ALMA Basics and Cycle 9 Capabilities

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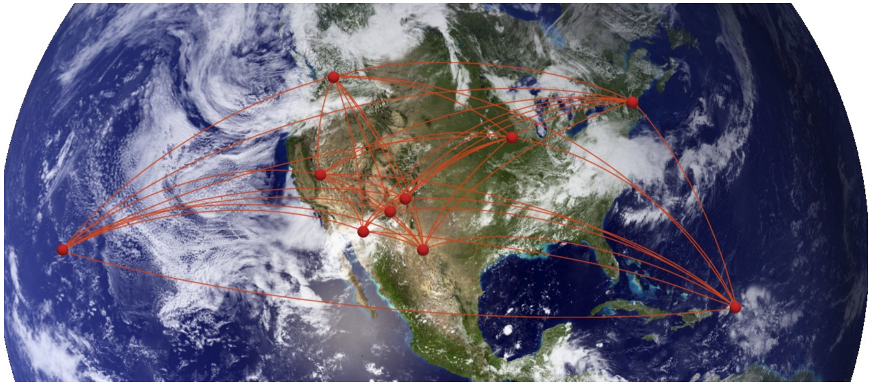
NRAO NSF AUI

National Radio Astronomy Observatory



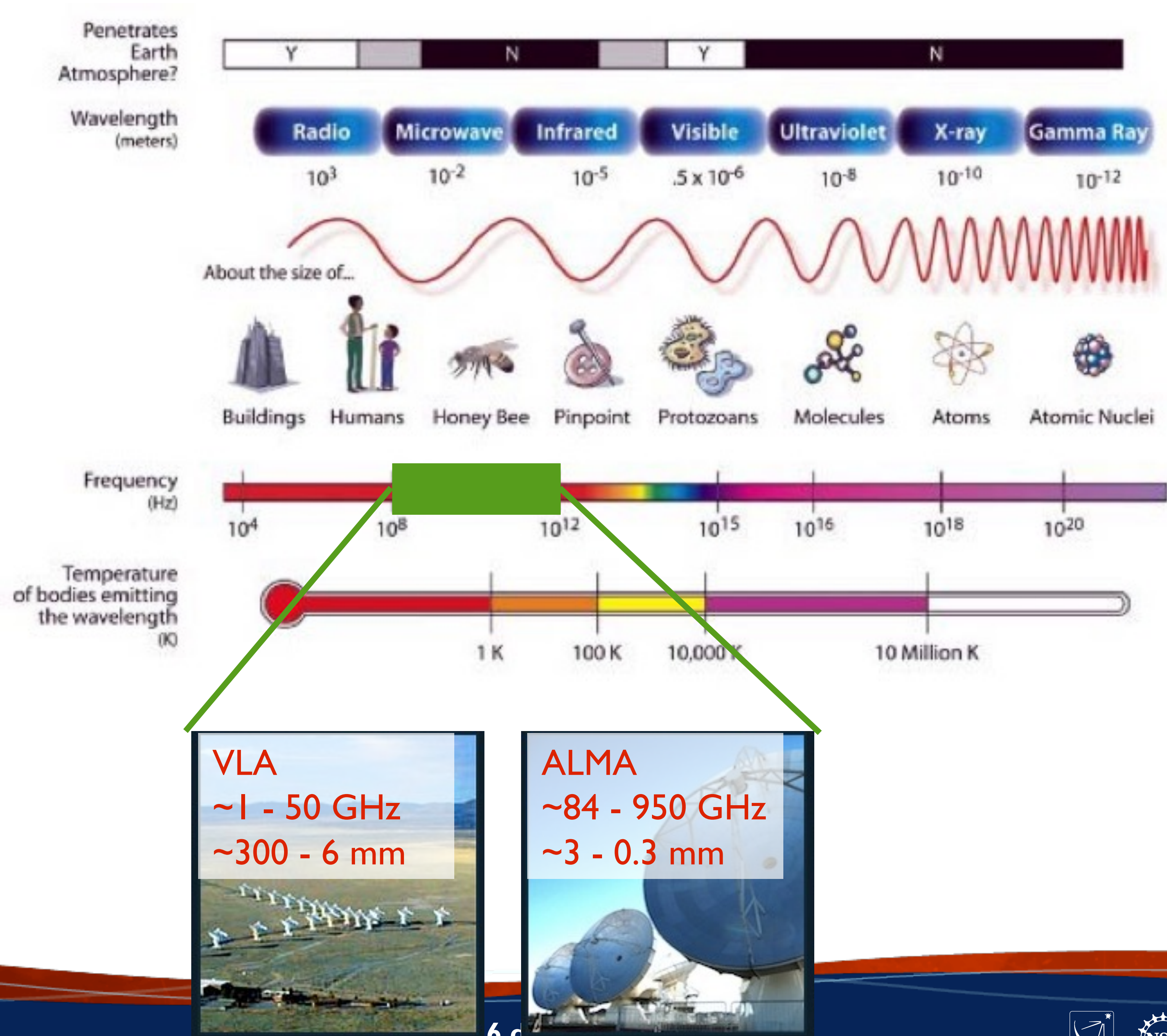
Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Very Long Baseline Array

NRAO:
One Observatory, Three World Class Facilities

Other Affiliated Telescopes and Observatories include the Green Bank Observatory (http://greenbankobservatory.org/). The VLBA was incorporated back into NRAO last year.

NRAO:
One Observatory, Three Facilities

Atacama Large Millimeter/submillimeter Array: a 66-antenna array in Chile


Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^{-2}
10^{-5}
$.5 \times 10^{-6}$
10^{-8}
10^{-10}
10^{-12}
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K
VLA
~1 - 50 GHz
~300 - 6 mm
ALMA
~84 - 950 GHz
~3 - 0.3 mm

Broad Science Topics with NRAO Telescopes

- Sun – coronal mass ejections, magnetic field activity
- Solar system, KBOs – atmospheres, astrometry, composition
- Star-forming regions – dust and gas environment, kinematics (infall, outflows, jets), proto-planetary disks, cores, chemistry, feedback, and natal cloud / star interactions
- Exoplanets – direct imaging, gaps in disks, kinematics
- Pulsars – neutron star physics, pulse morphology, gravity, ISM probe
- Galactic structure – spiral arms, bars, global atomic and molecular gas properties
- Nearby galaxies – molecular / atomic gas content and kinematics, dynamics of galaxies at high resolution, star formation, obscured SF, gas flow
- Galaxy groups and clusters – atomic and molecular gas across systems, star formation efficiency, kinematics, dynamical mass measurements
- Black holes – mass measurements, kinematics
- High redshift galaxies – extragalactic background light, source counts, star formation history and efficiency, evolution of gas content (atomic and molecular)
- Cosmology – H_0 measurement, SZE

What is ALMA?

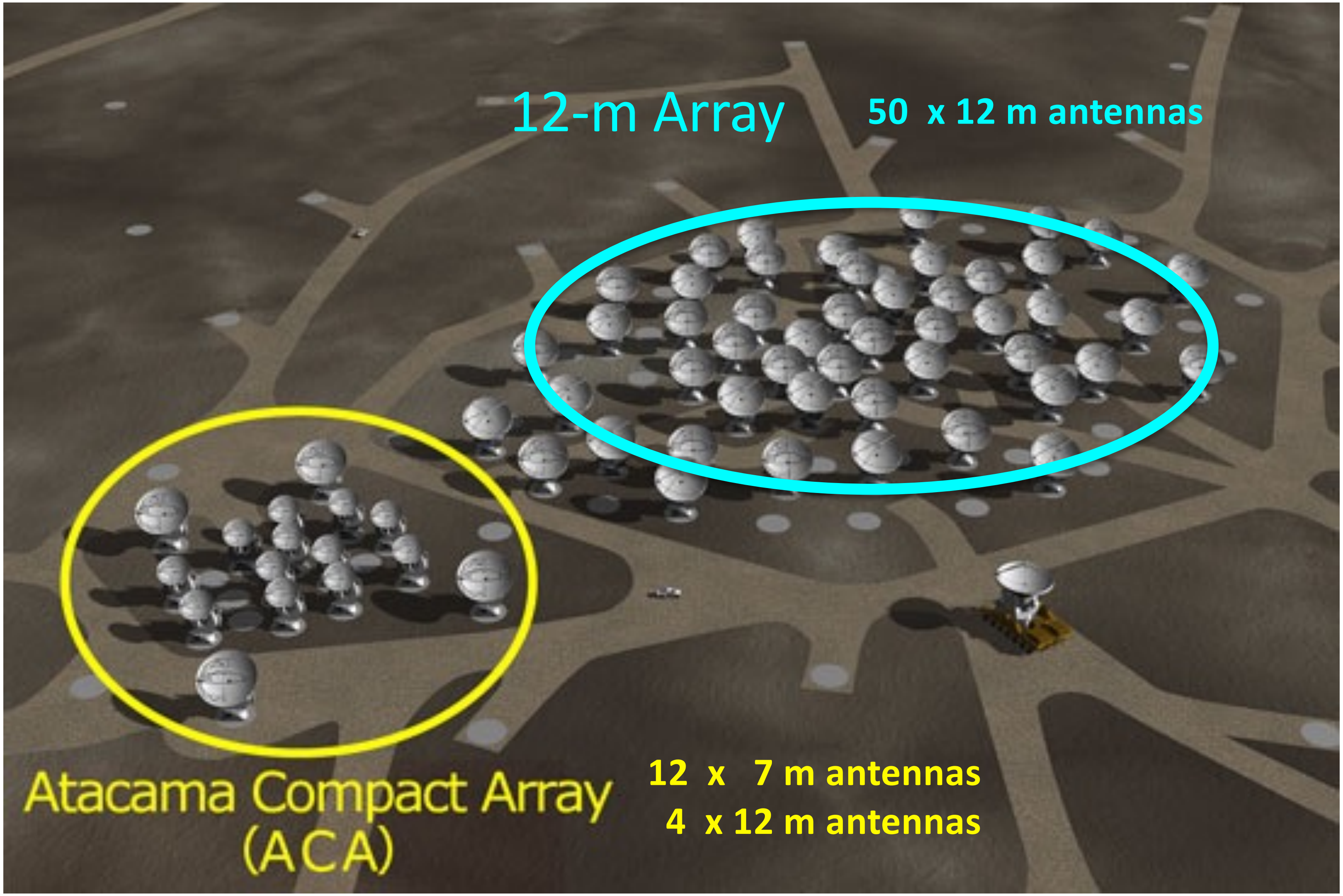
- 66 reconfigurable, high precision antennas

λ ~ 0.32 – 8.5mm.

- Array configurations between 150 meters and 16 kilometers: 192 possible antenna locations.

- Array Operations Site is located at 5000m elevation in the Chilean Andes.

- Provides unprecedented imaging & spectroscopic capabilities at mm/submm λ.


12-m Array
50 x 12 m antennas
Atacama Compact Array
(ACA)
12 x 7 m antennas
4 x 12 m antennas

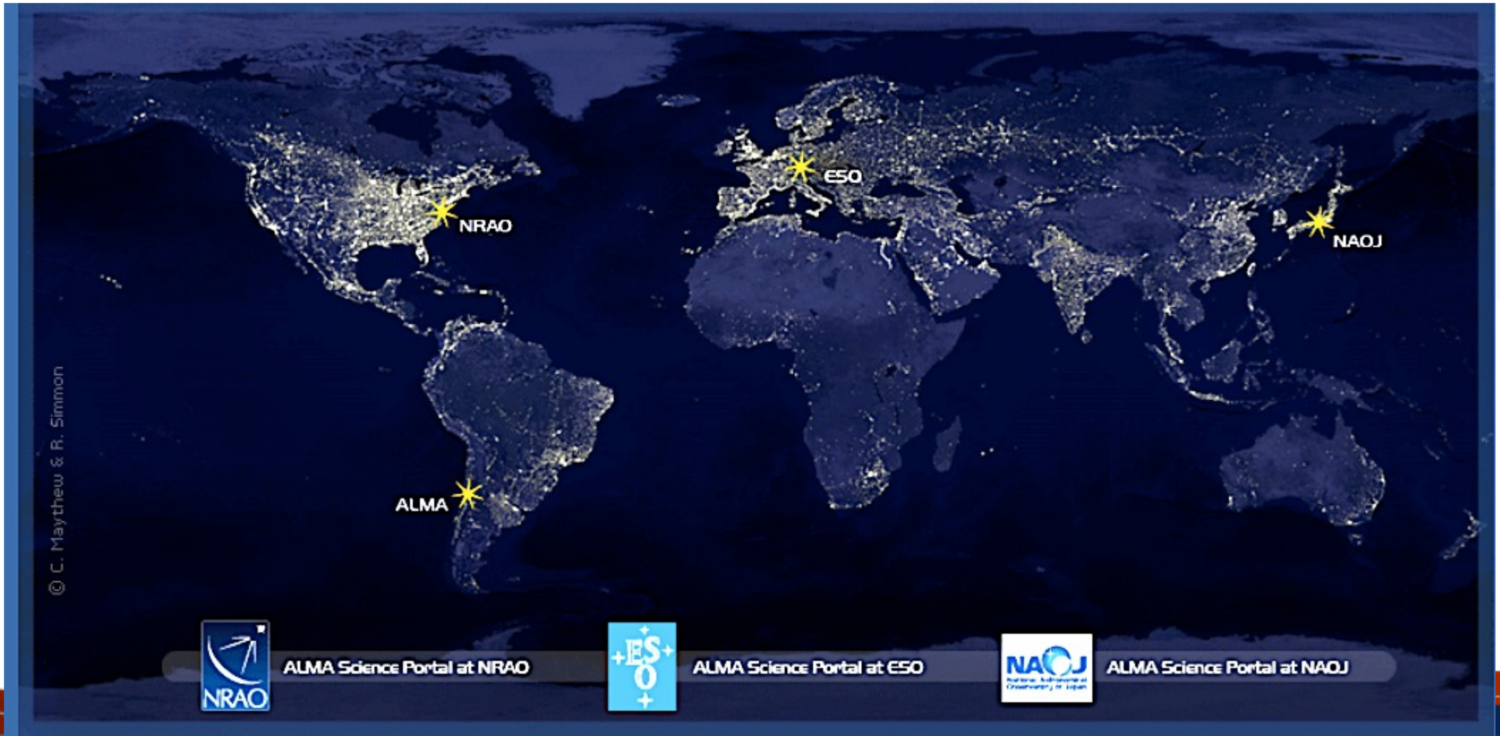
ALMA Operations

The Joint ALMA Observatory (JAO) is responsible for operations in Chile

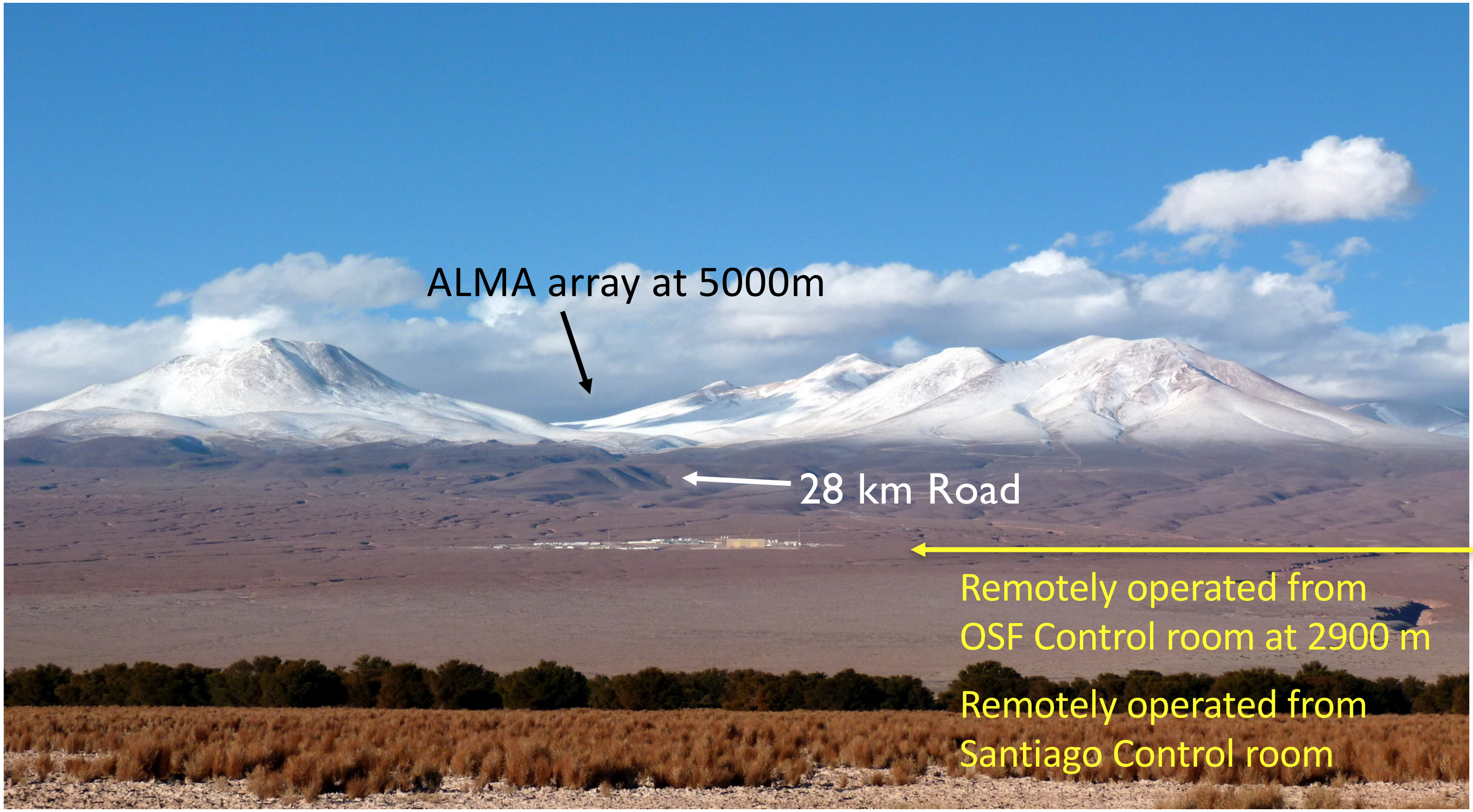
- Santiago Central Office
- Operations Support Facility (OSF)
- Array Operations Site (AOS)

ALMA User Support is centered at the ALMA Regional Centers:

- NA ARC – NRAO, NRC (NAASC)
- EU ARC + ARC Nodes (ESO …)
- EA ARC, ASIAA

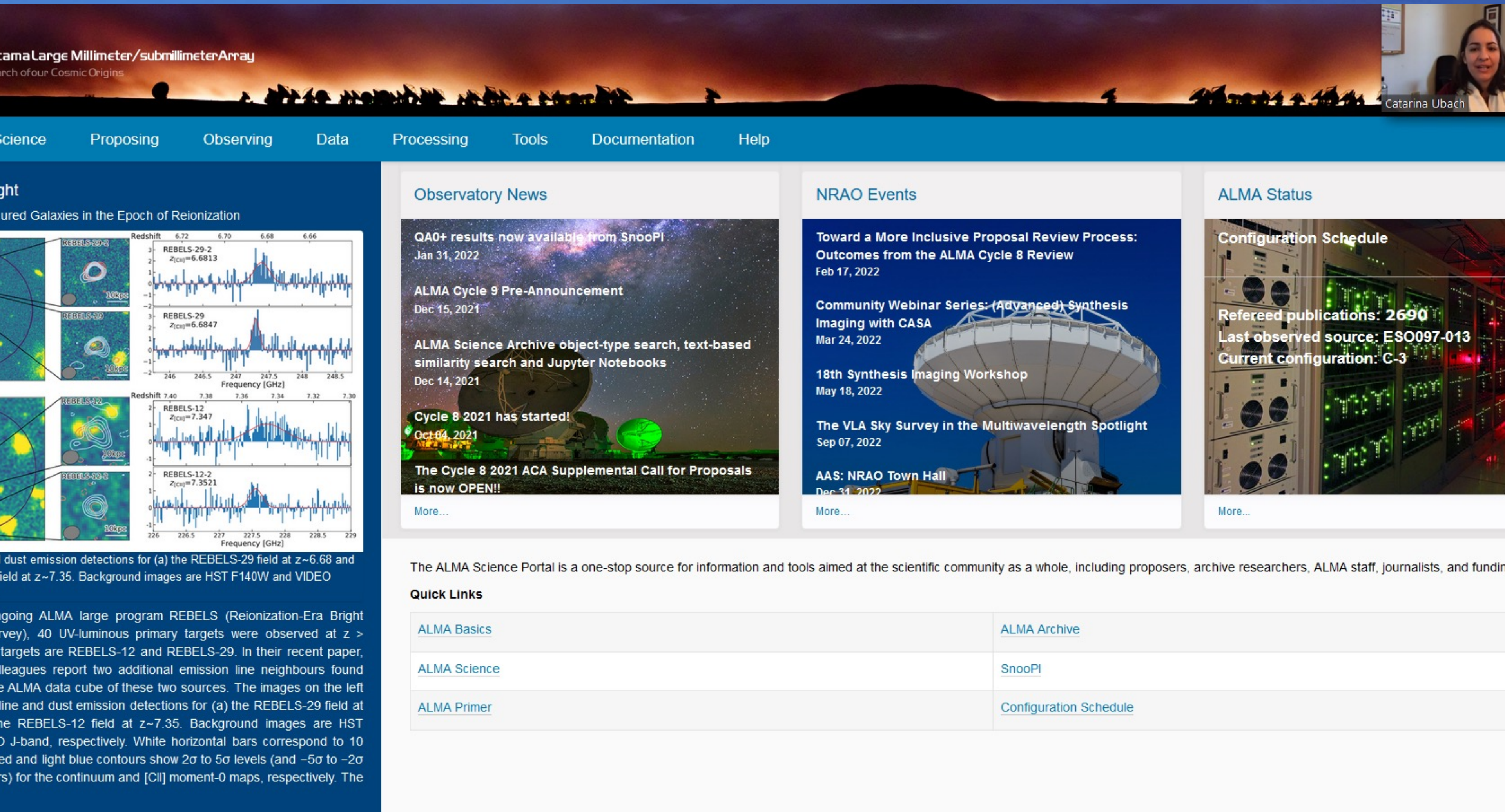


Remote Operation at the Operations Support Facility



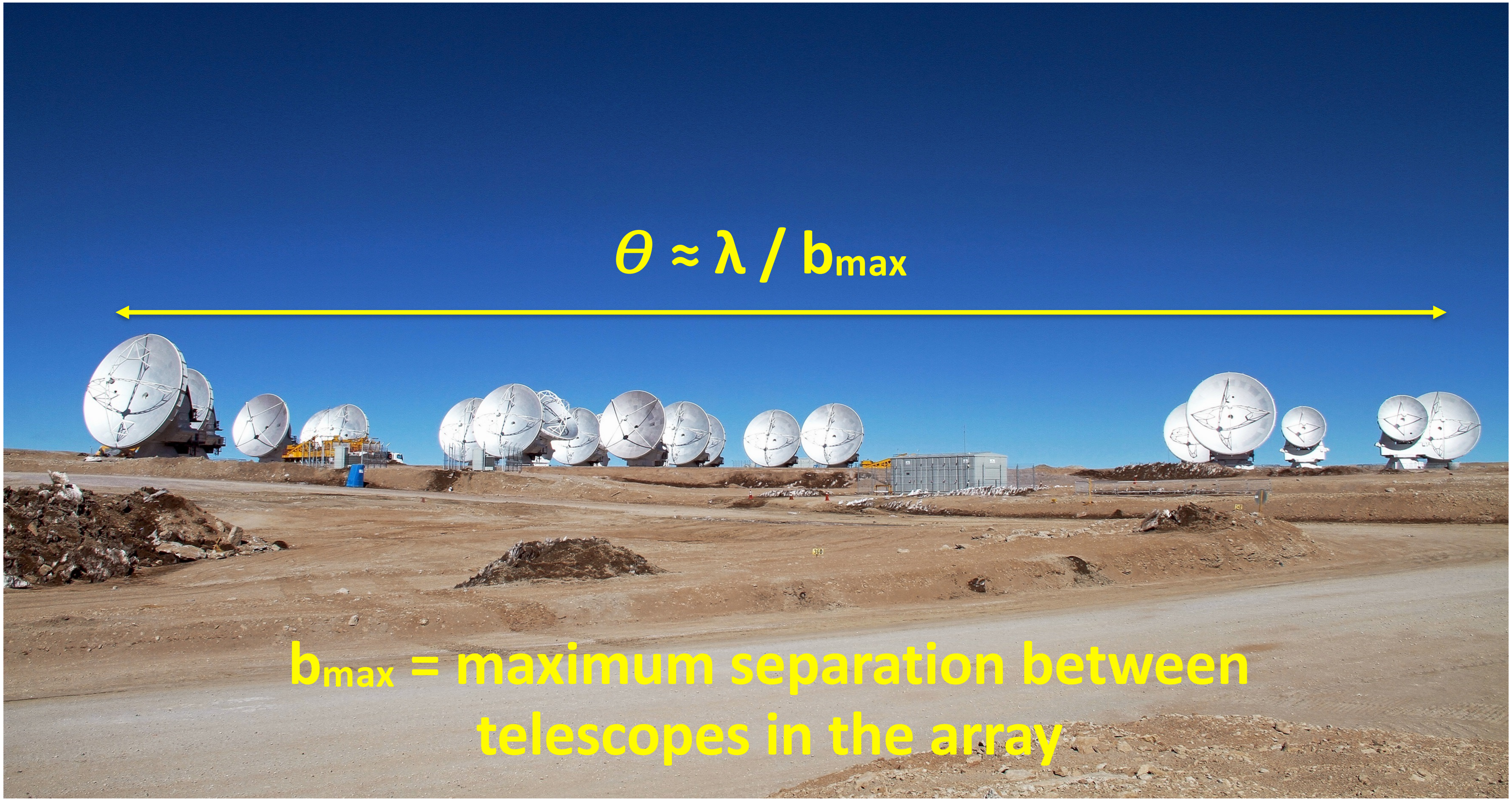
Array Operations Site

- 66 reconfigurable antennas
- Array configurations between 0.16 and 16 km

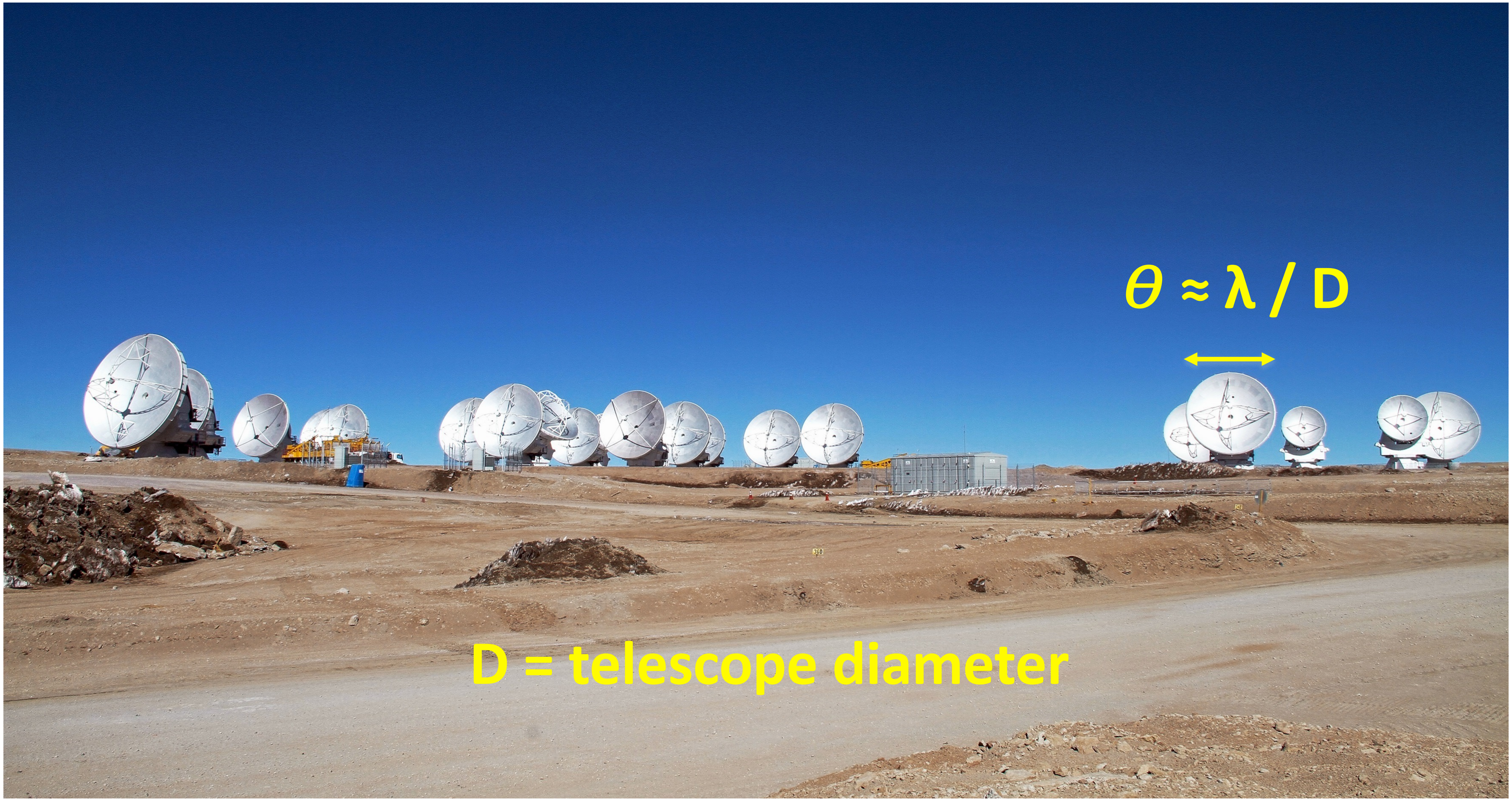


ALMA is a telescope for *all* astronomers

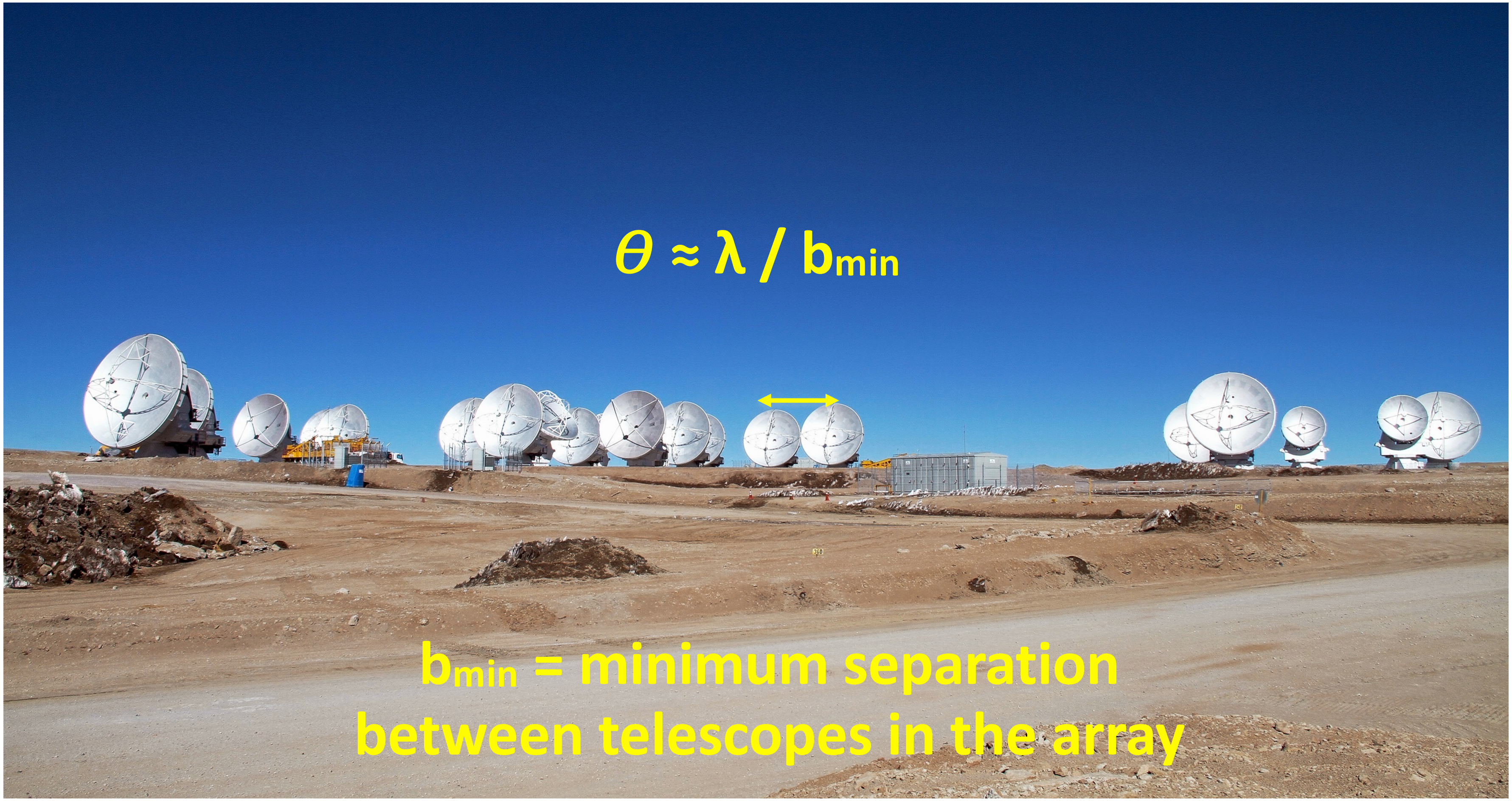
Angular Resolution



Field of View



Largest Angular Scale



Angular scales

Resolution

– given by the largest distance between antennas ($\sim\lambda / B_{max}$)

Field of view

– given by the diffraction limit of a single antenna ($\sim\lambda / D$)

– If source is larger than the field of view, then make a mosaic

Largest angular scale that can be imaged

– given by the shortest distance between antennas ($\sim\lambda / B_{min}$)

An interferometer is sensitive to a range of angular scales.

Observe in multiple configurations to decrease B_{min} and increase B_{max}.

$$\lambda / B_{max} < \theta < \lambda / B_{min}$$

ALMA in a Nutshell...

- Angular resolution down to 0.015” (at 300 GHz)
- Sensitive, precision imaging 84 to 950 GHz (3 mm to 320 µm)
- State-of-the-art low-noise, wide-band receivers* (8 GHz bandwidth)
- Flexible correlator with high spectral resolution at wide bandwidth
- Full polarization capabilities including circular.
- Estimated 1 TB/day data rate
- All science data archived
- Pipeline processing

ALMA is10-100 times more sensitive and has 10-100 times better angular resolution than current mm interferometers*

*With 90 Degree Walsh Switching in Bands 9 and 10, this gives 16 GHz of instantaneous bandwidth.

In either case, this is using the Time Division Mode (TDM) modes.

What is ALMA?

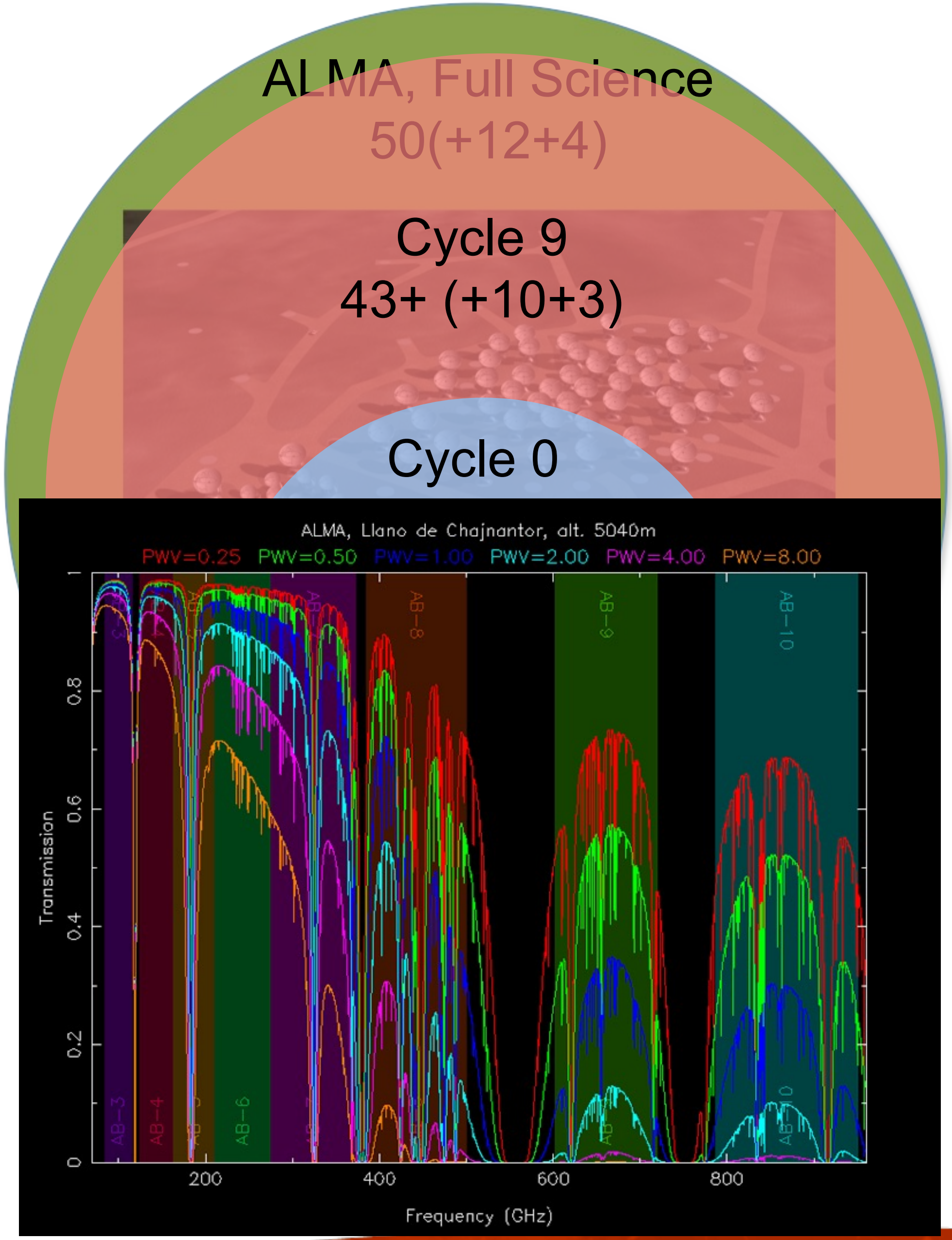
Collecting Area

Not only sensitivity but the collecting area (1.6 acres or 6600+ m2) + huge number of baselines provides excellent image fidelity

Spectral Coverage - Covers

ten atmospheric windows with 50% or more transmission above 35 GHz

https://almascience.nrao.edu/proposing/about-alma/atmosphere-model



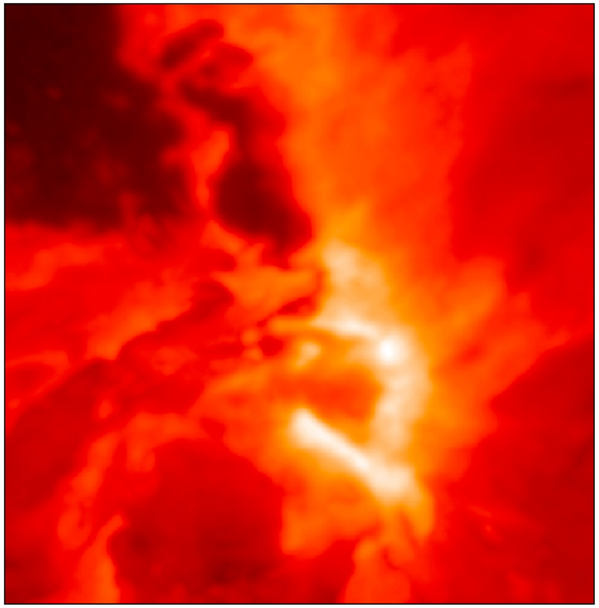
6 de Abril 2022

ALMA Current Status

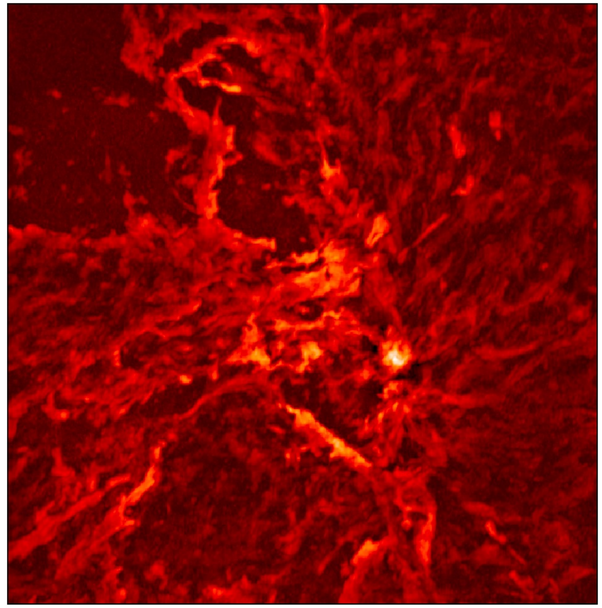
- Construction Project ended in September 2014
- Routine science observing has been out to **greater than 16 km baselines (C-10)** thanks to the highly successful Long Baseline Campaigns in 2014 and 2015
- **All 66 antennas accepted**
  - Currently all 66 antennas are at the high site (AOS), of which ~47 on average (up to max ~66) are being used for Cycle 9 observations
  - Some construction and verification items remain to be finished (e.g., wide-field polarization; various observing modes)
- The ACA (Atacama Compact Array) or Morita Array – up to 12x7m antennas and 4x12m antennas for TP observations – is currently being used for Cycle 7 observations
- More on Capabilities later…

Single dish + Interferometer

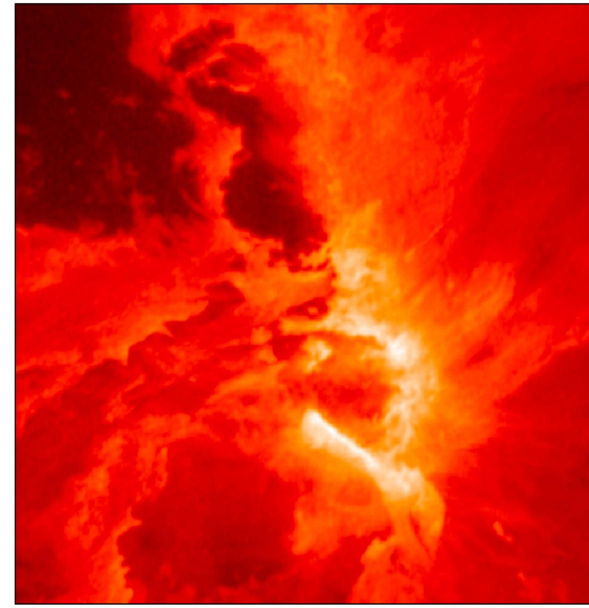
Single dish



Interferometer



Single dish + interferometer



Kong et al. (2018)

- 12m array reveals information on small spatial scales
- ACA reveals information on larger scales
- Combine both to recover small and large scales

Flux density and brightness temperature

$$S_\nu = \frac{2kT_B}{\lambda^2}\Omega$$

S_ν : flux density (Janskys) 1 Jansky = $10^{-26}\,\frac{\mathrm{Watt}}{\mathrm{meter}^2\ \mathrm{Hz}}$

Ω : solid angle of "beam" $\Omega = \frac{\pi\theta^2}{4\ln 2}$

T_B : Brightness temperature (Kelvin)

Sensitivity

$$\Delta S_\nu \propto \frac{k\ T_{sys}}{A\sqrt{N(N-1)\quad \Delta\upsilon \quad t_{int}}}$$

Kelvin-Boltzmann constant

System Temperature: product of sky and receiver

Area of 1 Antenna

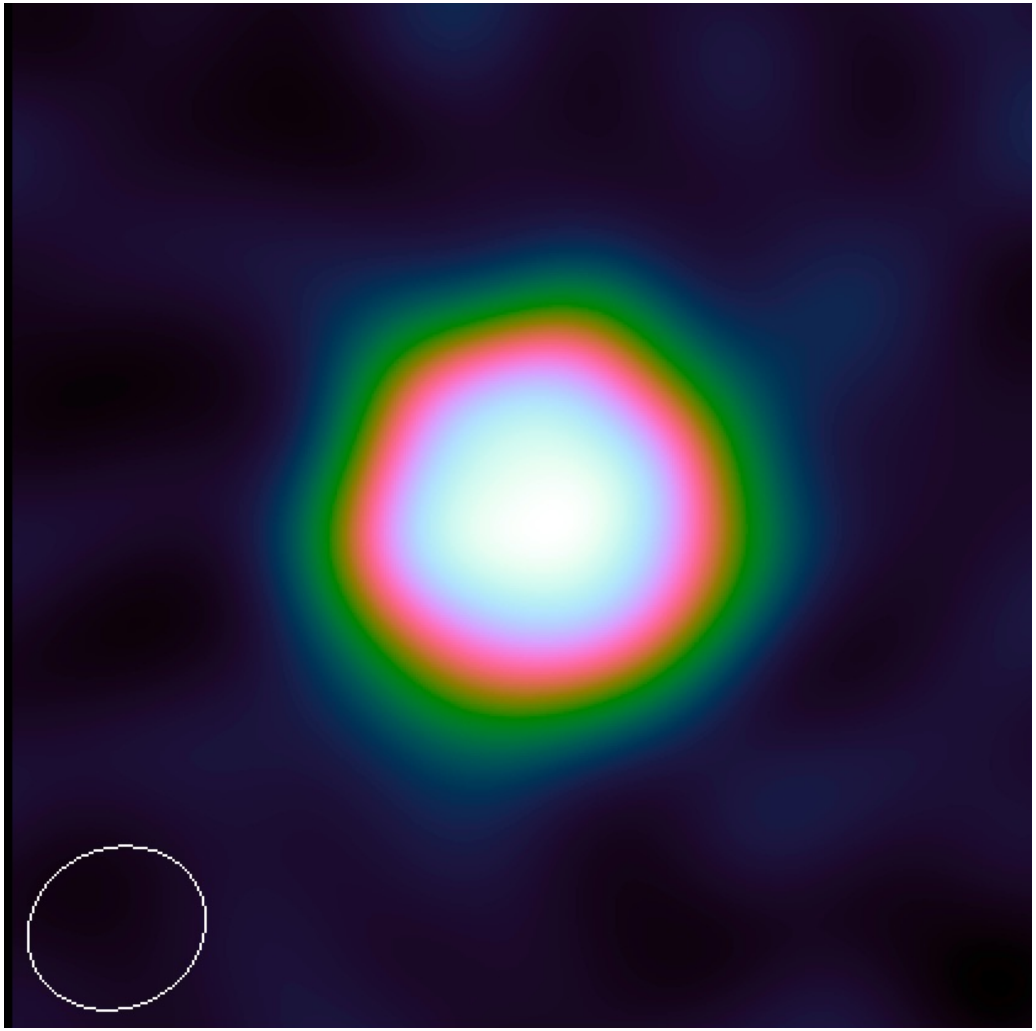
Number of Antennas

Frequency Resolution

Integration Time

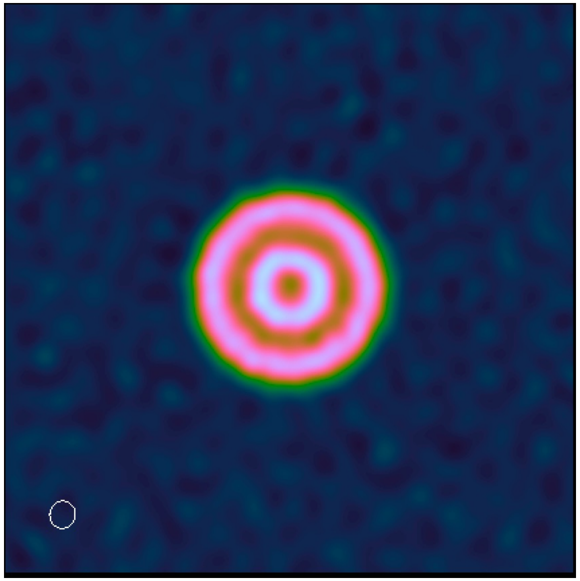
ΔS_ν : Independent of the angular resolution. However, $\Delta T_B \propto \frac{\Delta S_\nu}{\theta^2}$

Example: Imaging an extended source



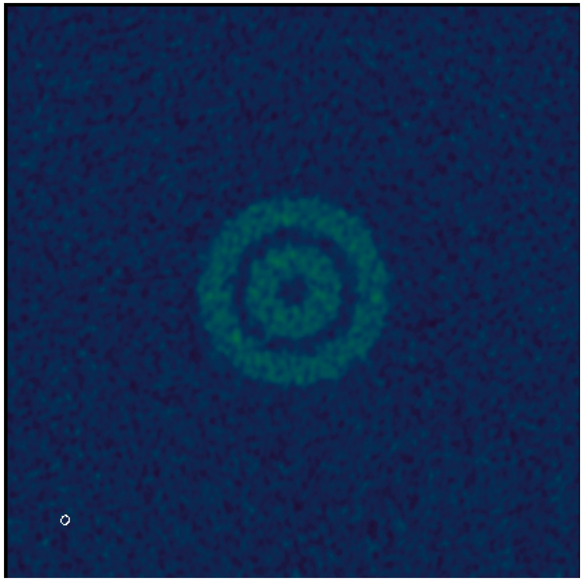
- Source diameter = 12”
- S_{tot} = 15 mJy

Example: Imaging an extended source



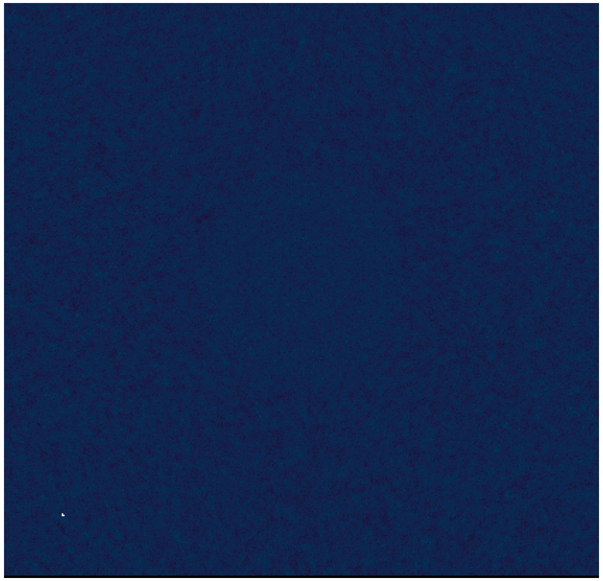
- Configuration 1 (3.5 h)
- θ = 1.7 arcsec @ 230 GHz
- ΔS_ν = 9.5 microJy / beam
- ΔT_B = 0.07 milliK

- $N_{beams} \sim (12/\theta)^2 \sim 50$
- $\langle S_\nu \rangle$ = 300 microJy / beam
- $\langle SNR \rangle \sim 32$



- Configuration 1 and 4
- θ = 0.52 arcsec
- ΔS_ν = 9.5 microJy / beam
- ΔT_B = 0.75 milliK

- $N_{beams} \sim (12/\theta)^2 \sim 532$
- $\langle S_\nu \rangle$ = 28 microJy / beam
- $\langle SNR \rangle \sim 3$



- Configuration 1, 4, and 8
- θ = 0.086 arcsec
- ΔS_ν = 9.5 microJy / beam
- ΔT_B = 27 milliK

- $N_{beams} \sim (12/\theta)^2 \sim 19000$
- $\langle S_\nu \rangle$ = 0.8 microJy / beam
- $\langle SNR \rangle \sim 0.1$

ALMA Cycle 9 Capabilities

ALMA in Cycle 9

- **In Cycle 9, the following technical capabilities will be available for the first time:**
  - **Fast Regional Mapping (FRM) for Solar Total Power observations.** The size of the field of view for Solar Total Power observations can be changed by PI.
  - **Spectral line Very Long Baseline Interferometry (VLBI).** This capability is offered in Band 3 only, in conjunction with the Global Millimeter VLBI Array (GMVA).
  - **Submillimeter VLBI.** A continuum VLBI capability will be offered for the first time in Band 7 (0.87 mm) in conjunction with the Event Horizon Telescope (EHT).
  - **Longer baseline high-frequency observations:** Band 8 up to C-10, Band 9 up to C-9, and Band 10 up to C-8. The band-to-band (B2B) calibration mode may be triggered for long baseline high frequency observations in order to find a suitably close and strong calibrator. Some science targets, particularly at the highest frequencies and longest baselines, may NOT BE POSSIBLE even with B2B (see Appendix 9.6 of the PG).
    - ***The total time allocated to projects requiring band-to-band calibration techniques may be limited to 45 hours. For more information about band-to-band calibration see Section 4.2 of this document or Section 10.5.3 of the Technical Handbook.***

ALMA Capabilities – NEW!!!

Band-to-Band calibration

- For observations in Band 7 and higher, observations requiring C-8 to C-10 may require Band-to-Band (B2B) calibration in order to find a nearby and sufficiently bright phase calibrator to ensure phase calibration quality. The ALMA Observing Tool will automatically check the availability of suitable phase calibrators during proposal validation and will automatically trigger the B2B mode where required.
- B2B observations are subject to the availability of suitable calibrators as checked by the ALMA-OT. Some science targets, particularly at the highest frequencies and longest baselines, may not be possible even with B2B. See Chapter 10 of the Technical Handbook.
- ***A maximum of 45 hours of Cycle 9 observing time will be available for observations requiring the B2B calibration mode.***

ALMA Capabilities

- **The Cycle 9 capabilities are fully described in Appendix A of the ALMA Proposers Guide available at https://almascience.nrao.edu/documents-and-tools. In summary:**
- **Number of antennas**
  - At least forty-three (43) antennas in the 12-m Array
  - At least ten (10) 7-m antennas (for short baselines) and three (3) 12-m antennas (for making single-dish maps) in the ACA
- **Receiver bands**
  - Receiver Bands 3, 4, 5, 6, 7, 8, 9, and 10 (wavelengths of about 3.1, 2.1, 1.6, 1.3, 0.87, 0.74, 0.44, and 0.32 mm, respectively)
- **12-m Array Configurations**
  - Cycle 9 includes configurations C-1 through C-10.
  - Maximum baselines between 0.16 km and 16.2 km depending on array configuration and subject to the following restrictions:
    - The maximum possible baseline for Bands 3, 4, 5, 6, 7, and 8 is 16.2 km.
    - The maximum possible baseline for Band 9 is 13.9 km.
    - The maximum possible baseline for Band 10 is 8.5 km.
  - Files containing ***representative*** antenna configurations for the 12-m and 7-m arrays suitable for Common Astronomy Software Applications (CASA) simulations are available from the ALMA Science portal (http://almascience.org/documents-and-tools/cycle8/alma-configuration-files)

ALMA Capabilities

- **Spectral line, continuum, and mosaic observations**
  - Spectral line and continuum observations with the 12-m Array and the 7-m Array in all bands
  - Single field interferometry (all bands) and mosaics (Bands 3 to 9) with the 12-m Array and the 7-m Array
  - Single-dish spectral line observations in Bands 3 to 8
- **Polarization**
  - Single-pointing, on-axis, full linear and circular polarization for both continuum and full spectral resolution observations in Bands 3 to 7 on the 12-m Array. The field of view of linear and circular polarization observations is limited to the inner one third and the inner one tenth of the primary beam, respectively.
  - Mosaicking of continuum linear polarization observations (Bands 3 to 7).
  - Up to a total of 75 hours of full polarization observations of a single field with the 7-m Array in stand-alone mode at the Main Call only (Bands 3 to 7).
    - Note that combined 7-m Array and 12-m Array polarization observations are not supported this cycle.

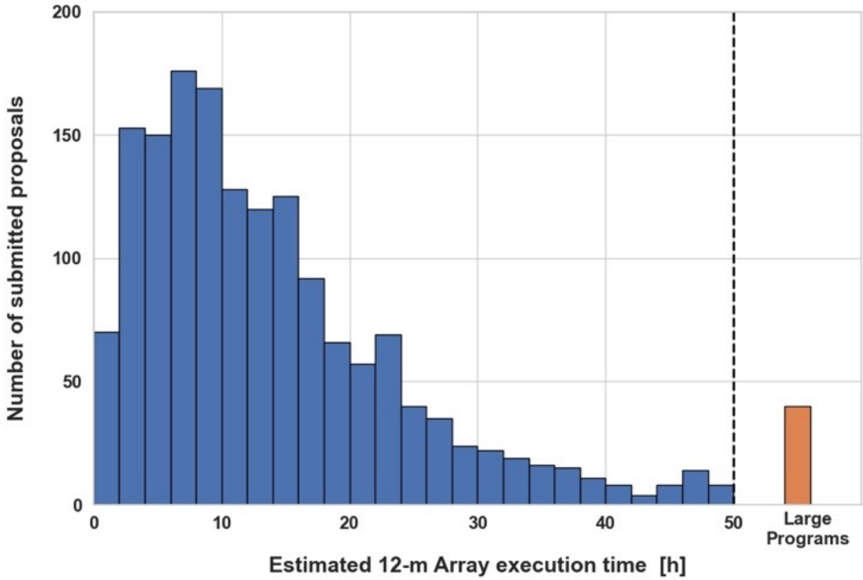
ALMA Capabilities

- **Observing Time:**
  - 4300 hours on the 12-m Array and 4300 hours on the Atacama Compact Array (ACA), also known as the Morita Array, for successful proposals in Cycle 9 (includes DDT, previous cycle Carryover and resubmissions)
  - Cycle 9 will not have a Supplemental CfP for stand-alone ACA observations. The community is encouraged to submit ACA projects in the LST range of 20h to 10h for the April 2022 deadline.
- **Observing Time (other notes):**
  - Proposals requesting more than 50 hours (Large Programs), will have priority to fill at least 10% of the observing queue (see Section 1.4 of the PG).
  - There is no longer a cap on the total time that can be allocated to Large Programs.
  - However, Large Programs will not be allowed to exceed 50% of the available time for a given LST range in any of the Cycle 9 configurations.

ALMA Capabilities

"Also encourage "medium size" proposals between 25 – 50 hours.

- But ALMA doesn't accept long proposals. I have a better chance of submitting a shorter proposal because it will be accepted, right?!?!?
- **WRONG!!!!**



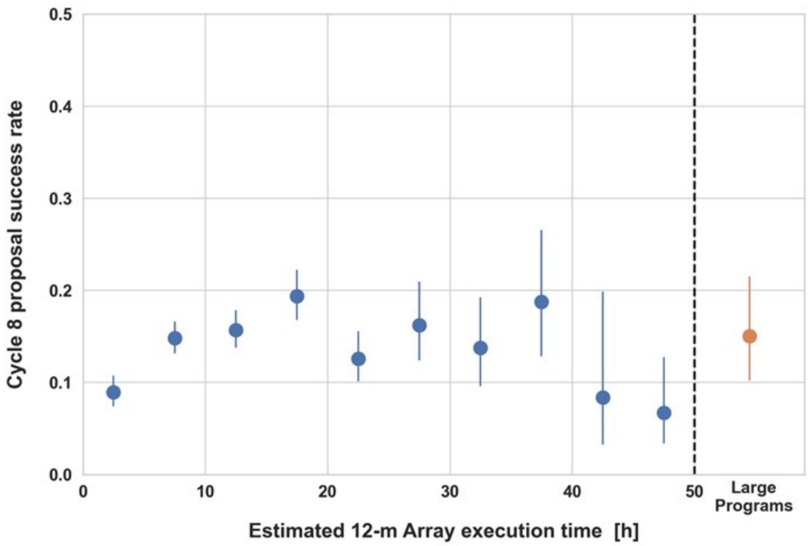


Figure 1: (Left) Number of proposals submitted as a function of the 12-m Array execution time in Cycle 8. (Right) The fraction of proposals (with 1sigma confidence intervals) that are assigned priority Grade A or B as a function of the estimated 12-m Array time.

ALMA Capabilities

ACA Supplemental Call:

- In Cycle 8, 2021 ALMA will offer a stand-alone ACA Supplemental Call for Proposals.
- The Supplemental Call will open on 08 September 2021 and the proposal deadline will be on 06 October 2021.
- Observations from the Supplemental Call will be scheduled from January 2022 to September 2022.
- The anticipated amount of time available will be announced in the Call. While stand-alone ACA proposals accepted from the Main Call may be assigned priority "A", "B", or "C", all accepted proposals from the Supplemental Call will be assigned priority "C".
- More information about the supplemental call can be found at: https://almascience.nrao.edu/proposing/7m-array-supplemental-call

NOT PLANNED FOR CYCLE 9!!!

Dual-Anonymous Proposal Review

- Proposals in Cycle 9 will implement a dual-anonymous process for proposal reviews. While proposers will still enter their names and affiliations in the Observing Tool, their identities will be concealed from the reviewers.
- **It will be the responsibility of the investigators to write their proposals such that anonymity is preserved.**
- Guidelines on how to prepare such proposals is available now in an ALMA Science Porta news item and, later, in the CfP - https://almascience.nrao.edu/news/items-for-planning-cycle-8-proposals.

Distributed Peer Review Process

- ALMA will adopt a distributed peer review process for scientific review of most proposals submitted to Cycle 9 2021.
- Distributed peer review will be used for all proposals requesting less than 50 hours on the 12-m Array, and ACA stand-alone proposals requesting less than 150 hours on the 7-m Array.
- In this review system, for each submitted proposal the PI (or one of the delegated co-Is) will be responsible for reviewing up to 10 other submitted proposals, thus increasing the involvement of the ALMA community in the review process.
- Large proposals will be reviewed by science review panels, as in previous cycles.
- **NOTE: Go to the Science Portal NOW! Log in and edit your preferences. That is how the distributed peer review will know how to assign projects – based on your area of selected expertise!**

ALMA Capabilities

Standard vs Non-Standard modes??? (STILL) GONE!

- Unlike in previous cycles, there will no longer be a distinction between standard and non-standard modes so… there is no more 20% cap on the time request for non-standard modes!!!
- Proposal types in Cycle 9 will include Regular, Very Long Baseline Interferometry (VLBI), Phased Array, Target of Opportunity, and Large Programs. VLBI proposals work in concert with the Global mm-VLBI Array (GMVA) or the Event Horizon Telescope (EHT).
- GMVA programs must also submit a proposal to the GMVA by its 1 February 2022 deadline. Additional information about proposing with ALMA using the GMVA was made available in the GMVA Call for Proposals in early January 2021.

However, Large Program Observing Modes will STILL be restricted. They CANNOT include:

- Time Critical or ToO Observations
- Full Polarization observations
- Solar observations
- VLBI or Phased Array observations
- Non-standard calibrations (user-defined calibrations selected in the OT)
- Bandwidth switching projects (having less than 1 GHz aggregate bandwidths over all spectral windows)
- Band-to-Band calibration projects
- Astrometric Observations
- **NOTE: Contact your local ARC for support NOW to help with preparing your large programs. The ARCs have both proposal preparation and data processing support available for your large programs. Review the documentation off the science portal on how to prepare “value added” data products.**

ALMA Capabilities

Full ALMA Operations (All Cycle 9 Capabilities plus):

- **Receiver bands**:
  - Include Bands 1 and 2
    - Band 1 summary report from 2019 June - https://zenodo.org/record/3240351.
    - Full ALMA Band 1 Science Case: http://arxiv.org/abs/1310.1604
    - Band 2 summary report from 2019 June - https://zenodo.org/record/3240407
- **Baselines:**
  - All observing bands out to 16 km.
- **Observing Time:**
  - Up to 4500 hours+ for successful proposals of PI programs expected on the 12m Array (includes DDT, Cycle 8+ Carryover and resubmissions)
- **Observing Modes:**
  - Full operations include full Stoke plus circular polarization at all observing bands including mosaics and Total Power

ALMA Timelines and Milestones

The ALMA Cycle 9 Timeline

Date	Milestone
24 March 2022	Release of Cycle 9 Call for Proposals, Observing Tool, and supporting documents, and opening of the Archive for proposal submission
21 April 2022 (15:00 UT)	Proposal submission deadline for Cycle 9 Call for Proposals
1 June 2022 (15:00 UT)	Deadline to submit reviews for the distributed peer review system
August 2022	Announcement of the outcome of the proposal review process
1 October 2022	Start of ALMA Cycle 9 Science Observations
30 September 2023	End of ALMA Cycle 9

WARNING!!!!

THERE IS NO SUCH THING AS A "LATE" PROPOSAL

"My internet is down…"

"My proposal won't validate…"

"My power went out…"

"I thought the time was 16UT not 15UT…"

"My dog at my proposal…"

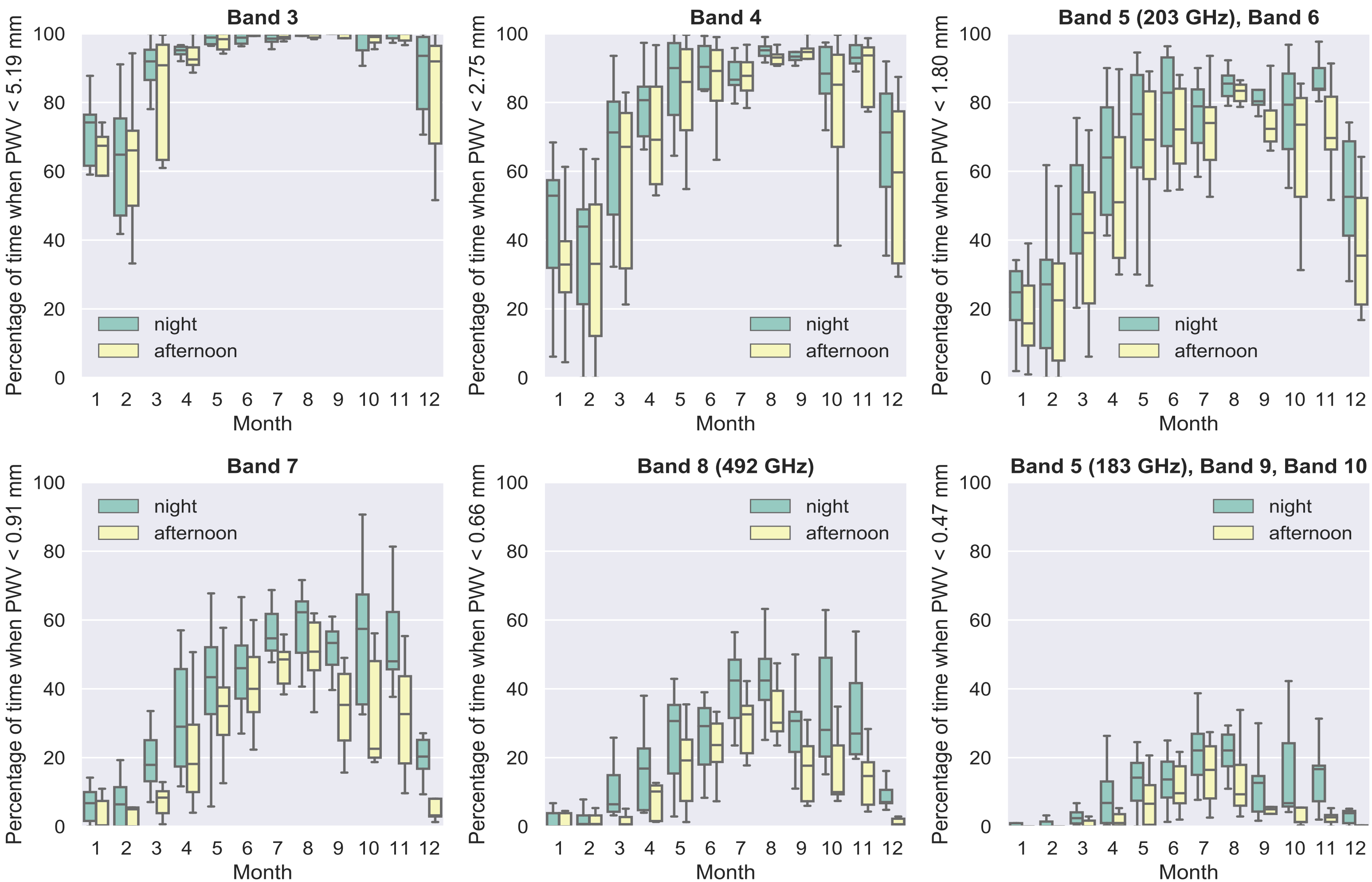
There is no excuse for a late proposal UNLESS the Observatory grants an extension.

ALMA Array Configuration Schedule (Cycle 9)

- Maximum baselines in Cycle 9 will be 16.2 km in configuration C-10.
- Configurations C-9 and C-10 with maximum baselines of 13.9 km and 16.2 km, respectively, will NOT again be available until Cycle 11.
- **NOTE: No PI observing takes place in Feb!**
- The forward-looking configuration schedule (through Cycle 11) can be found at: https://almascience.nrao.edu/observing/observing-configuration-schedule/long-term-configuration-schedule

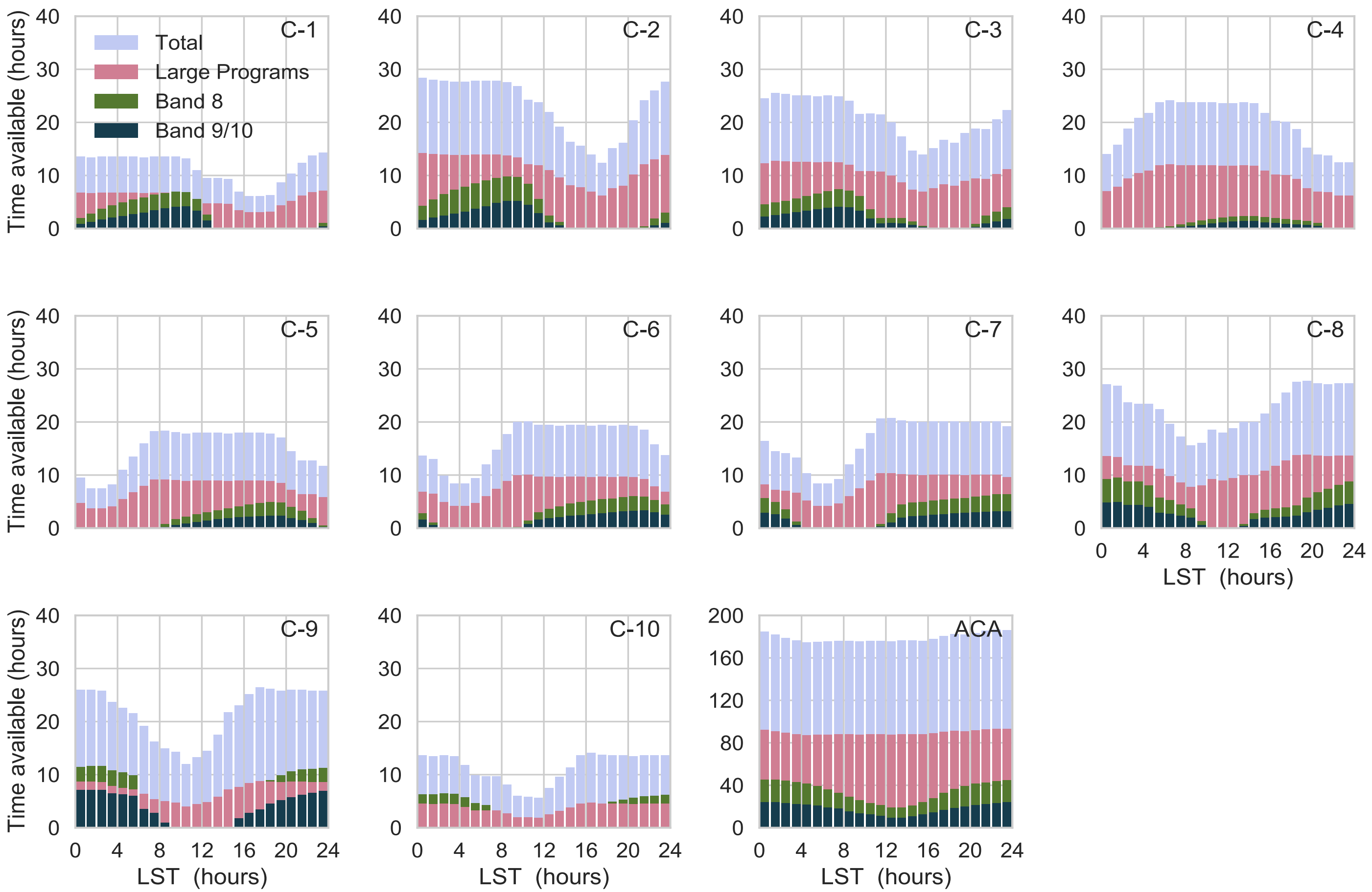
Start date	Config	Longest baseline	LST: Best conditions
1-Oct-22	C-3	0.50	22-10
20-Oct-22	C-2	0.31	23-11
10-Nov-22	C-1	0.16	1-13
30-Nov-22	C-2	0.31	2-14
20-Dec-22	C-3	0.50	4-15
10-Jan-23	C-4	0.78	5-17
1-Feb-23	No observations due to maintenance		
1-Mar-23	C-4	0.78	8-21
20-Mar-23	C-5	1.4	9-23
20-Apr-23	C-6	2.5	11-1
20-May-23	C-7	3.6	13-3
20-Jun-23	C-8	8.5	14-5
11-Jul-23	C-9	13.9	16-6
30-Jul-23	C-10	16.2	17-7
20-Aug-23	C-9	13.9	19-8
10-Sep-23	C-8	8.5	20-9

ALMA Observing Strategies (Cycle 9)



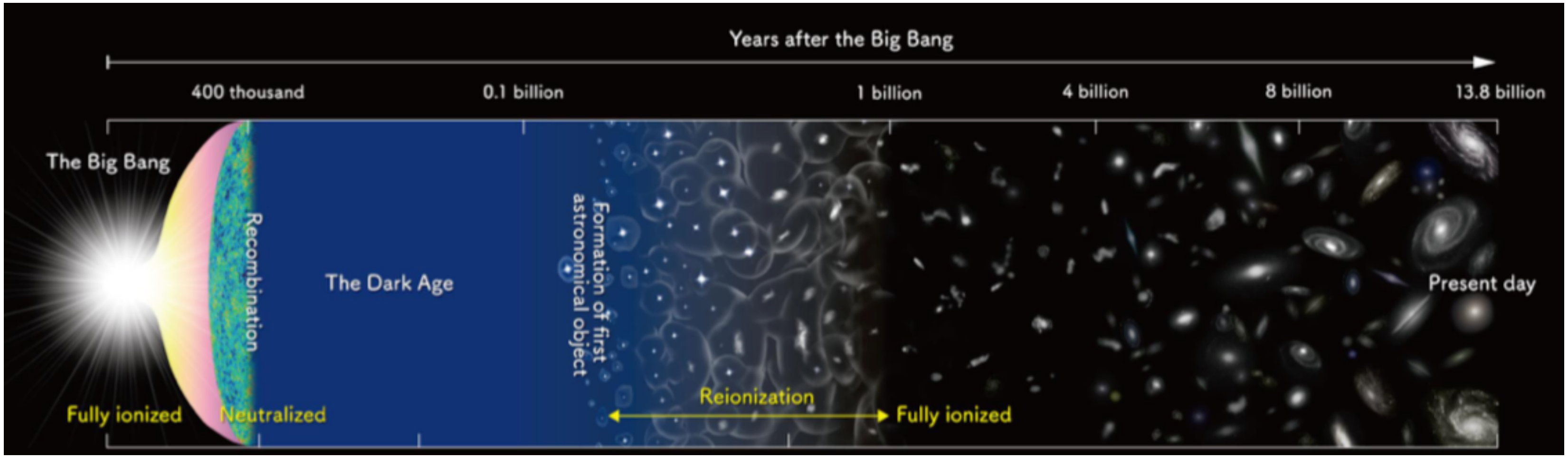
The percentage of time when the PWV is below the observing thresholds adopted for the various ALMA bands for night-time (green) and afternoon (yellow) and for an elevation of 60 degrees. The horizontal line within the box indicates the median. Boundaries of the box indicate the 25th- and 75th-percentile, and the whiskers indicate the highest and lowest values of the results. The data were obtained with the APEX weather station, ALMA measurements, and weather forecast data between September 2010 and February 2019.

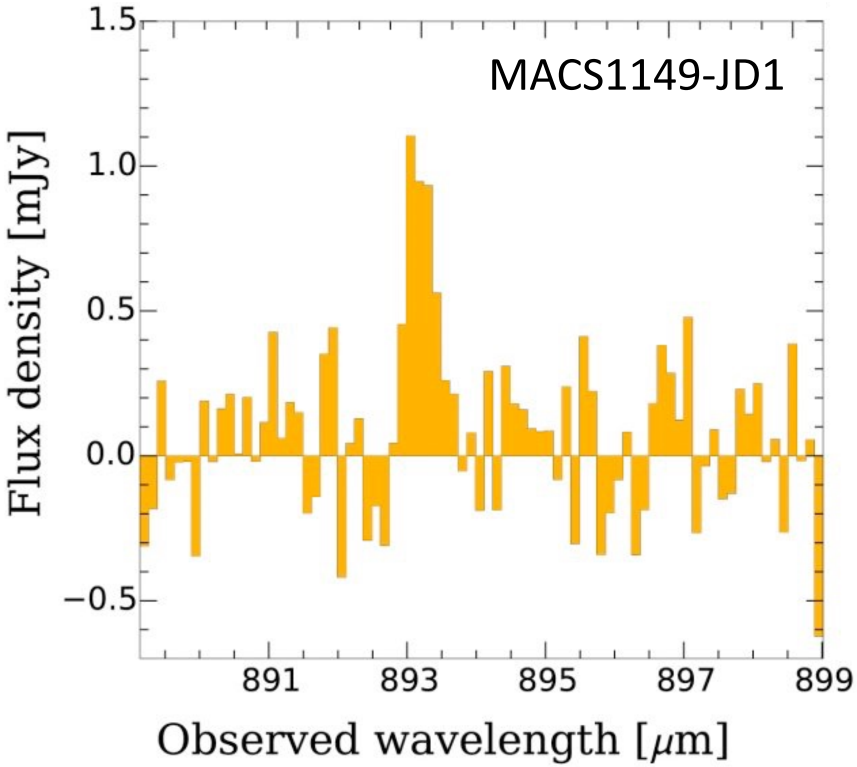
ALMA Observing Strategies (Cycle 9)



Estimated observing time available per configuration for executing PI projects, based on precipitable water vapor (PWV) only. For example, approximately 24 hours are expected to be available in C-4 at LST 05 h for all observations and up to 12 h of those may be allocated to Large Programs. The time available for Large Programs is shown in pink and time for high-frequency observations in green and dark blue. While Band 9 and 10 have the same PWV limits, Band 10 will only be offered up to C-8 in Cycle 9 – in the C-9 panel the histogram labeled "Band 9/10" only applies to Band 9. The configuration schedule and, consequently, the total number of hours available per configuration may change in response to proposal pressure (Section 4.3.3 of the Cycle 9 PG).

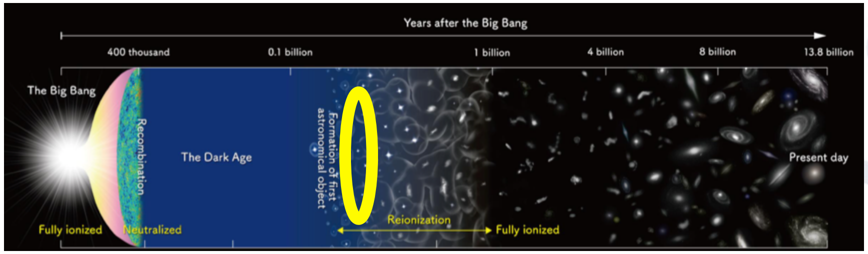
Science!

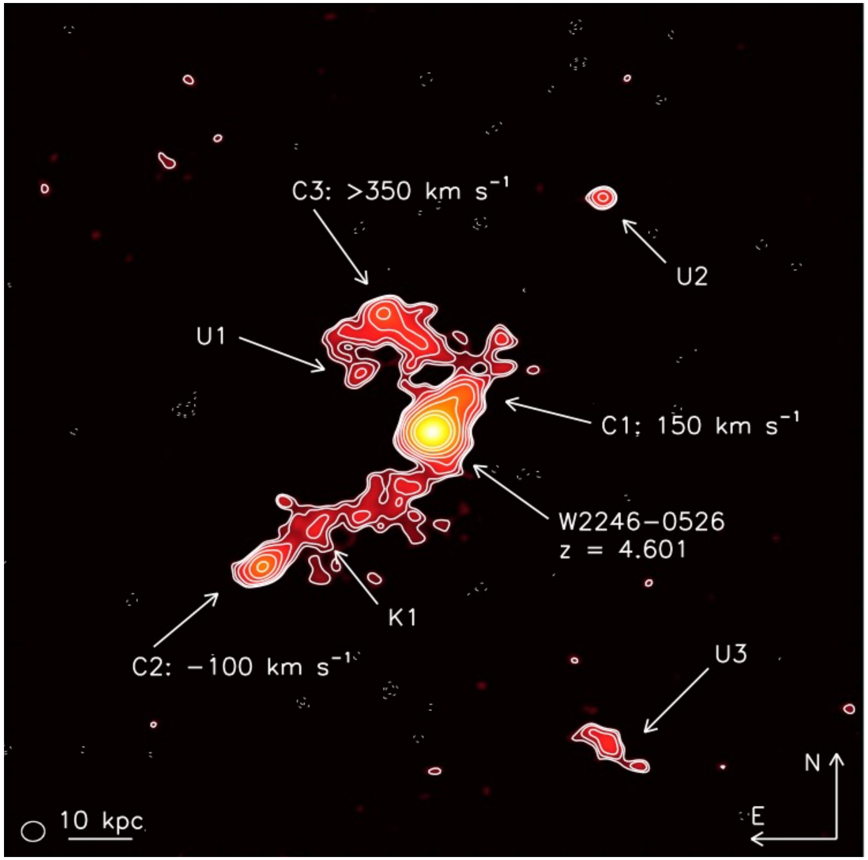

Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Present day
Fully ionized
Neutralized
Reionization
Fully ionized



- Locate the earliest galaxies a few hundred of million years after the Big Bang.
- Oxygen [OIII] present at z=9.11 (13.28 billion light-years away) when Universe is 350 Myr old!
- Implies star formation started 250 Myr after Big Bang!

Hashimoto et al. (2018)

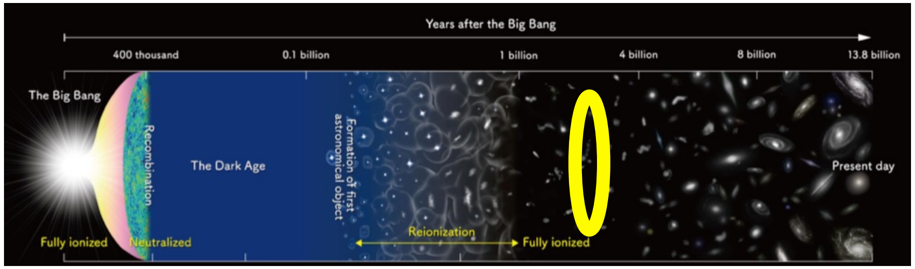




Diaz Santos et al. (2018)

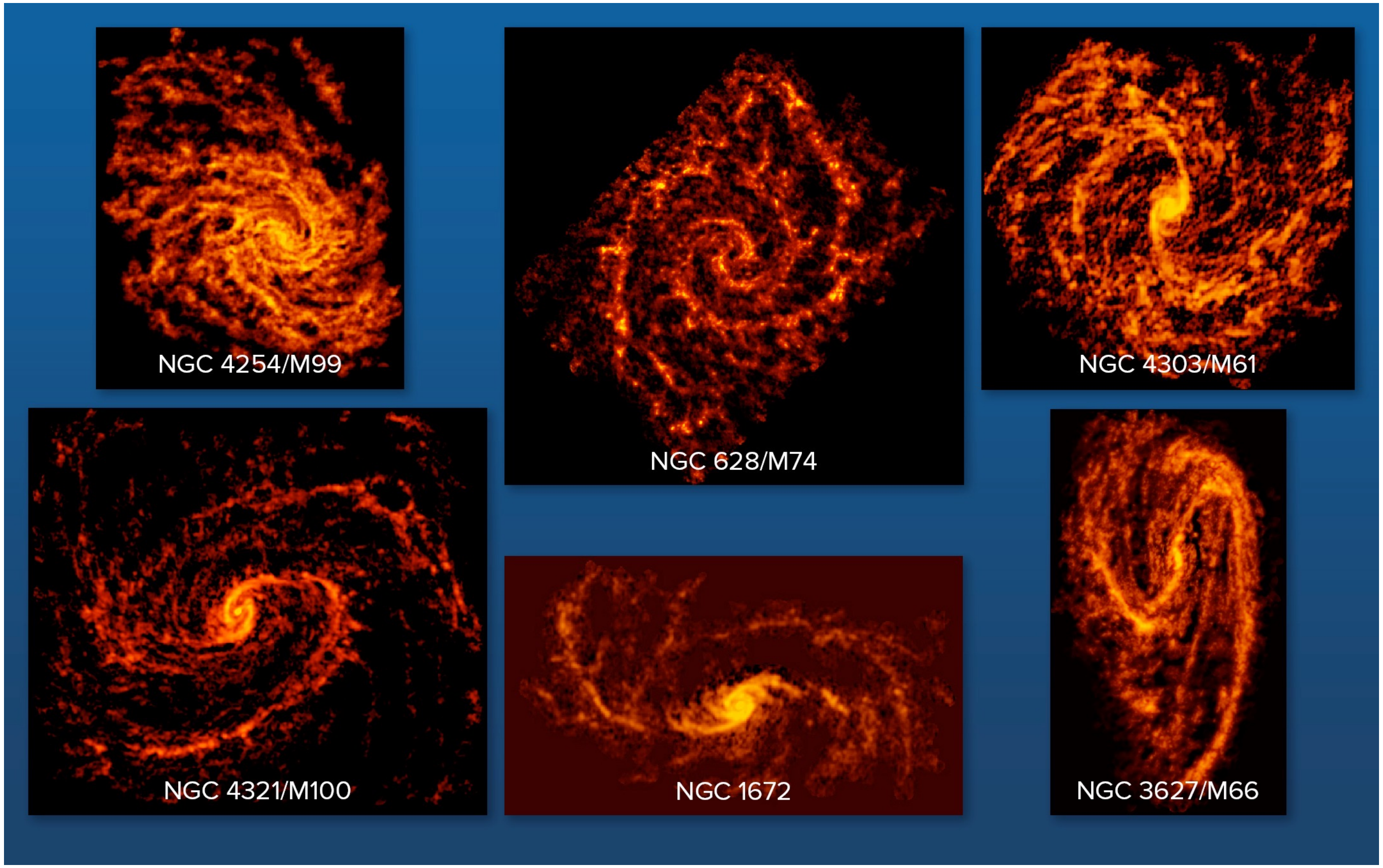
Galaxy mergers at redshift 4.6

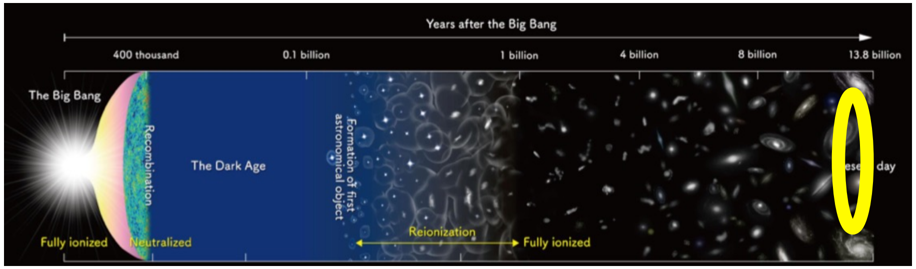
- W2246–0526: Most luminous known galaxy (z=4.6)
- ALMA dust continuum revealed at least 3 companion galaxies
- Dusty bridges show W2246-0526 is accreting is neighbors



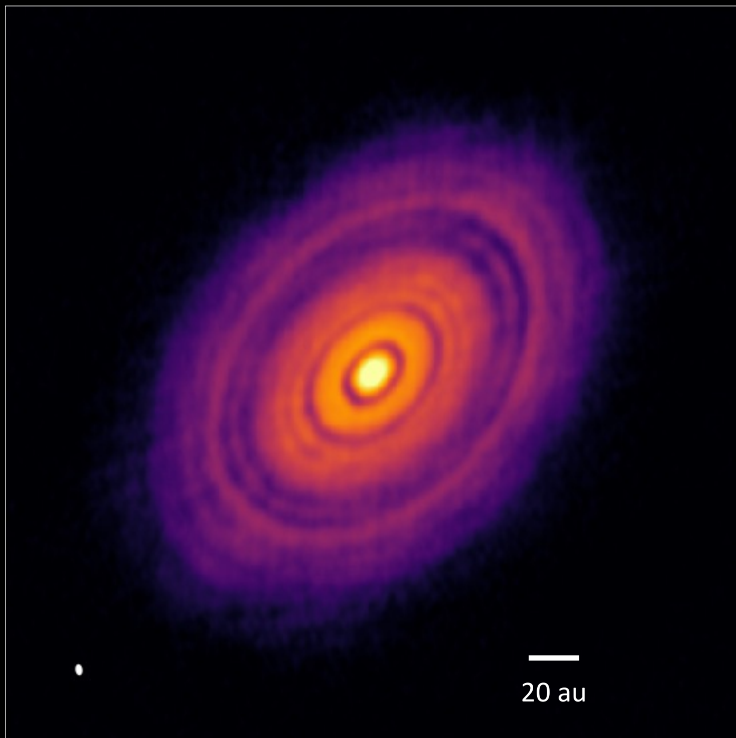
PHNAGS Large Program – Schinnerer et al; 17 papers.

- Sample of 74 nearby galaxies.
- CO observations.
- 100,000 molecular clouds.

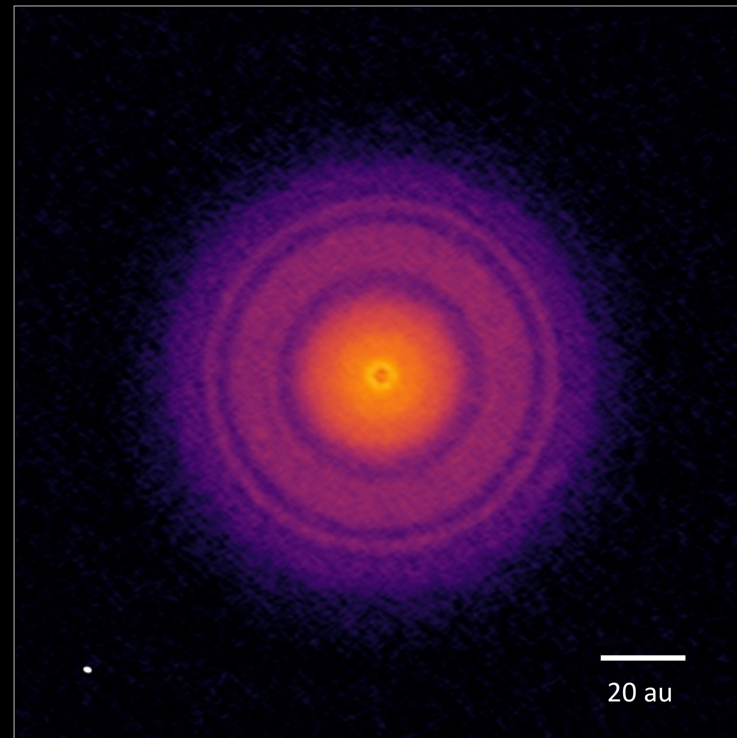




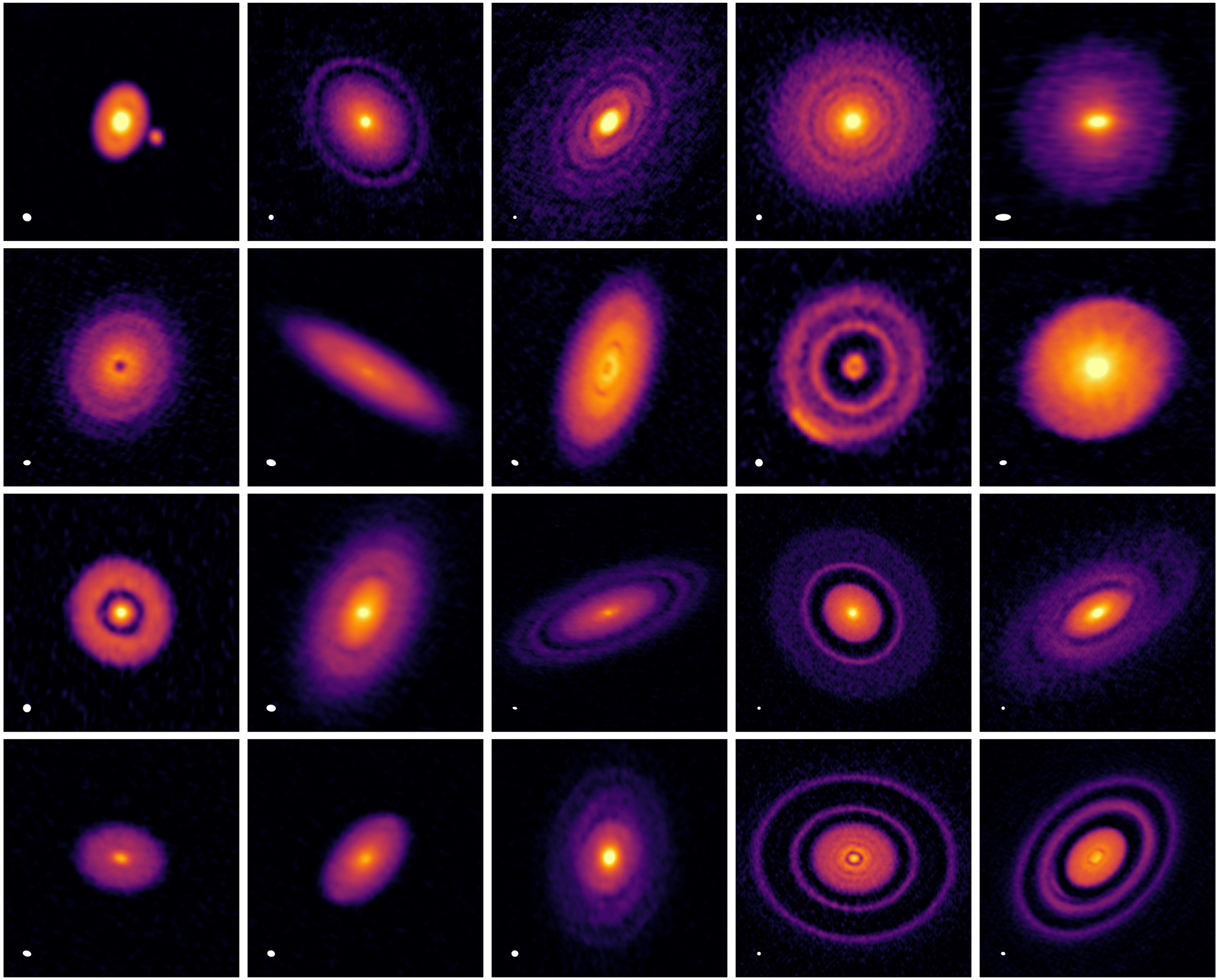
Proto-planetary disks with ALMA



ALMA Partnership+ 2015; Akiyama+ 2016



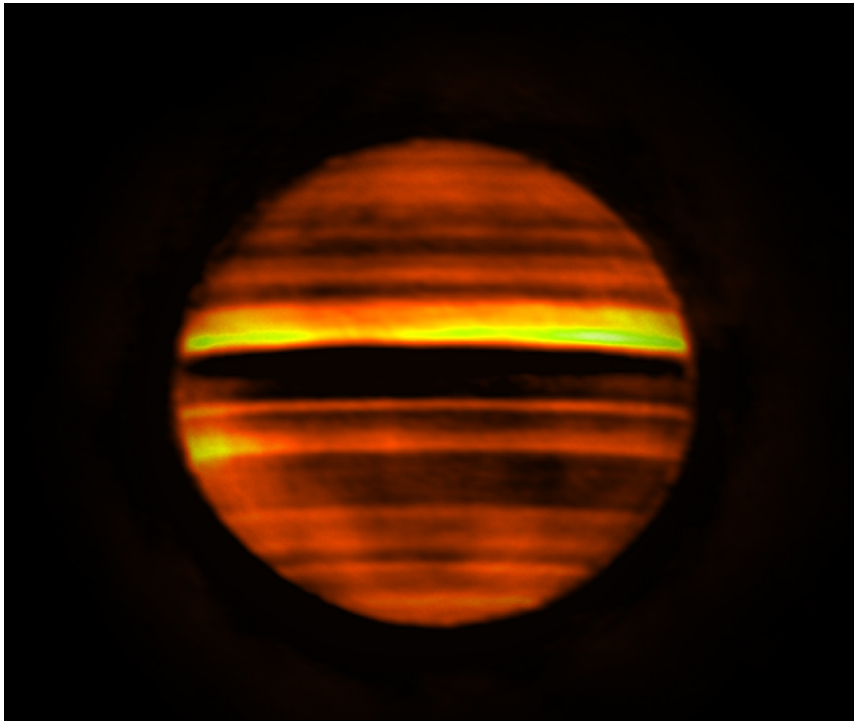
Andrews+ 2016; Huang+ 2018



DSHARP Cycle 4 Large Program – Andrews et al; 10 papers, 2019, ApJL 869

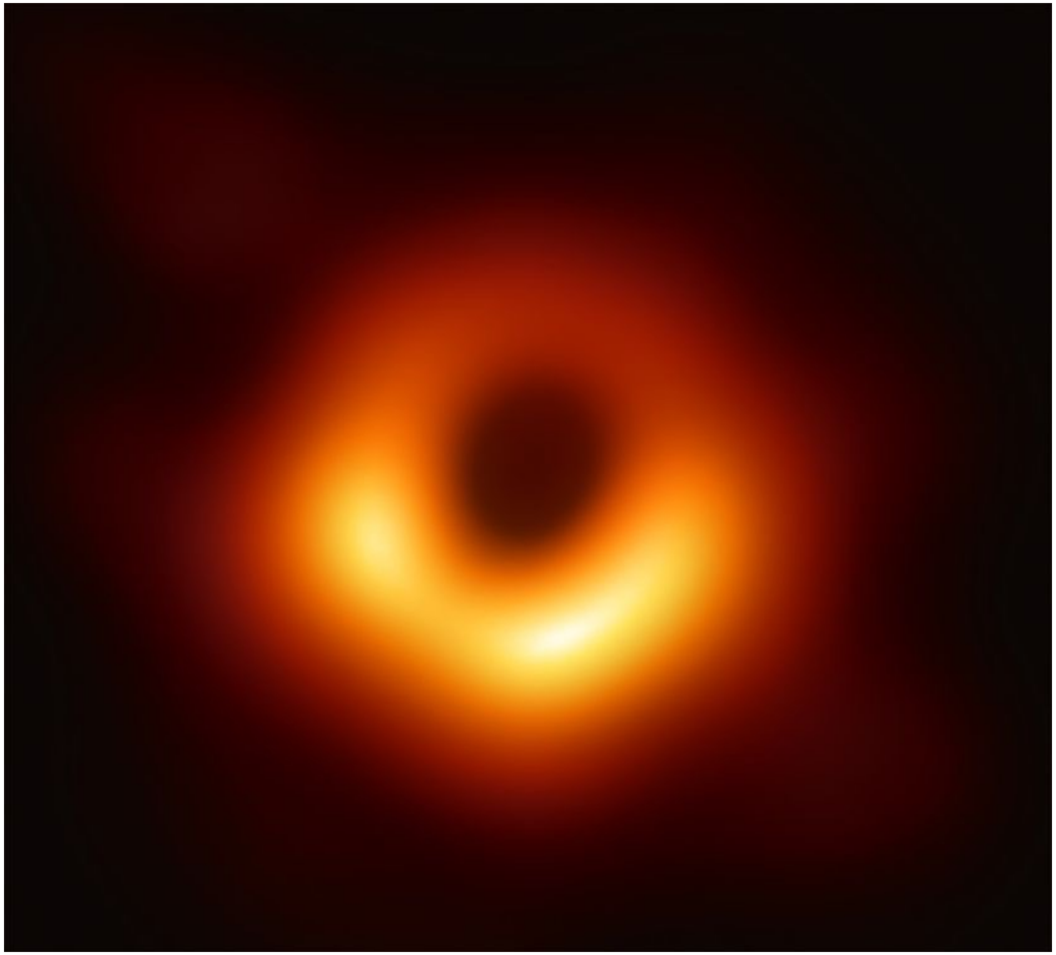
ALMA Millimeter Wavelength Images of Jupiter

- Jupiter at 1.3mm (mosaic of 17 pointings)
  - NH_3 dominates opacity, so the image can provide its 3 dimensional distribution
  - High brightness indicates lower NH_3 abundance
  - Dark areas indicate higher atmospheric opacity
- Imaged days after an outbreak in the South Equatorial Belt
  - Favored model: Eruptions triggered by energetic plumes via moist convection at base of water cloud, bringing up NH_3.



de Pater+ arXiv:1907.11820

EHT – 1st image of a black-hole shadow



2020 Breakthrough Prize

EHT Collaboration et al, 2019 - 6 papers in ApJL 875

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