NRAO

National Radio Astronomy Observatory

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

ALMA: The March to Early Science and Beyond

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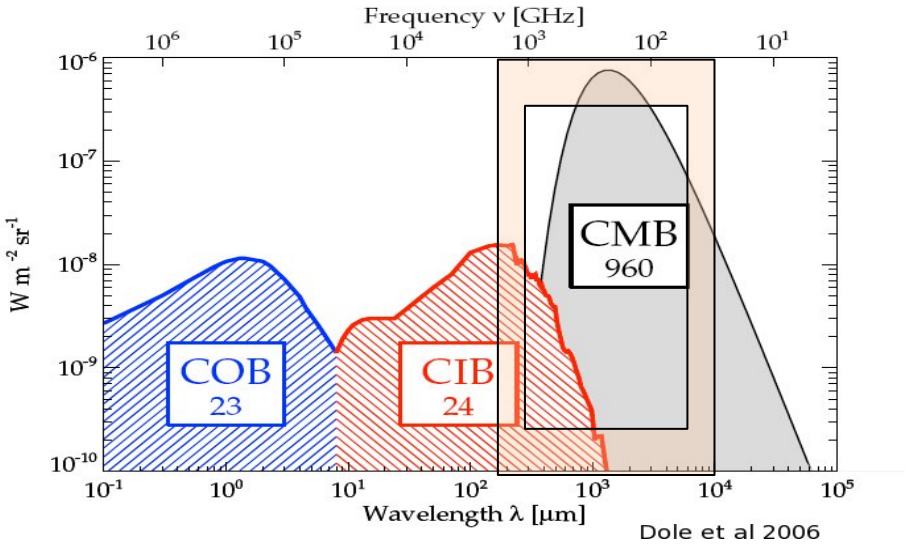
The mm/submm Spectrum: Focus of ALMA



- Millimeter/submillimeter photons are the most abundant photons in the cosmic background, and in the spectrum of the Milky Way and most spiral galaxies.
- ALMA range--wavelengths from 1cm to ~0.3 mm, covers both components to the extent the atmosphere of the Earth allows.

ALMA Science Requirements &Targets

ALMA

Design Reference Science Plan: potential science experiments

- Cosmic Dawn
  - First Stars and Galaxies
  - First Star Deaths: γ-ray Bursters
- Nearby Universe (Turner)
  - Galaxy Clusters
  - Galaxies
- Star Formation (Wilner)
  - Massive Stars
  - Normal Stars and Planets
- Stellar Systems (see DRSP)
  - Sun
  - Planets and Small Bodies

Science Requirements:

- *Spectral line CO/C+ in z=3 MWG < 24hrs*
- *Resolve ProtoPlanetaryDisks at 150 pc – gas/dust/fields*
- *Precise 0.1" imaging above 0.1% peak*

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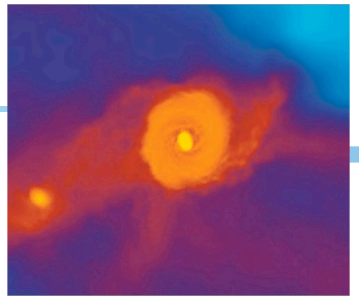
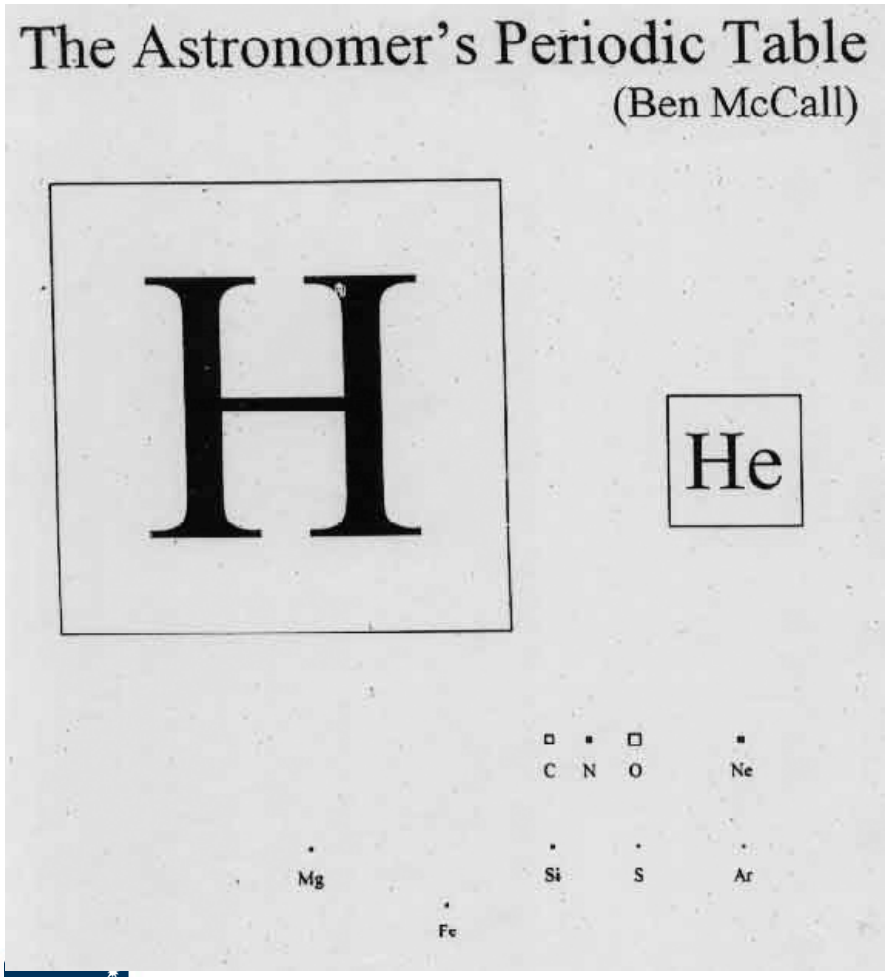
First Light



- Dark Matter structures concentrate matter shortly after t=0
- Molecular hydrogen (H_2, HD) forms from associative detachment
- Cooling of gas allows first stars, expected to be massive, to form
- This cooling via rotational lines of H_2 produces emission which shifts into potential ALMA bands at z~8, possibly observable from the first waves of star formation in massive proto-galaxies.
- Massive stars evolve, producing heavier elements, which are distributed throughout the protogalaxies via supernovae, which may appear as Gamma Ray Bursts (GRBs)
- Cooling then proceeds via the atomic fine-structure lines, which are redshifted into the ALMA bands
- ALMA should be able to observe
  - Rotational lines of H_2 from large mass accumulations forming the first stars
  - Emission from GRBs, probing the demise of those first stars
  - Emission from fine-structure lines as the first galaxies evolve

The Birth of Chemical Complexity



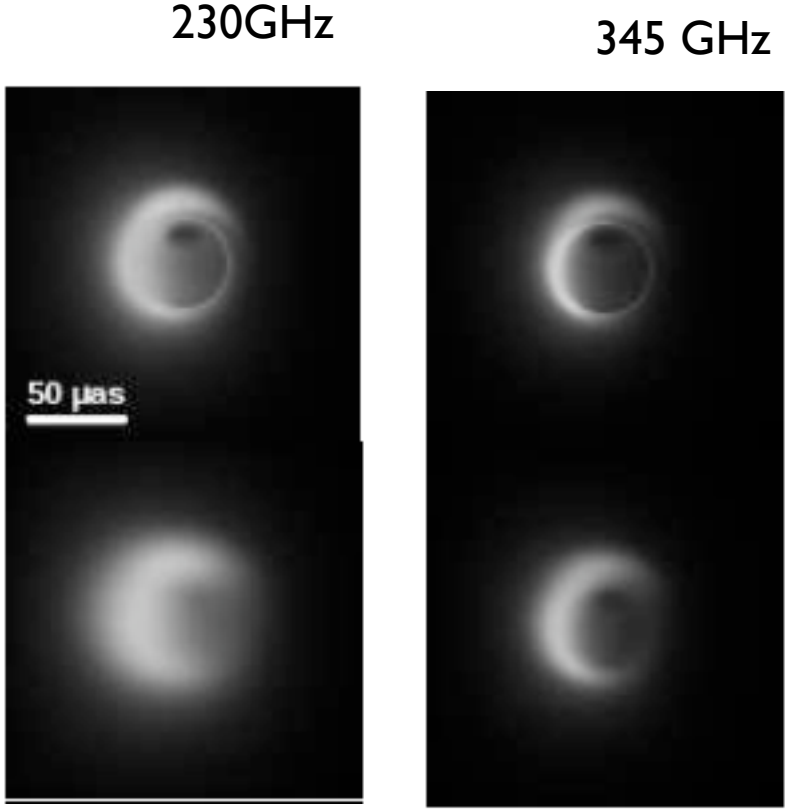
When chemistry got interesting
(H_3^+, H_2D^+, H_2, HD notwithstanding)

ALMA should be able to monitor the creation of

- O ([O I], [O III], OH, H_2O)
- C ([C I], [C II], CO, CH, CH^+, ^{13}C)
- N ([N II], NH, N_2H^+)

Imaging the Violent Hearts of Galaxies

- Very Long Baseline Interferometry
  - Not in the construction plan
  - ***ALMA Development*** upgrade
- Enable imaging of Sgr A* Black Hole
  - Model at right at 345 GHz
    - ALMA as an element of a worldwide array
- M87 BH also usefully imaged



The Goals Demand Transformational Performance

ALMA

Scientific discovery parameter space is greatly expanded!

- Best accessible site on Earth
- Highest performance receivers available
- Enormous collecting area (1.6 acres, or >6600 m^2)

- RESOLUTION

  nearly two orders of magnitude improvement

  - Site is high & dry, **and big!** 18km baselines or longer possible.
- WIDE WAVELENGTH COVERAGE WITH HIGH FIDELITY IMAGING

  factor of two or more improvement

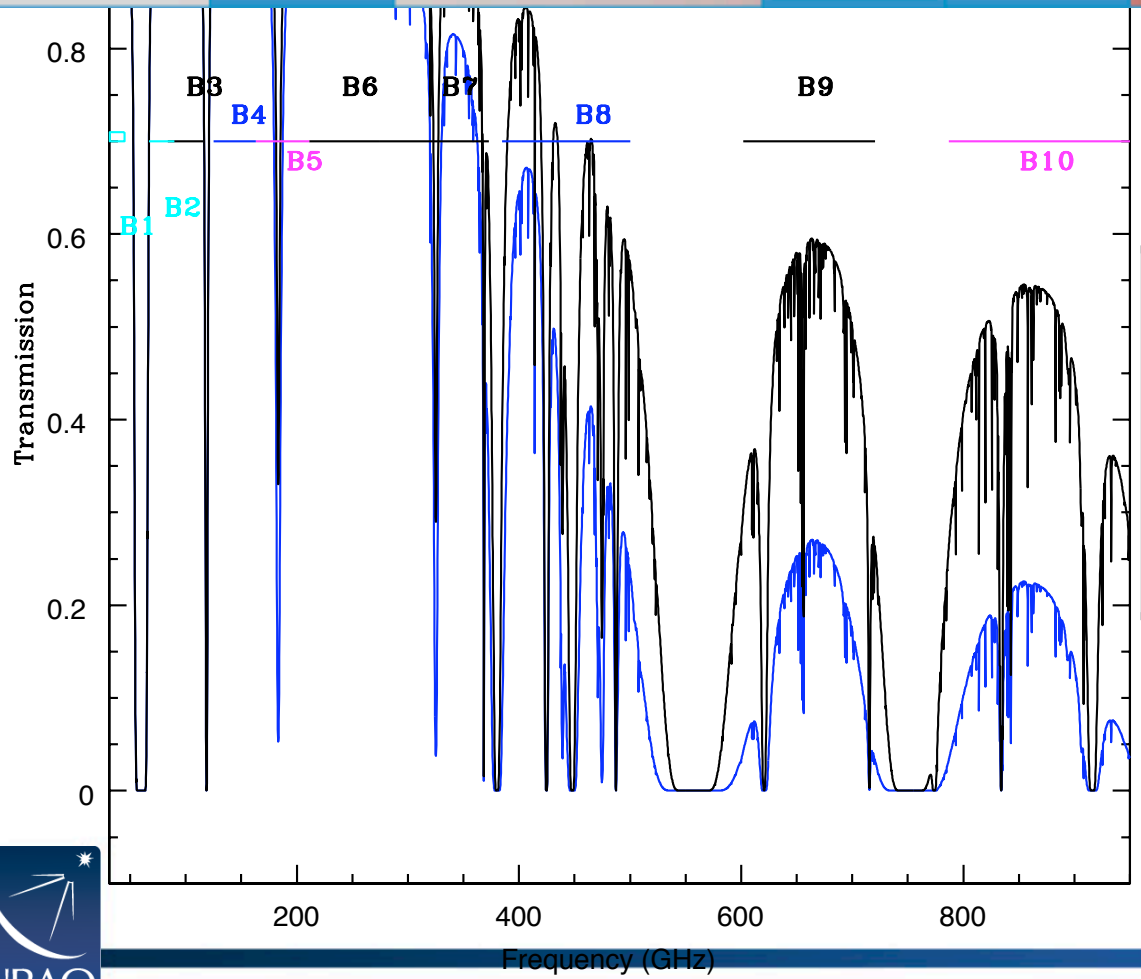
  - All windows offered by site with >50% transmission above 30 GHz
- WIDE BANDWIDTH: 16 GHz or 8 GHz times two polarizations

  factor of a few improvement

ALMA Bands and Transparency

ALMA

Bands:	3	4	5	6	7	8	9	10
Frequency (GHz)	84-116	125-163	163-211	211-275	275-373	385-500	602-720	787-950
Wavelength (mm)	3.57-2.59	2.40-1.84	1.84-1.42	1.42-1.09	1.09-0.80	0.78-0.60	0.50-0.42	0.38-0.32



Early Science: 3, 6, 7, 9

Full Science: 4, 5 (6 antennas only), 8

Early Operations: 5,10

Future Development: 1, 2, 11?

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Transformational Performance

ALMA

- ***ALMA Testing*** has begun verifying performance

- ***ALMA Early Science*** heralds the transformation
  - Sensitivity: 16 antennas: ~10% full ALMA
  - Imaging & Resolution: 120 baselines; up to ~0.4”
  - Wavelength Coverage: 4 of final 8 bands

  - ***Opening ALMA Discovery Space***

The Road to ALMA

43 km to Array Operations Site (AOS)
5,000m elevation

15 km to Operations Support Facility (OSF)
2,900m elevation

Operations Support Facilty (3000m level)

ALMA

Melco, AEM, and Vertex antenna assembly

Contractors camp

There are now >27 antennas in various stages of completion

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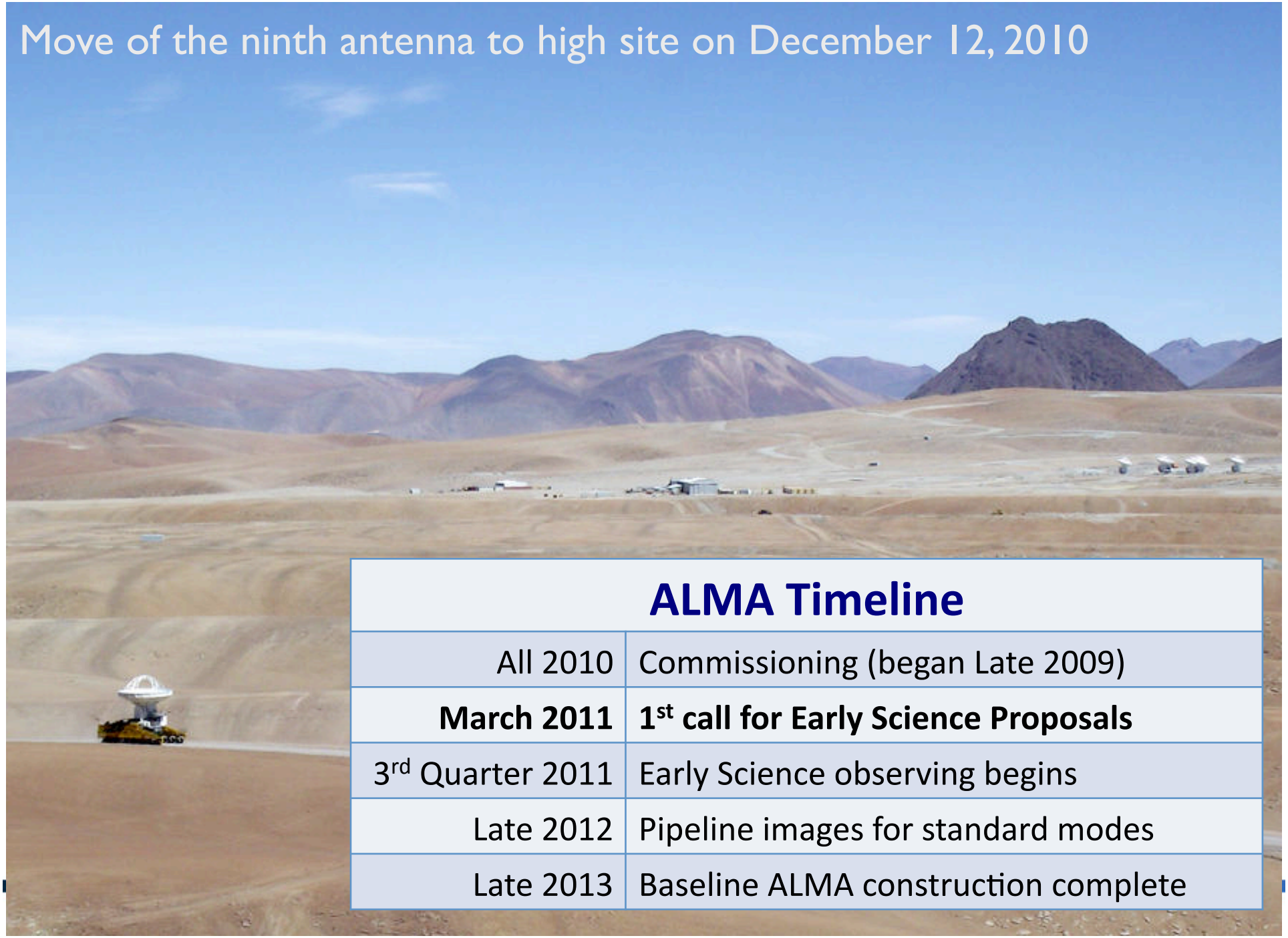
Progress at the Array Operations Site at 5000m → the "high site"

AOS Technical Building - completed 2008

Home of the ALMA 12-m and ACA correlators

Move of the ninth antenna to high site on December 12, 2010

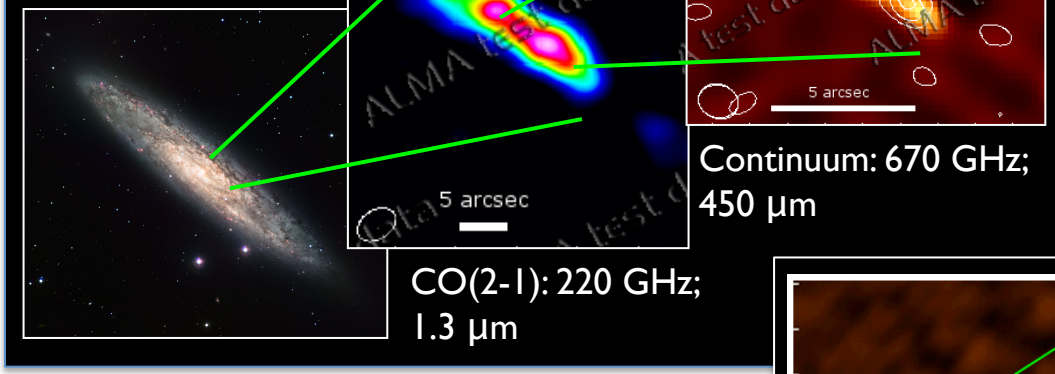


ALMA Timeline	
All 2010	Commissioning (began Late 2009)
March 2011	**1st call for Early Science Proposals**
3rd Quarter 2011	Early Science observing begins
Late 2012	Pipeline images for standard modes
Late 2013	Baseline ALMA construction complete

Commissioning: Stunning Test Images

ALMA

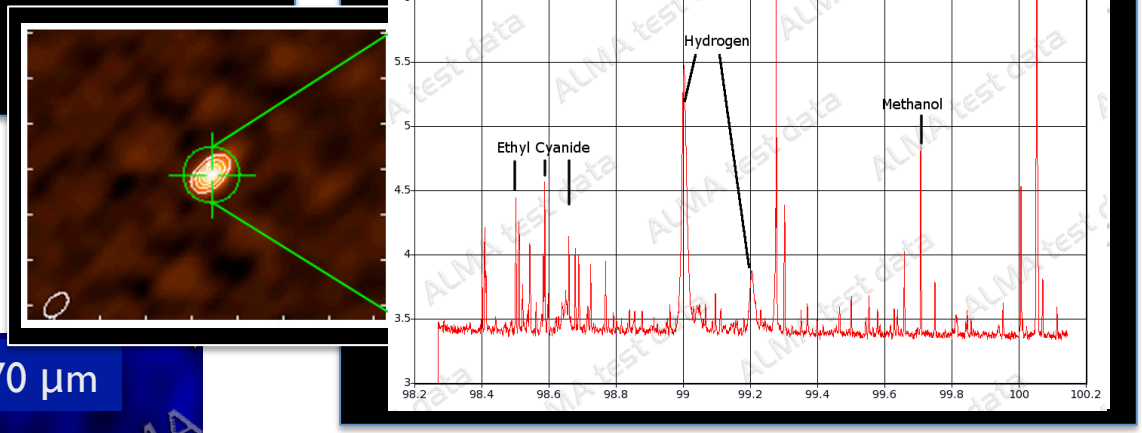
The heart of a star forming galaxy: NGC253

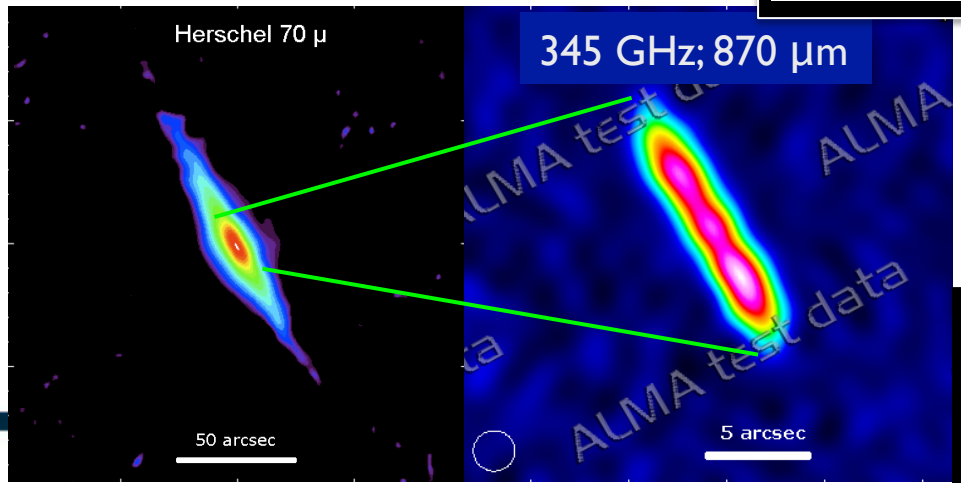


Continuum: 670 GHz; 450 μm

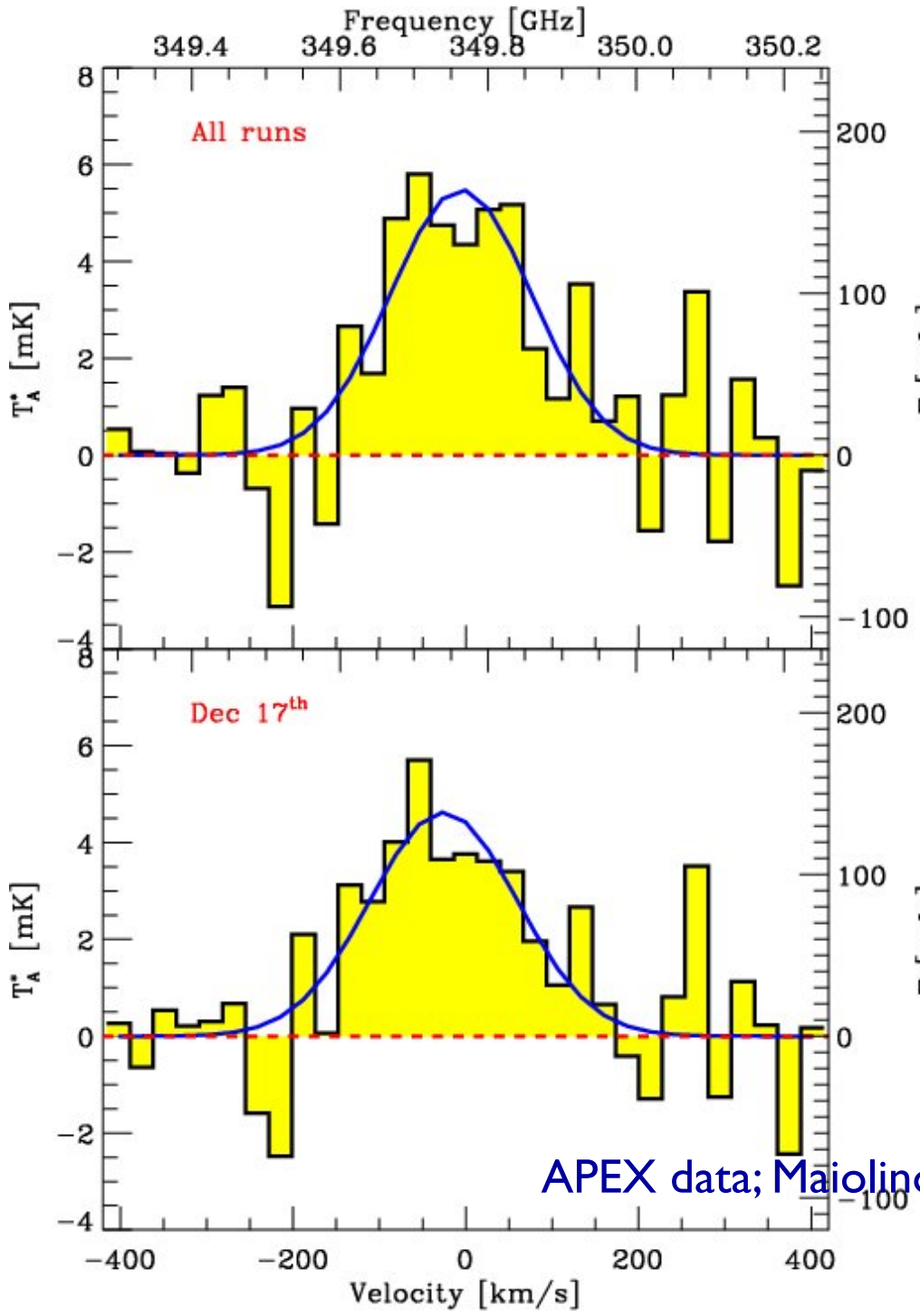
CO(2-1): 220 GHz; 1.3 μm

Spectral line forest from a Galactic massive protostar

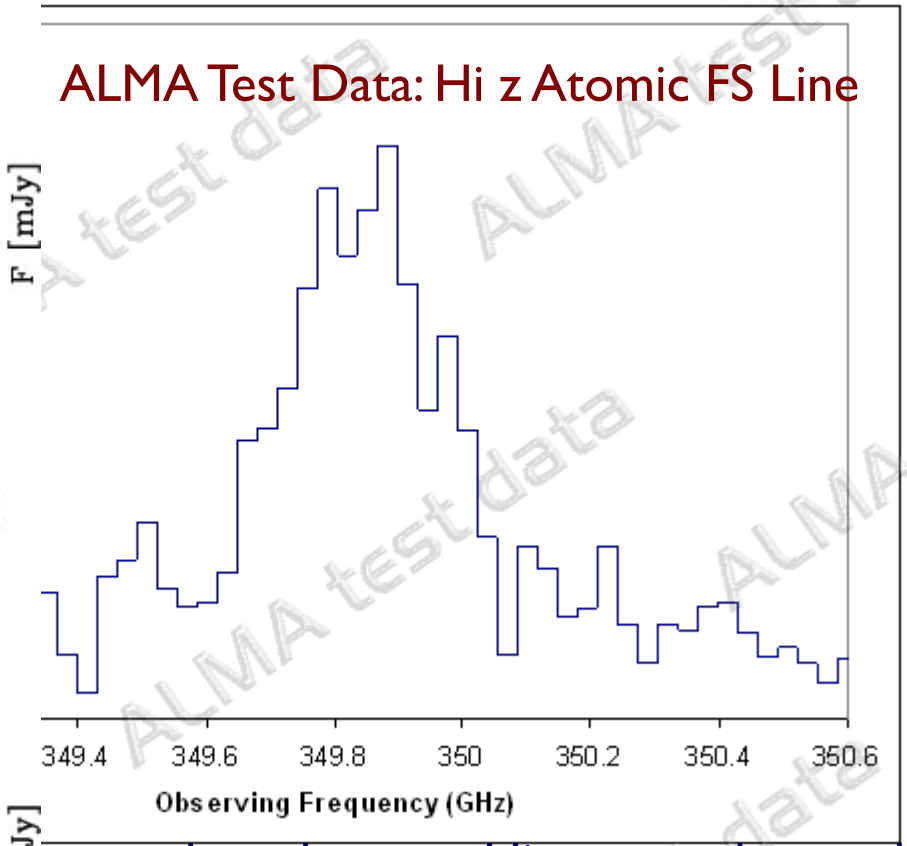




Dust continuum of the potentially planet forming debris disk: Beta Pictoris



ALMA

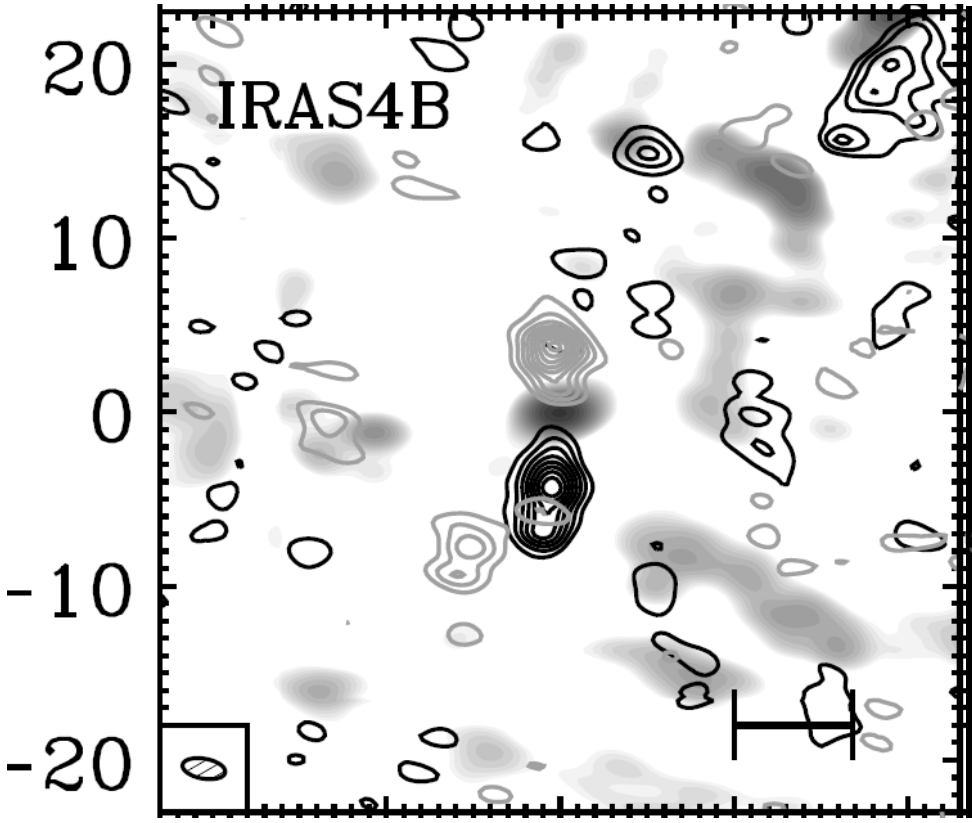


bserve broad spectral lines, we observed
is at a red-shift of z = 4.43. The object
elines, but the 158 micron line from
d in the spectrum, which is impressive
only one hour in total.

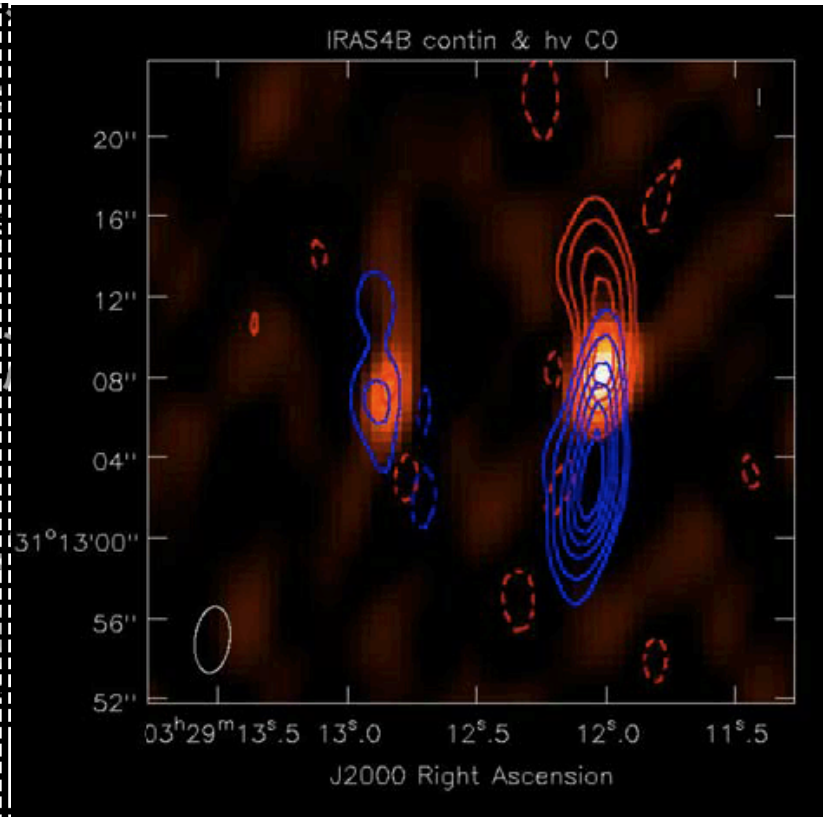
APEX data; Maiolino et al (2009)

Starforming Regions: Outflow

Jorgensen 2007 SMA COJ=3-2



ALMA/Dent 2010 CO J=3-2



- N.B. Flow at fainter eastern source B2; unseen before

Early Science Correlator Modes

- 3840 independent channels over 1.875 GHz
- For ES each baseband's spectral window must be identical:
  - multiple spectral windows per baseband not available
- The ACA Correlator not available

Expected ALMA *Early Science* Correlator Modes

Mode	Polariza-tion	Band-width per baseband (MHz)	Nchan	Spacing (MHz)	Mode	Polariza-tion	Band-width per baseband (MHz)	Nchan	Spacing (MHz)
1	Single	1875	7680	0.244	12	Double	58.6	3840	0.0153
2	Single	938	7680	0.122	13	Full	1875	1920	0.977
3	Single	469	7680	0.061	14	Full	938	1920	0.488
4	Single	234	7680	0.0305	15	Full	469	1920	0.244
5	Single	117	7680	0.0153	16	Full	234	1920	0.122
6	Single	58.6	7680	0.00763	17	Full	117	1920	0.061
7	Double	1875	3840	0.488	18	Full	58.6	1920	0.0305
8	Double	938	3840	0.244	69	Double	2000	128	15.625
9	Double	469	3840	0.122	70	Full	2000	64	31.25
10	Double	234	3840	0.061	71	Single	2000	256	7.8125
11	Double	117	3840	0.0305					

Optimum ES Projects

- Continuum Sensitivity: Better than 1 mJy 1 minute most bands; ~3mJy .4 mm
  - Weakest sources ever seen in submm emit ~1 mJy
  - With many more antennas, deep surveys will be more effective with full ALMA
- Spectral line sensitivity: ~1 Jy km s^{-1} in 1 minute at .4mm
  - ~30x better than current ~10m submm telescopes in one hour
  - Whole-band search, requiring ~15 tunings, feasible to good sensitivity
- Imaging performance good, but ~10x better with full ALMA
- Conclusion: Excellent sensitivity
  - Spatial surveys should await full ALMA
  - Line surveys practical with ALMA Early Science array on targeted objects

Science Verification Program

- First release of ALMA test data to the astronomy community will be through the ***Science Verification*** program
  - Observations designed to test ALMA systems and confirm their performance
    - continuum and line sensitivity
    - dynamic range and image fidelity
    - amplitude calibration
    - positional accuracy
    - Later tests: polarization, small mosaics, total power (zero-spacing) data
  - Data will be non-proprietary; available to all by ALMA Early Science Cycle 0 Call for Proposals
  - **See webpages for details of how to suggest targets**

ALMA Development

- ALMA partners invite Proposals for Studies relevant to the ALMA Development Plan with the aims of
  - Providing opportunities for groups within the North American partnership an opportunity to propose upgrades which may be implemented as part of the ALMA Development Plan
  - To support development of conceptual and detailed designs for upgrades
  - To encourage relevant long-term research and development
- Limited funding available to support groups for the studies, allocated competitively.
- NRAO will issue a Call for Studies soon with the expectation that funding will start this year.
- NRAO will engage the community strongly in ALMA Development, beginning with these Studies. Studies are solicited which enhance scientific capabilities of ALMA directly (enabling new science) or indirectly (improving data analysis tools, operations efficiency, or calibration).

ALMA Early Science initiates the transformation

- Sensitivity: ~10% full ALMA
- Resolution: up to ~0.4" (0.1" goal)
- Wavelength Coverage: 3-4 of final 8 bands (7 goal)
- Bandwidth: ~2x improvement

Begins this year!

www.almaobservatory.org

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership among Europe, Japan and North America, in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere, in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

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