Formation, Detection and the Distribution of Complex Organic Molecules with the Atacama Large Millimeter/submillimeter Array (ALMA)

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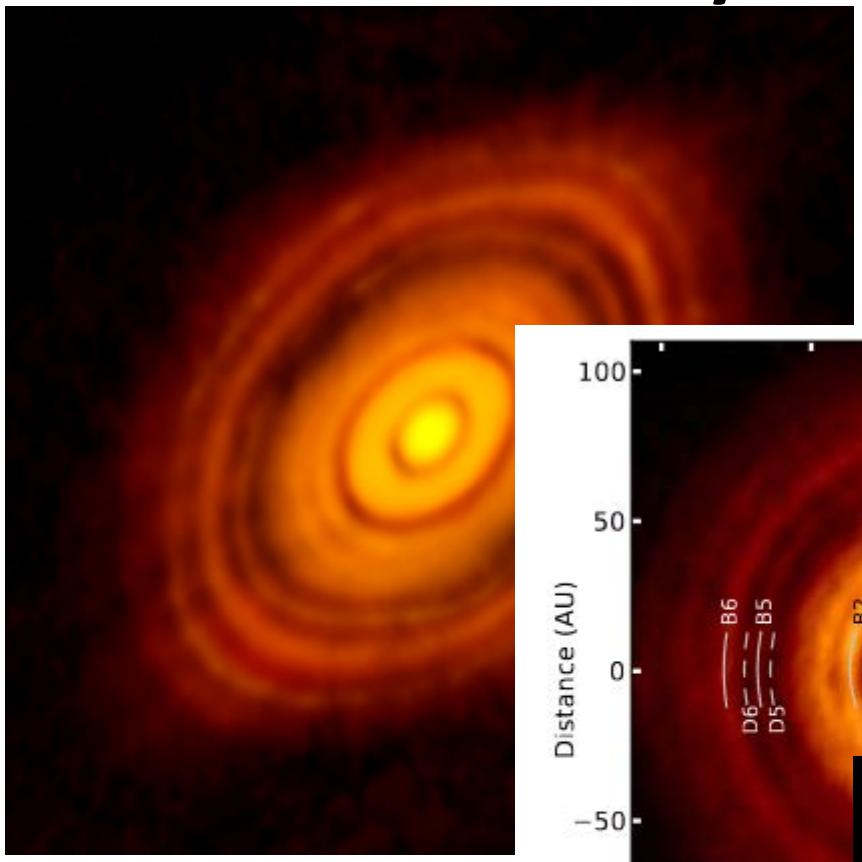
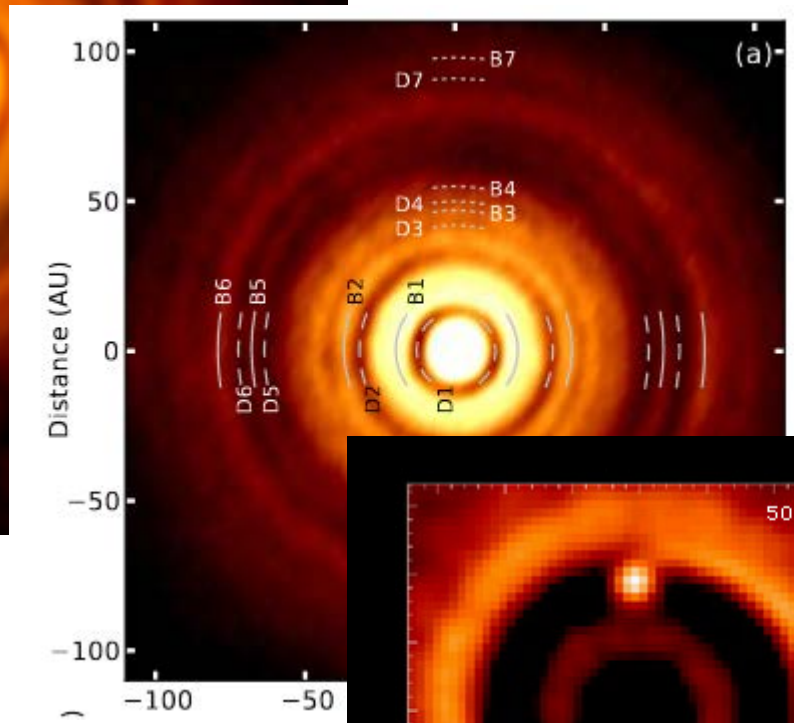
Joint ALMA Observatory – National Radio Astronomy Observatory

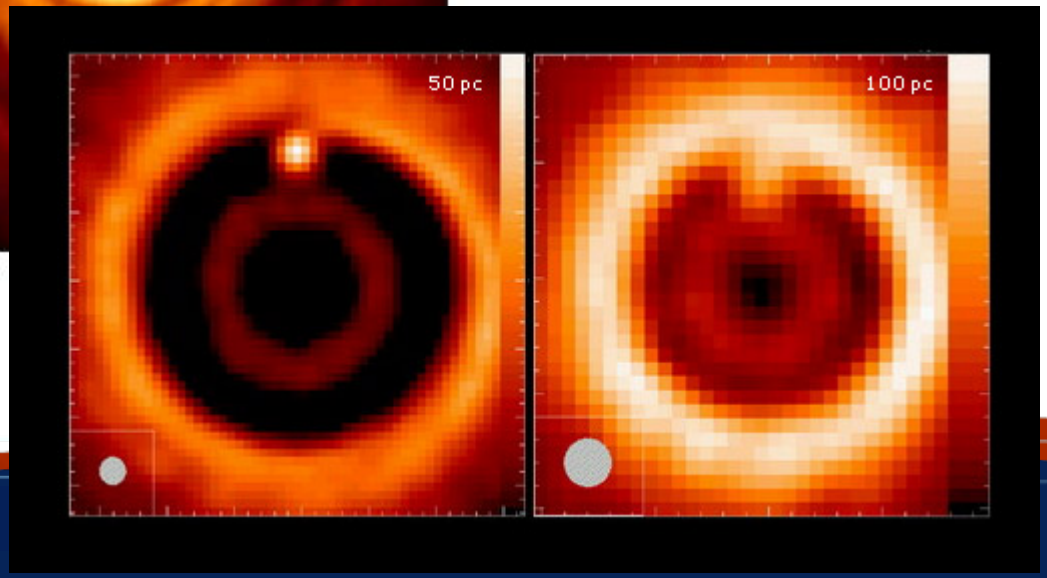
Overview

- Why imaging? What do we learn?
- State of the art imaging of capabilities before ALMA
- Newest ALMA results!
- What does the future hold for interferometric imaging of complex molecules?

Power of Many Long Baselines: HL Tau







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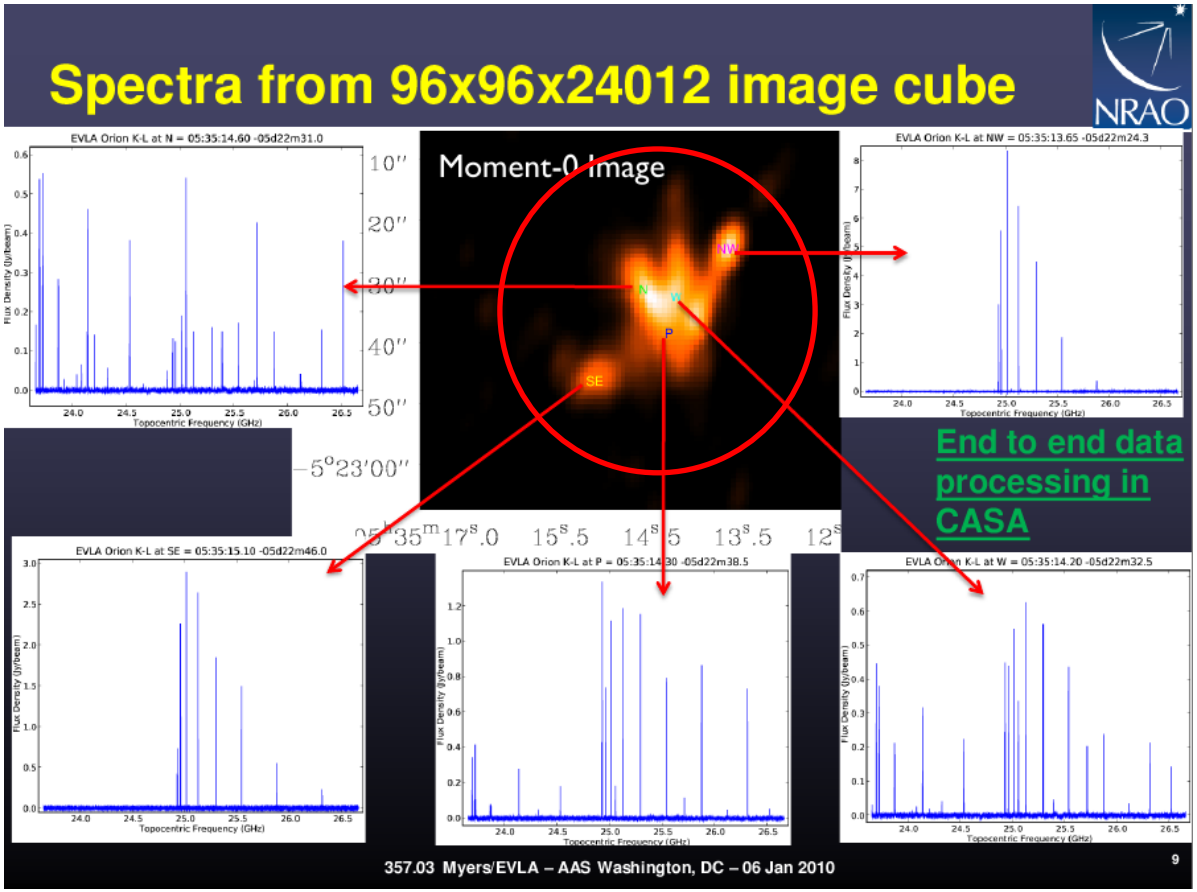
“Why Mapping?” (aren’t spectra good enough?)



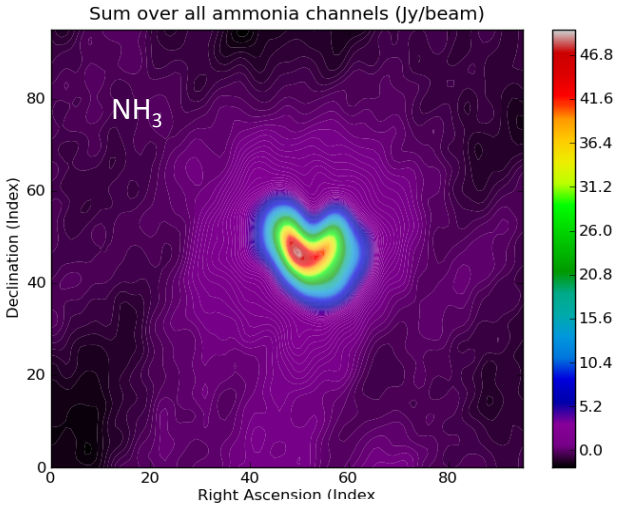
EVLA Demonstration Science
Orion KL, 3100 MHz Bandwidth

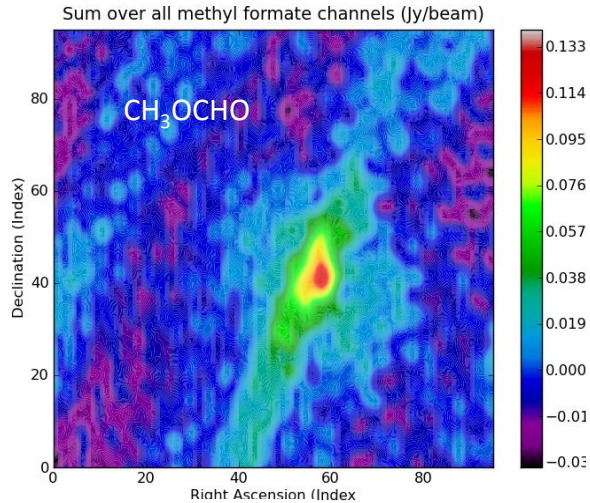
What molecules are present?
Spectrum identification by broadband rotational spectroscopy (Mixture Analysis)

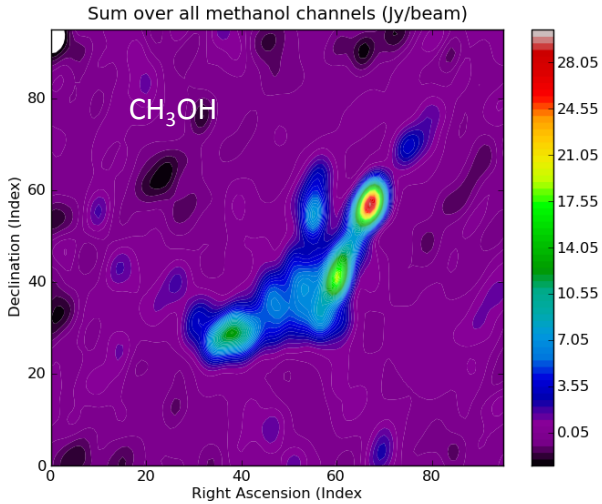
What are their “concentrations”?
Analysis of the intensity profile to determine the physical parameters

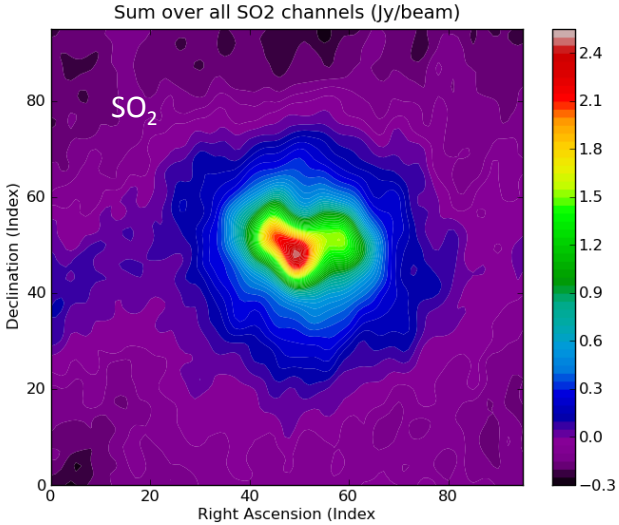
The ability to make “chemical images”
Images that examine the correlations of molecular column densities

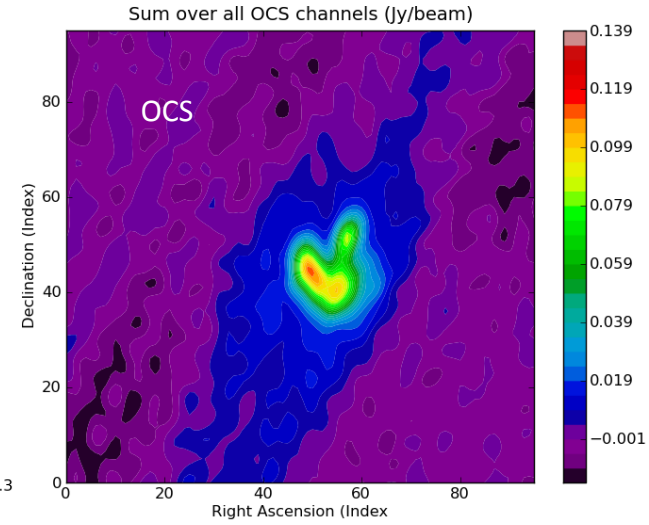
2D Line Assignments



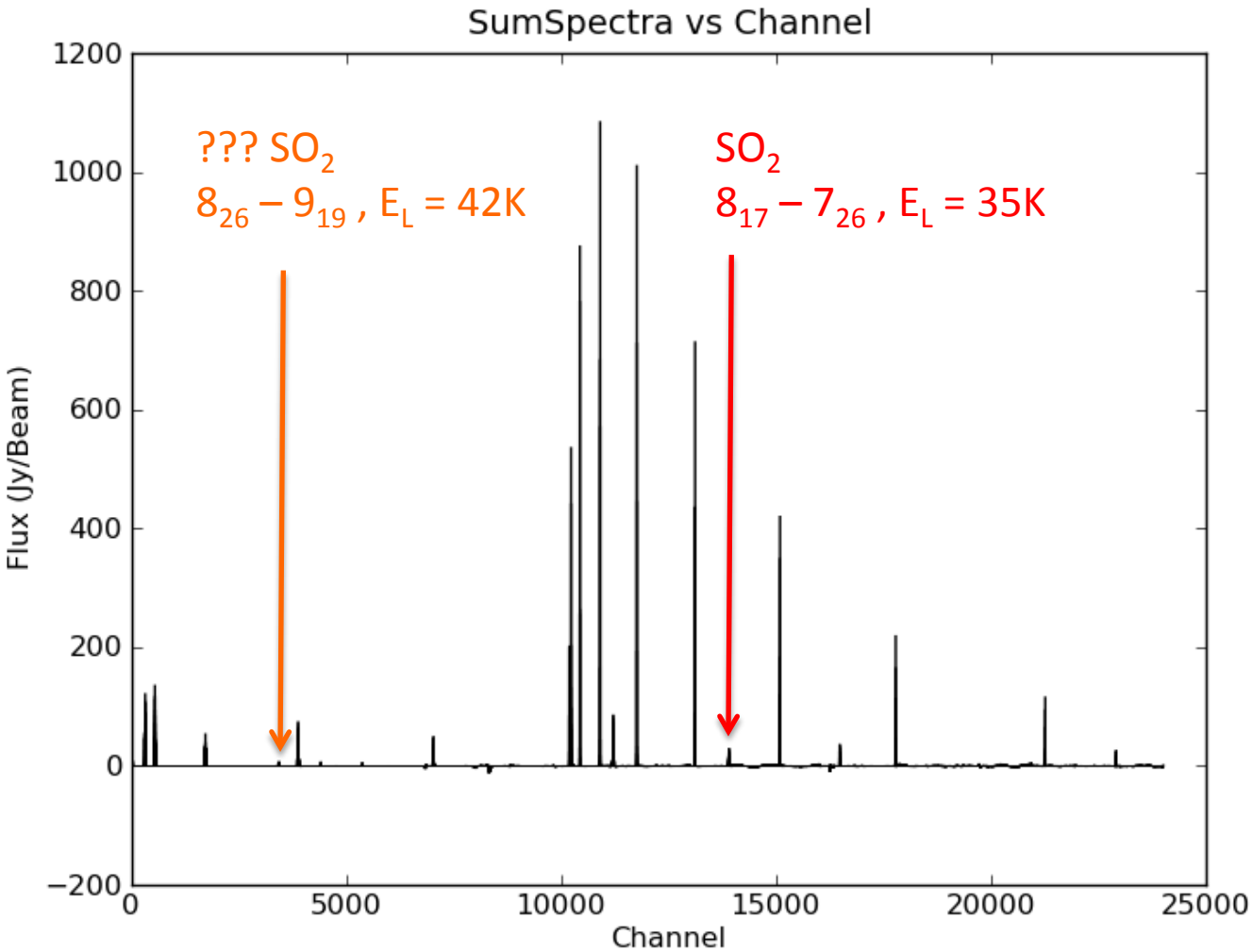








SO_2 Assignment



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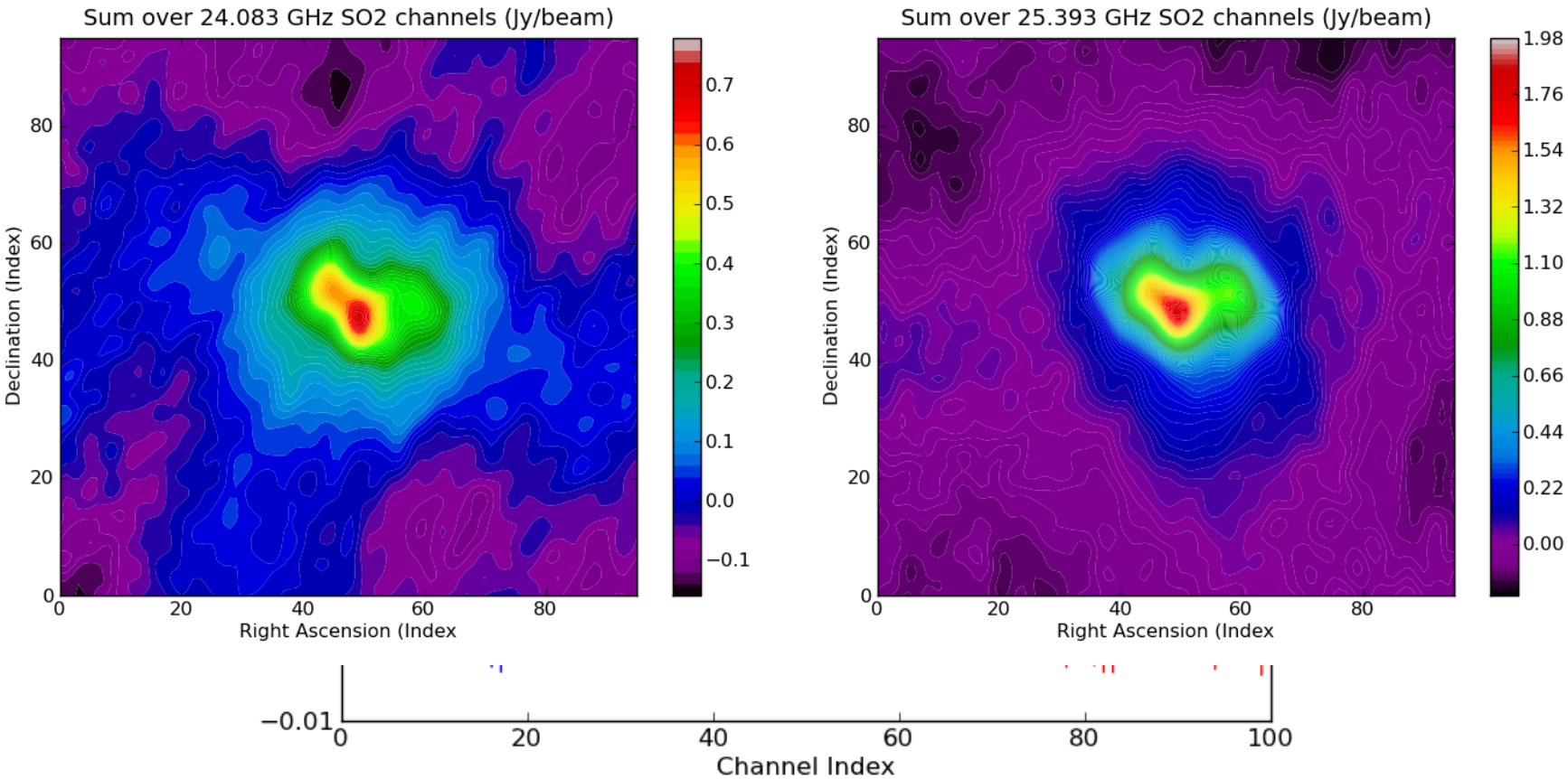

Image correlation provides further confidence in assignment

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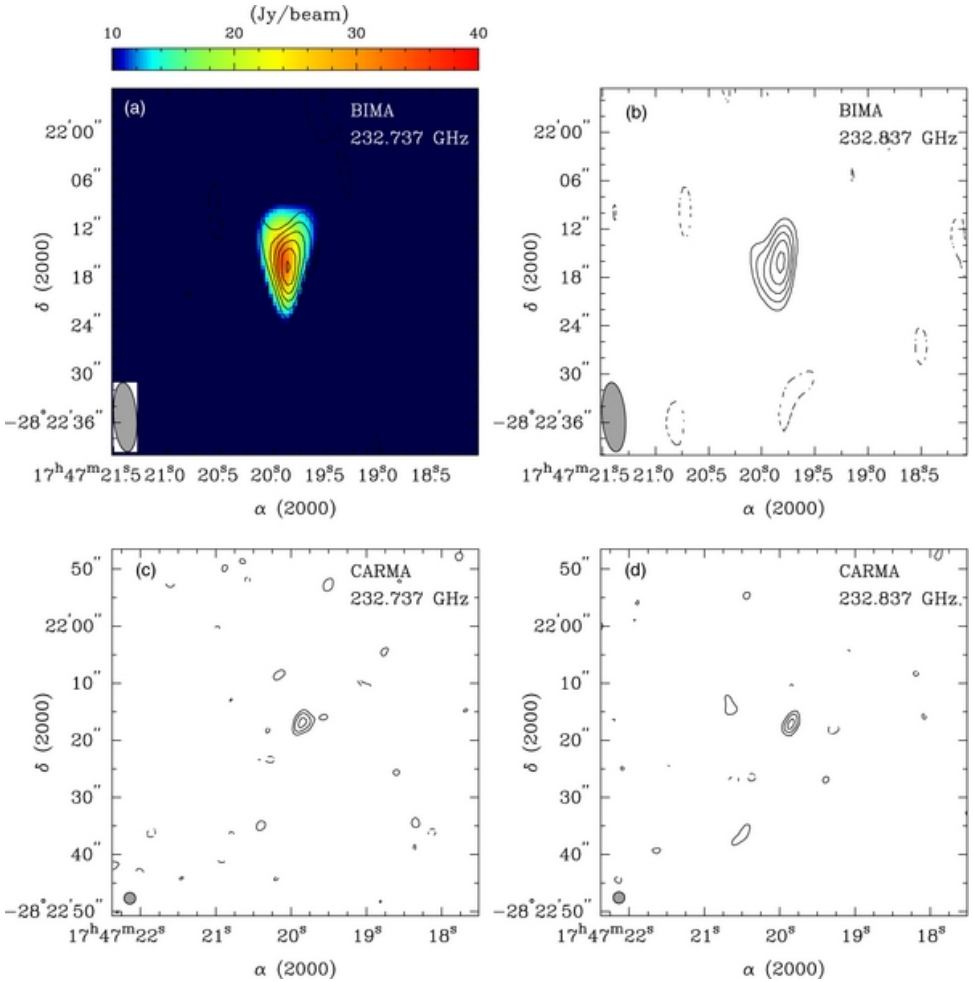
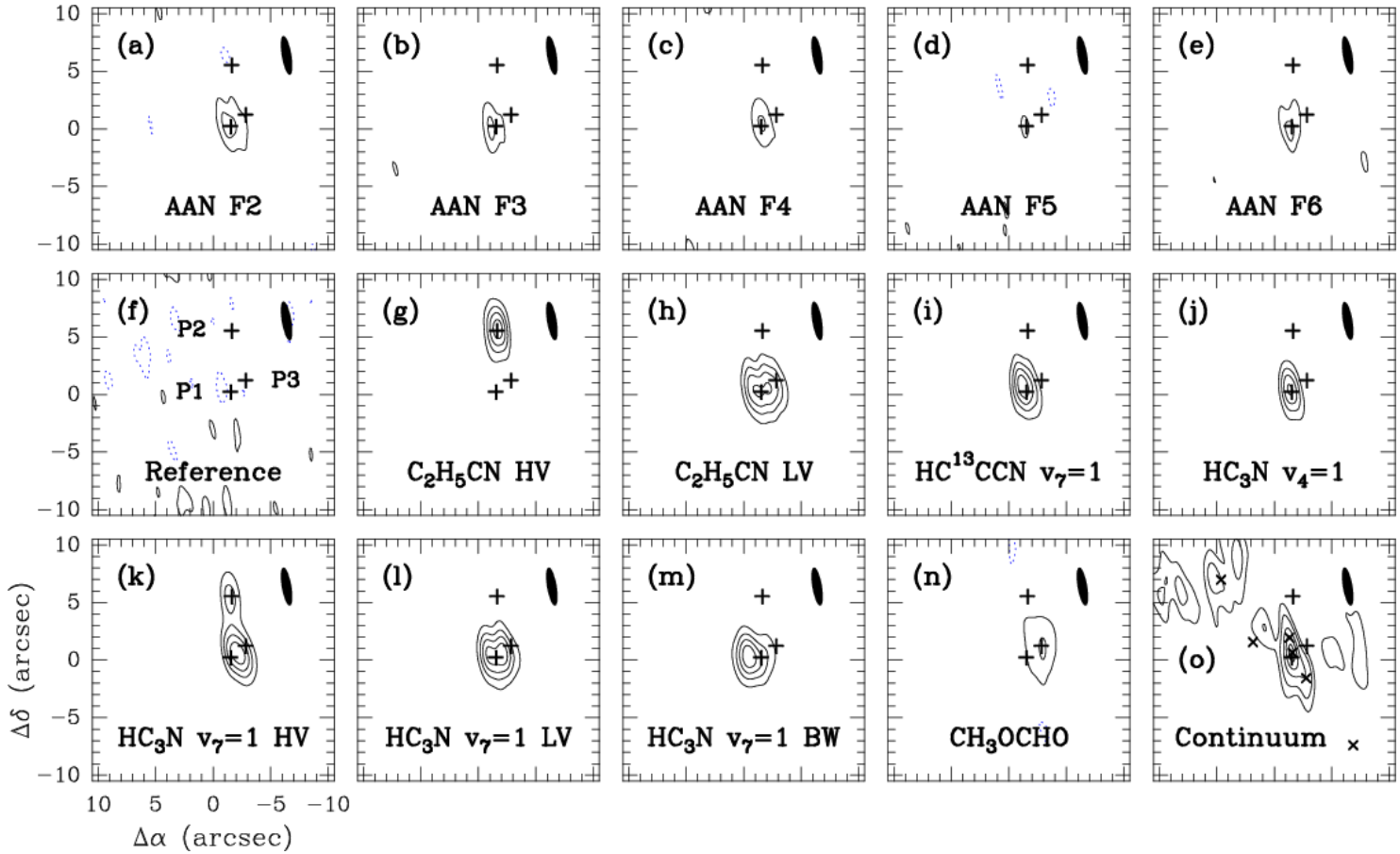
"State of the Art" millimeter wave imaging of complex molecules before ALMA – *Detection of interstellar urea*



(a) $(NH_2)_2CO$ contours of urea transitions overlaid on a Sgr B2N continuum map taken with the BIMA array. The continuum emission maps shown were made from channels which were deemed free from line emission. (b) $(NH_2)_2CO$ contours of the $21_{*,21}$–$20_{*,20}$ transition taken with the BIMA array. (c) $(NH_2)_2CO$ contours of the $20_{*,19}$–$19_{*,18}$ transition taken with the CARMA array. (Remijan et al. 2014, ApJ, 783, 77)

"State of the Art" millimeter wave imaging of complex molecules before ALMA – *Detection of interstellar amino-acetonitrile*



Integrated intensity maps (panels **a)** to **n)**) and continuum map (panel **o)**) obtained toward Sgr B2(N) with the Plateau de Bure interferometer at 82 GHz. Panels **a)** to **e)** show the amino acetonitrile (AAN) features (Belloche et al. 2008, A&A, 482, 179)

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ALMA Chemical Papers, Accepted Proposals and Publically Available Data:

- Cycle 0:
  - Expanding the frontiers of chemical complexity with ALMA
  - Tracing Evolution of Warm Carbon Chain Chemistry in L1527
  - Disks and complex organics in the inner regions of low mass protostars
  - Imaging the Peculiar CarbonChain Chemistry of IRAS 15398-3359 in Lupus
  - A 170 GHz wide Complete Spectral Scan of an IR pumped, Luminous Infrared Galaxy
  - A HIGH ANGULAR RESOLUTION STUDY OF THE DUST FORMATION ZONE OF IRC+10216
- Cycle 1:
  - Expanding the frontiers of chemical complexity with ALMA
  - A HIGH ANGULAR RESOLUTION STUDY OF THE DUST FORMATION ZONE OF IRC+10216
  - Pre-biotic molecules in low-mass protostars

ALMA Chemical Papers, Accepted Proposals and Publically Available Data:

- Cycle 2:
  - A survey of deuterium chemistry in protoplanetary disks
  - Formation of complex organics in solar-type protostars
  - A Complete Line Survey Observation in the 3-mm Band toward NGC 1068 for Diagnosing the Power Source in Galactic Nuclei
  - A search for extragalactic argonium, ArH+, a probe of the very atomic diffuse interstellar medium
  - Physical and chemical structure of massive proto-clusters
  - Search for new sulfur-species formed in H2S-bearing, UV-photoprocessed ice mantles in circumstellar regions. Mapping the D/H ratio of Complex Organic Molecules in IRAS16293-2422 to probe its dynamics and chemistry
  - A 3mm Line Survey of IRC+10216 : The chemical view of a C-rich object
  - Molecular oxygen in Orion
  - Resolving the Chemical and Physical Structure of the Disk Forming Zone in L1527
  - And so on…

ALMA Chemical Papers, Accepted Proposals and Publically Available Data:

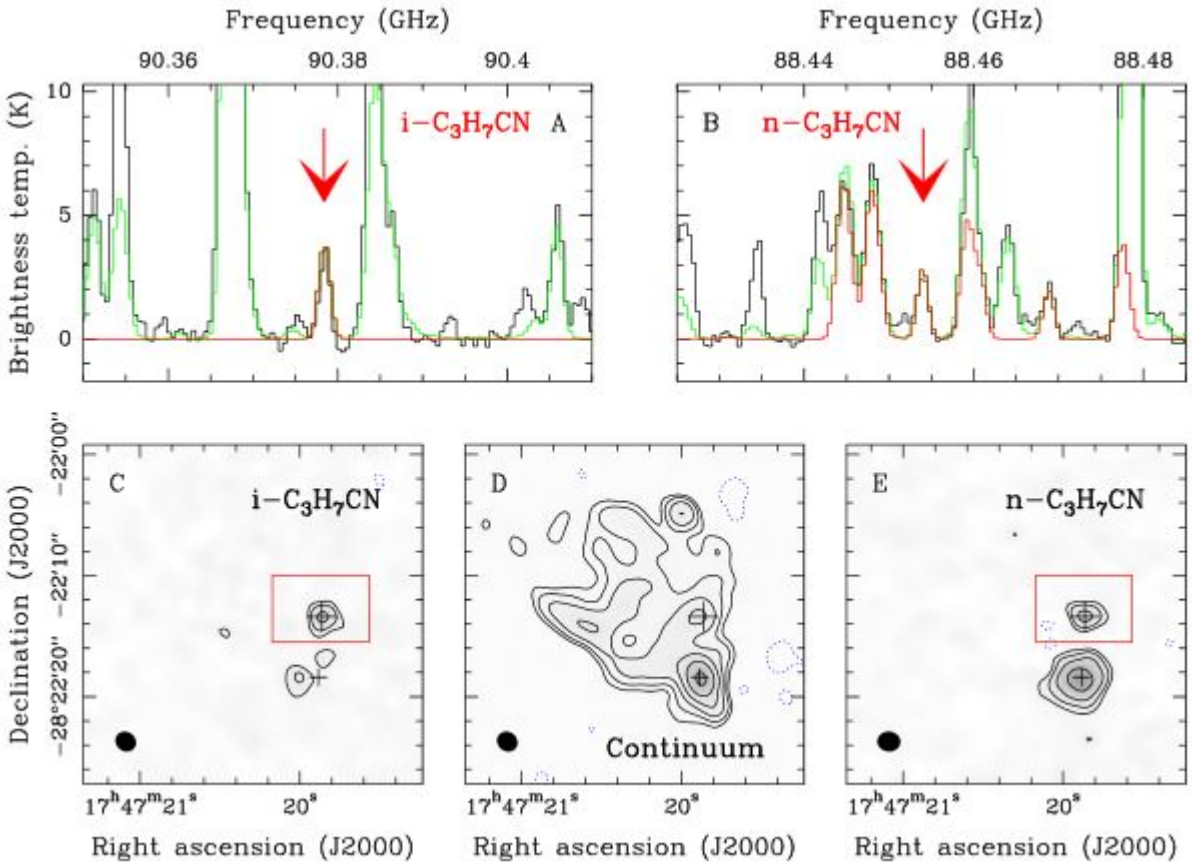
- *ALMA Multi-line Imaging of the Nearby Starburst NGC 253, Meier et al. ApJ, 2015*
- *Multimolecule ALMA observations toward the Seyfert 1 galaxy NGC 1097, Martin et al. ApJ, 2105*
- Si-bearing Molecules Toward IRC+10216: ALMA Unveils the Molecular Envelope of CWLeo, Velilla Prieto et al. ApJ, 2015
- **The comet-like composition of a protoplanetary disk as revealed by complex cyanides, Oberg et al. Nature, 2015**
- Molecular line emission in NGC 1068 imaged with ALMA. II. The chemistry of the dense molecular gas, Viti et al. A&A, 2014
- **Change in the chemical composition of infalling gas forming a disk around a protostar, Sakai et al. Nature, 2015**
- ALMA Measurements of the HNC and HC3N Distributions in Titan's Atmosphere, Cordiner et al. ApJ, 2015
- **Detection of a branched alkyl molecule in the interstellar medium: iso-propyl cyanide, Belloche et al. Science, 2014**
- Acetone in Orion BN/KL. High-resolution maps of a special oxygen-bearing molecule, Peng et al. A&A, 2013
- Detection of the Simplest Sugar, Glycolaldehyde, in a Solar-type Protostar with ALMA, Jorgensen et al. ApJL, 2012.
- ETC

ALMA Chemical Papers, Accepted Proposals and Publically Available Data: Take Home Message…

- ***A large fraction of observations approved on ALMA are chemical in nature… which is unlocking a truly chemical view of the universe.***

- Data are freely available from the ALMA archive or from the ALMA Science Verification page:
  - Orion KL Band 6: high resolution spectral survey:
  - https://almascience.nrao.edu/almadata/sciver/OrionKLBand6/

ALMA Observations of iso-propyl cyanide



Belloche et al. 2014, Science, 345, 1584

The detection utilized the combination of spectroscopic and spatial identification to confirm the detection

This detection suggests that branched carbon-chain molecules may be generally abundant in the ISM.

Starting to utilize the sensitivity of ALMA to expand the known molecular complexity in space.

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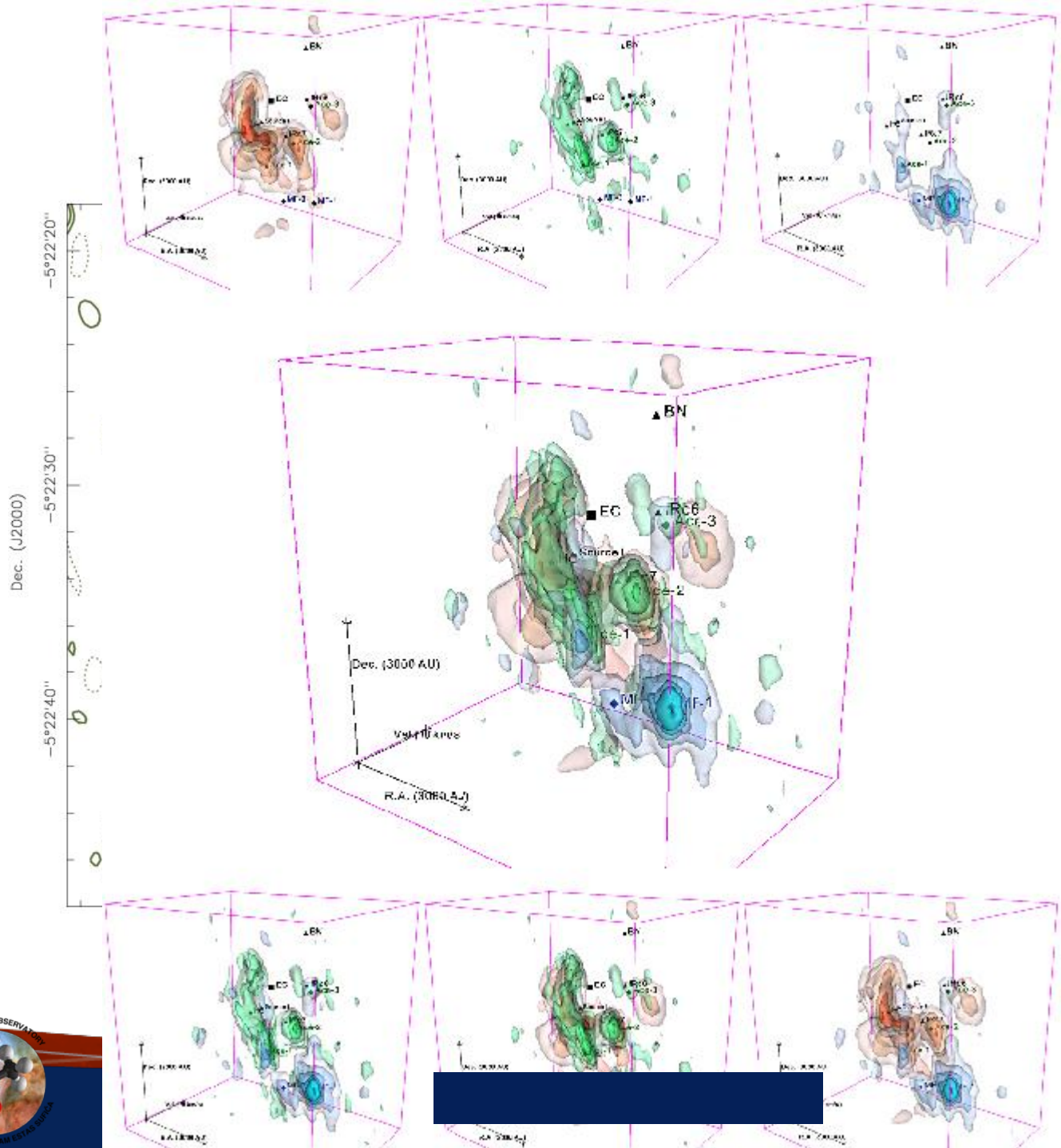

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l (CH3)2CO
the same
rion BN/KL. The
3 – 243,22 line
IHz is shown in
urs. The
,8 – 103,7 E/A
5.3 MHz and
are combined
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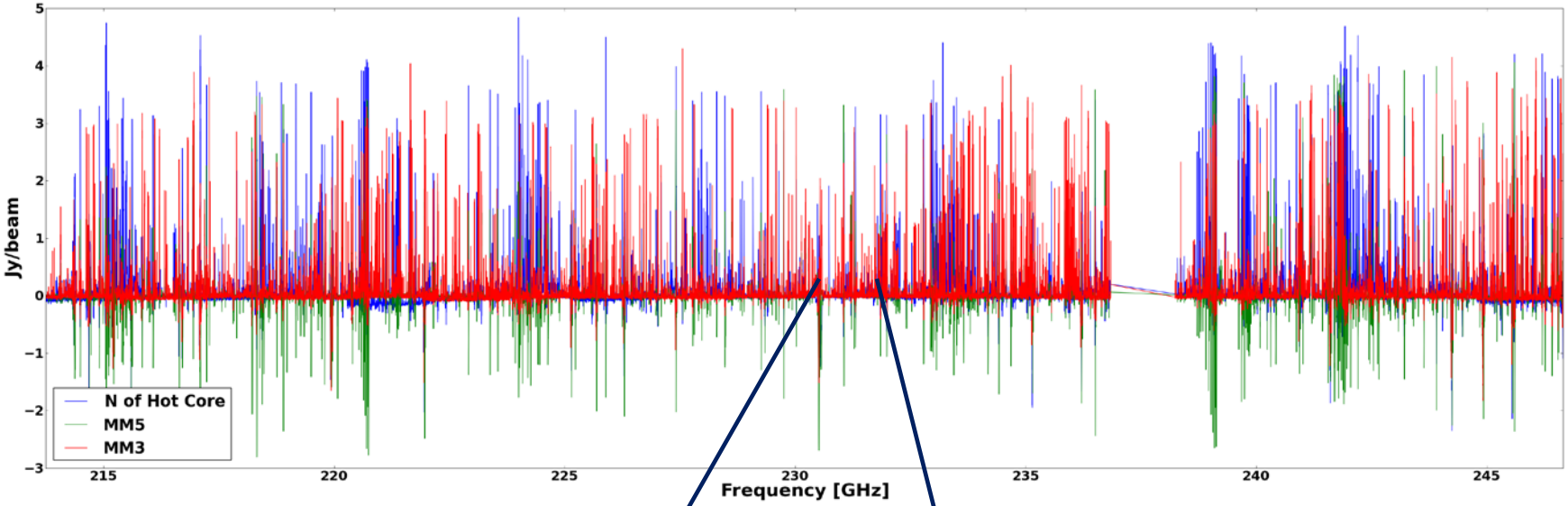
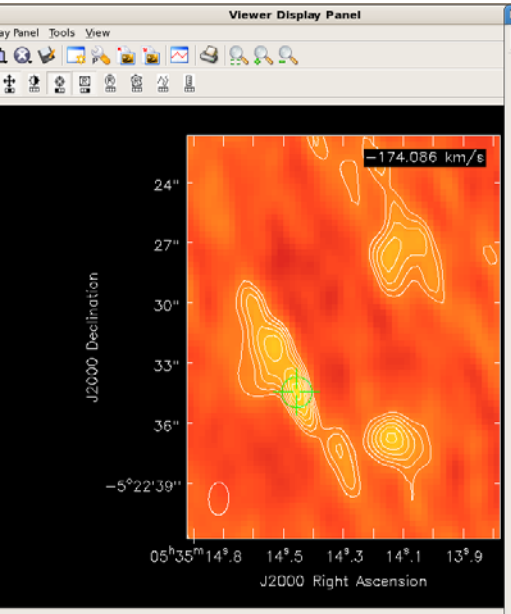
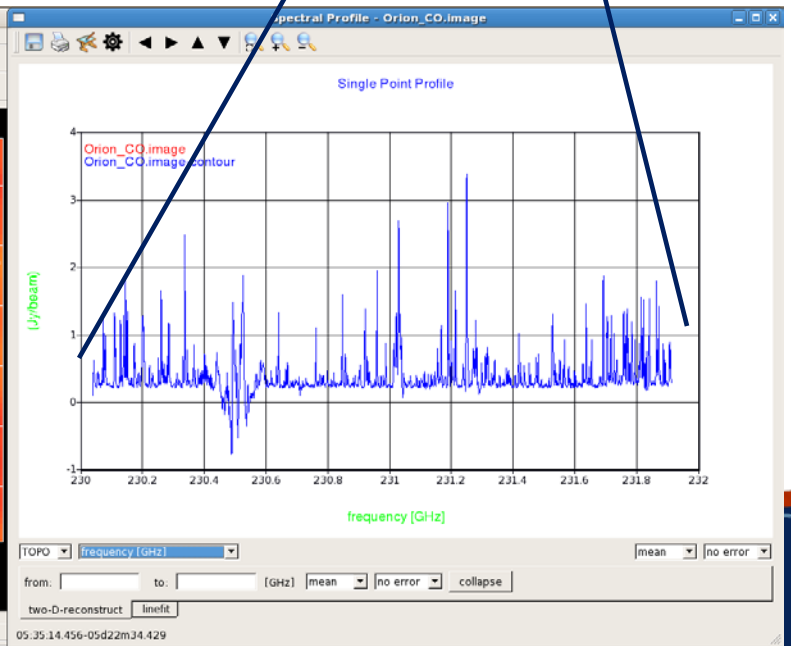
(CH3)2CO
.0 EE line at
is shown in
tours.

[redacted]

Broadband Spectral Line surveys are entering the interferometric era...







Orion Band 6 (214 – 246 GHz) – Publically available off www.almascience.org

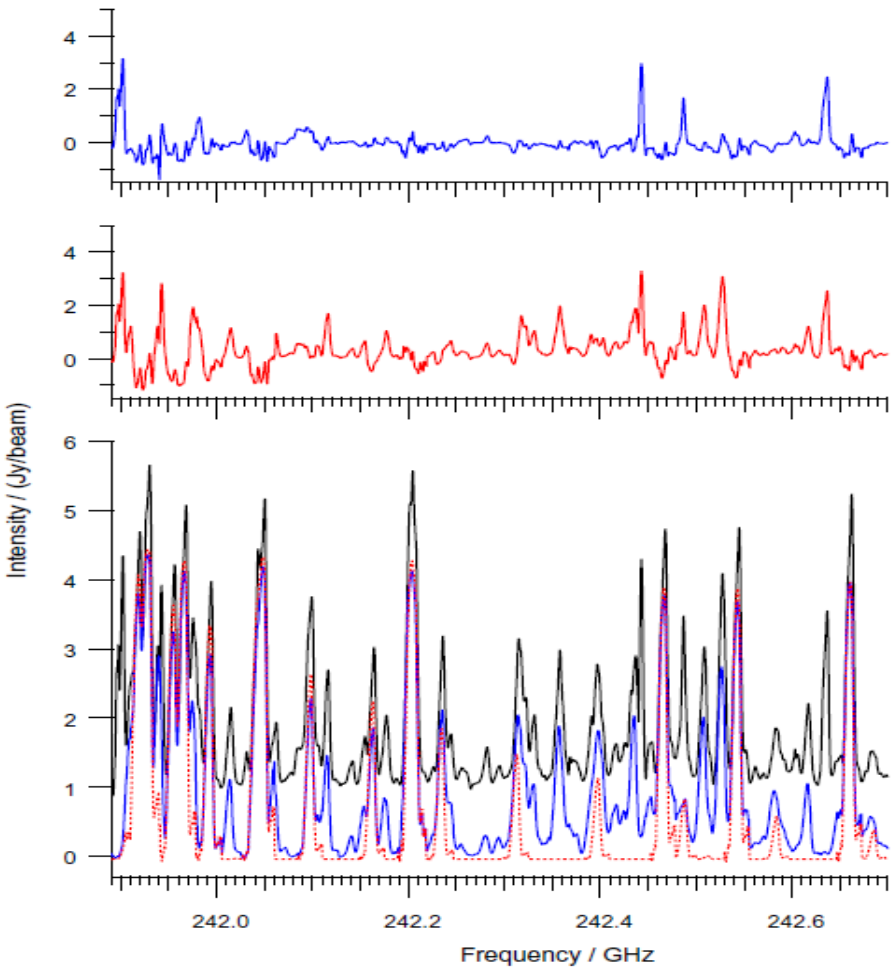
Where do we start???

Taken at a single PIXEL and there are 1024x1024 PIXELS

Broadband Spectral Line surveys are entering the interferometric era...

The results of the ALMA data compared to a laboratory prediction using the Complete Experimental Spectrum (CES) method outlined by Fortman et al. (2012).

These results show not only a new way to identify previously unidentified spectral features based on laboratory spectroscopy to astronomical observations but also gives new insights into the molecular complexity of regions such as Orion



see: http://www.nrao.edu/pr/2012/widespectra/

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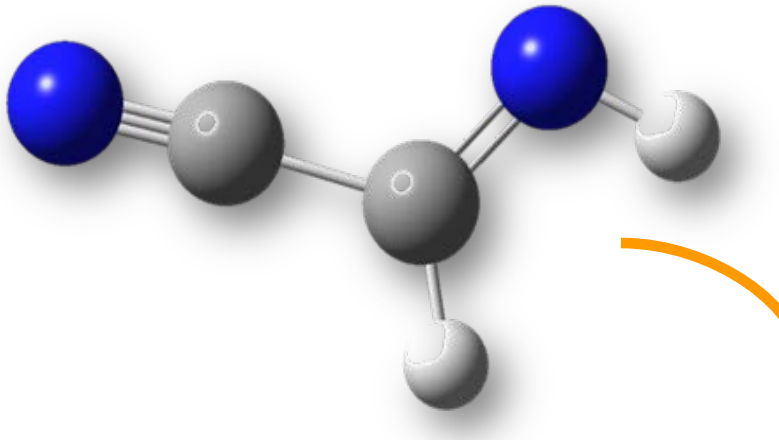
Trade-offs for doing Astrochemistry with ALMA:

- More Spectral windows/spectral coverage
  - Higher data rates – that will hurt and have to justify why in the technical justification/richer archive for use by all scientists (think of the chemists!)
  - Explain every spectral window in the science justification – will be painful especially if you are not familiar with what that particular transition traces/forge new collaborations
  - Larger image cubes – makes processing and imaging more difficult/Increase in discovery space and greater understanding of the source.

And someday, you may just serendipitously make the discovery that will explain how:



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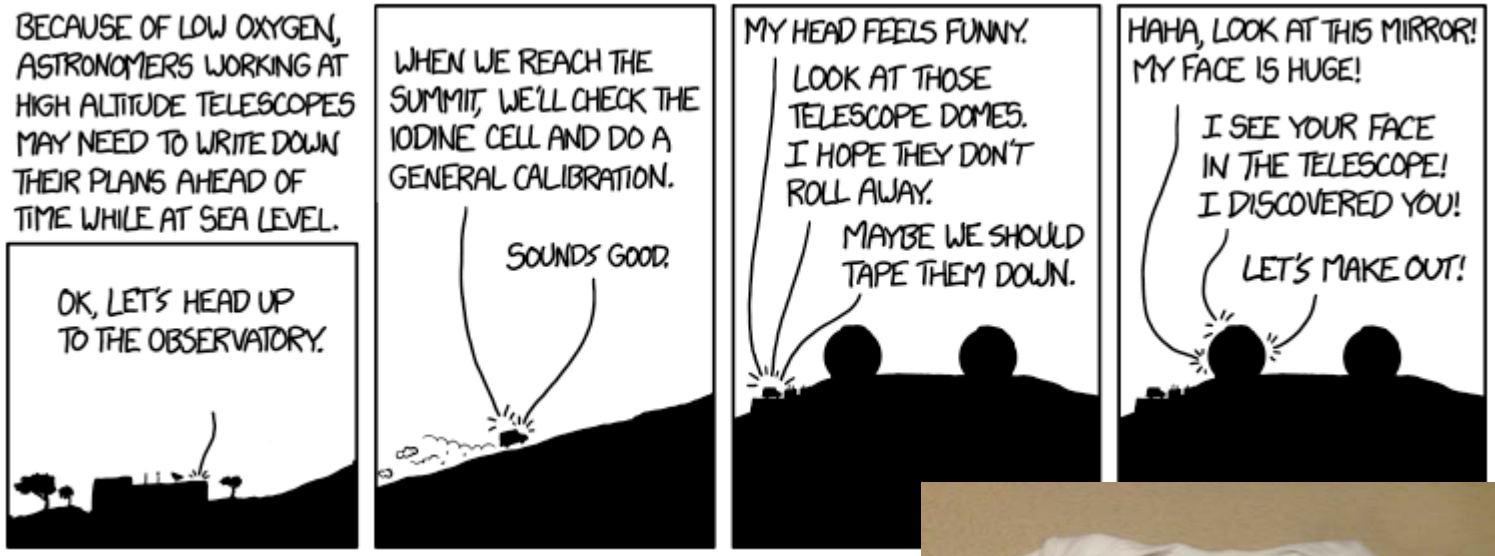
Questions, Comments, Concerns or Criticisms??



Get your ALMA "onesie" while supplies last!!!!

www.nrao.edu
science.nrao.edu

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

Capabilities for Cycle 3

- At least 36x12m antennas in the main array, and 10x7m antennas (for short baselines) and 2x12m antennas (for making single-dish maps) in the Morita-san Array (ACA)
- Receiver bands 3, 4, 6, 7, 8, 9, & 10
- Baselines up to 10 km for Bands 3, 4 and 6
- Baselines up to 5 km for Band 7
- Baselines up to 2 km for Bands 8, 9, and 10
- Both single-field interferometry and mosaics
- Spectral-line observations with all Arrays and continuum observations with the 12m Array and the 7m Array (except in Bands 9 and 10)
- Polarization at PI-specified frequencies (on-axis, continuum in Bands 3, 6 and 7 - no ACA, no mosaics, no spectral line, no circular polarization)
- Mixed correlator modes (both high and low frequency resolution in the same observation)

In Cycle 3, we expect that

- 75% of the time awarded will go to “standard modes”: projects with previously released capabilities with established reduction path through the pipeline
- 25% of the time awarded will go to “non-standard modes" - newly offered capabilities or modes not yet incorporated in the pipeline
  - this is data which cannot be processed by the pipeline at this time, which translates to manual data processing by ARC and JAO staff

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  -- All observations in Bands 8, 9 & 10
  (and narrow [< 100 MHz] spectral window observations in Band 7)
  -- Long baselines (> 2km)
  -- Polarization
  -- Spectral Scans
  -- External ephemeris observations
  -- Non-standard calibrations