

A review of (sub)mm band science and instruments in the ALMA era



Marcella Massardi

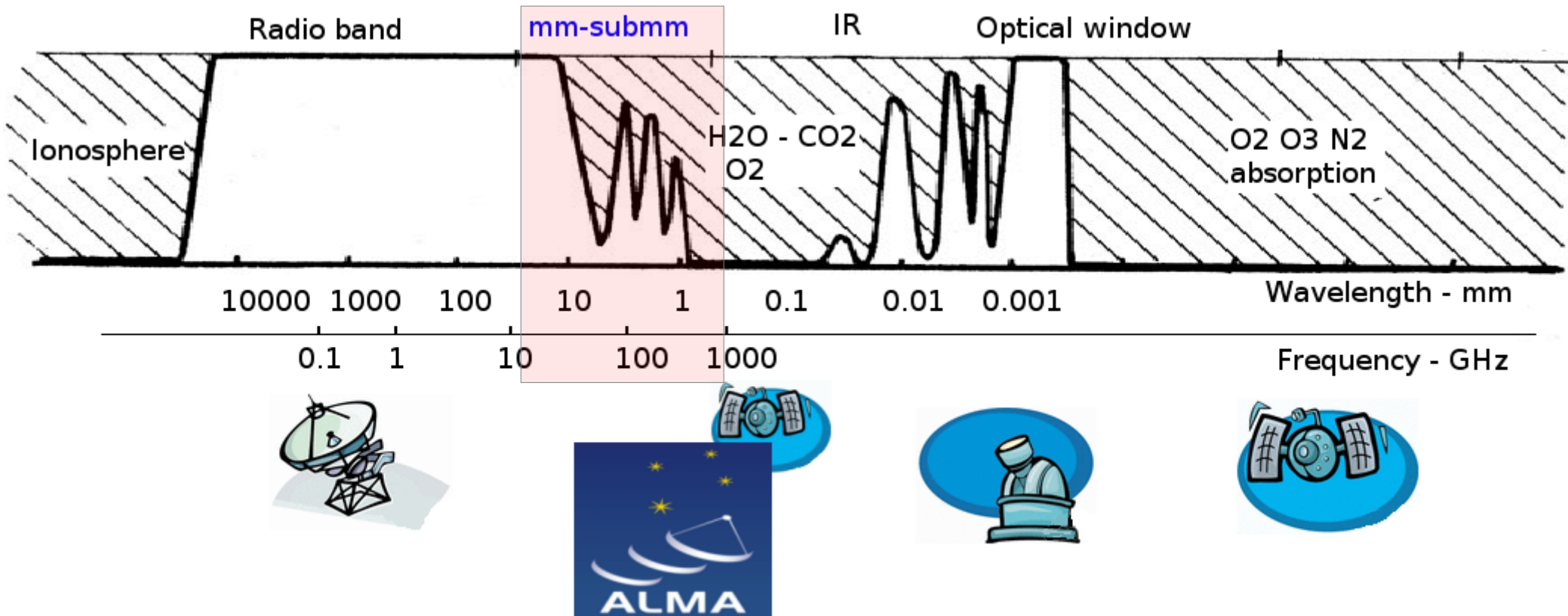
INAF- Istituto di Radioastronomia
Italian node of European ALMA Regional Centre



EUROPEAN ARC
ALMA Regional Centre || Italian

SISSA – March 2018

Outline



Signals in the (sub)mm bands

Observing instruments:

Interferometers (ALMA)

Science cases parade

Observing processes:

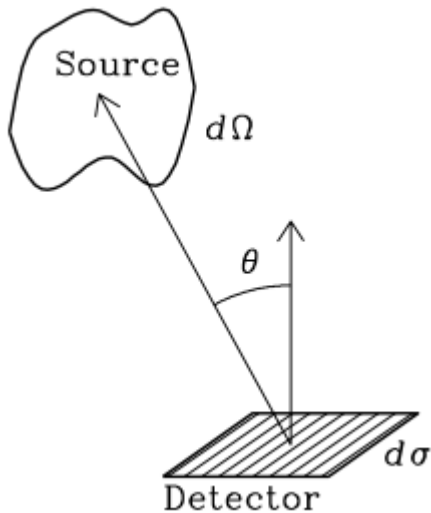
Proposals, archives & images
(with hands-on tutorial)

Observing instruments

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

Terminology: flux density

The **flux density** is the power of an electromagnetic wave passing through an infinitesimal surface



$$dP = I_\nu \cos \theta d\Omega d\sigma d\nu$$

dP = power, in watts,

$d\sigma$ = area of surface, m^2 ,

$d\nu$ = bandwidth, in Hz,

θ = angle between the normal to $d\sigma$ and the direction to $d\Omega$,

I_ν = brightness or specific intensity, in $\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$.

The **total flux** is the integral of dP over the solid angle subtended by the source

$$S_\nu = \int_{\Omega_s} I_\nu(\theta, \varphi) \cos \theta d\Omega,$$

Flux density is measured in Jansky

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

Brightness does not depend on distance d , while flux density scales as $1/d^2$

Terminology: Sensitivity and polarization

The rms noise in the signal for a radiometer is given by:

$$\Delta S_\nu = 2k \frac{T_{\text{sys}}}{A_e \sqrt{2t \Delta\nu}}$$

Diagram illustrating the components of the rms noise equation:

- k : Boltzmann constant
- T_{sys} : Brightness temperature corresponding to all the signals collected including source, atmosphere and instrument
- A_e : Effective collecting Area = #_antennas x dish_area x efficiency
- 2 : # of polarizations
- t : Time on source
- $\Delta\nu$: Bandwidth

Sensitivity can be improved by

- **getting lower T_{sys}** (= lowering the instrumental noise or choosing sites with low water vapour levels)
- **increasing the collecting area**
- **increasing the bandwidth and/or the integration time**

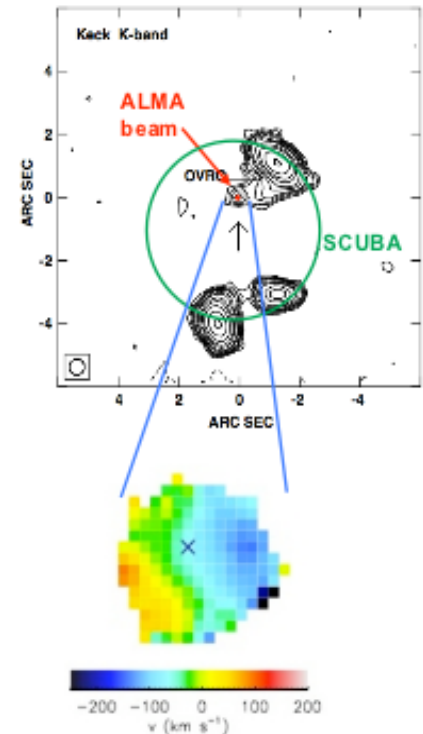
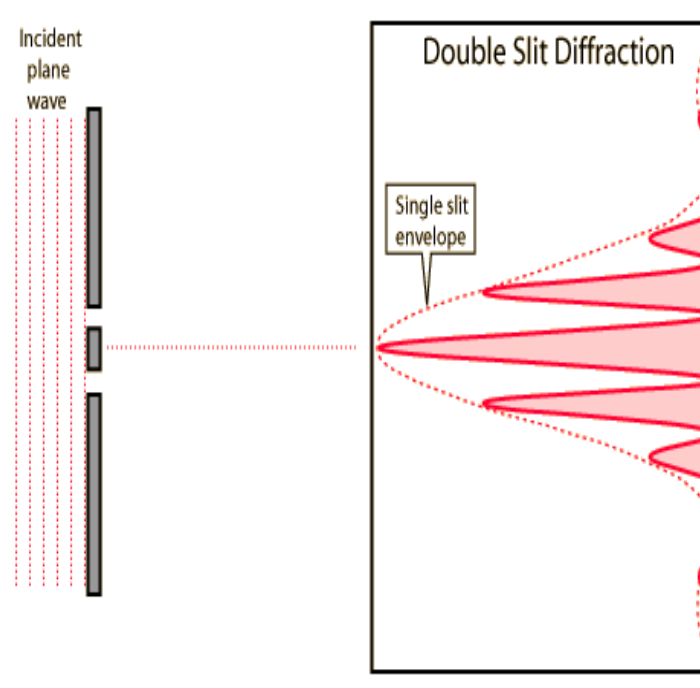
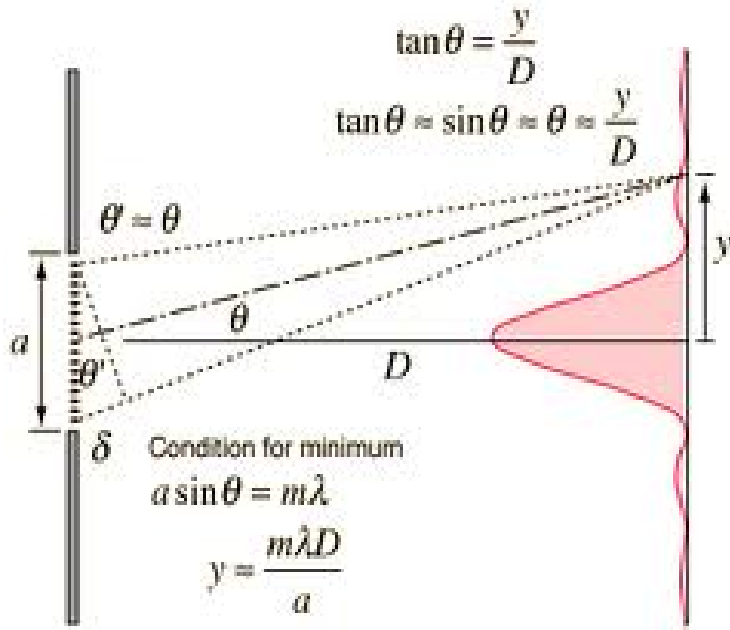
Receivers are couple of dipoles, so split the signal into **2 polarizations**
By combining the independent polarizations chains it can reconstruct all the Stokes parameters.

Terminology: resolution

Antennas work as apertures of diameter a at distance B (=baseline $\gg a$)

the **Resolution** for a wavelength λ is $\theta = \lambda/B$.

This is defined as **Synthesized Beam** and is equivalent to the resolution of a single dish of diameter B .



In the double slit diffraction the pattern is modulated by the single slit envelope, i.e. the response function of an interferometer is modulated in a region of size **FOV**= λ/a , with a the antenna radius, also called **Field of View or Primary Beam**.

Hence, **resolution decreases as the wavelengths decreases**.

Larger telescopes are needed to reach higher resolutions:

from space small instruments give low resolution & sensitivity
from ground larger instruments are possible.

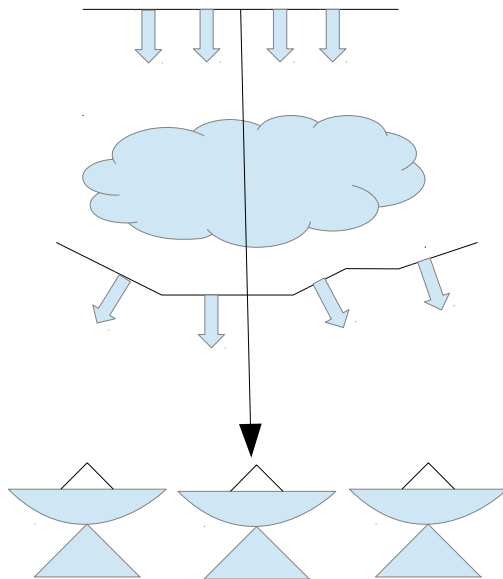
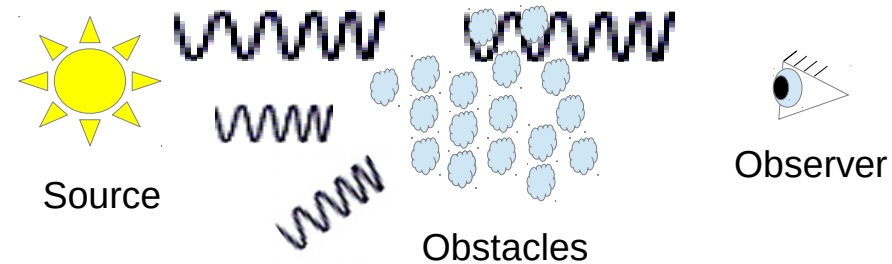
Terminology: signal “obstacles”

Obscuration & Scattering

Light **waves** path is deflected by irregularities in the propagation medium or irregularities on the reflection surface. Obstacles larger than the light wavelength obscure (reflect) it.

Water Vapour droplets mean size ranges between 10-15 micron and up to 100 micron in clouds.

Antenna Surface irregularities should be smaller than $\sim 1/10$ of the observing wavelength (~ 0.03 micron in submm).



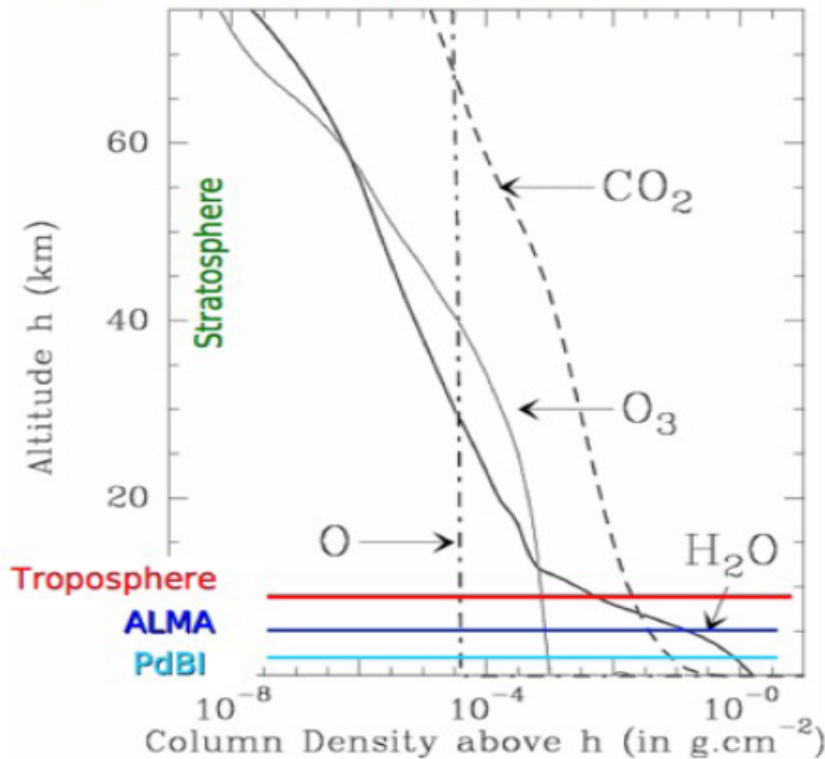
Decorrelation

Scattering of light paths has the consequence that two or more receivers looking at the same wavefront receive it in different times and from different direction. If deviations are too large it is no longer possible to reconstruct the original wavefront and compare the signals

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

Terminology: signal “obstacles”

Column density as function of altitude

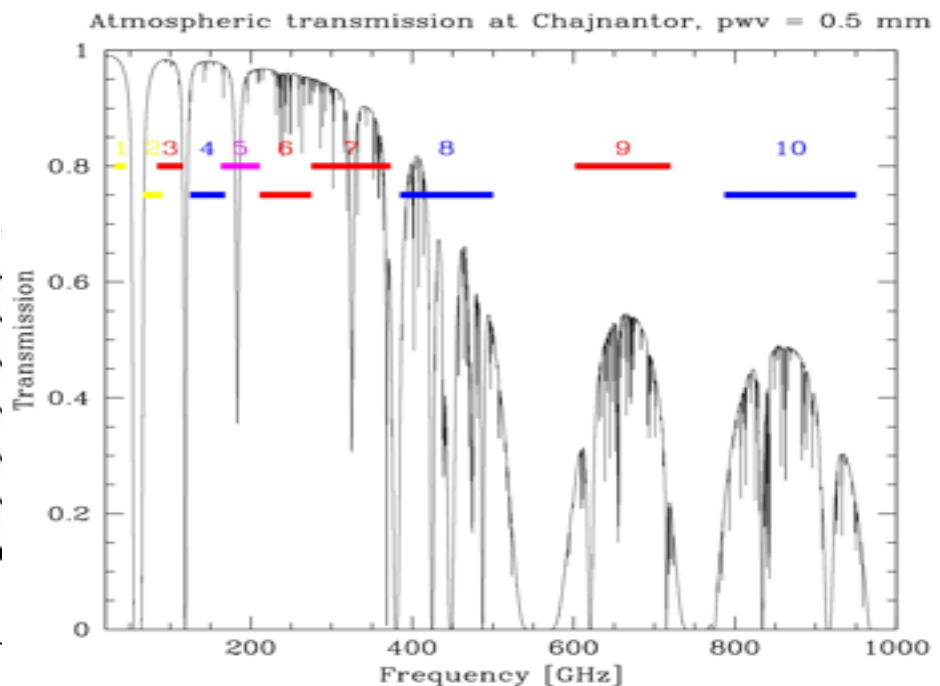
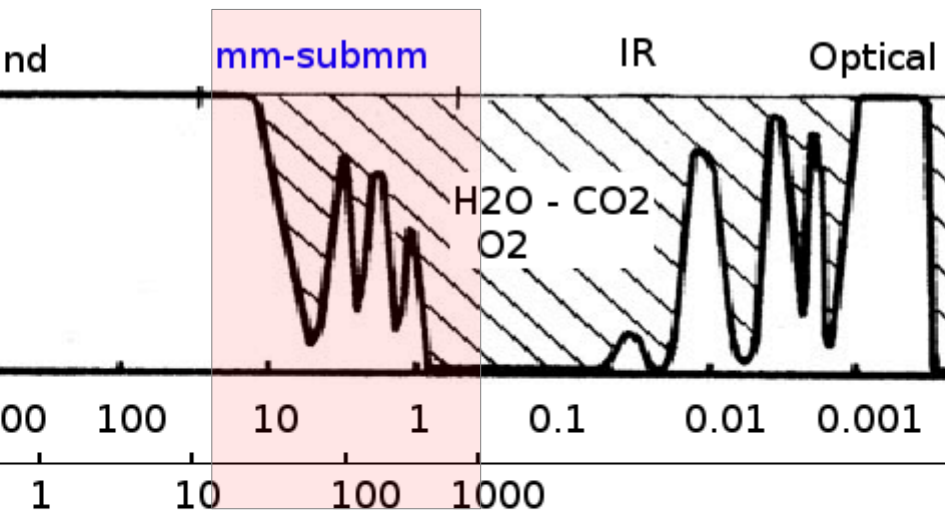


Absorption & Attenuation

Light can be absorbed by interacting with a medium and the **photon energy** is transmitted to the molecules or atoms of the medium. Light can be reemitted attenuated or changed in energy.

Molecular transitions and some atomic transitions are excited by mm wavelength and in our atmosphere they can absorb the signals.

Transmissivity is higher the smaller are the obstacles and the less dense is the medium along the line of sight.
Only some transmission bands are available in the submm and only from high and dry sites.



Instruments: bolometers

An incident radiation changes the temperature of the receiver that absorbs it.

The temperature variation is a measure of radiation intensity.

Bolometers are intrinsically broadband because the thermal effect is independent of frequency.

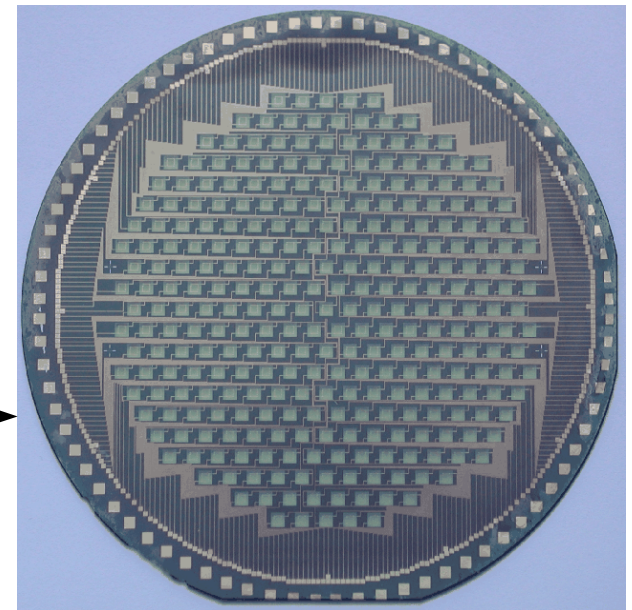
They are less sensitive to atmospheric variations.

Filters are needed for frequency determination.

They are **usually mounted on single dish**, hence limited in resolution to the antenna diameter.

To cover larger areas they are packed in arrays to increase the instantaneous Field Of View.

Instrument	Wavelength (microns)	F-o-V (sq-arcmins)	NEFD (mJy)	FWHM (arcsec)	Confusion (mJy)
SCUBA	450	4.2	400	7.5	0.25
	850	4.5	80	14	0.5
SCUBA-2	450	50	100	7.5	0.25
	850	50	30	14	0.5
Laboca-S	350	4	250	7	0.3
Laboca	850	11	110	18	0.8
SPIRE	250	32	29	18	2.6
	350	32	34	25	3.8
	500	32	37	35	5.4
AzTec	1100	2.4	3.5	5.5	0.06
MAMBO-2	1200	10	30	10	0.2



100 pc at $z > 1$ appear on arcsec scales

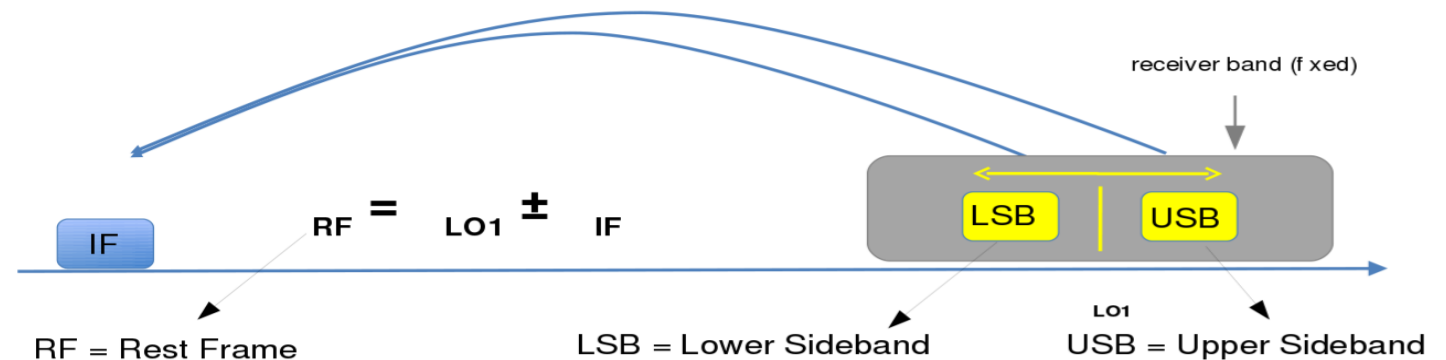
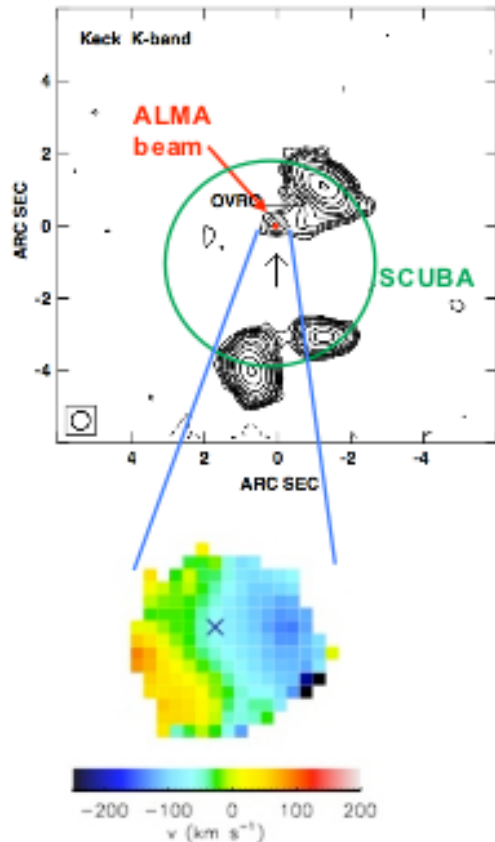
Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

Instruments: Coherent receivers

Coherent receivers preserve the phase of the signal: can be mounted on interferometers

Furthermore, by mean of heterodyne principles the frequency is shifted to fixed lower values, without changing any other property of the signal, by combining the received signal with that of a tunable **Local Oscillator**.

This allows to have the whole electronic chain working at the same frequency.



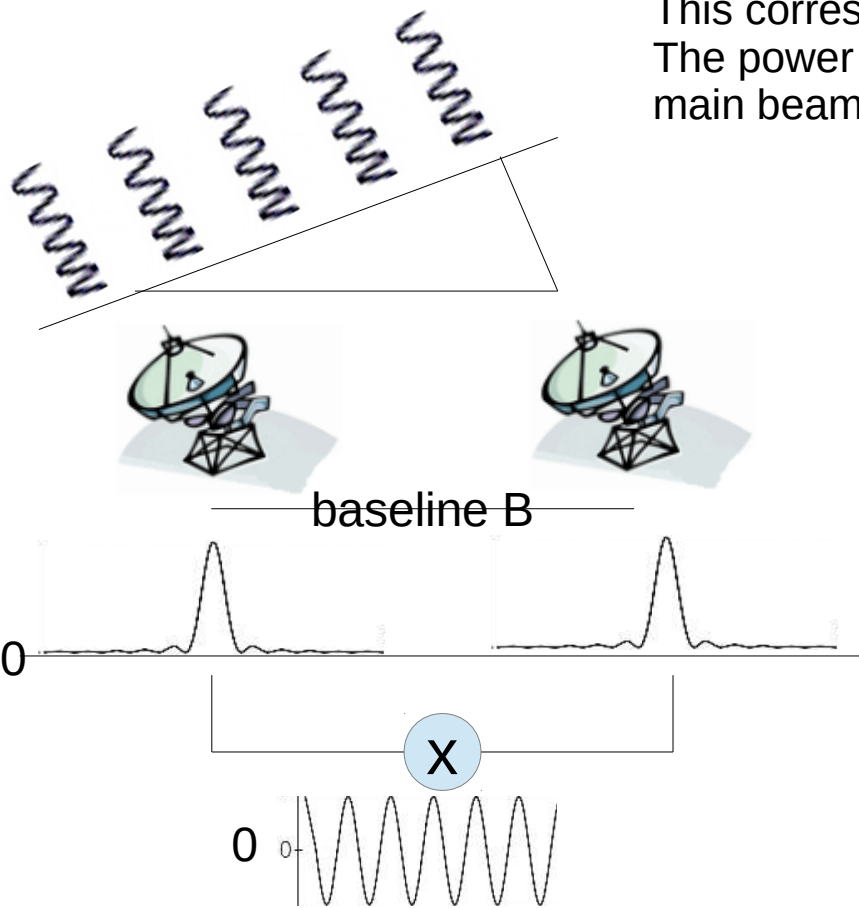
Name	Antennas [# × Diameter]	$\Delta\lambda$ [mm]	Max ang. resol. [asec]	Total area [m ²]
IRAM-PdBI	6 × 15m	1.2–3	0.35	1060
CARMA ^a	6 × 10.4m + 10 × 6m	1.2–3	0.1	792
NMA	6 × 10m	1.2–3	1	471
SMA	8 × 6m	0.35–1.2	0.1	226
eSMA ^b	SMA + 15m + 10.4m	0.87–1.2	0.2	488
ATCA ^c	6 × 22m ^d	3–12	2.	2280 ^d

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

Instruments: interferometers

A coherent combination of reflectors of diameter d at distance $B(>>d)$ give a resolution equivalent to that of a single reflector of diameter B .

The main (primary) beam (FOV) of an antenna is the solid angle where its power pattern (assuming to use it as a transmitter) is larger ($\theta=\lambda/d$). This corresponds to the range where it is more sensitive as a receiver. The power pattern in case of a far away point source is given by the main beam shape with amplitude equal to the source flux (total power).

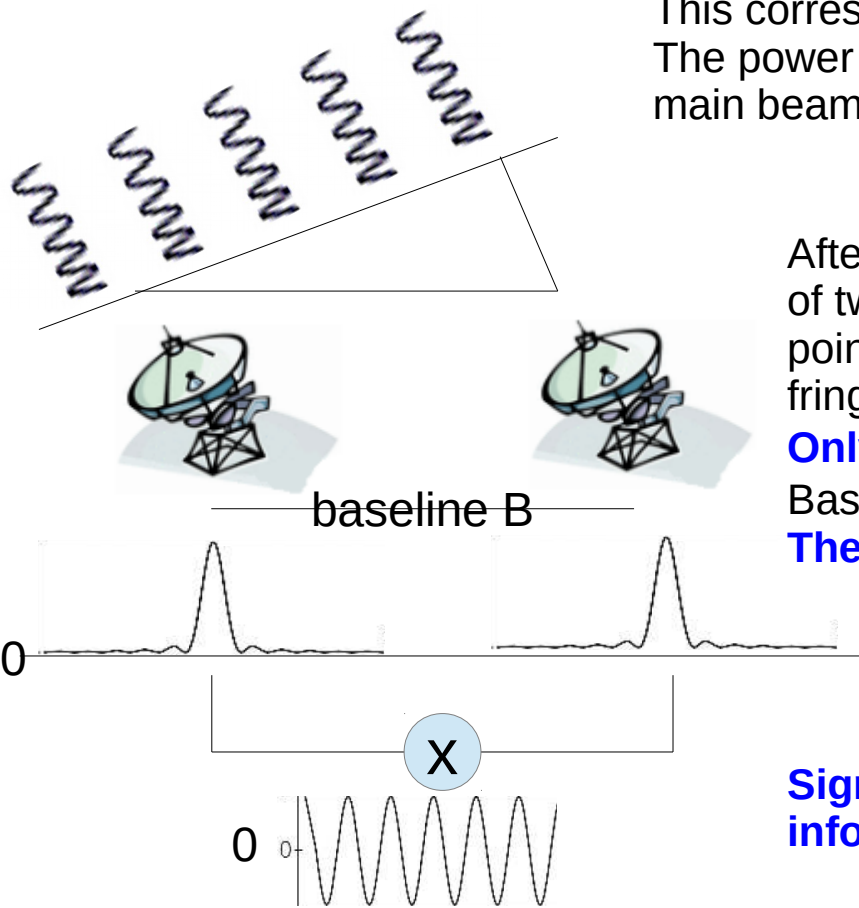


Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

Instruments: interferometers

A coherent combination of reflectors of diameter d at distance $B(>>d)$ give a resolution equivalent to that of a single reflector of diameter B .

The main (primary) beam (FOV) of an antenna is the solid angle where its power pattern (assuming to use it as a transmitter) is larger ($\theta=\lambda/d$). This corresponds to the range where it is more sensitive as a receiver. The power pattern in case of a far away point source is given by the main beam shape with amplitude equal to the source flux (total power).



After correcting for geometrical delays, allowing the comparison of two points of the same wavefront coming from a far away point source the output of the correlation of two signals is a fringe pattern centered around 0 (total power is lost).

Only the spatial component corresponding to $\theta=\lambda/B$ is preserved

Baselines equal to $2D$ identifies angular scales of the order of $\theta/2$.

The interferometer works as a filter in spatial scales.

Signals on multiple baselines can be combined to retrieve information on source structure (= aperture synthesis).

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

The visibility function

The incoming wave induces a electromagnetic voltage in the antennas (E is the wave amplitude)

$$U_1 \propto E e^{i\omega t}$$

$$U_2 \propto E e^{i\omega(t-\tau)}$$

The geometrical delay in the direction $s=s_0+ds$

$$\tau = \frac{1}{c} \mathbf{B} \cdot \mathbf{s}$$

The correlator works as a multiplier and time integrator with output

$$R(\tau) \propto \frac{E^2}{T} \int_0^T e^{i\omega t} e^{-i\omega(t-\tau)} dt$$

$$R(\tau) \propto \frac{\omega}{2\pi} E^2 \int_0^{2\pi/\omega} e^{i\omega\tau} dt$$

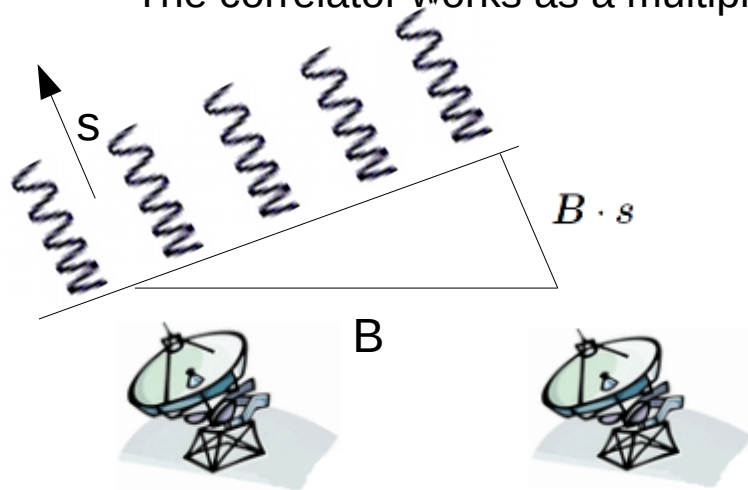
If $T \gg 2\pi/\omega$

that results in

$$R(\tau) \propto \frac{1}{2} E^2 e^{i\omega\tau}$$

The power induced by the source in terms of I and effective area from in the direction s ($P \propto E^2$)

$$dP = I_\nu \cos \theta d\Omega d\sigma d\nu \\ = A(s) I_\nu(s) d\Omega d\nu$$



The output of the correlator integrated over the source is the visibility function

$$r_{12} = A(s) I_\nu(s) e^{i\omega\tau} d\Omega d\nu$$

$$R(\mathbf{B}) = \iint_{\Omega} A(\mathbf{s}) I_\nu(\mathbf{s}) \exp \left[i 2\pi \nu \left(\frac{1}{c} \mathbf{B} \cdot \mathbf{s} \right) \right] d\Omega d\nu$$

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

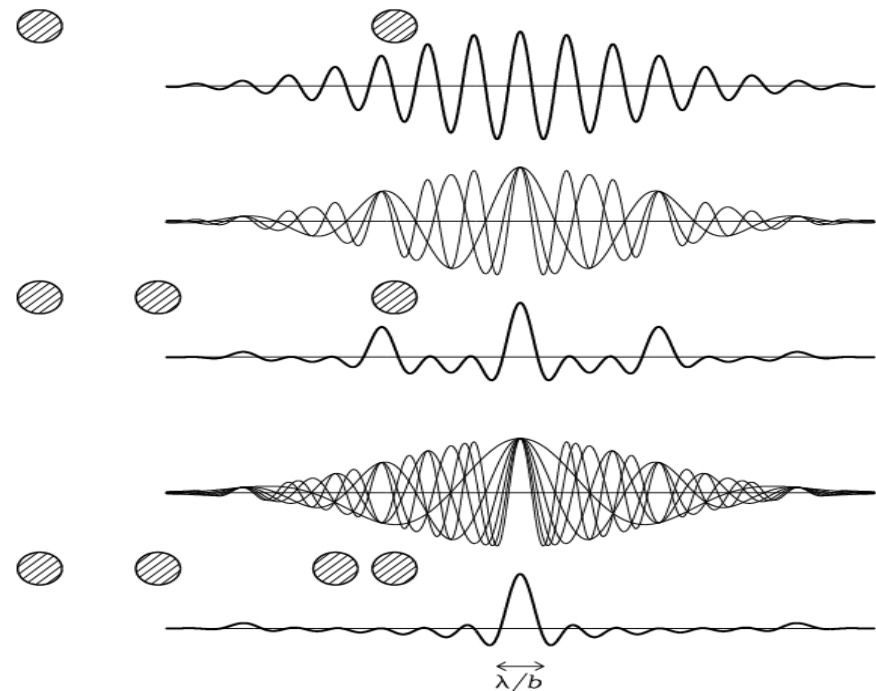
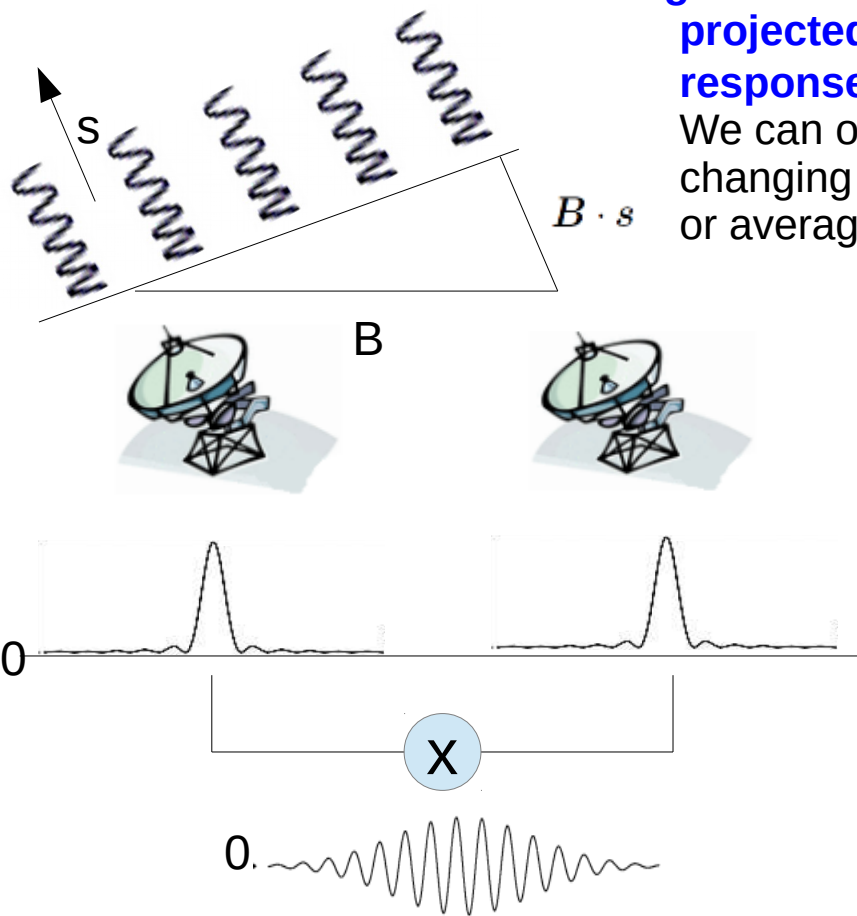
The visibility function: properties

Some **visibility function** properties:

$$R(\mathbf{B}) = \iint_{\Omega} A(\mathbf{s}) I_{\nu}(\mathbf{s}) \exp \left[i 2\pi \nu \left(\frac{1}{c} \mathbf{B} \cdot \mathbf{s} \right) \right] d\Omega d\nu$$

- **Amplitude is modulated by the main beam shape**
- **The phase is strictly connected with the source position**
- **Angular scales on the sky are associated with the size of the projected baseline needed to observe them and the FWHM of the response function width is the synthesized beam λ/B .**

We can observe more angular scales either changing the baseline or averaging the signal from N Antenna couples ($N(N-1)/2$)



Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

The visibility function: properties

Some visibility function properties:

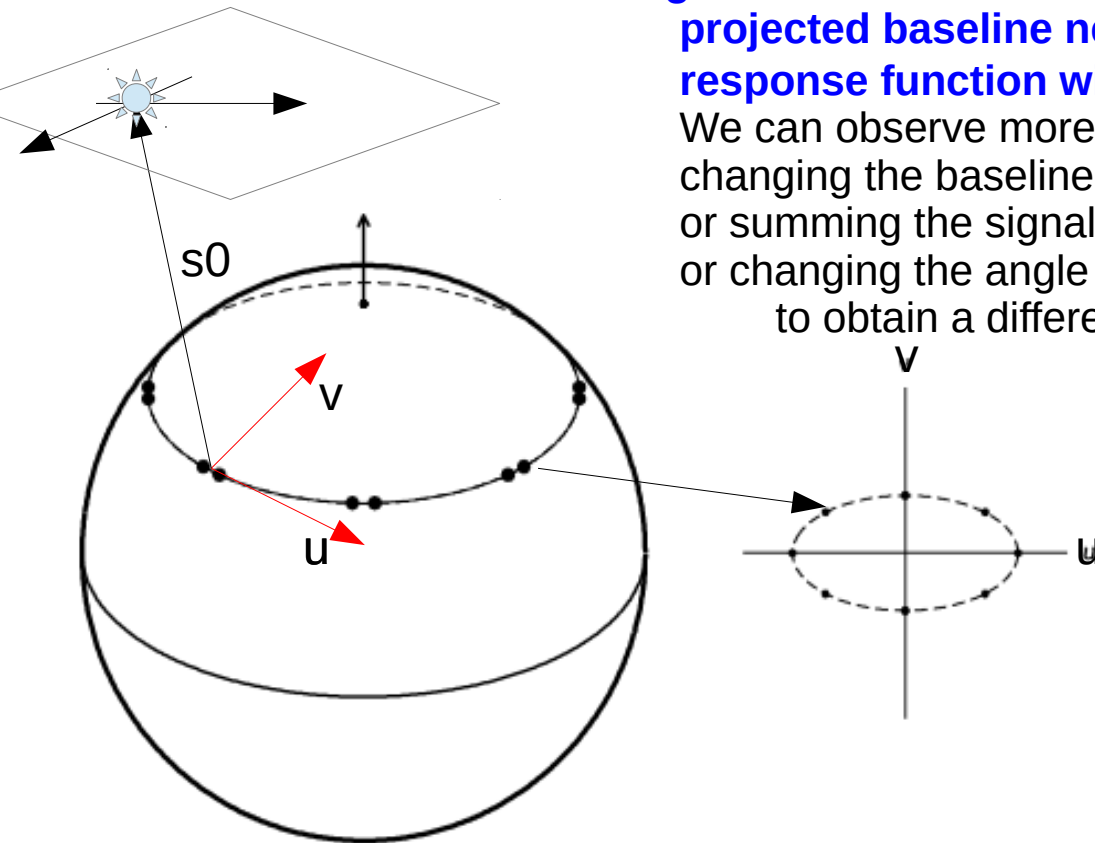
$$R(\mathbf{B}) = \iint_{\Omega} A(s) I_{\nu}(s) \exp \left[i 2\pi \nu \left(\frac{1}{c} \mathbf{B} \cdot \mathbf{s} \right) \right] d\Omega d\nu$$

- **Amplitude is modulated by the main beam shape**
- **The phase is strictly connected with the source position**
- **Angular scales on the sky are associated with the size of the projected baseline needed to observe them and the FWHM of the response function width is the synthesized beam λ/B .**

We can observe more angular scales either changing the baseline

or summing the signal from N Antenna couples $(N(N-1)/2)$

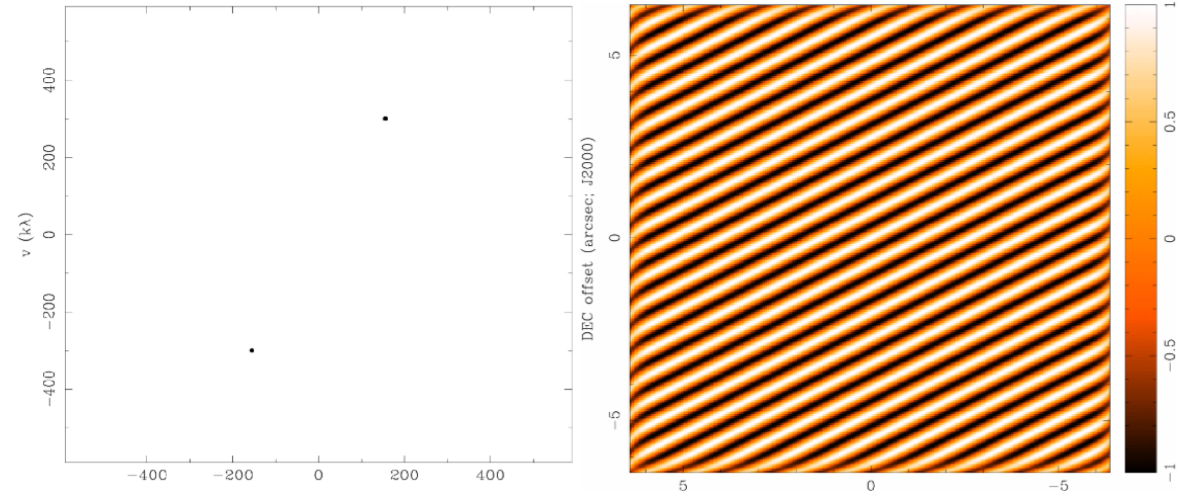
or changing the angle towards the target (exploiting the Earth rotation) to obtain a different projection of the same baseline.



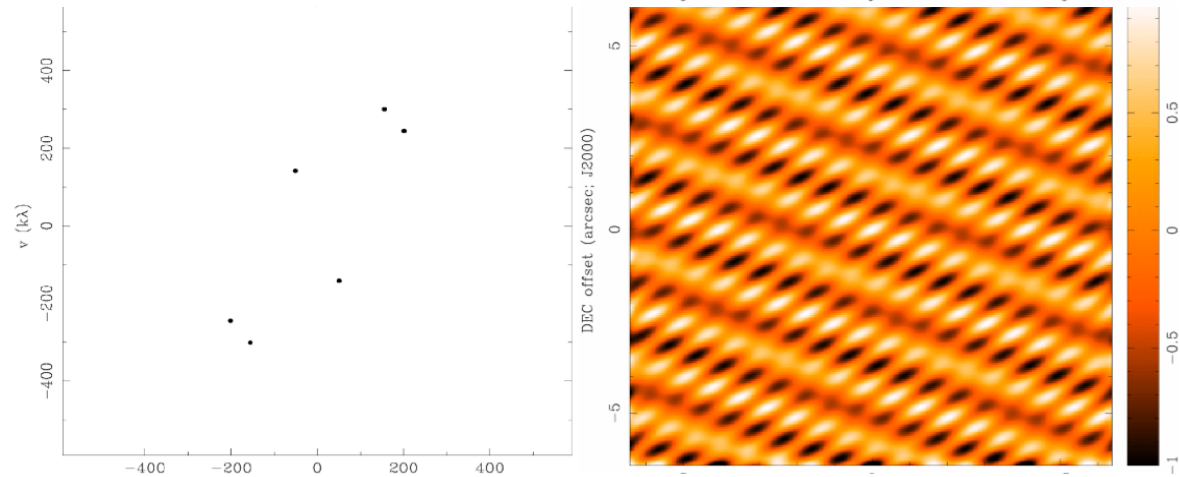
The projected baseline is described over the uv plane perpendicular to the direction to the phase center (s_0) with u and v towards E and N. The earth rotation generates elliptical loci on the uv plane in 12 hr which ellipticity depends on the telescope latitude and source declination.

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

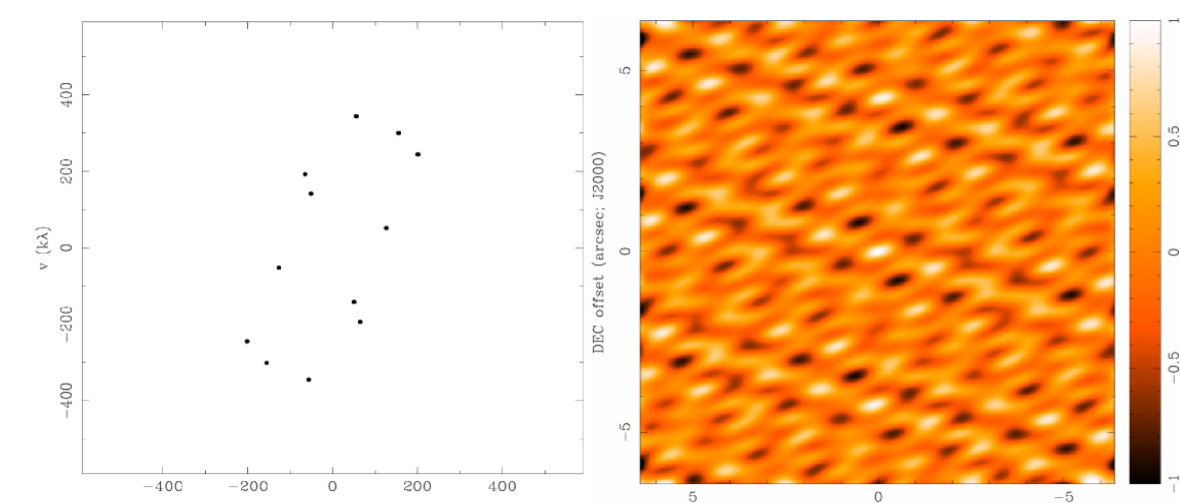
The visibility function: the uv plane



2 antennas

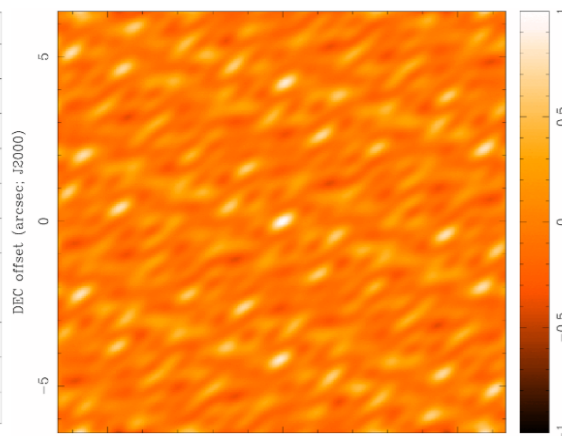
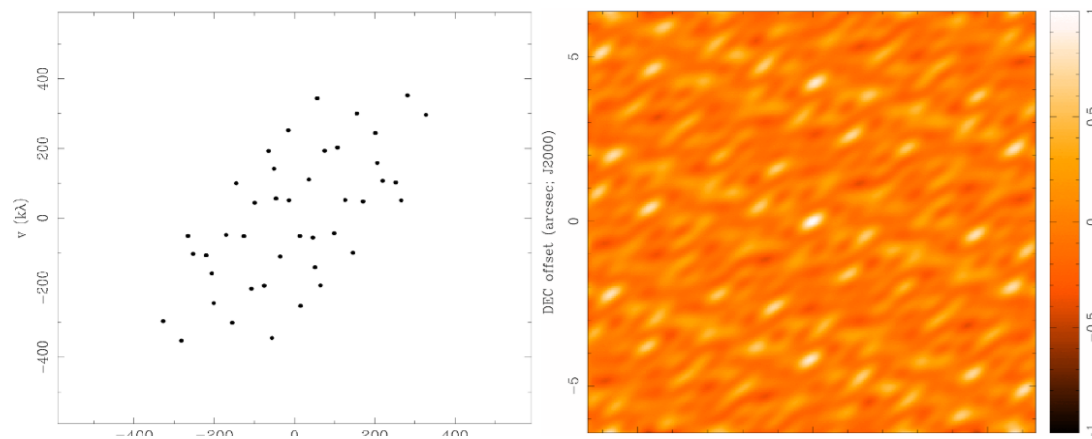


3 antennas



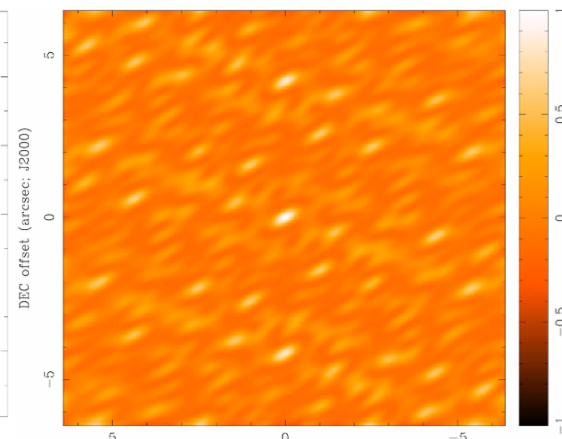
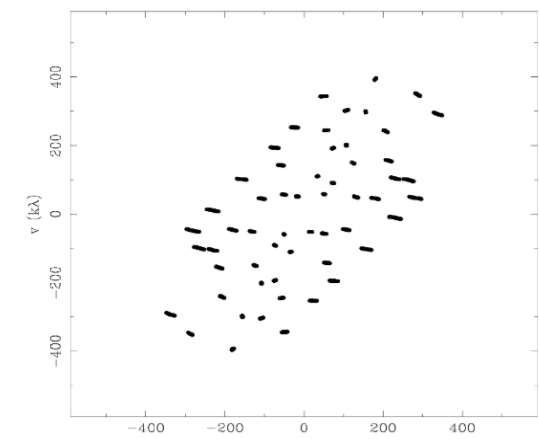
5 antennas

The visibility function: the uv plane

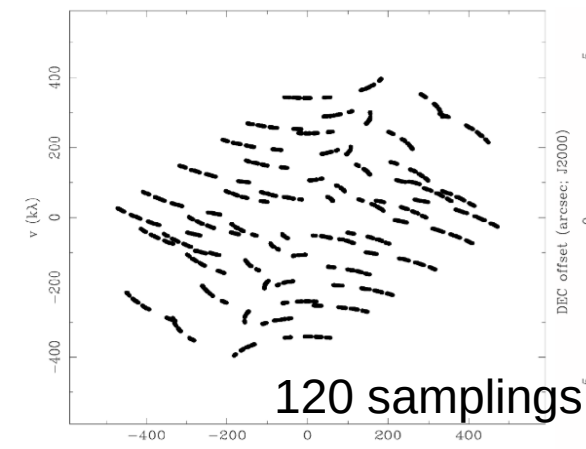


8 antennas

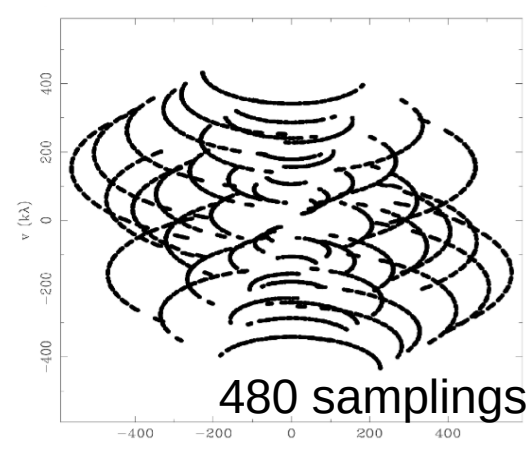
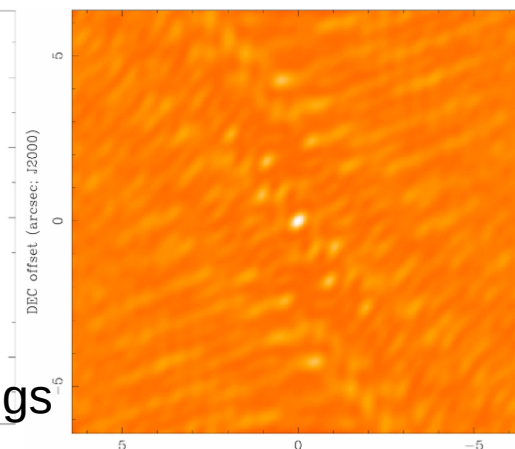
1 sampling



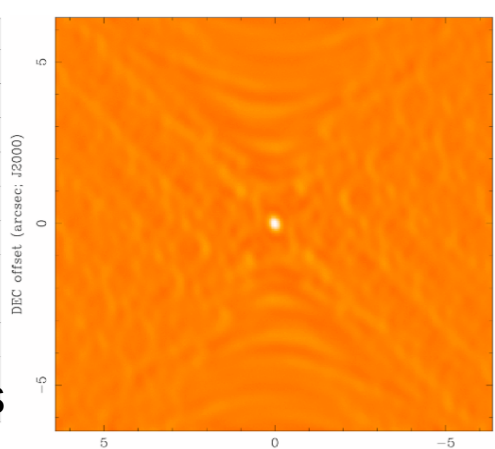
30 samplings



120 samplings



480 samplings



The visibility function: properties

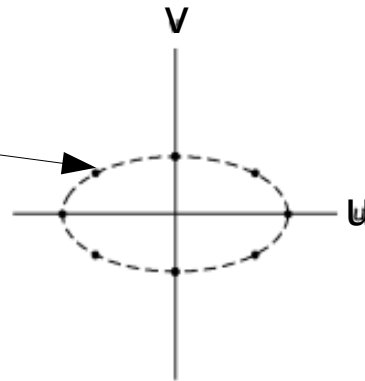
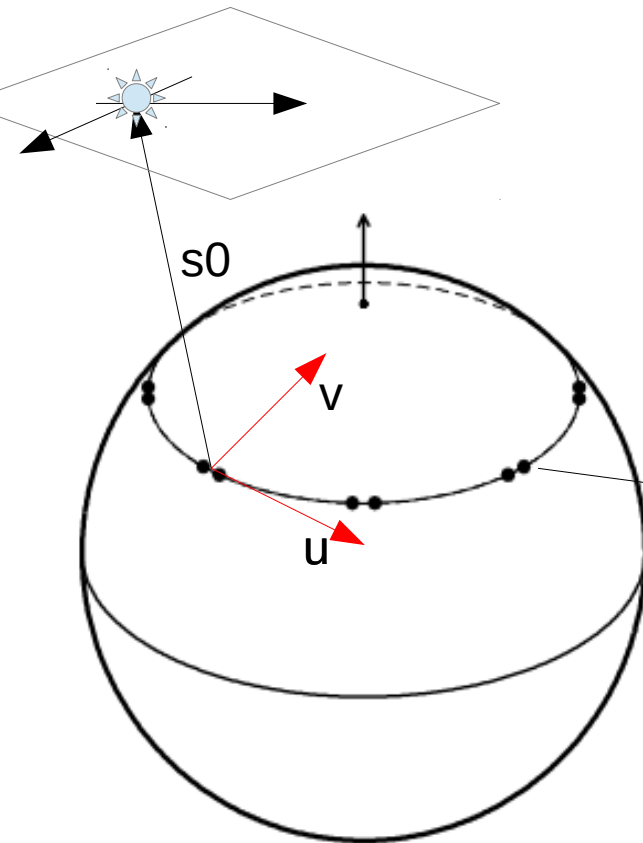
Some visibility function properties:

$$R(\mathbf{B}) = \iint_{\Omega} A(s) I_{\nu}(s) \exp \left[i 2 \pi \nu \left(\frac{1}{c} \mathbf{B} \cdot \mathbf{s} \right) \right] d\Omega d\nu$$

- **Amplitude is modulated by the main beam shape**
- **The phase is strictly connected with the source position**
- **Angular scales on the sky are associated with the size of the projected baseline needed to observe them and the FWHM of the response function width is the synthesized beam λ/B .**

We can observe more angular scales either changing the baseline

or summing the signal from N Antenna couples $(N(N-1)/2)$ or changing the angle towards the target (exploiting the Earth rotation) to obtain a different projection of the same baseline.



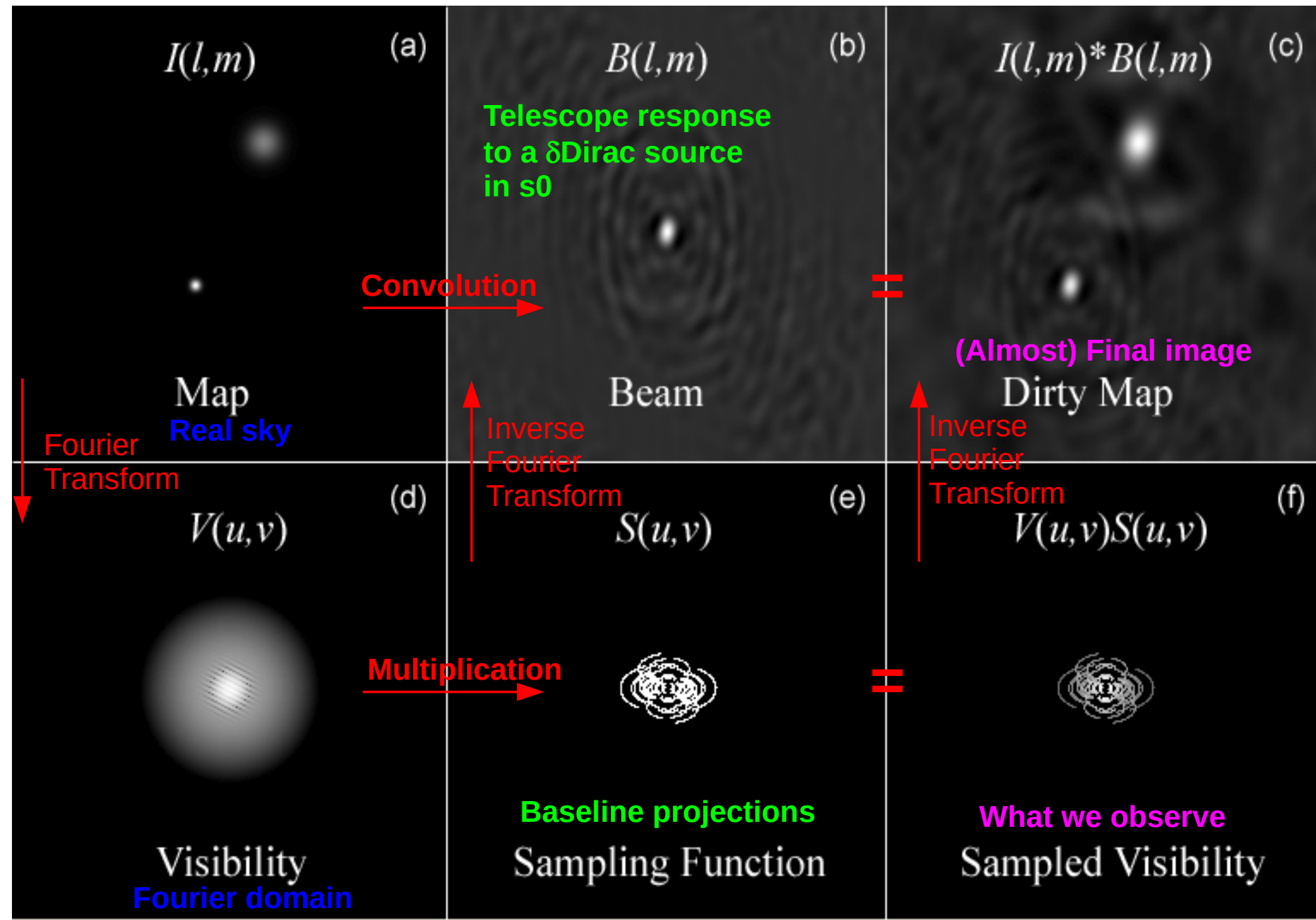
The projected baseline is described over the uv plane perpendicular to the direction to the phase center (s_0) with u and v towards E and N. The earth rotation generates elliptical loci on the uv plane in 12 hr which ellipticity depends on the telescope latitude and source declination.

- **Van Cittert- Zernike theorem: the visibility pattern is the Fourier transform of the brightness pattern**

Hence the inverse transformation of the uv plane gives the image of the real plane (filtered for the observed angular scales).

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

From the sky to the image



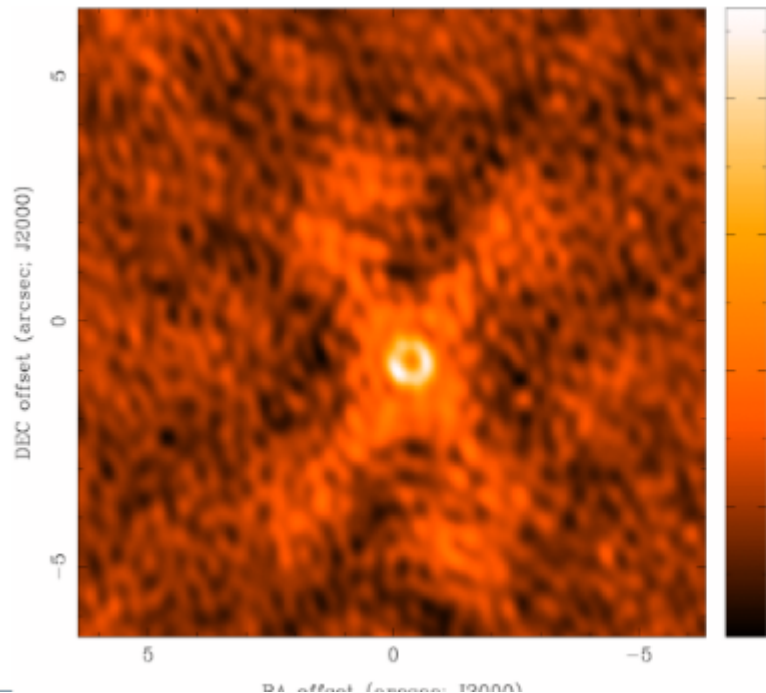
Deconvolution

$$R(\mathbf{B}) = \iint_{\Omega} A(\mathbf{s}) I_{\nu}(\mathbf{s}) \exp \left[i 2 \pi \nu \left(\frac{1}{c} \mathbf{B} \cdot \mathbf{s} \right) \right] d\Omega d\nu$$

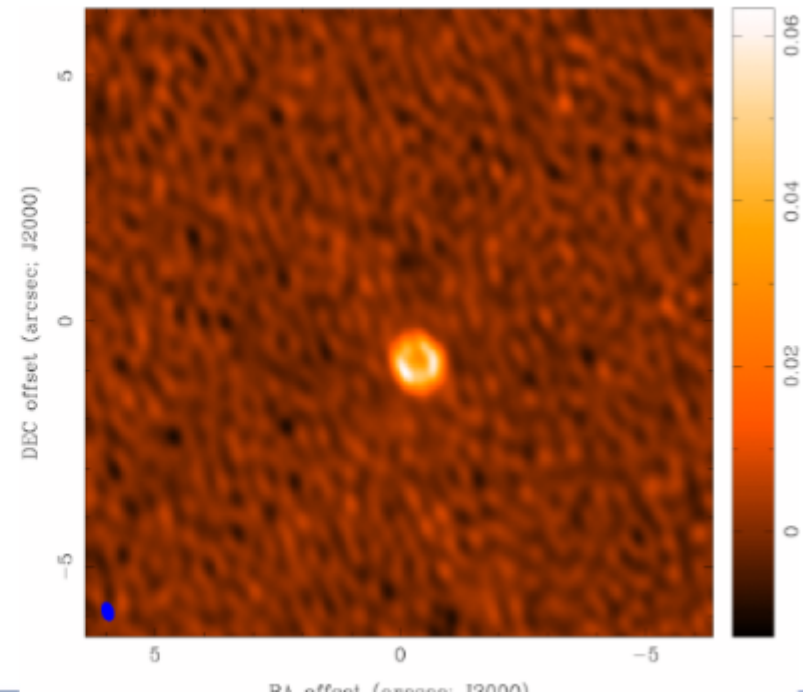
- Aims to find a sensible model of $I(\mathbf{s})$ compatible with data without sidelobes
- Uses non-linear techniques to interpolate/extrapolate samples of $R(u,v)$ into unsampled regions of the (u,v) plane
- Requires knowledge of beam shape $A(\mathbf{s})$ and a priori assumptions about $I(\mathbf{s})$

One of the most common algorithms in radio astronomy is the algorithm CLEAN (Hogbom 1974)

Dirty
Image



Cleaned
Image



The Atacama Large Millimeter Array

ALMA rationale

- The Atacama Large Millimeter Array is a **mm-submm reconfigurable interferometer**
- Inaugurated March 2013 on the Chajnantor plain (**5000m**, Chile)
- **The design of ALMA is driven by three key science goals:**

- The ability to detect spectral line emission from CO or [CII] in a normal galaxy like the Milky Way at a redshift of $z=3$, in less than 24 hours,

- > frequency bands, high sensitivity
- > study of star formation in galaxies up to high redshift, galaxy formation, Lensing, ...

- The ability to image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars in the nearest molecular clouds (150 pc),

- > high and low angular resolution, high spectral resolution
- > study of processes of star and planet formation, stellar evolution and structure, astrochemistry, ...

- The ability to provide precise high dynamic range ($=|image\ max/image\ min|$) images at an angular resolution of 0.1 arcsec.

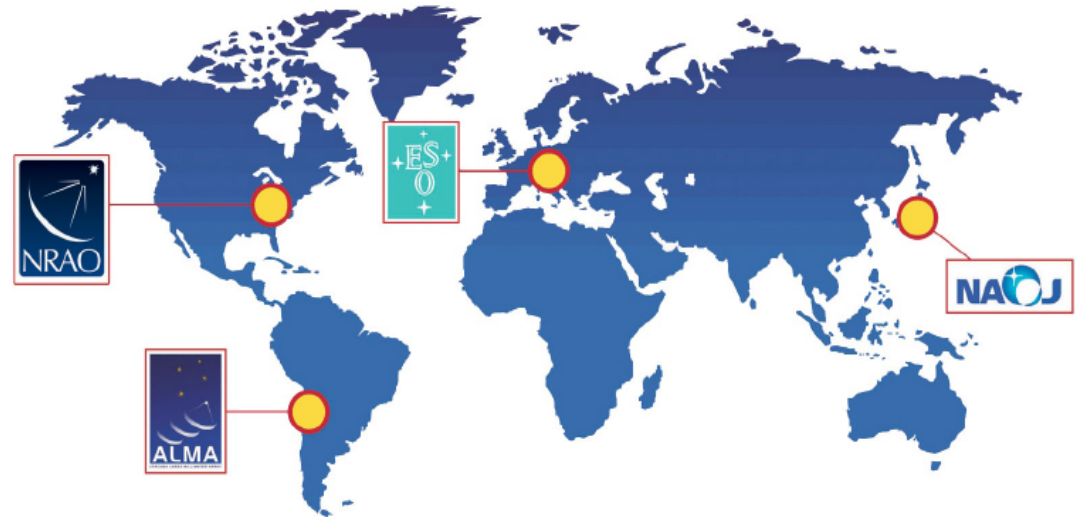
- > high angular resolution and sensitivity
- > galaxy dynamics, AGN core mechanisms, imaging of exoplanets, comets, asteroids, ...

ALMA organization

World wide collaboration

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

Contributors share the observing time

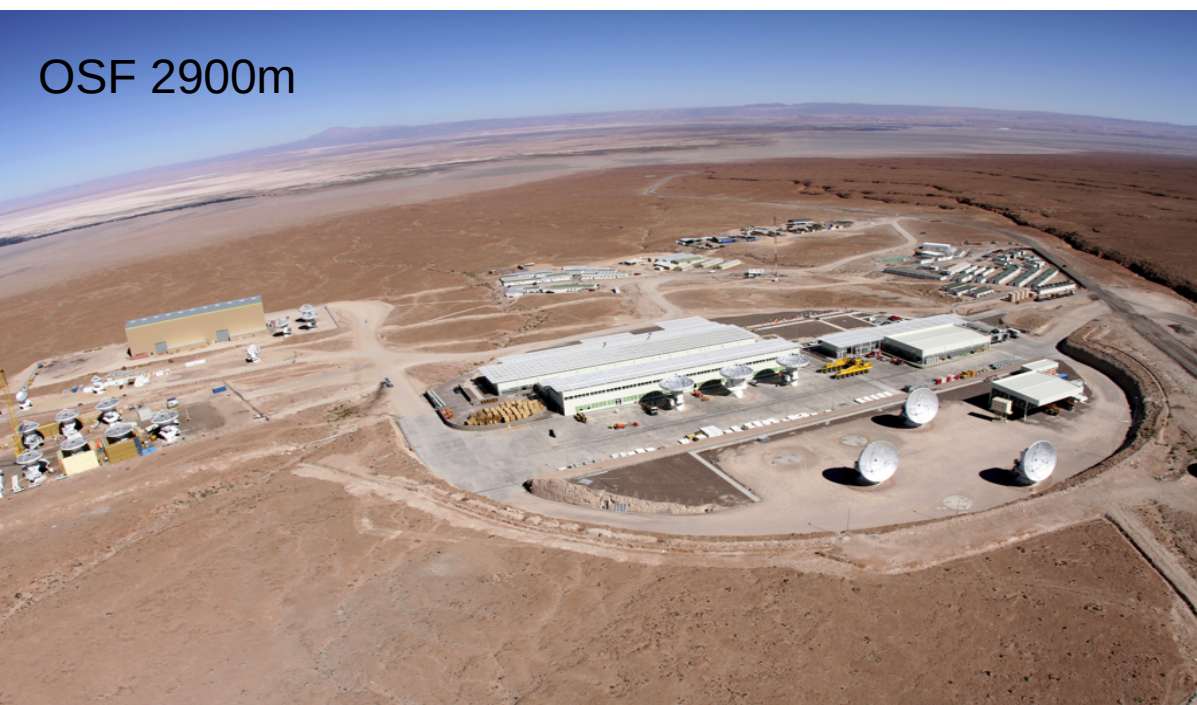
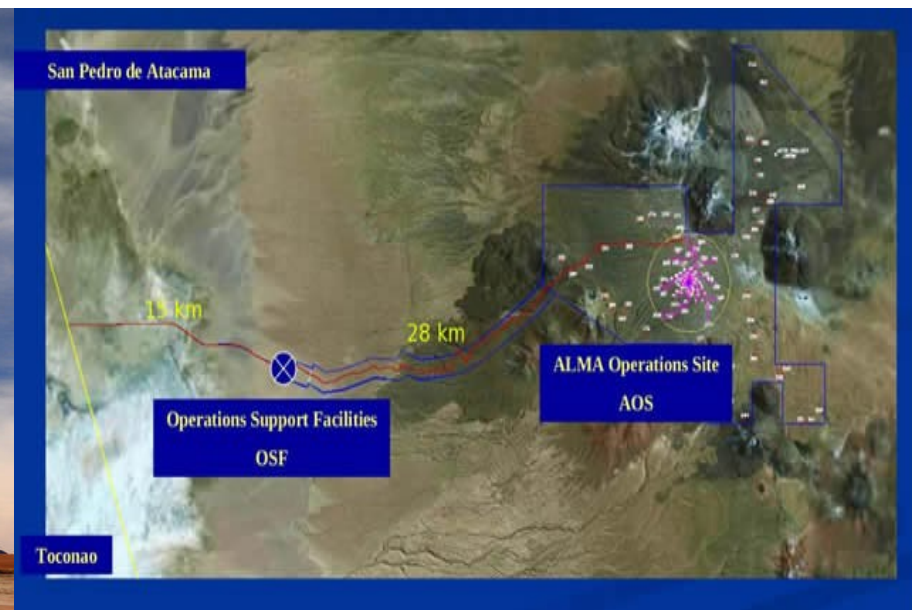


3 Sites in Chile

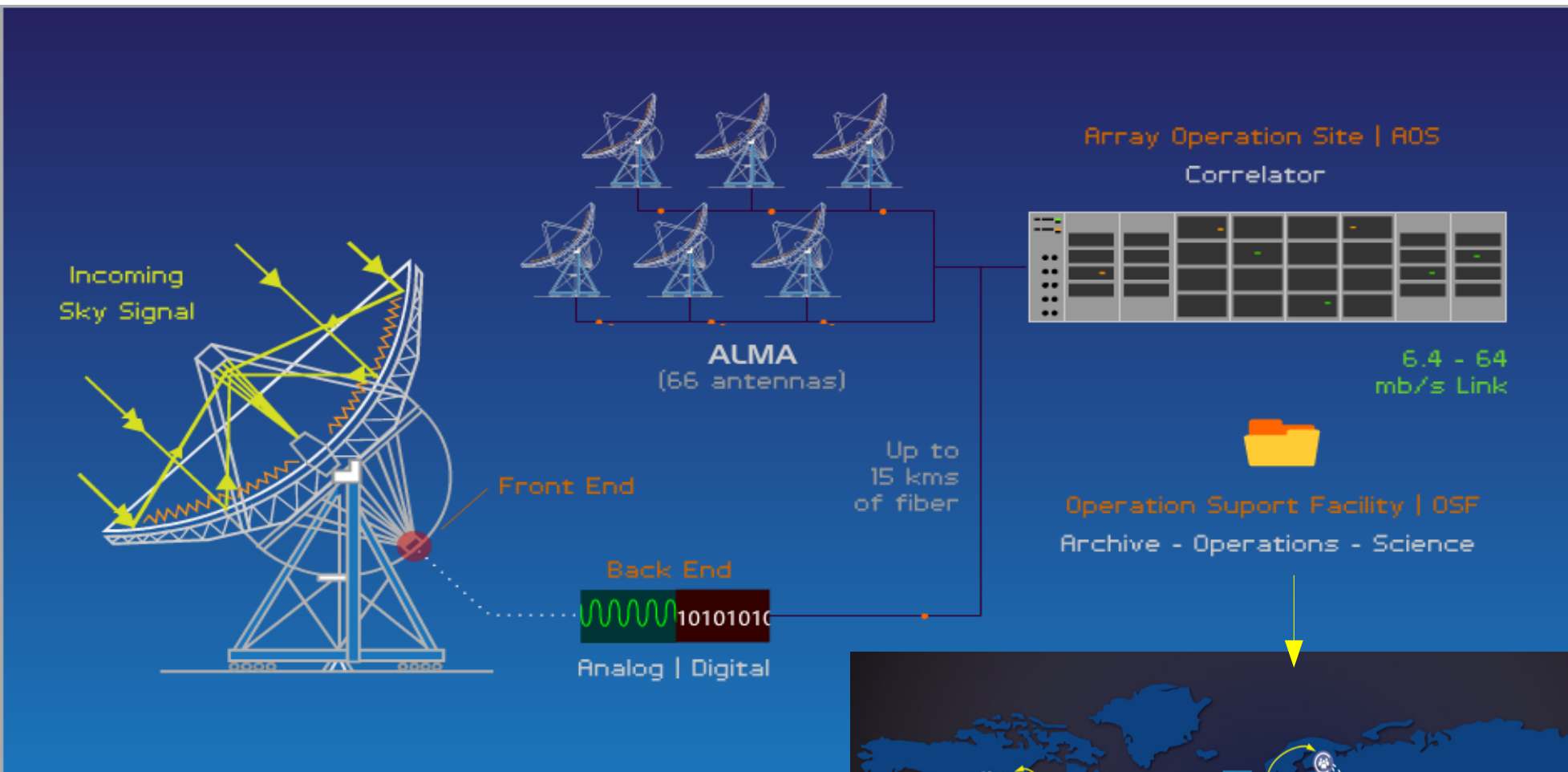
- **AOS**: ALMA Operations Site (5000m): Antennas, Correlator
- **OSF**: Operations Support Facility (3000m):
Labs, Antenna Assembly & Maintenance Operators, Astronomers
- **SCO**: Santiago Central Office:
 - Call for Proposals
 - Running ALMA
 - Data Reduction Pipeline
 - Quality Assessment



ALMA sites



ALMA data flow



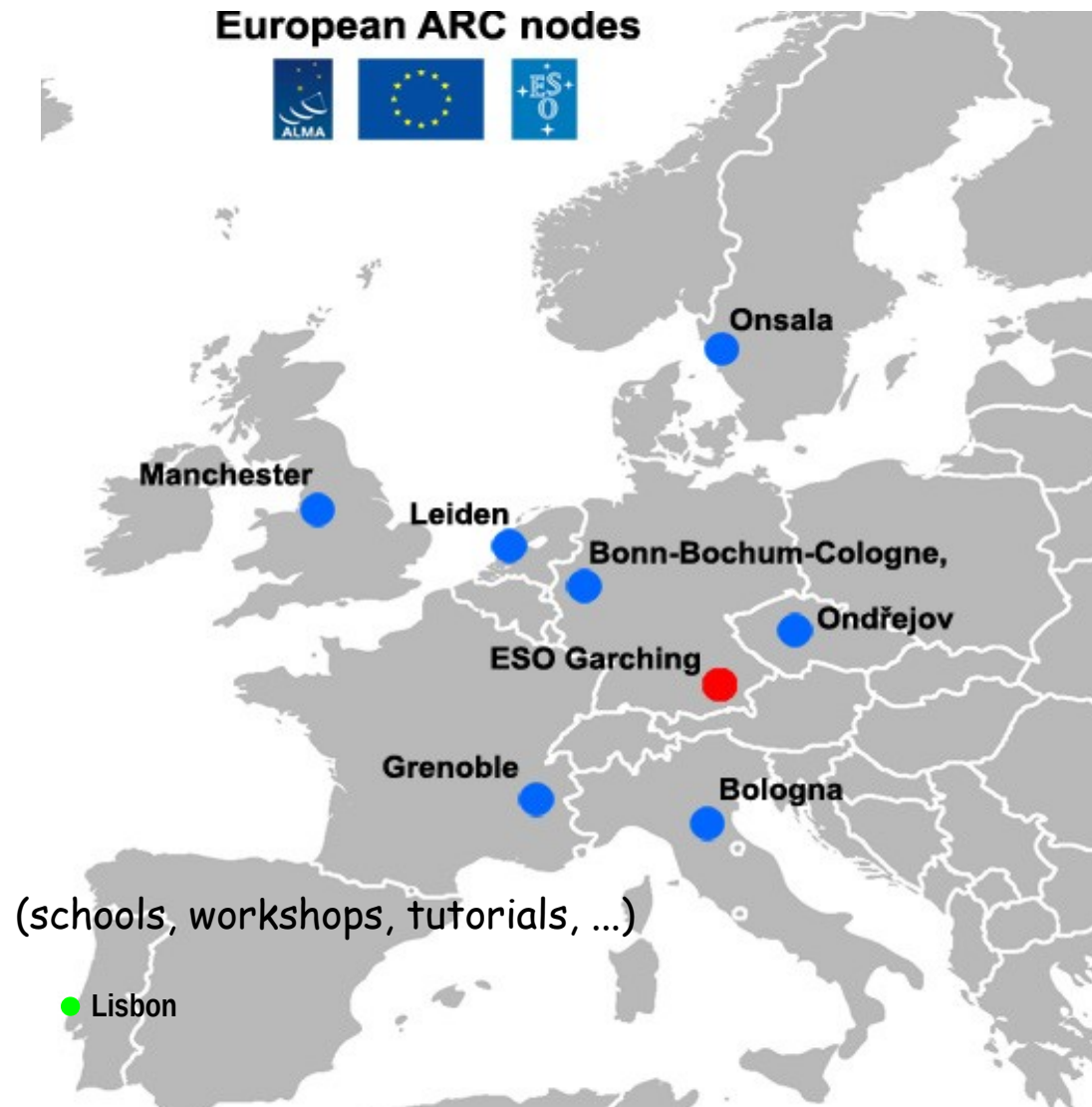
Data is collected, reduced and archived.
All the “almost” raw data is archived.

Each ARC hosts an archive mirror.



The ALMA Regional Centres (ARCs)

- **Interface between JAO and users**
- 1 ARC per Partner:
 - NRAO for North America
 - NAOJ for East Asia
 - **ESO for Europe (split in 7 nodes + 1CoE)**
- Operation support
 - Archive replication
 - Astronomer on duty
 - Software tools
- User support
 - Community formation and outreach
 - Phase 1 (proposal preparation)
 - Phase 2 (scheduling block preparation)
 - Data analysis, Archive mining
 - F2F user support, Helpdesk



Enter the ALMA world through the ALMA Science Portal

<http://almascience.eso.org/>

The screenshot shows the ALMA Science Portal homepage. The browser address bar displays <https://almascience.eso.org/>. The top navigation bar includes links for 'About', 'Science', 'Proposing', 'Observing', 'Data', 'Processing', 'Tools', 'Documentation', and 'Help'. The 'Proposing', 'Observing', 'Data', 'Tools', and 'Help' links are circled in red, orange, green, blue, and purple respectively. A pink text box in the top right corner reads 'Registration to access project management tools, Helpdesk and to be PI or co-I', with a 'Log in' button circled in pink. Below the navigation bar, there are sections for 'Observatory News', 'EU ARC News', and 'Status'. The 'Observatory News' section includes links for 'Additional Information for Feb 01, 2017', 'Release of a New Installment of Science V Jan 18, 2017', and 'Announcement of 3mm VLBI in Cycle 5 Jan 06, 2017'. The 'EU ARC News' section includes 'Current call Tools and info' and 'ALMA status page, SnooPI'. The 'Status' section includes 'ALMA Cycle 5 Pre-Announcement and Additional Information', 'Refereed publications: 618', and 'ion: C40-2'. A green text box in the center reads 'ALMA ARCHIVE, Calibrator catalogue and Science Verification data'. A blue text box on the right reads 'All the documents and tools (OT, OST, Sensitivity calculator,...)'. A purple text box on the right reads 'Access to Helpdesk for any request (FAQ, problems, request of face-to-face meeting of experts...)'. At the bottom, there is a 'Science Highlights' section with a plot titled 'Possible Disk Truncation in Ophiuchus Brown Dwarf'. The plot shows $\log(M_{\text{dust}}/M_{\oplus})$ on the y-axis (0.0 to 2.5) and $\log(M_{\text{star}}/M_{\odot})$ on the x-axis (0.0 to 2.5). Three dashed lines represent different disk truncation models: $M_{\text{disk}} = 10\% M_{\text{star}}$, $M_{\text{disk}} = 1\% M_{\text{star}}$, and $M_{\text{disk}} = 0.1\% M_{\text{star}}$. The plot shows data points for Ophiuchus brown dwarfs, with some points falling below the $1\% M_{\text{star}}$ line, indicating disk truncation. A text box next to the plot reads: 'The sensitivity, resolution and the wavelength of the observations are such that they are sensitive to the detection of planets hosting planets. In a recent Astronomy & Astrophysics sample of spectroscopically confirmed Ophiuchus brown dwarfs with infrared excesses.' The bottom of the page features a footer with links for 'Site Map', 'Accessibility', 'Contact', and 'Privacy Statement', and logos for 'ESO', 'NRAO', and 'NAOJ'.

Welcome to the Science P... X +

<https://almascience.eso.org/> 90% Cerca

jira ARC TWiki ALMA SP Dossier thématique - ... Oleoliti: 10 ricette fai-... Arcadia - Il mondo del... SAO/NASA ADS Custo...

Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

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

Log in

About Science **Proposing** **Observing** **Data** Processing **Tools** Documentation **Help** Search Site

Observatory News EU ARC News Status

Additional Information for Feb 01, 2017 **Current call Tools and info** preparation day 2017

Release of a New Installment of Science V Jan 18, 2017 **ALMA status page, SnooPI** days 2017

Announcement of 3mm VLBI in Cycle 5 Jan 06, 2017

ALMA Cycle 5 Pre-Announcement and Additional Information

Refereed publications: 618

ion: C40-2

ALMA ARCHIVE, Calibrator catalogue and Science Verification data

Science Highlights - Possible Disk Truncation in Ophiuchus Brown Dwarf

All the documents and tools (OT, OST, Sensitivity calculator,...)

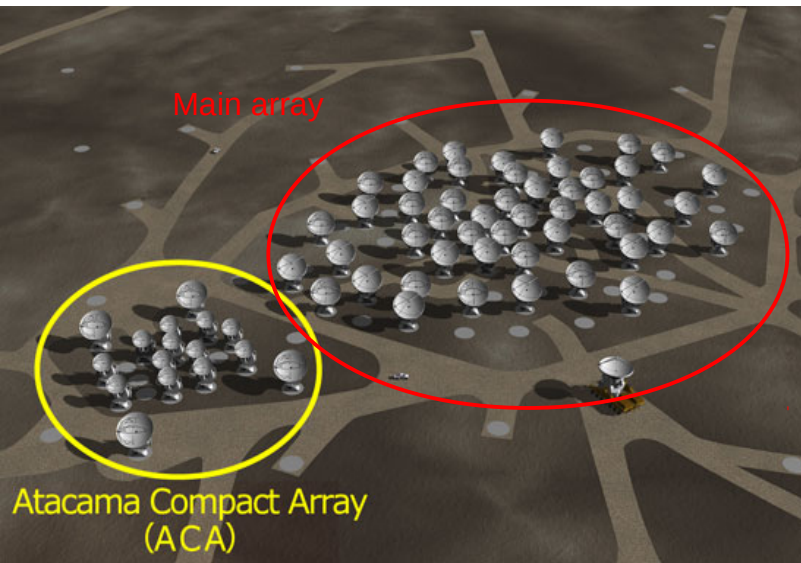
Access to Helpdesk for any request (FAQ, problems, request of face-to-face meeting of experts...)

Site Map Accessibility Contact Privacy Statement ESO NRAO NAOJ

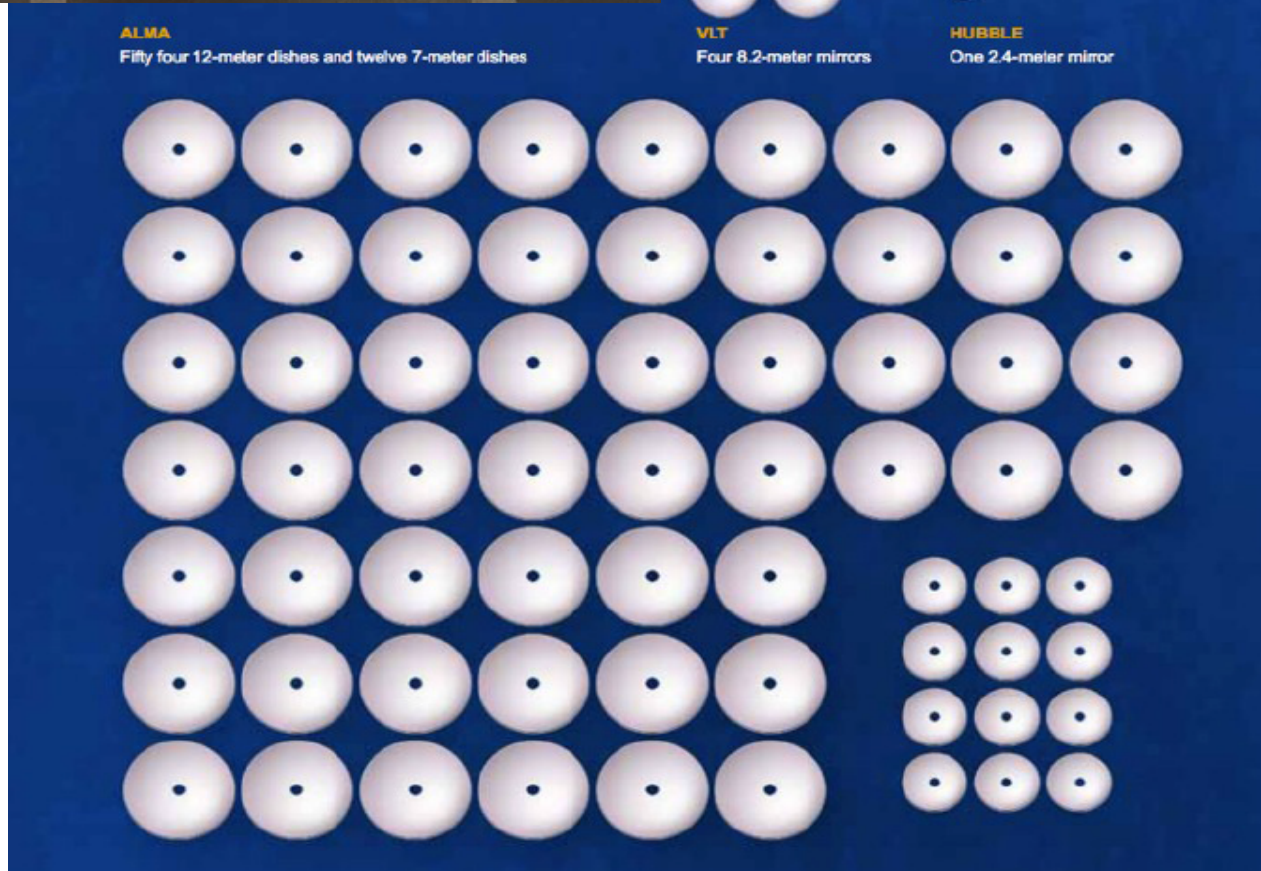
Chiedimi qualcosa

ITA 07:25 19/03/2017

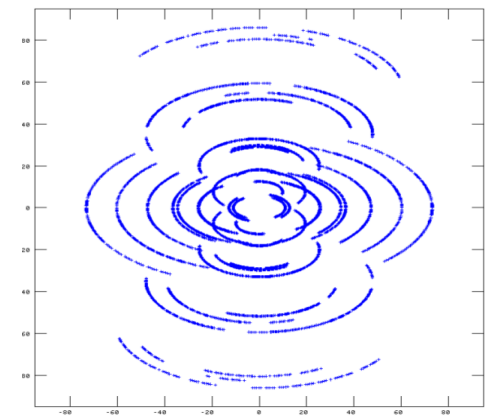
ALMA array(s)



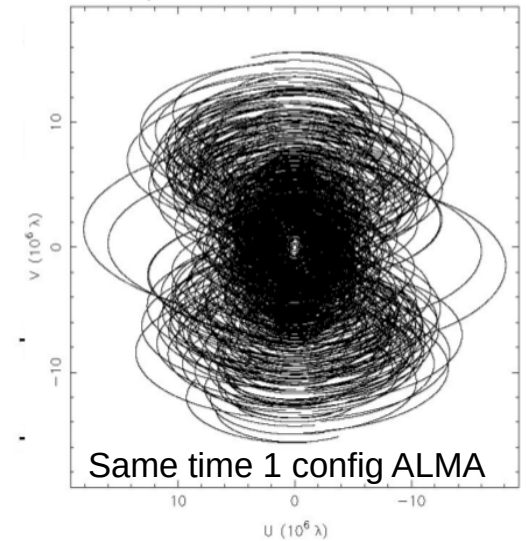
Antennas : **50x12m** main array + **(12x7m + 4x12m TP)** ACA
 Baselines : **15m ->150m-16km** + **9m->50m**



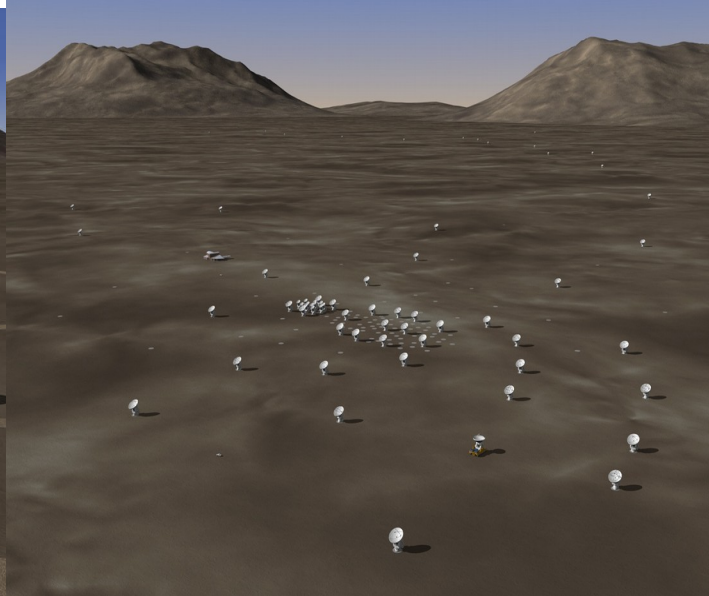
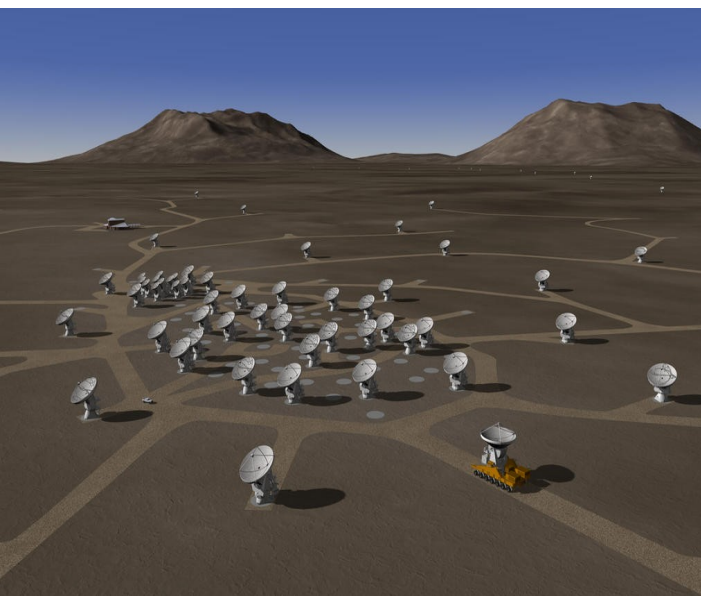
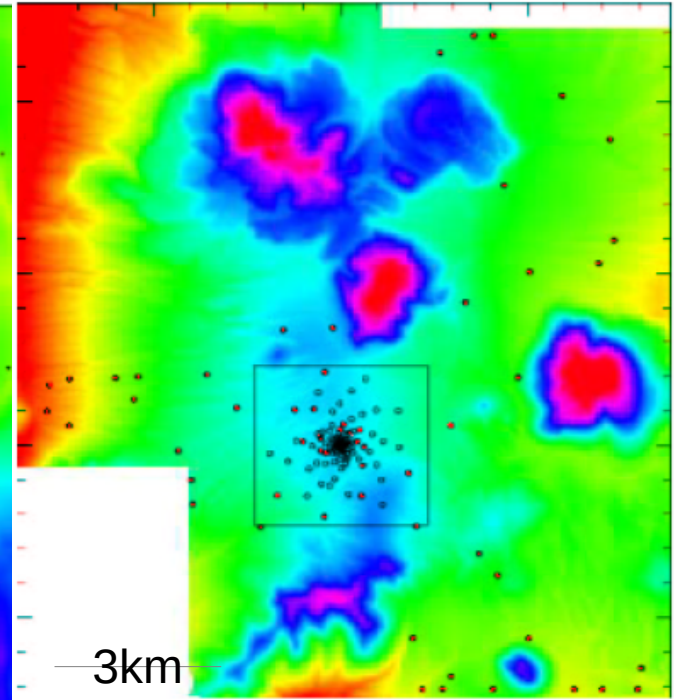
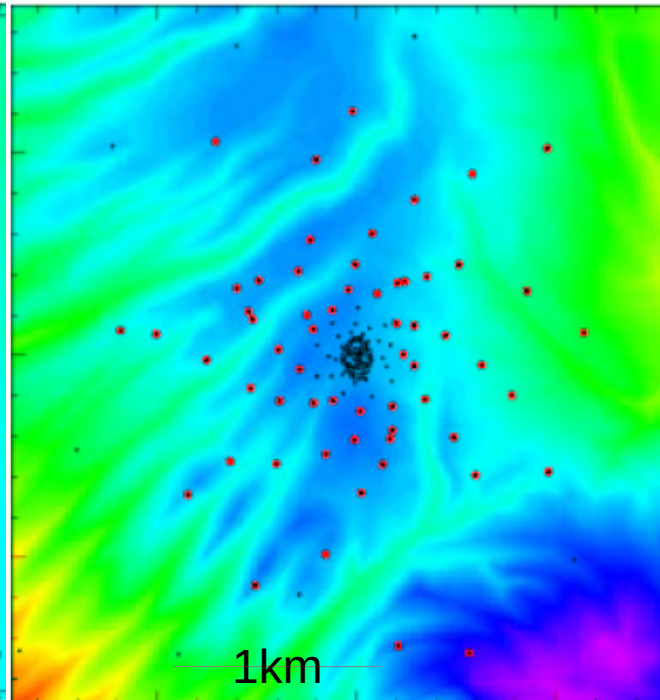
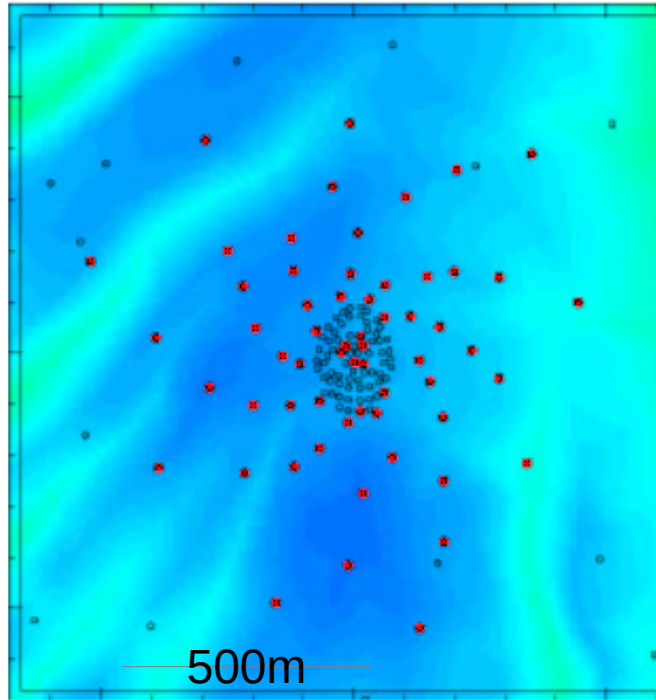
Few hr 2 config OVRO



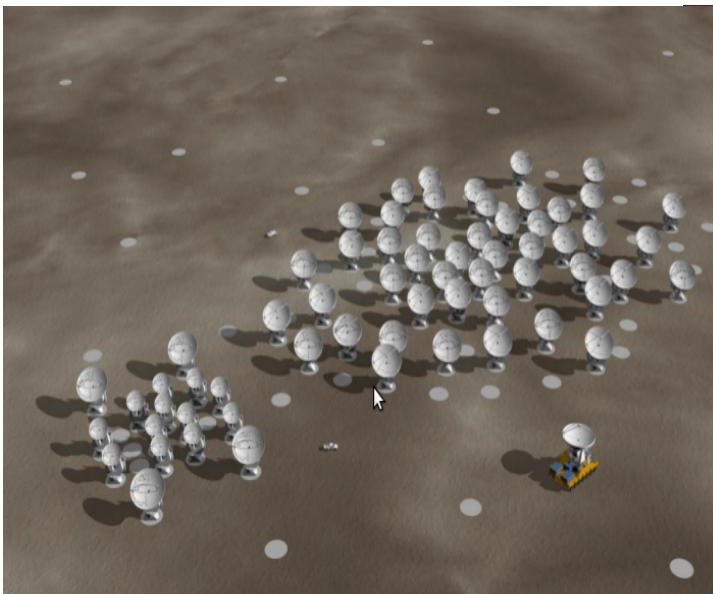
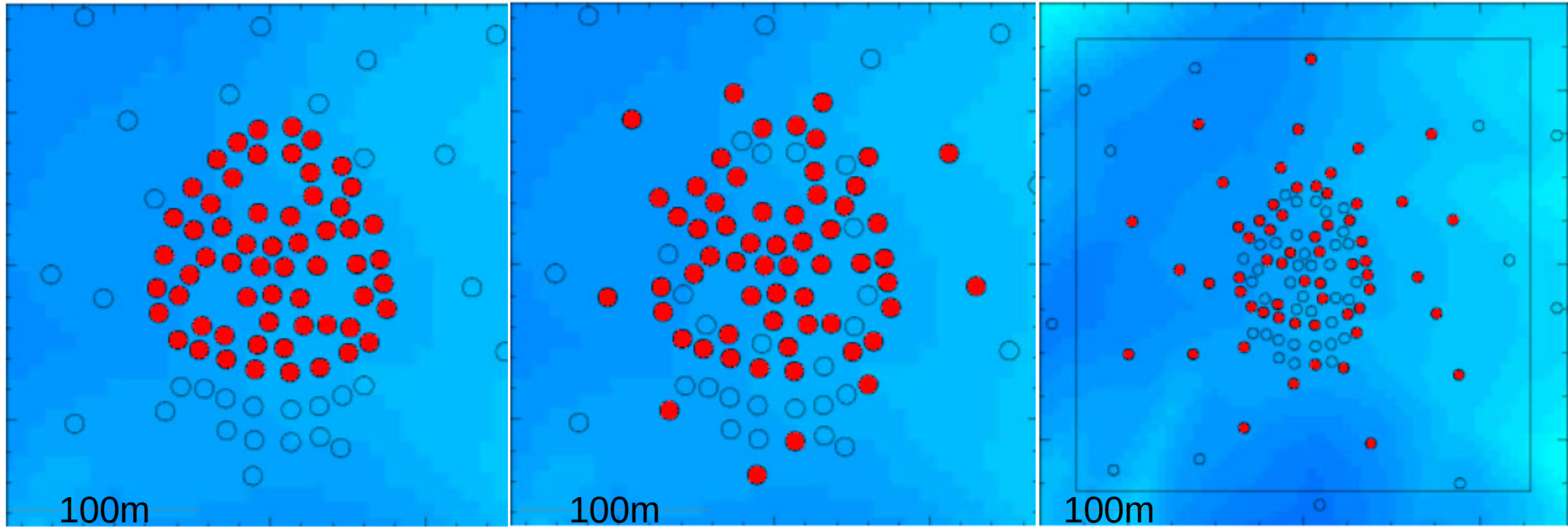
900GHz_50pc_ws_8 at 896.000 GHz in XX 2012 Jun 21



ALMA reconfiguration

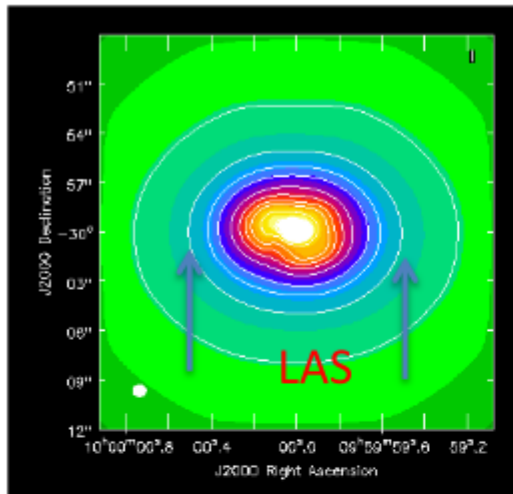


ALMA reconfiguration



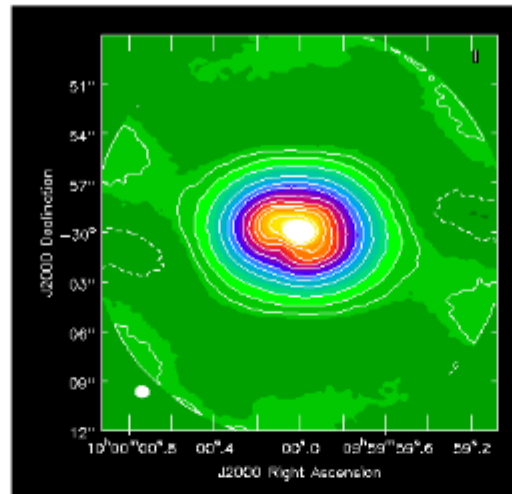
ALMA array(s)

MODEL



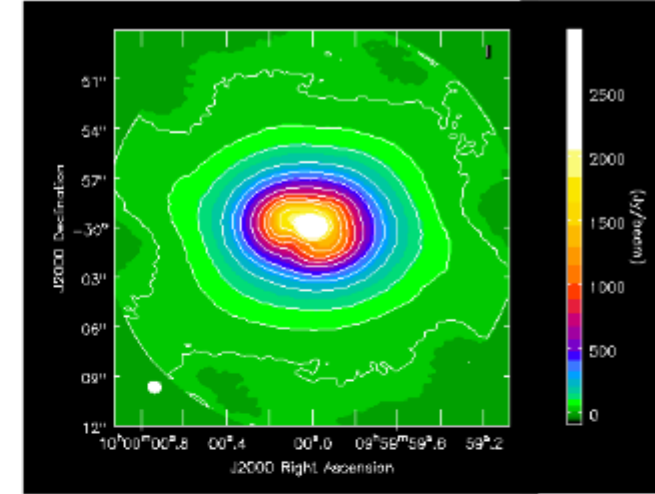
Restored flux 11000 Jy

12-m image



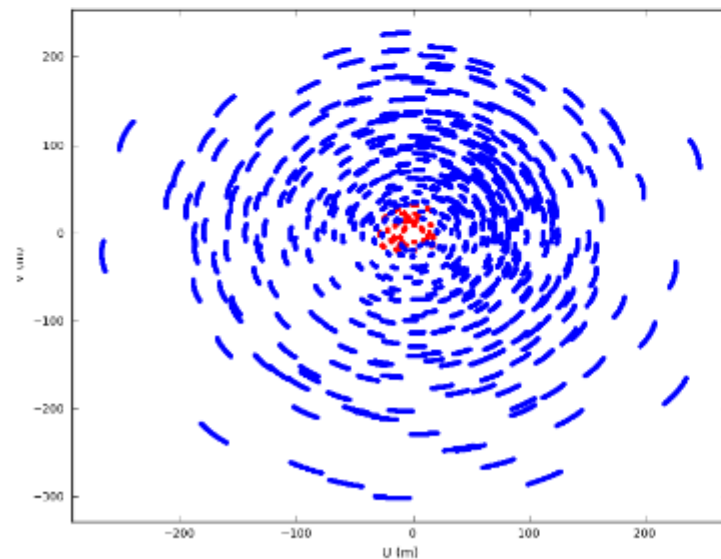
7000 Jy

12m+7m Image



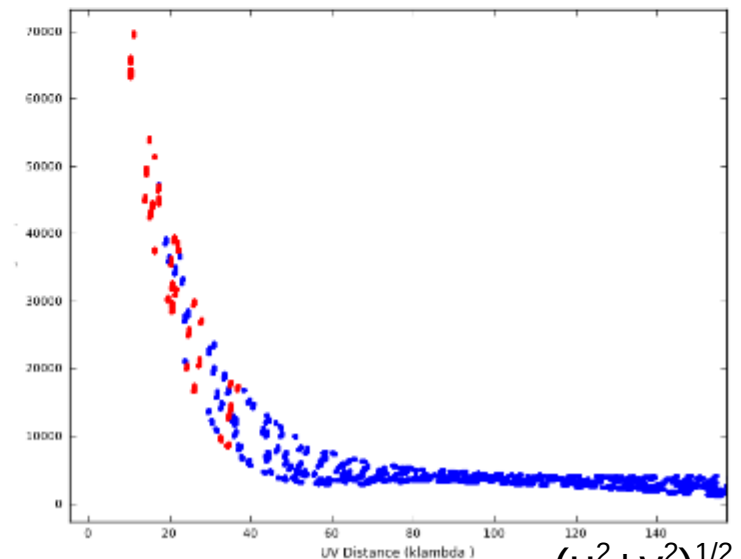
9000 Jy

Primary beam corrected: 20% cutoff: Contours: -20,20,50,100,200,300,400,600,800,1000,1200,1600,2000



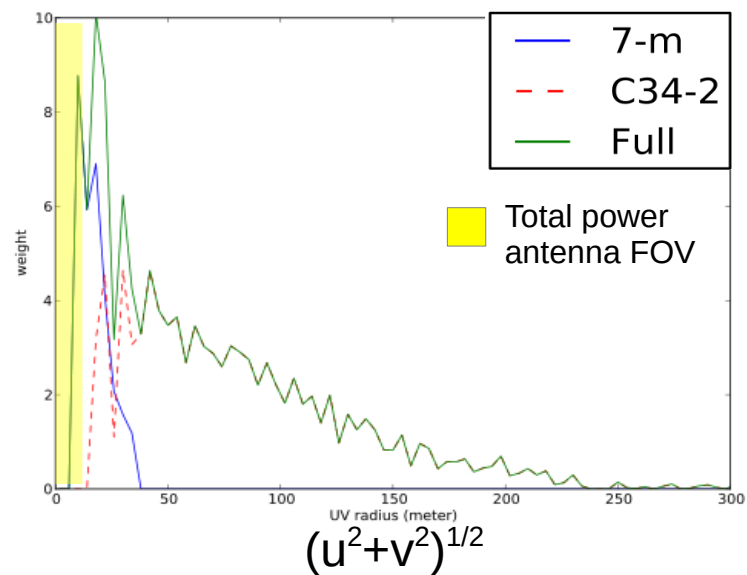
U-V coverage

(red=ACA, blue=ALMA12m)

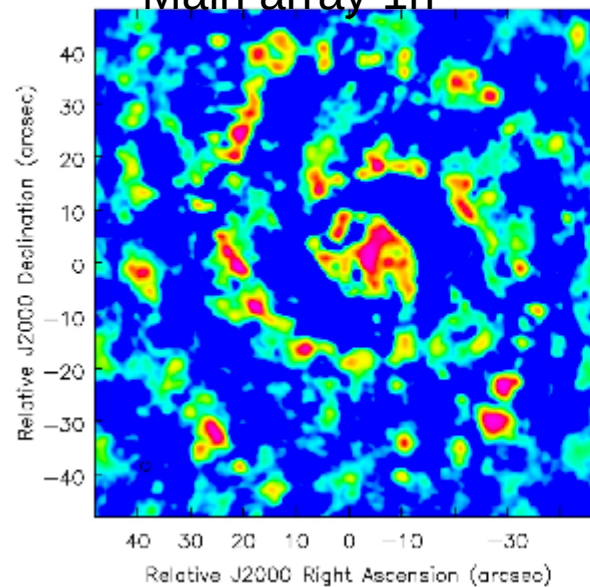


Amplitude vs uv-distance

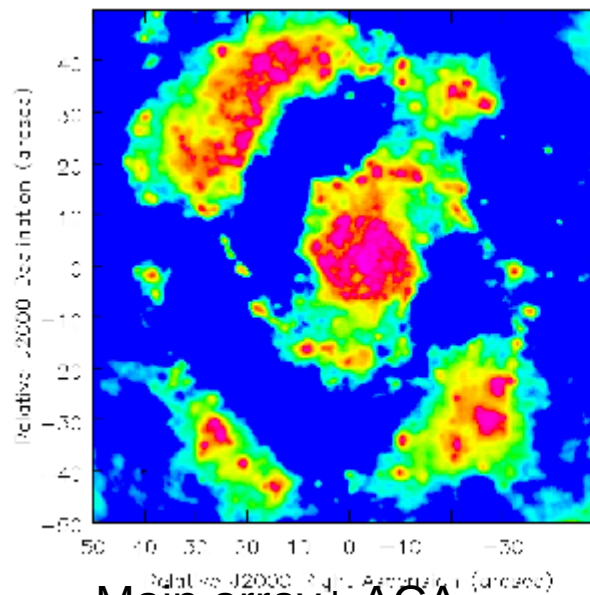
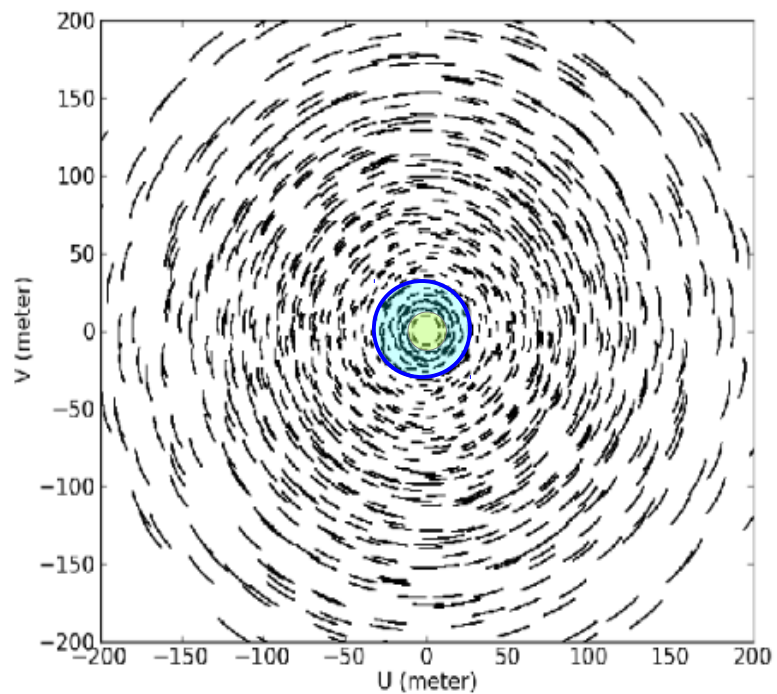
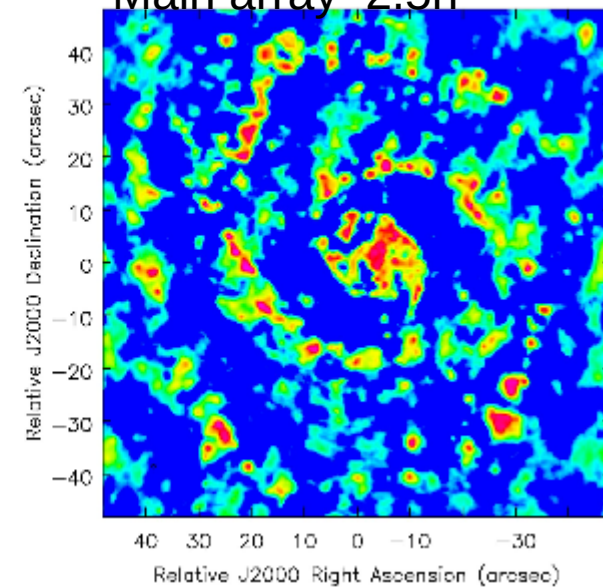
ALMA array(s)



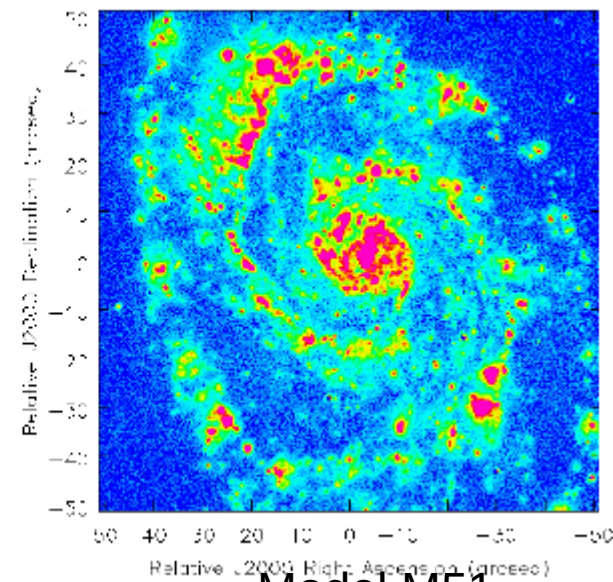
Main array 1h



Main array 2.5h



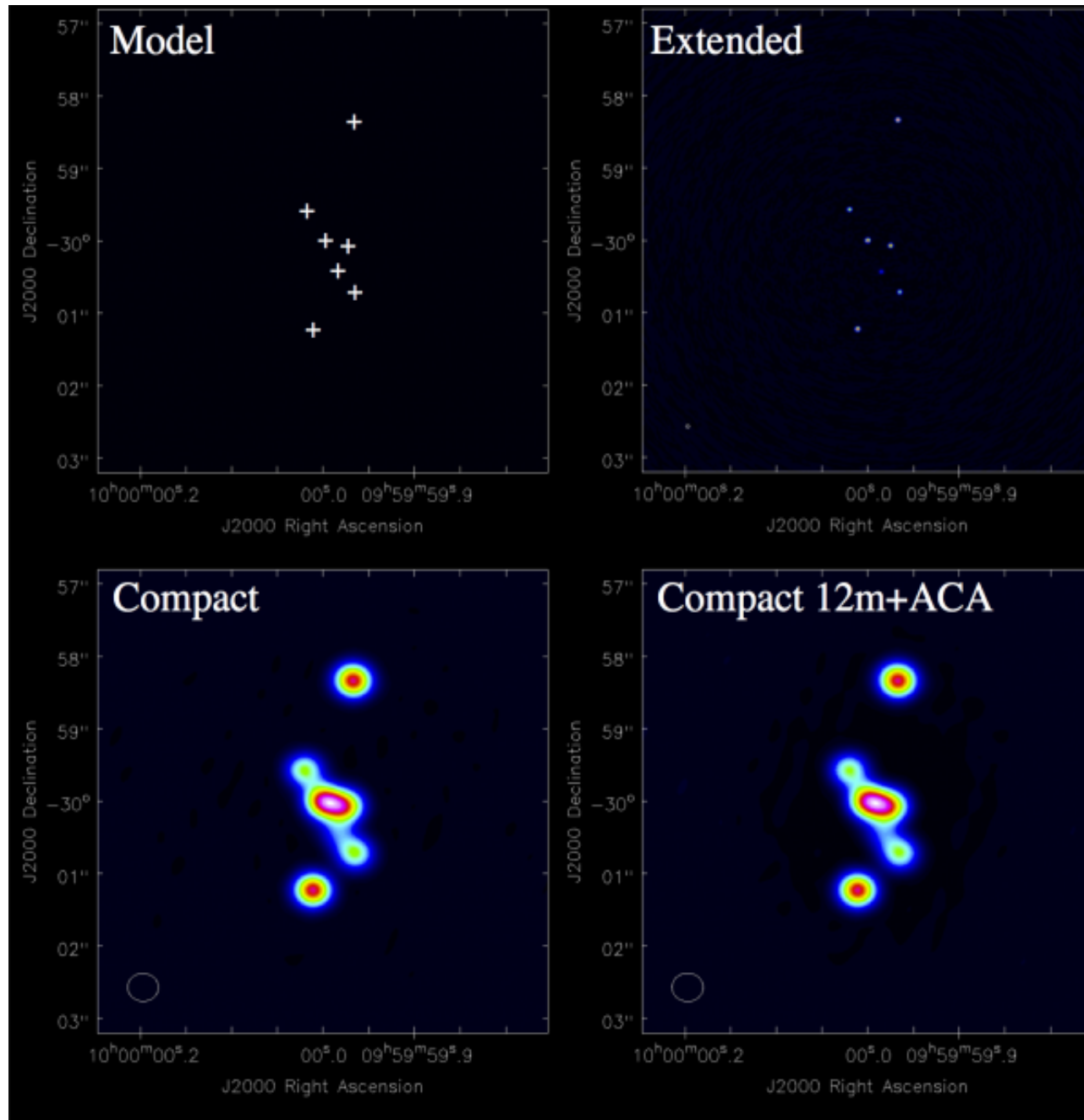
Main array+ ACA



Model M51

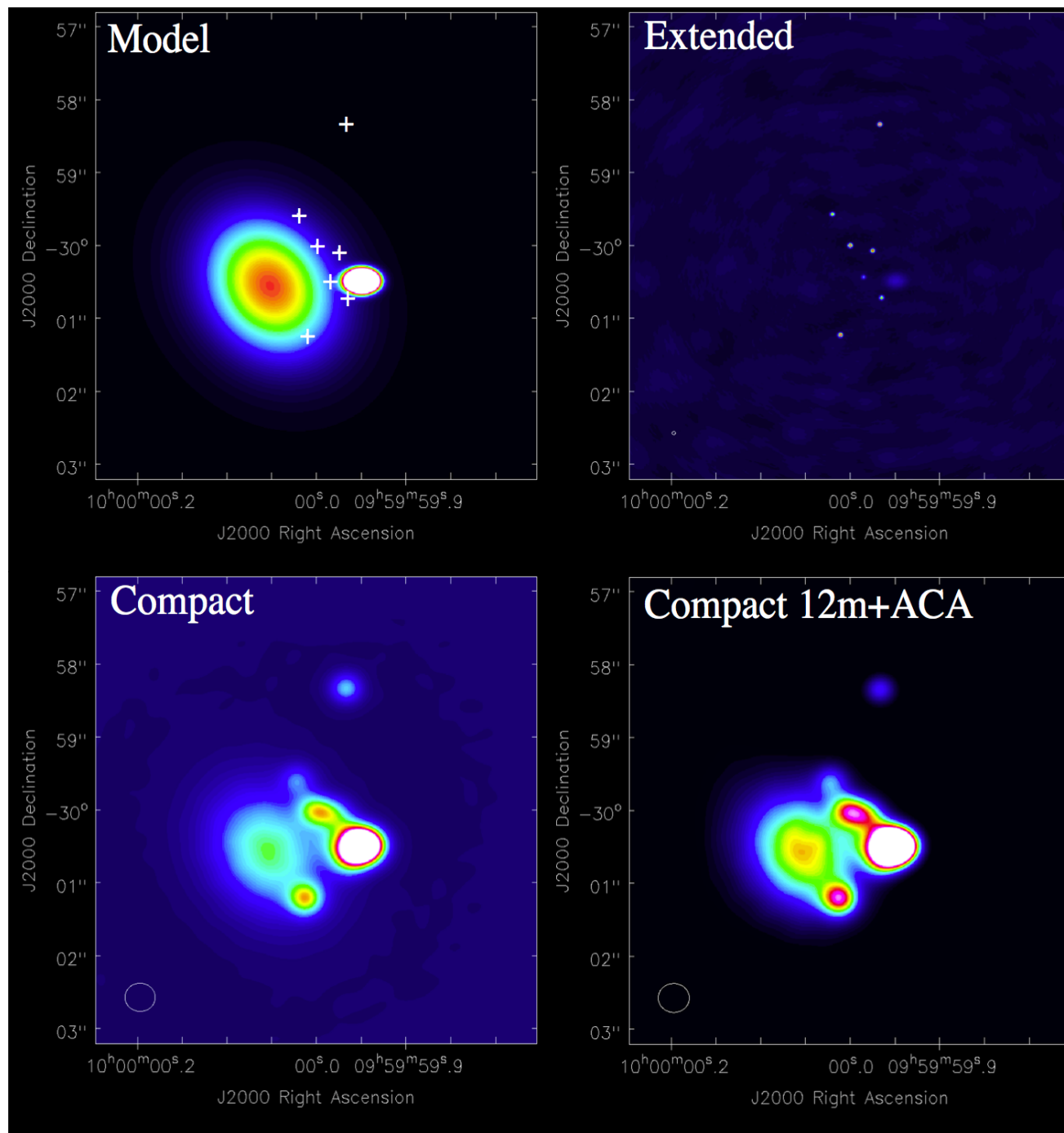
ALMA array(s)

Main array
for compact
objects



ALMA array(s)

ACA
for extended
objects



Make your ALMA simulations (Observation Support Tool)

<http://almaost.jb.man.ac.uk/>



Submit a request for a full simulation of ALMA capabilities for your target
Receive the results via e-mail

Array	Instrument	ALMA	Queue Status • Help
Sky Setup	Source model	OST Library: Central point source	Choose a library source model or
	Upload a FITS file	<input type="text"/> Browse...	You may upload your own model
	Declination	-35d00m00.0s	Ensure correct formatting of this s
	Image peak / point flux in mJy	0.0	Set to 0.0 for no rescaling of sour
Observation Setup	Central frequency in GHz	90	The value entered must be within
	Bandwidth in MHz	32	Use broad for continuum, narrow
	Required resolution in arcseconds	1.0	OST will choose config if instrumen
	Pointing strategy	Single	Selecting single will apply primary
	Start hour angle	0.0	Deviation of start of observation f
	On-source time in hours	3	Maximum duration is 24 hours
	Number of visits	1	How many times the observation i
	Number of polarizations	2	This affects the noise in the final n
Corruption	Atmospheric conditions	Good (PWV = 0.5 mm)	Determines level of noise due to v
Imaging	Imaging weights	Natural	This allows a resolution / sensitiv
	Perform deconvolution?	No (Return dirty image)	Apply the CLEAN algorithm to deconv

EUROPEAN ARC
ALMA Regional Centre || UK

ALMA Observation Support Tool

Job ID: 20110330175645 / Submitted by: casasola@ira.inaf.it

Overview

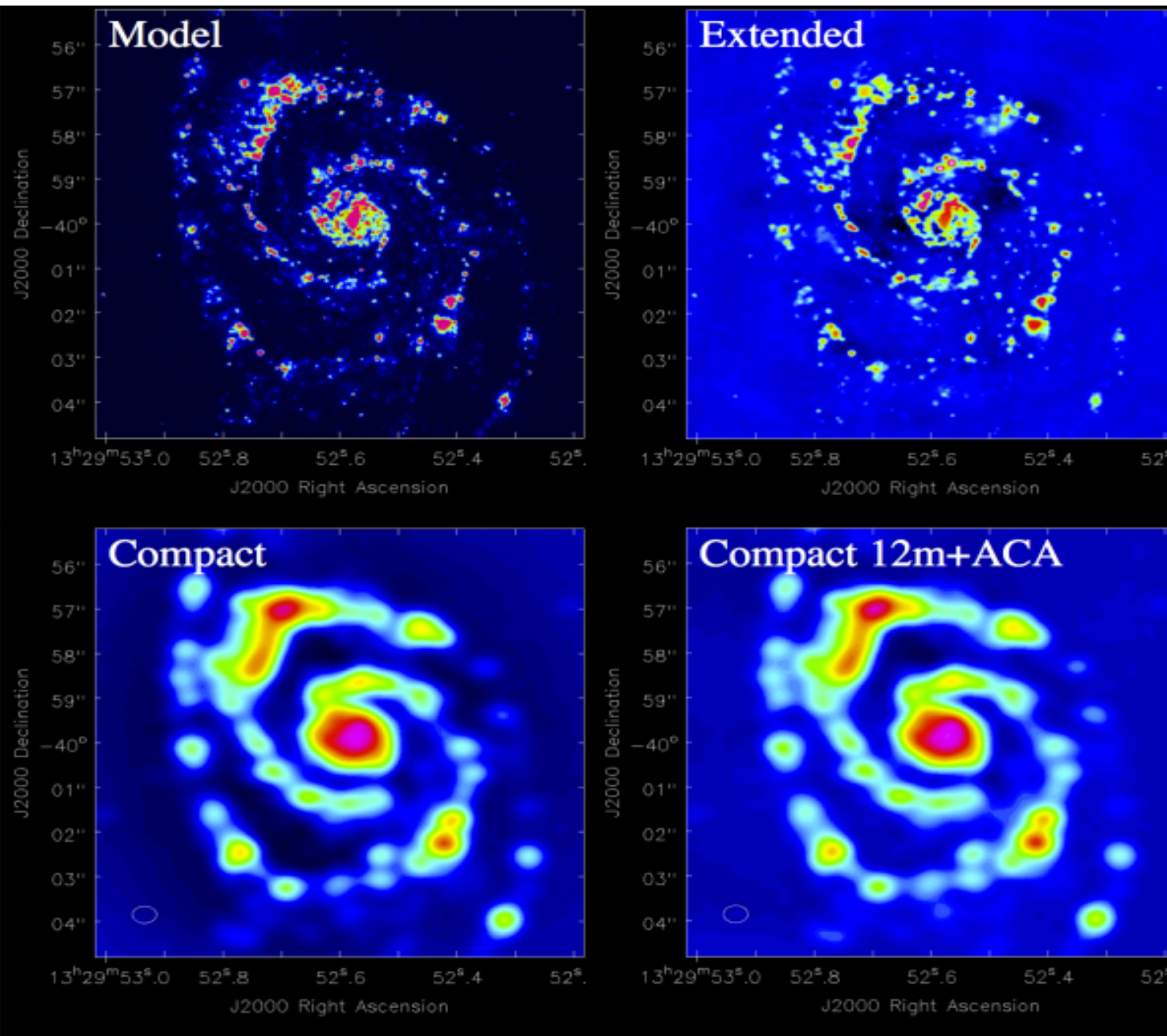
Click thumbnails to view full-size images. Left: linear colour scale, right: with histogram equalization.

Array configuration	Early Science ALMA (Compact Cycle 0, 125 m baseline)
Source model	All we ever see of stars are their old photographs
Maximum elevation	77.88 degrees
Central frequency	90 GHz = Band 3
Bandwidth	0.032 GHz
Track length	3 hours x 1.0 visits
System temperature	Tsys = Trec + Tsky = 37.0 + 4.42 = 44.15 K
PWV	0.5 mm
Theoretical RMS noise	0.000103323597098 Jy (in naturally-weighted map)
Restoring beam (resolution)	Major axis = 6.229 arcsec, minor axis = 5.176 arcsec, PA = 55.607 deg

Data products

Your simulated image
[Download FITS file](#)

Make your ALMA simulations (CASA simalma, simobserve, and simanalyze)



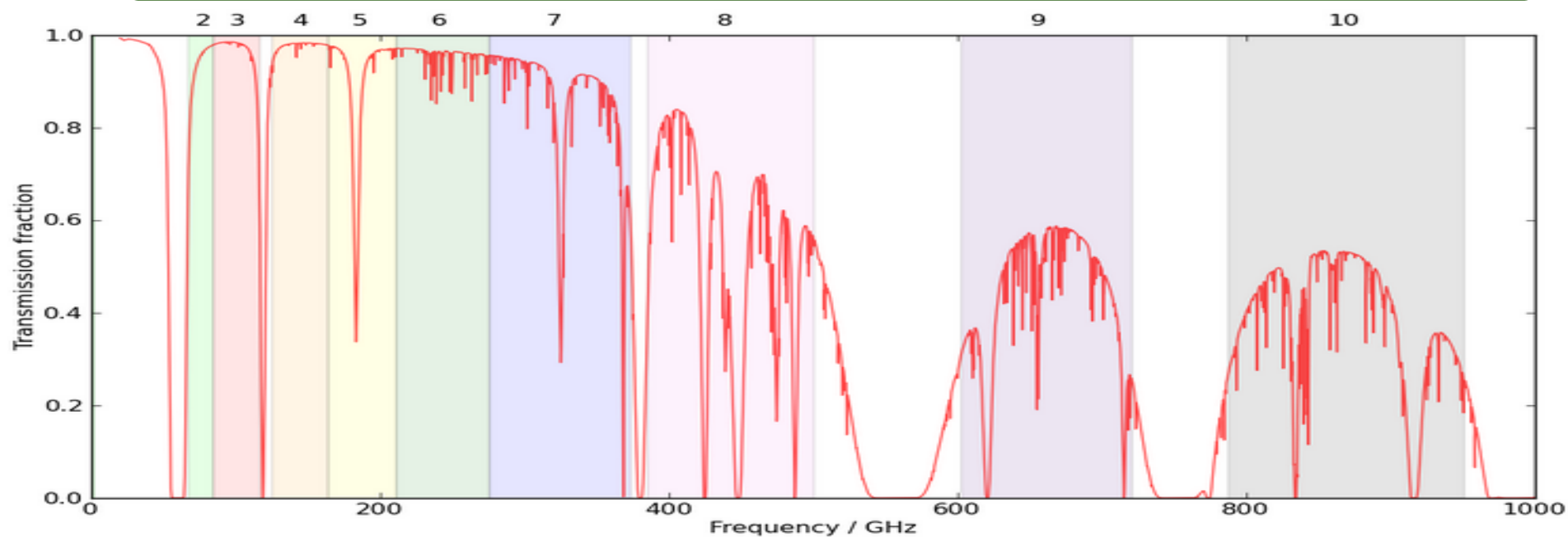
The task **simobserve** generates a data set with simulated visibilities based on an input model image.

The task **simanalyze** produces a cleaned image based on the simulated visibilities, and it generates some diagnostic images.

CASA also provides the task **simalma** that simplifies the steps needed to simulate ALMA observations that combine data from multiple arrays or multiple configurations.

ALMA bands

<i>Full Science Capabilities</i>					Most Compact		Most Extended	
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV _{50%} ")	Continuum Sensitivity (mJy/beam)	Angular Resolution (")	Spectral Sensitivity ΔT_{line} (K)	Angular Resolution (")	Spectral Sensitivity ΔT_{line} (K)
1	31.3-45	6.7-9.5	197-137	0.04	13-9	0.006	0.12-0.08	255
2	67-90	3.3-4.5	92-69	0.06	6-4.4	0.009	0.06-0.04	413
3	84-116	2.6-3.6	73-53	0.07	4.8-3.4	0.04	0.045-0.032	430
4	125-163	1.8-2.4	49-38	0.06	3.2-2.4	0.048	0.030-0.023	330
5	163-211	1.4-1.8	38-29	0.11	2.5-1.9	0.06	0.027-0.021	641
6	211-275	1.1-1.4	29-22	0.085	1.9-1.5	0.05	0.018-0.014	490
7	275-373	0.8-1.1	22-16	0.15	1.5-1.1	0.08	0.014-0.01	814
8	385-500	0.6-0.8	16-12	0.28	1.04-0.8	0.28	0.01-0.008	1900
9	602-720	0.4-0.5	10-8.6	1.1	0.66-0.55	0.9	0.006-0.005	8900
10	787-950	0.3-0.4	7.8-6.5	1.2	0.51-0.42	1.6	0.005-0.004	—

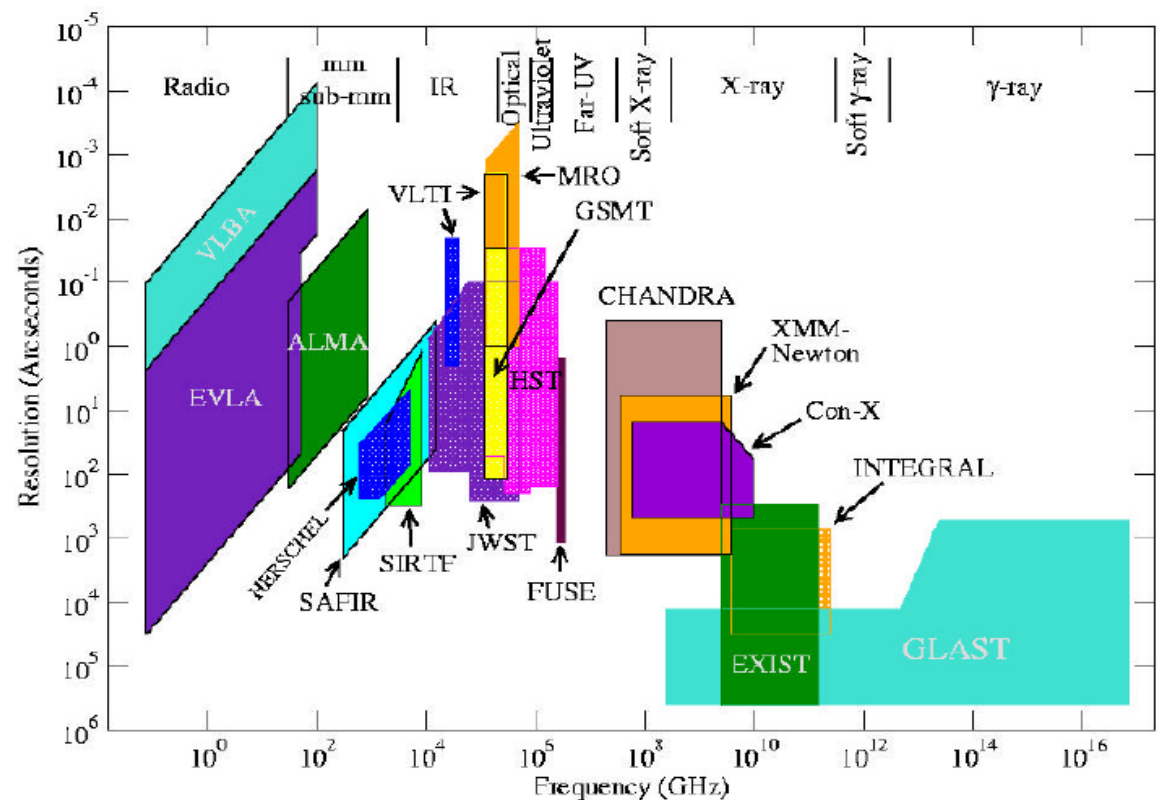


ALMA resolution

- Baselines length: **15m -> 150m-16km + 9m->50m**
- Resolution: **$0.2'' \times (300/\text{freq_GHz}) \times (1\text{km}/\text{max_baseline})$**
- FOV 12m array: **$17''/(300/\text{freq_GHz})$**
- FOV 7m array: **$29''/(300/\text{freq_GHz})$**

Up to 16km baselines, subarc
40 mas @ 100 GHz,
5 mas @ 900 GHz

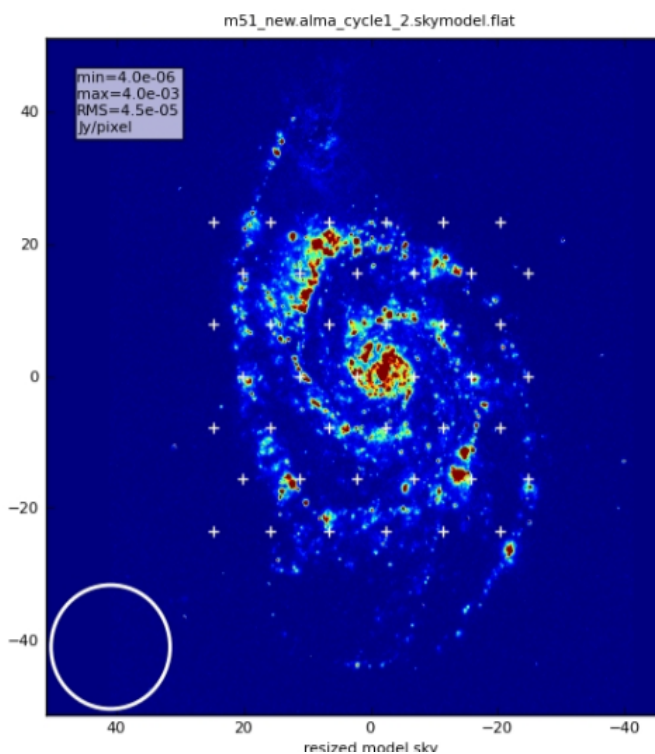
$$\theta = k \lambda / D$$



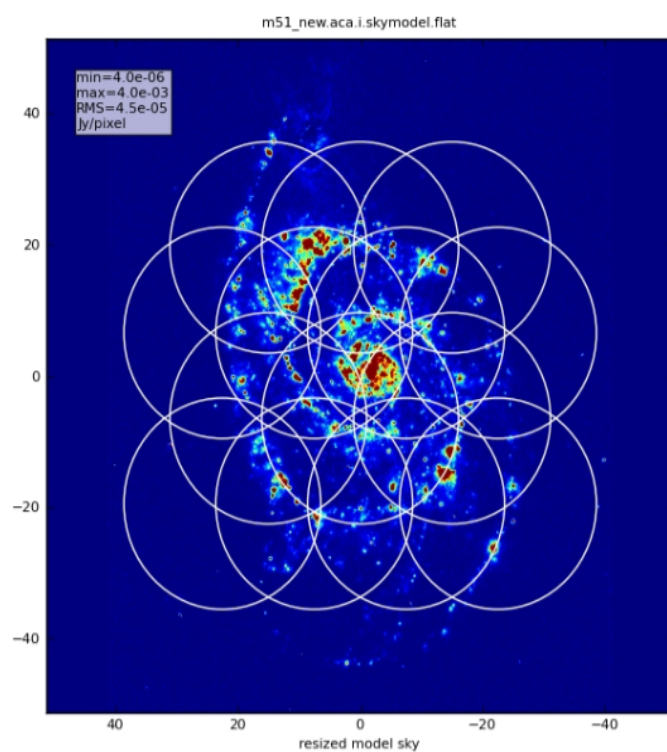
Mosaicking

Largest angular scales than that available to the shortest baseline cannot be observed.

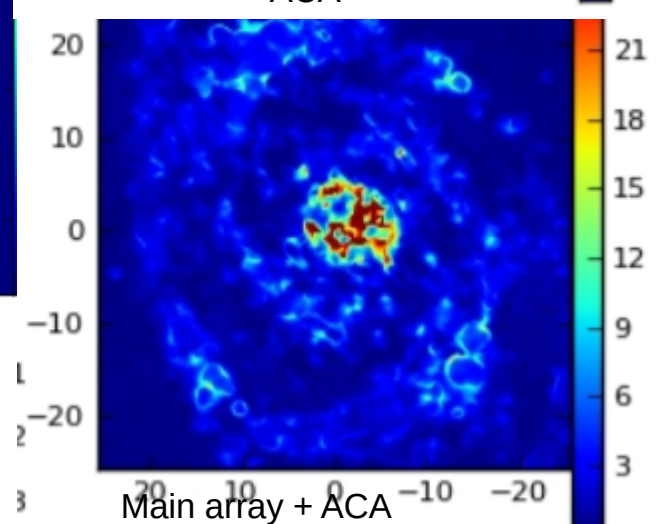
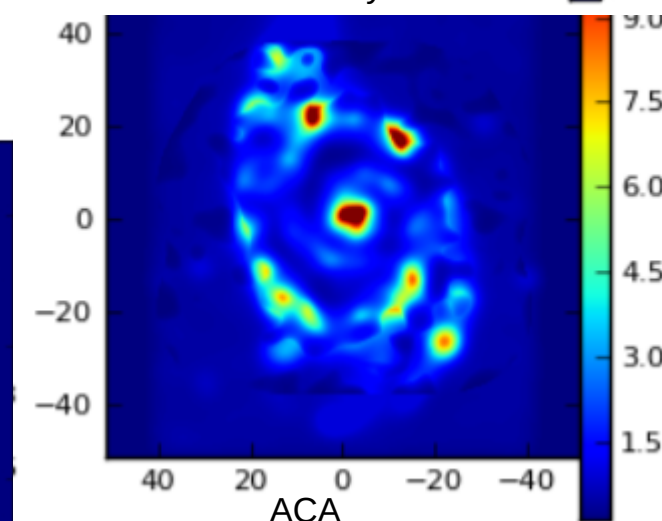
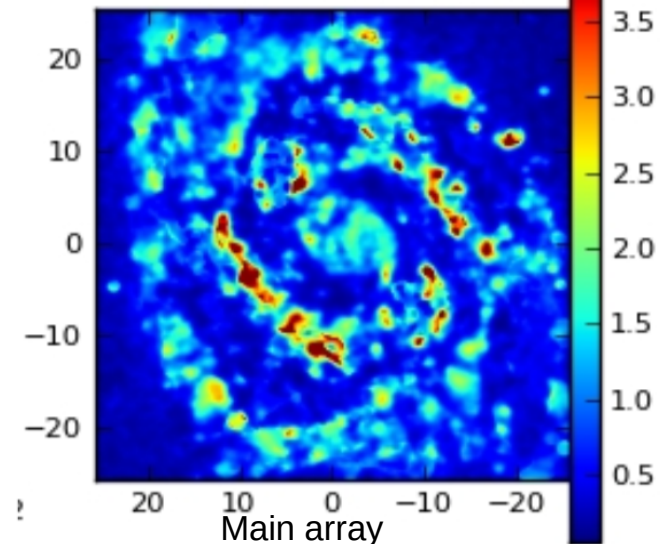
Details in the ranges available to the given baselines can be observed on larger region of the sky by mosaicking the region.



Model & 12m FOV



ACA Pointing map



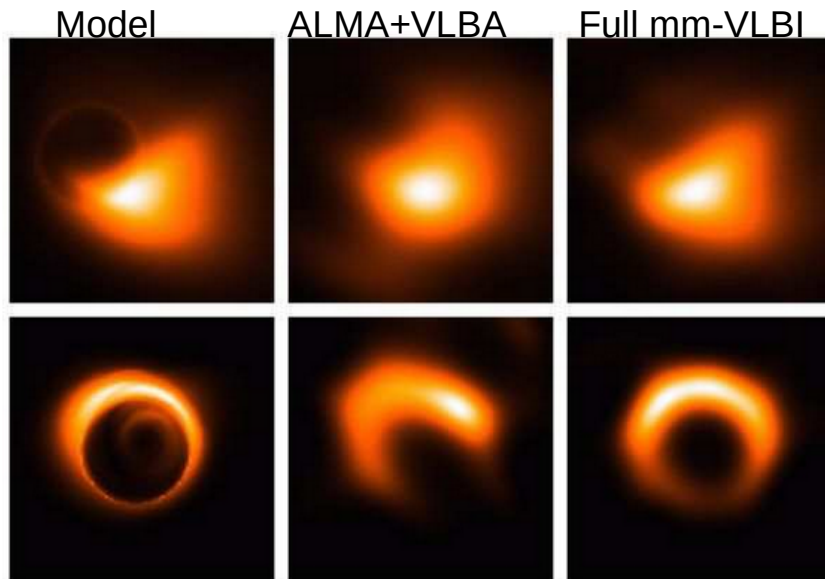
mm-VLBI with ALMA

Higher and higher resolutions can be obtained with longer baselines. **VLBI is a worldwide network of telescopes that matches simultaneous observations in different sites, exploiting the phase information to construct a world-wide interferometer.**

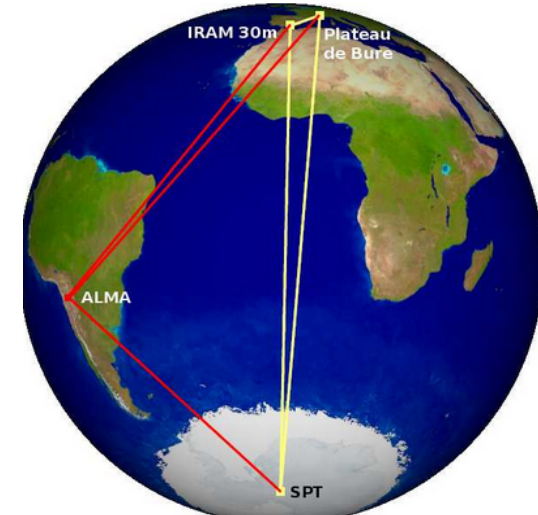
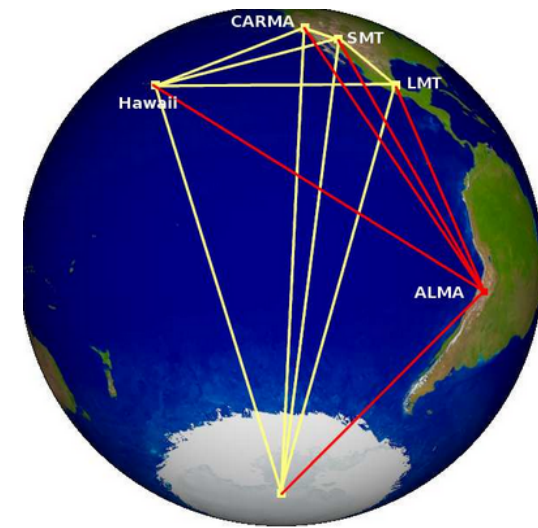
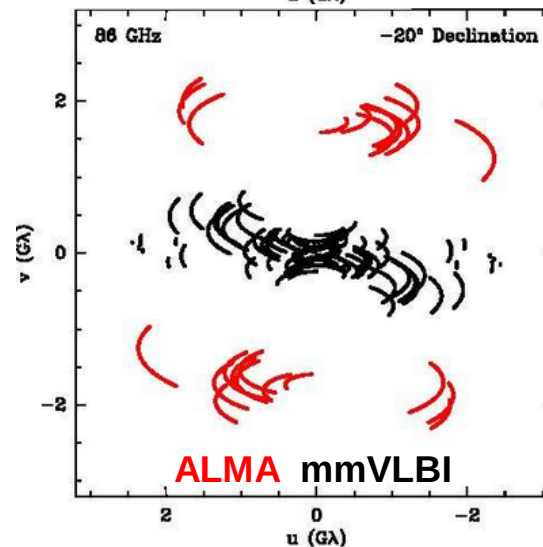
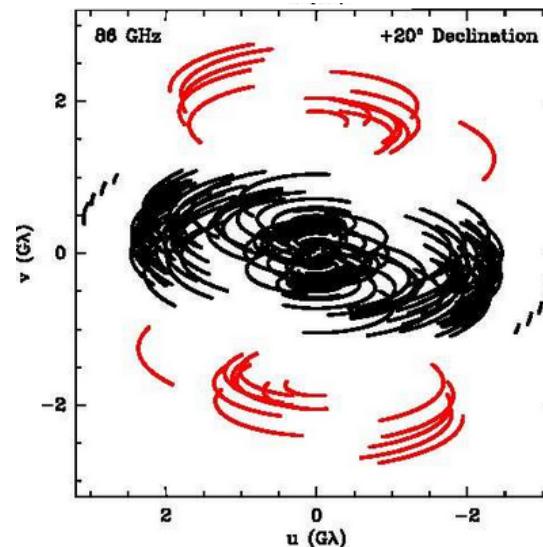
At 1 mm and a baseline of 9000 km offers resolution of about 20 microarcseconds

ALMA will be operating in the mm-VLBI since 2017 adding a strength in sensitivity. **Only sources with flux densities >100 mJy have been observable so far; ALMA will reduce it by more than an order of magnitude.**

This capability will allow the shadow of the event horizon in the black hole at the Galactic Centre, the relativistic jet flows in AGN and the dusty winds near stellar surfaces to be imaged



M87 models of different basis of the jet as observed by ALMA+CARMA+SMA+ SMT and by adding also PdBI



ALMA sensitivity

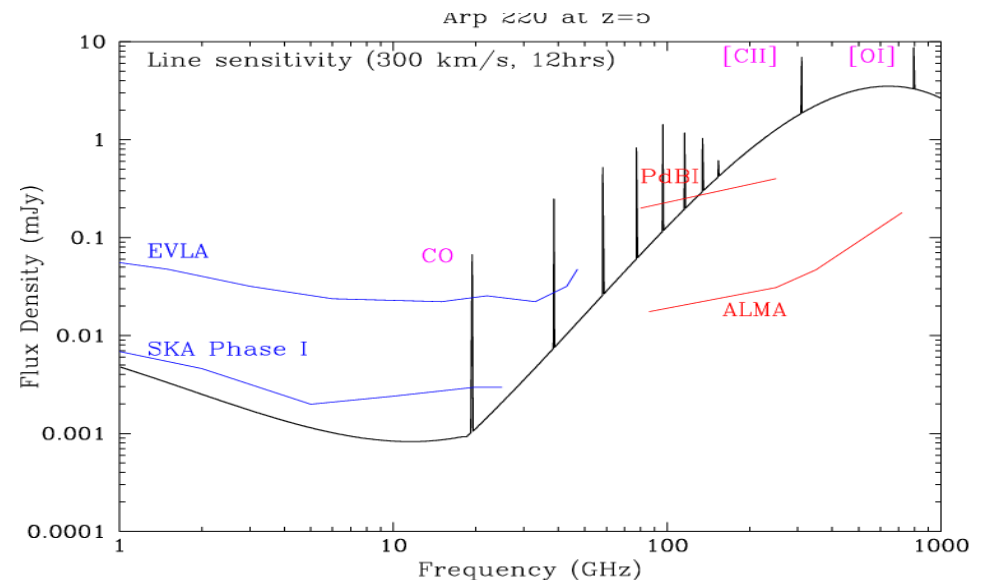
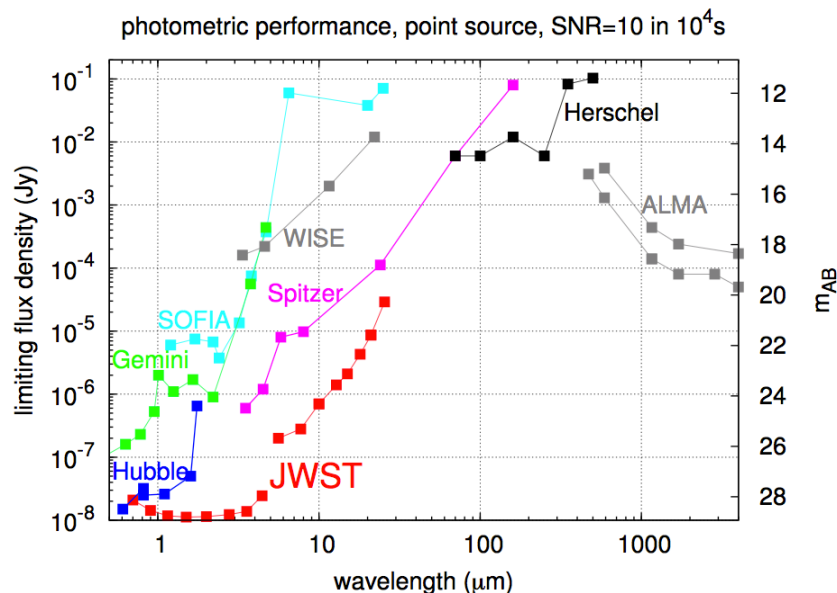
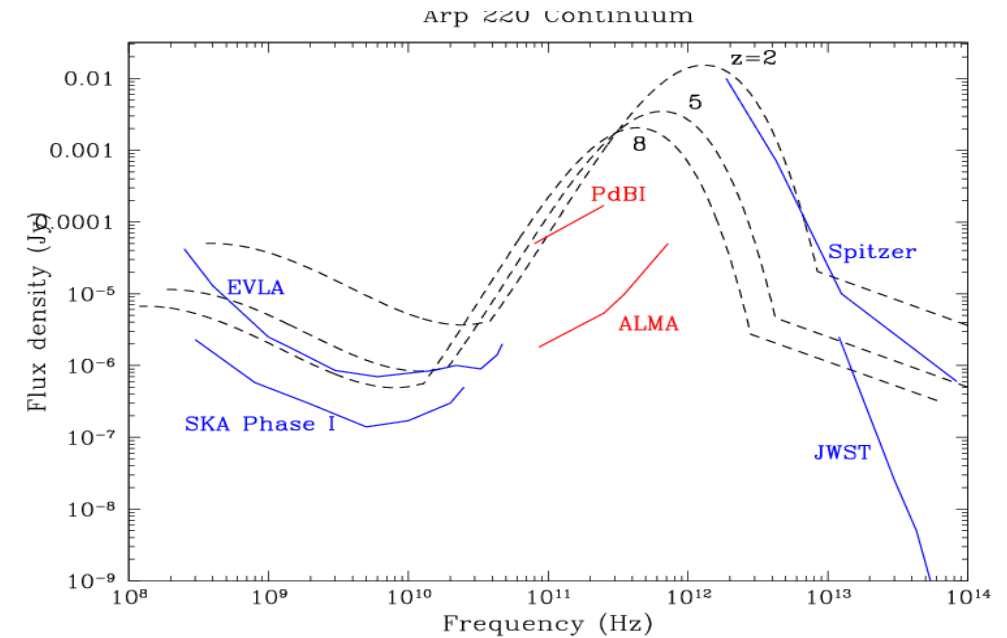
Dry site, low pwv, low T_{sys} , high sensitivity also at submm frequencies

>6500sqm of effective area and 1225 baselines
for the 12m array + Short spacings with ACA
Excellent instantaneous uv coverage
& high sensitivity

<0.05mJy @100 GHz in 1 hr

$$\Delta S_\nu = 2k \frac{T_{\text{sys}}}{A_e \sqrt{2t \Delta\nu}}$$

Receivers are couple of dipoles,
so split the signal into **2 polarizations**
By combining the independent
polarizations chains it can reconstruct
all the Stokes parameters



The Science Goal: Sensitivity Calculator

<http://almascience.eso.org/call-for-proposals/sensitivity-calculator>

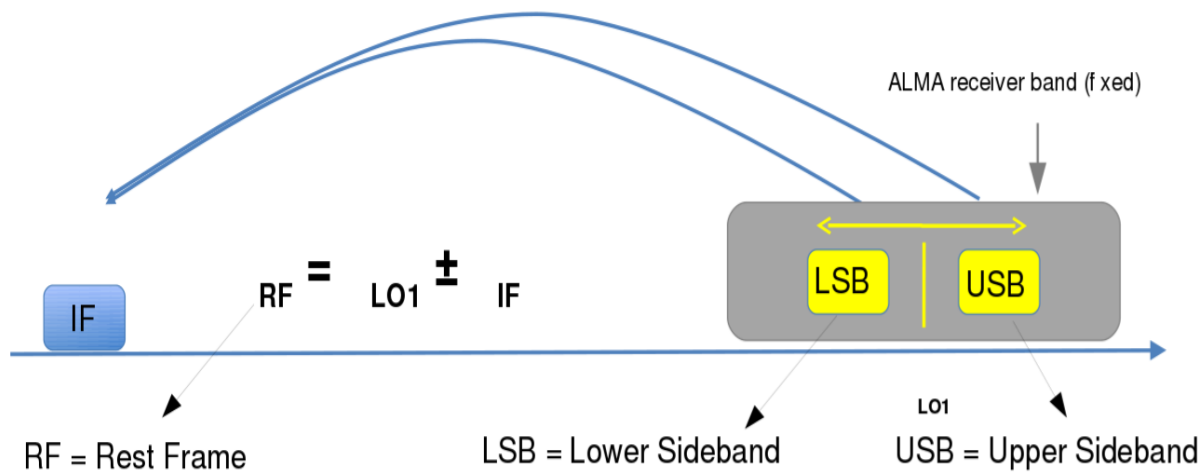
Common Parameters			
Dec	00:00:00.000		
Polarization	Dual		
Observing Frequency	345.00000	GHz	
Bandwidth per Polarization	0.00000	GHz	
Water Vapour Column Density	<input checked="" type="radio"/> Automatic Choice <input type="radio"/> Manual Choice		
tau/Tsky	0.913mm (3rd Octile)		
Tsys	tau0=0.158, Tsky=39.538		
	157.027 K		

Individual Parameters						
	12m Array		7m Array		Total Power Array	
Number of Antennas	34		9		2	
Resolution	0.00000	arcsec	5.974554 arcsec		17.923662 arcsec	
Sensitivity(rms)	0.00000	Jy	0.00000	Jy	0.00000	Jy
(equivalent to)	Infinity	K	0.00000	K	0.00000	K
Integration Time	0.00000	s	0.00000	s	0.00000	s

Integration Time Unit Option Automatic

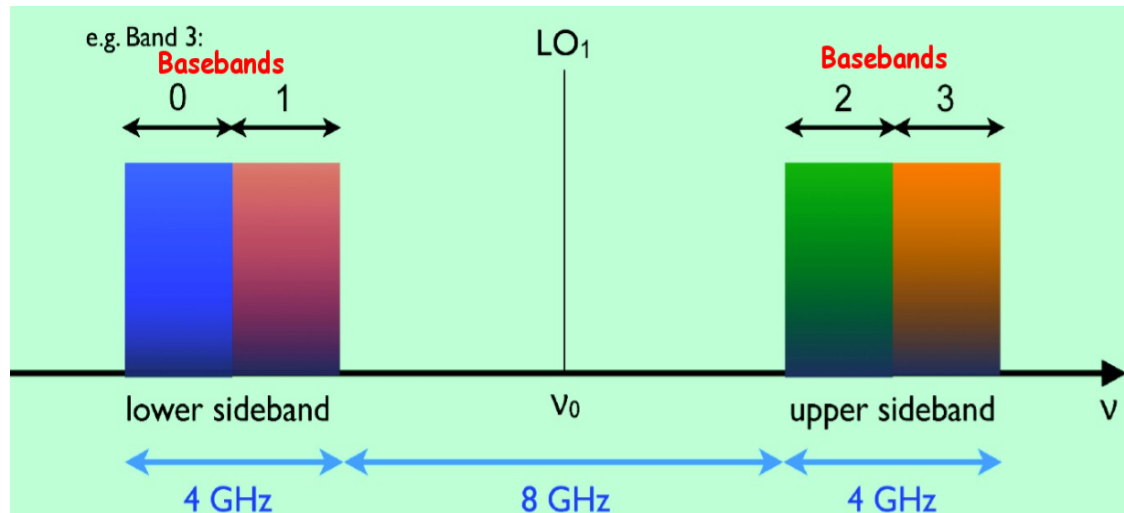
Calculate Integration Time Calculate Sensitivity

ALMA spectral properties



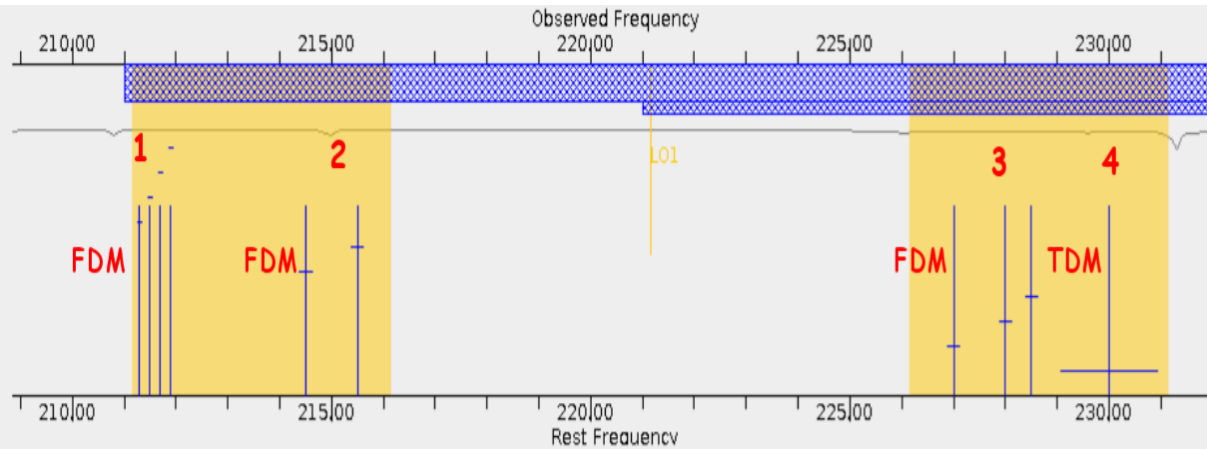
The coherent receivers map two frequency regions to an Intermediate Frequency by mixing the signal with a Local Oscillator.

The receivers allow up to **4 x 2 GHz-wide Basebands** that can be placed in one sideband or distributed between the 2 Sidebands.



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

ALMA spectral properties



Each baseband may be divided into one or more spectral windows by allocating a fraction of the correlator resources to each window.

Resolution

Typical purposes:

Spectral scans

Targeted imaging of moderately narrow lines: cold clouds / protoplanetary disks

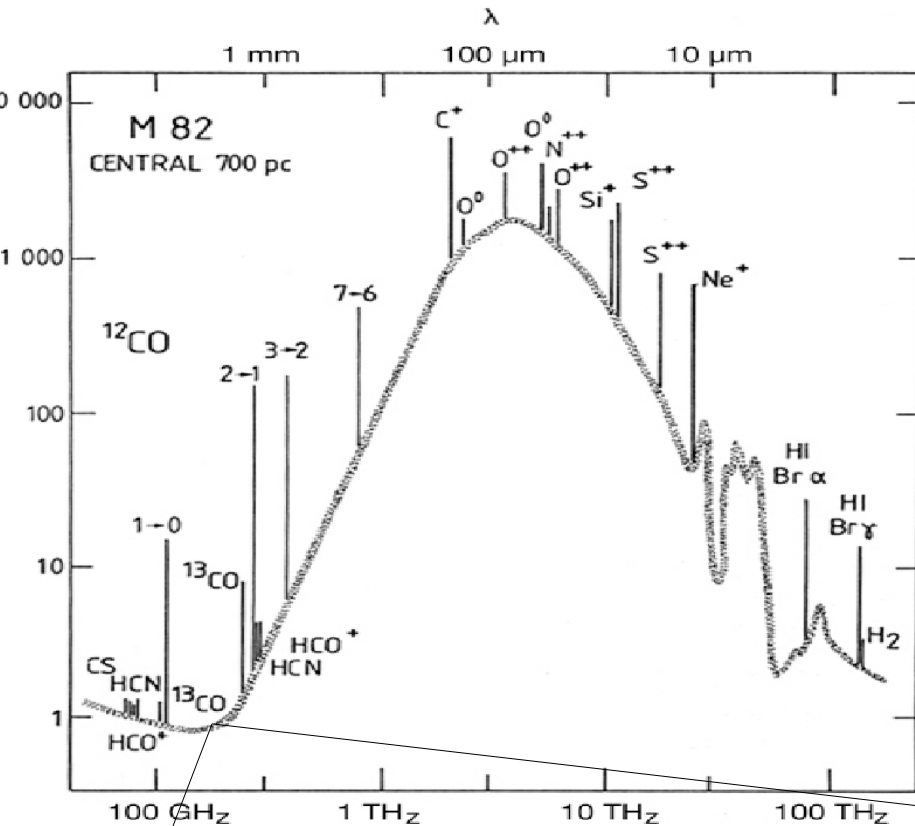
“Continuum” or broad lines

Mode	Polarization	Bandwidth per baseband (MHz)	Number of channels per baseband	Channel Spacing (MHz)	Velocity width at 300 GHz (km/s)
7	Dual	1875	3840	0.488	0.48
8	Dual	938	3840	0.244	0.24
9	Dual	469	3840	0.122	0.12
10	Dual	234	3840	0.061	0.06
11	Dual	117	3840	0.0305	0.03
12	Dual	58.6	3840	0.0153	0.015
6	Single	58.6	7680	0.00763	0.008
69	Dual	2000	128	15.625	15.6
71	Single	2000	256	7.8125	7.8

Frequency division mode: small bandwidth
High resolution (spectral lines)

Time division mode: large bandwidth
low resolution (continuum)

Continuum vs spectral line

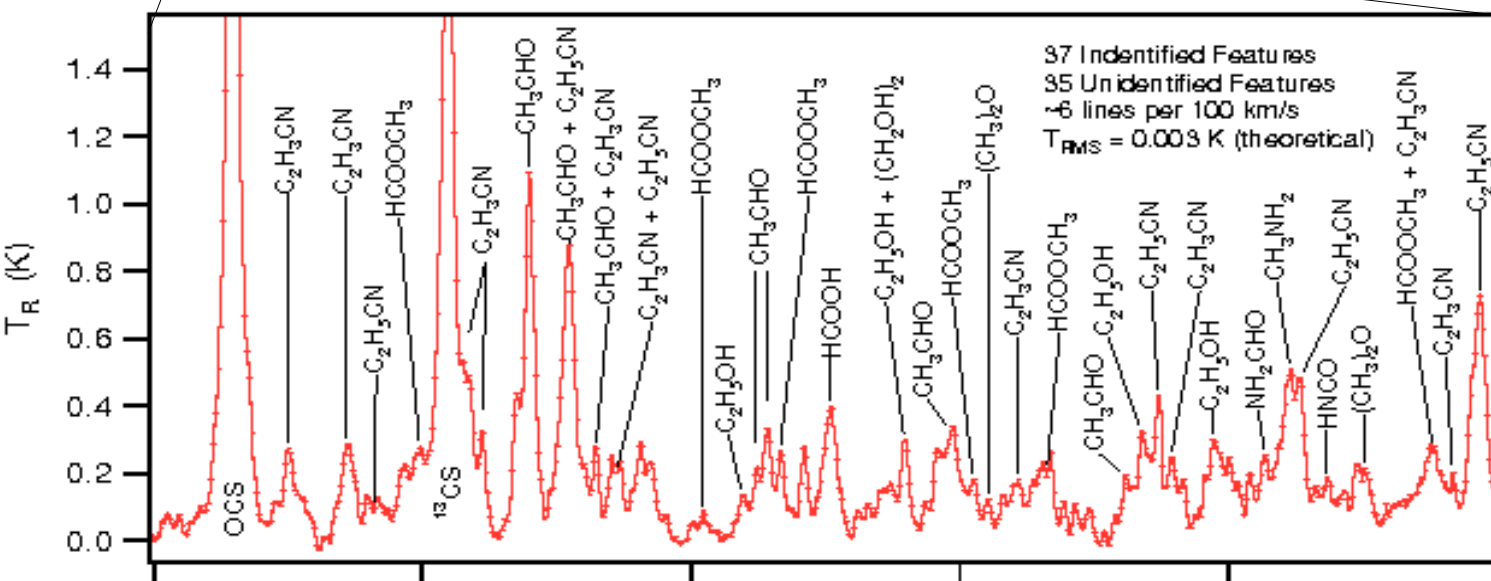


Digital correlators can be set up to different bandwidth and spectral resolution.
Sensitivity refers to a frequency range.

Continuum in mm-submm bands is dominated by dust and synchrotron.
Can be observed with large bandwidth and low spectral resolution (broad frequency channels)

Detailed spectra show a very rich chemistry.
The narrower are the spectral lines the higher is the spectral resolution requested to sample it.

Hence data products are 4D cubes:
Ra, dec, frequency channels, polarization products



Interferometers

Long story made short:

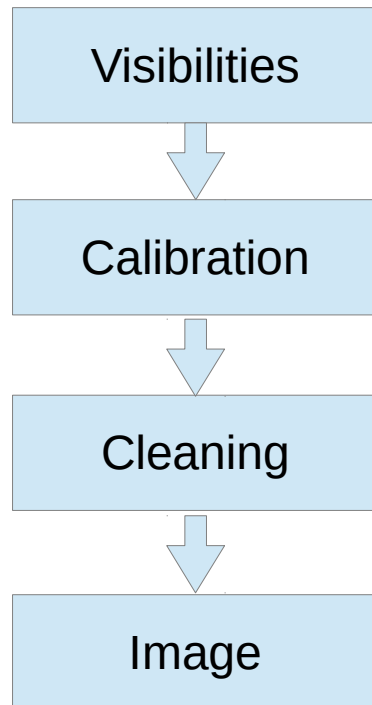
Interferometers are arrays of coherent reflectors that can simulate a single dish of size equivalent to the distance between the antennas, **that collect the amplitude and phase of the electromagnetic waves emitted on selected angular scales according to the array configuration.**

Given an array, sensitivity can be improved with larger bandwidth or longer time on source.

The collected data are not an image yet!!!

Radioastronomers call the collected values from each baseline **visibilities**.

The process to generate an image includes Calibration, Inverse Fourier Transform, Deconvolutions ... too much for this talk, sorry!



For more details about interferometry:

- Thompson, Moran, Swensson, *"Interferometry and Synthesis in Radio Astronomy"*
- Wilson, *"Introduction to mm and submm Astronomy"* (2009)