ALMA Cycle 10 Capabilities

ALMA Capabilities in Cycle 10

- **Observing Time**
  - 4300 hours anticipated on the 12-m Array + 4300 hours on the ACA (4300 each for the 7-m Array and Total Power Array)
  - **Cycle 10 will *not* include a Supplemental CfP for stand-alone ACA observations**
  - The community is encouraged to submit ACA stand-alone proposals for targets, especially in the LST range of 20h to 10h, for the May 2023 deadline
  - The community is also strongly encouraged to submit proposals in the highest frequency bands, Bands 8, 9 and 10
- **Proposal Review Process**
  - All proposals that are not Large Programs will be reviewed via Distributed Peer Review
  - Large Programs (>50 hours on the 12-m Array, >150 hours on the 7-m Array), will be reviewed by a panel
  - All Cycle 10 proposals will be dual-anonymous (it is the responsibility of investigators to preserve their anonymity when writing proposals)

ALMA Capabilities in Cycle 10

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!!!!**
- Most Cycle 9 proposals requested between 2 and 20 hours of 12-m Array time but the average time per proposal has increased over the cycles and the success rate of proposals was independent of proposal length up to at least 30 hours and maybe even higher up to about 40 hours

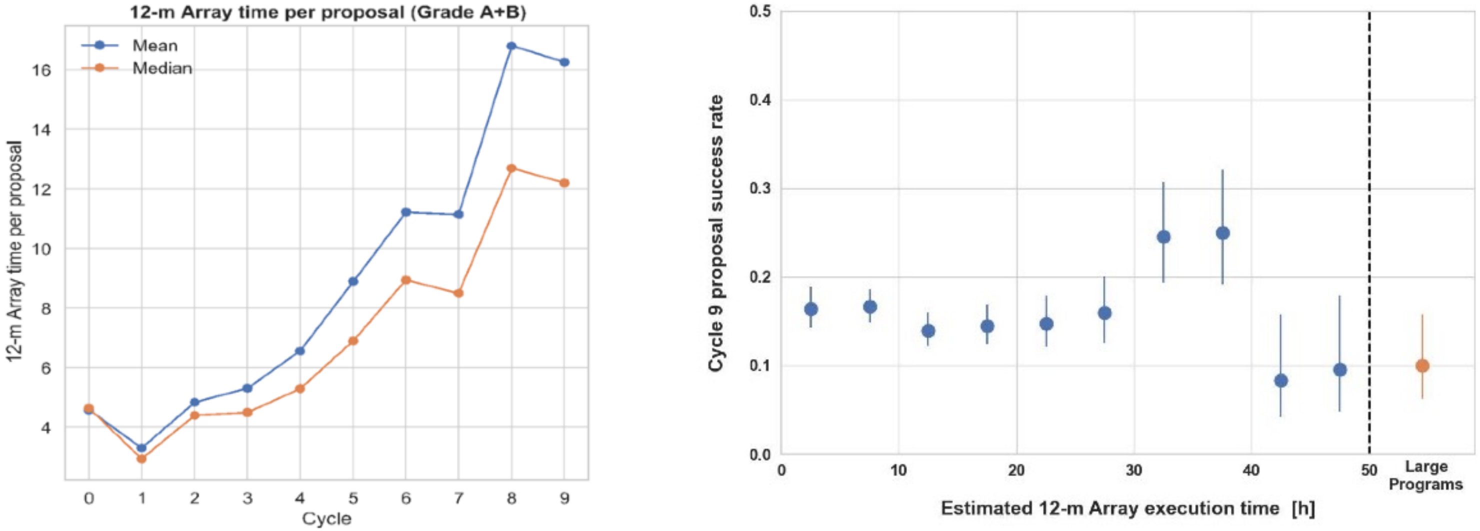


Figure 1: Cycle 9 - (Left) Requested 12-m Array time per proposal assigned Grade A or B. (Right) Fraction of proposals (with 1s confidence intervals) that are assigned Grade A or B as a function of the estimated 12-m Array time.

ALMA Capabilities – NEW in Cycle 10!!!

In Cycle 10, NEW technical capabilities will include:

- **Band 1 on the 12-m Array.** Observations for Stokes I only (no Stokes Q/U/V). Band 1 is anticipated to be available from March 2024 so is only available in configurations C-1 to C-6 (*not C-7 and C-8*). Frequency range 35-50 GHz (8.5-6 mm)
- **Spectral scans that include Total Power observations**
- **4x4-bit spectral mode for improved sensitivity on the 12-m Array (dual polarization only).**

  4x4 bit mode significantly reduces the time required for specific spectral-line observations to reach a given rms, by 25% (or a 12% increase in sensitivity for fixed spectral resolution and integration time). 4x4 bit mode is ***not*** recommended for continuum observations because it reduces the available bandwidth compared to the standard 2x2 bit mode.
- **Solar observations with full polarization in Band 3 using only the 12-m Array**
- **Phased array mode in Bands 1, 3, 6 and 7.** The total time available for this mode will be limited to 50 hours.
- **VLBI (continuum and spectral line) in Bands 1 ,3, 6 and 7,** including flexible tuning.

Joint Proposals also offered in Cycle 10 (see later slide)

ALMA Capabilities in Cycle 10

- **The Cycle 10 capabilities are be fully described in Appendix A of the ALMA Proposers Guide available at https://almascience.nrao.edu/proposing/proposers-guide (Cycle 10 version available from April 12). 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 1, 3, 4, 5, 6, 7, 8, 9, and 10 (wavelengths of about 7.5, 3.0, 2.0, 1.6, 1.3, 0.85, 0.65, 0.45, and 0.35 mm, respectively) ⍰ **Band 1 (7.5 mm) offered for the first time in Cycle 10, anticipated to be available from March 2024**
- **12-m Array Configurations**
  - Cycle 10 includes configurations C-1 through C-8. **(C-7 and C-8 not available in Band 1)**
  - Maximum baselines between 0.16 km and 8.5 km depending on array configuration
  - https://almascience.nrao.edu/observing/observing-configuration-schedule/long-term-configuration-schedule
  - 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 (https://almascience.nrao.edu/tools/casa-simulator)

ALMA Capabilities in Cycle 10

- **Spectral line, continuum, and mosaic observations**
  - Spectral line and continuum observations with the 12-m Array and the 7-m Array Bands 3-10. Band 1 only with the 12-m Array (spectral line and continuum).
  - Single field interferometry (Bands 3-10) and mosaics (Bands 3 to 9) with the 12-m Array and the 7-m Array. Band 1 only with the 12-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 in Bands 3 to 7 with the 12-m Array.
  - Single-pointing, on-axis, linear polarization with the stand-alone 7-m Array in Bands 3 to 7. The field of view is limited to the inner third of the primary beam. A maximum of 75 hours is offered for this mode.
    - Combined 7-m Array and 12-m Array polarization observations are *not* supported.

ALMA Capabilities in Cycle 10

Band-to-band phase calibration

- Observations in Bands 7-10 with the 12-m Array (new: any configuration) or the 7-m Array may require band-to-band (B2B) calibration in order to find a suitable nearby and sufficiently bright phase calibrator, to ensure phase calibration quality.
- The ALMA OT will *automatically* check the availability of suitable phase calibrators during proposal validation and will automatically trigger B2B where needed.
- Some science targets – especially in Band 10 and with the longest baselines (C-8 in Cycle 10) – may not be observable even with B2B. The ALMA OT will give an error and won’t validate the proposal if a target does not have a suitable calibrator.
- It is recommended to begin preparing High Frequency proposals – and validate in the OT – early to ensure there is a suitable phase calibrator available.
- A maximum of 65 hours is available for Band-to-Band on the 12-m Array; and a maximum of 85 hours on the 7-m Array.

ALMA Capabilities – Joint Proposals

- ALMA has entered into agreements with JWST, VLA and VLT.
- Joint Proposals must require observations with two or more observatories to achieve their scientific goals.
- A Joint Proposal is submitted to a single observatory, so it is no longer necessary to submit two separate proposals to each observatory, avoiding "double jeopardy" – just reviewed once.
- Starting in Cycle 10, ALMA will be able to allocate up to:
  - 115 hours of JWST time
  - Up to 5% of the available time on the VLA.
  - 50 hours of VLT time
- JWST can allocate up to 115 hours of ALMA time per cycle (starting with JWST cycle 2; Nov 2022; VLT and VLA can allocate up to 50 hours per year starting with Period 112 and Semester 2023B (CfP Feb & Jan 2023), respectively.
- See https://almascience.nrao.edu/news/alma-announces-joint-proposal-agreements-for-jwst-vla-and-the-vlt

ALMA Capabilities – Joint Proposals

- More information can be found in the respective Calls for Proposals.
- For ALMA, see the Cycle 10 Proposer's Guide.
- For VLA, see:
  - https://science.nrao.edu/observing/call-for-proposals/2023b/new-opportunity-joint-observations-with-alma and https://science.nrao.edu/observing/call-for-proposals/2023b/joint-proposals
- For VLT, see: https://www.eso.org/sci/observing/phase1/JointVLT-ALMA.html
- For JWST, see here.
- Some important notes:
  - Proposals need to clearly demonstrate that *both* ALMA and the other observatory observations are scientifically required.
  - Proposals must be submitted to the observatory that requires the most observing time ("Main observatory").
  - Proposals may not be submitted to both observatories at the same time.
  - If two or more non-ALMA observatories are required, ALMA must be the "Main observatory".
  - Joint Proposals submitted to ALMA must be explicitly specified as such using the "Is this a Joint Proposal?" button in the ALMA OT.

ALMA Capabilities in Cycle 10

Proposal types in Cycle 10 will include:

- Regular, VLBI, Phased Array, Target of Opportunity, and Large Programs.
- VLBI proposals work in concert with the Global mm-VLBI Array (GMVA) or Event Horizon Telescope (EHT). GMVA programs also had to submit a proposal to the GMVA by its 1 February 2023 deadline.

Restrictions on certain modes or proposal types:

- The distinction between “standard” and “non-standard” modes was removed starting in Cycle 8 2021 (in earlier cycles there was a 20% cap on the time request for non-standard modes)
- There are still some time caps on certain modes, however. Namely, high frequency observations requiring Band-to-Band phase calibration or full polarization observations on the 7-m Array.

Large Program Observing Modes are STILL restricted. They CANNOT include:

- Time Critical or ToO Observations
- Full Polarization observations
- Solar observations
- VLBI or Phased Array observations
- Bandwidth switching projects (having <1 GHz aggregate bandwidths over all spectral windows)
- Band-to-Band calibration projects
- Astrometric Observations
- Band 1 (in Cycle 10)

ALMA Capabilities in Cycle 10

Large Program Preparation and Support

- If you are planning to submit a Large Program, it is strongly recommended to 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.
- Large Programs require a Management Plan. This needs to describe both the team and their responsibilities within the project and the computing resources the team has access to for processing and storing the data. The ARCs offer access to computing resources. If it is the intention to utilize those resources, it is recommended you discuss and agree your computing needs with the ARC well in advance so you can include the use of these resources in the Management Plan.
- Review the documentation off the science portal on how to prepare “value added” data products.

ALMA Capabilities for Cycle 11++

- **Receiver bands**:
  - Band 2 (Band 2 summary report from 2019: https://zenodo.org/record/3240407)
- **Baselines:**
  - All observing bands out to 16 km.
- **Observing Modes:**
  - Full operations include full Stokes plus circular polarization at all observing bands including mosaics and Total Power

ALMA is getting a major upgrade in the next several years – the **Wideband Sensitivity Upgrade** – that will bring many new capabilities. See e.g. :

- https://public.nrao.edu/news/alma-correlator-upgrade/
- https://arxiv.org/abs/2211.00195
- https://science.nrao.edu/facilities/alma/science_sustainability/March22_WSU_Webinar_NAASC.pdf/view

—> This may potentially limit the rollout of other new capabilities in the short term.

ALMA Timelines and Milestones

The ALMA Cycle 10 Timeline

Date	Milestone
12 April 2023 (15:00 UT)	Release of Cycle 10 Call for Proposals, Observing Tool, and supporting documents, and opening of the Archive for proposal submission
10 May 2023 (15:00 UT)	Proposal submission deadline for Cycle 10 Call for Proposals
28 June 2023 (15:00 UT)	Deadline to submit reviews for the distributed peer review system
August 2023	Announcement of the outcome of the proposal review process
1 October 2023	Start of ALMA Cycle 10 Science Observations (anticipated)
30 September 2023	End of ALMA Cycle 10

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 ate my proposal…”

The Observatory won’t accept late proposals in such cases.

Submit proposals early and often. That way you:

- Always have a recent copy in the archive
- Know how long to expect validation and submission will take (in some cases, it may take much longer than you think)

Don’t try to submit for the first time 5 minutes before the deadline!!

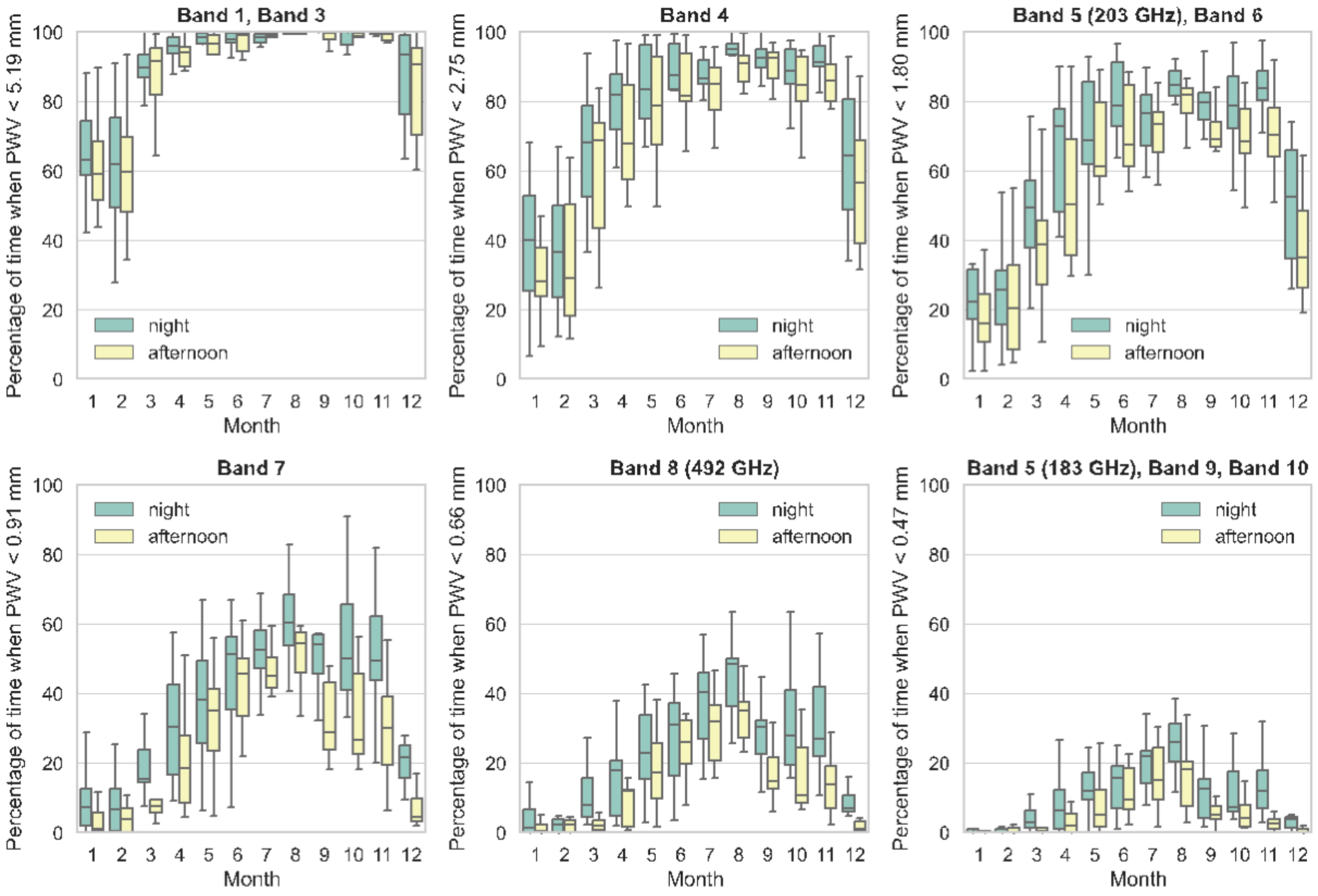
ALMA Array Configuration Schedule (Cycle 10)

- Maximum baseline in Cycle 10 will 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 NOT be available until Cycle 11.
- **NOTE: No PI observing takes place in February – maintenance shutdown!**
- The forward-looking configuration schedule (through Cycle 11) can be found at: https://almascience.nrao.edu/observing/observing-configuration-schedule/long-term-configuration-schedule

Cycle 10

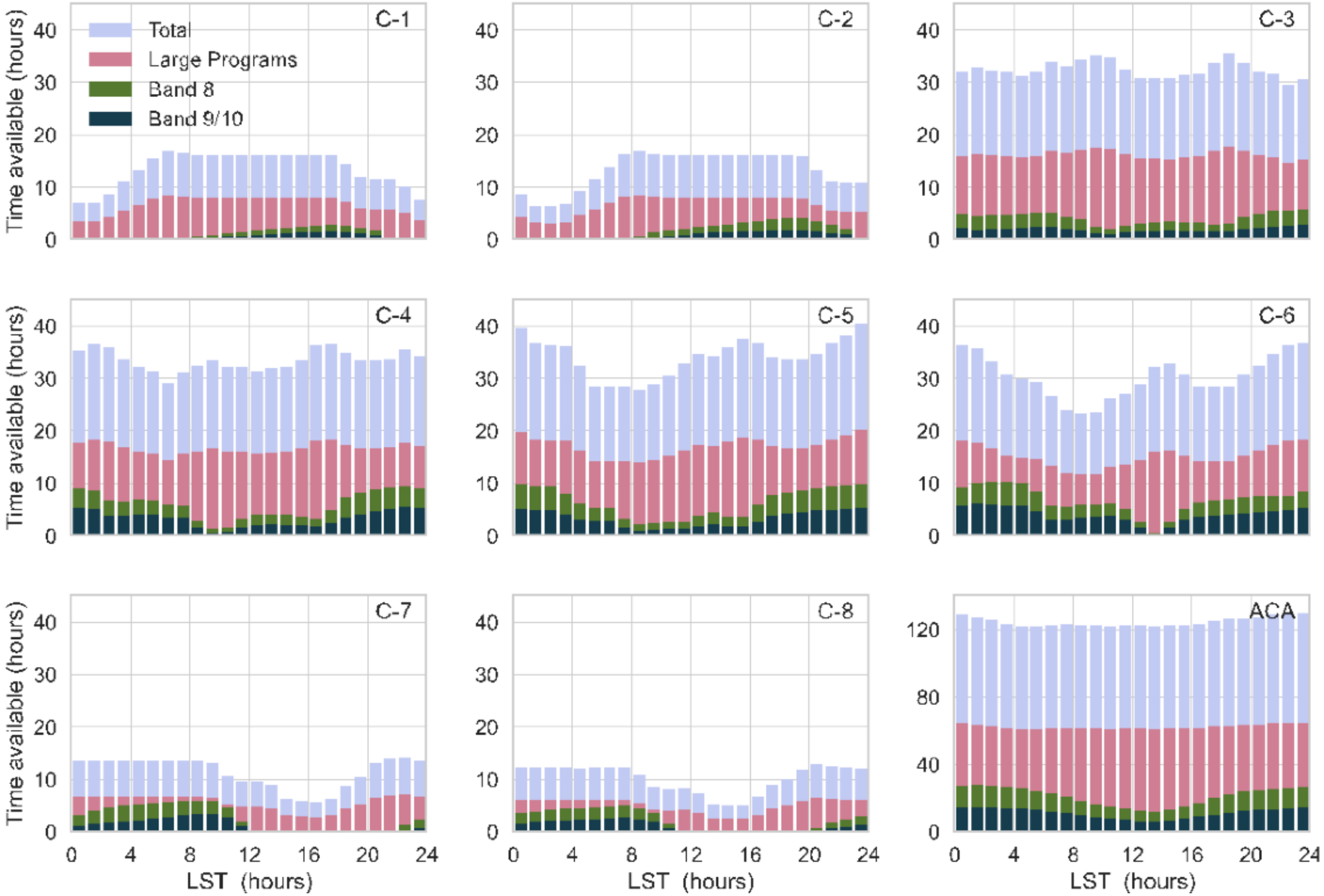
Start Date	Configuration	Longest baseline	LST: Best conditions
1-Oct-2023	C-8	8.5 km	22-10
20-Oct-2023	C-7	3.6 km	23-11
10-Nov-2023	C-6	2.5 km	1-13
1-Dec-2023	C-5	1.4 km	2-14
20-Dec-2023	C-4	0.78 km	4-15
10-Jan-2024	C-3	0.50 km	5-17
1-Feb-2024	No observations due to maintenance		
1-Mar-2024	C-1	0.16 km	8-21
26-Mar-2024	C-2	0.31 km	9-23
20-Apr-2024	C-3	0.50 km	11-0
10-May-2024	C-4	0.78 km	12-2
31-May-2024	C-5	1.4 km	13-4
23-Jun-2024	C-6	2.5 km	15-6
28-Jul-2024	C-5	1.4 km	17-7
18-Aug-2024	C-4	0.78 km	19-8
10-Sep-2024	C-3	0.50 km	20-9

ALMA Observing Strategies



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 January 2010 and January 2022.

ALMA Observing Strategies



Estimated observing time available per configuration for executing PI projects, based on precipitable water vapor (PWV) only. For example, approximately 30 hours are expected to be available in C-4 at LST 05 h for all observations and up to 15 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. 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 10 PG).

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.
  - Also can ask for a "NAASC Chat" through the f2f department which is more than a ticket but less than a full virtual f2f visit!

- **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

NAASC Sources of Support

- **Page Charges:** Upon request NRAO covers page charges for authors at US institutions when reporting results from ALMA/VLA. See: https://library.nrao.edu/pubsup.shtml

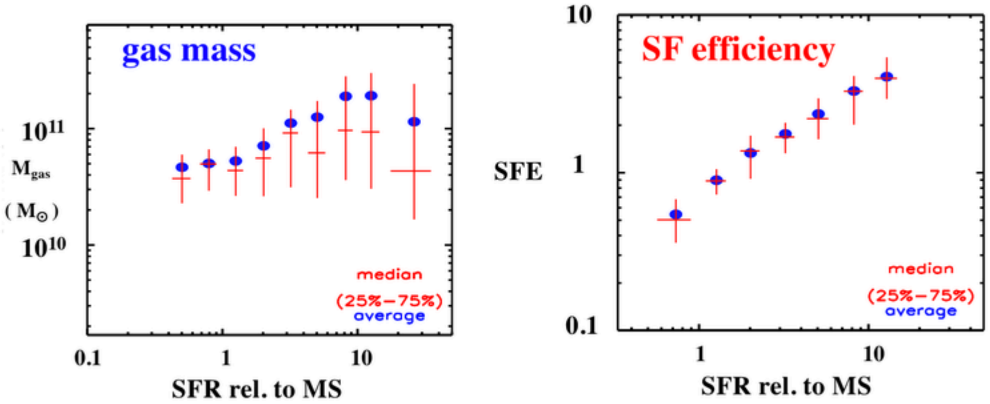
- **Face-to-face Visitor Support:** Upon request NRAO will cover the travel expenses of up to 2 people from 2 teams per week to come to the NAASC to get support for data reduction, proposal preparation, etc. We also have long term visitor support as well. See: https://science.nrao.edu/facilities/alma/visitors-shortterm

- **ALMA Ambassadors:** You too can become an ALMA Ambassador. For program eligibility visit: https://science.nrao.edu/facilities/alma/ambassadors-program

Supplementary material: science slides

ALMA Science Highlights: Star Formation rate drivers in early Universe galaxies

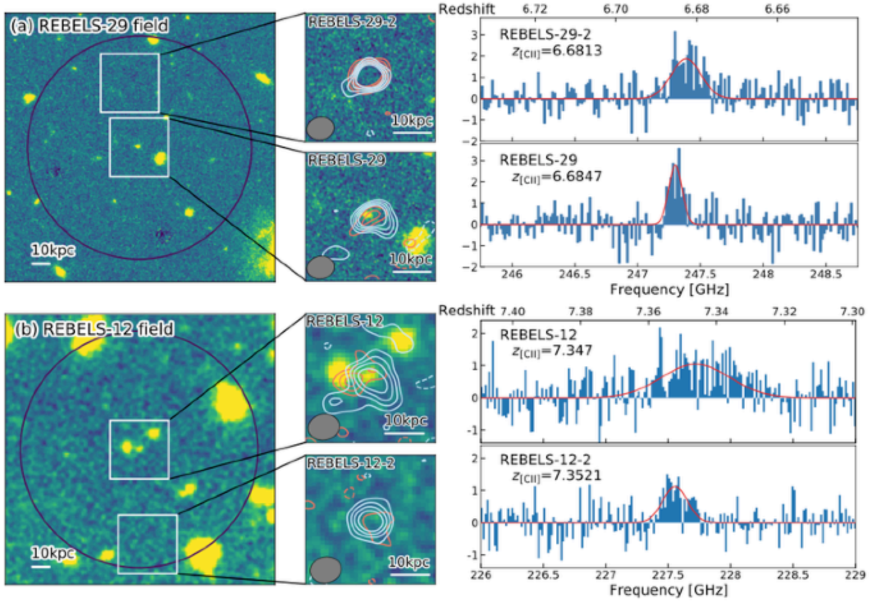
Scoville et al. (2023, ApJ, 943, 82) examined 708 COSMOS-field star-forming galaxies in the redshift range 0.3 to 4.5 to derive their star formation and ISM properties. For these studies, ALMA sub-millimeter dust continuum emission is used to estimate the amount of molecular gas in each galaxy, and the star formation rate (SFR) is estimated via extinction-corrected UV/optical emission and infrared light. **The authors find that the majority of the galaxies on the Main Sequence (MS) of star-forming galaxies have increases in SFRs due to increases in the molecular gas content, whereas galaxies above the Main Sequence (i.e., with high SFR per unit stellar mass) have increases in SFRs due to increases in the star formation efficiency.**



The measured gas masses and star formation efficiencies binned by star formation rate relative to the Main Sequence (MS), with the median for each bin as a horizontal line and the average as a blue circle. An increased rate of star formation per unit gas mass is apparent with increasing distance from the main sequence relative to the variation observed in the gas mass.

ALMA Science Highlights: Normal dust-obscured galaxies in the epoch of re-ionization

The ALMA large program REBELS (Reionization-Era Bright Emission Line Survey), observed 40 UV-luminous primary targets at z > 6.5. Among these targets are REBELS-12 and REBELS-29. In Fudamoto et al. (2021, Nature, 597, 489), two additional emission line neighbours found after inspecting the ALMA data cube of these two sources are reported.



The images on the left show [CII] 158 μm line and dust emission detections for (a) the REBELS-29 field at z~6.68 and (b) the REBELS-12 field at z~7.35. Background images are HST F140W and VIDEO J-band, respectively. White horizontal bars correspond to 10 proper kpc. Solid red and light blue contours show 2σ to 5σ levels (and −5σ to −2σ for dashed contours) for the continuum and [CII] moment-0 maps, respectively. The continuum subtracted [CII] spectra are shown at the native velocity resolution of 20 km/s. The two sources REBELS-29-2 and REBELS-12-2 were found serendipitously as companions to the central, UV-luminous targets, with emission lines at almost exactly the same frequencies as the central targets, accompanied with dust continuum emission at the same location. Their spatial and spectral proximity, and absence in optical/NIR images confirms these companions as unexpected, dusty star forming sources in the epoch of reionization.

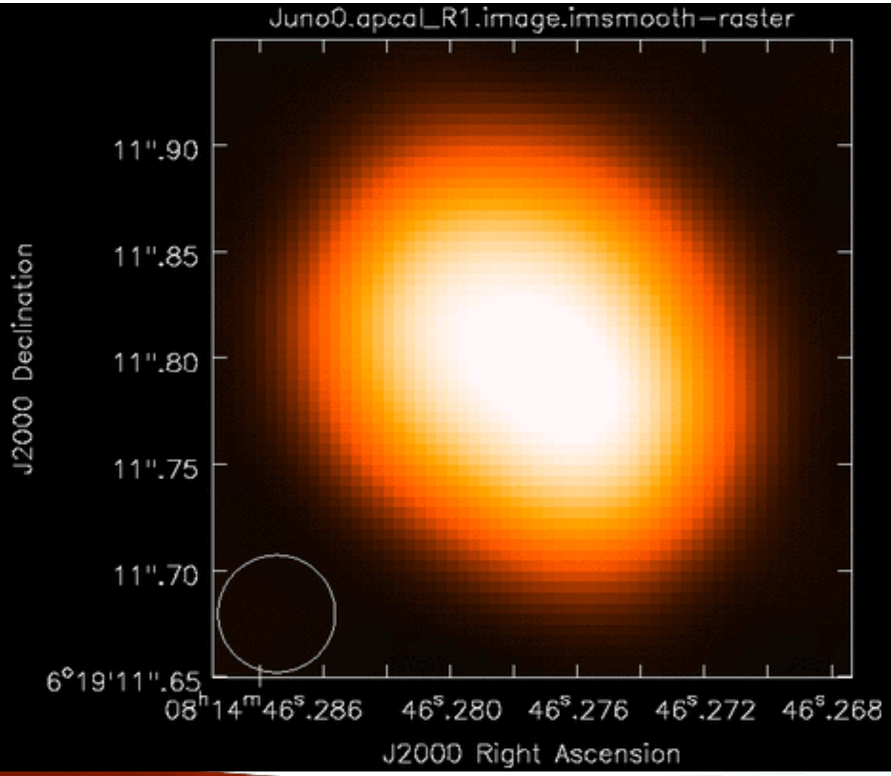
ALMA Science Highlights: Solar System

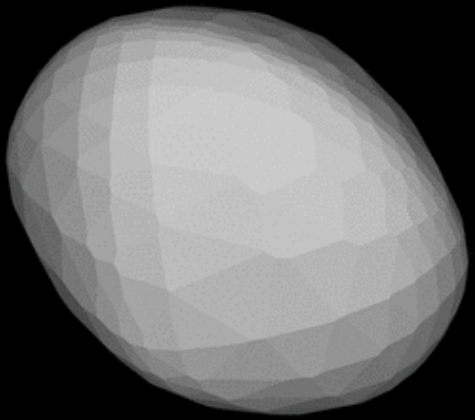
Band 6 Observations of Juno: Frequency = 233 GHz (Science Verification)

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)

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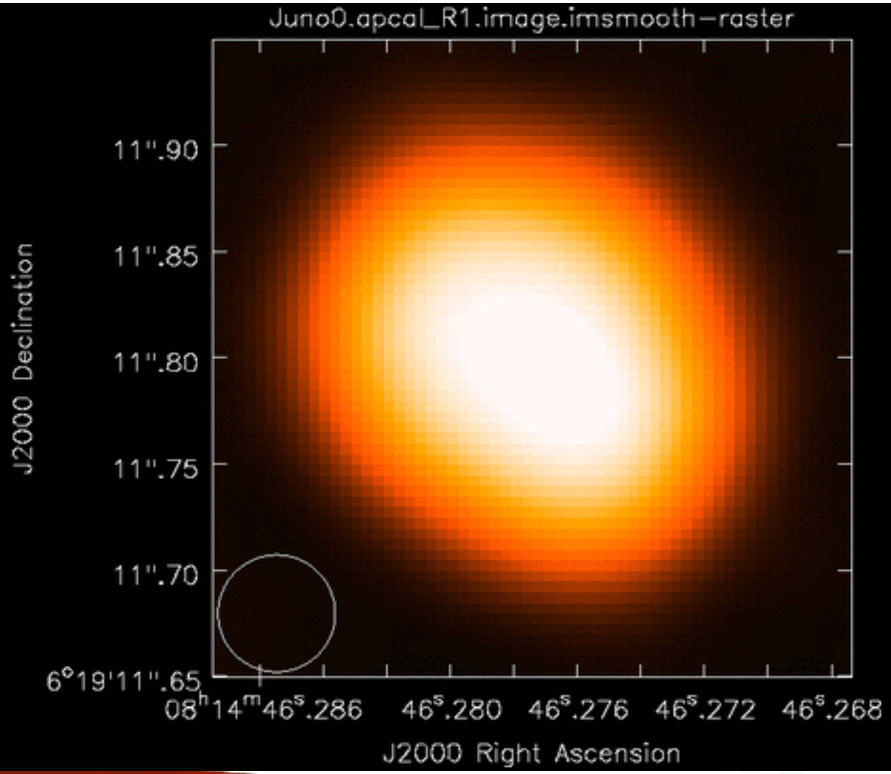
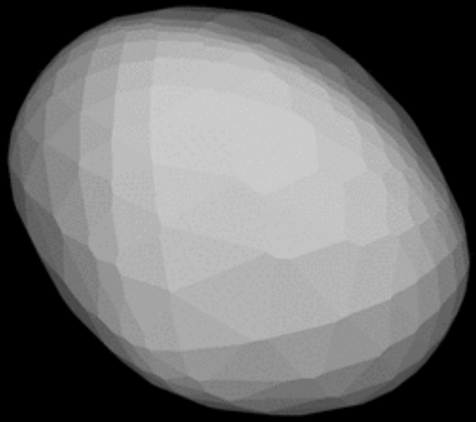


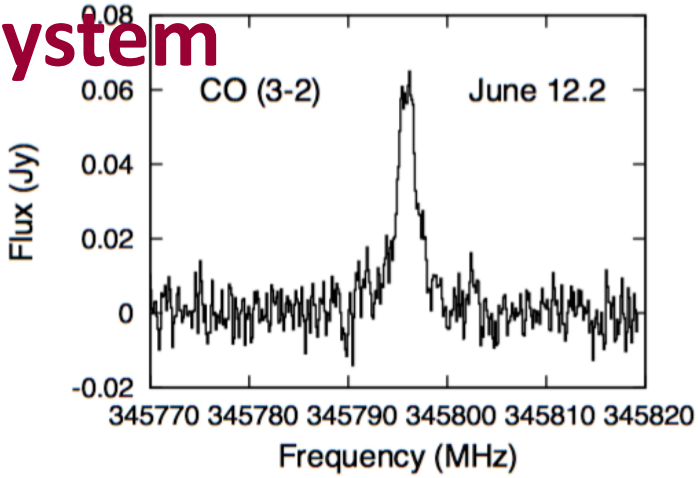


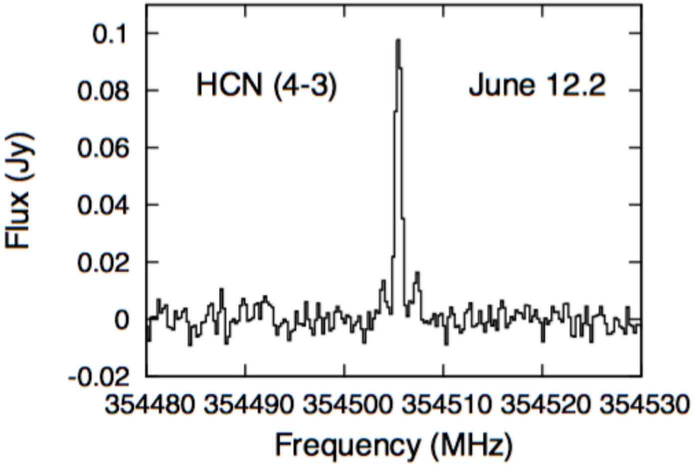
ALMA Image of Juno (ALMA Partnership, Hunter et al. 2015)

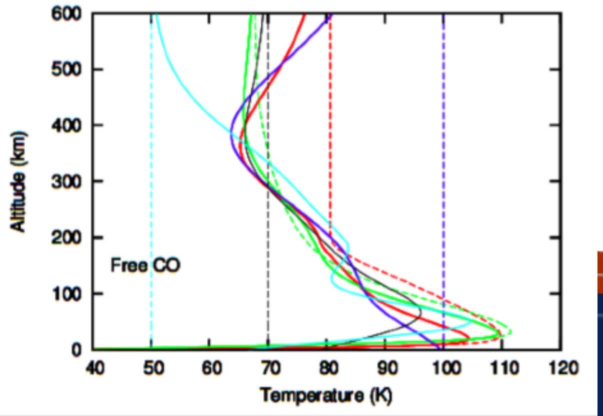
ALMA Science Highlights: Solar System

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

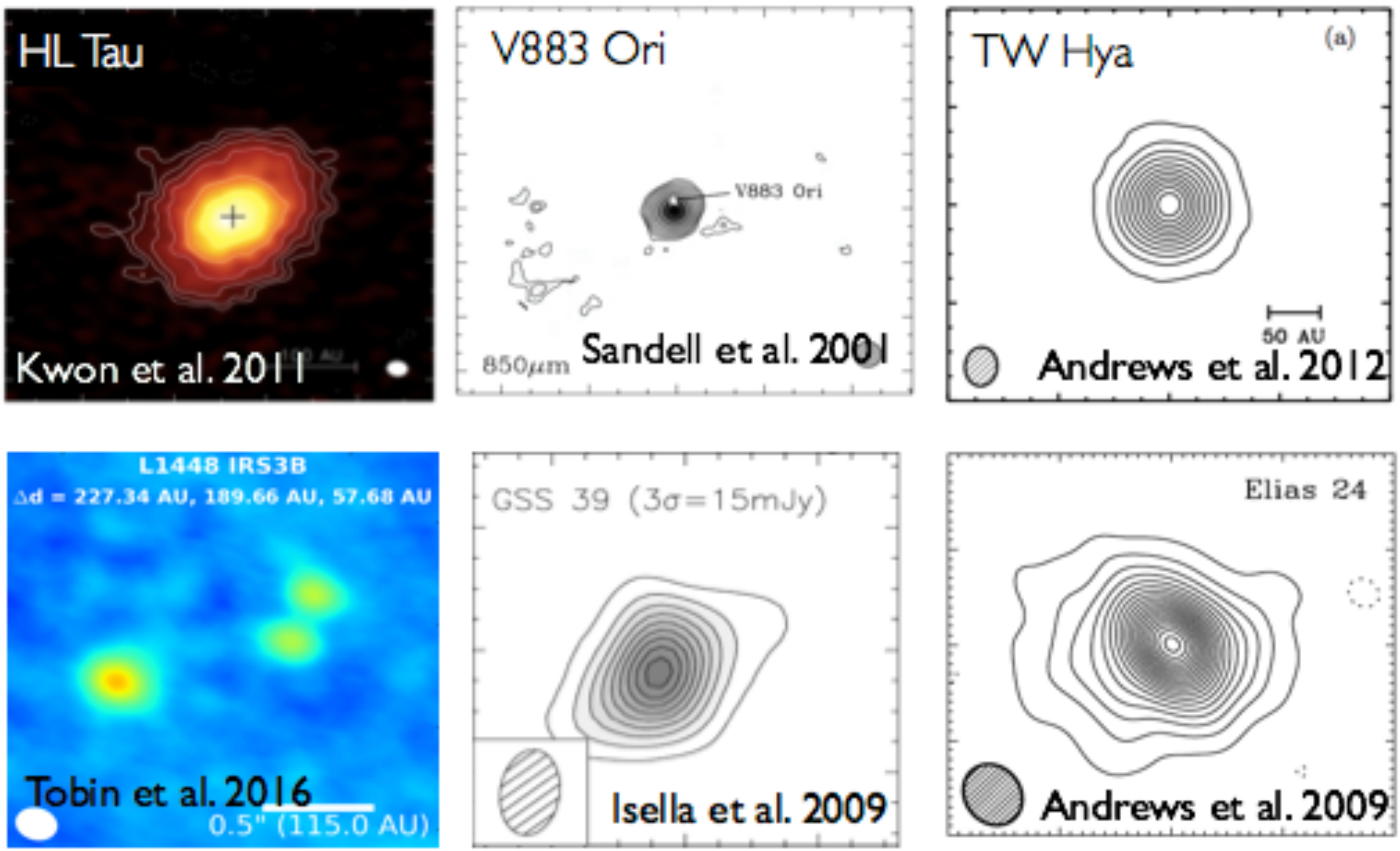






ALMA Science Highlights: Protoplanetary Disks

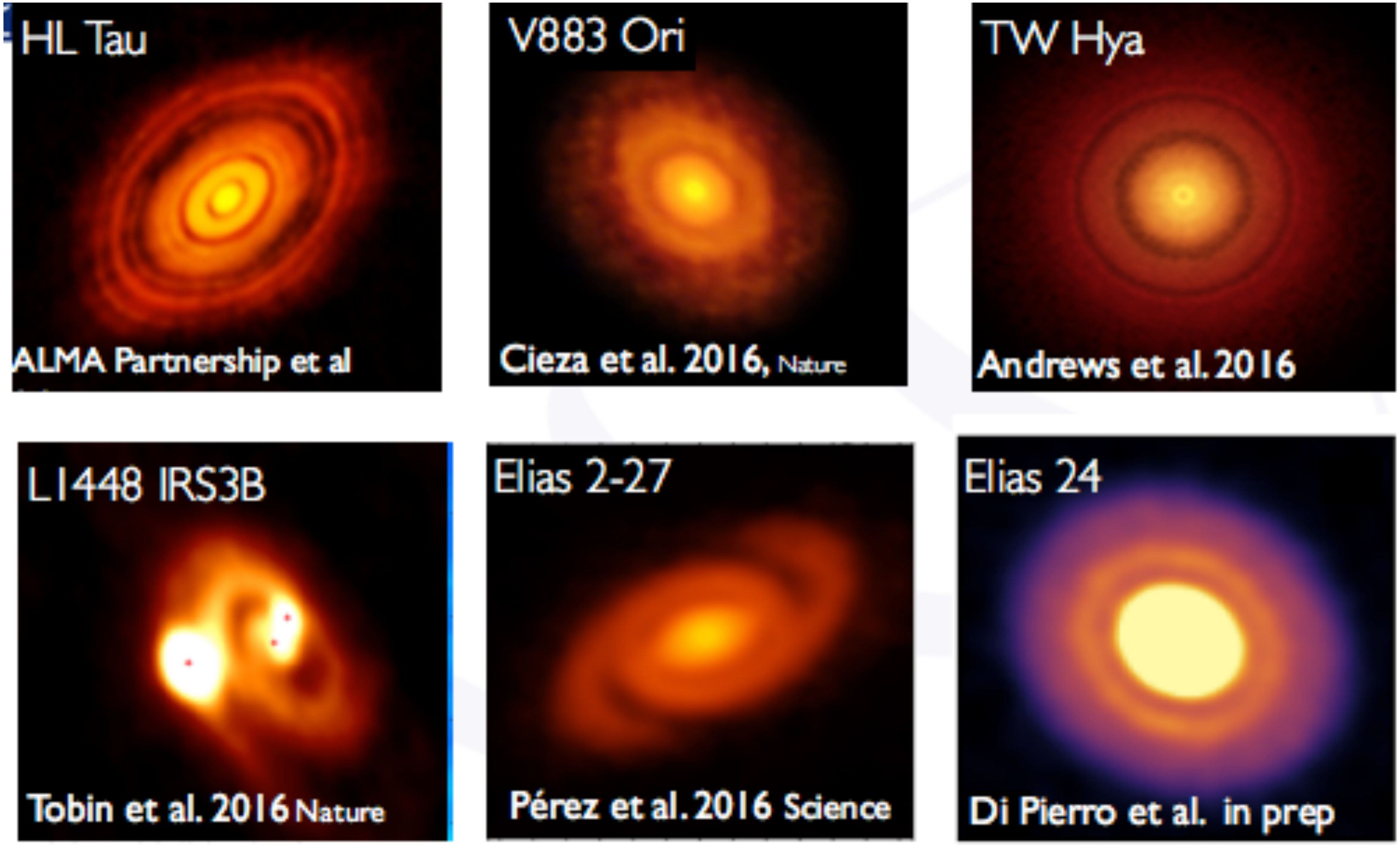
Protoplanetary Disks: Pre- ALMA



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

ALMA Science Highlights: Protoplanetary Disks

Protoplanetary Disks: With ALMA



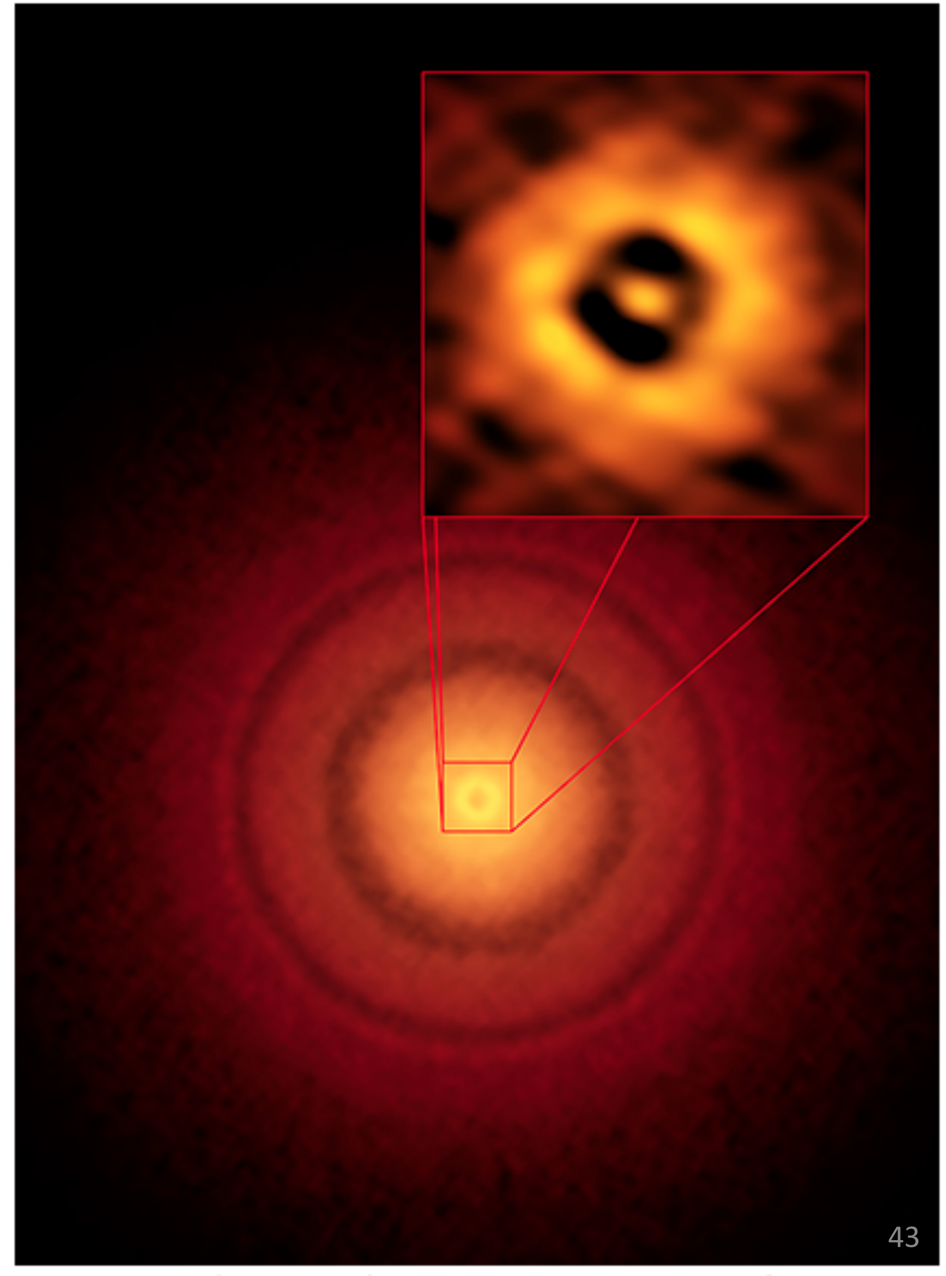
Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

ALMA Science Highlights: Protoplanetary Disks

TW Hydrae

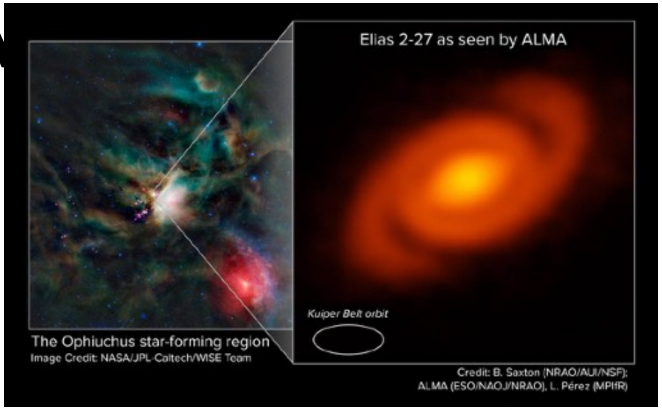
ALMA's better-than Hubble resolution details as small as the Earth's distance from the Sun may be discerned in this young (10Myr) nearby (175 light years) planet forming Sun-like star

Andrews et al. 2016



ALMA Science Highlights: Protoplanetary Disks

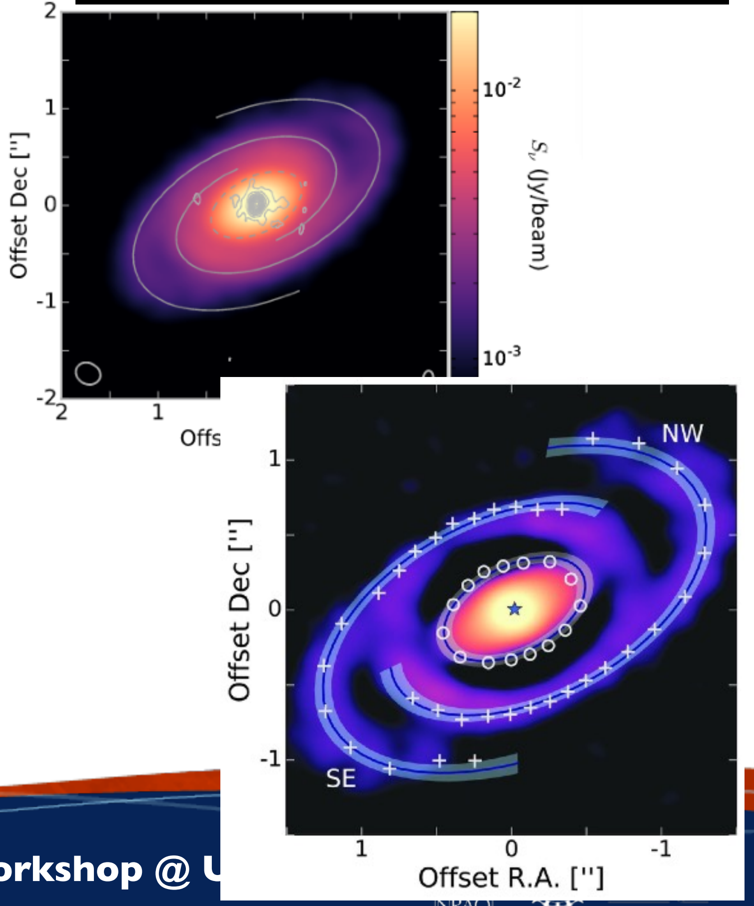
Protoplanetary Disks: With ALMA



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.

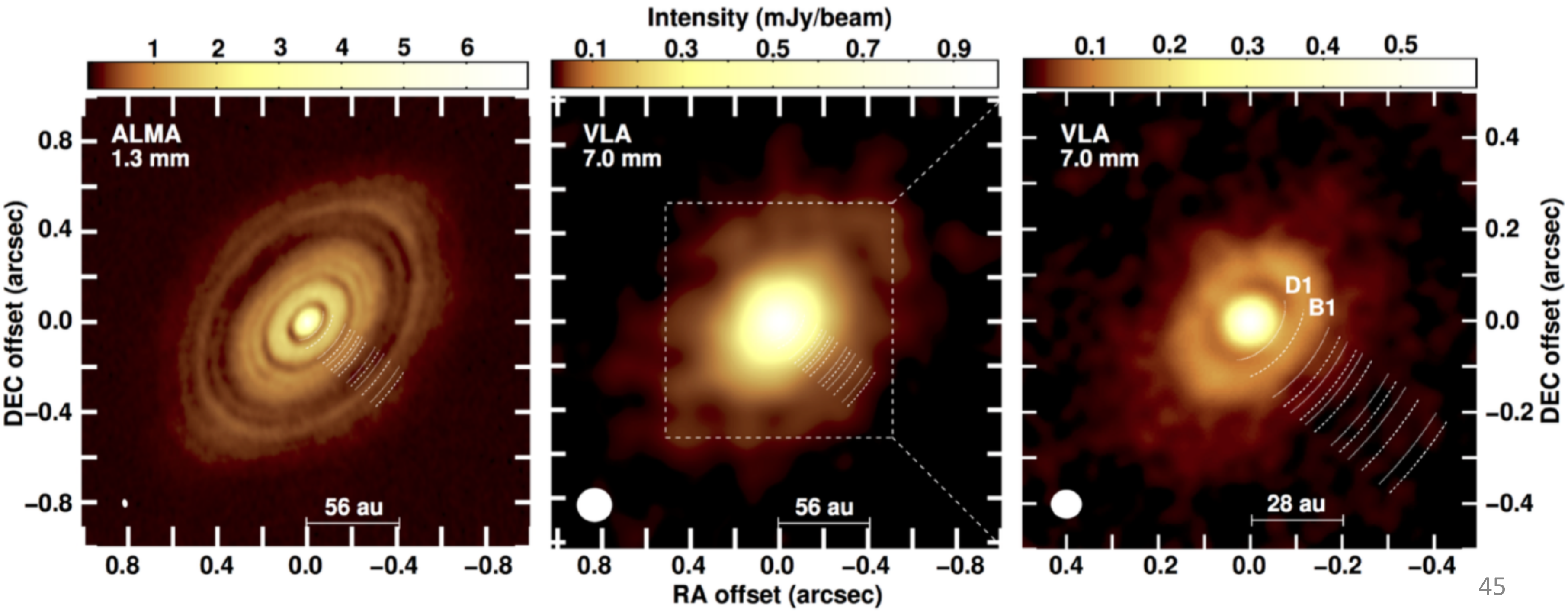


ALMA Science Highlights: Protoplanetary Disks

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

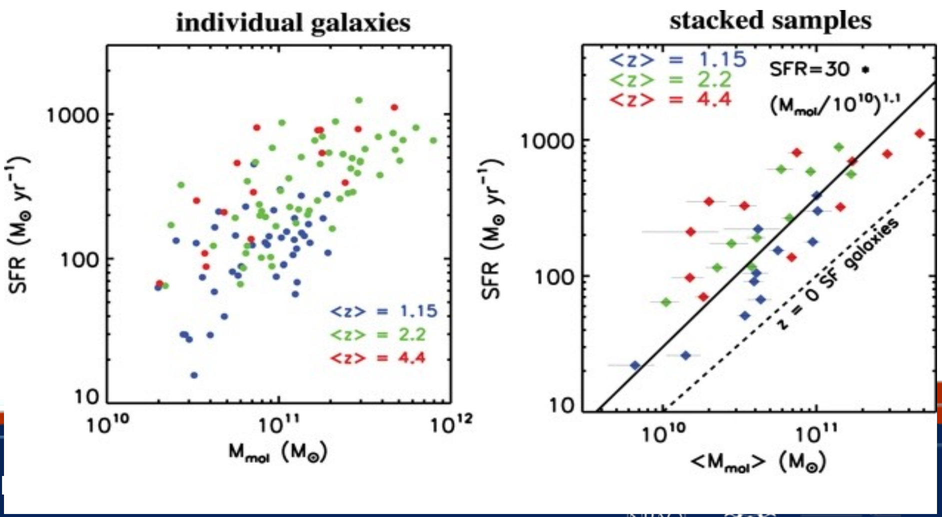
Carrasco-González et al. 2016



ALMA Science Highlights: Star Formation Peak

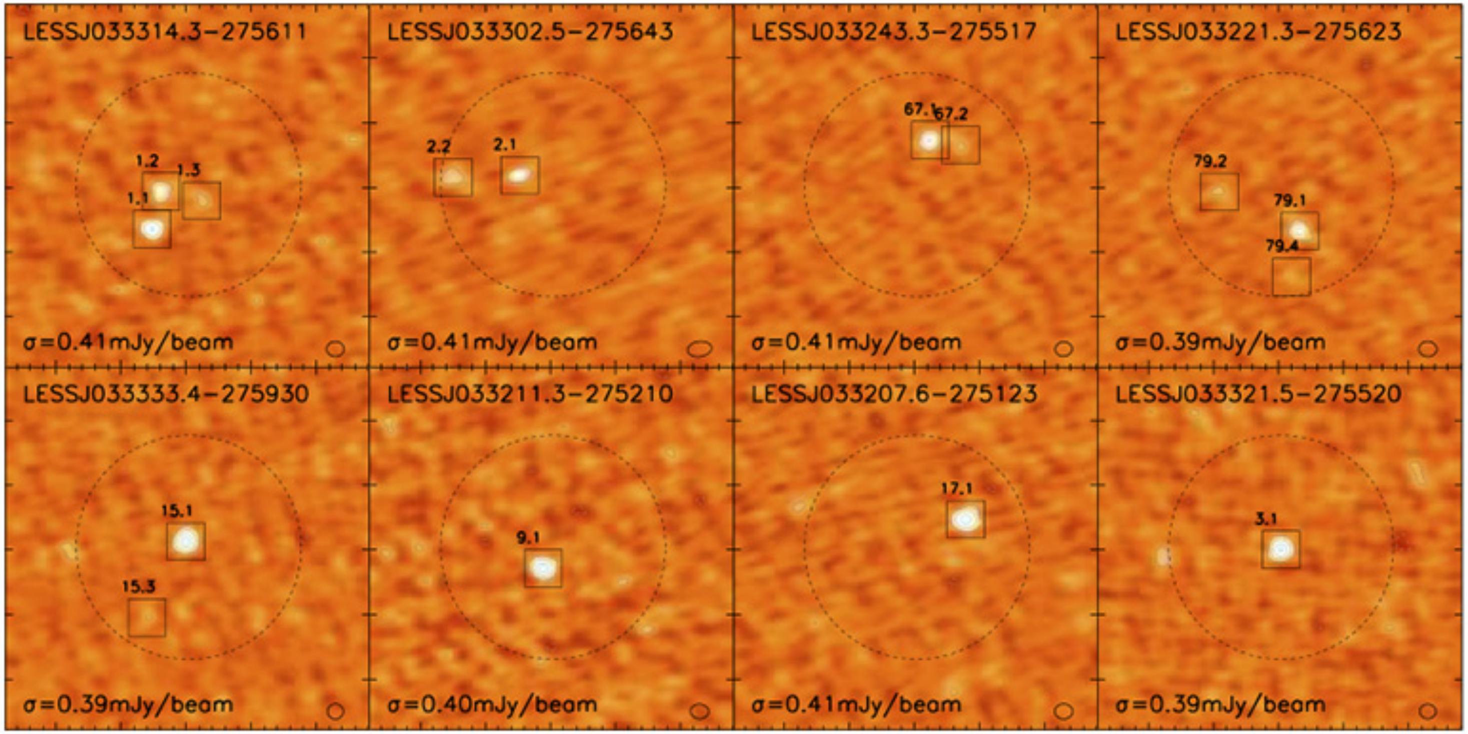
- Scoville et al. (2016 ApJ 820 83)
  - *"ISM Masses and the star formation law at z = 1 to 6: ALMA observations of dust continuum in 145 galaxies in the COSMOS survey field"*

- 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 surveys)



ALMA Science Highlights: the Distant Universe

Resolving High-*z* Submm Galaxies



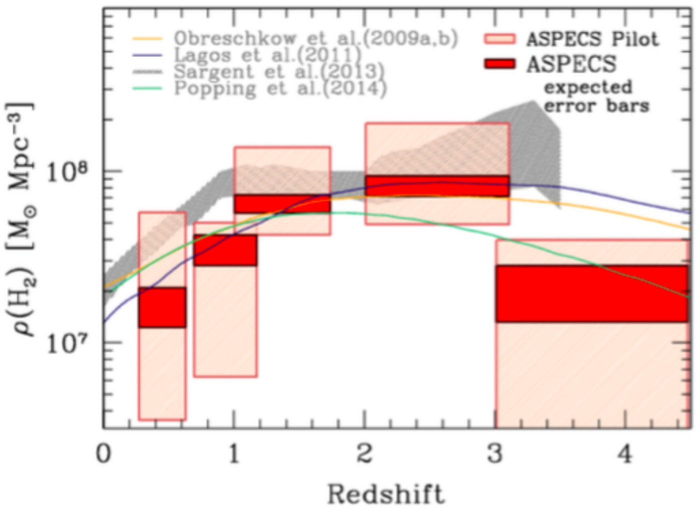
Hodge et al. 2013

- 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

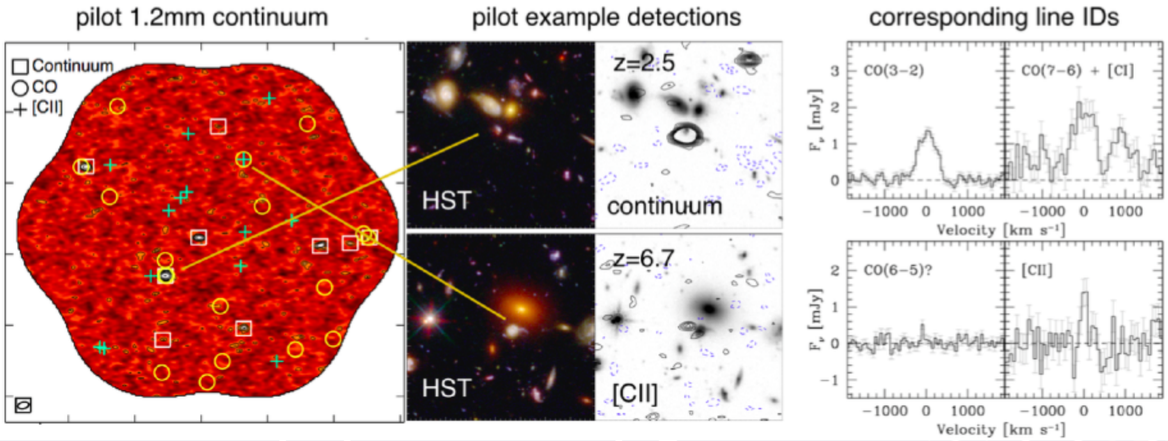
ALMA Science Highlights: the Distant Universe

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.

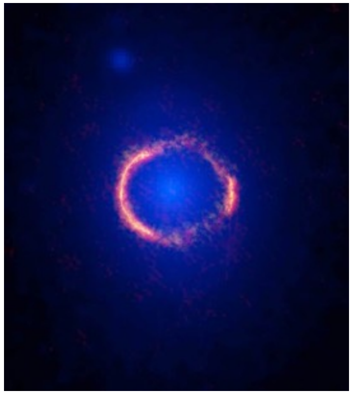


Examples of line and continuum sources from the ASPECS program, plus constraints on the dense gas history of the Universe (see papers by Walter, Decarli, Aravena)



ALMA Science Highlights: the Distant Universe

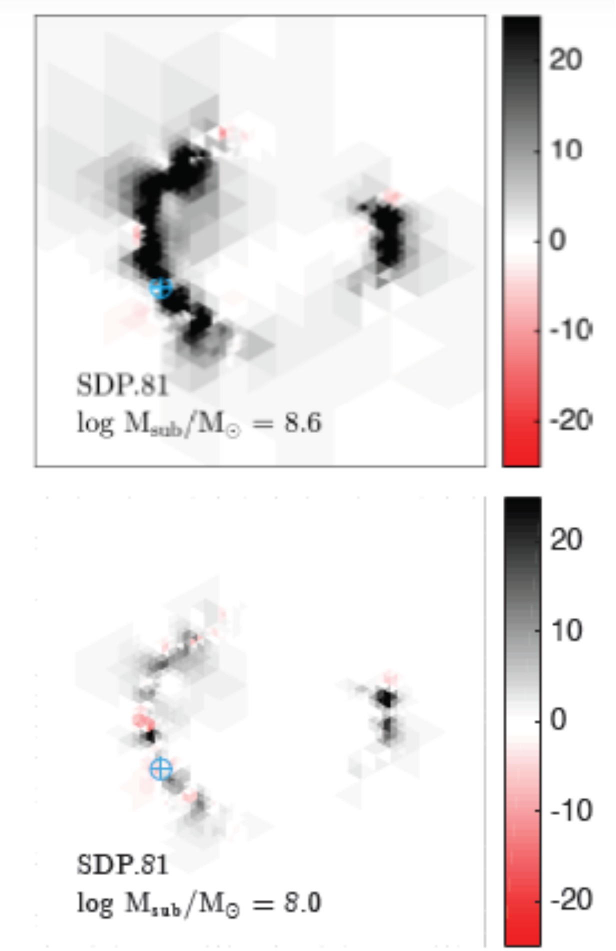
- Hezaveh et al (2016) show ALMA's potential to advance understanding of dark matter substructures
- ALMA's SDP.81 observations are analyzed to detect a subhalo with a mass of $10^{8.96\pm0.12}\,M_{sun}$
- Consistent with theoretical expectations



The SDP.81 system.

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

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

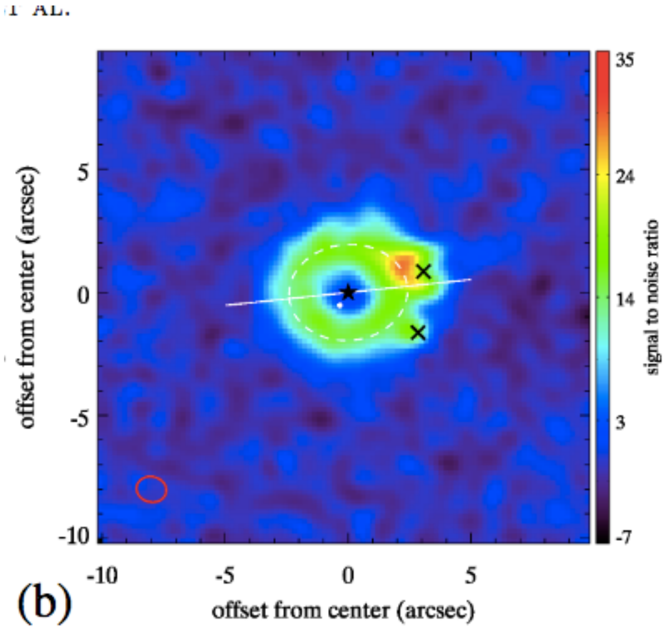


(Right Top) a map of parameter for a second subhalo of mass $10^{8.6}\,M_{sun}$ after inclusion of one subhalo of mass $10^{9}\,M_{sun}$ at the location of the blue symbol.
(Bottom) results from similar analysis for a lower mass subhalo, showing marginal improvement at another point near the first detection.

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}

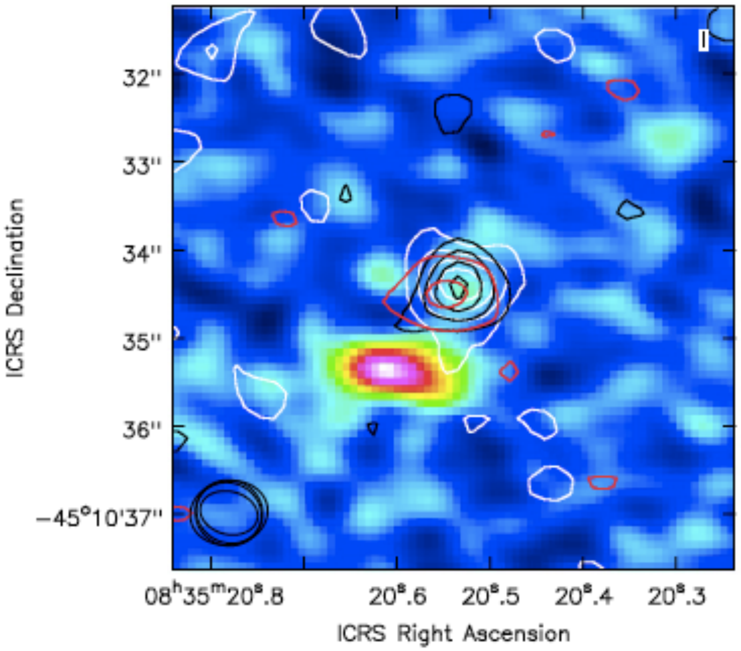


ALMA 1.3mm image of the Kuiper Belt analog disk around HD 95086 (black star). The optically imaged planet is represented by a white dot. The sources to the W are likely background galaxies, subtracted in this image. Disk major axis is white line. Su+ 2017 arXiv 1709.10129

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



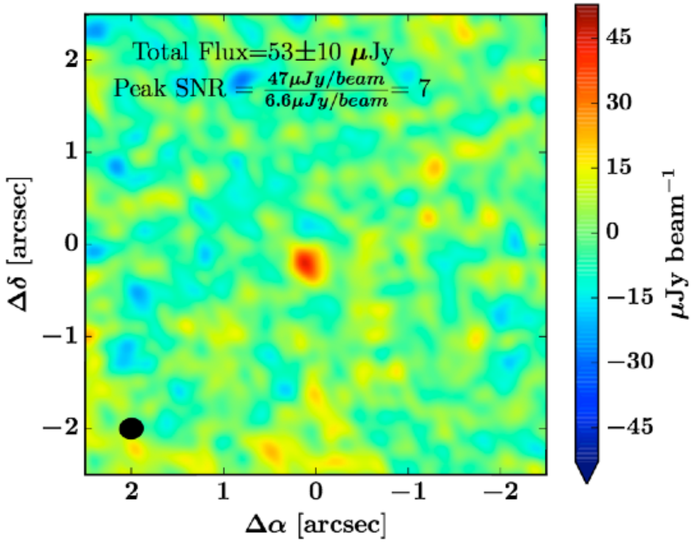
Vela Pulsar, ALMA B3,4,6 (contours) on B7 image; an extended structure, preliminarily detected in ground-based observations, may be a counter-jet protruding from the pulsar. (Mignani+, 2017)

Science Highlight (IV)

ALMA Characterizes TransNeptunian Object DeeDee

- 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*

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



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:

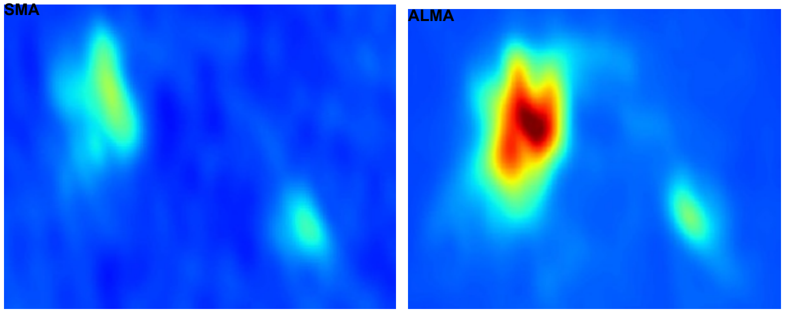
- Factors of 6-70x increase in L
- Sustained for many years (ongoing)

NGC6334I-MM1 dust continuum outburst is accompanied by:

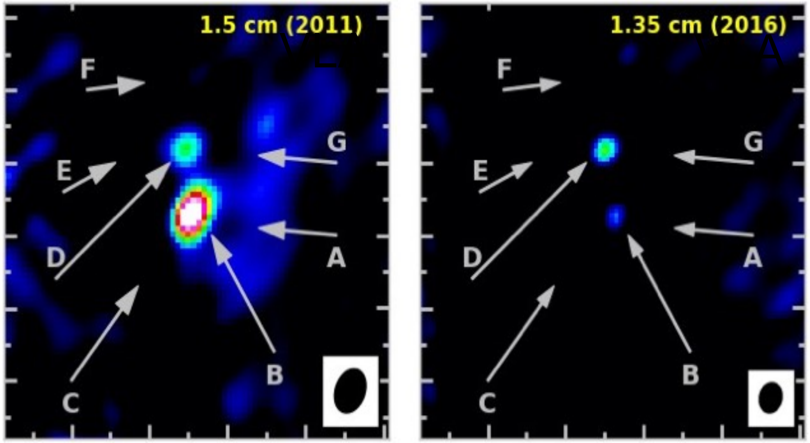
- Dimming of the HCHII region by a factor of 4: suppression of UV photons
- Candidate compact disk/outflow system: disk traced by hot SO_2, outflow traced by $C^{34}S$ and 6 cm jet direction, and maser flare
- **Consistent with a B4 ZAMS star accreting >= 0.1$M_\odot$ in a short period.**

  Understanding the details requires further monitoring and modeling

Hunter et al. 2017 ApJ 837, L29



Pre-outburst Post-outburst

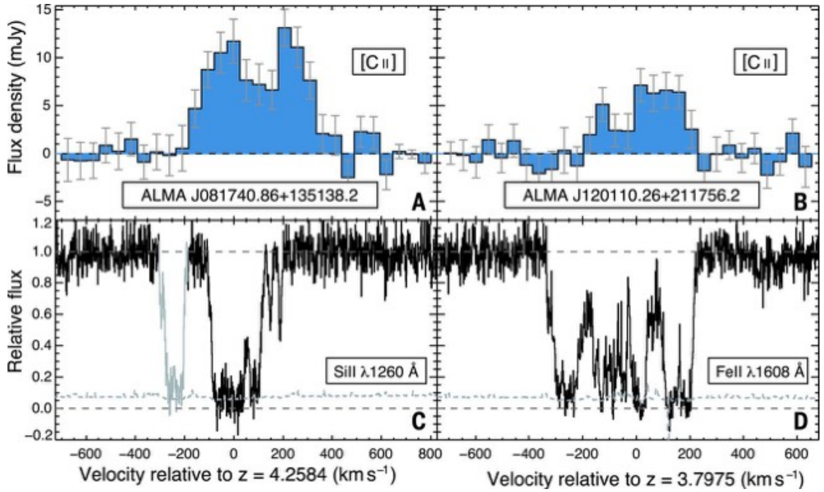


Science Highlight (VI)

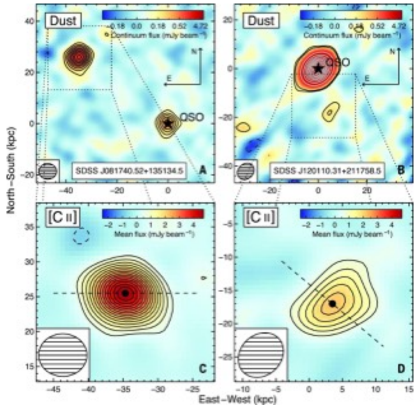
Marcel Neeleman et al. Science 2017;355:1285-1288

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.



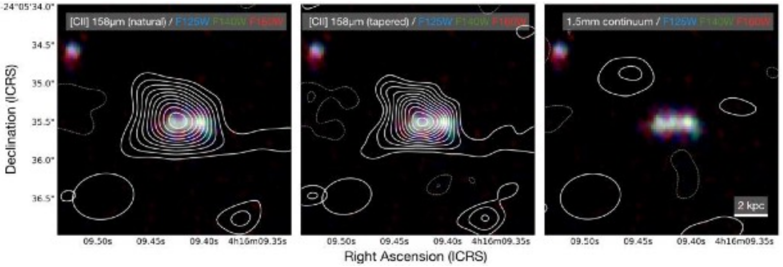
Host emission ([C II]) from the host galaxies A and B and QSO absorption (Si II and Fe II) features C and D.

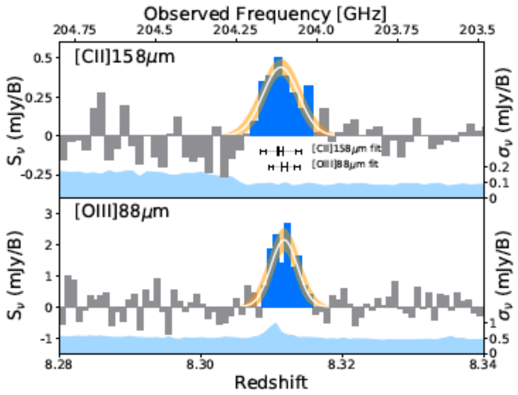


Above: The ≈400-GHz continuum emission near two QSOs (black stars). Axes give the relative physical (proper) distance at the DLA. Below: Mean flux density over the full [C II] 158-μm line profile displayed above. The dashed line is the measured major axis of the galaxy.

ALMA 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.





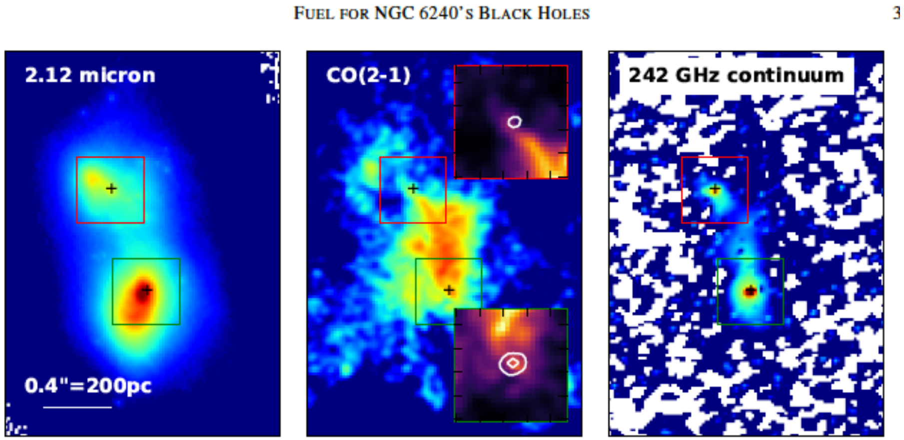
T. Bakx, Y. Tamura, T. Hashimoto, et. al. arxiv: 2001.02812

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.



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.

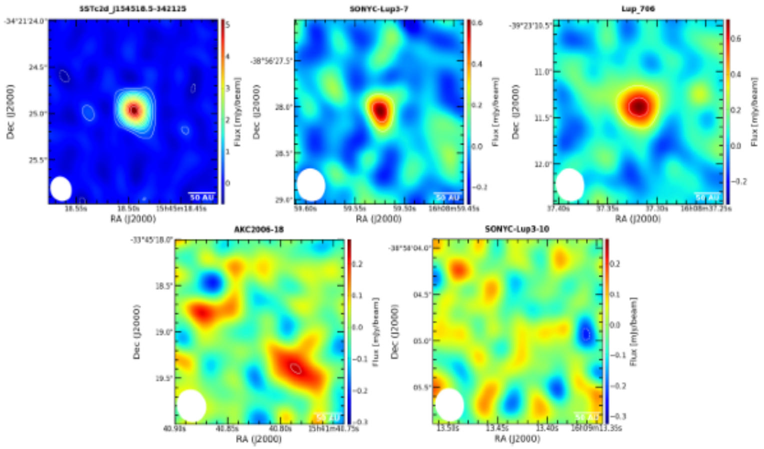
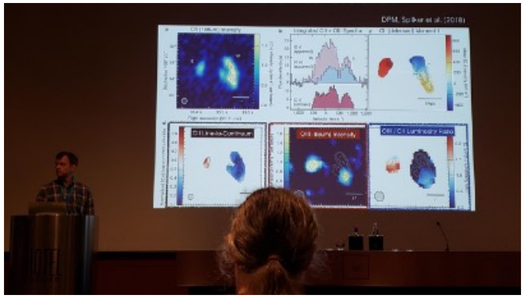


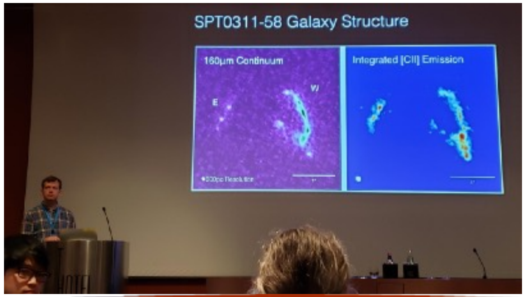
Fig. 2. Dust continuum images at 890 μm of the Lupus BDs disks survey from ALMA Band 7 observations. The beam size FWHM is $0.27'' \times 0.24''$ for the J154518.5-342125 map (robust parameter of -1), and $0.36'' \times 0.33''$ for the rest of the maps (robustness $= +0.5$). The average beam position 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 i Protoplanetary Disks

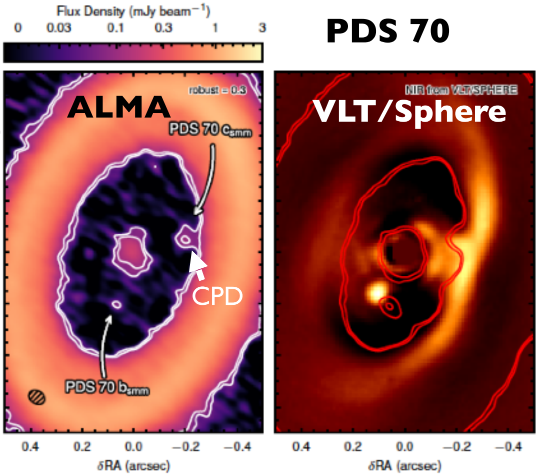
PDS 70 is 5 Myr old low mass (0.76M_{Sun}) T Tauri star 110 pc distant

- 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

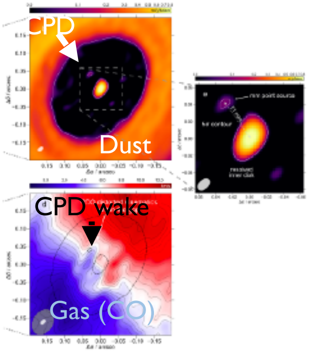
- arXiv:1906.06305: Perez et al. and 1906.06302: Casassus & Perez
- Surrounded by asymmetric dust ring at 20-40 AU
  - Within the gap at 7.8 AU lies a candidate CPD of dust mass 1 M_{Moon}
  - The feature coincides with a localized CO gas velocity kink and a Doppler-flip signature expected along the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

PDS 70



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

HD100546



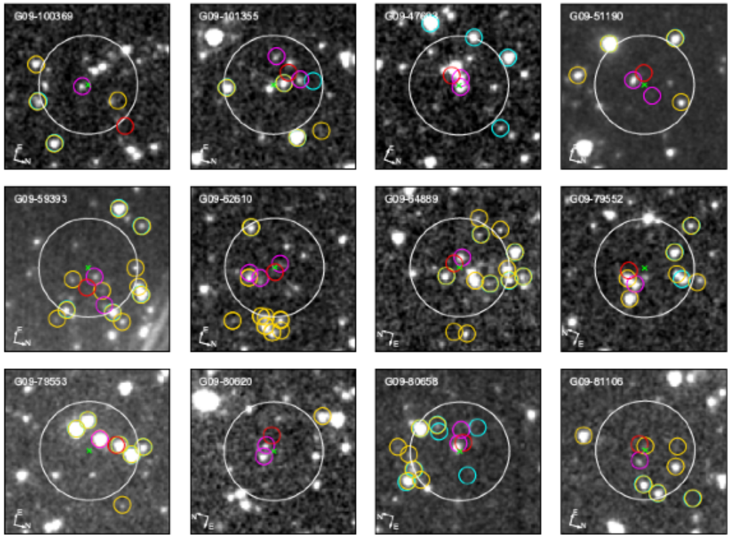
(L) Dust (greyscale) and (R) CO velocity anomaly (color) suggest a perturbation ('wake')

Ultrared dusty, star-forming galaxies:

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

Ma, Cooray et al arxiv: 1908.08043

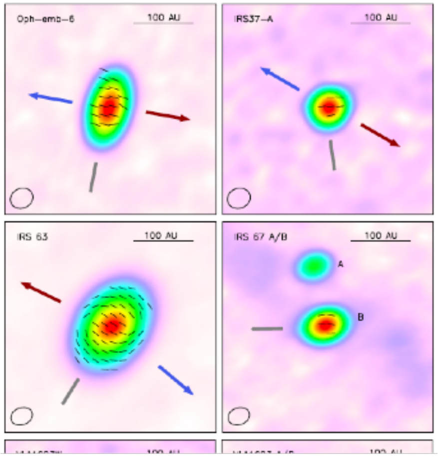
- High-resolution ALMA, NOEMA, and SMA data pinpoint 63 of the rare, intrinsically most dusty, luminous and massive galaxies in the early universe from the Spitzer catalog of Herschel-selected objects.
  - Interferometry pinpoints locations for secure ID as lensed or unlensed based on the morphology and field population
  - 65% unlensed, 27% multiple, <z>~3.3, $M_* \sim 3.7 \times 10^{11}\ M_\odot$, SFR~730 $M_\odot yr^{-1}$, $L_{Dust} \sim 9.0 \times 10^{12}\ L_\odot$, $M_{Dust} \sim 2.8 \times 10^{9}\ M_\odot$, 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

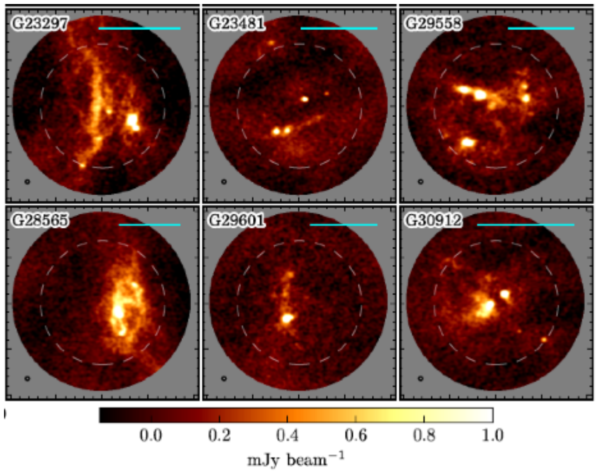


1.3 mm ALMA dust continuum images with polarization E-vectors at 0.25" = 35 au resolution

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

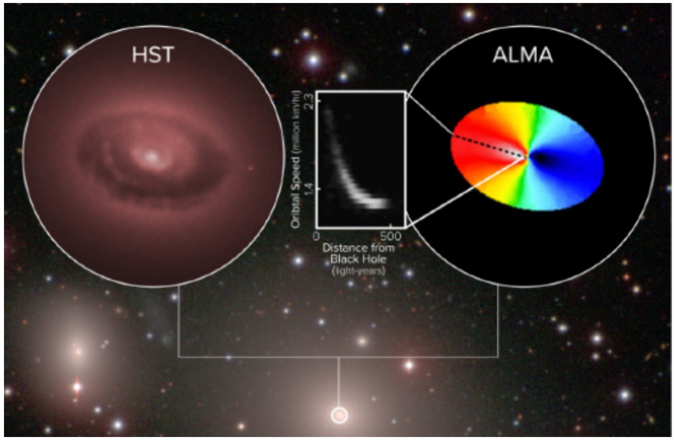
A close-up view of the cold CO (2-1) gas rotating around the supermassive blackhole:

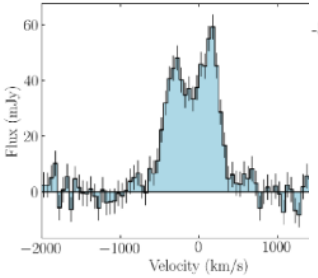
$M = 2.249 \times 10^{9} M_{\odot}$

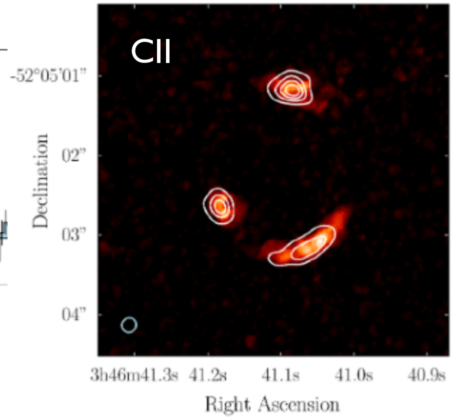
at the center of the elliptical galaxy NGC3258

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

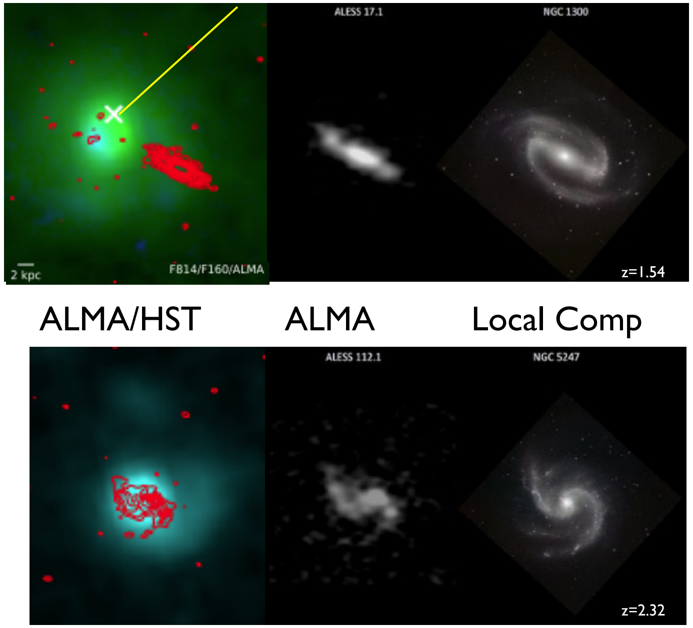
ALMA Images Nascent Galaxy Structure

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)

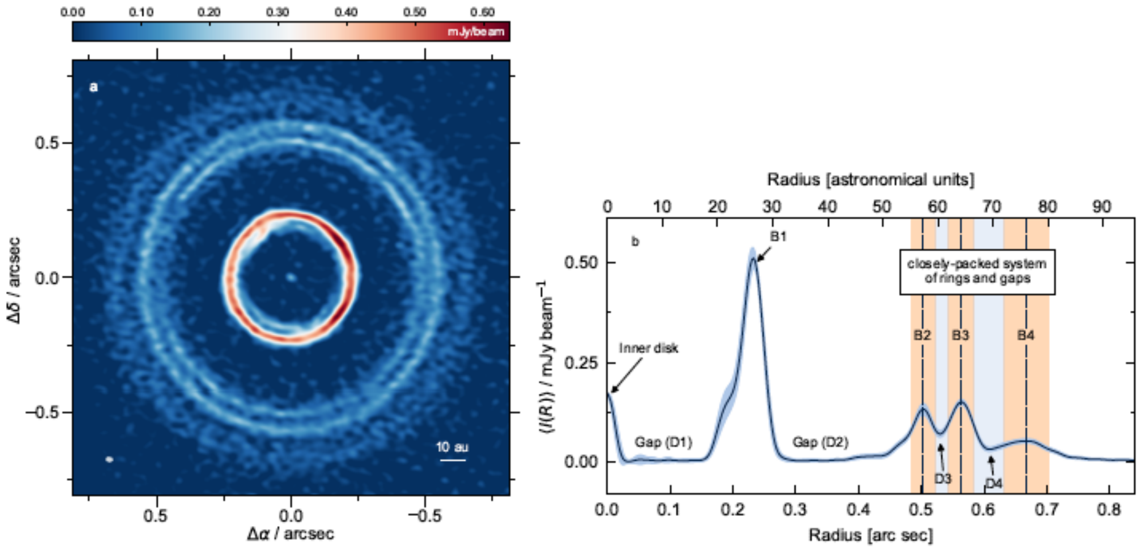
Hodge+ ApJ2019, in press.

Xray source/AGN



ALMA/HST ALMA Local Comp

HD169142

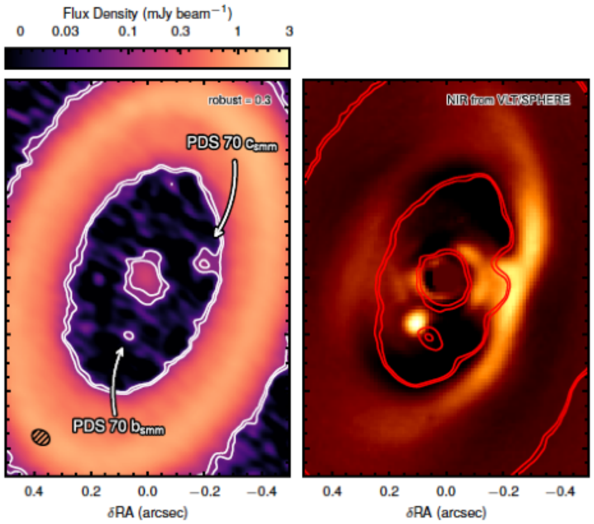


- Tight narrow rings in HD169142 are all produced by one planet. Core accretion, or any bottom up process, can thus produce planet embryos at 65AU and outside the orbit of inner giants in at least some disks.

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

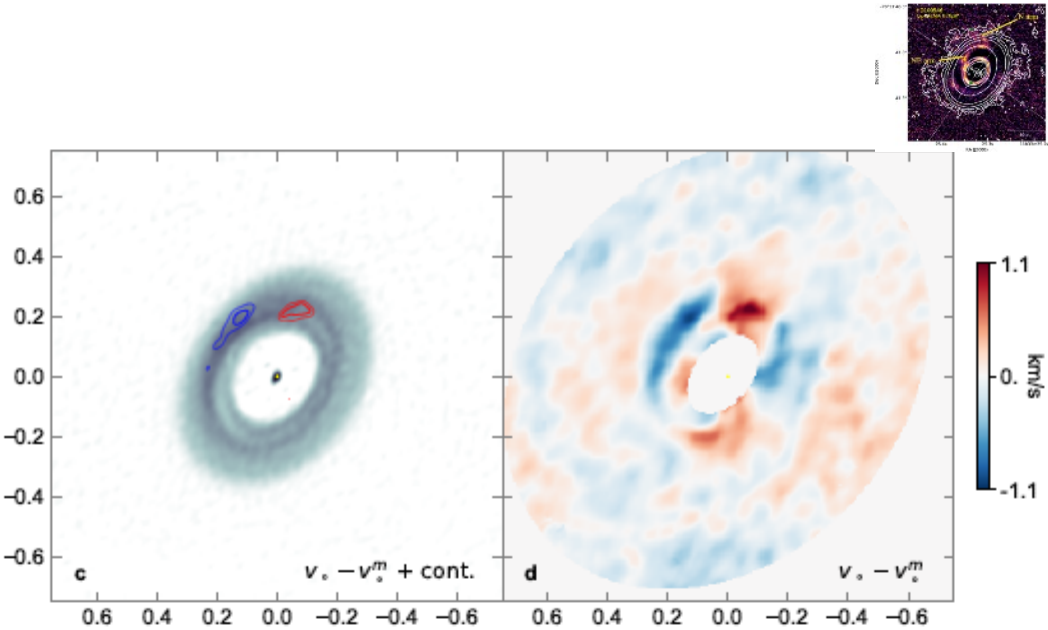


L) ALMA image showing rings of dust and a gap, which contains two planets
R) Near-IR image from VLT/Sphere

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^{o} 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

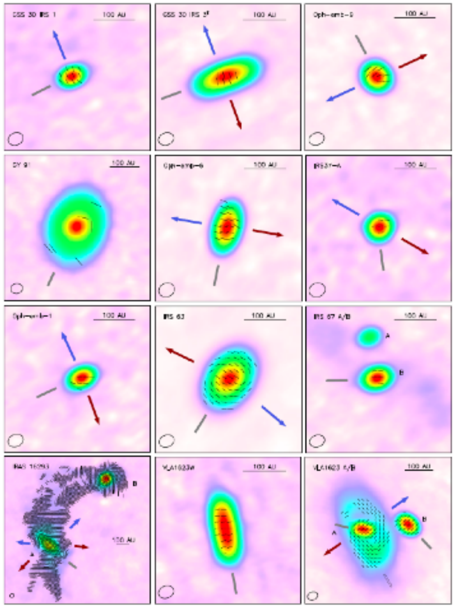
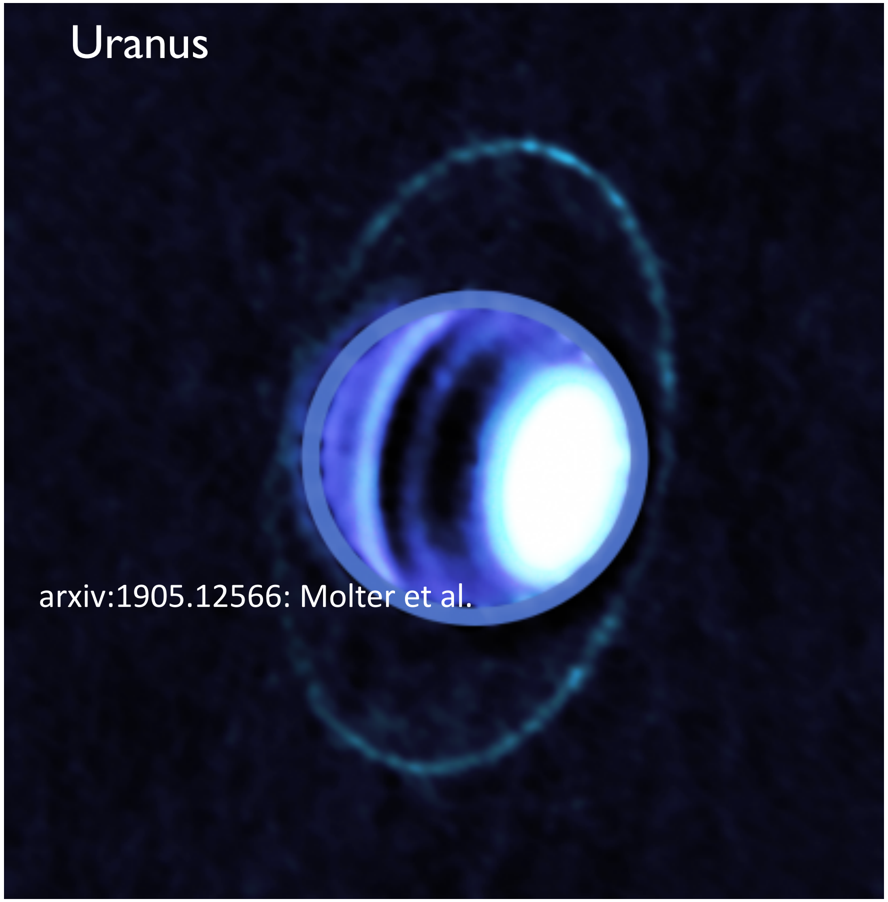


Figure 3. The 14 continuum sources with polarization detections. Background images show the Stokes I maps on a logarithmic color scale (see Appendix A for the flux scale) and the black line segments show the normalized e-vectors. Sources with ‡ are outside of the inner third of the primary beam FWHM. 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.

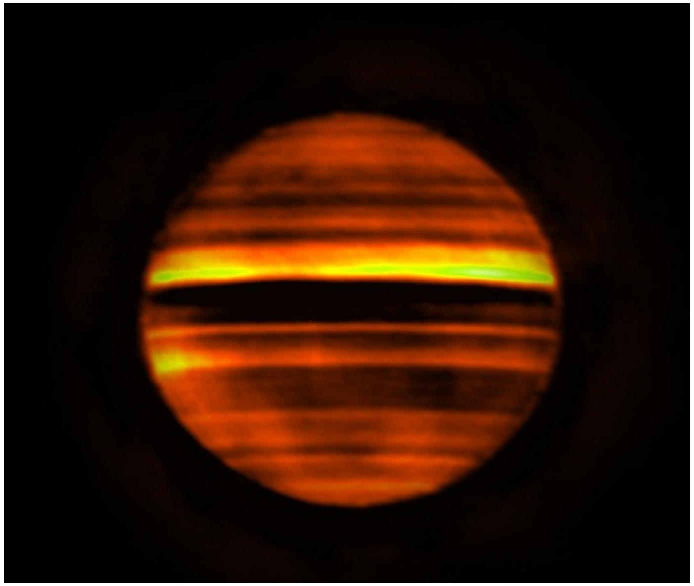


arxiv:1905.12566: Molter et al.

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.

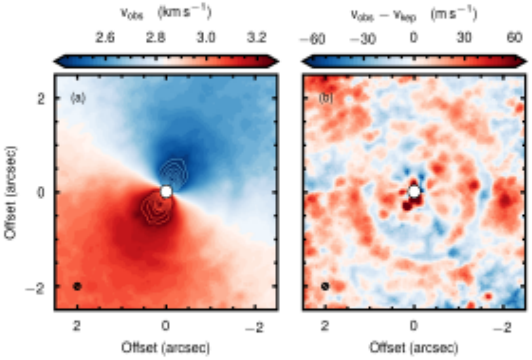


Using ALMA to Explore the Gas Reservoir of Planet Formation *(Cleeves+, AS2020)*

- 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

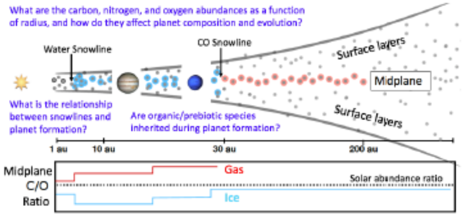
- Goal: find planets during formation, embedded in disk
  - High angular resolution optically using extreme adaptive optics seeking thermal or line (Hα) emission
  - High angular emission in the (sub)millimeter using ALMA, seeking circumplanetary disks, which could be seen to $0.03M_{lunar}$ but have 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

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