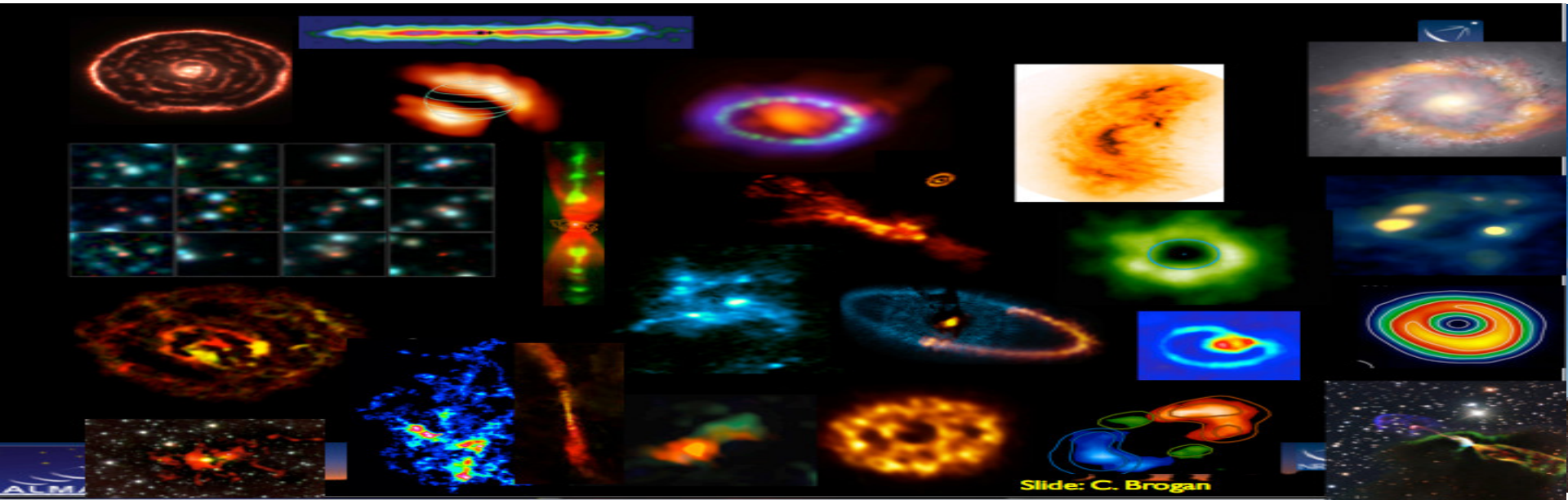


ALMA/NA Development Status

[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

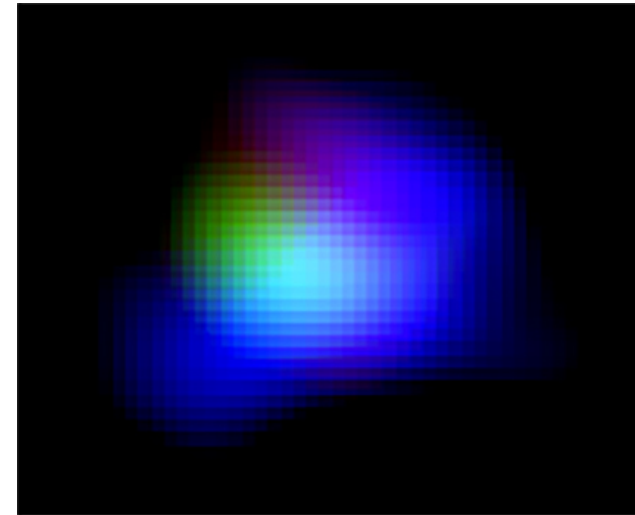
- First Billion Years
- Evolution of Galaxies and Black Holes
- Local galaxies, Milky Way and the ISM
- Star and planet formation, biosignatures, ingredients of habitable worlds—the H₂O trail
- The Sun Exoplanets and the Solar System

The First Billion Years: Metals, Dust, First Galaxies



- Science Drivers

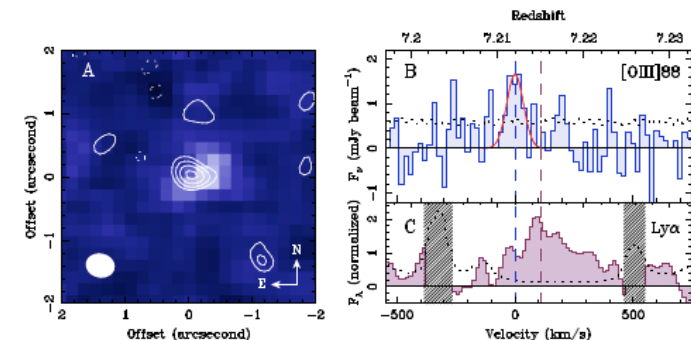
- Creation of the Metals, monitored through atomic and molecular lines
- The first cosmic ‘dust’
- These tracers enable characterization of the development of structures in the early Universe



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

- Instrumental needs

- Sensitivity, to detect weak signals
- Spectral grasp, to cover appropriate redshifted lines



Evolution of Galaxies and Black Holes



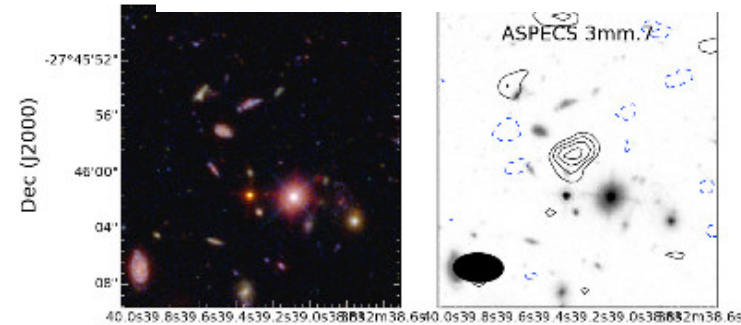
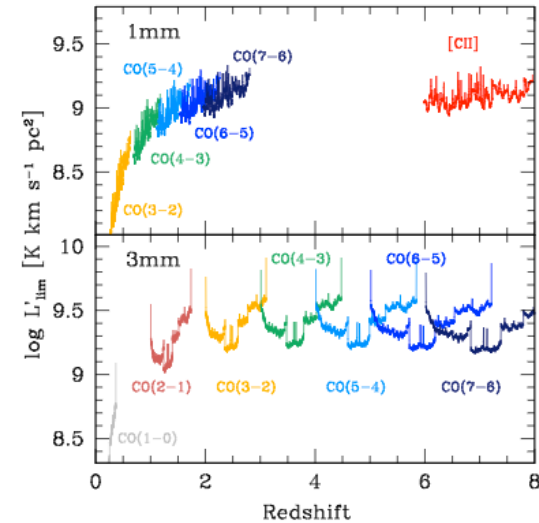
ASPECS Spectral coverage deCarli+ 2016

Science Drivers

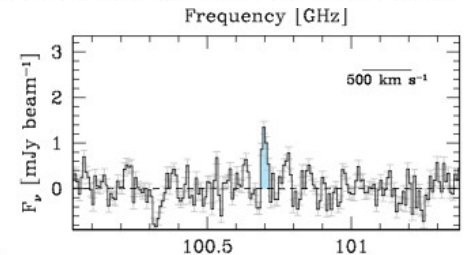
- Kinematics measure of nearby nuclear Black Hole mass
- Kinematics characterize galaxies through cosmic time
- Spectra characterize chemical content

Instrumental needs

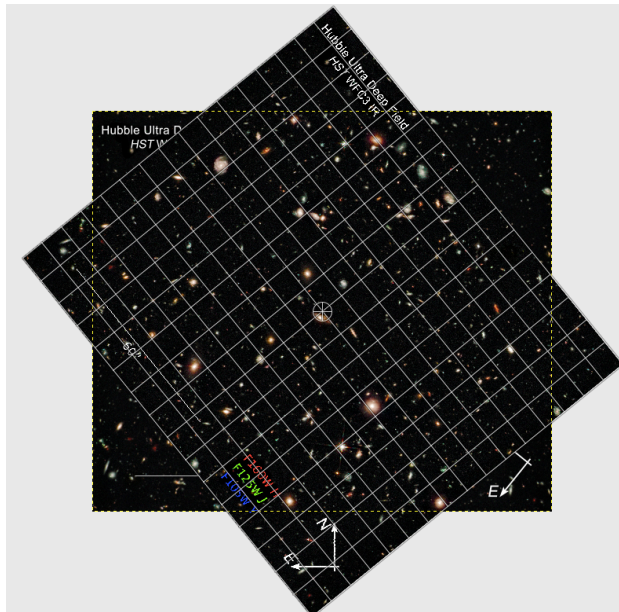
- Sensitivity: detecting weak signals
- High resolution, probing $R_{\text{galactocentric}} < 50 \text{ pc}$ regions
- Spectral grasp covers appropriate redshifted lines



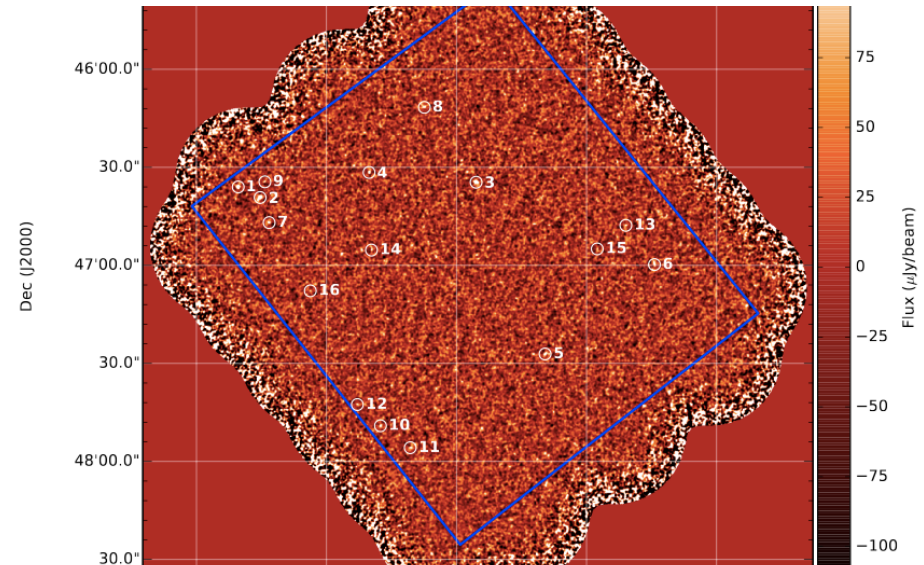
Weakest 3mm ASPECS detection. Walter+, 2016



HUDF – ALMA DF



WFC3/IR on HST



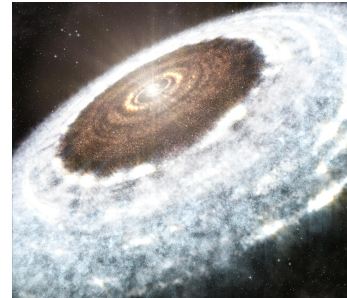
Dunlop et al (2016)

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 ($\langle z \rangle = 2.15$).

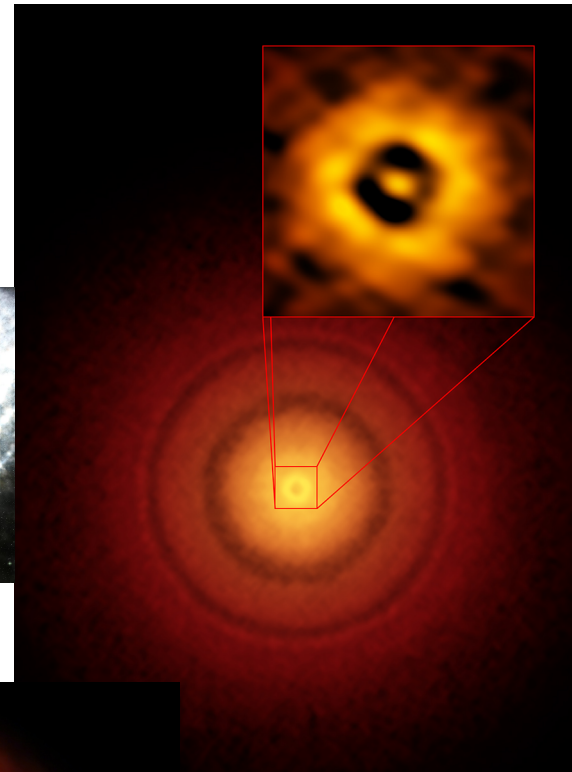
Star & Planet Formation, Ingredients of Habitable Worlds



- 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



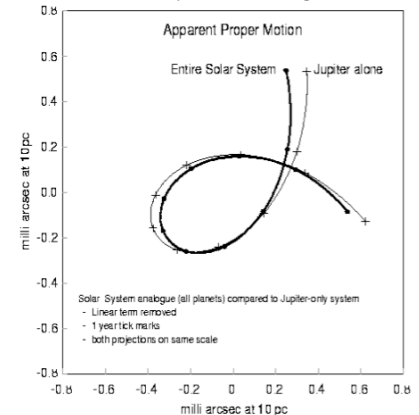
V883 Ori, Cieza+ 2016

Characterization of Planets

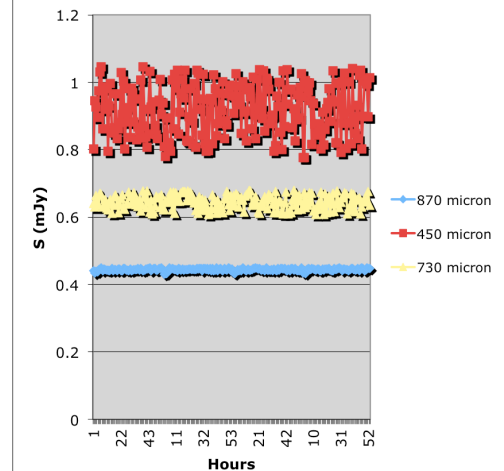


- Characterization of extrasolar planets
 - Astrometry: measuring stellar reflex motions
 - Transit measurements
- Planets at home
- Instrumental needs
 - Sensitivity,
 - Spectral grasp,
 - Spatial resolution,
 - Technique

Reflex Motion for Solar System Analogue in 10 Years
(Motion over 10 years viewed from 10 parsecs)



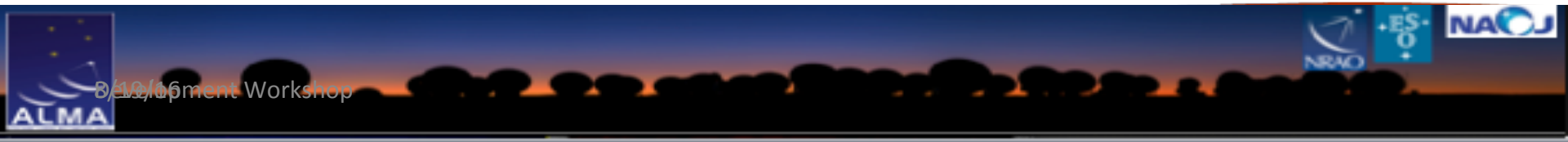
HD189733 SUBMM LIGHT CURVE



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 350 μ m 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

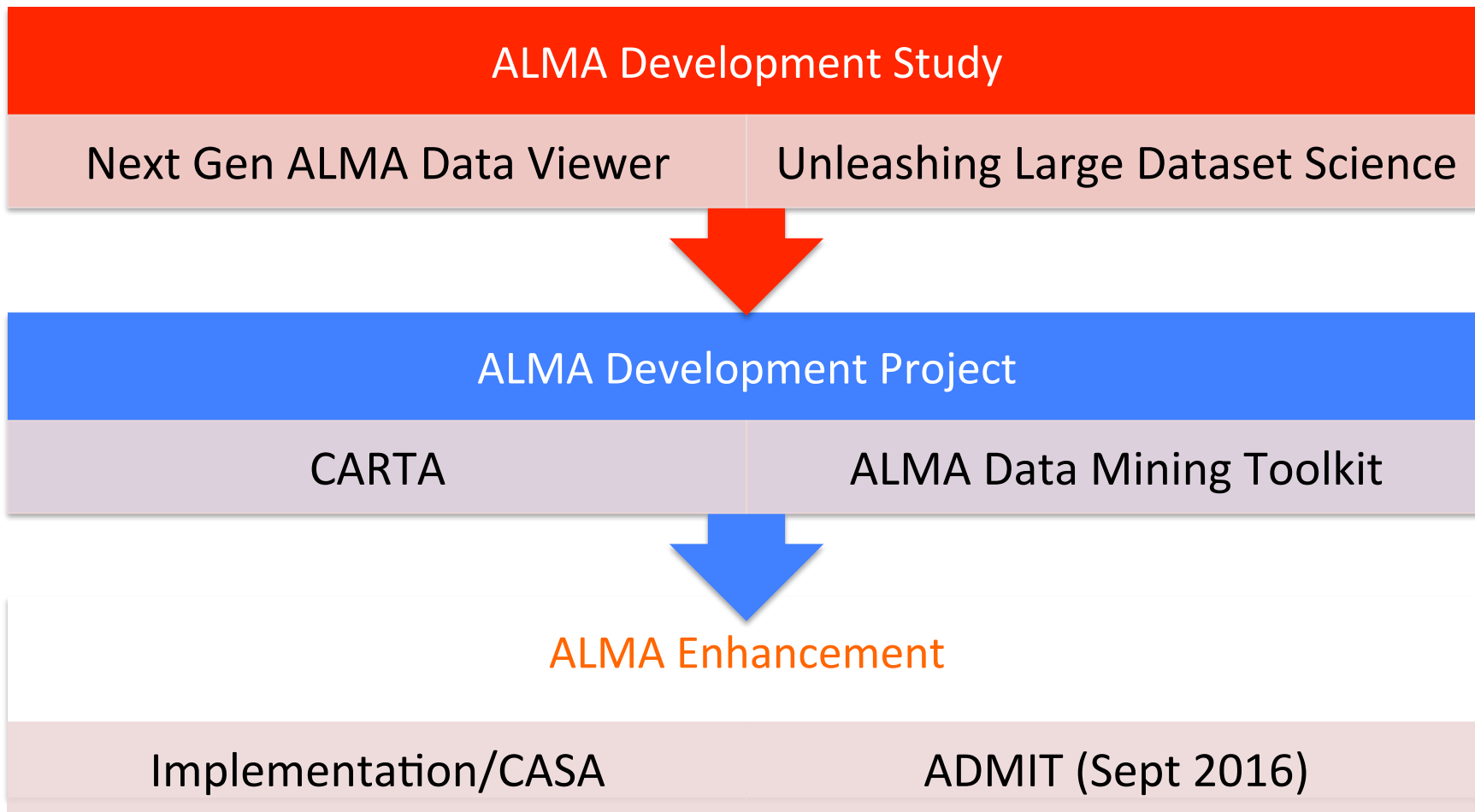
- Through responses to community Calls, ALMA partners craft a collection of *Studies* which detail the ultimate goals of the ALMA Development Vision
- As a result of *Studies*, *Projects* may be undertaken to improve capabilities or to realize new capabilities according to the Vision
- Prioritization 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

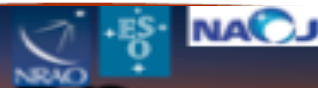
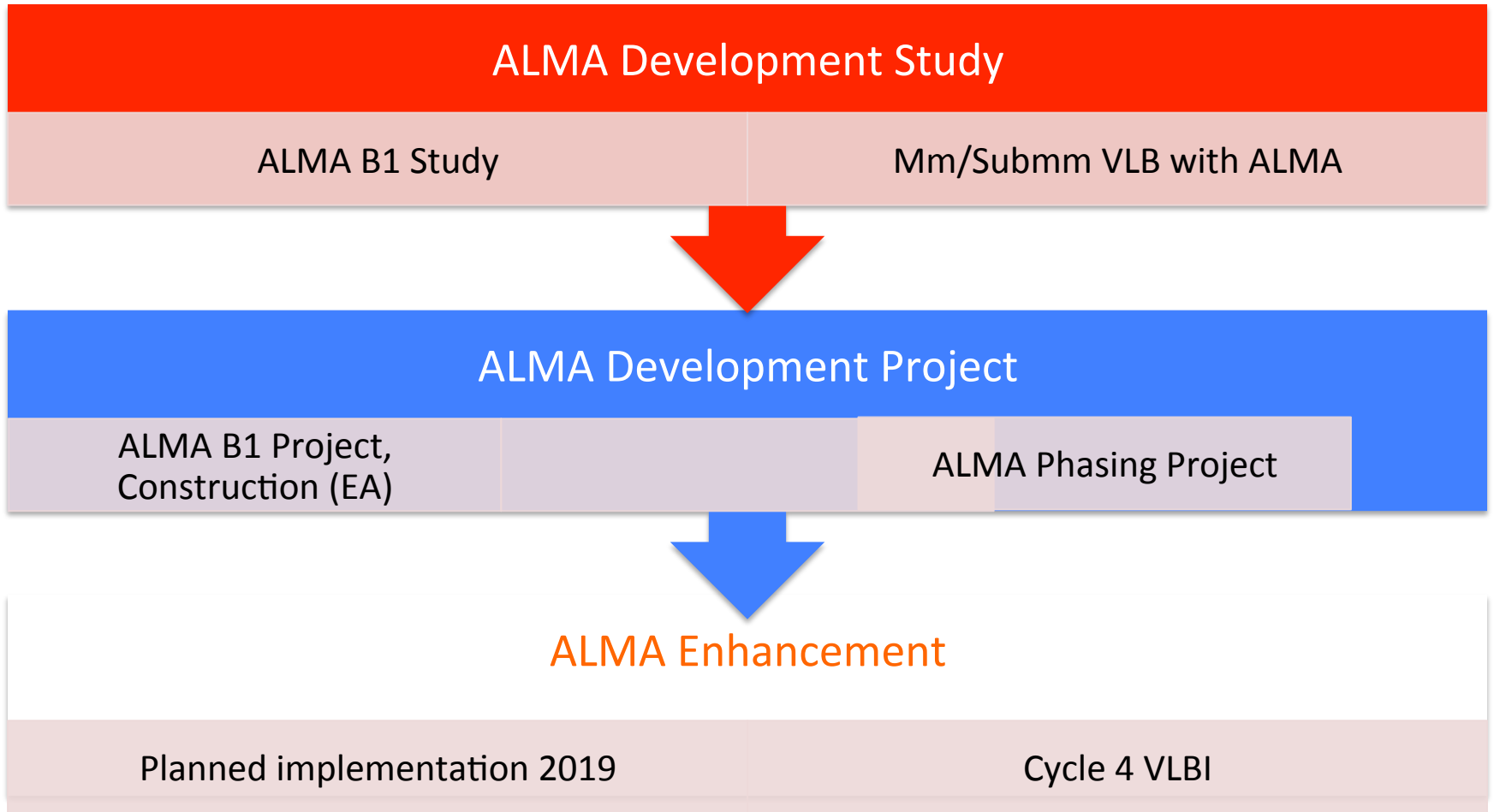


- ALMA NA Operations comprises NRAO and NRC-HIA but anyone in the NA Operations partnership may participate in Development
- **Projects** are large efforts, budget \geq \$.2M taking several years, culminating in major new capabilities or improvements
 - Begin with recommendation of ALMA Executive(s), 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



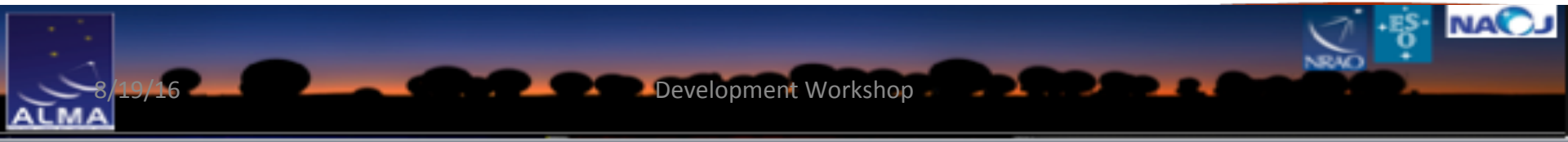
Progression of ALMA Development Components



A ROAD MAP FOR DEVELOPING ALMA

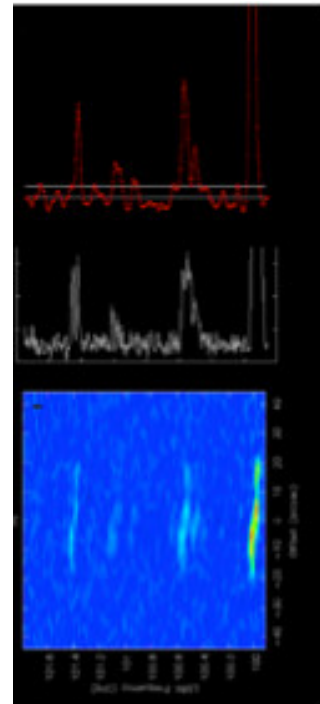
ASAC Recommendations for ALMA 2030

- **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

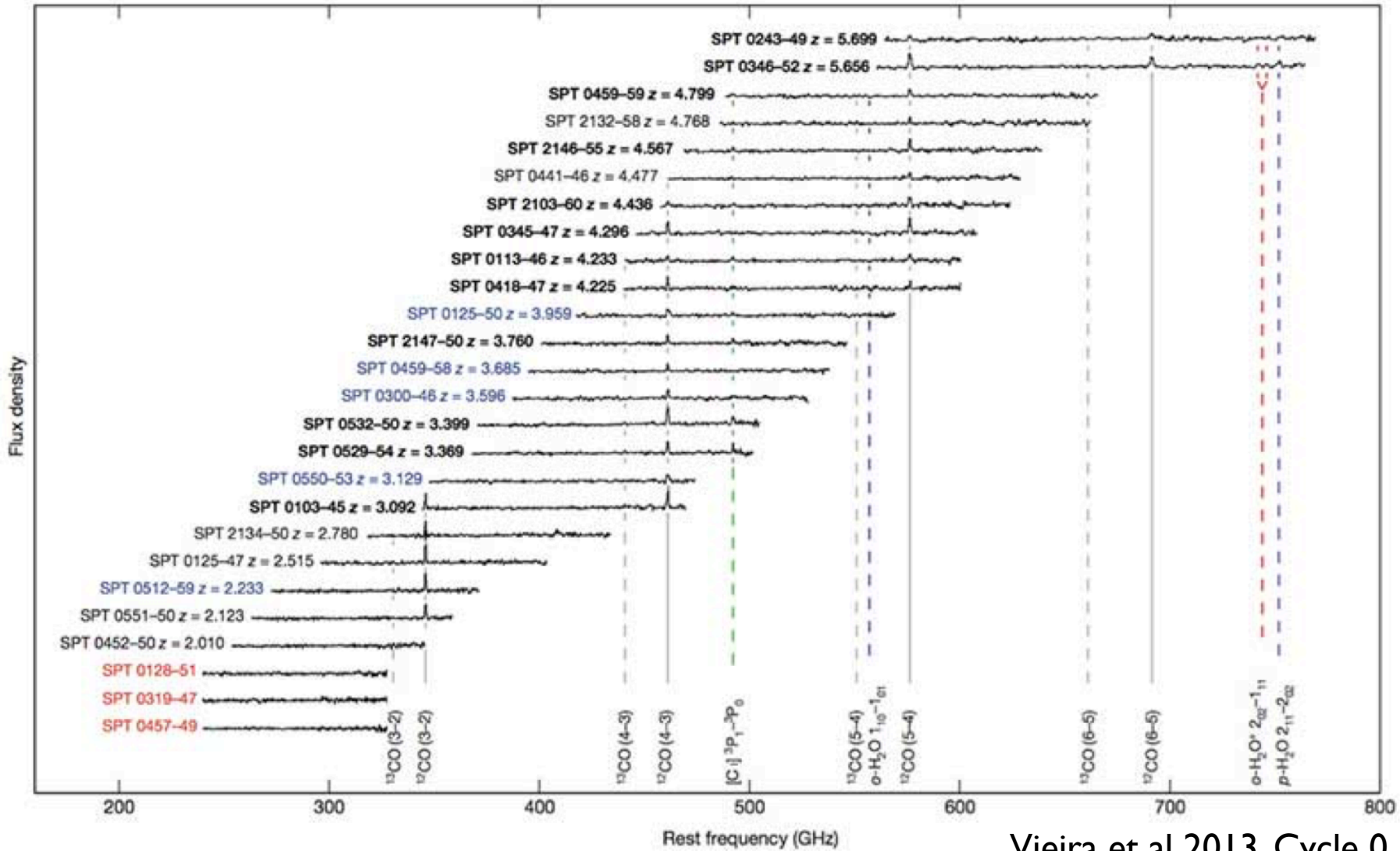
- Several studies increase usability via techniques
 - Community science tool development (T: Leroy, Ohio State)
 - Tool development and repository
 - Calibration Refinements for ALMA Imaging (T: Wilson, NRL)
 - Sought to improve water vapor modeling for ALMA site
 - Improving the Calibration of Atmospheric 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

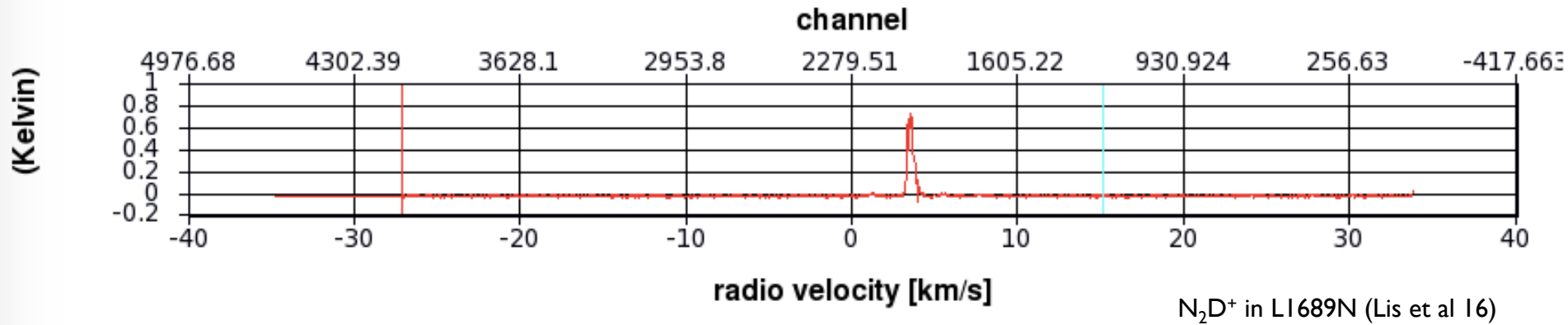


Vieira et al 2013, Cycle 0

Increased Bandwidth: Important for Narrow Lines



Elliptical Region Profile



- 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

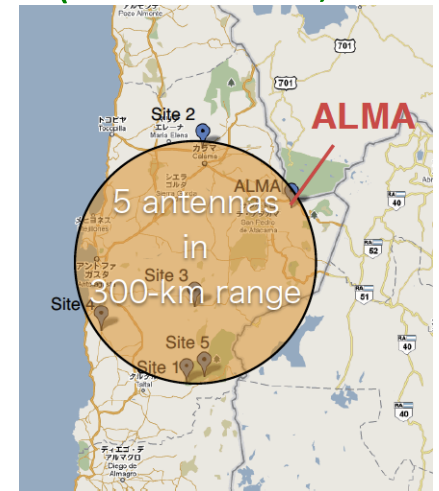
- ALMA Band 1 Production (EA+NA+UCh HW: Kemper, ASIAA)
 - Under way, expected availability on ALMA 2019
- ALMA Band 2 Prototype (NA EA HW: Saini, NRAO)
- *Design and components for ALMA B2/3 (EA ESO HW: iALMA, Manchester)*
- ALMA B5 Full Production (ESO, NA HW: Chalmers, SRON NRAO)
 - Being installed 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)

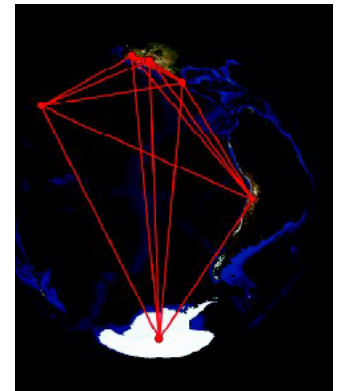
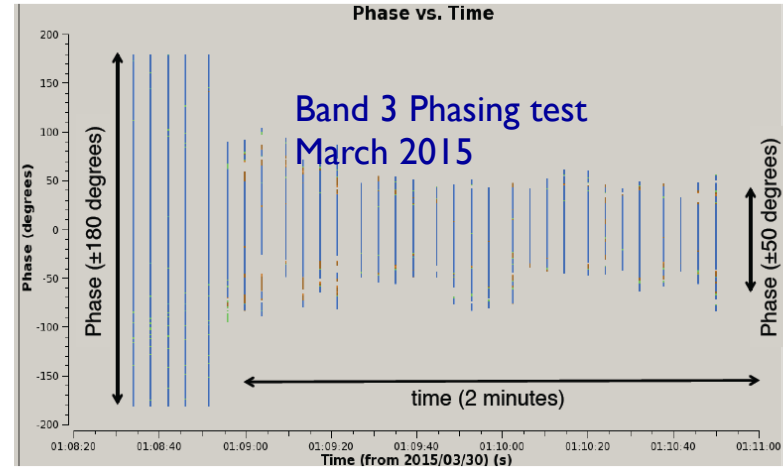


Phase-up ALMA and record the summed signal for mm/sub---mm

All 4 quadrants, both pols, 8 ChAvs/SW; 16-s scans with 4-s integrations

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**



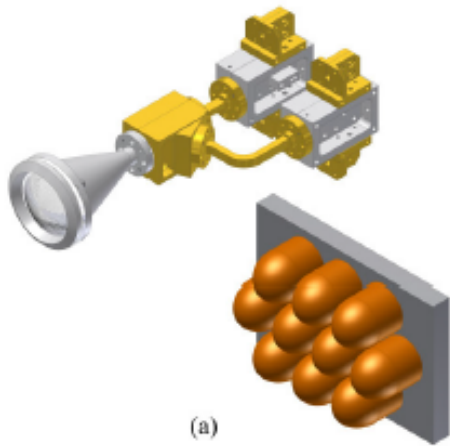
General relativity predicts that the shadow of a black hole should be circular (middle panel), but a black hole that violates the no-hair theorem could have a prolate (left) or oblate (right) shadow. Future images of nearby supermassive black holes will be able to test this prediction. (figures courtesy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

Increased Wide Field Imaging Speed



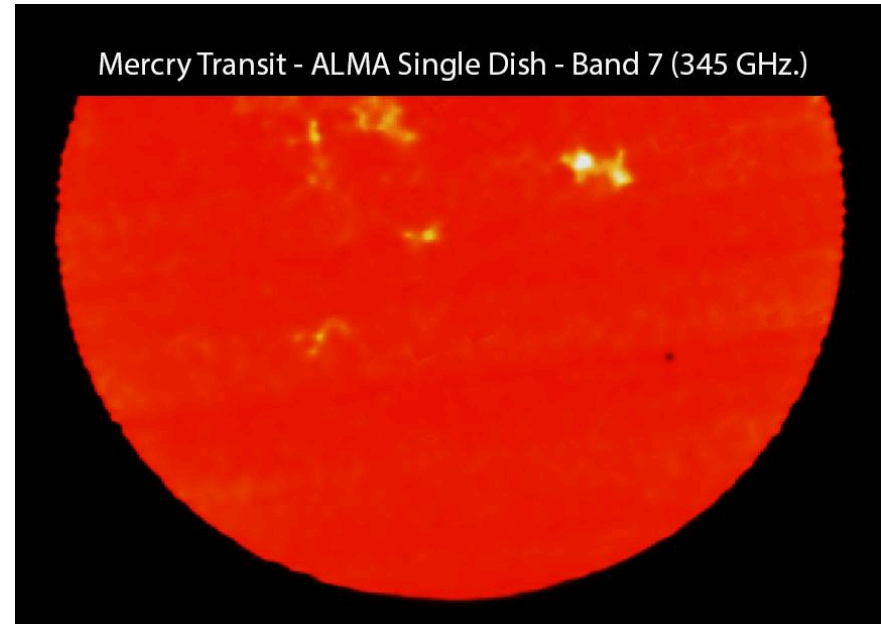
- Array receivers, fast imaging
 - Millimeter Camera (HW: Claude and Henke, NRC-HIA)
 - Solar Observing (NA, ESO, EA T: Bastian, NRAO +)

Asayama 2016



Henke et al 2014

Mercy Transit - ALMA Single Dish - Band 7 (345 GHz.)



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 steady-state value
- New Call for Studies also foreseen 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

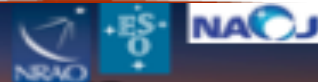


- The Development Vision Working Group will seek advice from throughout the ALMA community
 - Synergy with other large facilities (JWST, LSST, GMST/ELT, Ligo/Virgo/Kagra, FIR Explorer)
 - Seek to inform the vision from discourse with worldwide ALMA partners
- Several community meetings planned



Half a Decade of ALMA: Cosmic Dawns Transformed

- *NA Development Study proposals received 2 May; being refereed; additional Call in October*
- *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)





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.*

Enhancing ALMA

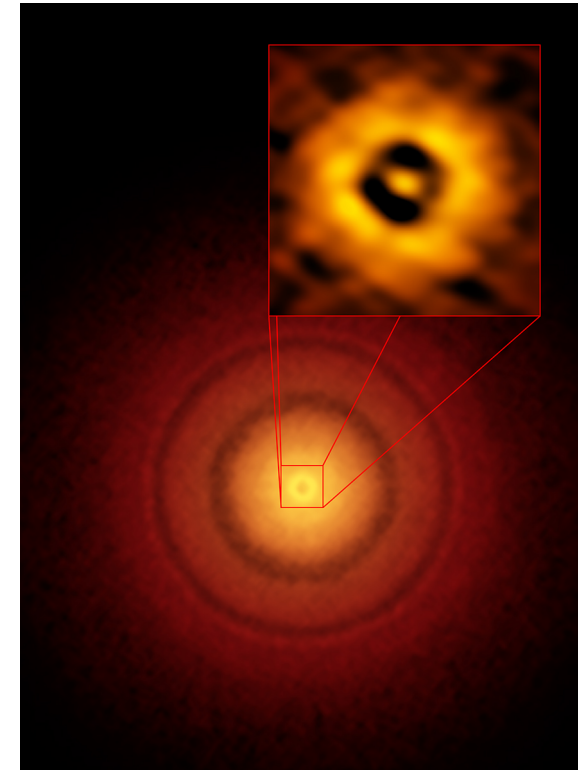
- ALMA is exceptional in
 - Providing submillimeter sky access (a unique interferometer at the highest frequencies).
 - ALMA's resolution is highest in these highest bands
 - Instrumentally, submm observing is a trying task
- High frequency weather is extremely limited (<15% of time concentrated in austral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