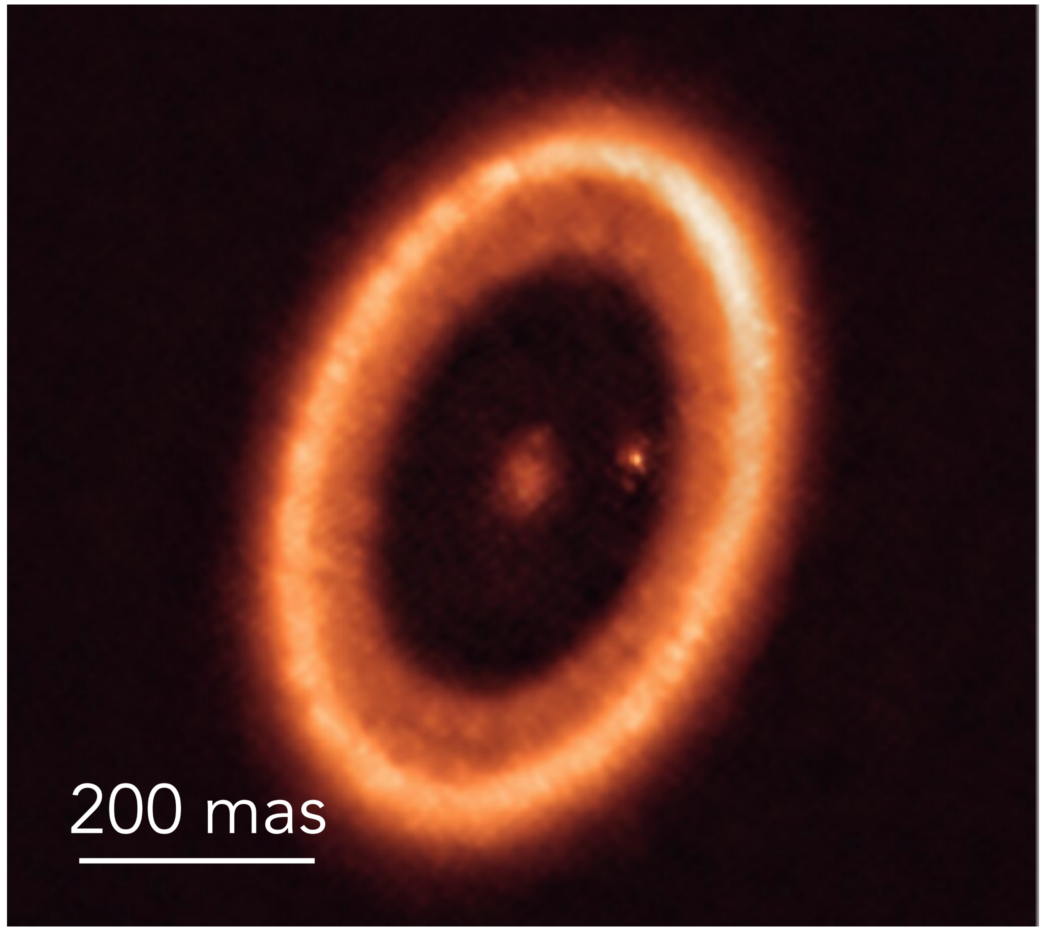
Observing planet forming disks with ALMA

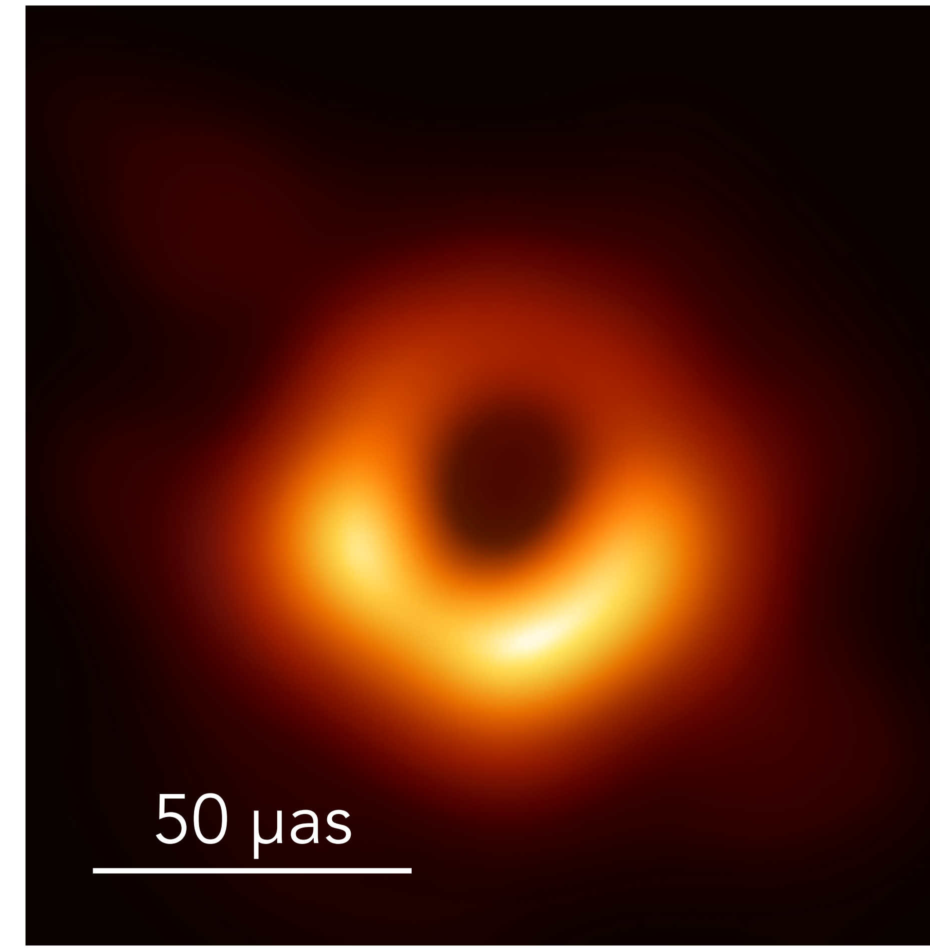
Basics of interferometry

Stefano Facchini

Need for high angular resolution



Planetary system in formation (Benisty+2021)



Torus orbiting a SMBH in M87 (EHT Collaboration+2021)

1 au at 100 pc is 10mas

The radius of the shadow of a Schwarzschild BH at 16.8 Mpc is 38 μas

Several fundamental physical processes occur on angular scales that are <1″

$\Theta(\mathrm{arcsec}) = 2\lambda_{\mathrm{cm}}/D_{\mathrm{km}}$ ⟶ antenna of 4 km to have 0.1″ a 2 mm

Interferometry is necessary to achieve such angular scales.

Aperture synthesis interferometry - background

For an interferometer formed by two antennas, it is possible to demonstrate that:

$$\Theta(\mathrm{arcsec}) = 2\lambda_{\mathrm{cm}}/B_{\mathrm{km}}$$

where *B* is the baseline, i.e. the projected distance of the two antennas

One-Mile Telescope

- Close to Cambridge, UK
- Opened in 1964
- 3 antennas of 18-m
- First aperture synthesis exploiting the Earth rotation

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ALMA
- Altiplan of Chajnantor
- First light in 2011
- 54 12-m, 12 7-m antennas

Going beyond a two element interferometer

A two element interferometer measures the Fourier transform of the sky brightness B, where (u,v) are the coordinates of the baseline, and Â is the primary beam correction

$$V(u,v) = Ae^{-i\phi} = \int \hat{A}(x,y)B(x,y)e^{-i2\pi(ux+vy)}dxdy$$

A is the amplitude, and ϕ is the phase of the complex visibility.

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- (u,v) are the spatial frequencies in the directions E-W e N-S, and represent the projected baseline in units of wavelength λ
- (x,y) are the relative distance from a reference point in the direction E-W e N-S
- (x=0,y=0) are known as “phase center”
- The phase ϕ contains information on the position of the structures with spatial frequencies (u,v) with respect to the phase center
- This FT relation is the van Cittert-Zernike theorem, on which aperture synthesis interferometry is based.

Going beyond a two element interferometer

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This means that if we have a measure of V(u,v),
we could reconstruct the sky brightness with a Fourier transform

$$B'(x,y) = \hat{A}(x,y)B(x,y) = \int V(u,v)e^{i2\pi(ux+vy)}dudv$$

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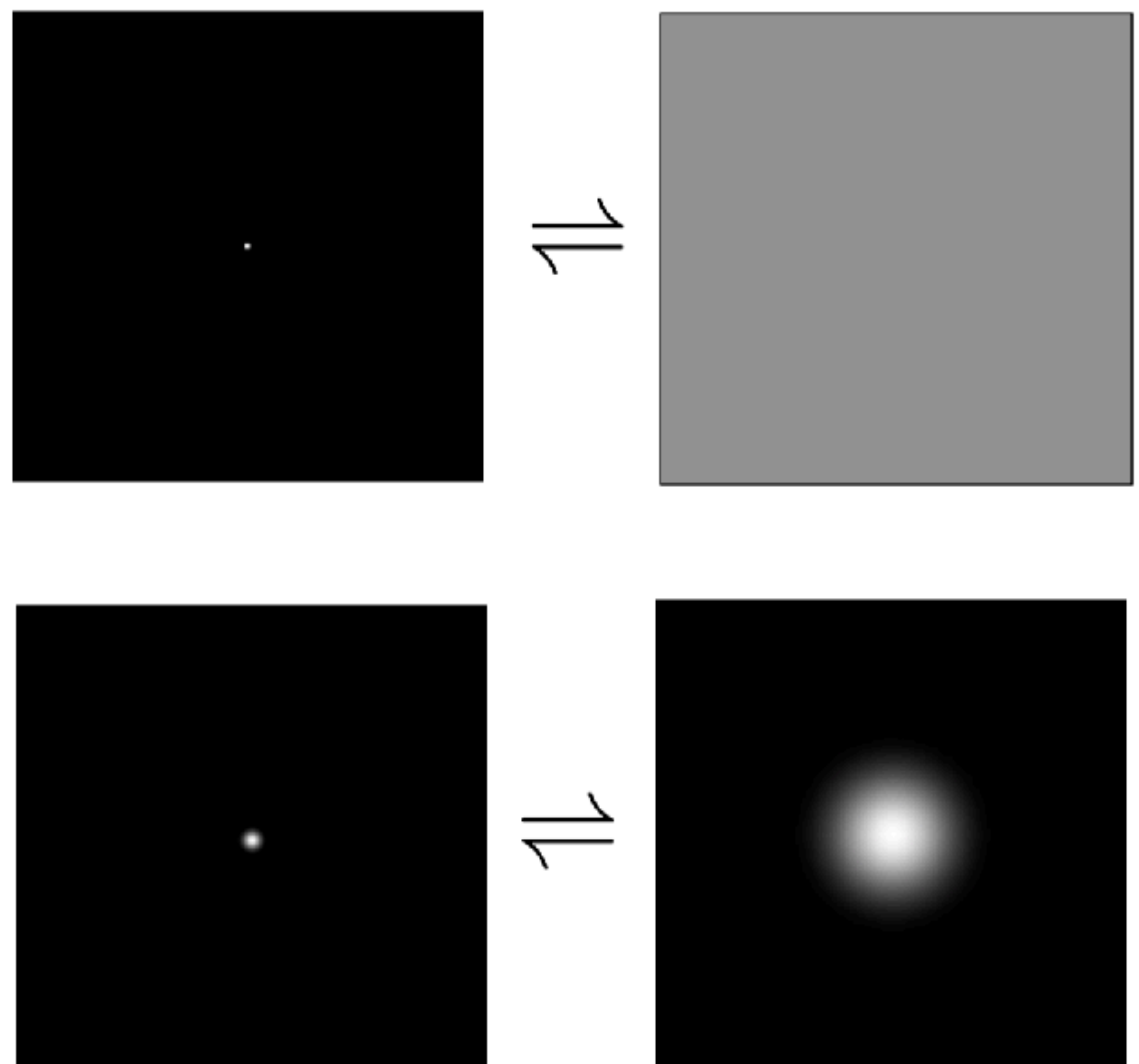
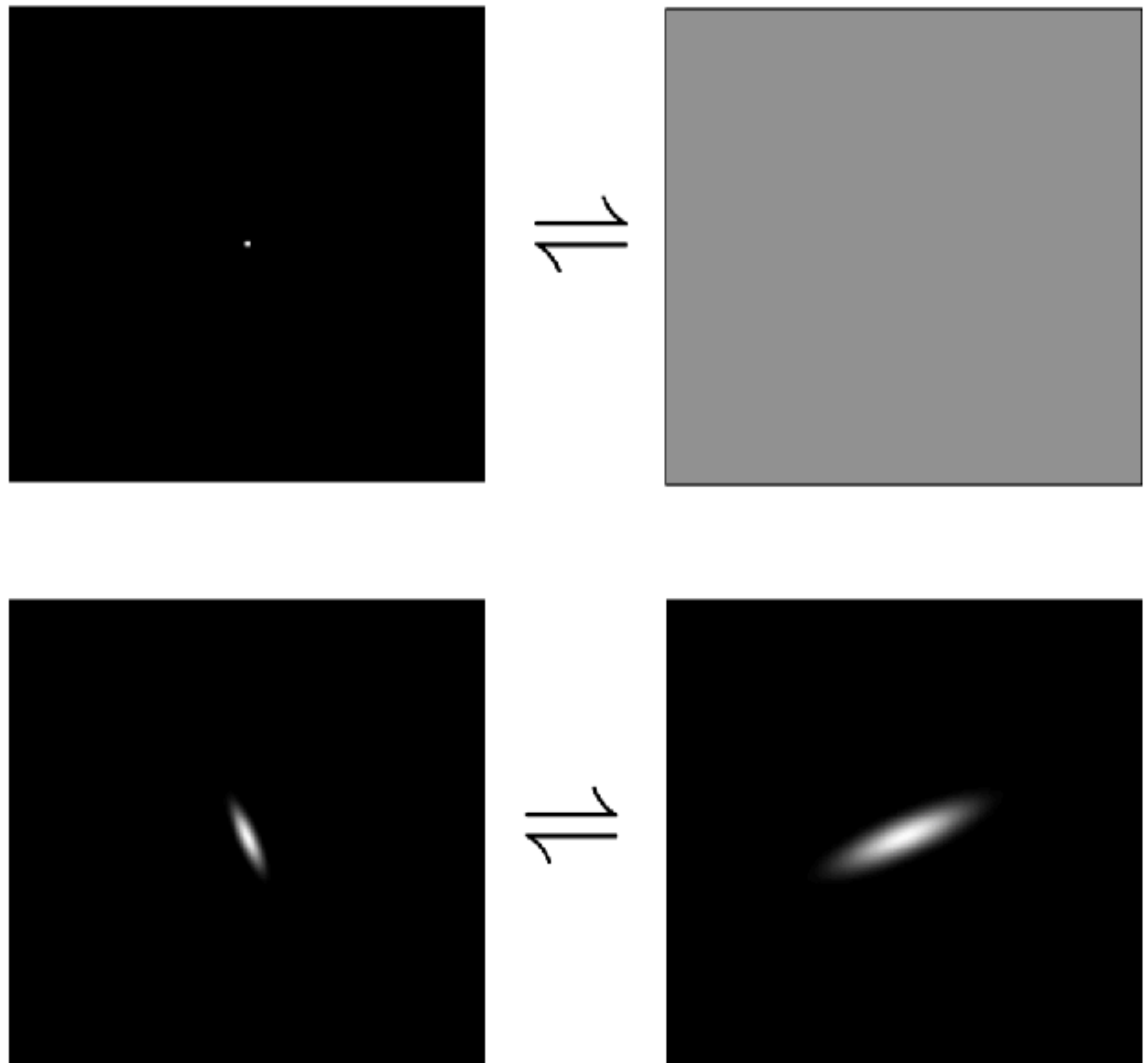
Information contained in amplitude and phase



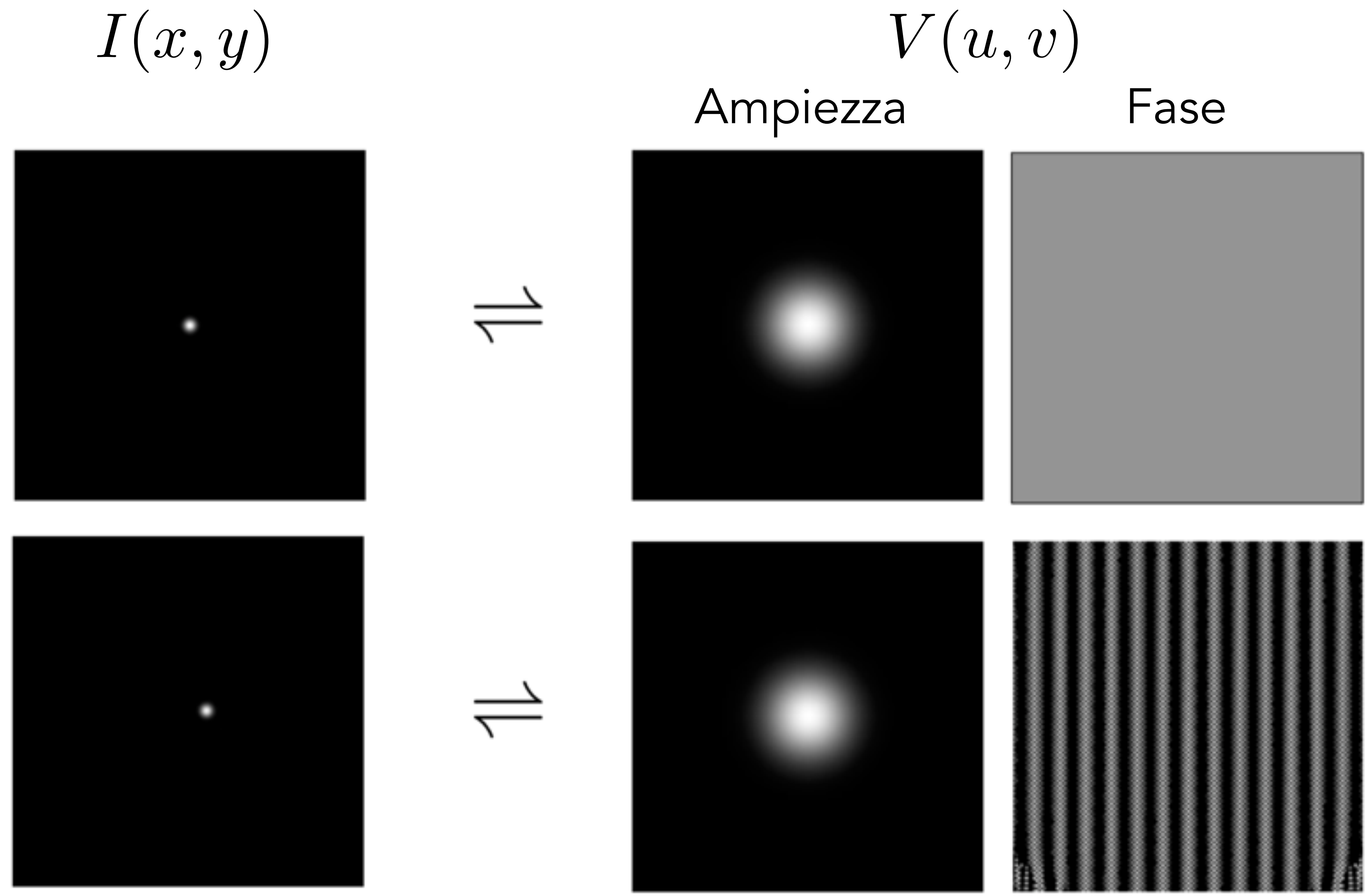
Information contained in amplitude and phase

$I(x, y)$ $\rightleftharpoons$ $A[V(u, v)]$



Information contained in amplitude and phase

The amplitude holds the information on the contribution of different spatial scales, the phase indicates where these spatial scales contribute to



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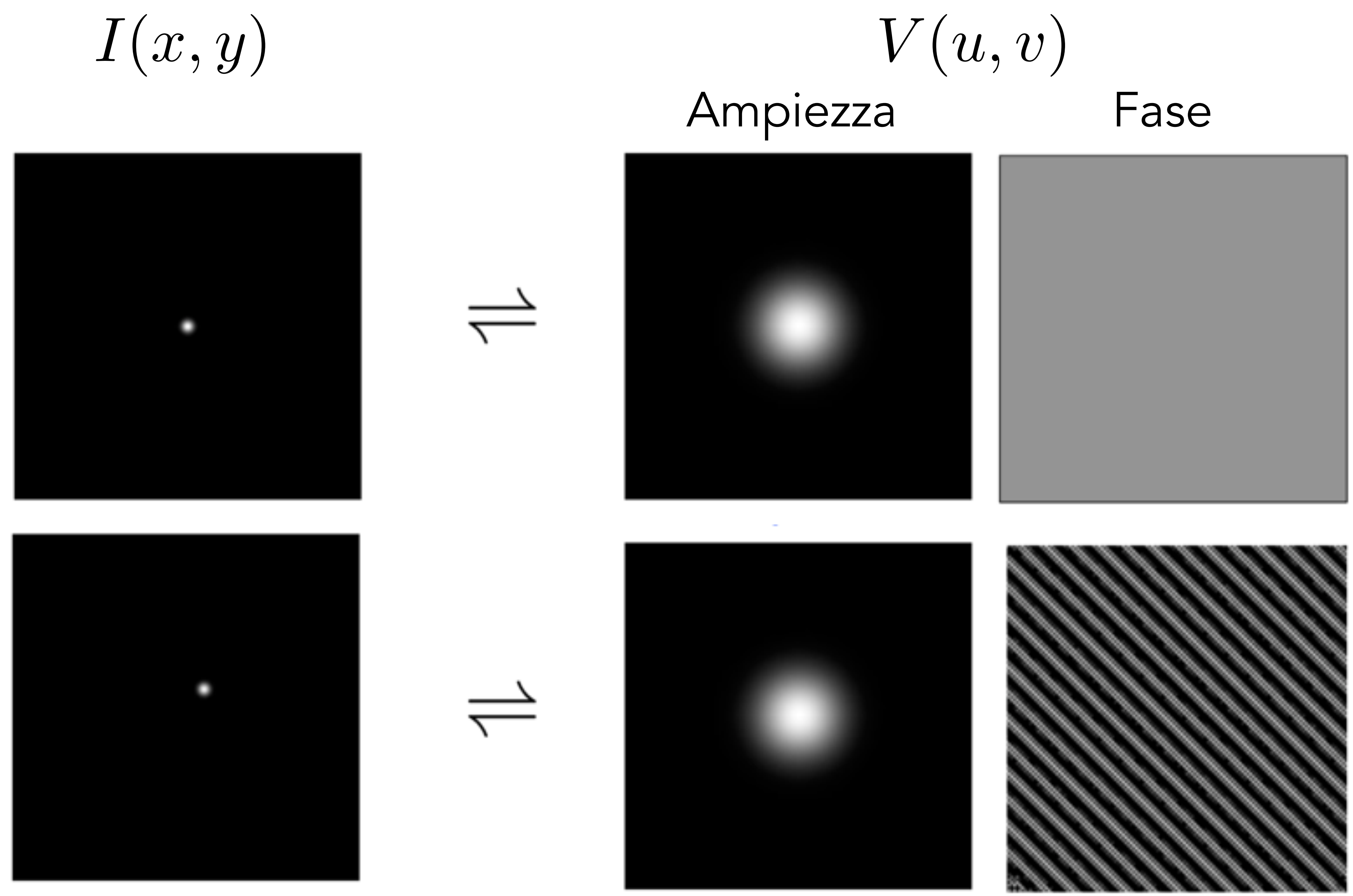


Questions we will try to answer in this (1?) h

How to obtain a V(u,v) as dense as possible?

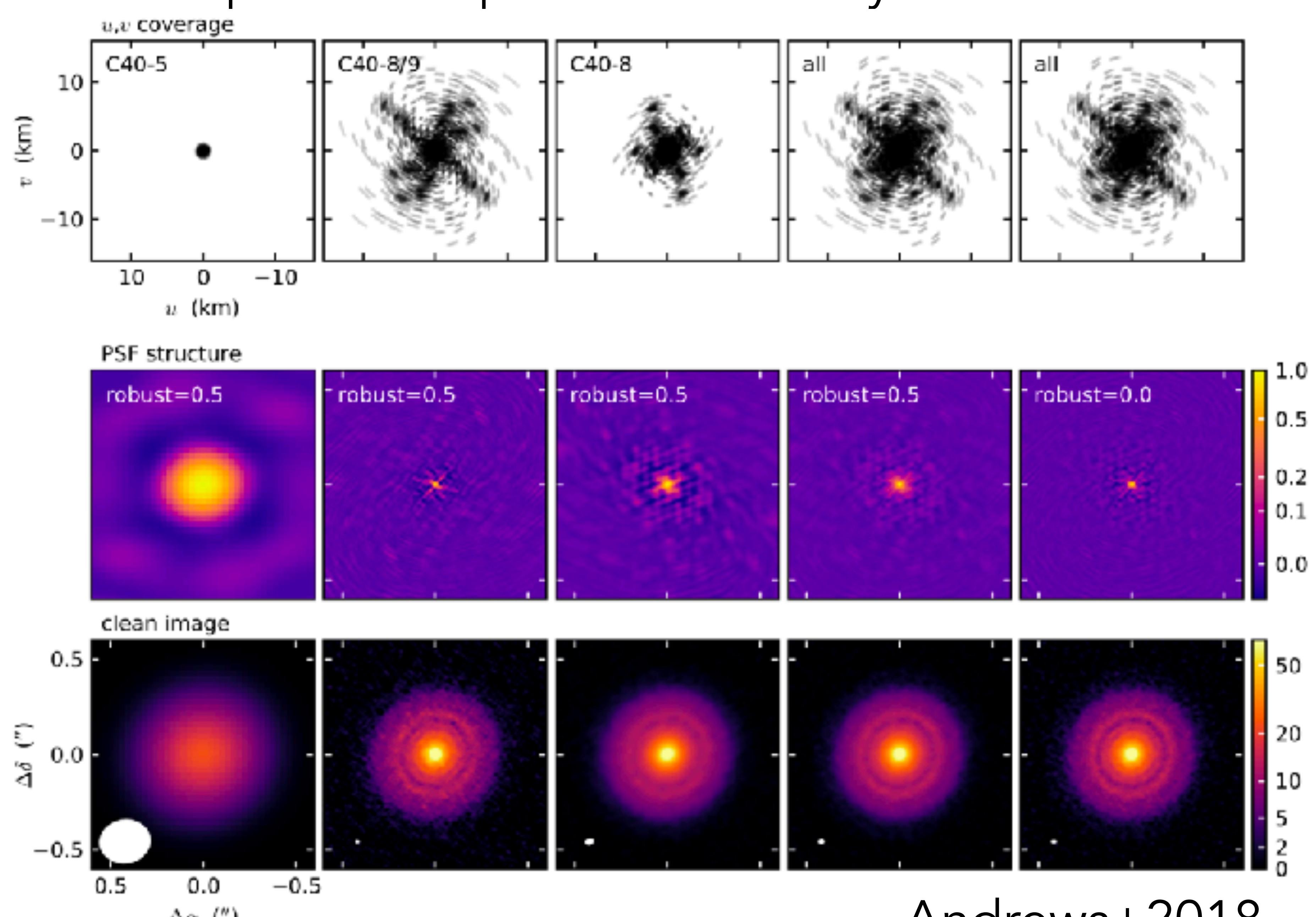
How to calibrate interferometric data (visibilities)?

How to reconstruct an image by having V(u,v,) measured in a discrete set of points?

How to maximize the sampling of V(u,v)?

Increase the number of antennas (number of visibilities is N(N-1)/2), where N is the number of antennas. The ALMA 12-m array has 50, ngVLA will have 244.

Use more configurations by moving antennas to physical pads to sample the uv-plane on as many scales as we can



Andrews+2018

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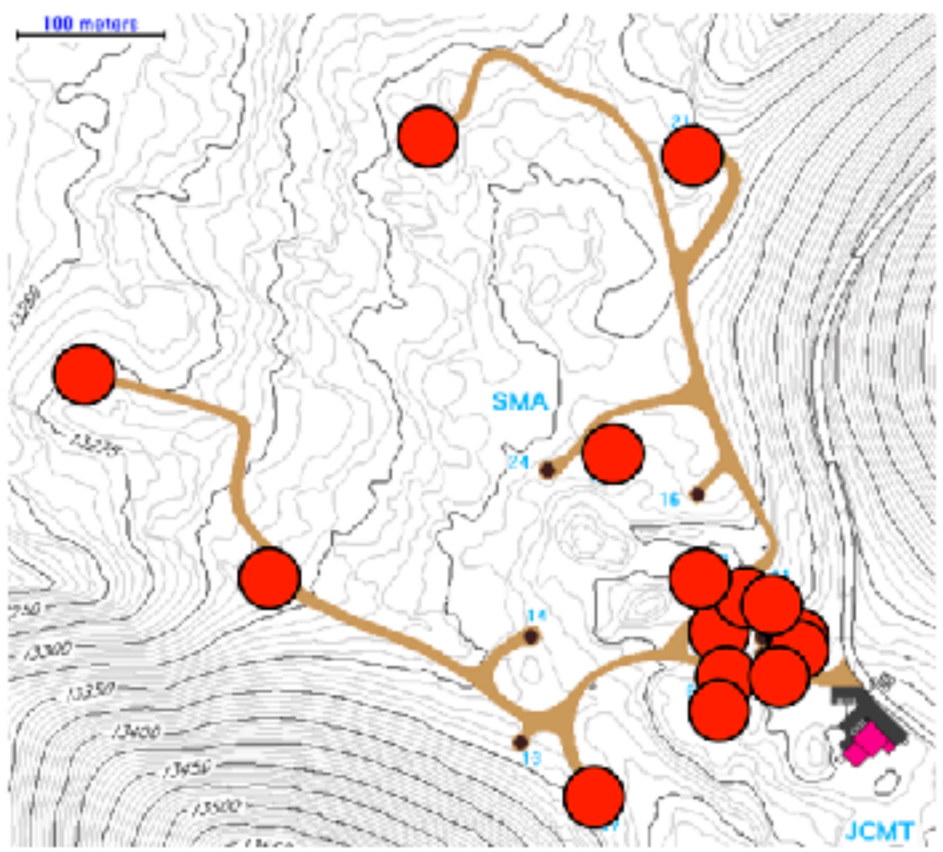
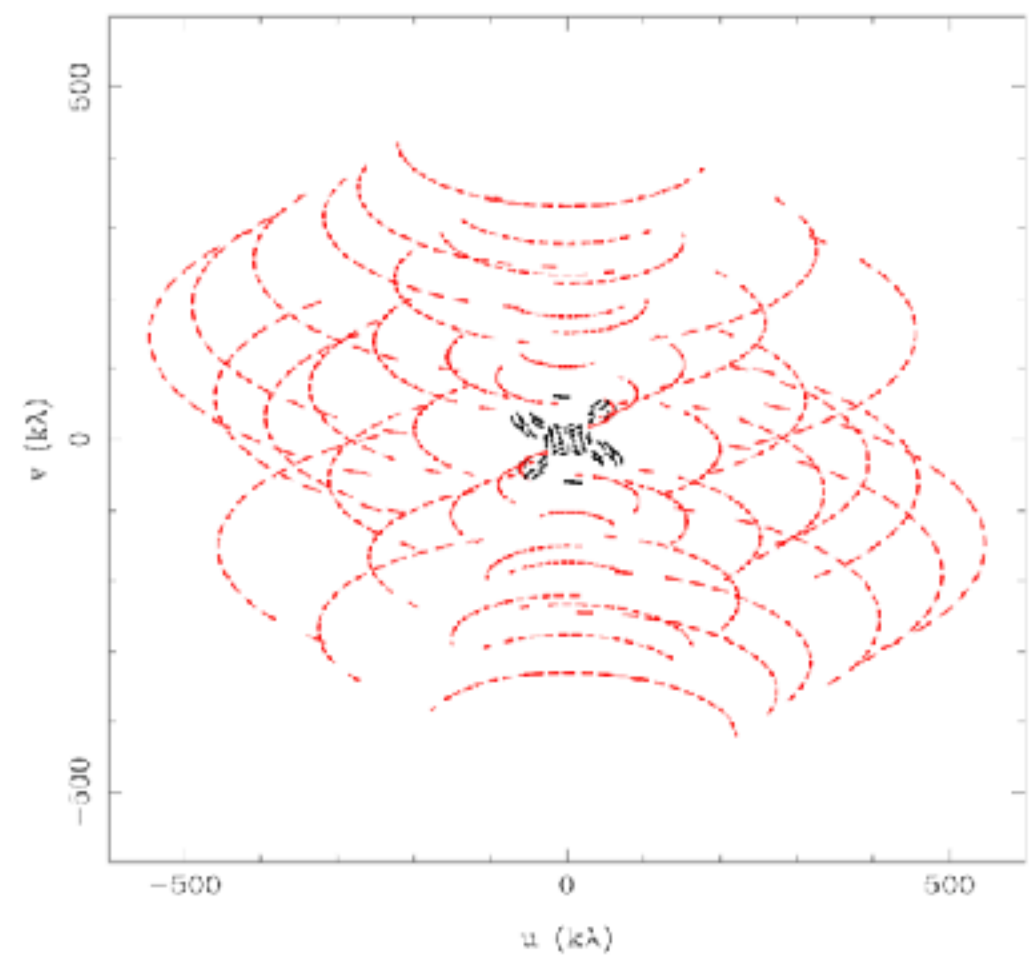
How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines
(Martin Ryle, Nobel prize in Physics in 1974)





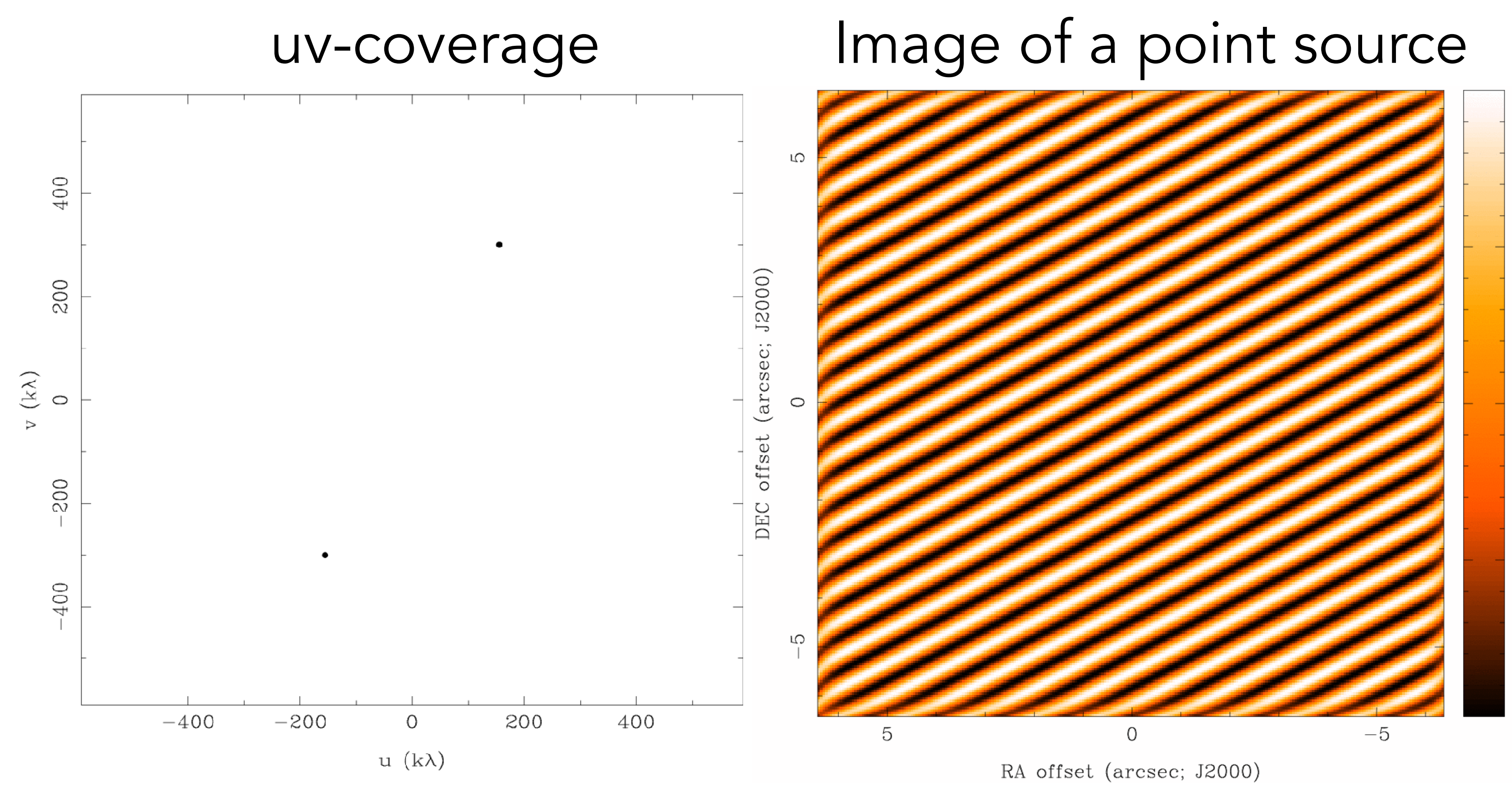
Examples of uv-tracks on SMA with 8 antennas at 345 GHz, Dec = -24 deg

How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

2 antenne



How to maximize the sampling of V(u,v)?

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3 antenne

uv-coverage

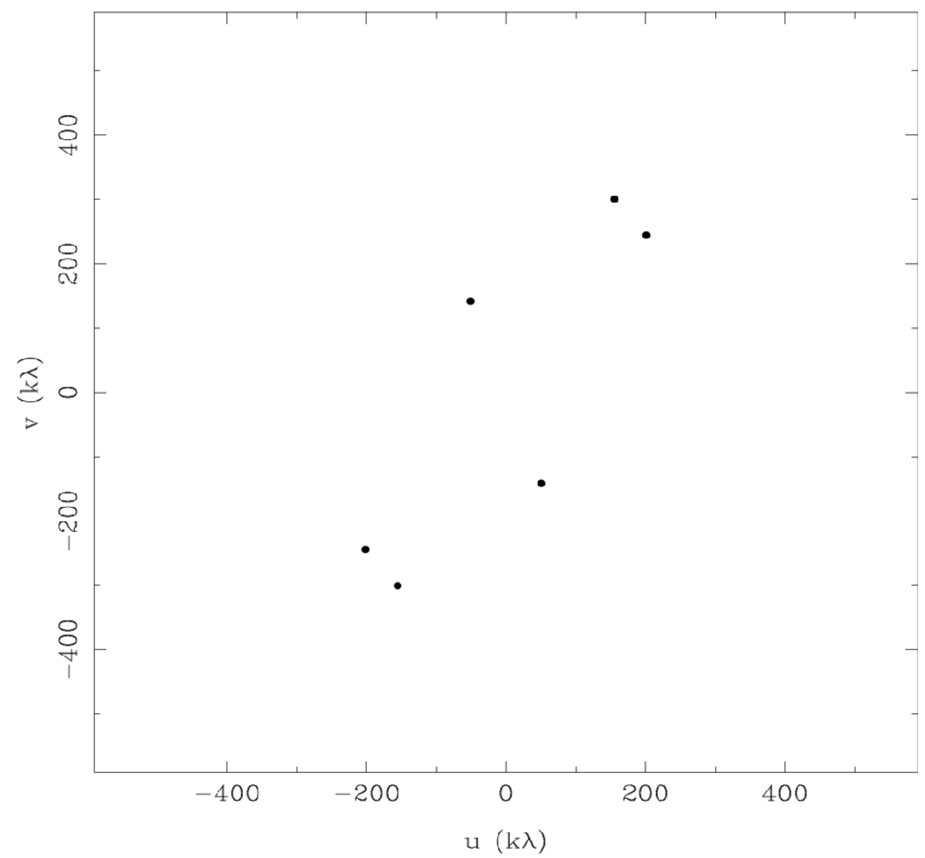
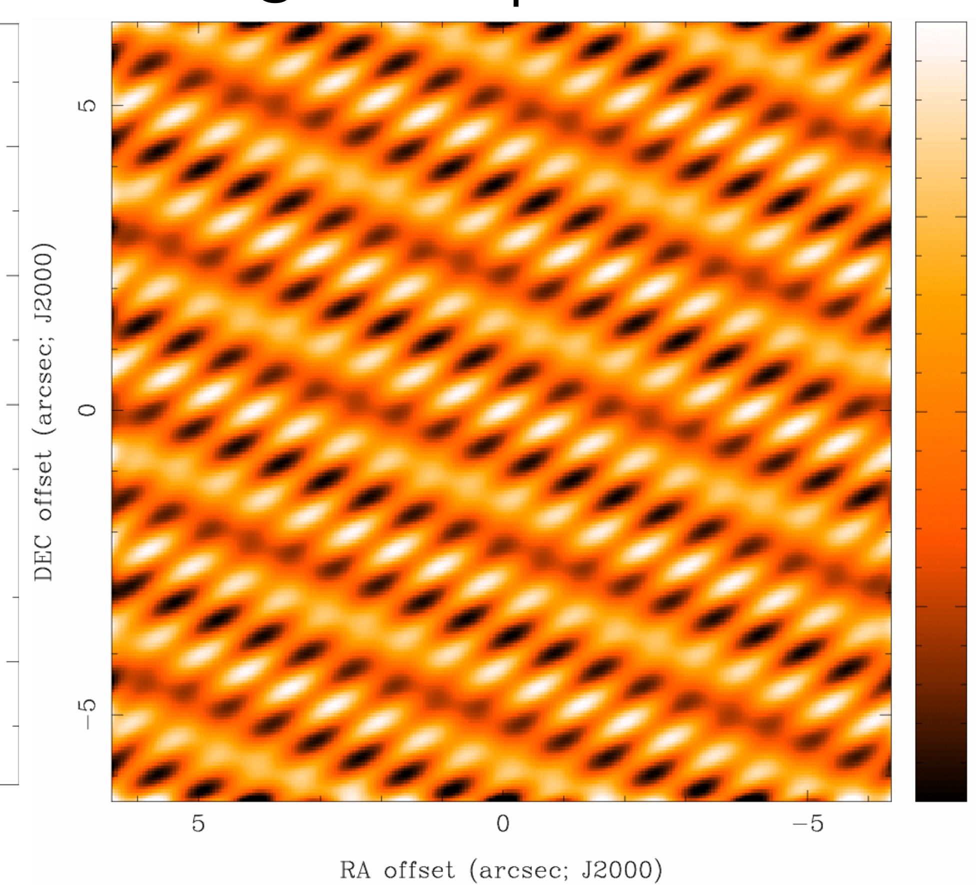


Image of a point source



How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

4 antenne

uv-coverage

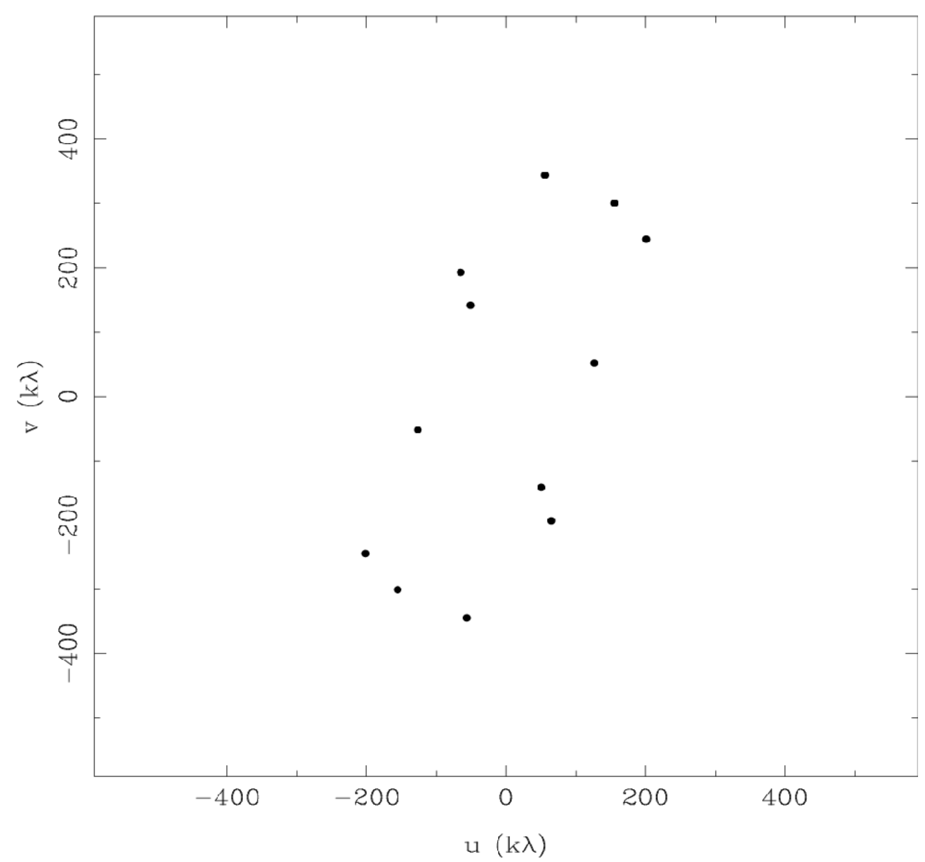
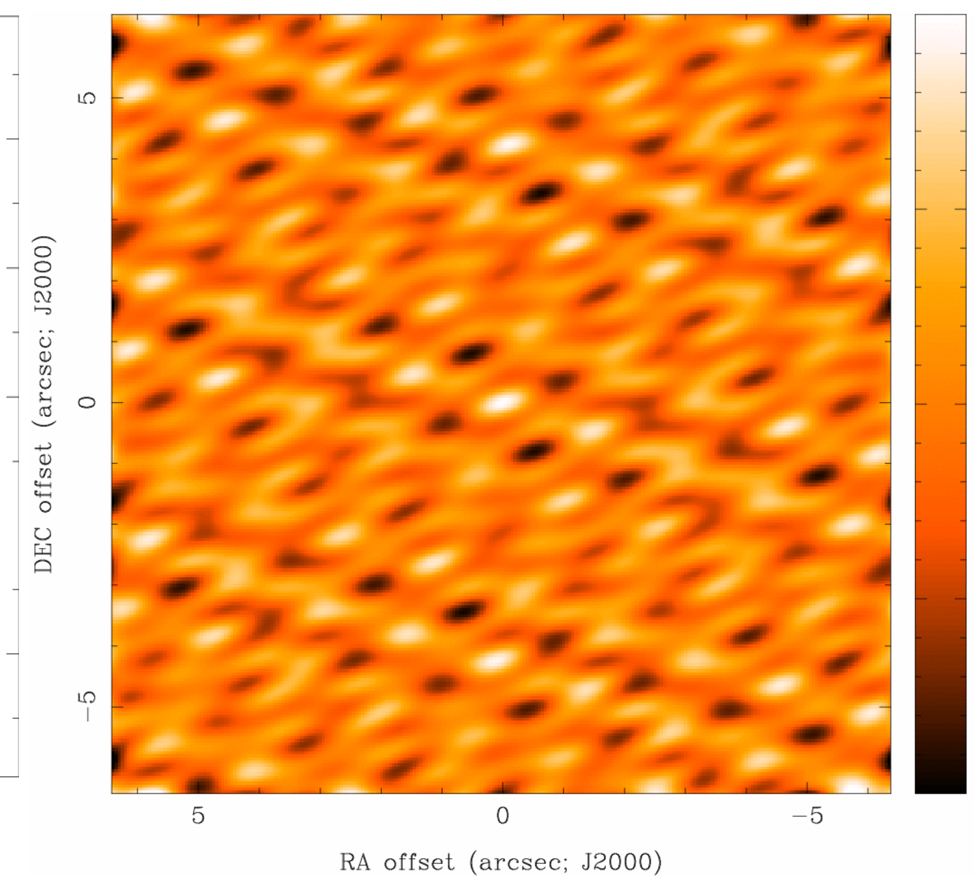


Image of a point source



How to maximize the sampling of V(u,v)?

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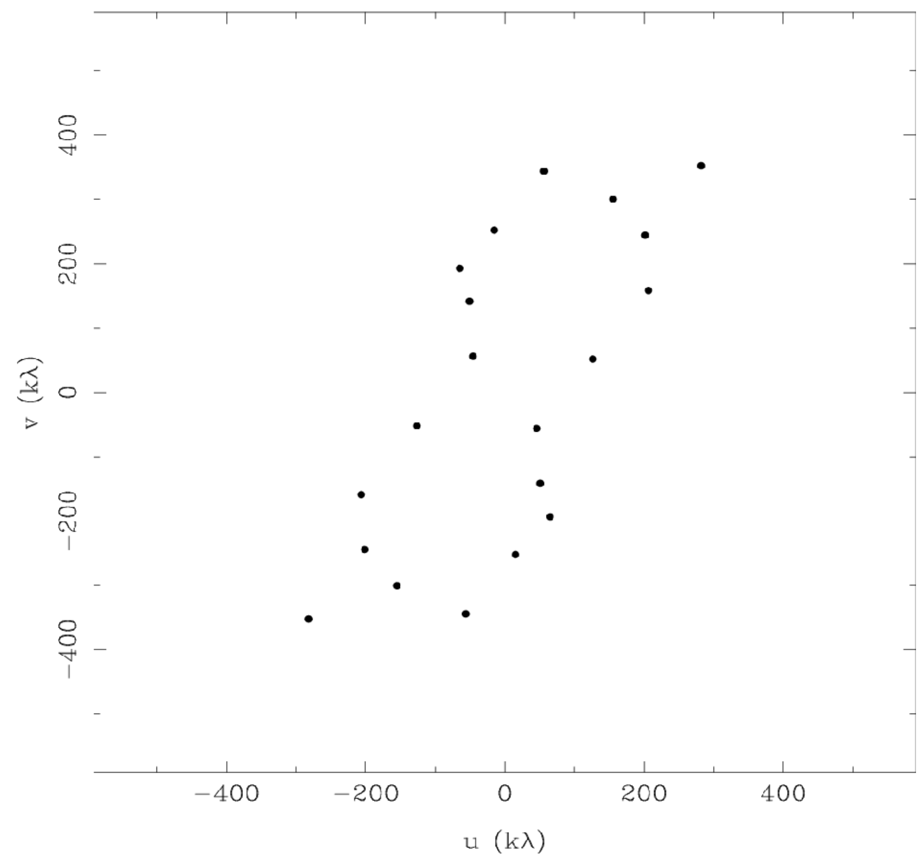
5 antenne

uv-coverage



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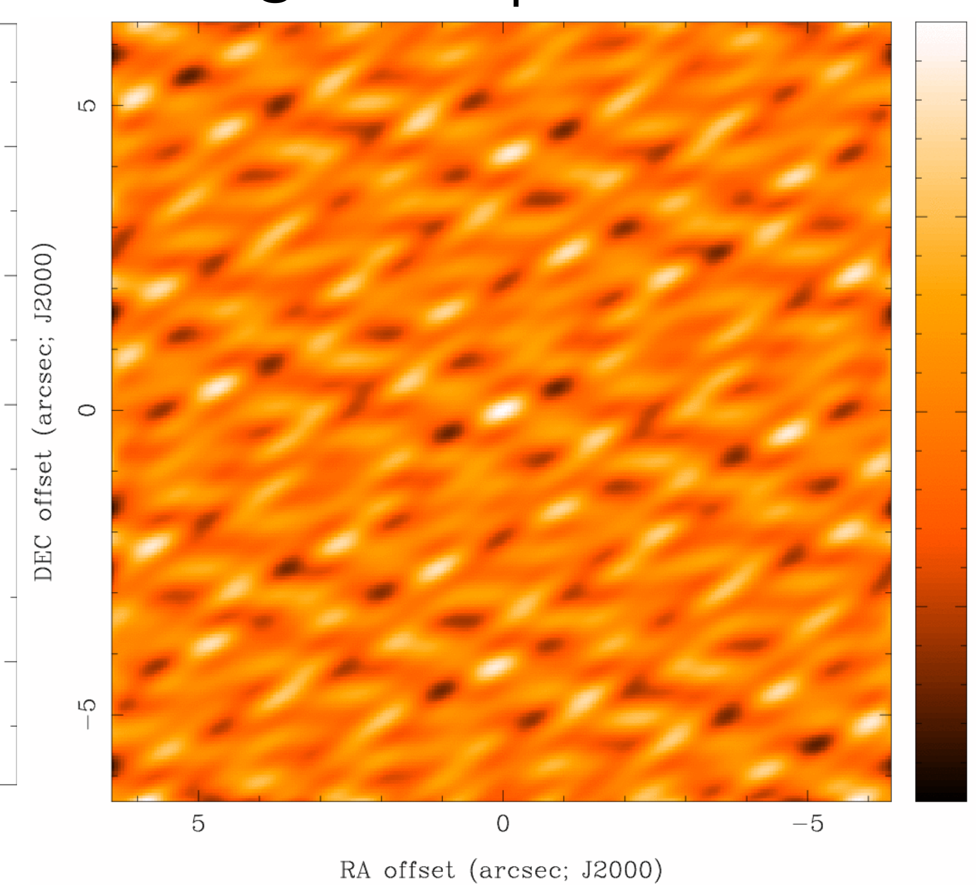

How to maximize the sampling of V(u,v)?

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6 antenne

uv-coverage

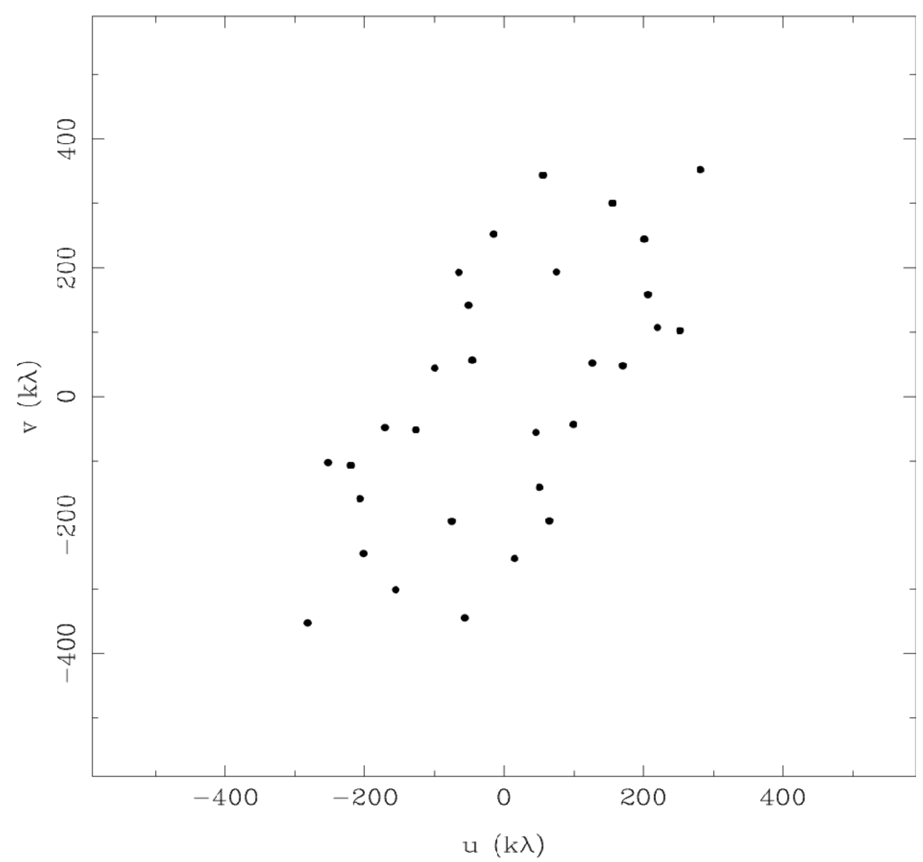
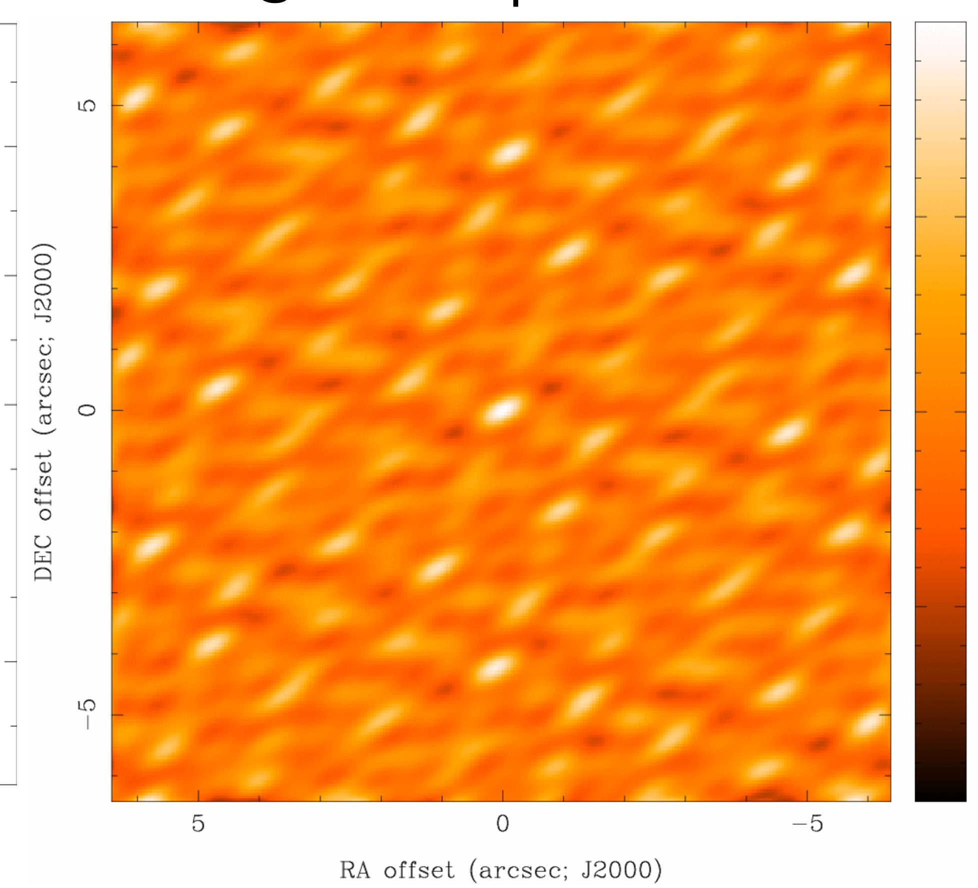


Image of a point source



How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

7 antenne

uv-coverage

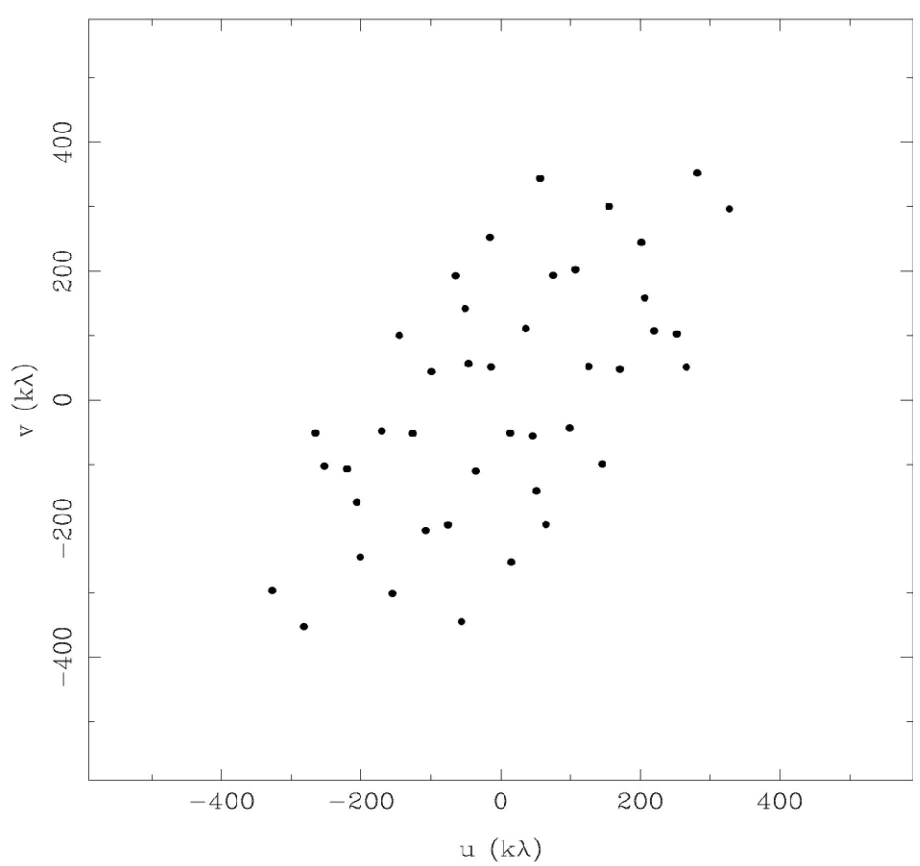
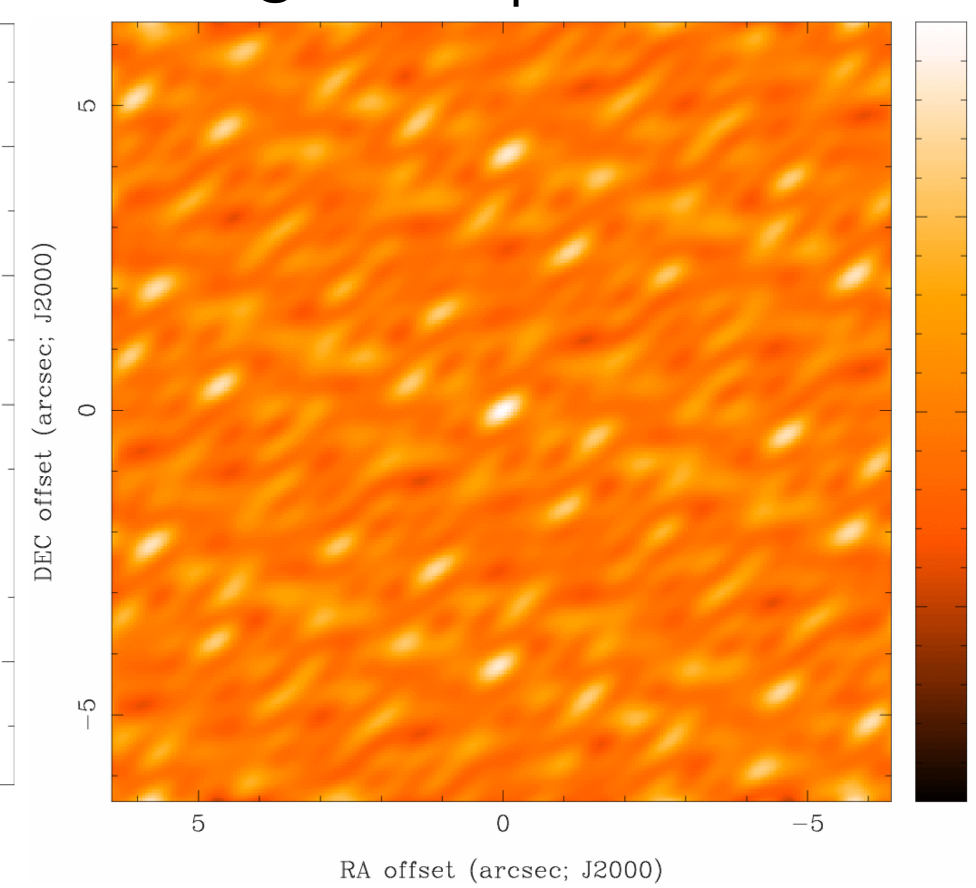


Image of a point source



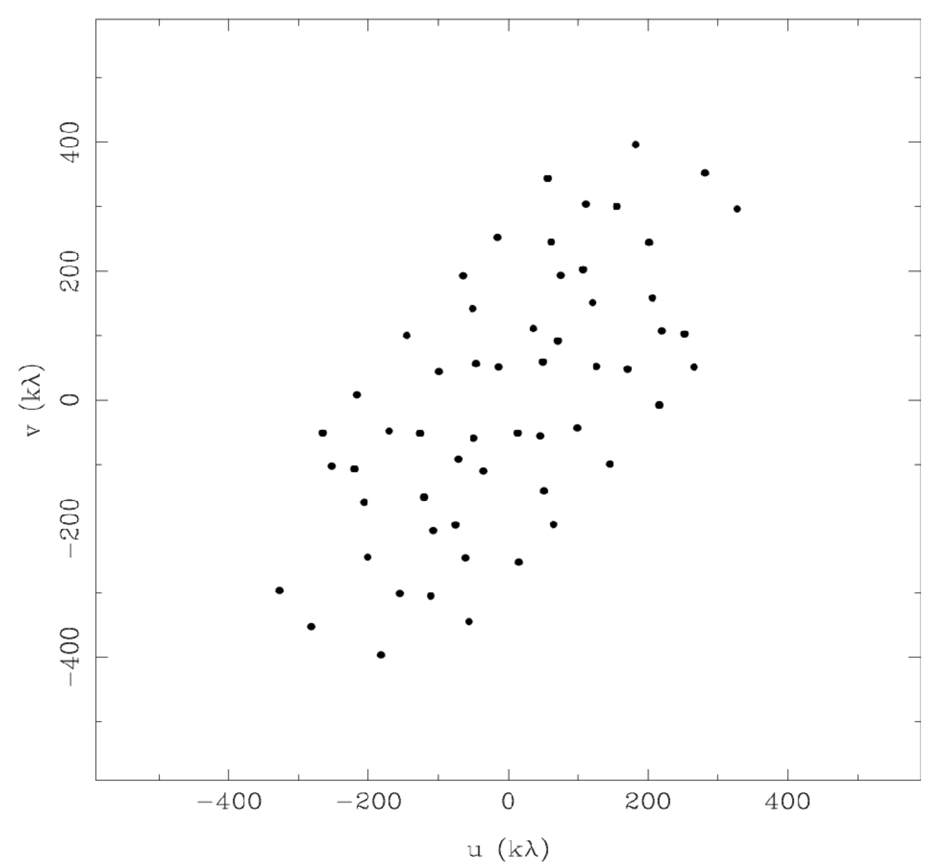
How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

8 antenne

uv-coverage



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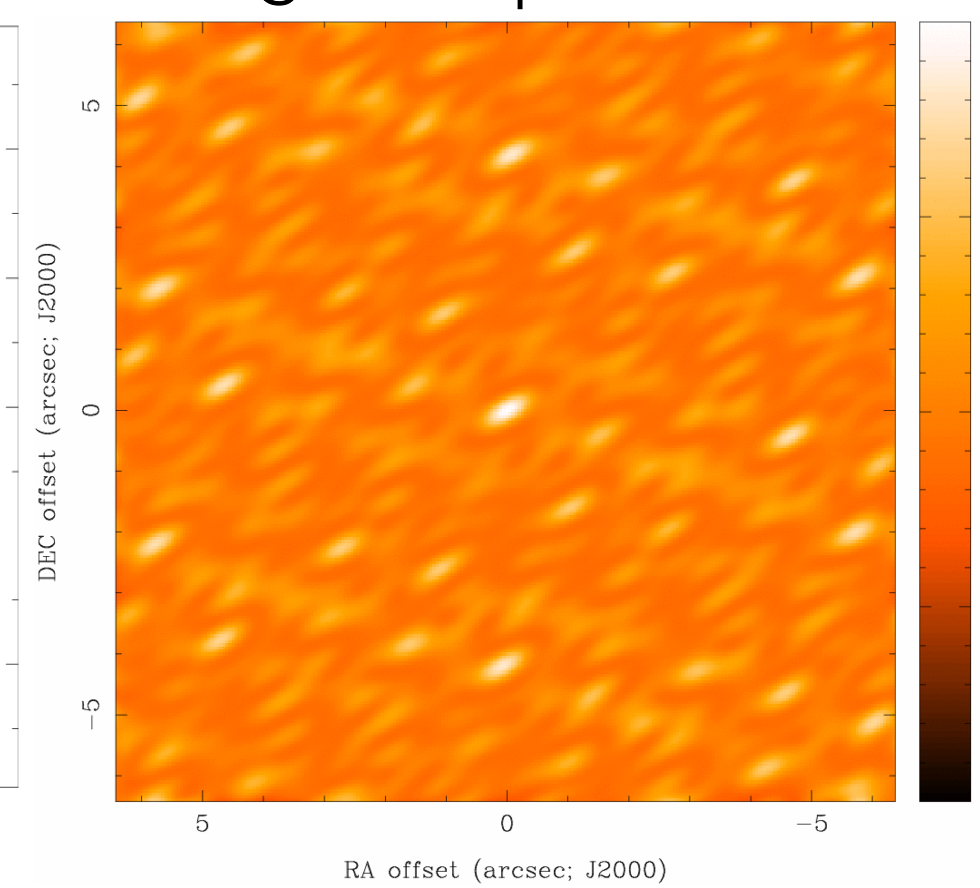


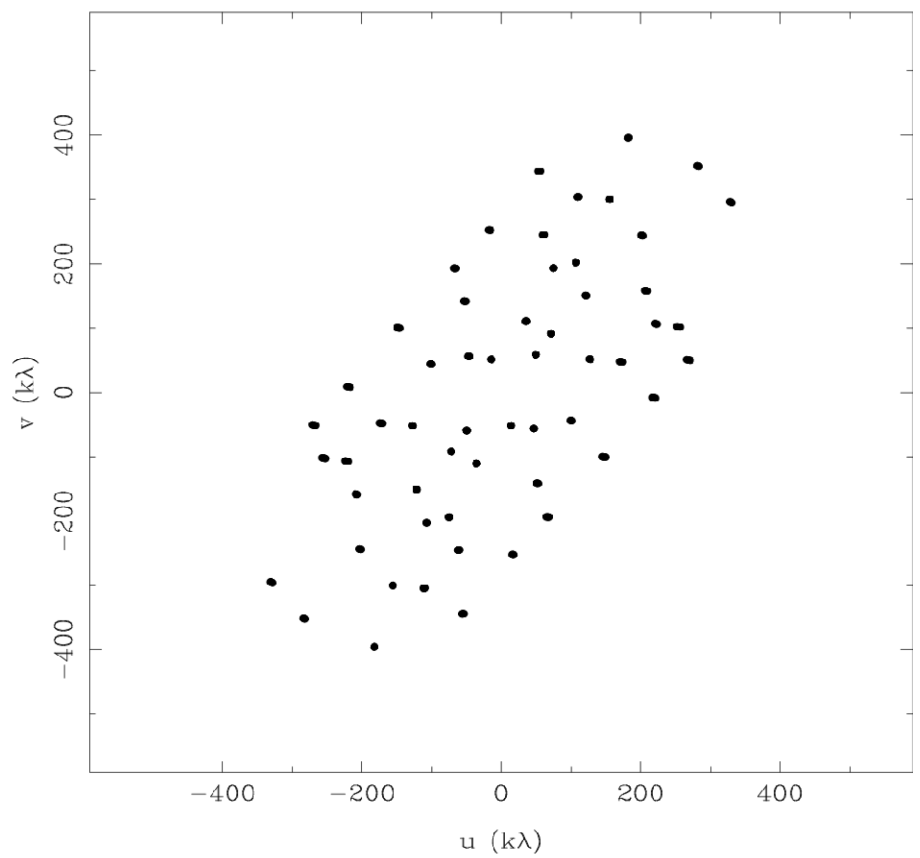
How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

8 antenne
6 samples

uv-coverage



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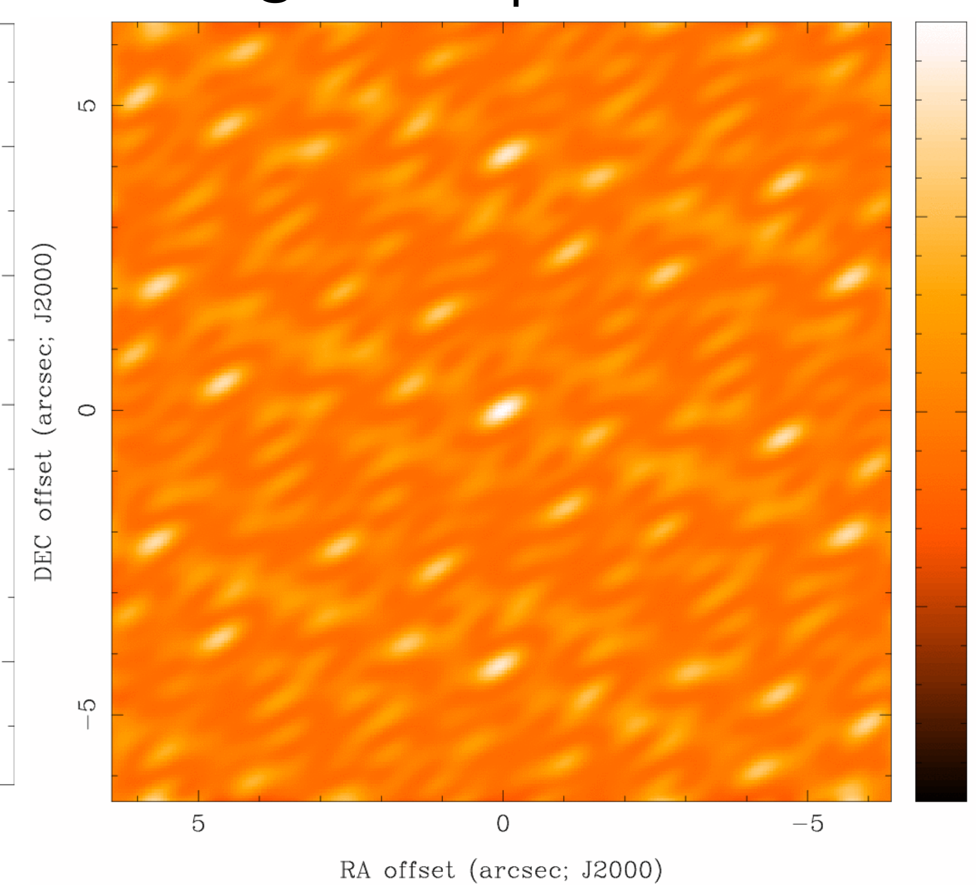


How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

8 antenne
30 samples

uv-coverage

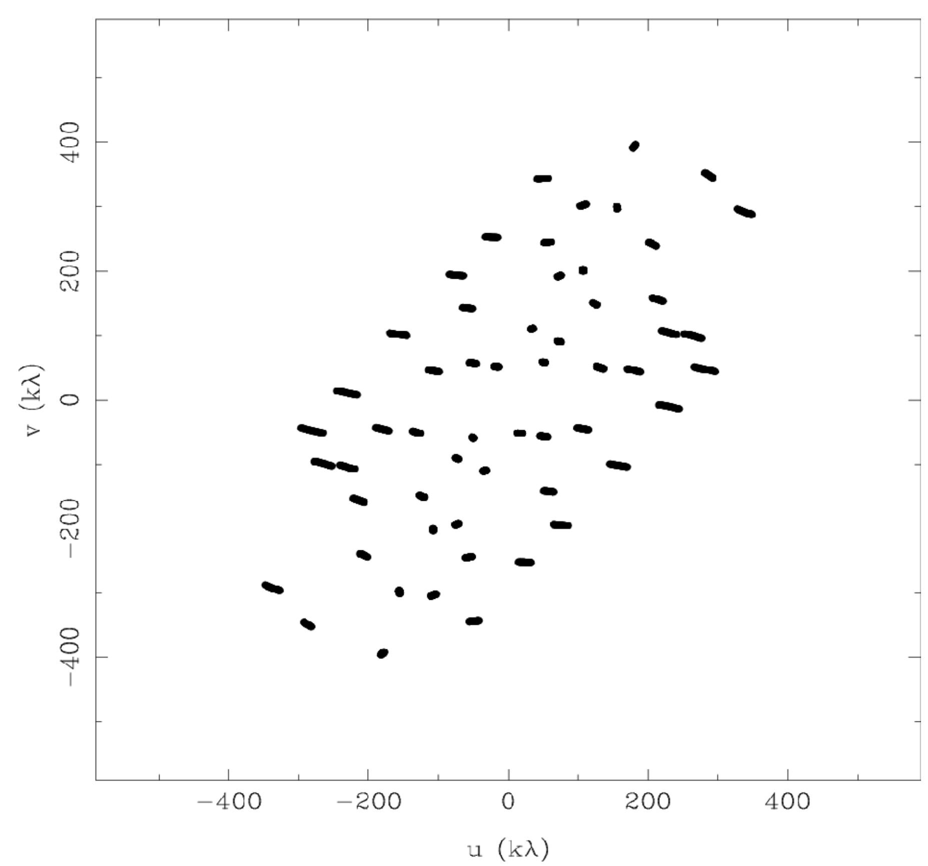
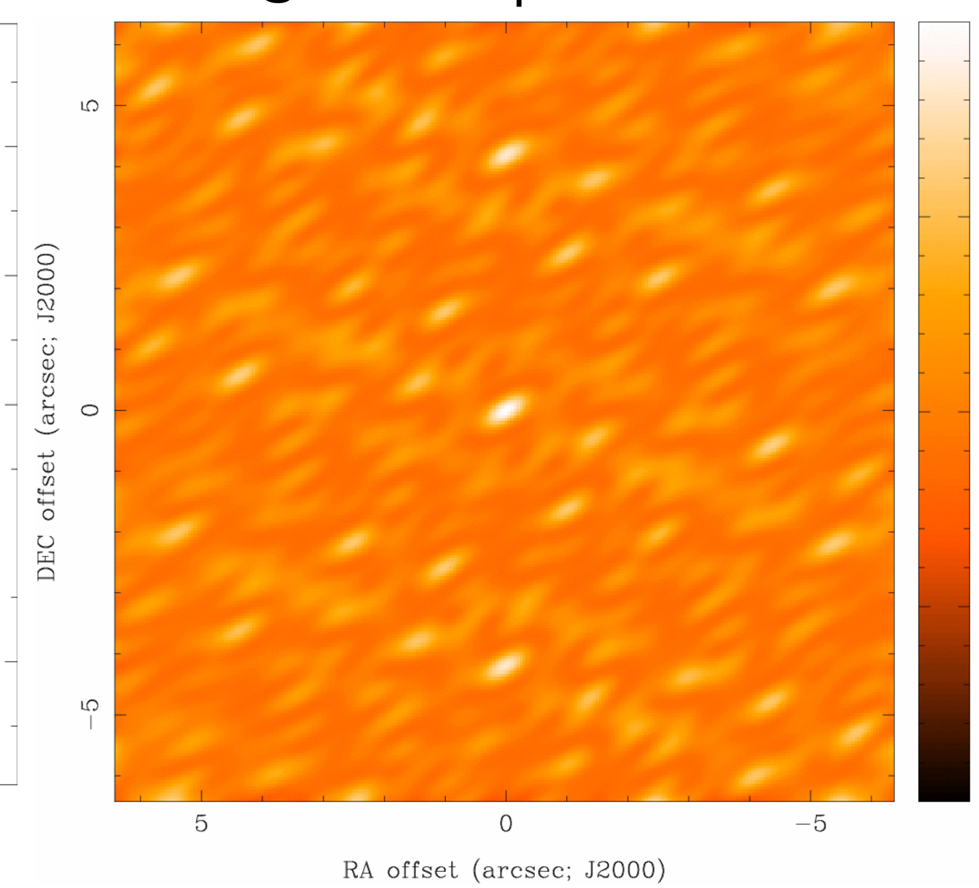


Image of a point source



How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

8 antenne
60 samples

uv-coverage

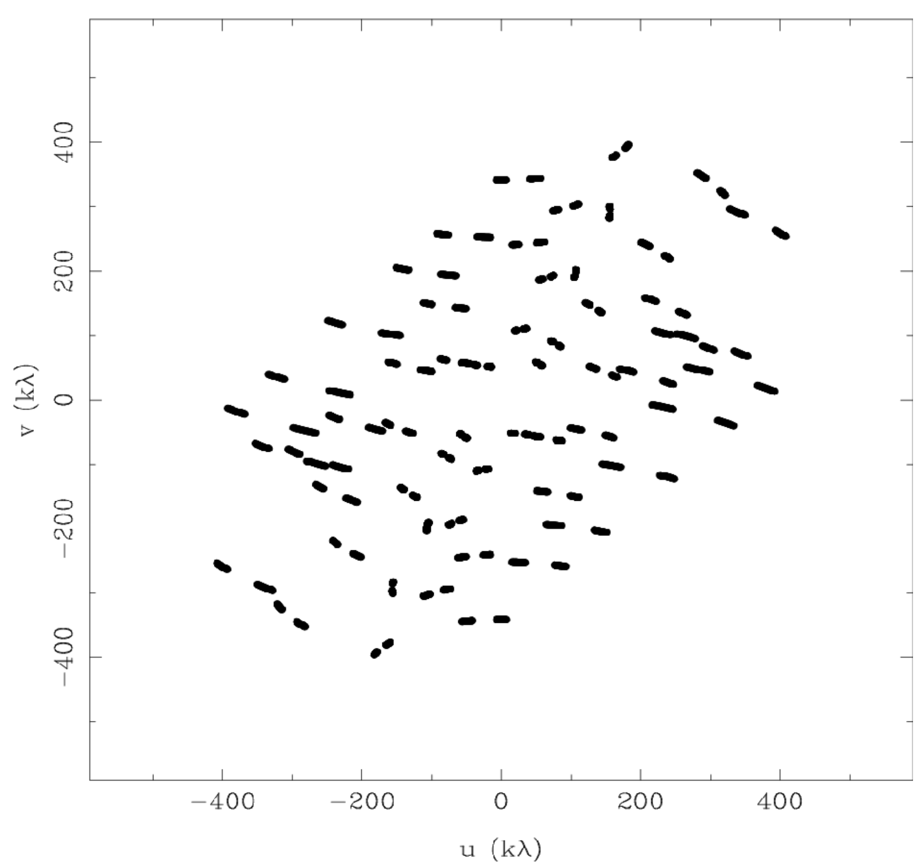
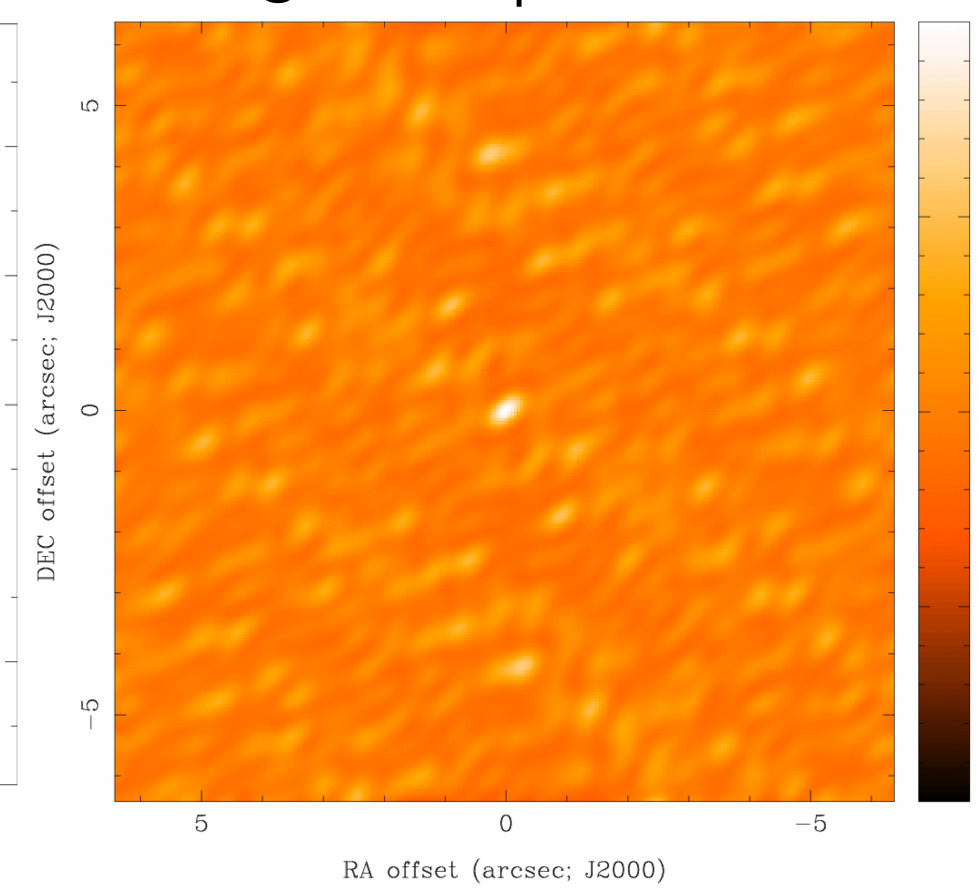


Image of a point source



How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

8 antenne
120 samples

uv-coverage

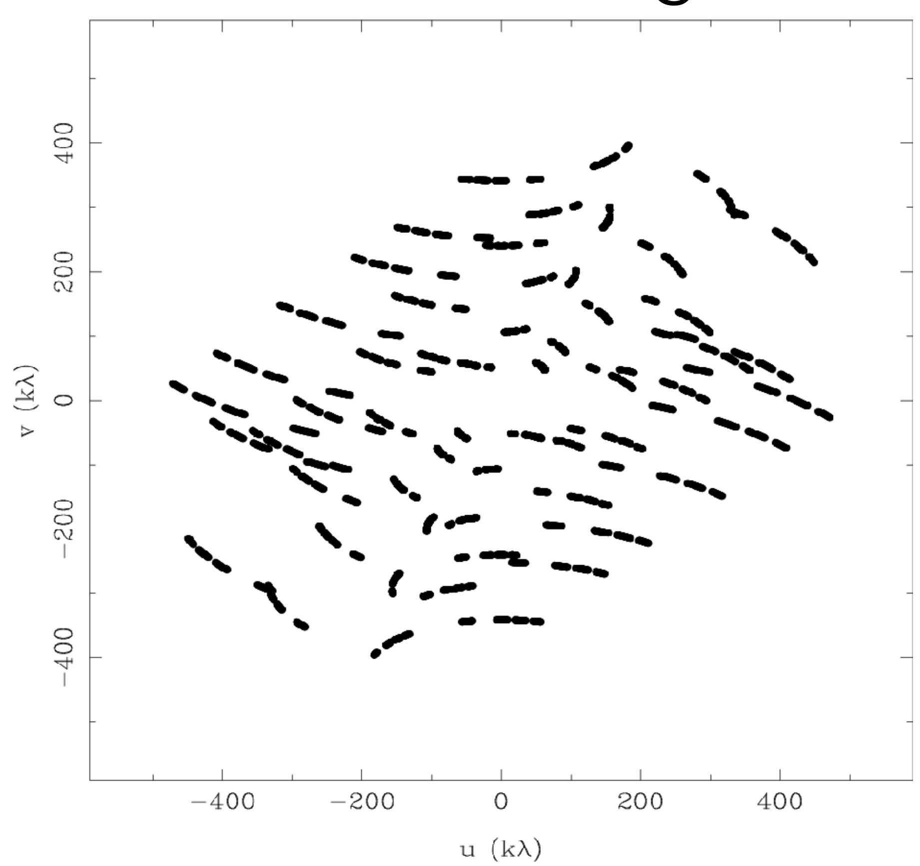
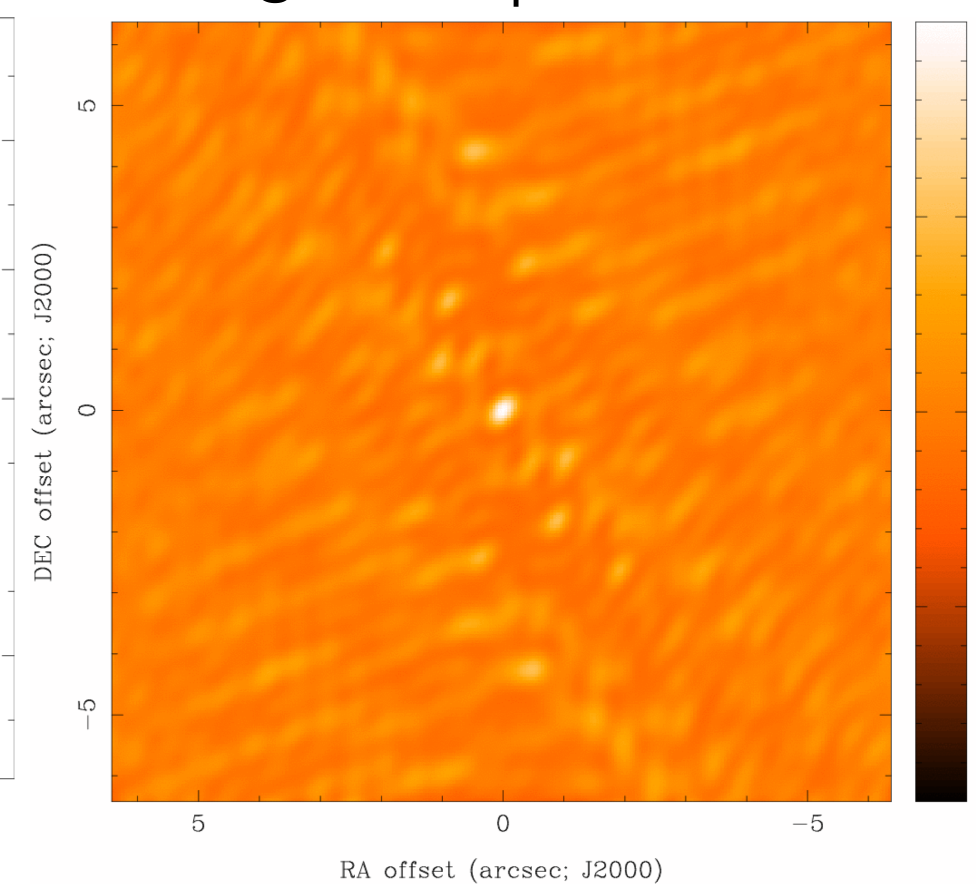


Image of a point source



How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

8 antenne
240 samples

uv-coverage

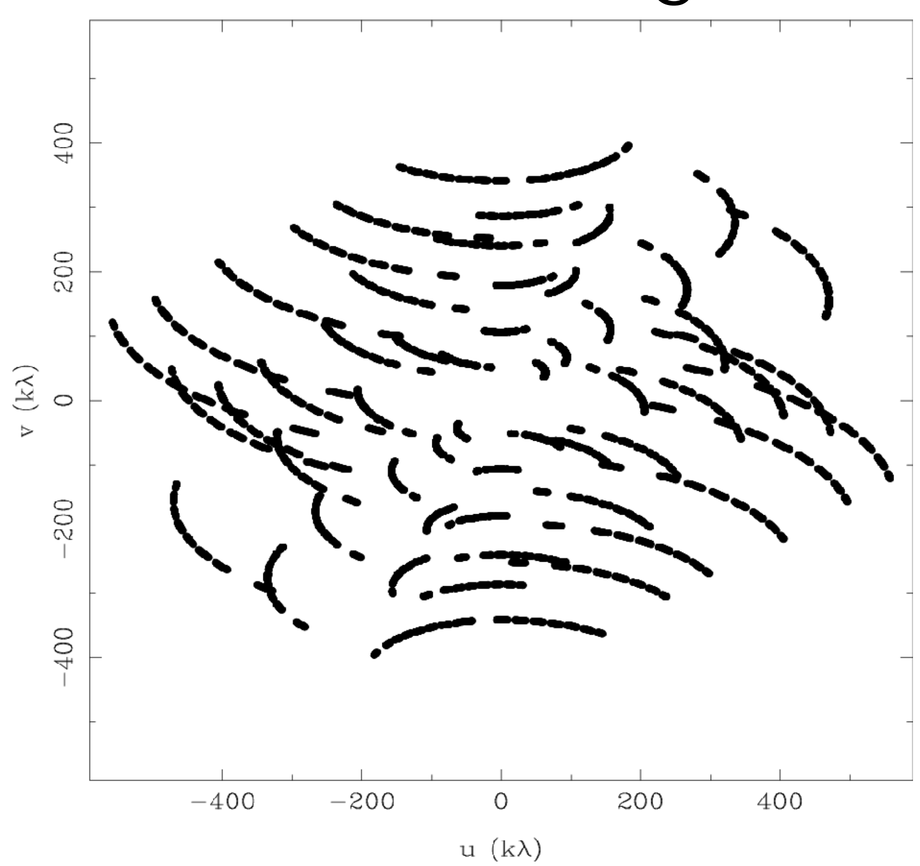
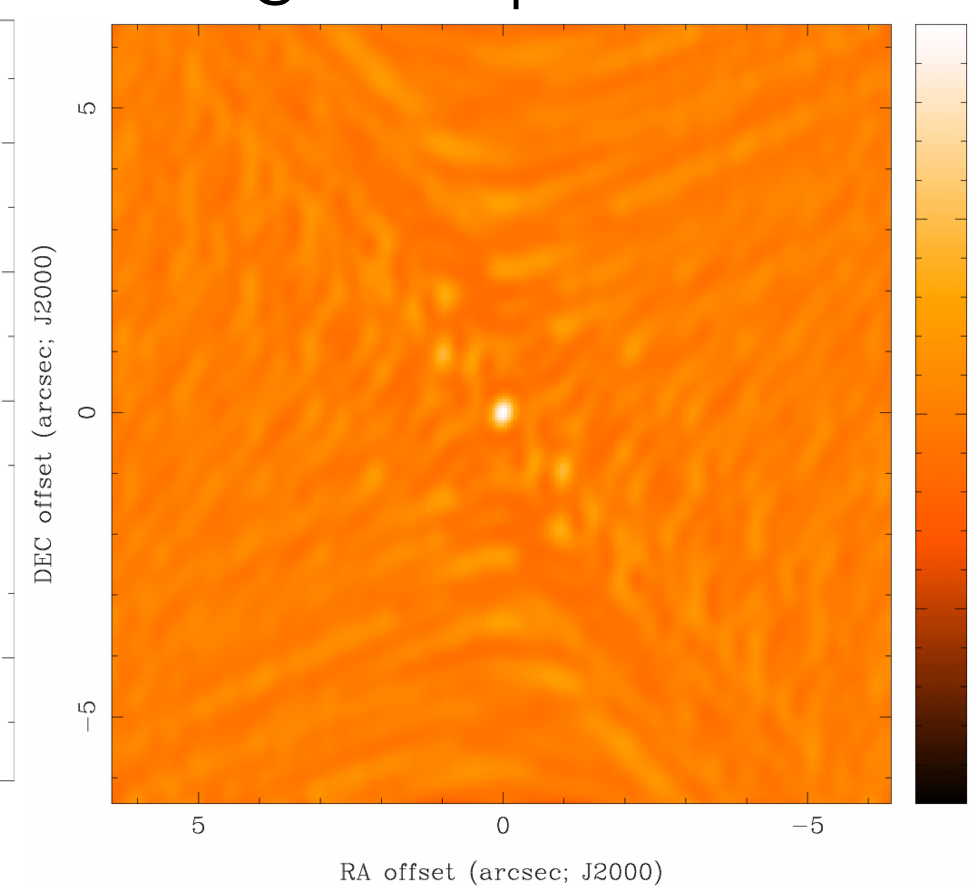


Image of a point source



How to maximize the sampling of V(u,v)?

Increase the number of antennas

Exploit the Earth rotation to sample different baselines

8 antenne
480 samples

uv-coverage

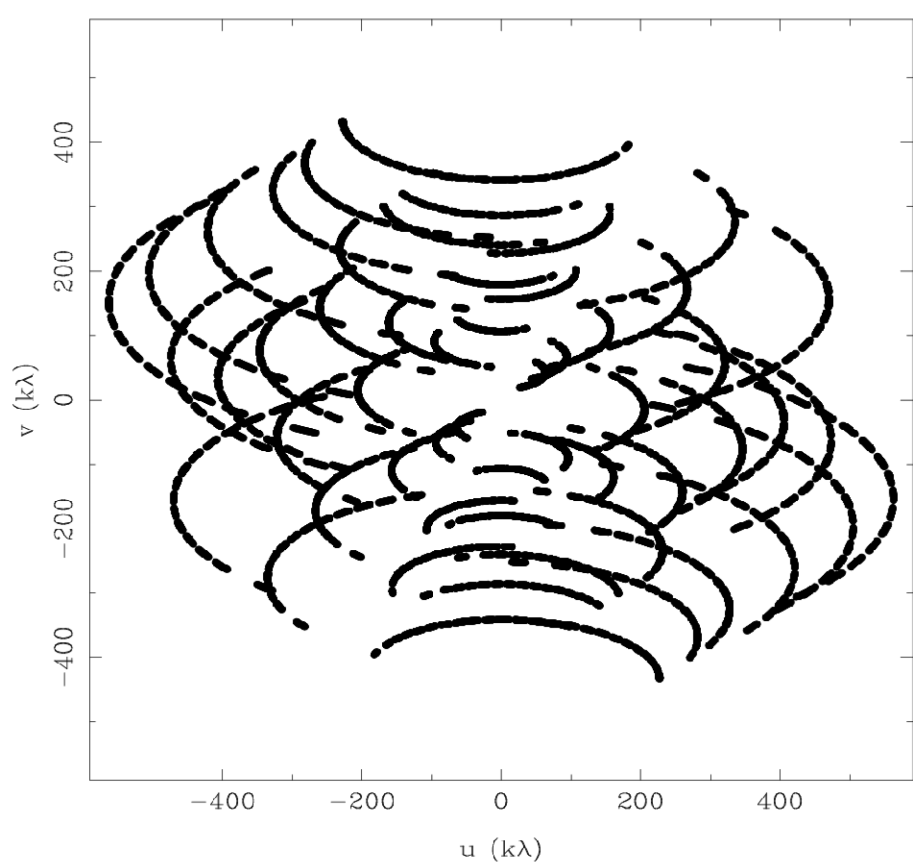
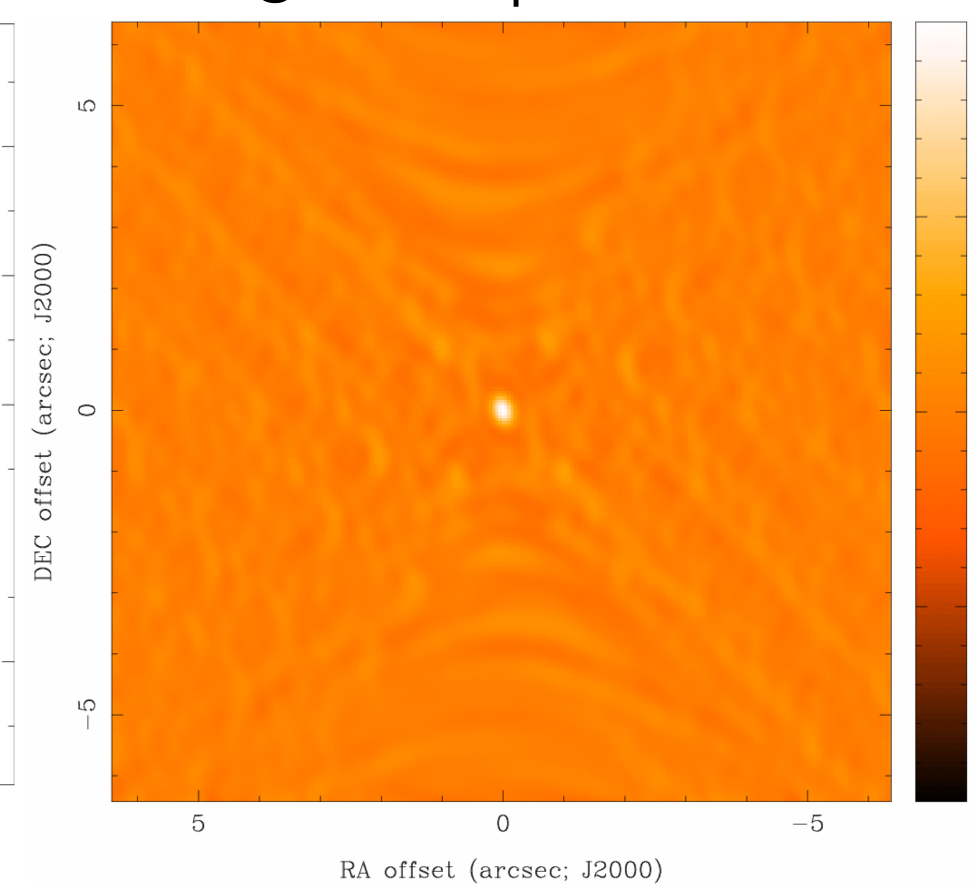
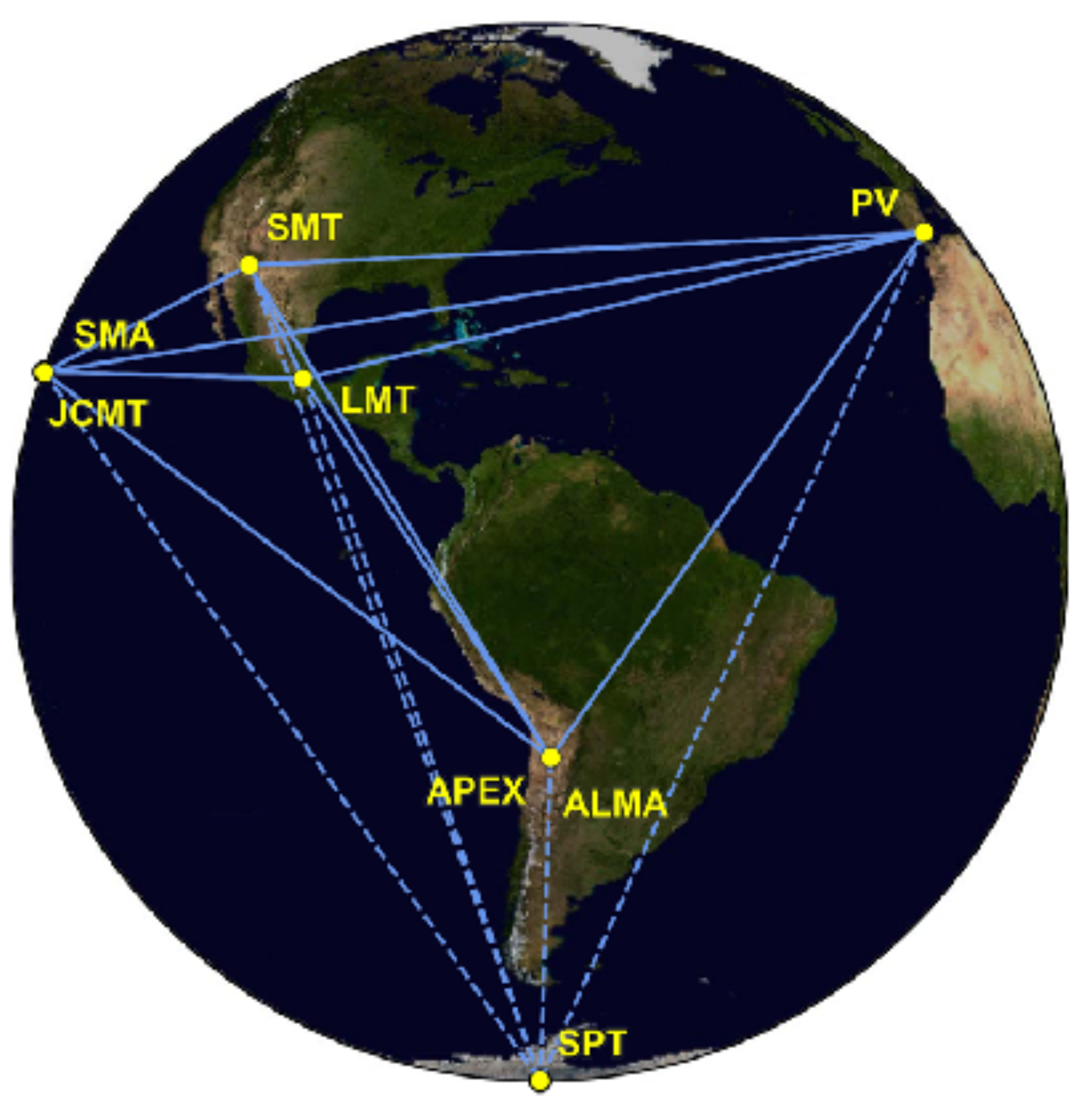


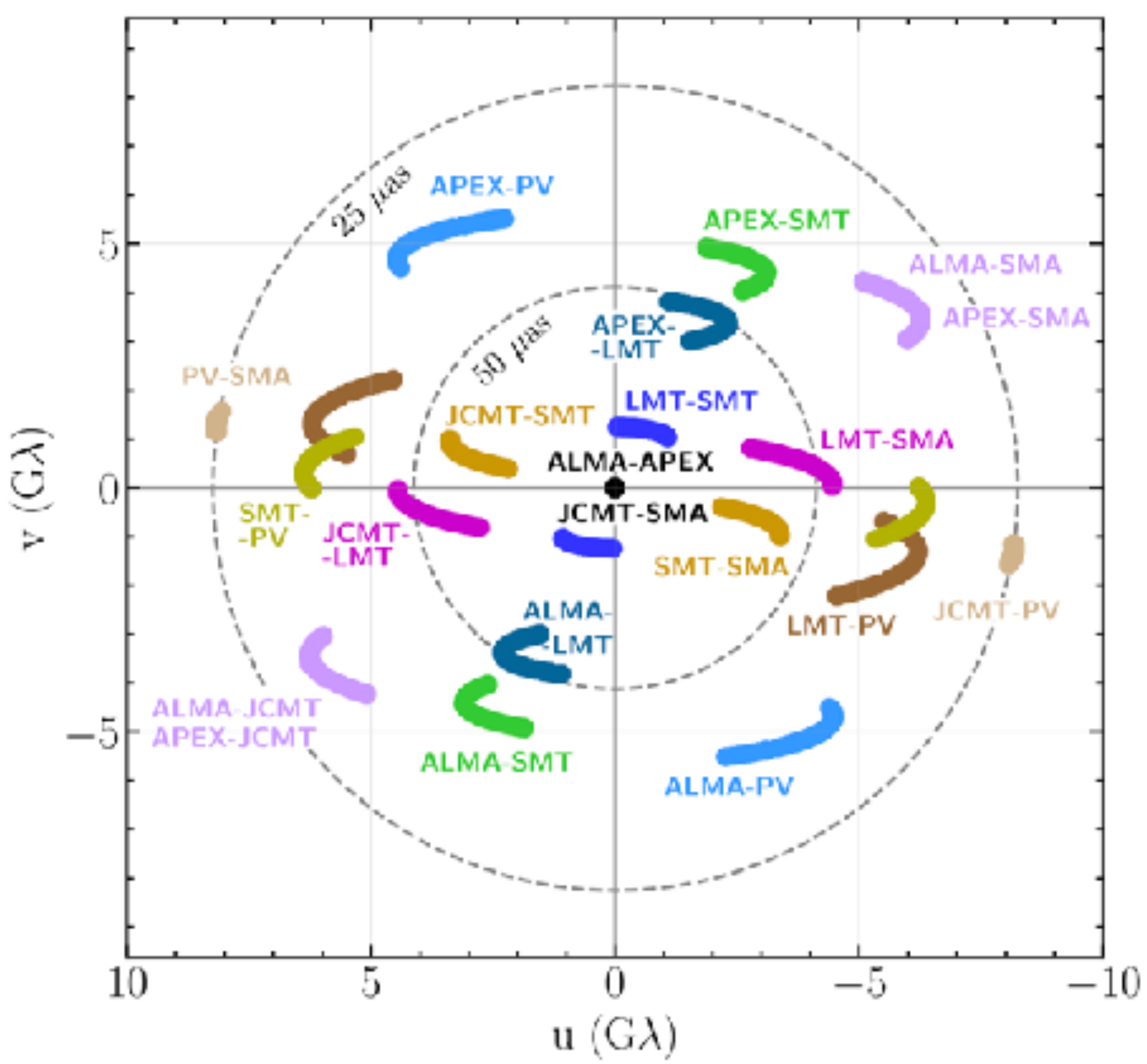
Image of a point source



Geographical constraints can lead to peculiar uv-tracks

uv-coverage of observations of BH in M87 of the Event Horizon Telescope (EHT)





Data calibration (examples from ALMA/VLA)

Fundamental equation of calibration

$$V_{ij}(t) = g_i(t) g_j^*(t) V^{\mathrm{true}}(t) + \epsilon_{ij}(t)$$

$V_{ij}(t)$	visibility measured between antennas i and j
$g_i(t)$	complex gain of antenna i
$V^{true}(t)$	true visibility
$\varepsilon_{ij}(t)$	noise

The linear dependance between Vij(t) and $V^{true}(t)$ depends on the array design. Note that the response associated to any pair of antennas does not depend on any other pair of antennas.
At any time *t*, we thus have N(N-1)/2 measures to obtain $g_i(t)$ for N antennas.

Why do we need to calibrate data?

A priori, we do not know the relation between $V_{ij(}t)$ and $V^{true}(t)$. In interferometry, calibrators are observed every hour, and the calibrations are not shared with other observations (differently from optical/IR telescopes) for the following reasons:

The gain functions depend on the troposphere and ionosphere, and how they affect the wave front. But these have a spatial dependance.

- The ionosphere can offset phase by 1°/s on baselines >10 km
- Electronics can change with time
- Other observations may not be optimized for another observation

Calibrators

The best way to solve the calibration equation is to use calibrators that are very well characterised and table: Best option is point sources that are bright in cm-mm. If they are point sources, the phase will be zero (assuming that the phase center corresponds to the location of the calibrator)

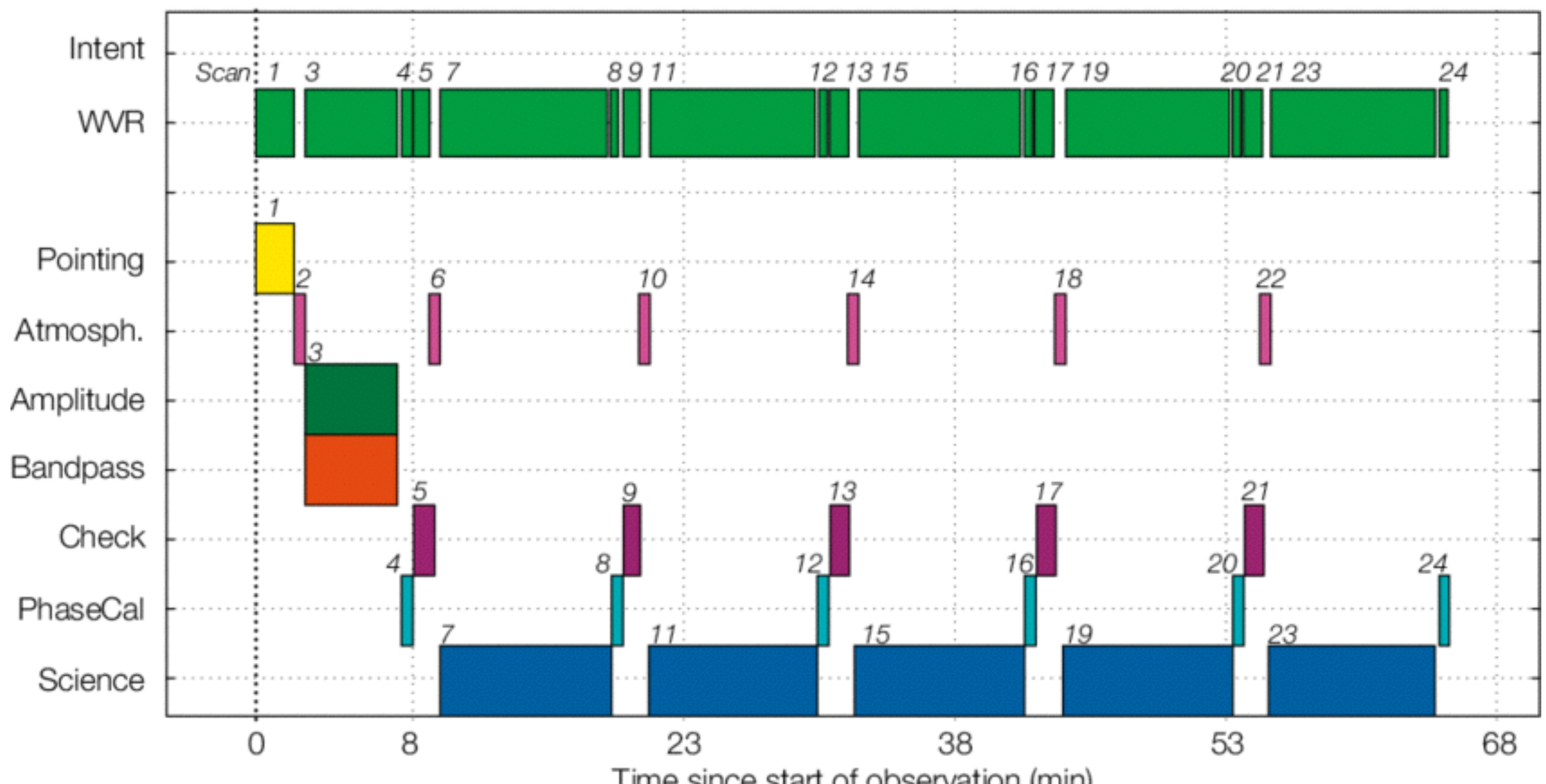
$$V_{ij}(t) = g_i(t)g_j^*(t)V^{\mathrm{true}}(t) + \epsilon_{ij}(t)$$

The gain functions are computed on the calibrators, and are then applied to the scientific observations (cross-calibration)

Example from ALMA data

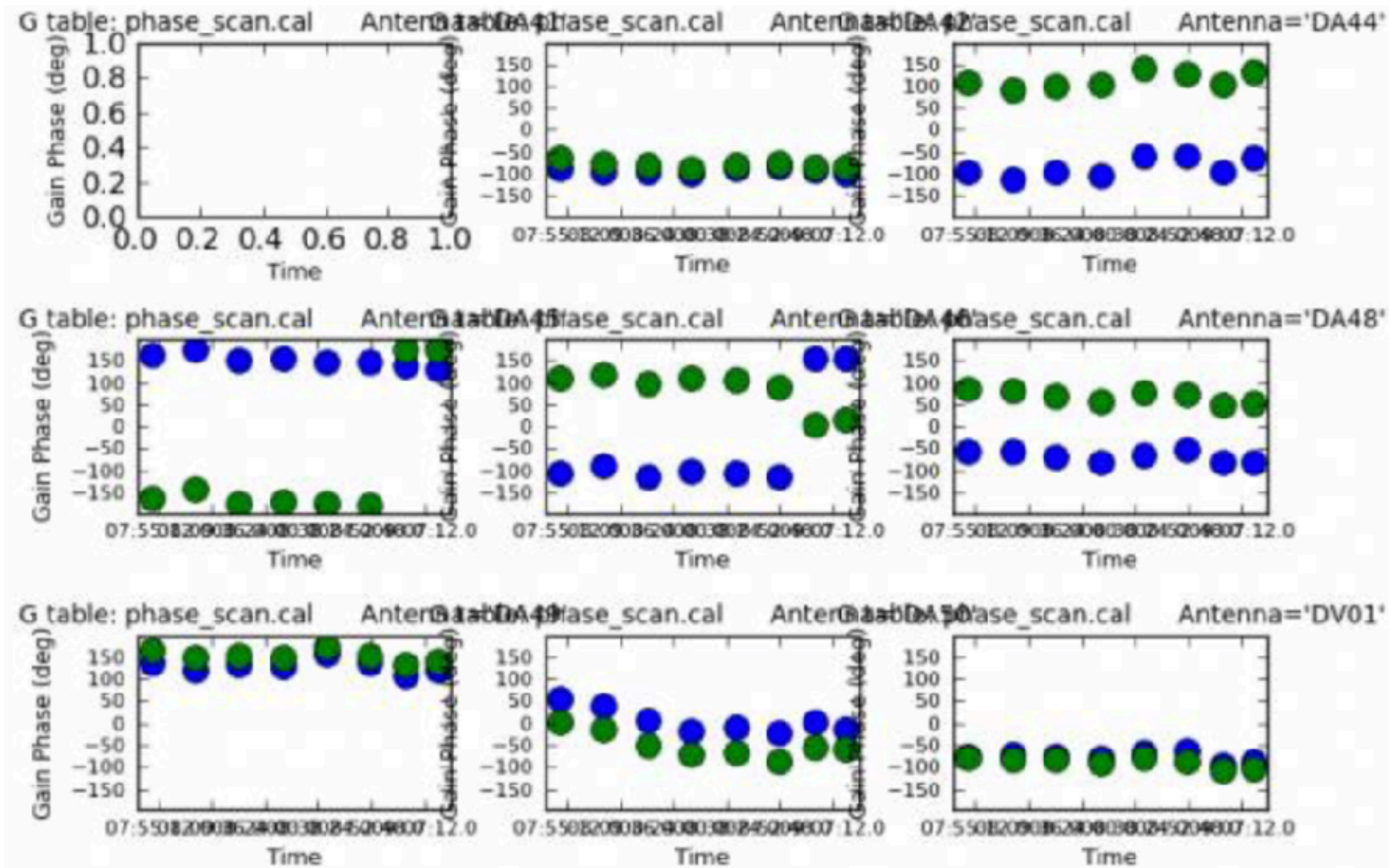
3 fundamental calibrations for every observation:

- Flux calibration
- Passband calibration (spectral dependance)
- Phase calibration



Example from ALMA data

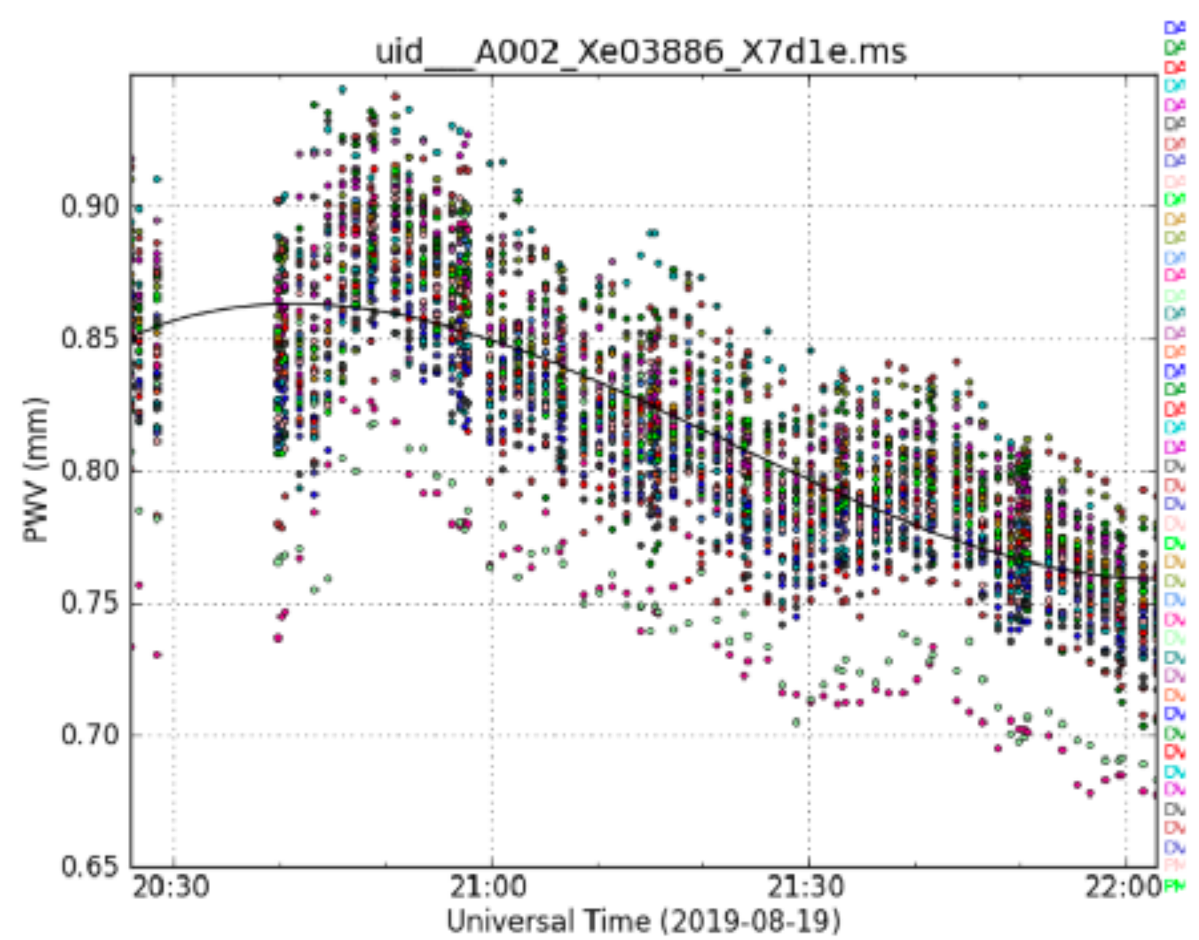
Gain functions computed using the phase-calibrator (two colors show two different polarizations).

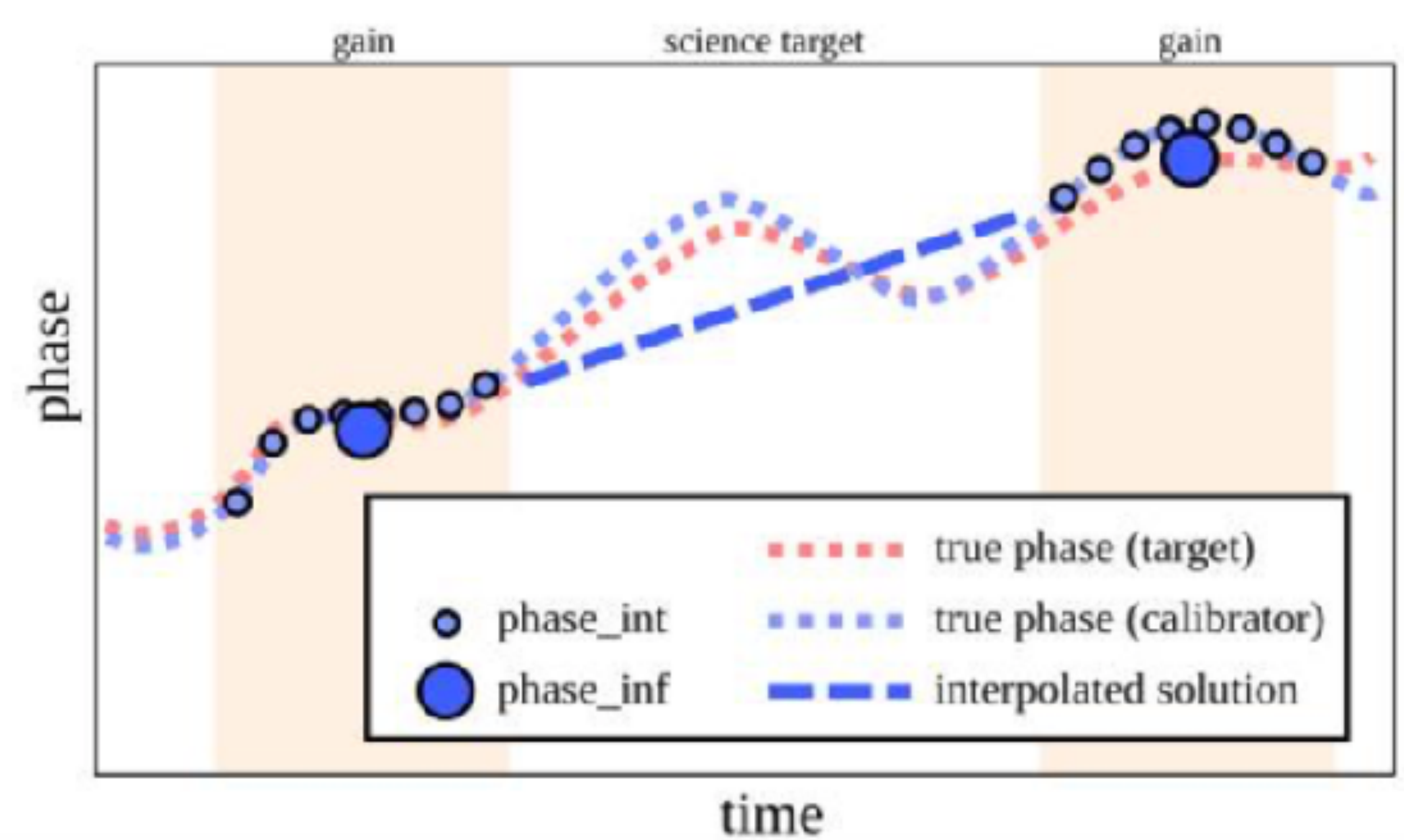


Self-calibration

If the astrophysical source is very bright, it is possible to solve the calibration equation using the source itself, after having applied the cross-calibration. This practise has the following advantages:

- The gain functions can be computed more frequently (both phase and amplitude)
- The gain functions are computed in the same of the source (pointing changes with calibrators)



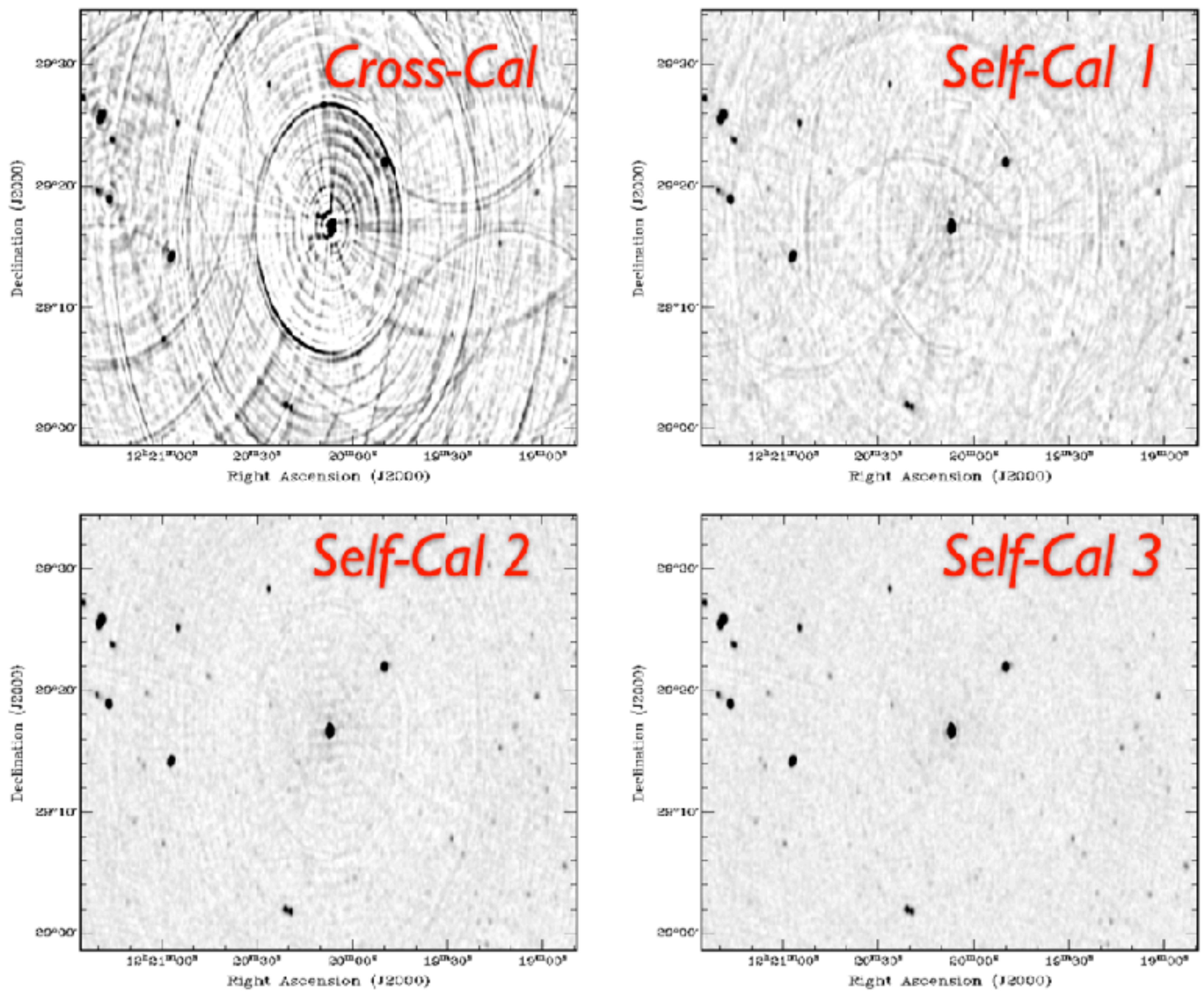


Self-calibration

It’s an iterative process:

1. I compute the image after having applied the cross-calibrations (we see soon how to make an image).
2. I use the Fourier transform of this image as V^{true} to compute the gain functions on a shorter time interval than the former one.
3. I re-compute the image and check that the quality has improved
4. I go back to point 2) and I keep going as long as my image quality improves (in this school we will not go into details of what ‘image quality’ means in interferometry, but for a first approach just use the snr.)

Examples of self-calibration



Examples of self-calibration

Cygnus A

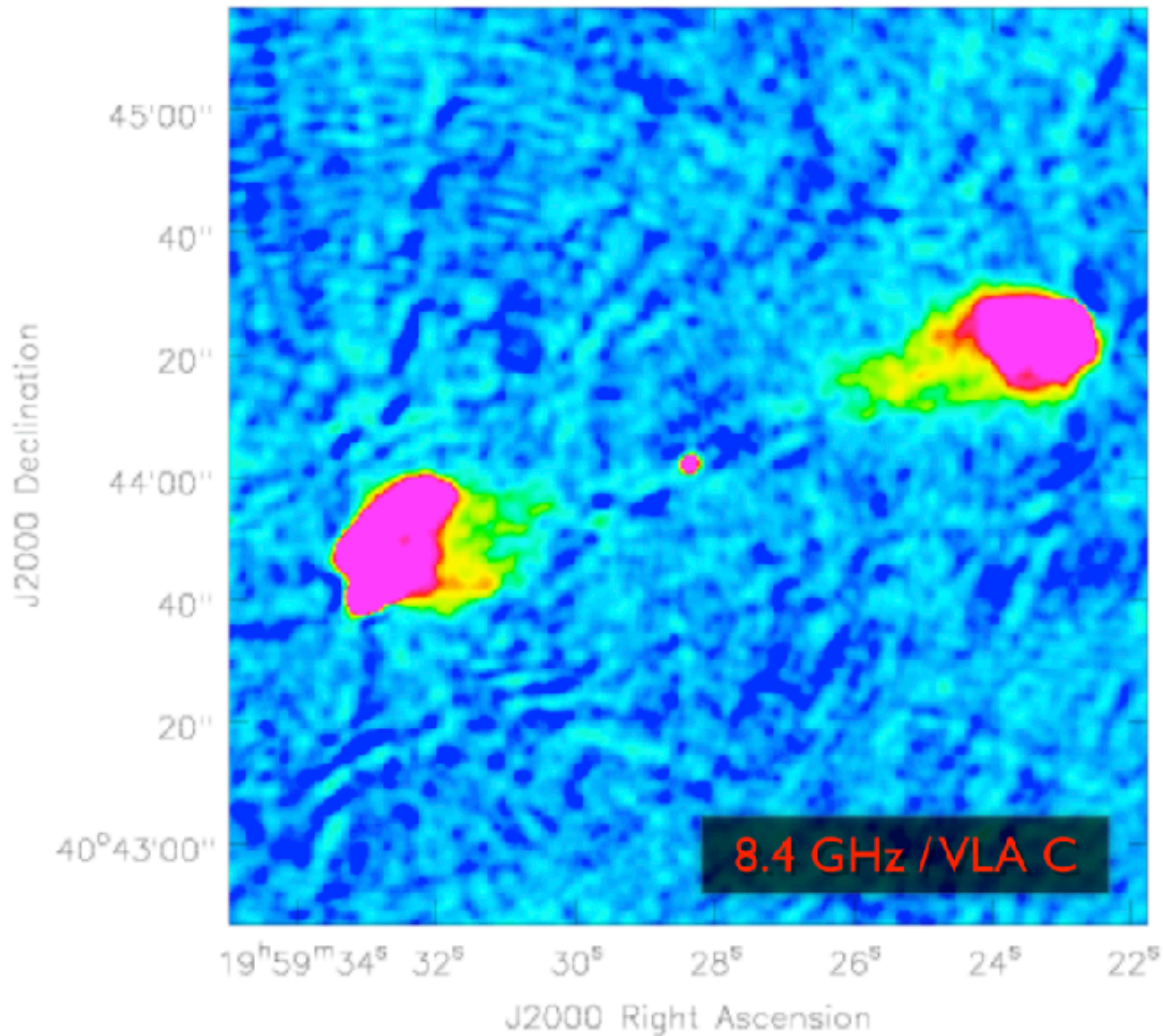
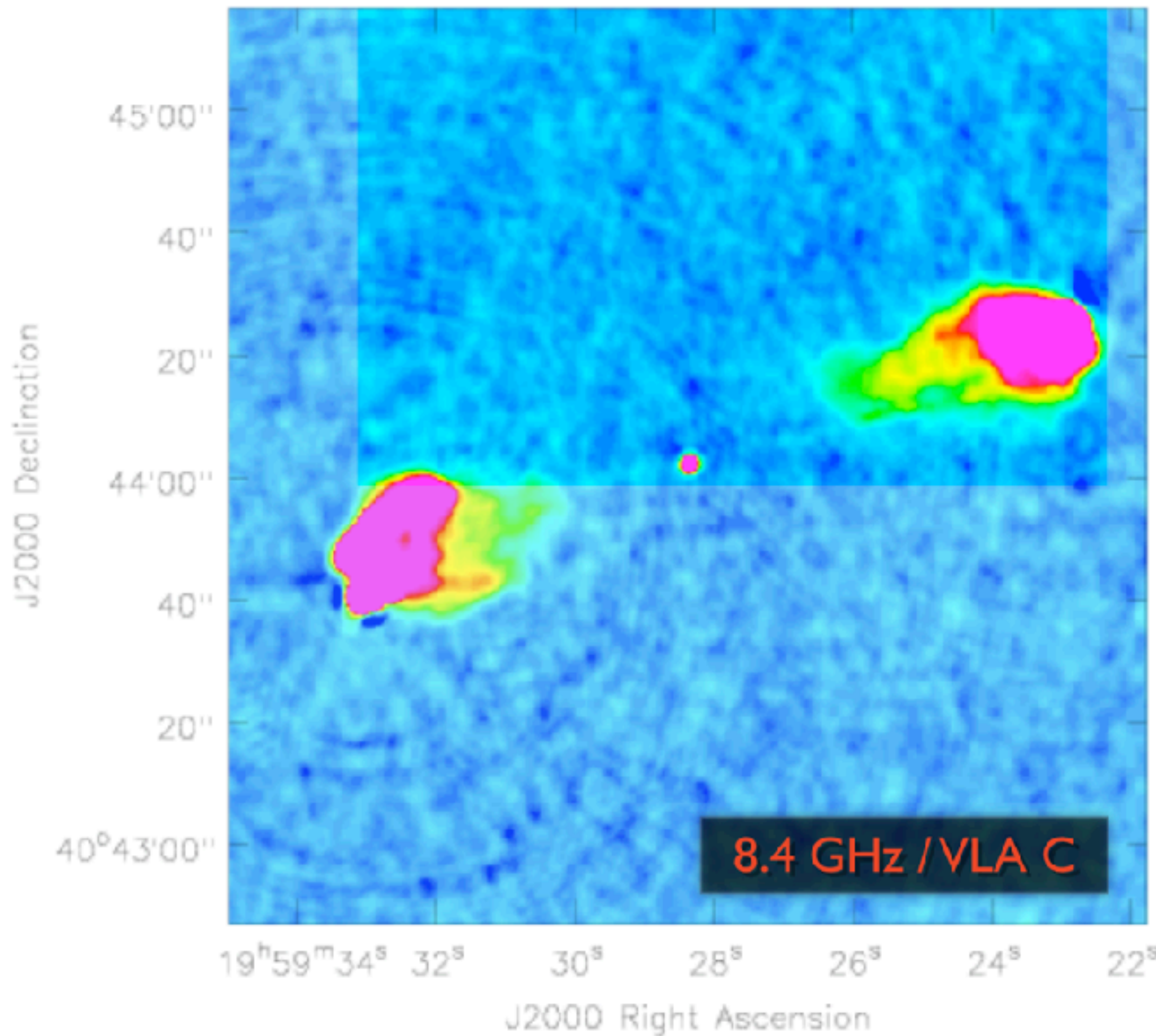


Image without self-calibration

Examples of self-calibration

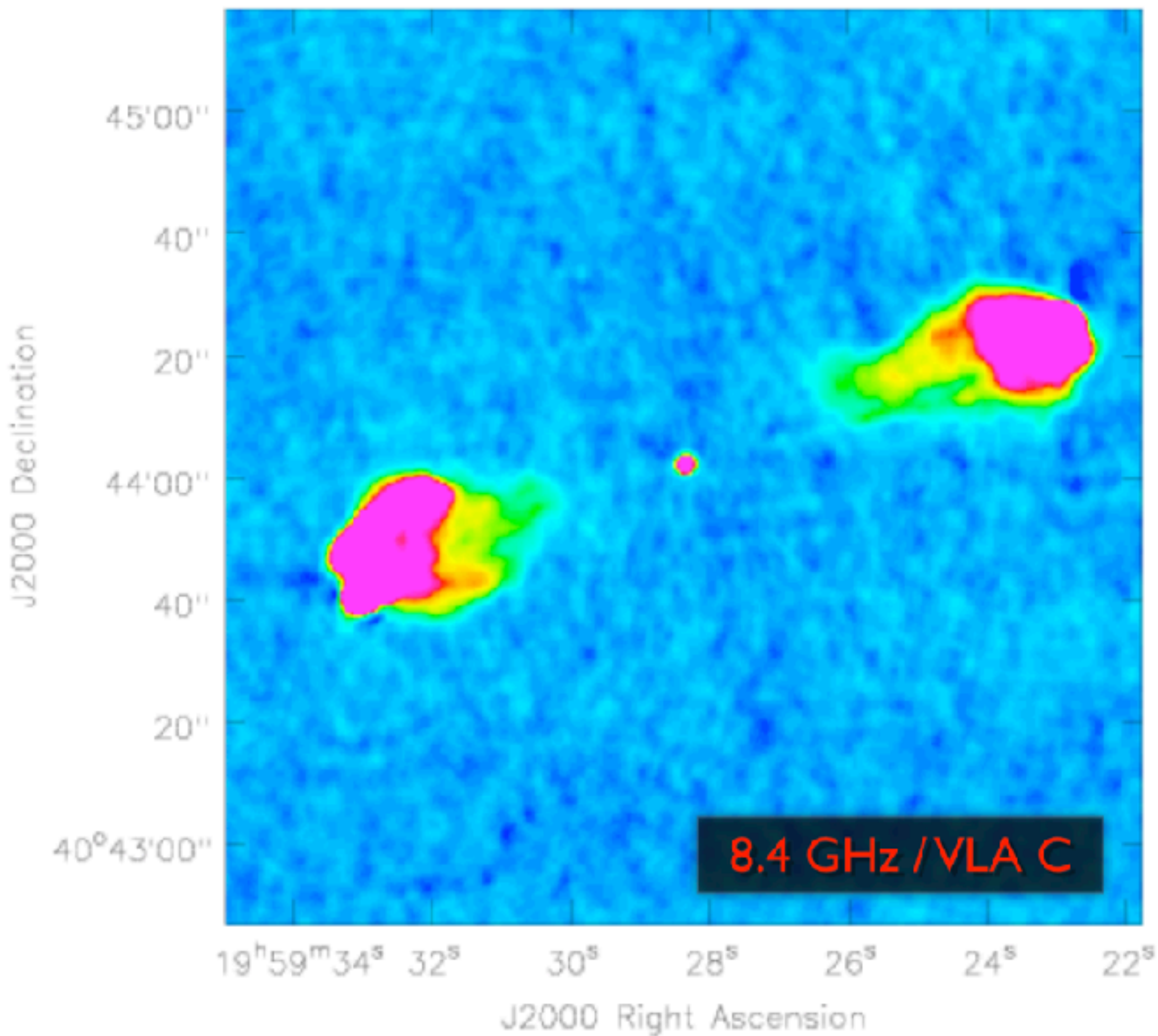
Cygnus A



After 1 phase self-cal

Examples of self-calibration

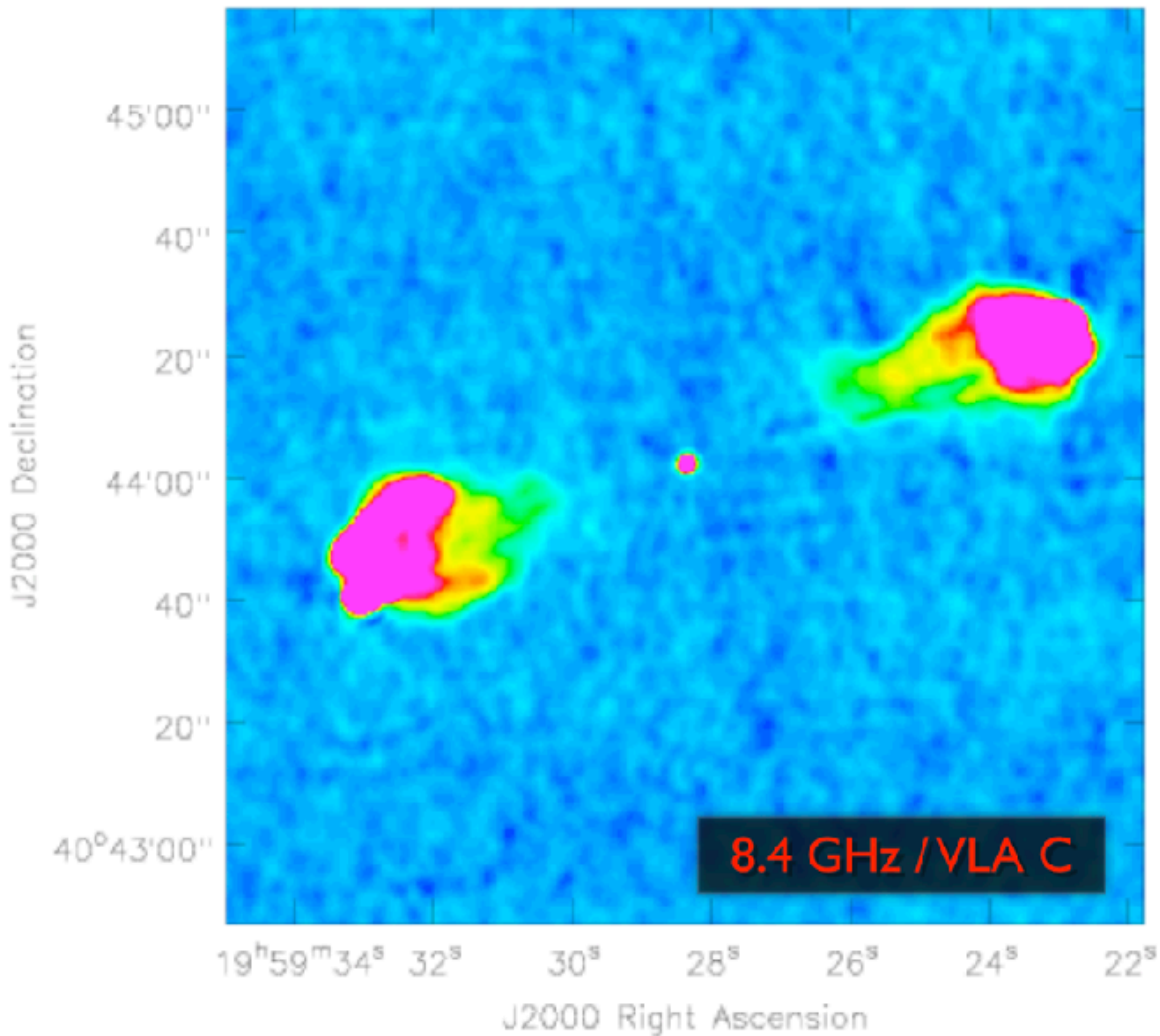
Cygnus A



After 1 phase and amplitude self-cal

Examples of self-calibration

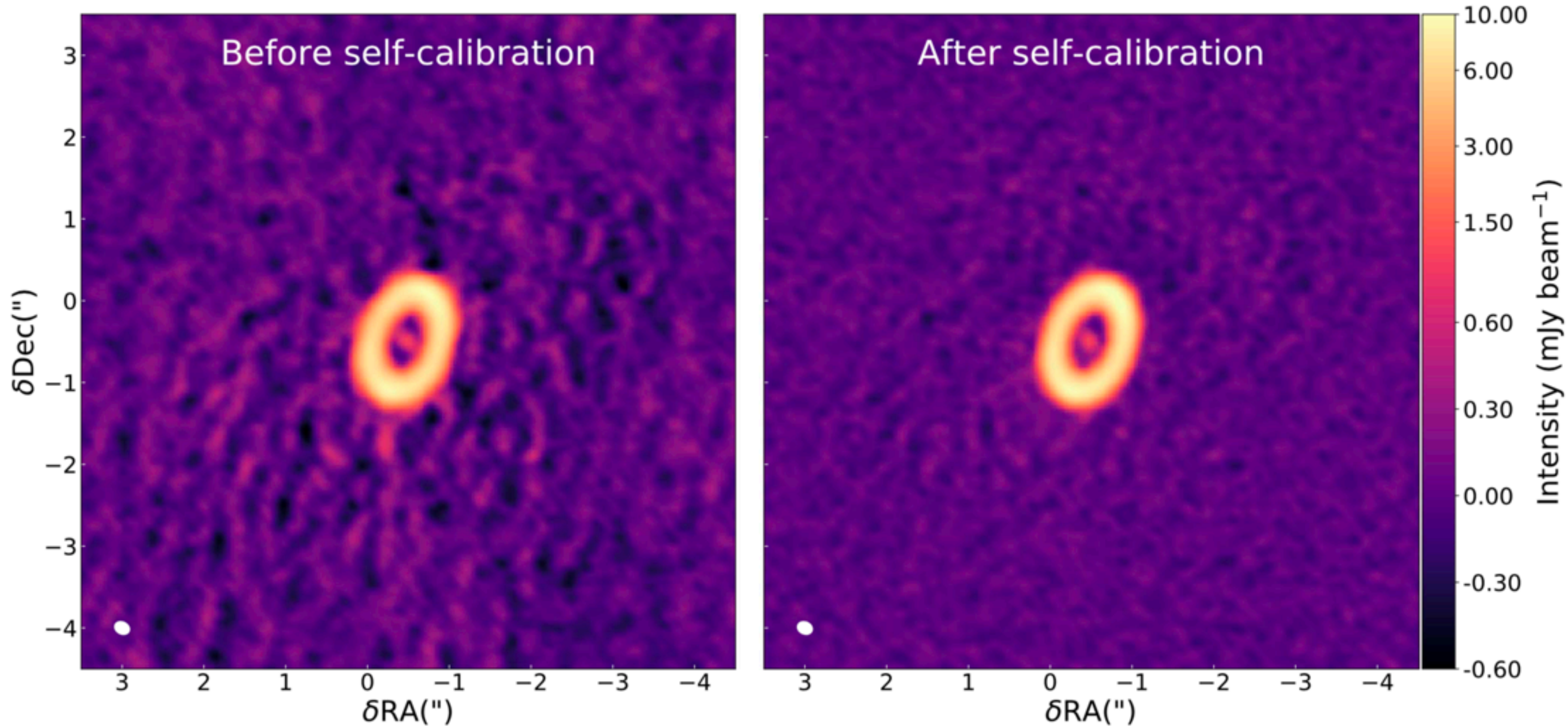
Cygnus A



After 4 rounds of phase and amplitude self-cal

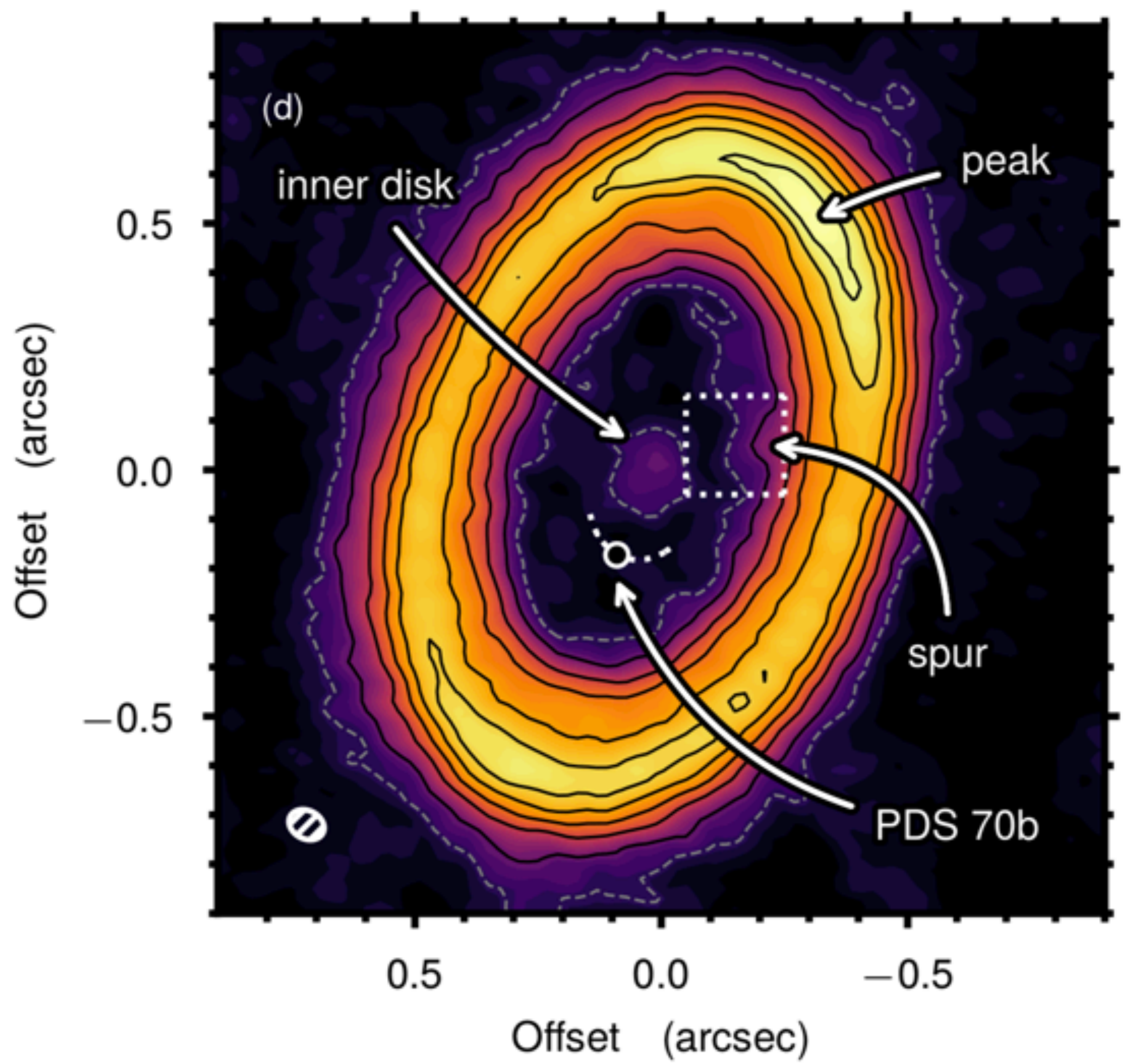
Examples of self-calibration

PDS 70: discovery of first circumplanetary disk

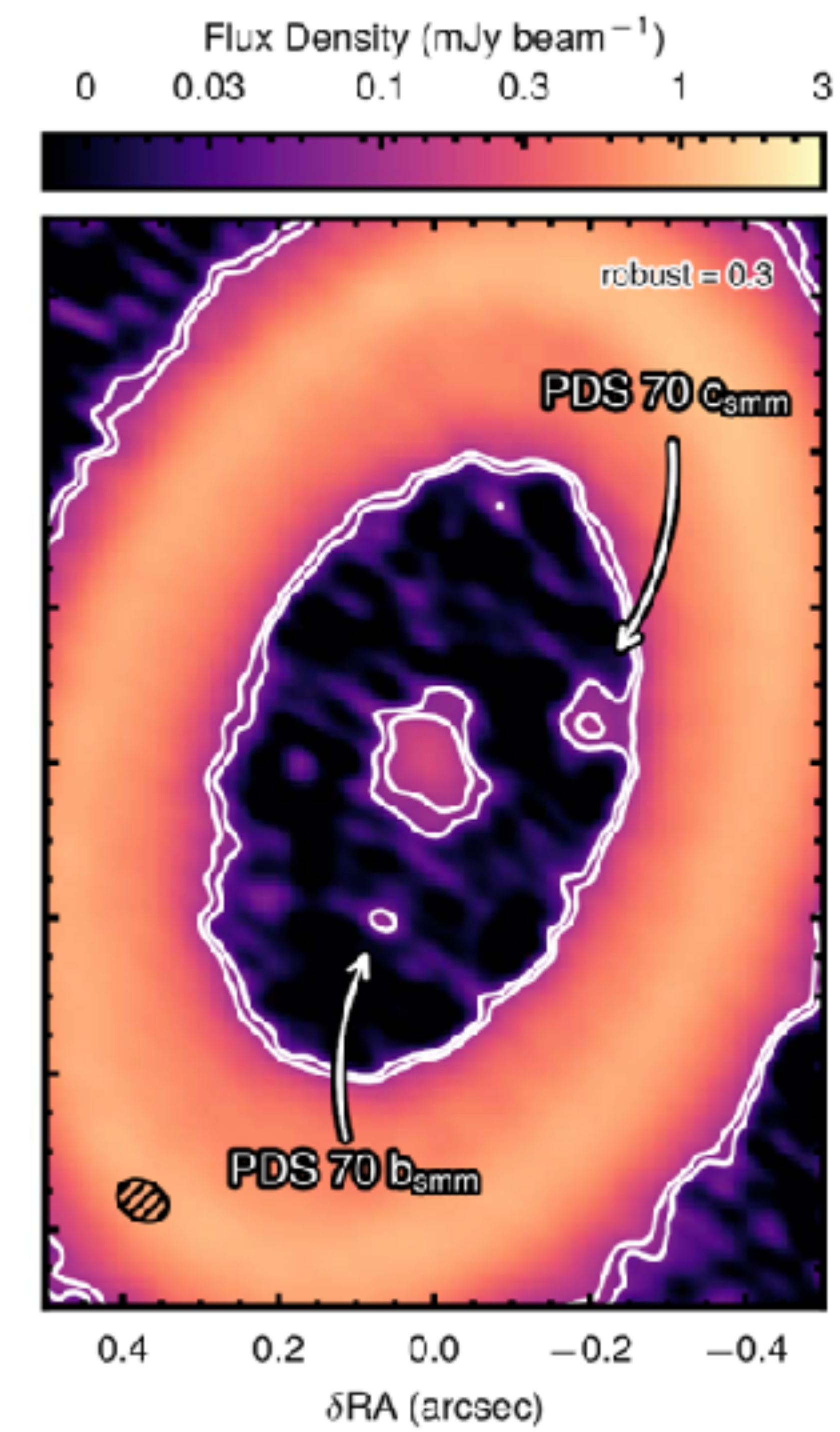


Examples of self-calibration

PDS 70: discovery of first circumplanetary disk



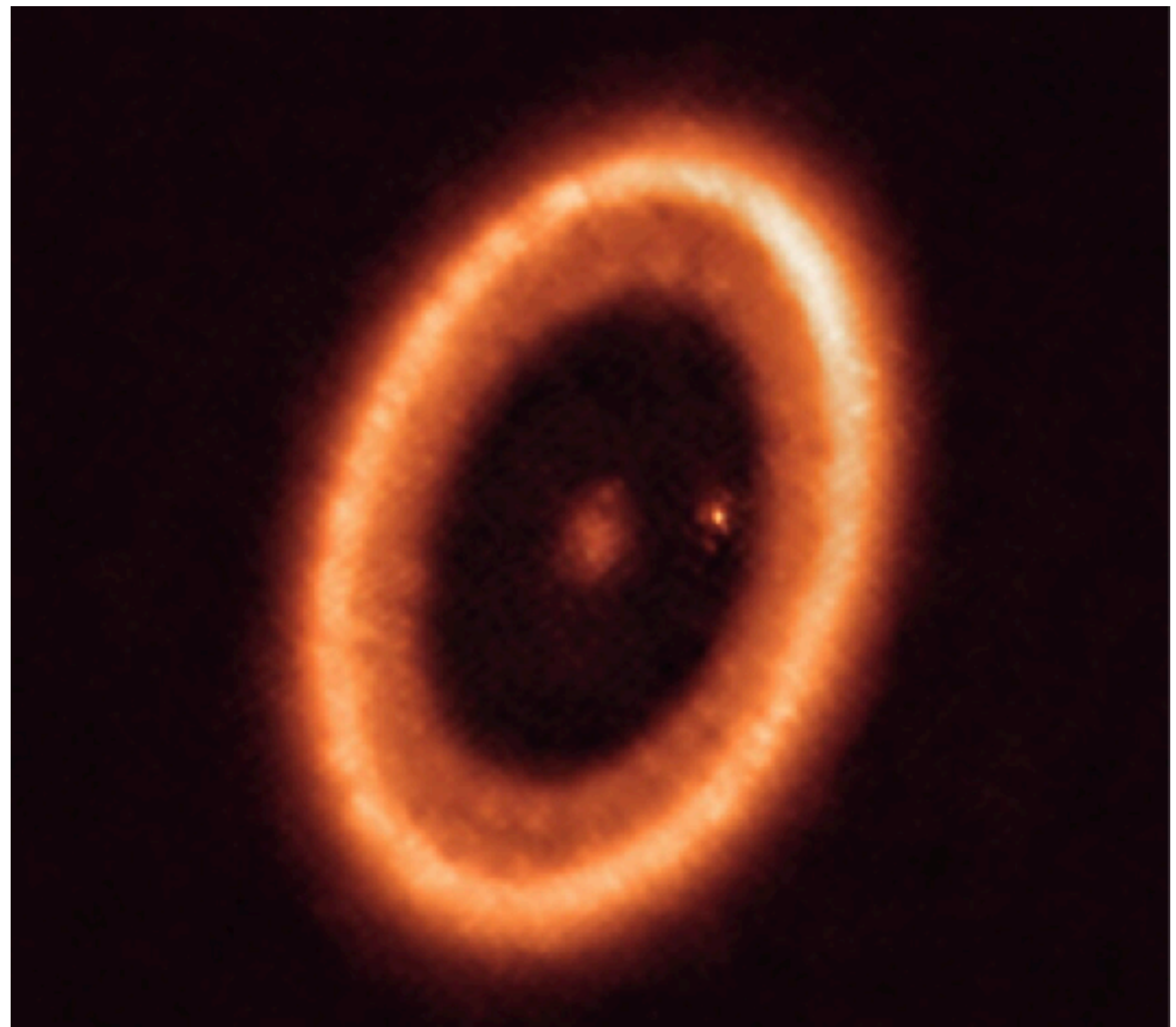
First attempt of self-cal (Keppler+2019)



Improved self-cal (Isella+2019)

Examples of self-calibration

PDS 70: discovery of first circumplanetary disk



Higher resolution data confirmed the presence of a candidate CPD (Benisty+2021)