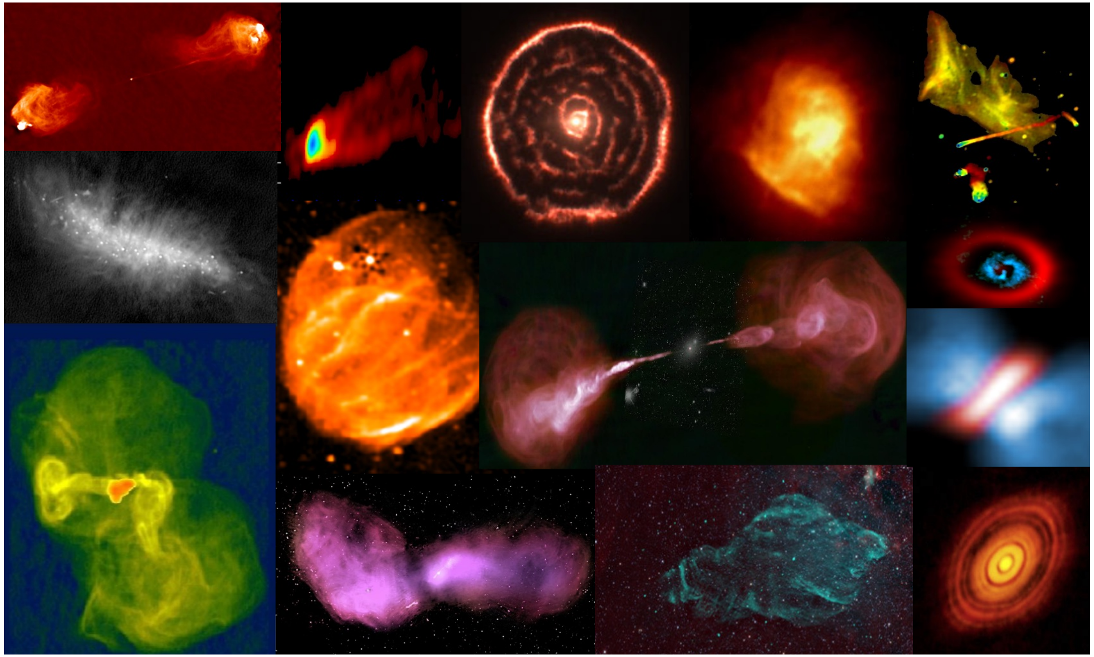
Introduction to Radio Astronomy (for Medical Imagers)



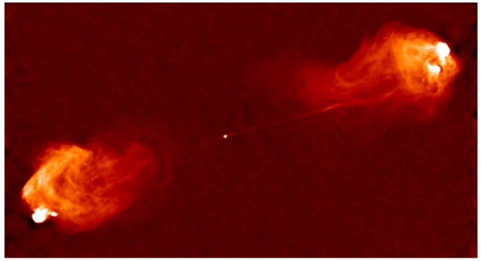
Urvashi Rau

Algorithm Scientist & CASA Software Engg. Group Lead
Data Management and Software Division
National Radio Astronomy Observatory, USA

i2i Workshop, NYU Langone (19 Oct 2023)

Radio Astronomy

Electromagnetic radiation from objects in space



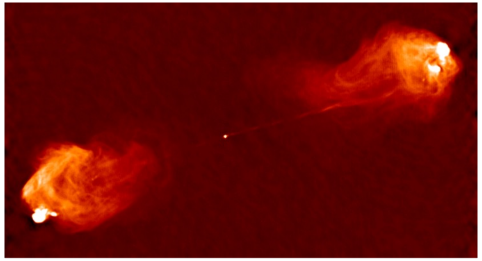
Measure Power Received at Radio Frequencies

Infer Physical Properties

Energetics
Emission/Absorption Physics
Chemical Composition
Magnetic Fields
Velocities
3D structure

Radio Astronomy

Electromagnetic radiation from objects in space



Spectral Power Flux Density

$$1\,Jansky = \frac{10^{-26}\ W}{m^2\ Hz}$$

Measured range : 10^4 Jy to 10^{-6} Jy

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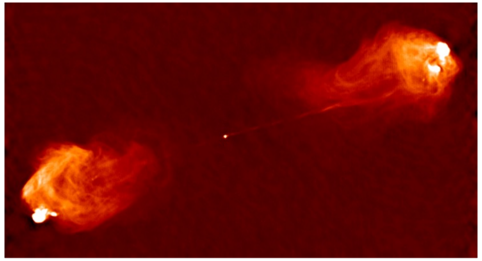

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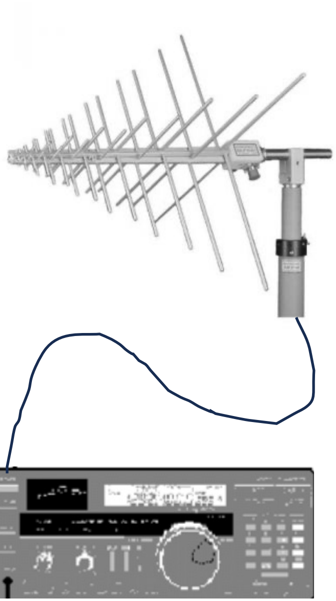

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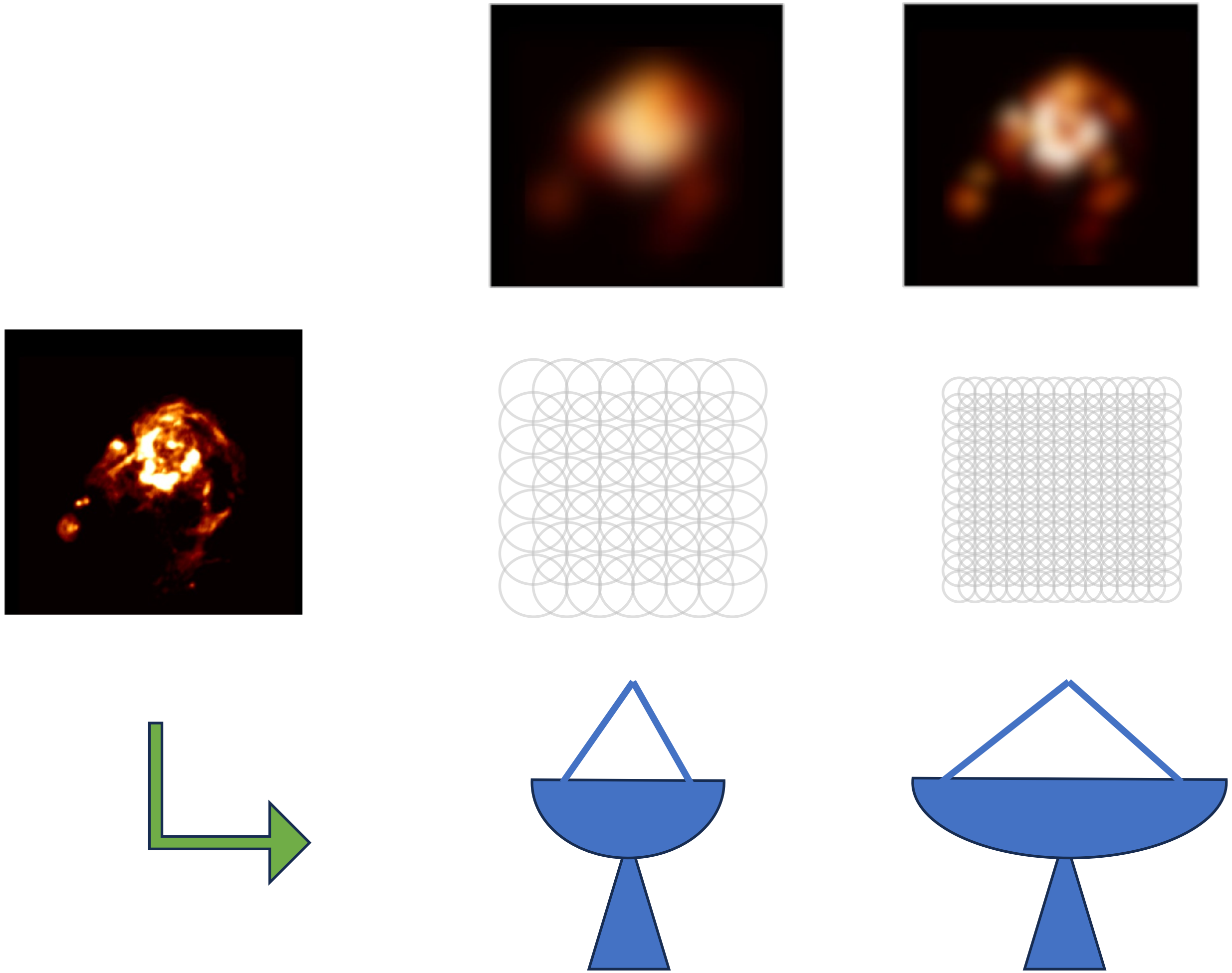
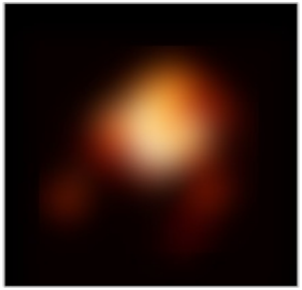
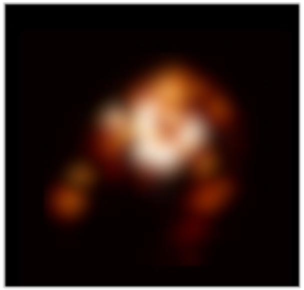
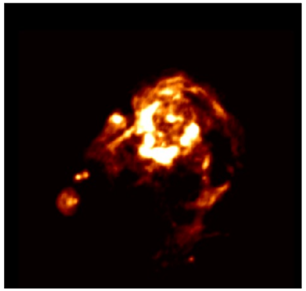
Images in Radio Astronomy

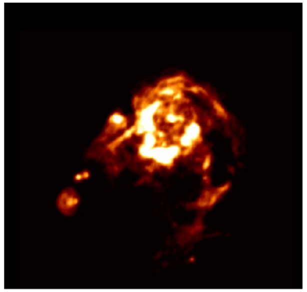


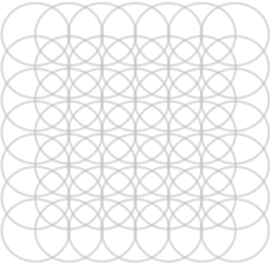
Images in Radio Astronomy

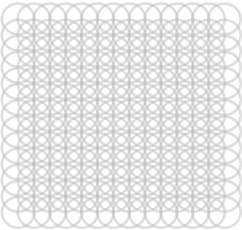








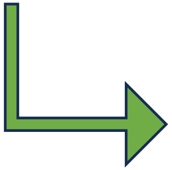


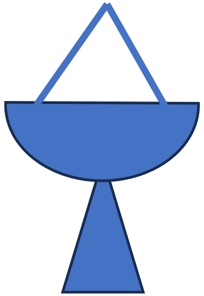


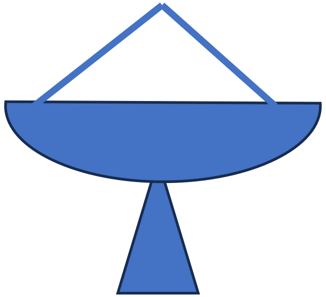
Aperture Synthesis

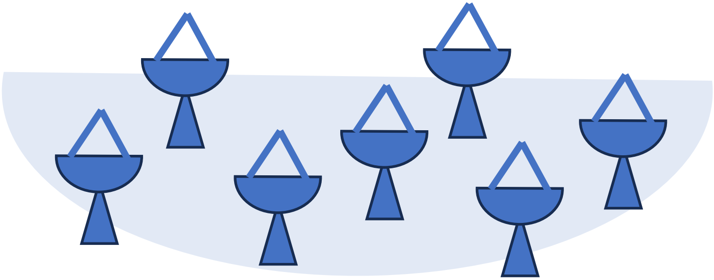
Measure spatial frequencies…

“ K-space Sampling “



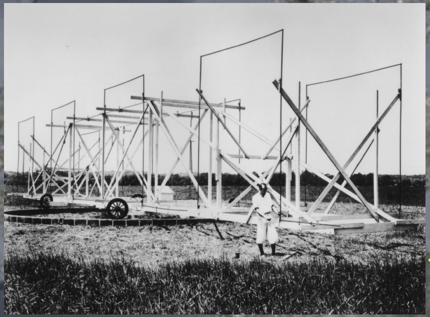






Radio Telescopes around the World

Radio Telescopes around the World

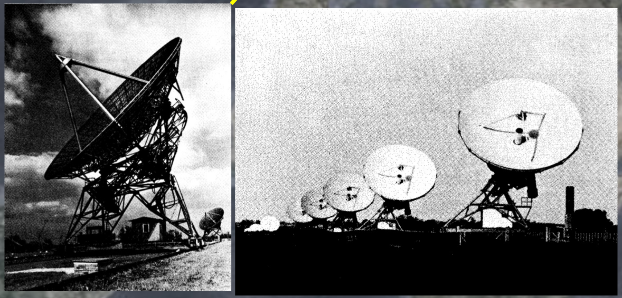


Karl Jansky (1933)

“Radio Waves from the Milky Way”

Grote Reber (1936)

“First All-Sky Radio Map”



Martin Ryle (1960+)

“First intentional sampling of spatial frequency (k-space) in radio astronomy”

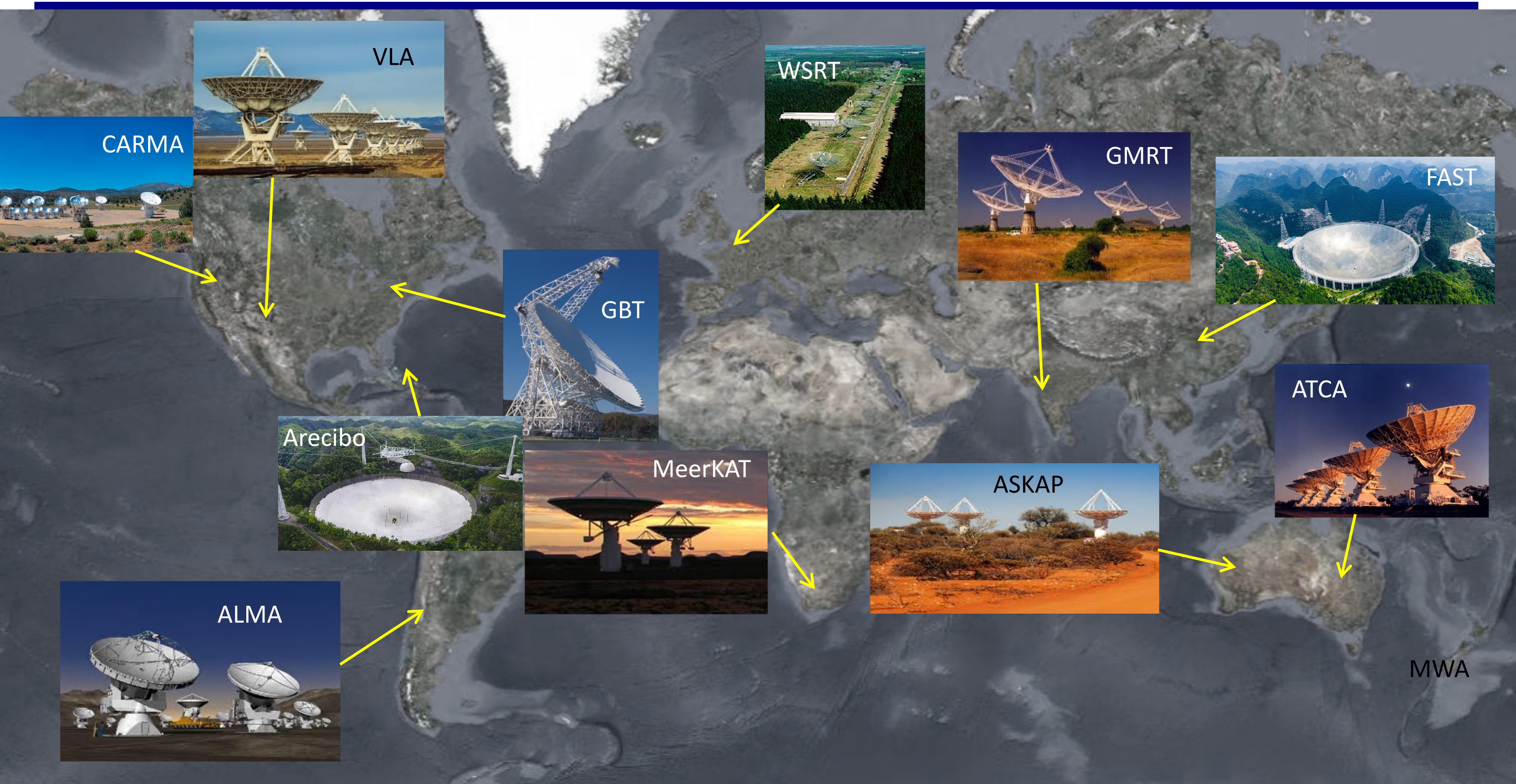
Physics Nobel Prize : 1974

McCready, Pawsey, Payne-Scott. (1946)

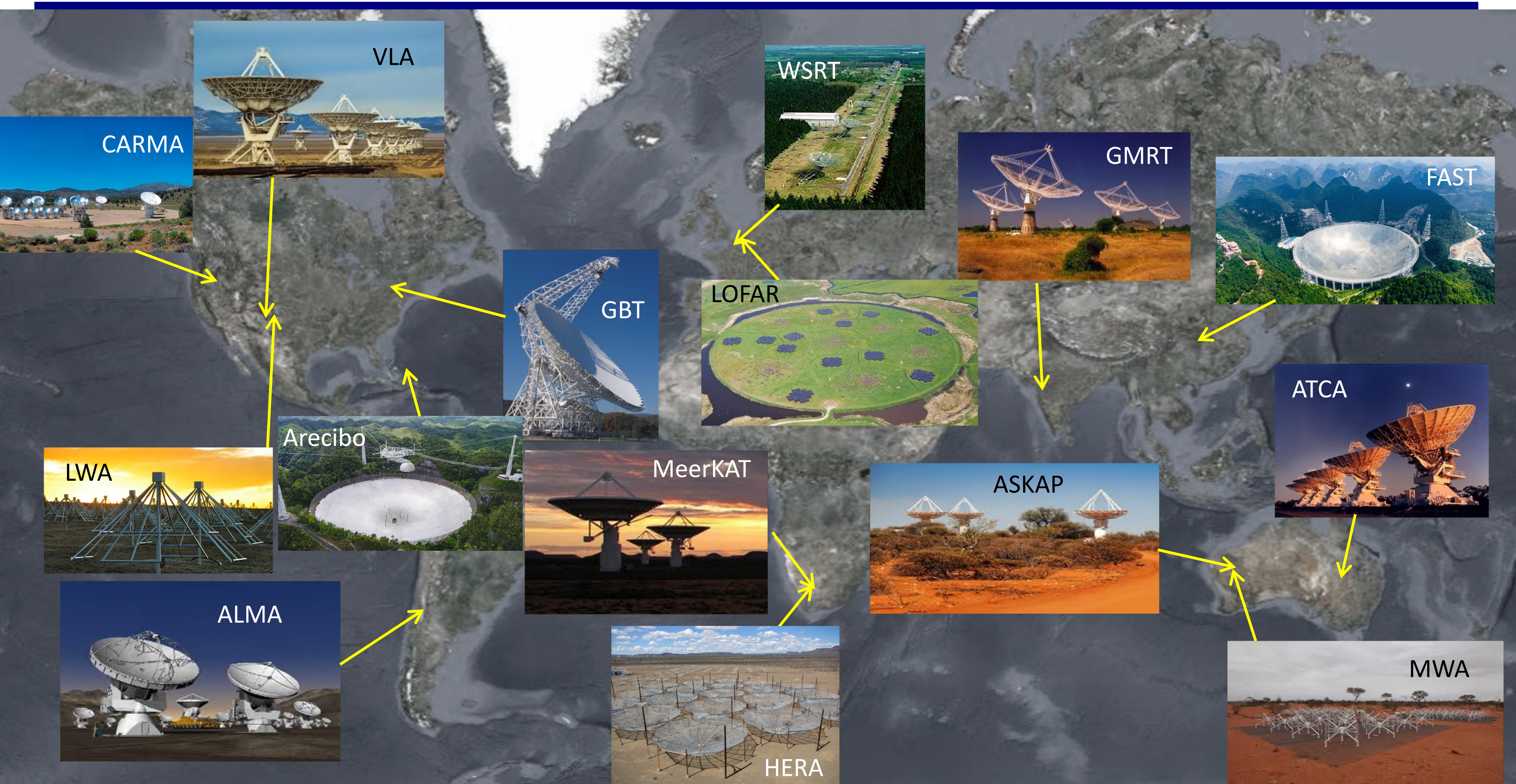
“Used wave interference to infer spatial scale”

Radio Telescopes around the World

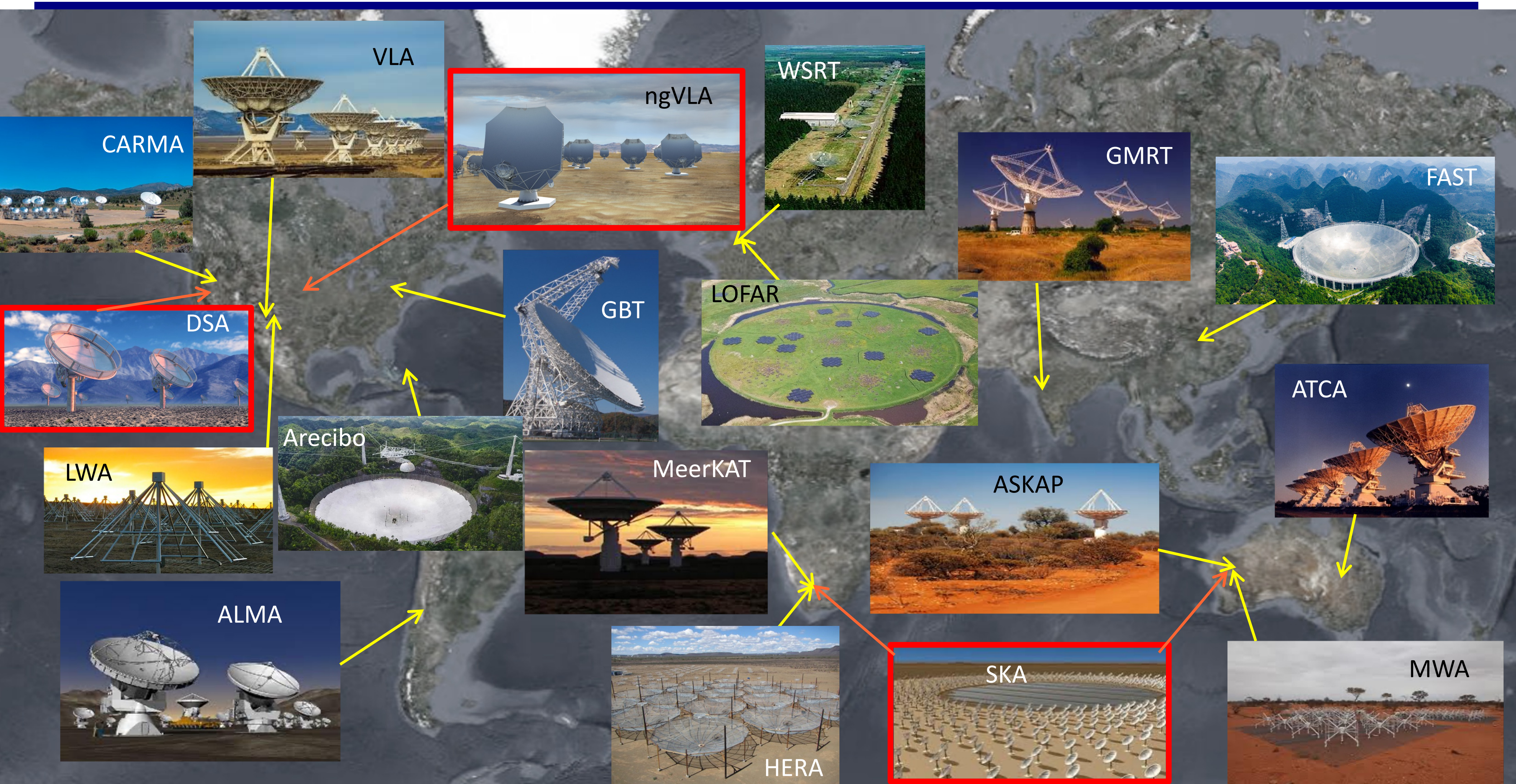
Radio Telescopes around the World



Radio Telescopes around the World

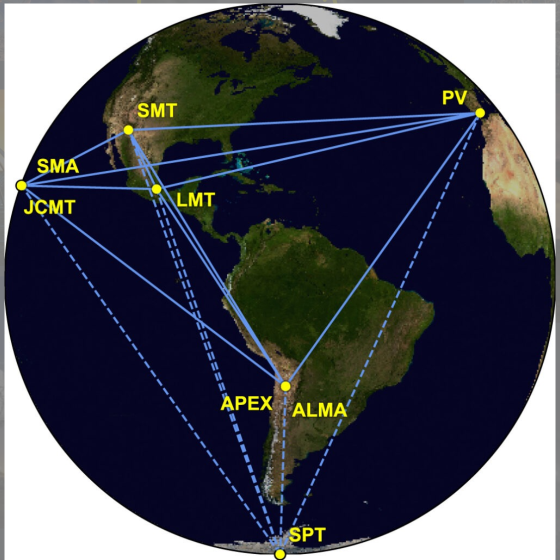


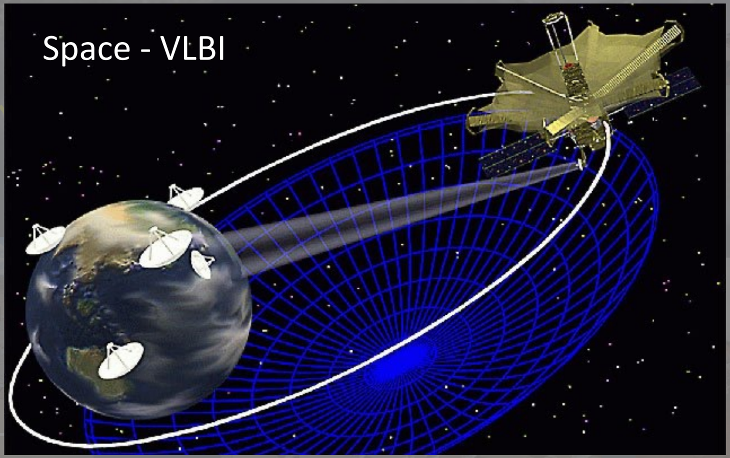
Radio Telescopes around the World



Radio Telescopes around the World

Event Horizon Telescope





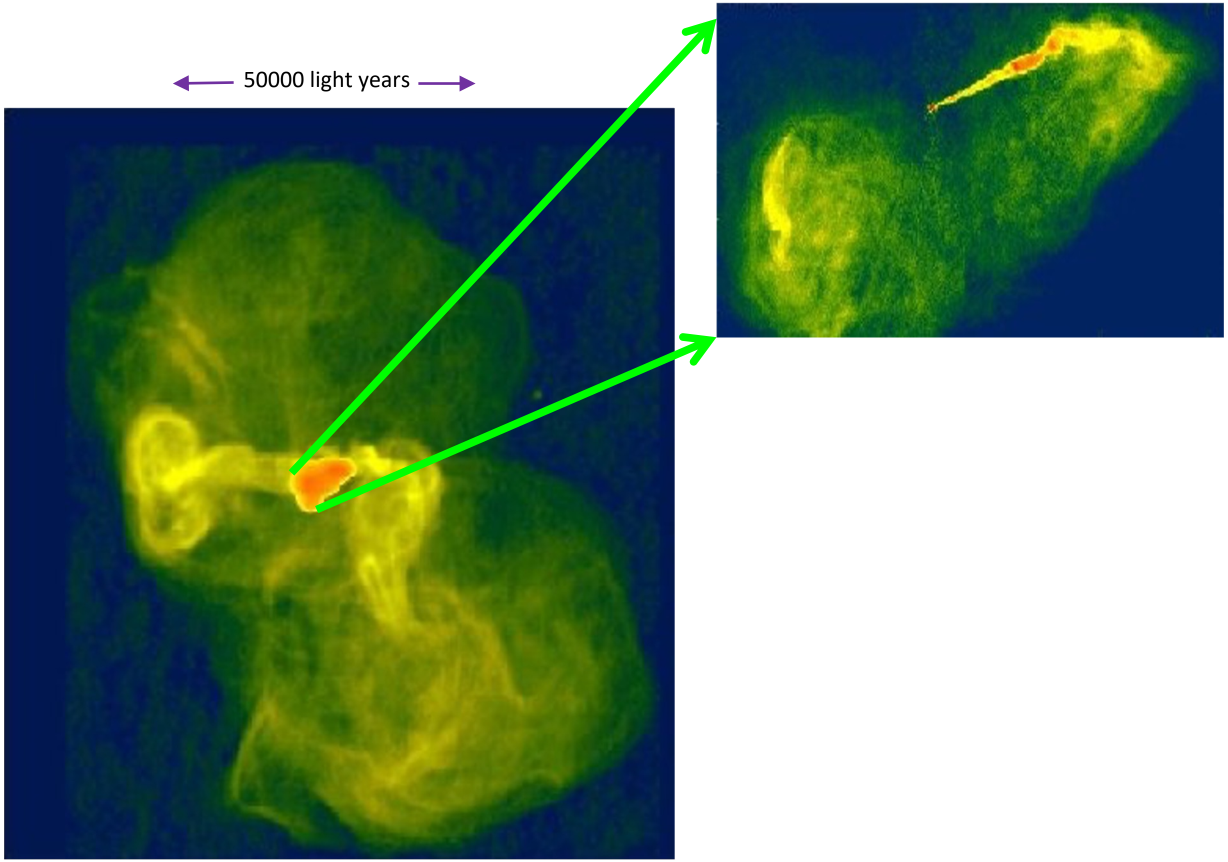
Images in Radio Astronomy : 2D brightness distribution

Space

Time

Frequency

Polarization



The M87 Radio Galaxy

Credits : NRAO

Images in Radio Astronomy : 2D brightness distribution

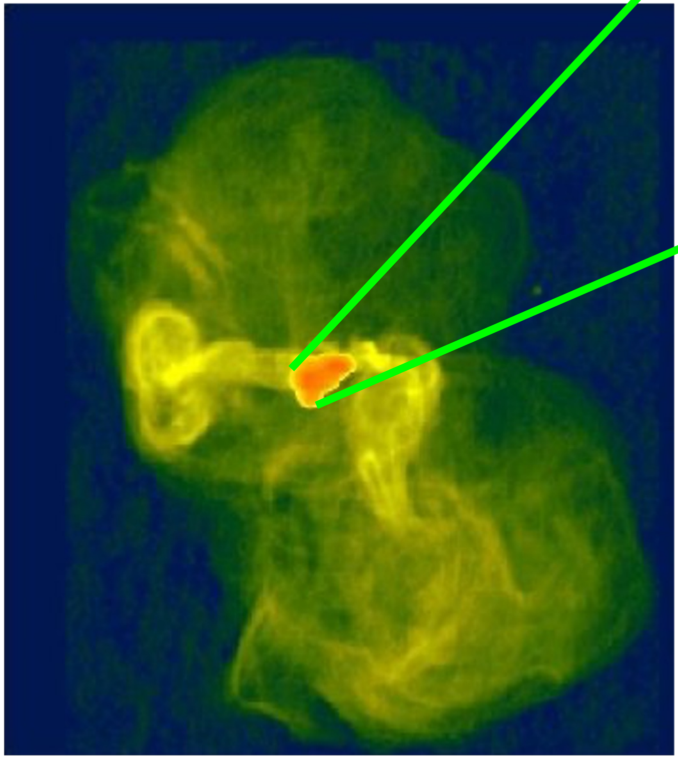
Space

Time

Frequency

Polarization

50000 light years



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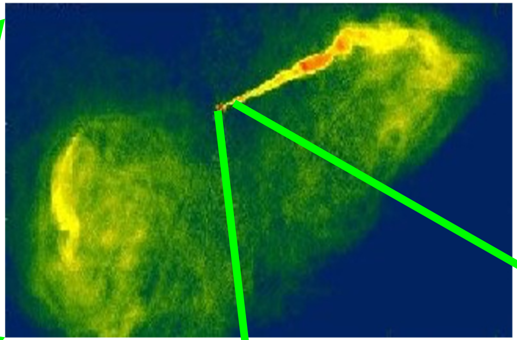
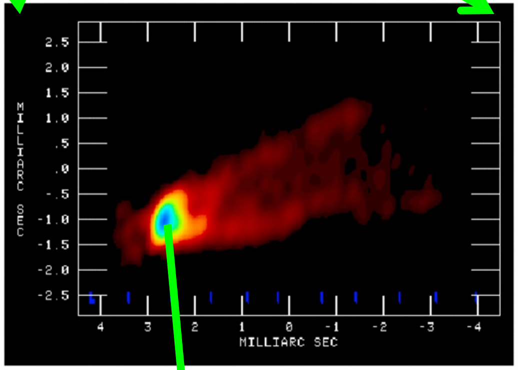
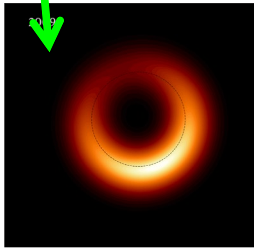






0.006 light years

Credits : NRAO, ALMA, Event Horizon Telescope collaboration

Images in Radio Astronomy : 2D brightness distribution

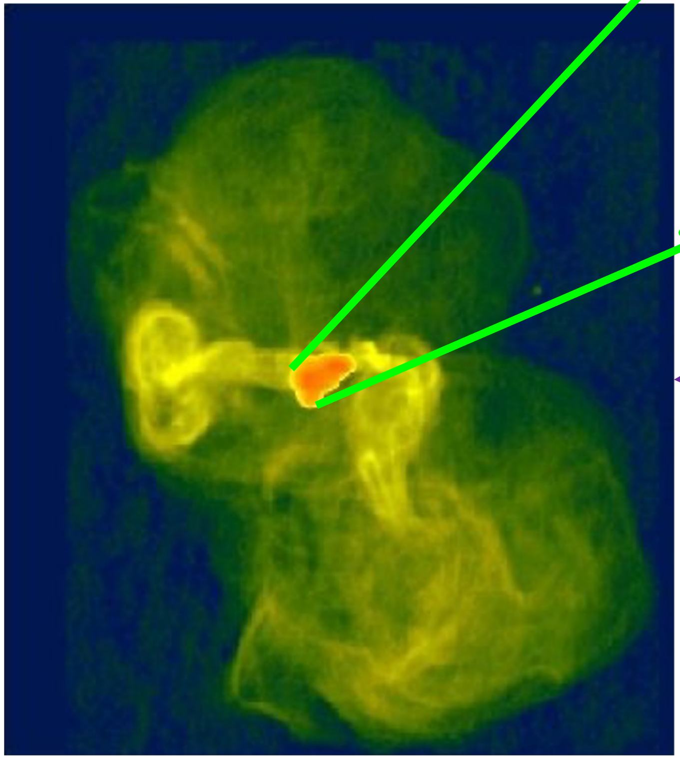
Space

Time

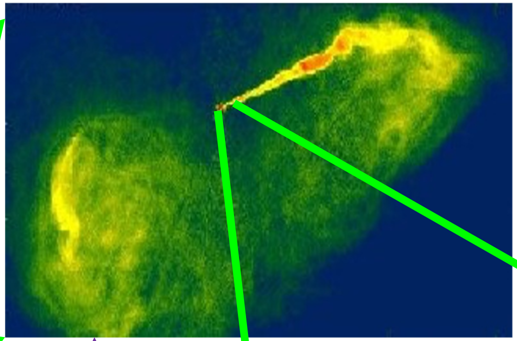
Frequency

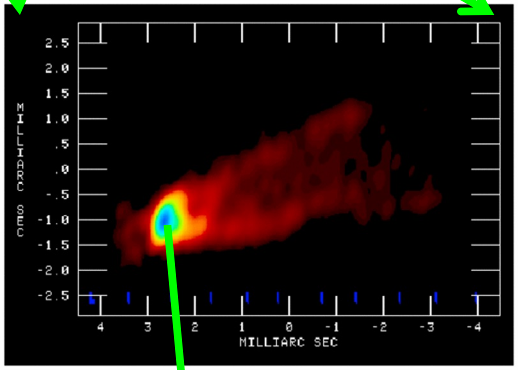
Polarization

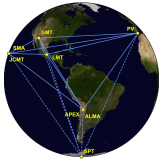
50000 light years

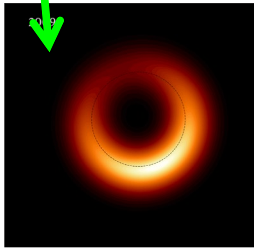


The M87 Radio Galaxy









0.006 light years

Credits : NRAO, ALMA, Event Horizon Telescope collaboration

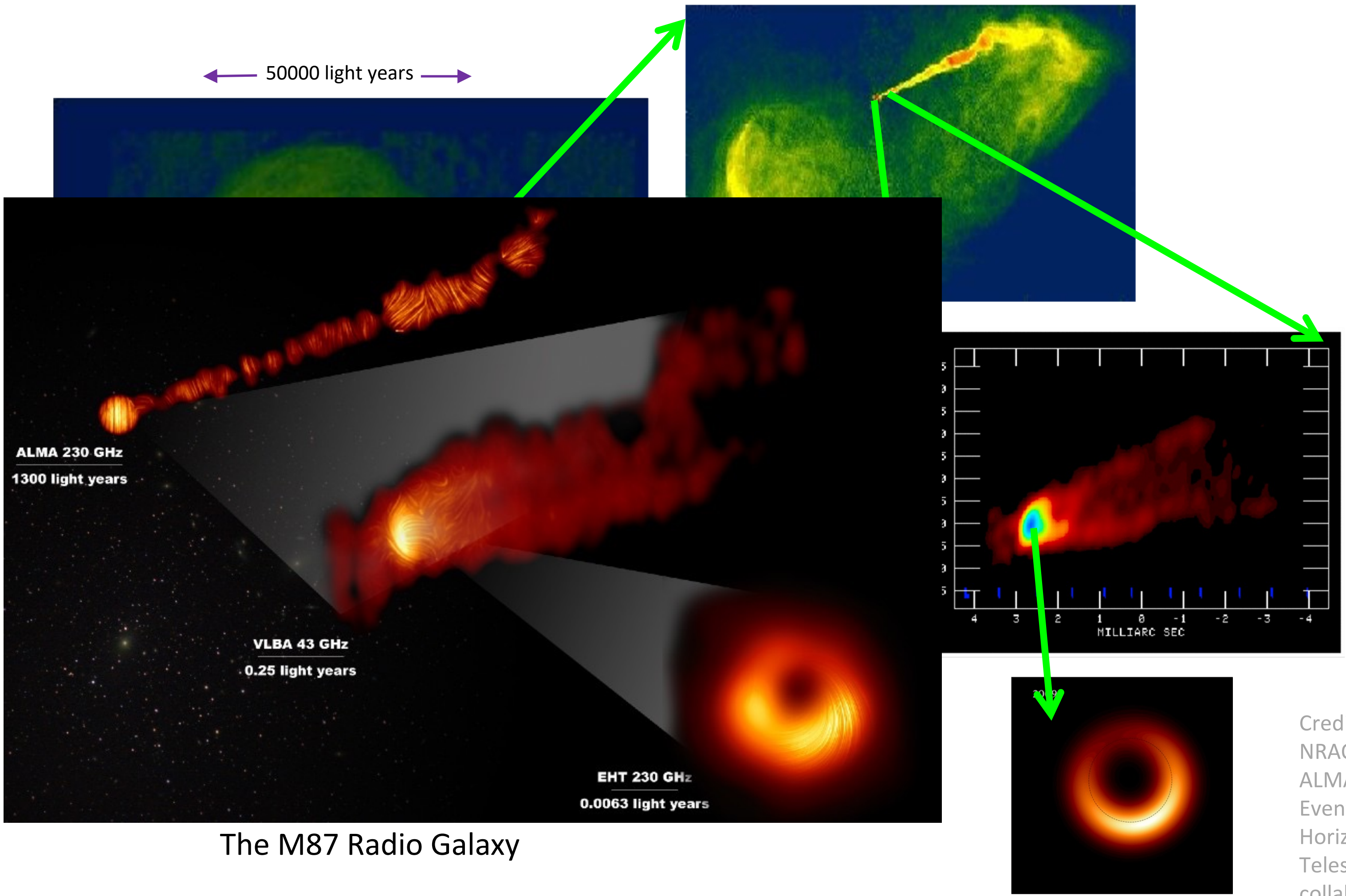
Images in Radio Astronomy : 2D brightness distribution + B-fields

Space

Time

Frequency

Polarization



The M87 Radio Galaxy

0.006 light years

Credits : NRAO, ALMA, Event Horizon Telescope collaboration

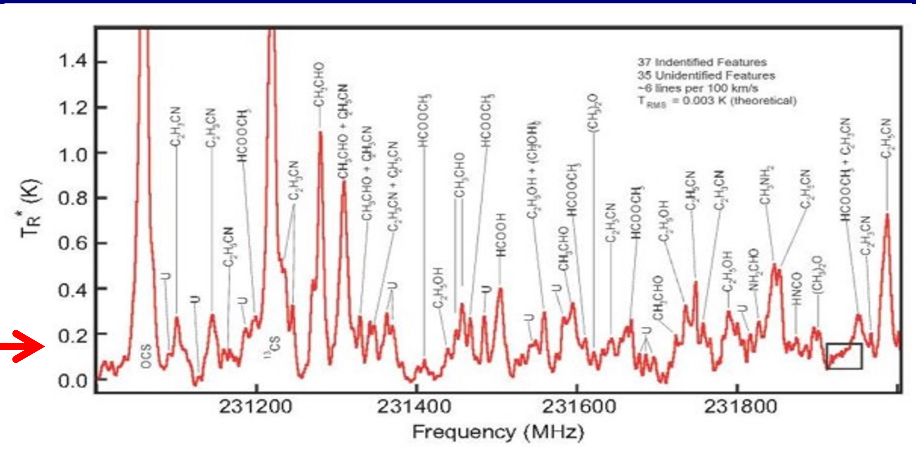
Images in Radio Astronomy : Spectral Lines + Doppler Shifts

Space

Time

Frequency

Polarization



Astro-chemistry tracers

+ Doppler shifts
trace physical velocity

M31 : Andromeda
Galaxy Rotation

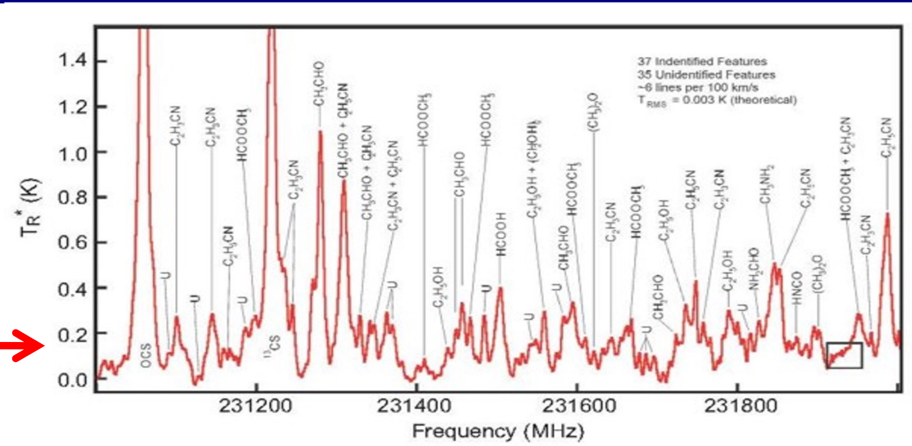
Images in Radio Astronomy : Spectral Lines + Doppler Shifts

Space →

Time

Frequency →

Polarization



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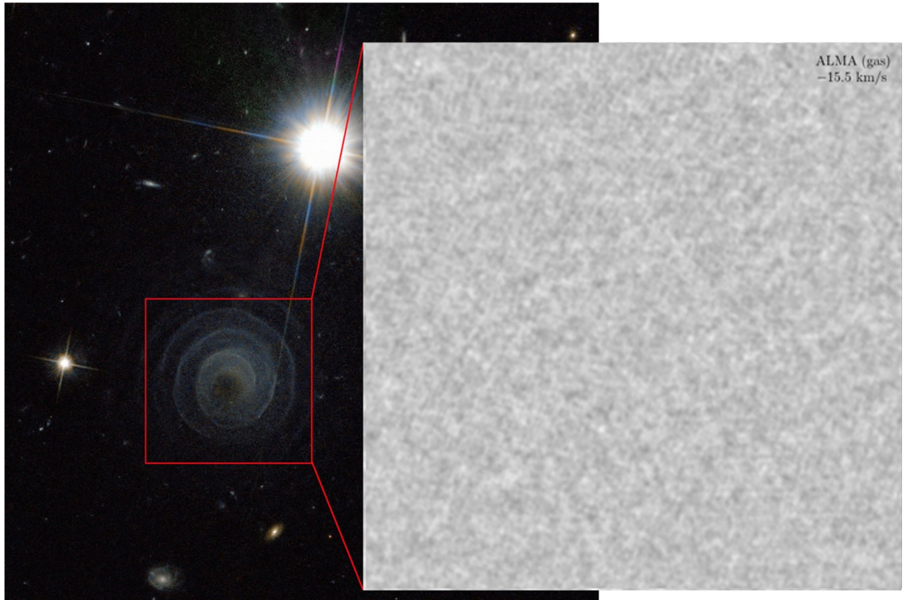


CO emission showing
a spiral-shell structure
around the AGB star
LL Pegasi and its
'stellar companion

(Kim et al, Nature Astro 2017.)

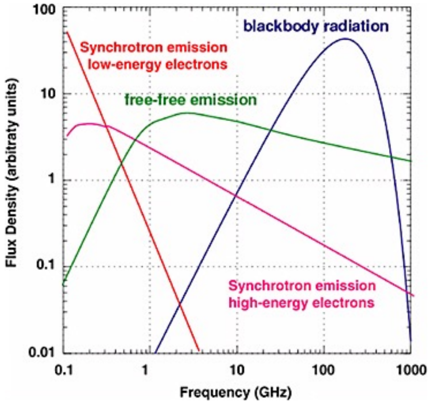
Images in Radio Astronomy : Emission Physics

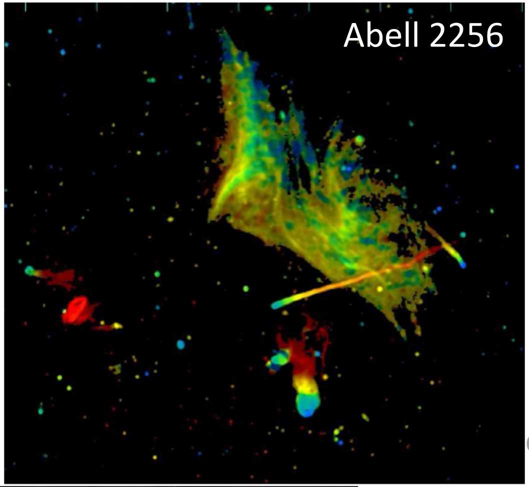
Space →

Time

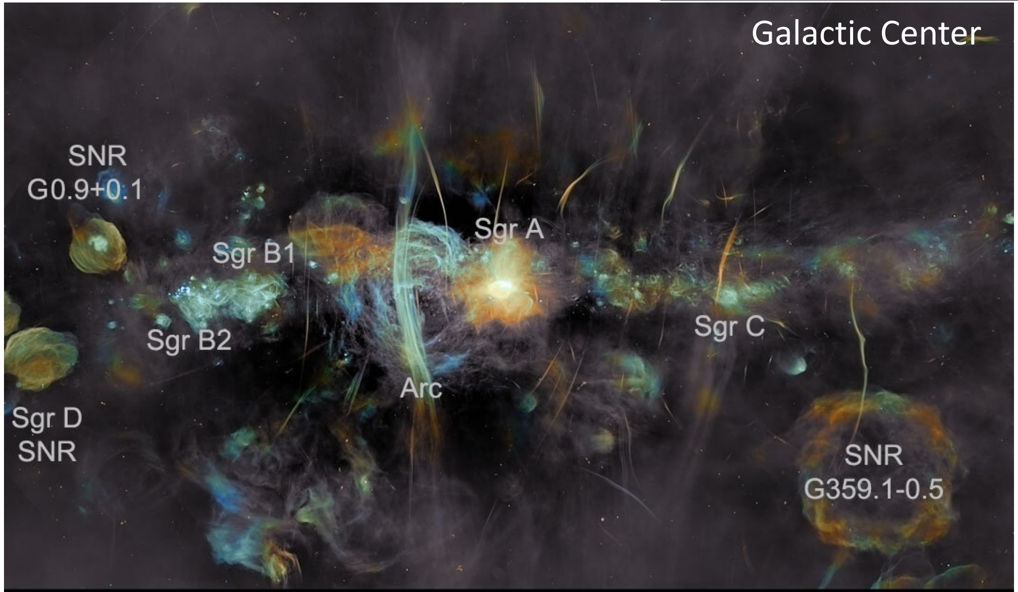
Frequency →

Polarization





Credits : F.Owen,NRAO



Color : Spectral slope

Credits : I.Heywood,SARAO

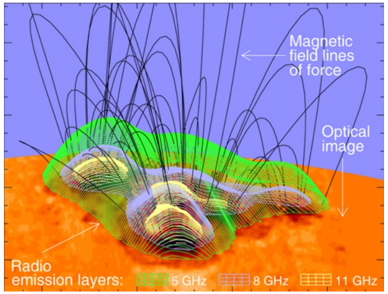
Images in Radio Astronomy : Magnetic Fields

Space

Time

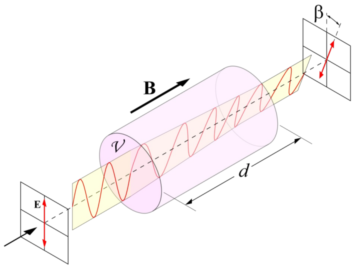
Frequency

Polarization



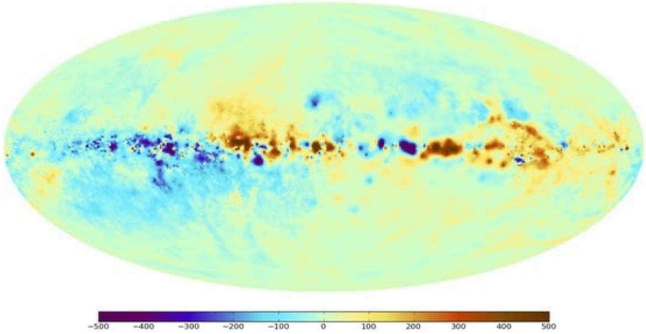
Coronal Magnetography

Traces B-field strengths
at difference heights above
the surface of the sun.

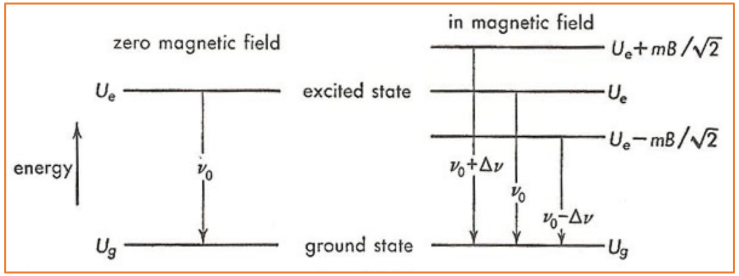


Faraday Rotation

Traces integrated
Line-of-Sight B-field
through medium of
propagation

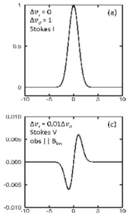


Credits : Max Planck Institute

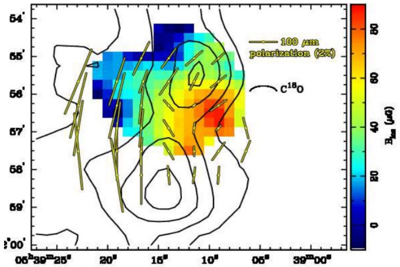


Zeeman Effect

Traces in-situ B-fields

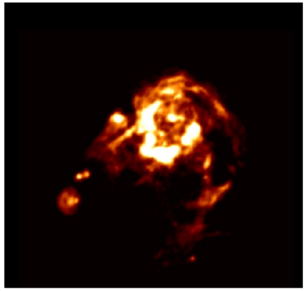


Observing
Frequency



Credits : Crutcher & Kemball, 2019

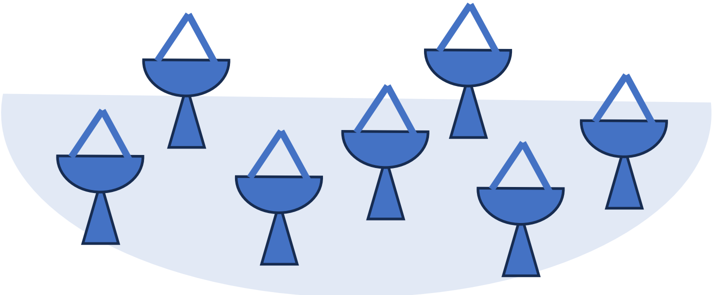
Radio Interferometric Imaging



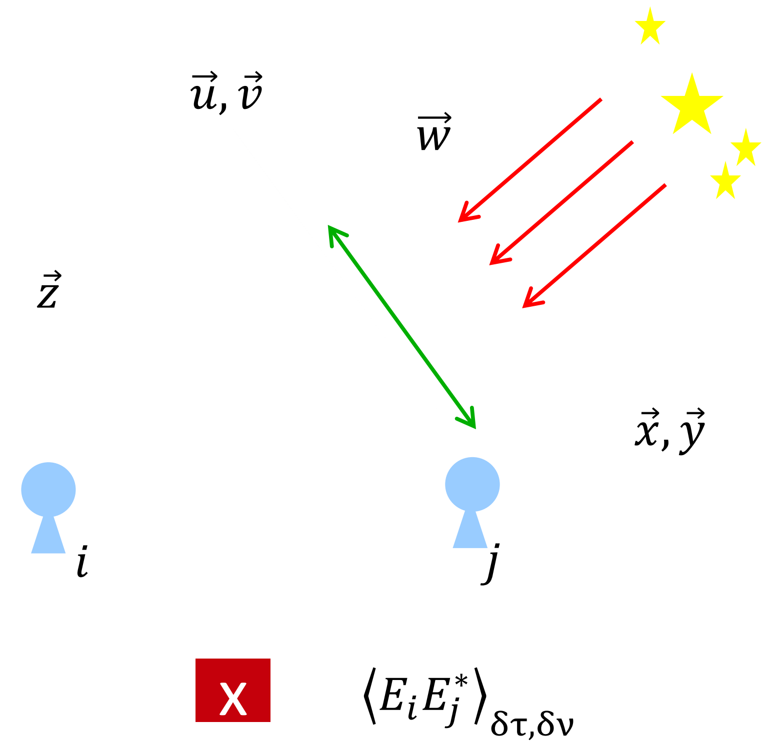
Aperture Synthesis

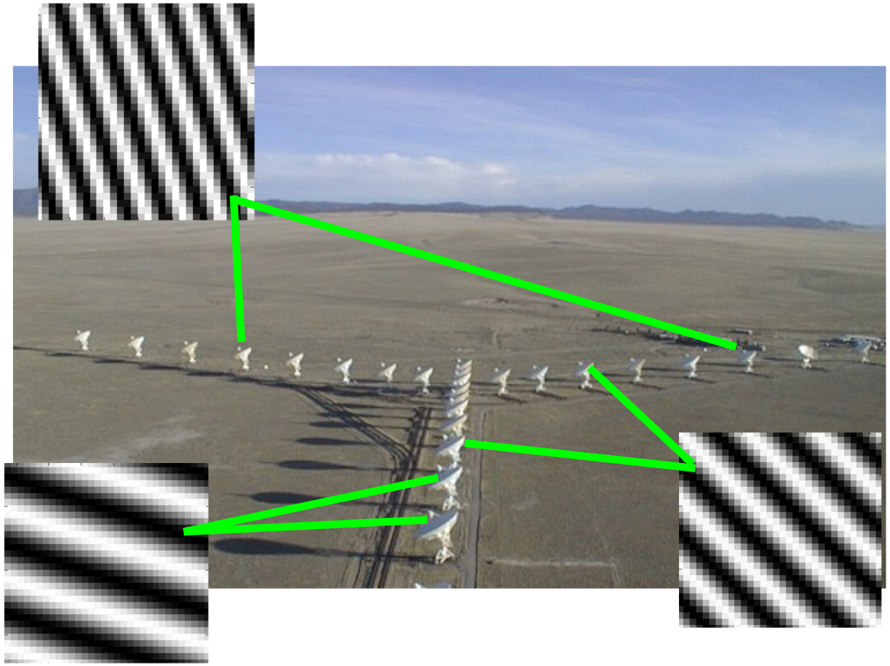
Measure spatial frequencies…

“ K-space Sampling “



Measuring spatial frequency components

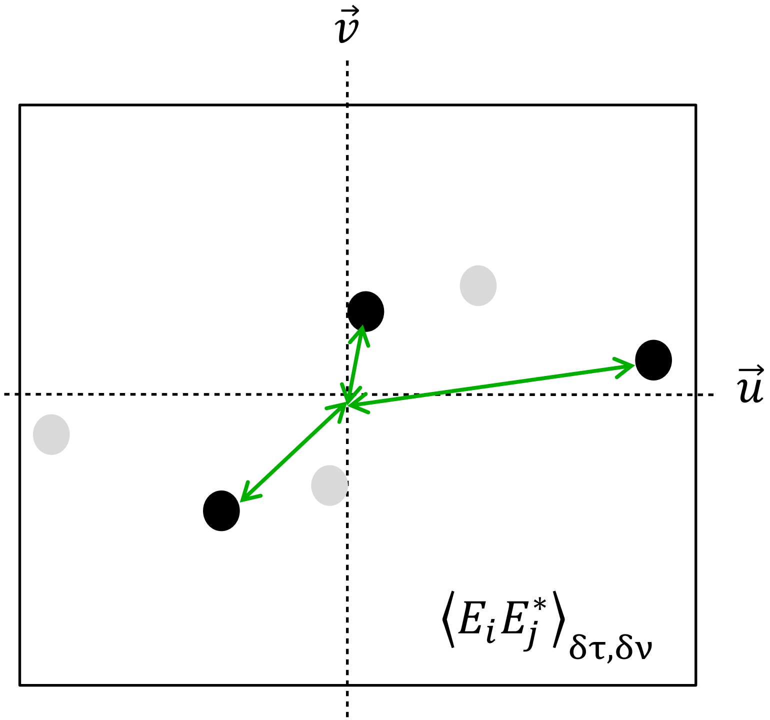




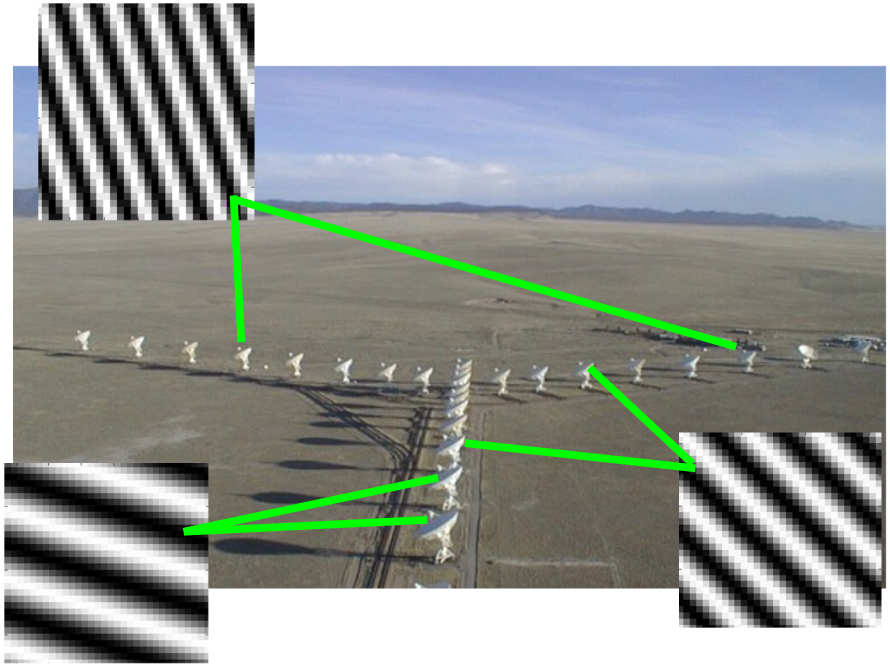
Imaging Interferometer : A detector array

Measure spatial coherence of incident E-field

Filling up the K-space



Sampling the " K-Space "



Imaging Interferometer : A detector array

(Spatial Frequency Domain, UV-domain)

Spatial Frequency (uv) coverage + Observed Image

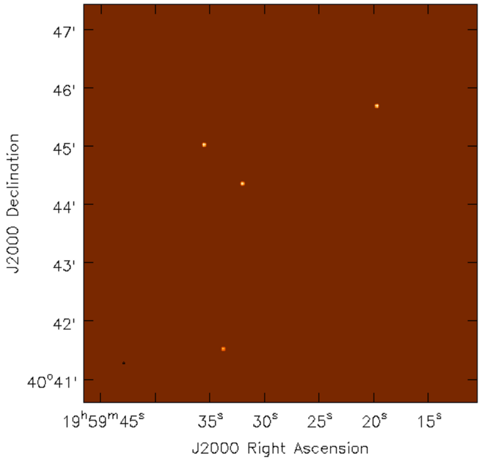
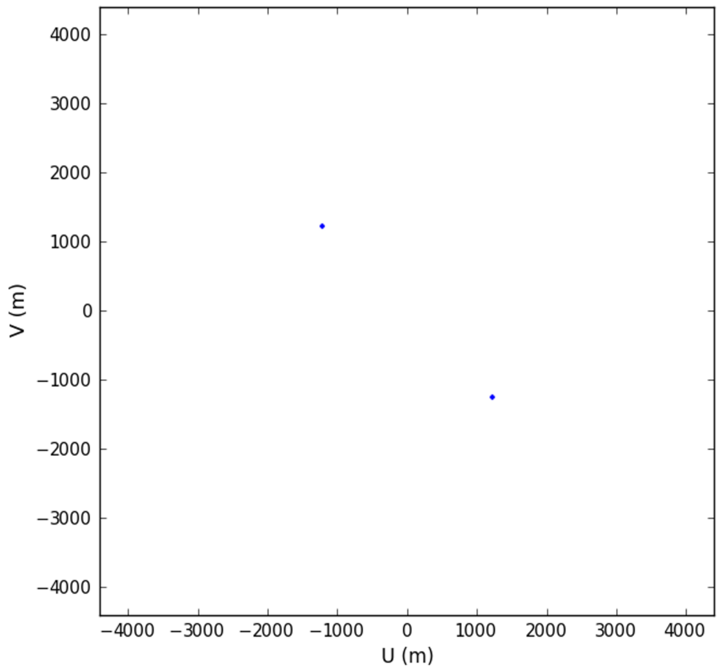
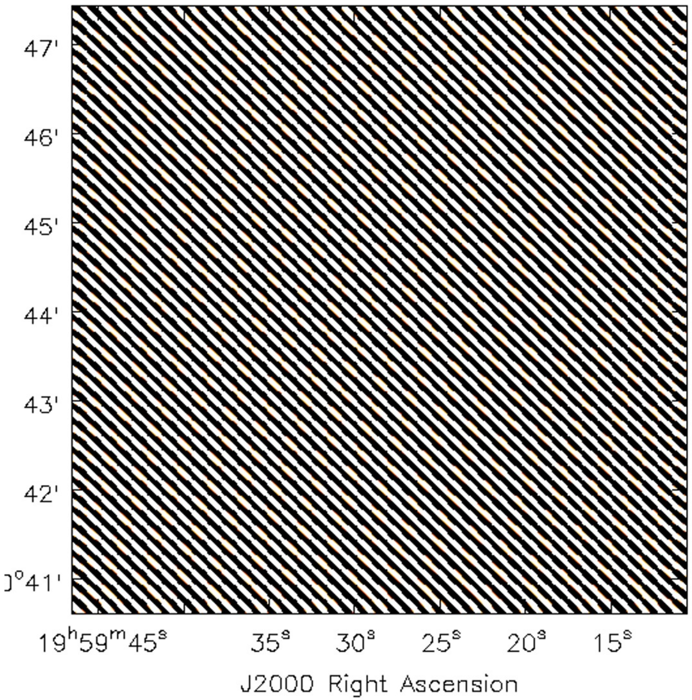


Image of the sky
using **2** antennas

$S(u,v)$



$I^{obs}(l,m)$



Spatial Frequency (uv) coverage + Observed Image

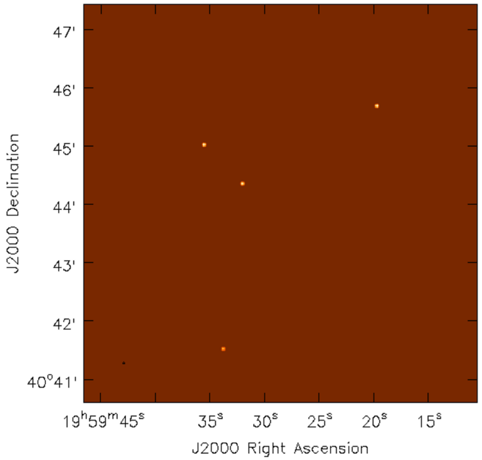
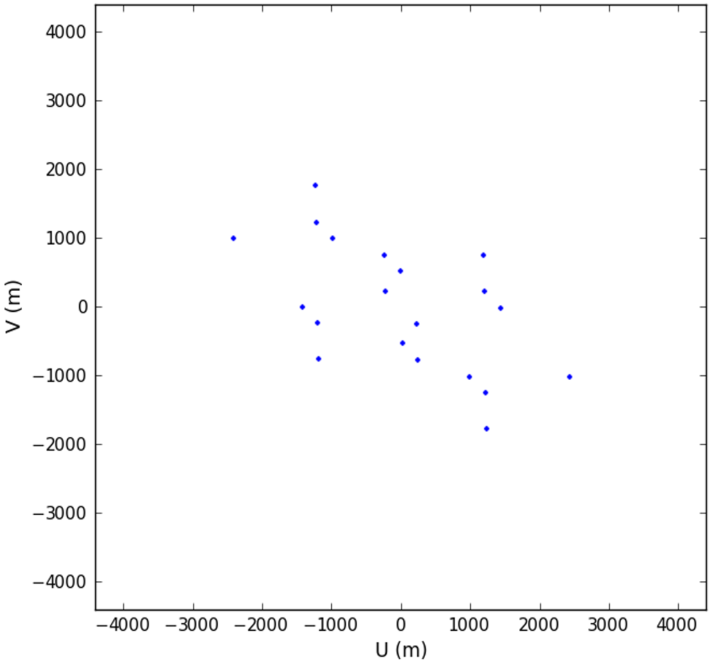


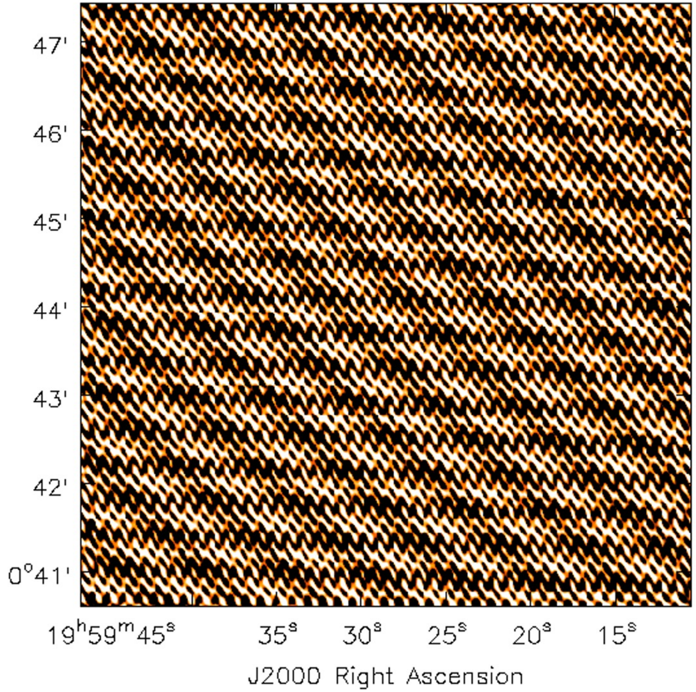
Image of the sky
using **5** antennas

"Aperture Synthesis"

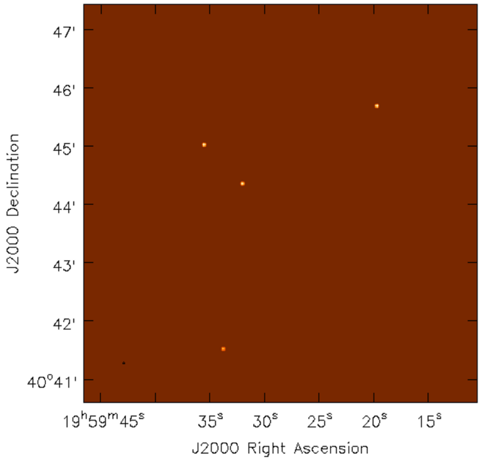
$S(u,v)$



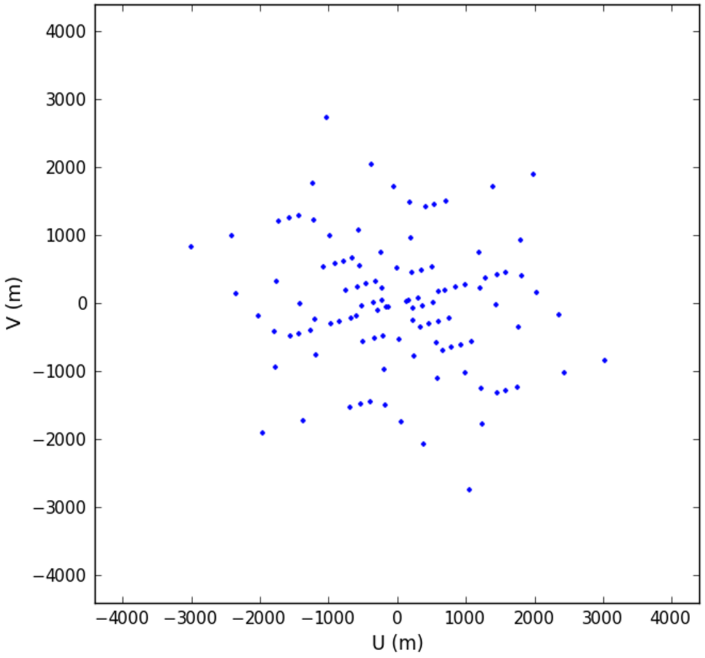
$I^{obs}(l,m)$



Spatial Frequency (uv) coverage + Observed Image



$S(u, v)$



$I^{obs}(l, m)$

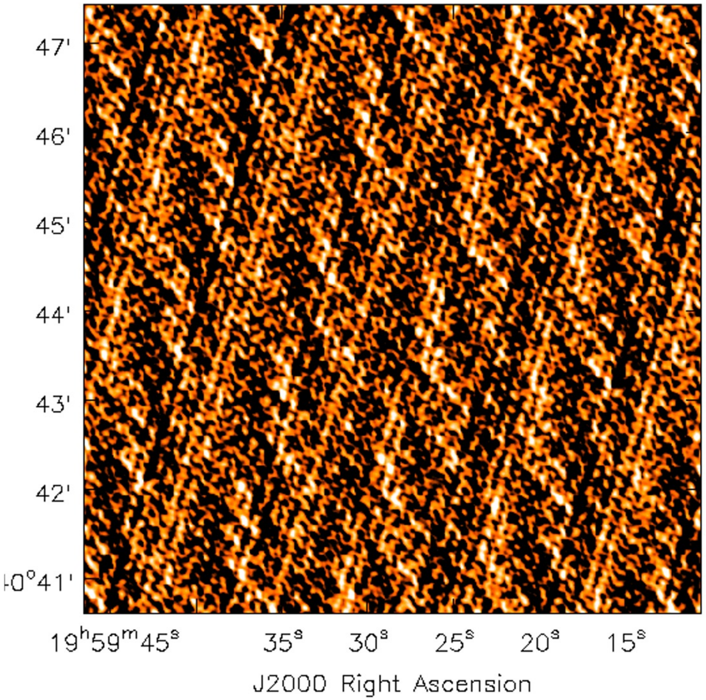
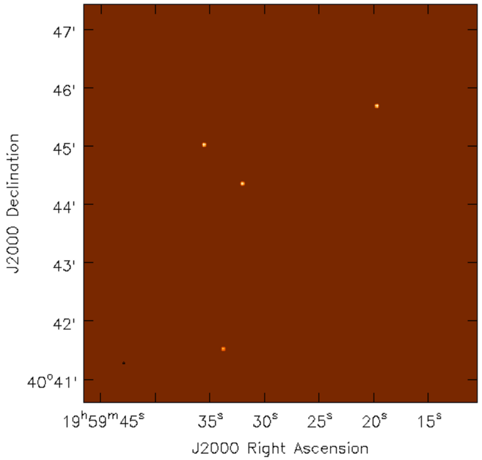


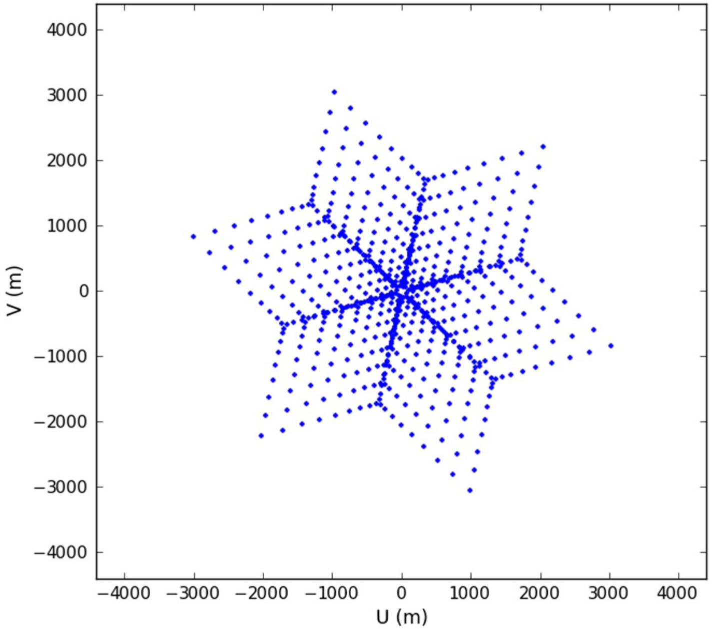
Image of the sky using **11** antennas

"Aperture Synthesis"

Spatial Frequency (uv) coverage + Observed Image



$S(u,v)$



$I^{obs}(l,m)$

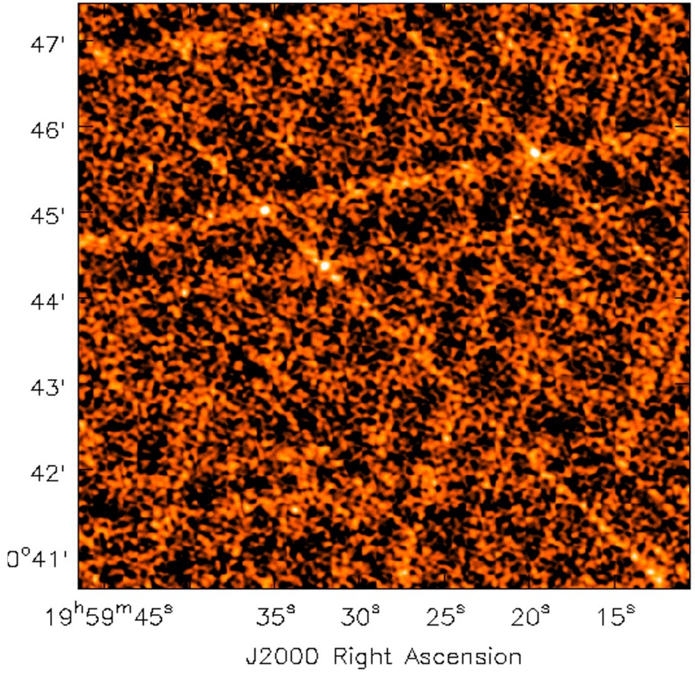
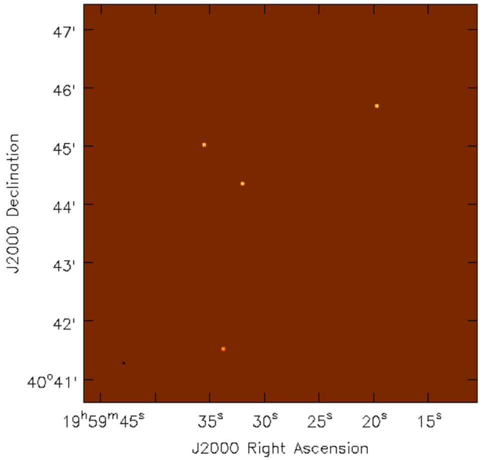


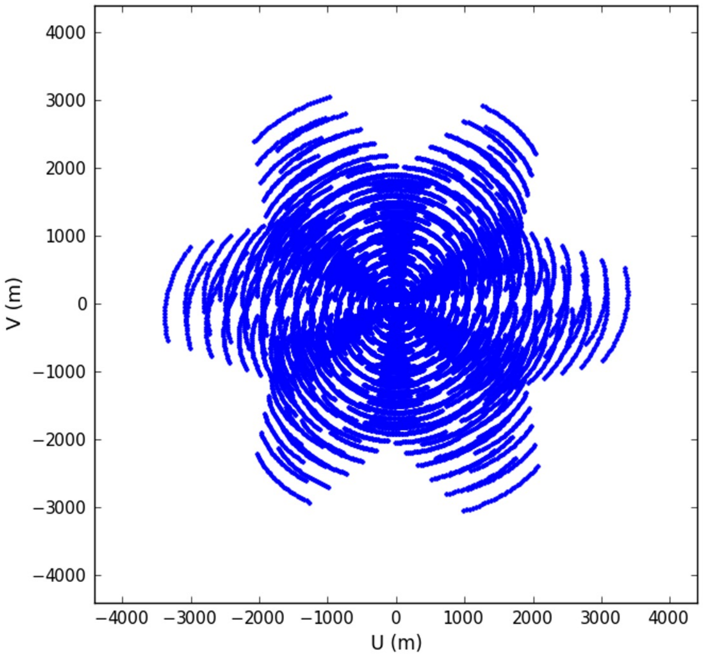
Image of the sky using **27** antennas

"Aperture Synthesis"

Spatial Frequency (uv) coverage + Observed Image



$S(u,v)$



$I^{obs}(l,m)$

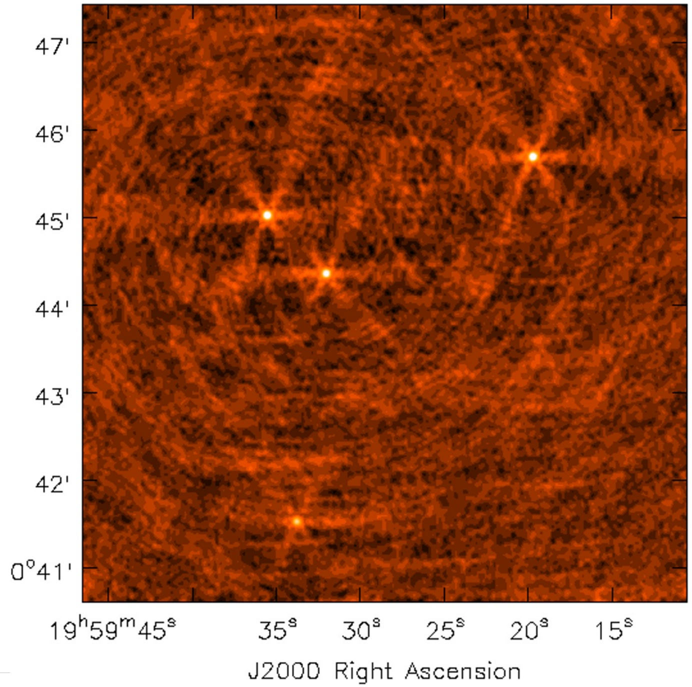
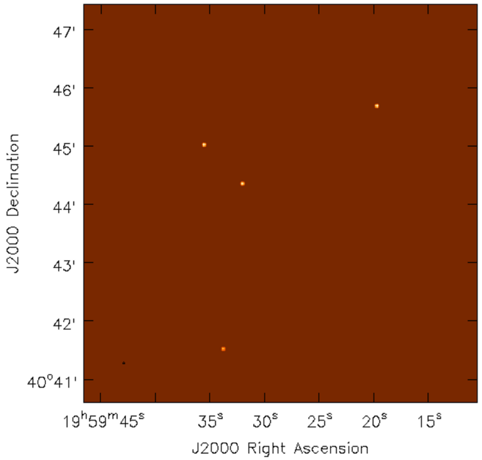


Image of the sky
using 27 antennas

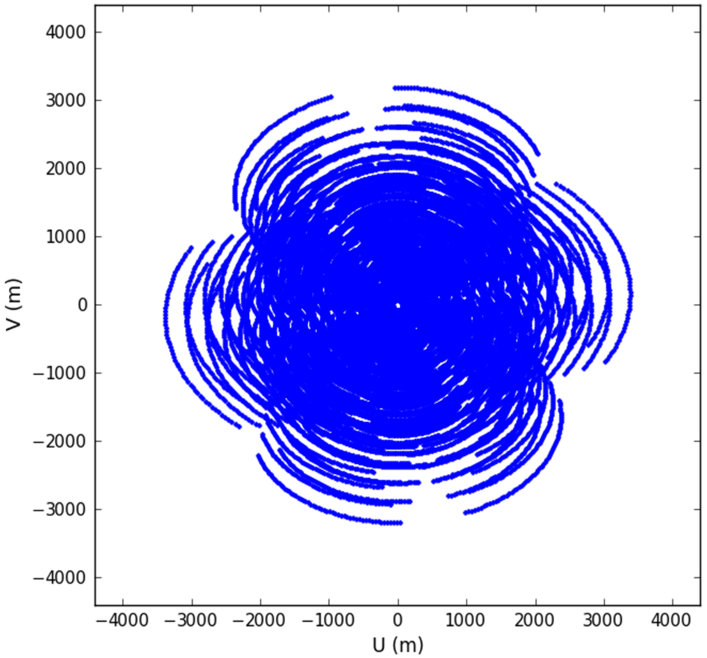
Observation : **2 hours**

"Earth Rotation Synthesis"

Spatial Frequency (uv) coverage + Observed Image



$S(u,v)$



$I^{obs}(l,m)$

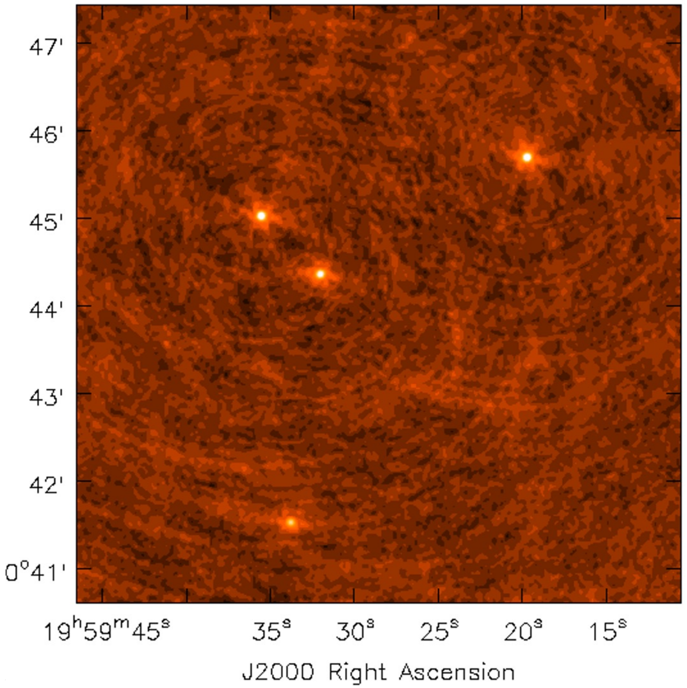


Image of the sky
using 27 antennas

Observation : **4 hours**

“Earth Rotation Synthesis”

Measurement Equation : Forward Problem

Observed Data

K-space Sampling

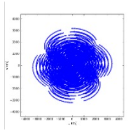
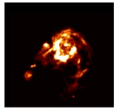


Image of Sky Brightness

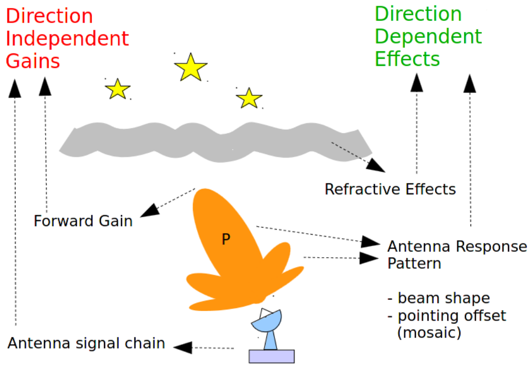


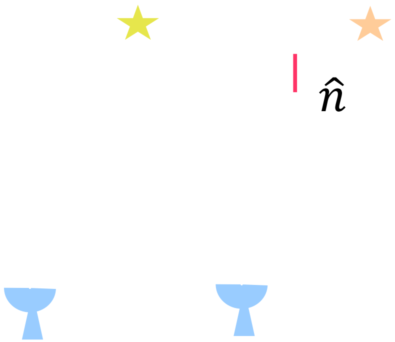
Noise

$$V\left(\overrightarrow{b_{ij}}\right) = M_{ij}(\nu,t)\ S_{ij}(\nu,t) \iiint M_{ij}\,(\vec{s},\nu,t)\ I^{sky}(\vec{s},\nu,t)\ e^{2\pi i\,(\overrightarrow{b_{ij}}\cdot\vec{s})}\ d^3\vec{s} \quad + \ n$$

Instrumental and Atmospheric Effects

Geometric effects





Measurement Equation : Forward Problem

Observed Data — **K-space Sampling** — **Image of Sky Brightness** — **Noise**

$$V(\overrightarrow{b_{ij}}) \;=\; M_{ij}(\nu,t)\;\; S_{ij}(\nu,t) \iiint M_{ij}\,(\vec{s},\nu,t)\;\; I^{sky}(\vec{s},\nu,t)\;\; e^{2\pi i\,(\overrightarrow{b_{ij}}\cdot\vec{s}\,)}\, d^3\vec{s} \;\;+\;\; n$$

Instrumental and Atmospheric Effects — **Geometric effects**

Same functional form as MRI => Similar image reconstruction problem

Measurement Equation : Solving

Observed Data

K-space Sampling

Image of Sky Brightness

Noise

$$V(\overrightarrow{b_{ij}}) = M_{ij}(\nu, t)\; S_{ij}(\nu, t) \iiint M_{ij}(\vec{s}, \nu, t)\; I^{sky}(\vec{s}, \nu, t)\; e^{2\pi i\,(\overrightarrow{b_{ij}}\cdot\vec{s})}\, d^3\vec{s} \quad + \; n$$

Calibration

Measurement Equation : Solving

Observed Data

K-space Sampling

Image of Sky Brightness

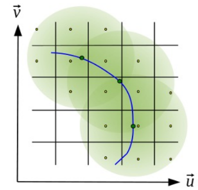
Noise

$$V(\overrightarrow{b_{ij}}) = M_{ij}(\nu,t)\ S_{ij}(\nu,t) \iiint M_{ij}(\vec{s},\nu,t)\ I^{sky}(\vec{s},\nu,t)\ e^{2\pi i\,(\overrightarrow{b_{ij}}\cdot\vec{s})}\, d^3\vec{s} + n$$

Calibration

Inverse Imaging

Gridding + iFFT



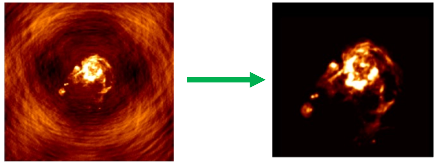
Measurement Equation : Solving

$$V(\overrightarrow{b_{ij}}) = M_{ij}(\nu,t)\ S_{ij}(\nu,t) \iiint M_{ij}(\vec{s},\nu,t)\ I^{sky}(\vec{s},\nu,t)\ e^{2\pi i\,(\overrightarrow{b_{ij}}\cdot\vec{s})}\, d^3\vec{s} \quad + \ n$$

- $V(\overrightarrow{b_{ij}})$: Observed Data
- $S_{ij}(\nu,t)$: K-space Sampling
- $I^{sky}(\vec{s},\nu,t)$: Image of Sky Brightness
- n: Noise

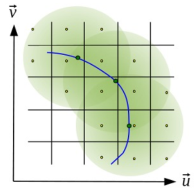
Calibration: $M_{ij}(\nu,t)$

Image Reconstruction: $S_{ij}(\nu,t)$, $I^{sky}(\vec{s},\nu,t)$



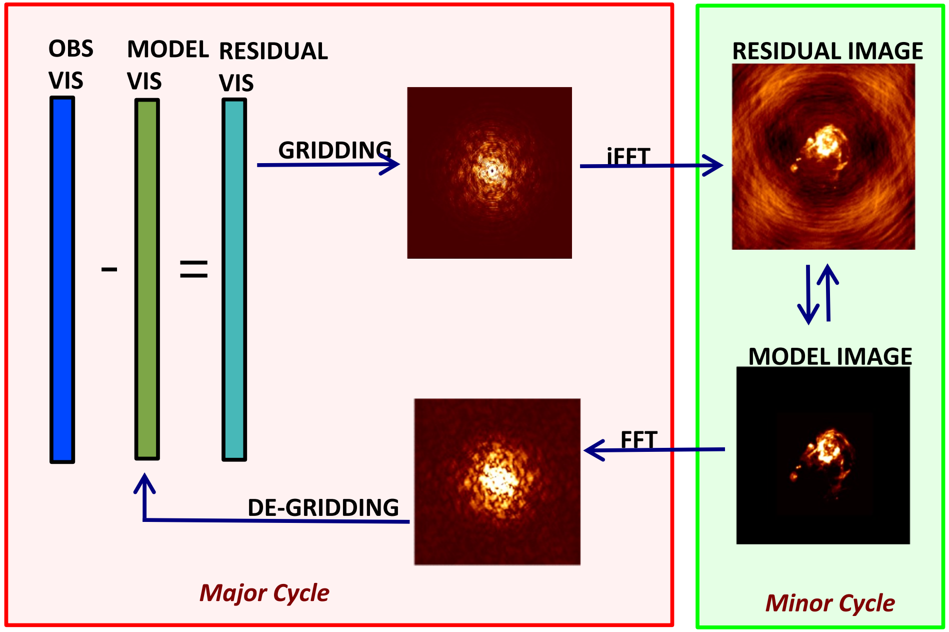
Inverse Imaging: $M_{ij}(\vec{s},\nu,t)$, $e^{2\pi i\,(\overrightarrow{b_{ij}}\cdot\vec{s})}$

Gridding + iFFT



Forward and Inverse Problems : Iterative Optimization algorithms

$$V^{obs} = [A]I^m + n \quad \Rightarrow \quad I^m = [A]^{-1}V^{obs}$$



Data regularization : L2 (chi-square)

Sky model

- Delta functions, Gaussians, Wavelets, etc, etc..
- Multi-frequency and time-variable models
- Astrophysics models (non-imaging)

Constrained Optimization

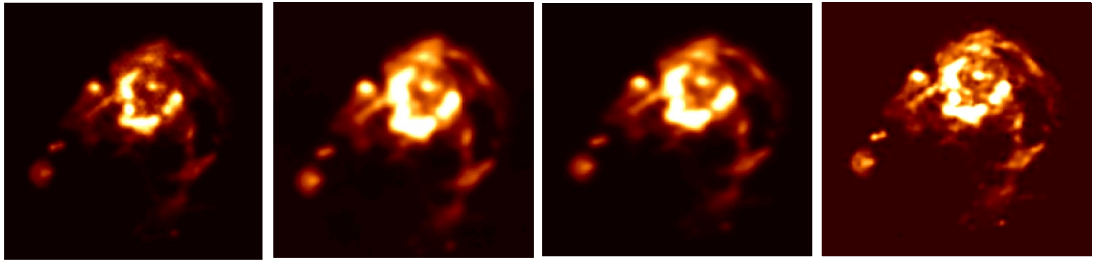
- Log power spectrum, positivity, smoothness
- Manual constraints : spatial masks, iteration control
- Greedy algorithms vs Parameterized solvers
- L1 , TV norm, etc…

Instrumental corrections

- Wide-field and wide-band antenna response patterns,
- Ionospheric refraction corrections
- 3D to 2D effects, K-space ‘hole’ effects.

Forward and Inverse Problems : Iterative Optimization algorithms

$$V^{obs} = [A] I^m + n \quad \Rightarrow \quad I^m = [A]^{-1} V^{obs}$$



Algorithmic variability

Data regularization : L2 (chi-square)

Sky model

- Delta functions, Gaussians, Wavelets, etc, etc..
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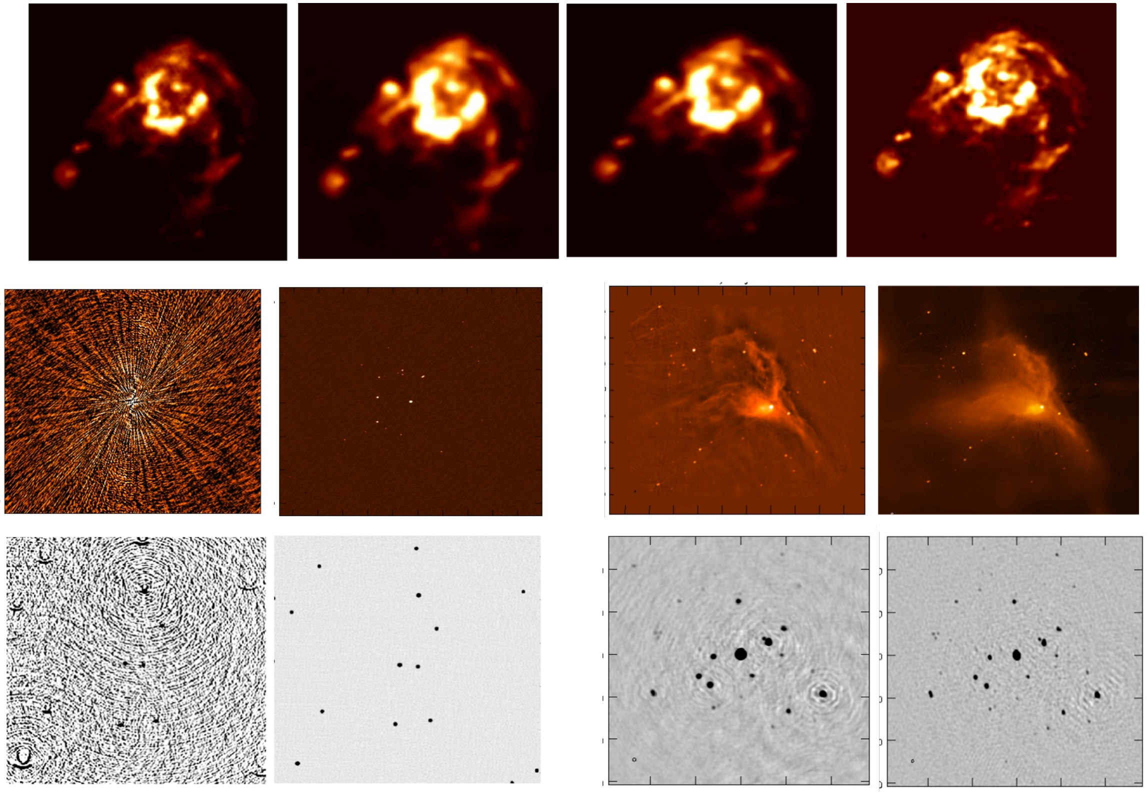
Forward and Inverse Problems : Iterative Optimization algorithms

$$V^{obs} = [A]I^m + n \quad \Rightarrow \quad I^m = [A]^{-1}V^{obs}$$



Data regularization : L2 (chi-square)

Sky model

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Constrained Optimization

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- L1 , TV norm, etc…

Instrumental corrections

- Wide-field and wide-band antenna response patterns,
- Ionospheric refraction corrections
- 3D to 2D effects, K-space 'k=0 hole' effects.

The R&D frontier

New Instruments : More sensitive, Lower image noise, Detect Fainter Sources
Larger Data Volume, Greater Algorithm Complexity

Algorithms :

- A variety of sky models, instrument models, objective functions and regularizers, optimization strategies, the use of priors, etc..

=> Increased exploration of Machine Learning.

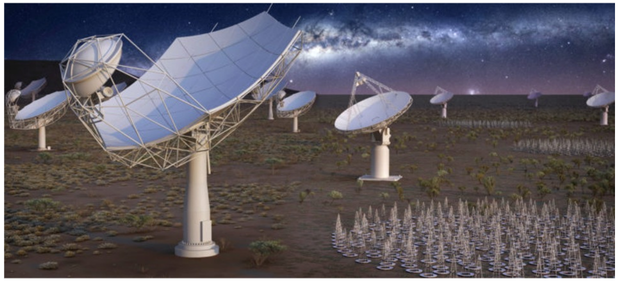
Compute Load :

- Data volumes : 10s to 100s of GB ➔ ngVLA/SKA : TeraBytes/PetaBytes/ExaBytes
- Image sizes : 10kx10k ➔ 200k x 200k pixels (with 10k channels and 4 pols)

=> High Performance and High Throughput Computing

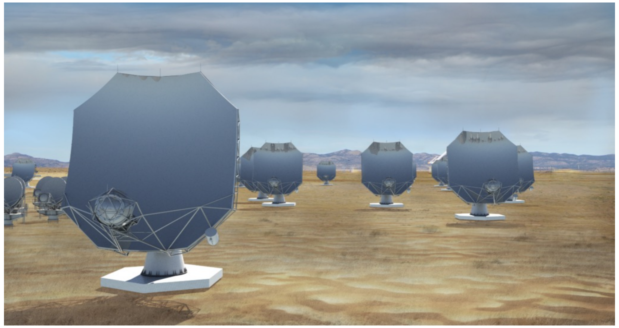
Automation :

- Data analysis pipelines that tune parameters for each dataset



Square Kilometer Array (skatelescope.org)

2K dishes, 1M antennas , 50 MHz – 30 GHz



Next Generation VLA (ngvla.nrao.edu)

263 dishes (2 types) , 1-100 GHz

Acknowledgements

NYU Langone

- Dan Sodickson. : Cells-To-Galaxies + Exploring the relation between medical imaging and radio astronomy
- Organizers of the i2i workshop

National Radio Astronomy Observatory

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- Many colleagues at NRAO

New Mexico Tech

- Ramyaa R. : Computer Science + ML