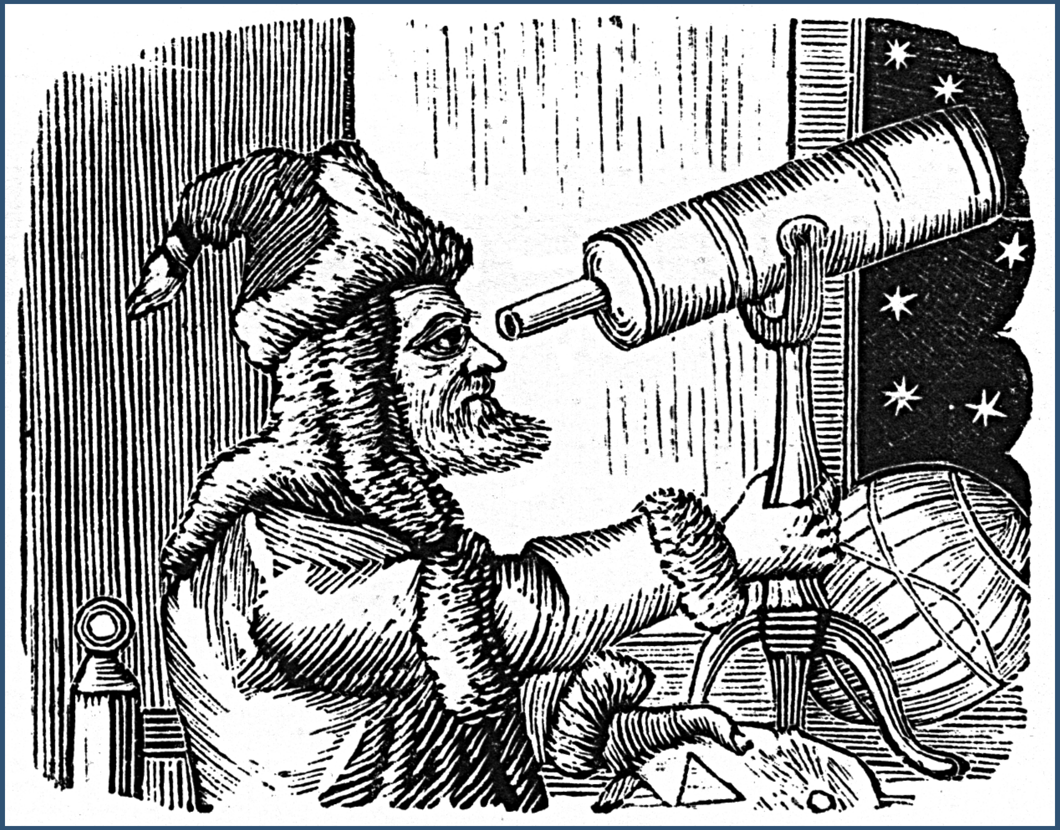
Light as a wave



- Can be represented entirely by a frequency and amplitude

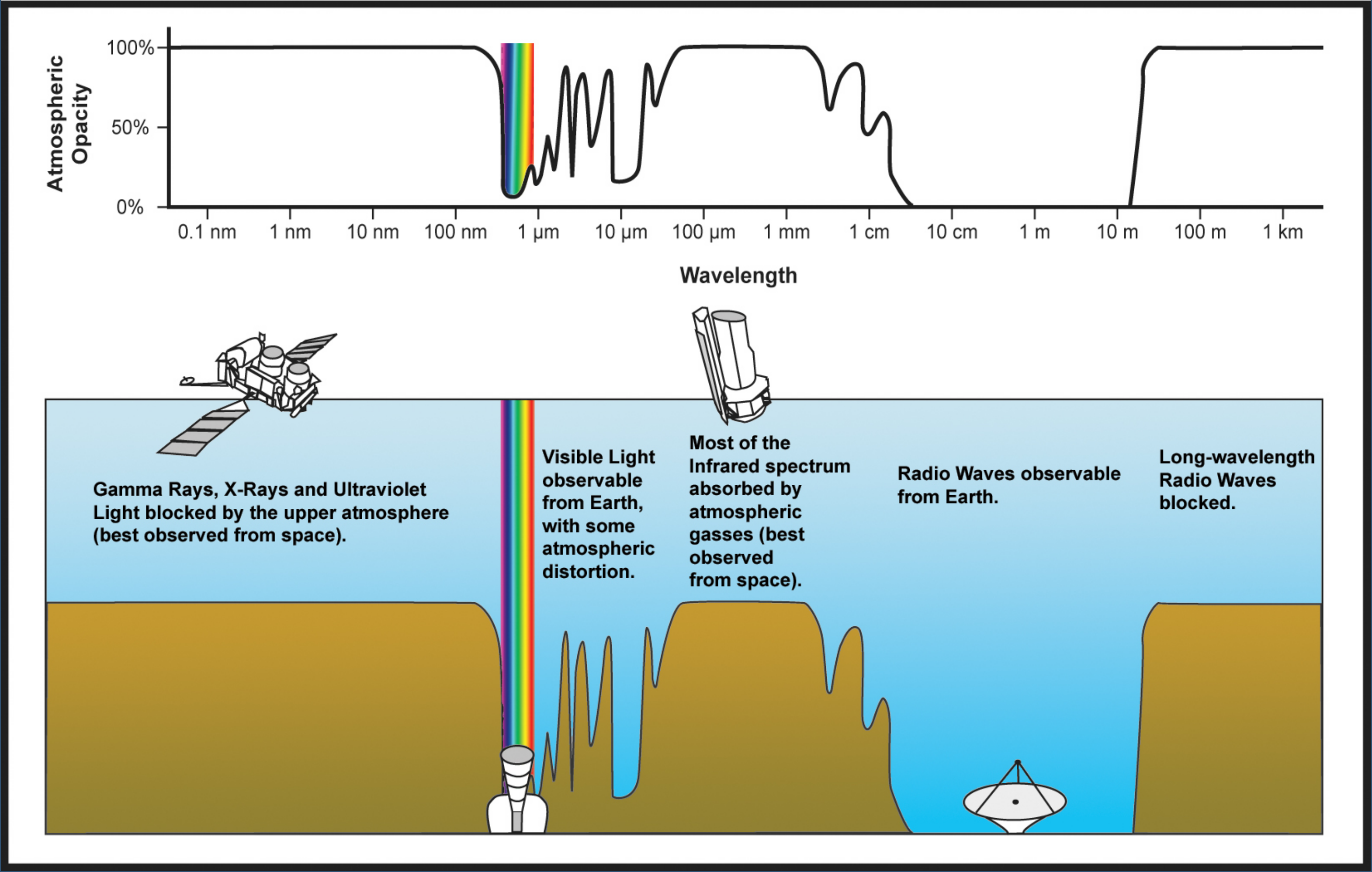
$$\lambda = c/\nu \qquad E = h\nu$$

Electromagnetic Spectrum

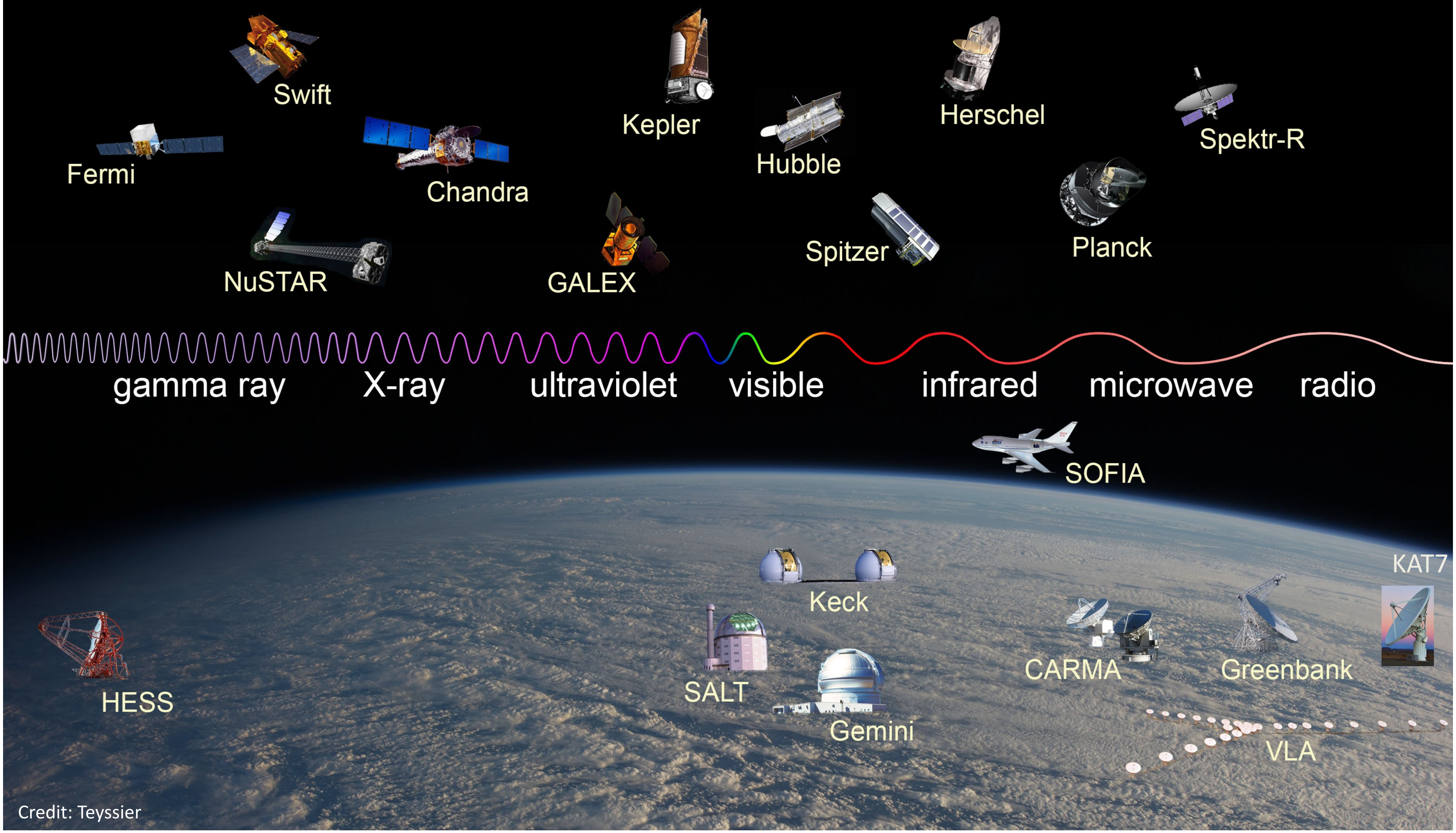


- Historically started with what we could see.
- Optical astronomy many hundreds of years old now.
- Lots of objects we could see.

Atmospheric Transmission



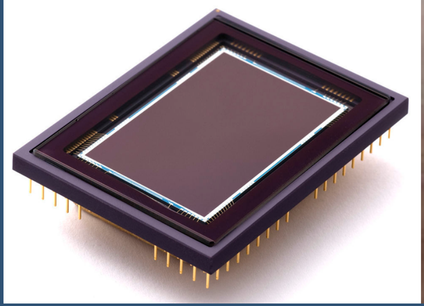
Atmospheric Transmission



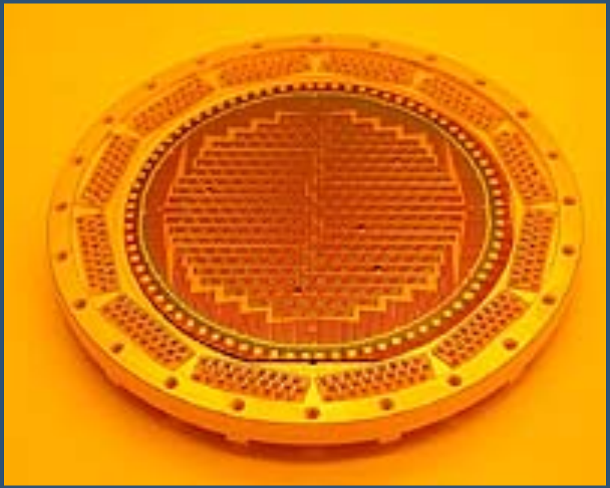
Credit: Teyssier

Different technologies

- Optical: started with single eyepiece, now onto CCDs.



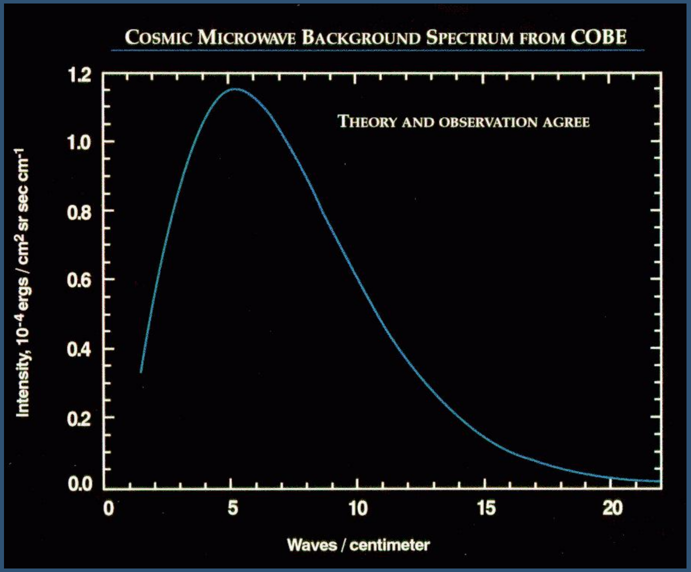
- Equivalent for radio are bolomoters.



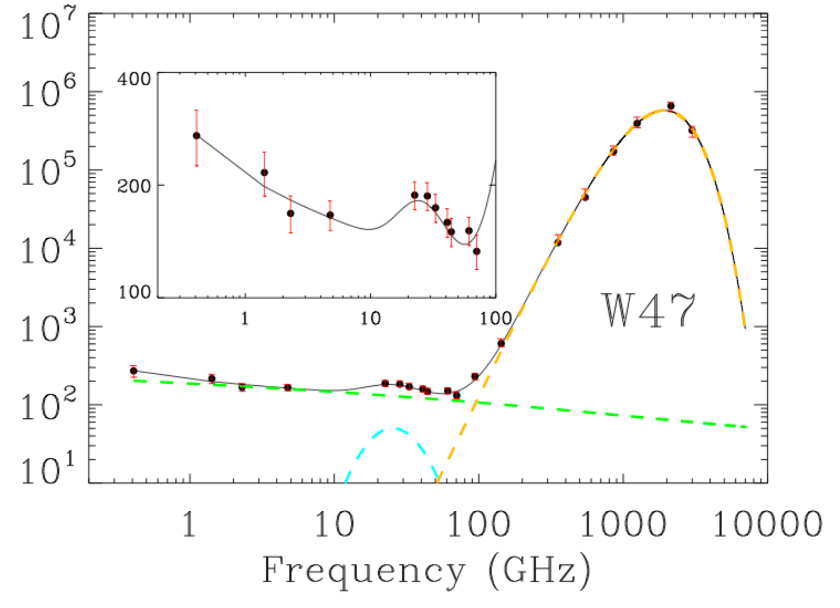
- Thermistors: Not coherent (phase preserving)

Different emissions

- Blackbody/Thermal



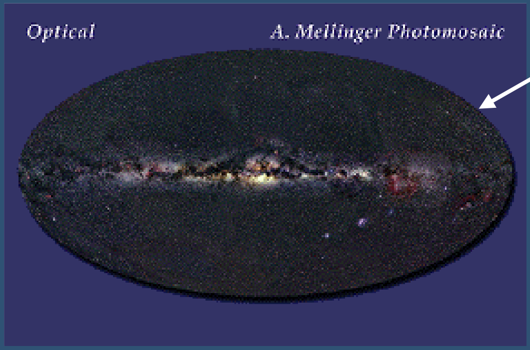
- Continuum/Non-thermal



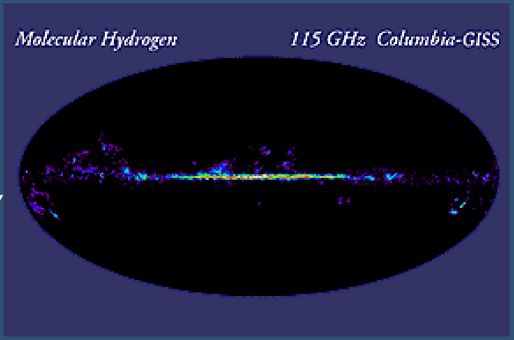
- Spectral line

Our Galaxy

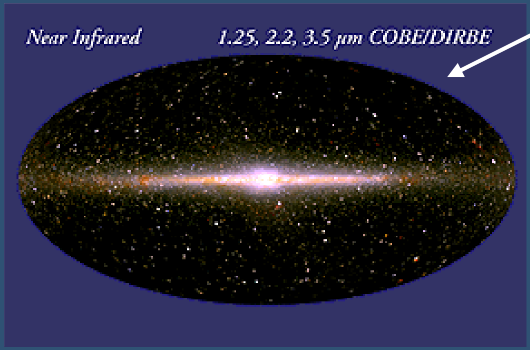
(At other wavelengths)



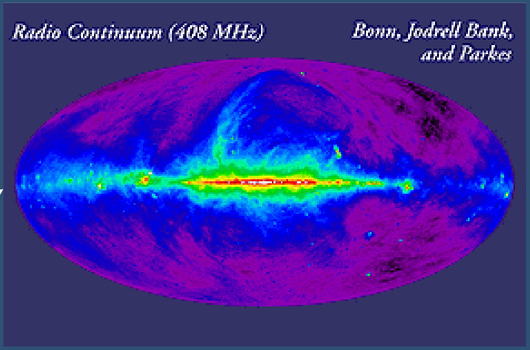
Old stars, dust obscuration



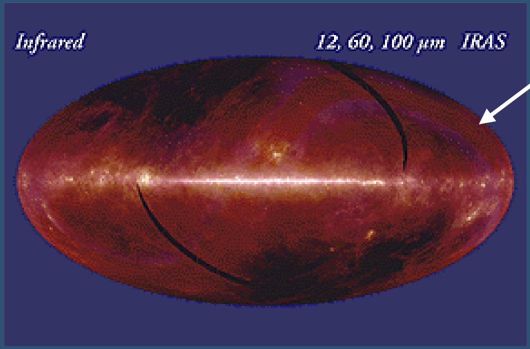
Cold molecules,
protostars & planets



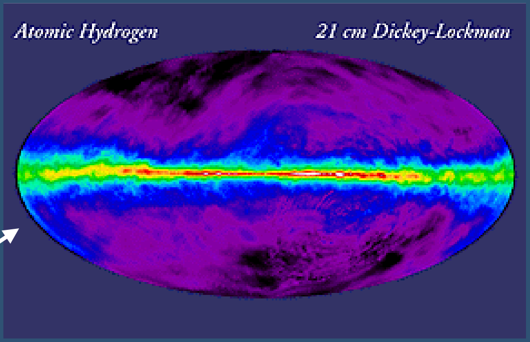
Young stars, close to the disk



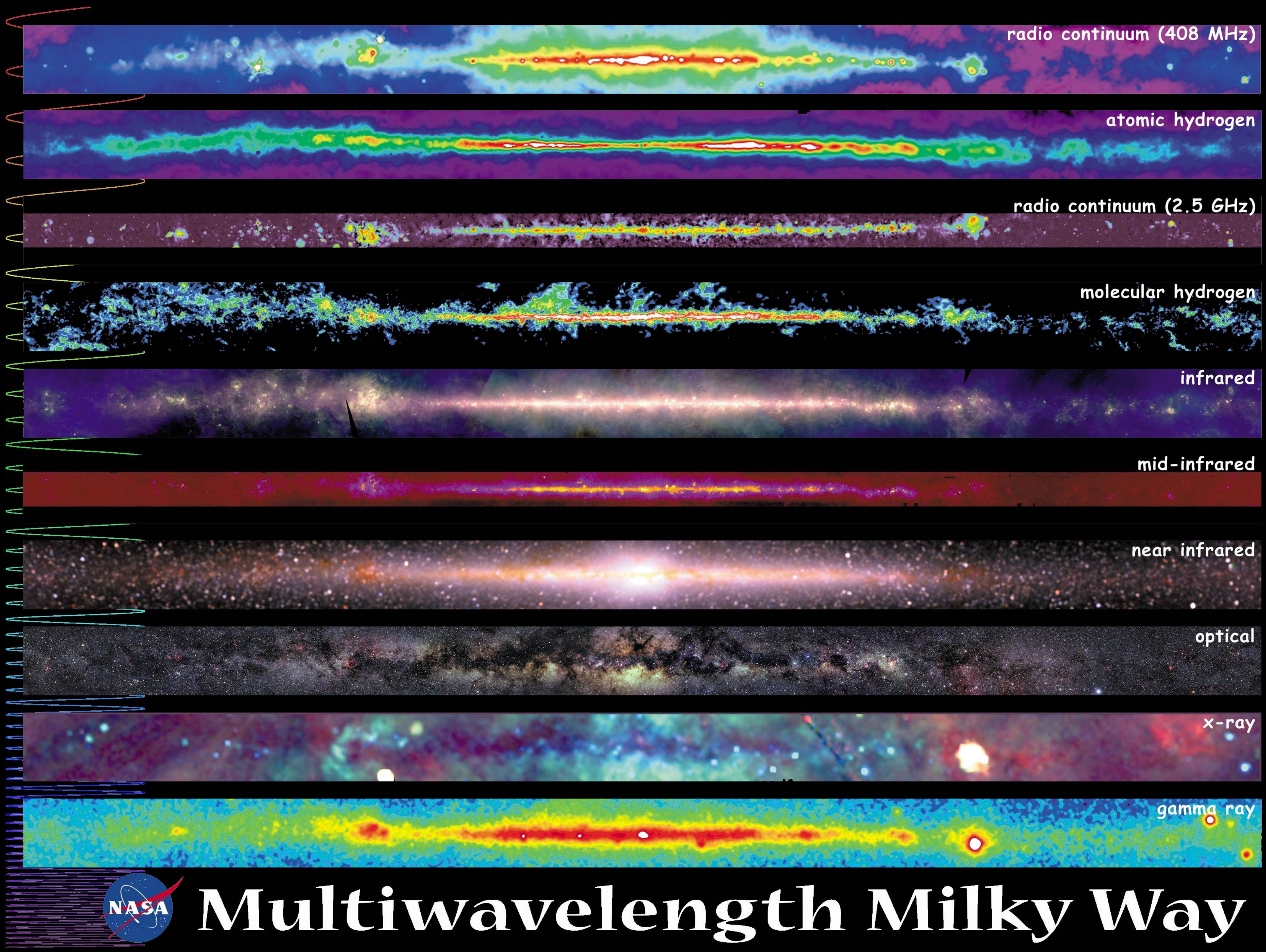
Synchrotron, supernova
remnants, magnetic fields



Dust emission



Neutral Hydrogen



Multiwavelength Milky Way

http://adc.gsfc.nasa.gov/mw

Lifecycle of Stars in a Galaxy

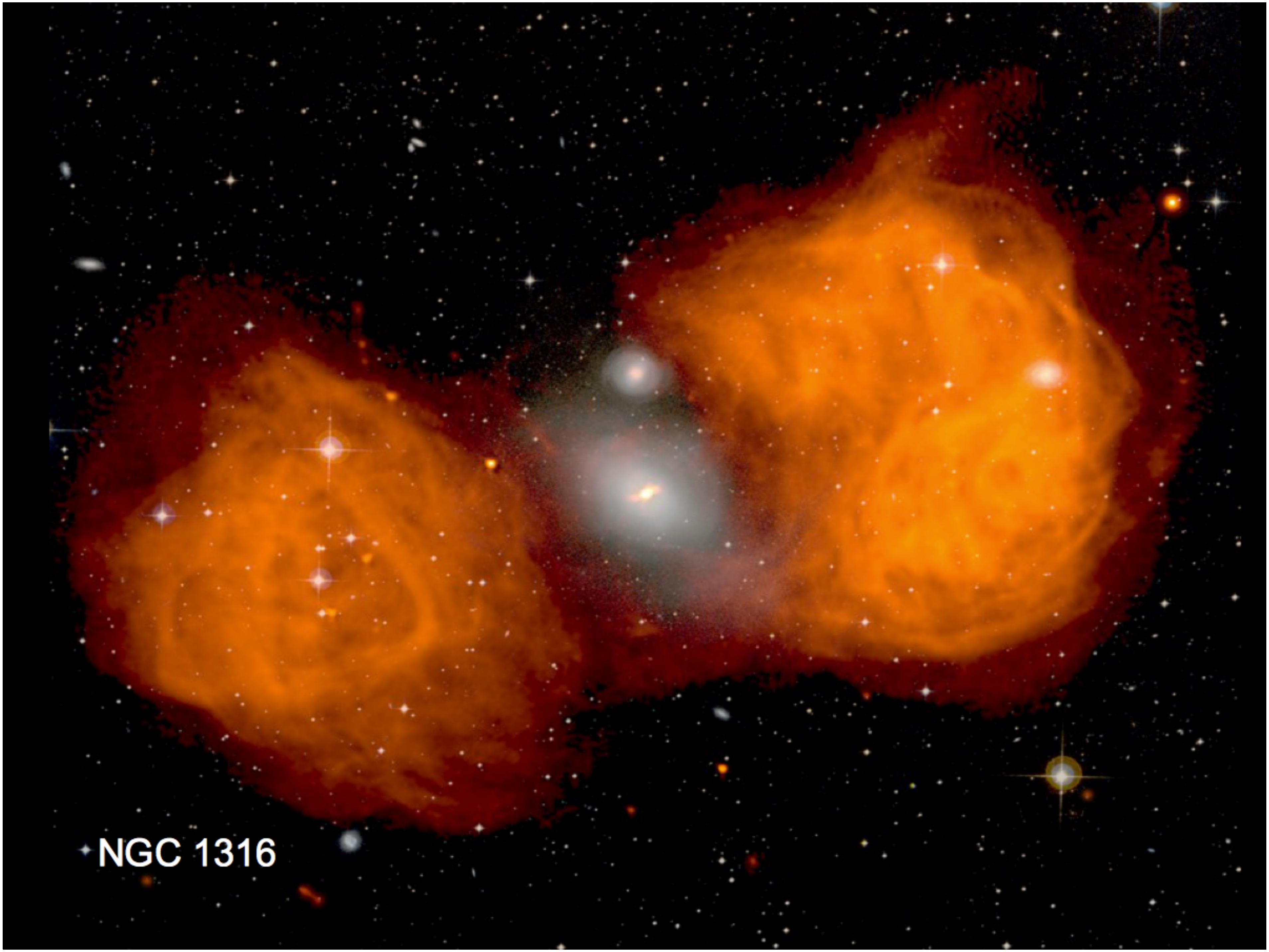
Ultraviolet and optical

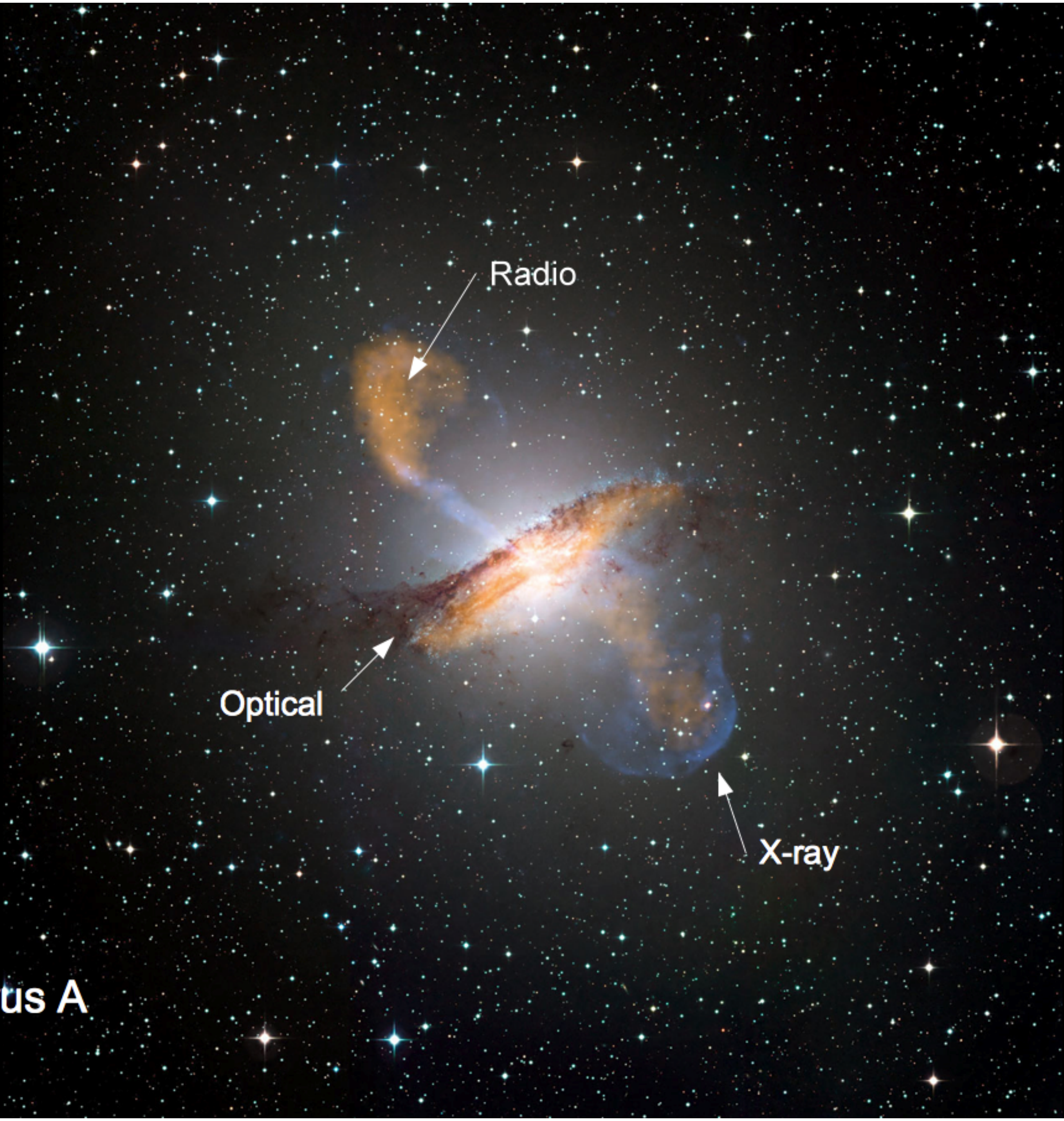
X-rays

infrared

radio

NGC 1316


NGC 1316



Centaurus A

Outline

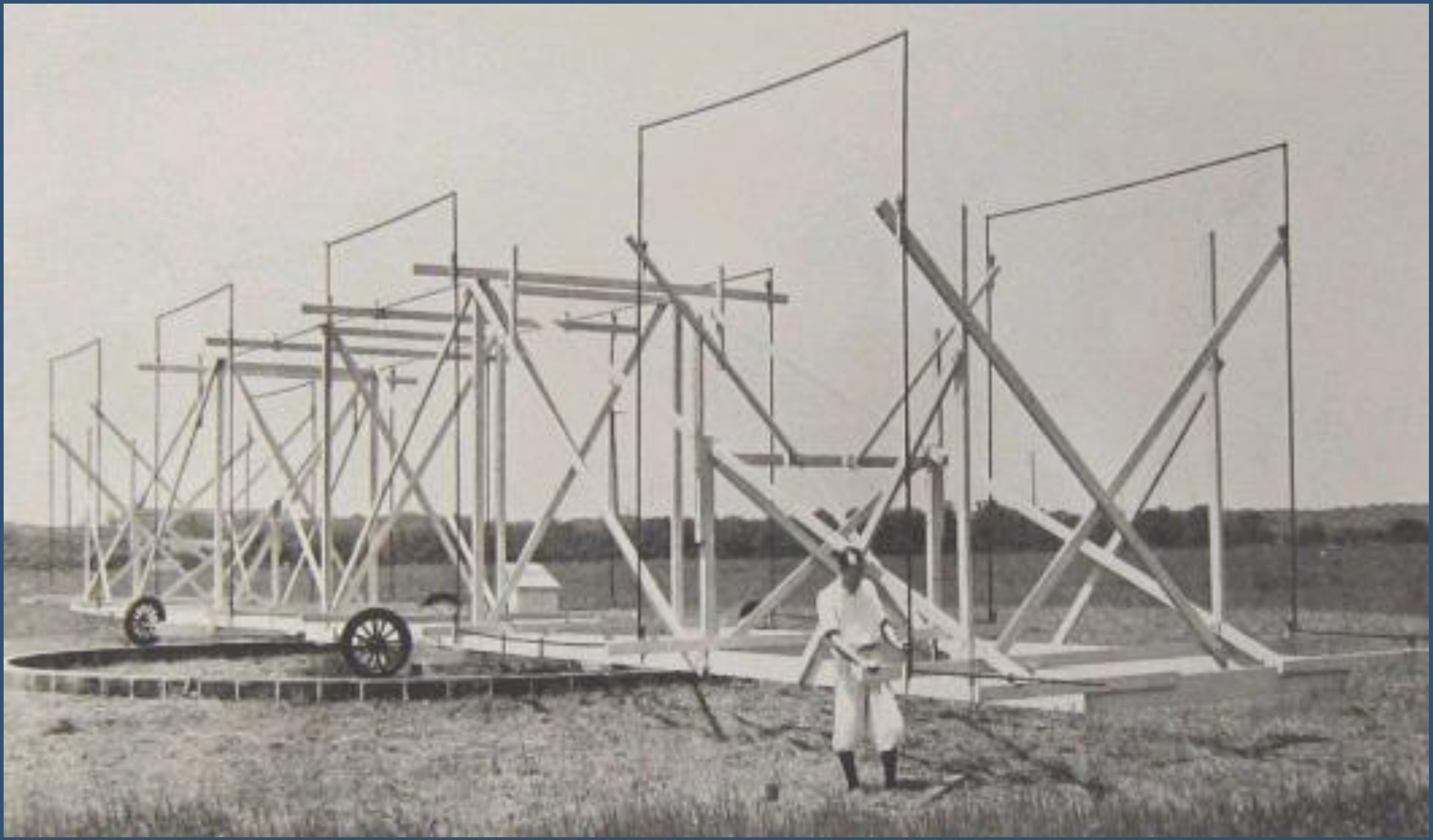
I. Quick review of astronomy
    I. Light is a wave
    II. Different wavelengths need distinct technology
    III. Different wavelengths probe different physics
II. Brief history of radio astronomy
III. Radio telescopes
IV. Interferometry in words
V. Interferometry in practice
VI. Applications of Interferometers
VII. Activities

History of Radio Astronomy

- Ancient Civilizations were birth of astronomy
- Optical Astronomy began with the telescope (Brahe, Galileo, 1600s)

Radio Astronomy really began as an accident, a side effect of development of military radar in early 20th century, and many of the drivers of the field, even in more recent years, have hailed from more of a practical engineering background rather than from a pure academic training.

Birth from thunderstorms



In 1931, while working at Bell Telephone Laboratories, Jansky was tasked with studying the direction of arrival of thunderstorm static.

He built a vertically polarized unidirectional antenna that was 30m long by 4m high, mounted on a circular track (a merry-go round, rather than a telescope). Rot: 20mins; 20.5MHz (14.6m)

Rotating signal found

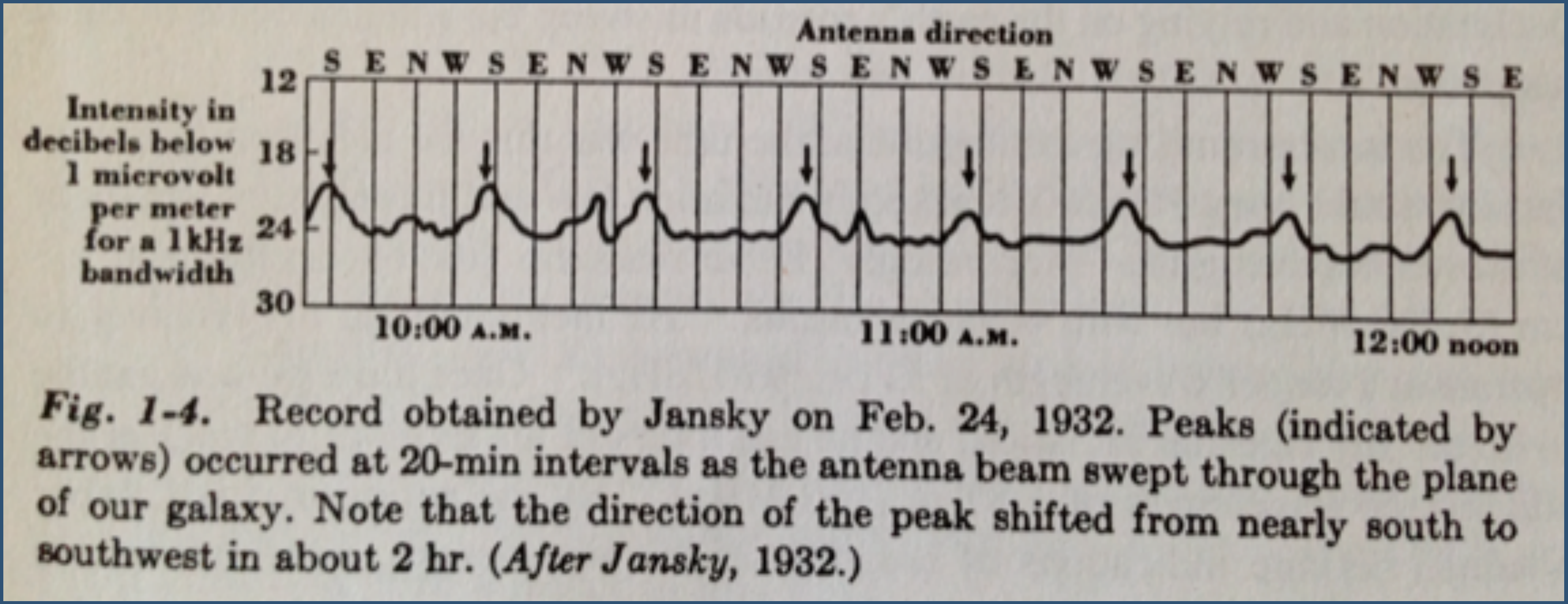


Fig. 1-4. Record obtained by Jansky on Feb. 24, 1932. Peaks (indicated by arrows) occurred at 20-min intervals as the antenna beam swept through the plane of our galaxy. Note that the direction of the peak shifted from nearly south to southwest in about 2 hr. (*After Jansky*, 1932.)

Found 3 results:

1. Static from local thunderstorms
2. Static from thunderstorms in south
3. Steady hiss of unknown origin

Repeatable (detected at 10m and 14.6m)

"Radiations are received any time the antenna is directed towards some part of the Milky Way system, the greatest response being obtained when the antenna points towards the center of the system. "

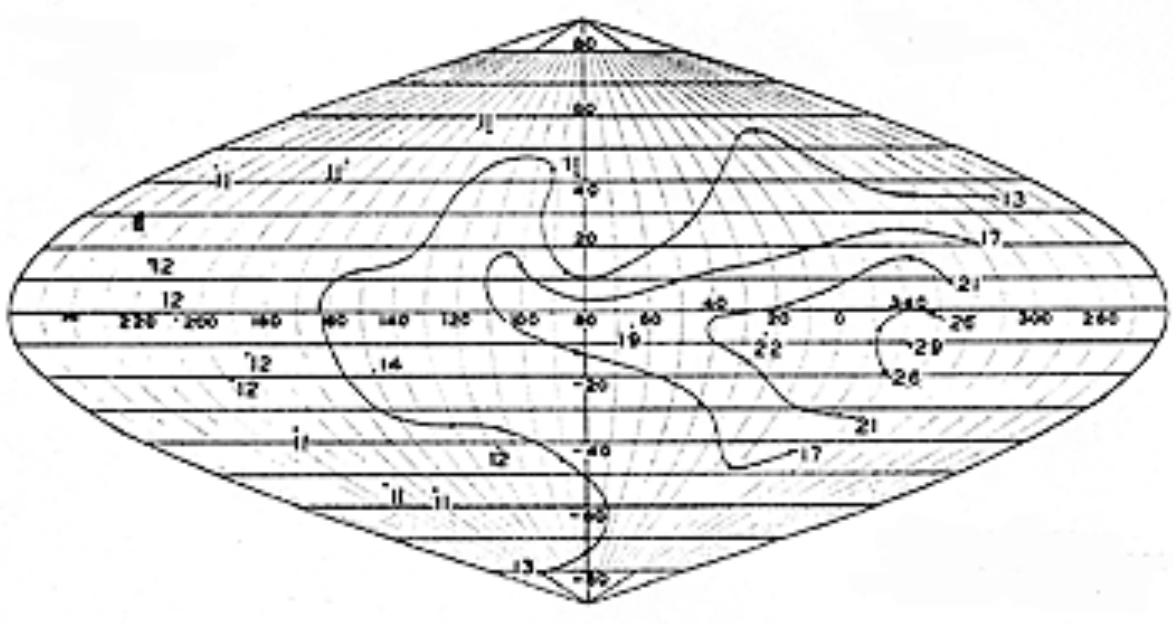
Credit: Kraus

Need for bigger telescopes

From an engineering standpoint, Jansky recognized that “this star static … puts a definite limit upon the signal strength that can be received from a given direction at a given time and when a receiver is good enough to receive that minimum signal it is a waste of money to spend any more on improving the receiver.” [unless you make the beam smaller]

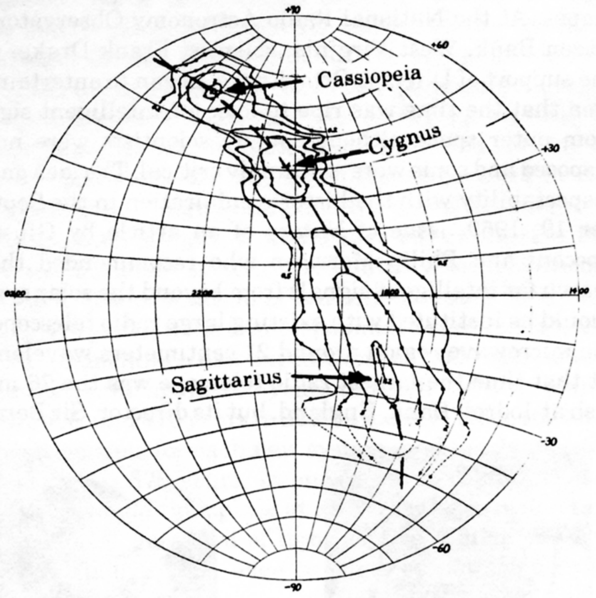
Proposed construction for 30m parabolic mirror antenna operating at meter wavelengths was denied.

Bell Labs moved him on to other projects.

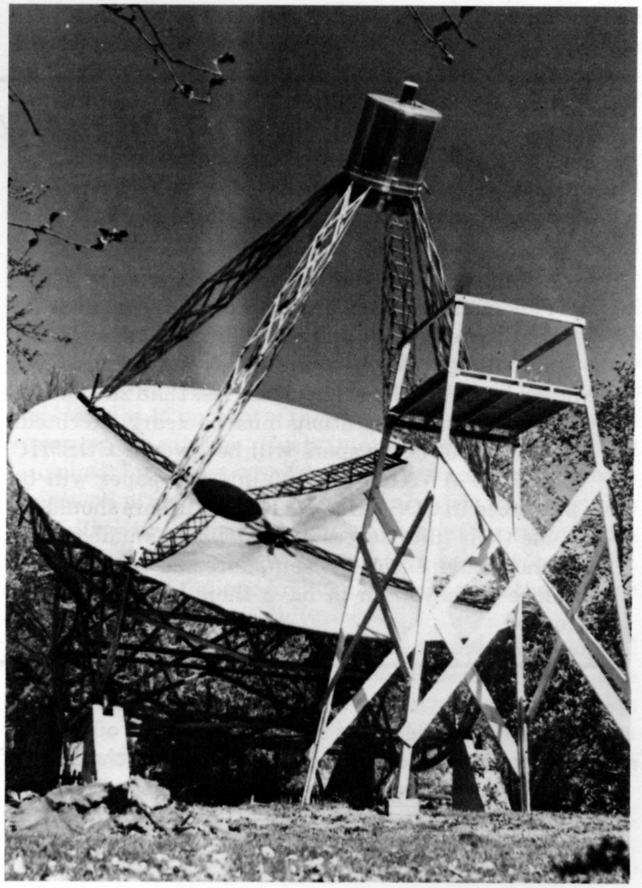


Grote Reber

- Built a 9.5m parabolic reflector telescope (1937).
- Assumed the radiation would obey blackbody, and be stronger at shorter wavelengths.
- No detection at 3.3GHz, 910MHz, and detection at 160MHz. (12 degree beam)



First map of the radio sky as produced by Grote Reber showing strong sources of radiation in Cassiopeia, in Cygnus and in Sagittarius, the center of the galaxy, the region from which Karl Jansky had detected radio emission.



Grote Reber's dish antenna at Wheaton, Illinois, in 1938, the prototype of the modern radio telescope.

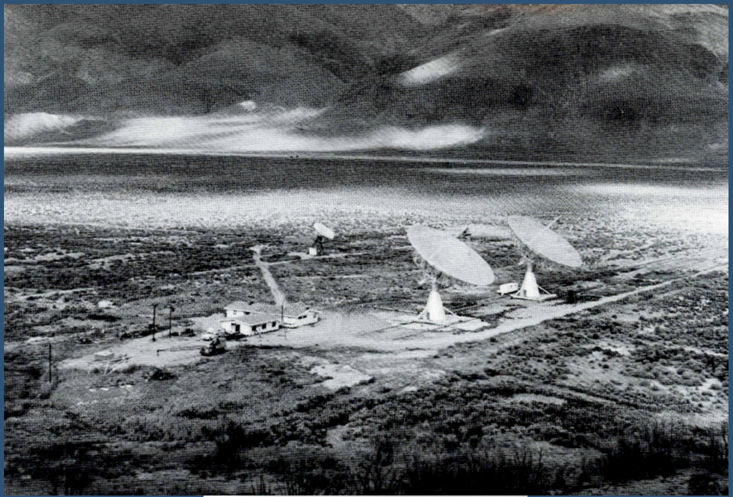
- Results almost not accepted for publication in the Astrophysical Journal

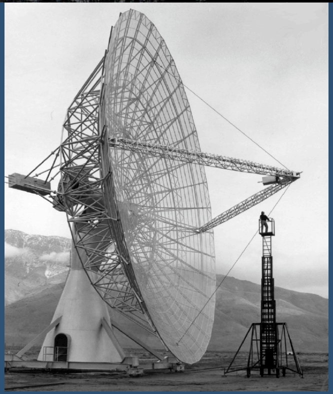
(some) Since Reber

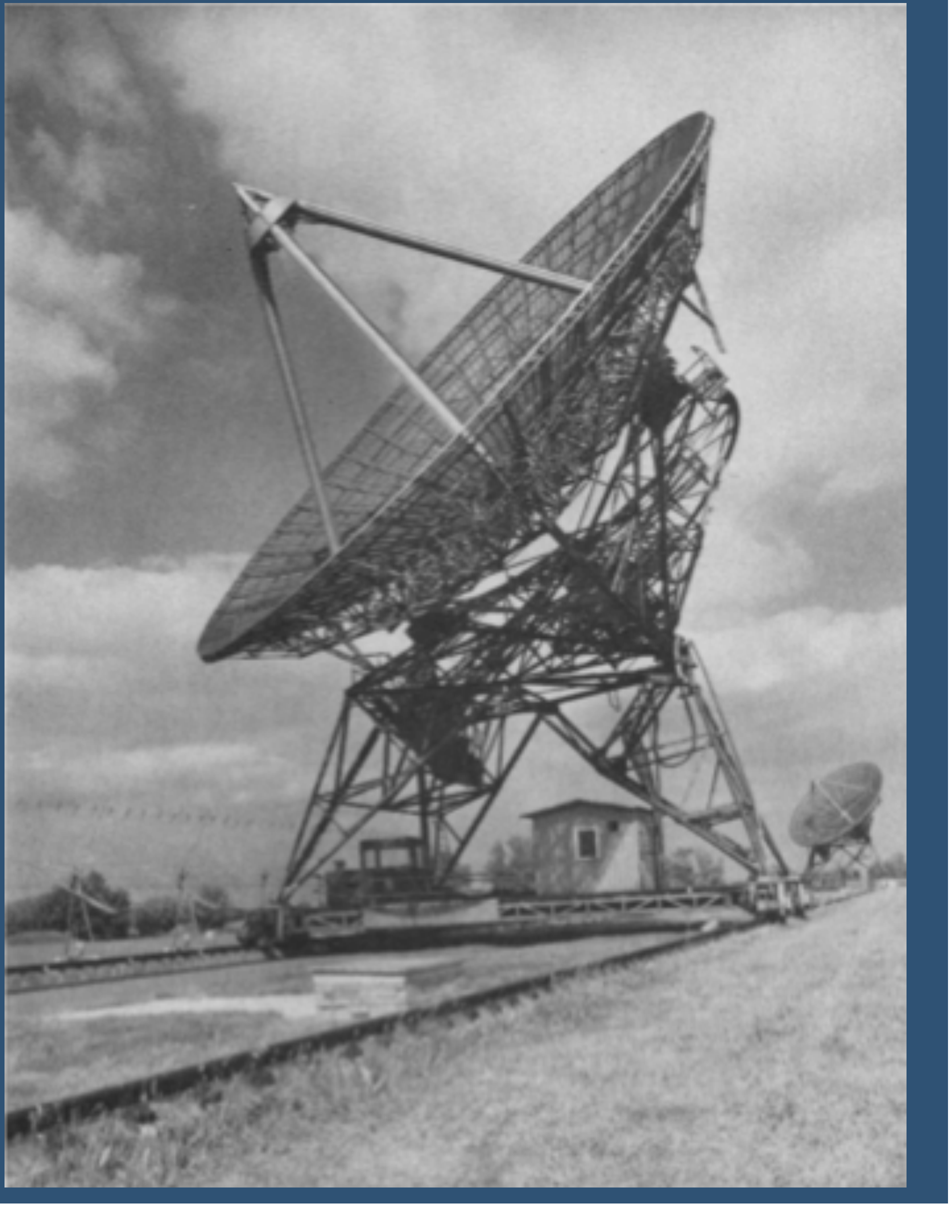
- Noone knew the culprit of these sources because we could not locate them accurately enough for optical follow-up.
- Many (bigger) telescopes were built in the next few decades (Leiden at 1.4GHz, Cambridge, …)
- Manchester: 76m diameter completed in 1957

Interferometers were needed

- 1950s: Cambridge One-Mile telescope
- 1958: OVRO interferometer







Outline

I. Quick review of astronomy
II. Brief history of radio astronomy
    I. Radio astronomy "began" with Karl Jansky (~1932)
    II. It was known by 1950 higher resolution was needed
III. Radio telescopes
IV. Interferometry in words
V. Interferometry in practice
VI. Applications of Interferometers
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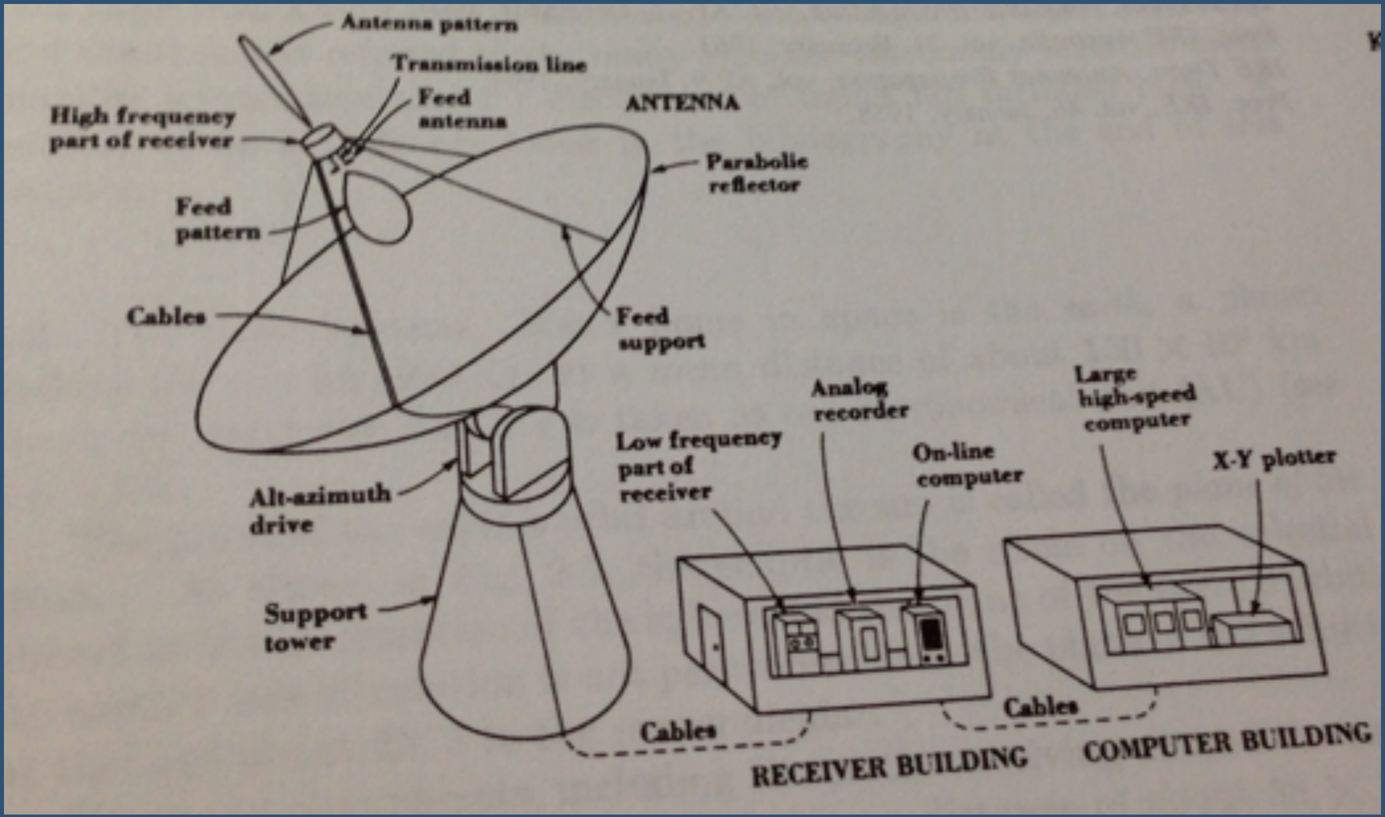
Radio Telescopes

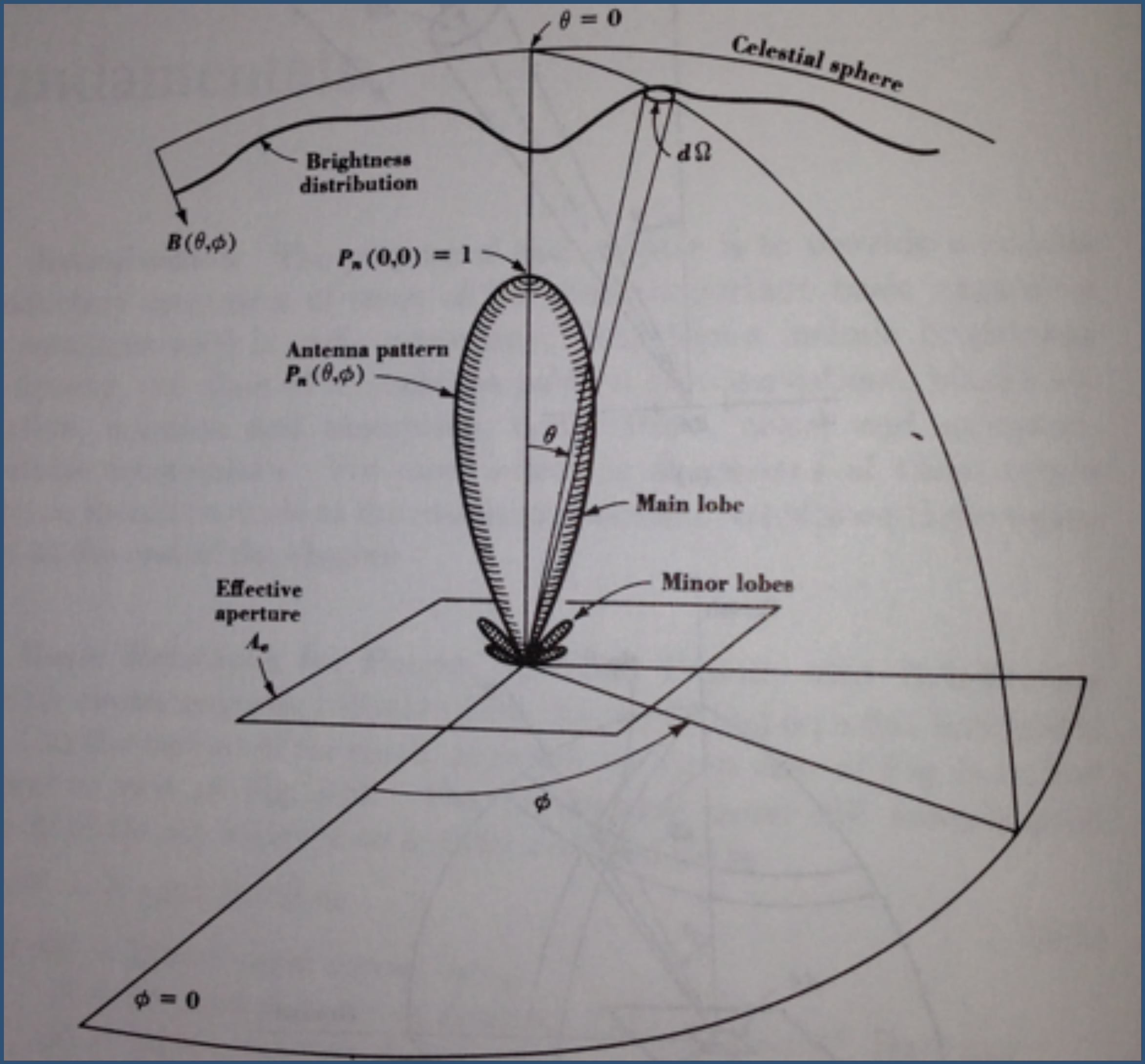
Reber: “The antenna-receiver combination acts like a bolometer, or heat-measuring device, in which the radiation resistance of the antenna measures the equivalent temperature of distant parts of space to which it is projected by the antenna response pattern”



Credit: Kraus

Different types

Antenna Patterns

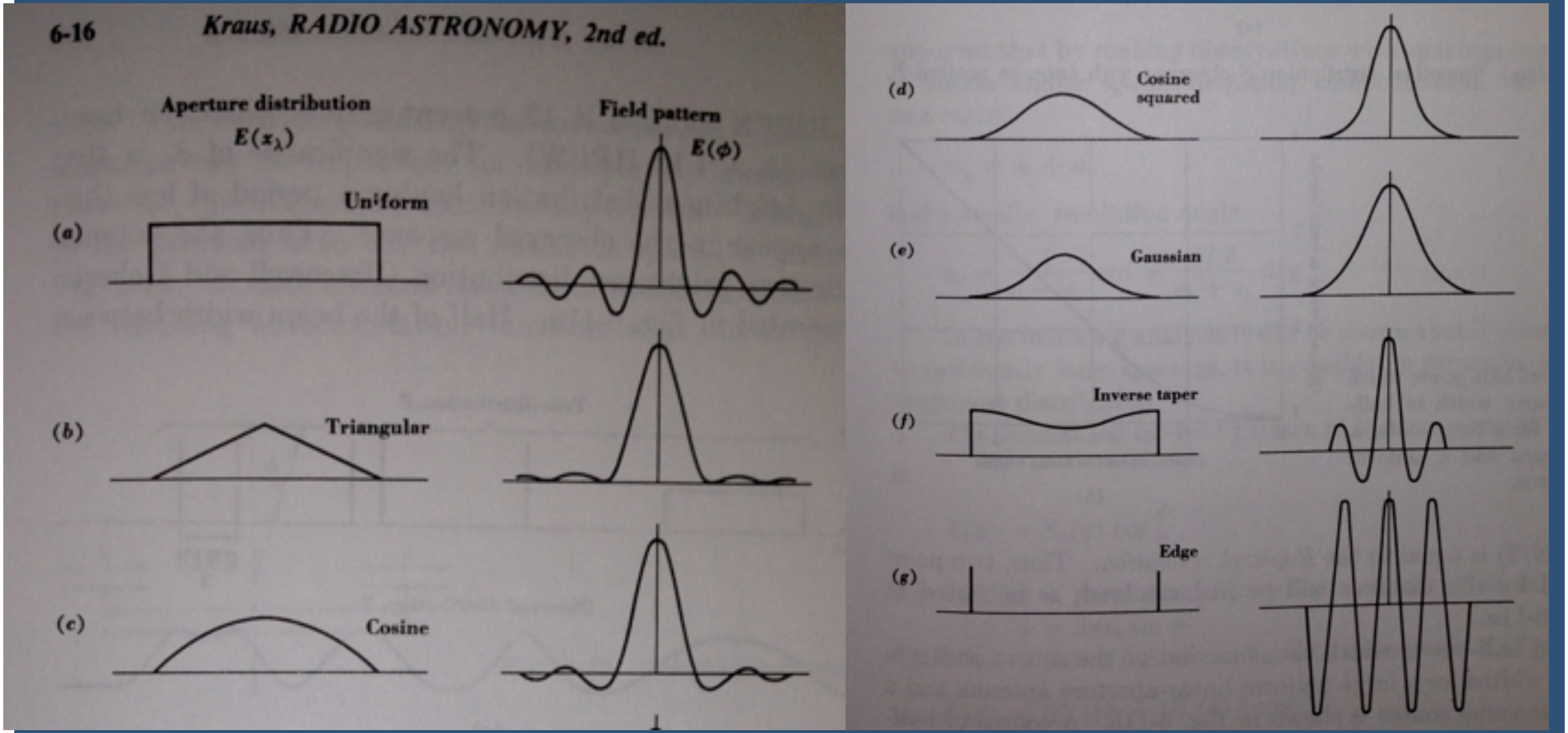


Near vs Far

sidelobe presence

Sample Patterns

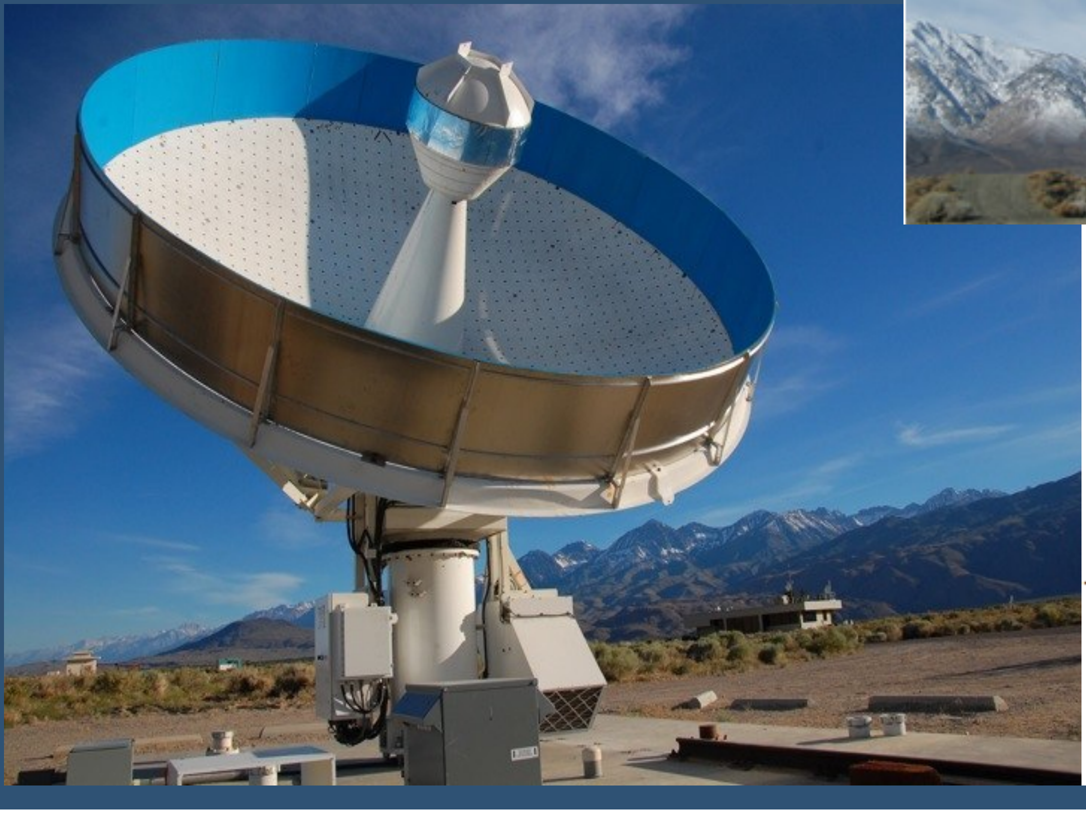
Antenna patterns are the Fourier Transform of the aperture distribution

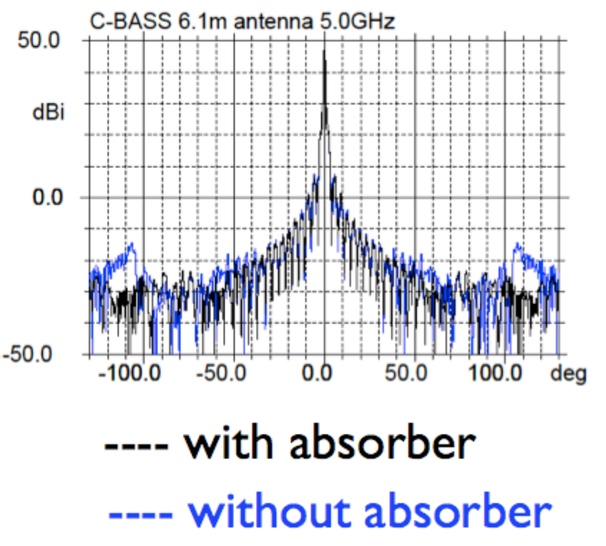


Sidelobe Mitigation

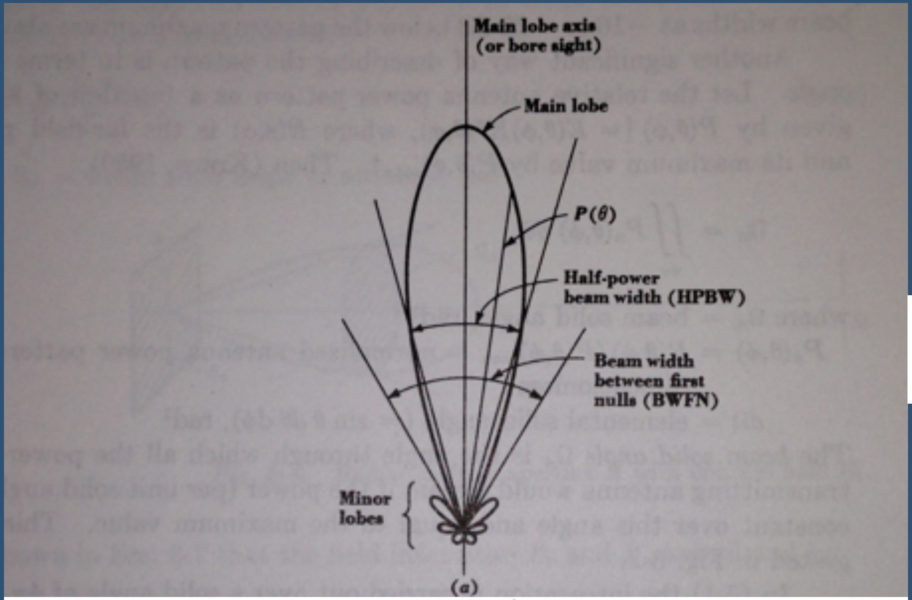
- Primary Edge Taper

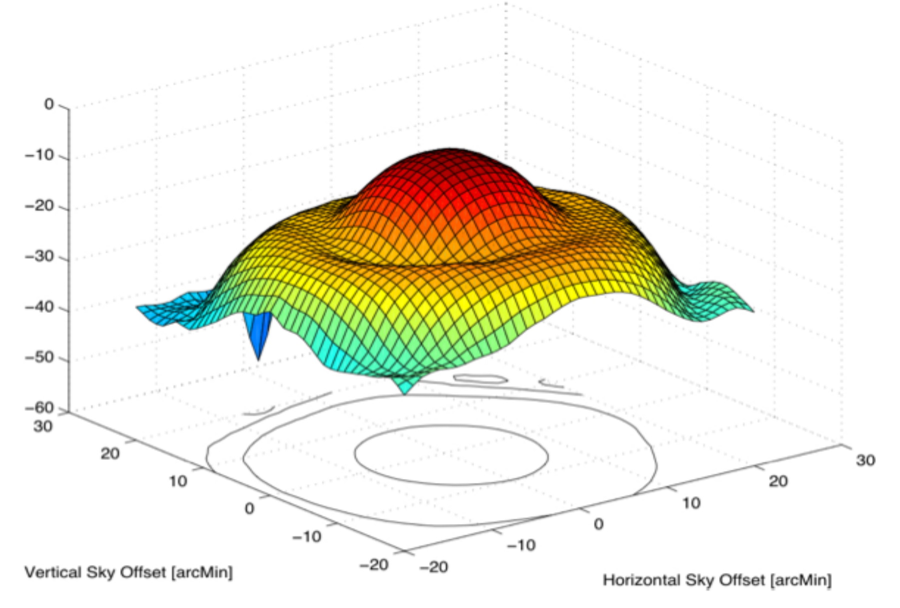
- Filling in the sidelobes





Antenna Properties





Full-Width at Half Maximum (FWHM): how wide the beam is at the point where it is 50% sensitive to the sky distribution. For Gaussian, given by:

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\,\sigma \approx 2.355\,\sigma.$$

Field of View (FOV): The largest angles the telescope is sensitive to.

Effective Area/Aperture Efficiency: How well a telescope collects all the radiation incident on it. This is related to the antenna gain by geometry and wavelength.

Surface accuracy.

Antenna Properties

Sensitivity: How faint an object a telescope can detect

$$\sigma_{th} = \frac{2k_B T_{sys}}{\eta_{ap}(\text{Area})} \cdot \frac{1}{\sqrt{\tau \Delta\nu}}$$

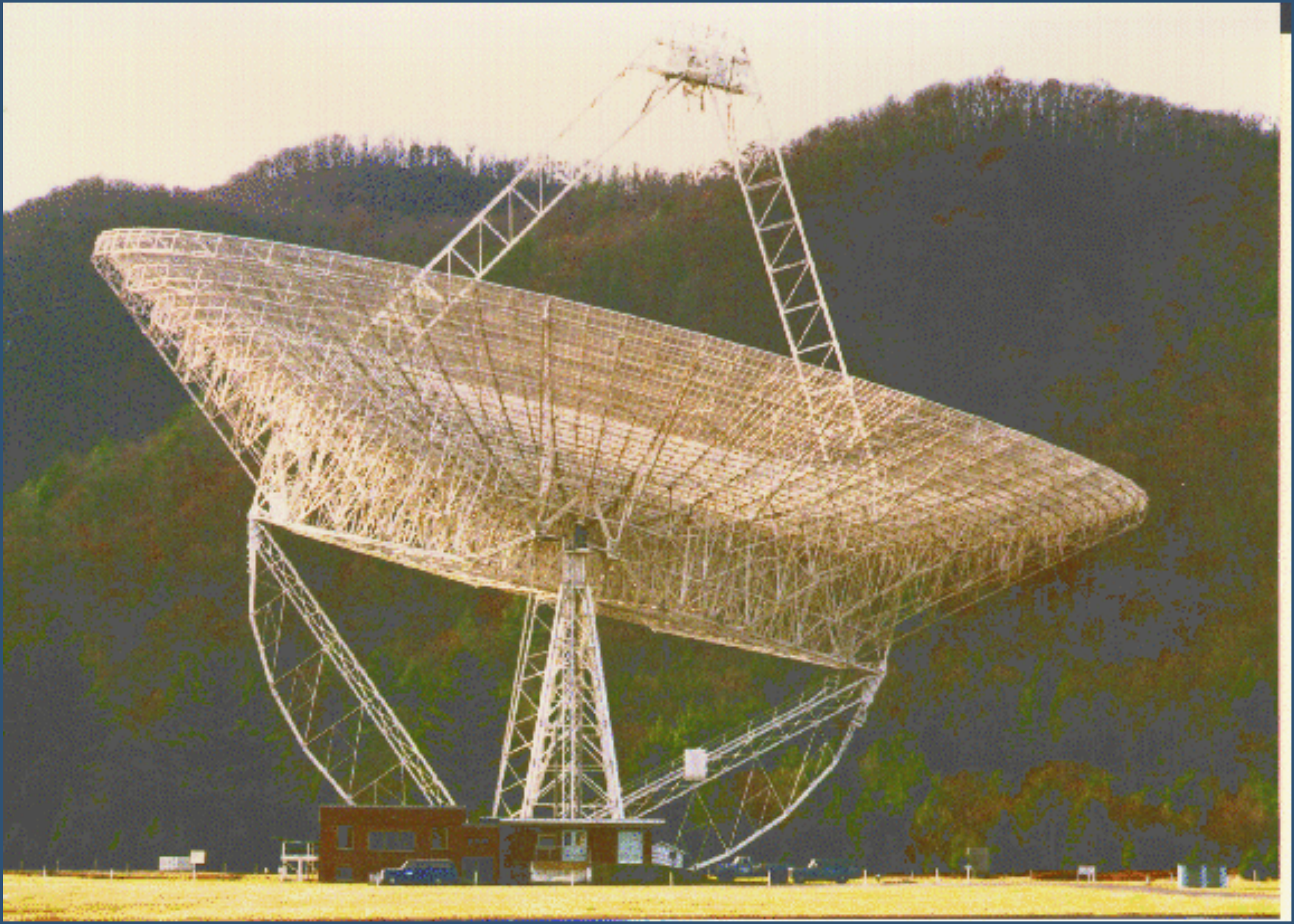
Resolution: The sharpest size the telescope can see.

$$\delta\theta \sim 1.22\frac{\lambda}{D}$$

Which is why we end up building really large structures!!

300 foot GBT telescope

Nov 15, 1988!



300 foot GBT telescope

Nov 16, 1988!

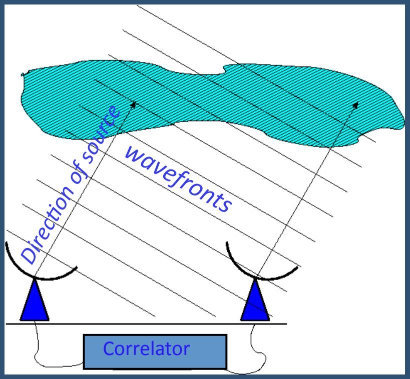
300 foot GBT telescope

Nov 16, 1988!

NOT IDEAL!!!

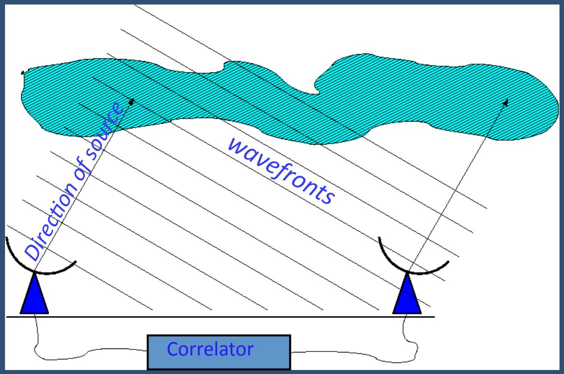
Interferometry

Resolution proportional to telescope separation



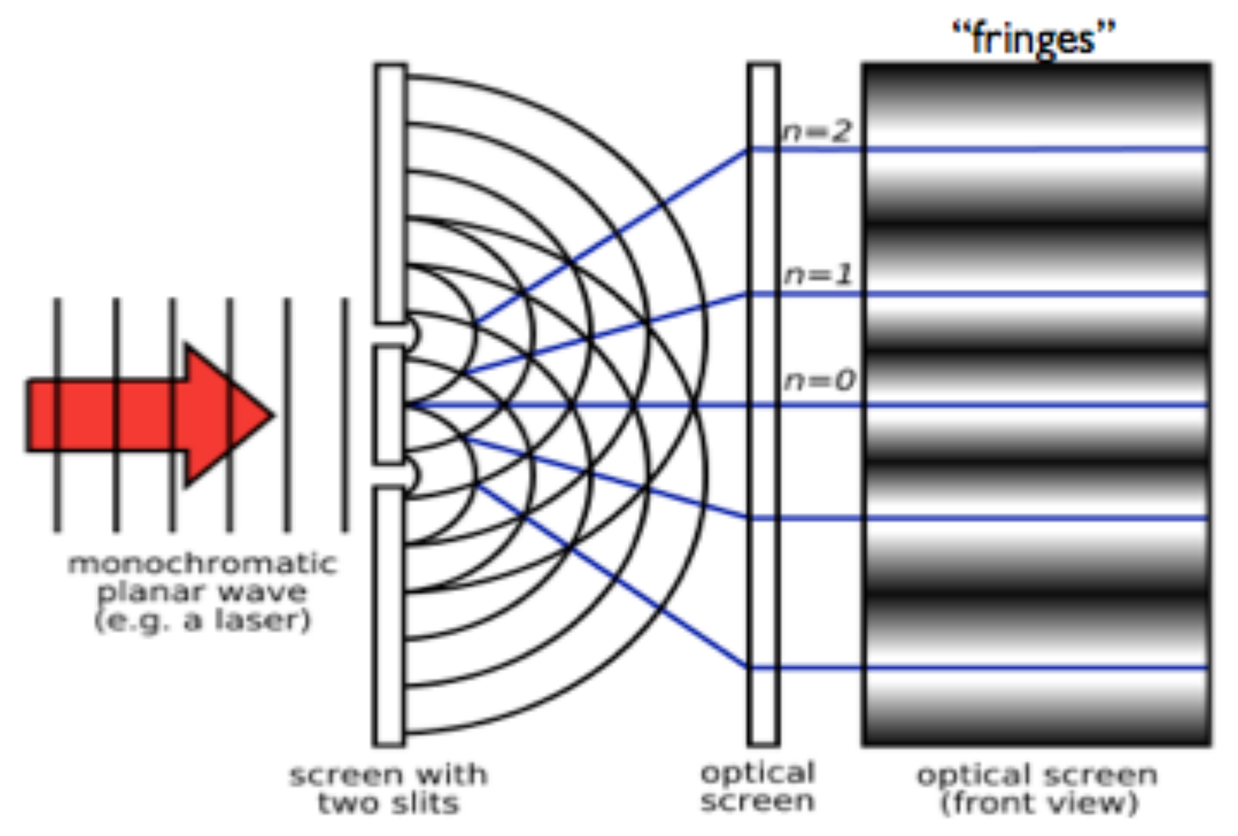
Allows for high resolution without building a giant telescope

Differences the atmosphere inherently (by comparing the signals from pairs of telescopes looking through the same patch of atmosphere, you can remove the common signal)



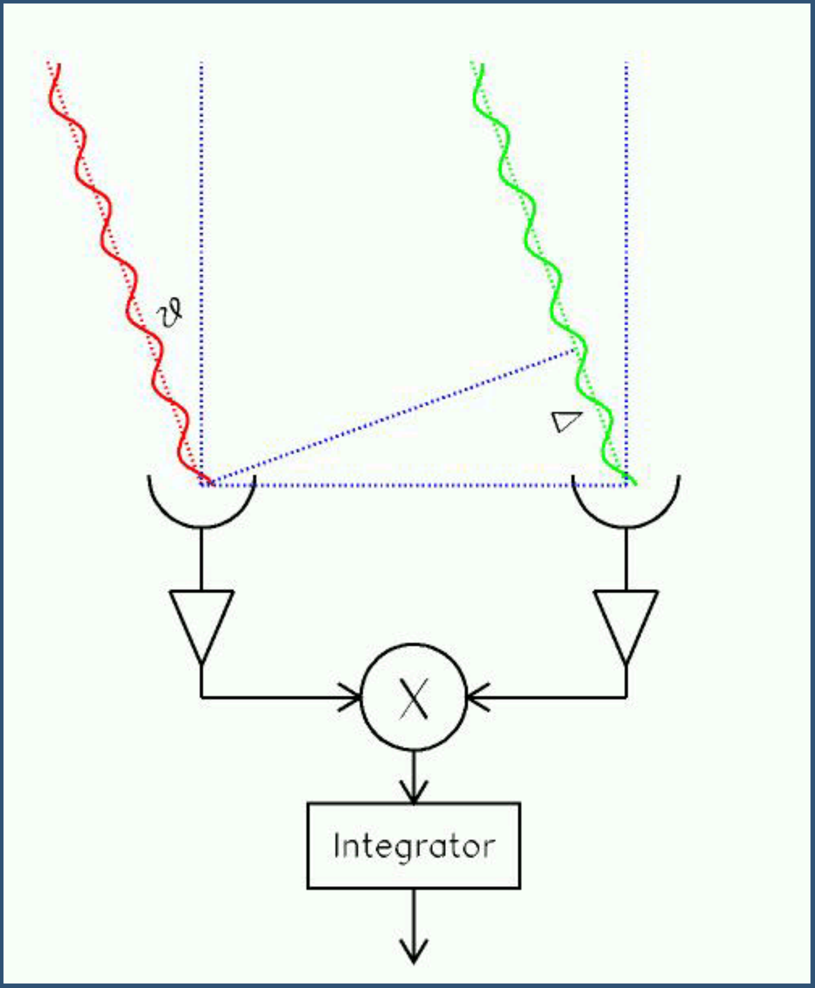
Interference pattern

- Young’s 2-slit experiment

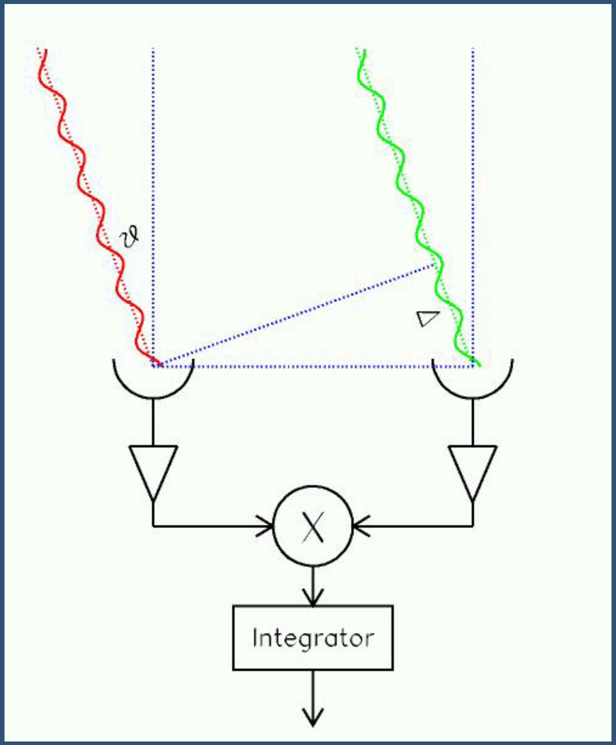


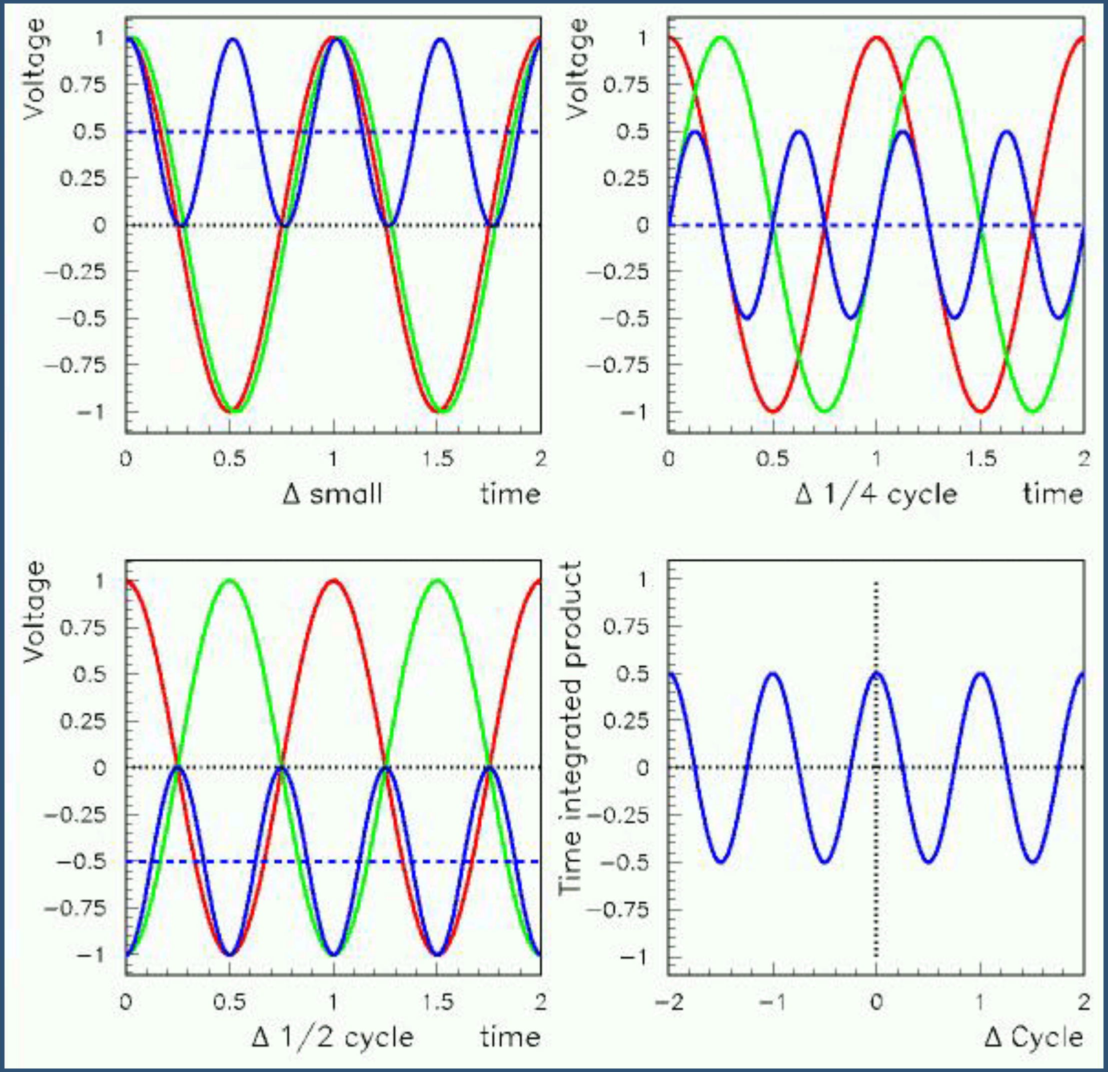
Interference pattern

- Combining from 2 telescopes leads to the same sort of pattern
- Need Coherent detectors

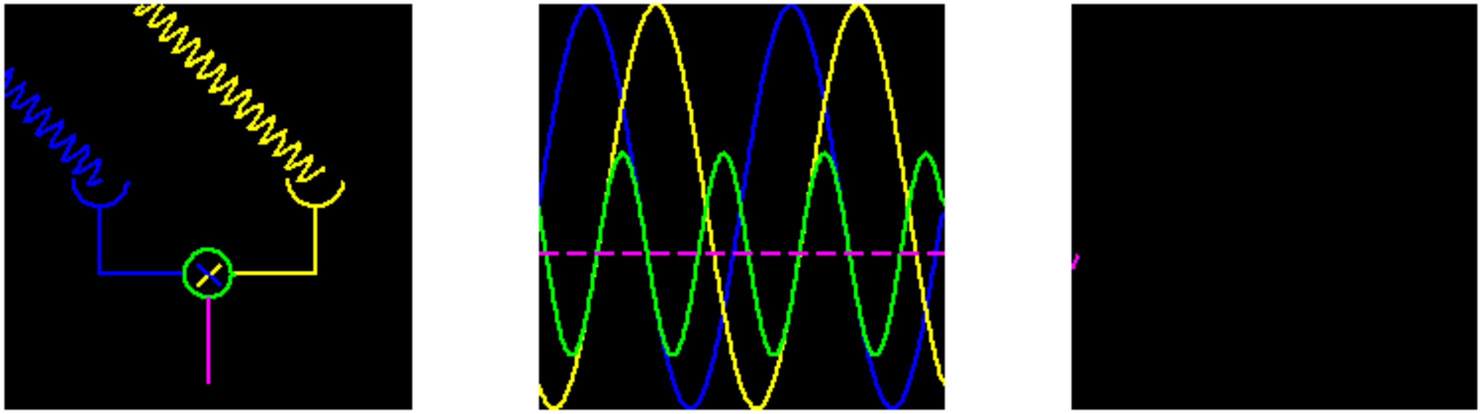


Waveforms


ϑ
Δ
X
Integrator

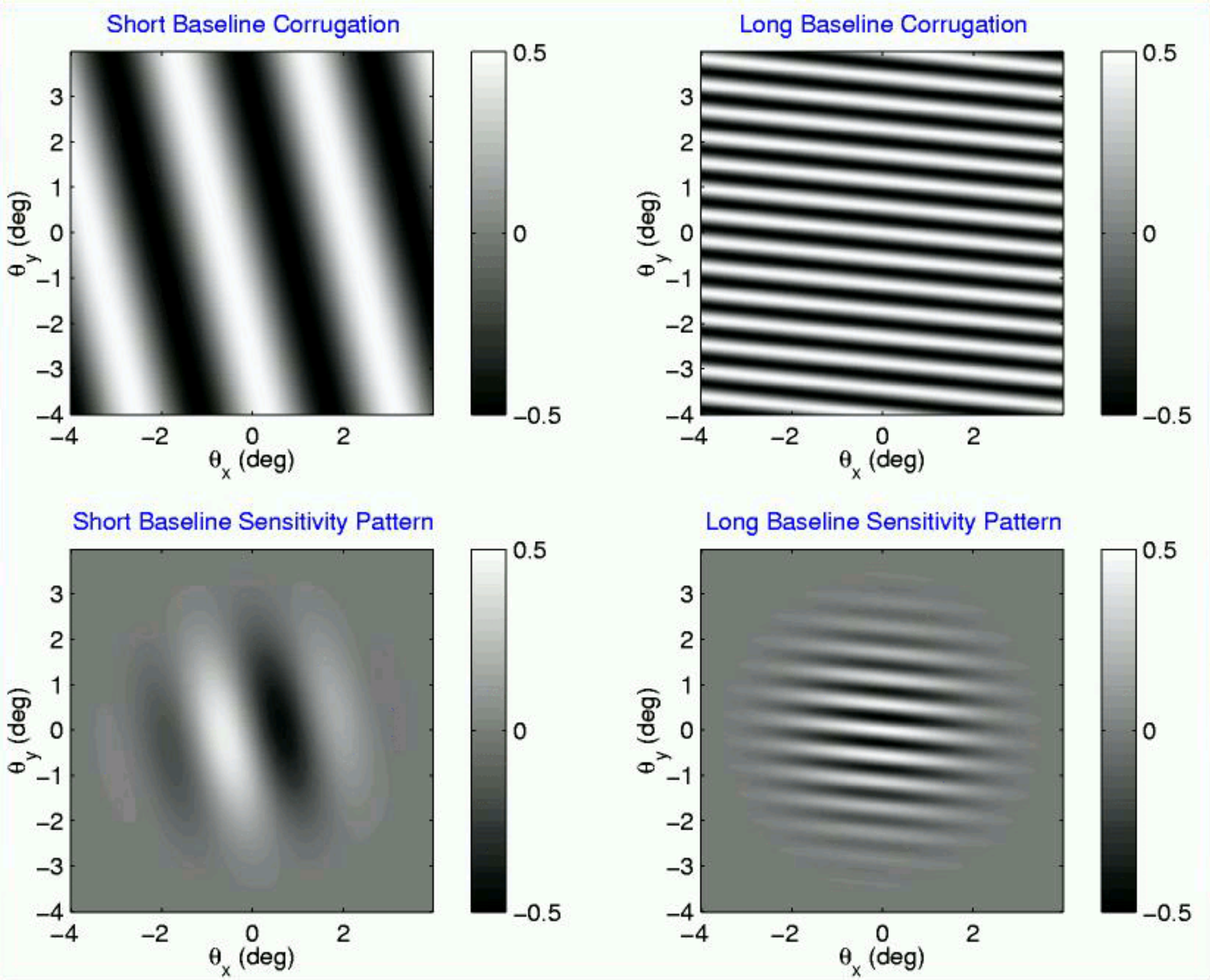

Voltage
1
0.75
0.5
0.25
0
−0.25
−0.5
−0.75
−1
0
0.5
1
1.5
2
Δ small
time
Δ 1/4 cycle
time
Δ 1/2 cycle
time
Time integrated product
−2
−1
0
1
2
Δ Cycle

Fringe pattern across the sky (1D)



Credit: Leitch

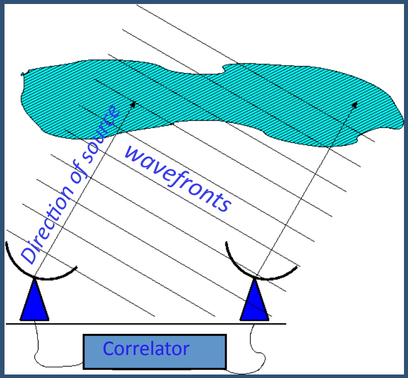
2D & Fold in primary beam (sensitivity)

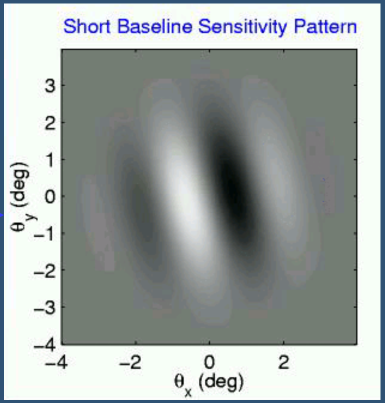


Interferometry

Resolution proportional to telescope separation

Allows for high resolution without building a giant telescope





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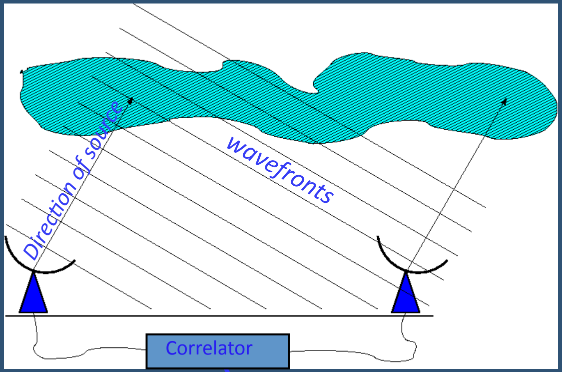
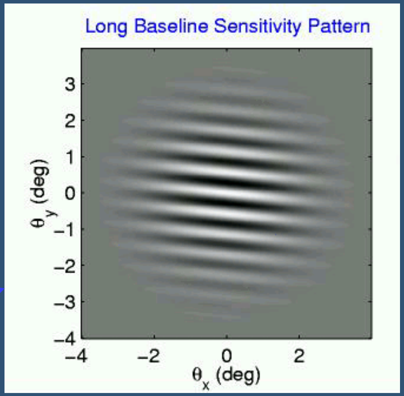




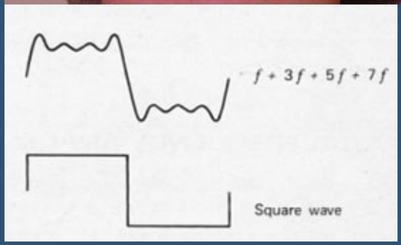
The Fourier Transform

An arbitrarily complex function can be represented as a sum of very simple functions (like sines and cosines)

Often used in analysis of audio signals

(Example: these functions are the 'fundamentals' and 'overtones' of music theory)

But what about a two-dimensional function? (like an image)



Joseph Fourier (1768-1830)

The Fourier Transform

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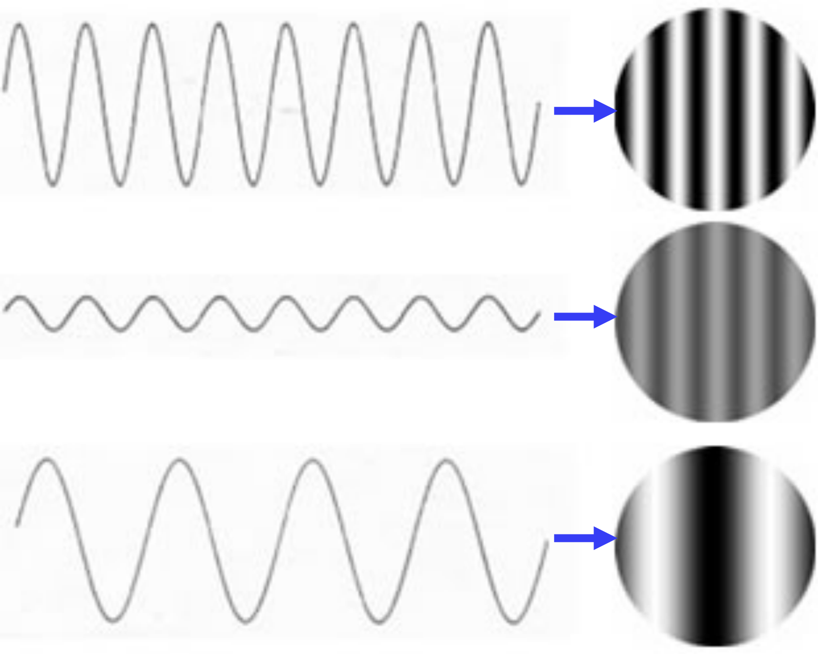
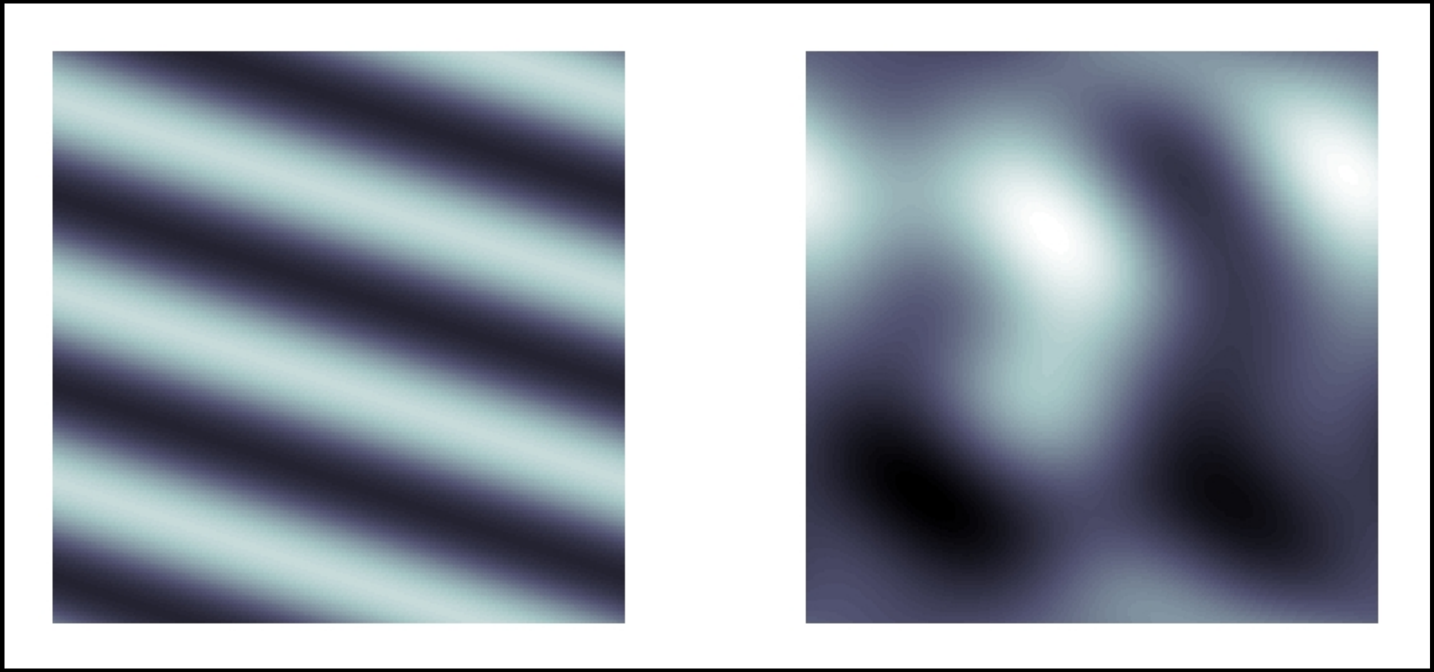


But what about a two-dimensional function? (like an image)

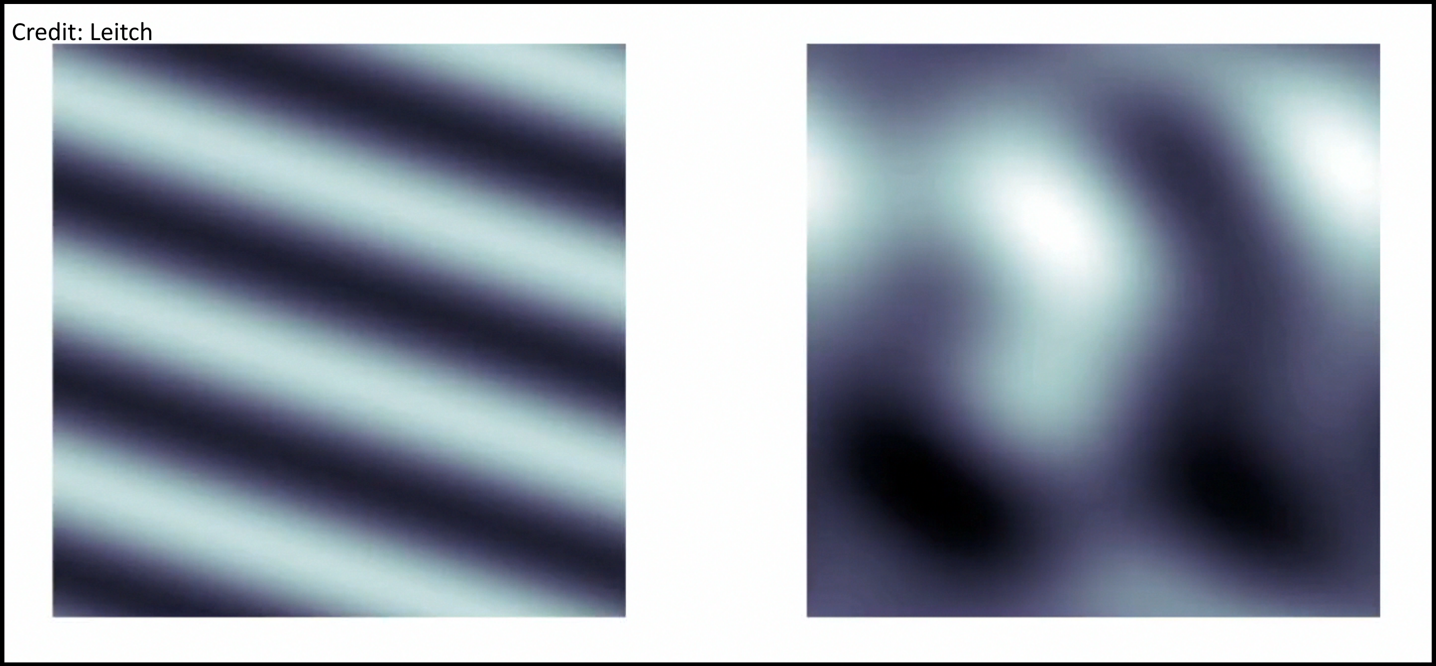
STILL TRUE!!!

How interferometers “see”



How interferometers “see”

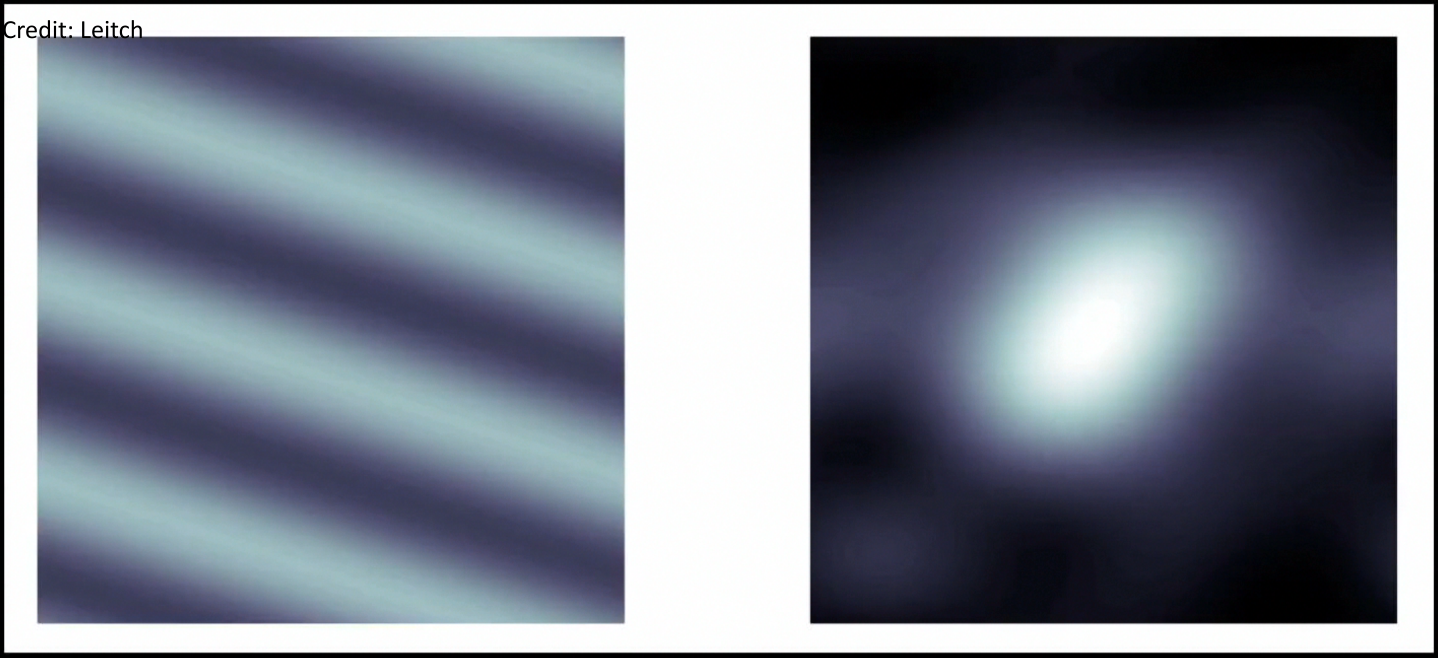
Adding all these ‘ripples’ together


Credit: Leitch

Produces this image

How interferometers "see"

Adding all these 'ripples' together



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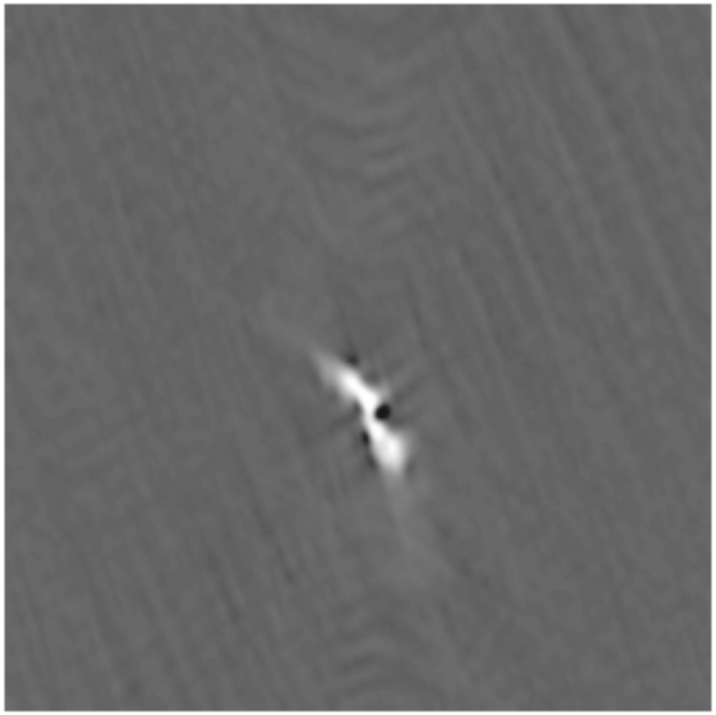
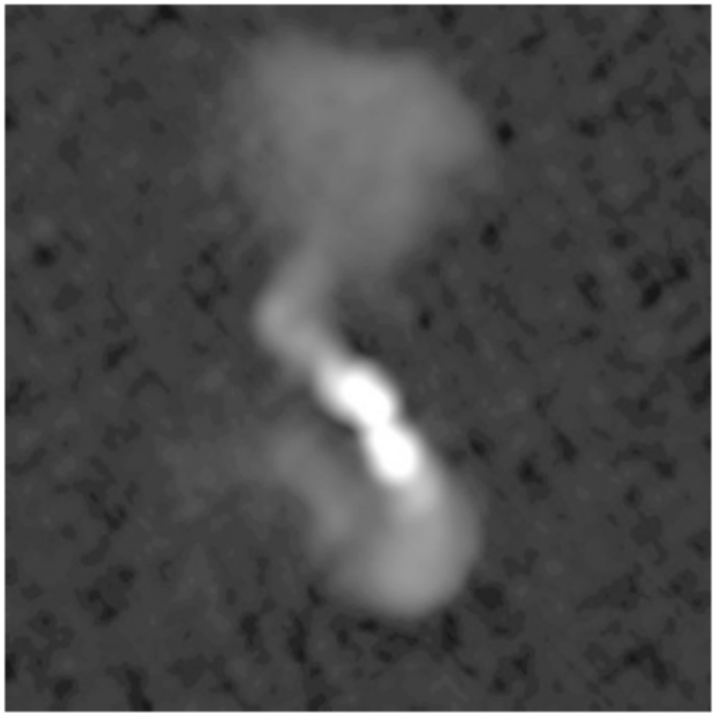
Produces this image



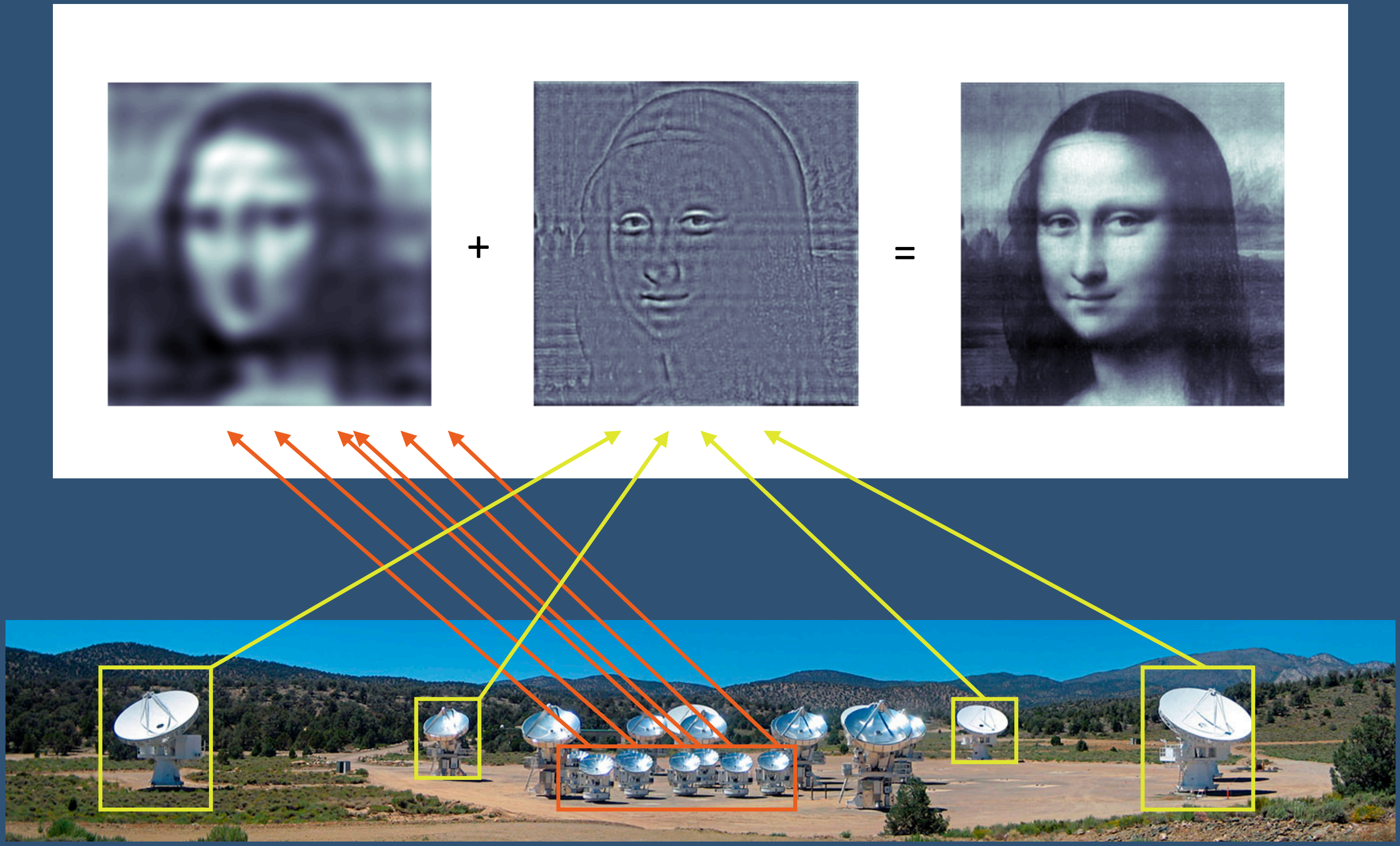
VLA A-configuration



VLA A+B+C-configuration

“Spatial Modes”

Short baselines (large scales) + *Long baselines (small scales)* = *The whole picture*



Advantages

- Higher resolution for not as much money
- Directly measure Fourier components
- Intrinsically stable; only correlated signals are detected
- Window functions are precisely calculable
- Radically different instrumentation and systematics than beam-swept experiments
- More “easily” calibrated

Dis-advantages

- Lower Sensitivity than comparable single dish
- No zero-spacing
- Minimum spacing you can not recover
- More complicated backend electronics.

Outline

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IV. Interferometry in words
    I. 1-D freq in time ~ 2D spatial freq (resolution)
    II. Extra dimension is the orientation angle
    III. By combining many baselines, you can recover the image.
V. Interferometry in practice
VI. Applications of Interferometers
VII. Activities

l-m on sky

(l,m,n): basis vectors on the sky for the source ("directional cosines of u,v,w")

(u,v,w): coordinate system on ground (in terms of wavelength)

$$u = {}^{B_x}\!/_{\lambda} \qquad v = {}^{B_y}\!/_{\lambda}$$

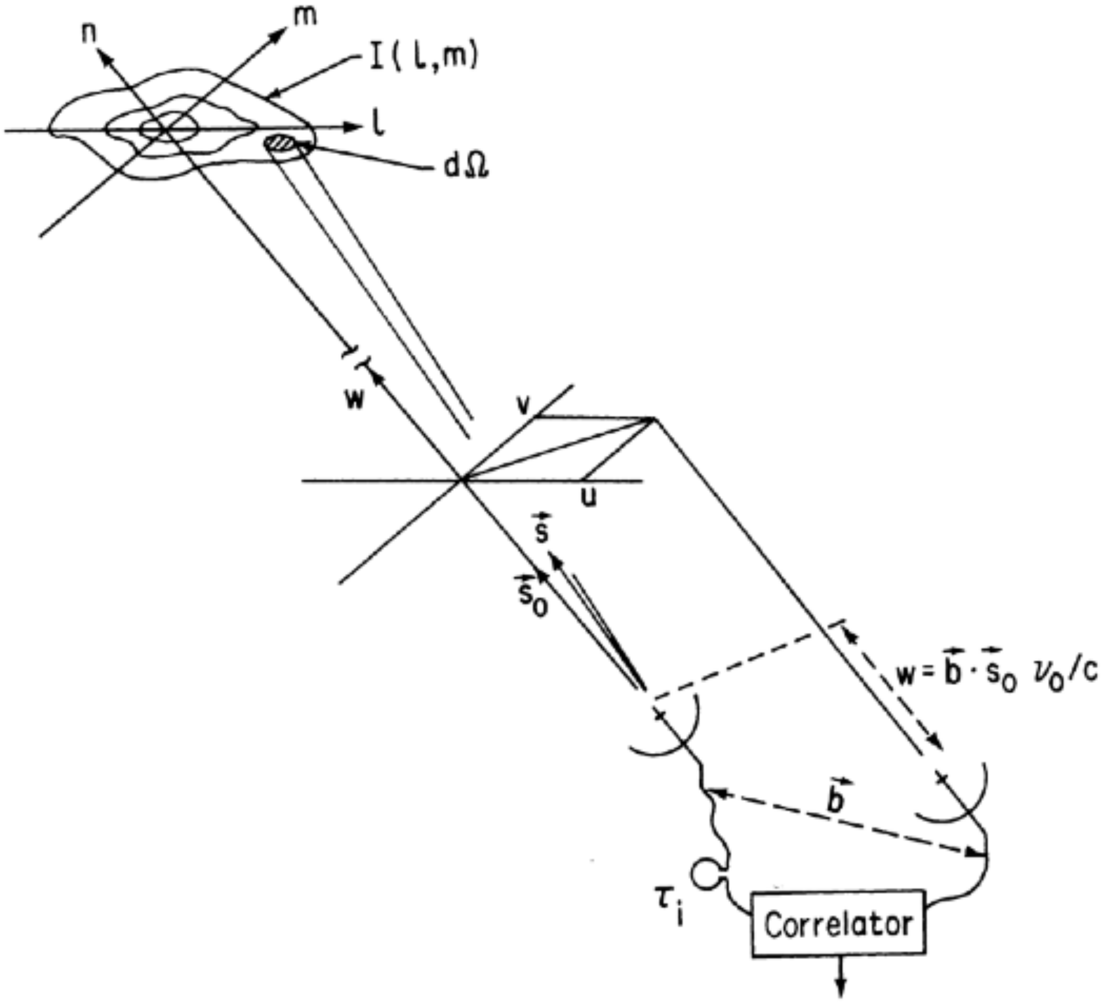


Figure 2–7. The (u, v, w) and (l, m, n) right-handed coordinate systems used to express the interferometer baselines and the source brightness distribution, respectively.

The Interferometric Equation

$$V(u,v,w) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} A_N(l,m)I(l,m) \times \exp\{-2\pi i[ul + vm + w(\sqrt{1-l^2-m^2} - 1)]\} \frac{dl\, dm}{\sqrt{1-l^2-m^2}}$$

In practice, you can (usually) approximate the sky as a flat plane, so the radical is approximately 1.

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

Antenna Pattern

Source Illumination

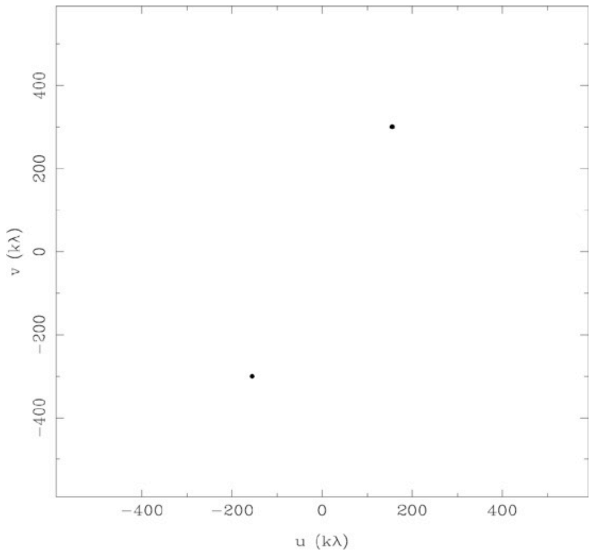
Incomplete Sampling of Fourier Plane

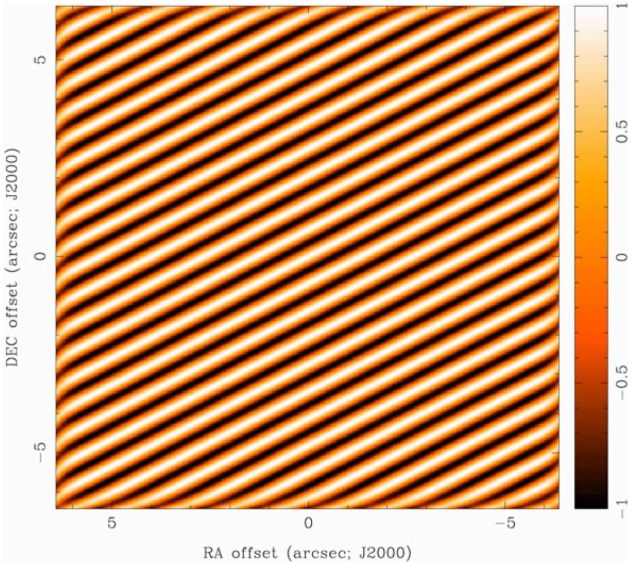
Dirty Beam Shape and N Antennas

David J. Wilner
Harvard-Smithsonian CfA

12th Synthesis Imaging Workshop
Socorro, June 9, 2010

- 2 Antennas

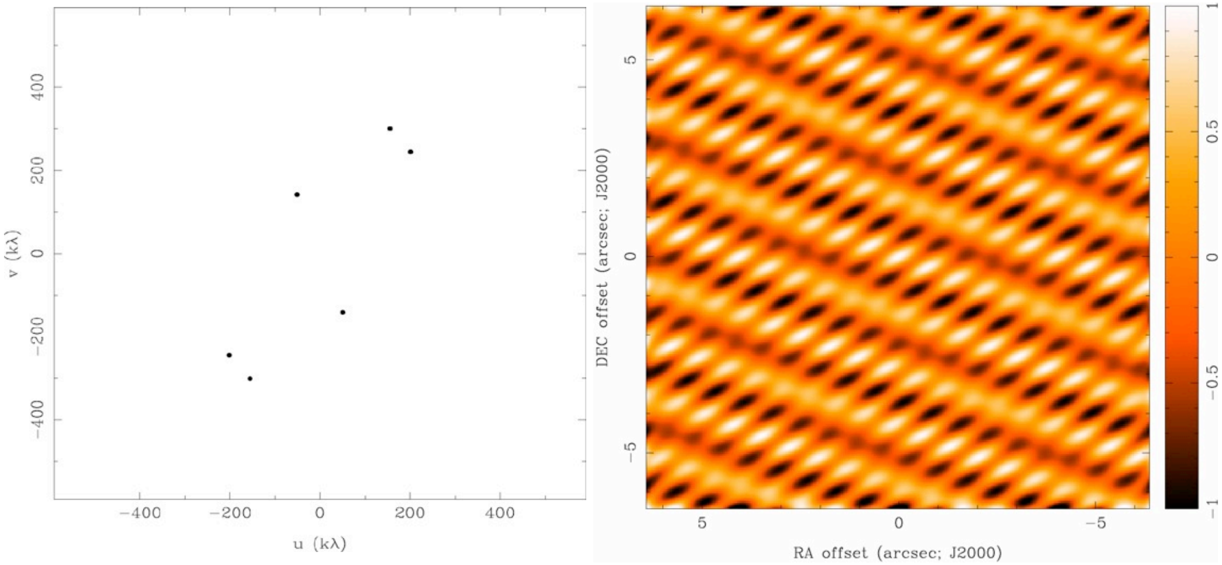




$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = D_\lambda \begin{bmatrix} \cos d \sin(H-h) \\ \sin d \cos\delta - \cos d \sin\delta \cos(H-h) \\ \sin d \sin\delta + \cos d \cos\delta \cos(H-h) \end{bmatrix}$$

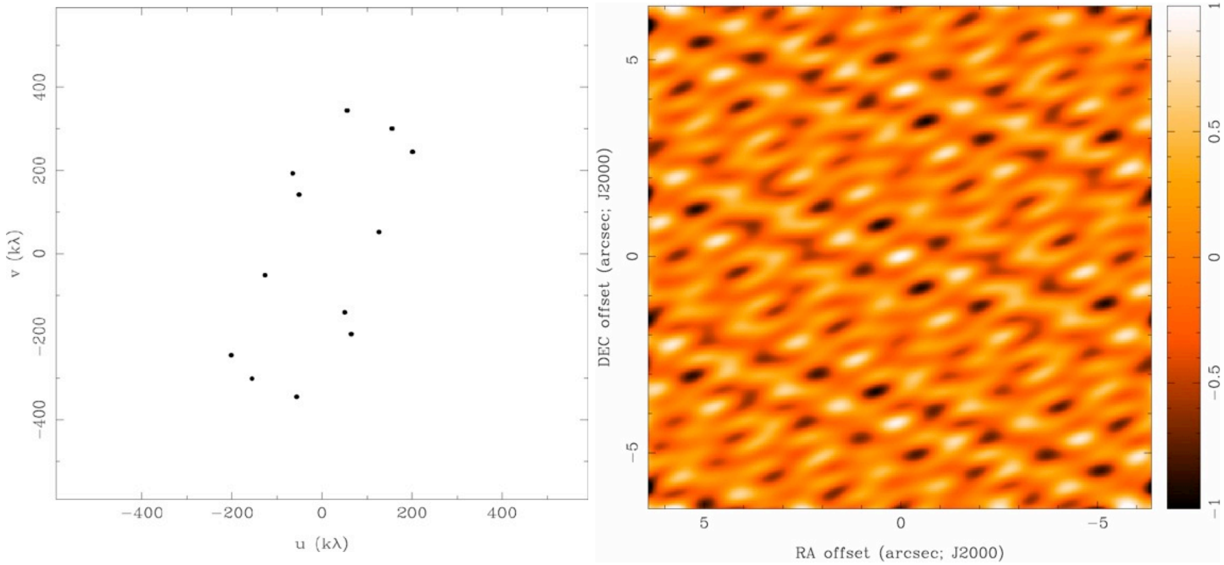
Dirty Beam Shape and N Antennas

3 Antennas



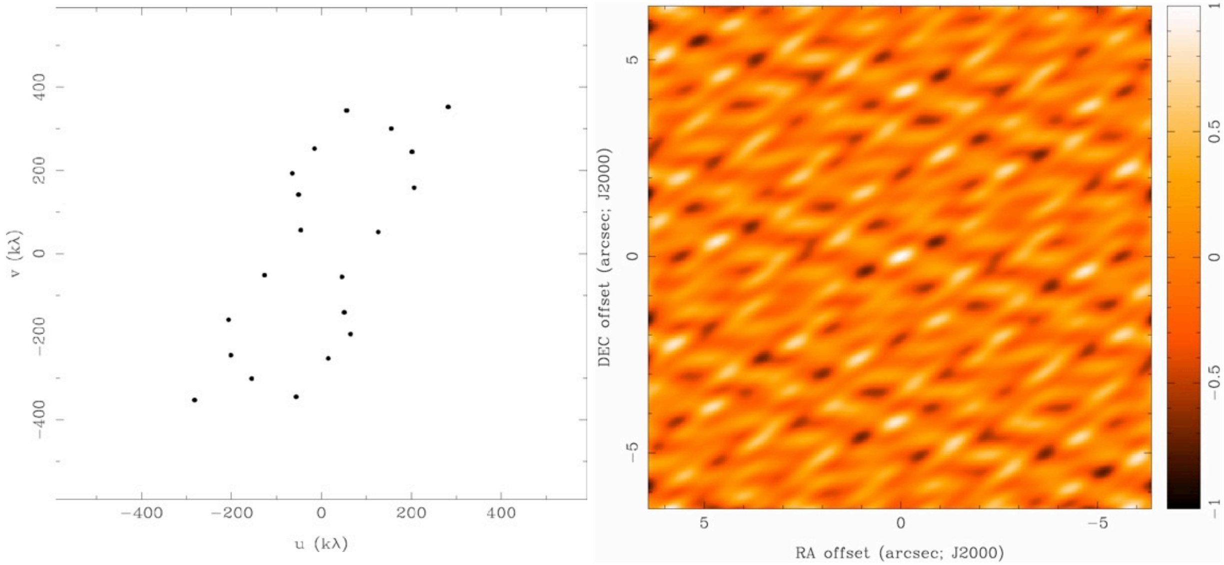
Dirty Beam Shape and N Antennas

4 Antennas



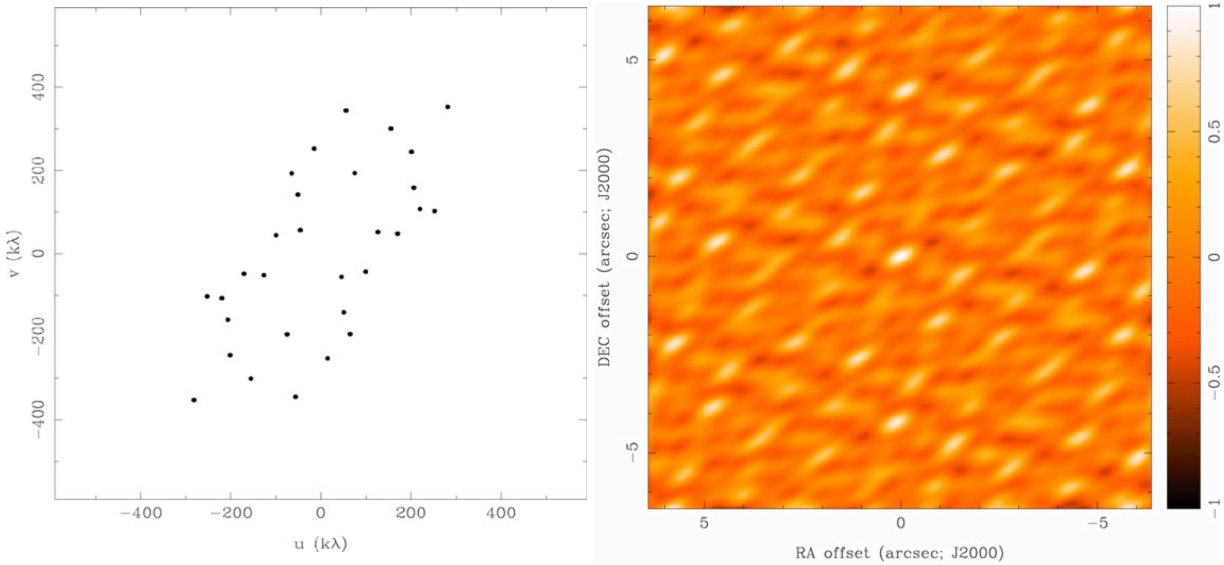
Dirty Beam Shape and N Antennas

5 Antennas



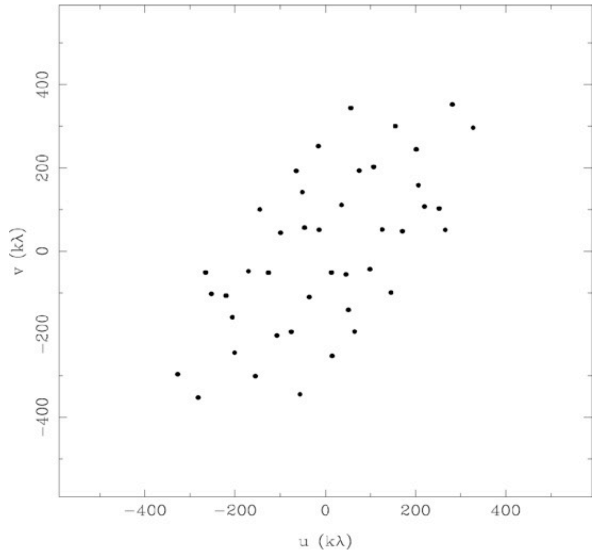
Dirty Beam Shape and N Antennas

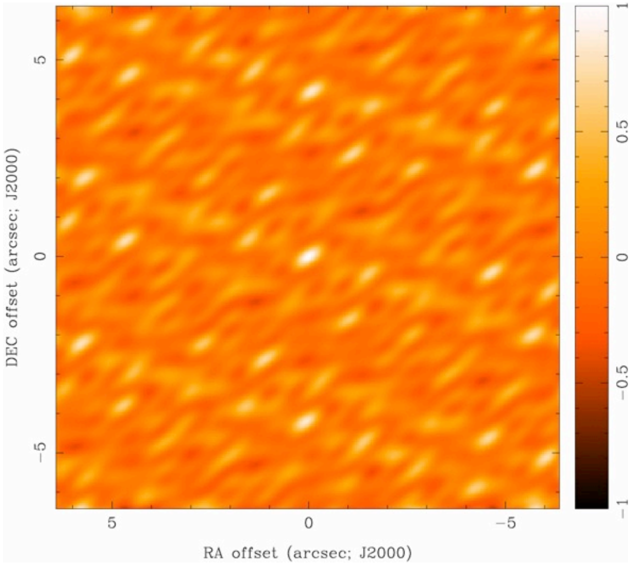
6 Antennas



Dirty Beam Shape and N Antennas

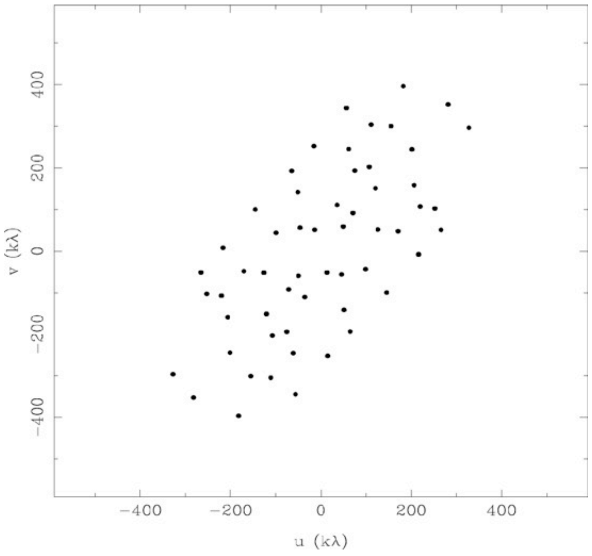
7 Antennas

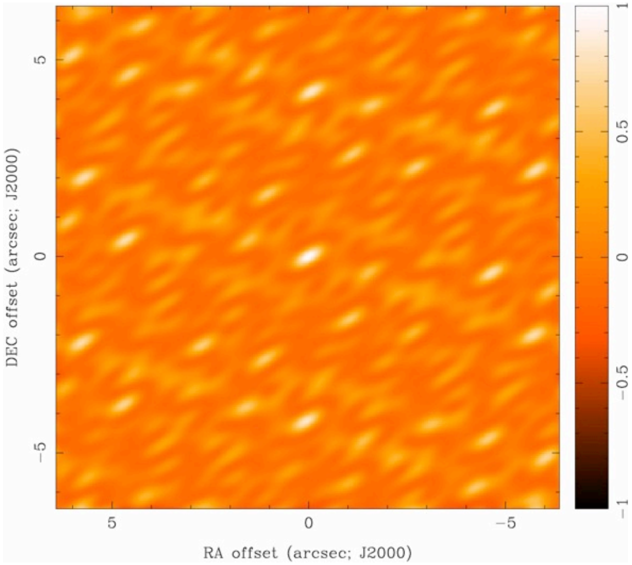




Dirty Beam Shape and N Antennas

8 Antennas

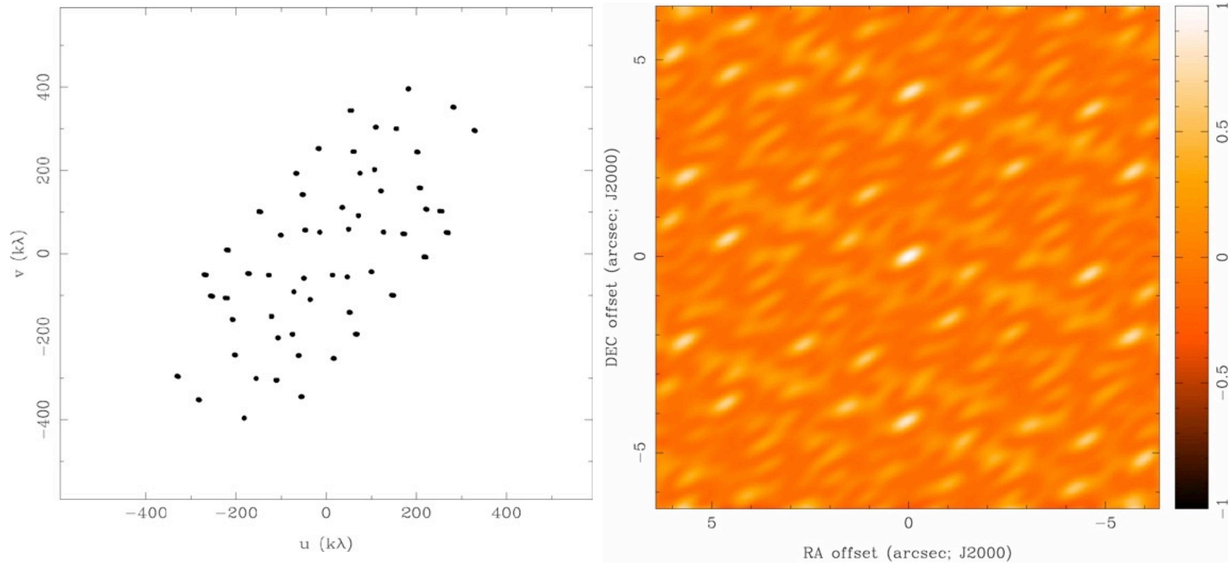




X

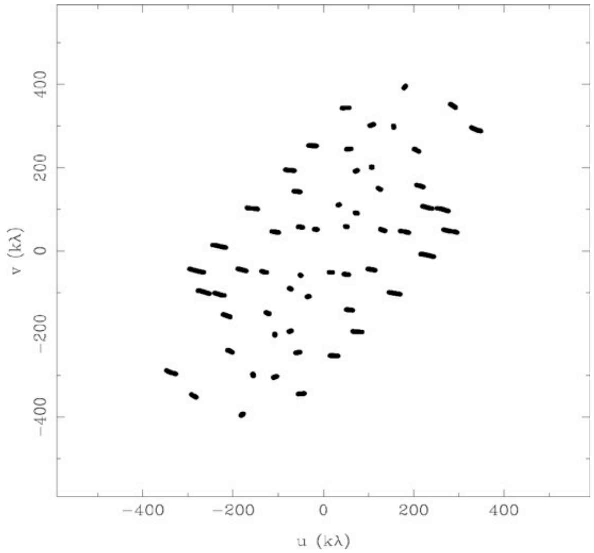
Dirty Beam Shape and N Antennas

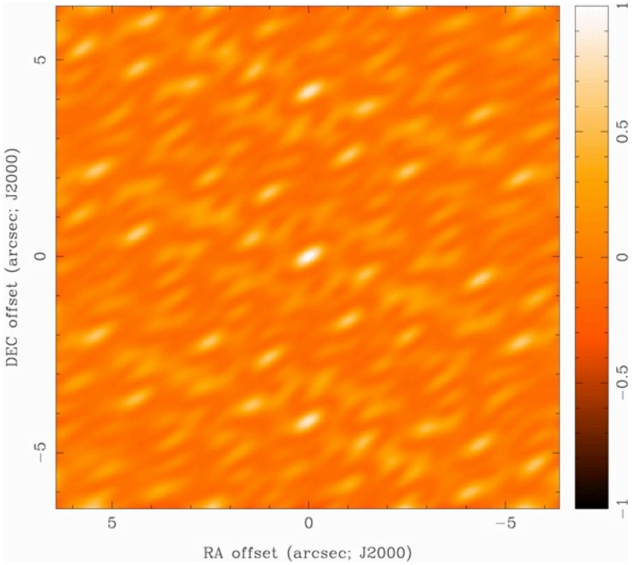
8 Antennas x 6 Samples



Dirty Beam Shape and N Antennas

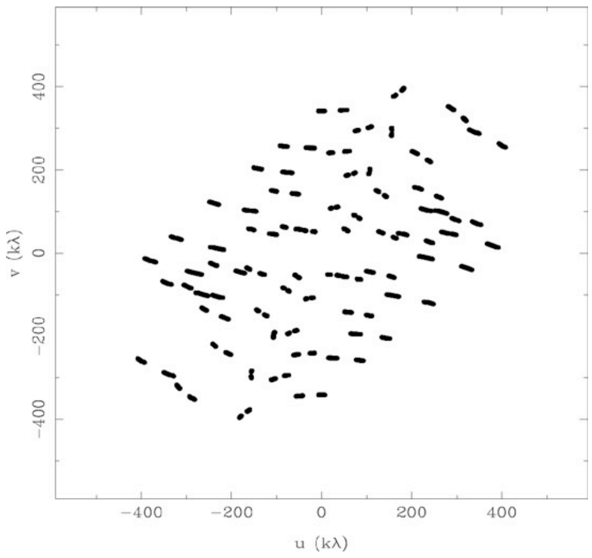
8 Antennas x 30 Samples

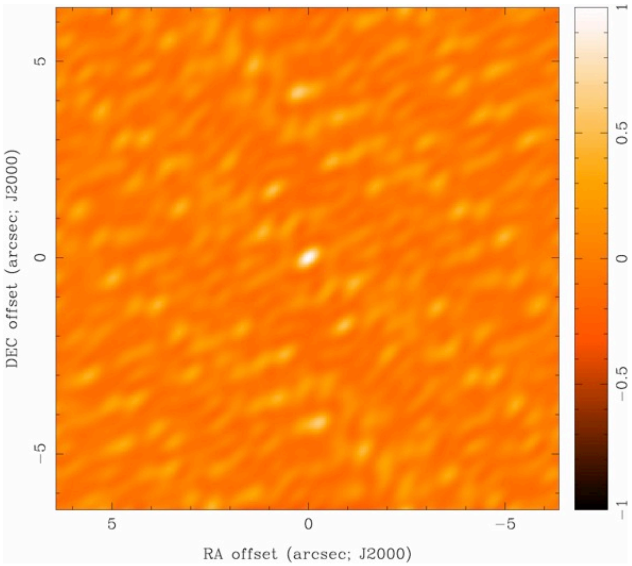




Dirty Beam Shape and N Antennas

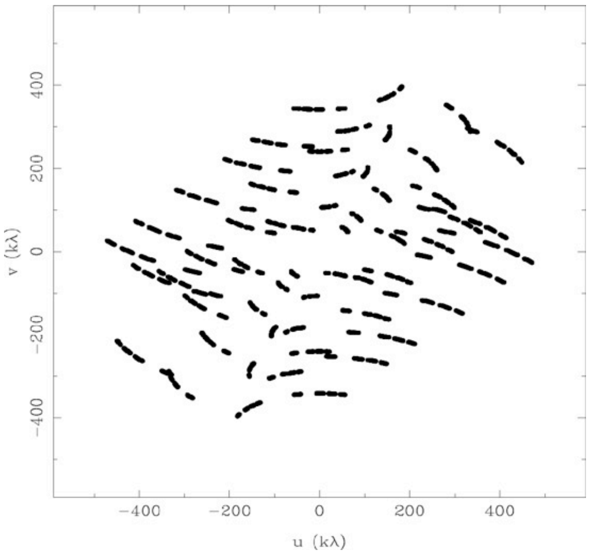
8 Antennas x 60 Samples

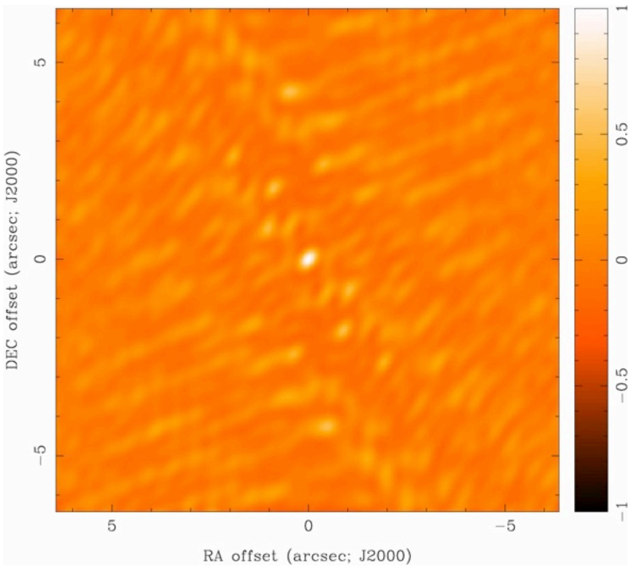




Dirty Beam Shape and N Antennas

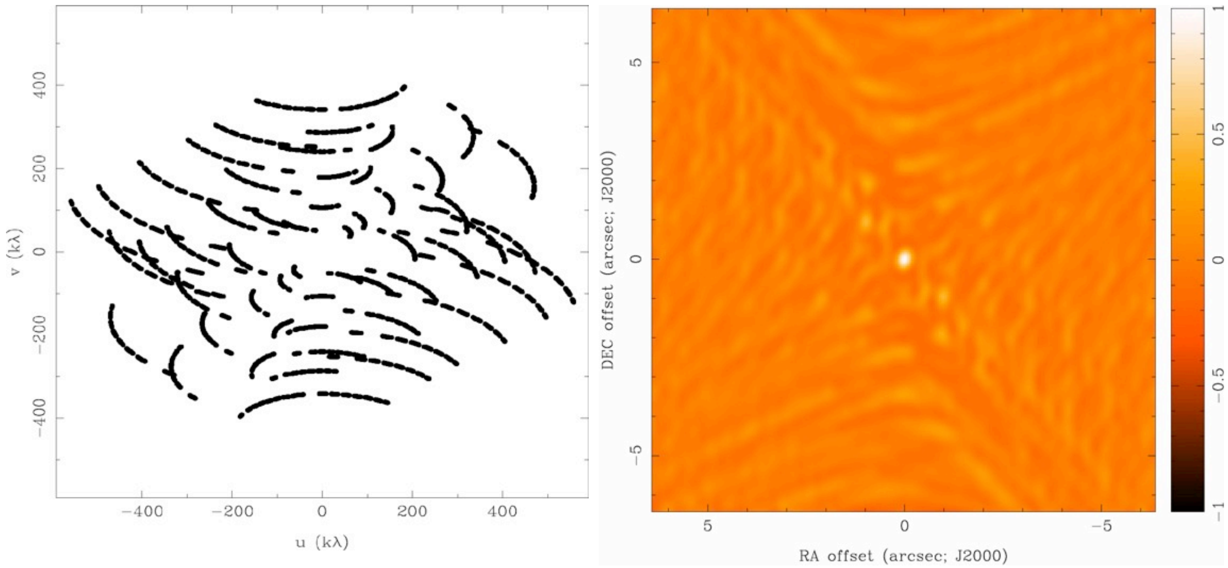
8 Antennas x 120 Samples





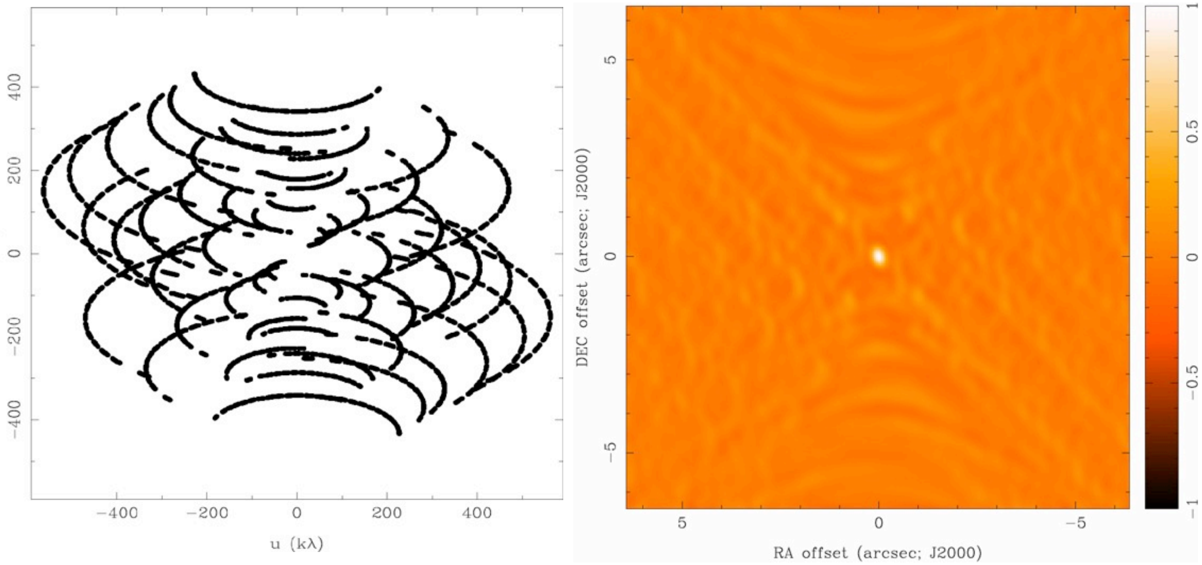
Dirty Beam Shape and N Antennas

8 Antennas x 240 Samples



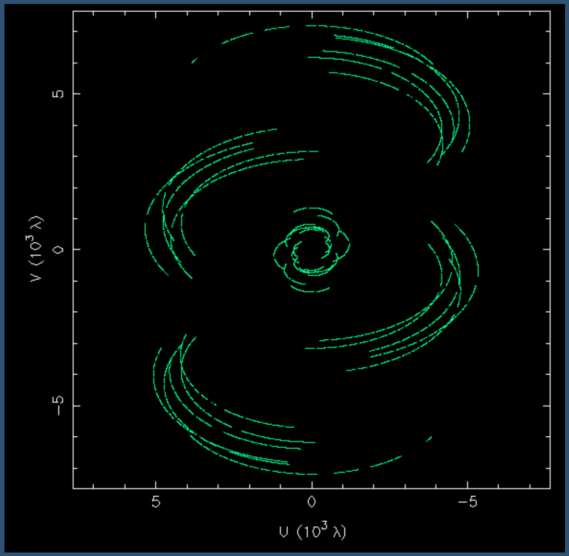
Dirty Beam Shape and N Antennas

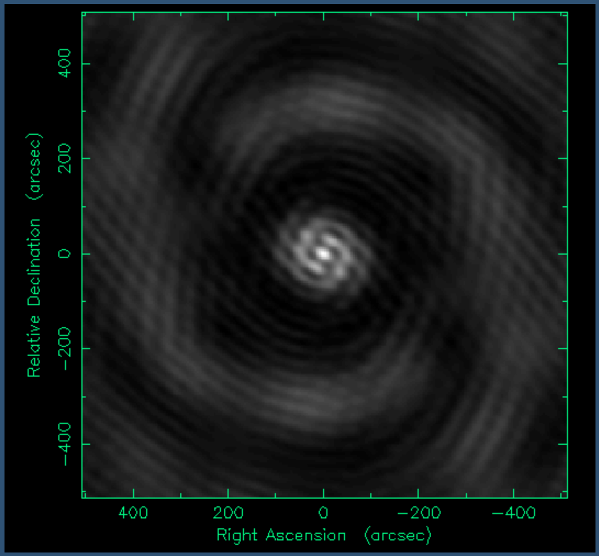
8 Antennas x 480 Samples

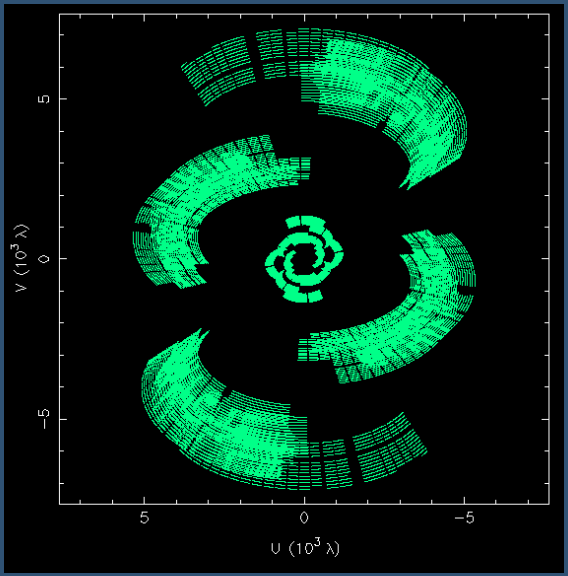


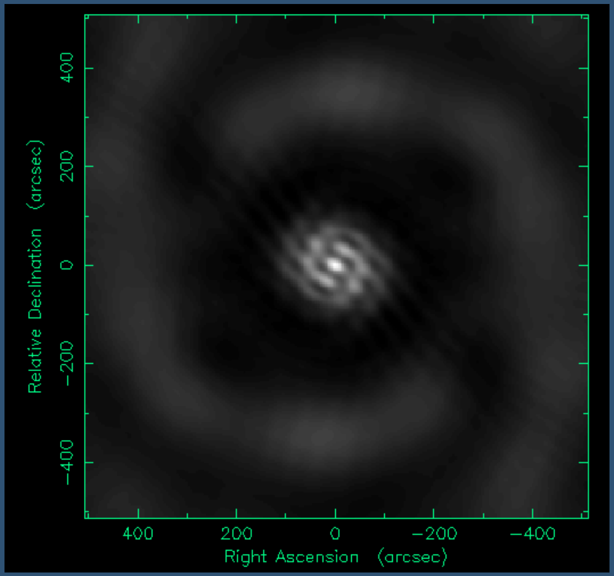
x

Bandwidth


5
0
−5
V (10^3 λ)
5
0
−5
U (10^3 λ)


400
200
0
−200
−400
Relative Declination (arcsec)
400
200
0
−200
−400
Right Ascension (arcsec)


5
0
−5
V (10^3 λ)
5
0
−5
U (10^3 λ)


400
200
0
−200
−400
Relative Declination (arcsec)
400
200
0
−200
−400
Right Ascension (arcsec)

Interferometer Properties

$$\delta\theta \sim \frac{\lambda}{D_{max}}$$

Resolution

$$\theta_{max} \sim \frac{\lambda}{D_{min}}$$

Largest Structure

$$\theta_{FOV} \sim \frac{\lambda}{D_{ant}}$$

Field of View

Total Number of Baselines

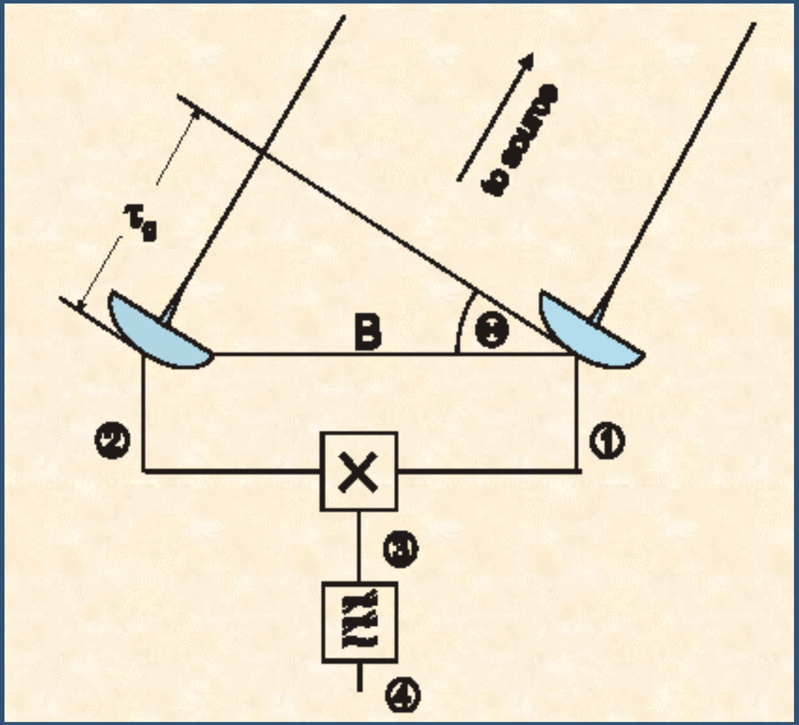
$$N_{bases} = \frac{N_{ant}(N_{ant}-1)}{2}$$

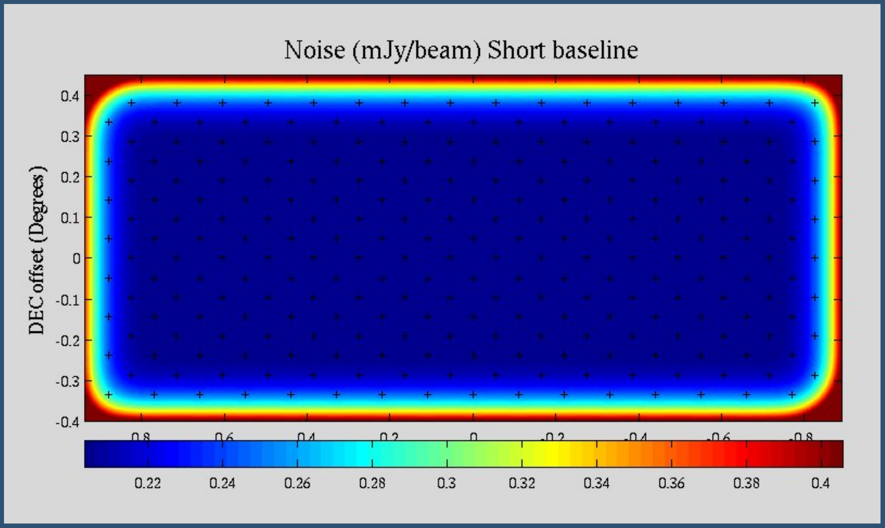
Sensitivity (of a SINGLE baseline)

$$\sigma_{interf} = \frac{2k_B\sqrt{T_{sys1}T_{sys2}}}{\sqrt{\eta_{ap1}\eta_{ap2}}(\mathrm{Area})} \cdot \frac{1}{\eta_{corr}\sqrt{\tau\Delta\nu}}$$

Simple, right?

- Geometric Delay Compensation
- Phase Switching
- Calibration
- Shadowing
- Mosaicking
- Etc…etc….etc….





It gets more complicated…

Application: Sunyaev-Zel'dovich Array (SZA)

Built to study clusters of galaxies via the SZ effect.

Eight 3.5m telescopes

30GHz and 90GHz

8GHz bandwidth correlator

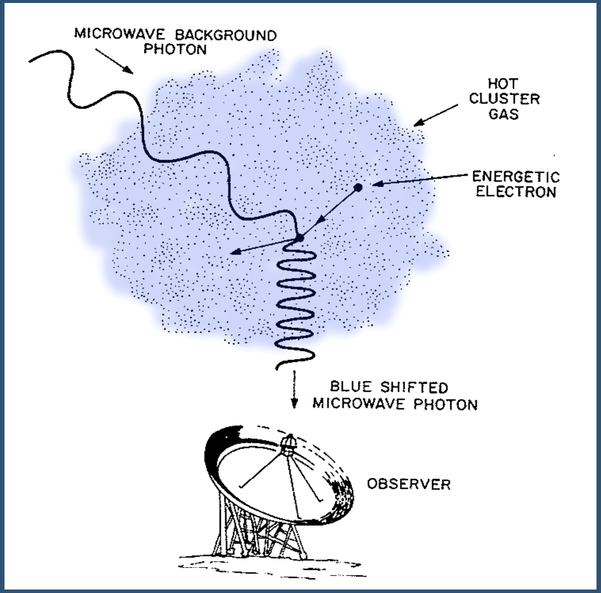
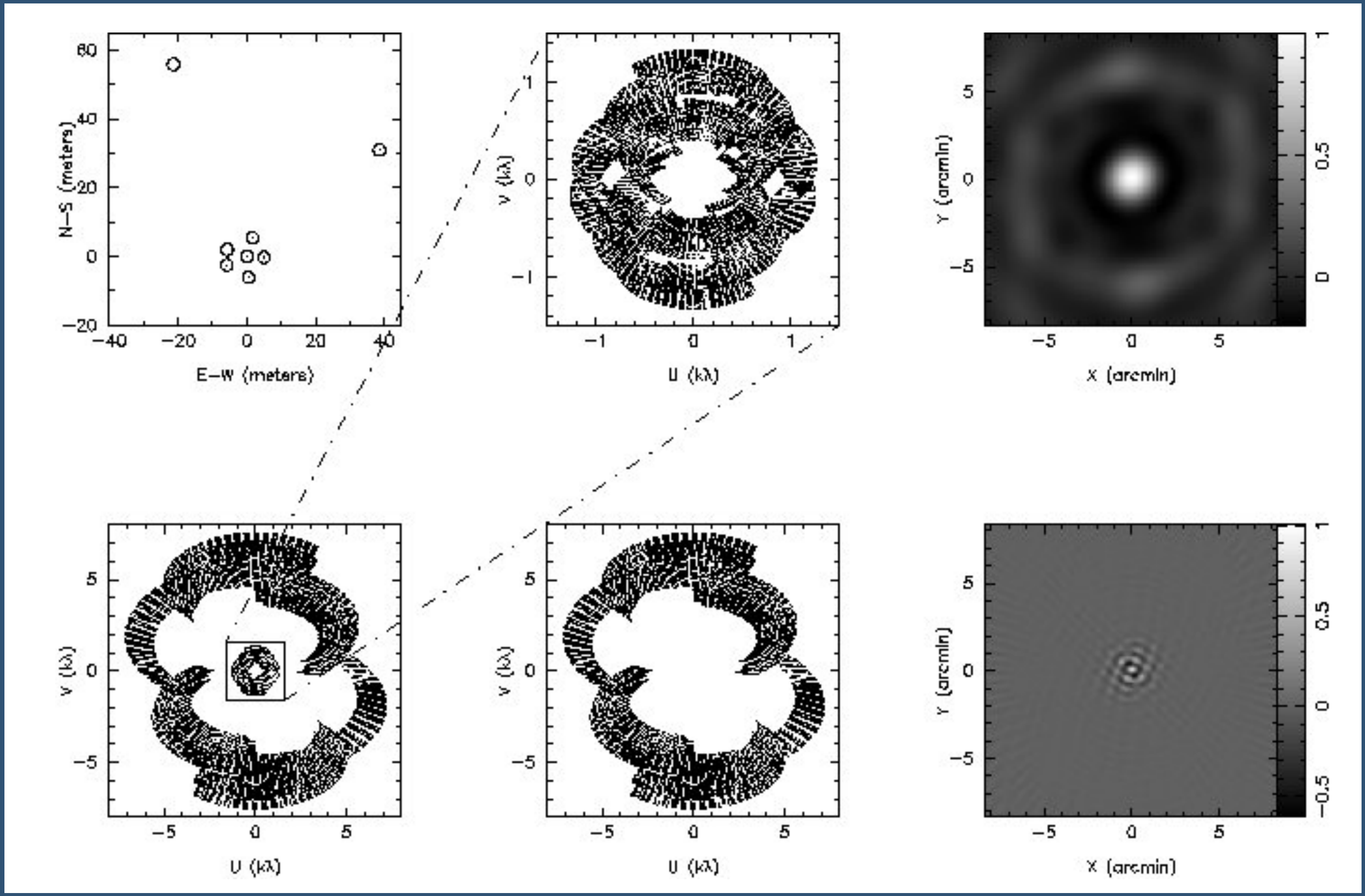


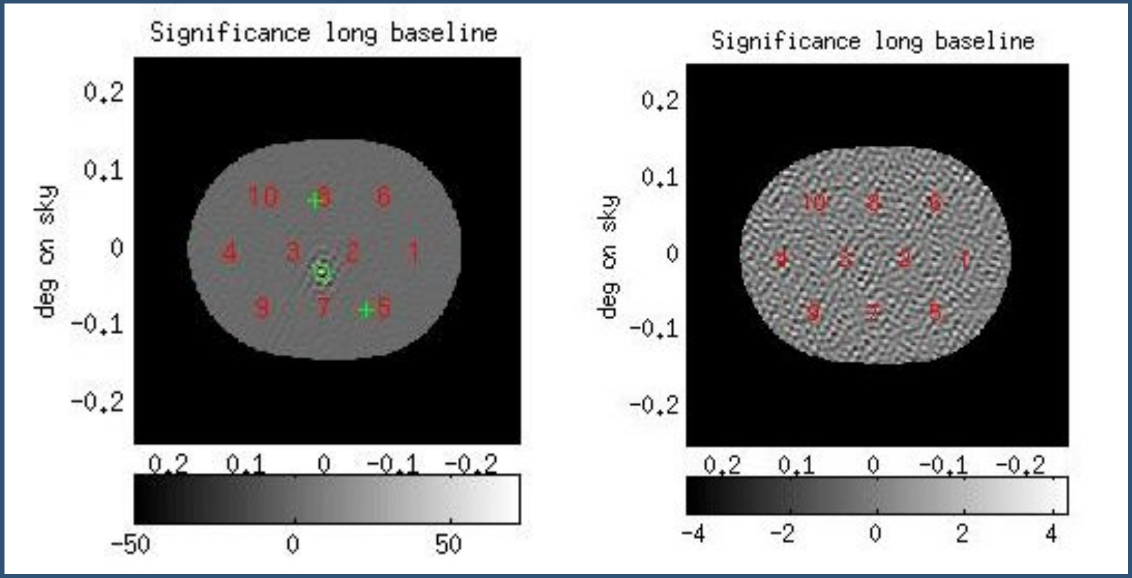
Photo Credit: Leitch

Application: Sunyaev-Zel'dovich Array (SZA)



Test of Survey on Cl0016+0016

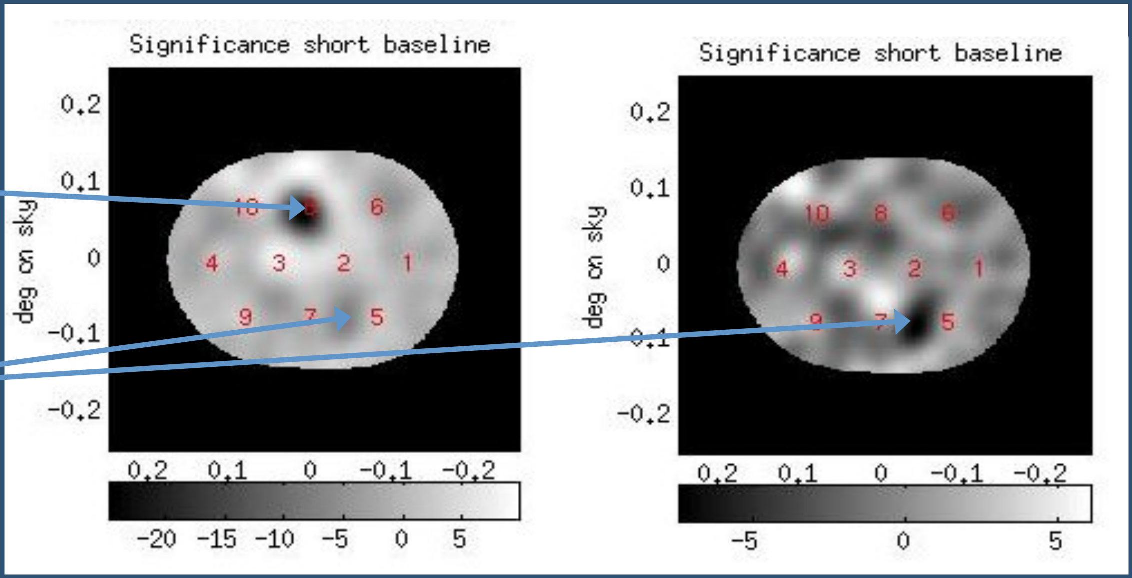
- 10 pointing Mosaic in 3-4-3 Hex Pattern
- 4.8 arcminute Separation
- Median rms 0.31mJy/beam
- Bright Radio Source at > 60 sigma



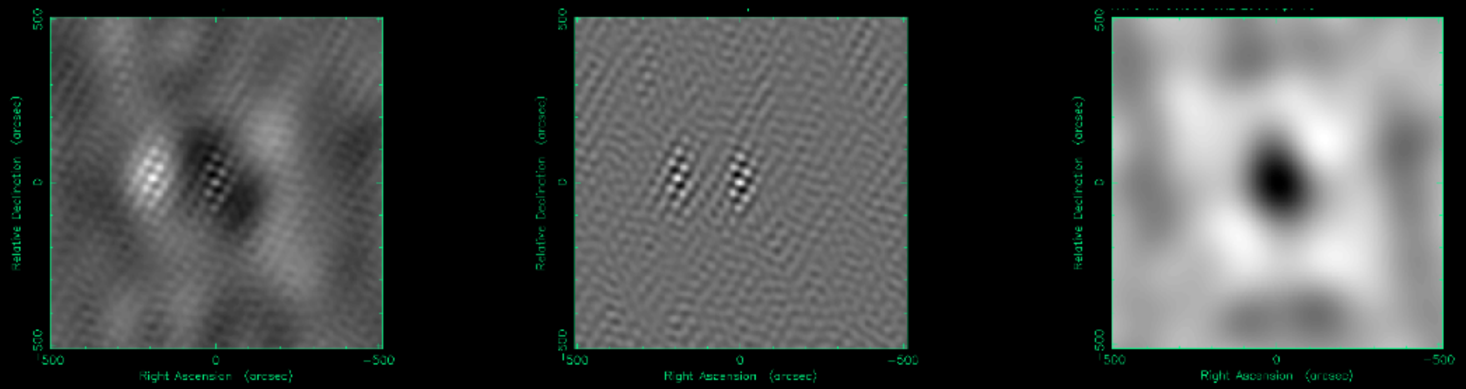
Two Clusters Detected

Cl0016+0016
M ~ 1.3 x 10^15 M_solar
(Hughes et al., 1995, ApJ448:L93)

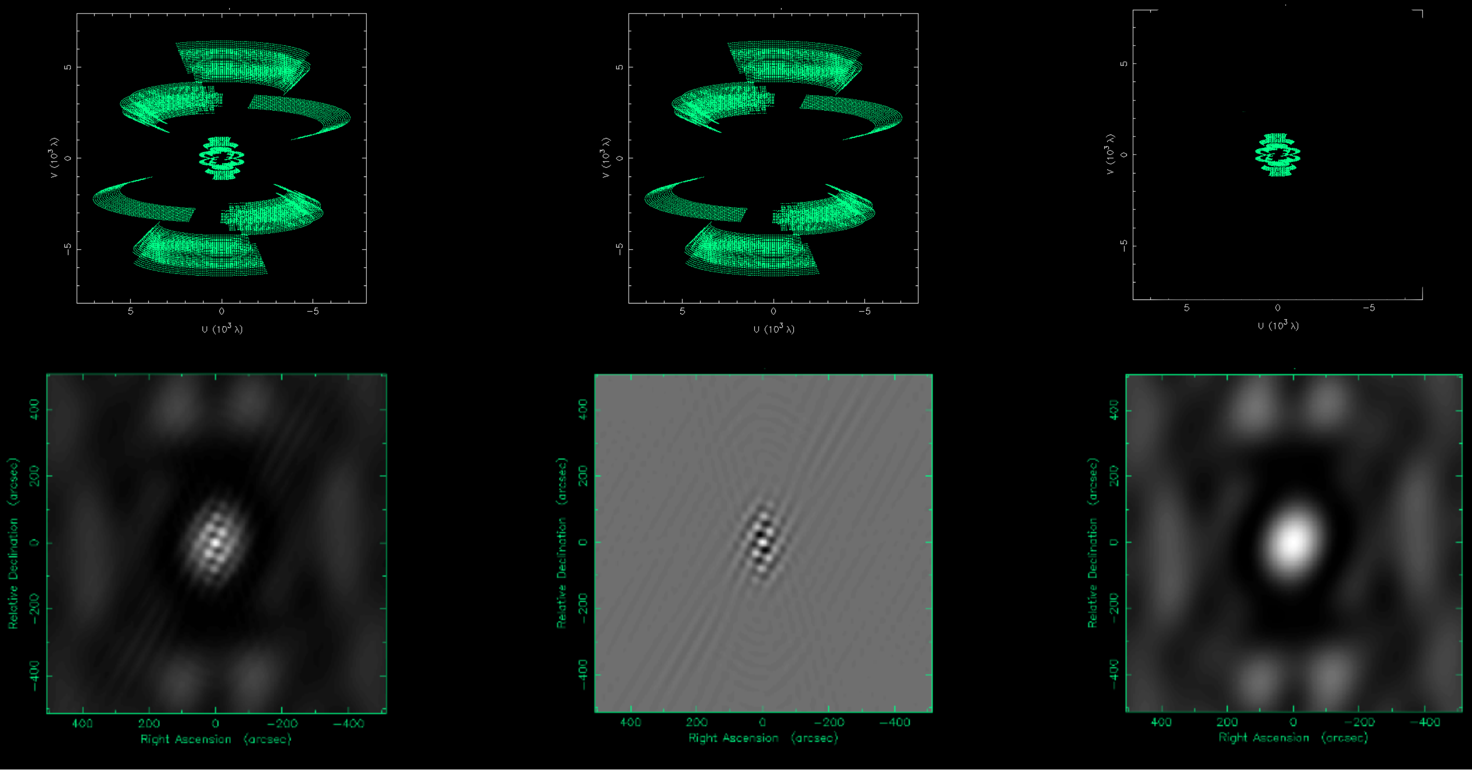
RXJ0018.3+1618
M ~ 5 x 10^14 M_solar
(Hughes & Birkinshaw, 1998, ApJ 497:645)



SZ Detection with the SZA



Combined *Long-only* *Short-only*



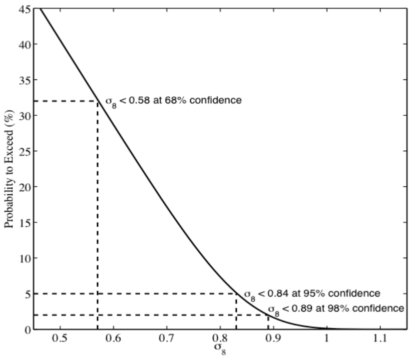
SZA results

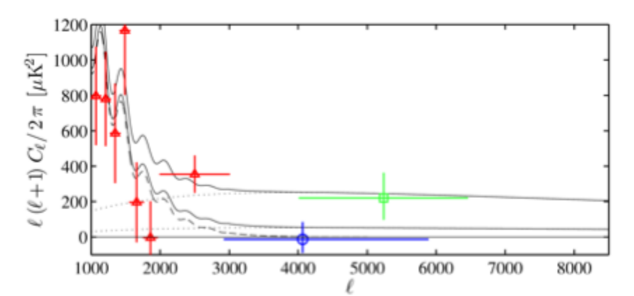
- Several Square Degree Survey
  - *Placed meaningful contraint on σ_8 (rms linear fluctuations in the mass distribution on scales of 8 Mpc)*
  - *Tests of Non-Gaussianity*
  - *Detection of Galactic AME*
  - *1st cm-wave source counts to mJy*
  - *Solved a tension between previous CMB experiments*

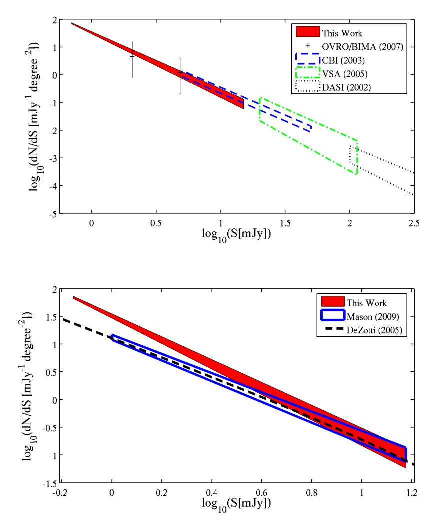
- Pointed Observations
  - Scaling Relations
  - Better Estimates of Cluster Observables/Scaling Relations

- Detailed Imaging of Clusters at 90GHz

- CMB anisotropy measurement







Possibilities!!!

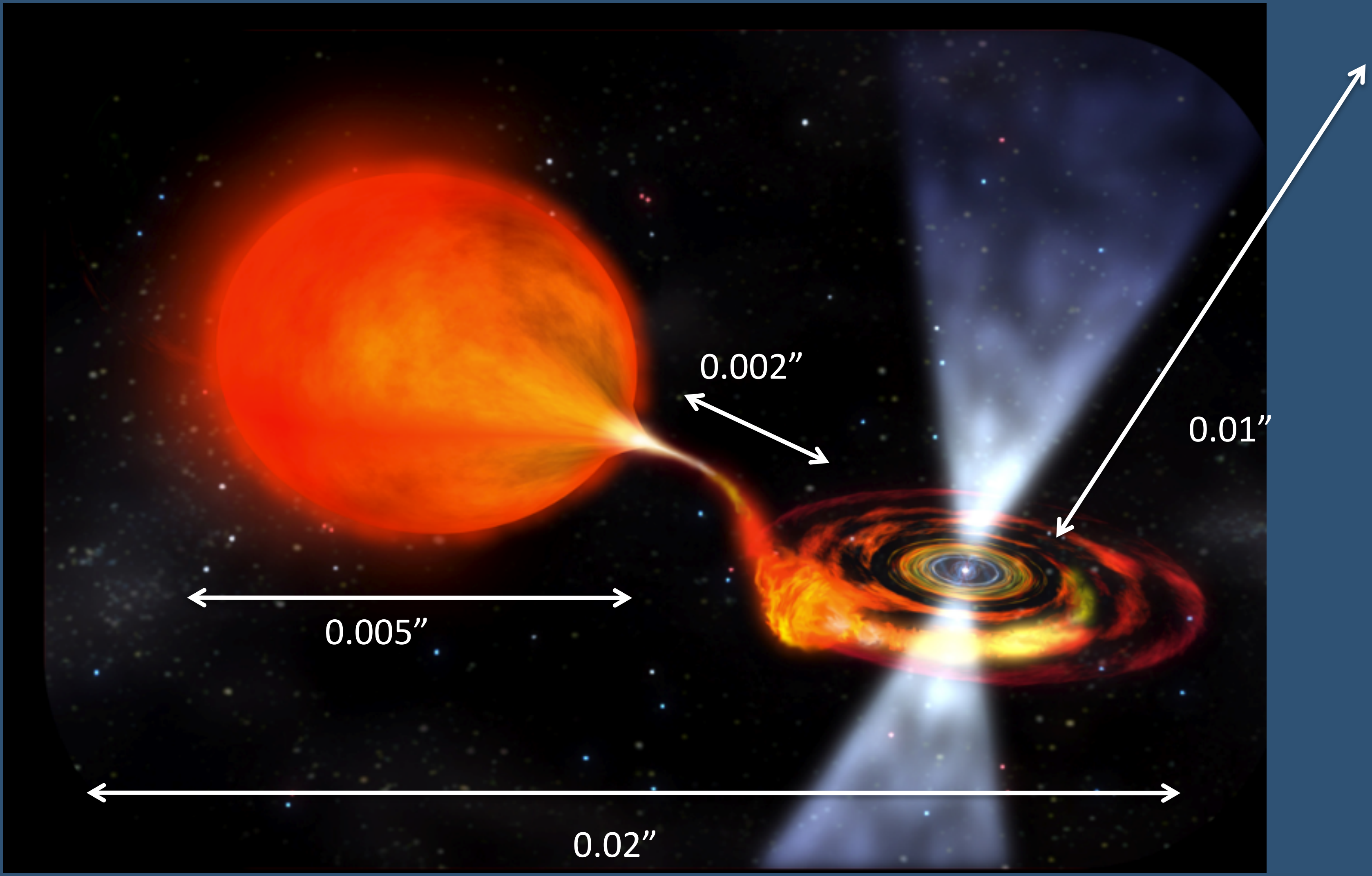
SZA was pretty small, just think of what you can do with KAT7 and MeerKAT!

Questions?

Artist's impression of the MeerKAT array

By IBM Research

Design your own!



Design your own!

Study objects like those. You want to be sensitive to the emission from each component, be able to separate them, and know the full emission of the system.

Observing frequency: 3-4GHz (synchrotron jets)
Observing time: 8 hours per object
Sensitivity required: 22µ Jy/beam
Aperture Efficiency: 0.6, Correlator Efficiency: 0.9
Tsys: 50K

$$\delta\theta \sim \frac{\lambda}{D_{max}}$$

Resolution

$$\theta_{max} \sim \frac{\lambda}{D_{min}}$$

Largest Structure

$$\sigma_{interf} = \frac{2k_B\sqrt{T_{sys1}T_{sys2}}}{\sqrt{\eta_{ap1}\eta_{ap2}}(\mathrm{Area})} \cdot \frac{1}{\eta_{corr}\sqrt{\tau\Delta\nu}} = \frac{2k_B\sqrt{50K*50K}}{\sqrt{0.6*0.6}(\mathrm{Area})} \cdot \frac{1}{0.9\sqrt{\tau\Delta\nu}} = 2.5*10^5 \frac{1}{(\mathrm{Area})\sqrt{\tau\Delta\nu}} \frac{Jy}{beam}$$

Area in m^2

Questions:

1. How far should your antennas be (what resolution do you need)?
2. How many antennas do you need?
3. How big will you make each antenna?
4. Where could you put such an instrument?

Just for comparison, what size optical telescope would you need for resolution?