ALMA: Imaging Structure Formation from Galaxies to Planets

A. Wootten, on behalf of the ALMA Partnership

Together Toward a More Ambitious ALMA

- Giacconi was a key player in bringing ESO, NSF and NAOJ astronomers and engineers together to define and build ALMA, the most powerful radio astronomy observatory in human history. As such it required harnessing the resources of many nations in order to produce its transformational science.
- Giacconi outlined his scientific vision for ALMA in his remarks at ALMA's Groundbreaking.

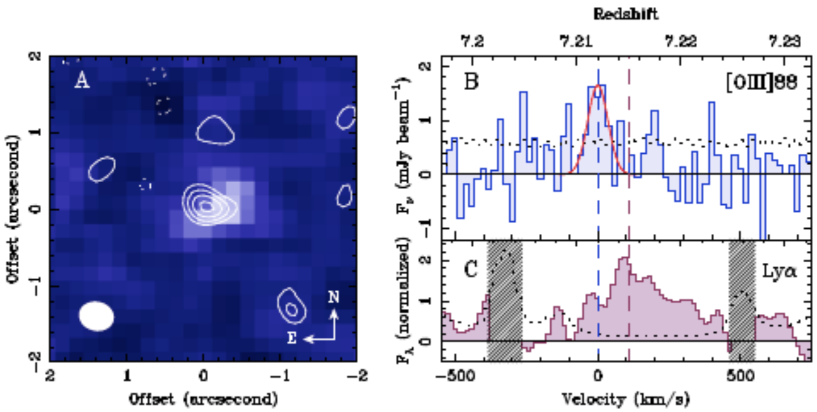
Riccardo Giacconi, President of AUI, noted the great scientific promise of ALMA.

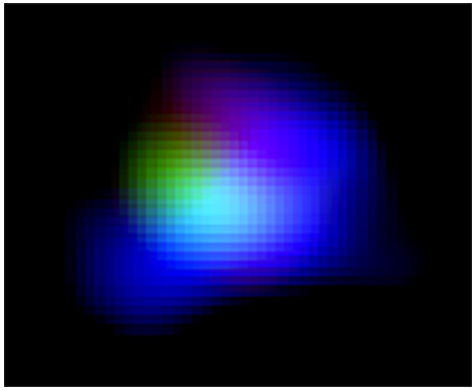
'ALMA will contribute to the all-wavelength attack on the fundamental problems of the origin of the Universe, of development of structures, and possibly of organic life.' -RG

Spectroscopic Evidence of First Metals

- *'ALMA will permit us to study the distant Universe and observe the first seeds of galaxy formation and the subsequent galaxy evolution'*
  - Creation of the Metals, monitored through atomic and molecular lines
  - The first cosmic 'dust'
  - These tracers enable characterization of the development of structures in the early Universe

Inoue+2016

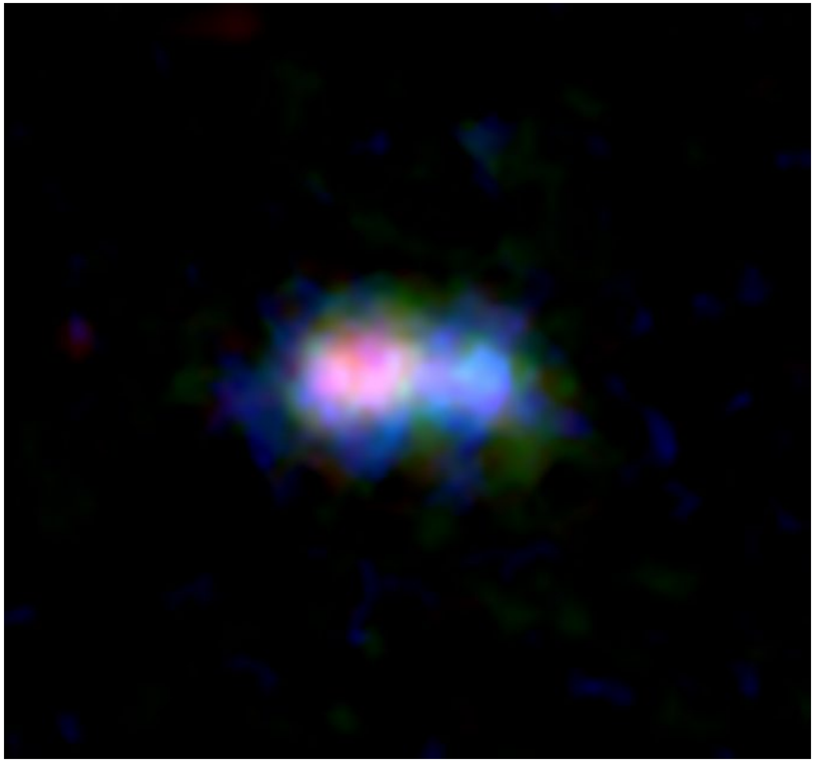
- 



l) [O III] 88μm @z=7.2 in SXDF-NB1006-2 imaged by ALMA r) Green: ALMA [OIII] Blue: Lyα, Red: UV

Metal Enrichment from Ancient Stars

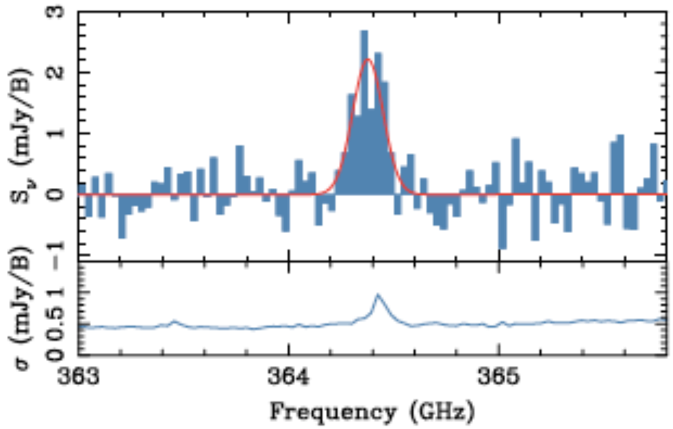
'ALMA will have unsurpassed sensitivity and imaging capabilities for molecular spectroscopic study of external galaxies and will be able to detect the first galaxies formed through their dust emission.'



Credit: ALMA (ESO/NAOJ/NRAO), NASA/ESA Hubble Space Telescope

How and when metal enrichment happened in the epoch of reionization (EoR) is one of the most fundamental questions in modern astronomy.

[OIII] in z=8.3118±0.0003 MACS0416_Y1

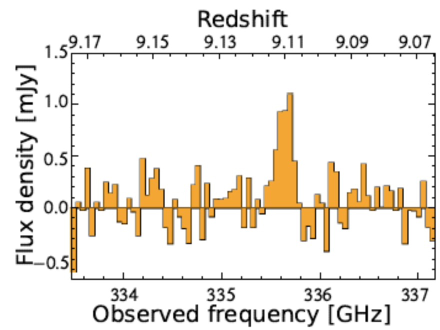


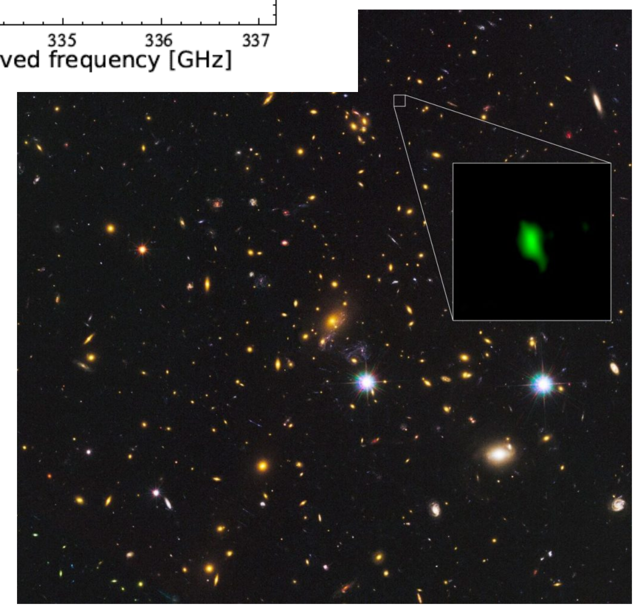
Tamura+ApJ 2019 arXiv:1806.04132

Most Distant Oxygen in the Universe

Hashimoto+ Nature 2018

- Redshift z=9.1096 for [O III] in MACS1149-JD1; universe was only 500 million years old.
- Suggests star formation ongoing there for ~250Myr and that this galaxy formed at z~15.4
- No mm continuum

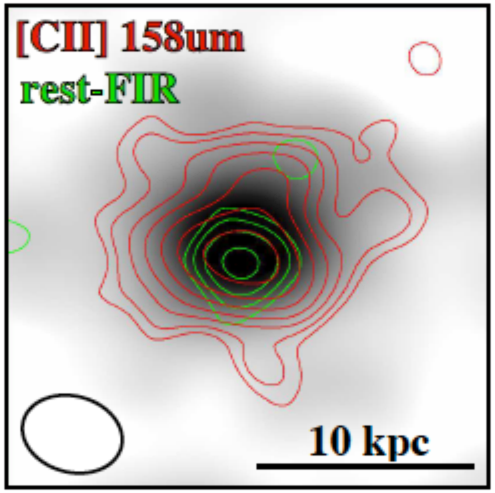




Carbon Halos in Distant Galaxies

Fujimoto+ arxiv:1902.06760

- Deep ALMA data on 18 galaxies each with a star-formation rate of ~10-70 $M_\odot$/yr with no signature of AGN whose [CII] lines are individually detected at z=5.153-7.142
  - Summed image reveals 10-kpc scale [CII] 158um halos (red) surrounding star-forming galaxies in the early Universe significantly more extended than the HST stellar continuum data (greyscale) by a factor of ~5; dust continuum (green) is also seen.
  - This evidences outflow remnants in the early galaxies.
- **ALPINE LP** will measure [CII] & FIR continuum in a sample of 122 main sequence star-forming galaxies spectroscopically confirmed to be at redshifts 4 < z < 6 in COSMOS and ECDFS.



Rest-frame UV emission of the ALMA-HST sample in the HST/H-band 4″ x 4″ image whose resolution is matched to the ALMA image. The red and green contours denote the 2, 2√2, 4, ... Xσ levels of the [Cii] line and the dust continuum emission, respectively. The ALMA synthesized beam is presented at the bottom left.

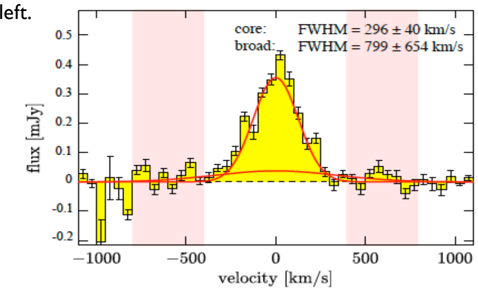


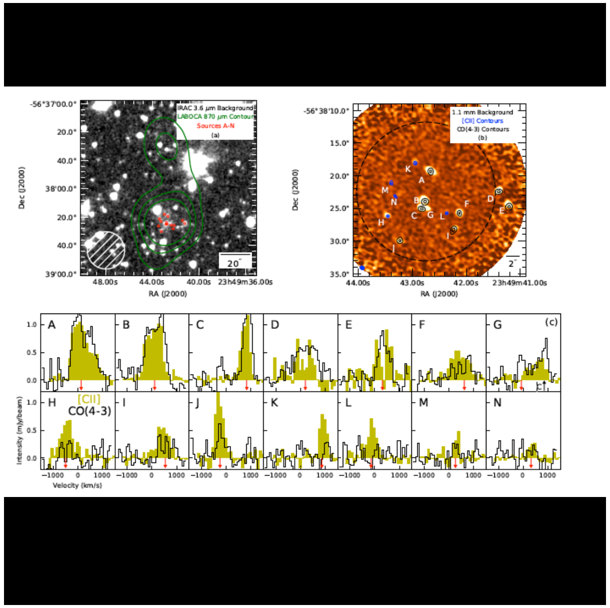
Figure 10. ALMA [C II]-line spectrum averaged over the ALMA-ALL sample. The spectrum is derived with the aperture diameter of 0″.4. The red curves denote the best-fit two (= core + broad) Gaussian component model. The shade regions indicate the velocity ranges in which the velocity-integrated intensity is tentatively detected at the 3.2σ level.

Proto Galaxy Cluster at z=4.3

'We have found that galaxies and clusters of galaxies were formed much earlier than we had thought'

- Dense concentration of 14 galaxies poised to form proto galaxy cluster
  - Seen when Universe was 1.4 by old
  - Individual galaxies form stars as much as 1,000x that in the Milky Way
  - Volume of this group is only 3x that of the present Milky Way galaxy
  - Identified 2010 With NSF's South Pole Telescope, confirmed with APEX, detailed imaging with ALMA

SPT2349-56



Embargoed for release on April 25, 2018 at 1:00 pm

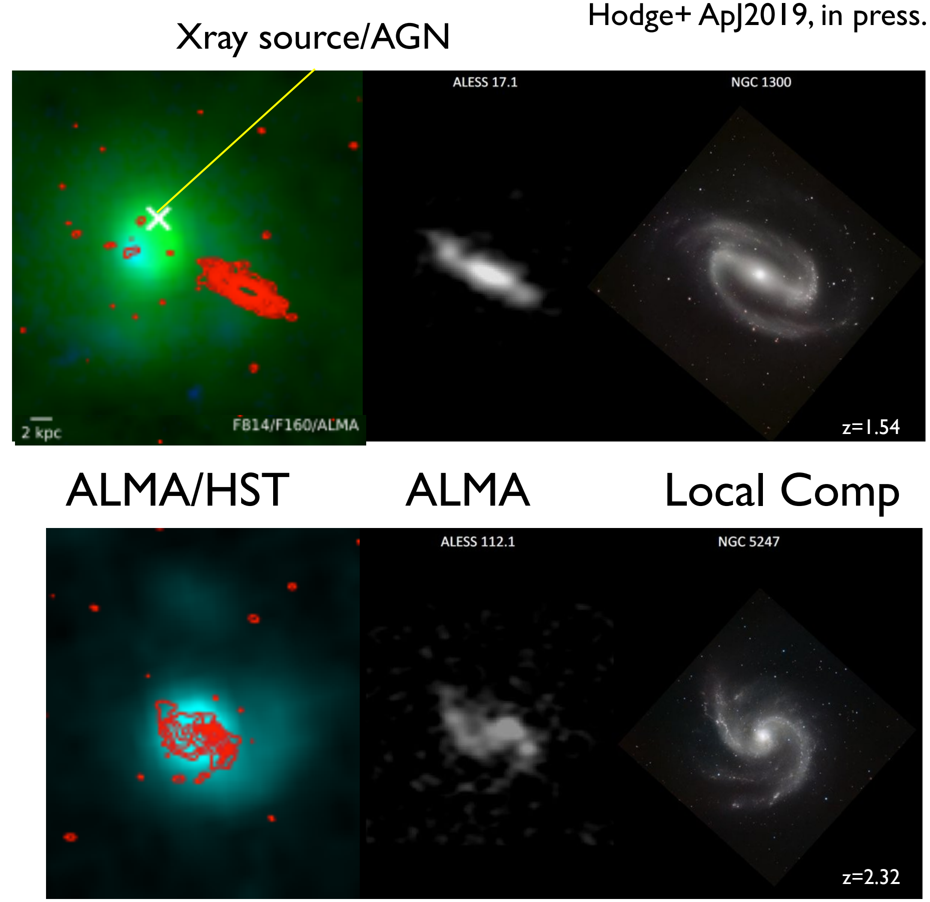
Miller+Nature556, 469 2018

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.



Physics at High Angular resolution in Nearby GalaxieS (PHANGS)

'ALMA will be able to study star formation cores in nearby galaxies and assess the role of morphology and environment in their dynamic and chemical evolution.'

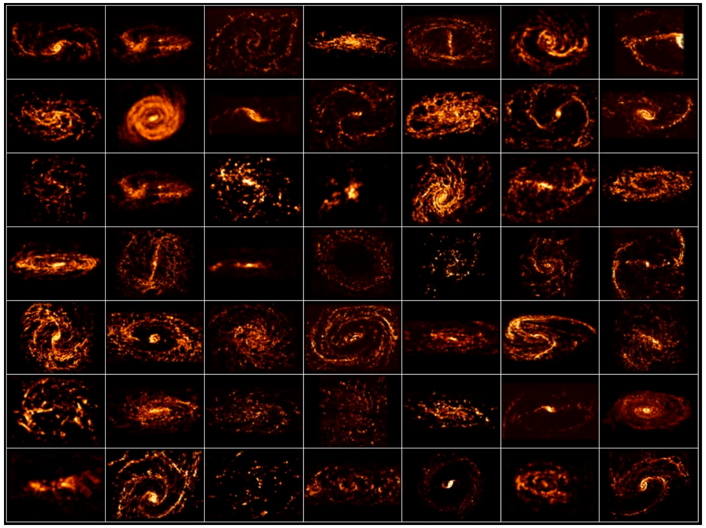
- Why do stars form more efficiently in some galaxies than others?

Why? Observations of100,000 clouds in 74 nearby galaxies are characterized to understand

- How is physics at or near the "cloud" scale affected by galaxy-scale conditions?
- How does this physics affect still smaller scale processes?
- How do these influence the evolution of whole galaxies?

How?
The velocity dispersion, σ, and surface density, Σ, of the molecular gas in nearby galaxies is measured from CO spectral line cubes with spatial resolution 45-120 pc, matched to the size of individual giant molecular clouds.

- Σ, σ, and P_{turb} increase with M, enhanced in central kpc of strongly barred galaxies relative to disks



PHANGS: 3D CO J=2-1 cubes detailing kinematics of 74 molecular galaxies (49 shown here)

Sun+ ApJ**860**, 172 (2018)

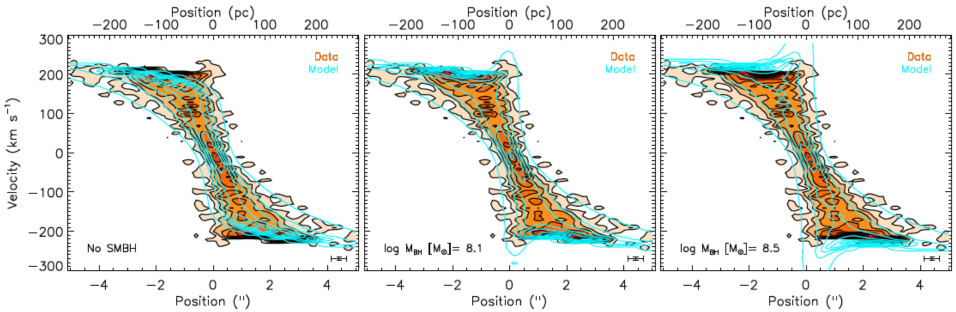
ALMA Measures Black Holes in Galactic Nuclei

'ALMA will offer unique capabilities to study super massive Black Holes in all galaxies including our own with the same angular resolution as the HST. ALMA can resolve the disks fueling the central Black Holes in galaxies as far as Virgo and yield geometry, physical conditions and kinematics of the gas.'

- ALMA is making a major contribution to understanding Black Hole demographics.
  - Through ***better-than HST resolution, of mass-tracing CO emission***
  - ***ALMA sensitively images and resolves massive circumnuclear disks***, the most sensitive probe of kinematics available near galactic nuclei.
  - Need well-behaved targets!

Table 1: ALMA Black Hole Mass Determinations

Source (GHz)	Distance (Mpc)	Resolution (pc)	M_{BH} $M_{\odot}$	Ref
NGC4526	16.4	20	$(4.5^{+4.2}_{-3.1})x10^8$	Davis+13 (CARMA)
NGC1332	22.3	4.8	$(6.64^{+0.65}_{-0.63})x10^8$	Barth+16
NGC 3665	34.7	95	$(5.75^{+1.49}_{-1.18})10^8$	Onishi+17 (CARMA)
NGC 4697	11.4	29	$(1.3^{+0.18}_{-0.17})10^8$	Davis+17
NGC 4429	16.5	13	$(1.5^{+0.15}_{-0.35})10^8$	Davis+18
NGC 0524	23.3	37	$(4.0^{+3.5}_{-2.0}10^8$	Smith+19
NGC 3504	13.6	2.5	$(1.02^{+0.18}_{-0.15})10^7$	Nguyen+19

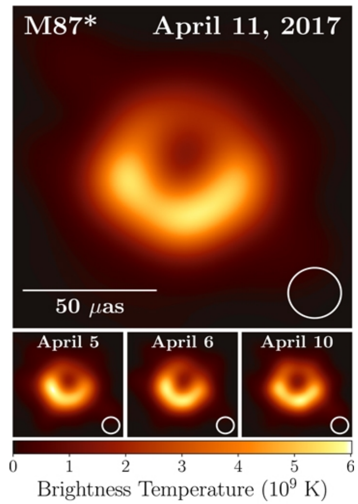


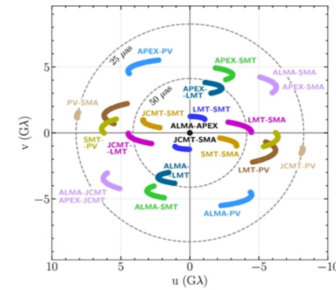
NGC4697:ALMA CO emission (color) compared to PVD Models (blue) differ only by SMBH mass   Davis+MNRAS 468,4675(2017)

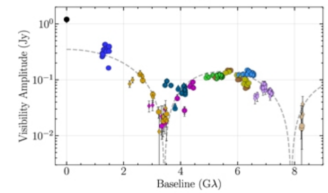
The Shadow of the M87 Supermassive Black Hole

'Finally, if used as the prime component in a worldwide VLBT network, ALMA would allow us to map the structure of active galactic nuclei to a resolution of 10 μarcsec, the highest resolution achievable in astronomy.'

- EHT imaged a dark shadow caused by gravitational light bending and photon capture at the M87 event horizon
- Image: an asymmetric bright emission ring of diameter 42.3 **μ**" roughly circular with a central brightness depression of roughly 10::1 flux ratio
  - Four day's observations show same diameter/width
  - Consistent with general relativity predictions for a Kerr Black Hole of mass 6.5 (+/-0.7) x 10^9 $M_\odot$ similar to other M87 estimates
  - Asymmetry: relativistic beaming of emission from plasma rotating close to the speed of light
- Powerful evidence for galaxy-centered supermassive black holes as central engines of active galactic nuclei

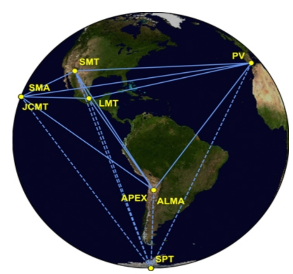






(above l) M87 EHT images. (r) (*u*, *v*) coverage for M87*, aggregated over all four days of the observations (below) The EHT Array: Note M87 is not visible to the SPT, which did not contribute to the image

EVENT HORIZON TELESCOPE COLLABORATION, ApJL 875, 1 (2019)

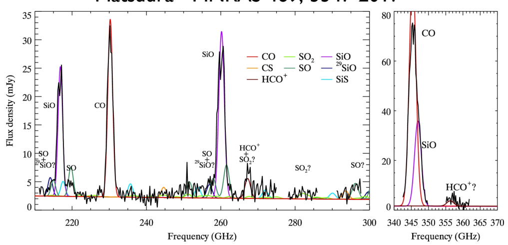


Molecular Emission from SN1987A

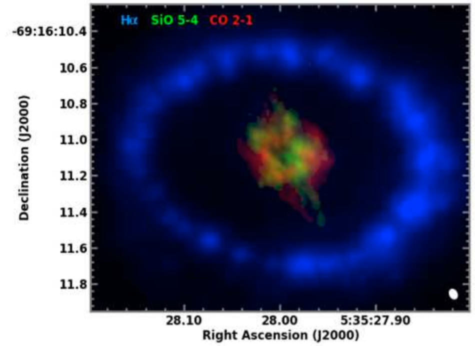
'The siting of ALMA in the southern hemisphere will permit detailed studies of the Large and Small Magellanic Clouds.'

- ALMA spectral survey shows:
  - Cold (20–170 K) CO, ^{28}SiO, HCO^{+} and SO, with weaker lines of ^{29}SiO from ejecta.
  - Low ^{29}Si and ^{30}Si abundances are consistent with nucleosynthetic models that show inefficient formation of neutron-rich isotopes in a low-metallicity environment, such as the Large Magellanic Cloud
- ALMA image shows:
  - Central molecular void, possibly owing to heating by radioactive nickel
  - Cold molecular gas whose 3D distributions differ
    - Clumpy mixed structure seen, as expected from asymmetric explosion but previously unseen
    - Molecules form torus or shell perpendicular to hot equatorial ring (blue on right)
    - SiO has greater extent than CO from the center, therefore non-spherical instabilities occurred

Matsuura+ MNRAS 469, 3347 2017



Abellan+ ApJ 842, 24 2017



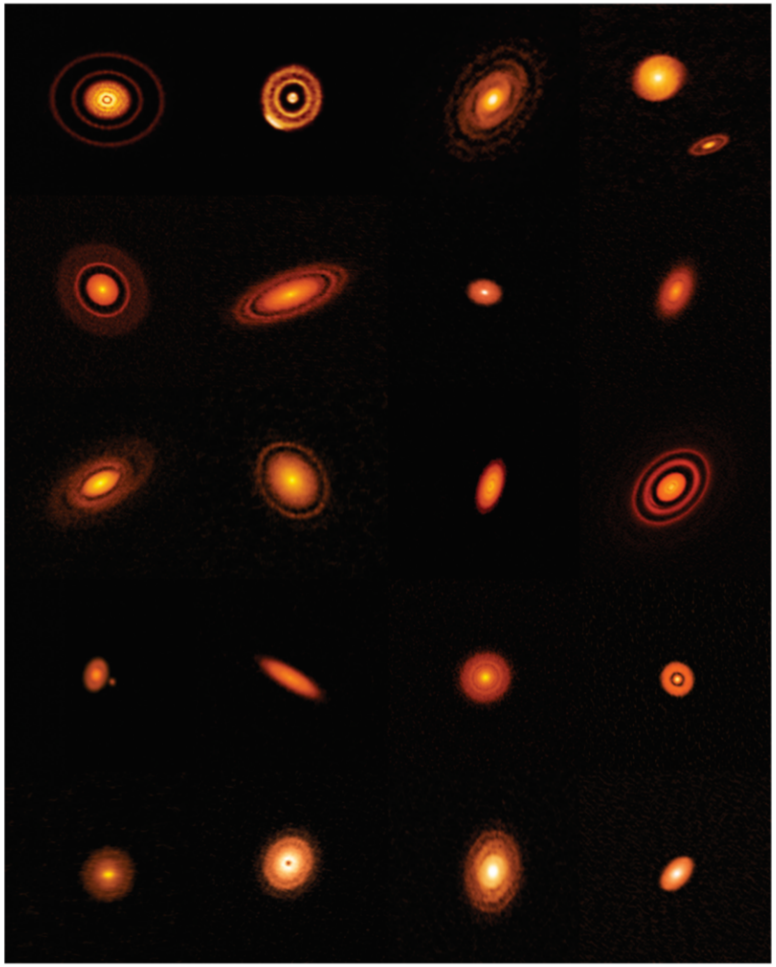
SN1987A: ALMA CO emission in red, SiO in green, hot gas in blue based on data from NASA's Chandra X-ray Observatory.

The Origin of Stars, Planets and Molecular Complexity

'The Study of organic molecules in interstellar space will provide indispensable clues to the origin of life in the Universe.'

DSHARP: Characterize substructures 20 nearby protoplanetary disks at very high resolution (0.035 arcsec, or 5 au FWHM)

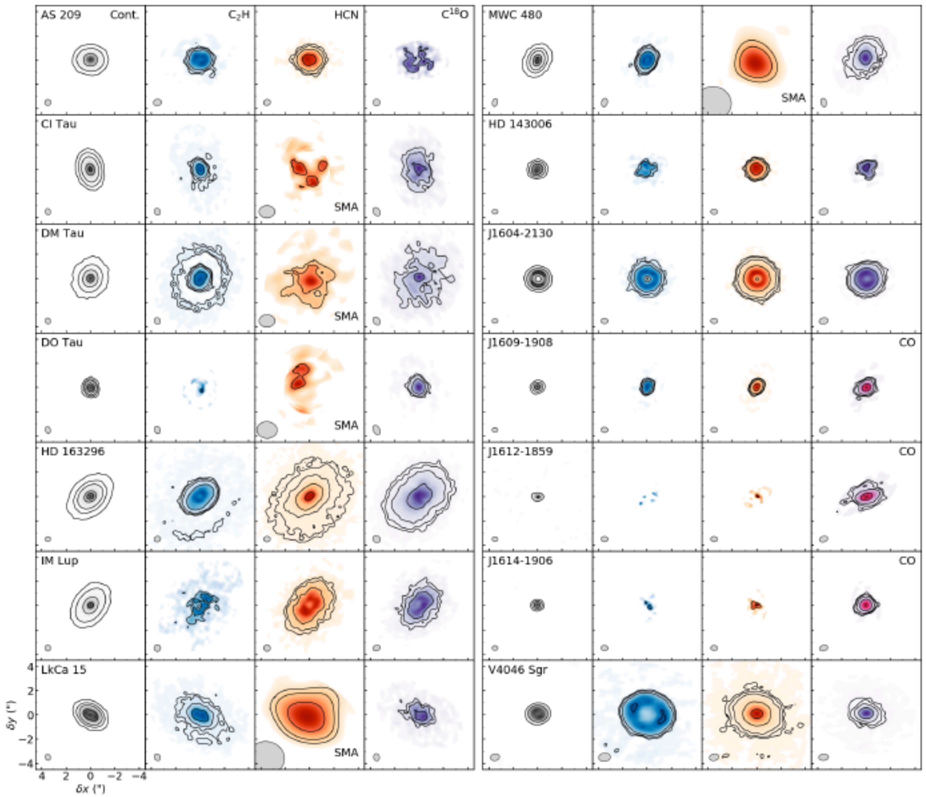
- Substructures ubiquitous in these large, bright disks.
- Most frequently manifested as *concentric, narrow emission rings and depleted gaps*, but also find Large-scale *spiral patterns* and Small arc-shaped *azimuthal asymmetries*



Andrews+ApJ869, L41 (2018)

Organics: C_2H, HCN, and $C^{18}O$ in a Heterogeneous sample of 14 disks

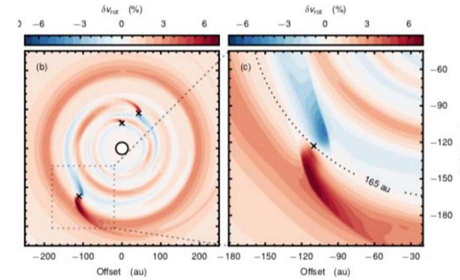
- C_2H and HCN in the inner ~200AU of most disks is moderately optically thick
- Sub-thermal emission suggested in the warm disk atmosphere, and/or beam dilution due to chemical substructure.
- Emission morphologies
  - Explained by the interplay between the local UV fluxes and atomic carbon abundances throughout the disk.
  - Disk-dependent overlap between atomic carbon zones and a high UV flux gives rise to compact vs. extended and ringed vs. ringless C_2H morphologies.
  - Models indicate moderate carbon depletion in the inner 100-200 AU and minimal carbon depletion at larger radii.



Bergner+ arxiv:1904.09315

Kinematic Detection of Planets in Formation

- CO images used by Teague+ to kinematically detect two embedded protoplanets in HD163296
  - Rotation curves betray substantial deviations caused by local radial pressure gradient perturbations ('wake')
  - Likely driven by gaps carved in gas surface density by Jovian mass planets
  - Modeling suggests two such planets, a 1 M_{Jup} planet at 83 au, and 1.3 M_{Jup} planet at 137 au.
- Pinte+ note local deviation between ^{12}CO J=2-1 *and* J=3-2 line data vs Keplerian velocity suggesting a 2 M_{Jup} planet at ~260 au.



(l) δvrot due to changes in local pressure. (r) A zoom in of the δvrot structure at the location of the outer planet. (**Teague+ arXiv:1805.10290**)

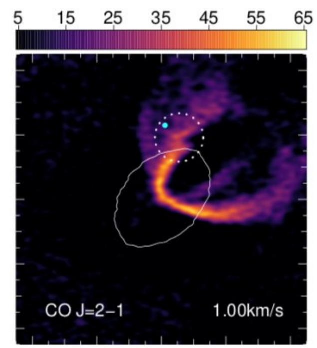
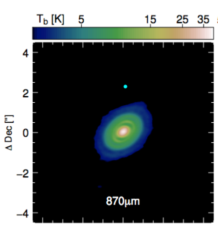


Image of ^{12}CO line emission at +1km s^{-1} from the systemic velocity shows a 'kink', the kinematic disturbance caused by a planet **(Pinte+ arXiv:1805.10293**)

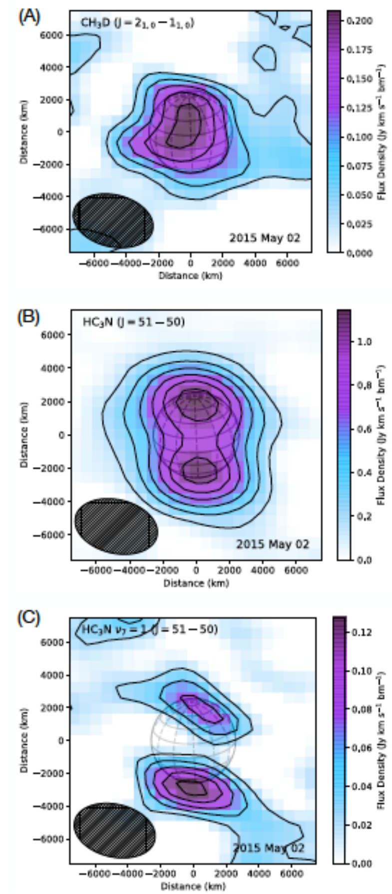


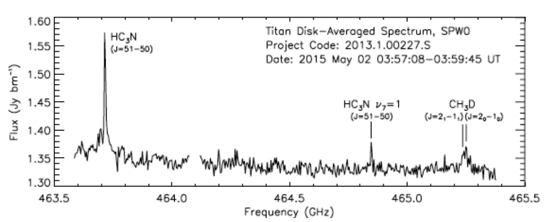
Dust image showing rings and Pinte+ planet candidate

Imaging Titan's Atmosphere

Thelen+AJ157, 219 (2019)

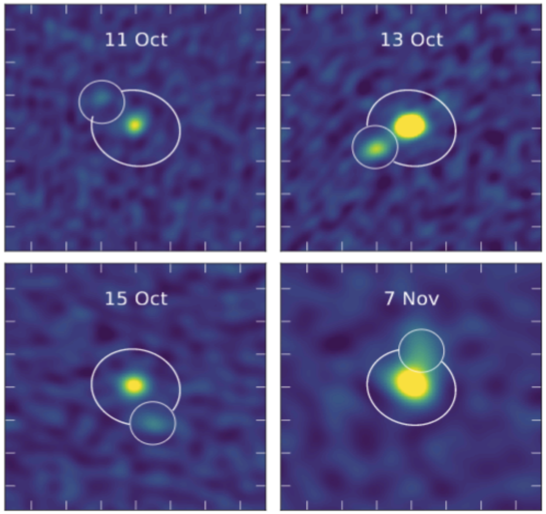
- CH_4: a primary constituent of Titan's atmosphere lacks mm lines which CH_3D possesses
  - CH_3D is detected by ALMA
  - D/H in CH_4 is ~ 10^{-4}
- ALMA data comparable to *Cassini-Huygens* CH_4 measurements
  - ALMA can make similar spatial resolution measurements to *C-H*
  - ALMA may enable measurement of latitudinal distribution of methane





Kuiper Belt Objects and their Moons

- Kuiper Belt objects provide the most direct information on physical conditions in the forming Solar nebula. ALMA is playing a crucial role role in determining the size and composition of dwarf planets in the Kuiper belt, and their moons.
- ALMA has imaged at 350GHz the KBO – moon systems: Orcus and Vanth, and Eris and Dysnomia, revealing orbital motions and determining the moon sizes (475 km and 700 km, respectively) and albedos. The results imply the moons have similar properties to other KBOs of comparable size.
- The results argue strongly against moons formed from an icy disk generated during a major collision. Moon capture, or co-formation of moon and planet, are more plausible models.



ALMA 350GHz observations of the Kuiper Belt dwarf planet Orcus, and its moon, Vanth. The images are centered on Orcus and the predicted position of Vanth is circled. Tick marks in the images are 200 mas

Brown&Butler, AJ154, 164 (2018)

Summary

- ALMA's international partnership* has succeeded in detailing Giacconi's scientific vision for ALMA as expressed in his remarks at ALMA's 2003 Groundbreaking.

*(ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan) and KASI (Republic of Korea), in cooperation with the Republic of Chile)

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