Introduction to Radio Astronomy

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Astronomy: A personal perspective

- The only source of information - the tiny amounts of radiation incident on the telescopes
  - You can only ‘observe’ not ‘experiment’
  - Observations + laws of physics + logic
- Telescopes tend to be marvelous feats of engineering
  - The most detailed characterisation of light possible
  - Measure very faint signals with very high accuracy
- Detective work – the art and science of logical deduction

- Over the years we have learnt an amazing amount about our grand universe from analysing a minuscule amount of light which happens reach our vantage point.

- Important lessons in humility and unity – The Pale Blue Dot

Andromeda: Our nearest galactic neighbour

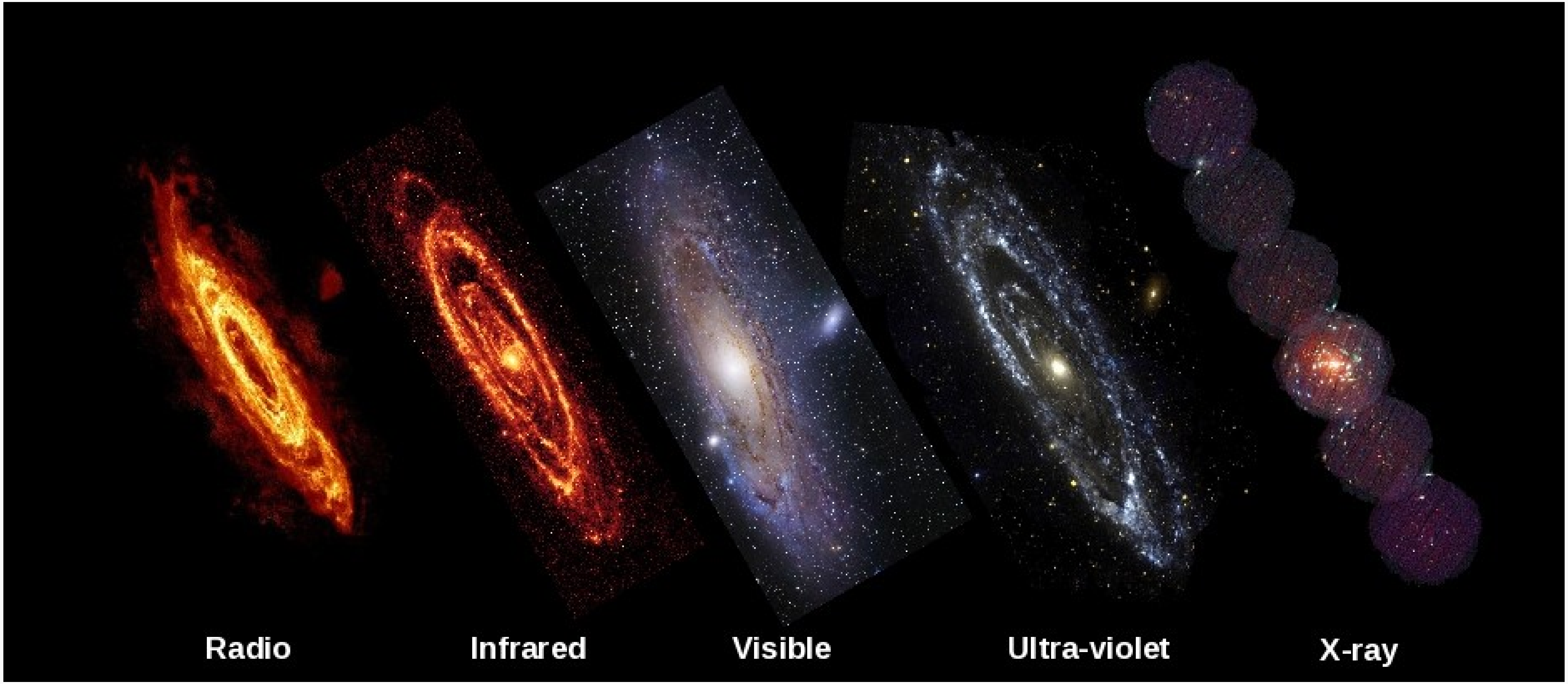
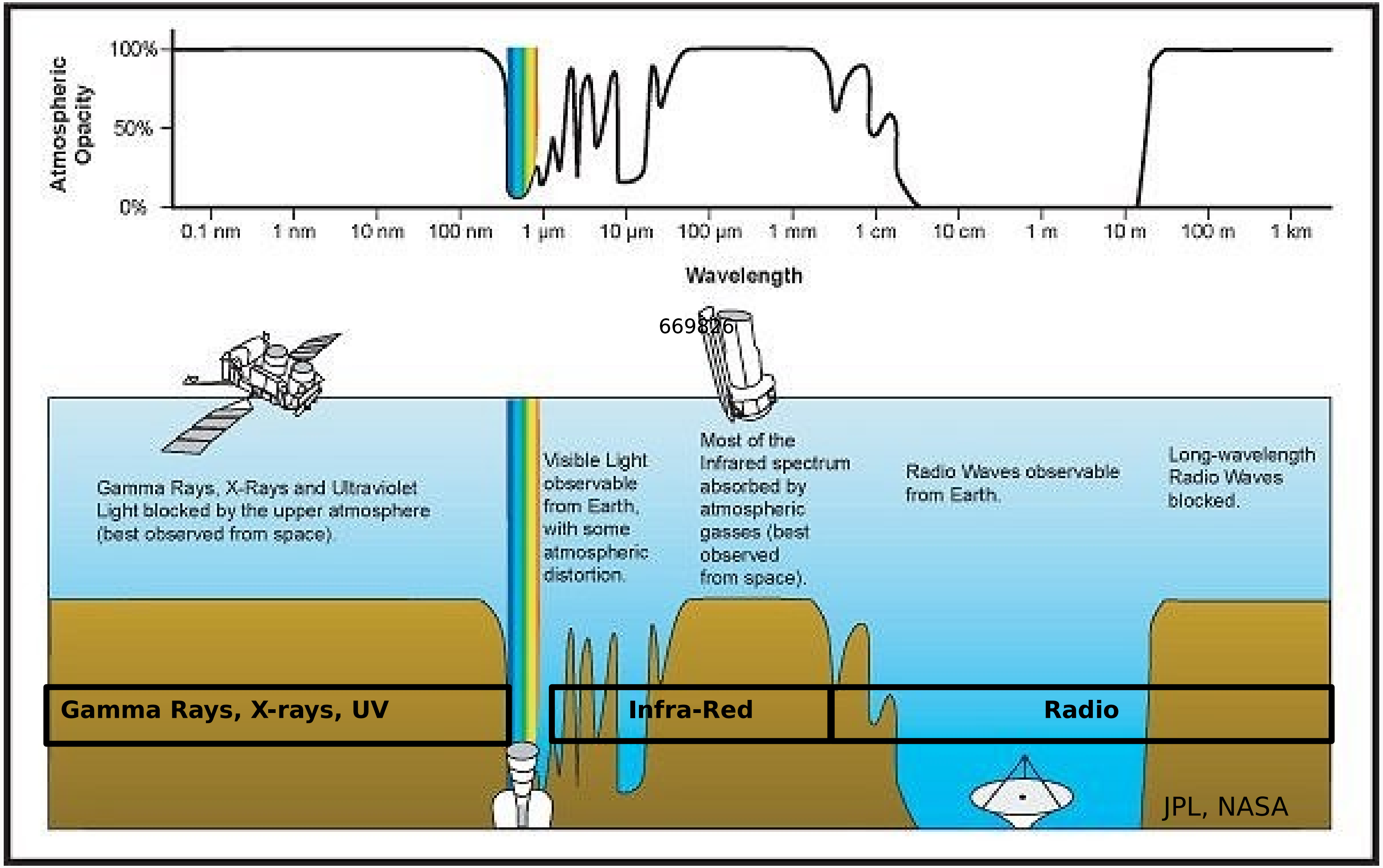
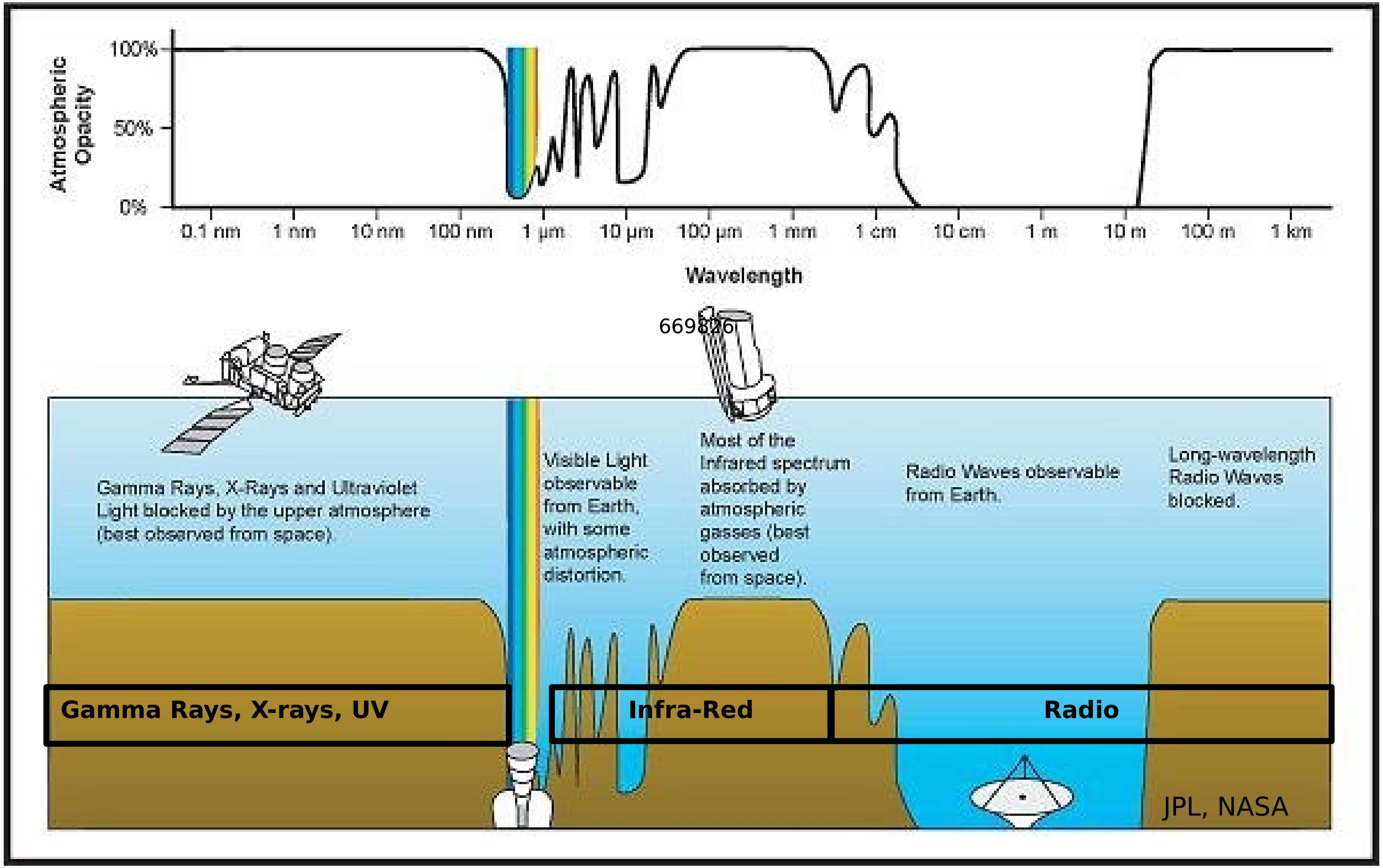


Image credits: Radio: WSRT/R. Braun; Infrared:NASA/Spitzer/K. Gordon; Visible: Robert Gendler; Ultraviolet: NASA/GALEX; X-ray: ESA/XMM/W. Pietsch

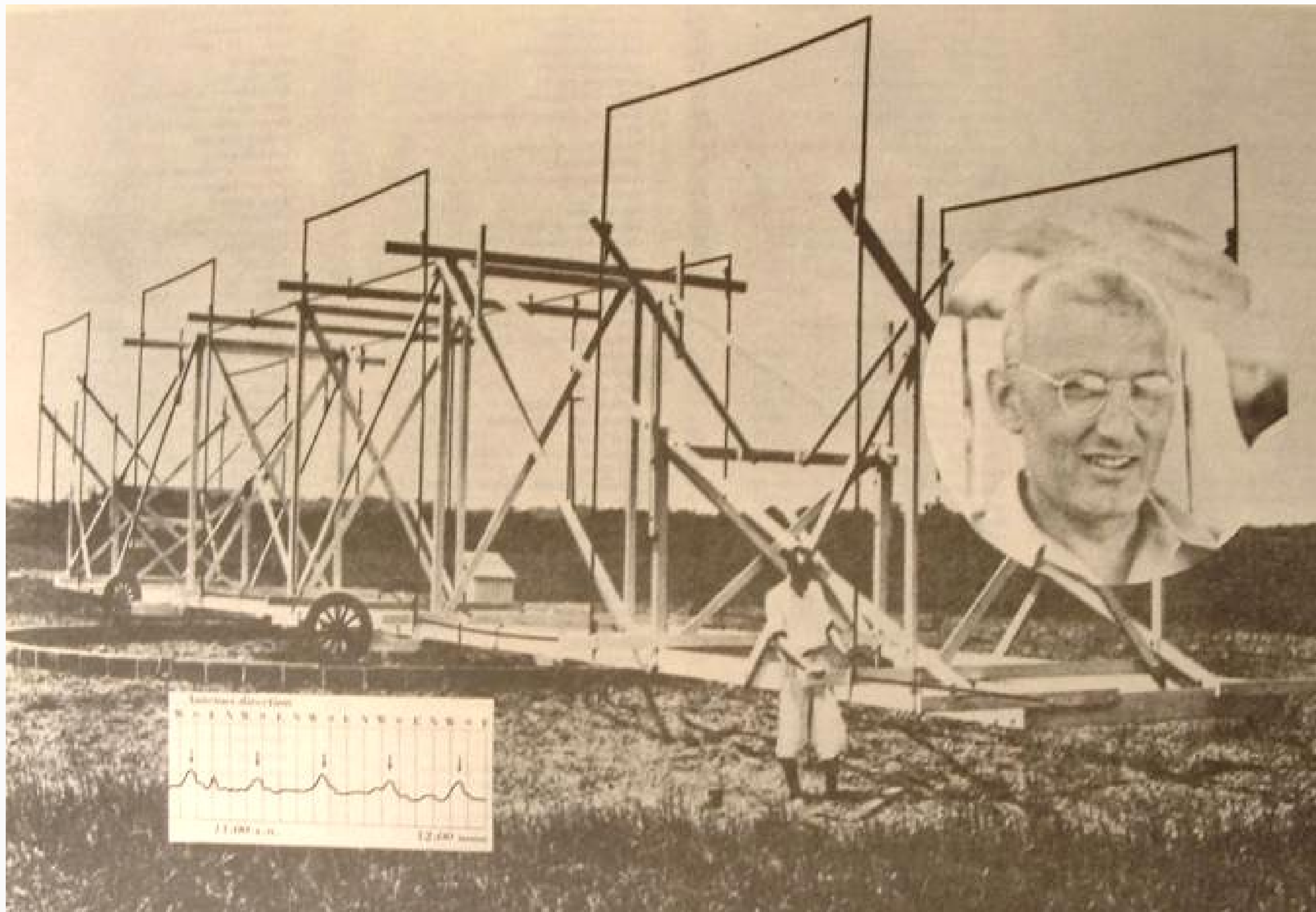
What Makes it to the Earth's Surface



What Makes it to the Earth's Surface



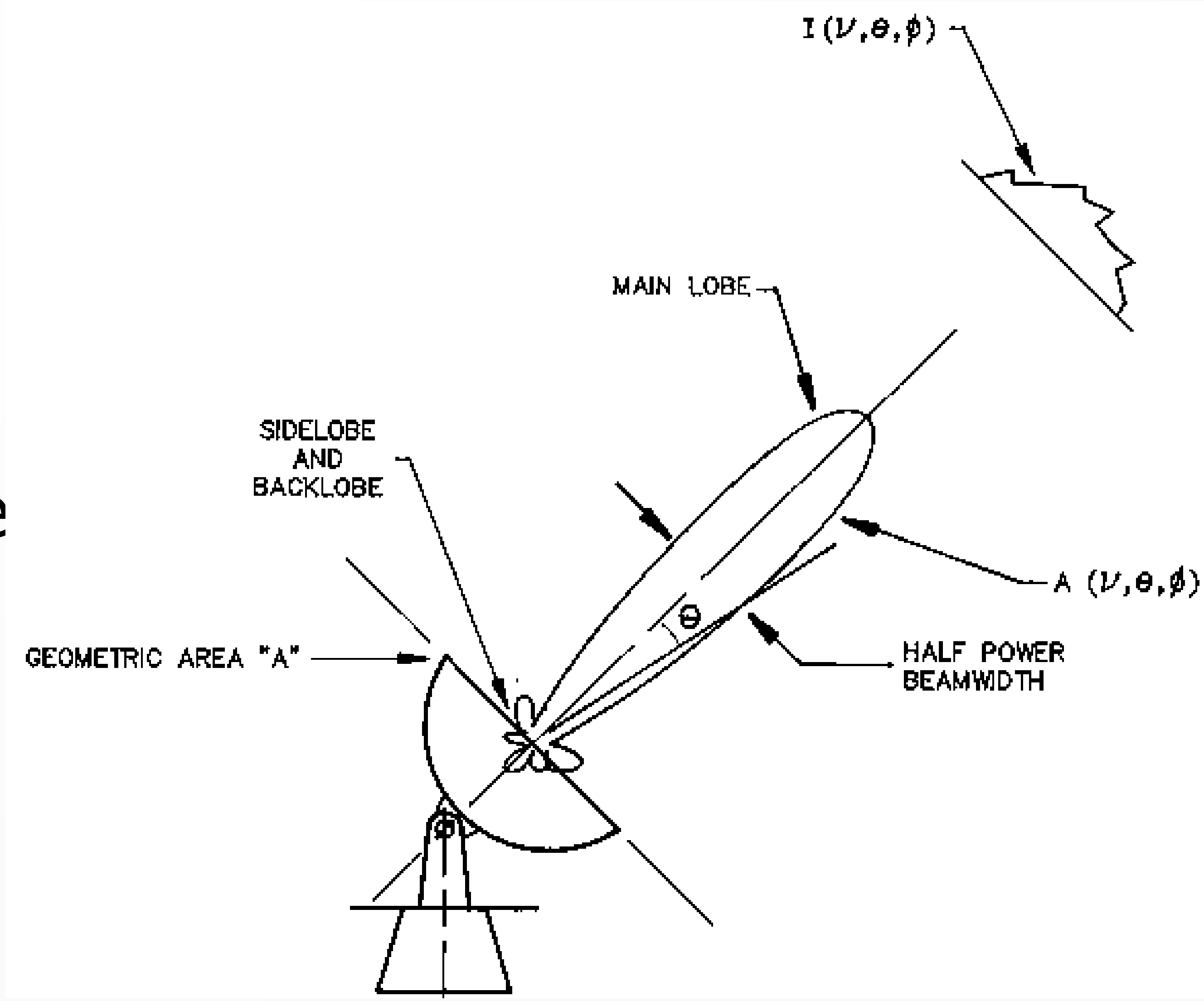
Karl Jansky: The Birth of Radio Astronomy



World's first radio telescope (20.5 MHz, circa 1936)

Beam size and Resolution

- Size of the main lobe in radians ~λ/D
- λ is the wavelength
- D is the diameter
- Better resolution require
  - Shorter wavelength (higher frequency)
  - Bigger telescopes



Radio Telescope: Basics

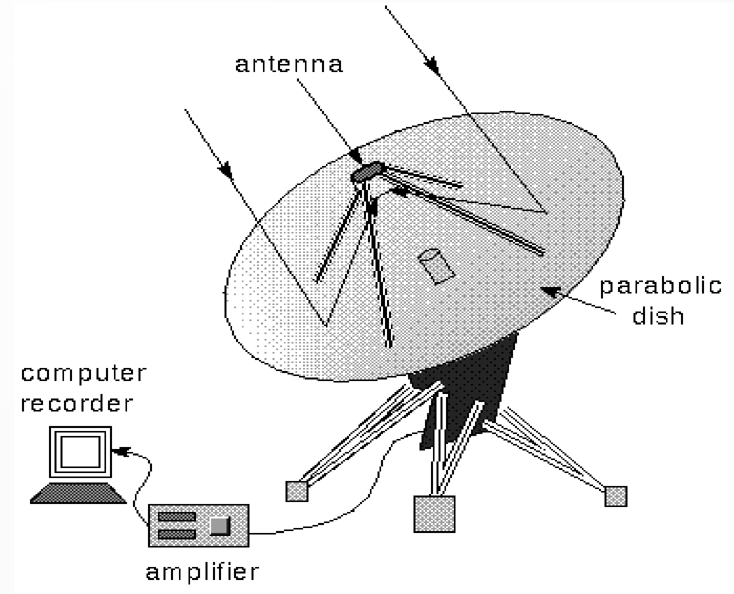
- Like your satellite dish... only more challenging :

  Celestial radio signals are VERY weak (& there is corruption due to noise !) ; unit of flux used is :

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

- Input radio power into a typical telescope is ~ -100 dBm ! (would take 1000 years of continuous operation to collect 1 milliJoule of energy !!)

- For high sensitivity (to see faint sources out to the distant reaches of the Universe) :
  - large dishes (several 10s of metres in diameter)
  - high quality, low noise electronics in the receivers
  - large bandwidths of observation
  - long integration times



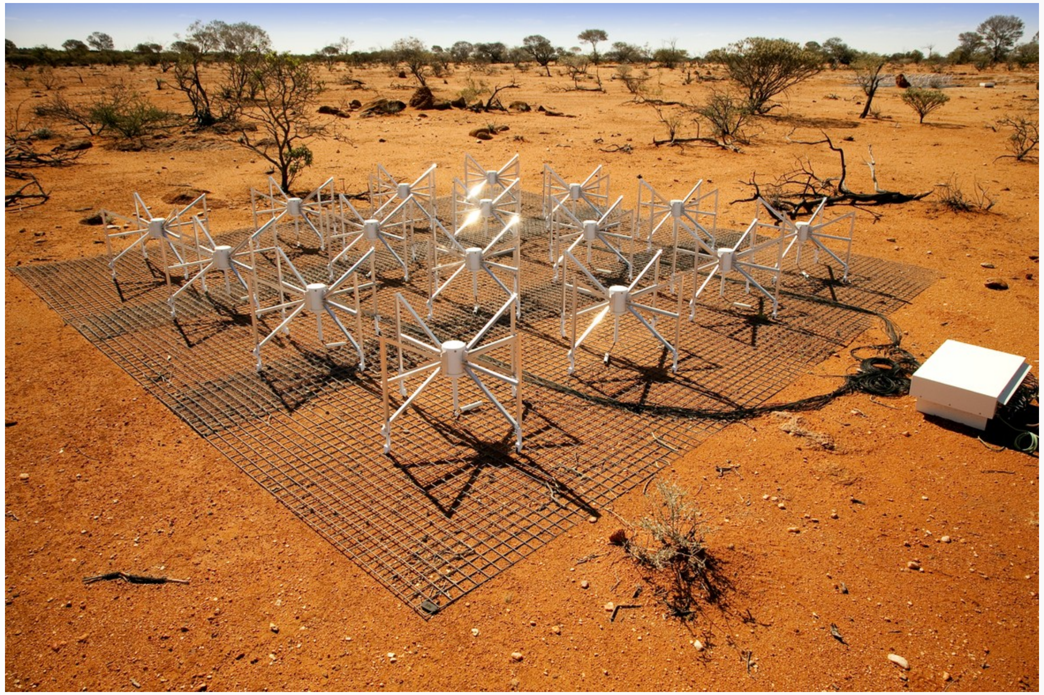
A radio telescope reflects radio waves to a focus at the antenna. Because radio wavelengths are very large, the radio dish must be very large.

What a variety!

f ~ 100 GHz, λ ~ 0.003 m
Diameter = 12 m
Surface: σ = 25 μm
Pointing: Δθ = 0.6 arcsec
Carbon fiber & invar reflector
Solid and heavy support members
Pointing meteorology structure inbuilt

f ~ 1 GHz, λ ~ 0.3 m
Diameter = 45 m
Surface: σ = 5 mm
Pointing: Δθ = 1 arcmin
Wire mesh reflector
Light weight support structure

No special pointing structure



F ~ 0.1 GHz, λ ~ 3 m
A collection of dipoles (4x4 = 16)
No curved surface
No moving parts,
Electronic pointing

The quest for resolution: Interferometry

- Resolution ~ λ/D
  - λ- wavelength of observation
  - D- size of aperture (diameter of lens/mirror)
- 1arc sec resolution requires D ~2×10^5 λ
  - λ = 8000 Å; D = 16 cm
  - For radio waves λ ranges from 0.5 mm to 10 km → D ~100 m to ~2×10^3 km
- Impossible to build apertures of required dimensions and surface accuracy
- *Interferometry - resolutions corresponding to the separation between the elements (telescopes)*

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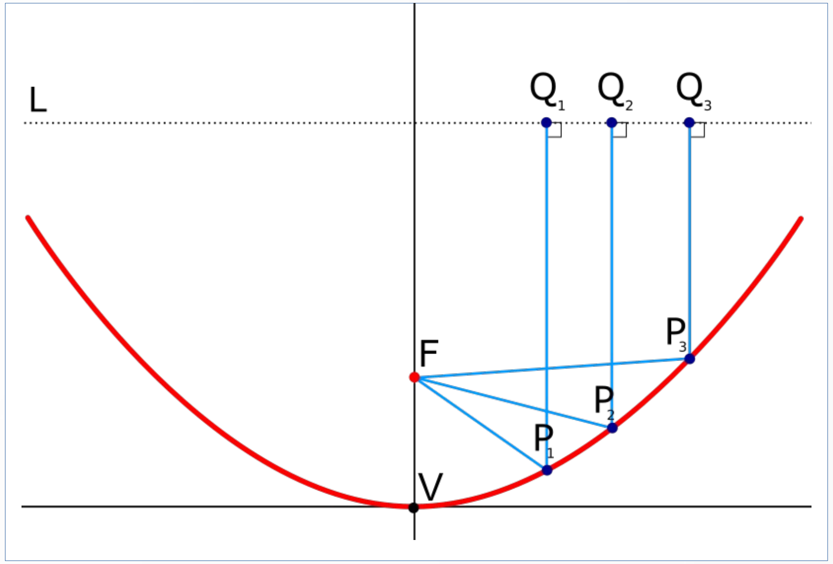
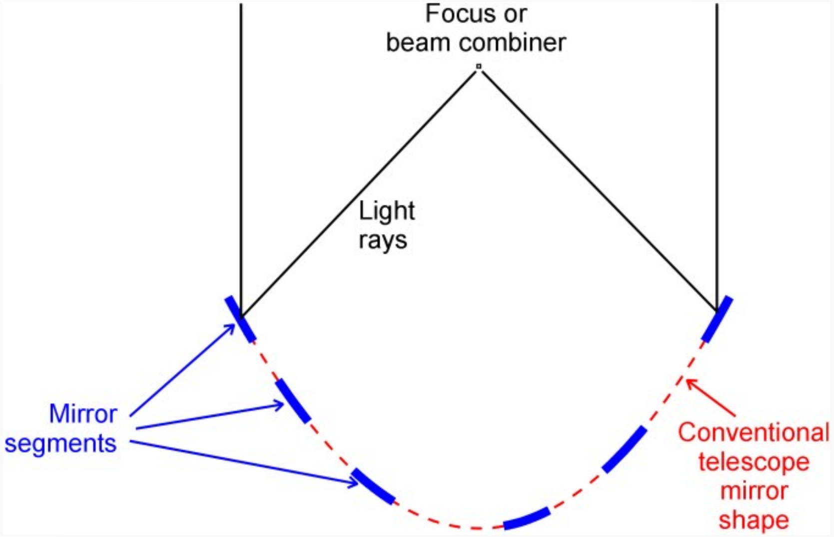
The Concept Behind an Interferometer

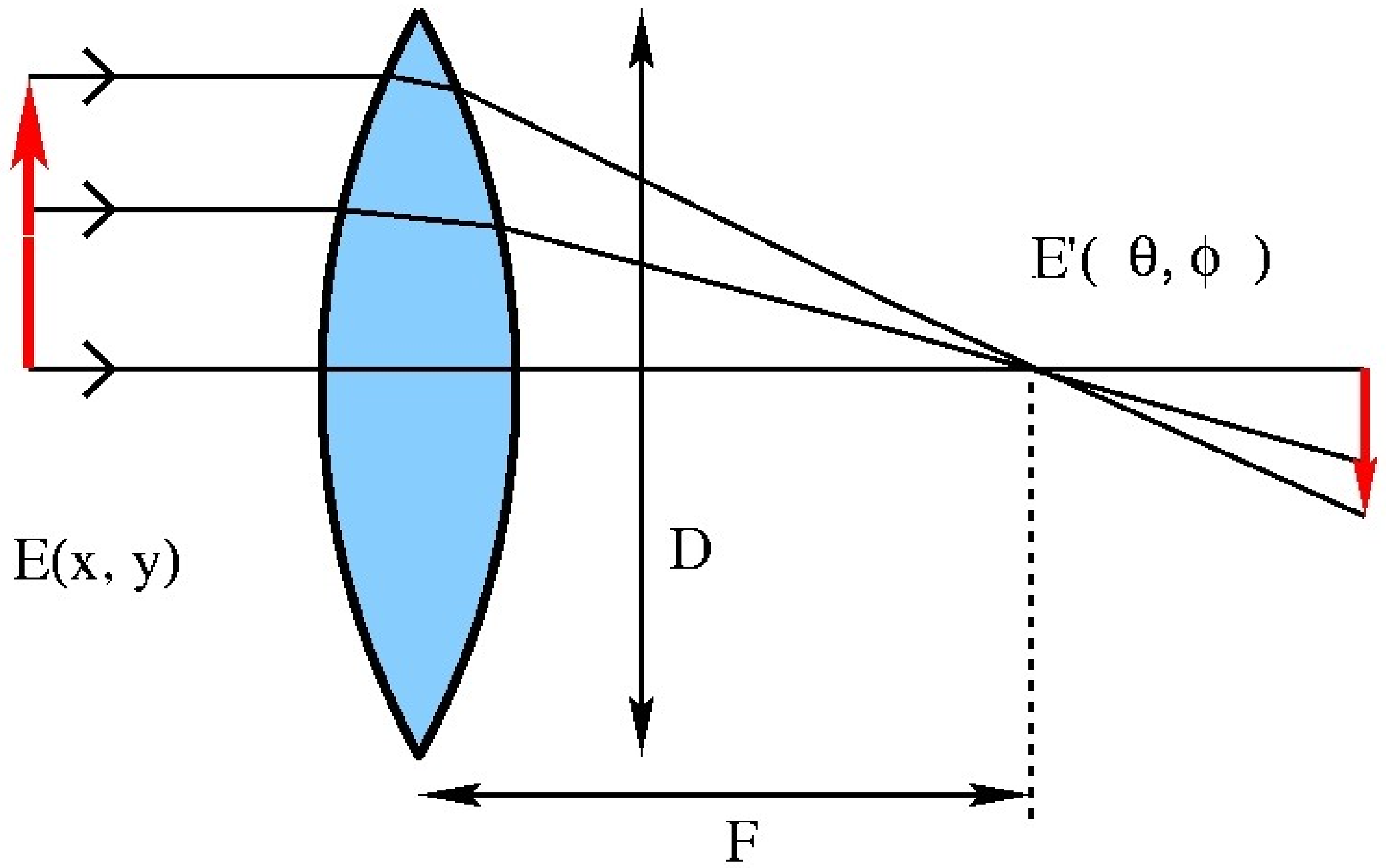
- The important property of a parabolic dish is that it adds parallel light rays coherently
- Parallel rays (from infinity) have equal path lengths to the focus, so they all arrive in phase
- This is still true if we remove segments of the parabola – remaining rays still reach focus in phase
- Now imagine moving the remaining segments of the dish off the surface of the paraboloid
- So long as we know very precisely where the segments are located, we can delay their signals appropriately and still add them together coherently
- This, in essence, is what an interferometer does





Images: wikipedia

Imaging with a lens (mirror)



It ensures that the optical path lengths from all points on a plane wavefront (perpendicular to the optical axis) to the focal point are the same.

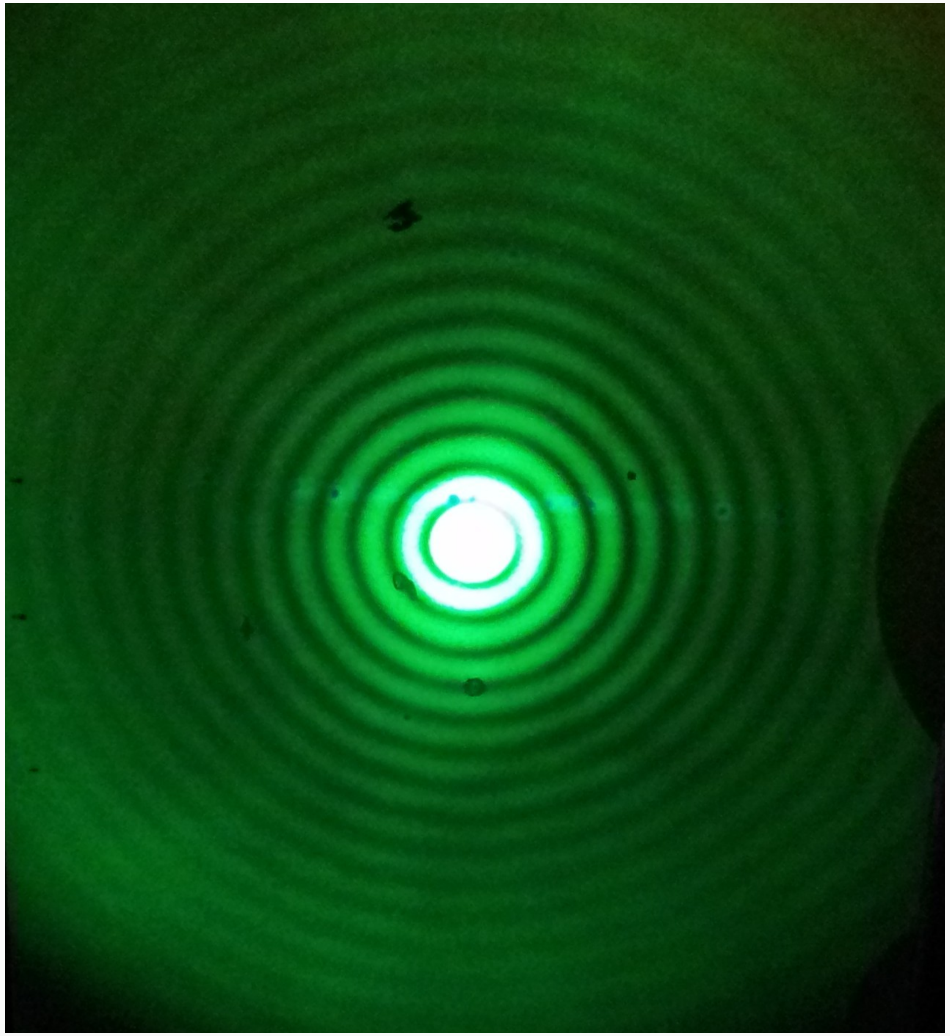
A more sophisticated perspective

Mathematically, a lens performs a Fourier Transform of the incident wavefront

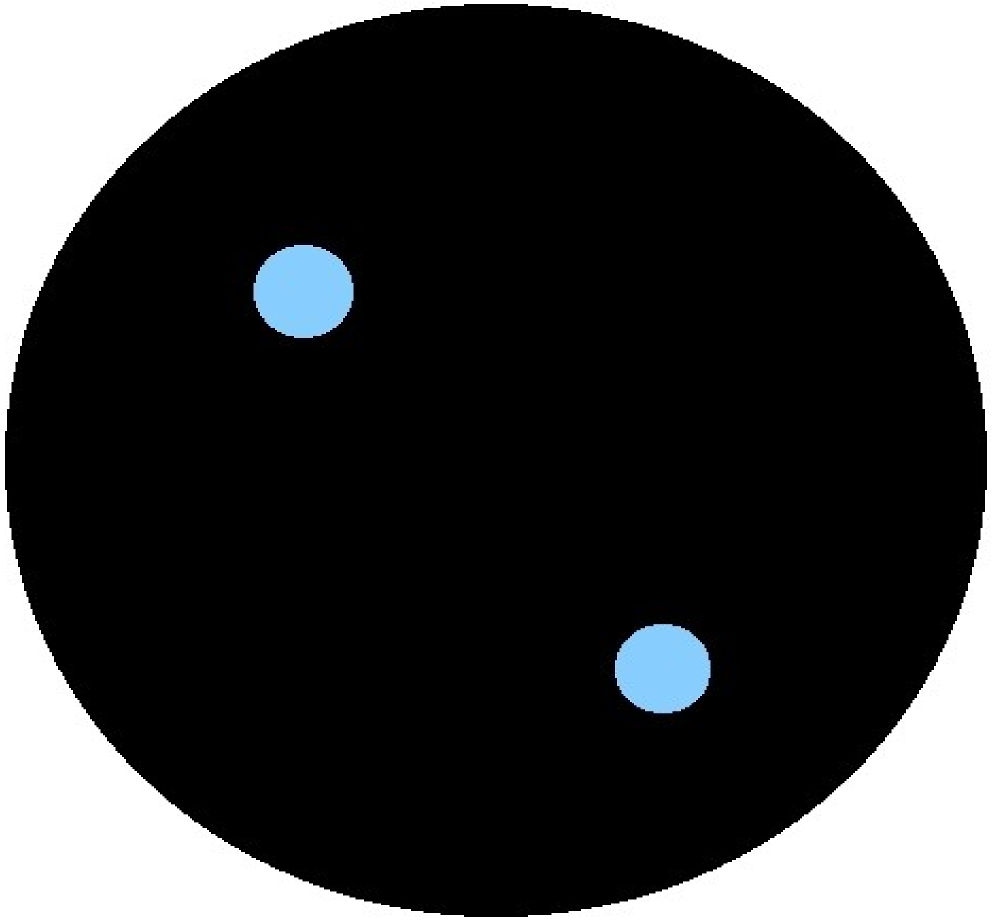
$$E(x,y) \leftrightarrow E'(\theta,\varphi)$$

A characteristic of optical imaging systems

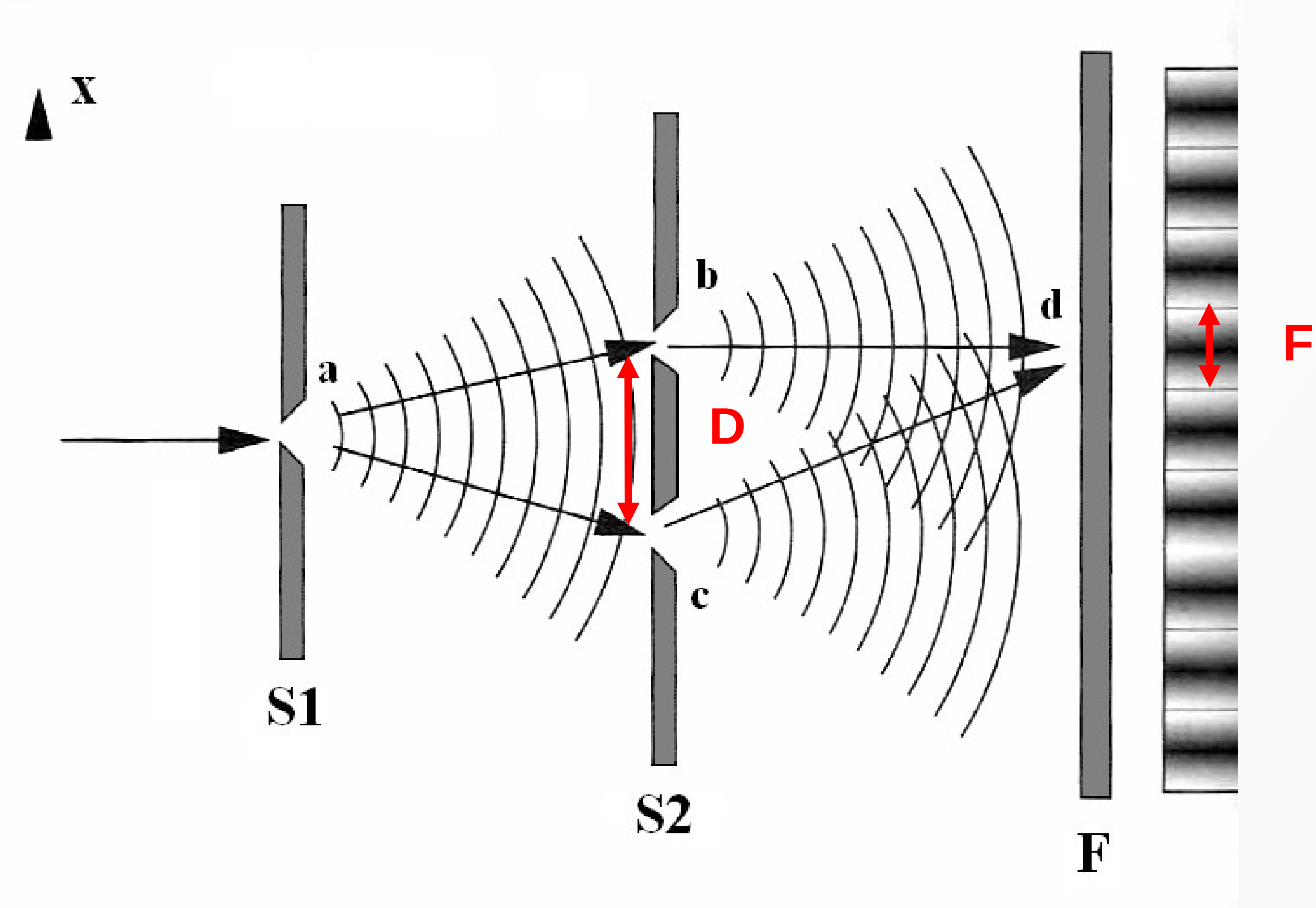
- Transfer function / Point source response / Point spread function (PSF) - Airy pattern
- Resolution = 1.22 λ/D



Imaging with an *unfilled* aperture



Young’s double slit experiment

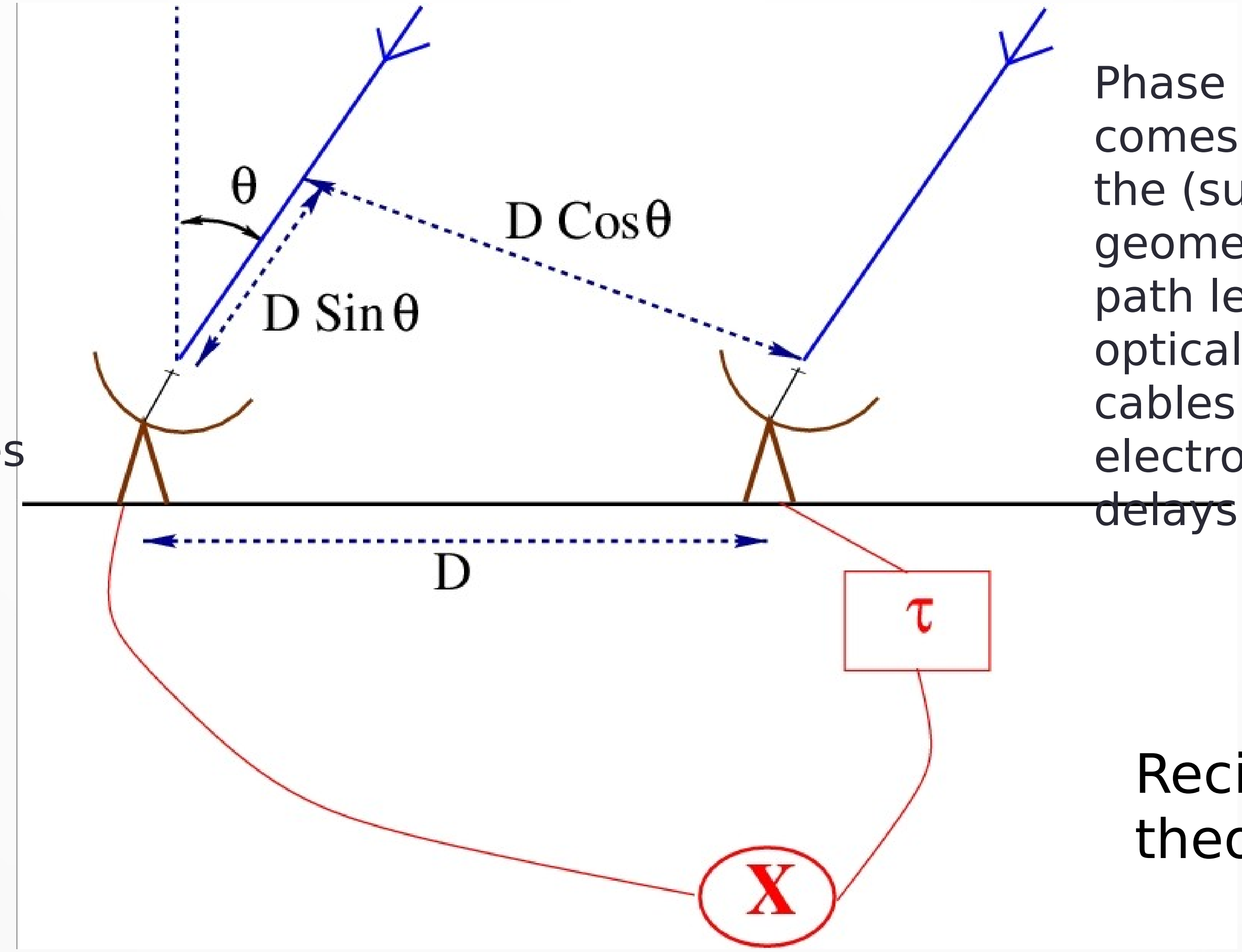


$D\uparrow$ - $F\downarrow$

$\lambda\downarrow$ - $F\downarrow$

Two element inteferometer

Slits → Telescopes



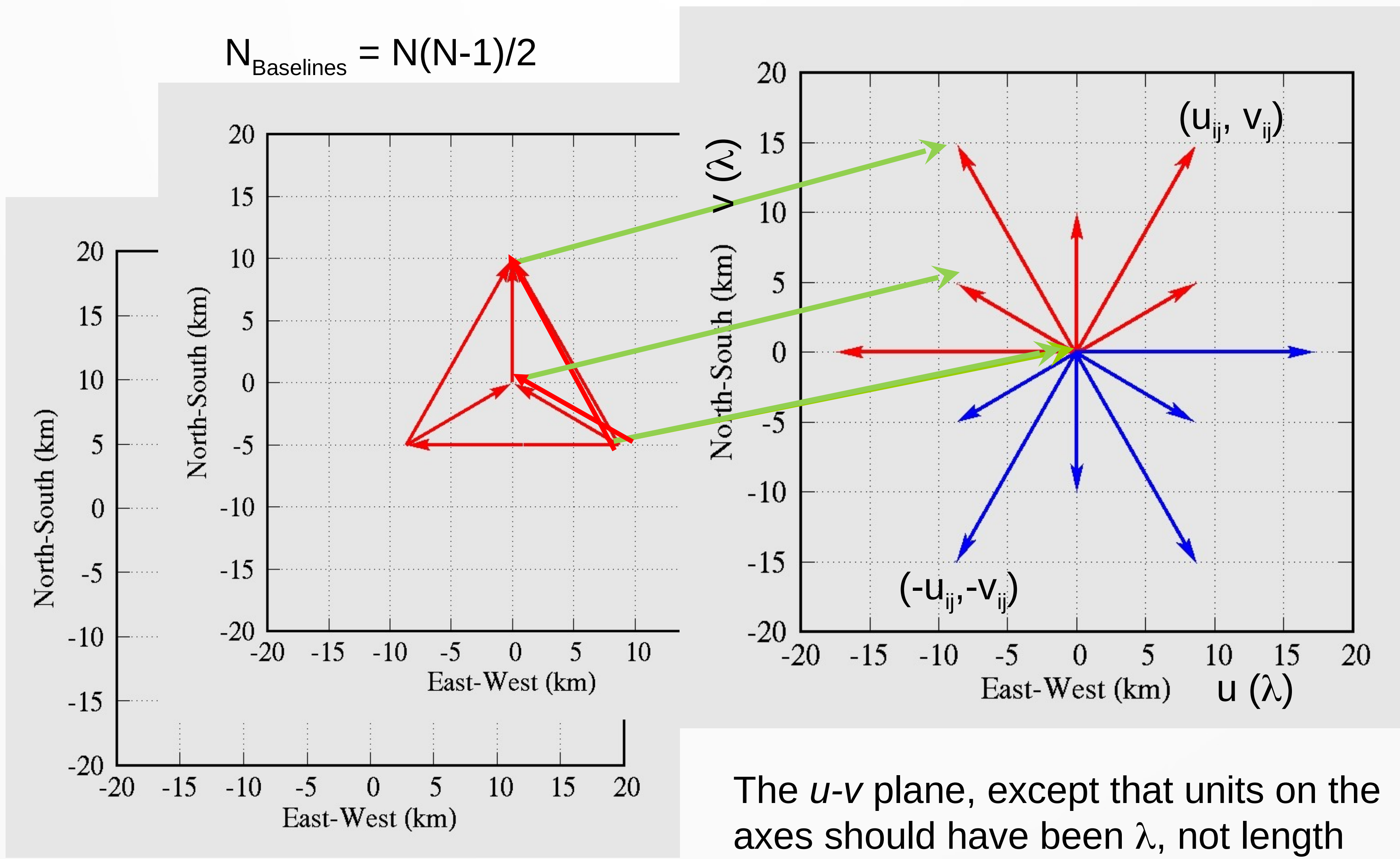
Phase comes from the (sum of) geometric path length, optical fiber, cables and electronic delays

Reciprocity theorem

Screen/Detector → Correlator

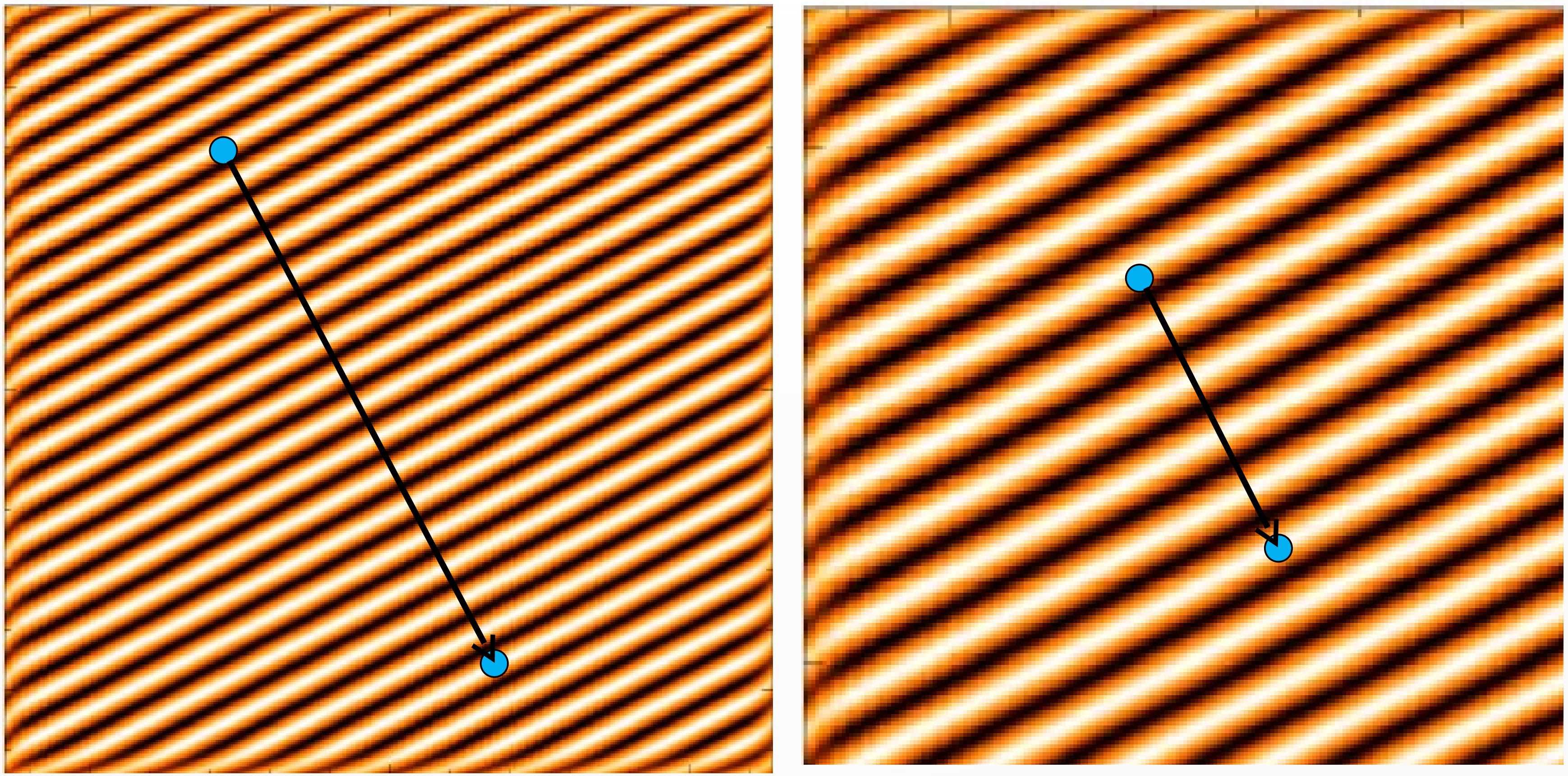
Baselines and *uv* plane

$N_{Baselines} = N(N-1)/2$



The *u*-*v* plane, except that units on the axes should have been λ, not length

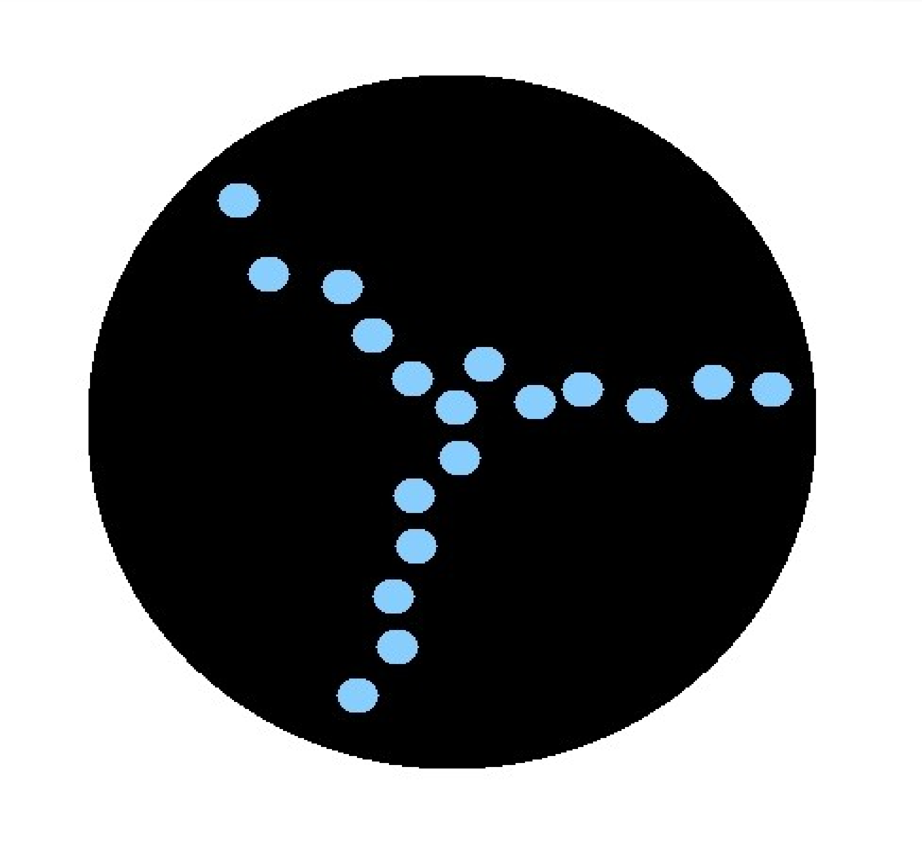
Sky response of a baseline



Cos 2π(ul + vm);
u,v – components of the baseline; l,m – coordinates in image plane

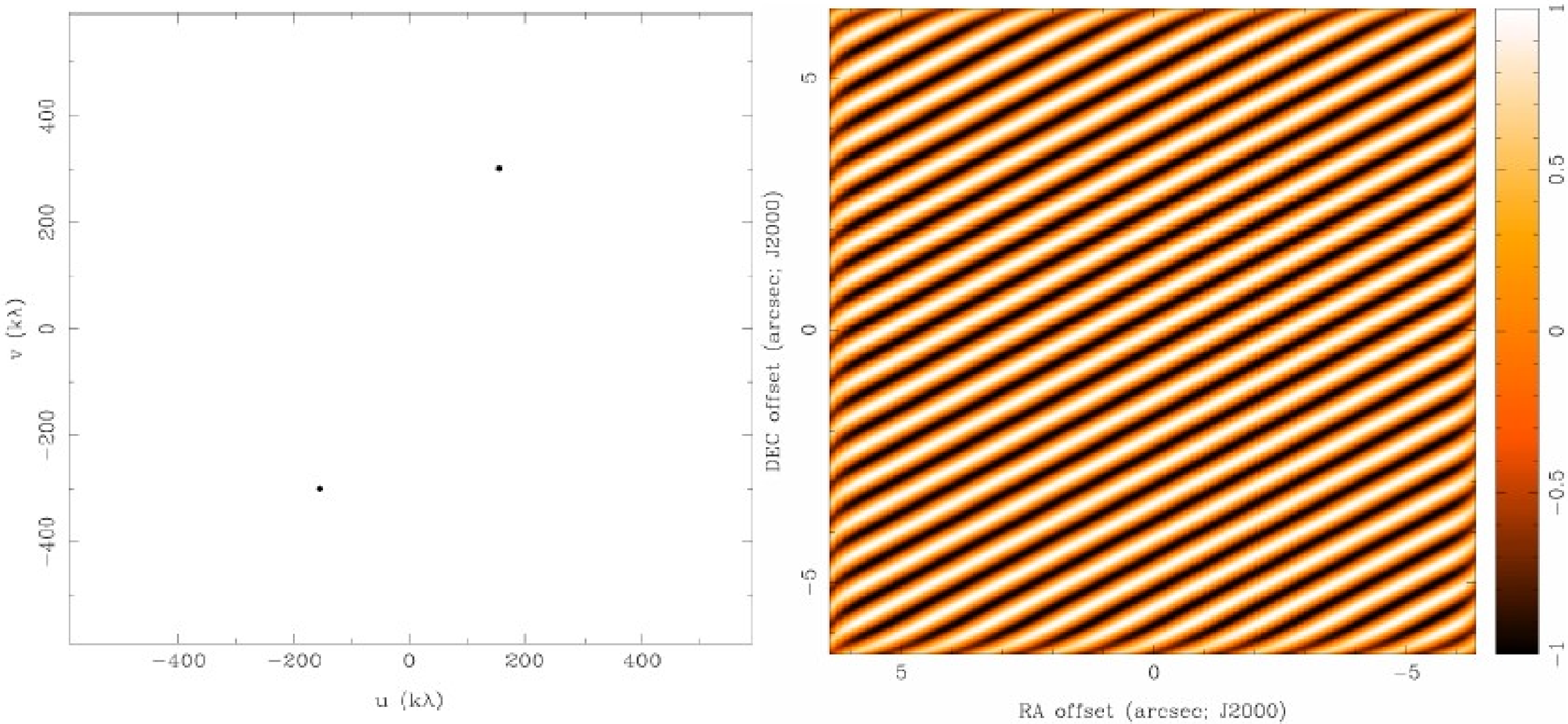
An N element interferometer

- ‘Baselines’ from N elements – N(N-1)/2
- Each of these will lead to a ‘fringe’ with different orientation and spacing
- The final response of the interferometer will be the superposition of fringes from all the baselines



Dirty Beam Shape and N Antennas

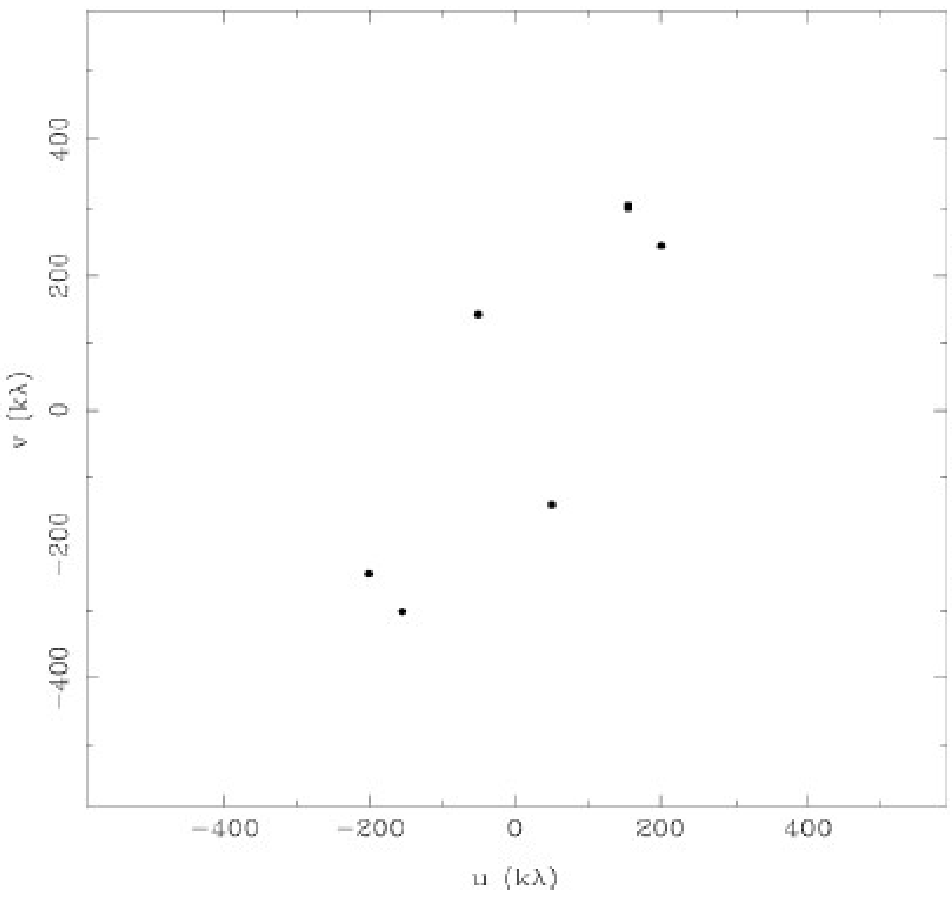
2 Antennas

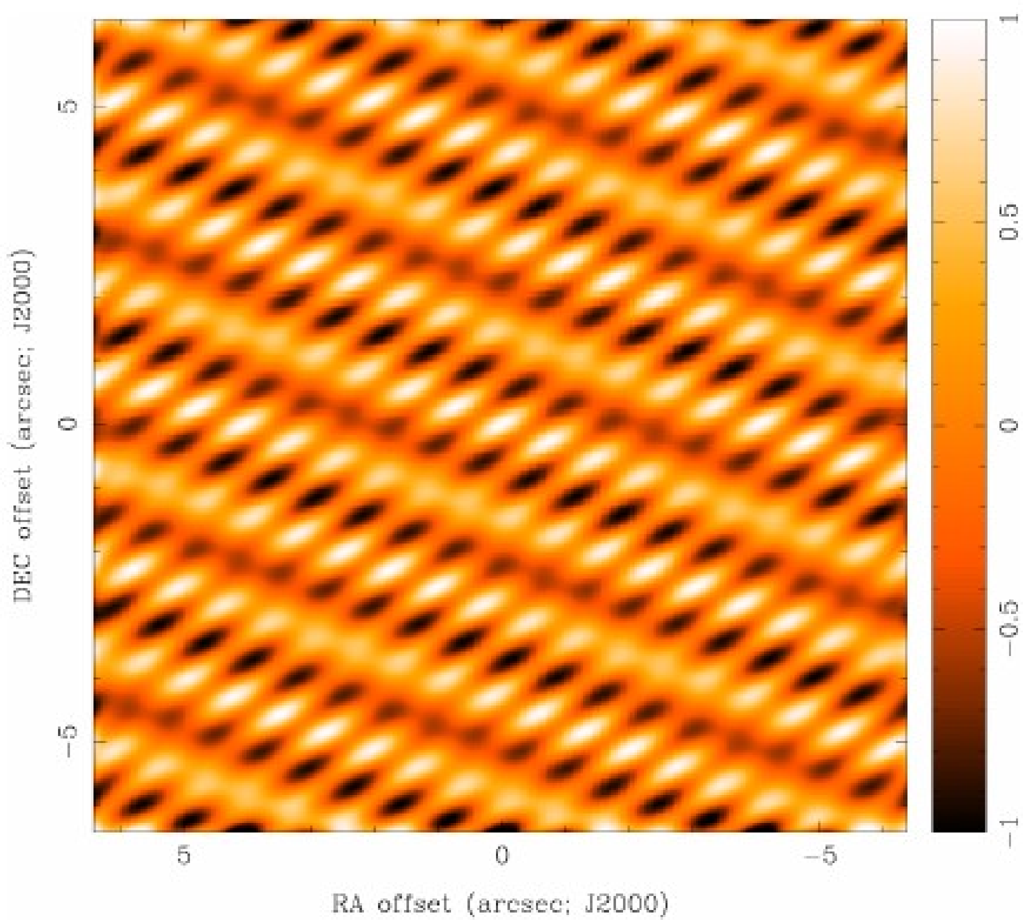


Courtesy David J. Vilner, Harvard-Smithsonian Center for Astrophysics, USA

Dirty Beam Shape and N Antennas

3 Antennas





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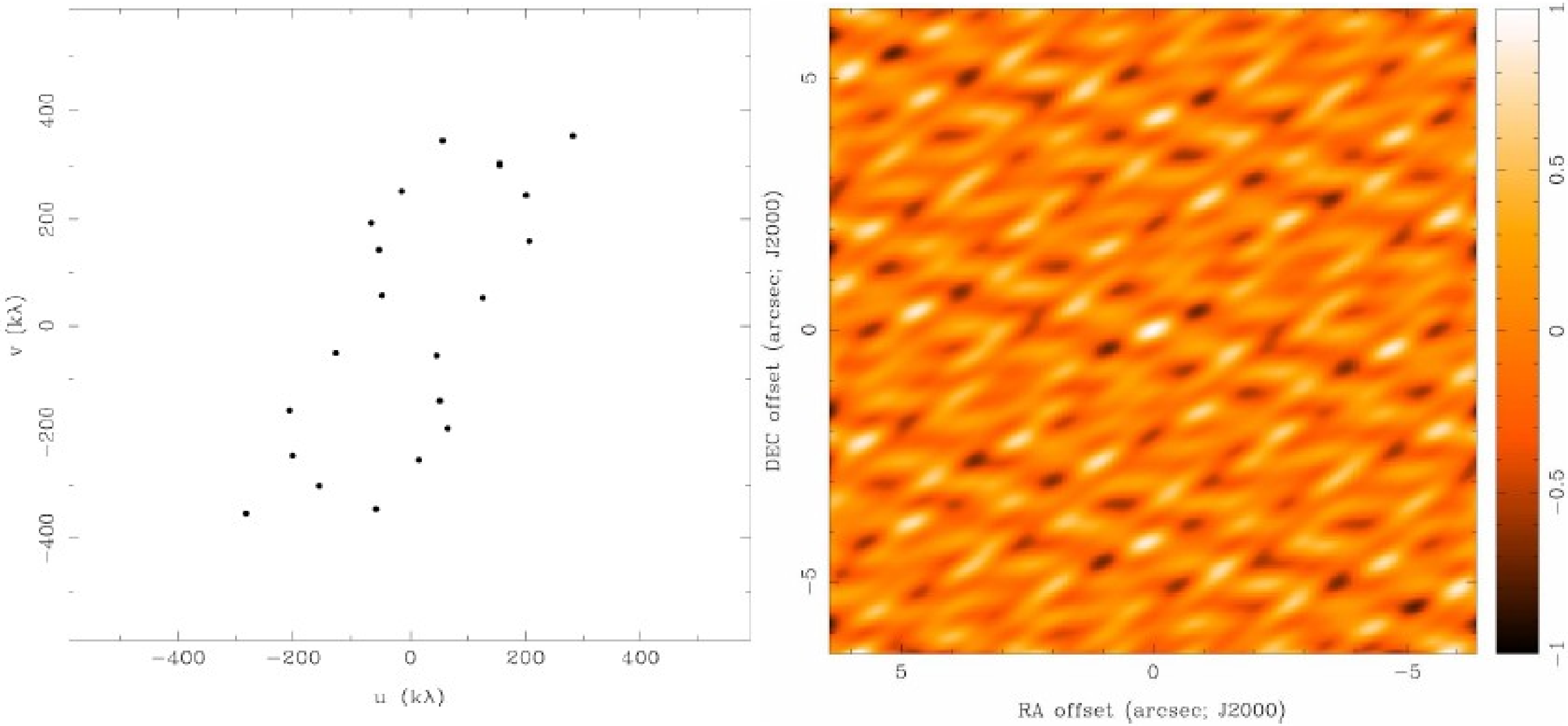
Dirty Beam Shape and N Antennas

5 Antennas



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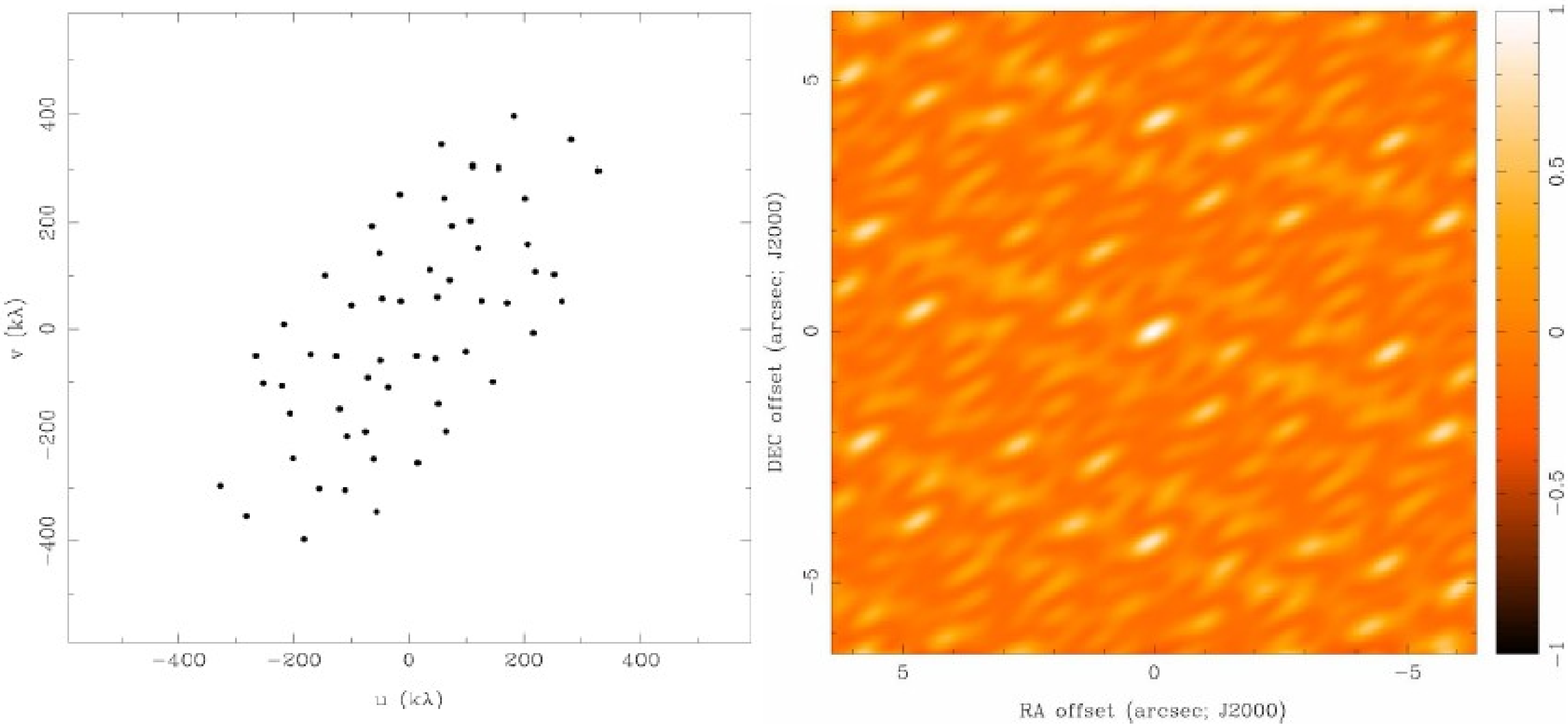
Dirty Beam Shape and N Antennas

8 Antennas



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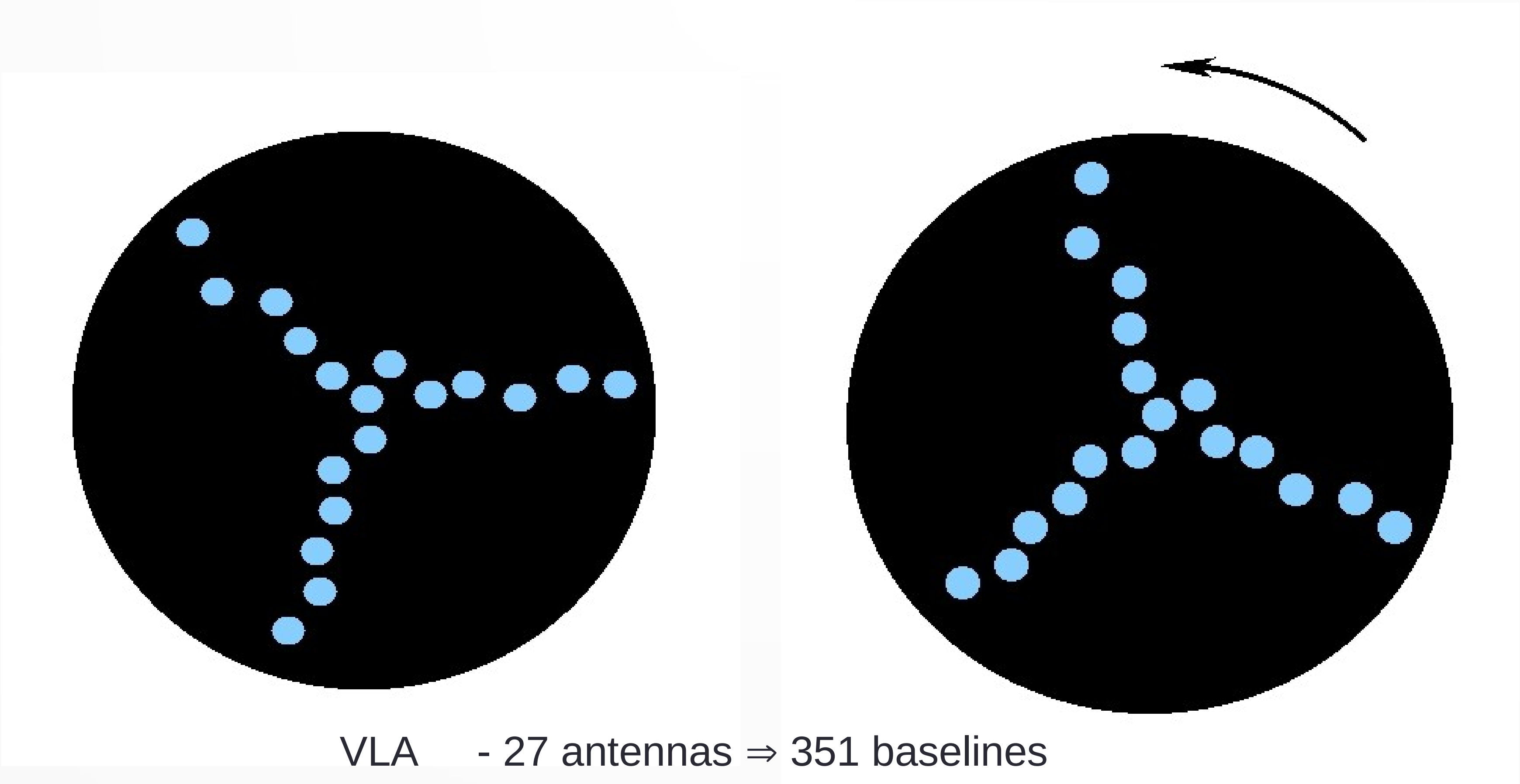
Synthesis imaging



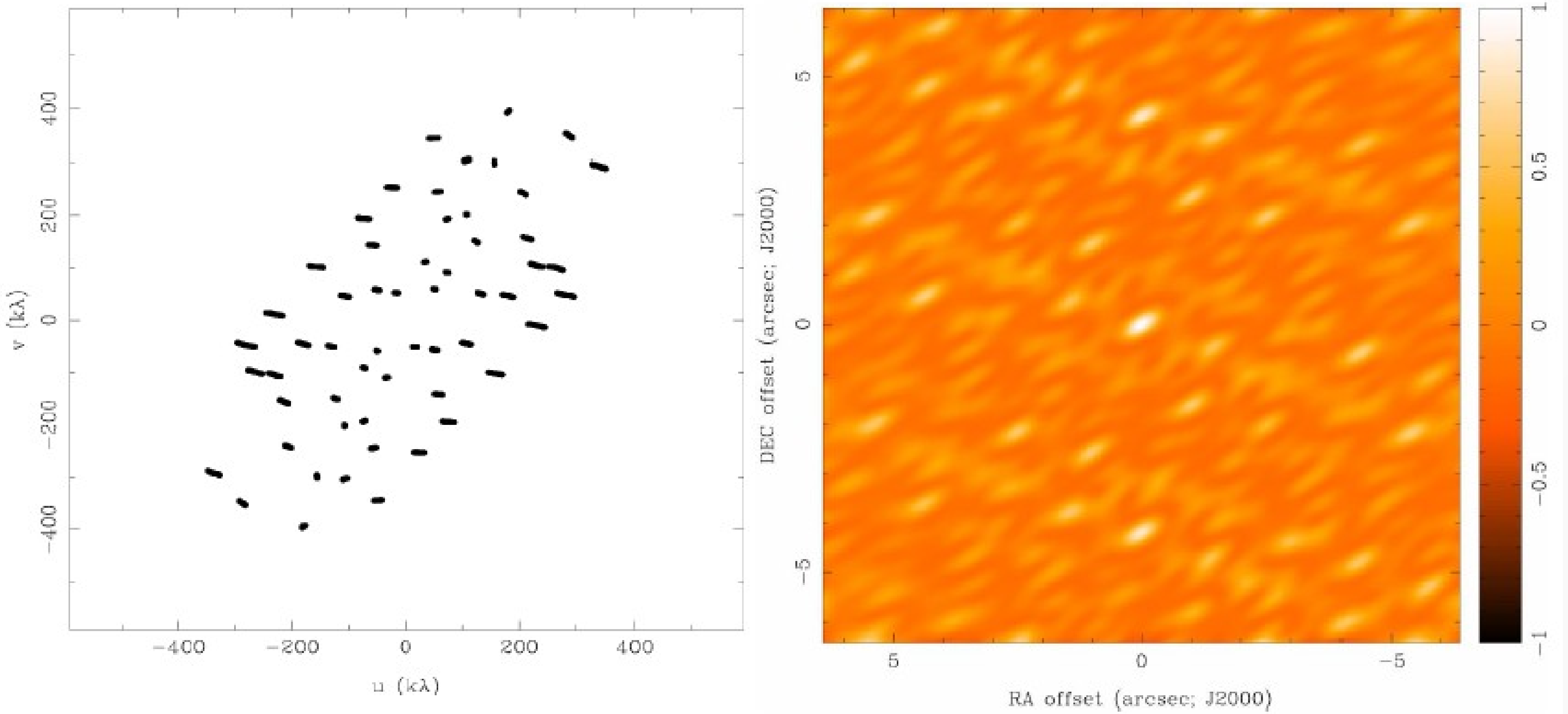
VLA - 27 antennas ⇒ 351 baselines

GMRT - 30 antennas ⇒ 435 baselines

MWA – 128 elements ⇒ 8,128 baselines

Dirty Beam Shape and N Antennas

8 Antennas x 30 samples



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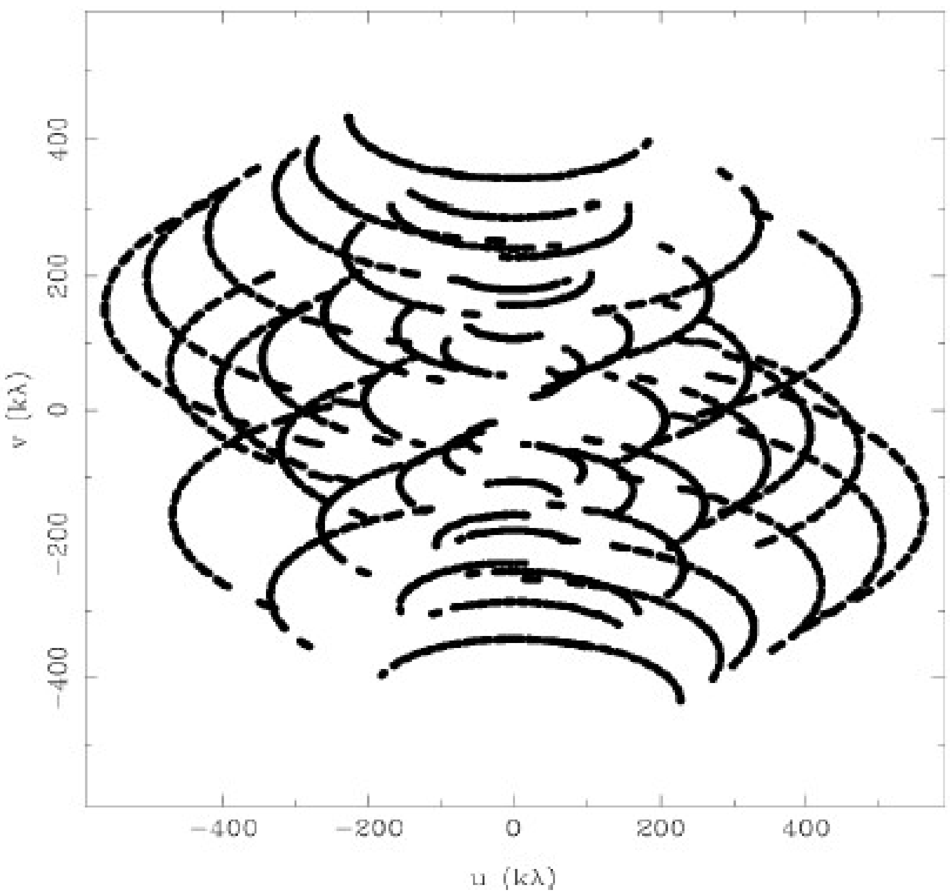
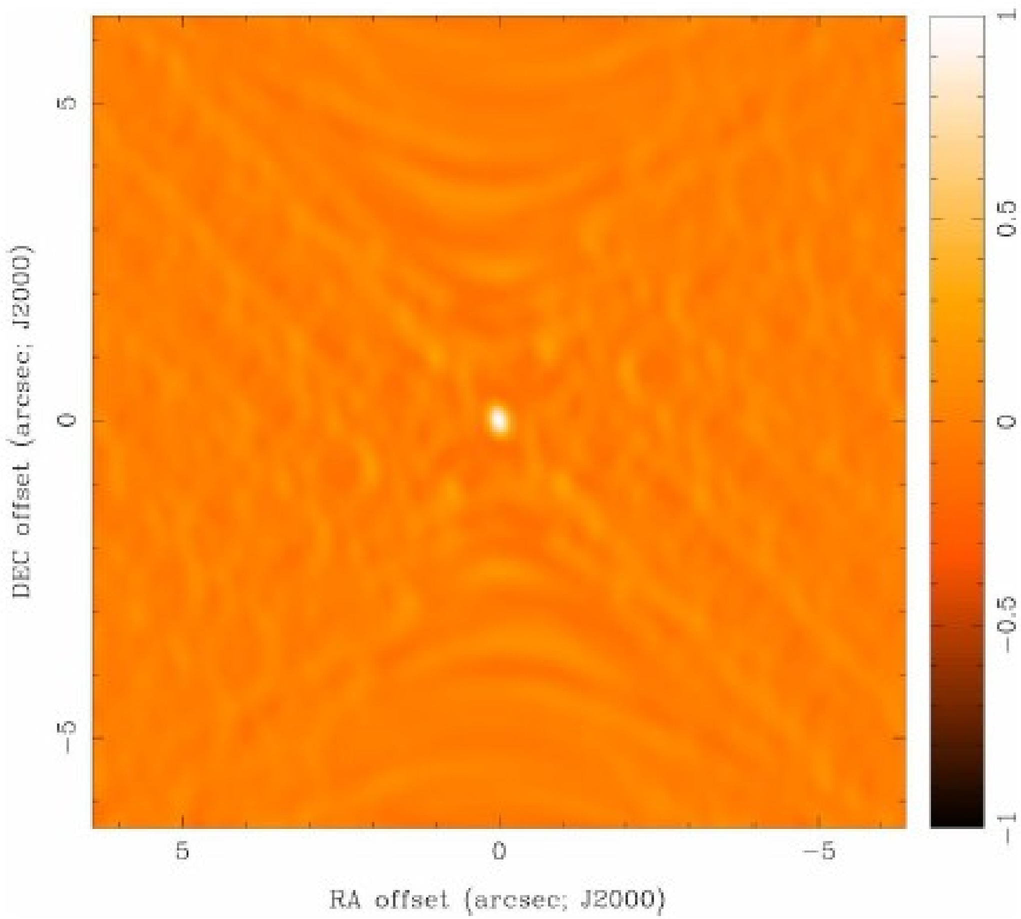
Dirty Beam Shape and N Antennas

8 Antennas x 480 samples





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Visibility – V(u,v)

- The fundamental Radio Astronomy measurable

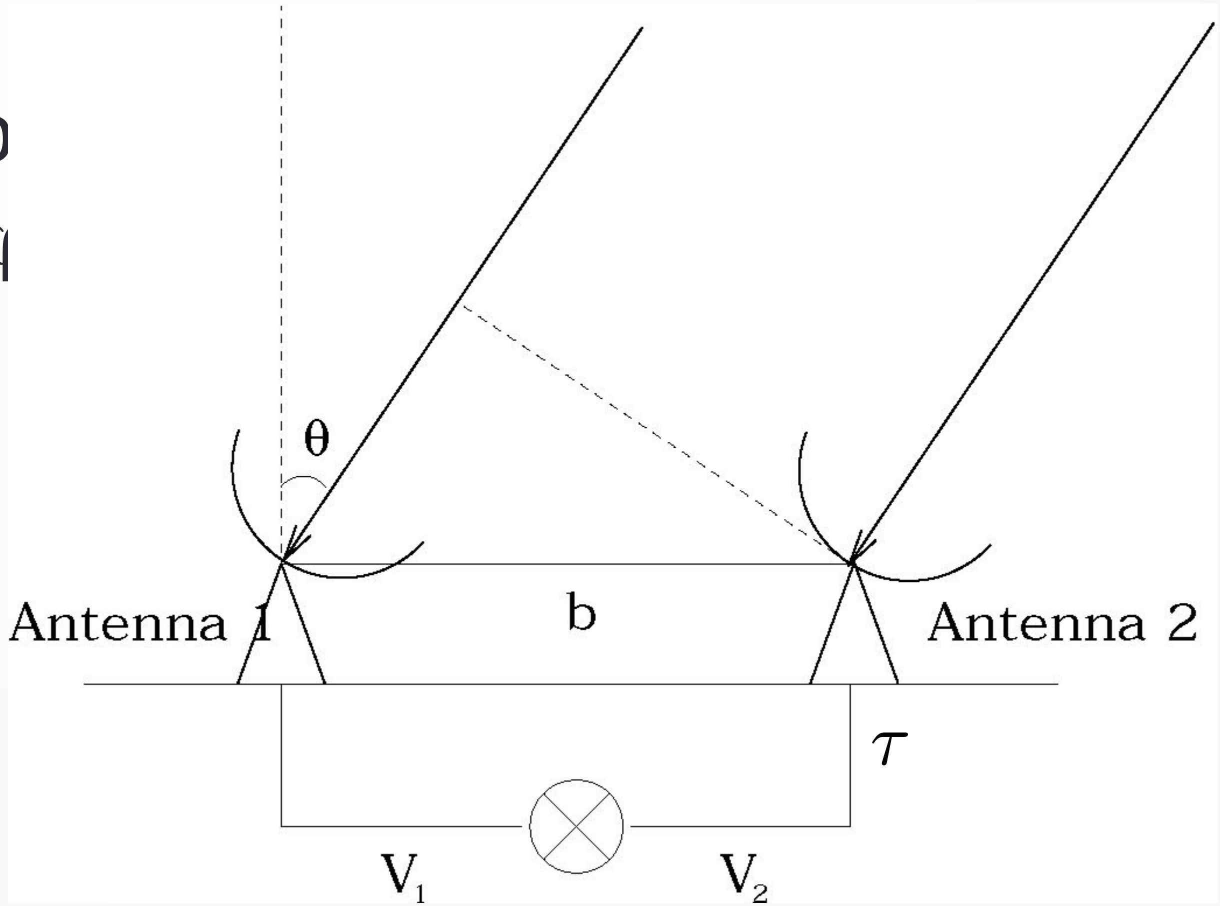
$$V_{ij}(u,v,t,\Delta t,\nu,\Delta\nu) =< V_i(...,t,...)V_j(...,t+\tau,...) >= \frac{V^2}{2}Cos(\omega\tau)$$

- van Cittert Zernike Theorem

V(u,v) is 2D Fourier Transfo Brightness distribution B(θ,φ

(T(x,y) in the following slides)

- Incoherent source,
- Small field of view
- Far-field



Rayleigh-Jeans Law and Brightness Temperature

Planck's law

$$B_\nu(T) = \frac{2\ h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1}$$ *W m⁻² Hz⁻¹ sr⁻¹*

$$B_\lambda(T) = \frac{2\ hc^2}{\lambda^5} \frac{1}{e^{hc/k_B \lambda T} - 1}$$ *W m⁻² Hz⁻¹ sr⁻¹*

At radio wavelengths $\frac{h\nu}{k_B T} << 1$

In this regime, the Plank's law reduces to the Rayleigh-Jeans Law

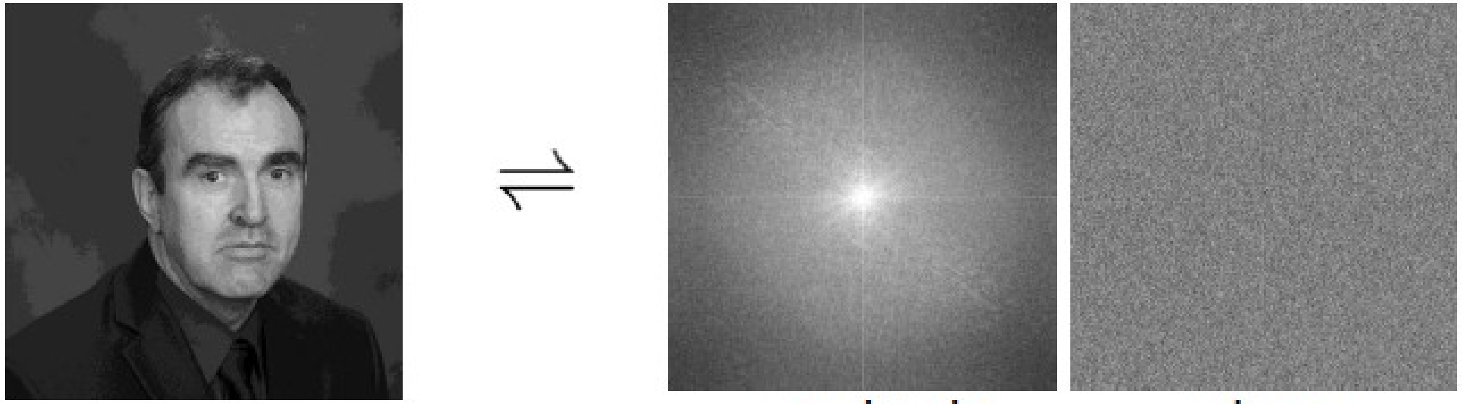
$$B_\nu(T) = \frac{2\ k_B T}{\lambda^2}$$

Visibilities

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

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

T(x,y) ⇌ V(u,v)



amplitude phase

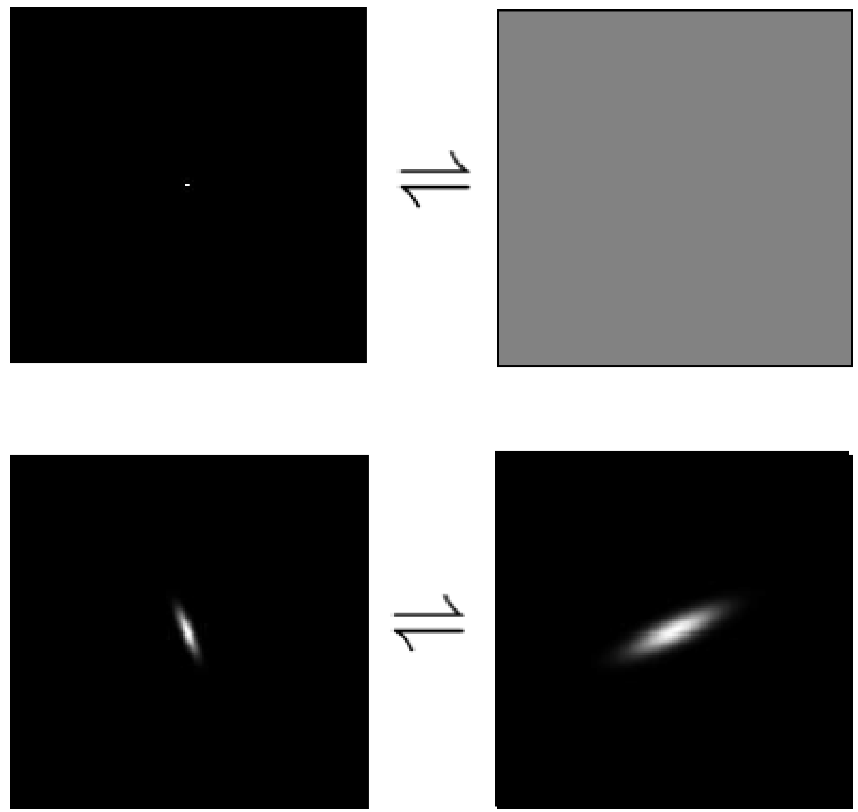
Courtesy David J. Vilner, Harvard-Smithsonian Center for Astrophysics, USA

Example 2D Fourier Transform Pairs

T(x,y) amp{V(u,v)}

δ function — constant

elliptical Gaussian — elliptical Gaussian



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

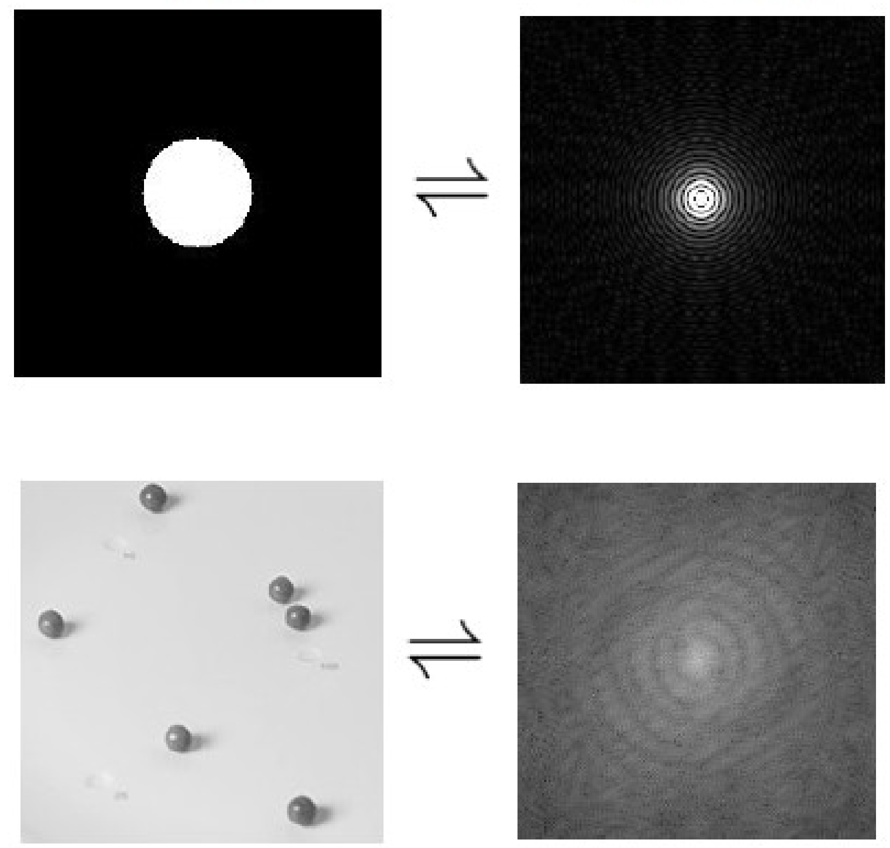
Courtesy David J. Vilner, Harvard-Smithsonian Center for Astrophysics, USA

Example 2D Fourier Transform Pairs

T(x,y) amp{V(u,v)}

disk

Bessel

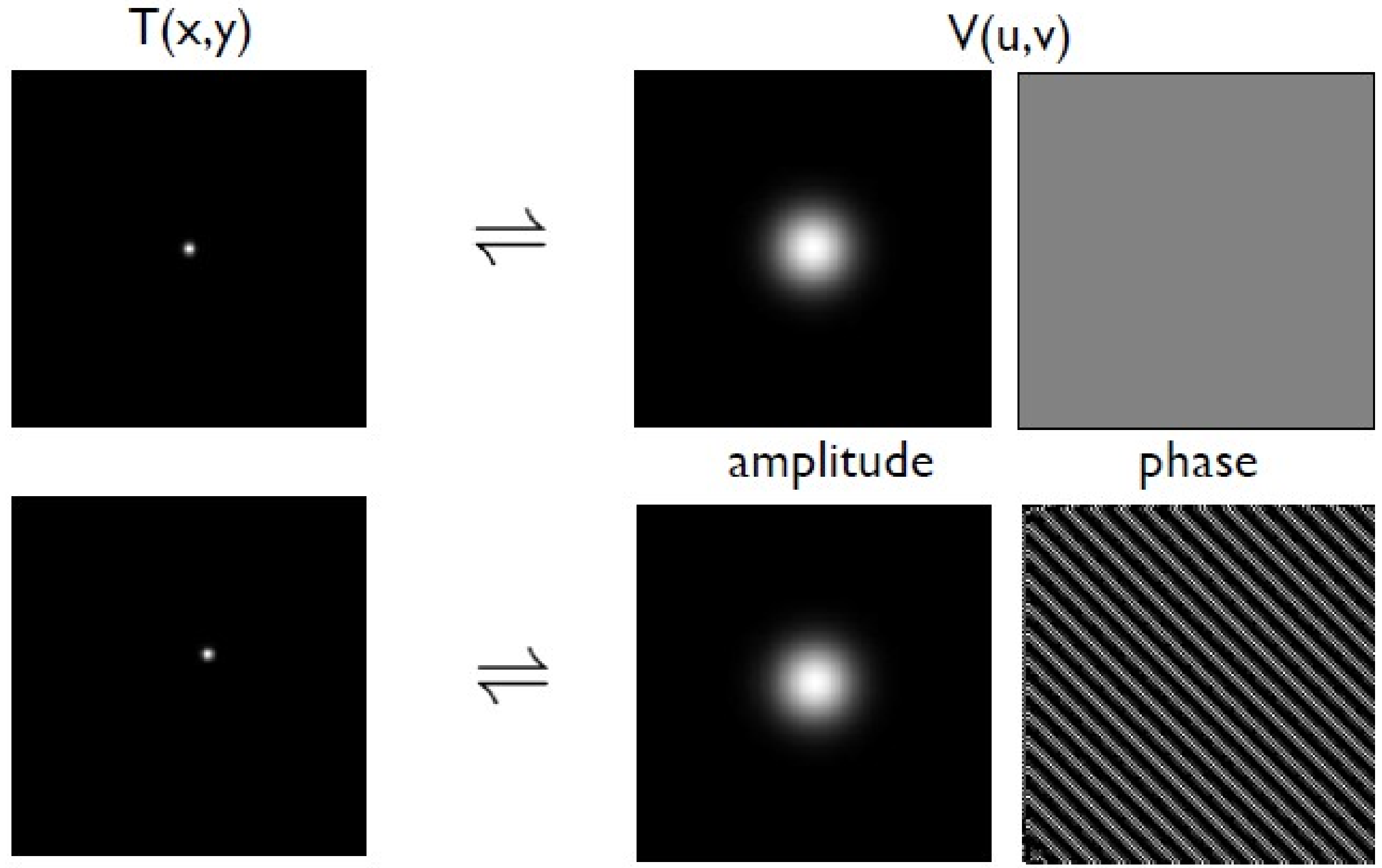


sharp edges result in many high spatial frequencies

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

Amplitude and Phase

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



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

The mathematical basis

- Brightness distribution in the sky is Fourier transform of the Visibilities

  $B(\theta,\varphi) \leftrightarrow V(u,v)$

  V(u,v) – The quantity measured by a baseline (amplitude, phase / real, imaginary)

- In the uv-plane, we measure visibilities only at a few places i.e. we have a sampling function

  $S(u,v) = \Sigma_k (u_k, v_k)$

- Point source response of an interferometer (PSF) is Fourier transform of S(u,v). It is also known as Point-Spread-Function or Dirty Beam

  $P(\theta,\varphi) \leftrightarrow S(u,v)$

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Putting it all together…

- The outcome of any measurement is the convolution of
  – The true measurable – the sky brightness - $B(\theta, \phi)$
  – The response function of the instrument (PSF)

- Referred to as the *Dirty image*
  – FT of the measured visibilities
  – Convolution of the PSF and the true sky brightness distribution

- To get true sky brightness distribution, one needs to
  – 'deconvolve' the PSF from the dirty image
  – 'calibrate' out the antenna response

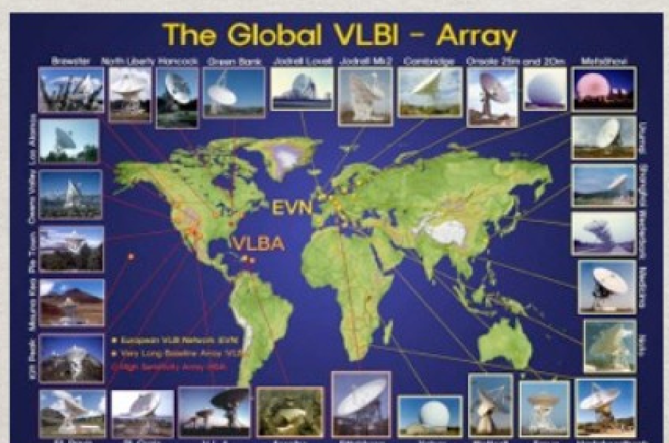
Radio Telescopes: Interferometers

VLA, 27 dishes, 25 m dia, 35 km bl

ALMA, 66 dishes, 12 & 7 m dia, 16 km bl

ATCA, 6 dishes, 22 m dia, 6 km bl

WSRT, 14 dishes, 25 m dia, 3 km



VLBI, many antenna around the world, including a satellite

LOFAR, 48 stations, ~50 m dia, 100s of km bl

Giant Metrewave Radio Telescope

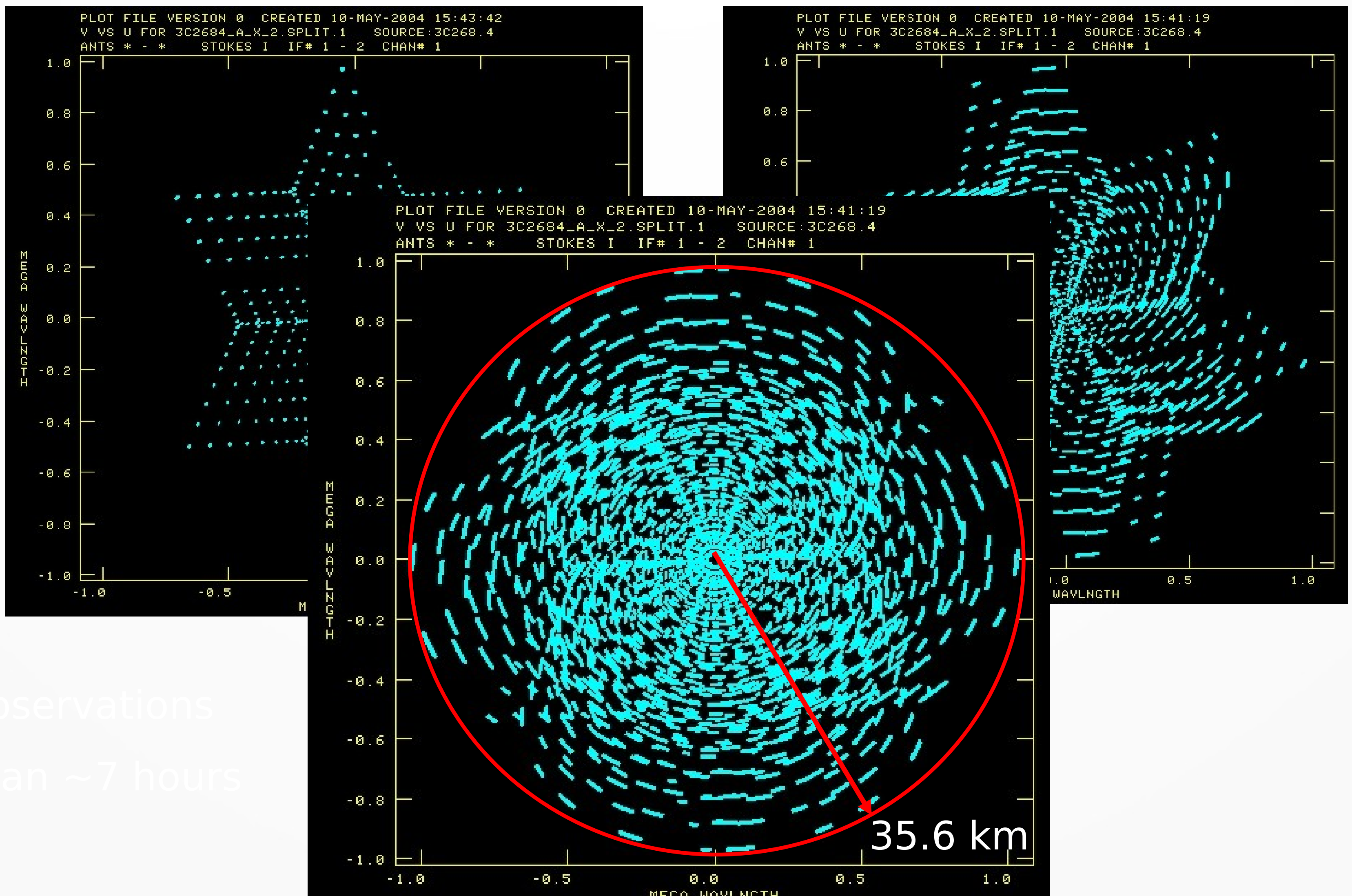
- GMRT is a world class facility for studying astrophysical phenomena at low radio frequencies (150 to 1450 MHz)
- Designed and built primarily by NCRA, during the 1990s.
- Array telescope consisting of 30 antennas of 45 metres diameter, operating at metre wavelengths -- the largest in the world at these frequencies

A real life example

- The Very Large Array (VLA)
- 8.43 GHz (λ = 3.56cm)
- 3C268.4
- Data courtesy Colin Lonsdale, MIT Haystack Observatory

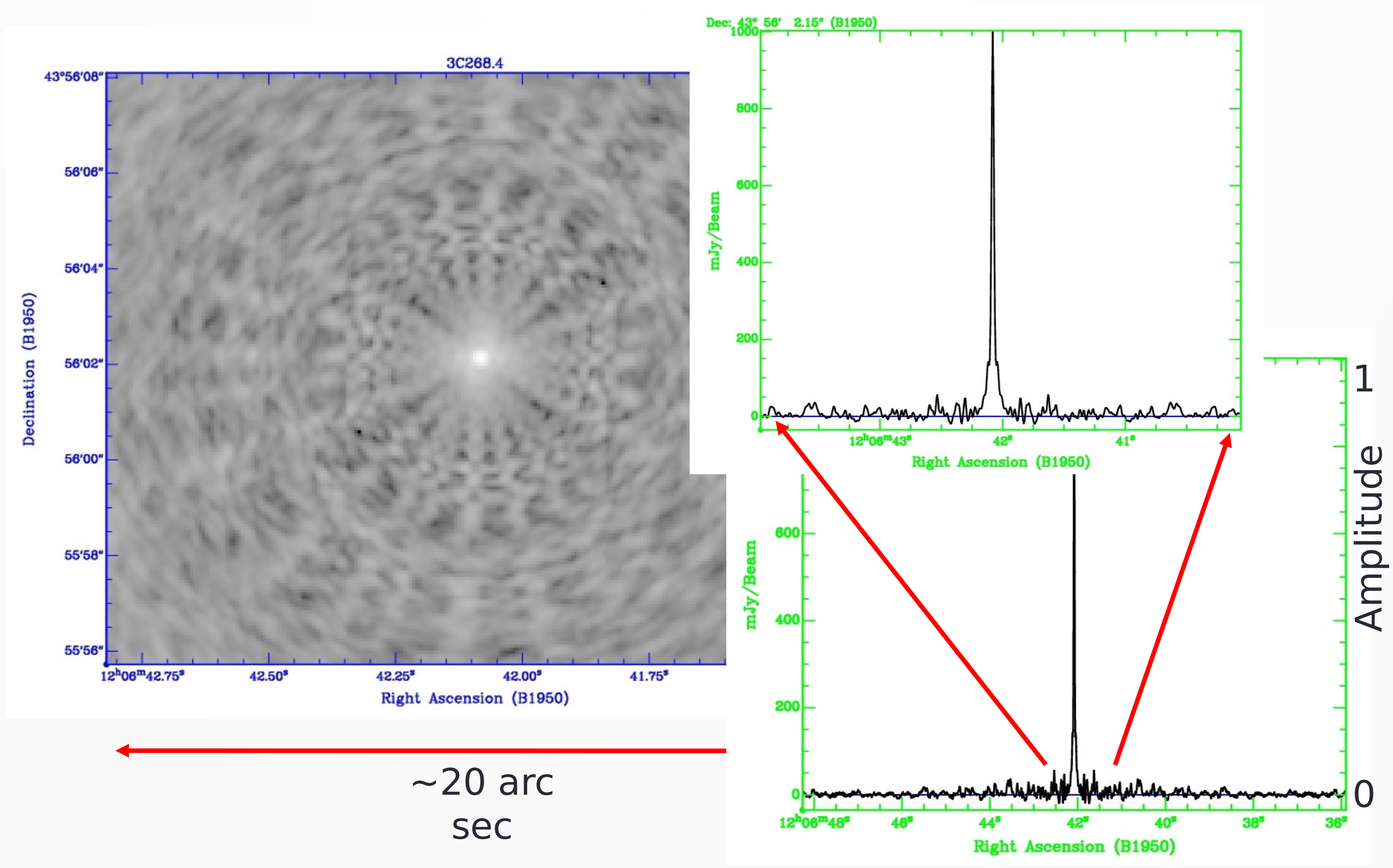
Image courtesy NRAO/AUI

Array configuration and *uv* coverage



Observations span ~7 hours

The interferometer response function
Point Spread Function



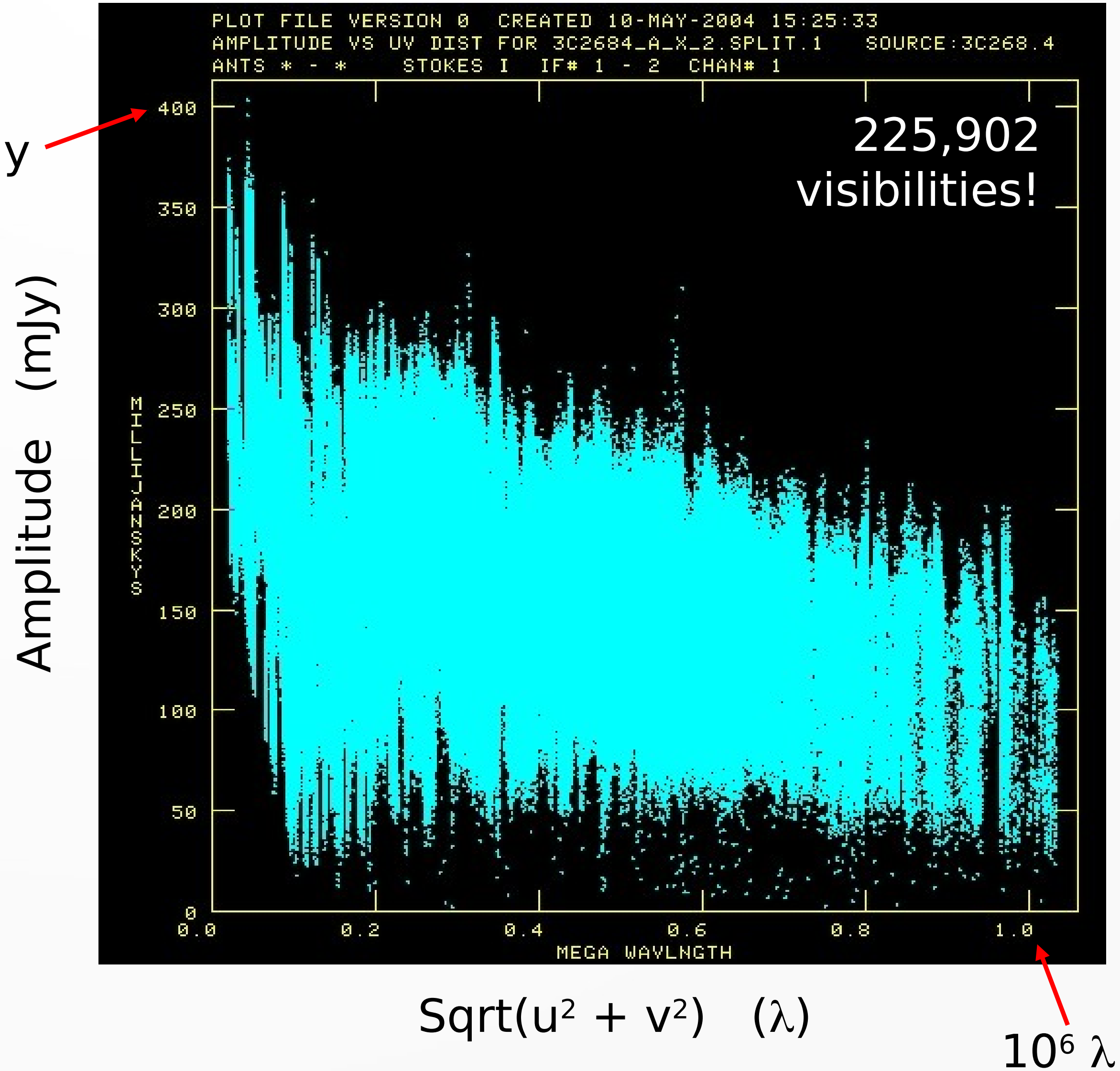
The measured cross-correlations

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

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

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

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

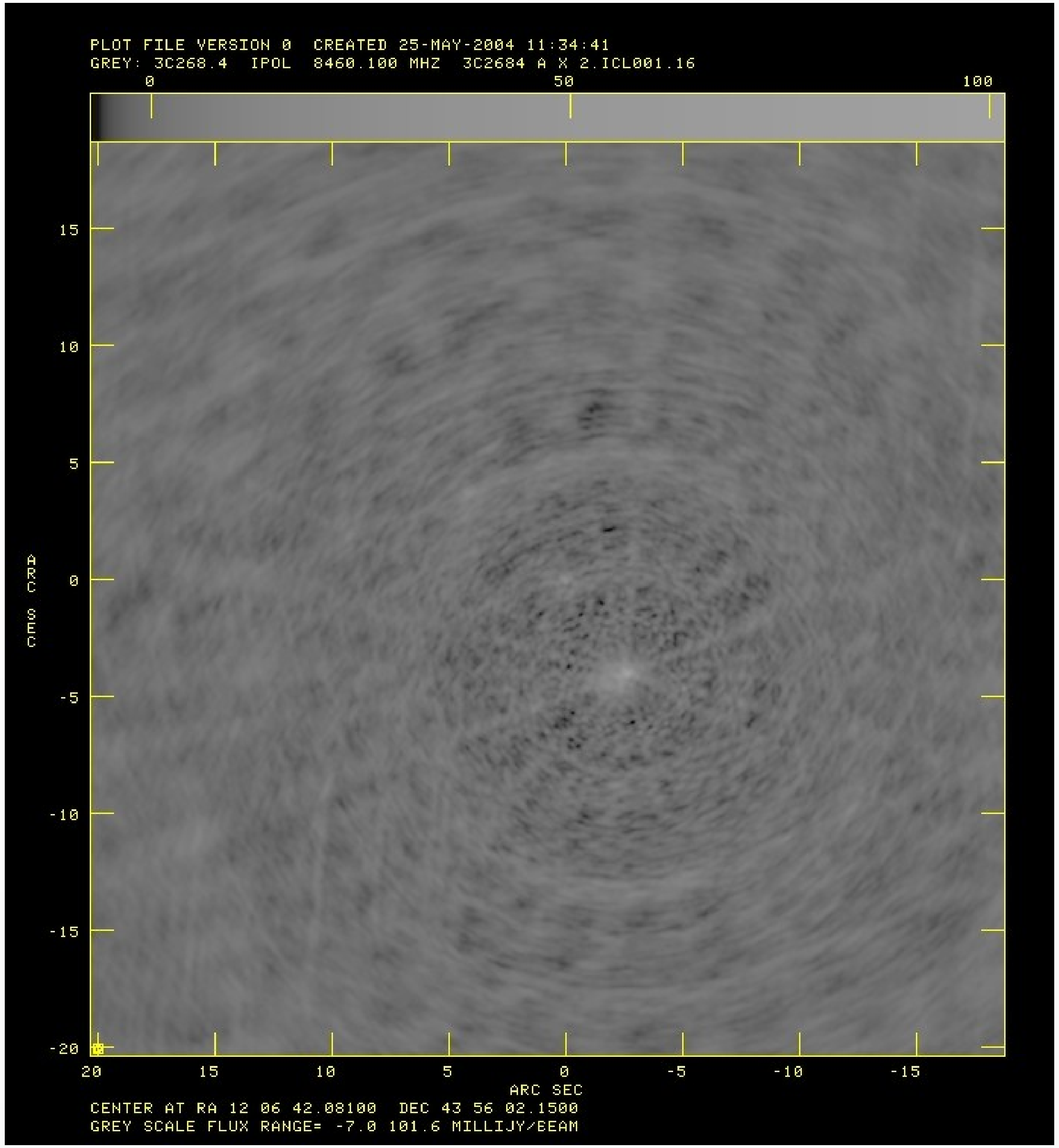


The FT of *gridded* visibilities

The *dirty* map

Convolution of the PSF with the Brightness distribution

Log scale



The problem of deconvolution

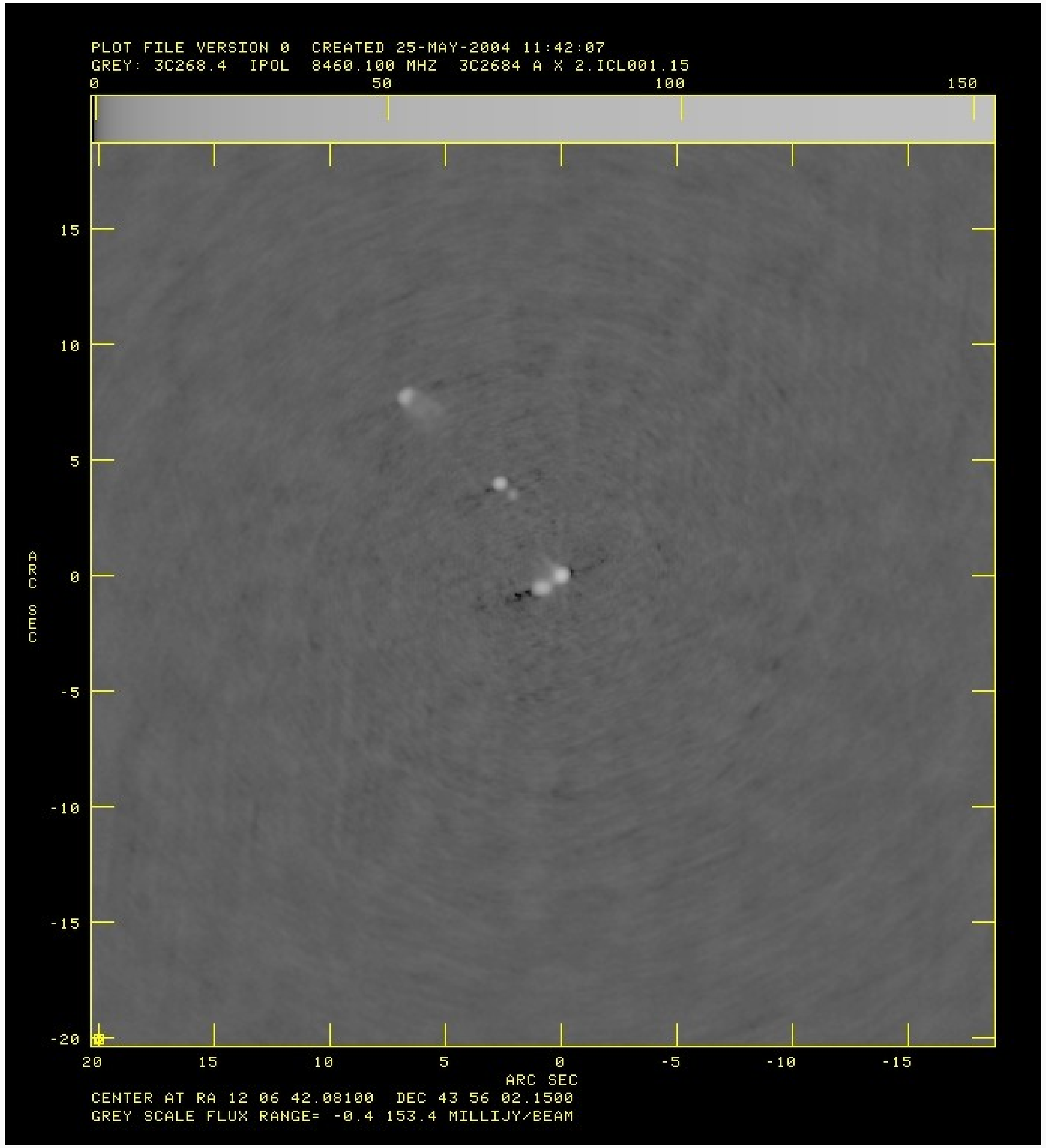
- The measurements from any instrument are really the *convolution* of the *transfer function* of the instrument and the input signal.
- In order to figure out the true input signal, it is necessary to *deconvolve* the *transfer function* from the measurements
- Radio Astronomy solutions
  - CLEAN algorithm(s)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

The CLEANed map

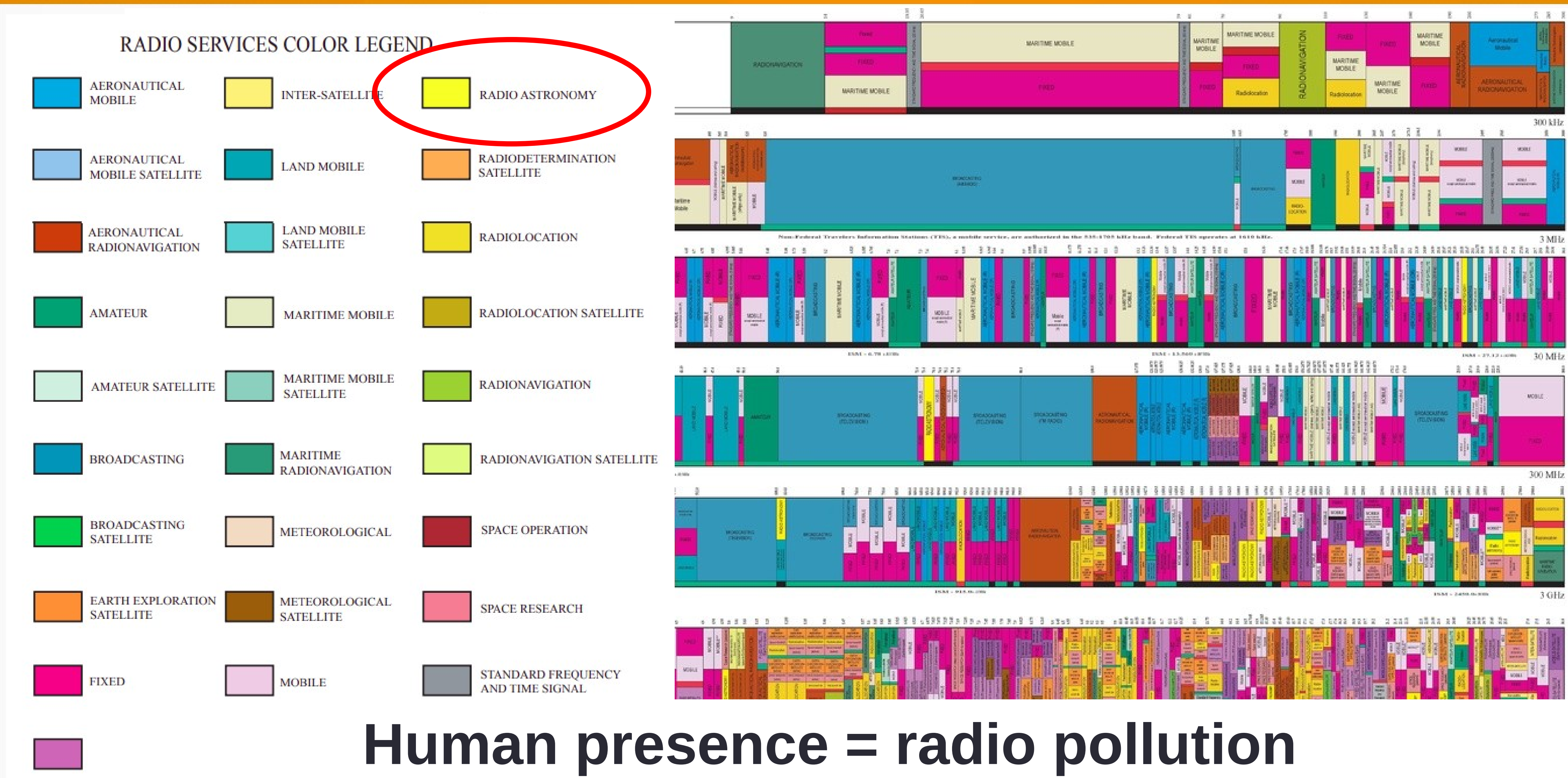
Actually, CLEANed and *Self-calibrated* map

- ~50,000 Clean iterations
- ~4000 Clean components
- Dynamic range ~5000
- Noise ~30 μJy/beam

Log scale



Radio Analog of Dark Sky Problem



Human presence = radio pollution

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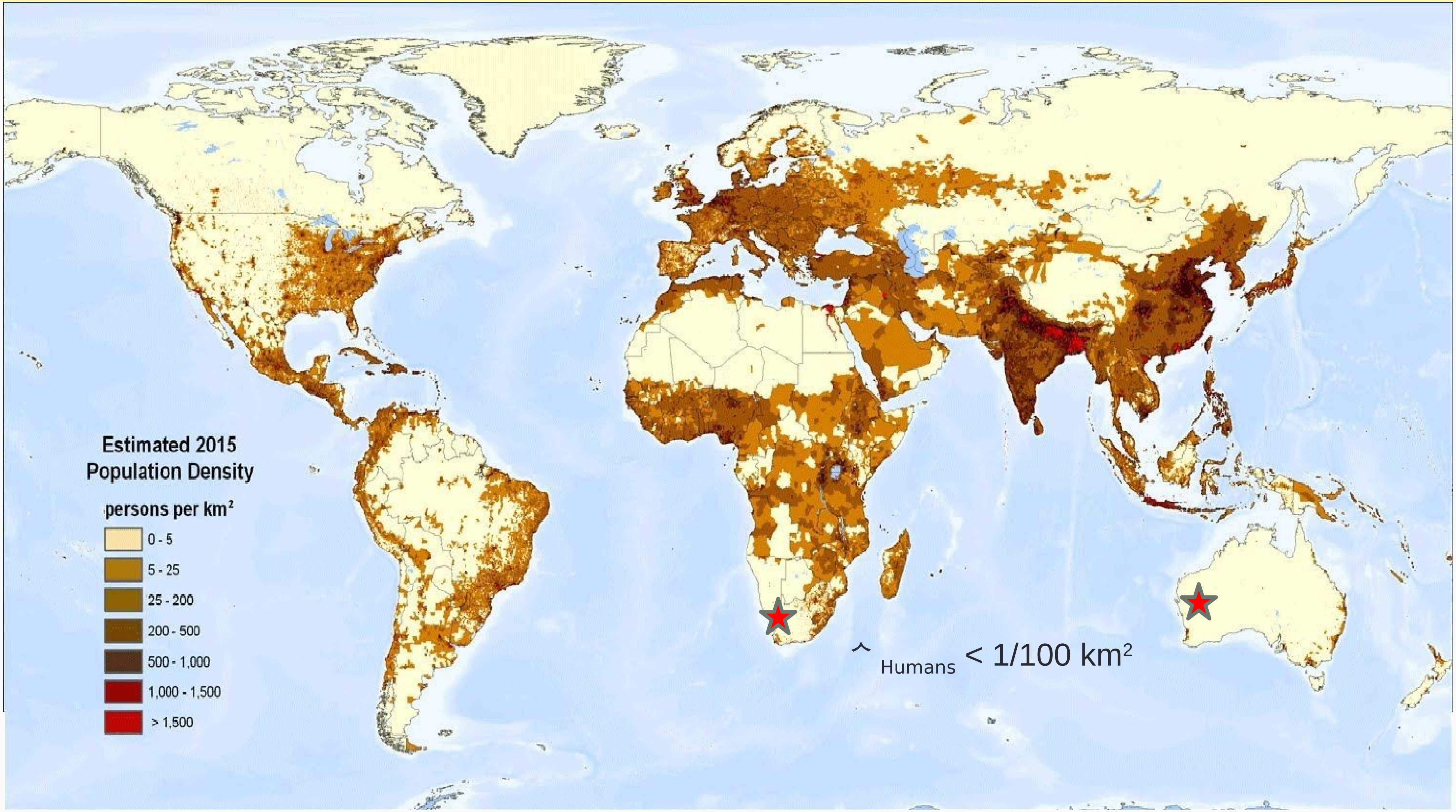
Population Density

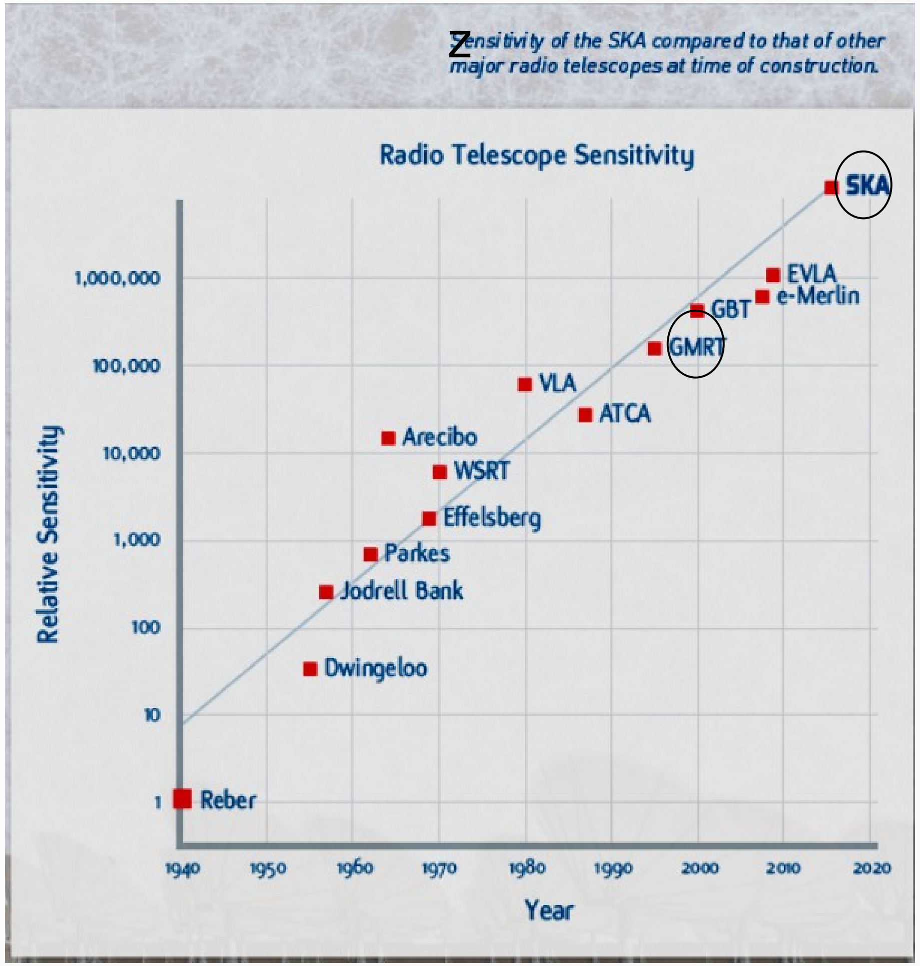


The Square Kilometre Array

- The SKA is the most ambitious Radio Astronomy project ever attempted
- 1 square km (1,000,000 m^2) collecting area (~30 x GMRT!) ⇒ ~3000 small sized antennas, with larger field of view
- High resolution ⇒ antennas spread out over distances up to 3000 km, but connected in real-time (by optical fiber)

- Wide frequency range: 70 MHz - 10 GHz
- Location : Australia AND South Africa (radio quiet regions, far away from human habitat)
- Cutting edge science in all frontline areas

- SKA Phase-1 construction phase just started - completion expected by 2027.



Radio telescope sensitivities over the years
SKA will be 50x better than today's best !

The challenges and opportunities

- Characteristics of new instruments
  - 1-2 orders of magnitude improvements in sensitivity and imaging fidelity
  - Gather more detailed and higher SN information about the sky
    - Ability to solve more challenging astrophysics problems
  - Assumptions/approximations made in most of the present analysis no longer valid
    - Require more sophisticated analysis algorithms
  - Higher sensitivity => need to reduce ‘systematics’ in the analysis
    - Requires deeper understanding of the instrument, the sky and the analysis procedures

- Not only will they enable new and exciting science, the process of getting to the new science requires really exciting research in its own right

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Thanks

Questions