mm-Astronomy: a review of (sub)mm band science and instruments in the ALMA era

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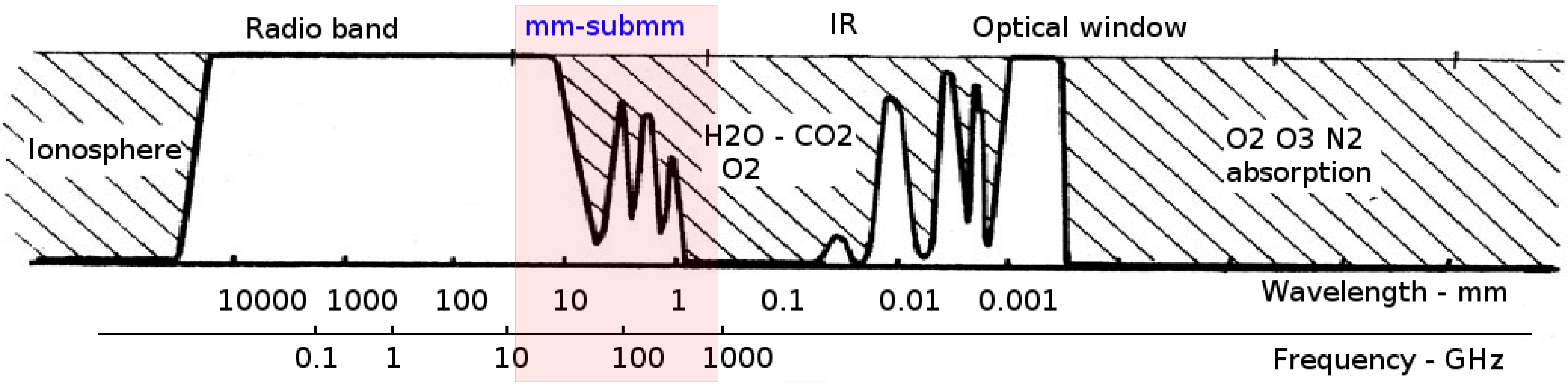
EUROPEAN ARC
ALMA Regional Centre || Italian

SISSA – May 2019

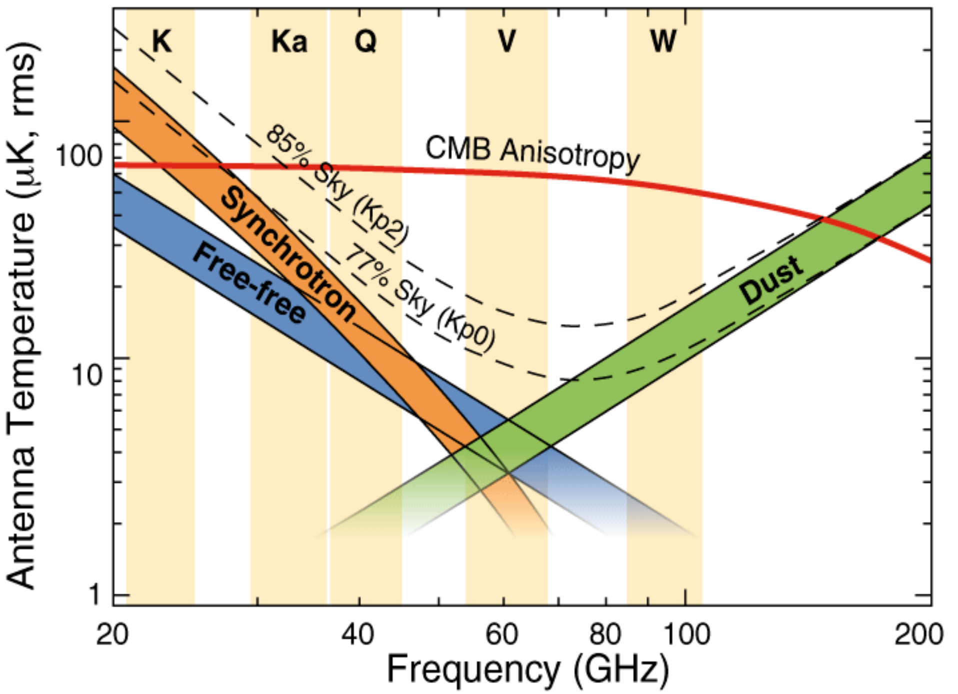
Why should I go (sub)mm?

The signals



The (sub)mm band ranges between 30-1000 GHz

- **CMB:** mm includes the “cosmological windows”
- **Synchrotron:** peaking at radio bands but still
- significant in the mm regime
- **Dust emission:** peaking in the submm
  up to high z (negative k correction)
  CIB constitutes about 50% of galaxy emissions
  Of this, 70% is due to dust
- **Molecular lines:** Molecular clouds are
  associated to structure formation and
  dense regions
  Extinction is large in molecular clouds
  at NIR and optical bands but not in (sub)mm



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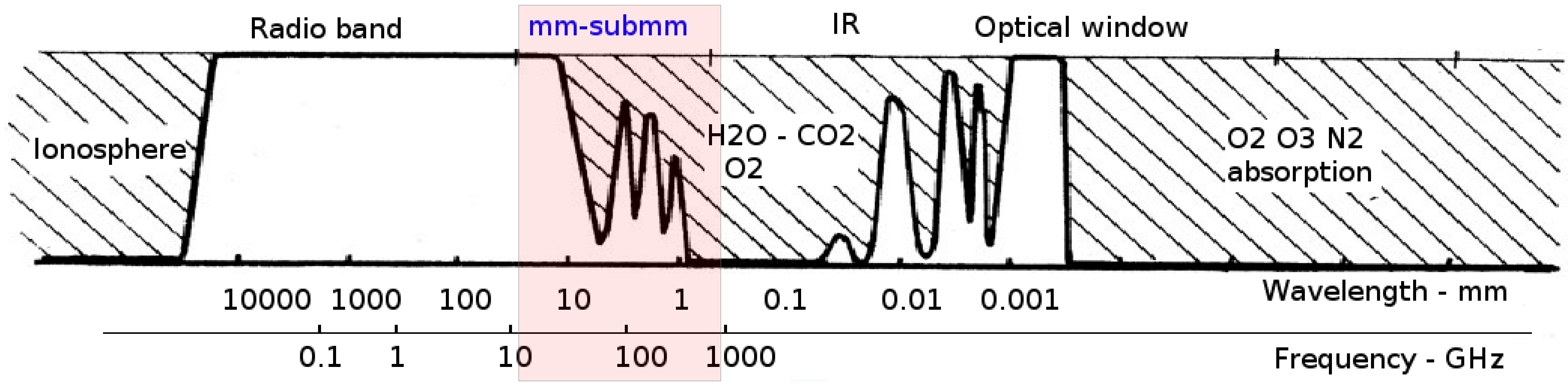

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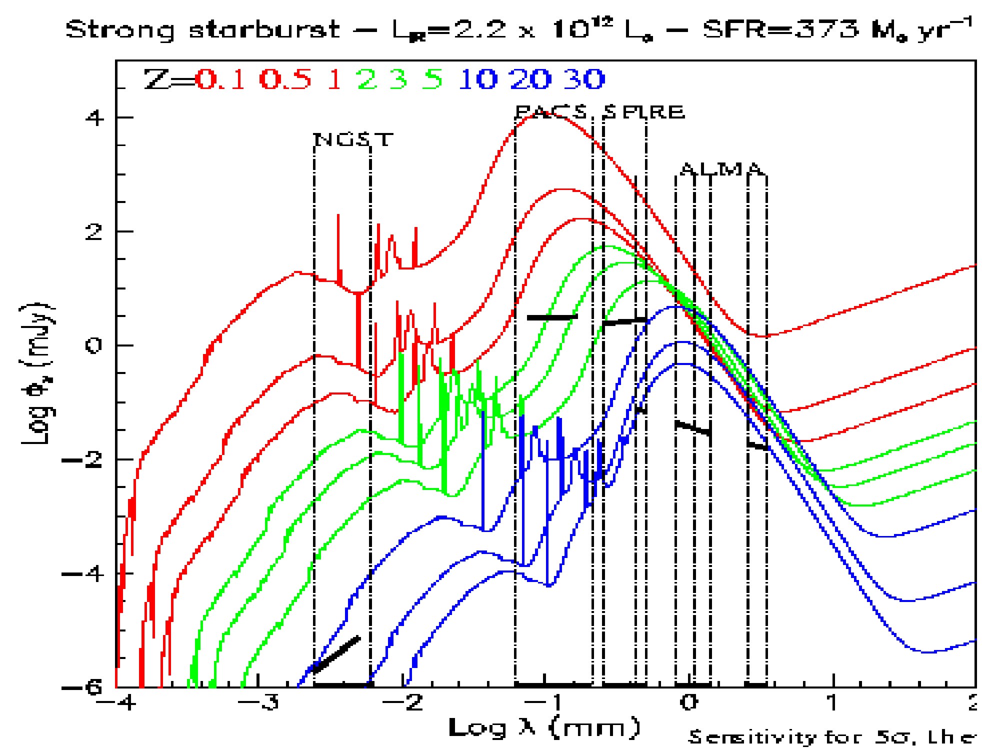

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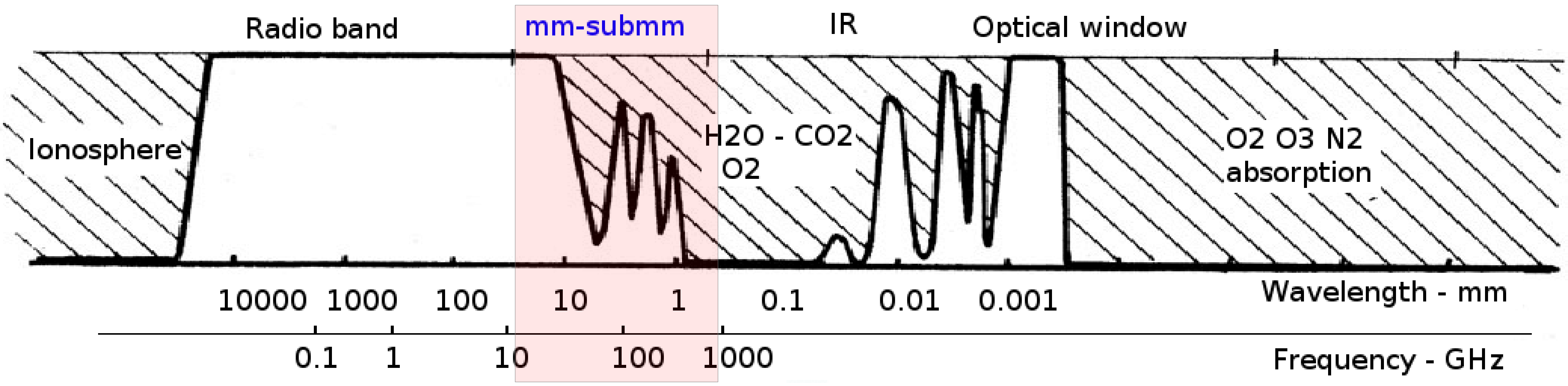

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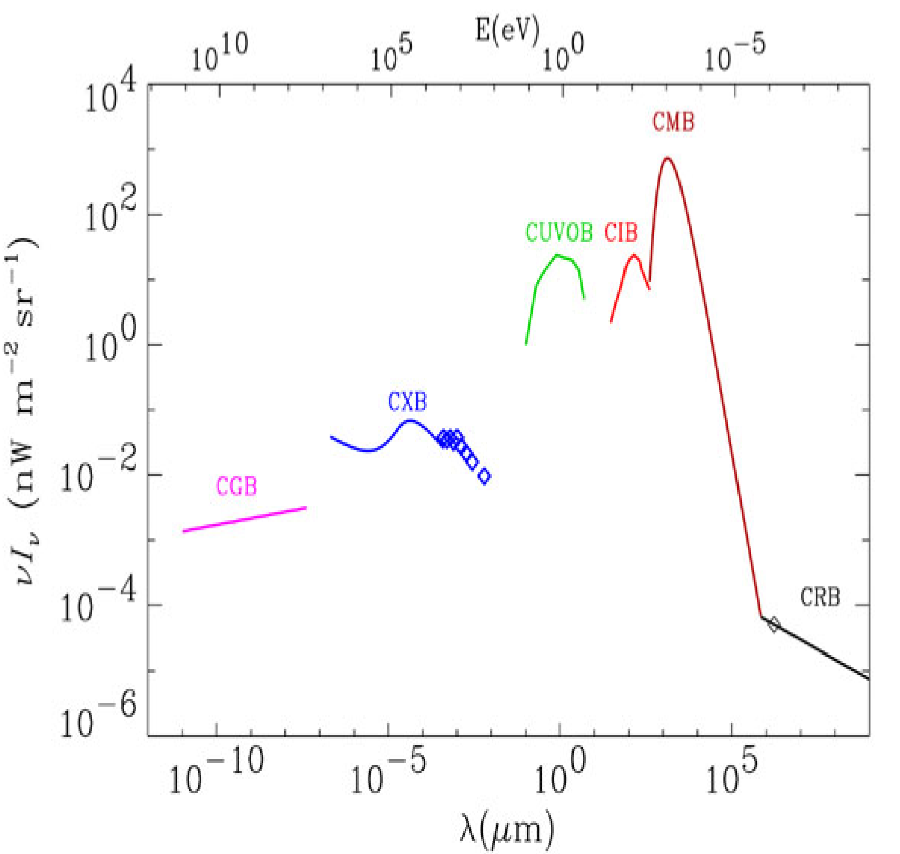

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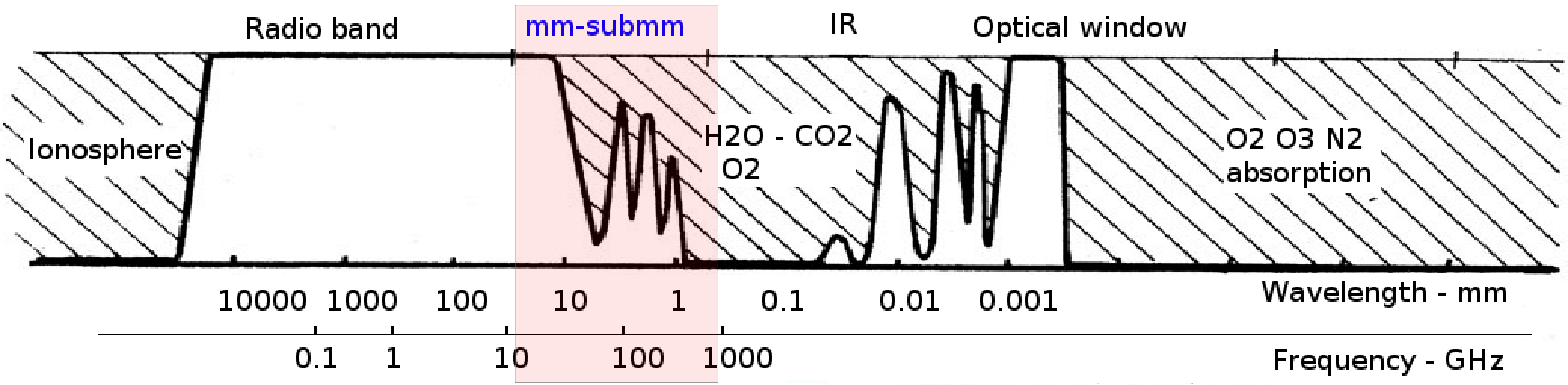

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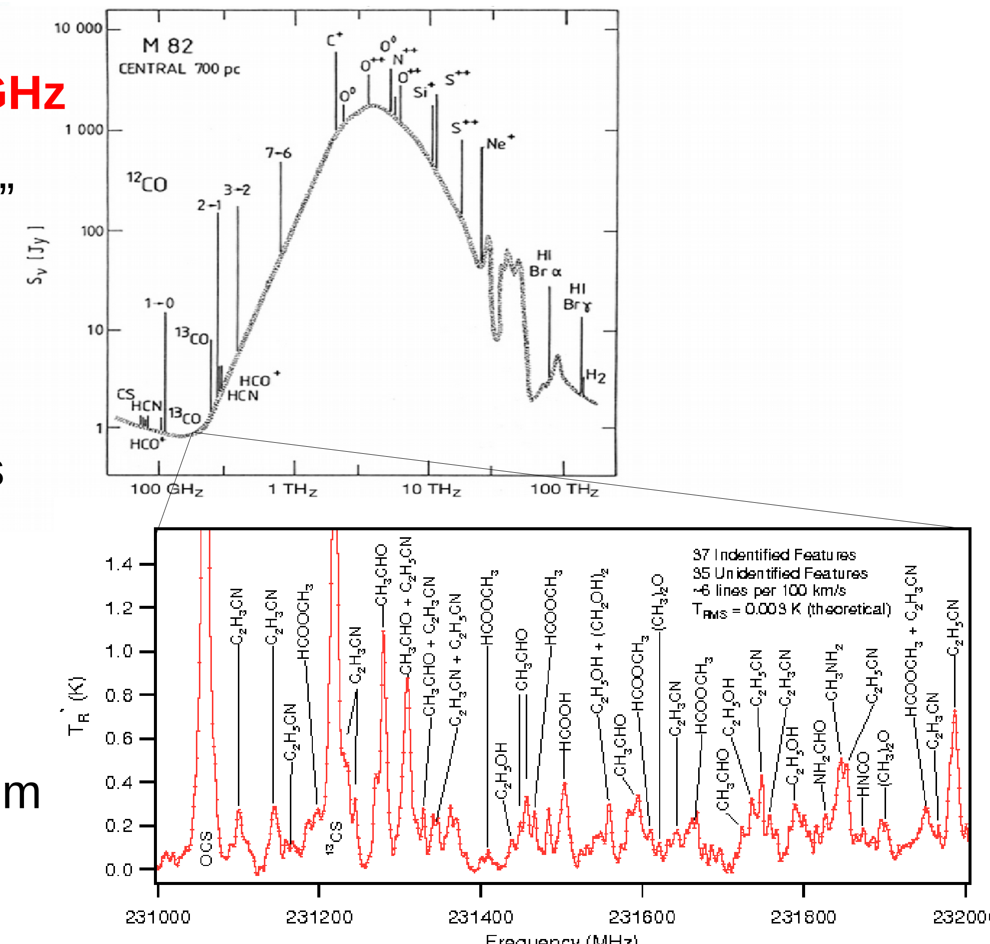
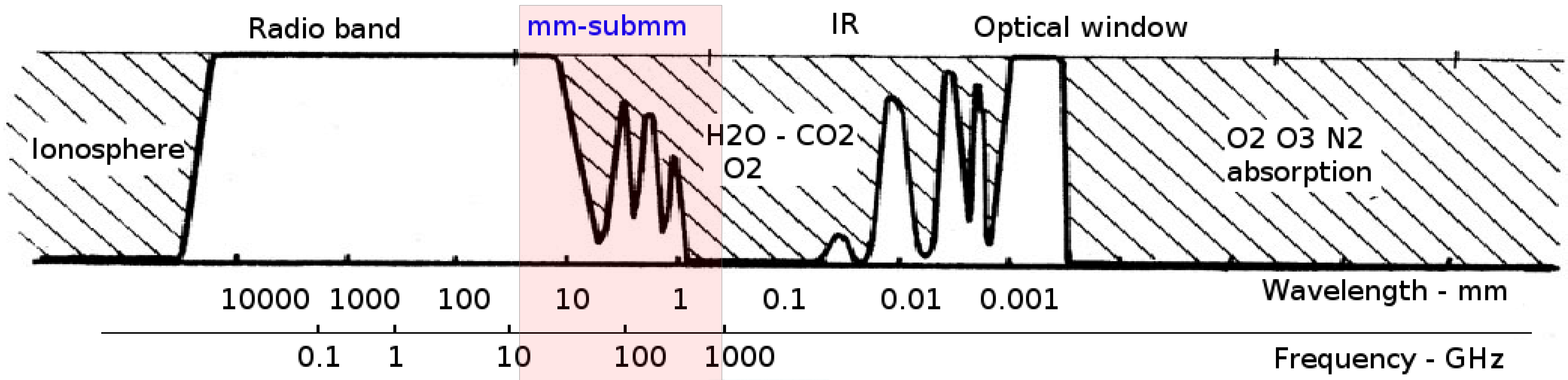
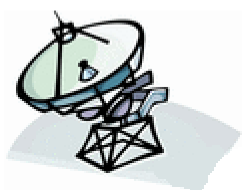
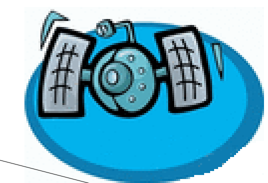


The instruments

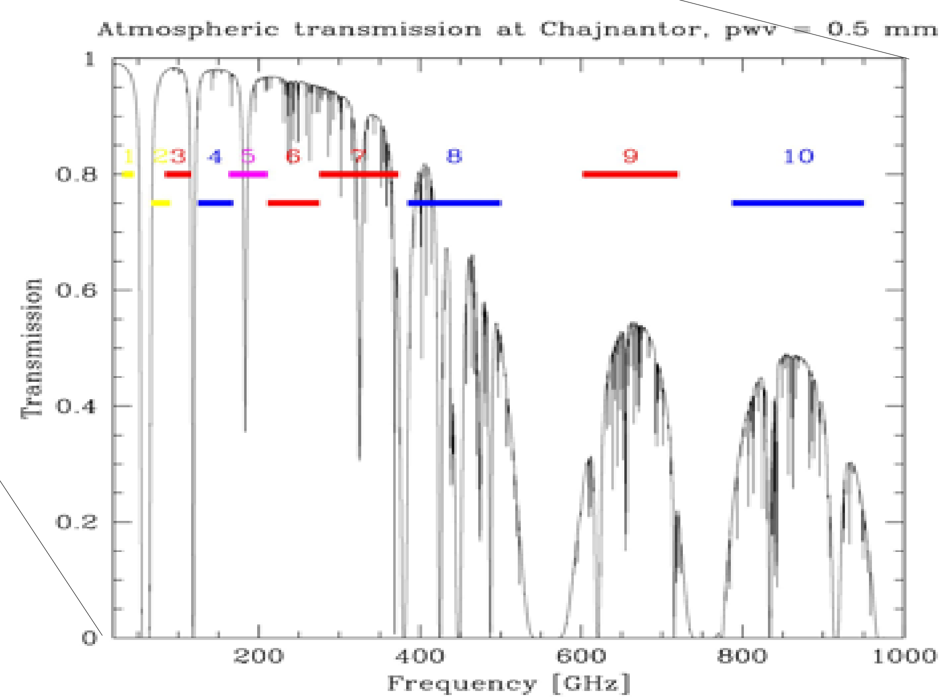




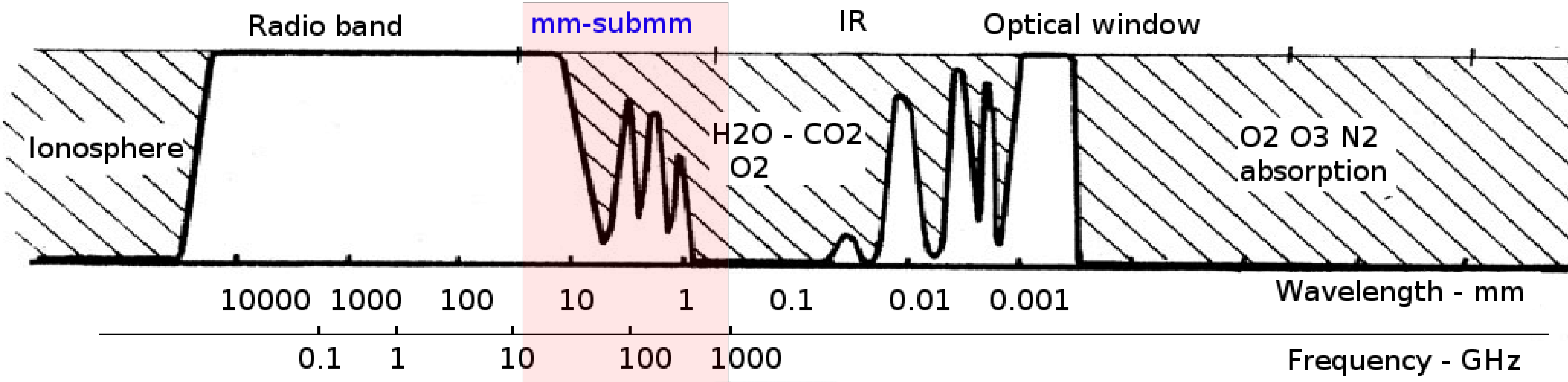


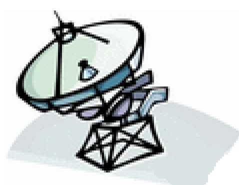
Most typically it is observed from space/balloons but few transmissivity bands are allowed also from the ground in dry sites.

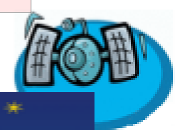
Allows higher resolution than radio bands but coherent receivers could be used

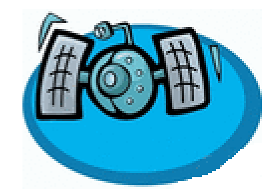


Outline









Observing instruments: **Interferometers (ALMA)**

Signals in the (sub)mm bands

Science cases parade

Observing processes: **Proposals, archives & images**

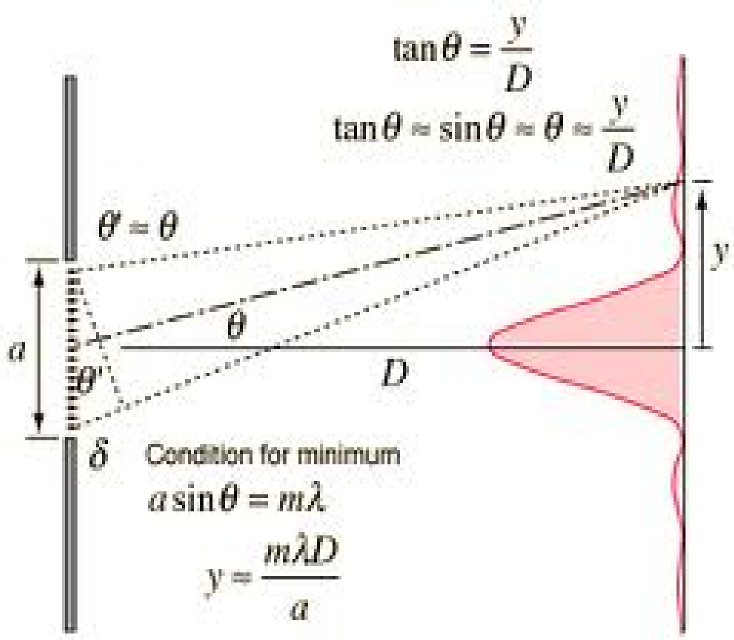
How to extract science from images: hands-on tutorial

Observing instruments

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

Resolution for diffraction limited telescopes

Single dish antennas or single mirror telescopes work as apertures of diameter a
the Resolution for a wavelength λ is $\theta=\lambda/a$



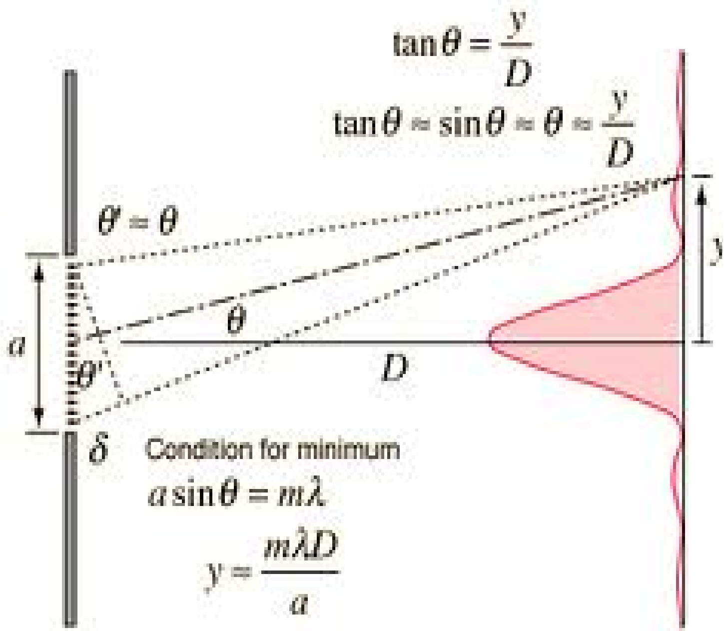
Hence, **resolution decreases as the wavelengths decreases**.
Larger telescopes are needed to reach higher resolutions

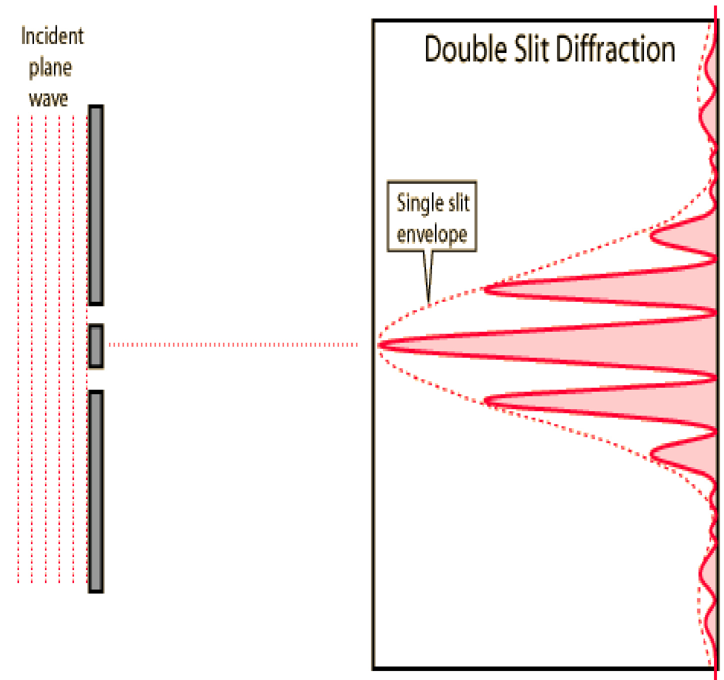
For example, Hubble Space Telescope λ~1μm and a of 2.4 m → Θ ~ 0.13 arcsec

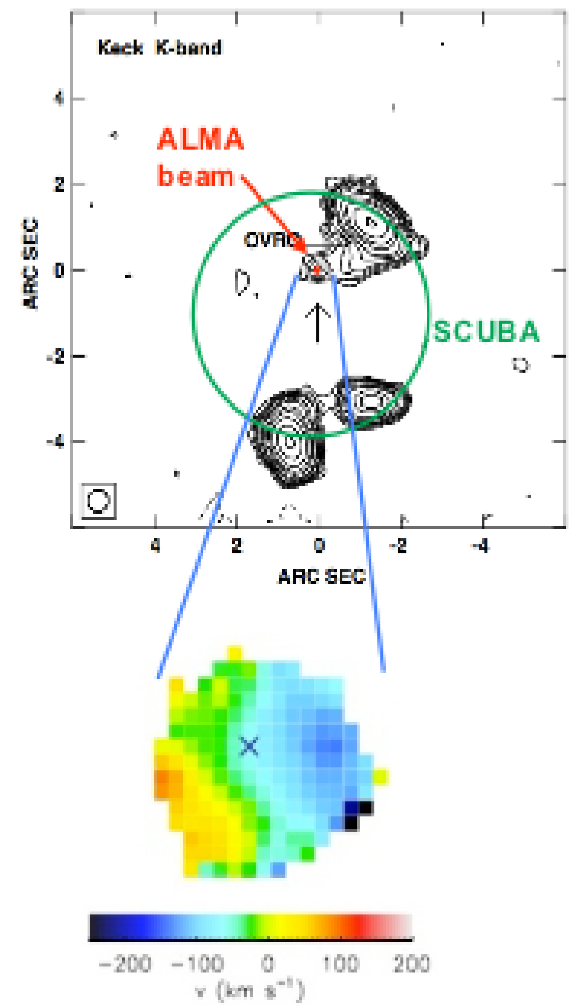
For the same resolution at 1mm we need a 2km telescope!

Resolution in interferometers

Interferometers work as arrays of apertures of diameter a at distance B (=baseline >>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.







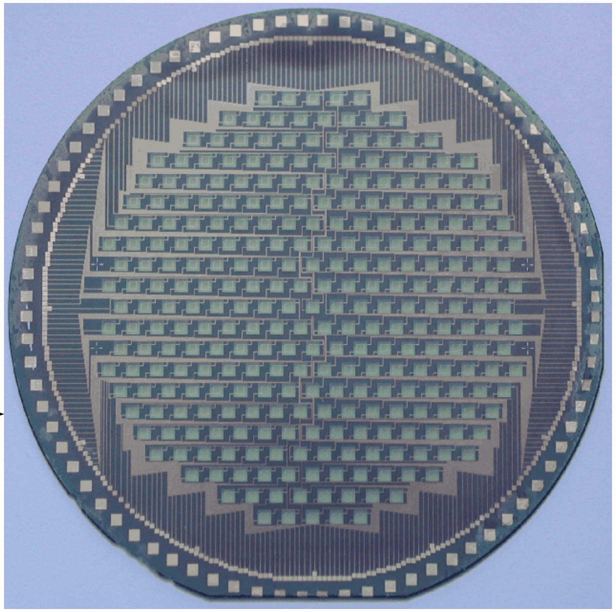
In the double slit diffraction the pattern is modulated by the single slit envelope, i.e. the response function of an interferometer is modulated in a region of size **FOV=λ/a** also called **Field of View or Primary Beam.**

From space small instruments give low resolution from ground larger instruments are possible with **Aperture Synthesis**.

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

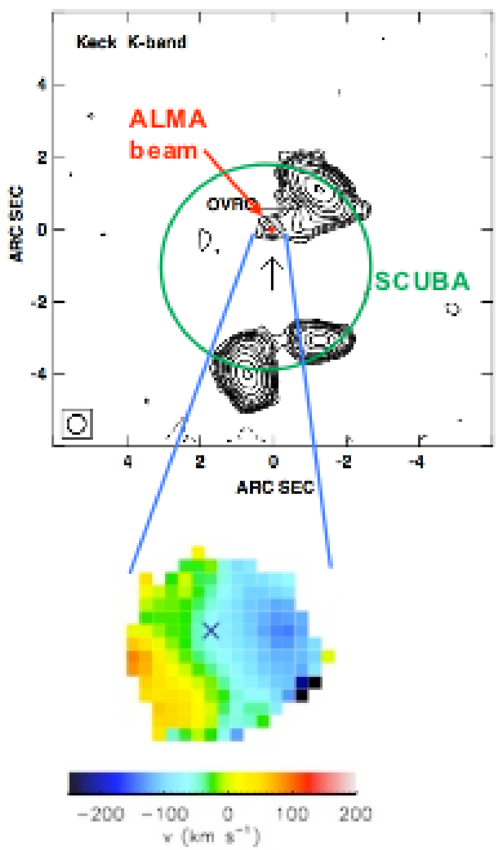


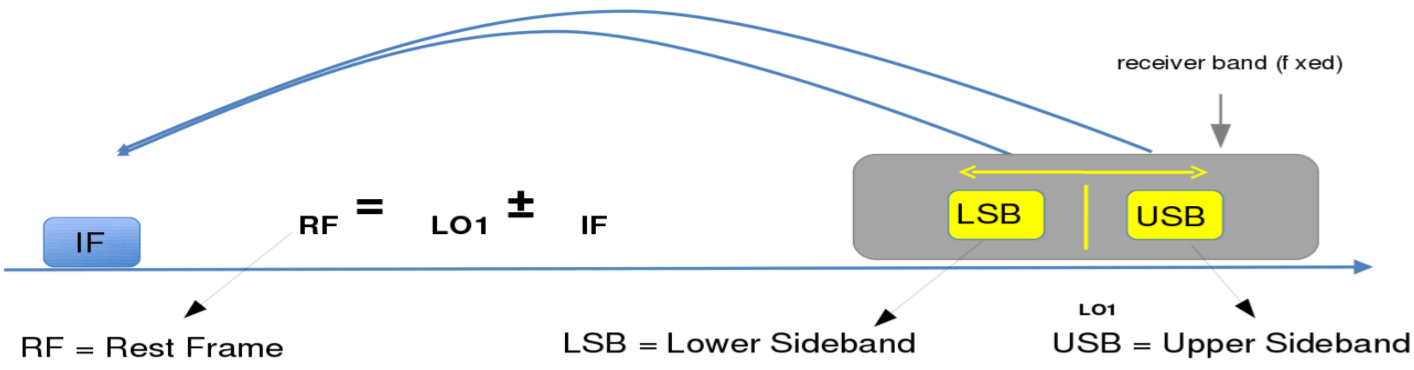
100 pc at z>1 appear on arcsec scales

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.





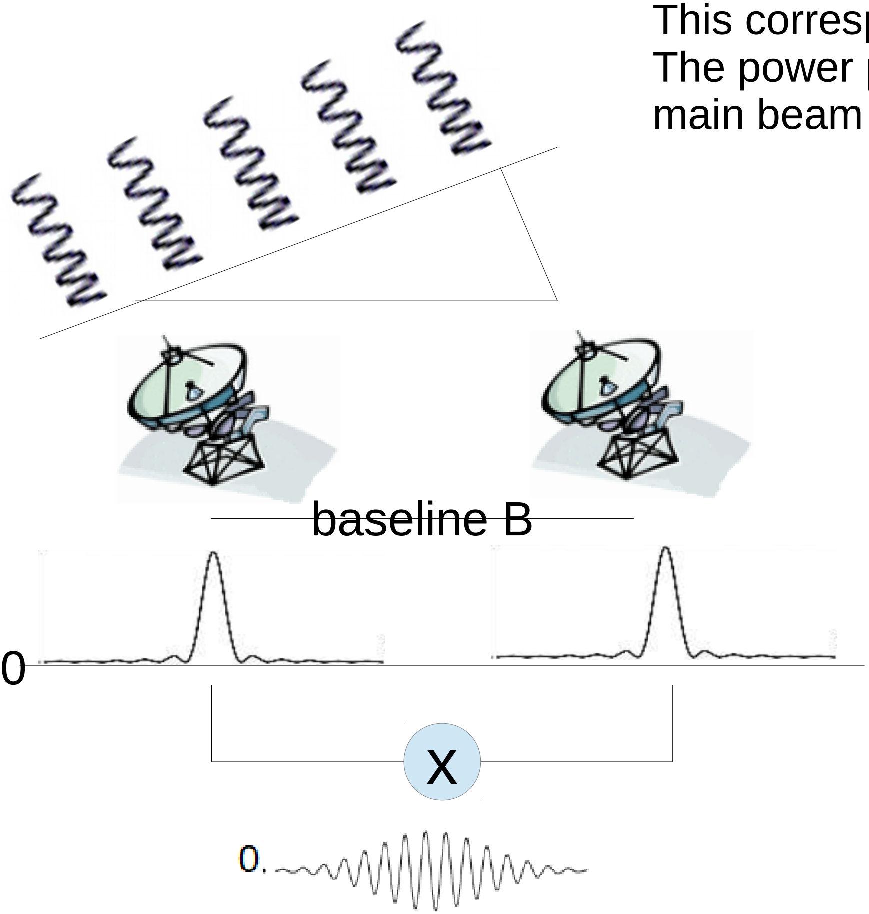
Name	Antennas [# × Diameter]	$\Delta\lambda$ [mm]	Max ang. resol. [asec]	Total area [m^2]
IRAM-PdBI	6 × 15m	1.2–3	0.35	1060
CARMA[a]	6 × 10.4m + 10 × 6m	1.2–3	0.1	792
NMA	6 × 10m	1.2–3	1	471
SMA	8 × 6m	0.35–1.2	0.1	226
eSMA[b]	SMA + 15m + 10.4m	0.87–1.2	0.2	488
ATCA[c]	6 × 22m [d]	3–12	2.	2280[d]

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).



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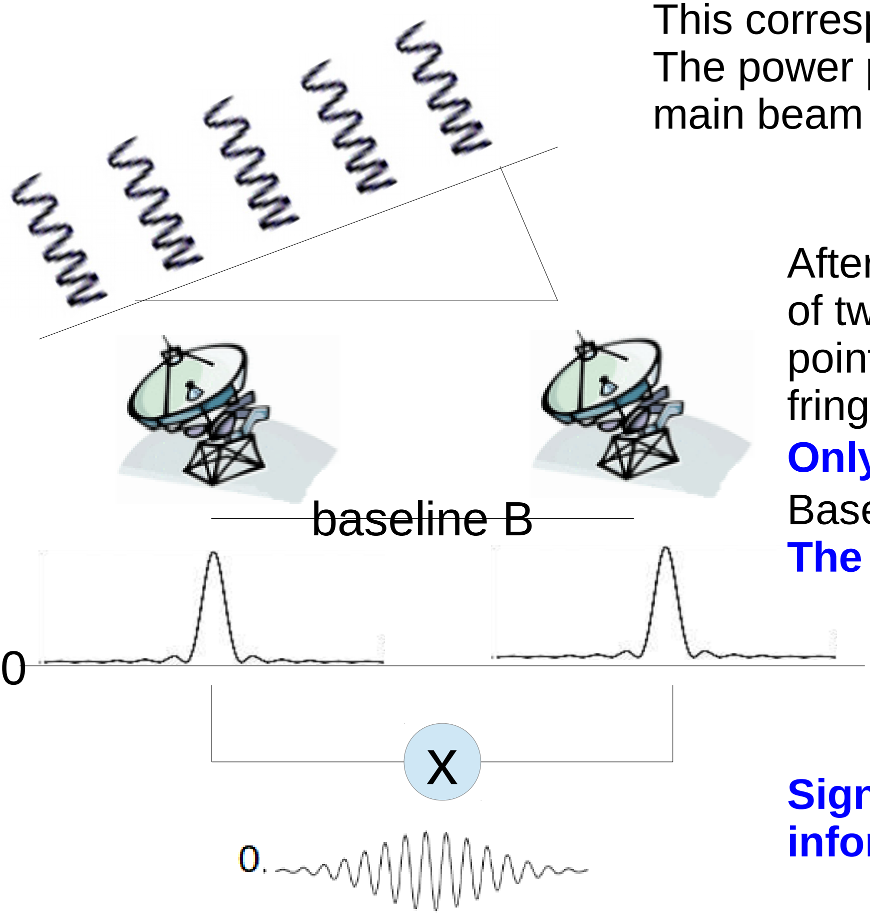


After correcting for geometrical delays, allowing the comparison of two points of the same wavefront coming from a far away point source the output of the correlation of two signals is a fringe pattern centered around 0 (total power is lost).
Only the spatial component corresponding to $\theta=\lambda/B$ 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)

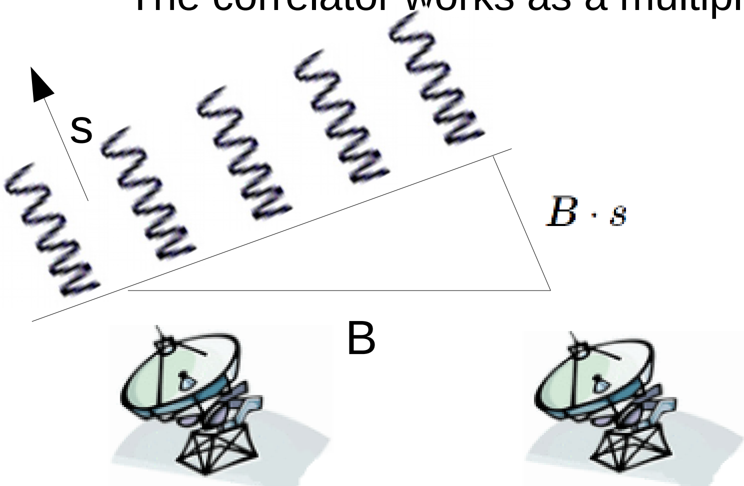
$$U_1 \propto E\,\mathrm{e}^{\,\mathrm{i}\,\omega t} \qquad U_2 \propto E\,\mathrm{e}^{\,\mathrm{i}\,\omega\,(t-\tau)}$$

The geometrical delay in the direction s=s0+ds

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

The correlator works as a multiplier and time integrator with output

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



If T>>2π/ω

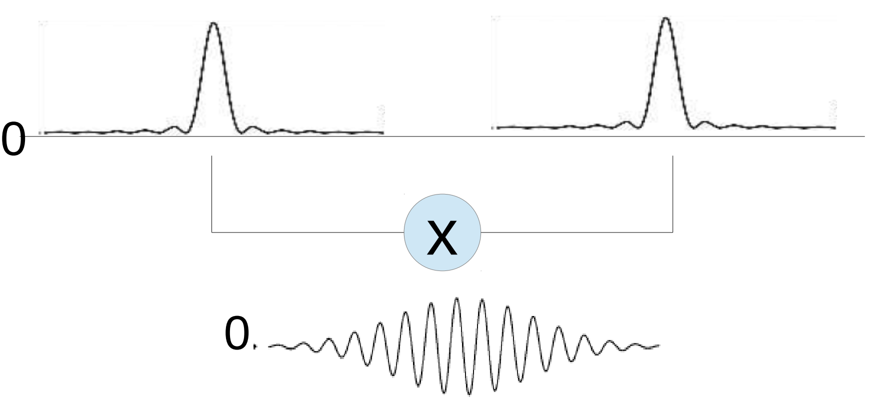
$$R(\tau) \propto \frac{\omega}{2\pi}E^2 \int_0^{2\pi/\omega} \mathrm{e}^{\,\mathrm{i}\,\omega\tau}\,\mathrm{d}t$$

that results in

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

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

$$\mathrm{d}P = I_\nu \cos\theta\,\mathrm{d}\Omega\,\mathrm{d}\sigma\,\mathrm{d}\nu$$
$$= A(\boldsymbol{s})I_\nu(\boldsymbol{s})\,\mathrm{d}\Omega\,\mathrm{d}\nu$$



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

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

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

Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

The visibility function: properties

Some **visibility function** properties:

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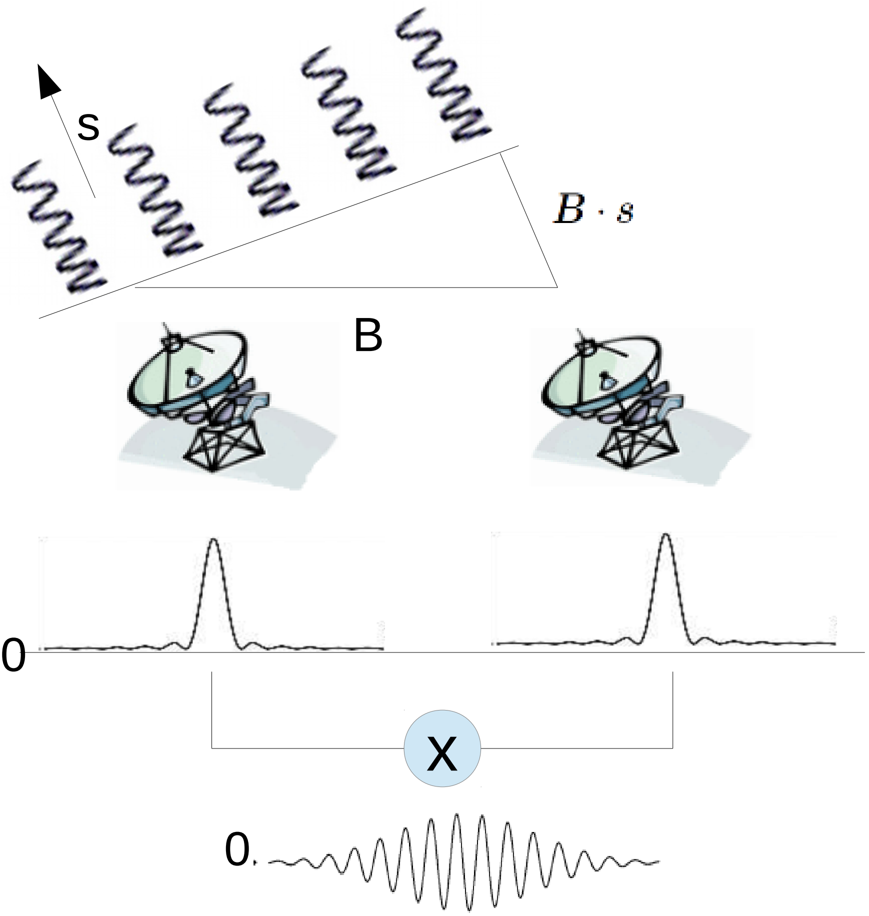
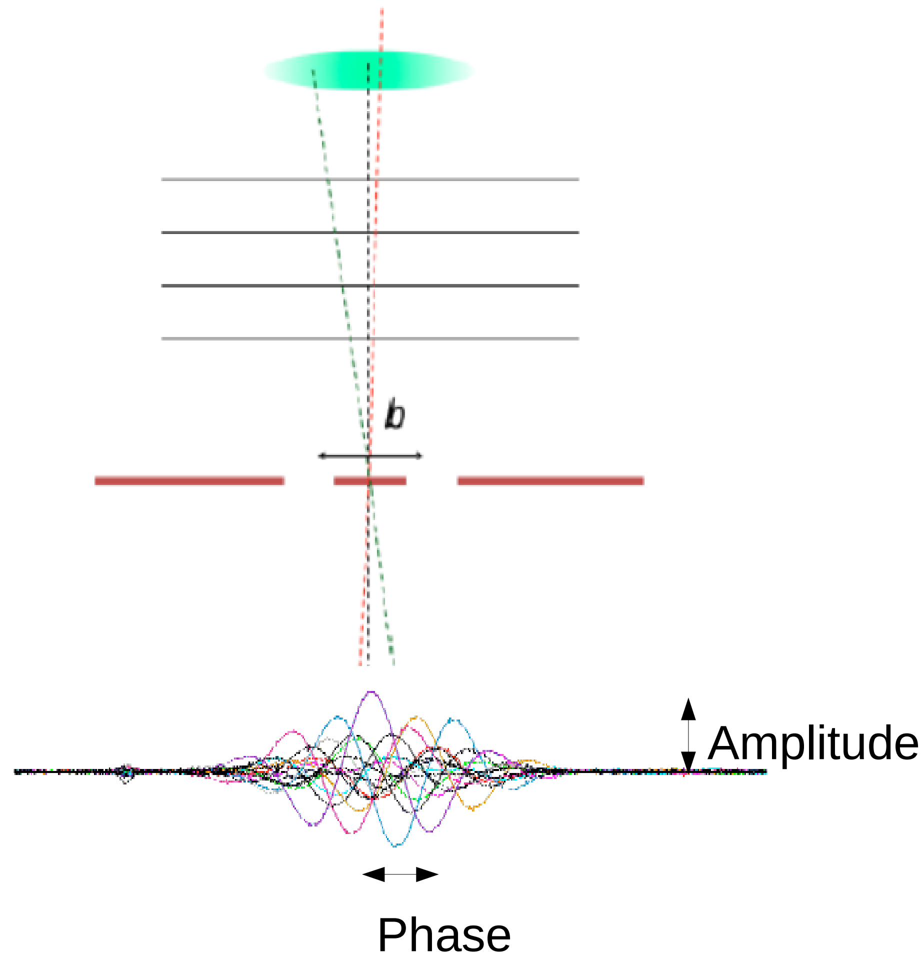
- **Amplitude is modulated by the main beam shape**
- **The phase is strictly connected with the source position**





Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

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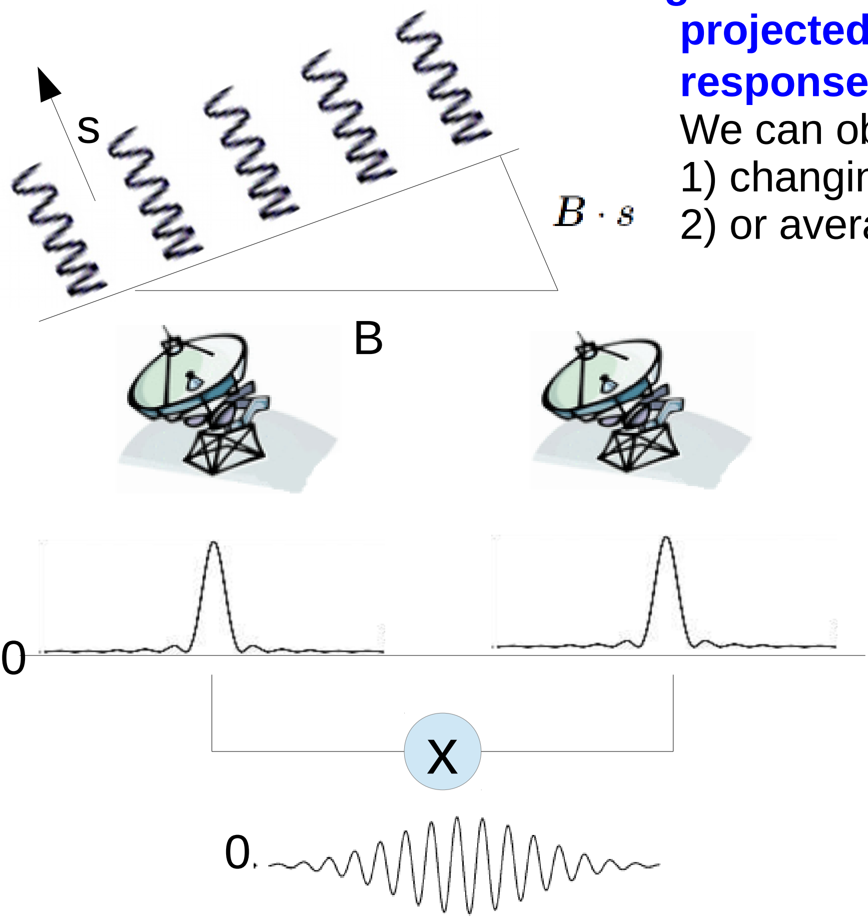
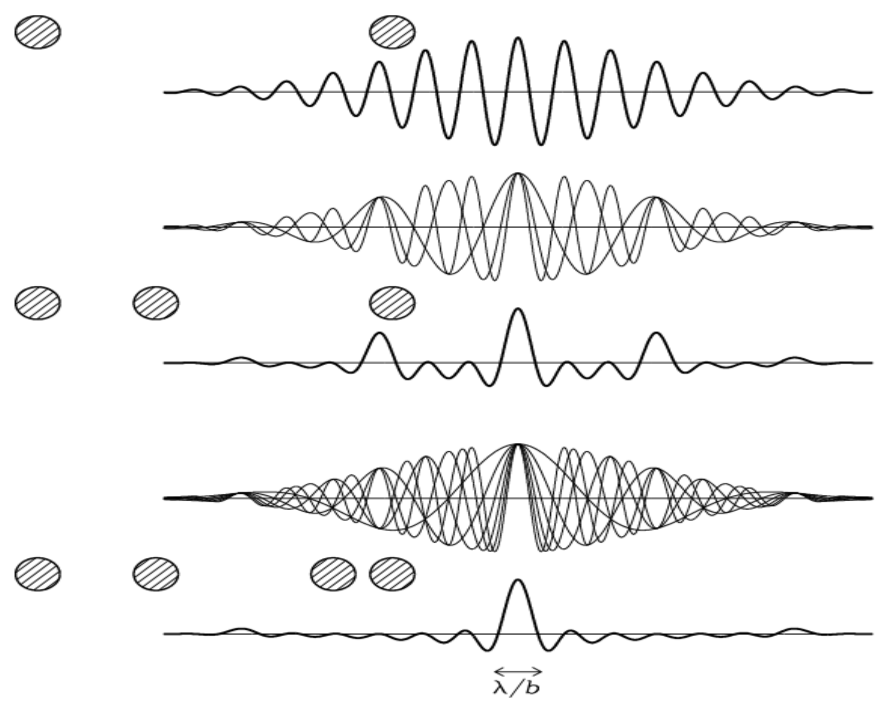
- **Angular scales on the sky are associated with the size of the projected baseline needed to observe them and the FWHM of the response function width is the synthesized beam λ/B.**

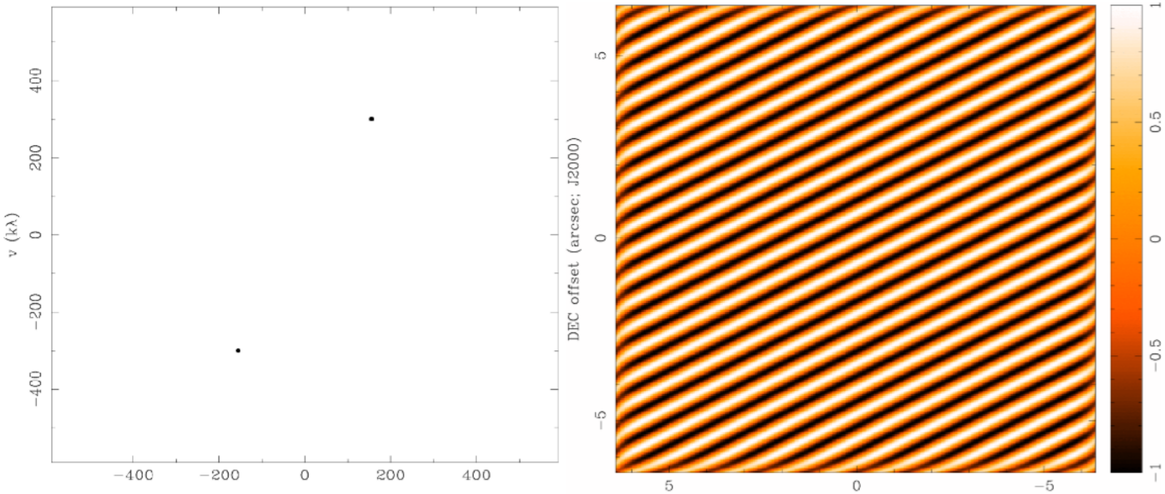
We can observe more angular scales either
1) changing the baseline
2) or averaging the signal from N Antenna couples (N(N-1)/2)



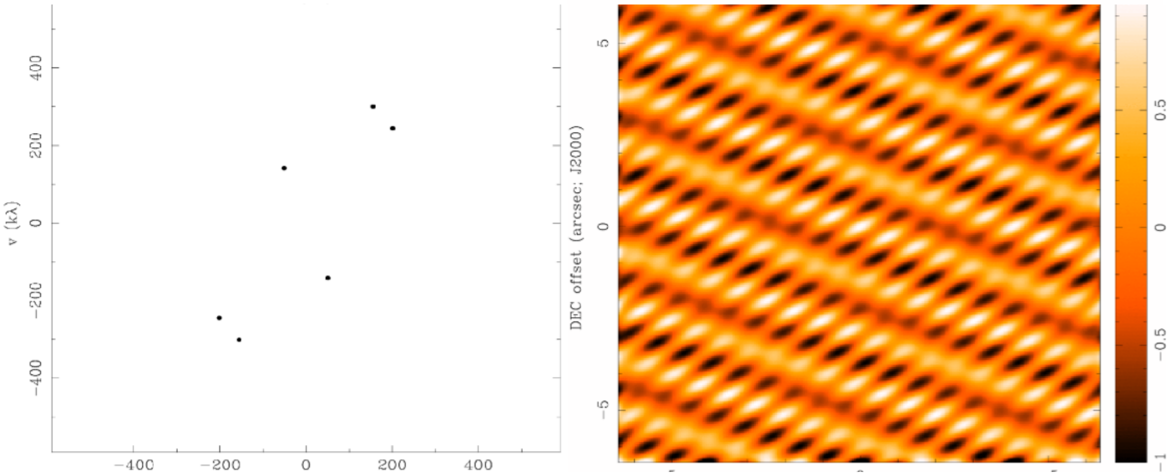


Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

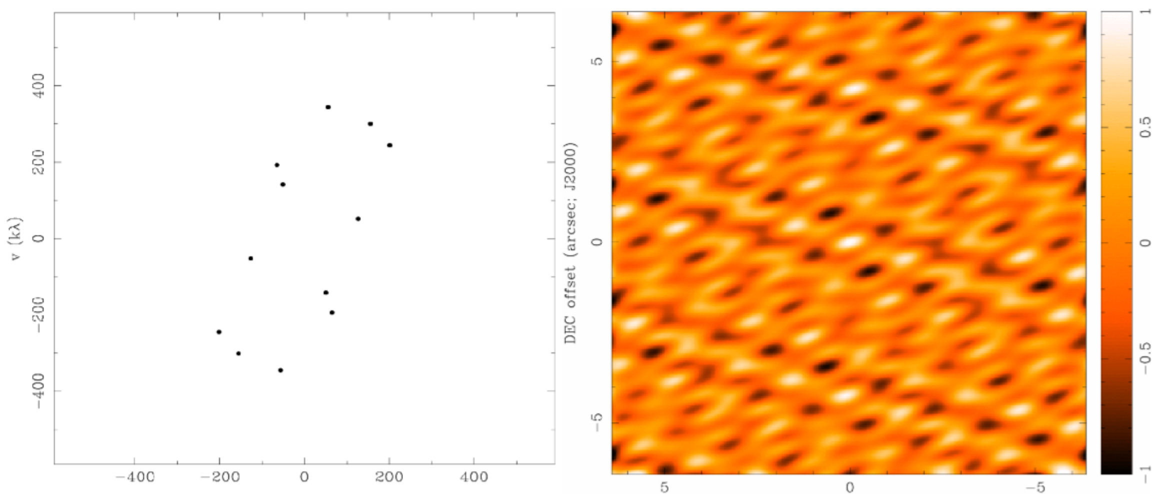
The visibility function: the uv plane



2 antennas



3 antennas



5 antennas

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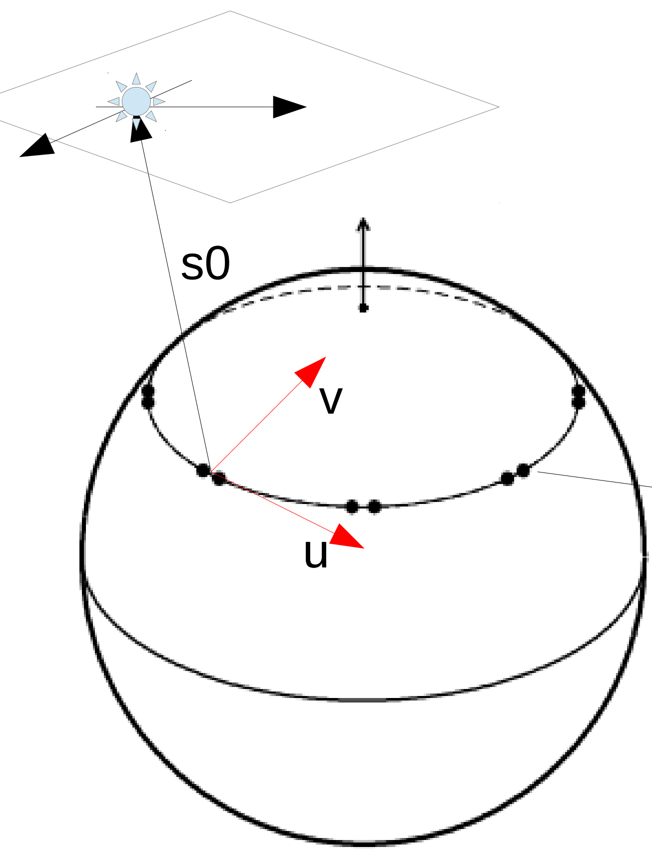
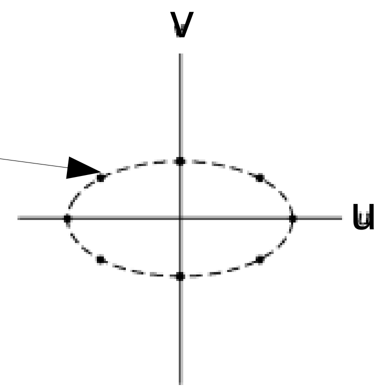
  3) or changing the angle towards the target (exploiting the Earth rotation) to obtain a different projection of the same baseline.

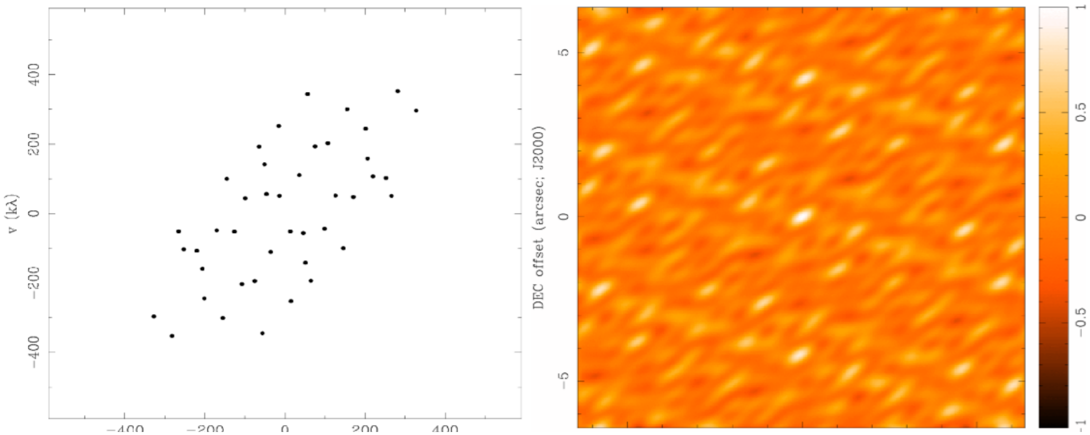




The projected baseline is described over the uv plane perpendicular to the direction to the phase center (s0) with u and v towards E and N. The earth rotation generates elliptical loci on the uv plane in 12 hr which ellipticity depends on the telescope latitude and source declination.

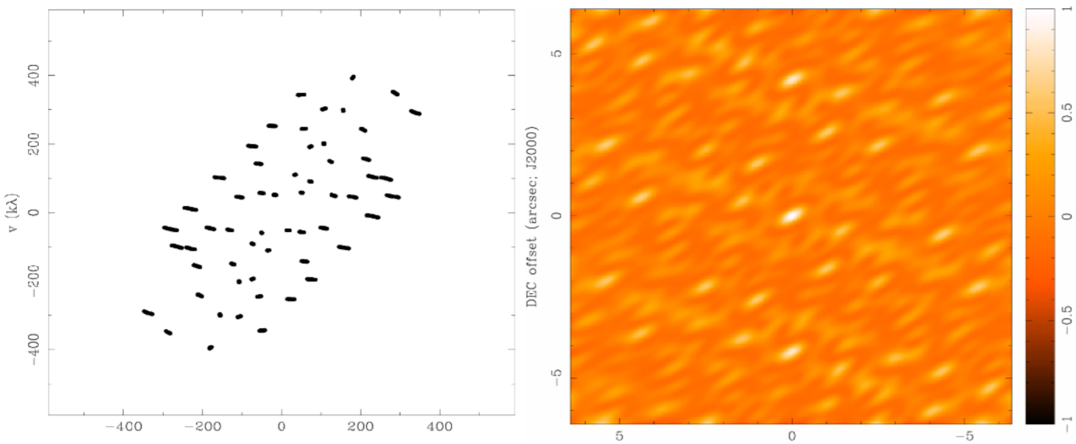
Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

The visibility function: the uv plane

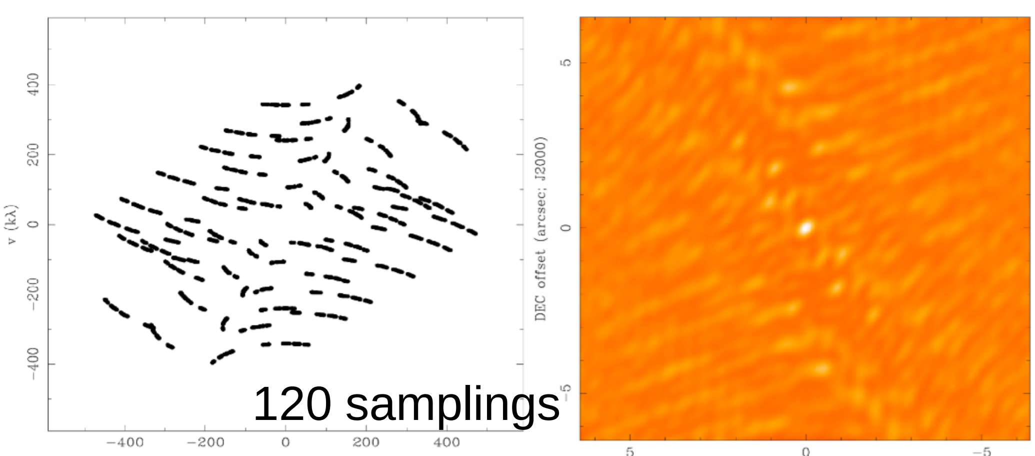


8 antennas

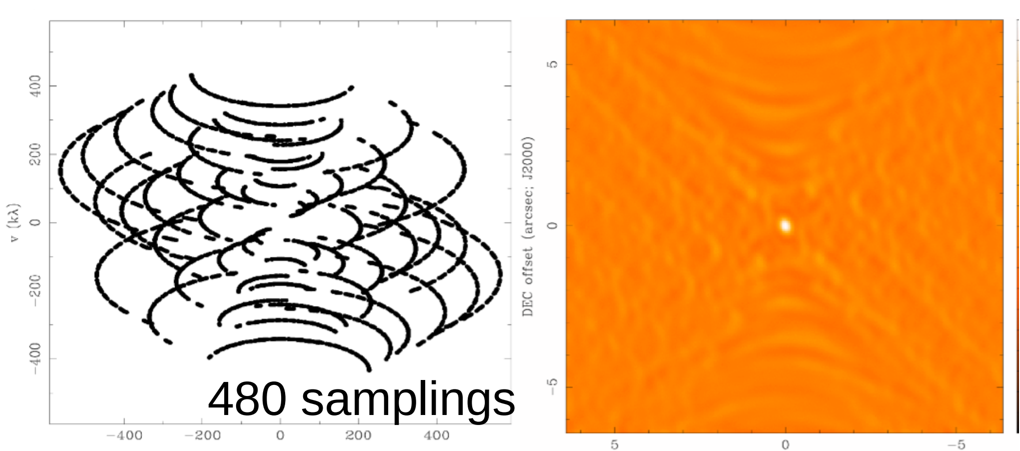
1 sampling



30 samplings



120 samplings



480 samplings

V(u,v) and baseline

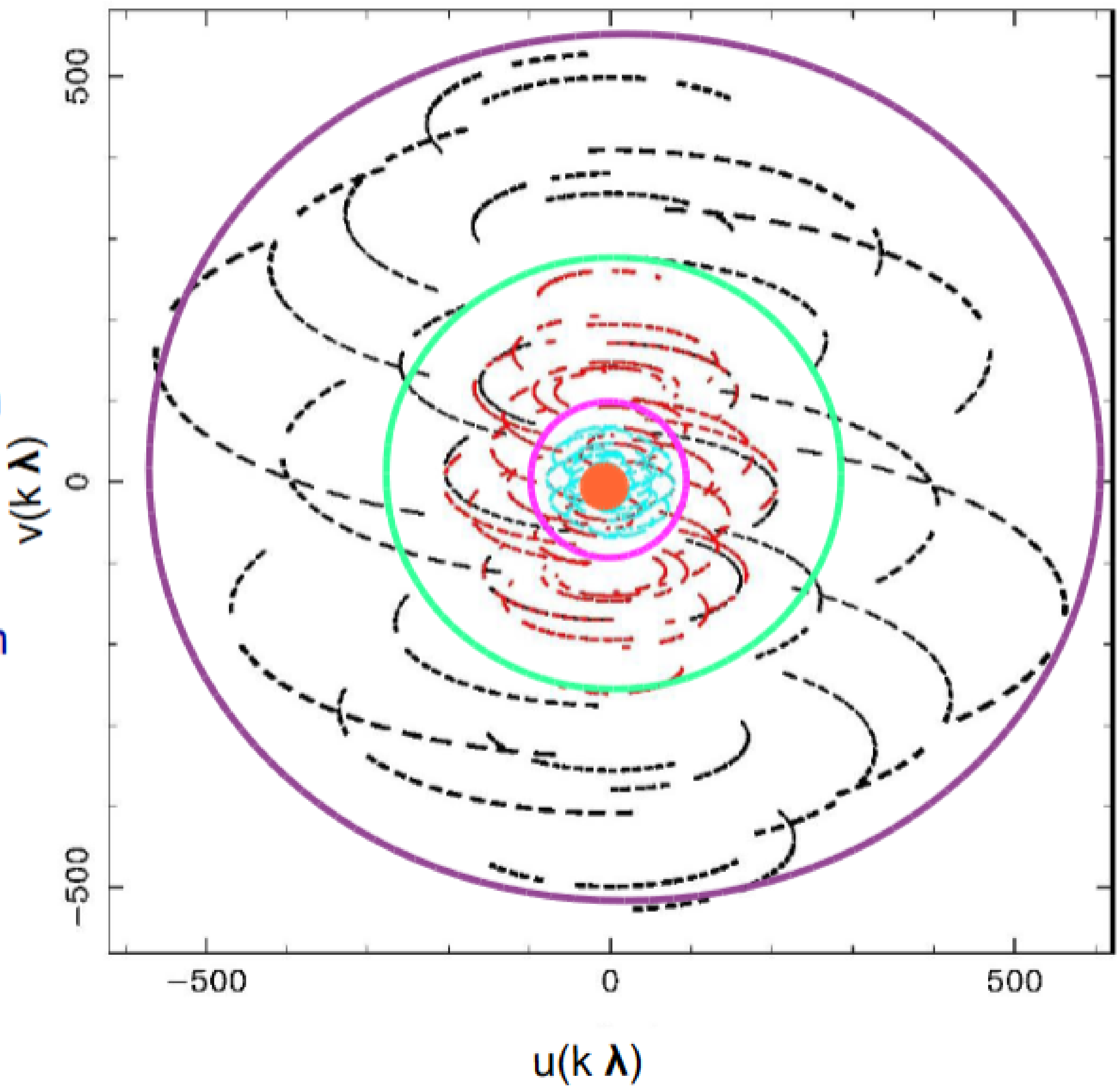
$\Theta_{res} \sim \lambda / B_{max}$
where B_{max} is the maximun baseline (uv distance)

Long (u,v) distance:
long baseline,
measure more compact emission

Small (u,v) distance:
short baseline,
measure more extended emission

Zero spacing:
missing
limit on observable largest scale

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



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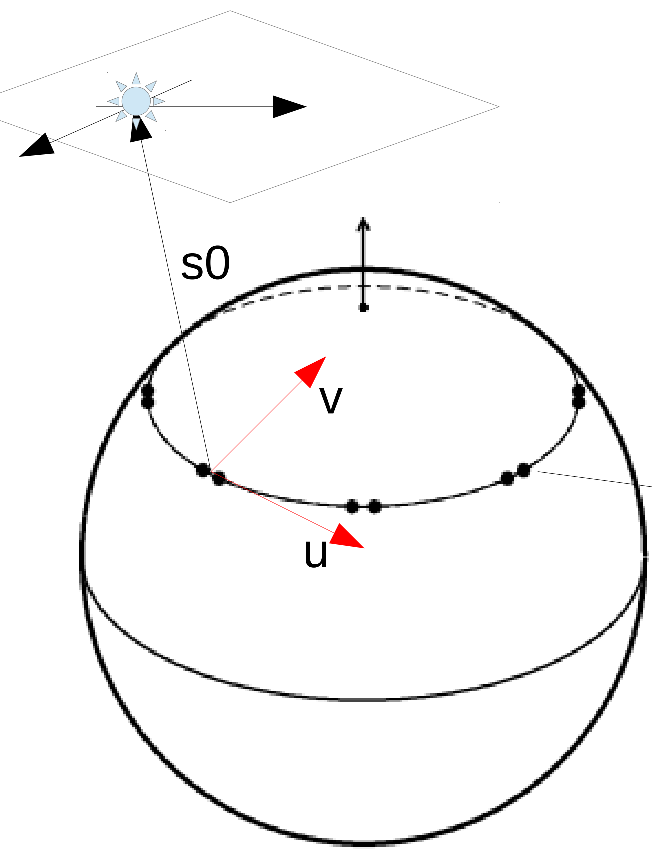
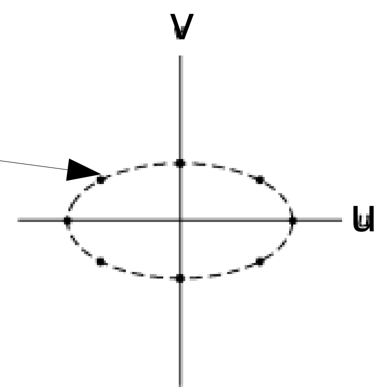
  or changing the angle towards the target (exploiting the Earth rotation)
  to obtain a different projection of the same baseline.





The projected baseline is described over the uv plane perpendicular to the direction to the phase center (s0) 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).

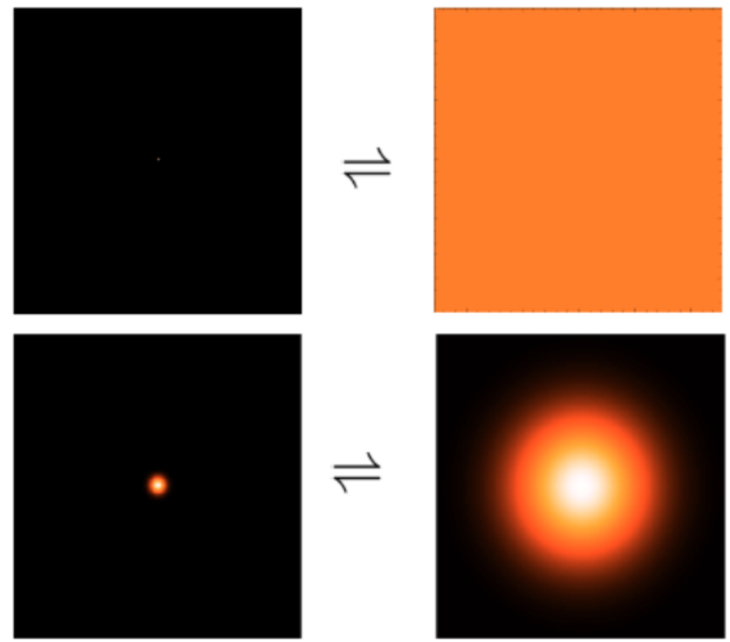
Receiving system: ATMOSPHERE + ANTENNA + RECEIVER + BACKEND

Some 2D Fourier Transform Pairs

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

δ Function ⇌ Constant

Gaussian ⇌ Gaussian

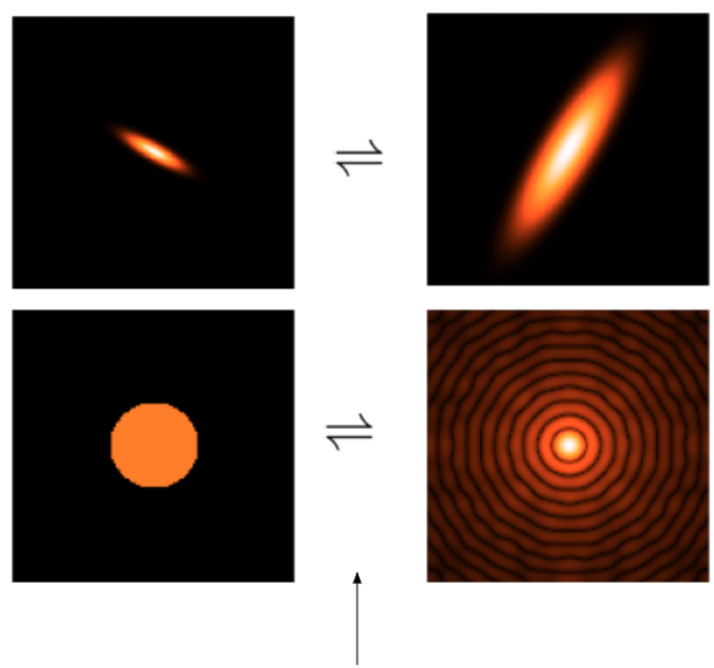


narrow features transform to wide features (and vice-versa)

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

elliptical Gaussian ⇌ elliptical Gaussian

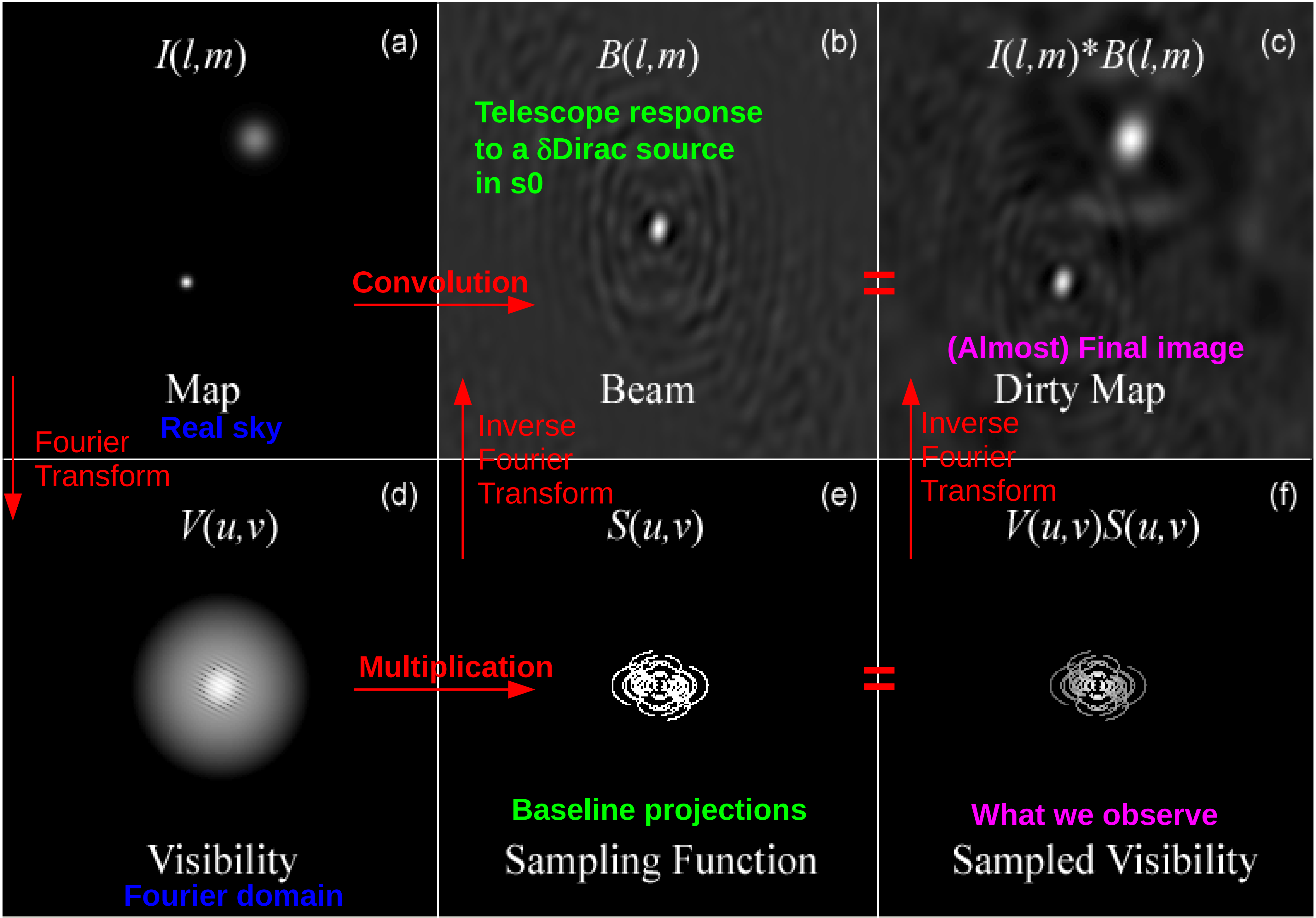
Disk ⇌ Bessel



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

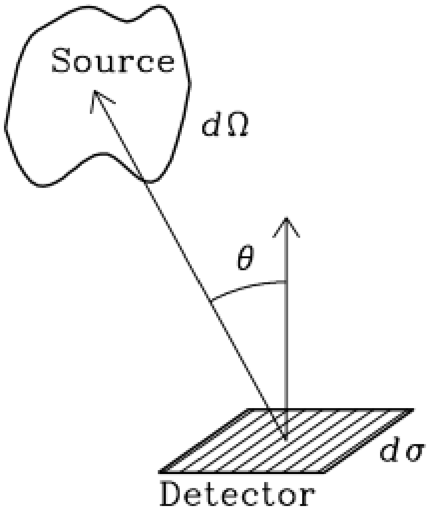
Calibration on V(u,v)

From the sky to the image



Flux density

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



$$\mathrm{d}P = I_\nu \cos\theta \, \mathrm{d}\Omega \, \mathrm{d}\sigma \, \mathrm{d}\nu$$

$\mathrm{d}P$ = power, in watts,
$\mathrm{d}\sigma$ = area of surface, m^2,
$\mathrm{d}\nu$ = bandwidth, in Hz,
θ = angle between the normal to $\mathrm{d}\sigma$ and the direction to $\mathrm{d}\Omega$,
I_ν = brightness or specific intensity, in $\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$.

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

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

Flux density is measured in Jansky

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

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

Sensitivity and polarization

The rms noise in the signal for an interferometer is given by:

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

$$\sigma_T = \frac{\sigma_S\,\lambda^2}{2\,k\,d\Omega_{\rm array}}\ [{\rm K}]$$

Boltzmann k

Brightness temperature corresponding to all the signals collected including source, atmosphere and instrument

Time on source

# of polarizations

Bandwidth

Effective collecting Area= dish_area x efficiency

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

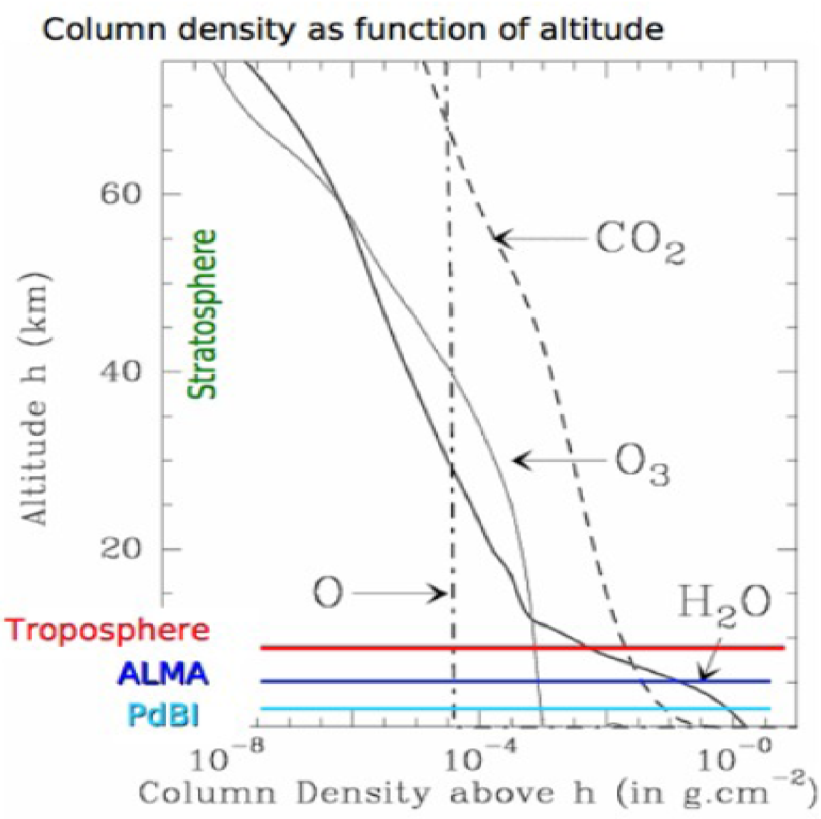
FOV area=1.14(λ/a)^2

Sensitivity can be improved by

- **getting lower Tsys** (= 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.

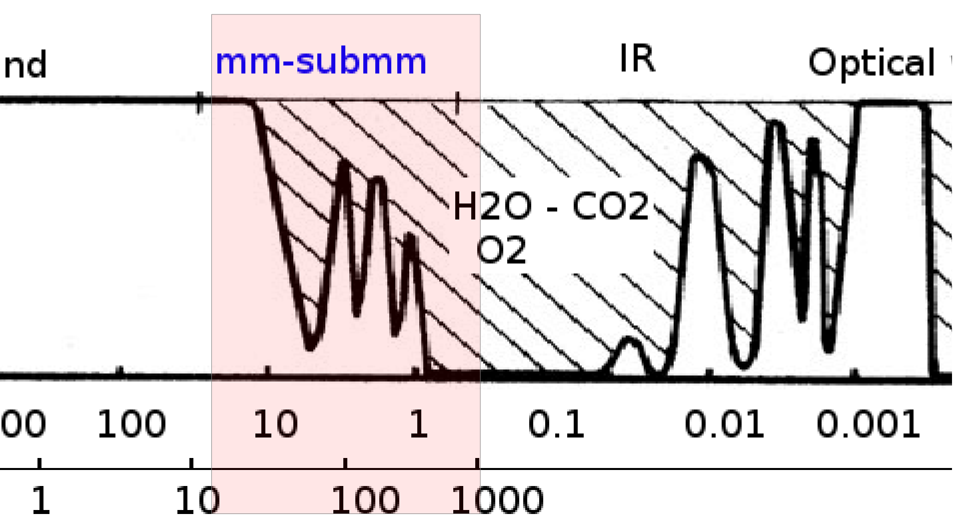
Signal "obstacles"

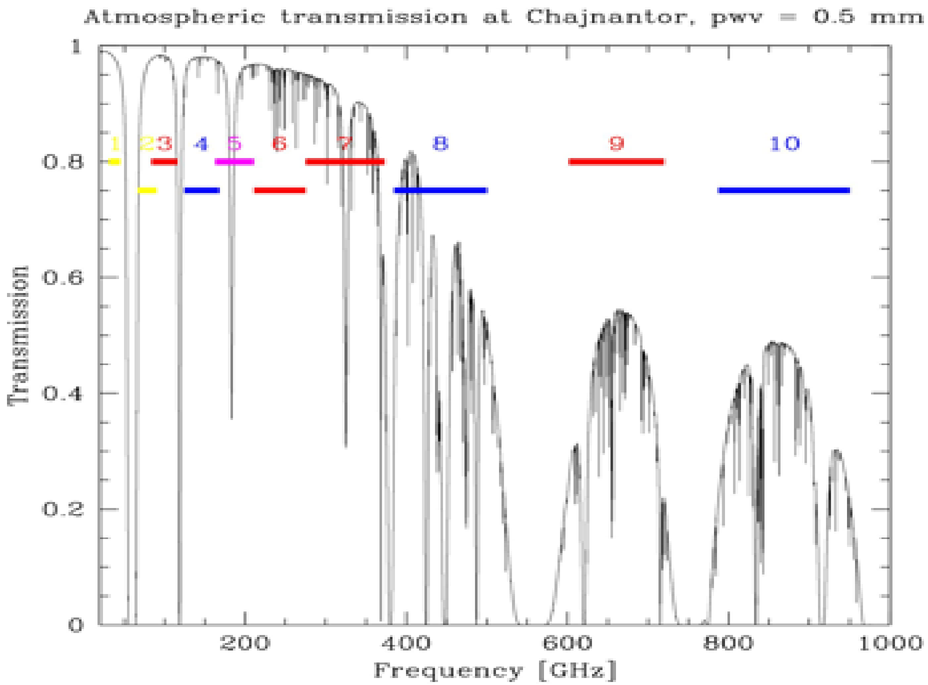


Absorption & Attenuation
Light can be absorbed by interacting with a medium and the **photon energy** is transmitted to the molecules or atoms of the medium. Light can be reemitted attenuated or changed in energy.

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

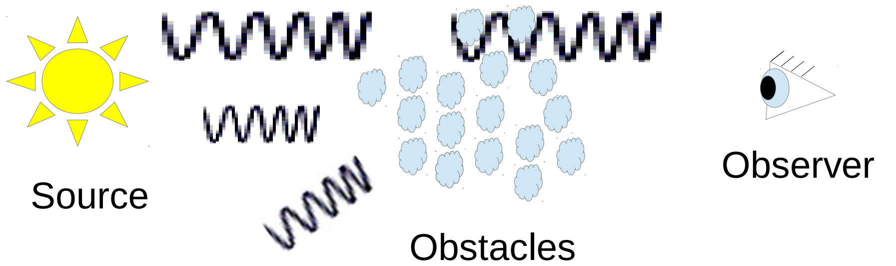
Transmissivity is higher the smaller are the obstacles and the less dense is the medium along the line of sight.
Only some transmission bands are available in the submm and only from high and dry sites.





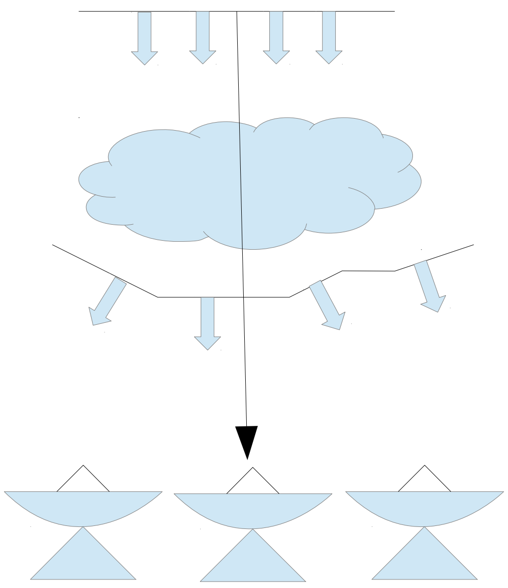
Signal "obstacles"

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 obscurate (reflect) it.



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

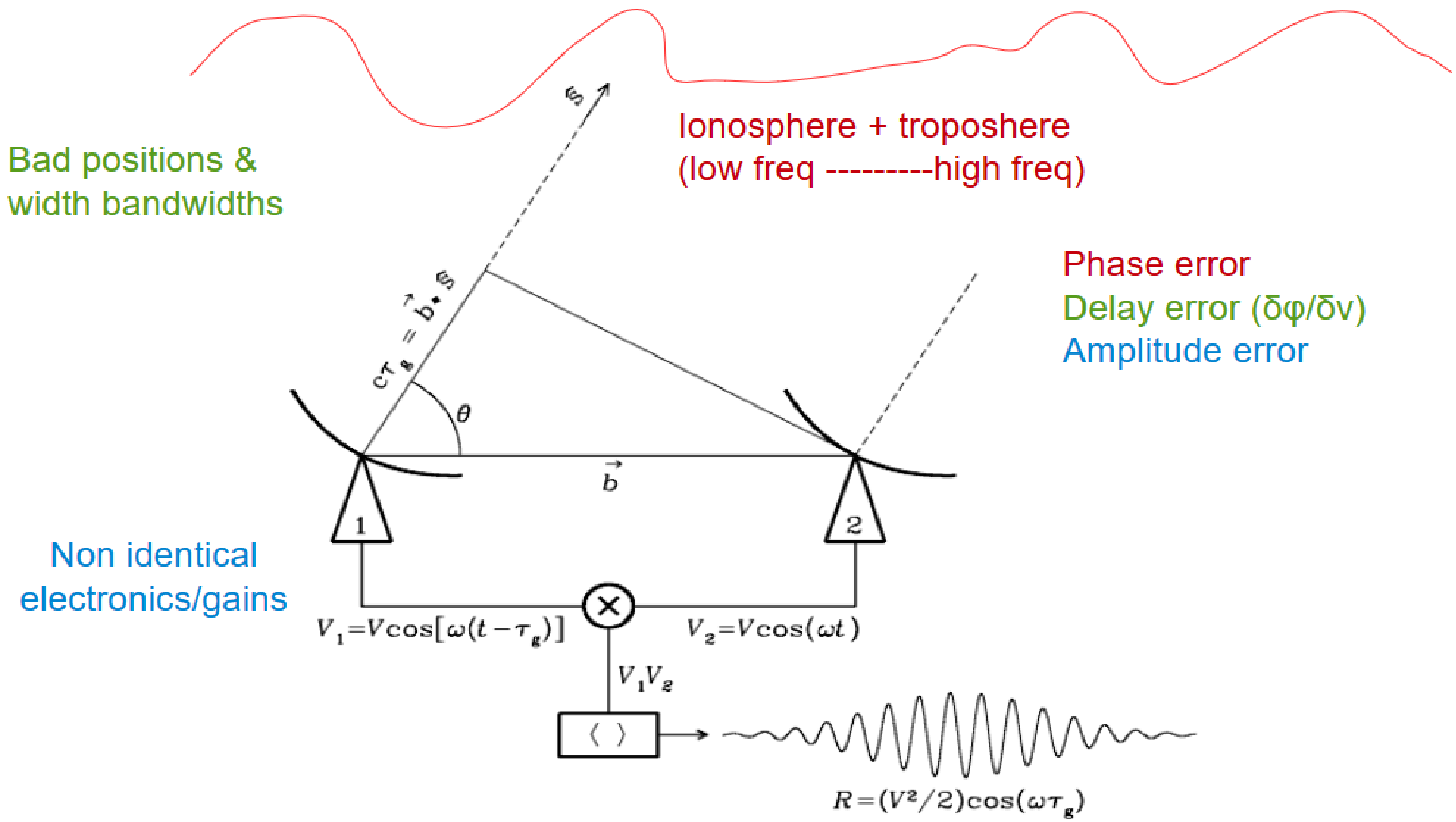
Antenna Surface irregularities should be smaller than ~1/10 of the observing wavelength (~0.03micron in submm).



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

Calibration in interferometry: why ?



$$V_{ij}^{obs}(A,\varphi) = G_i \, G_j \, V_{ij}^{true}(A,\varphi)$$

$$G_i = K_i \, B_i \, J_i \, D_i \, E_i \, P_i \, T_i \, F_i$$

where K = geometric compensation, B = Bandpass response, J= electronic gains, D=polarization leakage, E= antenna voltage pattern, P= parallactic angle,T= troposphere effects,F=ionospheric faraday rotation

$$G_i(\nu,t) = B_i(\nu) J_i(t)$$

Calibration in interferometry: observational strategy in the mm

We need to calibrate A, Φ vs t, ν of Visibilities

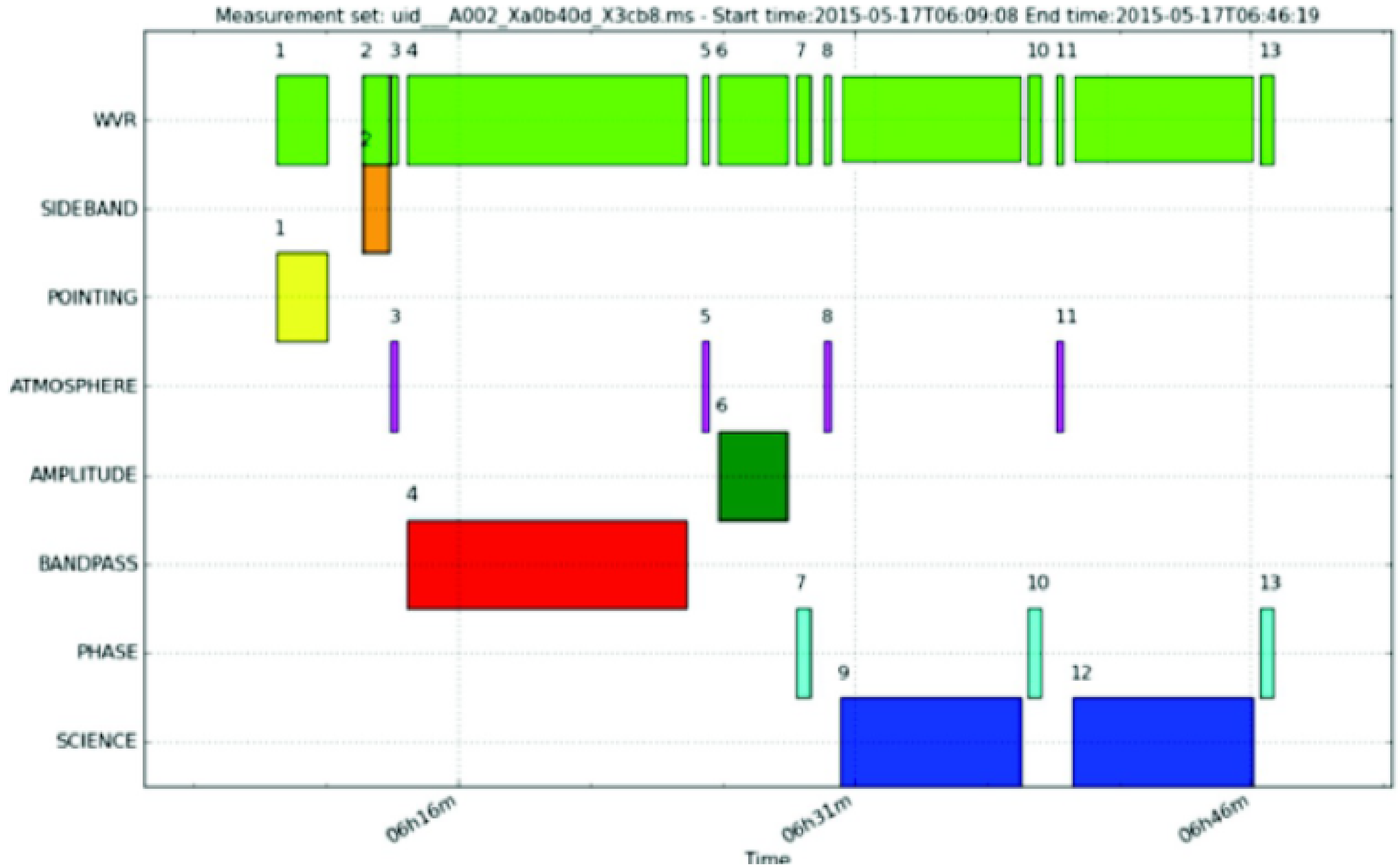
Φ vs t: Troposphere

% corr → K: Tsys

K→ Jy

A, Φ vs ν

Φ vs t: Troposphere



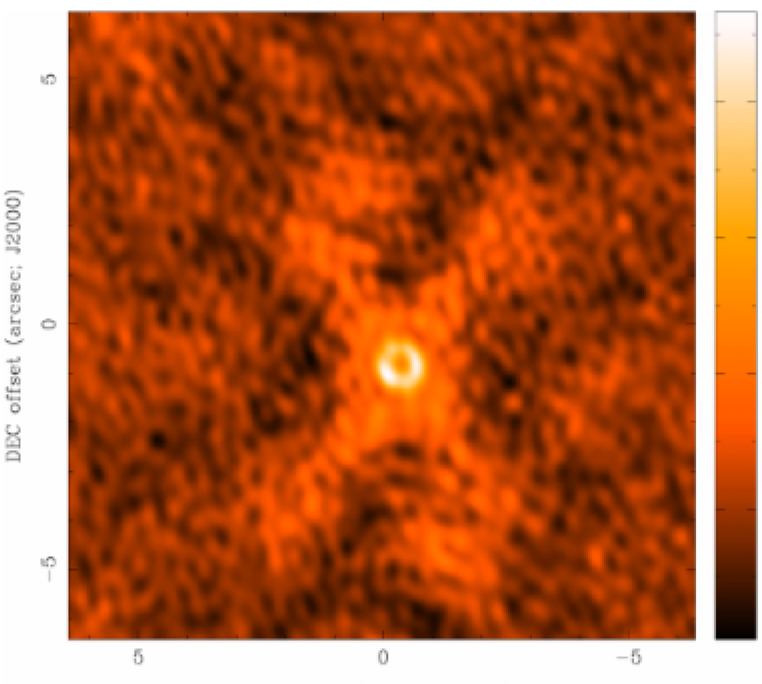
Deconvolution

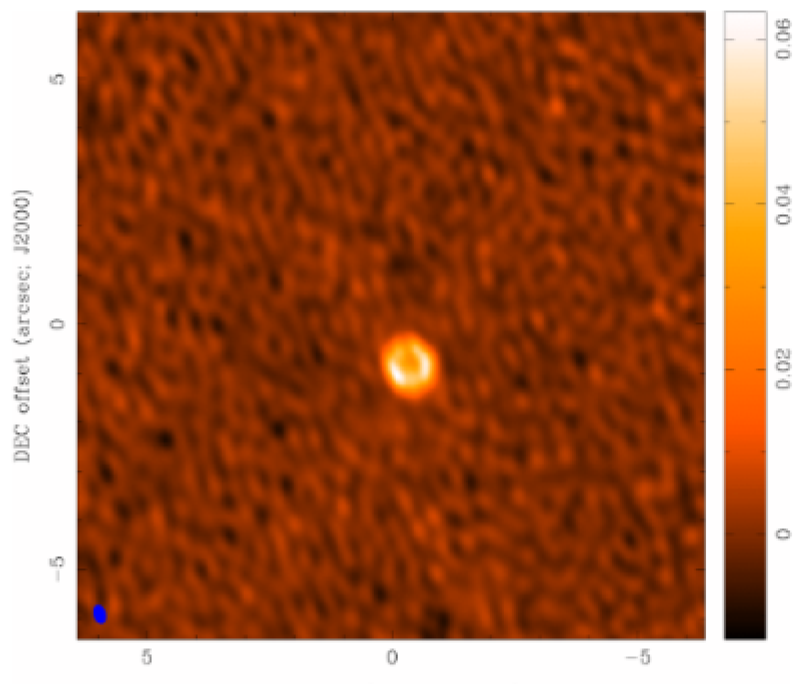
$$R(\boldsymbol{B}) = \iint_{\Omega} A(\boldsymbol{s}) I_{\nu}(\boldsymbol{s}) \exp\left[\mathrm{i}\, 2\pi\nu \left(\frac{1}{c} \boldsymbol{B} \cdot \boldsymbol{s} \right) \right] \mathrm{d}\Omega \, \mathrm{d}\nu$$

- Aims to find a sensible model of I(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(s) and a priori assumptions about I(s)

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

Dirty Image





Cleaned Image

Deconvolution - Classic CLEAN

Hogbom 1974, Clark 1980, Cotton-Schwab 1984

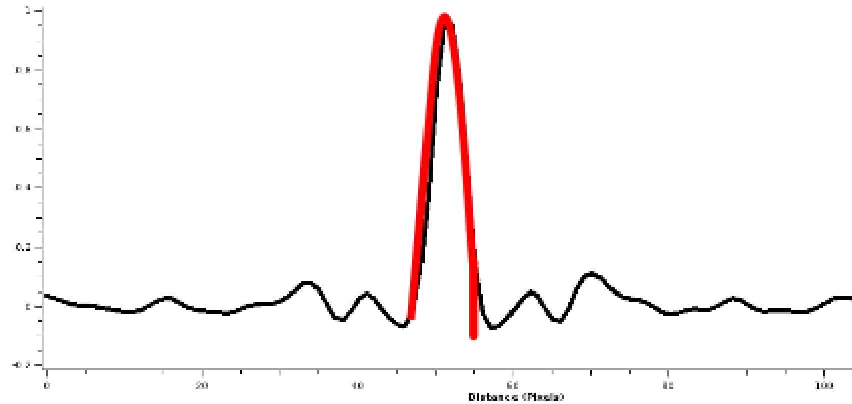
Basic assumption: **each source is a collection of point sources**

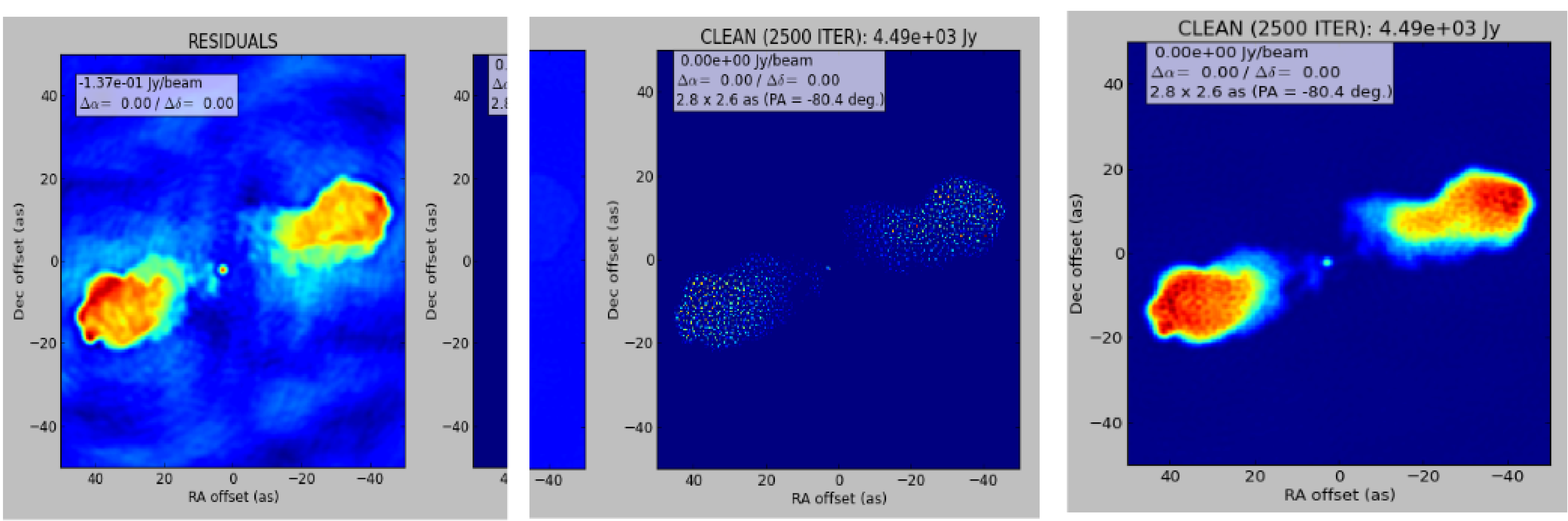
- Initializes the residual map to the dirty map and the Clean component list to an empty value
- Identifies the pixel with the peak of intensity **(Imax)** in the residual map
- and adds to the clean component list a fraction of Imax = g Imax
- **Multiplies the clean component by the dirty beam** and subtract it to
- the residual
- Iterates until **stopping** criteria are reached
- |Imax| < multiple of the rms (when rms limited),|Imax| < fraction of
- the brightest source flux (when dynamic range limited)
- **Multiplies the clean components by the clean beam** an elliptical
- gaussian fitting the central region of the dirty beam

  → restoring

Dirty beam

Clean beam



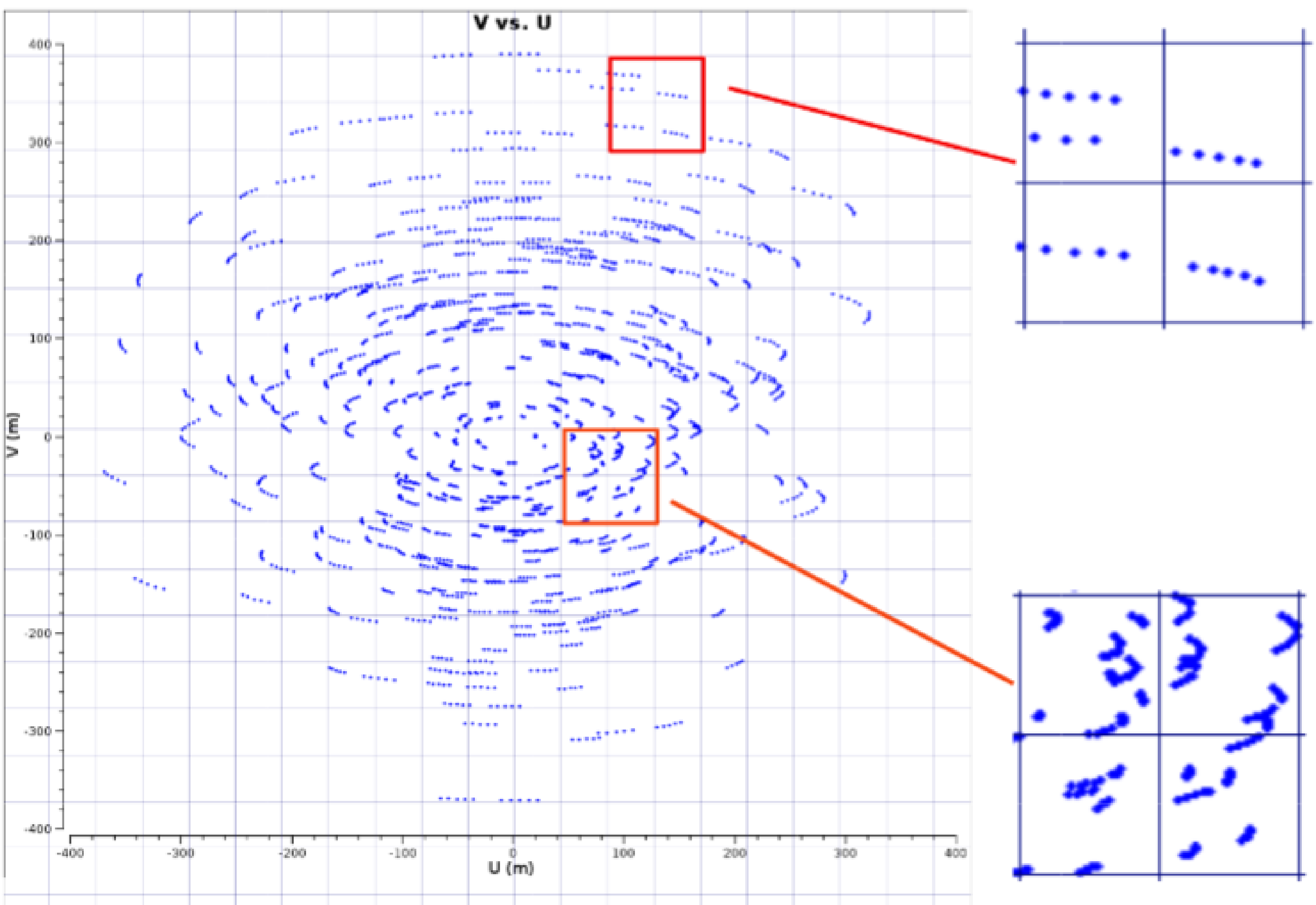


But

…. some uv ranges are sampled more than others

- **Gridded visibilities are** → $V(u,v) = W(u,v)\ V'(u,v)$

Tipically, short spacing
are sampled more than long



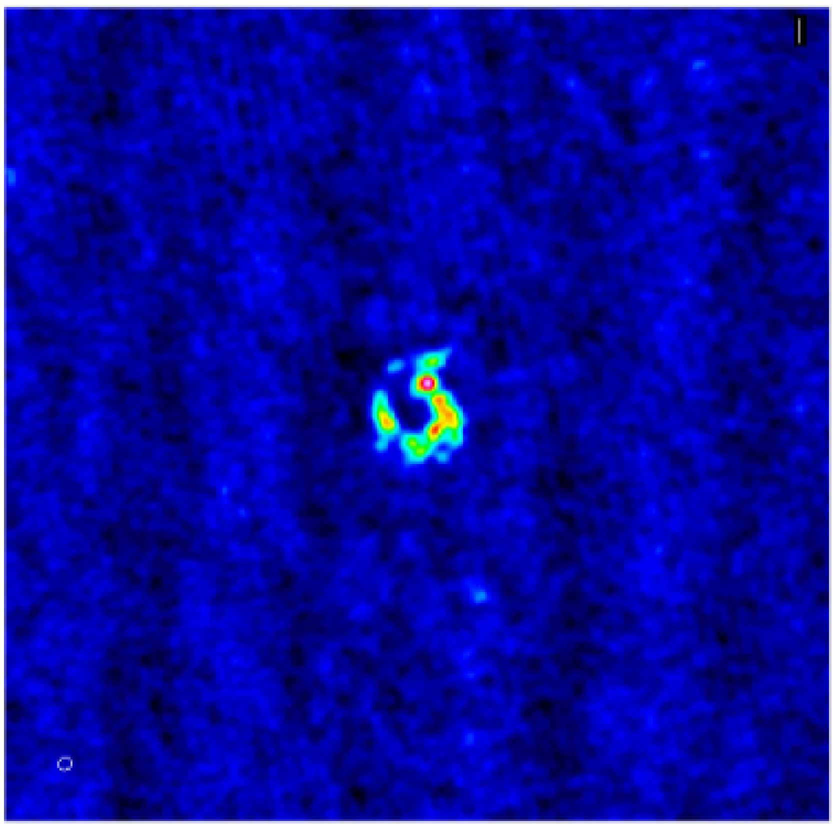
Different weighting **W(u,v)** :

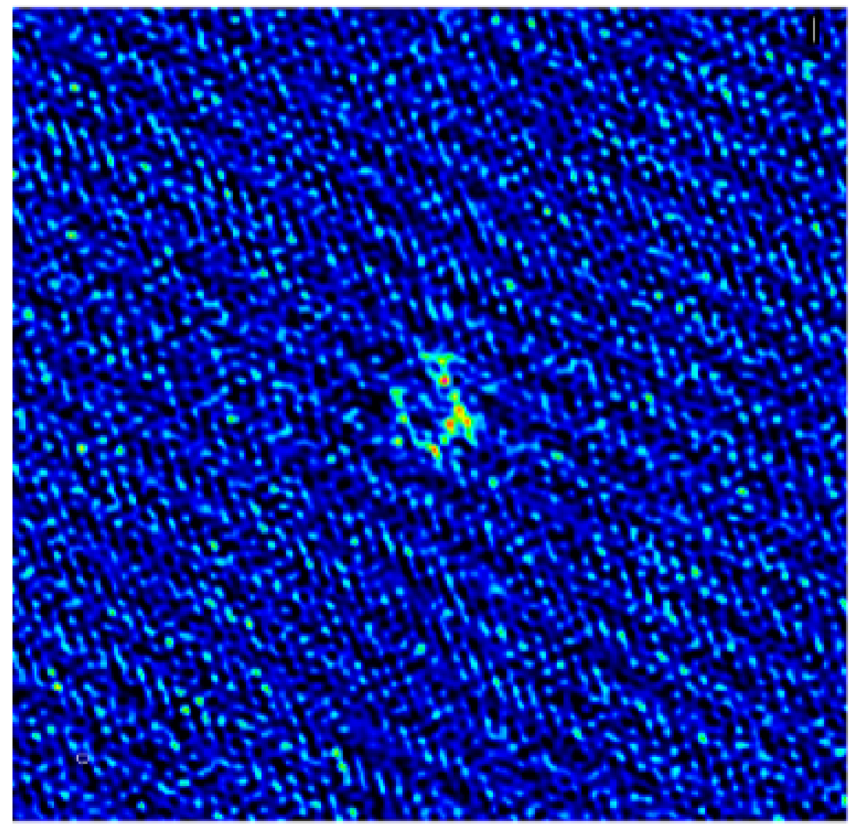
- Uniform:
  long baseline, < ϑres
- Natural:
  short baseline, < rms
- **Briggs:** intermediate
  → provided in the ALMA archive images

Weighting effects on the image

Natural
res = 0.29" x 0.23"
rms = 0.8 mJy/beam

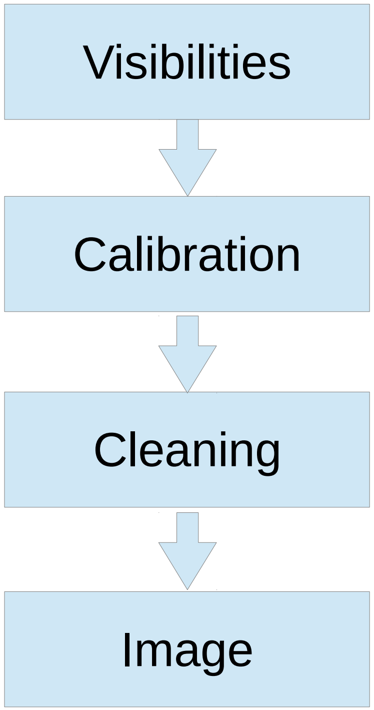
Uniform
res = 0.24"x0.17"
rms = 3 mJy/beam





Note: Other different final images are possible (uv tapering, uv range selection, multi-scale, wide field) depending on the science case

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 …

Different weighting schemes generates different images

For more details about interferometry:

- Thompson, Moran, Swensson, *"Interferometry and Synthesis in Radio Astronomy"*

- *Wilson, "Introduction to mm and submm Astronomy" (2009)*

The Atacama Large Millimeter Array

ALMA rationale

- The Atacama Large Millimeter Array is a **mm-submm reconfigurable interferometer**
- Inaugurated March 2013 on the Chajinantor 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.

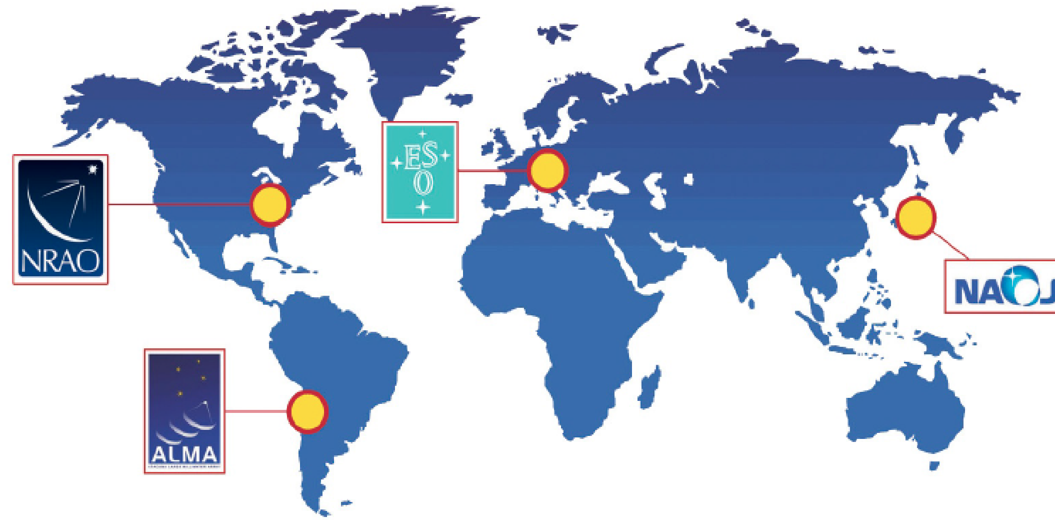
-> high angular resolution and sensitivity
-> galaxy dynamics, AGN core mechanisms,
imaging of exoplanets, comets,
asteroids, ...

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

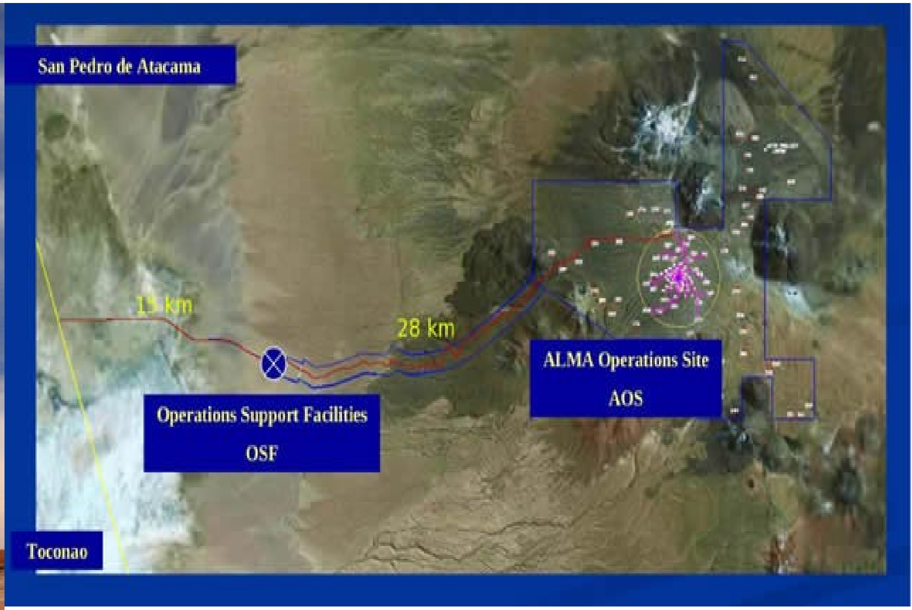


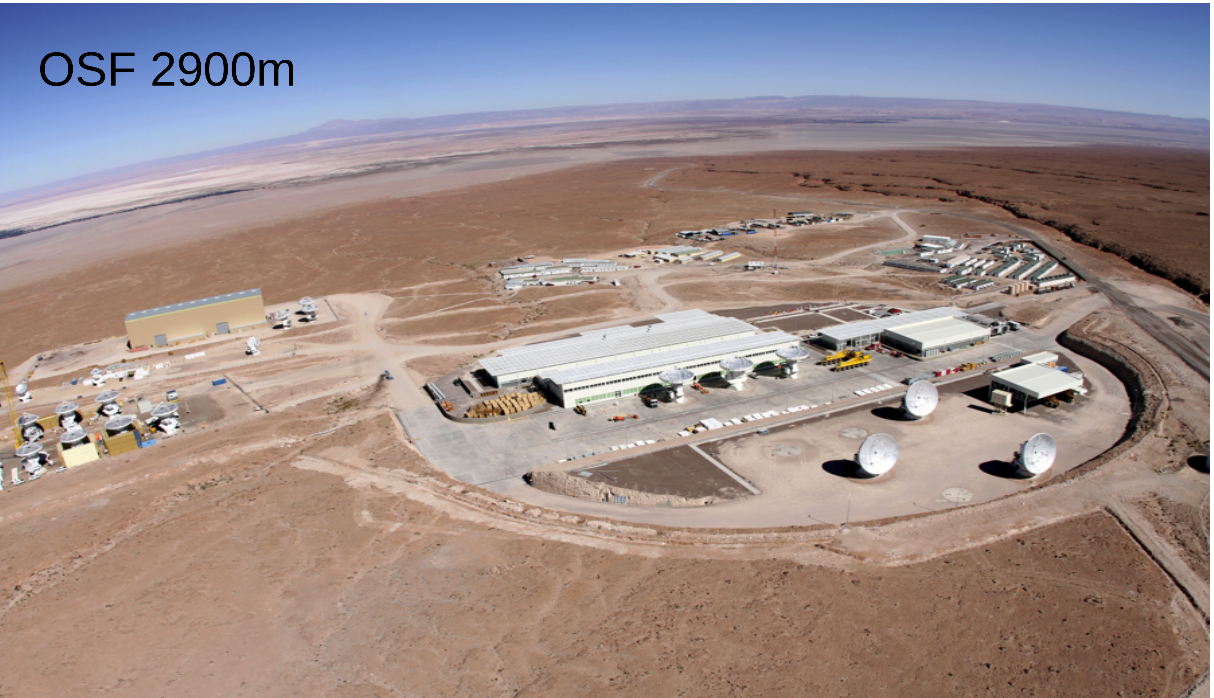
3 Sites in Chile

- 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

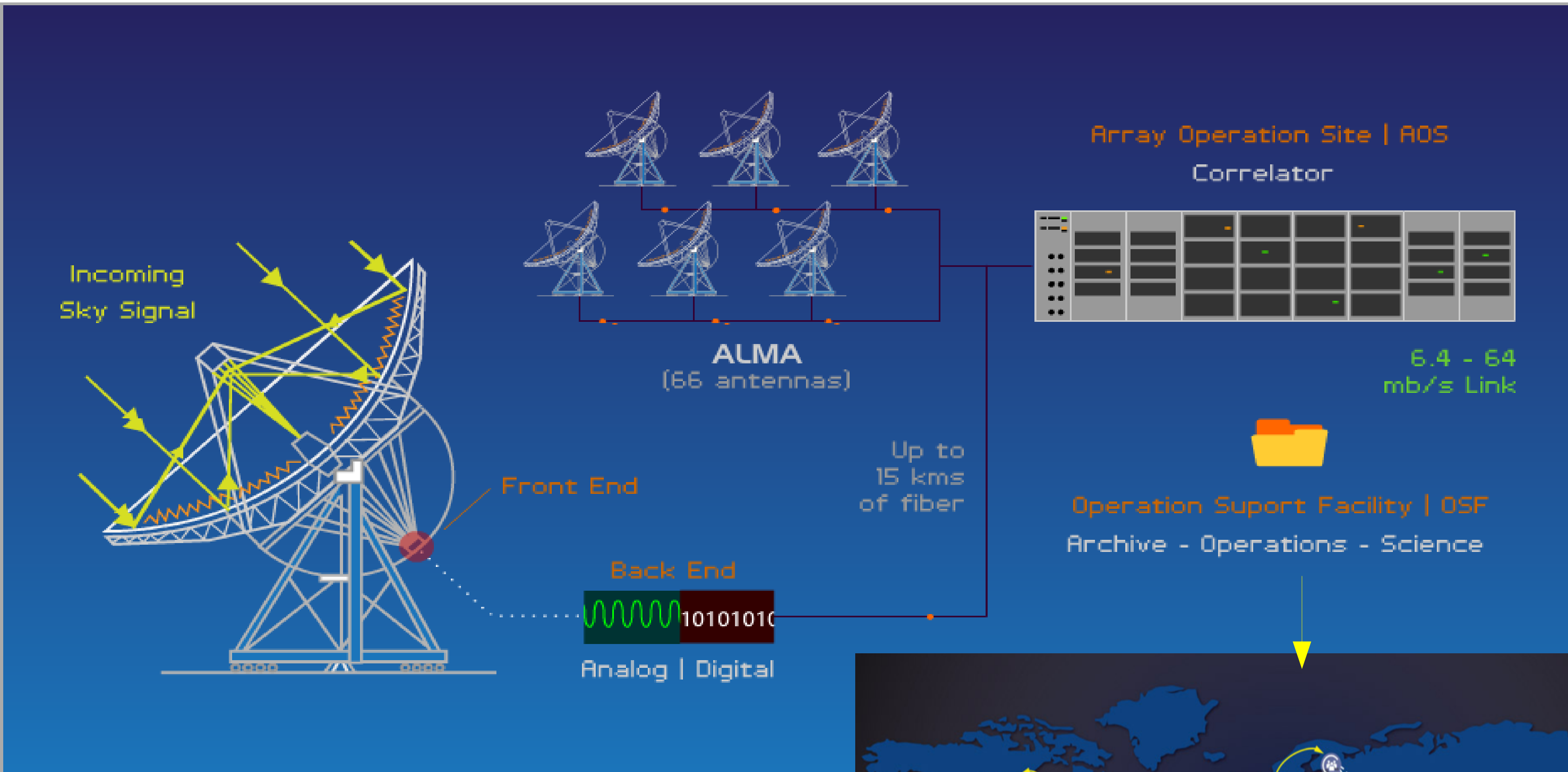
ALMA sites


AOS 5000m


San Pedro de Atacama
15 km
28 km
ALMA Operations Site
AOS
Operations Support Facilities
OSF
Toconao


OSF 2900m

ALMA data flow



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

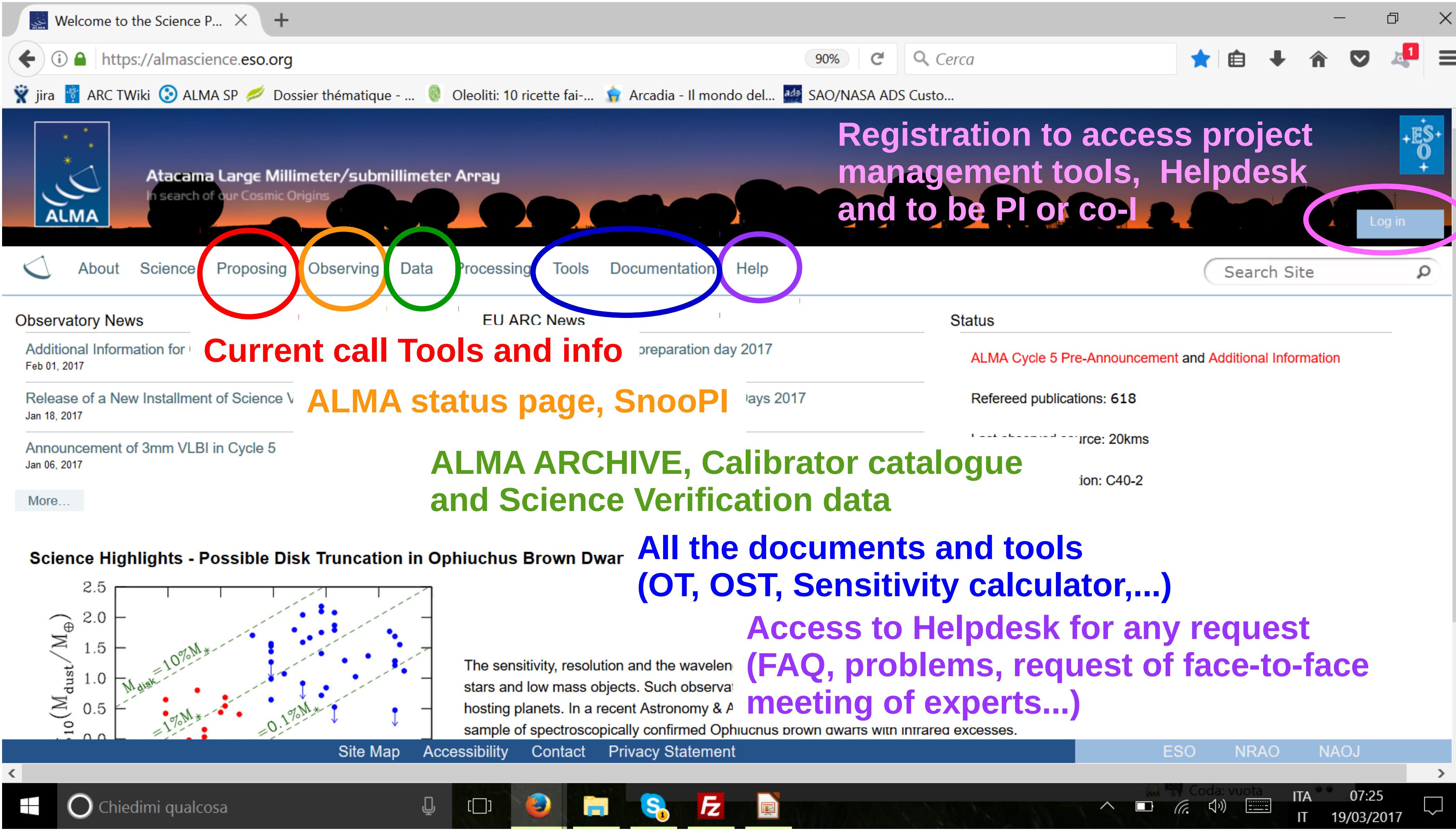
Each ARC hosts an archive mirror.

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 (schools, workshops, tutorials, ...)
  - Phase 1 (proposal preparation)
  - Phase 2 (scheduling block preparation)
  - Data analysis, Archive mining
  - F2F user support, Helpdesk

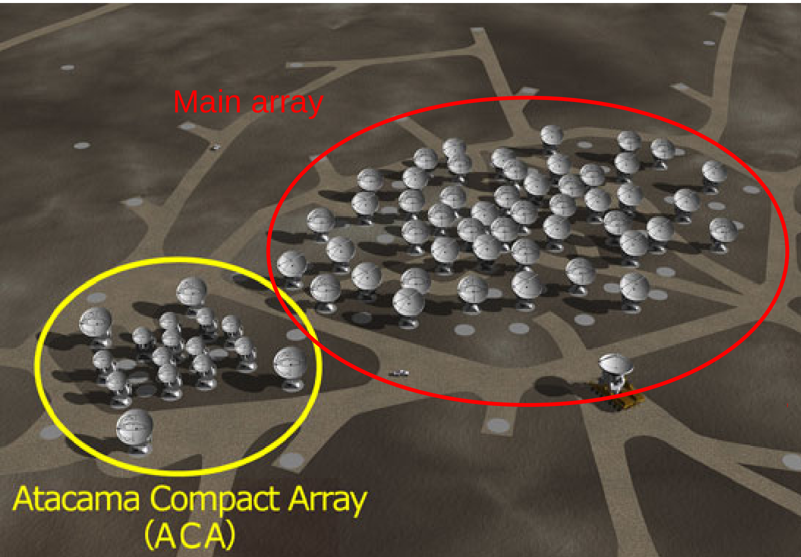
Enter the ALMA world through the ALMA Science Portal

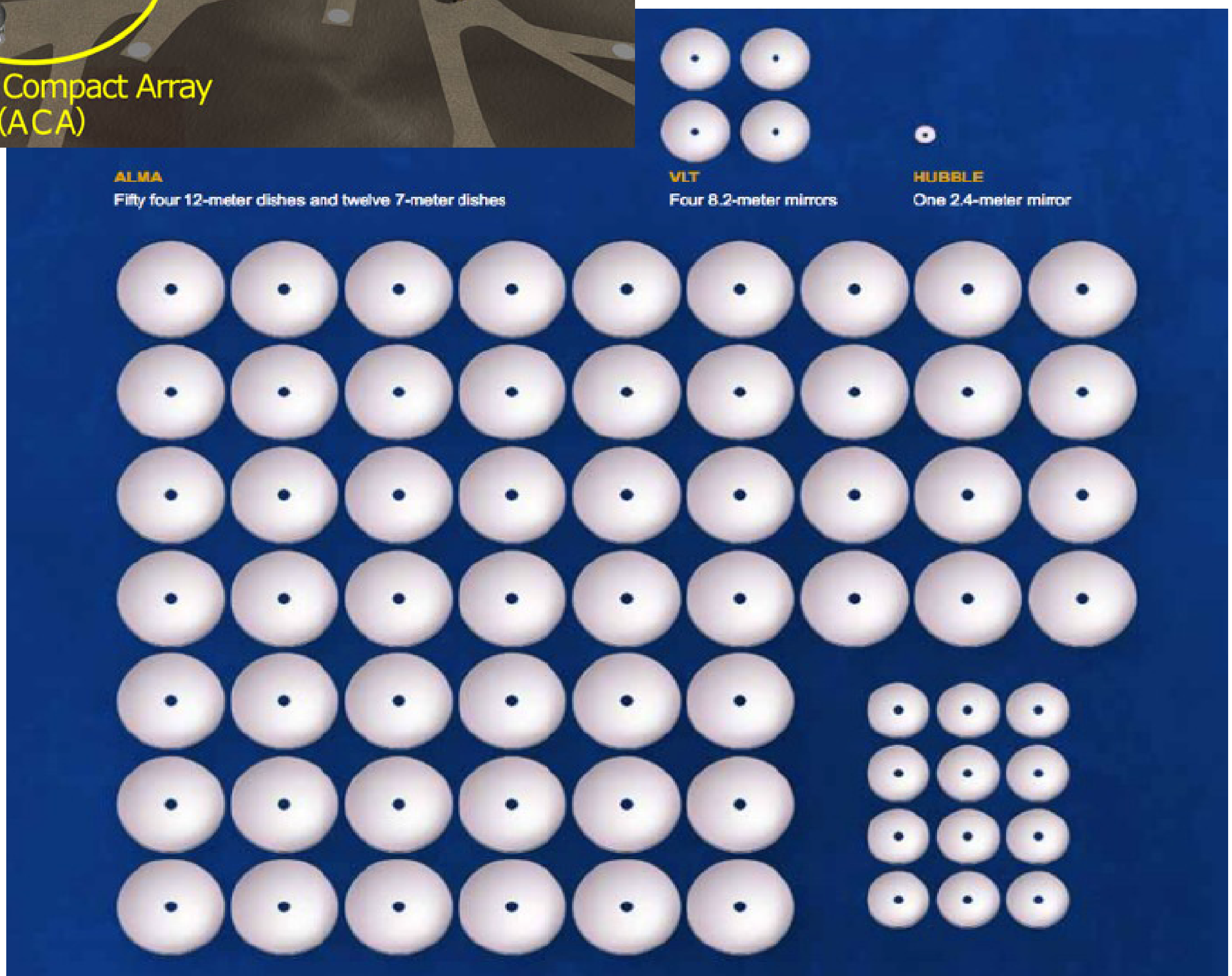
http://almascience.eso.org/



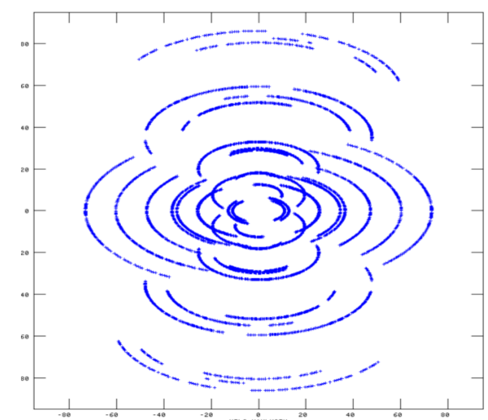
ALMA array(s)

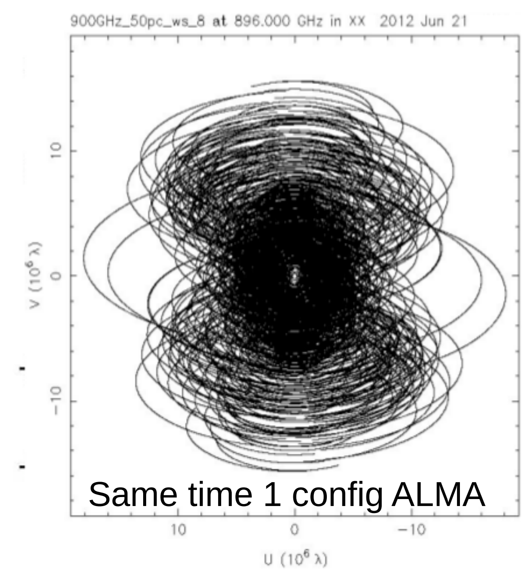
Antennas : **50x12m** main array + (**12x7m + 4x12m TP**) ACA
Baselines : **15m ->150m-16km** + **9m->50m**





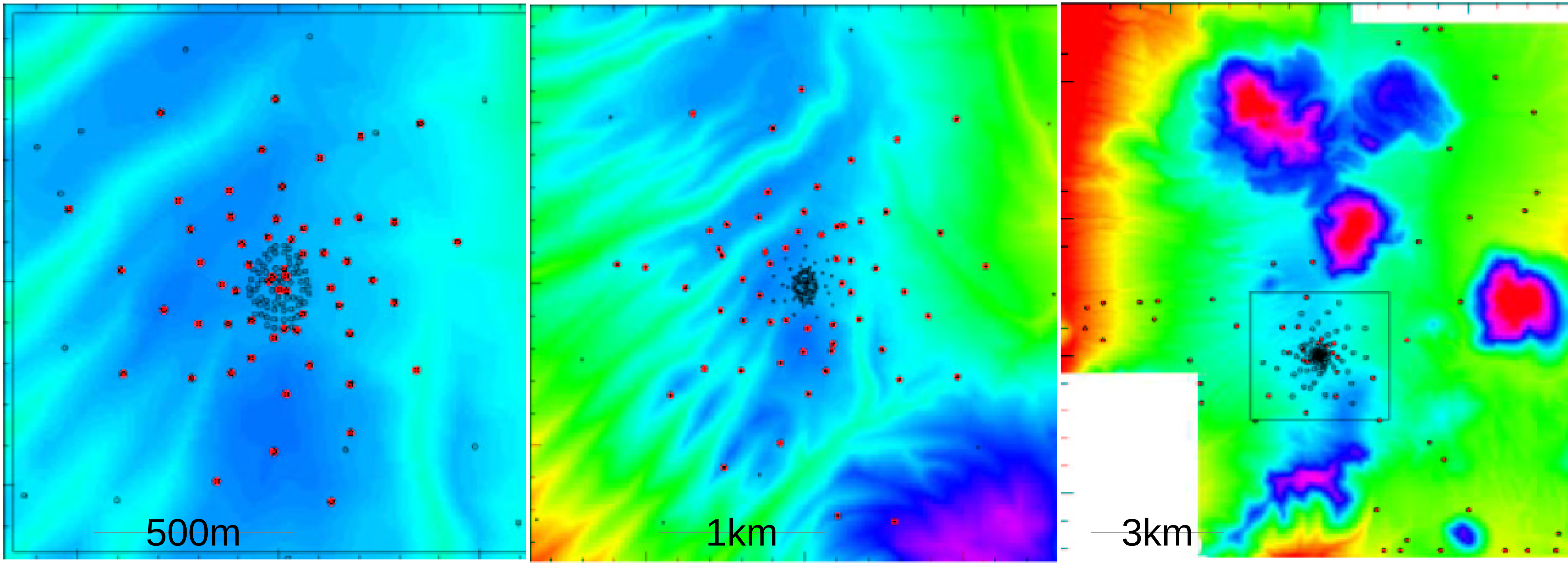
Few hr 2 config OVRO

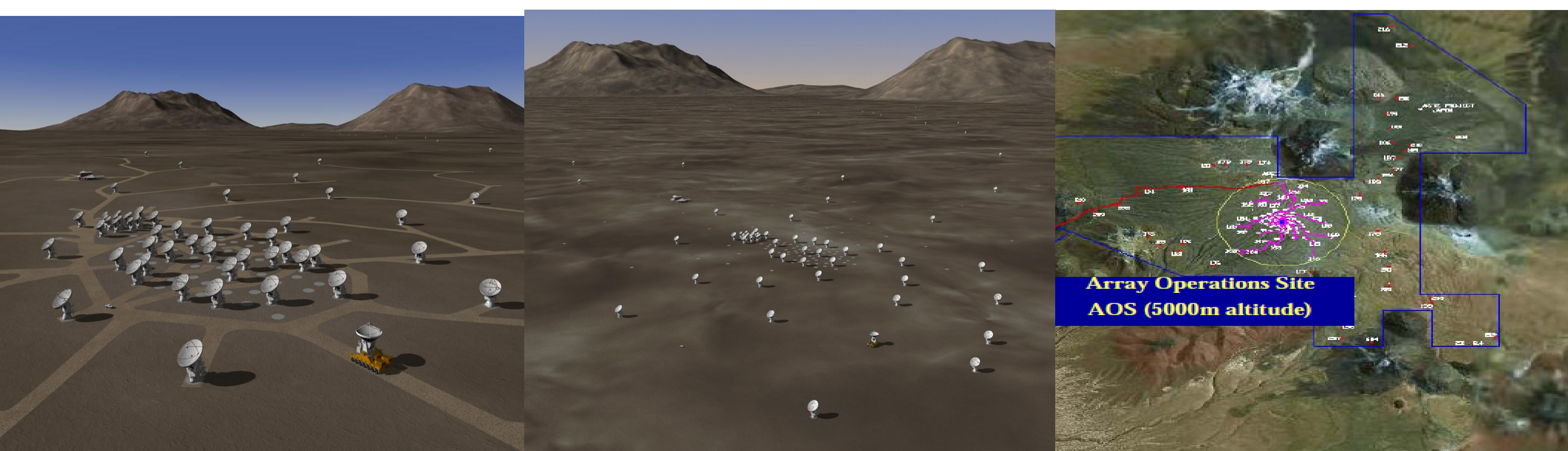




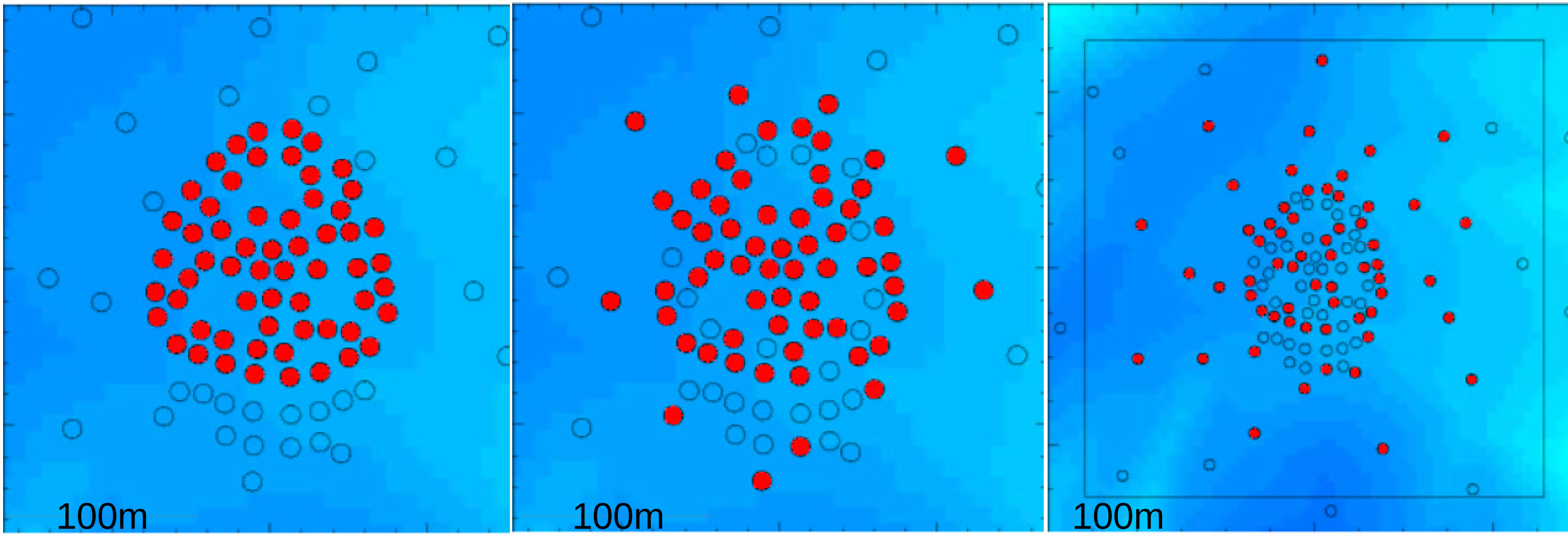
Same time 1 config ALMA

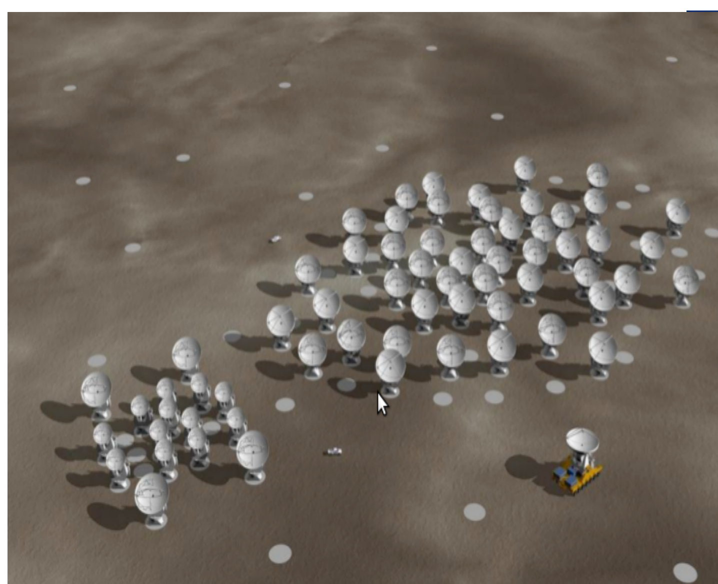
ALMA reconfiguration





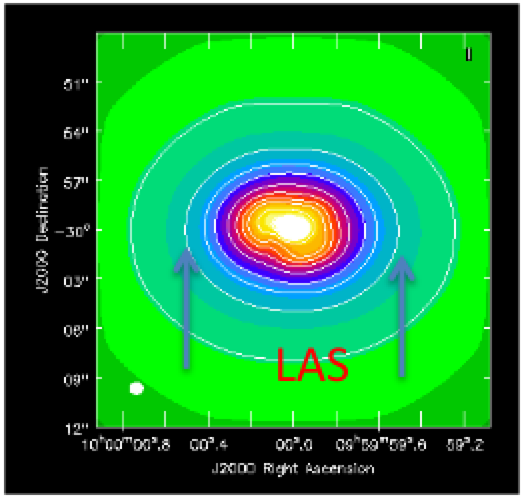
ALMA reconfiguration



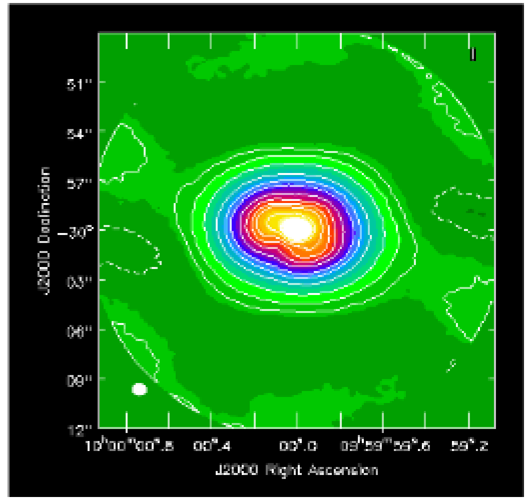


ALMA array(s)

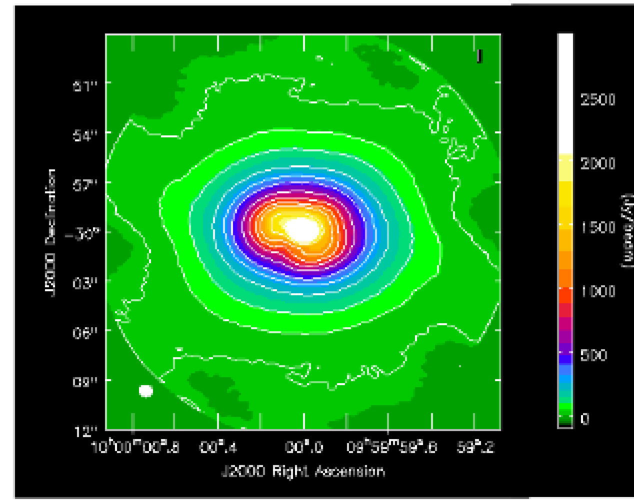
MODEL



12-m image

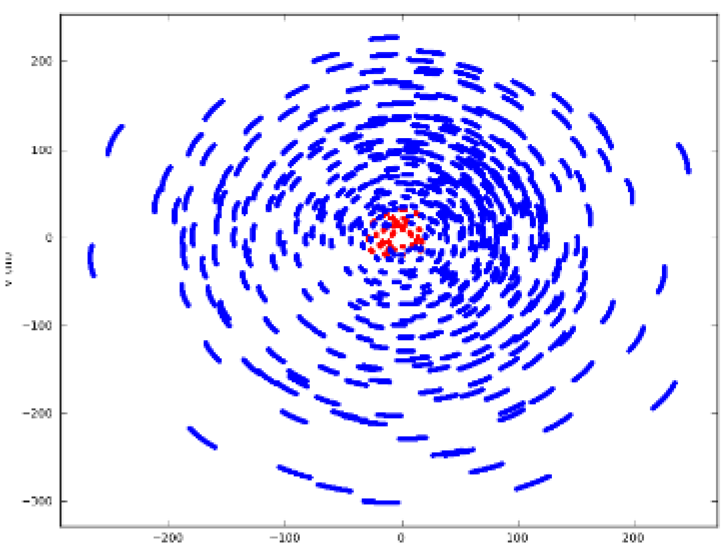


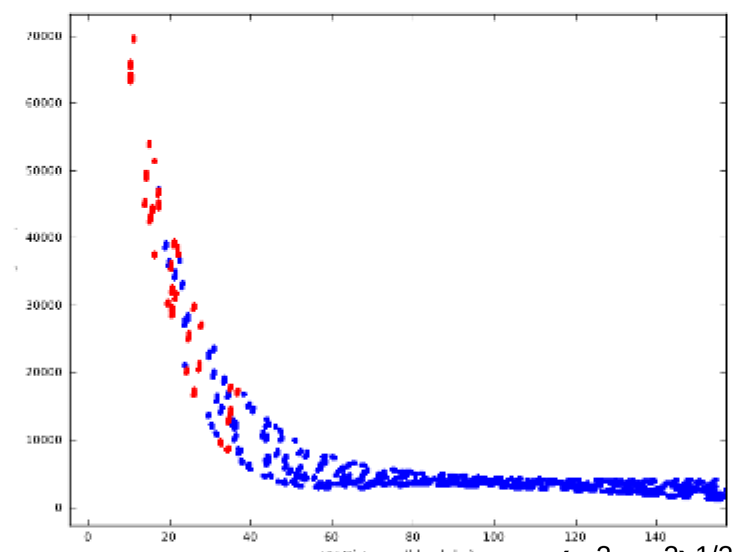
12m+7m Image



Restored flux 11000 Jy 7000 Jy 9000 Jy

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

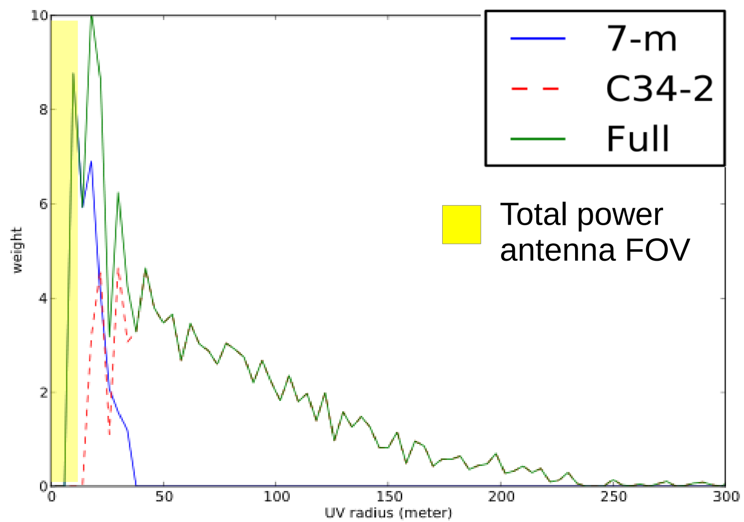




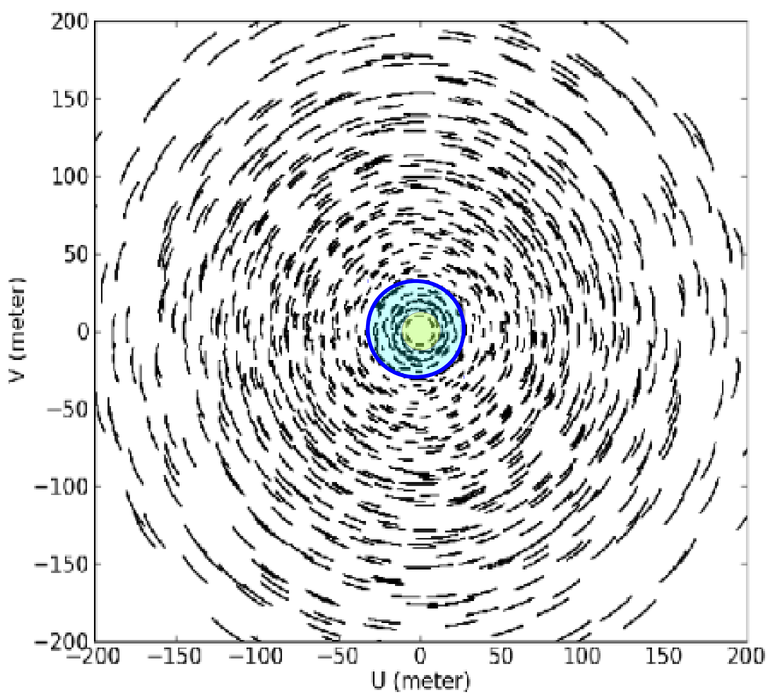
$(u^2+v^2)^{1/2}$

U-V coverage (red=ACA, blue=ALMA12m) Amplitude vs uv-distance

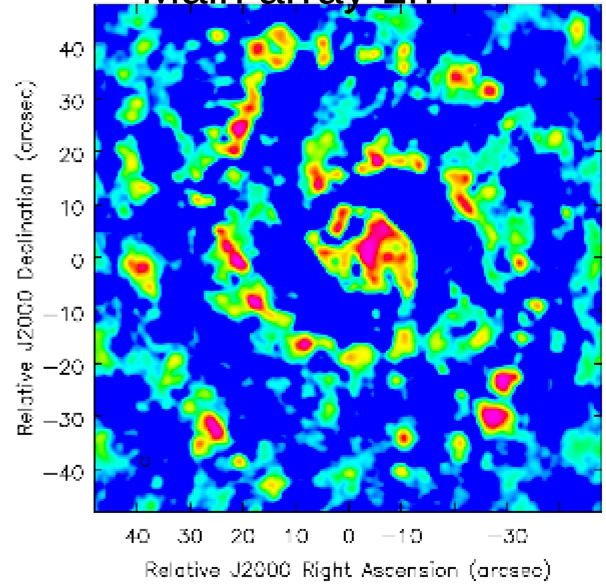
ALMA array(s)



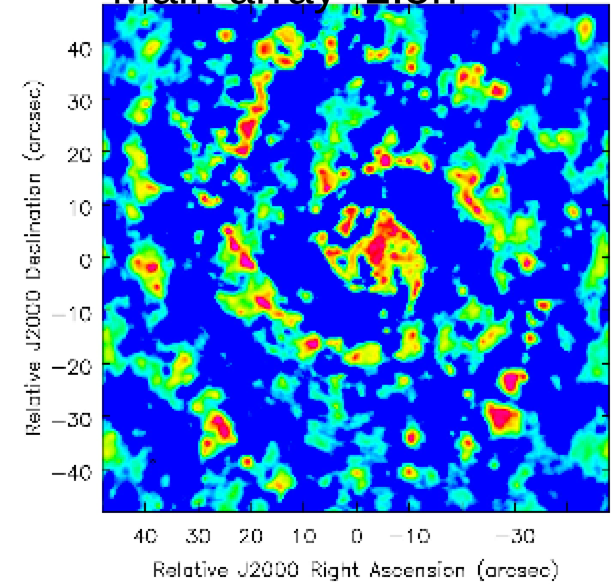
$(u^2+v^2)^{1/2}$

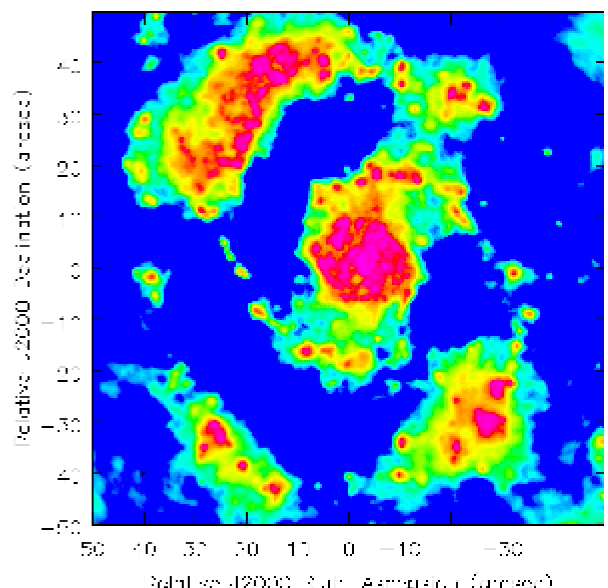


Main array 1h

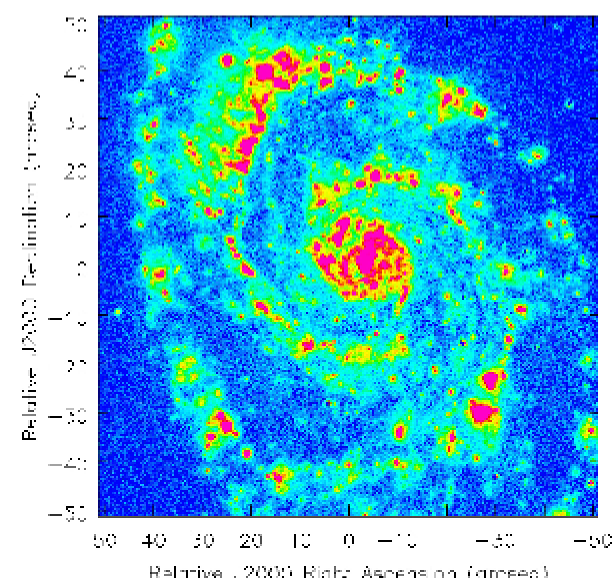


Main array 2.5h





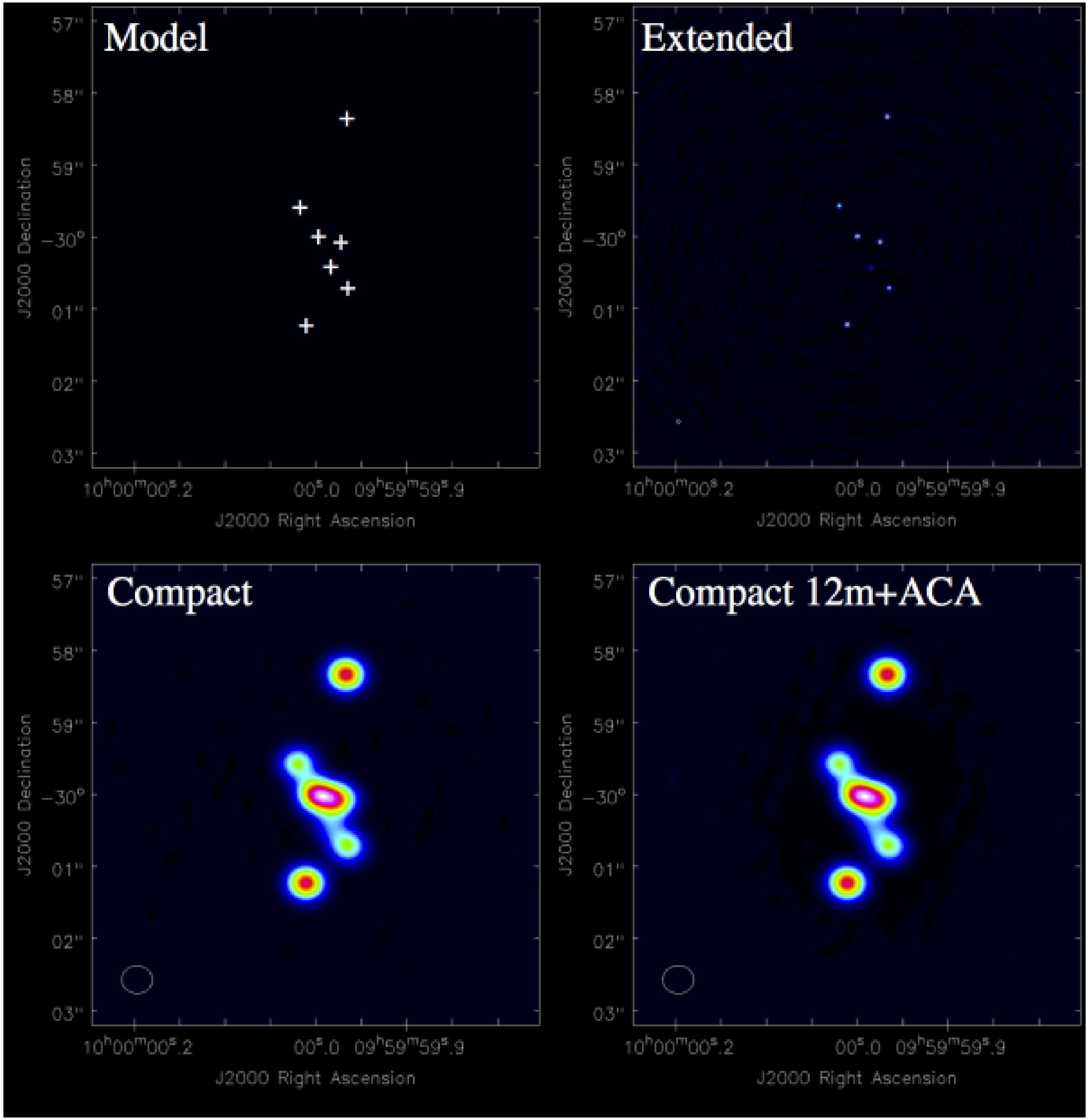
Main array+ ACA



Model M51

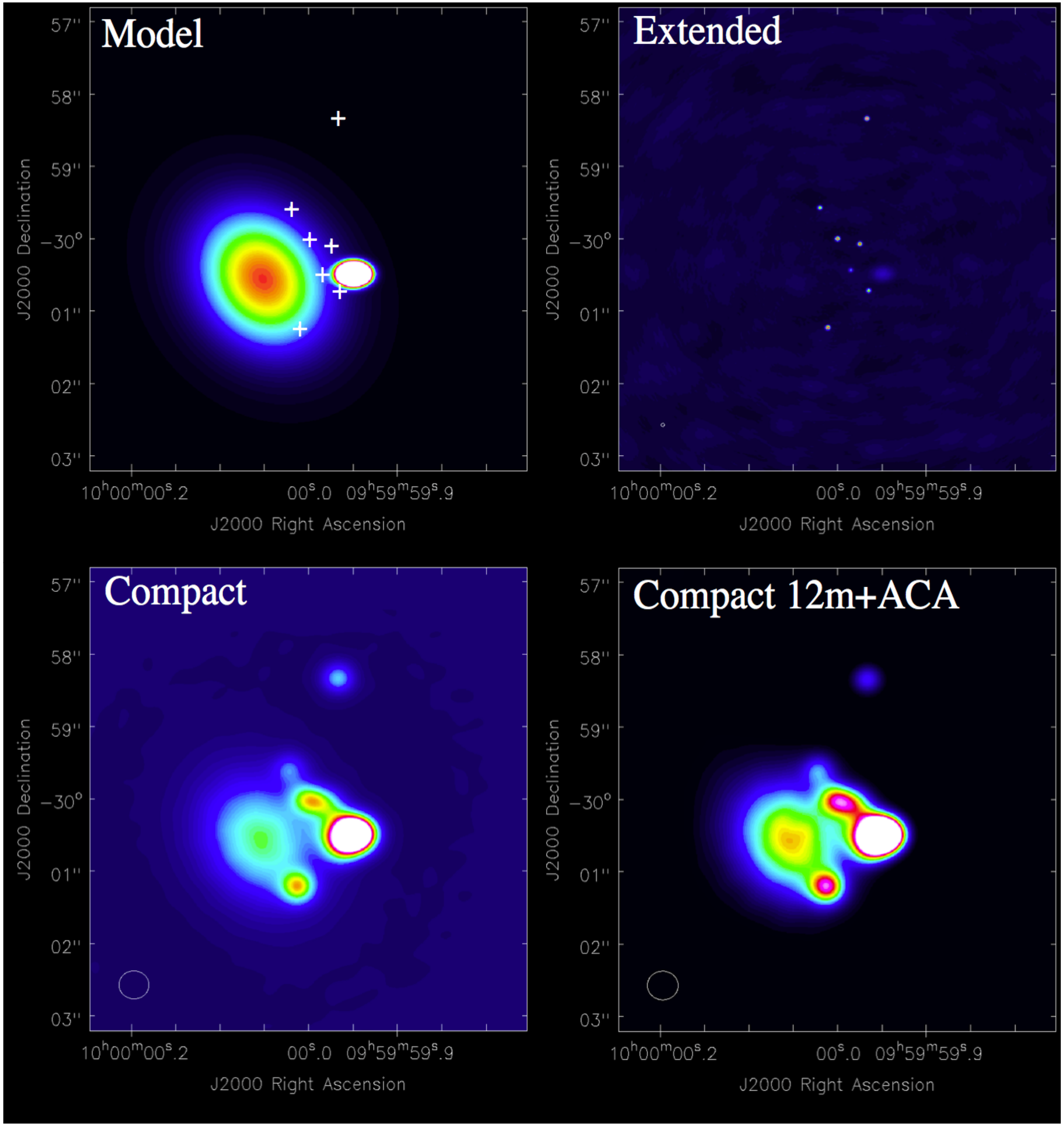
ALMA array(s)

Main array
for compact
objects



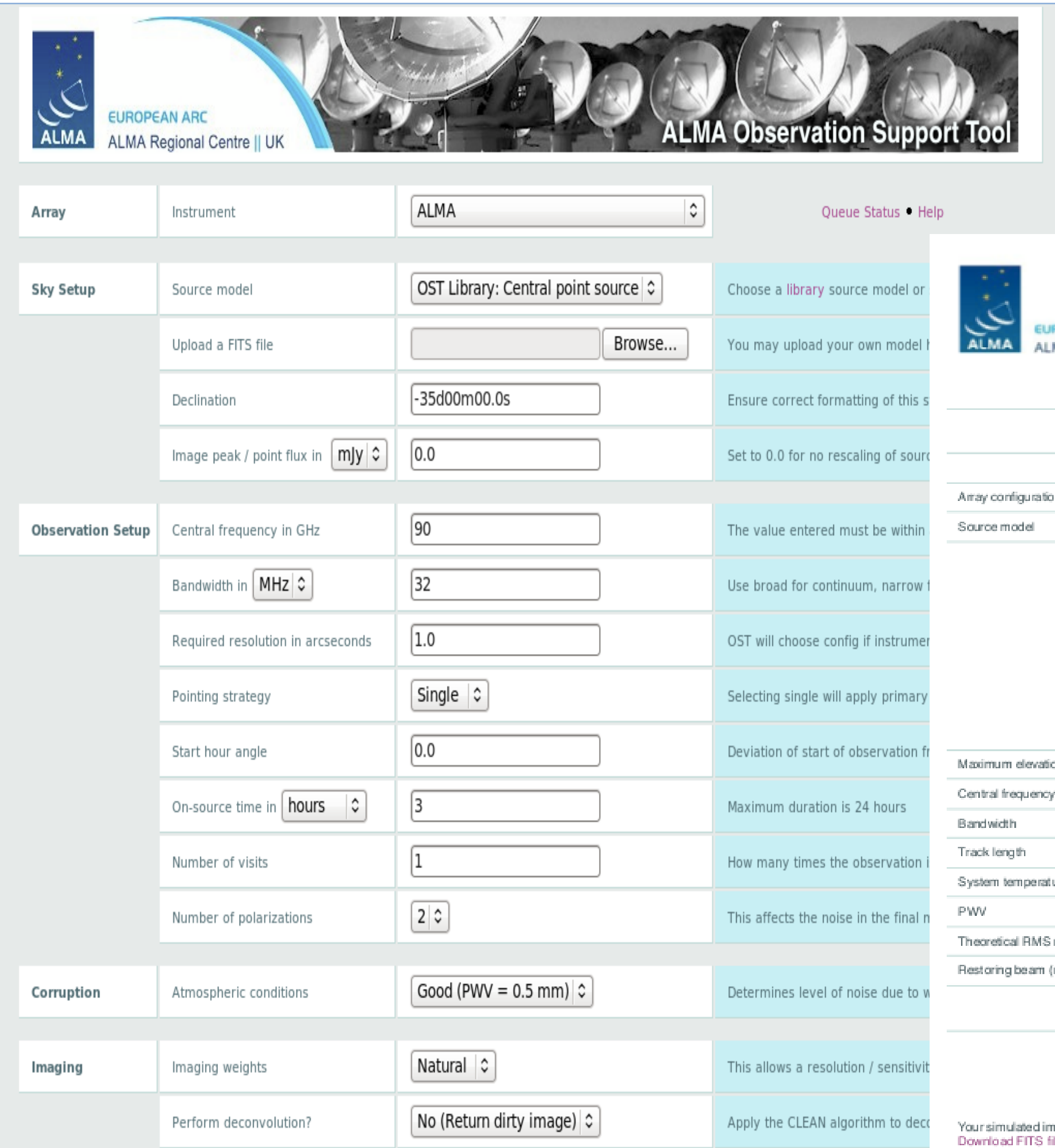
ALMA array(s)

ACA
for extended
objects



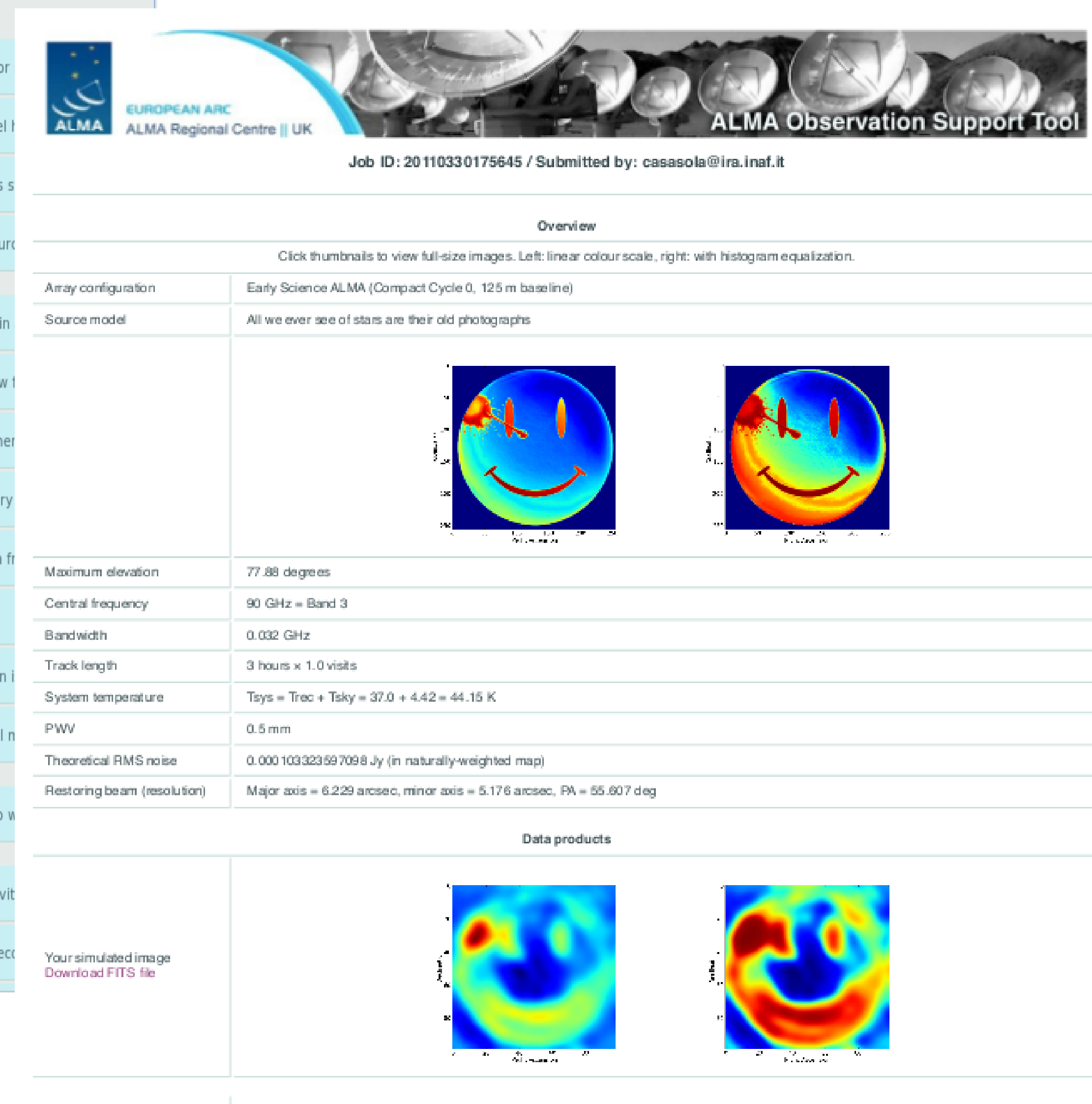
Make your ALMA simulations (Observation Support Tool)

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

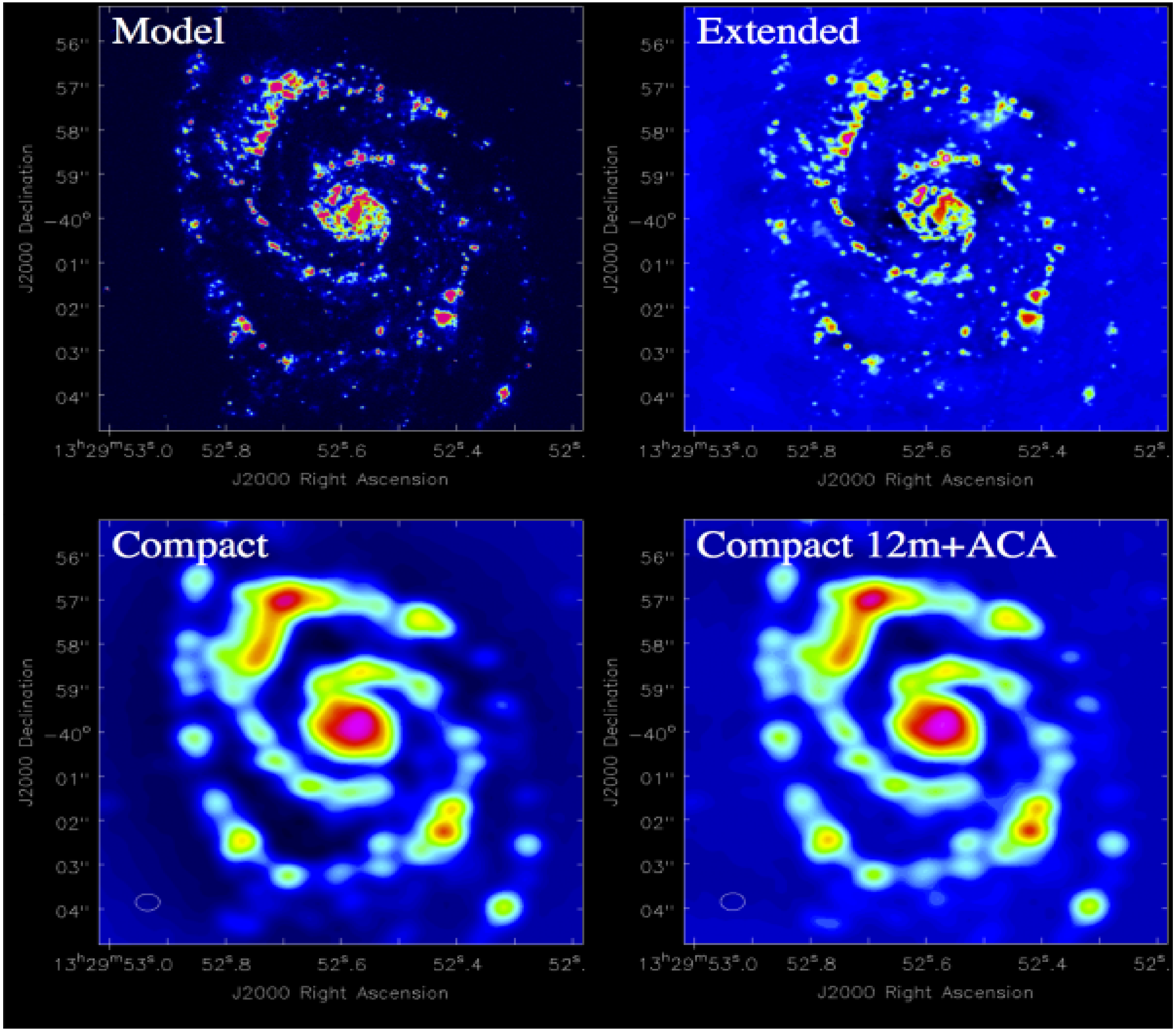


Submit a request for a full simulation of ALMA capabilities for your target

Receive the results via e-mail



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



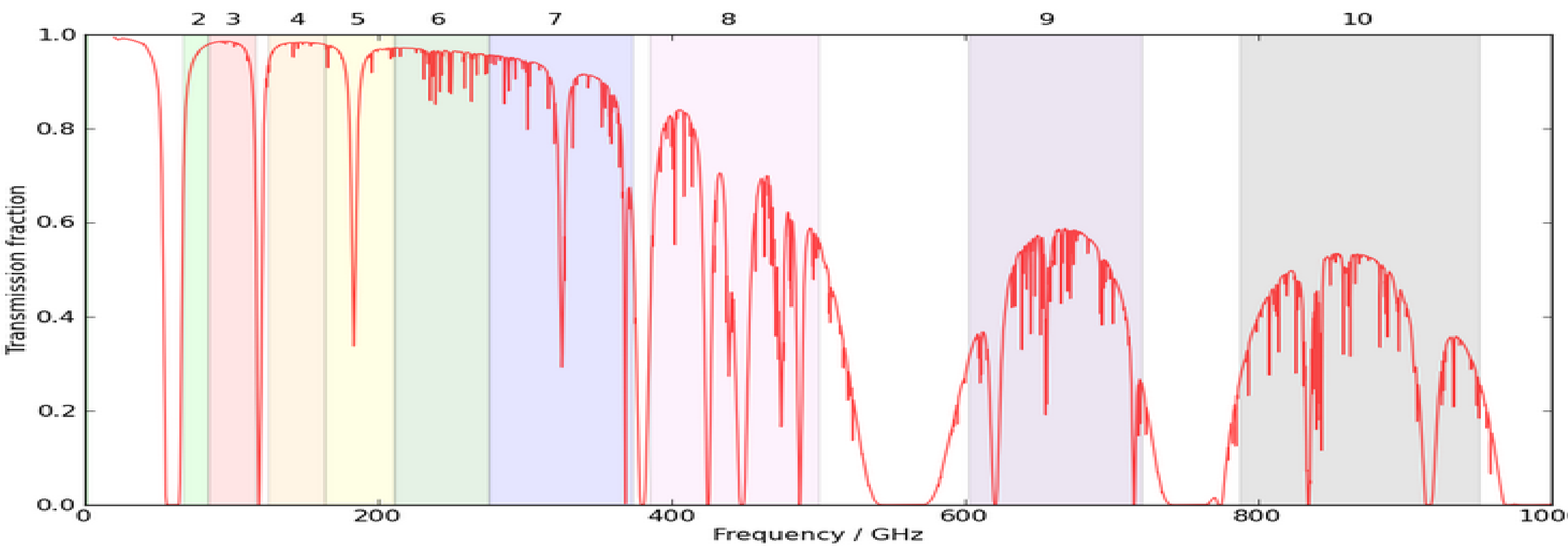
The task **simobserve** generates a data set with simulated visibilities based on an input model image.

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

Full Science Capabilities					Most Compact		Most Extended	
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ")	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	—

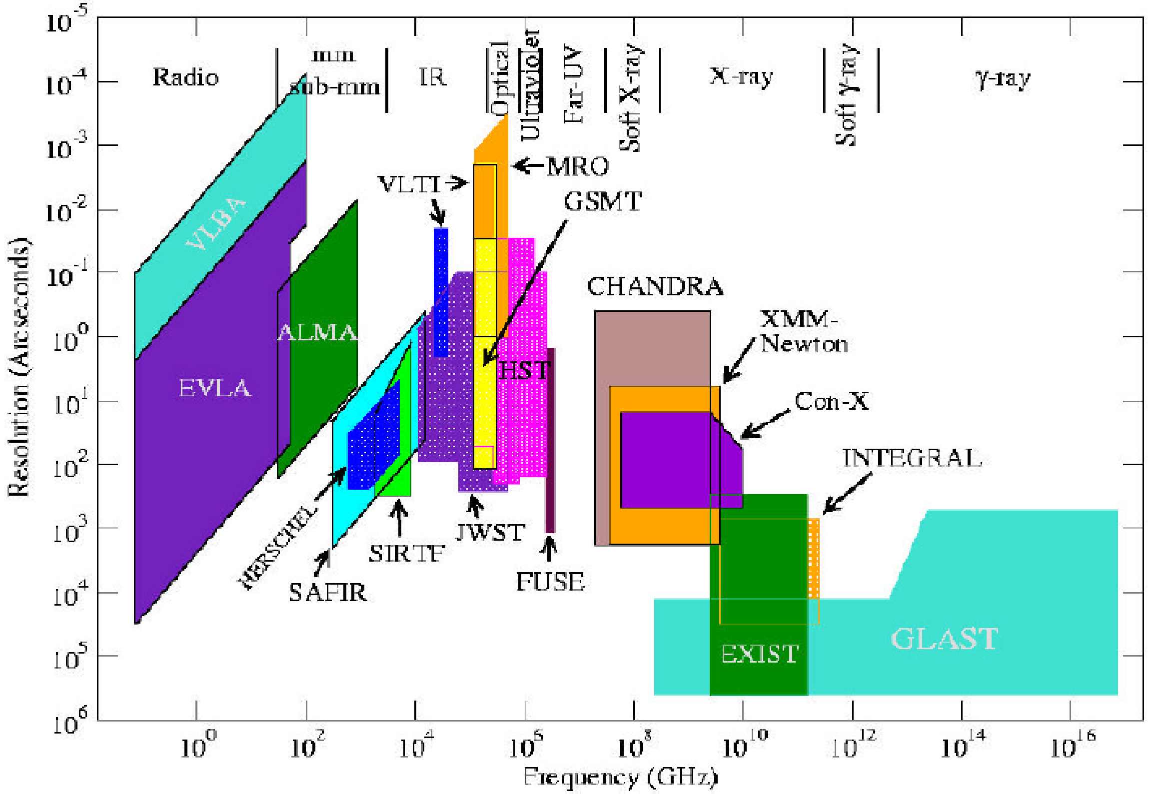


ALMA resolution

- Baselines length: **15m ->150m-16km + 9m->50m**
- Resolution: **0.2” x (300/freq_GHz)x(1km/max_baseline)**
- FOV 12m array: **17”/(300/freq_GHz)**
- FOV 7m array: **29”/(300/freq_GHz)**

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

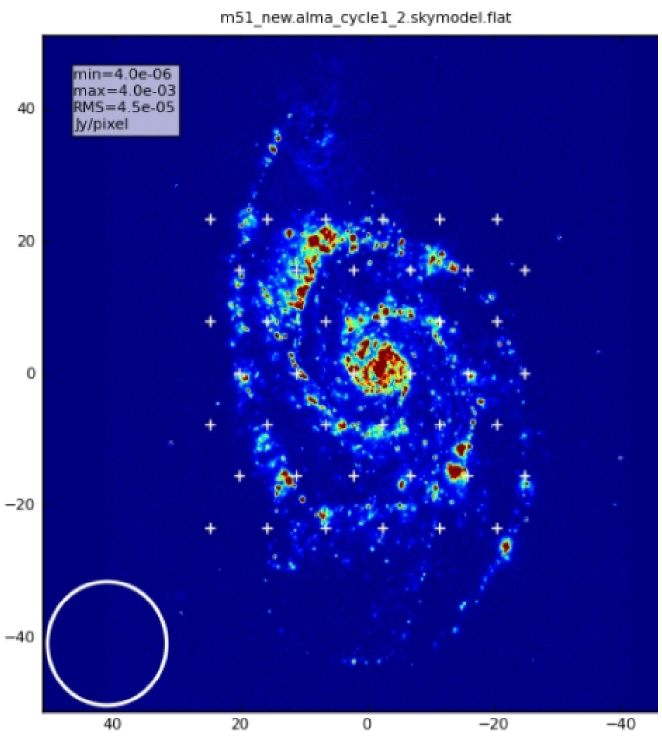
$$\theta = k\lambda/D$$



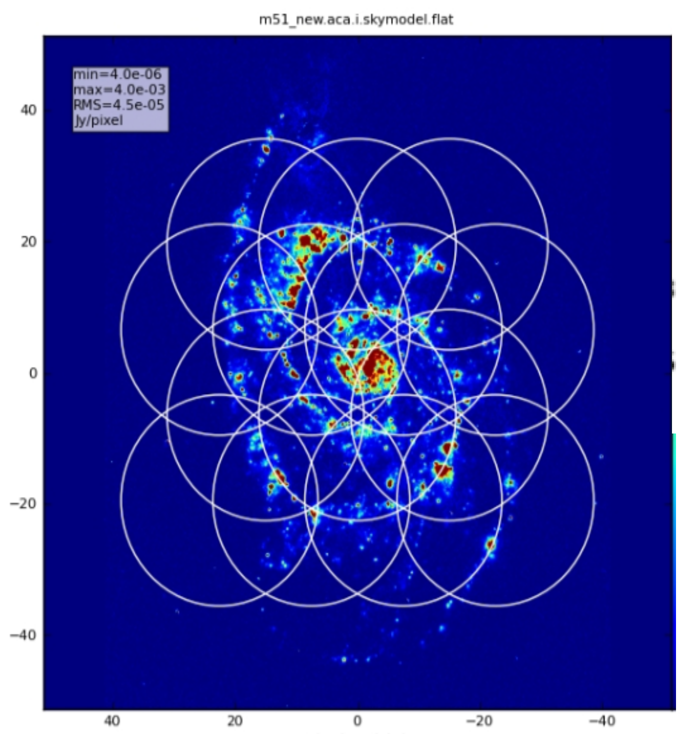
Mosaicking

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

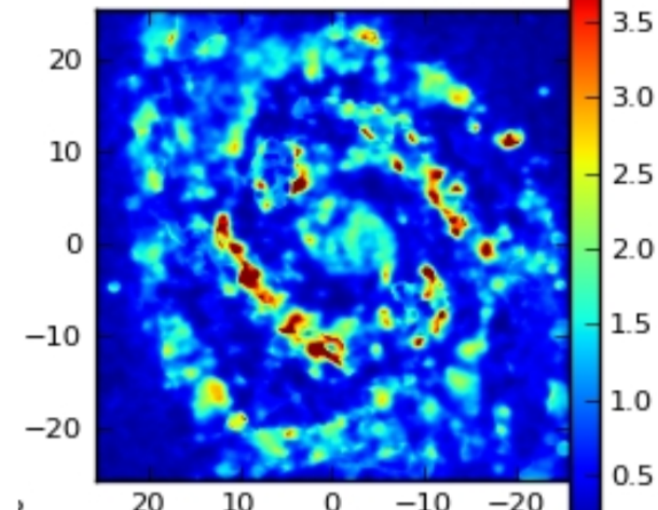
Details in the ranges available to the given baselines can be observed on larger region of the sky by mosaicking the region.



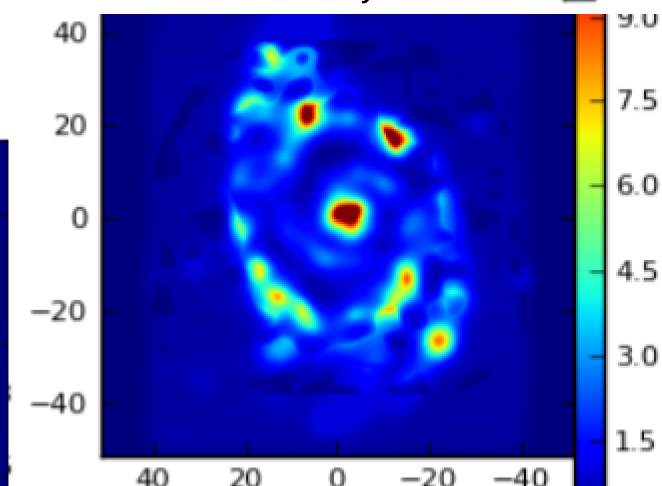
Model & 12m FOV



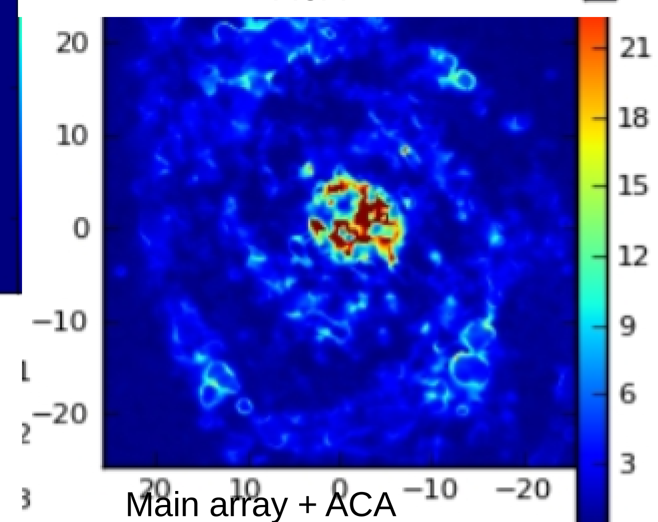
ACA Pointing map



Main array



ACA



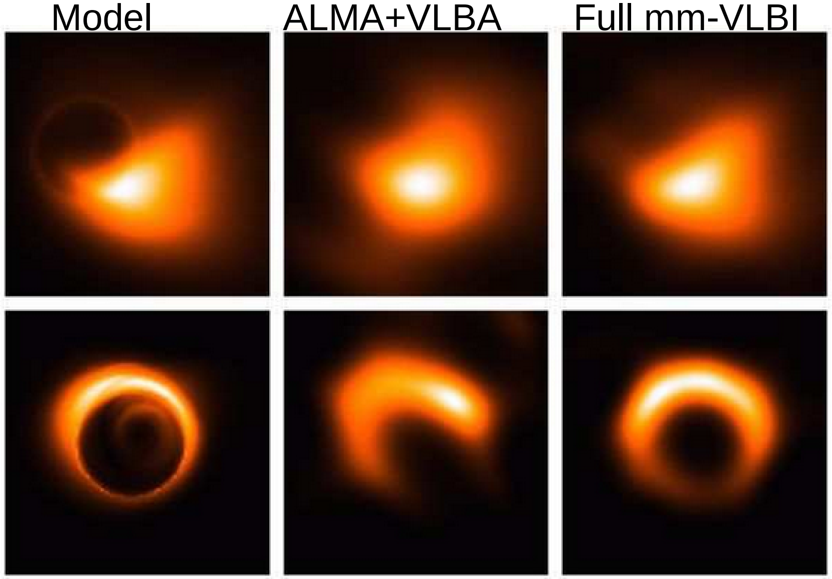
Main array + ACA

mm-VLBI with ALMA

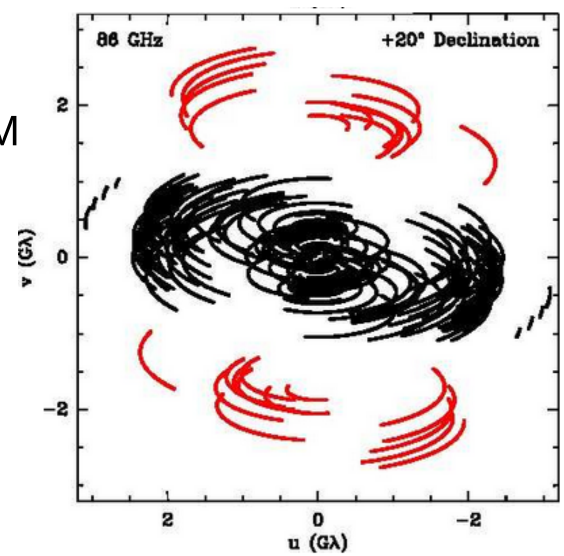
Higher and higher resolutions can be obtained with longer baselines. **VLBI is a worldwide network of telescopes that matches simultaneous observations in different sites, exploiting the phase information to construct a world-wide interferometer.**
At 1 mm and a baseline of 9000 km offers resolution of about 20 microarcseconds

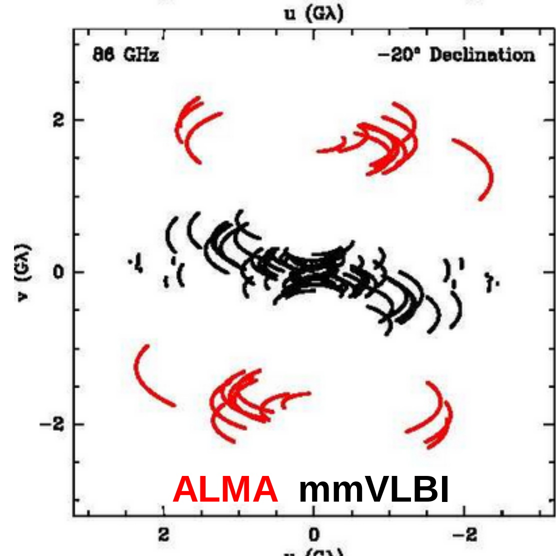
ALMA will be operating in the mm-VLBI since 2017 adding a strength in sensitivity. **Only sources with flux densities >100 mJy have been observable so far; ALMA reduces it by more than an order of magnitude.**

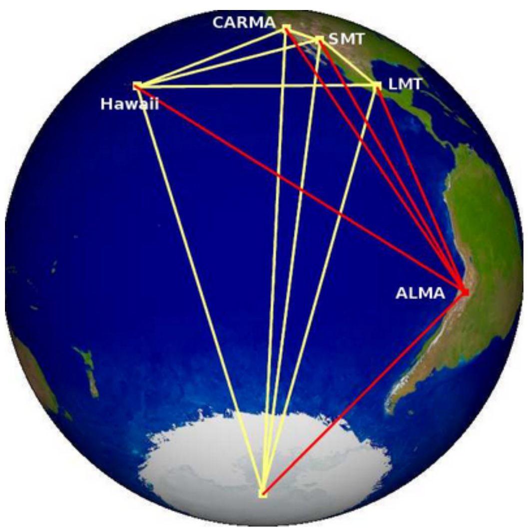
This capability will allow the shadow of the event horizon in the black hole at the Galactic Centre, M the relativistic jet flows in AGN and the dusty winds near stellar surfaces to be imaged

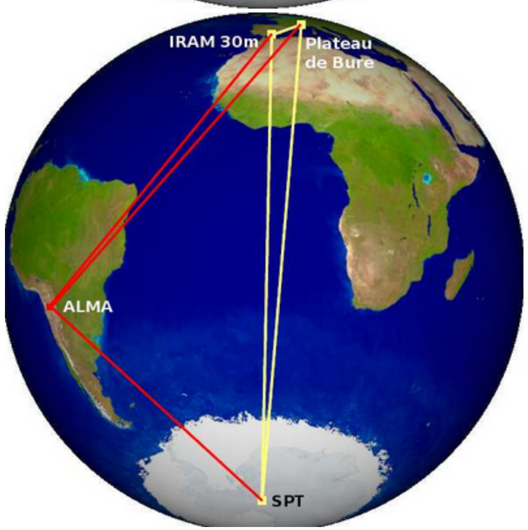


M87 models of different basis of the jet as observed by ALMA+CARMA+SMA+ SMT and by adding also PdBI







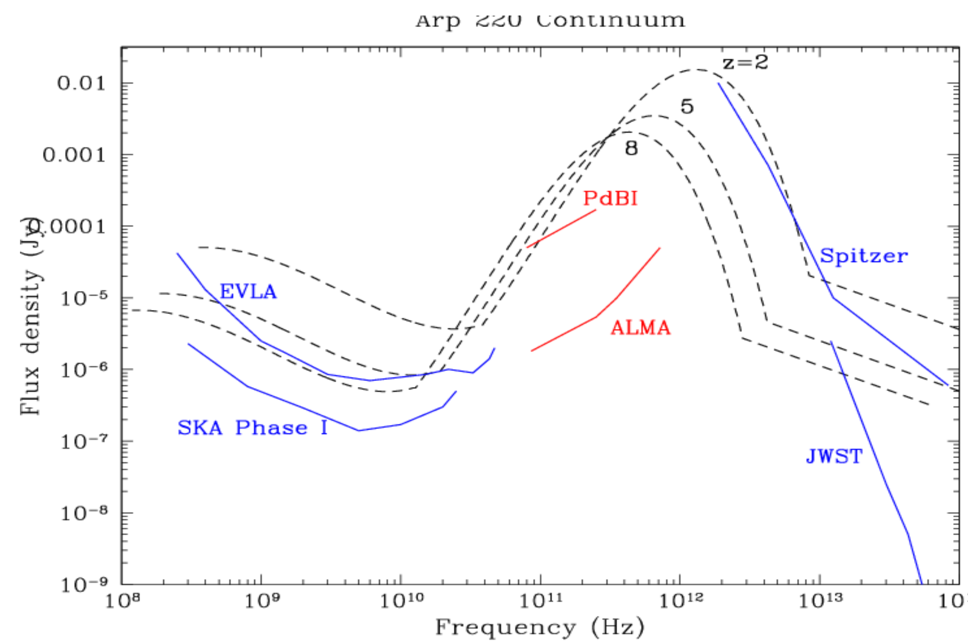


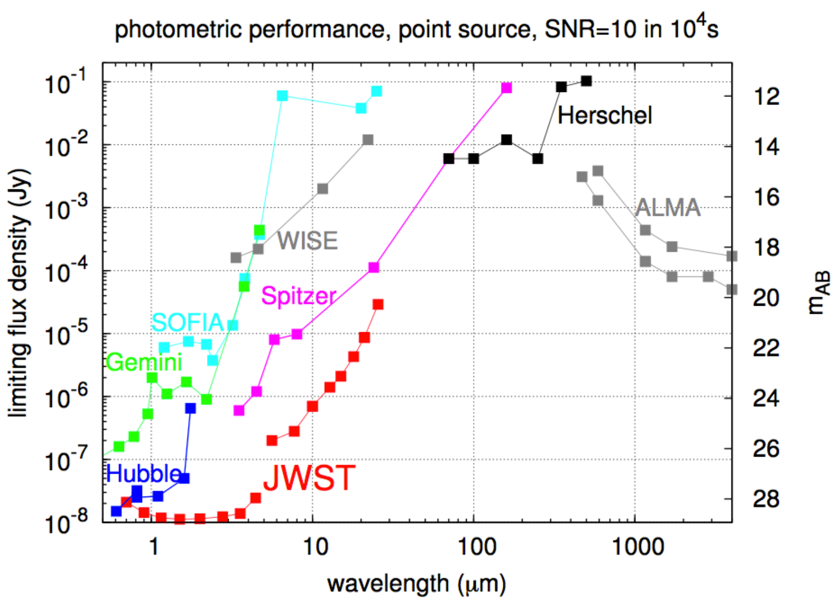
ALMA sensitivity

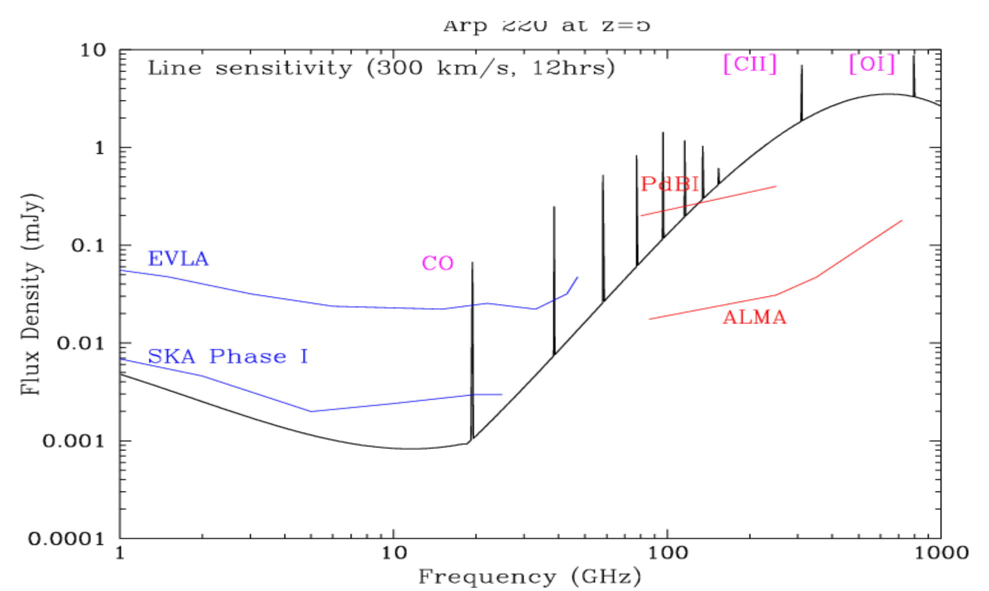
Dry site, low pwv, low Tsys, high sensitivity also at submm frequencies

>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

$$\Delta S_\nu = 2\,k\,\frac{T_{\rm sys}\,e^{\tau}}{A_{\rm e}\sqrt{2t\,\Delta\nu}}$$

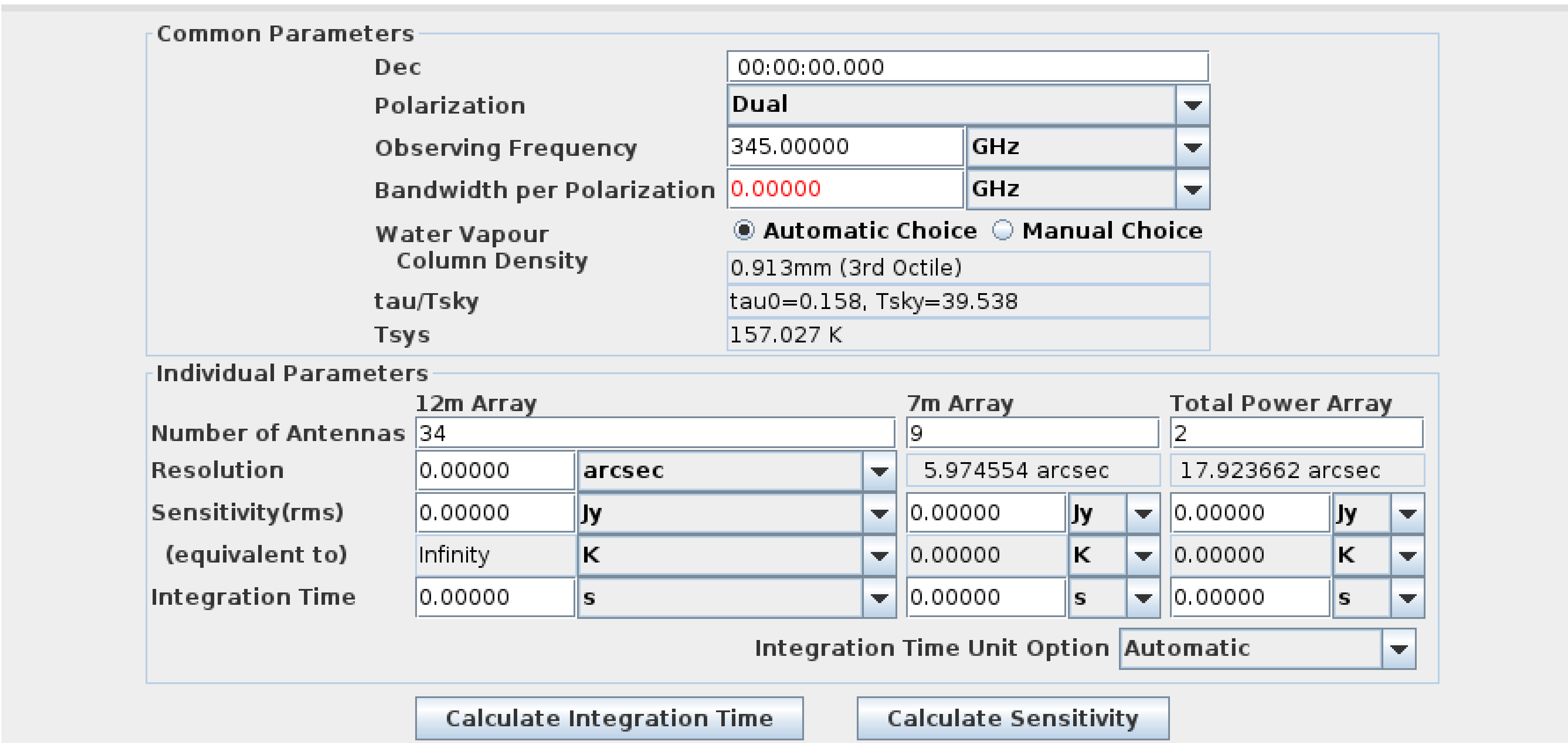




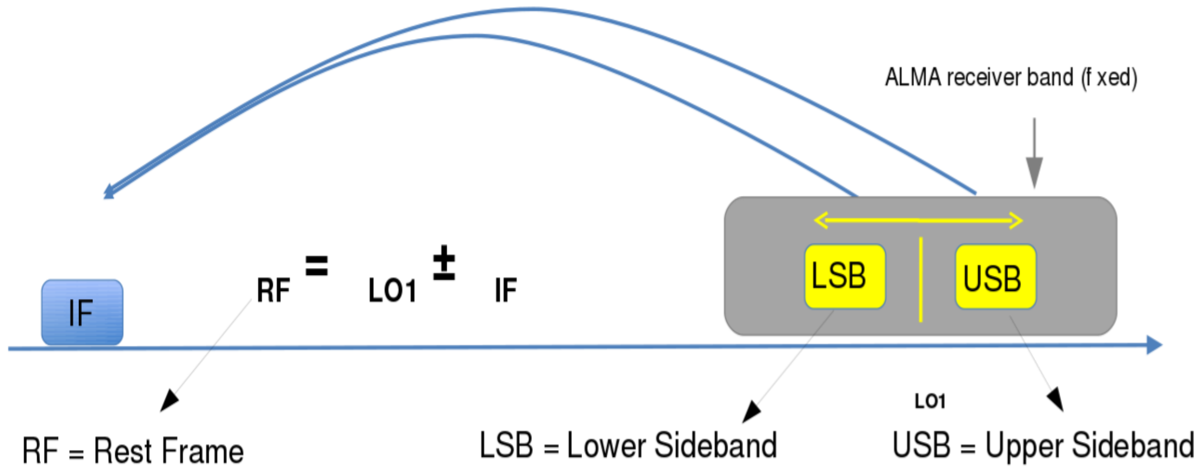


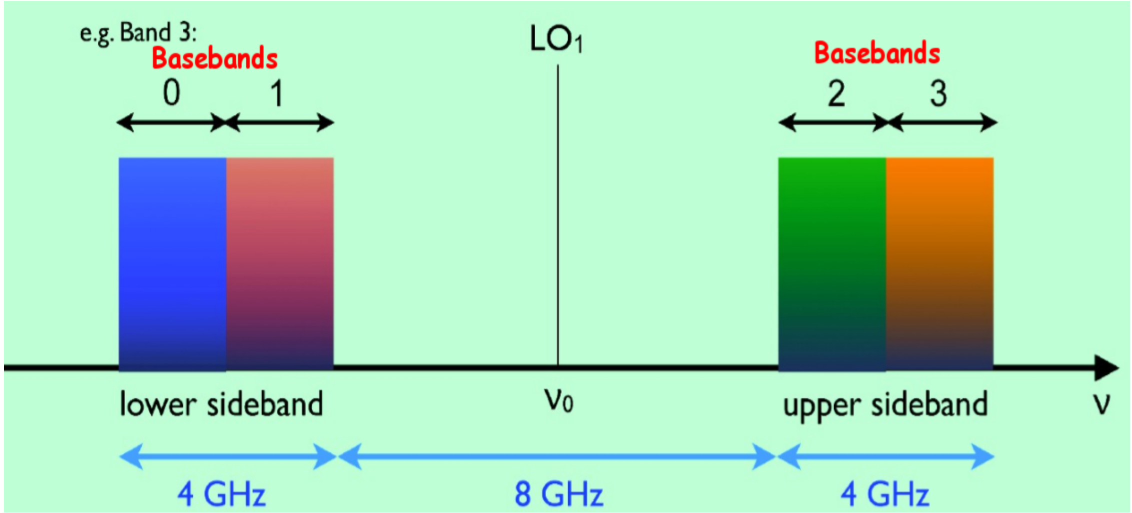
The Science Goal: Sensitivity Calculator

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



ALMA spectral properties



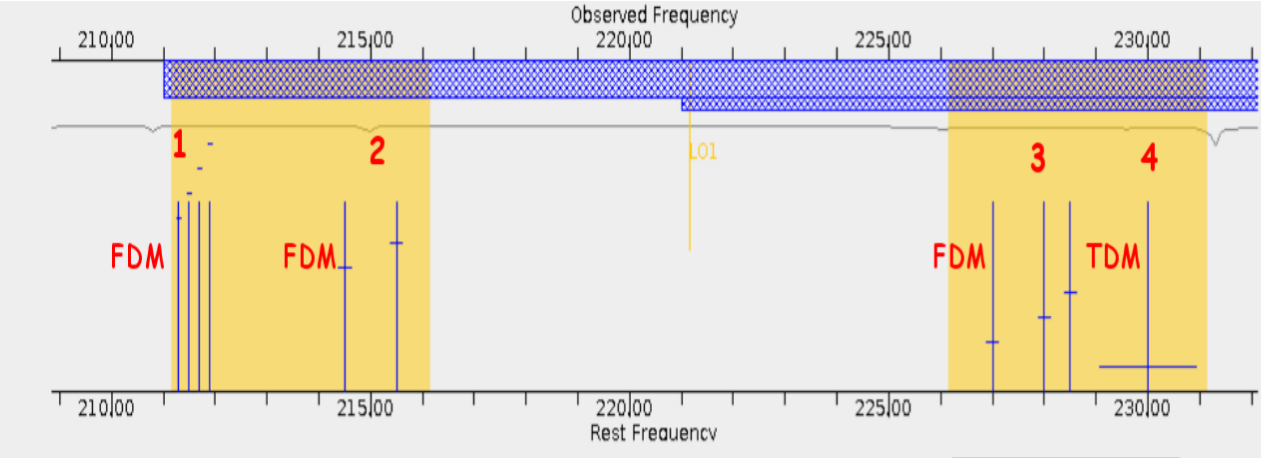


The coherent receivers map two freq regions to an Intermediate Frequency by mixing the signal with a Local Oscillator.

The receivers allows 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.

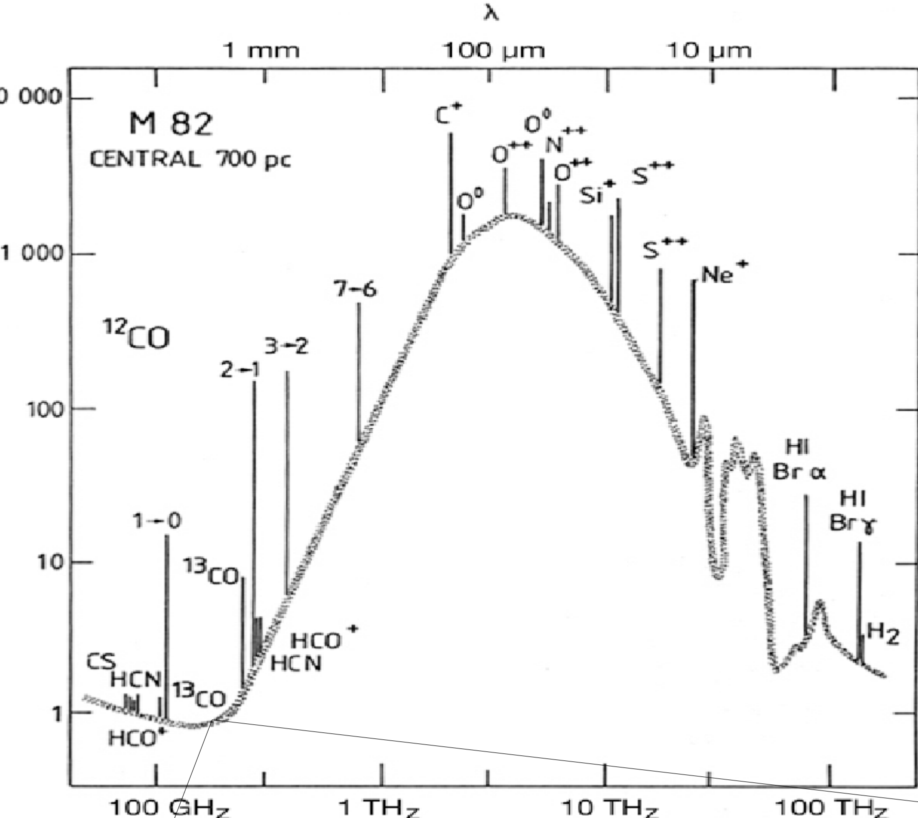
Resolution

Typical purposes:	Mode	Polari-zation	Bandwidth per baseband (MHz)	Number of channels per baseband	Channel Spacing (MHz)	Velocity width at 300 GHz (km/s)
Spectral scans	7	Dual	1875	3840	0.488	0.48
	8	Dual	938	3840	0.244	0.24
Targeted imaging of moderately narrow lines: cold clouds / protoplanetary disks	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
"Continuum" or broad lines	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