ALMA Development Overview

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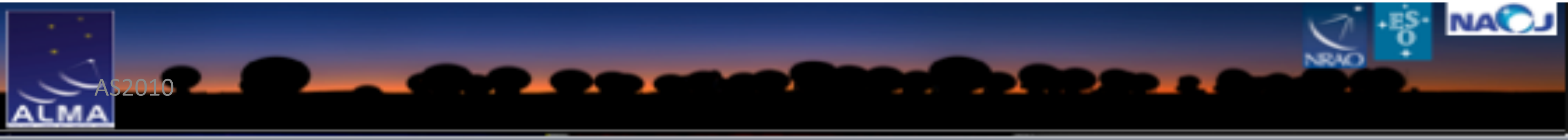
Slide: C. Brogan

The ALMA Partnership

- ALMA is a global partnership in astronomy to deliver a truly transformational instrument
  - North America (US (NSF), Canada (NRC), Taiwan (NSC))
  - Europe (via ESO)
  - East Asia (Japan (NINS), Taiwan (AS), Korea (KASI))
- Located on the Chajnantor plain of the Chilean Andes at 16500'
- ALMA is operated as a single Observatory with scientific access via regional centers
  - North American ALMA Science Center (NAASC) is in Charlottesville;
  - SCs for ESO in Garching; NAOJ in Mitaka
- Construction completed on NSB-approved budget and on time.
- Just completed Call for Fifth year (Cycle 4) of PI science
  - Over 1600 proposals received

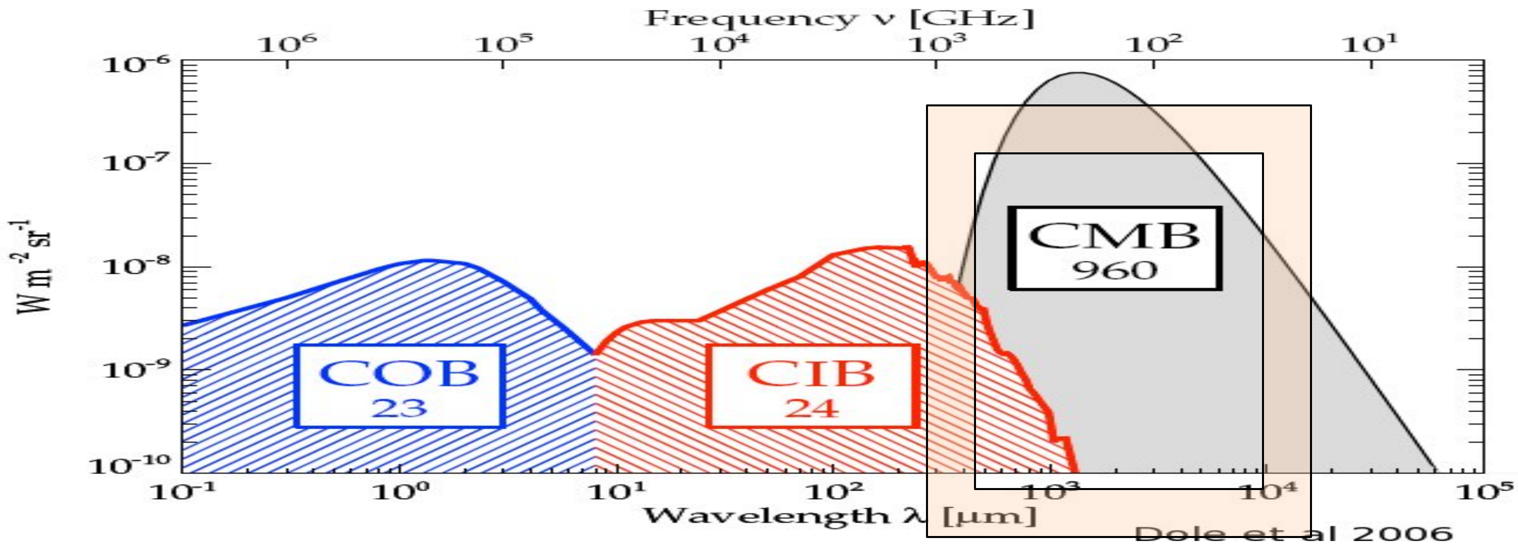


A ROAD MAP FOR DEVELOPING ALMA

ALMA Science Advisory Comm (ASAC) Recommendations for ALMA 2030

- Finish the Scope of ALMA (B1 + B2 receivers, VLB capability)
  - Detailed in **ALMA Scientific Specifications and Requirements**
  - Recommended development paths from ASAC:
    - 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 mapping.
- What are the NA/ALMA objectives?
  - Augment ALMA scientific capabilities while benefitting NA goals.
  - E.g. Band 2 (67-93 GHz) has clear complementarities with ngVLA and GBT; a prototype is under development in Charlottesville.
  - Next Generation Correlator also has clear complementarities with ngVLA.

The mm/Submm Spectrum: Focus of ALMA



- Millimeter/submillimeter photons are the most abundant photons in the cosmic background, and in the spectrum of the Milky Way and most spiral galaxies.
  - Most important component is the 3K Cosmic Microwave Background (CMB)
  - After the CMB, the strongest component is the CIB/THz component, which carries most of the remaining radiative energy in the Universe, and 40% of that in for instance the Milky Way Galaxy.
- ALMA range--wavelengths from 1cm to ~0.3 mm, covers both components to the extent that the atmosphere of the Earth allows.
- CIB is a focus of THz astronomy. How much power is in spectral lines?

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?

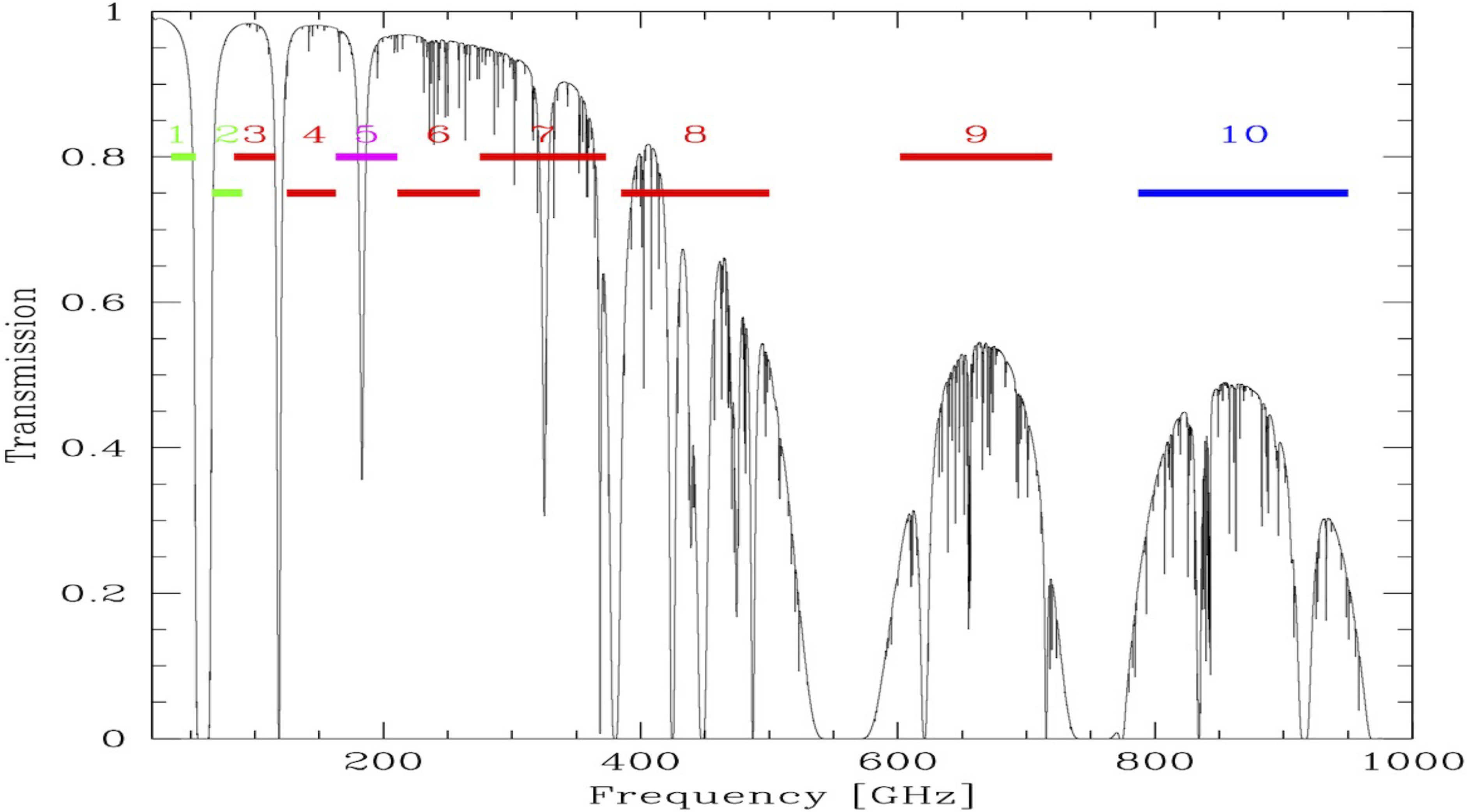
ALMA Operational Phases

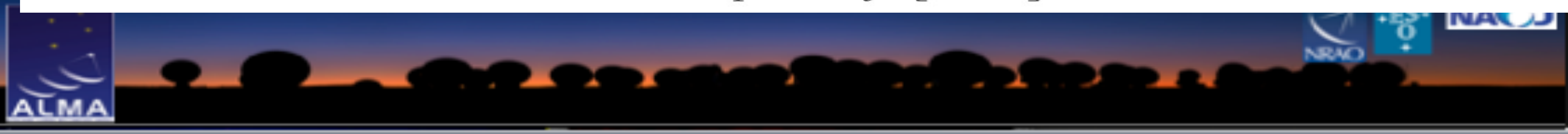
- Construction and commissioning concluded.
- Extension of ALMA capabilities continues.
- Continued Development was featured in the Ops Plan, reviewed by Intl Committee and by NSF Committee then adopted by ALMA Board.
  - No funding agency funds a ‘pig in a poke’. The character of development must be defined.
  - The Ops plan provides funding for Studies to define the character and implementation of possible new capabilities
  - ALMA Development Studies funded by the Development funding lines in the three parties form the fabric for ‘ALMA 2030’ recommendations made by the ASAC
  - ALMA is currently in the process of fashioning a plan for the next decades

Technical Specifications

- 50 12-m antennas, 12 7-m antennas, 4 TP 12m antennas at 5000 m altitude site.
  - >43 12m + >10 7-m +> 3 TP operational at a given time for 'Steady State'
- Surface accuracy ±25 μm, 0.6" reference pointing in 9m/s wind, 2" absolute pointing all-sky. Antennas in compliance for nominal conditions.
- Array configurations between 150m to ~15 -16km. Demonstrated.
- 10 bands in 31-950 GHz + 183 GHz WVR. Only 7 included in construction phase; 1 added since.
- 35-50 GHz "1" passed CDR, implementation expected ca 2019
- 67-90 GHz "2" prototypes under construction
- 84-116 GHz "3"
- 125-169 GHz "4"
- 163-211 GHz "5" in commissioning, implementation expected 2017
- 211-275 GHz "6"
- 275-373 GHz "7"
- 385-500 GHz "8"
- 602-720 GHz "9"
- 787-950 GHz "10"
- 8 GHz BW, dual polarization.
- Flux sensitivity 0.2 mJy in 1 min at 345 GHz (median cond.).
- Interferometry, mosaicing & total-power observing
- VLB capability added beginning 2016
- Correlator: 4096 channels/IF (multi-IF), full Stokes.
- Data rate: 6MB/s average; peak 60 MB/s.
- All data archived (raw + images), pipeline processing.

Key Design Elements: ALMA Bands





Specifications Breed Transformational Performance

- With these specifications, ALMA has improved
  - Existing sensitivity, by about two orders of magnitude
    - Best accessible site on Earth
    - Highest performance receivers available
    - Enormous collecting area (1.6 acres, or >6600 m^2)
  - Resolution, by nearly two orders of magnitude
    - Not only is the site high and dry but it is big! 16km baselines or longer have been accommodated.
  - Wavelength Coverage, by a factor of two or more
    - Take advantage of the site by (eventually) covering all atmospheric windows with >50% transmission above 35 GHz
  - Bandwidth, by a factor of a few
    - Correlator now processes 16 GHz or 8 GHz times two polarizations
- Scientific discovery parameter space is greatly expanded!

Development Items for ALMA 2010-2020

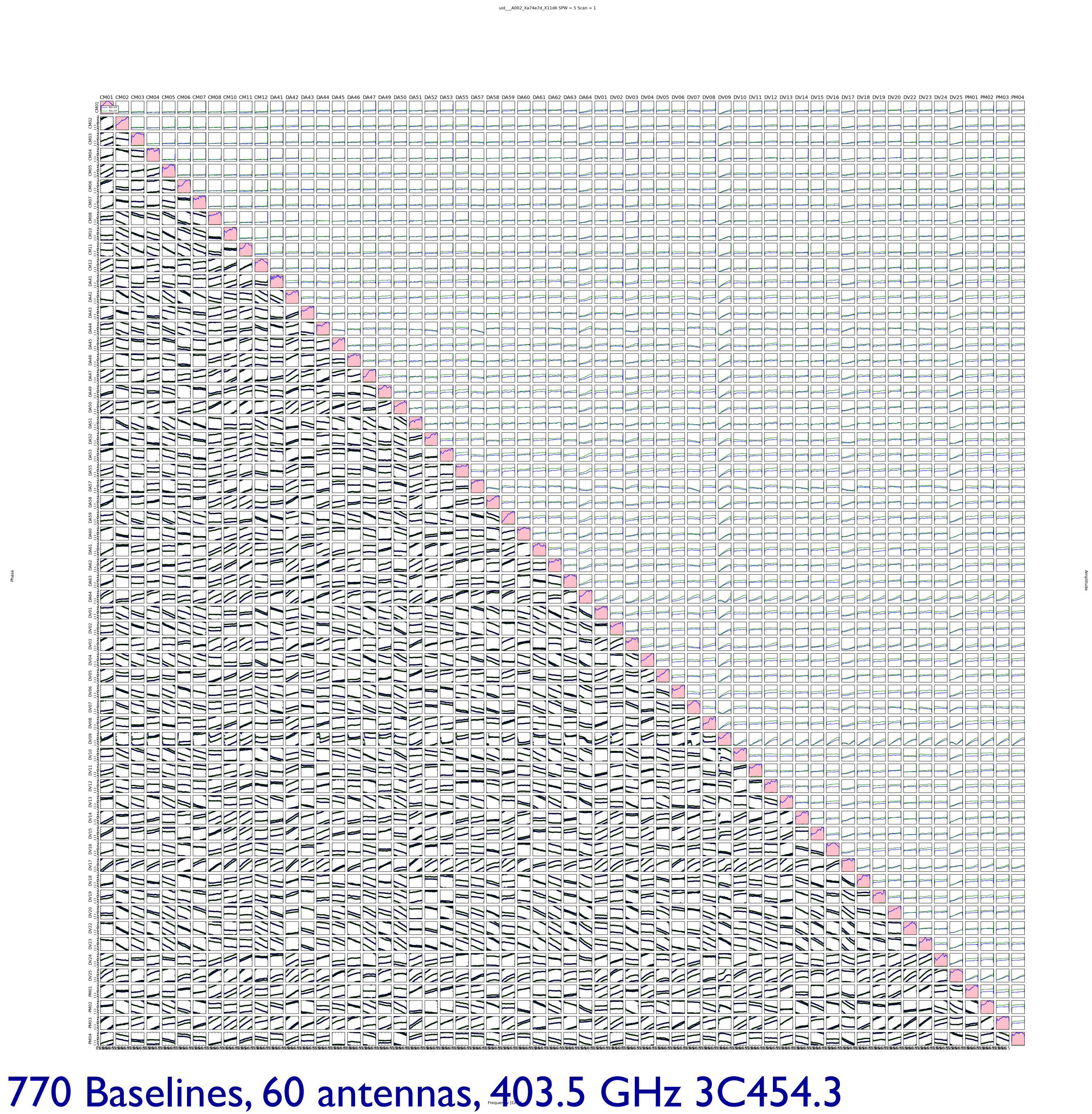
- Science clearly benefits from improving
  - Throughput (collecting area, instantaneous bandwidth, uv coverage)
  - Bandwidth (all accessible frequencies)
  - Resolution
- Many other possibilities
  - ASAC Report
  - Correlator upgrade
  - Longer connected baselines
  - Are any science goals endangered to whose realization development could contribute?

ALMA Science Requirements

ALMA now essentially meets three "level I" science goals:

- *The ability to detect spectral line emission from CO or C^+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation;*
- *The ability to image the gas kinematics in a solar-mass protostellar/protoplanetary disk at a distance of 150 pc, enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation;*
- *The ability to provide precise images at an angular resolution of 0.1"*

- **Demonstrated goals**
  - High Fidelity Imaging.
  - Routine sub-mJy Continuum / mK Spectral Sensitivity.
  - Wideband Frequency Coverage.
  - Wide Field Imaging through Mosaicing.
  - Submillimeter Receiver System (..& site..).
  - Full Polarization Capability.
  - System Flexibility (hardware/software).
  - Ease of use—PI receives calibrated data and reference image from ALMA Resource Center, all archived.

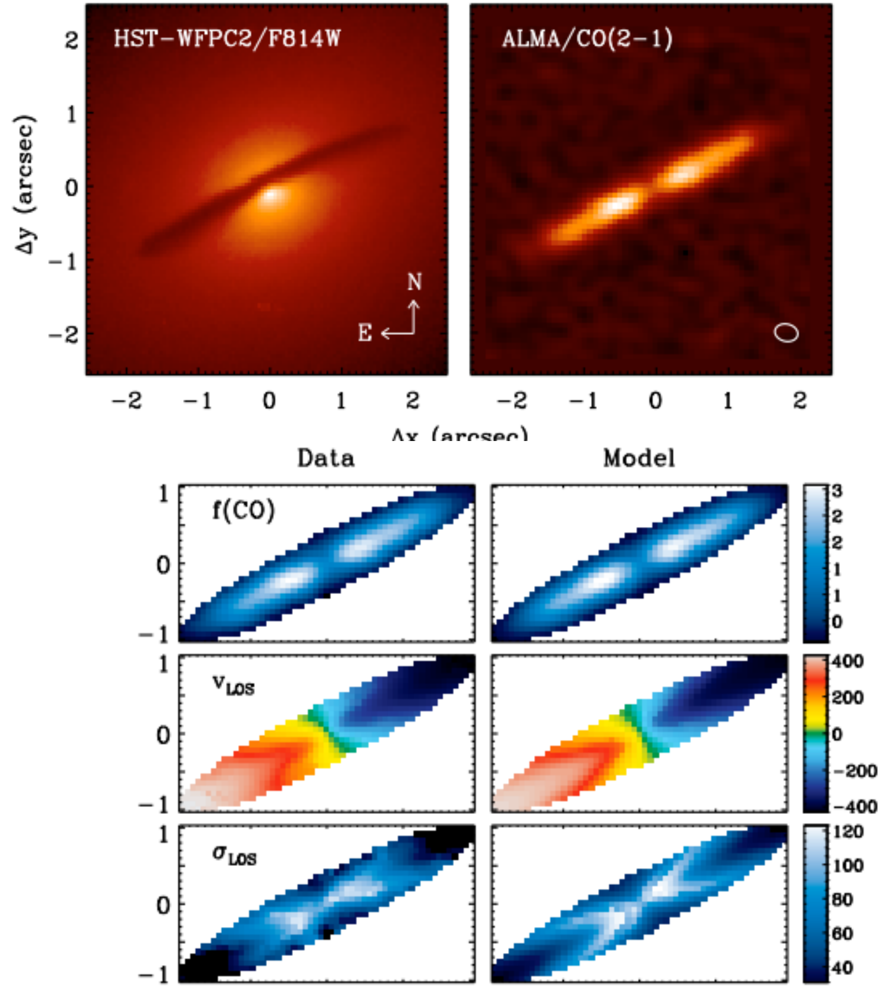


1770 Baselines, 60 antennas, 403.5 GHz 3C454.3

ALMA Measures NGC 1332 Black Hole

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

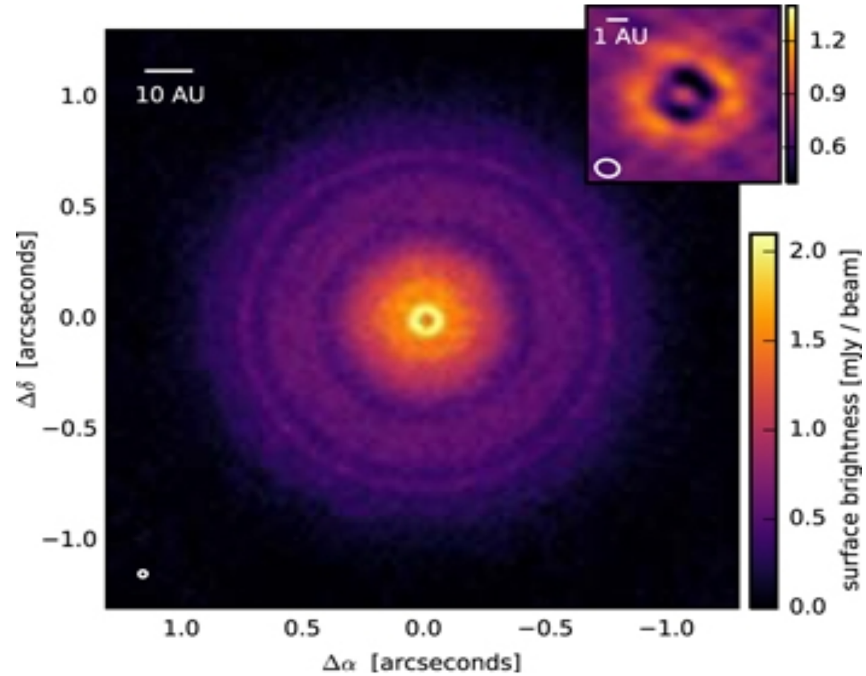
- CO J=2-1 emission measured in the circumnuclear disk of NGC1332.
- Resolution of 0.044" (4.8pc) resolution at 22.3Mpc demonstrates ALMA imaging, high resolution
- Disk shows regular rotation with central high velocity component suggesting a compact central mass
- Authors find $M_{BH} = (6.64^{+0.65}_{-0.63}) \times 10^8 M_\odot$
- 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.

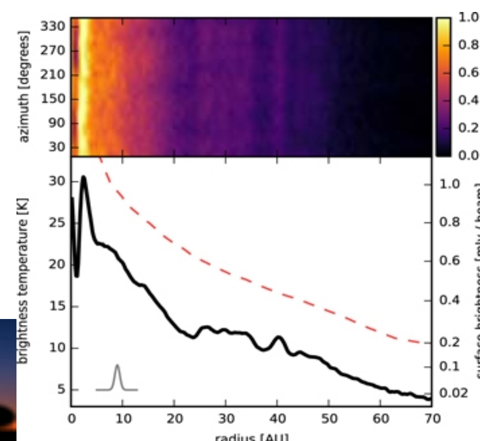


Ringed Substructure and a Gap at 1 AU in TW Hya

Andrews, Sean M.; Wilner, David J.; Zhu, Zhaohuan; Birnstiel, Tilman; Carpenter, John M.; Pérez, Laura M.; Bai, Xue-Ning; Öberg, Karin I.; Hughes, A. Meredith; Isella, Andrea; Ricci, Luca ApJ820,L40

- 870 µm continuum, 20mas (1AU resolution)
- Bright zones, narrow (1–6AU) dark annuli of modest contrast trace concentrations of solids halted in inward radial drift, perhaps at local gas pressure maxima.
- Related to condensation fronts of major volatile species?
- Disk–young planet interaction: Narrow dark annulus at ~1AU?





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, 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 Band 5, and will for the remaining Bands and other capital investments

(A Few) Science Drivers

- Protostars, protoplanetary disks and their evolution
  - 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)
  - 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

Possible Development Areas

- Sensitivity--could achieve that of 8 additional antennas with each of
  - Use of all available 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 ~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

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/June with deadline in September*
- *EU Workshop on Development: May 25-27, 2016 (Chalmers, Sweden)*
- *NA Development splinter session at AAS 14 June*
- *NA Development workshop: 24 August 2016 @NAASC*
- *September 2016: 'Current and Future Development Activities at ALMA' presentation/panel discussion at the ALMA international conference.*

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