The Atacama Large Millimeter Array (ALMA)
And a look toward the future

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ALMA

VCI Vienna February 21st, 2022

ALMA Operations Site (AOS) at 5000m

High: 17,000 feet – very low water content
Large, flat expanse – ideal for large-scale construction
Accessible

66 high-precision antennas

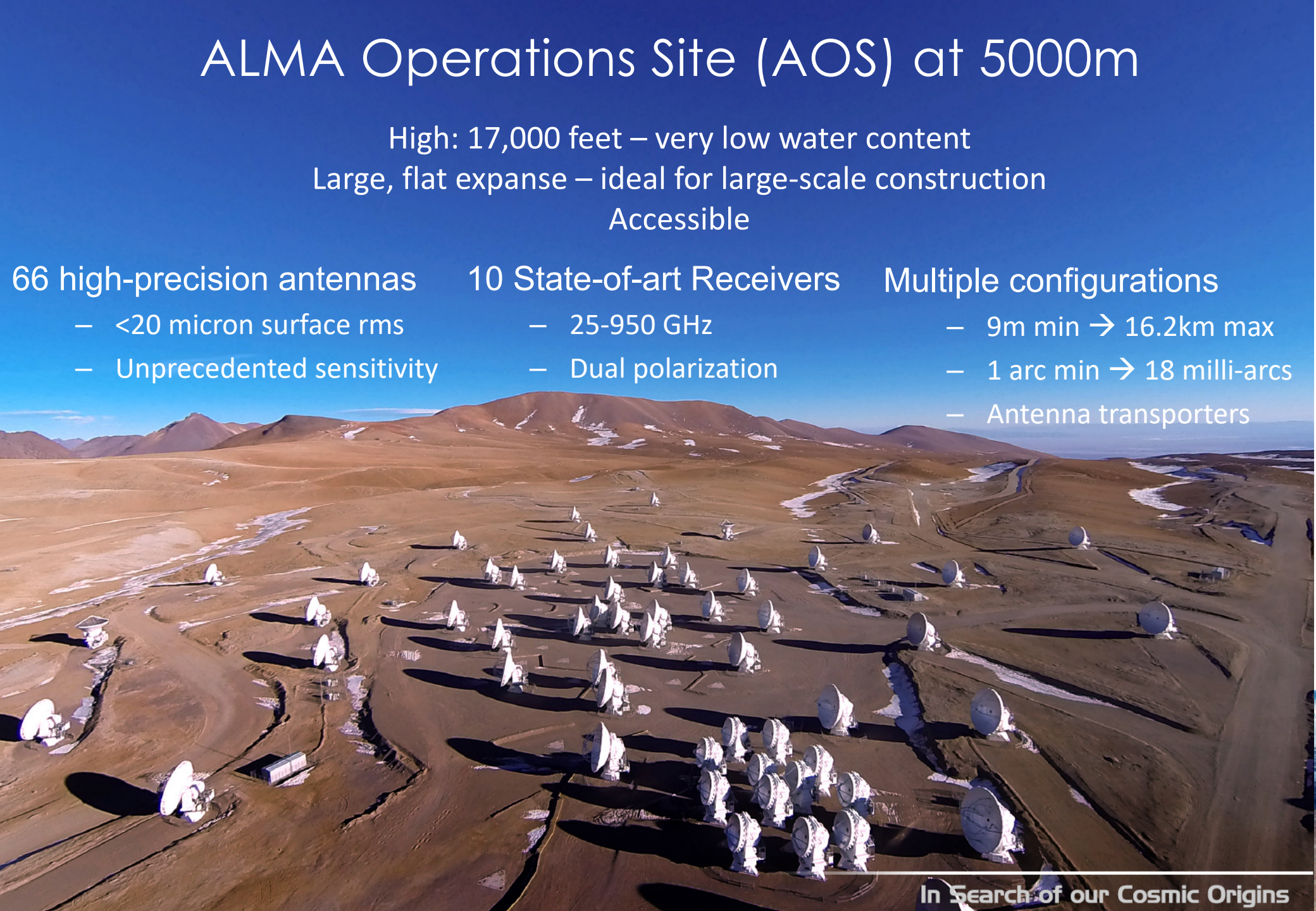
- <20 micron surface rms
- Unprecedented sensitivity

10 State-of-art Receivers

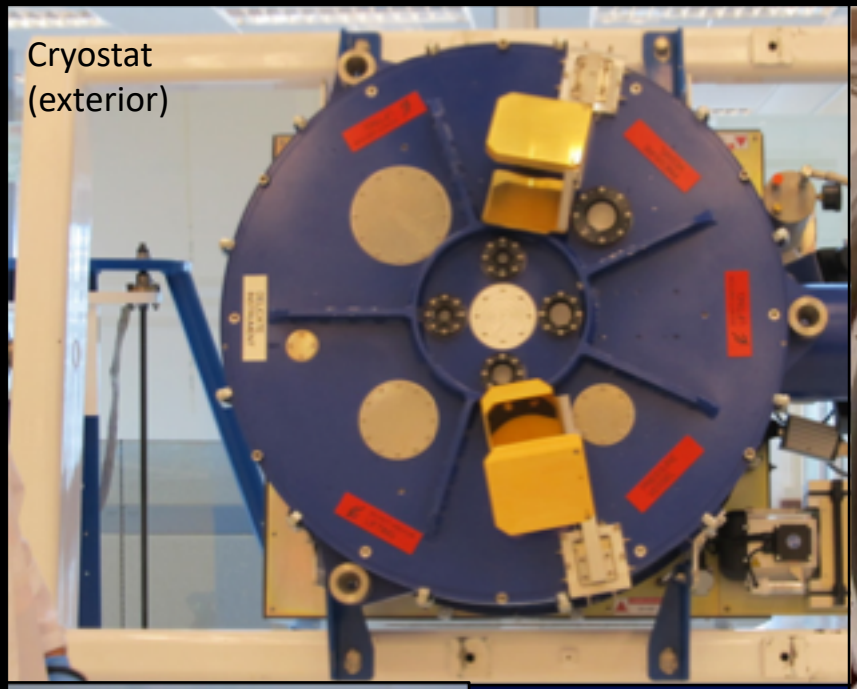
- 25-950 GHz
- Dual polarization

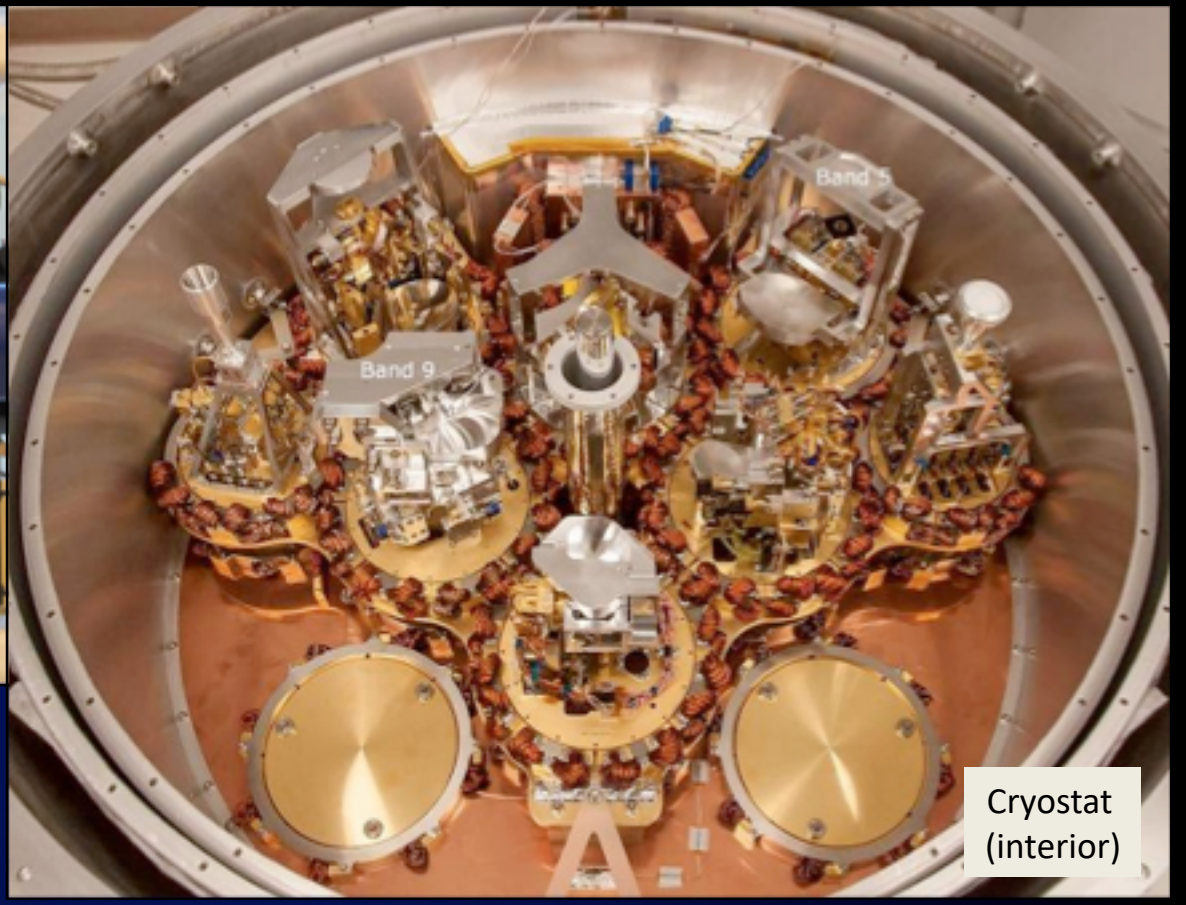
Multiple configurations

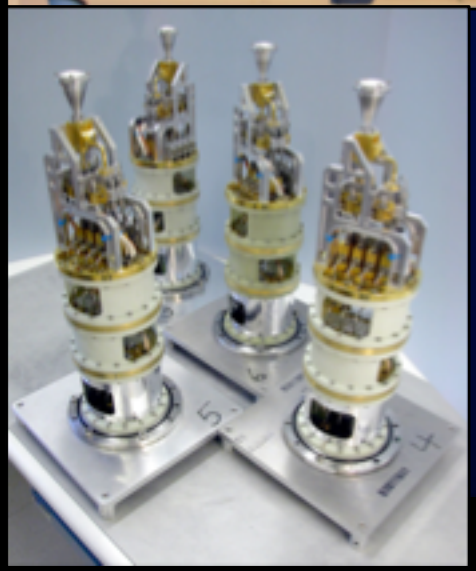
- 9m min → 16.2km max
- 1 arc min → 18 milli-arcs
- Antenna transporters

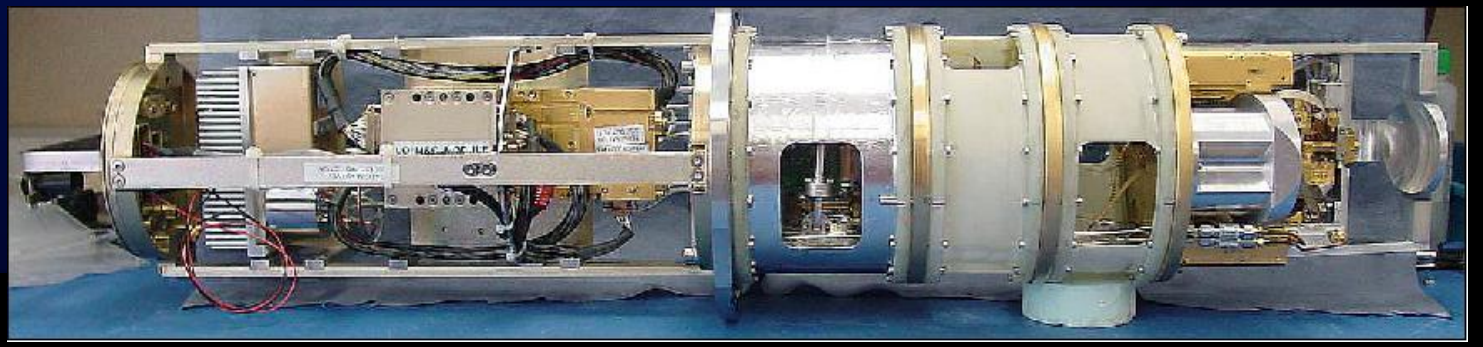


ALMA Front Ends – superconducting detectors



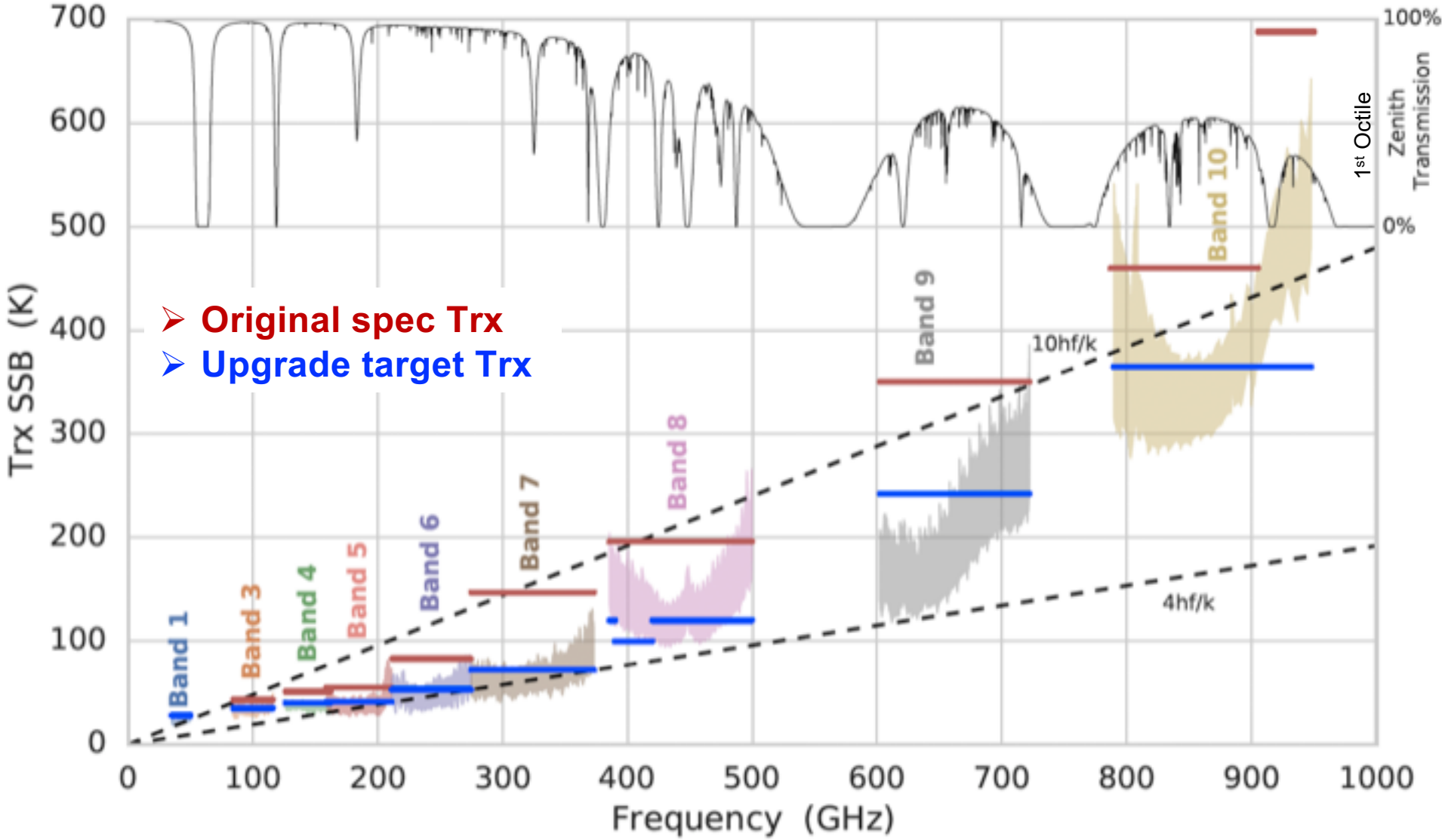






Receiver Noise Performance

Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins



ALMA Correlators

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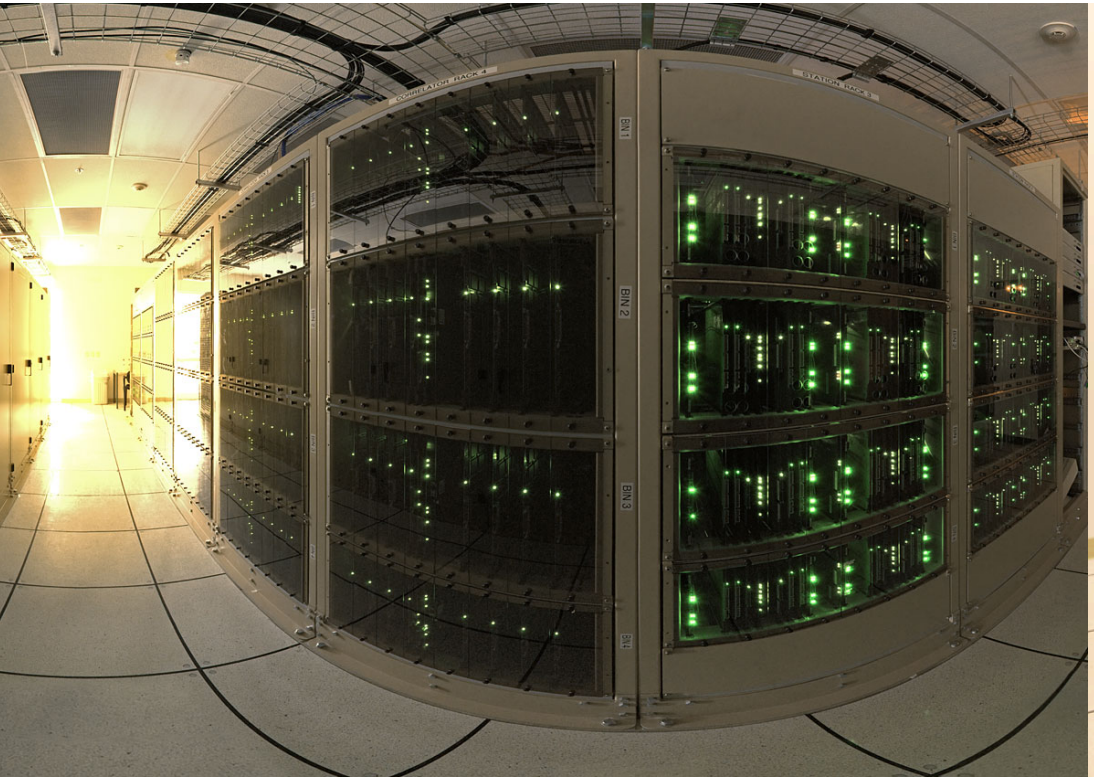
In search of our Cosmic Origins

12-m array correlator



ACA correlator

10-yrs of Operations – at steady state?

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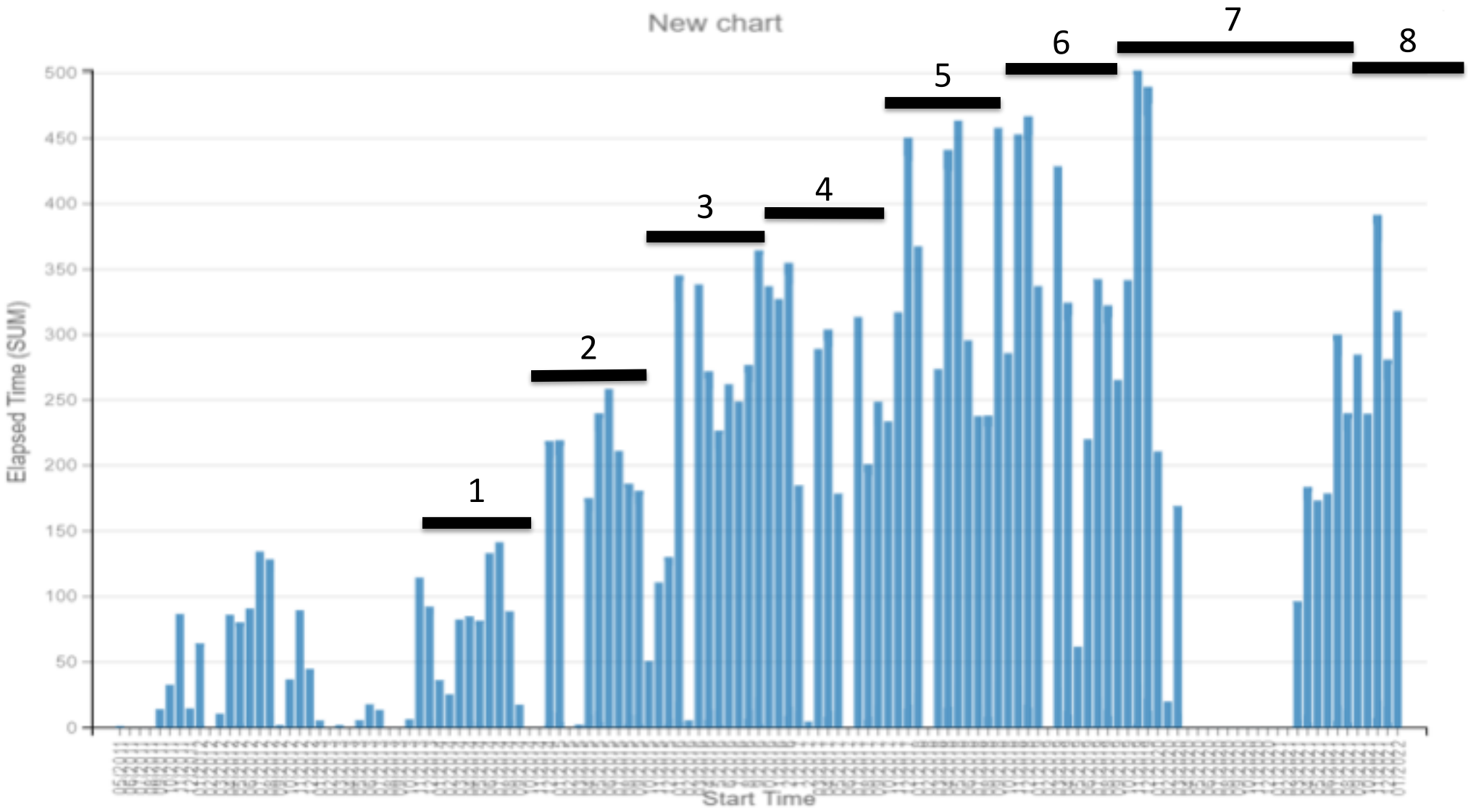

Proto-planetary disks before ALMA

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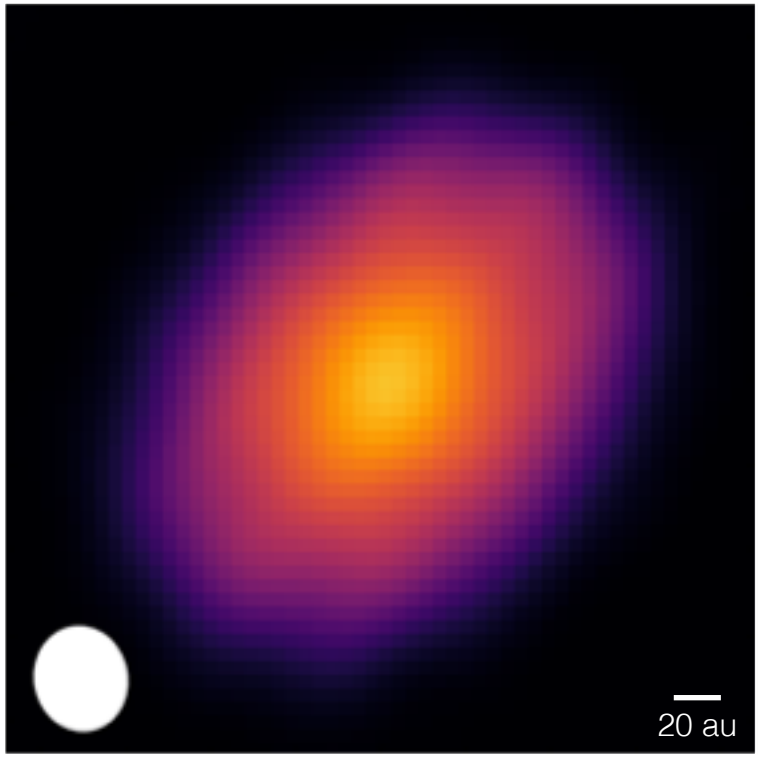
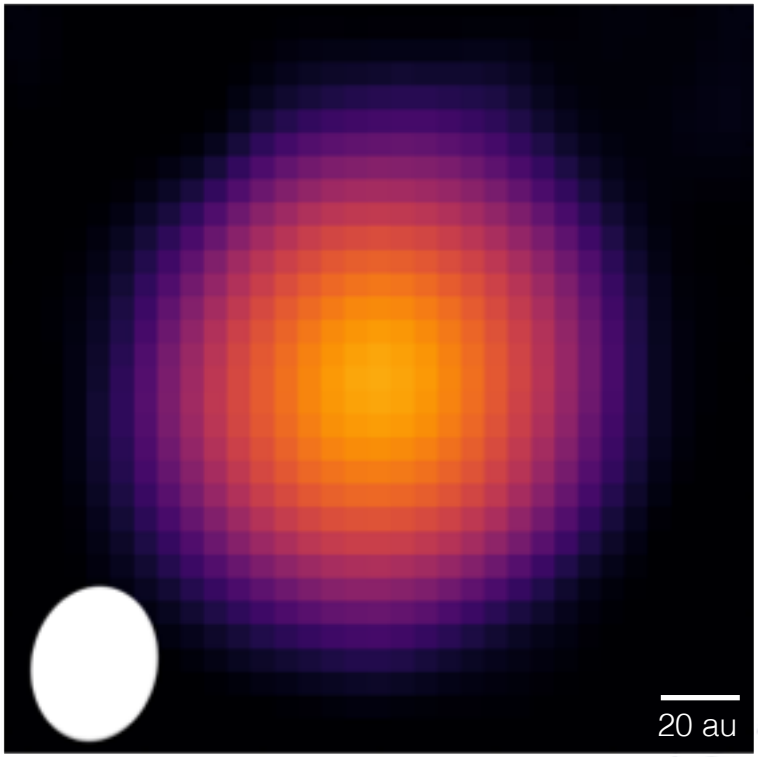


Kwon+ 11



Andrews+ 12

The state-of-the-art observation of two proto-planetary disks in 2011

Proto-planetary disks with ALMA

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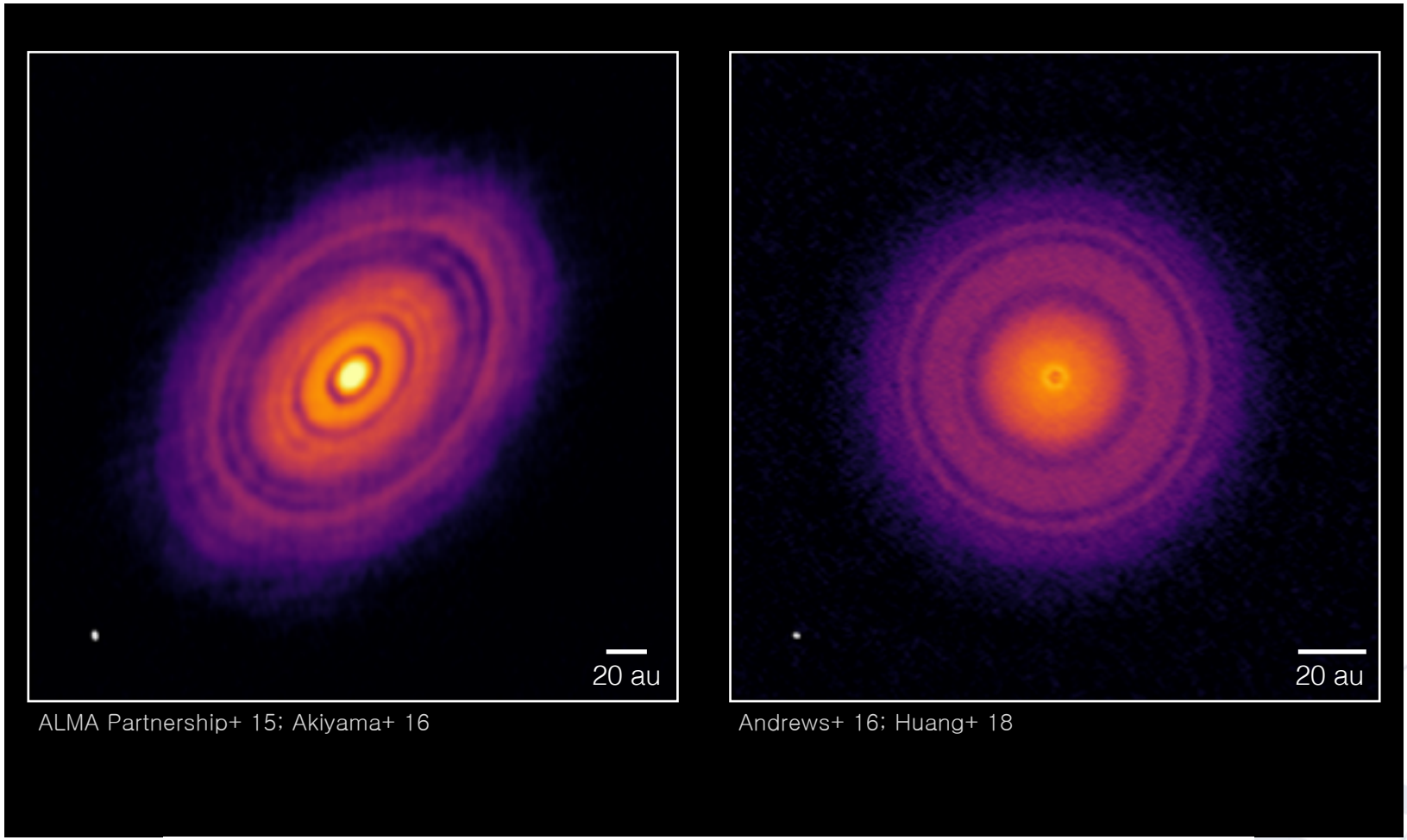

ALMA Partnership+ 15; Akiyama+ 16

Andrews+ 16; Huang+ 18

ALMA is a game changer for many areas of astrophysical research

Spectroscopy of high-redshift galaxies

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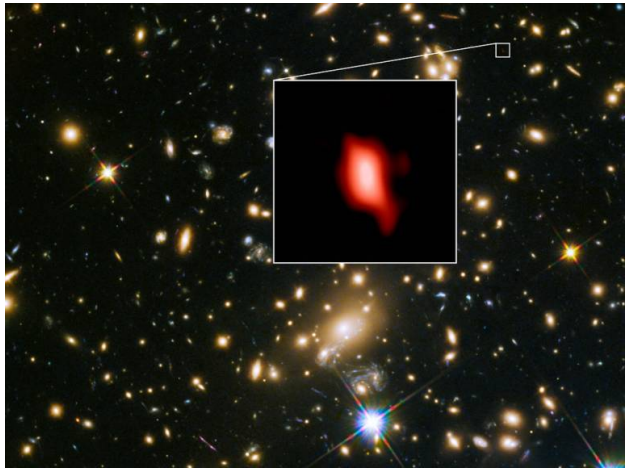
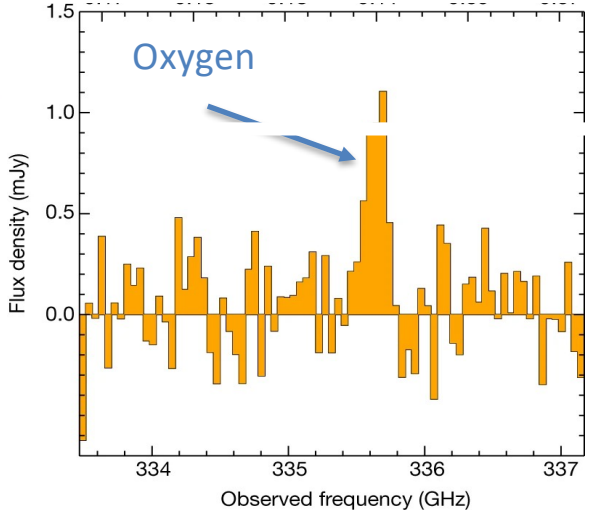
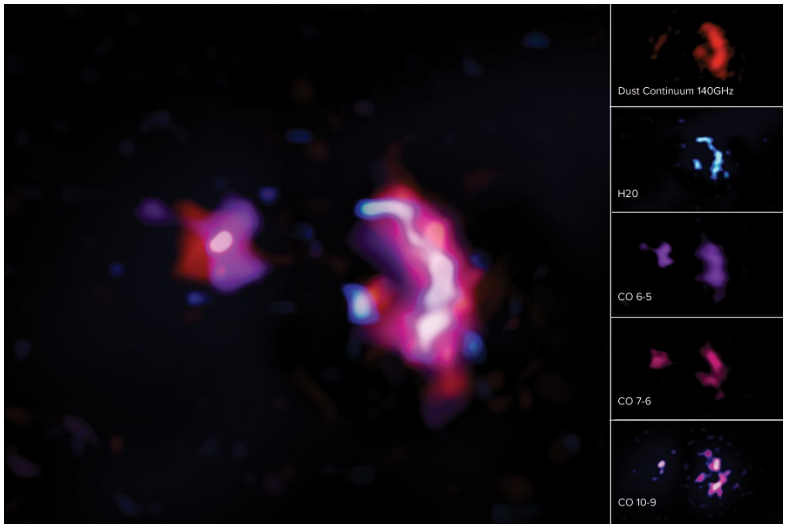




Galaxies present at z~9, when Universe was only 500 million years old!
Detecting water molecules at z~7



EHT – 1st image of a black-hole shadow

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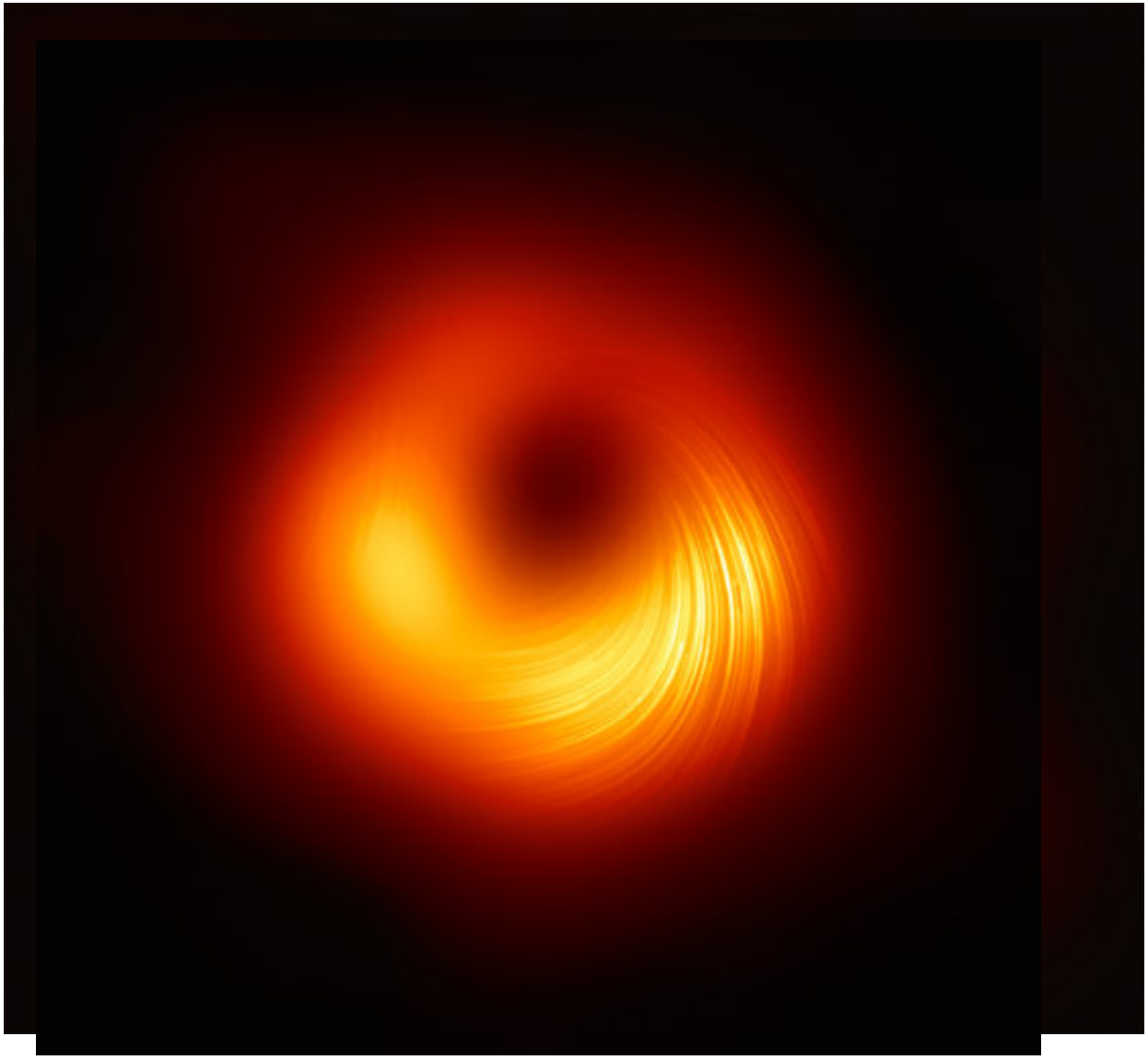
In search of our Cosmic Origins



2020 Breakthrough Prize

EHT Collaboration et al, 2019

- 6 papers in ApJL 875

March 2021

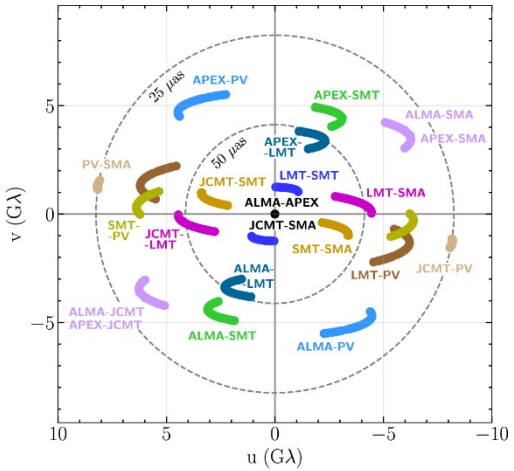
Polarization Observations

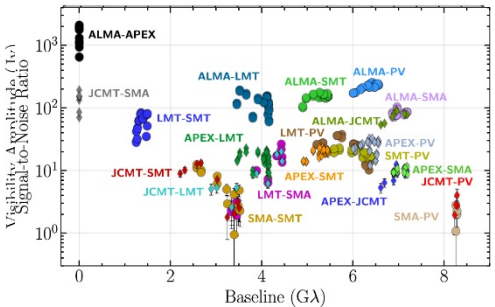
- 2 papers in ApJL 910

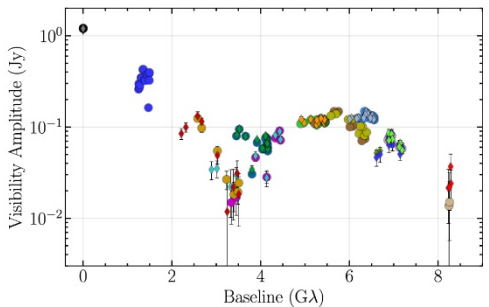
EHT – The Role of ALMA in the EHT

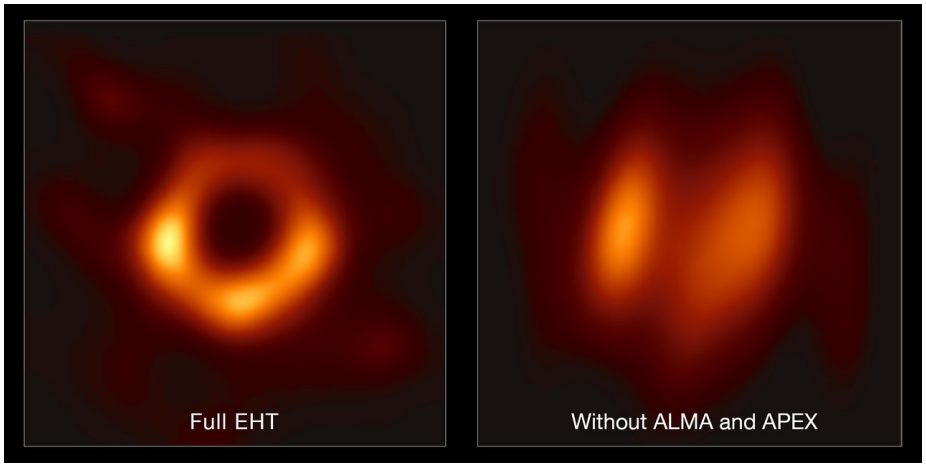
Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

- The EHT is an array of telescopes distributed across the globe
  - Measures 'visibilities' (Fourier components) of radio brightness
  - Resolution ~ wavelength/maximum separation of a pair of telescopes
  - At 1.3mm, and the EHT having baselines from 160m to 10,700km
  - Resolution ~ 25 micro arcseconds
  - Earth rotation ensures every telescope pair samples different spatial frequencies.
- ALMA was phased-up = response of each element are combined
  - takes advantage of the collecting area of 50 12-m antennas
  - Dramatically increases the signal to noise for antenna pairs with ALMA
  - Improves calibration accuracy and reliability
- ALMA was essential to the successful image of the BH in M87









ALMA is a stunning success!

Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

The partnership has brought together a total of 22 countries

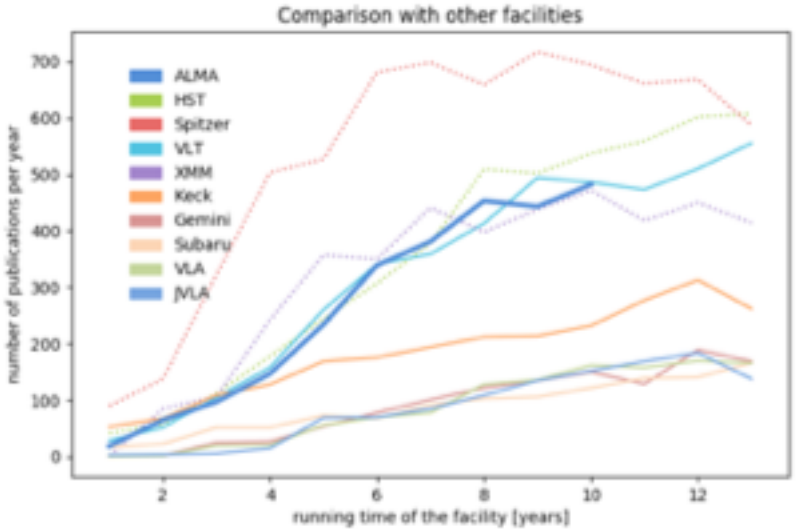
- Human and technological capital
- Complimentary and Technical expertise

to successfully build an outstanding facility in a challenging location

The **science return has been astounding,** similar to other leading facilities e.g. HST, XMM, VLT

From the International Visiting Committee report (2019):

> *"The Atacama Large Millimeter/submillimeter Array (ALMA) is a stunning success.*
>
> *ALMA's spectacular record of scientific discovery, extending from the Solar System to the farthest reaches of the Universe, is a justified source of pride for its partners.*
>
> *An equally impressive aspect of the Observatory, however, is the evident skill, motivation, and dedication to its mission displayed by the entire ALMA team, who operate in a challenging environment both physically (i.e. at extreme elevation) and organizationally (i.e. with a globally distributed structure). ALMA deserves to have continued high priority with its partners."*

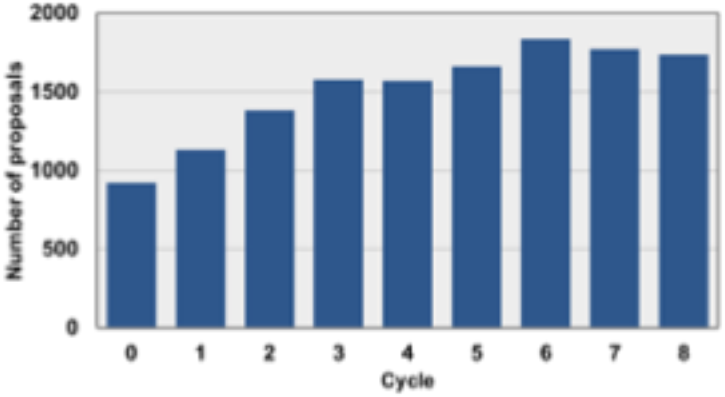


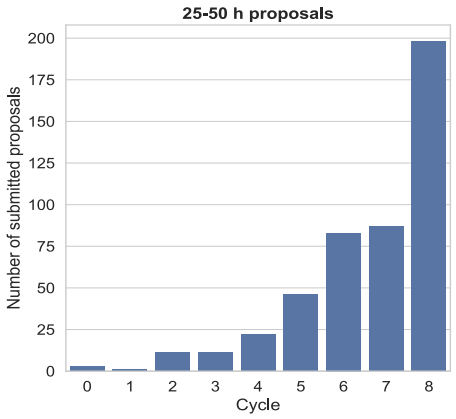
Community use – ever increasing demand

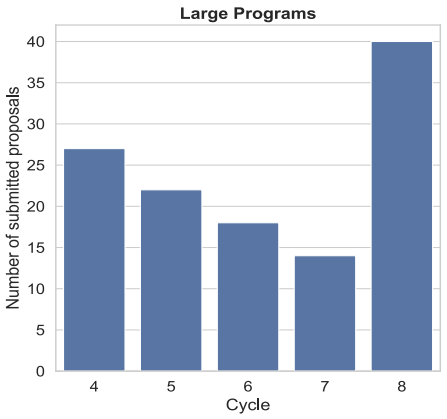
Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

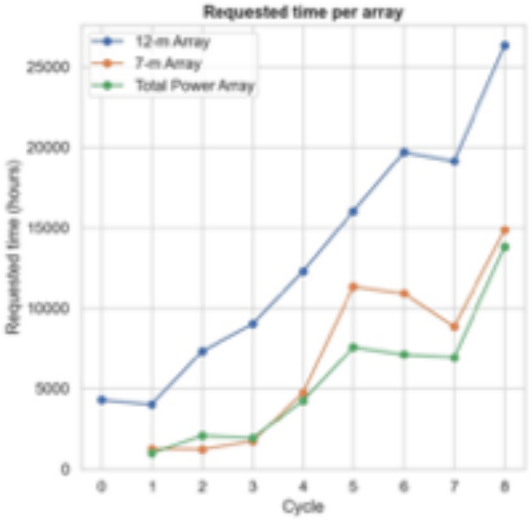
Latest Cycle – Cycle 8 :

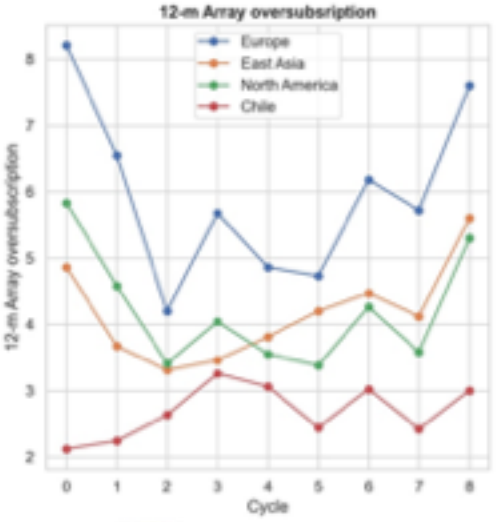
- # of proposals ~1800
- Total number, proposal size, oversubscription, Large Programs -- all increasing
  - ~26,000+hrs requested – 4300 hrs offered – Oversubscription >6
  - ~3x # of Large Programs (>50hrs) vs Cycle 7
  - Similar for 25-50hrs programs
- 1st time with a Dual-anonymous process
- Distributed review model for <25hrs
  - 1st ever large-scale deployment
  - 1016 reviewers for 1497 proposals (~15000 reviews)
- Panel reviews for >25hrs
  - 39 reviewers for 238 proposals
- Observations scheduled for 486 proposals











Looking to the future

Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

- Been interest in thinking about how to advance the capabilities of ALMA since 2013
- 2015: ALMA Development Working Group
  - Propose a prioritized science-driven vision for next 5-15yrs
- Led to the ALMA Development Roadmap in 2018

ORIGINS OF GALAXIES

Trace the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z=2–4) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.

Line sensitivity
Bandwidth for survey speed

ORIGINS OF CHEMICAL COMPLEXITY

Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (~10-100 au) by performing full-band frequency scans at a rate of 2-4 protostars per day.

Line sensitivity
Bandwidth for survey speed

ORIGINS OF PLANETS

Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone (~ 1 au) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.

Angular resolution
Bandwidth for continuum sensitivity

Wide-band sensitivity upgrade

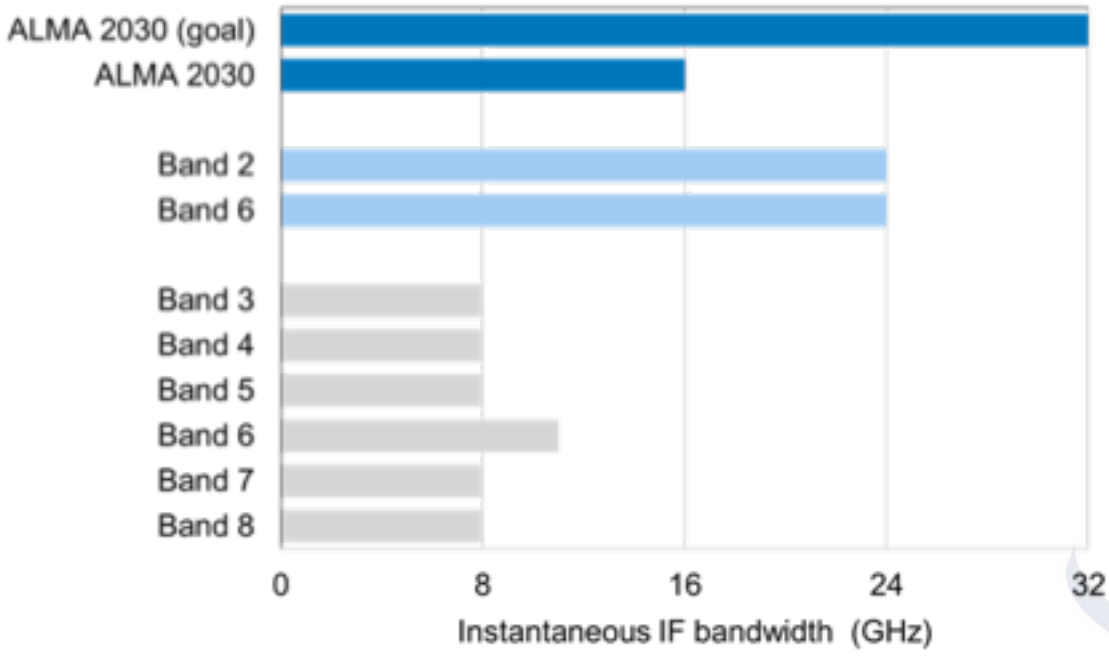
Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

- Receivers
  - bandwidth – both RF and IF (8 ->16 GHz)
  - receiver temperature - 30-40%
- digital transmission system
- correlator (with improved efficiency)
- data processing and archive

Higher Speed Observations
- 2.3-4.7x faster spectra
- 4.7x faster continuum

Increased spectral range

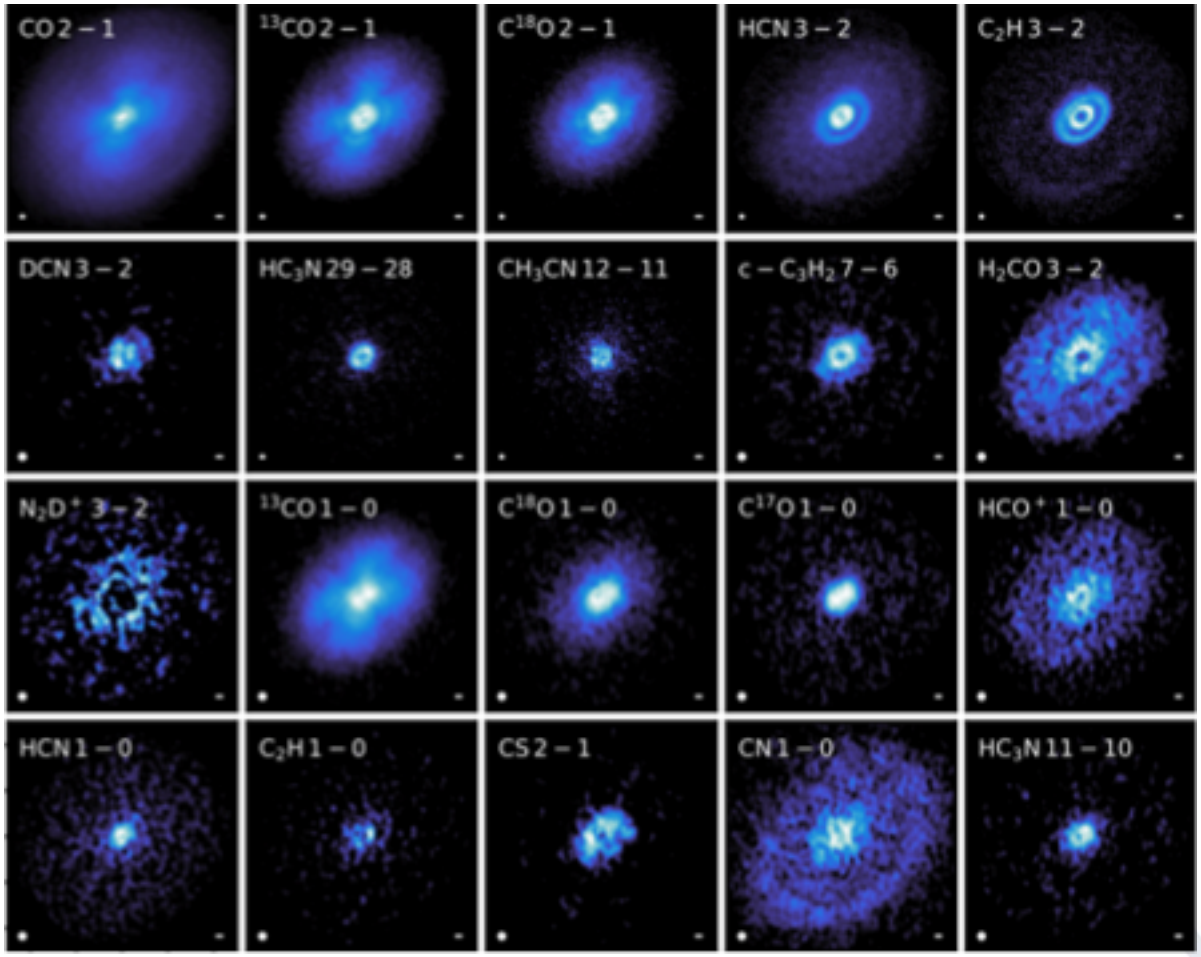
=> major upgrade of the entire signal chain - from Front-end through to data processing & archive



The ALMA2030 Advantage - MAPS

Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

The 20 molecular faces of the HD 163296 disk



Öberg et al. (2021; MAPS Large Program)

The ALMA2030 Advantage - MAPS

Atacama Large Millimeter/submillimeter Array
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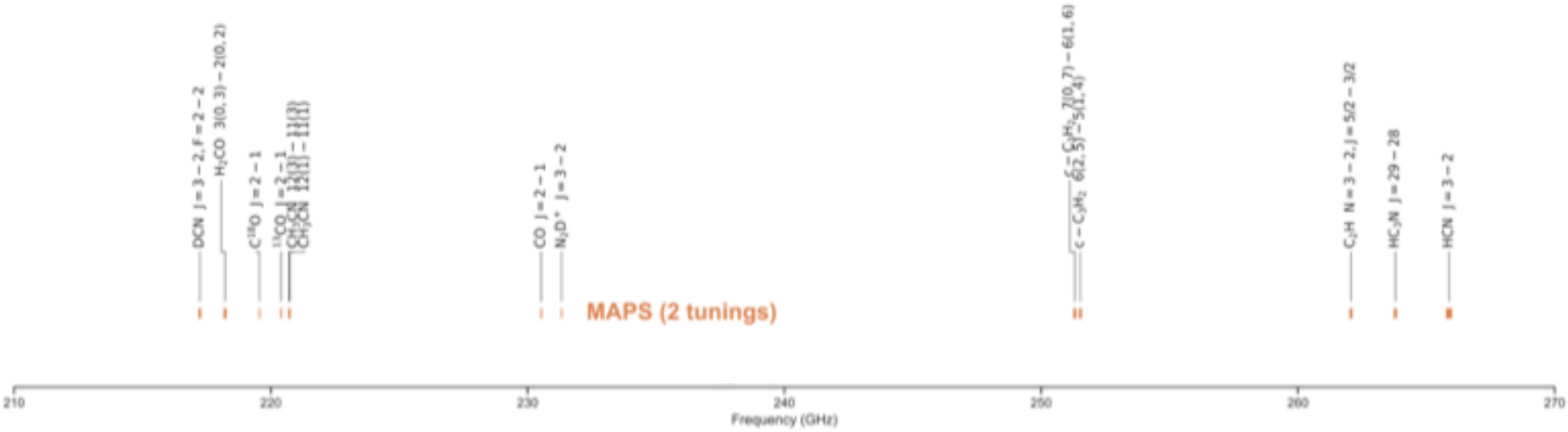

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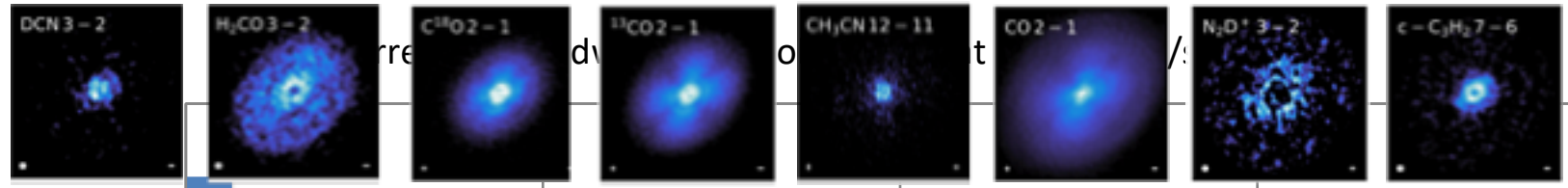

MAPS (2 t

ALM

ALMA203

C_2H 3 – 2	DCO^+ J=3-2	c-C_3H_2 3(3,0)-2(2,1)	H_2S 2(2,0)-2(1,1)	SiO J=5-4	c-C_3H_2 6(0,6)-5(1,5)	HC_3N J=24-23	H_2CO 3(2,1)-2(2,0)
$C^{15}N$ N=2-1	SO 3Σ 6(5)-5(4)	SO_2 11(1,11)-10(0,10)	$C^{17}O$ J=2-1	t-HCOOH 10(4,6)-9(4,5)	H_2CO 3(1,2)-2(1,1)	CN N=2-1	c-C_3H_2 4(3,2)-3(2,1)
HC_3N J=25-24	^{13}CS J=5-4	H_2CS 7(0,7)-6(0,6)	$C^{34}S$ J=5-4	H_2CS 7(1,6)-6(1,5)	c-C_3H_2 3(2,1)-2(1,2)	CS J=5-4	HC_3N J=27-26
t-HCOOH 11(2,10)-10(2,9)	SO 3Σ 2(3)-3(2)	c-C_3H_2 5(2,3)-4(3,2)	SO 3Σ 5(6)-4(5)	SO 3Σ 8(9)-8(8)	HC_3N J=28-27	c-C_3H_2 5(3,3)-4(2,2)	$HC^{18}O^+$ J=3-2

… and up to 40 additional spectral windows!

- ALMA is an extraordinary achievement
  - a very successful multi-national collaboration involving 22 countries
  - world-leading facility
  - High-tech, precision facility in a challenging location and environment
  - Globally distributed operations and scientific support

- ALMA's contributions to science are stunning
  - scientific legacy is/will be profound
  - Our role in the EHT was fundamentally important to its success

- Community demand for ALMA is very strong – and continues to grow

- Looking to the future
  - Improve receiver sensitivity, at least 2x IF bandwidth
  - Increased observing speed (5x) and larger spectral reach (50x)
  - Increased spectral resolution
  - Lots of development work already underway
  - Synergies with other new facilites e.g. JWST

- ALMA's future is very, very exciting.

Thank you