NYU Langone Health

From Innerspace to Outer Space: Why? A Preamble

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Radiology Department

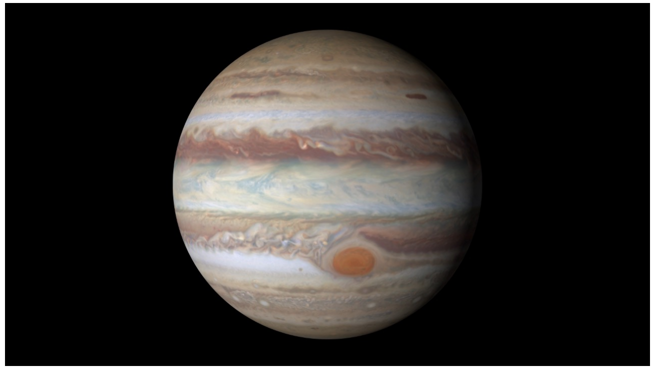
Conflicts of Interest

- None relevant

Overview

- Medical imaging and astronomy work at vastly different scales; however, there are many parallels between them:
- “Remote sensing” of regions where cannot directly sample
- Reliance on Fourier methods
- Inverse problems to find underlying structure from data/observations
- Reliance on modeling; need for calibration, deconvolution of “psf”
- Need to account for effects of intervening “medium”
- Multispectral/multimodality/multidimensional imaging in both
- Associated visualization issues
- Potential for machine learning approaches

My Background



- PhD in Astrophysics from Princeton (1971)
  - Thesis on modeling the atmosphere of Jupiter from observations (combining UV, visible, IR data)
  - However, I wanted to do work more directly related to people
  - I was also fascinated by the concept of the body as a mechanism- e.g., Leonardo, Descartes, Helmholtz…
- MD and radiology residency at UCSF
  - Research on modeling perfusion from dynamic CT enhancement data
- Subsequent clinical and research work on cardiovascular MRI
  - Quantitative perfusion and function imaging with MRI

Some of my Research Approaches/Activities

- Astronomers were early users of digital imaging, “multispectral” data
- Trying to model quantitative imaging of Jupiter for my thesis, I found discrepancies between visible (terrestrial) and far-UV (space) data
- I showed that these data could be reconciled if there were suitable small absorbing particles high in the atmosphere of Jupiter; these were subsequently found to be present by tracking a space probe fly-by
- In radiology, most people have approached imaging as qualitative pattern recognition; I was trained to see images as spatially distributed data
- My subsequent research has focused on using quantitative imaging to better understand physiology/pathophysiology, particularly cardiovascular

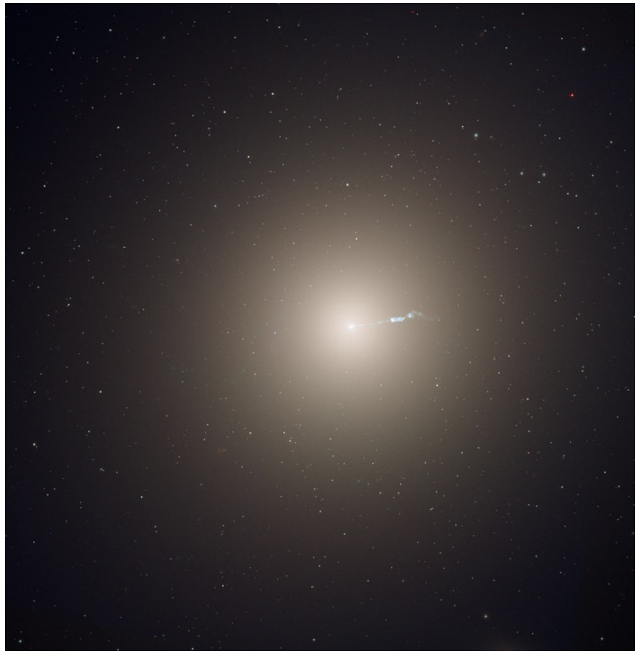
Medical Imaging and Astronomy Work at Vastly Different Scales (“Heavenly and Human Bodies”)

- Human perception (initial observations of both):
  - Visual spectrum, about 380 to about 750 nanometers
  - Times: ~fractions of a second to seconds
  - Angular resolution ~ 0.017° (augmented by optics)
  - Dynamic range depends on overall brightness
- Astronomical structures (“heavenly bodies”):
  - Solar system: cms (through remote probes) to orbits (AU ~1.5 x 10^8 km)
  - Galaxies: light years to billions of light years
  - Times: seconds to billions of years
- Human structures (“bodies”):
  - Organs ~cms; cells ~microns
  - Times ~fractions of a second to years

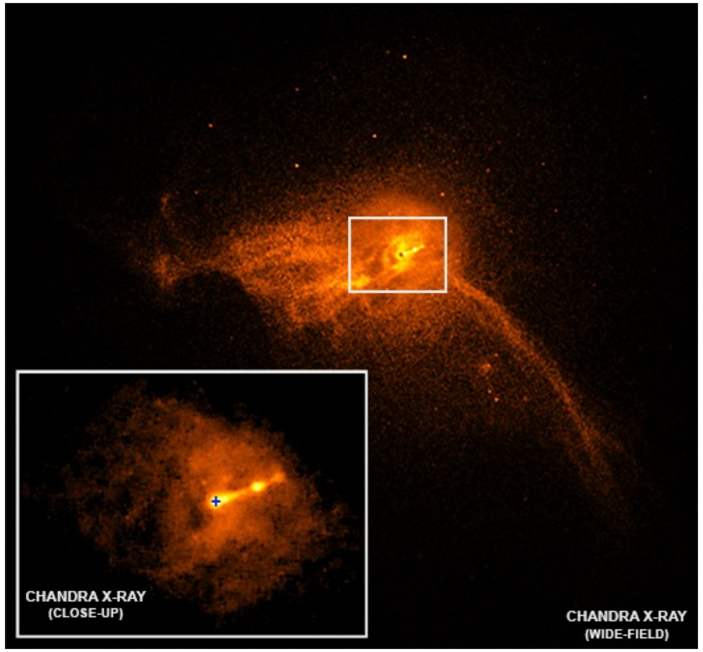
However, Both Depend on “Remote Sensing” to Explore Inaccessible Regions

- Direct sampling of solar system possible only where can reach with probes; otherwise dependent on passively received signals
- Invasive imaging of humans has risks, changes the nature of the system being studied; so medicine primarily relies on indirect imaging
- Even “invasive” sampling methods rely heavily on imaging guidance
- Suitable analysis of imaging data for both can reveal underlying structures and aspects of their nature
- Both domains rely on modeling of underlying structures, and on physics of imaging, to gain understanding

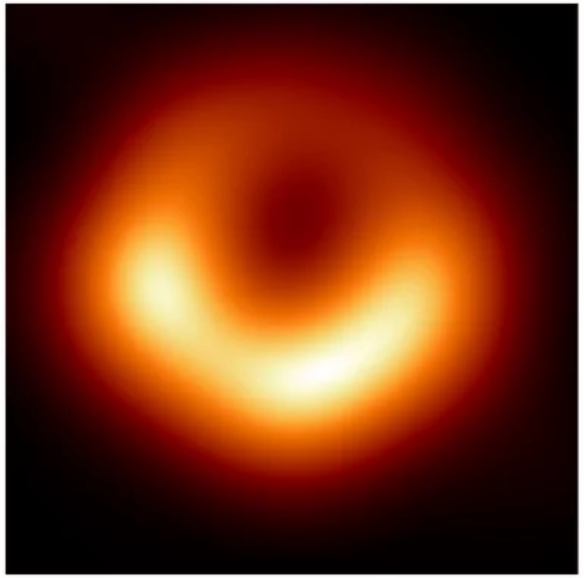
M87 Elliptical Galaxy with Jet and Black Hole



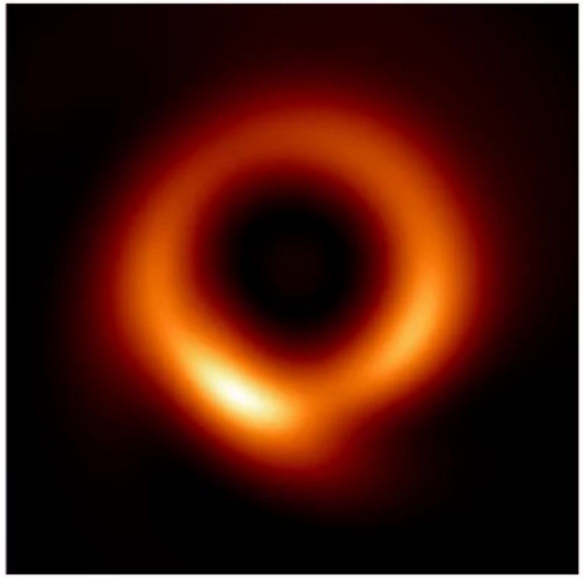
Hubble Space Telescope
(optical image)



Chandra X-ray Observatory
(x-ray space telescope)



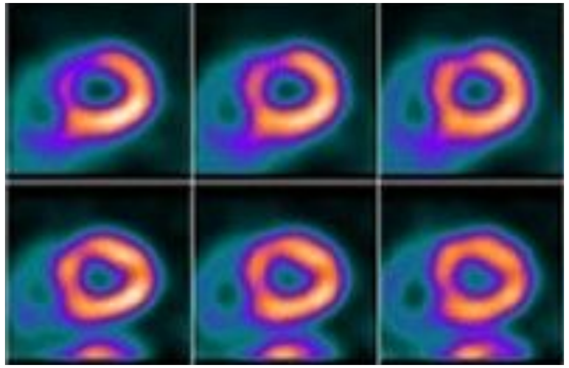
2019



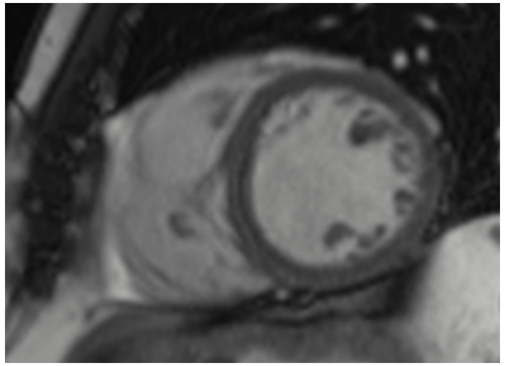
2023

Event Horizon Telescope
(radio waves)

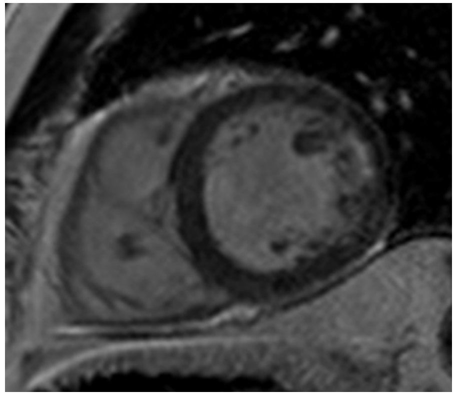
Cardiac Imaging Examples



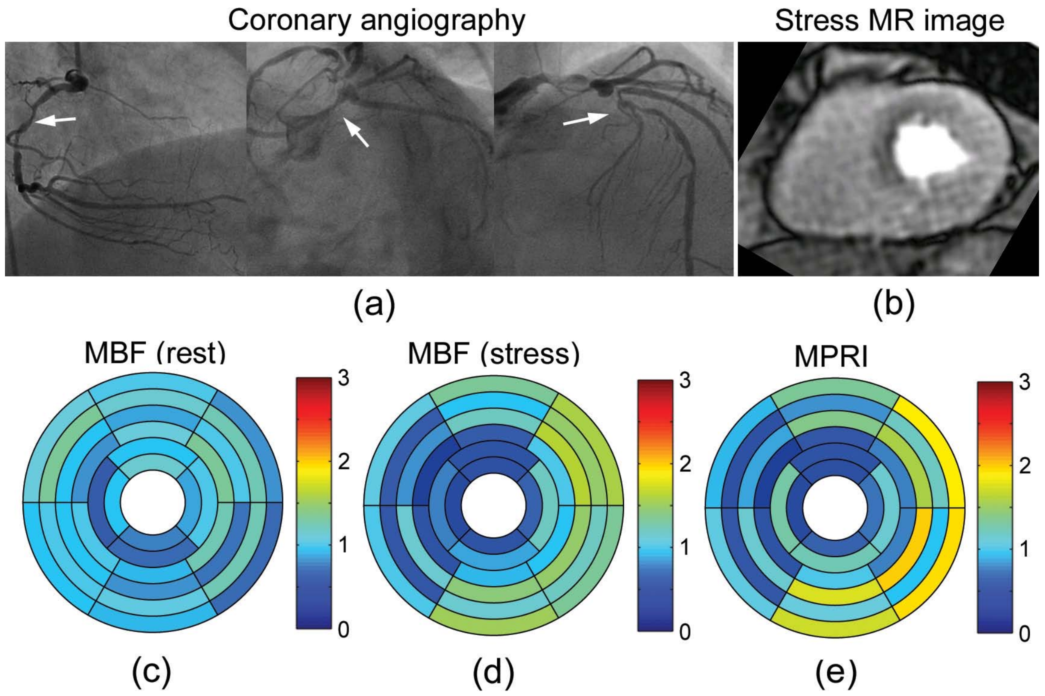
Radionuclide



Cine MRI



LGE MRI



Quantitative MRI perfusion

Resolution Limits (Spatial and Temporal)

- Astronomy:
  - “Lens” apertures; detector arrays (size, spacing)
  - Interferometry baselines
  - Data sampling rates (limited by SNR)
  - Observation durations limited by resources
- Medical Imaging:
  - Can use MRI detector arrays (size, spacing)
  - Gradient limits in MRI
  - Data sampling rates (limited by SNR)
  - Imaging durations limited by resources, patient tolerance

Inverse Problems in Both Kinds of Imaging

- How to study underlying structures and their properties from limited indirect observations?
- Need calibration of detectors
- Limited by undersampling of available data
  - Rely on “regularization” to make problems tractable
- Can use modeling of structures and imaging processes
  - Relate “forward” and “backward” propagation of data; can iterate
- Need to account for effects of intervening/surrounding medium
  - Absorption, scattering, “refraction”/distortion
- Need deconvolution of “point spread functions” in space and time
- “Big data”-scale (terabyte) data processing challenges

Multispectral, Multidimensional, and Multimodality Imaging in Both Domains

- Multispectral/spectroscopic imaging
  - “Color”/brightness, spectrum for star classification
  - “Relaxation times” and spectra for MRI tissue classification
- Data can extend well beyond visual spectrum (x-ray to UV; IR to RF)
- Combine data from different kinds of sources
  - Overlay astronomical observations ranging from gamma ray to radio astronomy
  - Radionuclide tracer imaging overlaid with anatomic images from MRI or CT
- Can turn temporal series data into underlying time-related variables
  - Orbits of exoplanets or around black holes; gravitational radiation effects
  - MRI contrast kinetics for modeling tissue perfusion, delayed enhancement
  - MRI of tissue kinetics or deformation

Visualization Challenges for Both Domains

- Limits of human eye-brain combination for comprehending displays
  - Flat retinas- only stereo, shaded, interactive slice/angle displays available for adding depth information
  - Mapping other kinds of data to visual displays
  - Trichromatic color vision- limited information content of color
  - Nonlinear/uncalibrated subjective perception of color and brightness
  - Limited ability to integrate separately presented displays
- How to efficiently/effectively explore large multidimensional (space/time/”spectrum”) data sets?

Both Have Potential for Using Machine-Learning Approaches

- Can learn automated classification from images (annotated data sets/”self-supervised”)
- Can learn processes for image reconstruction from raw data
- Potential for “super-resolution” image reconstructions
- Potential for combined analysis of mixed data sets

Conclusions

- Despite the great apparent differences in their subjects, there is much in common between the tools of medical and astronomical imaging
- Solutions developed for data handling (e.g., image reconstruction/analysis/display) in one domain may have potential applications in the other
- More scientific exchange between the two domains may help lead to advances in the corresponding methods used in both

NYU Grossman School of Medicine

Thank you

NYU Langone Health

From Inner Space to Outer Space : How?

Klaas Prüssmann, PhD

Urvashi Rau, PhD

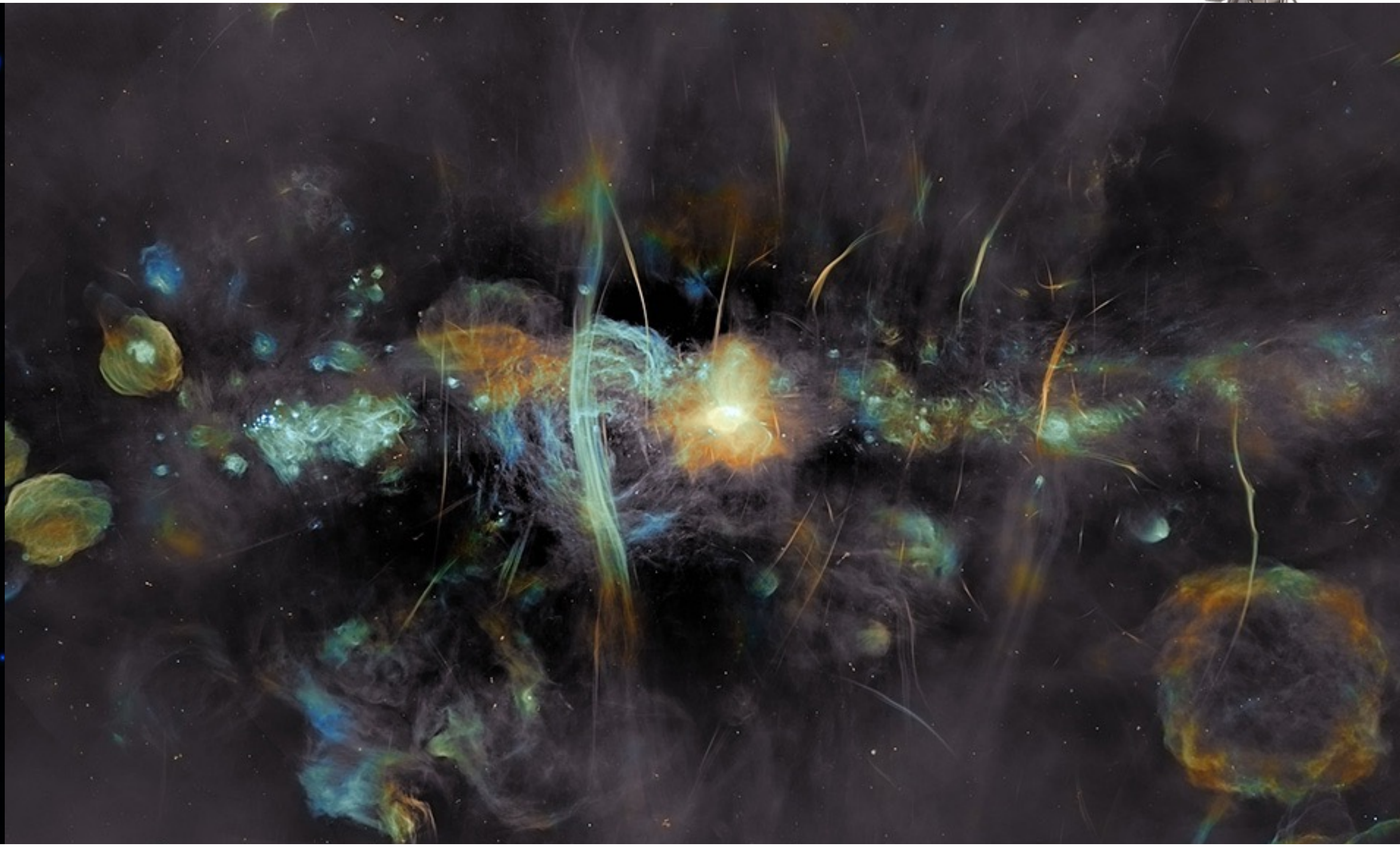
Imaging in Astronomy

Objects in space emit electromagnetic radiation

Imaging in Astronomy

Crab Nebula

Credit: G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.; NRAO/AUI/NSF; A. Loll et al.; T. Temim et al.; F. Seward et al.; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI



Center of the Milky Way galaxy

Credit : SARAO, Heywood et al (2022), J.C. Munoz-Mateos

Imaging in Astronomy

What we measure :

Intensity of the received power
EM Polarization
Spectral structure
Time-variability

Quantitative !

What we infer :

Temperature, Energetics,
Emission Physics
Chemical Composition
Magnetic Fields
Velocities , 3D structure
Age of the source

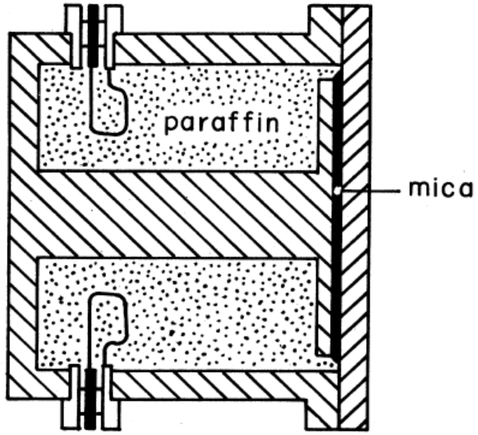
Why ?   To study new Physics

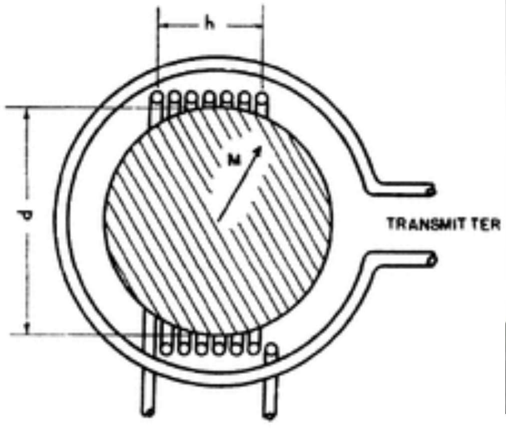
MRI: Looking inward

NMR

- Spin states of of atomic nuclei in background magnetic field
- Transitions (‘spin flips’) can be induced by on-resonant exciation
- When coherent, the nuclei give off radio signals
- Discovered 1945, by Edward Purcell und Felix Bloch
- Shared Nobel Prize in 1952

Edward M. Purcell





Felix Bloch

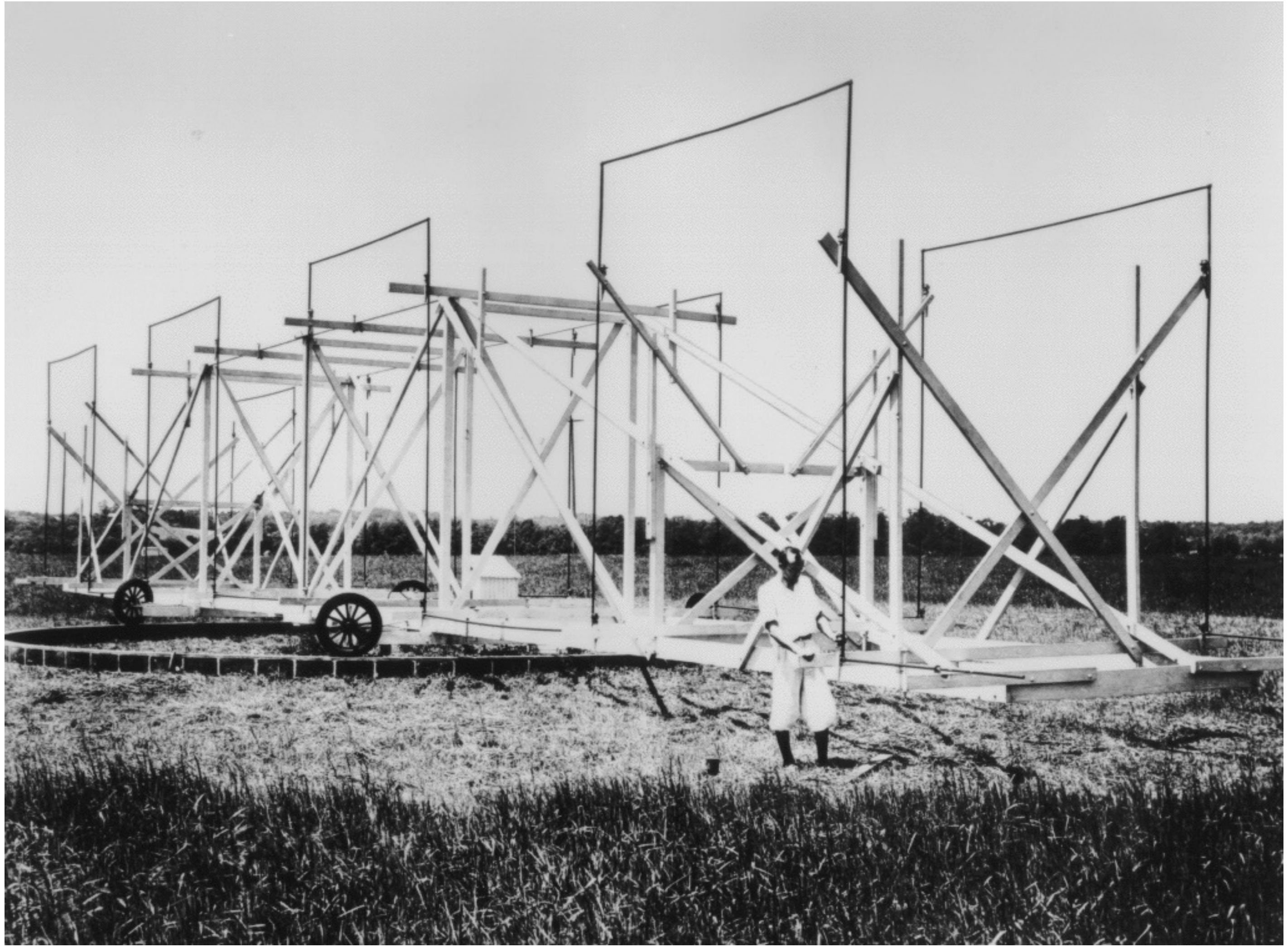
21 cm Hydrogen line…. from space

- Predicted by Van de Hulst (1945)
- Measured by Ewen & **Purcell** (1950)

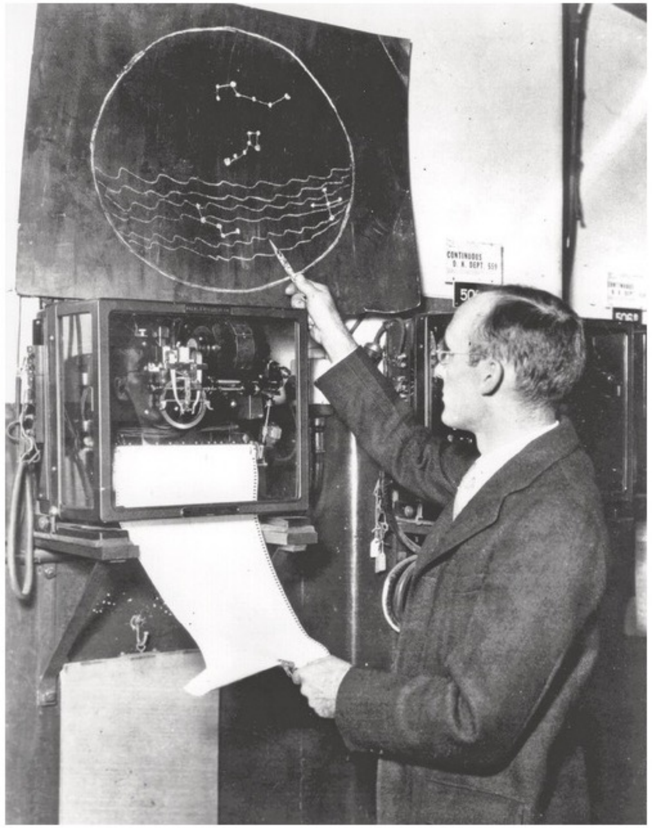
➔ The same Purcell (of NMR fame)

(Radio : Electron spin-flip transition)

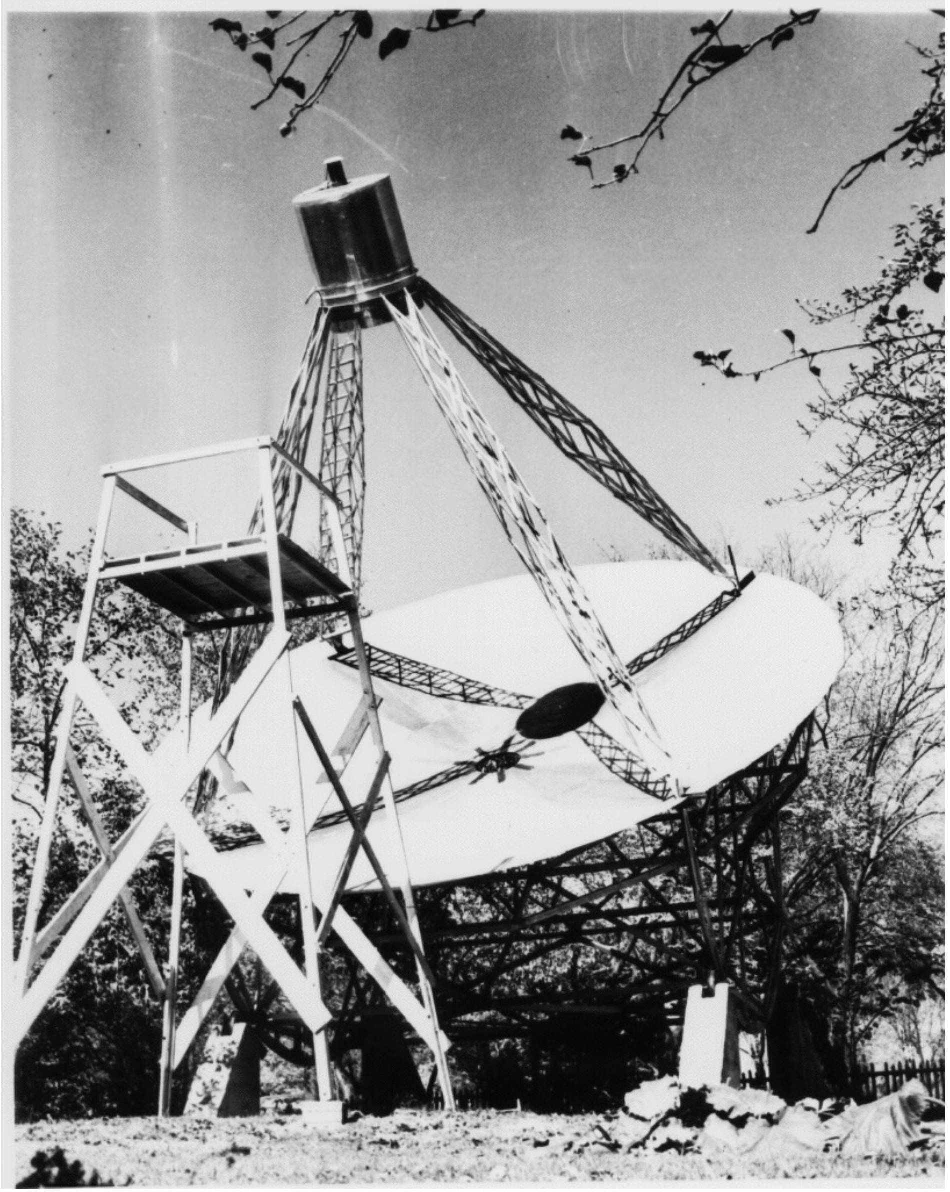
Radio Waves from the Milky Way



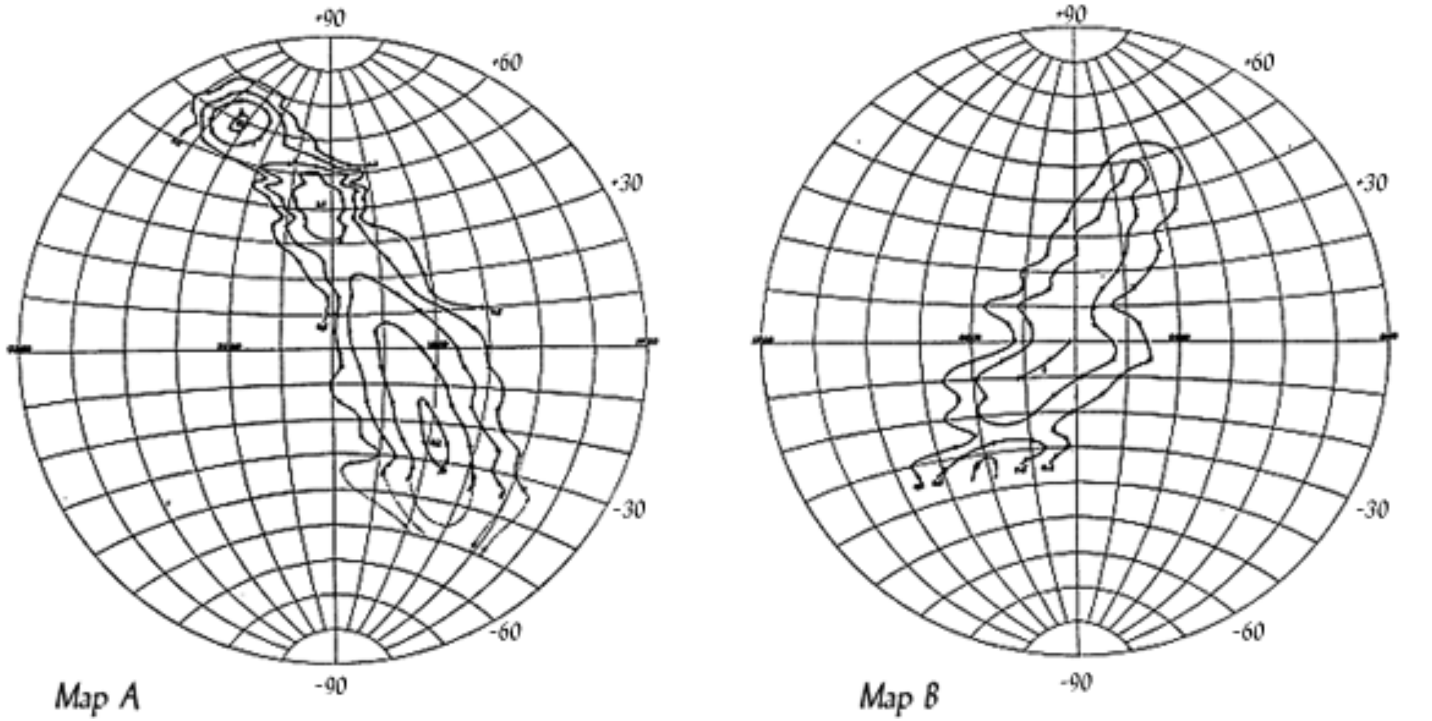
Karl Jansky (1933)



First All-sky Radio Map

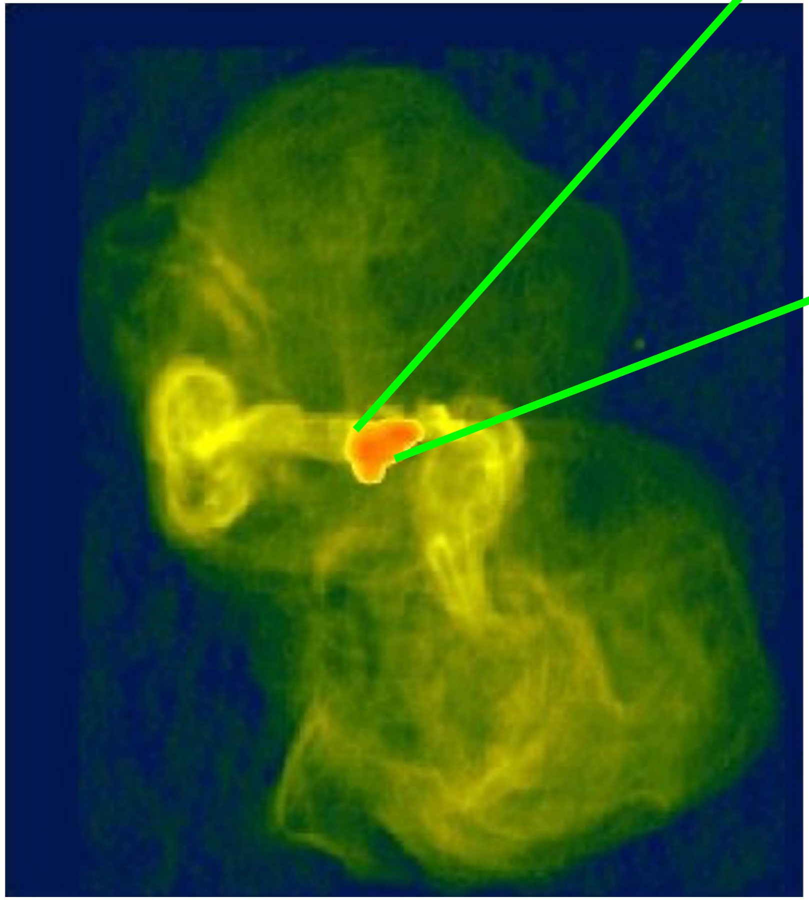


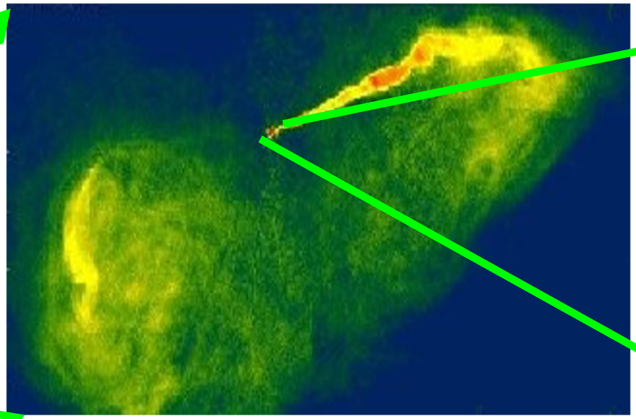
Grote Reber (1936)

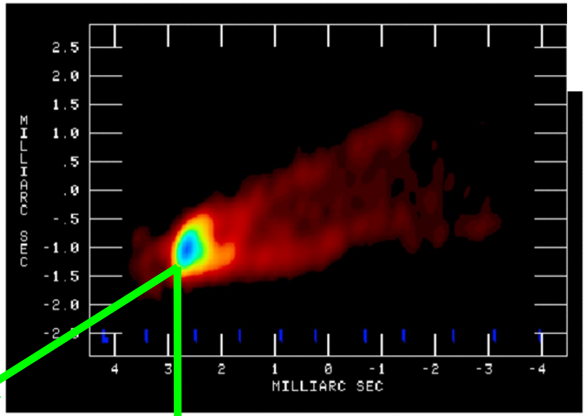


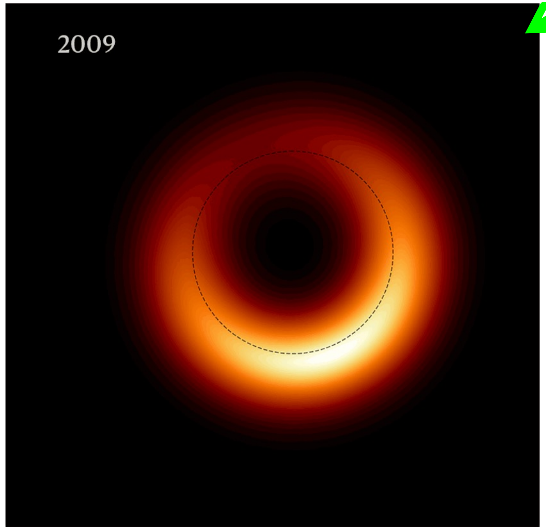
Imaging different spatial scales

50000 light years

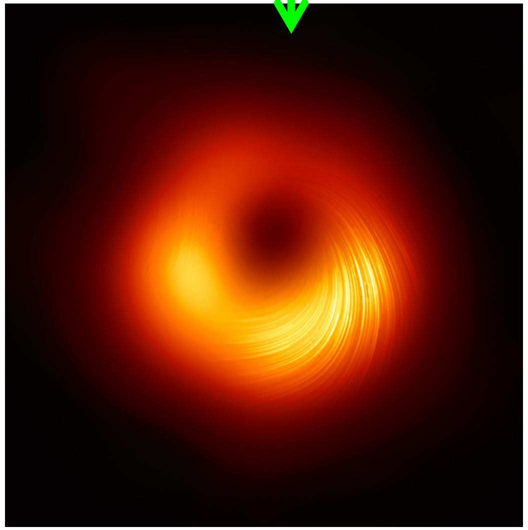








0.006 light years

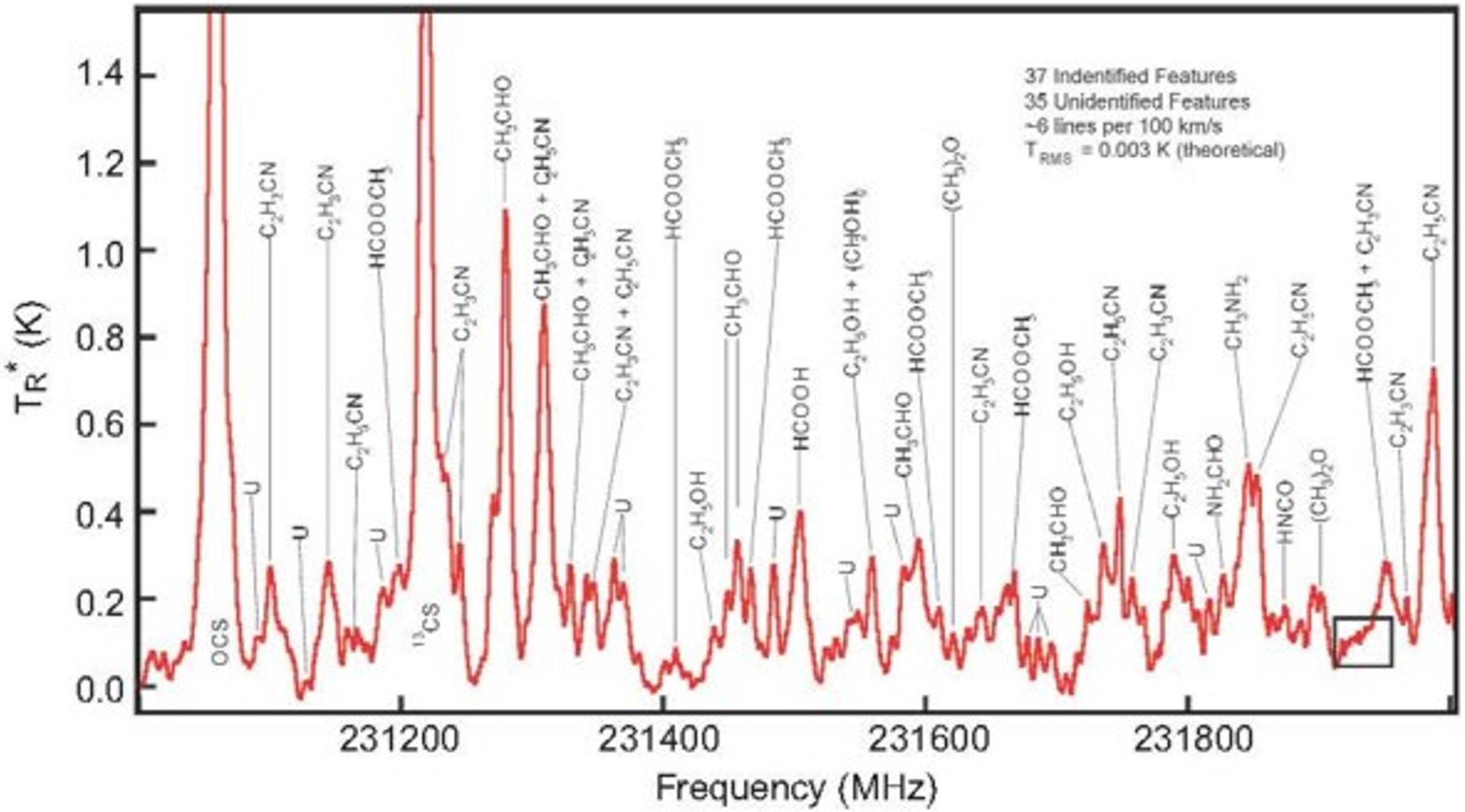


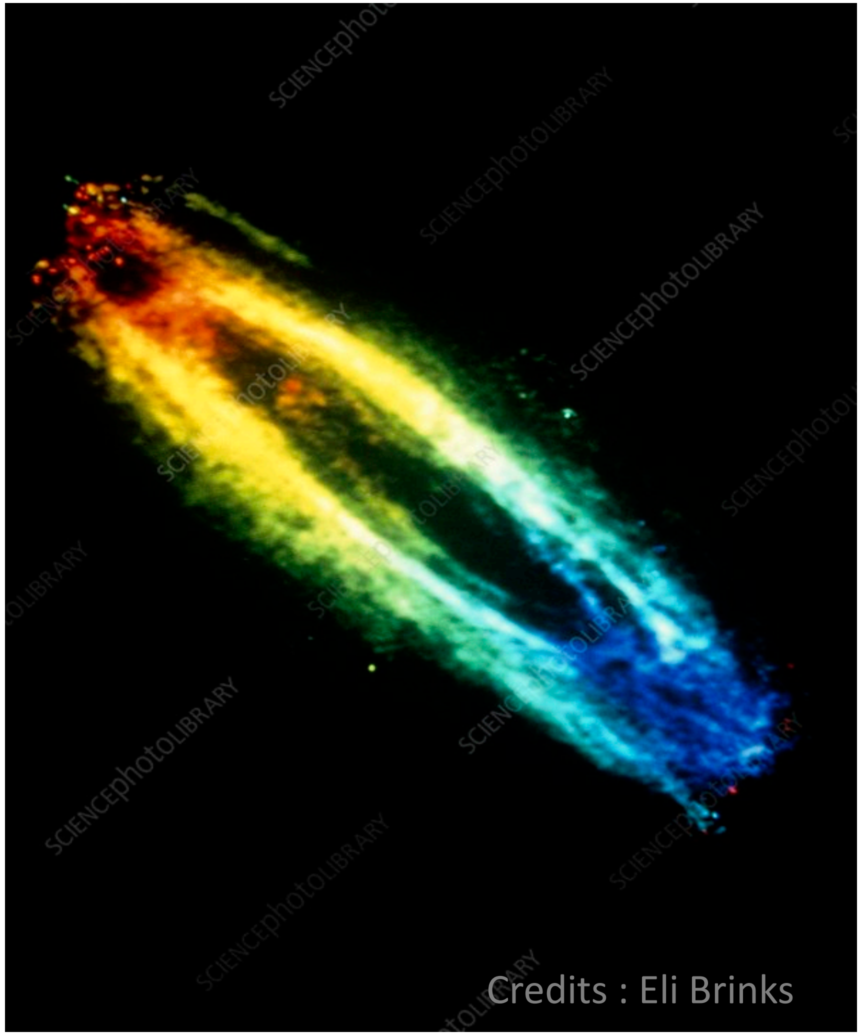
Credits :
NRAO,
ALMA,

Event
Horizon
Telescope
collaboration

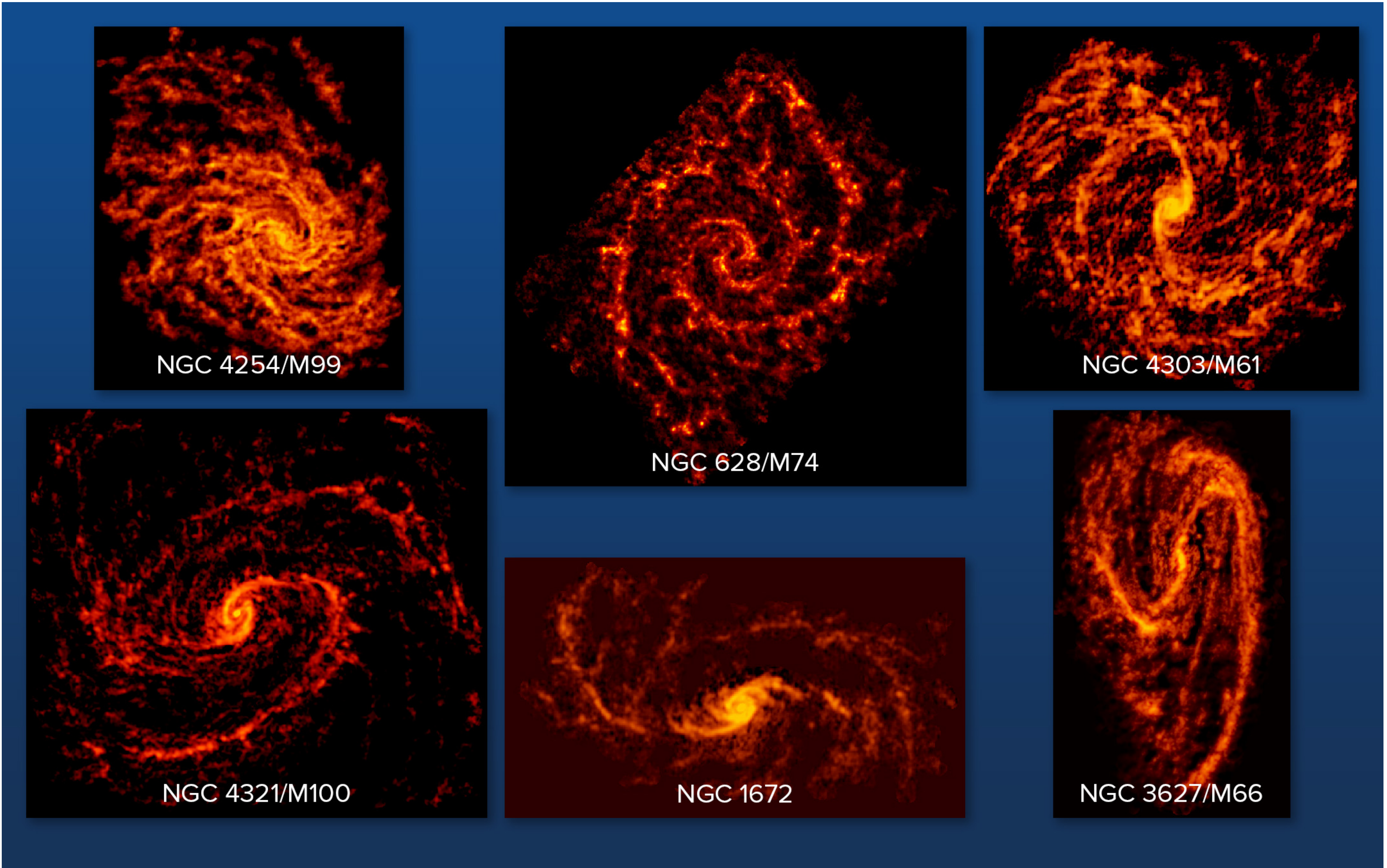
The M87 Radio Galaxy

Spectral Encoding : Chemistry + Doppler Shifts





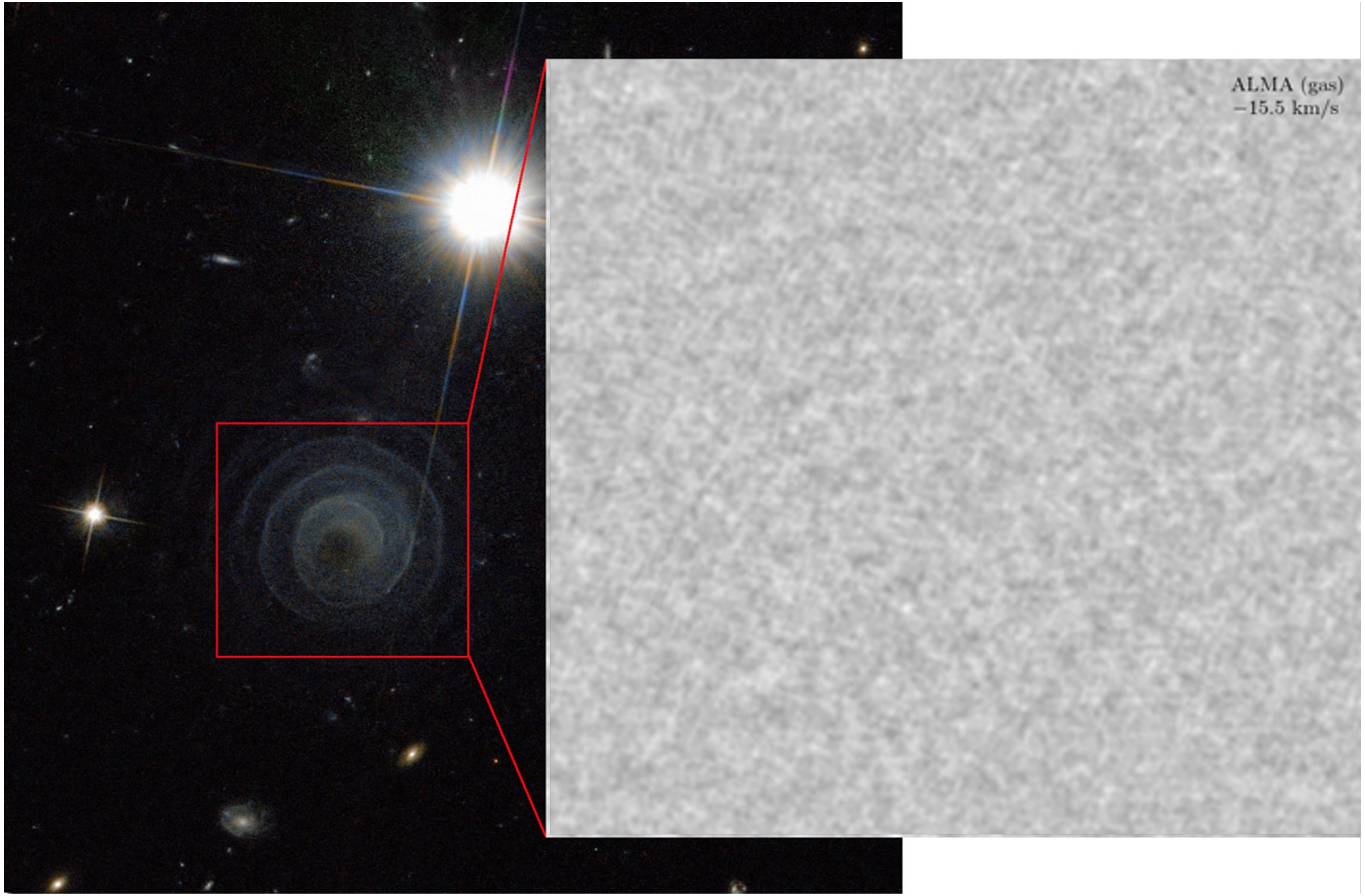
CO line : Tracer of star-formation



Star-Forming Clouds in Disk Galaxies

Credits: ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton

3D structure (spatio-spectral encoding)

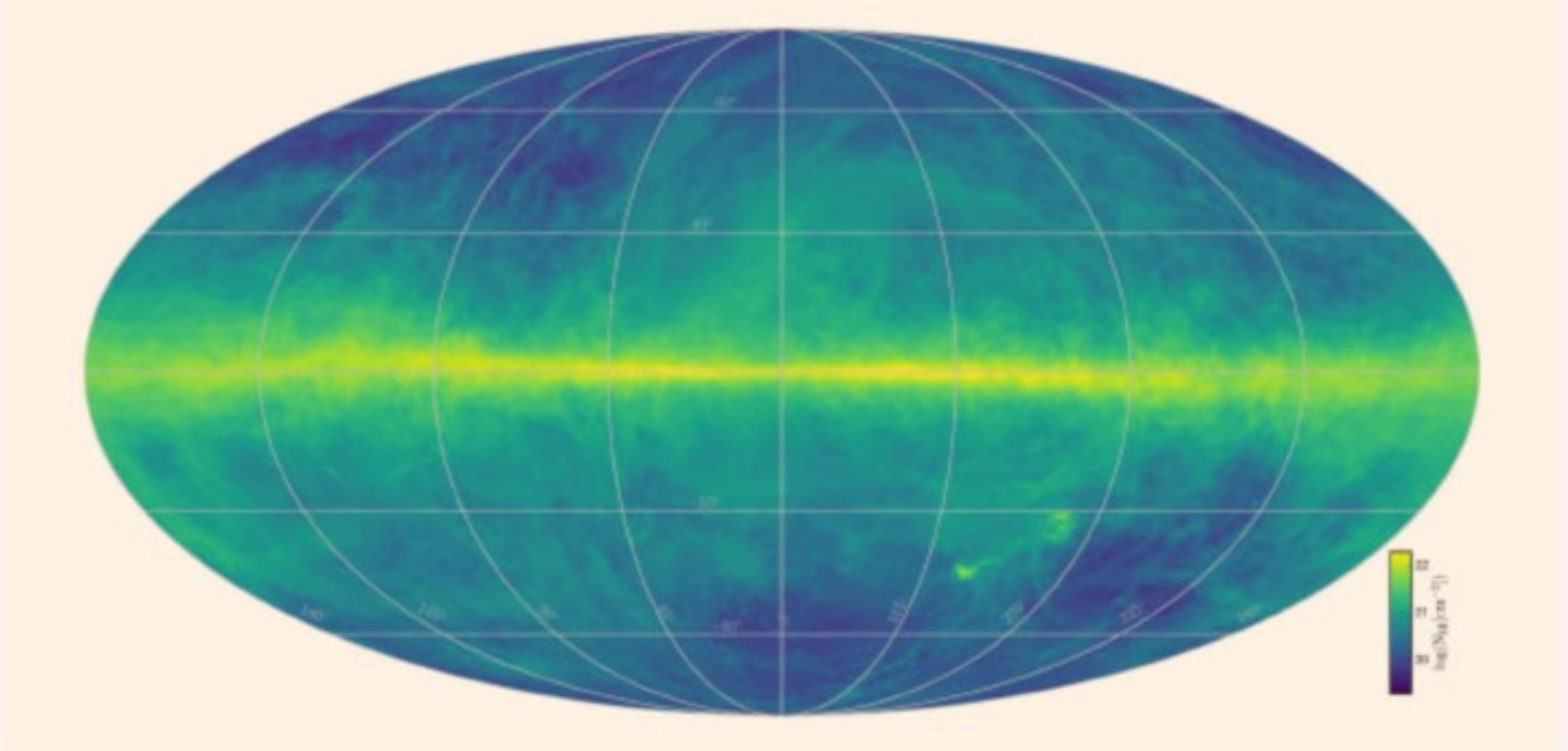


CO emission

- Spiral-shell structure around the AGB star LL Pegasi and its stellar companion

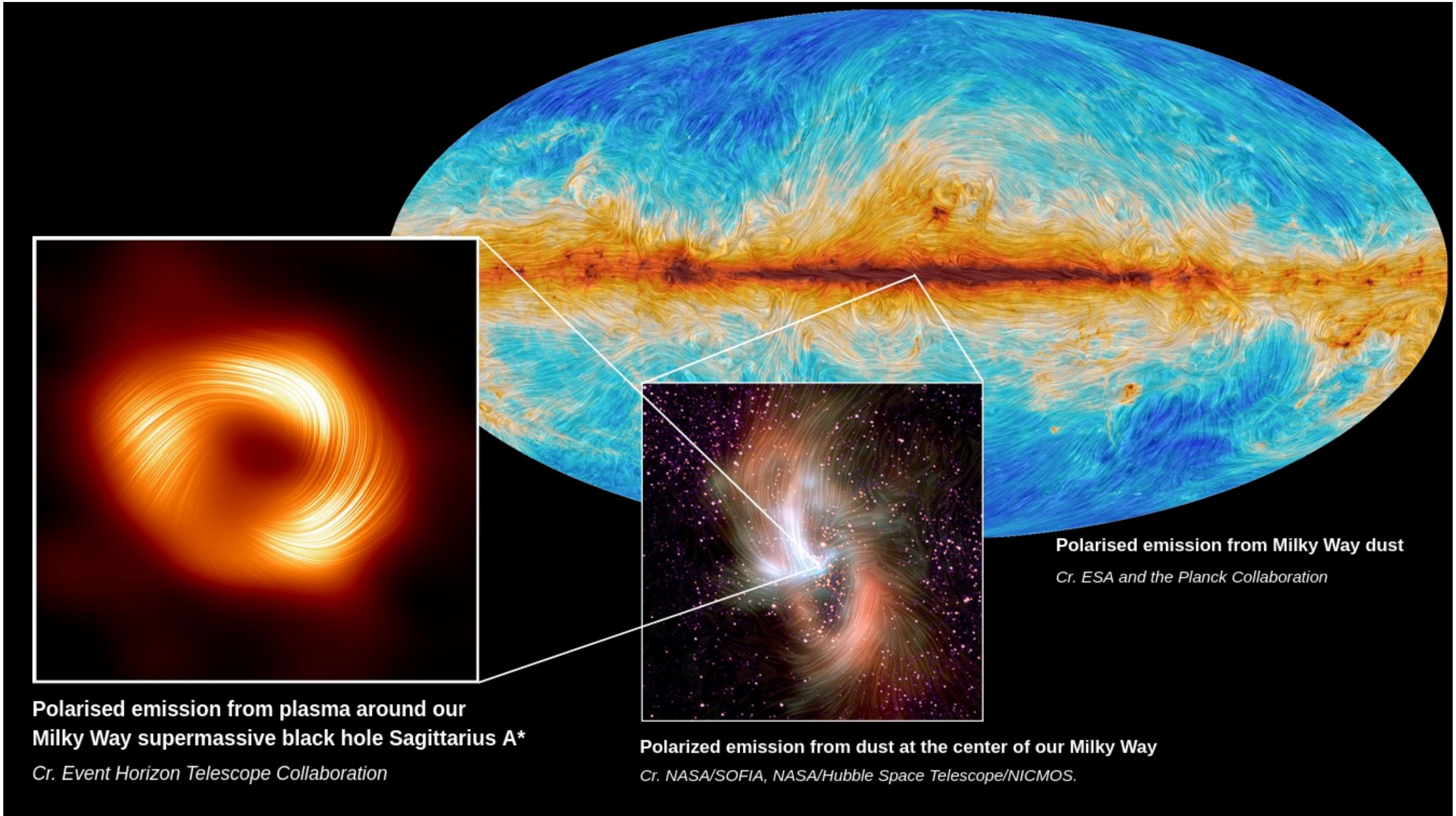
(Kim et al,
Nature Astro 2017.)

Hydrogen in the Milky Way

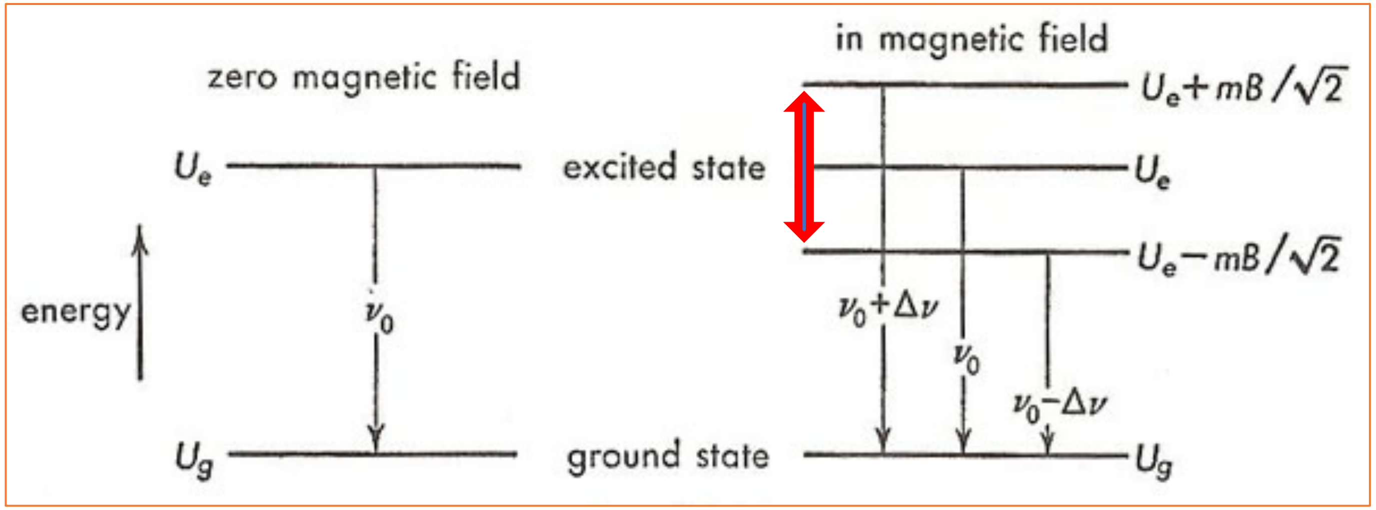


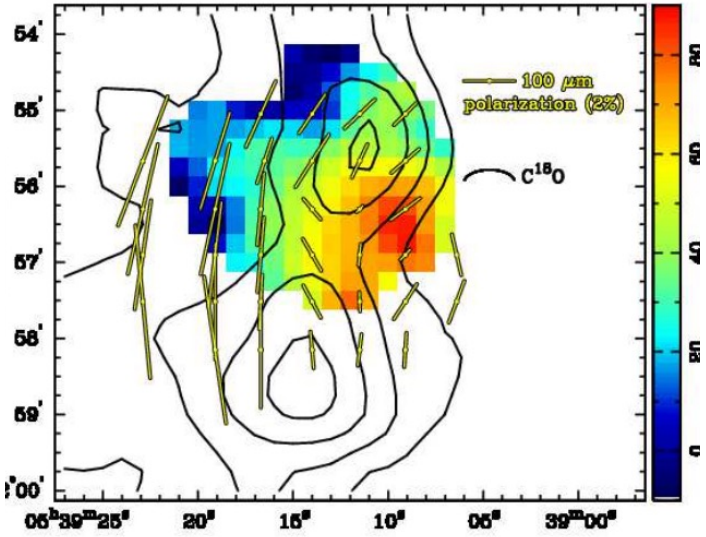
This HI4PI map was produced using data from the 100-m Max-Planck radio telescope in Effelsberg, Germany and the 64-m CSIRO radio telescope in Parkes, Australia. The image intensity reflects the total hydrogen content. The plane of the Milky Way Galaxy runs horizontally across the middle of the image. Image credit: Benjamin Winkel / HI4PI Collaboration.

B-field direction (polarization angle)

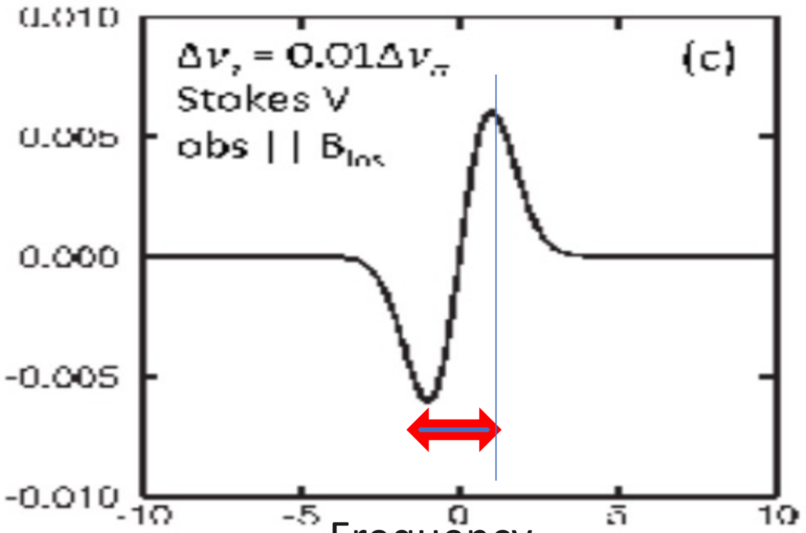


In-situ B-field strength (Zeeman effect)





Stokes V



Frequency

B-field from OH Zeeman lines

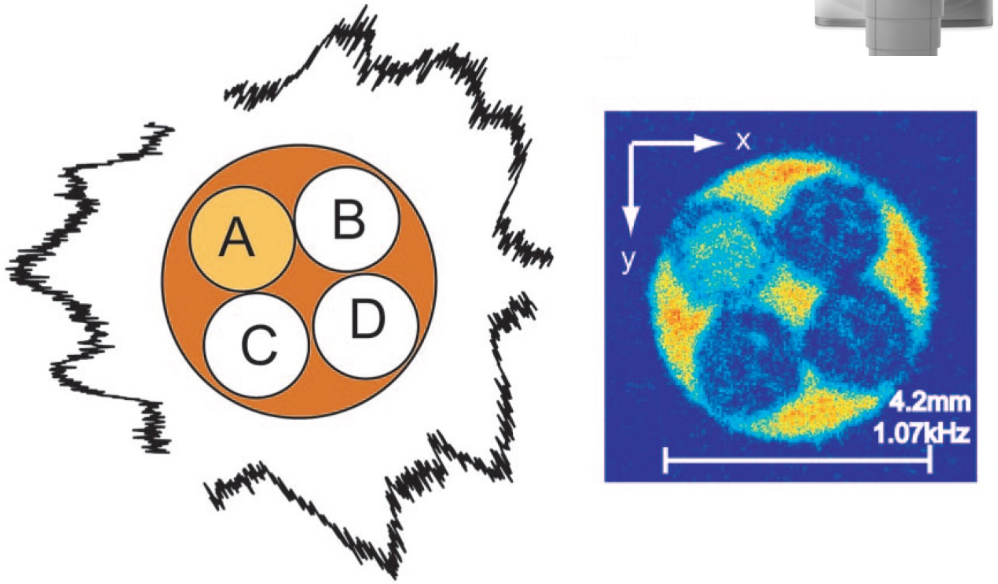
NGC2024 star-forming region

Credits : Crutcher & Kemball, 2019

MRI from natural emission?

Natural emission = very convenient !

We can actually do that, too: spin-noise imaging
- no RF excitation
- just random (thermal) coherence
- very insensitive though



N Müller, A Jerschow, PNAS 103:18 (2006)

Better: RF excitation for strong, coherent signal

But signals still only in the μW range, compare to kW for excitation

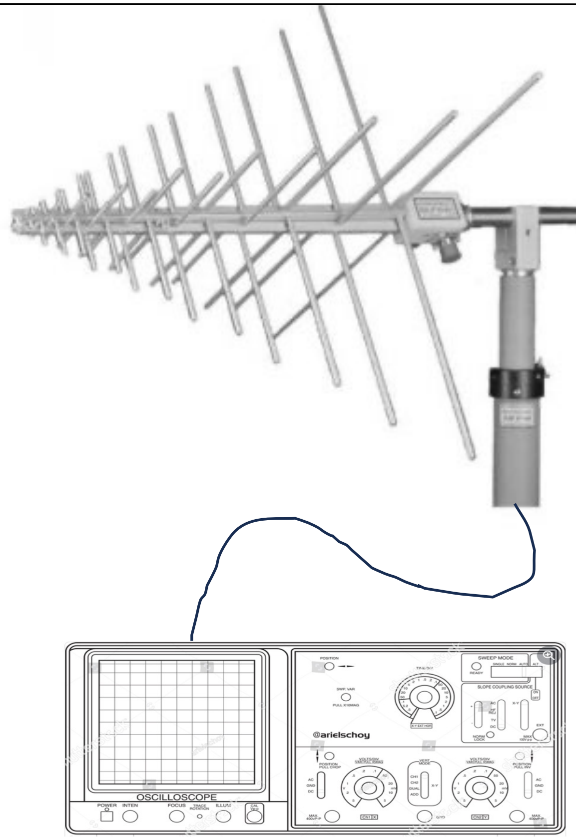
Reflects the fact that NMR is weak

Downside: low SNR   Upside: nuclei are largely transparent to signal from kin requirement for looking into the body

What do we measure ?

Spectral Power Flux Density

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



... and noise

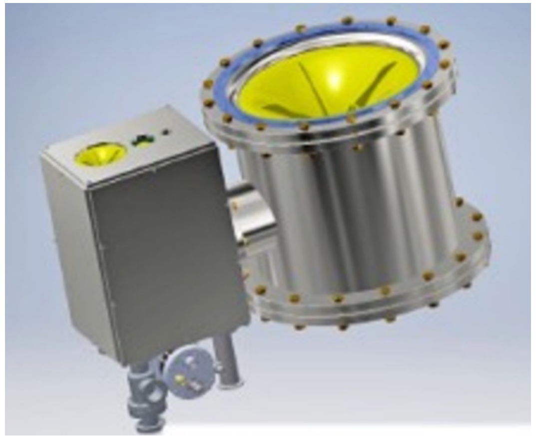
Very weak signals...

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

(We also look through the atmosphere/ionosphere + RF interference)

Increasing SNR

- Use dishes to increase collecting area



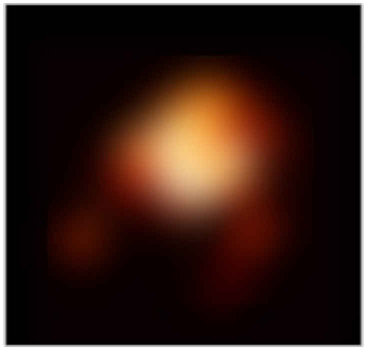
- Cooled receivers
- Low noise amplifiers

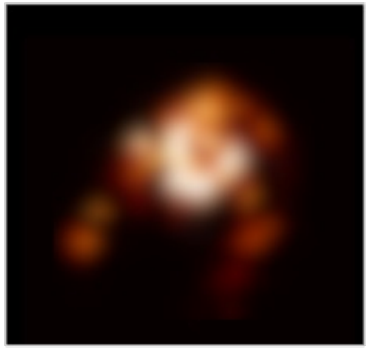
Accumulate data in time and frequency

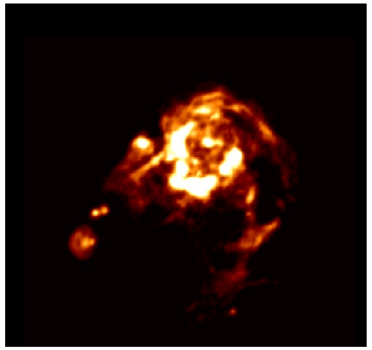
Sky : 2.7K
Ambient : 300K
Current instruments : ~ 20 K

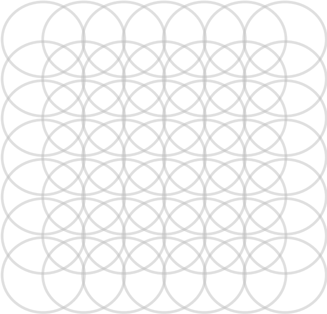
(Ref. CDL, NRAO)

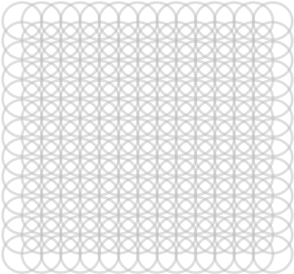
How do we make an image ?

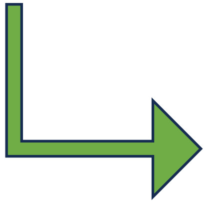


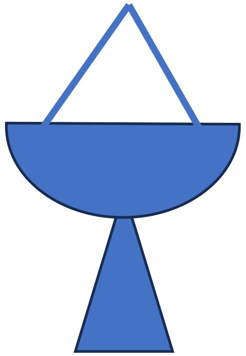


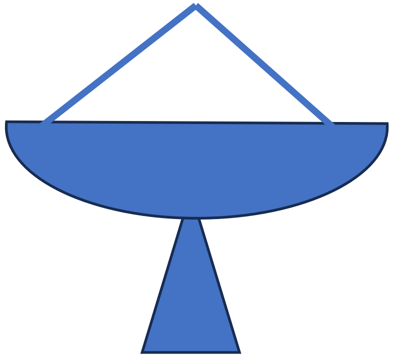












Raster Scan

Angular resolution

$$\theta = 1.22 \ \lambda/D$$

D is limited by structural constraints

The largest single-dish telescopes

Green Bank Telescope, USA

Arecibo, Puerto Rico, USA

The largest single-dish telescopes

Green Bank Telescope, USA

Arecibo (1963 - 2020)

The largest single-dish telescopes

Green Bank Telescope, USA

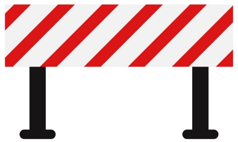
FAST, China

MRI and Optics

Diffraction limit: $\Delta x \geq \dfrac{\lambda}{2\,NA}$ $\quad \lambda = 10 - 100\ cm \quad \Rightarrow$ **useless resolution**

<u>Propagation</u> encodes source positions in <u>spatial</u> field patterns

Maxwell: $\dfrac{\partial^2}{\partial t^2}\vec{E}(\vec{r}) = -\dfrac{\omega^2}{c^2}\Delta\vec{E}(\vec{r})$ limits their spatial frequency to $\dfrac{\omega}{c}$



<u>Instead</u>: **Lauterbur's gradient encoding**

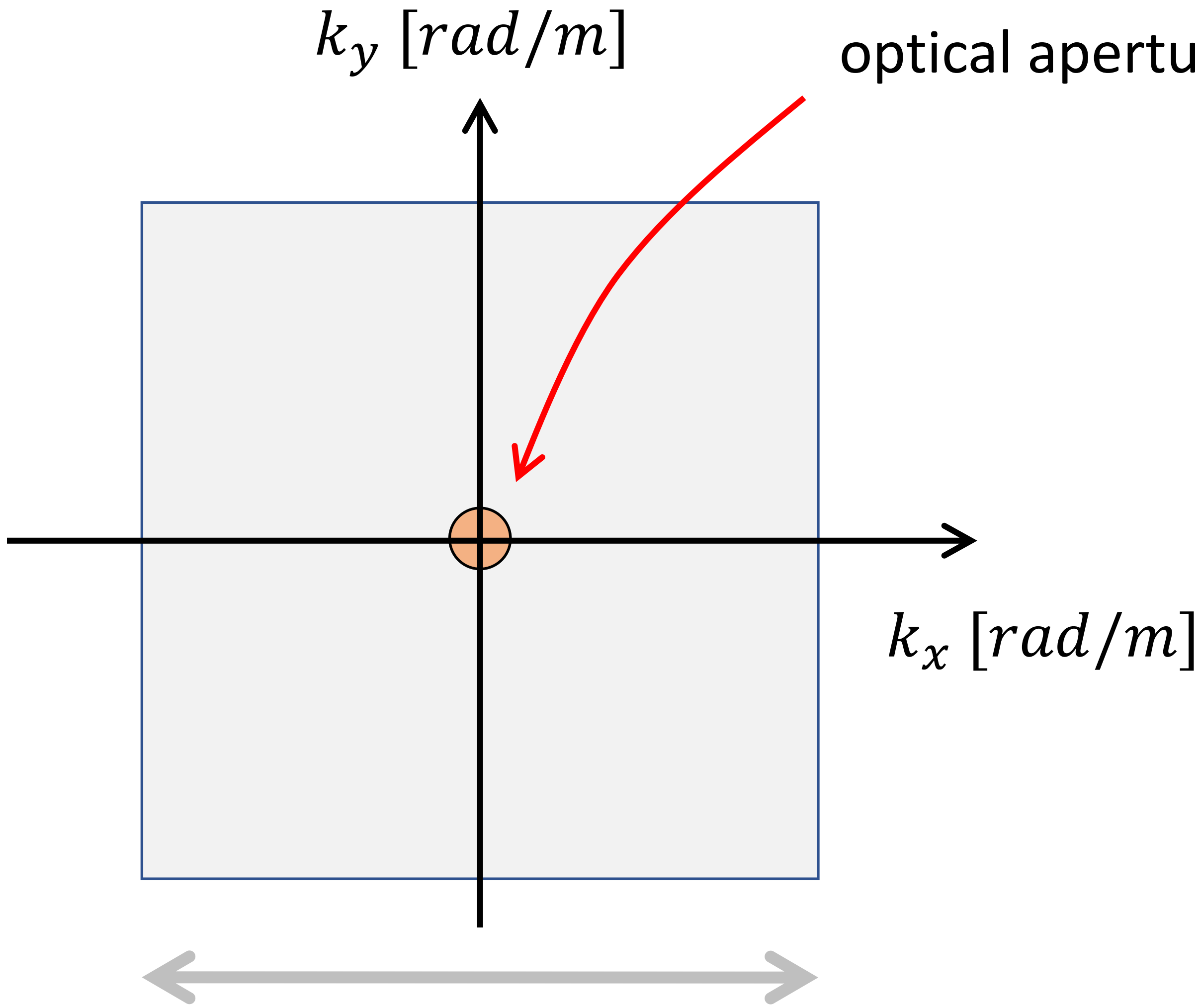
Bloch: $\dfrac{\partial}{\partial t}M_{xy}(\vec{r},t) = i\,\gamma\big(B_0 + \boldsymbol{\vec{G}(t)}\cdot\vec{r}\big)M_{xy}(\vec{r},t)$

<u>Precession</u> encodes source positions in <u>temporal</u> field patterns

Paul C. Lauterbur
Nobel Prize 2003

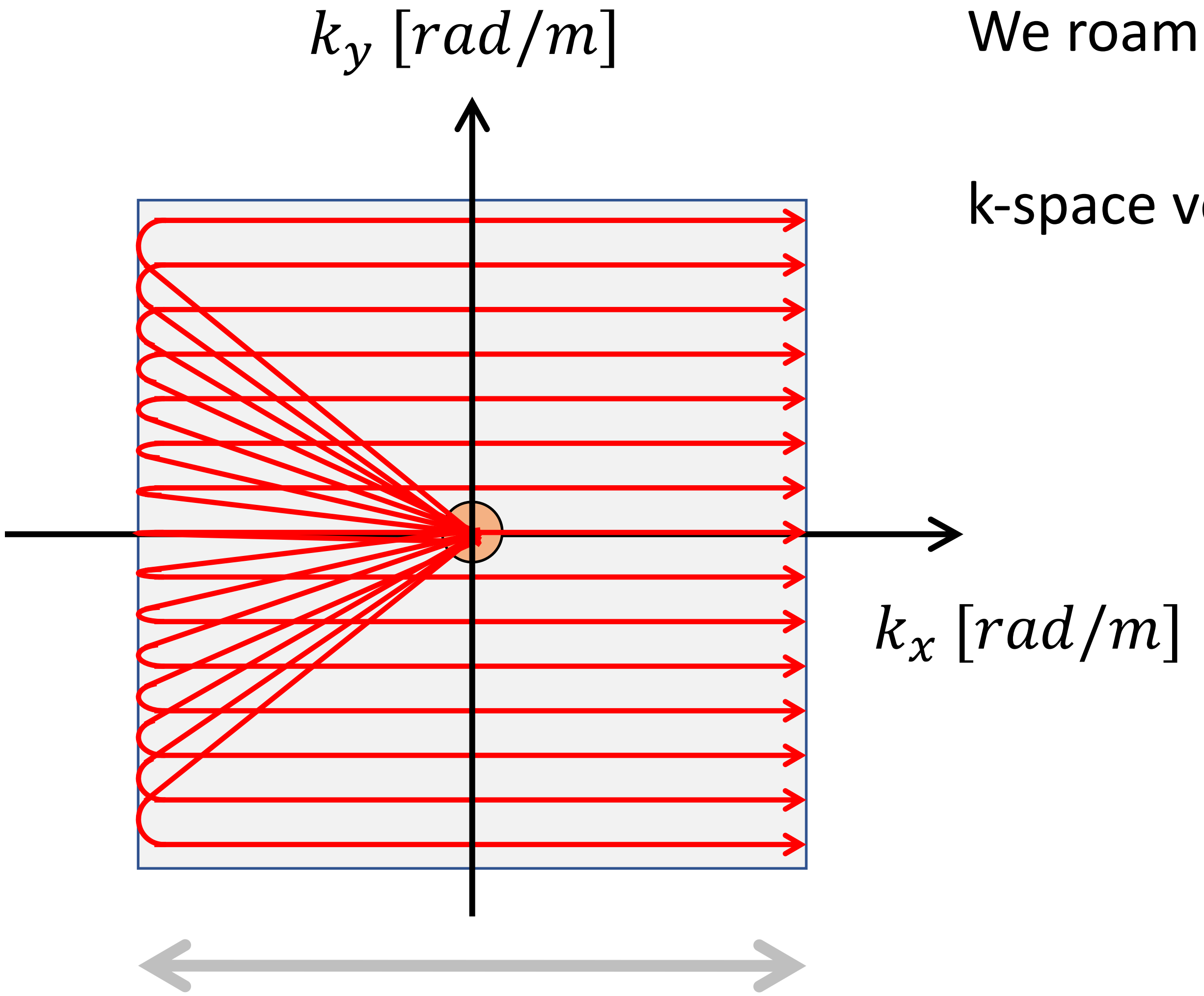
Enter k-space

optical aperture $\quad |\vec{k}| \le \dfrac{\omega}{c} = \dfrac{2\pi}{\lambda}$



aperture needed: $2\pi/\Delta x$

Enter k-space



aperture needed: $2\pi/\Delta x$

We roam free in k-space!

k-space velocity $$\frac{d\vec{k}(t)}{dt} = \gamma \vec{G}(t)$$

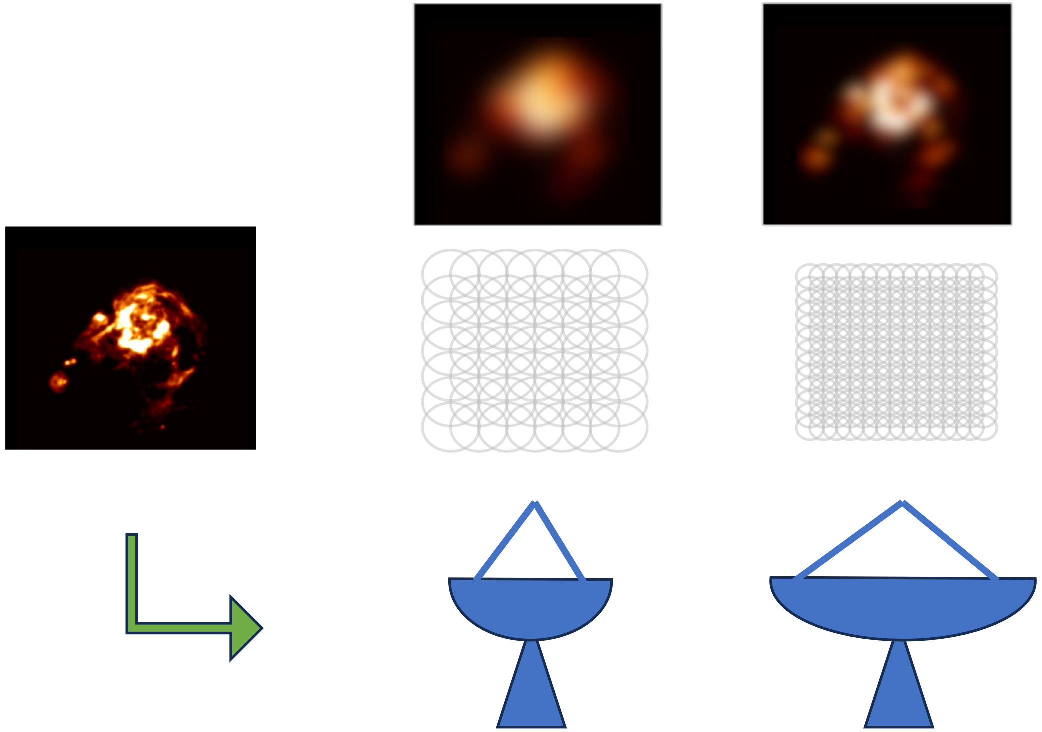
Resolution <u>not limited</u> by

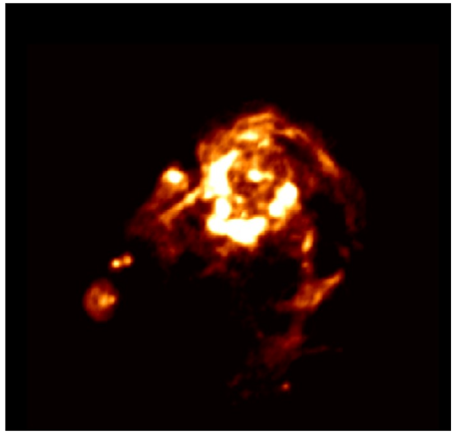
- electrodynamics
- size of the equipment

!

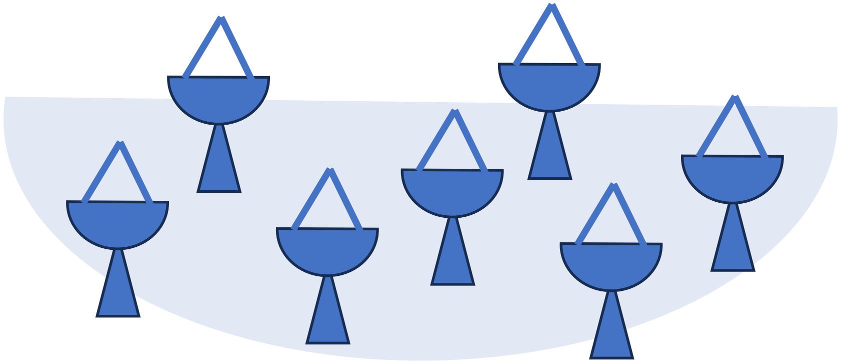
<u>But encoding takes time</u>

Going beyond single dishes ?

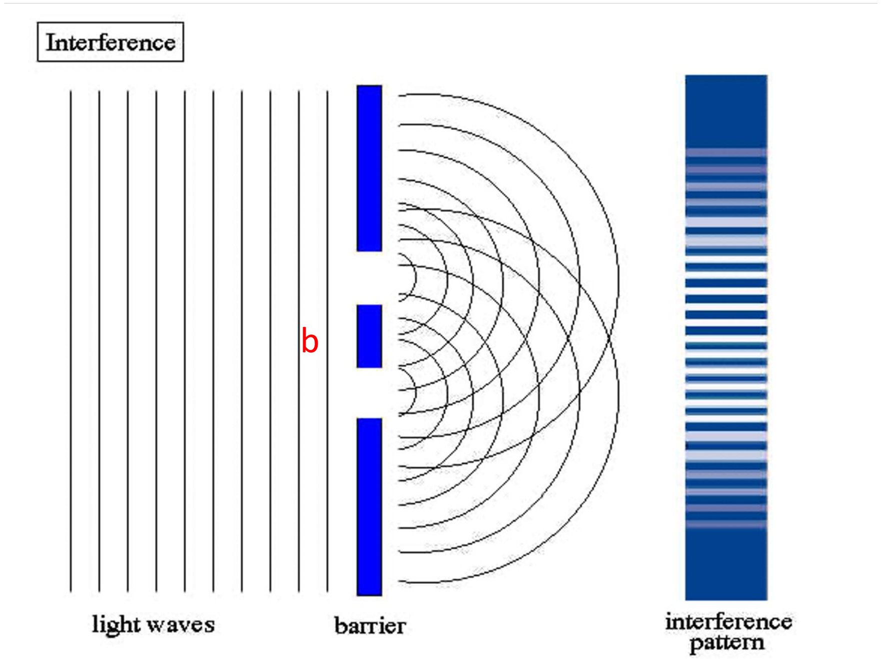




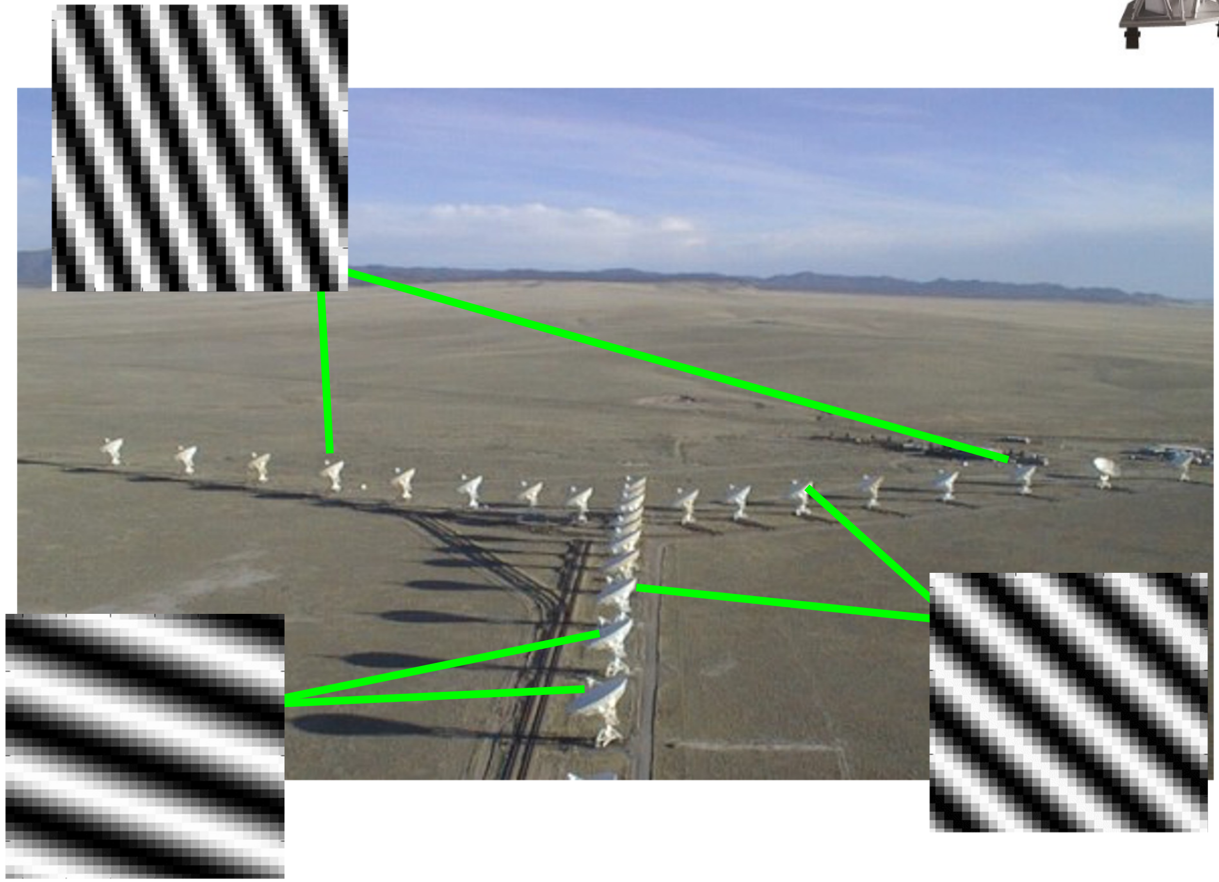
Aperture Synthesis



Aperture Synthesis



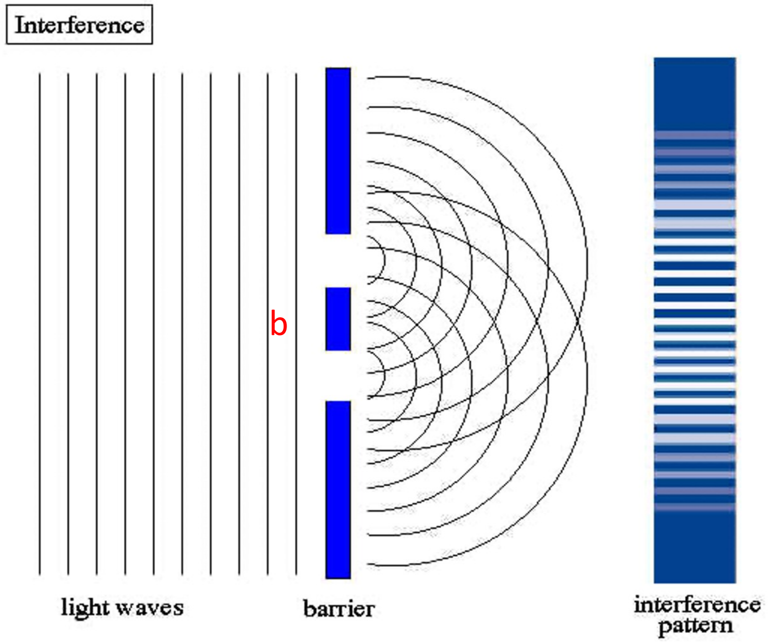
Young's double-slit experiment



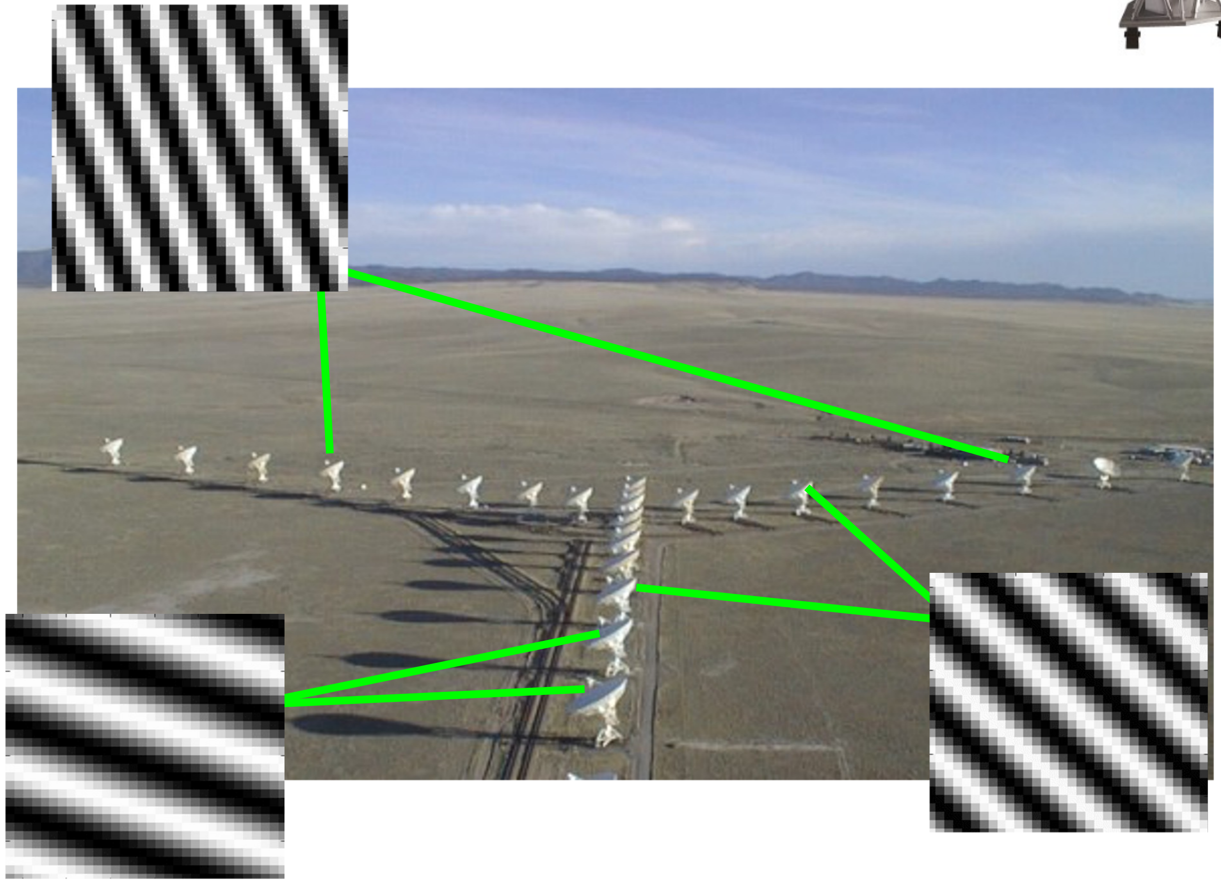
Aperture = infinite pairs of slits

Each pair of slits sees 1 Fourier component

Aperture Synthesis

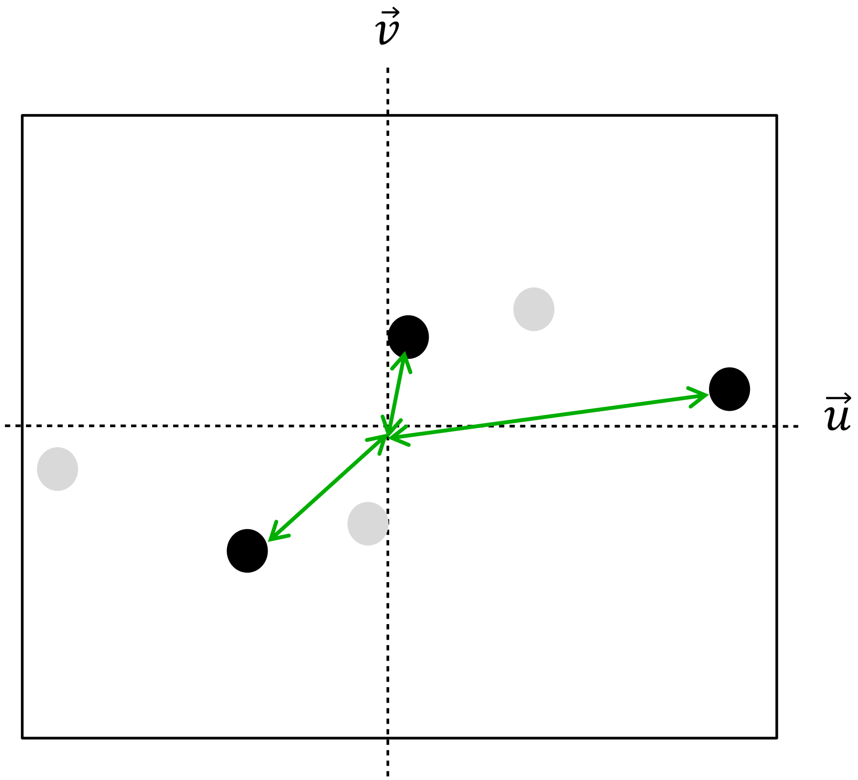


Young's double-slit experiment

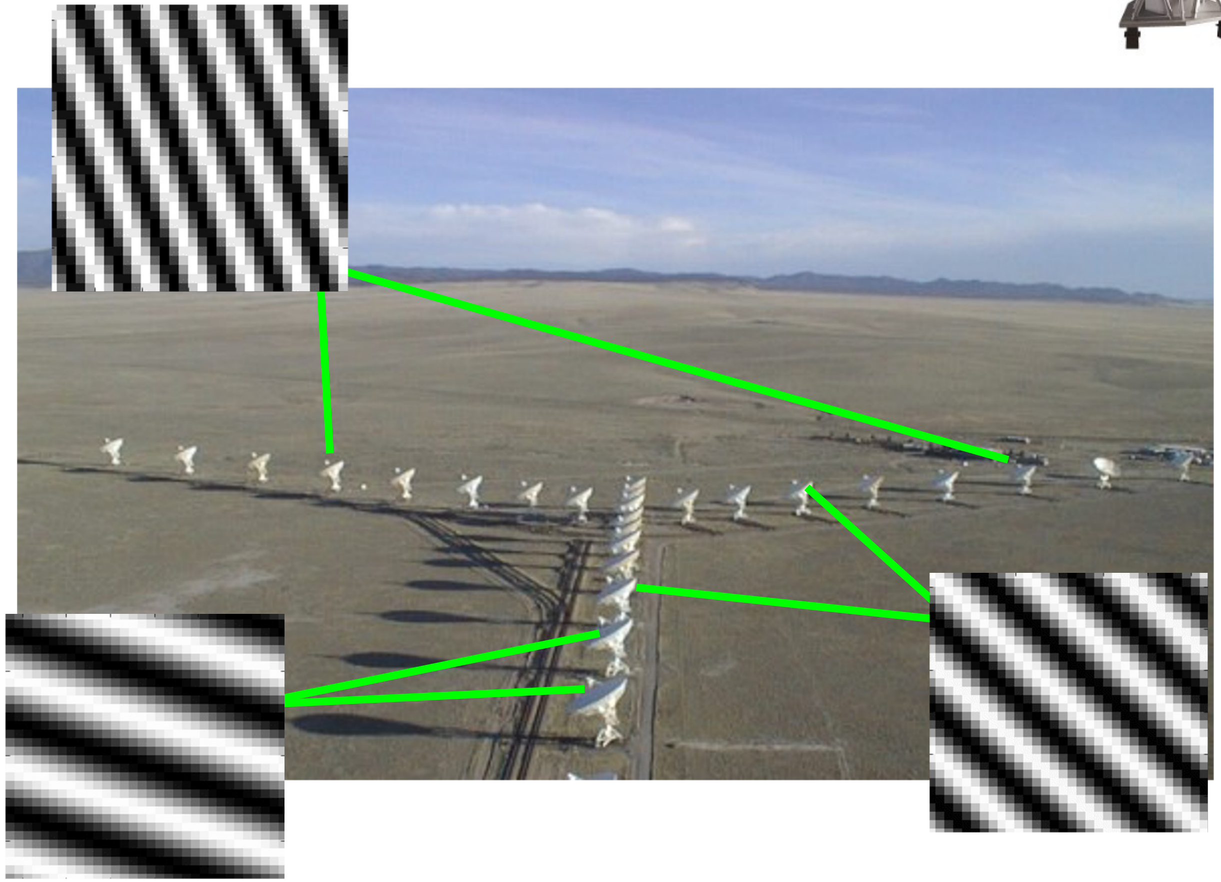


Measure the spatial coherence of the incident E-field at each pair of detectors

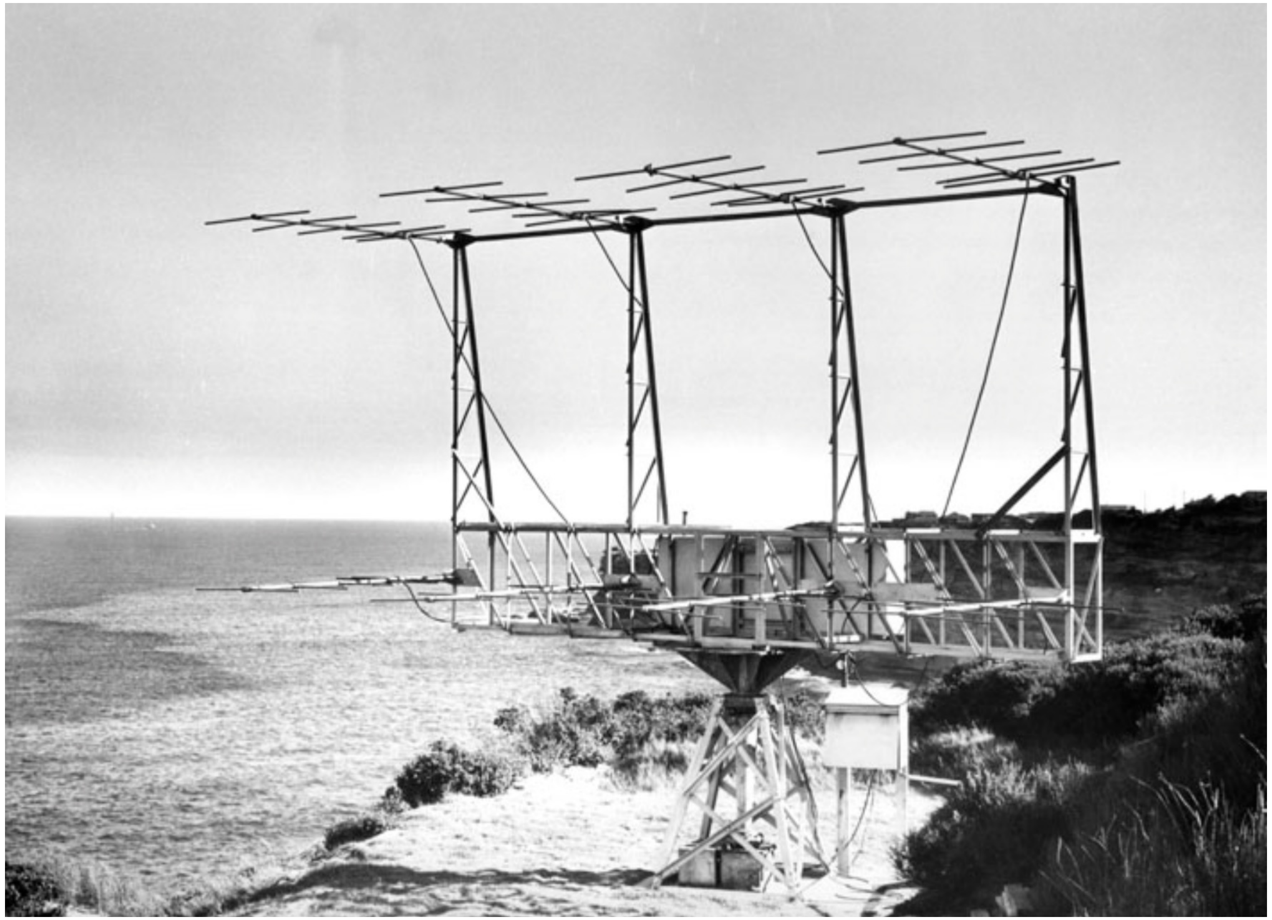
Aperture Synthesis



K-space encoding



First Fourier encoding



McReady, Pawsey, Payne-Scott (1946)

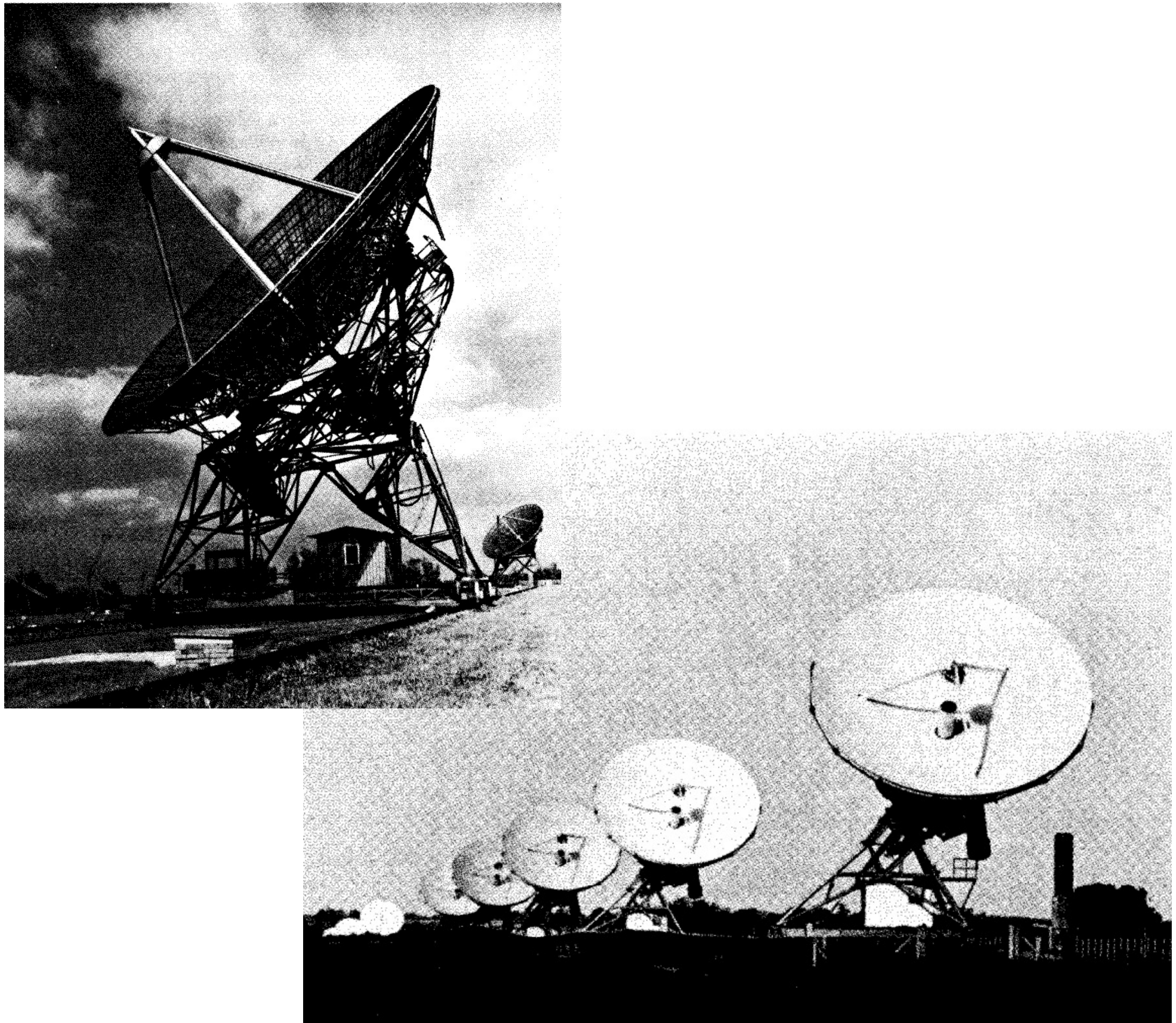
Sea-Cliff Interferometer

Time-series

→ Interference pattern

→ Angular size of the source

First Aperture Synthesis in Astronomy

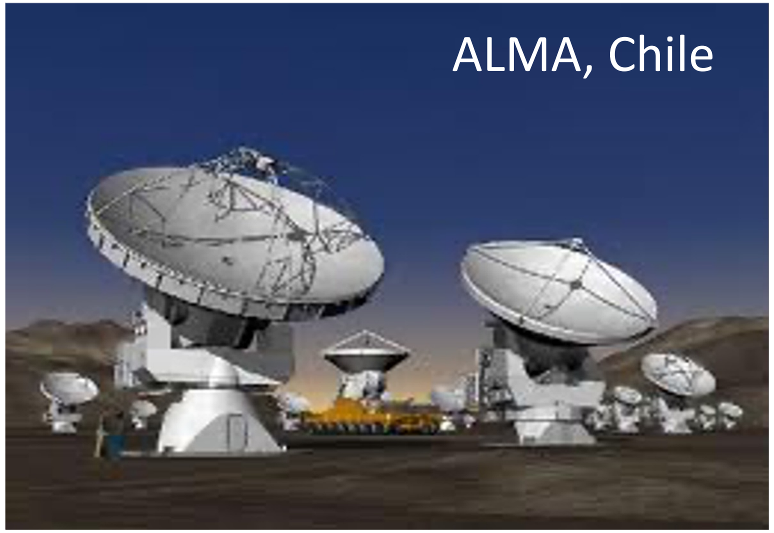


Martin Ryle (1960+)

First intentional K-space sampling

Nobel Prize (1974)

Today's interferometers – dish arrays

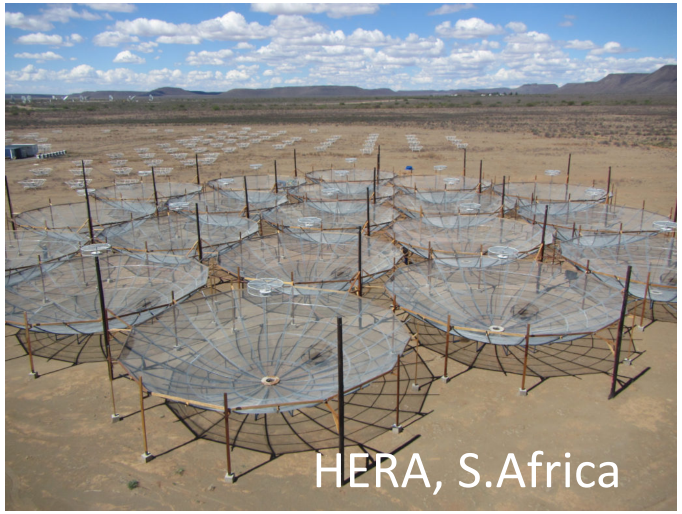


Today’s interferometers – aperture arrays

LOFAR, Netherlands

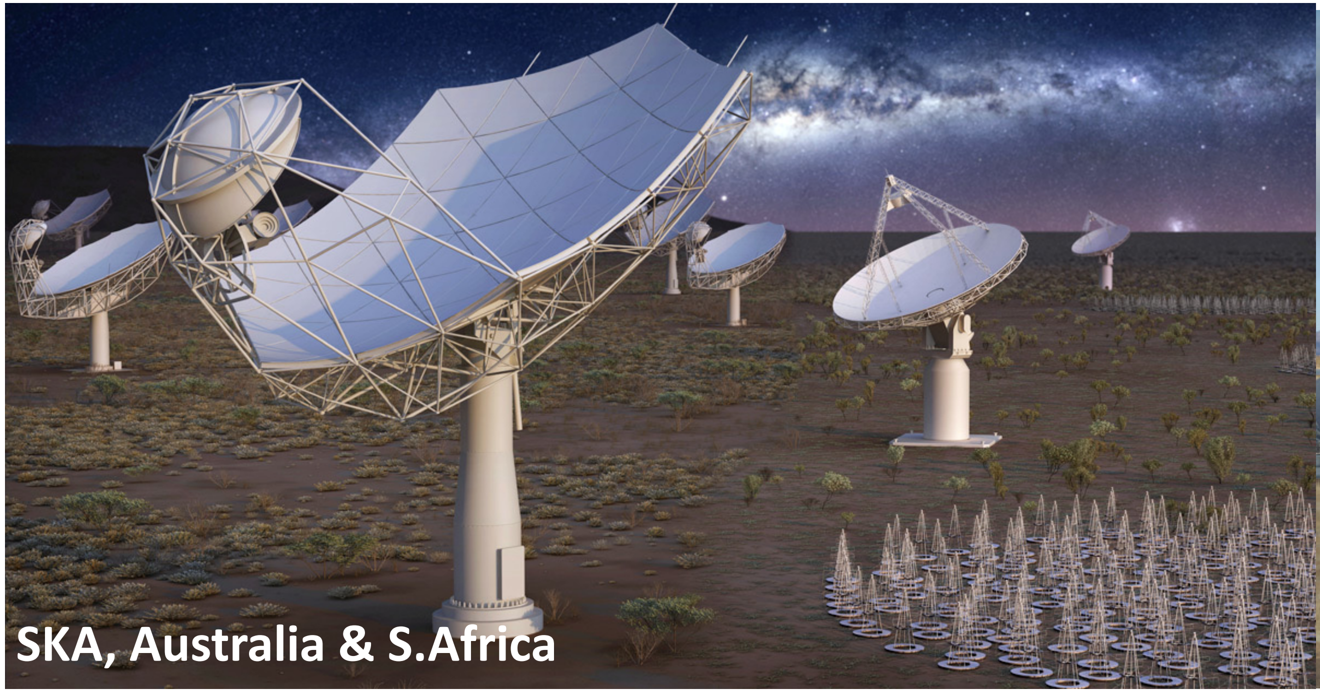
MWA, Australia

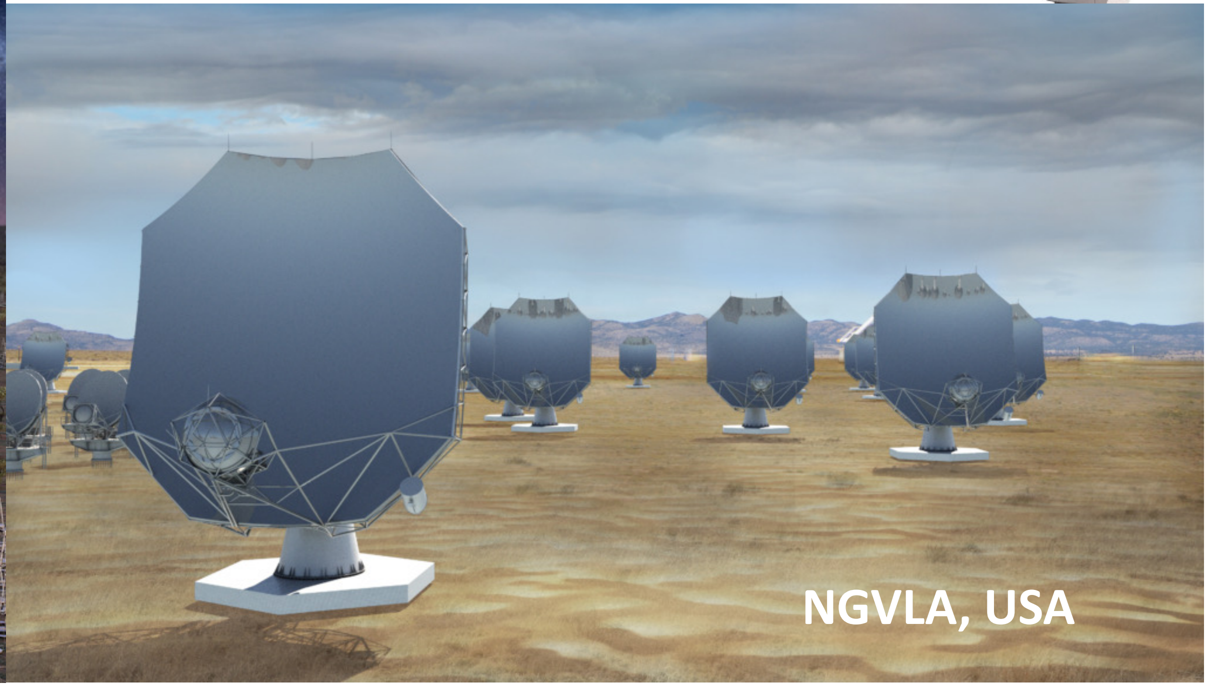
LWA, USA



HERA, S.Africa

Next generation (future) instruments





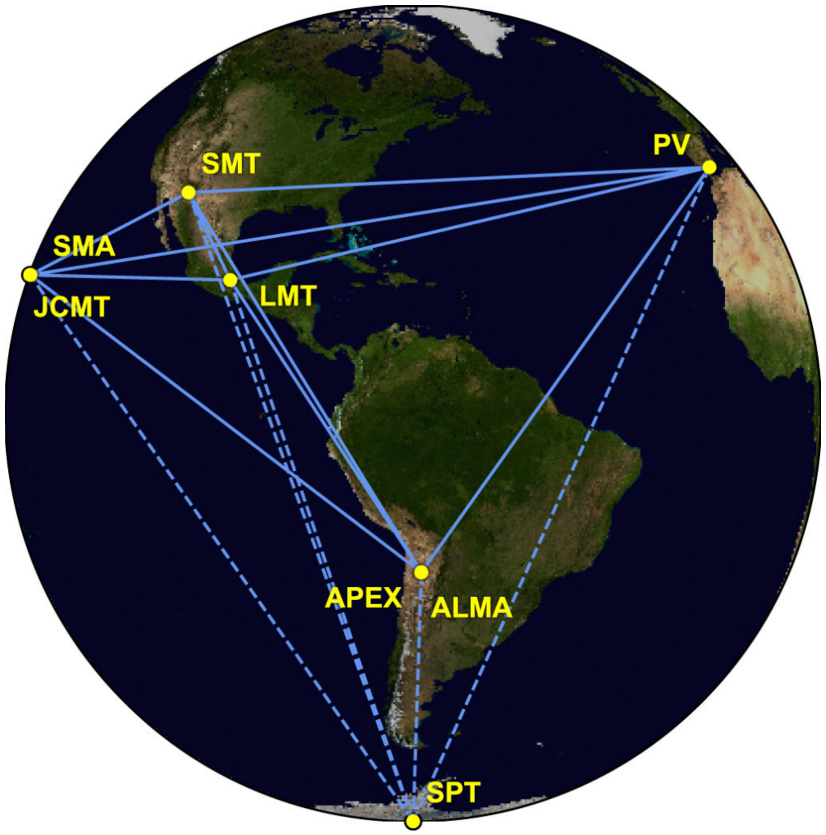
Designed for O(10) increase in :

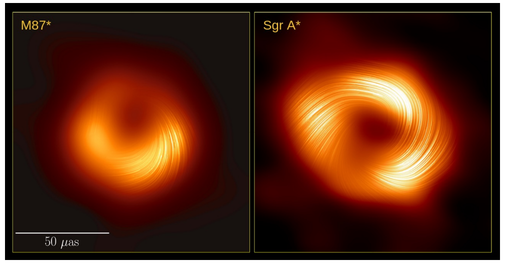
K-space coverage,   Collecting Area

…… and computing cost.

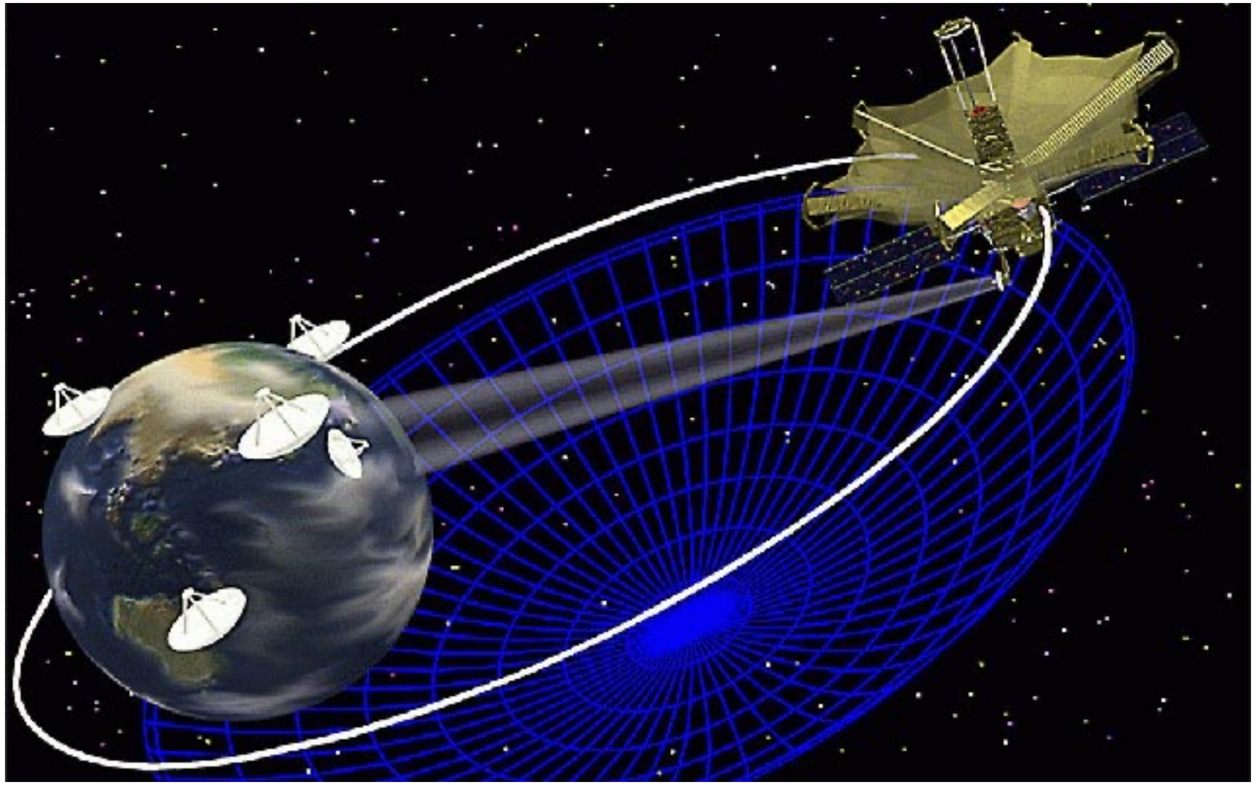
Very long baseline interferometry

Very (very) long baseline interferometry



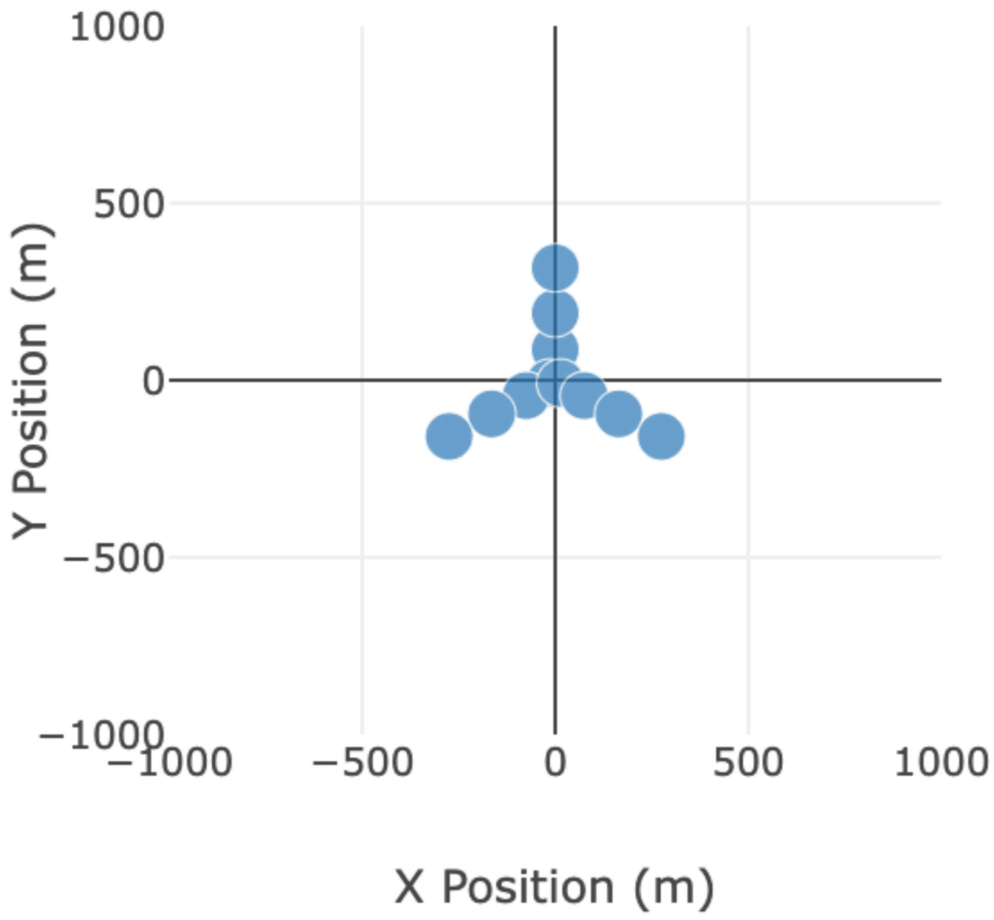


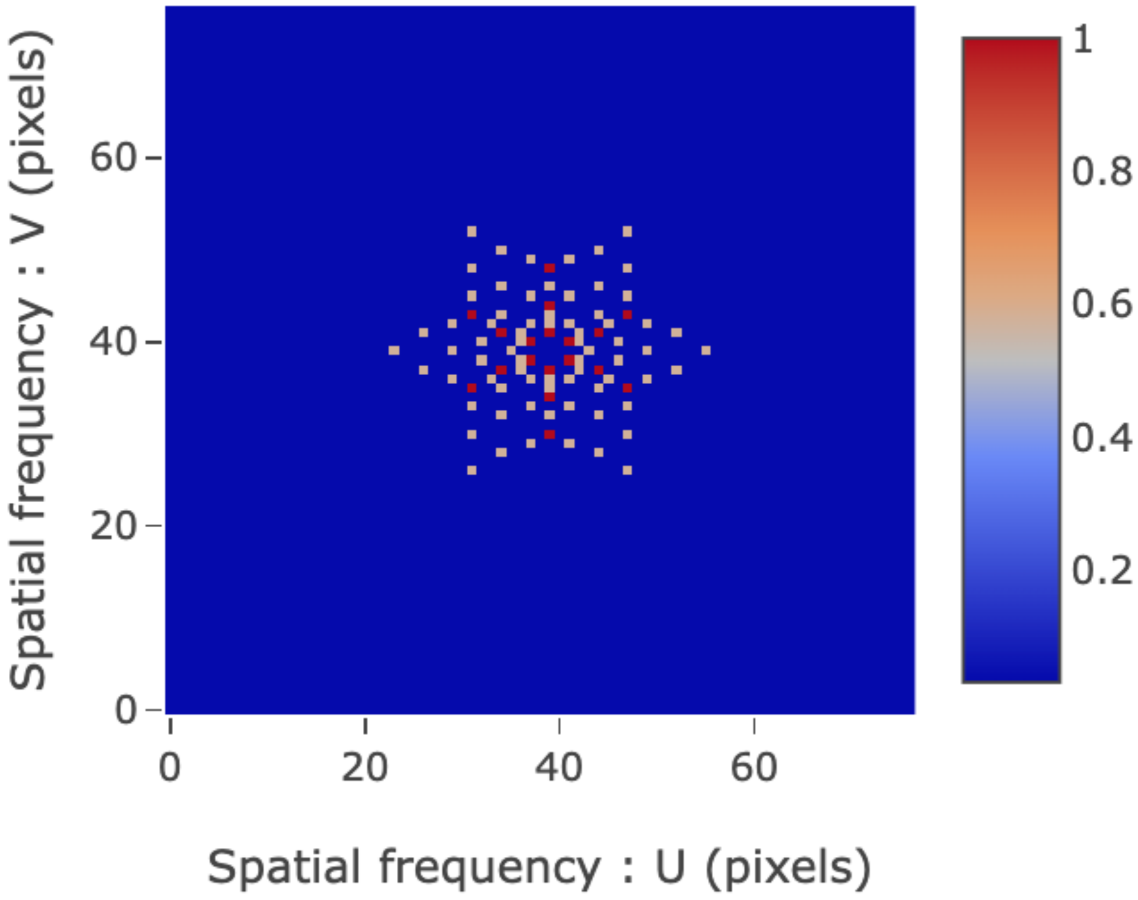
Event Horizon Telescope



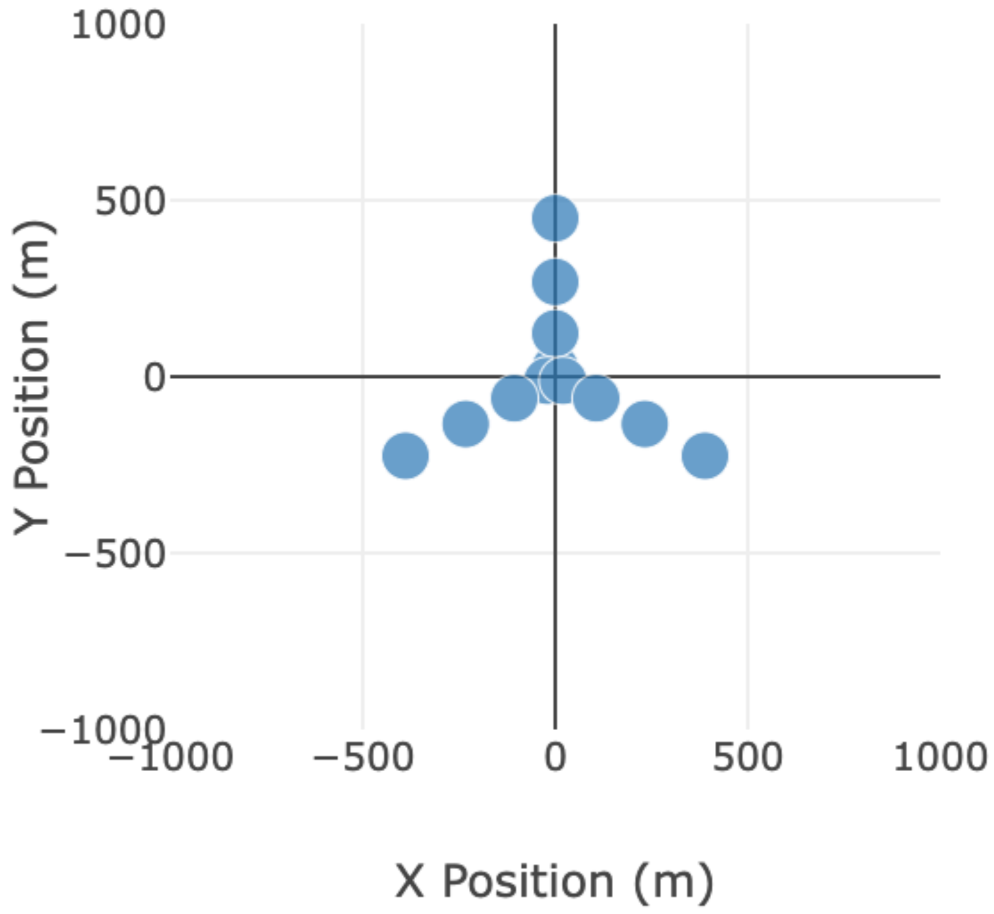
Space - VLBI

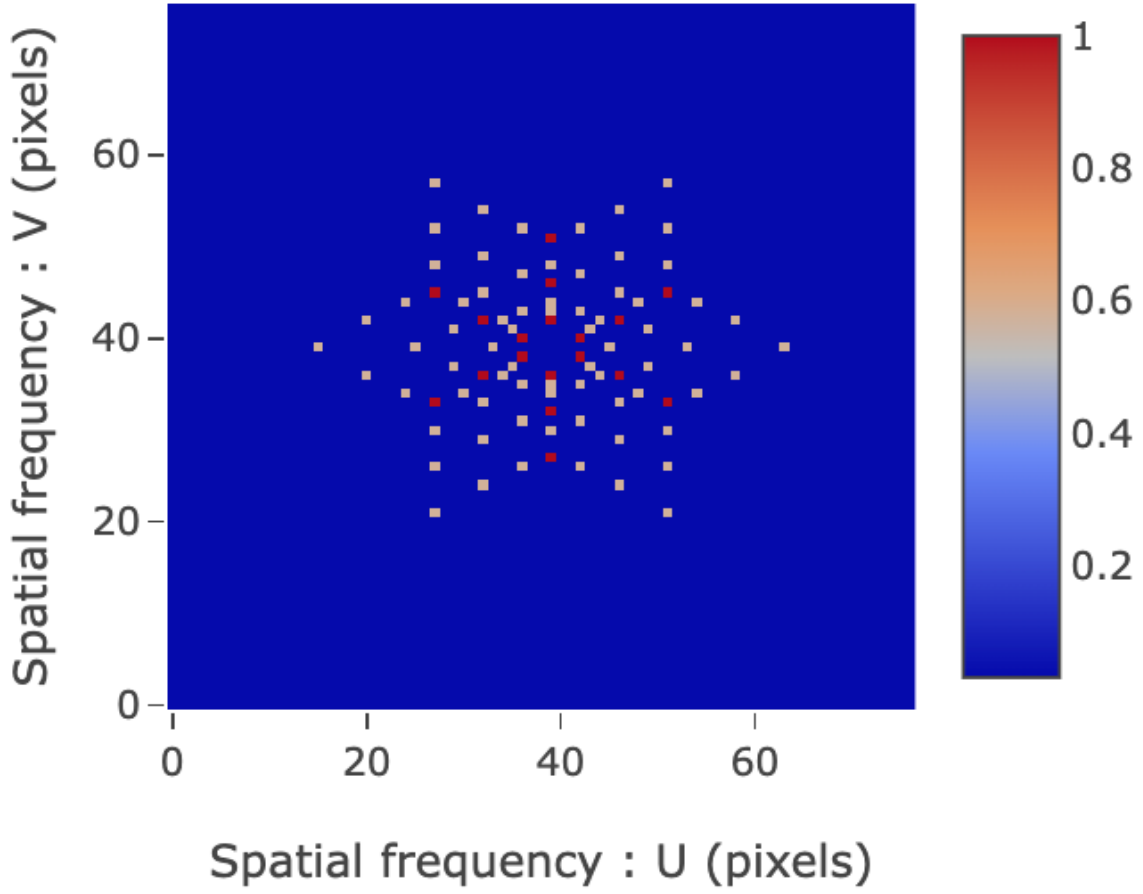
What does our K-space coverage look like?



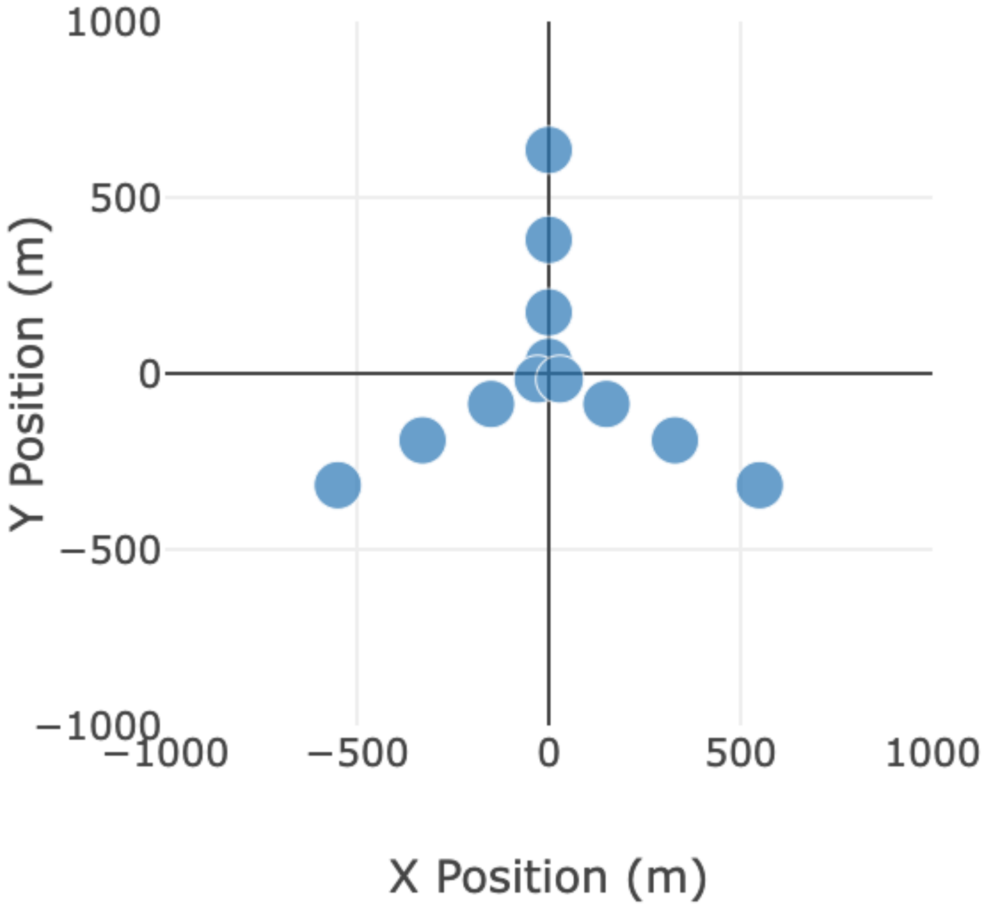


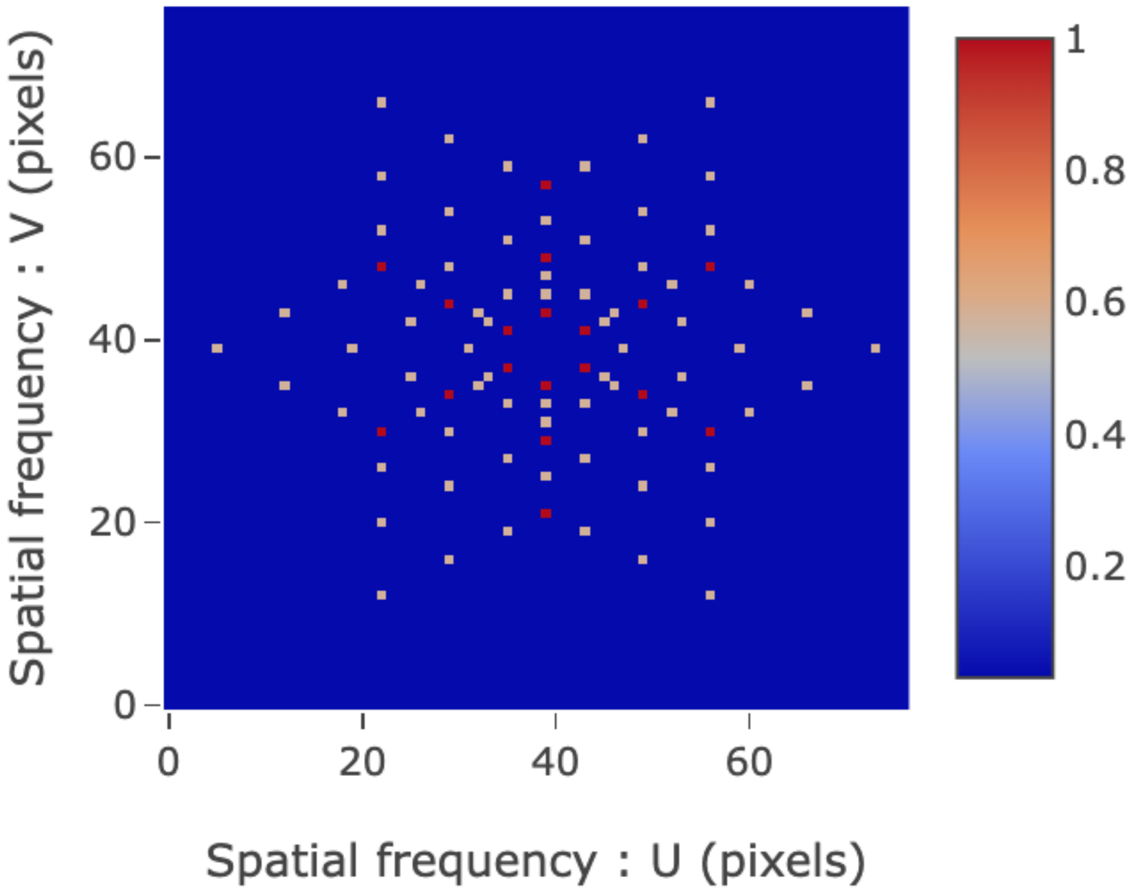
What does our K-space coverage look like?



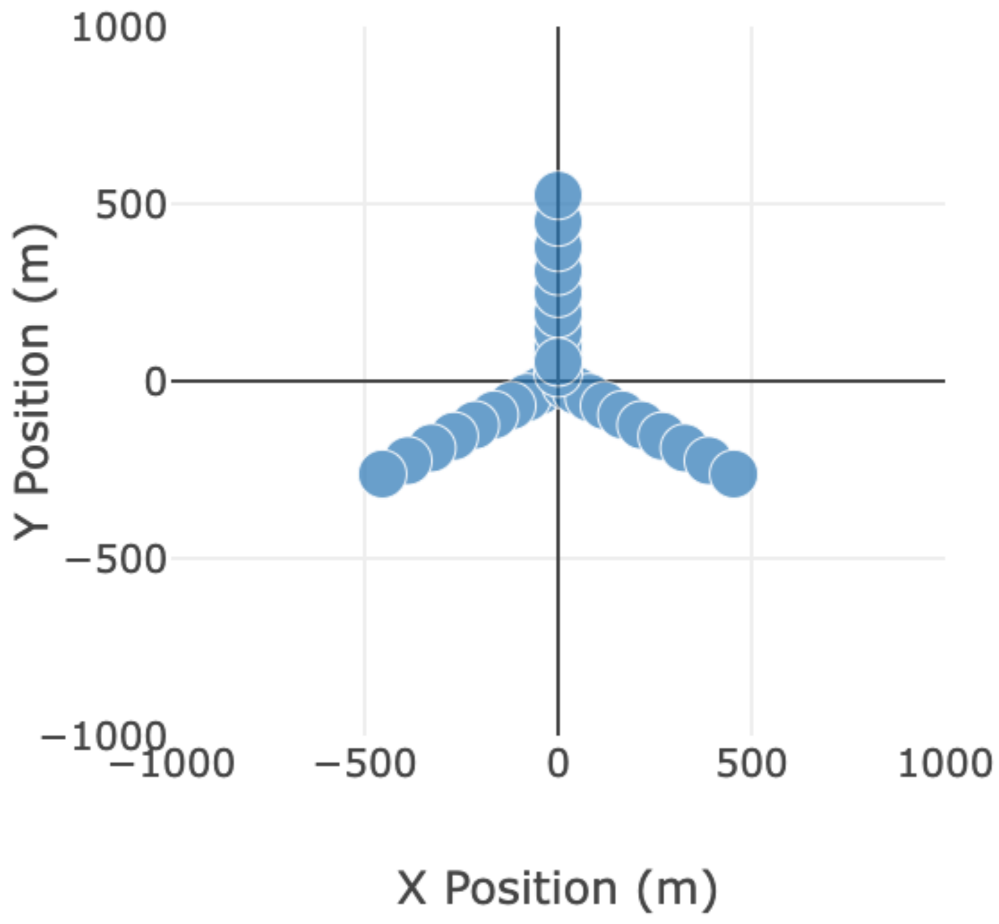


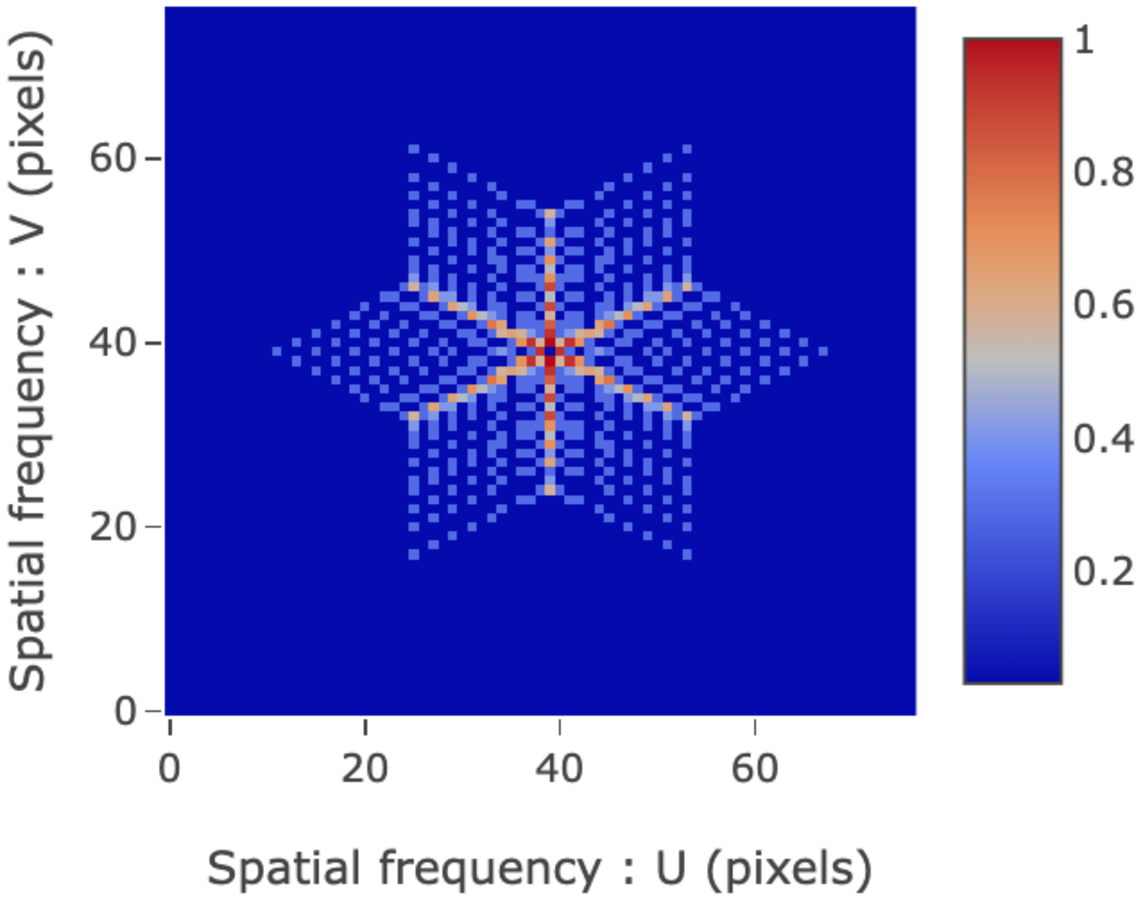
What does our K-space coverage look like?



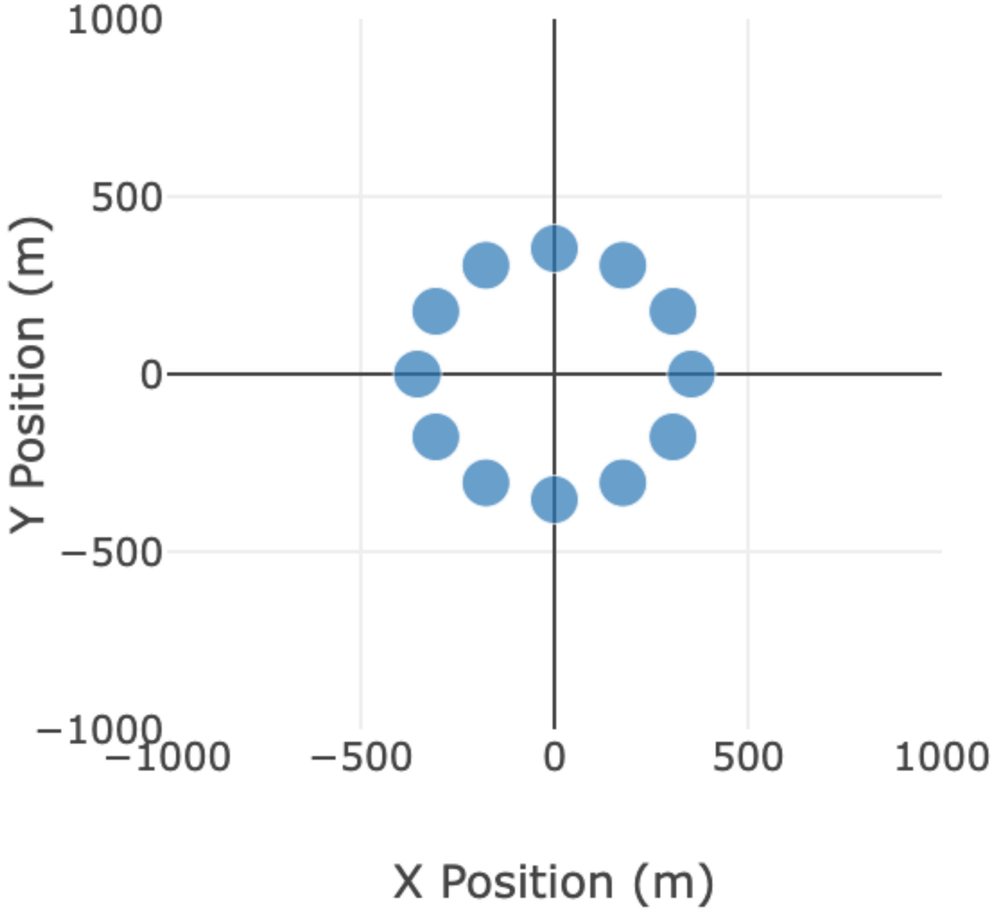


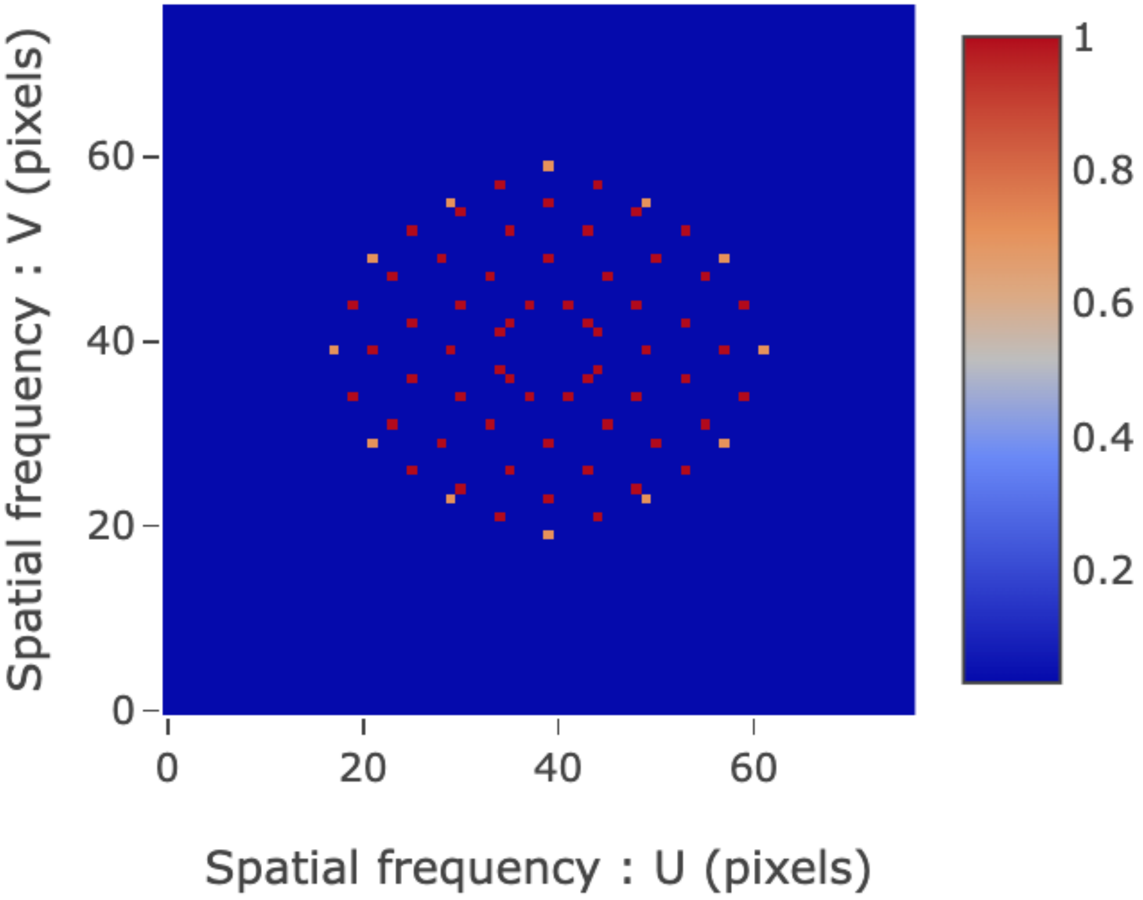
What does our K-space coverage look like?



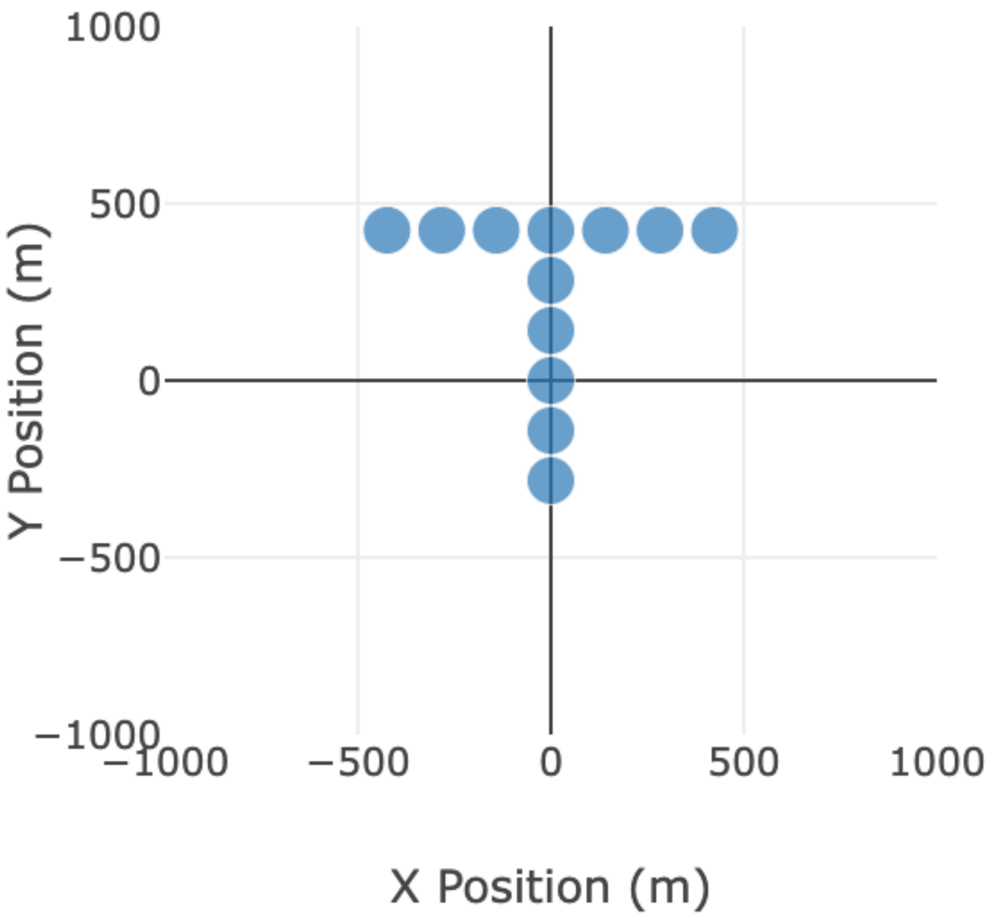


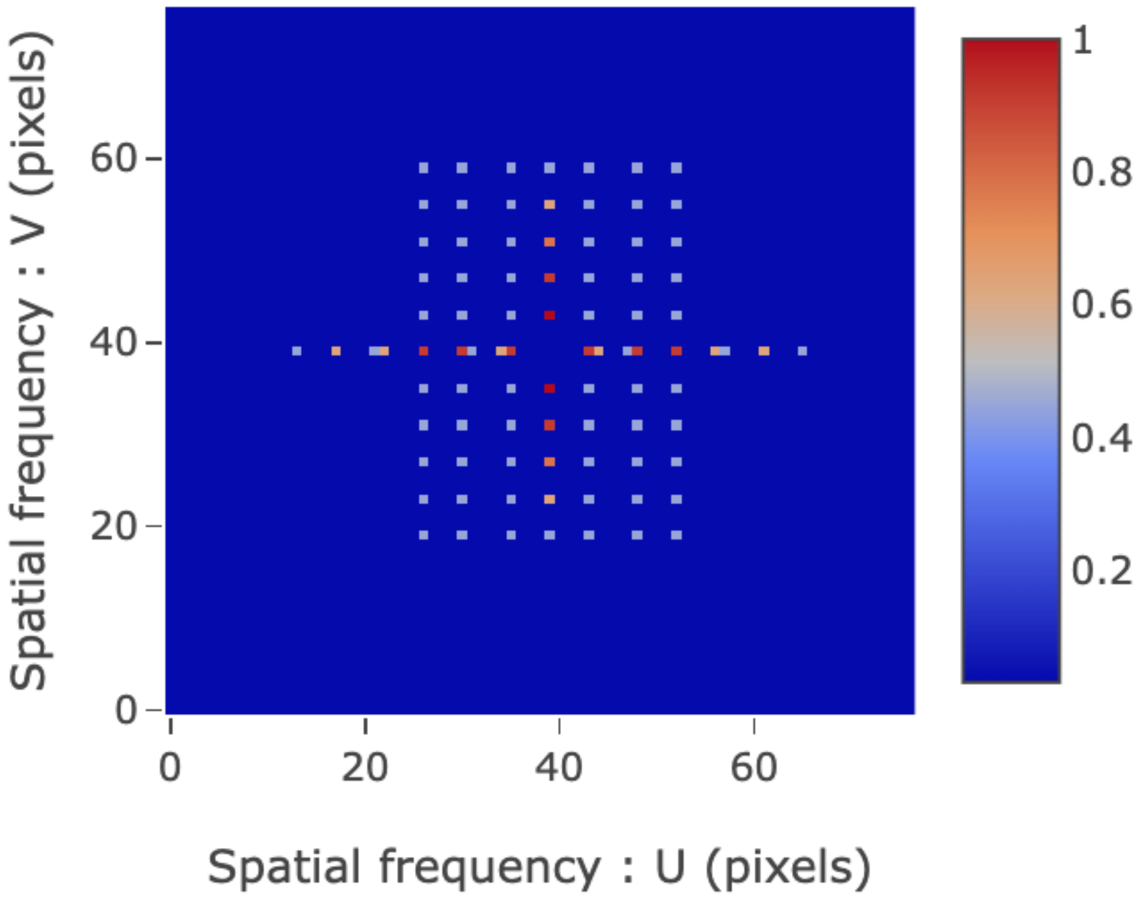
What does our K-space coverage look like?



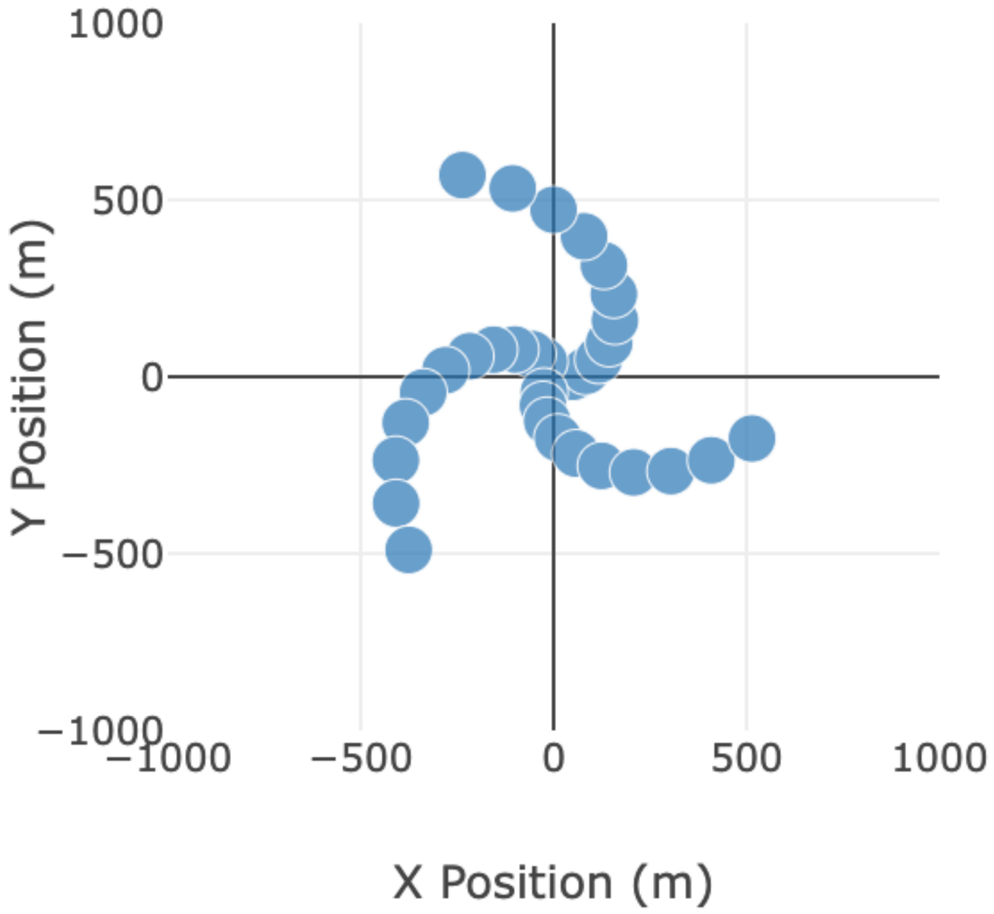


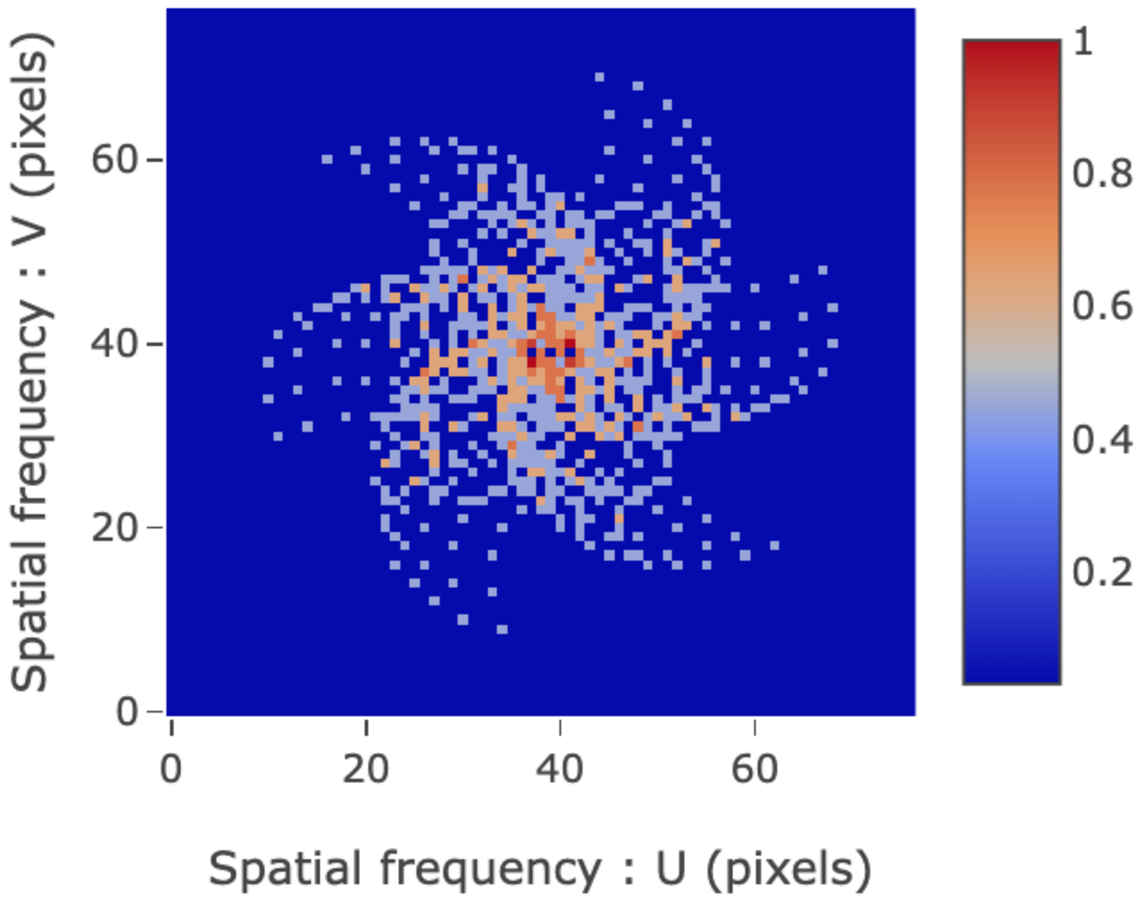
What does our K-space coverage look like?



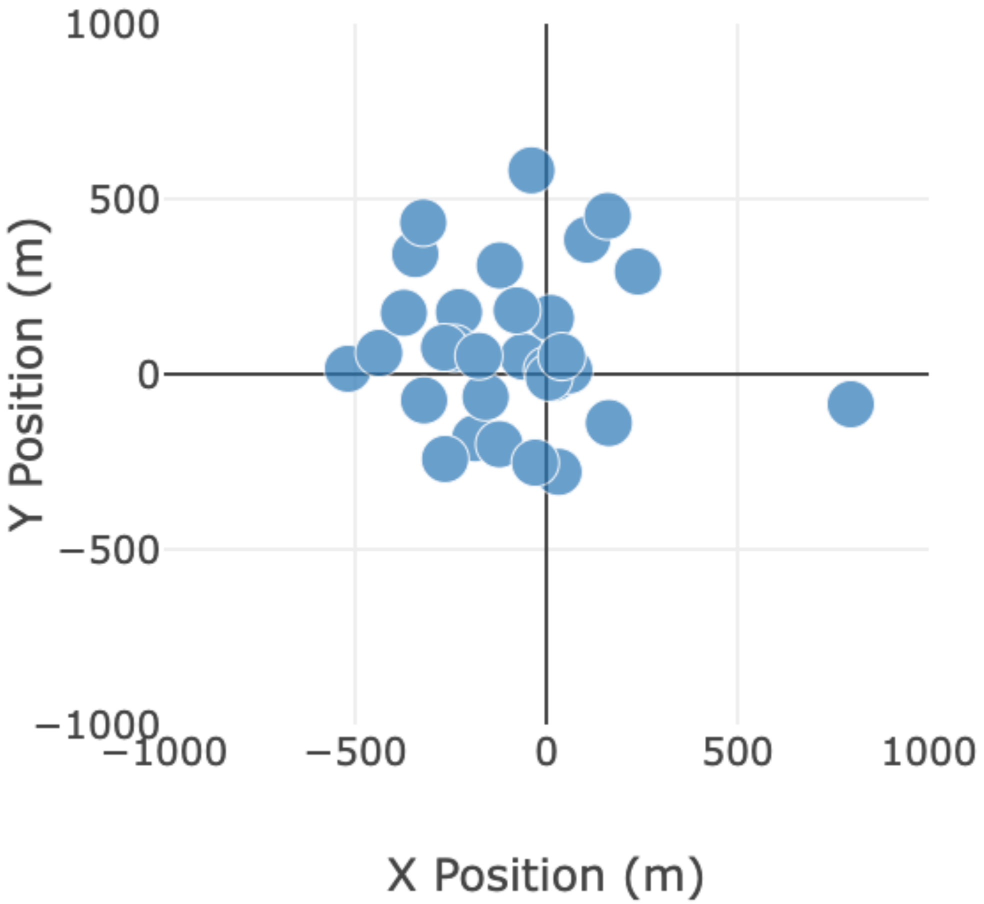


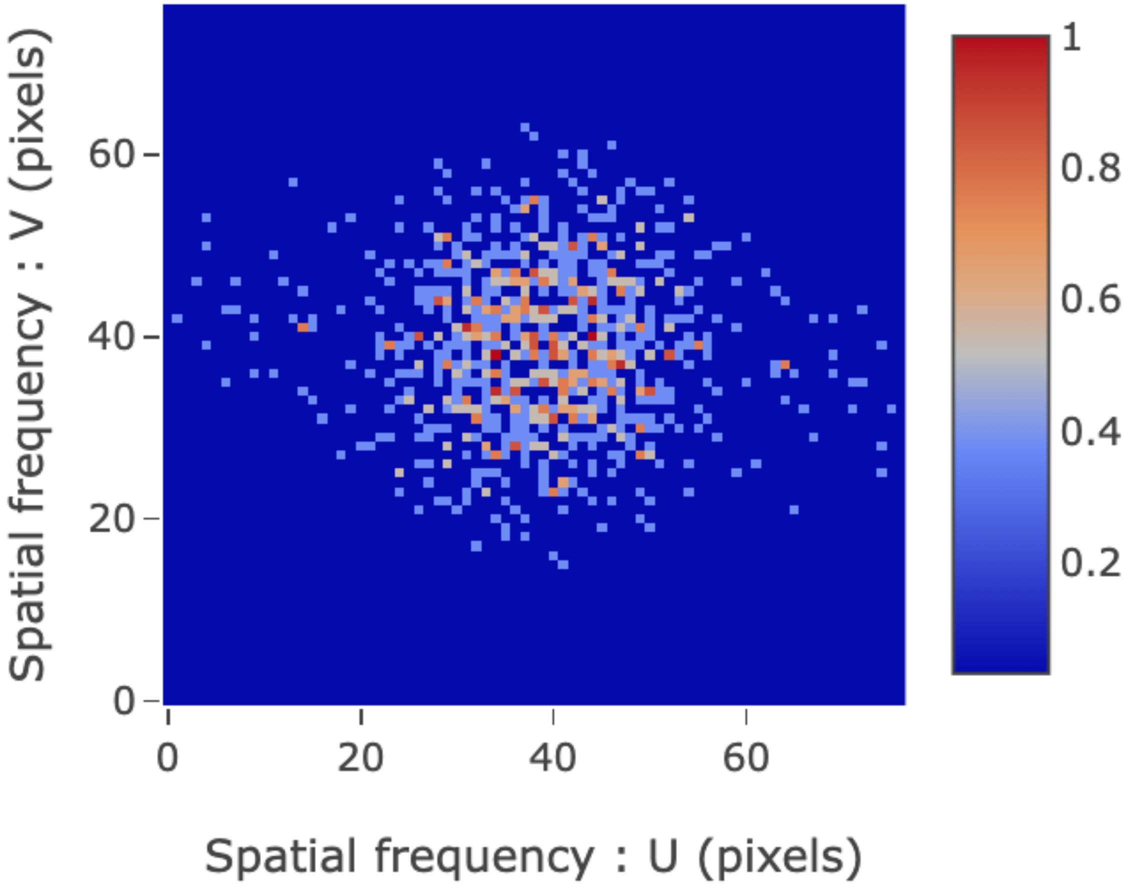
What does our K-space coverage look like?





What does our K-space coverage look like?





Imaging Quality ?

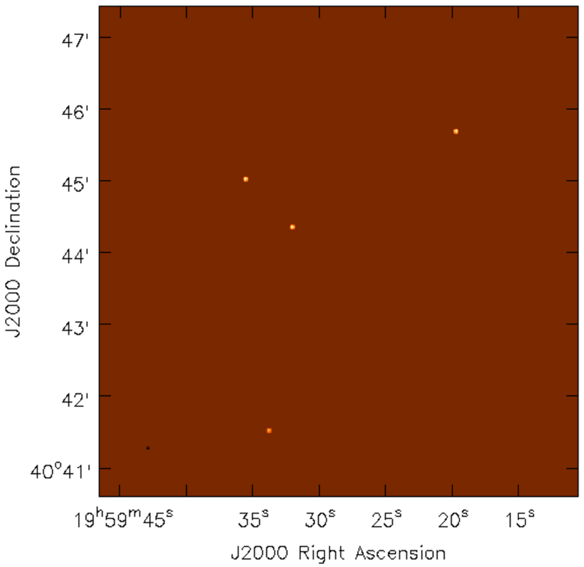
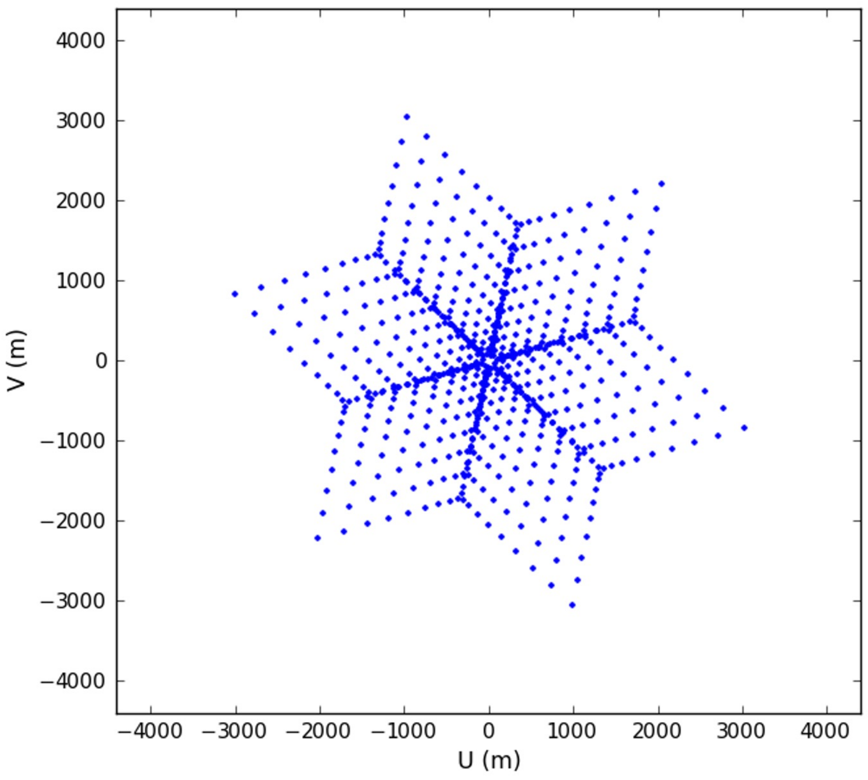


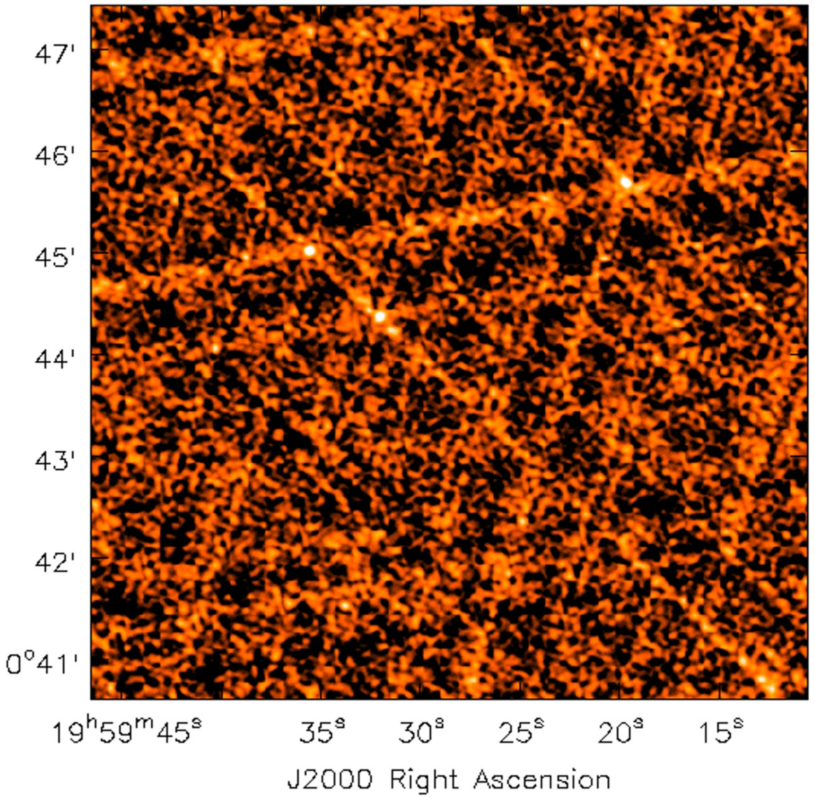
Image of the sky
using **27** antennas

“Aperture Synthesis”

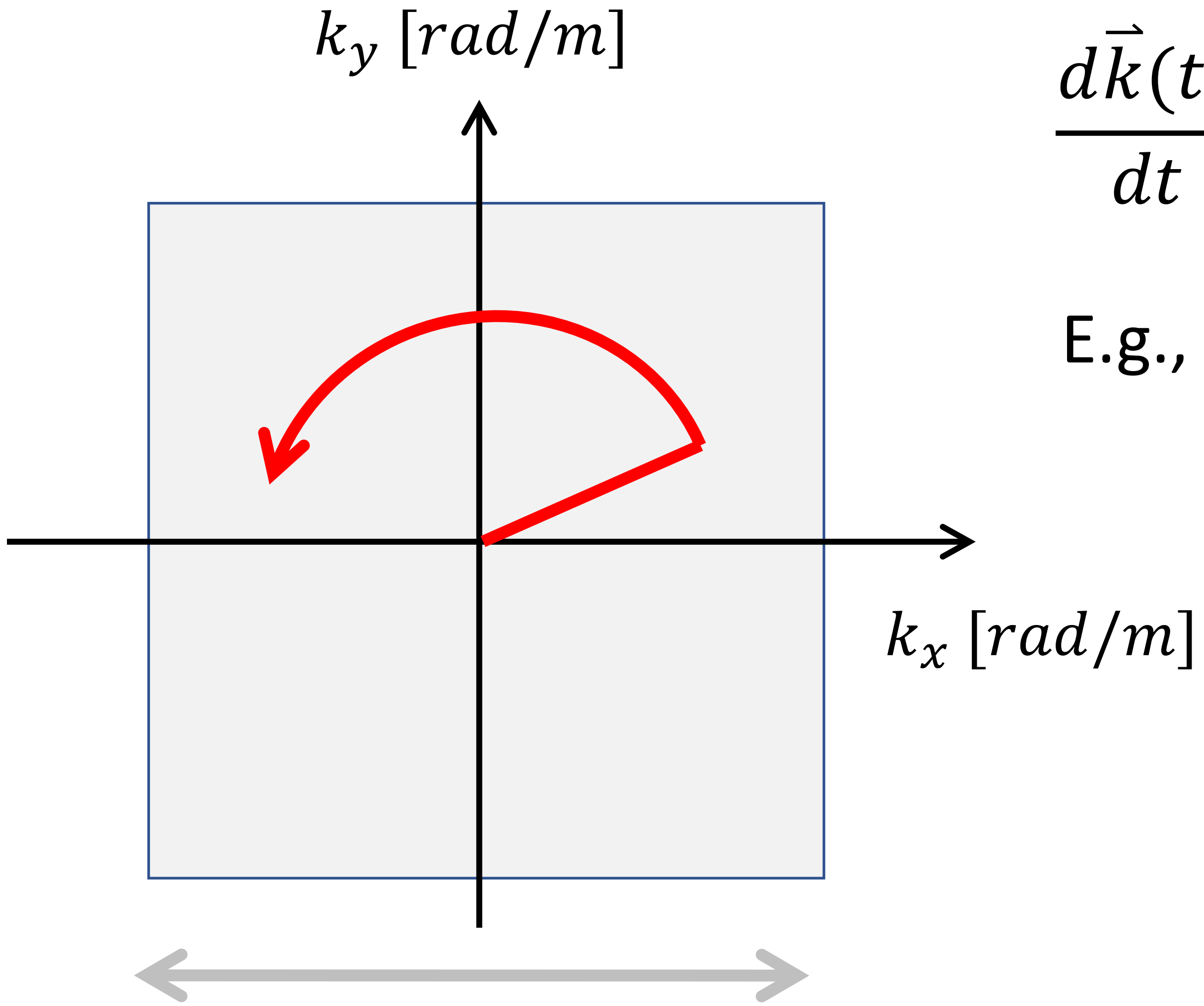
$S(u,v)$



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



Curves in k-space?

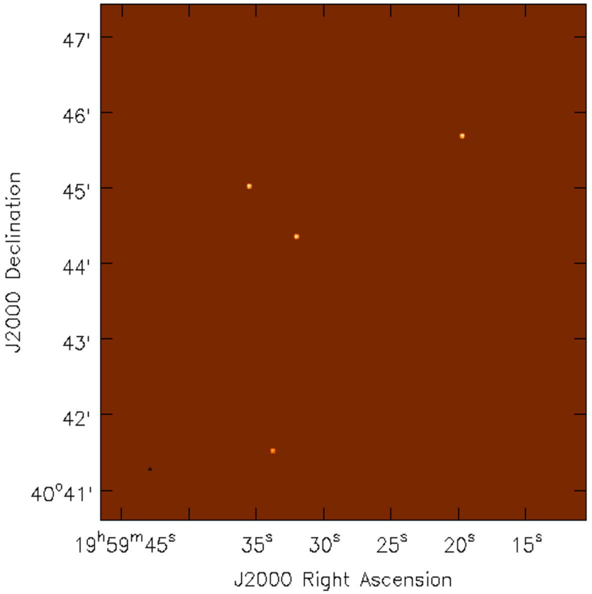


aperture needed: $2\pi/\Delta x$

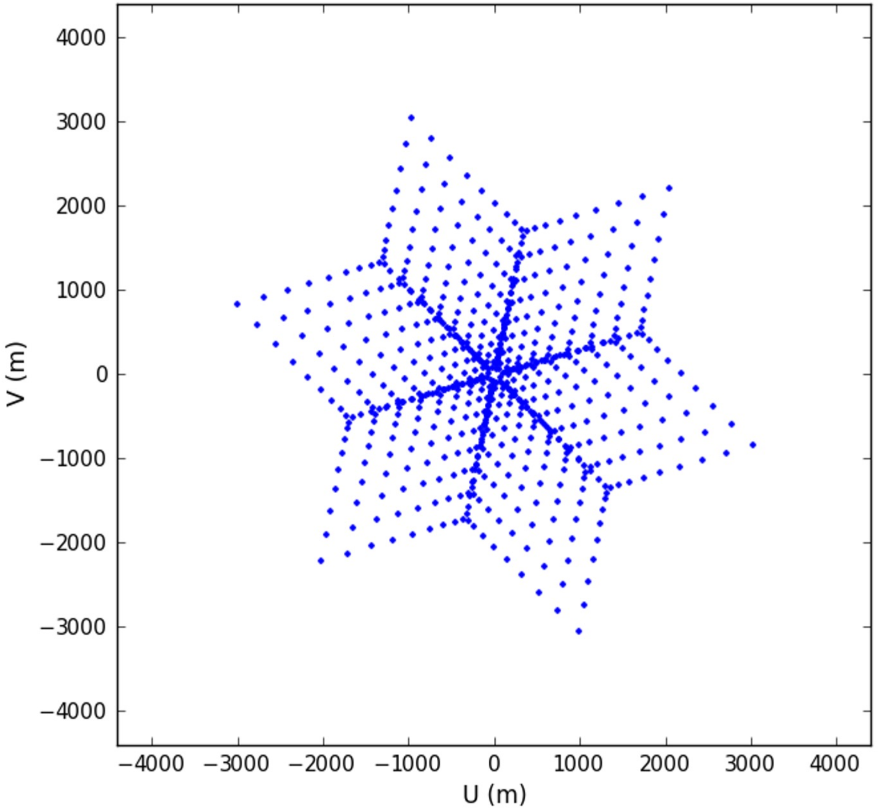
$$\frac{d\vec{k}(t)}{dt} = \gamma \vec{G}(t)$$ k-space velocity

E.g., **arcs**, do you put dishes on rails?

Aperture Synthesis



$S(u,v)$



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

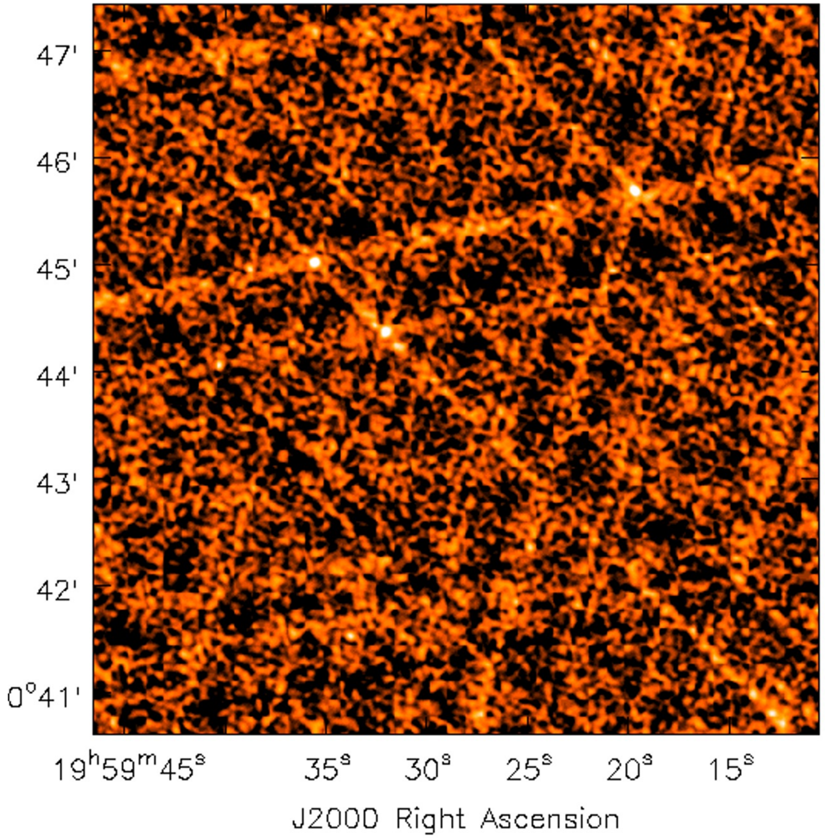


Image of the sky using 27 antennas

Observation : **1 second**

Earth Rotation Synthesis

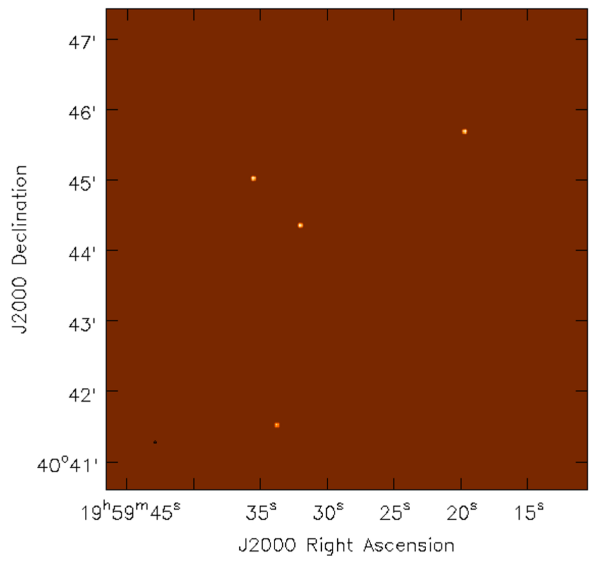
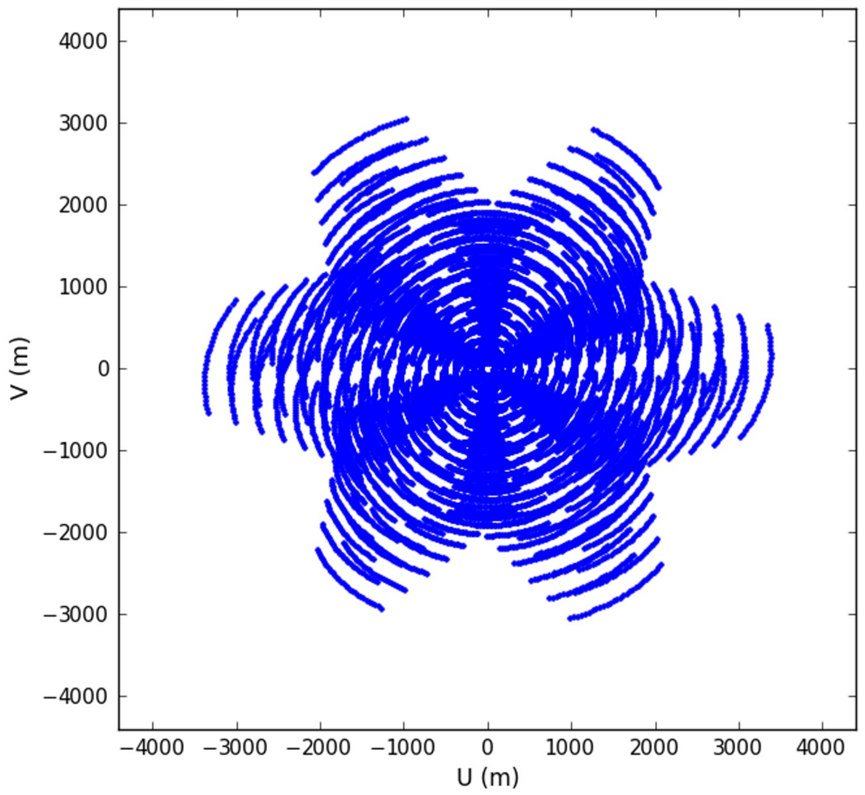


Image of the sky using 27 antennas

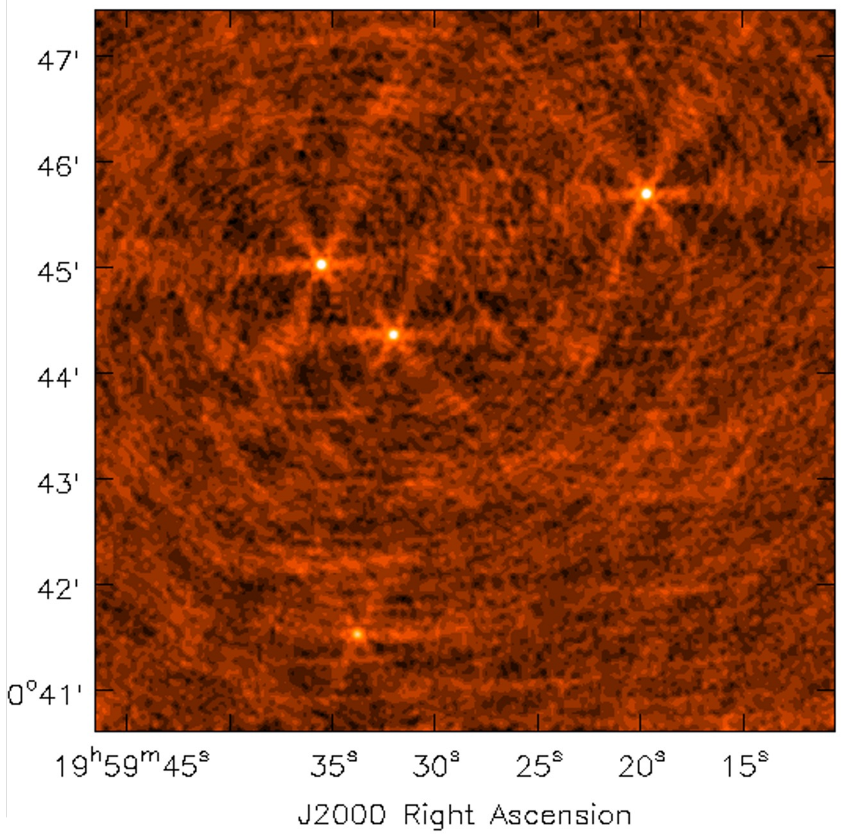
Observation : **2 hours**

"Earth Rotation Synthesis"

$S(u,v)$



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



Earth Rotation Synthesis

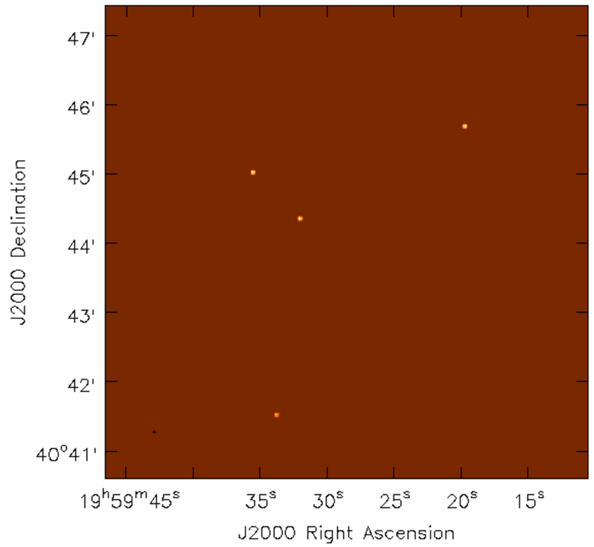
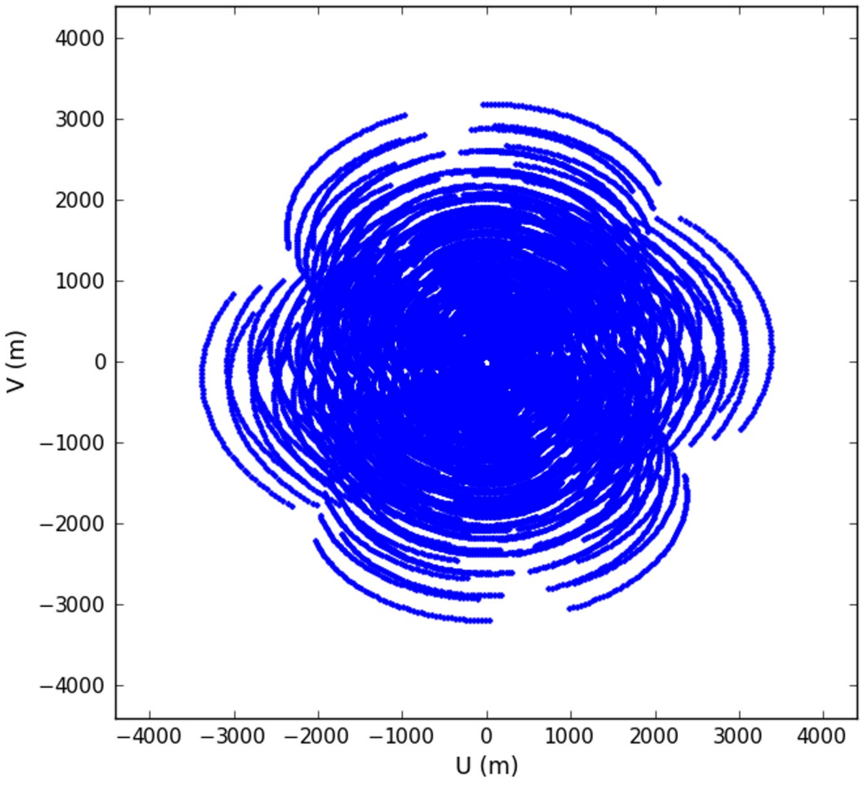


Image of the sky using 27 antennas

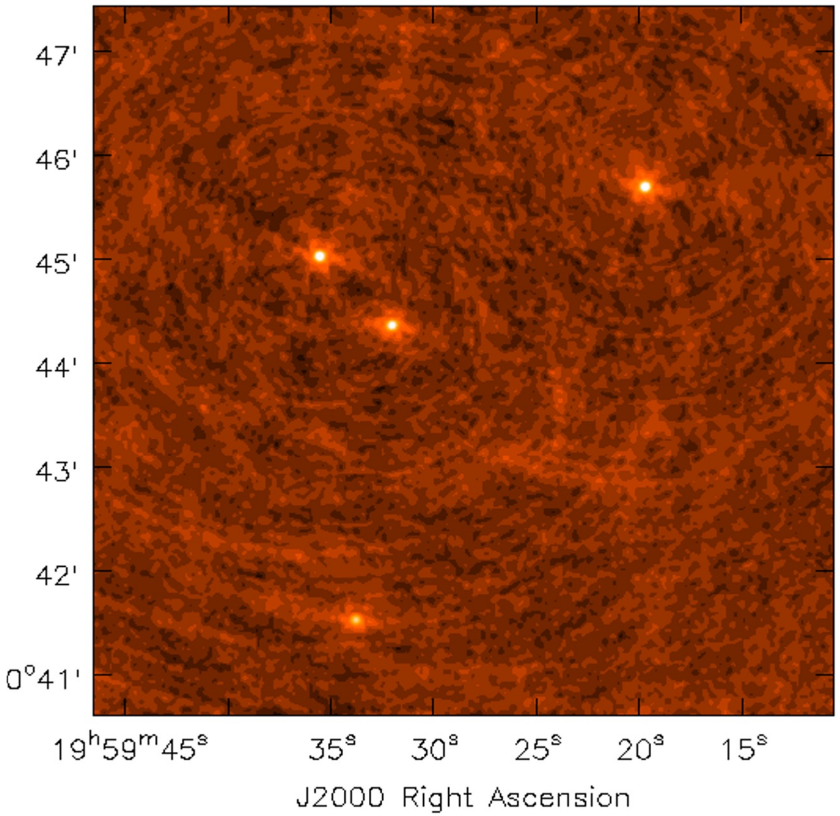
Observation : **4 hours**

"Earth Rotation Synthesis"

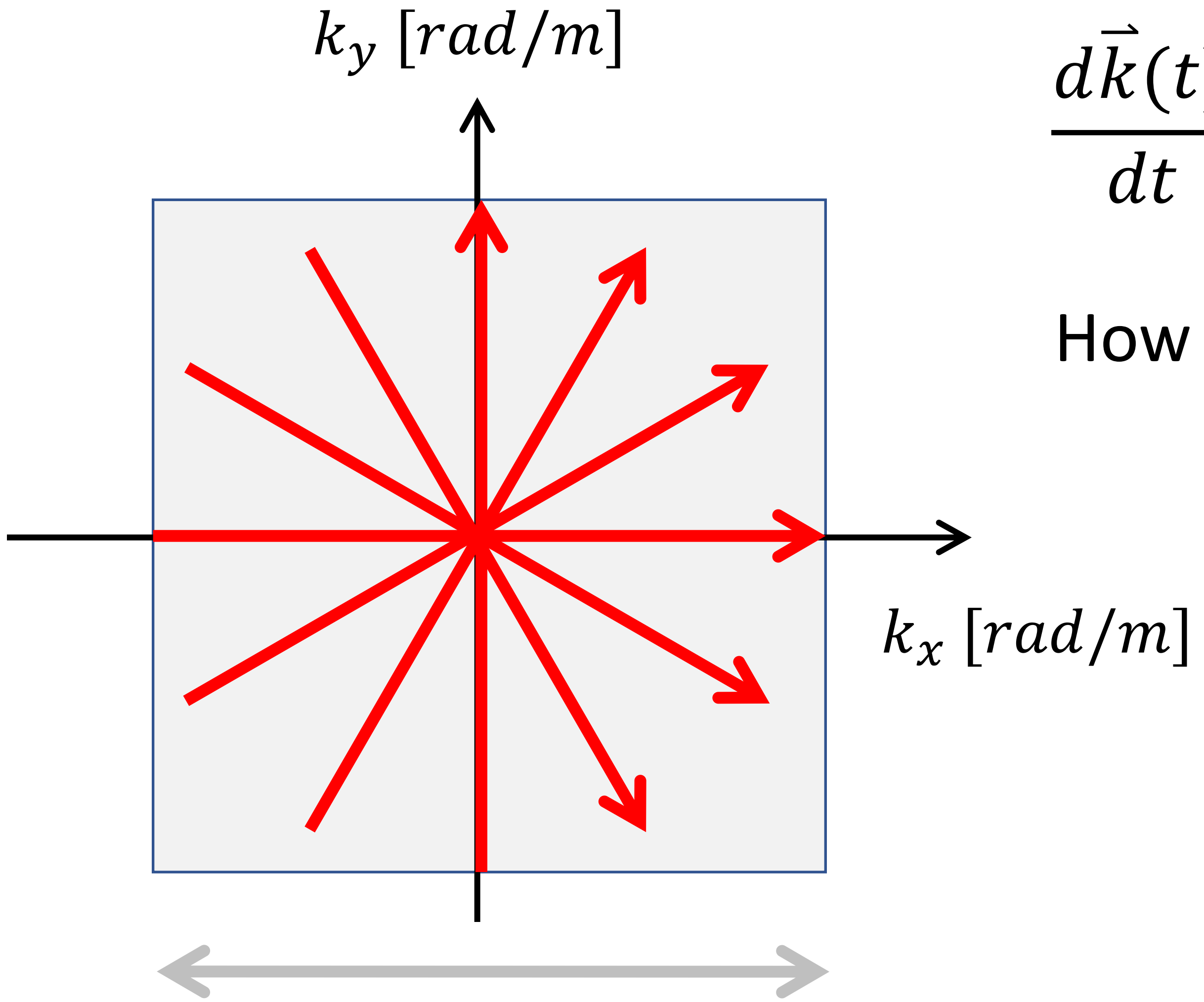
$S(u, v)$



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



Radial sampling

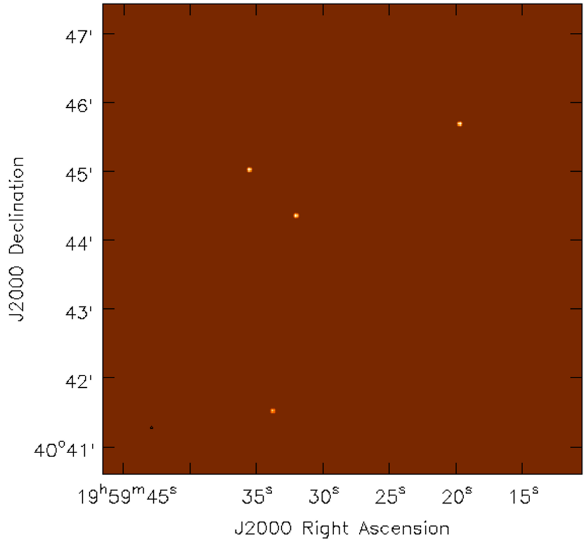


aperture needed: $2\pi/\Delta x$

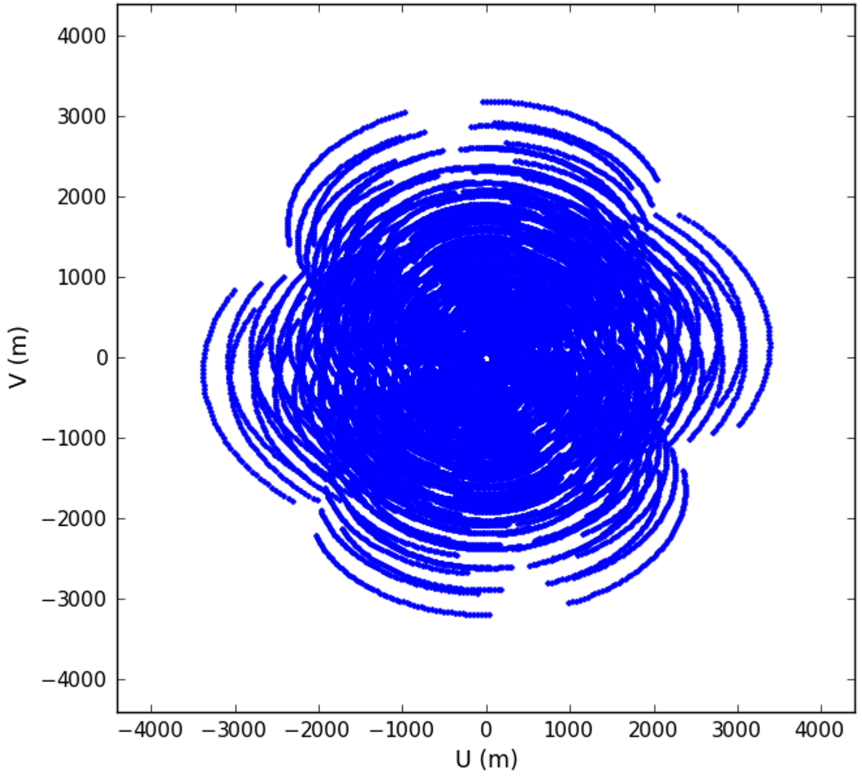
$$\frac{d\vec{k}(t)}{dt} = \gamma \vec{G}(t)$$ k-space velocity

How about **radial**?

Earth Rotation Synthesis



$S(u,v)$



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

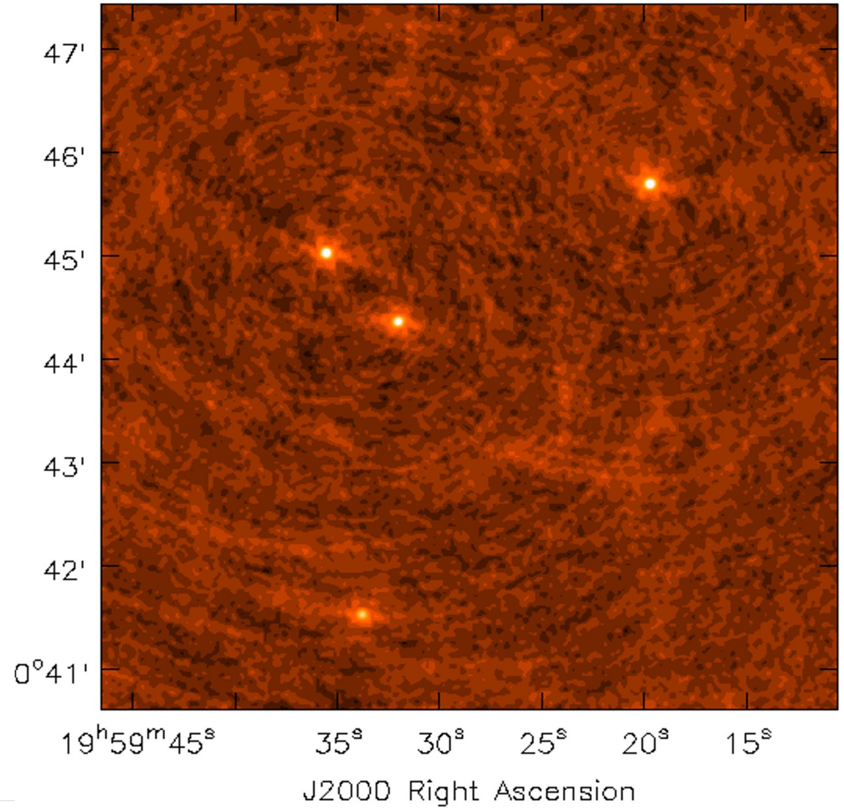


Image of the sky
using 27 antennas
Observation : 4 hours

Channels : 1.5 GHz

Multi-Frequency synthesis

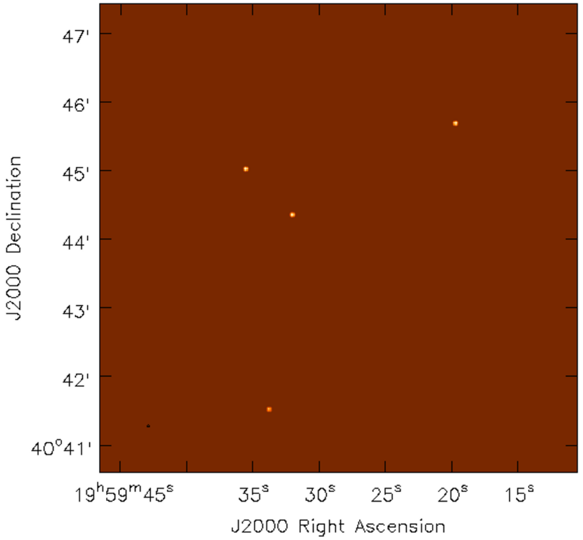
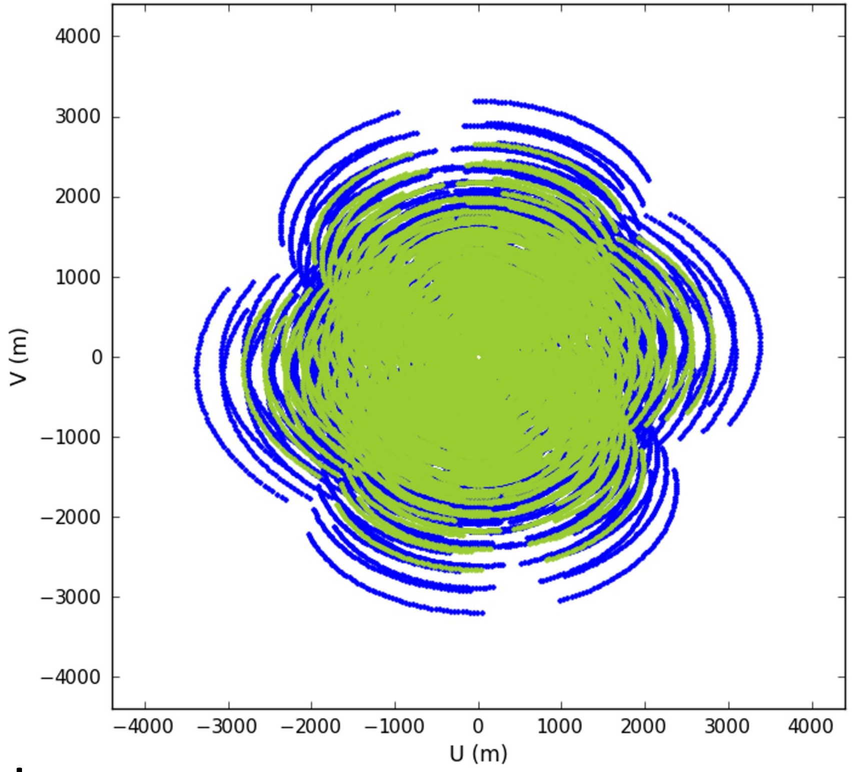


Image of the sky
using 27 antennas
Observation : 4 hours

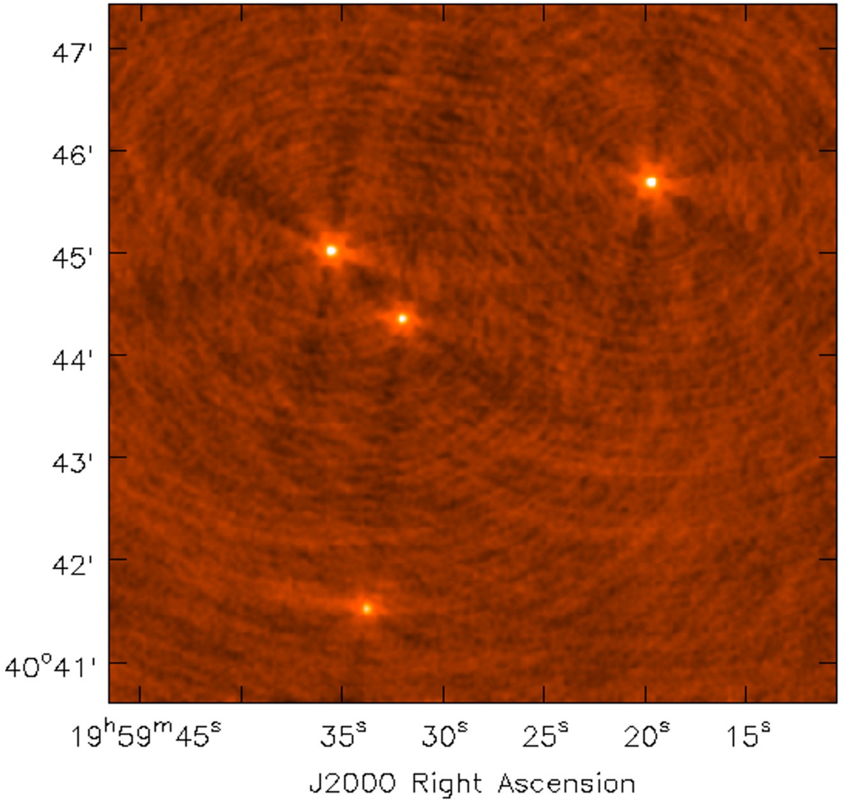
Channels : 1.0 GHz, 1.5 GHz

“Multi-Frequency Synthesis”

$S(u,v)$



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



Multi-Frequency synthesis

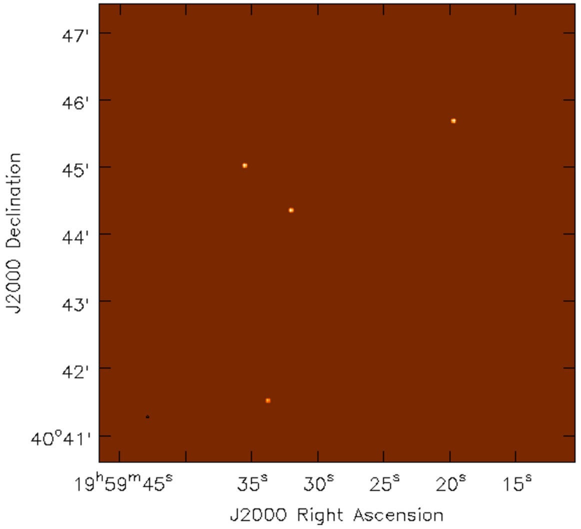
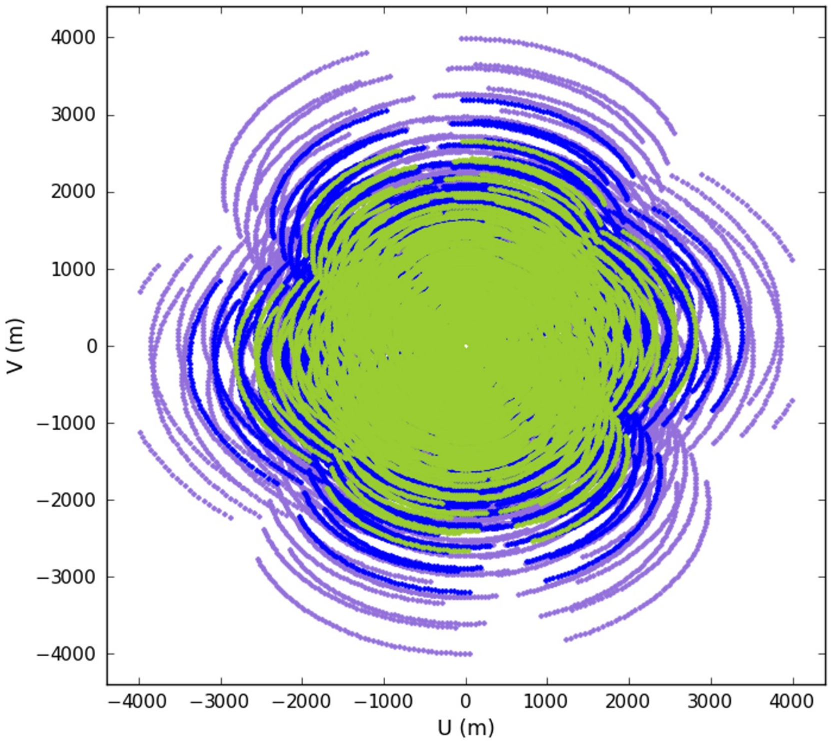
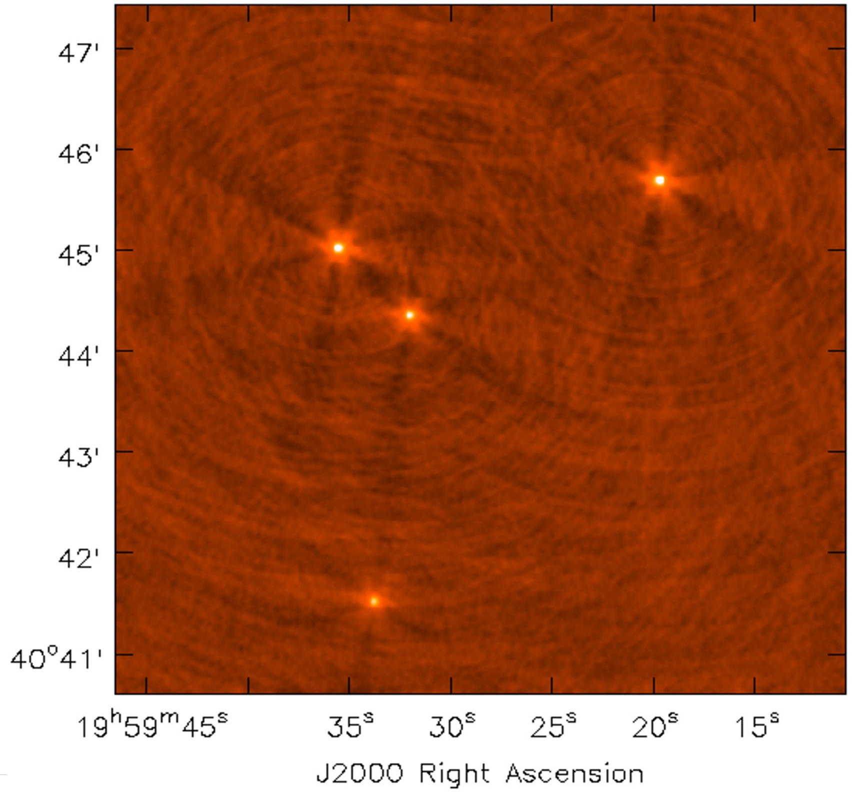


Image of the sky
using 27 antennas
Observation : 4 hours

$S(u, v)$



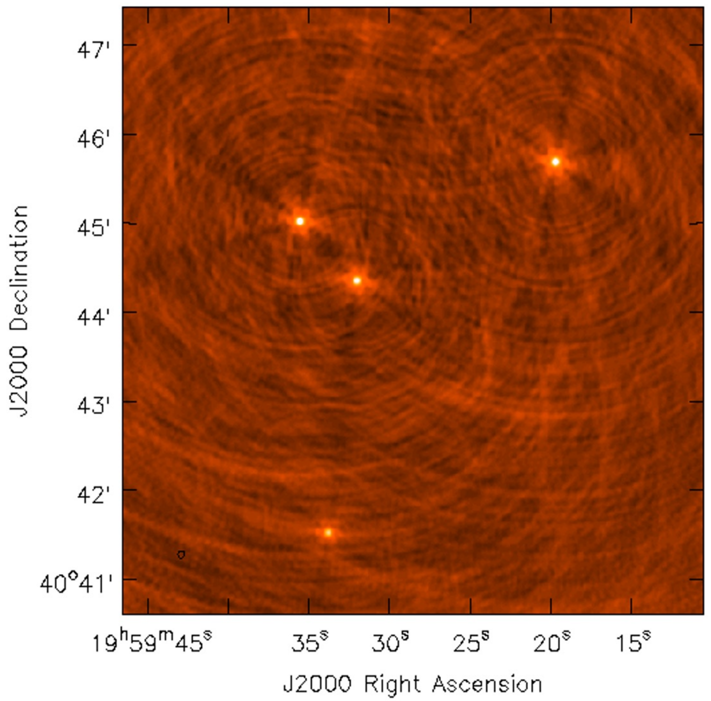
$I^{obs}(l, m)$



Channels : 1.0 GHz, 1.5 GHz, 2.0 GHz

"Multi-Frequency Synthesis"

The observed image



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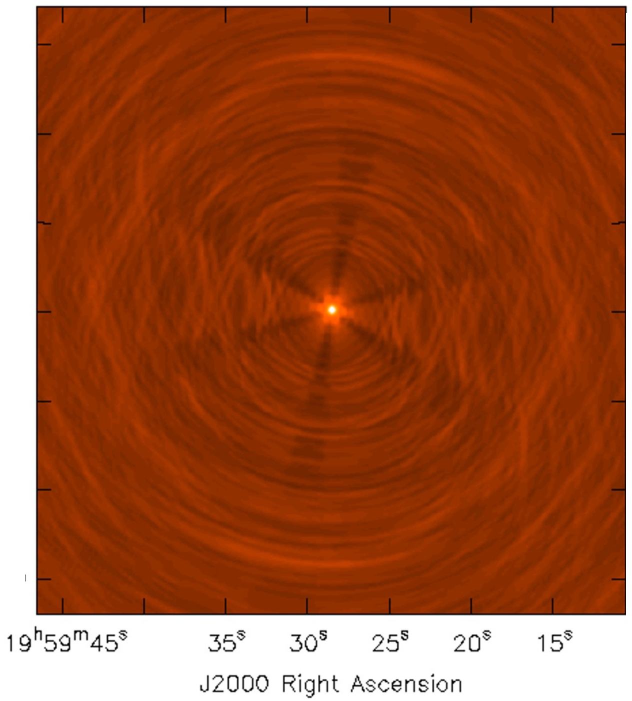
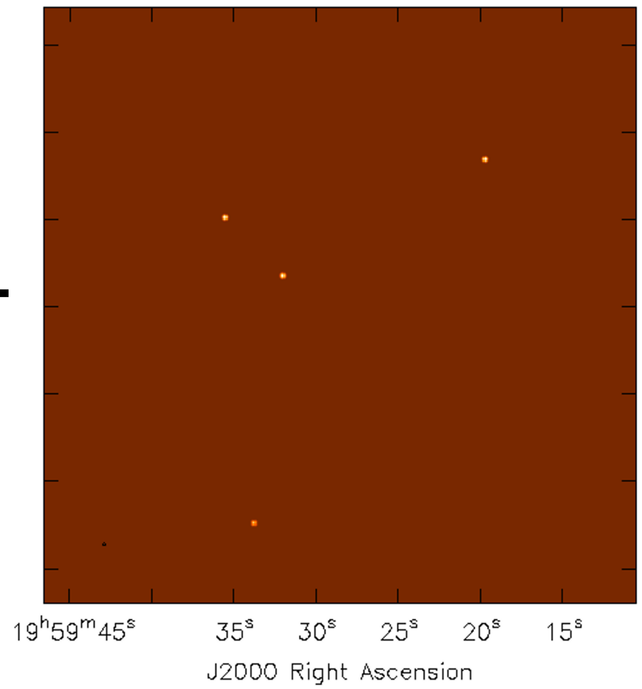


$\ast$



The "CLEAN" algorithm (Hogbom 1974, Clark 1980, Cotton-Schwab 1983, ...)

Sparse Sky Model, Non-linear reconstruction (iterative), L2 data normalization, Greedy regularization

Compressed sensing

Compressed sensing in MRI

- started in 2005
- permits deliberate undersampling → <u>save time</u>
- widely deployed, in research and commercially
- favored sampling: random, center-heavy

Magnetic Resonance in Medicine 58:1182–1195 (2007)

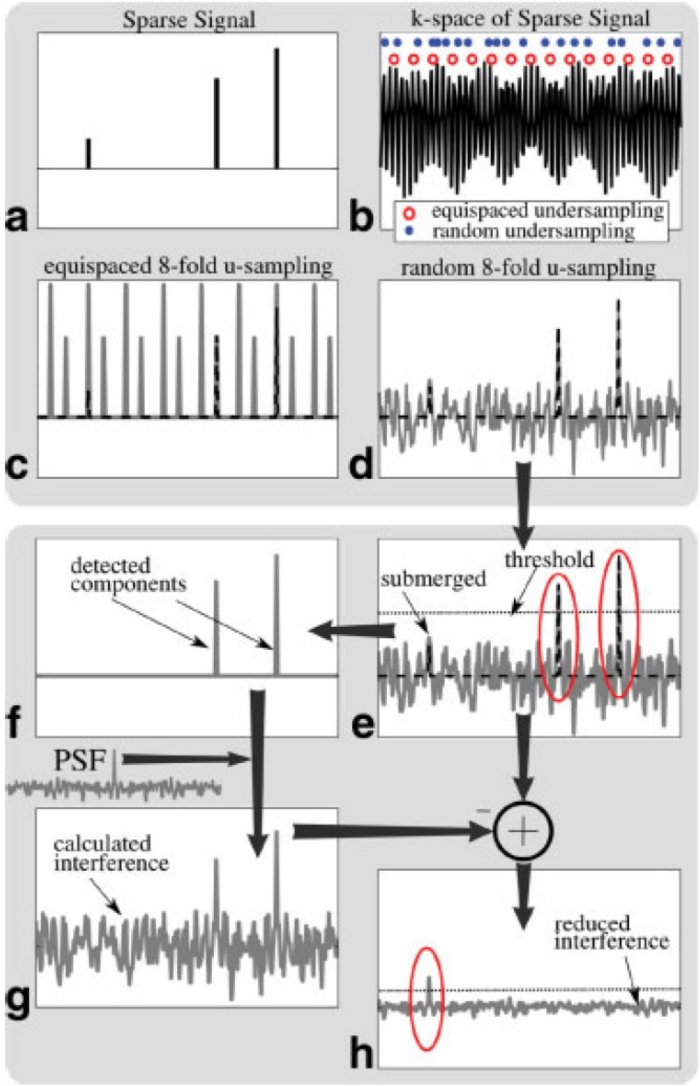
Sparse MRI: The Application of Compressed Sensing for Rapid MR Imaging

Michael Lustig,[1*] David Donoho,[2] and John M. Pauly[1]

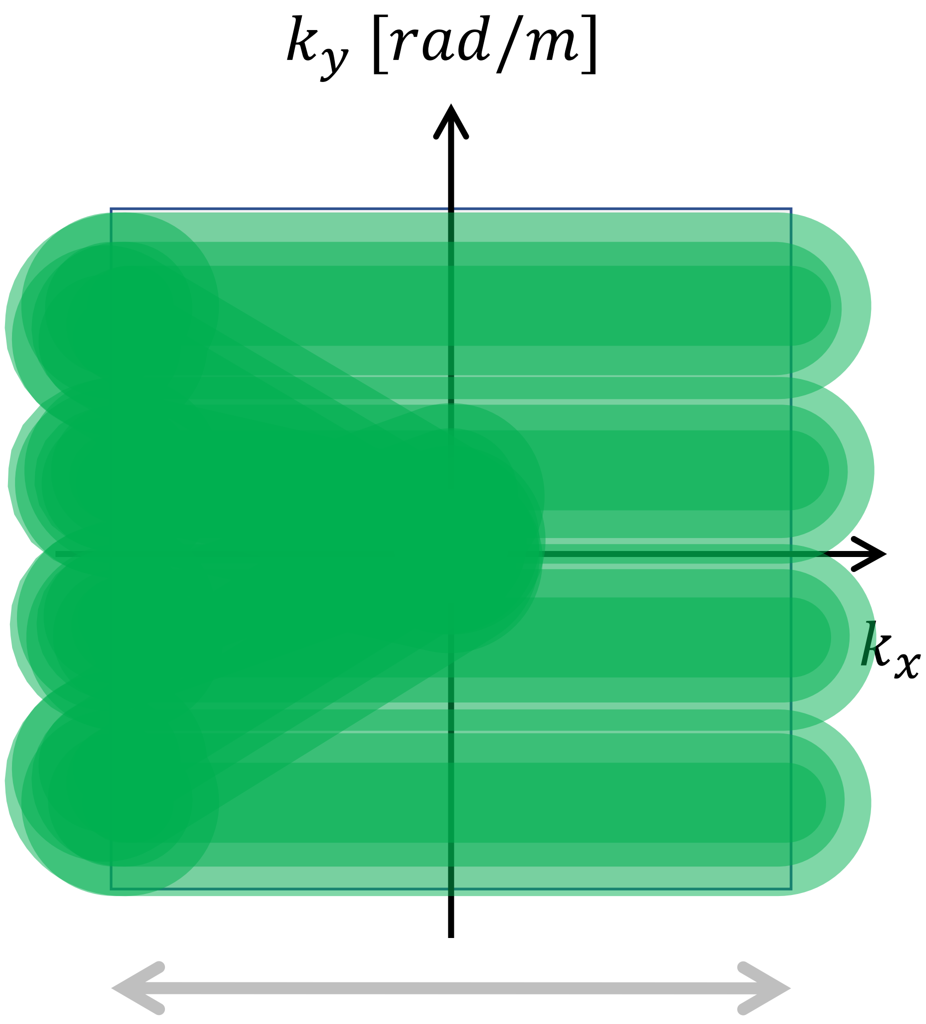
The sparsity which is implicit in MR images is exploited to significantly undersample *k*-space. Some MR images such as angiograms are already sparse in the pixel representation; other, more complicated images have a sparse representation in some transform domain–for example, in terms of spatial finite-differences or their wavelet coefficients. According to the recently developed mathematical theory of compressed-sensing, images with a sparse representation can be recov-

groups: (a) Methods generating artifacts that are incoherent or less visually apparent, at the expense of reduced apparent SNR (1–5); (b) Methods exploiting redundancy in *k*-space, such as partial-Fourier, parallel imaging, etc. (6–8); (c) Methods exploiting either spatial or temporal redundancy or both (9–13).

In this article we aim to exploit the sparsity which is



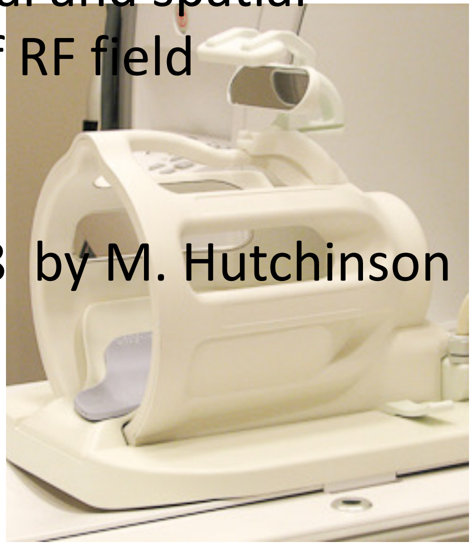
Parallel MRI

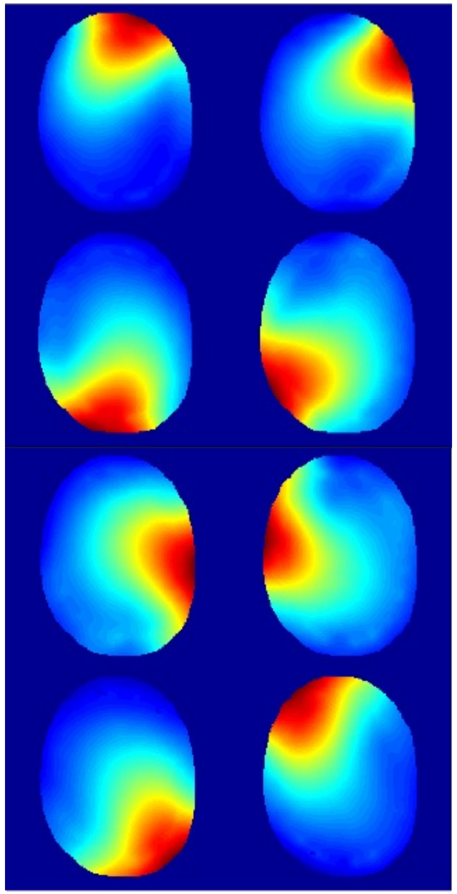


aperture needed: $2\pi/\Delta x$

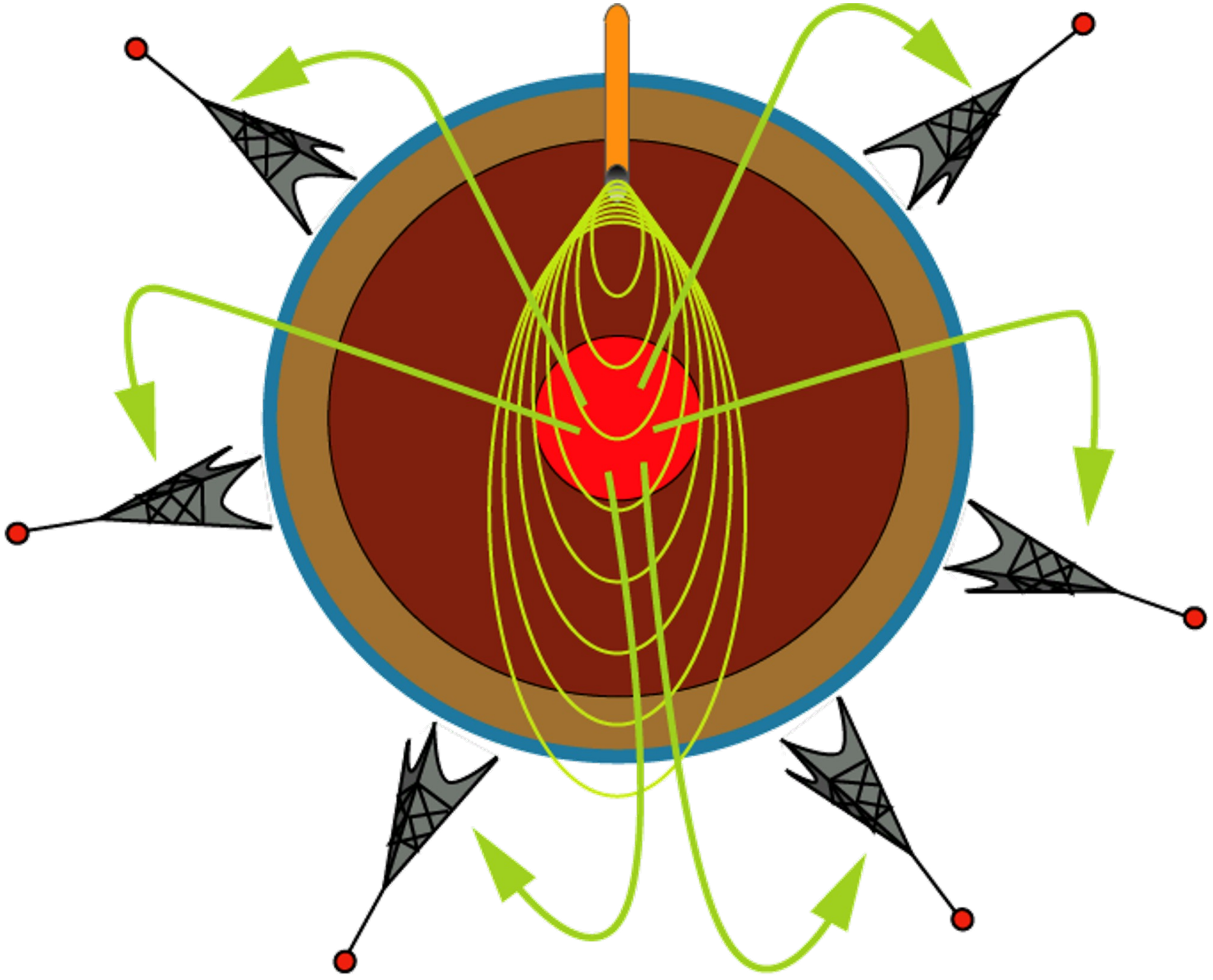
Parallel MRI:

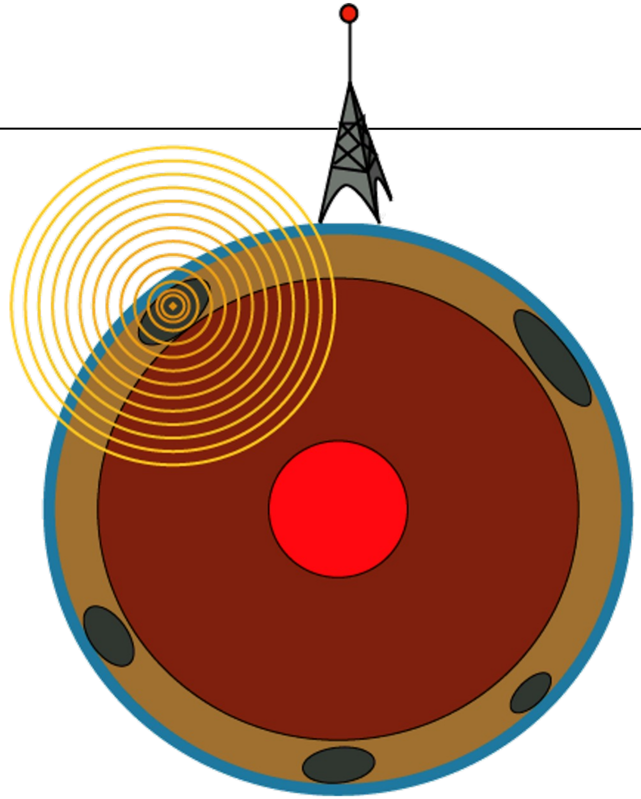
- capture near-field by array detection
- broadens and samples aperture
- enables undersampling, saving time
- **saves time / increases FOV**
- taps into both temporal and spatial degrees of freedom of RF field
- widely deployed
- first conceived in 1988 by M. Hutchinson





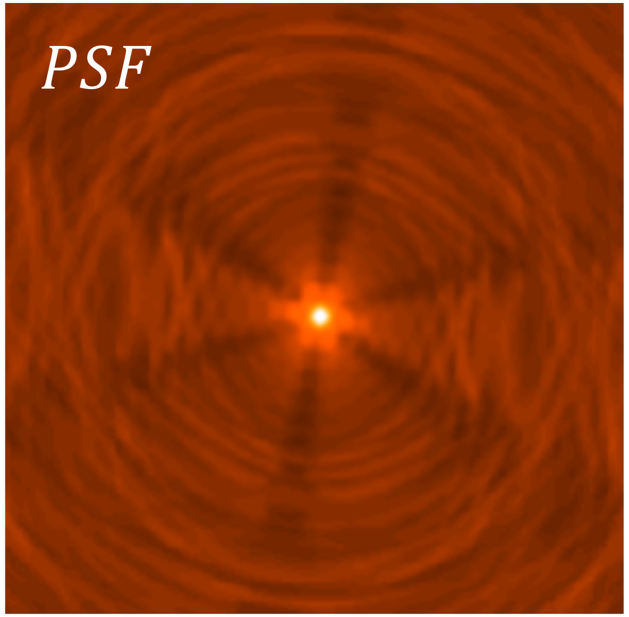
Planetary parallel MRI

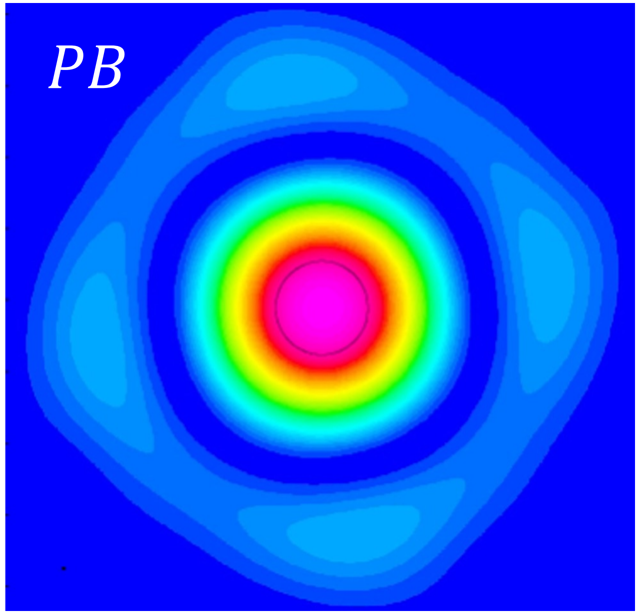




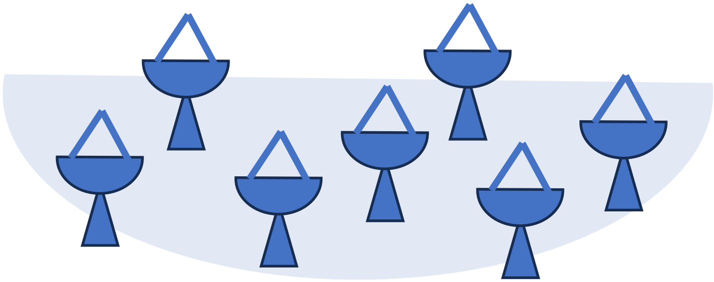
Courtesy: M. Hutchinson

Instrument Response

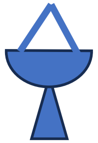




$$I^{obs} = PSF * \left\lfloor PB \cdot I^{sky} \right\rfloor$$



Angular Resolution

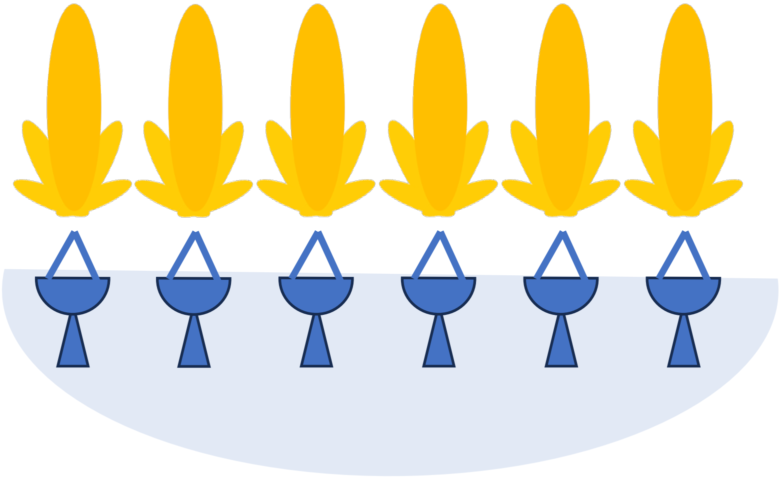


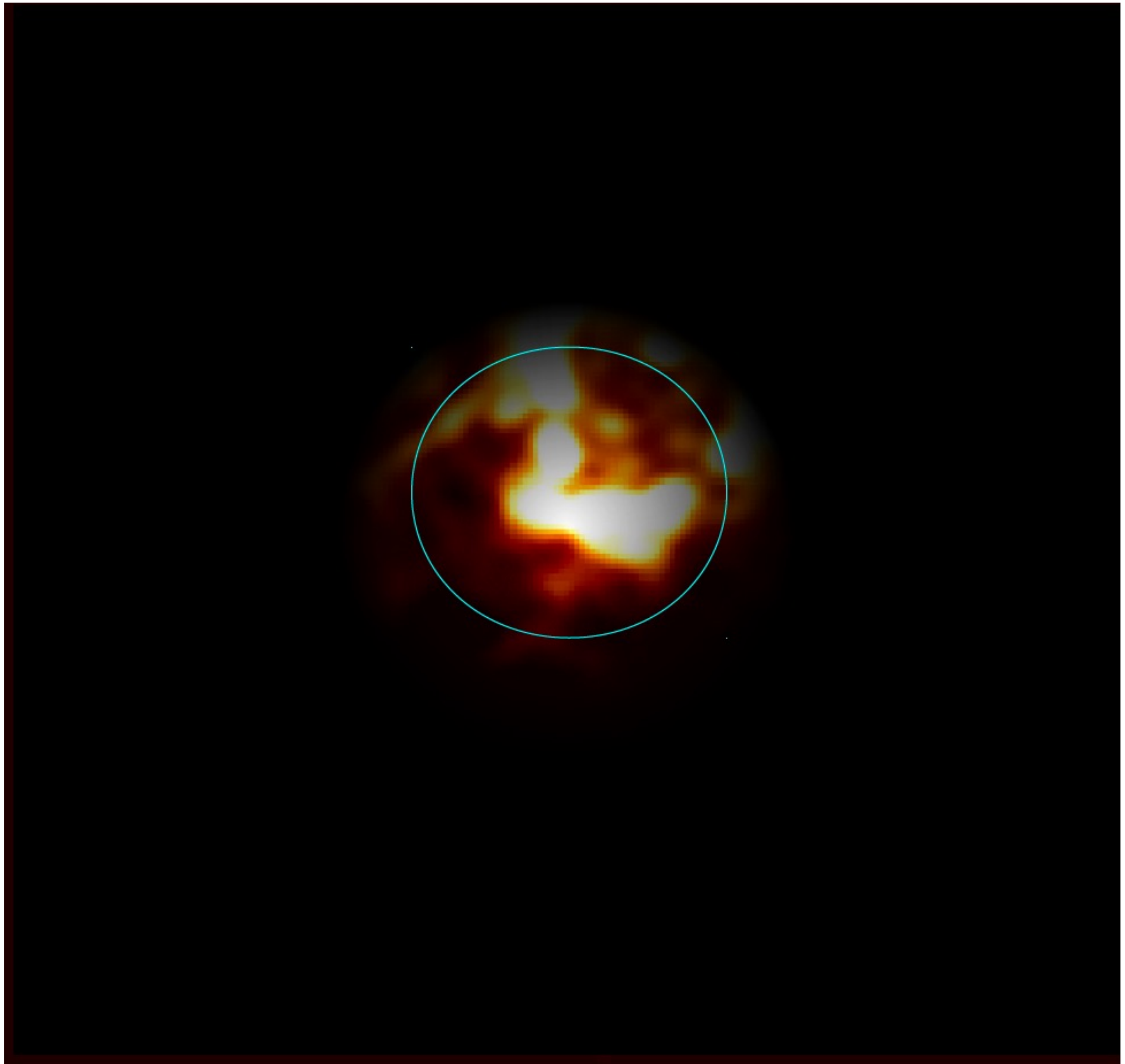
Field of View

Image a finite field-of-view

Image from

one "pointing"

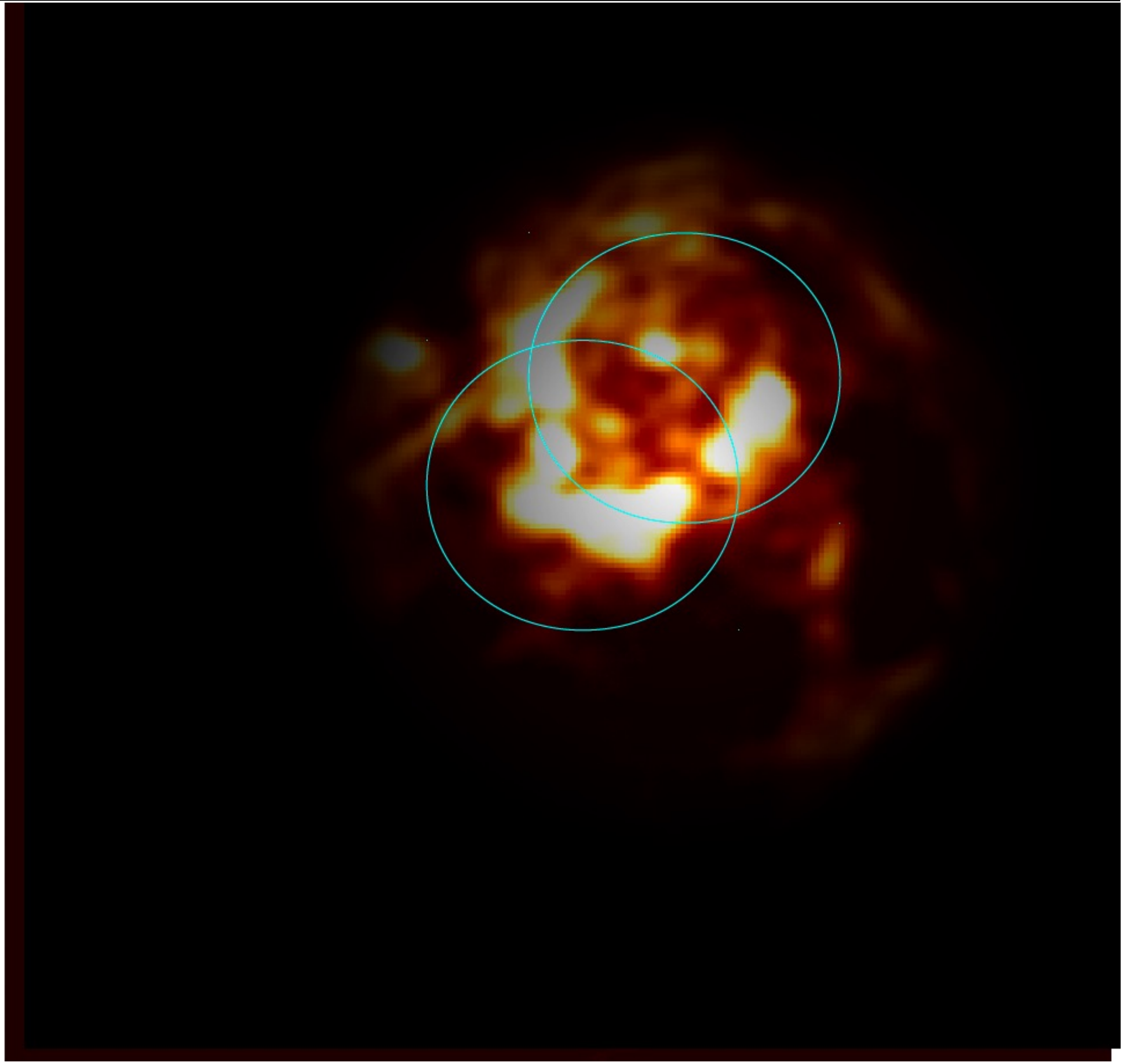




Increase the field-of-view

Increase field-of-view

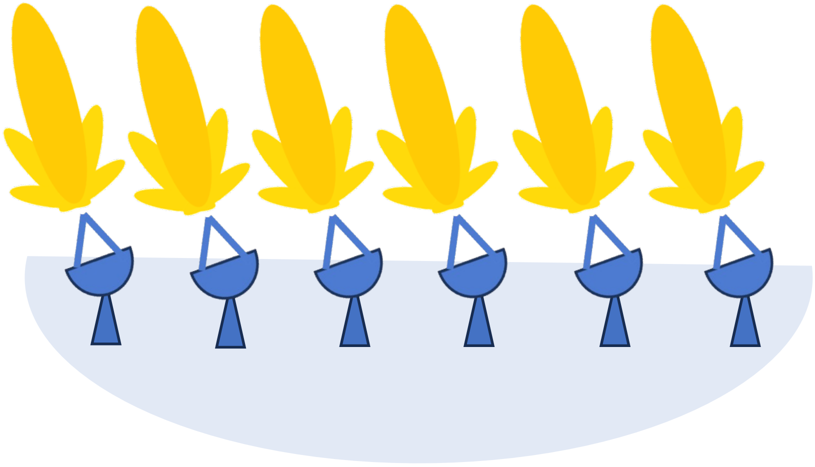
multiple “pointings”

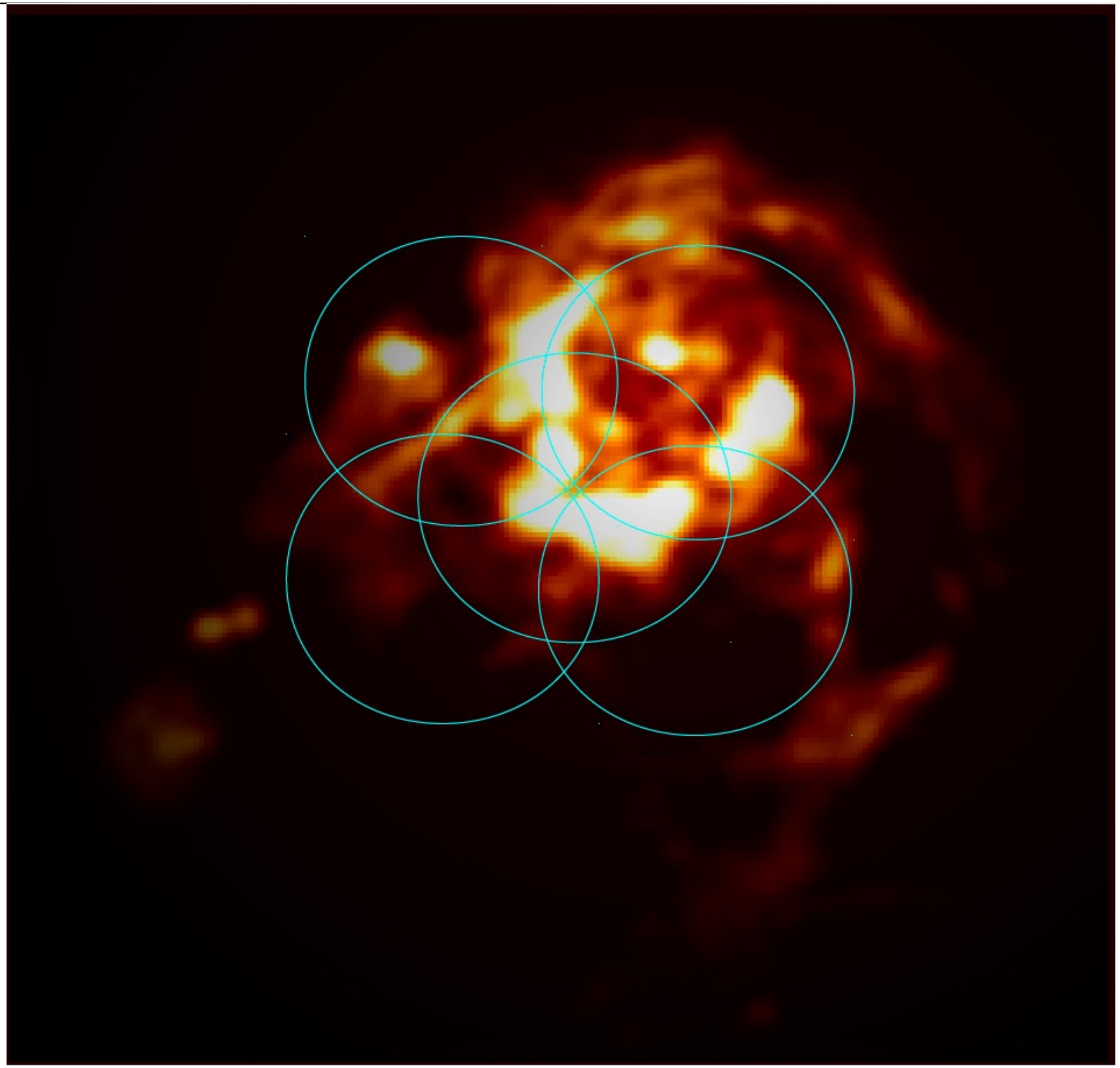


Increase the field-of-view

Increase field-of-view

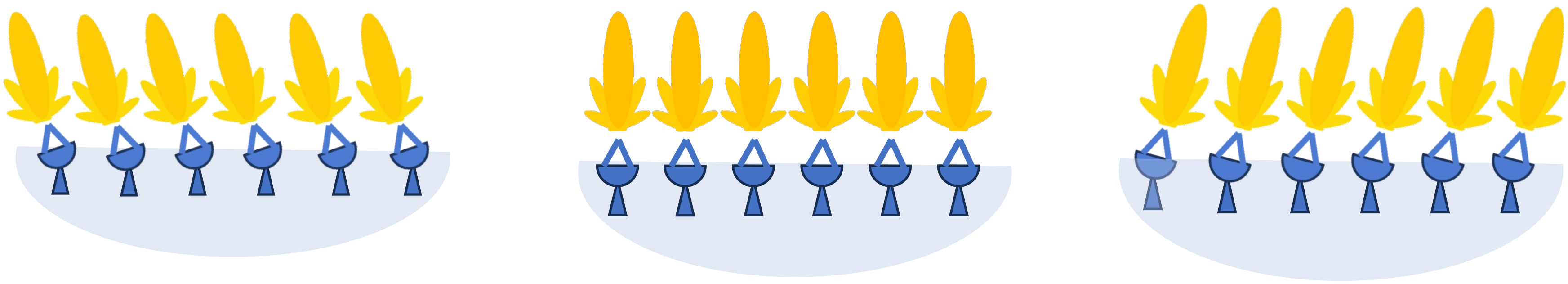
multiple “pointings”





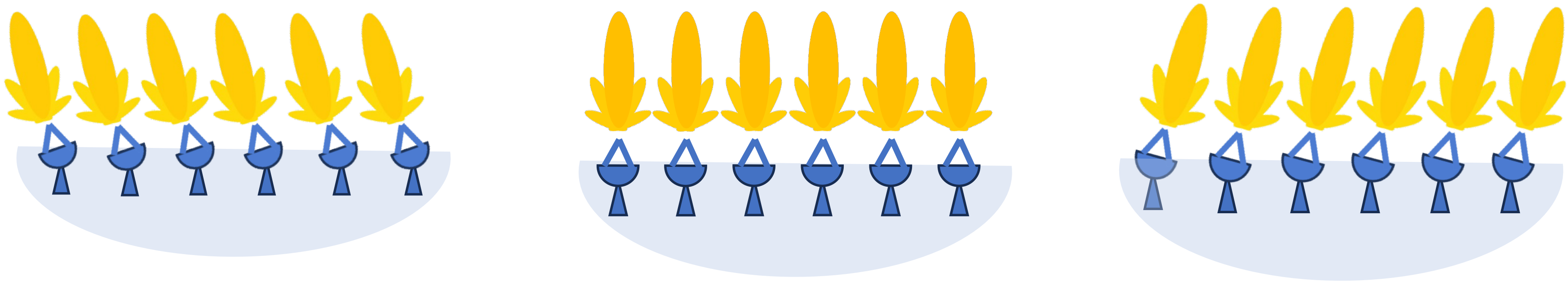
Mosaic Imaging

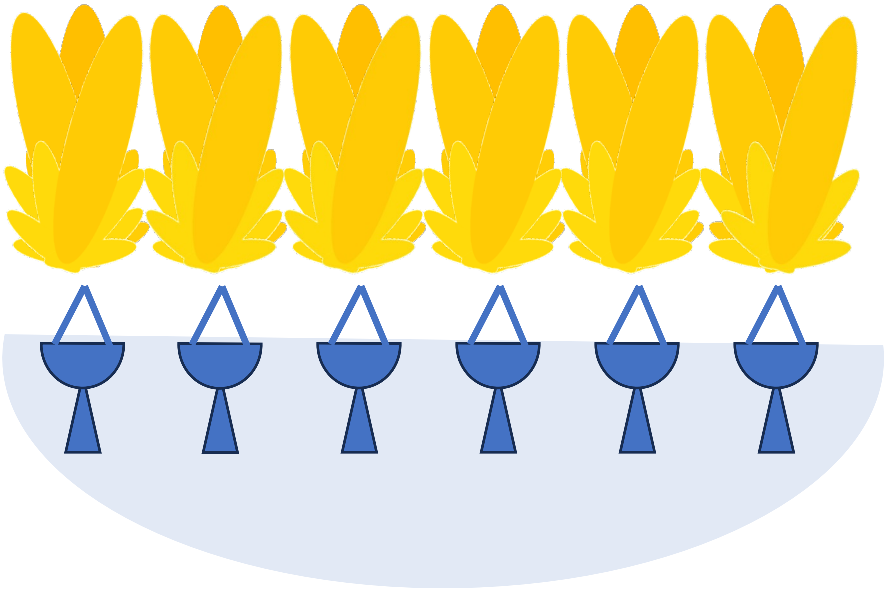
Raster
in time



Mosaic Imaging

Raster
in time





Multiple Beams
in parallel

System of equations in MR

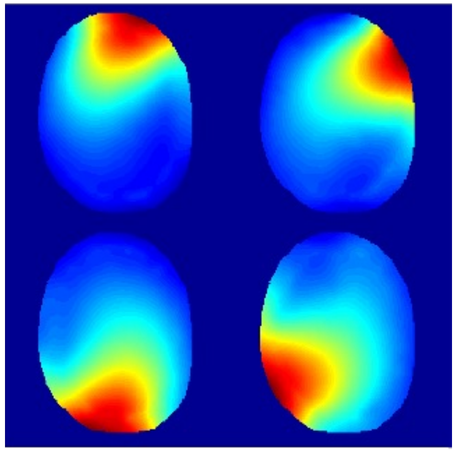
coil sensitivity

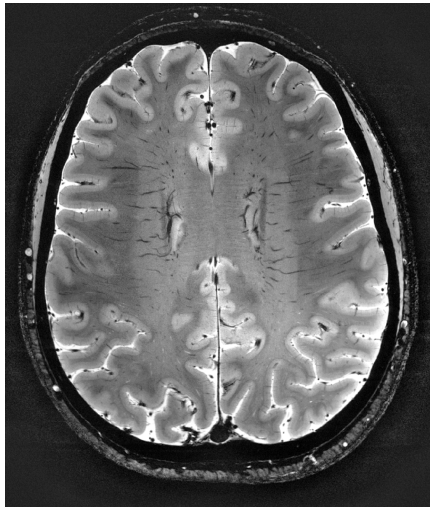
magnetization

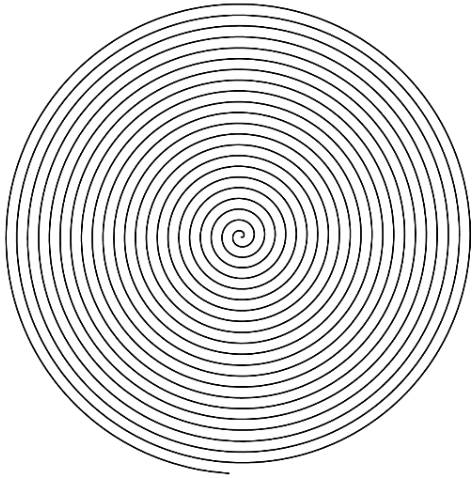
k-space trajectory

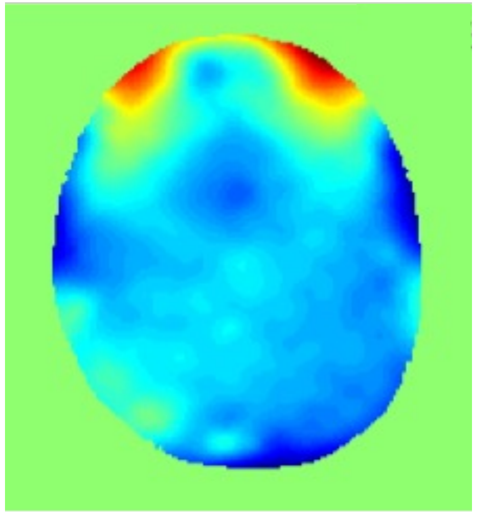
magnetic field perturbation

$$m_{c,t} = \int s_c(\vec{r})\,\rho(\vec{r})\,e^{i\vec{k}(t)\cdot\vec{r}}\,e^{i\Delta\phi(\vec{r},t)}\,d^3r$$

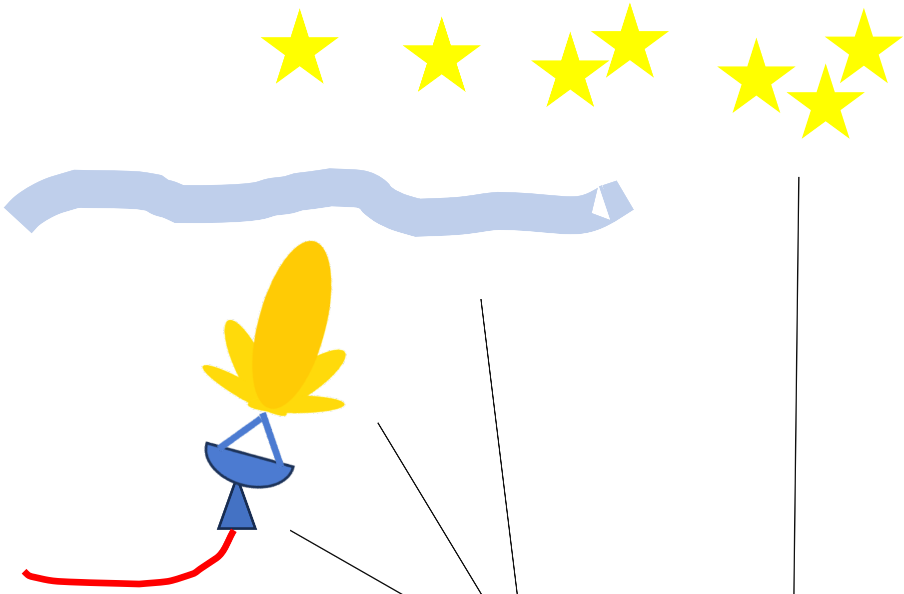


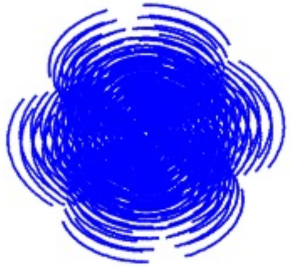


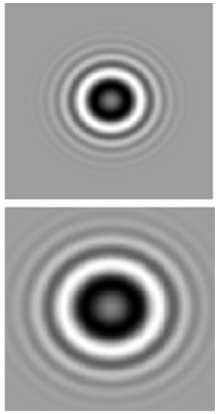




System of equations in Radio Interferometry







$$V_{b,c,t} = \int M_c(\vec{r}, b, t)\, I^{sky}(\vec{r})\, e^{i\vec{k}_b \cdot \vec{r}}\, e^{i\Delta\phi(\vec{r})}\, d^3r$$

antenna sensitivity

sky brightness

k-space trajectory

3D -> 2D projection effects

We share signal equations

coil sensitivity

k-space trajectory

magnetization

magnetic field perturbation

$$m_{c,t} = \int s_c(\vec{r})\, \rho(\vec{r})\, e^{i\vec{k}(t)\cdot\vec{r}}\, e^{i\Delta\phi(\vec{r},t)}\, d^3r$$

$$V_{b,c,t} = \int M_c(\vec{r}, b, t)\, I^{sky}(\vec{r})\, e^{i\vec{k}_b\cdot\vec{r}}\, e^{i\Delta\phi(\vec{r})}\, d^3r$$

antenna sensitivity

sky brightness

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3D -> 2D projection effects

Reconstruction in MRI

Discretize signal model: $E\boldsymbol{x} = \boldsymbol{m}$

Minimize suitable cost function, default: $L = \|E\boldsymbol{x} - \boldsymbol{m}\|_2^2$

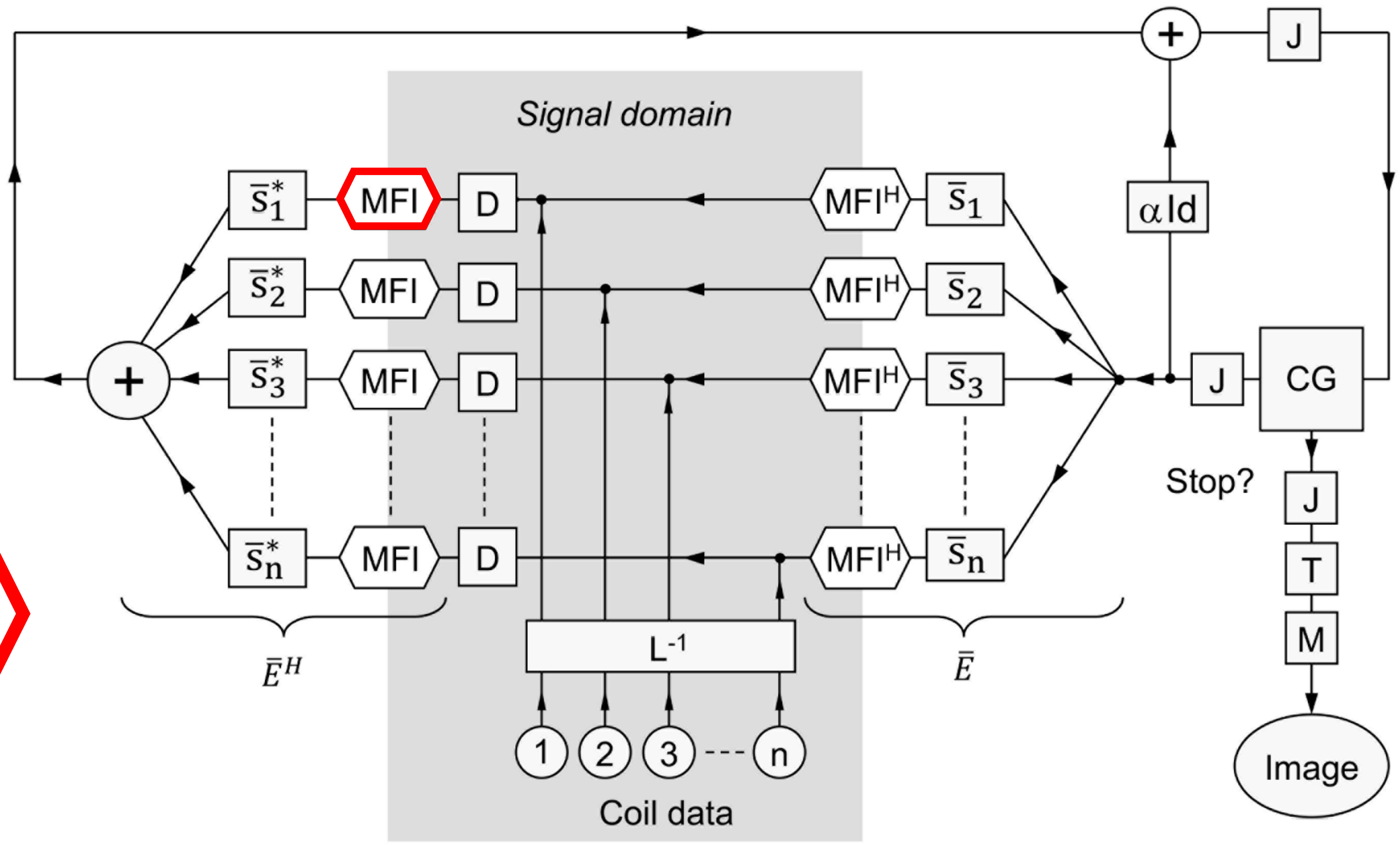
For regularization, add cost term: $L = \|E\boldsymbol{x} - \boldsymbol{m}\|_2^2 + \lambda R(\boldsymbol{x})$

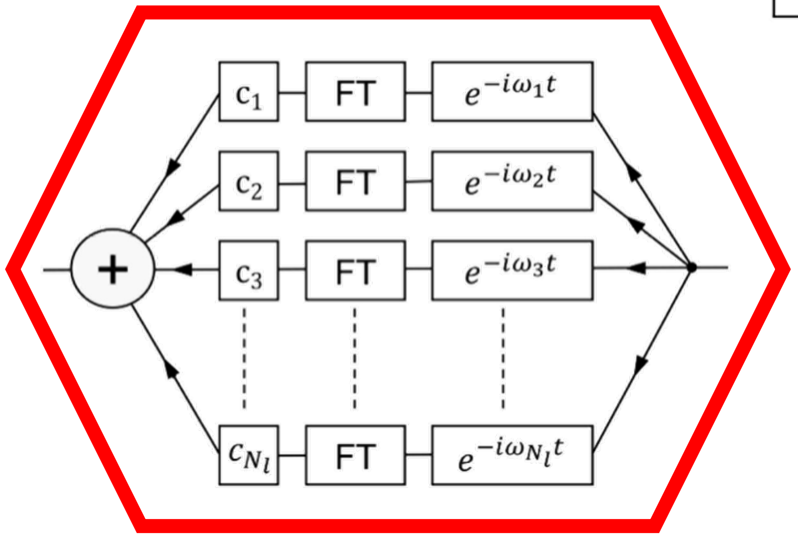
Or combine costs and constraints, e.g., $L = \|C\boldsymbol{x}\|_1 \quad s.t. \|E\boldsymbol{x} - \boldsymbol{m}\|_2 < \epsilon$

Popular cost terms: $\|C\boldsymbol{x}\|_2$, $\|C\boldsymbol{x}\|_1$, $TV(\boldsymbol{x})$, trained networks

Popular transforms: Fourier, wavelet, low-rank modeling, …

Reconstruction in MRI

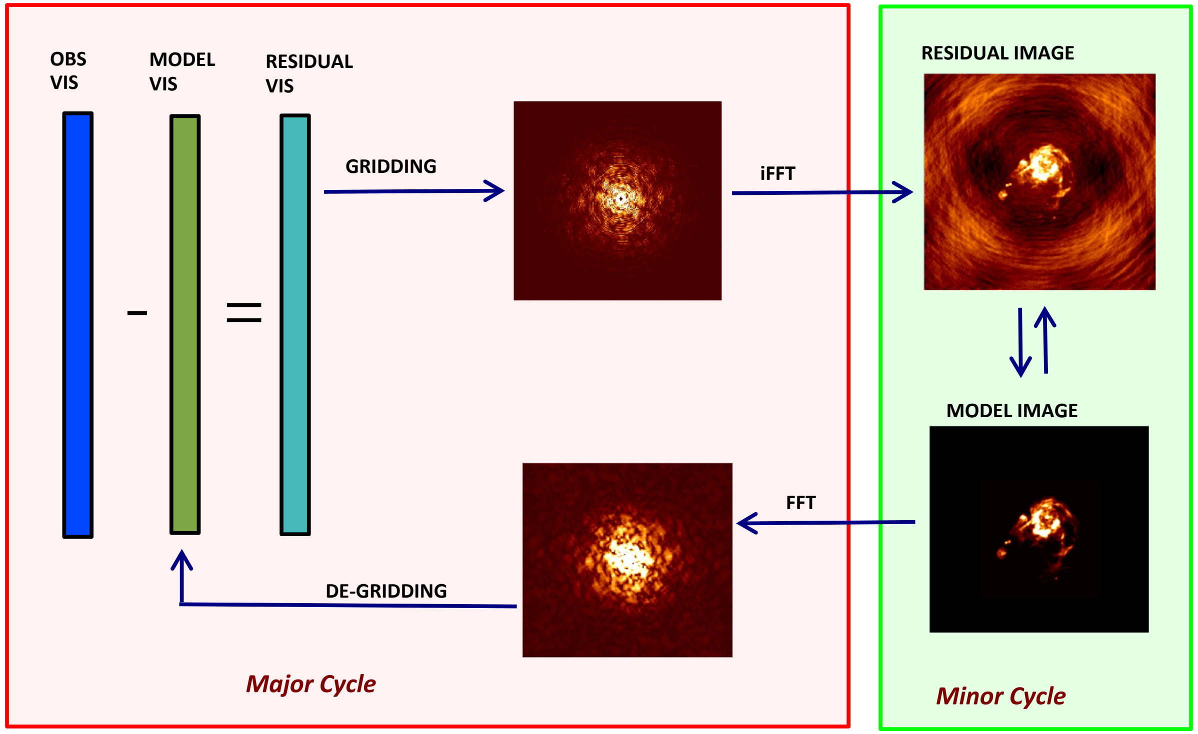




Reconstruction in radio interferometry

$$V^{obs} = [A]\, I^{m} + n \quad \longrightarrow \quad \min\left\{ \left\| V^{obs} - [A]\, I^{m} \right\|_2^2 + \lambda\, R(I^{m}) \right\}$$

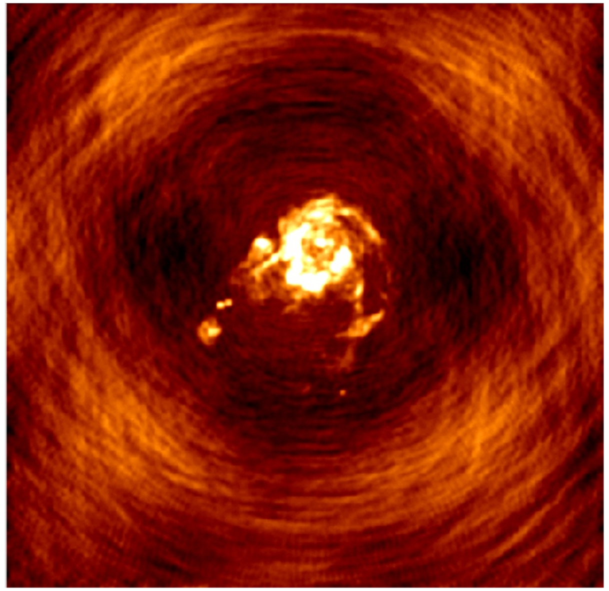
Data/Instrument domain Image Domain



Algorithm Ingredients

- Sky Model
- Priors & Regularizers
- Optimization Strategy
- Instrumental Corrections
- Knowns vs Unknowns

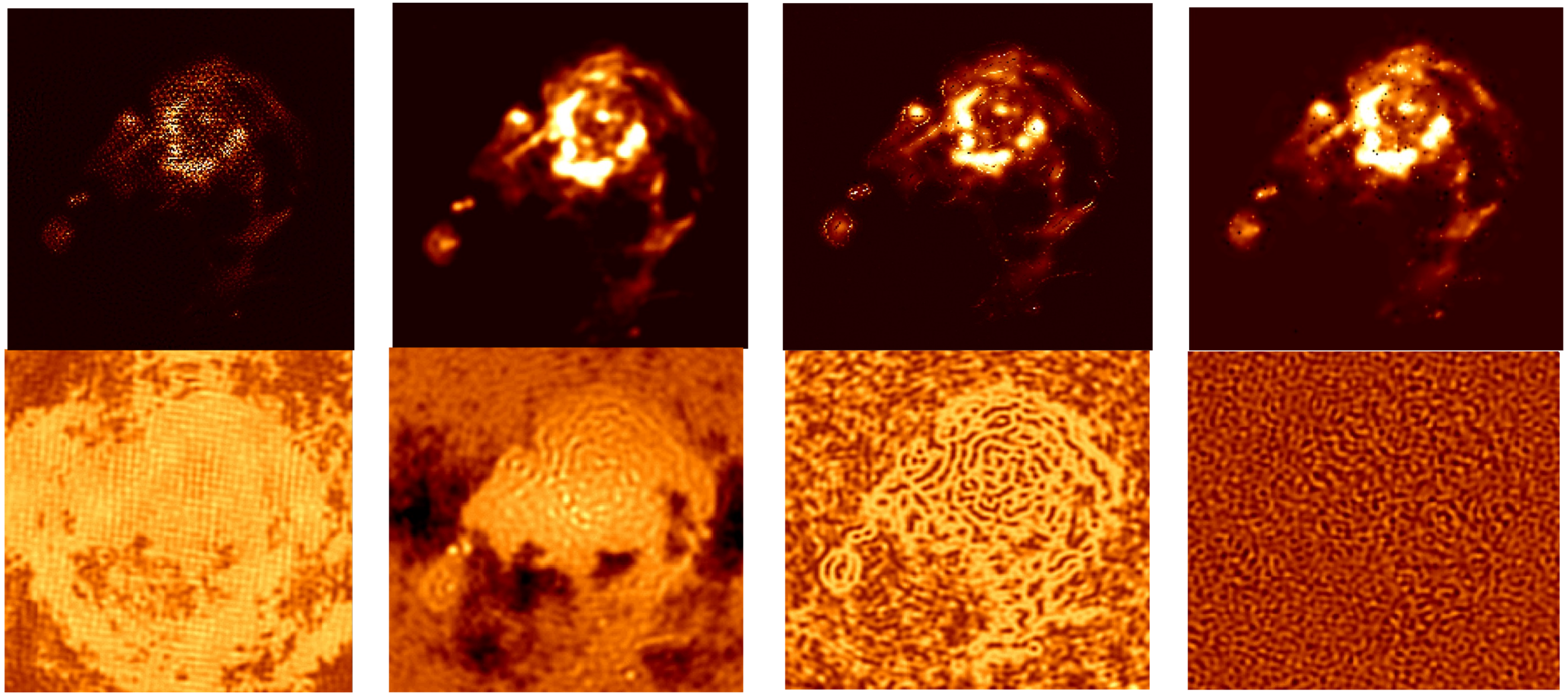
Algorithm Variability



CLEAN	MEM	MS-CLEAN	ASP
Point source model	Point source model with a smoothness constraint	Multi-Scale model with a fixed set of scale sizes	Multi-Scale model with adaptive best-fit scale per component

Model

Residual



elephAnt In the room

coil sensitivity

magnetization

k-space trajectory

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$$m_{c,t} = \int s_c(\vec{r})\, \rho(\vec{r})\, e^{i\vec{k}(t)\cdot\vec{r}}\, e^{i\Delta\phi(\vec{r},t)}\, d^3r$$

$$V_{b,c,t} = \int M_c(\vec{r}, b, t)\, I^{sky}(\vec{r})\, e^{i\vec{k}_b\cdot\vec{r}}\, e^{i\Delta\phi(\vec{r})}\, d^3r$$

antenna sensitivity

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Personal take:

- Potential for ML supporting reconstruction is huge and in a wide-open, creative space
- Seems greatest for harnessing prior knowledge about imaging targets

  e.g., image plausibility metrics for given anatomy
- Learning is tempting also for instrumental corrections (e.g. gradient heating, …)
- Learning is data-hungry: minimize the degrees of freedom to address in this way
- Let's make sure we do not learn what we already know, can know, or can measure
- Let's keep in mind that ML-informed processing cannot add fresh information, only blend in prior knowledge.

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Practical considerations when designing an AI/ML (or any!) algorithm

- Accuracy : What features can we trust ?
- Robustness : How does it handle imperfect input data ?
- Generalizability : Does it work for all types of source structures ?
- Interpretability : Can we understand its biases ?
- Compute Cost : Can we afford it ?
- Usability : How well can it fit within application workflows ?

Let’s keep the conversation going …