Five years after the first ALMA call

EUROPEAN ARC
ALMA Regional Centre || Italian

Marcella Massardi

Italian ARC ALMA Science Tour 2016

ALMA rationale

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, …

- 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, …

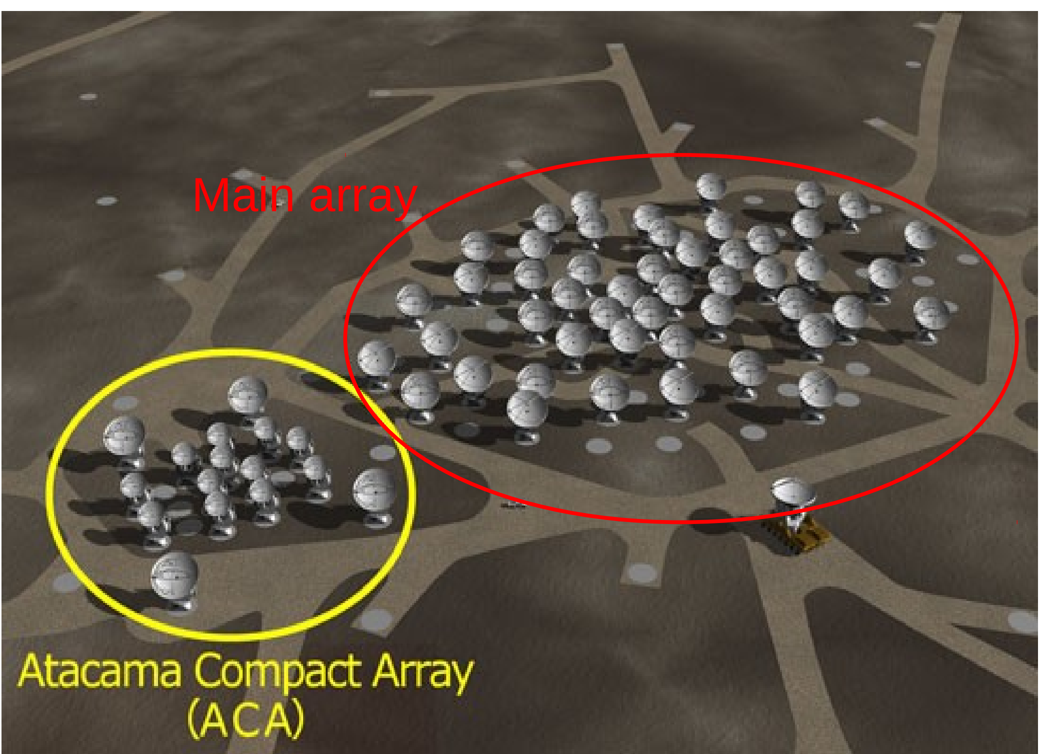
- The ability to provide precise high dynamic range (=|image max/image min|) images at an angular resolution of 0.1 arcsec

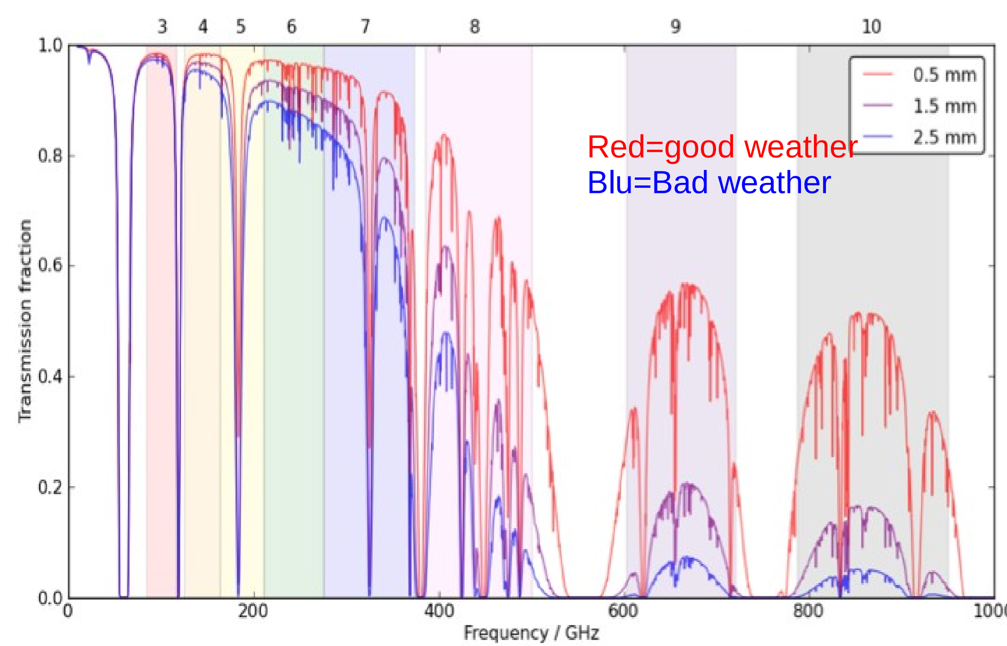
-> **high angular resolution and sensitivity**
-> galaxy dynamics, AGN core mechanisms, imaging of exoplanets, comets, asteroids, ...

ALMA full array

The Atacama Large Millimeter Array is a **mm-submm reconfigurable interferometer**

- Antennas: **50x12m** main array + **12x7m** ACA **+ 4x12m** Total Power
- Baselines length: **15m ->150m-16km** + **9m->50m**
- Frequency range: **10 bands between 30-900 GHz** (0.3-10 mm)
- Bandwidth: **2 GHz x 4 basebands**
- Polarimetry: Full Stokes capability
- Velocity resolution: **As narrow as 0.008 × (Freq/300GHz) km/s**
  ~0.003 km/s @ 100 GHz, ~0.03 km/s @ 950 GHz





ALMA full array

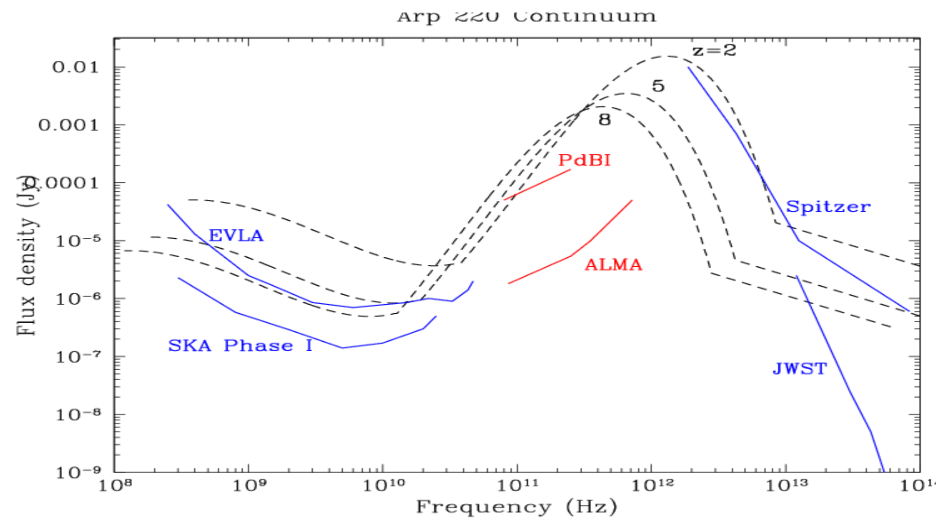
An interferometer reconstructs an image of the sky at fixed spatial scales
(i.e. measures single points in the Fourier domain)
corresponding to the projection of the baselines (i.e. distances among the antennas) on the sky.

Sensitivity

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

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

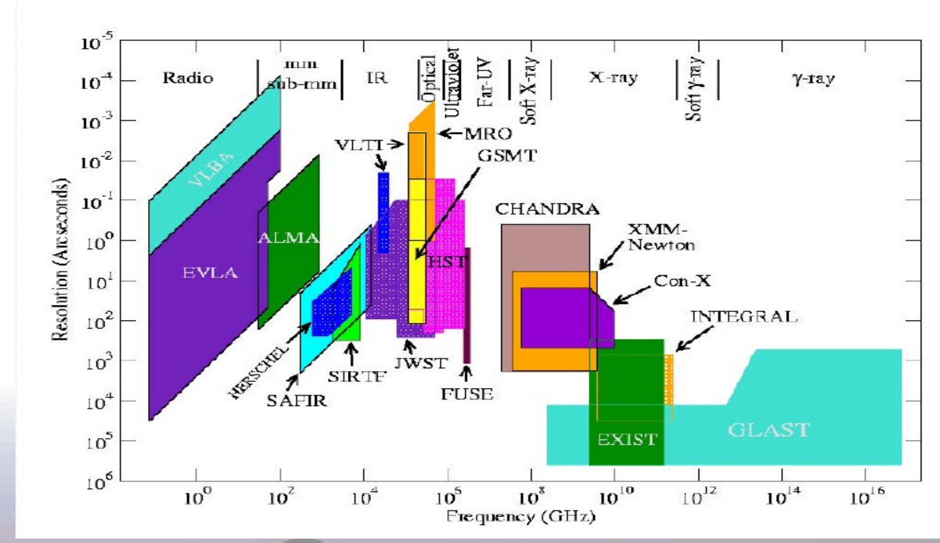
<0.05mJy @100 GHz in 1 hr



Spatial scales

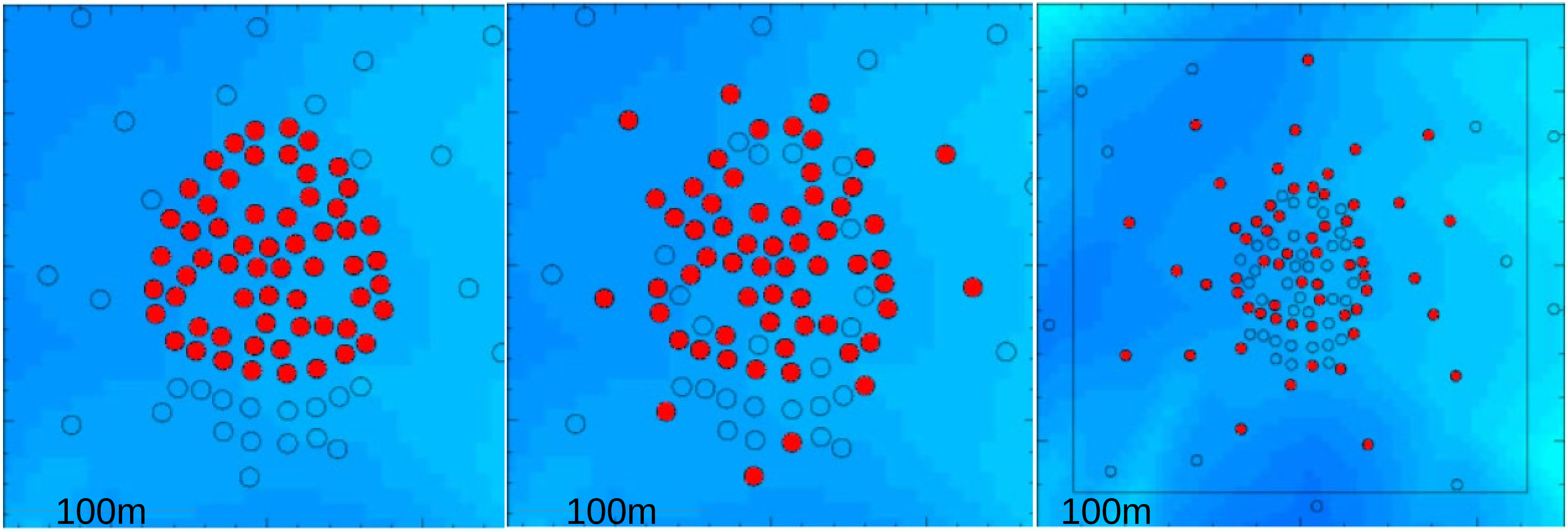
$$\theta = k\,\lambda/D$$

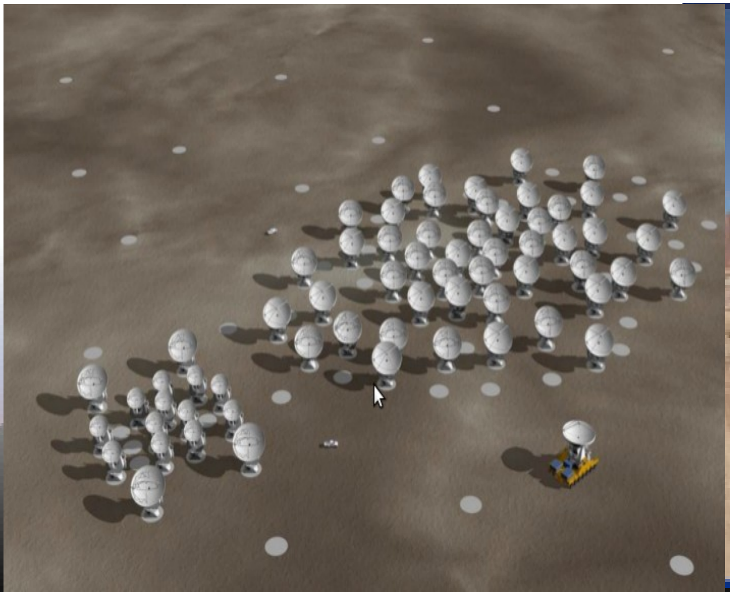
- **Resolution:**
  0.2” x (300GHz / freq) x (1km / max_baseline)
- **Largest angular scale:**
  1.4” x (300GHz / freq) x (150m / min_baseline)

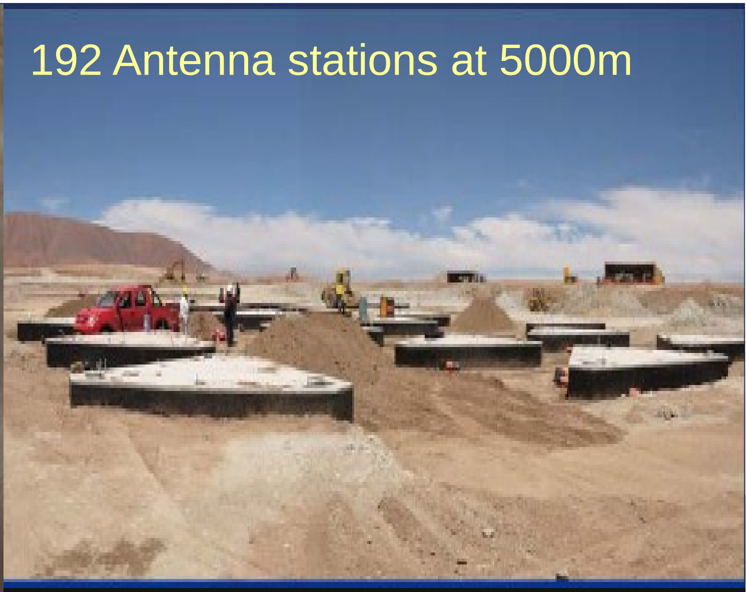


- **FOV 12m array: 17” / (300GHz / freq)**
- **FOV 7m array: 29” / (300GHz / freq)**

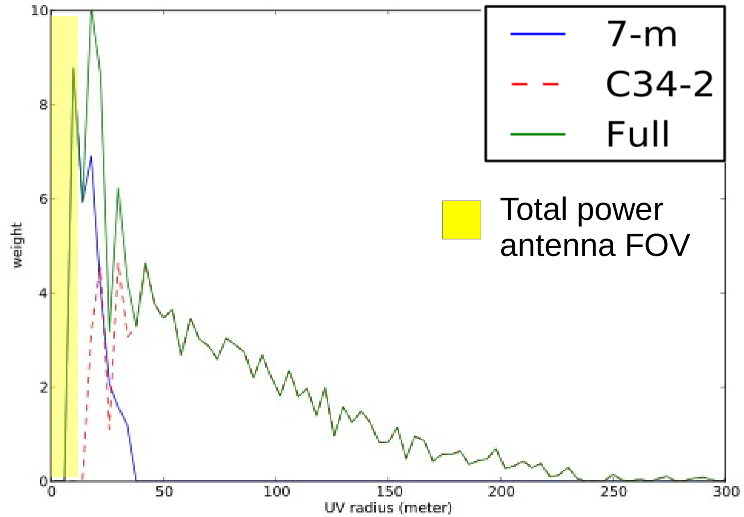
ALMA main array reconfiguration



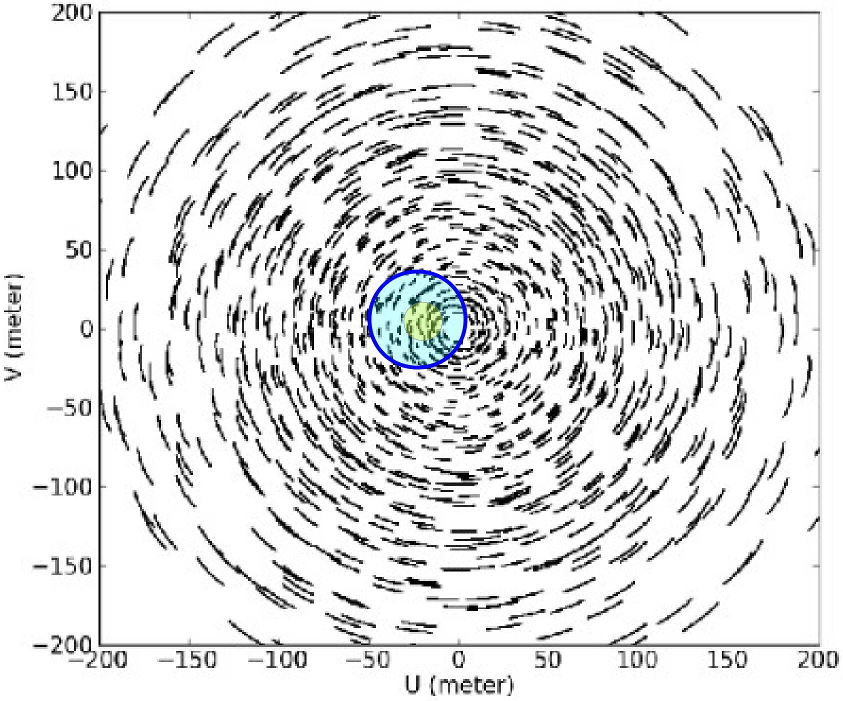




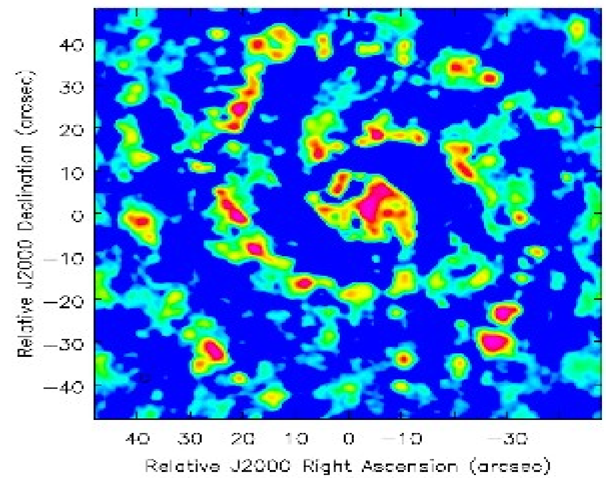
ALMA array(s)



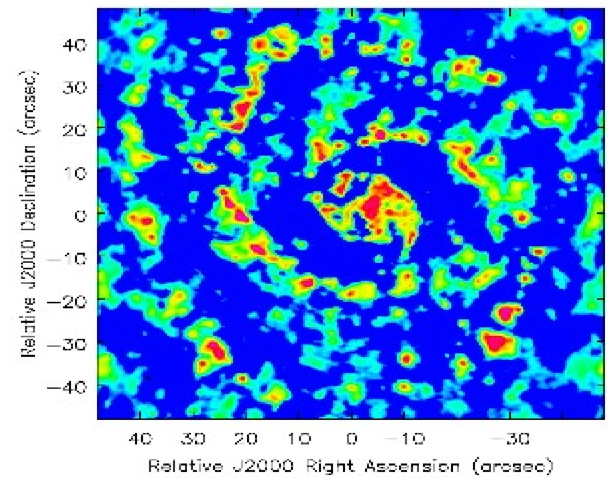
$(u^2+v^2)^{1/2}$

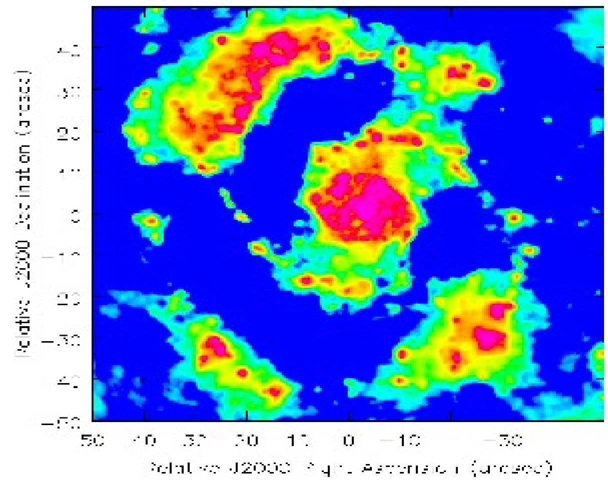


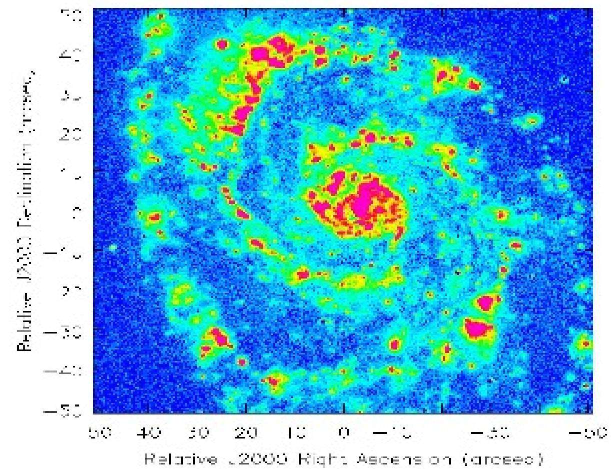
Main array 1h



Main array 2.5h







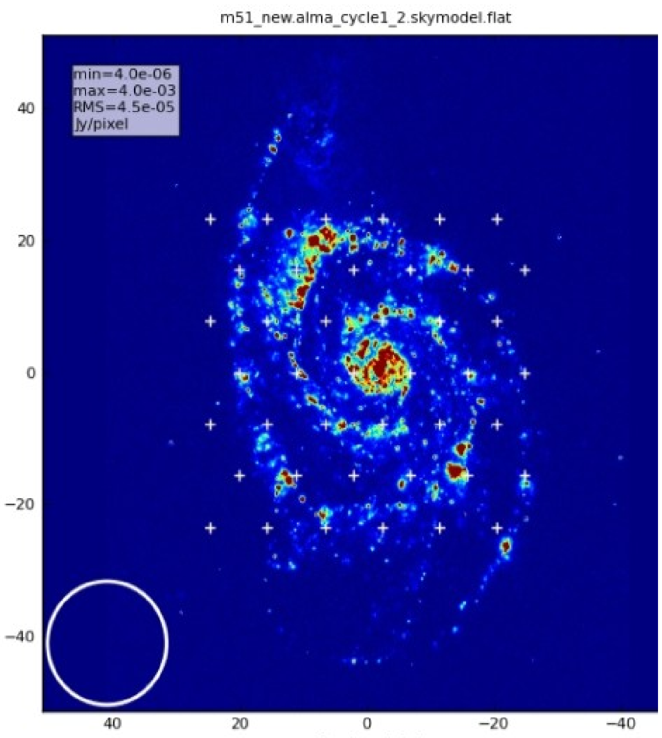
Main array+ ACA

Model M51

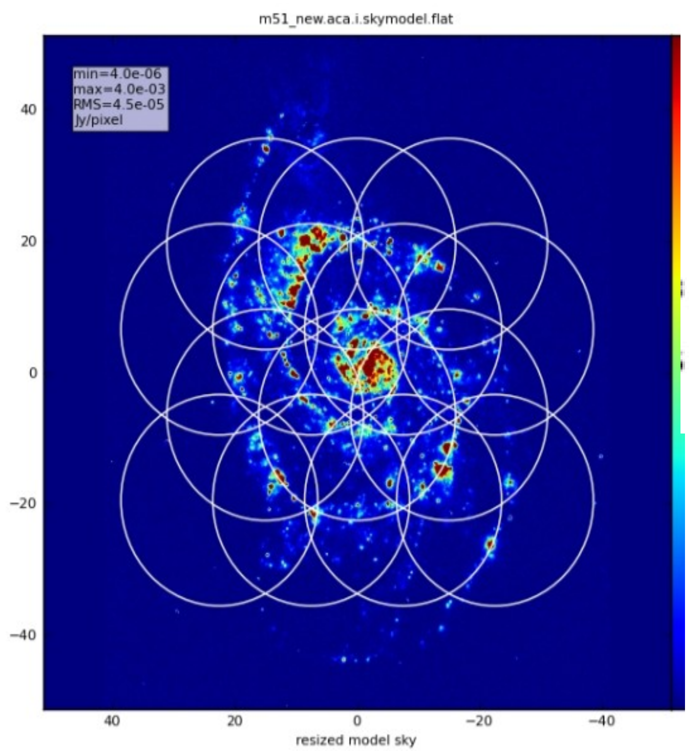
Mosaicking

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

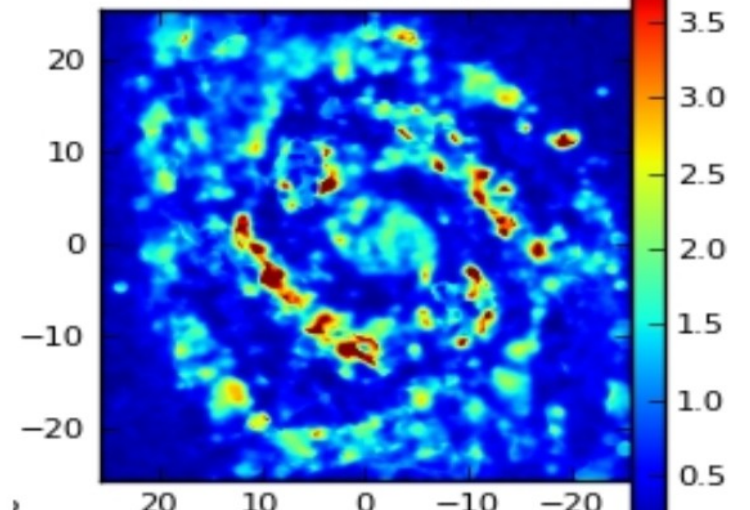
Details in the ranges available to the given baselines can be observed on larger region of the sky by mosaicking the region.



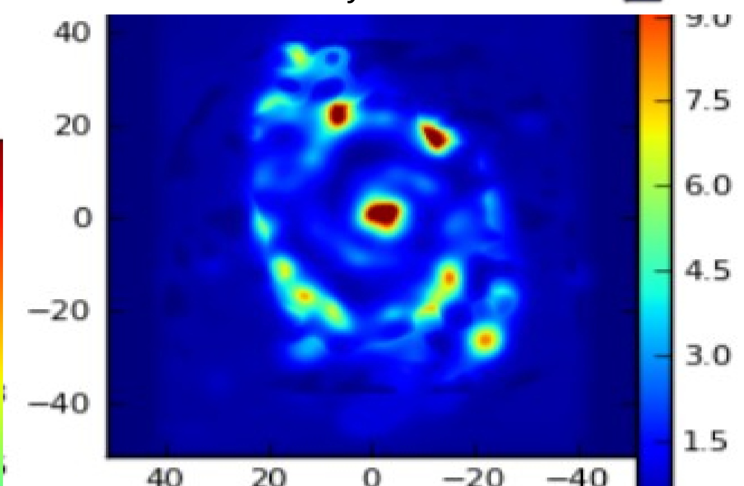
Model & 12m FOV



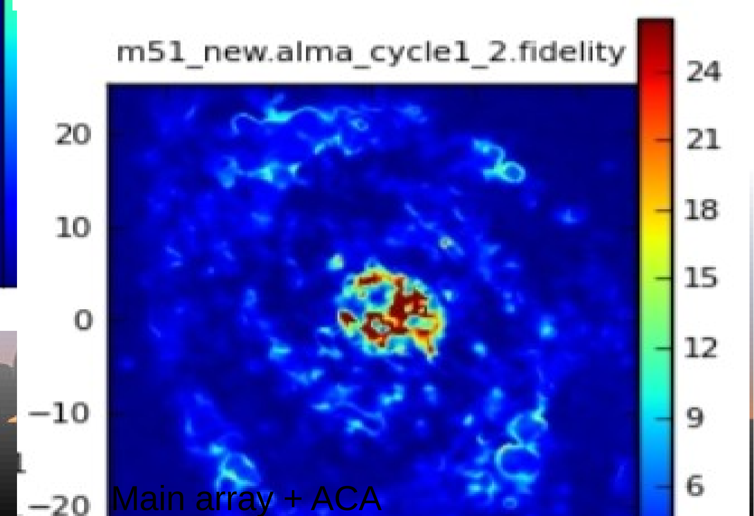
ACA Pointing map



Main array



ACA



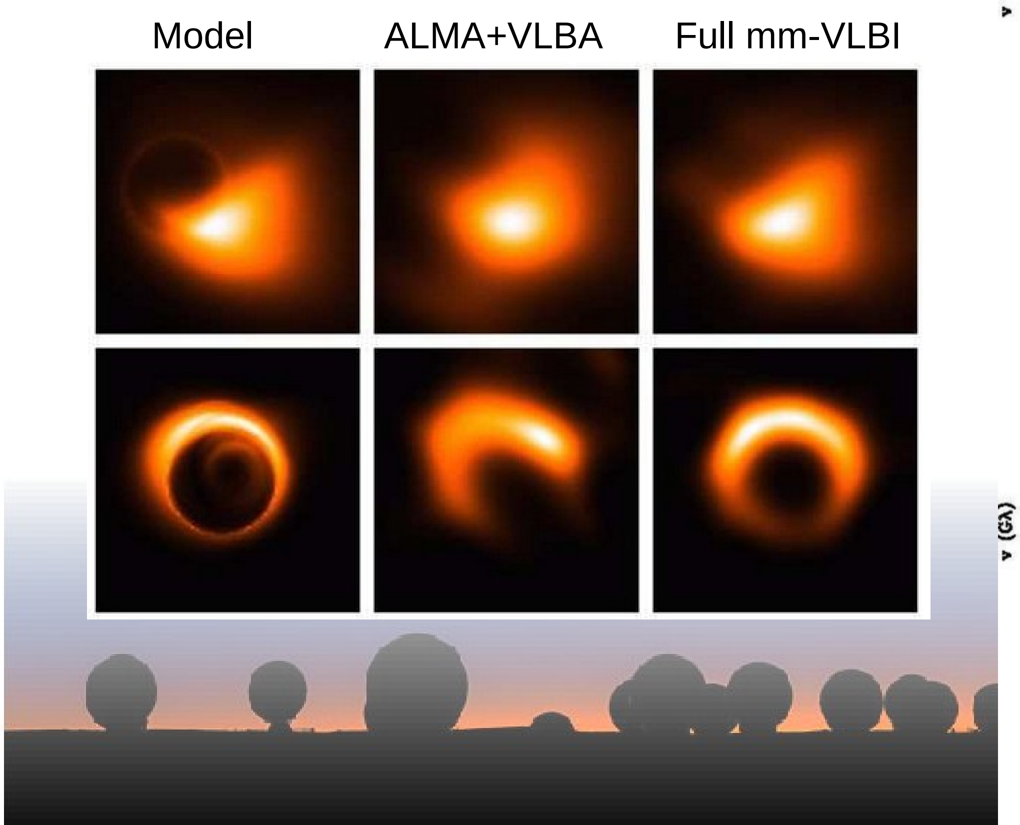
Main array + ACA

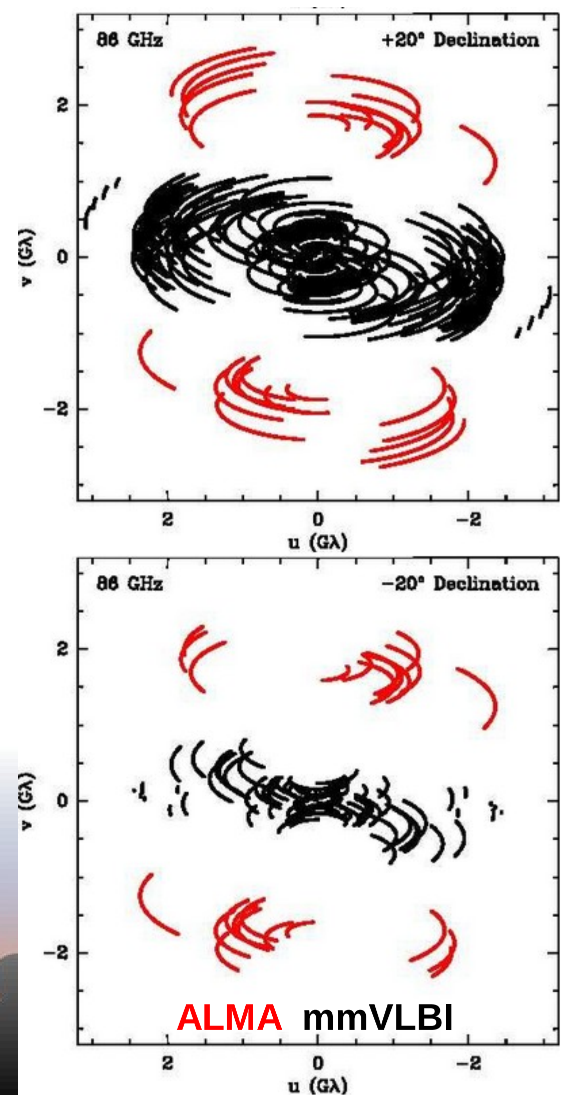
mm-VLBI with ALMA

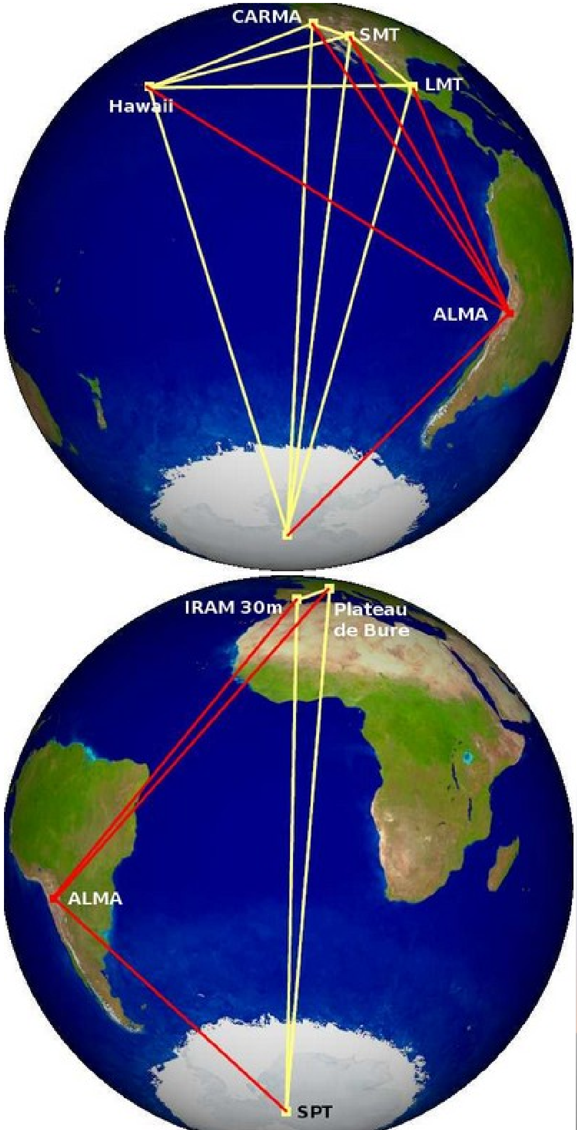
VLBI is a worldwide network of telescopes that matches simultaneous observations in different sites, exploiting the phase information to construct a world-wide interferometer.

At 1 mm and a baseline of 9000 km offers resolution of about 20 microarcseconds
ALMA will increase the sensitivity by more than an order of magnitude

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



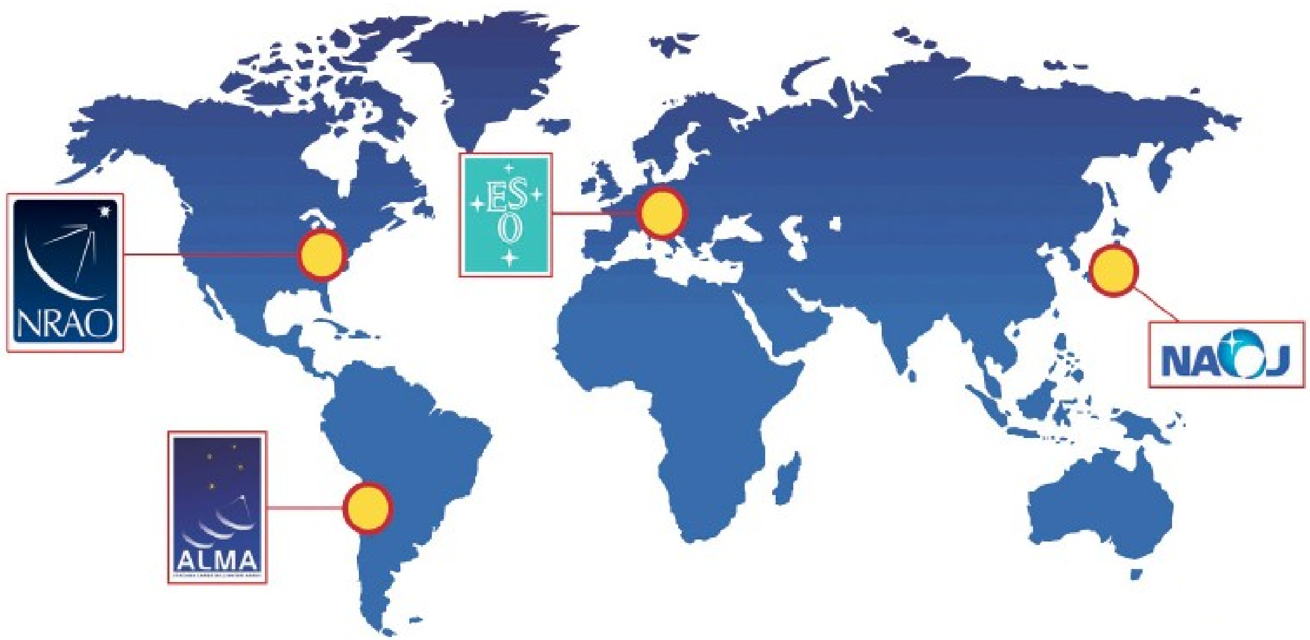




ALMA organization

ALMA is a world wide collaboration

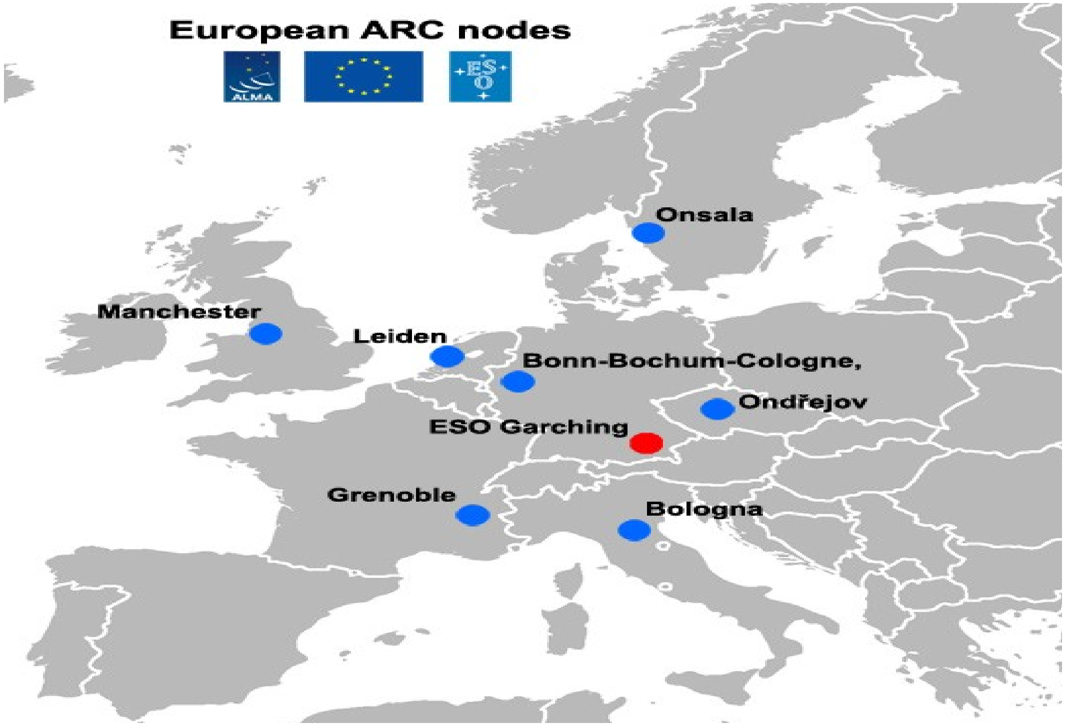
Contributors share the observing time an host a mirror of the archive

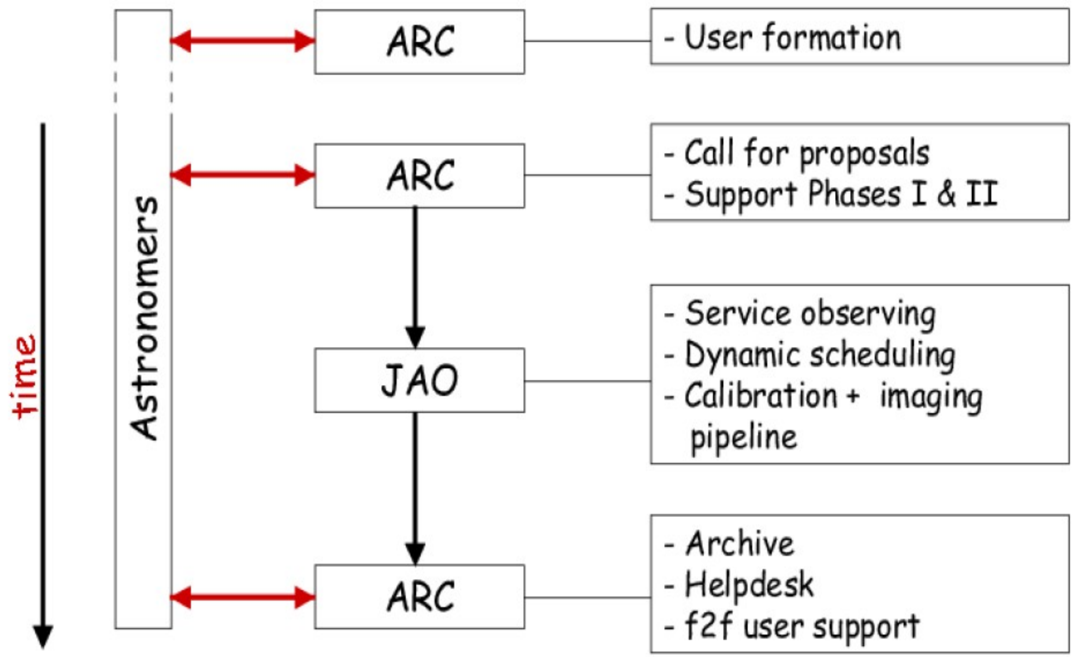


- Europe: **ESO** (14 countries) → 30%
- North America: **NRAO** (USA, Canada) → 30%
- East Asia: **NAOJ** (Japan, Taiwan) → 20%
- Chile → 10%

The ALMA Regional Centres (ARCs)

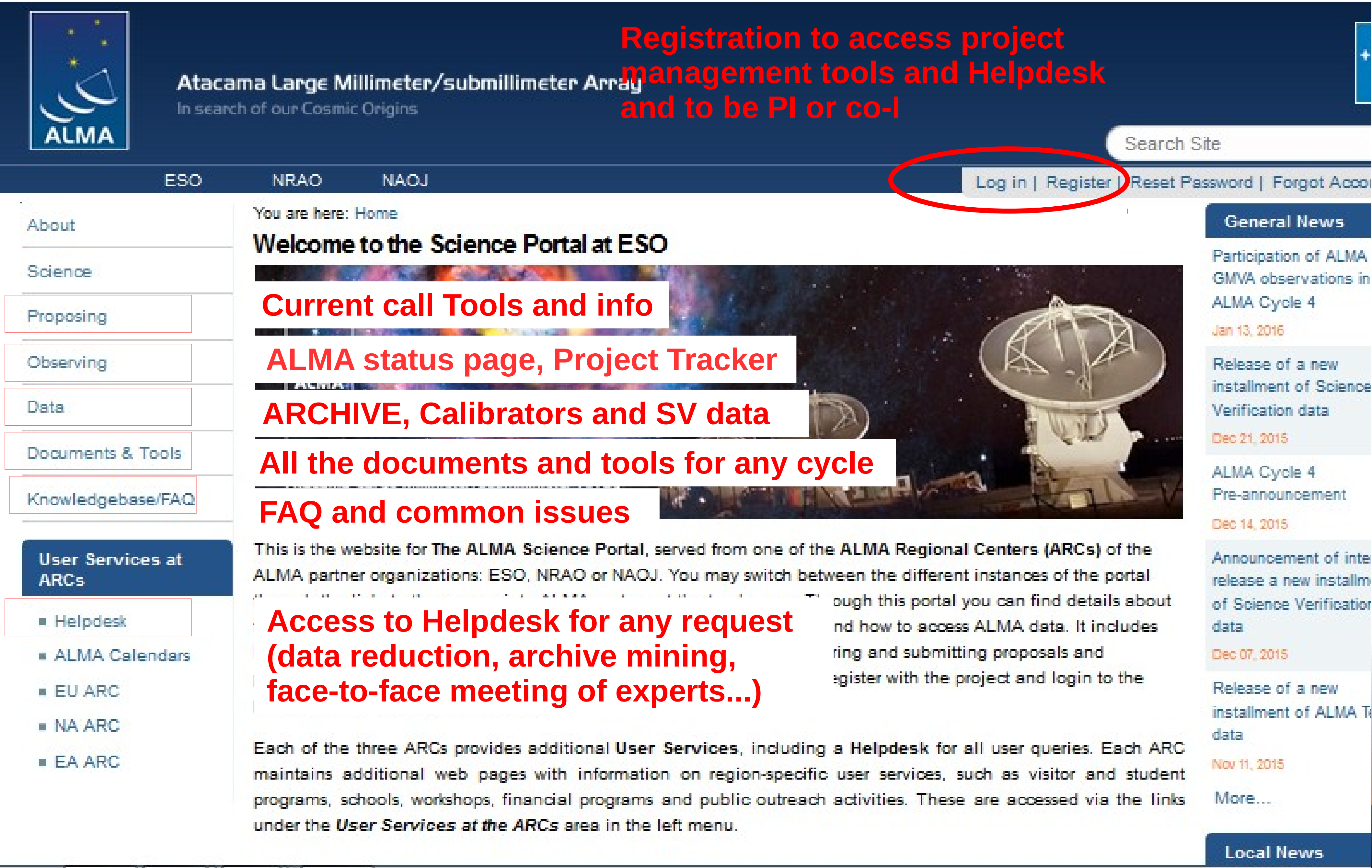
- **Interface between JAO and users**
- 1 ARC per Partner:
  - NRAO for North America
  - NAOJ for East Asia
  - ESO for Europe (split in 7 nodes + 1CoE)
- Operation support
  - Archive replication
  - Astronomer on duty
  - Software tools
- User support
  - Community formation and outreach
  - Phase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

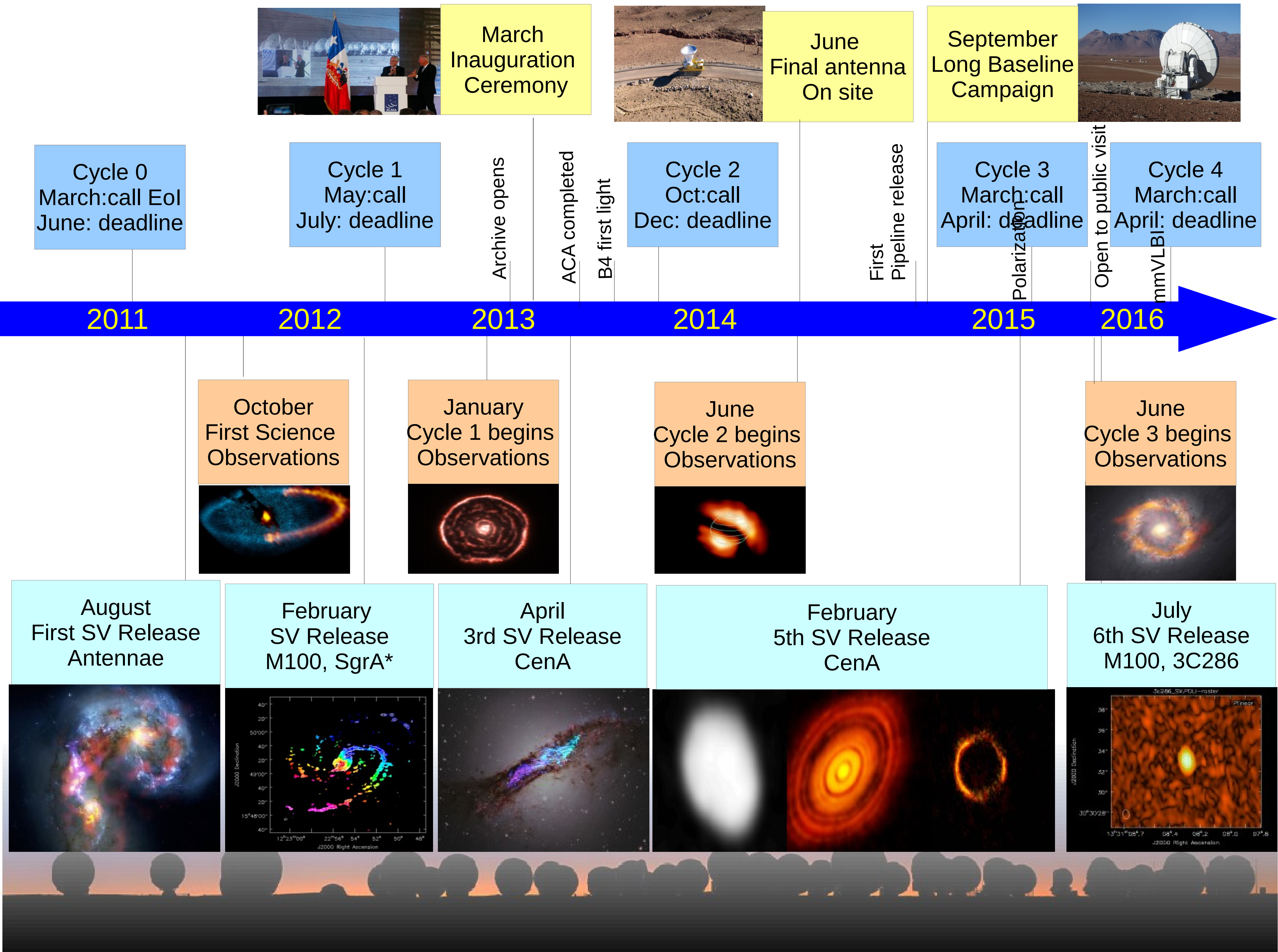




Enter the ALMA world through the ALMA Science Portal

http://almascience.eso.org/



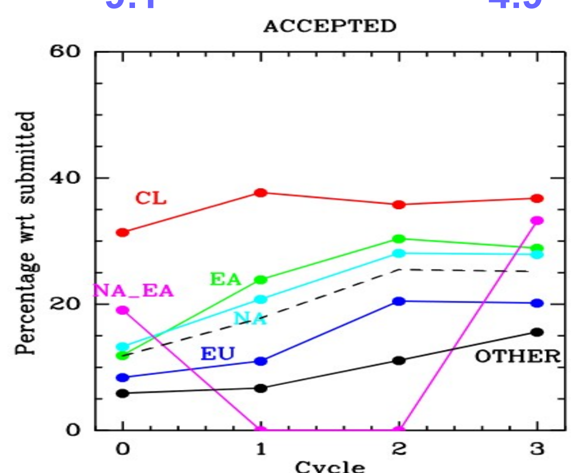


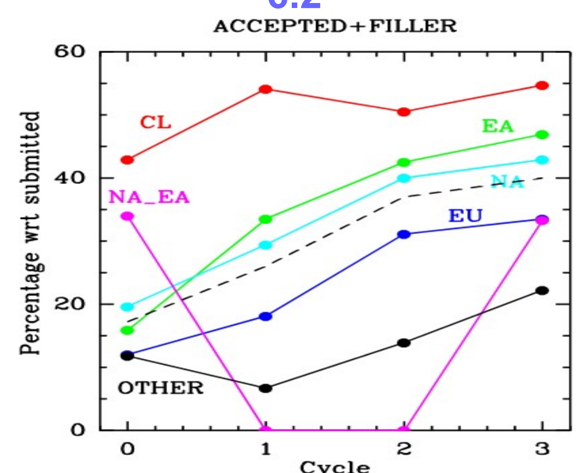
March Inauguration Ceremony
June Final antenna On site
September Long Baseline Campaign
Cycle 0 March:call EoI June: deadline
Cycle 1 May:call July: deadline
Archive opens
ACA completed
B4 first light
Cycle 2 Oct:call Dec: deadline
First Pipeline release
Cycle 3 March:call April: deadline
Polarization
Open to public visit
Cycle 4 March:call April: deadline
mmVLBI
2011
2012
2013
2014
2015
2016
October First Science Observations
January Cycle 1 begins Observations
June Cycle 2 begins Observations
June Cycle 3 begins Observations
August First SV Release Antennae
February SV Release M100, SgrA*
April 3rd SV Release CenA
February 5th SV Release CenA
July 6th SV Release M100, 3C286

Early Science Cycles

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

	Cycle 0 Sep. 2011 - Jan. 2013	Cycle 1 Jan. 2013 - May. 2014	Cycle 2 Jun. 2014 - Oct. 2015	Cicle 3 Oct 2015 - Oct 2016
Telescope				
Hours dedicated to Science	**800**	**800**	**2000**	2100
Antennas	**> 12x12-m**	**> 32x12m +9x7m+2TP**	**> 34x12m +9x7m+2TP**	**> 36x12m +10x7m+2TP**
Receiver bands	3, 6, 7, 9	3, 6, 7, 9	**+4, 8**	**+10**
Wavelengths [mm]	3, 1.3, 0.8, 0.45	3, 1.3, 0.8 0.45	+2, 0.7	
Baselines	up to 400 m	**up to 1000 m**	**up to 1500m**	**up to 10km**
Polarisation	single-dual	single dual	**full**	**full**
Proposal outcome				
Submitted	917	1133	1381	1578
Highest priority	112	198	354	402
Filler	51	93	159	236
Success rate	12% (18%)	17% (25%)	26% (37%)	25% (40%)
Pressure factor global	**8.2**	**5.8**	**3.9**	**3.9**
Pressure factor Europe	**12.3**	**9.1**	**4.9**	**6.2**





Early Science Cycles in Italy

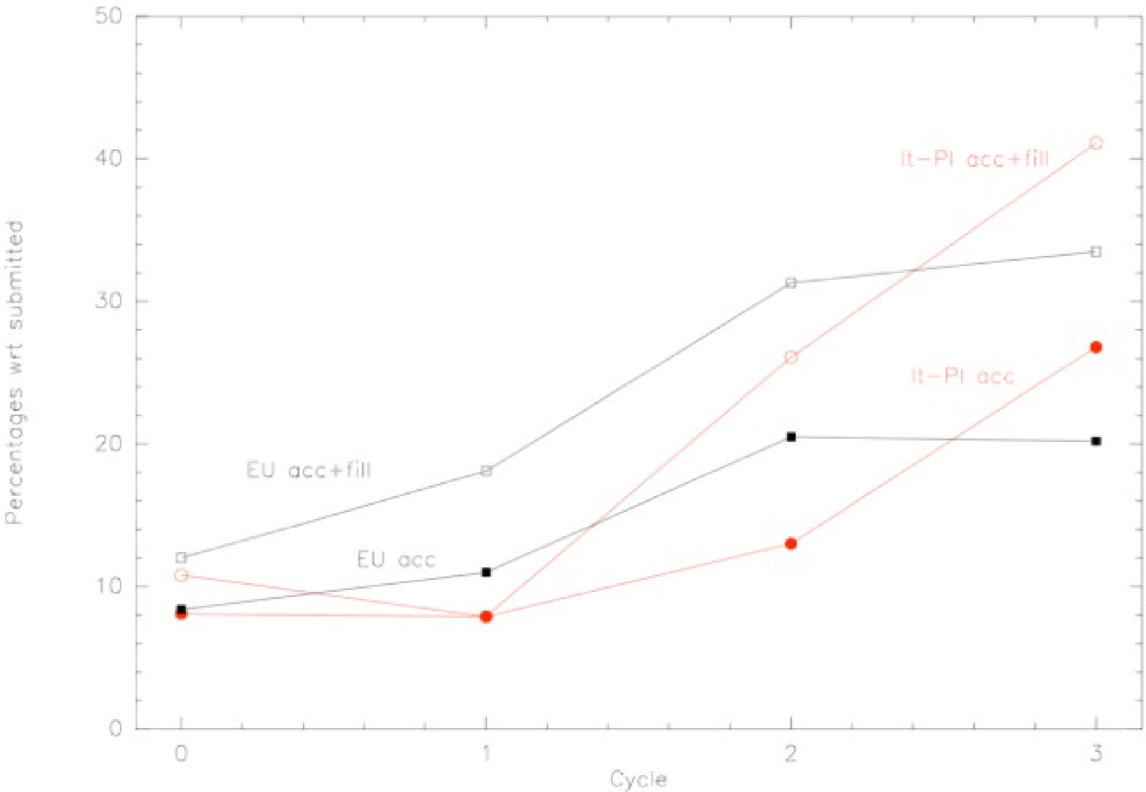


Table 1: **Italian PI and Co-I proposals**

Cycle	Code	submitted proposals props PI	number of unique PI	number of unique Co-I	number of unique PI/Co-I	accepted proposals PI props top[a]	PI props fill[b]	Co-I props top[a]	Co-I props fill[b]	unique Co-I
0	2011.0	37	32	136	144	3	1	12	6	32
1	2012.1	38	33	151	158	3	0	16	10	32
2	2013.1	46	42	159	166	6	6	44	22	77
3	2015.1	56	47	171	183	15	8	51	37	117

[a] "top" means proposals accepted with highest priority (categories A, B).
[b] "fill" means a proposal of grade C, to be observed as "filler" when no higher-priority proposal is available at a certain time.

In Cycle 3 we reaped what we sew!

Table 4: **Cycle 3: comparison between countries / ARC-nodes**

Selected Countries (nodes)	PI-proposals subm	top[b]	%	top+fil[c]	%	w.r.t. EU-EX totals[a] % subm	% top[b]	% top+fil[c]
NL+B (Leiden)	68	14	20.6	19	27.9	10.4	10.5	8.6
S+DK+SU (Onsala)	49	13	26.5	19	38.8	7.5	9.8	8.6
UK (Manchester)	135	20	14.8	44	32.6	20.5	15.0	20.0
I (Bologna)	56	15	26.8	23	41.1	8.5	11.3	10.5
F+E+D[MPG][d] (Grenoble)	205	52	25.4	80	39.0	31.2	39.1	36.4
D[e]+A+CH (Bonn-Cologne)	51	9	17.6	16	31.4	7.8	6.8	7.3

[a] For the EU executive in Cycle 3: 657 proposals submitted, 133 (20.2%) accepted with top priority, 220 (33.5%) accepted including fillers.

ALMA Cycle 4 (preannounced capabilities)

Proposal submission deadline 21 April 2016

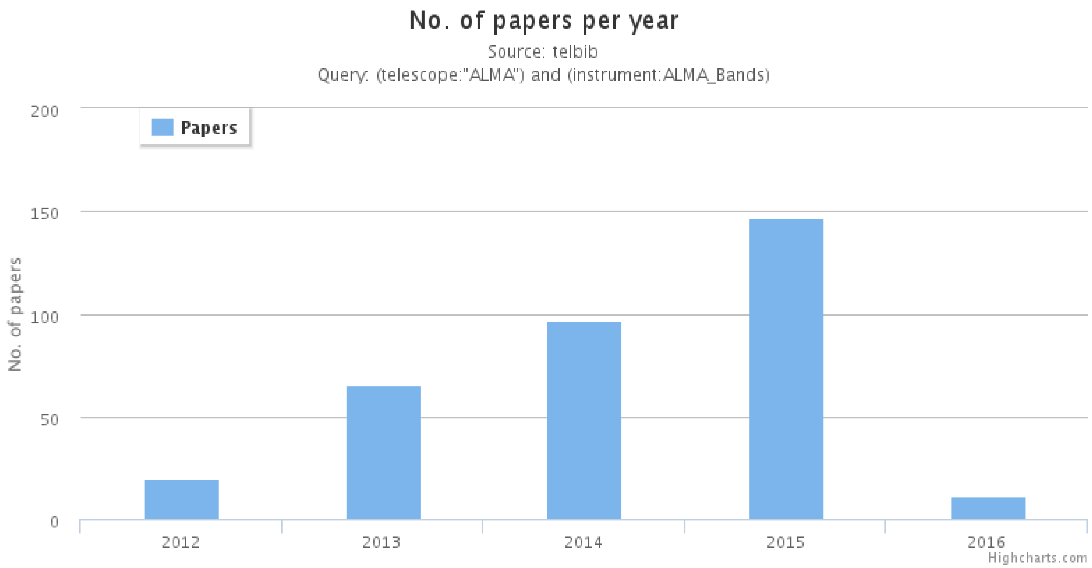
Observing epoch	Oct 2016 - Oct 2017		
Hours dedicated to Science	3000		
Antennas	> 40x12m +10x7m+3TP		
Receiver bands	3,4, 6,	7,	8, 9, 10
Wavelengths [mm]	3, 2, 1.3,	0.8,	0.7, 0.45, 0.35
Baselines	up to 12.8km,	5.3km,	2.7km
Polarisation	full (with some limitations)		

News

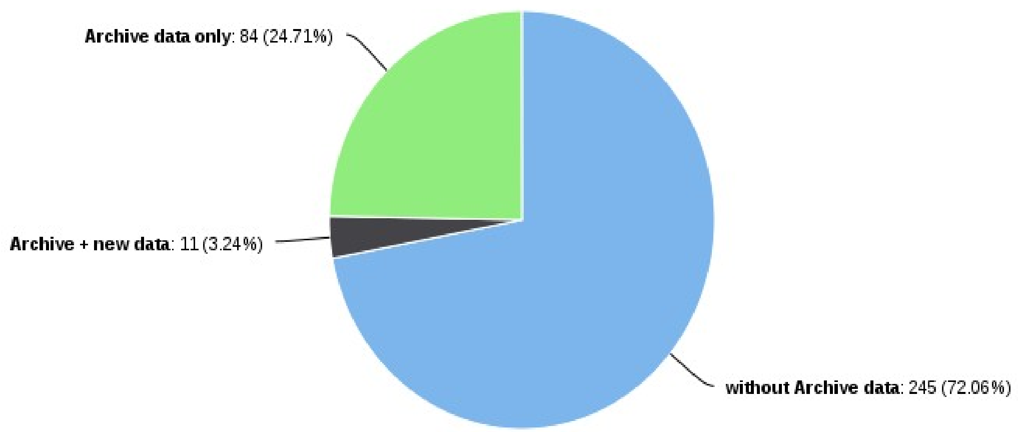
- ACA standalone
- Large programs (>50hr of observations not splittable in smaller programs)
- mmVLBI (with some restrictions)
- Solar observations

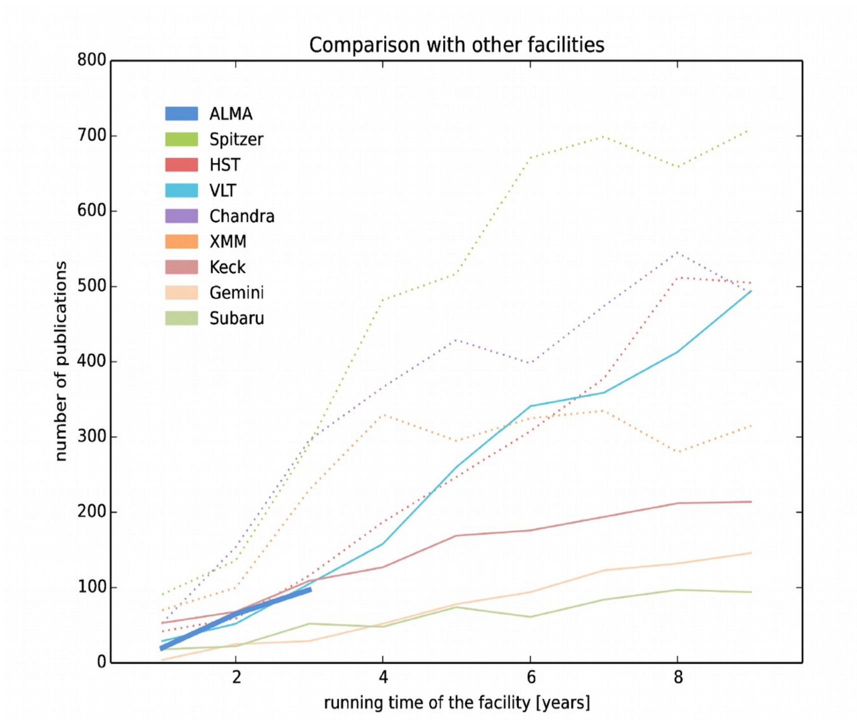
Italian ALMA Proposal Preparation Day
April 11-12 2016
Bologna, Osservatorio di Radioastronomia (ARC)
Register on www.alma.inaf.it

Publication statistics & Archive usage



340 papers including ALMA data





General words: ALMA pros for science

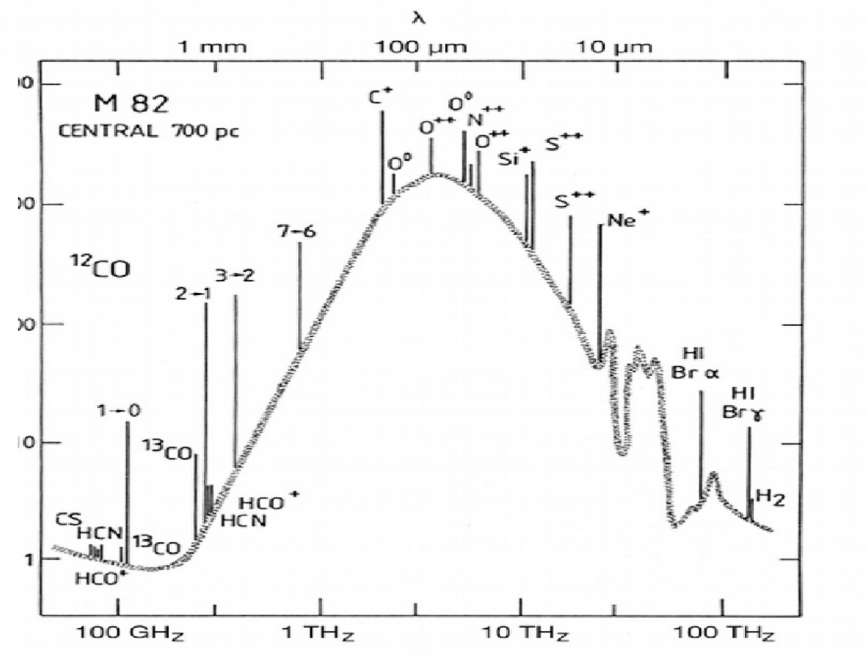
Sub(mm) is characterized by dust and rich chemistry.

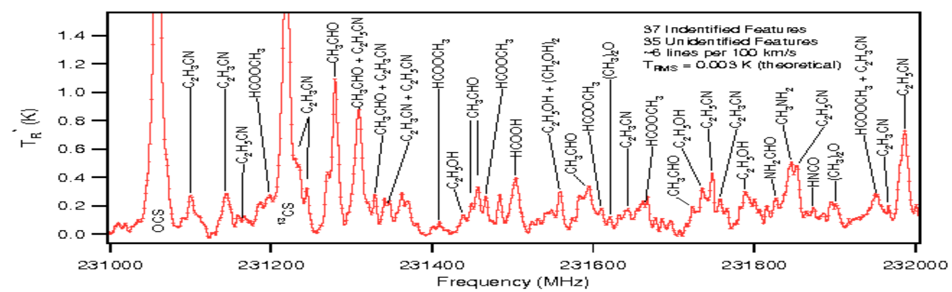
Dust and moleculae are mostly (but not only) associated with forming structures.

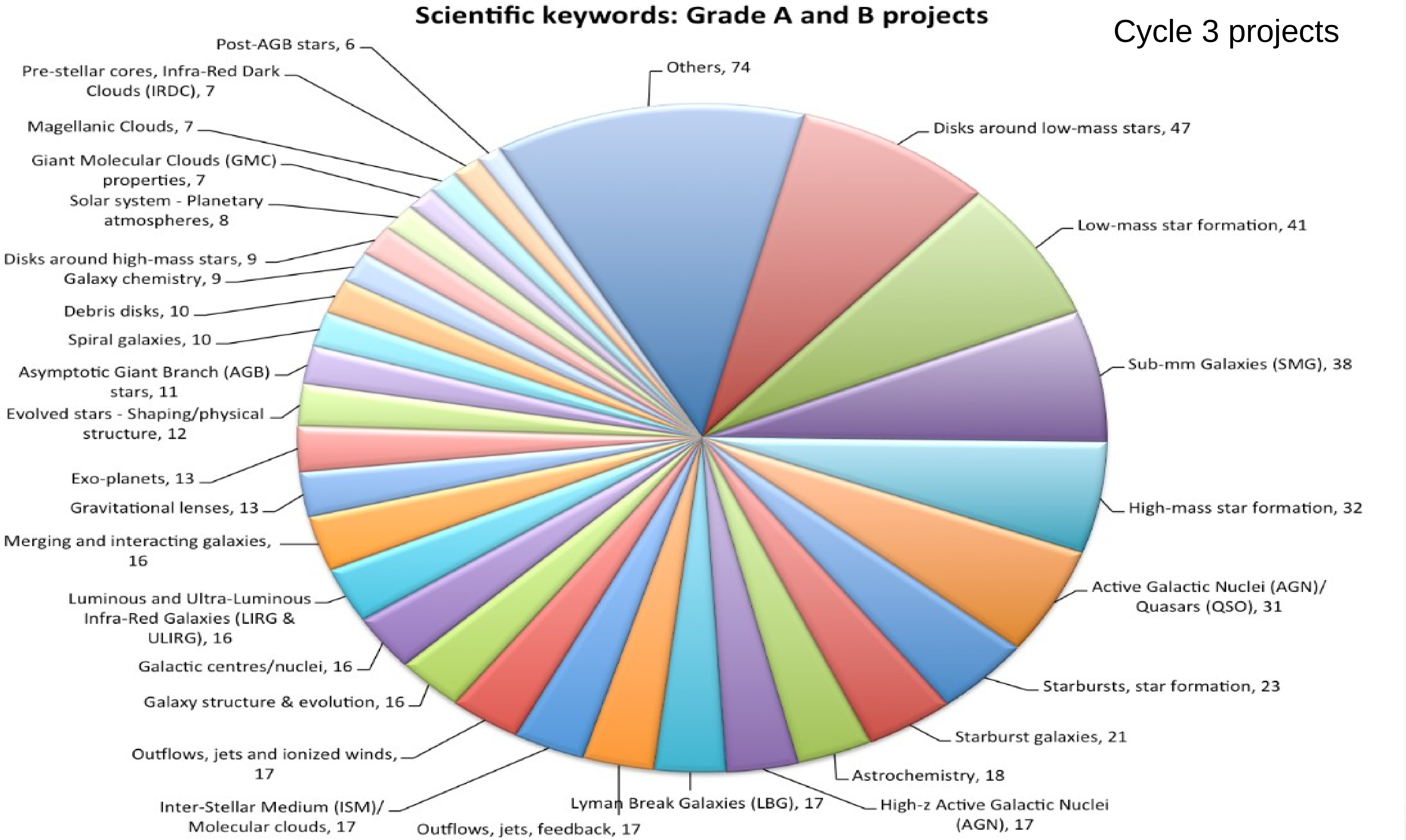
Hence **sub(mm) helps studying structure formation.**

Higher resolution and sensitivity allows to go farther so to investigate a deeper sky region, getting more sources and more statistics on populations.

Higher spectral resolution allows to detect more narrow lines and more details from broad lines, and hence investigate chemical compositions, source dynamics and pressure and temperature structures.

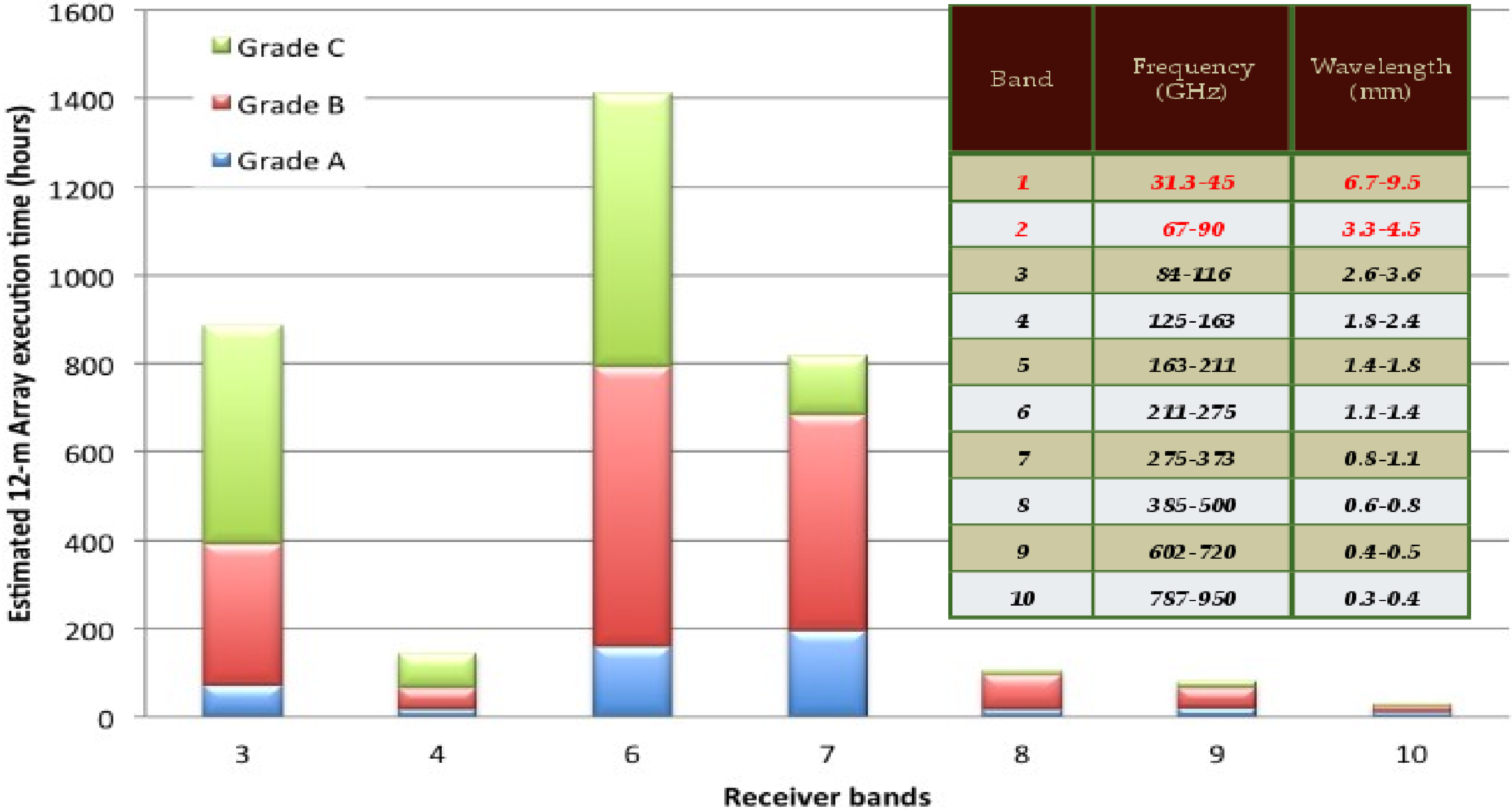





Scientific keywords: Grade A and B projects
Cycle 3 projects
Others, 74
Disks around low-mass stars, 47
Low-mass star formation, 41
Sub-mm Galaxies (SMG), 38
High-mass star formation, 32
Active Galactic Nuclei (AGN)/ Quasars (QSO), 31
Starbursts, star formation, 23
Starburst galaxies, 21
Astrochemistry, 18
High-z Active Galactic Nuclei (AGN), 17
Lyman Break Galaxies (LBG), 17
Outflows, jets, feedback, 17
Inter-Stellar Medium (ISM)/ Molecular clouds, 17
Outflows, jets and ionized winds, 17
Galaxy structure & evolution, 16
Galactic centres/nuclei, 16
Luminous and Ultra-Luminous Infra-Red Galaxies (LIRG & ULIRG), 16
Merging and interacting galaxies, 16
Gravitational lenses, 13
Exo-planets, 13
Evolved stars - Shaping/physical structure, 12
Asymptotic Giant Branch (AGB) stars, 11
Spiral galaxies, 10
Debris disks, 10
Galaxy chemistry, 9
Disks around high-mass stars, 9
Solar system - Planetary atmospheres, 8
Giant Molecular Clouds (GMC) properties, 7
Magellanic Clouds, 7
Pre-stellar cores, Infra-Red Dark Clouds (IRDC), 7
Post-AGB stars, 6

Cycle 3 projects

Receiver bands: Grades A, B and C projects



Band	Frequency (GHz)	Wavelength (mm)
1	31.3-45	6.7-9.5
2	67-90	3.3-4.5
3	84-116	2.6-3.6
4	125-163	1.8-2.4
5	163-211	1.4-1.8
6	211-275	1.1-1.4
7	275-373	0.8-1.1
8	385-500	0.6-0.8
9	602-720	0.4-0.5
10	787-950	0.3-0.4

Planets & small bodies

Surface studies

- Temperature mapping
- Shaping morphologies

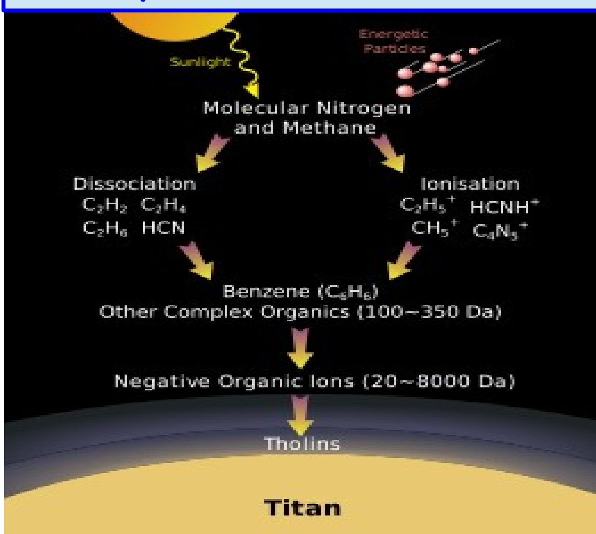
Atmospheric studies

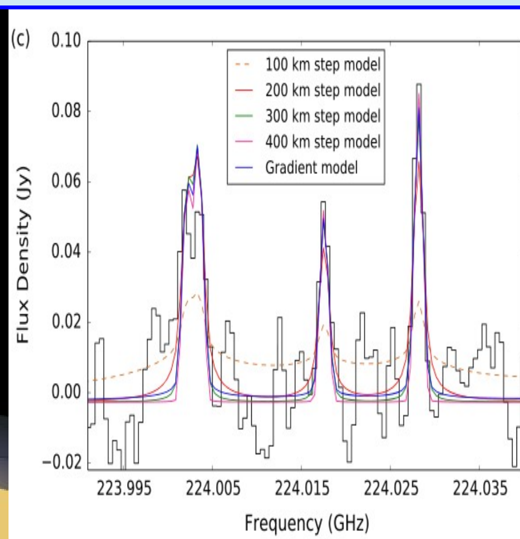
- Chemical abundances for production models
- Line profiles for 3D **structures and dynamics (seasonal variations and climate models)**

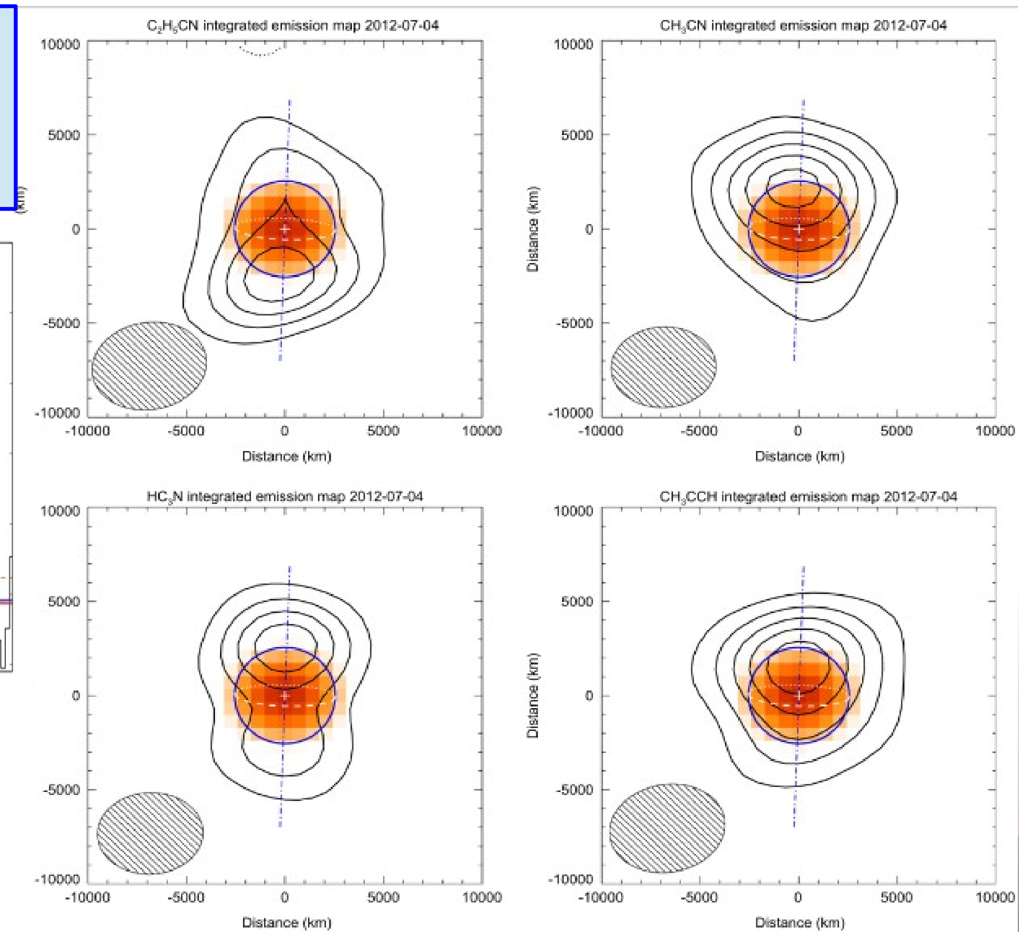
Calibrations

Ethil Cyanide on Titan (Cordiner et al. 2015)

- Cycle 0 – 16 antennas
- 1.2 hr on-source
- Band 7 (0.85 mm): *SO2, SO, HDO and CO*
- **spatial resolution 1.2-2.4"" (for a disk of 11")**







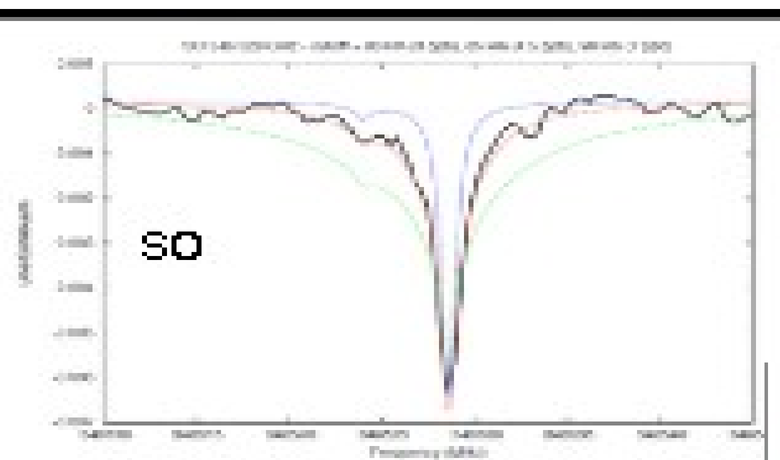
Planets & small bodies

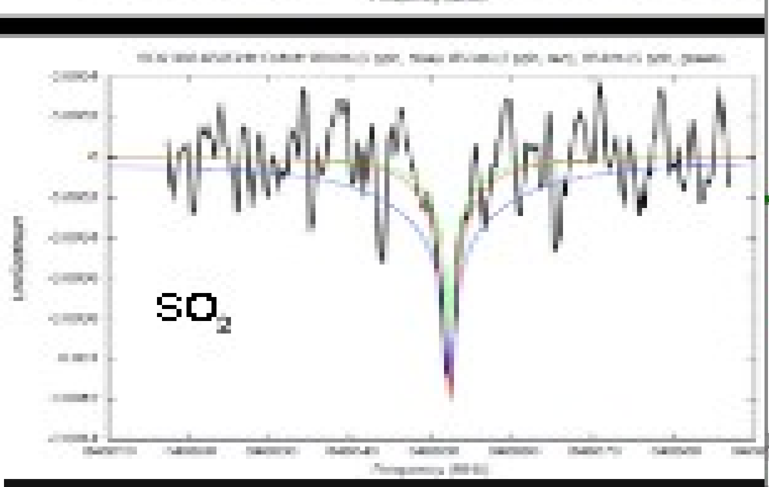
Surface studies
- Temperature mapping
- Shaping morphologies

Atmospheric studies
- Chemical abundances for production models
- Line profiles for 3D **structures and dynamics (seasonal variations and climate models)**

Calibrations

Sulphur and water mapping in Venus mesosphere (Moullet et al. 2013)





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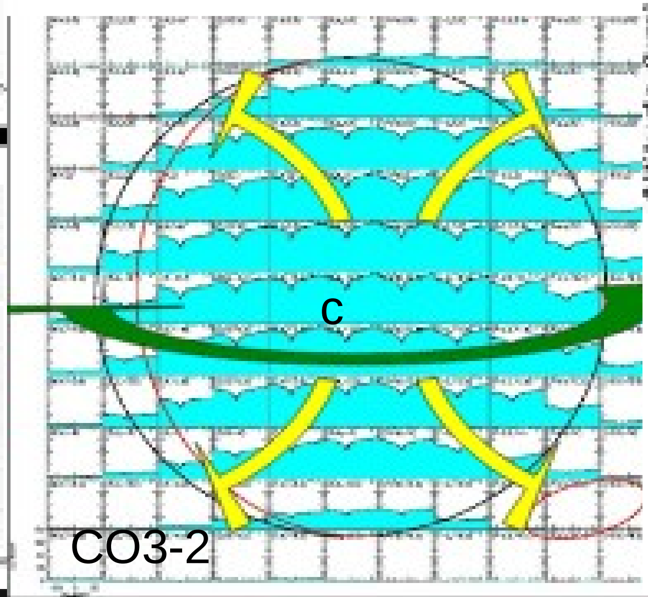
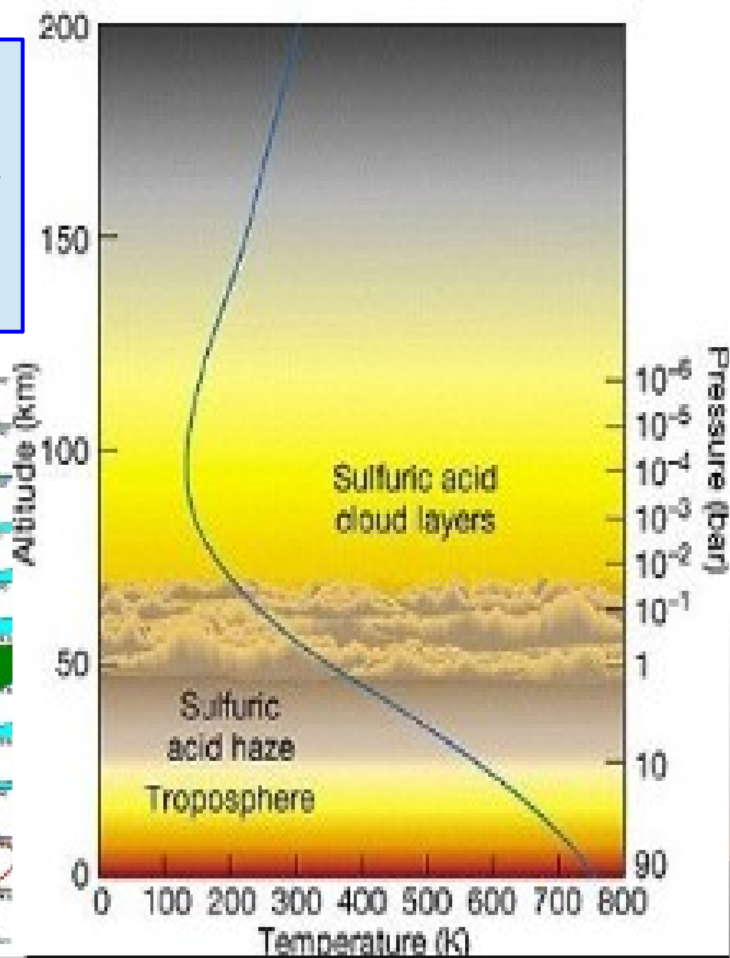
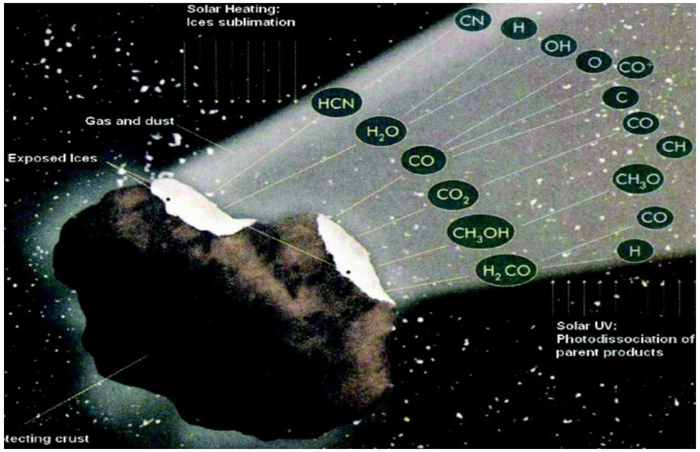


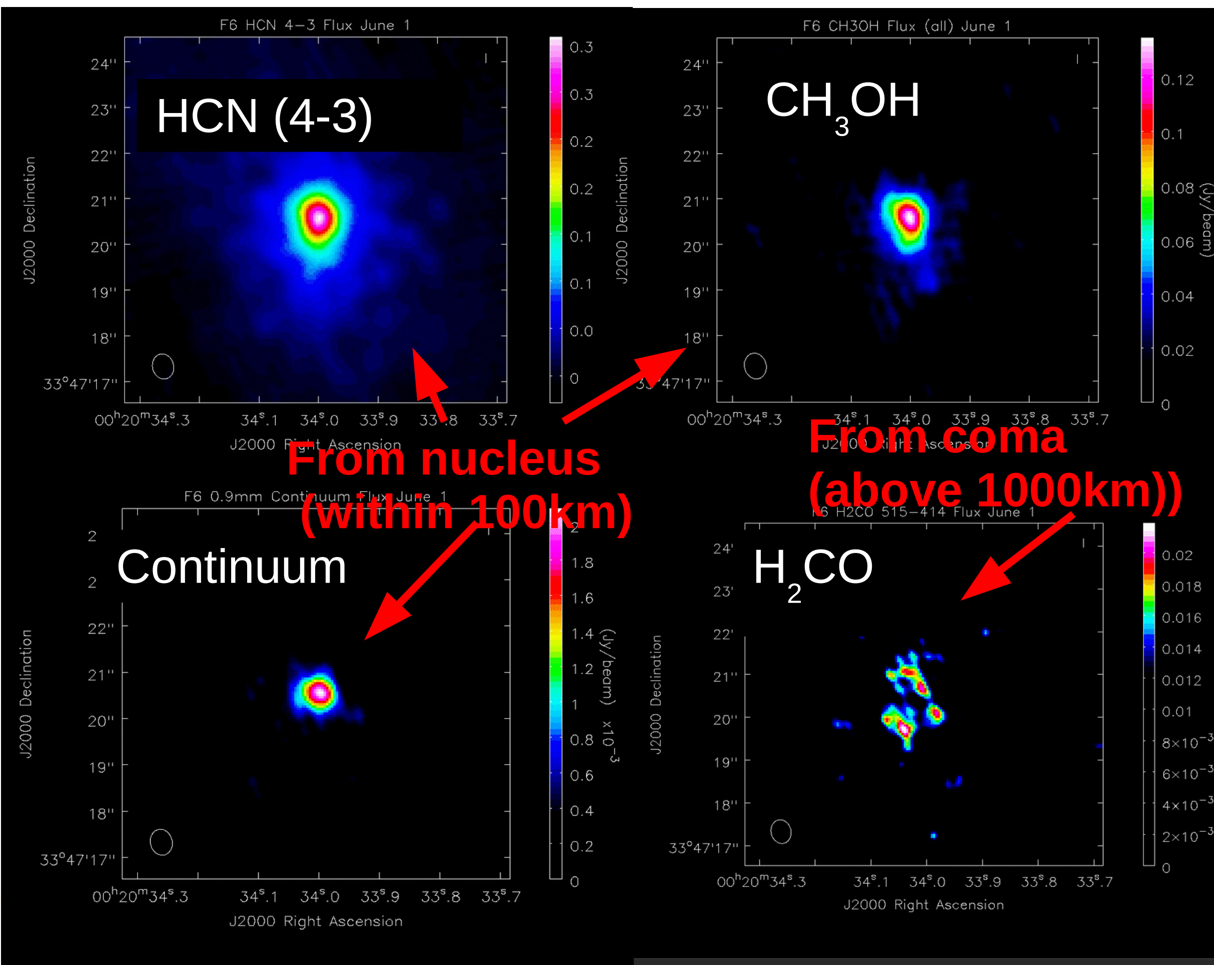


Comets & small bodies



Comets composition and structure may provide information about the physical and chemical conditions in the Early Solar System.

Observing **small bodies** will allow to **image their surfaces**, determine their sizes and orbits.



Comet C/2012 F6 Lemmon
(Cordiner et al. 2014)

- Cycle 1 Director's Discretionary Time proposal 30 antennas
- 1.2 hr on-source
- Band 7 (0.8-0.9 mm): HCN, CH_3OH, H_2CO
- Spatial resolution 0.4 arcsec
- Spectral resolution 0.4km/s

Comets & small bodies

Comets composition and structure may provide information about the physical and chemical conditions in the Early Solar System.

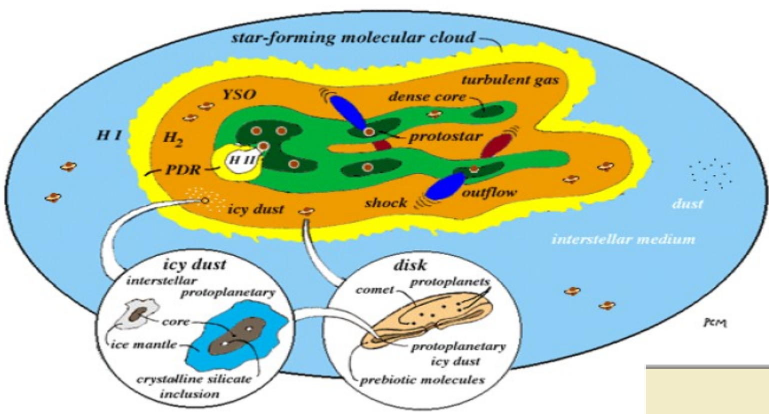
Observing **small bodies** will allow to **image their surfaces**, determine their sizes and orbits.

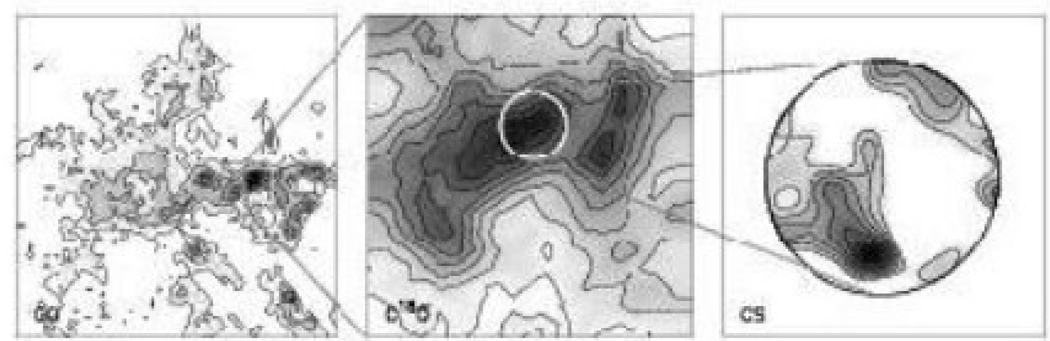
High resolution Juno (ALMA Partnership et al. 2015).

- Science Verification Cycle 2
- 3x15min on-source
- Band 6
- 10km baselines: res=0.042"=60km @1.97AU Diameter =259+-4km

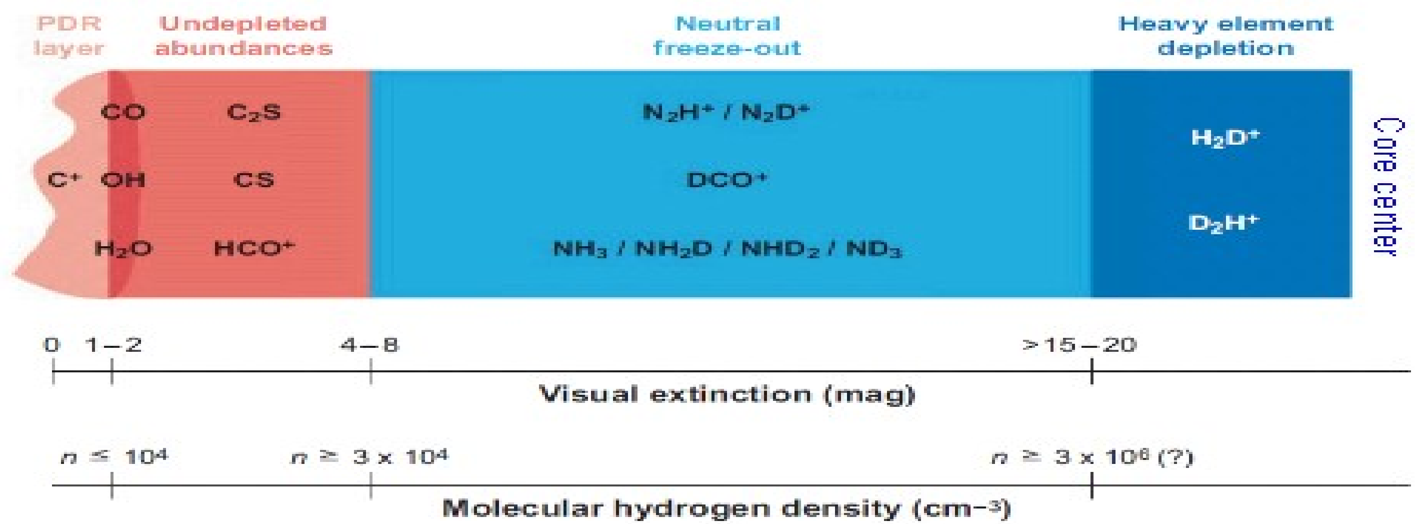
ISM structure and chemical enrichment

The ISM is constituted by 90% of H, 9% of He and traces of other components
80% of H2 is in giant molecular clouds, peaking in the Galactic center.
Molecular clouds are highly structured complexes made of clumps (where clusters can form) and cores (where a single or binary star form).
The chemical complexity of ISM is still an open question (e.g. aminoacids in ISM)





	Clouds[a]	Clumps[b]	Cores[c]
Mass ($M_\odot$)	$10^3 - 10^4$	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3–10^4	10^4–10^5



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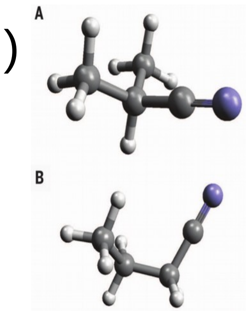
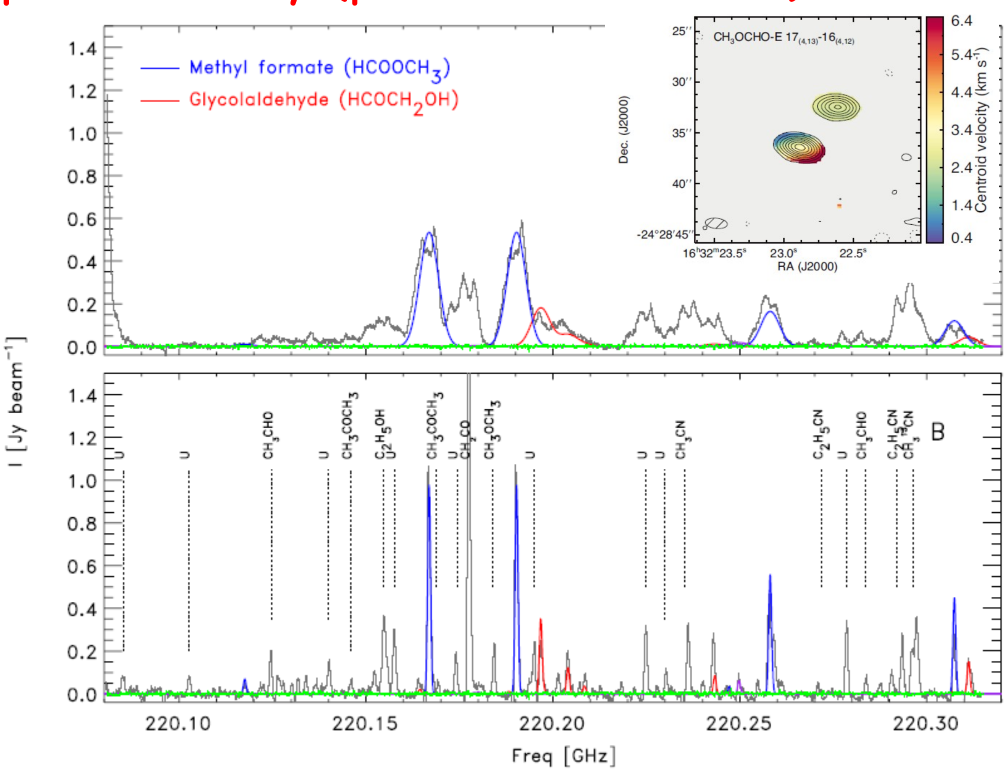
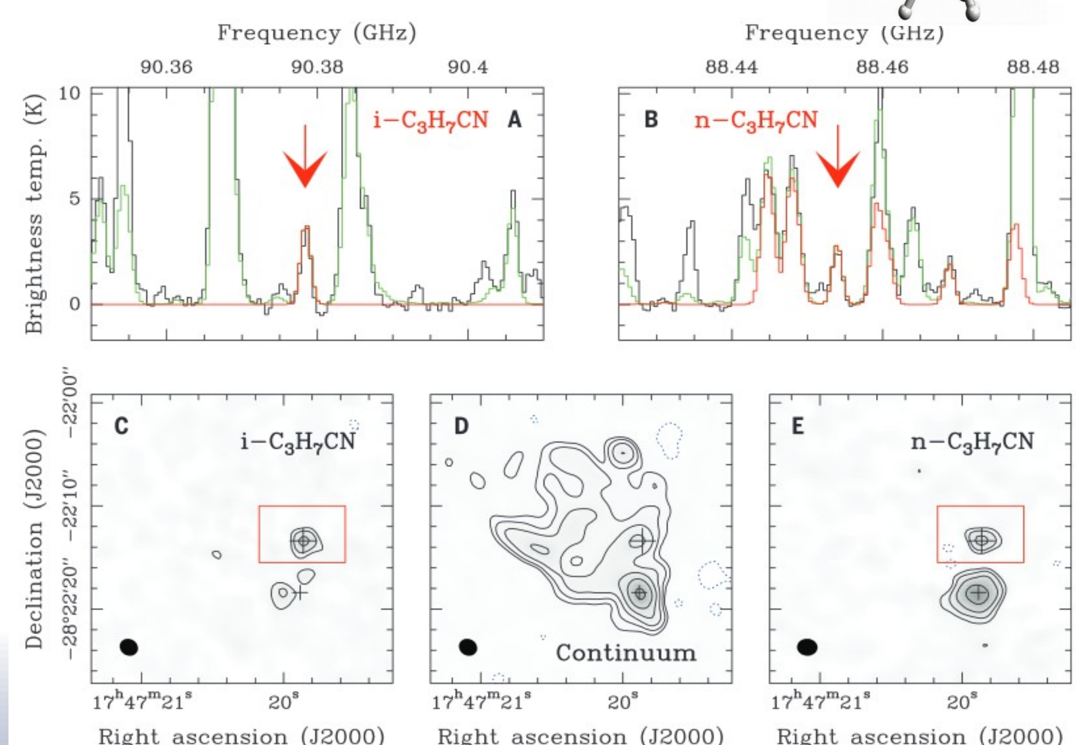


Glicolaldehyde in IRAS16293-2422 proto-binary (Pineda et al. 2012)



Iso-methyl cyanidein a hot core (Belloche et al. 2014)

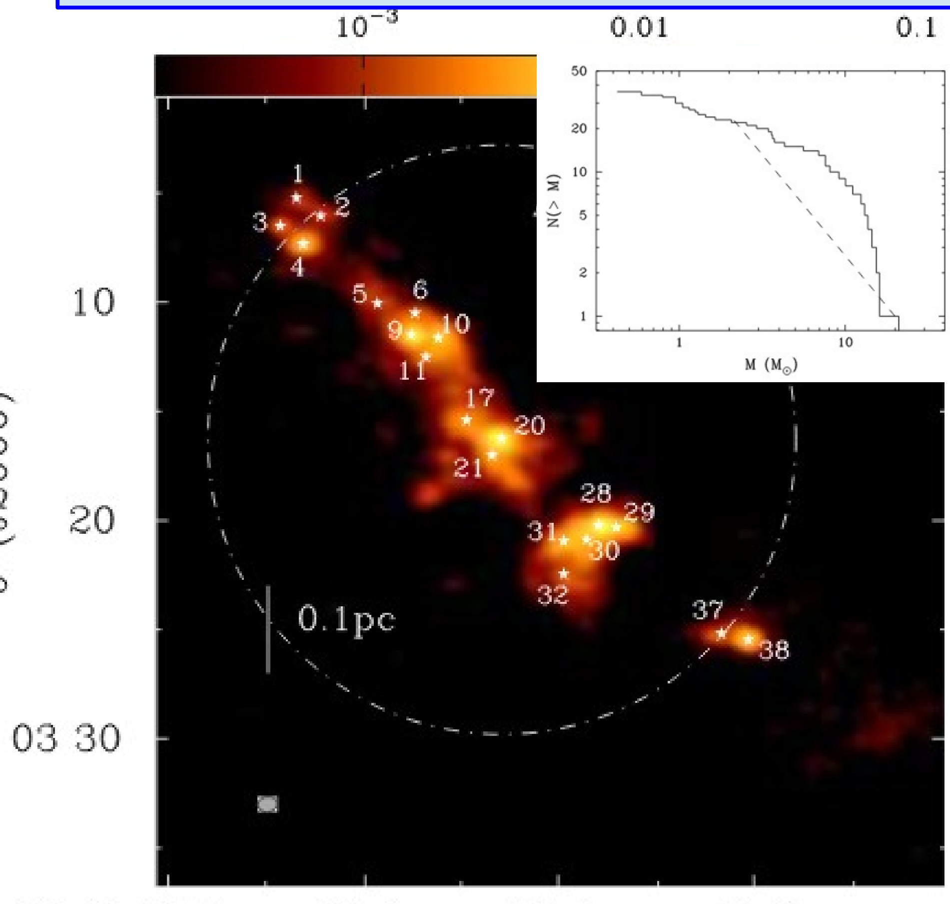


Star formation

The earliest stages of star formation should be bound prestellar cores of which the mass can be measured via thermal dust emission.
High angular resolution can measure the dust fragments down to subsolar masses.

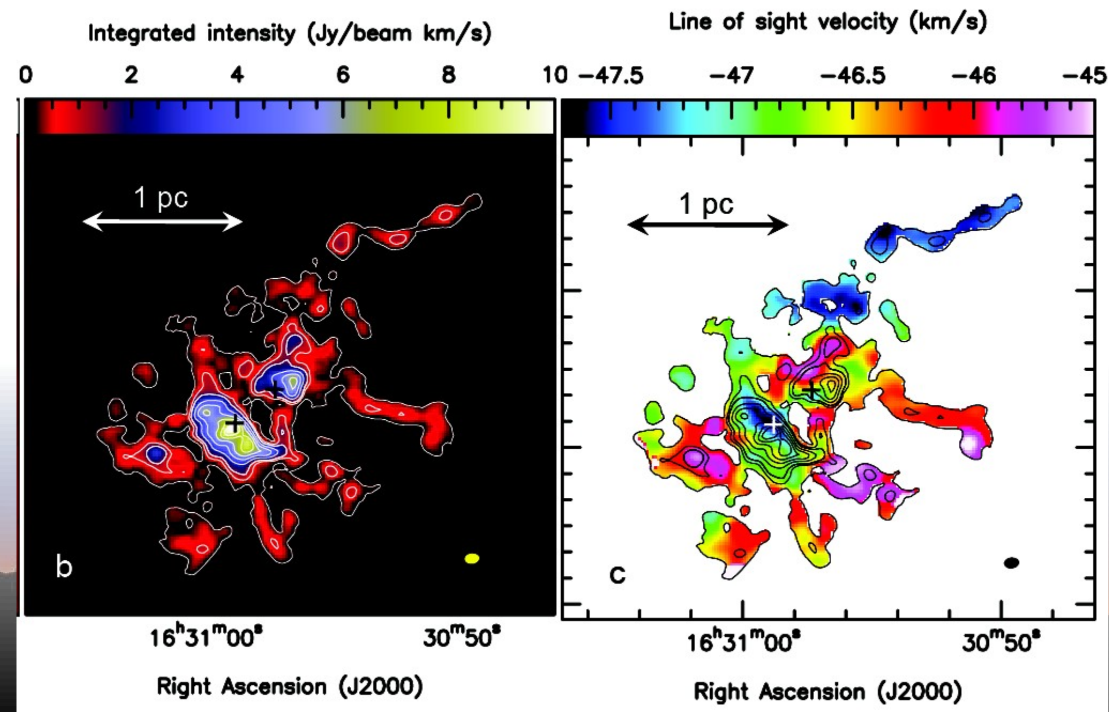
Fragmentation in G28.34 IR dark cloud
Arbouring massive star formation
(Zhang et al. 2015)

- Cycle 0 – 29 antennas
- Band 6
- **Angular resolution ~ 0.8''**



Network of cold, dense, pc-long filaments in SDC335: a global collapse along filaments (Peretto et al. 2013)

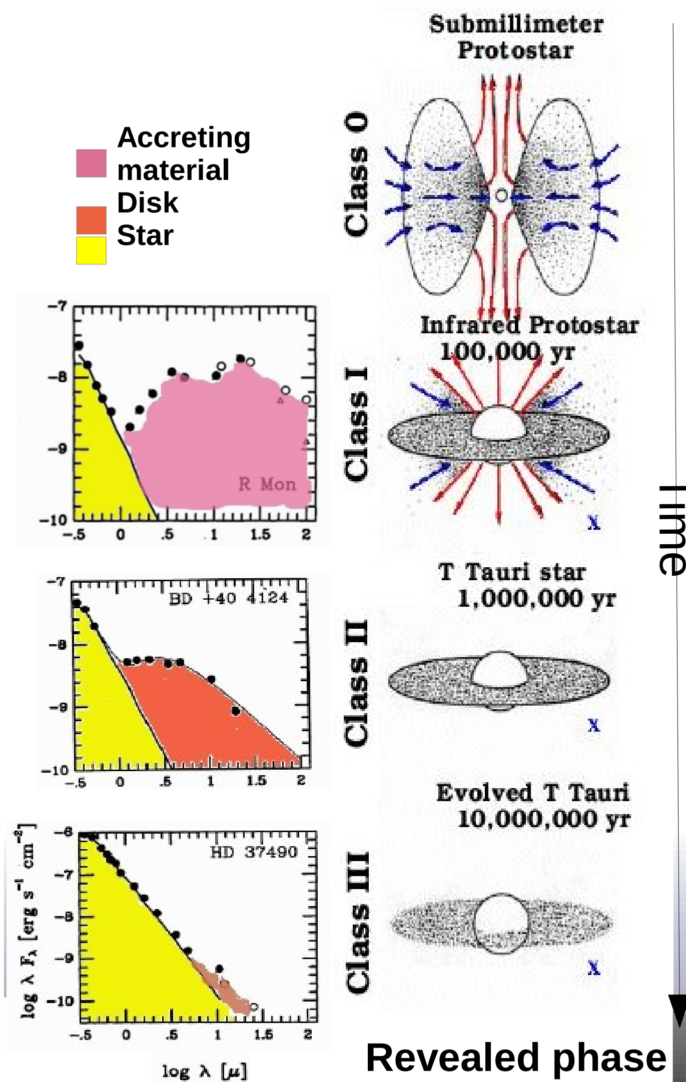
- 3mm continuum, CH_3OH(13-12), N_2H^+(1-0)
- 16 antennas, 11 mosaic points
- Beam = 5.6'' x 4.0''
- Vel. Resolution = 0.1 km/s
- Continuum rms 0.40 mJy/beam
- Line rms 14 mJy/beam



Disks everywhere!

Massive star loose disc more rapidly than low-mass star of same age.
For star masses 0.04<M<10Msun the disk is typically 1% of the star mass.

For O-type star no disk were detected (before ALMA) in submm indicating very short disk life or a different formation scenario.



Revealed phase

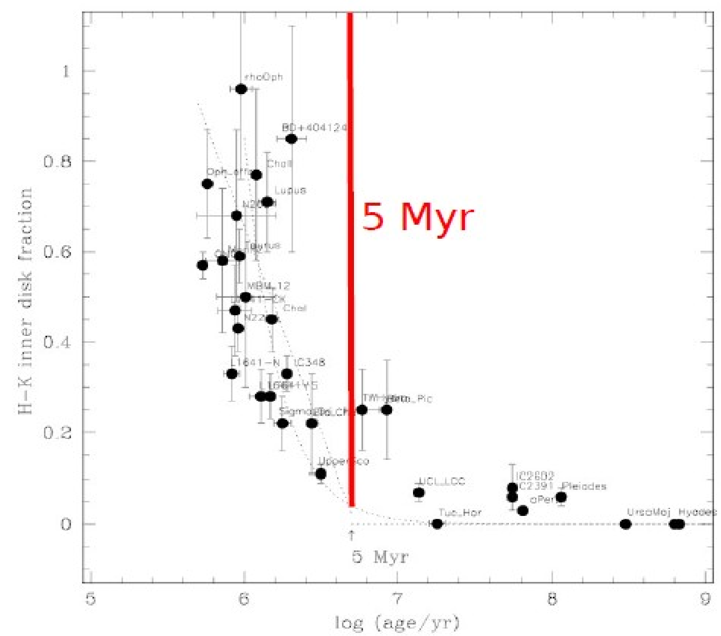
Observables

Dusty environment
Infall
Outflows

Disk
Outflows
Infall

Disk without accretion

Protoplanetary disk



(Hillebrand et al. 2005)

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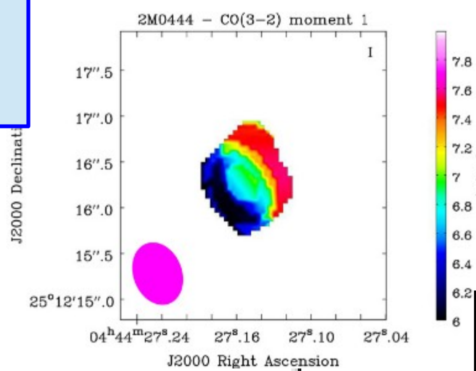
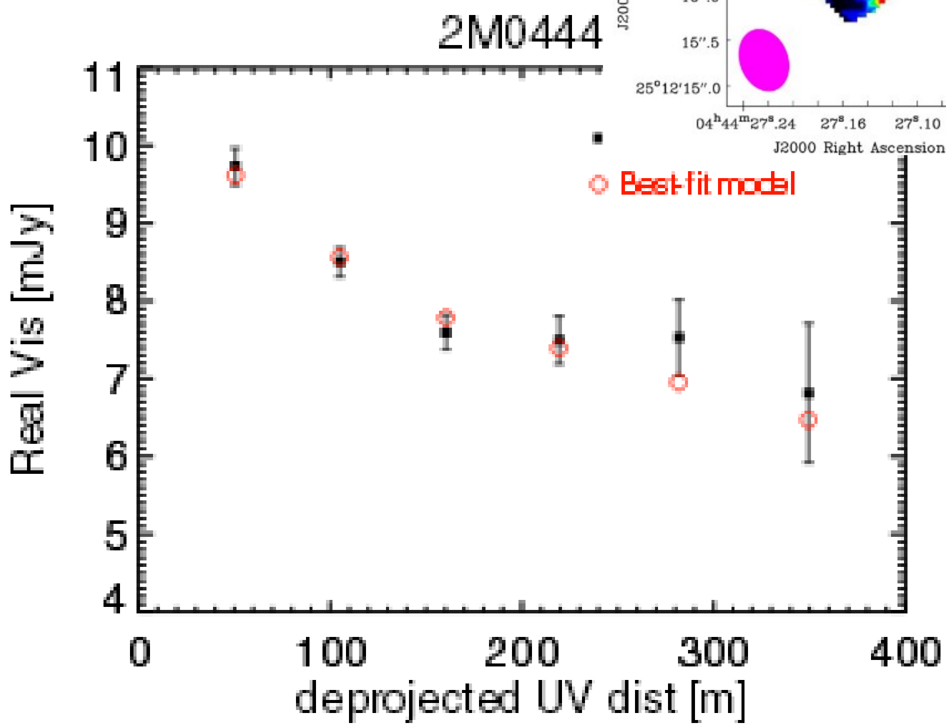
Disk around brown dwarfs (Ricci et al. 2014)

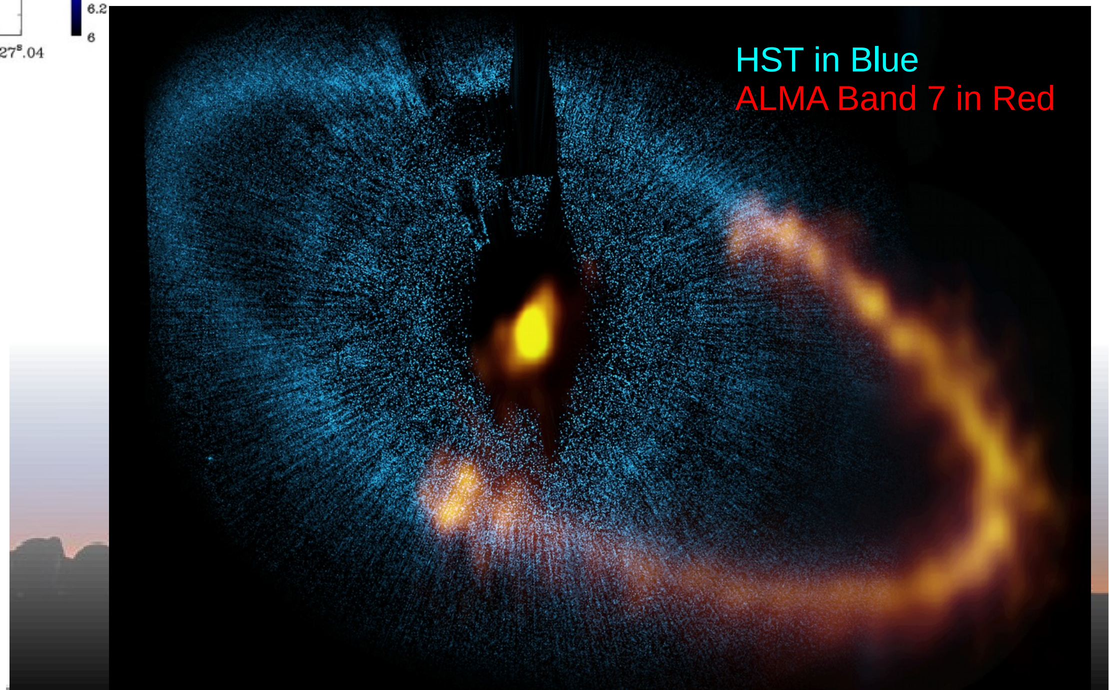
- Cycle 0 – 29 antennas
- Band 6
- **Angular resolution ~ 0.8'**





Disk around Fomalhaut A3V (Boley et al. 2012)

- Band 7 – continuum
- 140 min on source
- rms~0.06 mJy/beam
- **Angular resolution ~1.5''**



Disks everywhere!

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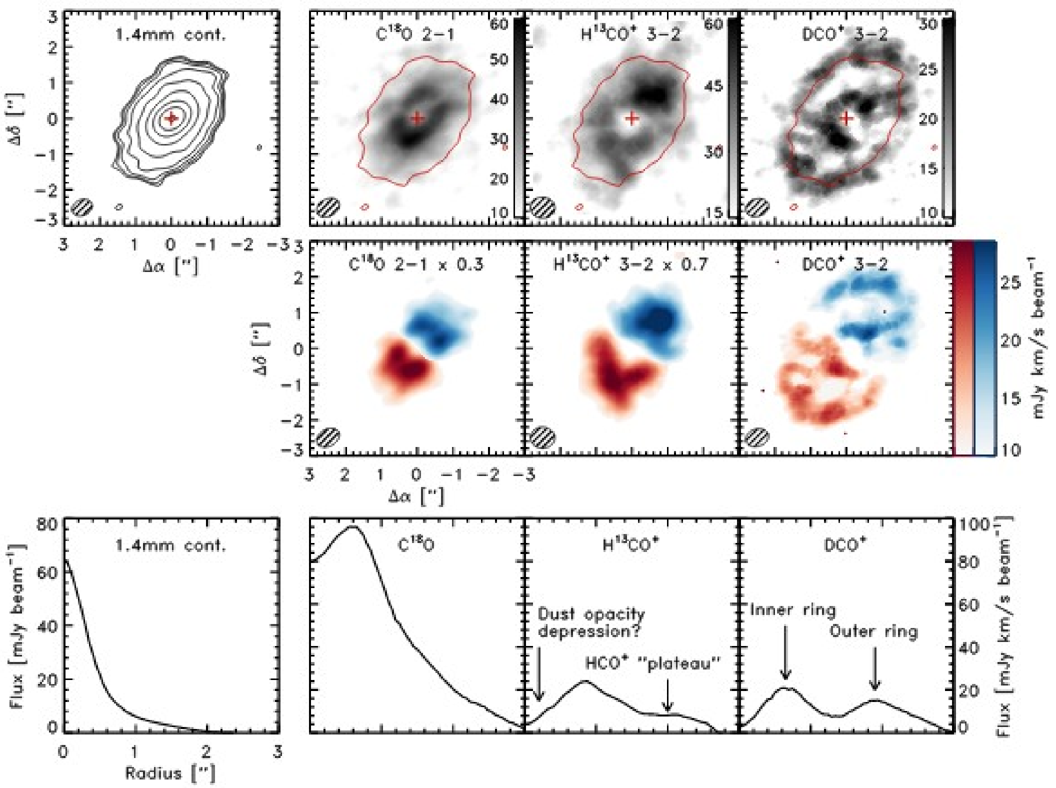
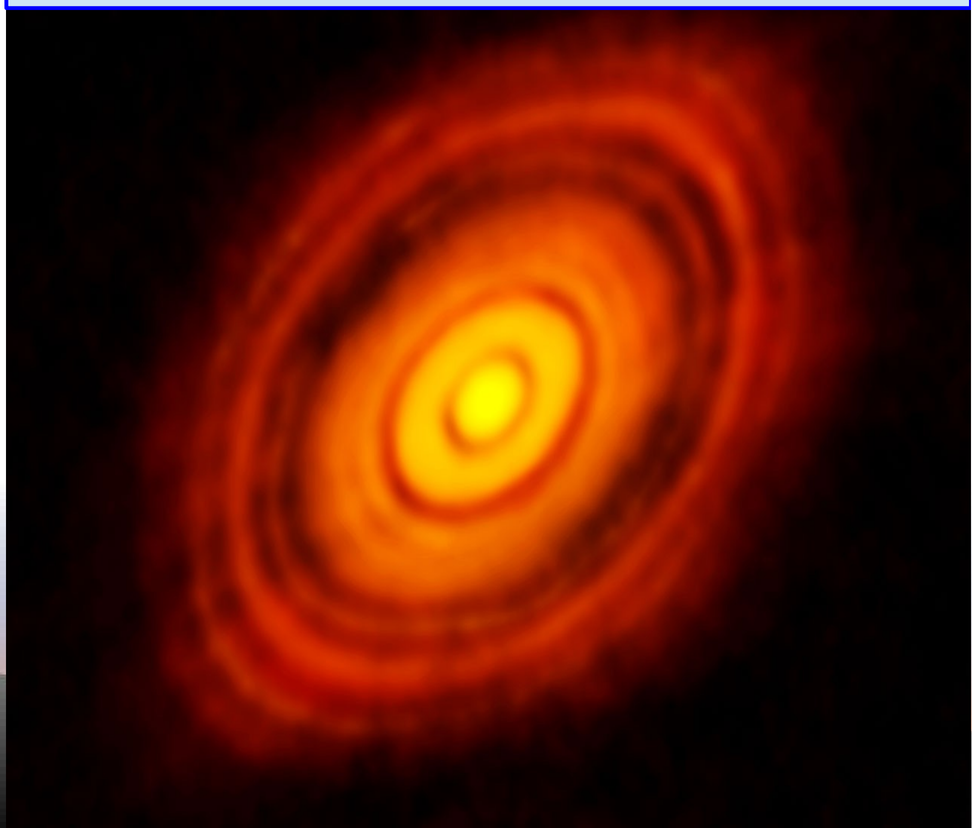
IM-Lup:T-Tauri disk (Oeberg et al. 2015)

- Cycle 1 – 32 antennas
- Band 6
- **Angular resolution ~ 0.6''**



HL-Tau: young T-Tau star
(ALMA Partnership 2015)

- Long Baseline Campaign SV
- Band 3, 6,7 – continuum
- **Angular resolution ~ 85 x 61 mas, 35 x 22 mas, and 30 x 19 mas**



Disks everywhere!

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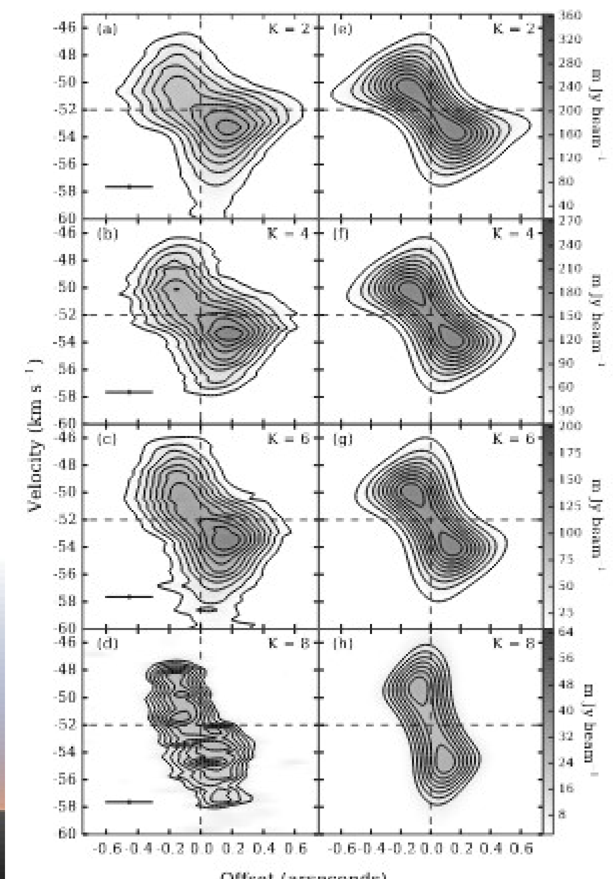
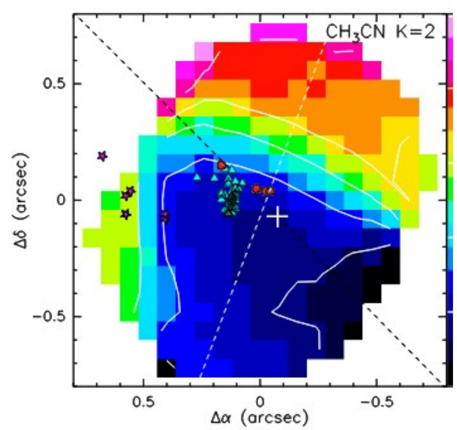
For star masses 0.04<M<10Msun the disk is typically 1% of the star mass.

For O-type star no disk were detected (before ALMA) in submm indicating very short disk life or a different formation scenario.

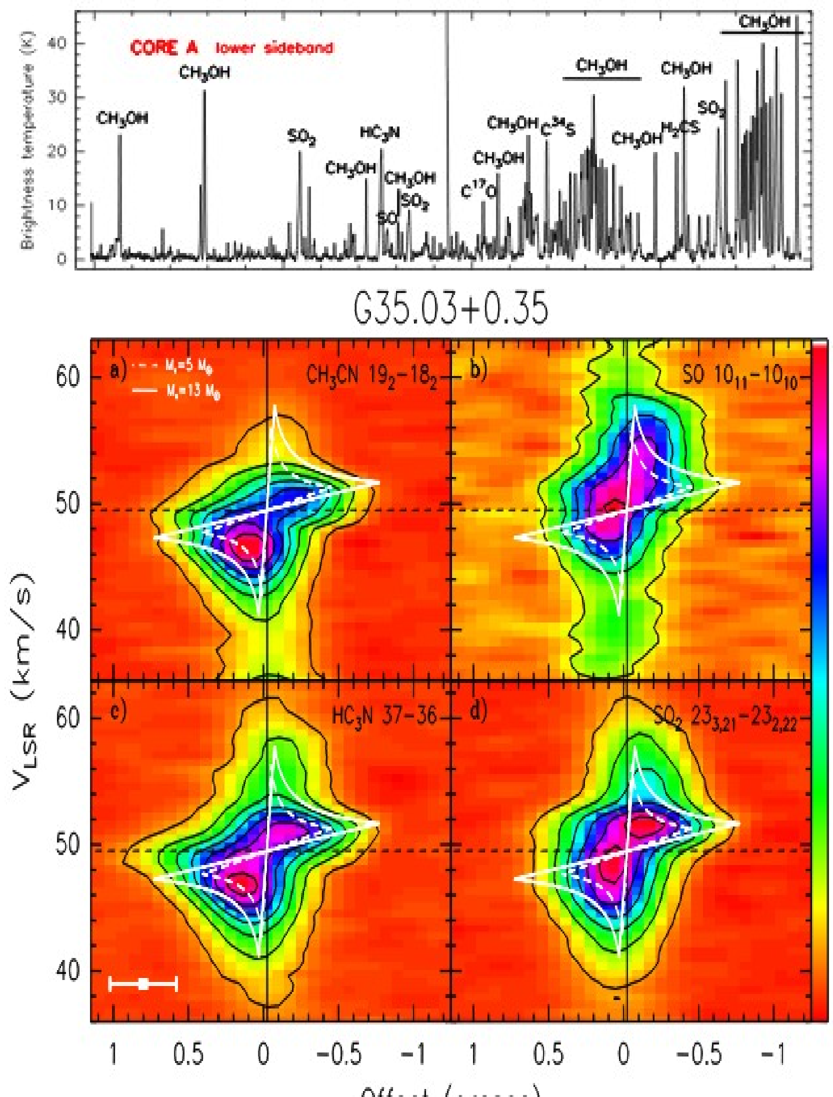
Disk around O star (Johnston et al. 2015)

- Cycle 1 – 29 antennas
- Band 6
- **Angular resolution ~ 0.3''**



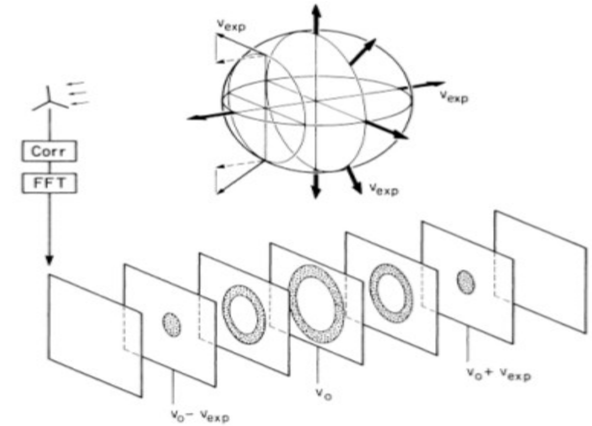


Disk around B star (Beltran et al. 2015)

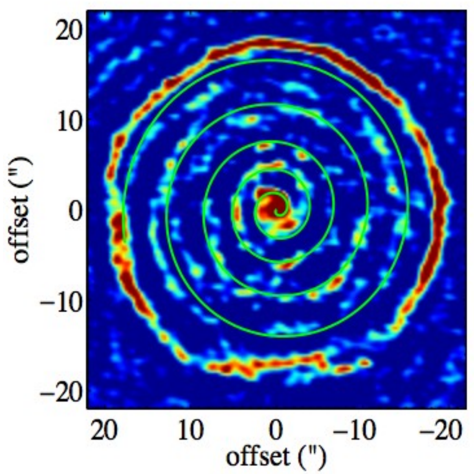


AGB stars

AGB stars (last stages of 0.6-10 Msun stars) are typically long-period variables, and suffer mass loss in the form of a stellar wind.
Thermal pulses produce periods of even higher mass loss and may result in detached shells of circumstellar material..
For an envelope expanding with constant velocity the iso-velocity curves are circles

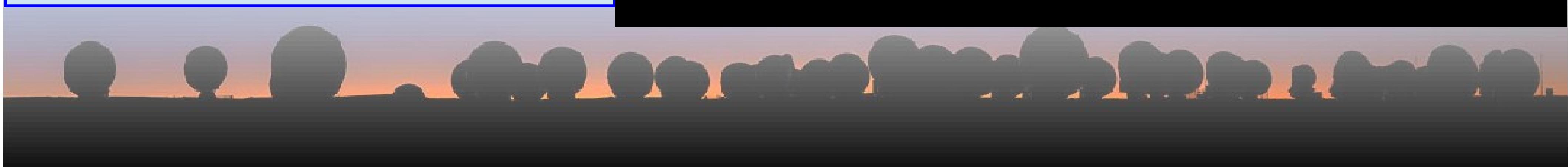


R-Sculptoris (Maercker et al. 2012, Vlemmings et al. 2013)



CO(3-2) Velocity Channel Movie

- ~15 antennas, ~4 hrs
- Band 7: CO(3-2),
- **resolution = 1.3''**
- 45 pointed mosaics (50'' x 50'' field)

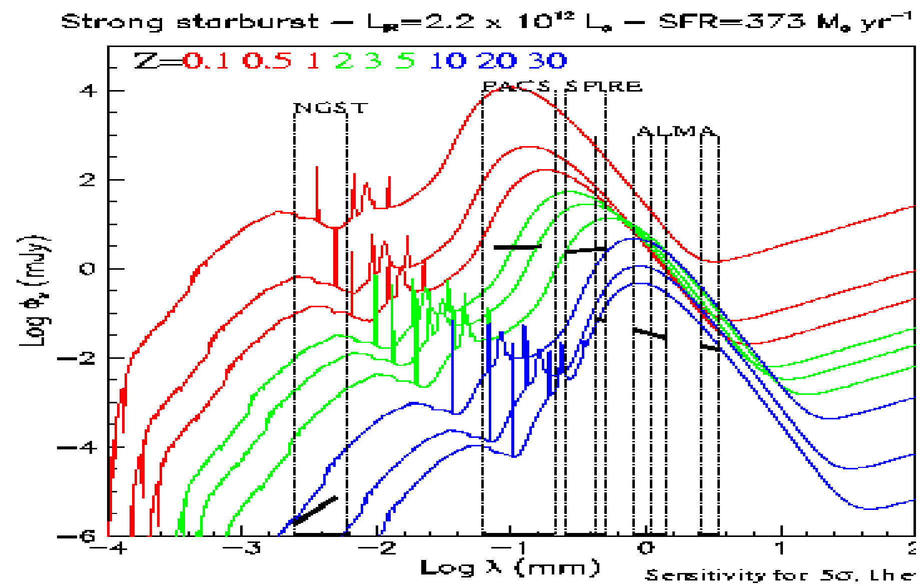


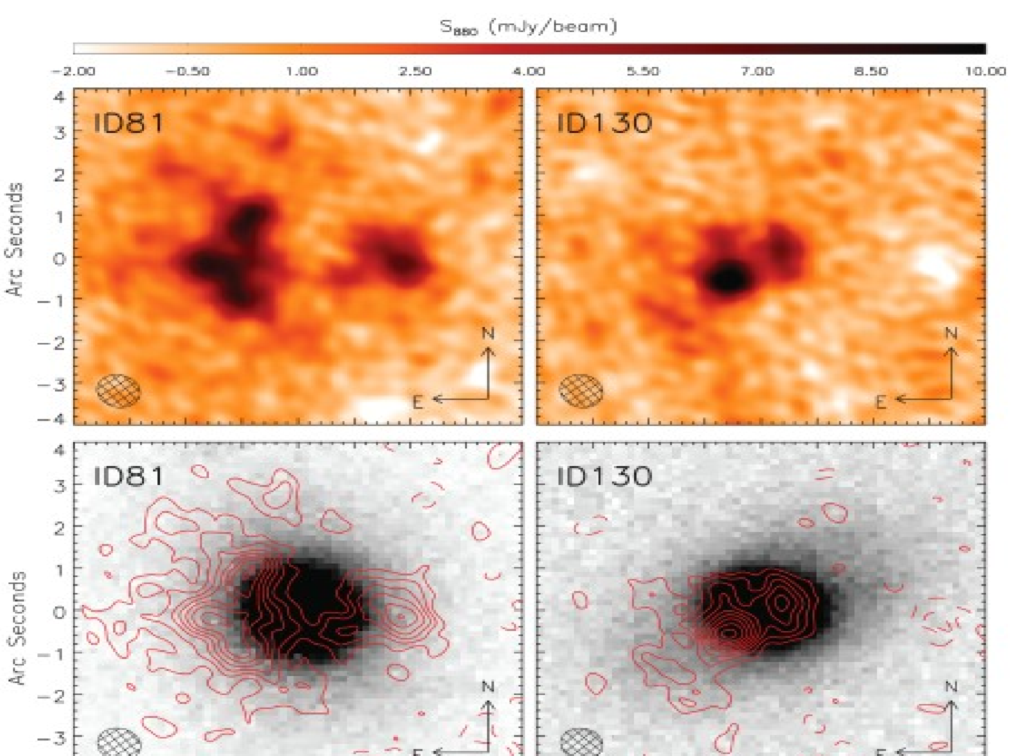
Extragalactic science in (sub)mm

At high redshift the prominent **IR dust thermal bump** (which dominates the SED in starburst galaxies) is shifted into the submm band.

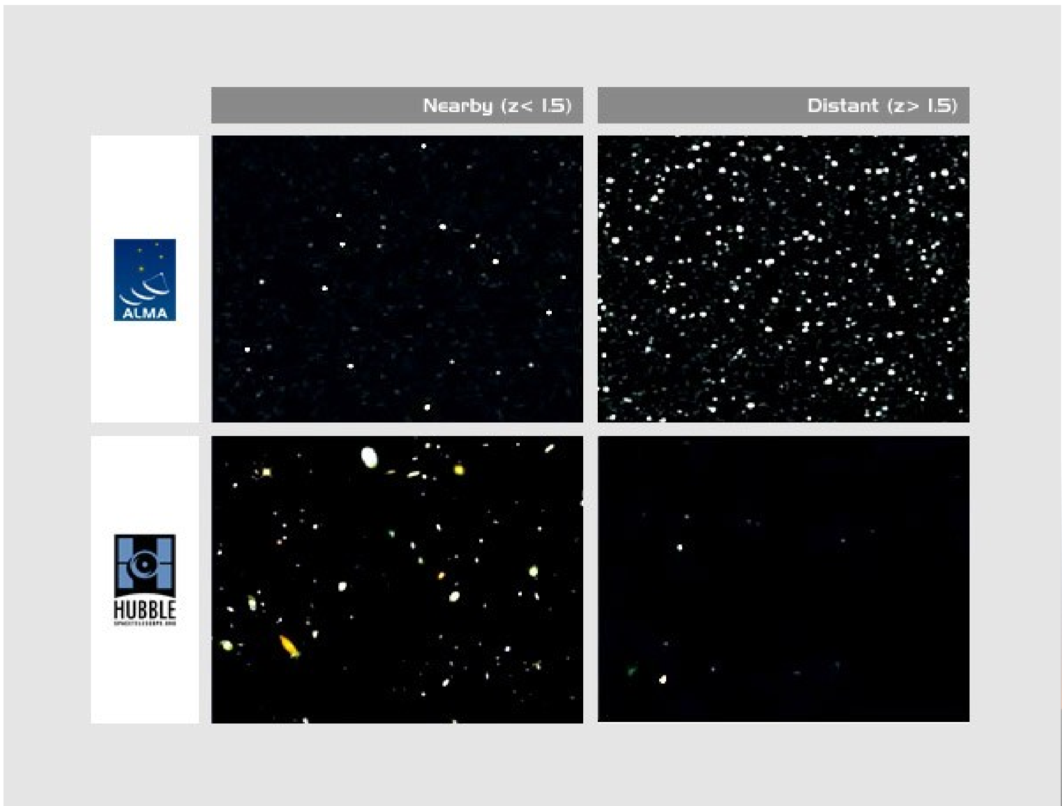
Negative k correction: for 1<z<10 galaxy flux density remain constant for $0.8<\lambda<2$mm. High-z galaxies look brighter than low-z & more high_z than low_z in deep fields.

Obscuration is not an issue as in optical bands





(Negrello et al 2010)



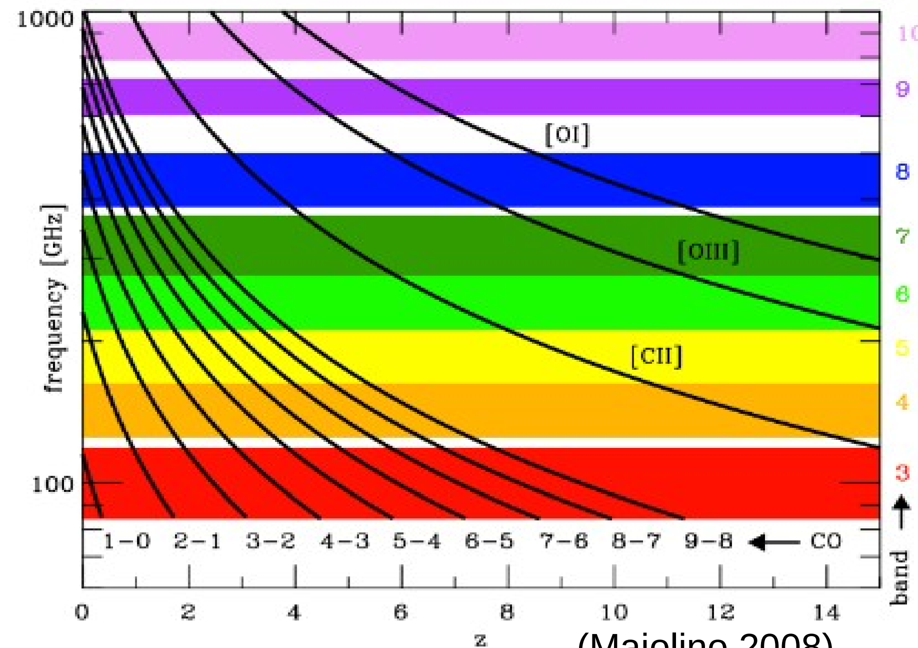
Molecular lines

CO is a tracer of H_2

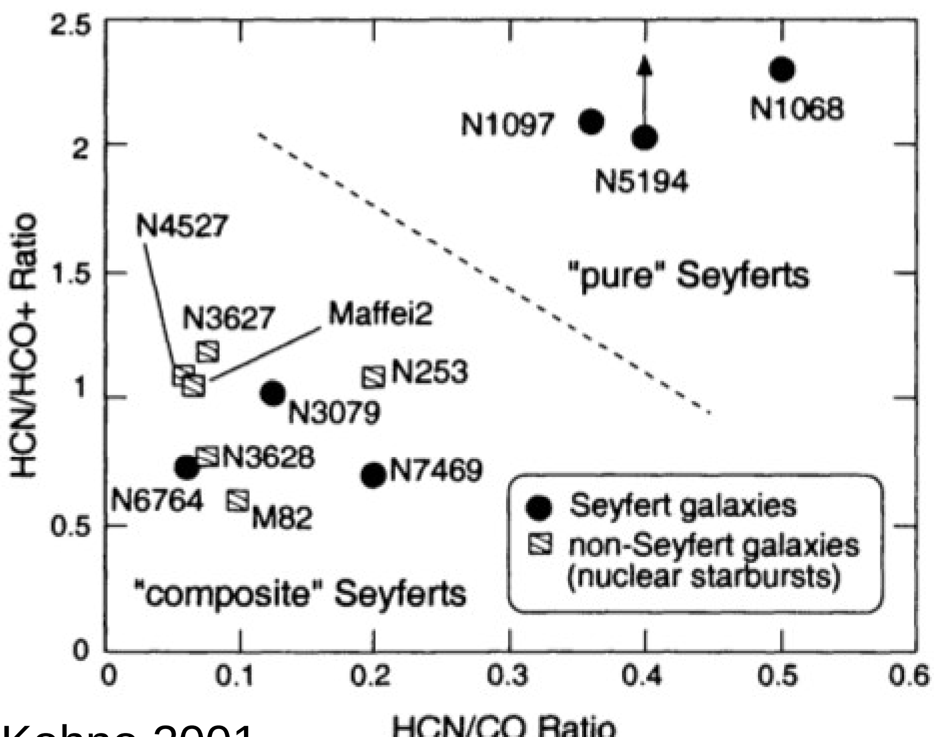
[CII]158 μm and the [OI]63 μm fine structure lines
are the two main coolants of the ISM and
are redshifted into the (sub)mm bands at z > 2–4

HCN, HCO+ and other high density tracers are
powerful tools to distinguish PDR (associated
to SF regions) from XDR (associated to AGN).

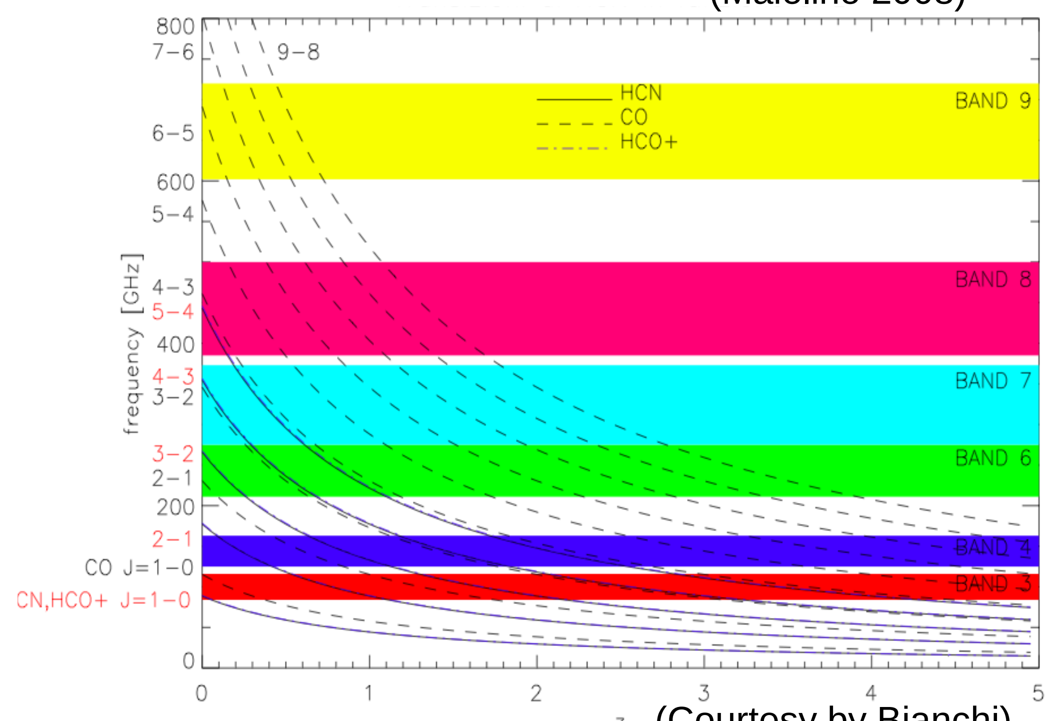
In most of the ALMA band more than one line is
observable for the higher redshifts.



(Maiolino 2008)



Kohno 2001

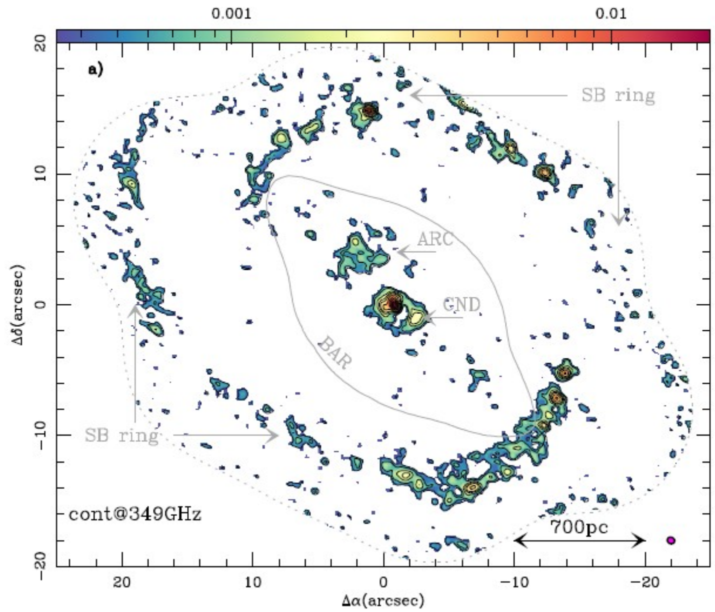


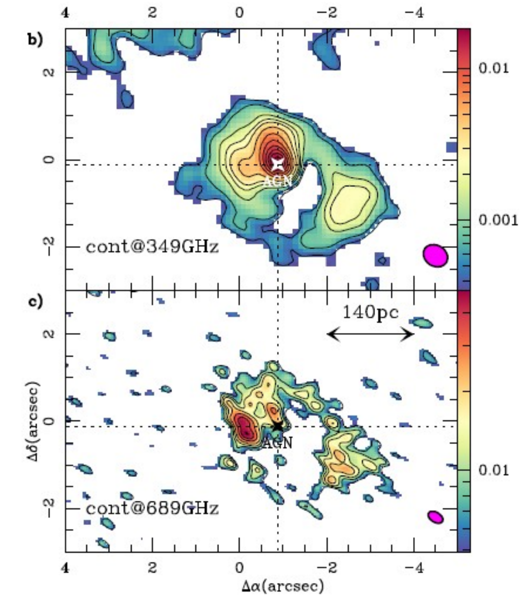
(Courtesy by Bianchi)

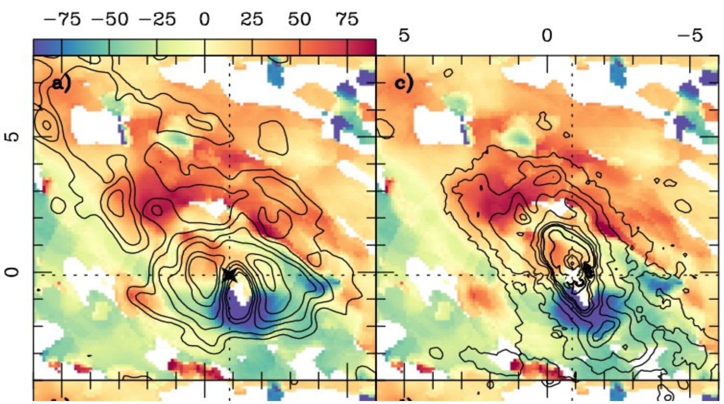
ALMA observations of NGC1068, a Sy2 @14Mpc (Garcia-Burrillo et al 2014)

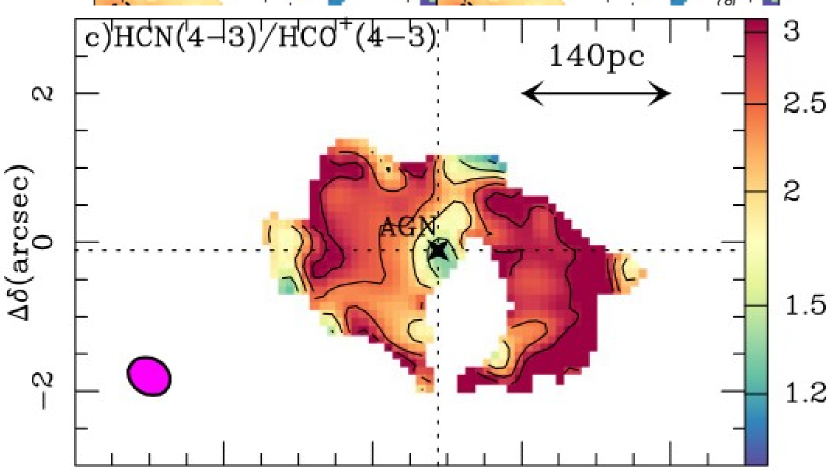
- Band 7 (350GHz)
  CO(3-2), HCN, HCO+(4-3), CS(7-6)
- ~18-27 antennas,
- ~138min (11 pointing mosaic)
- Resolution ~ 0.6''x0.5''=35 pc

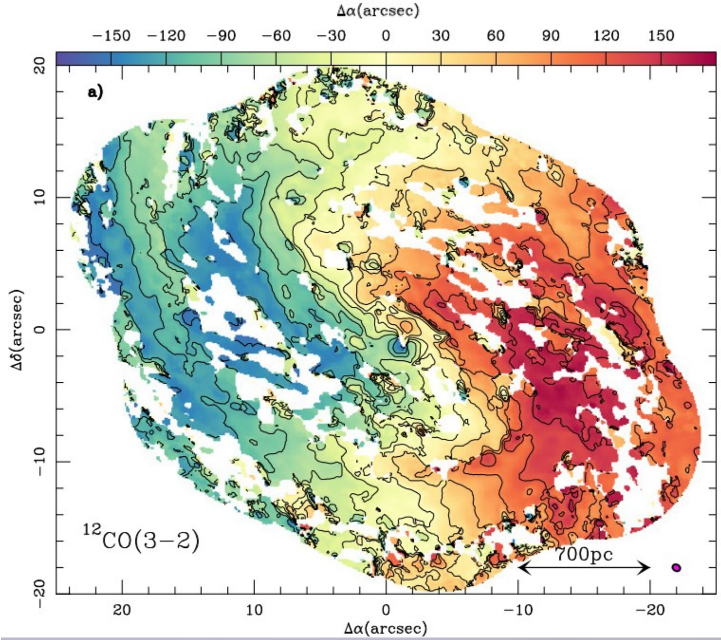
- Band 9 (690GHz)
  CO(6-5)
- ~21-27 antennas,
- ~52min (1 pointing)
- Resolution ~ 0.4''x0.2''=20 pc

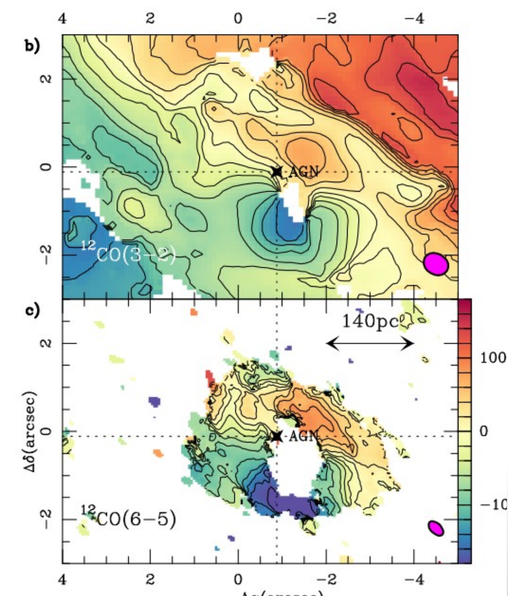






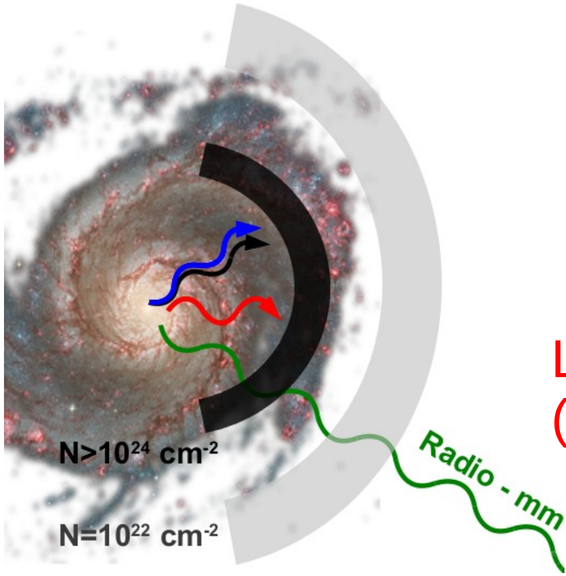






(Krips et al. 2011)

Observations in highly obscured galactic cores

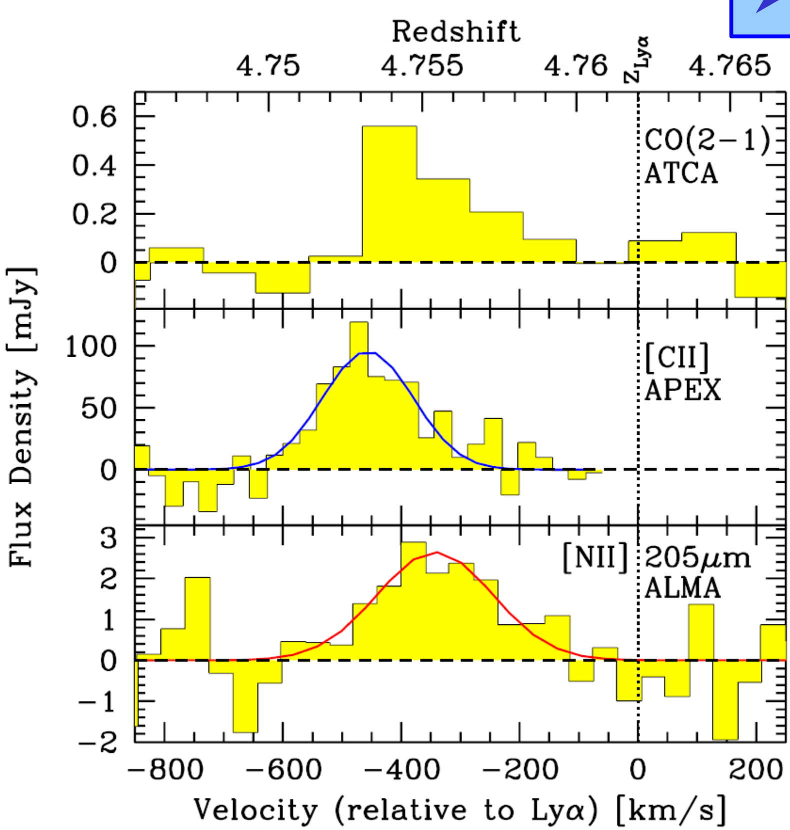


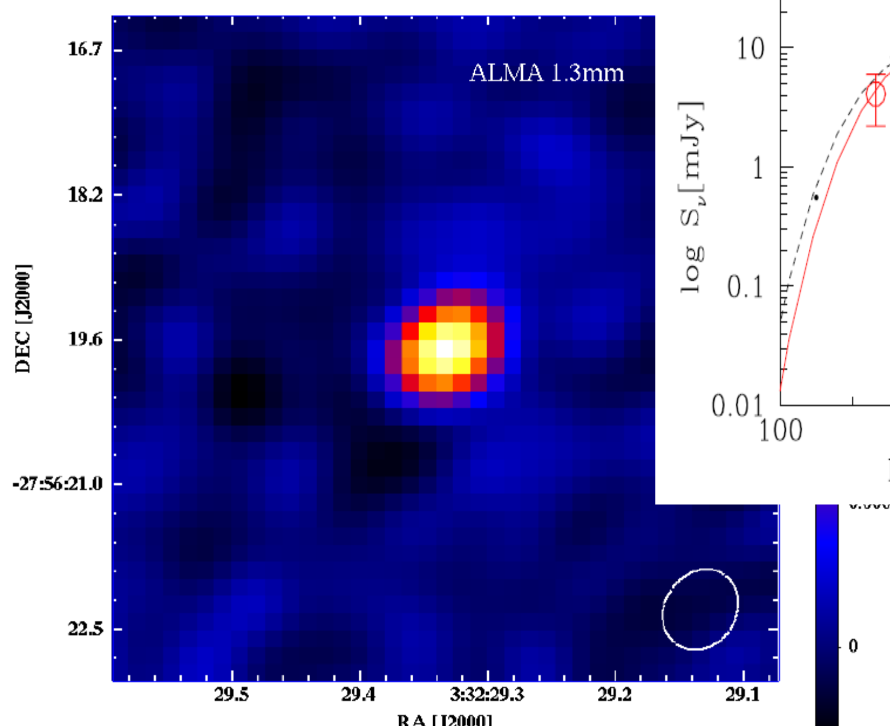
In highly obscured systems, only radio and mm-wave radiation can penetrate large columns of dust and gas and is the only tracer of the obscured regions of compact luminous infrared galaxies

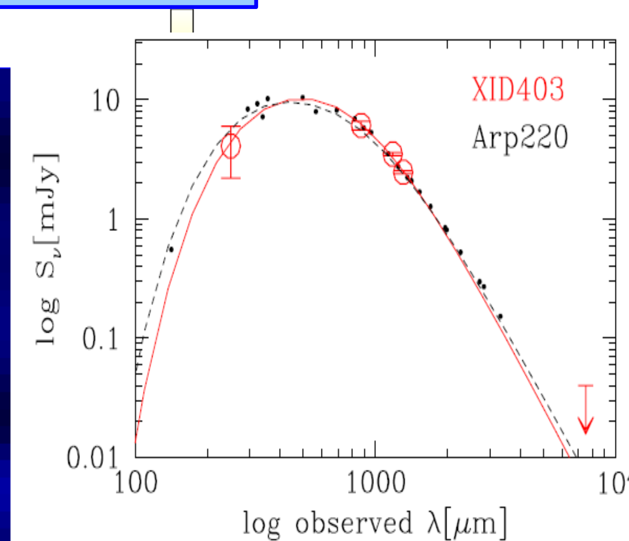
LESS J033229.4-275619: an obscured SMG at z = 4.76 (Gilli et al. 2013, Nagao et al. 2013, De Breuck et al. 2014)

- Band 6 - line
- 18 antennas,
- 3.6 hrs,
- 1.5'' res

- Band 6 -continuum
- 17 antennas,
- 23 min,
- 0.75'' res



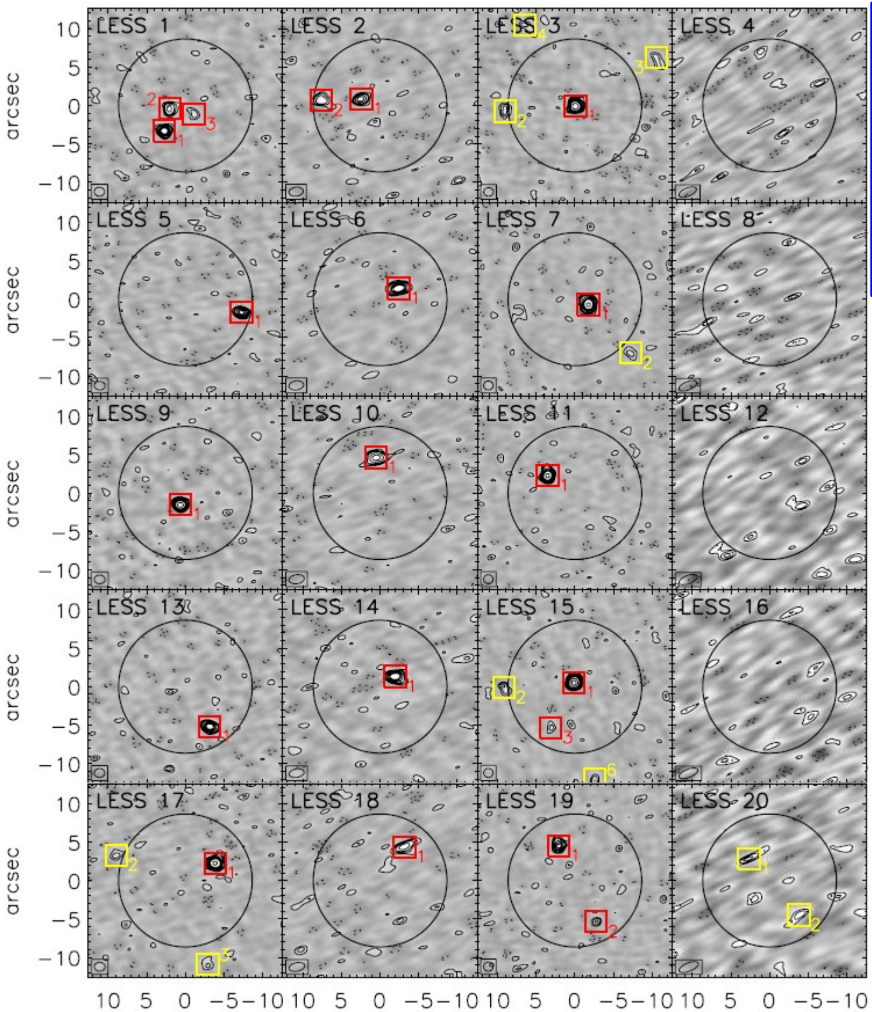




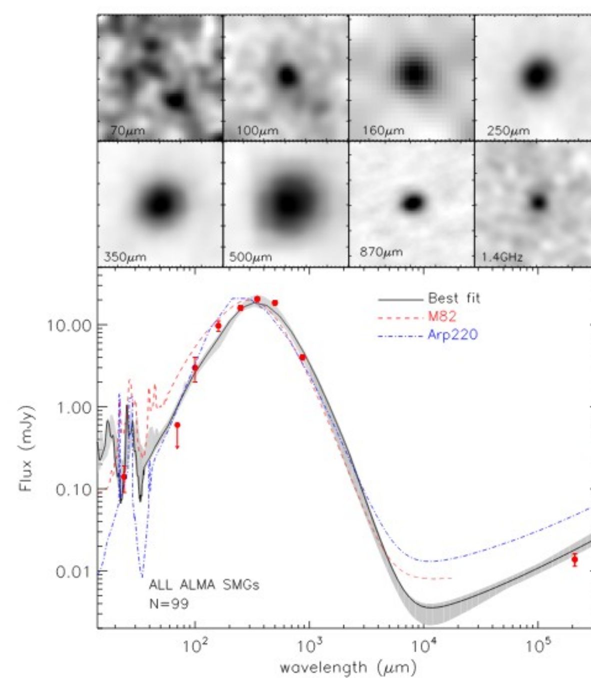
(sub)mm galaxy populations

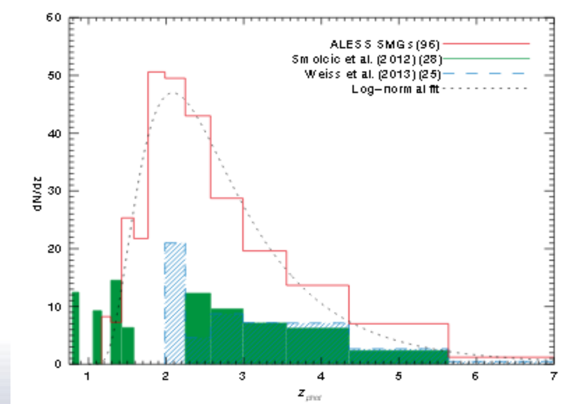
The power in the infrared is comparable to the power in the optical.
Locally, the infrared output of galaxies is only one third of the optical output.
This implies that **infrared galaxies grow more luminous with increasing z faster than optical galaxies.**
SMGs are the high redshift counterparts of local massive elliptical galaxies
(ULIRGs L_FIR>10^{12} L_sun), with AGN activity obscured by the high dust content.

An ALMA survey of submm in the Extended Chandra Deep Field South
Smail et al. 2015, Hodge et al 2013; Karim et al. 2013; Simpson et al. 2013, Swinbank et al. 2014….)

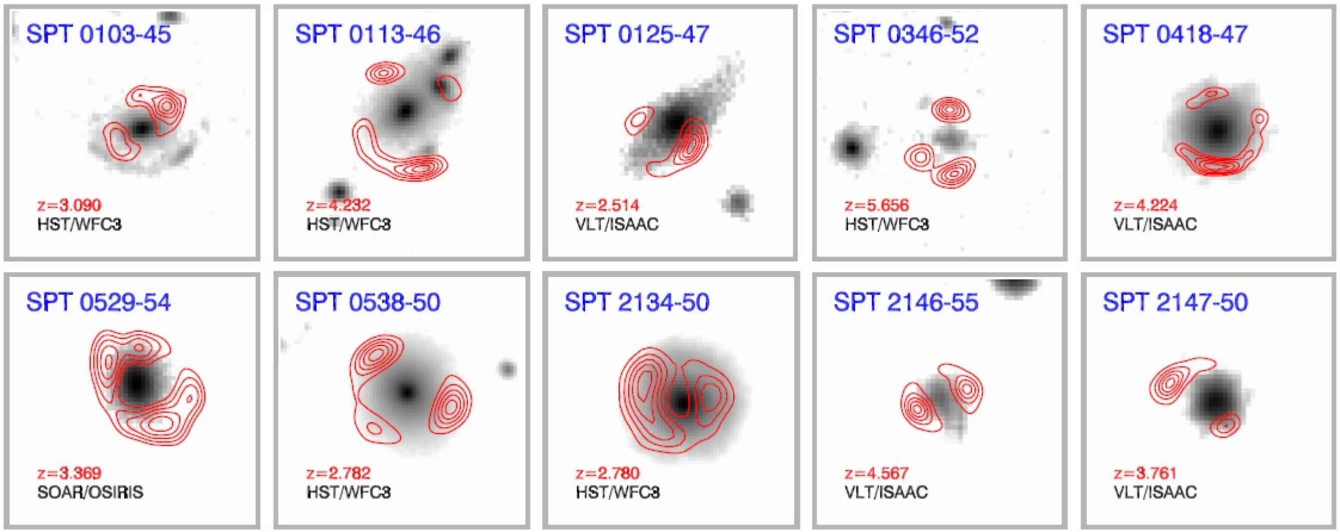


- 870 **μ**m (Band 7) follow-up of a LABOCA Extended Chandra Deep Field South Submm Survey (LESS)
- **122 submm sources**
- ~15 antennas, FOV = 17", **2 min/source**
- rms < 0.6 mJy/beam (**x3 deeper than LABOCA**)
- Resolution ~1.5" (**x10 better than LABOCA**)

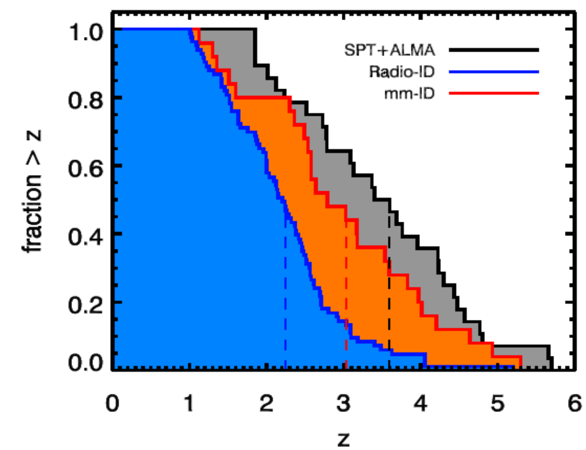


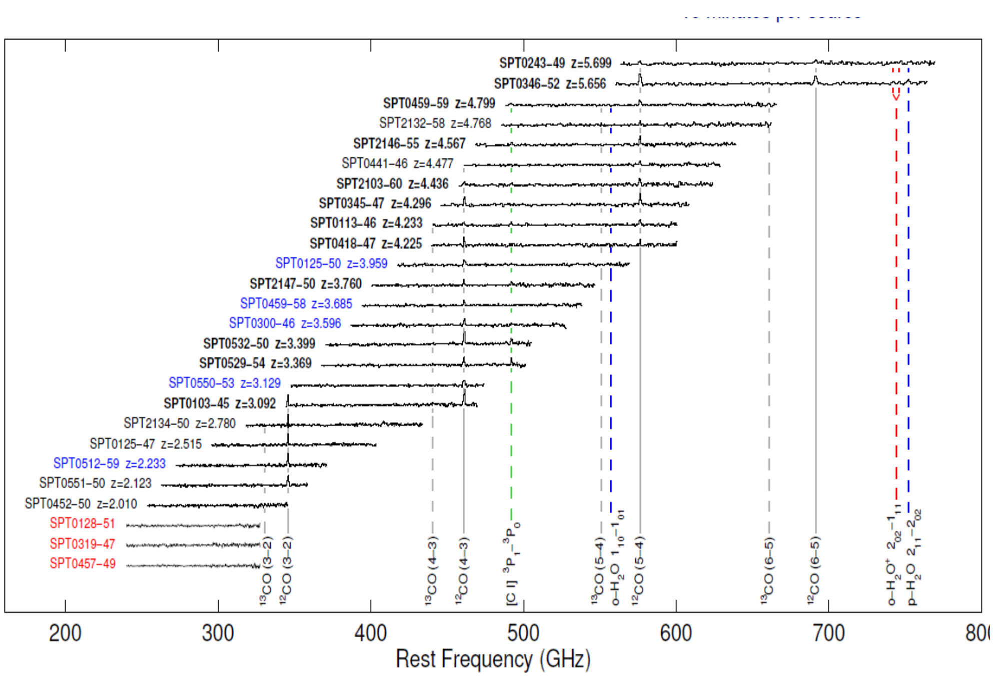


ALMA Observations of SPT Discovered, Strongly Lensed, Dusty, star-forming Galaxies(Hezaveh et al. 2013, Vieira et al. 2013, Spilker et al. 2014)



- ~15 antennas,
- ~4 hrs (~80 sec/source)
- Band 3 (spectroscopy)
- Band 7 (imaging)
- Resolution ~ 1.5''



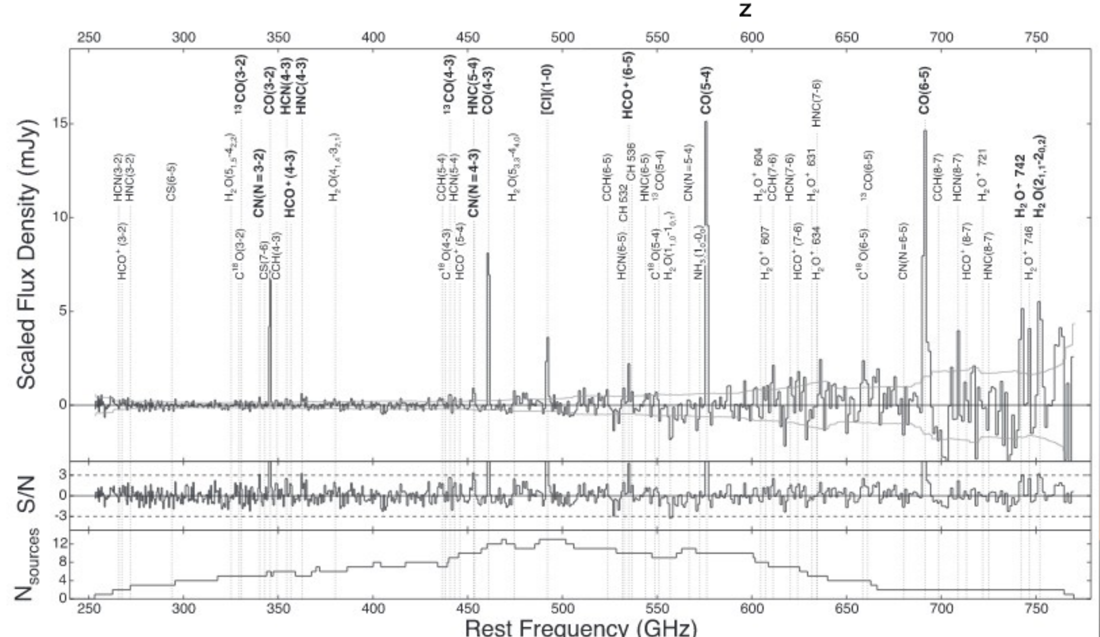


Bold = unambiguous redshift from ALMA

black = single lines with ALMA, confirmed with C+ or CO(1-0) with APEX or ATCA

blue = single line detected with redshift, most likely redshift from photo-z

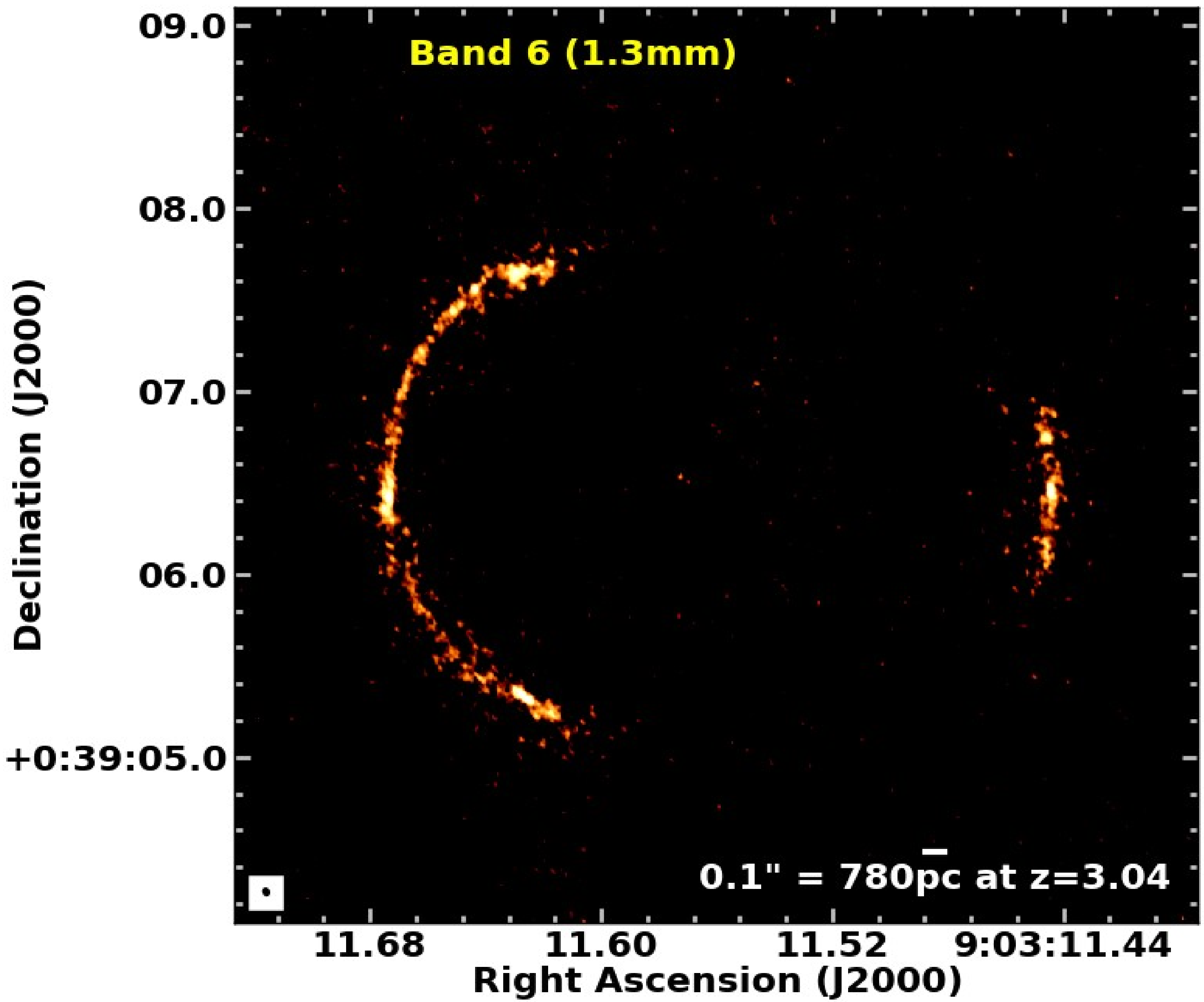
red = no line detected

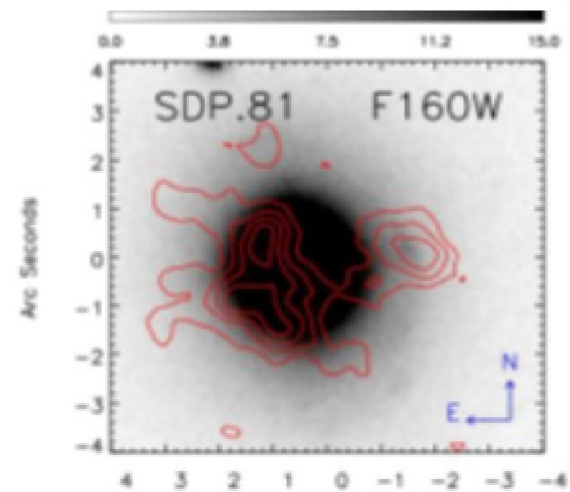


Sdp.81 (ALMA Partnership 2015)

Lensed submm galaxy at z=3.042 lensed by an elliptical galaxy at z=0.299

Resolution 60 x 54 mas, 39 x 30 mas and 31 x 23 mas in Bands 4, 6, and 7
(20-80x better than SMA and PdBI) corresponding to few tenth of pc in source plane

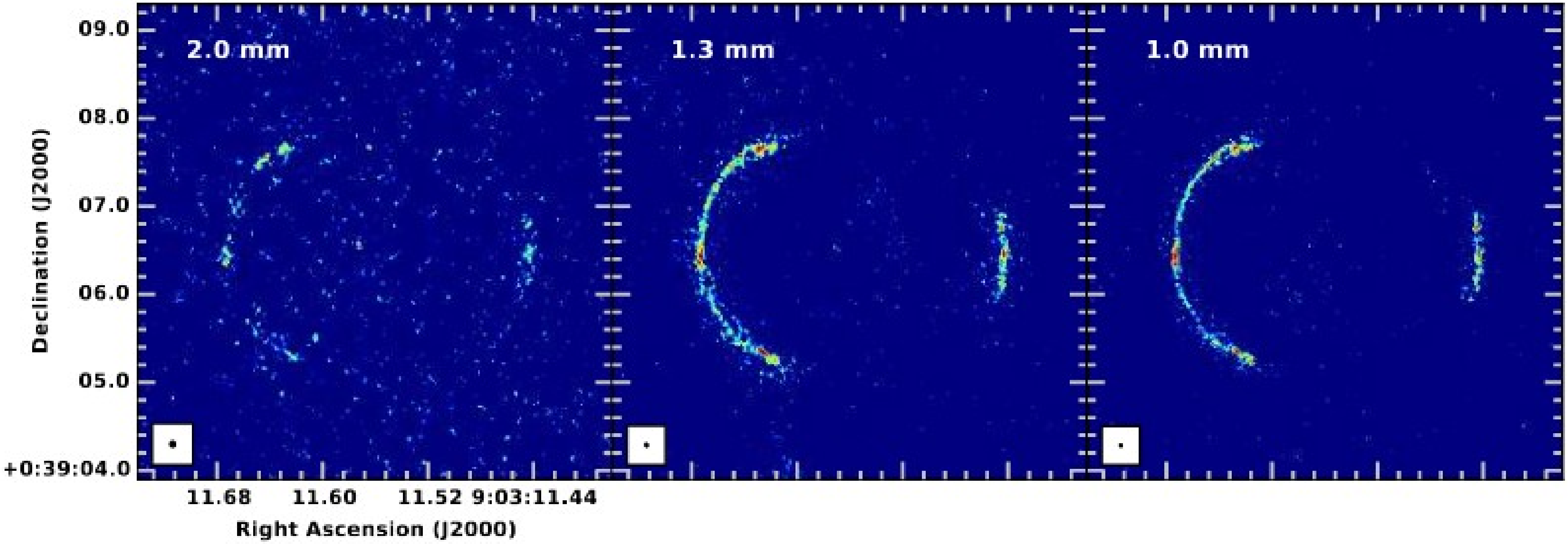




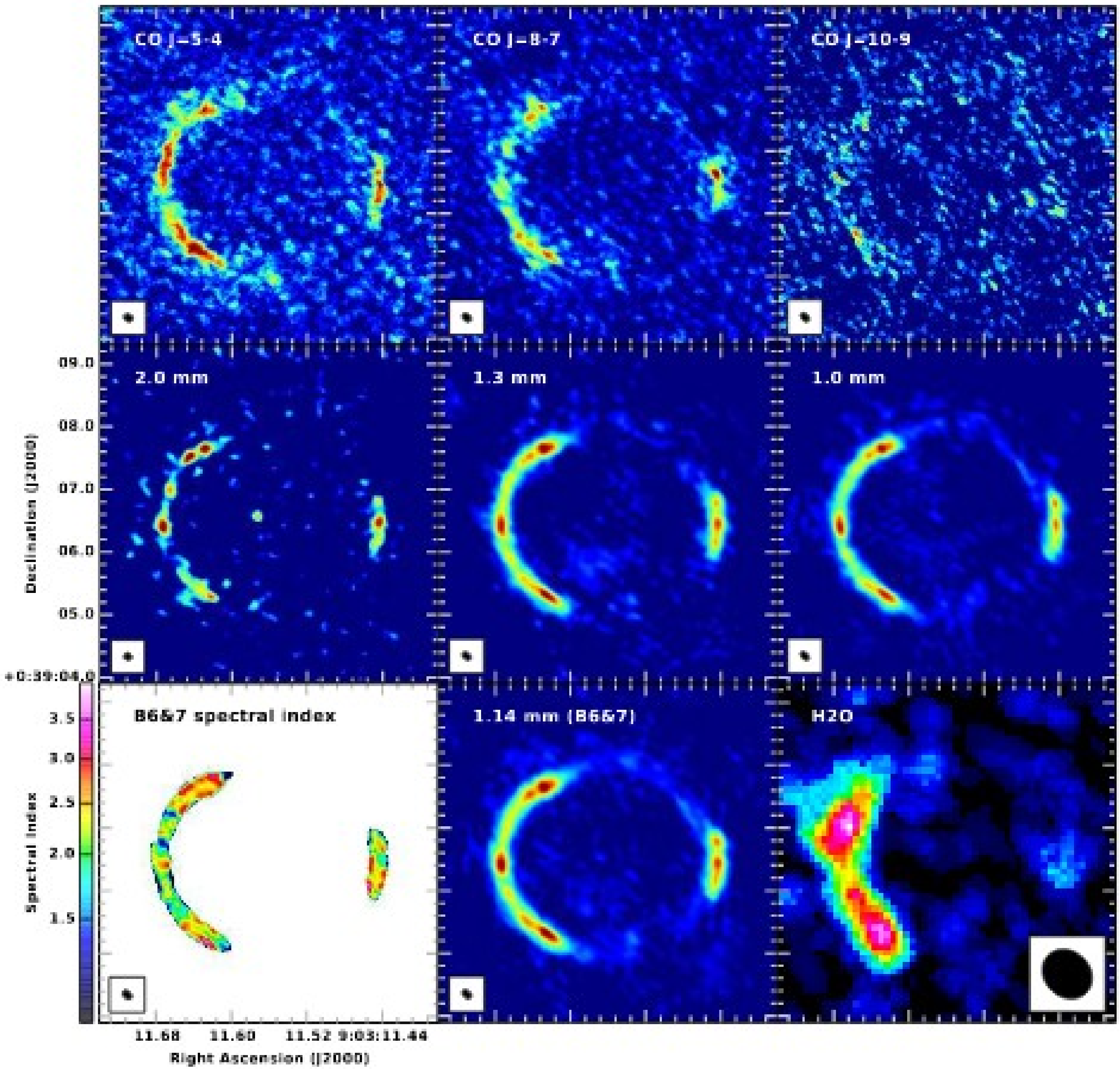
- Science Verification
- ~22-35 antennas,
- ~9-12hrs/band
- Band 4,6,7 (CO5-4. H2O, CO8-7, CO10-9)

Sdp.81 (ALMA Partnership 2015)

Continuum emission



Sdp.81 (ALMA Partnership 2015)



Conclusions

… and many many others....

Visit

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(for publications with ALMA data)

www.almatelescope.org

(for news and press releases)

www.almascience.eso.org

(for alma status, proposals, and archive mining)

www.alma.inaf.it

(for the Italian ARC)

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