ALMA: a new instrument for science in the submm band

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ALMA basics

ALMA status

ALMA organization and tools

Science topics for ALMA

ALMA numbers

- The Atacama Large Millimeter Array is a **mm-submm reconfigurable interferometer**
- **World wide collaboration:**

  Europe: ESO (14 countries),

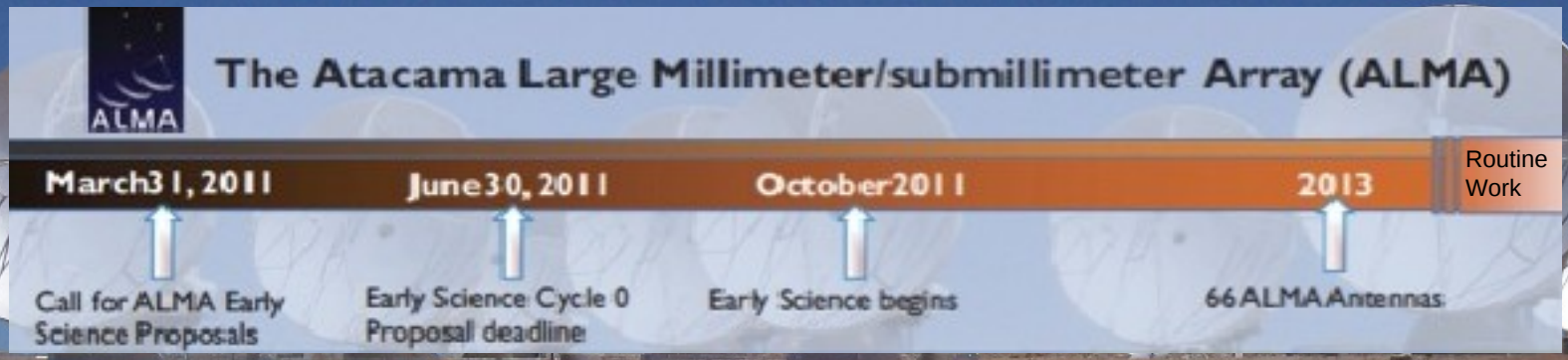
  North America: NRAO (USA, Canada),

  East Asia: NAOJ (Japan, Taiwan),

  Chile

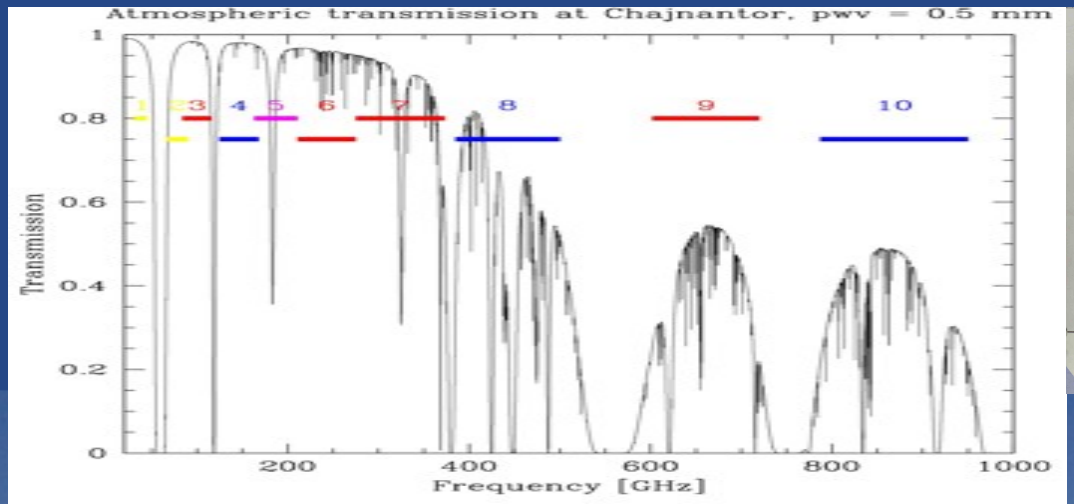
  Contributors share the observing time

- Currently under construction on the Chajinantor plain (**5000m**, Chile)

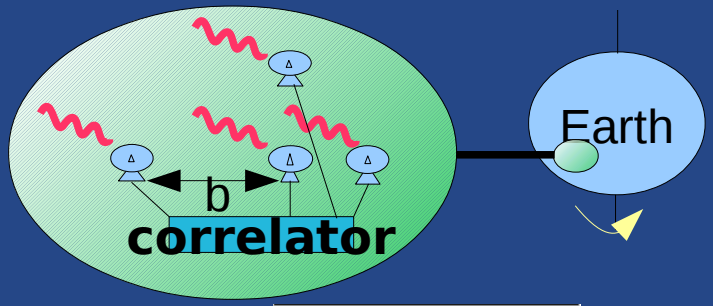


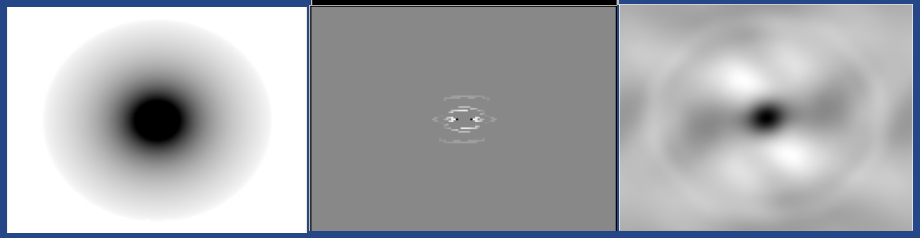
ALMA numbers

- Antennas: **50x12m** main array + (**12x7m + 4x12m**) ACA
- Baselines length: **15m ->150m-16km** + **9m->50m**
- Frequency range: **10 bands between 30-900 GHz** (0.3-10 mm)
- Heterodine receivers operating on 2x8GHz (or 10 GHz for b6)
- Bandwidth: **2 GHz x 4basebands for each of 2 polarisations**
- **70 correlator modes**: 31MHz-2GHz / 8192 ch / single, dual, full polarisation product
- **Mosaic** capability



Interferometry in a nutshell





Object | Fourier space | Image space

An interferometer reconstructs an image of the sky at fixed spatial scales (i.e. measures single points in the Fourier domain) corresponding to the projection of the baselines on the sky.

Imaging quality depends on the Fourier space coverage,
i.e. on the number of baselines (N(N-1)/2).
Resolution depends on the baseline length.
Sensitivity depends on effective collecting area, integration time, bandwidth.
Water vapour effects get worse as the frequency increases

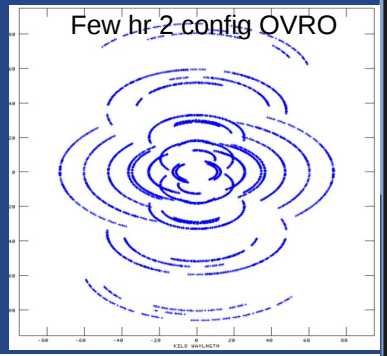
Noise in the image

$$\sigma_{image} = \frac{k_b T_{sys}}{A\eta}\sqrt{\frac{2}{t\ \Delta\nu\ n_{pol}\ N(N-1)}}$$

Angular resolution

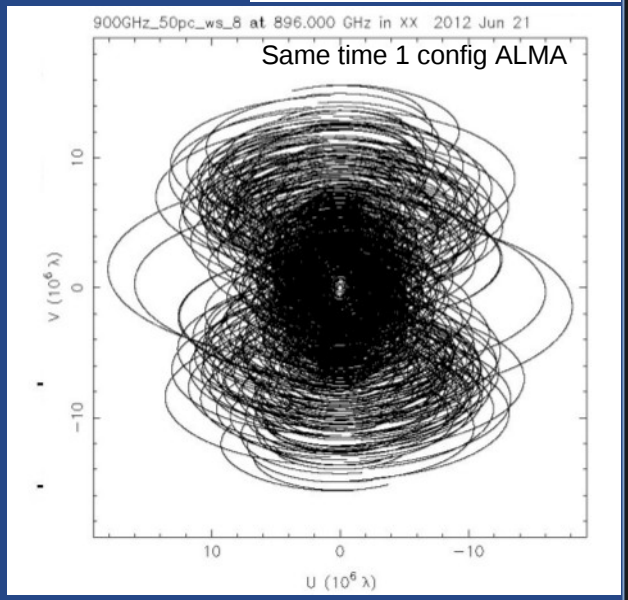
$$\theta = 1.33\frac{\lambda}{b_{max}}$$

ALMA numbers



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



Up to 16km baselines, subarcsec resolution
0.2" x (300/freq_GHz)x(1km/max_baseline)
40 mas @ 100 GHz,
5 mas @ 900 Ghz
FOV 12m array: 20.3"/(300/freq_GHz)

Flexibility in spectral and spatial studies

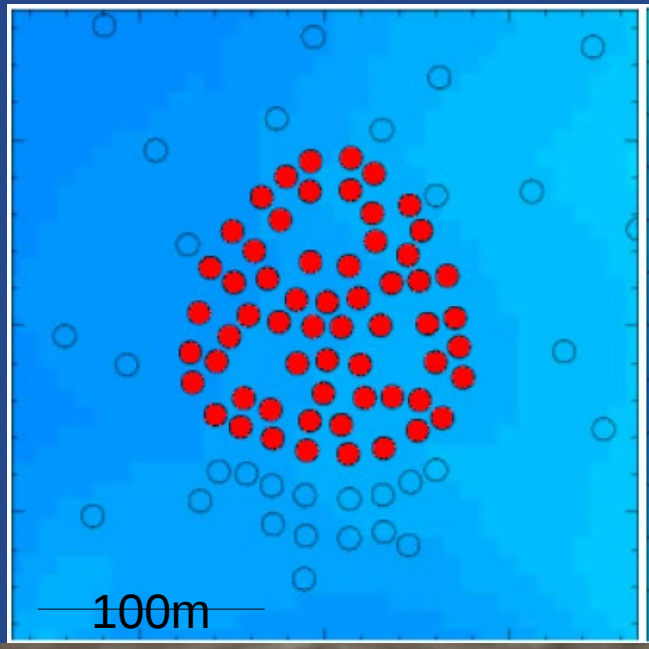
Noise in the image

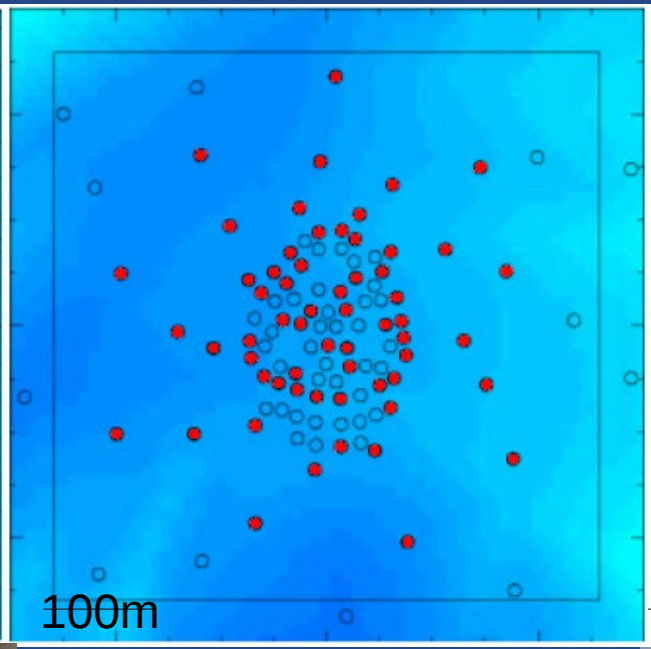
$$\sigma_{image} = \frac{k_b T_{sys}}{A\eta}\sqrt{\frac{2}{t\ \Delta\nu\ n_{pol}\ N(N-1)}}$$

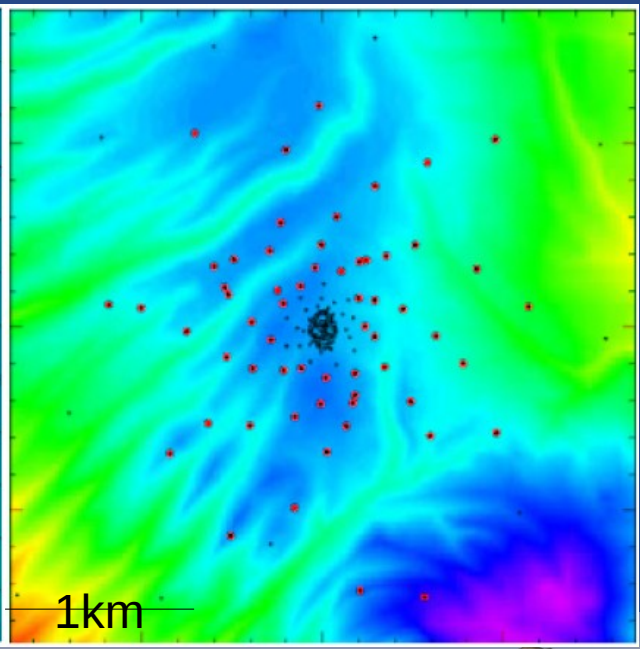
Angular resolution

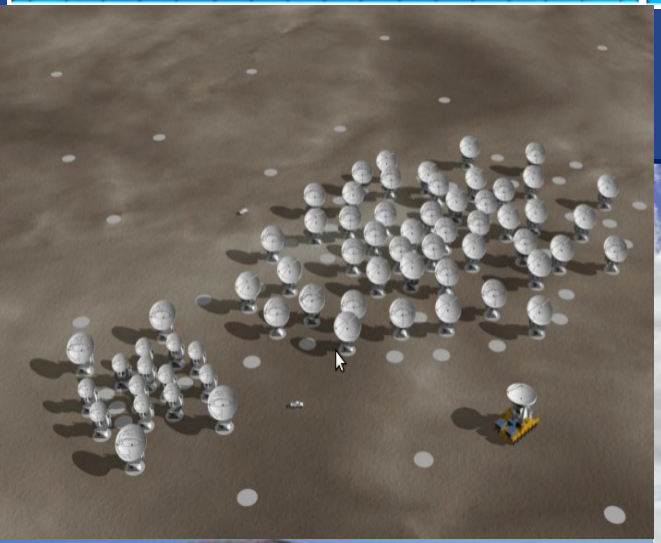
$$\theta = 1.33\frac{\lambda}{b_{max}}$$

ALMA reconfiguration

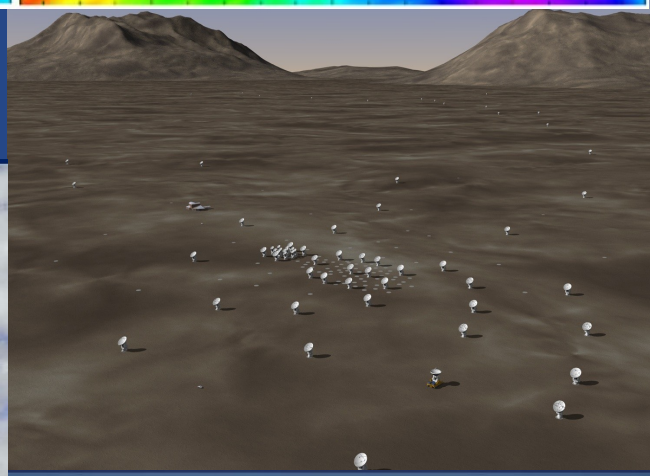








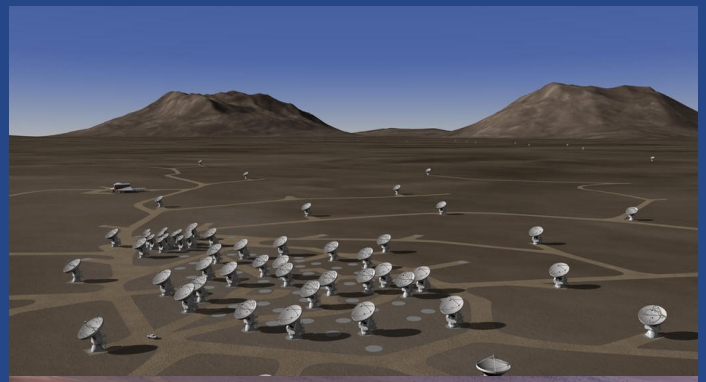
Antenna transporter



Antenna stations at 5000m

ALMA sites: OSF

ALMA sites:AOS



First ESO antenna at AOS (July 2011)

Currently:
18 antennas at AOS

(http://www.almaobservatory.org/)

ALMA current phases

Science Verification

- On-going tests to observe known sources to validate the output of ALMA
- Data public: not for science

http://almascience.eso.org/alma-data/science-verification

Early Science

- 31 March: call for proposals and ALMA Science Portal opening
- 29 April: deadline for notice of intent (not compulsory): 601 received!!!
- 1 June: opening of the archive for proposal submission
- 30 June: proposal submissione deadline
  - » **919 proposals received**! TAC evaluation on-going
- 30 September 2011 - 30 June 2012: ES Phase 0 observations (500-700 h)

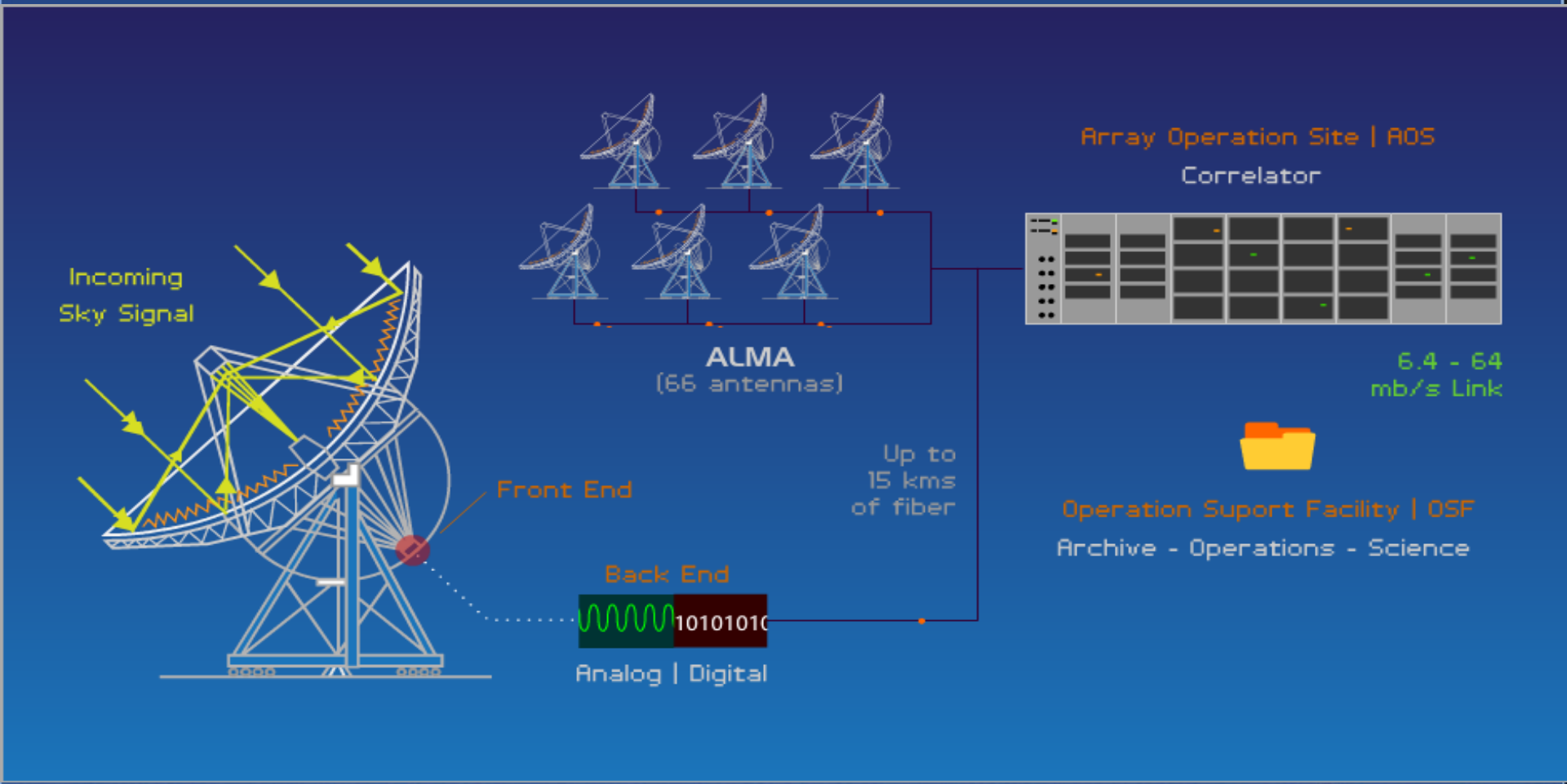
http://almascience.eso.org/call-for-proposals

	Full array	Early Science
Frequency range:	**10 bands 30-900 GHz**	**4 bands (3, 6, 7, 9)**
Antennas:	**50x12m +** ACA	min**16x12m** (no ACA)
Sensitivity	**0.15 mJy in 1 min at 230 GHz**	**0.5 mJy in 1 min at 230 GHz**
Max baseline:	150**m-16km**	**2 configs: 18-125m** **36-400m**
Resolution:	**20 mas @ 230 GHz** **70 correlator modes**	**1000 mas @ 230 GHz** **14 correlator modes**
	Mosaic capability	**Limited mosaic** capabilities
	Pipeline reduction in Chile	Reduction @ ARCs

Band	Lower frequency [GHz]	Upper frequency [GHz]	Type
3	84	116	2SB
6	211	275	2SB
7	275	373	2SB
9	602	720	DSB

Band	Frequency [GHz]	Angular Resolution ["]	Maximum Scale ["]	T_{bc} [mK]	Flux [mJy]	T_{bl} [K]	Field of View ["]
Properties of the Compact Configuration (baselines of ~18 m to ~125 m)							
3	100	5.3	21	0.65	0.14	0.030	62
6	230	2.3	9	1.0	0.20	0.029	27
7	345	1.55	6	1.8	0.37	0.043	18
9	675	0.80	3	15	3.2	0.27	9
Properties of the Extended Configuration (baselines of ~36 m to ~400 m)							
3	100	1.56	10.5	7.6	0.14	0.35	62
6	230	0.68	4.5	11	0.20	0.34	27
7	345	0.45	3.0	20	0.37	0.50	18
9	675	0.23	1.5	175	3.2	3.1	9

ALMA data flow



ALMA organization

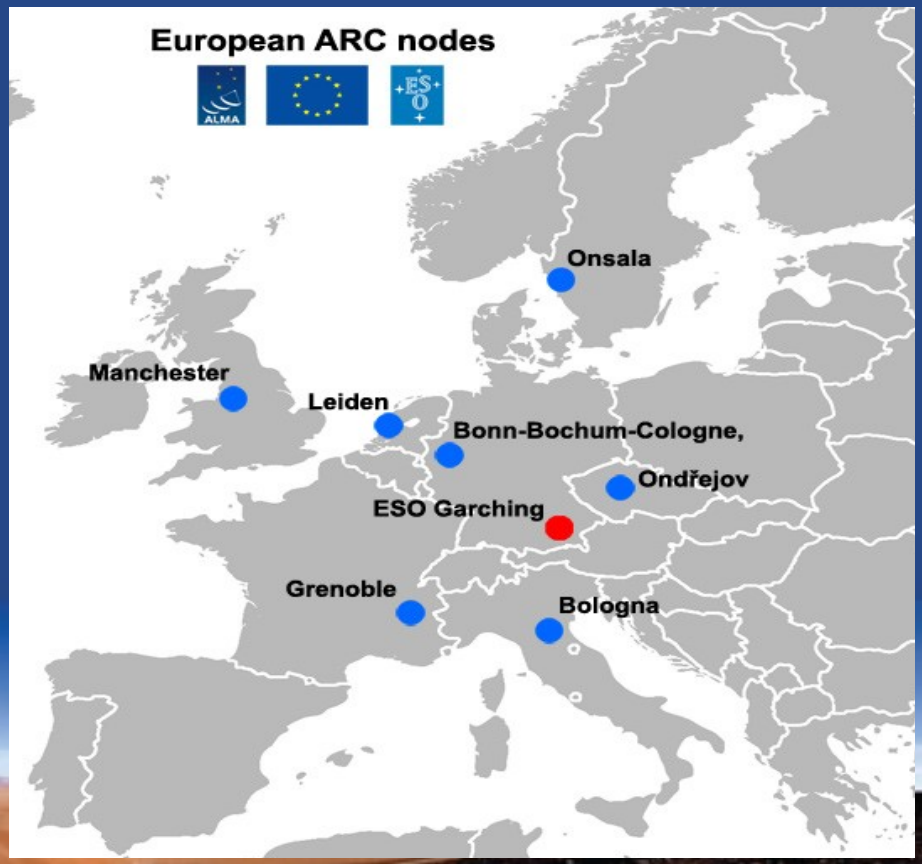
- 3 sites in Chile
  - AOS: ALMA operations site (5000 m)
    - Antennas, correlator
  - OSF: Operations support facility (3000 m)
    - Labs, antenna assembly and maintenance
    - Operators, astronomers
  - SCO: Santiago central office
    - JAO (Joint ALMA observatory)
      - » Calls for proposals
      - » Running ALMA
      - » Data reduction pipeline
      - » Quality assessment
    - Archive
- ALMA Regional Centers

The ALMA Regional Centers (ARC)

- **Interface between JAO and users**
- 1 ARC per Partner:
  - NRAO for North America
  - NAOJ for East Asia
  - ESO for Europe
- 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

The European ARC

- ESO European ARC distributed over a 7-nodes network
- ARC center at ESO: core tasks
  - Proposal handling
  - Archive
  - Data product support (ALMA data and software)
  - Helpdesk
- **ARC nodes**:
  - Face to face support
  - User formation
  - Advanced tools



The Italian ARC node

- Hosted by the IRA in Bologna
  - ARC Manager: Jan Brand
  - 1 tenured position (Massardi)
  - 4 Post-Docs (Casasola, Mignano, Paladino, Rossetti)
  - 1 system manager (Bedosti)
  - 1 ESO ALMA co-funded fellow (Boissier)
  - contributions from 6 members of IRA permanent staff
- **User support**
  - **Face to face (ALMA software, CASA)**
  - **Polarimetry, mosaicing, GRIDDING computations**
- Community formation
  - In 2010: community day and CASA tutorials
  - In 2011: tutorials or ALMA ES
  - Tutorials and seminars on CASA and ALMA science @ schools in Italy

Fundamentals of ALMA observations

ALMA will be dynamically scheduled in service mode

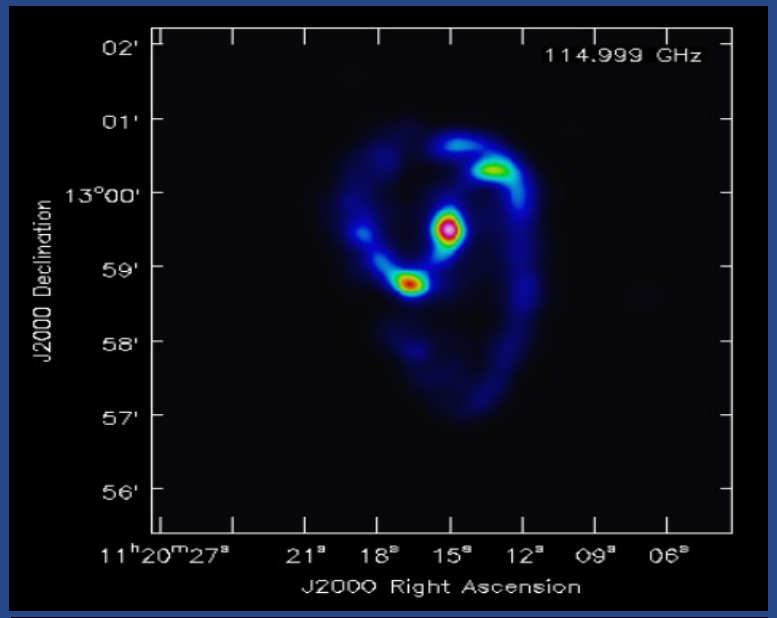
Some tools:
- the Science Portal and the Helpdesk (SP)
- the Observing Tool (OT)
- the Splatalogue
- the Common Astronomy Software Application (CASA)
- the Observation Support Tool (OST)

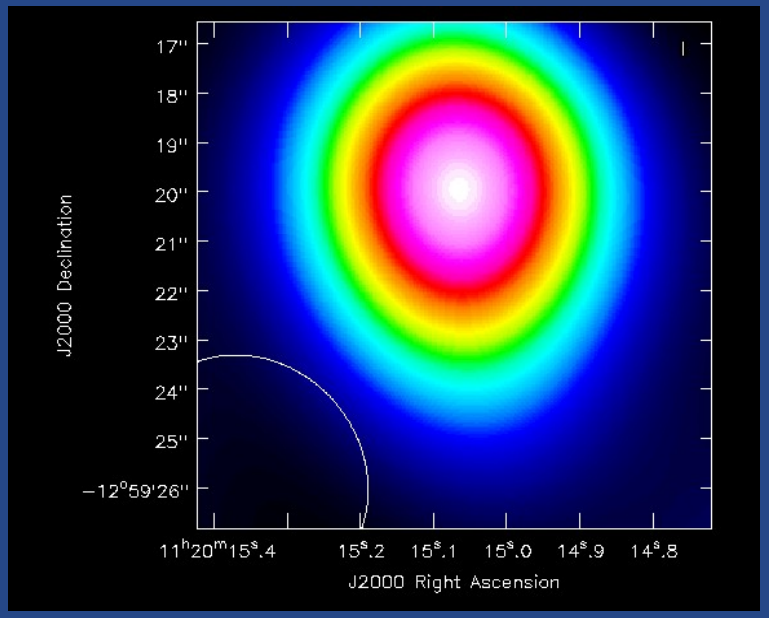
Thought to be suited both for experienced and non experienced observers.

Care about the limitations in resolution and sensitivity before the full array will be available!

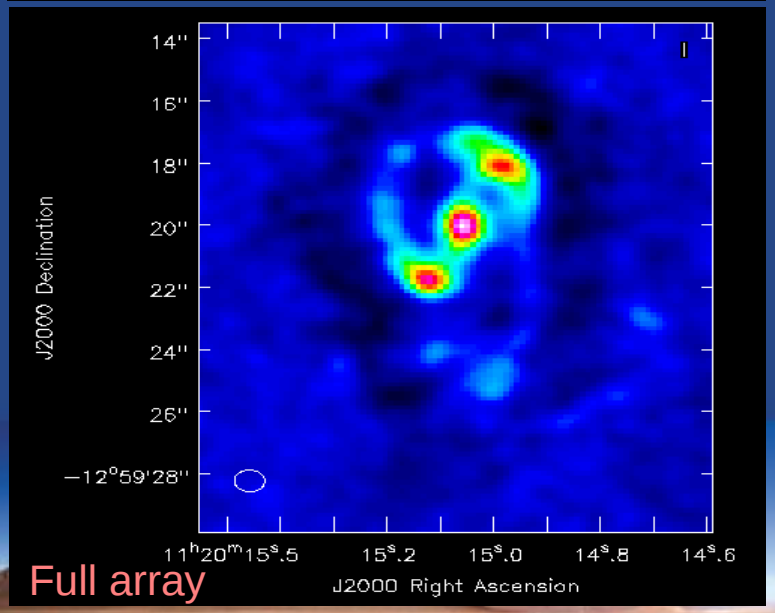
ALMA simulations (CASA simdata)

Simulation of NGC3627 @ z=0.1

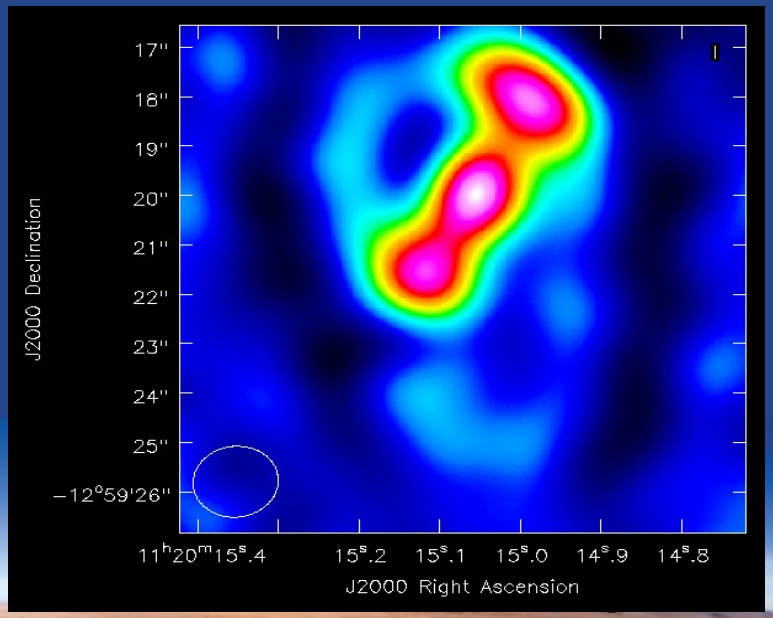




Early Science
Baseline 250m



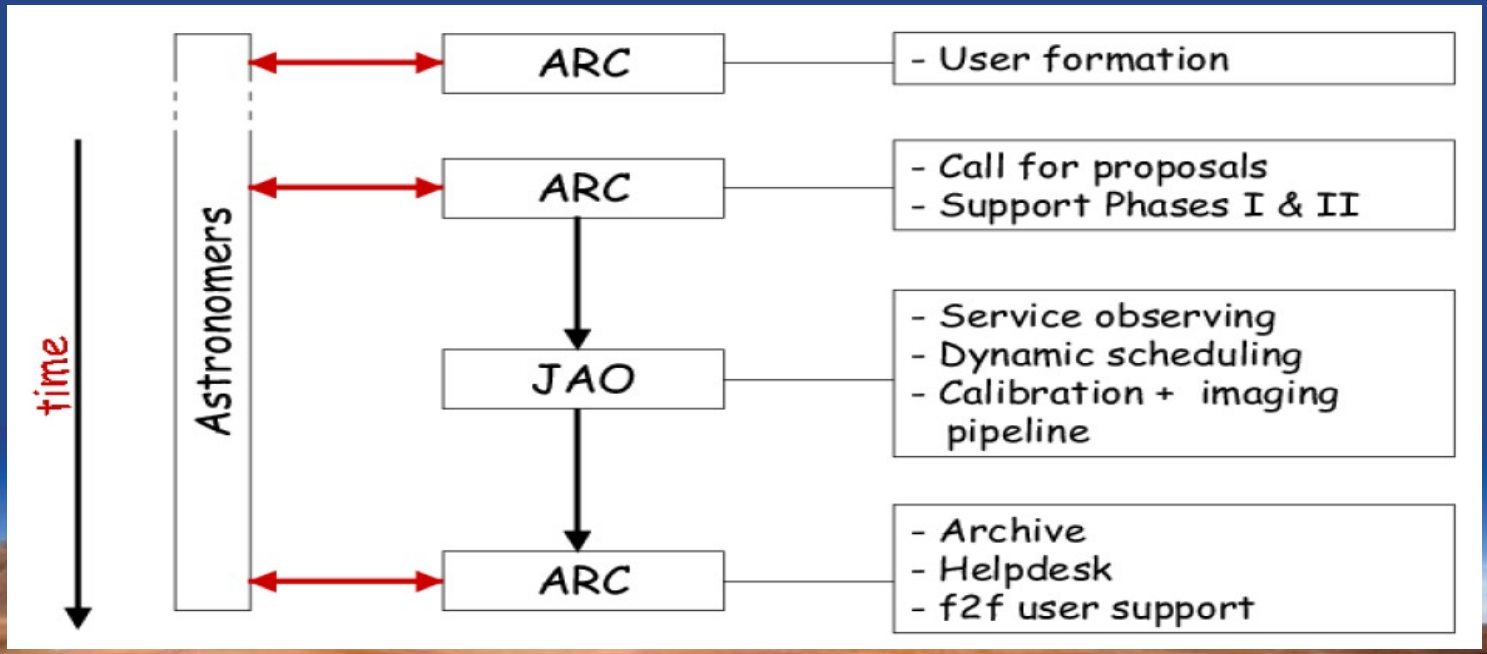
Full array



Early Science
Baseline 450m

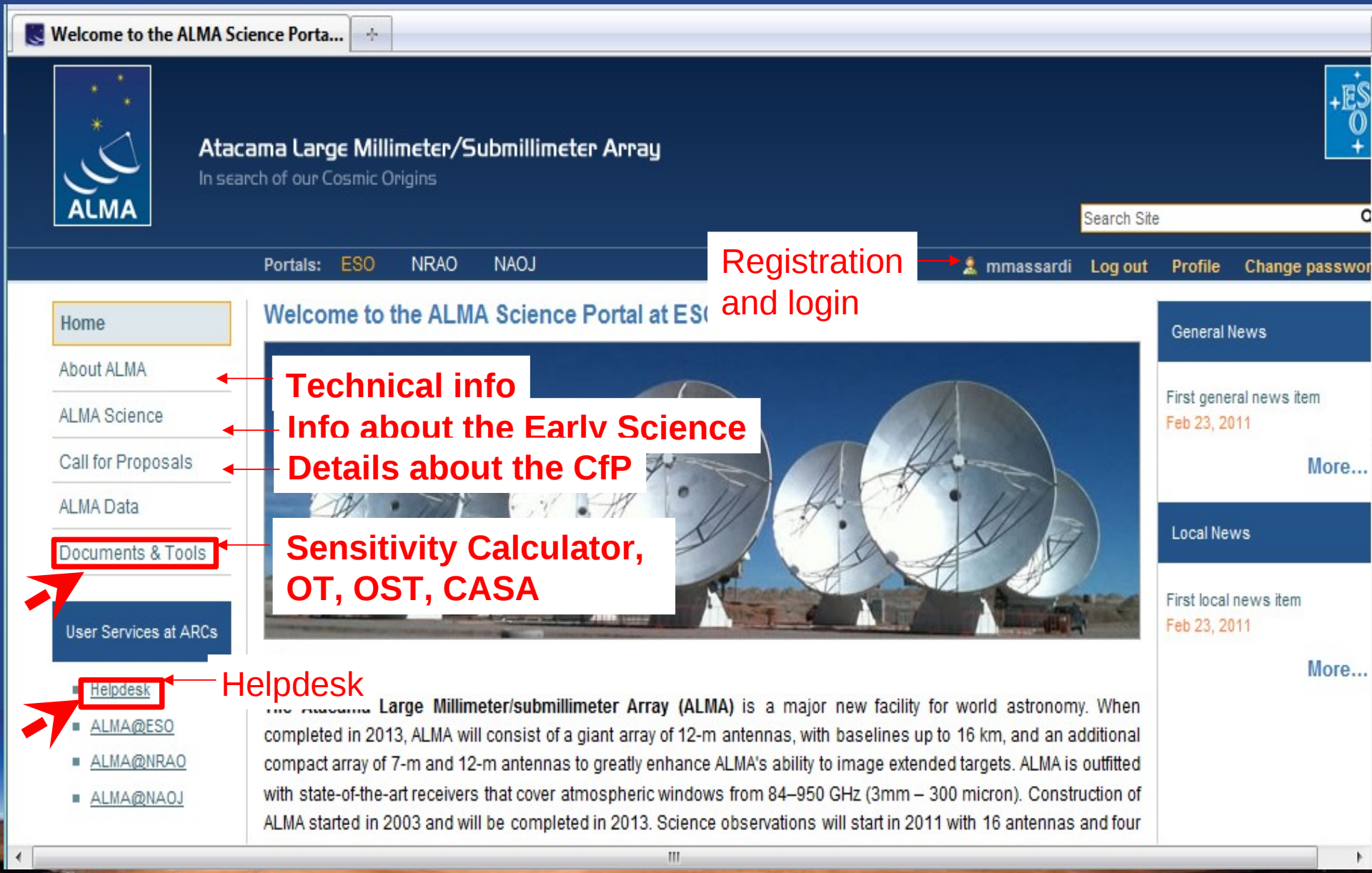
ALMA project checklist

Have a good idea!	
Estimate required configuration	(CASA, Splatalogue, OST, OT)
Write the proposal idea in pdf docs (max 5 page)	
Register to the Science Portal	(SP)
PHASE I – Proposal submission	(OT, SP, Helpdesk)
TAC evaluation	
PHASE II – Observing program submission for accepted proposals	(OT, SP, Helpdesk)
Observations	
Data reduction and analysis	(CASA)

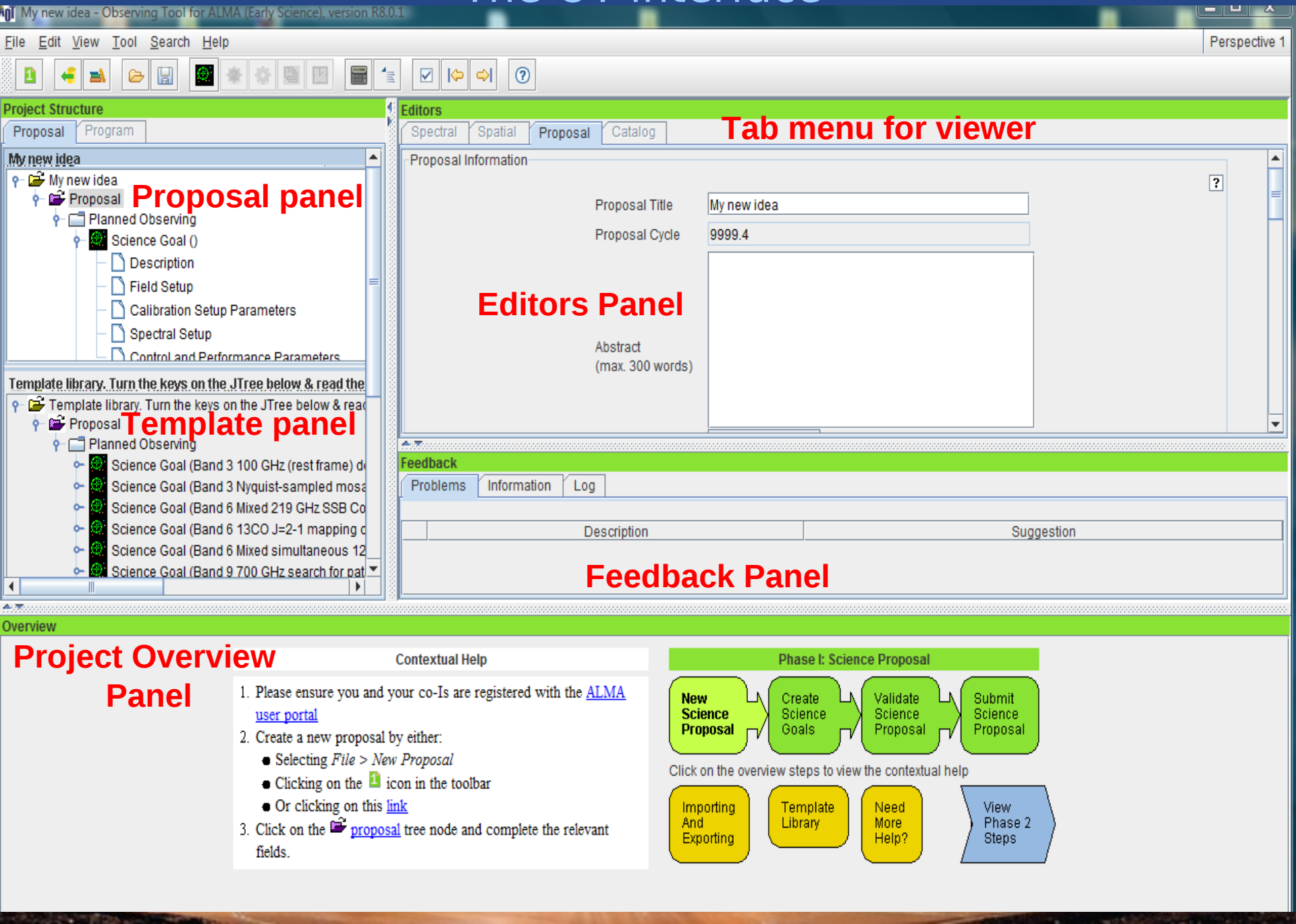


The ALMA Science Portal

http://almascience.org/



The OT interface



Proposal Review process

Proposals will be reviewed by an **international proposal review committee**.
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.

PHASE II observing programs

Investigators will be notified of the result of the ALMA Proposal Review process via email and successful investigators will be invited to submit a detailed observing plan.
The ALMA Observing Tool (OT) is used to prepare individual Scheduling Blocks (SBs, about 30min for weather reasons)
The best SBs at any moment will be observed (science, weather, project status

These will be used by the ALMA Scheduling Software to ensure that the observations are carried out under the required weather conditions.
The ALMA Regional Centers (ARC) will provide support to investigators in the Phase II process.

Once the Phase II preparation is finished the Scheduling Blocks will be submitted to the ALMA site and scheduled according to rank and requested observing conditions.
Investigators will be able to track the status of their project with the **ALMA Project Tracker.**

...and then?

For the ALMA full array a pipeline will be operating
PIs will receive fully reduced images+raw data+scripts

For Early Science the pipeline is being assessed
"...ALMA staff will conduct quality assurance on ALMA data..."
PIs will receive raw data+ quality assessment scripts

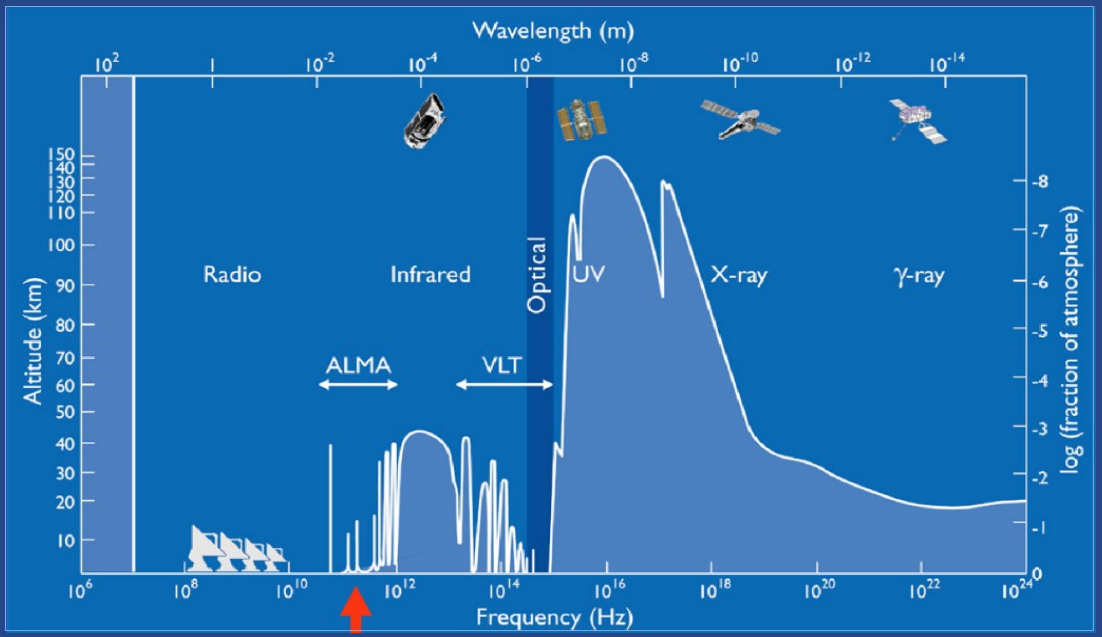
Proposer experience in radio-mm interferometry is required to reduce Early Science data.
Support can be requested to the ARCs.

CASA scripting helps in calibration & reduction.

Care for the huge amount of data!!!

ALMA science in the submm band

The submm band

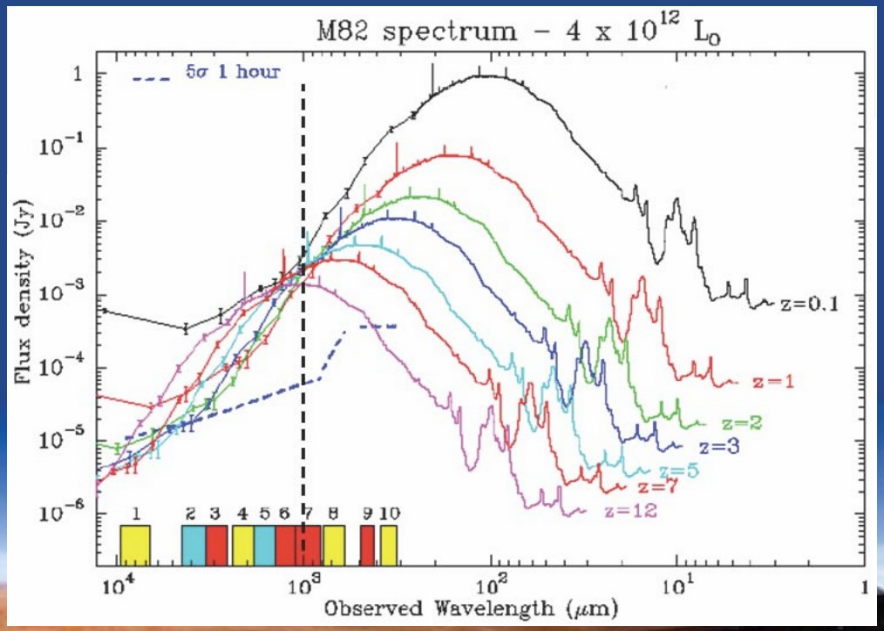


Mostly observed from space because of atmospheric opacity
Region of thermal emission from dust grains and chemical elements in dust.

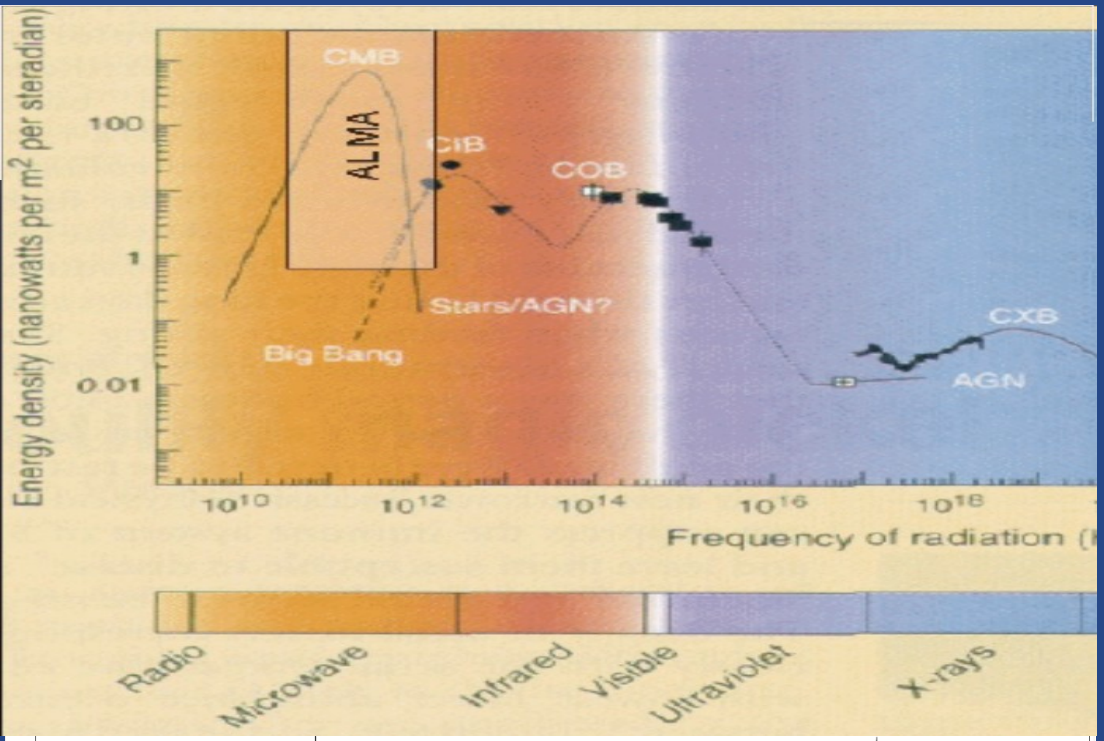
-> Good for observing dusty-obscured environments like those surroundings forming structures

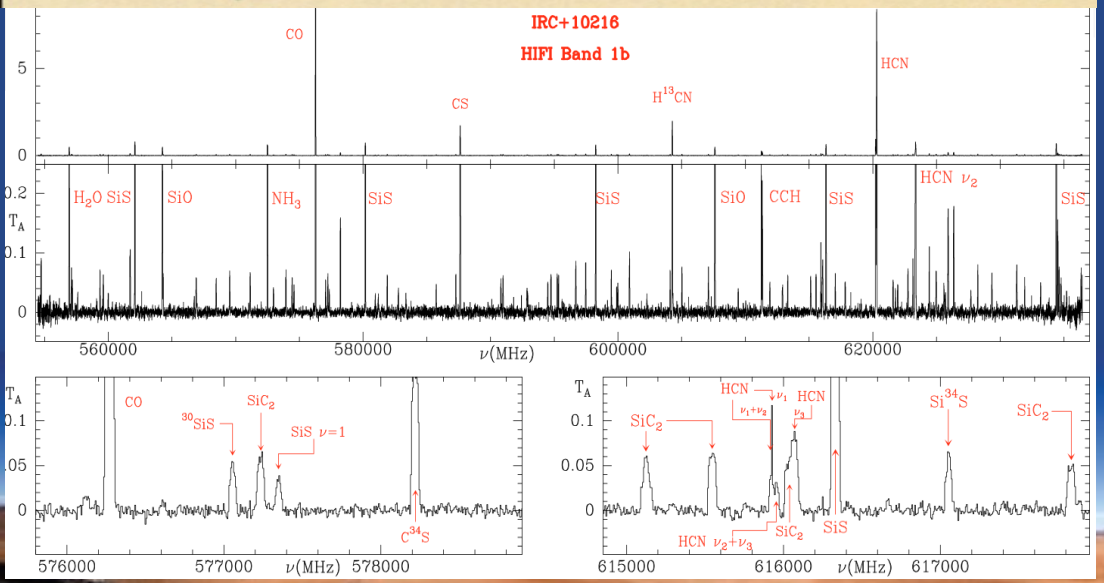
Thanks to the steep rising with freqs of the dust continuum spectrum inverse k-correction compensate for the decrease of brightness as the redshift increases

-> Good for high redshift studies



The submm band





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Region of thermal emission from dust grains.

-> Good for observing dusty-obscured environments like those surroundings forming structures

Thanks to the steep rising with freqs of the dust continuum spectrum inverse k-correction compensate for the decrease of brightness as the redshift increases

-> Good for high redshift studies

About 50% of emitted radiation in Universe is in the submm.

Region of emissions from chemical components in dust grains.

-> Good for characterize the chemical enrichment in dusty envelopes (stars, planets...)

Dust is in forming structures

-> Good for structure formation studies

3 main science/constructive goals

1. Detect and map CO and [C II] in a Milky Way galaxy at z=3 in less than 24 hours of observation

-> frequency bands, spectral resolution, large collecting area

-> study of star formation in galaxies up to high redshift, galaxy formation, strong lensing, ...

2. Map dust emission and gas kinematics in protoplanetary disks up to 500 ly far away

-> high baseline number, ACA, high spectral resolution and flexibility

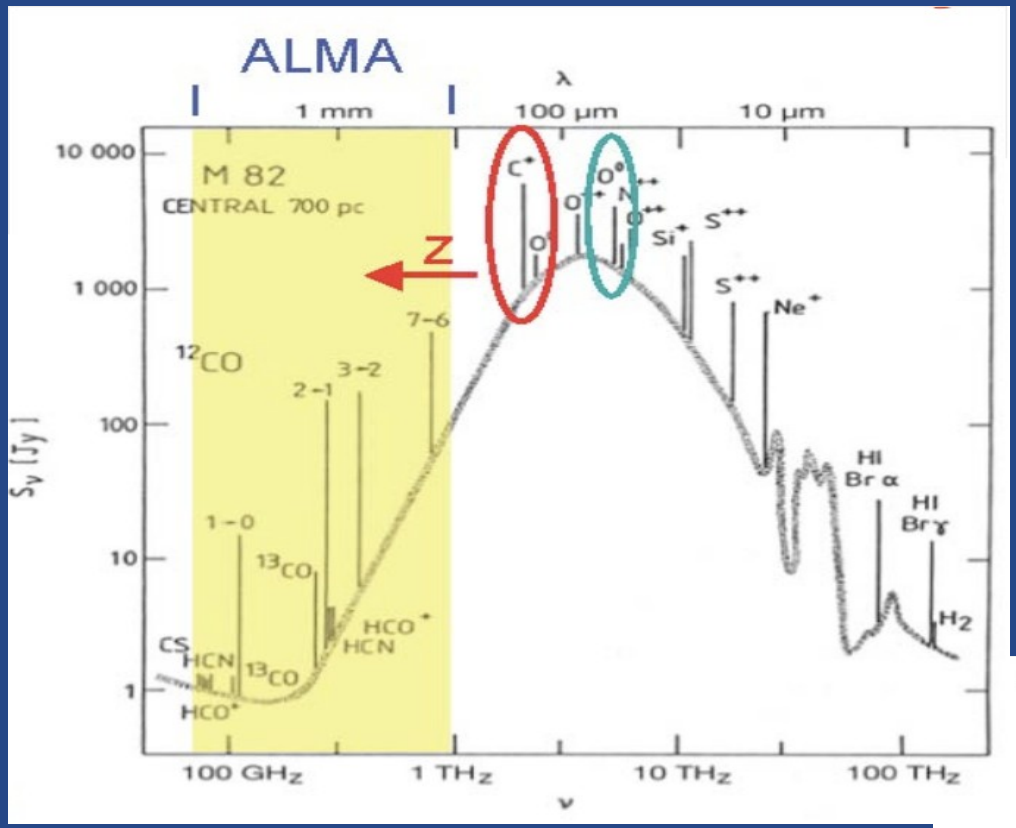
-> study of processes of star and planet formation, stellar evolution and structure, astrochemistry, ...

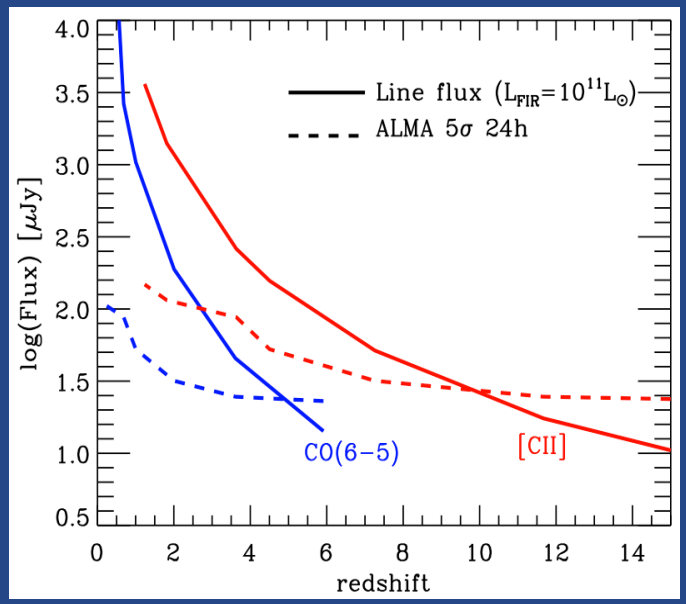
3. Provide high fidelity imaging in the (sub)millimeter at 0.1 arcsec resolution

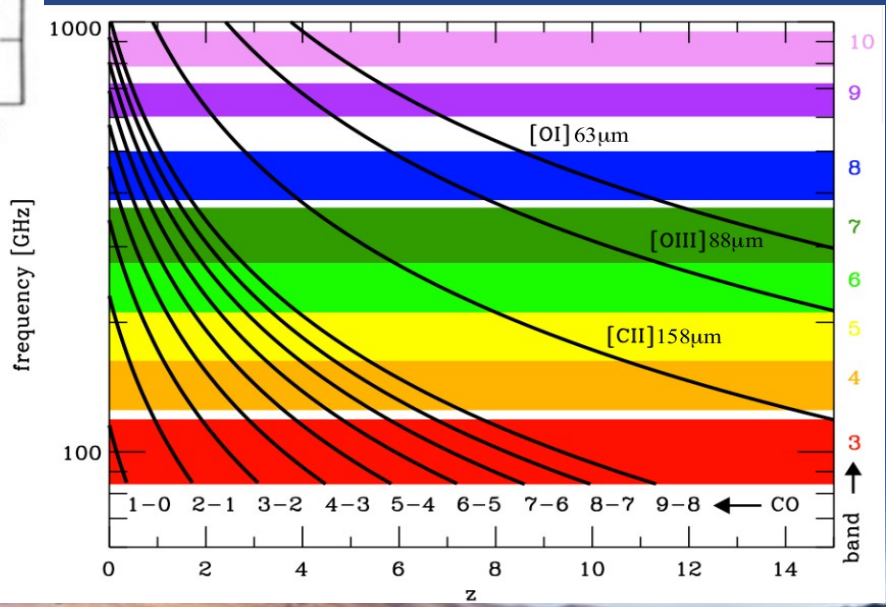
-> long baselines

-> galaxy merging, AGN core mechanisms, imaging of exoplanets, comets, asteroids, ...

CO and CII in galaxies



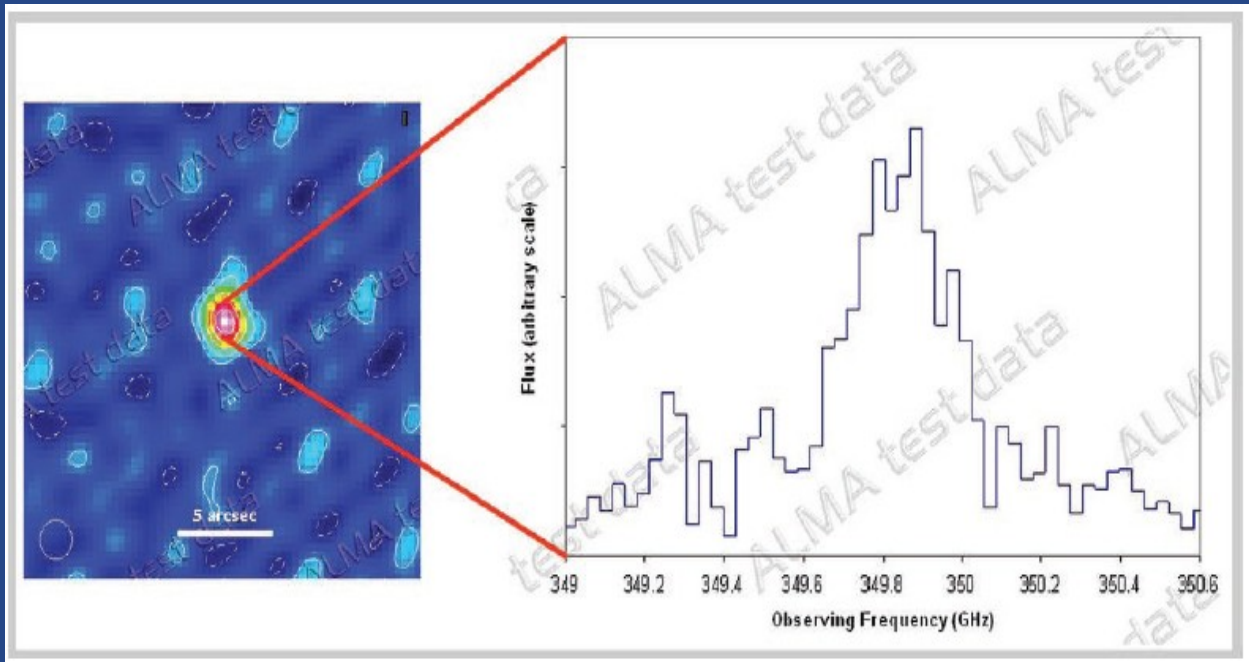




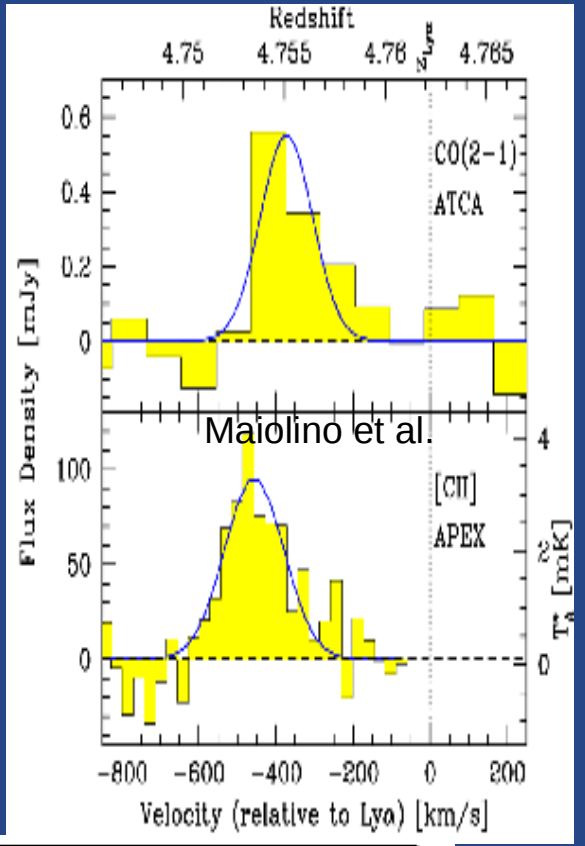
CO is a tracer of neutral H2 and hence its abundance measures the interstellar gas mass.

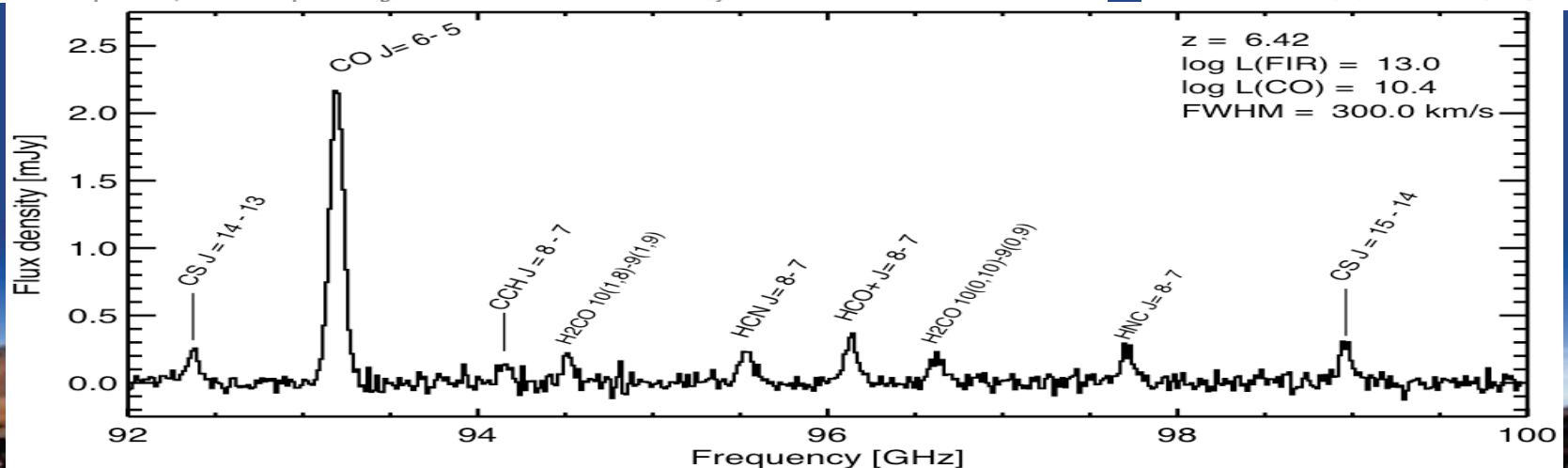
Fine transitions lines redshifted in submm are the major responsible for radiative cooling in galaxies.

High redshift universe: SV data

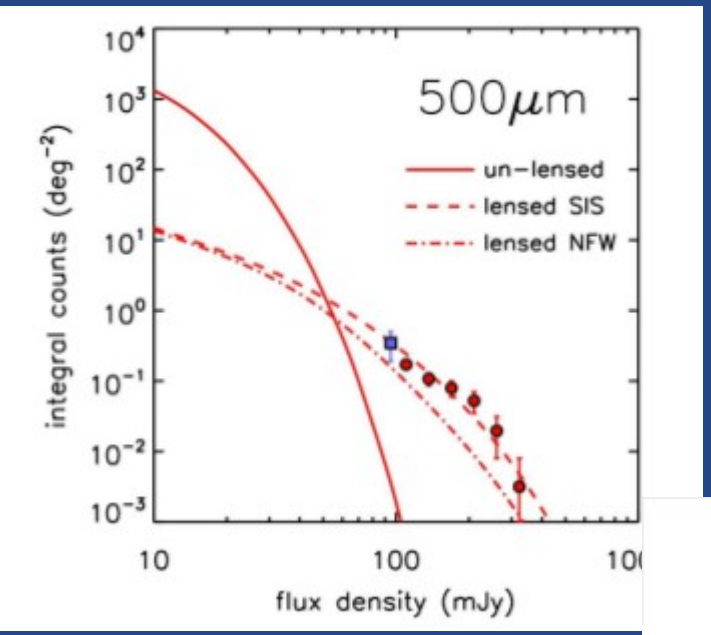


As a test of ALMA's ability to observe broad spectral lines, we observed the quasar BRI 0952-0115, which is at a redshift of z = 4.43. The object is again unresolved on short baselines, but the 158 micron line from ionized carbon is clearly detected in the spectrum, which is impressive given that this observation took only one hour in total.



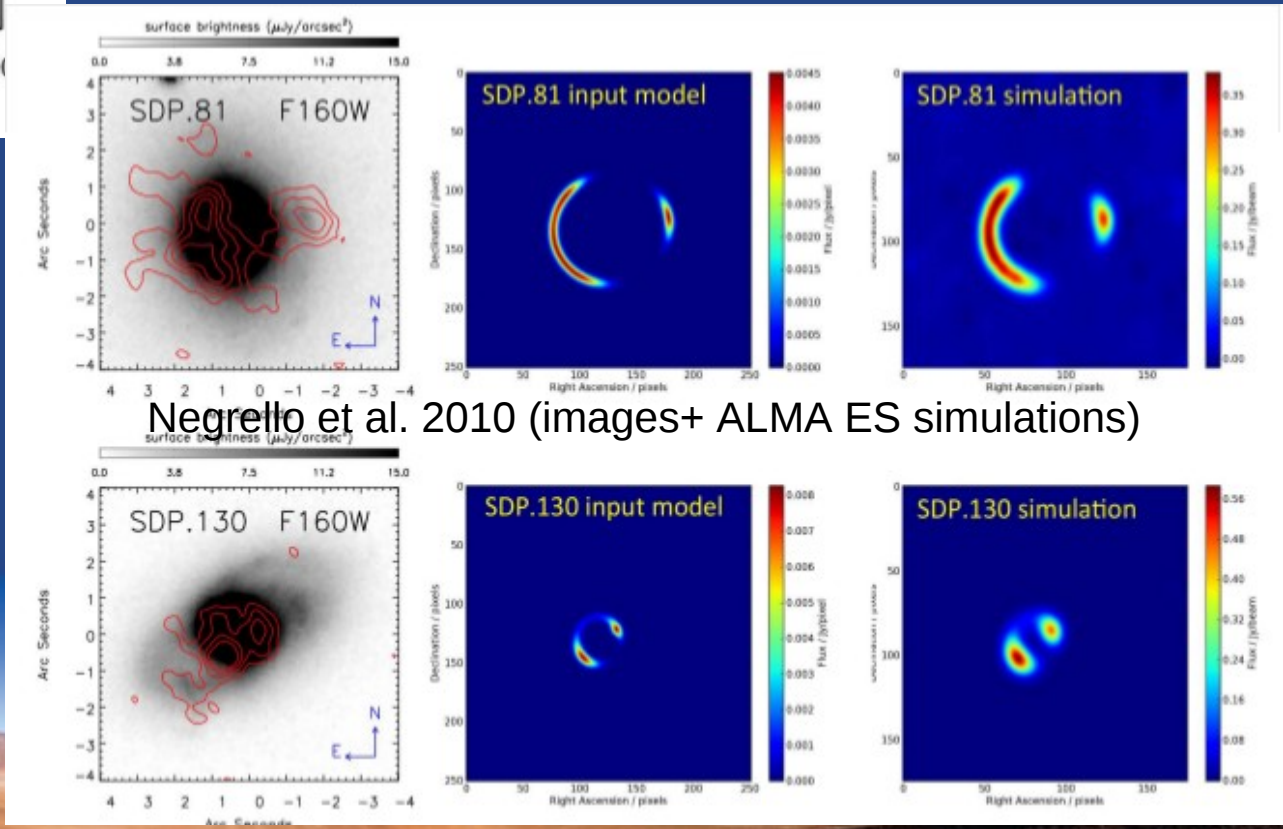


High redshift universe: lensed galaxies



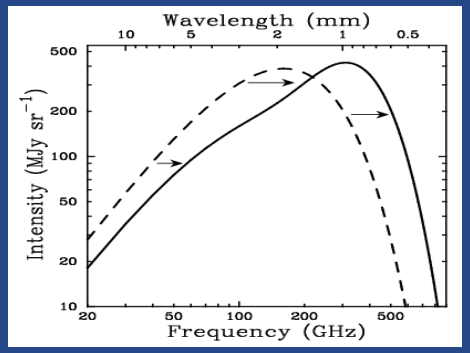
The source counts for SMGs show a high flux density tail that is due to faint high redshift objects amplified by strong lensing.
Submm observations can extract the info from this targets with no absorption or obscuration due to the lens (as in optical bands happens).

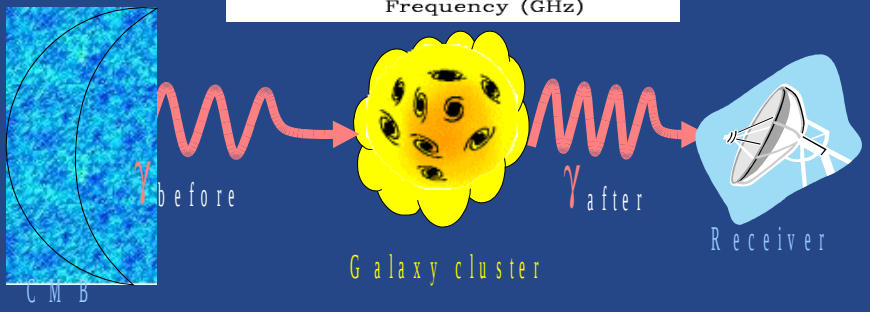
ALMA will allow to reconstruct the source counts, identify galaxy structure at high-z (exploiting the amplification due to lensing) and constrain the models of galaxy formation.



Negrello et al. 2010 (images+ ALMA ES simulations)

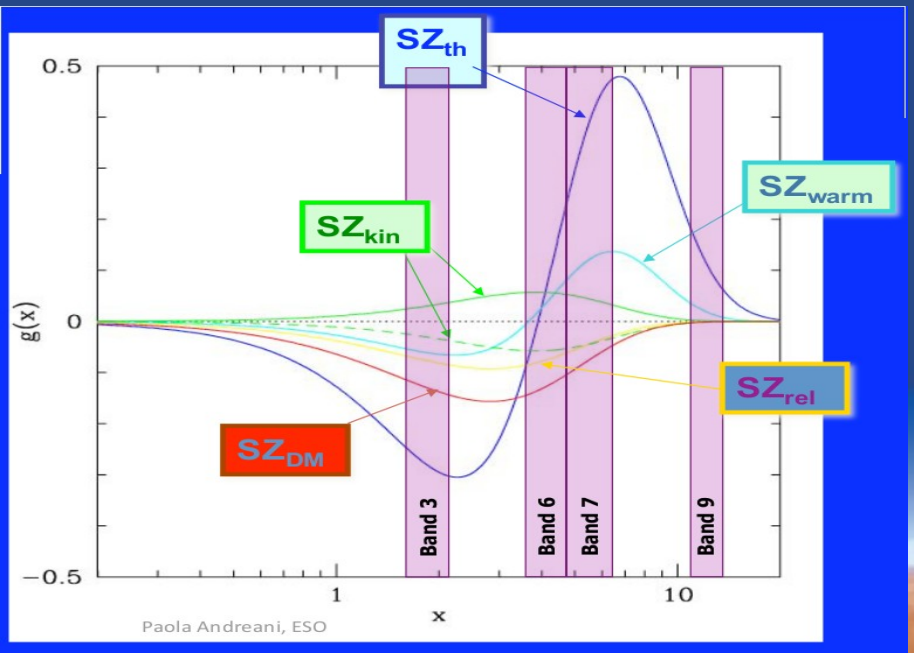
High resolution SZ





The SZ effect is the variation of CMB spectrum in the direction of a hot e- cloud. The variation does not depend on z and is positive in the ALMA bands with a well defined profile depending on the properties of the cloud.
With high resolution/sensitivity observation it has to be observable in galaxy clusters and AGN jets.

Recent observations have pointed out that high z clusters are more morphologically complex and less virialized than closer ones and merging events can affect the comparison between SZ and X-ray and hence the cosmological outcome of SZ analysis.
ALMA will allow to map the ICM, study merging events, AGN shocks, rotation of ICM, kinetic SZE from various electron components, subclumps...



Cl0152-1357 @20 GHz with ATCA

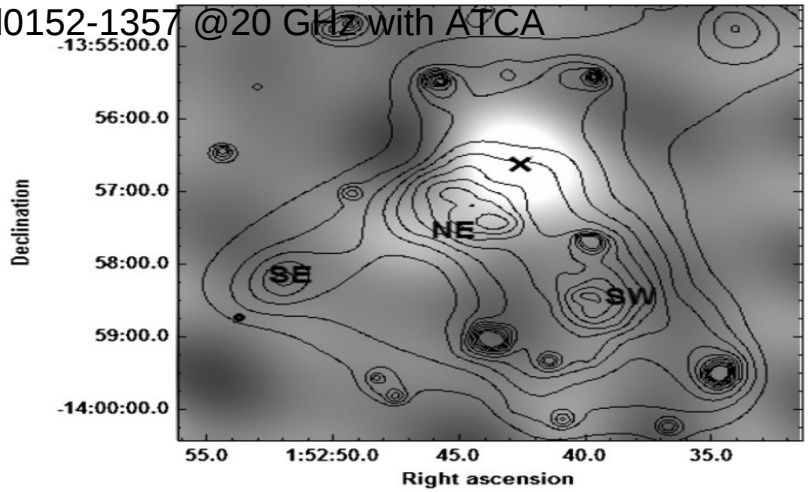


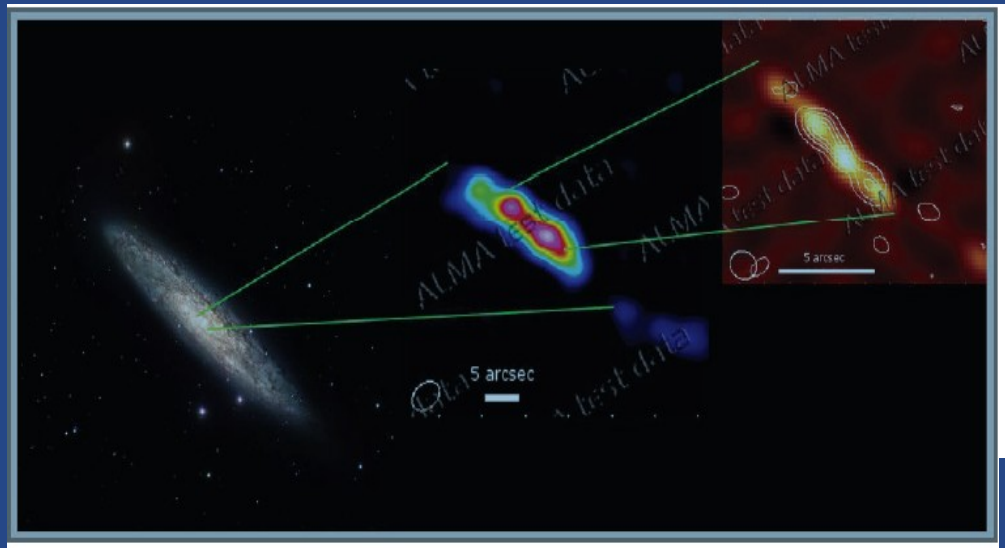
Figure 2. *XMM-Newton* contours (Maughan et al. 2006) superimposed on the 18 GHz ATCA image for Cl J0152−1357. The cross indicates the position of the SZ peak. Flags indicate the peaks of the subclumps mentioned in the text. The contours are taken from an X-ray image, adaptively smoothed to 3σ significance. The lowest contour is set to three times the background level, and subsequent contours are logarithmically spaced.

MM et al. 2010

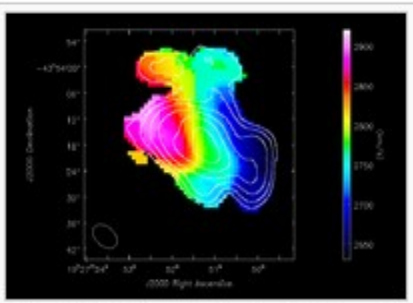
AGN studies

(Viviana)

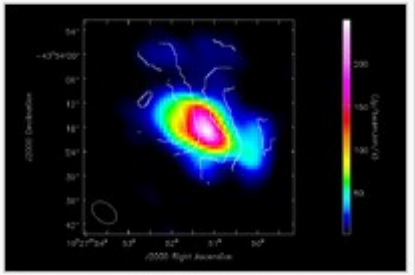
High resolution of local galaxies: SV data



This shows the well-known spiral NGC253, with an optical image of the whole galaxy on the left (credit: ESO). The ALMA test images show dense clouds of gas in the central regions of the galaxy: (middle) the CO J = 2-1 line at 230 GHz and (right) the continuum and CO J = 6-5 line at 690 GHz.



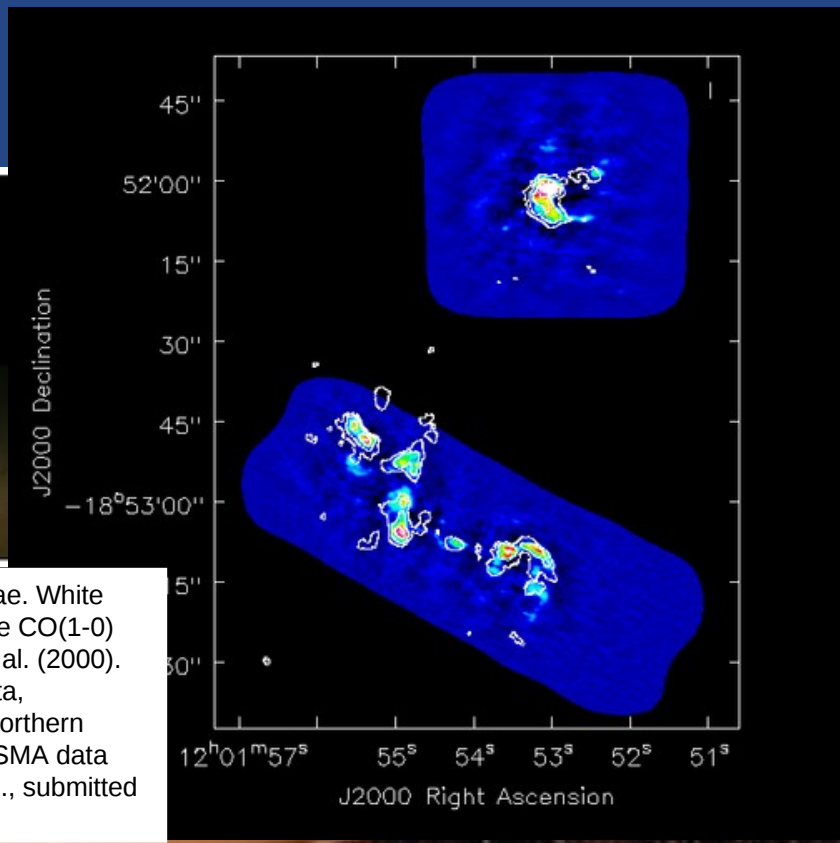
The CO(1-0) velocity field of NGC3256, with contours of the total line emission map overlaid



The CO(1-0) "moment 0" total intensity maps of NGC3256, with contours of the velocity field overlaid

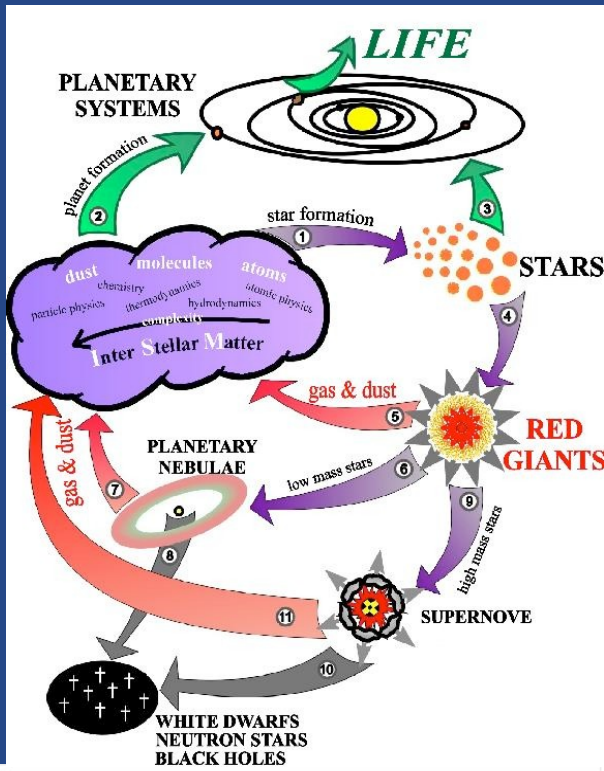
By investigating close galaxies ALMA will allow to unveil merging mechanism, chemical structure, density distribution to an unprecedented level of details.

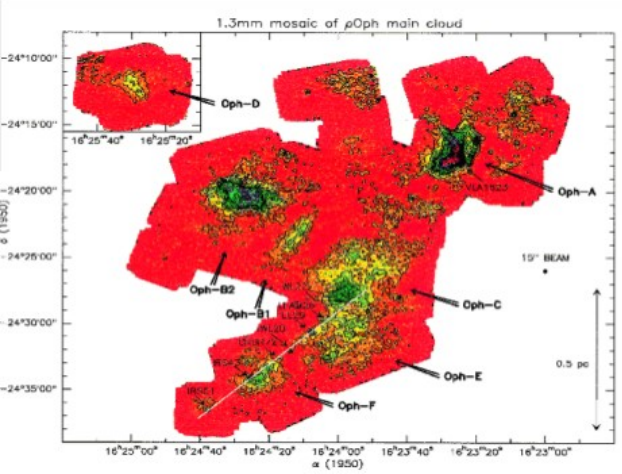
HST image of the Antennae. White contours correspond to the CO(1-0) intensity map in Wilson et al. (2000). Colour image is ALMA data, combining southern and northern mosaics. Contours show SMA data (Ueda, Iono, Petitpas et al., submitted to ApJ).

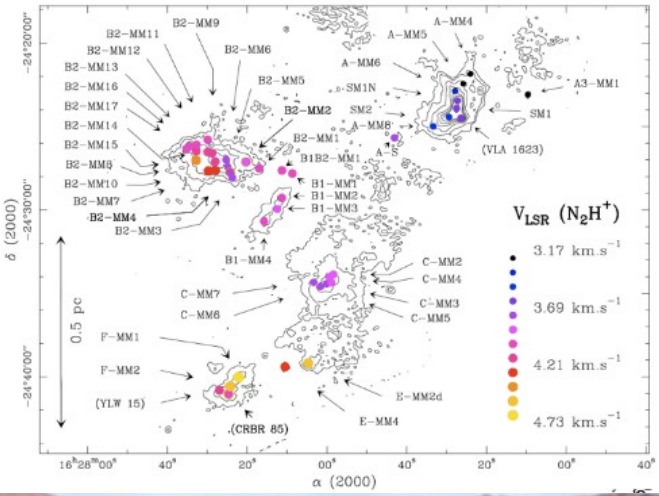


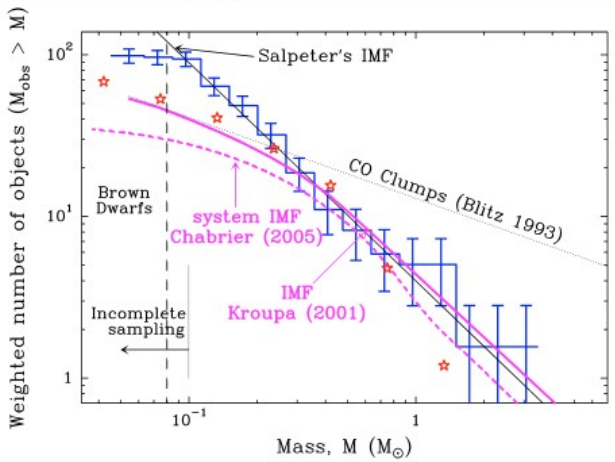
Prestellar disks & evolved stars

With angular resolution down to 0.01” ~1 AU at 150 pc, 30 AU at 3 kpc and spectral resolution as high as 0.01 km/s ALMA will allow to
- study outflow evolution;
- study the parameters of outflows;
- detect circumstellar disk in high-mass (proto)stars;
- study the interaction of disks and outflows;
- derive the mass of the central (proto)star from studies of kinematics
- determine the role of turbolence, gravitation and dissipation in the various stages of stellar evolution
- image the structure of proto stellar disk that will allow to identify the origin of the IMF





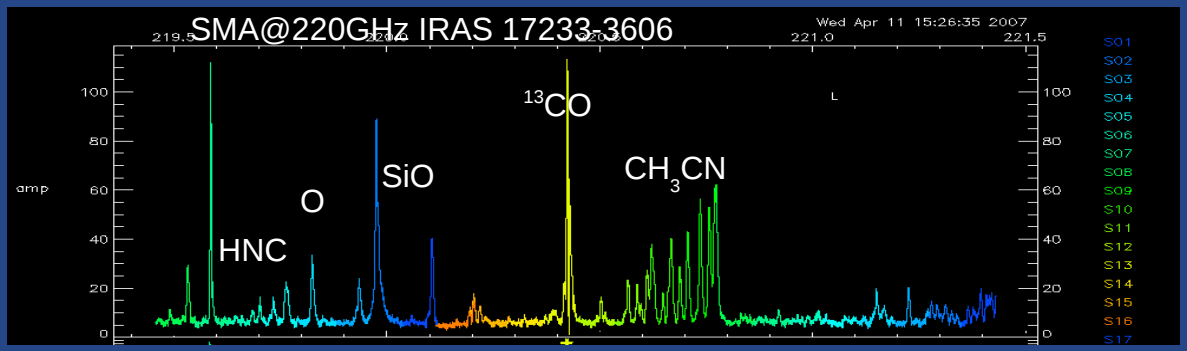


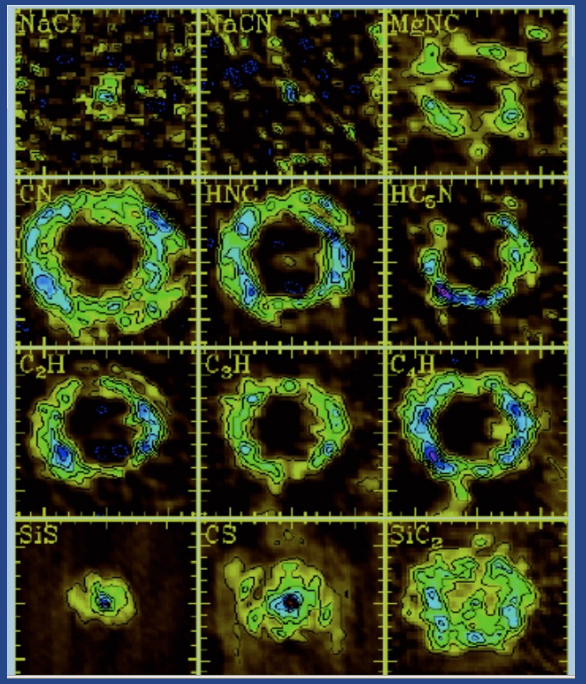


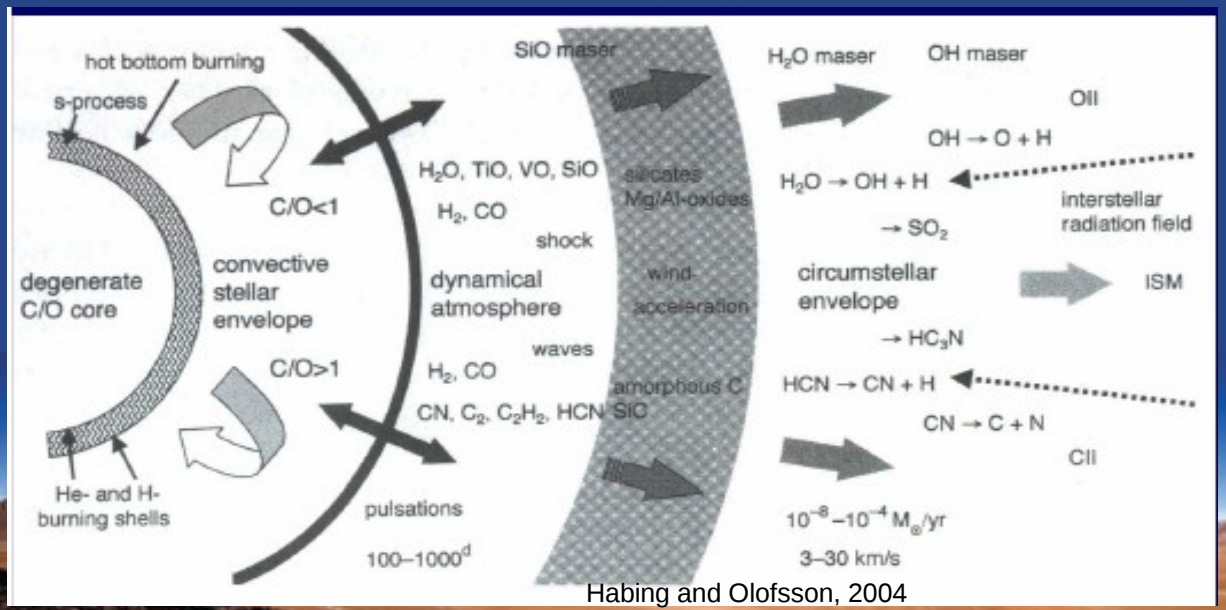
Evolved stars

With angular resolution down to 0.01” ~1 AU at 150 pc, 30 AU at 3 kpc and spectral resolution as high as 0.01 km/s ALMA will allow to

-study the mechanism of emission of stellar winds in evolved stars
-verify the structure of shocks in postAGB stars obscured in other bands



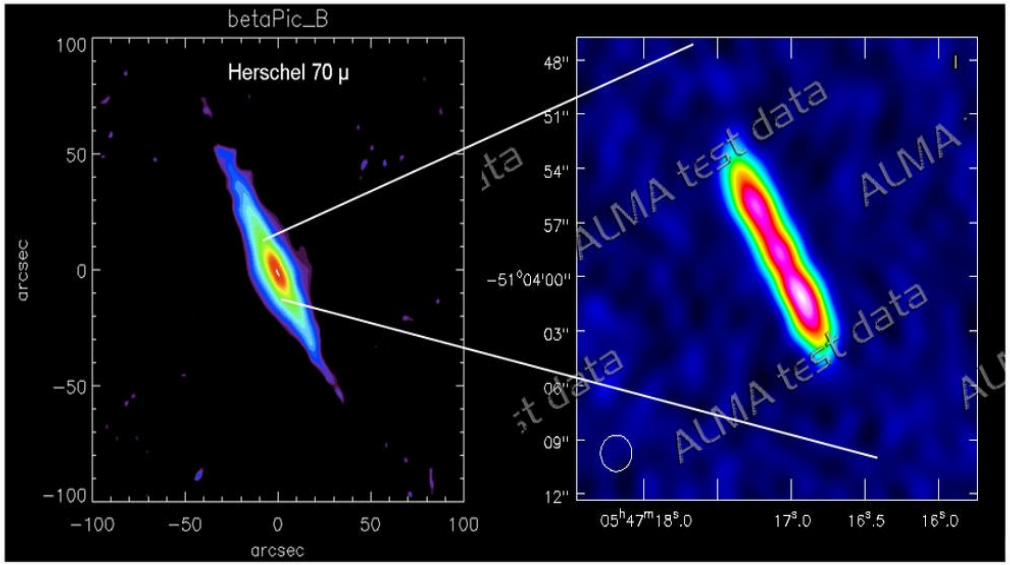


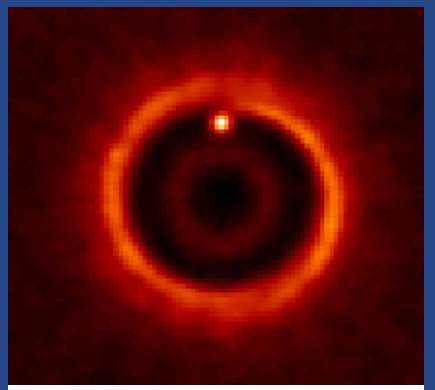


Habing and Olofsson, 2004

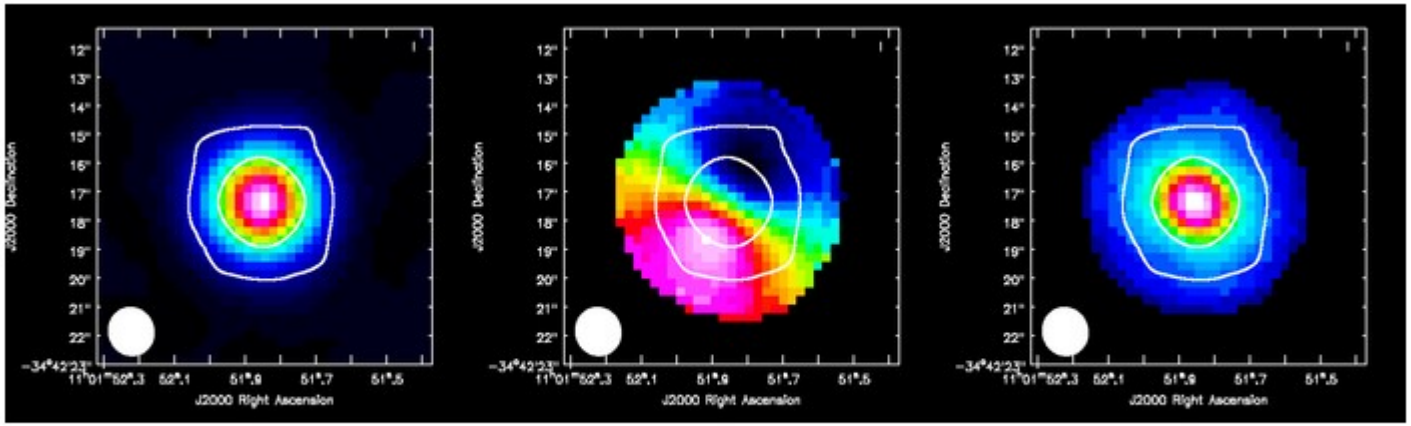
Protoplanetary disks: SV data

Figure 27: *ALMA Test Data (Nov 2010). Emission from the debris disk surrounding the star Beta Pictoris. On the left is a 70μm image from Herschel, (Olofsson et al., SDP Presentations, Madrid, Dec 2009) and on the right is the ALMA test data at 870 μm (Band 7) showing the denser material in the central region. © ALMA (ESO/ NAOI/NRAO)*





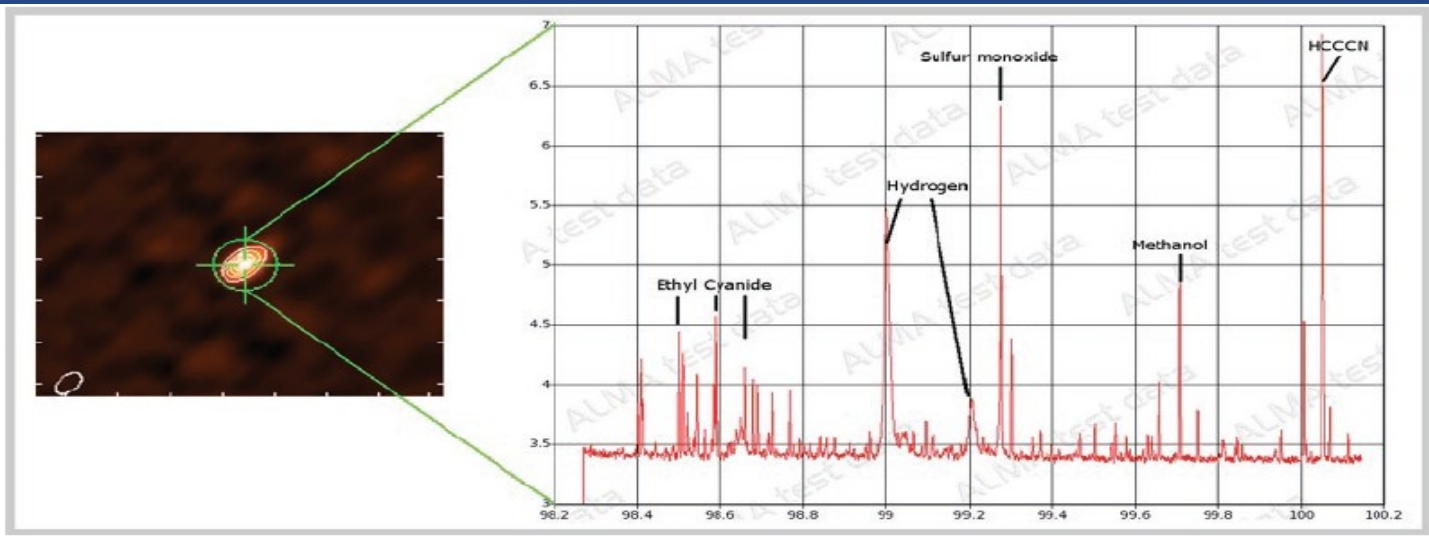
Simulation of proto-planetary disk with a Jupiter-mass planet orbiting at 5 AU. Frequency 950 GHz, 10 km baselines, 8 hours integration.

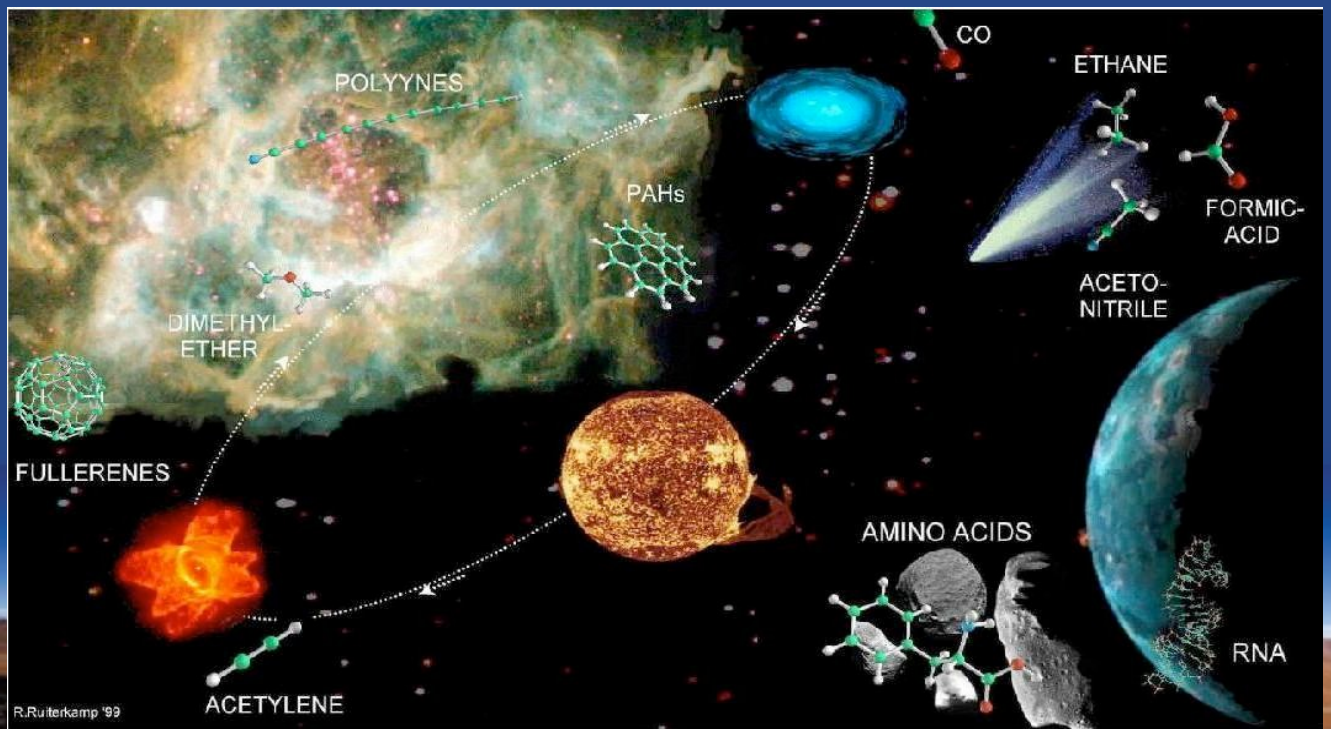


ALMA HCO+(4-3) moment maps from TW Hya, with white continuum contours at 3 and 100 sigma. From left to right: integrated intensity, intensity weighted velocity field, intensity weighted velocity dispersion are shown.

Spectral survey: SV data

An example of ALMA's potential as a spectroscopic instrument: on the left is the map of the molecular "hot core" G34.26+0.15, which is unresolved with the short baselines that we are presently using, so the "image" is not very interesting whereas a section of the spectrum near 100 GHz shows a "forest" of molecular lines. A few of the chemical species that are responsible for the emission lines are identified on the plot.





Interstellar molecules, observed in comets, solar system, galaxies at high z, are excellent probes of the physical structure and dynamics of such regions. Molecules play an active role in the energy balance of clouds. Interstellar space is a unique laboratory for chemical processesnot normally found on Earth.

...and a lot more!
(just to remember: 919 proposal being examinated means a lot of science ideas...
and this is only the first call for ES)

Summary

- **ALMA is a unique instrument in the (sub-)mm (0.3 to 10 mm) range**
  - Unequaled sensitivity
    - Large collecting area (7200 m^2), excellent dry site (5000 m altitude)
    - e.g. 6 uJy in 6h @ 230 GHz
  - Great imaging capabilities
    - 50 antennas +ACA, variable configuration
    - High resolution (15km = 40 mas @ 100 Ghz,5 mas @ 900GHz)
  - Flexible spectral configuration
  - Pipeline reduced data
- **Early Science is on-going**
  - min16 antennas, baselines up to 450m, reduced capabilities, wrt full array
- **Tools are designed to help the experienced AND non experienced user to use ALMA.**
  - Access to the ALMA world through the Science Portal

Summary

- **ALMA is a unique instrument in the (sub-)mm (0.3 to 10 mm) range**
  - Submm band ALMA properties are good to investigate
    - dusty-obscured environments like those surroundings forming structures
    - high redshift galaxies and galaxy formation mechanisms
    - galaxy clusters structure via SZ effect up to very high-z
    - AGN inner regions
    - Local galaxies structure, interaction, chemical abundances and profiles
    - Molecular star forming clouds structure
    - IMF in early stellar phases
    - Stellar evolution
    - AGB to PN transition phases
    - Protoplanetary disk formation
    - Chemical enrichments in many astrophysical environments (in the out-of-the-Earth lab!)
    - ...

Welcome to the ALMA era !!!!!

Contact the Helpdesk and your ARC node for support

Italian ARC node web: http://www.alma.inaf.it
Email: help-desk@ira.inaf.it
Helpdesk: https://alma-help.nrao.edu/

Useful links:
ALMA SP: http://almascience.org/
ALMA PRIMER FOR ES: http://almatelescope.ca/ALMAPrimer.pdf
ALMA CfP: http://almascience.eso.org/call-for-proposals

Credits:
Some material for this lecture has been taken from lectures by P. Andreani, V. Casasola, R. Maiolino, L. Testi, G. Umana