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

National Science Foundation

Associated Universities, Inc.

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ALMA: Current Status

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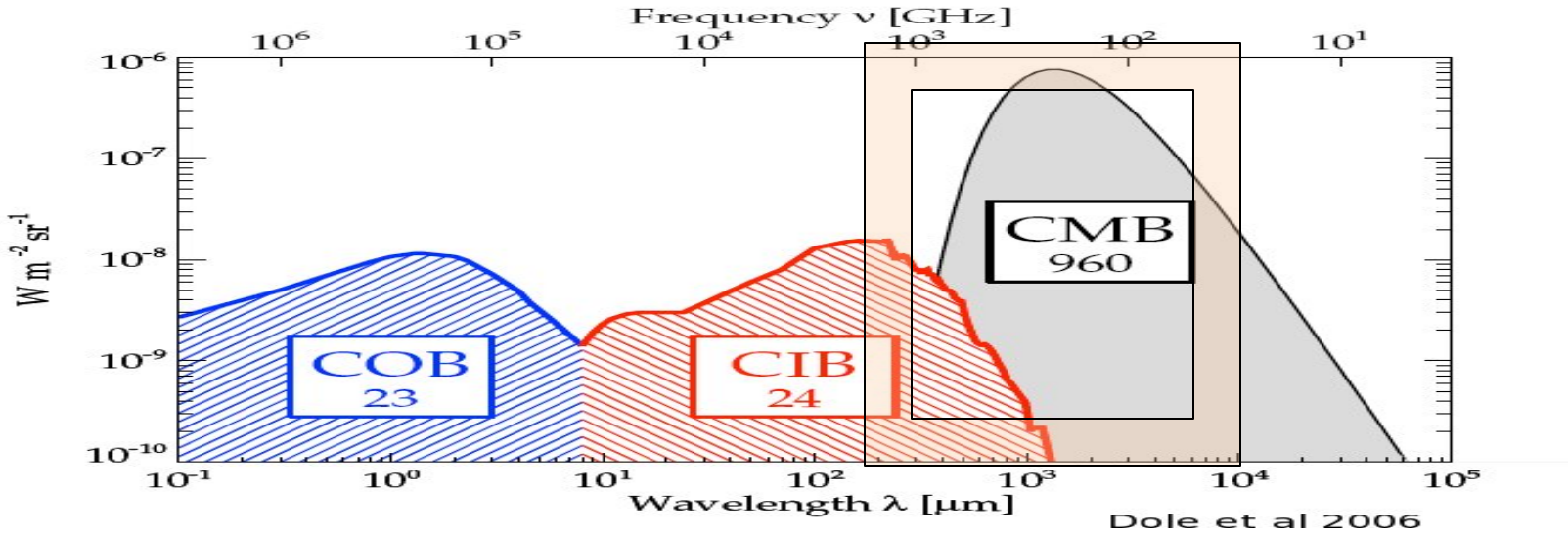
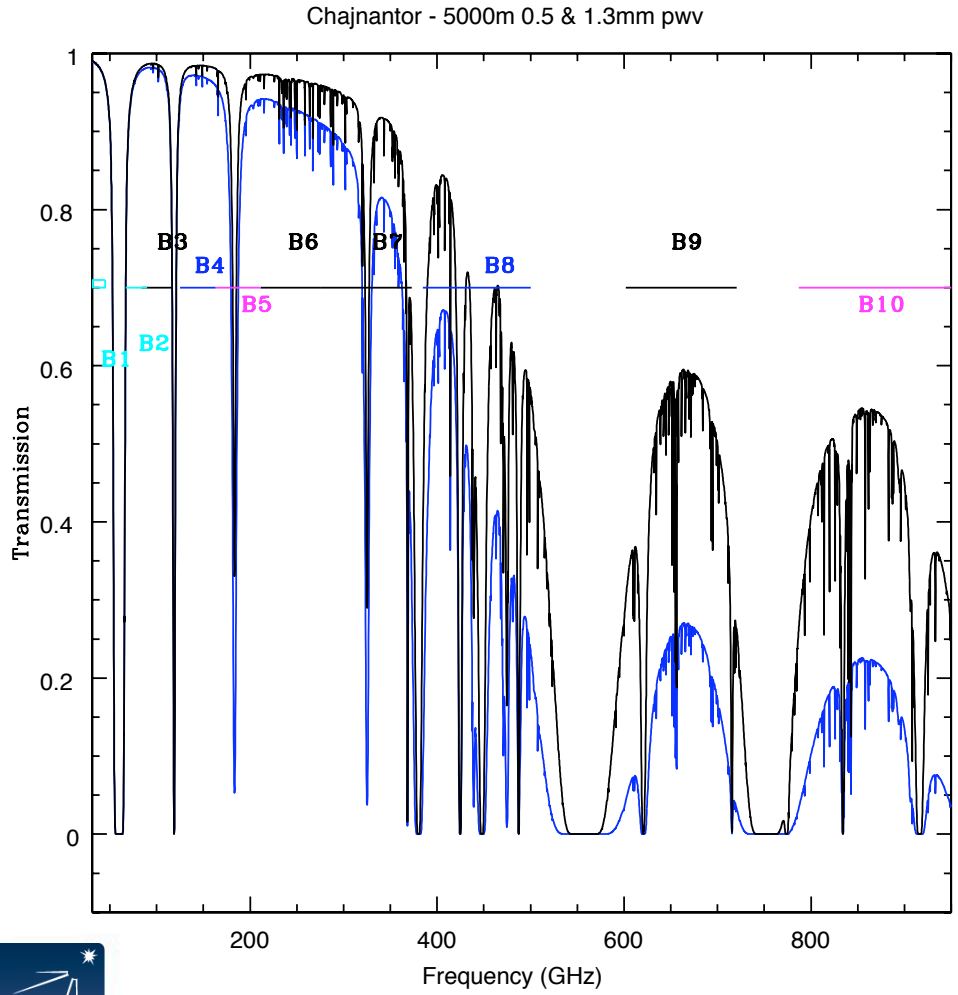
The mm/submm Spectrum: Focus of ALMA



- 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 Bands and Transparency



Early Science:

- 3mm 'B3'
- 1.3mm 'B6'
- .8mm 'B7'
- .45mm 'B9'

Full Science:

- 2mm 'B4'
- 1.6mm 'B5' (6 only)
- .6mm 'B8'

Early Operations:

- .35mm 'B10'

Development:

- 9mm 'B1'
- 4mm 'B2'
- Other bands ('B11'?)

ALMA Science Requirements

Project ensures ALMA meets three "level I" science goals:

- *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*

- These require the instrument to have certain characteristics:
  - High Fidelity Imaging.
  - Routine sub-mJy Continuum / mK Spectral Sensitivity.
  - Wideband Frequency Coverage.
  - Wide Field Imaging Mosaicing.
  - Submillimeter Receiver System (..& site..).
  - Full Polarization Capability.
  - System Flexibility (hardware/software).

Specifications Demand Transformational Performance

ALMA

- With these specifications, ALMA improves
  - Existing sensitivity, by about ***two orders of magnitude***
    - ***Best accessible site*** on Earth
    - ***Highest performance receivers*** available (for 7 of 10 'bands')
    - ***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! 18km baselines or longer may be accommodated.
  - Wavelength Coverage, by a factor of two or more
    - Take advantage of the site by covering all atmospheric windows with >50% transmission above 30 GHz
  - Bandwidth, by a factor of a few
    - Correlator processes 16 GHz or 8 GHz times two polarizations
- Scientific discovery parameter space is greatly expanded!

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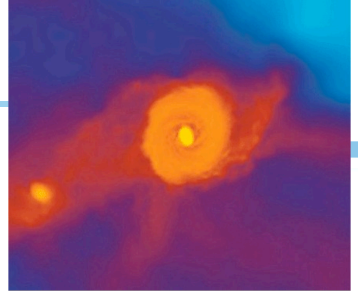
Transformational Performance

- ***ALMA Testing*** has begun verifying performance
  - Sensitivity: 9 antennas, 1 hr ~0.25mJy 5σ at 100GHz
  - Imaging and Spatial Resolution: >36 baselines; to ~1”
  - Wavelength Coverage: 4 of 7 bands; 3mm to 0.45mm
  - Bandwidth: Full 16 GHz, 2 polarizations
  - Verified Test Data examples released
  - Science Verification Data being collected, to be released.
  - *Beginning the Discovery Space Expansion*
- ***ALMA Early Science Cycle 0*** heralds the transformation
  - Sensitivity: 16 antennas; ~10% full ALMA;
  - Imaging & Resolution: 120 baselines; up to ~0.2”
  - Wavelength Coverage: 4 of final 7 full bands (7 goal)
  - *Continuing the Discovery Space Expansion*

ALMA Science Targets

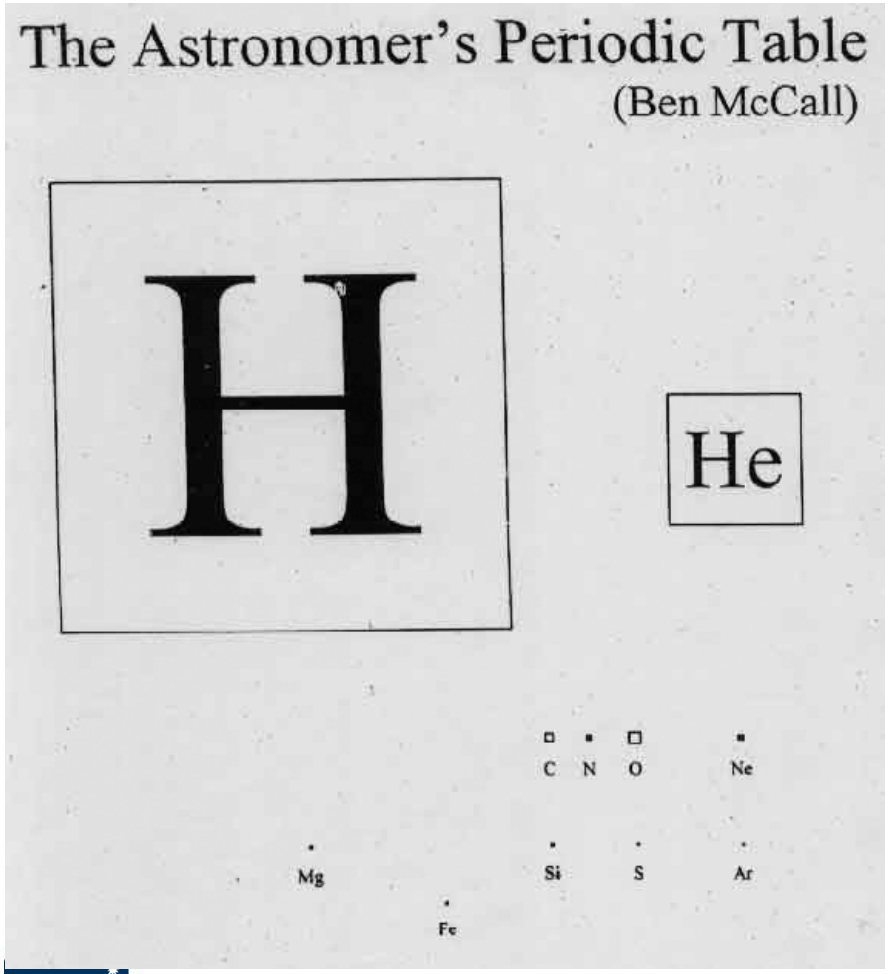
- Design Reference Science Plan contains a suite of potential science experiments
- Cosmic Dawn
  - First Stars and Galaxies
  - First Star Deaths: Gamma Ray Bursters
- Nearby Universe
  - Galaxy Clusters
  - Galaxies
- Star Formation
  - Massive Stars
  - Normal Stars and Planets
- Stellar Systems
  - Sun
  - Planets and Small Bodies

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 ([C II] reaches B10 for z~1)
- 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)

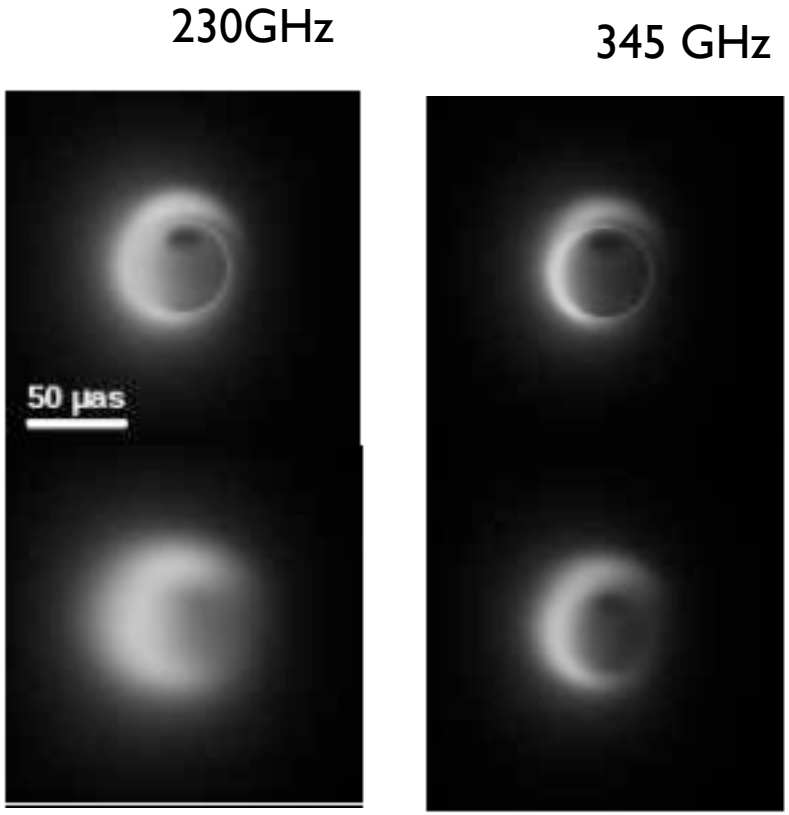
ALMA should be able to monitor the creation of

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

N.B. [C II] 8<z<11 the bright [C II] line falls in sparsely populated B5.

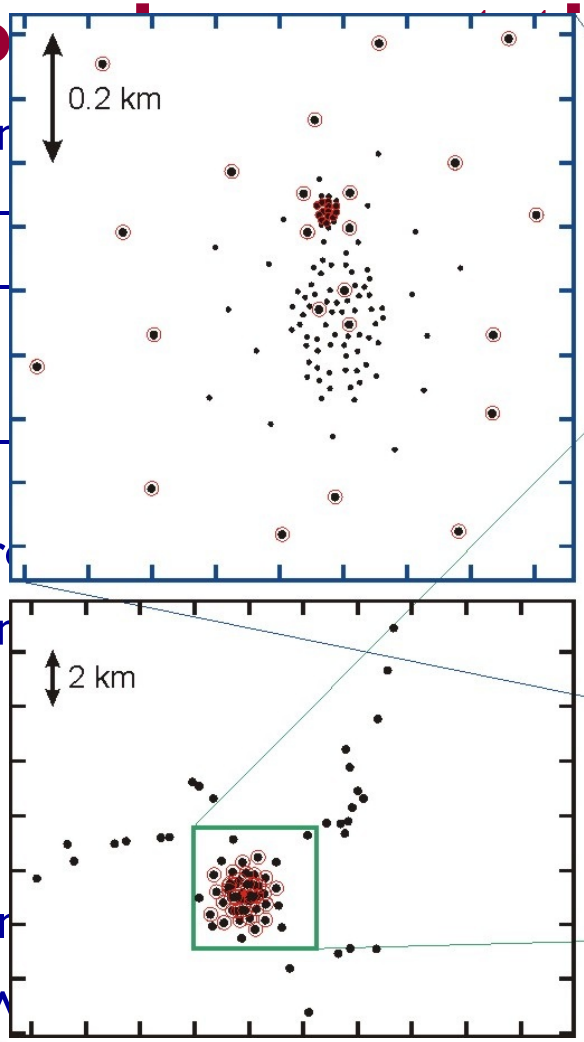
Imaging the Violent Hearts of Galaxies

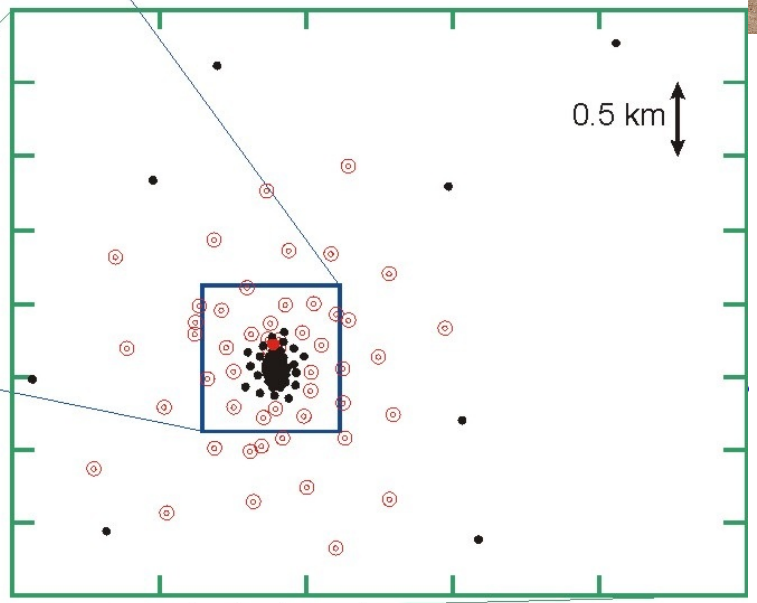
- Very Long Baseline Interferometry
  - Not in the construction plan
  - ***ALMA Development*** upgrade
- Enable imaging of Sgr A* Black Hole
  - Model at right at 345 GHz
    - ALMA as an element of a worldwide array
  - M87 BH also usefully imaged

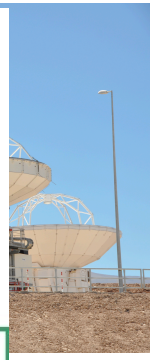


Ho

- Ar
- Fr
- Ar
  - to
- Fir
- Tw







Aggressive perhaps success-oriented schedule!

Correlator Modes: OT and testing

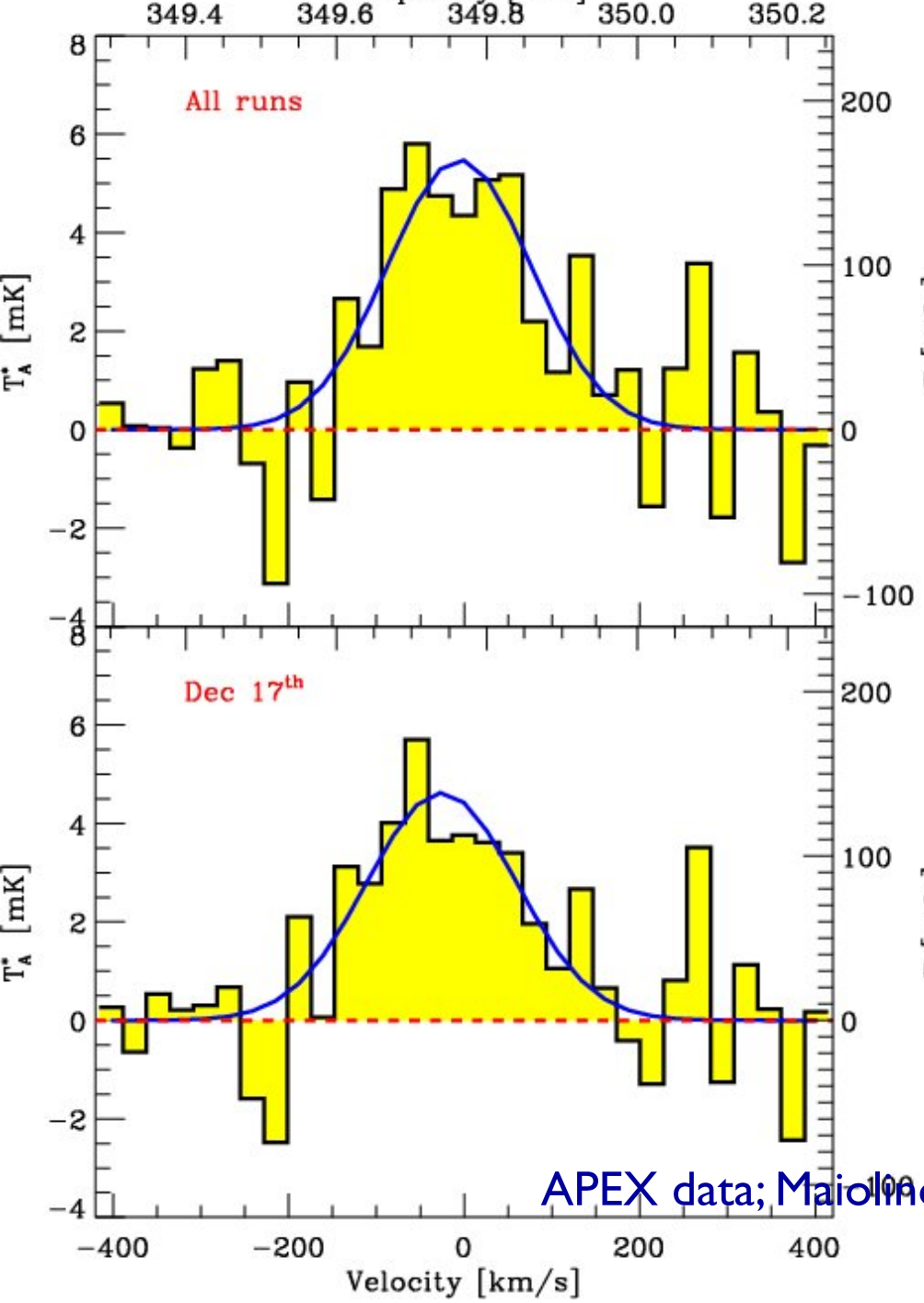
- Correlator modes
  - N.B. subband channels summed at edges, leaving 3840 independent channels over 1.875 GHz except in TDM mode.
- Multiple spectral windows per baseband will not be available ES
  - Each baseband's spectral window must have identical characterisics (number of channels, polarizations, bandwidth)
  - Full polarization modes not available for Cycle 0
- The ACA Correlator is also under test.

Astronomical Validation

- The Commissioning and Science Verification (CSV) team has run a number of tests to validate the performance of the array
- Test Data have been obtained; several test images have been released
- First release of ALMA test data to the astronomy community will be through the ***Science Verification*** program
  - Observations of objects designed to test ALMA systems and confirm their performance
    - Early tests will include continuum and line sensitivity; dynamic range and image fidelity; amplitude calibration; , small mosaics positional accuracy
  - Data from these tests will be available by shortly after the ALMA Early Science Cycle 0 Call for Proposals
  - Later tests include polarization and total power (zero-spacing) data
  - See webpages for details of how to suggest targets

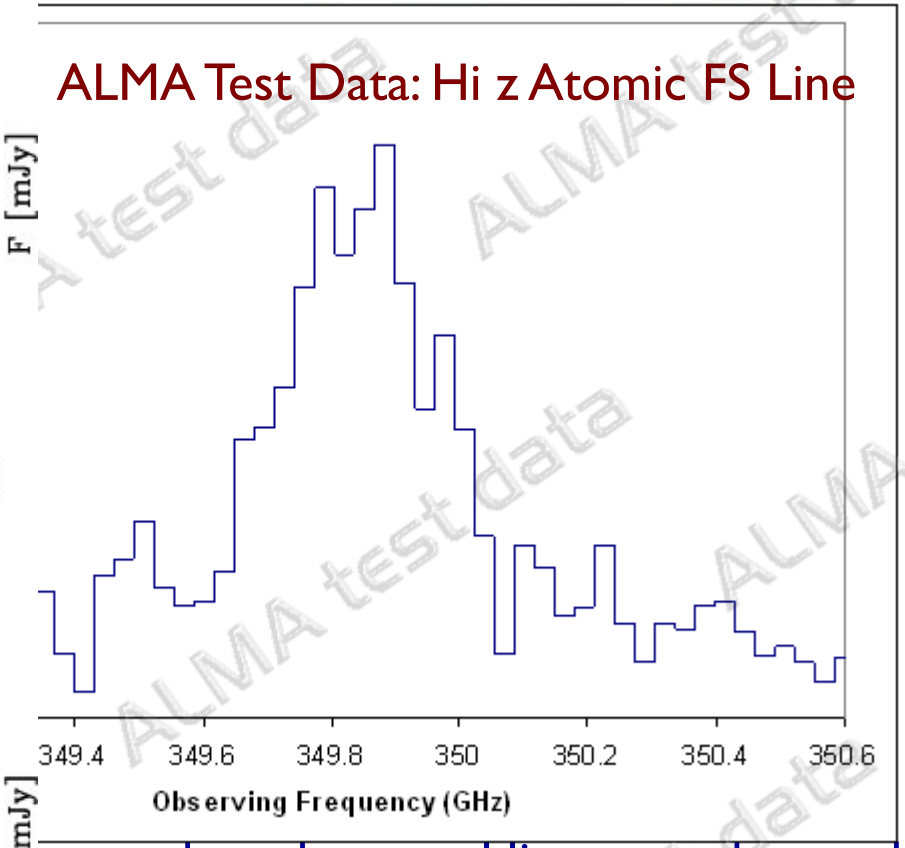
Distant Galaxies with ALMA Early Science

- 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: ~3 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, but ~10x better with full ALMA
- Conclusion: Excellent sensitivity
  - Spatial surveys should await full ALMA (only 700 hours total Cycle 0)
  - Line surveys practical with ALMA Early Science array on targeted objects



ALMA

ALMA Test Data: Hi z Atomic FS Line



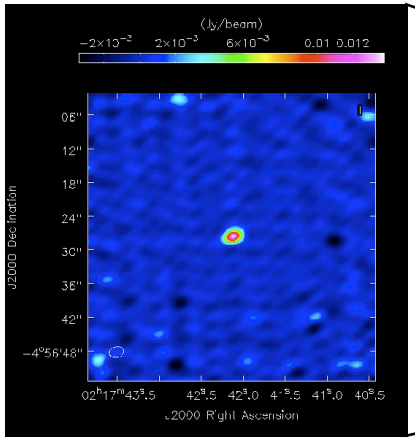
bserve broad spectral lines, we observed
, which is at a red-shift of z = 4.43. The
ort baselines, but the 158 micron line
etected in the spectrum, which is
vation took only one hour in total.

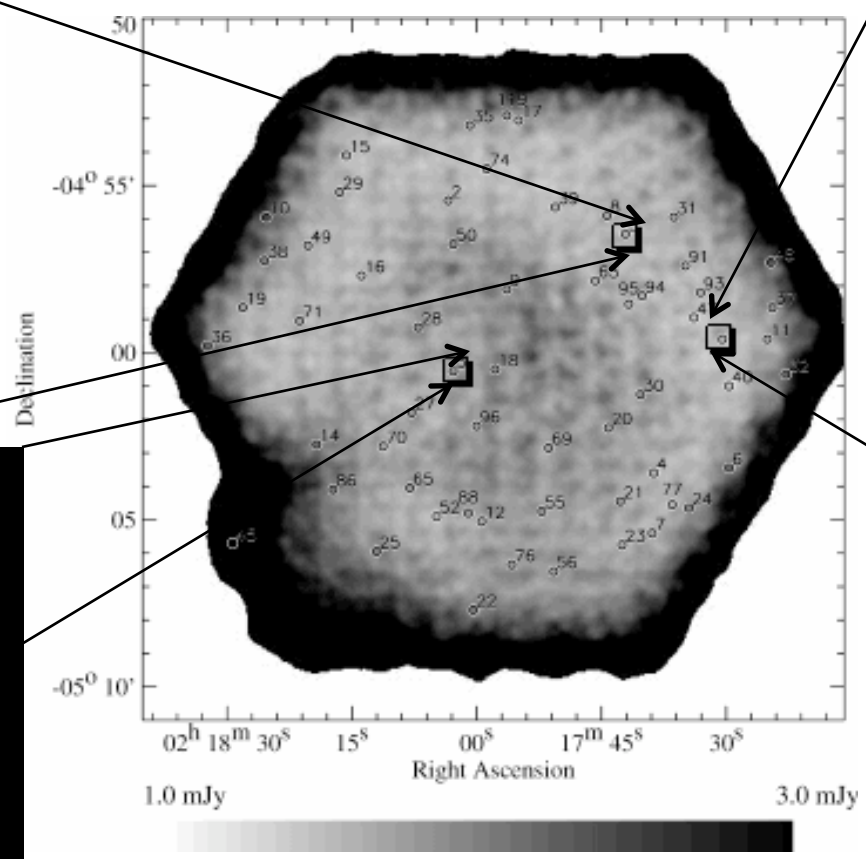
APEX data; Maiolino et al (2009)

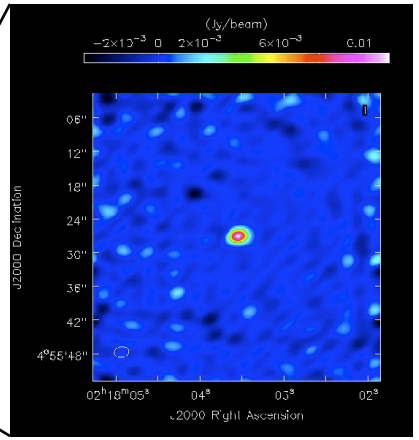
ALMA Astronomical ValidationObserving Modes: Extragalactic: Faint Continuum (High z) *TEST DATA*

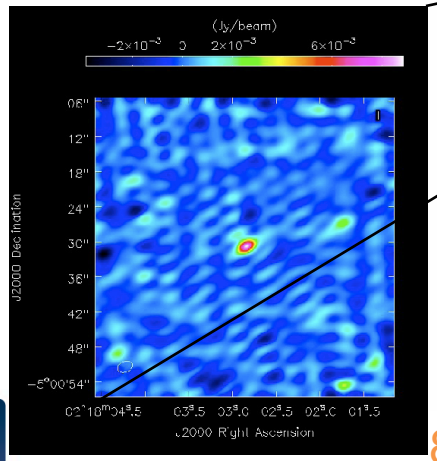
- 850.3; S_{345}=8.8 mJy

850.1; S_{345}=10.45 mJy





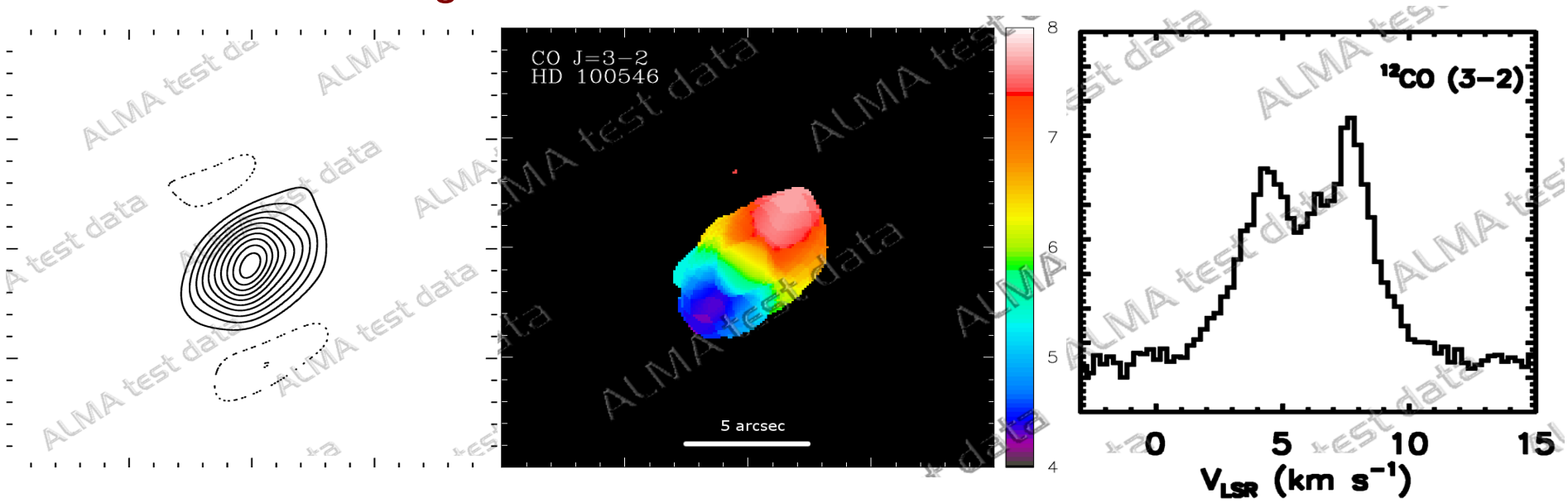




850.5; S_{345}=8.5 mJy

Coppin et al (2006)

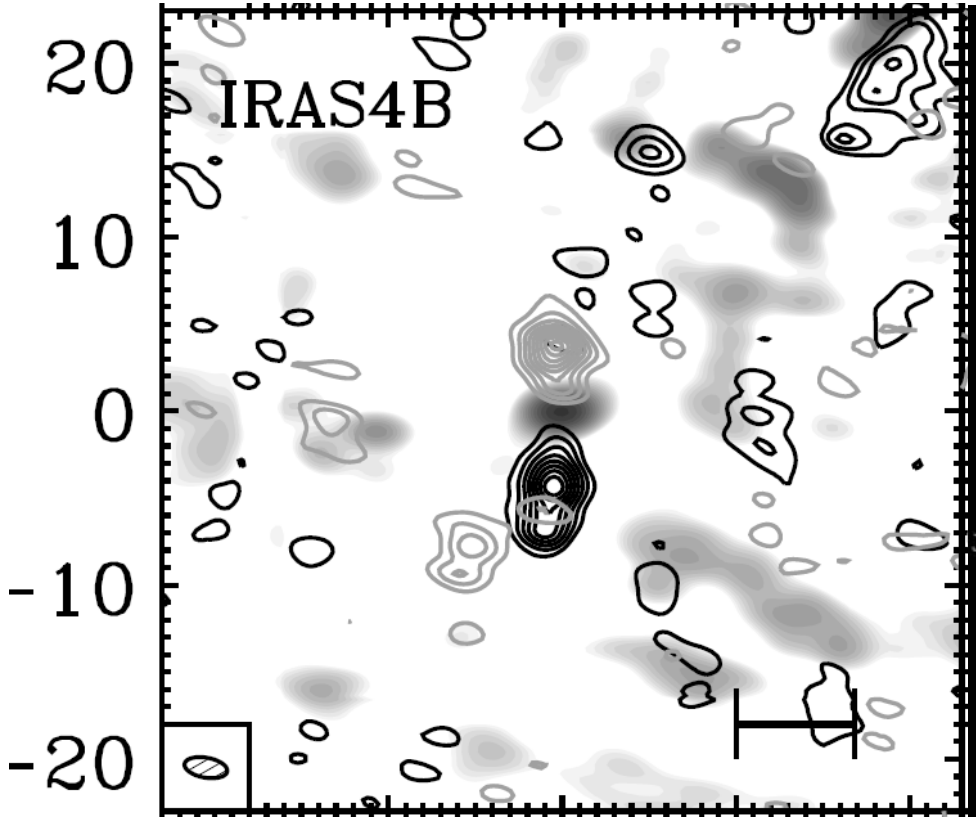
ALMA Test Data: Young Disc



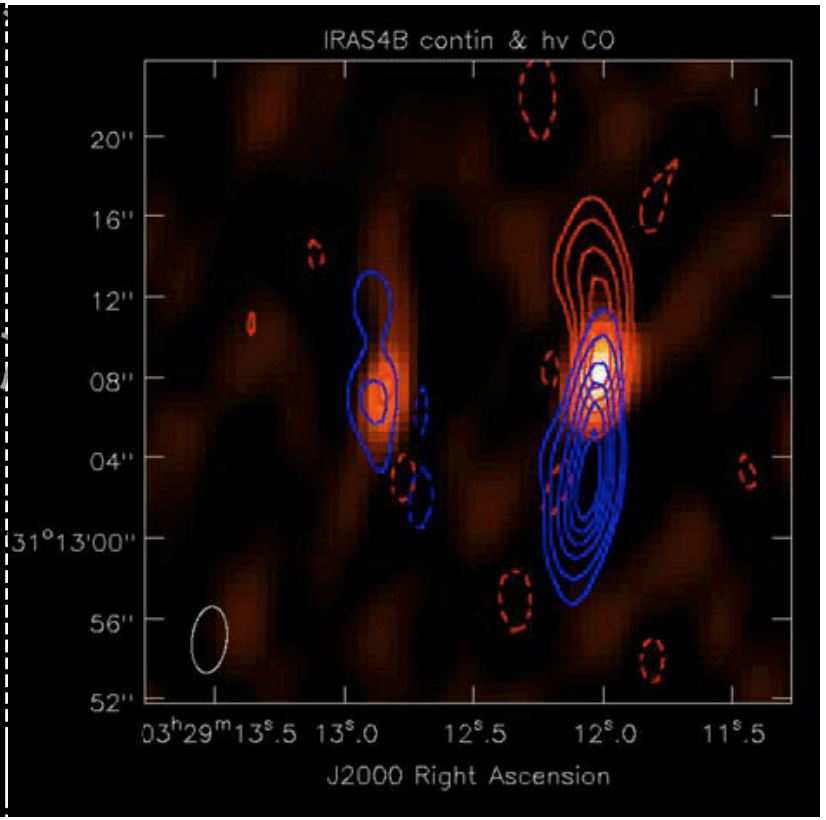
- This is an object in our own galaxy. It is a young star which is still surrounded by a disc of gas. Here we are observing the carbon monoxide J = 3-2 line at 0.8mm (345 GHz) in the disc. (The star itself is not visible here.) The integrated flux is shown as contours on the left, while the spectrum at the peak of the emission is on the right, showing, via the Doppler effect, that the gas is moving at different speeds. In the middle is the average velocity of the gas at each point in the image, indicated by the color. This shows a characteristic pattern created by the rotation of the disc around the star.

Starforming Regions: Outflow

Jorgensen 2007 SMA COJ=3-2



ALMA/Dent 2010 CO J=3-2

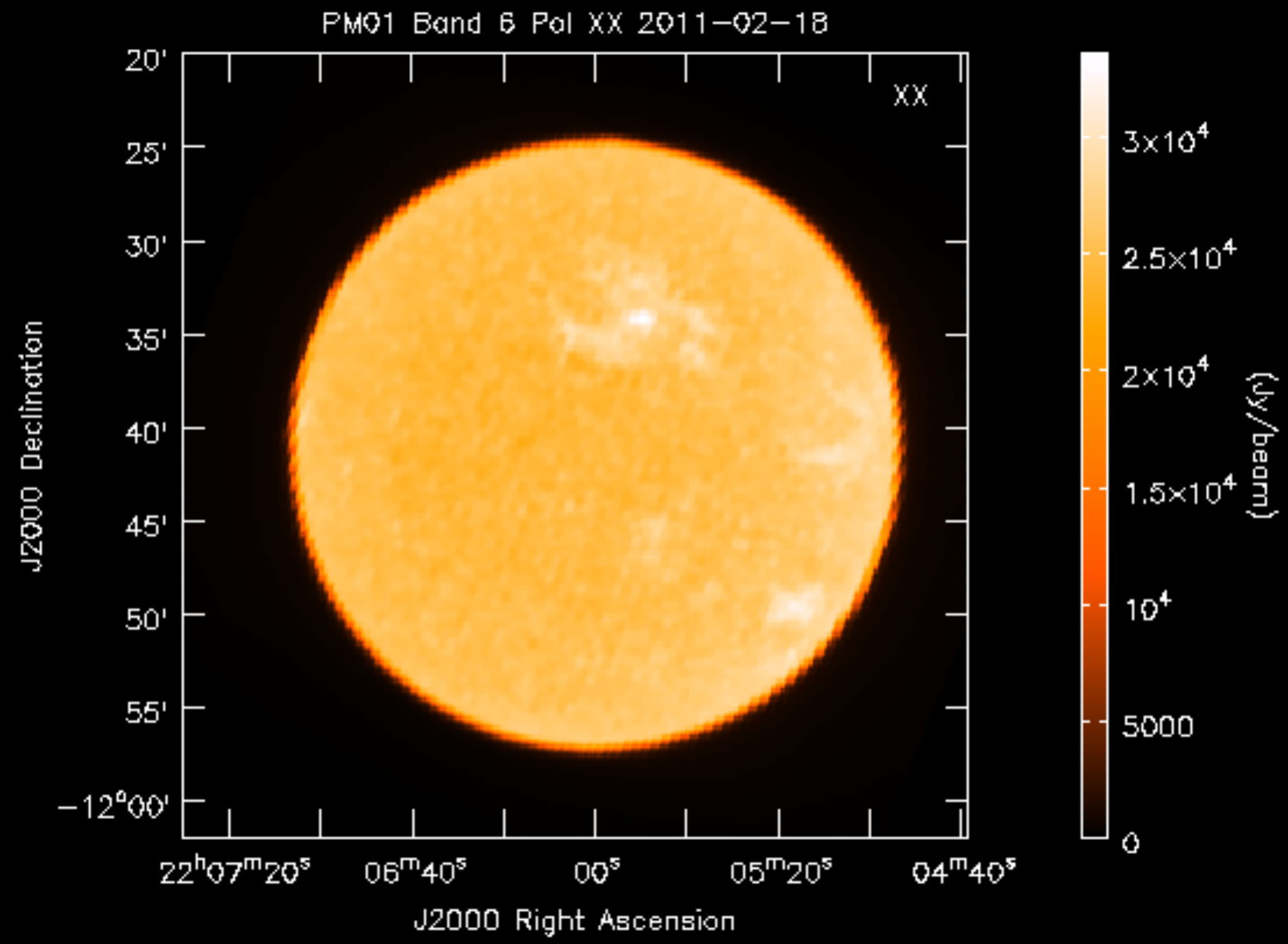


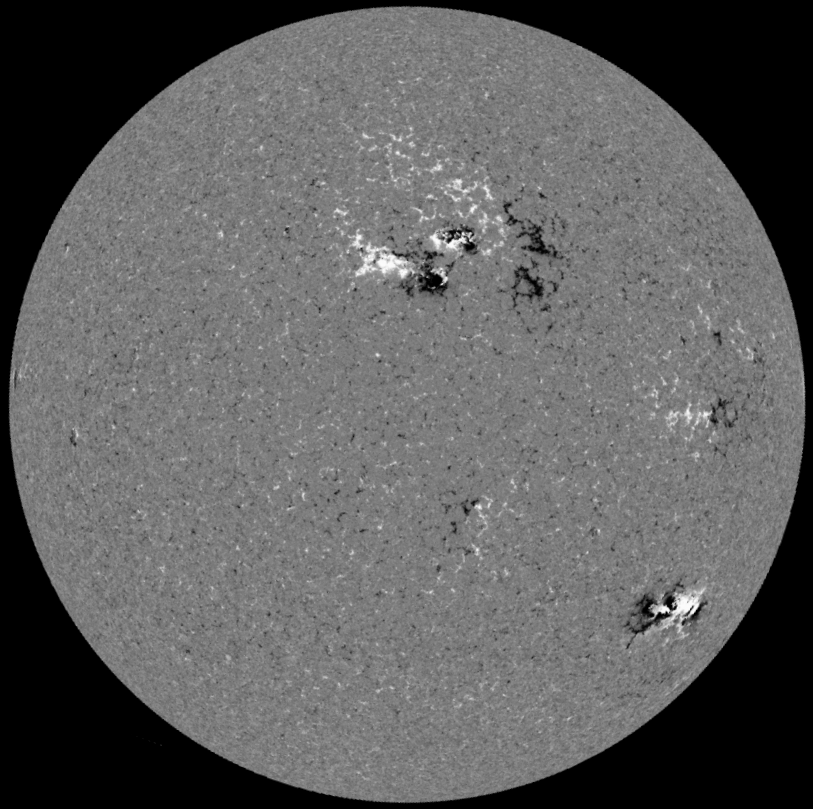
- N.B. Flow at fainter eastern source B2; unseen before

Sun at 1.3mm

- ALMA antennas surfaces are designed to scatter at optical and IR wavelengths, so that the Sun may be observed without damage to the antennas or the receivers.
- Normally an attenuator is required in front of the receivers for solar observing because the signals are so strong. However, the high level of water vapour in the atmosphere at the OSF (Operations Support Facility at 2900m) in February 2011 provided the necessary attenuation to make total power OTF images which also serve to test new software features.
- Lewis Knee and Asayama-san set up the observations and Sawada-san provided the data reduction scripts.
- Note that the receivers are still strongly saturated, no doubt causing some non-linearity, and that no calibration has been applied – the flux scale is arbitrary. The surface features are however clearly real!

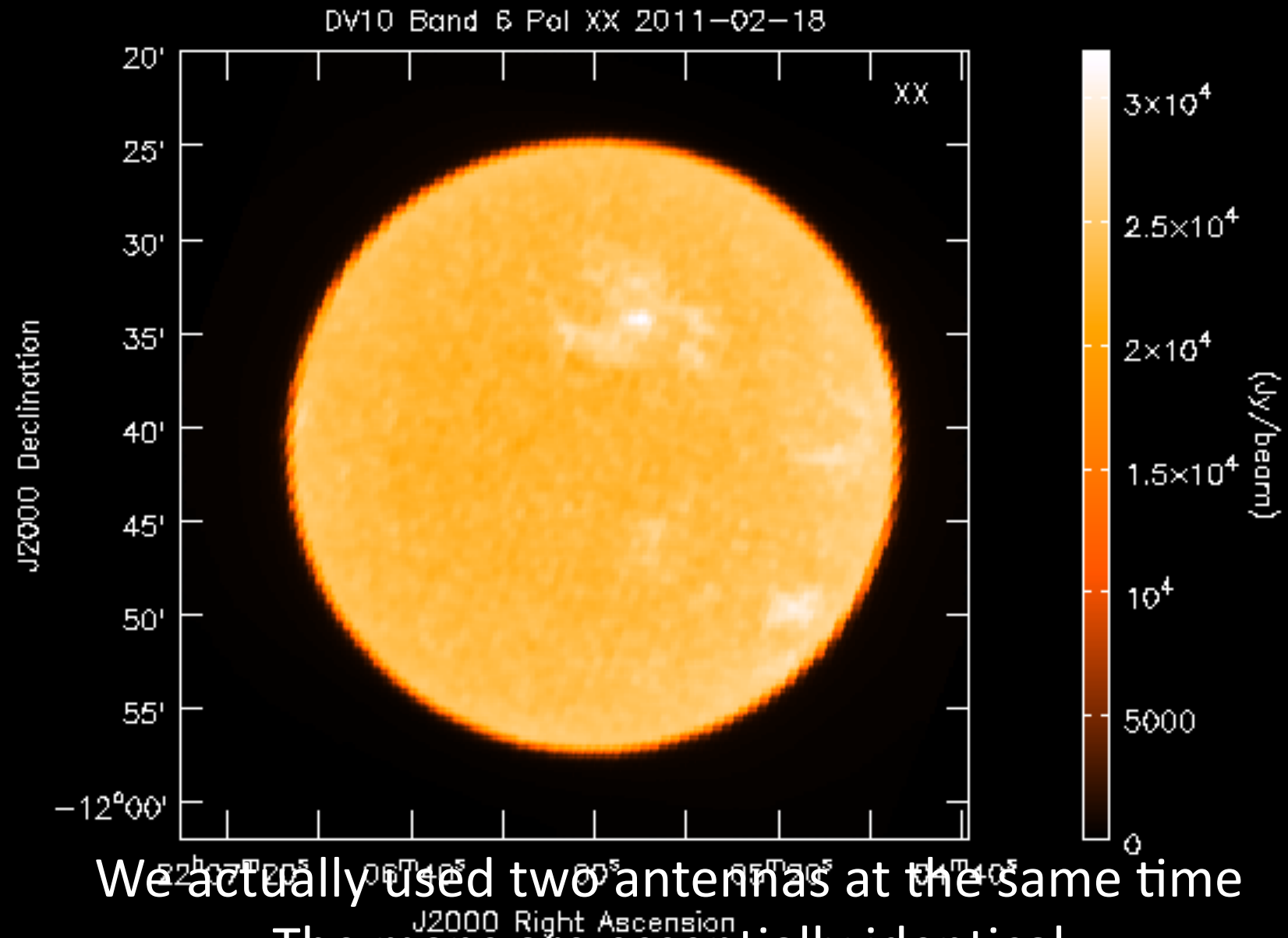
ALMA


PM01 Band 6 Pol XX 2011-02-18
XX
20'
25'
30'
35'
40'
45'
50'
55'
−12°00'
J2000 Declination
22h07m20s
06m40s
00s
05m20s
04m40s
J2000 Right Ascension
3x10^4
2.5x10^4
2x10^4
1.5x10^4
10^4
5000
0
(Jy/beam)



SDO HMI Magnetogram Image

http://sohowww.nascom.nasa.gov/data/realtime/



We actually used two antennas at the same time

The maps are essentially identical

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 this Workshop. 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 Cycle 0*** initiates the transformation
  - Sensitivity: ~10% full ALMA
  - Resolution: up to ~0.2”
  - Wavelength Coverage: 4 of final 8 bands (7 goal)
- ***Begins this year***
- ***ALMA Development*** continues the transformation through the Operations period, engaging the community in the process.

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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