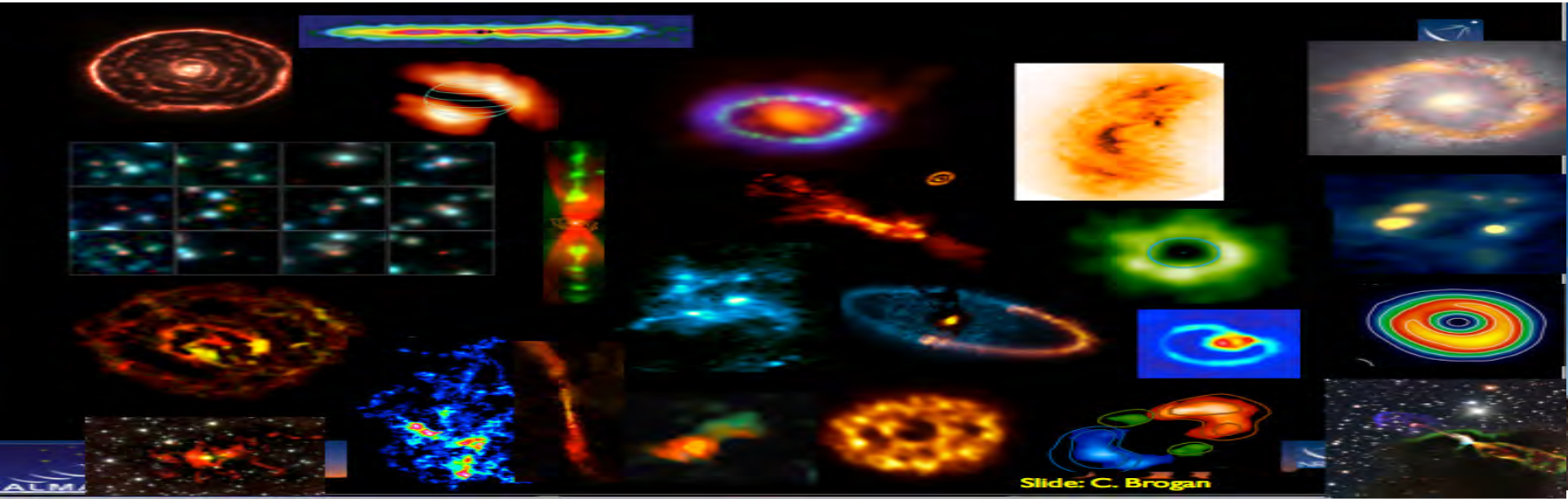
# Sustaining ALMA Science in the Next Decade and Beyond




## A Short Overview

Al Wootten

Jeff Mangum

Atacama Large Millimeter/submillimeter Array

Karl G. Jansky Very Large Array

# Introduction

- Global partnership (shared cost ~1.3 billion 2006$):
  - North America (37.5%: US, Canada, Taiwan)
  - Europe (37.5%: ESO)
  - East Asia (25%: Japan, Taiwan, Korea)
  - In collaboration with Chile as host nation

- Unique high, dry site:
  - 5000m (16,500 ft) in Chilean Atacama desert
  - *Submm sky access through atmosphere*

- 66 submillimeter/millimeter telescopes:
  - 12-m Array – 50 x 12-m
  - Atacama Compact Array (ACA) - 12x7-m, 4x12-m
  - *Spectral line sensitivity: 6600 $m^2$ collecting area*

- Completed 2014

# Sustaining ALMA Science

- Sustaining ALMA's transformational science requires upgrading ALMA to maintain and expand its capabilities.
- The ALMA Operations Plan envisaged and funds an ongoing program of development and upgrade.
- That science sustainability program, ramped up to full funding in 2015 has created new opportunities.
- Vanguard programs identified by the scientific community summarized in ***'ALMA2030: A Roadmap for Developing ALMA'***
- *Studies Reports at science.nrao.edu>NAASC>Development*
- Several projects have been implemented at ALMA
- A Call is now open for funding new Projects

# Goals

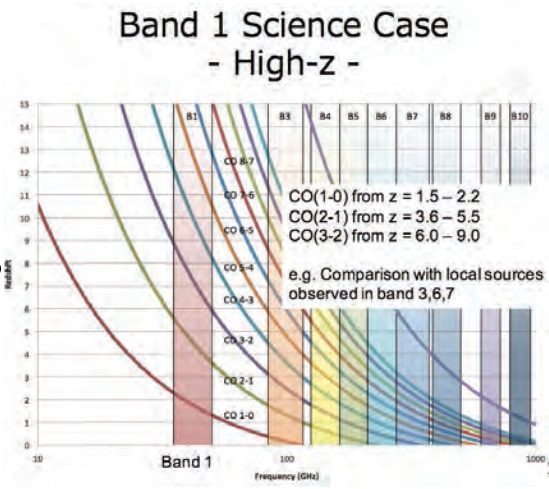
- Identify and support community science priorities, identifying critical drivers
- ALMA uses community strengths in hardware, software and techniques to fund studies to define and enable a science-driven upgrade plan, funded as projects
- Science Sustainability: Identify those community science priorities 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

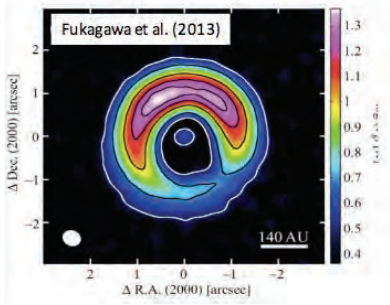
- Finish the Scope of ALMA (B1 + B2 +B5 receivers, VLB capability)
  - Detailed in **ALMA Scientific Specifications and Requirements** (ALMA-90.00.00.00-001-B-SPE)
- ALMA2030
  - 1. Improvements to the ALMA Archive: enabling gains in usability and impact for the observatory.
  - 2. Larger bandwidths 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 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



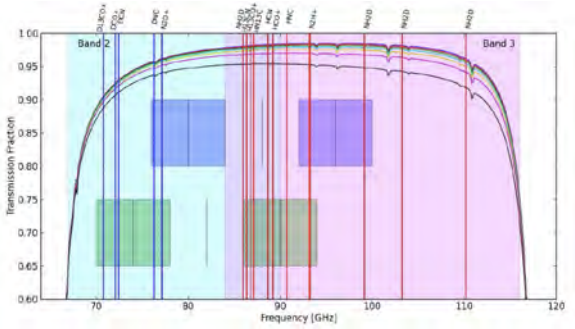

Iono. 2016



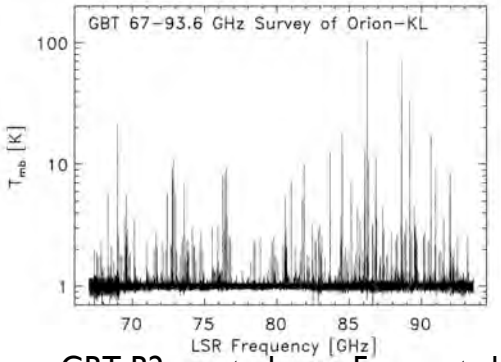

HD142527; Fukugawa et al (2013)

# ALMA Band 2$^{plus}$ Science Case Summary

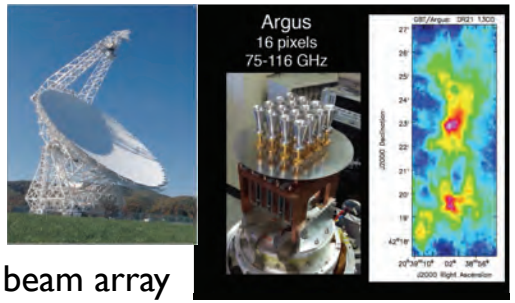
- ***Design:*** 2x 8GHz x 2polzn; 67-95$^{+}$GHz; One prototype built
- **Stellar and Planetary Origins –** *Deuterium species* and *dense gas tracers:* keys for studies of cold cloud cores from which stars and planets form.
- **Galaxies Across Cosmic Time –** CO(1-0) at intermediate redshifts where 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



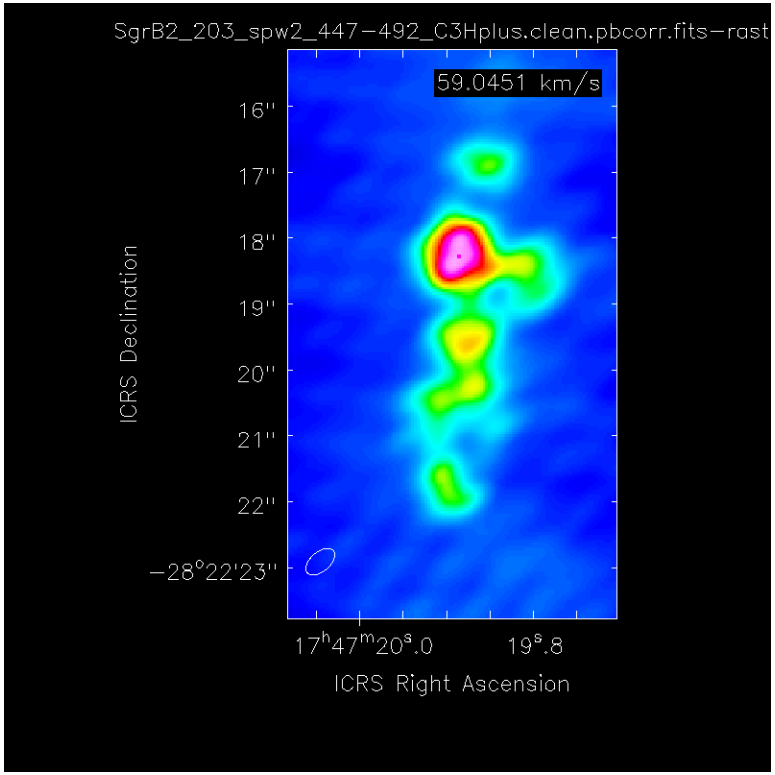
GBT B2 spectral scan: Frayer et al



GBT/ARGUS 16 beam array

# ALMA Band 5 (163-211 GHz)

- Key science:
  - Distant [C II] 8<z<10.5
  - Water in the Universe
- Currently being installed on ALMA
  - Led by ESO/NOVA/GARD; LO components from NA
  - Funding from ALMA Development and EU
  - Excellent noise figure ($T_{rx}$~45K), extended LO
- Commissioning, science verification data available on portal
- Science opportunities in Cycle 5 (April Deadline)



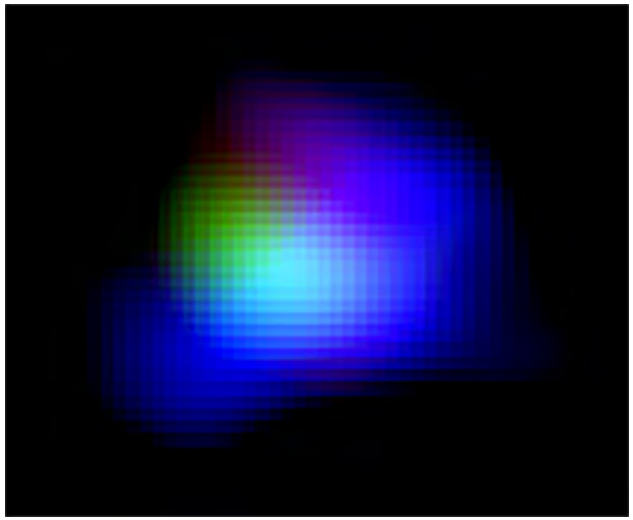

SgrB2N Image from ~12 antennas; SV data

# ALMA Science Frontiers

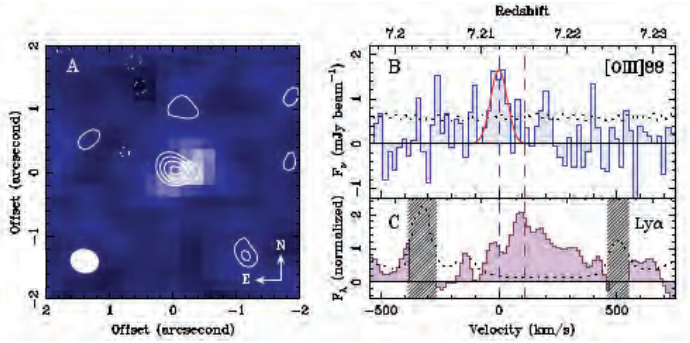
- First Billion Years
  - Good probes include CO, [C II], O and N lines
  - ALMA Band 5 available for Cycle 5: [C II] 8<z<10.5 SV data!
- Evolution of Galaxies and Black Holes
  - Phased ALMA at 3 and 1mm scheduled for Cycle 4
- Local galaxies, Milky Way and the ISM
  - ALMA Data Mining Toolkint (ADMIT) available
- Star and planet formation, biosignatures, chemistry of disks and their offspring
  - Correlator upgrades provide more bandwidth, resolution
- Exoplanets, the Sun and the Solar System

# The First Billion Years

- ALMA Explores the Creation of O, N and C
  - 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+ arXi 1607.02520)
  - [C II] ASPECS study: 14 6<z<8 candidates
    - [CII] source density significantly higher than predicted current models (Aravena+ arXiv:1607.06772)
  - Band 5 enables ALMA exploration of [C II] 8<z<10



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

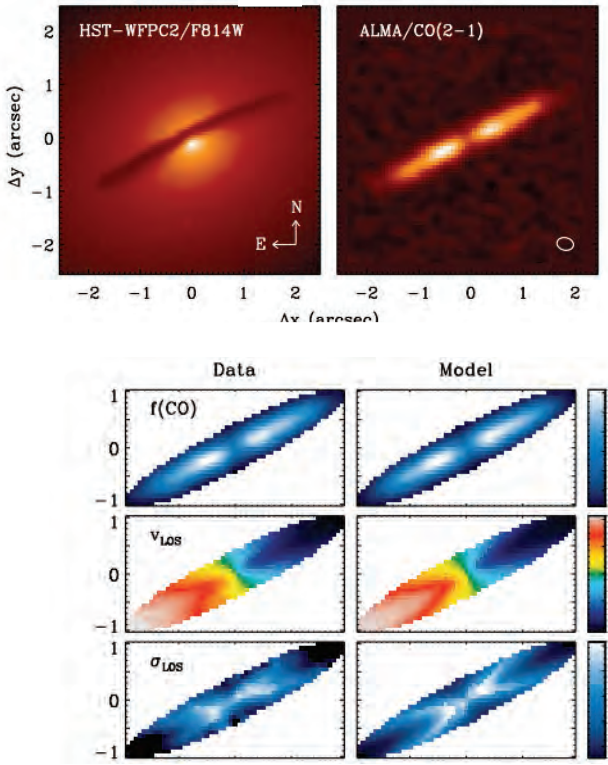



First Oxygen

# Evolution of Galaxies 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

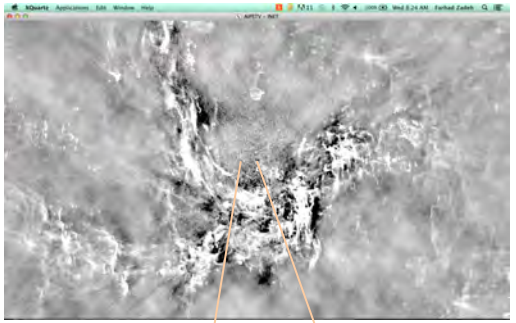
NGC1332: Barth et al.




Through ***better-than HST resolution ALMA sensitively images massive accretion disks***, the most sensitive probe of kinematics available near galactic nuclei.

# Sgr A*: Our Own Central Black Hole

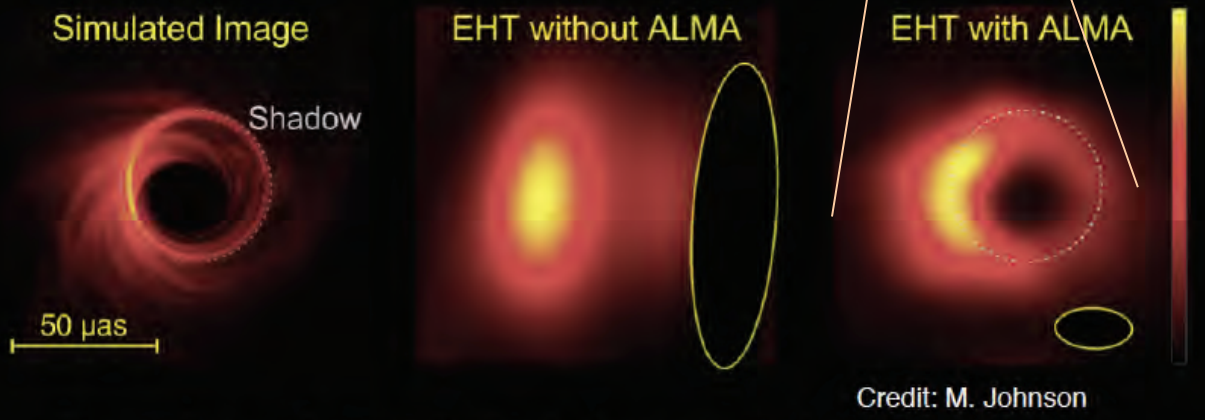
- Phased ALMA: funded with ALMA Development Funds + NSF MRI + Partners
- 7.5 GHz BW
- 64 Gbps aggregate
- Dual polzn Full stokes
- 30 μas ALMA-MK 1.3mm
- Mode offered Cycle 4
  - 22 submitted; 9 (3 at 3mm and 6 at 1.3mm) queued



Galactic Center 34GHz
Yasuf-Zadeh et al (2016)

L.Matthews

Approved APS Science for Cycle 4:
Imaging the Shadow of a Supermassive Black Hole: Sgr A* at 1.3mm
*Team: EHT Consortium, S. Doeleman PI*

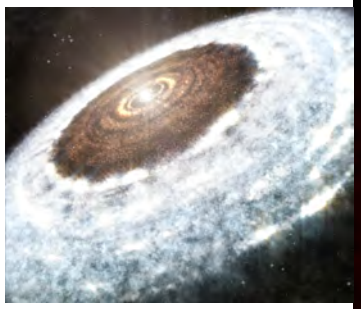



Credit: M. Johnson

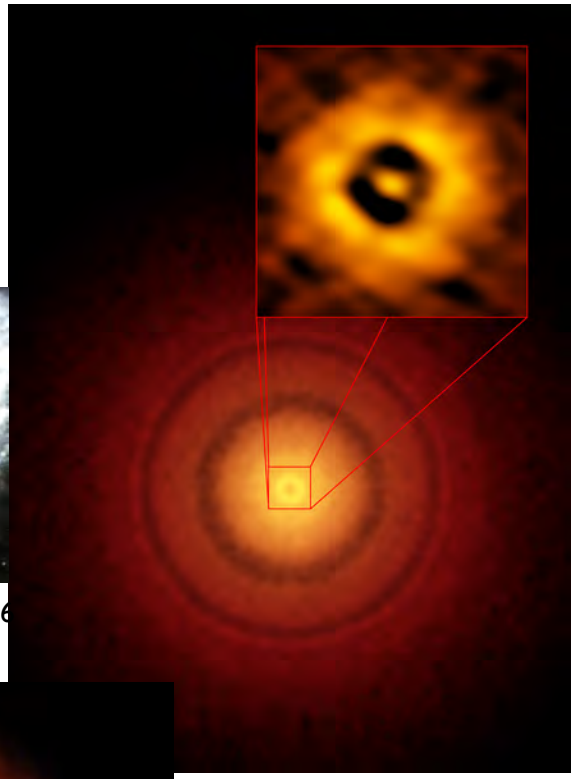
- Observations with an earth-sized telescope at λ~1 mm are needed to resolve structures around Sgr A* on event horizon scales (~30μas).
- The boost in sensitivity of phased ALMA, coupled with its geographical location, will be key to recovering predicted signatures of strong field gravity—including the "shadow" cast by the BH on the surrounding plasma.

# 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 $H_2O$, Cieza+ 2016

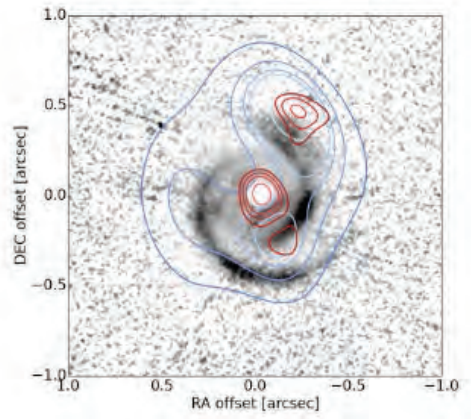


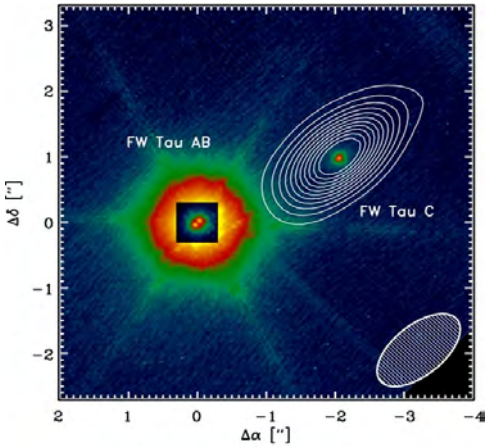
TW Hya Andrews et al 2016


V883 Ori, Cieza+ 2016

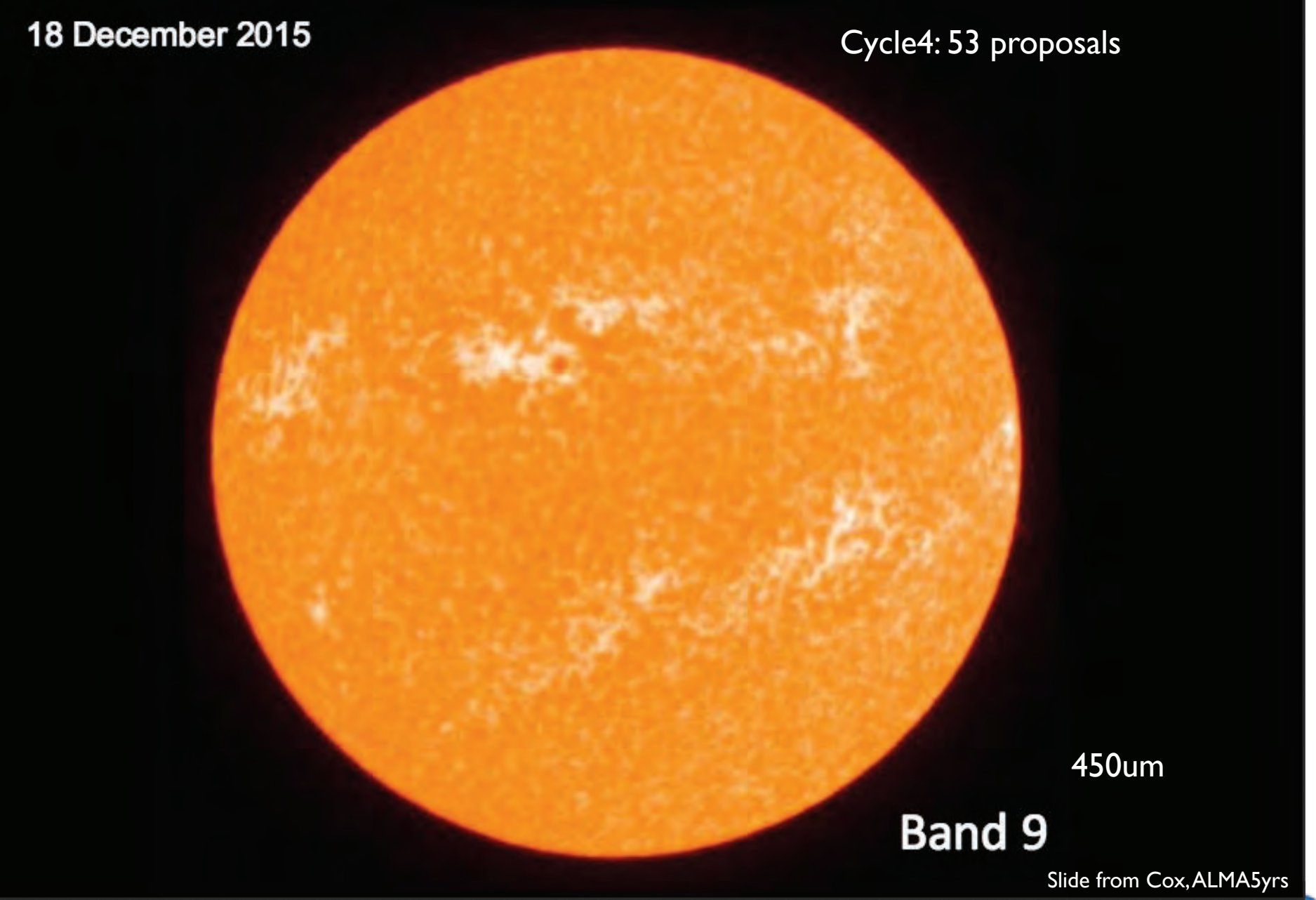
# Exoplanets

- 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



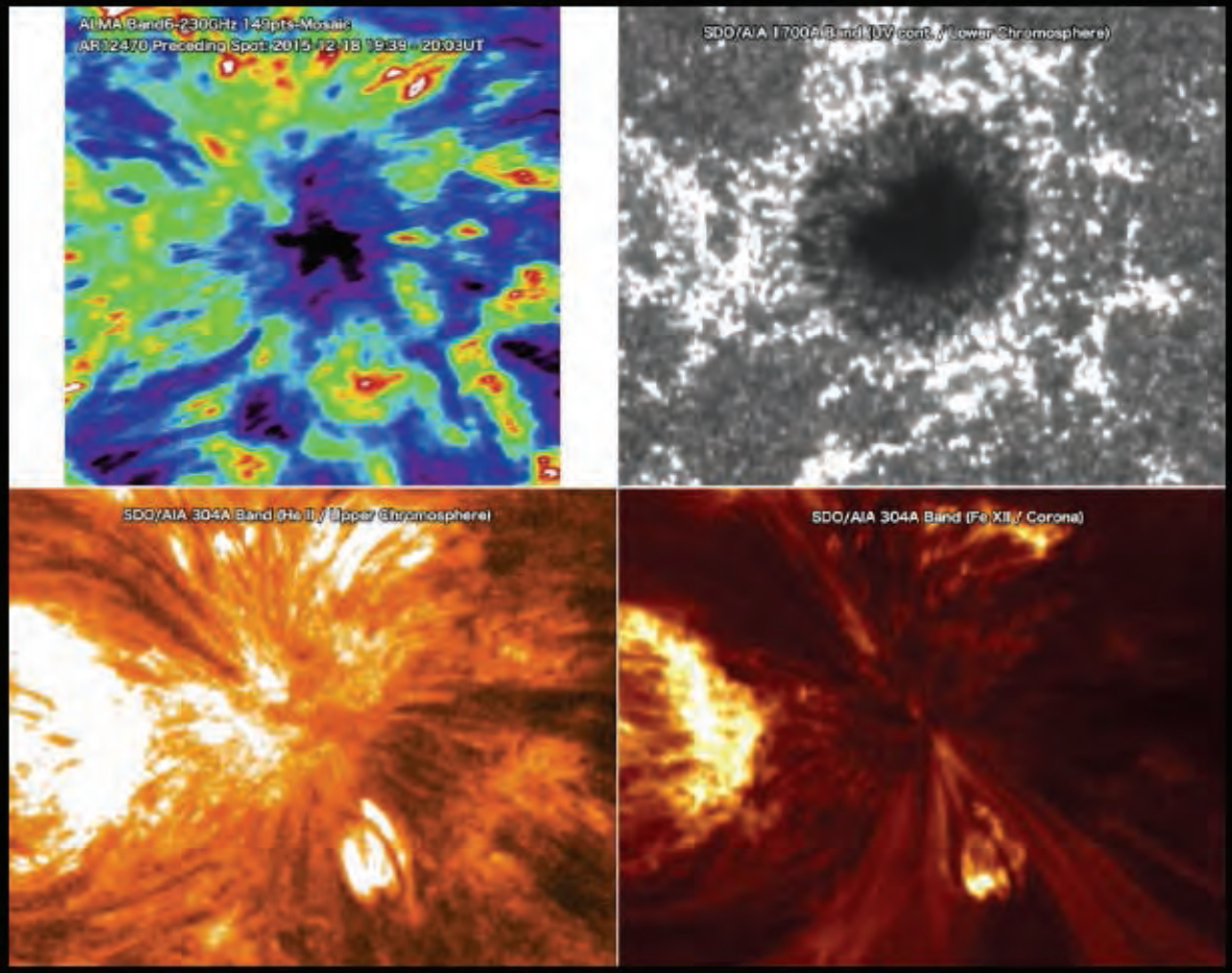




Kraus, A.+ 2015 ApJ798, L23




Slide from Cox, ALMA5yrs

# Interferometric Image of the Sun with ALMA




Slide from Cox, ALMA5yrs

# 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

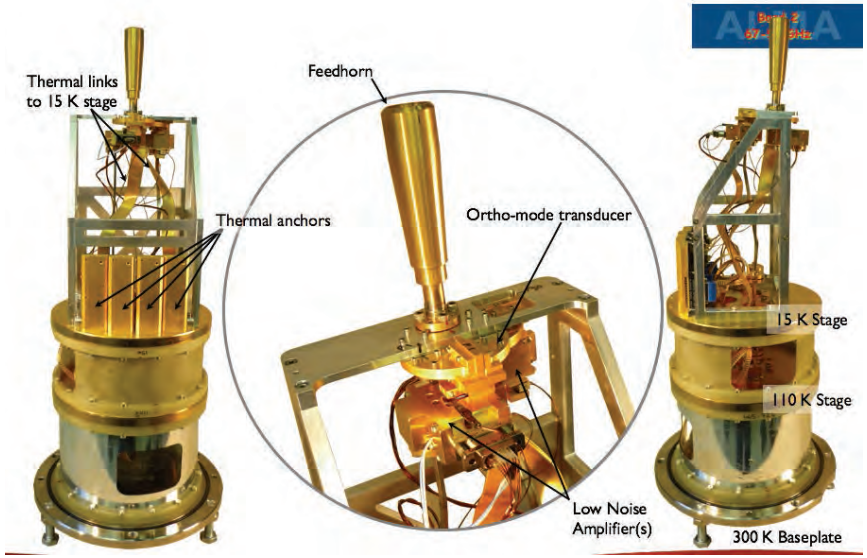
# Some Possible Strategic Initiatives

- 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)

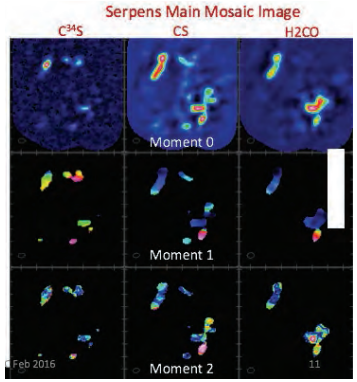
# NA Development Program

**Current Project Overview**

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

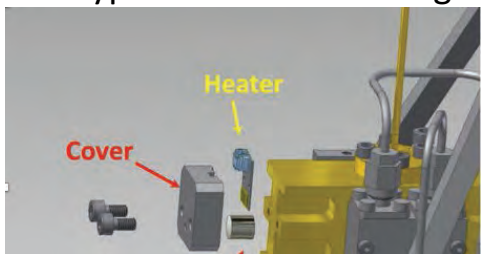



Design & Testing of a Prototype 67-95GHz Cartridge



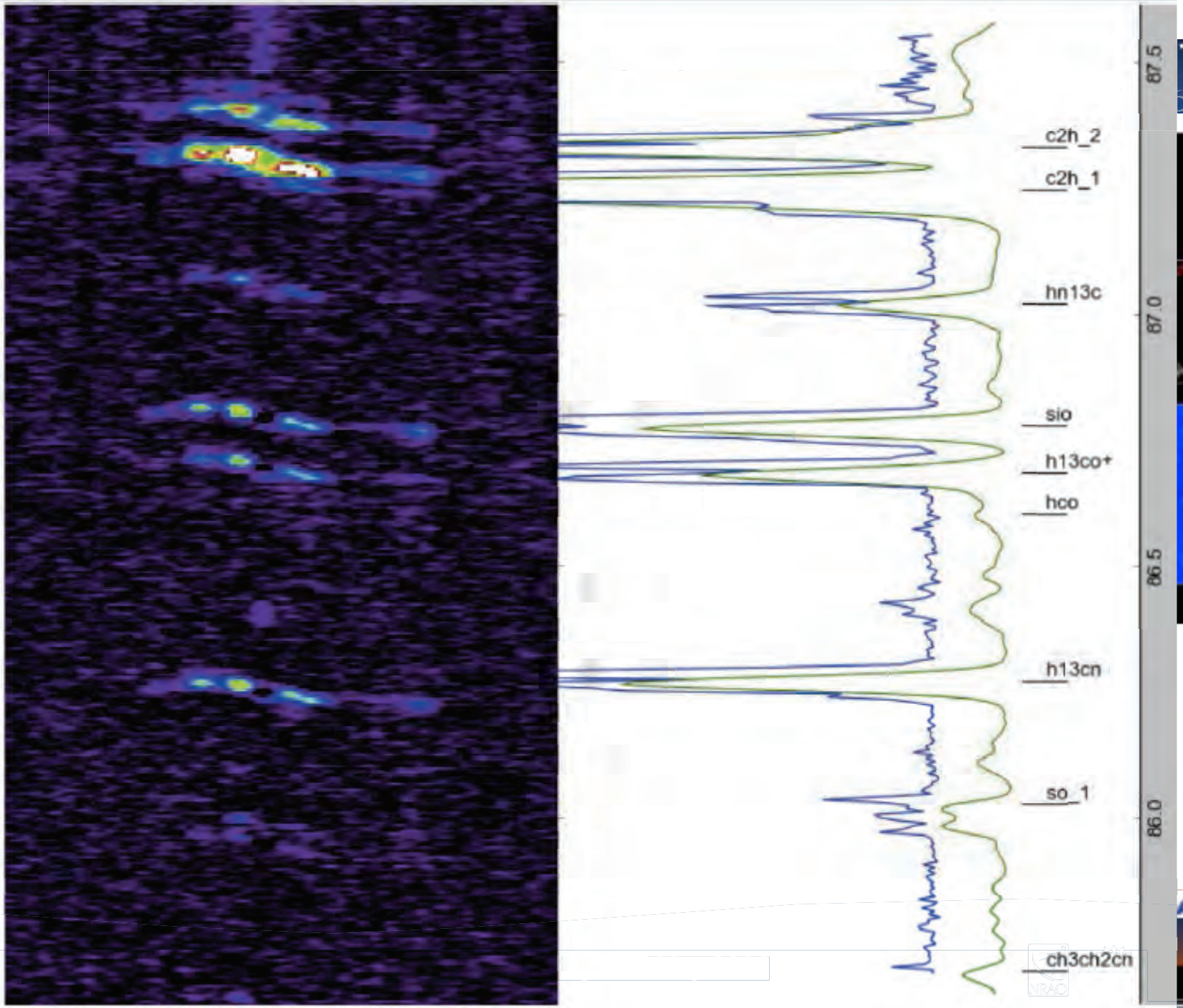

ADMIT products are delivered with data packages, also archived (currently independently)

Fiber Optic Project




Band 3 CCA Heater Installation for Deflux Operation

***Three Projects continue during FY2017.***


c2h_2
c2h_1
hn13c
sio
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hco
h13cn
so_1
ch3ch2cn
87.5
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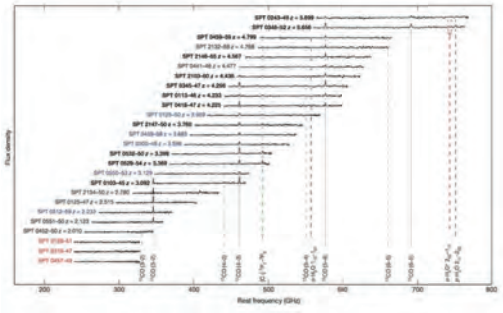
# NA Development Program

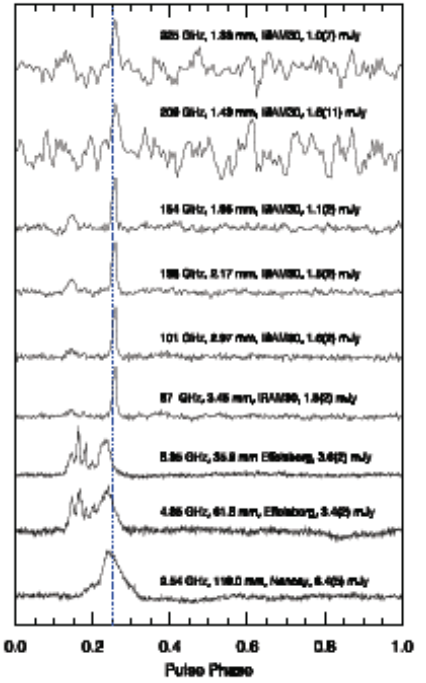
## Cycle 3 Study Overview

Focus on ALMA2030 science improvements:

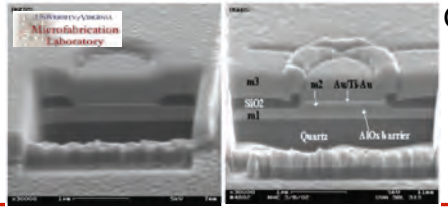
- Correlator upgrade:
  1. Delivering more channels, higher spectral resolution and wider bandwidth
  2. Next generation correlator
- Maximizing point source sensitivity, spatial resolution
  1. Extending VLB phasing to B7, optimize phasing, data reduction
  2. Enable a phased ALMA for pulsars & transients
- 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






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




Galactic Center magnetar at mm λ

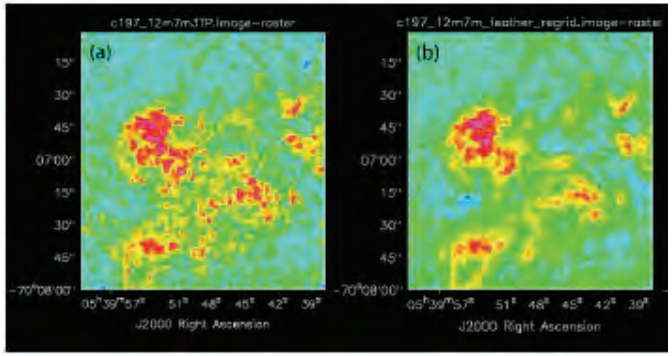
***Seven Cycle 3 Studies underway.***

# NA Development Program

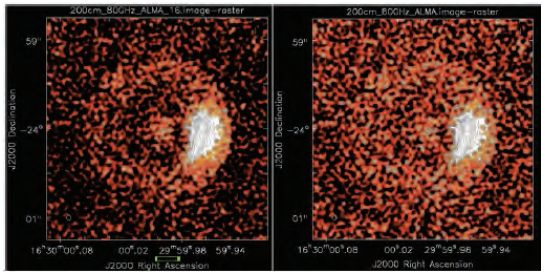
## Cycle 4 Study Overview

Acting on ALMA2030 vision:

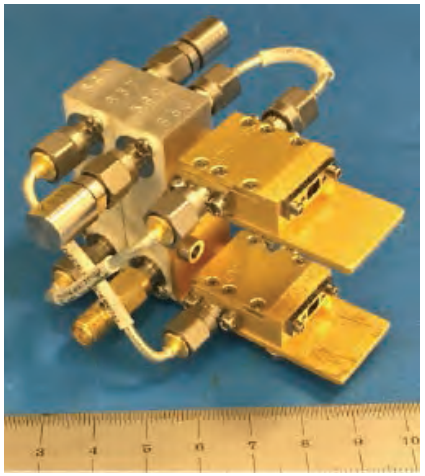
- Increasing receiver sensitivity, bandwidth
  1. Upgraded ALMA B3 mixer block
  2. 2nd generation SIS receiver development
- Expanding ALMA's processing bandwidth
  1. Upgrade of Backend Antenna Article to match correlator upgrade
- Improved data use
  1. Improved interactive CLEAN
  2. Improved imaging 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.

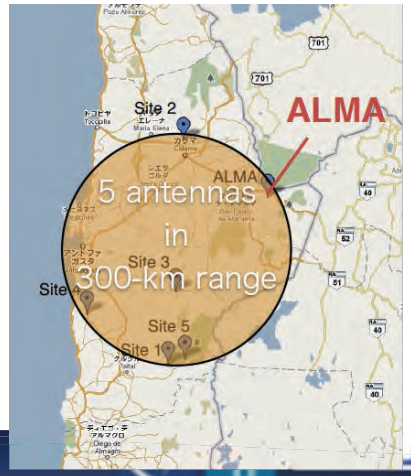


Development of 2nd Generation SIS Receivers for ALMA: Prototype balanced B6 amplifier 4-12 GHz

***Six Cycle 4 Studies underway.***

# 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?
  - Extend baselines to ~30Km for beam matching?
  - ***October Workshop planned, Japan***



# Immediate Future

- Projects
  - NA issued Call 10 October; Overall funding pool is expected to be larger than previously, $11.5M. 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 1 March 2017. Expect to offer new two-year Strategic Study category.
  - ESO: Studies Call ended September 2016: received 17 proposals, selection complete, implementation proposal submitted to ESAC/STC

– NB: EA process differs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