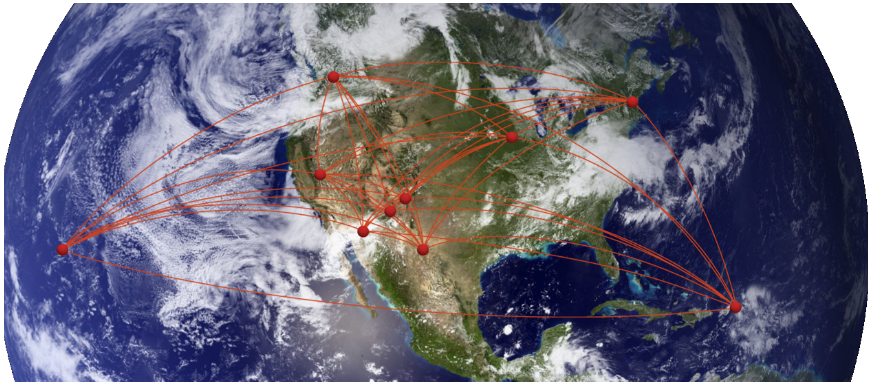
ALMA Basics and Cycle 8 2021 Capabilities

National Radio Astronomy Observatory



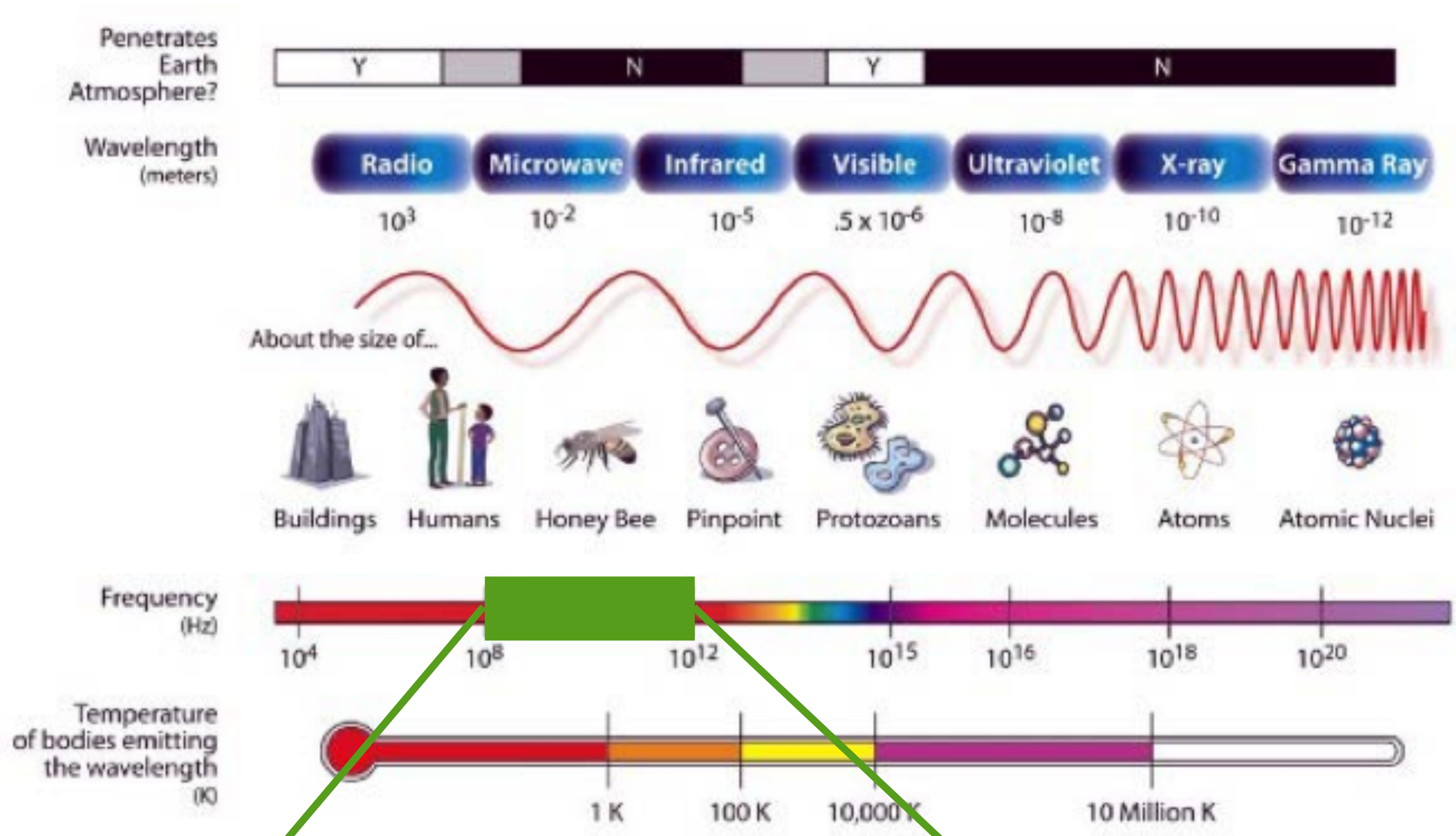
Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Very Long Baseline Array

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?

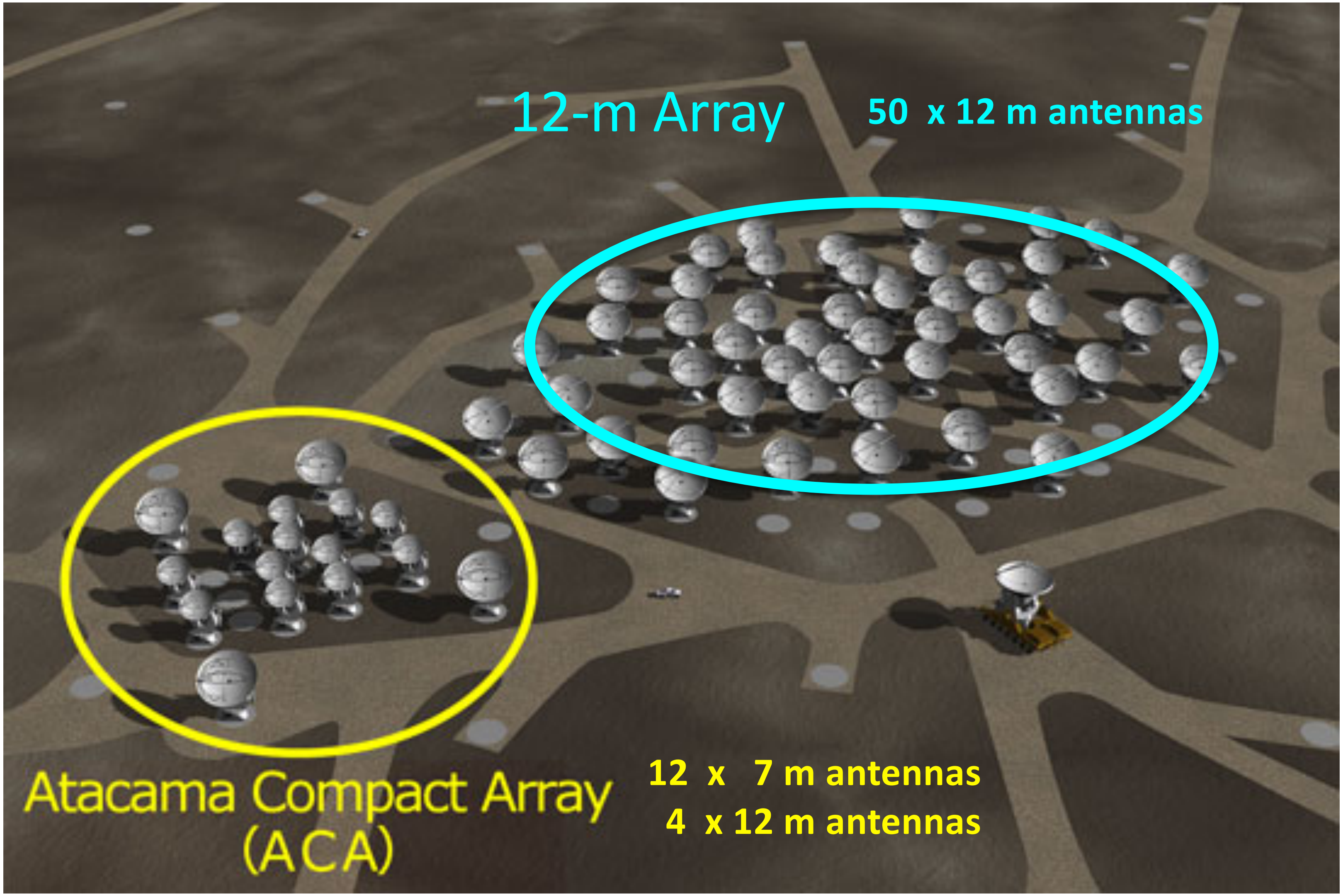
- 66 reconfigurable, high precision antennas

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

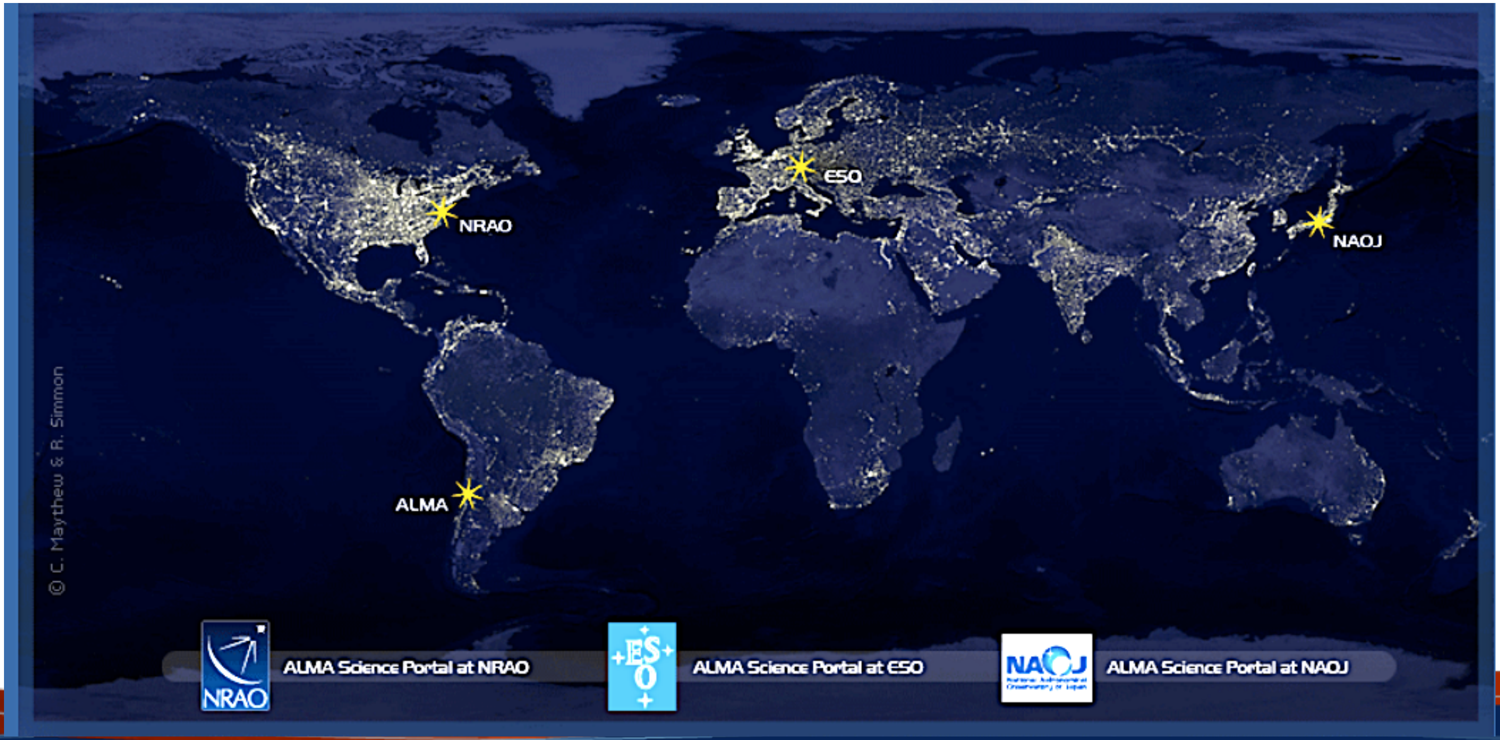
ALMA Operations

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

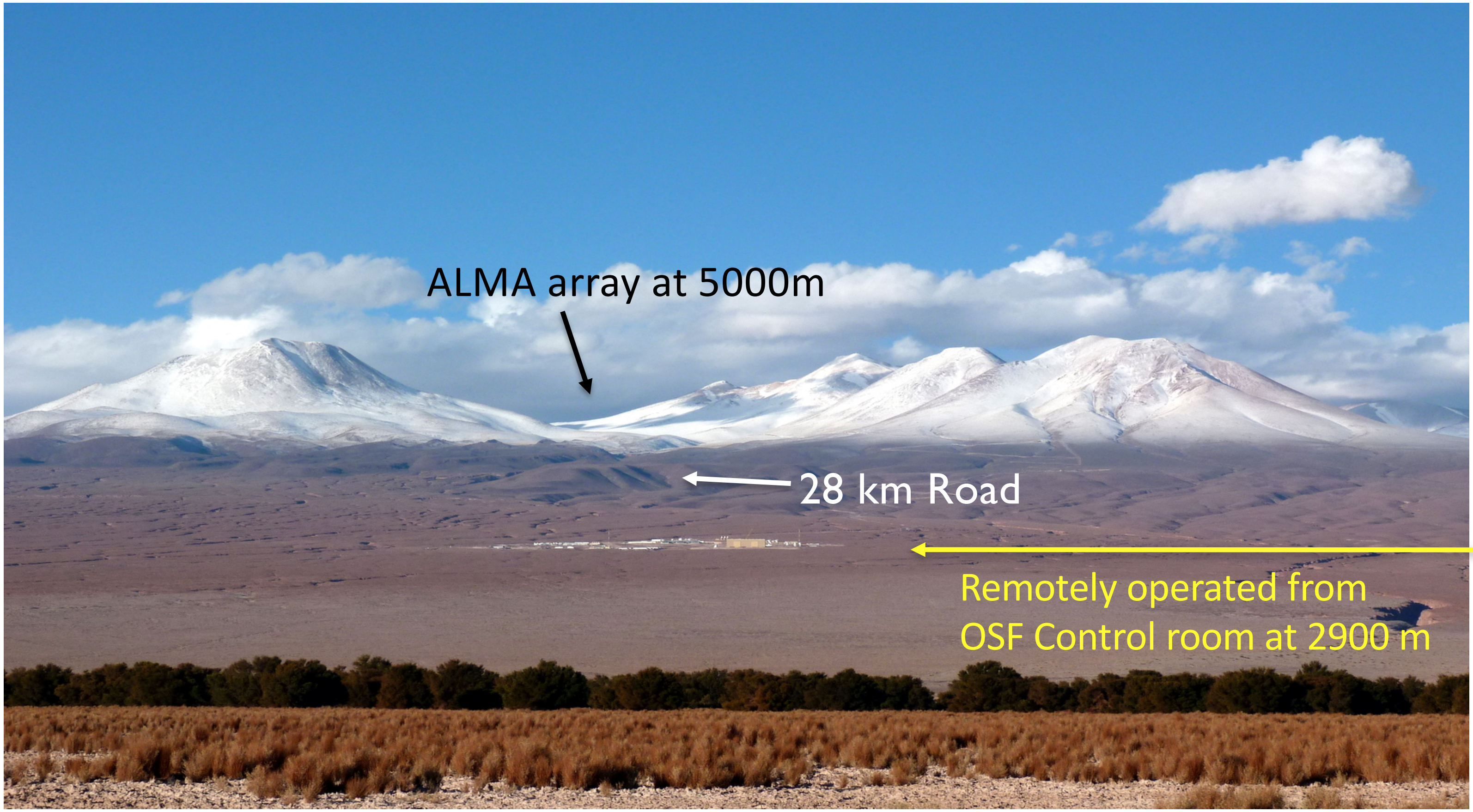
- Santiago Central Office
- Operations Support Facility (OSF)
- Array Operations Site (AOS)

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

http://youtu.be/YMISe-C8GUs

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

Atacama Large Millimeter/submillimeter Array

In search of our Cosmic Origins

Search Site

Log in

About | Science | Proposing | Observing | Data | Processing | Tools | Documentation | Help

Cycle 8 Documents

Call for Proposals

Documentation supporting the current ALMA Call for Proposals – **Cycle 8**. Documents from previous Cycles are provided here.

Document	Description
ALMA Proposer's Guide	Contains all pertinent information regarding the ALMA Call for Proposals
ALMA Technical Handbook	A comprehensive description of the ALMA observatory and its components
ALMA Users' Policies	The long-term core policies for use of the ALMA and ALMA data by the science community
Observing With ALMA - A Primer	Introduction to interferometry and how to use ALMA
ALMA Proposal Template	LaTeX format. Recommended but not mandatory
ALMA Proposal Review Process	The latest version of the ALMA Principles of the ALMA Proposal Review Process

Contents

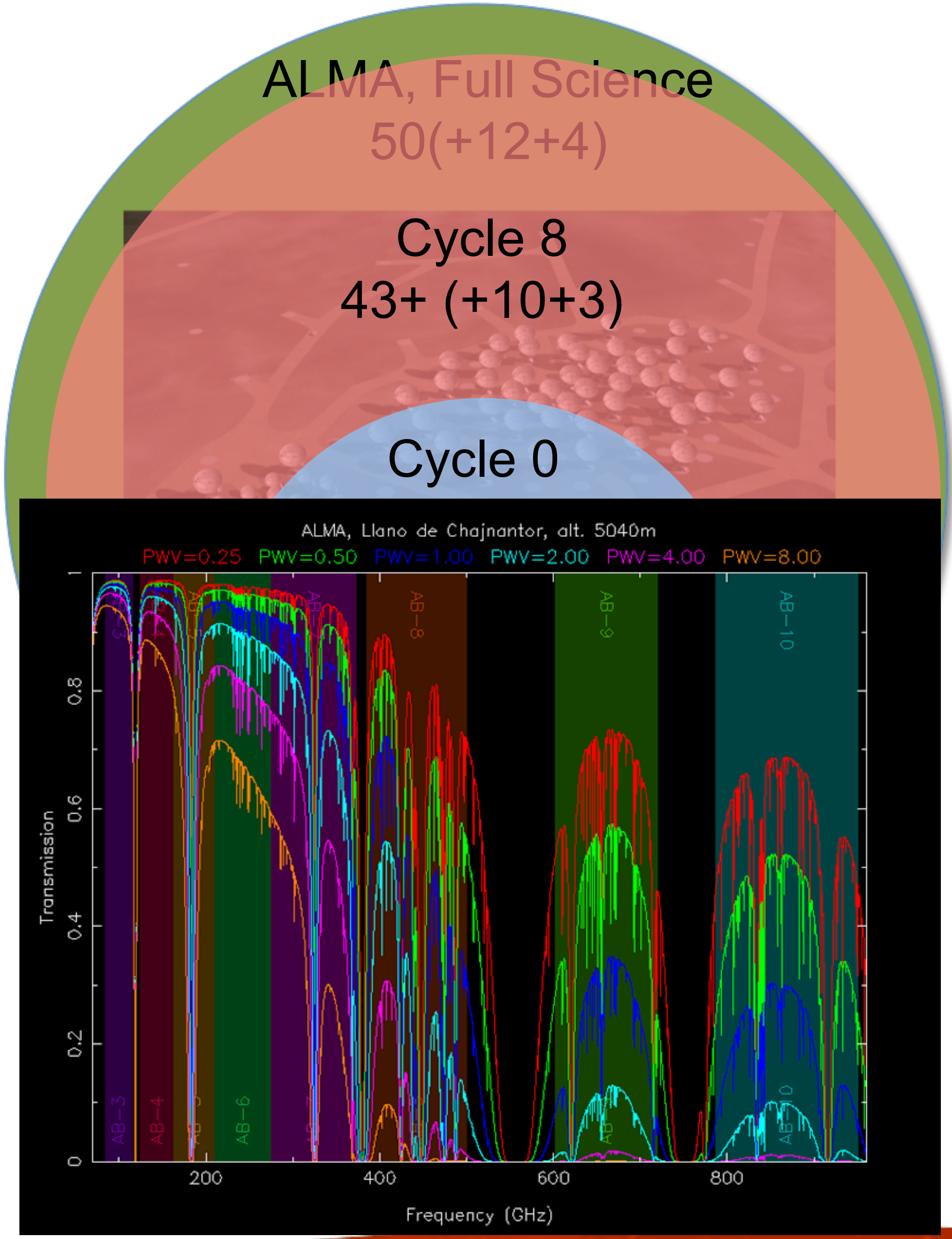
ALMA is a telescope for *all* astronomers

You do not need to be an expert to propose :-)

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

ALMA Current Status

- Construction Project ended in September 2014
- Routine science observing has been out to **greater than 16 km baselines (C43-10)** 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 7 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… however, first on to science!

ALMA Cycle 8 Capabilities

ALMA Capabilities

- **The Cycle 8 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**
  - Maximum baselines for the antenna configurations will vary from 0.16 km to 8.5 km. Configurations C-9 and C-10 will not be offered in Cycle 8.
  - Maximum baselines of 3.6 km for Bands 8, 9 and 10
  - Maximum baselines of 8.5 km for Bands 3 to 7
  - 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, 4, 5, 6, and 7 on the 12-m Array.
  - Linear polarization imaging of a compact source on-axis in both continuum and full spectral resolution modes is feasible at the level of 0.1% (3 sigma) fractional polarization for the very brightest calibrators, and 0.2% (3 sigma) level for a typical observation.
  - The minimum detectable degree of circular polarization is 1.8% of the peak flux for both continuum and full spectral resolution observations. (NOTE that Zeeman observations have not been fully commissioned and should be discouraged from proposing.)
  - 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 in Cycle 8

In Cycle 8 we continue to operate as what is been defined as "Steady State Operations"*

- **In Cycle 8, the following technical capabilities will be available for the first time:**
  - Solar observations in Band 5
  - VLBI observations of faint science targets (correlated flux density <500 mJy within an unresolved core on ALMA baselines up to 1 km). These observations will be done in passive phasing mode, where it is recommended to have a bright calibrator within 5 deg of the science target.
  - High-frequency observations (Bands 9 and 10) with the stand-alone 7-m Array
  - Mosaicking of continuum linear polarization observations (Bands 3 to 7)
  - Spectral scans with the 7-m Array
  - 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

ALMA Capabilities

- **Observing Time:**
  - 4300 hours for successful proposals of PI programs expected on the 12m Array (includes DDT, Cycle 4 Carryover and resubmissions)
  - 3000 hours available on the ACA*
  - 3000 hours available on the Total Power Array*
    - ~2500? Hours of ACA time will be available through the Supplemental Call in mid-Cycle 8.
- **Observing Time (other notes):**
  - Strongly encourage ACA only observations in a wide range of science and large observing times.
  - Also encourage "medium size" proposals of about 10-30 hours
  - ALMA encourages PIs to submit larger, more ambitious proposals. Therefore, there is no longer a cap on the total time that can be allocated to Large Programs. Further, Large Programs and proposals that require more than 25 hours on the 12-m Array will have first priority to fill at least 10% of the observing queue.

ALMA Capabilities

"Also encourage "medium size" proposals of about 10-30 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!!!!**

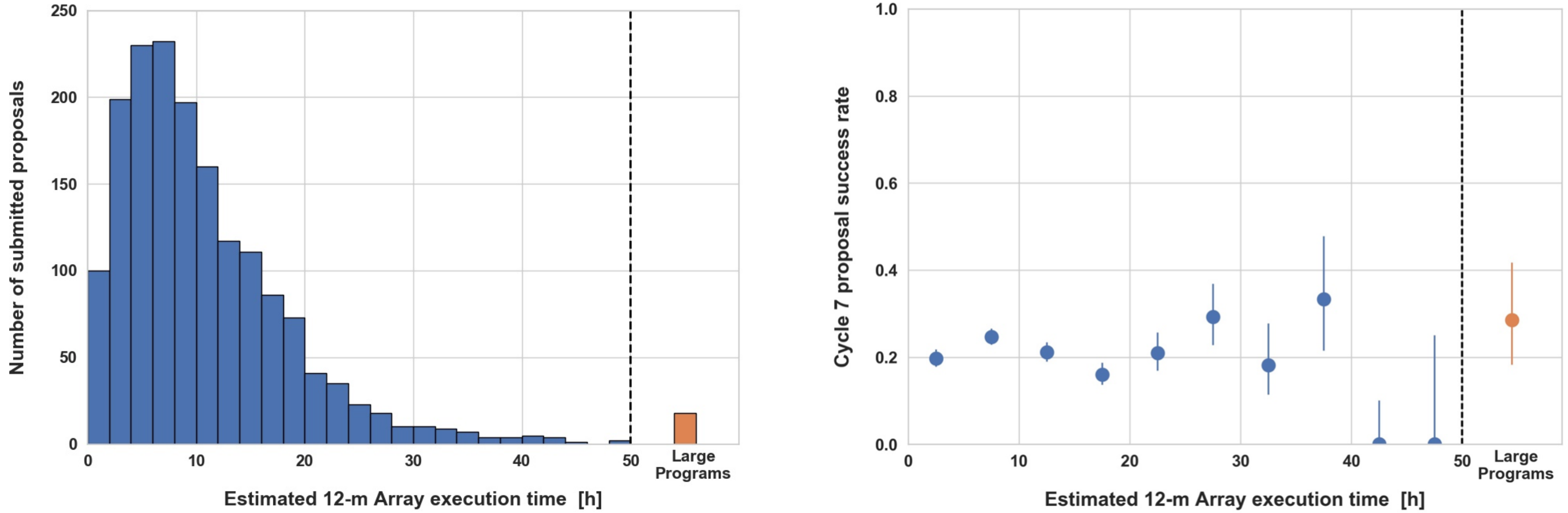


Figure 1: (Left) Number of proposals submitted as a function of the 12-m Array execution time in Cycle 7. (Right) The fraction of proposals (with 1sigma confidence intervals) that are assigned priority Grade A or B as a function of the estimated 12-m Array time.

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

ALMA Capabilities – NEW!!!

Dual-Anonymous Proposal Review

- Proposals in Cycle 8 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 8 2021.
- Distributed peer review will be used for all proposals requesting less than 25 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 and proposals requesting 25 hours or more on the 12-m Array 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??? 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 8 will include Regular, Very Long Baseline Interferometry (VLBI), Target of Opportunity, and Large Program. 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 2021 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:

- Polarization observations
- Bandwidth switching projects (having less than 1 GHz aggregate bandwidths over all spectral windows)
- Solar observations
- VLBI observations
- Non-standard calibrations (user-defined calibrations selected in the OT)
- 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 8 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. Same may never be considered a standard mode
- **Observing Time:**
  - Up to 4500 hours+ for successful proposals of PI programs expected on the 12m Array (includes DDT, Cycle 7+ 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 8 Timeline

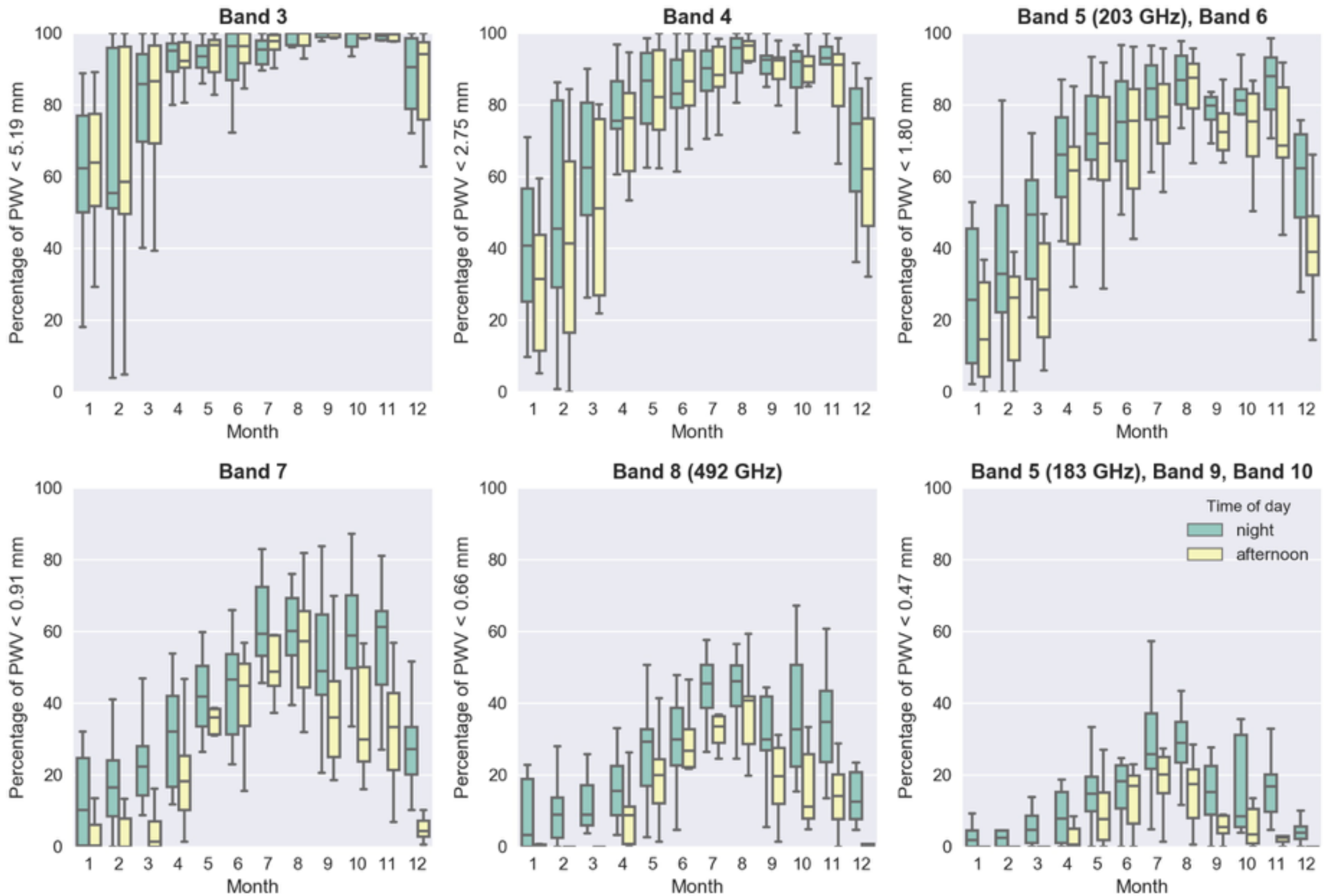
Date	Milestone
17 March 2021 (15:00UT)	Release of Cycle 8 Call for Proposals, Observing Tool & supporting documents and Opening of the Archive for proposal submission.
21 April 2021 (15:00 UT)	**Proposal submission deadline**
August 2021	Announcement of the outcome of the Proposal Review Process
08 September 2021 (15:00 UT)	Call for Proposals and Supplemental Call submission server opened
October 2021	Start of ALMA Cycle 8 Science Observations
06 October 2021 (15:00 UT)	**Deadline to submit Supplemental Call proposals**
September 2022	End of ALMA Cycle 8

ALMA Array Configuration Schedule (Cycle 8)

- Antenna configurations for the main 12-m array will use a new nomenclature in Cycle 8.
  - Configurations will be called C-1, C-2, and so on up to C-10, with C-1 having similar characteristics to the C43-1 configuration of Cycle 7, and likewise for the others.
  - Cycle 8 will NOT include the two longest baseline 12-m array configurations, C-9 and C-10.
- Maximum baselines in Cycle 8 will therefore be 8.5 km in configuration C-8.
- Configurations C-9 and C-10 with maximum baselines of 13.9 km and 16.2 km, respectively, will again be available in Cycle 9.
- **NOTE: No PI observing takes place in Feb!**
- The forward-looking configuration schedule (through Cycle 9) can be found at: https://almascience.nrao.edu/observing/observing-configuration-schedule/long-term-configuration-schedule

Start date	Configuration	Longest baseline	LST for best observing conditions
2021 October 1	C-8	8.5 km	~ 22h – 10h
2021 October 20	C-7	3.6 km	~ 23h – 11h
2021 November 10	C-6	2.5 km	~ 1h – 13h
2021 December 01	C-5	1.4 km	~ 2h – 14h
2021 December 20	C-4	0.78 km	~ 4h – 15h
2022 January 10	C-3	0.50 km	~ 5h – 17h
2022 February 1-28	No observations due to February Maintenance		
2022 March 1	C-1	0.16 km	~ 8h – 21h
2022 March 26	C-2	0.31 km	~ 9h – 23h
2022 April 20	C-3	0.50 km	~ 11h – 1h
2022 May 10	C-4	0.78 km	~ 13h – 3h
2022 May 31	C-5	1.4 km	~ 15h – 5h
2022 June 23	C-6	2.5 km	~ 16h – 6h
2022 July 28	C-5	1.4 km	~ 17h – 7h
2022 August 18	C-4	0.78 km	~ 19h – 8h
2022 September 10	C-3	0.5 km	~ 20h – 9h

ALMA Observing Strategies (Cycle 8)



- Box and whisker plots of the percentage of time that the precipitable water vapor (PWV) is less than the thresholds adopted for the various ALMA bands versus the month of the year. Results are shown for both night time (green) and mid-afternoon (yellow), and assume a source elevation of 60 degrees. The horizontal line within a box indicates the median, the boundaries of a box indicate the 25th- and 75th -percentile of the distribution, and the whiskers indicate the highest and lowest values of the distribution. The PWV measurements were obtained by the APEX weather stations between 2007 and 2017.

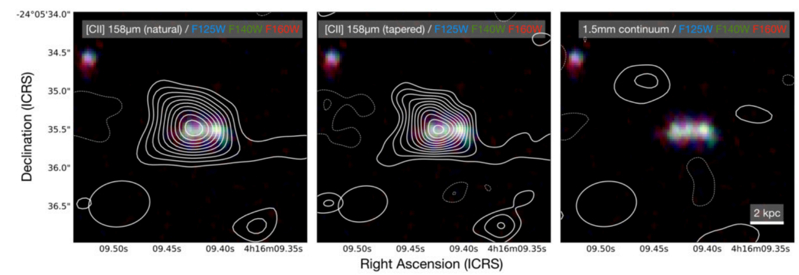
NAASC Sources of Support

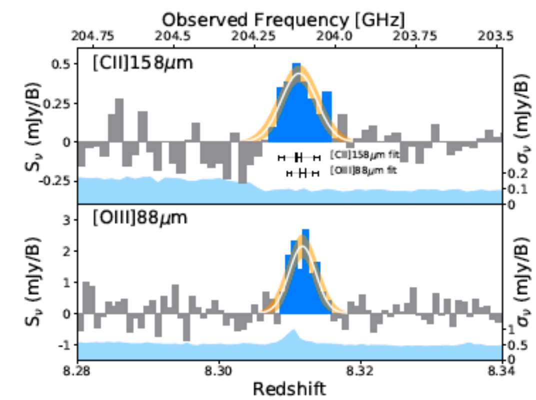
- **ALMA Helpdesk:** User support is a priority so questions are usually answered within 48 hours (with around the clock staffing in the week leading up to the proposal deadline) - https://help.almascience.org
- **Student Observing Support:** Successful ALMA proposals will be invited to apply for up to $35k to support undergraduate or graduate student involvement - https://science.nrao.edu/opportunities/student-programs/sos
- **NAASC Financial Support for Workshop/Conferences:** The NAASC invites scientists to apply for funding in support of upcoming conferences and workshops. - https://science.nrao.edu/facilities/alma/community1/NAASC-Conference-and-Workshop-Support
- **Page Charges:** Upon request NRAO covers page charges for authors at US institutions when reporting results from ALMA/VLA - https://library.nrao.edu/pubsup.shtml
- **Face-to-face Visitor Support:** Upon request NRAO will cover the travel expenses of up to 2 people from 2 teams per week to come to the NAASC to get support for data reduction, proposal preparation, etc… We also have long term visitor support as well - https://science.nrao.edu/facilities/alma/visitors-shortterm
- **ALMA Ambassadors:** You too can become an ALMA Ambassador. For program eligibility visit - https://science.nrao.edu/facilities/alma/ambassadors-program

ALMA Science Highlights

ALMA uncovers the [CII] emission and warm dust continuum in a z = 8.31 Lyman break galaxy

- ALMA detection of the [CII] 157.7 μm emission from the Lyman break galaxy (LBG) MACS0416_Y1 at z = 8.3113
- The luminosity ratio of [OIII] 88 mu to [CII] is 9.31 $\pm$ 2.6,
  - indicative of hard interstellar radiation fields and/or a low covering fraction of photo-dissociation regions.
  - The emission of [CII] is cospatial to the 850 mu dust emission (90 mu rest-frame, from previous campaigns),
  - Peak [CII] emission does not agree with the peak [OIII] emission, suggesting that the lines originate from different conditions in the interstellar medium.
  - We fail to detect continuum emission at 1.5 mm (160 μm rest-frame placing a strong limit on the dust spectrum
  - suggests an unusually warm dust component (T > 80 K, 90% confidence limit), and/or a steep dust-emissivity index beta_dust} > 2), compared to galaxy-wide dust emission found at lower redshifts (typically T ~30 – 50 K, beta_dust}~ 1 – 2).
- If such temperatures are common, this would reduce the required dust mass and relax the dust production problem at the highest redshifts.
- We recommend a more thorough examination of dust temperatures in the early Universe, and stress the need for instrumentation that probes the peak of warm dust in the Epoch of Reionization.





T. Bakx, Y. Tamura, T. Hashimoto, et. al. arxiv: 2001.02812

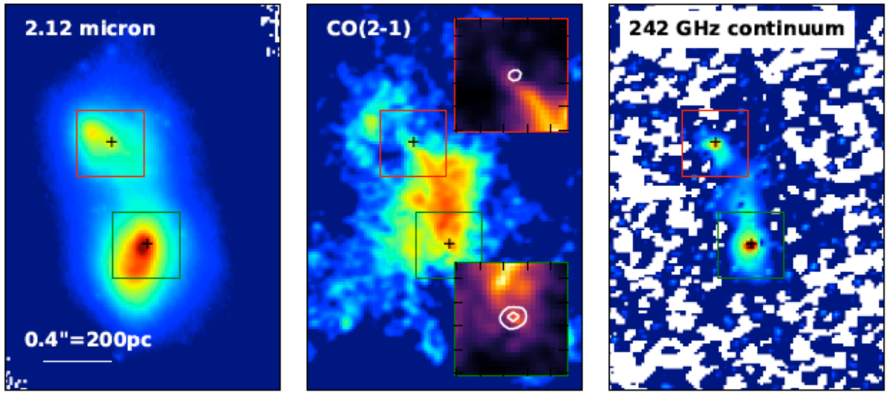
How Much 'Black Hole' Mass is Molecular?

How to Fuel an AGN: Mapping Circumnuclear Gas in NGC6240 with ALMA

Medling, Privon, Barcos-Muñoz+ 2019 arXiv 1910:12967

- Significant molecular gas mass contaminates dynamical black hole mass measurements; an important discovery showing a critical need for high resolution observations of molecular gas such as these with Band 6 at 30x60pc resolution. Up to 90% of the inferred mass in the southern nuclear region is molecular!
- In the south nucleus, and in the sum of the two, these corrections are sufficient to reduce the implied black hole masses to within the scatter of black hole scaling relations.
- dynamical black hole mass measurements must resolve this small scale – or correct for the gas mass present – to measure accurate black hole masses. The two black holes in this work show different levels of correction, with gas masses making up 5%-11% of the original black hole mass measurement in the north and 6%-89% in the south black hole.
- The amount of gas near a quiescent black hole could be minimal compared to that around a gas-rich obscured AGN like NGC 6240; this variability must be characterized before statistical corrections can be made to other black hole mass measurements.

FUEL FOR NGC 6240'S BLACK HOLES 3



Left : Keck NIRC2 K-band image of NGC 6240, highlighting the two nuclei (Max et al. 2005).
Center: ALMA Band 6 moment 0 maps of CO(2-1) integrated over 1200 km s^{-1}. Insets: nuclear regions in a different color scale for clarity, with continuum contours from right panel overlaid. Images are rescaled in each panel to show structure; details in Notes.
Right : Rest frequency 242 GHz continuum contours from the same dataset peak at the locations of the two AGN. Note that the millimeter continuum lines up with the kinematic centers of the K-band disks and not the photocenters, due to the large amount of dust present between the two nuclei that attenuates half of each disk even in the near-infrared.

Brown Dwarf Protoplanetary Disks

E. Sanchis, L. Testi, A. Natta, C. F. Manara, B. Ercolano, T. Preibisch, T. Henning, S. Facchini, A. Miotello, I. de Gregorio-Monsalvo, C. Lopez, K. Mužić, *I. Pascucci*, A Santamaría-Miranda, A. Scholz, M. Tazzari, S. van Terwisga, *J. P. Williams*

- New 890 μm continuum ***ALMA*** observations of 5 brown dwarfs (BDs) with infrared excess in Lupus, in combination with 4 BDs previously observed, allowed us to study the mm properties of the full known BD disk population of this nearby star-forming region.
  - 5 out of the 9 BD disks show dust emission.
  - BD disks are extremely compact--only one source is marginally resolved.
  - These BDs have low estimated accretion rates, and assuming that the mm-continuum emission is a reliable proxy for the total disk mass, disk dust masses are very low.
- This suggests that either BD systems are unable to form planets, or, more likely, rocky planetary cores are formed within the first Myr
- Examples of low mass objects—brown dwarfs—show that even in nearby Lupus, ALMA's sensitivity and resolution are scarcely adequate.

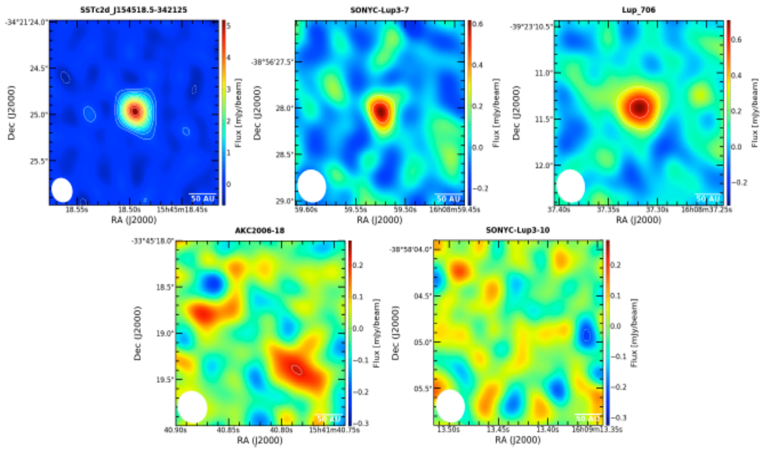
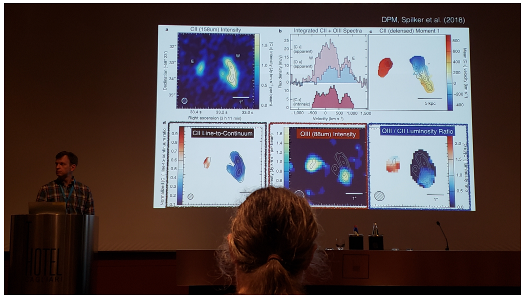


Fig. 2. Dust continuum images at 890 μm of the Lupus BDs disks survey from ALMA Band 7 observations. The beam size FWHM is $0.27'' \times 0.24''$ for the J154518.5-342125 map (robust parameter of -1), and $0.36'' \times 0.33''$ for the rest of the maps (robustness $= +0.5$). The average beam position angle is $PA = 28^{\circ}$. The contours are drawn at increasing (or decreasing) 3σ intervals as solid (dashed) lines.

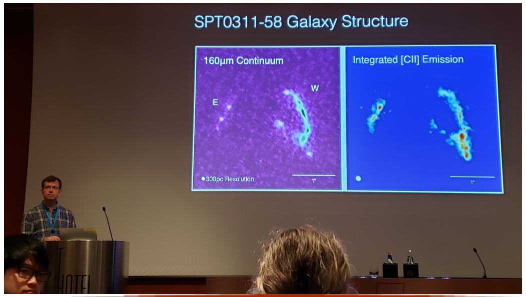
Massive Galaxy Formation in the Reionization Era

Dan Marrone

- ALMA finds many z~6-7 objects, or which many cluster or merge.
  - Galaxy Formation must have begun earlier.
  - South Pole Telescope survey with ALMA followup very productive
  - ~80 spectroscopic redshifts median z=3.9.
  - Summed spectrum shows many lines.



- Spotlight on SPT0311-58
  - Image may be lensed.
  - [CII] shows two sources little magnified.
  - Few 10^11 solar masses shortly after t=0! Spilker+18.
  - OIII emission extent limited.
  - 50milliarcsec ALMA observations show structures.



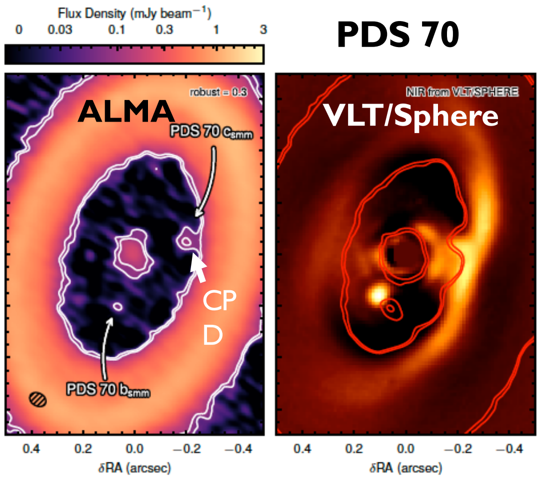
ALMA Observes Planet Formation in Protoplanetary Disks

PDS 70 is 5 Myr old low mass (0.76M_{Sun}) T Tauri star 110 pc distant

- arXiv:1906.06308: Isella et al.
- Surrounded by dust rings at 74 and 10 AU
- In the inter-ring gap, it harbors two VLT-detected Jovian mass planets, b and c
- ALMA image of closer-in, PDS70b, shows dust trailing it
- The image also shows a **circumplanetary disk (CPD) around PDS70c**, with M_{dust}~.002 to .004 M_{Earth}

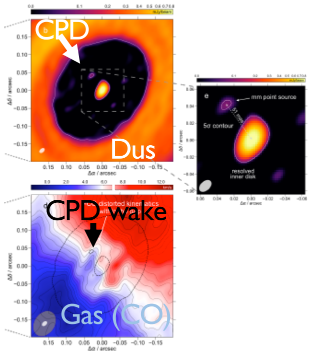
HD 100546 is 4.8 Myr old Be star (~2.2M_{Sun}) 103 pc distant

- arXiv:1906.06305: Perez et al. and 1906.06302: Casassus & Perez
- Surrounded by asymmetric dust ring at 20-40 AU
    - Within the gap at 7.8 AU lies a candidate CPD of dust mass 1 M_{Moon}
    - The feature coincides with a localized CO gas velocity kink and a Doppler-flip signature expected along the spiral wakes
- **Observations like these are pushing the limits of ALMA's current spectral line sensitivity**



(L) ALMA image showing rings of dust and a gap, which contains two planets. (R) Near-IR image from VLT/Sphere

HD100546



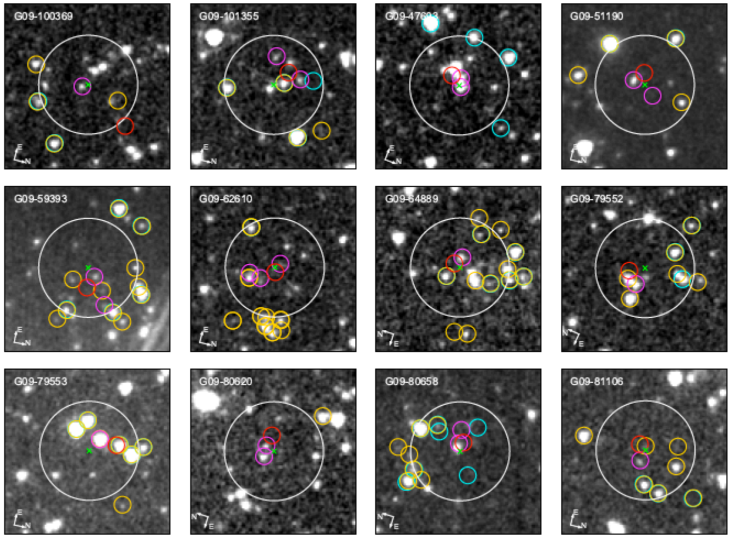
(L) Dust (greyscale) and (R) CO velocity anomaly (color) suggest a perturbation ('wake')

Ultrared dusty, star-forming galaxies:

The most luminous, massive, and active galaxies in the early universe.

Ma, Cooray et al arxiv: 1908.08043

- High-resolution ALMA, NOEMA, and SMA data pinpoint 63 of the rare, intrinsically most dusty, luminous and massive galaxies in the early universe from the Spitzer catalog of Herschel-selected objects.
  - Interferometry pinpoints locations for secure ID as lensed or unlensed based on the morphology and field population
  - 65% unlensed, 27% multiple, <z>~3.3, M_*~3.7×10^{11} $M_\odot$, SFR~730 $M_\odot yr^{-1}$, L_{Dust} ~9.0×10^{12} $L_\odot$, M_{Dust}~2.8×10^9 $M_\odot$, and V-band ~4.0
  - All more extreme than ALESS field
- Conclude stellar mass density at z~5 is significantly lower than that of the massive, quiescent galaxies at lower redshifts.
- Cannot account for the majority of the star-forming progenitors of the massive, quiescent galaxies. Our sample is limited by the flux density levels probed by Herschel thus contains more FIR-luminous and rarer DSFGs than the progenitors of the massive, quiescent galaxies found in NIR surveys.
- The HyLIRGs identified are potentially extremely valuable for galaxy evolution study; they present the most luminous, massive, and active galaxies in the early universe.



60" x 60" Spitzer/IRAC cutouts centered on the Herschel positions (green cross). Magenta circle show high-resolution positions from ALMA, NOEMA, and/or SMA.

New Understanding of Galactic Star formation

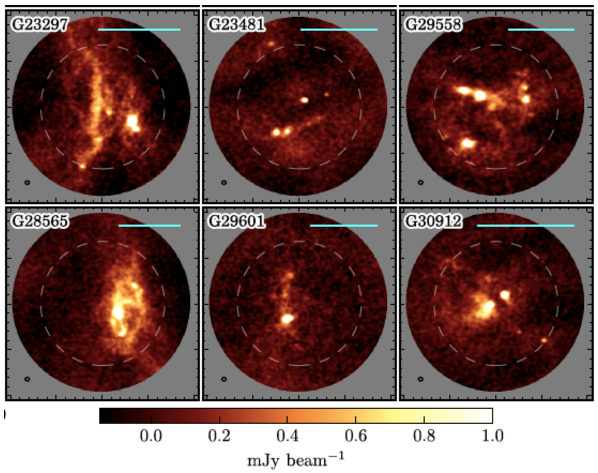
Low Mass Young Stellar Objects in Ophiuchus

1.3 mm ALMA dust continuum images with polarization E-vectors at 0.25" = 35 au resolution

14/37 detected at current sensitivity

Majority consistent with dust self-scattering in optically thick disks rather than magnetic fields

Sadavoy et al. 2019, ApJS, 245, 2



Significant fragmentation at an early stage in massive starless clump candidates suggest hierarchical fragmentation process

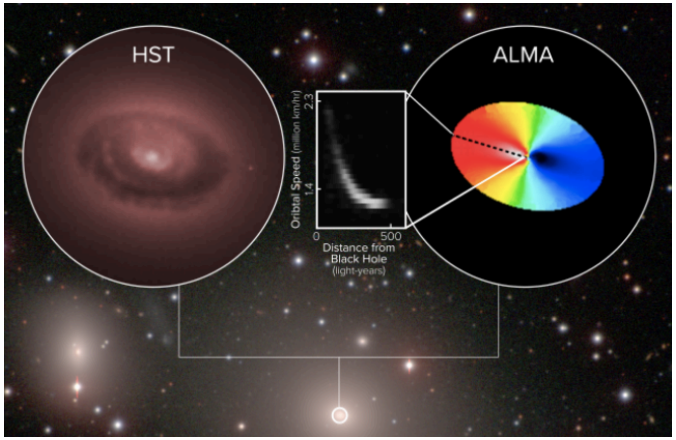
Svoboda et al. 2019, ApJ, 886, 36

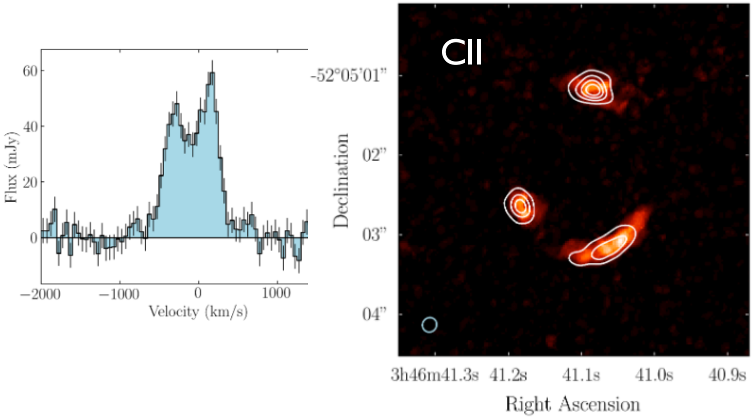
Building Monsters

A close-up view of the cold CO (2-1) gas rotating around the supermassive blackhole:
$M = 2.249 \times 10^9 M_\odot$
at the center of the elliptical galaxy NGC3258

Resolution 0.1" = 150 pc

Boizelle, et al. 2019, ApJ, 881, 10





[CII] line in SPT0346-52: A lensed galaxy at z =5.6559 (Wei et al. 2013) undergoing a major merger

- Lensing magnification ~5.6 ± 0.1
- L_{FIR} =1.23 10^{14} L_{sun}
- Star formation rate density, is 4200 $M_\odot$ yr^{-1} kpc^{-2} -- one of the highest of any known galaxy (Spilker et al. 2015 2016)

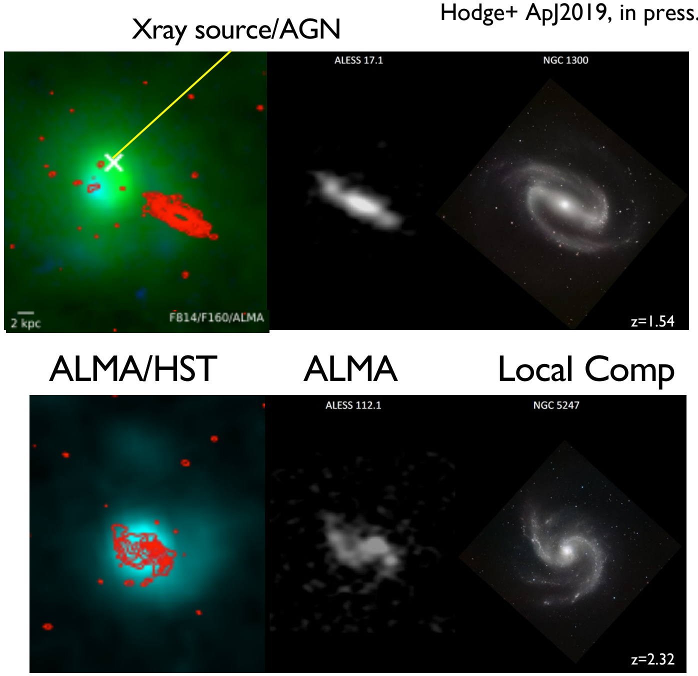
Litke et al. 2019, ApJ,, 870, 80L

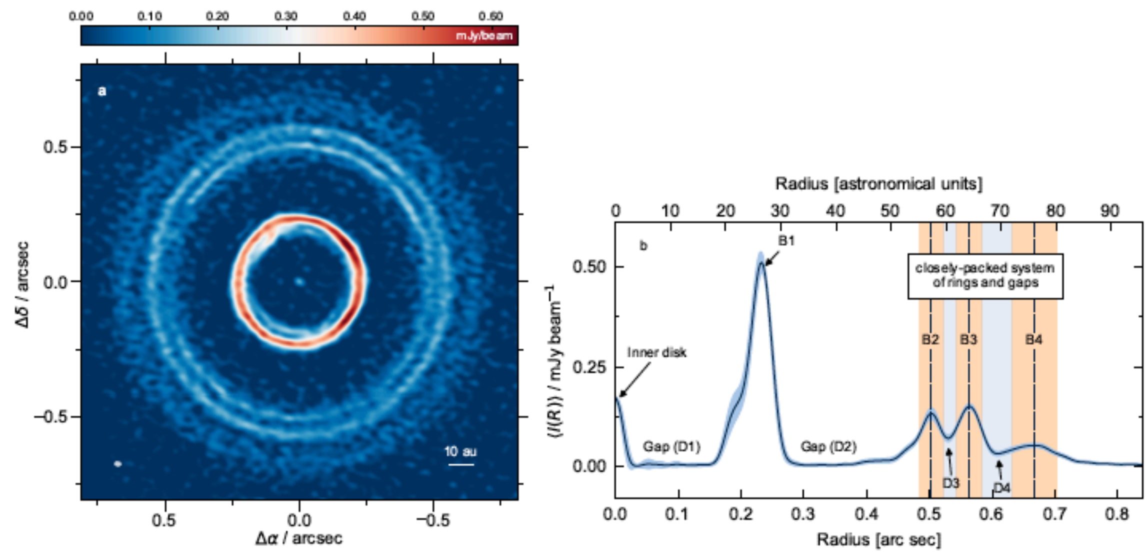
ALMA Images Nascent Galaxy Structure

ALMA 0.07" (0.5kpc) imaging of rest-frame FIR emission from 6 SMGs at z~1.5 < z < 4.9

- Robust sub-kpc structure on underlying exponential disks (FWHM ~few kpc)
- Often poor correlation with HST: ALMA seeing heavily dust-obscured cores only
- Structures suggest spiral arms, edge-on nuclear emission (bars)

Hodge+ ApJ2019, in press.



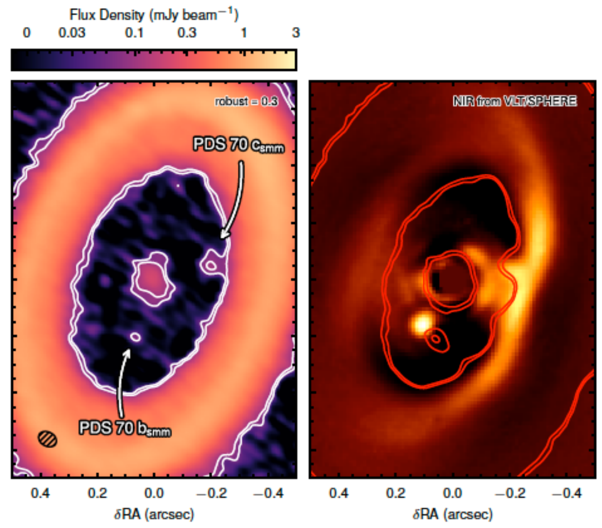


- Tight narrow rings in HD169142 are all produced by one planet. Core accretion, or any bottom up process, can thus produce planet embryos at 65AU and outside the orbit of inner giants in at least some disks.

ALMA Images Circumplanetary Disks I. PDS70

arXiv:1906.06308 Isella, Benisty, Teague, Bae, Keppler, Facchini, Pérez

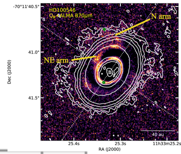
- ALMA's revolutionary images of Circumstellar Disks transformed ideas of how planets form
- Circumplanetary disks-requiring higher sensitivity and resolution-have now been identified
  - These disks may regulate the flow of material from disk to protoplanet
  - They also may provide material for the formation of planetary moons
- PDS70 is 5 Myr old low mass ($0.76M_{Sun}$) T Tauri star 110 pc distant
  - It is surrounded by rings of dust at 74 and 10AU from the star
- In the inter-ring gap, it harbors two VLT-detected Jovian mass planets, b and c
  - ALMA image of the closer-in, PDS70b, shows dust trailing it
  - The image also shows such a disk around PDS70c, whose IR and H characteristics suggest it is a full-fledged planet
    - For the CP disk, M_{dust}~.002 to .004 M_{Earth}
    - Optical, NIR, and (sub)millimeter observations are highly complementary,
      - probing diverse aspects of planet accretion processes and
      - are affected by different systematic errors.
- ALMA's relative astrometric accuracy is comparable to that achieved in the optical/NIR and is not contaminated by direct or scattered stellar light



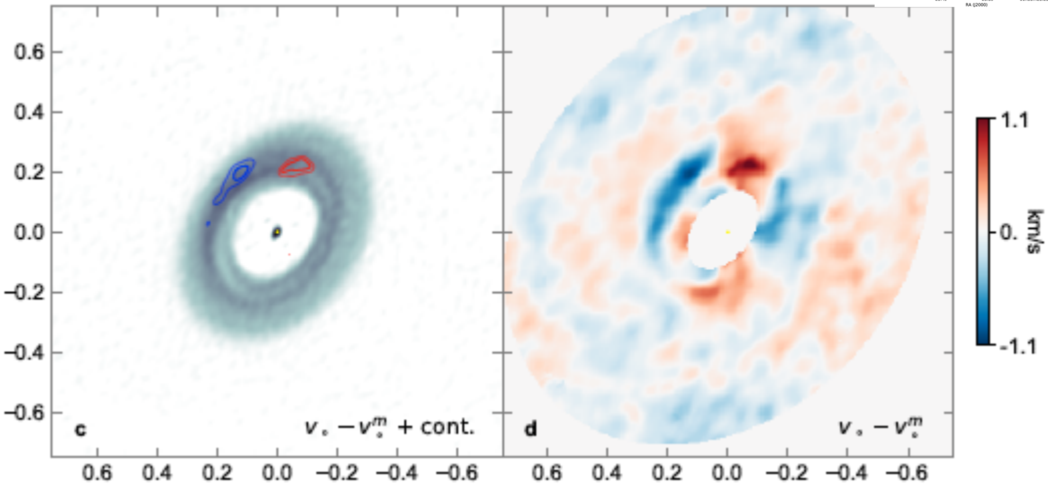
L) ALMA image showing rings of dust and a gap, which contains two planets
R) Near-IR image from VLT/Sphere

ALMA Images Circumplanetary Disks II. HD100546

arXiv:1906.06305: Perez, Casassus, Hales, Marino, Cheetham, Zurlo, Cieza, Dong, Alarcon, Benitiez-Llambay and Fomalont and 1906. 06302 Casassus and Perez



- Circumstellar disks grow planets; giant planets interact dynamically with the whole disk
  - Growth of planets should be regulated by an accreting circumplanetary disk (CPD) and its immediate environment
  - Characterization of the CPD, is critical to develop planet formation theories.
- HD100546 is 4.8 Myr old low mass (~2.2M_{Sun}) Be star 103 pc distant
  - It is surrounded by dust in an asymmetric ring at 20-40 AU and 15M_{Earth} of dust 1.8AU from the star; gas extends more than 300AU in an extended disk.
    - Within the gap at 7.8AU lies an unresolved feature which may be a CPD of dust mass 1 M_{Moon}
    - The feature coincides with a localized CO velocity kink
    - VLT/Sphere observations exclude a stellar companion
  - A second feature shows a Doppler-flip signature expected along the spiral wakes, within the continuum ring



(L) Dust (greyscale) and R CO velocity anomaly (color) suggest a perturbation ('wake') at PA~5° r~0.25" within the dust disk. Inset: SPHERE/ZIMPOL data show a spiral feature (Pineda+18 ApJ 871)

Dust Polarization Toward Embedded Protostars in Ophiuchus with ALMA

Sarah I. Sadavoy, Ian W. Stephens, Philip C. Myers, Leslie Looney, John Tobin, Woojin Kwon, Benoit Commercon, Dominique Segura-Cox, Thomas Henning, Patrick Hennebelle 1909.02591

- 0.25" (35AU) resolution 1.3mm dust polarization images
- 37 Oph YSOs (all embedded protostars plus others)
- 9/14 of detected sources consistent with dust self-scattering in optically thick disks
  - All 6 youngest (Class 0) sources detected
  - 44% of Class I sources detected
  - no agreement between the polarization morphology on clump scales as seen from monolothic telescopes with the polarization morphology detected on < 100 au scales from the ALMA data
- Dust polarization may not be a good tracer of magneticfield structures on disk scales, particularly for inclined disks
- Remaining sources may trace magnetic fields

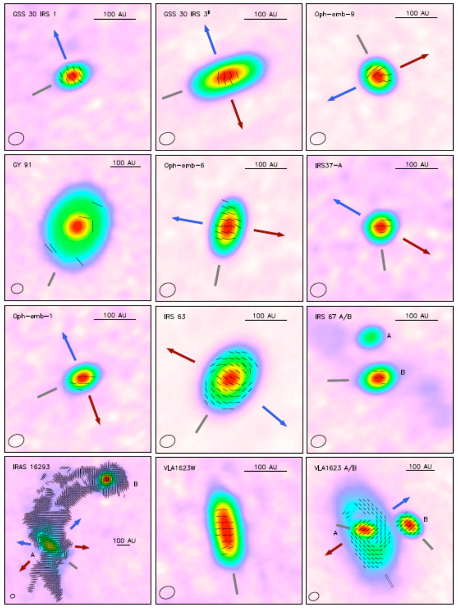
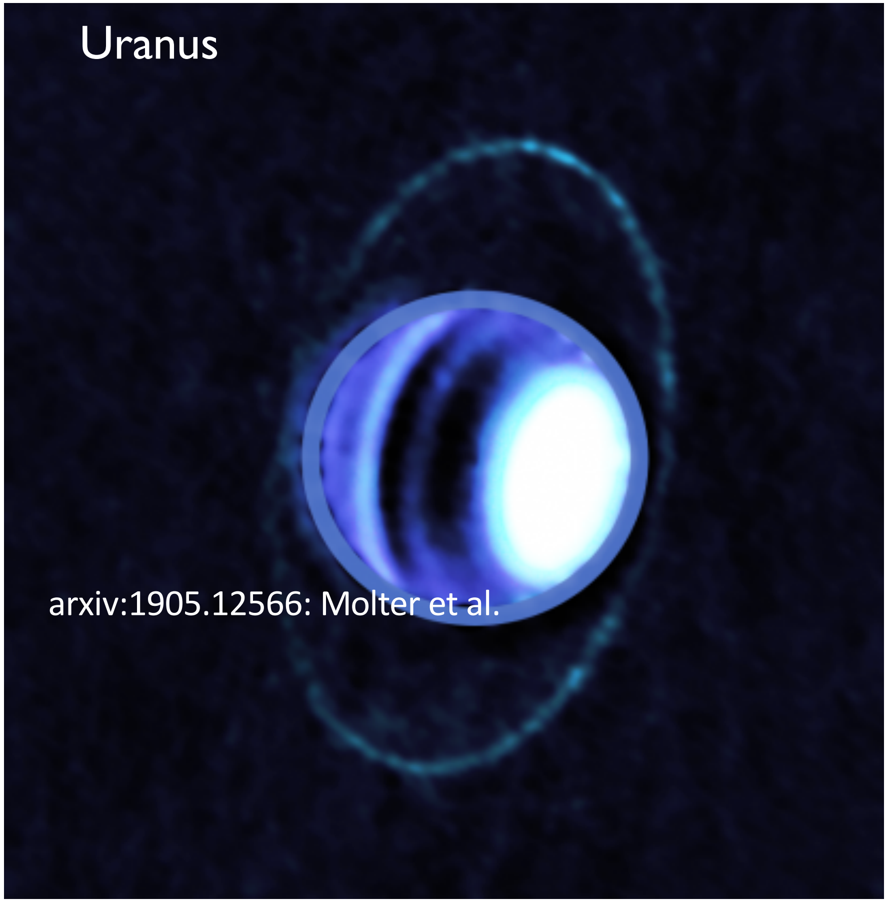


Figure 3. The 14 continuum sources with polarization detections. Background images show the Stokes I maps on a logarithmic color scale (see Appendix A for the flux scale) and the black line segments show the normalized e-vectors. Sources with ‡ are outside of the inner third of the primary beam FWHM. The blue and red arrows indicate the outflow position angle, if known (see Section 4.1 for details). The grey bars show the semi-major axis position angle of the continuum sources detected in polarization, except IRAS 16293B as this source is near face-on and does not have a well constrained continuum position angle. For VLA 1623 A, we show two grey bars: the solid one shows the position angle of the compact disk from Harris et al. (2018) and the open one shows the position angle of the extended disk.

Extraordinary ALMA Images of Our Own Backyard

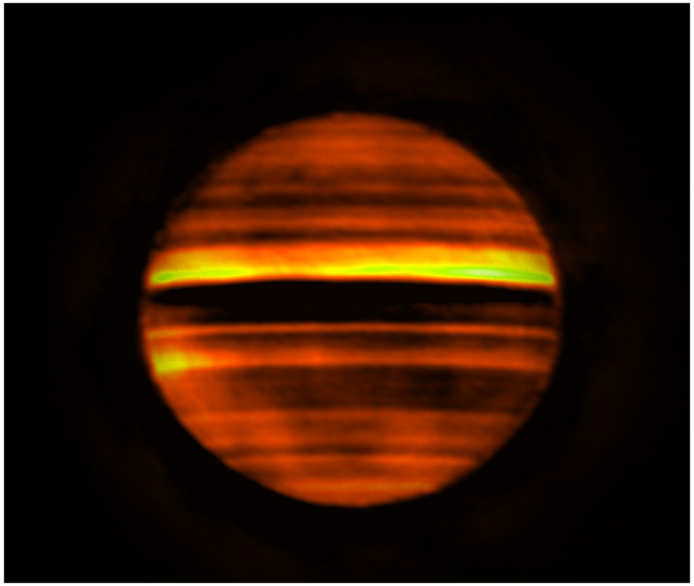
- Thermal emission from the Uranus **ε** ring shows micron-sized dust is not present in the ring system.
- Confirms the hypothesis, proposed based on radio occultation results (Gresh et al. 1989), that the main rings are composed of centimeter-sized or larger particles
- Temperature of rings: 77+-2K
- The other main rings are visible in a radial (azimuthally-averaged) profile at millimeter wavelengths.



ALMA Millimeter Wavelength Images of Jupiter

de Pater+ arXiv:1907.11820

- 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.

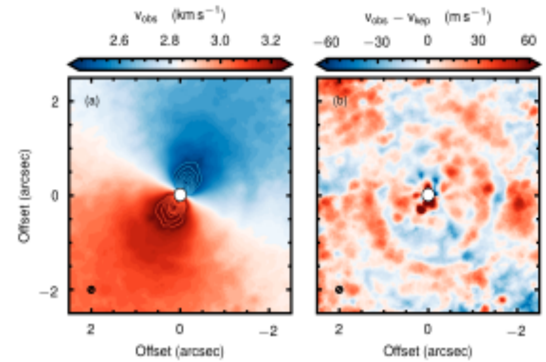


Using ALMA to Explore the Gas Reservoir of Planet Formation *(Cleeves+, AS2020)*

- Recently the DSHARP Large Program produced 20 protoplanetary disk images, continuum emission from dust
- Dust only explores a fraction of the disk story: disk gas
  - traces 99% of a protoplanetary disk's mass,
  - encodes all of the kinematic information, and
  - reveals the chemical reservoir for planet formation.
- To read the gas story requires both spatially and spectrally resolving key diagnostic line emission at relevant physical scales with ALMA
  - Key emission lines are inherently ~2 orders of magnitude less sensitive than the continuum.
- Current limitations of ALMA become apparent.
  - Presently, ALMA needs 130 hr to achieve ~10 -15 au resolution for spectroscopic study of only 5 targets (Oberg Large Program)
  - Solar mass star disks reside at distances of~140 pc
  - Massive star forming environment targets (e.g., Orion), lie beyond 400 pc.
- Cleeves et al (AS2020) find a 5-10x increase in spectral sensitivity coupled with an increase in spectral agility and bandwidth will both
  - dramatically improve our capability to directly detect protoplanets and
  - massively expand the sample size of surveys investigating the chemical environment in which exoplanets form.
- Key improvements: (1) Spectral Line Sensitivity (2) Spectral agility and bandwidth

Kinematic Detection of Planets in Formation

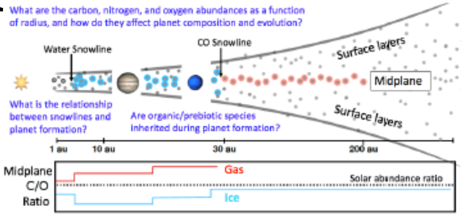
- Goal: find planets during formation, embedded in disk
  - High angular resolution optically using extreme adaptive optics seeking thermal or line (Hα) emission
  - High angular emission in the (sub)millimeter using ALMA, seeking circumplanetary disks, which could be seen to $0.03M_{lunar}$ but have not
  - Gas kinematic perturbations from embedded protoplanets (e.g. spiral wakes), producing orbital clearing or perturbed gas rotational velocity, seen in some sources
- Definitive identification would come through direct imaging of wake spiral pattern
  - May occur throughout the entire disk (visible to ALMA, or in NIR to JWST or ELTs)
  - Pattern is larger, allowing more distant or lower resolution detection; sensitivity still needed
- Example: TW Hya, nearest (60pc) disk: ALMA 6.6 hr, ^{12}CO(3-2) achieved 8au resolution revealed azimuthal structure, hinting at planet-driven features.



TW Hya at 8au resolution (Huang+18) l) ^{12}CO(3-2) r) residual with bulk Keplerian motion removed. Note hints of planet-driven features

Forming Planet Chemical Environment

- Chemistry highlights planet formation physics (e.g. through snowlines) and actively evolves as the planets form: both CO and water are depleted in disk surfaces relative to the ISM
  - Disk chemistry may control planetary composition but no disk chemical survey is available
  - Link between disk surface and icy planet-forming midplane unclear
  - Weak COM emission critical to determine interstellar prebiotic material inheritance
- ALMA's limited spectral surface brightness sensitivity limits our understanding
  - Understanding planetary chemical inheritance requires simultaneous observation of diagnostic lines; in particular an improvement of ALMA's
    - spectral sensitivity
    - increased bandwidth (≥2)
    - high spectral resolution
  - by 5-10x in the 2030 era

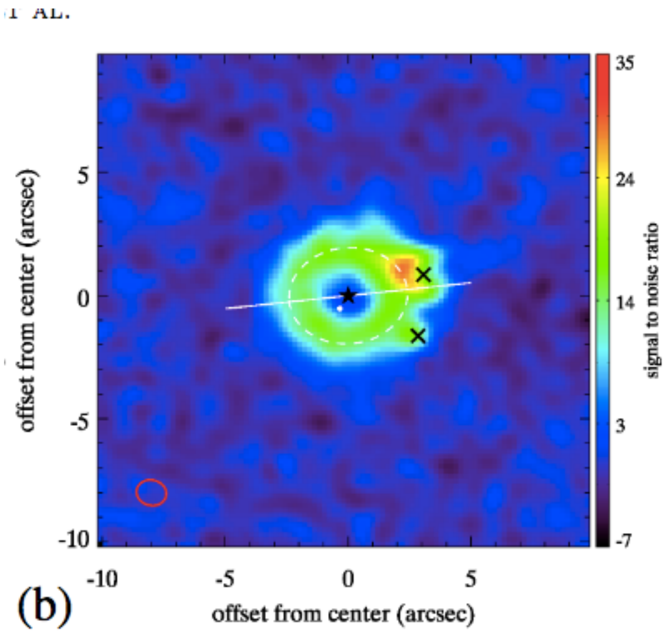


- This can be achieved by a combination of Increased collecting area, improved receivers and increases in bandwidth, efficiency and data rates of the ALMA signal processing system

Science Highlight (1)

ALMA Images First Kuiper Belt Analogue Around Sun-like Star

- HD 95086 is a 1.6 M_{sun} A star about 17 Myr years old, 83.8 pc from the Sun
- HD 95086 hosts a directly-imaged ~4M_{Jup} planet about 57 AU from the star
- ALMA has imaged a debris disk outside the planetary orbit
  - The disk is inclined 30°
  - The disk extends from an inner radius ~100 AU to an outer radius ~320 AU.
  - A bright source near the edge of the ring is almost certainly a background galaxy.
  - A second planet may shepherd the inner edge of the cold disk, could be 0.2-1.5 M_{jup}

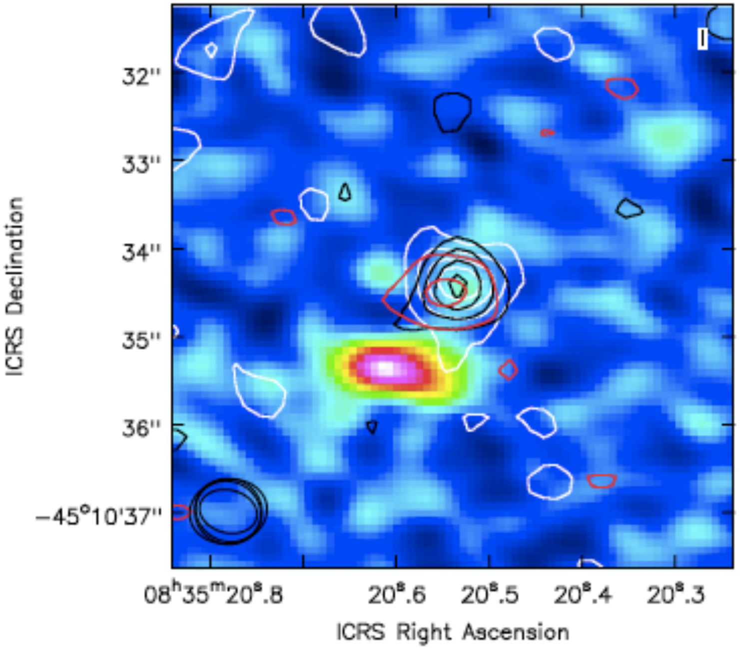


ALMA 1.3mm image of the Kuiper Belt analog disk around HD 95086 (black star). The optically imaged planet is represented by a white dot. The sources to the W are likely background galaxies, subtracted in this image. Disk major axis is white line. Su+ 2017 arXiv 1709.10129

Science Highlight (2)

ALMA Images Vela Pulsar

- ALMA Development Study results on pulsar observations are now available for download through the Science Verification page of the ALMA Science Portal.
  - Successful measurement of pulsar profiles were achieved on Vela
- Detections in non-time resolved mode were made on Vela, SgrA* magnetar, and Crab pulsar.
  - Vela pulsar was detected in ALMA Bands 3, 4, 6 and 7 (see B7 image)
  - Extended structure seen in B7 may be a counter-jet protruding from the pulsar



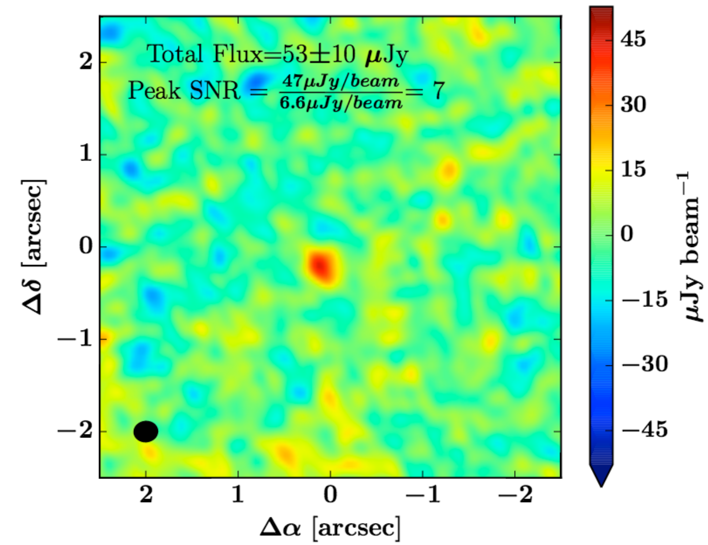
Vela Pulsar, ALMA B3,4,6 (contours) on B7 image; an extended structure, preliminarily detected in ground-based observations, may be a counter-jet protruding from the pulsar. (Mignani+, 2017)

Science Highlight (IV)

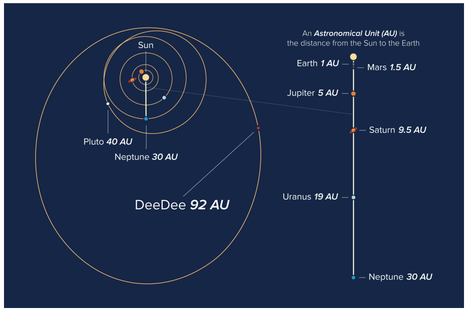
ALMA Characterizes TransNeptunian Object DeeDee

Gerdes et al., 2017 *ApJL*, **839**, L15.

- ALMA imaged 2014 UZ_{224}, or DeeDee*, measuring its thermal properties
- DeeDee lies at 92 AU from the Sun, twice the distance of Pluto. It's the 2nd most distant confirmed Solar System object, with a surface at 30K.
- ALMA data suggest a diameter of 635km, 2/3 that of Ceres; DeeDee is a dwarf planet candidate.
- Very dark, its albedo is only 13%.
  - **short for "Distant Dwarf*



Above: ALMA 1.3mm image



Left: DeeDee in the Solar System

Science Highlight (V)

ALMA Catches, Characterizes Massive Star Outburst

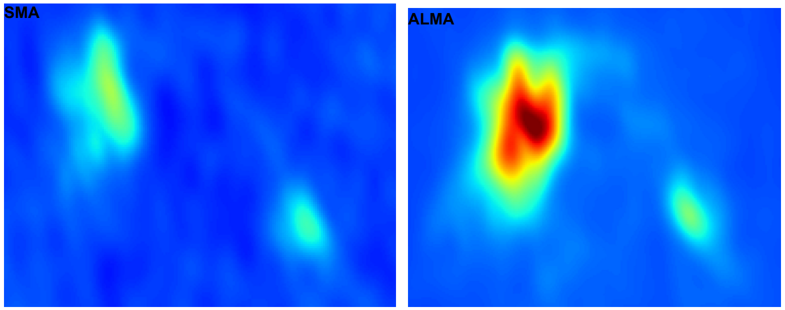
Recent outbursts in YSOs show similar features:

- Factors of 6-70x increase in L
- Sustained for many years (ongoing)

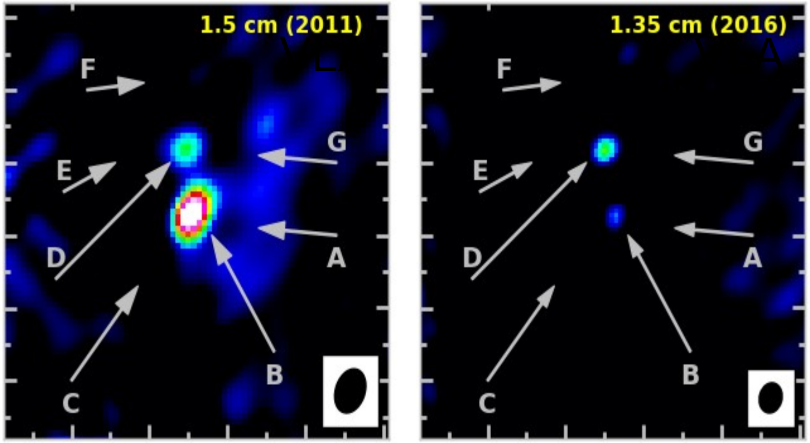
NGC6334I-MM1 dust continuum outburst is accompanied by:

- Dimming of the HCHII region by a factor of 4: suppression of UV photons
- Candidate compact disk/outflow system: disk traced by hot SO_2, outflow traced by $C^{34}S$ and 6 cm jet direction, and maser flare
- **Consistent with a B4 ZAMS star accreting >= $0.1M_{\odot}$ in a short period. Understanding the details requires further monitoring and modeling**

Hunter et al. 2017 ApJ 837, L29



Pre-outburst Post-outburst

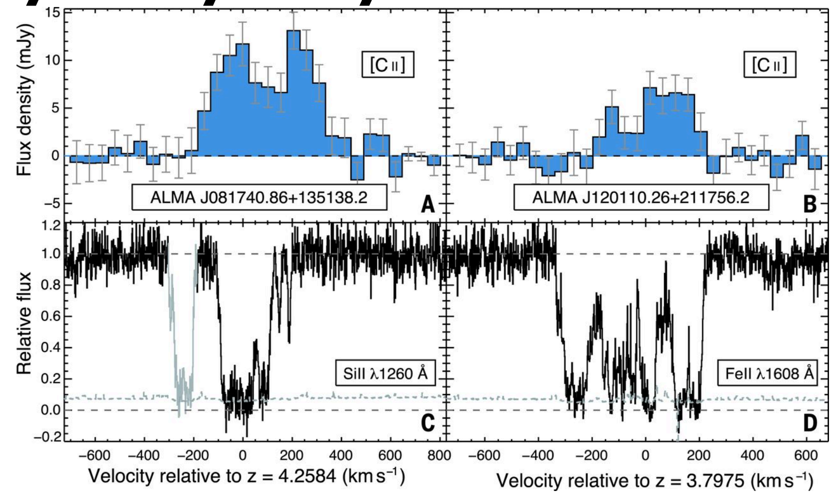


Science Highlight (VI)

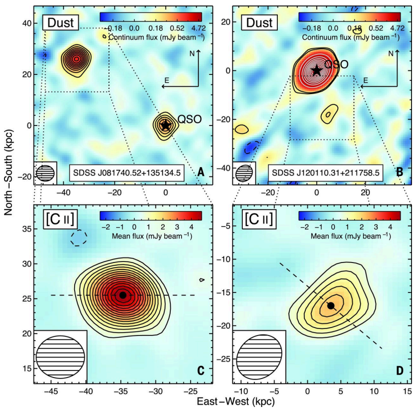
Marcel Neeleman et al. Science 2017;355:1285-1288

ALMA: SuperHaloes Surround Early Milky-Way-like Galaxies

- With ALMA, US astronomers observed young Milky-Way like galaxies at z~4 and probed their haloes by measuring even more distant QSOs through them.
- QSO-galaxy offsets probe the galaxy halo far beyond the ~5kpc extent of [C II] emission
  - The host galaxy has enriched its inner gaseous halo
  - The halo is bound to the host, will eventually be accreted and enrich star-forming gas.



Host emission ([C II]) from the host galaxies A and B and QSO absorption (Si II and Fe II) features C and D.



Above: The ≈400-GHz continuum emission near two QSOs (black stars). Axes give the relative physical (proper) distance at the DLA. Below: Mean flux density over the full [C II] 158-μm line profile displayed above. The dashed line is the measured major axis of the galaxy.

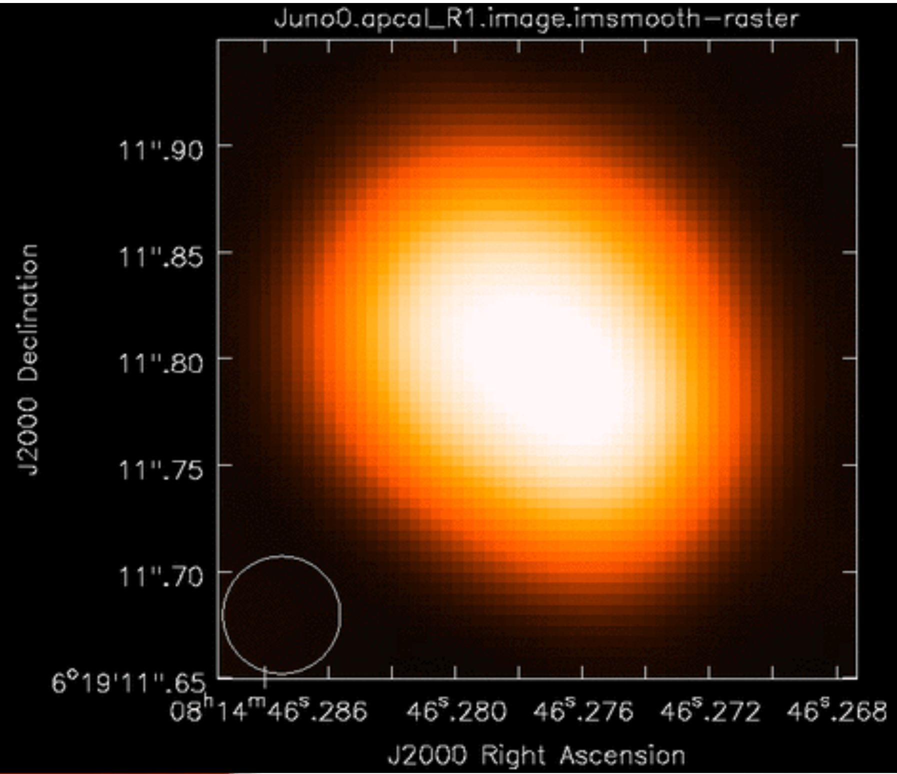
ALMA Science Highlights: Solar System

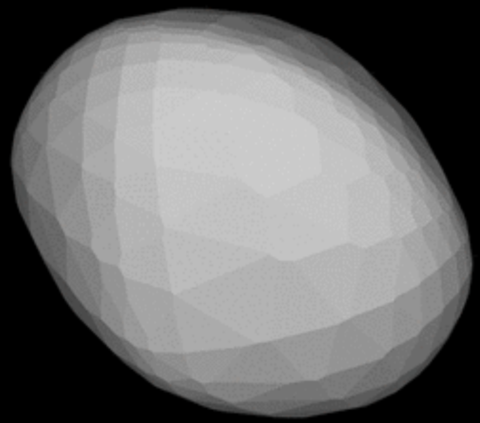
Band 6 Observations of Juno: Frequency = 233 GHz (Science Verification)

Five consecutive executions over 4.4 hours

Beamsize ~ 0.04”x0.03” (~60x45 km)

Model: Durech et al. 2010: **Database of Asteroid Models from Inversion Techniques**



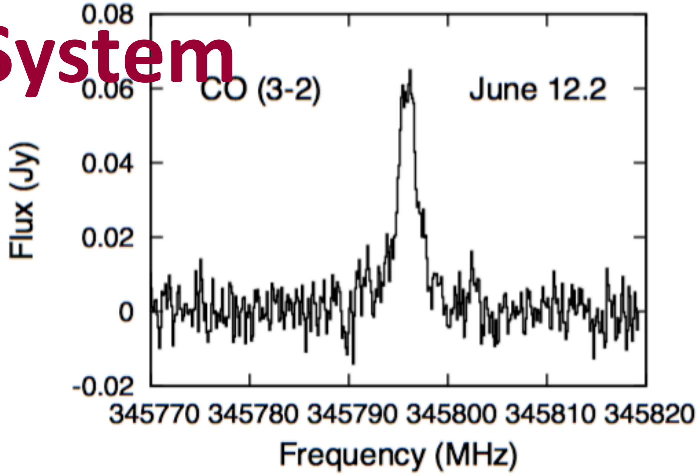


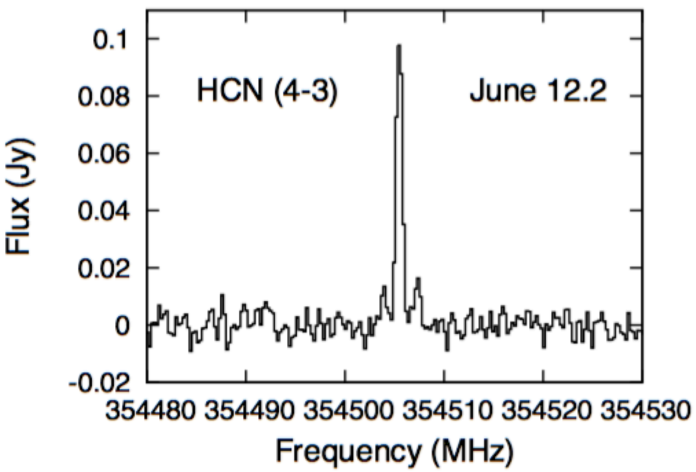
ALMA Image of Juno (ALMA Partnership, Hunter et al. 2015)

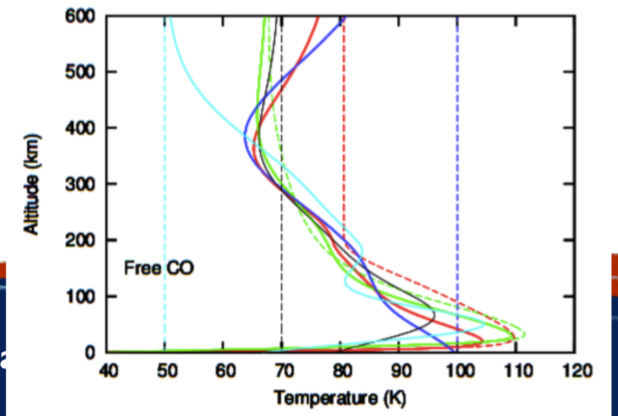
ALMA Science Highlights: Solar System

ALMA detects organics on Pluto

- ALMA has detected CO(3-2) and HCN (4-3) on Pluto (Lellouche et al. 2016)
- The lines probe the abundances and temperature of Pluto's atmosphere up to ~450 km and ~900 km.
- The dayside temperature profile shows a well-marked temperature decrease (i.e., mesosphere) above the 30-50 km stratopause, with T= 70 K at 300 km
    - In agreement with New Horizons solar occultation data.
- The HCN line shape implies a high abundance in the upper atmosphere (450 – 800 km)
    - Suggests a warm (>92 K) upper atmosphere

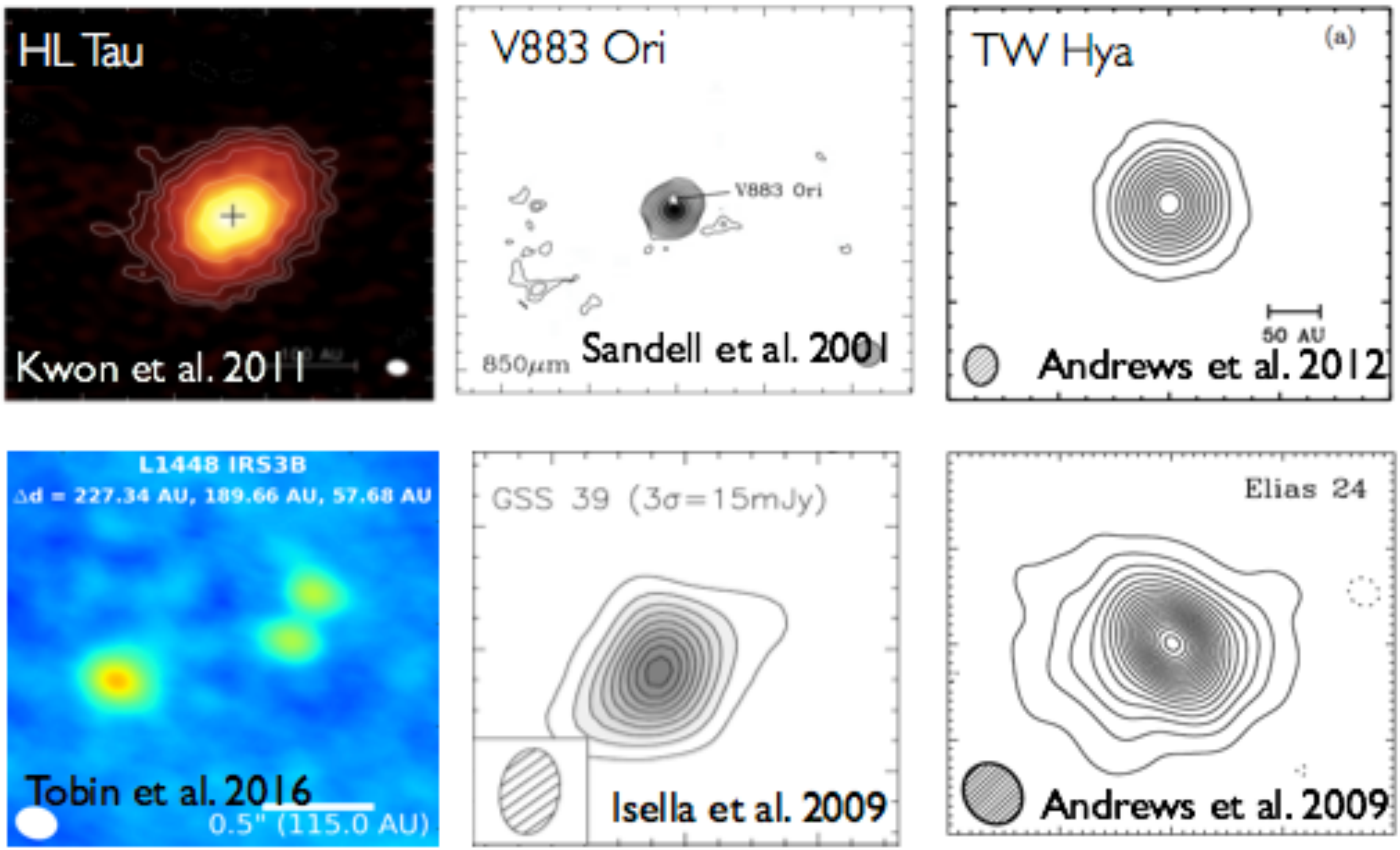






ALMA Science Highlights: Protoplanetary Disks

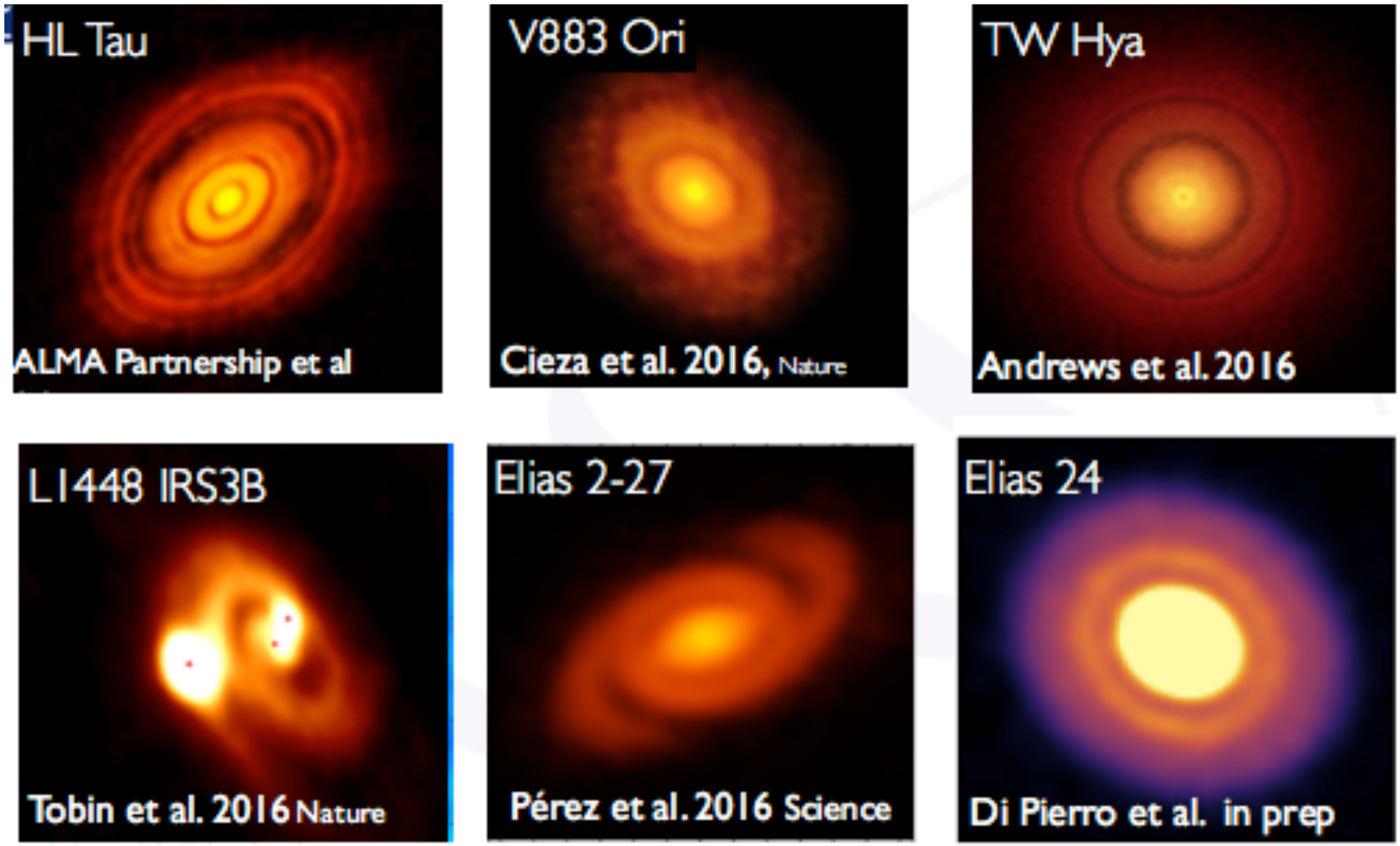
Protoplanetary Disks: Pre- ALMA



Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

ALMA Science Highlights: Protoplanetary Disks

Protoplanetary Disks: With ALMA

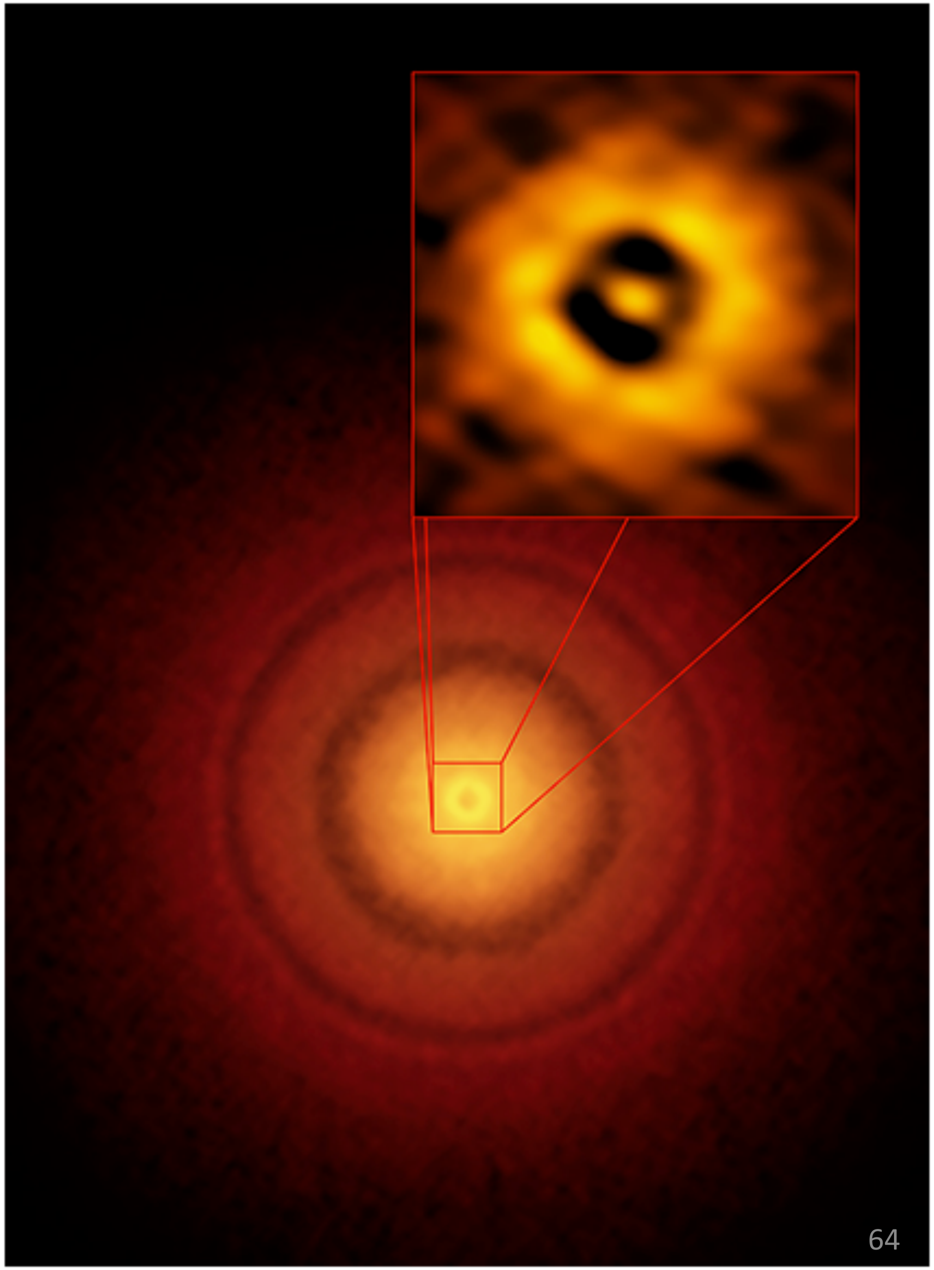


Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

ALMA Science Highlights: Protoplanetary Disks

TW Hydrae

ALMA's better-than Hubble resolution details as small as the Earth's distance from the Sun may be discerned in this young (10Myr) nearby (175 light years) planet forming Sun-like star



Andrews et al. 2016

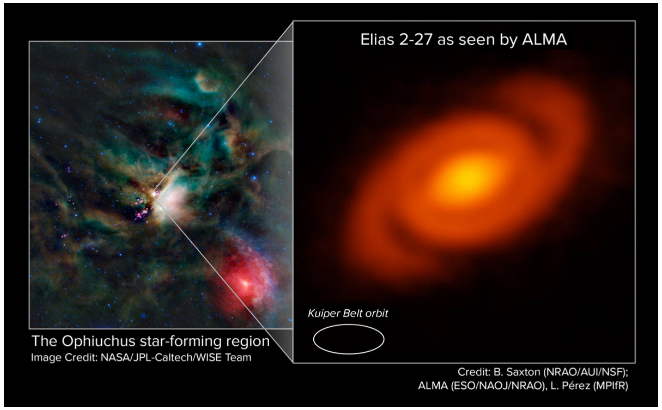
ALMA Science Highlights: Protoplanetary Disks

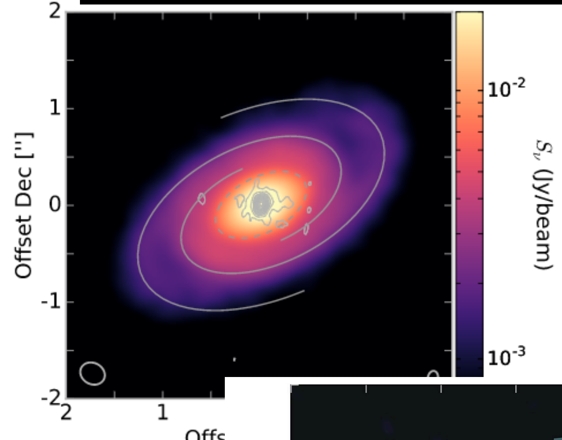
Protoplanetary Disks: With ALMA

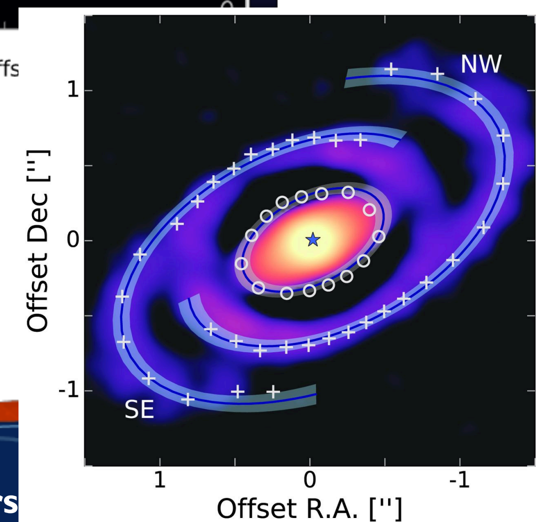
A Spiral Density Wave Observed in a Protoplanetary Disk

Perez et al. Science 353, 1519 (2016)

- Gravitational instabilities in protoplanetary disks might be excited by e.g. planet-disk interactions or gravitational instabilities
- Disk mid-plane structure provides a sensitive probe for these instabilities; optical observations probe the disk surface but radio wavelength observations probe the disk density structure.
- ALMA imaging (dust and CO, 33 AU resolution) reveals two symmetric spiral arms (r~150AU) emanating from an elliptical emission ring (r~71AU) in the disk Elias 2-27, in the nearby ρ Oph cloud
- A spiral density wave fits the observations well. Fragmentation of such spirals remains the only plausible formation mechanism for planets and companions at large disk radii, where core-accretion becomes inefficient.





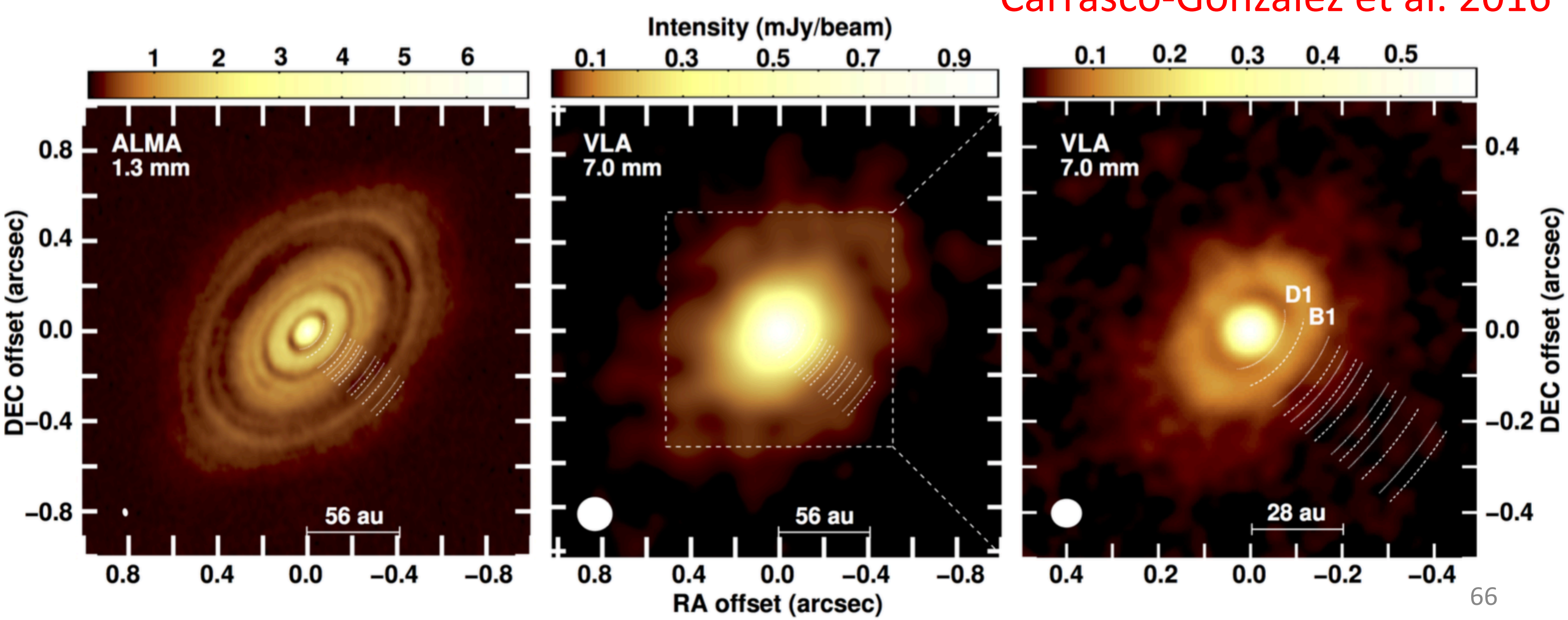


ALMA Science Highlights: Protoplanetary Disks

Protoplanetary Disks: With ALMA and VLA

- Emission from inner regions of HL Tau still optically thick at ALMA wavelengths
- VLA can image the disk at comparable resolution to ALMA at 7mm where emission is optically thin
- Combination of ALMA+VLA helps differentiate between formation theories with info on grain growth, fragmentation, and formation of dense clumps: suggest HL Tau disk is in very early stage of planet formation with planets not yet in the gaps but set for future formation in the bright rings

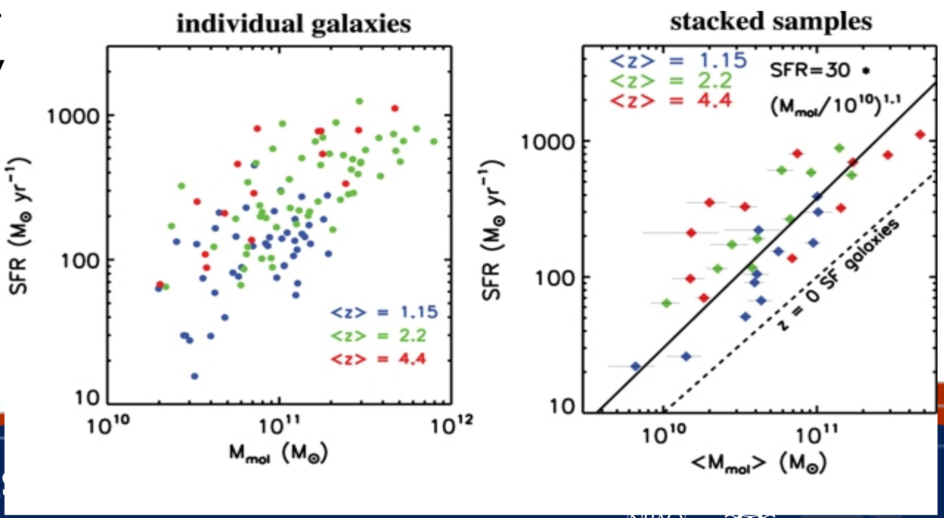
Carrasco-González et al. 2016



ALMA Science Highlights: Star Formation Peak

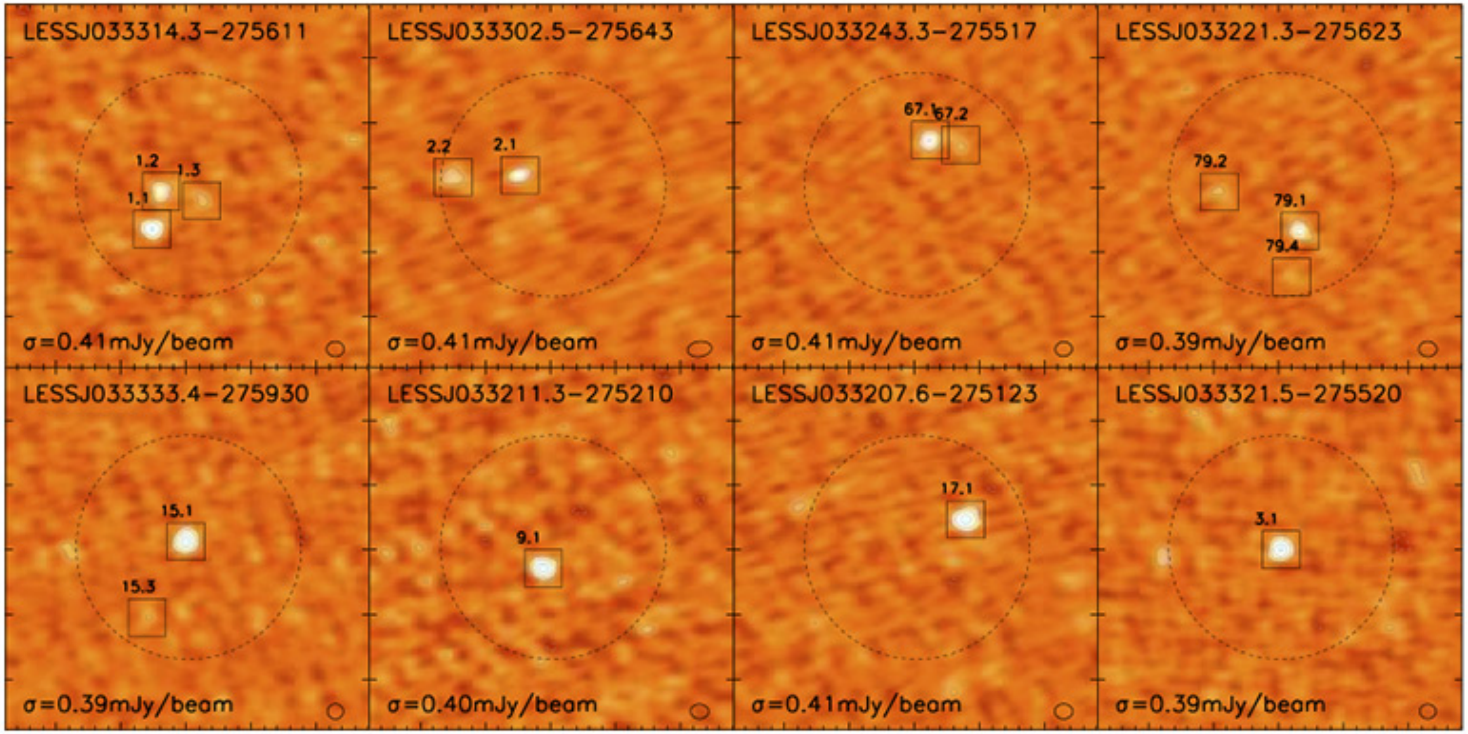
- Scoville et al. (2016 ApJ 820 83)
  - *"ISM Masses and the star formation law at z = 1 to 6: ALMA observations of dust continuum in 145 galaxies in the COSMOS survey field"*

- ALMA Cycle 2 observations of long-wavelength dust emission were used to probe the evolution of the star-forming interstellar medium (ISM). Sample size: 145 galaxies
- Found a single high-z star formation law -- an approximately linear dependence on the ISM mass and an increased star formation efficiency per unit gas mass at higher redshift.
- Several notable conclusions from the survey – among them:
- At z > 1, the entire population of star-forming galaxies has ~2–5 times shorter gas depletion times than low-z galaxies.
  - => **different mode of star formation in the early universe**
  - most likely dynamically driven by compressive, high-dispersion gas motions—a natural consequence of the high gas accretion rates.
- 36 citations to date (power of well-designed surv



ALMA Science Highlights: the Distant Universe

Resolving High-*z* Submm Galaxies



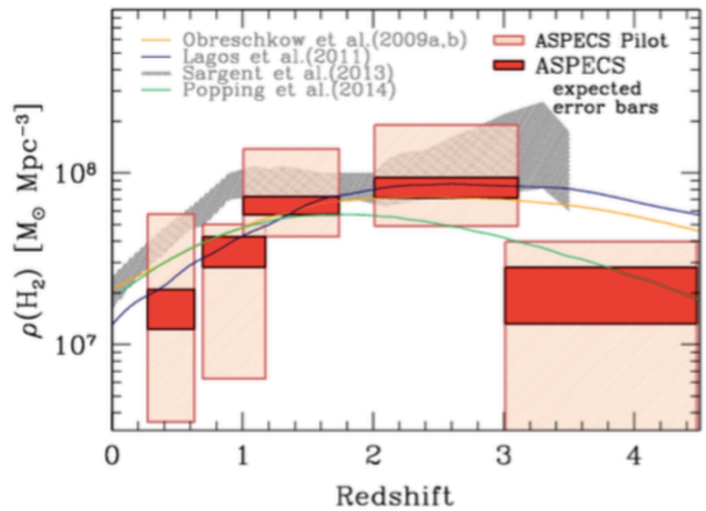
Hodge et al. 2013

- 126 submm sources observed with ALMA at 870 μm
- 2x deeper, 10x higher angular resolution than previous surveys
- **99 sources detected in 88 fields, integration time ~120 sec (!!)**
- Significant multiplicity (35-50%) found at 0.2” resolution

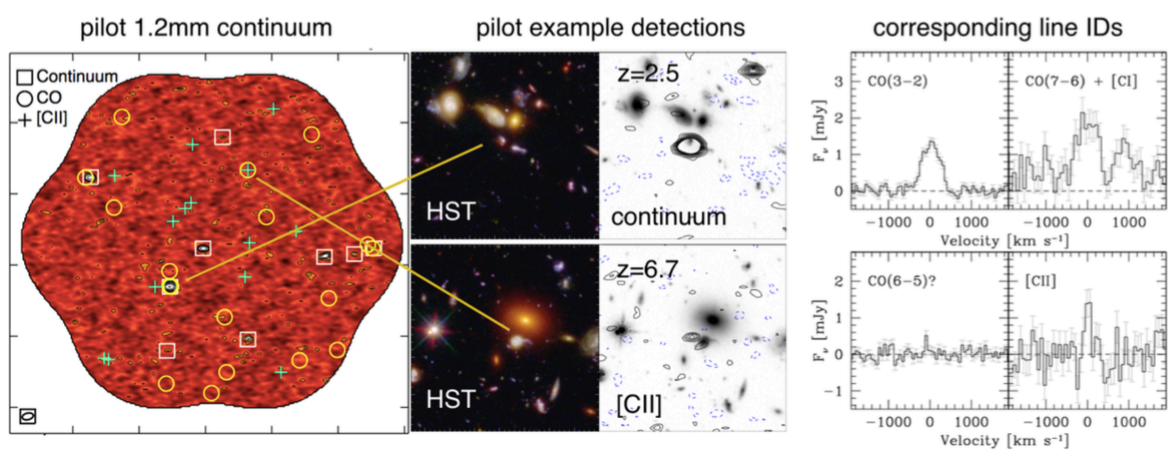
ALMA Science Highlights: the Distant Universe

ALMA Deep Fields: a new era of cosmological surveys

- ALMA has opened a new window on the cosmos: large volume surveys for cold gas throughout the Universe = the fuel for star formation. ASPECS is the first line deep field, involving full frequency scans of Band 3 and 6 in the Hubble UDF.
- 21 candidate line galaxies were detected, including CO emission from galaxies at z=1 to 5, and [CII] at z > 6, plus 9 dust continuum sources at 1.2mm
- These data determine the dense gas history of the Universe, the necessary complement to the star formation history of the Universe.

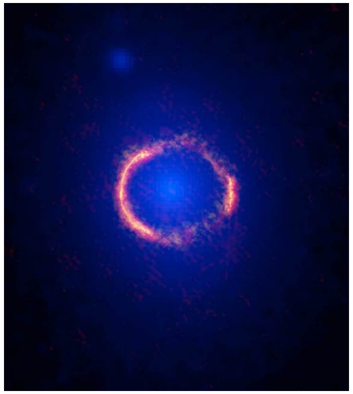


Examples of line and continuum sources from the ASPECS program, plus constraints on the dense gas history of the Universe (see papers by Walter, Decarli, Aravena)



ALMA Science Highlights: the Distant Universe

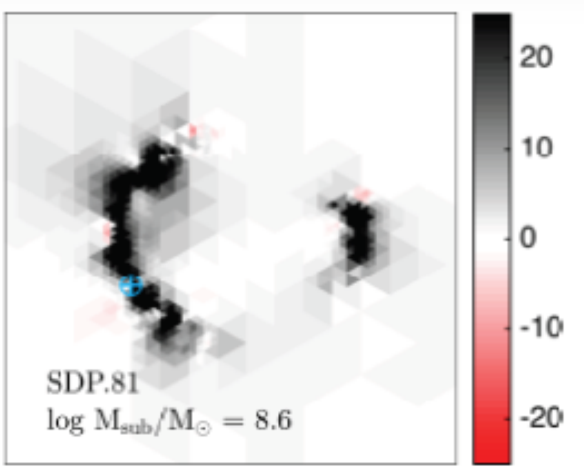
- Hezaveh et al (2016) show ALMA's potential to advance understanding of dark matter substructures
- ALMA's SDP.81 observations are analyzed to detect a subhalo with a mass of $10^{8.96\pm0.12}$ M_{sun}
- Consistent with theoretical expectations

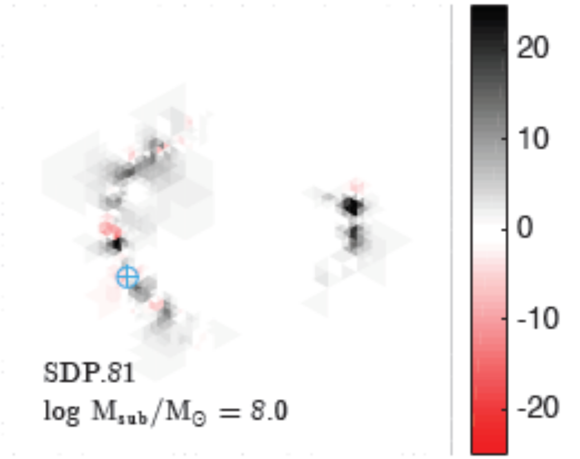


The SDP.81 system.

Blue: HST/WFC3 F160W data shows lensing elliptical at z~0.3

Red: ALMA Bands 4/6/7 combined emission.





(Right Top) a map of parameter for a second subhalo of mass $10^{8.6}$ M_{sun} after inclusion of one subhalo of mass 10^9 M_{sun} at the location of the blue symbol.
(Bottom) results from similar analysis for a lower mass subhalo, showing marginal improvement at another point near the first detection.

www.nrao.edu
science.nrao.edu
public.nrao.edu

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.