

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



Marcella Massardi

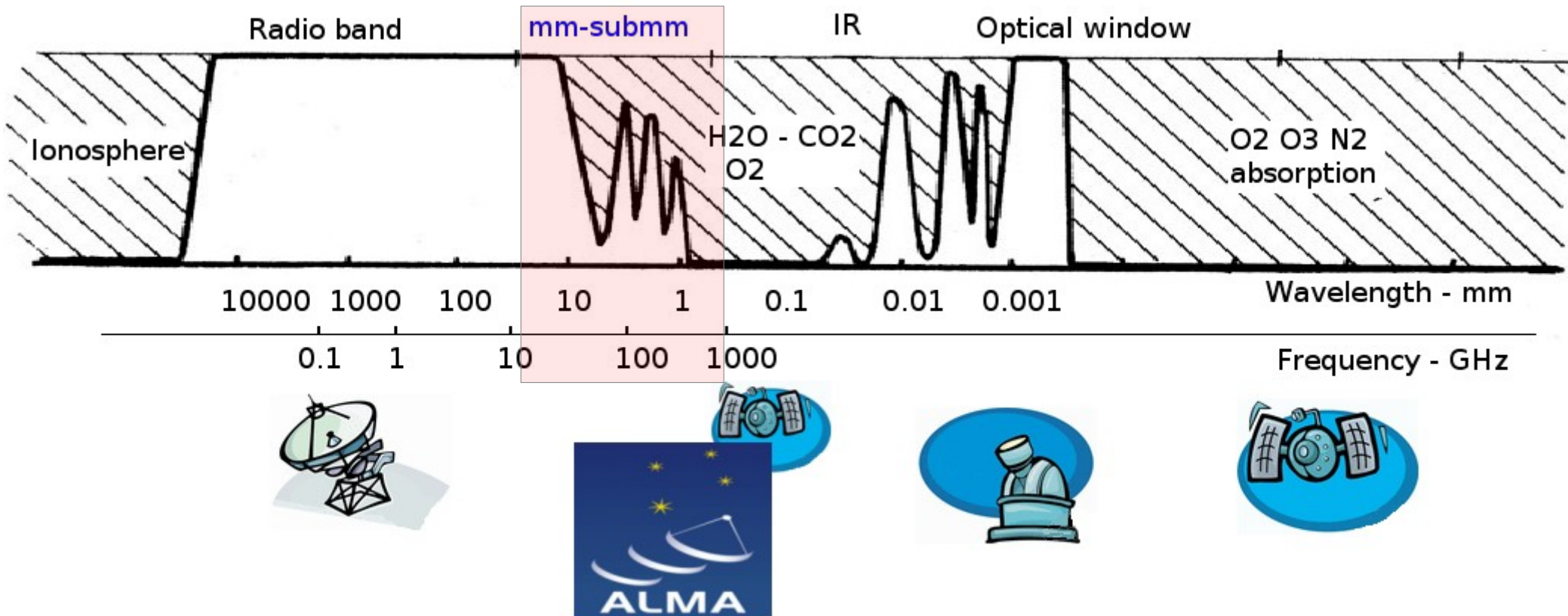
INAF- Istituto di Radioastronomia  
Italian node of European ALMA Regional Centre



EUROPEAN ARC  
ALMA Regional Centre || Italian

SISSA – December 2015

# Outline



Signals:

Synchrotron  
Dust  
Molecular lines

Observing instruments:

Interferometers (ALMA)

Science cases

Observing processes:

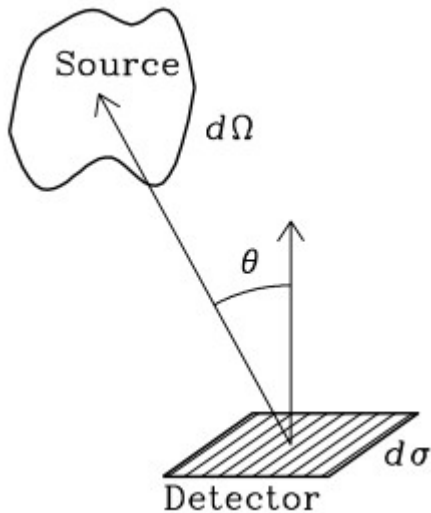
Proposals and archives

# 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,  $\text{m}^2$ ,

$d\nu$  = bandwidth, in Hz,

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

$I_\nu$  = 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 k
- $T_{\text{sys}}$ : 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  $T_{\text{sys}}$**  (= lowering the instrumental noise or choosing sites with low water vapour levels)
- **increasing the collecting area**
- **increasing the bandwidth and/or the integration time**

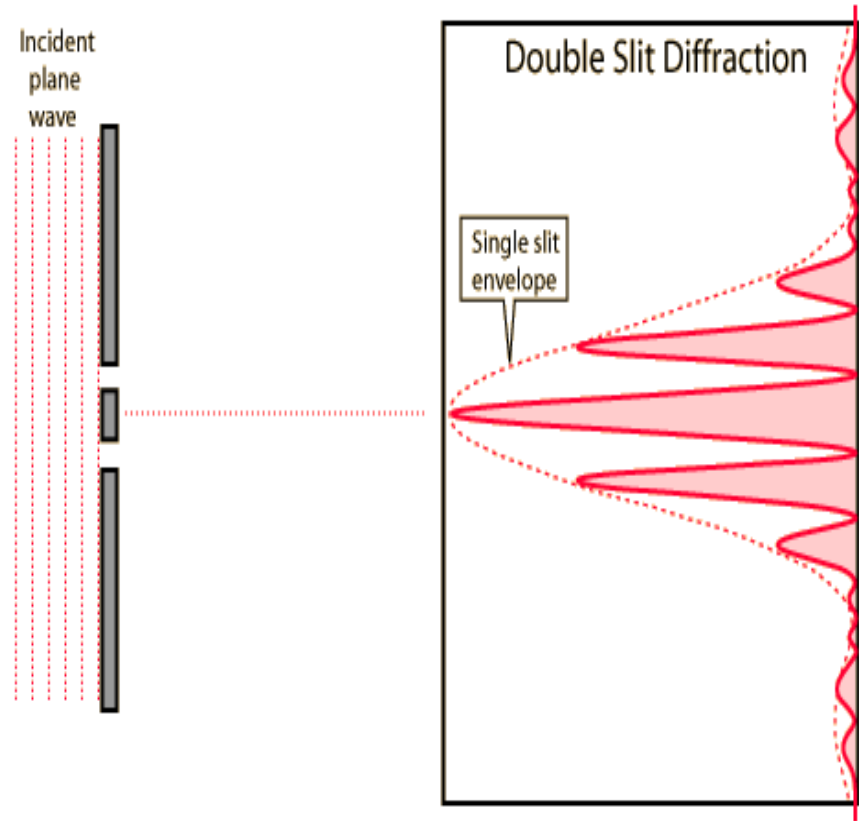
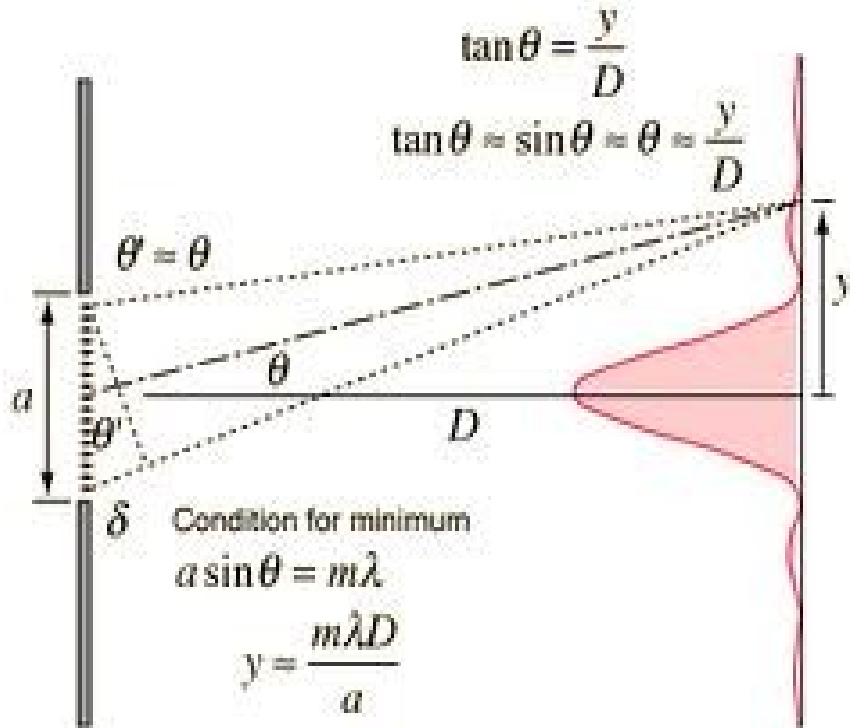
Receivers are couple of dipoles, so split the signal into **2 polarizations**  
By combining the independent polarizations chains it can reconstruct all the Stokes parameters.

# Terminology: resolution

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

the **Resolution** for a wavelength  $\lambda$  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** $=\lambda/a$ , 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.

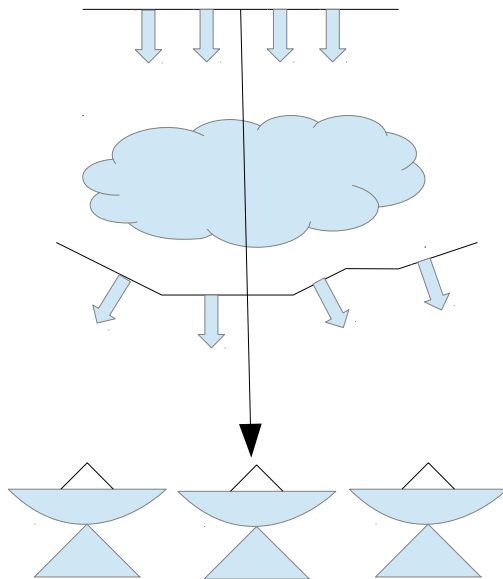
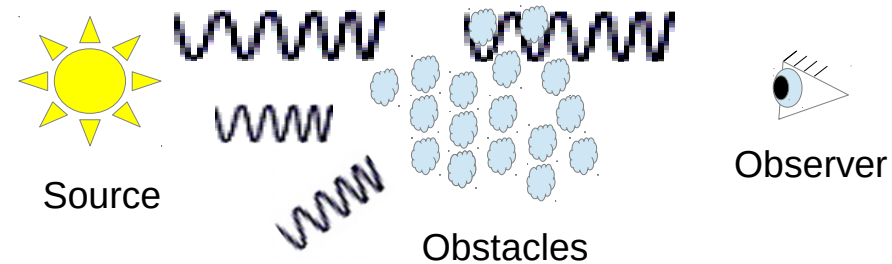
# Terminology: signal “obstacles”

## 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 ( $\sim 0.03$  micron in submm).



## Decorrelation

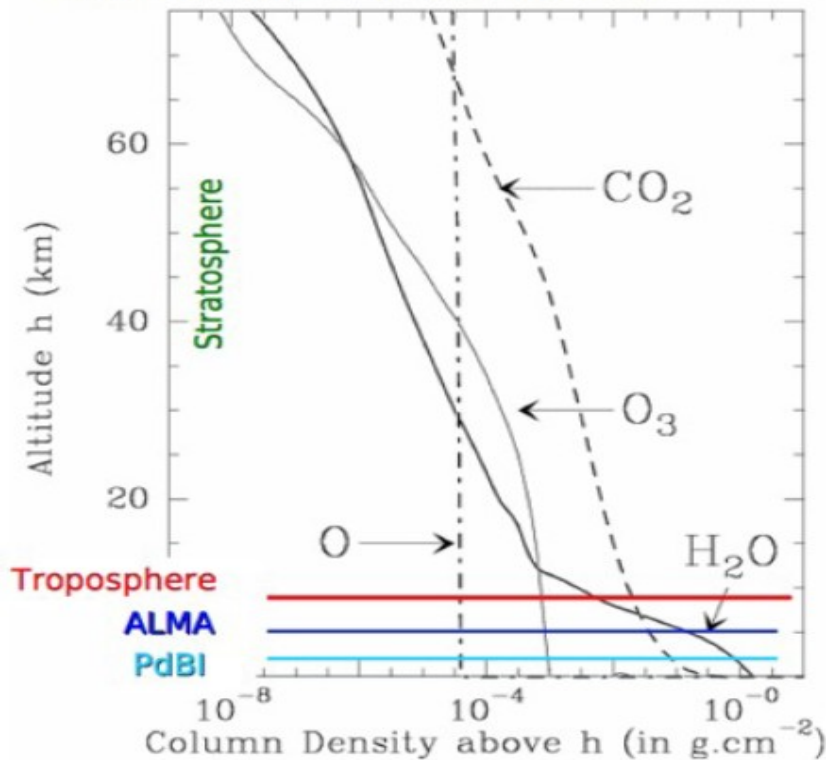
Scattering of light paths has the consequence that two or more receiver looking at the same wavefront receive it in different times and from different direction. If deviations are too large it is no longer possible to reconstruct the original wavefront and compare the signals

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND



# Terminology: signal “obstacles”

Column density as function of altitude

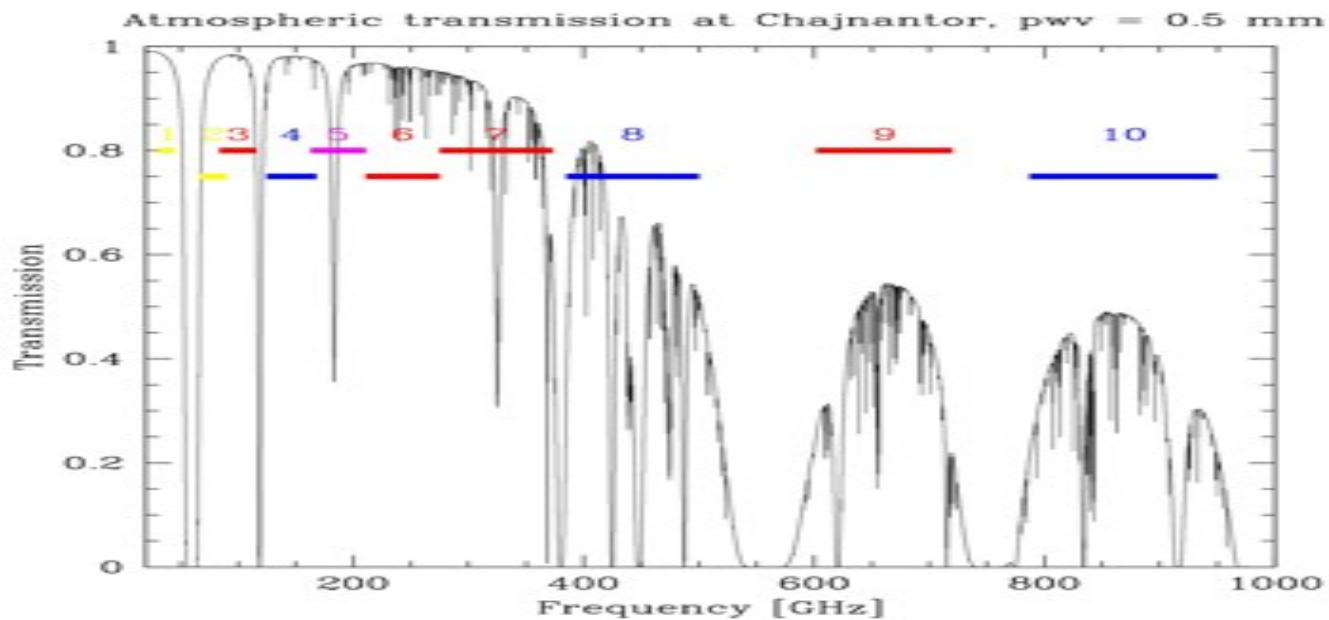
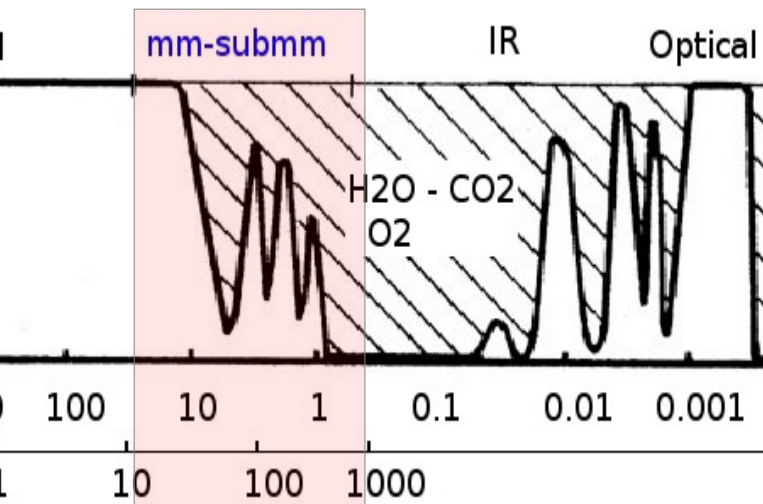


## Absorption & Attenuation

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 re-emitted 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.**

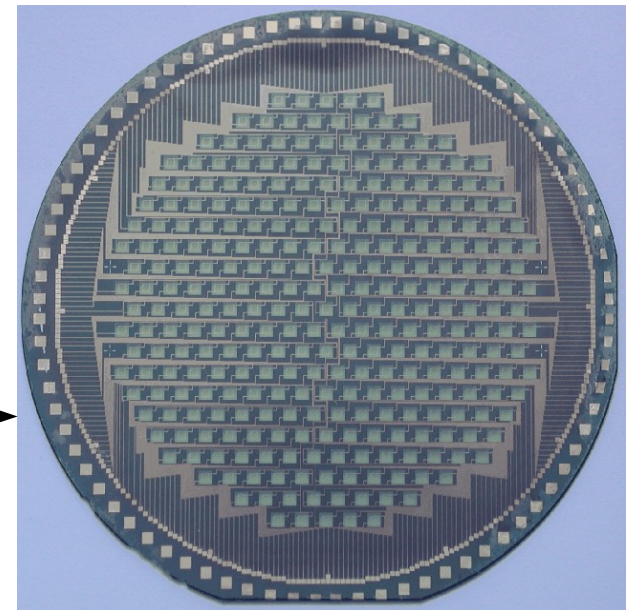
**Bolometers are intrinsically broadband** because the thermal effect is independent of frequency. They are less sensitive to atmospheric variations.

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.

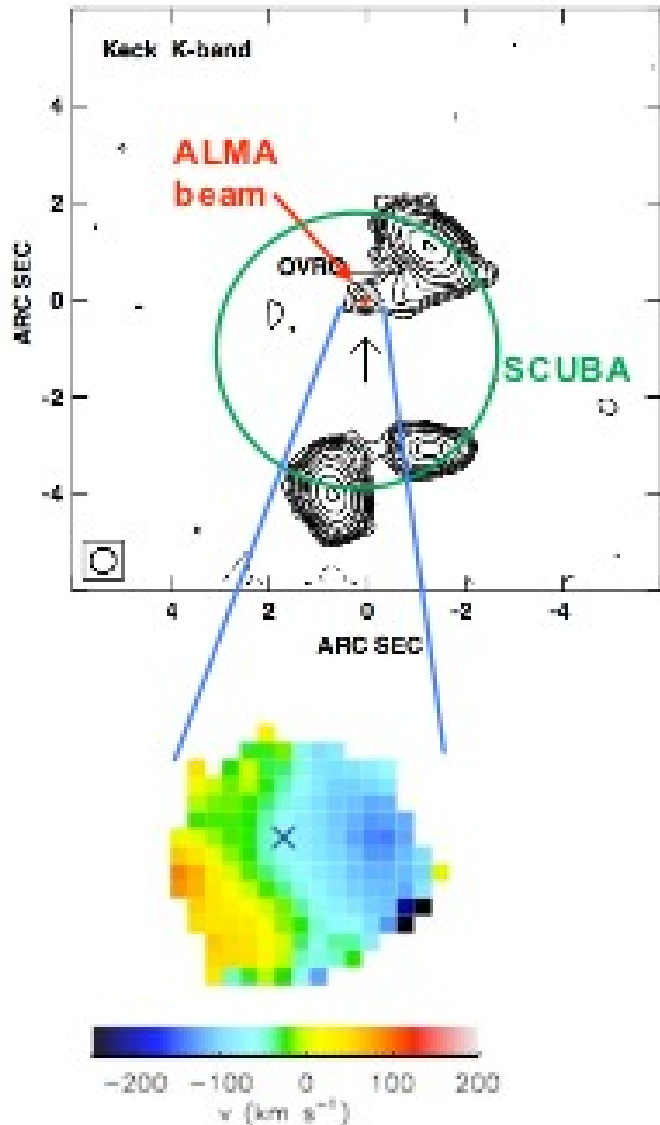
Instrument	Wavelength (microns)	F-o-V (sq-arcmins)	NEFD (mJy)	FWHM (arcsec)	Confusion (mJy)
SCUBA	450	4.2	400	7.5	0.25
	850	4.5	80	14	0.5
SCUBA-2	450	50	100	7.5	0.25
	850	50	30	14	0.5
Laboca-S	350	4	250	7	0.3
Laboca	850	11	110	18	0.8
SPIRE	250	32	29	18	2.6
	350	32	34	25	3.8
	500	32	37	35	5.4
AzTec	1100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

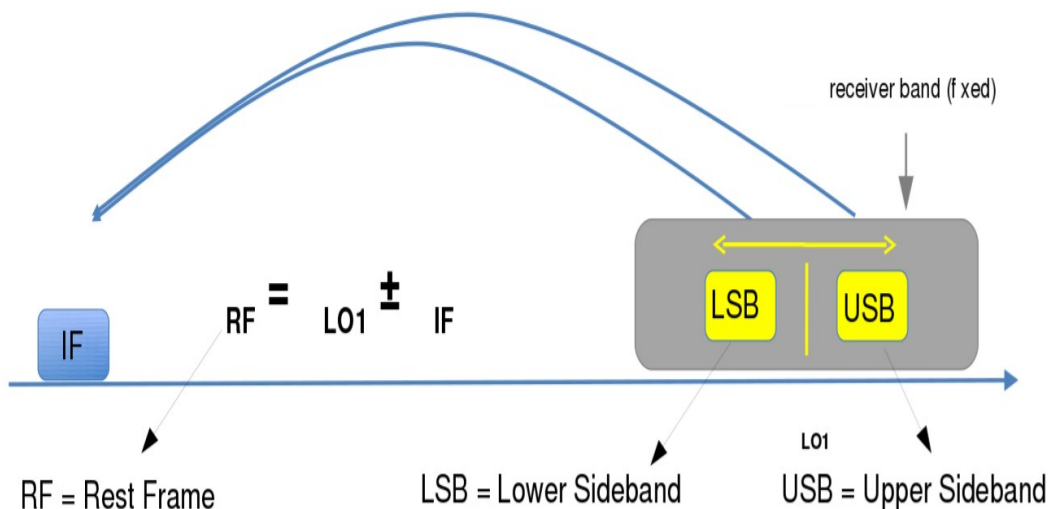
# Instruments: Coherent receivers



**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.



Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

# Instruments: Coherent receivers

Name	Antennas [# × Diameter]	$\Delta\lambda$ [mm]	Max ang. resol. [asec]	Total area [m <sup>2</sup> ]
IRAM-PdBI	6 × 15m	1.2–3	0.35	1060
CARMA <sup>a</sup>	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 <sup>b</sup>	SMA + 15m + 10.4m	0.87–1.2	0.2	488
ATCA <sup>c</sup>	6 × 22m <sup>d</sup>	3–12	2.	2280 <sup>d</sup>

Notes:

<sup>a</sup> CARMA is the merging of the former OVRO (6×10.4m antennas) and BIMA (10×6m antennas) arrays.

<sup>b</sup> eSMA is the combination of SMA with the JCMT and CSO.

<sup>c</sup> ATCA can observe at much lower frequencies, down to  $\lambda = 20\text{cm}$ , the specifications given here only refer to the observing capabilities at mm wavelengths.

<sup>d</sup> At  $\lambda = 3\text{mm}$  only 5 of the ATCA antennas can be used, for a total collecting area of 1900 m<sup>2</sup>.

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

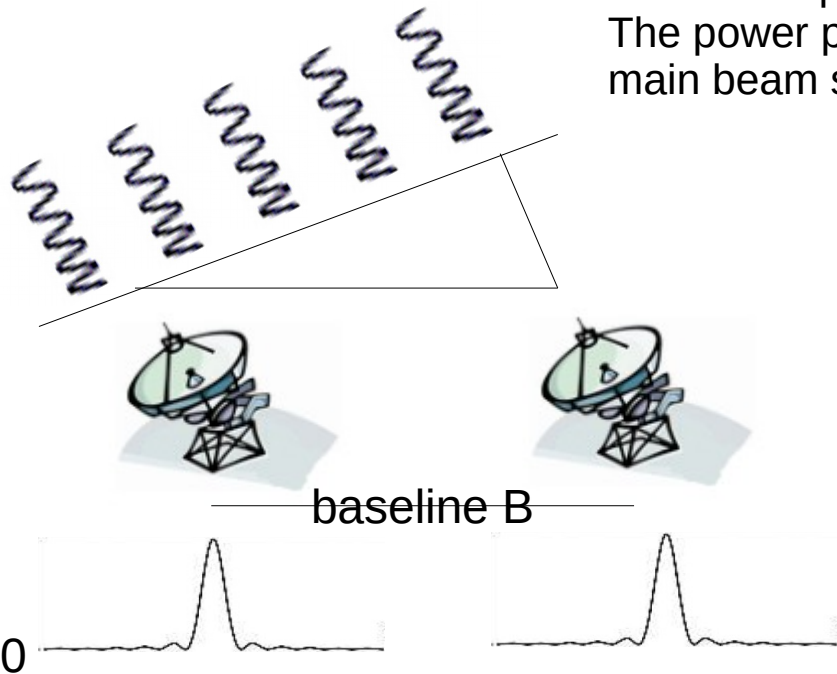
# Instruments: interferometers

**A coherent combination of reflectors of diameter  $d$  at distance  $B(>>d)$  gives 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

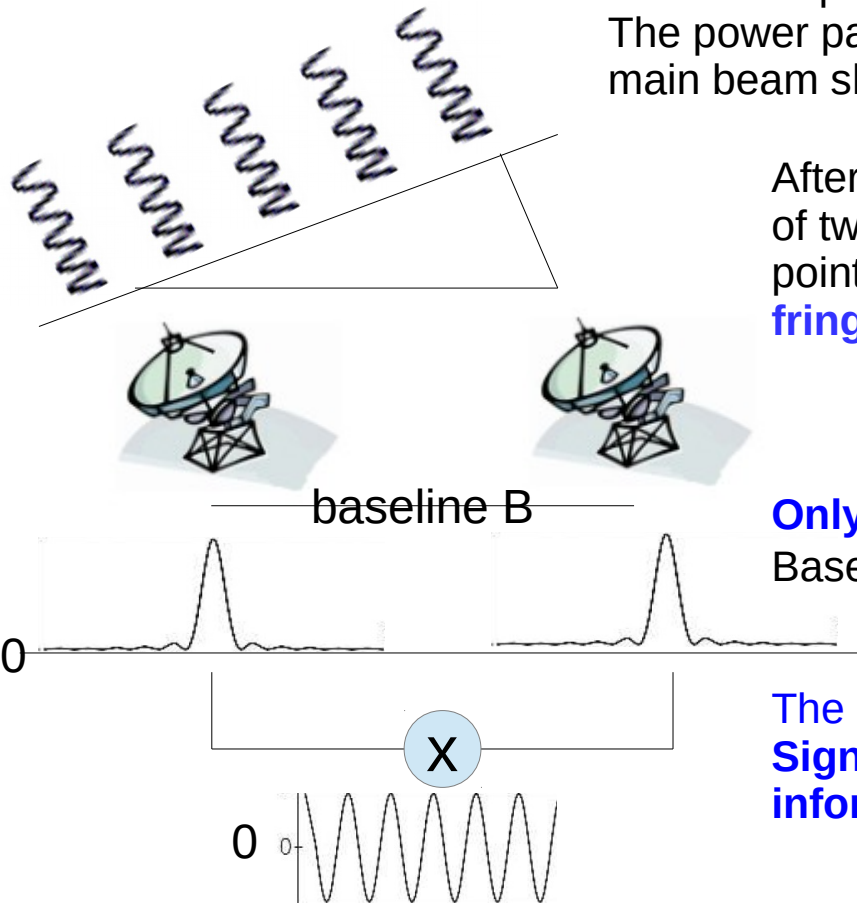
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After correcting for geometrical delays, allowing the comparison of two points of the same wavefront coming from a far away point source **the output of the correlation of two signals is a fringes pattern centered around 0 (total power is lost).**

**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

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

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

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

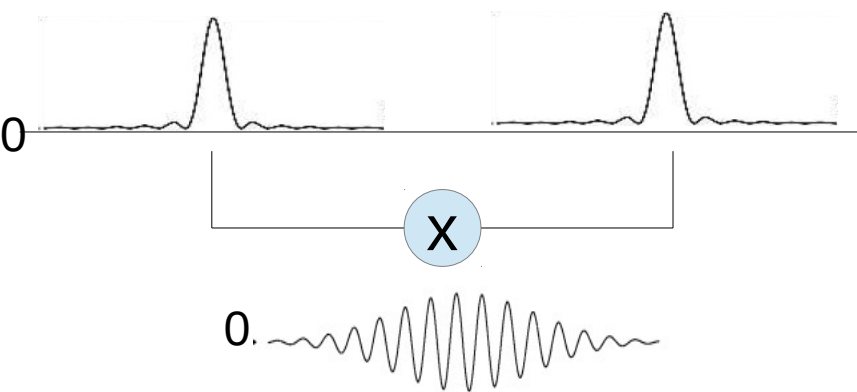
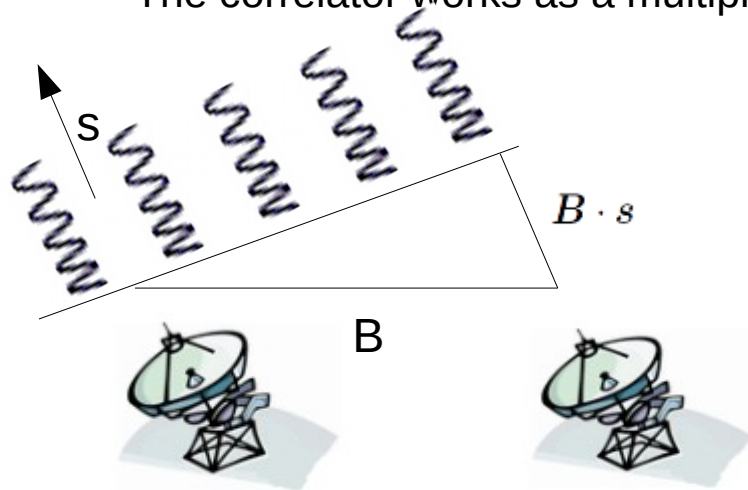
that results in

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

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

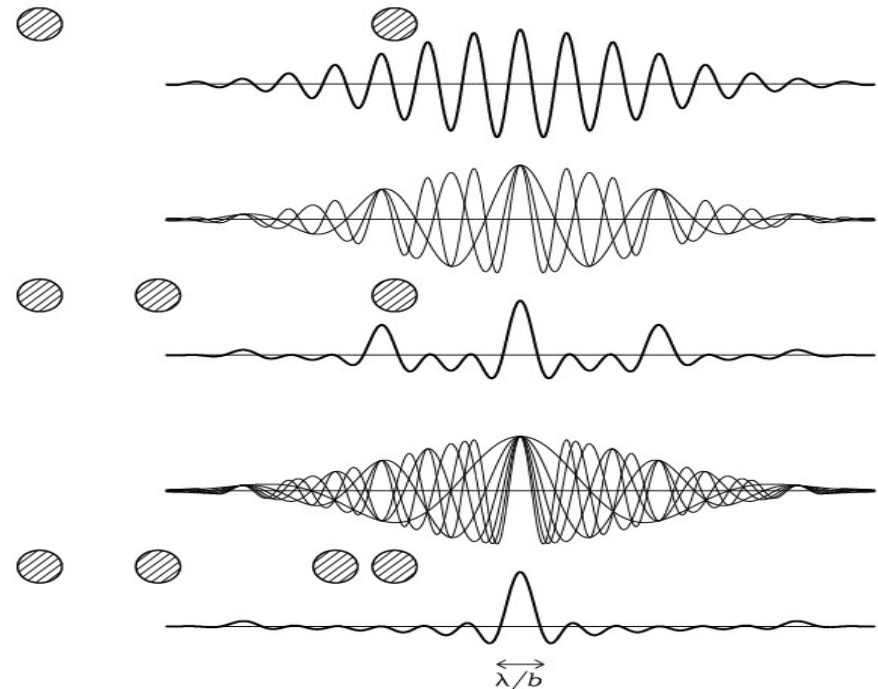
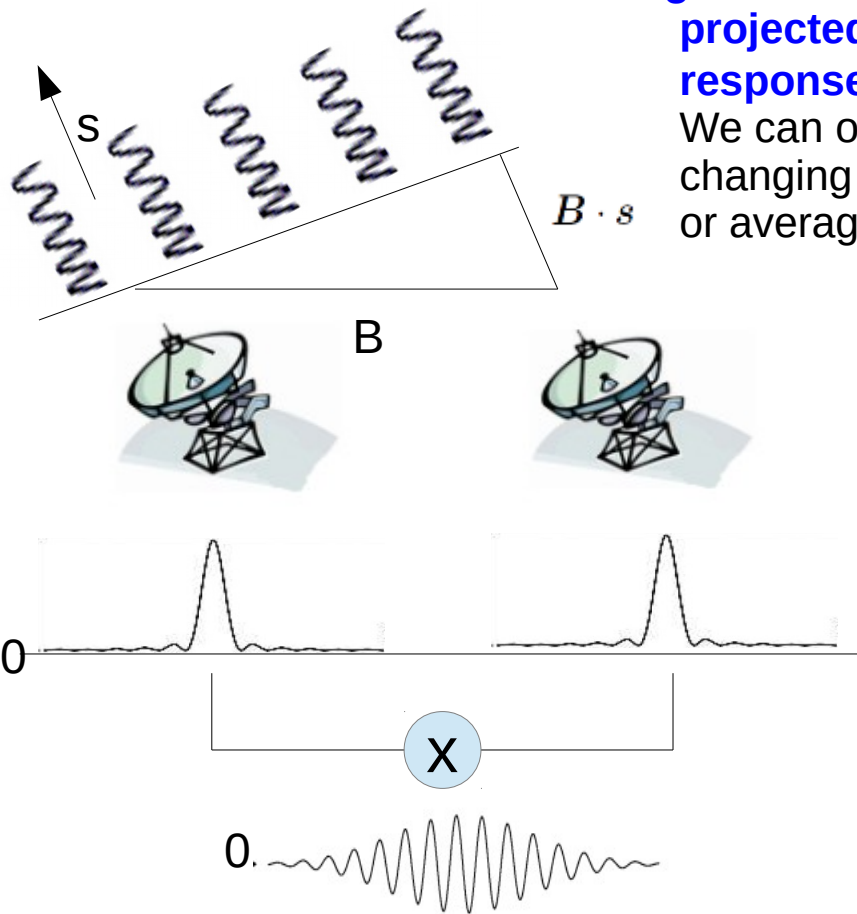
Some **visibility function** properties:

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

- **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  $\lambda/B$ .**

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

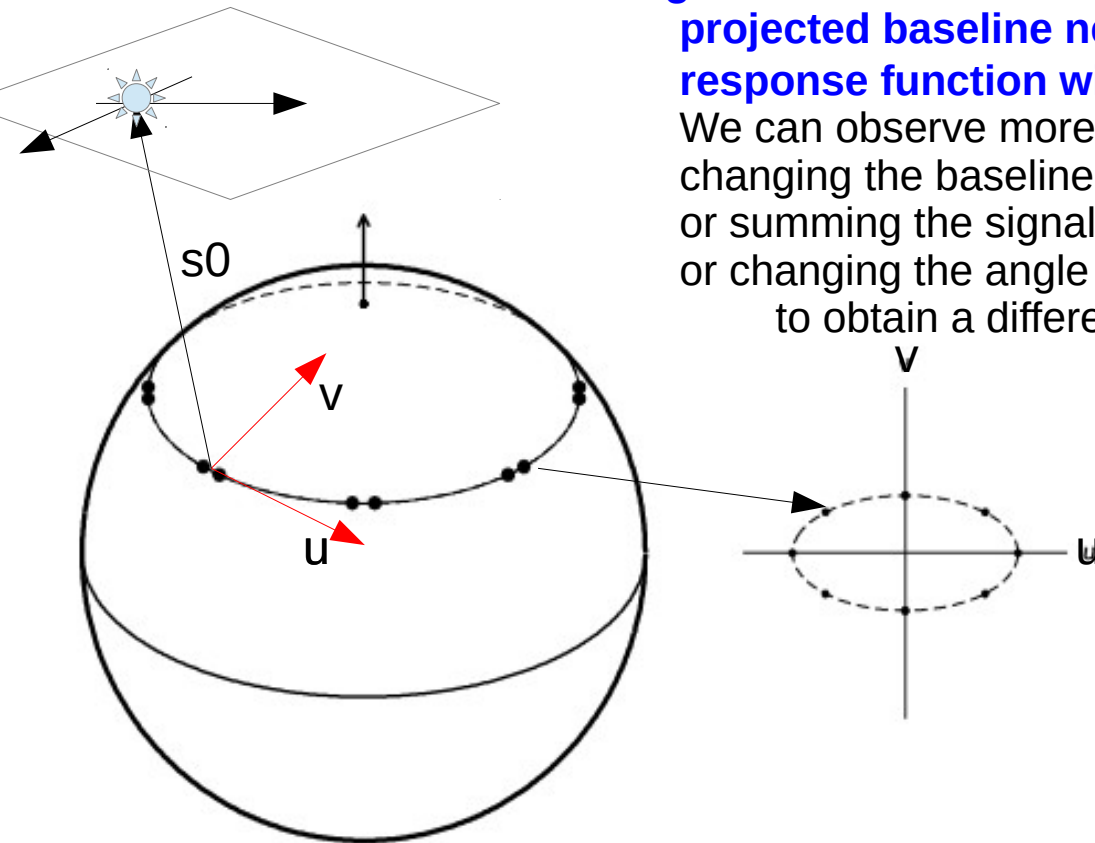
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or summing the signal from  $N$  Antenna couples  $(N(N-1)/2)$  or changing the angle towards the target (exploiting the Earth rotation) to obtain a different projection of the same baseline.



**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: properties

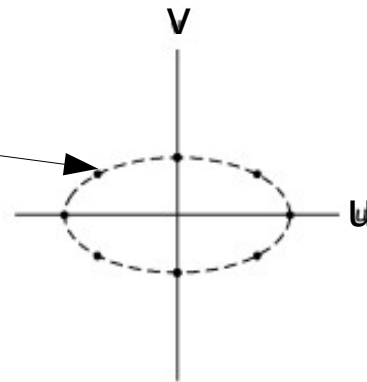
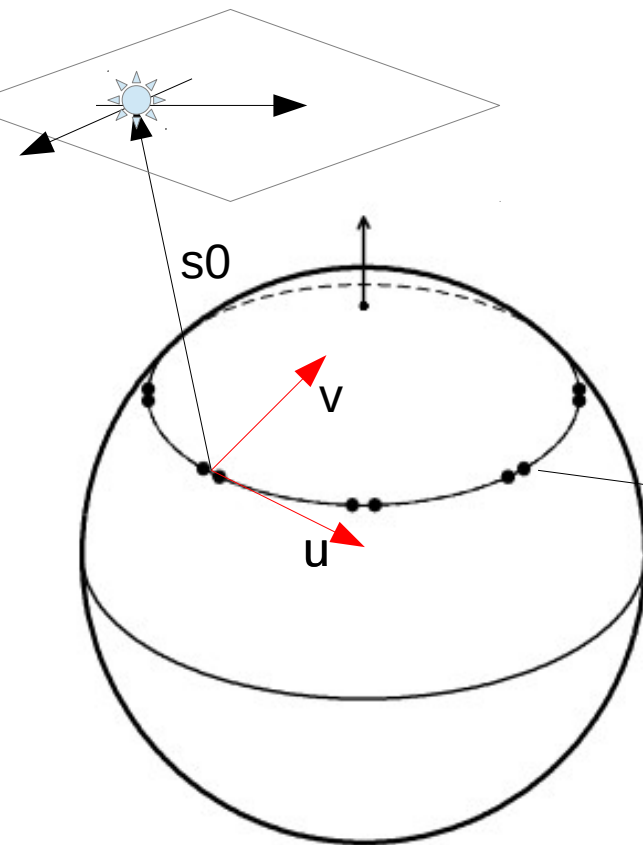
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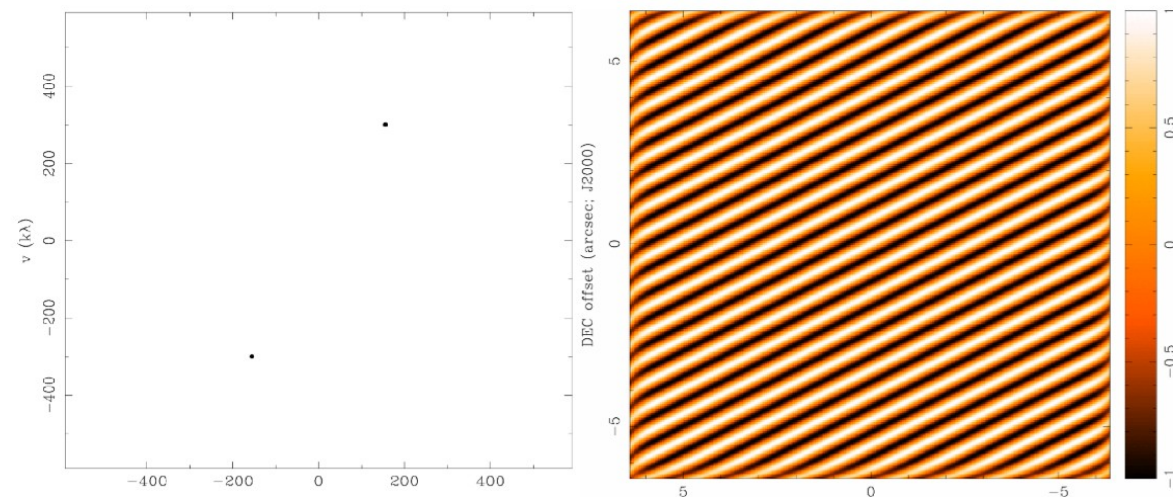
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- **Van Cittert- Zernike theorem: the visibility pattern is the Fourier transform of the brightness pattern**

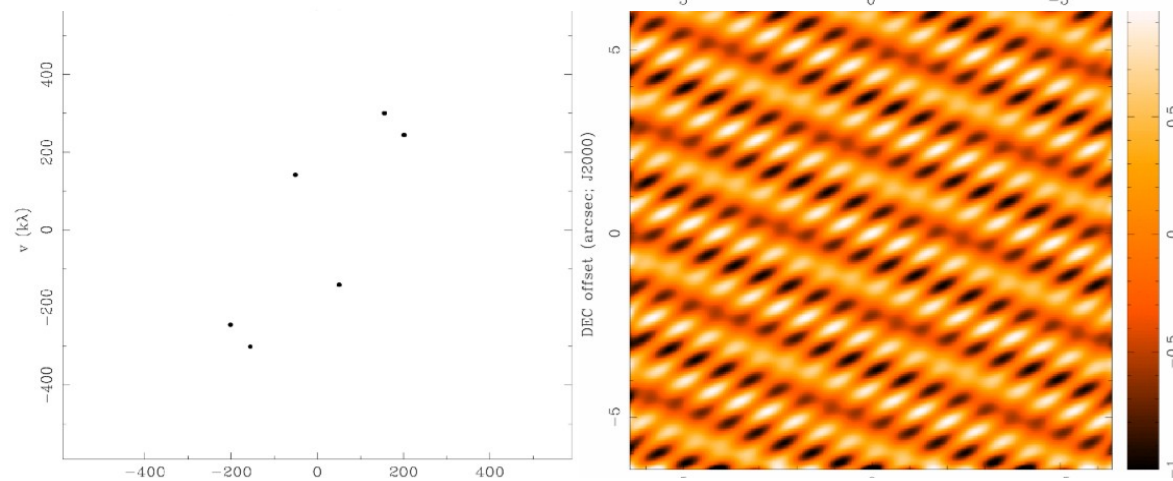
Hence the inverse transformation of the  $uv$  plane gives the image of the real plane (filtered for the observed angular scales).

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

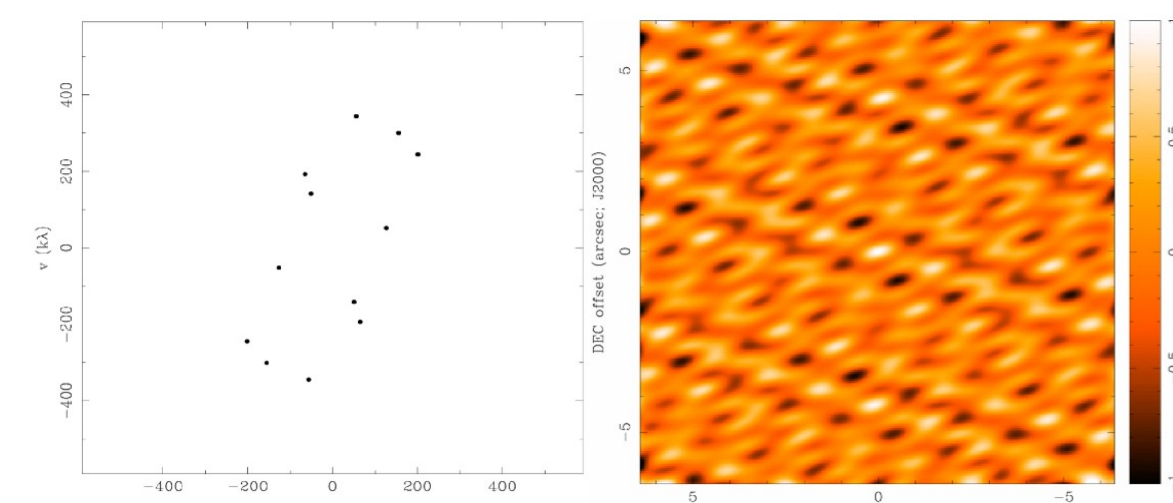
# The visibility function: the uv plane



2 antennas

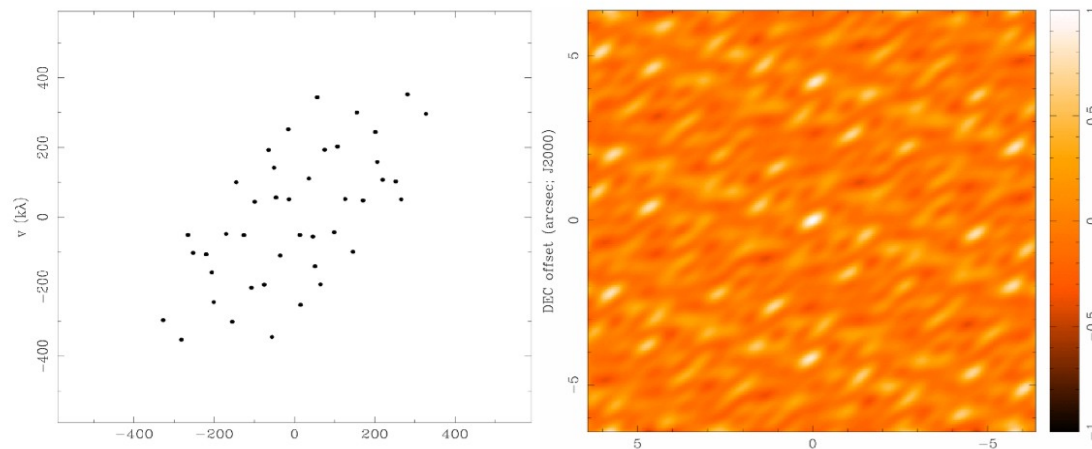


3 antennas



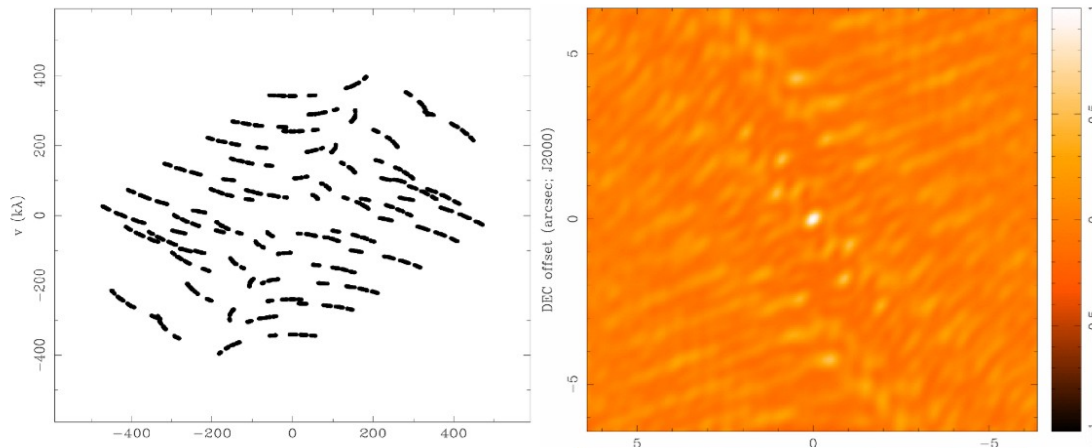
5 antennas

# The visibility function: the uv plane

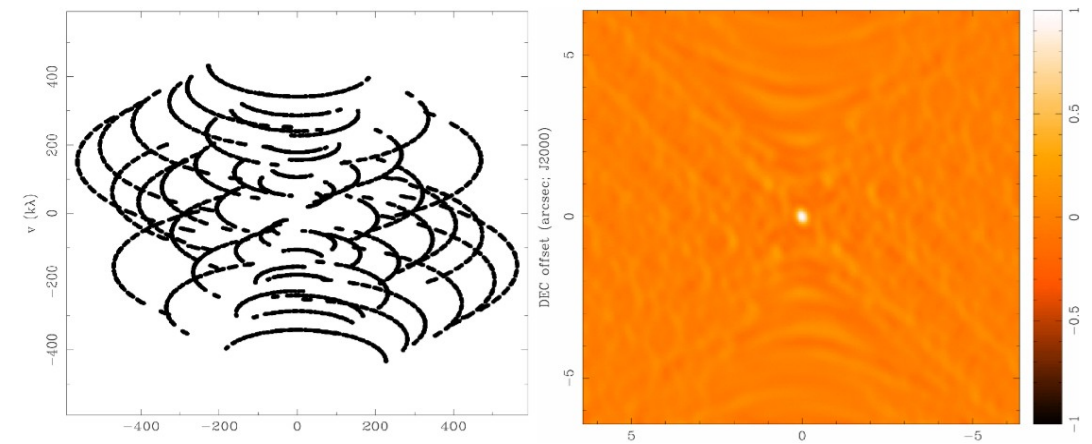


8 antennas

1 sampling

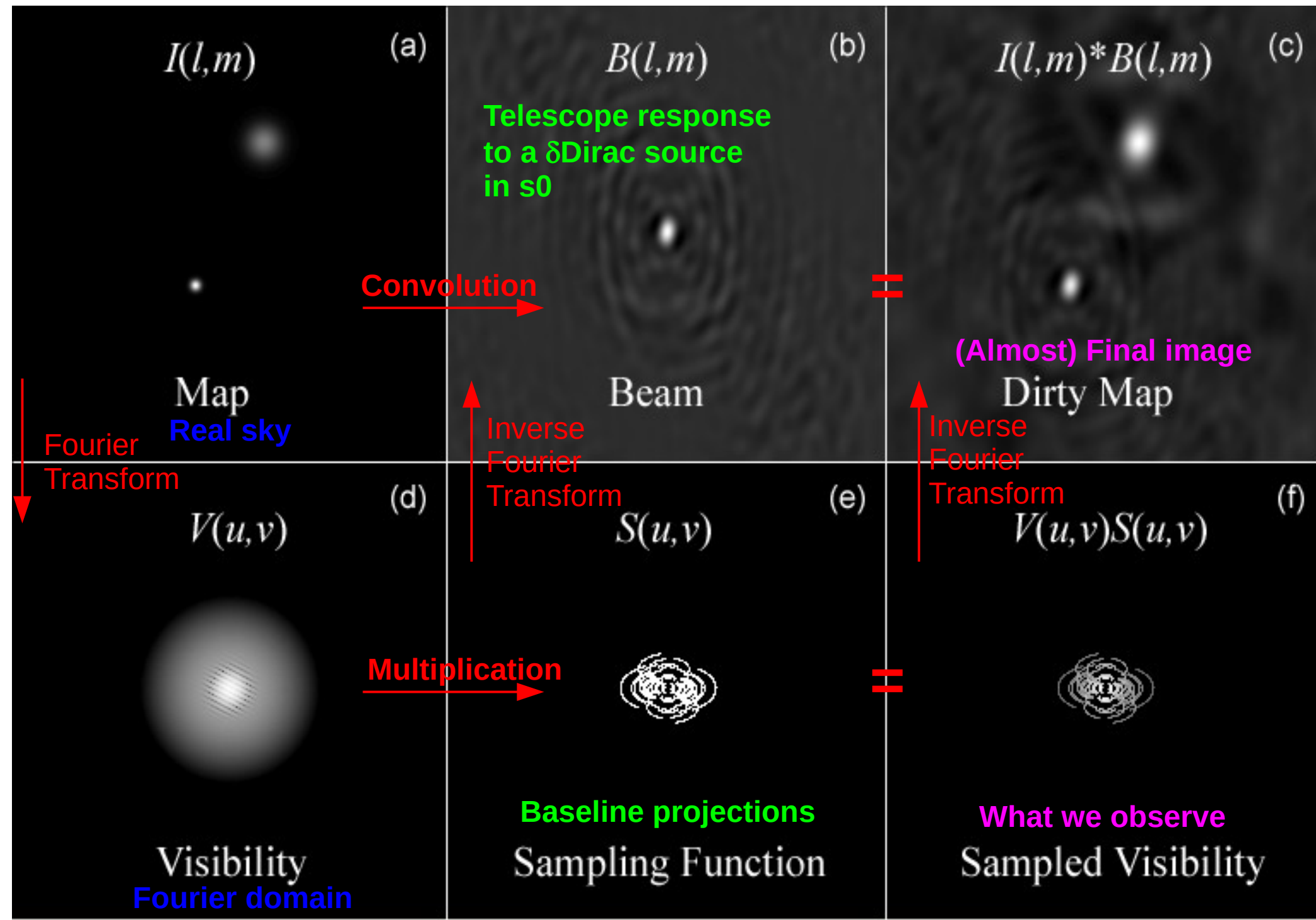


120 samplings



480 samplings

# From the sky to the image





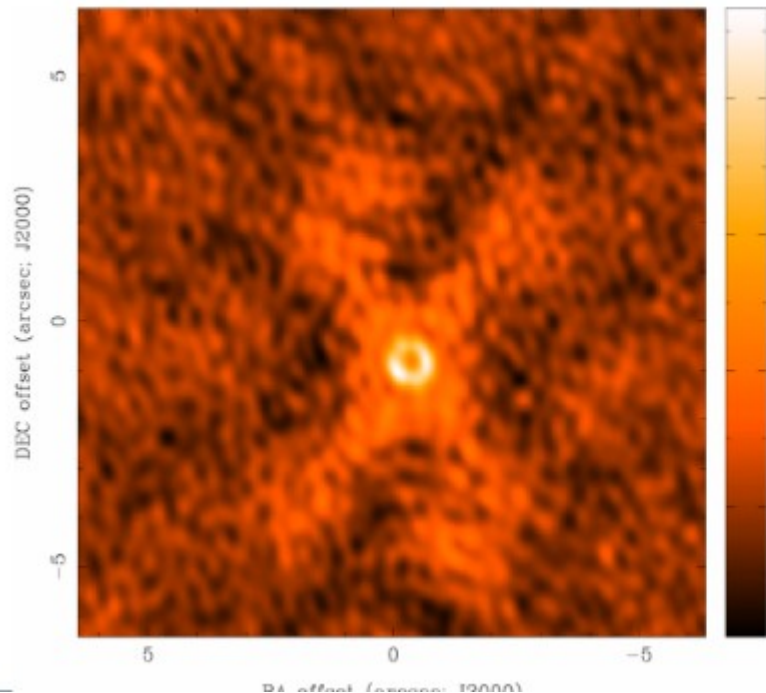
# Deconvolution

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

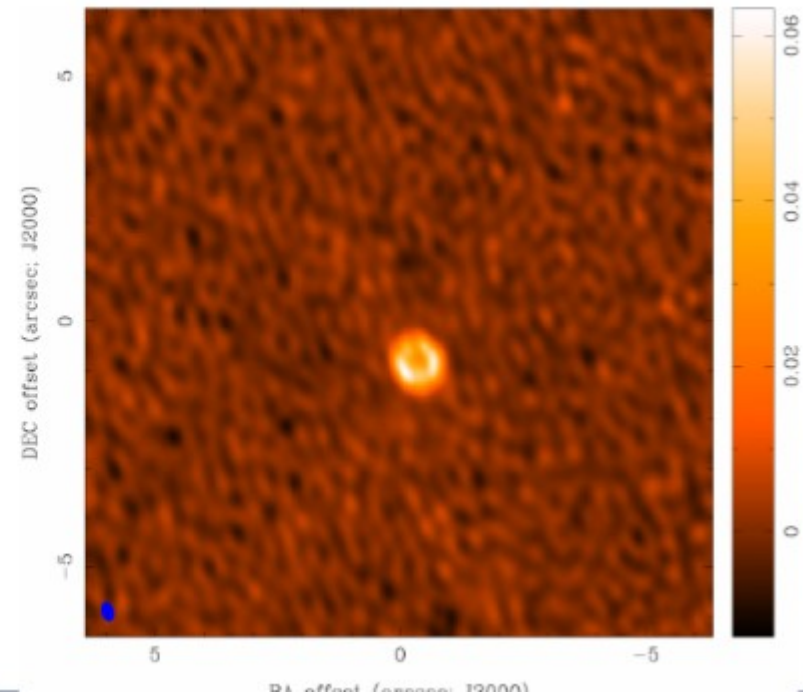
- Aims to find a sensible model of  $I(\mathbf{s})$  compatible with data without sidelobes
- Uses non-linear techniques to interpolate/extrapolate samples of  $R(u,v)$  into unsampled regions of the  $(u,v)$  plane
- Requires knowledge of beam shape  $A(\mathbf{s})$  and a priori assumptions about 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

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.**

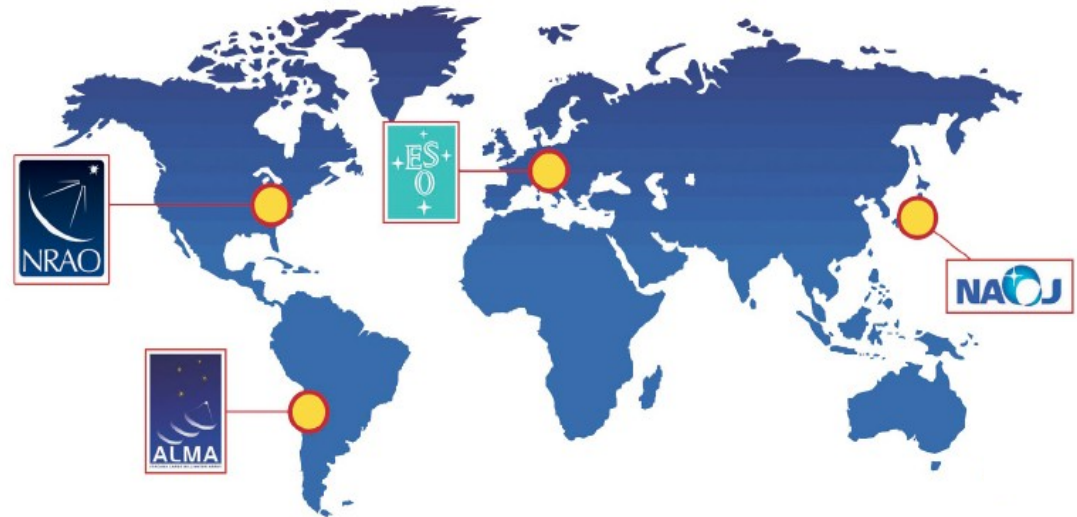
- > high angular resolution and sensitivity
- > galaxy dynamics, AGN core mechanisms, imaging of exoplanets, comets, asteroids, ...

# 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

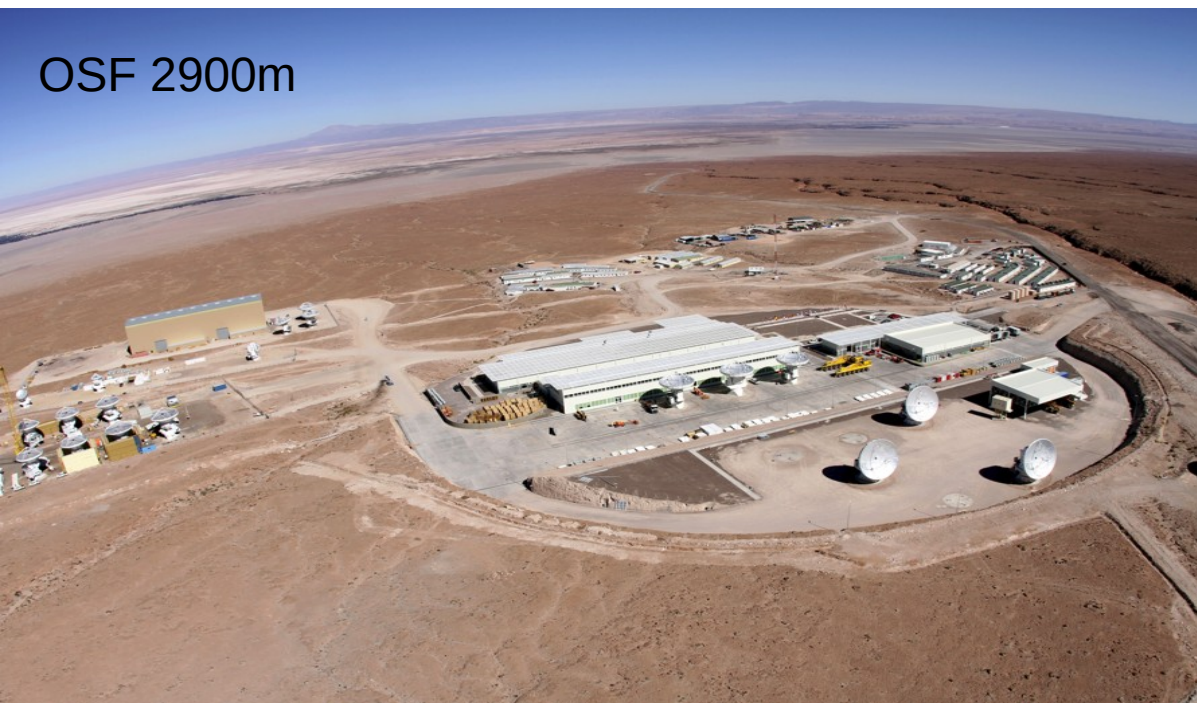
- **AOS**: ALMA Operations Site (5000m): Antennas, Correlator
- **OSF**: Operations Support Facility (3000m):  
Labs, Antenna Assembly & Maintenance Operators, Astronomers
- **SCO**: Santiago Central Office:
  - Call for Proposals
  - Running ALMA
  - Data Reduction Pipeline
  - Quality Assessment



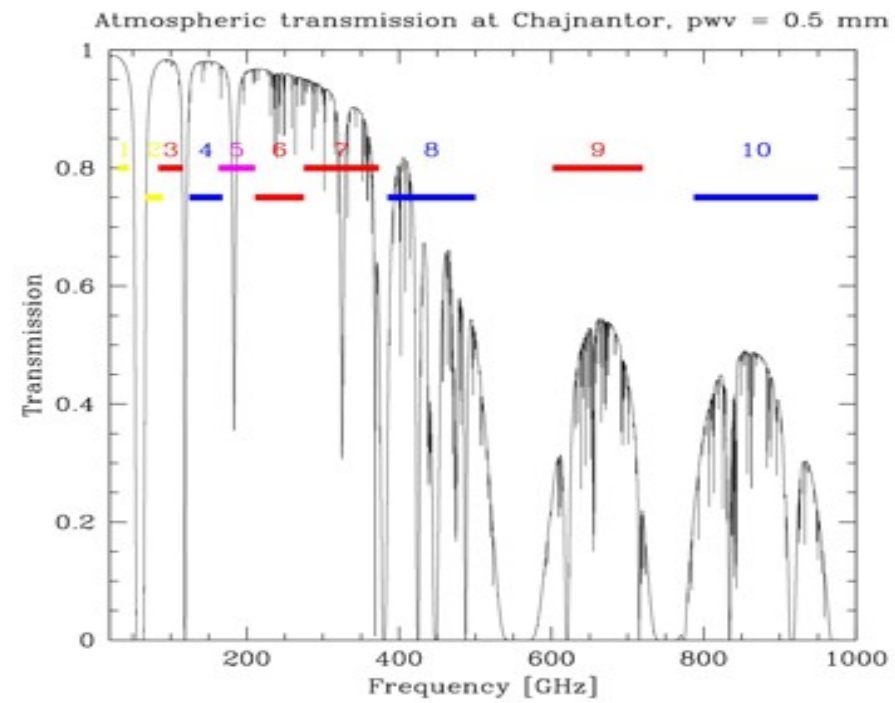
# ALMA sites



AOS 5000m

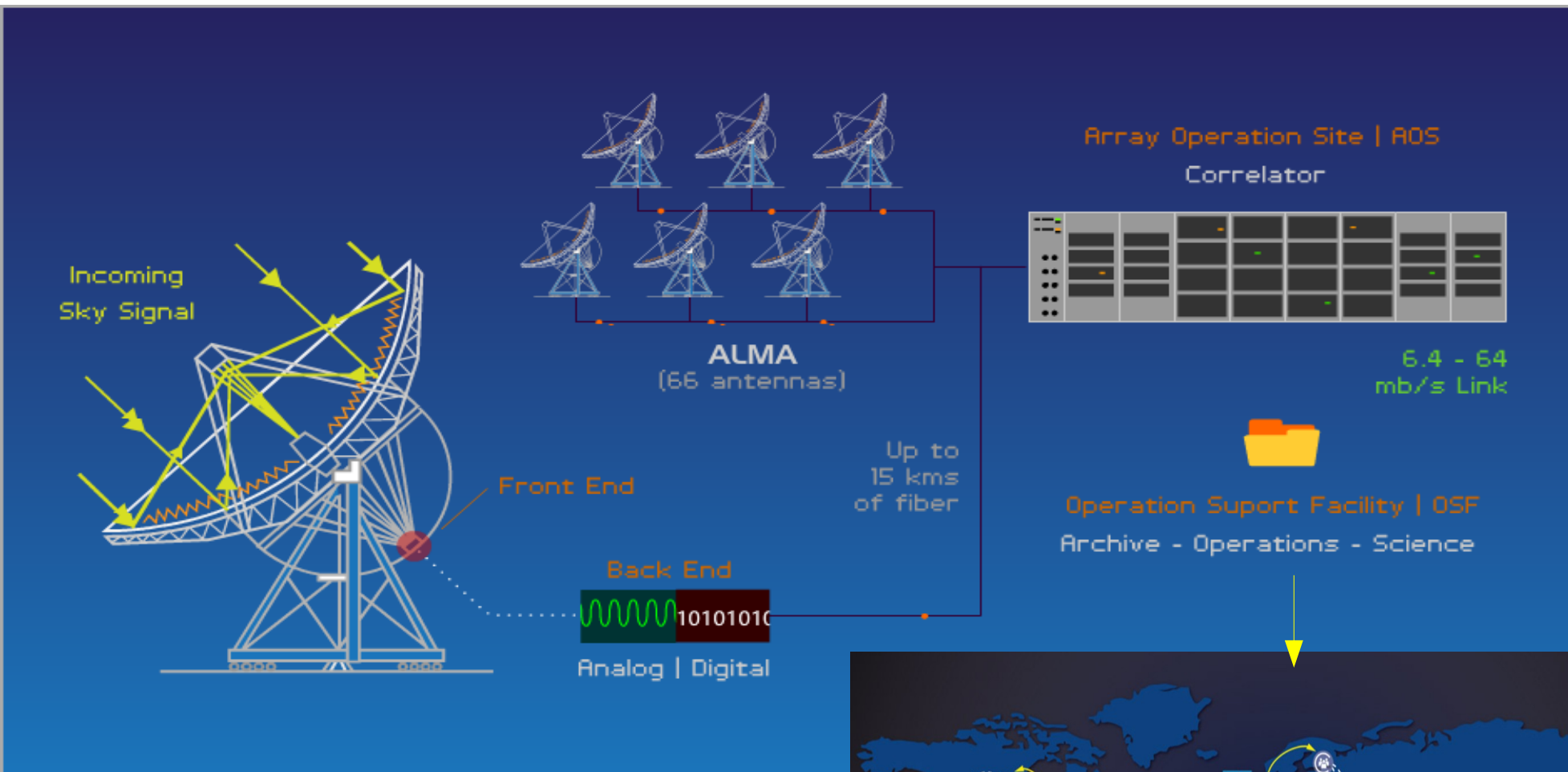


OSF 2900m





# ALMA data flow



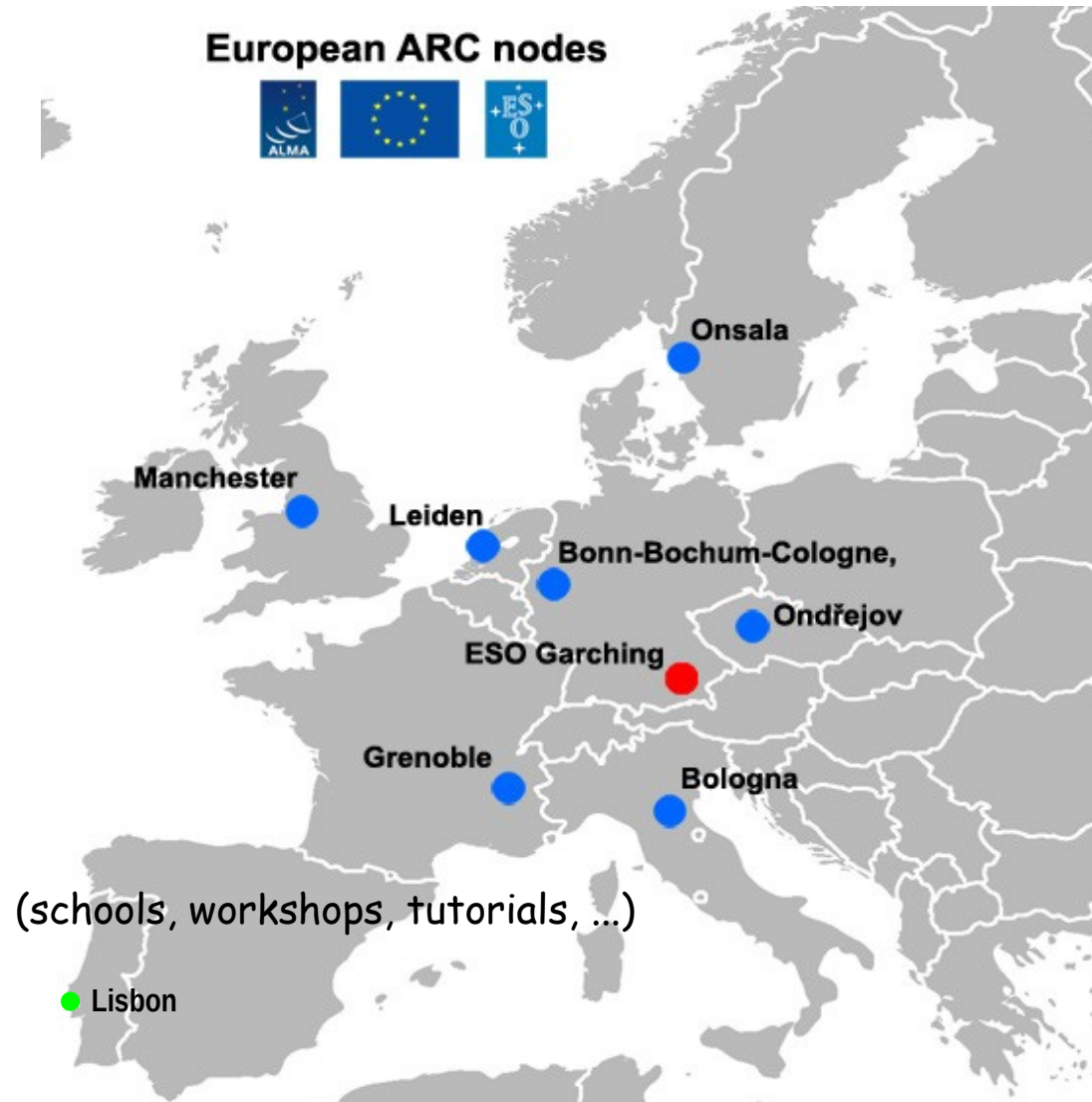
Data is collected, reduced and archived.  
All the “almost” raw data is archived.

**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/>



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



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

Search Site

Log in | Register | Reset Password | Forgot Account

About

Science

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Observing

Data

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Welcome to the Science Portal at ESO

Current call Tools and info

ALMA status page, Project Tracker, Archive Calibrators and SV data

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



Cycle 3 Call for Proposals

The Cycle 3 Call for Proposals is now open for scientific observations that will be scheduled from October 2015 to September 2016. The proposal submission deadline is 15:00 UT on April 23, 2015.

... of the ALMA partner ... the links to the ... capabilities of ALMA, how ... to propose for observing time, and how to access ALMA data. It includes links to all official ALMA documents and tools, including those for preparing and submitting proposals and processing ALMA data. In order to access some of the tools, users must register with the project and login to the portal via the links at the top banner.

General News

ALMA Cycle 3 Call for Proposals is now open  
Mar 24, 2015

Resubmission of unfinished Cycle 1 and 2 proposals for the Cycle 3 proposal review  
Mar 24, 2015

Release of Science Verification data from the ALMA Long Baseline Campaign  
Feb 17, 2015

Announcement of intent to release a new installment of Science Verification data  
Feb 02, 2015

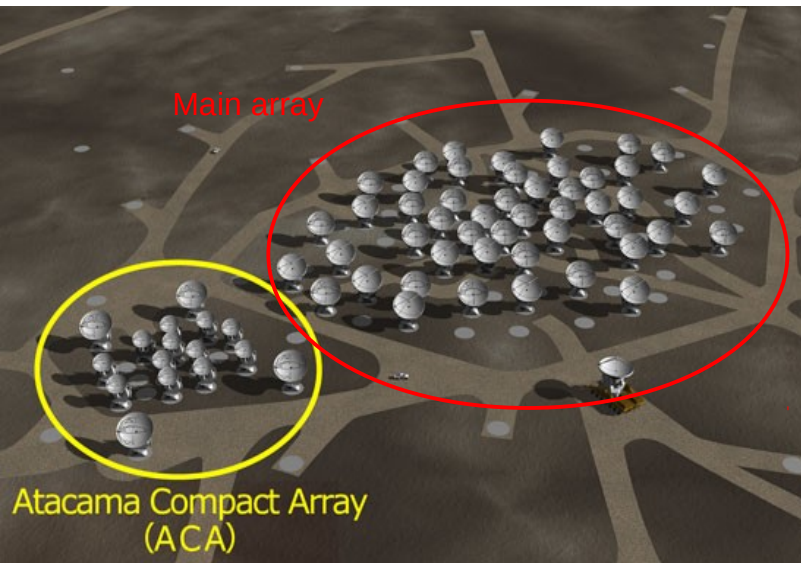
ALMA Cycle 3 Pre-announcement  
Dec 08, 2014

More...

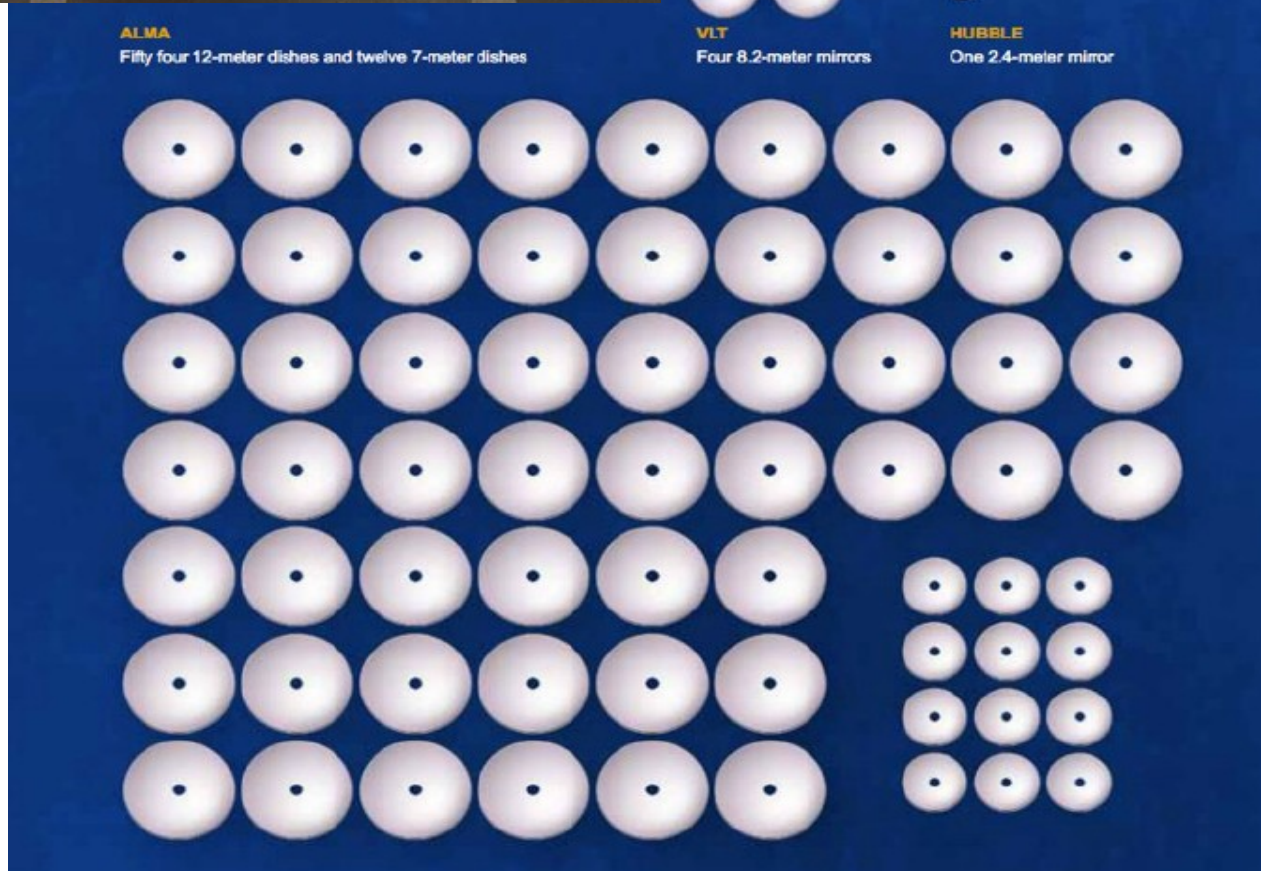
Access to Helpdesk for any request (FAQ, problems, request of face-to-face meeting of experts...)



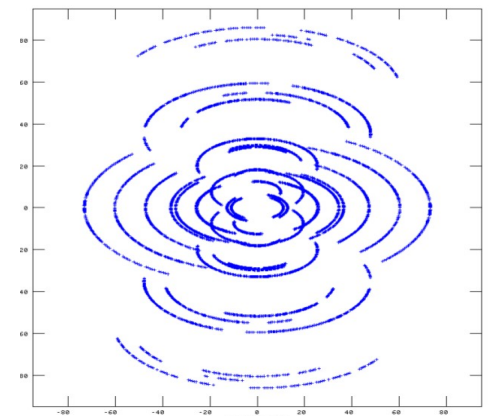
# ALMA array(s)



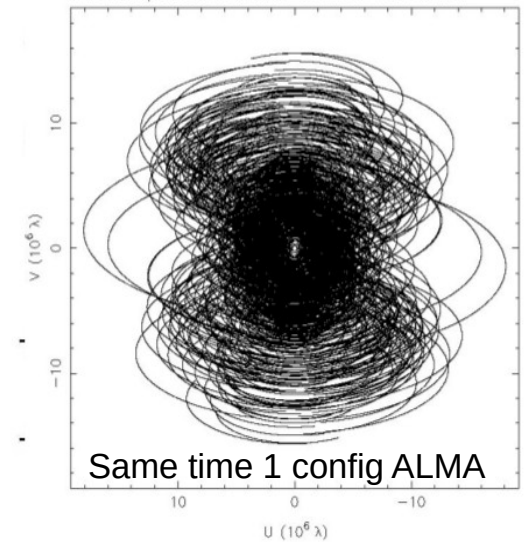
Antennas : **50x12m** main array + **(12x7m + 4x12m TP)** ACA  
 Baselines : **15m ->150m-16km** + **9m->50m**



Few hr 2 config OVRO

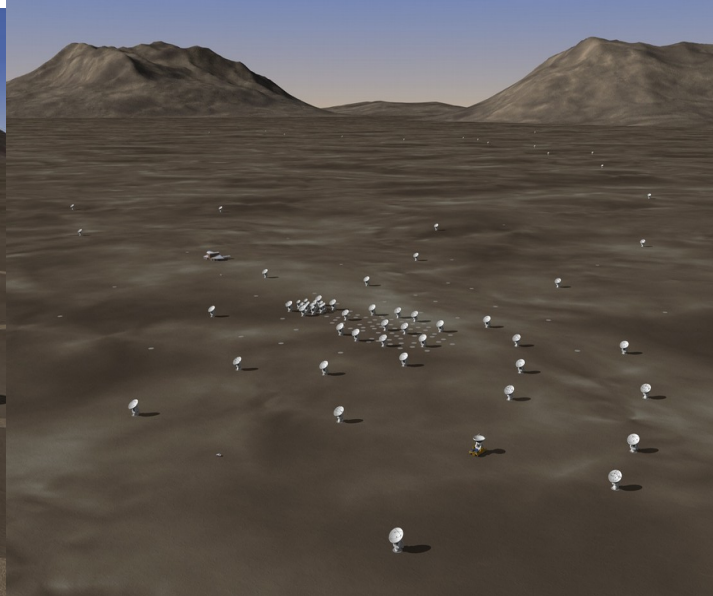
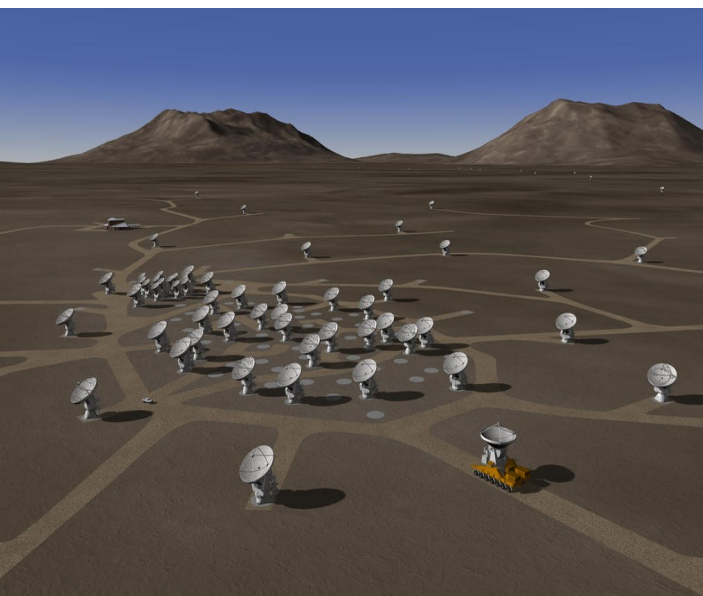
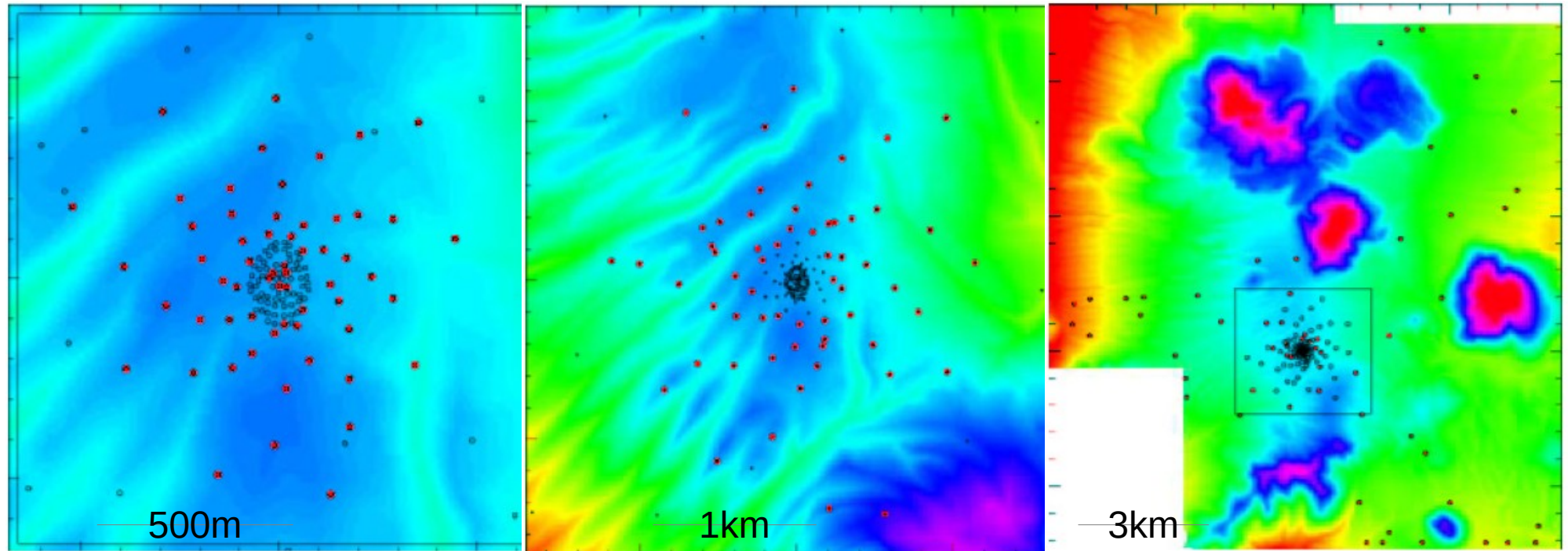


900GHz\_50pc\_ws\_8 at 896.000 GHz in XX 2012 Jun 21



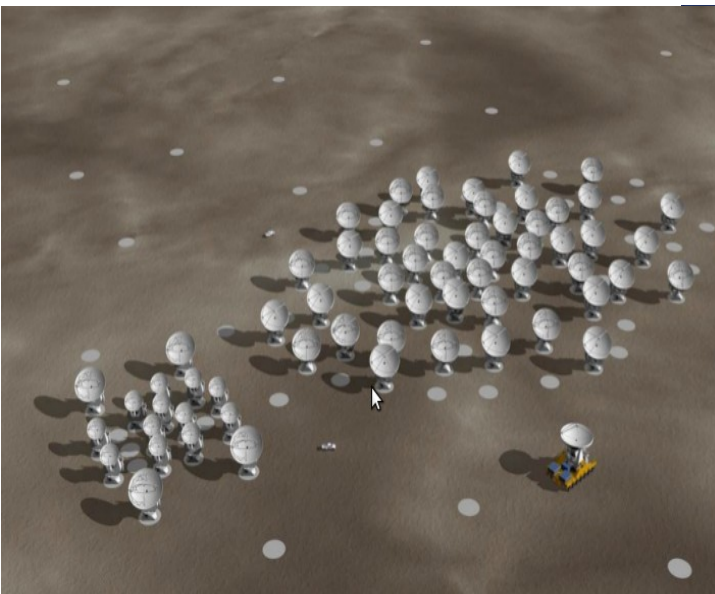
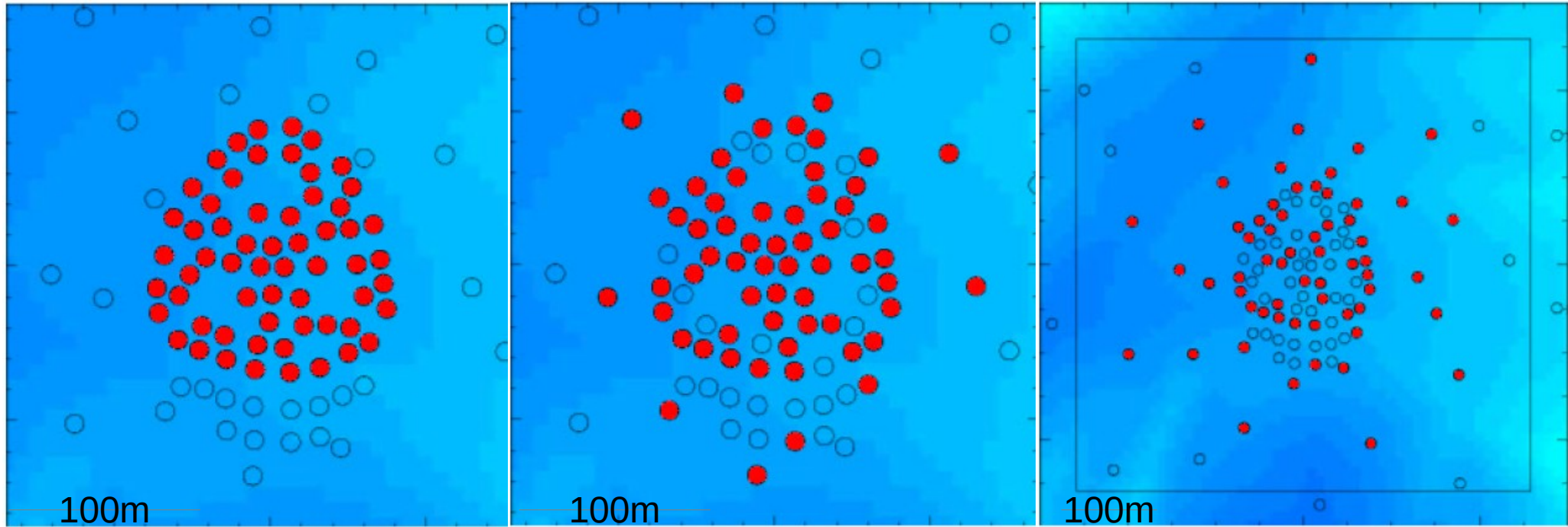


# ALMA reconfiguration



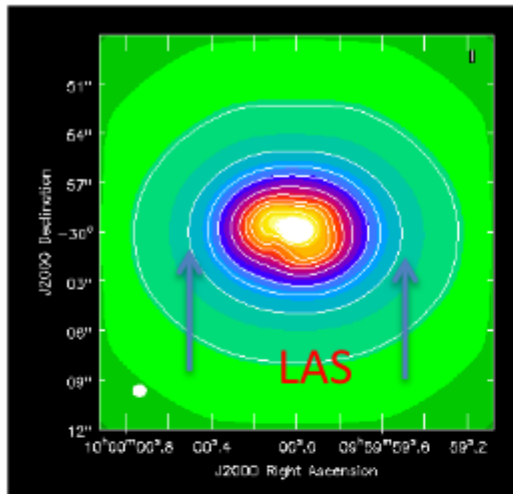


# ALMA reconfiguration



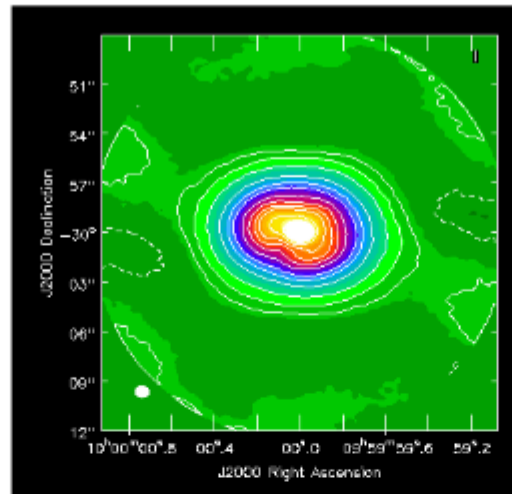
# ALMA array(s)

MODEL



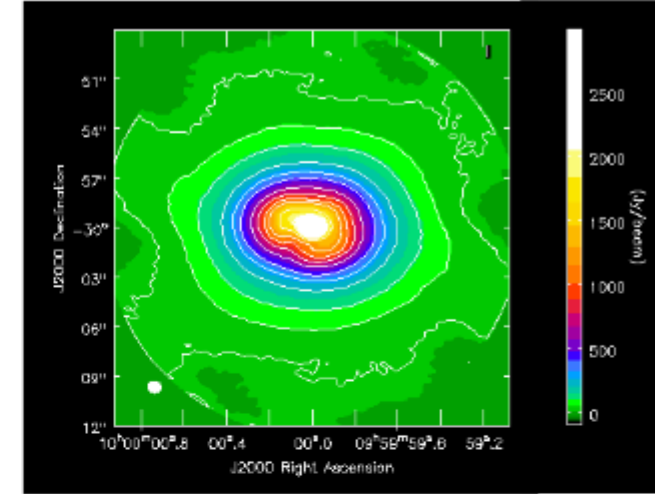
Restored flux 11000 Jy

12-m image



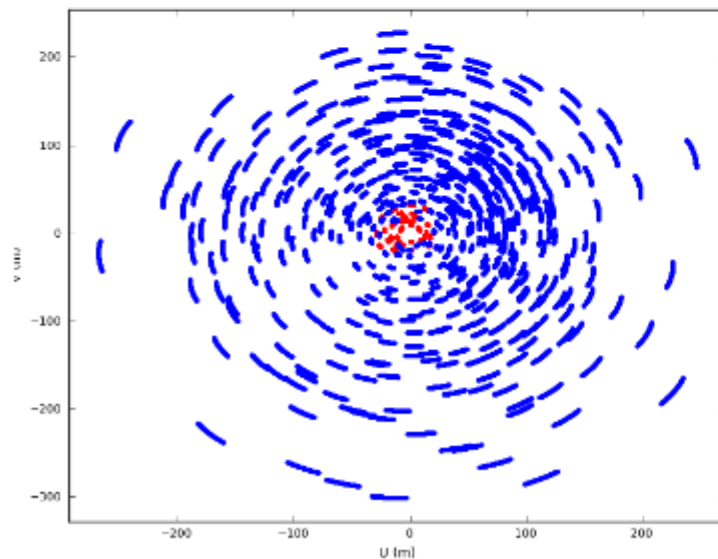
7000 Jy

12m+7m Image



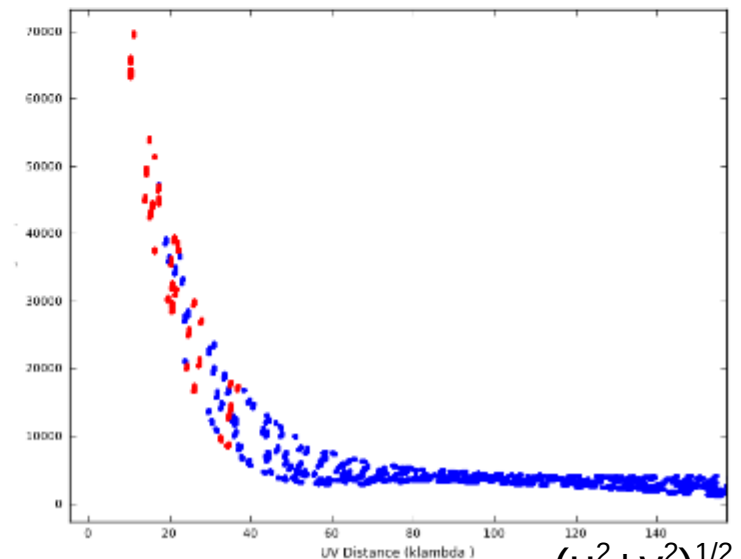
9000 Jy

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



U-V coverage

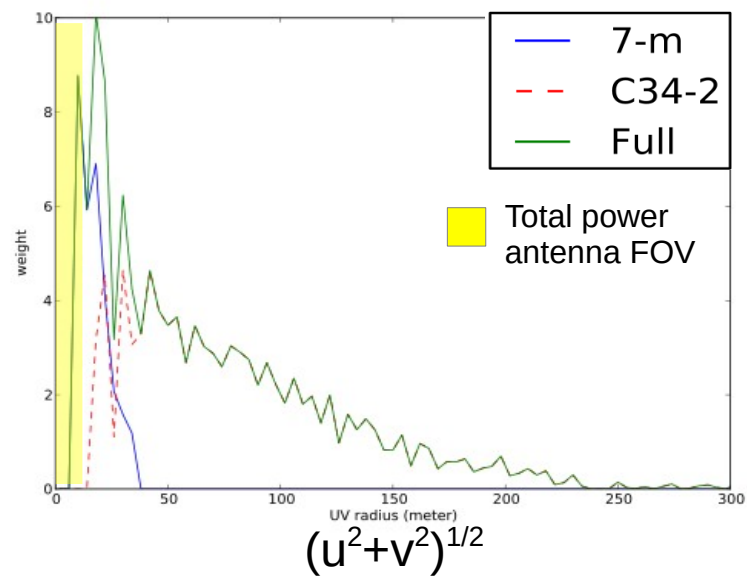
(red=ACA, blue=ALMA12m)



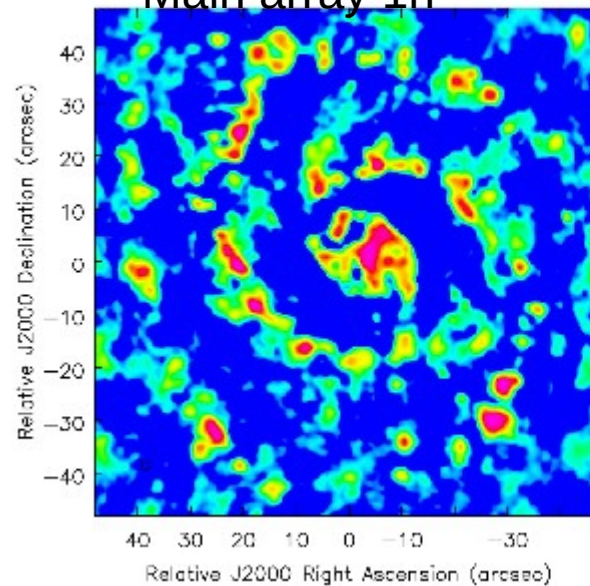
Amplitude vs uv-distance



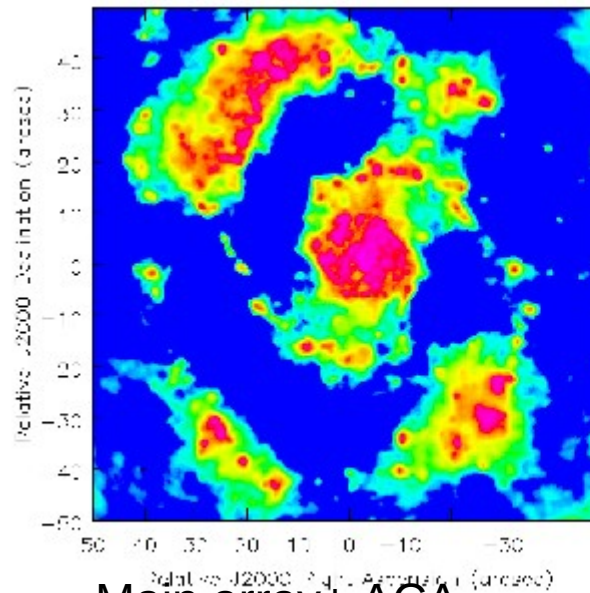
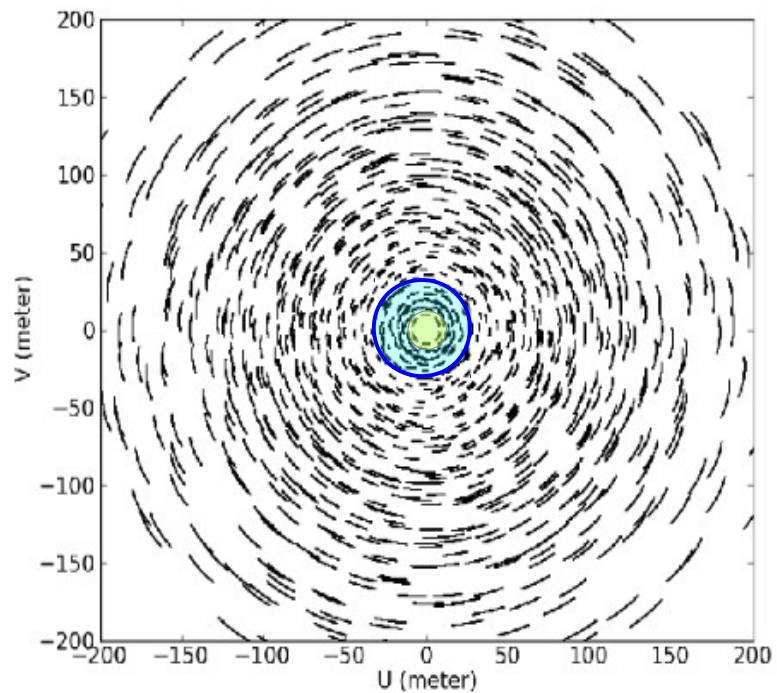
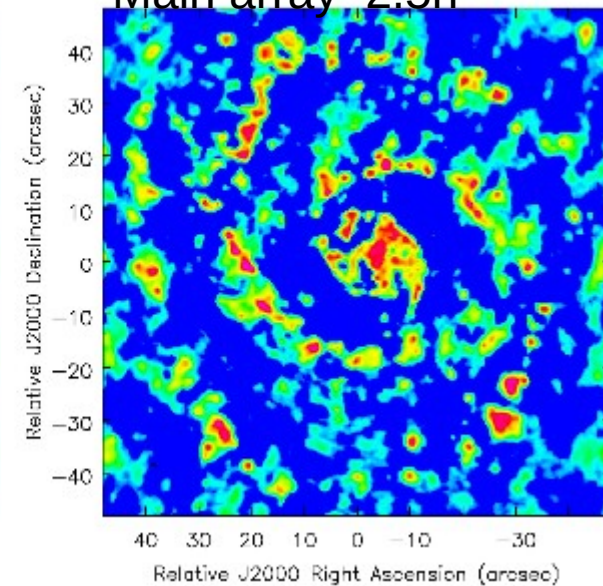
# ALMA array(s)



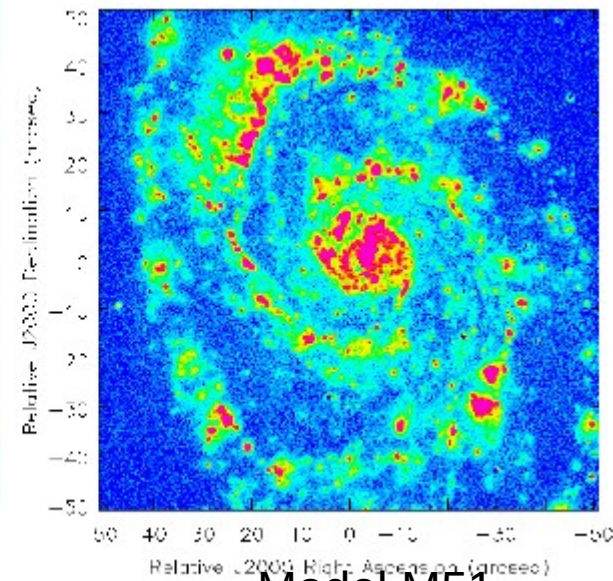
Main array 1h



Main array 2.5h



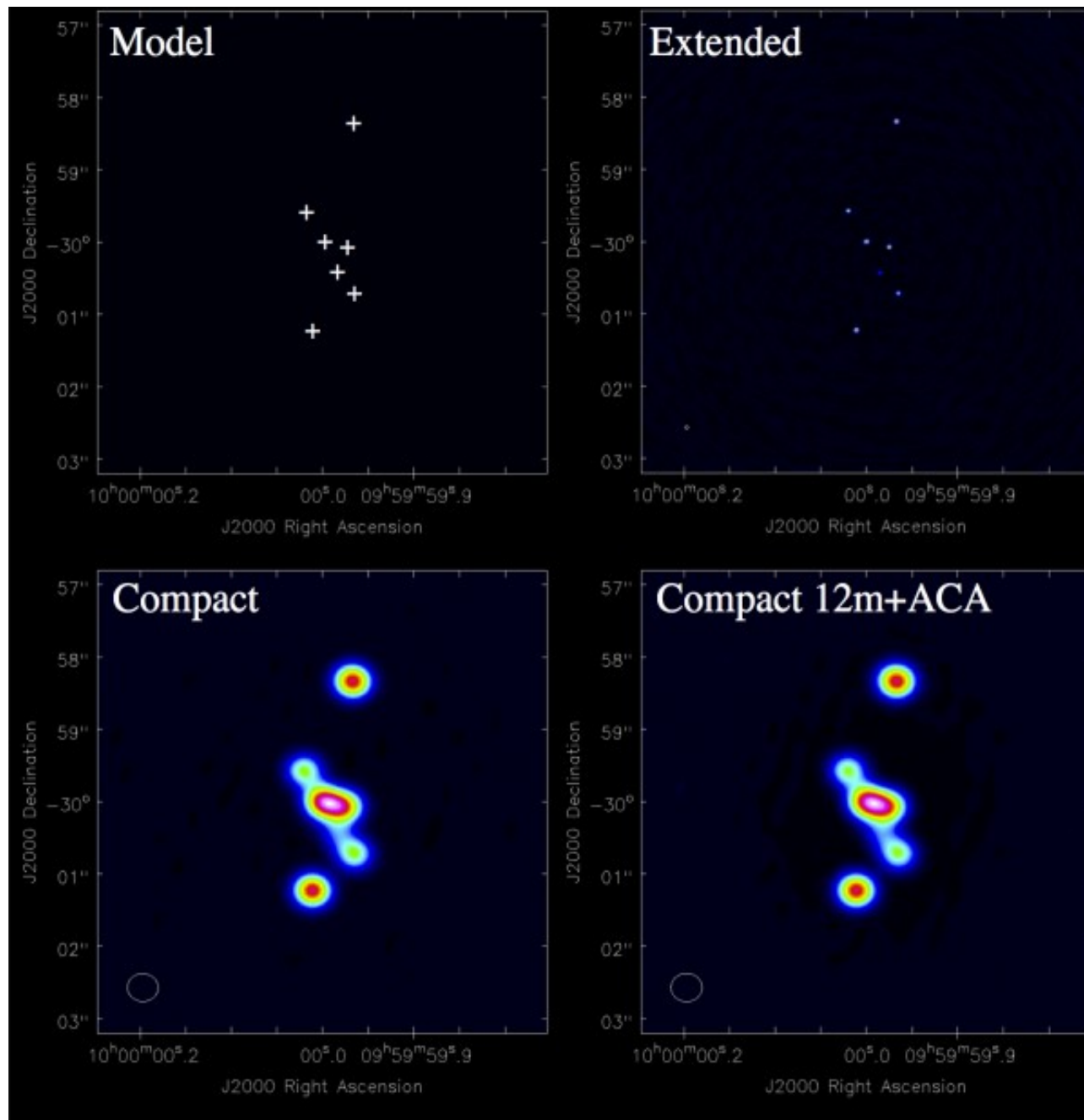
Main array+ ACA



Model M51

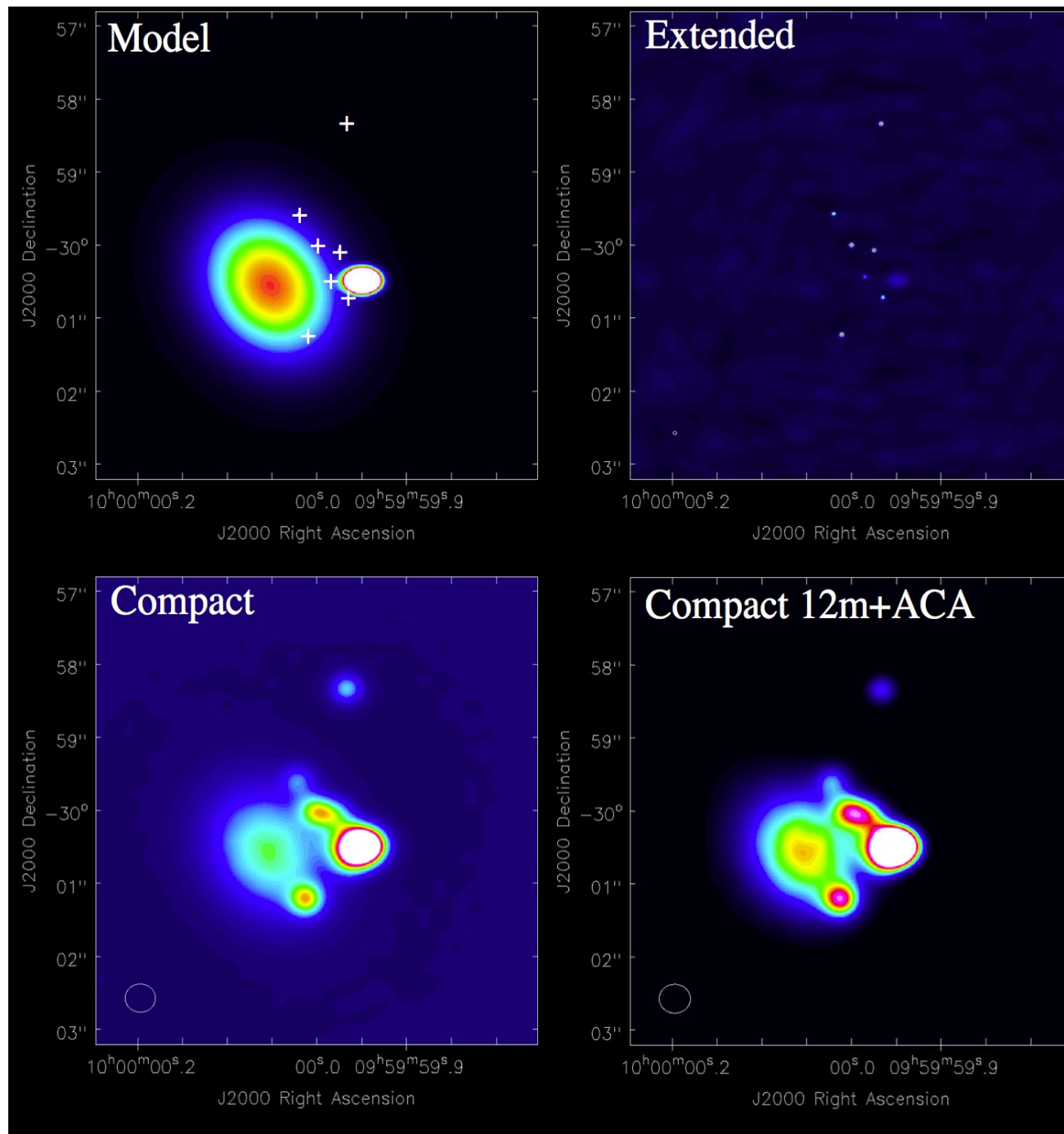
# ALMA array(s)

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





ALMA Regional Centre || UK




ALMA Observation Support Tool

Array	Instrument	ALMA	<a href="#">Queue Status</a> • <a href="#">Help</a>
Sky Setup	Source model	OST Library: Central point source	Choose a library source model or
	Upload a FITS file	<input type="text"/> <a href="#">Browse...</a>	You may upload your own model
	Declination	-35d00m00.0s	Ensure correct formatting of this s
	Image peak / point flux in <a href="#">mJy</a>	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 <a href="#">MHz</a>	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 <a href="#">hours</a>	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



ALMA Regional Centre || UK

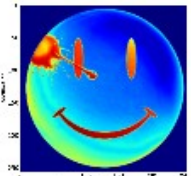
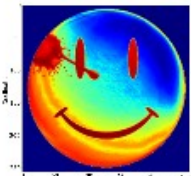


ALMA Observation Support Tool

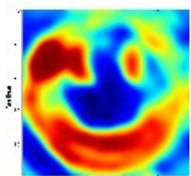
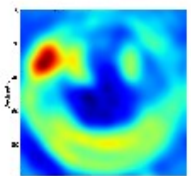
Job ID: 20110330175645 / Submitted by: [casasola@ira.inaf.it](mailto:casasola@ira.inaf.it)

### 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	$T_{\text{sys}} = T_{\text{rec}} + T_{\text{sky}} = 37.0 + 4.42 = 41.42 \text{ K}$
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

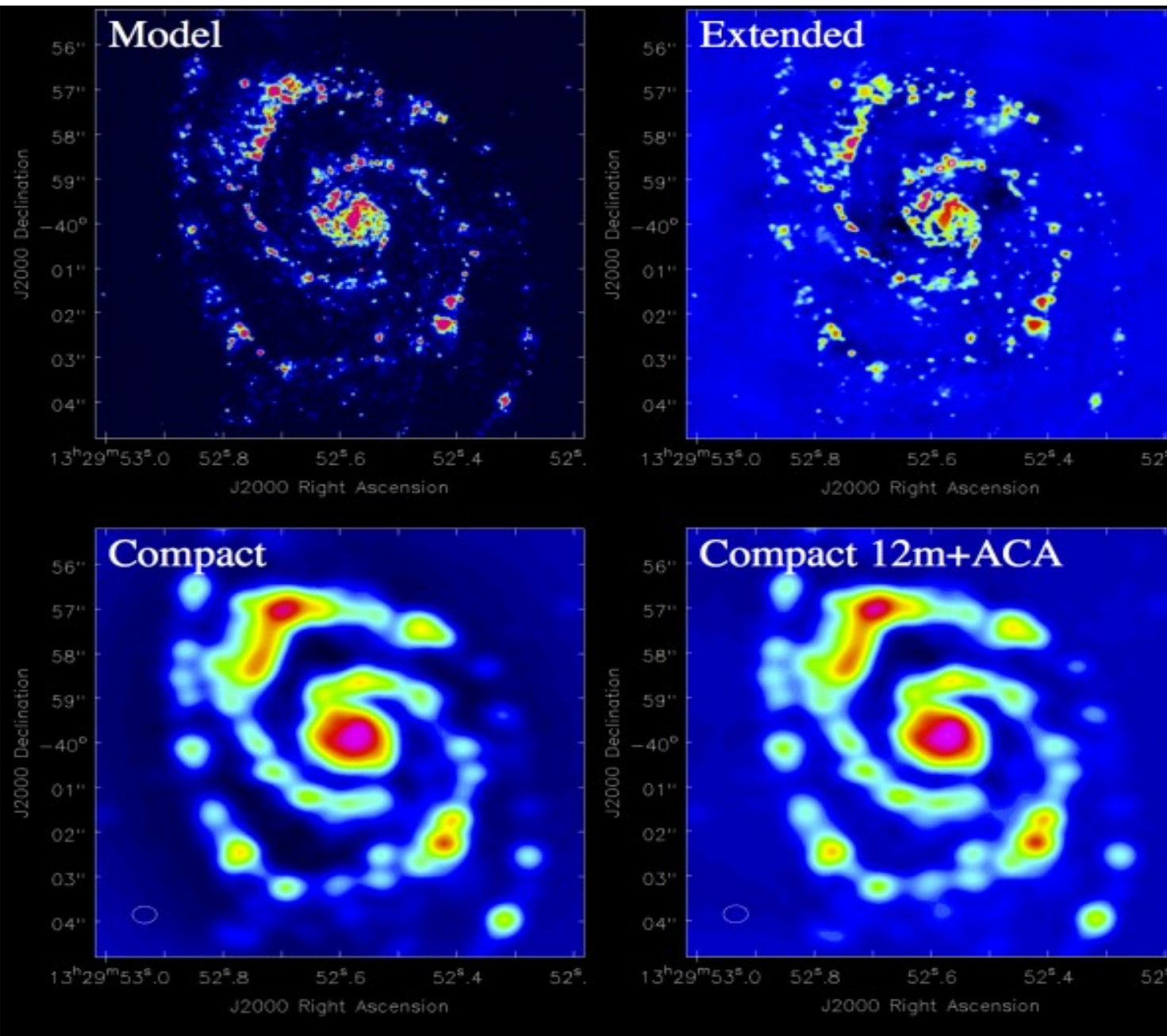
### Data products



Your simulated image  
[Download FITS file](#)



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



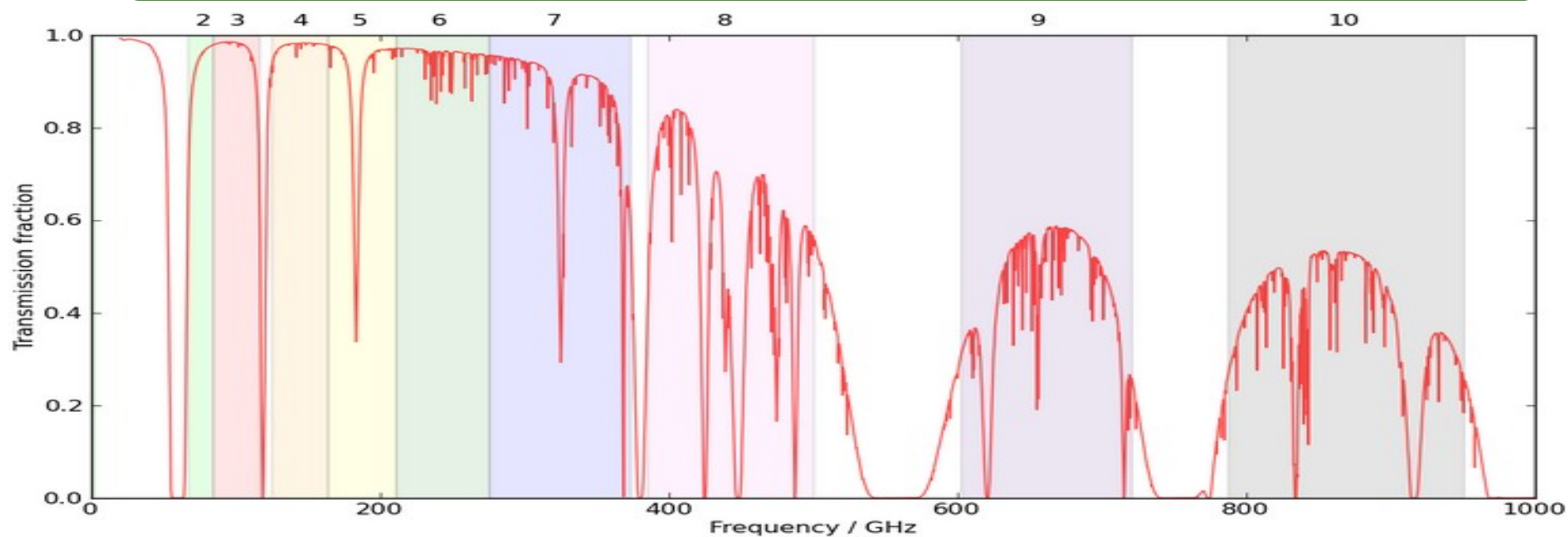
The task **simobserve** generates a data set with simulated visibilities based on an input model image.

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

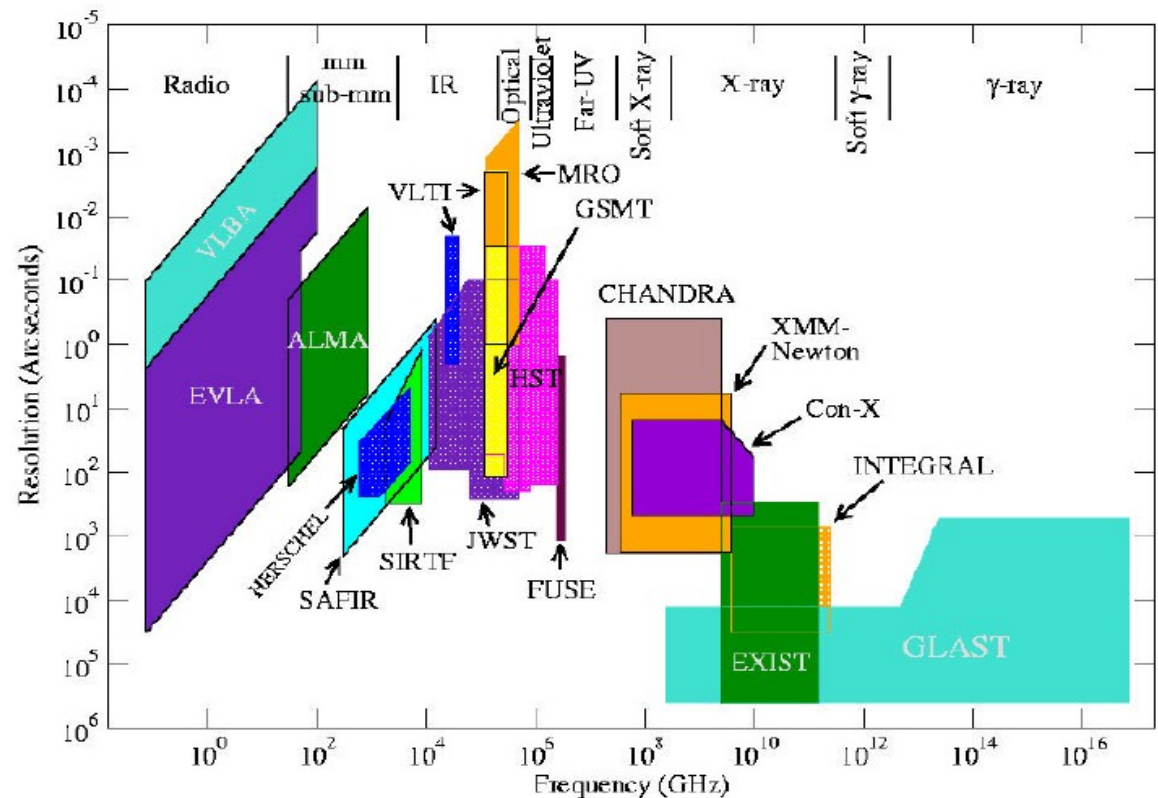


# ALMA resolution

- 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**

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

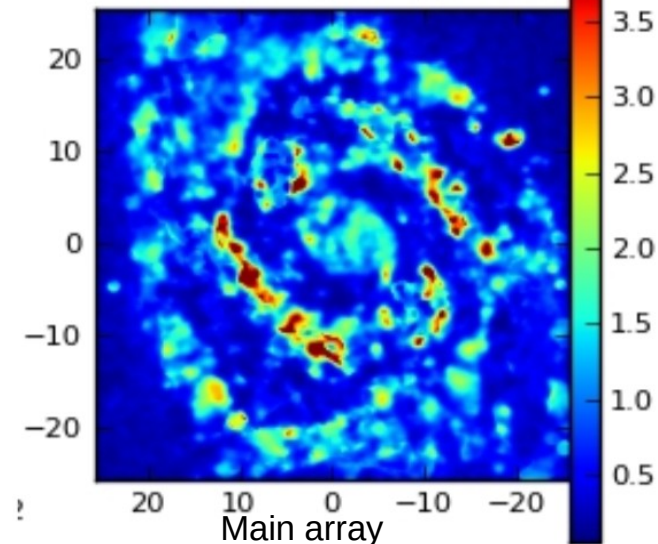




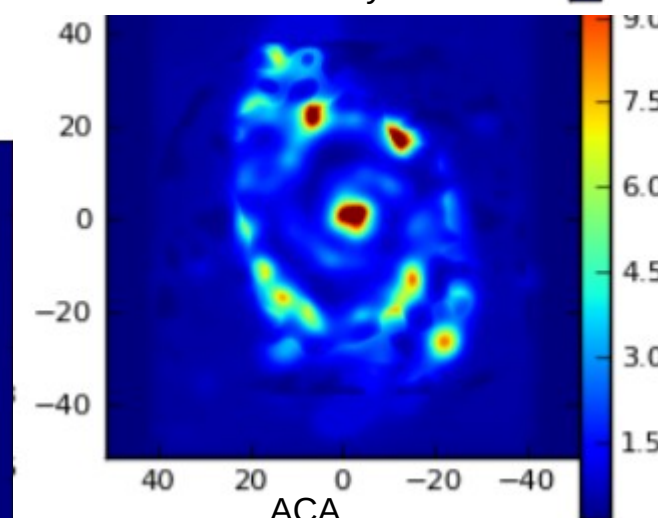
# Mosaicking

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

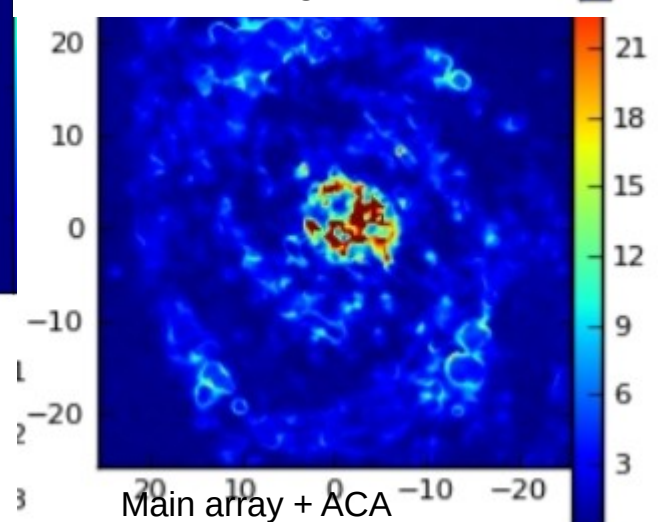
Details in the ranges available to the given baselines can be observed on larger region of the sky by mosaicking the region.



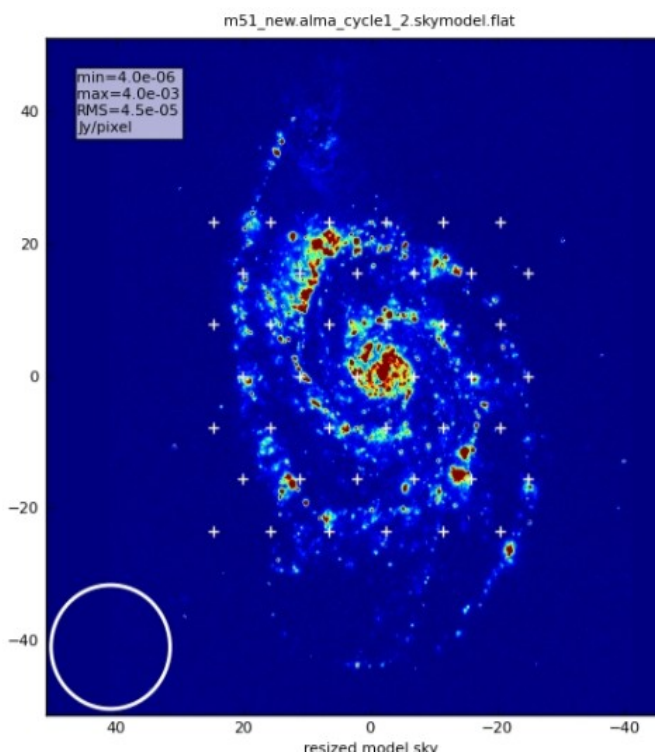
Main array



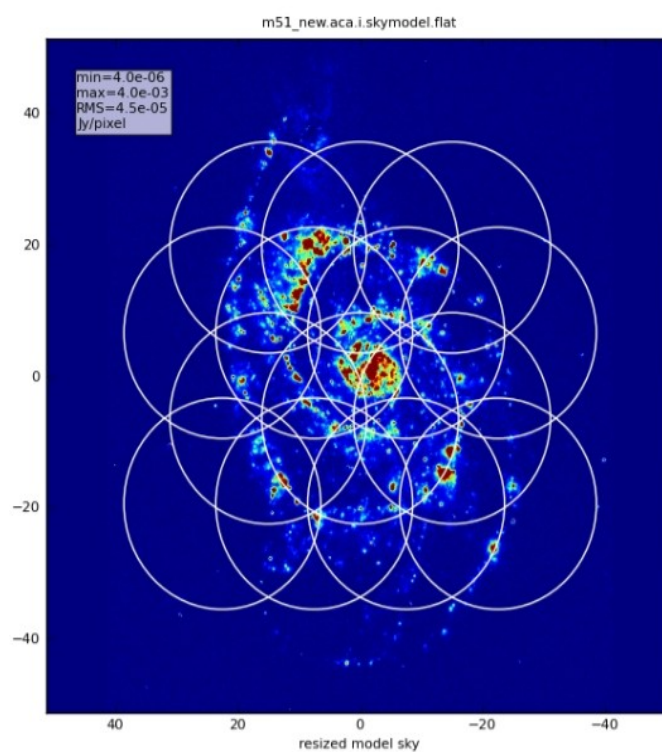
ACA



Main array + ACA



Model & 12m FOV



ACA Pointing map

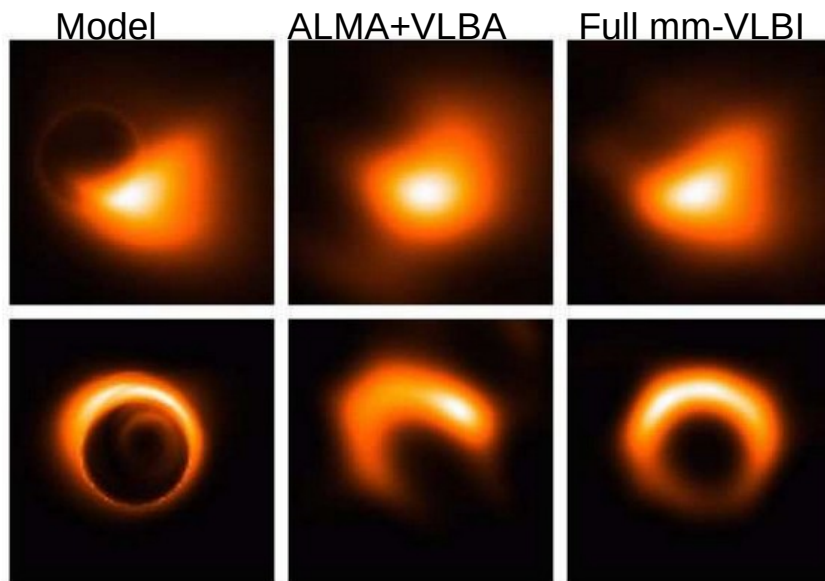
# mm-VLBI with ALMA

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.**

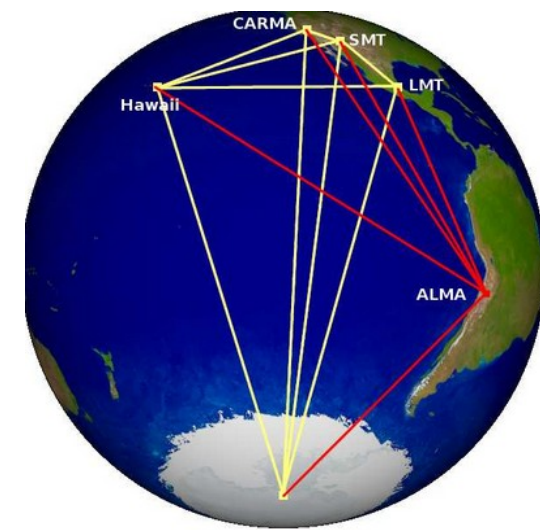
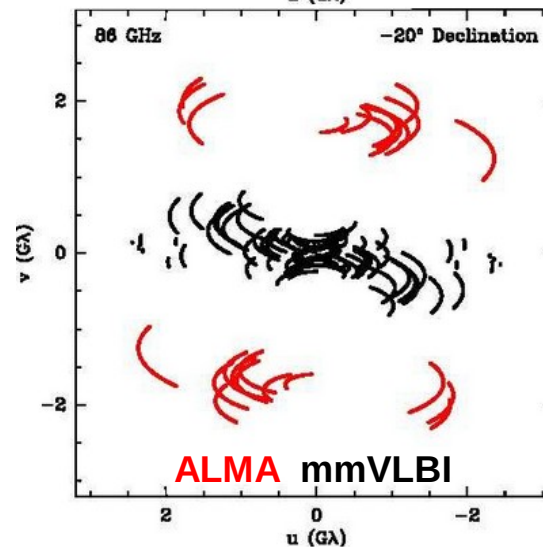
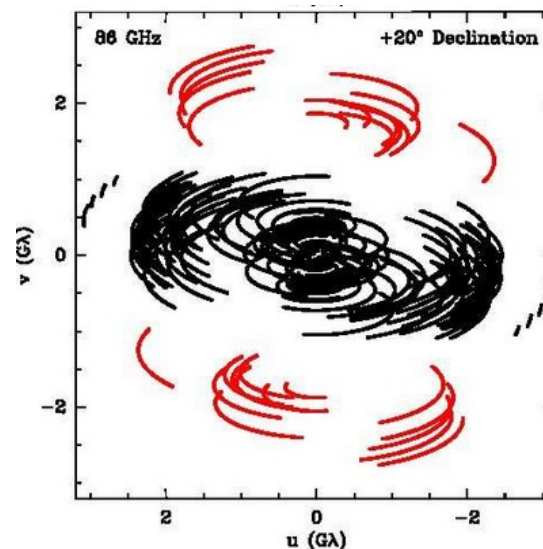
**At 1 mm and a baseline of 9000 km offers resolution of about 20 microarcseconds**

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

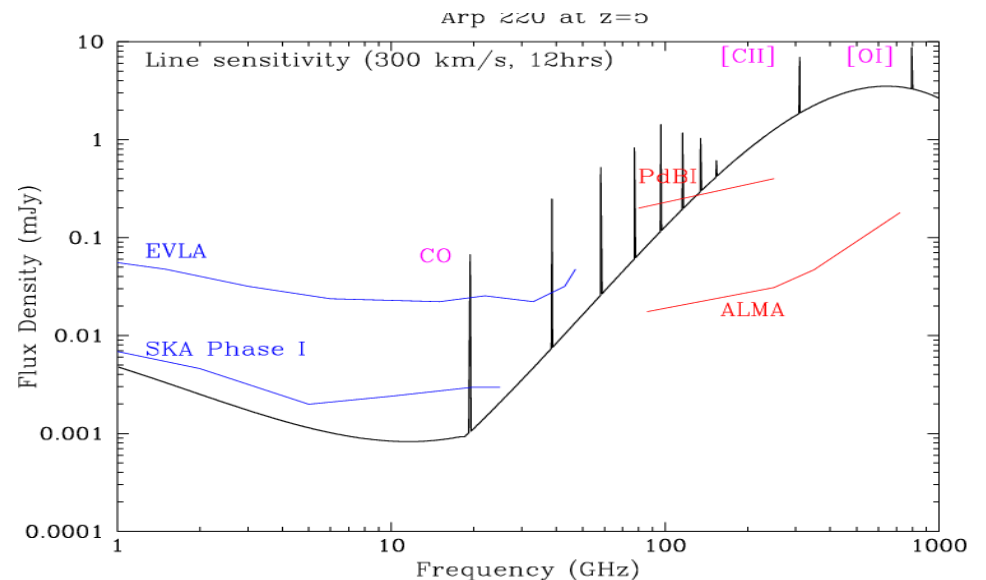
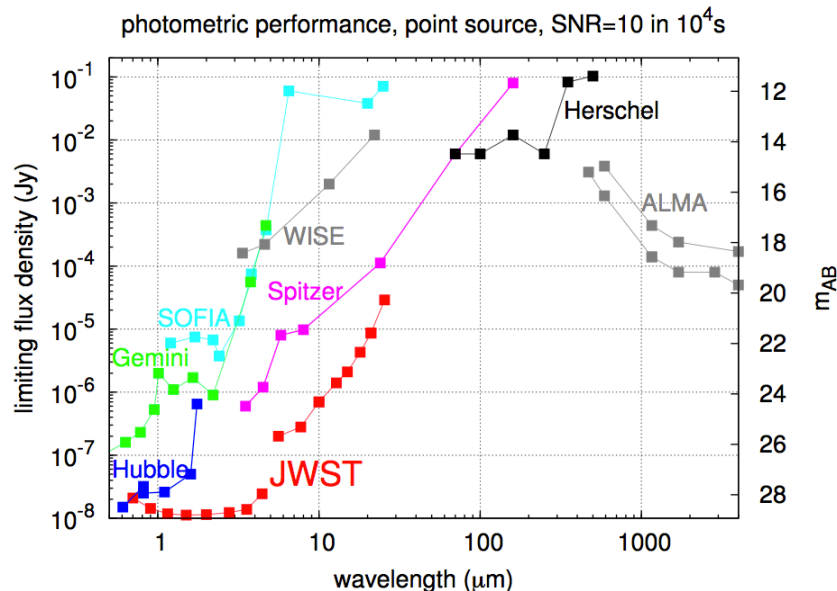
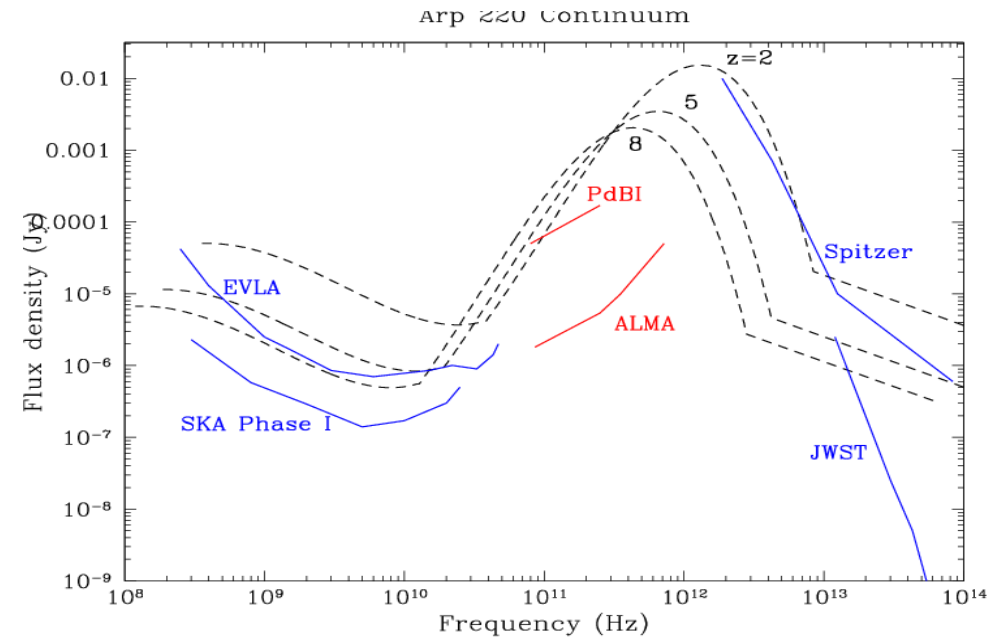
Dry site, low pwv, low Tsys, high sensitivity also at submm frequencies

>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

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

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>

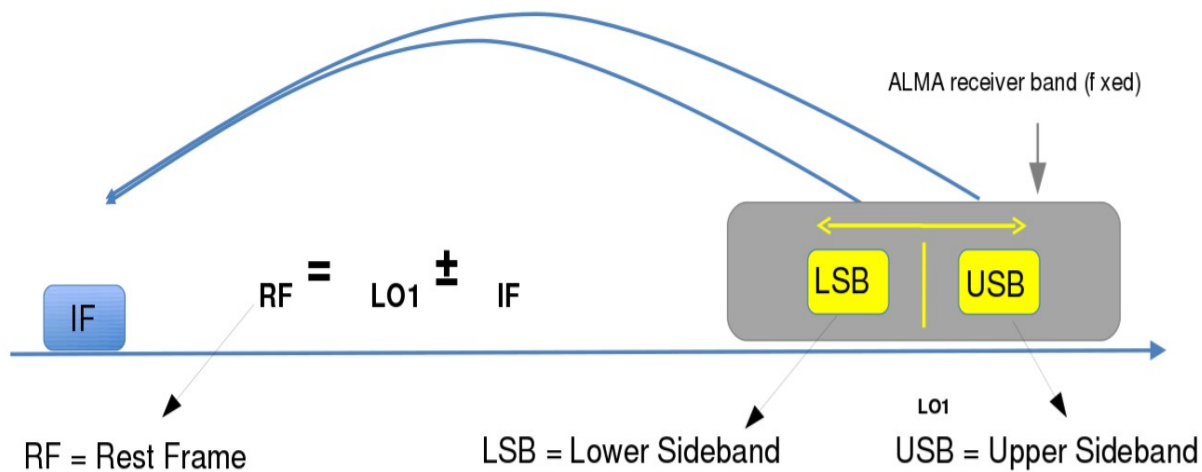
Common Parameters			
Dec	00:00:00.000		
Polarization	Dual		
Observing Frequency	345.00000	GHz	
Bandwidth per Polarization	0.00000	GHz	
Water Vapour Column Density	<input checked="" type="radio"/> Automatic Choice <input type="radio"/> Manual Choice		
tau/Tsky	0.913mm (3rd Octile)		
Tsys	tau0=0.158, Tsky=39.538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

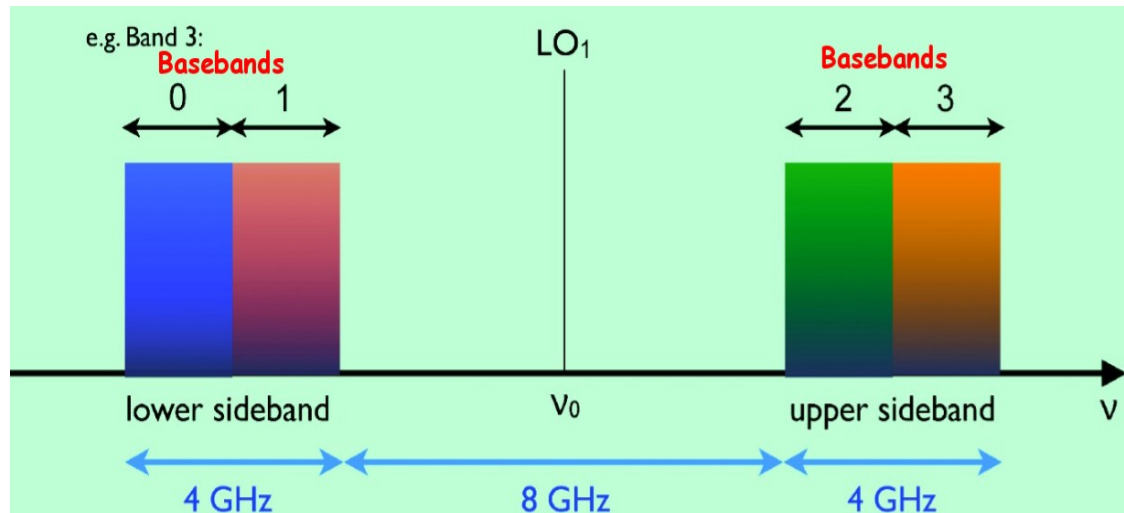
Calculate Integration Time Calculate Sensitivity

# ALMA spectral properties



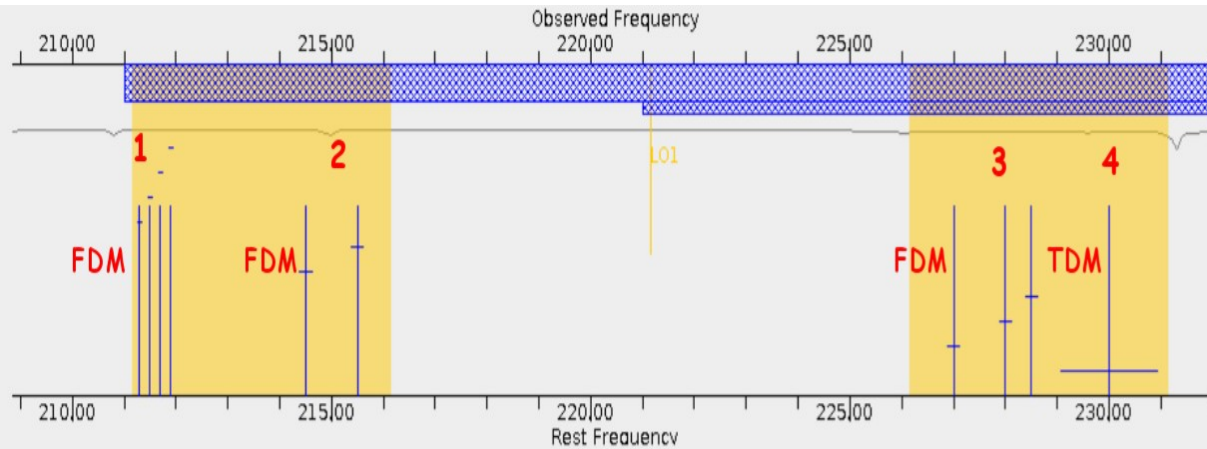
The coherent receivers map two frequency regions to an Intermediate Frequency by mixing the signal with a Local Oscillator.

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

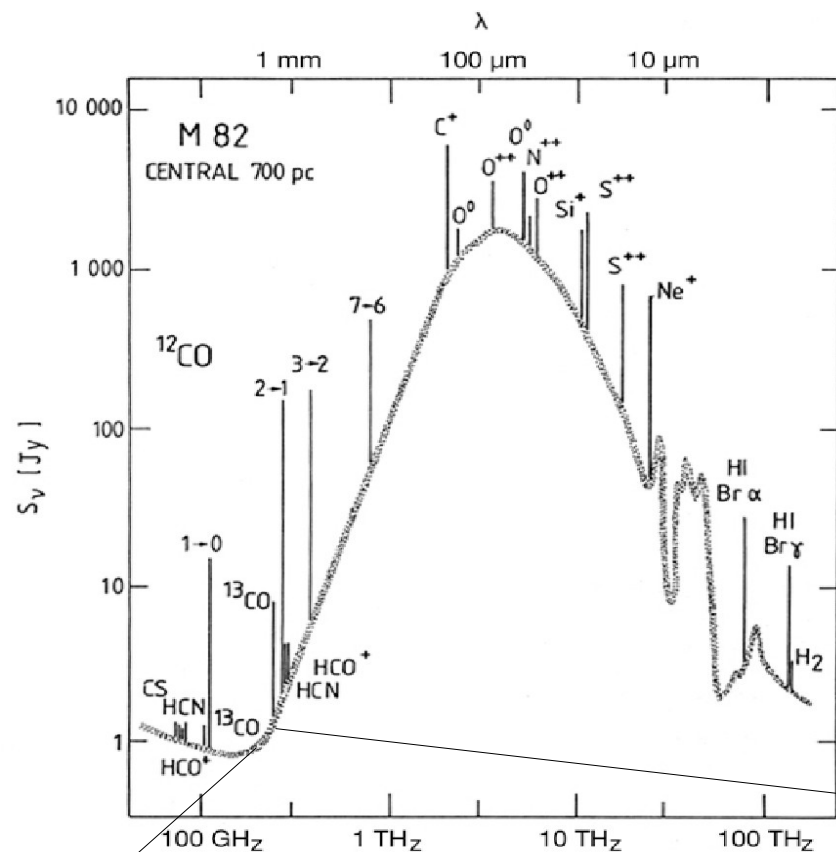
“Continuum” or broad lines

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



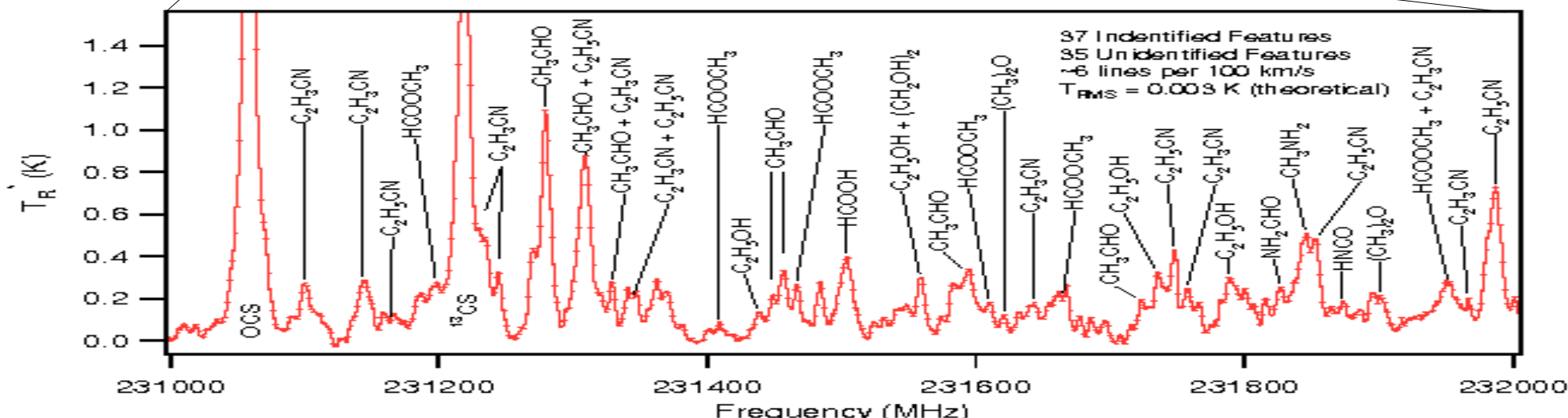
Digital correlators can be set up to different bandwidth and spectral resolution.

Sensitivity is calculated then on 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:

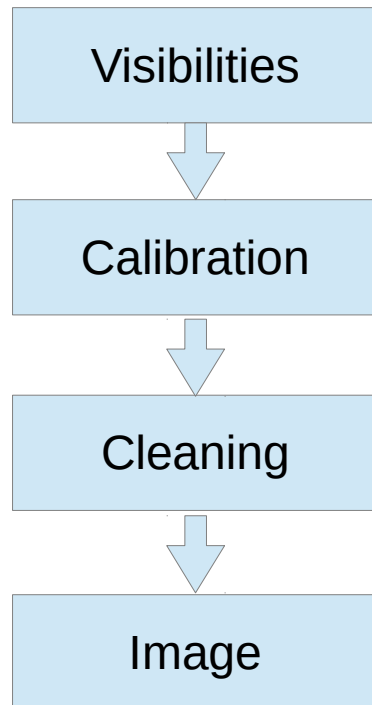
**Interferometers are arrays of coherent reflectors** that can simulate a single dish of size equivalent to the distance between the antennas, **that collect the amplitude and phase of the electromagnetic waves emitted on selected angular scales according to the array configuration.**

**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**.

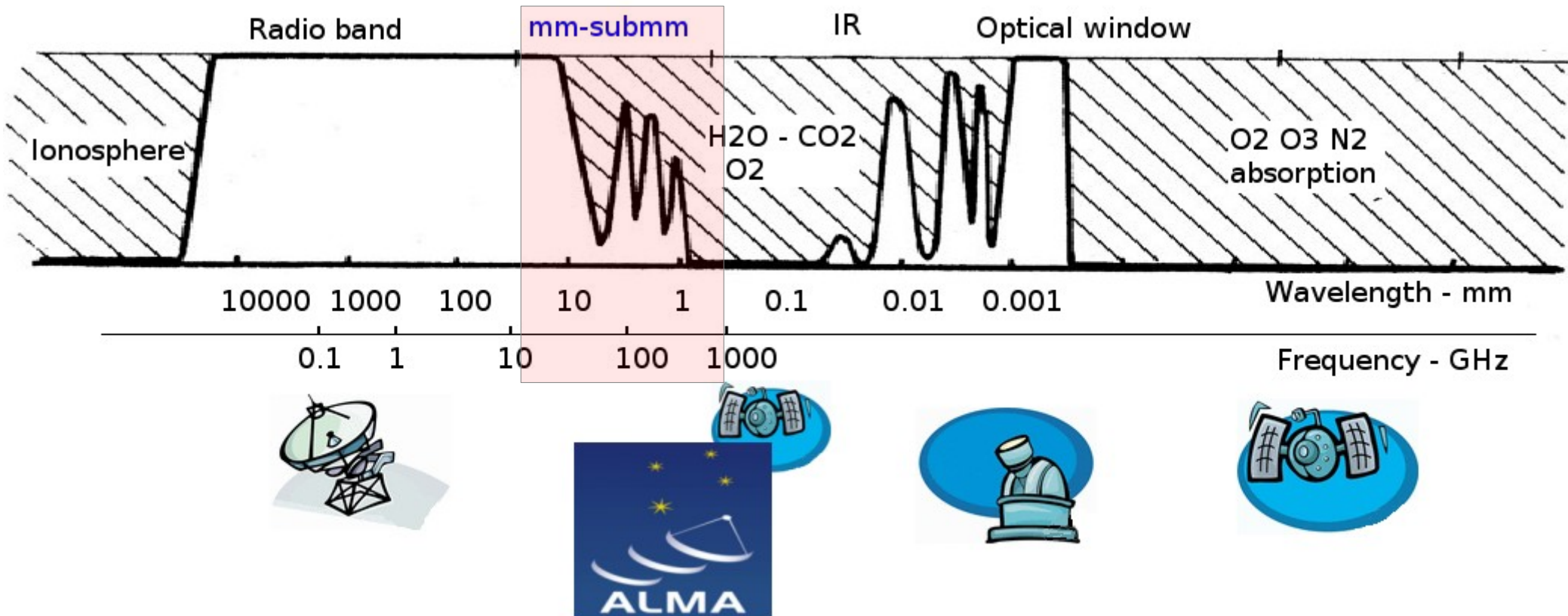
The process to generate an image includes Calibration, Inverse Fourier Transform, Deconvolutions ... too much for this talk, sorry!



For more details about interferometry and ALMA:

- **ALMA School**, Italian ARC, Bologna, 9-12 February 2016 (see [www.alma.inaf.it](http://www.alma.inaf.it))
- Thompson, Moran, Swensson, *"Interferometry and Synthesis in Radio Astronomy"*

# Outline



Signals:

Synchrotron  
Dust  
Molecular lines

Observing instruments:

Interferometers (ALMA)

Science cases

Observing processes:

Proposal and archives



# Tips to write a proposal

# The proposal review process

## **Proposals will be reviewed by an international peer review committee.**

The peer review by committee is a group of hopefully well informed peers examines your proposal, ranks it against other proposals, and then allocates resources to the highest ranked proposals.

There will at least one Review Panel for each of the **main themes**:

Cosmology and the High Redshift Universe

Galaxies and Galactic Nuclei

ISM, Star Formation/protoplanetary Disks and their Astrochemistry, Exoplanets

Stellar Evolution, the Sun and the Solar System

The ranked proposals from the different panels and sub-panels will be merged into a single ranked list in the ALMA Proposal Review Committee (APRC) and assigned a letter grade A through D:

A the proposal will be carried over to the following cycle if it is not finished

B the proposal should be finished during the current cycle but will not be carried over to the next cycle.

C are 'filler' programs observed when no A or B can be scheduled

D proposals will not be observed.

Now, this process is NOT perfect,

**BUT it is NOT a lottery, or fundamentally flawed and/or fixed.....**

**DO NOT let that idea impact on how you write ..**

**Everything you can do to give your proposal a broader context, make it easier to read, more enjoyable, more clear, ... all will help your chances**

# What should a proposal look like?

- Should have a good, readable **“Executive Summary”** that sets the research in context, sets out the big issues in a field, says what you will do, and how the results from that will address the big issues.
- Should have a **well set out background** that expands on the context and big questions in the field.
- Should clearly **explain why the observations you propose are critical** for answering those questions
- Should clearly **demonstrate the observations / research is technically feasible**, that the time / resources requested are appropriate
- Should clearly **demonstrate that your team will be able to do the work**, and/or has a track-record for having done similar work in the past.
- Should include **“only” useful figures**
- **Must be readable and should be pleasurable to read.**

# The technical justification

**The Technical Justification** should fully justify the technical aspects of the requested observations and should address the following aspects:

- **sensitivity**
- **resolution**
- **array configuration**
- **imaging**
- **correlator setup**
- **calibration**
- **scheduling/time constraints**
- **special constraints on standard observing mode**
- **any non-standard choices**

The technical justification must be very, very clear – say what your assumptions, required S/N, number of pointings etc are, so your reasoning can be reproduced by the technical assessors.

Try to know/understand the telescope or ask to someone who knows it

# What to never do

- Do not ignore the grading or funding criteria.
- Don't submit proposals that are badly written – if English is not your first language, get a collaborator to proof read or rewrite it for you.
- Don't ask for the wrong instrument, the wrong amount of time, or the wrong semester.
- Don't rage at the panels - its not their fault they didn't have enough money or telescope time last time
- Don't waffle - less is more
- **Don't use jargon & acronyms**
- **Don't assume everyone knows this scientific area is the most compelling thing ever done.**

## Few tips

- **Tell a story.** Make your proposal and enjoyable narrative that leads the reader from point to point.
- **“Close the Loop”**
- **Frame your project as an experiment** (“Hypothesis and Testing”) rather than data gathering.
- Think seriously about the risks of a “new class of object” discovery project.
- Avoid the evil “Constrain”
- **The more you “quantify” the better you get the point** (i.e. avoid generic “more, much, less, few” but give numbers to give the idea that you have already dirty hands on the matter)

RS  
RV  
VLM  
SMBH  
AGN  
FIR

FR II  
ULIRG  
ERO  
SMG

CDFS  
PCCS  
EMU  
WALLABY  
POSSUM  
DINGO  
APEX  
SCUBA  
WTHDIM



# Ask yourself...

- Would you want to read this proposal? Late at night? On a plane? Along with 80 others just like it?
- Would you be able to read and understand this proposal in under 5m per page?
- Can you FIND the main points in the proposal without reading the whole thing in all its gory detail?
- Imagine its your hard earned money, would you pay for this project?

**It's not the reader's job to understand your proposal  
... its your job to make them understand it.**

**Readers are looking for enjoyable,  
understandable proposals to read that  
present innovative ideas for new research**

# A project lifetime: phase 1 Proposal submission

PI has a good idea!

PI estimates **feasibility**

PI splits project in **Science Goals**

PI writes the science case in pdf  
and register to the Science Portal

Simulations are not compulsory  
(Sensitivity Calculator, OST, CASA)

**Minimum proposed observational unit including targets  
in the same sky region that roughly share the same  
calibration and spectral setup**

Max 4 page, font no smaller than 12, all included (<20MB)  
[www.almascience.org](http://www.almascience.org)

## PHASE I – Proposal submission

TAC evaluation

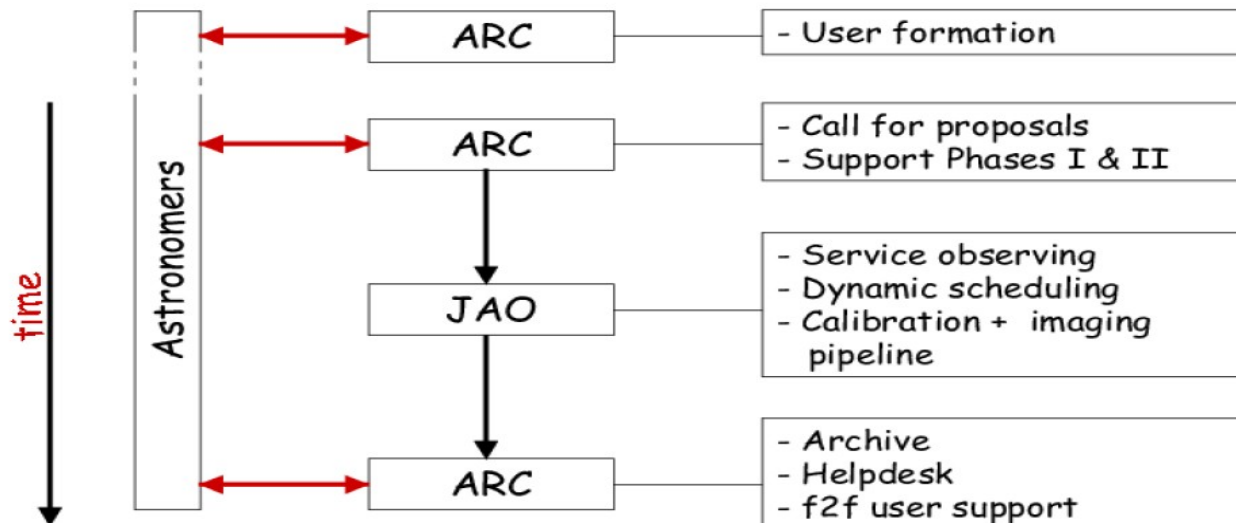
With the ALMA Observing Tool (OT)

A copy of the project with the project ID must be saved  
and should be used for any resubmission within the deadline

**A**=high ranked pass to Cycle 4 if not finished

**B**=high ranked but not passed over

**C**=maybe filler (depends on time shares and ranking)



# The ALMA Observing Tool

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ALMA Data

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## Observing Tool

The ALMA Observing Tool (OT) is a Java application used for the preparation and submission of ALMA Phase I (observing proposal) and Phase II (telescope runfiles for accepted proposals) materials. The current Cycle 0 release of the OT is configured for the Early Science Capabilities of ALMA as described in the [Cycle 0 Call For Proposals](#). Note that in order to submit proposals you will have to register with the ALMA Science Portal beforehand.

### Download & Installation

The OT will run on most common operating systems, as long as you have Java installed (and no known problems). The ALMA OT is available in two flavours: WebStart and tarball.

The **WebStart** application has the advantage that the OT is automatically downloaded and installed. Note that the WebStart does not work with the OpenJDK Linux installations. If this is the case, the tarball installation of the OT should be used.

The **tarball** must be installed manually, however it has the advantage of being able to run on older versions of Java 6. For Linux users we also provide a download of the tarball. Please use this if you have any problems running the OT tarball installation.



### Webstart Download Page

**First Time Users:** When you use the ALMA OT Webstart for the first time, it will download a large amount of shared resources (on the order of 130 MB) to your host, taking a few minutes to do so. This will only happen the first time, or when a revised version of the OT is released. Subsequent use of the OT will be much faster.



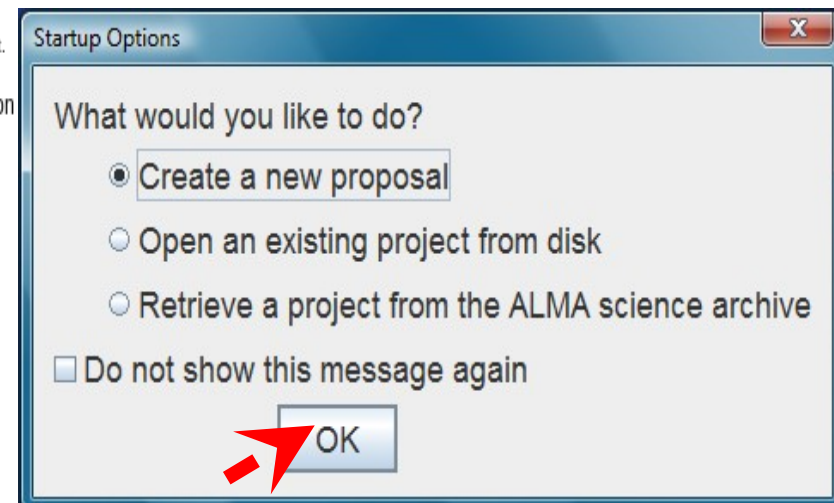
Click the OT Logo to bring up a download window, which should give you the option of saving the OT to your Desktop if you will be using it regularly.

### Documentation

Extensive documentation is available to help you work with the OT and optimally prepare your proposal:

**OT is a java-based client program,**  
runs on Linux (various distr.),  
MacOS (10.5-10.6), Windows (>XP).

The graphic interface allows one to get help/feedback and hints even with small knowledge of the system.



# Proposals with the ALMA Observing Tool

My new idea - Observing Tool for ALMA (Early Science), version R8.0.1

File Edit View Tool Search Help

Perspective 1

**Project Structure**

Proposal Program

My new idea

- My new idea
  - Proposal
    - Planned Observing
      - Science Goal ()
        - Description
        - Field Setup
        - Calibration Setup Parameters
        - Spectral Setup
        - Control and Performance Parameters

**Template library. Turn the keys on the JTree below & read the**

- Template library. Turn the keys on the JTree below & read the
  - Proposal
    - Planned Observing
      - Science Goal (Band 3 100 GHz (rest frame) d
      - Science Goal (Band 3 Nyquist-sampled mosa
      - Science Goal (Band 6 Mixed 219 GHz SSB Co
      - Science Goal (Band 6 13CO J=2-1 mapping c
      - Science Goal (Band 6 Mixed simultaneous 12
      - Science Goal (Band 9 700 GHz search for pat

**Editors**

Spectral Spatial Proposal Catalog

Tab menu for viewer

Proposal Information

Proposal Title: My new idea

Proposal Cycle: 9999.4

Abstract (max. 300 words)



**Feedback**

Problems Information Log

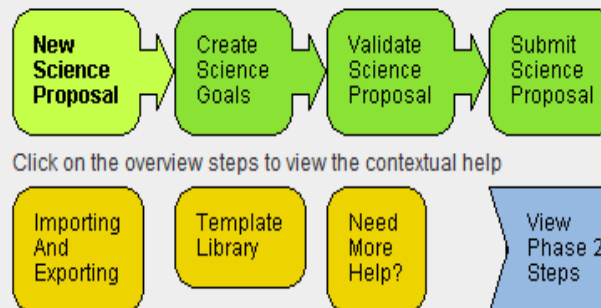
Description	Suggestion

## Project Overview Panel

Contextual Help

1. Please ensure you and your co-Is are registered with the [ALMA user portal](#)
2. Create a new proposal by either:
  - Selecting *File > New Proposal*
  - Clicking on the  icon in the toolbar
  - Or clicking on this [link](#)
3. Click on the  [proposal](#) tree node and complete the relevant fields.

Phase I: Science Proposal



(see Viviana & Rosita's talks)



# Early Science Cycles

Early Science observations are conducted on a best effort basis  
to allow community to observe with incomplete, but already superior array,  
with priority given to the completion of the full ALMA capabilities

## Past & current ALMA Early Science cycles:

	<b>Cycle 0</b> Sep. 2011 - Jan. 2013	<b>Cycle 1</b> Jan. 2013 - May. 2014	<b>Cycle 2</b> Jun. 2014 - Oct. 2015	<b>Cycle 3</b> Oct 2015 - Oct 2016
<b>Telescope</b>				
Hours dedicated to Science	<b>800</b>	<b>800</b>	<b>2000</b>	2100
Antennas	<b>&gt; 12x12-m</b>	<b>&gt; 32x12m +9x7m+2TP</b>	<b>&gt; 34x12m +9x7m+2TP</b>	<b>&gt; 36x12m +10x7m+2TP</b>
Receiver bands	3, 6, 7, 9	3, 6, 7, 9	<b>+4, 8</b>	<b>+10</b>
Wavelengths [mm]	3, 1.3, 0.8, 0.45	3, 1.3, 0.8, 0.45	+2, 0.7	
Baselines	up to 400 m	<b>up to 1000 m</b>	<b>up to 1500m</b>	<b>up to 10km</b>
Polarisation	single-dual	single dual	<b>full</b>	<b>full</b>
<b>Proposal outcome</b>				
Submitted	917	1133	1381	1578
Highest priority	112	198	354	402
Filler	51	93	159	236
Success rate	12% (18%)	17% (25%)	26% (37%)	25% (40%)

## Pressure factors (highest priority projects)

- Cycle 1: Europe: 9.1 (global ALMA: 5.8)
- Cycle 2: Europe: 4.9 (global ALMA: 3.9)
- Cycle 3: Europe: 6.2 (global ALMA: 3.9)

# ALMA Cycle 4

Proposal submission deadline 21 April 2016

Oct 2016 -  
Oct 2017

## Telescope

Hours dedicated to Science  
Antennas

2100

> 40x12m  
+10x7m+3TP

Receiver bands  
Wavelengths [mm]

3,4, 6,  
3, 2, 1.3,

7,  
0.8,

8, 9, 10  
0.7, 0.45, 0.35

Baselines

up to 12.8km,  
full (with some limitations)

5.3km,

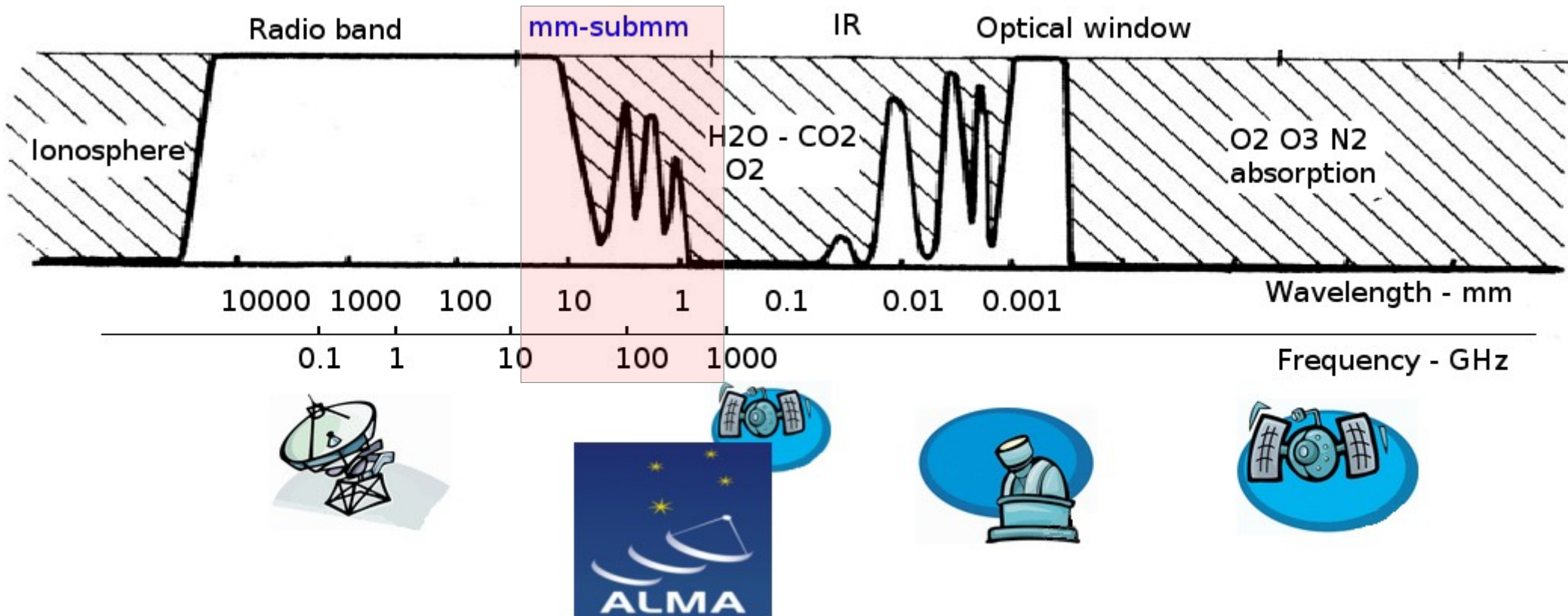
2.7km

Polarisation

## News

- ACA standalone
- Large programs (>50hr of observations not splittable in smaller programs)
- mmVLBI
- Solar observations

# Outline



**Signals:**

**Synchrotron  
Dust  
Molecular lines**

**Observing instruments:**

**Interferometers (ALMA)**

**Science cases**

**Observing processes:**

**Proposal and archives**