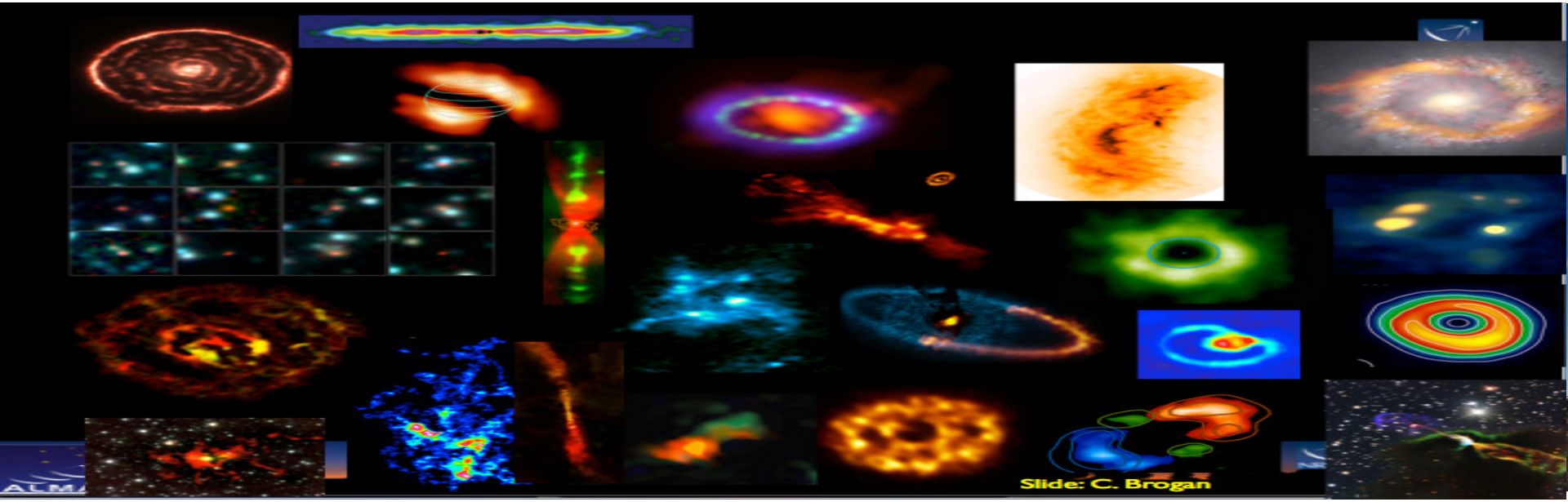
# ALMA/NA Development Status

ALMA Future Science Development Program Workshop




## A Short Overview

Al Wootten

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

# ALMA/NA Strategic Goals

- Fifteen years have passed since ALMA specifications were written and construction began
- ALMA now operates at or close to the original requirements
- Cutting-edge technology has advanced tremendously over the past decade and a half
- The community, ALMA Science Advisory Committee and Integrated Science Team have written ALMA2030, an initial framework for developing ALMA to address their scientific vision
- We engage the community to outline a strategy that will enable ALMA to remain at the forefront of astronomical discovery

# Goals

- Identify and support community science priorities, identifying critical drivers
- Using community strengths in hardware, software and techniques to fund studies to define and enable a science-driven upgrade plan for ALMA
- Identify those community science priorities which can produce transformational results at the horizon and plan for their realization

# ASAC Recommended Development Paths

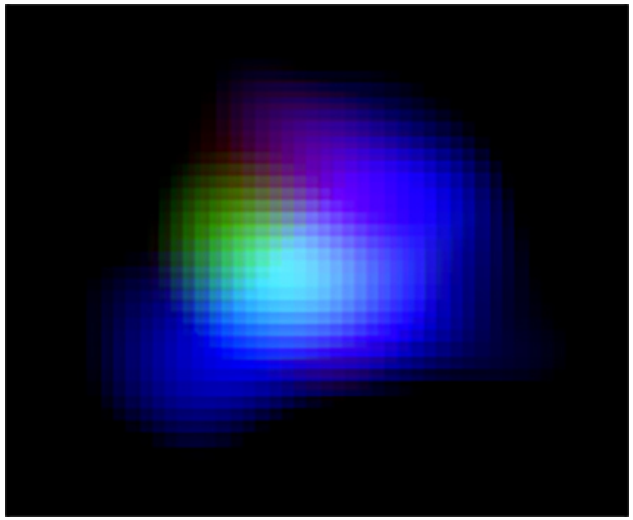
- Finish the Scope of ALMA (B1 + B2 receivers, VLB capability)
  - Detailed in **ALMA Scientific Specifications and Requirements** (ALMA-90.00.00.00-001-B-SPE)
- 1. Improvements to the ALMA Archive: enabling gains in usability and impact for the observatory.
- 2. Larger bandwidths and better receiver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

# ALMA Science Frontiers

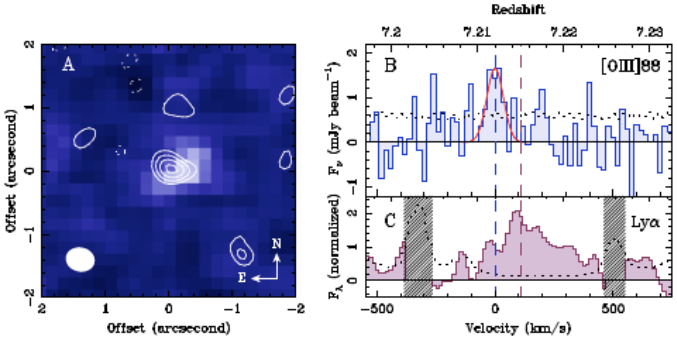
- First Billion Years
- Evolution of Galaxies and Black Holes
- Local galaxies, Milky Way and the ISM
- Star and planet formation, biosignatures, ingredients of habitable worlds—the $H_2O$ trail
- The Sun Exoplanets and the Solar System

# The First Billion Years: Metals, Dust, First Galaxies

- Science Drivers
  - 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
- Instrumental needs
  - Sensitivity, to detect weak signals
  - Spectral grasp, to cover appropriate redshifted lines



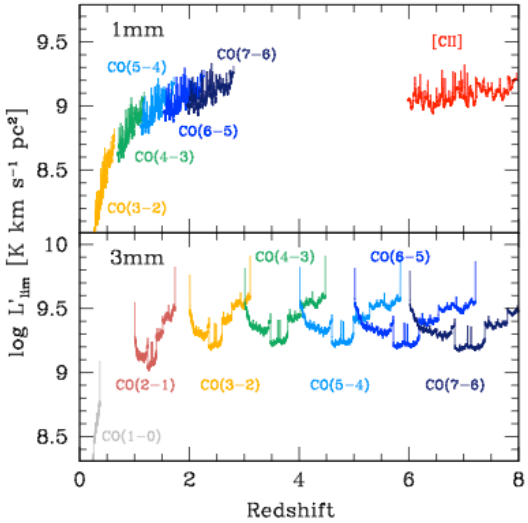
[O III] 88μm @z=7.2 in SXDF-NB1006-2 imaged by ALMA (Inoue et al 2016). Blue: Lyα, Red: UV

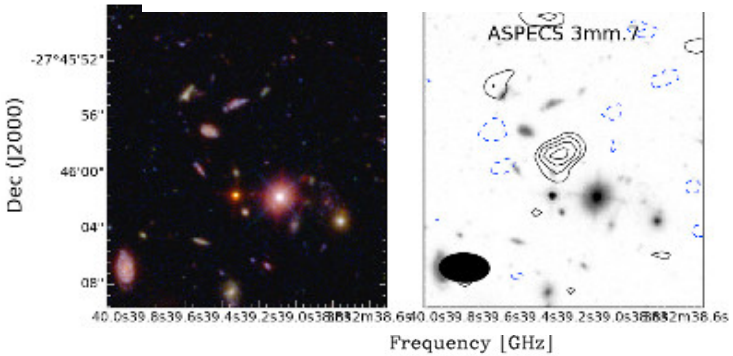


# Evolution of Galaxies and Black Holes

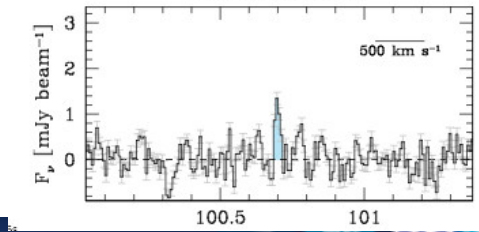
- Science Drivers
  - Kinematics measure of nearby nuclear Black Hole mass
  - Kinematics characterize galaxies through cosmic time
  - Spectra characterize chemical content
- Instrumental needs
  - Sensitivity: detecting weak signals
  - High resolution, probing $\mathcal{R}_{\text{galactocentric}}$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

ASPECS Spectral coverage deCarli+ 2016

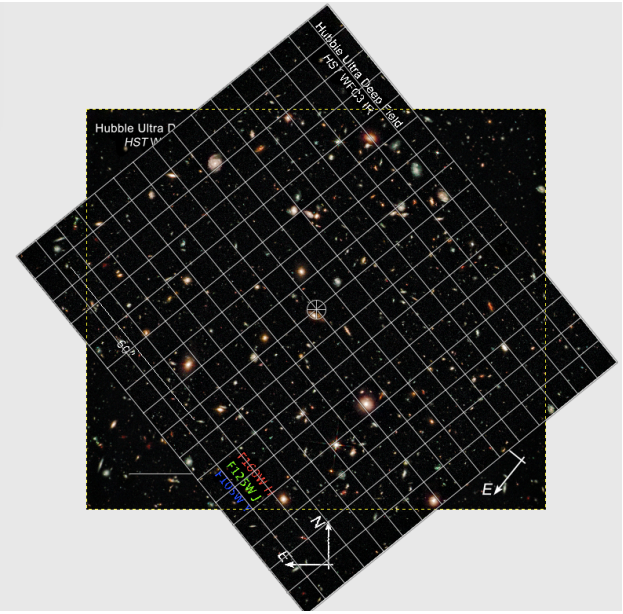


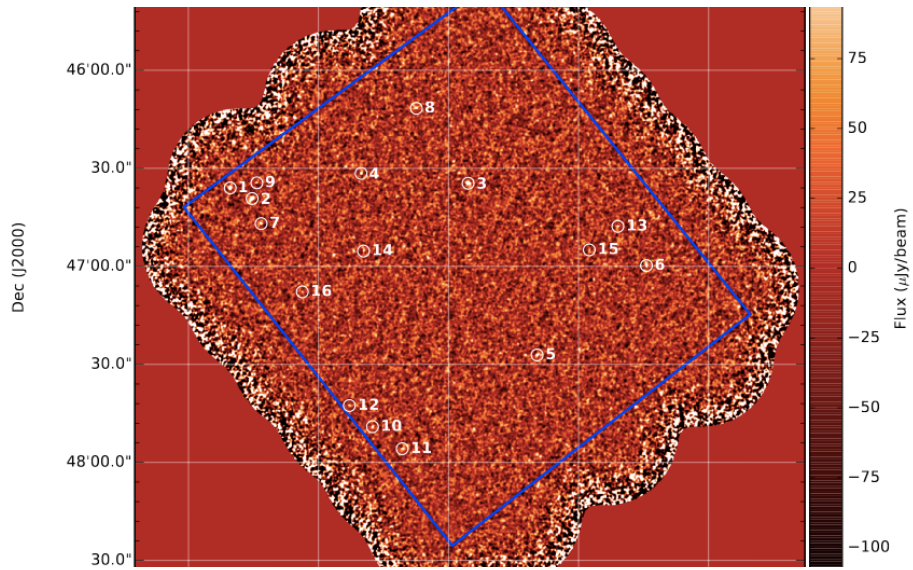

Weakest 3mm ASPECS detection. Walter+, 2016



# HUDF – ALMA DF




WFC3/IR on HST

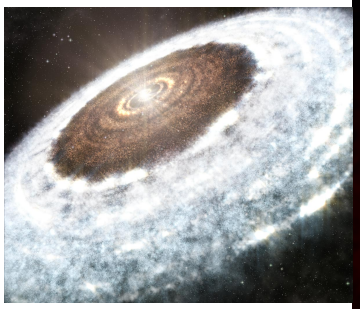



Dunlop et al (2016)

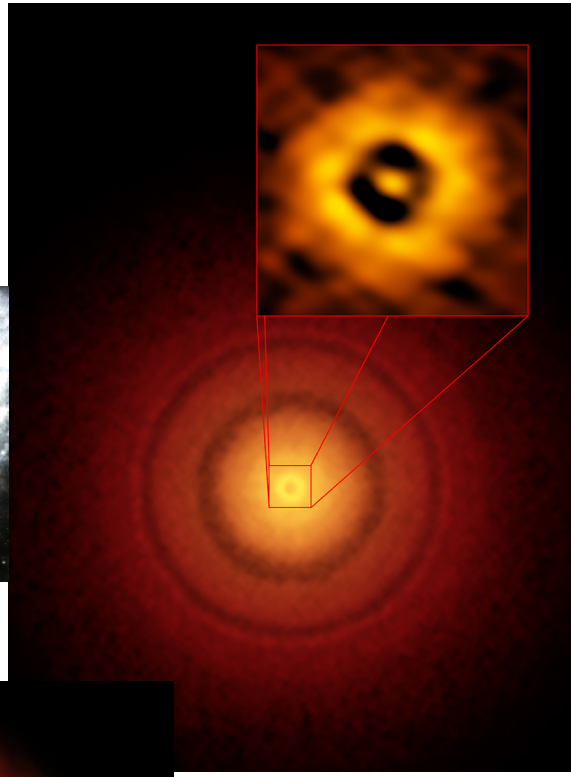
Deep ALMA 1.3mm imaging covering in 45 pointings the full 4.5 sq arcmin of the Hubble Ultra Deep Field (HUDF) reaching 35 microJy, at a resolution of 0.7 arcsec. 16 sources with flux densities S(1.3) > 120 microJy, all with secure galaxy counterparts with robust redshifts (<z> = 2.15).

# Star & Planet Formation, Ingredients of Habitable Worlds

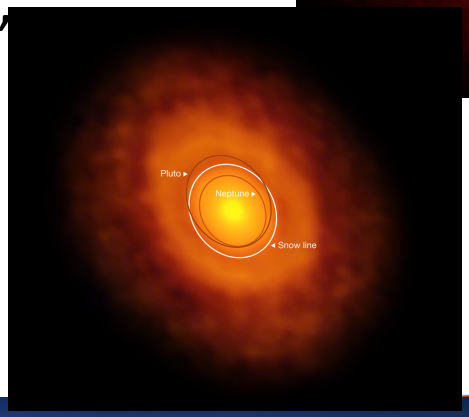
- Disk structure and composition
  - around stars and around planets;
  - disk evolution
- Instrumental needs
  - Sensitivity,
  - Spectral grasp,
  - Spatial and spectral resolution,
  - Imaging precision



V883 Ori, Cieza+ 2016



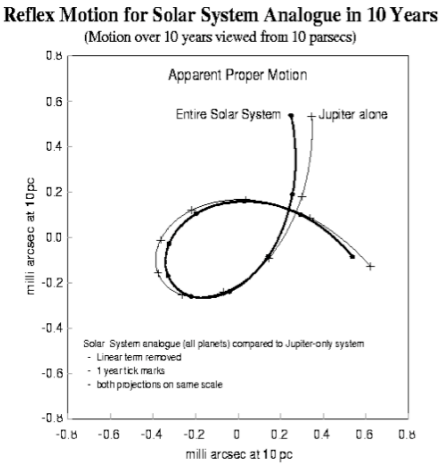
TW Hya Andrews et al 2016

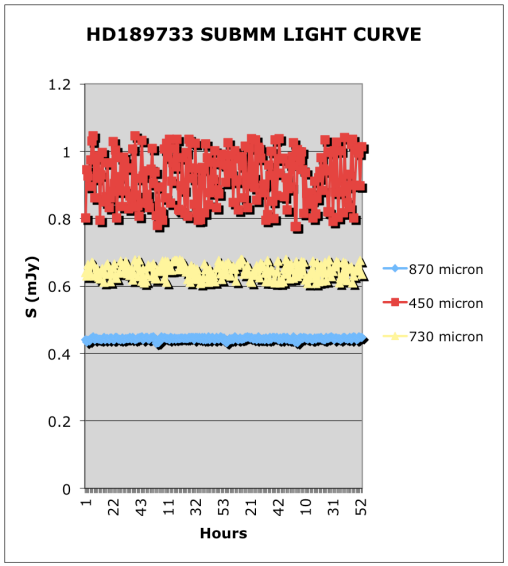



V883 Ori, Cieza+ 2016

# Characterization of Planets

- Characterization of extrasolar planets
  - Astrometry: measuring stellar reflex motions
  - Transit measurements
- Planets at home
- Instrumental needs
  - Sensitivity,
  - Spectral grasp,
  - Spatial resolution,
  - Technique



# 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

# ALMA Development

- ALMA Operations included development funds
  - Ramped up to steady-state level by FY2015
  - First priority was to build to unfunded specifications (receiver bands, VLBI)
- ALMA Integrated Science Team working with the ALMA Science Advisory Committee (ASAC), developed ***PATHWAYS TO DEVELOPING ALMA*** (ALMA2030)
- Using information gleaned from various sources, ***Pathways*** informs discussions leading to assembly of a roadmap for ALMA improvements

# Development Areas

- Sensitivity--could achieve that of 8 additional antennas with each of
  - Use of additional antennas (near-term)
  - Correlator accuracy (spectral line, near-term)
  - Increased bandwidth, correlator upgrade to 2x or 4x
- Resolution—5millarcsec
  - Imaging disks down to habitable zone scales (continuum). Near 350µm corresponds to 16 km, difficult; at lower frequencies ~20-60km, requires longer baselines
- Field of View
  - Some gains possible with efficiency improvement, On-the-fly
  - Multi-pixel or beam-forming arrays; more important at shorter wavelengths probably

# ALMA/NA 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)

- Opening Spectral Windows
  - Building a next generation receiver (2x16GHz) for B2+
  - SIS foundry work for high frequency junctions
  - Upgrading Band 6, Band 3 to the next generation
- Preparing for Longer Baselines -> Higher Angular Resolution
  - Upgrade of the CLOA (see talk, not yet funded)
- Increasing Imaging Speed
  - Array receivers on a limited part of the array (see talks, not yet funded)

# Process

- Through responses to community Calls, ALMA partners craft a collection of *Studies* which detail the ultimate goals of the ALMA Development Vision
- As a result of Studies, *Projects* may be undertaken to improve capabilities or to realize new capabilities according to the Vision
- Studies and Projects follow ALMA2030 pathways
- Prioritization then leads to a *Plan* to achieve Vision
- Current goals include
  - *Maximizing sensitivity and throughput by increasing bandwidth*
  - *Completing and upgrading receiver complement to provide that bandwidth*

# ALMA Development Overview

- ALMA NA Operations comprises NRAO and NRC-HIA but anyone in the NA Operations partnership may participate in Development
- Projects are large efforts, budget ≥$.2M taking several years, culminating in major new capabilities or improvements
  - Begin with recommendation of ALMA Executive(s), perhaps in response to a Community Call
  - Need approval of ALMA Development Steering Committee, ASAC and recommendation of ALMA Director to ALMA Board
- Studies and small projects are shorter term, lower budget endeavors
  - Normally, Studies are initiated by a Community Call for Ideas
  - May lead to projects, singly or collectively
  - Funding at discretion of ALMA Executives
- Both are guided by a constellation of potential improvements, many listed in a document known as 'ALMA2030'

# Progression of ALMA Development Components

| ALMA Development Study | |
|---|---|
| Next Gen ALMA Data Viewer | Unleashing Large Dataset Science |

| ALMA Development Project | |
|---|---|
| CARTA | ALMA Data Mining Toolkit |

| ALMA Enhancement | |
|---|---|
| Implementation/CASA | ADMIT (Sept 2016) |

# Progression of ALMA Development Components

## ALMA Development Study

- ALMA B1 Study
- Mm/Submm VLB with ALMA

## ALMA Development Project

- ALMA B1 Project, Construction (EA)
- ALMA Phasing Project

## ALMA Enhancement

- Planned implementation 2019
- Cycle 4 VLBI

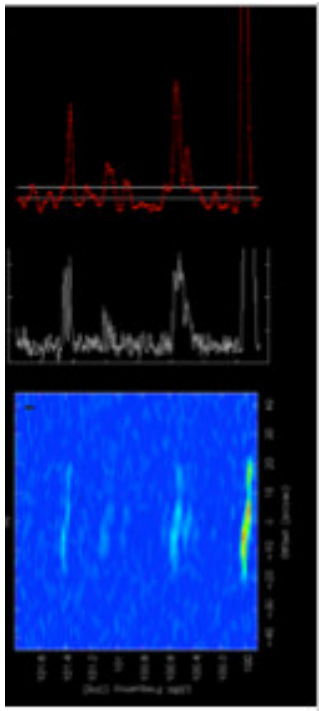
# A ROAD MAP FOR DEVELOPING ALMA

ASAC Recommendations for ALMA 2030

- 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)
- Recommended development paths (ASAC)
  - 1. Gains in ALMA usability and impact through improved data access.
  - 2. Larger spectral grasp, better receiver sensitivity enable gain in speed.
  - 3. Longer baselines: enabling qualitatively new science.
  - 4. Increasing wide field mapping speed: enabling efficient mapping.
- What are the NA objectives?
  - Augment ALMA scientific capabilities while benefitting NA goals.
  - E.g. B2 has clear complementarities with ARO, GBT and ngVLA.
  - Next Generation Correlator also has clear complementarities.

# Gains in ALMA Usability and Impact

- 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 Alberta)
      - Replaces CASA viewer with enhanced functionality
    - *Xclass extensions (SW: Schilke, U. Koln)*
      - *Provides models of spectral line observations*
    - Feature Extraction and Data Cube Visualization through Topology (SW: Rosen, U. S. Florida)
      - New visualization tools for data cubes



ADMIT line view

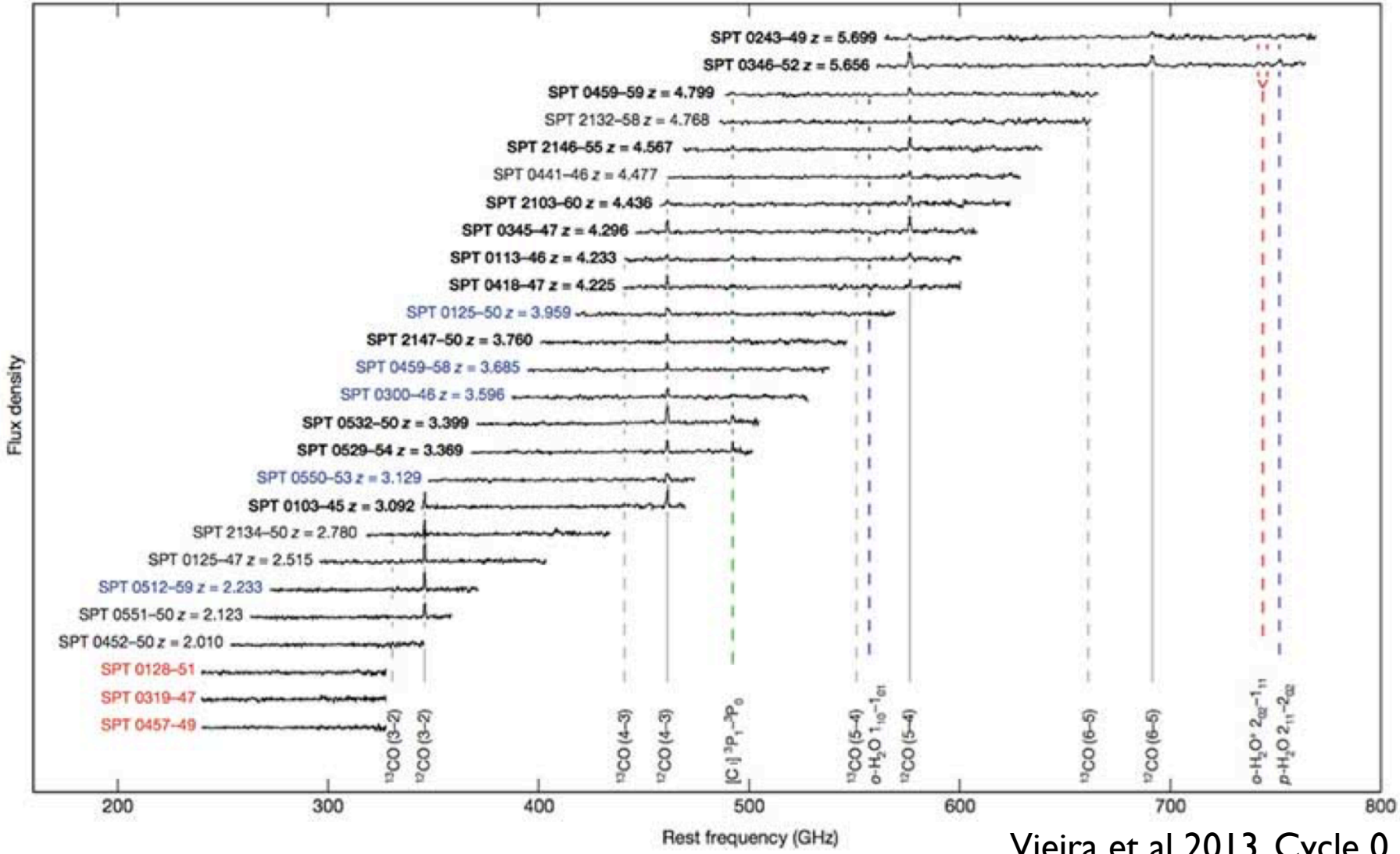
# Data Usability Tools

- Several studies increase usability via techniques
  - Community science tool development (T: Leroy, Ohio State)
    - Tool development and repository
  - Calibration Refinements for ALMA Imaging (T: Wilson, NRL)
    - Sought to improve water vapor modeling for ALMA site
  - Improving the Calibration of Atmospheric Spectral Features (T: Hunter, NRAO)
    - Coarse calibration cannot accurately model the atmosphere, which has narrow lines

# Increased spectral grasp: Speed gain

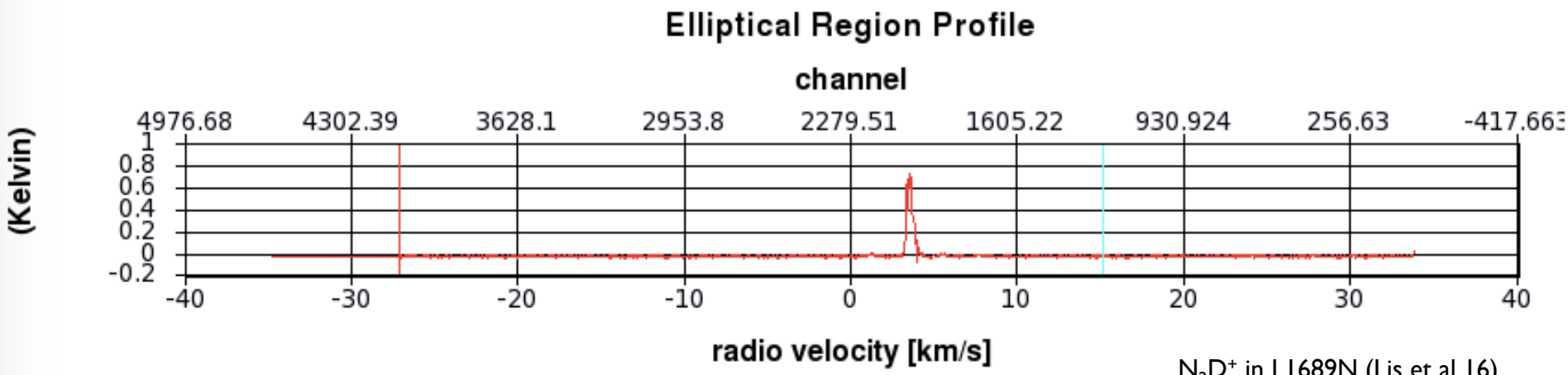
- Increased bandwidth, resolution
  - Spectral Resolution/Bandwidth Correlator Upgrade (HW: Lacasse, NRAO
    - New chips provide 8x channels, 4bit mode, double bandwidth to current correlator
      - Higher continuum, spectral line sensitivity
      - Broader frequency range for redshift or astrochemical 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 receiver; 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)

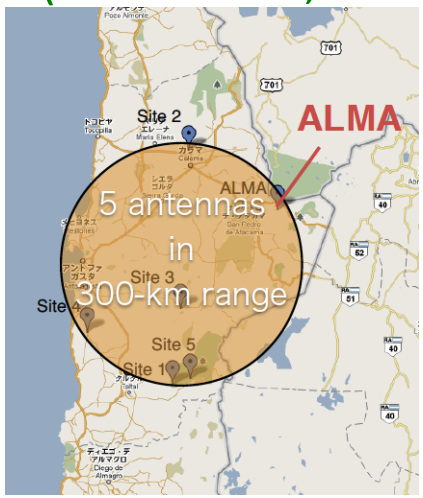
- For high resolution, ALMA's current configuration provides 58 MHz spectral windows, only ~70 km/s at 300 GHz.
- With modern chips, one could achieve the same resolution over ~550 km/s, covering another 6 lines.

# 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)
  - *Design and components for ALMA B2/3 (EA ESO HW: iALMA, Manchester)*
  - 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 for ALMA B9 (ESO HW: NL)*
    - *Prototype to be installed on APEX*
  - 2nd Generation ALMA Band 10 receiver (HW: Kerr, NRAO)
    - Report available
- Technological Advances
  - Advanced Materials & On-wafer Chip Evaluation (HW: Lichtenberger, U. Va.)
  - *High Critical Current Density SIS Junction Device Development (EA HW)*

# Longer Baselines Enable Qualitatively New Science

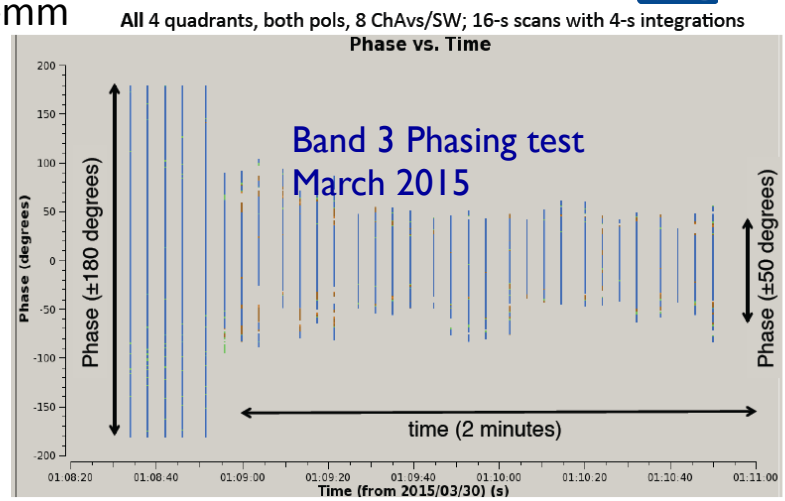
- VLB and connected element arrays
  - ALMA Phasing Project (NA, ESO, EA HW/SW: Doeleman, MIT +)
    - Offered for Cycle 4 (1 Oct 2016=30 Sept 2017)
  - ALMA Phasing System Extensions and Enhancements (HW/SW: Matthews, MIT)
  - Pulsars, Magnetars and Transients with Phased ALMA (SW: Cordes, Cornell)
  - *ALMA Extended Array (EA T: Kameno)*



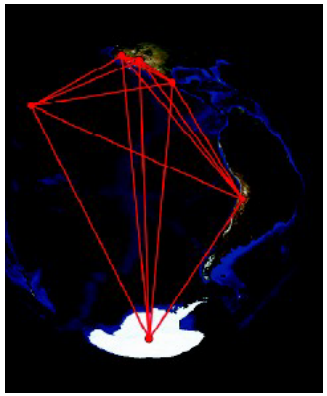
# ALMA Phasing Project (APP) (Development Project – NA)

Phase-up ALMA and record the summed signal for mm/sub---mm VLBI:

- Project accepted in 2012, CDR in May 2013
- Hardware Accepted: Dec 2014
  - Includes new extremely accurate Hydrogen maser clock now used throughout ALMA
- Commissioning: Jan-Sept 2015
- Initially only continuum, spectral lines later



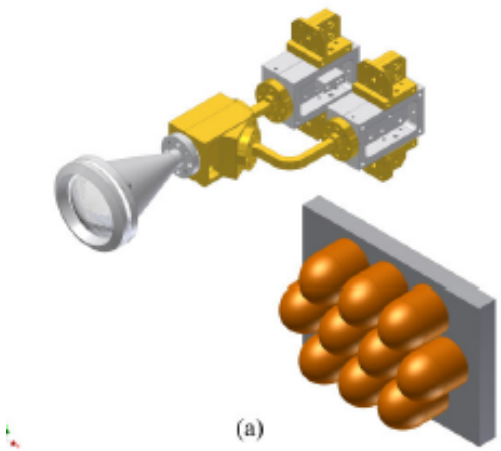

- Key Science: Testing general relativity using the black hole shadow



General relativity predicts that the shadow of a black hole should be circular (middle panel), but a black hole that violates the no-hair theorem could have a prolate (left) or oblate (right) shadow. Future images of nearby supermassive black holes will be able to test this prediction. (figures courtesy D. Psaltis and A. Broderick)

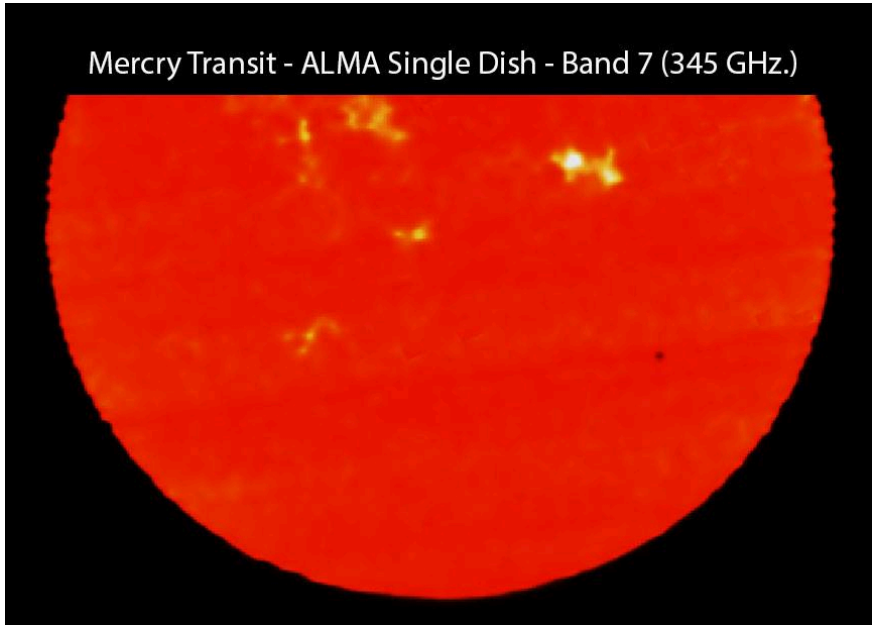
# Increased Wide Field Imaging Speed

- Array receivers, fast imaging
  - Millimeter Camera (HW: Claude and Henke, NRC-HIA)
  - Solar Observing (NA, ESO, EA T: Bastian, NRAO +)




Henke et al 2014

Asayama 2016



# Immediate Future

- NA intends to launch a new Call for Projects 10 October
  - Overall funding pool is expected to be larger than previously, before Development funding reached its stedy-state value
- New Call for Studies also forseen during FY2017
  - 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

# Community Input Meetings

- The Development Vision Working Group will seek advice from throughout the ALMA community
  - Synergy with other large facilities (JWST, LSST, GMST/ELT, Ligo/Virgo/Kagra, FIR Explorer)
  - Seek to inform the vision from discourse with worldwide ALMA partners
- Several community meetings planned

# Half a Decade of ALMA: Cosmic Dawns Transformed

- *NA Development Study proposals being initiated; additional Call in March 2017*
- *EU Development Studies Call: May with deadline in September*
- *EU Workshop on Development: May 25-27, 2016 (Chalmers, Sweden)*
- *NA Development splinter session at AAS 14 June*
- *NA rms community workshop 3-5 Aug, Baltimore*
- *NA Development workshop: 24 August 2016 @NAASC*
- *September 2016: 'Current and Future Development Activities at ALMA' presentation/panel discussion at the ALMA international conference.*

# Half a Decade of ALMA: Cosmic Dawns Transformed

20-23 September 2016, Indian Wells, CA (near Palm Springs)

To register and submit an abstract (now open!) visit: http://go.nrao.edu/ALMA5years

**Invited Talks & Speakers**

Galaxy Formation and Evolution I: Cosmic Evolution (Caitlin Casey)
Galaxy Formation and Evolution II: Gas & Star Formation Properties (Linda Tacconi)
Galactic Centers: Star Formation, AGN, Black Holes & ULIRGs (Masatoshi Imanishi)
Nearby Galaxies I: Normal Galaxies (Karin Sandstrom)
Nearby Galaxies II: Starburst & Super Star Clusters (Kazushi Sakamoto)
Massive Star Formation (Jill Rathborne)
Low Mass Star Formation (Adele Plunkett)
Chemical Evolution During Star and Planet Formation (Jeong-Eun Lee)
Protostellar Disks & Planet Formation (Laura Perez)
Debris Disks (Brenda Matthews)
Stars and Stellar Evolution (Leen Decin)
Solar System (Arielle Moullet)
Synergy between ALMA and JWST (Klaus Pontoppidan)
ALMA after 5 Years (Pierre Cox)
Future ALMA (John Carpenter, Al Wootten, Neal Evans)
Conference Summary (Anneila Sargent)

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# Enhancing ALMA

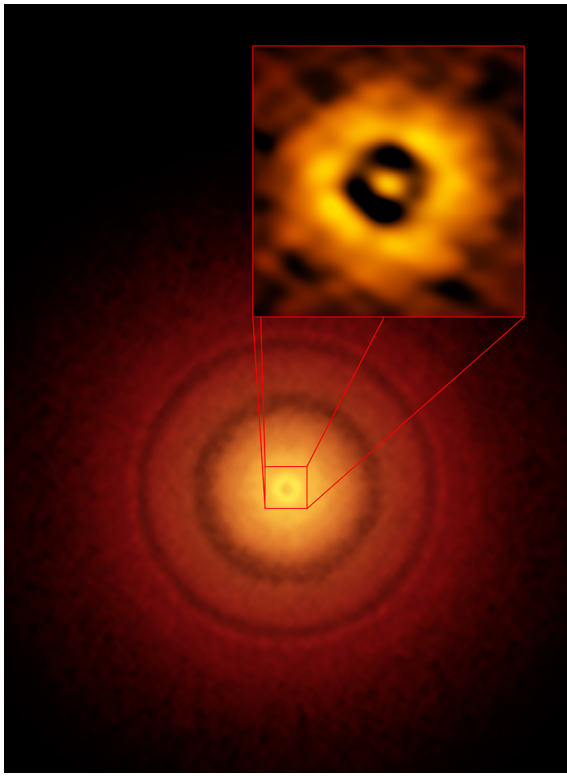
- ALMA is exceptional in
  - Providing submillimeter sky access (a unique interferometer at the highest frequencies).
  - ALMA's resolution is highest in these highest bands
  - Instrumentally, submm observing is a trying task
- High frequency weather is extremely limited (<15% of time concentrated in austral winter)
- One goal could be to enhance access to these exceptional capabilities?

# ALMA's Future

- The original specifications and most construction contracts were let ~15 years ago; those specifications are mostly demonstrated
- Technology has advanced tremendously since
- The community is outlining a new vision to extend ALMA science into the future
- ALMA Development funds enable studies which can underpin that vision
  - Studies are available at NAASC Development website, they are open to community participation
  - SACs and science team combined these into a palette of possible upgrades summarized in 'ALMA2030'
  - Community now engaged in transforming these elements and others into a science-driven vision for the next 5-15 years
- ALMA Development Projects fund upgrades to ALMA to achieve that vision, as they have for Bands 1 (35-50GHz) and 5 (163-211GHz), and will for the remaining Bands and other capital investments

# (A Few) Science Drivers

- Protostars, protoplanetary disks and their evolution
  - First Galaxies
    - From metal formation in the first stars, to the peak of star formation (sensitivity, spectral grasp)
    - Identification, imaging, composition and kinematics of the first galaxies (sensitivity, resolution, spectral grasp)
    - Particular synergy with large total power instruments
  - Galaxies
    - Probing central masses whether starbursts or black holes
    - Characterizing chemical content and understanding its message
  - Disk composition,
    - around stars and around planets;
    - disk evolution (sensitivity, spectral grasp, resolution, imaging precision)
  - Characterization of planets (sensitivity, resolution)
    - Astrometry: measuring stellar reflex motions
    - Transit measurements (sensitivity, spectral grasp)



TW Hya Andrews et al 2016