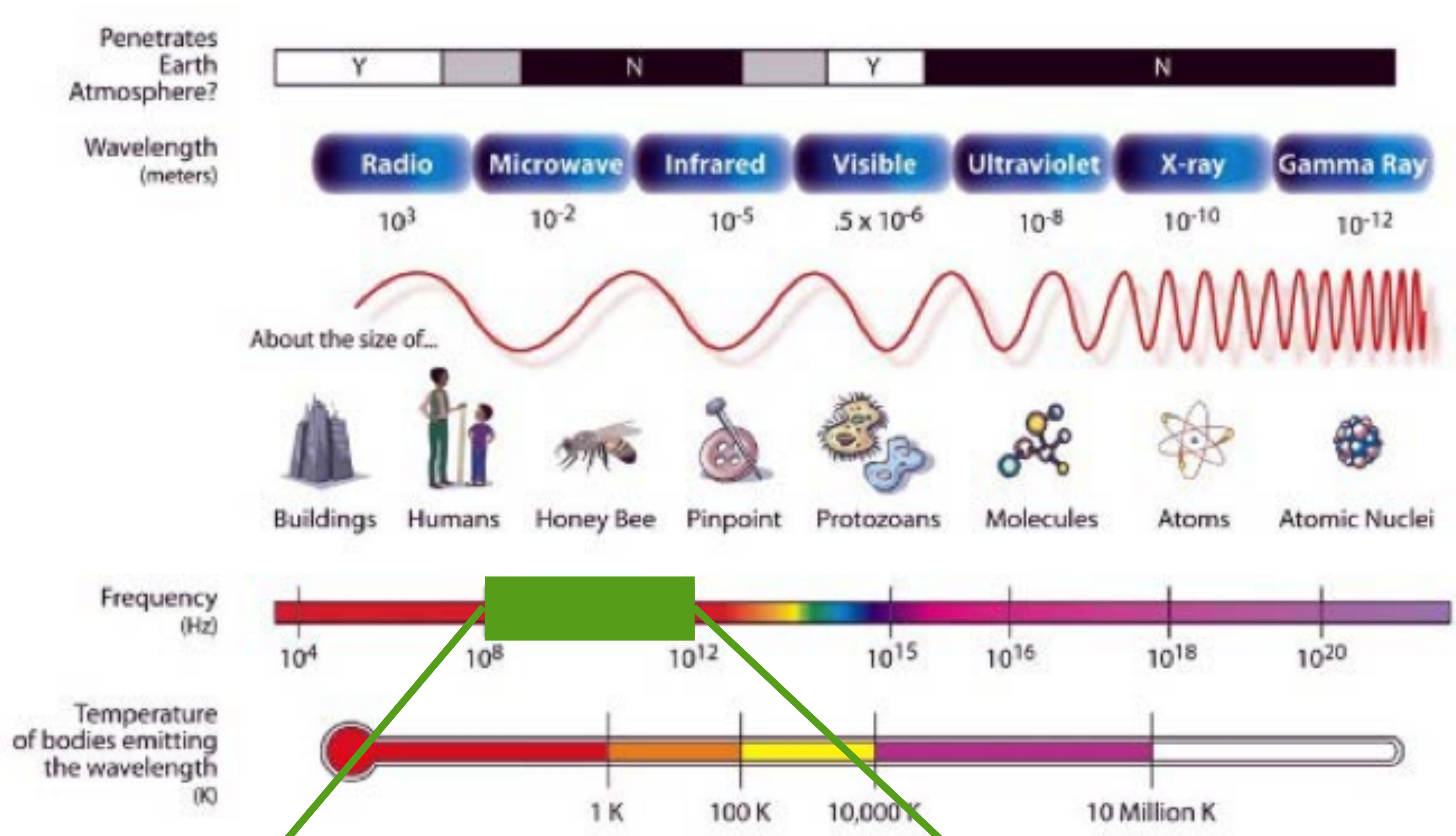
ALMA Basics & Science Highlights

Presenter: Emily Moravec

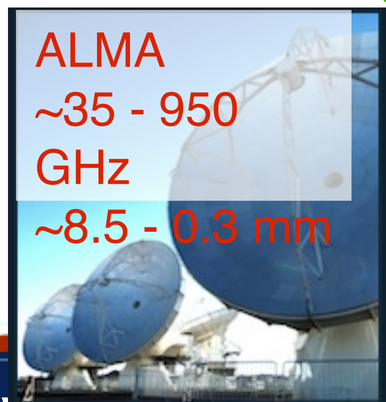
Slide Author: Catherine Vlahakis

National Radio Astronomy Observatory: One Observatory, Three World Class Facilities

- Other Affiliated Telescopes and Observatories include the Green Bank Observatory (http://greenbankobservatory.org/).
- NRAO also operates the Central Development Laboratory and the Next Generation Very Large Array Project.


Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^{3}
10^{-2}
10^{-5}
$.5 \times 10^{-6}$
10^{-8}
10^{-10}
10^{-12}
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^{4}
10^{8}
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K


VLA
~1 - 50 GHz
~300 - 6 mm


ALMA
~35 - 950 GHz
~8.5 - 0.3 mm

NRAO:
One Observatory,
Three World Class Facilities

Atacama Large Millimeter/submillimeter Array:
a 66-antenna array in Chile

What is ALMA?

- A global partnership to deliver a revolutionary millimeter/submillimeter telescope array (in collaboration with Chile)
  - North America
  - Europe
  - East Asia
- Array Operations Site is located at 5000m elevation in the Chilean Andes
- 66 reconfigurable, high-precision antennas
- Array configurations between 150 m and 16.2 km
- 192 possible antenna locations
- Main Array: 50 x 12-m antennas
- Atacama Compact Array (ACA) or Morita Array: 12 x 7-m antennas plus 4 x 12-m antennas for Total Power (7-m Array and TP Array)
- Receiver bands cover 35-950 GHz (since Cycle 10)
- Provides unprecedented imaging and spectroscopic capabilities at mm/submm wavelengths

What is ALMA?

- Array configurations with baselines between 160 meters and >16 kilometers
- 192 possible antenna locations

http://youtu.be/YMISe-C8GUs

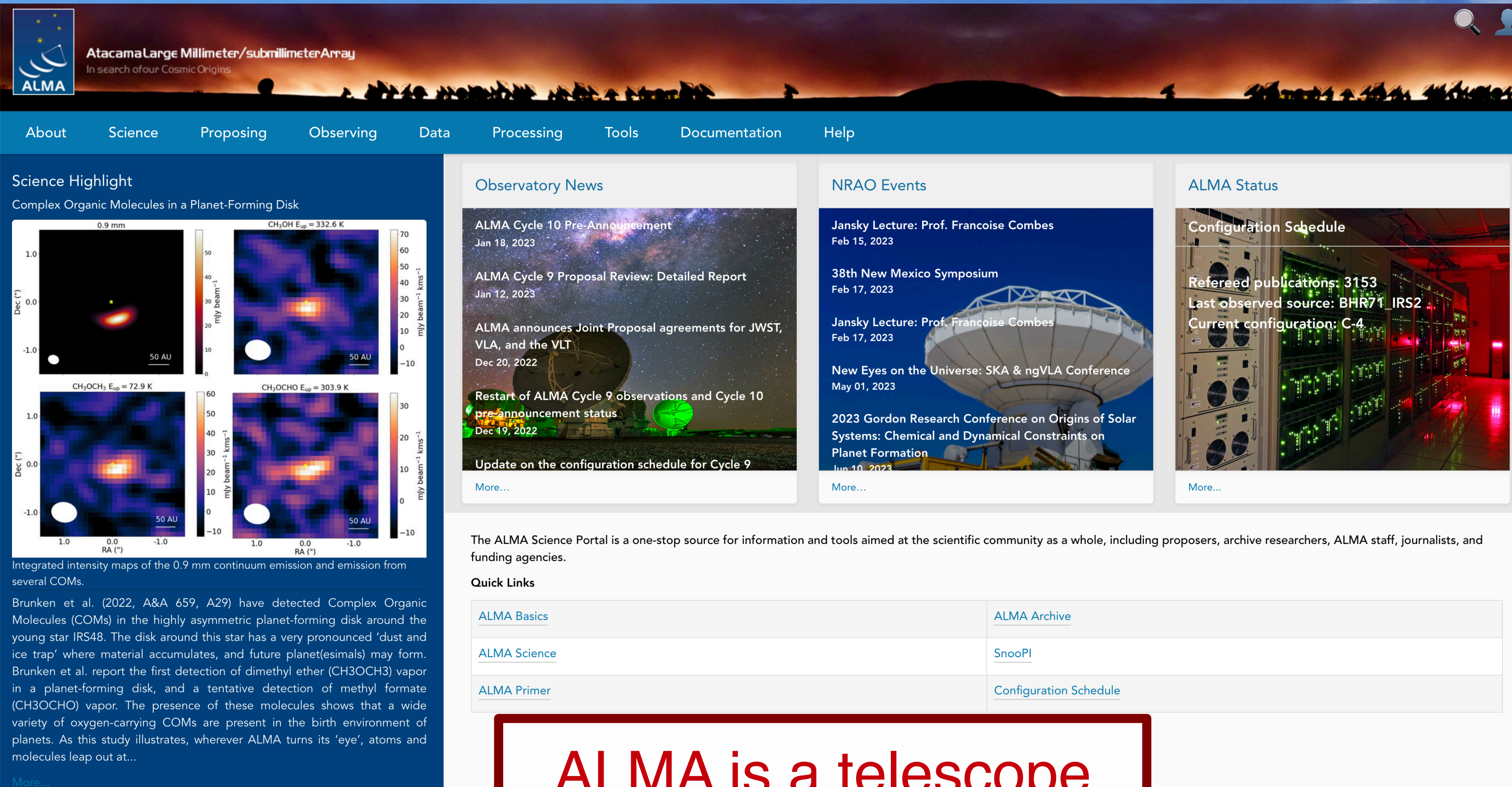
ALMA in a Nutshell

- Angular resolution down to ~0.01" (slightly less in longest configurations but not in Cycle 10)
- Sensitive, precision imaging from 35 to 950 GHz (8.5 mm to 0.32 mm). Band 1 (35-50 GHz) starting in Cycle 10.
- State-of-the-art low-noise, wide-band receivers* (7.5 GHz useable bandwidth)
- Flexible correlator with high spectral resolution at wide bandwidth
- Full polarization capabilities including circular.
- Estimated 1 TB/day data rate
- All science data archived
- Pipeline processing

ALMA is 10-30+ times more sensitive and has 10-30 times better angular resolution than other current mm interferometers

In either case, this is using the Time Division Mode (TDM) modes.

ALMA Science Portal: https://almascience.nrao.edu/ - documentation, info, news and more!

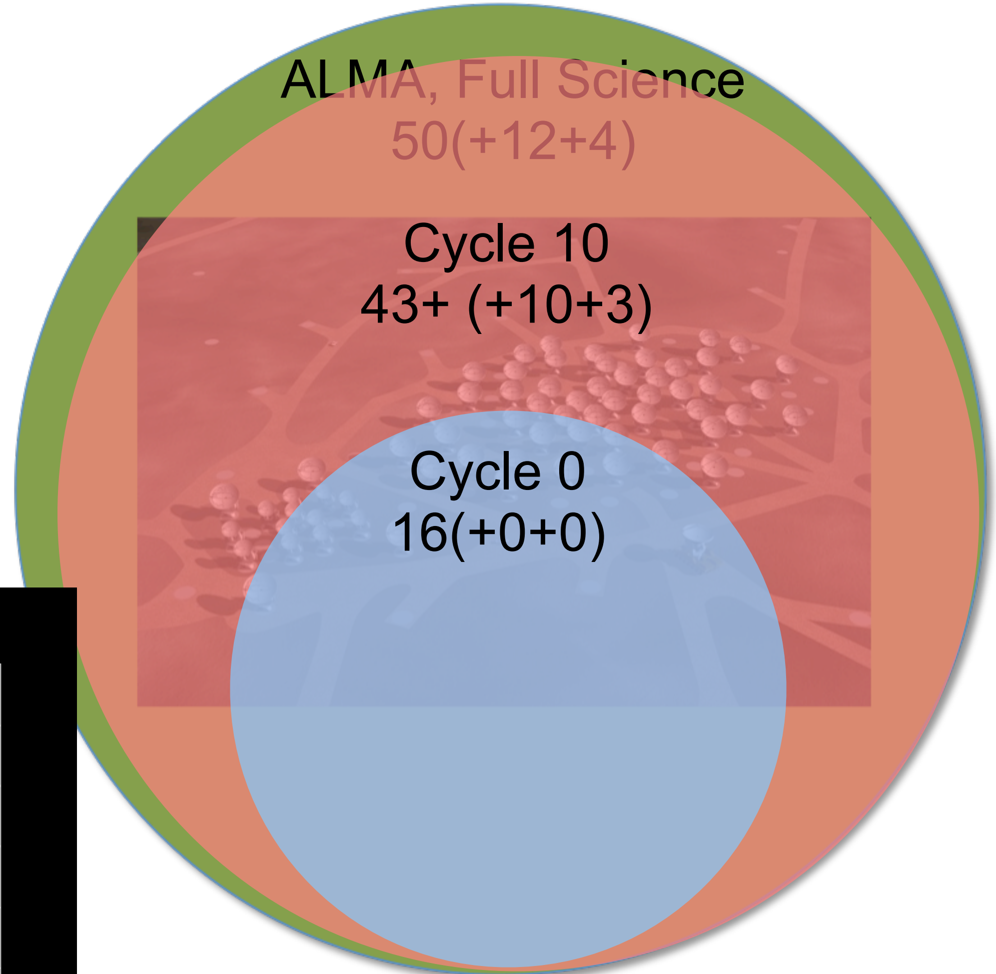


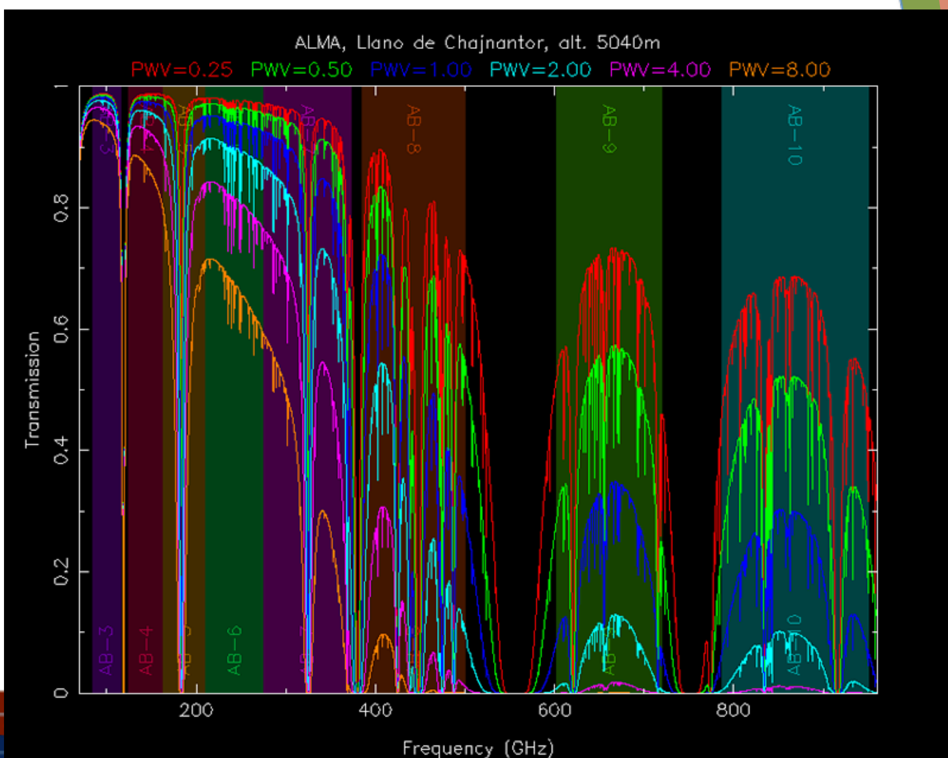
ALMA is a telescope for *all* astronomers

What is ALMA?

Collecting Area

Not only sensitivity but the collecting area (1.6 acres or 6600+ m2) + huge number of baselines provides excellent image fidelity





Spectral Coverage

Covers ten atmospheric windows with 50% or more transmission above 35 GHz

ALMA Current Status

- Construction Project ended in September 2014
- Routine science observing has been out to **greater than 16 km baselines (C-10)** thanks to the highly successful Long Baseline Campaigns in 2014 and 2015
- **66 antennas: 54 12-m antennas (incl. 4 for TP) + 12 7-m antennas**
  - Nominally, minimum of 43 antennas and potentially up to maximum of 50 (usually up to 46 or 47) antennas are used for PI science observations on the 12-m Array
  - Nominally, minimum 10 antennas and up to a maximum of 12 antennas are used for the 7-m Array
  - Antennas not used for PI science are usually undergoing maintenance
- 9 out of the 10 bands are now offered as of Cycle 10 (only Band 2 remaining to come in future)
- More on Capabilities later… however, first on to science!

Broad Science Topics with NRAO Telescopes

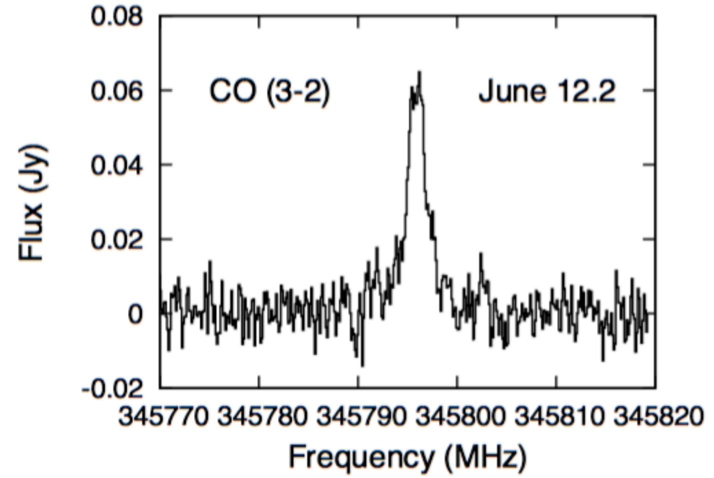
- Sun – coronal mass ejections, magnetic field activity
- Solar system, KBOs – atmospheres, astrometry, composition
- Star-forming regions – dust and gas environment, kinematics (infall, outflows, jets), proto-planetary disks, cores, chemistry, feedback, and natal cloud / star interactions
- Exoplanets – direct imaging, gaps in disks, kinematics
- Pulsars – neutron star physics, pulse morphology, gravity, ISM probe
- Galactic structure – spiral arms, bars, global atomic and molecular gas properties
- Nearby galaxies – molecular / atomic gas content and kinematics, dynamics of galaxies at high resolution, star formation, obscured SF, gas flow
- Galaxy groups and clusters – atomic and molecular gas across systems, star formation efficiency, kinematics, dynamical mass measurements
- Black holes – mass measurements, kinematics
- High redshift galaxies – extragalactic background light, source counts, star formation history and efficiency, evolution of gas content (atomic and molecular)
- Cosmology – H_0 measurement, SZE

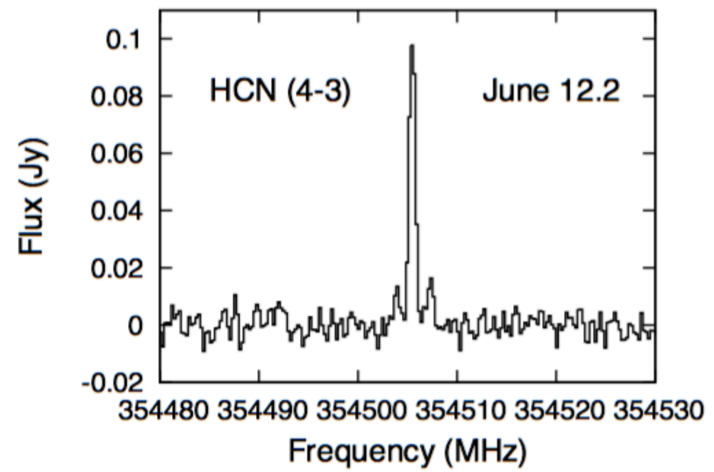
Science Highlights

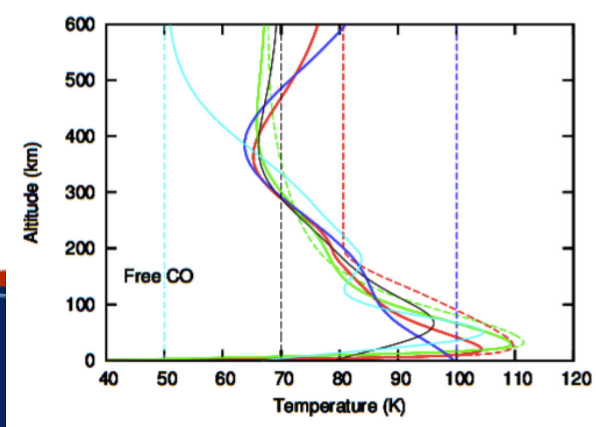
ALMA Science Highlights: Solar System

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



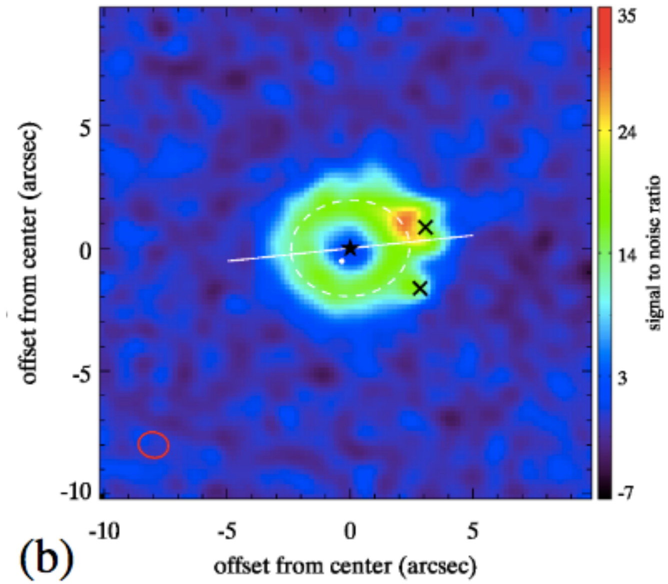




ALMA Science Highlights: Solar System

ALMA Images First Kuiper Belt Analogue Around Sun-like Star

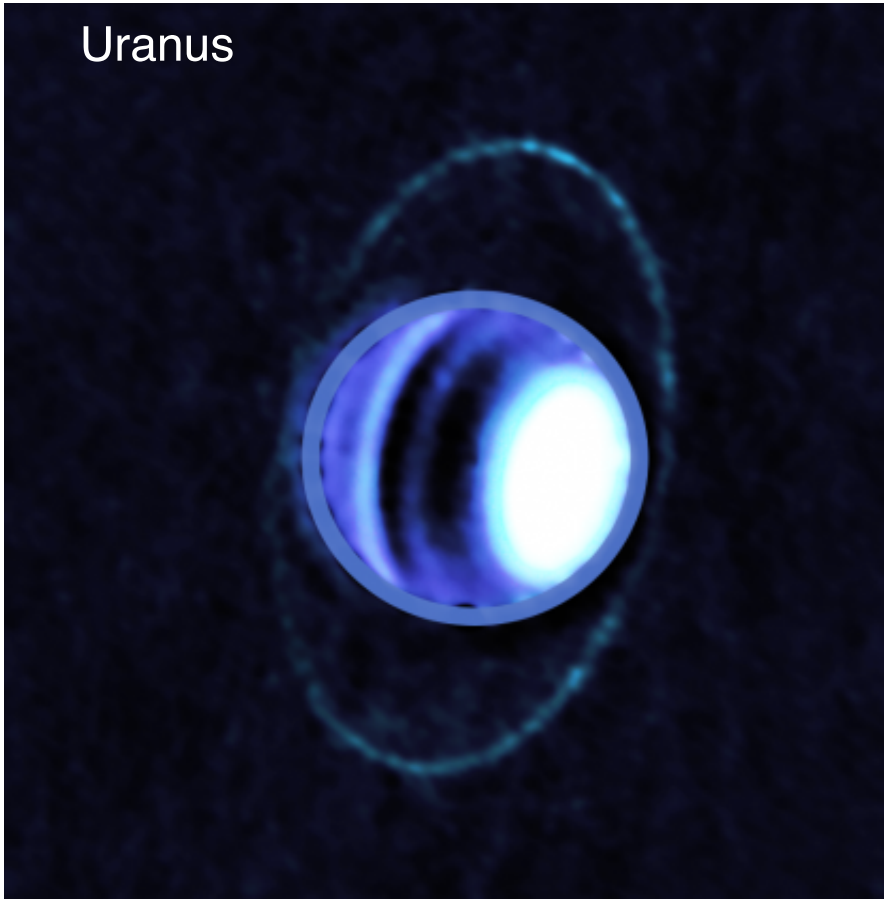
- HD 95086 is a 1.6 M_{sun} A star about 17 Myr years old, 83.8 pc from the Sun
- HD 95086 hosts a directly-imaged ~4M_{Jup} planet about 57 AU from the star
- ALMA has imaged a debris disk outside the planetary orbit
  - The disk is inclined 30^{o}
  - The disk extends from an inner radius ~100 AU to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

ALMA Science Highlights: Solar System

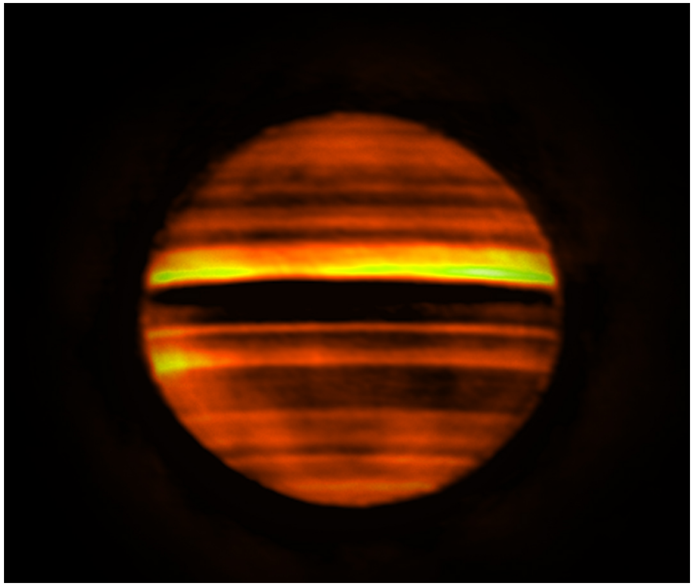
- Thermal emission from the Uranus ε ring shows micron-sized dust is not present in the ring system.
- Confirms the hypothesis, proposed based on radio occultation results (Gresh et al. 1989), that the main rings are composed of centimeter-sized or larger particles
- Temperature of rings: 77+-2K
- The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



arxiv:1905.12566: Molter et al.
arxiv1907.11820: de Pater et al.

ALMA Science Highlights: Solar System

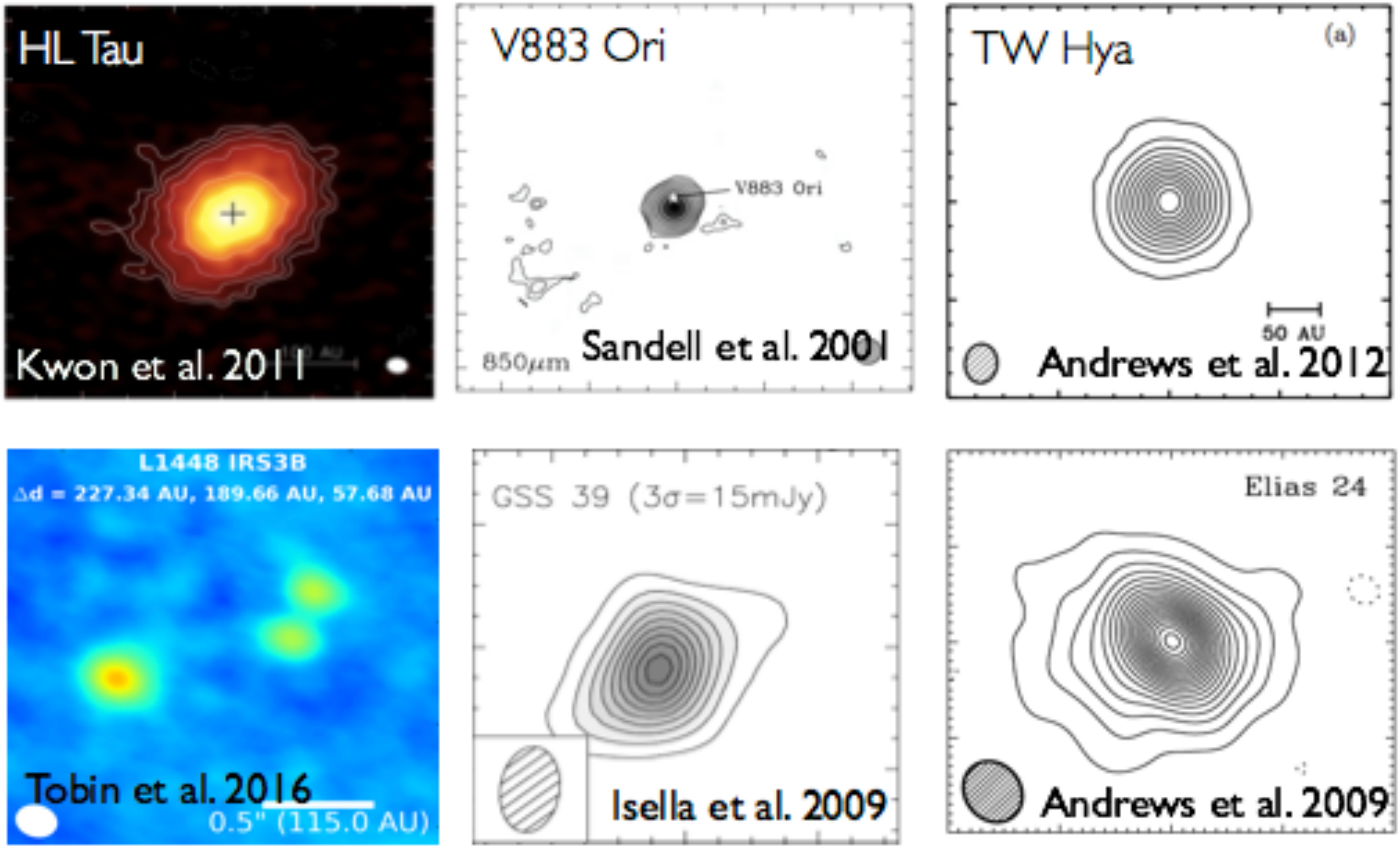
- Jupiter at 1.3mm (mosaic of 17 pointings)
  - NH_3 dominates opacity, so the image can provide its 3 dimensional distribution
  - High brightness indicates lower NH_3 abundance
  - Dark areas indicate higher atmospheric opacity
- Imaged days after an outbreak in the South Equatorial Belt
  - Favored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



de Pater+ arXiv:1907.11820

ALMA Science Highlights: Protoplanetary Disks

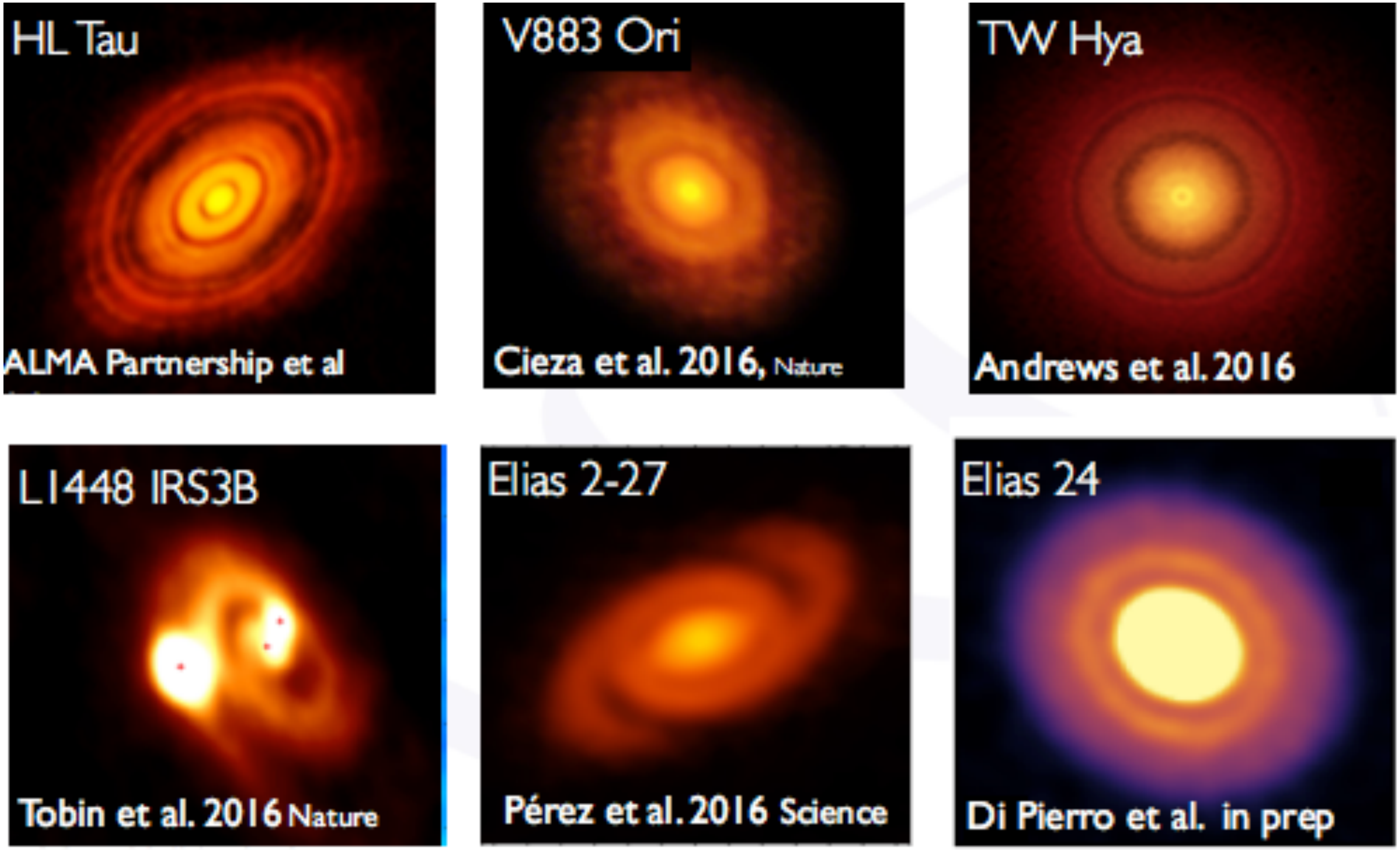
Protoplanetary Disks: Pre- ALMA



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

ALMA Science Highlights: Protoplanetary Disks

Protoplanetary Disks: With ALMA



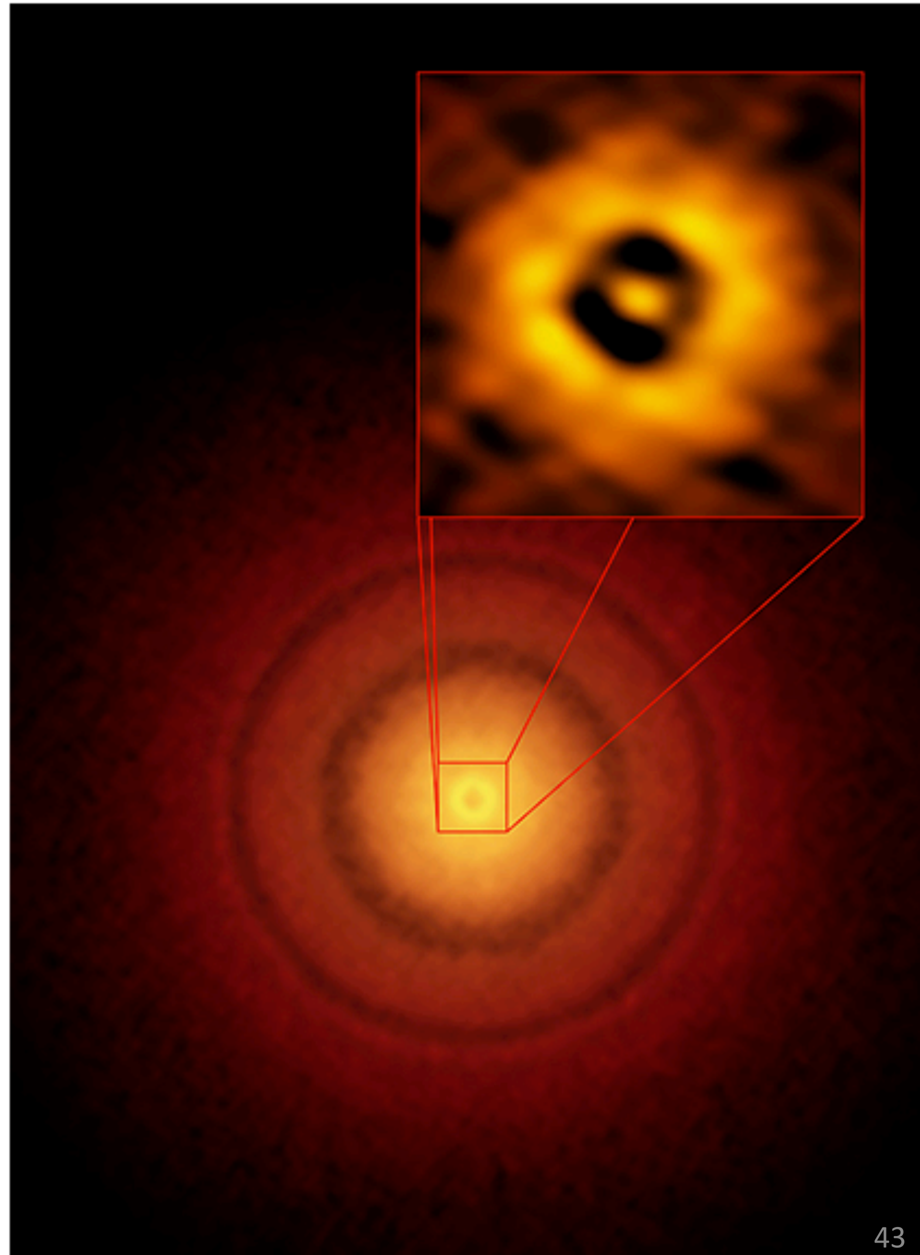
Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

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

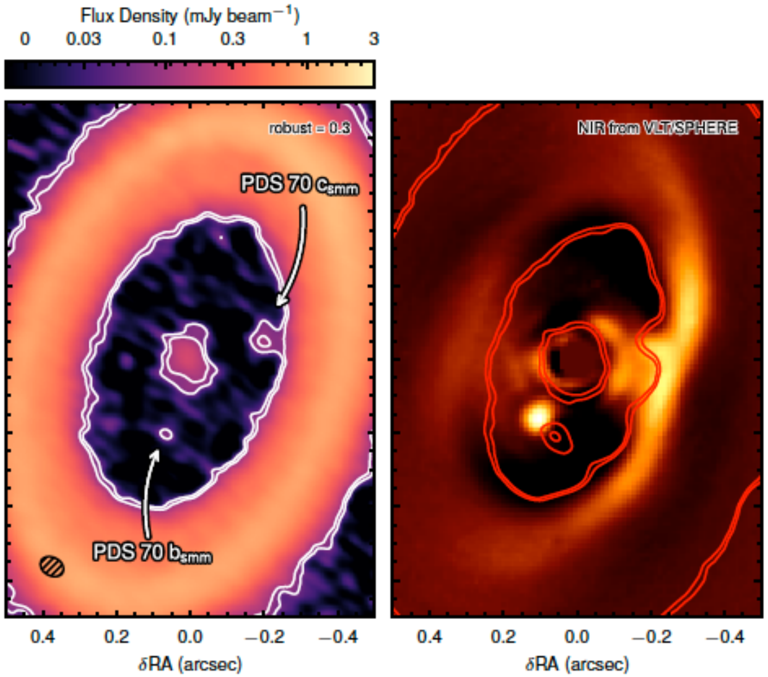


ALMA Science Highlights: Protoplanetary Disks

Circumplanetary Disks

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 Science Highlights: Protoplanetary Disks

Dust Polarization Toward Embedded Protostars in Ophiuchus

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

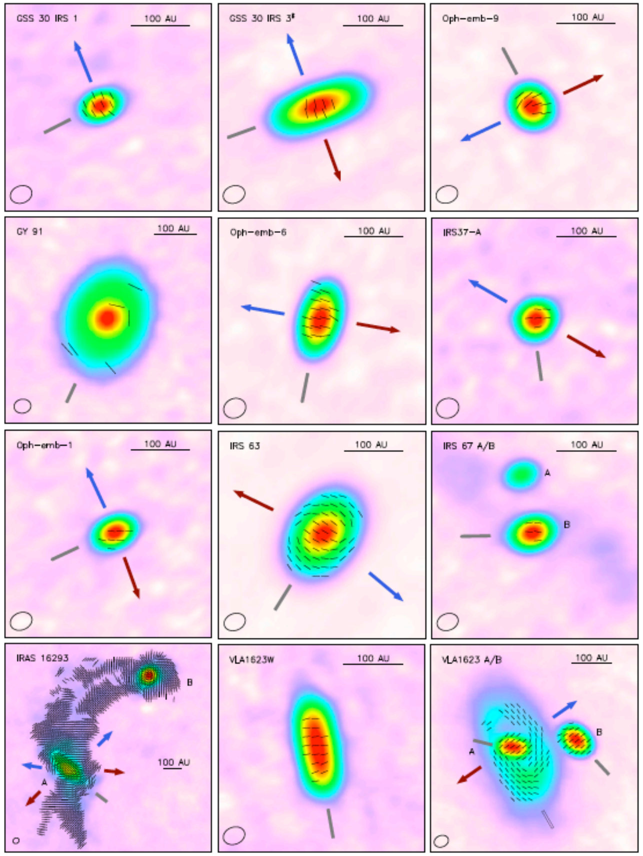
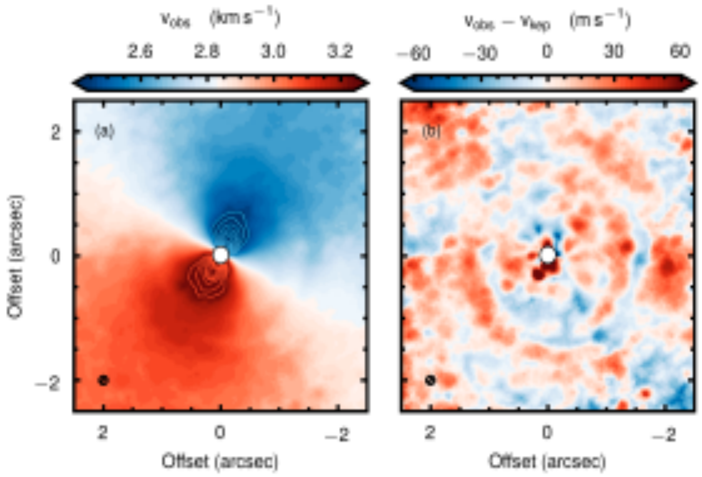


Figure 3. The 14 continuum sources with polarization detections. Background images show the Stokes I maps on a logarithmic color scale (see Appendix A for the flux scale) and the black line segments show the normalized e-vectors. Sources with ‡ are outside of the inner third of the primary beam FWHM.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

ALMA Science Highlights: Planets

Kinematic Detection of Planets in Formation



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

- 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.

ALMA Science Highlights: Galactic Star Formation

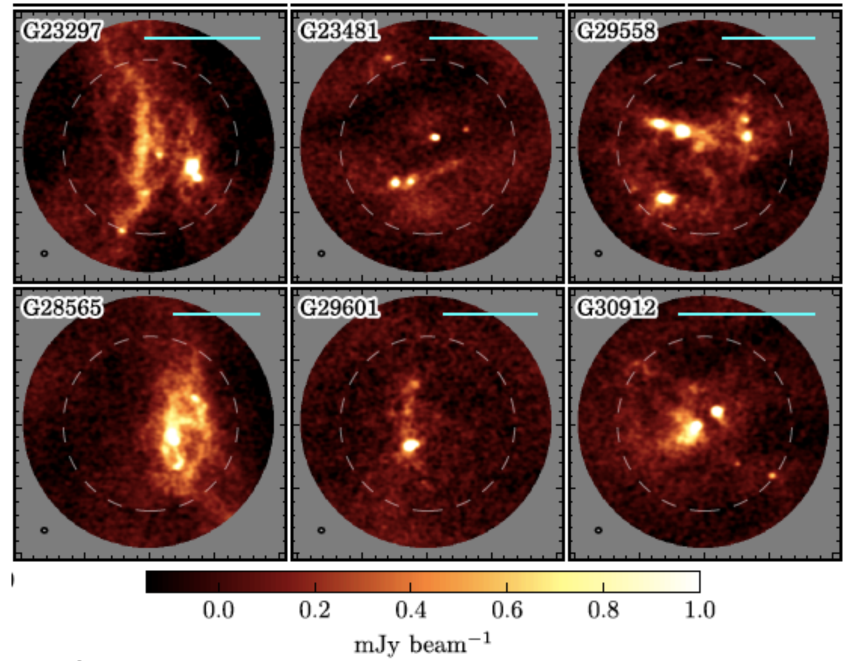
Low Mass Young Stellar Objects in Ophiuchus

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



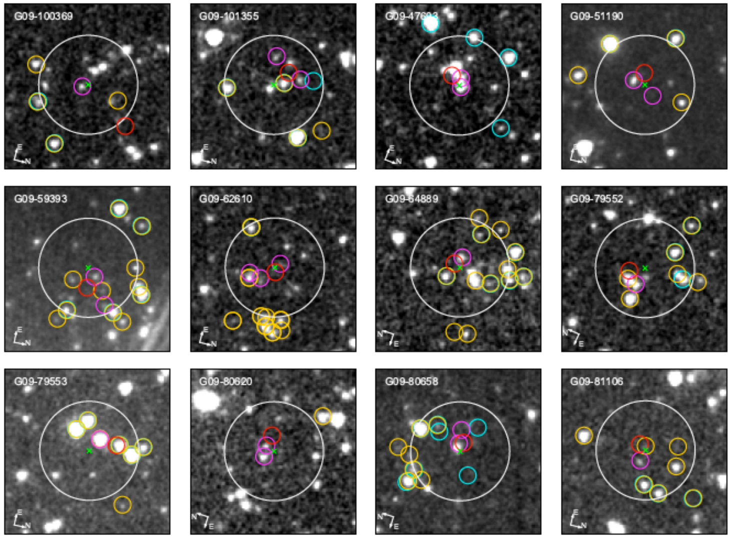
Significant fragmentation at an early stage in massive starless clump candidates suggest hierarchical fragmentation process

Svoboda et al. 2019, ApJ, 886, 36

ALMA Science Highlights: Ultrared dusty, star forming galaxies

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.

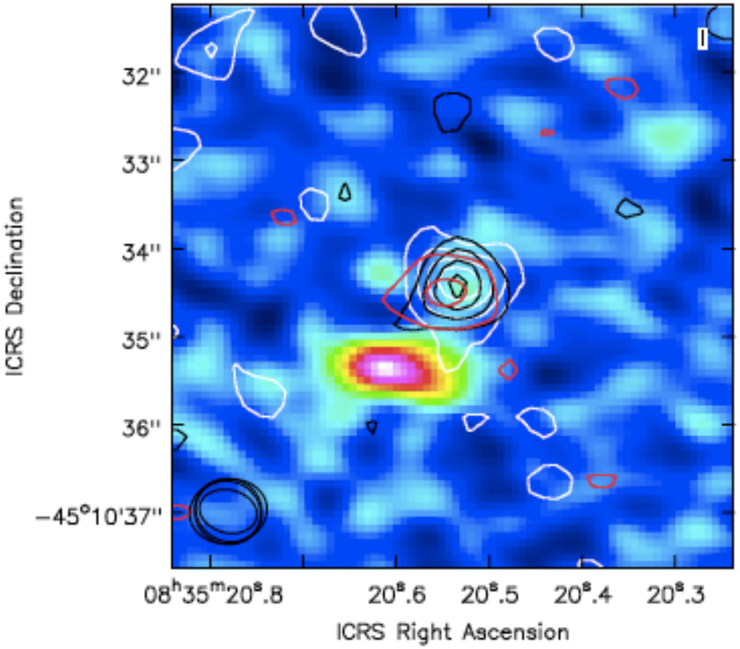


60” x 60” Spitzer/IRAC cutouts centered on the Herschel positions (green cross). Magenta circle show high-resolution positions from ALMA, NOEMA, and/or SMA.

ALMA Science Highlights: Vela Pulsar

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 Highlights: Star Outburst

ALMA Catches, Characterizes Massive Star Outburst

Recent outbursts in YSOs show similar features:

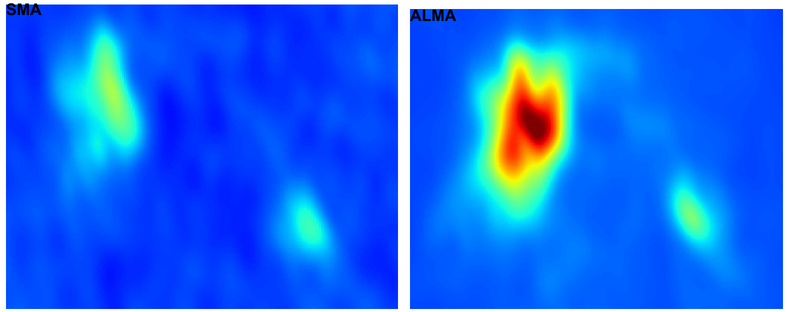
- Factors of 6-70x increase in L
- Sustained for many years (ongoing)

NGC6334I-MM1 dust continuum outburst is accompanied by:

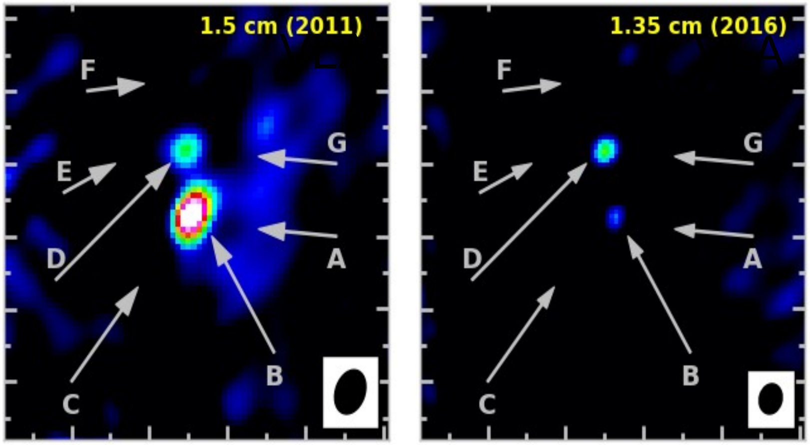
- Dimming of the HCHII region by a factor of 4: suppression of UV photons
- Candidate compact disk/outflow system: disk traced by hot SO_2, outflow traced by $C^{34}S$ and 6 cm jet direction, and maser flare
- **Consistent with a B4 ZAMS star accreting >= 0.1$M_{\odot}$ in a short period.**

Understanding the details requires further monitoring and modeling

Hunter et al. 2017 ApJ 837, L29



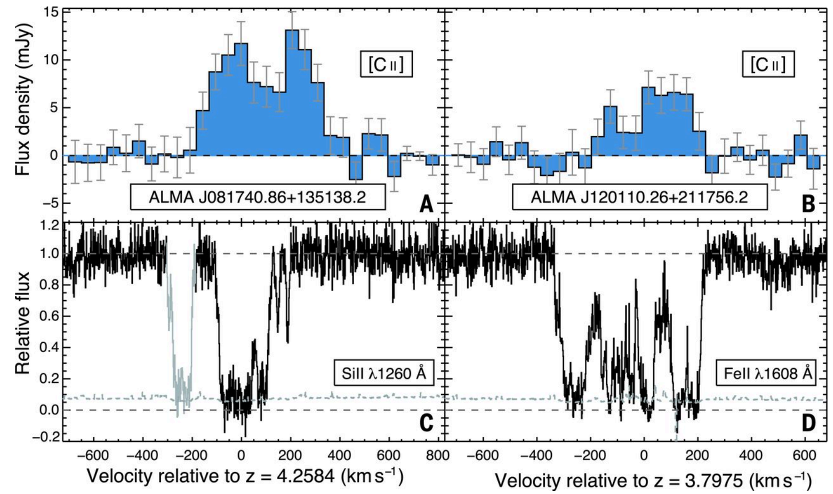
Pre-outburst Post-outburst



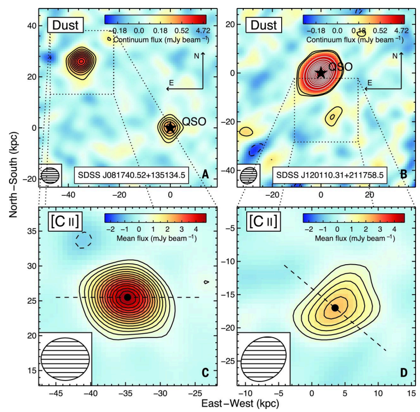
ALMA Science Highlights: Galaxies

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.



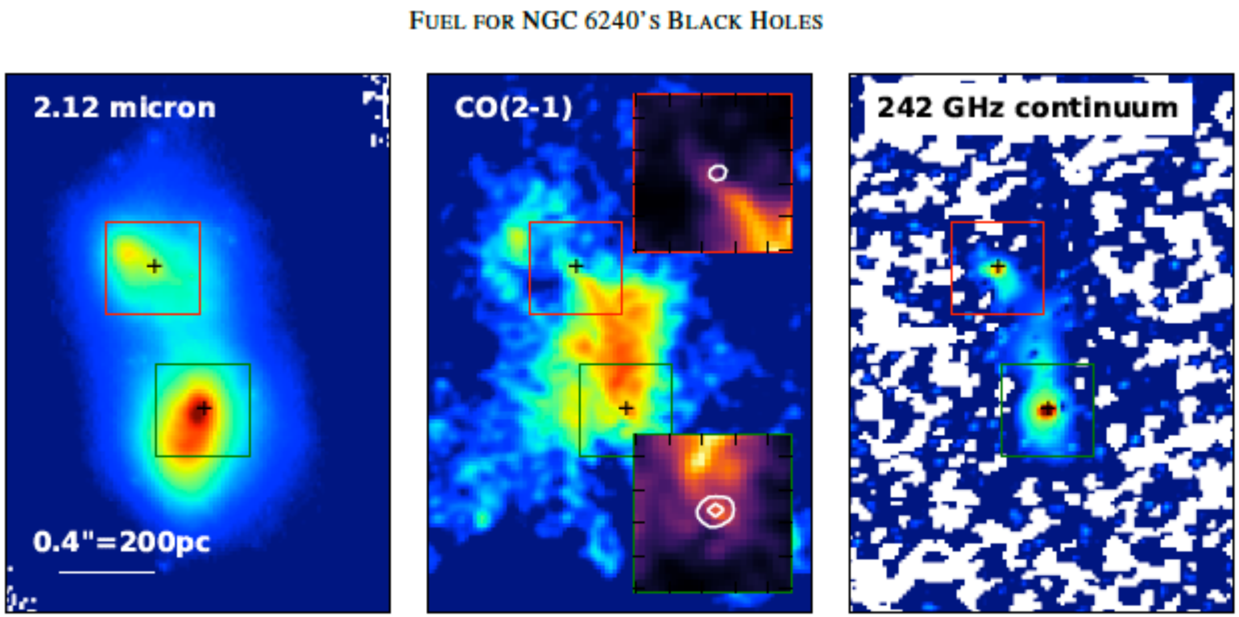
Above: The ≈400-GHz continuum emission near two QSOs (black stars). Axes give the relative physical (proper) distance at the DLA. Below: Mean flux density over the full [C II] 158-μm line profile displayed above. The dashed line is the measured major axis of the galaxy.

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

ALMA Science Highlights: AGN

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

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



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.

- 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.

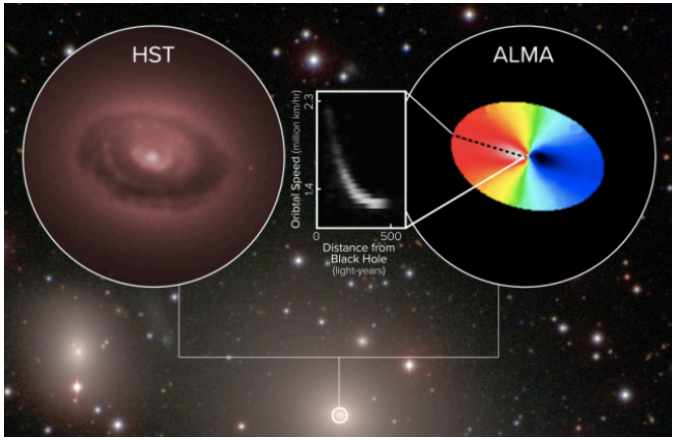
ALMA Science Highlights: AGN

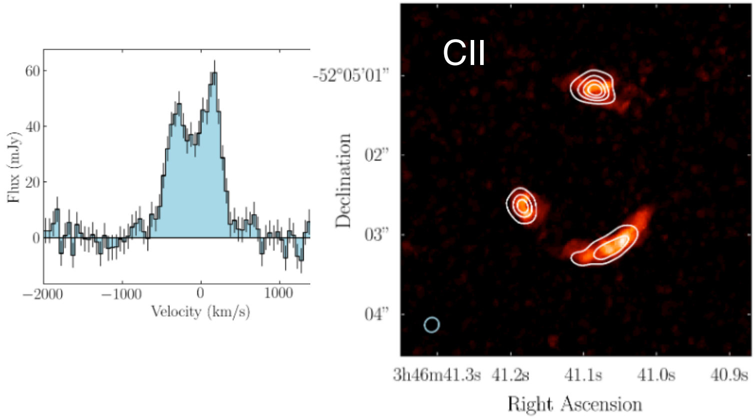
Building Monsters

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

Resolution 0.1” = 150 pc

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





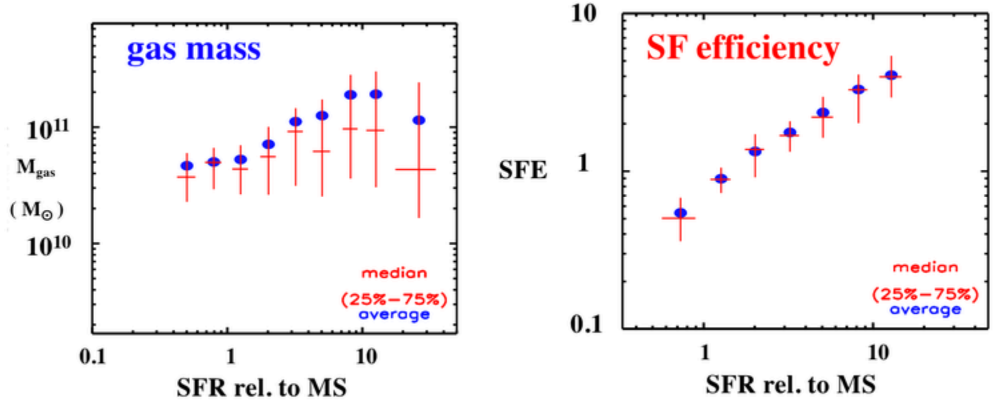
[CII] line in SPT0346-52: A lensed galaxy at z =5.6559 (Wei et al. 2013) undergoing a major merger

- 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 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.**

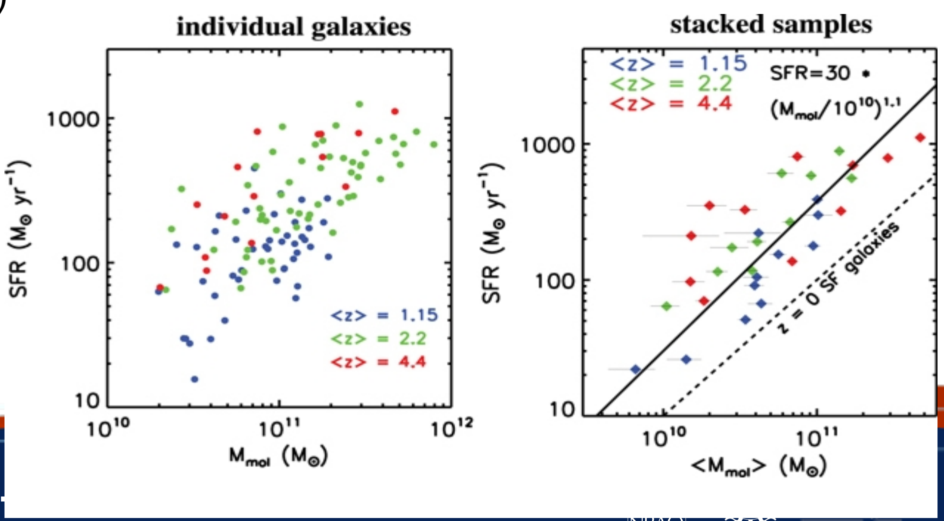


The measured gas masses and star formation efficiencies binned by star formation rate relative to the Main Sequence (MS), with the median for each bin as a horizontal line and the average as a blue circle. An increased rate of star formation per unit gas mass is apparent with increasing distance from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

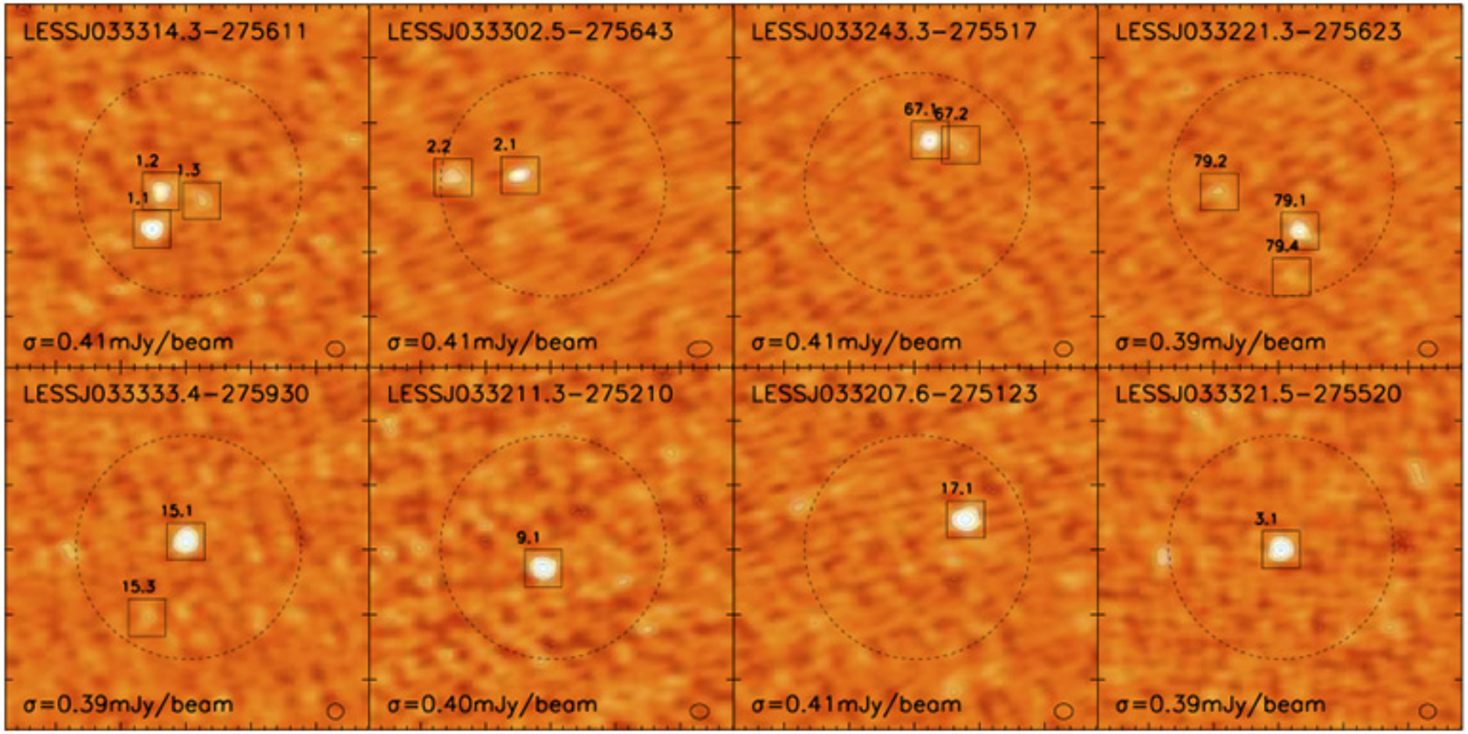
ALMA Science Highlights: Star Formation Peak

- 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

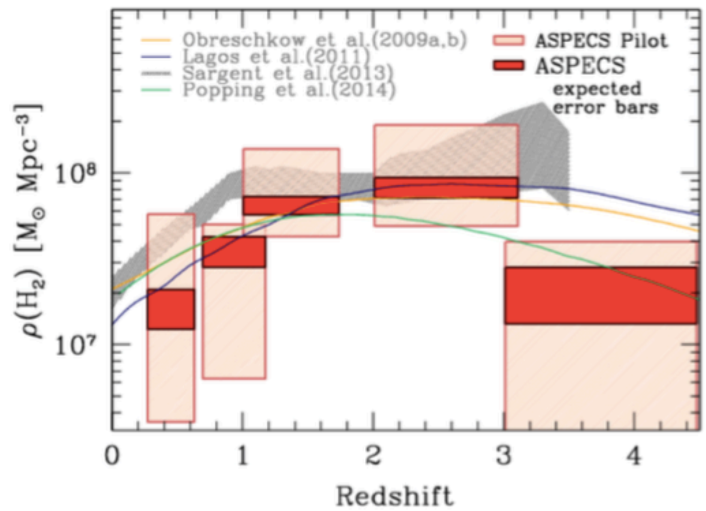


Hodge et al. 2013

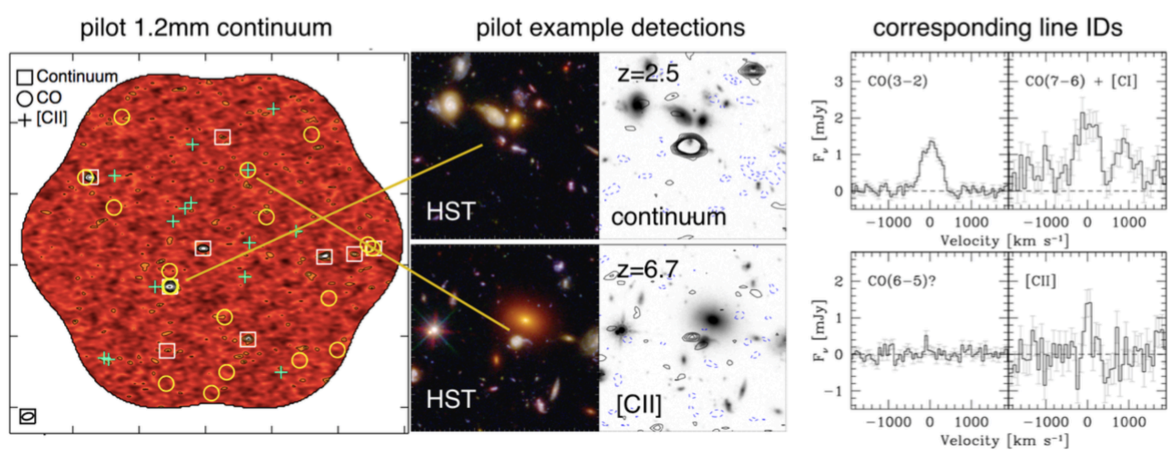
ALMA Science Highlights: the Distant Universe

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)



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

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