Harvey Liszt

NRAO & ALMA, Charlottesville VA

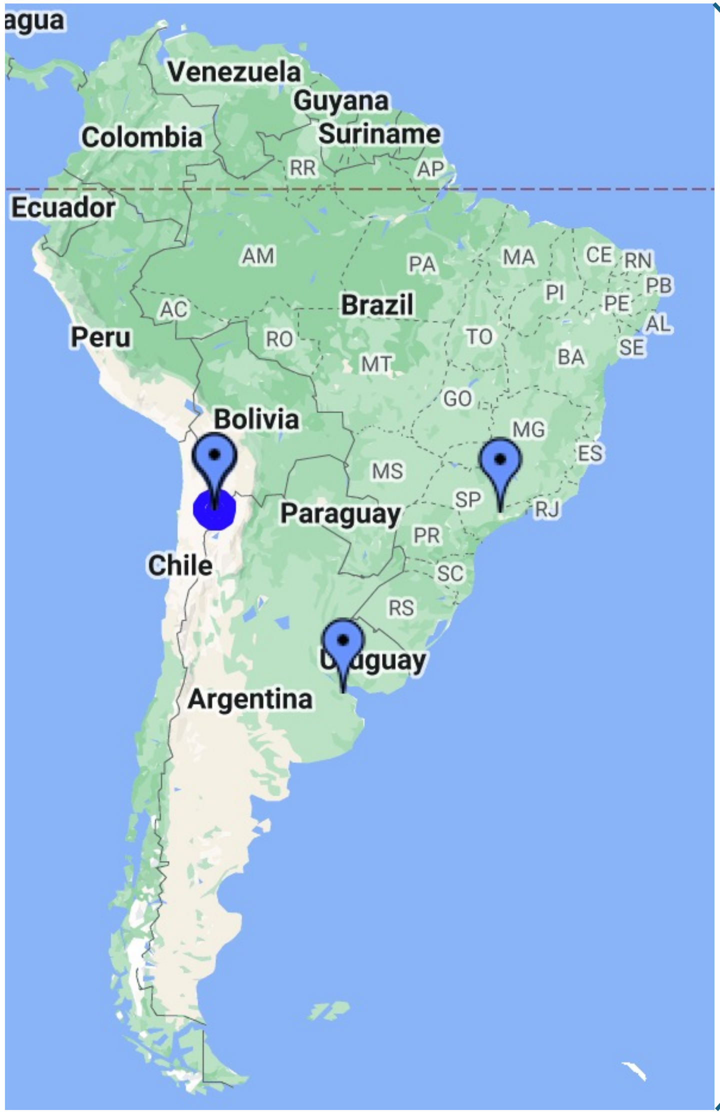
THE ALMA TELESCOPE and ITS SCIENCE

https://www.almascience.org/

The project organization

- Partners
  - North America 37.5%
    - National Radio Astronomy Observatory (US) and Herzberg Institute (Canada)
    - ALMA regional center (ARC) in Charlottesville and a node in Victoria, BC
  - Europe 37.5 %
    - European Southern Observatory on behalf of its member states
    - ARC HQ in Garching (Munich) Germany and ARC nodes in Holland, Sweden …
  - East Asia 25%
    - National Astronomical Observatory of Japan and partners in Taiwan and Korea
    - ARC HQ in Mitaka (Tokyo) Japan and ARC nodes in Taiwan, Korea
  - Chile receives 10% of the observing time as the host nation
    - The great majority of all ground-based astronomy development occurs in Chile
    - The Joint ALMA Observatory (JAO) has HQ in Santiago on the ESO campus

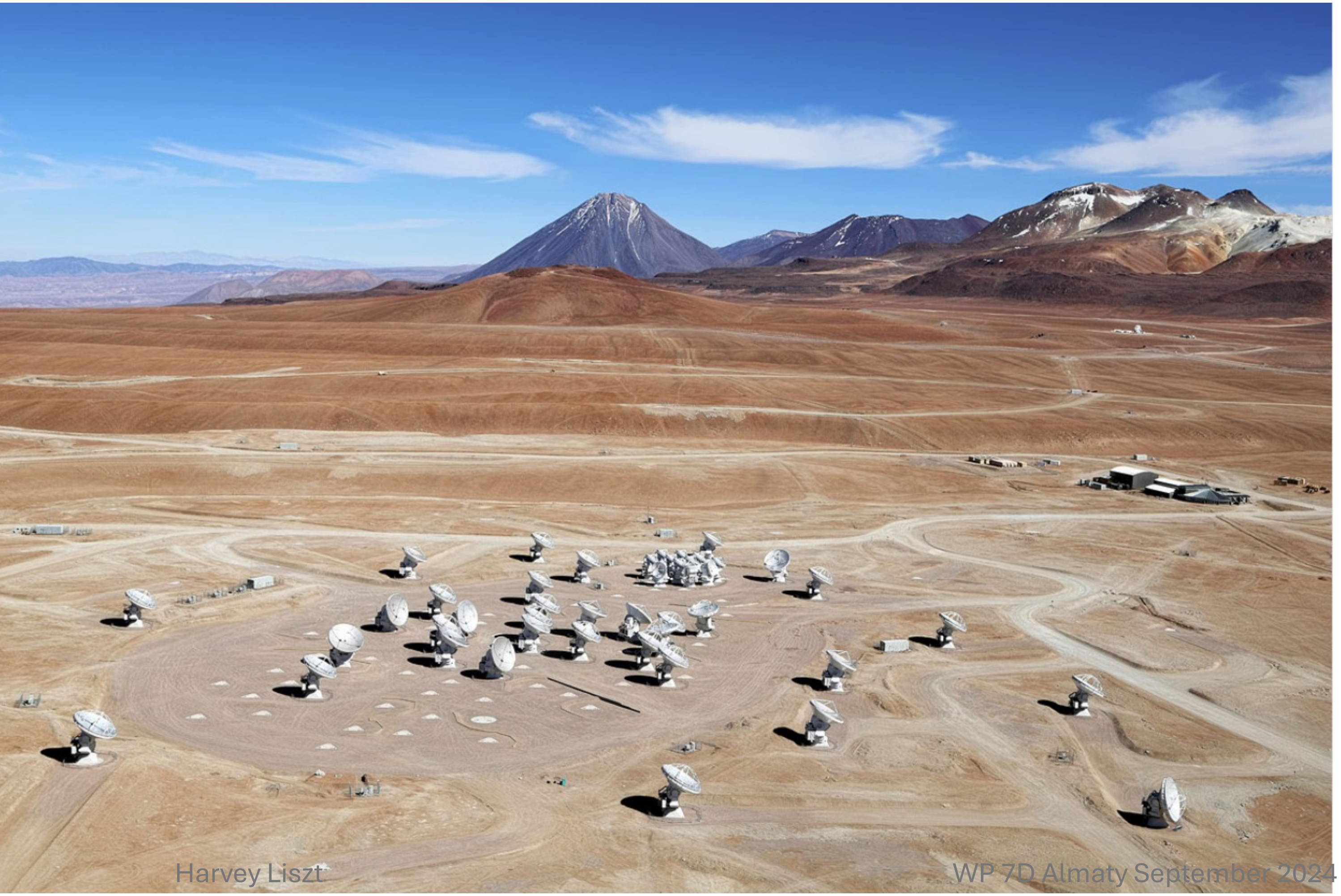
The place



The ALMA Off Site Facility at 2900 m altitude during construction

The hardware at 5000m

- 50 x 12m reconfigurable antennas
  - Separations (baselines) 160 m-16.2 km



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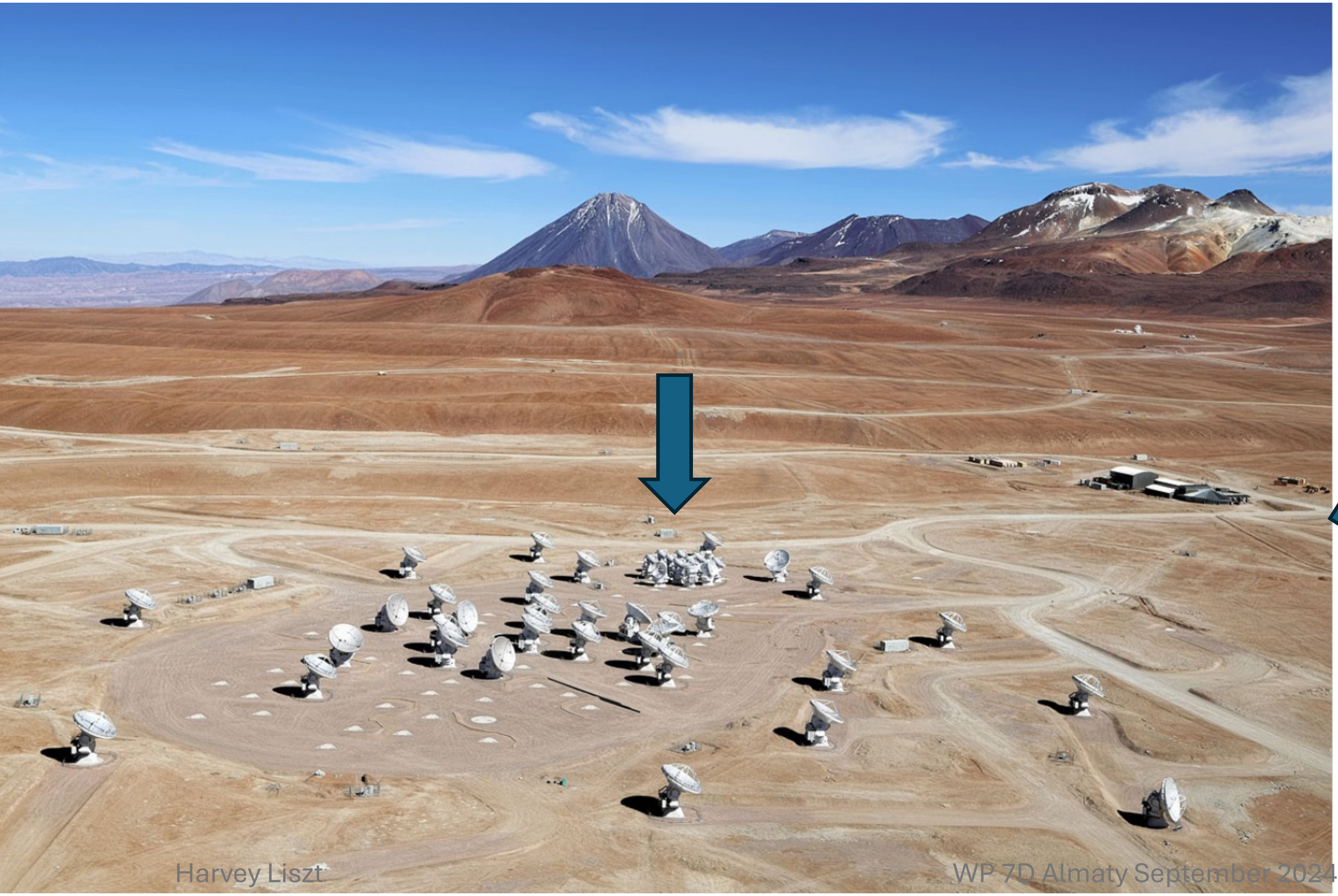
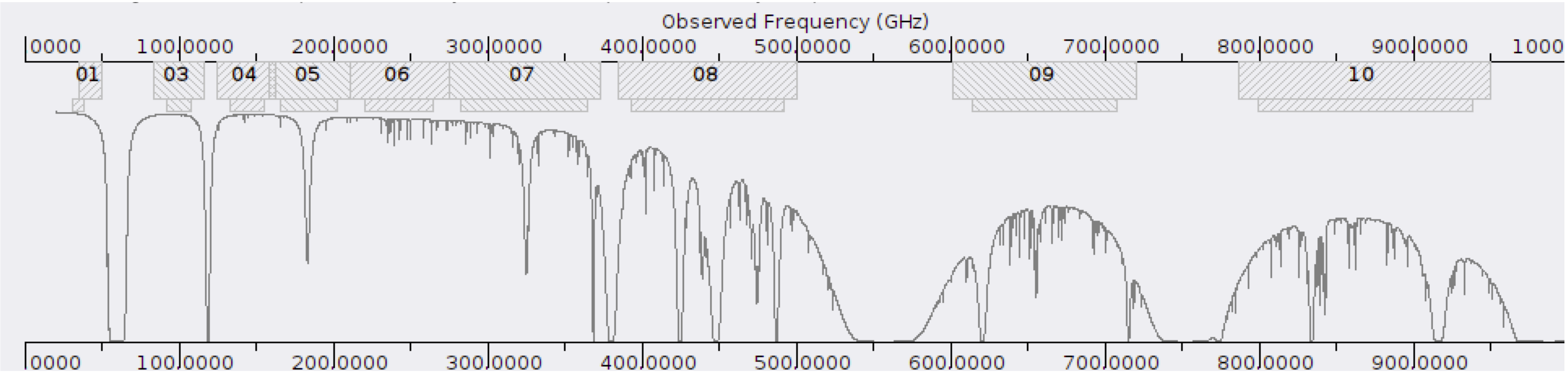


- 12 x 7m fixed antennas
    - Baselines 9 – 49 m
- 4 x 12m antennas
    - Used alone and paired

The spectral coverage and angular resolution

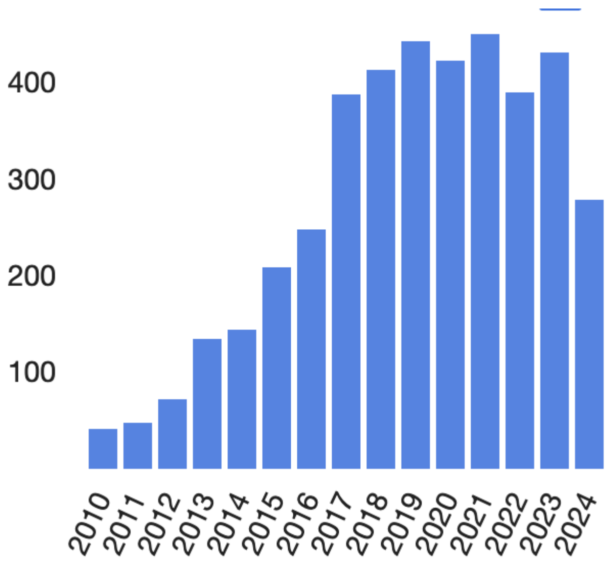
- 10 Receiver bands 35 – 950 GHz (best conditions shown below)



Angular resolution
12m: 0.13”-7.5”
7m: 29”

Angular resolution
12m: 0.006”-0.37”
7m: 1.4”

The science



- 1750 refereed papers with “ALMA” in title
  - 4100 with “ALMA” as keyword or in abstract
- 1750 proposals submitted in Cycle 11, 2024
  - 2/3 new, 1/3 rollovers
- Competition is terrible and this may seem very remote
- **BUT THERE IS TIME FOR NON-PARTNER PROPOSALS**
  - See the ALMA Proposers guide
- **AND THE DATA ARCHIVE IS OPEN**
  - **An aspect of NRAO’s “open skies” policy**
  - Raw+reduced data are available 1 year after delivery to the proposer
  - ALMA papers have references to project codes

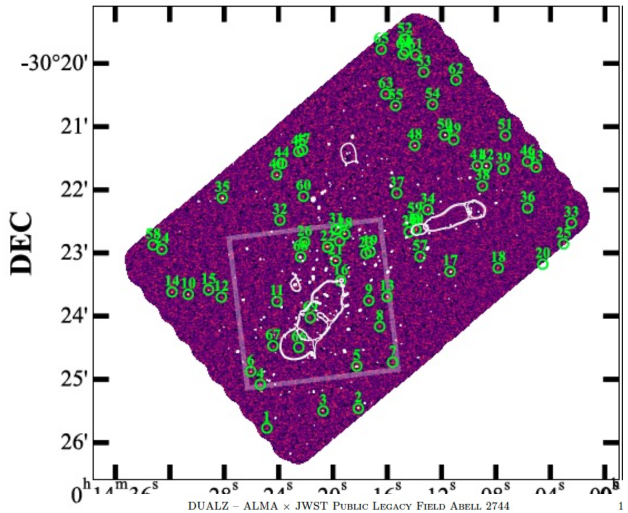
ALMA Science Frontiers

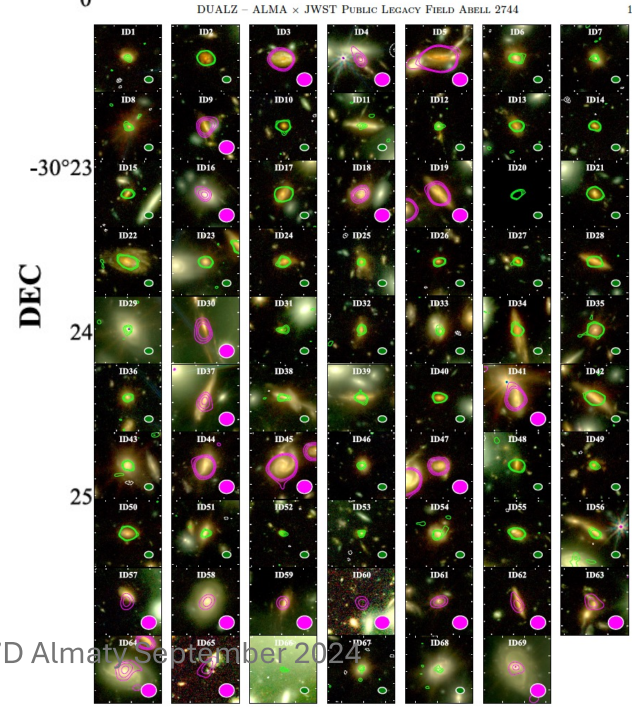
- Early Universe
  - Why are there galaxies a few x 10^8 years after the Big Bang?
  - Radiation redshifted to lower frequency by factors ~10 (more?)
  - Star formation heavily shrouded by heated dust, so radiation is at IR wavelengths that we see redshifted as radio waves
    - Why is there so much dust hiding the early Universe light?
  - Synergy with James Webb Space Telescope working in near IR

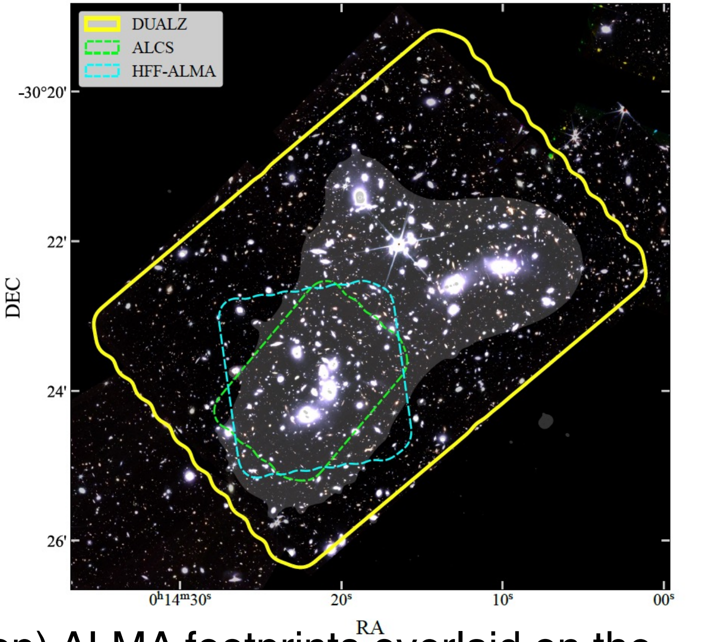
DUALZ – Deep UNCOVER-ALMA Legacy High-Z Survey

Fujimoto+ arXiv:2309.07834

- Deep ALMA 1.2 mm continuum imaging of massive galaxy cluster Abell 2744 in a 4′x6′ 30-GHz-wide mosaic to a sensitivity of σ = 32.7 μJy.
- Detect 69 dust continuum sources at S/N ≳ 5.0 with median redshift z=2.3 and intrinsic 1.2-mm flux 0.24 mJy.
  - 27 have been spectroscopically confirmed, leveraged by the latest NIRSpec observations, remainder have photometric z from HST, NIRCam, and ALMA.
  - One ALMA [C II]158 μm line emitter at z = 6.3254±0.0004, confirmed by NIRSpec
- IR counterparts undisturbed; suggesting these objects are not mergers.
- Eight are HST-dark; two JWST-dark among ALMA sources, including some face on.
- Infrared luminosity function up to z ~ 10 is assessed—authors find it consistent with predictions from galaxy formation models







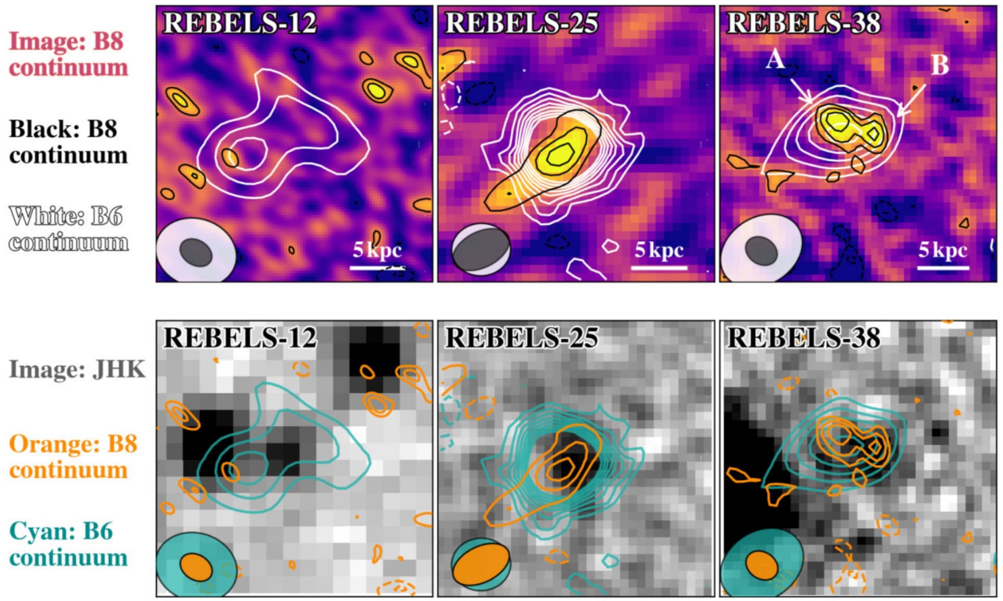
(top) ALMA footprints overlaid on the NIRCam RBG (R: F444W, G: F356W, B: F277W) map of A2744 taken in UNCOVER. Green: ALMA HFF; Cyan ALMA ALCS. White shaded: highly magnified (>2).
(l) ALMA Band 6 continuum mosaic maps without primary beam correction; green circles are ALMA sources. white lines denote the μ = 200magnification curve at z = 6. Below: postage stamp maps.

Cold dust and low [O III]/[C II] ratios: an evolved star-forming population at redshift 7

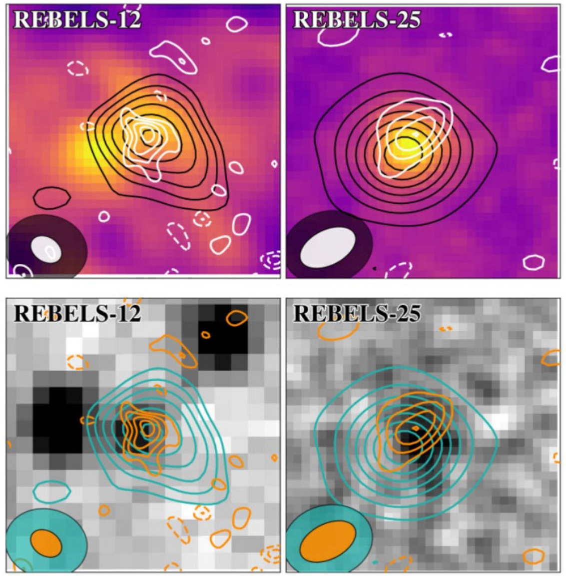
Algera+ 2024MNRAS.527.6867A

- ALMA Band 8 (rest-frame 90 μm) continuum observations of three massive ($M \approx 10^{10}\ M_{sun}$) galaxies at $z \approx 7$
    - [C II]158 μm and underlying dust continuum emission
    - Optically thin modified blackbody fits suggest $T_{dust} \approx 30 - 35$ K in two dual-band detected targets
    - Hence, they are colder than most known galaxies at $z \sim 7$with $M_{dust} \approx 10^8\ M_{sun}$, albeit still consistent with models of high-redshift dust production.
    - Furthermore we detect [O III]88 μm emission in both REBELS-12 and REBELS-25,
    - There, L[O III] /L[C II] ≈ 1 − 1.5 – low compared to the L[O III] /L[C II] ~ 2 − 10 observed in the known z ~ 6 population thus far.
    - We argue the lower line ratios are due to a comparatively weaker ionizing radiation field reflecting the less starbursty nature of our targets
        - However the possibility of REBELS-12 being a merger of an [O III]-bright and [O III]-faint component prevents the unambiguous interpretation of its [O III]/[C II] ratio.
    - Nevertheless, a low burstiness forms a natural explanation for the cold dust temperatures and low [O III]λλ4959, 5007 + H β equivalent widths of REBELS-25 and REBELS-38.
- These observations provide evidence for the existence of a massive, dust-rich galaxy population at $z \approx 7$ which has previously experienced vigorous star formation, but is currently forming stars in a steady, as opposed to bursty, manner.

B8 continuum emission at the 2σ , 3σ , and 4σ levels where σ is the local RMS in the image; overlaid white contours show B6; bottom row shows the same B6 (cyan) and B8 (orange) contours on top of stacked ground-based JHK-imaging

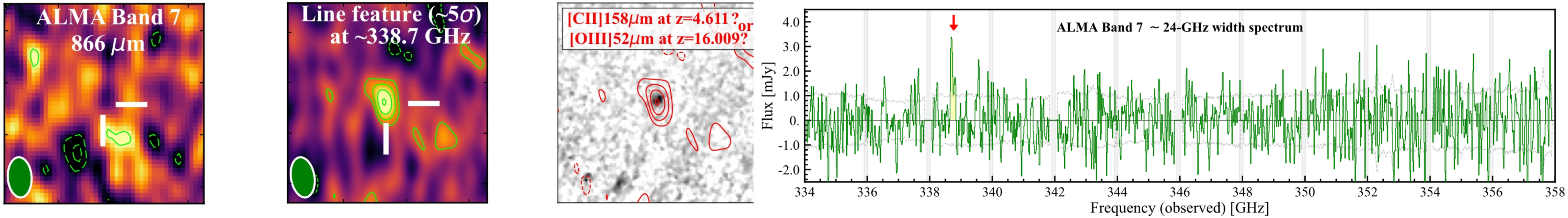


The REBELS sources here have low Td, high Md, M* and [O III]/[C II] ratios. This implies that they may be relatively evolved star-forming galaxies already at z≈7.



(l) Moment-0 maps of the [O III] emission in REBELS-12 and REBELS-25 (white contours), on top of [C II] emission (black contours) and Band 6 dust continuum emission;
Lower: The moment-0 maps on top of stacked JHK images; [O III] and [C II] are shown in orange and cyan, respectively, for visual clarity.

ALMA FIR View of Ultra High-redshift Galaxy Candidates at z ~ 11–17: Blue Monsters or Low-z Red Interlopers?
Fujimoto+ arXiv:2211.03896



- Despite sustained effort to explore high redshifts at z > 10 – the first few hundred million years in our history of the universe – only GNz11 at z~10.603 has been spectroscopically confirmed (GNz11; Oesch+ 2016; Jiang+ 2021, Bunker+ 2023 via its rich NIRSpec spectrum).
- Authors present ALMA Band 7 DDT observations of S5-z17-1, a remarkably bright galaxy candidate at zphot=16.7+1.9−0.3 (MUV=−21.6), S5-z17-1, identified in JWST Early Release Observation data of Stephen's Quintet.
- Dust continuum at 866 μm is not detected, ruling out the possibility that S5-z17-1 is a low-z dusty starburst with a star-formation rate of ≳ 30 M⊙ yr−1.
- A 5.1σ line feature at 338.726 ± 0.007 GHz exactly coincides with the JWST source position, with a 2% likelihood of the signal being spurious.
  - The most likely line identification would be [O iii]52μm at z = 16.01 or [C ii]158μm at z = 4.61, whose line luminosities do not violate the non-detection of the dust continuum in both cases.

ALMA Science Frontiers

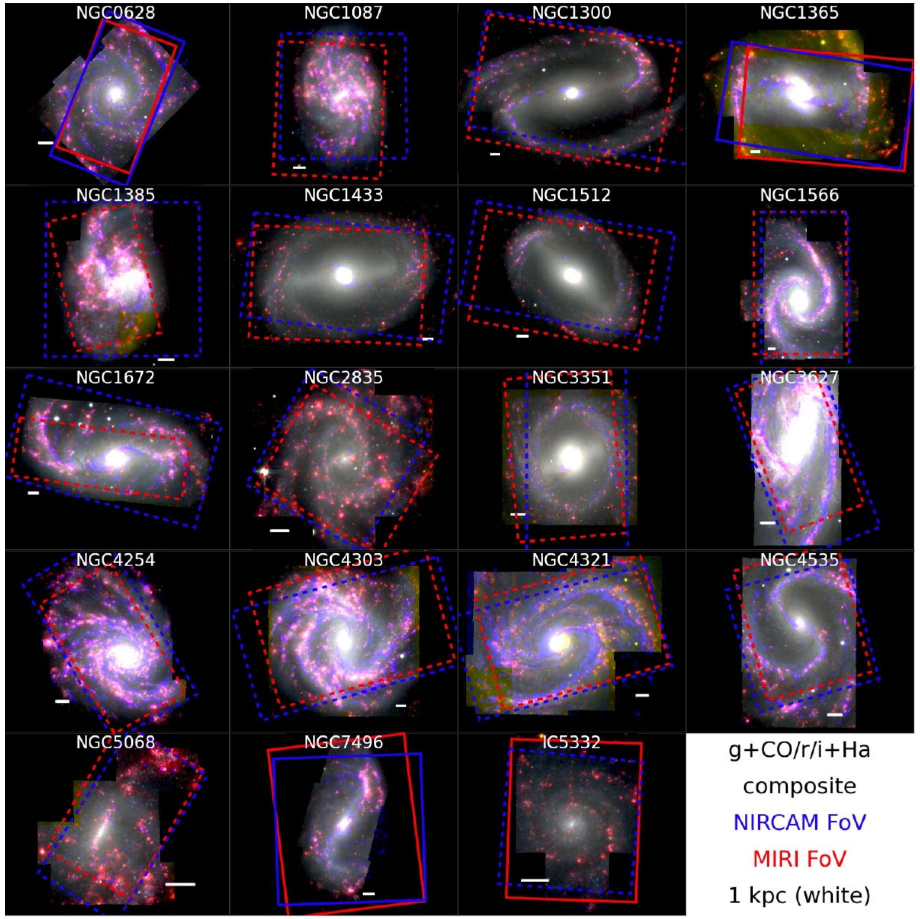
- Evolution of galaxies and their black holes
  - How did the observable galaxies form?
  - How much does the structure of a galaxy change over its lifetime?
  - What controls the star formation history of a galaxy?

The PHANGS-JWST Treasury Survey: Star Formation, Feedback, and Dust Physics at High Angular Resolution in Nearby GalaxieS

Lee+ 2023ApJ...944L..17L

PHANGS-JWST is a 112.6 hour program to image 19 nearby galaxies (D < 20 Mpc) in eight filters from 2m to 21m using NIRCam (F200W, F300M, F335M, F360M) and MIRI (F770W, F1000W, F1130W, and F2100W).

The PHANGS-JWST nearby spiral galaxy sample features overlapping coverage from ***ALMA***, HST, and VLT-MUSE and other facilities presenting our NIRCam and MIRI observing strategy.

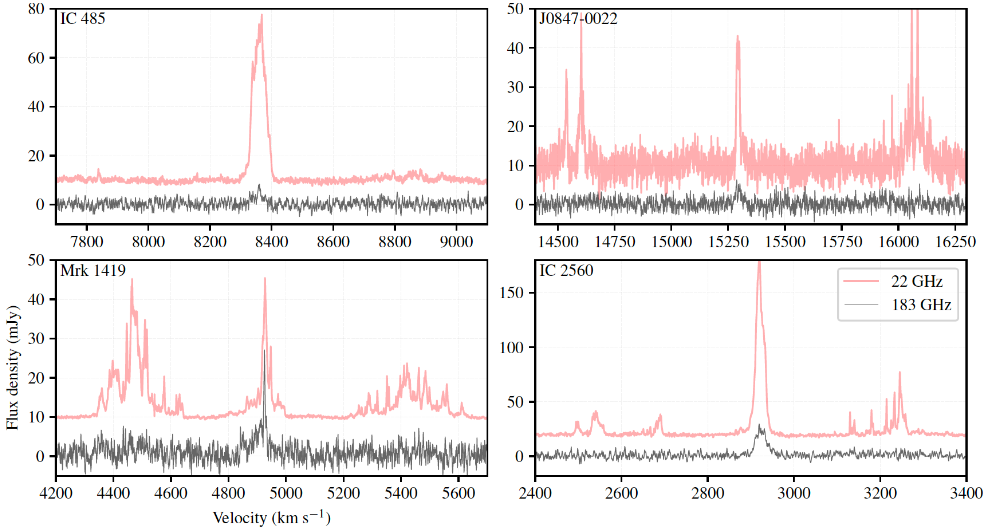


Composite gri+H+CO images for the 19 galaxies in the PHANGS-JWST Treasury program. The gri+H images are constructed from VLT MUSE full-eld spectral mapping (Emsellem et al. 2022), with H line emission in red, and combined with ***ALMA CO(2-1)*** (Leroy et al. 2021) maps, with CO(2-1) flux in blue. JWST NIRCam and MIRI footprints have been dened to overlap existing MUSE, ALMA, and HST data. Footprints shown with dashed lines represent observations that have not been executed at time of writing (October 2022), and may rotate slightly due to the range of allowed orient angles specied for the target. The JWST sample spans a factor of 50 in stellar mass and SFR, and a factor of 100 in CO surface density (Table 2). It includes galaxies with prominent dust lanes, a full range of stellar bar, bulge, spiral arm morphologies, as well as nuclear starbursts and AGN activity.

183GHz water megamasers in active galactic nuclei: a new accretion disk tracer

Pesce, Braatz, Henkel, Humphreys. Impellizzeri, and Kuo. arXiv 2302.02572

- ALMA surveyed 20 22GHz ortho-H_2O megamaser systems for 183 GHz para-H_2O maser emission, finding 13.
- High S/N ratios achieved enable a coarse mapping of the 183 GHz maser system
  - Masers appear to be distributed similarly to those seen in VLBI maps of the 22 GHz system in the same galaxy
  - May be tracing the circumnuclear accretion disk at larger orbital radii than are occupied by the 22 GHz masers.

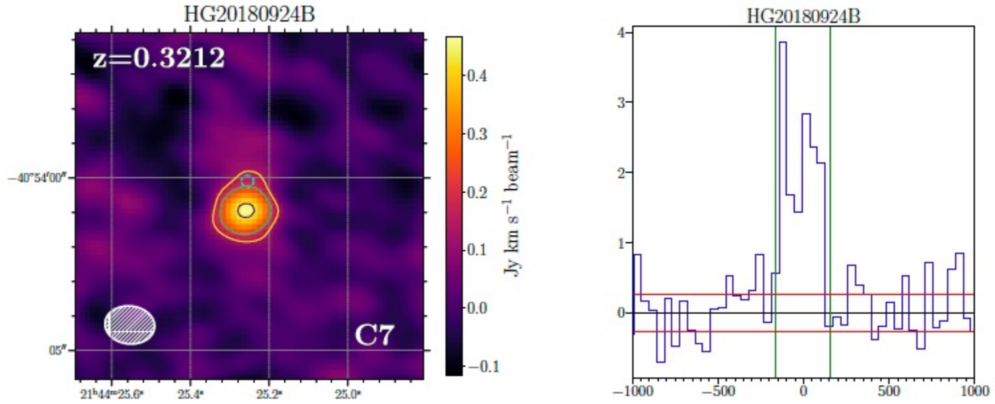


Comparison of ALMA 183 GHz spectra (in black) with their 22GHz counterparts (in red, vertically offset). The 183 GHz spectra have been boxcar smoothed across 10 channels, corresponding to a 2kms^{-1} post-averaging spectral resolution.

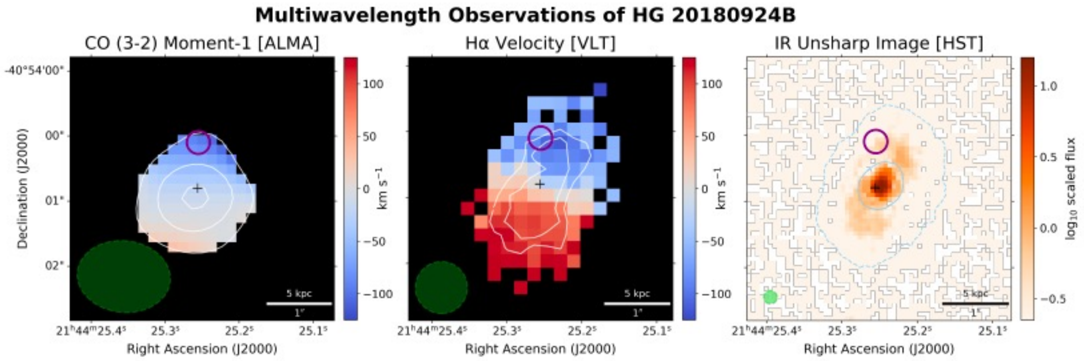
Constraining the Molecular Gas Content of Fast Radio Burst (FRB) Host Galaxies

Chittidi+ arXiv:2304.10377

- More than 600 FRBs reported, thanks to instruments such as *CHIME*; only ~30 FRB hosts are published
    - Optical counterparts to FRBs have been conducted but thus far these have only yielded non-detections
    - Work on FRB host galaxy demographics has shown diverse properties in stellar masses and star formation rates
- What population hosts FRBs?
    - Milky Way magnetar SGR 1935+2514 with an FRB-like burst (CHIME/FRB Collaboration et al. 2020) provides strong evidence that FRBs could in principle be powered by magnetars, providing further support to the association with young stellar populations.
    - Conversely, the localization of a FRB originating from within a globular cluster in Messier 81 (Bhardwaj et al. 2021; Kirsten et al. 2022) points towards a much older stellar population
- Authors present irst general census of the molecular gas content of ASKAP FRB hosts via ALMA to establish their connection to other relevant physical parameters, such as the Star Formation Rate and stellar mass, needed for determining the ISM conditions, and thus pinpointing the stellar progenitors that could give rise to FRBs.
    - Target strongest of the low-JCO transitions expected to be redshifted into the ALMA bands (namely Bands 6 and 7 for the CO J=3-2 line).
    - Sought emission from five FRB host galaxies, three of which are studied for the first time
    - Detected molecular gas in two new FRB host galaxies, tripling the existing number of known detections.
    - The detected hosts HG20180924B, HG20190714A, and HG20200430A have Mgas = 0:2 ⍰ 3:13 109M , gas = 0:08⍰0:13, and tdep = 0:65⍰5:05 Gyr.
    - Result suggests that FRBs may have host environments with molecular gas fractions higher than local galaxies
    - Larger sample is needed; In general z is unknown; searches more efficient with the ***Wideband Sensitivity Upgrade*** in place.



Moment-0 (velocity-integrated) map of CO(3 - 2) emission from FRB host galaxy HG20180942B; FRB localization is indicated by the cyan dotted ellipse



Multiwavelength comparison of HG20180924B, to same spatial scale is the same, purple ellipse marks the FRB position and its uncertainty. The shaded green ellipses are the beam size, seeing, and PSF of the observations, left to right, respectively. Left: moment-1 map of ALMA CO(3-2) emission from ALMA; center: H velocity from VLT-MUSE and right is a visually-enhanced IR HST image.

The ALPINE-ALMA [C ii] survey: Characterisation of Spatial Offsets in Main-Sequence Galaxies at $z \sim$ 4–6

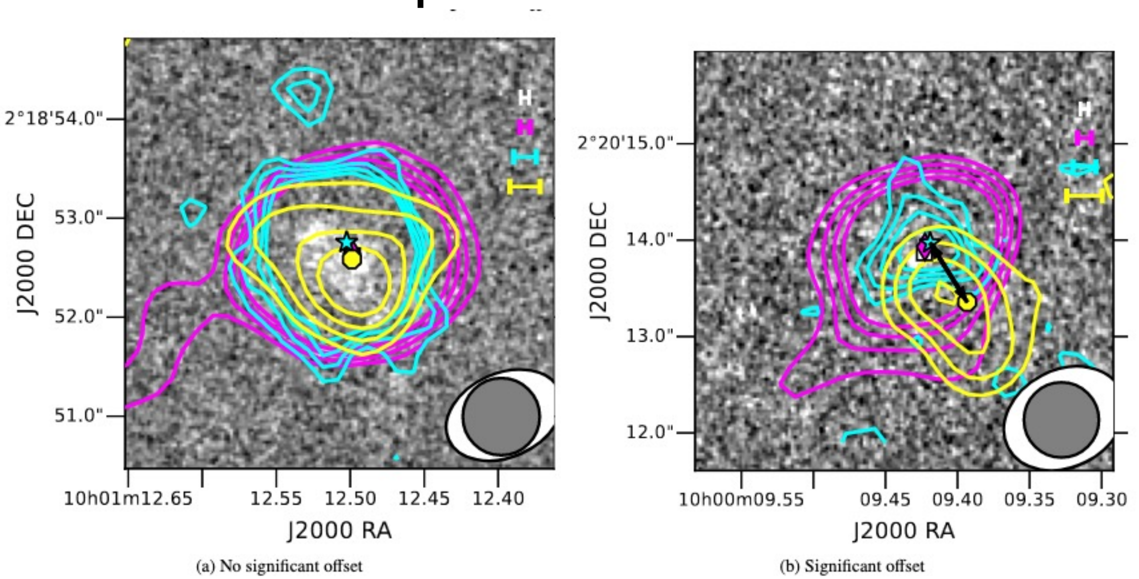
Killi+ arXiv:2401.07982

A sample of main-sequence star-forming galaxies at $z \sim$4–6 from the ALPINE dataset is studied.

54 galaxies are studied that were detected in

- [C ii] and FIR continuum emission in ALMA data,
- UV emission in HST data,
- and optical emission in K-band UltraVISTA data,

Authors exclude [C ii]-mergers or multi-component systems based on Romano et al. (2021) and Jones et al. (2021).



(a) A galaxy (VUDS_COSMOS_5101218326) with no significant offset among any of the emissions (see Sec. 4) vs (b) a galaxy(DEIMOS_COSMOS_683613) with a significant offset between FIR continuum all other emissions. UV HST image is shown as a grey-scale back-ground with [C ii] (fuchsia), optical (cyan), and FIR continuum (yellow) overlaid.

The existence of significant spatial offsets in ~30 percent of the sample indicates that it is possible for main-sequence galaxies at $z \sim$ 4–6 to have the bulk of the stars spatially offset from the bulk of the interstellar medium. Future simulations and observations must therefore take into account that the emission observed across wavelengths may be coming from different, spatially segregated regions of the galaxy.

We require large number statistics and higher resolution observations and simulations to identify the processes driving spatial offsets.

One could perform this analysis on the REBELS sample (already shown to have spatial offsets in Inami et al. 2022), which has different SFRs and M★, but similar angular resolution as ALPINE.

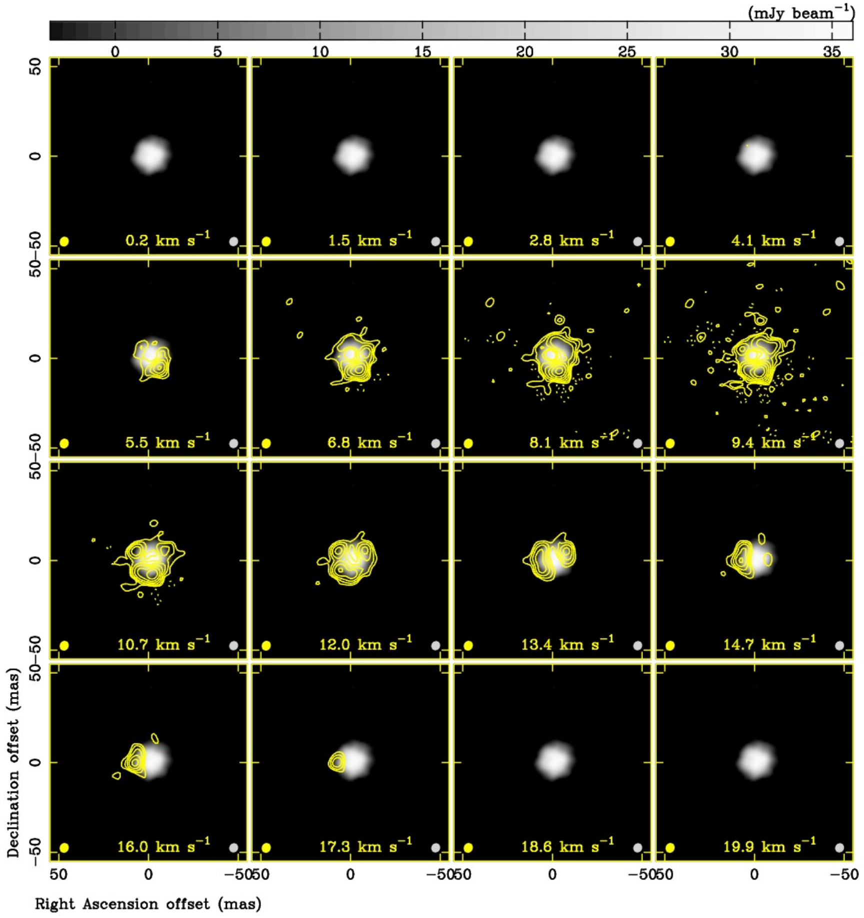
ALMA Science Frontiers

- How do stars evolve?
  - Stars are not always as stable and peaceful as the Sun is now
  - Some evolved stars have very extended molecular atmospheres
    - In “carbon stars” the ratio C/O > 1, reversed from normal

ALMA High-frequency Long Baseline Campaign in 2021: Highest Angular Resolution Submillimeter Wave Images for the Carbon-rich Star R Lep

Asaki+ [2023:arXiv2310.09664A]

- ALMA employed phase-referencing and self-calibration to image HCN maser lines in the carbon-rich evolved star R Lep, a Mira-type variable, at **891 GHz with baselines up to 16 km.**
  - Images of the continuum and HCN maser achieved angular resolutions of 13, 6, and 5 mas in ALMA Bands 8, 9 and 10, respectively.
  - Results were obtained via use of calibration at a lower more atmospherically transparent frequency, with results extended to higher frequencies.
  - Results were then compared to Self-calibration taking advantage of the compact strong stellar atmospheric emission in the maser line.
  - The image coherence of the Band 10 continuum image calibrated with B2B phase referencing alone of 70% is also larger than the 61% achieved on the single channel for the HCN maser.
    - We attribute this to the fact that the continuum emission is centrally focused, whereas the HCN maser emission forms a ring structure wherein the distribution of flux changes slightly before and after self-cal, i.e., we are applying a rule to measure image coherence for pointlike sources to something that has an extended distribution.



HCN maser cube in Band 10 (yellow contours) at **890.8 GHz**, from the J = 10 − 9 transition between the (1110) and (0400) vibrationally excited states, averaging every four velocity channels of the synthesized image cube with the velocity width of 0.3 km s^{-1}. The continuum emission in Band 10 is shown as a background grayscale gradation. The image cube was created after applying the amplitude and phase self-cal solutions derived using the HCN maser emission at v_{LSRK} = 9.4 km s^{-1}.

Atmospheric Blobs around IRC+10216 Unveiled with a Resolution of One Stellar Radius

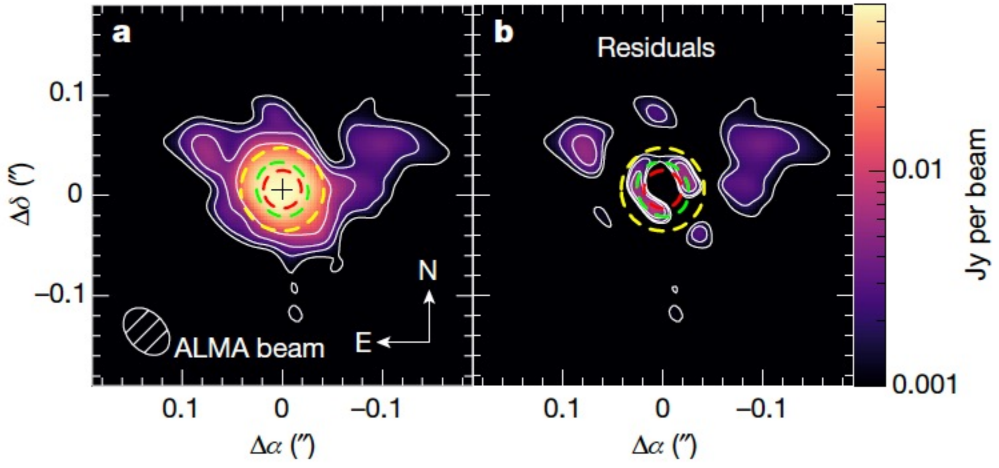
Velilla-Prieto, (2023) Nature, Volume 617, Issue 7962, p.696-700

A bright central source (yellow) highlights the 7mm photospheric size, beyond which are other features, either expelled dusty gas clumps or dust-embedded companions.

Lines of HCN, SiS and SiC_2 appear at different radii and in different clumps, interpreted as large convective cells in the photosphere, as seen in Betelgeuse.

These convective cells coalesce with pulsation, causing anisotropies that, together with companions shape the circumstellar envelope.

These images change our views on the formation of molecules and dust in the upper atmosphere. Different molecular species selectively appear depending on local physical conditions, a fact pf critical importance in regard to the mechanisms that later drive the winds of intermediate mass stars and the ensuing circumstellar chemistry



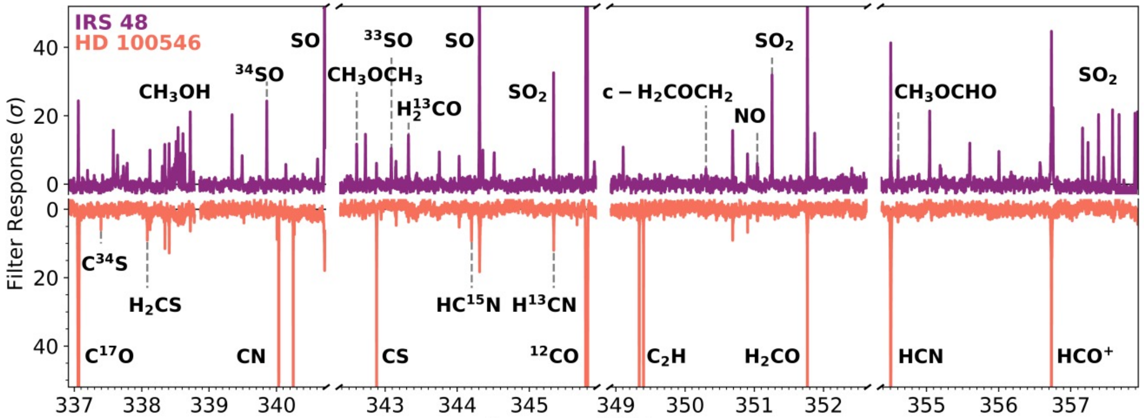
ALMA images of 1mm continuum emission from IRC+10216
Left: The red contour, centered at the position of the estimated Gaussian centroid, shows photosphere size in the near infrared; the yellow contour shows the radio photosphere size at 7 mm from the analysis of high-resolution Very Large Array (VLA) observations. Right: Map of the residuals of the fit, showing a horseshoe-shaped structure approximately 25 mas from the center of the bright central source.

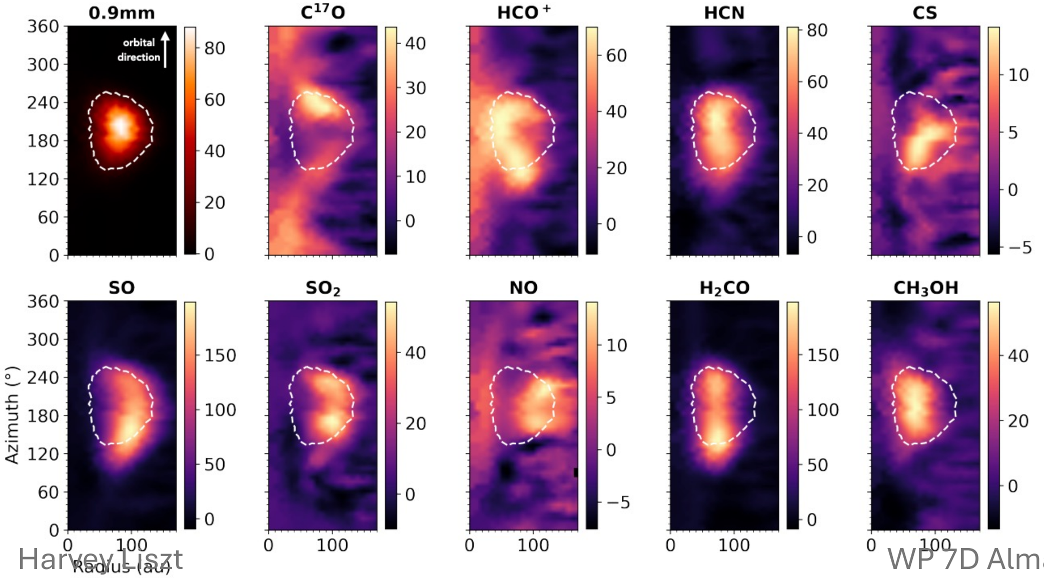
ALMA Science Frontiers

- Star and planet formation
  - How do stars form?
  - How do solar systems and planets form around them?
  - Where will we find habitable planetary systems?

An ALMA molecular inventory of warm Herbig Ae disks: An ALMA molecular inventory of warm Herbig Ae disks:
I. Molecular rings, asymmetries and complexity in the HD 100546 disk ;
II. Abundant complex organics and volatile sulphur in the IRS 48 disk

Booth+ arXiv:2401.04001, 2402.04002





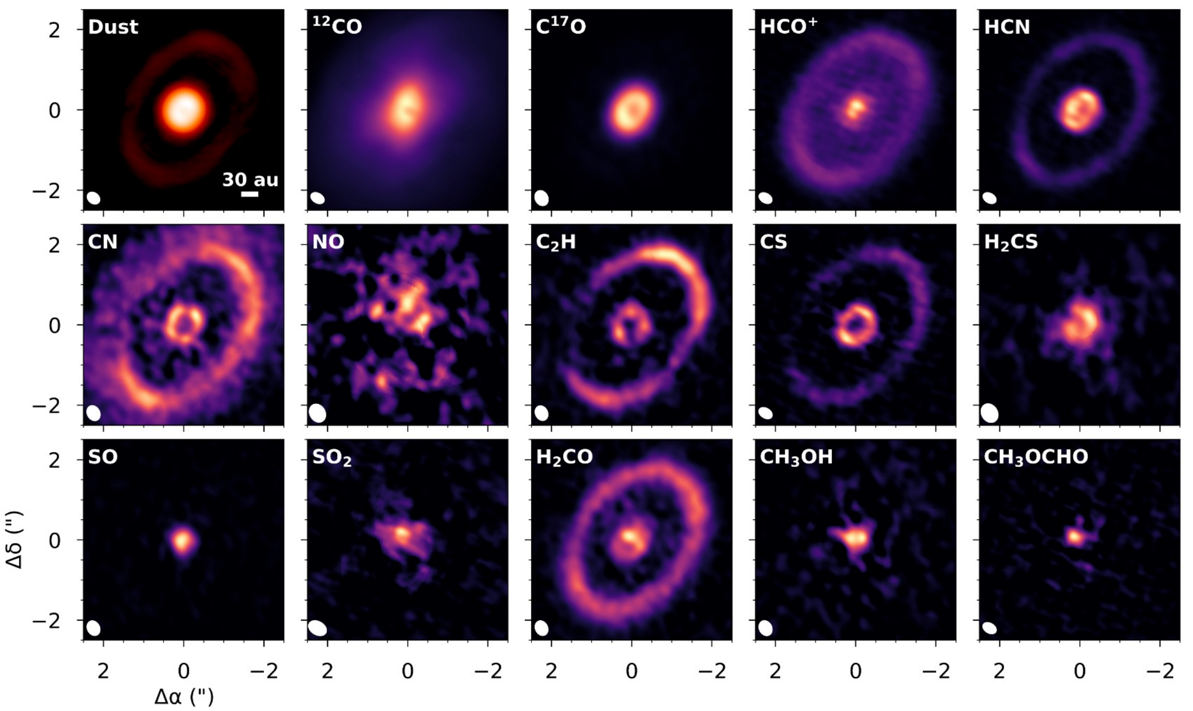


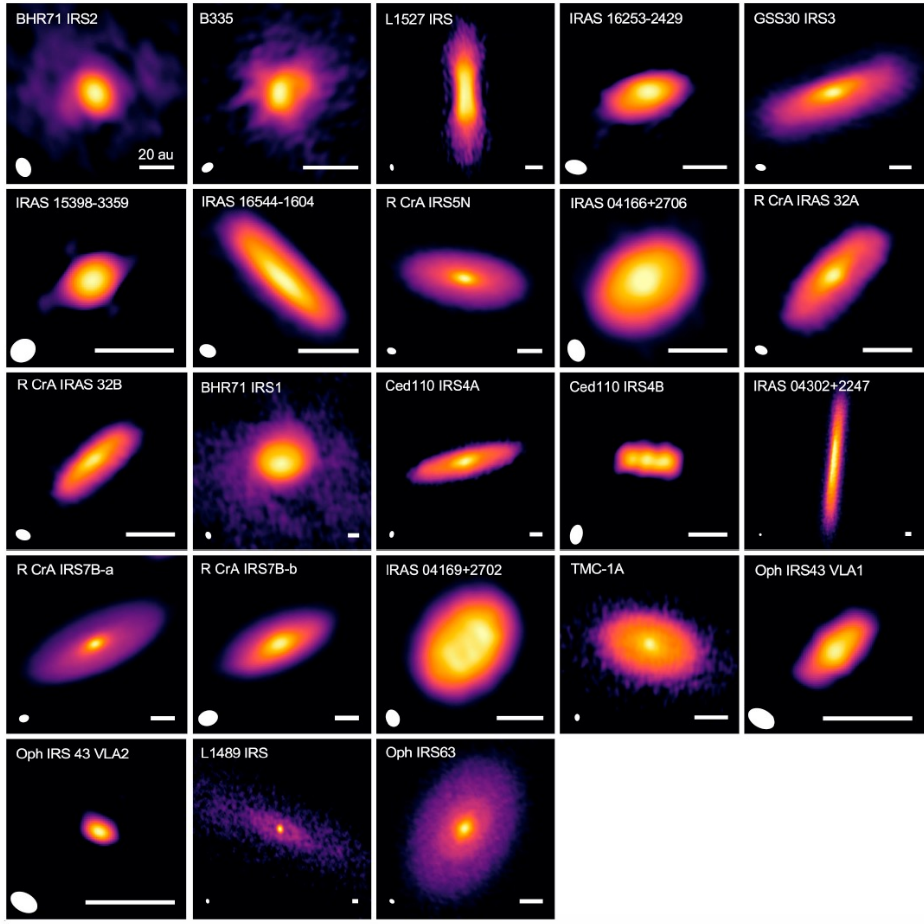
Figure 2. Integrated intensity maps of the 0.9 mm dust continuum emission and molecular line emission from the HD 100546 disk. The continuum map is shown on a log color scale to highlight the weak outer ring of millimetre emission. The beam is shown in the left-hand corner of each panel.

- (l) Polar de-projection of the HD 100546 integrated intensity maps which highlight the azimuthal asymmetry in the dust and molecular rings at ≈200 au.
- *The efficiency of these types of observations will improve dramatically with the planned Wideband Sensitivity Upgrade for ALMA which will increase both the simultaneously observable bandwidth and the imaging speed (Carpenter et al. 2023).*

Early Planet Formation in Embedded Disks (eDisk)

Ohashi, N.; Tobin, J., Jørgensen, J. Takakuwa, S. Sheehan, P. Aikawa, Y. Li, Zhi-Yun, Looney, L., Williams, J. et al.
ApJ 951, 2023.

- A Large ALMA Program focused on substructures, particularly rings and gaps, in protoplanetary disks around very young stars
  - Did at least some planet formation start during the embedded stages of star formation?
  - ALMA imaged disks around youngest (12 Class 0 and 7 Class I) protostars in nearby (<200 pc) star-forming regions through 1.3 mm continuum observations at a resolution of ~7 au (0.″04).
  - Continuum emission, mostly arising from dust disks around the protostars, shows few of the distinctive substructures, such as rings and spirals, seen in more evolved (Class II) disks.
  - These data suggest that substructures quickly develop in disks when the systems evolve from protostars to Class II sources
  - CO isotopologue and other lines reveal the presence of Keplerian motion in the disks around protostars, providing us with the dynamical mass of the central protostars.
- The set of eDisk papers provide first results for individual sources to constrain these pivotal stages in the formation and early evolution of protostars and their disks.



Enlarged continuum images. Images are presented in order of T_{bol} with beam size and the scale of 20 au shown in the lower left and lower right corners of each panel, respectively

OH as a probe of the warm-water cycle in planet-forming disk

Zannese+ arXiv:2402.12256

- PDRs4All: Water, combining two of the most abundant elements, is a key ingredient for the emergence of life as we know it. Yet, its destruction and reformation in space remain unprobed in warm gas.
- OH is detected by JWST with high rotational/vibrational motion in a planet-forming disk exposed to UV radiation.
- These observations, coupled with ALMA disk observations and quantum calculations, unveil the ongoing photodissociation of water and its gas-phrase reformation.
- The OH emission is detected from the vicinity of the d203-506 photoevaporating protoplanetary disk where there is bright H_2 emission, in a photo-evaporative wind, revealing active gas-phase oxygen chemistry fueled by warm H_2.
- The d203-506 system is an almost edge-on disk seen in silhouette against the bright background. Its ALMA measured radius is $R_{out} = 98 \pm 2$ au, and its total mass is estimated to be about ten times the mass of Jupiter Kinematic studies with ALMA indicate that the stellar mass of the host star is below 0.3 $M_{\odot}$. In the bright spot, we detect a very active warm-water chemistry.
- The OH rovibrational lines in the near-infrared are attributed to chemical excitation by the key reaction $O + H_2 \rightarrow OH + H$, which seeds the formation of water in the gas phase. The detection of extremely rotationally excited OH is the smoking gun of water photodissociation.
- The observed highly excited rotational lines of OH in the mid-infrared are telltale signs of H_2O destruction by FUV radiation.
- These results show that under warm and irradiated conditions, water is destroyed and efficiently reformed through gas-phase reactions.
- We infer that, in this source, the equivalent of Earth oceans' worth of water is destroyed per month and replenished.
- This warm-water cycle could reprocess some water inherited from cold interstellar clouds and explain the lower deuterium fraction of water in Earth's oceans compared with that found around protostars.

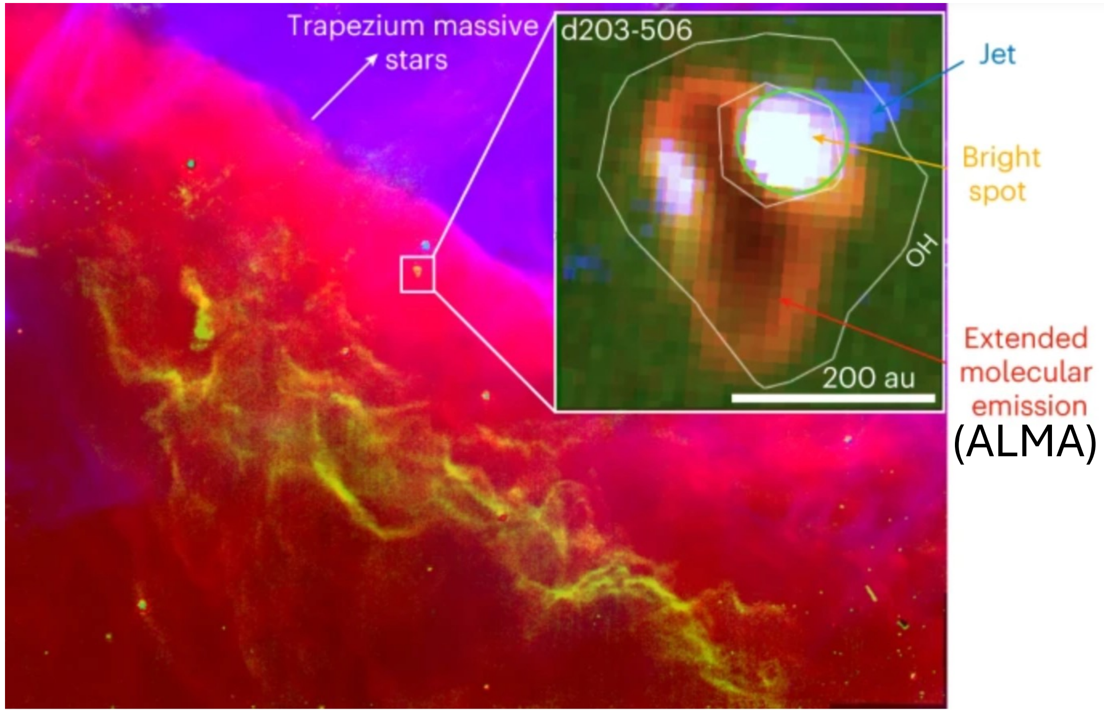
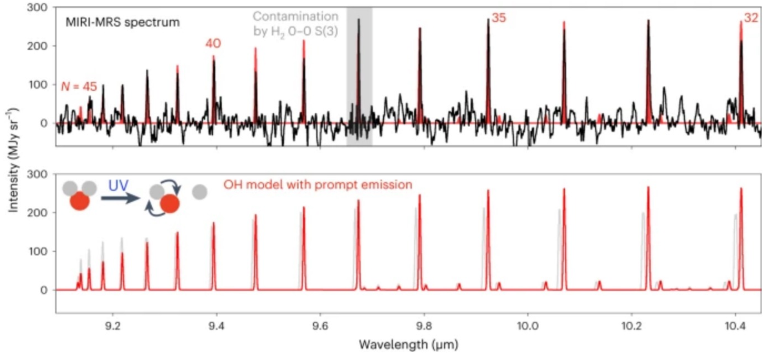


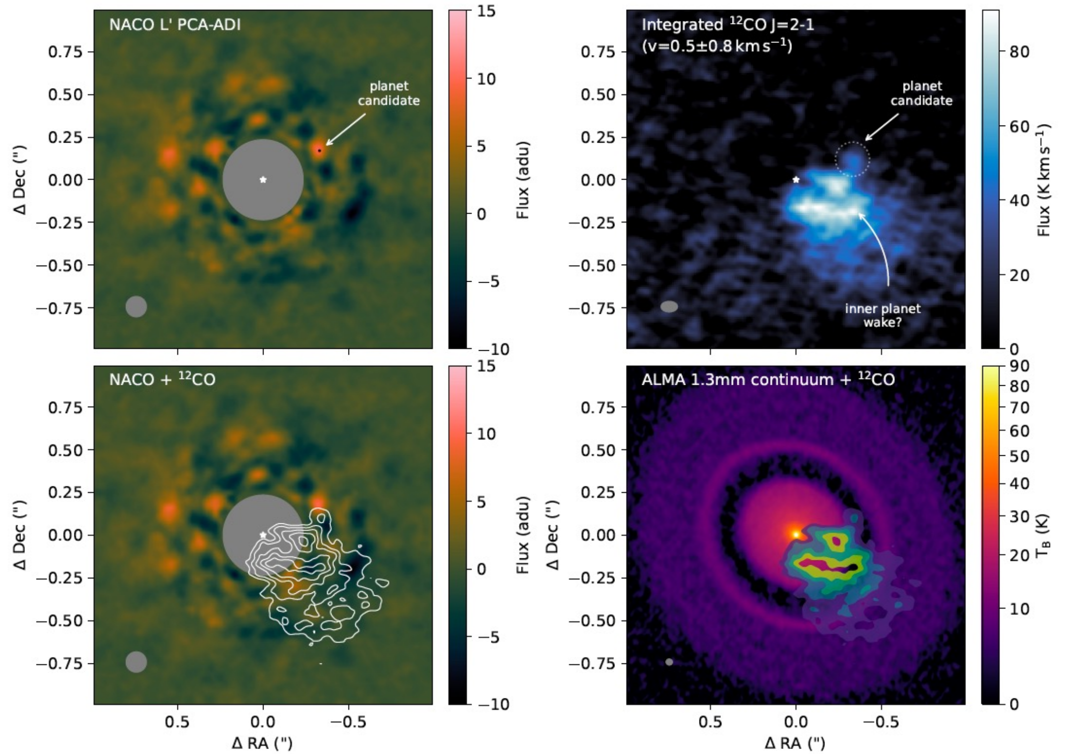
Fig. 2: Evidence for H_2O photodissociation from OH rotational lines detected by MIRI-MRS.



Kinematic and thermal signatures of the directly imaged protoplanet candidate around Elias 2-24

Pinte+ ArXiv: 2301.08759

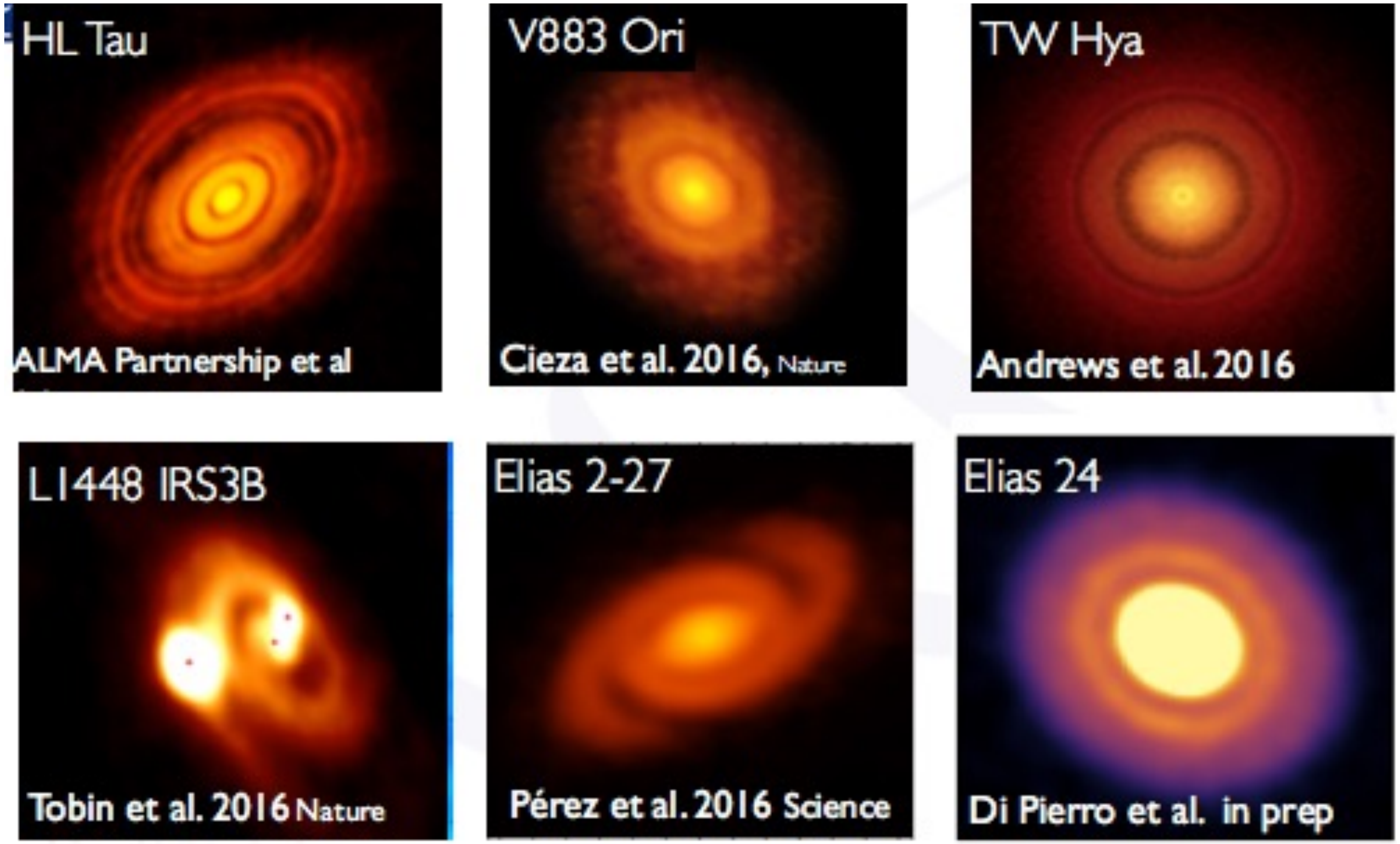
- First planet detection using both disk kinematic imaging (ALMA) and direct detection (NACO-VLT), which constrains protoplanet mass and luminosity
  - Used reimaged ALMA-DSHARP (Andrews+2018) CO for Kinematics, Jorquera+2021 NACO data (L' band); a bright spot in the latter identified as a planet candidate aligns with a CO spot detached from an isovelocity curve.
    - From NACO, a separation of 0.37±0.04" (51.8 au) at a PA of 298.4±4.6°.
    - A bright CO spot close to the NACO L' candidate, detached from the expected location of the emitting region along the isovelocity curve in the ALMA data inside the 1.3mm continuum dust gap.
    - We do not detect any emission in the channel where the isovelocity curve would correspond to the location of the planet candidate, preventing detection of a potential velocity kink as seen in HD 163296, HD97048 or AS209.
    - Due to the missing emission in subsequent channels, it is not possible to determine if the velocity gradient is from the global Keplerian rotation of the disc or from additional velocity perturbations near the planet candidate.
  - Because the disc isovelocity curve overlaps the planet location, where we expect a velocity kink (v ~1.8 km/s), it is not possible to estimate a robust planet mass from kinematics. *Deeper isotopic or other molecular observations are needed.*
- A CO counterpart of the J21/NACO planet candidate is seen.
  - CO shows velocity shift, line broadening and local increased disk temperature as predicted by models of planet-disk interaction.
  - Kinematic structures can be explained by a 8MJup planet or a 3MJup accreting planet.
  - Cloud contamination prevents an accurate planet mass estimation. Higher-J and/or less abundant isotopologues/molecules can alleviate this; **ALMA's wideband sensitivity upgrade can aid in assessing the role of the planet.**



Kinematic counterpart of the protoplanet candidate detected around Elias2-24. Top left: re-imaging of the NaCo L'-band PCA-ADI computed in concentric annuli with 20 principle components subtracted. The bright source discovered by Jorquera et al. (2021) is re-detected. Top right: ALMA 12CO J=2-1 integrated line intensity between -0.375 and 1.375 km s-1, revealing a CO spot detached from the isovelocity curve, as well a potential spiral arm. Bottom:NaCo image (left) and ALMA band 6 continuum (right) with integrated 12CO emission overlaid.

ALMA Science Highlights: Protoplanetary Disks

Protoplanetary Disks: With ALMA



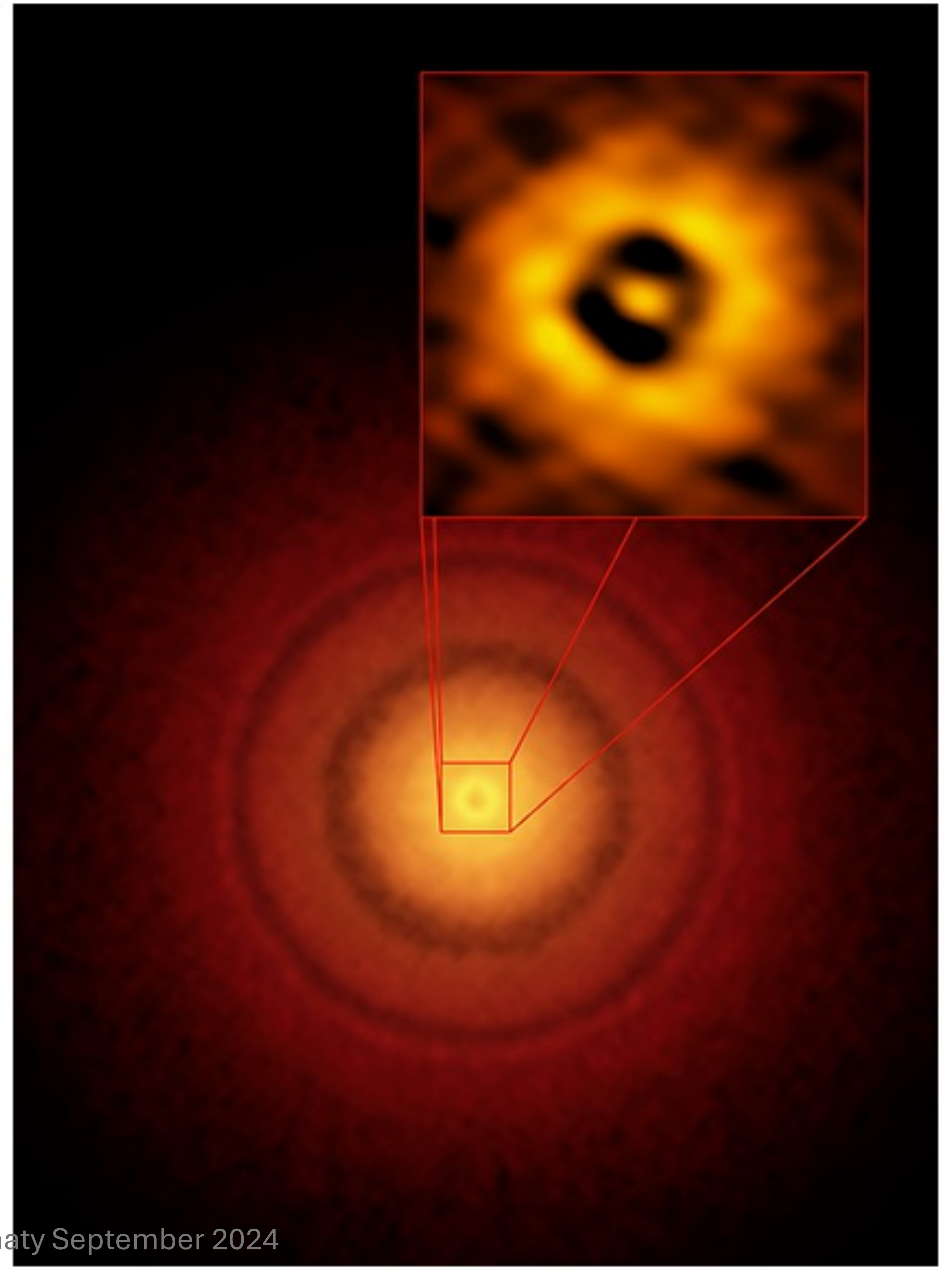
Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

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



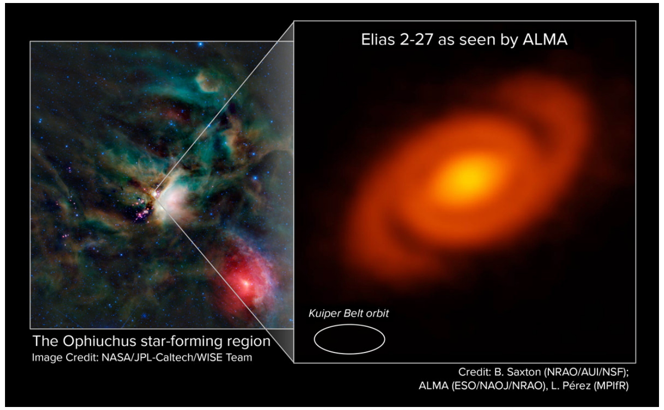
ALMA Science Highlights: Protoplanetary Disks

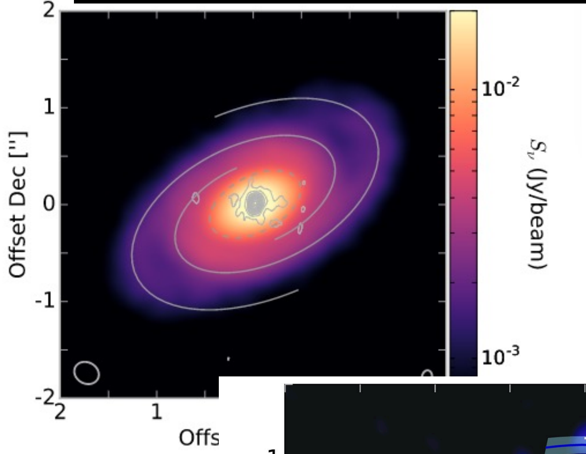
Protoplanetary Disks: With ALMA

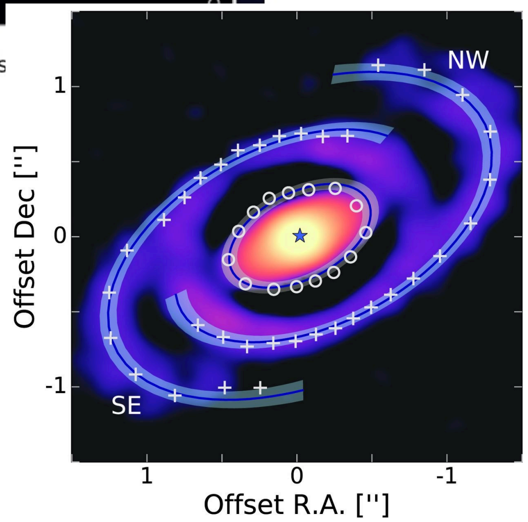
A Spiral Density Wave Observed in a Protoplanetary Disk

Perez et al. Science 353, 1519 (2016)

- Gravitational instabilities in protoplanetary disks might be excited by e.g. planet-disk interactions or gravitationa 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.





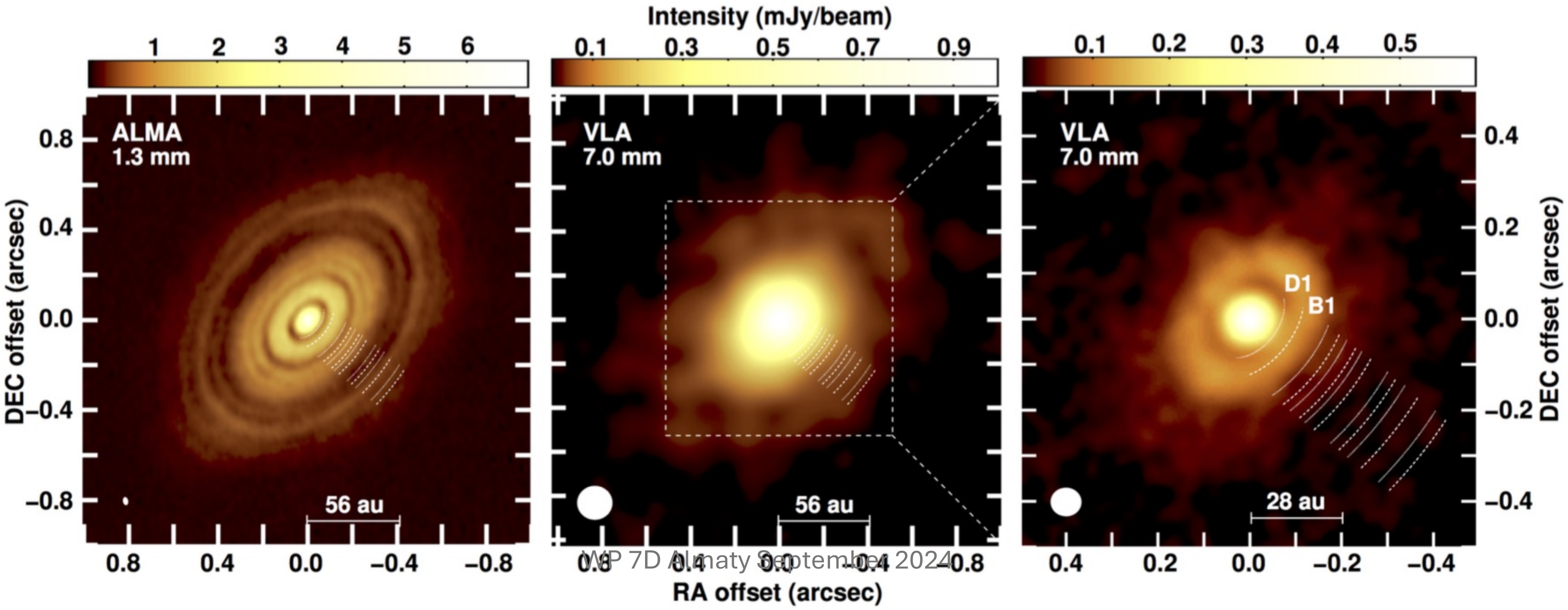


ALMA Science Highlights: Protoplanetary Disks

Protoplanetary Disks: With ALMA and VLA

Carrasco-González et al. 2016

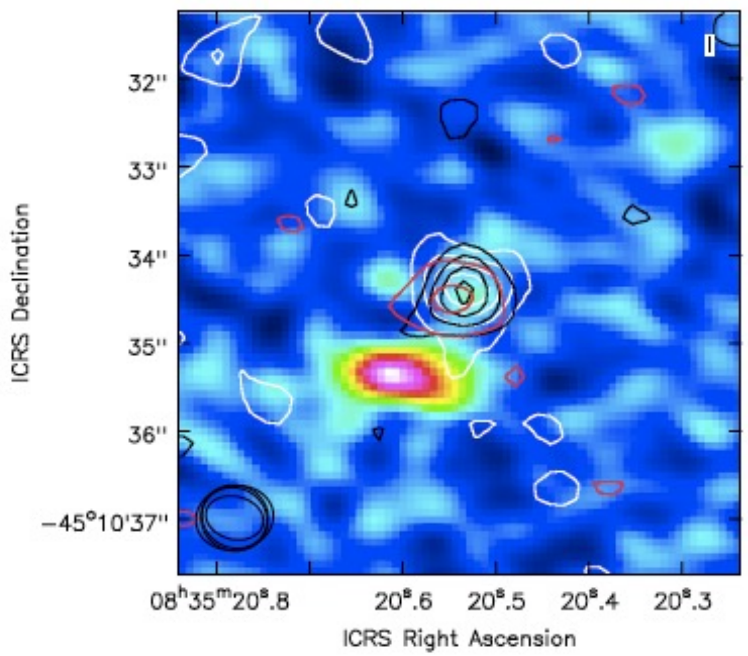
- Emission from inner regions of HL Tau still optically thick at ALMA wavelengths
- VLA can image the disk at comparable resolution to ALMA at 7mm where emission is optically thin
- Combination of ALMA+VLA helps differentiate between formation theories with info on grain growth, fragmentation, and formation 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



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



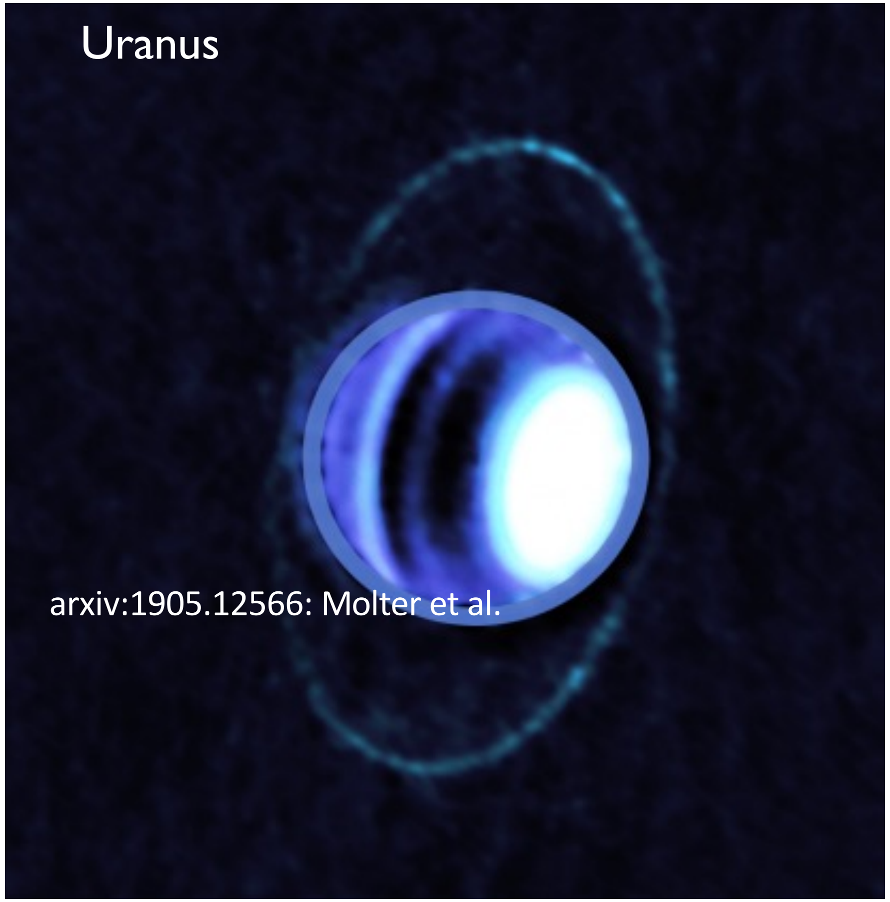
Vela Pulsar, ALMA B3,4,6 (contours) on B7 image; an extended structure, preliminarily detected in ground-based observations, may be a counter-jet protruding from the pulsar. (Mignani+, 2017)

ALMA Science Frontiers

- Sun and Solar System
  - How did our solar system evolve?
  - Why are we here? Why is there a “we”?

Extraordinary ALMA Images of Our Own Backyard

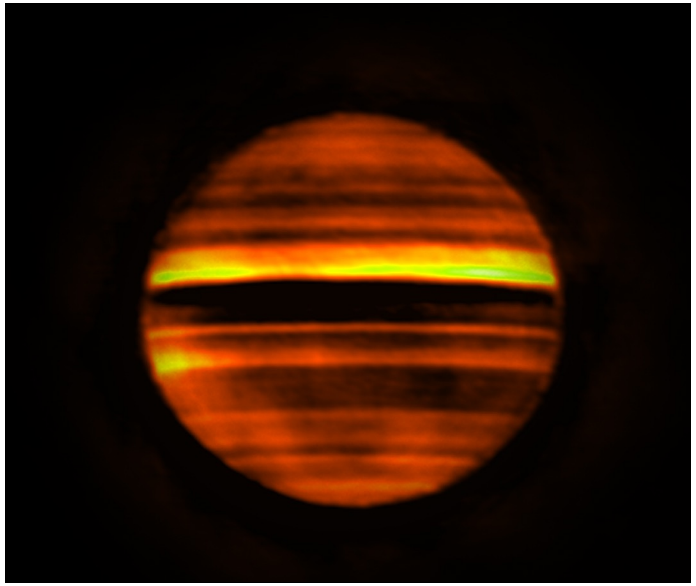
- Thermal emission from the Uranus **ε** ring shows micron-sized dust is not present in the ring system.
- Confirms the hypothesis, proposed based on radio occultation results (Gresh et al. 1989), that the main rings are composed of centimeter-sized or larger particles
- Temperature of rings: 77+-2K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



ALMA Millimeter Wavelength Images of Jupiter

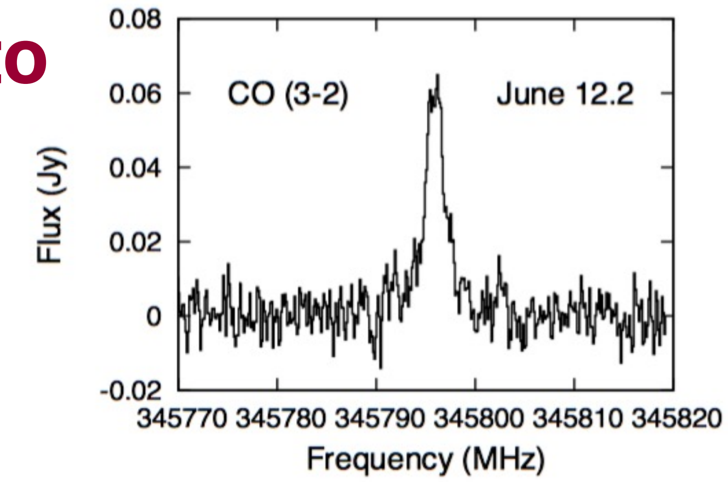
de Pater+ arXiv:1907.11820

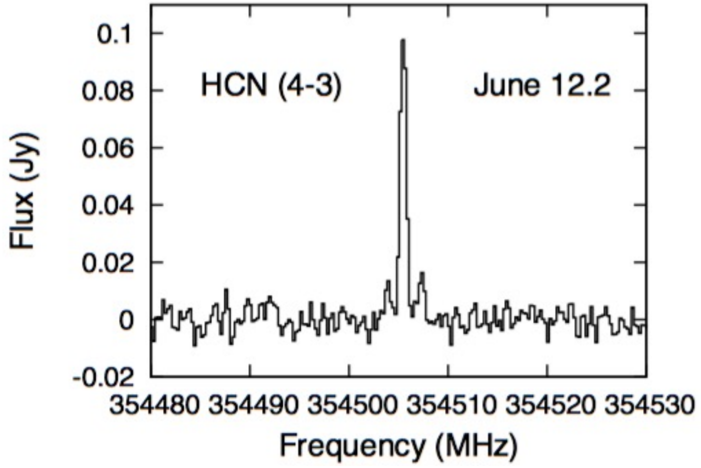
- Jupiter at 1.3mm (mosaic of 17 pointings)
  - NH_3 dominates opacity, so the image can provide its 3 dimensional distribution
  - High brightness indicates lower NH_3 abundance
  - Dark areas indicate higher atmospheric opacity
- Imaged days after an outbreak in the South Equatorial Belt
  - Favored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

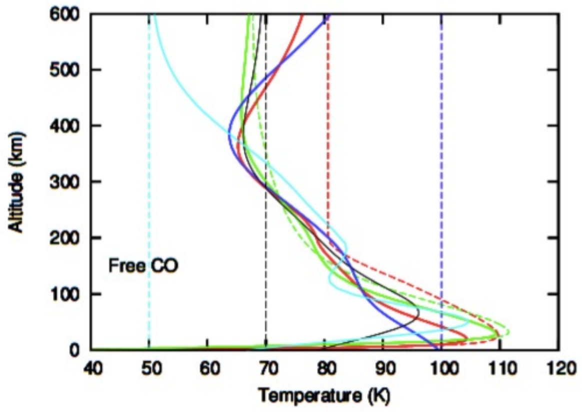


ALMA Detects organics on Pluto

- 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

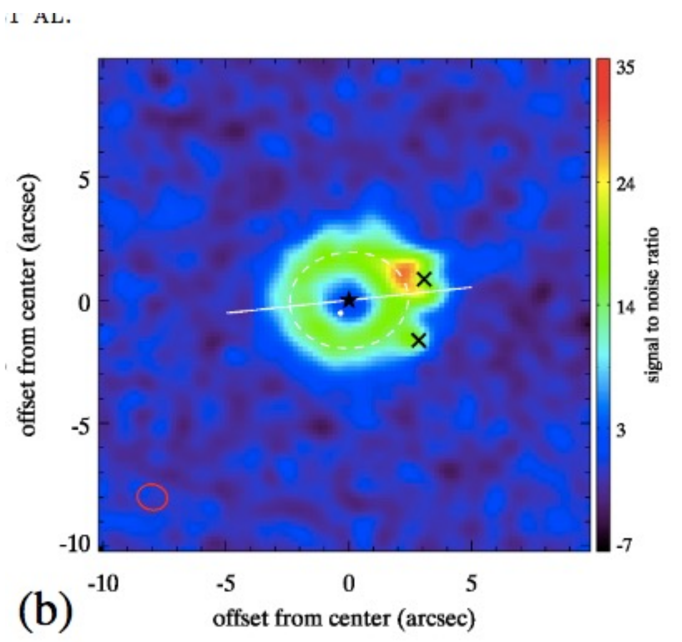






ALMA Images First Kuiper Belt Analogue Around Sun-like Star

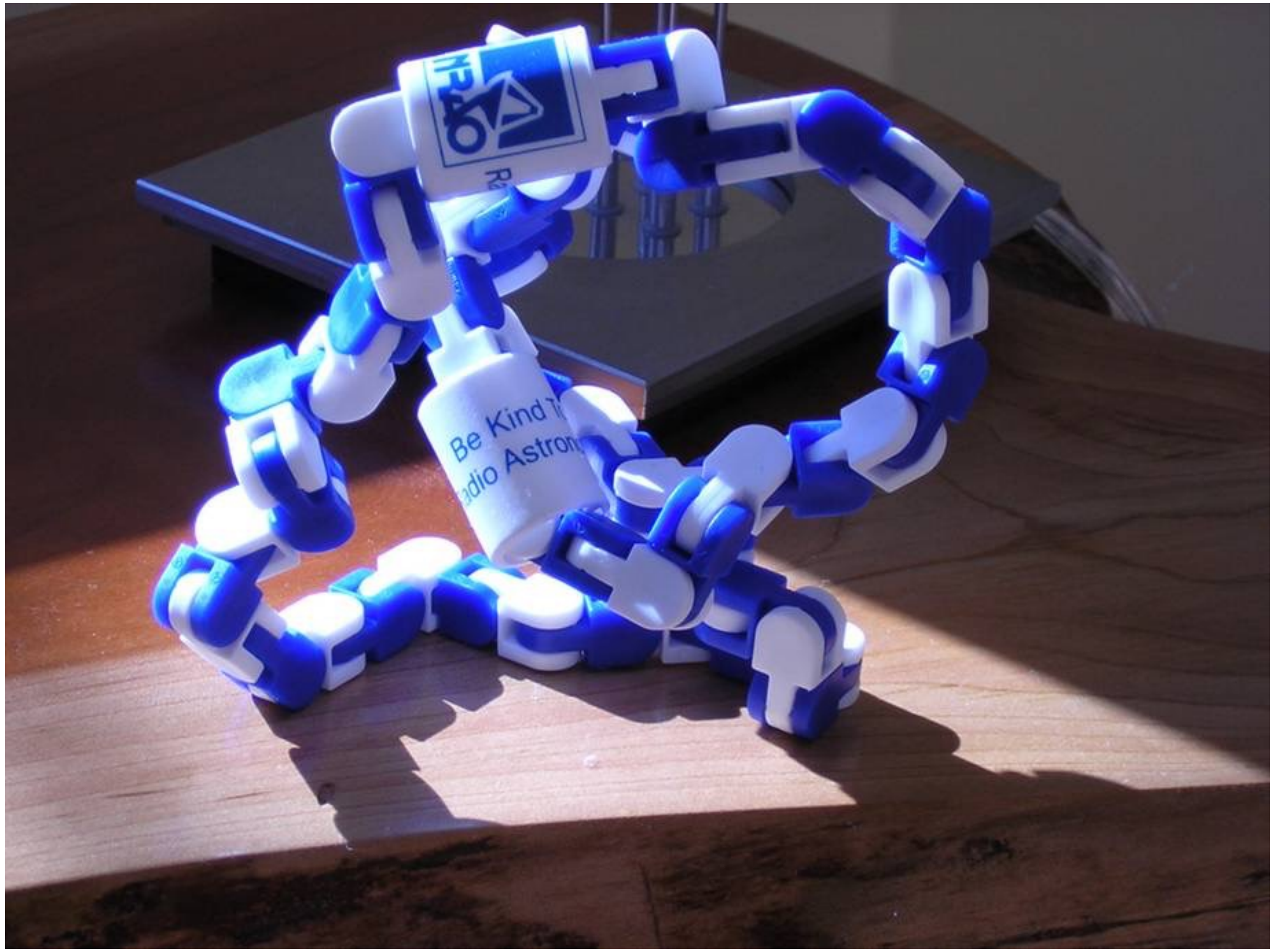
- HD 95086 is a 1.6 M_{sun} A star about 17 Myr years old, 83.8 pc from the Sun
- HD 95086 hosts a directly-imaged ~4M_{Jup} planet about 57 AU from the star
- ALMA has imaged a debris disk outside the planetary orbit
    - The disk is inclined 30°
    - The disk extends from an inner radius ~100 AU 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

Thank you for listening!!



www.cv.nrao.edu/~hliszt/WP7D/ALMA-ALMATYSeptember2024.pptx

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