A Brief Introduction to Radio Interferometry

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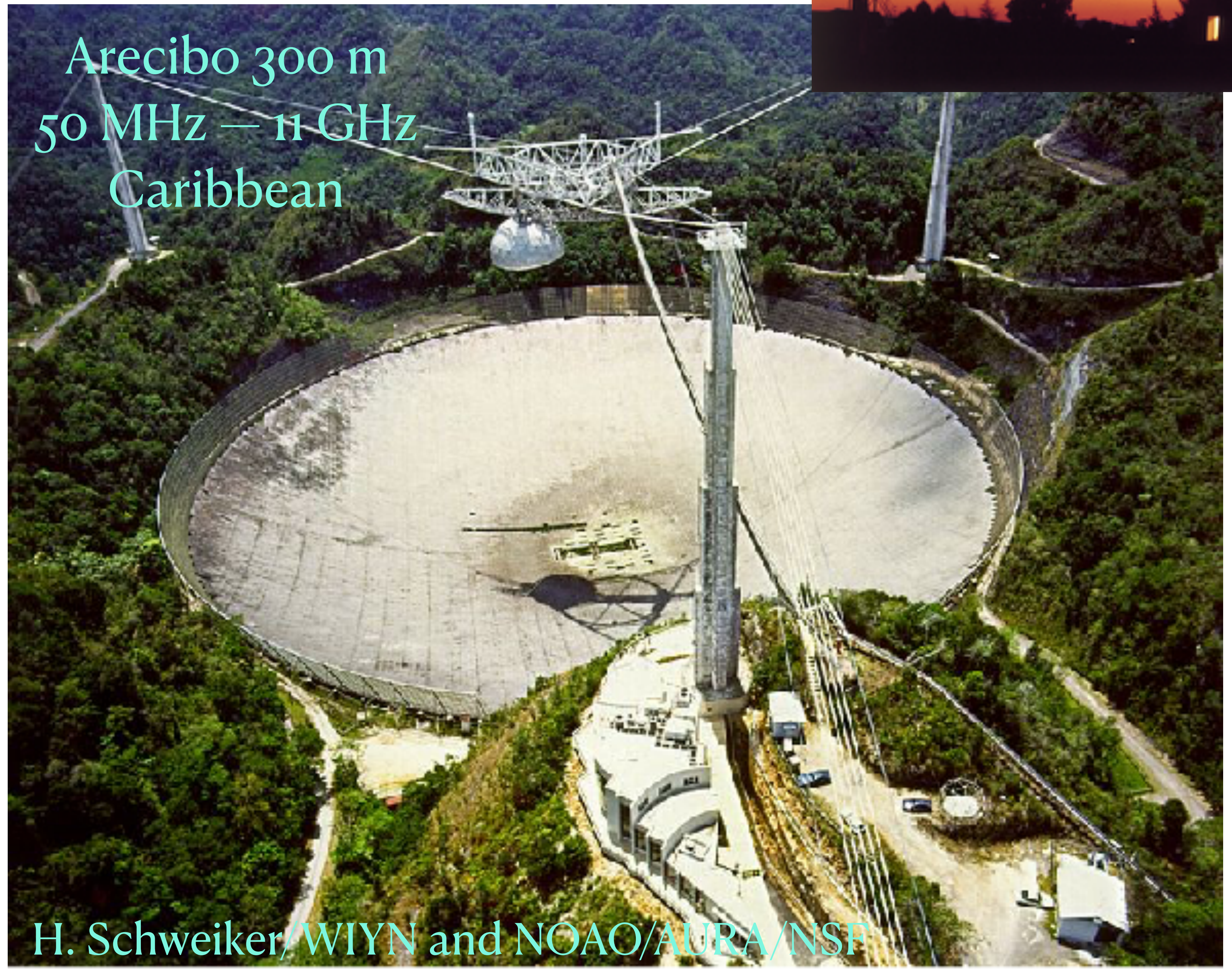
Introduction

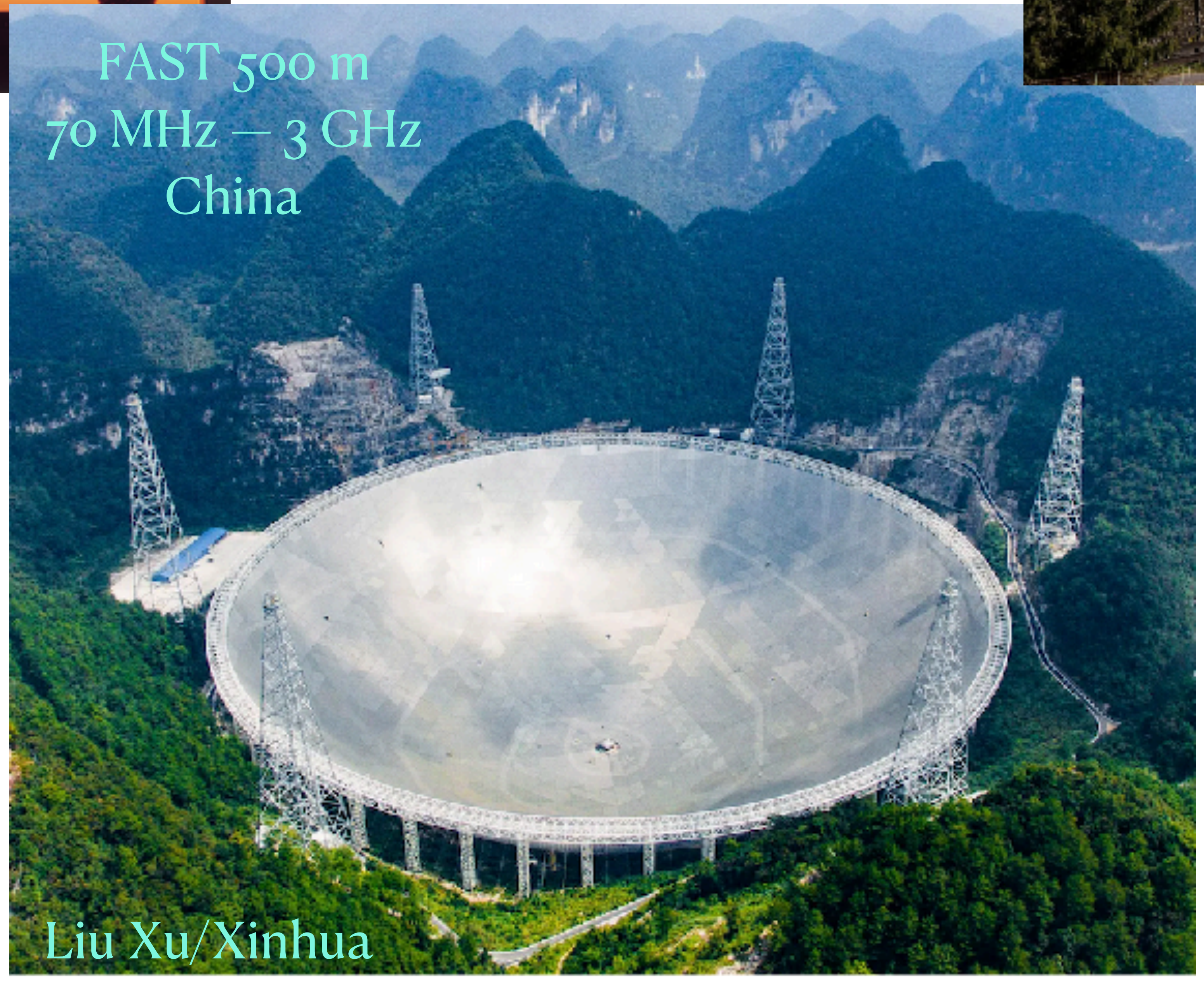
Credit: NSF/NRAO/AUI/VLA

Radio emission mapping

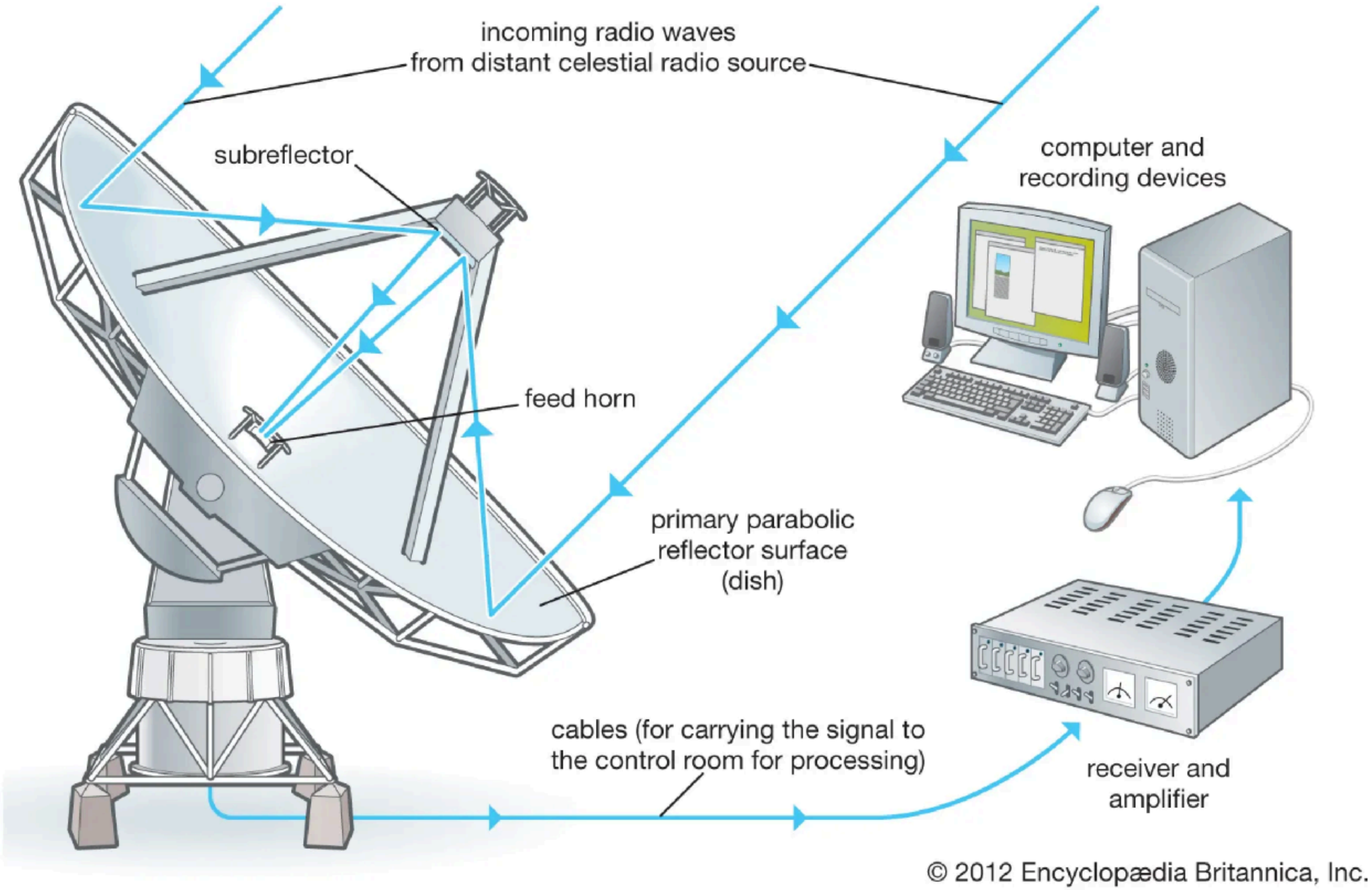
Electromagnetic spectrum

Single-dish radio telescopes





Components of single-dish radio telescopes



Angular resolution

★ Angular resolution is the ability to separate two point sources into separated sources.

Well resolved Just resolved Unresolved

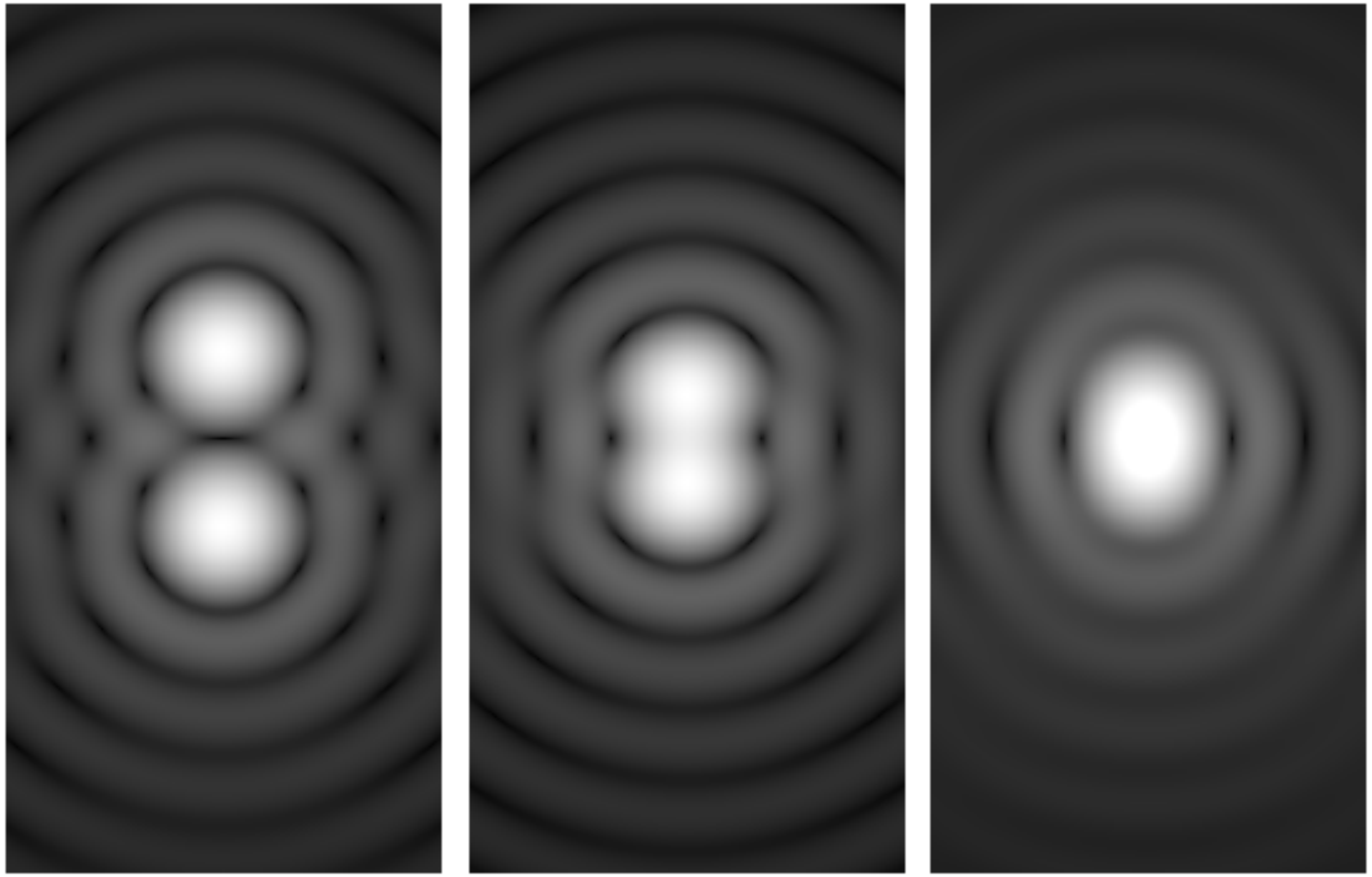


Image credit: Spencer Bliven

Angular resolution (cont.)

30 arcmin
1800 arcsec

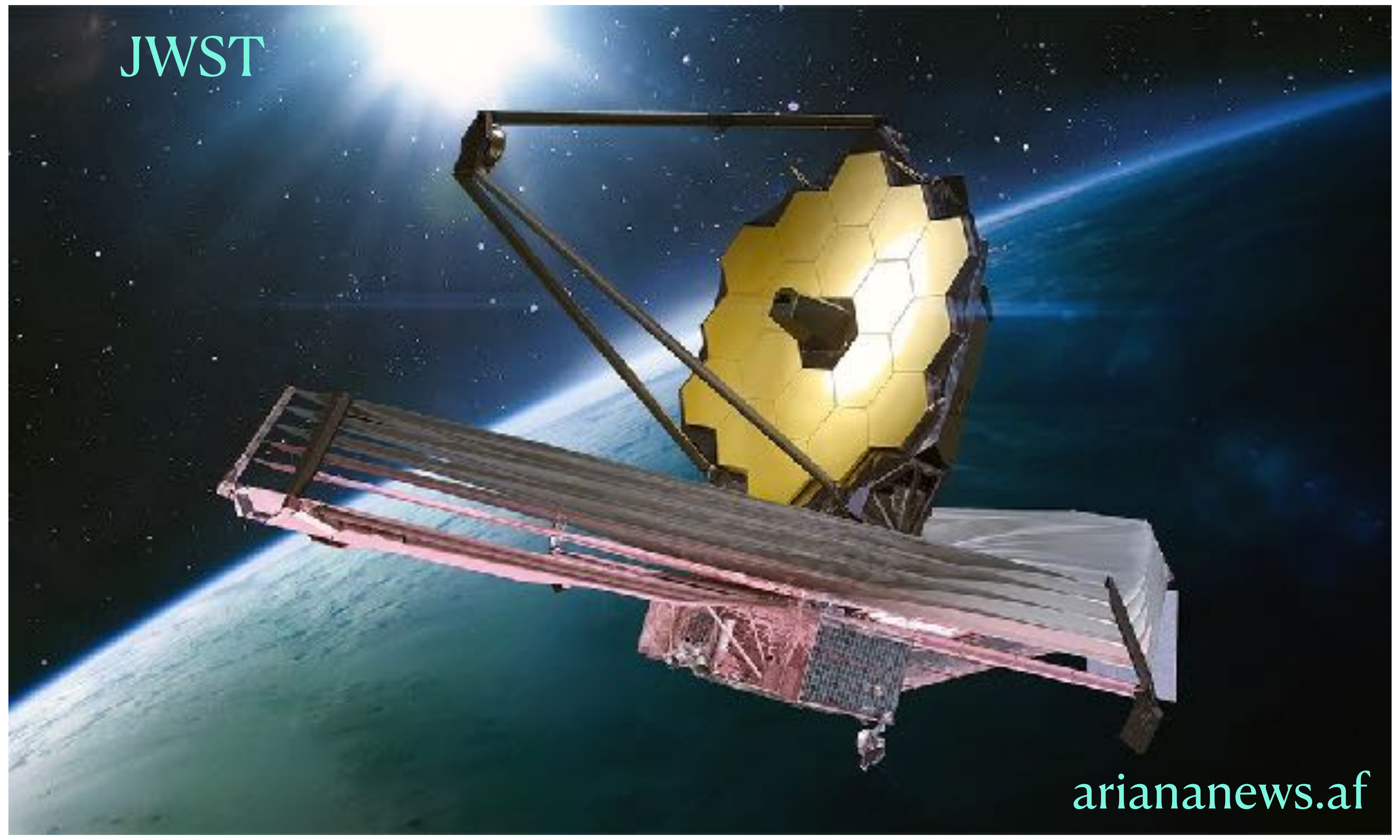
★ Resolution is the ability to separate two point sources into separated sources.

★ $\theta \approx 1.22 \times \frac{\lambda}{D}$ [rad]

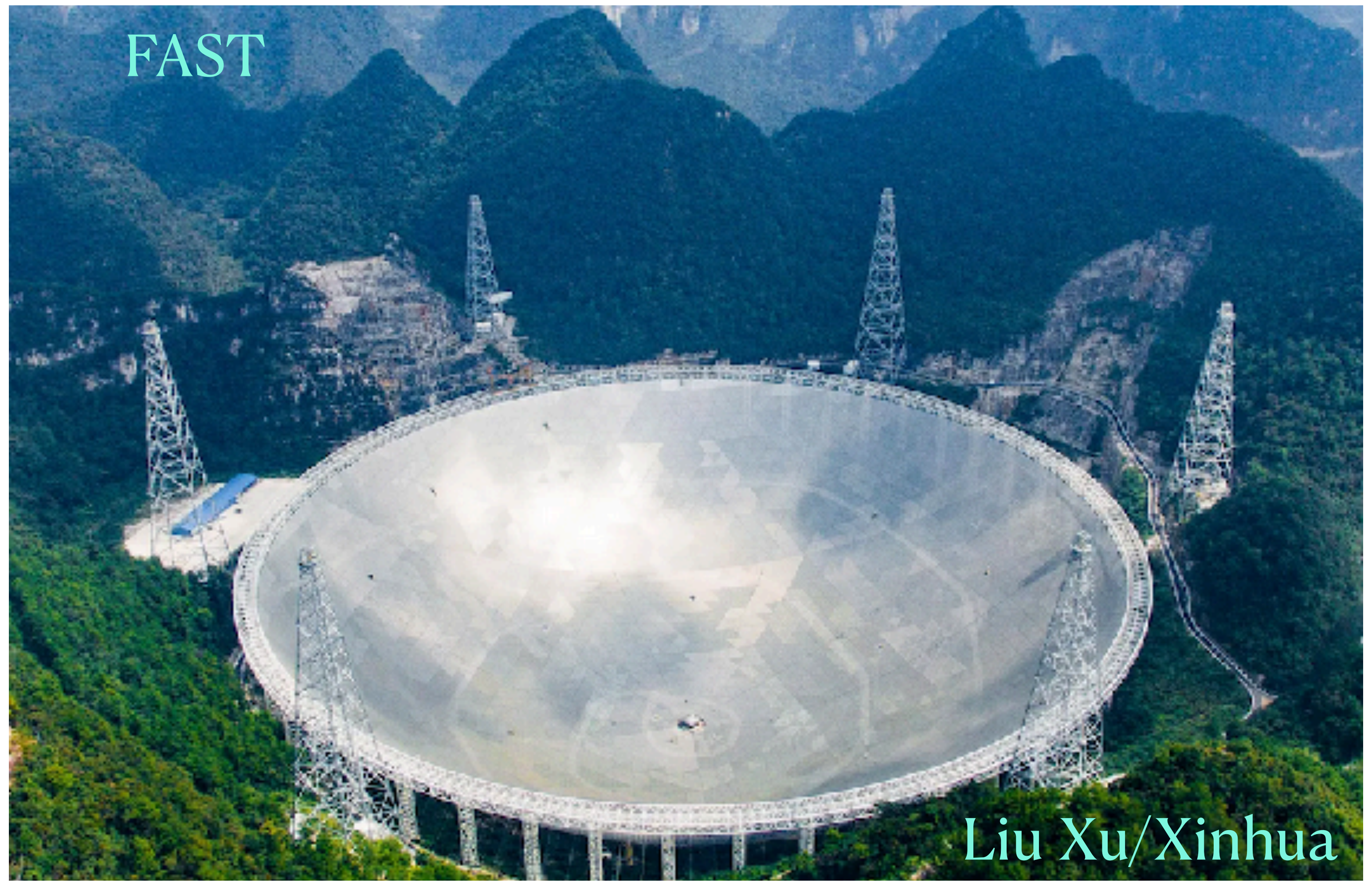
λ: wavelength

D: telescope diameter

$\theta = 50\, arcsec$
$\lambda = 0.5\, \mu m, D = 2.1\, cm$

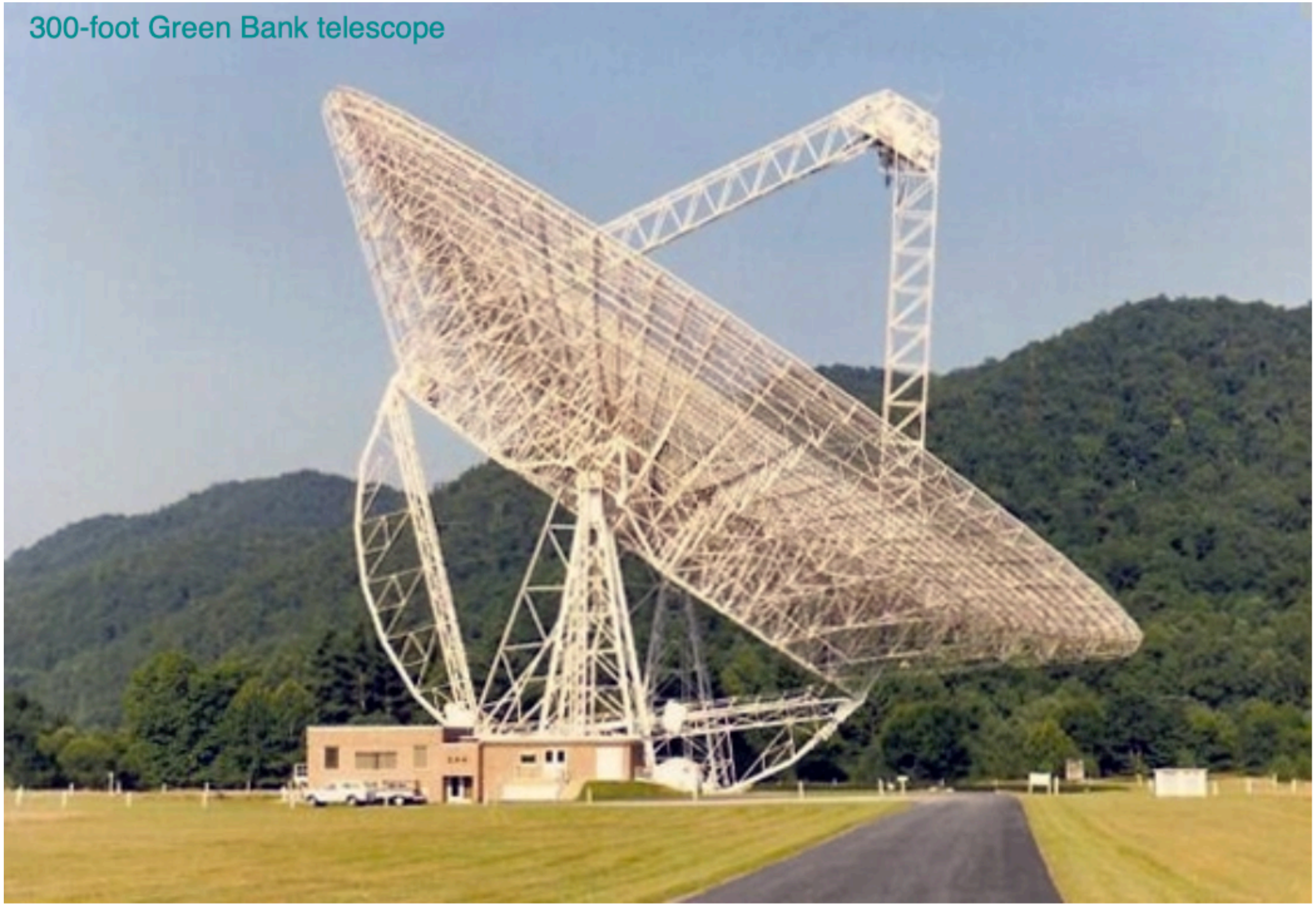


$\theta = 0.02\, arcsec$
$\lambda = 0.6\, \mu m, D = 6.5\, m$



$\theta = 100\, arcsec$
$\lambda = 0.2\, m, D = 500\, m$

300-foot single disk telescope in Green Bank



- Diameter: 100 m
- Frequency: 234 MHz — 5 GHz
- Resolution: 2.8 arcmin — 1 degree
- Pointing accuracy: 2 arcmin
- Weight: 600 tons
- Location: Green Bank, US

300-foot Green Bank telescope

November 16, 1988

Radio interferometers

★ Radio interferometer is a combined array of multiple single dishes, used to create high-resolution images of astronomical sources using aperture synthesis technique.

★ $\theta \approx 1.22 \times \frac{\lambda}{B}$ [rad]

λ: wavelength

B: **distance between pairs of telescopes** (baseline)

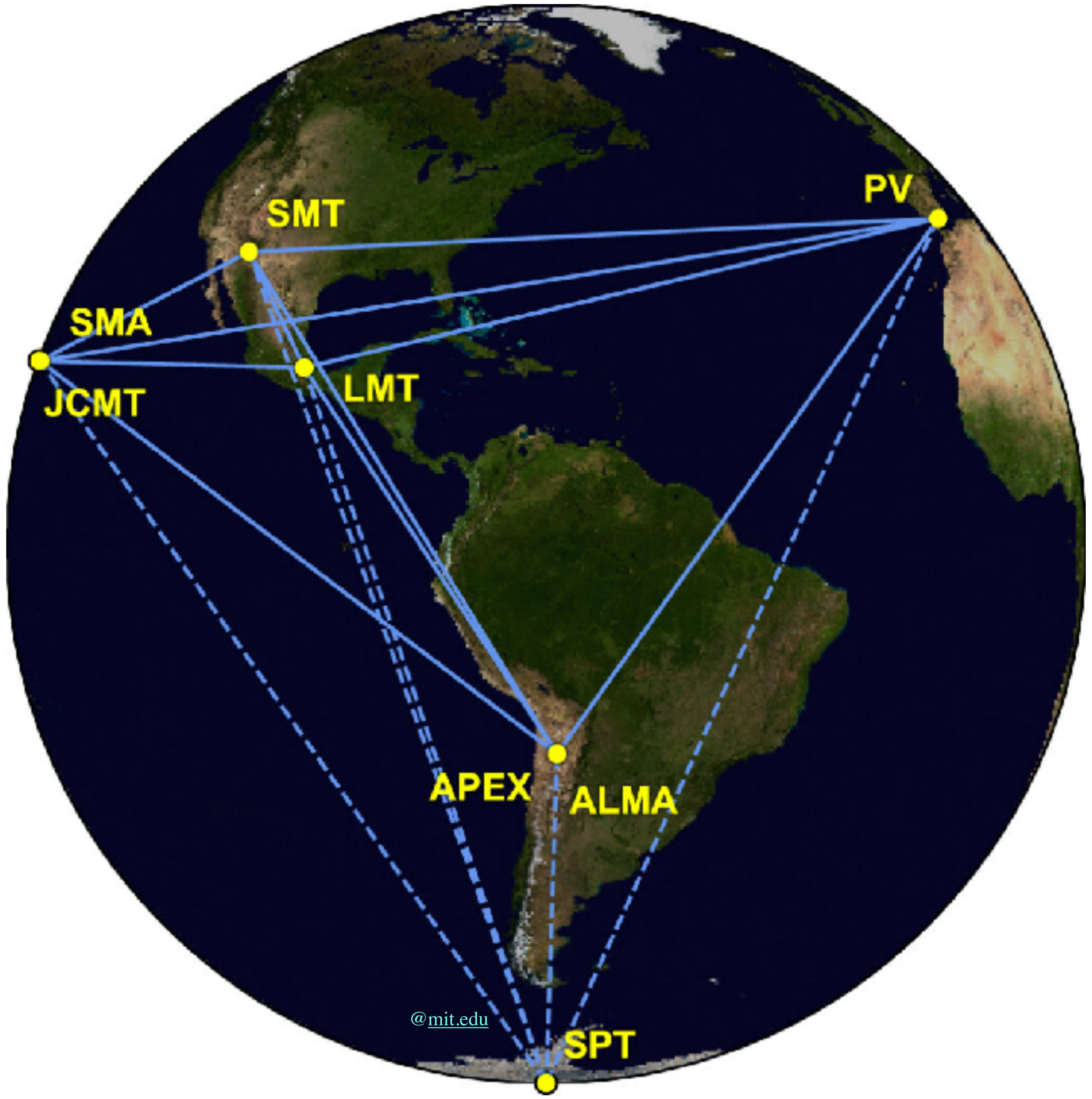
$$\theta = 1.4\,arcsec$$

$$\lambda = 0.2\,m,\, B = 36.4\,km\,\text{(A conf.)}$$

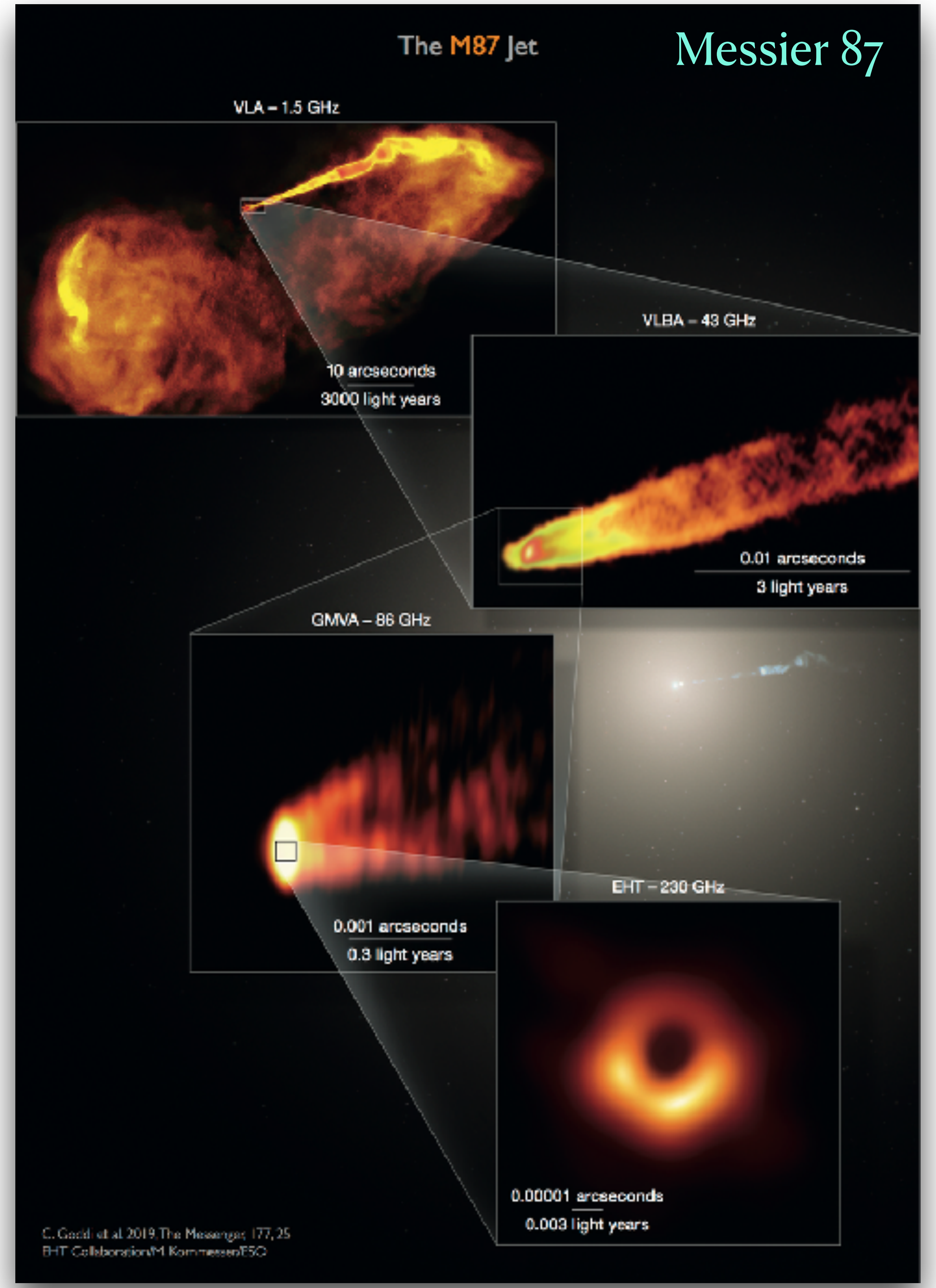
Some radio interferometers

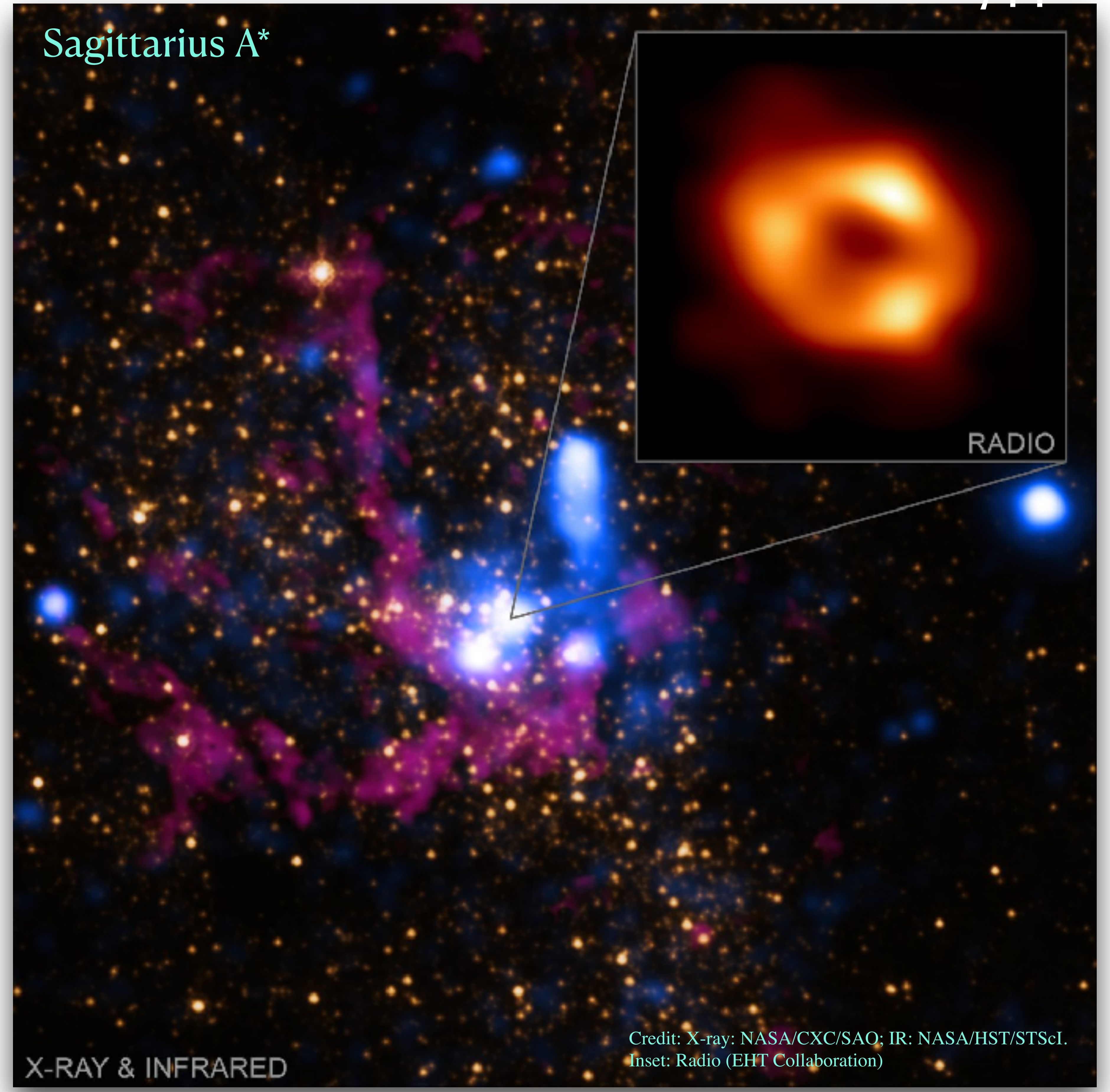
- **LOFAR**: LoLSS (42 - 66 MHz), LoTSS (120 - 168MHz)
- **MeerKAT**: UHF & L wide-band
- **GMRT**: Band 2 (120 - 250 MHz), 3 (250 - 500 MHz), 4 (550 - 850 MHz), 5 (1050 - 1450 MHz)
- **VLA**: Band P (350 MHz), L (1.5 GHz), S (3 GHz), ..., Q (45 GHz)
- **WSRT**: 120 MHz - 8.3 GHz
- **ASKAP**: 0.7 - 1.8 GHz
- **SKA**: 50 MHz to 14 GHz (to be built)
- …

Very-Long-Baseline Interferometry (VLBI)



Event Horizon Telescope





- Frequency: 230 — 450 GHz
- Baseline: ~ Earth size
- Resolution: 25 micro arcsec at 1.3 mm (230 GHz)

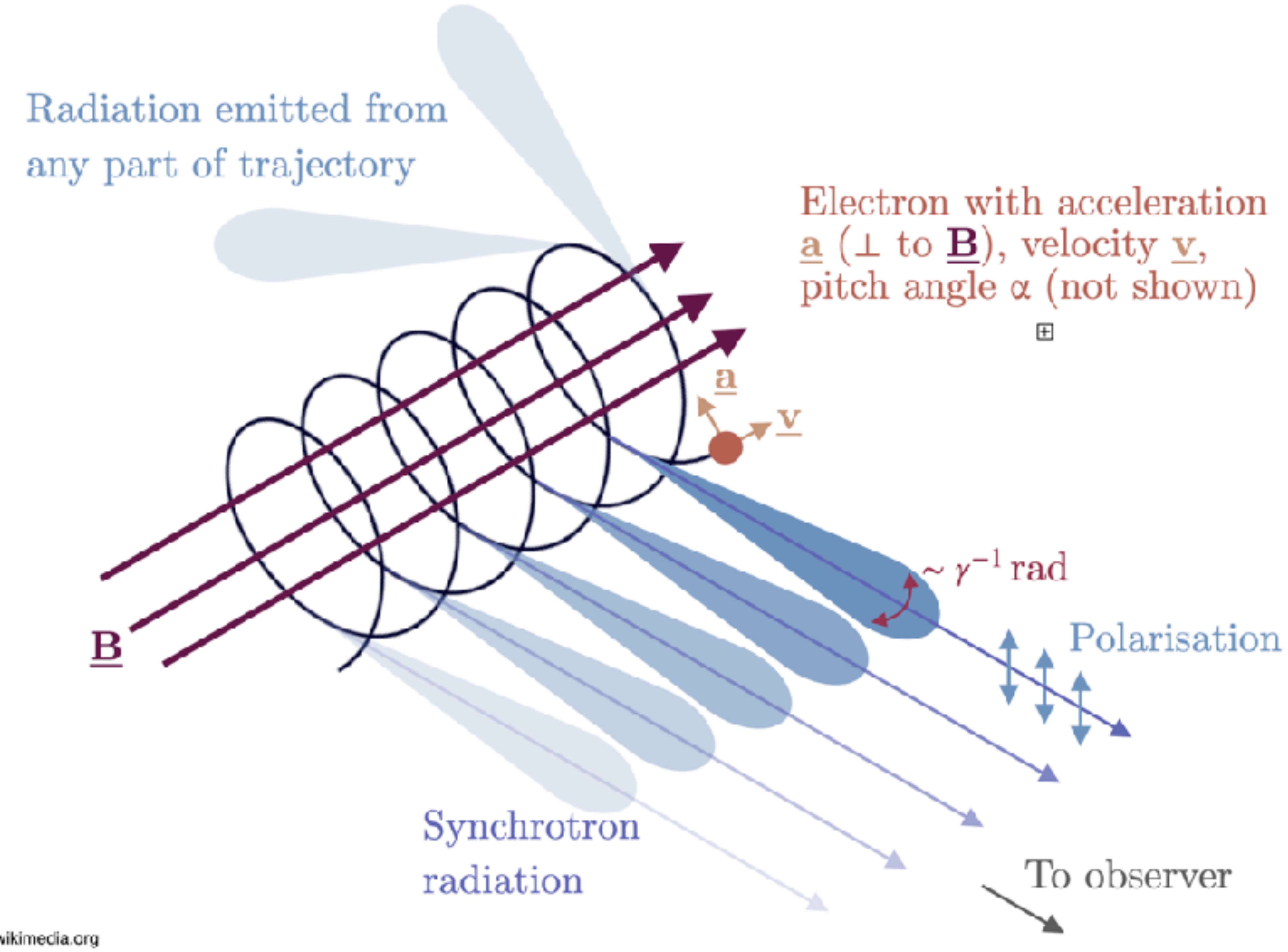
Radio Emission Mechanisms

Credit: NSF/NRAO/AUI/VLA

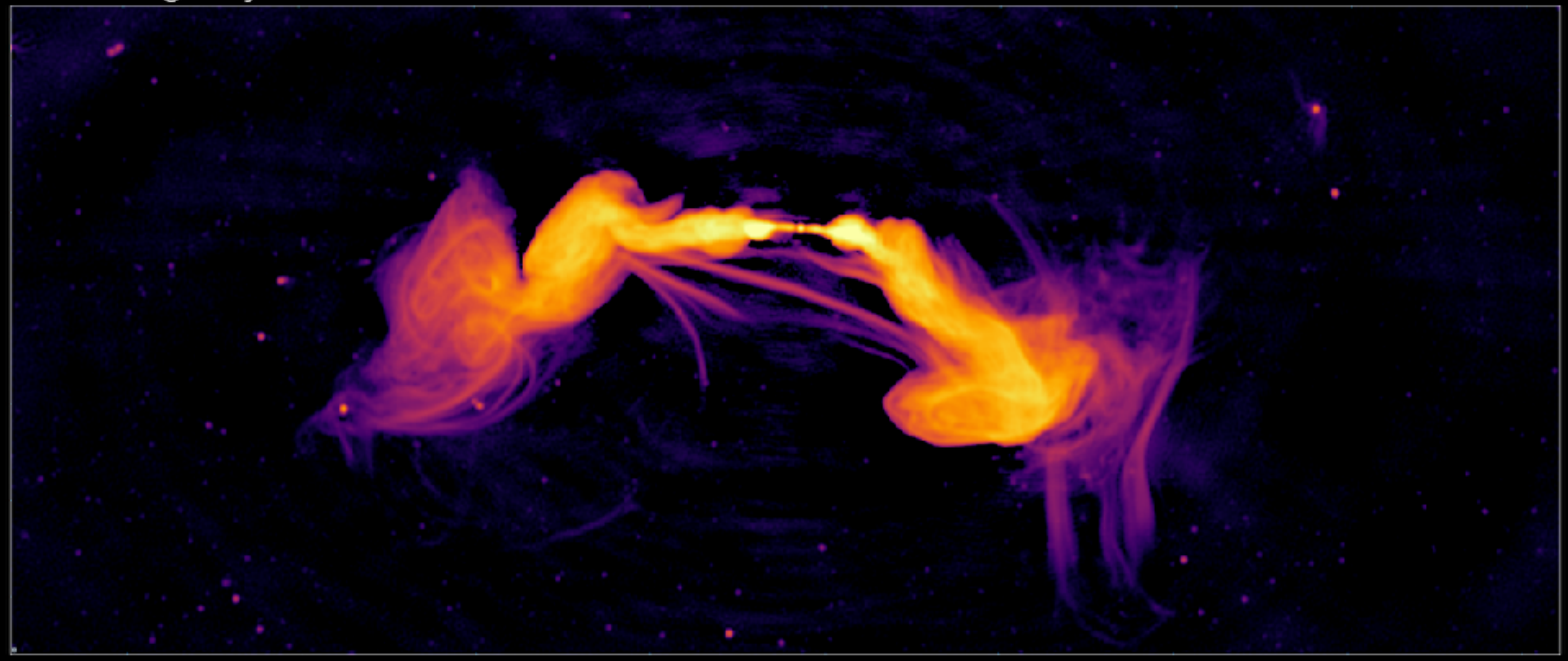
Synchrotron radiation

★ Synchrotron radiation caused by charged particles spiralling along B field

- Non-thermal continuum emission ∝ distribution of CRe + B field strength
- B field orientation



wikimedia.org

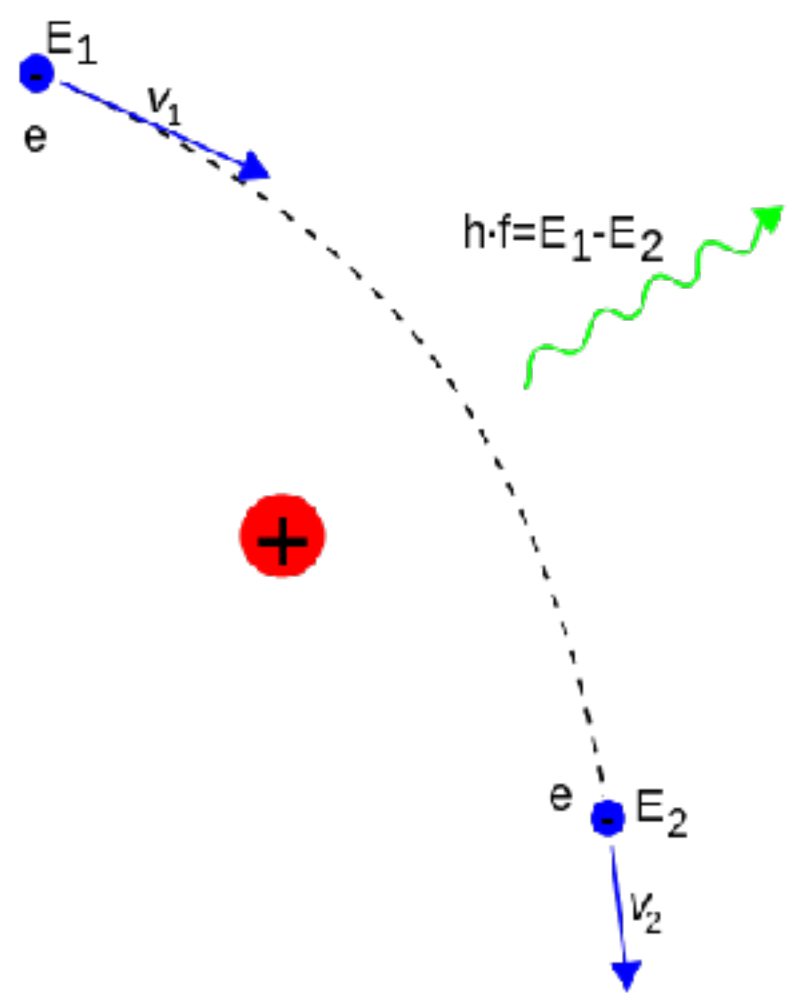


"Collimated synchrotron threads linking the radio lobes of ESO 137-006", M. Ramatsoku et al. 2020, A&A
MeerKAT Radio Telescope image at 1000 MHz
Image credits: Rhodes University / INAF / SARAO

Bremsstrahlung radiation

★ Bremsstrahlung emission emitted by charged particles that de-accelerate when deflected by another charged particles.

- Thermal continuum process (T dependent)
- Mass of ionised gas
- Distribution of thermal electrons
- Rate of ionising photons



Free-free (bremsstrahlung) emission

W51 - One of the largest star factories in the Milky Way

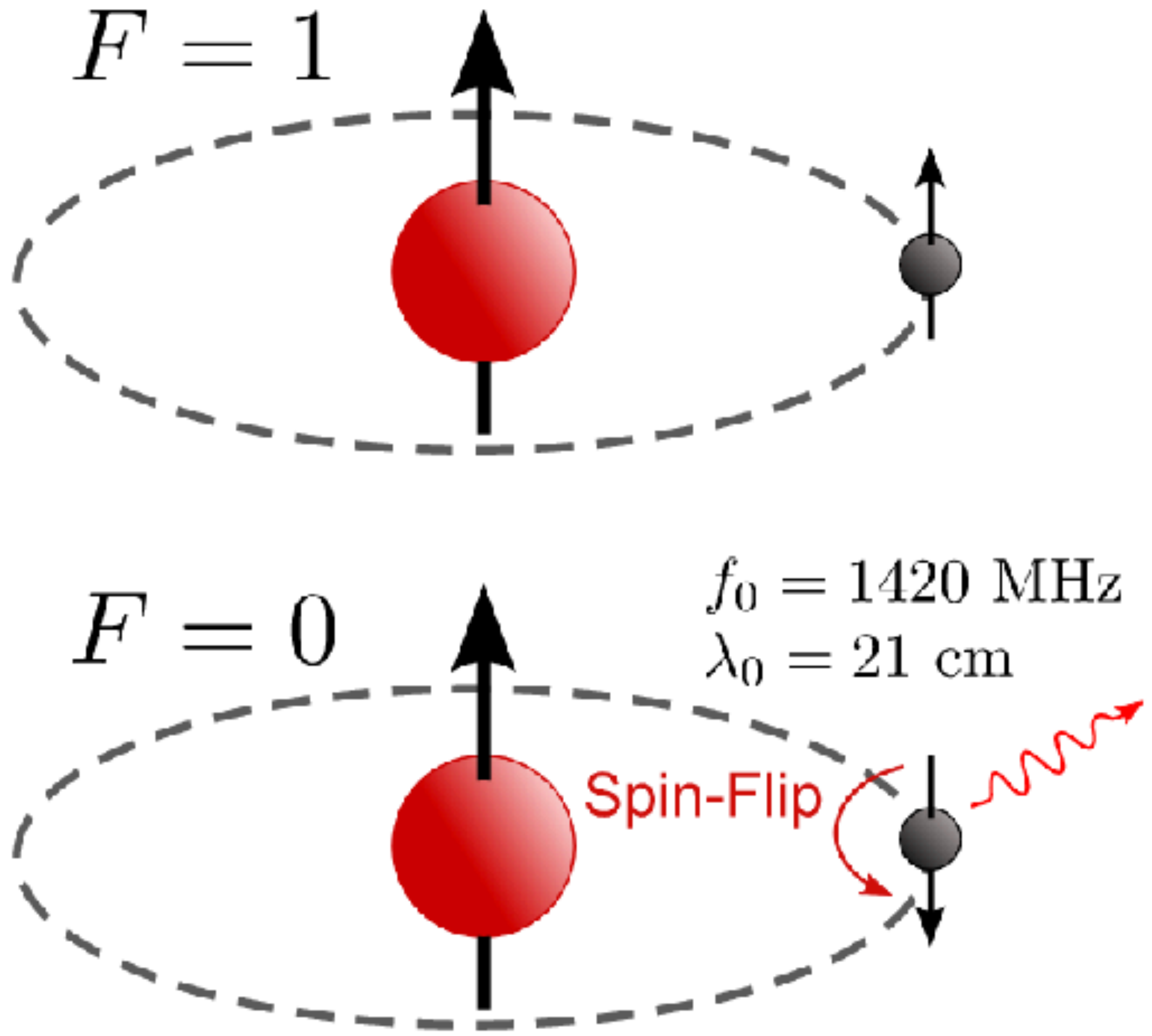
Spectral line

★ Transitions energy levels of atoms and molecules

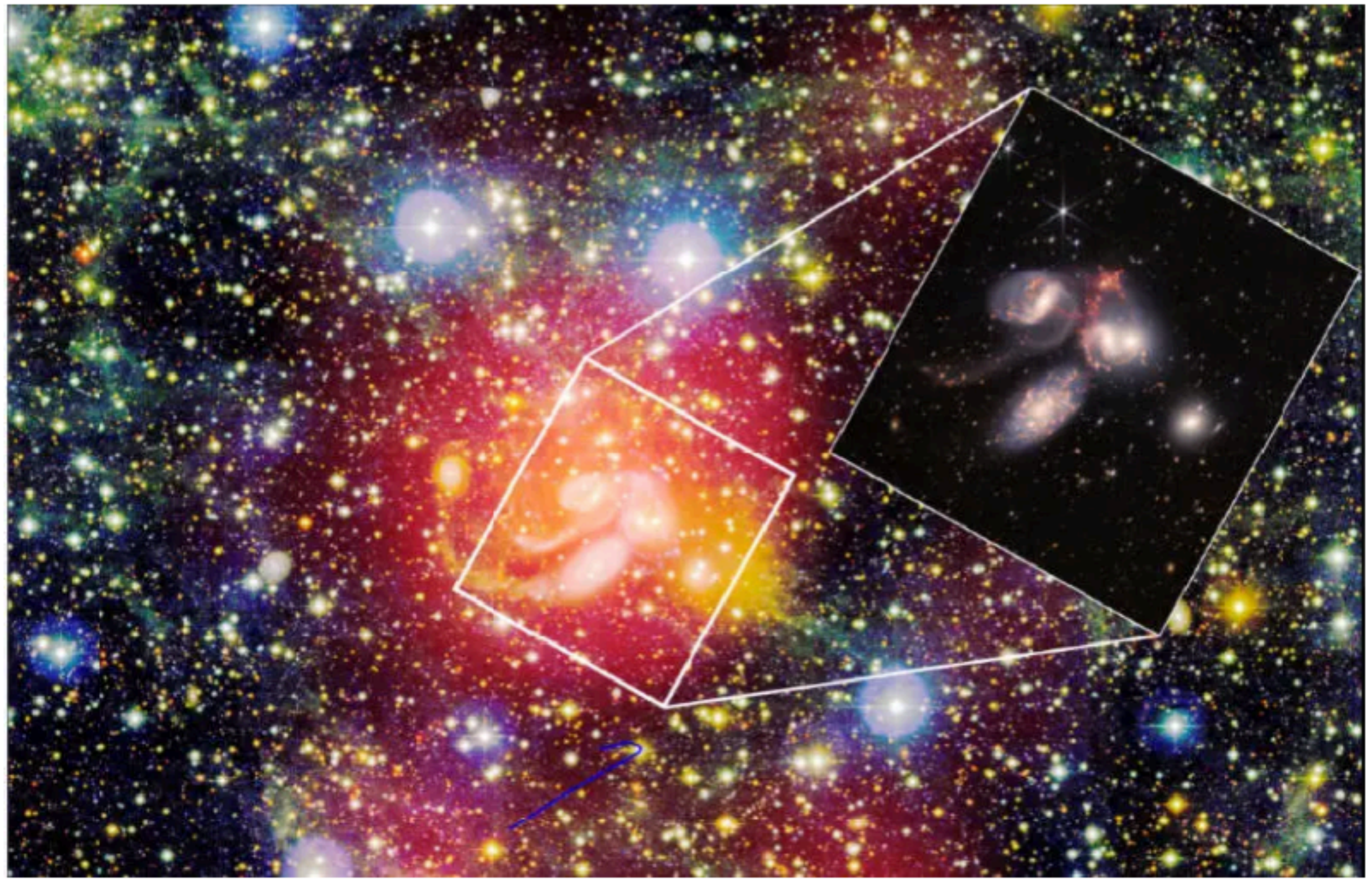
★ Temperature, densities, chemical composition of thermal gas

★ Light-of-sight velocity (Doppler effect)

★ B field strength (Zeeman effect)



wikipedia.org

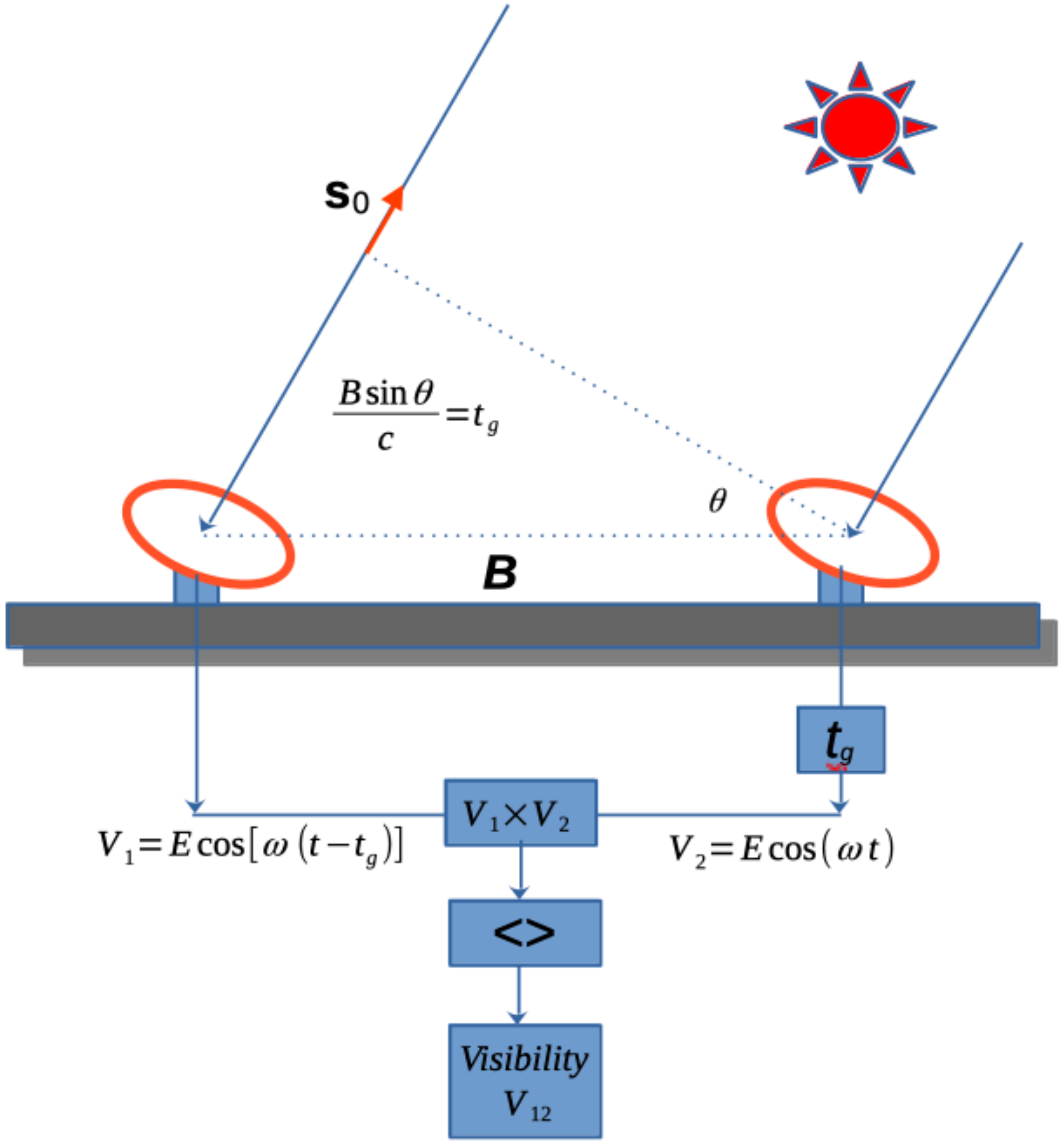


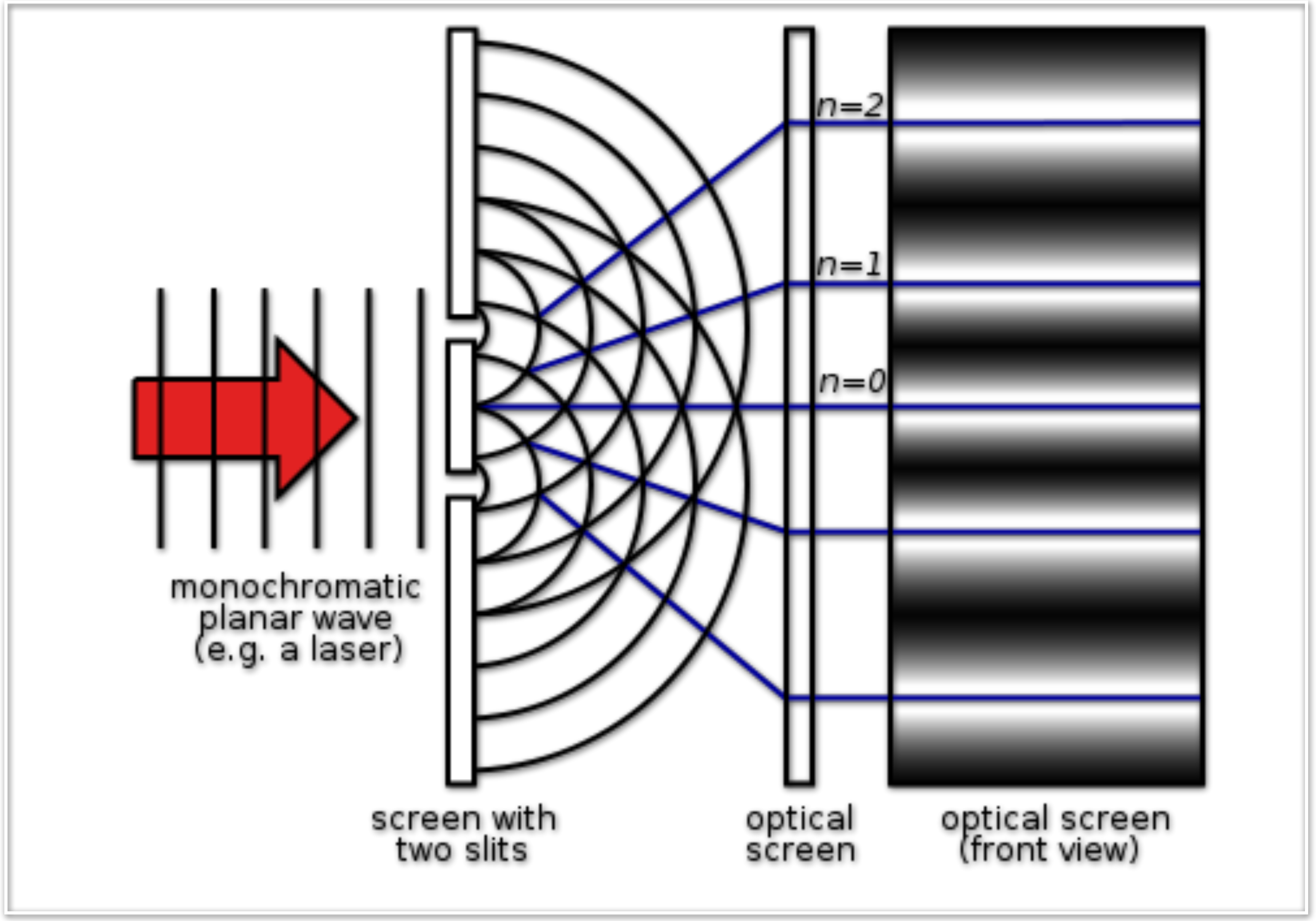
A map of the atomic hydrogen (HI) 21-cm line emission (shown as the red haze) in the vicinity of Stephan's Quintet, a famous compact group of galaxies discovered in 1887, overlaid on a deep optical color image. Credit: NASA, ESA, CSA, and STScI

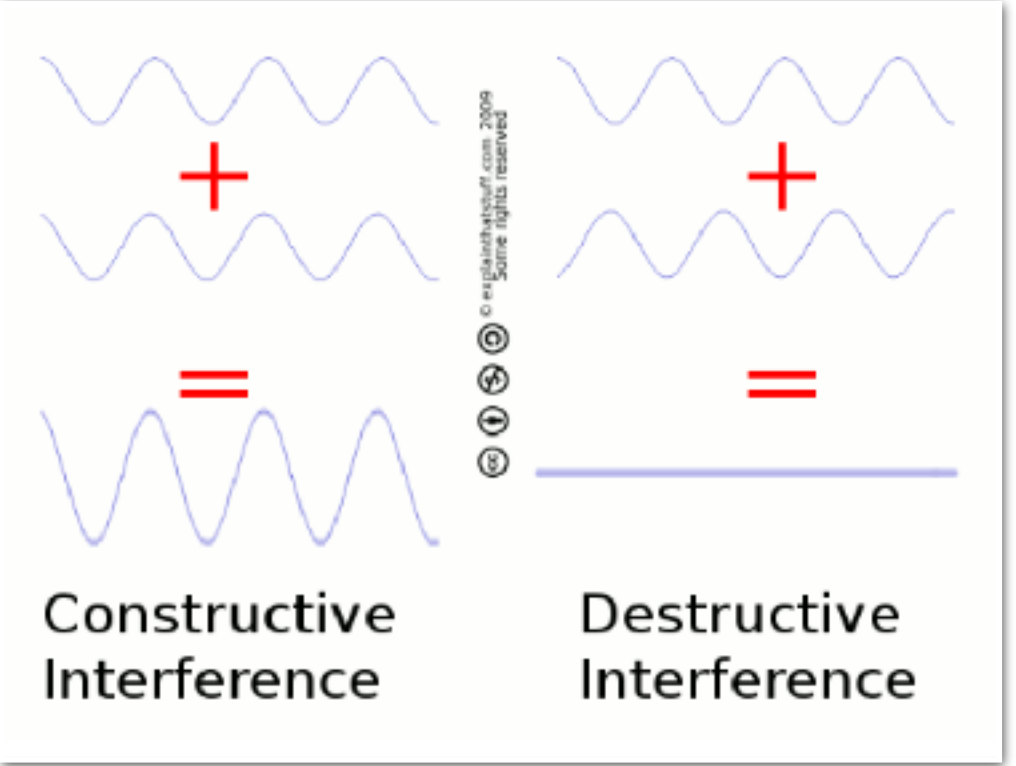
Basics of Radio Interferometers

Credit: NSF/NRAO/AUI/VLA

Two-Antena Radio Interferometer







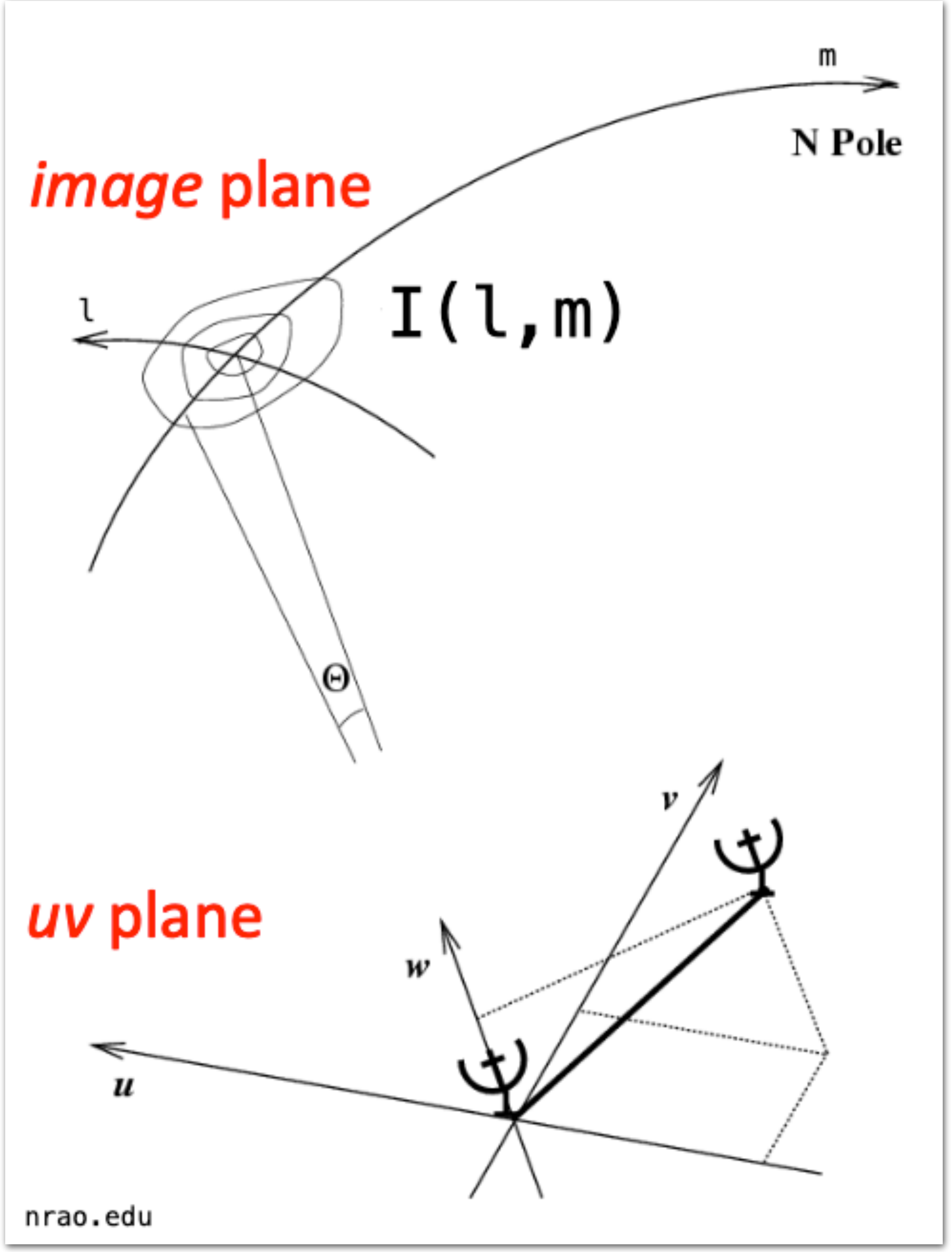
Visibility & sky brightness

★ Radio interferometer converts sky brightness $I(l, m)$ into visibility $V(u, v)$ by Fourier transform of $I(l, m)$,

$$V(u, v) = \mathscr{F}[I(l, m)] = \iint I(l, m)e^{-2\pi i(ul+vm)}dldm$$

★ To recover the sky brightness, invert-Fourier transform of $V(u, v)$ is required.

$$I(l, m) = \mathscr{F}^{-1}[V(u, v)] = \iint V(u, v)e^{2\pi i(ul+vm)}dudv$$



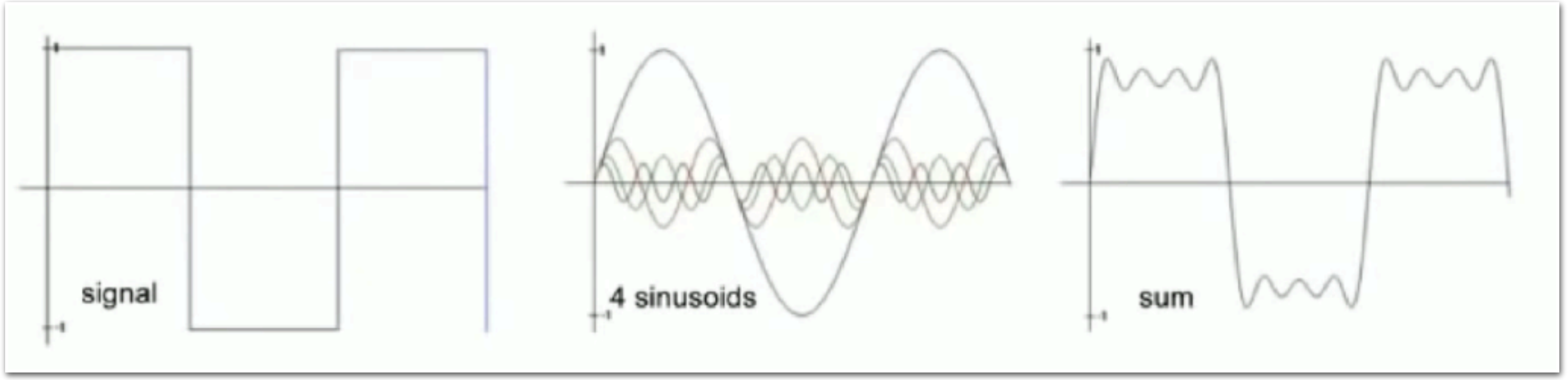
Fourier transform

★ Fourier transform is a transform that decomposes a signal into a combination of sinusoidal functions.

$$\hat{f}(k) = \int f(x) e^{-2\pi ikx} dx$$

★ Fourier inversion transform

$$f(x) = \int \hat{f}(k) e^{2\pi ikx} dk$$

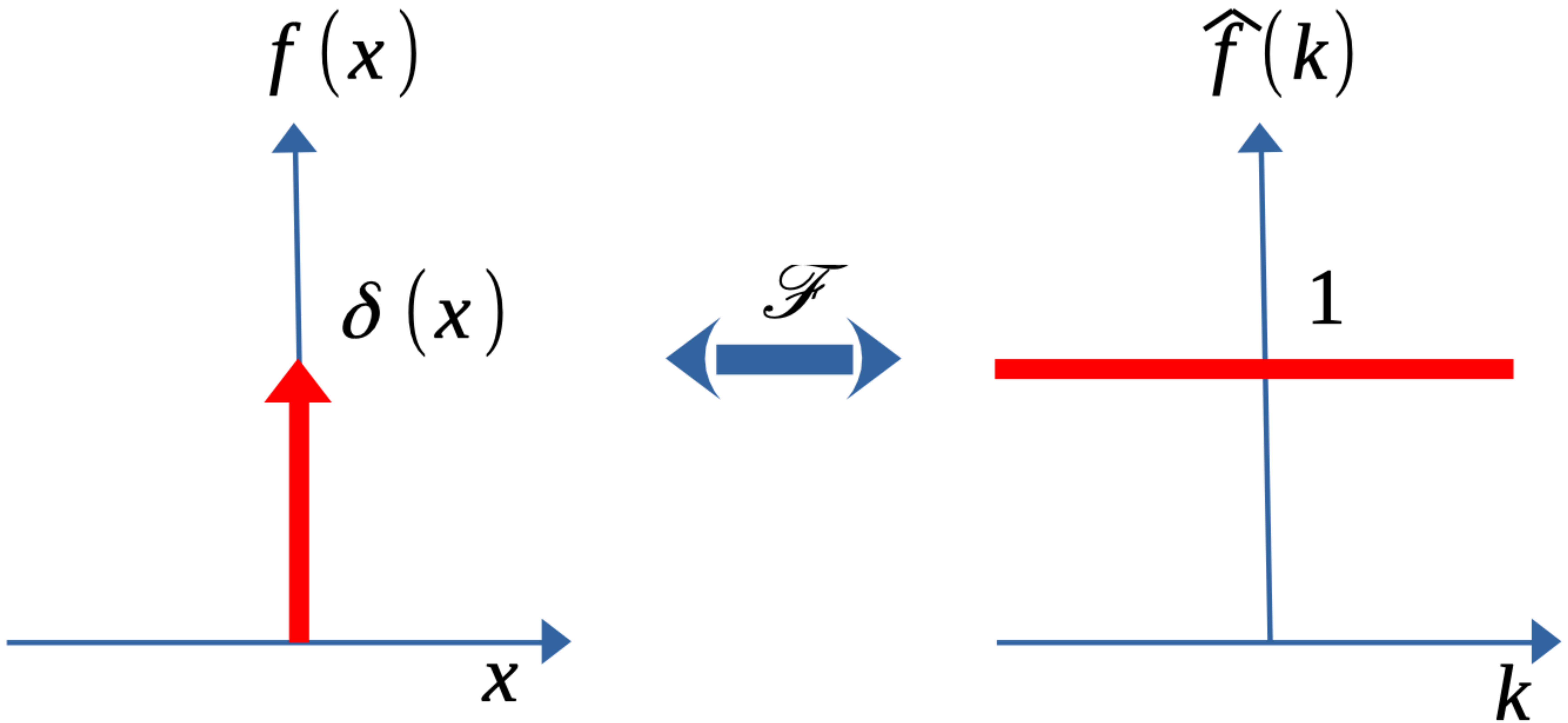


$$f(x) = \frac{\pi}{4}[sin(2\pi kx) + \frac{1}{3}sin(6\pi kx) + \frac{1}{5}sin(10\pi kx) + \ldots]$$

Fourier transform (cont.)

★ Fourier transform of a delta function $f(x) = \delta(x)$,

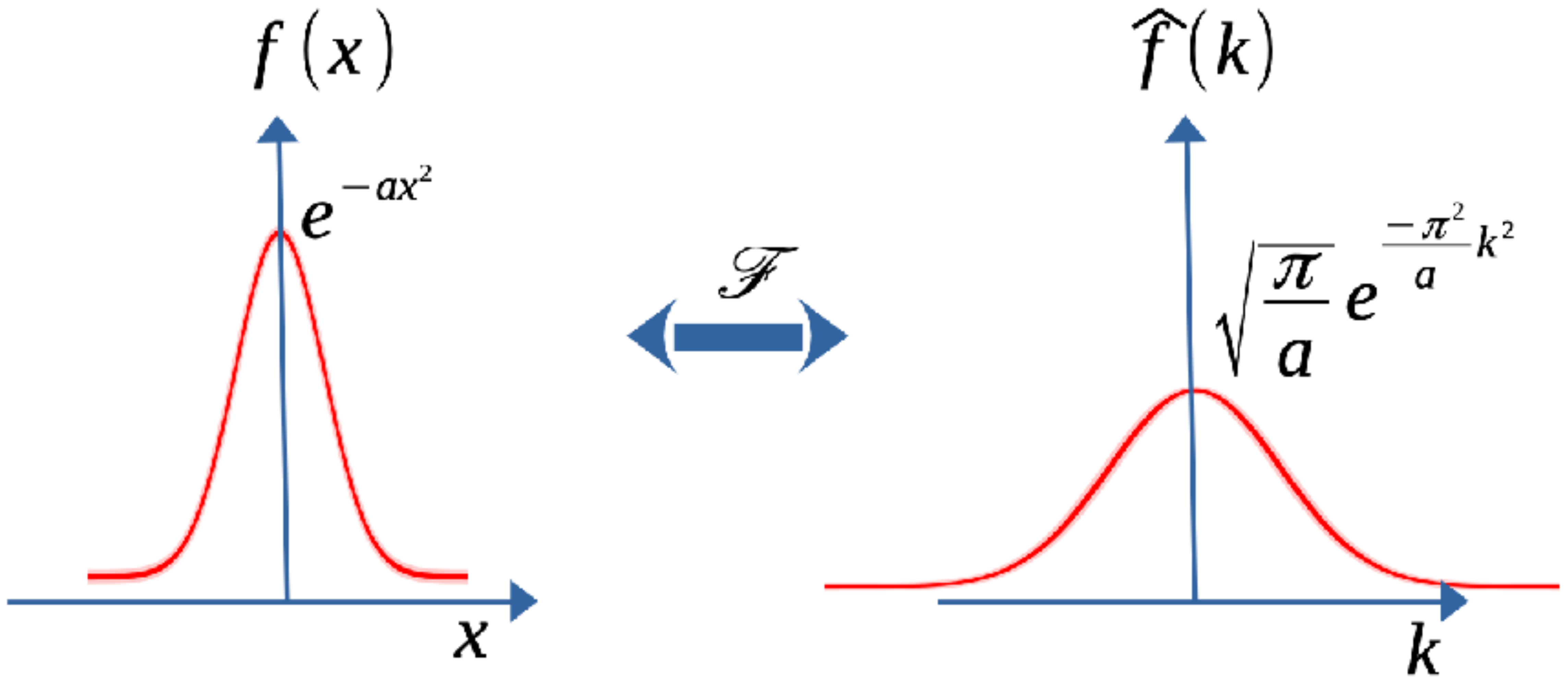
$$\hat{f}(k) = \mathcal{F}(\delta(x)) = \int \delta(x) e^{-2\pi i k x} dx = 1$$



Fourier transform (cont.)

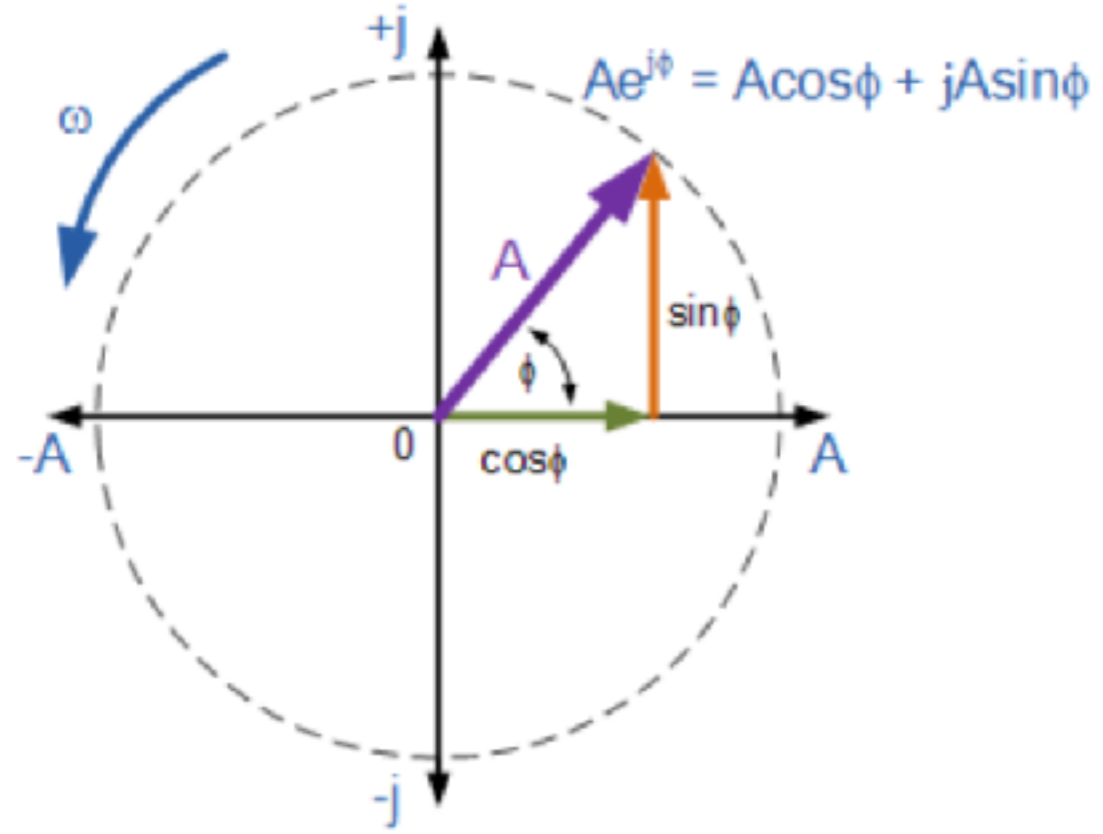
★ Fourier transform of a Gaussian function $f(x) = e^{-ax^2}$,

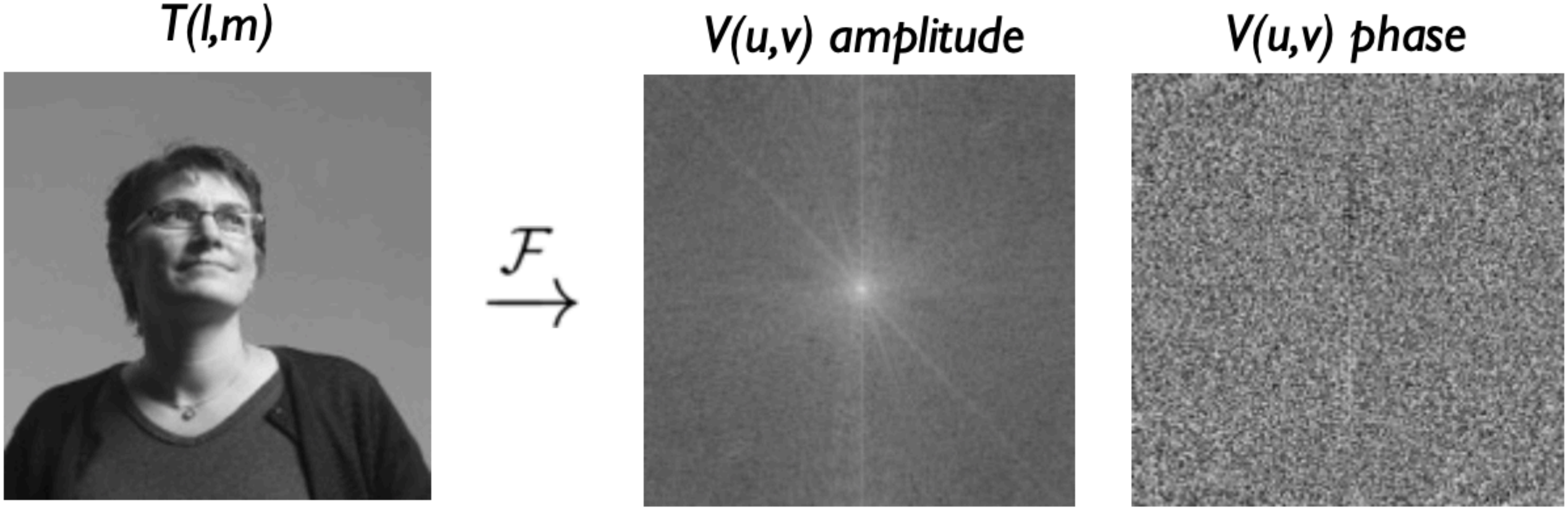
$$\hat{f}(k) = \mathscr{F}(f(x)) = \int e^{-ax^2} e^{-2\pi ikx} dx = \sqrt{\frac{\pi}{a}} e^{\frac{-\pi^2}{a} k^2}$$



Visibility complex components

★ Visibility is a complex quantity: amplitude + phase components.
Amplitude —> source brightness.
Phase —> source position.



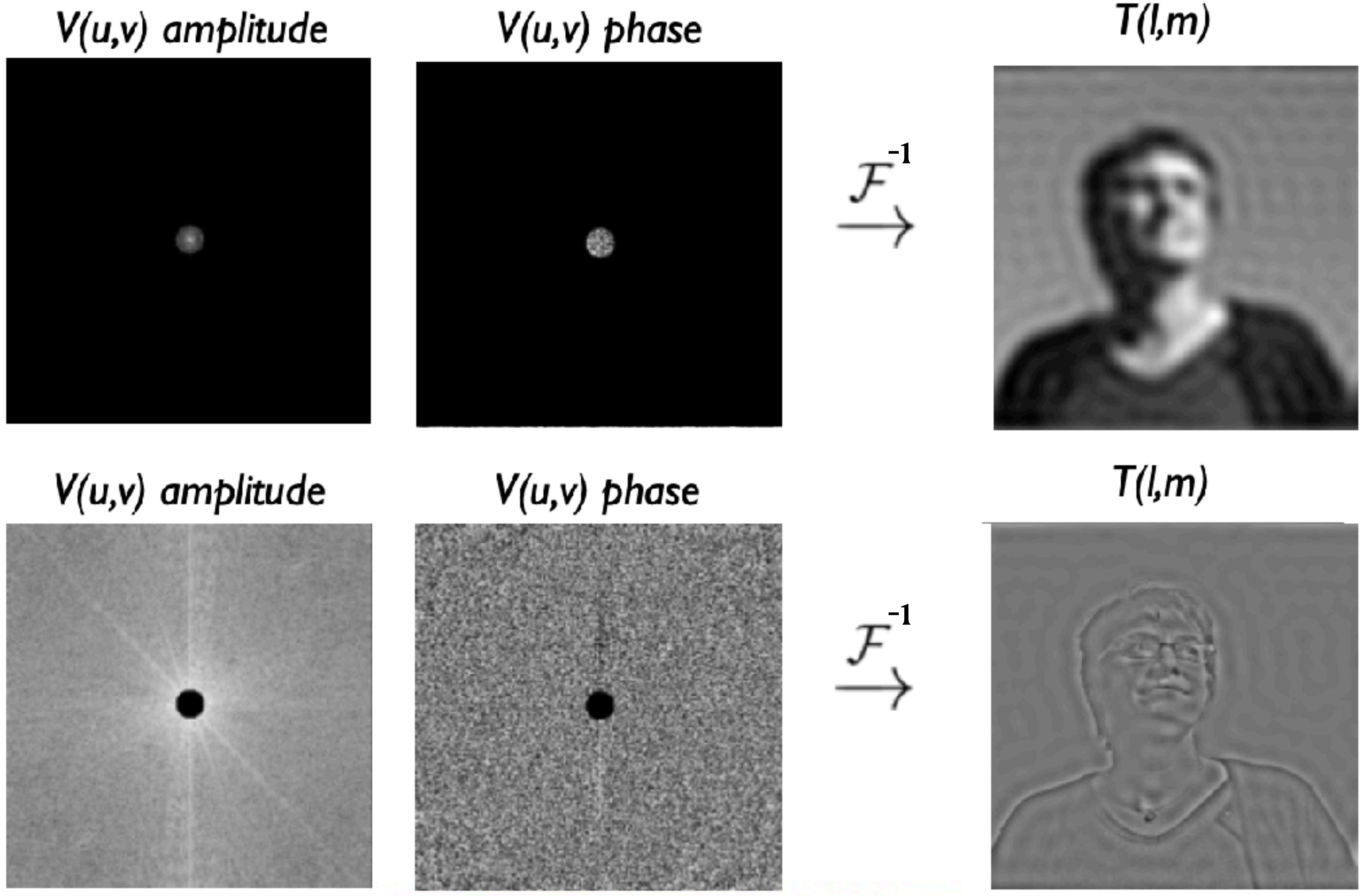


@David J. Wilner

(u,v) space

★ Inner region of (u,v) space —> large-scale structure of the source

★ Outer region of (u,v) space —> small-scale structure of the source



@David J. Wilner

Imaging

Credit: NSF/NRAO/AUI/VLA

Imaging

★ To obtain map of sky brightness, Fourier inversion transform, or deconvolution, is used.

$$I(l, m) = \mathscr{F}^{-1}[V(u, v)]$$

★ Due to discrete sampling in uv space, $V(u, v) \rightarrow V(u, v)\, S(u, v)$.

Here $S(u, v)$ is the sampling function.

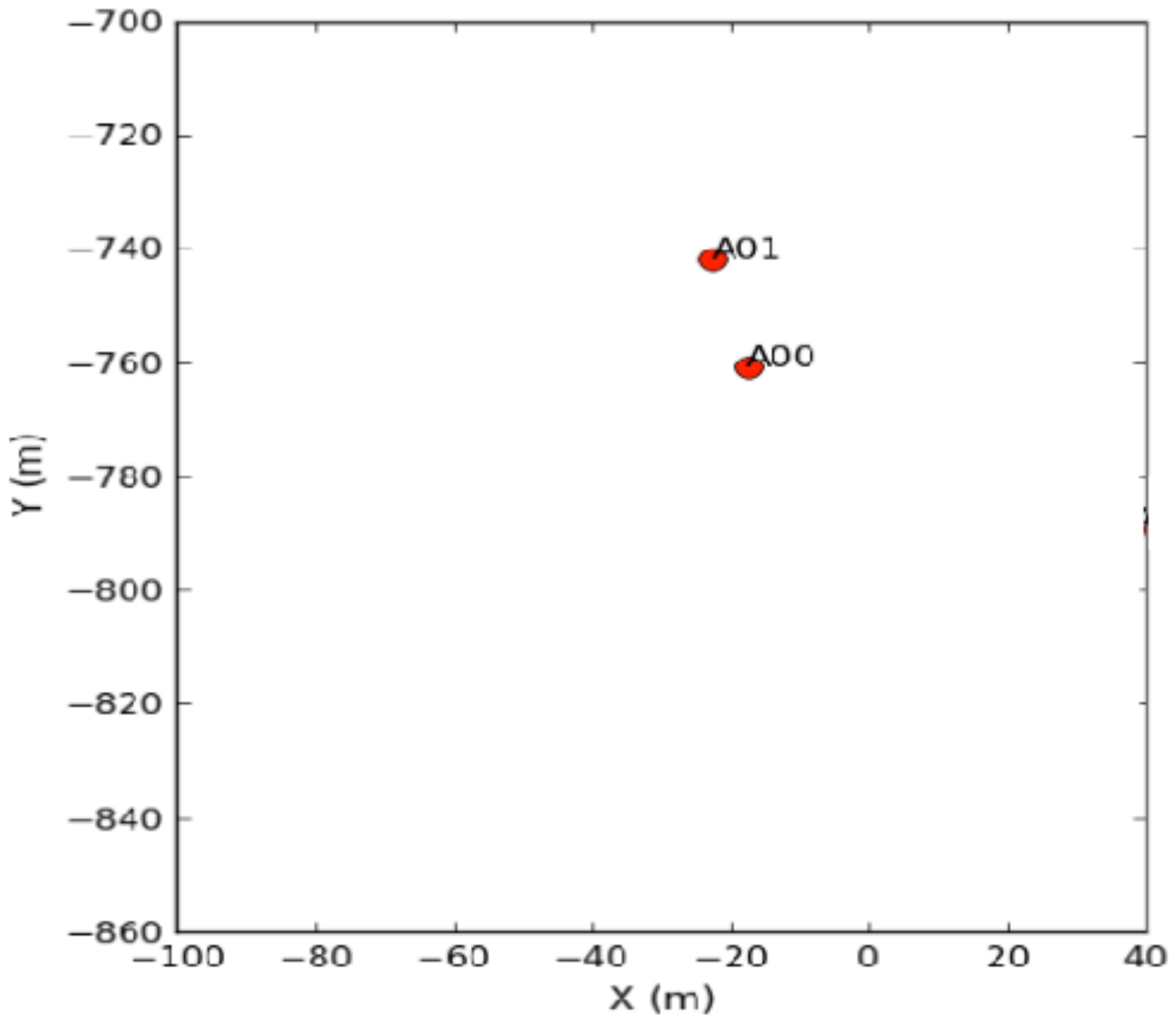
$$I^D(l, m) = \mathscr{F}^{-1}[V(u, v)\, S(u, v)]$$

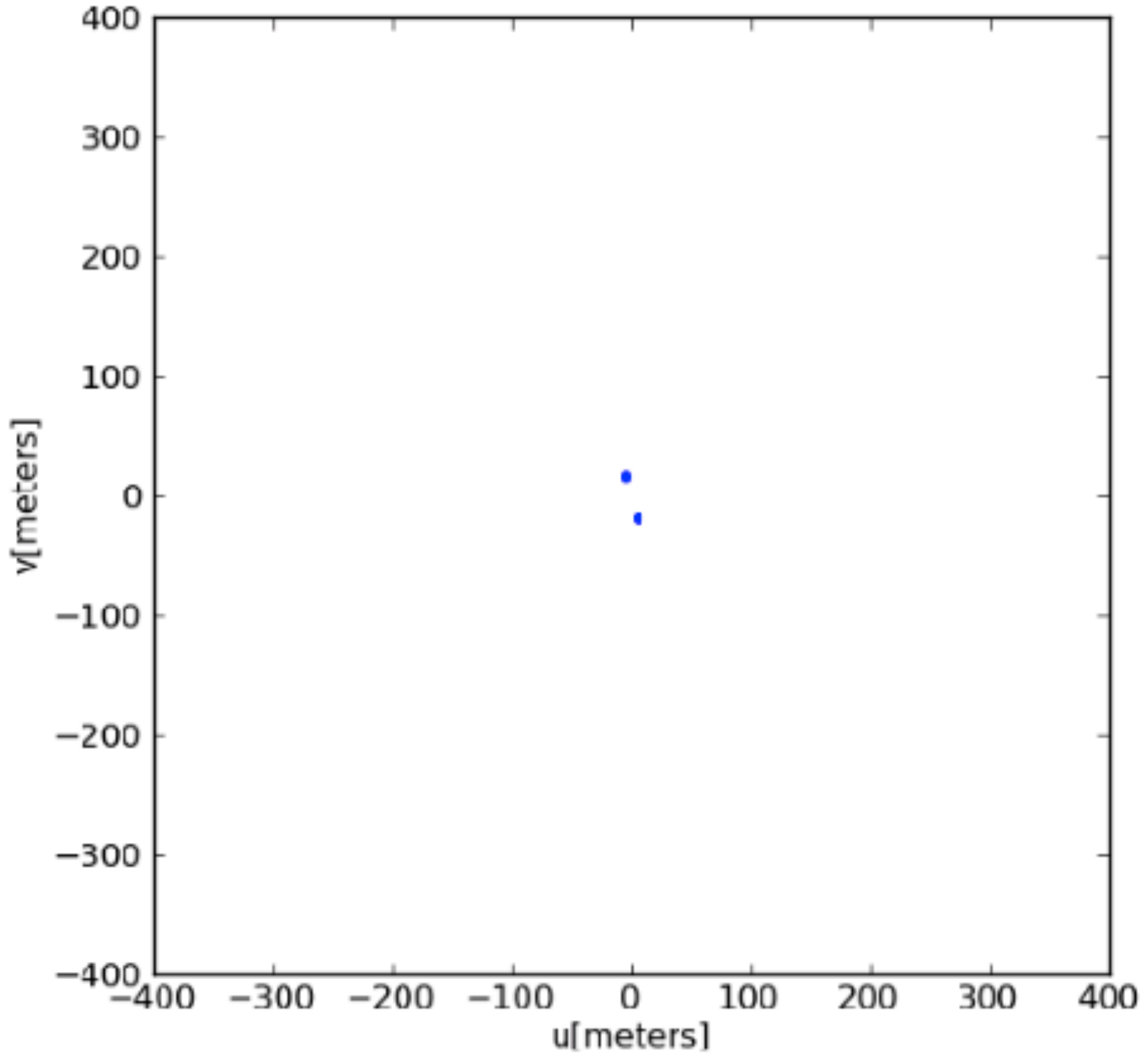
★ Recover "true" sky brightness, solve for $I(l, m)$.

$$I^D(l, m) = I(l, m) * s(l, m)$$

Here $s(l, m)$ is the point spread function.

(u,v) sampling: two antenna





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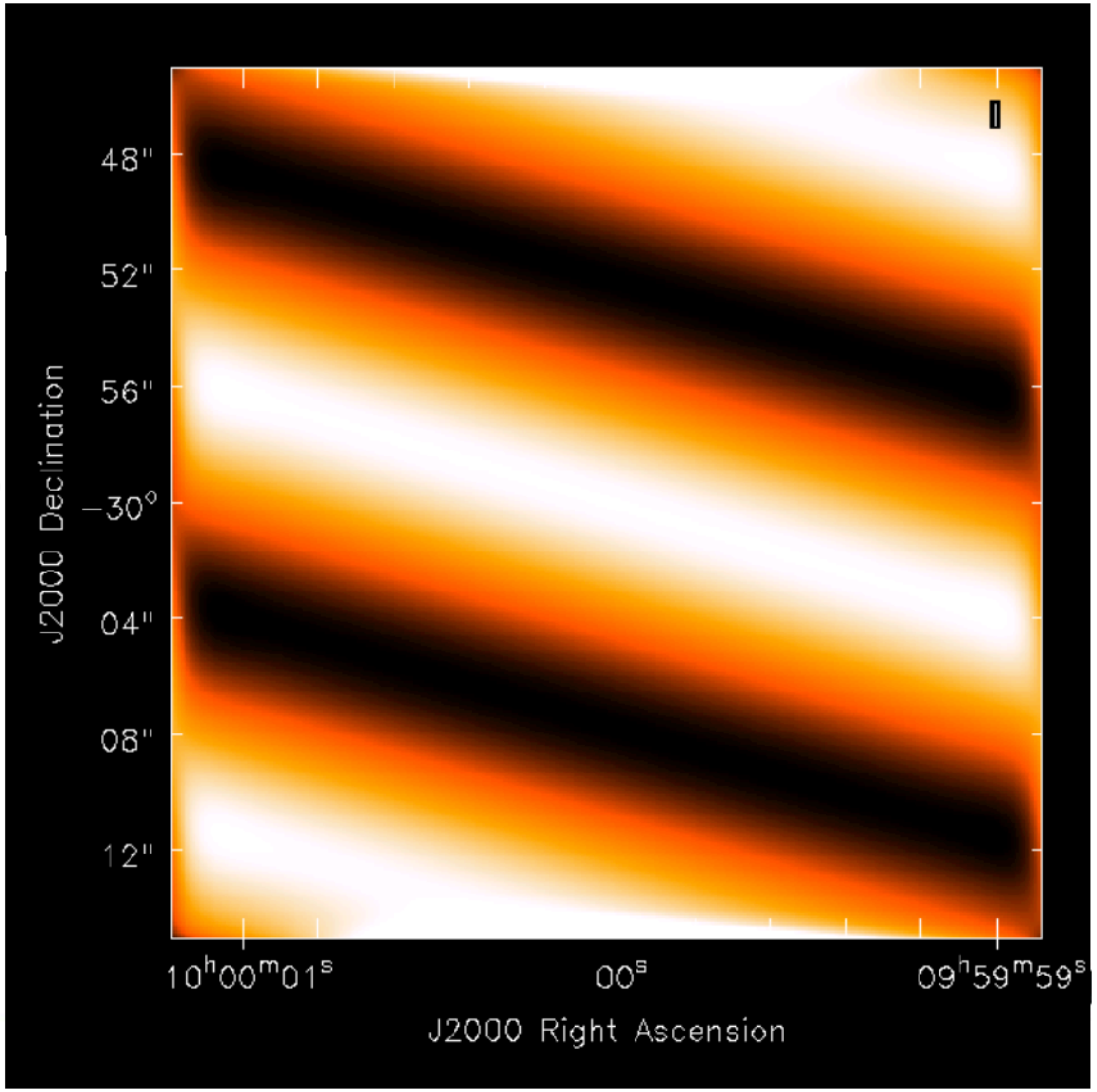

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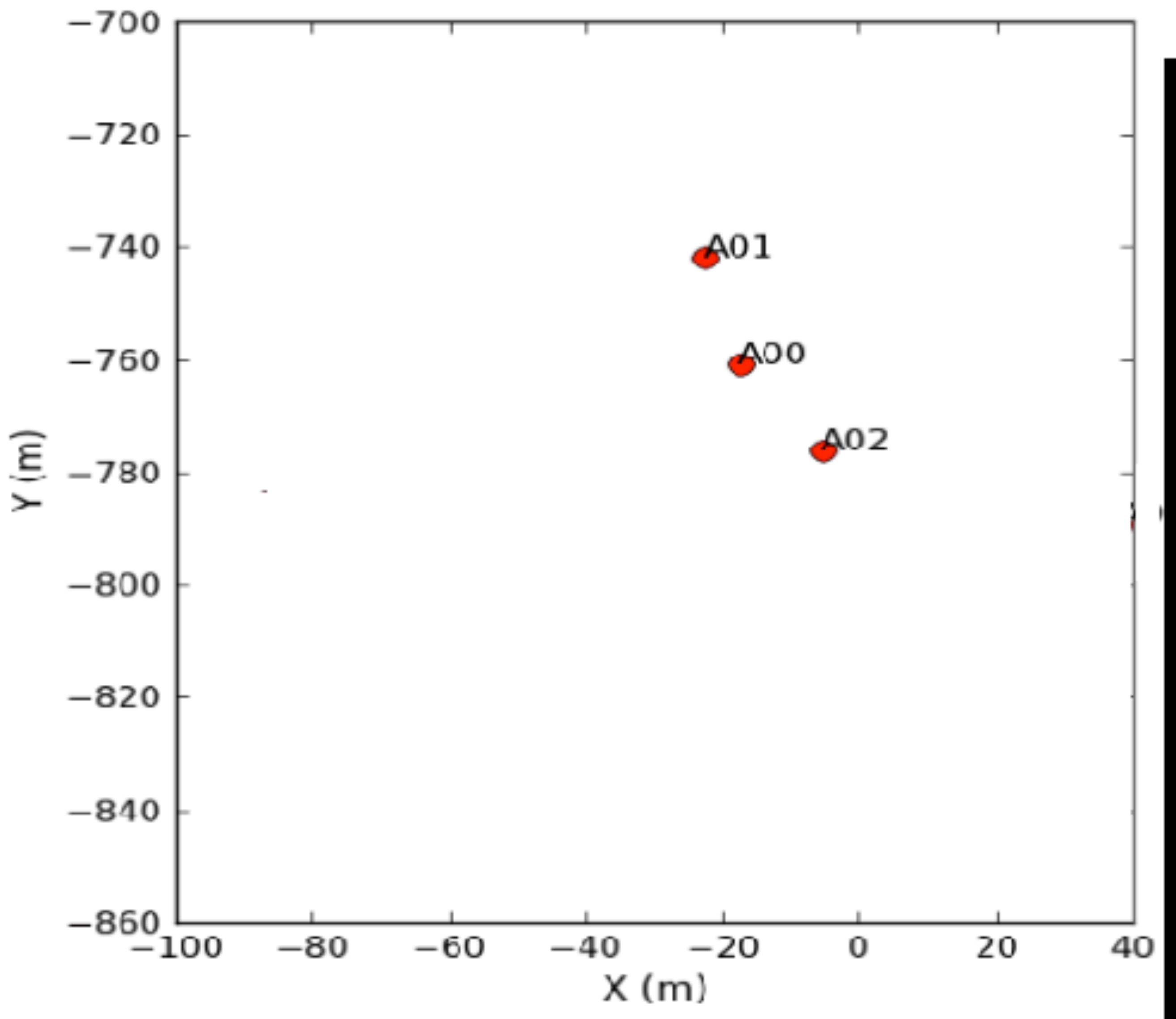
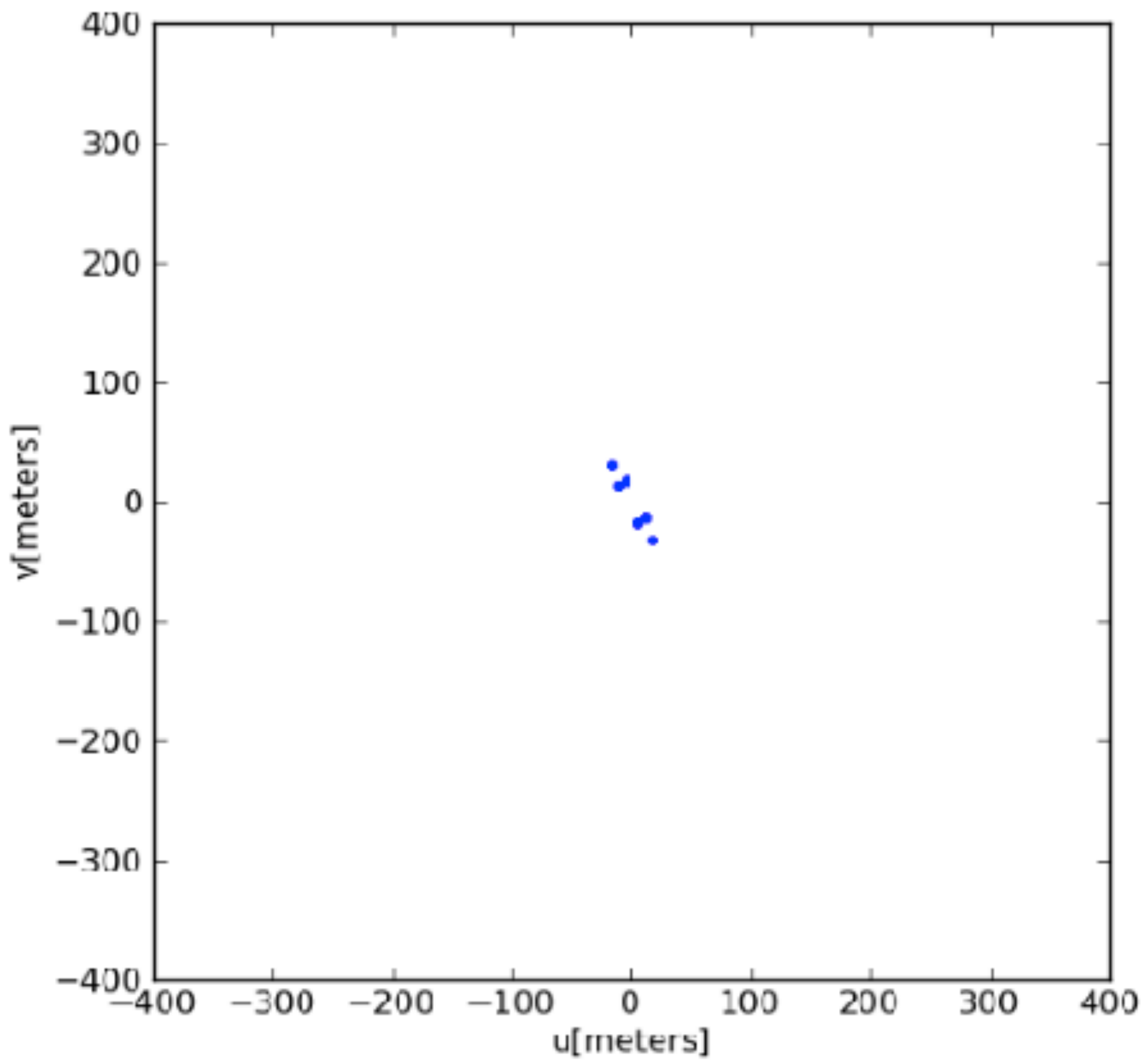
True sky

(u,v) sampling: three antenna





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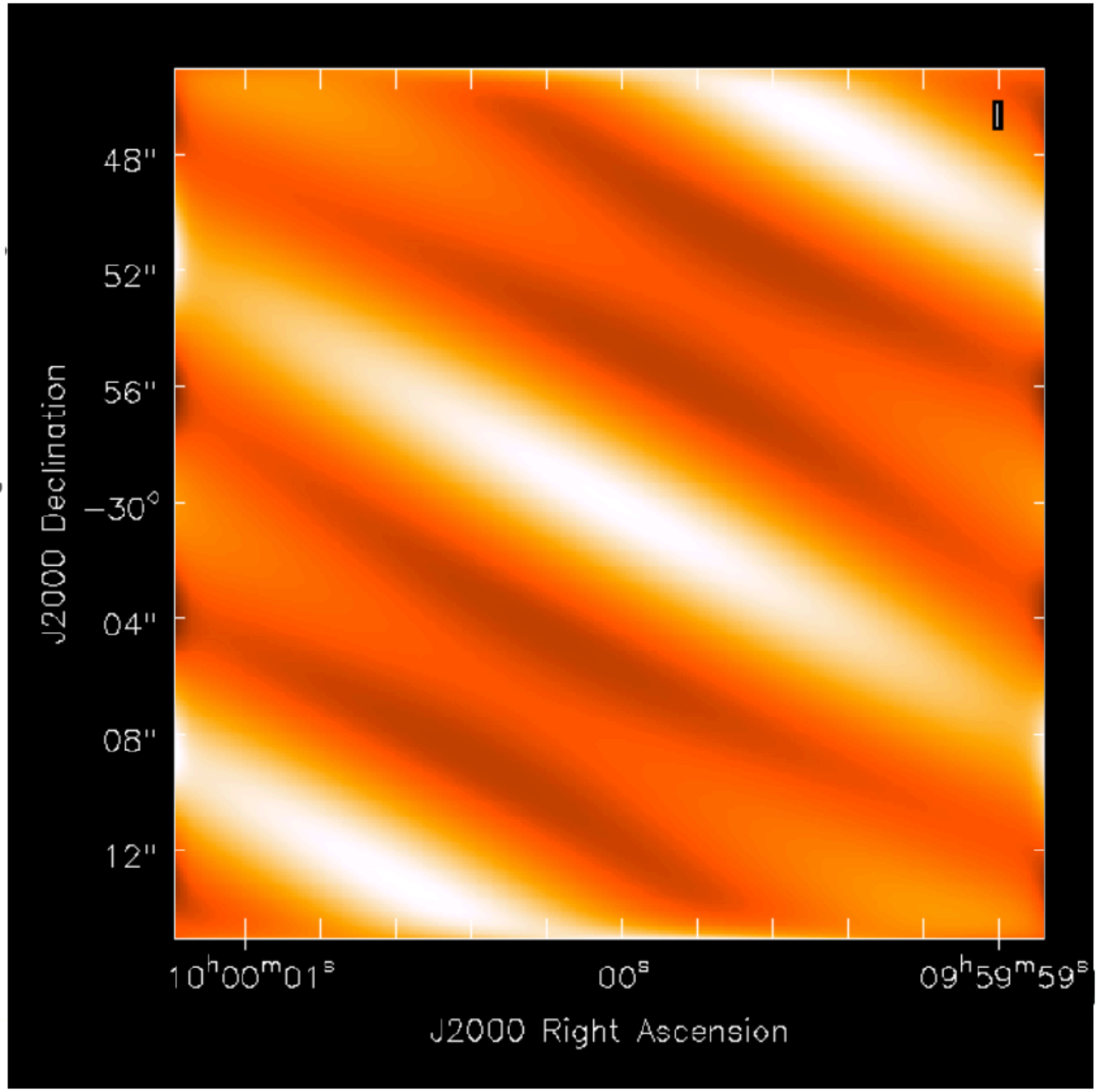

True sky

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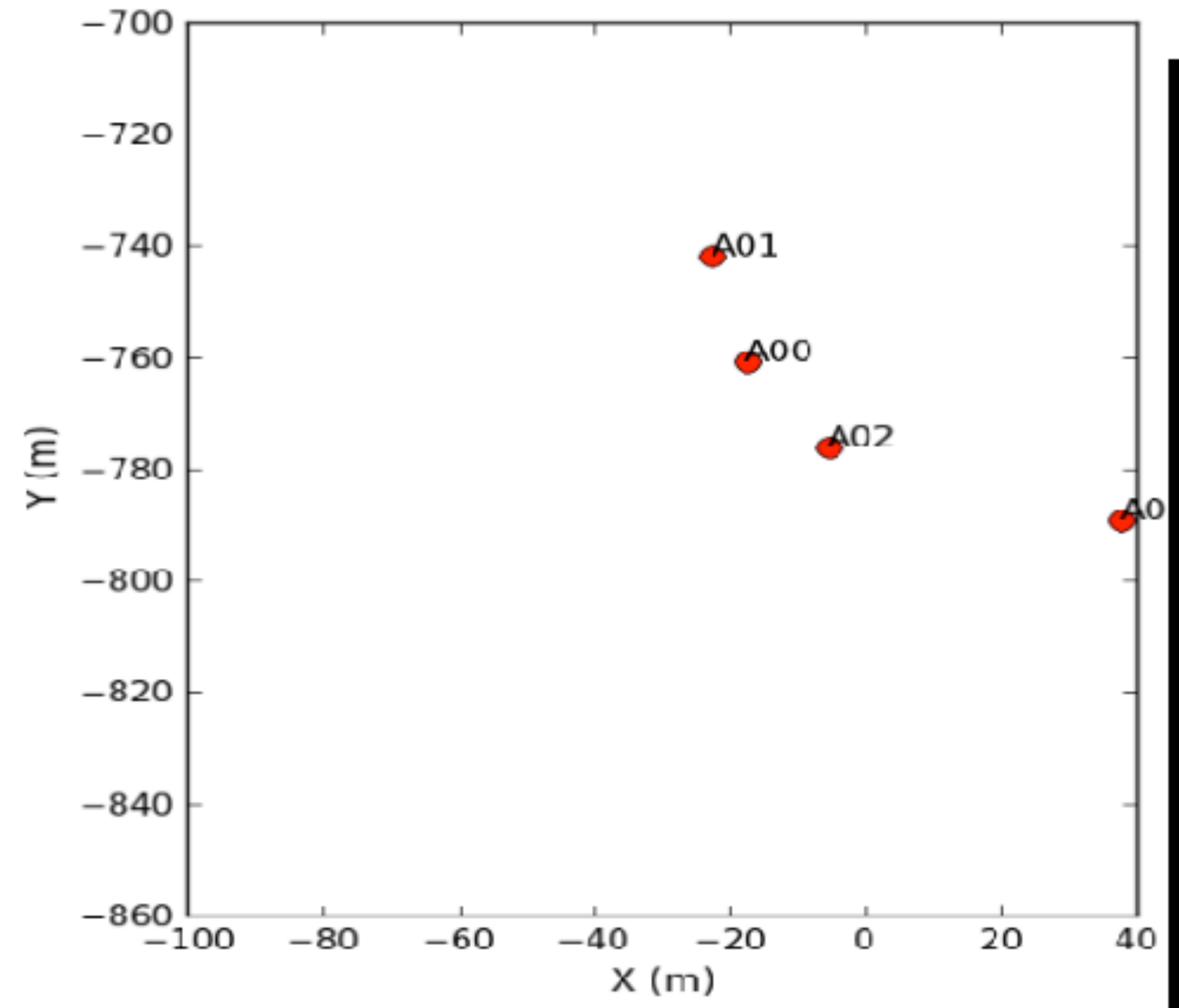
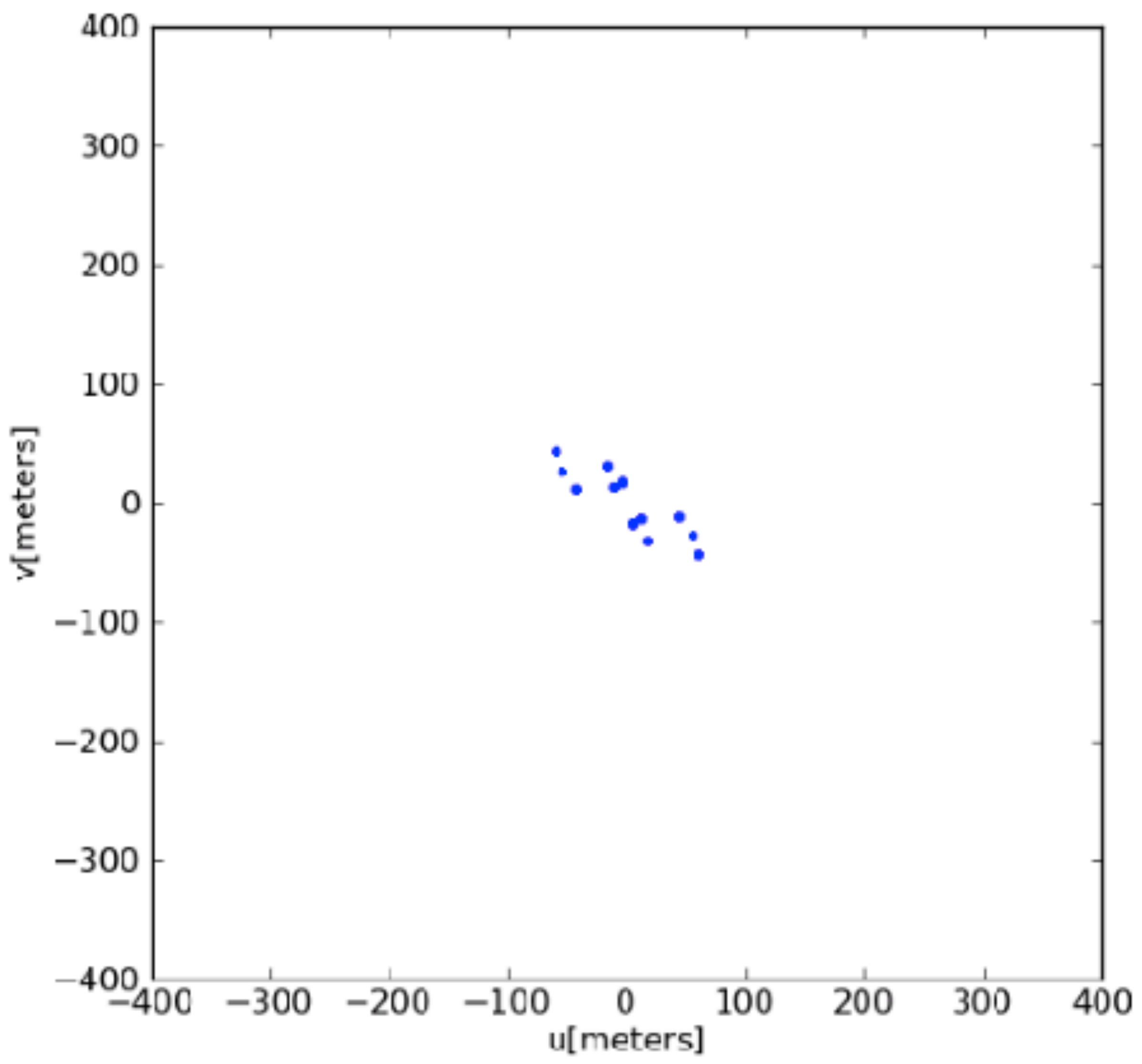
(u,v) sampling: four antenna





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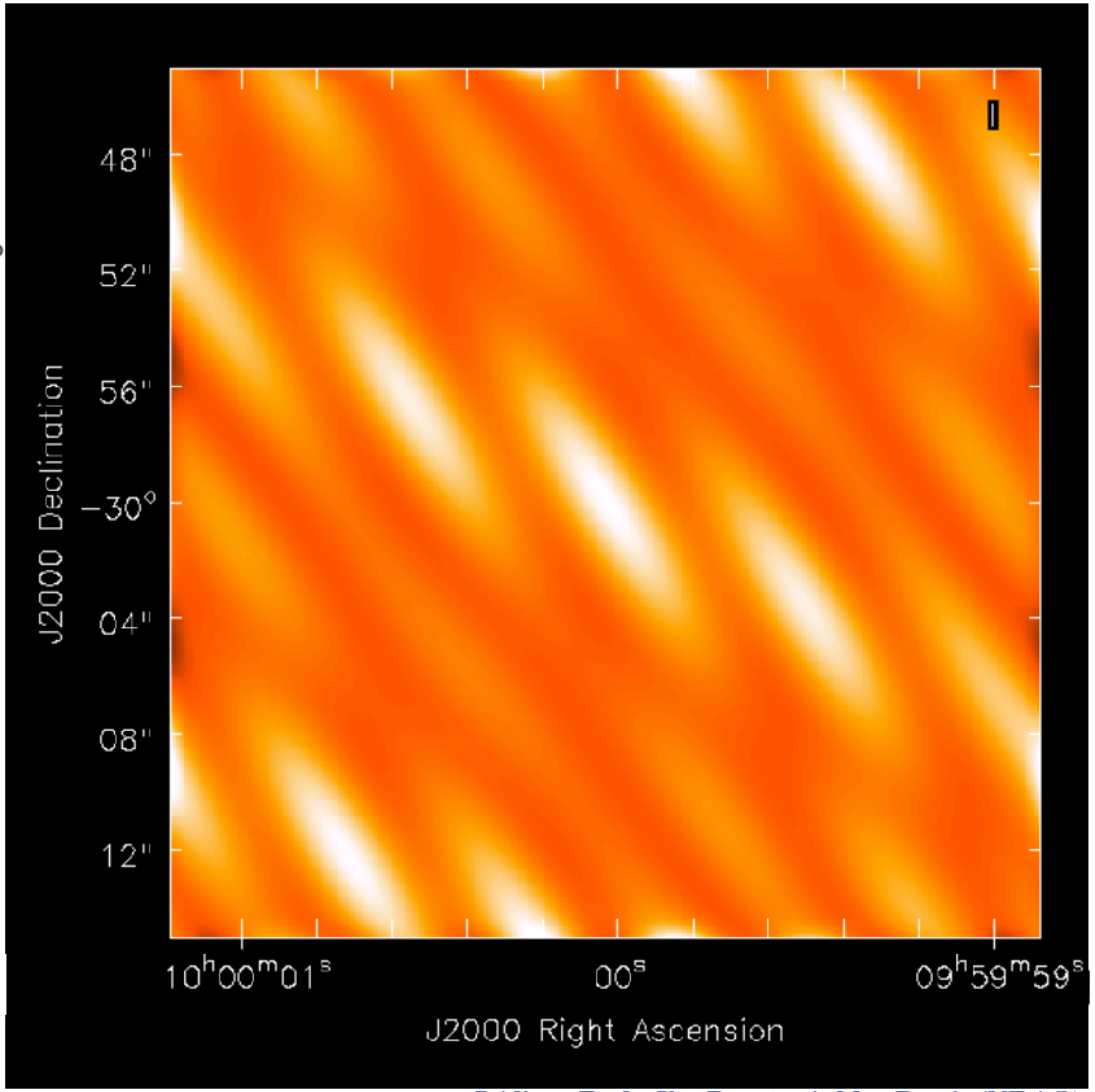

True sky

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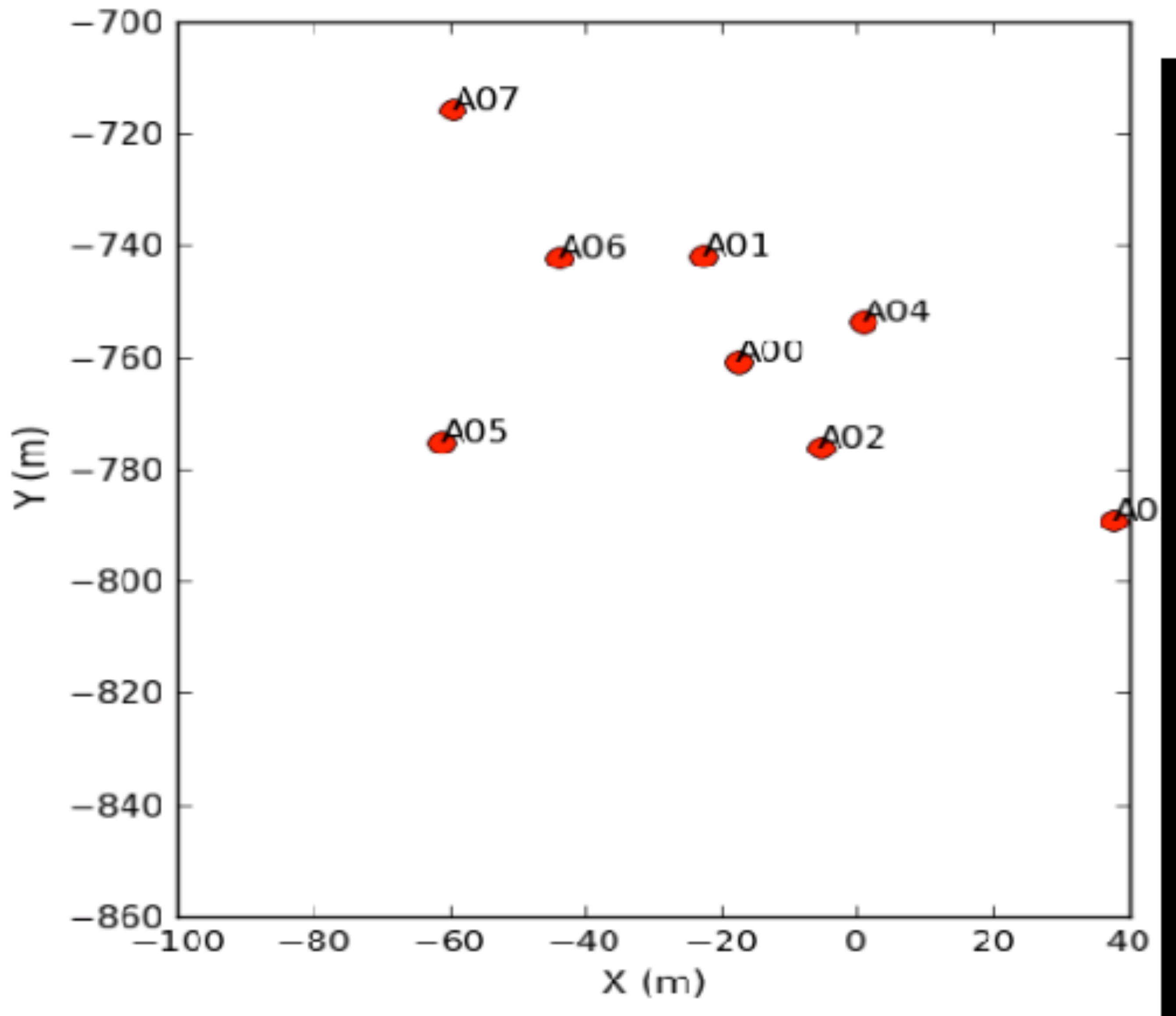
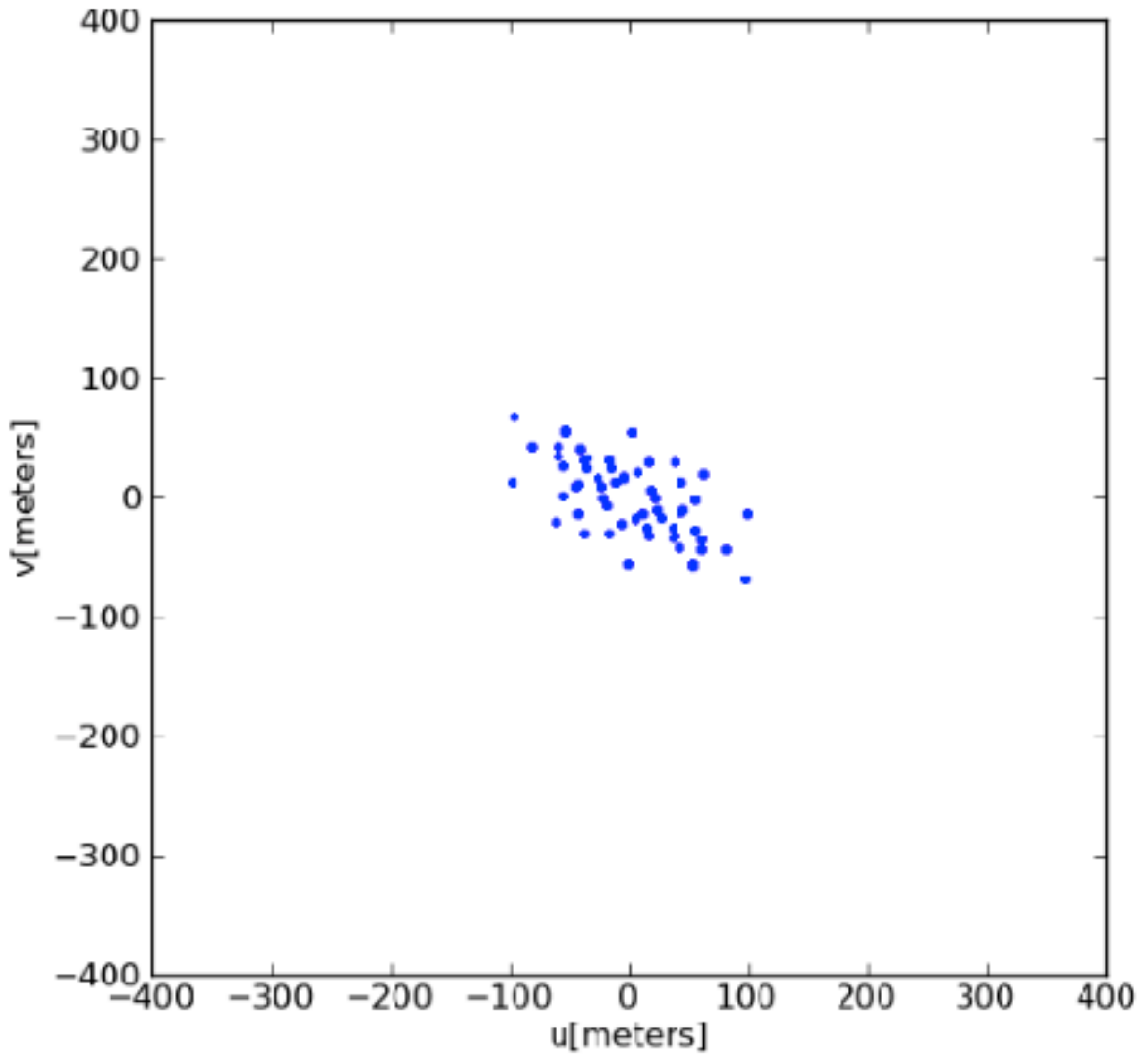
(u,v) sampling: eight antenna





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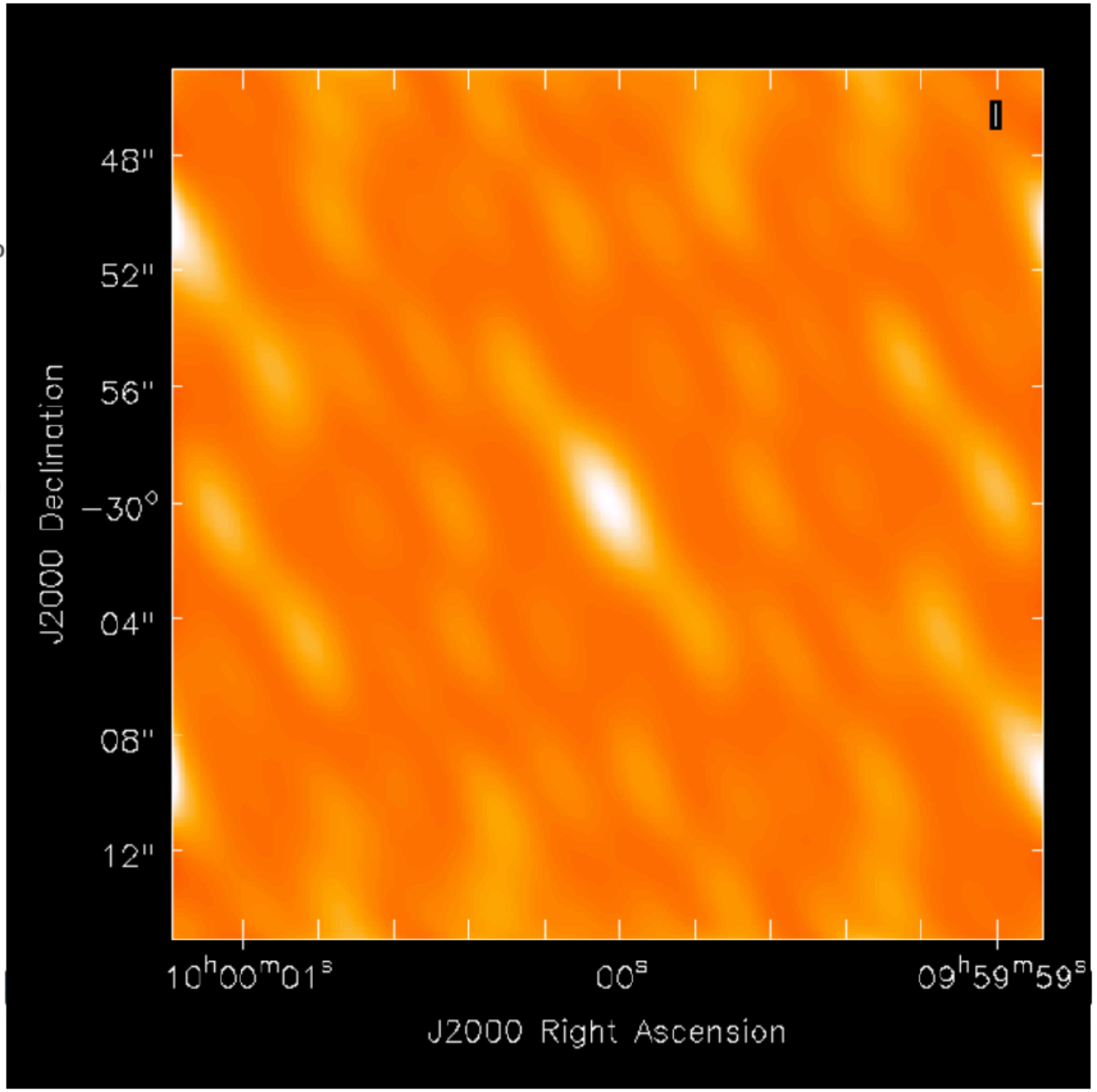

True sky

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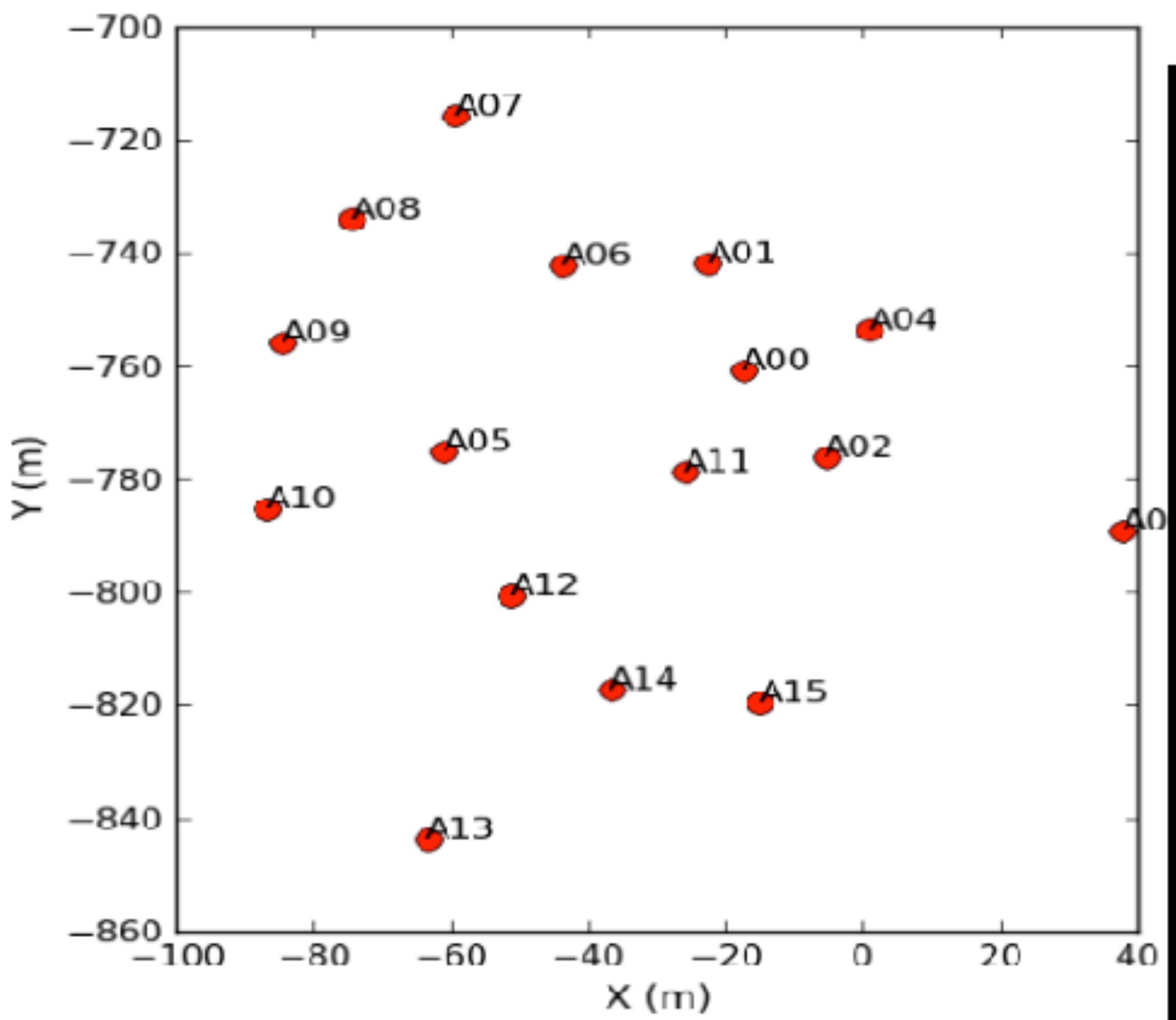
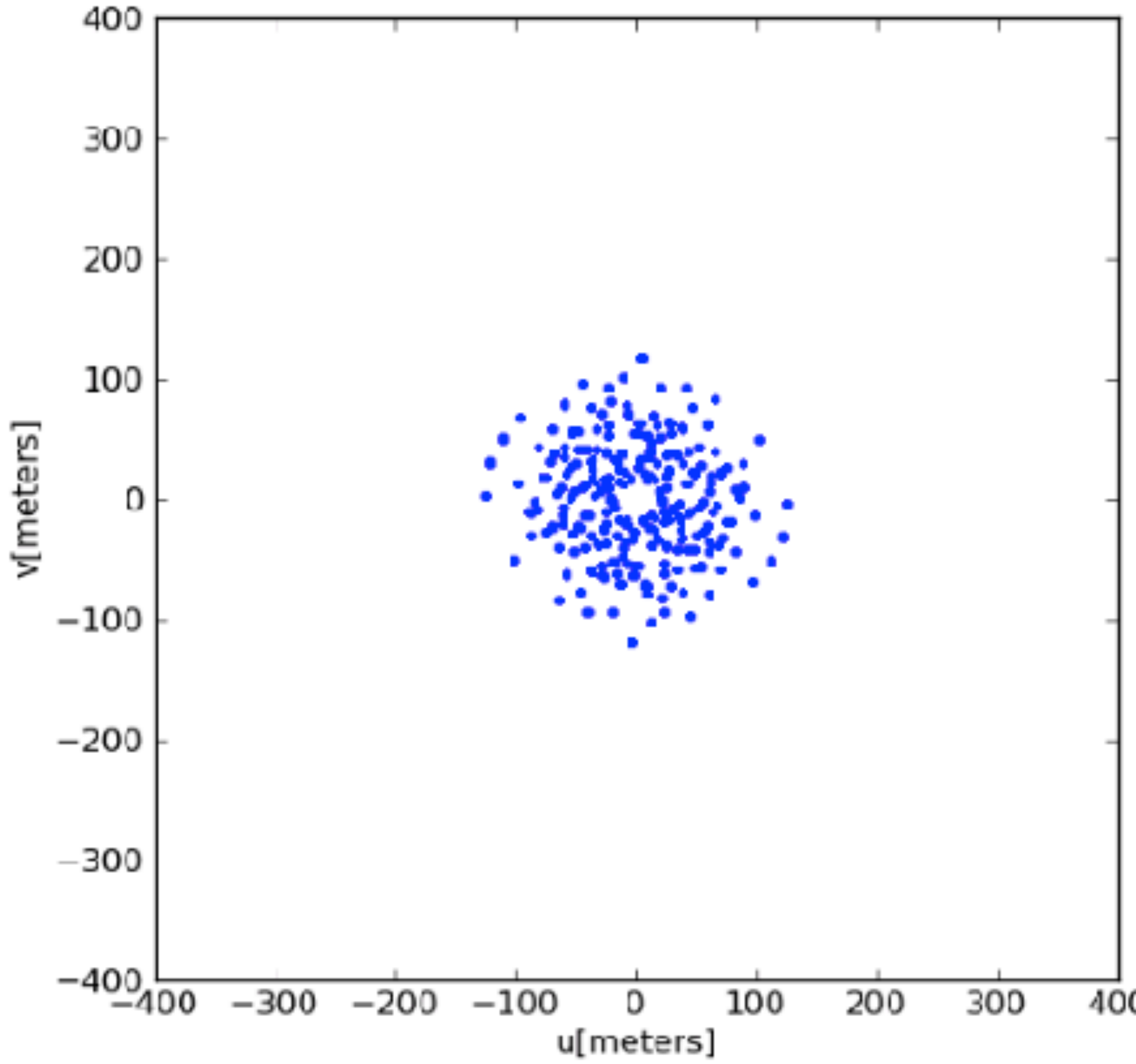
(u,v) sampling: 16 antenna - compact





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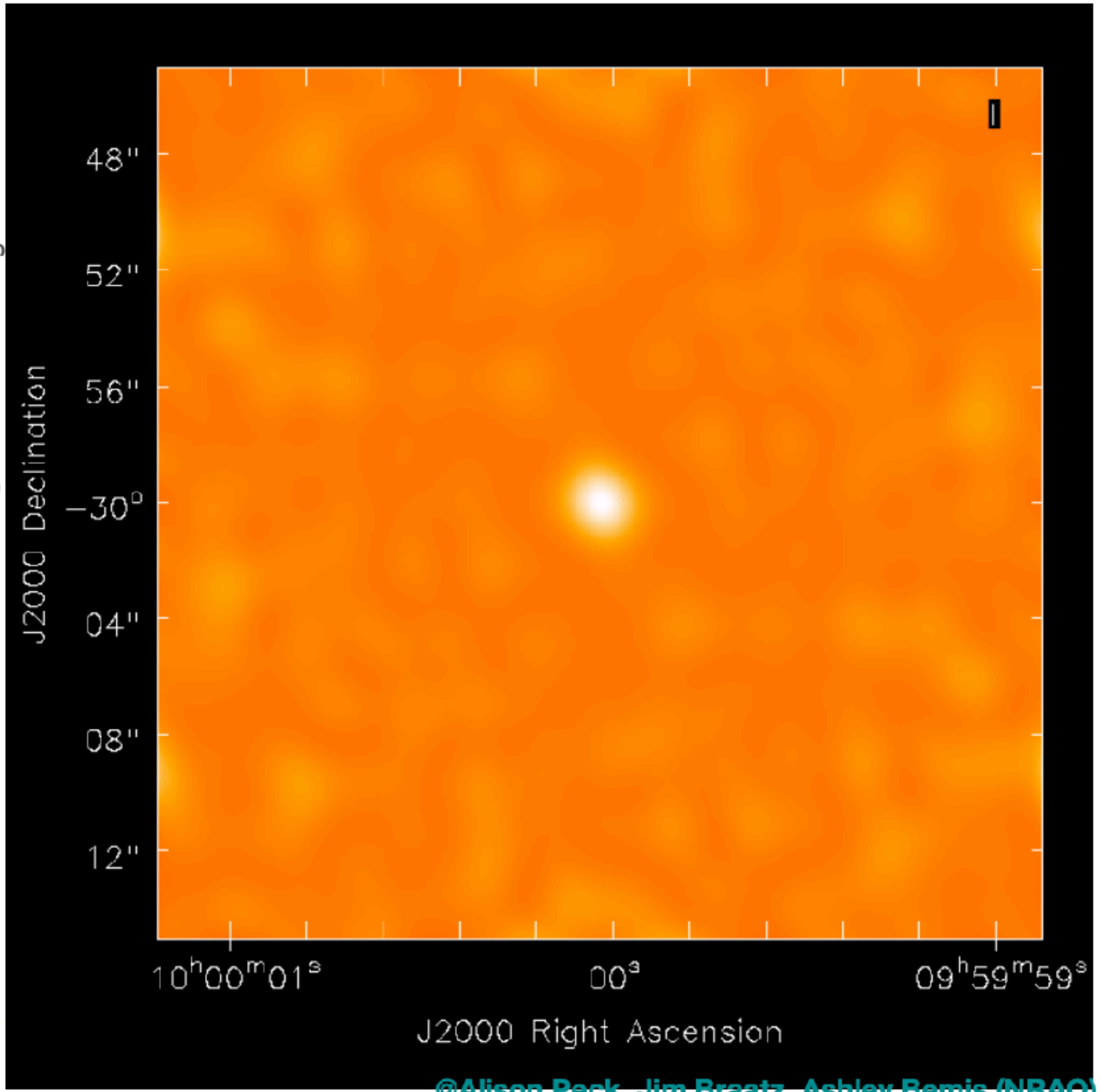

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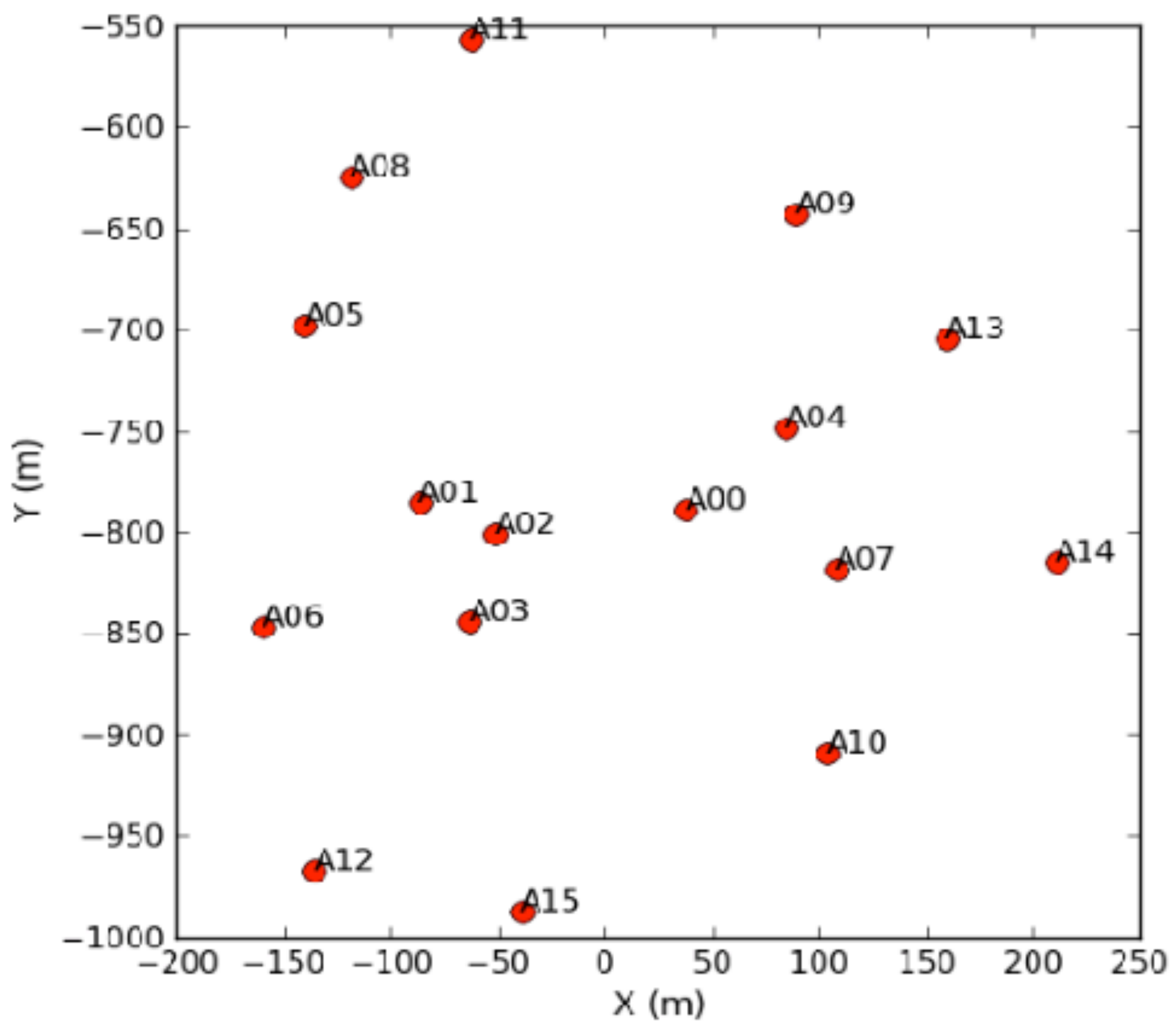
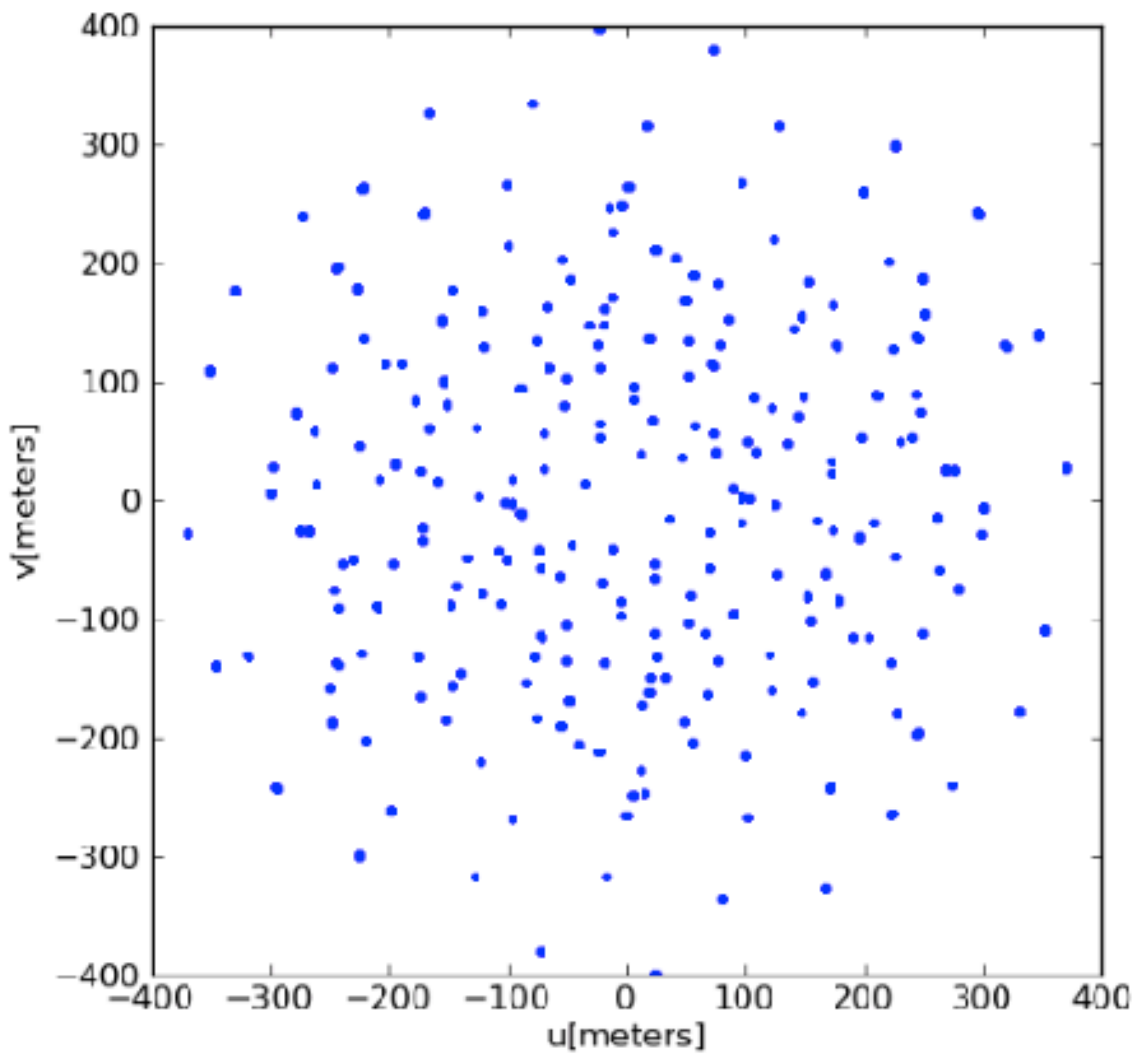
True sky

(u,v) sampling: 16 antenna - extend





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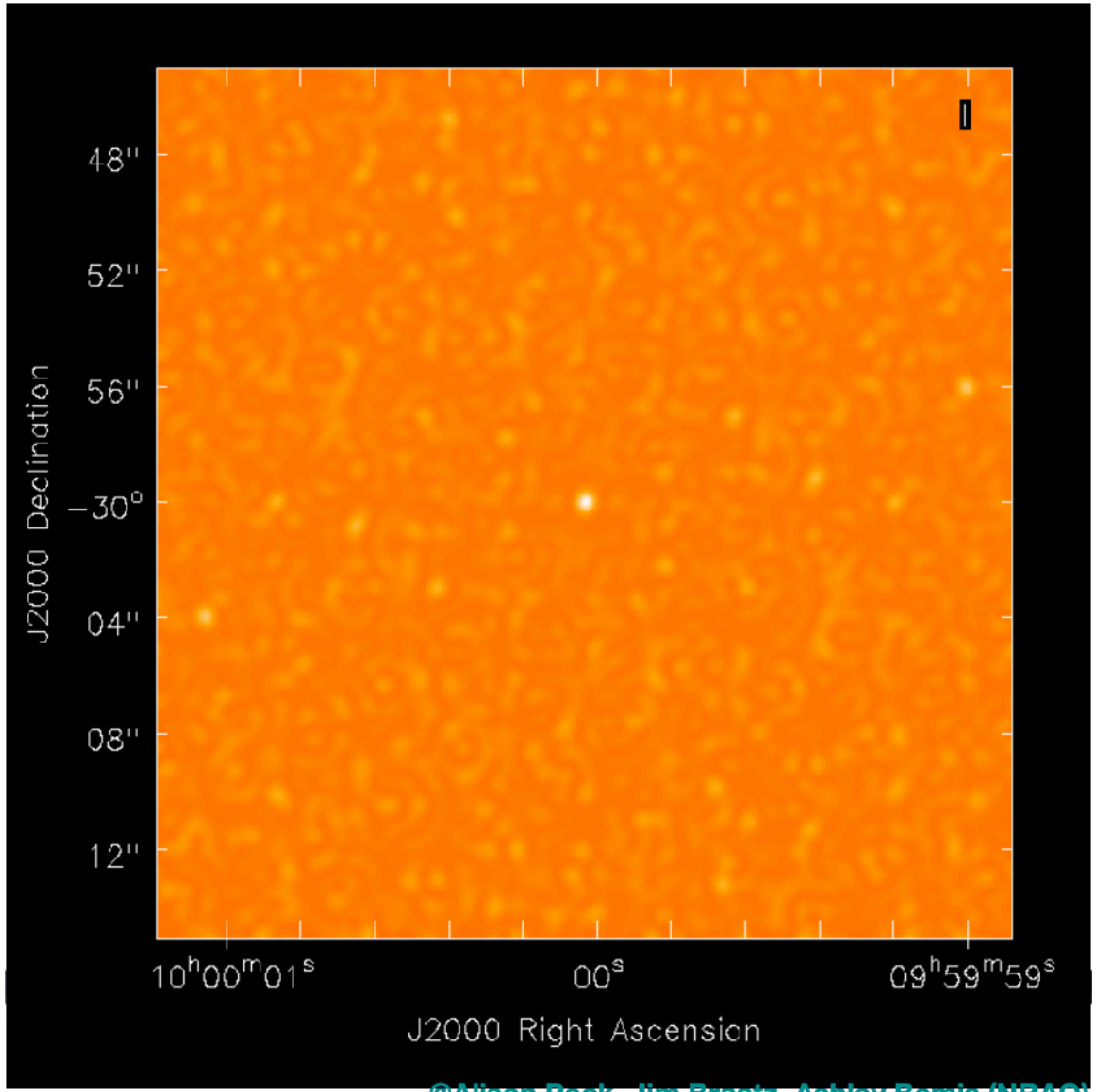

True sky

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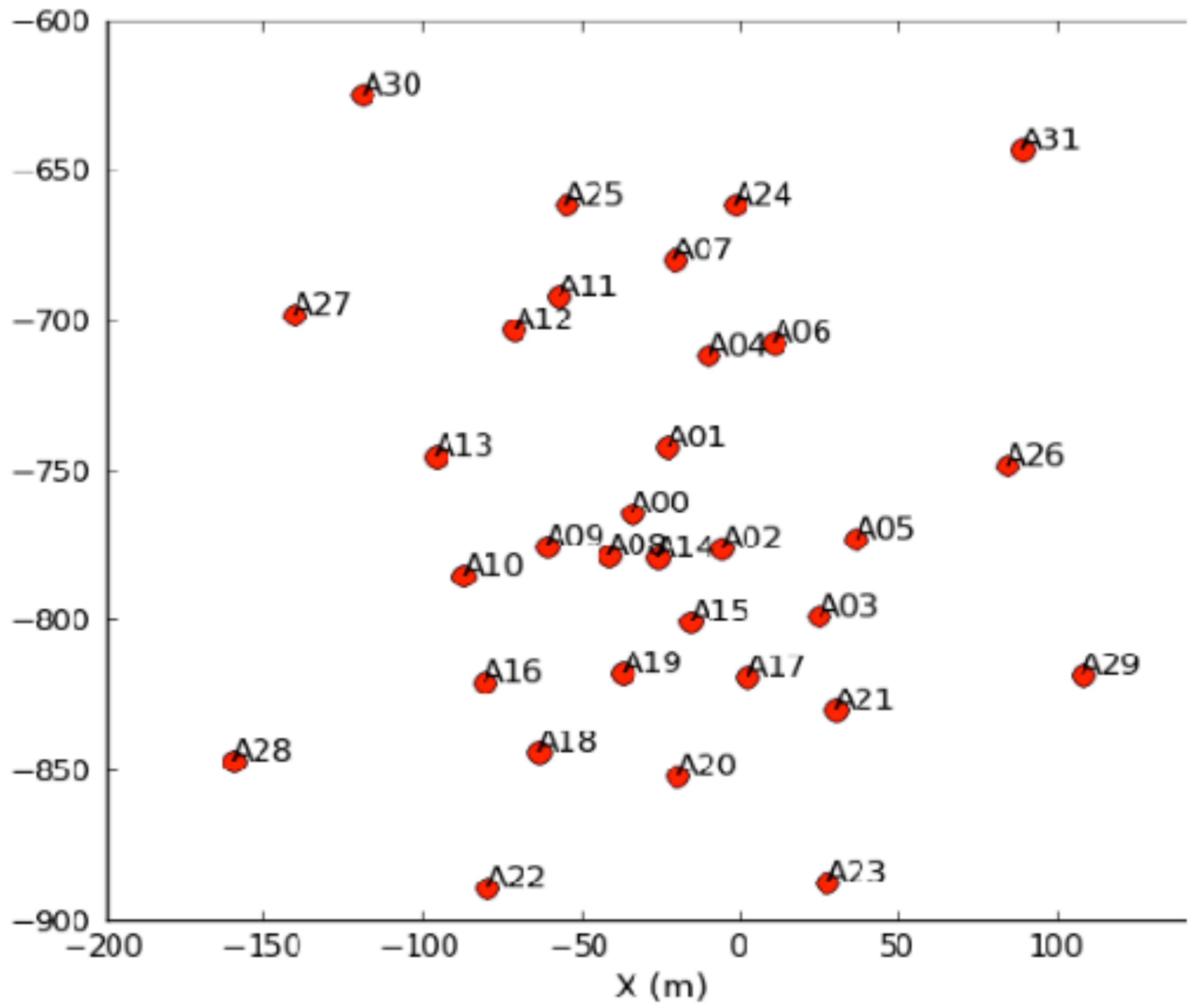
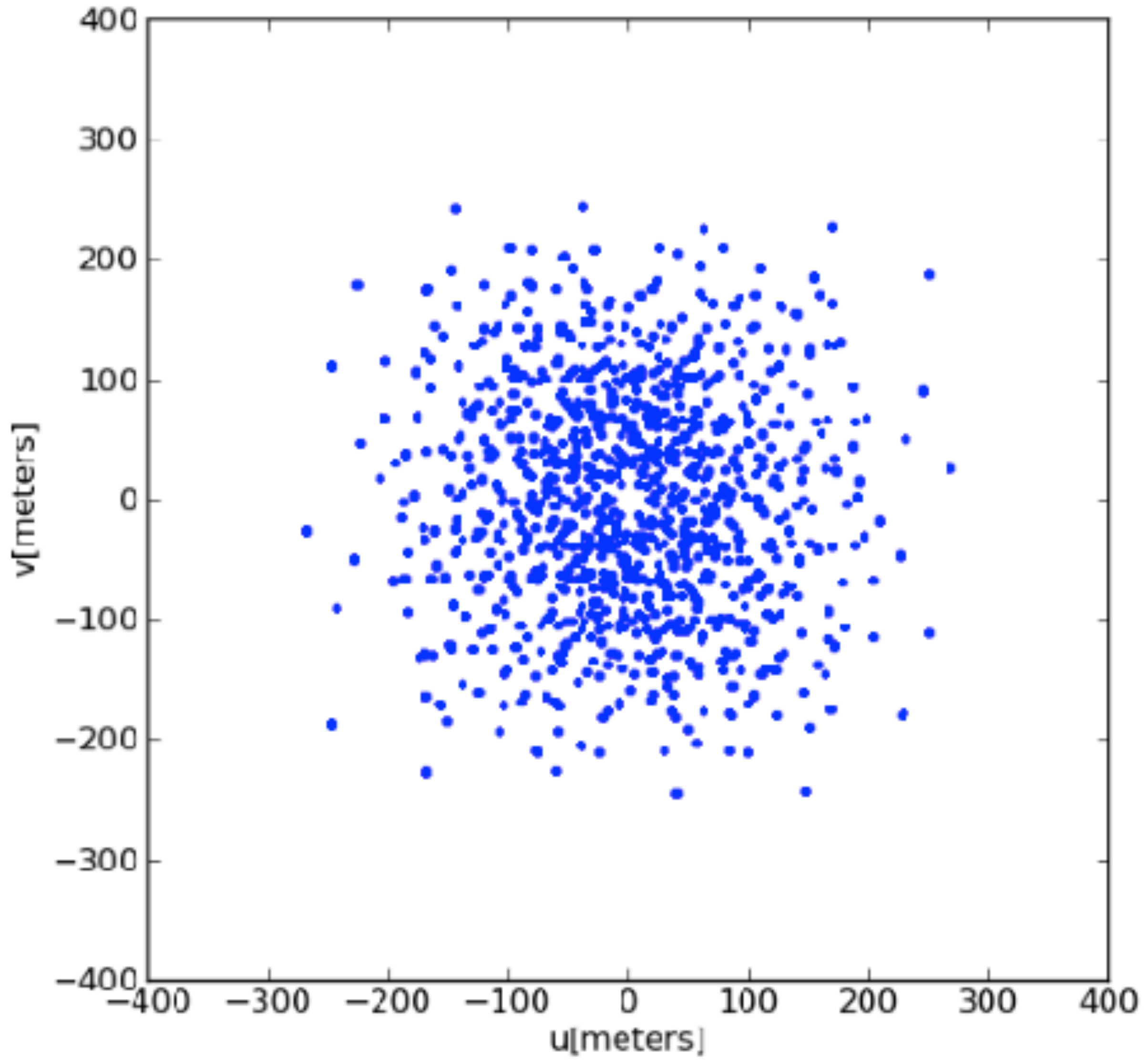
(u,v) sampling: 32 antenna





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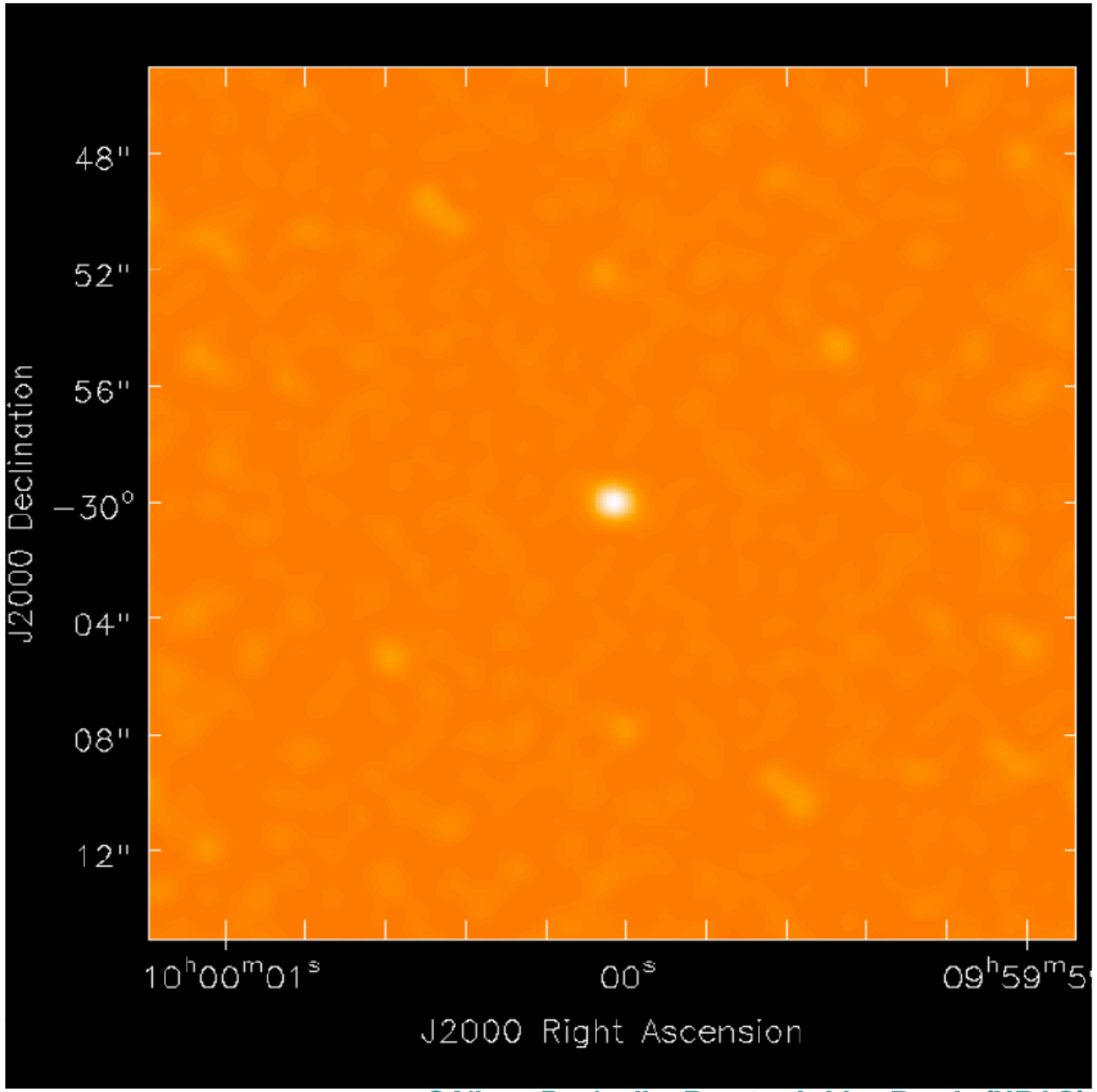

True sky

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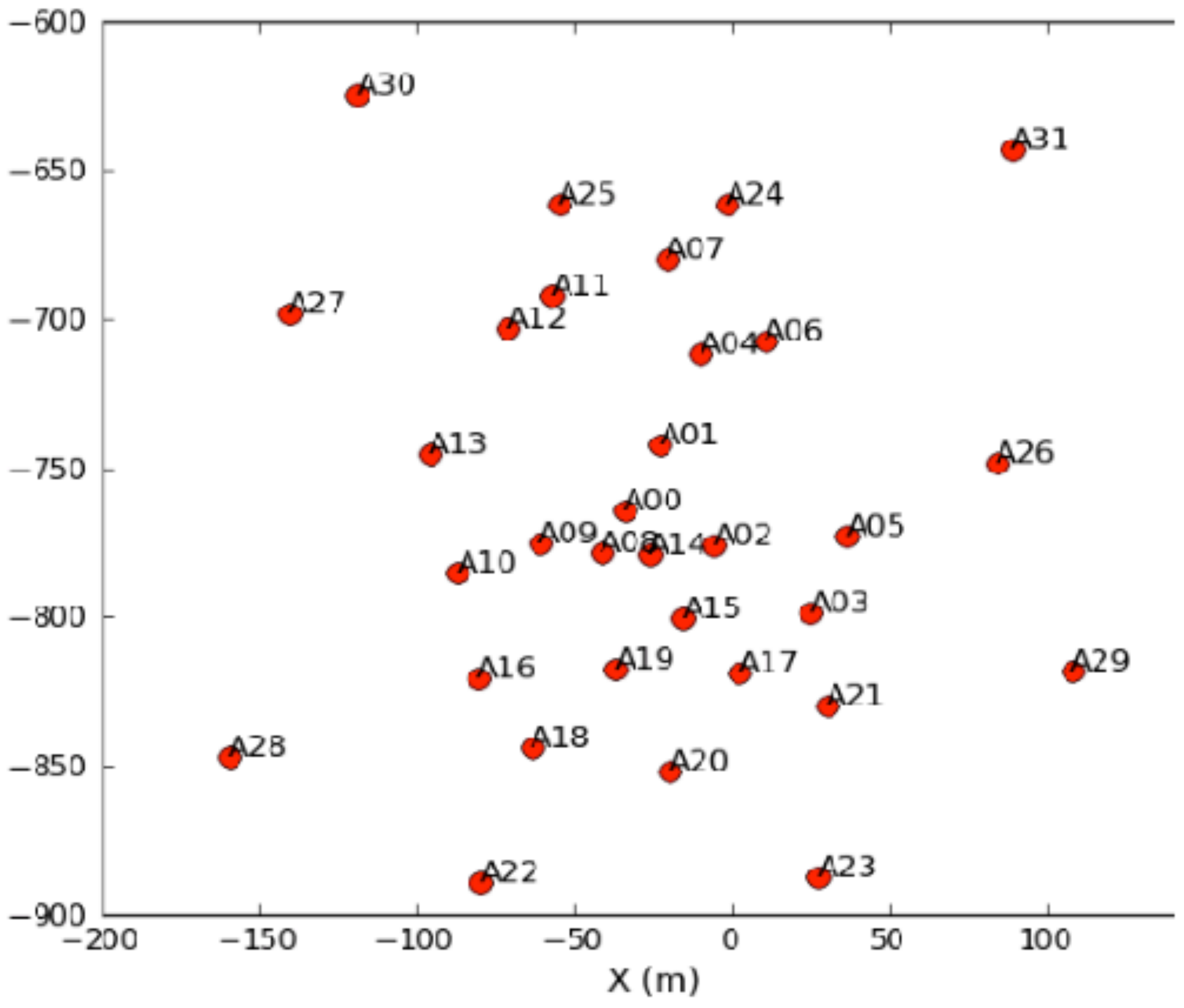
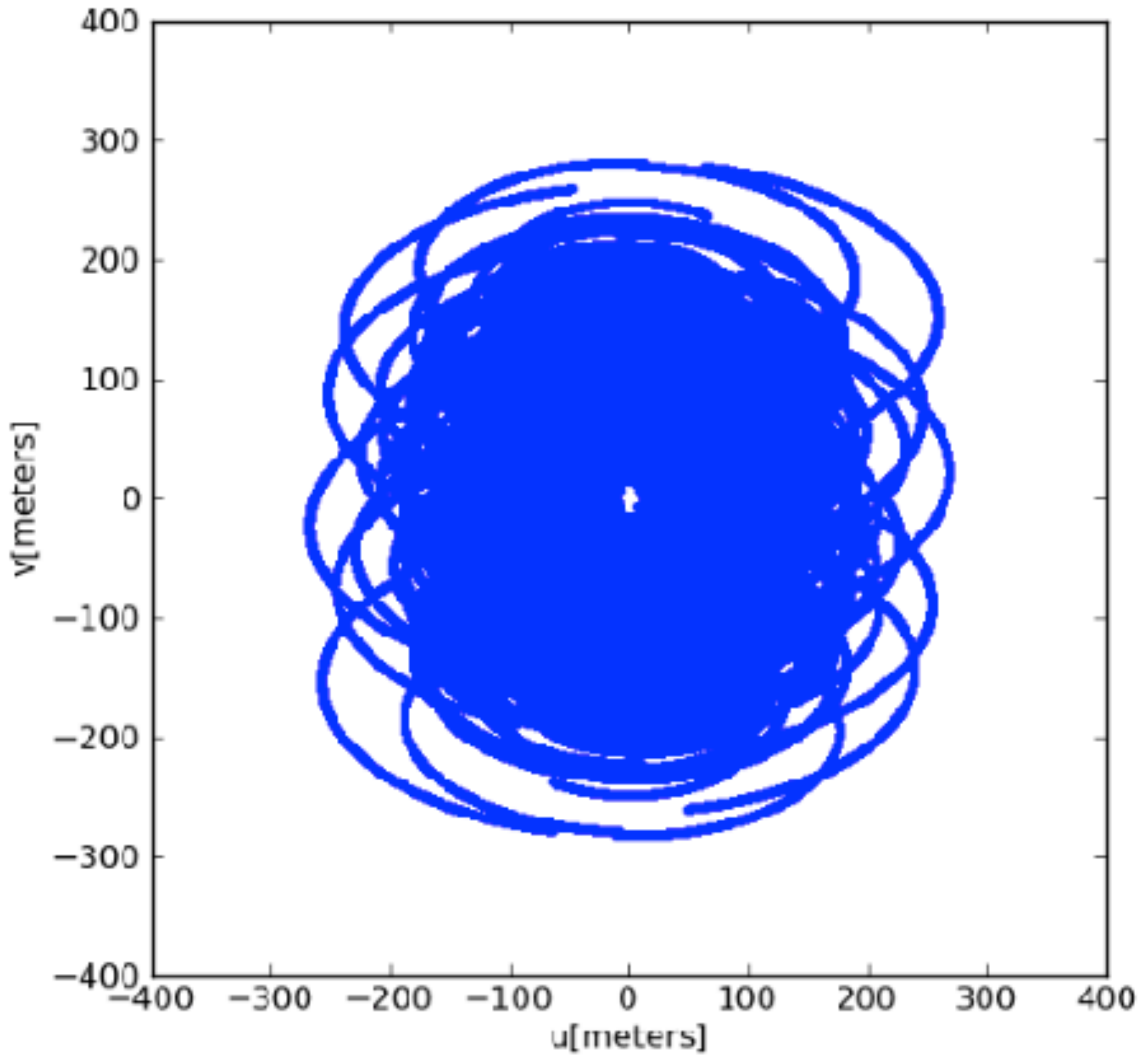
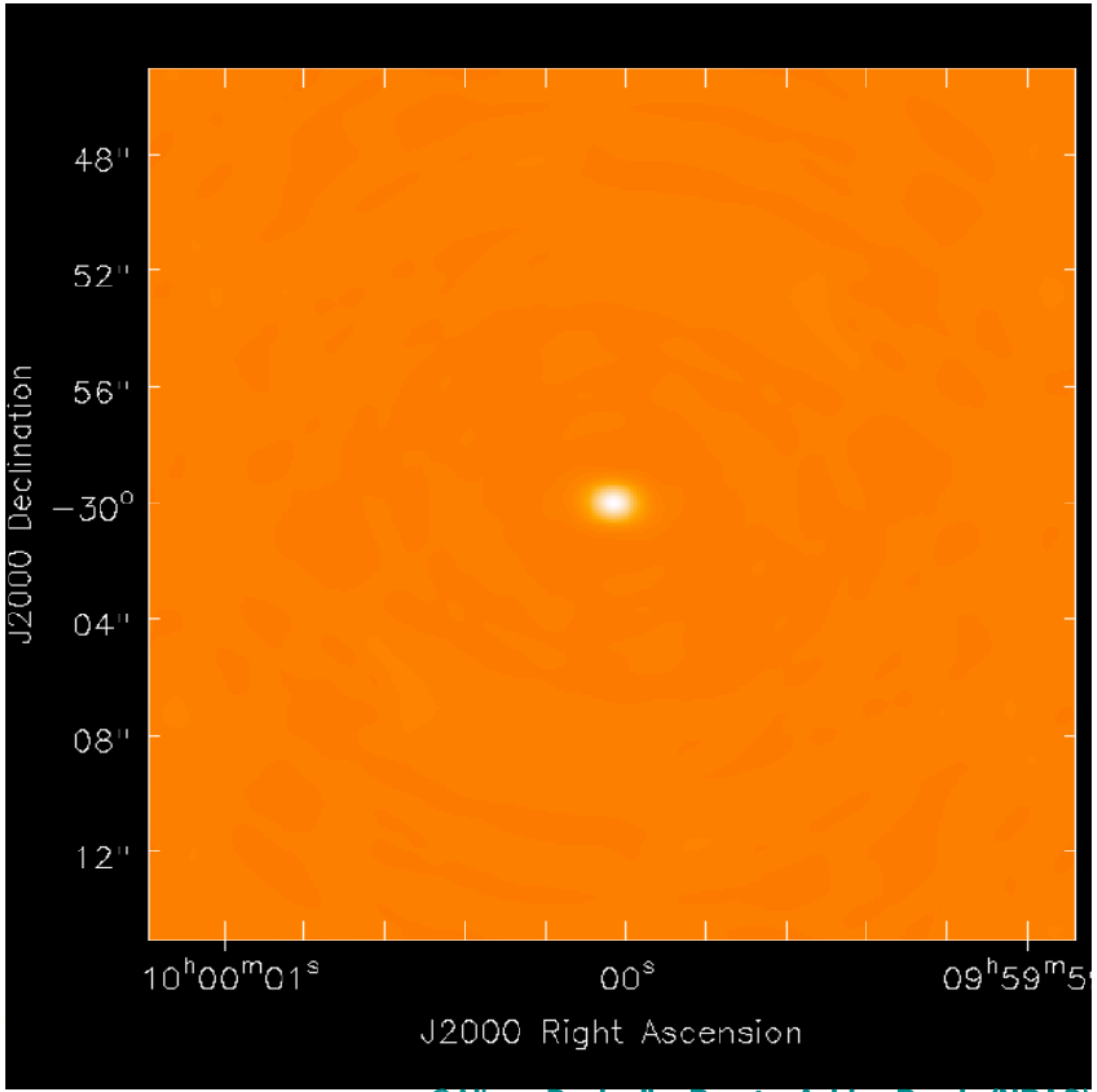
(u,v) sampling: 32 antenna





Exploiting Earth rotation

Recovered image



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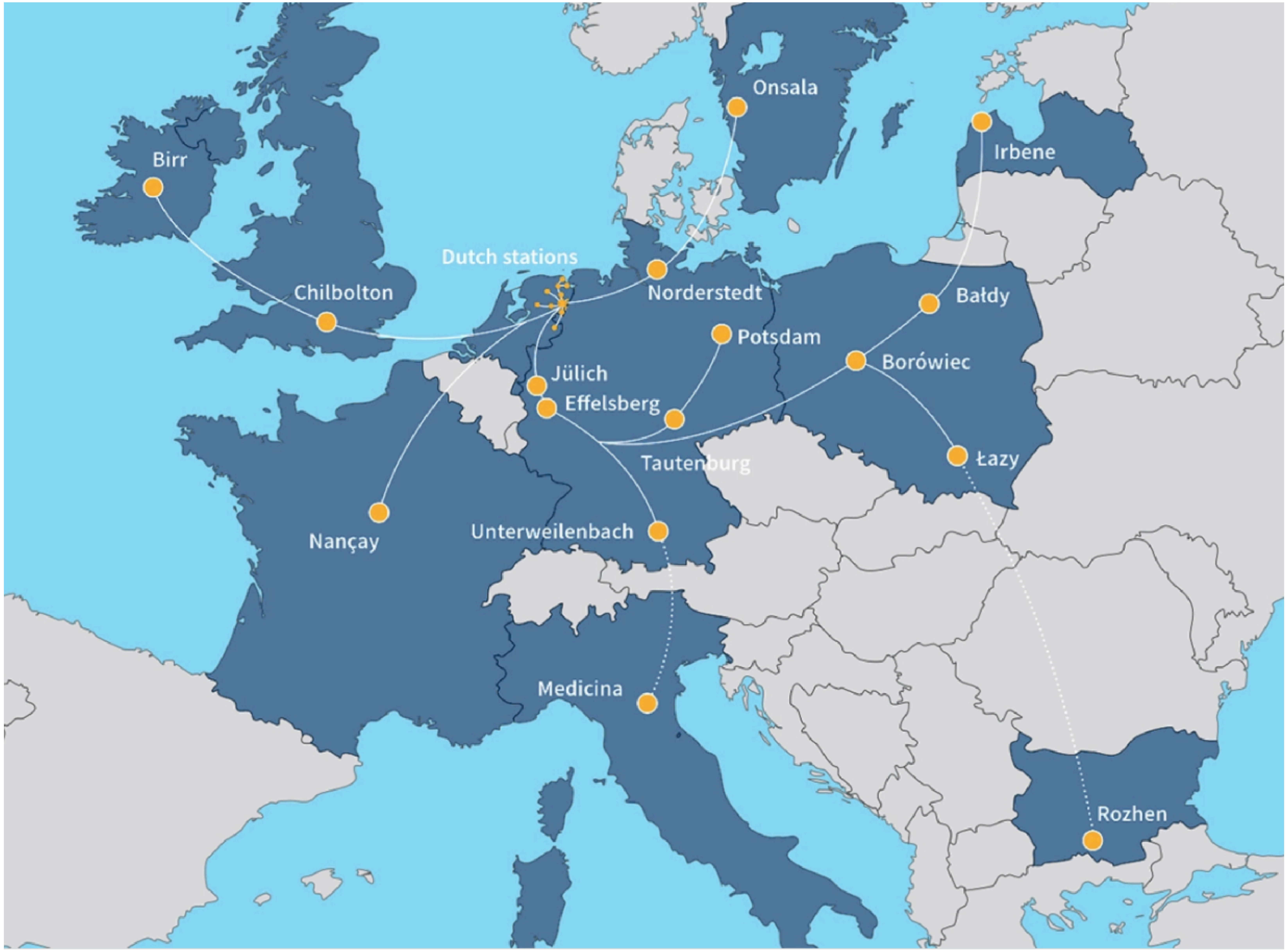
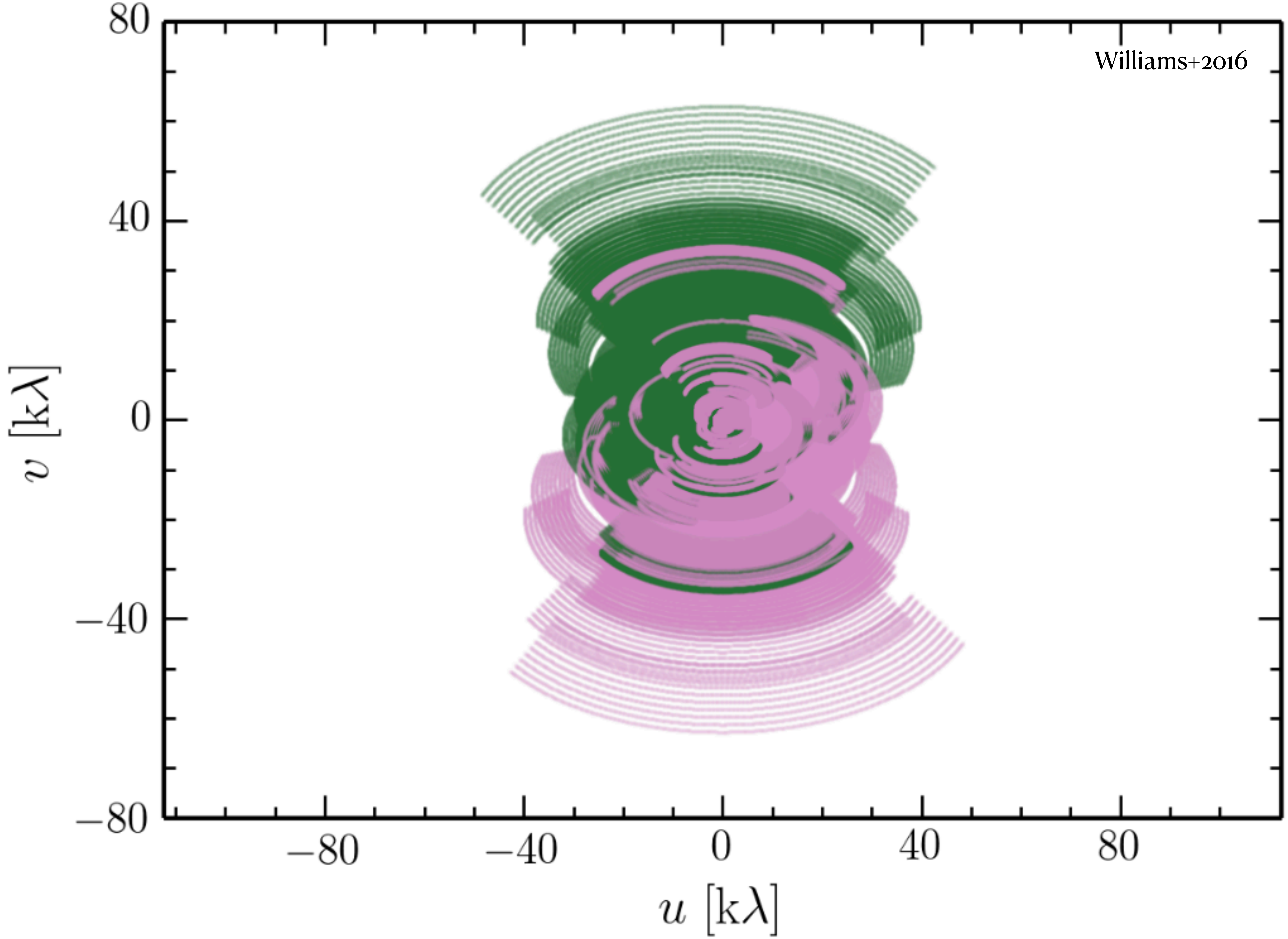
True sky

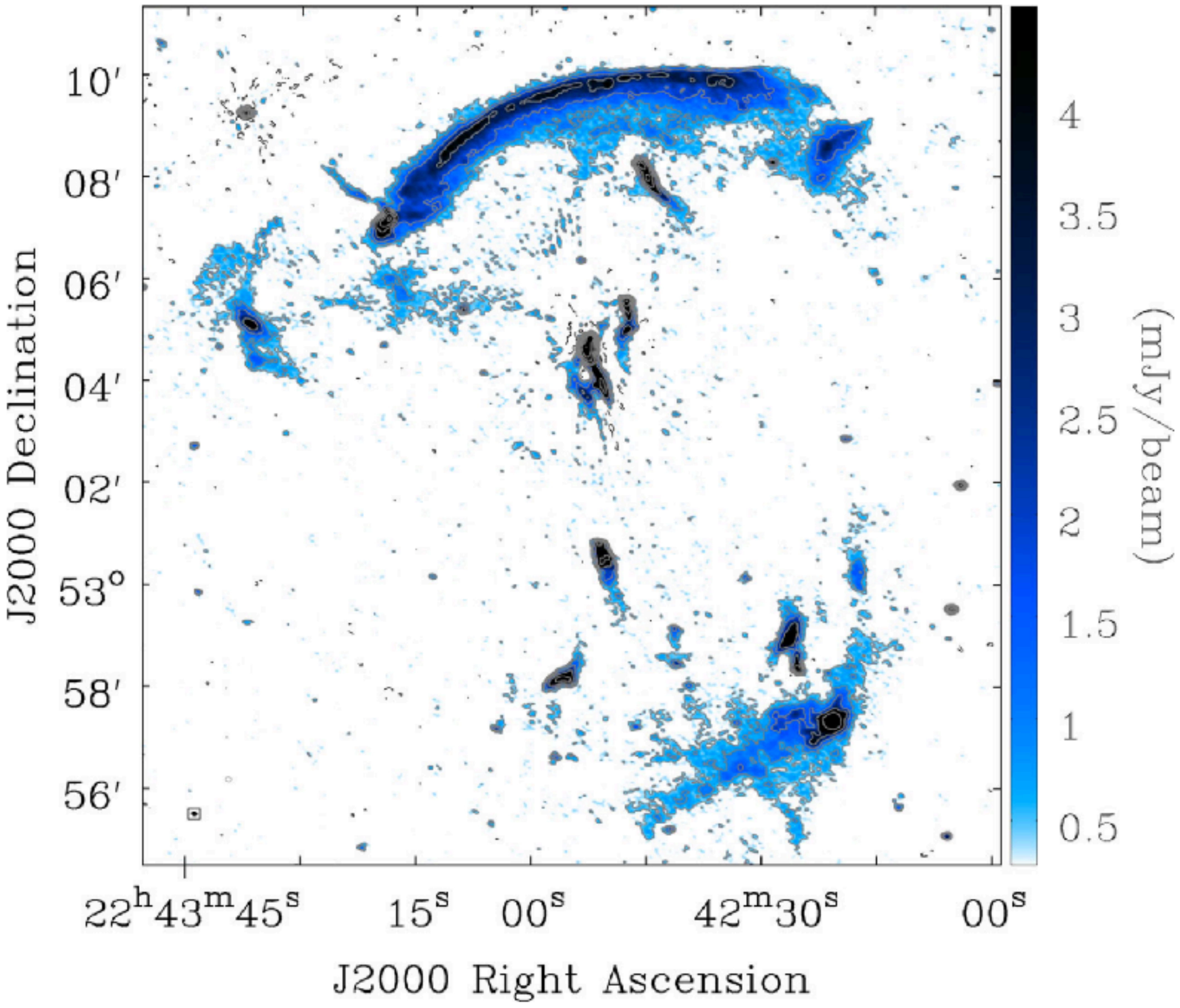
(u,v) sampling: LOFAR



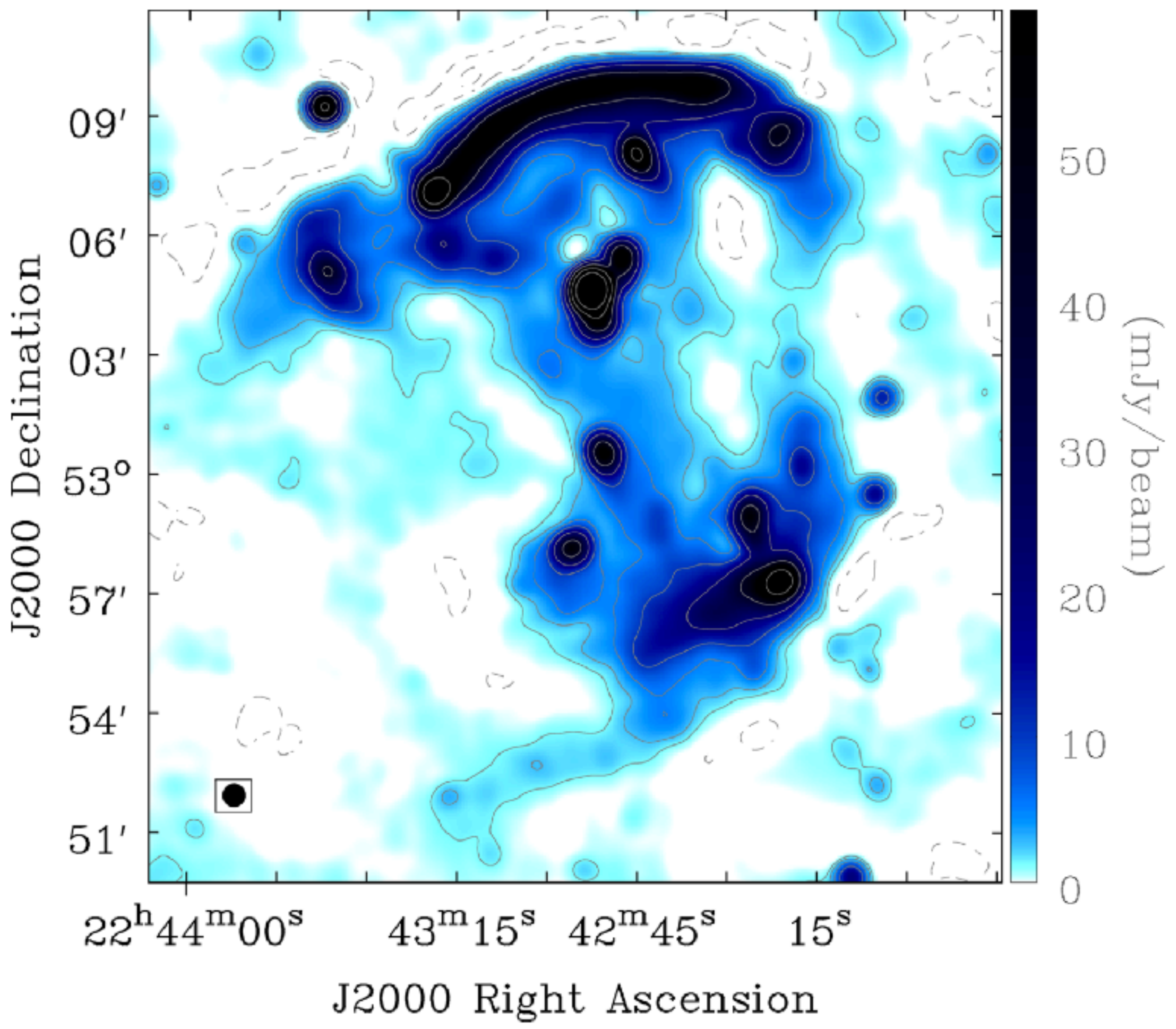
(u,v) sampling: LOFAR



uv weighting



Briggs weighting, robust -0.25



Briggs weighting, robust 0.5
(more weights on short baselines)

Take-away messages

★ Astronomical radio sources are observable from the ground.

★ Multiple physical processes emit radio waves.

★ Radio interferometers provide a mean of high spatial resolution mapping radio sources.

★ Radio interferometers transform the sky brightness into visibility data that can be converted back with deconvolution technique.

Thanks very much for your attention!