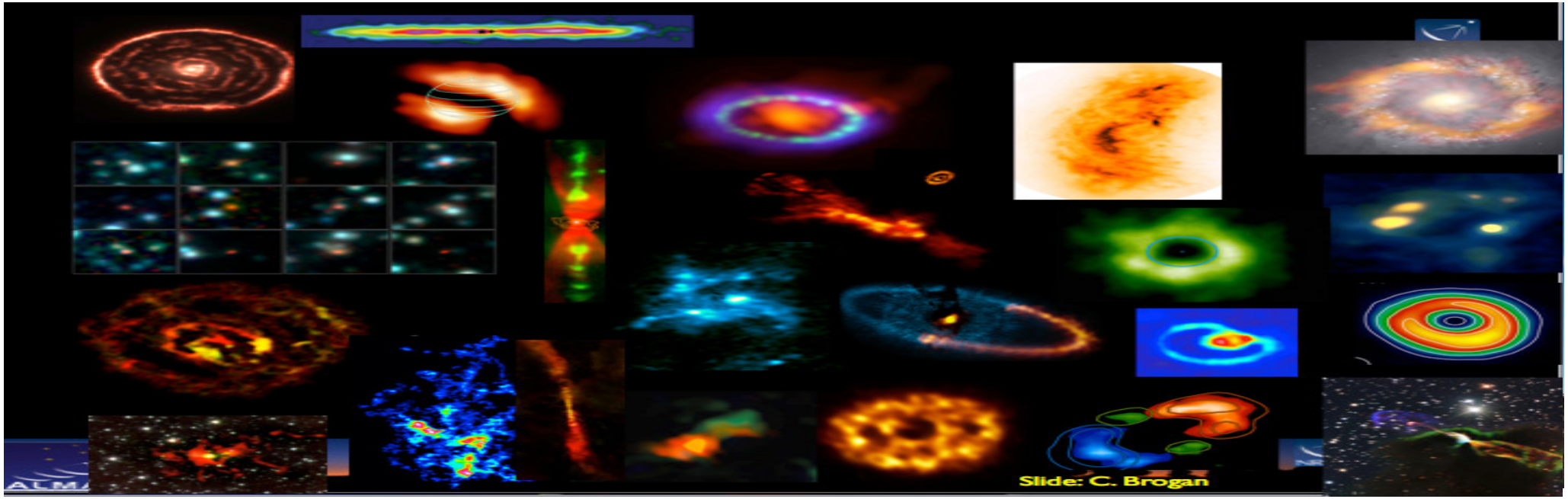
Sustaining ALMA Science Through 2030
A North American Perspective



A Short Overview

Al Wootten

ALMA, A WORLDWIDE COLLABORATION

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array

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 in the ALMA Memo Series or as Development Reports; 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 roadmap for the next 5-15 years
- ALMA Development Projects fund upgrades to ALMA to achieve that vision, as they have for Bands 1 (35-51GHz) and 5 (163-211GHz), and will for the remaining Bands and other capital investments

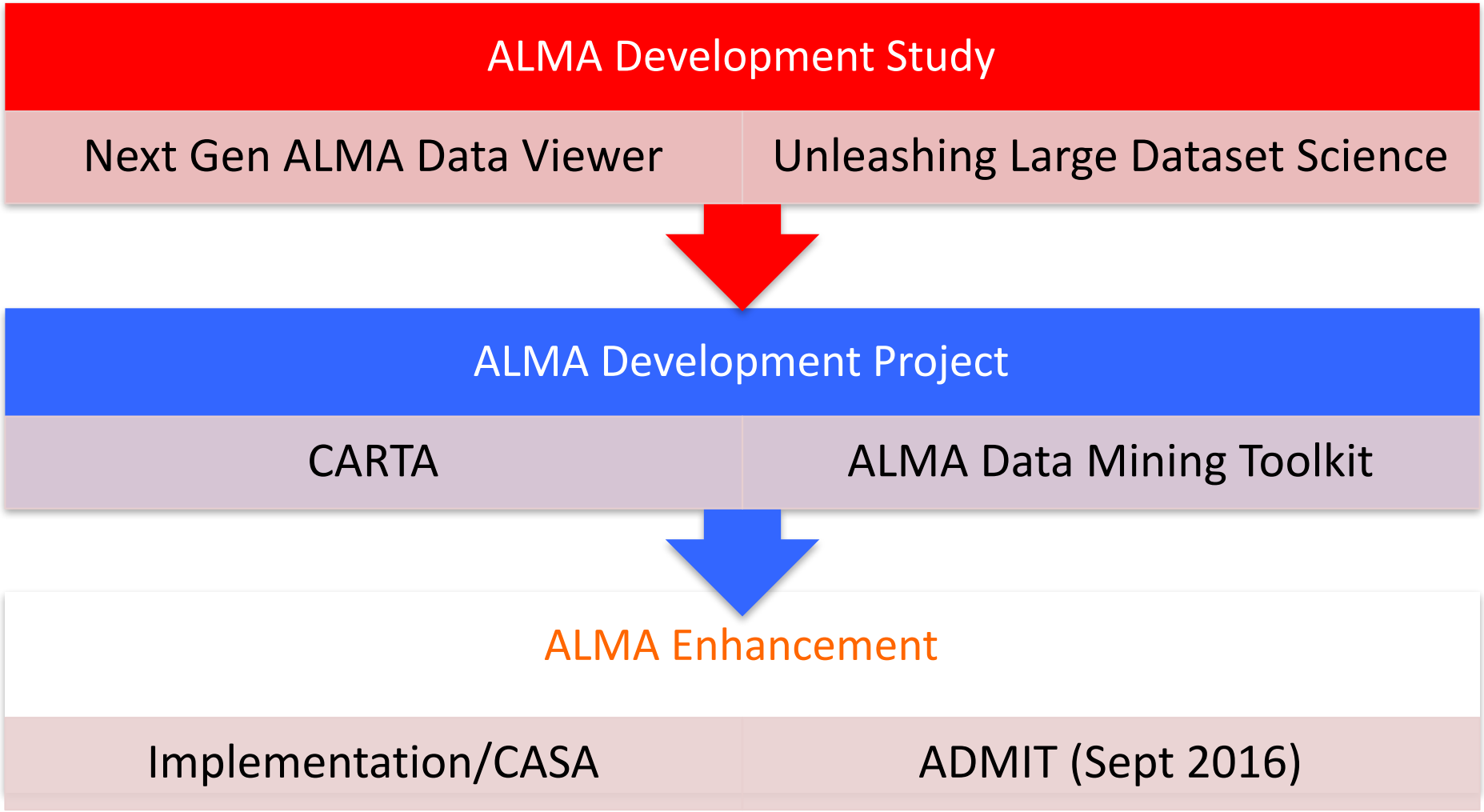
ALMA Development

- ALMA Operations included development funds
  - Ramped up to steady-state level by FY2015
  - First priority was to build to unfunded requirements (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
- All depends on protecting spectrum! [*See Liszt talk]*

ALMA Development Overview

- ALMA Operations comprises many organizations in many countries and many entities participate in Development in parallel but slightly different fashion
- Projects are large pan-ALMA 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 Management Team (JAO, EA, EU, NA), ASAC advice 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 published document known as 'ALMA2030'
- A specific upgrade program is currently under review, 'ALMA Development Roadmap'

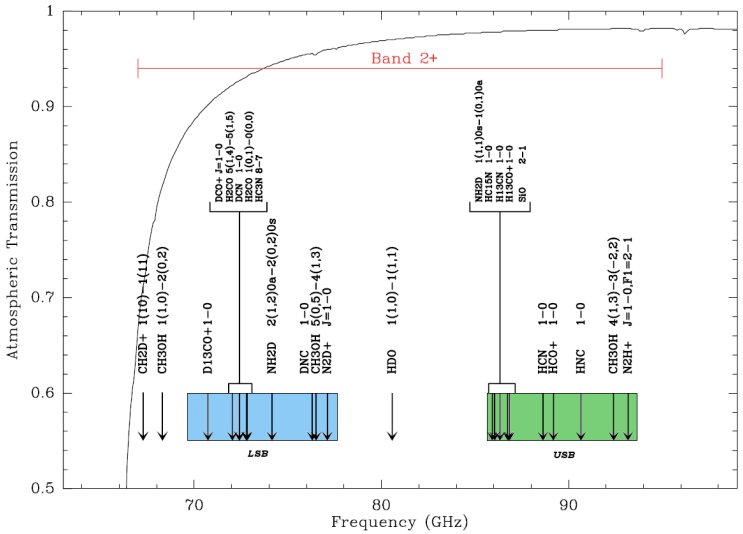
Progression of ALMA Development Components



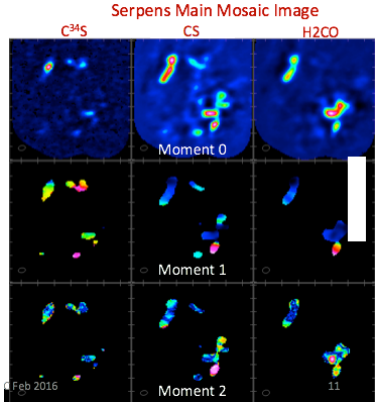
NA Development Program

Current Project Overview

- ***Correlator Upgrade [See Amestica talk]***
- ***ALMA Phasing Project upgrade [See Matthews talk]***
- Fiber optic connection ALMA to JAO improves PI data delivery
- B3 upgrade to deliver improved TP stability
- Recently delivered ADMIT and CARTA projects for improved archive use
- New ALMA Band 2+ provides new science: ***sensitive*** access to redshifted CO 'desert' and deuterated light molecules passed PDR May 2017
  - *NRAO + NAOJ, suspended*

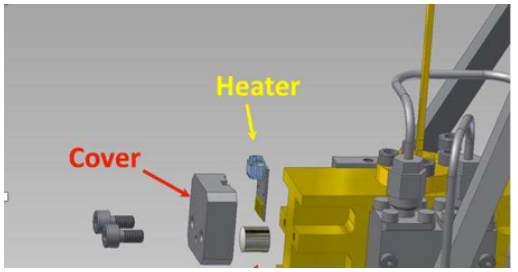


Design & Testing of a Prototype 67-95GHz Cartridge PDR May 2017: NRAO/CDL developed the most sensitive receiver for this frequency range ever tested.



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

Fiber Optic Project

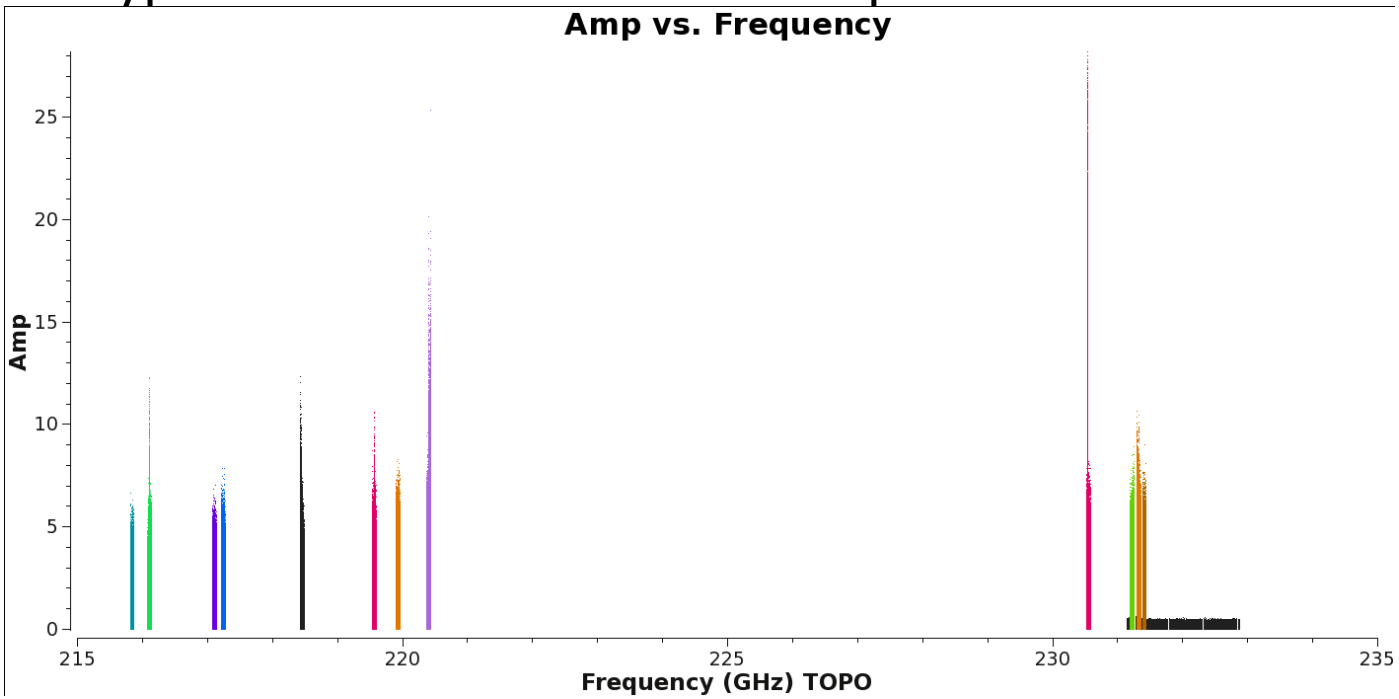


Band 3 CCA Heater Installation for Deflux Operation

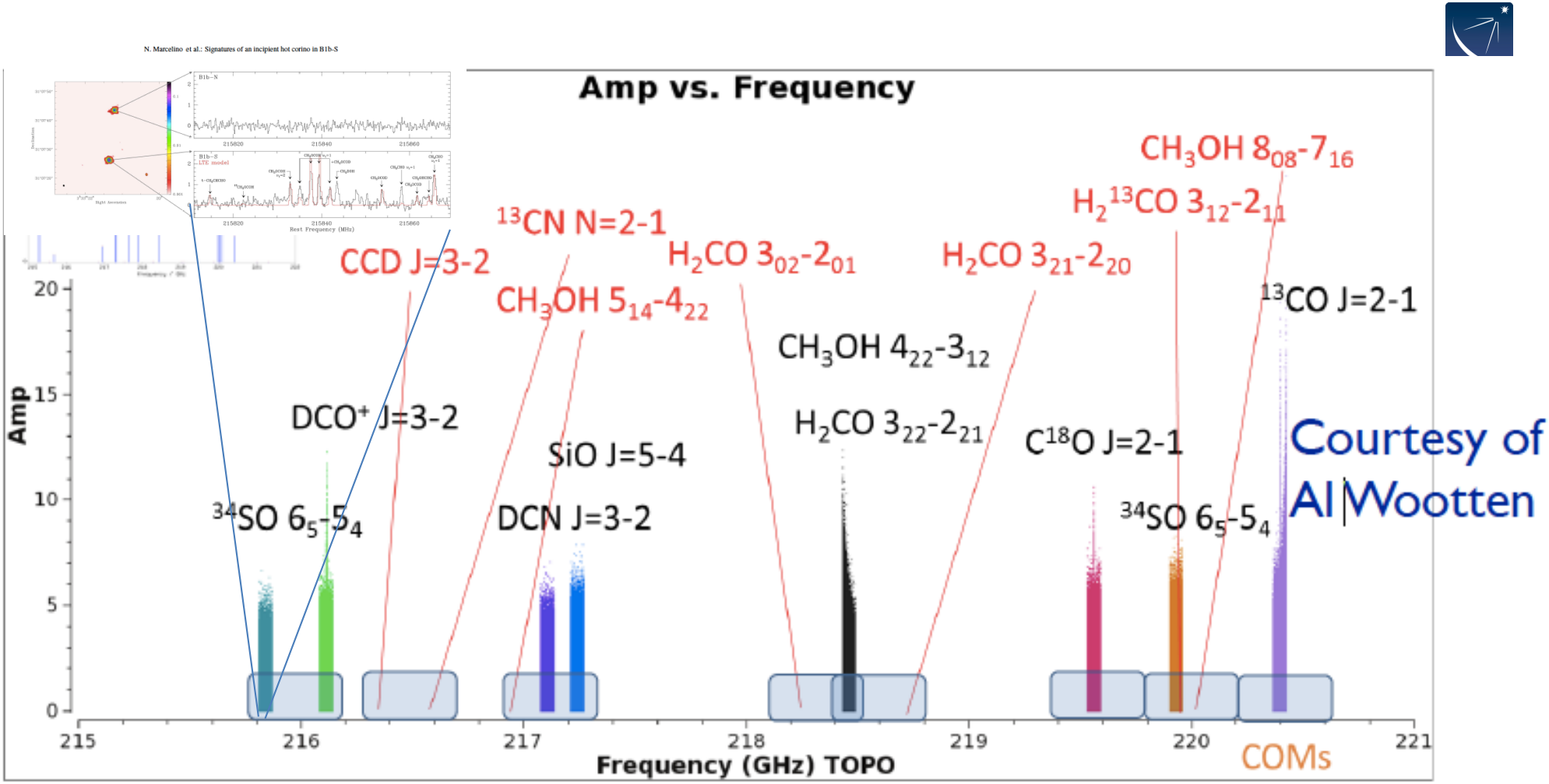
Three Projects continue during FY2017.

Correlator Upgrade
Key to ALMA2030 Goals

Typical Current Correlator Setup: Starved for BW at High Resolution



- 12 high resolution 58 MHz windows available (need one low res window for continuum)
- Many ***lines cannot be covered***
- Upgraded correlator provides broader windows at high resolution, in addition to higher resolution across them
- Capable of doubling current spectral grasp, to 2x4GHzx2polx2SB

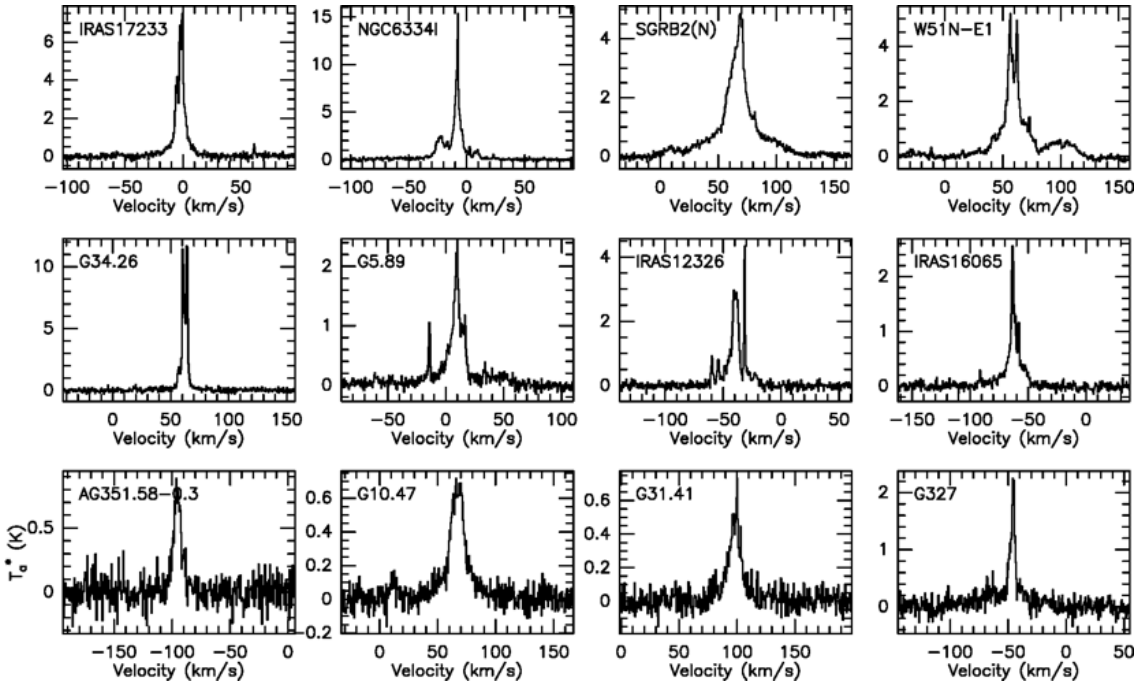


- In Red are important lines that are missed with current correlator
- Upgraded correlator accesses all the missed lines at the current resolution, using wider filters, shown in blue.

EU Development Program

Current Project Overview

- New ALMA Band 5 (163-211 GHz) provides new science:
  - Follow the Water!
    - 183 GHz water line
  - [CII] at 8.0 < z < 10.65
  - Consortium of GARD, NOVA, NRAO, ESO, NAOJ
  - Public Data available (SV)
- ALMA Alarm System

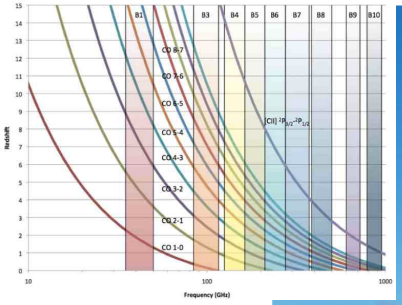


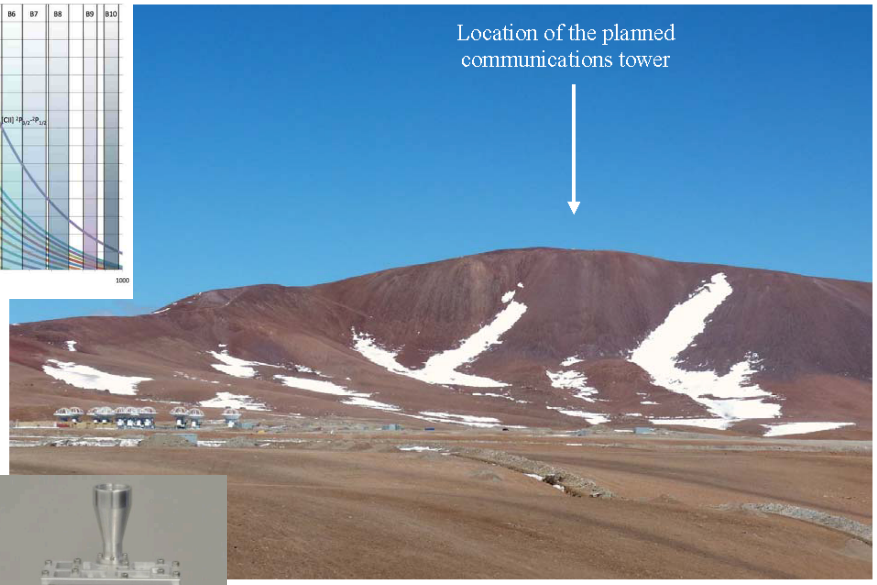
SEPIA/Apex data Wyrowski+ 2017

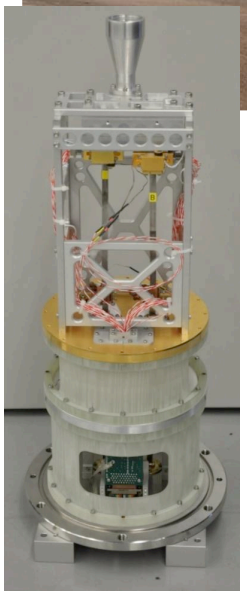
EA Development Program

Current Project Overview

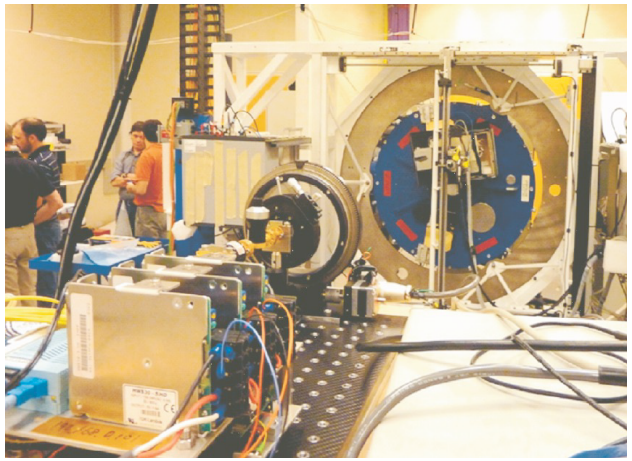
- Band 1 (35-51 GHz) enables new science: *[Morata talk]*
  - Optically thin dust in disks
  - High z CO
  - T_{rx} ~25K; ASIAA, with NAOJ, U of Chile, NRAO, HIA; available ca 2020
- GPU Spectrometer for TP (w/KASI)
- Band 5 Integration and Testing
- Band 2, 2+3 optics
- Artificial Calibration Source
  - Beacon at Chajnantor
  - 100 GHz delivered
  - 230/345 GHz 2018
- High Critical Current Density (Jc) SIS Junction Device Development (esp Wideband RF/IF and THz devices)







Band 1 Receiver



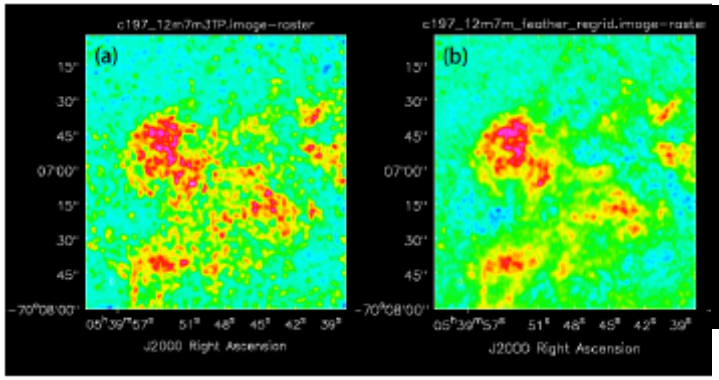
ACS acceptance at OSF

NA Development Program

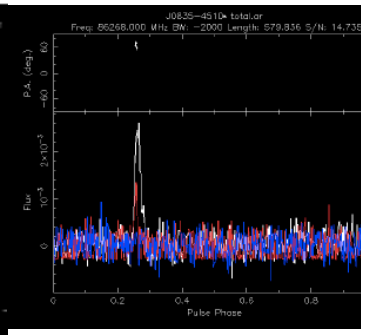
Cycle 4 Study Overview

Acting on ALMA2030 roadmap:

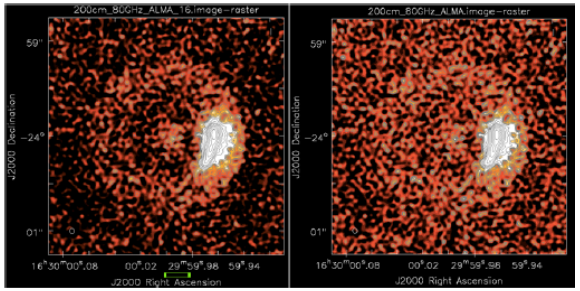
- Increasing receiver sensitivity, bandwidth
  1. Upgraded ALMA B3 mixer block - Henke
  2. 2nd generation SIS receiver development –Kerr*
  3. The Next Generation ALMA *Correlator [Weintroub talk]*
- Expanding ALMA's processing bandwidth
  1. Upgrade of Backend Antenna Article to match correlator upgrade - Ford
- 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* *[Matthews]*
- *Previously:* ALMA Pulsar Capability (Cordes)



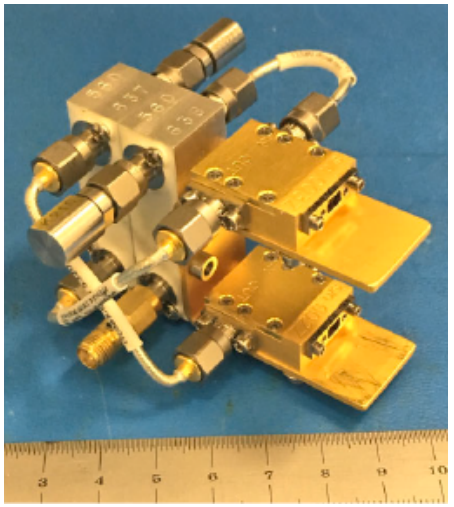
Total Power Map to Visibilities (TP2VIS)
a) Joint deconvolution b) Current mode



Pulse profile of the Vela pulsar at 86 GHz



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

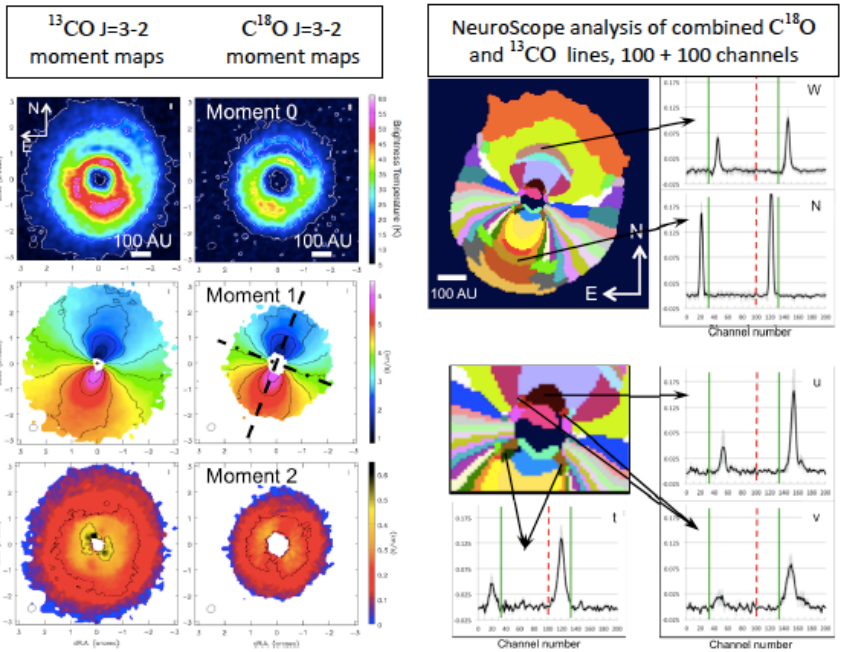
Five Cycle 4 Studies underway.

NA Development Program

Cycle 5 Study Overview

Acting on the ALMA2030 vision:

- Increasing receiver sensitivity, bandwidth
  - *2nd Generation SIS Receiver Development* – Kerr [*See Noroozian talk]*
- Expanding ALMA's processing bandwidth
  - *Quantum-Limited Very-Wideband 4-Kelvin RF and IF Amplifiers for ALMA* – Noroozian *[see talk]*
- Improved data characterization
  - *Neural Network Analysis of ALMA Datasets* – Merenyi *[see talk]*
- Full-field primary beam models will be developed for use in imaging software
  - *Full-Mueller Mosaic Imaging with ALMA*, PI Sanjay Bhatnagar *[see talk]*



Neural Network analysis highlights departures from Keplerian disk motion in HD142527

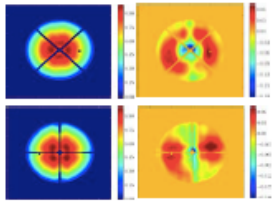


Figure 2A: The average real and imaginary parts of DA (top row) and DV antennas (bottom row) [Kundert et al, 2016]

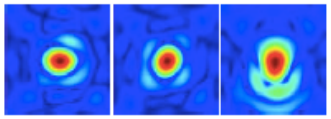


Figure 2B: Range of antenna-to-antenna variations in PB derived from aperture illuminations shown in Fig. 2A.

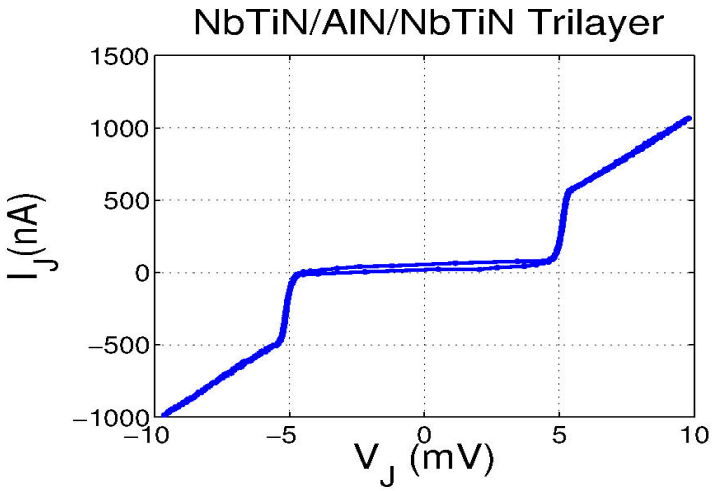
Imaging with different antennas

Four Cycle 5 Studies Commenced FY2018.

We are excellently positioned for the next generation of ALMA SIS mixers

SIS Material Systems suitable for 2nd gen ALMA

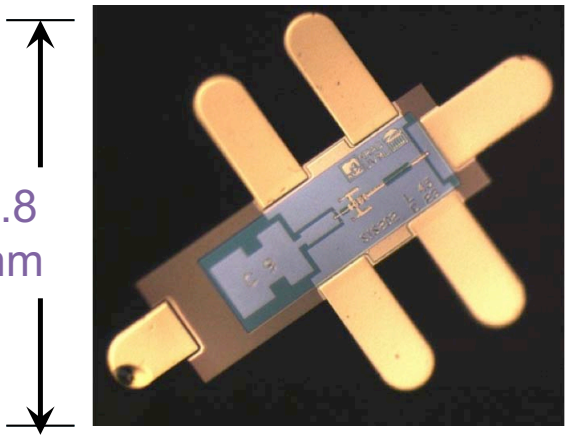
- Nb/Al-AlN/Nb (B6, B7)
- Nb/Al-AlN/NbTiN (B8-B10)
- NbTiN/AlN/NbTiN (B10)



SOI Architecture *(3-5um Si chip w/beamleads)*

- More accurate chip size and registration to metallization
- No time intensive lapping-thinning/dicing required
- Close to drop in chip placement in waveguide block

All NbTiN 5mV gap



Miscellaneous

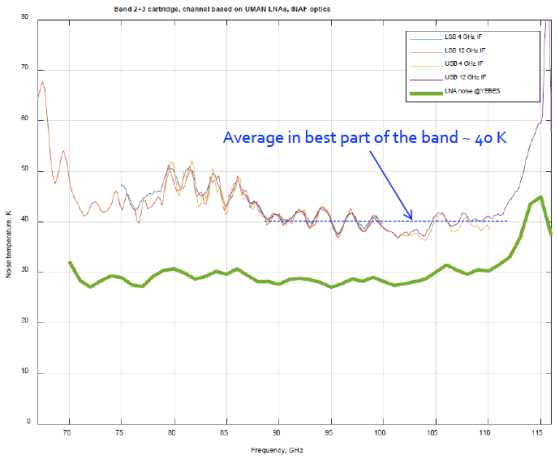
- Developing rapid, whole wafer, dc cryogenic probing/screening of mixer chips
- Miscellaneous circuits (superconducting RF & IF Hybrids & LO Couplers)

EU Development Program

Study Overview

Acting on the ALMA2030 vision:

- Band 2+3 (ESO, INAF, UManc, NAOJ, RAL, UChile)
  - Passive Component
  - InP MMIC LNAs for ALMA Band 2+3
  - Band 2+3 Prototype (PDR 11/17; ongoing)
- SIS Junction Technology Development (Belitsky, GARD)
- Evolution of the ALMA Observing Tool (Bridger, UKATC)
- Digitization and Digital Signal Processing for 16GHz on-sky bandwidth (Alain Baudry)
- Digital ALMA Front End (NOVA, Baryshev)
- 2SB upgrade for Band 9 (NOVA, Baryshev)
- Solar Observations (pending ALMA Memo)
- XClass/MAGIX integration in CASA
- ARTIST prototype interface



➢ For comparison, the NRAO/CRAL Band 2+ prototype cartridge would have ~ **32 K average noise temperature**, if Si-lenses were to be used.

B2+3 LNA performance (From PDR, Nov 2017)

Amplifier Type	Estimated Trx (67-90 GHz)	Notes
NRAO/CRAL	37.9 K	**HDPE optics**, 38.5 K Measured Average.
NRAO/CRAL (Predicted)	31.4 K	For low loss Si-lens case (if available).
LNF (Predicted)	43.9 K	**HDPE optics**, assumes added stage for extra gain.
Manchester (Predicted)	43.5 K	**HDPE optics**, assumes added stage for extra gain.

Estimates are based on noise cascade using measured amplifier noise performances.

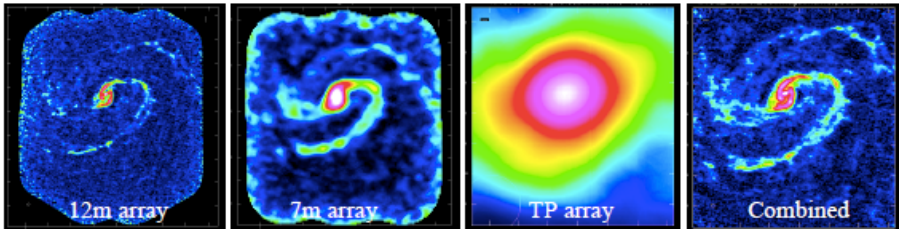
B2+; B2+3 receiver performance (K. Saini et al 2017)

EA Development Program

Study Overview

Acting on the ALMA2030 vision:

- ALMA Calibration Source
  - Calibration at bands 3,6,7
- High Critical Current Density (Jc) SIS Junction Device Development (including Wideband RF/IF and THz devices)
- GPU Spectrometer for Total Power array (with KASI)
  - Supplements the ACA correlator
  - Separates auto-correlationfrom cross-correlation, maintaining 32-bit quantization and eliminating re-quantization loss in the decimation.



Complete Flux Recovery using 12m+7m+TP

Immediate Future

- Projects
  - Next: Follow many steps in Principles of ALMA Development,
    - Correlator Upgrade, PDR 28Feb-1Mar 2018, then to ALMA Board.
    - ALMA Band 2+ or B2+3 developing metrics for comparison.
- Studies
  - New Calls every three years at ESO (2019), probably FY2019 in NA, yearly discussions in EA
- ALMA Development Roadmap:
  - The ALMA Development Working Group proposed a science-driven vision for the medium (5 years) to longer term (5 to 15 years) development of ALMA
  - Presented to ALMA Board, under discussion with science committees, international instrumental teams.

Roadmap Input

- Recommendations from the ASAC ALMA2030 report
  - Increased throughput
  - Longer baselines
  - Focal plane arrays
  - Archive development
- Numerous regional workshops in 2016 and the ALMA-wide conference in Palm Springs, CA, URSI meetings
- Numerous technical reports from the ALMA Development Program
- Further SAC input on Science Goals and long-baseline science
- Submitted by ALMA with initial feedback from the ALMA Board (November 2017), ASAC

Development Priorities

To Realize the Roadmap

- Broader IF bandwidth; upgrade components
  - Spectrometer and digitizer upgrades *[see Amestica, Weintroub talks]*
  - Receiver upgrades (B1, B2+, then B6/7, B3, B9) *[see Morata, Noroozian talks]*
  - Results:
    - Improved spectral sensitivity and coverage
    - Better continuum sensitivity
- Longer baselines, more antennas, focal plane arrays
  - Improved spectral sensitivity and imaging
  - Wide field imaging
  - Beyond basic Development

Proposed New Science Drivers

- **Origins of Galaxies**
  - Follow the cosmic evolution of key bio-elements from the beginning of galaxy formation (z>6) through the peak of star formation (z=2–4) by imaging key cooling lines, both atomic ([CII], [OIII]) and molecular (CO), at a rate of 1-2 galaxies per hour.
- **Origins of Chemical Complexity**
  - Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to 10 au scales by performing full-band frequency scans at a rate of 2-4 forming Sun-like stars per day.
- **Origins of Planets**
  - Image planet formation in the dust continuum in nearby (150 pc) protoplanetary disks to resolve the Earth forming region (~1 au) at wavelengths shorter than 1mm and the Jovian-planet region (~3–10 au) at 3–10 mm.

Increase Bandwidth and Throughput

- Goal
  - Increase IF bandwidth to ≥ 8 GHz and upgrade the associated electronics, correlator, and archive
  - Directly impacts all three science drivers
- Recommendations
  - Bands 7, 6, 3, and 9 have priority, with Bands 7 and 6 deemed to have equal priority
  - Technical and scientific working group should be formed to produce top-level requirements
  - Technical working group should be formed to flow down top-level requirements to all aspects of the system
  - A team should be developed to coordinate developments over entire system

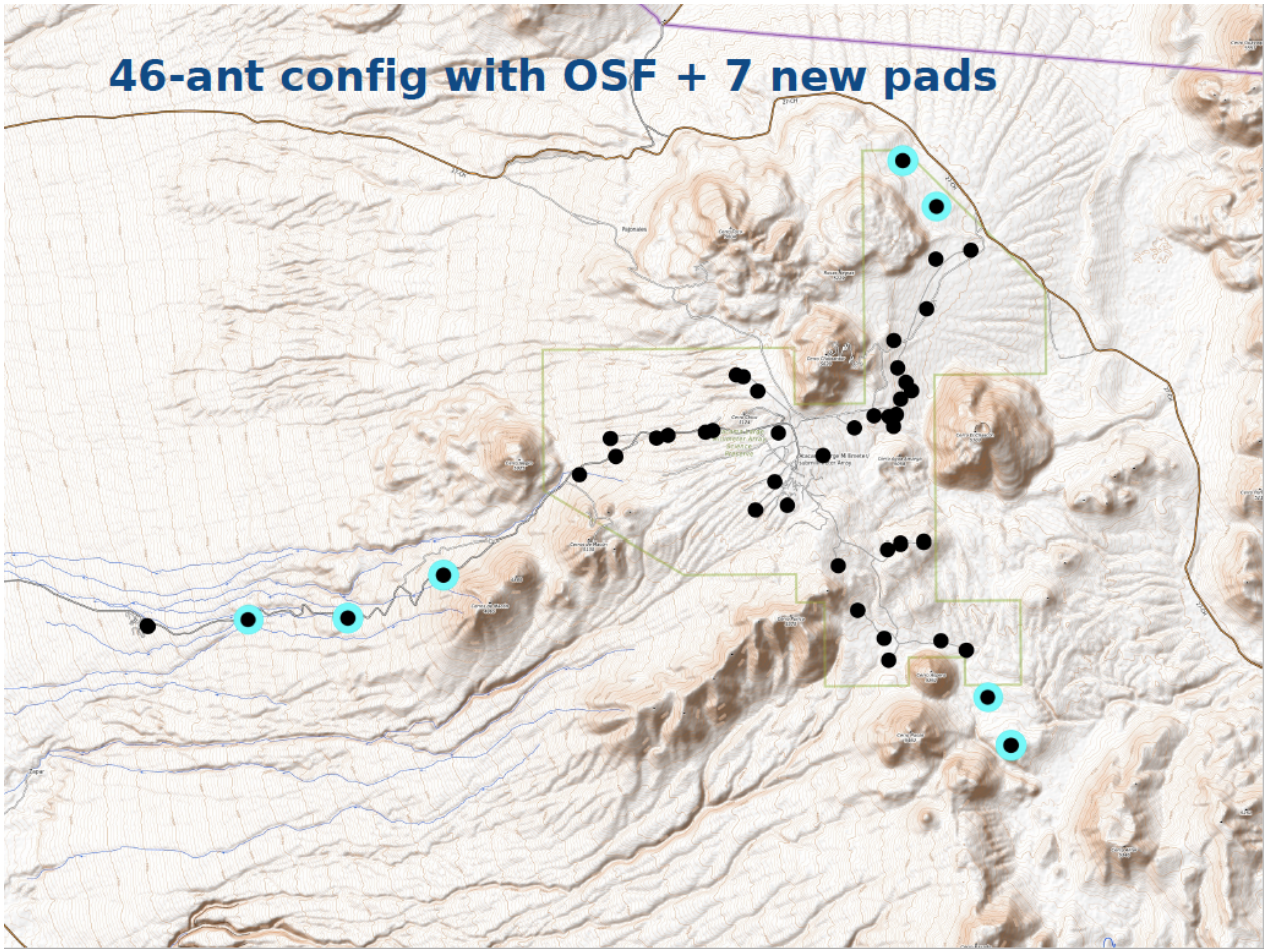
Longer Baselines?

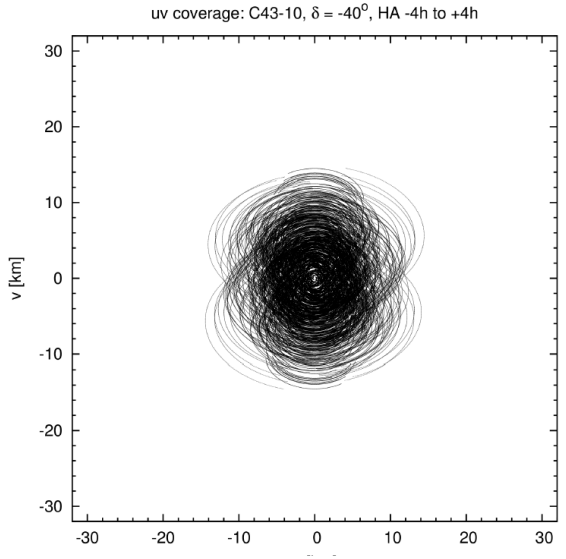
Workshop Oct 2017

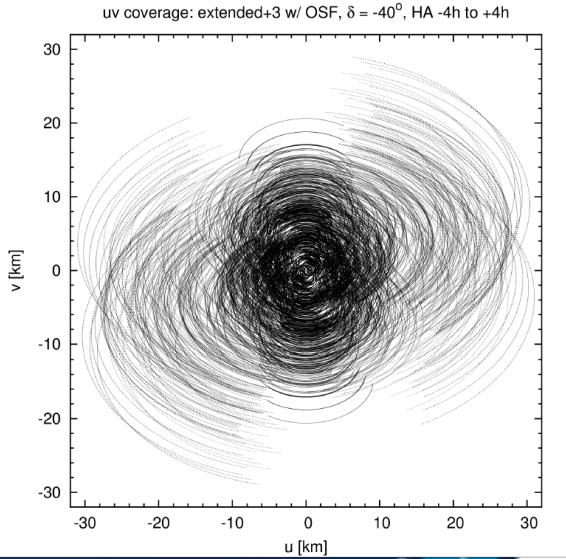
- Goal
  - Expand baseline lengths by a factor of 2-3
  - Directly impacts Disks & Planets science driver
- Recommendations
  - Science appears compelling, but simulations are needed to inform technical requirements
  - Studies are needed to assess technical and operational feasibility
    - Extension to ~26 km may be fairly straightforward (N. Phillips)

Possible ~26km Array

(B1~B7; Phillips)



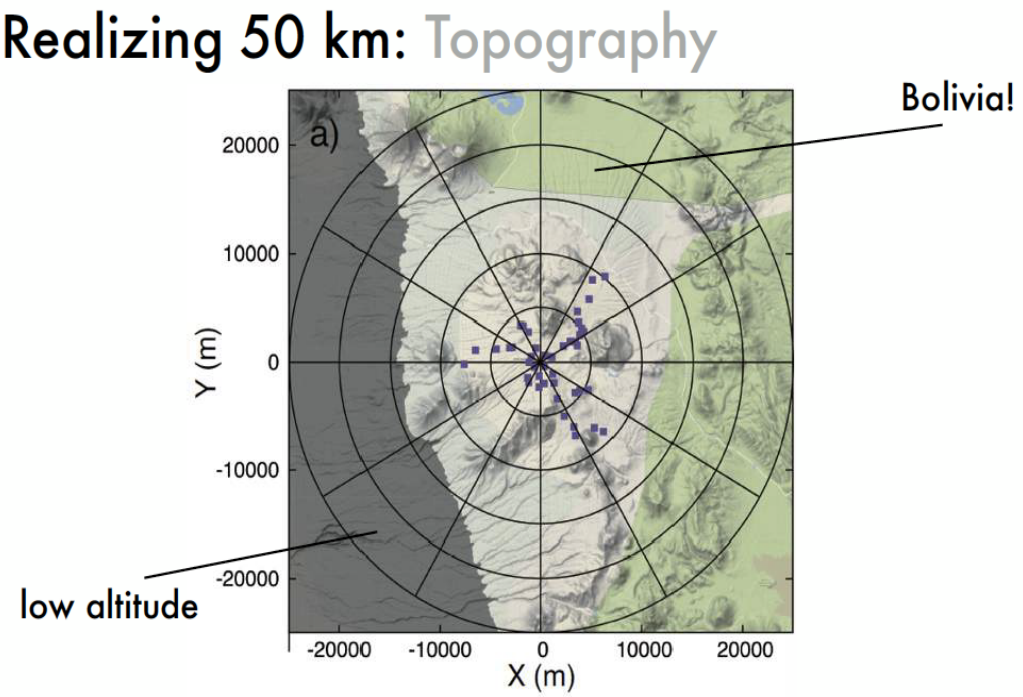




To 50 km?

T. Saito study)

- ALMA with 50km Baselines?
  - Severely limited by topography!
  - Could operate to at least 300 GHz
    - Assume 8 GHz bandwidth
    - Add Nine Fixed 12m antennas on 50km baselines
  - Could achieve 5-15 mas resolution in 9 hour full synthesis images



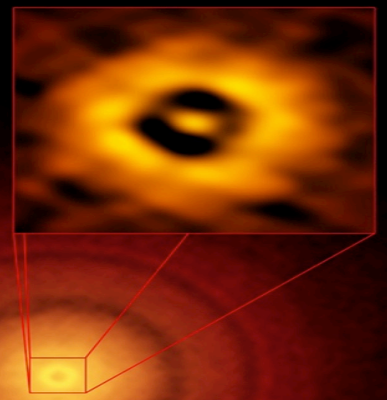
AtLAST

- **Atacama Large-Aperture Submm/mm Telescope (AtLAST)**
- **ESO-HQ, Garching b. München, Germany**
- **January 17-19, 2018**

Magnetic Fields or Turbulence: Which is the critical factor for the formation of stars and planetary disks?

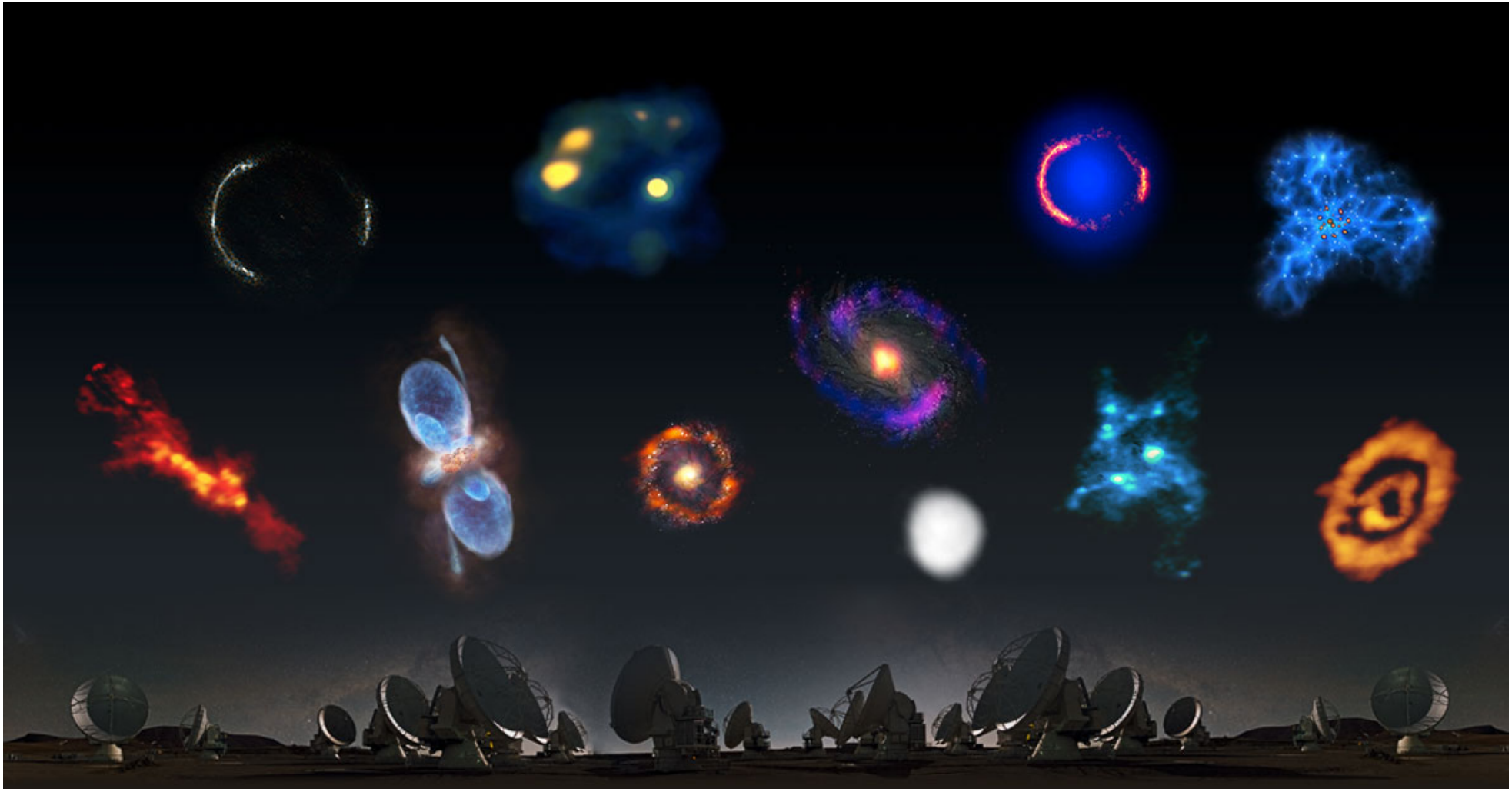
- 6-9 Feb 2018, National Tsing Hua University, Hsinchu, Taiwan
- Discussions on all aspects of star and planetary disk formation, such as
  - Magnetic field and turbulence measurements
  - Molecular cloud structure and dynamics
  - Formation of protoplanetary disks
  - Chemical contents of molecular cores and disks
  - Star formation efficiency

- http://events.asiaa.sinica.edu.tw/workshop/20180206/index.php



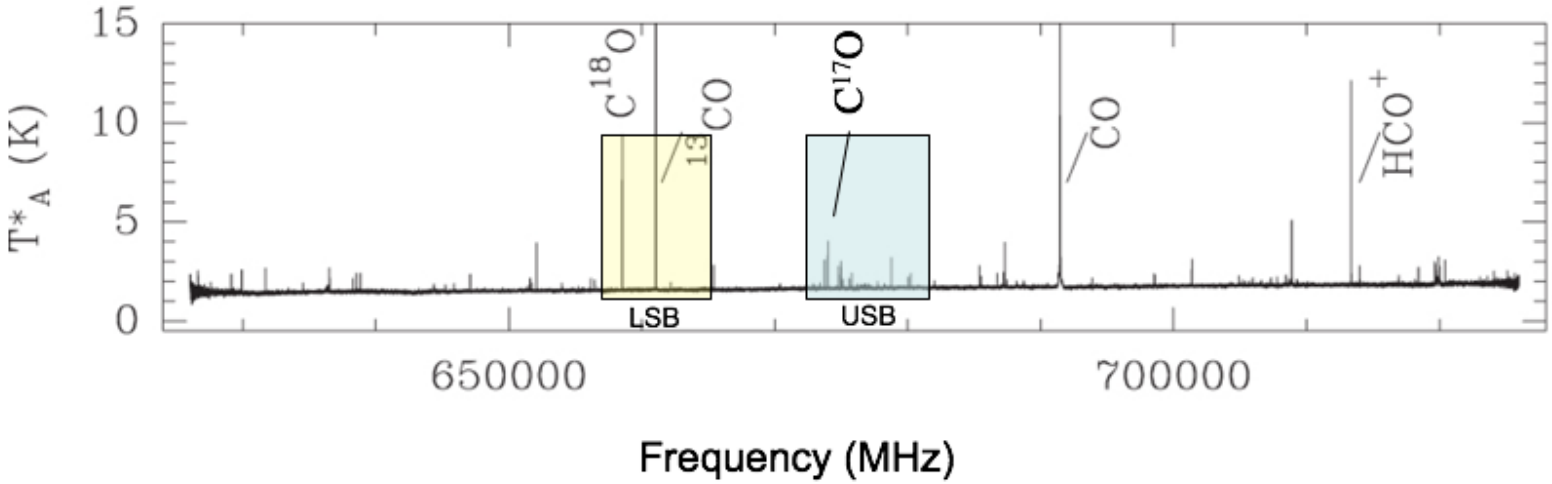
New Horizons in Solar Systems

A Joint NAASC-NRC Conference
Victoria, BC, May 2019



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

Upgraded Correlator Nets More Lines



- Many CO isotopomers fall within a part of the Herschel HEXOS spectral scan in a portion of ALMA Band 9 (611-720 GHz) showing the spectral grasp of the current baseline correrlator (8 GHz x 2 polarizations) compared to that from the upgraded correlator (2 x 8GHz x 2 polarizations). From Tahani et al. 2016.
- For high resolution, ALMA's current configuration provides 58 MHz spectral windows, only ~70 km/s at 300 GHz. With the correlator upgrade, one could achieve the same resolution over ~550 km/s.