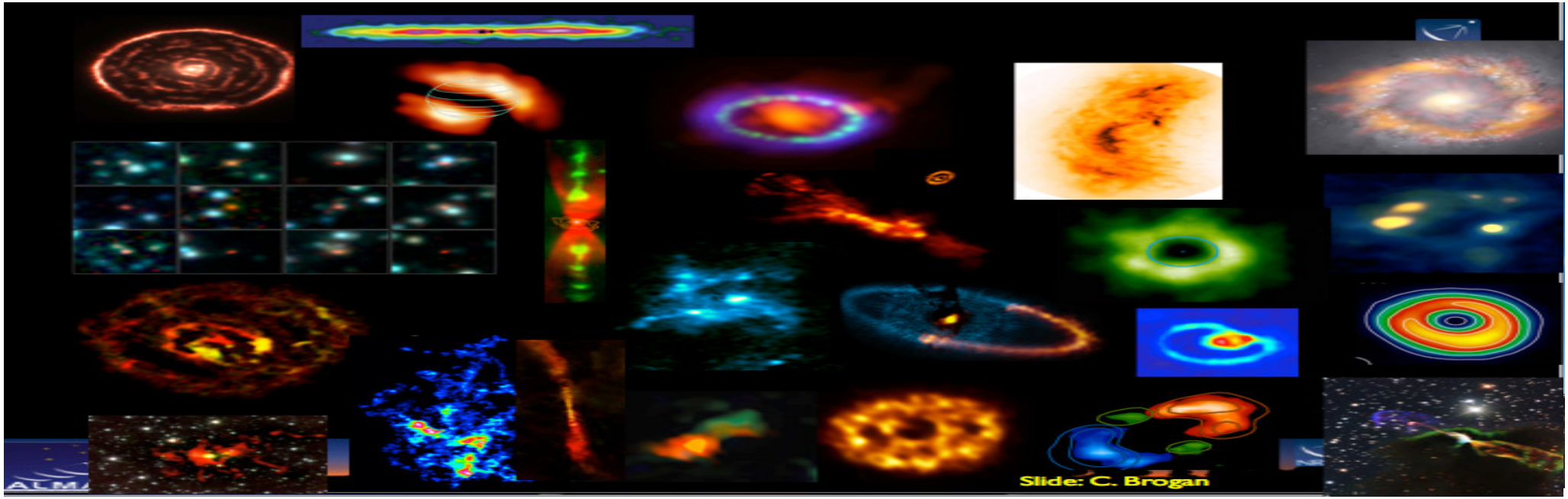
ALMA Science: Now and Through the Next Decade



A Short Overview

Al Wootten

Atacama Large Millimeter/submillimeter Array

Karl G. Jansky Very Large Array

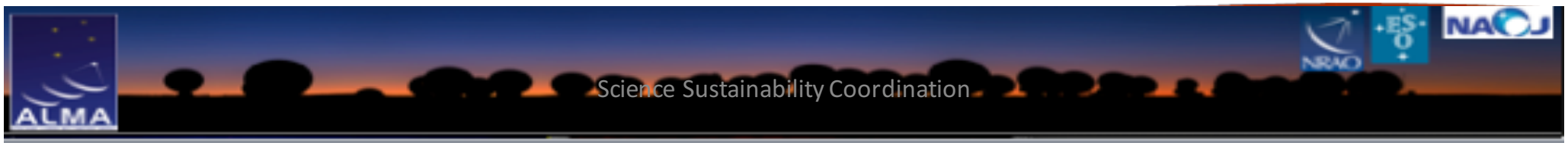
NSF

Associated Universities, Inc.

NRAO

Goals

- Identify and support community science priorities, identifying critical drivers
- ALMA uses community strengths in hardware, software and techniques to fund studies to define and enable a science-driven upgrade plan, funded as projects
- Science Sustainability: Identify those community science priorities which can produce transformational results at the horizon and plan for their realization
- Synergy with other instruments (JWST, SOFIA, GBT, EVLA)



ASAC Recommended Development Paths

- Finish the Scope of ALMA (B1 + B2 receivers, VLB capability)
  - Detailed in **ALMA Scientific Specifications and Requirements** (ALMA-90.00.00.00-001-B-SPE)
- ALMA2030
  - 1. Improvements to the ALMA Archive: enabling gains in usability and impact for the observatory.
  - 2. Larger bandwidths and better receiver sensitivity: enabling gains in speed.
  - 3. Longer baselines: enabling qualitatively new science.
  - 4. Increasing wide field mapping speed: enabling efficient imaging.

ALMA Science Frontiers

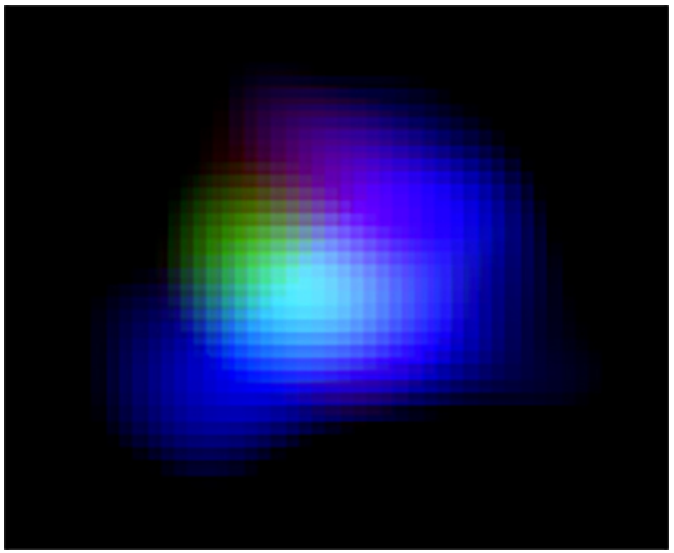
- First Billion Years
- Evolution of Galaxies and Black Holes
- Local galaxies, Milky Way and the ISM
- Star and planet formation, biosignatures, chemistry of disks and their offspring
- Exoplanets, the Sun and the Solar System

Current state: just-completed conference '***Half Decade of ALMA: Cosmic Dawns Transformed***'

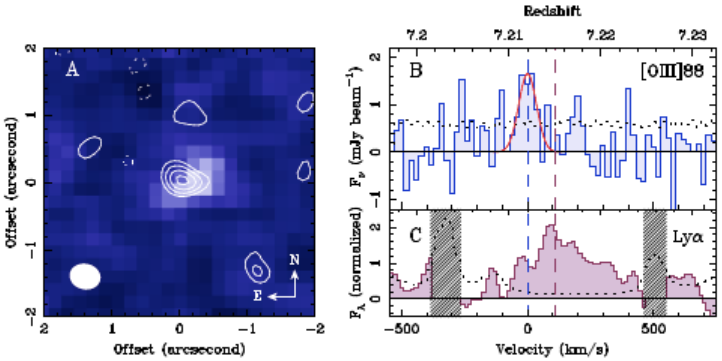
The First Billion Years

ALMA Explores the Creation of O, N and C

- Science Drivers
  - Creation of the Metals, monitored through atomic and molecular lines, and 'dust'
  - These tracers enable characterization of the development of structures in the early Universe
- Recent Science
  - Detection of [O III] 88µm @z=7.2: the most distant spectroscopically confirmed Oxygen
  - [N II] 205µm: distant Nitrogen
    - Low [NII] emission relates to low dust abundance and low metallicity at z=5-6 in some galaxies (Pavesi+ arXiv:1607.02520)
  - [C II] ASPECS study: 14 6<z<8 candidates
    - [CII] source density significantly higher than predicted by current models (Aravena+ arXiv:1607.06772)

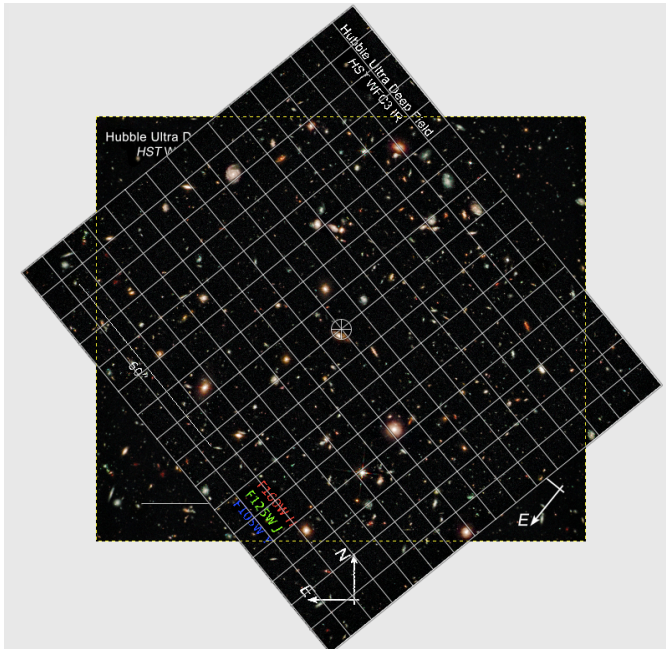


[O III] 88µm @z=7.2 in SXDF-NB1006-2 imaged by ALMA (Inoue et al 2016). Blue: Lyα, Red: UV

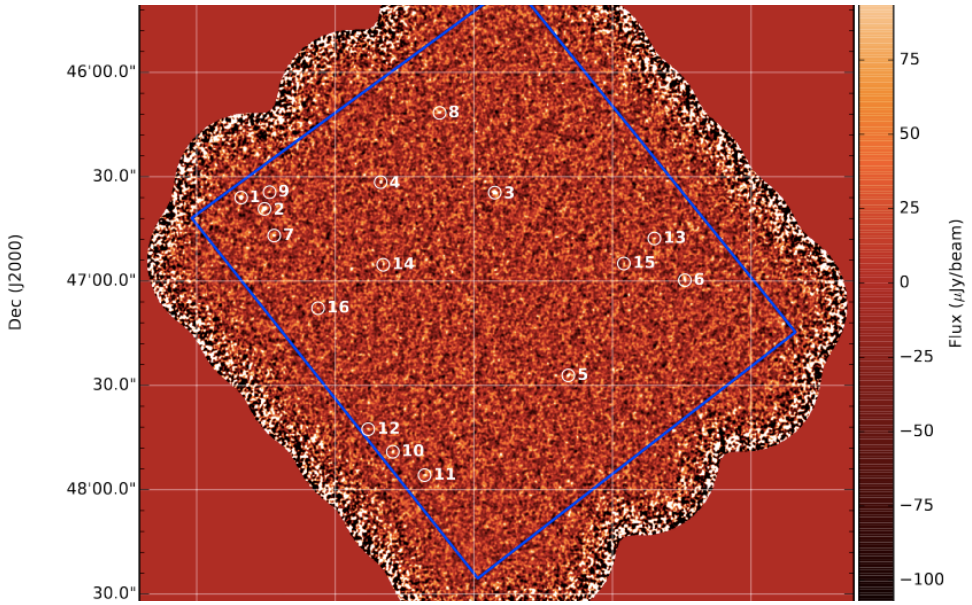


First Oxygen

Evolution of Galaxies: Deep Field Surveys



WFC3/IR on HST



Dunlop et al (2016)

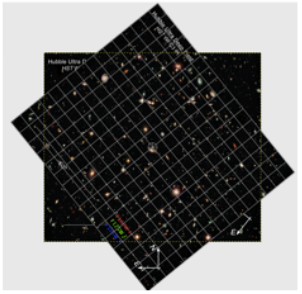
Instrumental needs

- Sensitivity: detecting weak signals
- Spectral grasp covers appropriate redshifted lines
- Field of View to include varied sources

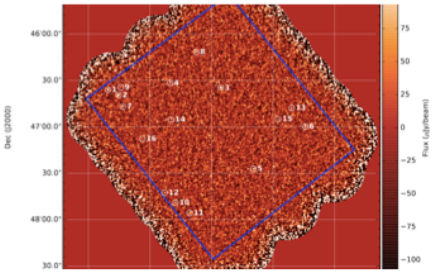
ALMA Spectroscopic Survey in the Hubble Ultra Deep Field

ASPECS

- Unbiased census of molecular gas and dust in (z>0.5) galaxies
  - ALMA full B3 (84-115 GHz), B6 (212-272 GHz) line scans (Walter+ arXiv:1607.06768
  - [C II] ASPECS study: 14 6<z<8 candidates
    - [CII] source density significantly higher than predicted by current models (Aravena+ arXiv:1607.06772)
  - CO luminosity functions evolves to z~1-2, excess at the bright end (deCarli+ arXiv:1607.06770)
    - Galaxies with $M_*>10^{10}M_{sun}$ are predicted to be 2-3x less gas rich than observed

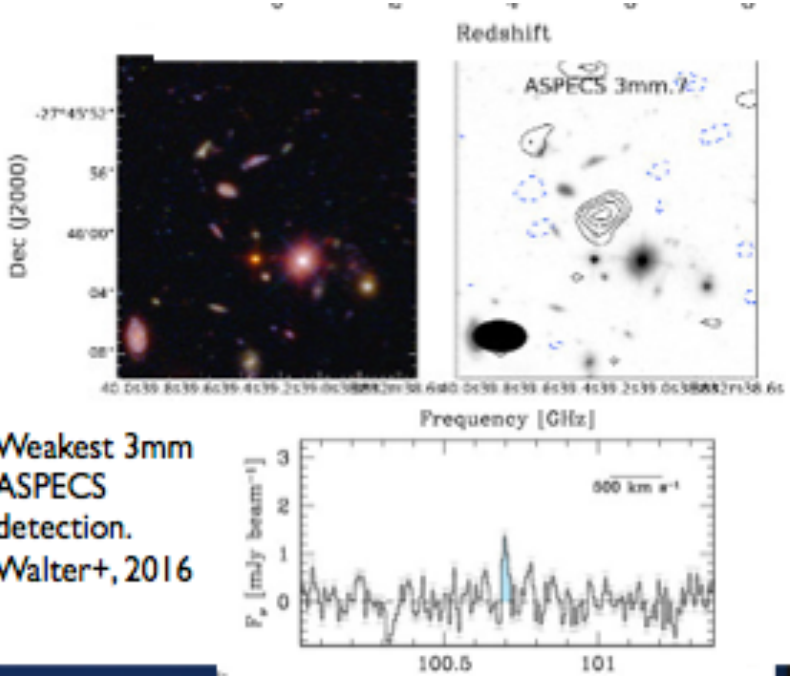


WFC3/IR on HST



Dunlop et al (2016)

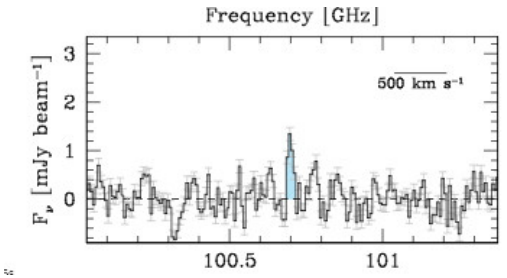
Continuum Comparison HUDF (left) ALMA (right)

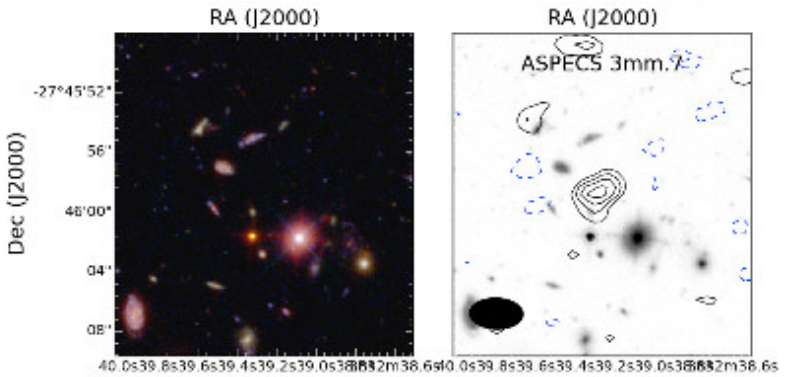


Evolution of Galaxies and Black Holes

- Science Drivers
  - Kinematics characterize galaxies through cosmic time
  - Spectra characterize chemical content
  - Kinematics measure of nearby nuclear Black Hole mass
- Instrumental needs
  - Sensitivity: detecting weak signals
  - Spectral grasp covers appropriate redshifted lines
  - High resolution, probing $\mathcal{R}_{\text{galactocentric}}$<50pc regions

Weakest 3mm ASPECS detection. Walter+, 2016



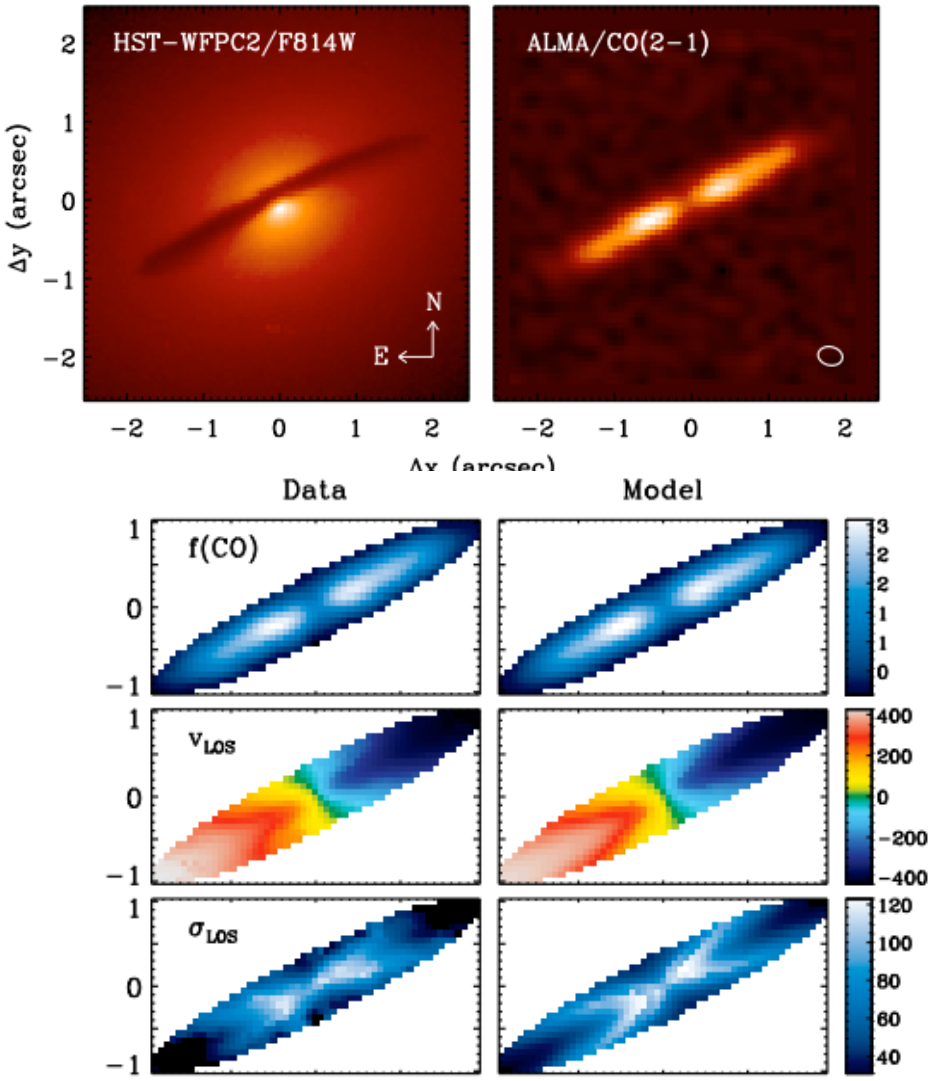


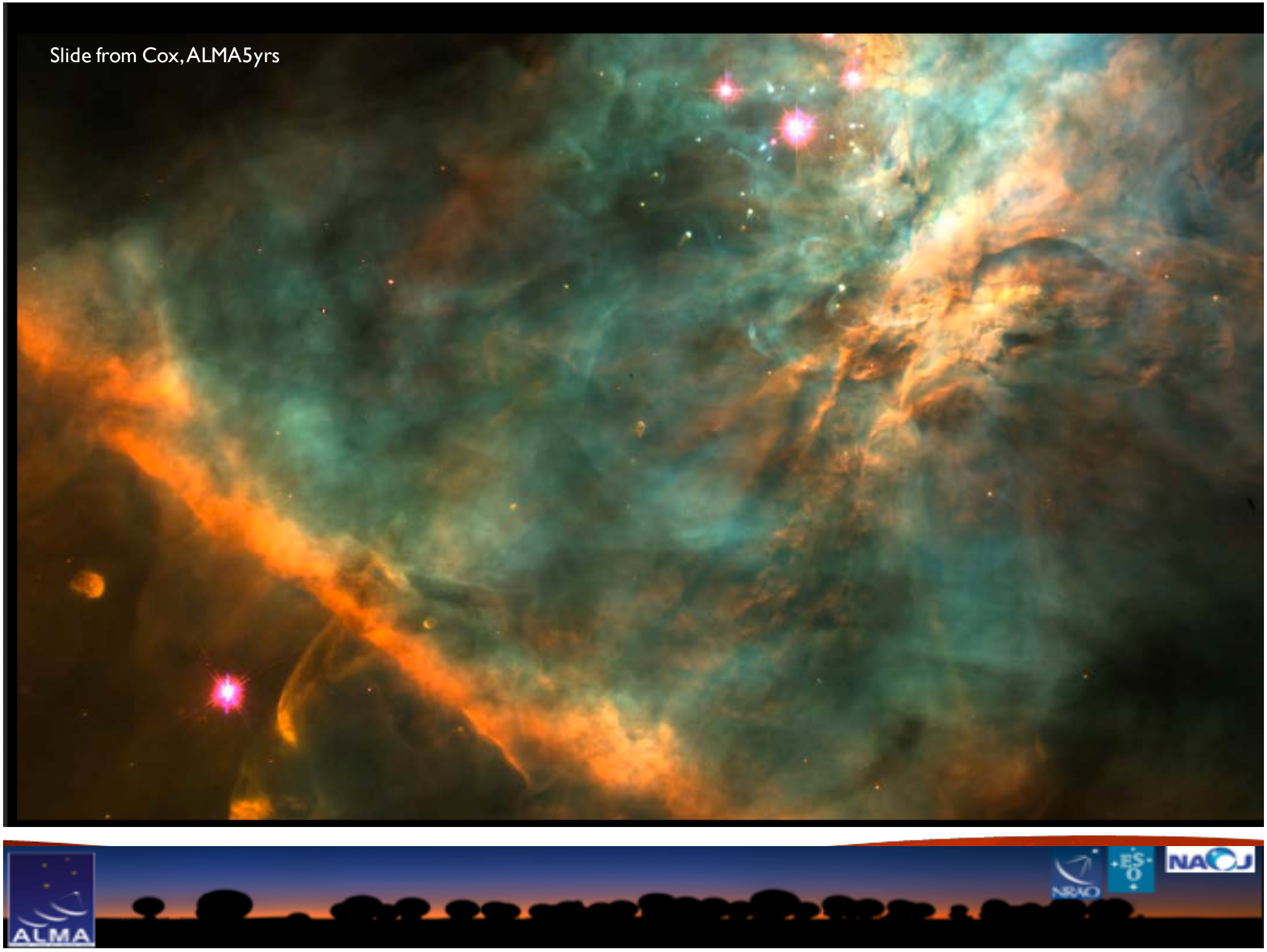
ALMA Measures the Black Hole in NGC 1332

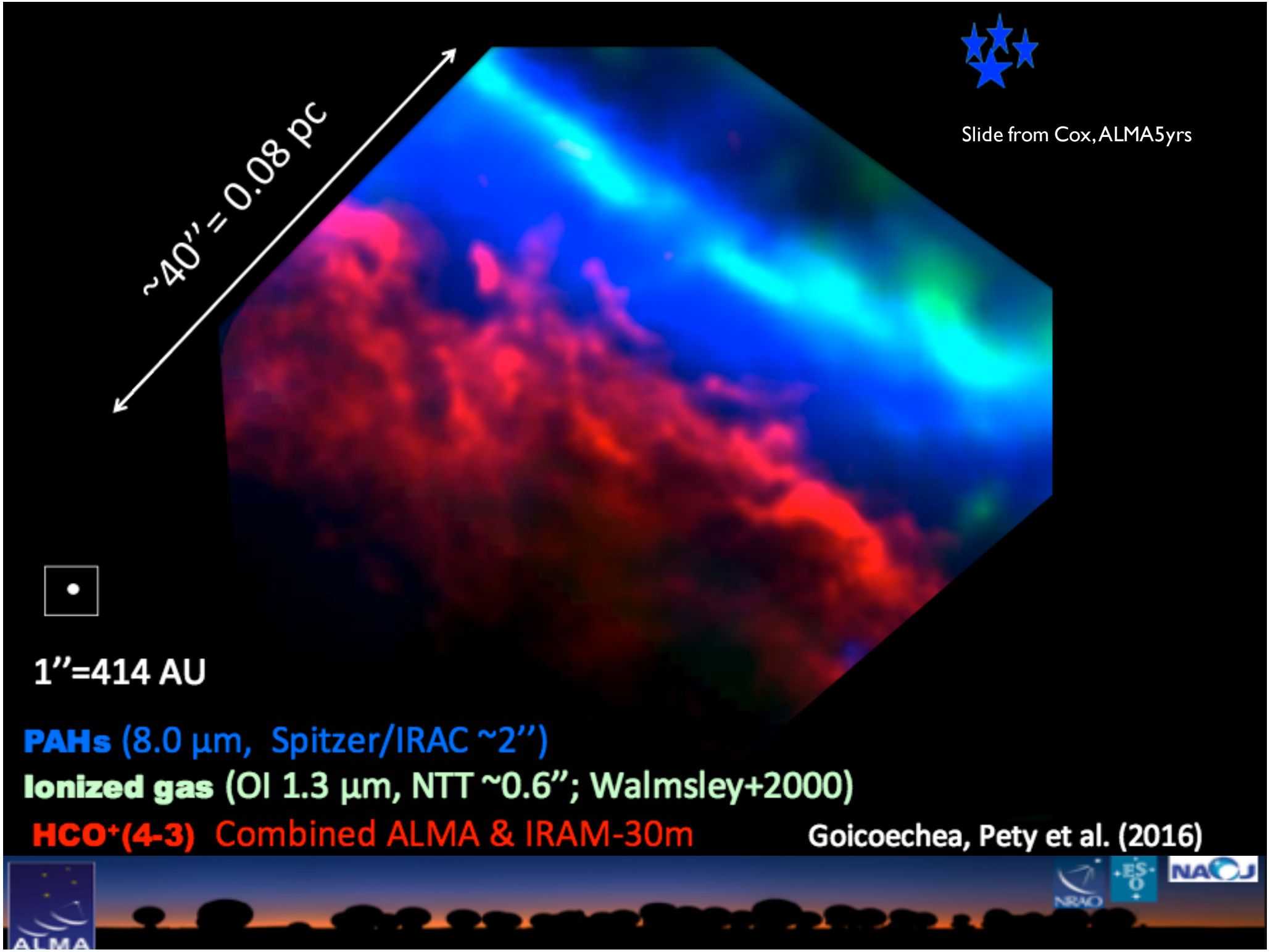
AARON J. BARTH, BENJAMIN D. BOIZELLE, JEREMY DARLING, ANDREW J. BAKER, DAVID A. BUOTE, LUIS C. HO, and JONELLE L. WALSH ArXiv:1605.01346

- CO J=2-1 emission measured in the circumnuclear disk of NGC1332.
- Resolution of 0.044" (4.8pc) resolution at 22.3Mpc demonstrates ALMA imaging, high resolution
- Disk shows regular rotation with central high velocity component suggesting a compact central mass
- Authors find

  $M_{BH} = (6.64^{+0.65}_{-0.63}) \times 10^8 M_\odot$
- ALMA is poised to make a major contribution to understanding Black Hole demographics.
  - Through ***better-than HST resolution***
  - ***ALMA sensitively images massive accretion disks***, the most sensitive probe of kinematics available near galactic nuclei.

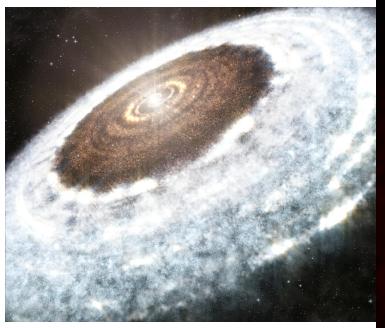



Slide from Cox, ALMA5yrs
ALMA
NRAO
ESO
NAOJ

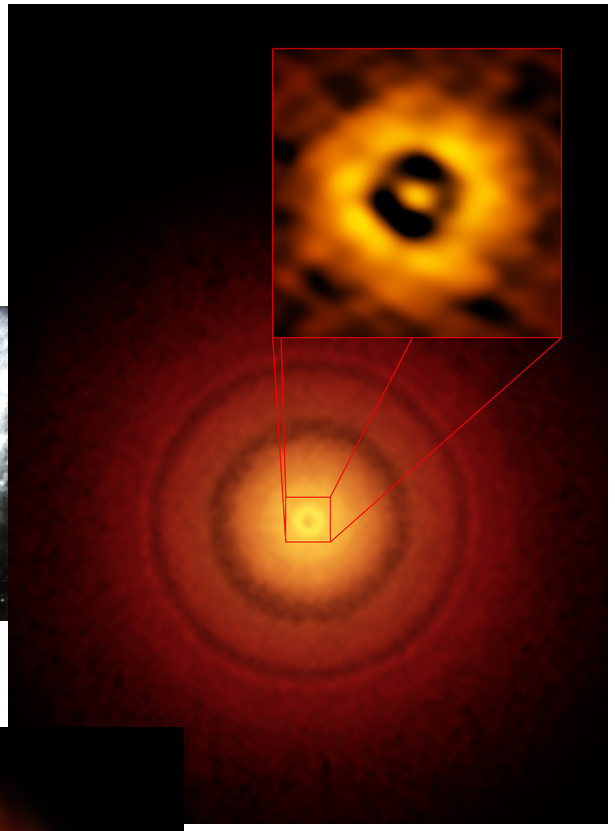

~40'' = 0.08 pc
Slide from Cox, ALMA5yrs
1''=414 AU
PAHs (8.0 µm, Spitzer/IRAC ~2'')
Ionized gas (OI 1.3 µm, NTT ~0.6"; Walmsley+2000)
HCO+(4-3) Combined ALMA & IRAM-30m
Goicoechea, Pety et al. (2016)

Star & Planet Formation, Ingredients of Habitable Worlds

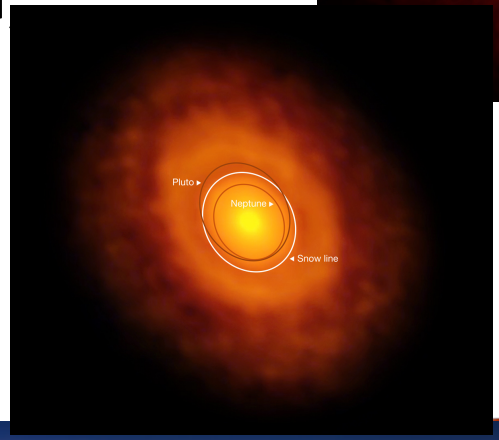
- Disk structure and composition
  - around stars and around planets;
  - disk evolution
- Instrumental needs
  - Sensitivity,
  - Spectral grasp,
  - Spatial and spectral resolution,
  - Imaging precision



V883 Ori, Cieza+ 2016



TW Hya Andrews et al 2016

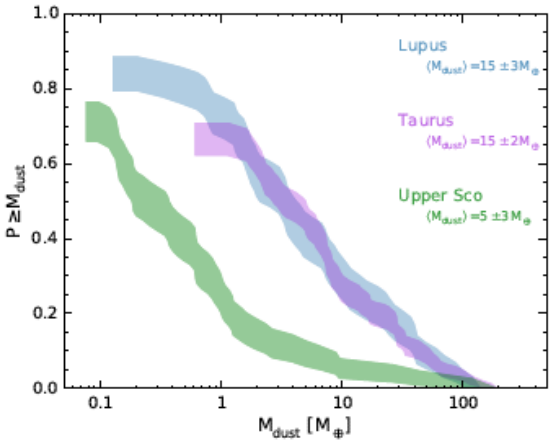


V883 Ori, Cieza+ 2016

ALMA Survey of Lupus Protoplanetary Disks I: Dust and Gas Masses

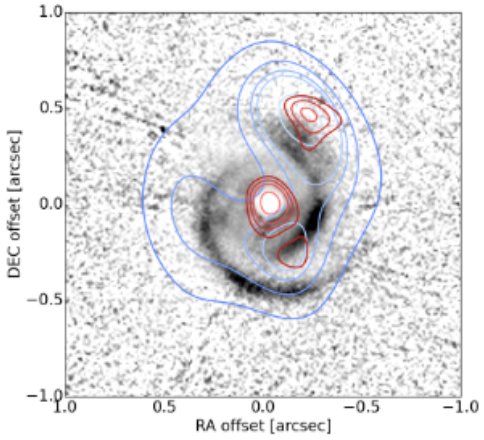
Megan Ansdell, Jonathan P. Williams, Nienke van der Marel, John M. Carpenter, Greta Guidi, Michiel Hogerheijde, Geoff S. Mathews, Carlo F. Manara, Anna Miotello, Antonella Natta, Isa Oliveira, Marco Tazzari, Leonardo Testi, Ewine F. van Dishoeck, Sierk E. van Terwisga http://arxiv.org/abs/1604.05719

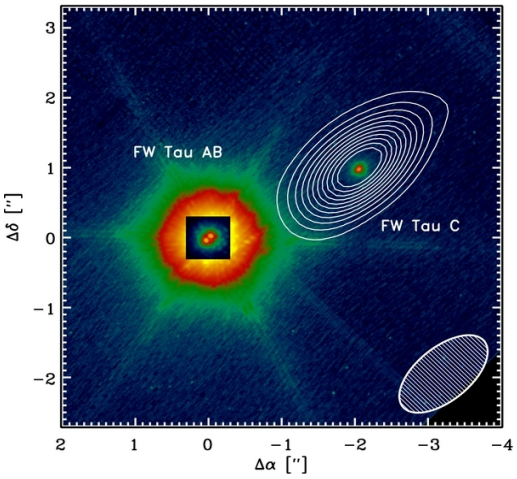
- ALMA survey of 89 protoplanetary disks around nearby young stars
- Findings: *Similar overall dust distributions in Lupus and Taurus*
  - M_{dust} correlates non-linearly with M_*,
  - For the first time a tentative positive correlation is found between between M_{gas} and M_*
- Rapid gas depletion is inferred: planet formation complete by ~few Myr, may explain unexpected prevalence of superEarths



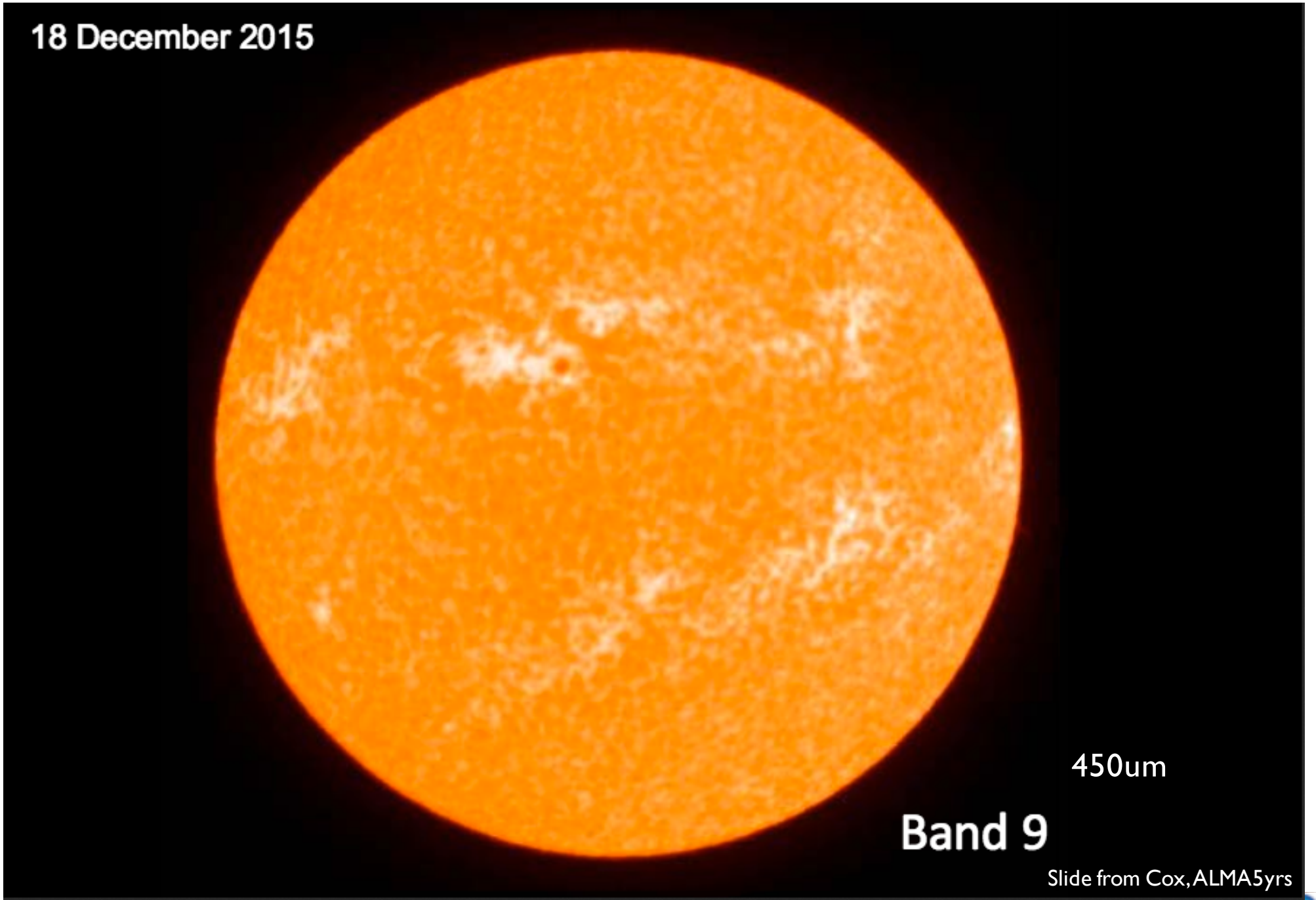
Exoplanets

- Detection of Exoplanets and their signatures demands
  - Sensitivity,
  - Spatial resolution,
  - Excellent imaging (many baselines)
- Direct detection may involve, for ALMA
  - Imaging: close in proto-giant planets
  - Nearby hot giants (~brown dwarf size)
  - Transit detection of hot giant planets
- Protoplanetary environments:
  - Rings or protolunar environments
  - Volatization of ices in young planets



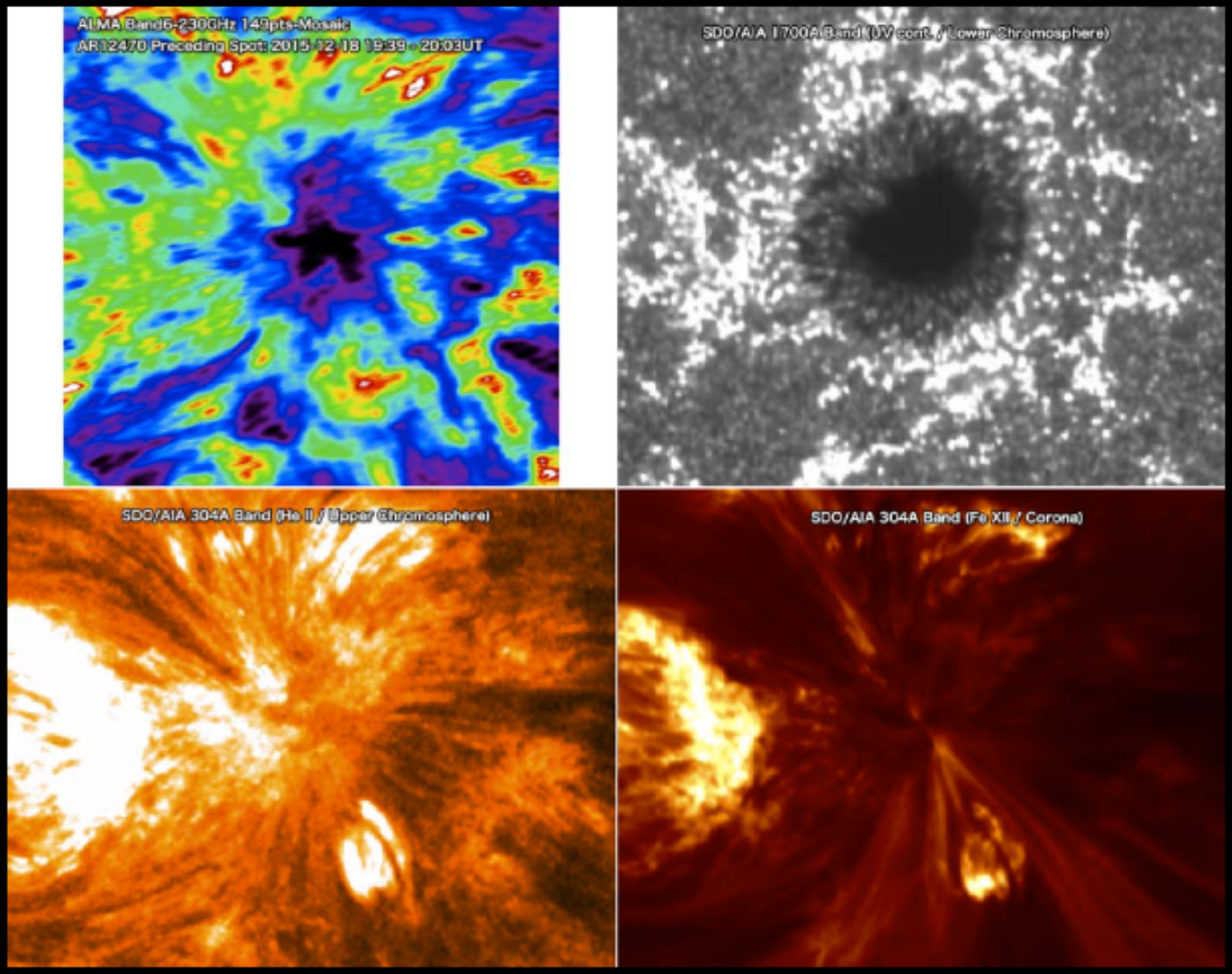


Kraus, A.+ 2015 ApJ798, L23



Slide from Cox, ALMA5yrs

Interferometric Image of the Sun with ALMA



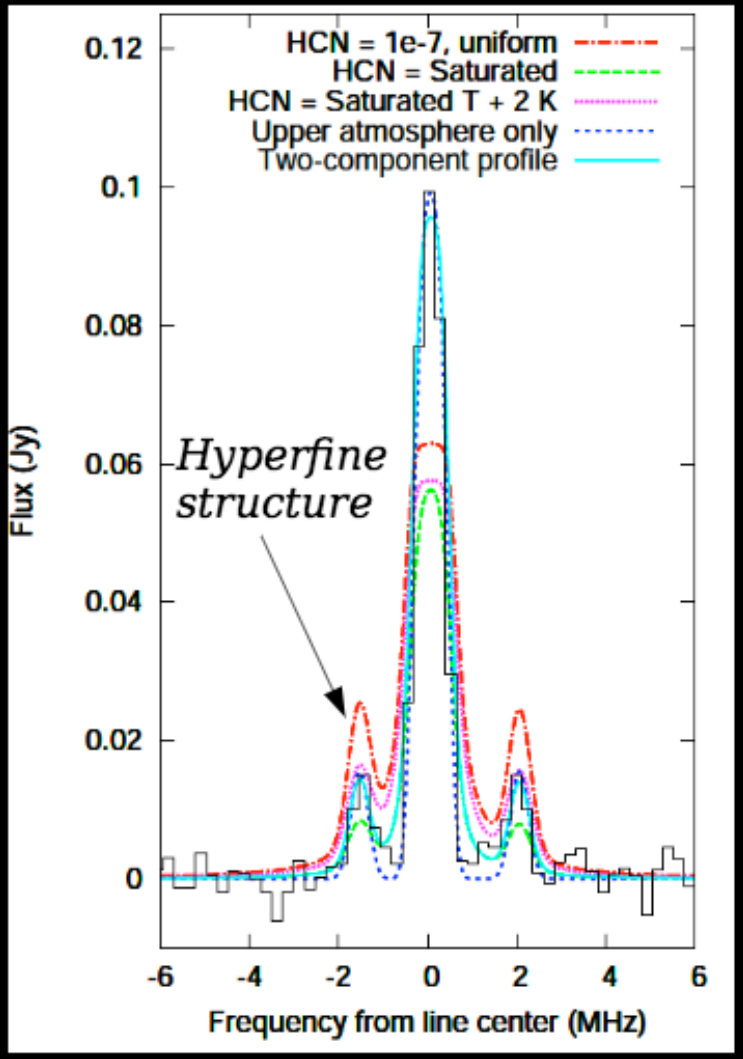
Slide from Cox, ALMA5yrs

Pluto's atmosphere

Slide from Moullet, ALMA5yrs

First detection of HCN
(expected photochemical product),
Abundant: 4.10^{-5} at 800 km

→ suggest warm layer > 300 km
→ additional HCN source
Mid-atmosphere
→ HCN abundance indicates
supersaturation



Lellouch et al., 2016

Development Items for ALMA 2010-2030

- Science clearly benefits from improving
  - Throughput (collecting area, instantaneous bandwidth, uv coverage)
  - Spectral Grasp (Expand to all accessible frequencies)
  - Spatial and frequency resolution
- Many other possibilities
  - ASAC ***ALMA2030*** Report
  - Identify science goals development could nourish to *sustain* cutting edge science output

Development Areas

- Sensitivity--could achieve that of 8 additional antennas with each of
  - Use of all ALMA antennas (*Combined Array*, near-term)
  - Correlator accuracy (spectral line, near-term)
  - Increased bandwidth, correlator upgrade to 2x or 4x
- Resolution
  - Spatial: 5millarcsec to image disks down to habitable zone scales (continuum) enable precise astrometry. Near 350µm corresponds to 16 km, difficult; at lower frequencies ~20-60km, requires longer baselines
  - Frequency: Resolve infall signatures in cold clouds; correlator upgrade
- Field of View
  - Some gains possible with efficiency improvement, On-the-fly interferometry
  - Multi-pixel or beam-forming arrays; more important at shorter wavelengths probably

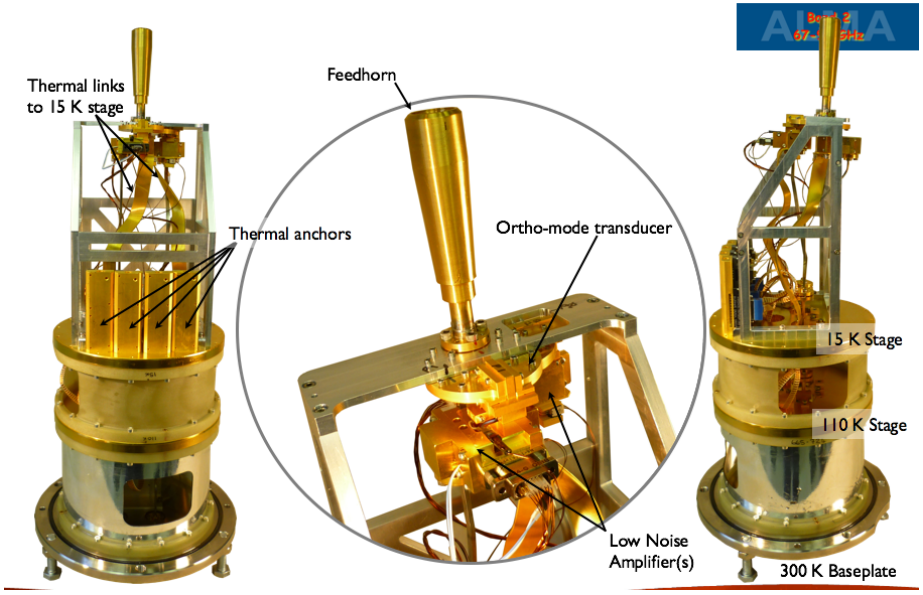
Some Possible Strategic Initiatives

- Improving Bandwidth / Sensitivity:
  - Upgrading the baseline correlator
  - Defining the next generation correlator
  - Upgrading the backend to accommodate the upgraded correlator and
  - Upgraded Receivers
- Expediting Data to Publication
  - CASA, pipeline, SRDP software for improving the user data experience (ADMIT, CARTA, data structure explorations)

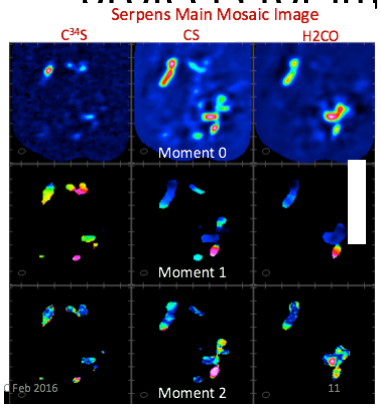
NA Development Program

Current Project Overview

- New alma Band (2+) provides new science: access to redshifted CO 'desert' and deuterated light molecules
- Fiber optic connection improves PI data delivery
- B3 upgrade delivers improved TP stability
- Recently delivered ADMIT and CARTA projects for improved archive use

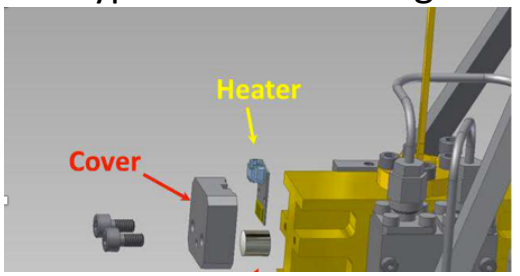


Design & Testing of a Prototype Band 2 Cartridge



ADMIT products are delivered with data packages, also archived

Fiber Optic Project



Band 3 CCA Heater Installation for Deflux Operation

Three Projects continue during FY2017.

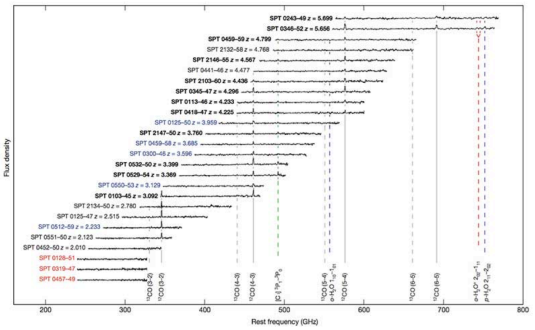
NA Development Program

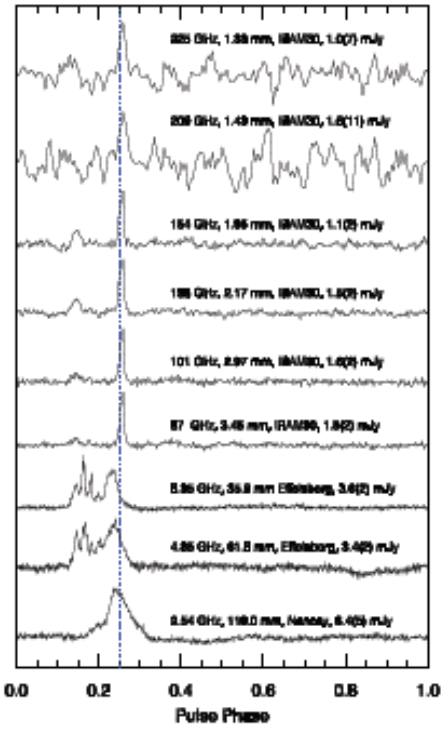
Cycle 3 Study Overview

Focus on ALMA2030 science improvements:

- Correlator upgrade:
  1. Delivering more channels, higher spectral resolution and wider bandwidth
  2. Next generation correlator
- Maximizing point source sensitivity, spatial resolution
  1. Extending VLB phasing to B7, optimize phasing, data reduction
  2. Enable a phased ALMA for pulsars & transients
- Improved data use
  1. Improved calibration through atmospheric spectral features
  2. Data cube visualization enhancements
- Increased sensitivity
  1. 2nd generation receiver mixer studies

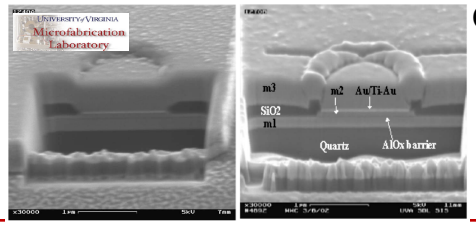
Spectral Resolution & Bandwidth Upgrade of the ALMA Correlator





Galactic Center magnetar at mm λ

Below, UVA SiO_x evaporation (left) versus SiO_2 sputtering (right)



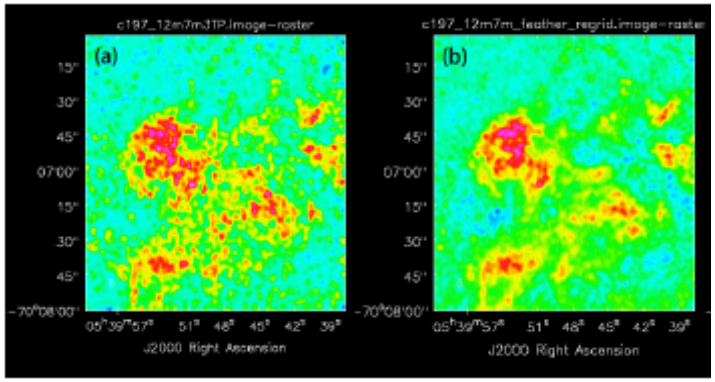
Seven Cycle 3 Studies underway.

NA Development Program

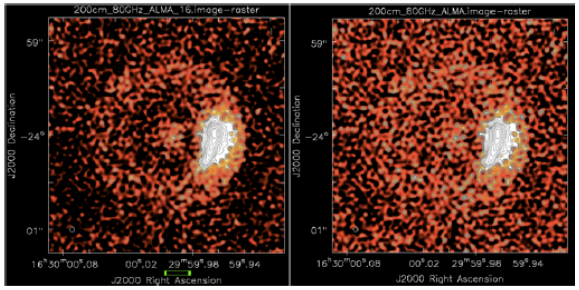
Cycle 4 Study Overview

Acting on ALMA2030 vision:

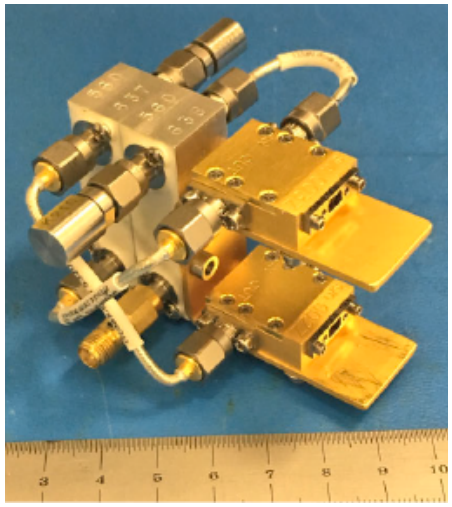
- Increasing receiver sensitivity, bandwidth
  1. Upgraded ALMA B3 mixer block
  2. 2nd generation SIS receiver development
- Expanding ALMA's processing bandwidth
  1. Upgrade of Backend Antenna Article to match correlator upgrade
- Improved data use
  1. Improved interactive CLEAN
  2. Improved imaging with combined arrays
- Maximizing point source sensitivity and resolution
  1. Weak source and spectral line VLBI



Total Power Map to Visibilities (TP2VIS)
a) Joint deconvolution b) Current mode



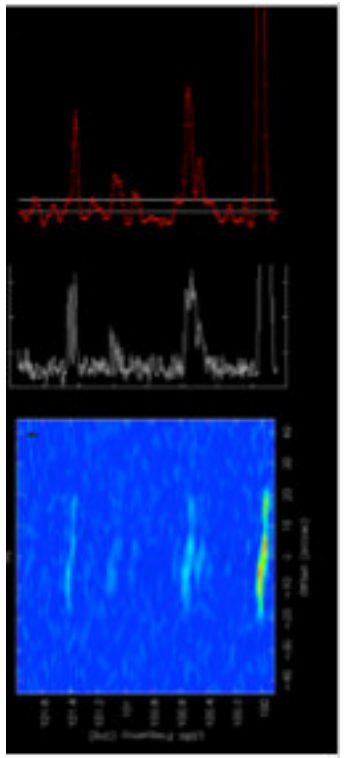
A protoplanetary disk simulation: r: current bandwidth l: upgraded 2x BW.



Development of 2nd Generation SIS Receivers for ALMA: Prototype balanced B6 amplifier 4-12 GHz

Six Cycle 4 Studies underway.

Gains in ALMA Usability and Impact



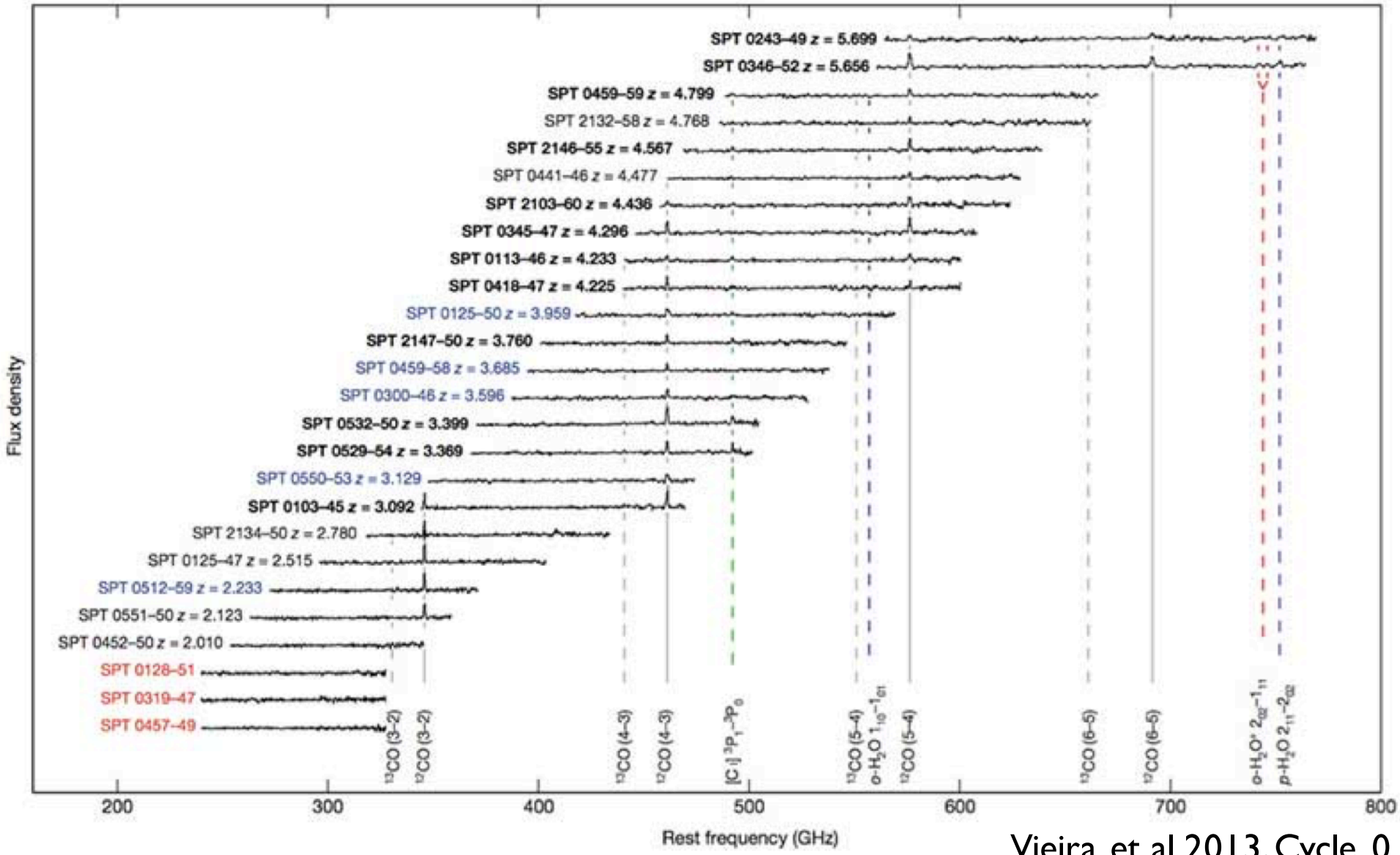
ADMIT line view

- Enhanced data access and usability
  - Three current NA Projects, one NA, one Eu Study move in this direction via *Hardware* or *Software*:
    - AOS-JAO fiber connection (HW: JAO, ESO)
      - Improved connectivity, data flow to ARCs
    - ADMIT data miner (SW: Mundy, PI, U. Md, U. Illinois)
      - Archival spectral line data characterized for all lines
    - CARTA data visualizer (SW: Rosolowsky, PI, U. Alberta)
      - Replaces CASA viewer with enhanced functionality
    - *Data analysis software extensions (SW: Schilke, U.Koeln + NBI + Allegro)*
      - *Provides MAGIX optimization, XClass, ARTIST, automatic line identification*
    - Feature Extraction and Data Cube Visualization through Topology (SW: Rosen, U. S. Florida)
      - New visualization tools for data cubes

Increased spectral grasp: Speed gain

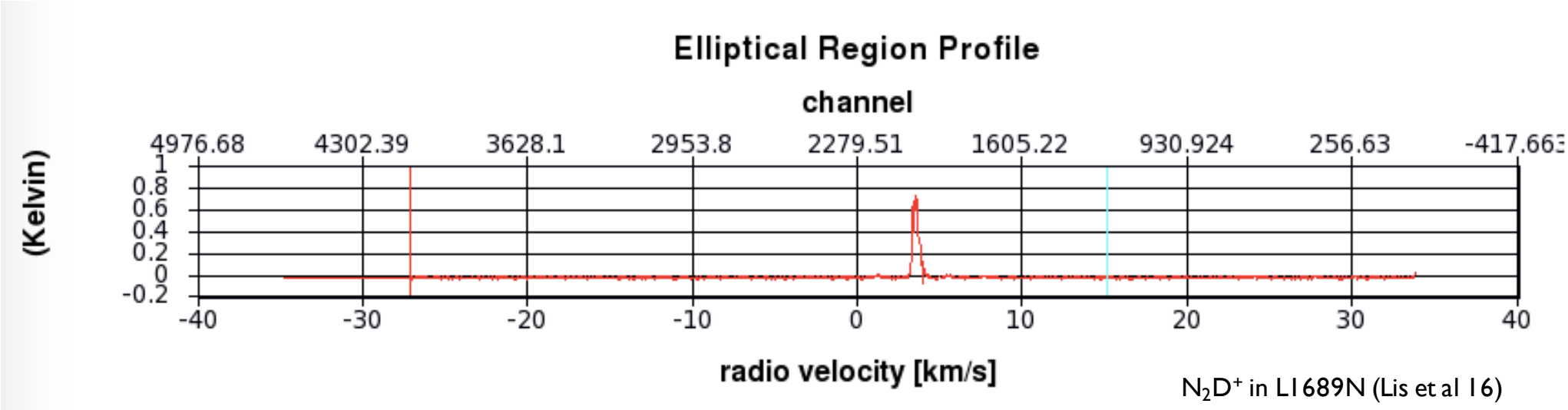
- Increased bandwidth, resolution
  - Spectral Resolution/Bandwidth Correlator Upgrade (HW: Lacasse, NRAO)
    - New chips provide 8x channels, 4bit mode, double bandwidth to current correlator
      - Higher continuum, spectral line sensitivity
      - Broader frequency range for redshift or astrochemical searches
    - Velocity resolution improved, important for lower frequencies
  - Digital Correlation and Phased Array Architectures (HW: Weintroub, SAO)
    - New correlator design replaces baseline correlator using modern architecture
  - *Develop new digitizers design to improve bandwidth (ESO HW: Baudry, U. Bdx)*
    - *Signals digitized at antenna; bandwidth improvements on path to correlator*
  - *GPU spectrometer for TP array (EA HW: KASI)*

Increased Bandwidth Importance in Distant Galaxies



Vieira et al 2013, Cycle 0

Increased Bandwidth: Important for Narrow Lines



N_2D^+ in L1689N (Lis et al 16)

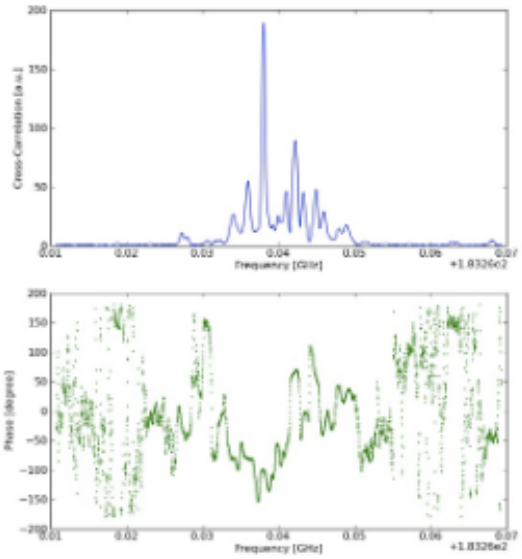
- For high resolution, ALMA's current configuration provides 58 MHz spectral windows, only ~70 km/s at 300 GHz.
- With modern chips, one could achieve the same resolution over ~550 km/s, covering another 6 lines.

Increased sensitivity: Speed gain

- Receiver Upgrades
  - ALMA Band 1 Production (EA+NA+UCh HW: Kemper, ASIAA)
    - Under way, expected availability on ALMA 2019
  - ALMA Band 2 Prototype (NA EA HW: Saini, NRAO)
  - *ALMA Band 2+3 Prototype (UMan+INAF+ESO+EA+UCh HW: Yagoubov, ESO)*
    - *Optics (EA: Gonzalez, NAOJ)*
  - ALMA B5 Full Production (ESO, NA HW: Chalmers, SRON NRAO)
    - Being installed on ALMA, planned available Cycle 5
  - 2nd Generation ALMA Band 6 receiver (HW: Kerr, NRAO)
    - Report available
  - *Upgrade to 2SB ALMA B9 (NL ESO HW: Baryshev, NOVA)*
    - *Prototype to be installed on APEX*
  - 2nd Generation ALMA Band 10 receiver (HW: Kerr, NRAO)
    - Report available
  - ALMA Calibration Source: Calibration at Bands 3,6,7 (EA HW: Kiuchi, NAOJ)
- Technological Advances
  - Advanced Materials & On-wafer Chip Evaluation (HW: Lichtenberger, U. Va.)
  - *High Critical Current Density SIS Junction Device Development (EA HW)*

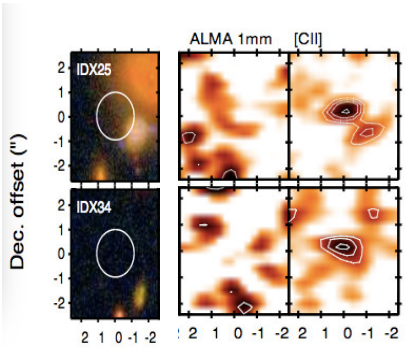
ALMA Band 5 Science Case Summary

- ***Design:*** 2x 4GHz x 2polzn; 163-211 GHz
- **Following Water in Star and Planet Forming Regions–** The 183 GHz line of water emits strongly in many environments and may be measured by ALMA under oft-encountered superb atmospheric conditions; also the 203 GHz line of $H_2{}^{18}O$ may be measured.



Laing. 2016

- **Galaxies Across Cosmic Time –** [C II] and related atomic lines at high redshifts where evolution occurs rapidly. [C II] ASPECS study: 14 6<z<8 candidates; [CII] source density significantly higher than predicted by current models (Lower object z=7.491; upper z=6.357; no optical ID)

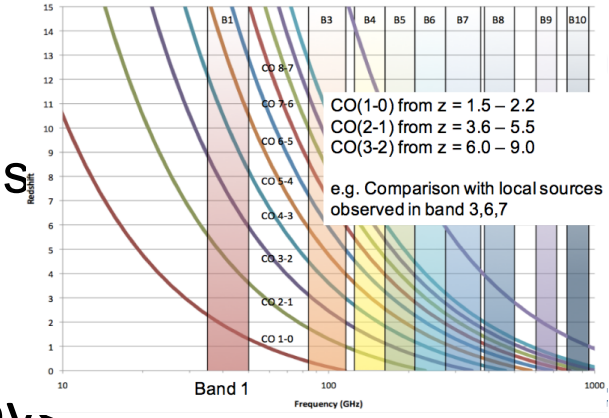


Aravena et al 2016

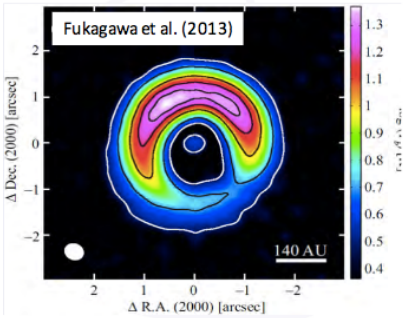
ALMA Band 1 Science Case Summary

- ***Design:*** 1x 8GHz x 2polzn; 35-50^{+}GHz
- **Galaxies Across Cosmic Time –** CO(1-0) at intermediate redshifts where the evolution of galaxies is proceeding rapidly.
- **S-Z Effect** - Follow-up imaging of the large clusters discovered in low resolution (~1') surveys to detect and image shocks, cluster mergers, ICM substructure, physical state of the ICM (electron density, temp).
- **Origin of Planets –** Dust particles emit very inefficiently at wavelengths longer than their size. Band 1 will observe large (cm size) dust particles in proto-planetary disks

Band 1 Science Case
- High-z -



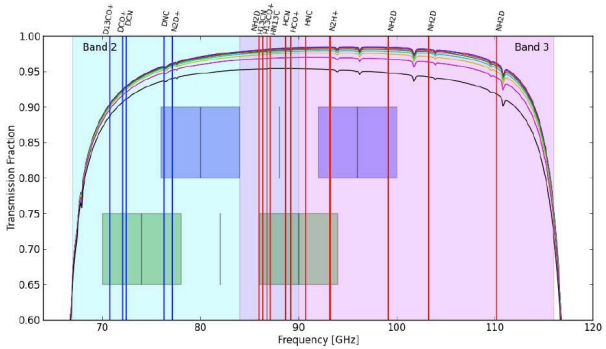
Iono. 2016



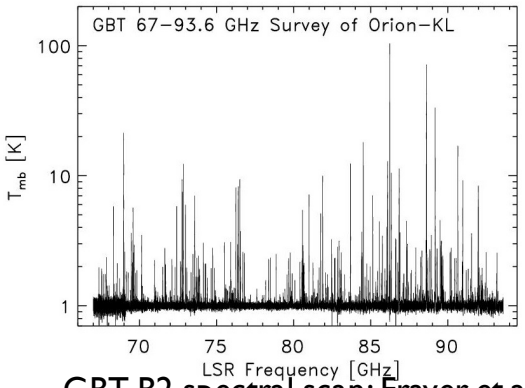
HD142527; Fukugawa et al (2013)

ALMA Band 2^{plus} Science Case Summary

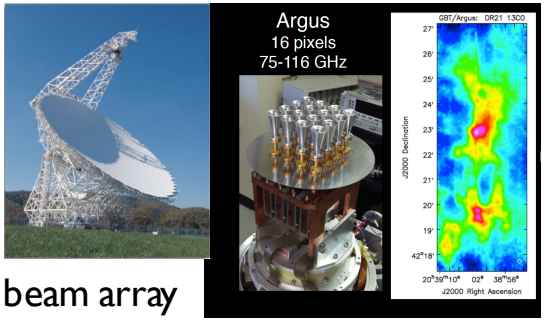
- ***Design:*** 2x 8GHz x 2polzn; 67-95^{+}GHz; One prototype built
- **Stellar and Planetary Origins –** *Deuterium species* and *dense gas tracers:* keys for studies of cold cloud cores from which stars and planets form.
- **Galaxies Across Cosmic Time –** CO(1-0) at intermediate redshifts where the evolution of galaxies is proceeding rapidly and dense gas tracers, such as HCN and HCO+, in local star-forming galaxies.
- **Origin of Life –** Complex organic molecules and pre-biotic molecules in the ISM and comets which are key for studying the conditions from which life eventually forms (unexplored frequencies --- substantial discovery potential in astro/bio-chemistry).



Fuller et al. 2016



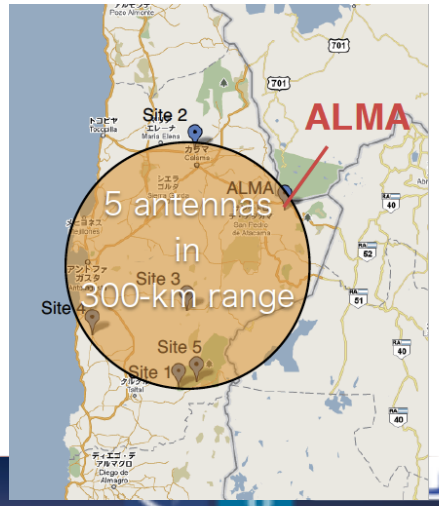
GBT B2 spectral scan: Frayer et al



GBT/ARGUS 16 beam array

Longer Baselines Enable Qualitatively New Science

- VLB arrays
  - ALMA Phasing Project (NA, ESO, EA HW/SW: Doeleman, MIT +)
    - Offered for Cycle 4 (1 Oct 2016=30 Sept 2017)
  - ALMA Phasing System Extensions and Enhancements (HW/SW: Matthews, MIT and others)
    - VLBI capability for B7, spectral lines
  - Pulsars, Magnetars and Transients with Phased ALMA (SW: Cordes, Cornell and others)
    - Phased array software for temporal monitoring
  - *ALMA Extended Array (EA T: Kameno)*
- Connected element array extension?
  - Suggestion to extend baselines to ~30Km for



Immediate Future

- Projects
  - NA issued Call 10 October; Overall funding pool is expected to be larger than previously, before Development funding reached its steady-state value. Projects need not be preceded by ALMA-funded Study; may be externally or jointly funded.
  - ESO: Several projects ready for approval
- Studies
  - NA: New Call March 2017. Some studies which could not be funded during the current Call may be accommodated, should PIs be able to garner resources, address concerns expressed in reviews
  - ESO: Studies Call ended last month 2016: received 17 proposals, selection complete, implementation proposal submitted to ESAC/STC

– NB: EA process differs

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