ALMA Science Highlights

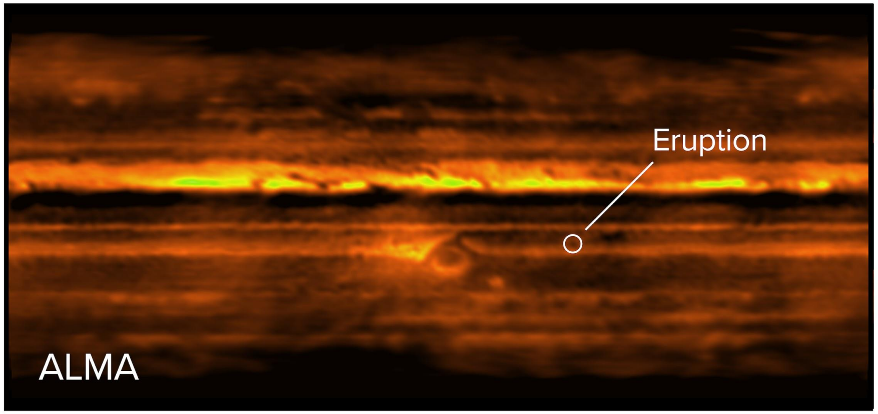
- Solar system
- Protoplanetary Disks
- Astrochemistry
- Star Formation
- Nearby Galaxies
- Active galactic nuclei
- High-redshift Universe

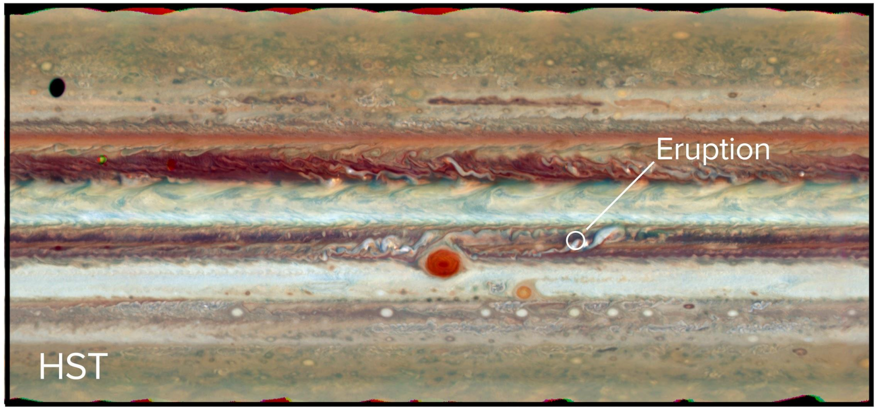
ALMA Science: Solar System

Millimeter wavelength images of Jupiter

de Pater+ arXiv:1907.11820

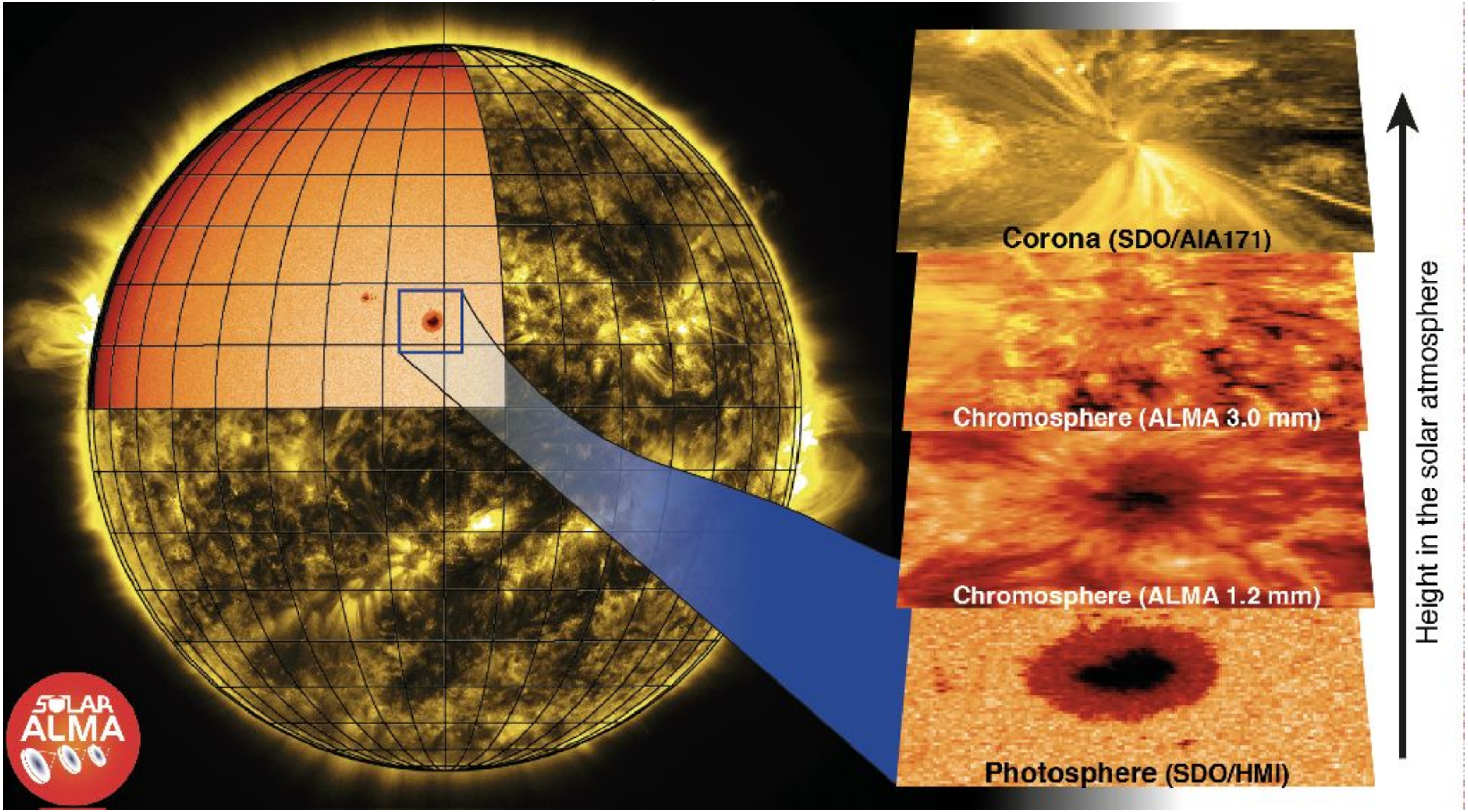
- Jupiter at 1.3mm
  - NH_3 dominates opacity, so the image can provide its 3 dimensional distribution
  - High brightness indicates lower NH_3 abundance
  - Dark areas indicate higher atmospheric opacity
- Imaged days after an outbreak in the South Equatorial Belt
  - Favored model: Eruptions triggered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





ALMA Science: Solar System

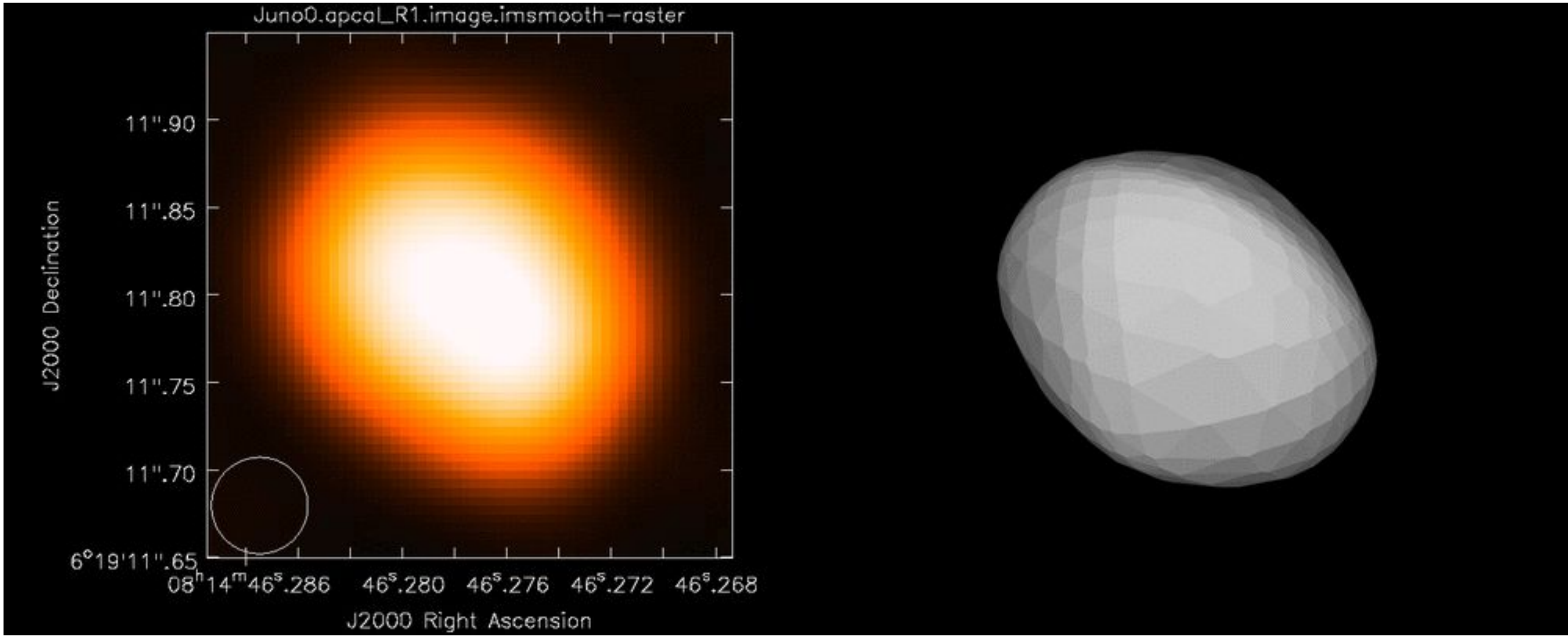
Multi-wavelength Solar observations



Millimeter solar emission primarily probes the chromosphere, making ALMA an excellent tool for studying energy transport and heating in the outer layers of the solar atmosphere at high spatial, temporal, and spectral resolution.

ALMA Science: Solar System

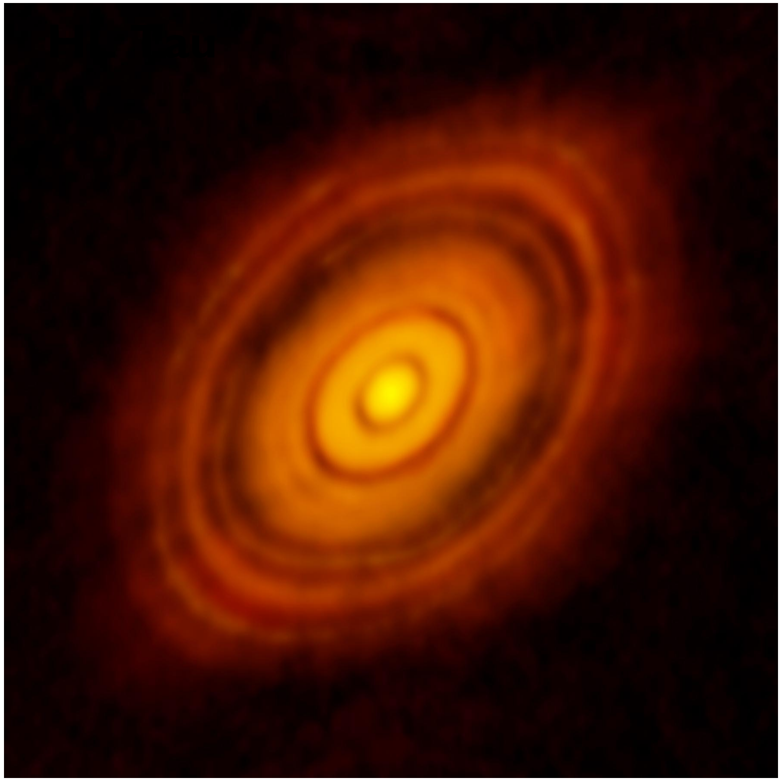
Science Verification - 3D modeling of Juno



ALMA Partnership; Hunter et al. 2015

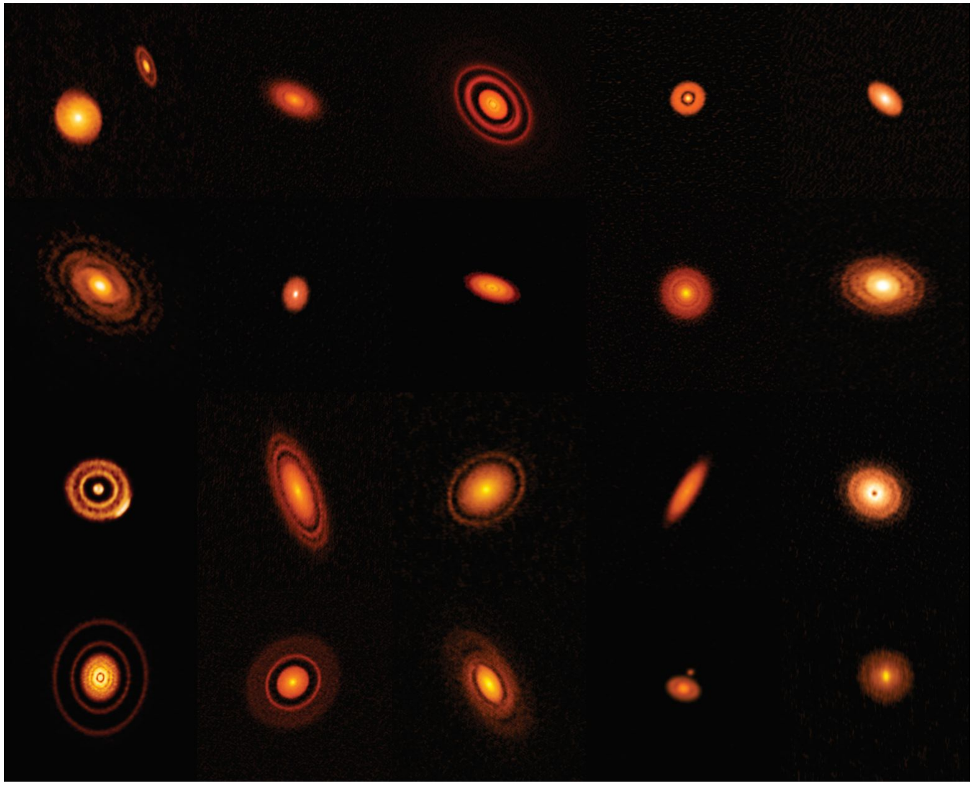
ALMA observations of thermal emission from Juno constrain the shape, composition and surface properties of the asteroid

ALMA Science: Proto-planetary Disks



Revolutionary 2014/2015 ALMA long-baseline science verification observations reveal planets forming in a million-year-old protoplanetary disk

ALMA large program:
Disk Substructures at High Angular Resolution Project (DSHARP)

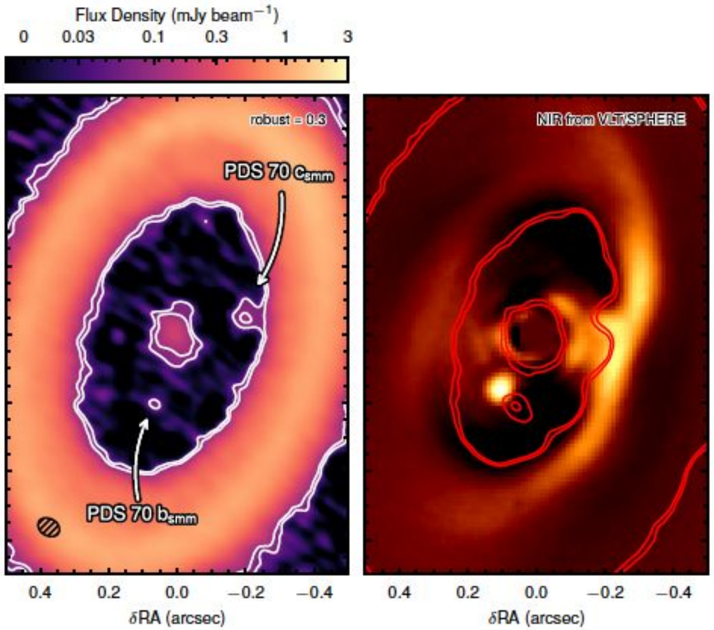


Andrews et al. 2018

ALMA Science: Circumplanetary Disks

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

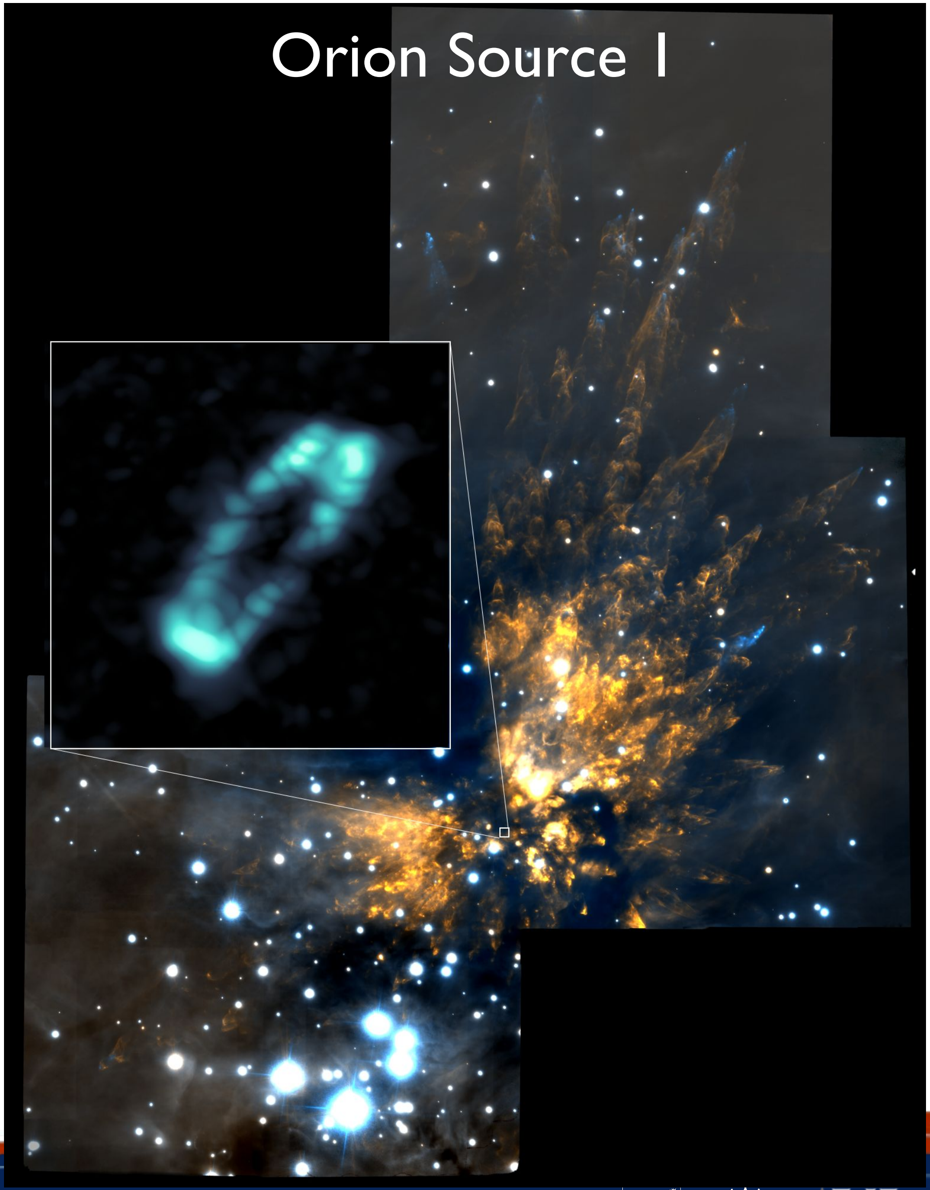
- **PDS70** is a 5 Myr old low-mass (0.76M_{Sun}) T Tauri star 110 pc away surrounded by rings of dust at 74 and 10AU from the star
- In the inter-ring gap, it harbors two VLT-detected Jovian mass planets, b and c
- PDS70c shows a circumplanetary disk, whose IR and H characteristics suggest it is a full-fledged 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 Science: Astrochemistry

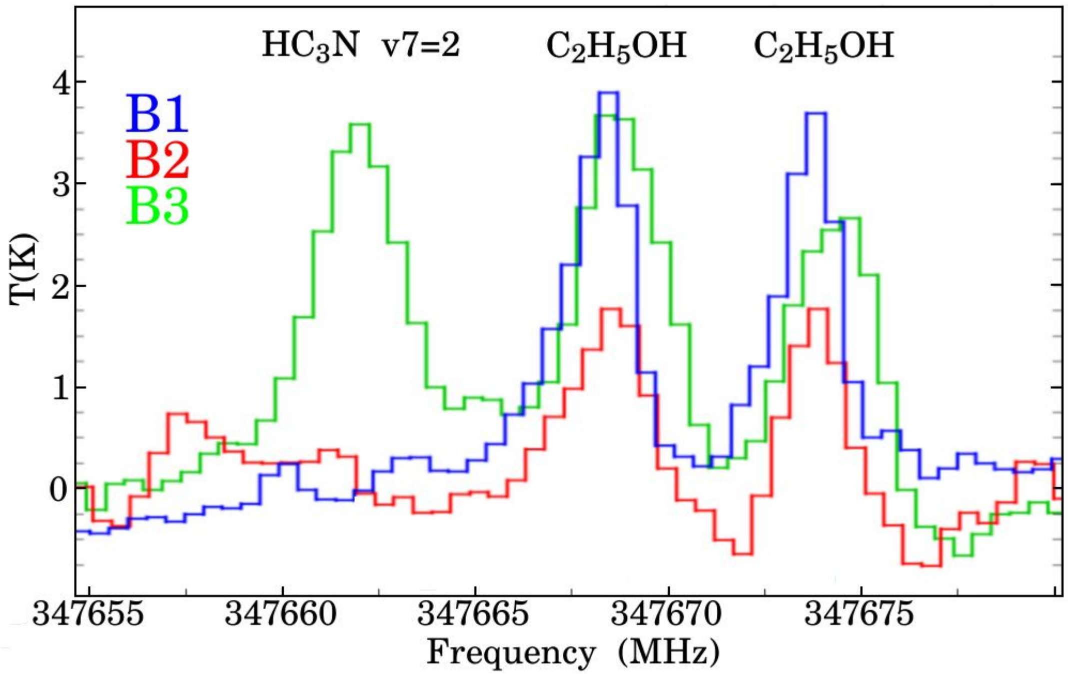
Ginsburg et al. 2019

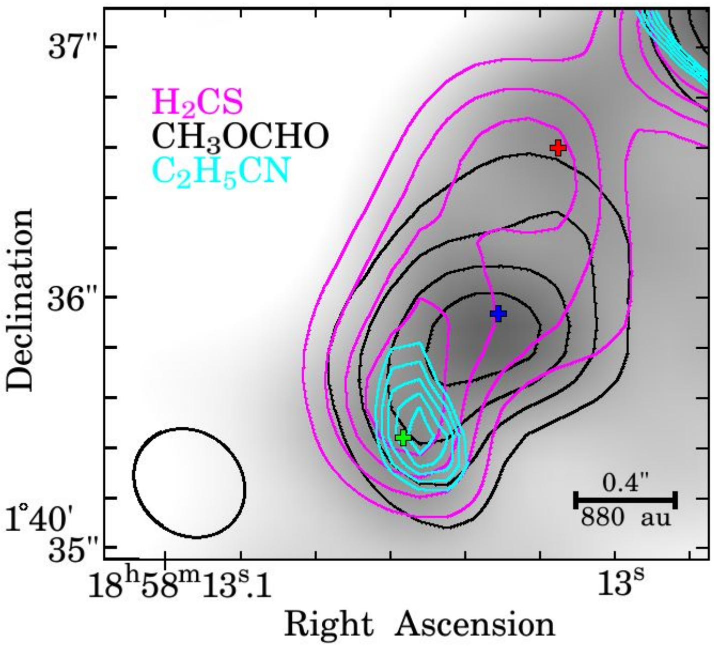


First detection of salt (NaCl) in a protostellar dust disk… a new means of identifying protostars in dusty star-forming regions

ALMA Science: Star Formation

ALMA observations of chemical differences across a candidate Keplerian disk located in star-forming region G35.20-0.74N



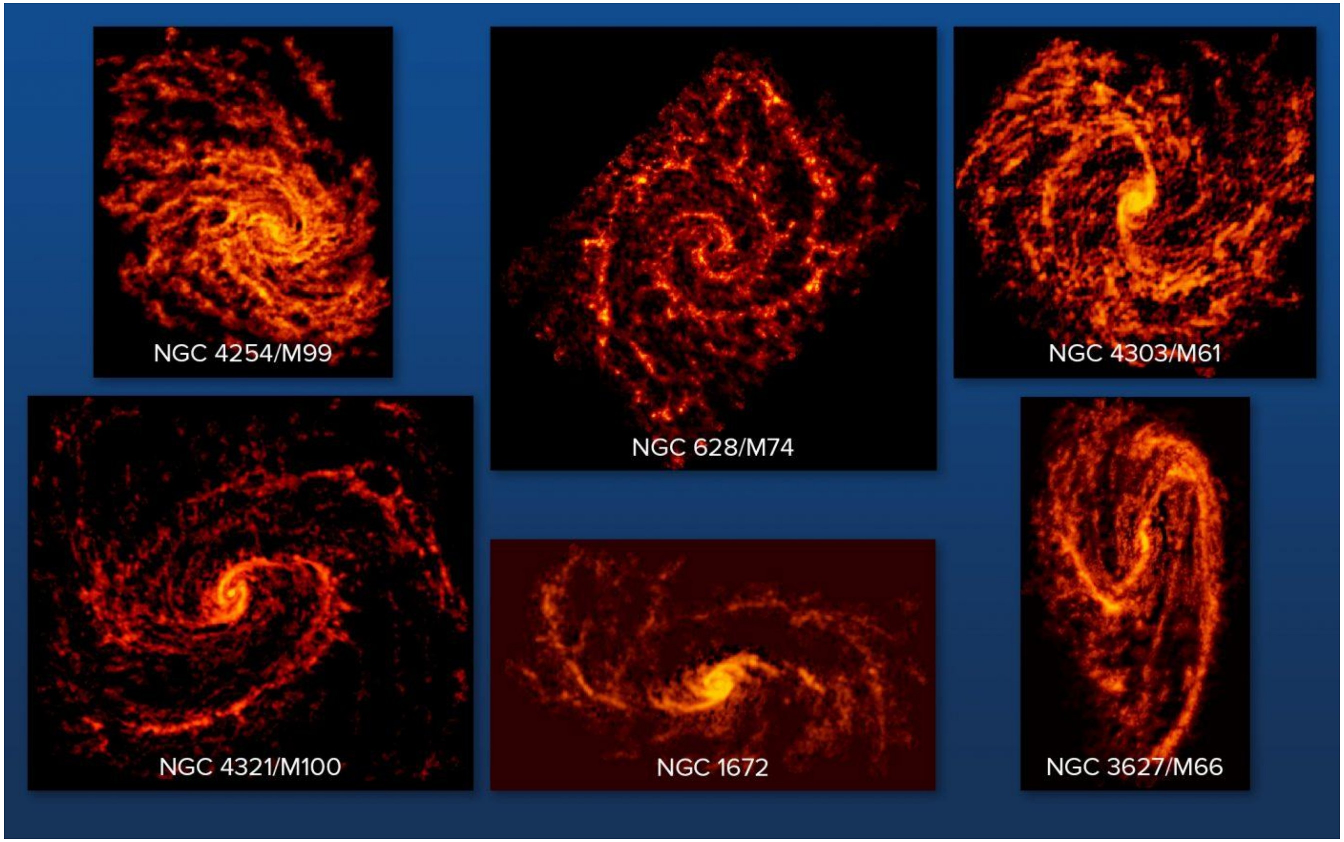


Allen et al. 2017, 2018

Chemistry in a massive star-forming region can constrain protostar age and multiplicity

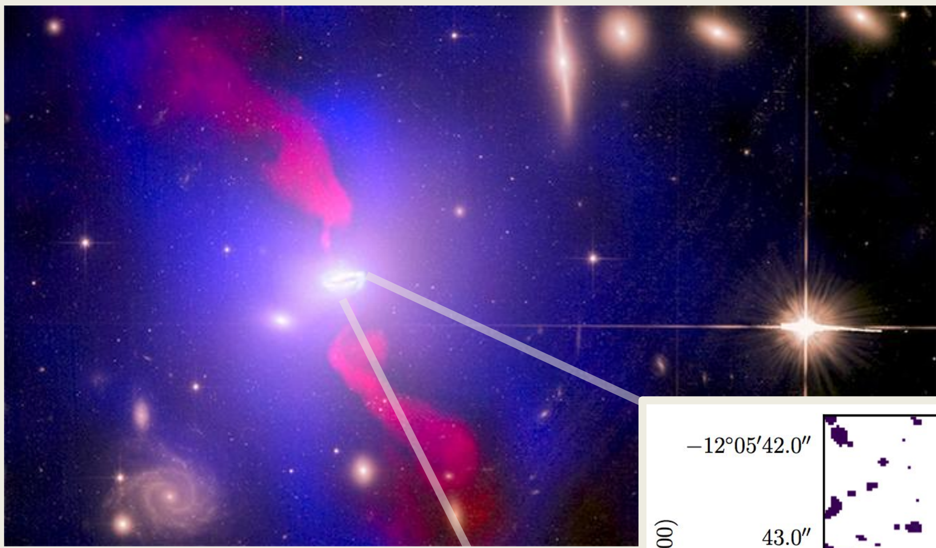
ALMA Science: Nearby Galaxies

Physics at High Angular Resolution in Nearby GalaxieS
PHANGS-ALMA: PI's - Rosolowsky and Leroy

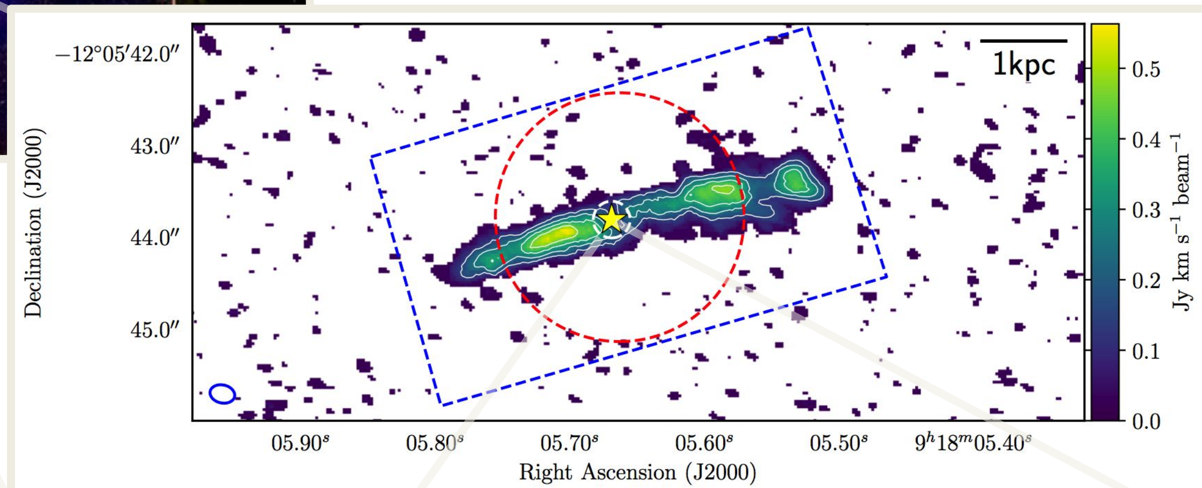


ALMA Cycle 5 large program to survey nearby galaxies in CO(2-1) to study the connection between cloud-scale physics and star formation in galaxies spanning a wide range of conditions

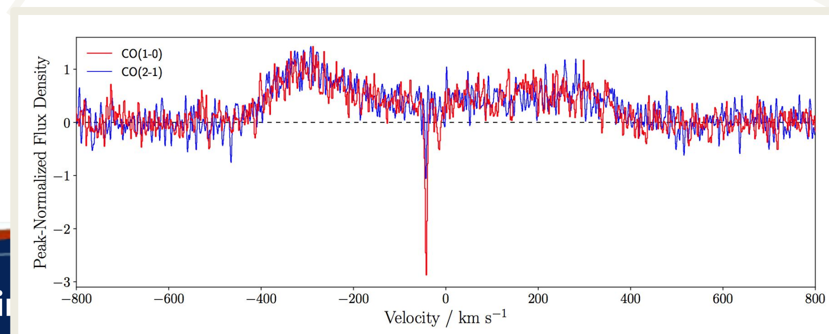
ALMA Science: Active Galactic Nuclei



HST (optical/UV), Chandra (X-ray), and VLA (radio) image of radio galaxy Hydra A

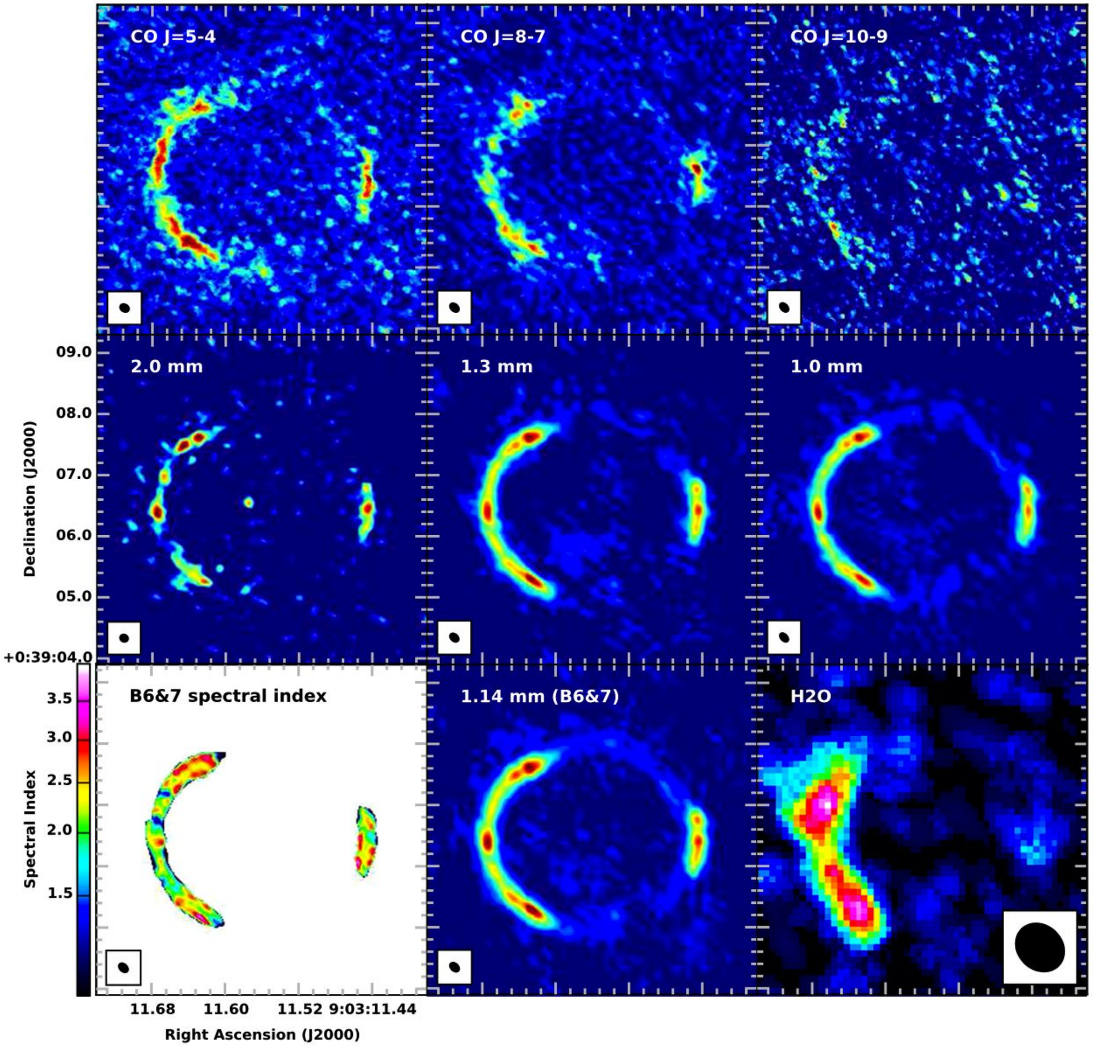


ALMA detects CO absorption against core of a powerful AGN – new insights into SMBH accretion

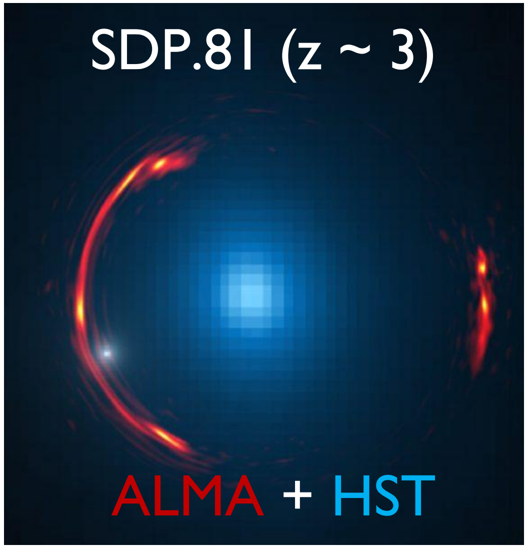


Rose et al. 2019

ALMA Science: High-redshift Universe



Long-baseline ALMA Science Verification observations of gravitationally lensed dusty galaxy



Distortions in the ring revealed the presence of a dark matter subhalo – important for constraining cosmological models

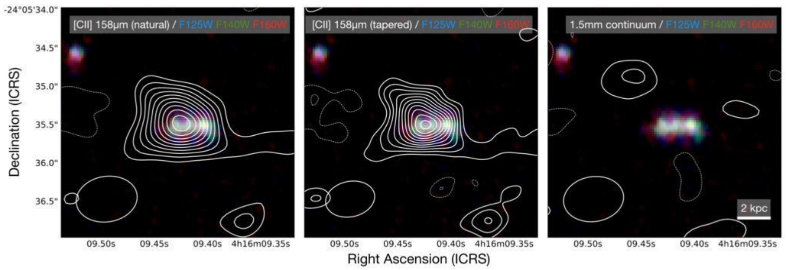
ALMA Partnership 2015; Hezaveh et al. 2016

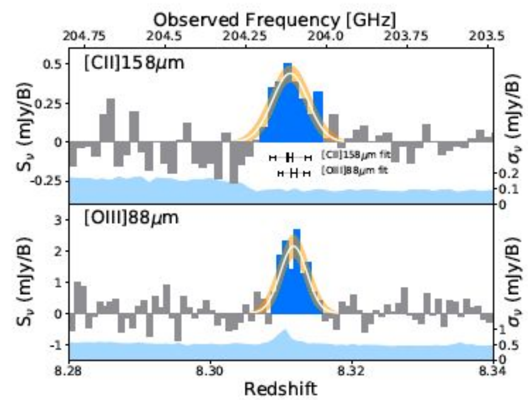
Additional Science Slides

ALMA Science: High-redshift Universe

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

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





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

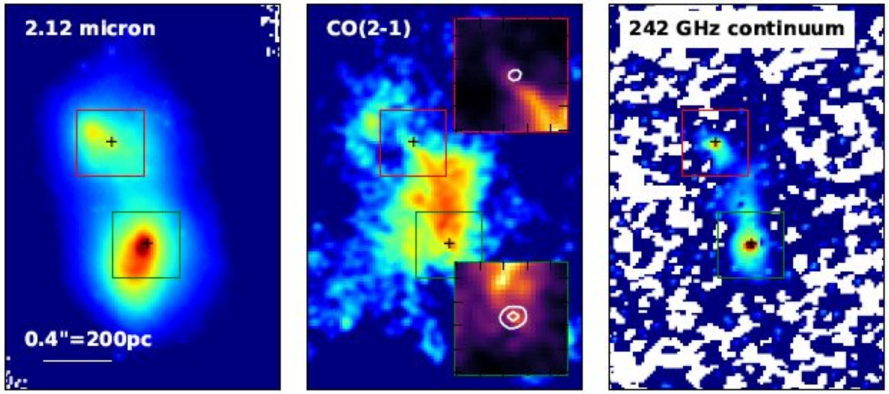
How Much 'Black Hole' Mass is Molecular?

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

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

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

FUEL FOR NGC 6240'S BLACK HOLES 3



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

Brown Dwarf Protoplanetary Disks

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

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

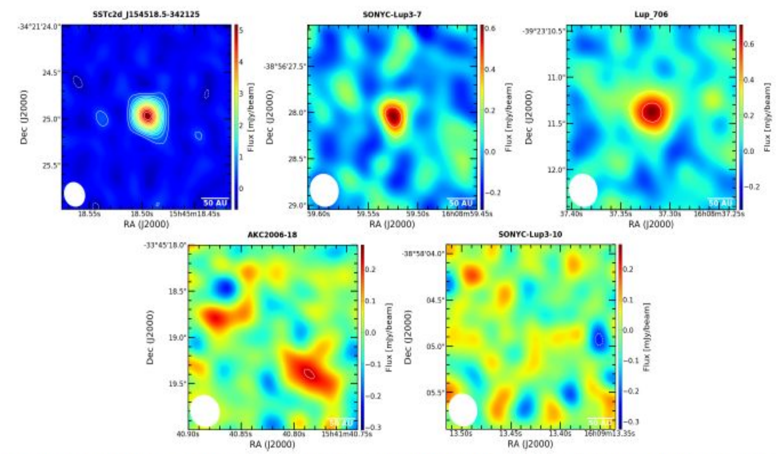
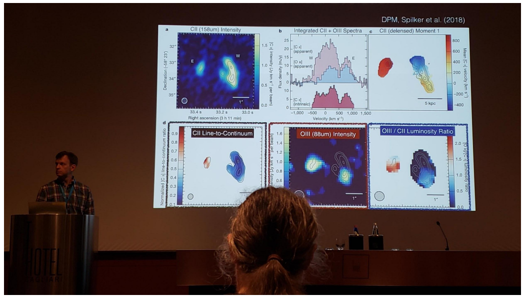


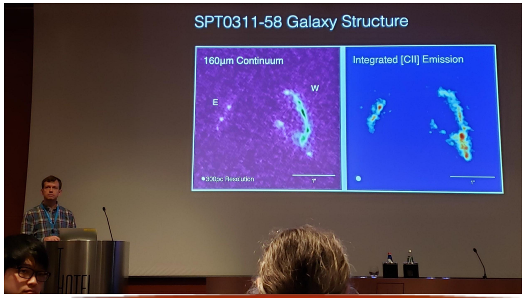
Fig. 2. Dust continuum images at 890 μm of the Lupus BDs disks survey from ALMA Band 7 observations. The beam size FWHM is $0.27'' \times 0.24''$ for the J154518.5-342125 map (robust parameter of -1), and $0.36'' \times 0.33''$ for the rest of the maps (robustness $= +0.5$). The average beam position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

Massive Galaxy Formation in the Reionization Era

Dan Marrone

- ALMA finds many z~6-7 objects, or which many cluster or merge.
  - Galaxy Formation must have begun earlier.
  - South Pole Telescope survey with ALMA followup very productive
  - ~80 spectroscopic redshifts median z=3.9.
  - Summed spectrum shows many lines.
- Spotlight on SPT0311-58
  - Image may be lensed.
  - [CII] shows two sources little magnified.
  - Few 10^11 solar masses shortly after t=0! Spilker+18.
  - OIII emission extent limited.
  - 50milliarcsec ALMA observations show structures.



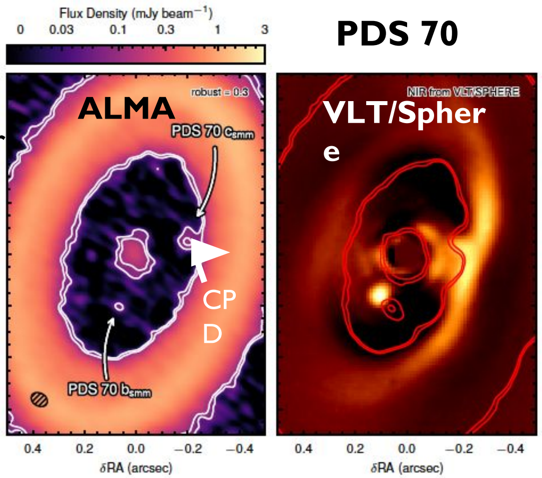


ALMA Observes Planet Formation in Protoplanetary Disks

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

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

PDS 70

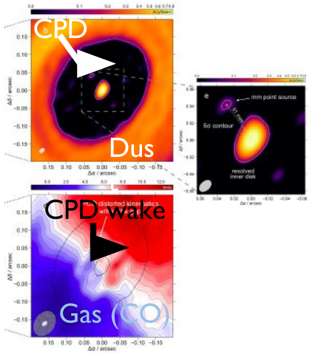


(L) ALMA image showing rings of dust and a gap, which contains two planets. (R) Near-IR image from VLT/Sphere

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

HD100546



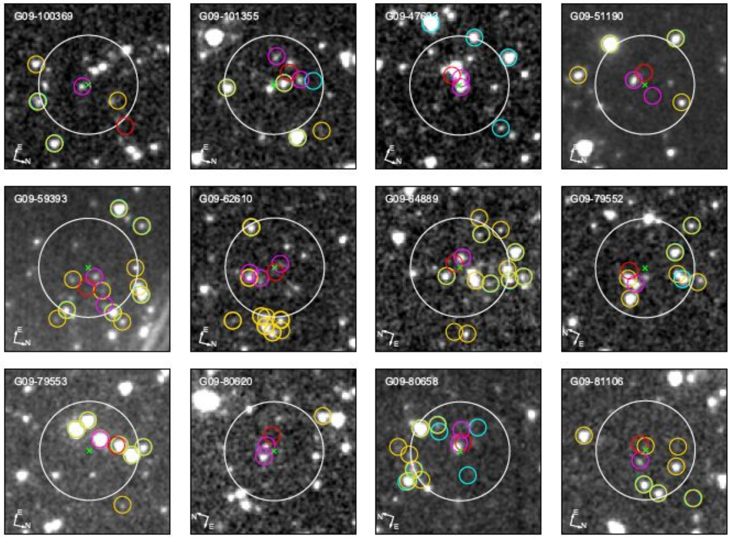
(L) Dust (greyscale) and (R) CO velocity anomaly (color) suggest a perturbation ('wake')

Ultrared dusty, star-forming galaxies:

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

Ma, Cooray et al arxiv: 1908.08043

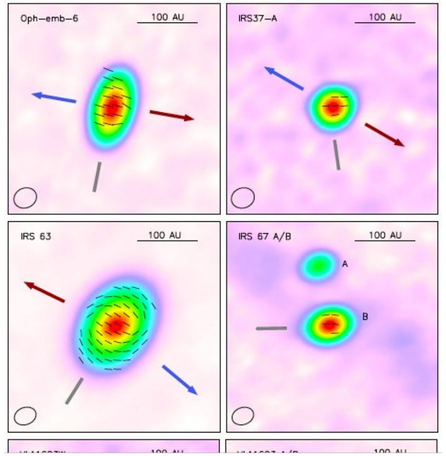
- High-resolution ALMA, NOEMA, and SMA data pinpoint 63 of the rare, intrinsically most dusty, luminous and massive galaxies in the early universe from the Spitzer catalog of Herschel-selected objects.
  - Interferometry pinpoints locations for secure ID as lensed or unlensed based on the morphology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



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

New Understanding of Galactic Star formation

Low Mass Young Stellar Objects in Ophiuchus

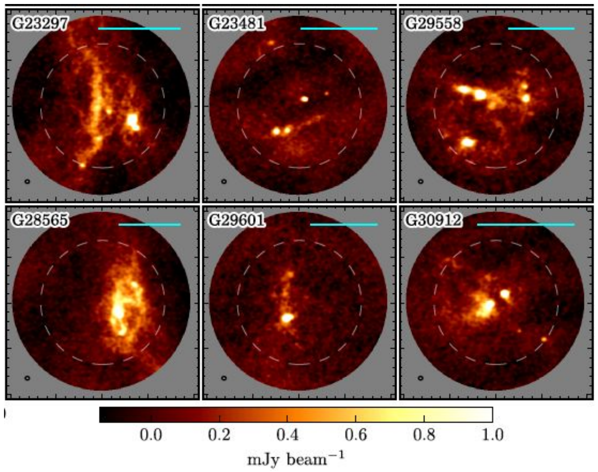


1.3 mm ALMA dust continuum images with polarization E-vectors at 0.25" = 35 au resolution

14/37 detected at current sensitivity

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

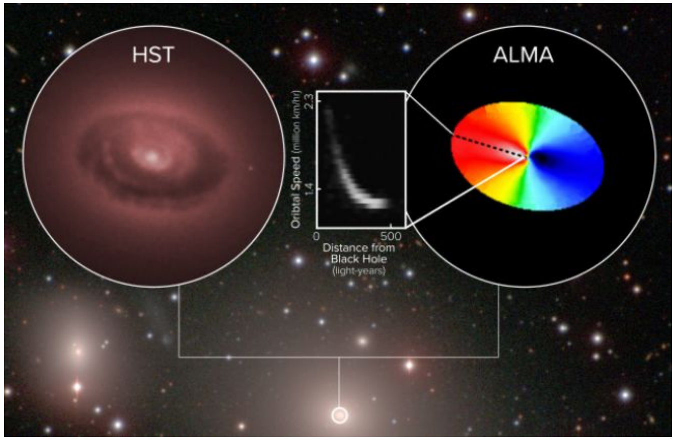
Sadavoy et al. 2019, ApJS, 245, 2



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

Svoboda et al. 2019, ApJ, 886, 36

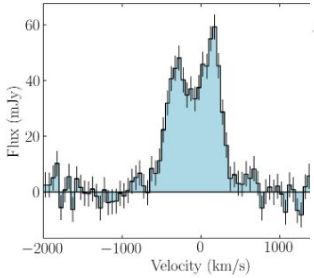
Building Monsters

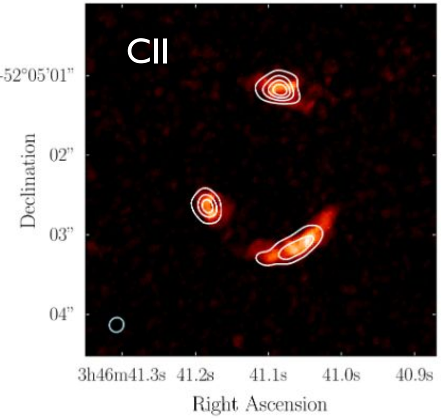


A close-up view of the cold CO (2-1) gas rotating around the supermassive blackhole:
$M = 2.249 \times 10^9 M_\odot$
at the center of the elliptical galaxy NGC3258

Resolution 0.1” = 150 pc

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





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

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

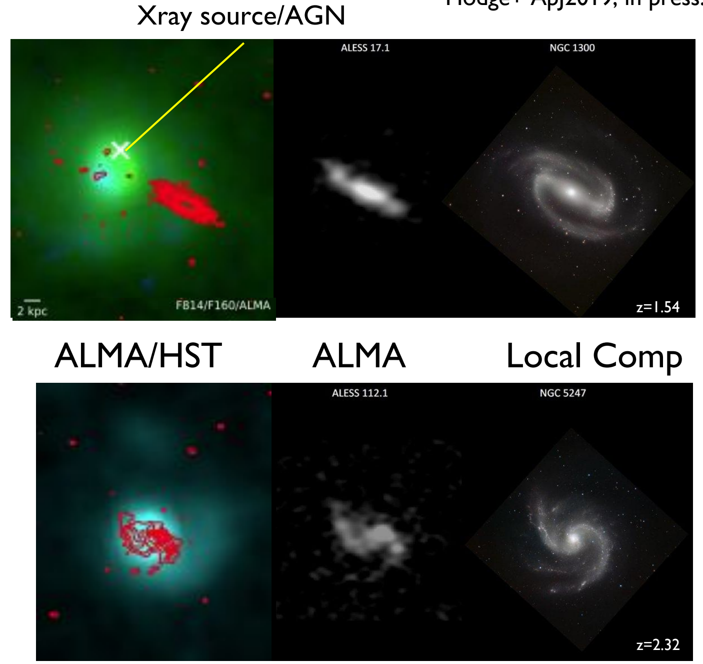
Litke et al. 2019, ApJ,, 870, 80L

ALMA Images Nascent Galaxy Structure

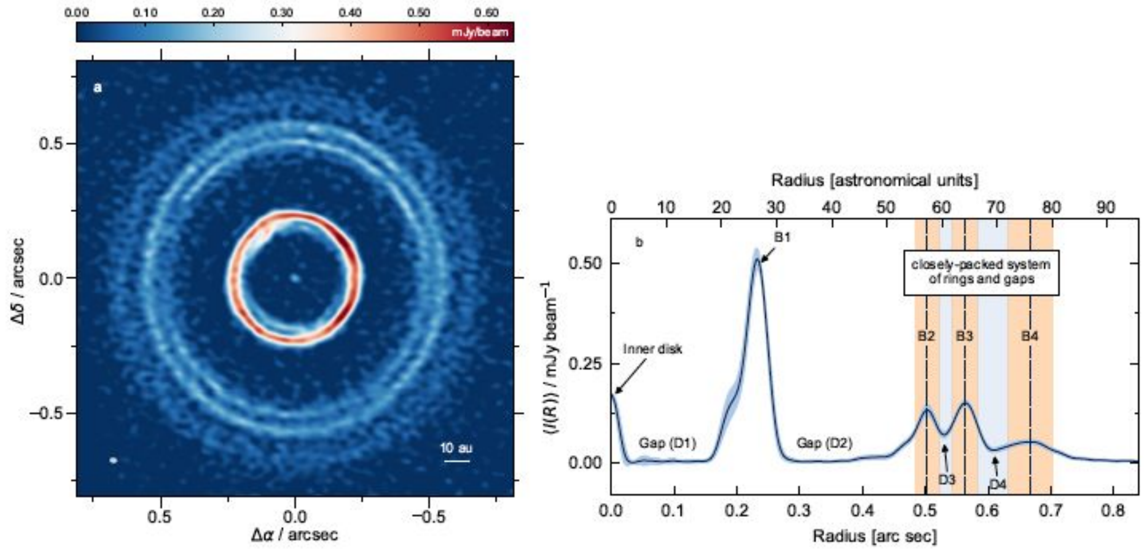
ALMA 0.07" (0.5kpc) imaging of rest-frame FIR emission from 6 SMGs at z~1.5 < z < 4.9

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

Hodge+ ApJ2019, in press.



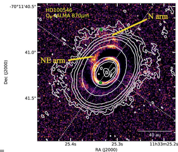
Circumplanetary disks



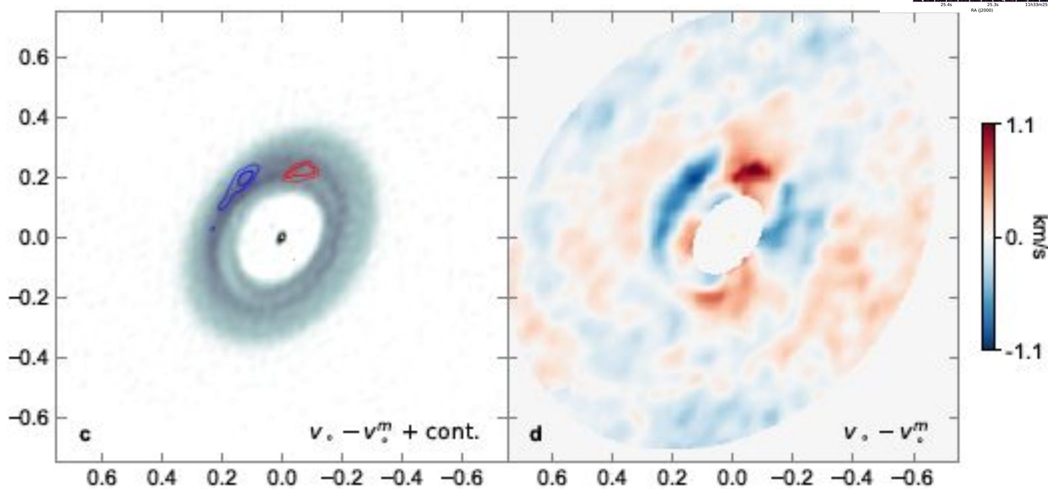
- Tight narrow rings in HD169142 are all produced by one planet. Core accretion, or any bottom up process, can thus produce planet embryos at 65AU and outside the orbit of inner giants in at least some disks.

ALMA Images Circumplanetary Disks II. HD100546

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



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



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

Dust Polarization Toward Embedded Protostars in Ophiuchus with ALMA

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

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

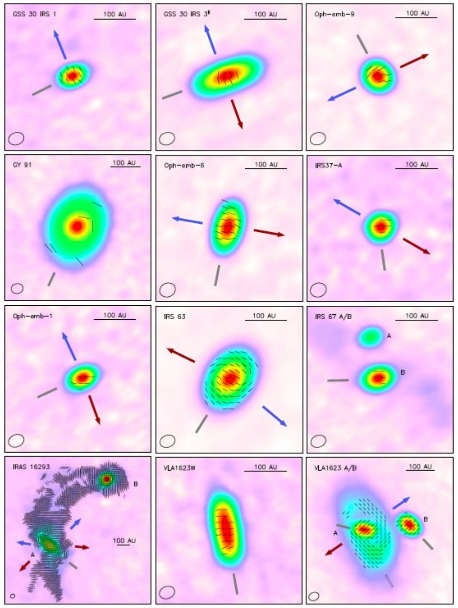
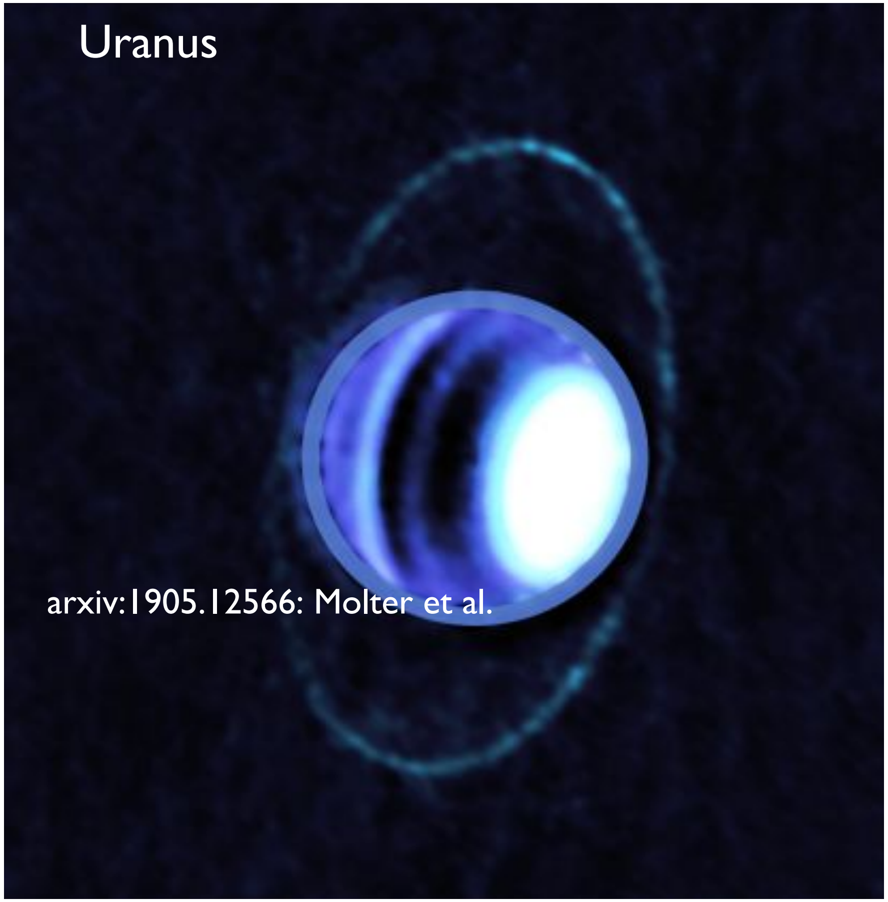


Figure 3. The 14 continuum sources with polarization detections. Background images show the Stokes I maps on a logarithmic color scale (see Appendix A for the flux scale) and the black line segments show the normalized e-vectors. Sources with ‡ are outside of the inner third of the primary beam FWHM.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

Extraordinary ALMA Images of Our Own Backyard

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

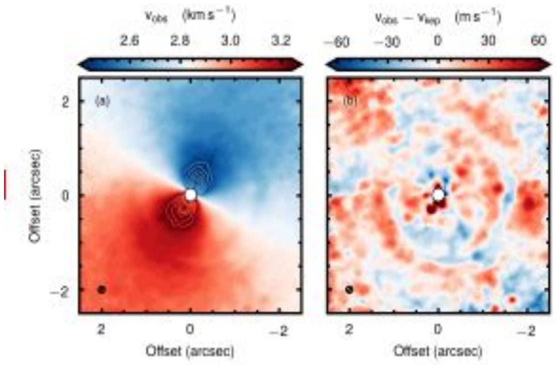


Using ALMA to Explore the Gas Reservoir of Planet Formation *(Cleeves+, AS2020)*

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

Kinematic Detection of Planets in Formation

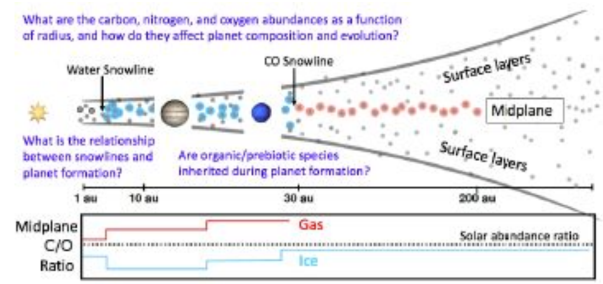
- Goal: find planets during formation, embedded in disk
  - High angular resolution optically using extreme adaptive optics seeking thermal or line (Hα) emission
  - High angular emission in the (sub)millimeter using ALMA, seeking circumplanetary disks, which could be seen to $0.03M_{lunar}$ but have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



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

Forming Planet Chemical Environment

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

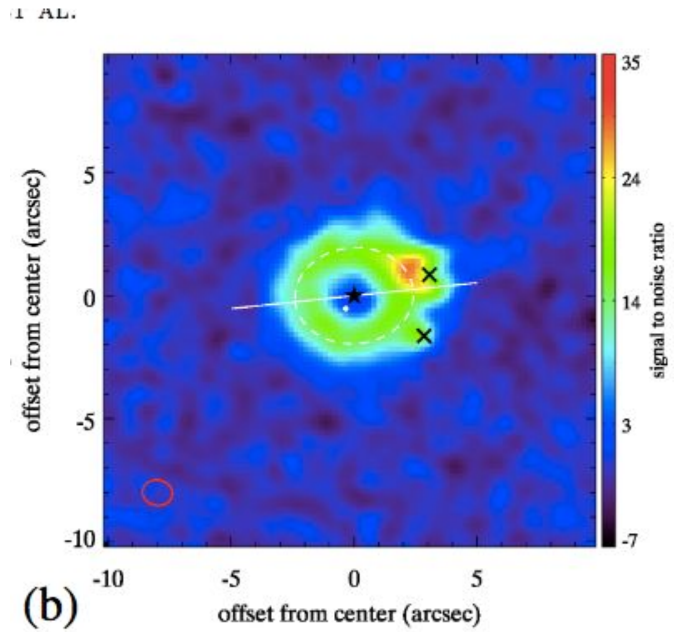


- This can be achieved by a combination of Increased collecting area, improved receivers and increases in bandwidth, efficiency and data rates of the ALMA signal processing system

Science Highlight (1)

ALMA Images First Kuiper Belt Analogue Around Sun-like Star

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

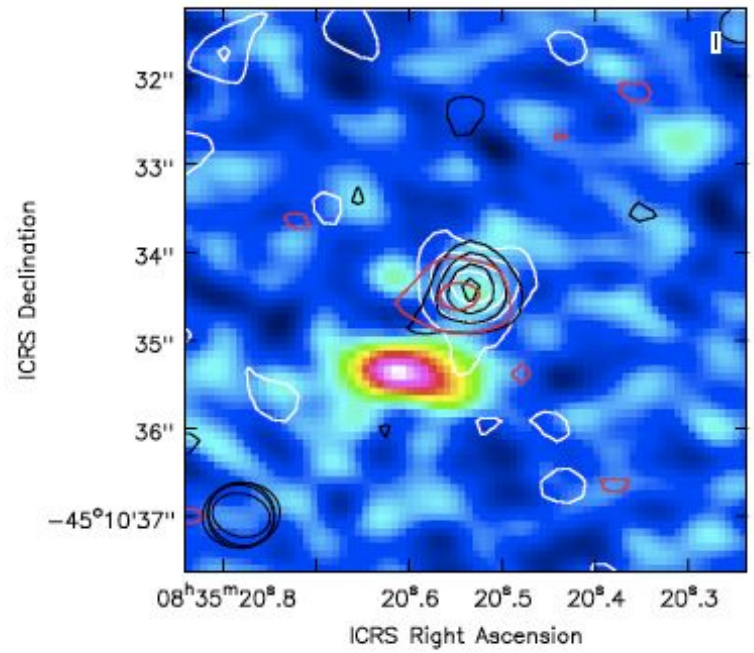


ALMA 1.3mm image of the Kuiper Belt analog disk around HD 95086 (black star). The optically imaged planet is represented by a white dot. The sources to the W are likely background galaxies, subtracted in this image. Disk major axis is white line.
Su+ 2017 arXiv 1709.10129

Science Highlight (2)

ALMA Images Vela Pulsar

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

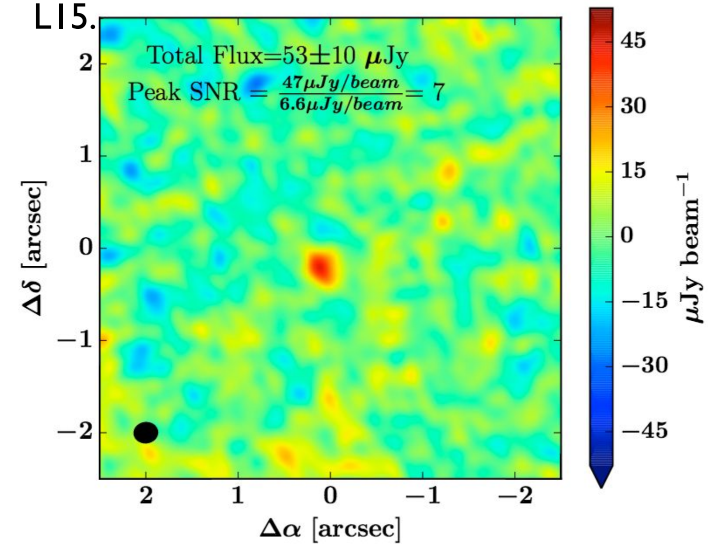


Vela Pulsar, ALMA B3,4,6 (contours) on B7 image; an extended structure, preliminarily detected in ground-based observations, may be a counter-jet protruding from the pulsar. (Mignani+, 2017)

Science Highlight (IV)

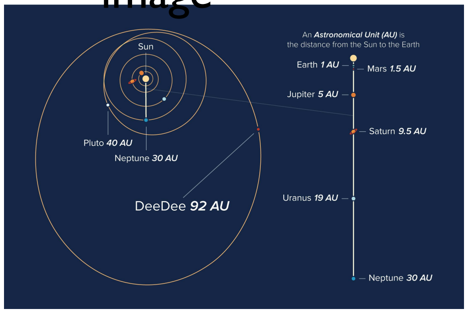
ALMA Characterizes TransNeptunian Object DeeDee

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



Above: ALMA 1.3mm image

- 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*



Left: DeeDee in the Solar System

Science Highlight (V)

ALMA Catches, Characterizes Massive Star Outburst

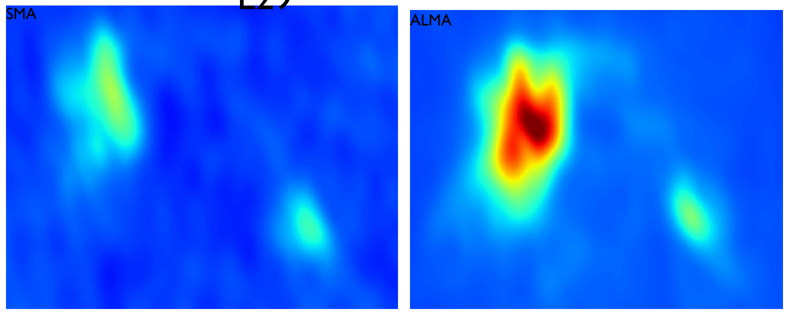
Recent outbursts in YSOs show similar features:

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

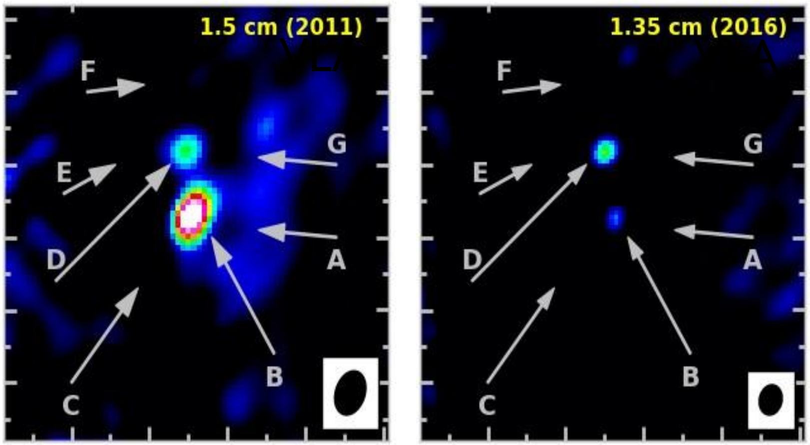
NGC6334I-MM1 dust continuum outburst is accompanied by:

- Dimming of the HCHII region by a factor of 4: <u>suppression of UV photons</u>
- 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

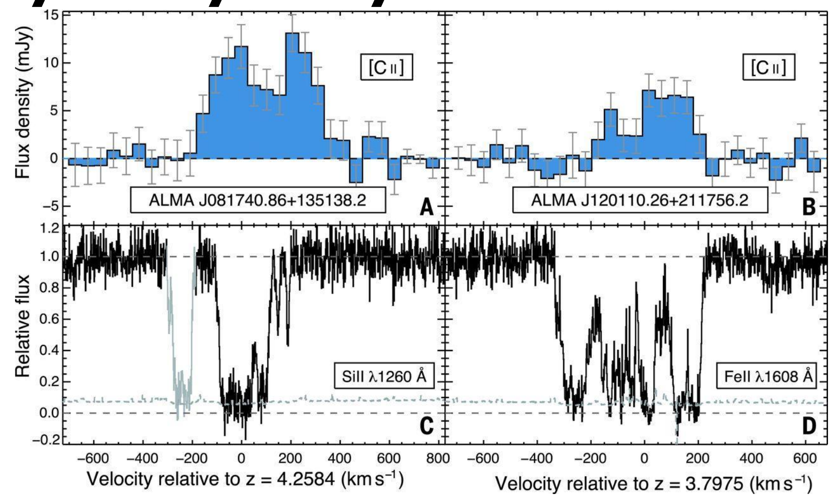


Science Highlight (VI)

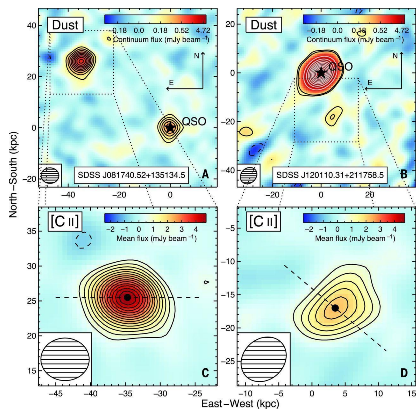
Marcel Neeleman et al. Science 2017;355:1285-1288

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.

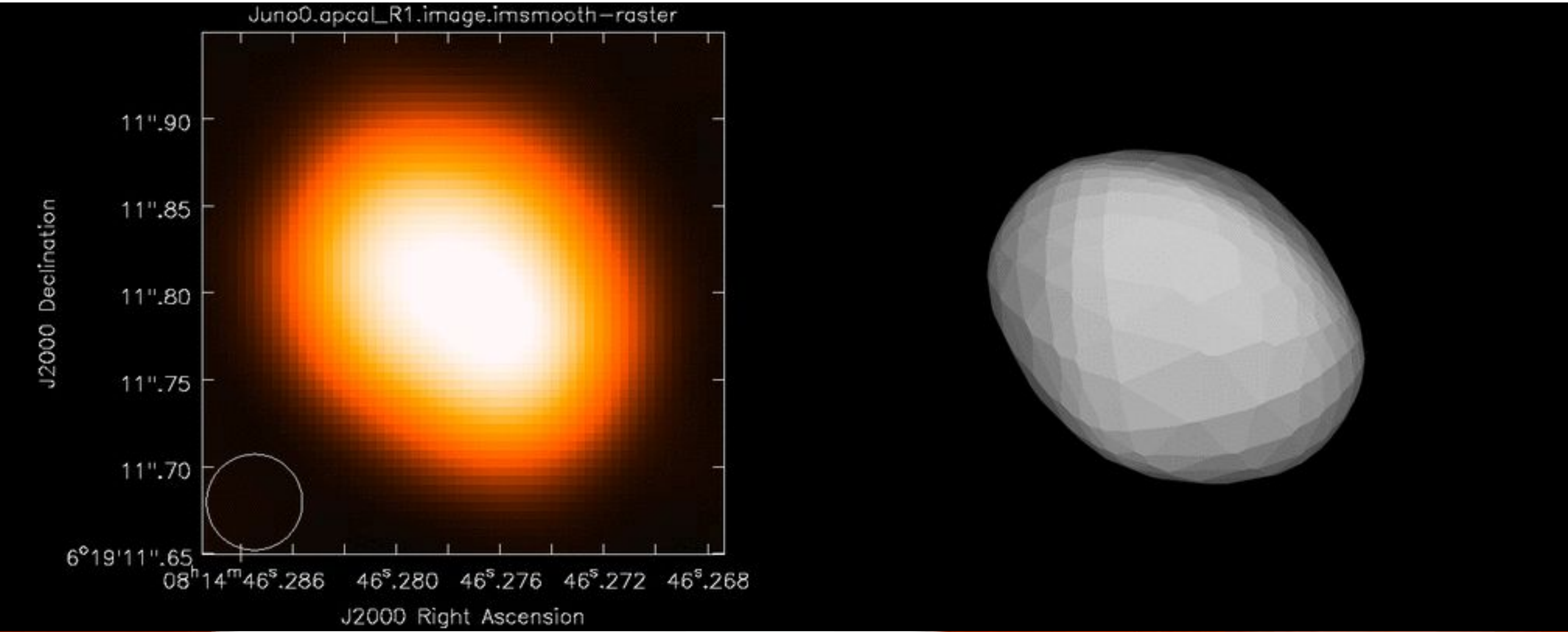
ALMA Science Highlights: Solar System

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

Five consecutive executions over 4.4 hours

Beamsize ~ 0.04”x0.03” (~60x45 km)

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

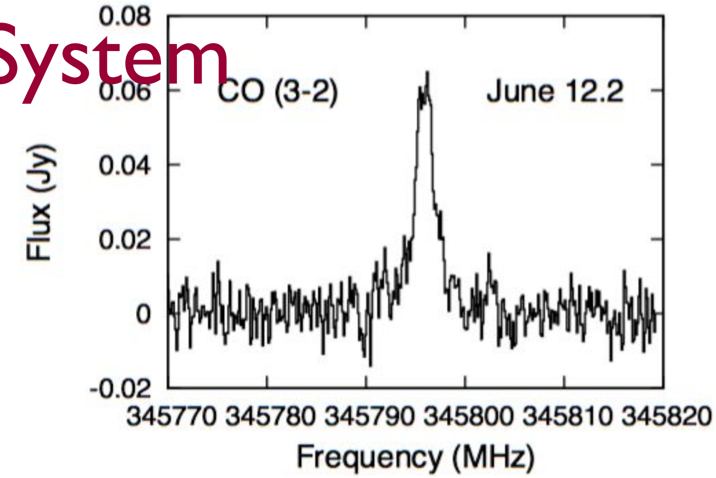


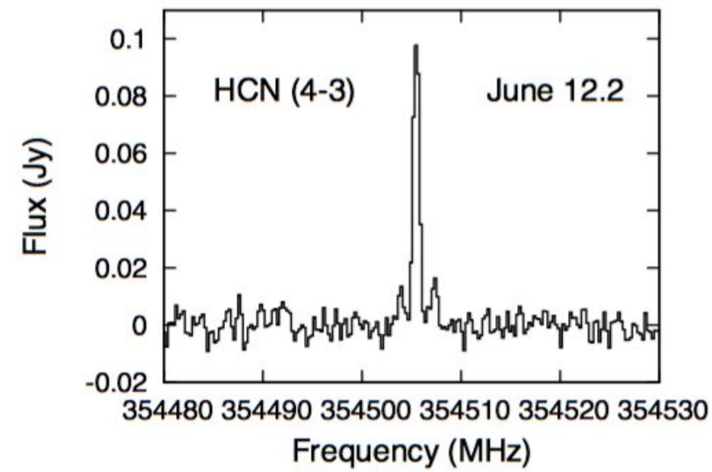
ALMA Image of Juno (ALMA Partnership, Hunter et al. 2015)

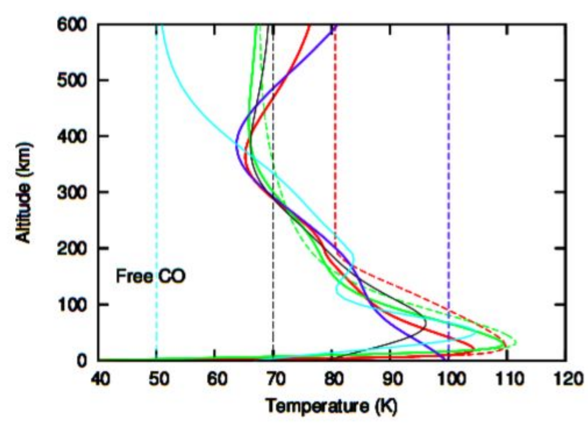
ALMA Science Highlights: Solar System

ALMA detects organics on Pluto

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

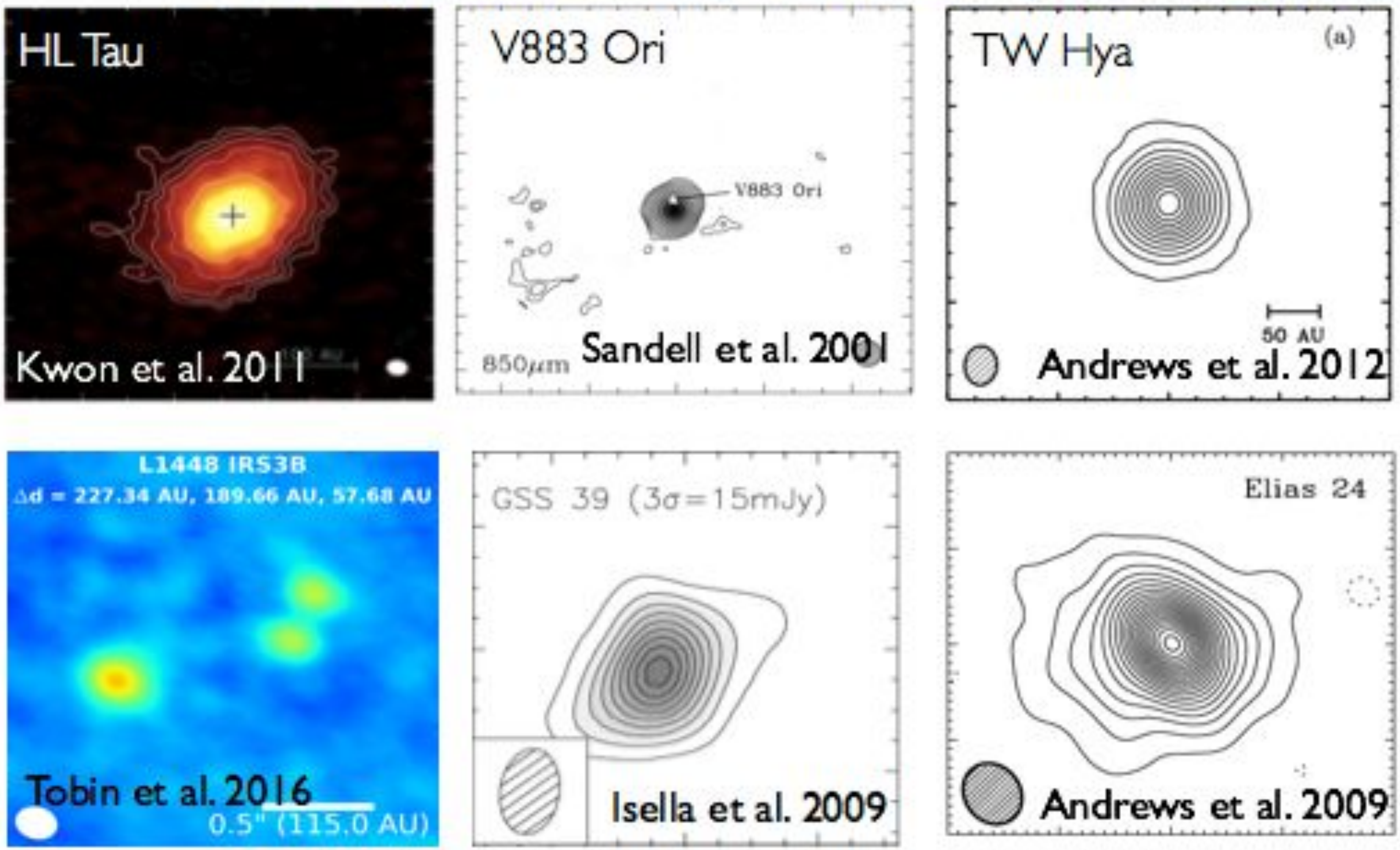






ALMA Science Highlights: Protoplanetary Disks

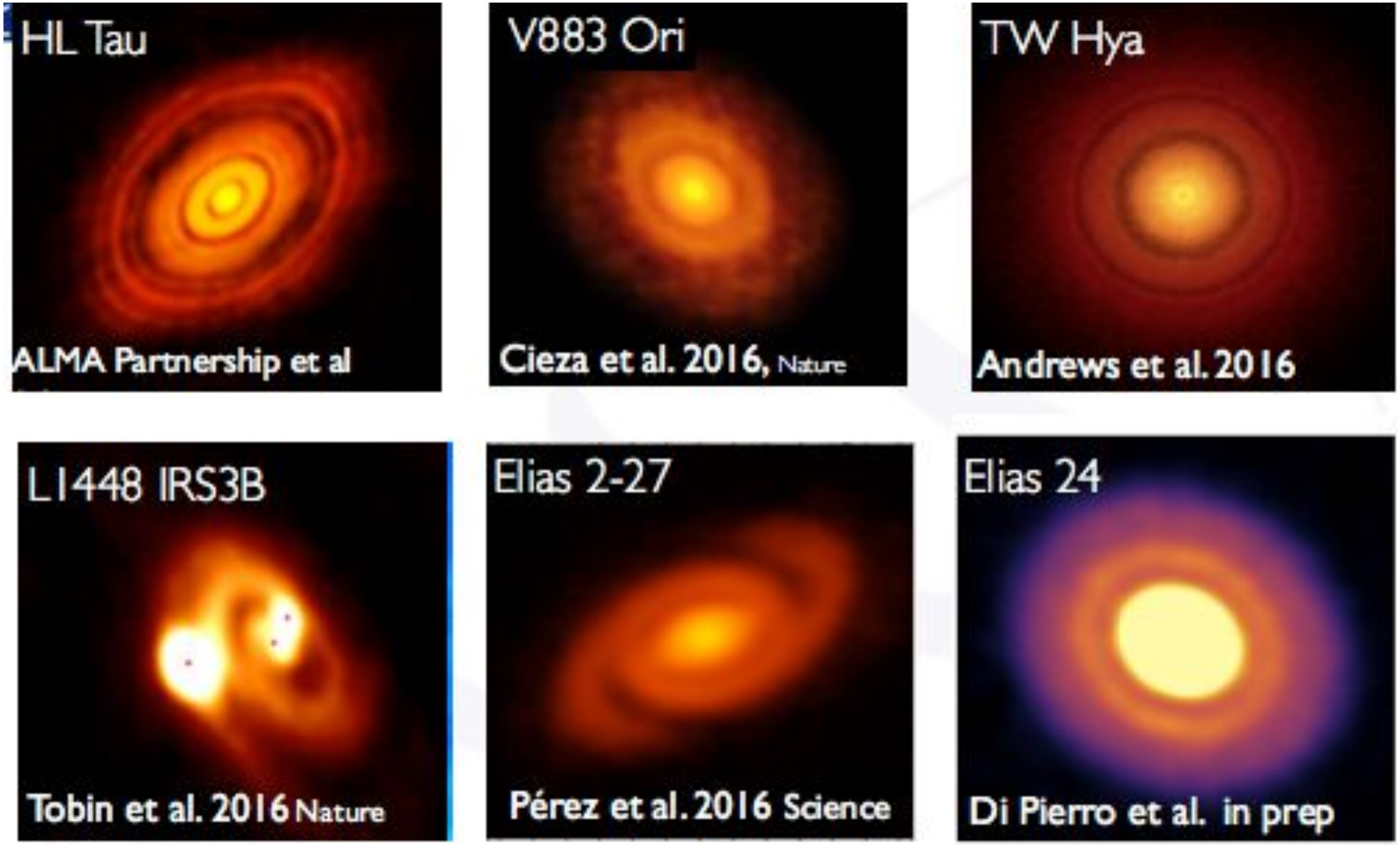
Protoplanetary Disks: Pre- ALMA



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

ALMA Science Highlights: Protoplanetary Disks

Protoplanetary Disks: With ALMA



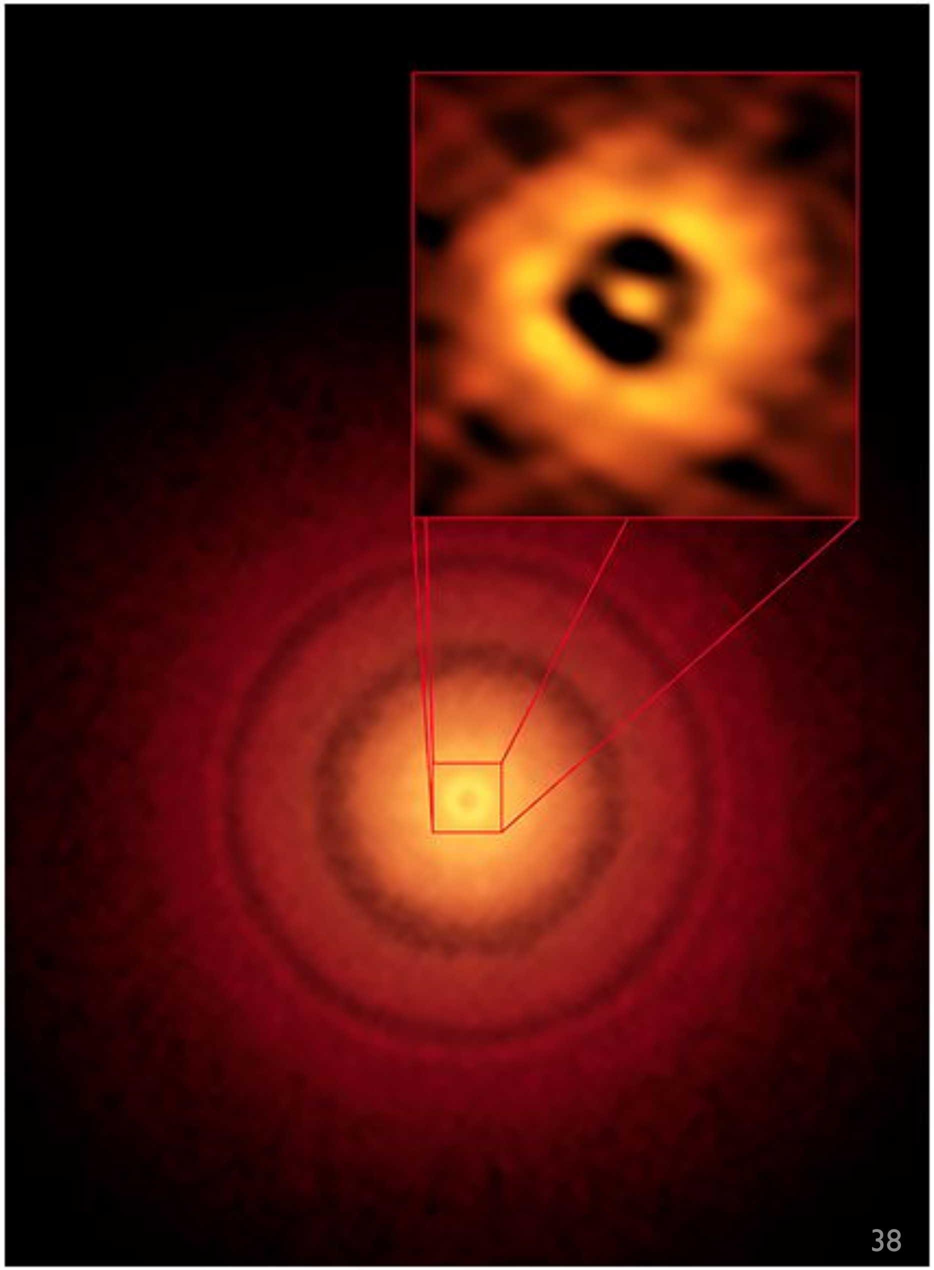
Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

ALMA Science Highlights: Protoplanetary Disks

TW Hydrae

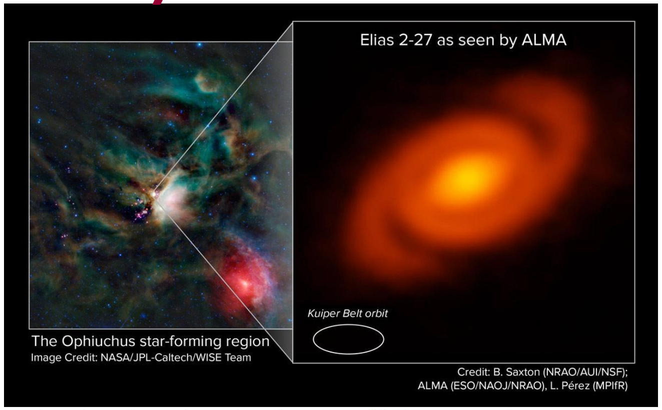
ALMA's better-than Hubble resolution details as small as the Earth's distance from the Sun may be discerned in this young (10Myr) nearby (175 light years) planet forming Sun-like star

Andrews et al. 2016



ALMA Science Highlights: Protoplanetary Disks

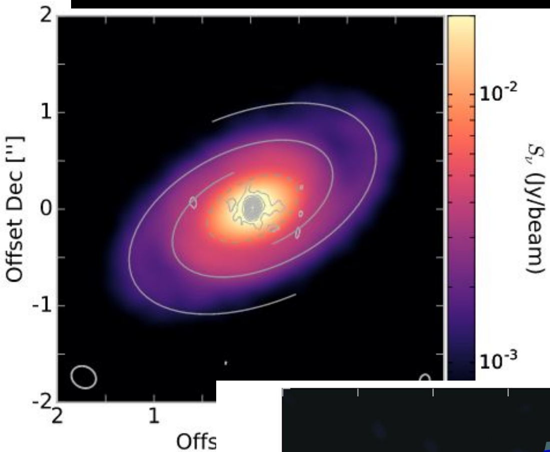
Protoplanetary Disks: With ALMA

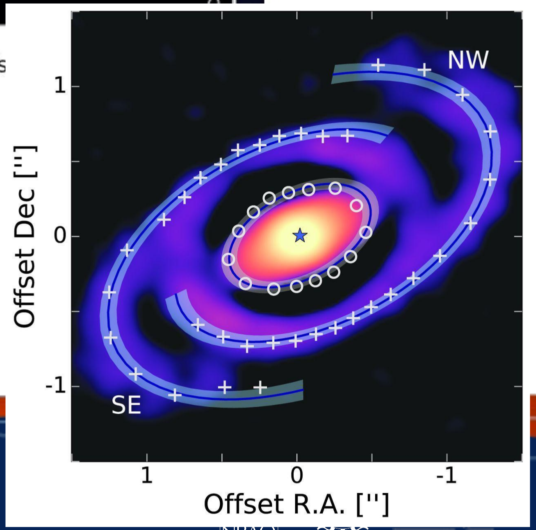


A Spiral Density Wave Observed in a Protoplanetary Disk

Perez et al. Science 353, 1519 (2016)

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



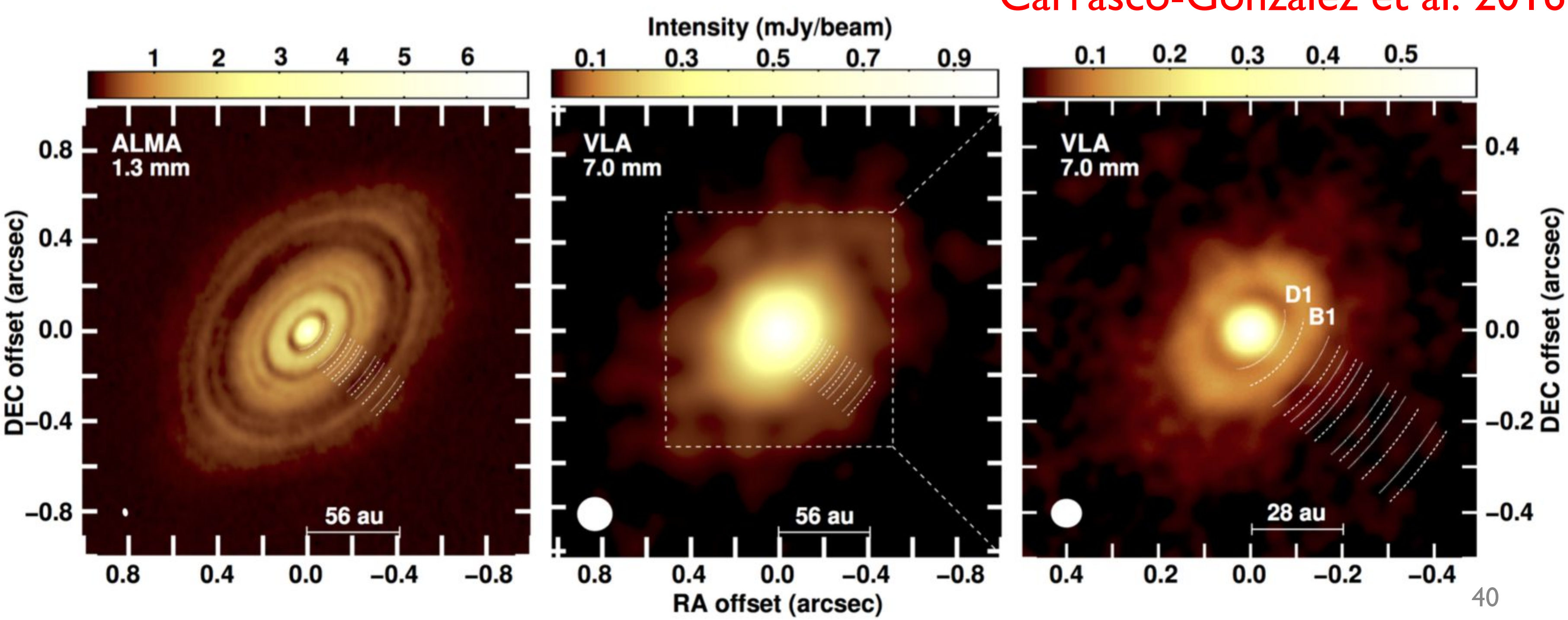


ALMA Science Highlights: Protoplanetary Disks

Protoplanetary Disks: With ALMA and VLA

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

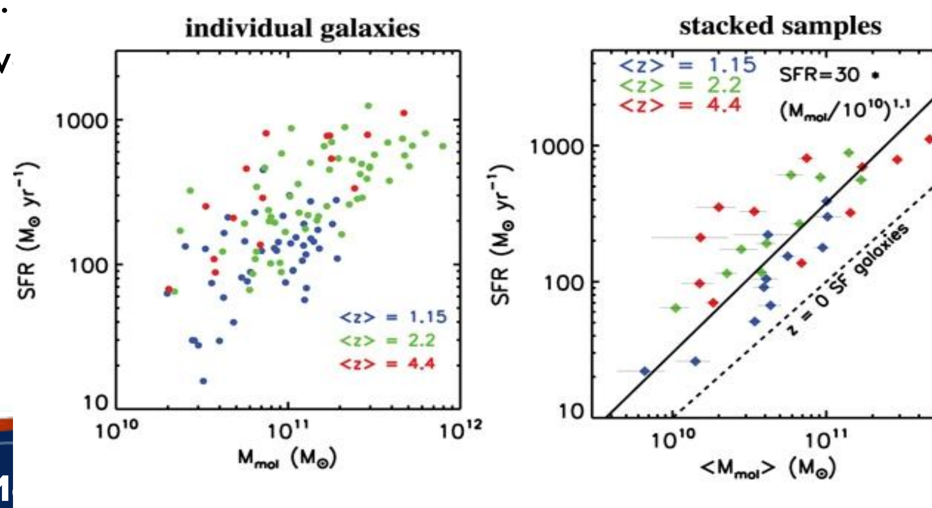
Carrasco-González et al. 2016



ALMA Science Highlights: Star Formation Peak

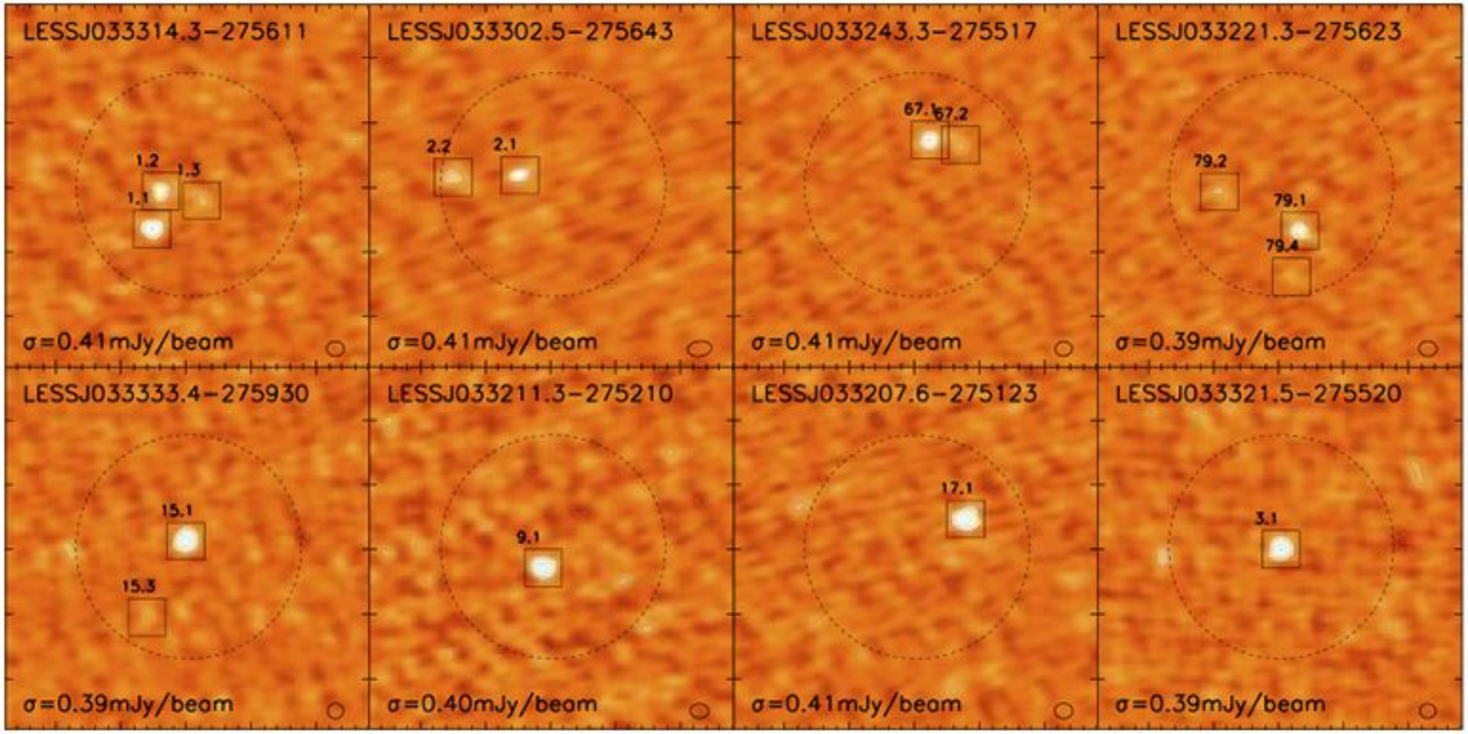
- Scoville et al. (2016 ApJ 820 83)
  - *"ISM Masses and the star formation law at z = 1 to 6: ALMA observations of dust continuum in 145 galaxies in the COSMOS survey field"*

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



ALMA Science Highlights: the Distant Universe

Resolving High-z Submm Galaxies



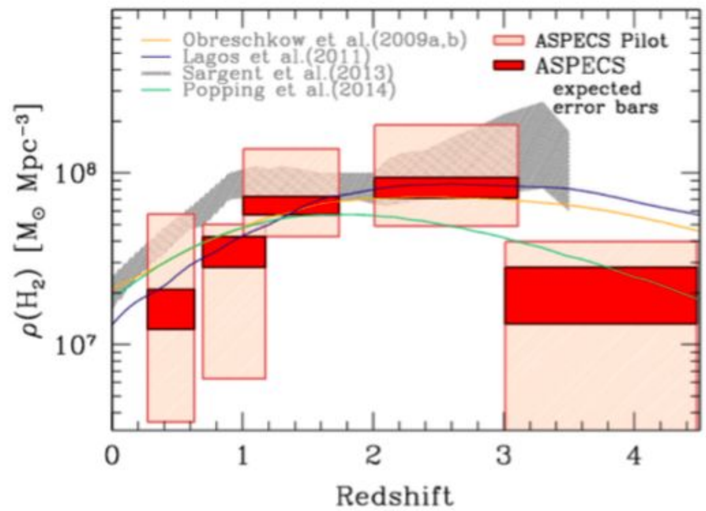
Hodge et al. 2013

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

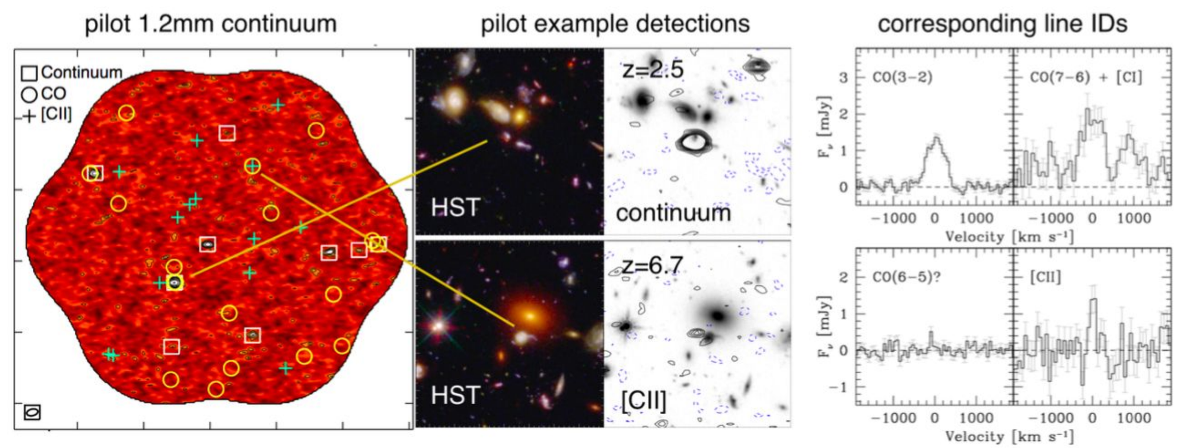
ALMA Science Highlights: the Distant Universe

ALMA Deep Fields: a new era of cosmological surveys

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

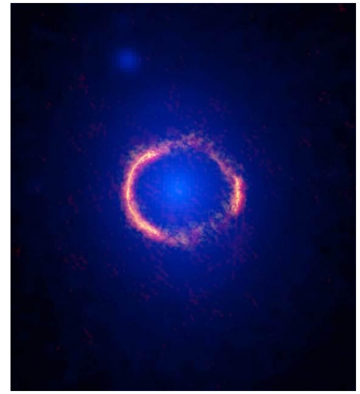


Examples of line and continuum sources from the ASPECS program, plus constraints on the dense gas history of the Universe (see papers by Walter, Decarli, Aravena)



ALMA Science Highlights: the Distant Universe

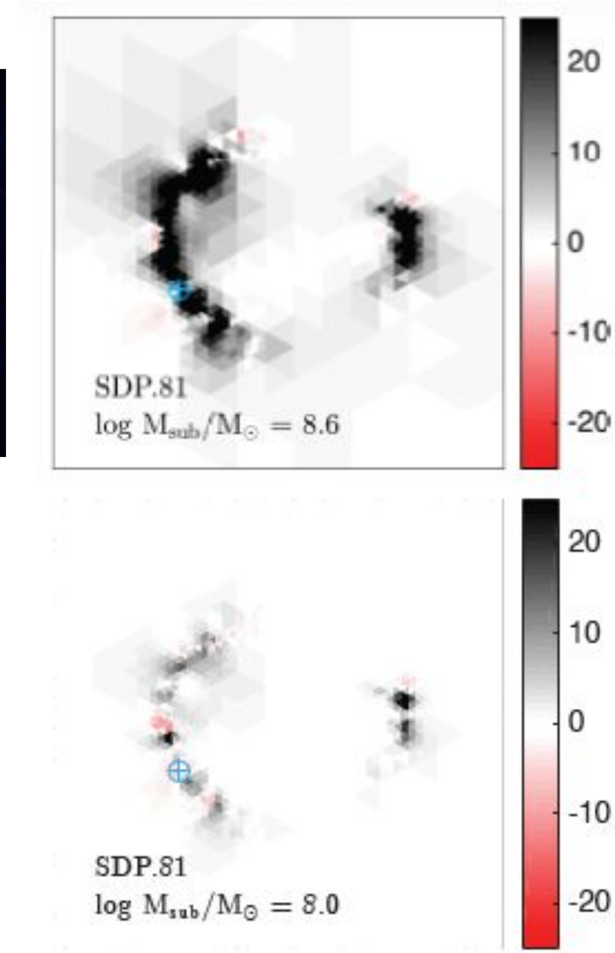
- Hezaveh et al (2016) show ALMA's potential to advance understanding of dark matter substructures
- ALMA's SDP.81 observations are analyzed to detect a subhalo with a mass of $10^{8.96 \pm 0.12}\ M_{sun}$
- Consistent with theoretical expectations



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.

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