# Observing with ALMA

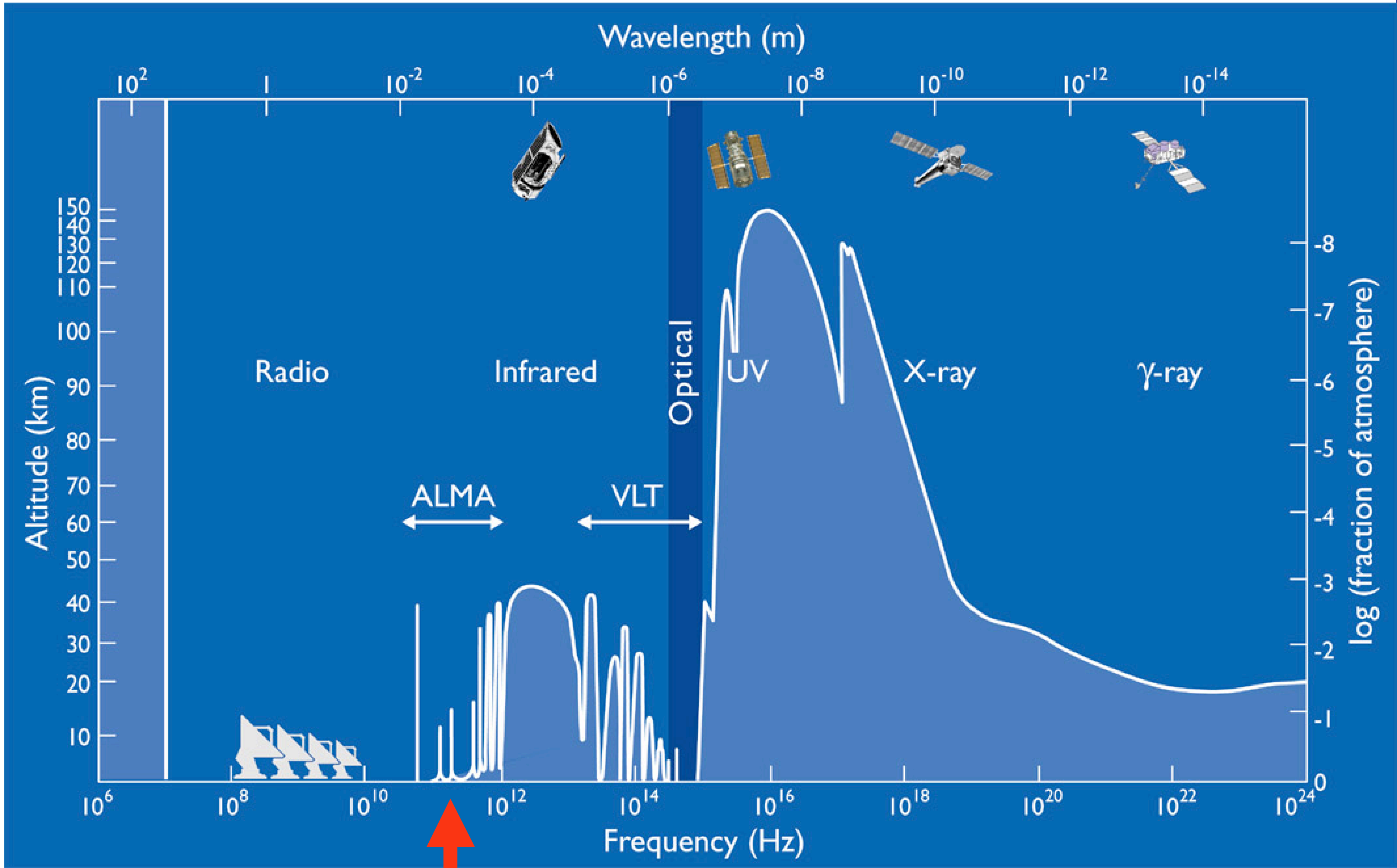
1. How ALMA works
2. How you submit a proposal and get ALMA data
3. What kind of ALMA images and spectra you get



Paola Andreani, ESO

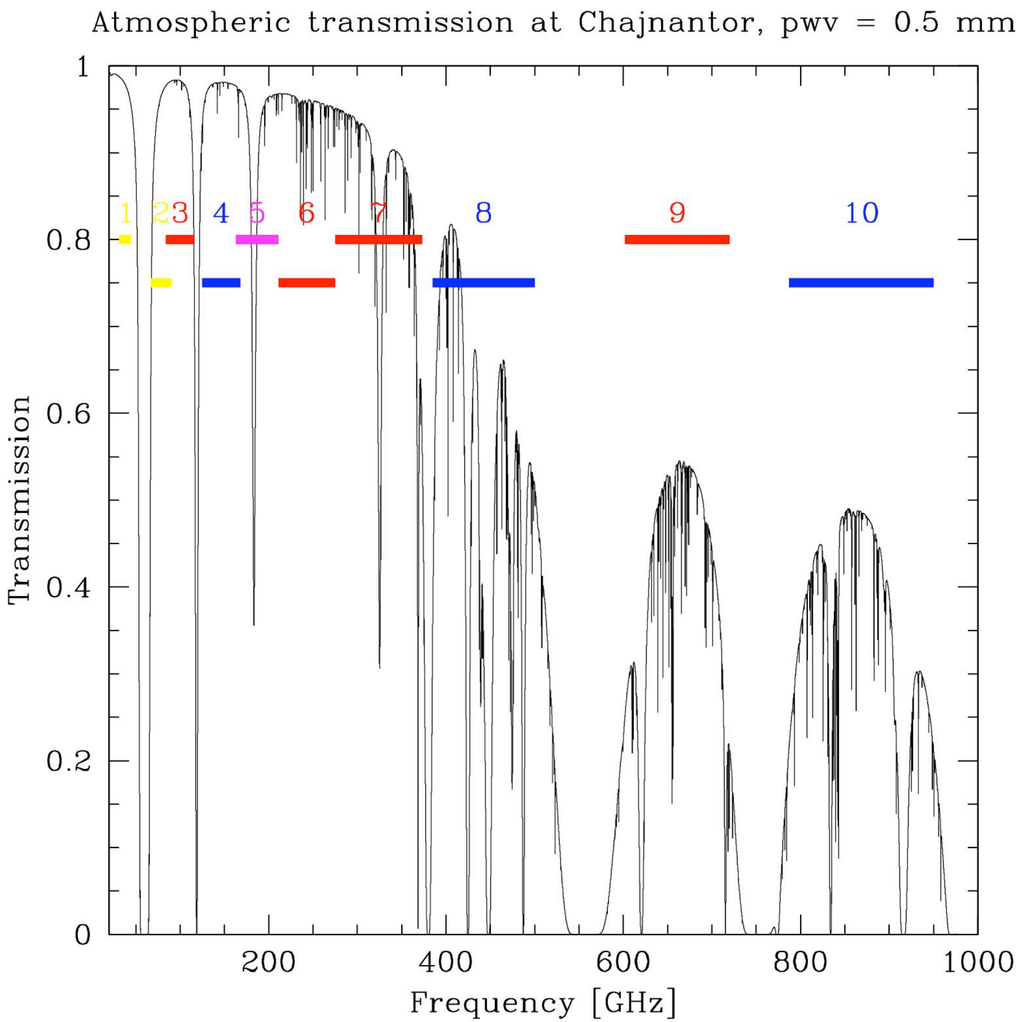
# How ALMA works
# What must done to make it work

# ALMA WAVELENGTHS




30-950 GHz = 10-0.3 mm

# Transparent site allows full spectral coverage




**1 mm = 300 GHz**

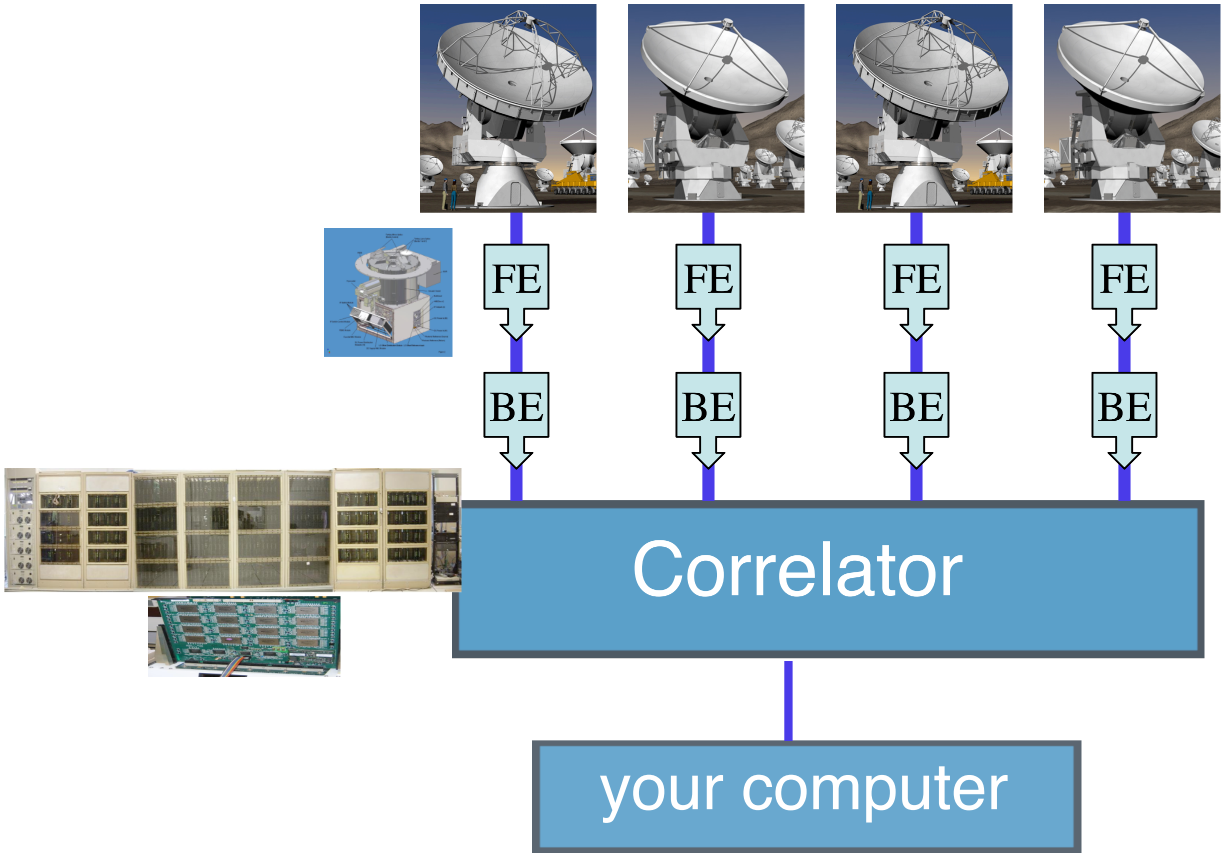
**transmission strong function of water column (*pwv*)**

**significant effects of troposphere λ<1 cm**

- optical depth
- atmospheric emission
- increased demands on calibrations

**Need high and dry site**

# How does ALMA work?




50 antennas, each with up to 10 receivers

In the receiver (FE) the signal is amplified and down-converted

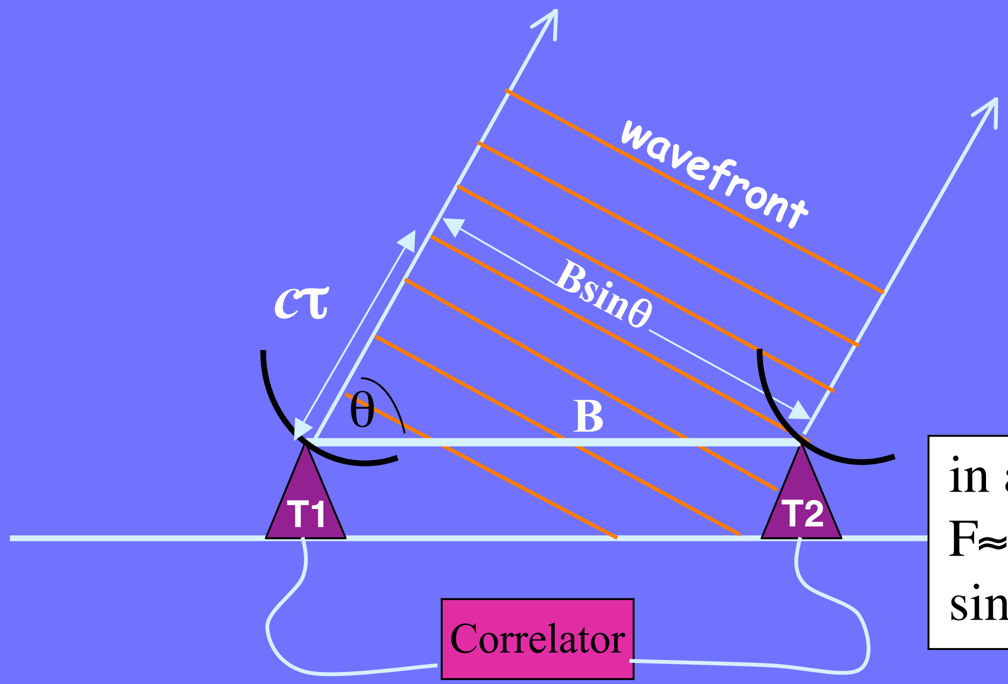
Back-end (BE) transfers the signal to the correlator

Correlator multiplies and integrates signals of all antennas
($10^{16}$ flops (floating point operation per second))

output: complex visibilities

# Basic Concepts

- An interferometer measures coherence in the electric field between pairs of points (baselines).




$\tau = B\sin\theta / c$

$F \propto \sin 2\pi\nu t \, \sin 2\pi\nu(t-\tau)$
$\approx \cos(2\pi B\sin\theta/\lambda)$

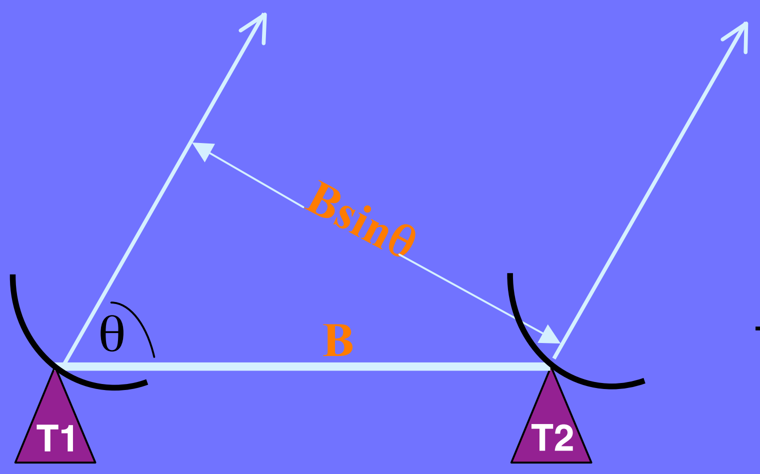
in a continuum band $\Delta\nu$ and centre $\nu_0$
$F \approx \cos(2\pi B\sin\theta\nu_0/c)$
$\sin(\pi B\sin\theta \, \Delta\nu/c)/\pi B\sin\theta \, \Delta\nu/c$

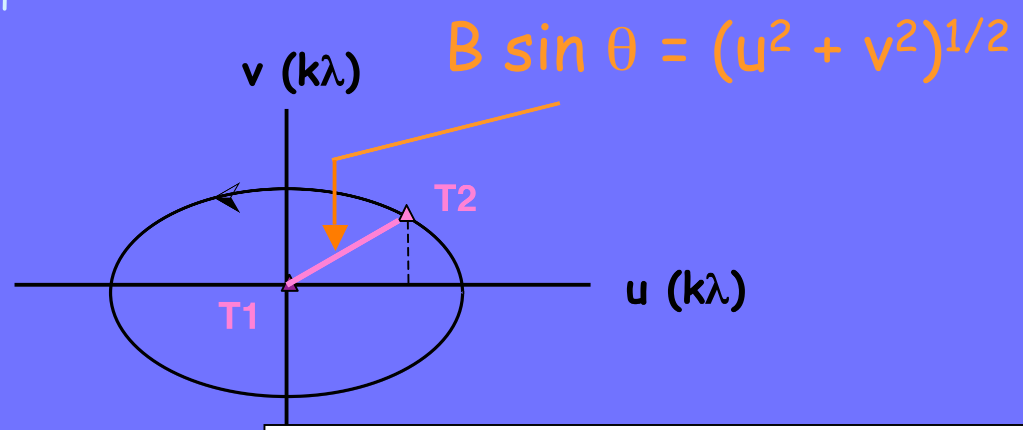
- Because of the geometric path difference $c\tau$, the incoming wavefront arrives at each antenna at a different phase.

**For good image quality: many baselines**
**n antennas: n(n-1)/2 spacings**
**(ALMA 50 antennas: 1225 baselines)**

# Aperture Synthesis

- As the source moves across the sky (due to Earth's rotation), the **baseline vector** traces part of an ellipse in the (u,v) plane.



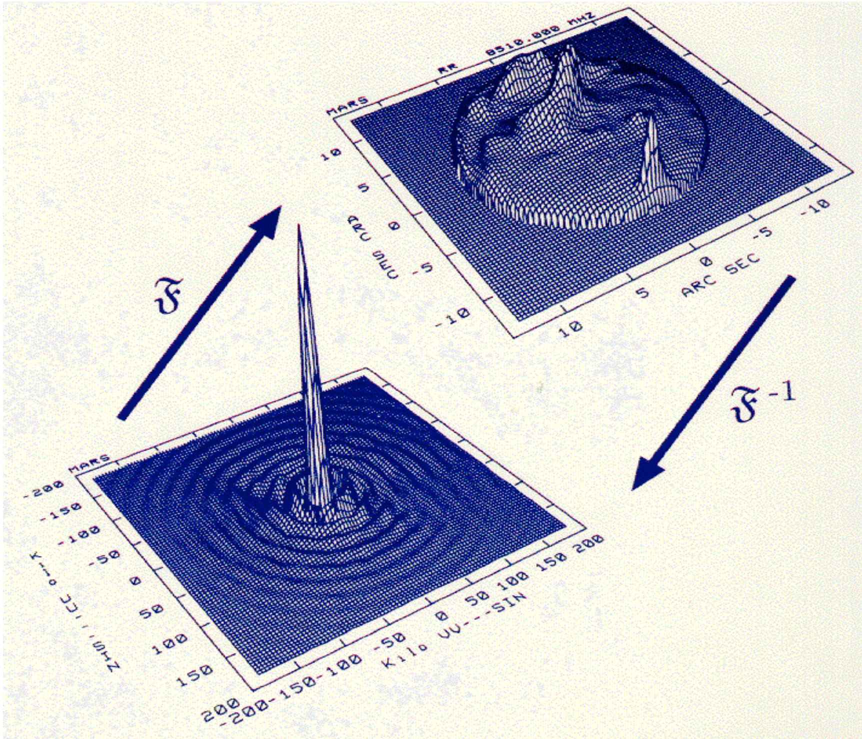

**Actually we obtain data at both (u,v) and (-u,-v) simultaneously, since the two antennas are interchangeable. Ellipse completed in 12h, not 24!**

resolution of the fringes determined by the length of B projected onto a plane ⊥ to the direction of the sources

# Synthesis observing

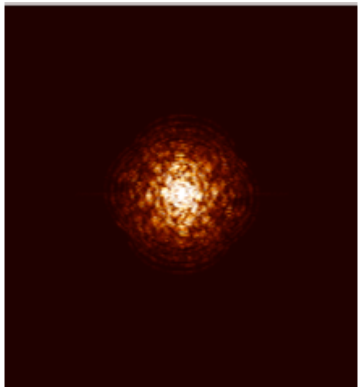
- Correlate signals between telescopes: visibilities
- Assign the visibilities to correct position on the u-v disc
- Fourier Transform the u-v plane : image

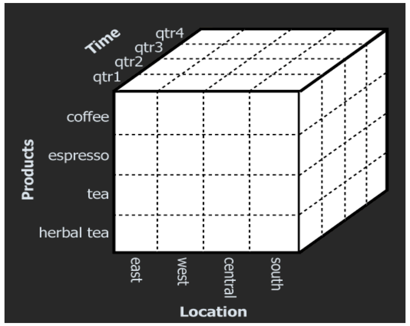
Complex visibility
$V=|V|e^{j\phi}=\int A_N(\sigma)I(\sigma)e^{-j2\pi B\bullet\sigma}\, d\Omega$



# ALMA data

visibilities → Fourier Transform → Data cubes





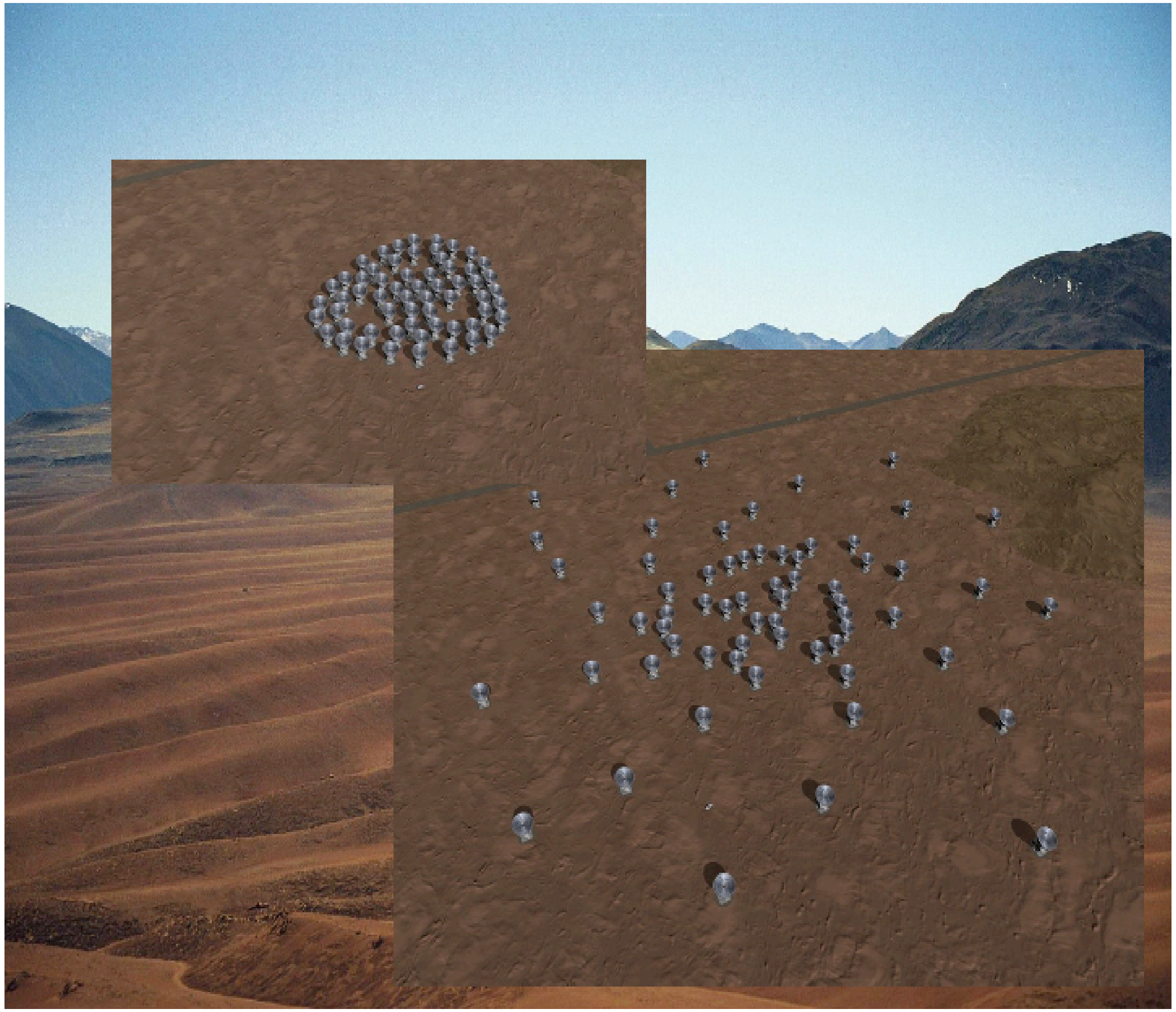

All ALMA observations will result in data cubes!

ALMA is an “IFU” *(integral field unit)* with up to ~>$10^6$ spaxels

*(spaxel is the spatial sampling element by analogy to a pixel),*

each with up to ~8000 resolution elements!

# ALMA Configurations



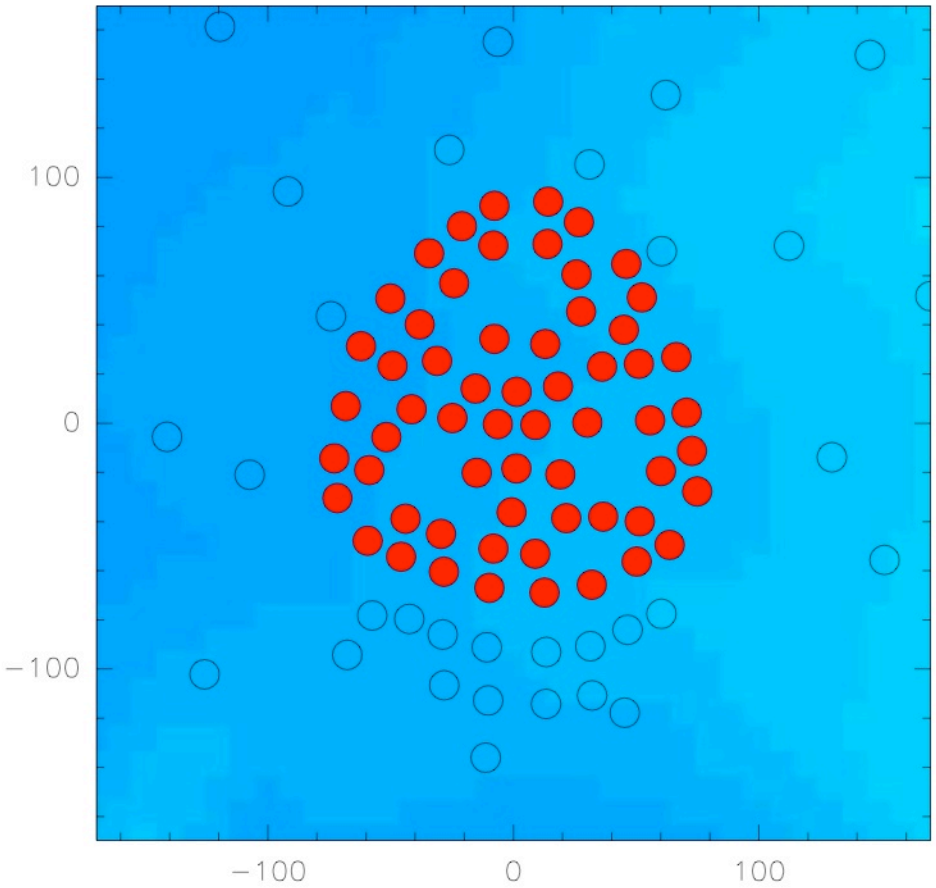
ALMA will be
a "breathing" array

resolution defined
by longest baseline

largest spatial scale
determined by
shortest baseline

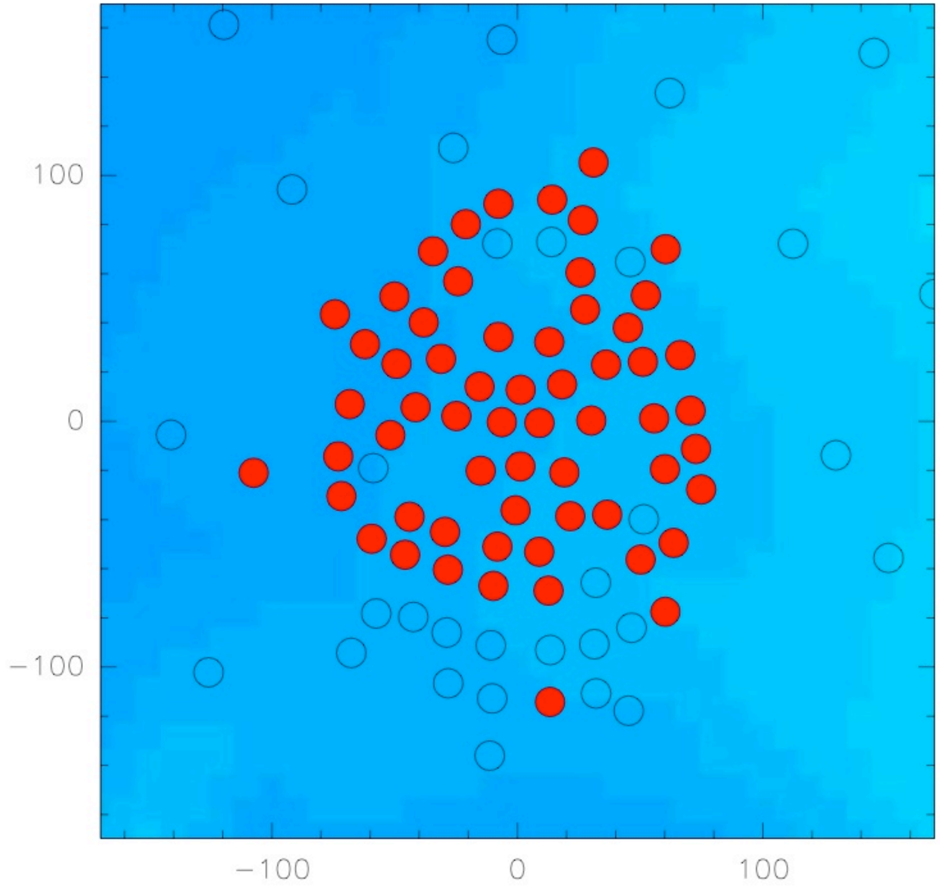
# ALMA Configurations

Compact Configuration



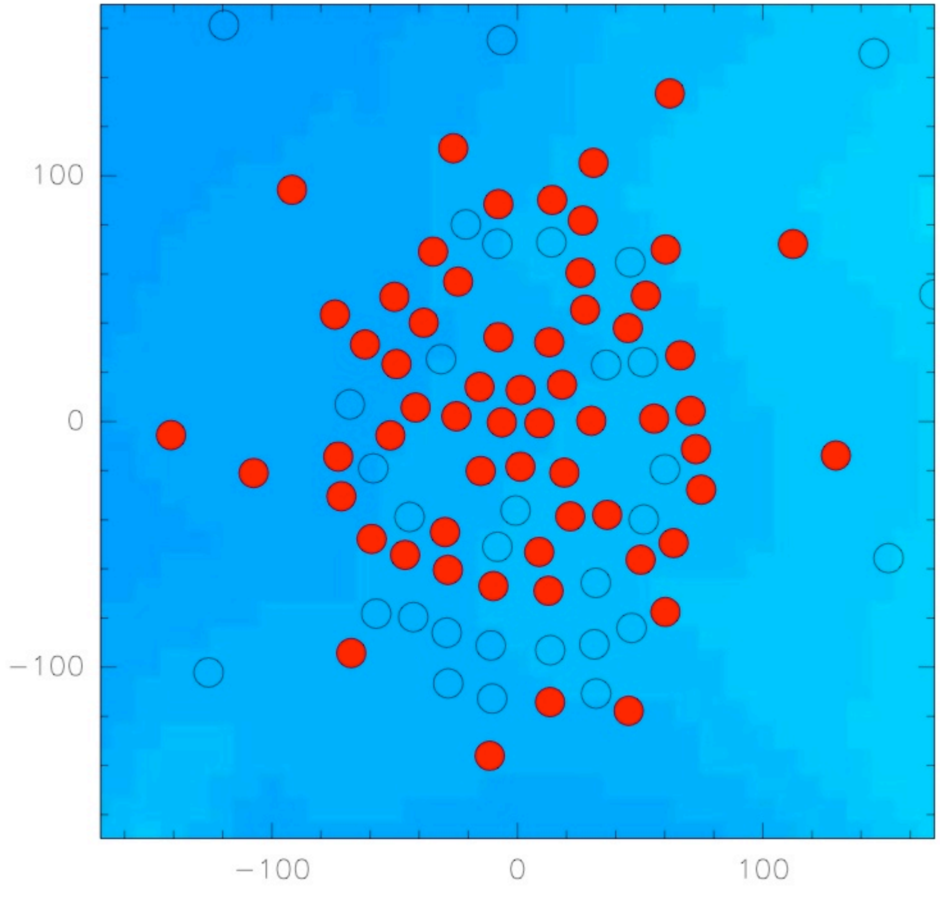
# ALMA Configurations

Configuration
Number 4



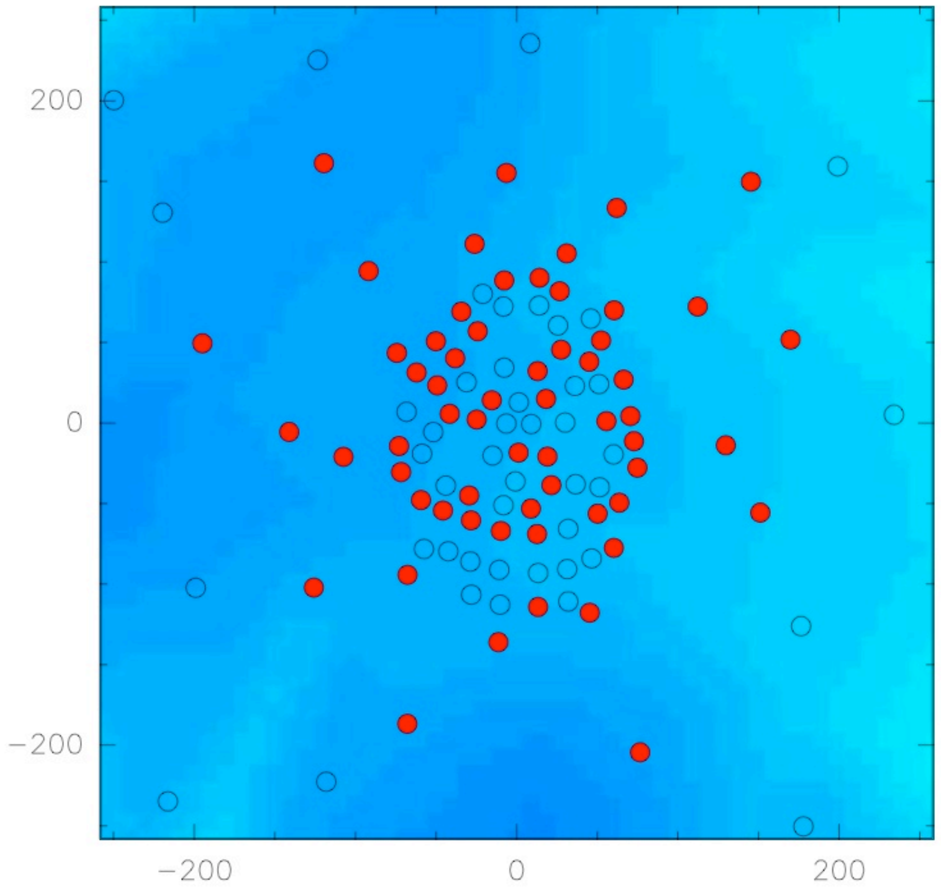
# ALMA Configurations

Configuration
Number 7



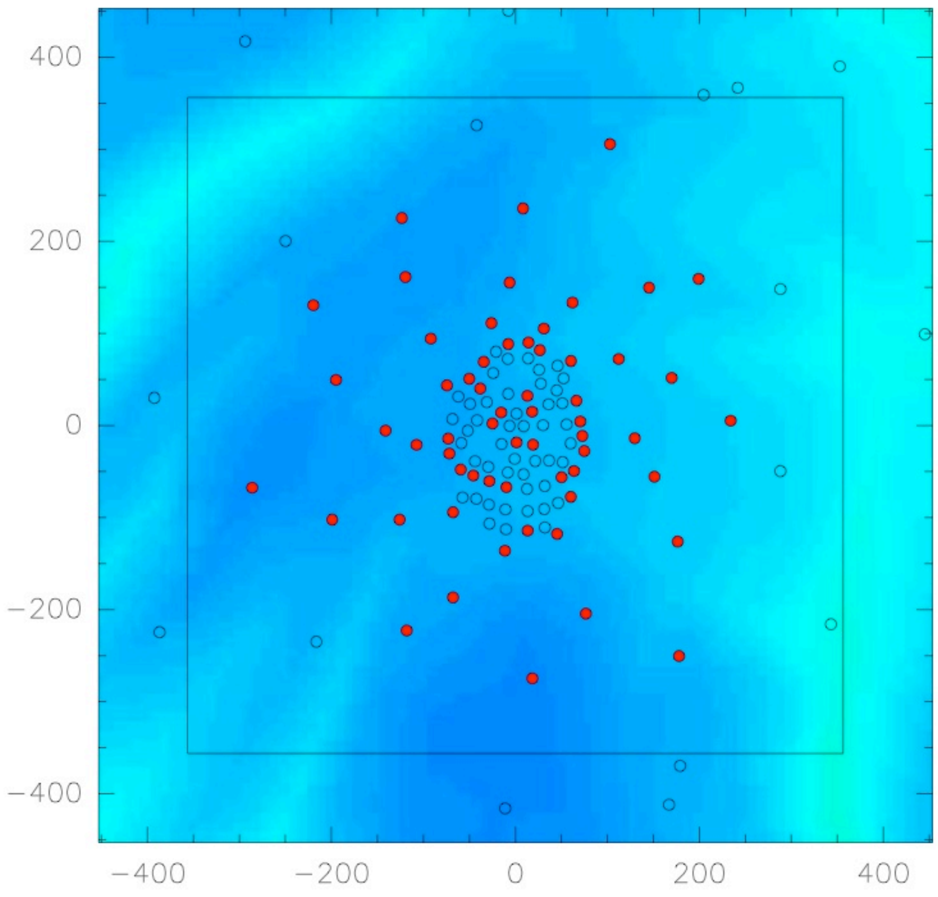
# ALMA Configurations

Configuration
Number 10



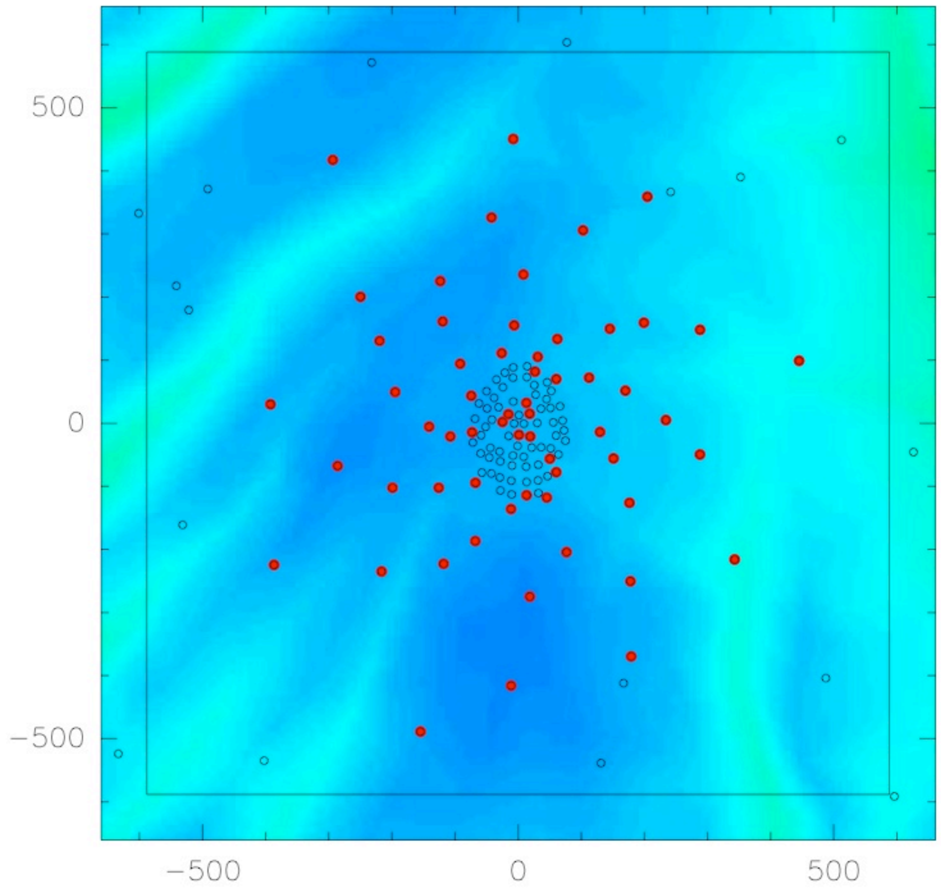
# ALMA Configurations

Configuration
Number 14



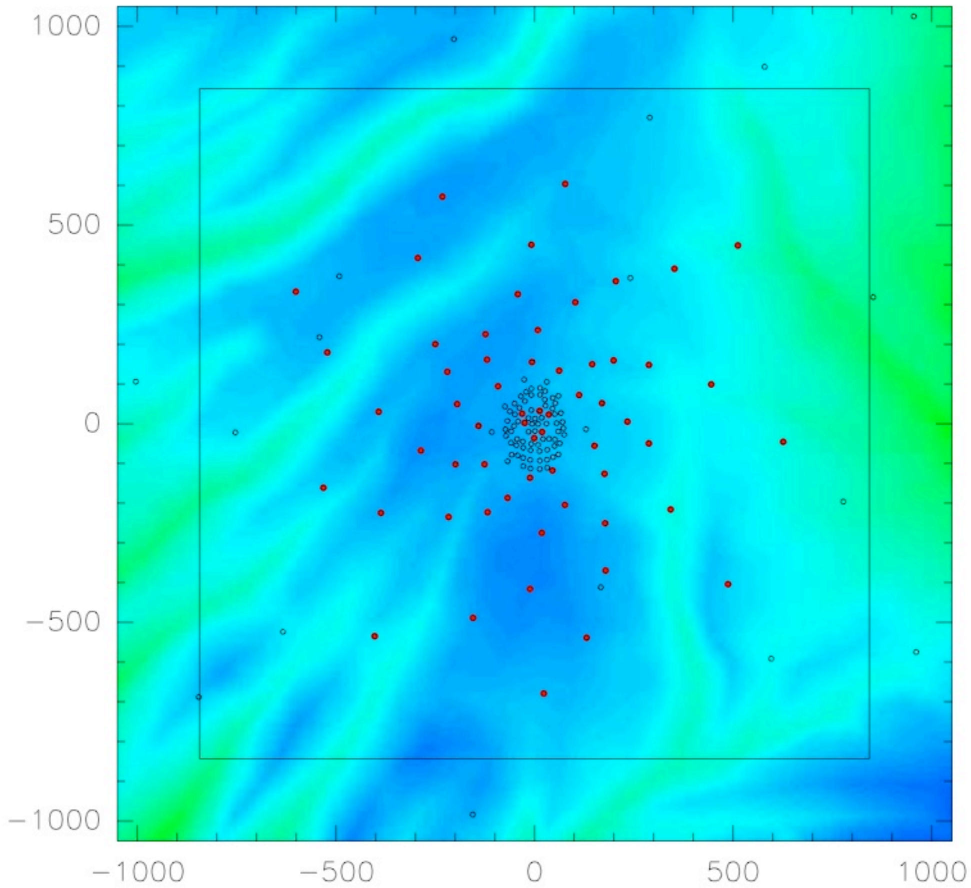
# ALMA Configurations

Configuration
Number 19



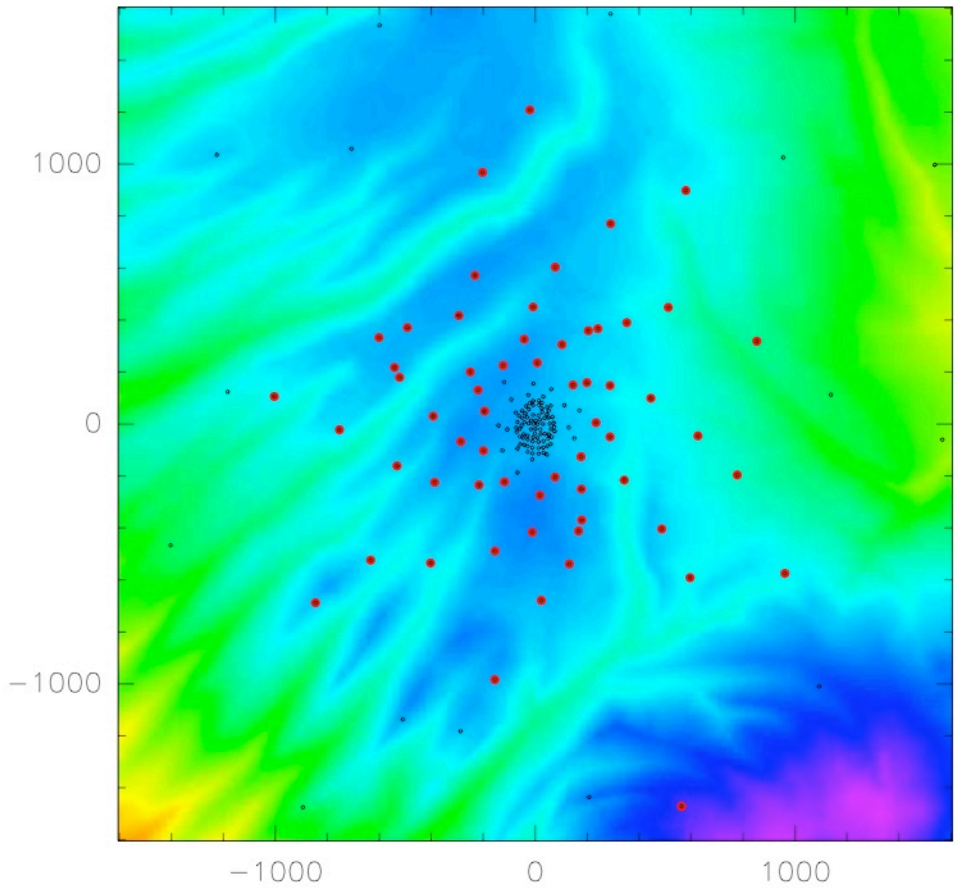
# ALMA Configurations

Configuration
Number 23



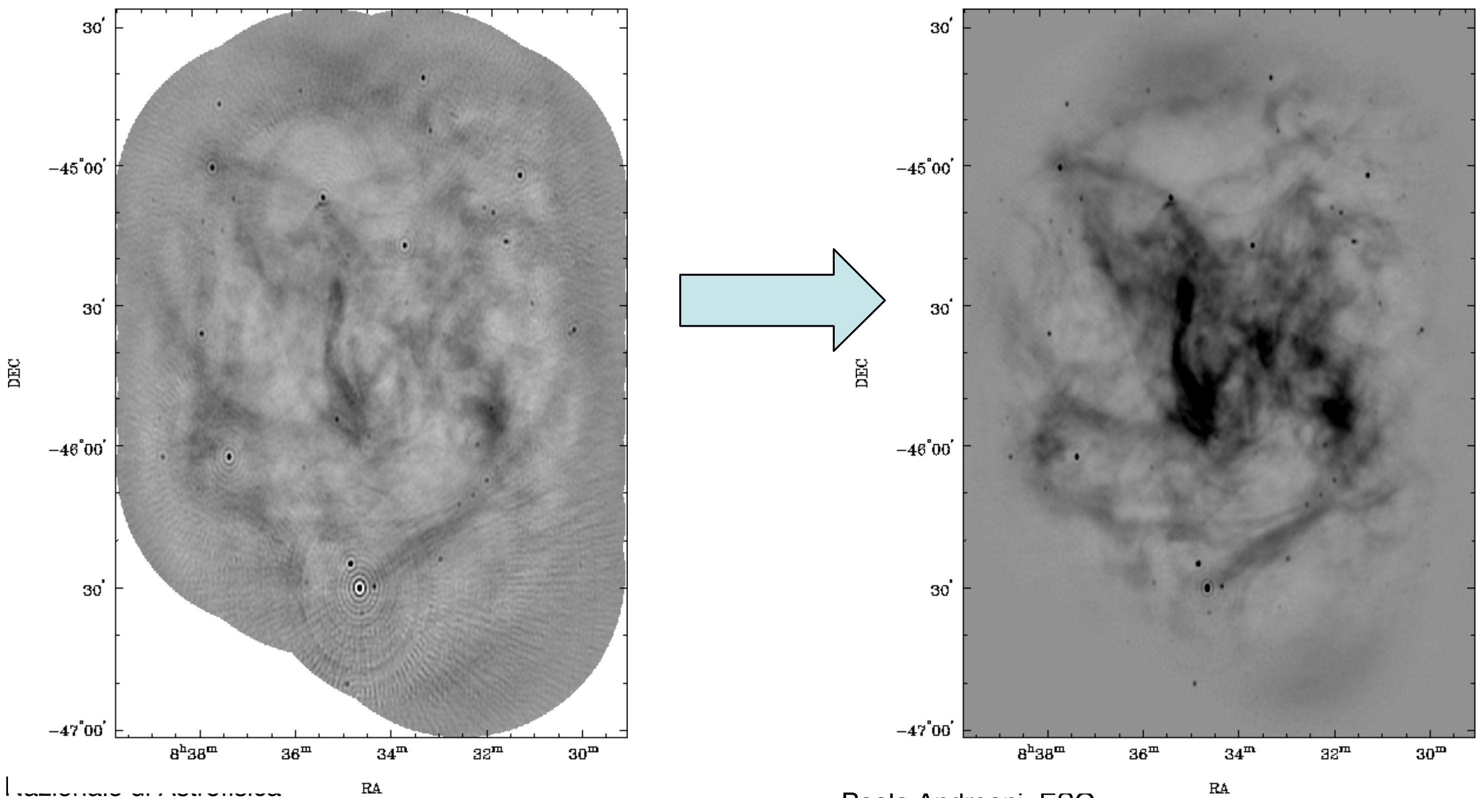
# ALMA Configurations

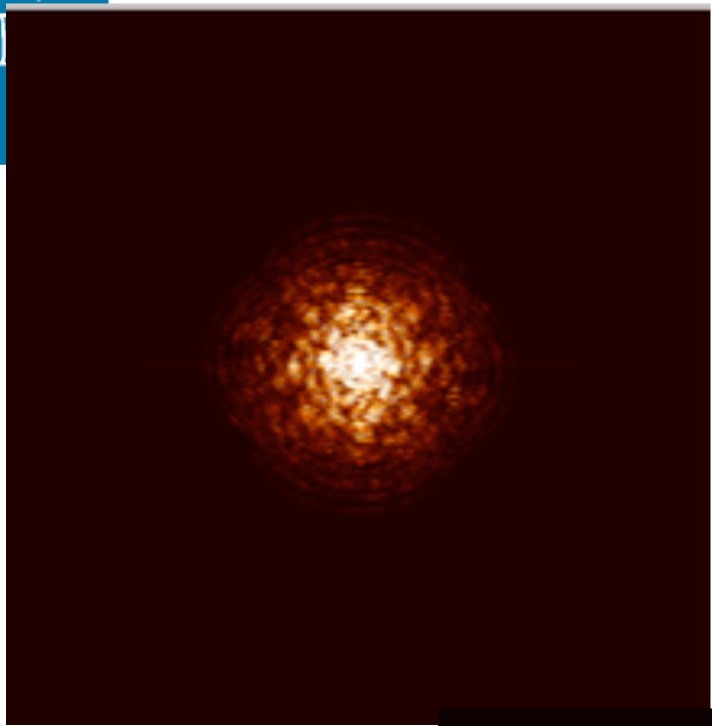
Configuration Number 28



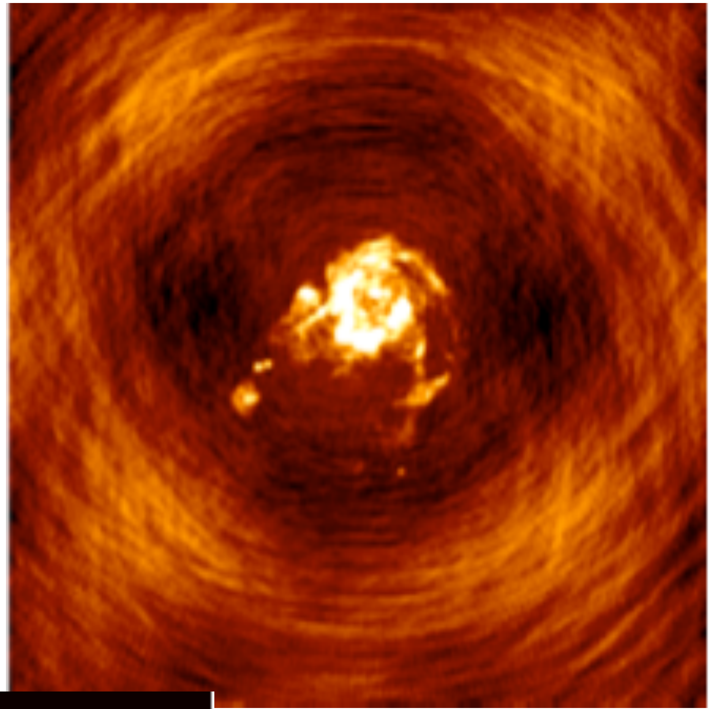
# Deconvolution

- There are gaps in u-v plane. Need algorithms such as CLEAN and Maximum Entropy to guess the missing information
- This process is called deconvolution



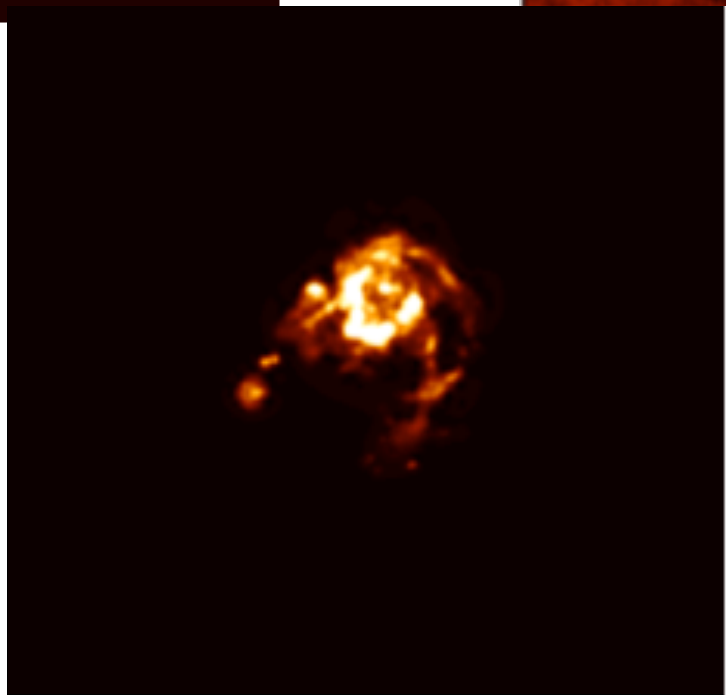


visibilities



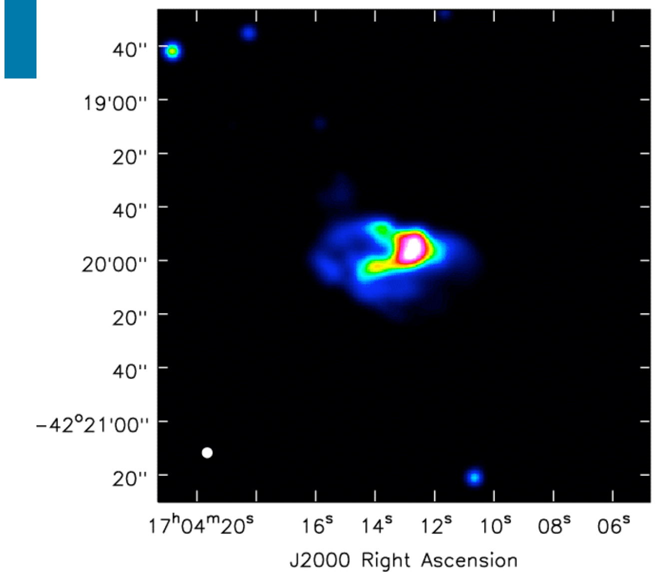
dirty image

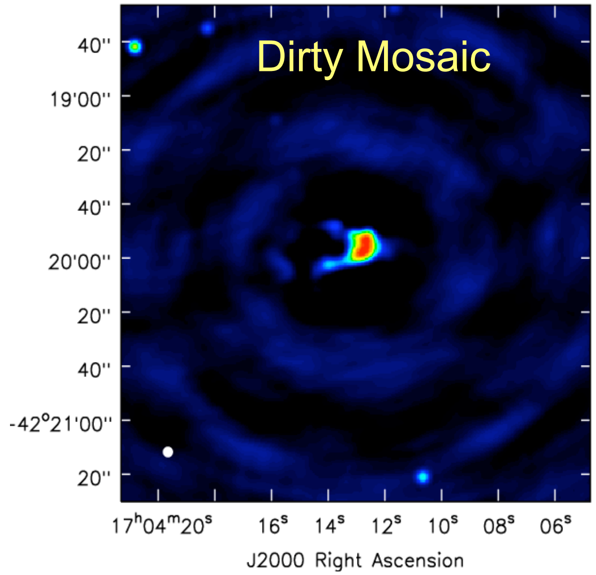
Contains only spatial frequencies where visibility was measured

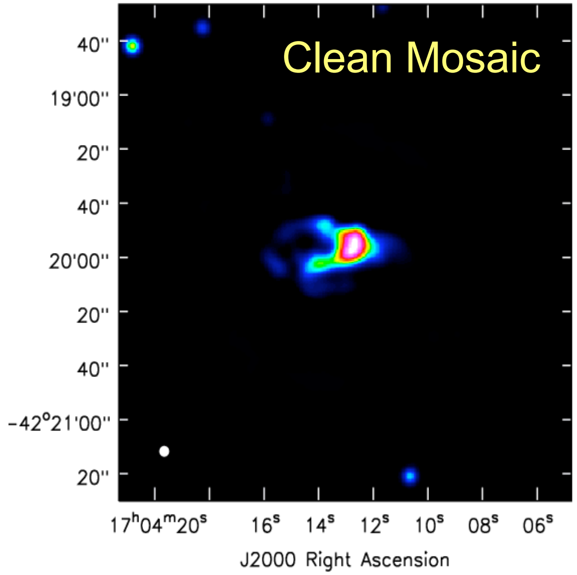


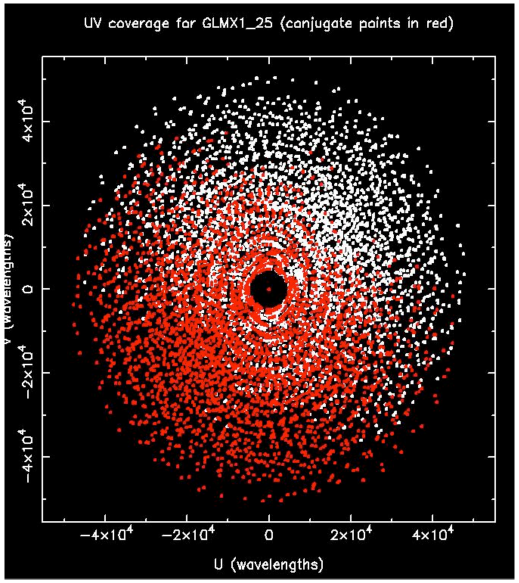
clean image

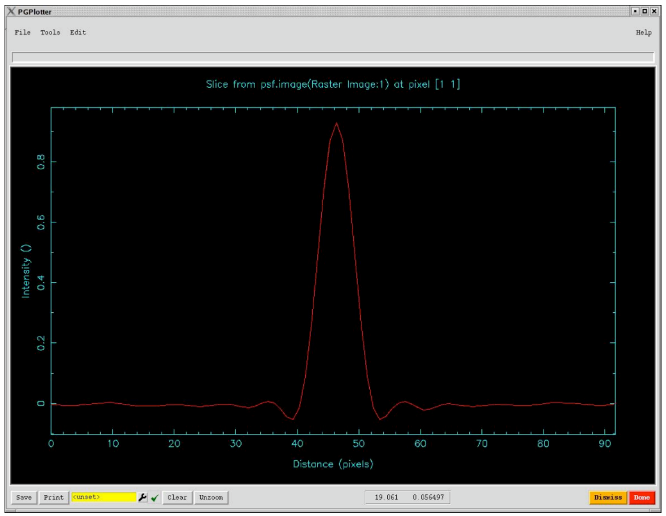
# ALMA Imaging Simulations

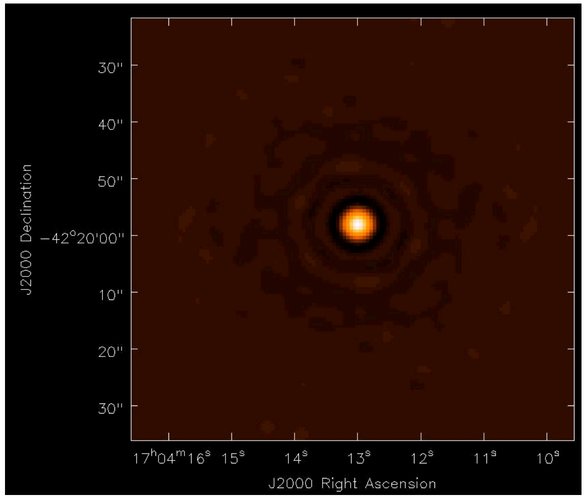


# Key performance numbers

- **Baseline range 15m – 14.5 km + ACA + single dish**
- **Spatial resolution/ arcsec ≈ 0.2(λ/mm)/(max baseline/km)**

  **in compact configuration (200 m): from 0.4" at 675 GHz to 2.8" at 110 GHz**

  **in most extended configuration (14.7 km): from 0.006" at 675 GHz to 0.038" at 110 GHz**

*This is the **synthesized beam**: the inverse Fourier transform of a (weighted) u-v sampling distribution: **"point spread function"***

*The **primary beam** is the average of the response to incident power as function of the angle away from antenna axis: **"field of view"**.*

*This is only dependent on frequency and antenna size, so independent of configuration.* For 300 GHz: primary beam=17"

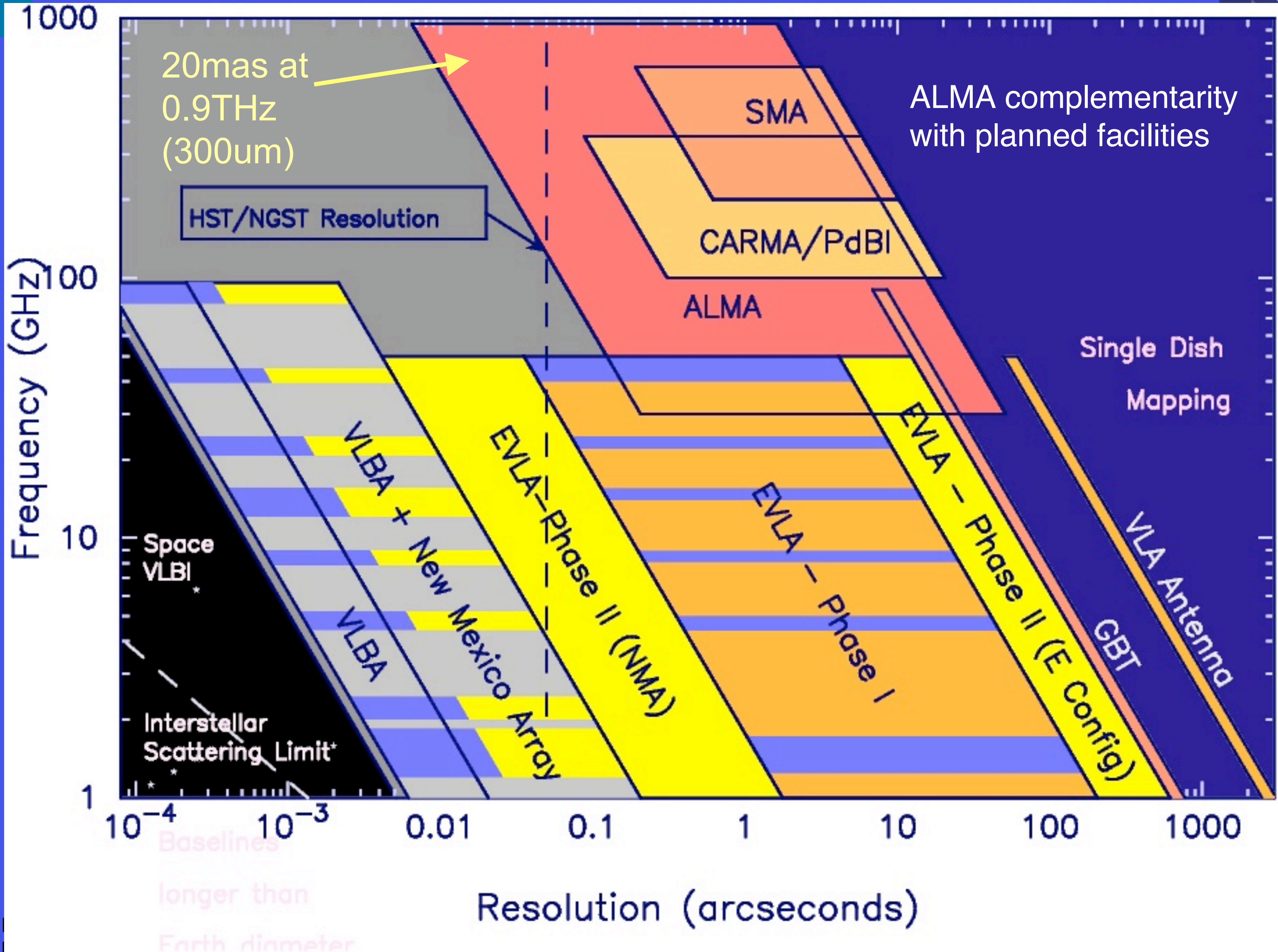
# Sampling of large spatial scales

1 Mpc corresponds to ~125 arcsec at z = 1

| $\nu$ | Primary beam $\lambda$/D | | Minimum $\lambda$/D | | Resolution |
|---|---|---|---|---|---|
| GHz | arcsec | | arcsec | | arcsec |
| | 12m | 7m | Compact | ACA | Compact |
| 35 | 170 | 291 | 116 | 199 | 10 |
| 110 | 56 | 99 | 37 | 64 | 3.1 |
| 230 | 27 | 46 | 18 | 31 | 1.5 |
| 345 | 18 | 31 | 12 | 21 | 1.0 |

Also combine with 12m (single-dish) observations

# Giant Steps: Frequency and resolution



# Key performance numbers

## Spectrally

from 3.8kHz to 2 GHz
  0.01 km/s at 110 GHz (R=30,000,000)

A total bandwidth of 16 GHz can be observed (=48000km/s in band 3)
Up to 8192 channels (=spectral resolution elements)

“the back-end is very flexible”: user can select many overlapping or disjoint spectral regions with different resolutions

**Wide bandwidth (8 GHz/polarization), low noise temperatures, good site and antennas, … excellent continuum sensitivity**

**Full polarization**

# Sensitivity

Noise $S = 2k/A_{eff} \; T_{sys}/\sqrt{N(N-1)\,\Delta\nu t_{int}}$

2k/Aeff Tsys : SEFD (system equivalent flux density)
(K to Jy conversion)
N: number of antennas
$\Delta\nu$ bandwidth in Hz
$t_{int}$ integration time in s

typical sensitivities in 10 min:
**line**: few mJy (per 1 km/s)
**continuum**: few tens of µJy

***If ALMA would observe a 1mJy source with Δν=2GHz for 1000 years, the total energy accepted would be equal to the kinetic energy of a falling snowflake!***

# Sensitivity in 1 minute

| $\nu$ | $\Delta S$ | $\Delta T_B$ |
|---|---|---|
| GHz | mJy | K |
| 110 | 0.06 | 0.0013 |
| 150 | 0.07 | 0.0010 |
| 250 | 0.14 | 0.0028 |
| 345 | 0.25 | 0.0040 |
| 409 | 0.38 | 0.0057 |
| 675 | 1.33 | 0.014 |
| | 0.46 | 0.0059 |
| 850 | 5.9 | 0.080 |
| | 1.1 | 0.014 |

RMS for 2 polarizations, each with 8GHz bandwidth; elevation of 50$^{o}$. Brightness temperatures are for a maximum baseline of 200m; 50 antennas

Median PWV = 1.5mm

Best 5% PWV = 0.35mm

ALMA Memo 276

Some receivers will exceed specification

Sensitivity calculator available at http://www.eso.org/projects/alma/science/bin/sensitivity.html

# The support to the users: the ALMA Regional Centers (ARCs)

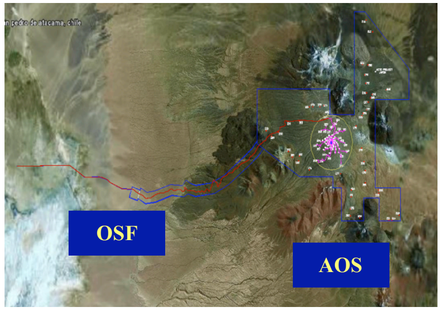
# Science Operations

## Astronomer's perspective

### Principles:

- Non-experts should be able to use ALMA
- Dynamic scheduler to match observing conditions
- Reliable and consistent calibration
- Data public in timely fashion

# ALMA in operations




**San Pedro (OSF)** Operations Support Facilities

- **array scheduling + operations**
  - **quick-look reduction**
  - **maintenance and repair antennas + instruments**


**Santiago (SCO)** Santiago Central Office

- **issues of calls**
  - **TAC (Time Allocating Committee) process**
  - **SB (Scheduling Block) checks**
  - **pipeline data reduction**
  - **quality assessment**
  - **production of archive**

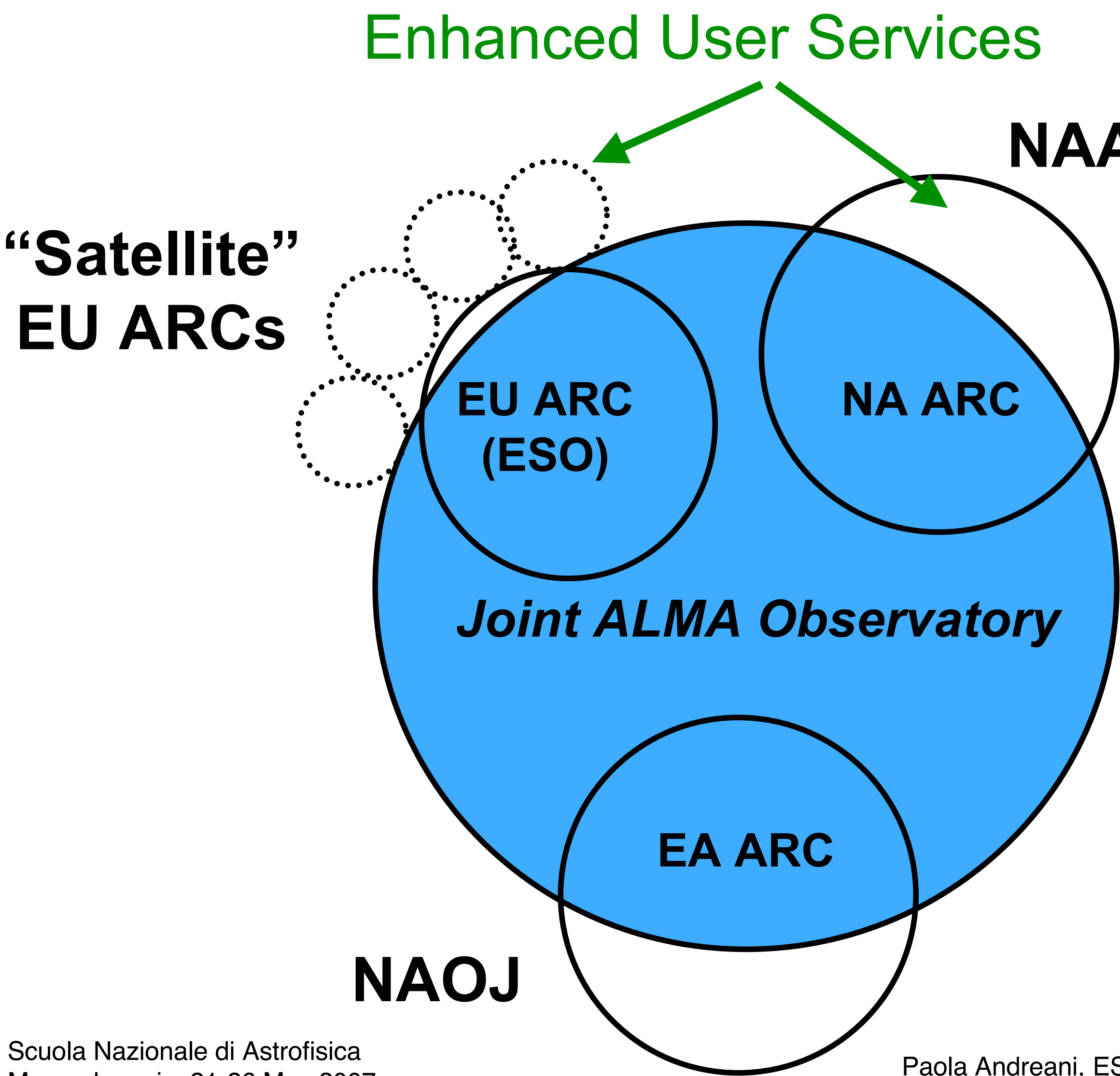
# Data flow

*"Every astronomer, including novices to aperture synthesis techniques, should be able to use ALMA"*

Data flow:

1. Data taking
2. Quality Assurance (QA) programme
3. Data reduction pipeline
4. Archive
5. User

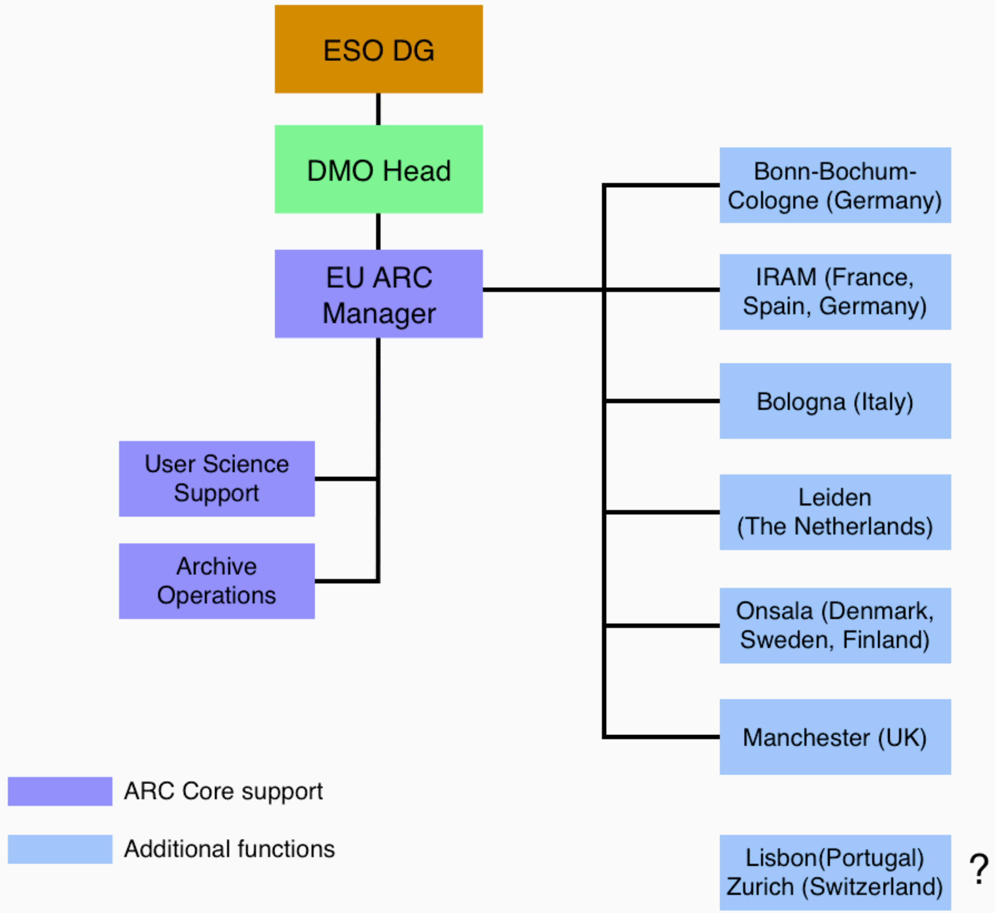
# ALMA Operations:
# Three ALMA Regional Centers - ARCs

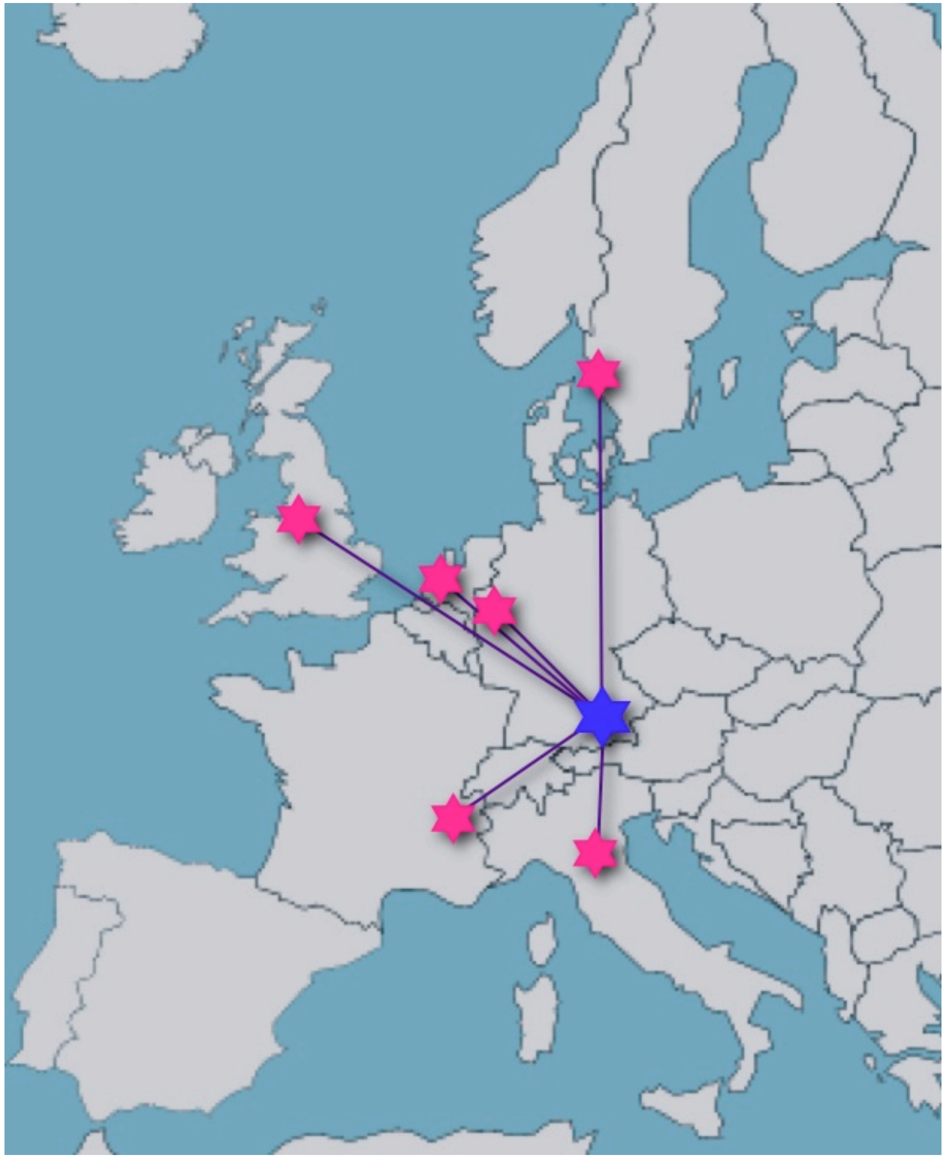



ARCs provide basic user interface, as well as basic archive, software, and hardware maintenance and development

Enhanced services are needed to provide advanced user support, algorithm development, student programs, EPO, grants

## ARC Europe


ESO DG
DMO Head
EU ARC Manager
User Science Support
Archive Operations
Bonn-Bochum-Cologne (Germany)
IRAM (France, Spain, Germany)
Bologna (Italy)
Leiden (The Netherlands)
Onsala (Denmark, Sweden, Finland)
Manchester (UK)
Lisbon(Portugal) Zurich (Switzerland)
?
ARC Core support
Additional functions



# Science Operations

- Phase I + II proposals through ARCs (time estimator, end-to-end data simulator)
- Scheduling blocks to OSF
- All data taken in service mode, dynamic scheduler selects programmes according to science rating weather conditions, array configuration, consistent calibration
- Pipeline data reduction, quality control, archive
- Data deliveries from the ARCs

# Getting ALMA time

**Phase I**

- Joint ALMA Observatory issues calls
- Register in the ALMA web page
- Prepare a proposal with the ALMA Observing tool
- If s/he needs a help address to one of the ARC node

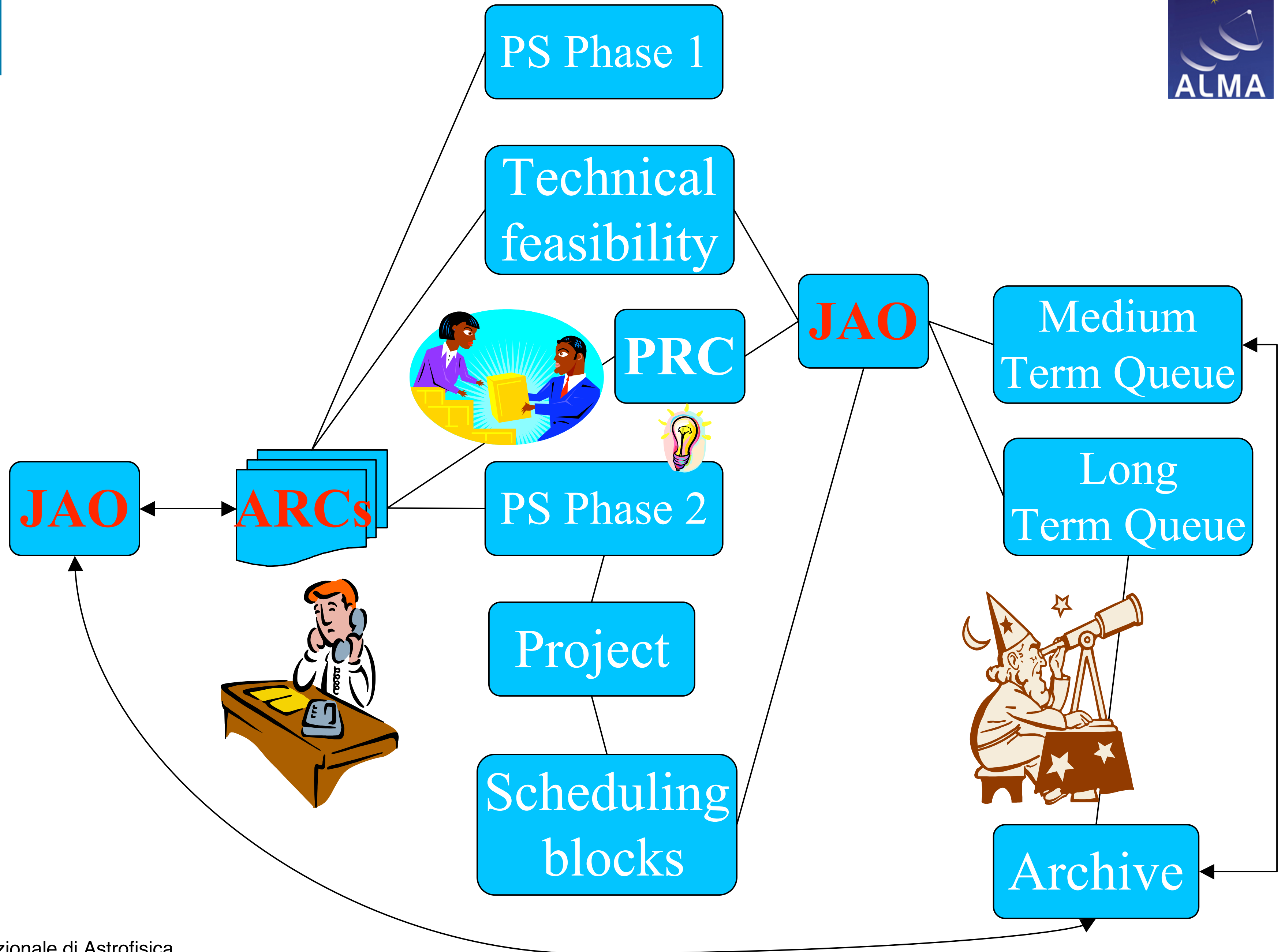
➢ European ARC provides documentation, proposal preparation and submission help

➢ ALMA Observatory (with ARCs help) coordinates refereeing process

➢ Program Review Committee ranks proposals

- Executives approval

# ALMA DATA FLOW



# Getting ALMA time

**Phase II**

- Phase I: Proposals are submitted using ALMA Observing Tool
  - Phase II: Successful PIs submit observing program using the Observing Tool
  - Preparation of the SBs
  - European ARC helps with observation planning and verifies observing schedule

# Planning the observations

- **What frequency?**

**spectral line, continuum emission**

**tradeoff between resolution, FOV, surface brightness sensitivity**

**look at the noise level in flux density/beam area**

- **What baseline?**

**resolution ($\lambda/B_{max}$ maximum B)**

**maximum spatial scale ($\lambda/B_{min}$ minimum B)**

- **Field of View?**

**primary beam ($\lambda/D$)**

**mosaic of many pointings?**

- **Spectral resolution?**

**compromise between bandwidth and resolution set by maximum number of correlator channels setup**

- **How long?**

**signal to noise ratio S/N**

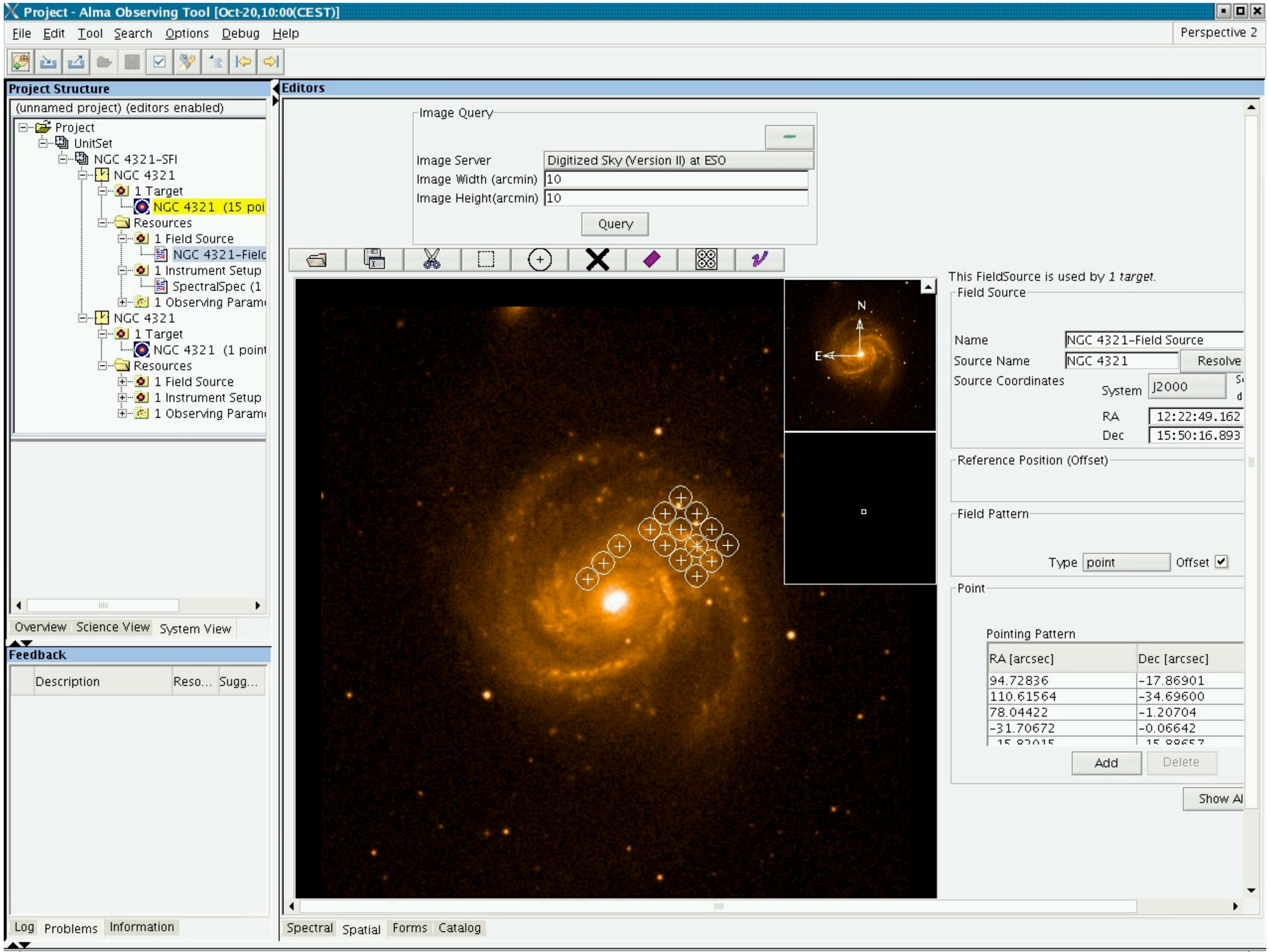
**imagine fidelity**

- **More advanced considerations: polarization, more configuration, +ACA +SD**

# ALMA Observing tool

- SW  tool to construct a full Observing Project
- Split Observing Programs in two parts:
- a Phase I Observing Proposal: emphasis on the scientific justification of the proposed observations.
- a Phase II Observing Program submitted only if observing time has been granted.
- Set of Scheduling Blocks (SBs) are required to drive observing with ALMA.
- the SB is the smallest (indivisible) unit that can be scheduled independently. It is self contained and usually provides scientifically meaningful data.
- the SB contains a full description of how the science target and the calibration targets are to be observed
- sets of SBs can be combined with a description for the post processing of the data, ultimately resulting in an image.

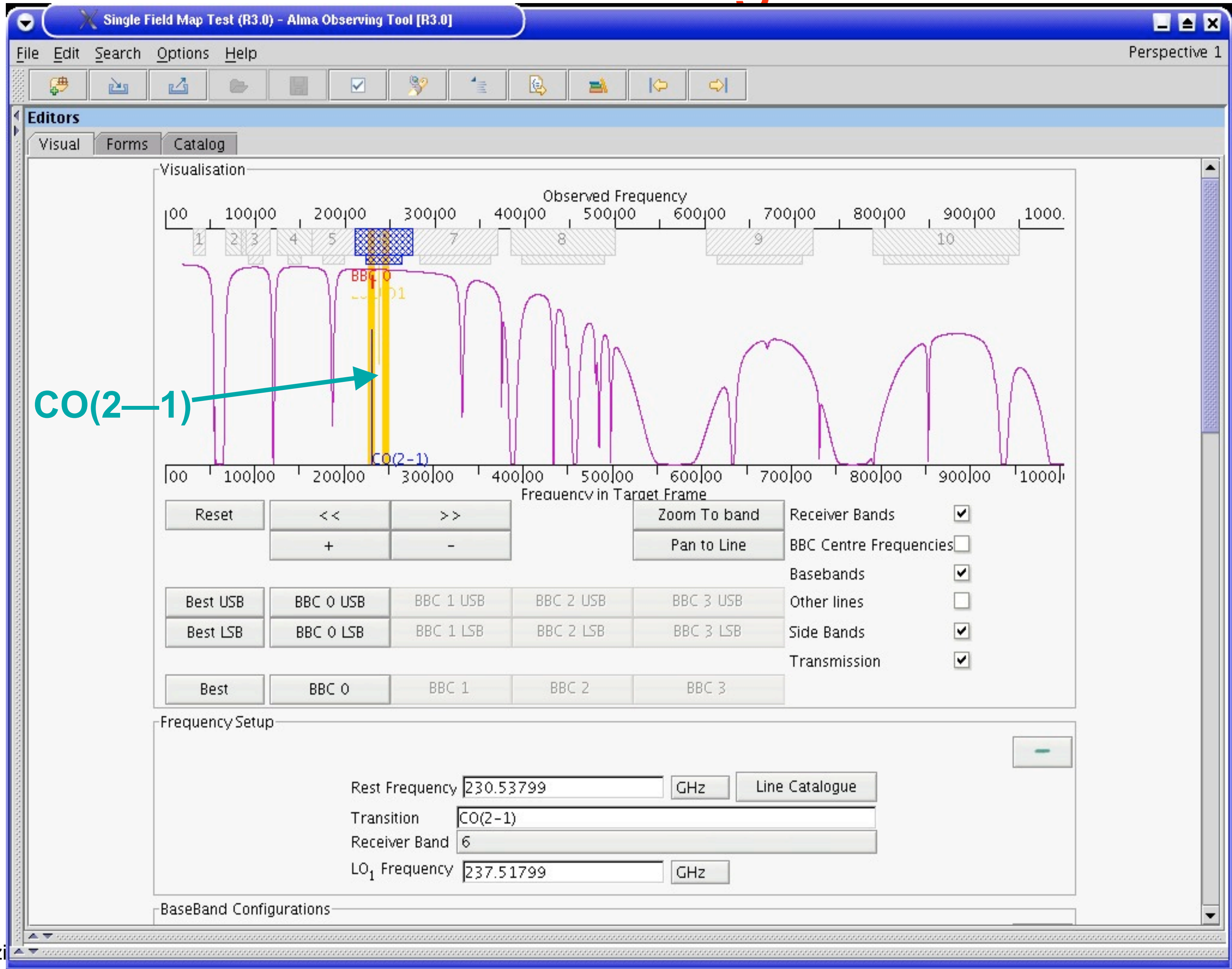
# ALMA Observing tool



# ALMA Observing tool

- the OT is equipped with two ‘Views’:
- “‘Science View’ (main): inputs the science requirements of their observing program: the area to be observed for each target, required sensitivity and frequencies.
- ‘System View’ (developing new observing modes): (or expert mode) provides with a complete set of parameter fields that enable a detailed specification of each scheduling block: the observing process of science and calibration targets, including data acquisition and reduction recipes. These parameters include the frequency setting of the local oscillator, the upper and lower side bands, the correlator parameters and the selection of the basebands and subband sets within each baseband.
- Whichever ‘View’ is used, SBs must be created.
- The required SBs will be constructed by the system and the user will only be bothered with system parameters when this is absolutely necessary, in general detailed parameters will be determined from the science input.

# ALMA Observing tool



# Getting ALMA data

- Queue based dynamic scheduling
  - Programs are composed of 30-60 min scheduling blocks
- Raw data passed through multi-tiered quality assurance
  - Combination of on-site duty astronomer, ARC staff, and automated checks
- Data proceeds to pipeline and archiving
  - Data available from ARC (ESO) within ~2 weeks (TBD)
  - Pipeline products (images and calibrated u-v data), raw data, and off-line data processing software made available to PIs
    - Pipeline available towards end of construction
  - Expert hands-on data reduction help from ARC nodes staff provided on request, helpdesk also available at ESO

# Data handling - archive

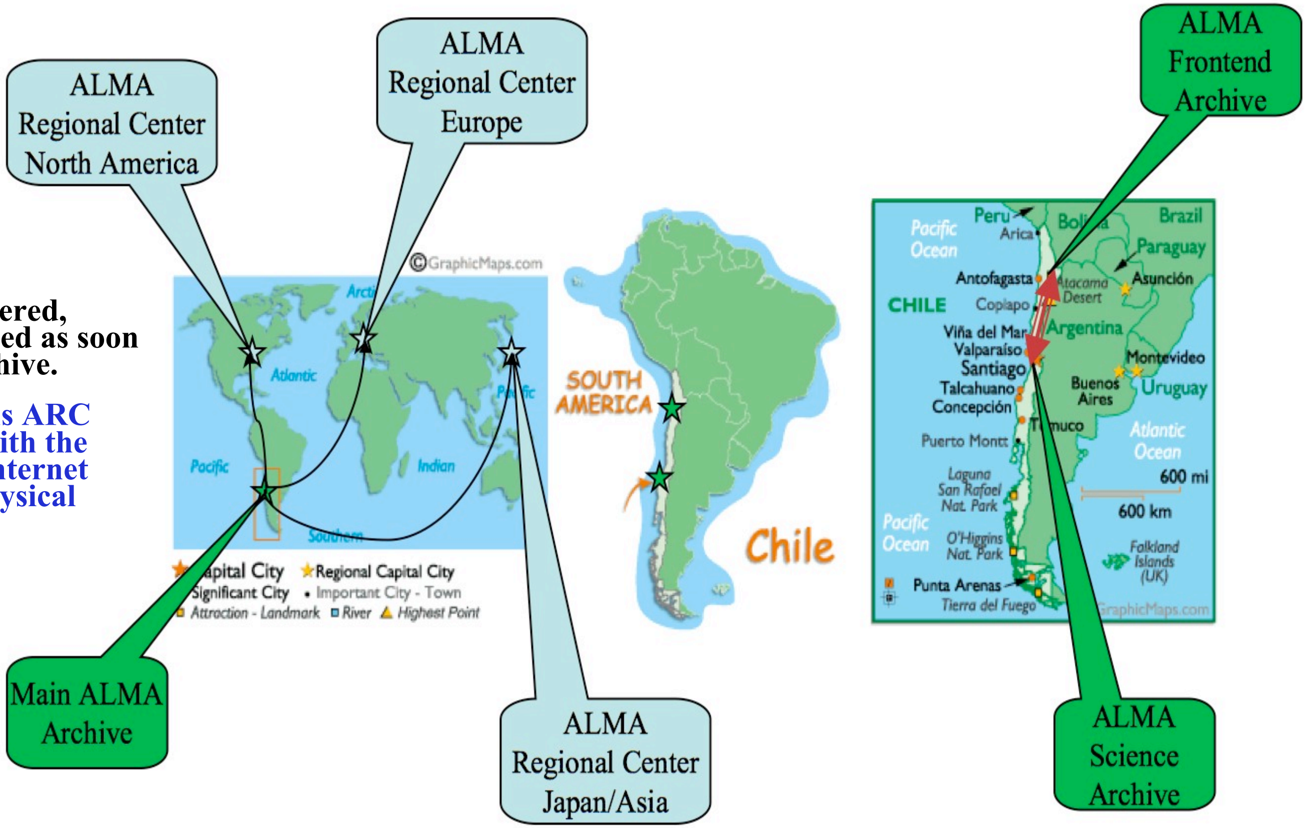
| | The 12-m array | ACA |
|---|---|---|
| Average over Sustained Period | 6 Mbytes/sec | 0.36 Mbytes/sec |
| Peak Rates | 60 Mbytes/sec | 3.6 Mbytes/sec |

The central archive:

- shall be located in Chile
- it will contain all raw and calibration data, all data products produced by the standard pipeline (i.e., calibrated images and/or spectra, reduction and imaging scripts), monitor (engineering) data (i.e. the shift log relative of each observing run, logs of all operations carried out by the array, environmental and site-condition data, and QA parameters, copies of all accepted observing proposals (including scientific justification) along with observing and reduction scripts as submitted and as run.
- The ALMA science pipeline shall be co-located with the main archive and mirrored at the ARCs.

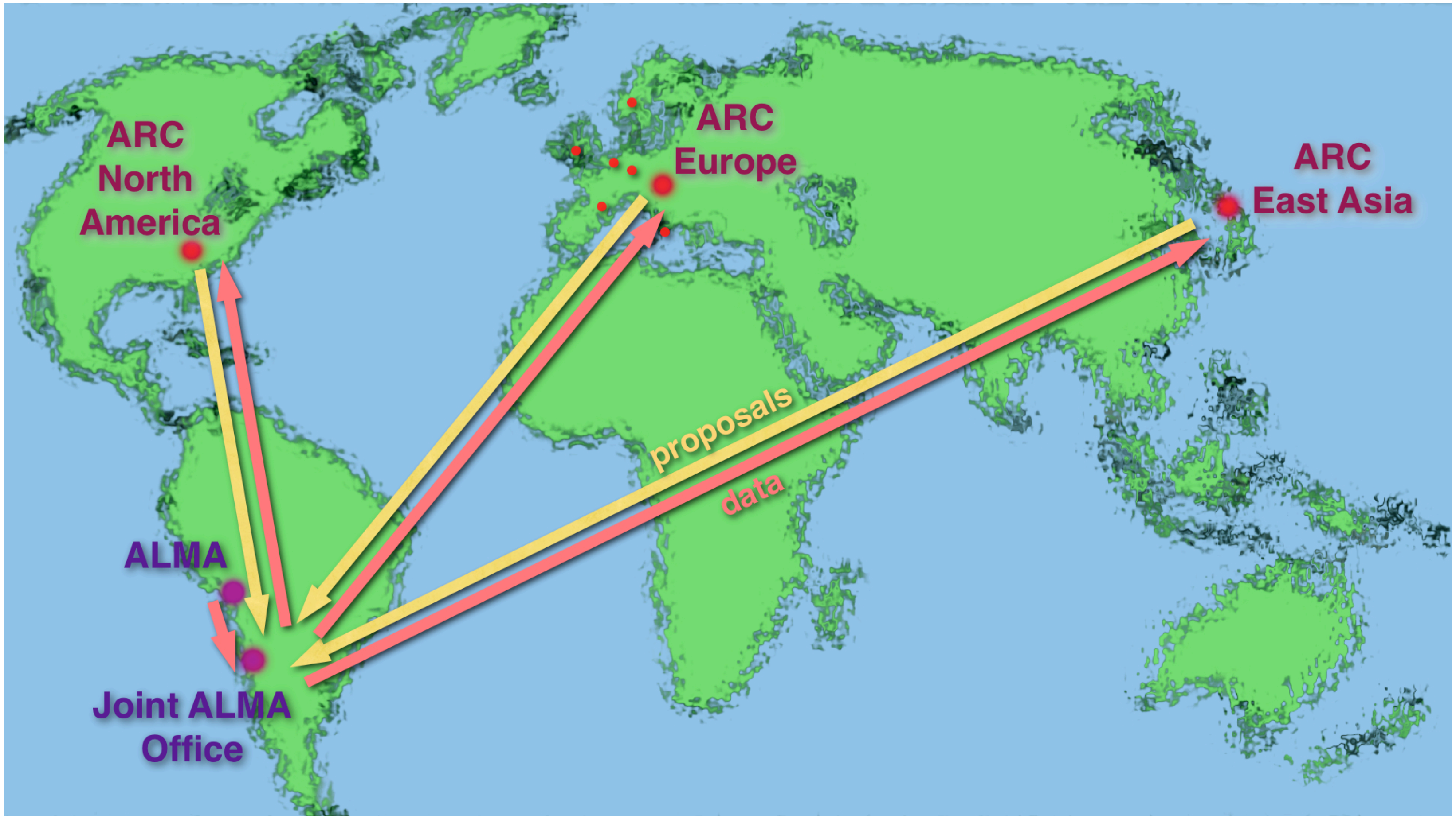
# The ALMA distributed system

## Archive nodes at the OSF, SCO and the ARCs




- **•ARC archive nodes delivered, commissioned and activated as soon as possible after SCO archive.**
- **•During science operations ARC nodes are synchronized with the central archive through internet (small data sets) or via physical media.**

**OSF connected to SCO via high-bandwidth. It MUST be always possible to operate ALMA even if the internet link does not work**


ARC
North
America
ARC
Europe
ARC
East Asia
proposals
data
ALMA
Joint ALMA
Office

# Science deliverables

- The Joint ALMA Observatory delivers the following items:
  - *uv* plane astronomical source and calibration data
  - Processed images
  - Off-line data reduction software
  - Software tools for proposal and observation preparation
  - ALMA Users Manual
- Before the is pipeline operational (i.e. during the first ~12 months of ES operations), the raw *uv* data delivered to the user automatically (with any necessary calibration data and system logs). Users shall have access to ALMA-produced data processing and imaging modules and cookbooks for these modules.
- After the central pipeline system is operational, raw (correlated) *uv* data will no longer be delivered automatically to the end-users. These data will be available to end-users from their regional ARC archive node.

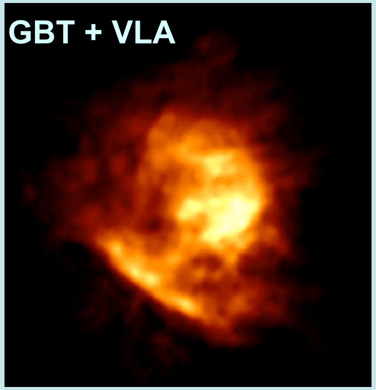
# ALMA data reduction

- After every observation:
- Data reduction pipeline starts
  - Flagging (data not fulfilling given conditions)
  - Calibration (antenna, baseline, atmosphere, …)
    bandpass, phase and amplitude, flux
  - Fourier transform (u-v to map)
  - Deconvolution
  - (Mosaicking, combination, ACA and main array,…)
- Output: fully calibrated u-v data sets and images or cubes (x,y,freq) → Archive
- Pipeline part of CASA (f.k.a. aips++)

# Pipeline and Off-line Data Reduction Software

## CASA (Common Astronomy Software Applications)

❖ CASA is written in C++, Java, and Python

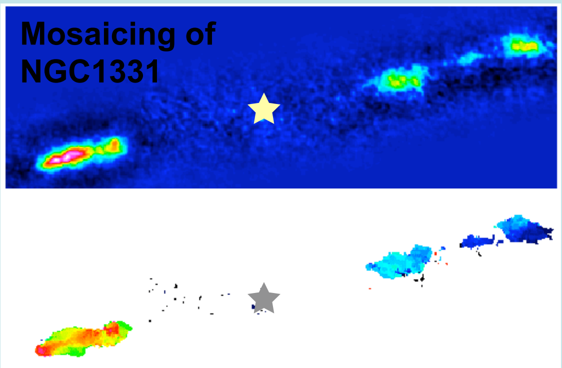



➢ Internal & External testing ongoing

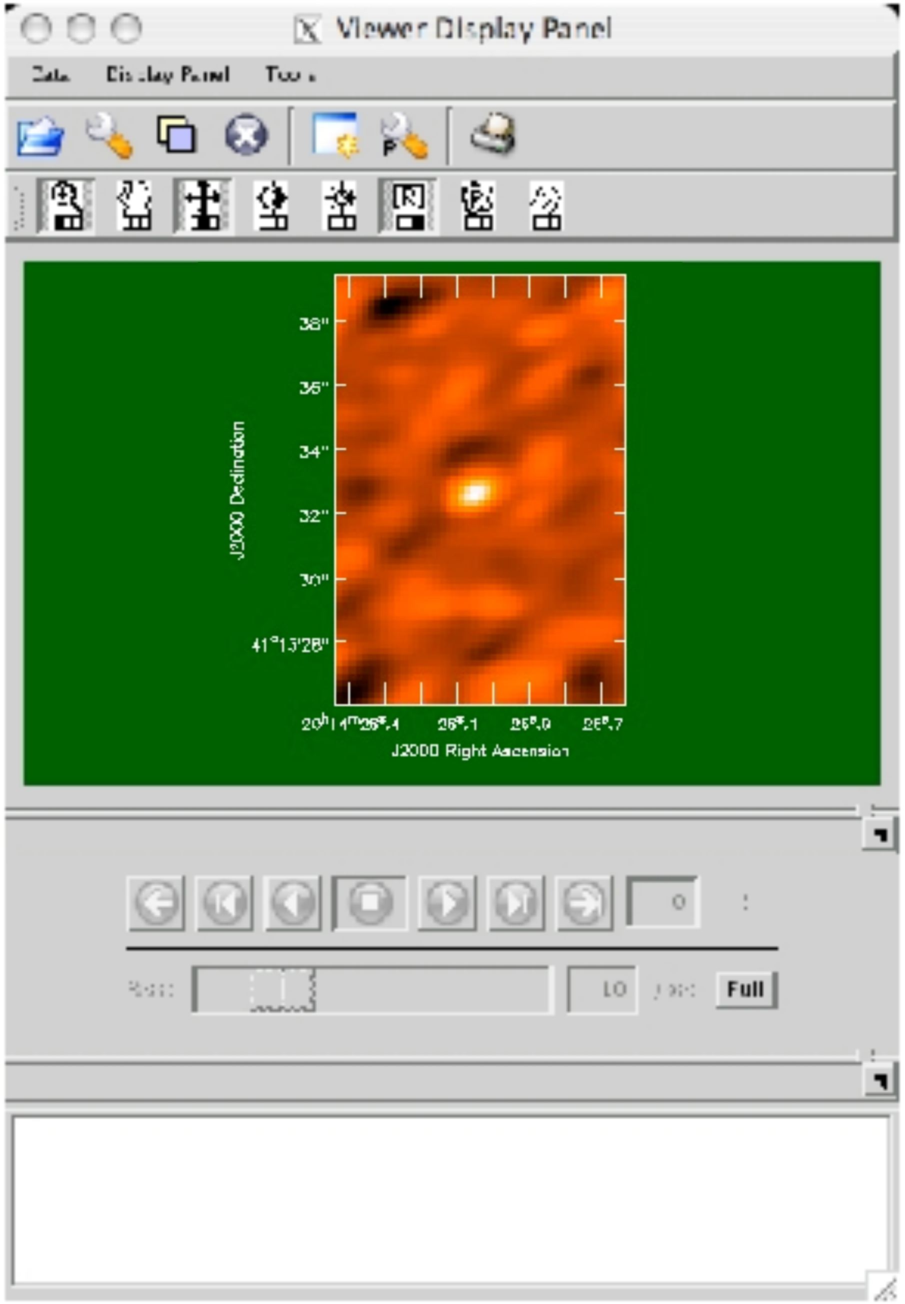
➢ Completed tests (1) Basic imaging, (2) Mosaicing, and (3) Single dish + interferometric data combination using VLA, BIMA, and PdBI datasets

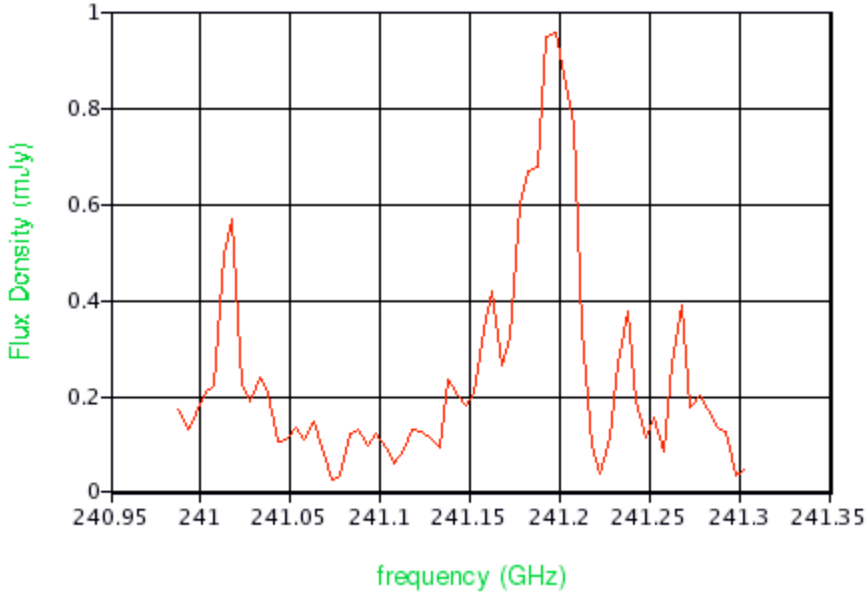
## CASA β-release end 2007

❖ Pipeline testing and development underway

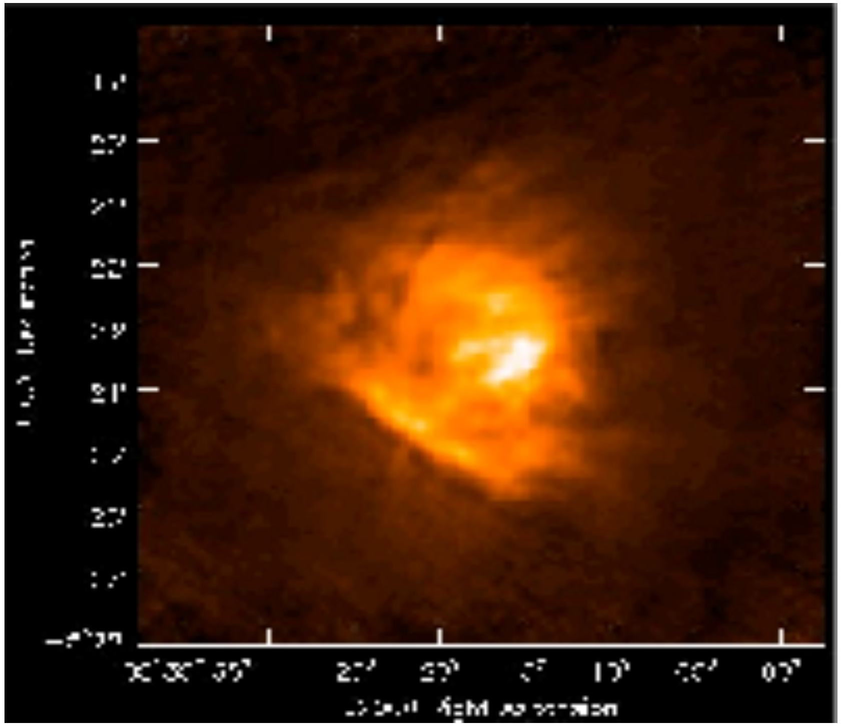


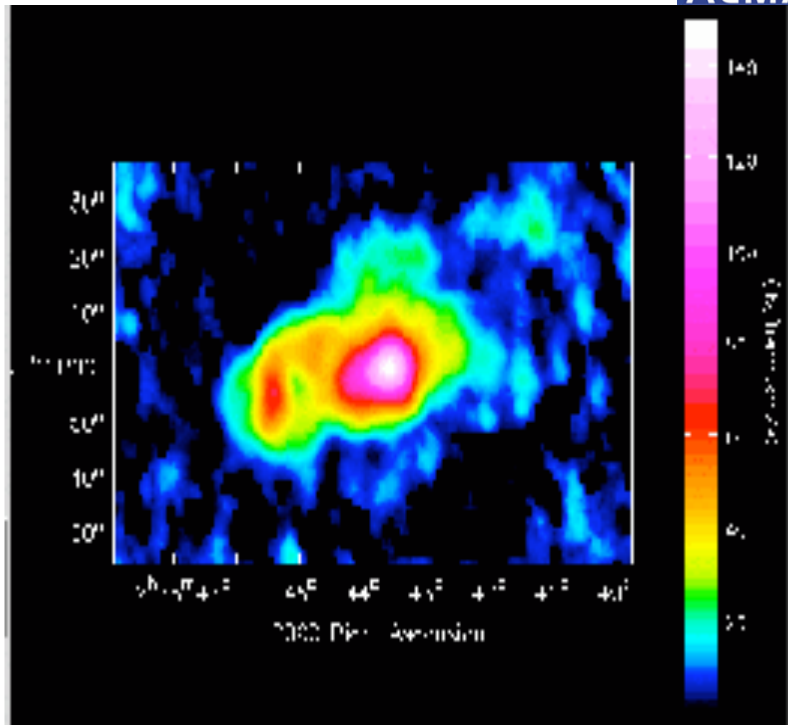
# Example of the viewer: $CH_3OH$ in IRAS 20126+4104



# Data reduction



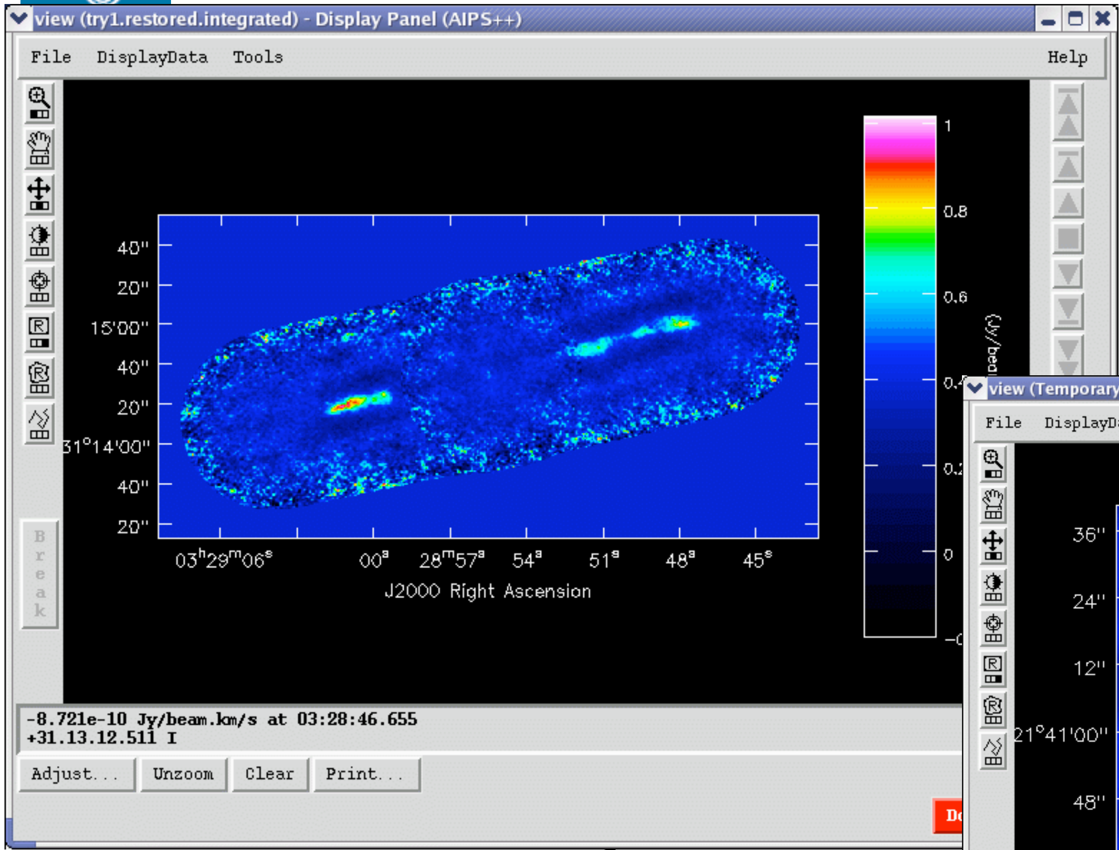


**Orion nebula continuum:**
**Combination of single dish + interferometric**
**(VLA+GBT joint deconvolution)**

**BIMA CO**

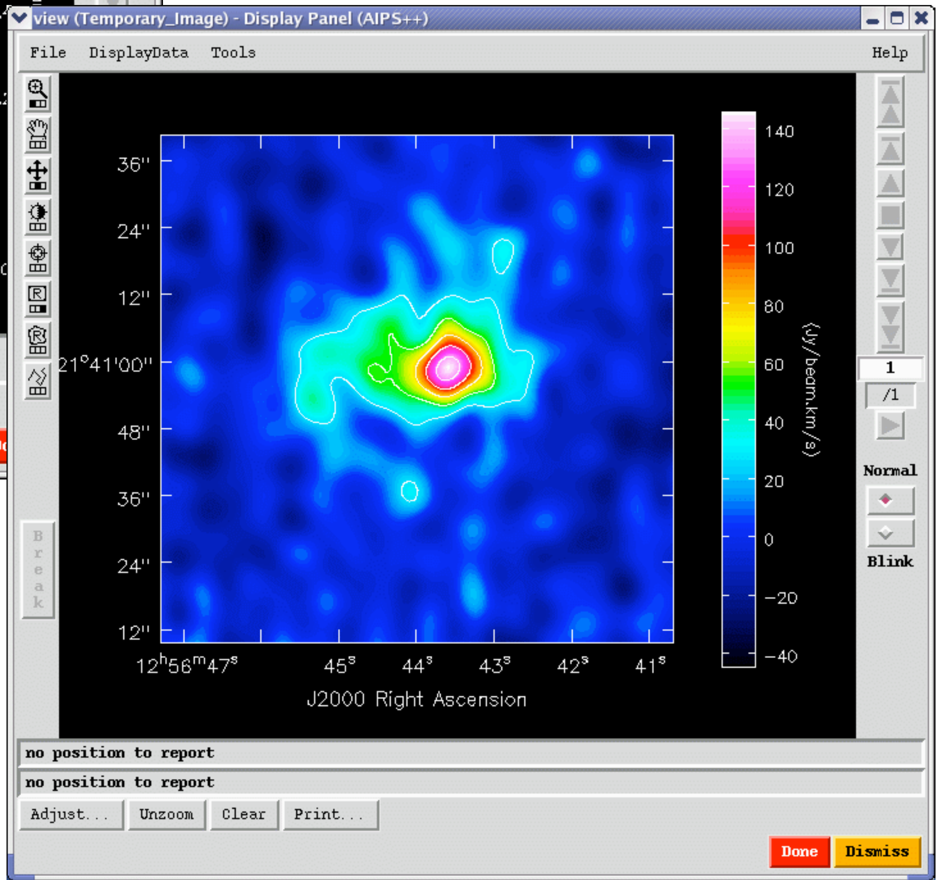
- All ALMA data will be reduced using the ALMA offline reduction and imaging package. This package is based on the C++ code base in AIPS++ with some fairly major changes to optimize it for ALMA and a redisigned user interface is  For many observations the automated calibration and imaging pipelines will produce reference images suitable for analysis.

# Mosaic interferometry - reduction & imaging




- BIMA SONG CO(J=1-0) at 3 mm
- 7 field mosaic, 4 spectral windows
- low S/N

NGC 4826



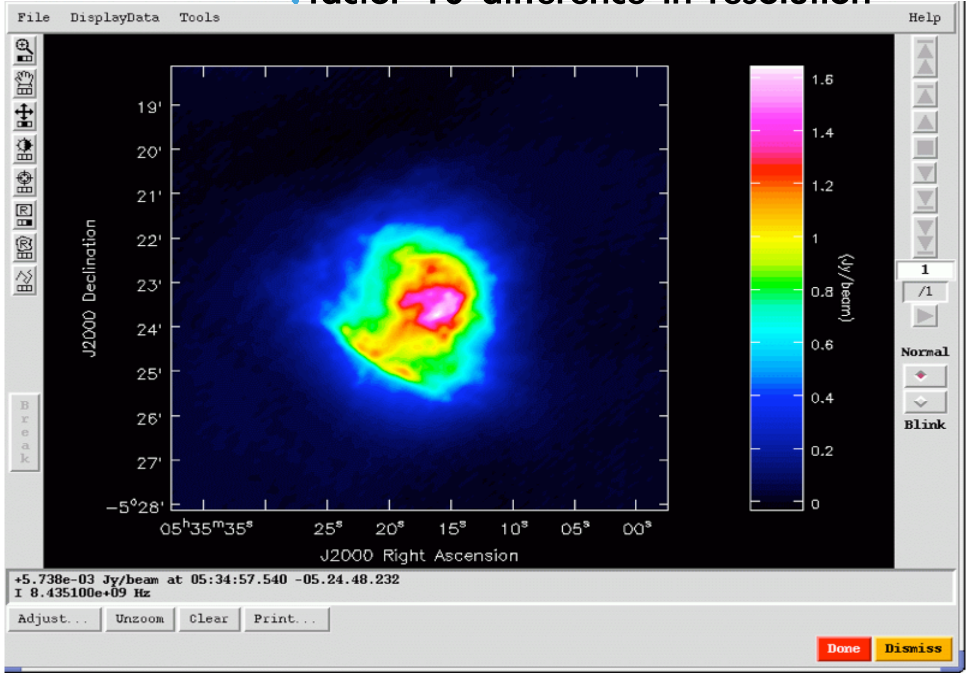

Molecular outflow

NGC 1333, CLEANed

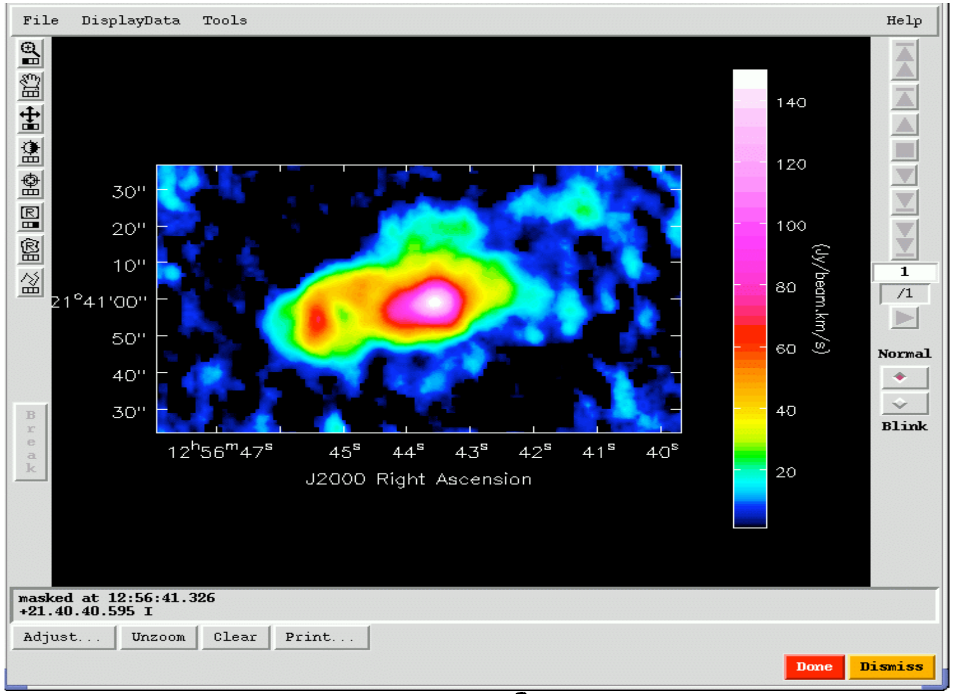
- a VLA mosaic (SiO(J=1-0) at 7 mm)
  - 10 fields in linear mosaic, 2 spectral windows
  - high S/N

- 3.6cm continuum,
- VLA image + GBT OTF map,
- high S/N VLA map
- factor 10 difference in resolution

CO(J=1-0) at 3 mm
combined BIMA mosaic with 12m OTF map
low S/N BIMA map, 12m striping
factor 3 difference in resolution




Orion, feathered




NGC 4826, feathered

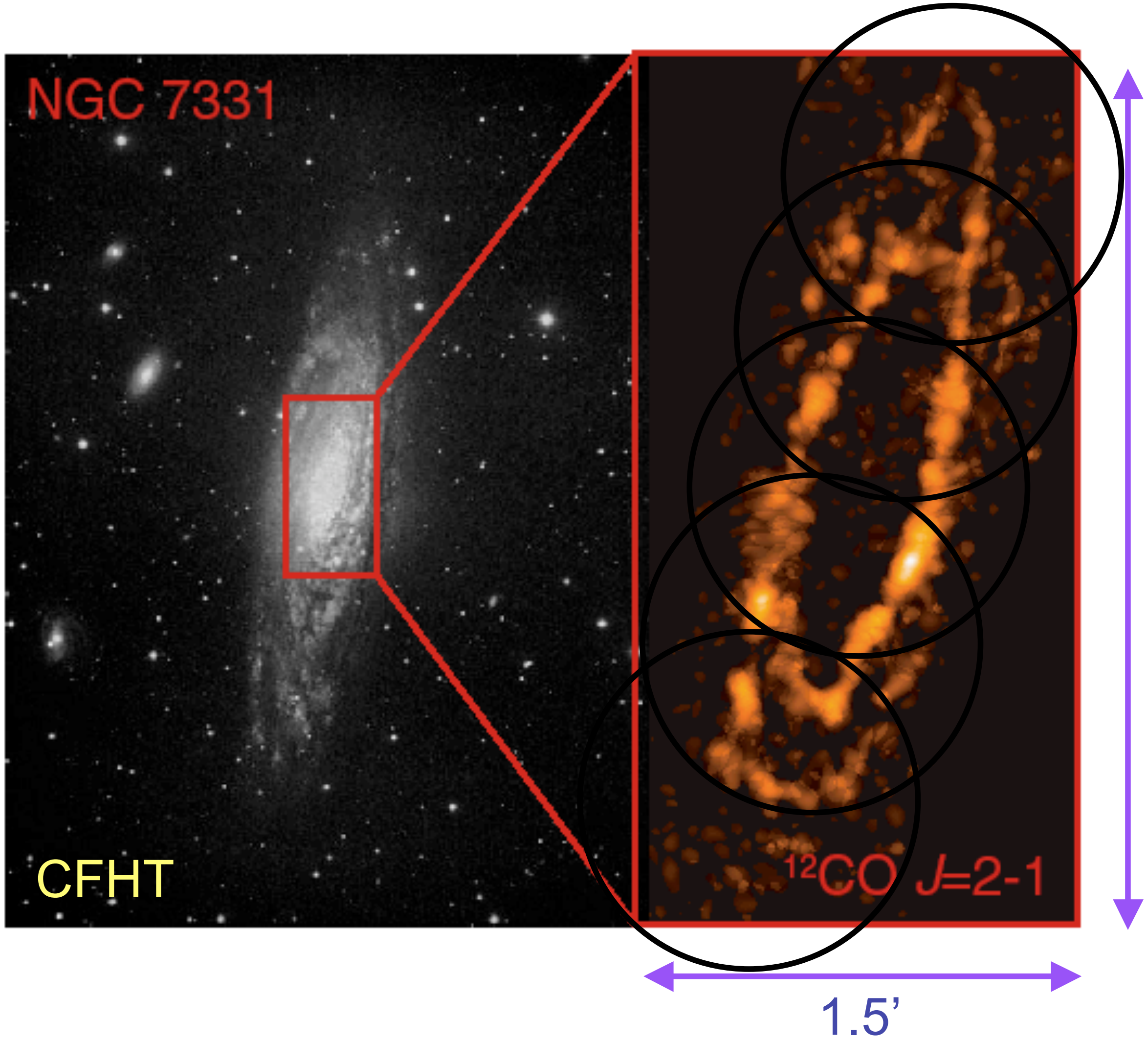
- **combine synthesis mosaics with single dish data**
  - **Image "feathering" (2 images "feathered" together in Fourier plane).**
  - **Joint deconvolution (single dish image is input as a 'default' model subtracted from the uv data, and the resulting dirty image is deconvolved)**

# What ALMA will 'see': examples of ALMA data



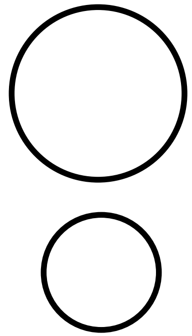
Paola Andreani, ESO

# Why do we need all those telescopes? ⇨ Mosaicing and Precision Imaging



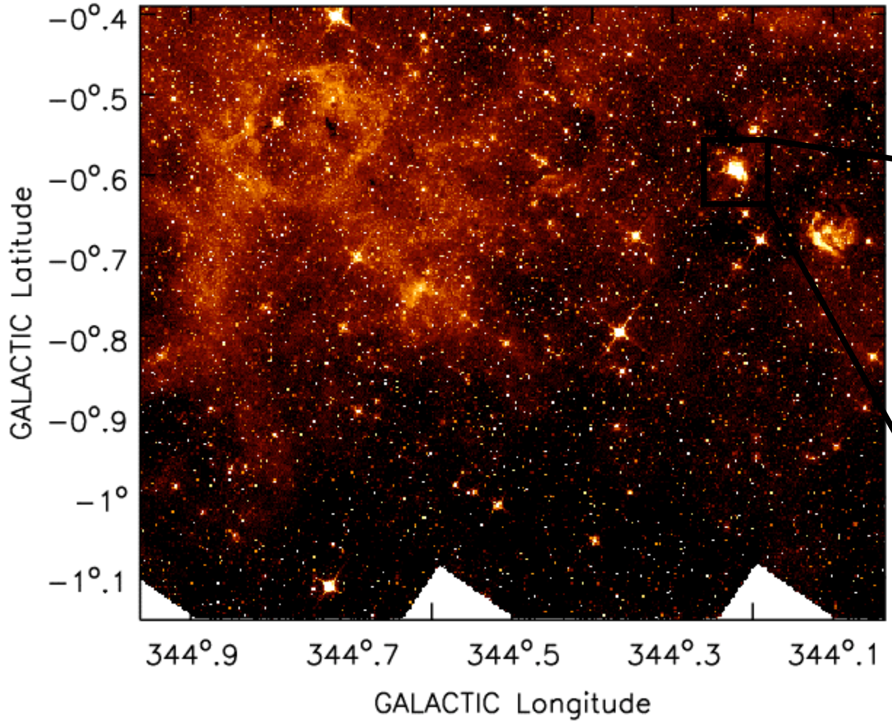

SMA ~1.3 mm observations

- Primary beam ~1'
- Resolution ~3"

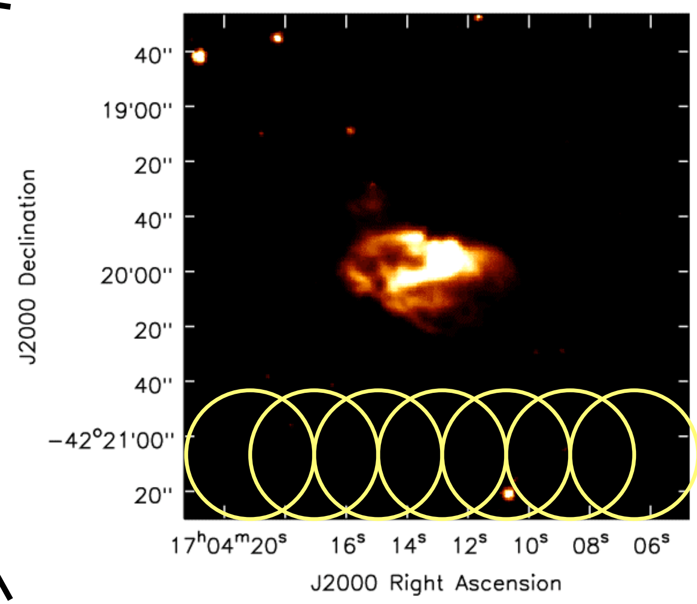



*Petitpas et al. 2006, in prep.*

# ALMA Mosaicing Simulation



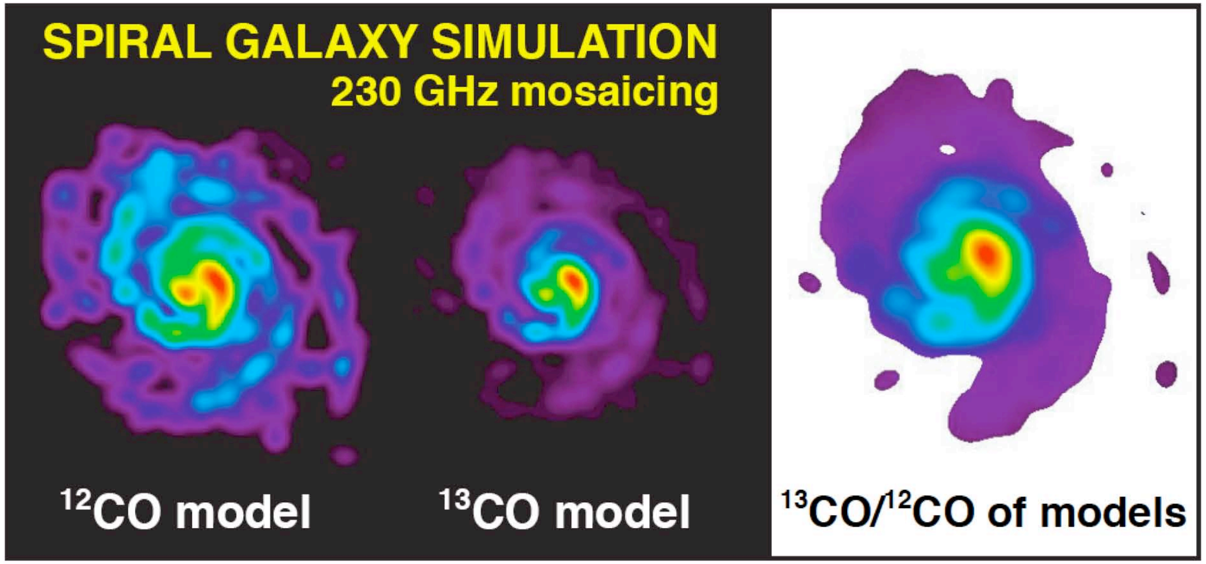

*Spitzer* GLIMPSE 5.8 μm image

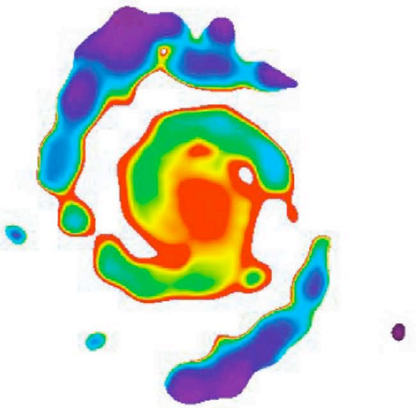



- Aips++/CASA simulation of ALMA with 50 antennas in the compact configuration (< 100 m)
- 100 GHz 7 x 7 pointing mosaic
- +/- 2hrs

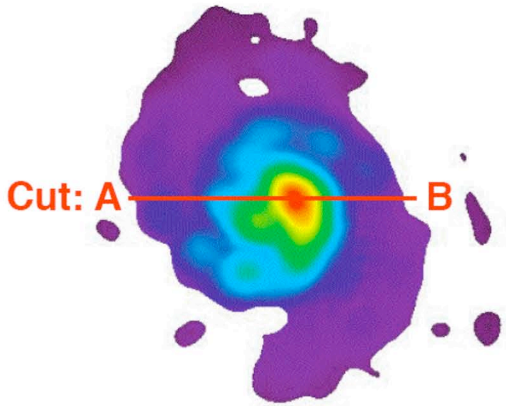
# Image Fidelity Improved by ACA (1)

*Simulation (Tatematsu, Tsutsumi et al. )*

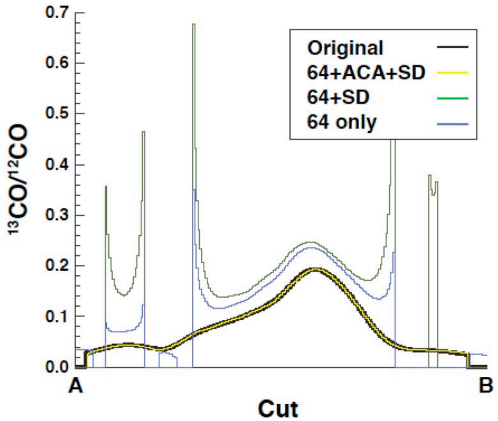


64+SD

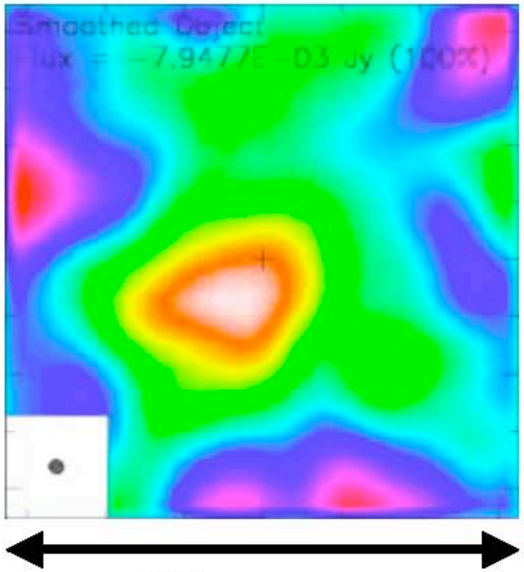



64+ACA+SD



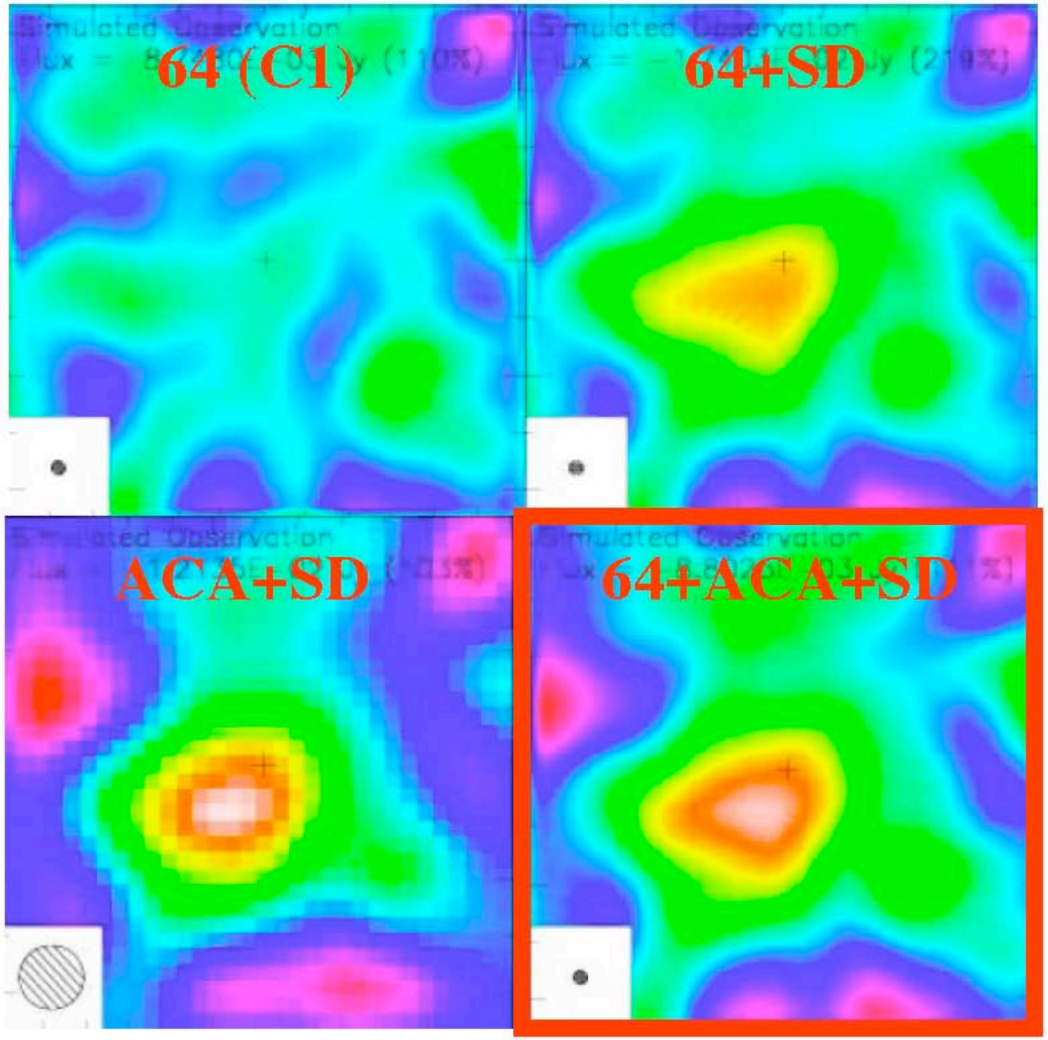
# Image Fidelity Improved by ACA (2)

**SZ effect**
RXJ1347–1145
NRO 150GHz data
(Komatsu et al. 2001)




–0.22 mJy/beam

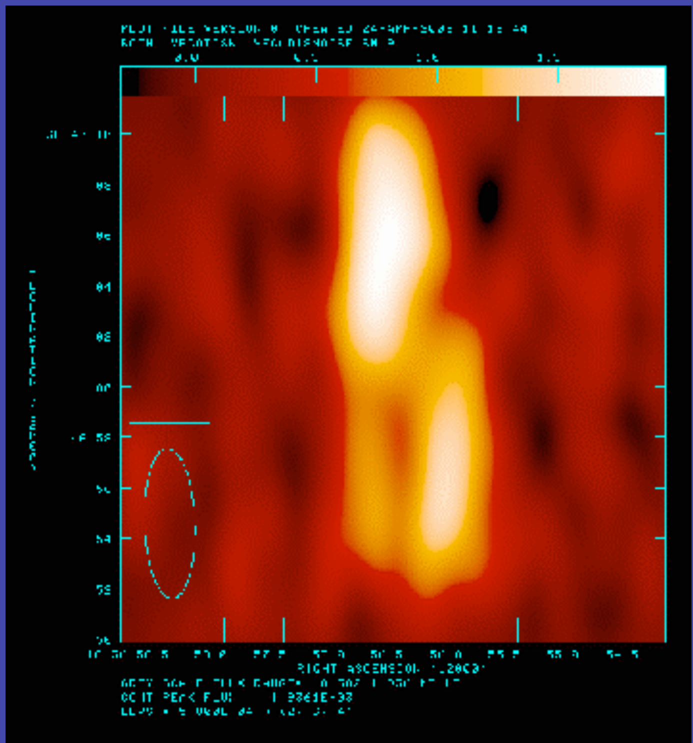
*Simulation (Kitayama, Tsutsumi et al. )*



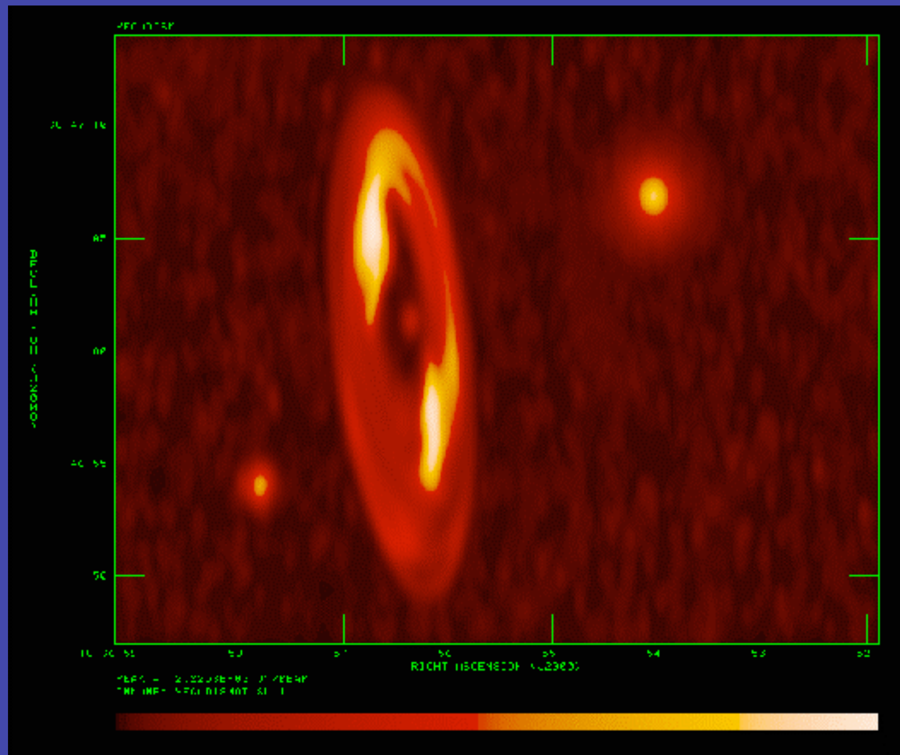

13-field mosaic, 18 min (64), 72 min (ACA)

# Dusty Disks in our Galaxy: Physics of Planet Formation

## Vega debris disk simulation: PdBI & ALMA

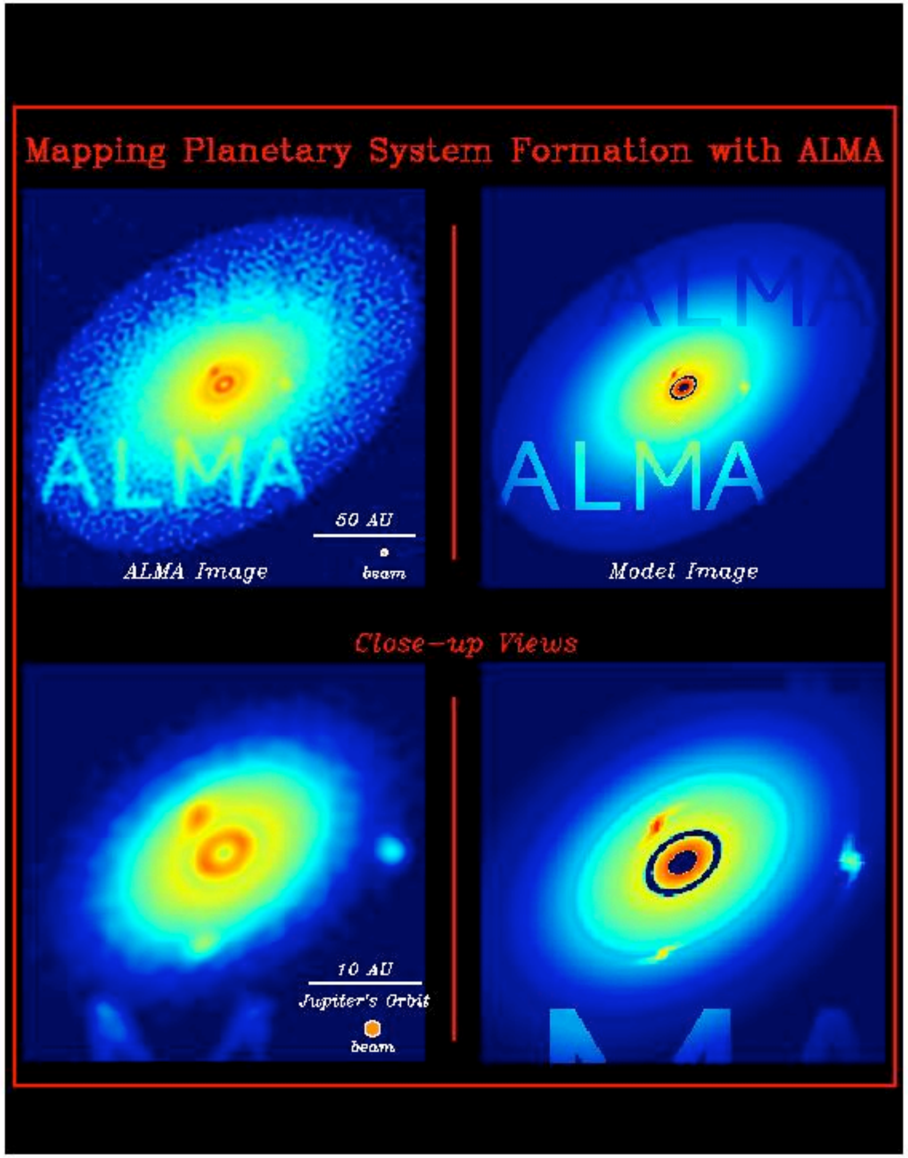


Simulated PdBI image



Simulated ALMA image

# ALMA Simulation of planetary system formation

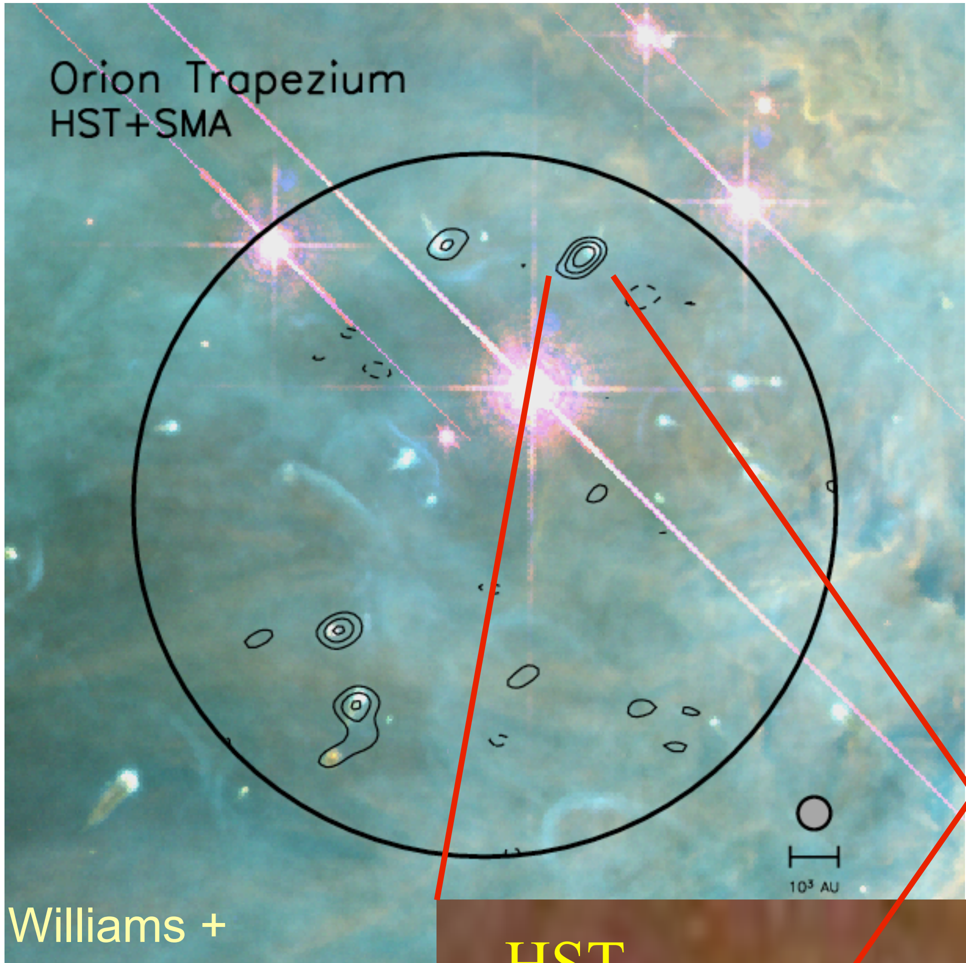



Observed Model

* 140 AU disk
* inner hole (3 AU)
* gap 6-8 AU
* forming giant planets at:
  9, 22, 46 AU with local
  over-densities
* ALMA with 2x over-density
* ALMA with 20%
  under-density
* Each letter 4 AU wide,
  35 AU high

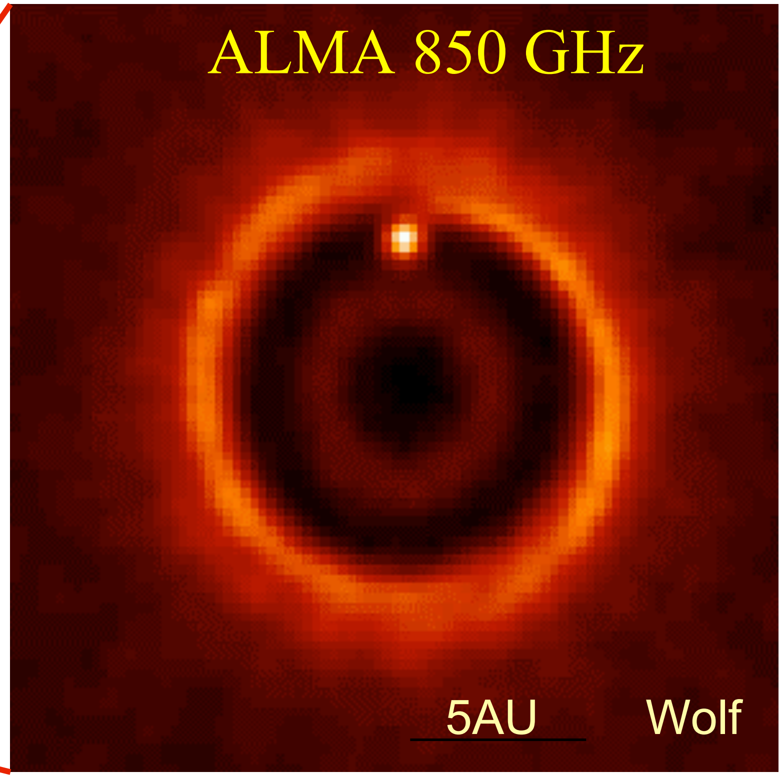
Observed with 10 km array
At 140 pc, 1.3 mm

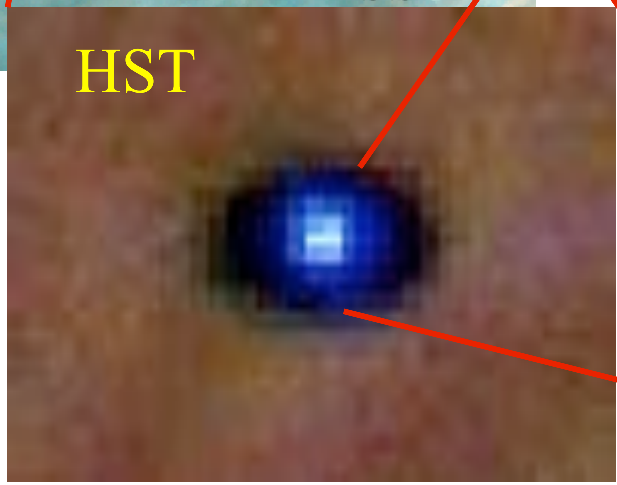
(Mundy)



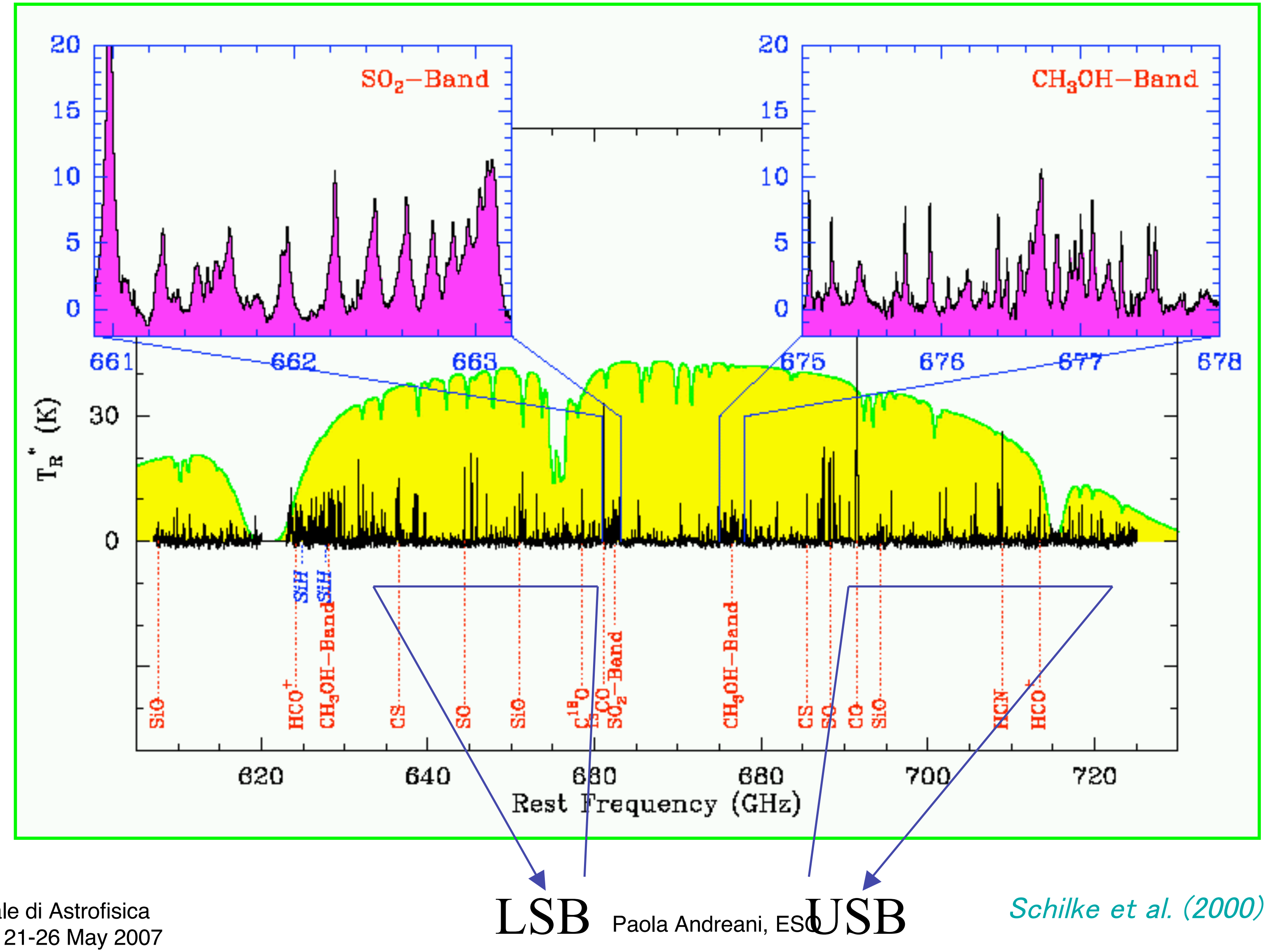

# Birth of planets

- $M_{planet}$ / $M_{star}$ = 1.0 $M_{Jup}$ / .5 $M_{sun}$
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus



# Orion at 650 GHz (band 9) : A Spectral Line Forest




*Schilke et al. (2000)*