Short intro to ALMA and interferometry

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ALMA Science Archive School
Italian ARC node headquarters, 5-7 October 2022

OPTICON RadioNet Pilot

What is ALMA?

It is an ambitious project

The **Atacama Large Millimeter/submillimeter Array** (**ALMA**) is a

reconfigurable interferometer

observing at **millimeter and submillimeter wavelengths**

in the Atacama Desert of northern Chile

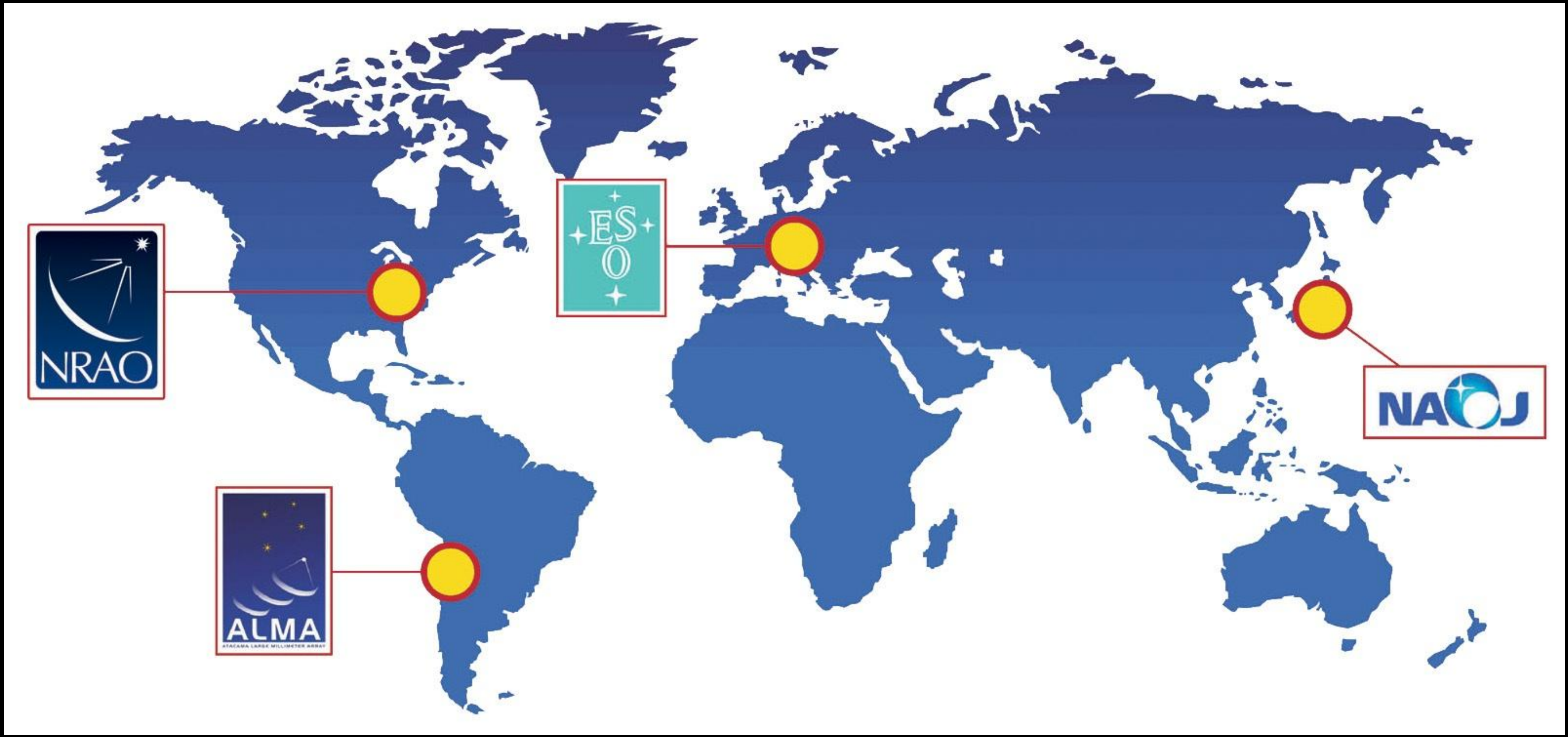
Latest Cycle 9 capabilities **here**

ALMA organization

Word wilde Collaboration

- **Europe: ESO (14 countries)**
- **North America: NRAO (USA, Canada)**
- **East Asia: NAOJ (Japan, Taiwan)**
- **Chile**

Contributors share the observing time

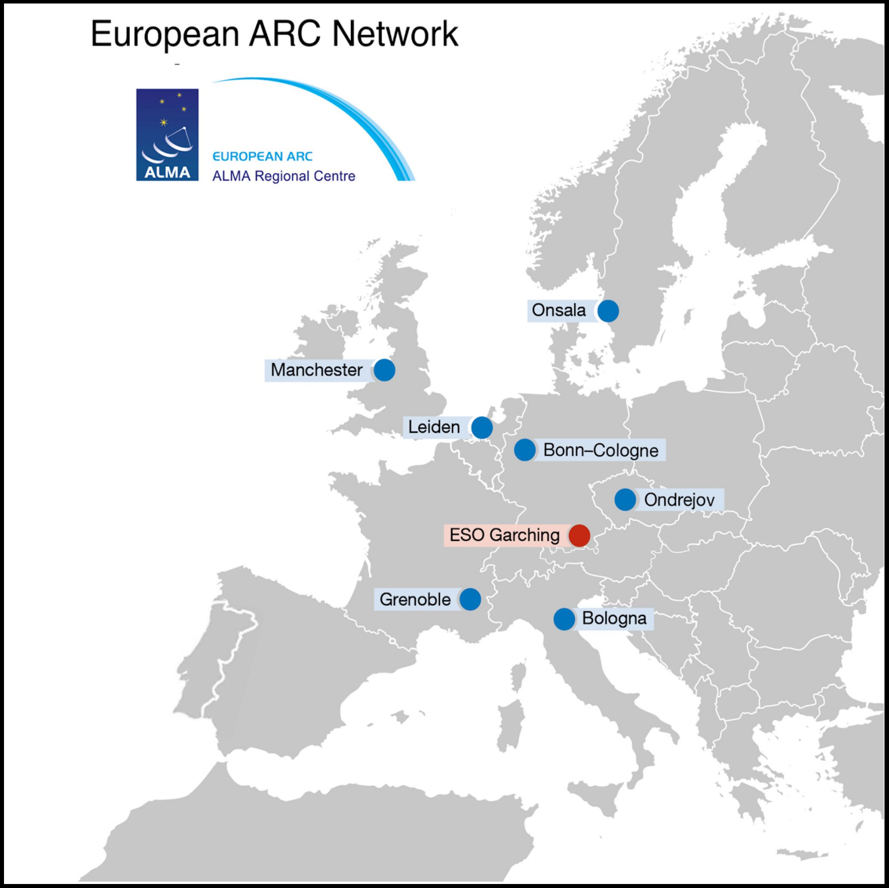


ALMA regional centers (ARCs)

- *Interface between observatory and users*
- 1 ARC per Partner
  - NRAO for North America
  - NAOJ for East Asia
  - ESO for Europe (split in 7 nodes)

The European ARC nodes

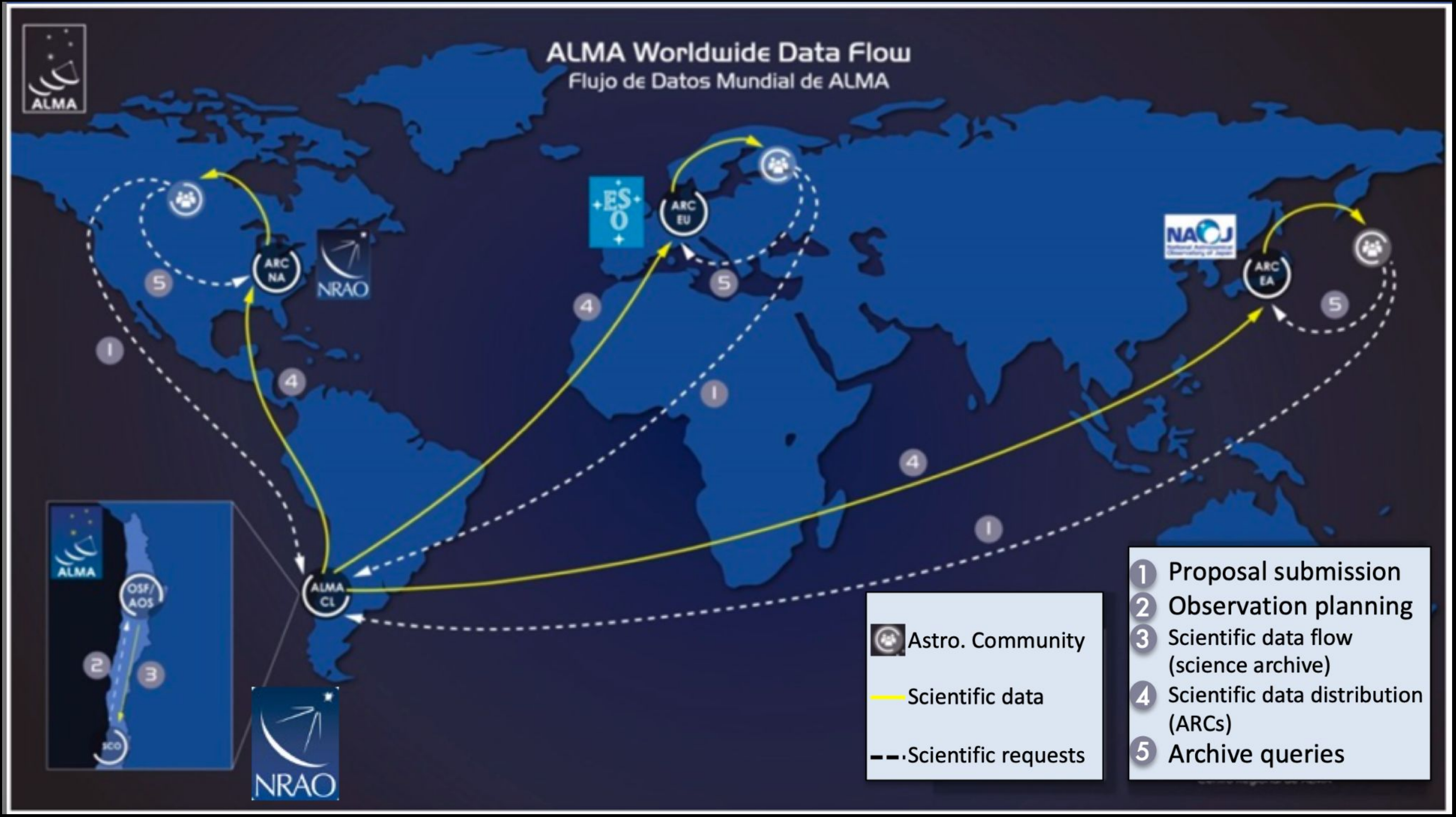
- ***Operation support***
  - Archive replication
  - astronomer on duty
  - software tools
- ***User support***
  - Community formation and outreach
  - from proposal preparation to observation
  - archive mining
  - f2f and advanced user support
  - Quality assessment



!!! Improving the ALMA User experience !!!

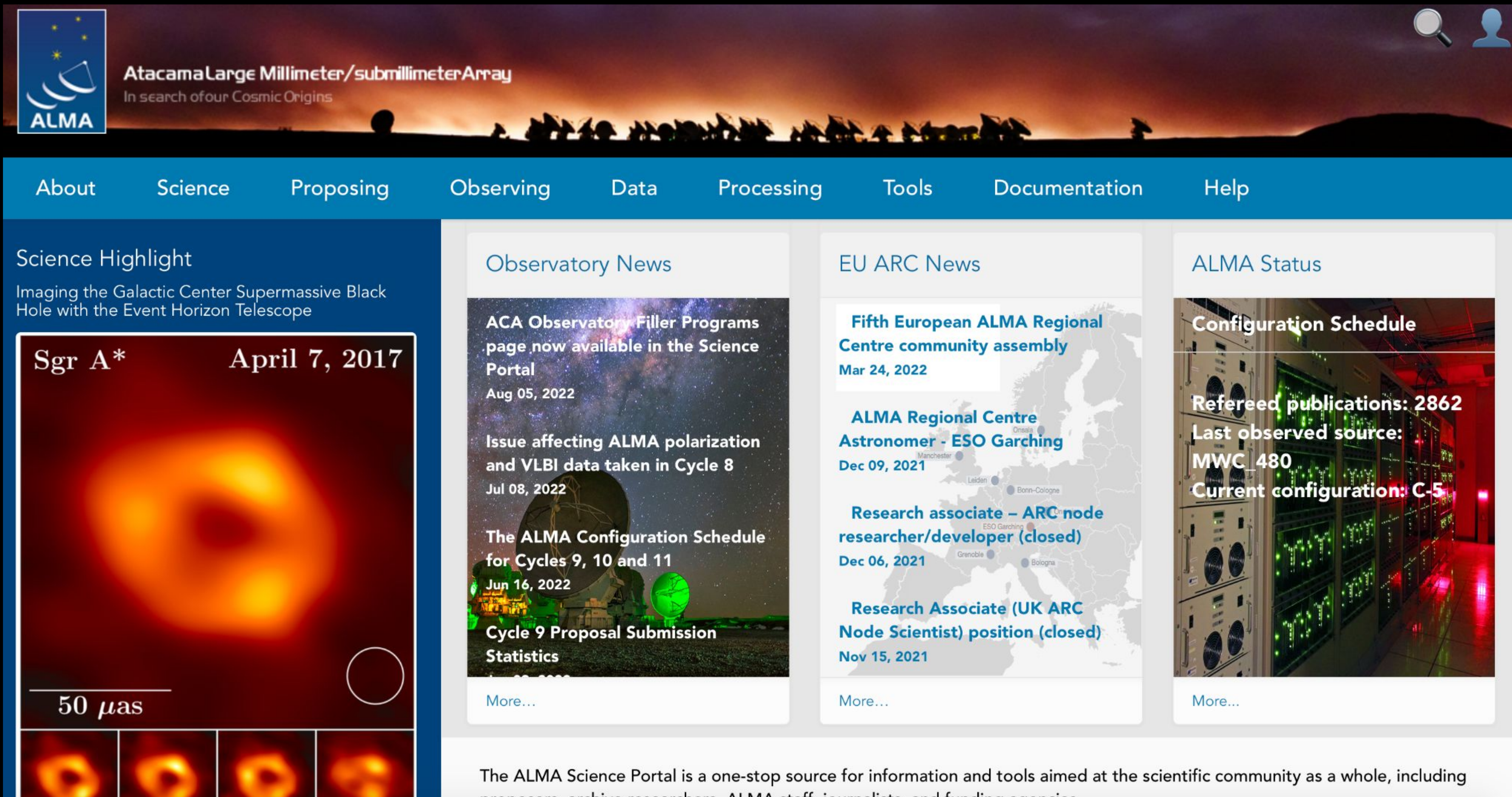
ALMA data flow

Each ARC hosts an **archive mirror**



Enter the ALMA world through the ALMA Science Portal

http://almascience.eso.org/



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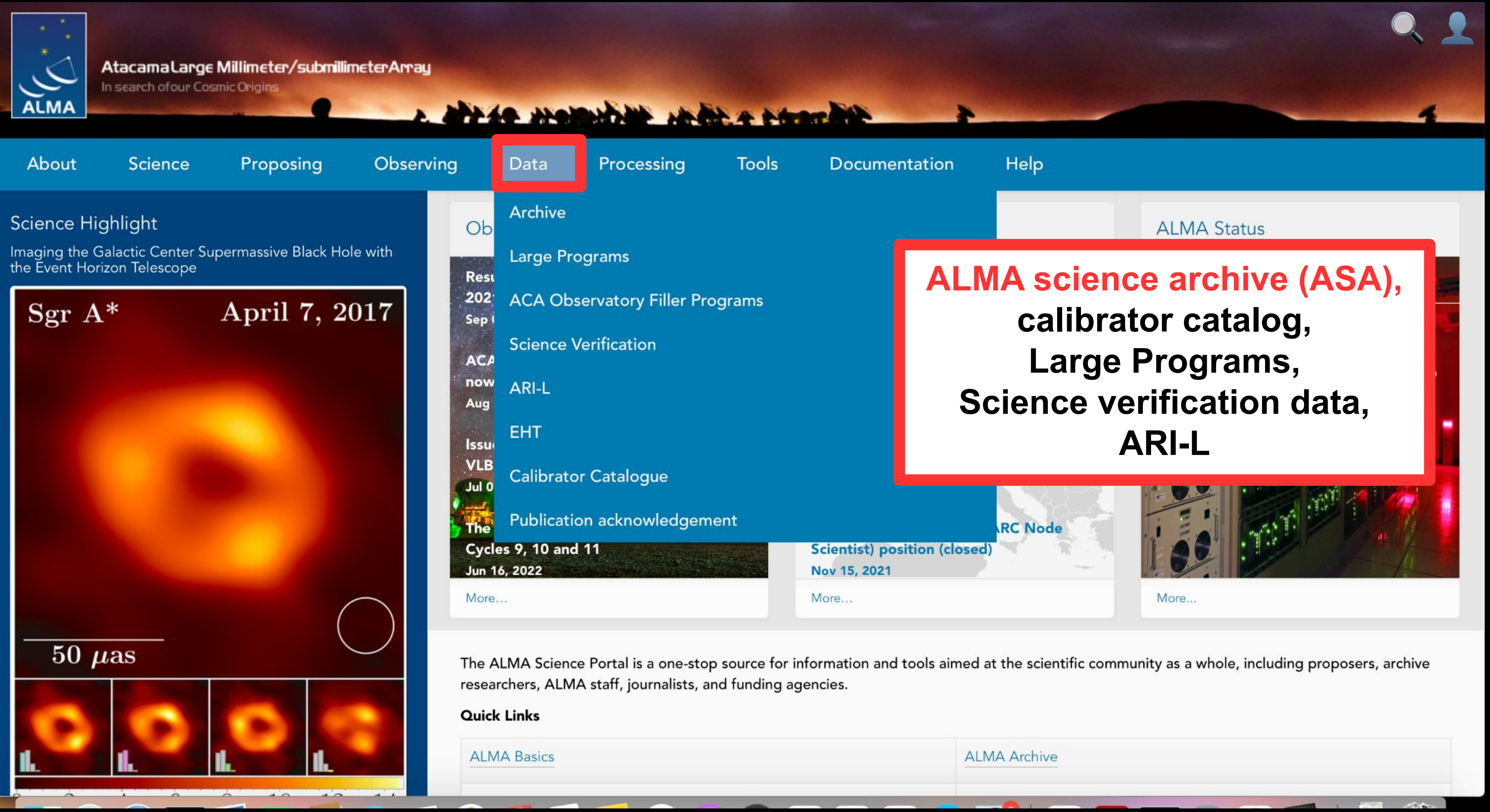

ALMA science archive (ASA),
calibrator catalog,
Large Programs,
Science verification data,
ARI-L

See also George presentation on 'ALMA Science Archive content'

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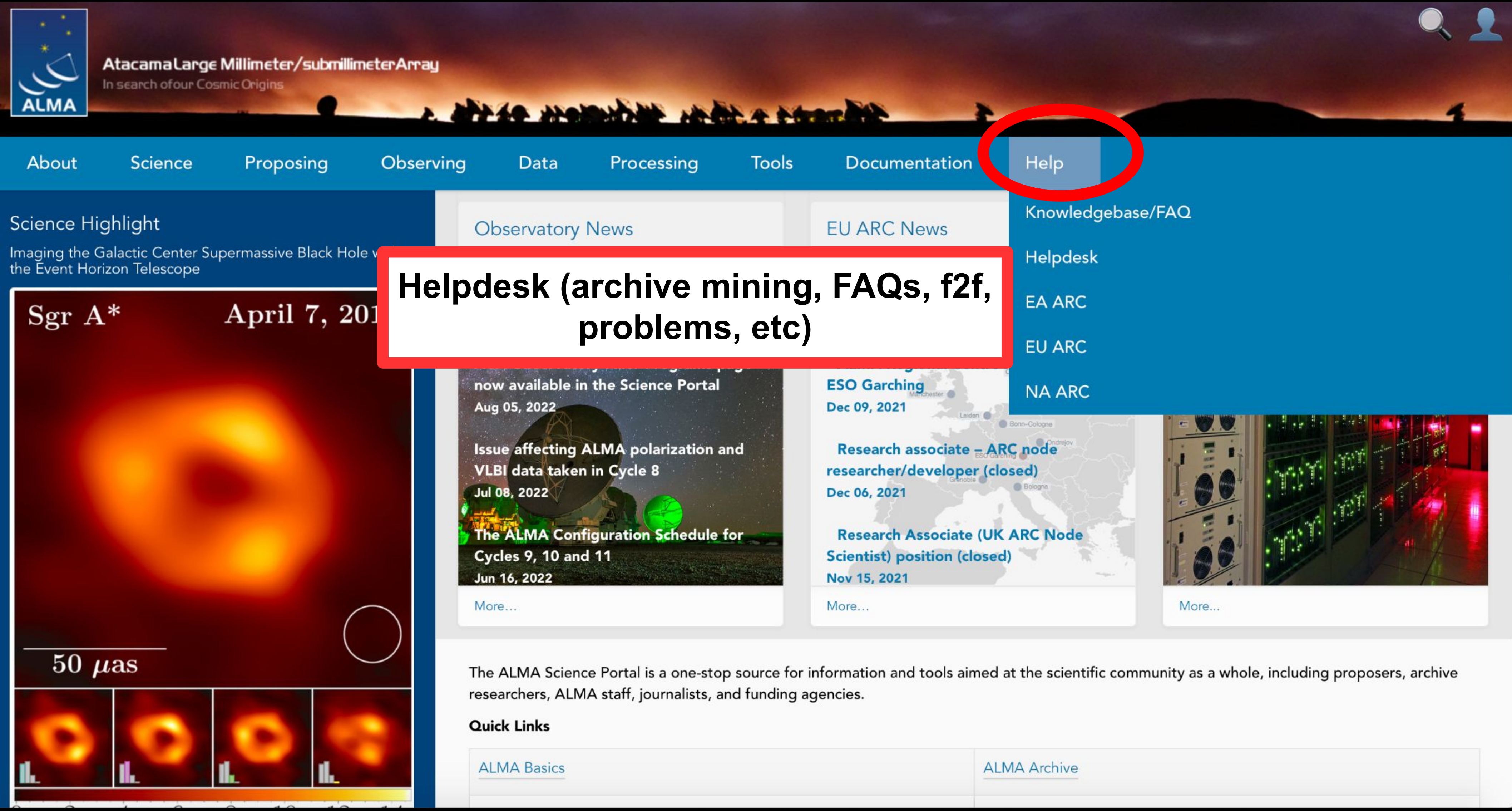

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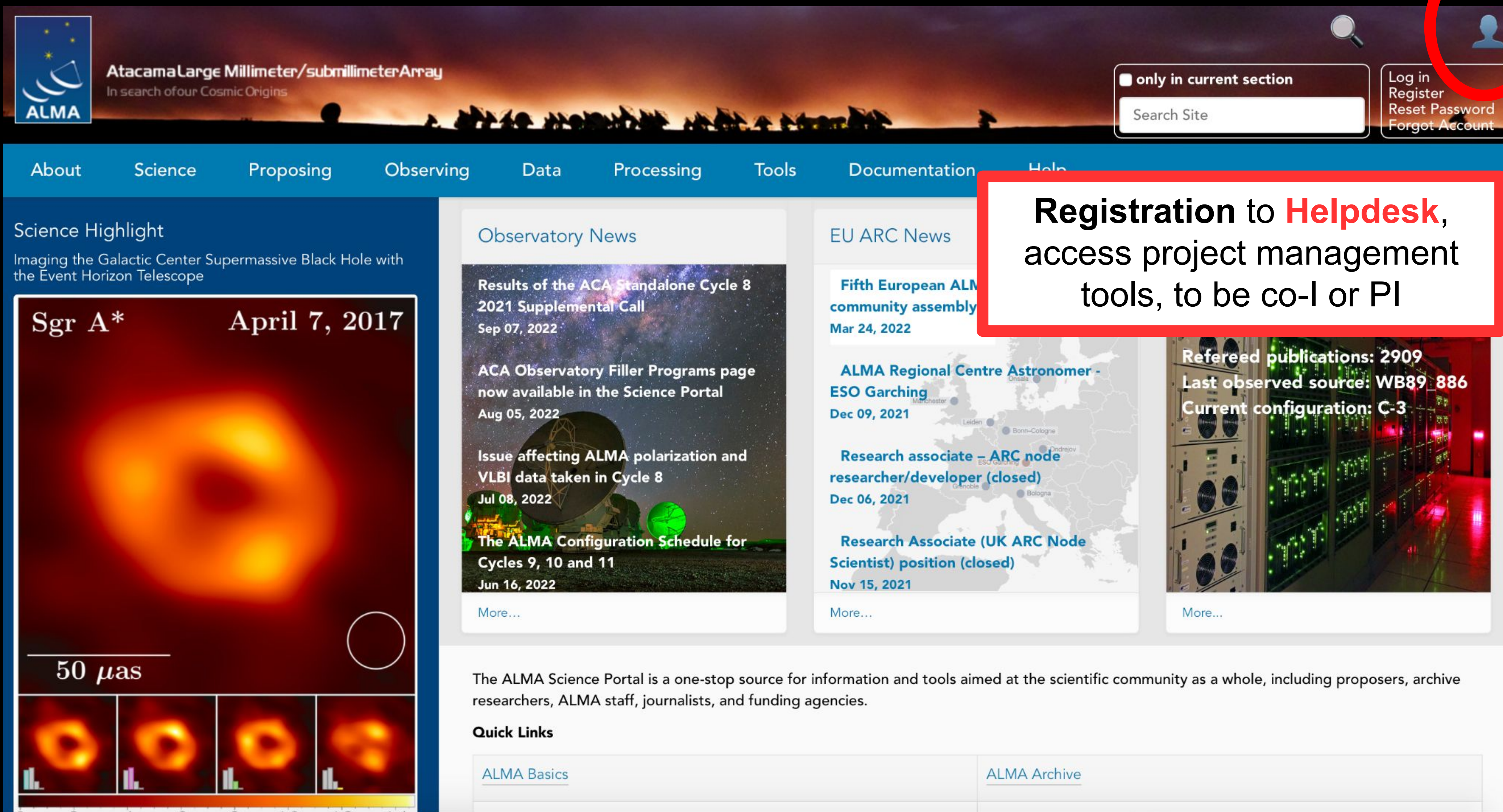
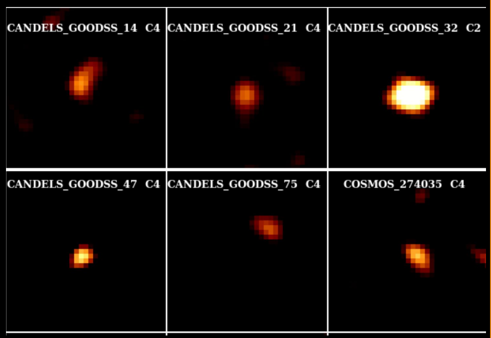


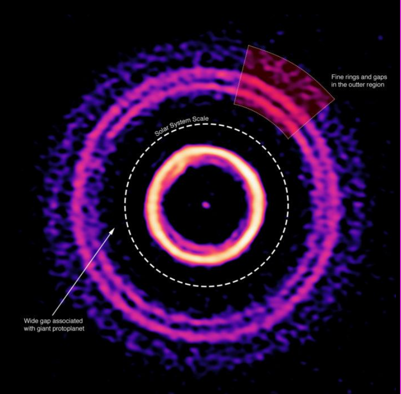
Registration to **Helpdesk**, access project management tools, to be co-I or PI

Why ALMA? The main 'science drivers' ('level 1 science goals')

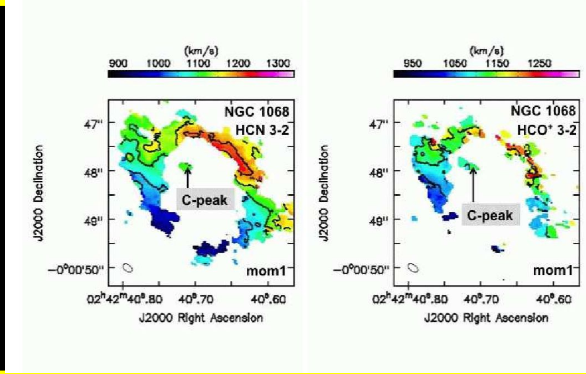
1. Spectral line emission from C+ in a normal galaxy like the Milky Way at a redshift of z=3, in less than 24 hours



2. Image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars in the nearest molecular clouds (150 pc)



3. Provide precise high dynamic range (=|image max/image min|) images at an angular resolution of 0.1 arcsec



More info in the ALMA Science Primer

+

from the latest ALMA press releases

Why ALMA is ALMA?

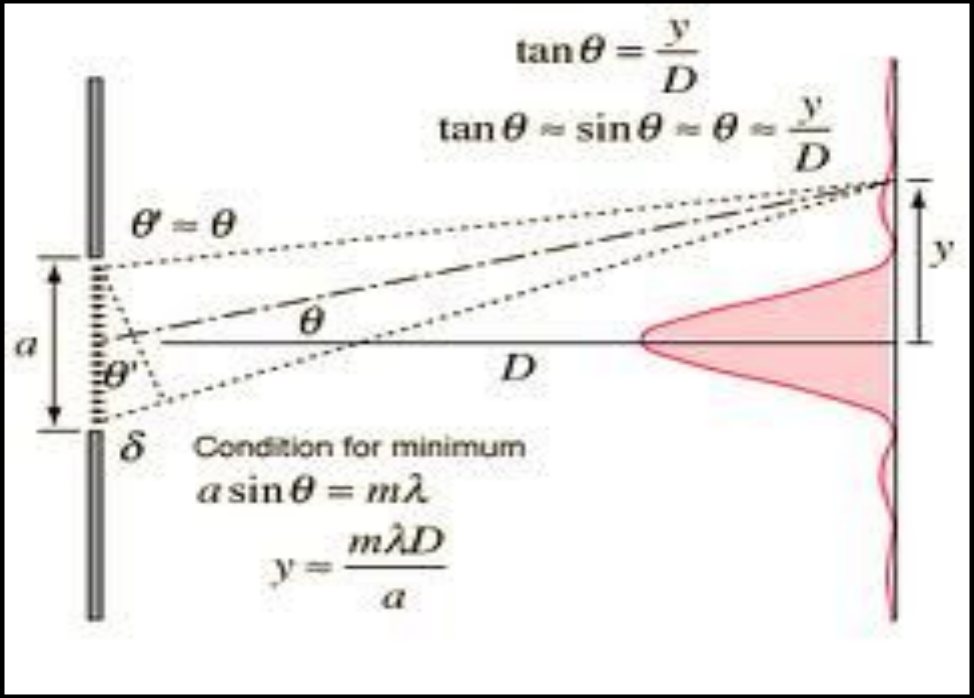
The science cases define the ALMA requirements in terms of:

- high angular resolution
- observing frequencies
- high sensitivity
- mapping of different spatial scales
- high spectral resolution

ALMA is a flexible instrument

→ **reconfigurable interferometer**
→ observing **at (subm)mm**
→ in the Atacama Desert (5000m)
→ **composite instrument**
→ **peculiar spectral setups**

Why ALMA is an interferometer?



Angular resolution of diffraction-limited telescope is

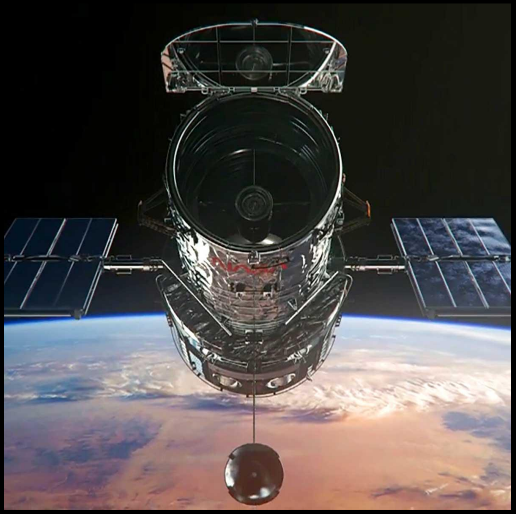
$\Theta \sim \lambda/D$ radians

where D is the diameter of the telescope and λ is the wavelength of observations

For example, Hubble Space Telescope

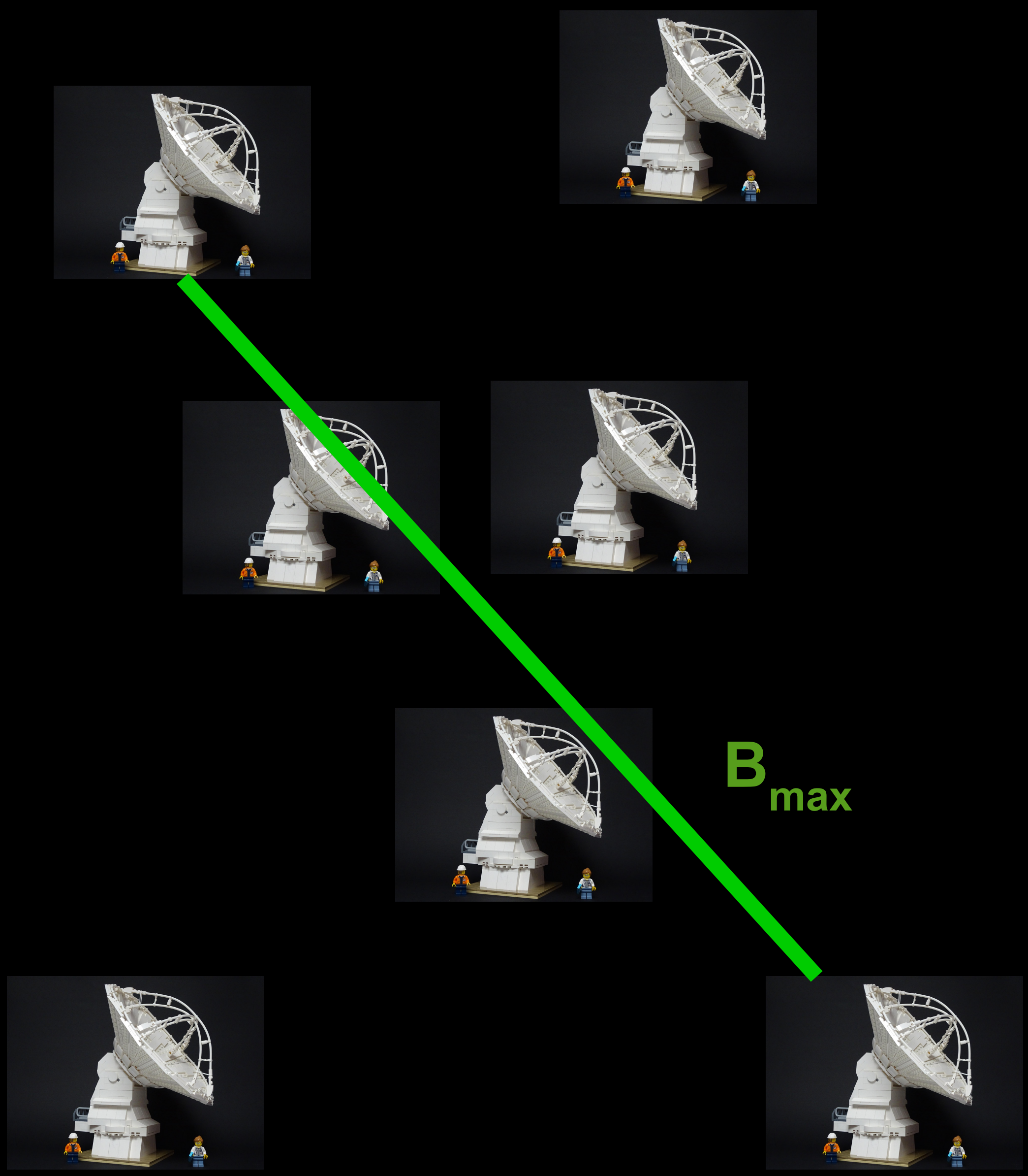
- $\lambda \sim 1\mu m$ and D of 2.4 m → $\Theta \sim 0.13$ arcsec

To reach that angular resolution for **λ=1 mm observations**
→ it is necessary a **2 km-diameter dish**



Interferometry is needed

because of the limitations of building large single dish telescopes

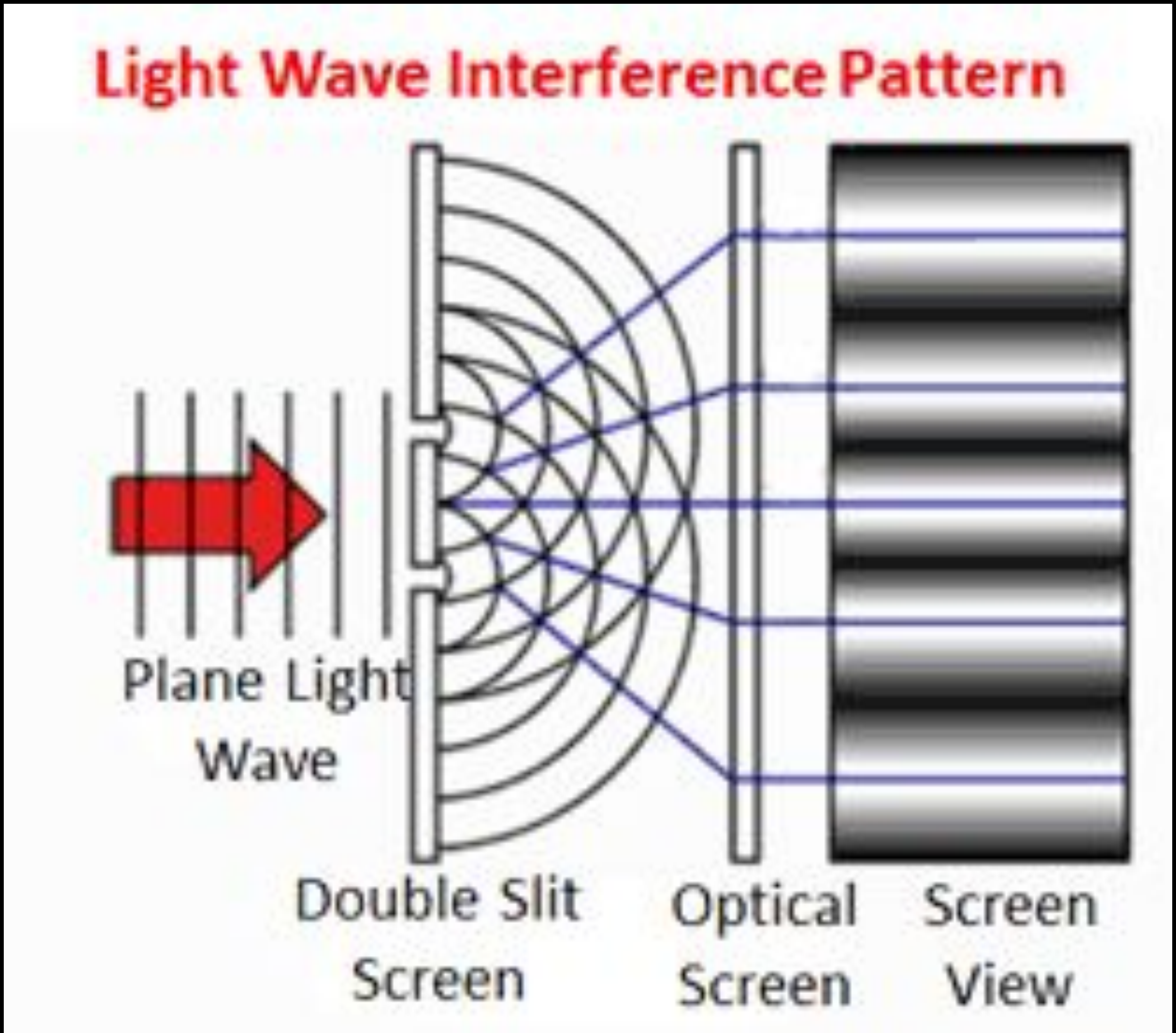


Basics:

- N antennas over a region
- **B** is the baseline = distance between two antennas
- **$\theta \sim \lambda / B_{max}$** where B_{max} is the maximum distance between two antennas in the array
- **θ** is also referred as **Synthesized Beam**

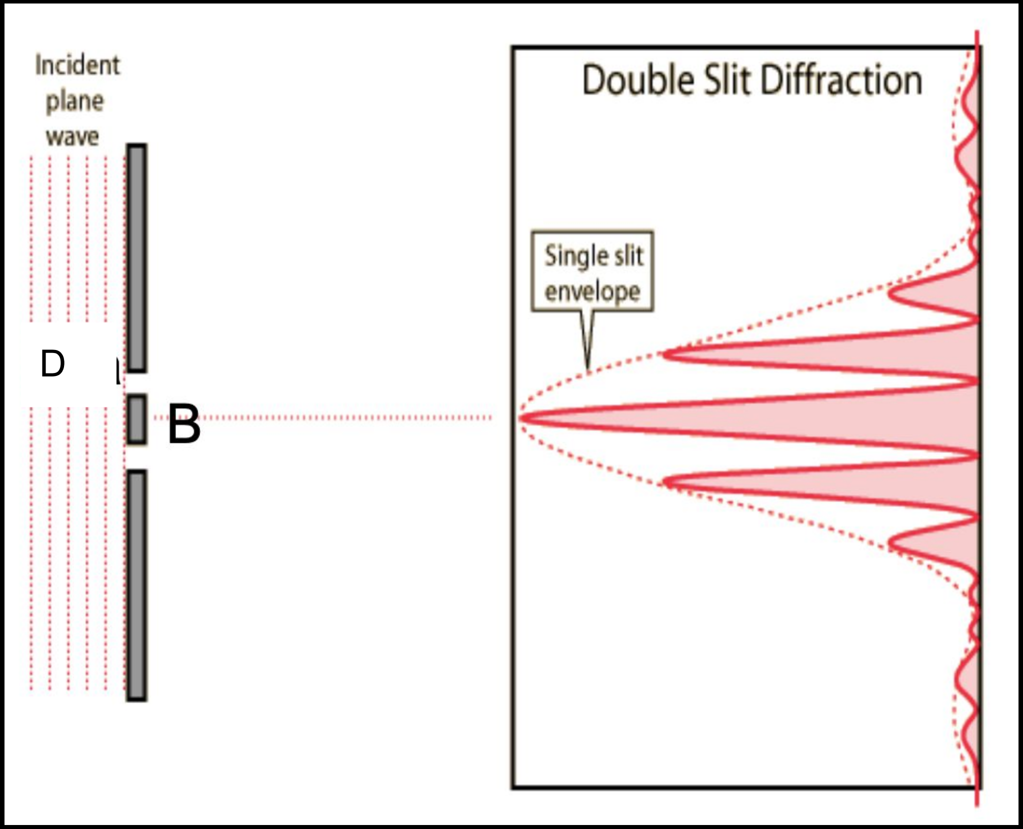
Interferometry: the basics

Pair of radio telescopes work like a **2-slit** **Young's experiment**



An interferometer of N antennas measures the **interference pattern** produced by **N(N−1)/2 independent** pairs of apertures

Diffraction pattern from an array



FOV=λ/D
is
Field of View or Primary Beam.

The response function of an interferometer is modulated in a region of FoV size

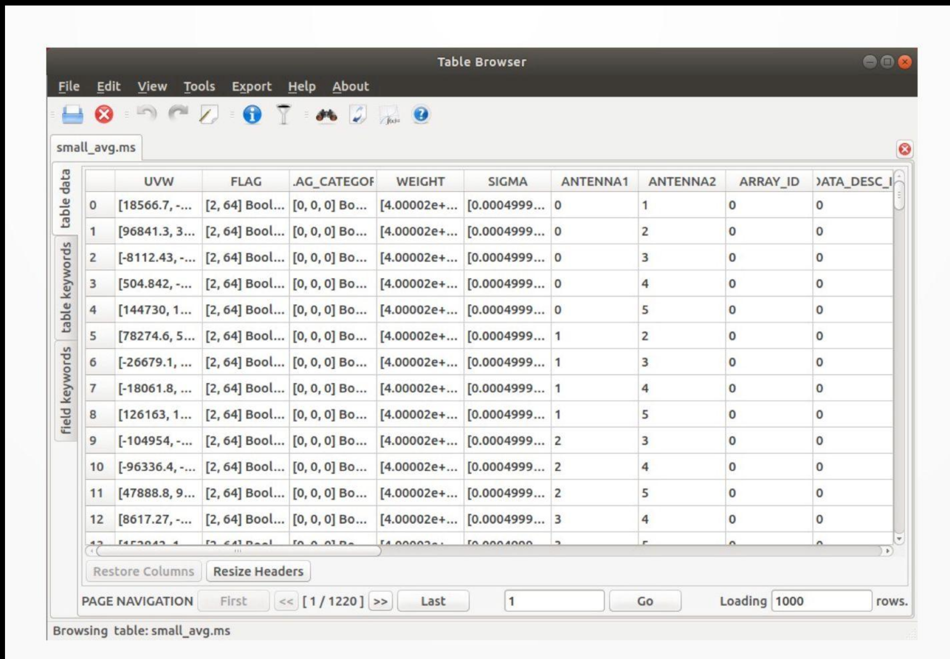
→ ASA final images are primary beam corrected

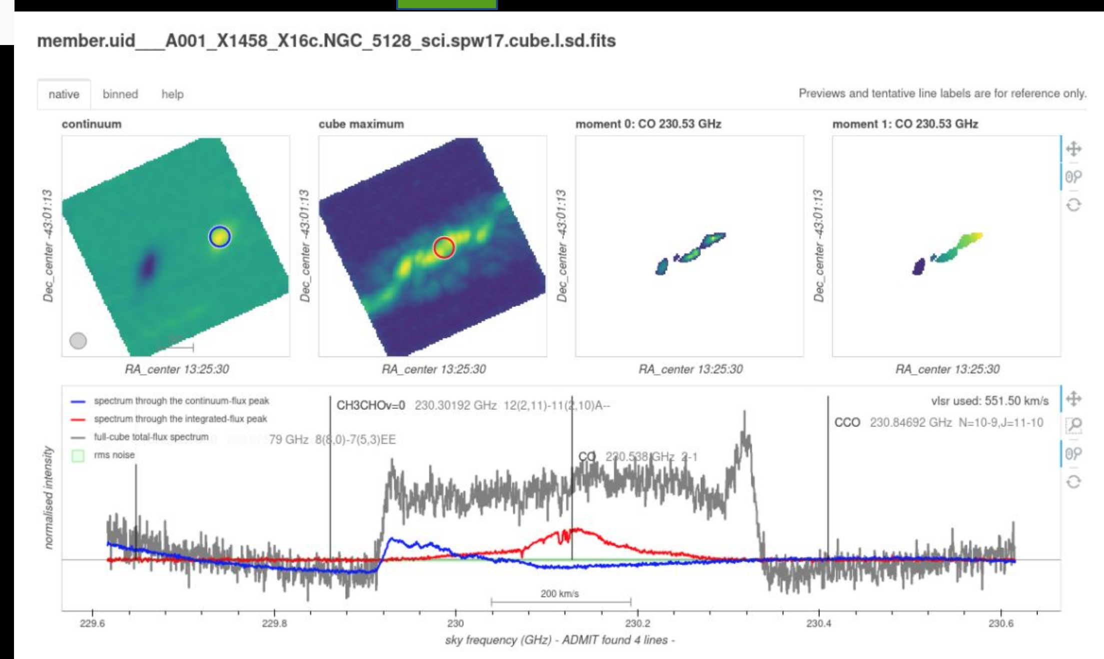
!!! See Luke talk 'ALMA imaging basics' !!!

What ALMA observes and produces?

!!! See George talk ‘ALMA archive content’!!

Raw data (i.e. visibilities) are stored in TABLES





IMAGES are FITS files

Visibility and Sky Brightness

The Fourier Theory (FT) states that any well behaved signal (including imaging) can be expressed as **sum of sinusoids.**

(van Cittert-Zernike theorem)

Fourier space/domain

$$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dxdy$$

$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} dudv$$

Image space/domain

For small fields of view, the **complex visibility V(u,v) is the 2D Fourier Transform of the brightness on the sky (T(x,y))**

Brightness temperature vs Flux density

Rayleigh-Jeans law:

$$S = \frac{2\,k\,T\,\Omega_S}{\lambda^2}$$

Flux density S in Jy

$$\Omega_S = \frac{\pi\,\theta_b^2}{4\,ln2}$$

- k Boltzmann constant
- Ω_s solid angle (steradian)
- θ_b HPBW of a gaussian

1 Jy = 10^{-26} W m^{-2} Hz^{-1} = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}

$$T = \frac{\lambda^2\,S}{2\,k\,\Omega_S}$$

Temperature T in Kelvin

Interferometric maps are measured in brightness unit I in Jy/beam

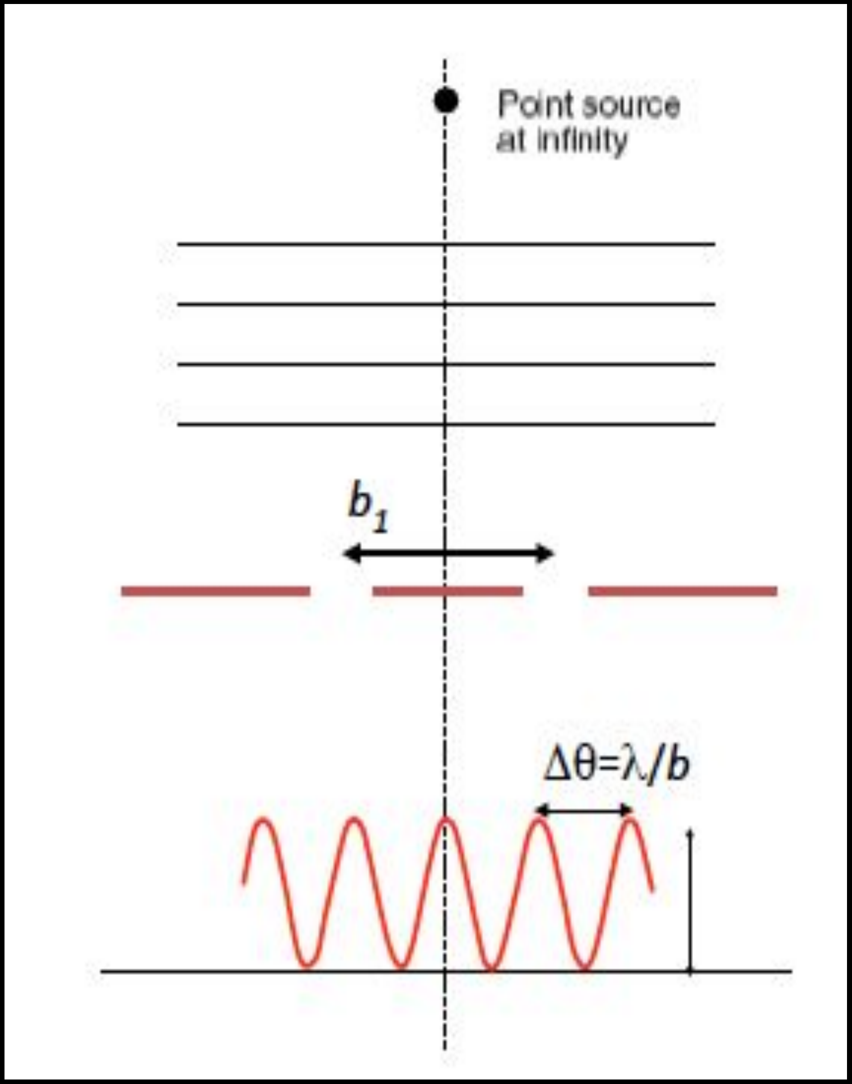
I =S/beam

$$T = 1.36\,\frac{\lambda^2}{\theta_{maj}\,\theta_{min}}\,I$$

cm (λ), mJy/beam (I), arcsec ($\theta_{maj}\,\theta_{min}$)

See also ALMA primer series on 'Estimating ALMA Sensitivity Using Single Dish Data'

The visibility properties



Visibility (V)

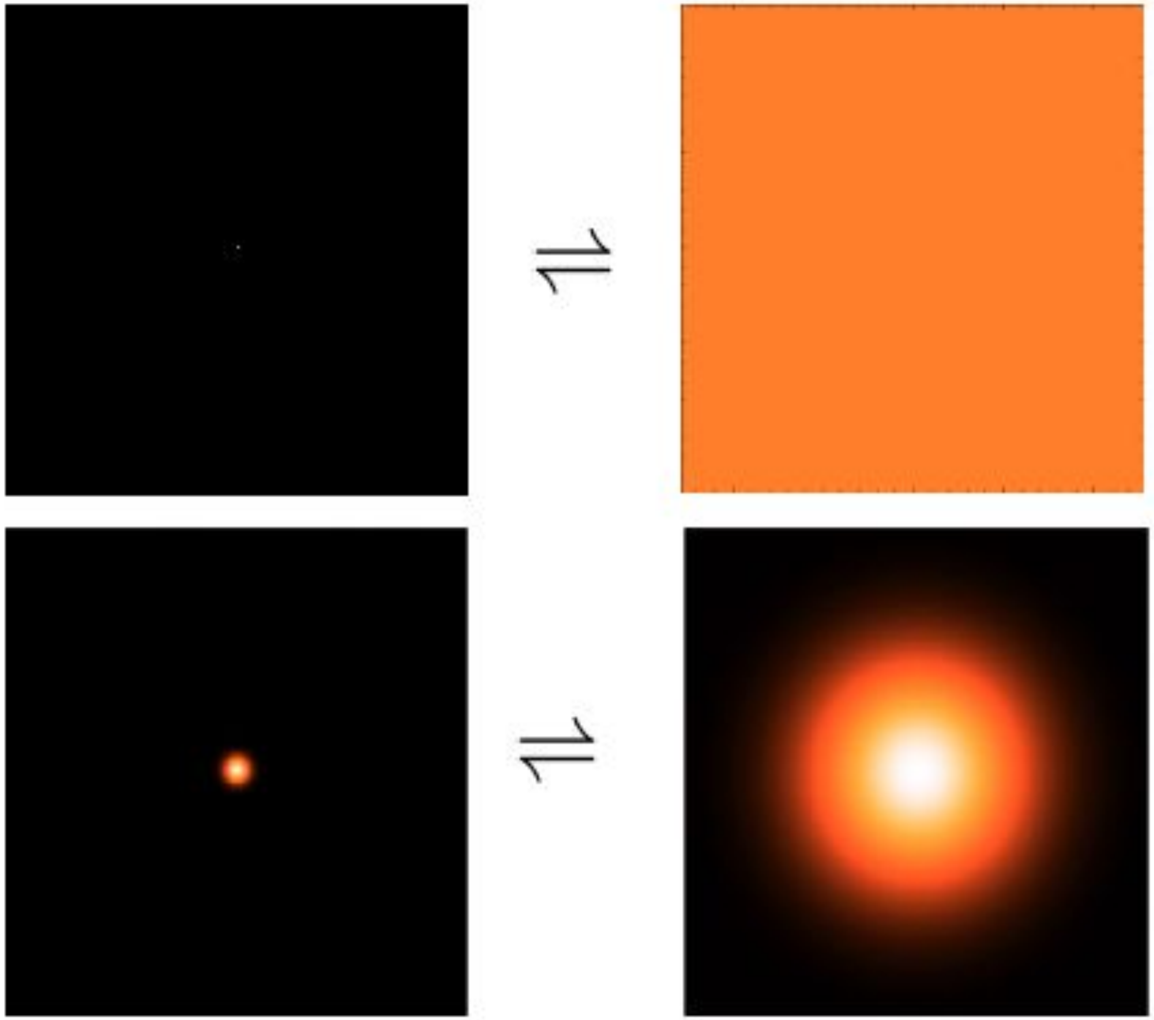
$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{Fringe\ Amplitude}{Average\ Intensity}$$

$V = A\, e^{-i\phi}$ where:

- A is amplitude tells “how much” of a certain frequency component
- ϕ is the phase “where” the component is located

Some 2D Fourier Transform Pairs

T(x,y) | Amp{V(u,v)}



δ Function ⇌ Constant

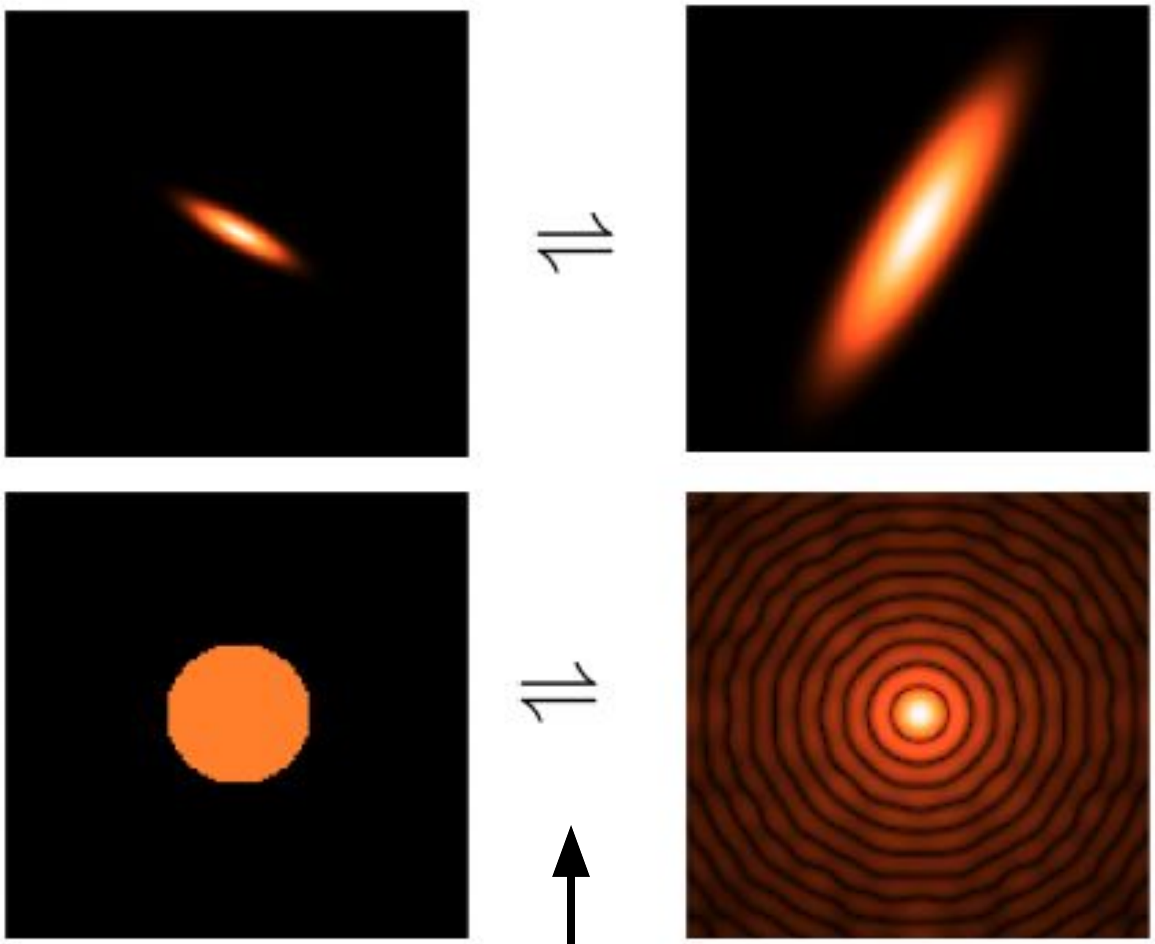
Gaussian ⇌ Gaussian

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

2D Fourier Transform Pairs

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

elliptical Gaussian



elliptical Gaussian

Disk

Bessel

Imaging from V(u,v) to T(x,y)

Calibration on V(u,v)

!!! See Luke talk ‘ALMA imaging basics’
+ Rosita talk on ‘ALMA calibration basics !!!

The image and u,v planes

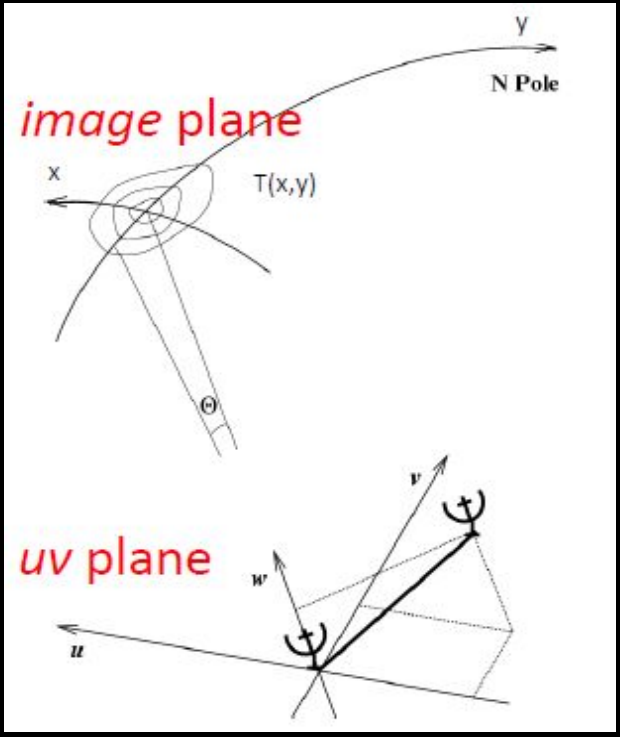
(van Cittert-Zernike theorem)

Fourier space/domain

$$V(u,v) = \int\int T(x,y)e^{2\pi i(ux+vy)}dxdy$$

$$T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$$

Image space/domain

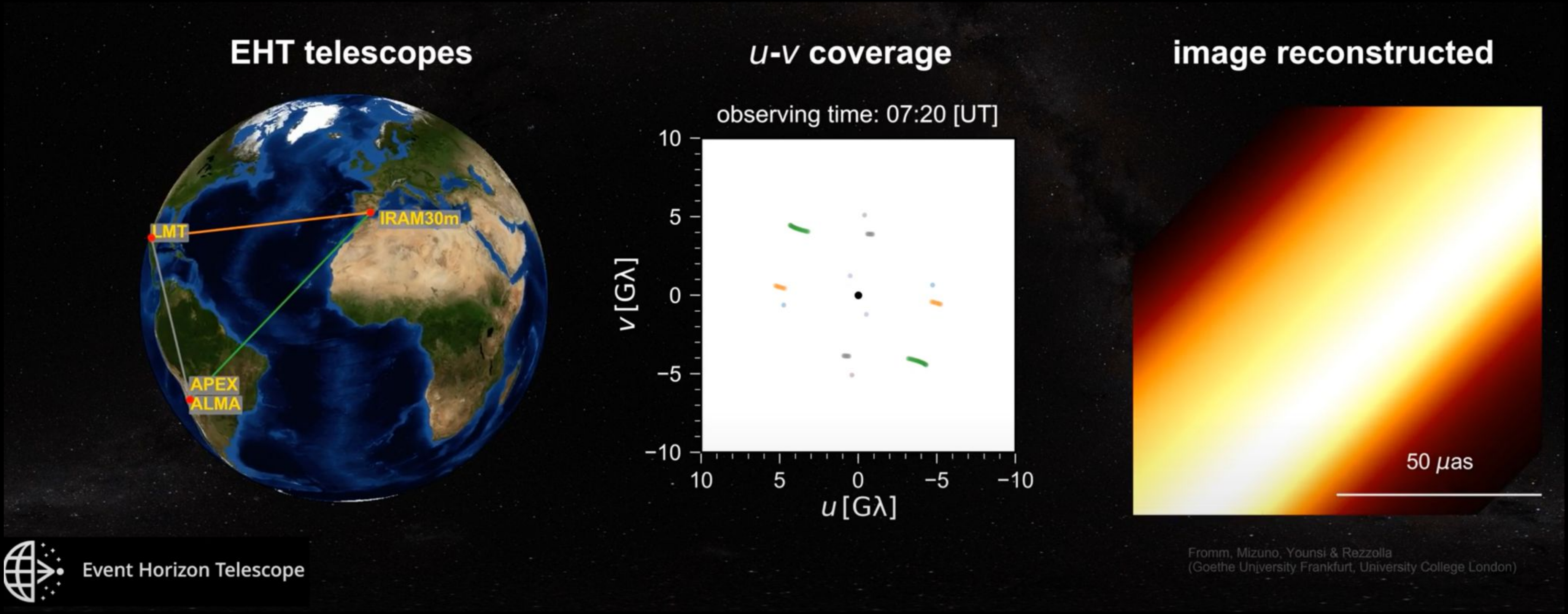


- **u,v (wavelengths)** are spatial frequencies in E-W and N-S, i.e the E-W and N-S component of the projected baselines

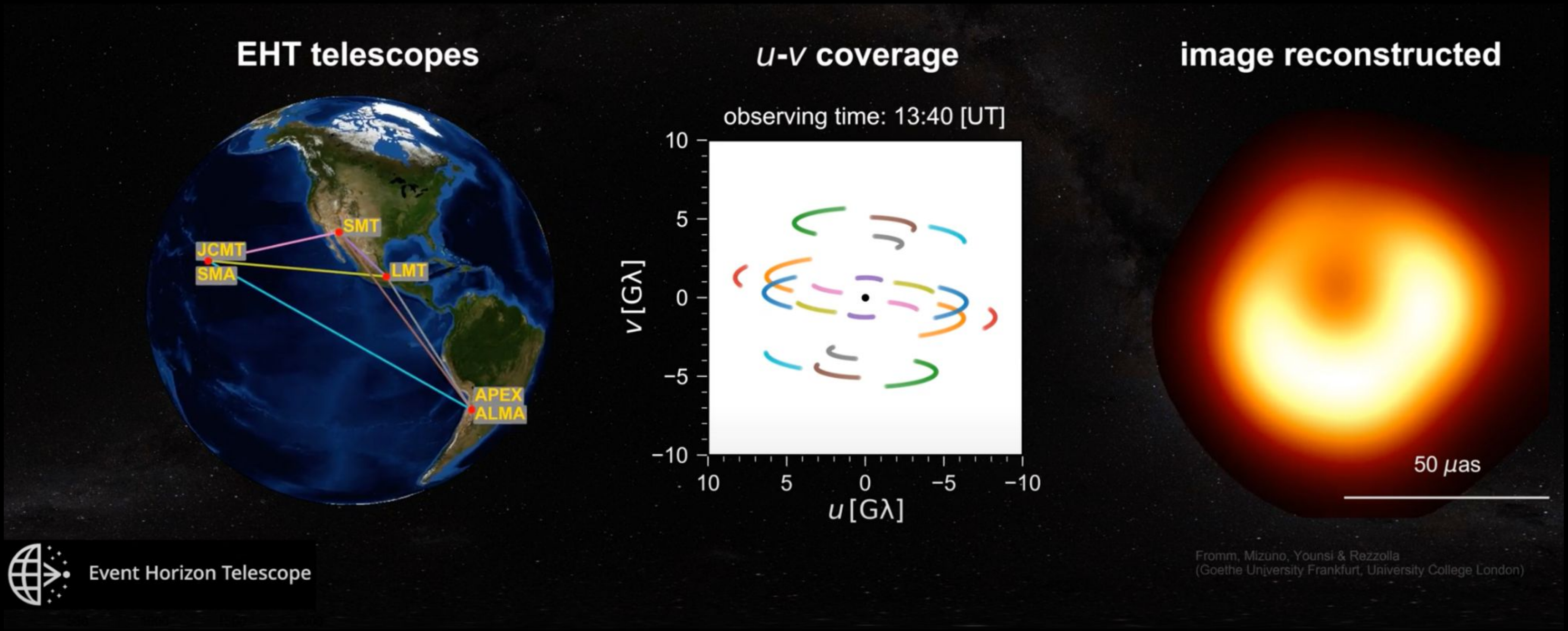
- **x,y (rad)** are angles in tangent plane related to a reference position in the E-W and N-S directions

!!! The (u,v) coverage is crucial: it determines the image fidelity !!!

The image fidelity

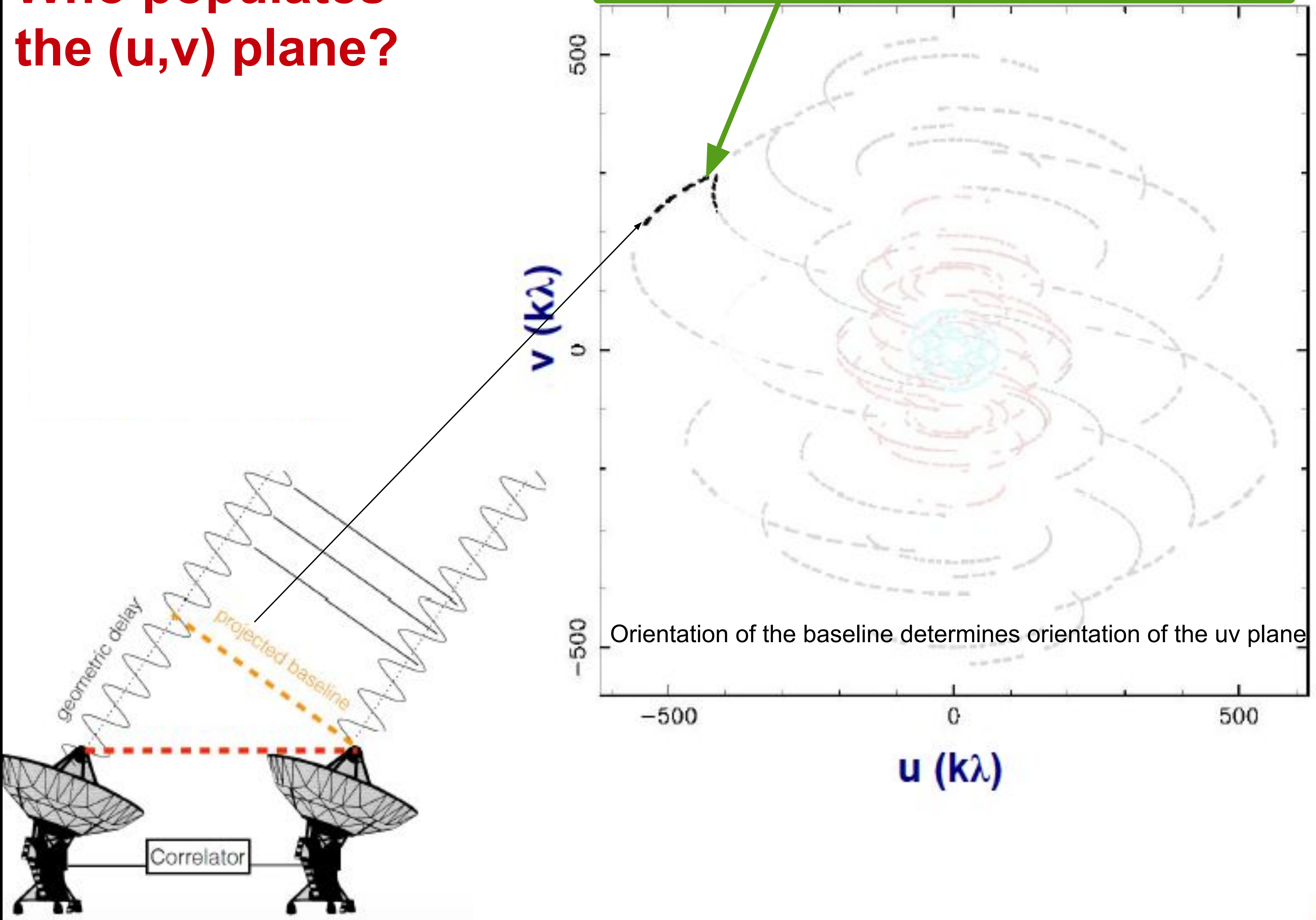


The image fidelity



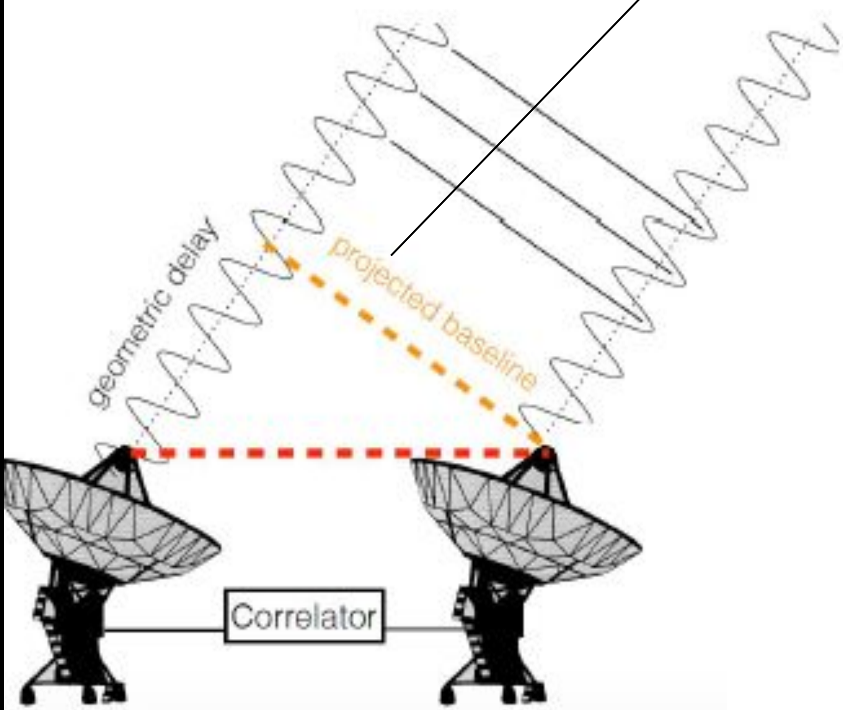
Who populates the (u,v) plane?

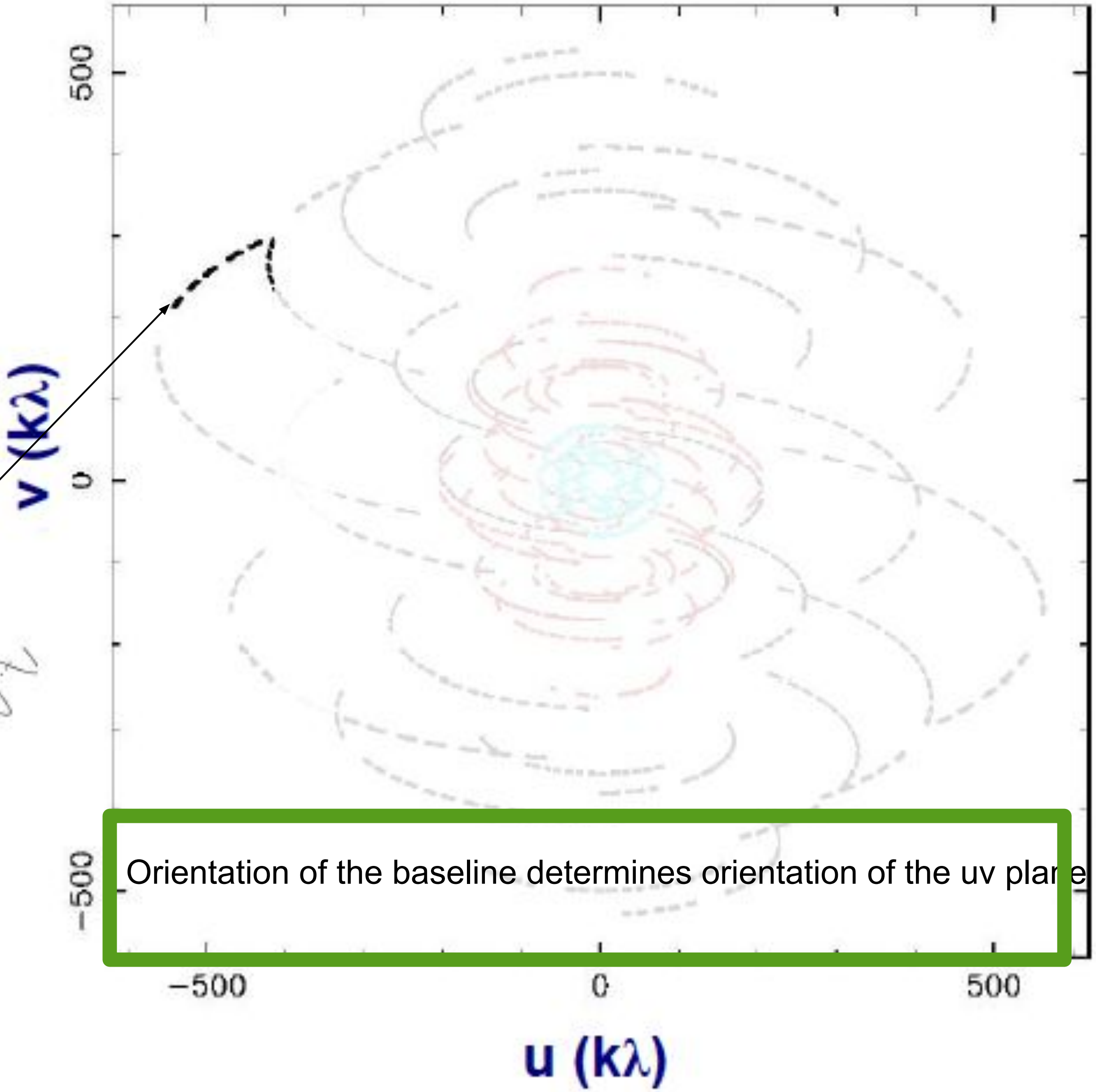
Each antenna pair → a point in the (u,v) plane



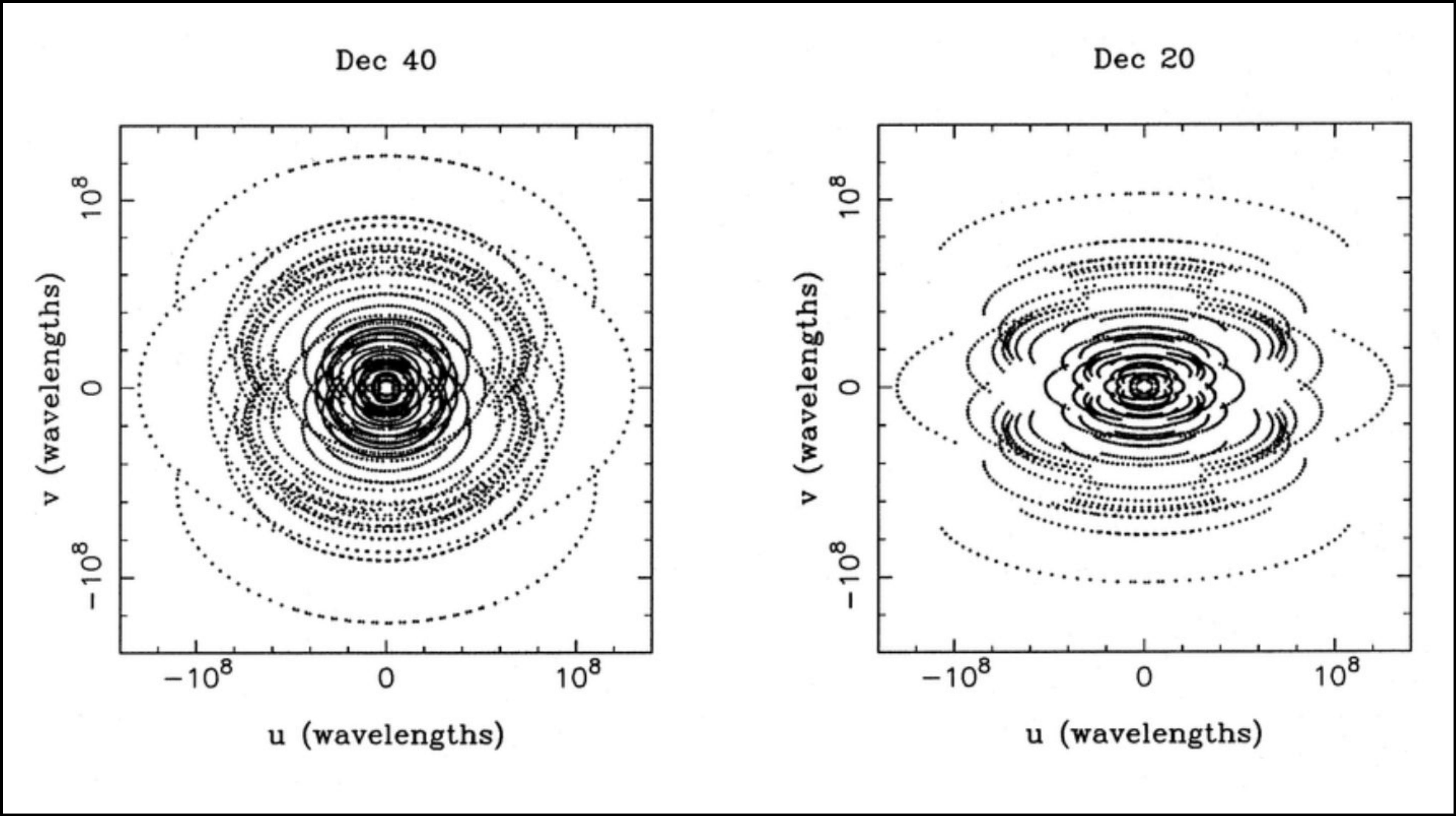
NB: the projected baseline!!

Each antenna pair → a point in the (u,v) plane





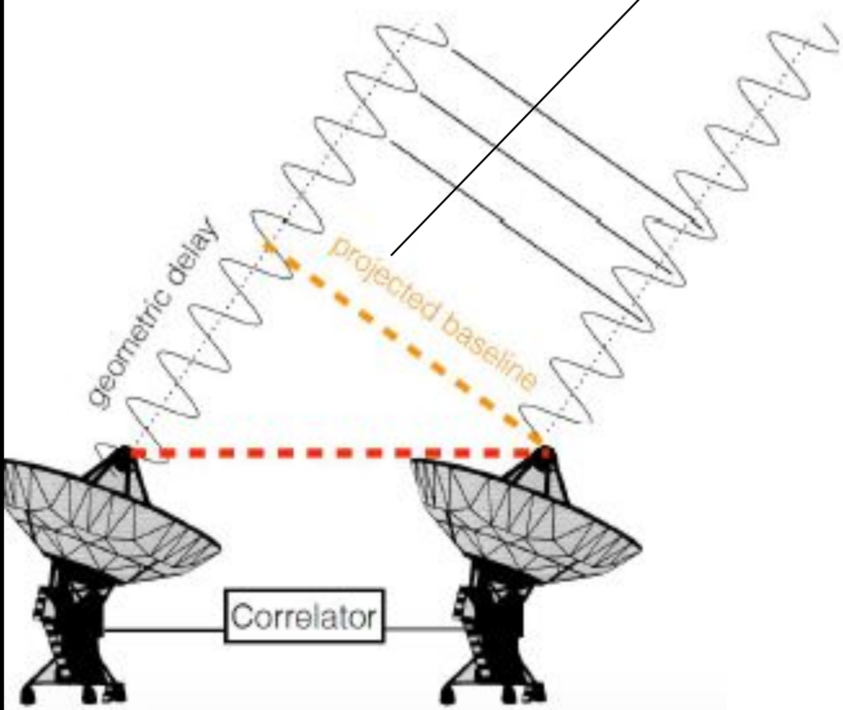
The uv plane orientation depends on the source position

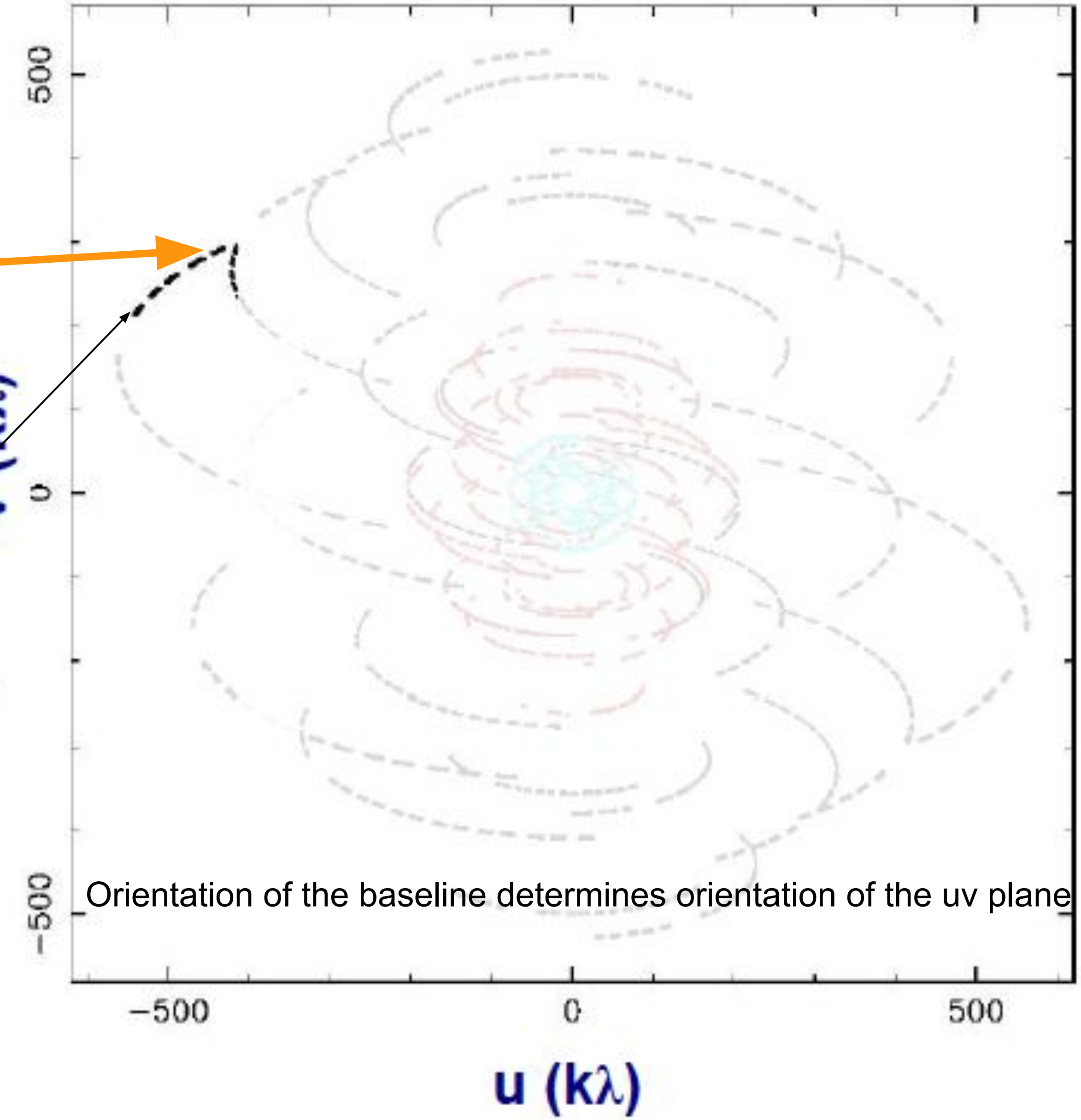


How many (u,v) points?

Each antenna pair → a point in the (u,v) plane

1 V for each:
- integration time,
- channel,
- projected baseline,
- correlation



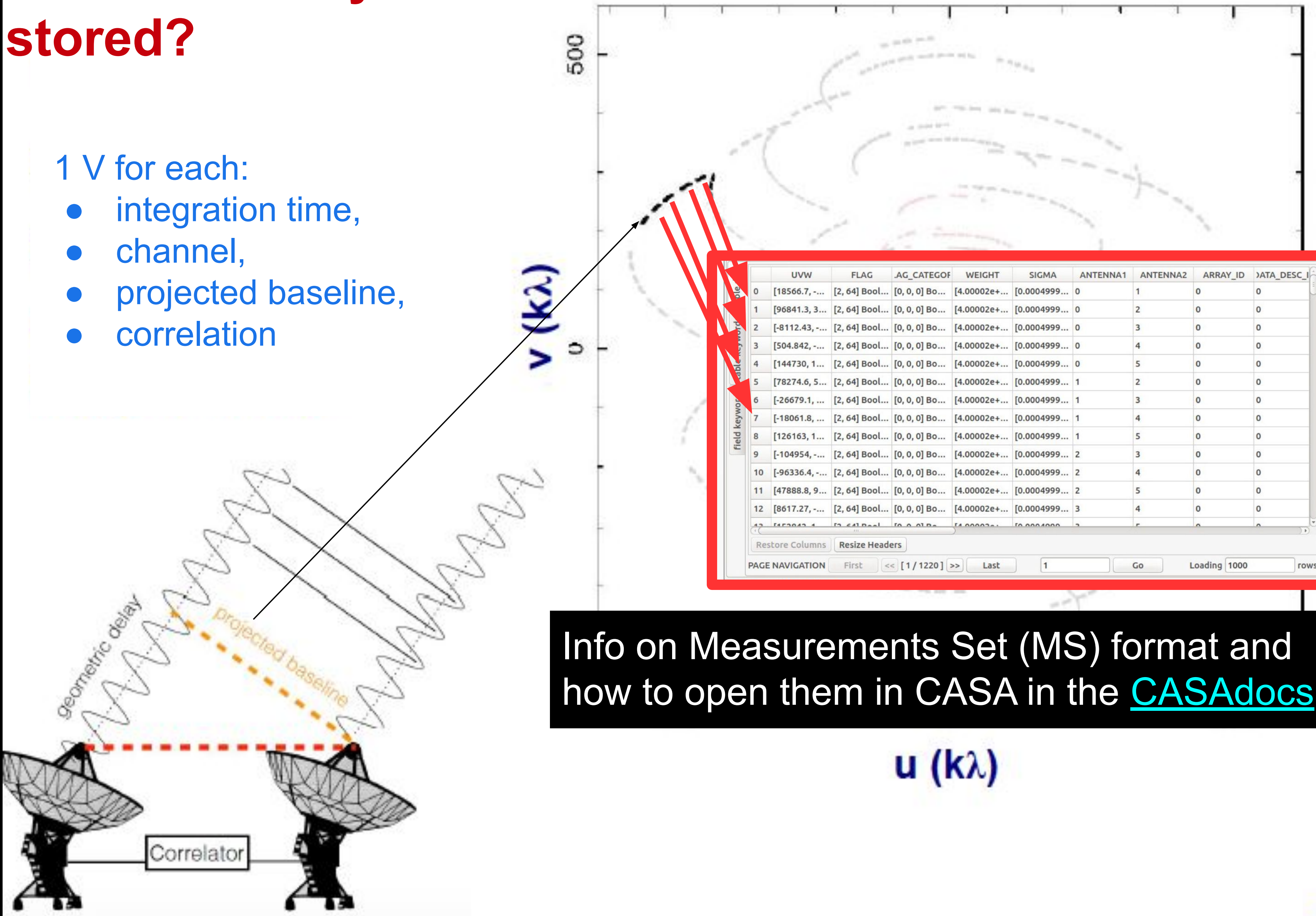


Where are they stored?

Each antenna pair → a point in the (u,v) plane

1 V for each:

- integration time,
- channel,
- projected baseline,
- correlation



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0	[18566.7, -...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	0	1	0	0
1	[96841.3, 3...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	0	2	0	0
2	[-8112.43, -...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	0	3	0	0
3	[504.842, -...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	0	4	0	0
4	[144730, 1...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	0	5	0	0
5	[78274.6, 5...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	1	2	0	0
6	[-26679.1, ...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	1	3	0	0
7	[-18061.8, ...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	1	4	0	0
8	[126163, 1...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	1	5	0	0
9	[-104954, -...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	2	3	0	0
10	[-96336.4, -...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	2	4	0	0
11	[47888.8, 9...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	2	5	0	0
12	[8617.27, -...	[2, 64] Bool...	[0, 0, 0] Bo...	[4.00002e+...	[0.0004999...	3	4	0	0

Restore Columns | Resize Headers

PAGE NAVIGATION First << [1 / 1220] >> Last 1 Go Loading 1000 rows.

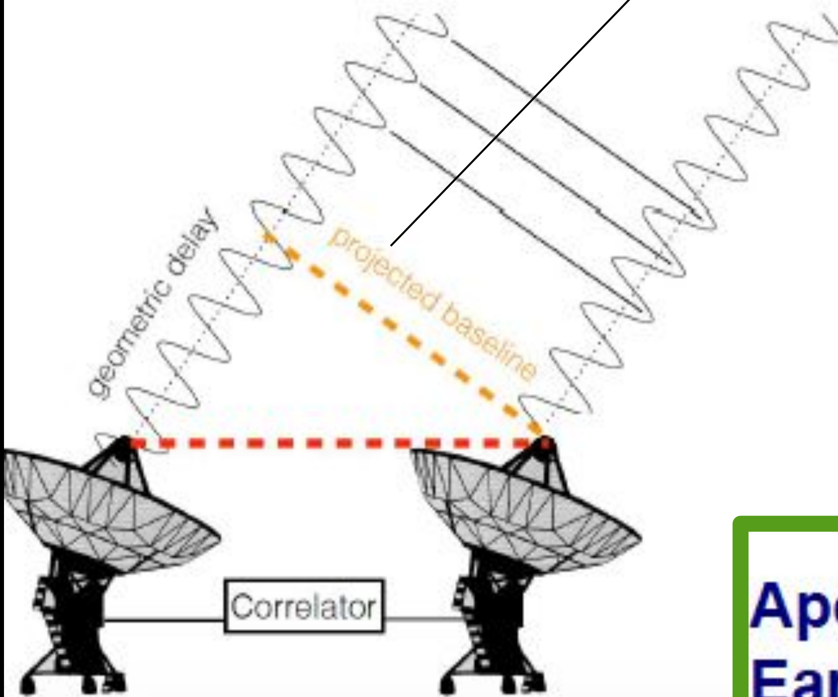
Info on Measurements Set (MS) format and how to open them in CASA in the [CASAdocs]

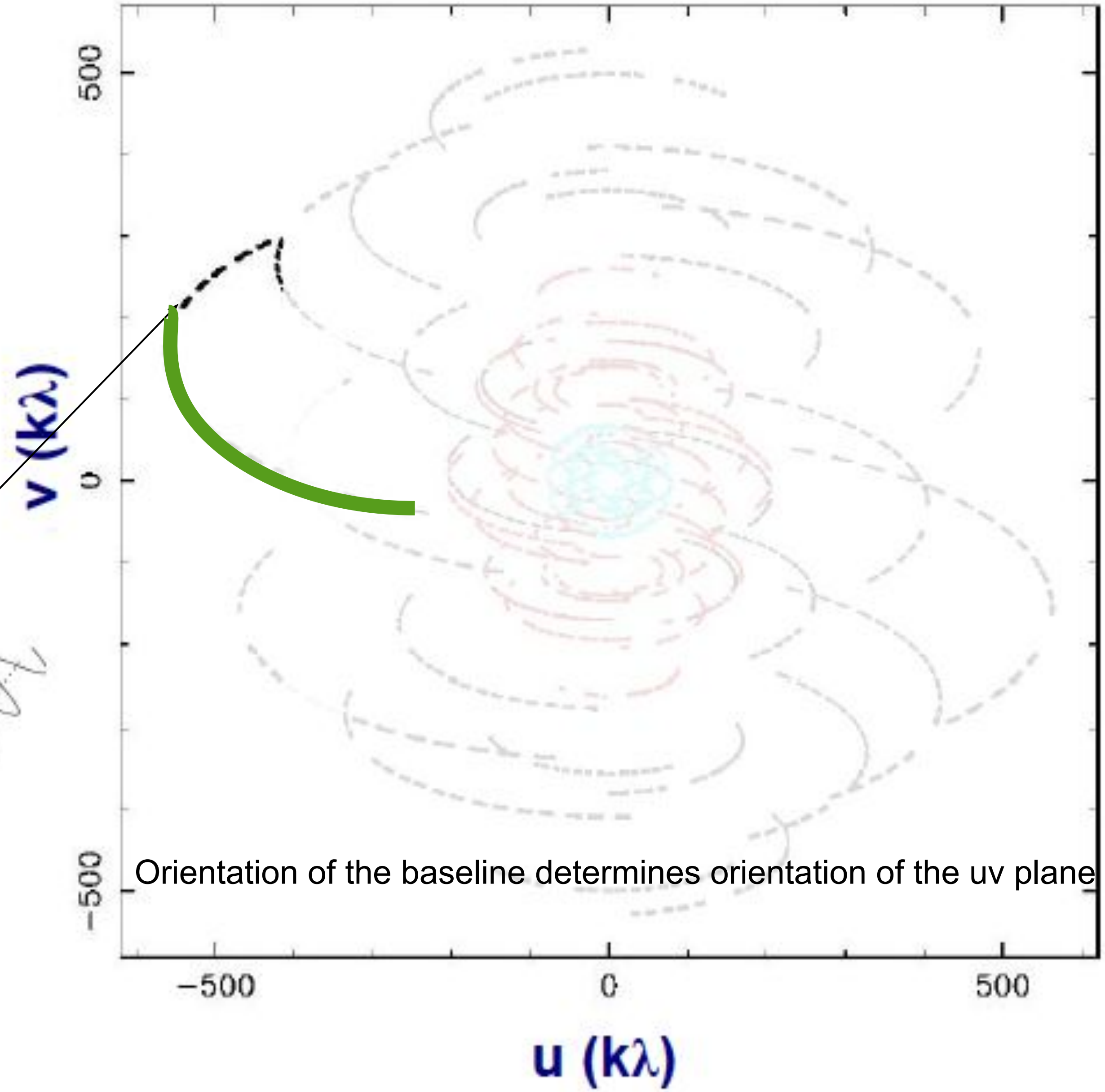
How cover the (u,v) plane?

Each antenna pair → a point in the (u,v) plane

1 V for each:

- integration time,
- channel,
- projected baseline,
- correlation





Aperture synthesis:
Earth rotation helps covering the uv plane

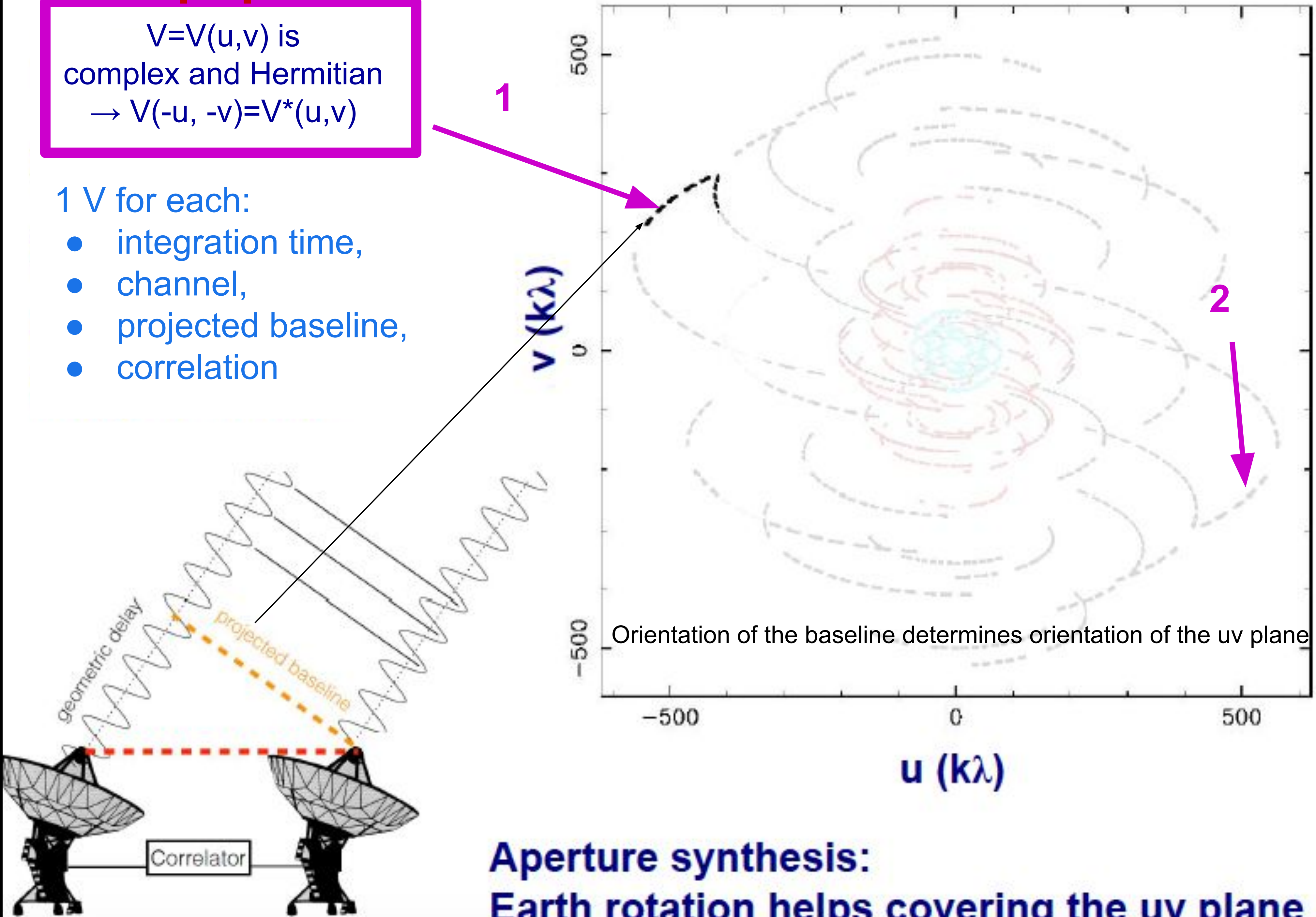
How it populates?

V=V(u,v) is
complex and Hermitian
→ V(-u, -v)=V*(u,v)

1 V for each:

- integration time,
- channel,
- projected baseline,
- correlation

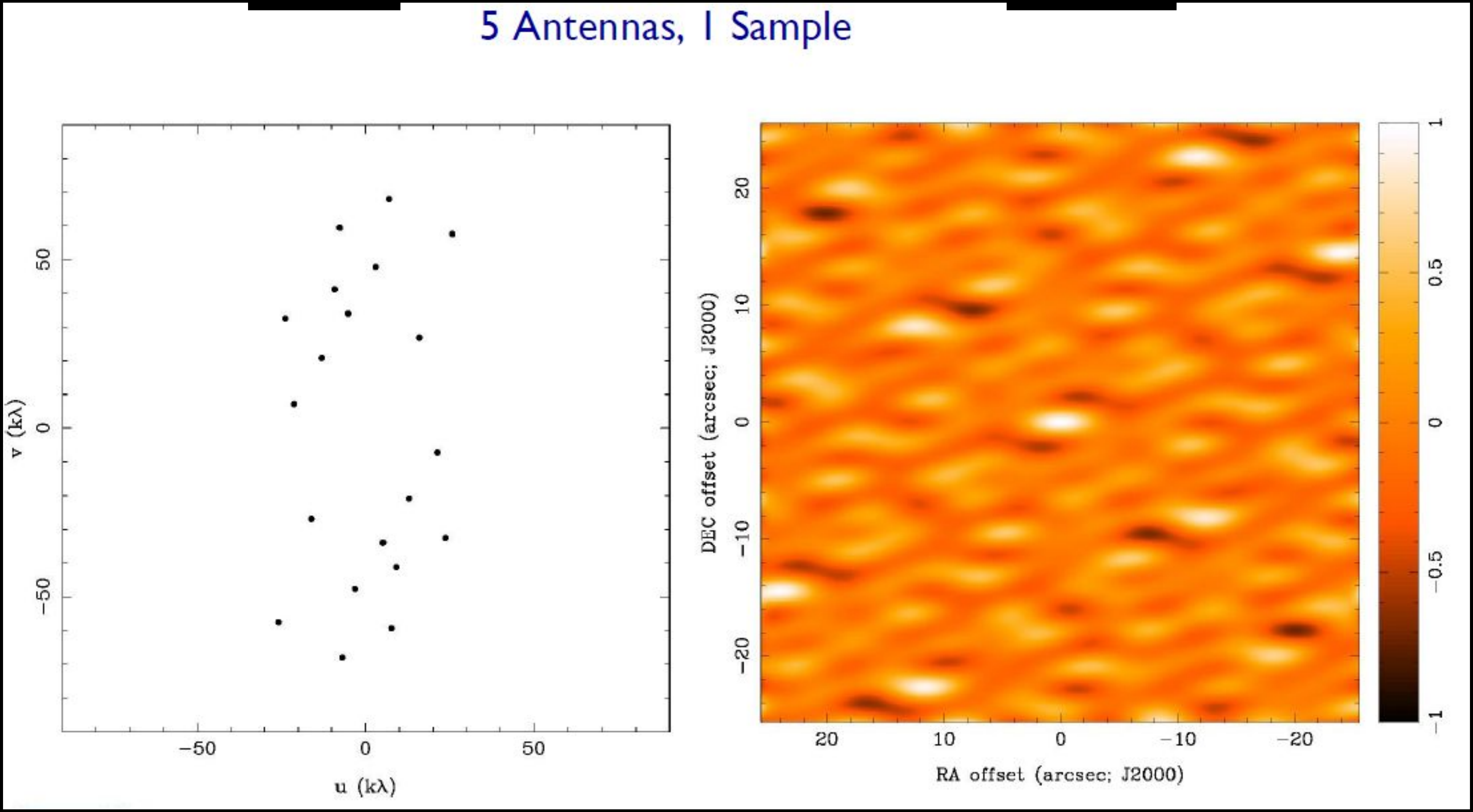
Each antenna pair → a point in the (u,v) plane



Aperture synthesis:
Earth rotation helps covering the uv plane

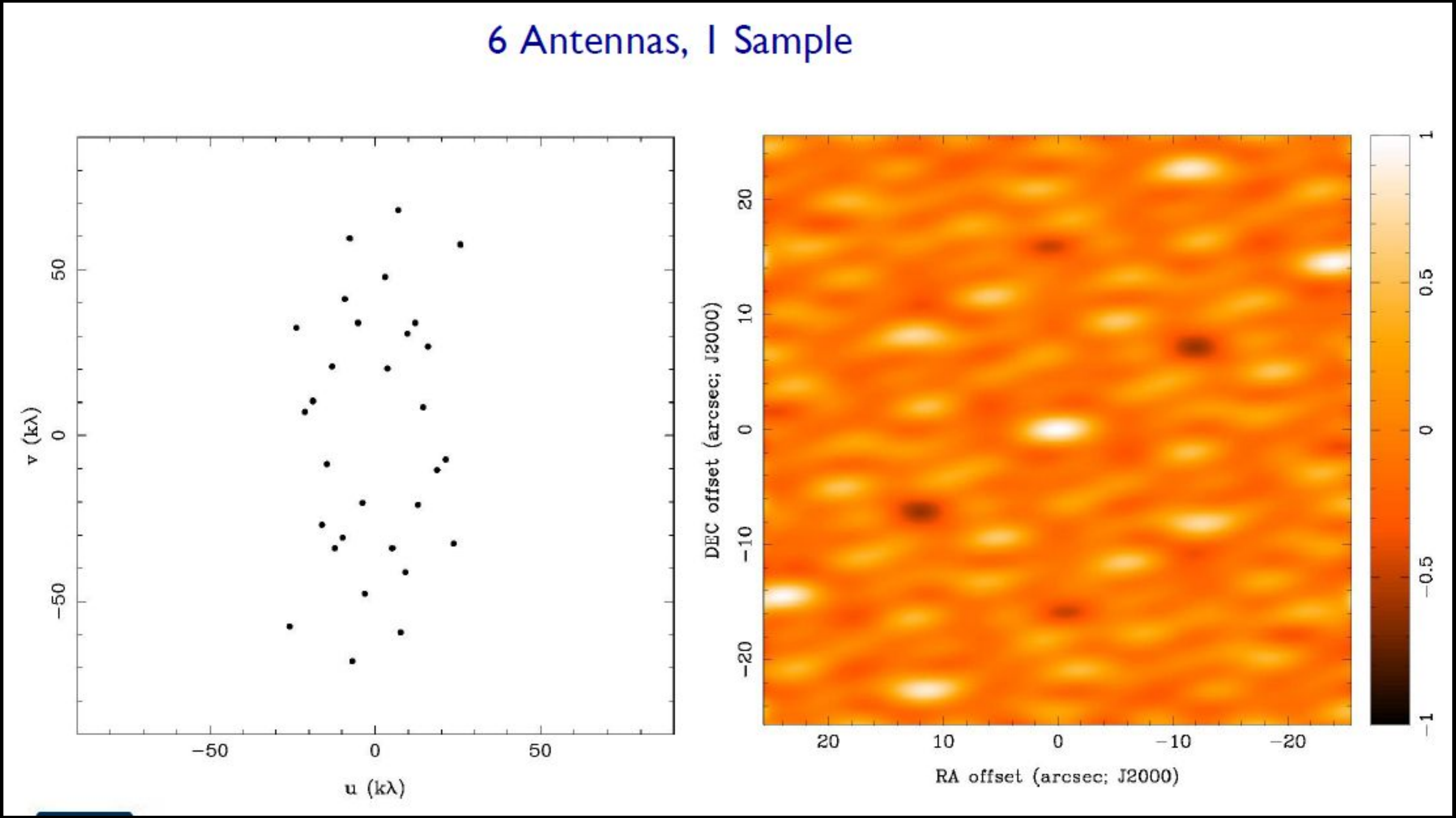
PSF shape vs N ants, time

(u,v) PSF



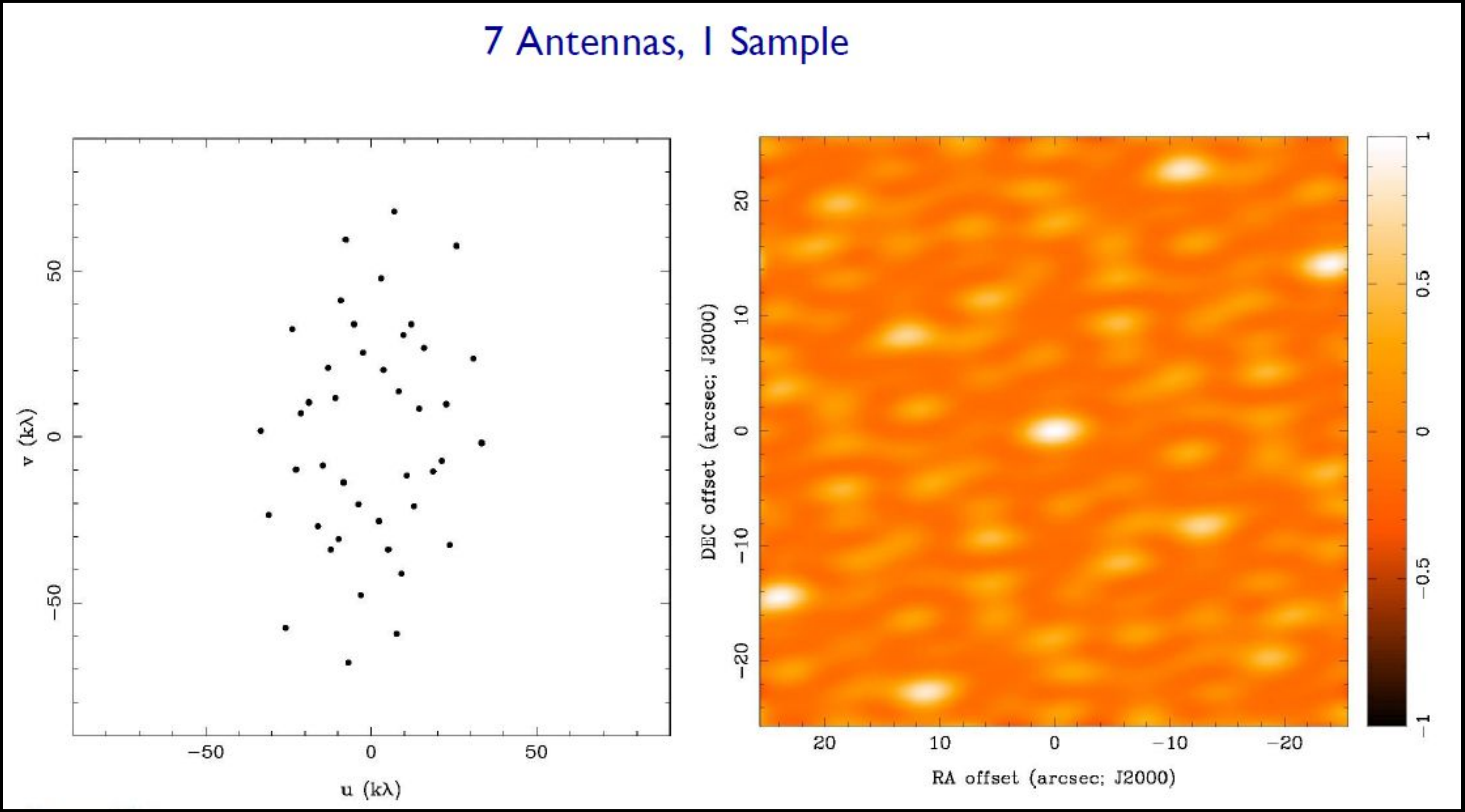
PSF shape vs N ants, time

> N ants



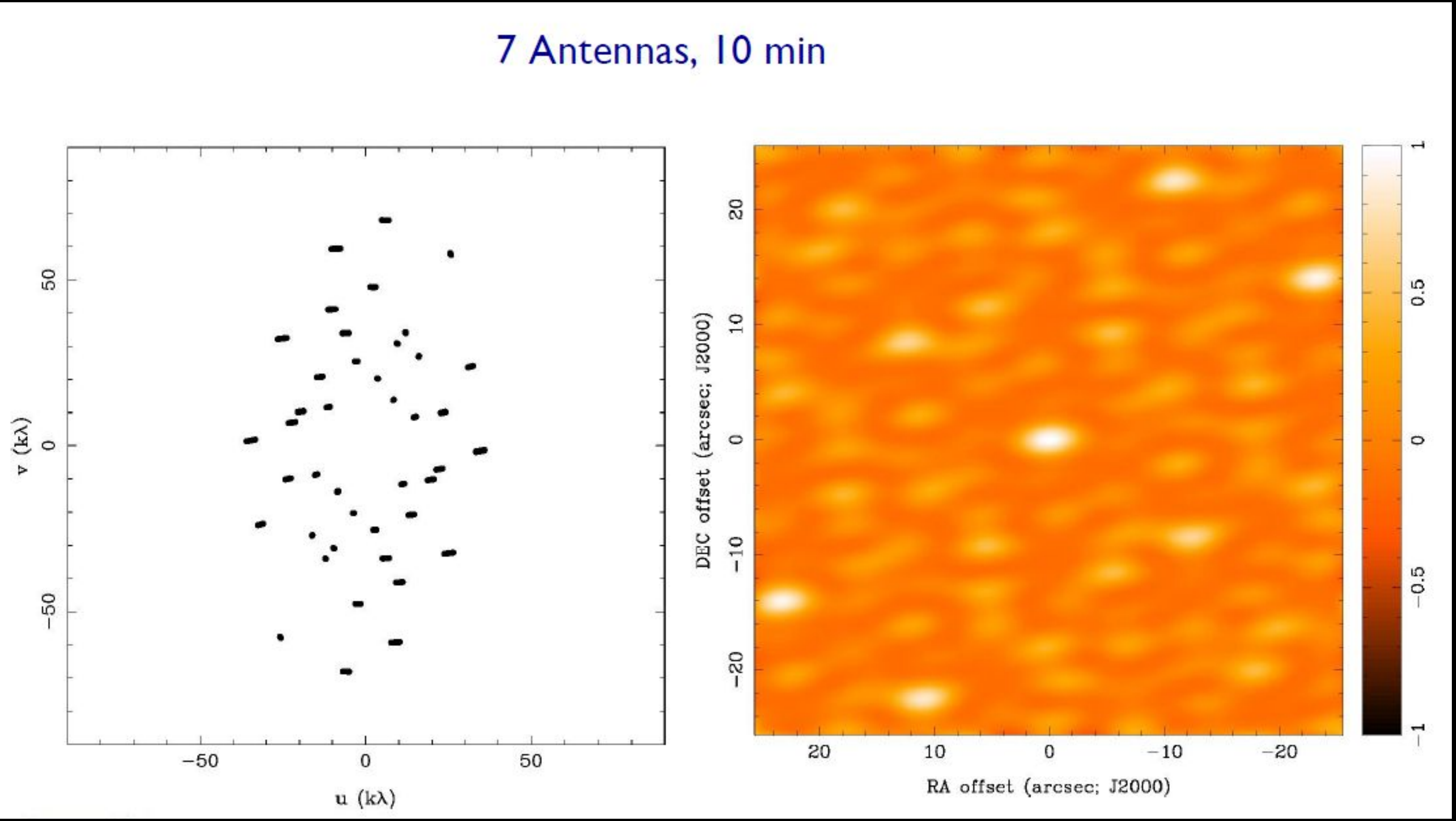
PSF shape vs N ants, time

> N ants



PSF shape vs N ants, time

> time



PSF shape vs N ants, time

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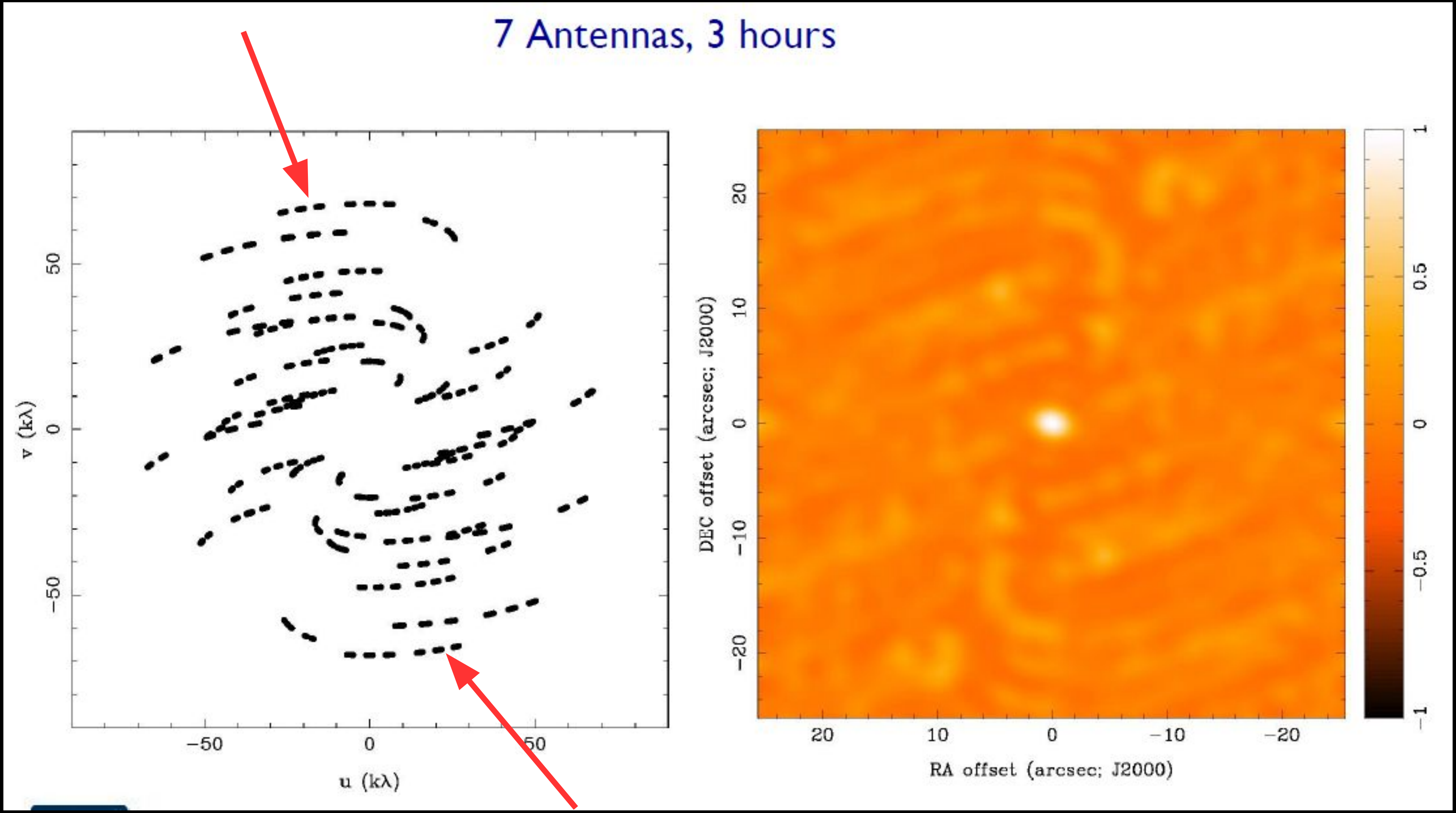

PSF shape vs N ants, time

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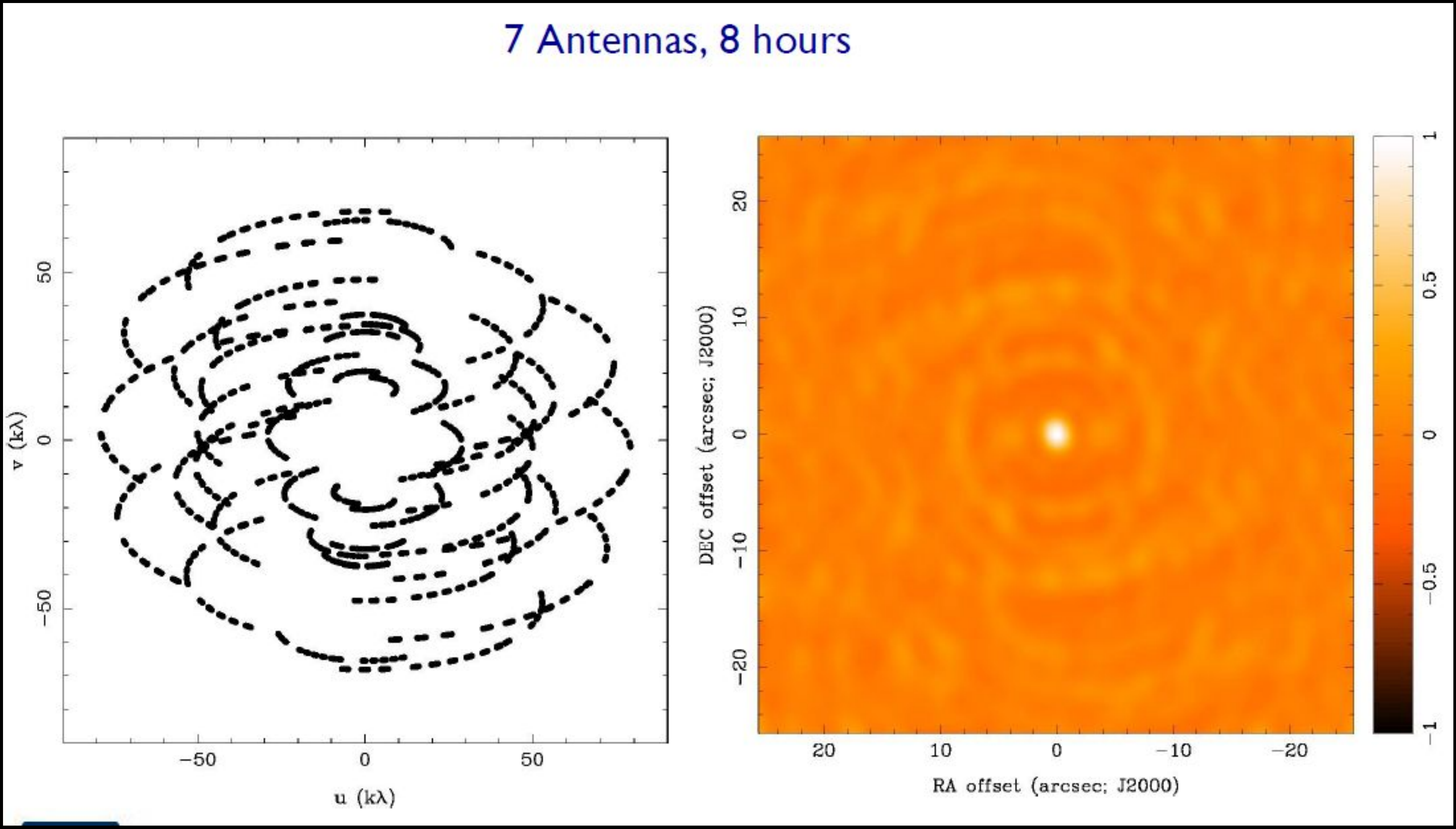
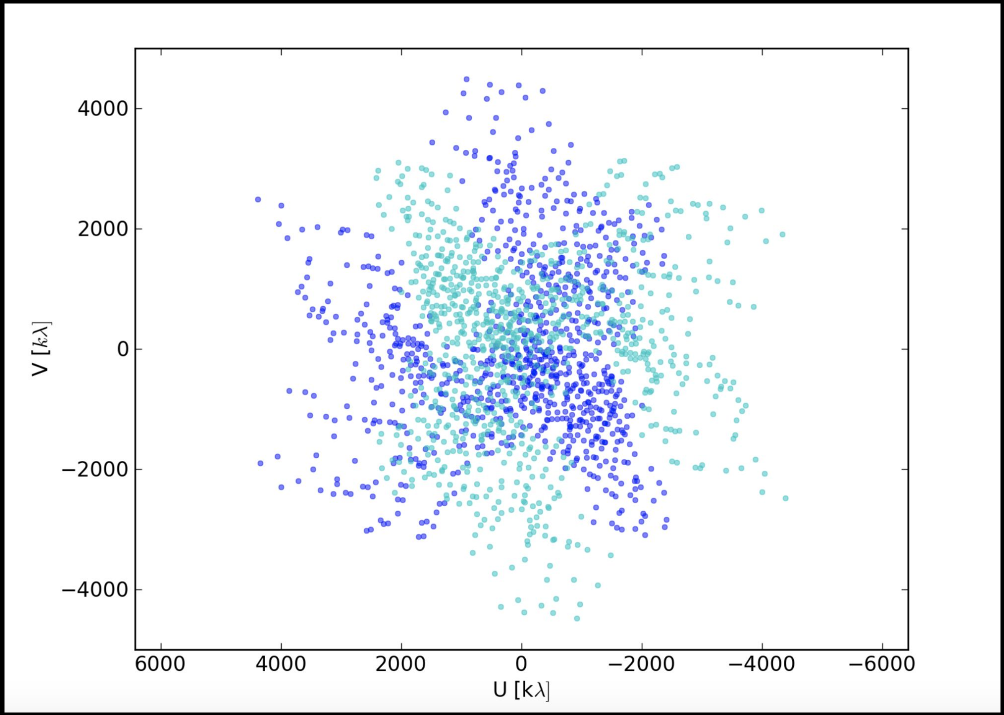
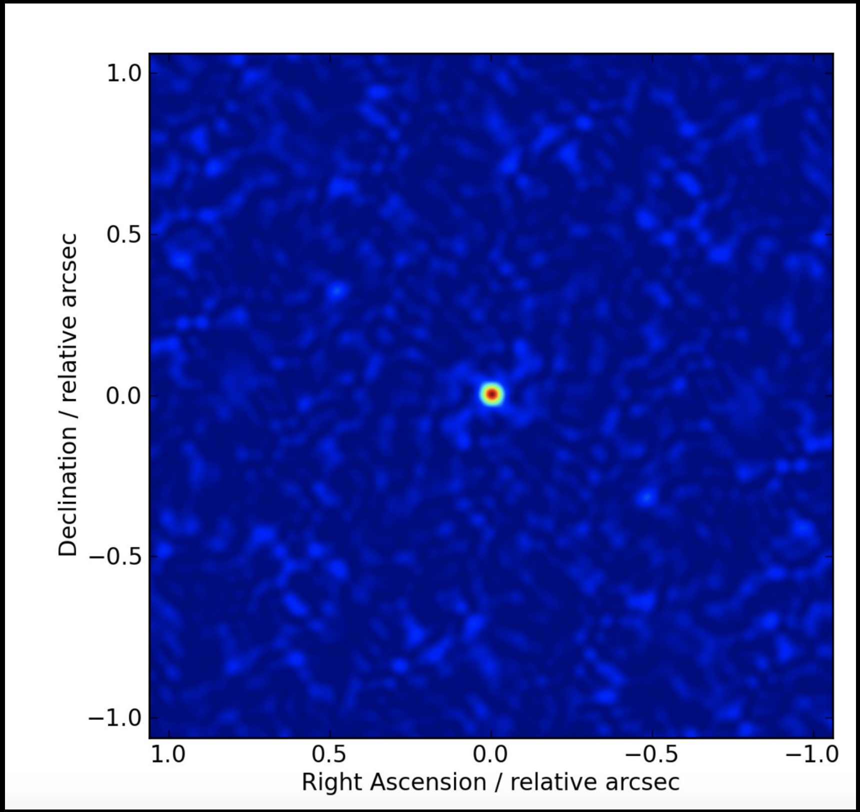


ALMA 66 antennas, 20 sec

ALMA has a quasi-instantaneous uv coverage!!



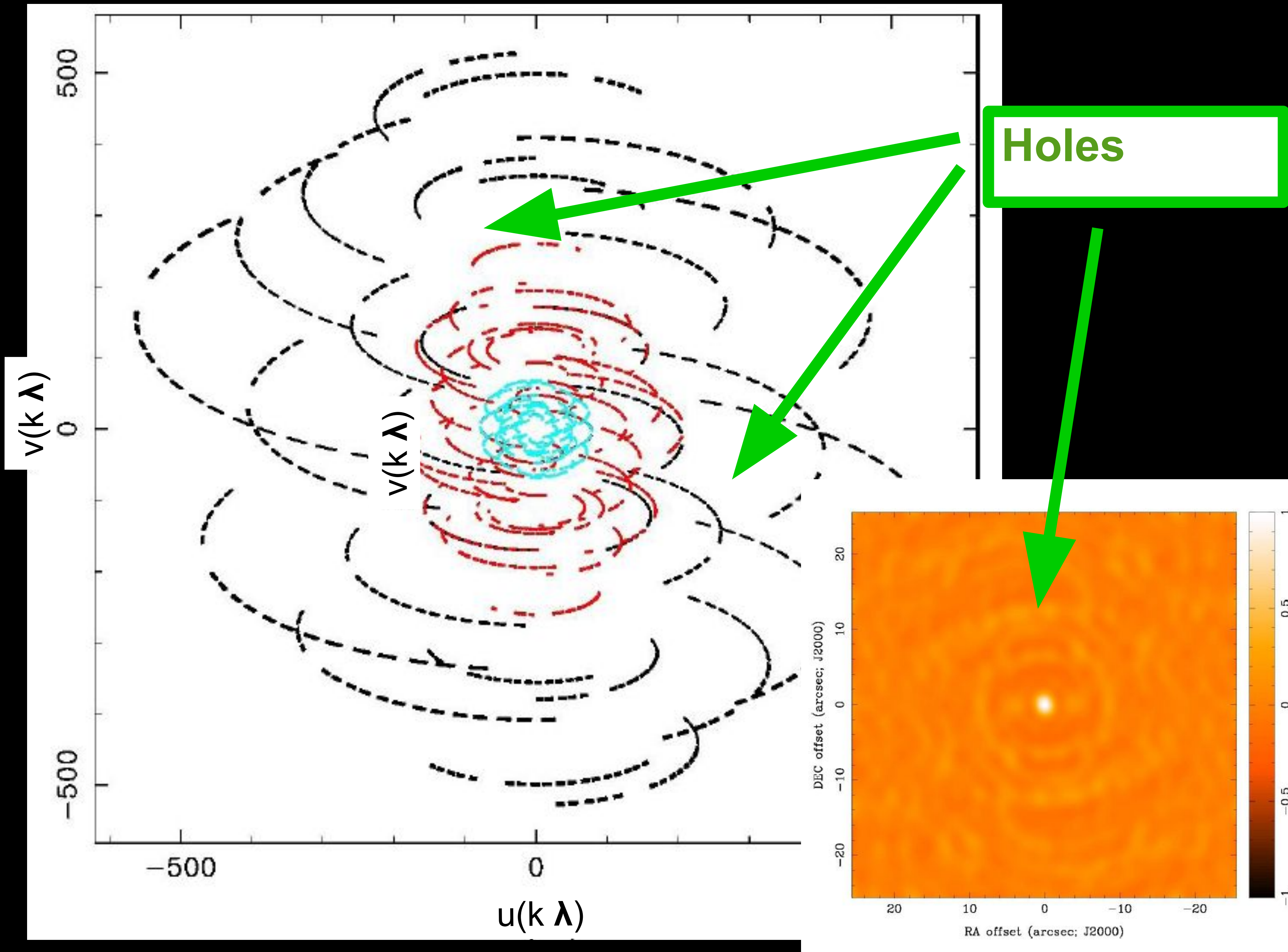


To simulate the PSF of ALMA observations with different integration time and N antennas:

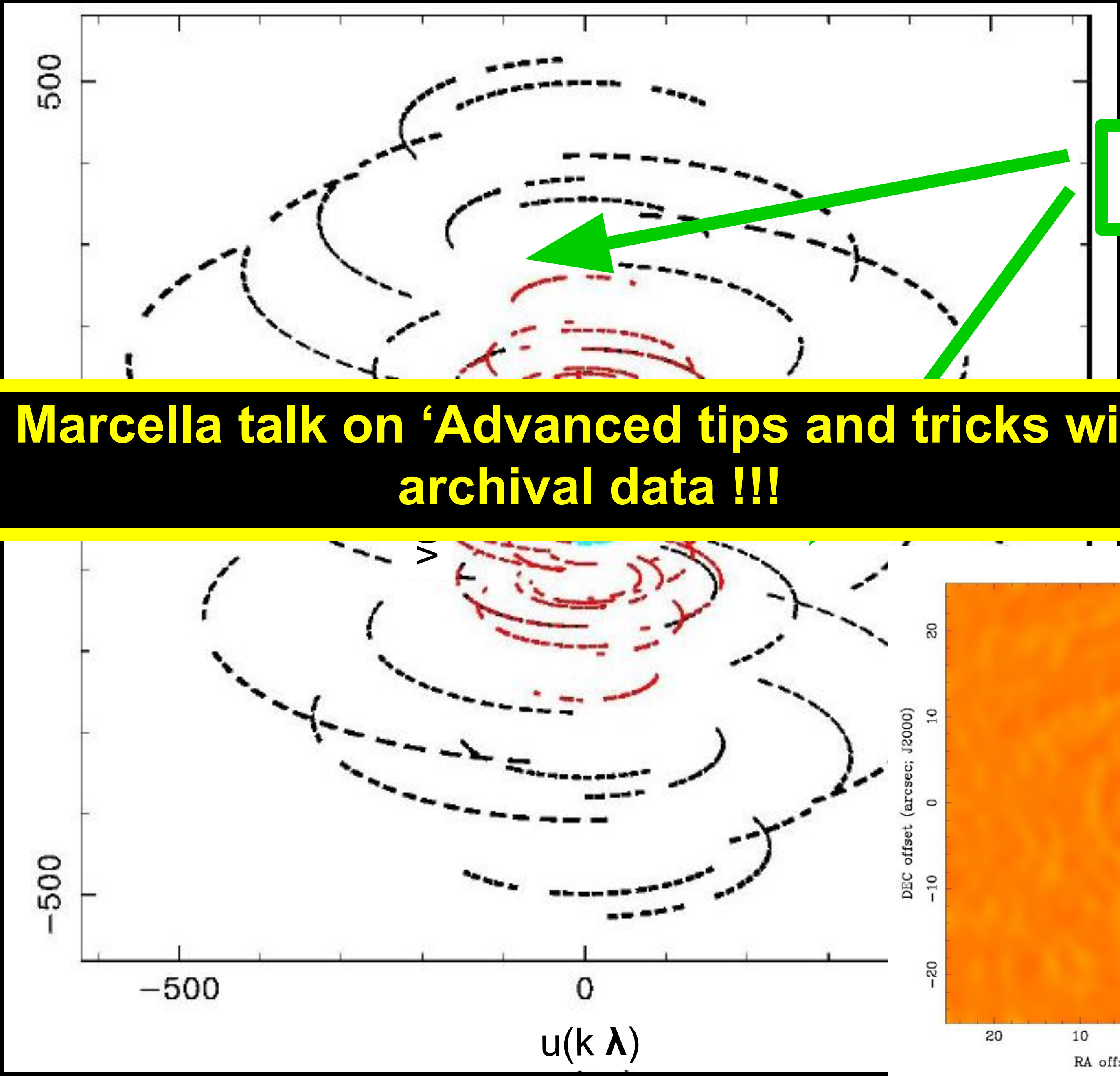
* APSynSim: See also i-TRAIN on ApSynSIm

* ALMA Observation Support Tool

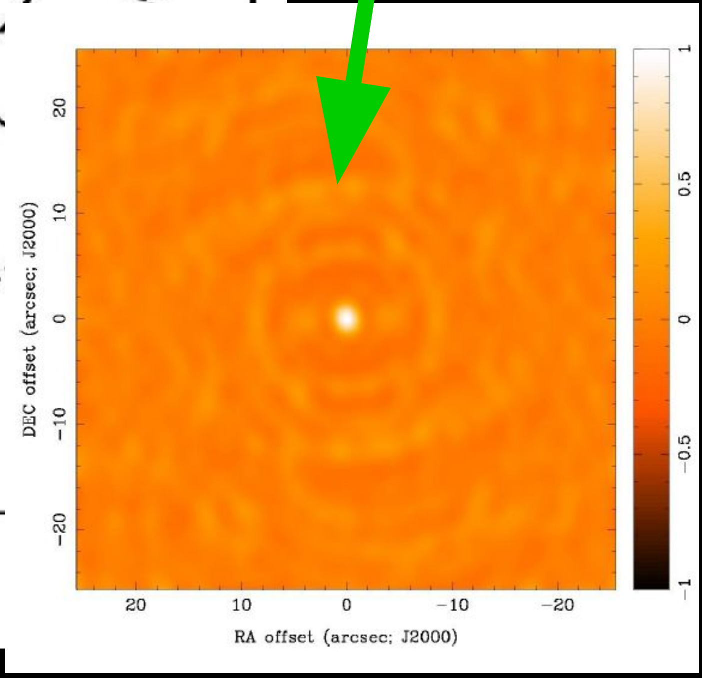
Not perfect (u,v) coverage → less image quality



Not perfect (u,v) coverage → less image quality

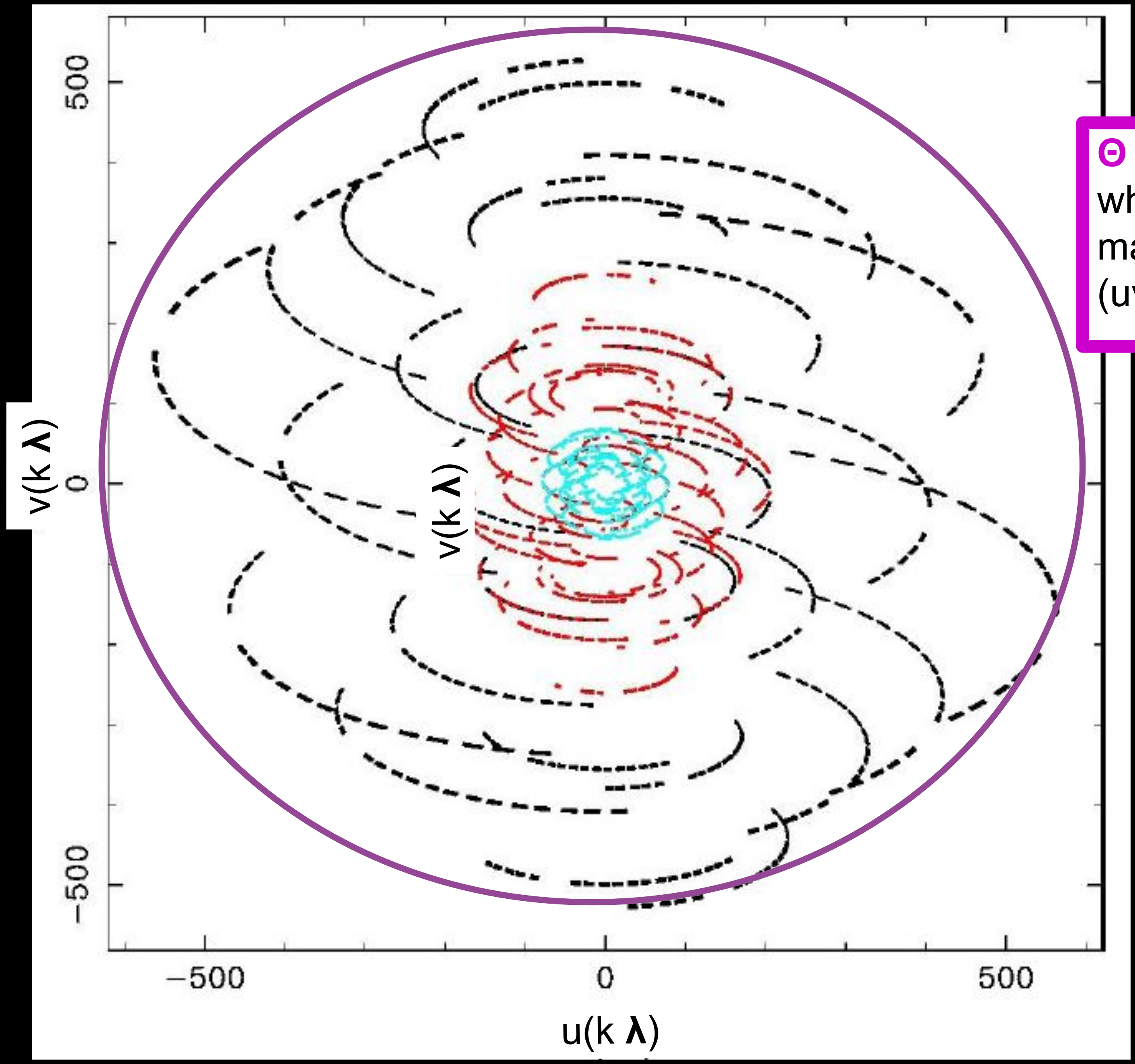


Holes



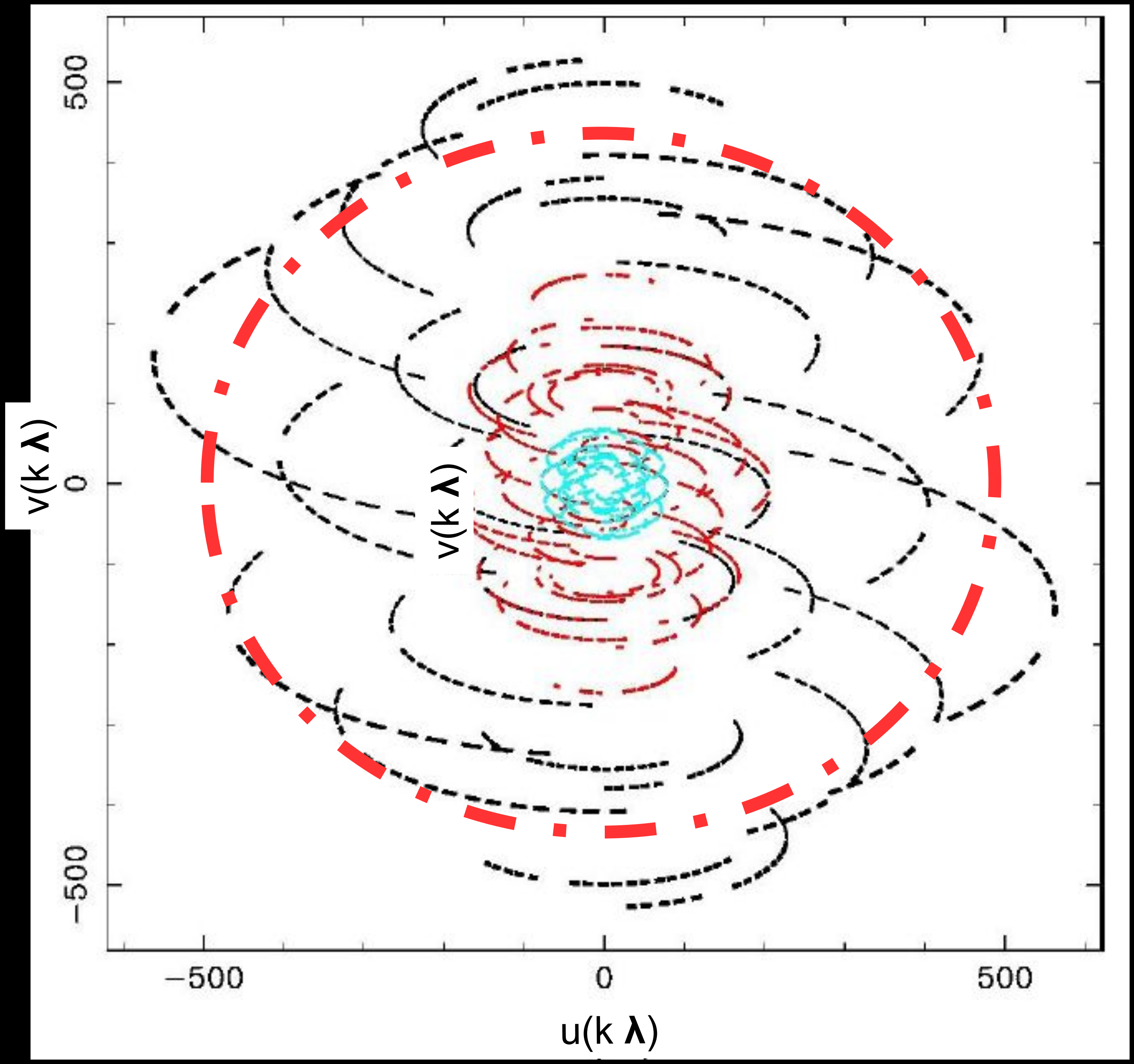
!!! see Marcella talk on ‘Advanced tips and tricks with ALMA archival data !!!

Highest angular resolution

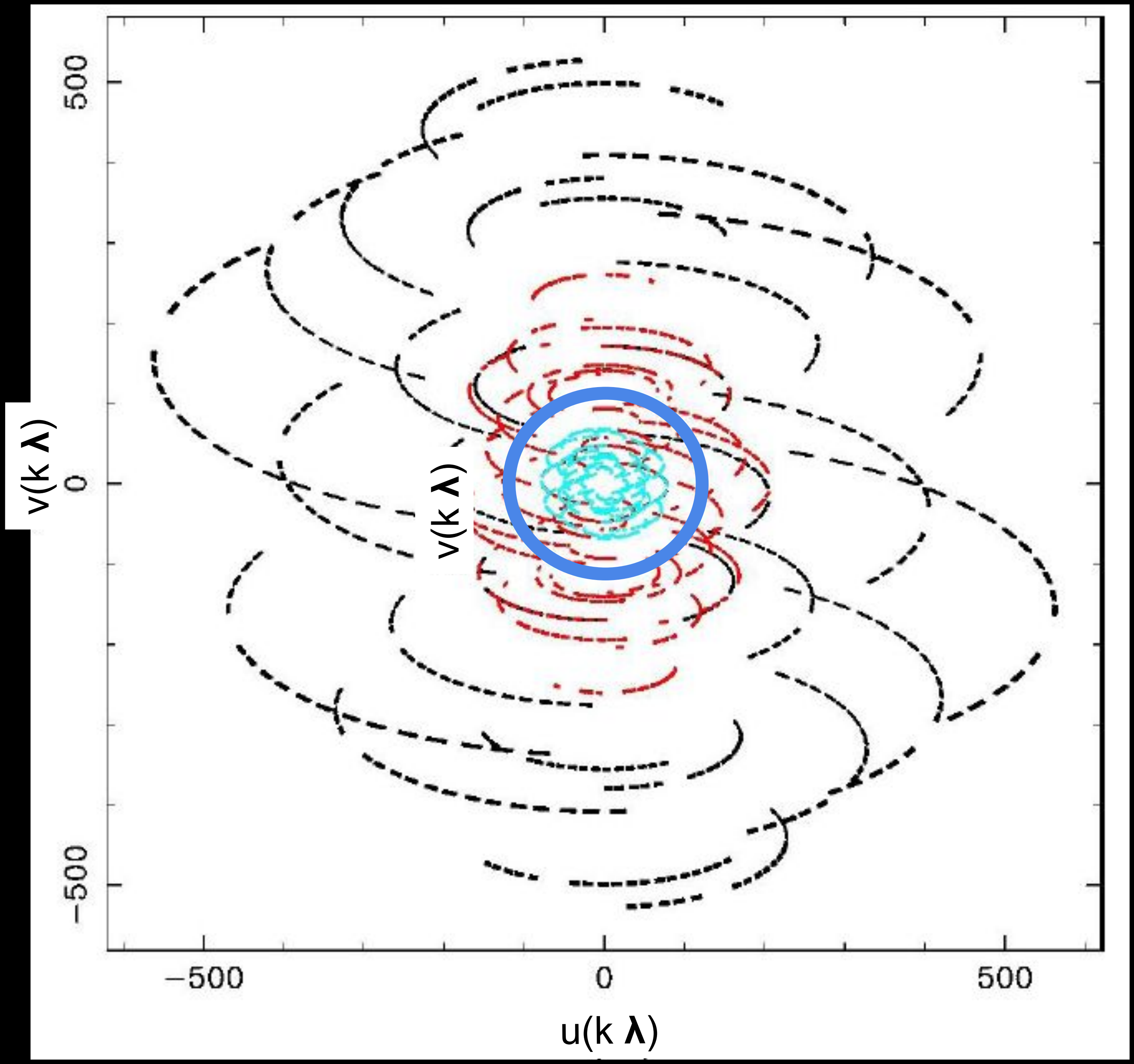


$\Theta_{res} \sim \lambda / B_{max}$
where B_{max} is the maximun baseline (uv distance)

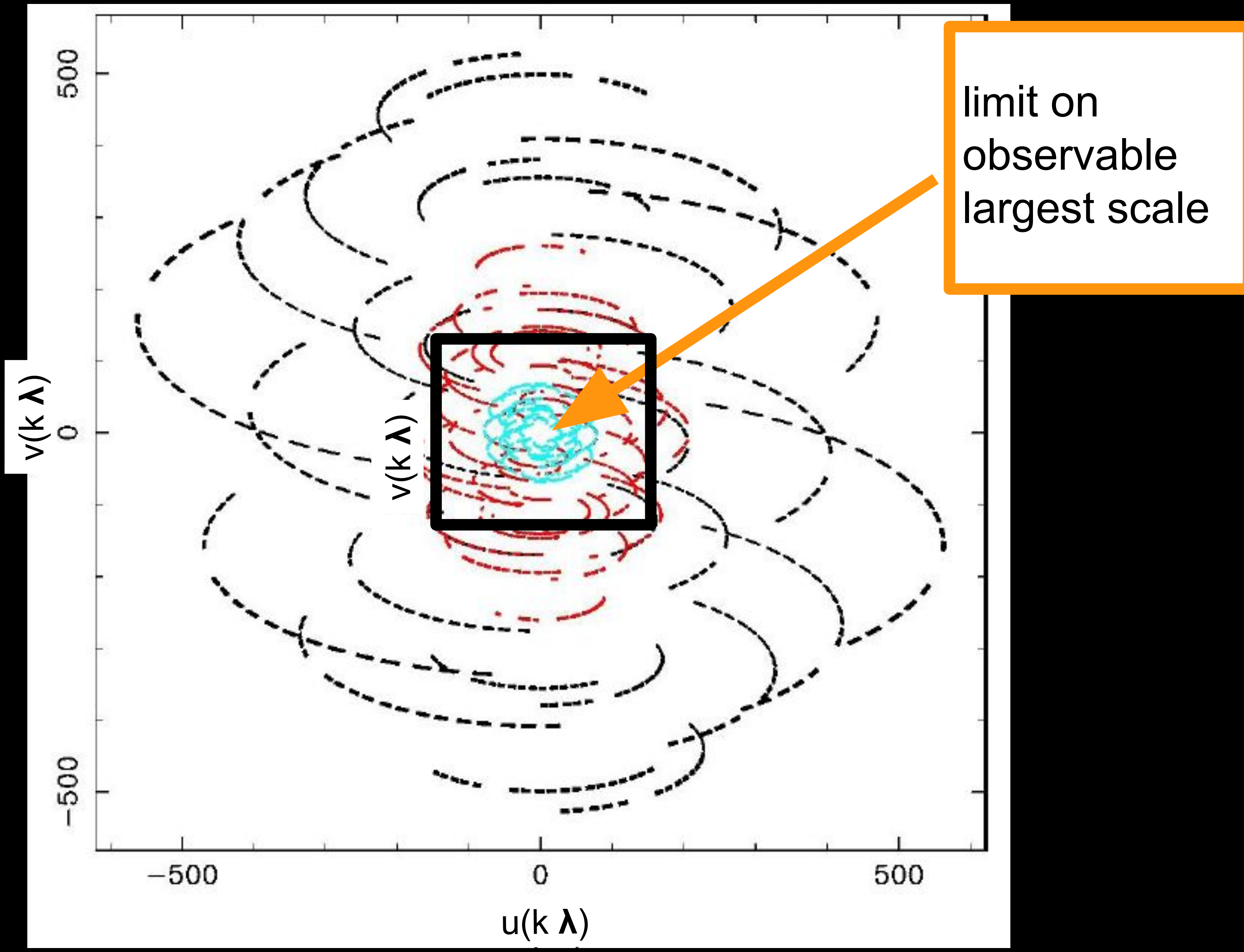
Long (u,v) distance → compact emission



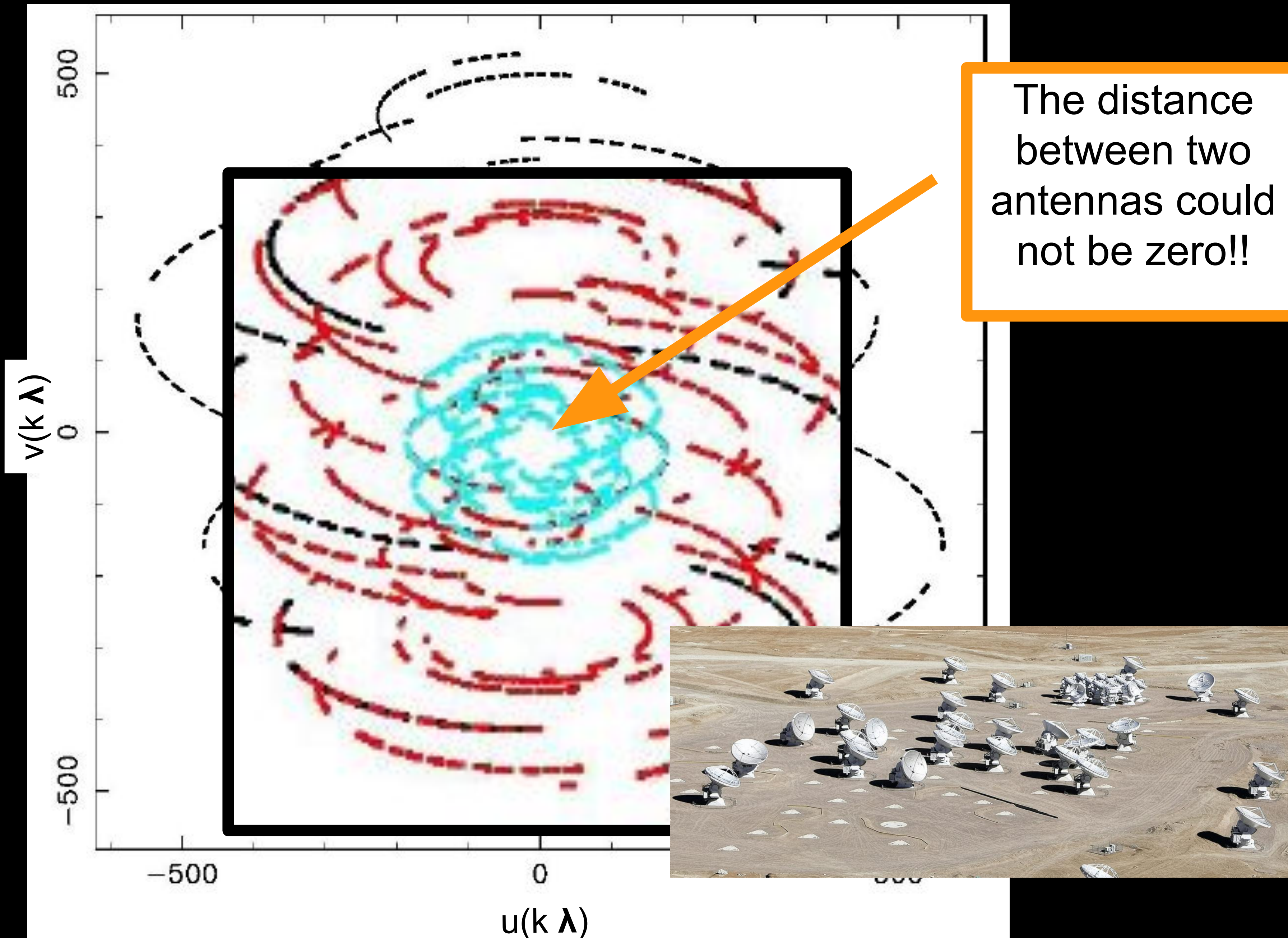
Small (u,v) distance → extended emission



No zero spacing → missing flux



Why the missing zero spacing

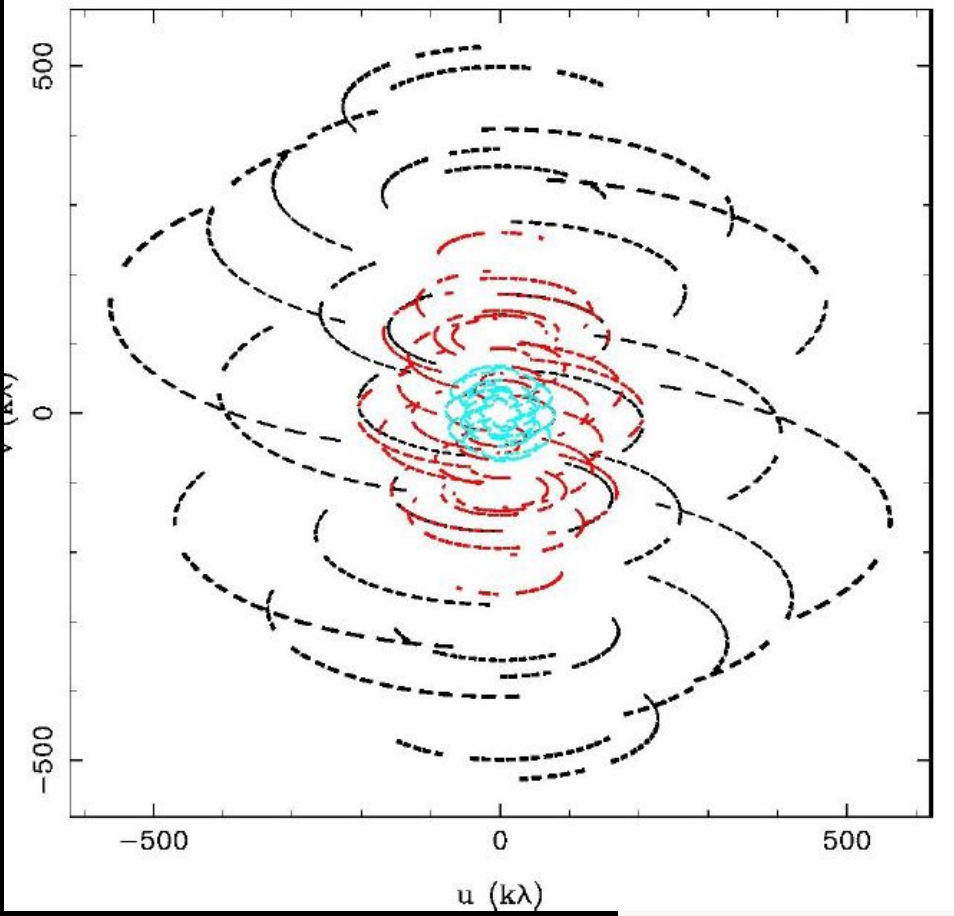


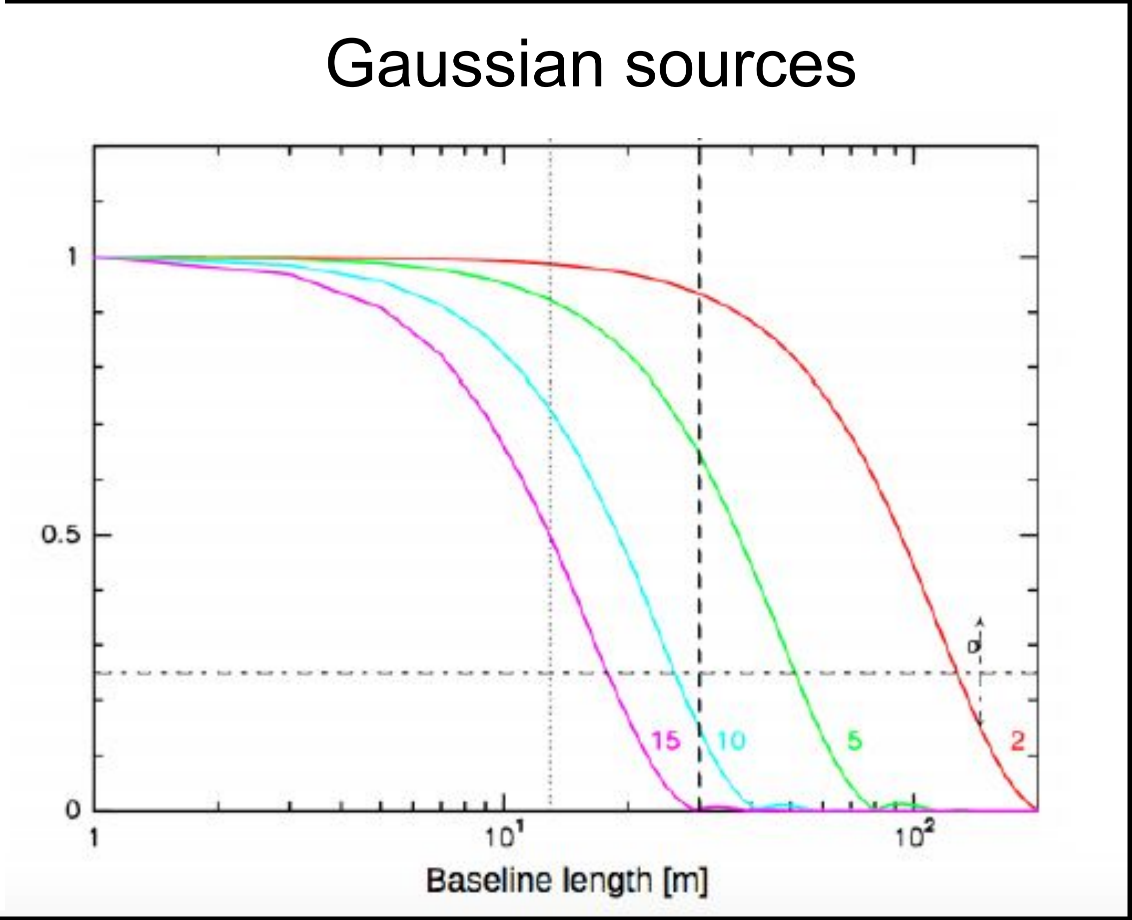
The distance between two antennas could not be zero!!

(u,v) sampling vs Maximum recoverable scale (MRS)

$$\Theta_{MRS} \sim \lambda / B_{min}$$

Zero spacing is missing in interferometry
→Filtering of large scale emission

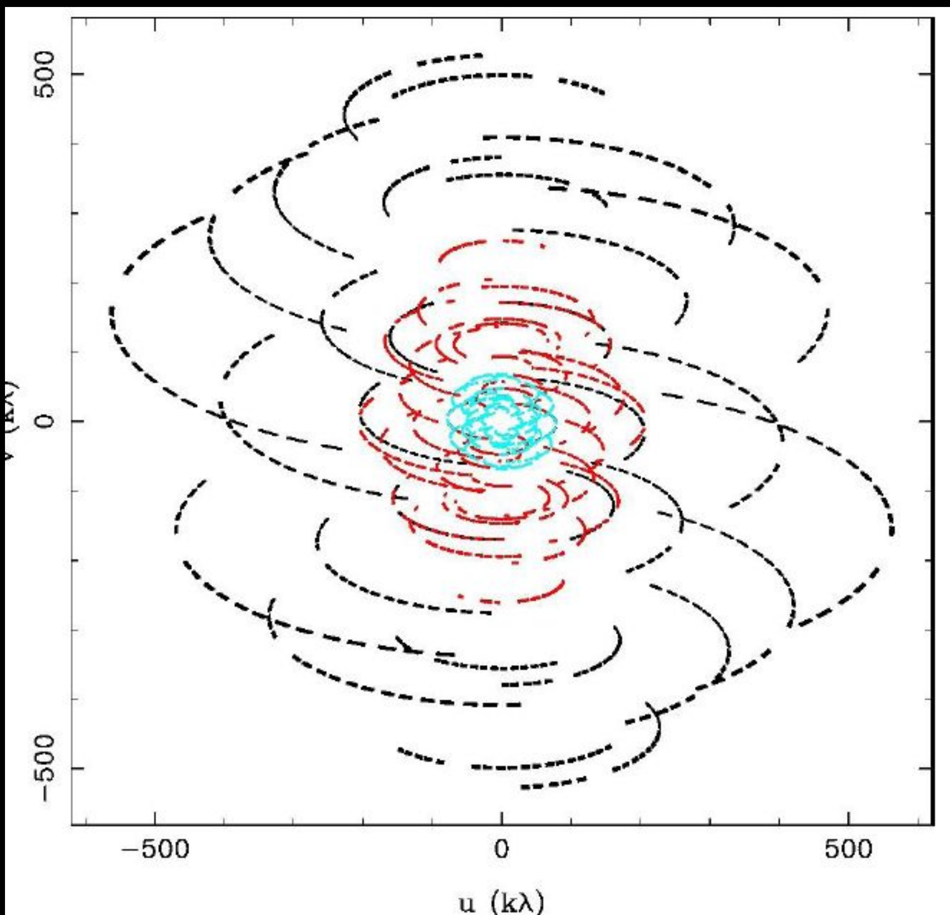


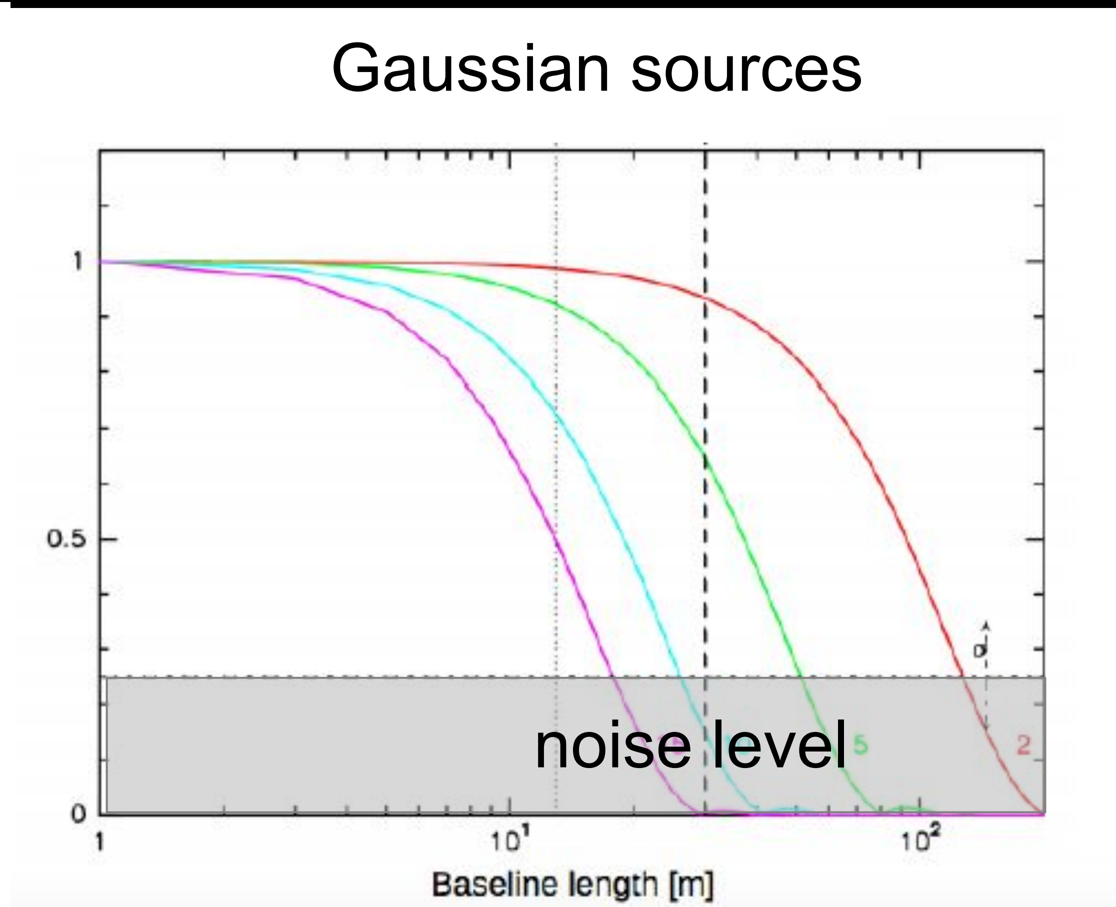


(u,v) sampling vs Maximum recoverable scale (MRS)

$$\Theta_{MRS} \sim \lambda / B_{min}$$

Zero spacing is missing in interferometry
→Filtering of large scale emission

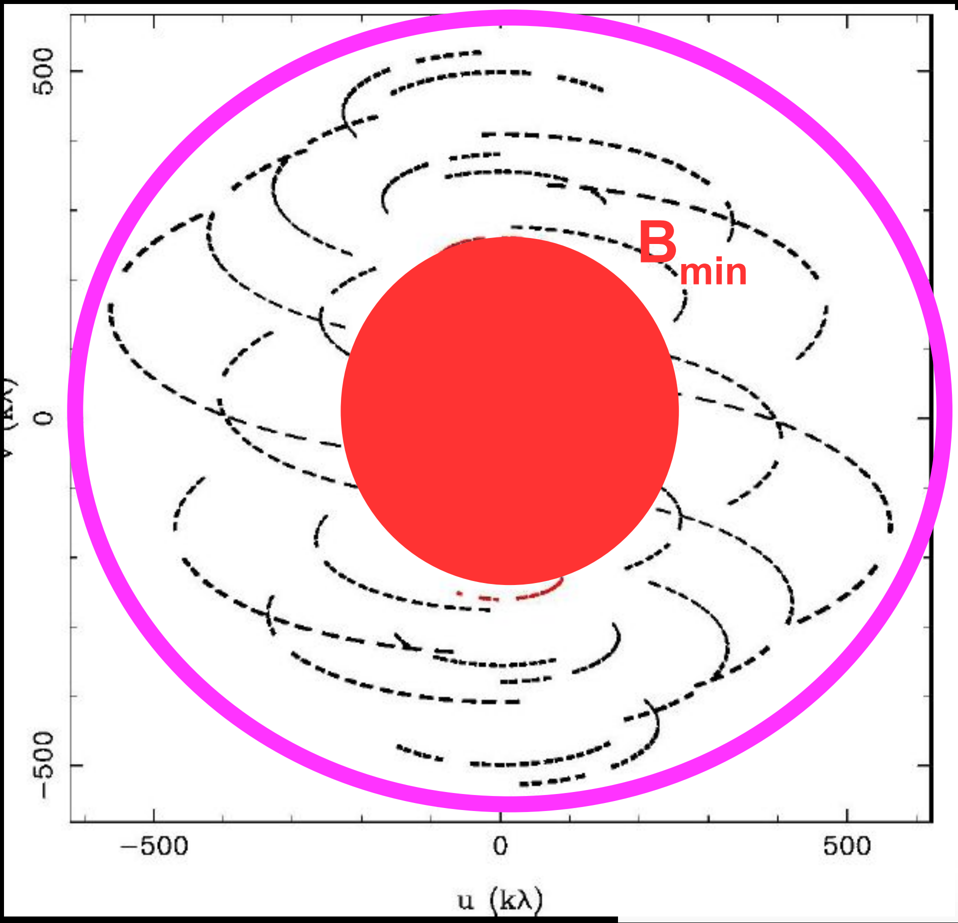


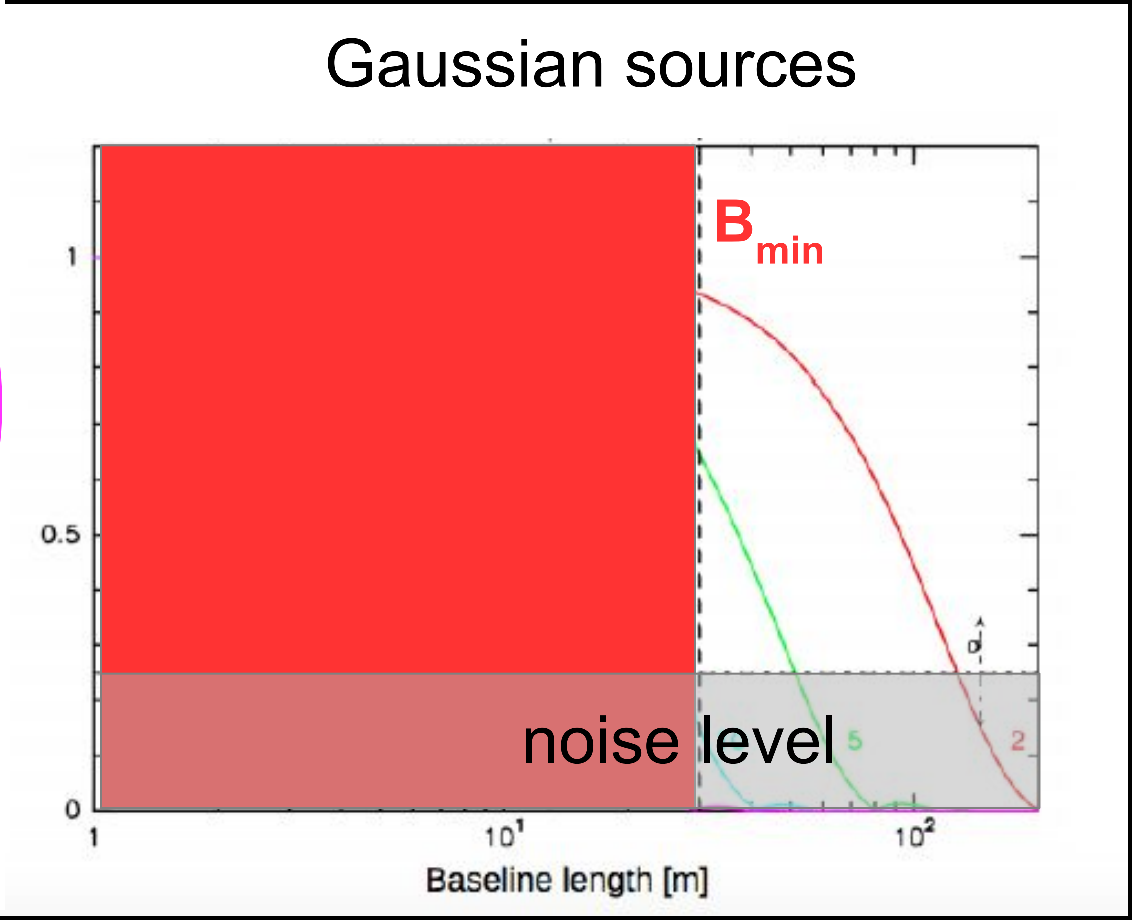


(u,v) sampling vs Maximum recoverable scale (MRS)

$$\Theta_{MRS} \sim \lambda / B_{min}$$

The filtered large scale emission depends to Bmin

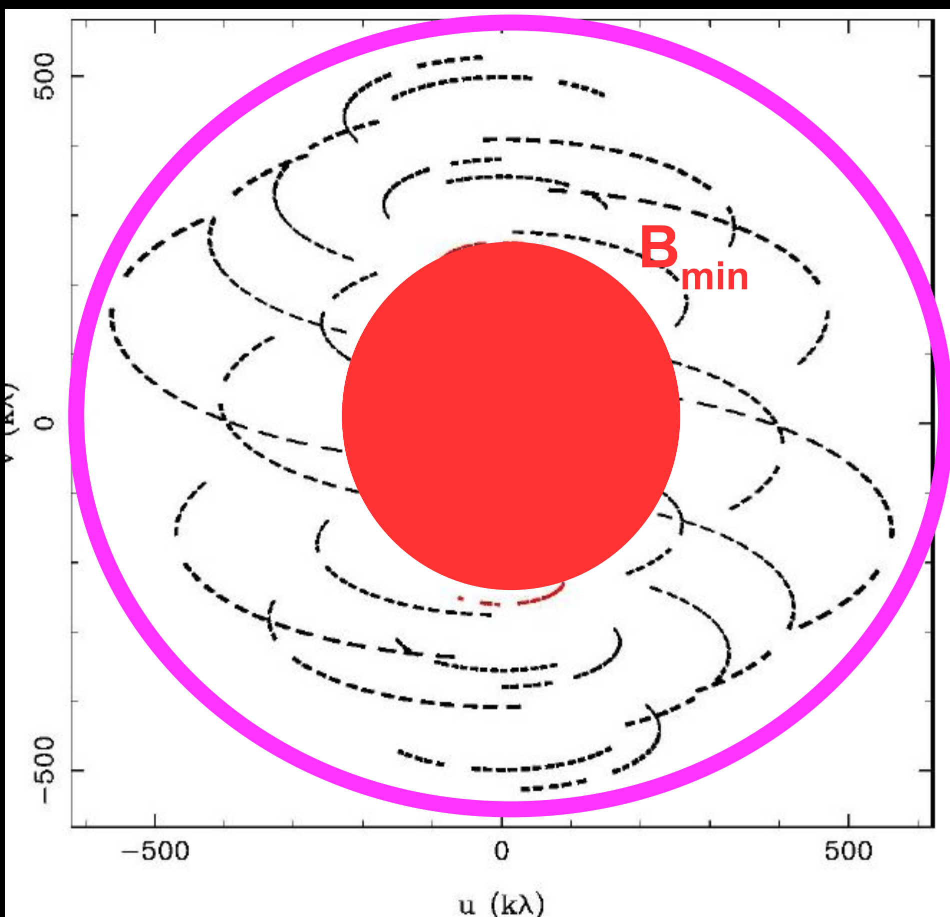


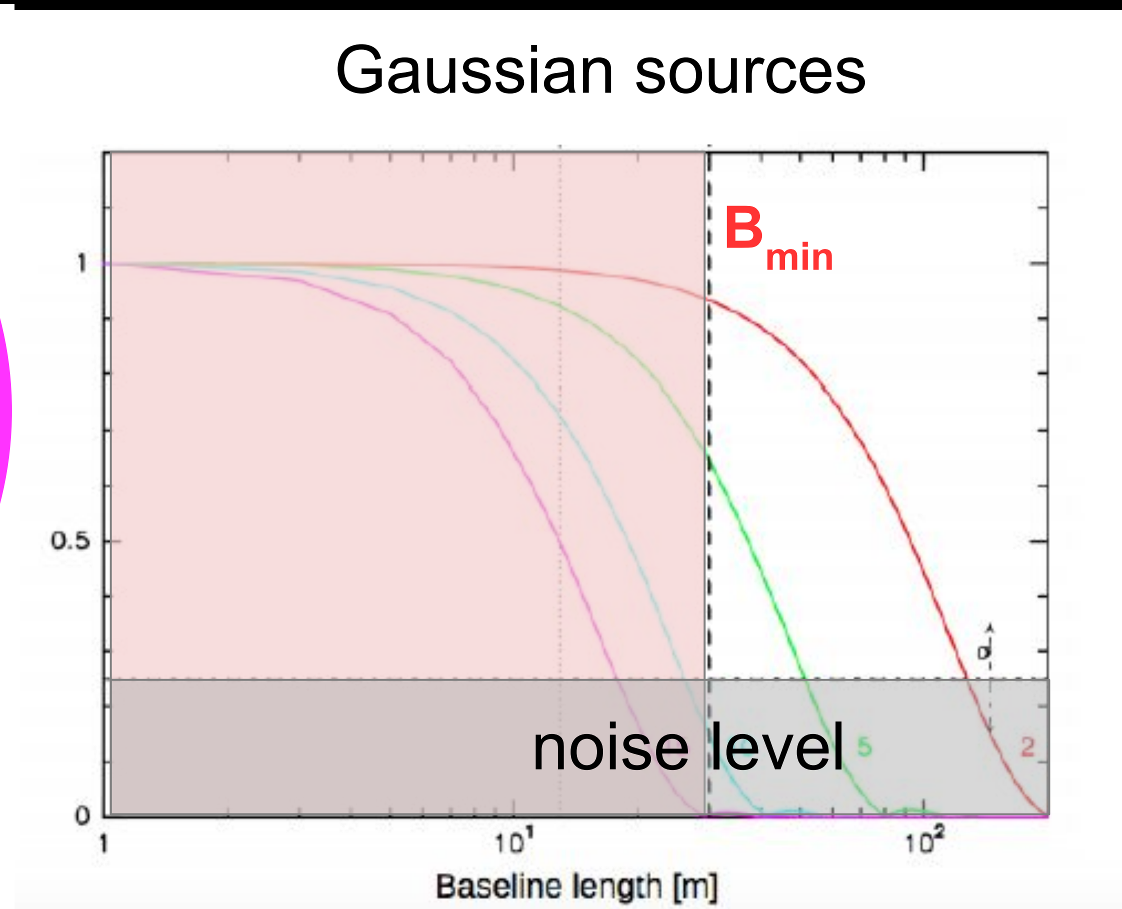


(u,v) sampling vs Maximum recoverable scale (MRS)

$$\Theta_{MRS} \sim \lambda / B_{min}$$

The filtered large scale emission depends to Bmin

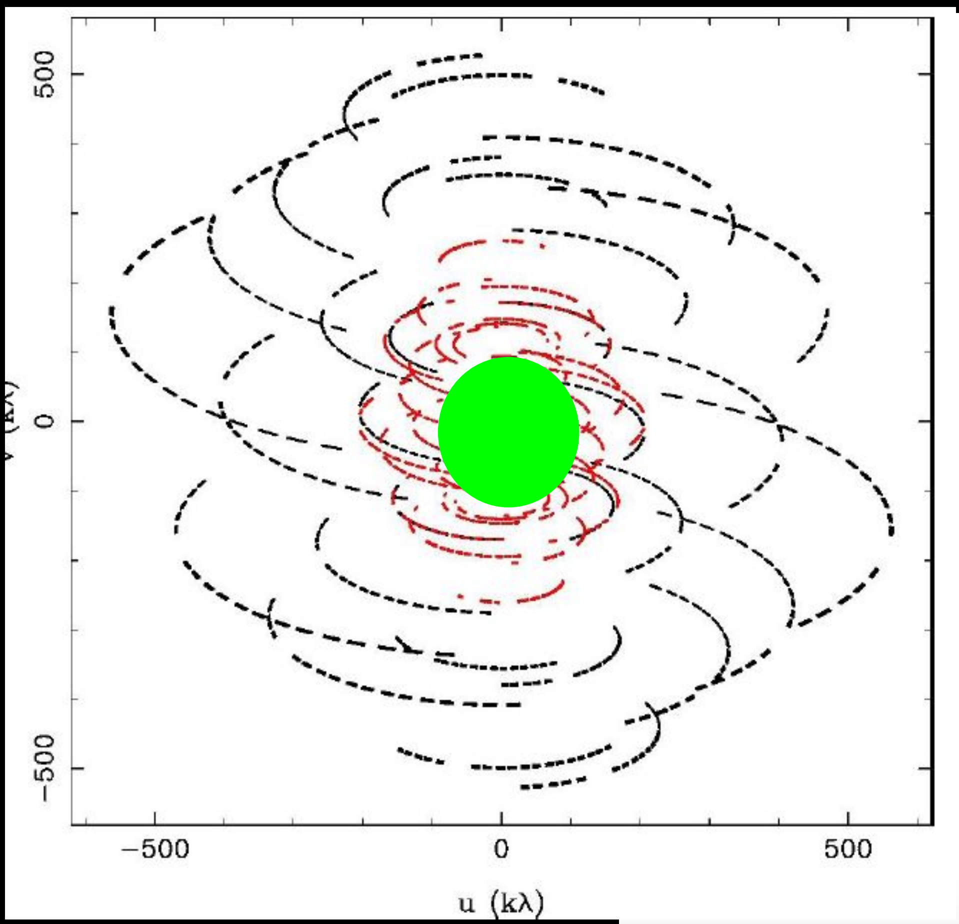


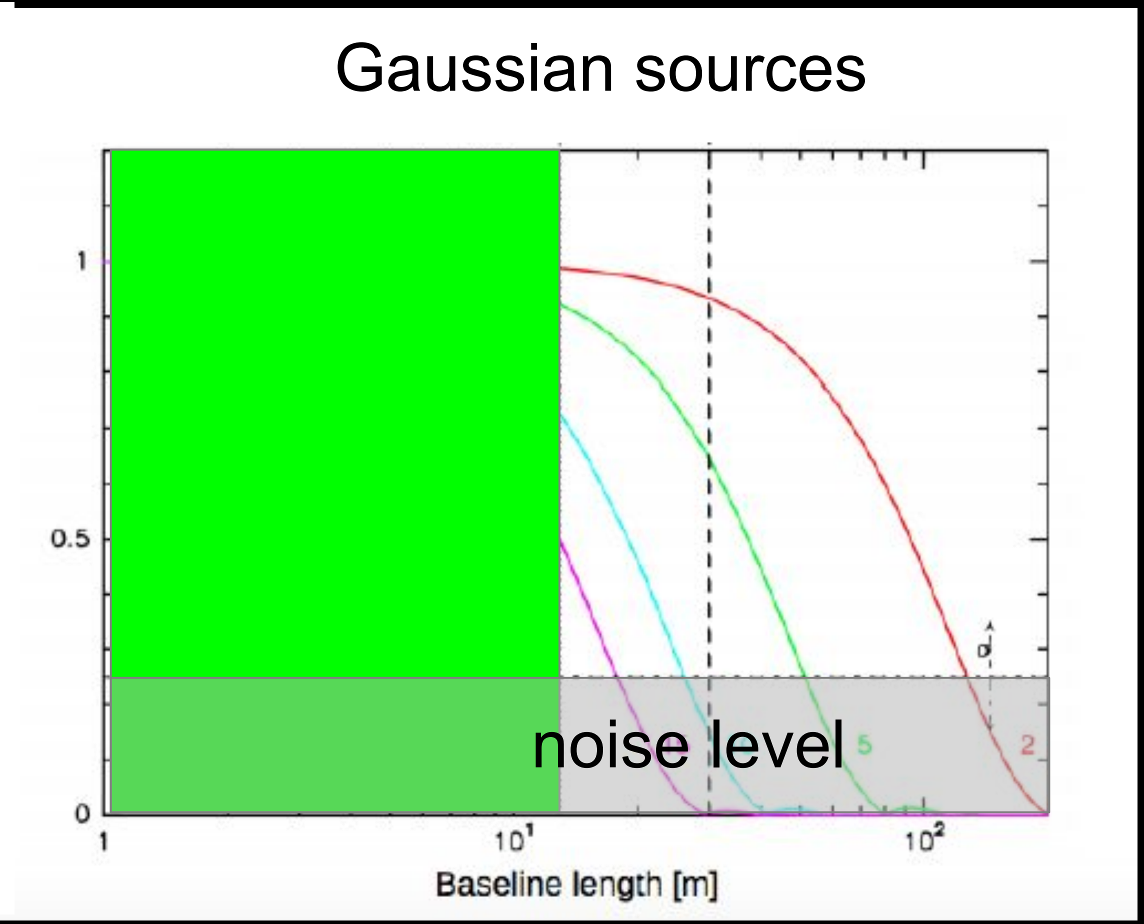


(u,v) sampling vs Maximum recoverable scale (MRS)

$$\Theta_{MRS} \sim \lambda / B_{min}$$

More compact is the array configuration, less is the filtered large scale emission

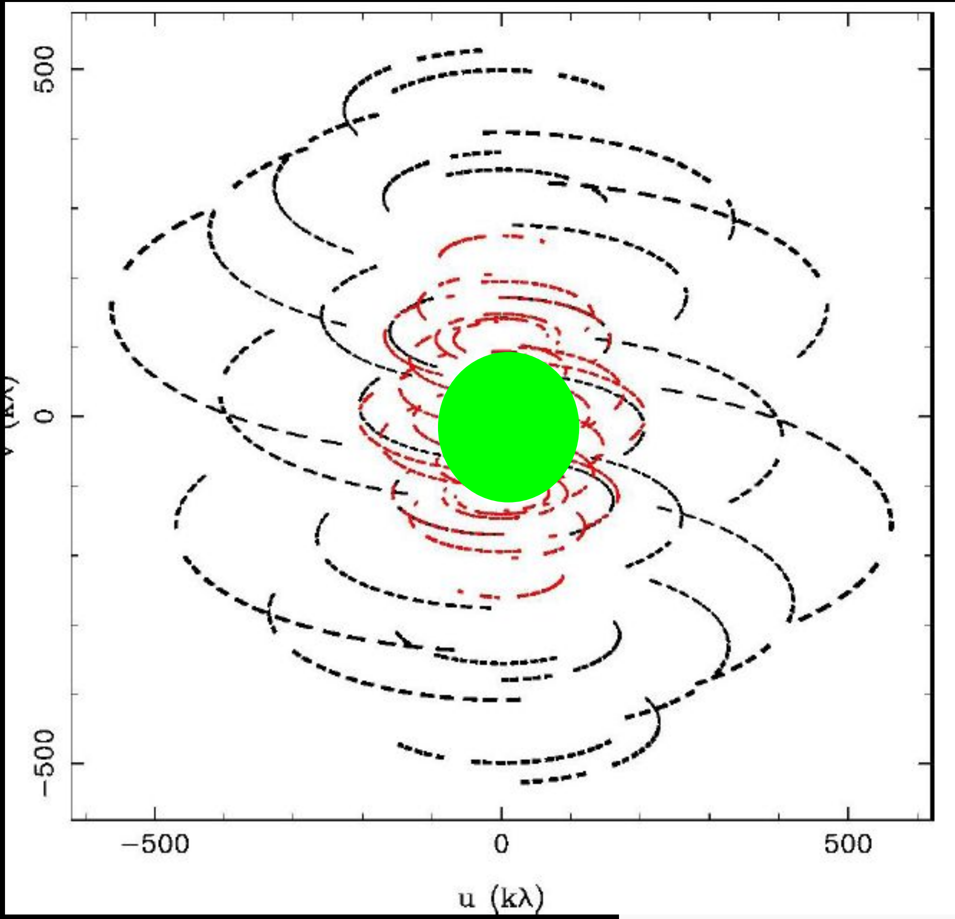


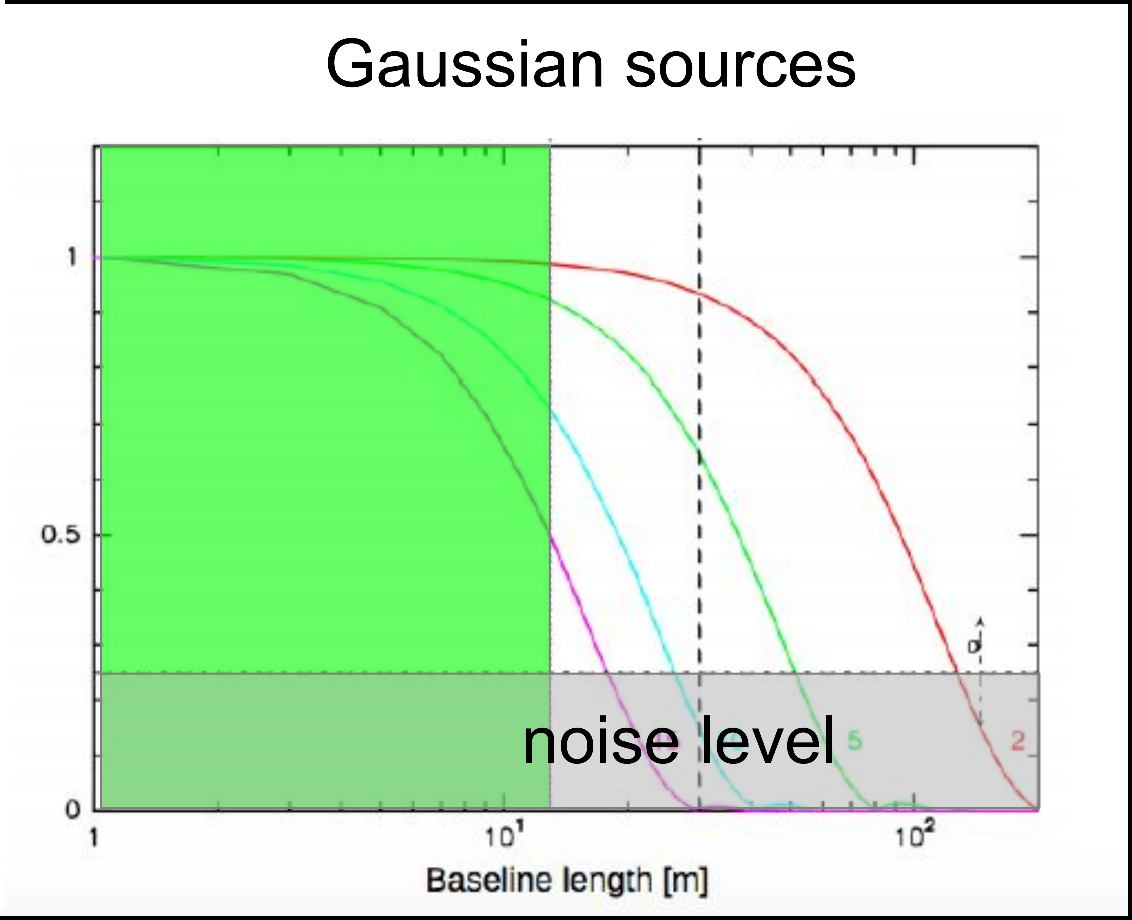


(u,v) sampling vs Maximum recoverable scale (MRS)

$\Theta_{MRS} \sim \lambda / B_{min}$

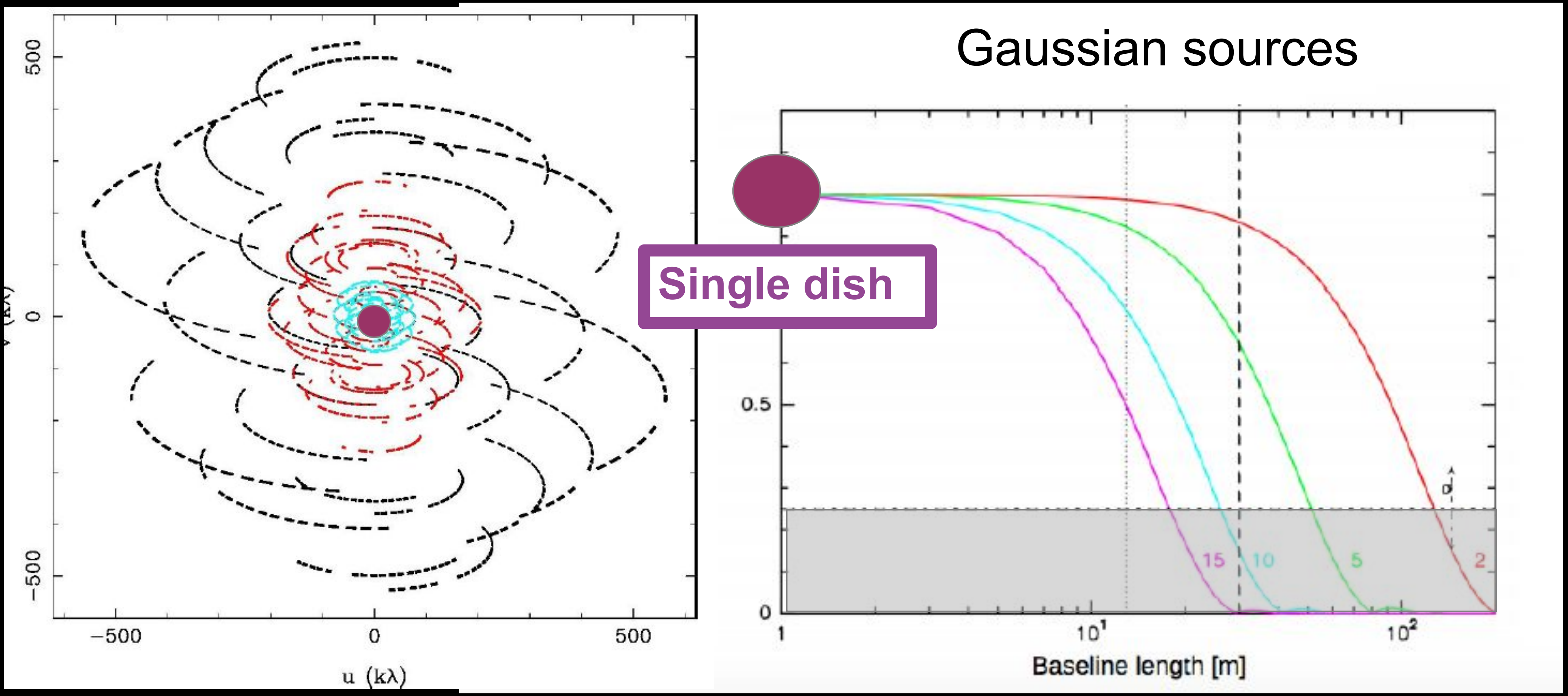
More compact is the array configuration, less is the filtered large scale emission



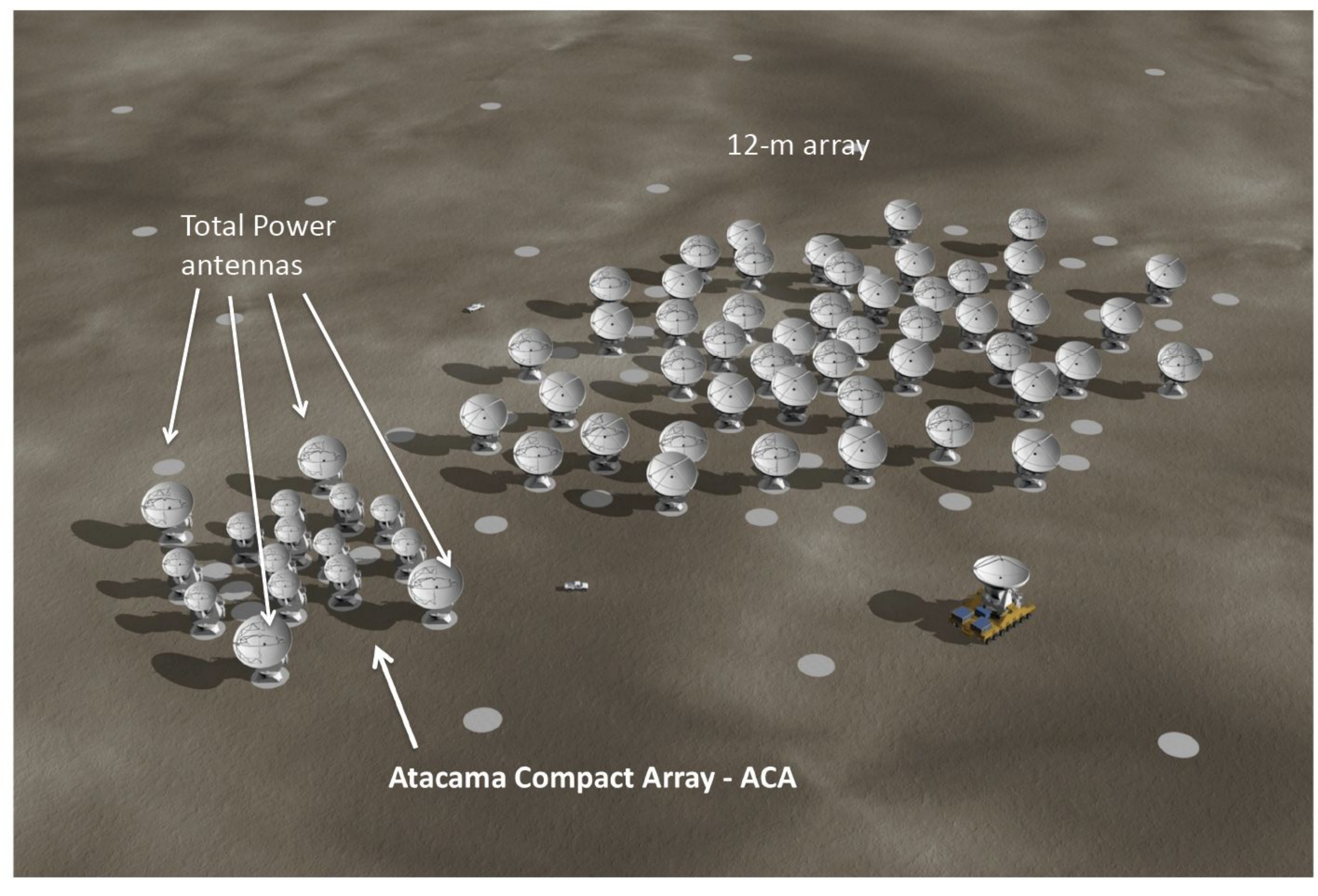


(u,v) sampling vs Maximum recoverable scale (MRS)

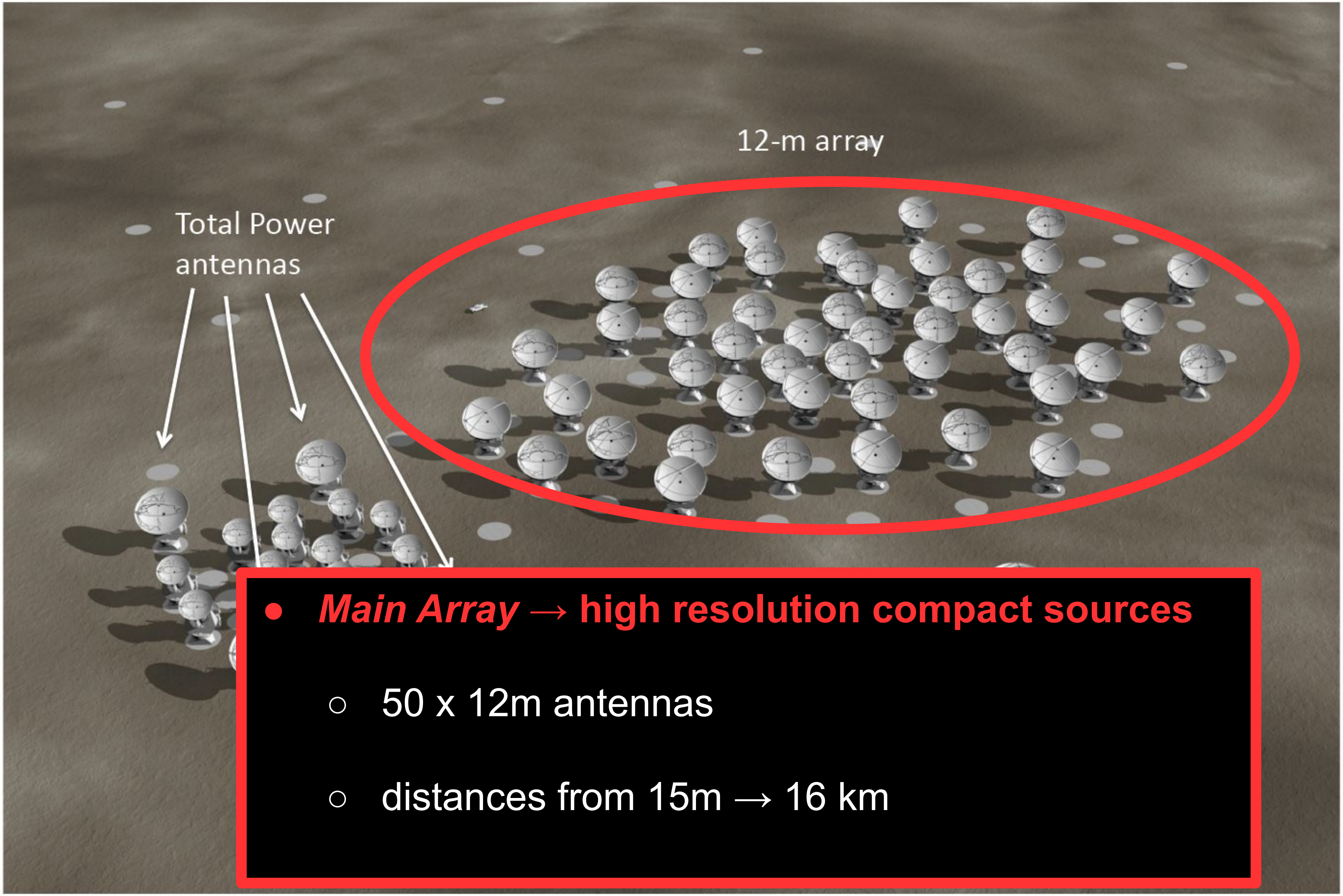
Pair of antennas have physical distance
→ interferometry can not observe zero space flux
→ We need total power observations to recover the zero spacing flux



ALMA is a composite interferometry

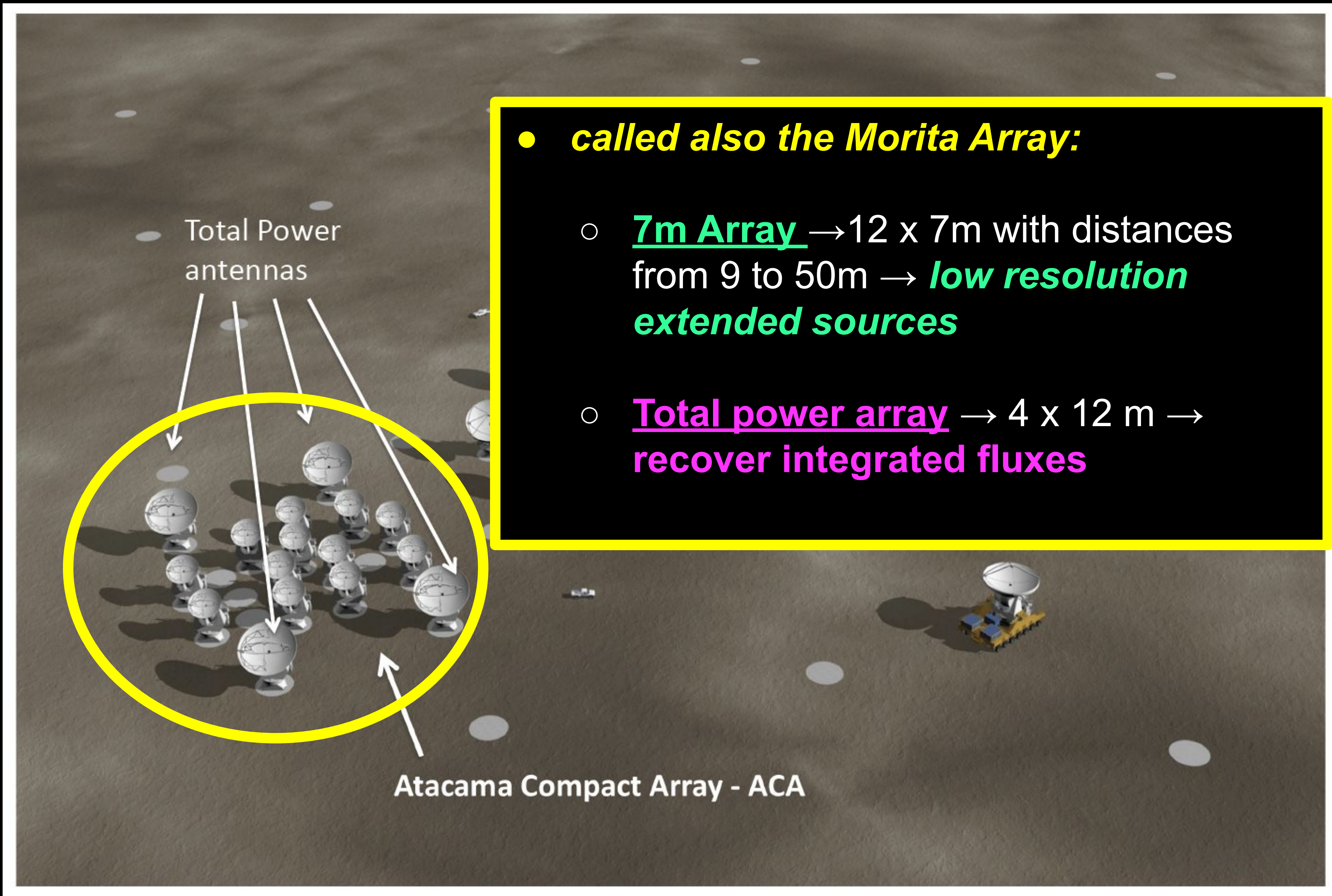


ALMA Main Array



- ***Main Array*** **→ high resolution compact sources**
    - 50 x 12m antennas
    - distances from 15m → 16 km

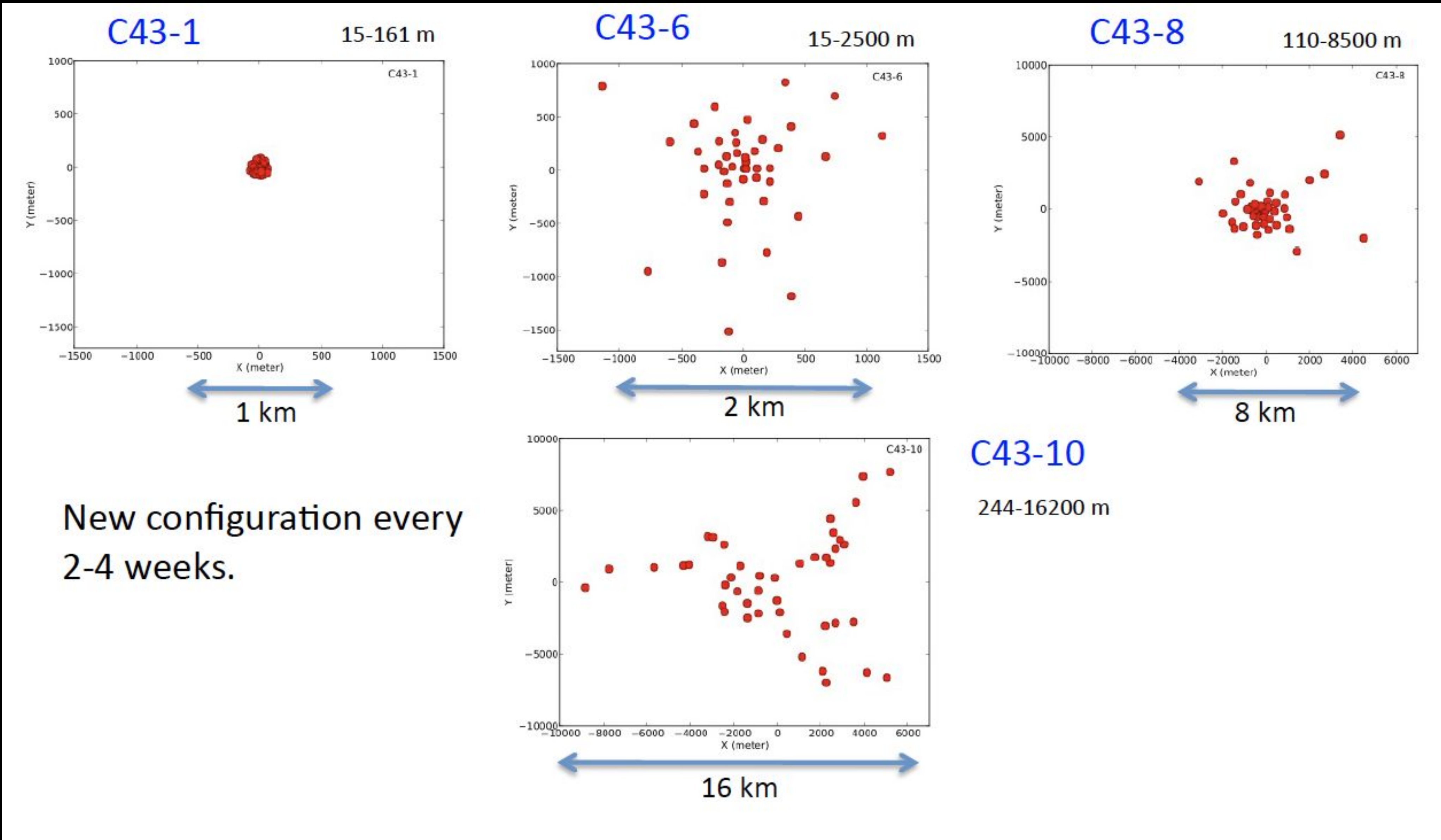
ALMA compact array (ACA)



- ***called also the Morita Array:***
  - <u>**7m Array**</u> →12 x 7m with distances from 9 to 50m → ***low resolution extended sources***
  - <u>**Total power array**</u> → 4 x 12 m → **recover integrated fluxes**

ALMA is a reconfigurable interferometer - 1

10 configurations for Cycle → [ALMA technical handbook: Chapter 7]



ALMA is a reconfigurable interferometer - 2

different angular resolution and **MRS** → *ALMA technical handbook: Chapter 7*

	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Configuration									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C43-1	θ_{res} (arcsec)	3.38	2.25	1.83	1.47	0.98	0.74	0.52	0.39
	θ_{MRS} (arcsec)	28.5	19.0	15.4	12.4	8.25	6.19	4.38	3.27
C43-2	θ_{res} (arcsec)	2.30	1.53	1.24	1.00	0.67	0.50	0.35	0.26
	θ_{MRS} (arcsec)	22.6	15.0	12.2	9.81	6.54	4.90	3.47	2.59
C43-3	θ_{res} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.22	0.16
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.48	1.86
C43-4	θ_{res} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.14	0.11
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.73	1.29
C43-5	θ_{res} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.084	0.063
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.03	0.77
C43-6	θ_{res} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.047	0.035
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.63	0.47
C43-7	θ_{res} (arcsec)	0.21	0.14	0.11	0.092	0.061	0.046	0.033	0.024
	θ_{MRS} (arcsec)	2.58	1.72	1.40	1.12	0.75	0.56	0.40	0.30
C43-8	θ_{res} (arcsec)	0.096	0.064	0.052	0.042	0.028	0.021	0.015	0.011
	θ_{MRS} (arcsec)	1.42	0.95	0.77	0.62	0.41	0.31	0.22	0.16
C43-9	θ_{res} (arcsec)	0.057	0.038	0.031	0.025	0.017	0.012	0.0088	-
	θ_{MRS} (arcsec)	0.81	0.54	0.44	0.35	0.24	0.18	0.13	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.023	0.018	0.012	0.0091	-	-
	θ_{MRS} (arcsec)	0.50	0.33	0.27	0.22	0.14	0.11	-	-

angular resolution =

0.2” x (300GHz / freq) x (1km / max_baseline)

ALMA is a reconfigurable interferometer - 3

different angular resolution and **MRS** → *ALMA technical handbook: Chapter 7*

	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Configuration									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
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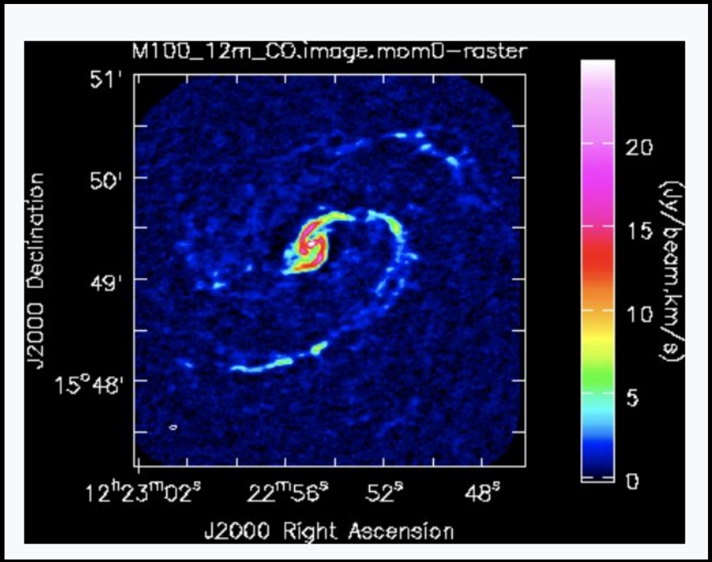
C43-2	θ_{res} (arcsec)	2.30	1.53	1.24	1.00	0.67	0.50	0.35	0.26
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.47	2.59
C43-3	θ_{res} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.22	0.16
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.48	1.86
C43-4	θ_{res} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.14	0.11
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.73	1.29
C43-5	θ_{res} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.084	0.063
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.03	0.77
C43-6	θ_{res} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.047	0.035
	θ_{MRS} (arcsec)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.63	0.47
C43-7	θ_{res} (arcsec)	0.21	0.14	0.11	0.092	0.061	0.046	0.033	0.024
	θ_{MRS} (arcsec)	2.58	1.72	1.40	1.12	0.75	0.56	0.40	0.30
C43-8	θ_{res} (arcsec)	0.096	0.064	0.052	0.042	0.028	0.021	0.015	0.011
	θ_{MRS} (arcsec)	1.42	0.95	0.77	0.62	0.41	0.31	0.22	0.16
C43-9	θ_{res} (arcsec)	0.057	0.038	0.031	0.025	0.017	0.012	0.0088	-
	θ_{MRS} (arcsec)	0.81	0.54	0.44	0.35	0.24	0.18	0.13	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.023	0.018	0.012	0.0091	-	-
	θ_{MRS} (arcsec)	0.50	0.33	0.27	0.22	0.14	0.11	-	-

Maximum Recoverable Scale (MRS)=

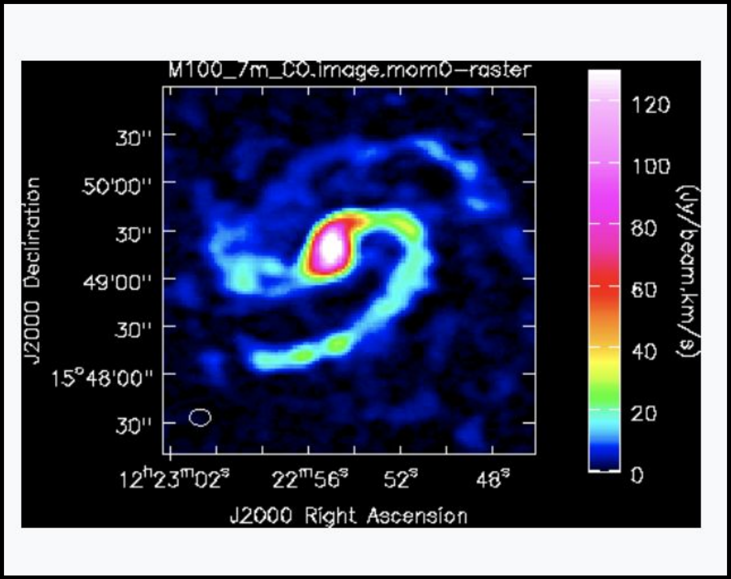
1.4” x (300GHz / freq) x (150m / min_baseline)

ALMA could map different angular scales

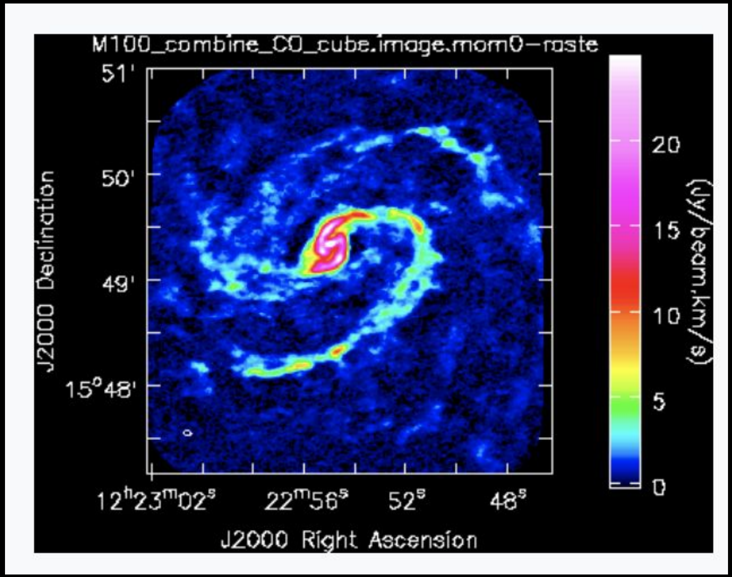
12 m



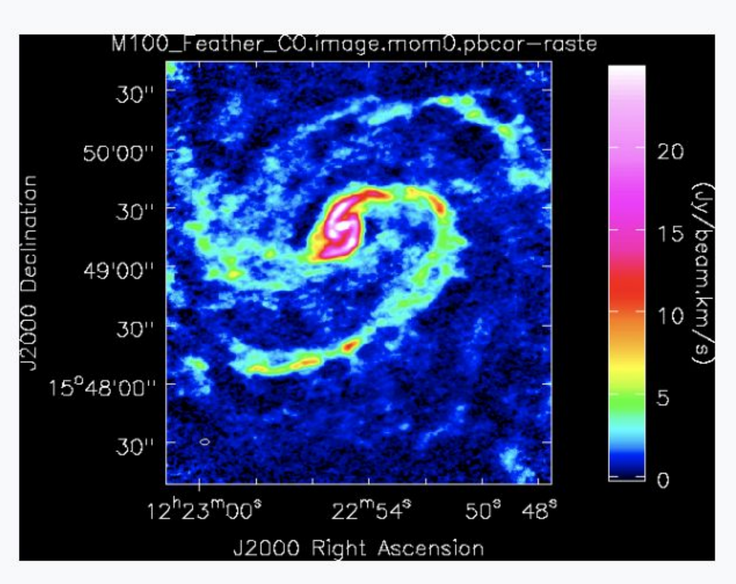
7 m



12m + 7m



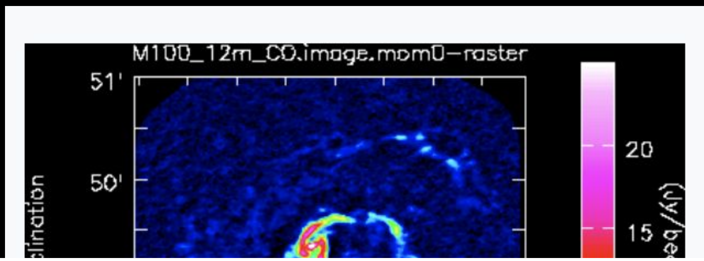
12m + 7m + TP

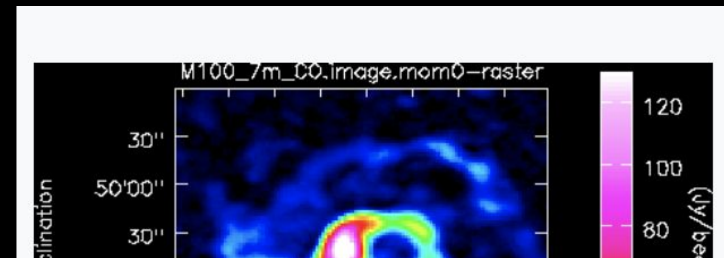


ALMA could map different angular scales

12 m

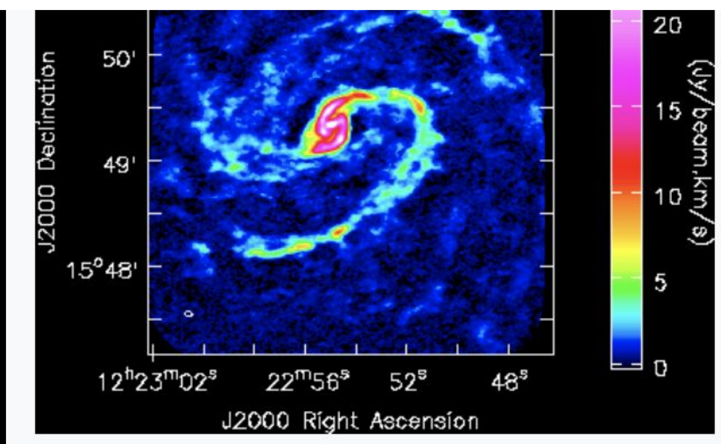
7 m

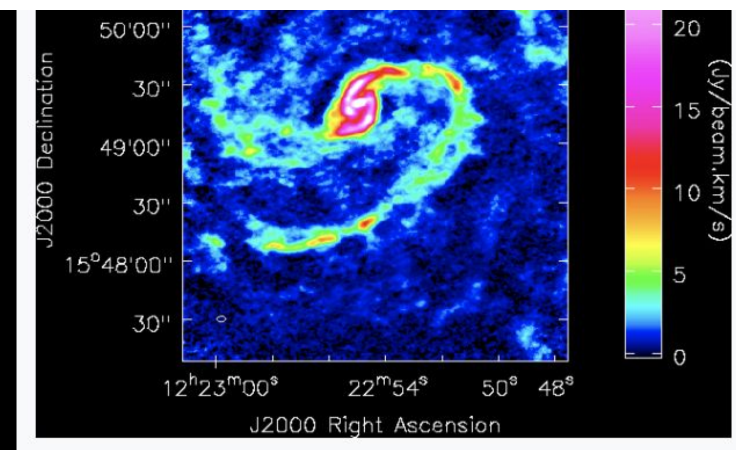




[More info on ALMA data combination in the CASA guide M100 Band3 Combine 5.4]

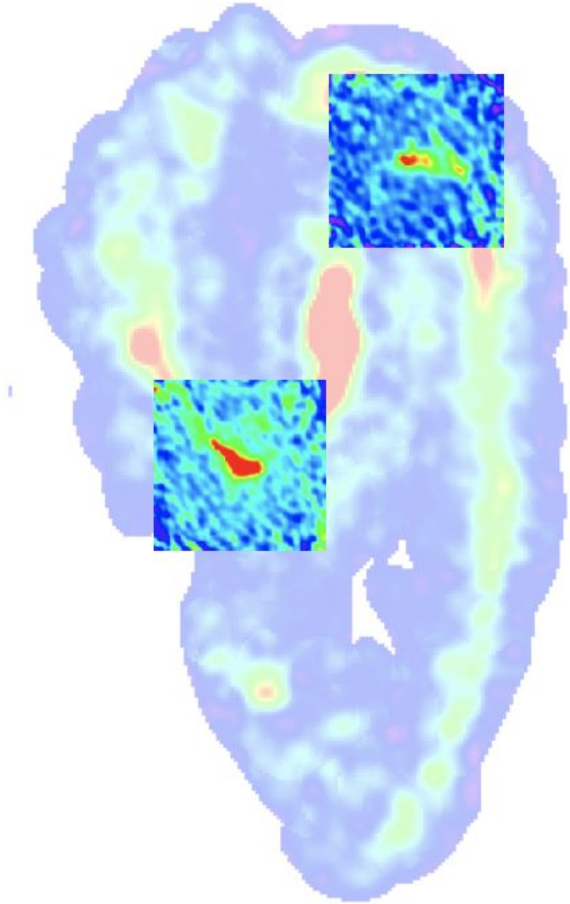
see also Marcella talk on ‘Advanced tips and tricks with ALMA archival data !!!





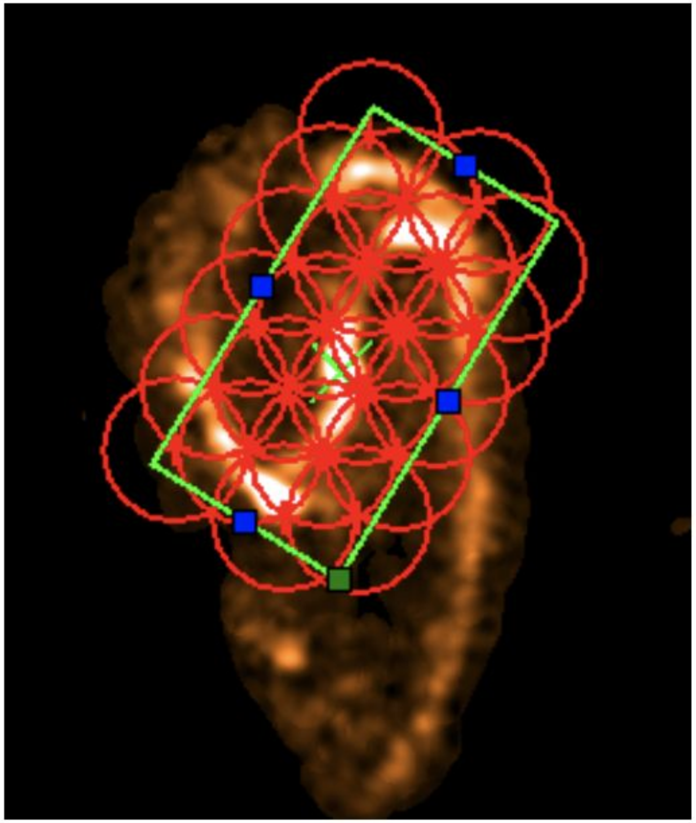
ASA DATA field of view and mosaics - 1

FOV 12m (arcsec) = 17 x (300 GHz/f)
FOV 7m (arcsec) = 29 x (300 GHz/f)



CO(1-0) with IRAM PdBI

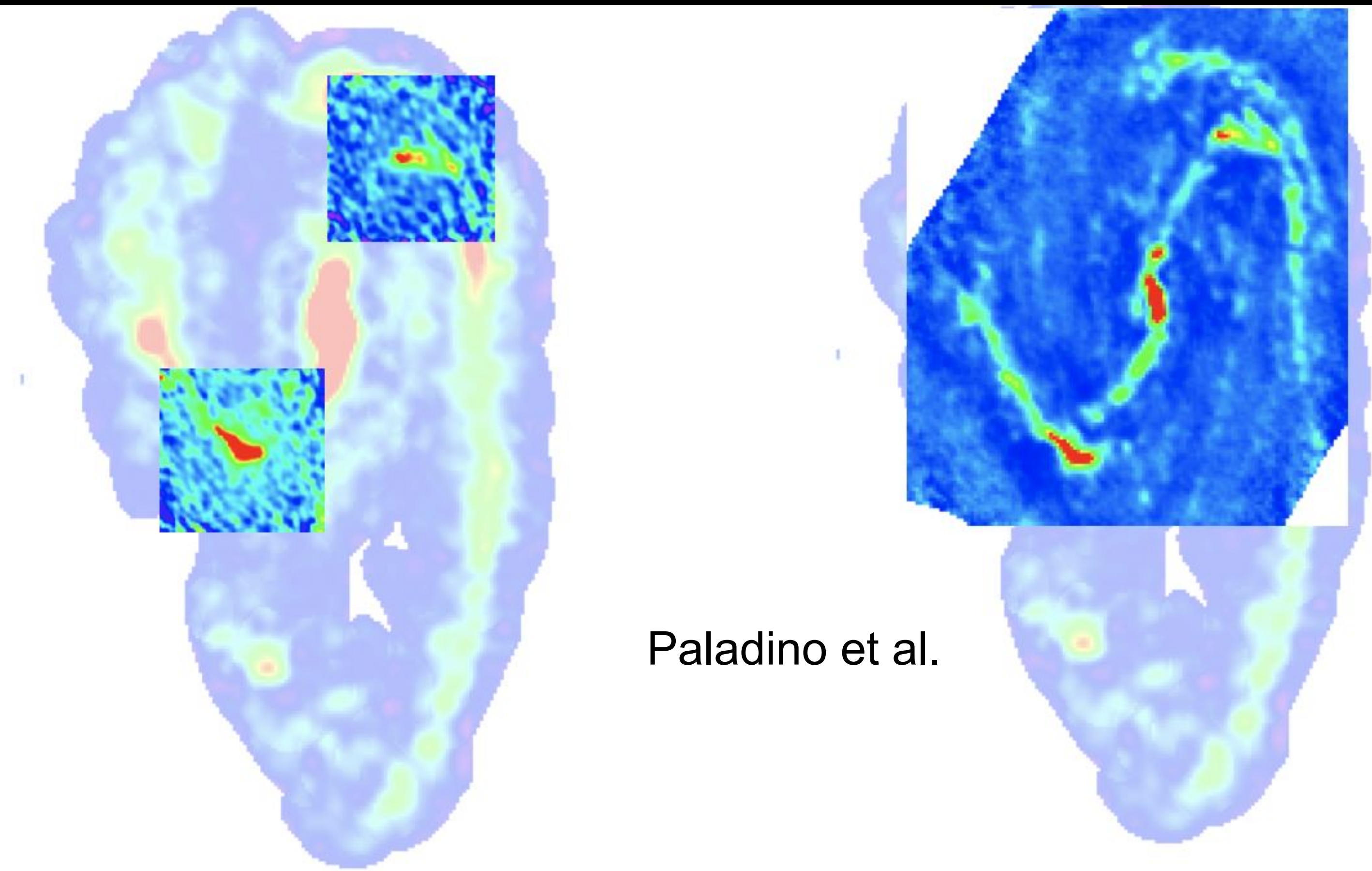
Paladino et al. 2008



Proposal ALMA Cycle3
Mosaic of 22 pointings in band 3

ASA DATA field of view and mosaics - 2

FOV 12m (arcsec) = 17 x (300 GHz/f)
FOV 7m (arcsec) = 29 x (300 GHz/f)



CO(1-0) with IRAM PdBI
Resolution ~ 2 arcsec ~ 100 pc
8 hrs per pointing

CO(1-0) with ALMA
Resolution ~ 2 arcsec ~ 100 pc
Observing time 1.5 hrs

ALMA sensitivity

T_{sys} is the system temperature ($=T_{atm} + T_{rx}$)

Boltzmann k

$$\sigma_S \approx \frac{2\,k\,T_{\rm sys}}{A_{\rm eff}\,\sqrt{n(n-1)} \times \Delta\nu \times \eta_{\rm pol} \times t_{\rm int}}\ [\rm Jy]$$

Time on source

# of polarizations

Bandwidth

Effective collecting Area= dish_area x efficiency

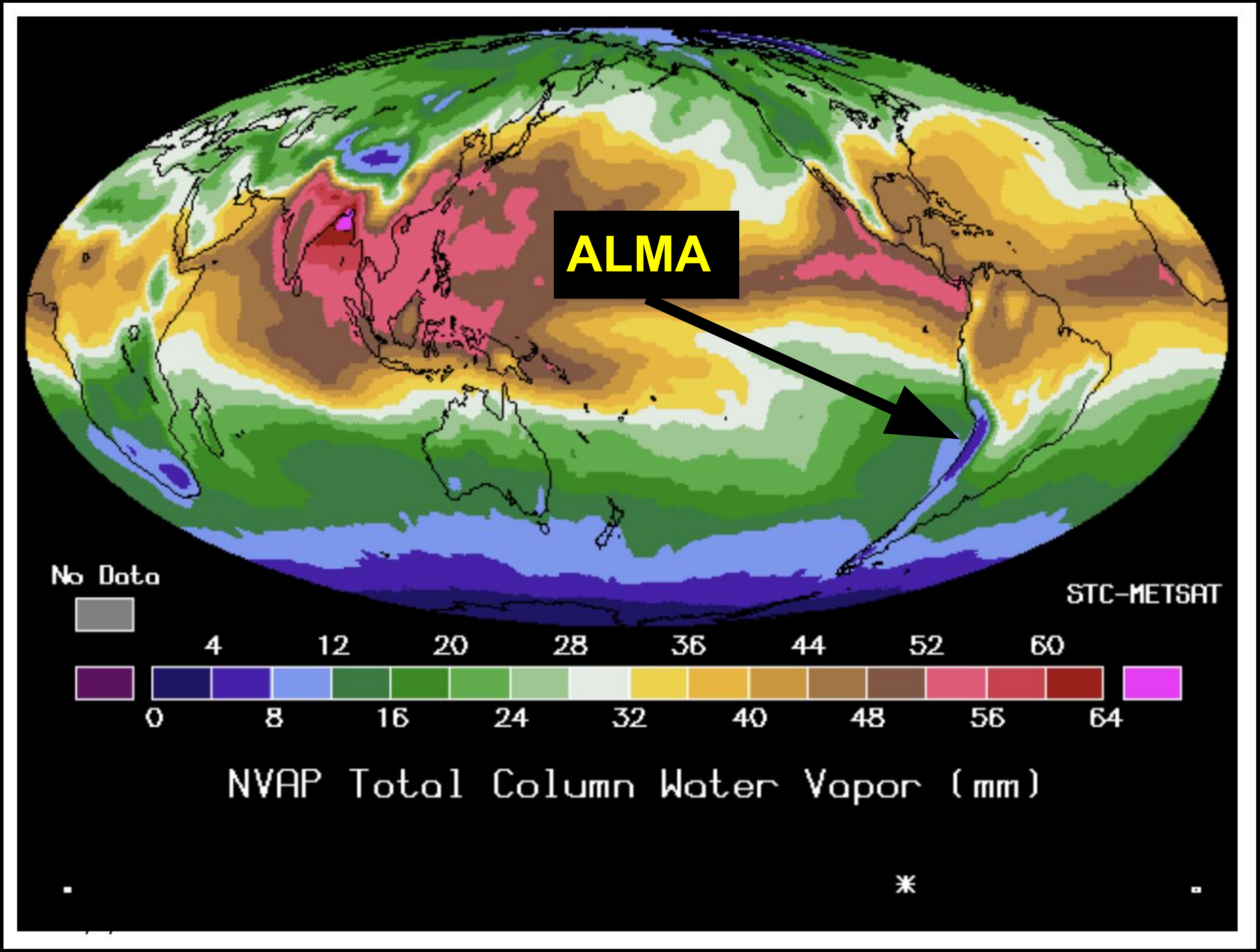
n = # of antennas

n(n-1)/2 = # of baselines

Low values thanks to:

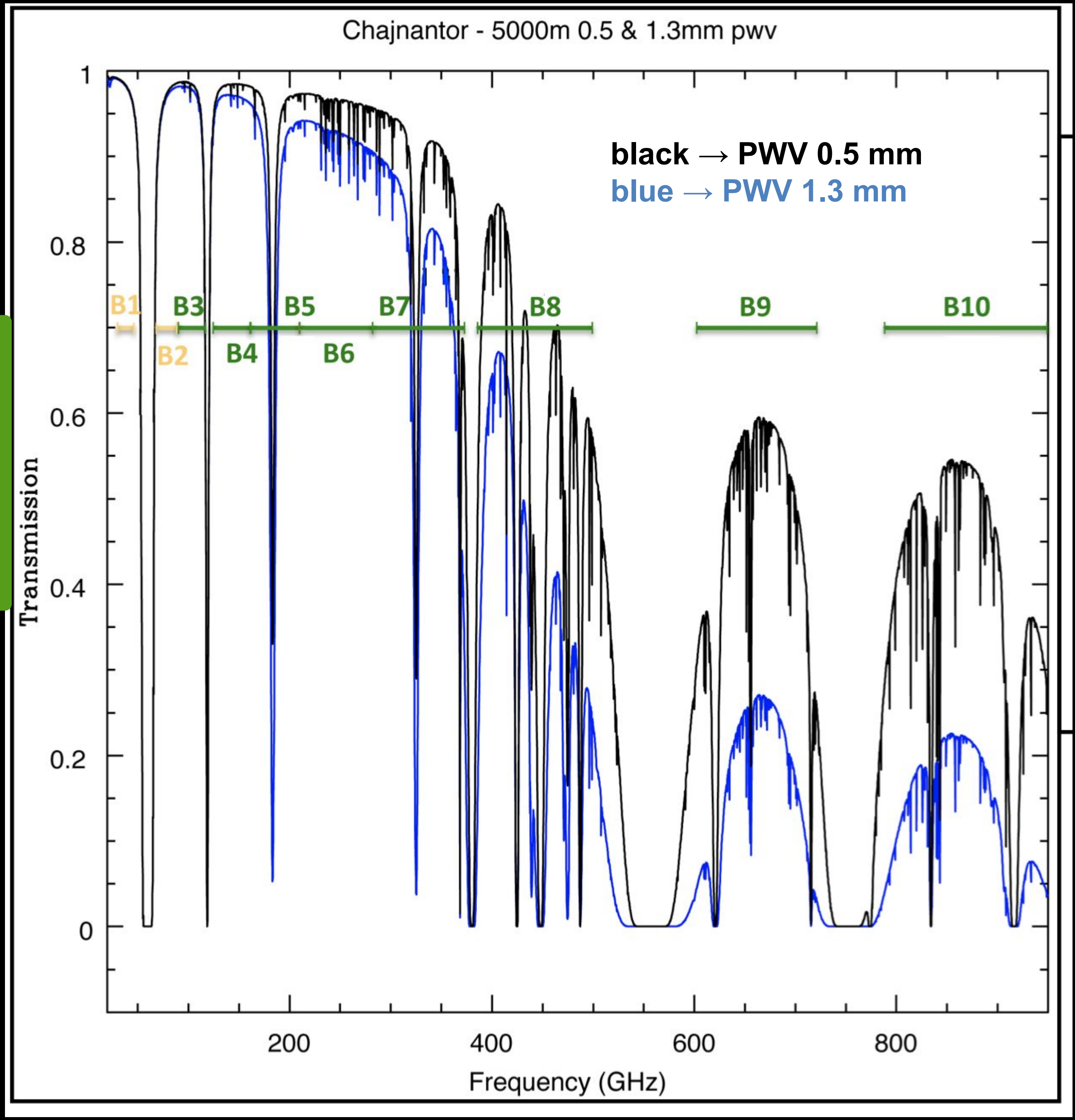
- **low T_{sys}** (= lowering instrumental noise or atmospheric noise, i.e choosing sites with low water vapour levels)
- large **collecting area and/or # of antennas**
- large **bandwidth and the observing time**

ALMA is at very dry site



ALMA observing site & frequencies

ALMA technical handbook: Chapter 4



Dry site → higher frequencies observable

!!! See Rosita tomorrow talk on 'ALMA data calibration basics' !!!

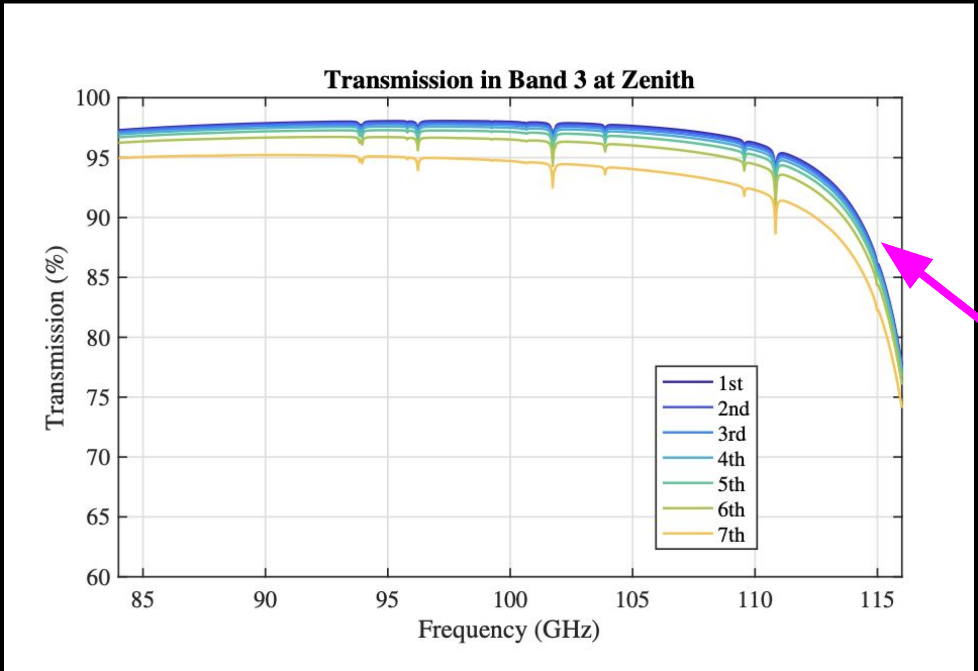
ALMA bands

ALMA Band	Wavelength coverage (mm)	Noise Temperature (K) Specification	Frequency (GHz)	Produced by	Receiver Technology	First light
1	6–8.6	32	35 – 50	TBD	HEMT	TBD
2	2.6–4.5	47	67 – 116	OSO (Sweden) / NOVA (Netherlands) / INAF (Italy) / NAOJ (Japan)	HEMT	TBD
3	2.6–3.6	60	84 – 116	HIA (Canada)	SIS	2009
4	1.8–2.4	82	125 – 163	NAOJ (Japan)	SIS	2013
5	1.4–1.8	105	163 – 211	OSO (Sweden) / NOVA (Netherlands)	SIS	2016
6	1.1–1.4	136	211 – 275	NRAO (US)	SIS	2009
7	0.8–1.1	219	275 – 373	IRAM (France)	SIS	2009
8	0.6–0.8	292	385 – 500	NAOJ (Japan)	SIS	2013
9	0.4–0.5	261	602 – 720	NOVA (Netherlands)	SIS	2011
10	0.3–0.4	344	787 – 950	NAOJ (Japan)	SIS	2012

ALMA technical handbook: Chapter 4

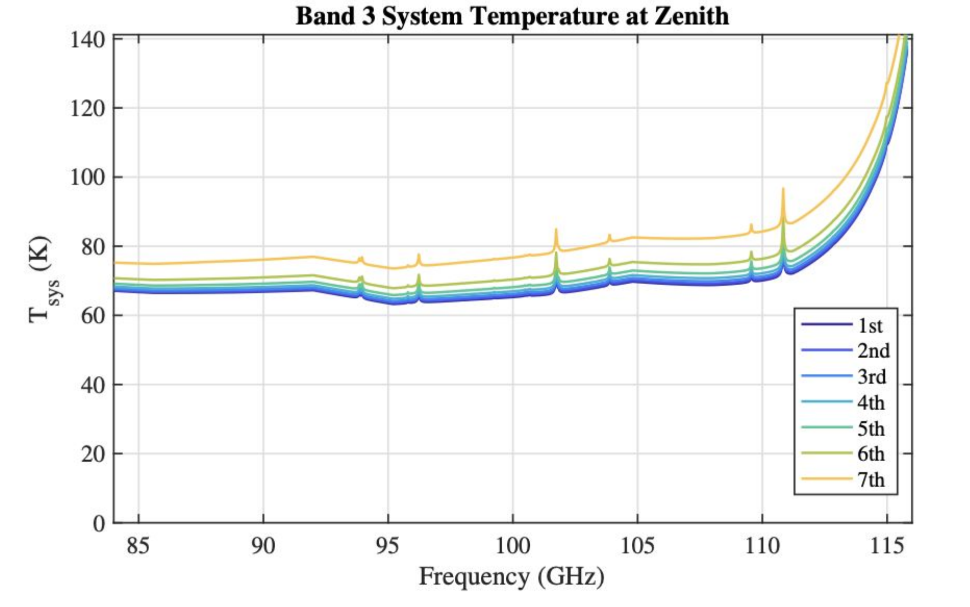
Lowest Tsys - the ALMA B3

BAND 3 - 100 GHz



edge of an O_2 **absorption** line at 118.5 GHz

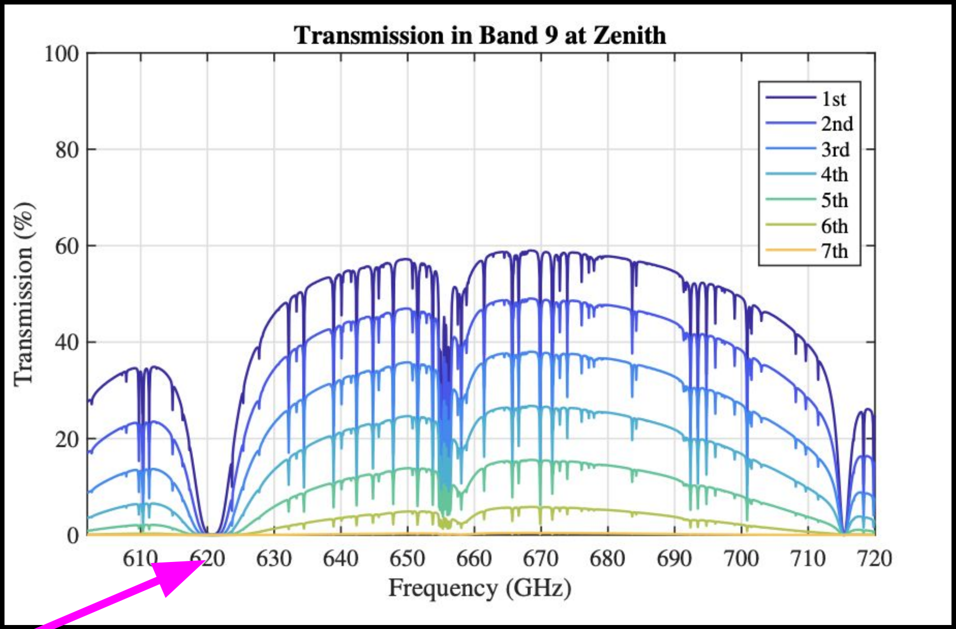
Tsys < 100 K below 100 GHz



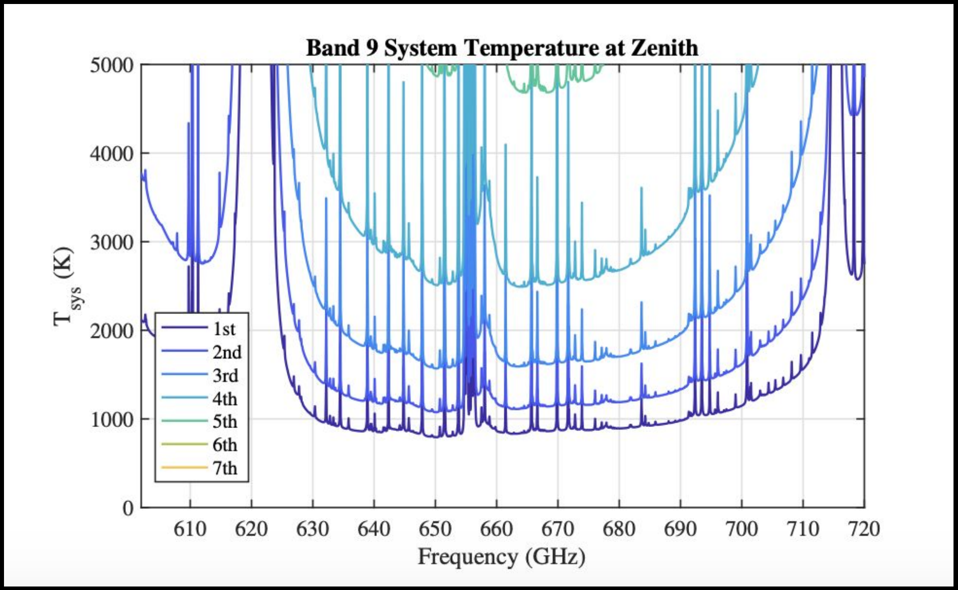
ALMA technical handbook: Chapter 4

Higher Tsys - ALMA B9

BAND 9 - 660 GHz



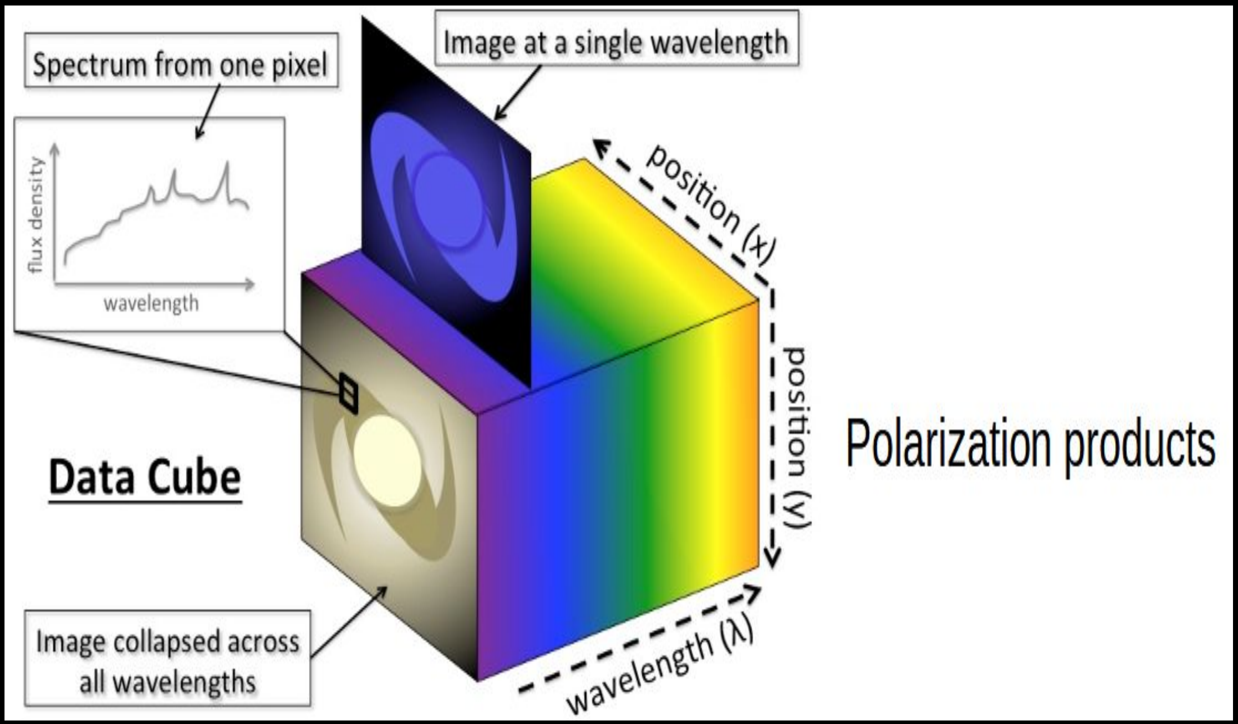
presence of **wings of pressure-broadened H_2O** at 620 GHz.



Tsys > 1000 K above 600 GHz

ALMA technical handbook: Chapter 4

ALMA spectral resolution



An image is a **cube** with (possible) dimensions **Right Ascension, Declination, frequency, polarization (I, Q, U, V)**

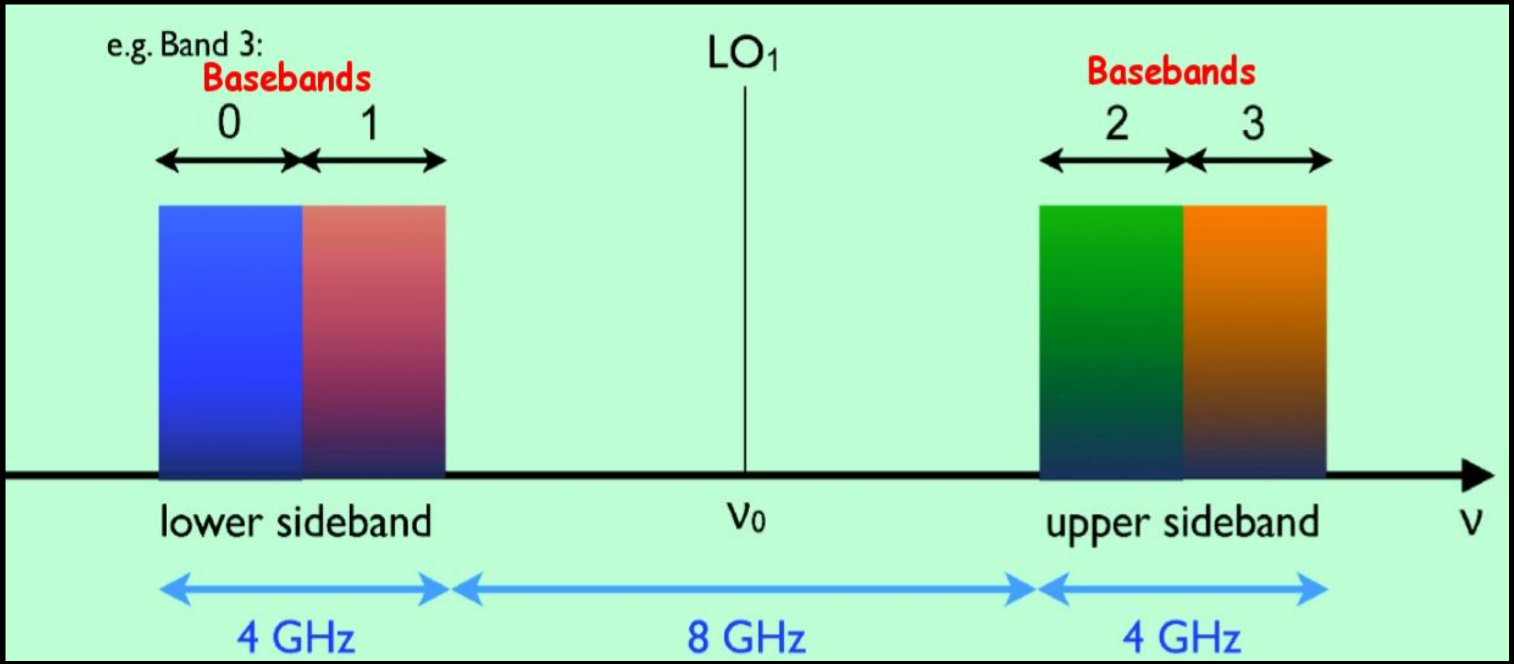
ASA Image units are **Jy/beam**

!!! See tomorrow tutorial on 'CARTA' !!!

The **spectral resolution** is the **minimum separation in frequency** whereby adjacent features can be distinguished

Maximum spectral resolution depends on how the correlator is set.

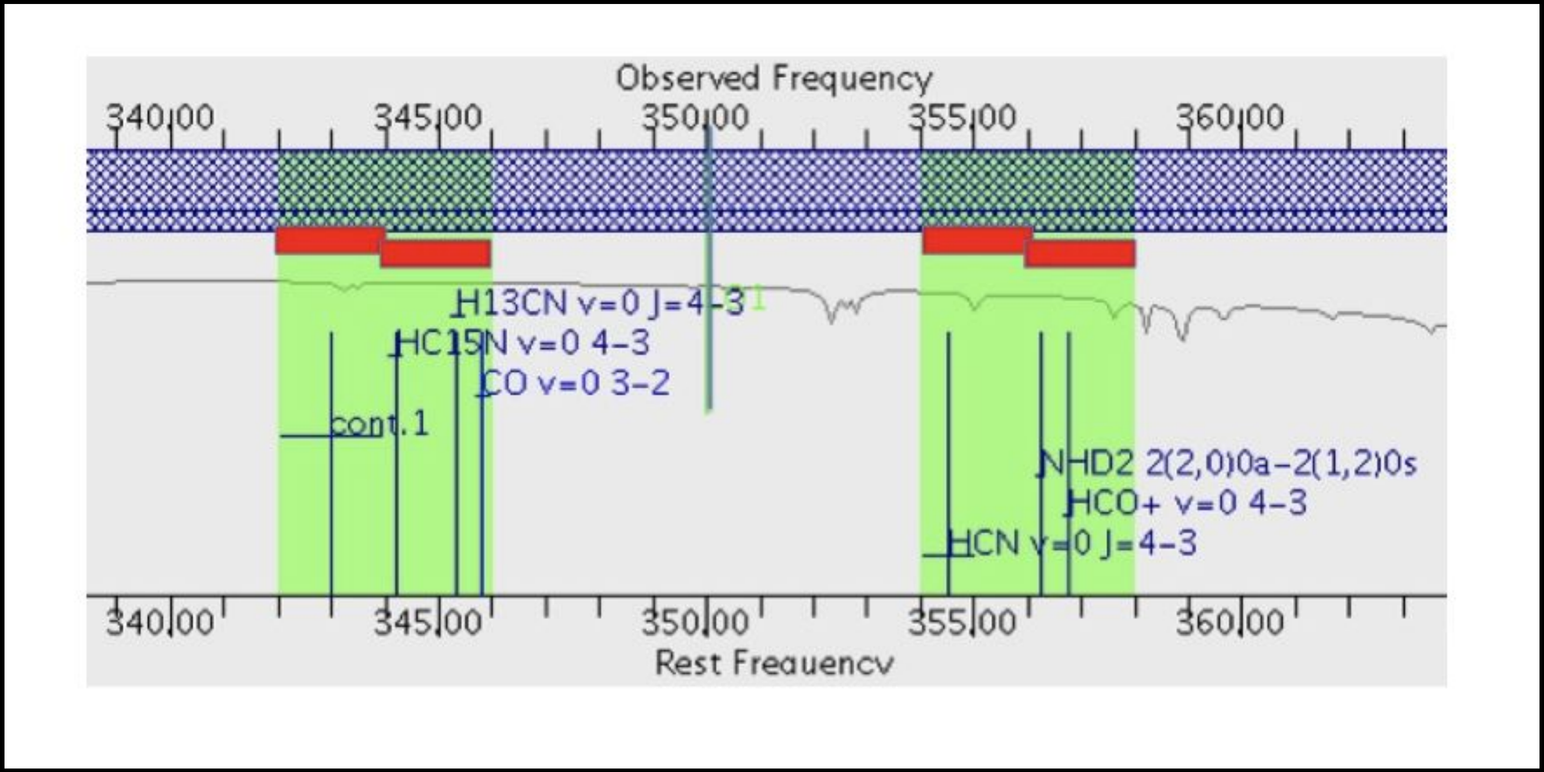
ALMA data bandwidth



The receivers allows up to **4 x 2 GHz-wide basebands** that can be placed in one sideband or distributed between the 2 Sidebands separated by 8 GHz.
→ **cover the gap with spectral scan!**

A maximum available **8 GHz bandwidth** is achieved when the 4 basebands are chosen not to overlap.

ALMA spectral windows



Each baseband may be divided into **one or more spectral windows** depending on the spectral resolution needed.

Archival data reflect the **PI choices**

ALMA correlator -1

Large number of modes → high flexibility for different science cases

FDM → Frequency division mode

small bandwidth
high resolution (spectral lines)

TDM → Time division mode

large bandwidth low resolution (continuum)

The PI can request to **bin the channels** at the correlator stage (i.e. reduce the resolution in the data) to reduce the data rate

Table 2: *Spectral Capabilities per baseband for observations in dual polarization*

Mode	Polar- ization*	Band width (MHz)	Nchan	Chan. Spacing (MHz)	Spectral Resolution† 300 GHz (km/s)
FDM	*Dual*	*1875*	*3840*	*0.488*	*0.98*
FDM	*Dual*	*938*	*3840*	*0.244*	*0.49*
FDM	*Dual*	*469*	*3840*	*0.122*	*0.24*
FDM	*Dual*	*234*	*3840*	*0.061*	*0.12*
FDM	*Dual*	*117*	*3840*	*0.0305*	*0.061*
FDM	*Dual*	*58.6*	*3840*	*0.0153*	*0.031*
TDM	*Dual*	*2000‡*	*128*	*15.625*	*31.2*

from ALMA Science Primer

ALMA correlator -2

Large number of modes → high flexibility for different science cases

Typical purposes:

- spectral scan
- moderately narrow lines
- Continuum or broad lines

Table 2: *Spectral Capabilities per baseband for observations in dual polarization*

Mode	Polar-ization*	Band width (MHz)	Nchan	Chan. Spacing (MHz)	Spectral Resolution† 300 GHz (km/s)
FDM	*Dual*	*1875*	*3840*	*0.488*	*0.98*
FDM	*Dual*	*938*	*3840*	*0.244*	*0.49*
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TDM	*Dual*	*2000‡*	*128*	*15.625*	*31.2*

from ALMA Science Primer

ALMA project types

The project code encloses information on the project itself:

2011 . 1 . 01234 . S

year of submission of the first proposal

sequential number of the call for proposal issued in that year

sequential number of submitted proposal

Letter to identify some of the classes of project:
S= STANDARD
T= TARGET OF OPPORTUNITY
V= VLBI
L= LARGE PROGRAM

ALMA technical handbook: Chapter 8

Observing modes: Solar, mosaic, single field, polarization, spectral line

What archived for each project type?

- **S and T** : raw data and QA2 scripts and products
- **V** : phased visibilities
- **L** : raw data and QA2-light/pipeline scripts and products. PIs are requested to feed additional/final products to be distributed as "external"

ASA DATA quality assessment (QA)

ALMA QA aims to check if the final data products reached the desired PI angular resolution and sensitivity **i.e. ALMA performs science-goal-oriented service data analysis**

QA0:
near-real time verification of weather and hardware issues carried out on each execution block immediately after the observation.

QA1:
verification of longer-term observatory health issues like absolute pointing and flux calibration.

QA2:
offline calibration and imaging (using CASA) of a completely observed MOUS. Performed by expert analysts distributed at the JAO and the ARCs with the help of the ALMA Pipeline. Results are archived and given to the PI.

QA3: (optional)
PIs may request re-reduction, problem fixes, possibly re-observation

ALMA technical handbook: Chapter 11

ALMA DATA quality assessment (QA)

ALMA QA aims to check if the final data products reached the desired PI angular resolution and sensitivity **i.e. ALMA performs science-goal-oriented service data analysis**

QA0:
near-real … cution
block imr

In the ASA, QA2 passed and semi-passed with some exceptions
→ **!!! see George talk on 'ASA data content' !!!**

QA1:
verificatio
calibratio

QA2:
offline calibration and imaging (using CASA) of a completely observed MOUS. Performed by expert analysts distributed at the JAO and the ARCs with the help of the ALMA Pipeline. Results are archived and given to the PI.

QA3: (optional)
PIs may request re-reduction, problem fixes, possibly re-observation

ALMA technical handbook: Chapter 11

Summary in practice

- **Field of View**
  → single pointing or mosaic?

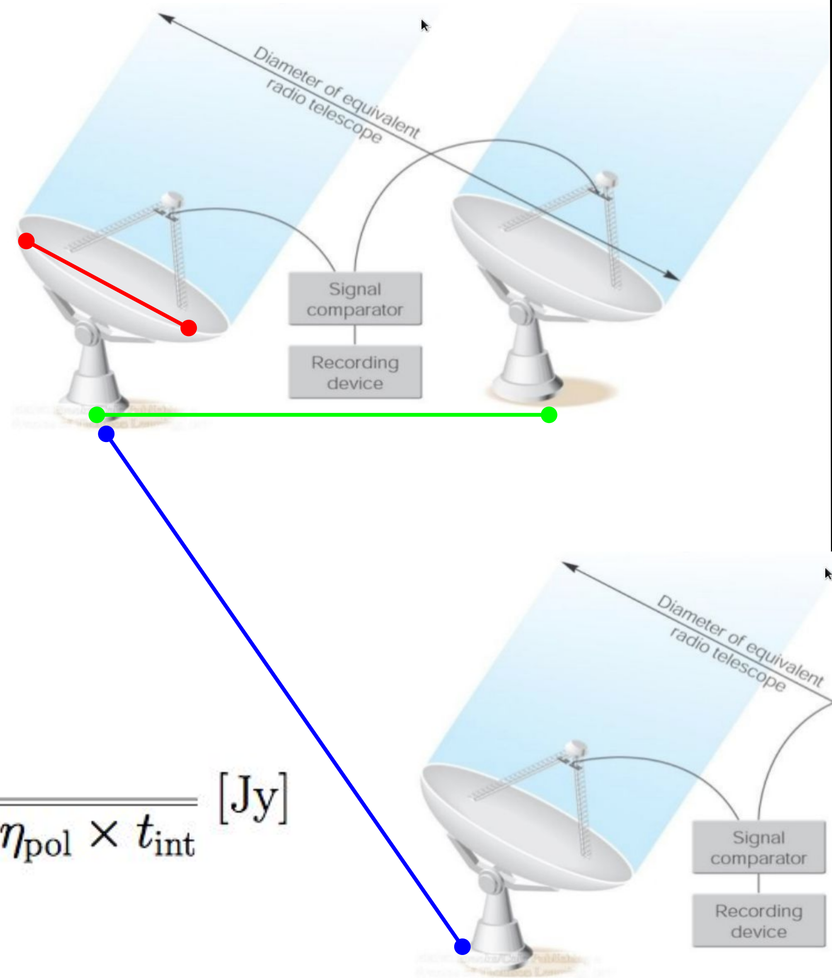
$$FOV \propto \frac{\lambda}{D}$$

- **Angular resolution**
  → array configuration?

$$\theta_{res} \approx \frac{\lambda}{B_{max}}$$

- **Maximum recoverable scale**
  → total power observations?

$$\theta_{MRS} \approx \frac{\lambda}{B_{min}}$$



- **Sensitivity**
- → Δν of spectral obs?

$$\sigma_S \approx \frac{2\,k\,T_{sys}}{A_{eff}\,\sqrt{n(n-1)\times\Delta\nu\times\eta_{pol}\times t_{int}}}\ [\mathrm{Jy}]$$

- Interferometer measures **V(u,v) = FT (T(x,y))**
  → Calibration of V(u,v) (=A, Φ vs ν t), imaging is FT^{-1} (V(u,v))

- In the mm, the **troposphere effects** on Φ (due to PWV and dry components) are dominant and increase with ν and b → high ν and long b observations more difficult.

- **Image fidelity** strongly depends on the (u,v) coverage and source dynamic range
  → best (u,v) coverage, selfcal needed?

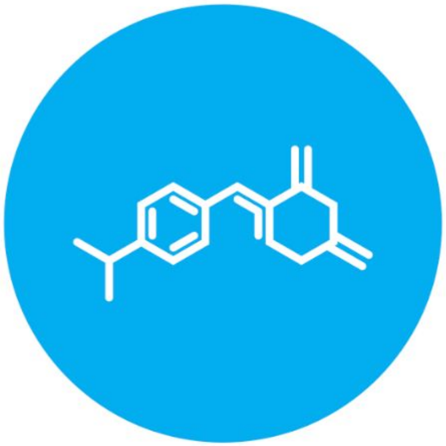
Perspectives

ALMA development Roadmap 2030

The Working Group proposes the following fundamental science drivers for ALMA developments over the next decade:

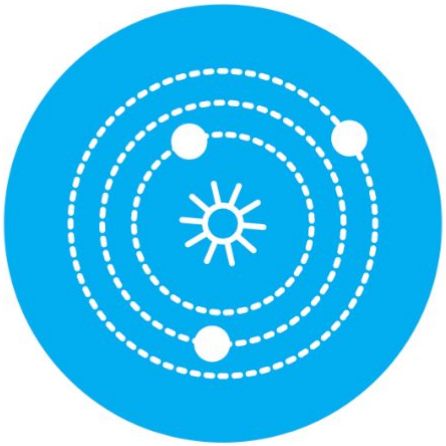
ORIGINS OF GALAXIES

Trace the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z=2–4) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.



ORIGINS OF CHEMICAL COMPLEXITY

Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (~10-100 au) by performing full-band frequency scans at a rate of 2-4 protostars per day.



ORIGINS OF PLANETS

Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone (~ 1 au) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.

The next year ASA development

ALMA development Roadmap 2030

5. ARCHIVE DEVELOPMENT

The Working Group concurs with the ALMA 2030 report that the ALMA Science Archive will become the primary source for an increasing number of publications. The ability to efficiently mine the archive contents is therefore vital for the community and ALMA's future. With the expansion of the receiver bandwidth and the upgraded correlator envisioned here, not only will the archive capacity need to be increased, but also the capabilities will need to be enhanced to exploit the rich repository of spectra.

The current ALMA archive provides the basic functionality to search and download data, and the complementary Japanese Virtual Observatory (JVO) provides impressive functionality to visualize data cubes. In addition, the ALMA Archive Working Group has produced a 5-year development plan that will provide additional functionality to facilitate archival research. While the cost of further archive upgrades is likely much less than envisioned for the package of receiver, digital system, and correlator, careful planning is nonetheless required to anticipate the needs of the community.

The Working Group recommends that a committee is formed and tasked with prioritizing the scientific functionality that will be needed in the ALMA archive over the next decade, with particular attention toward mining the archival spectra produced by the receiver upgrades.

Acknowledgement using ALMA science archive

!! REMEMBER to add it to link your paper in the ASA!!

About | Science | Proposing | Observing | Data | Processing | Tools | Documentation | Help

Publication acknowledgement

Publications making use of ALMA data must include the following statement in the acknowledgement:

"This paper makes use of the following ALMA data: ADS/JAO.ALMA#2011.0.01234.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ."

Please substitute the place-holder project code 2011.0.01234.S with the code of the data used. Have data from multiple projects been used, please specify this as "*This paper makes use of the following ALMA data: ADS/JAO.ALMA#2011.0.01234.S, ADS/JAO.ALMA#2011.0.02345.S, ADS/JAO.ALMA#2011.0.03456.S. ...*"

North American authors

In addition, publications from NA authors must include the standard NRAO acknowledgement:
"*The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.*" .

Science Verification data

For Science Verification data, the codes have the following form: ADS/JAO.ALMA#2011.0.0000X.SV, where X=1 for the TW Hya dataset, X=2 for the NGC3256 dataset, X=3 for the Antennae mosaic, etc.

For Science Verification data which is labeled "Commissioning Test data", the codes have the form ADS/JAO.ALMA#2011.0.0000X.E, where X=1 for the GRB 110715A dataset, X=2 for the Pluto Band 7 TDM dataset, etc.

Calibrator Catalogue data

For all Calibrator Catalogue data please use the fixed project code: ADS/JAO.ALMA#2011.0.00001.CAL.

Thank you and enjoy the school!