ALMA: Moving Beyond First Fringes to Transformative Science

Al Wootten
ALMA/NA Project Scientist
NRAO

Northwestern University

A System of Complementary Telescopes Under an Open Skies Policy

- ⬭ Atacama Large Millimeter Array (ALMA)
- ● Robert C. Byrd Green Bank Telescope (GBT)
- ✶ Very Large Array (VLA)
- △ Very Long Baseline Array (VLBA) Station

Sample Key Science Projects using NRAO facilities

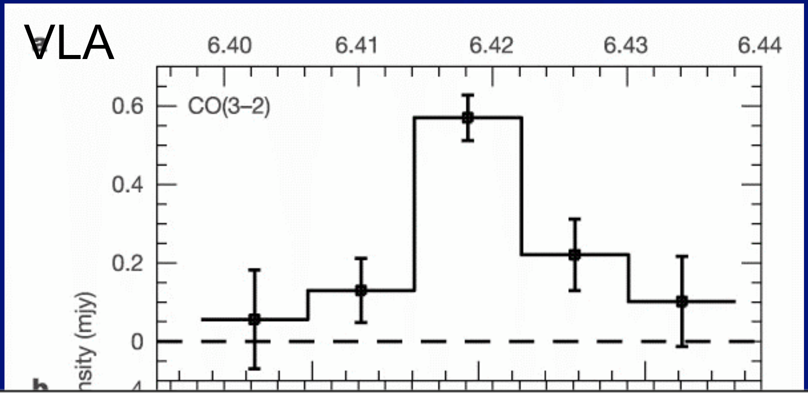
- Megamaser Cosmology Project
- Gravitational Wave Detection by Pulsar Timing
- Millisecond Pulsar timing in Globular Clusters
- PMS star parallax, proper motion, binary orbits, exoplanets
- Exoplanet search around M dwarf stars
- Biomolecule survey toward the Galactic center
- GLAST/VLBA blazar and pulsar studies
- Microquasars
- Astrometric grid for PanStarr and LSST

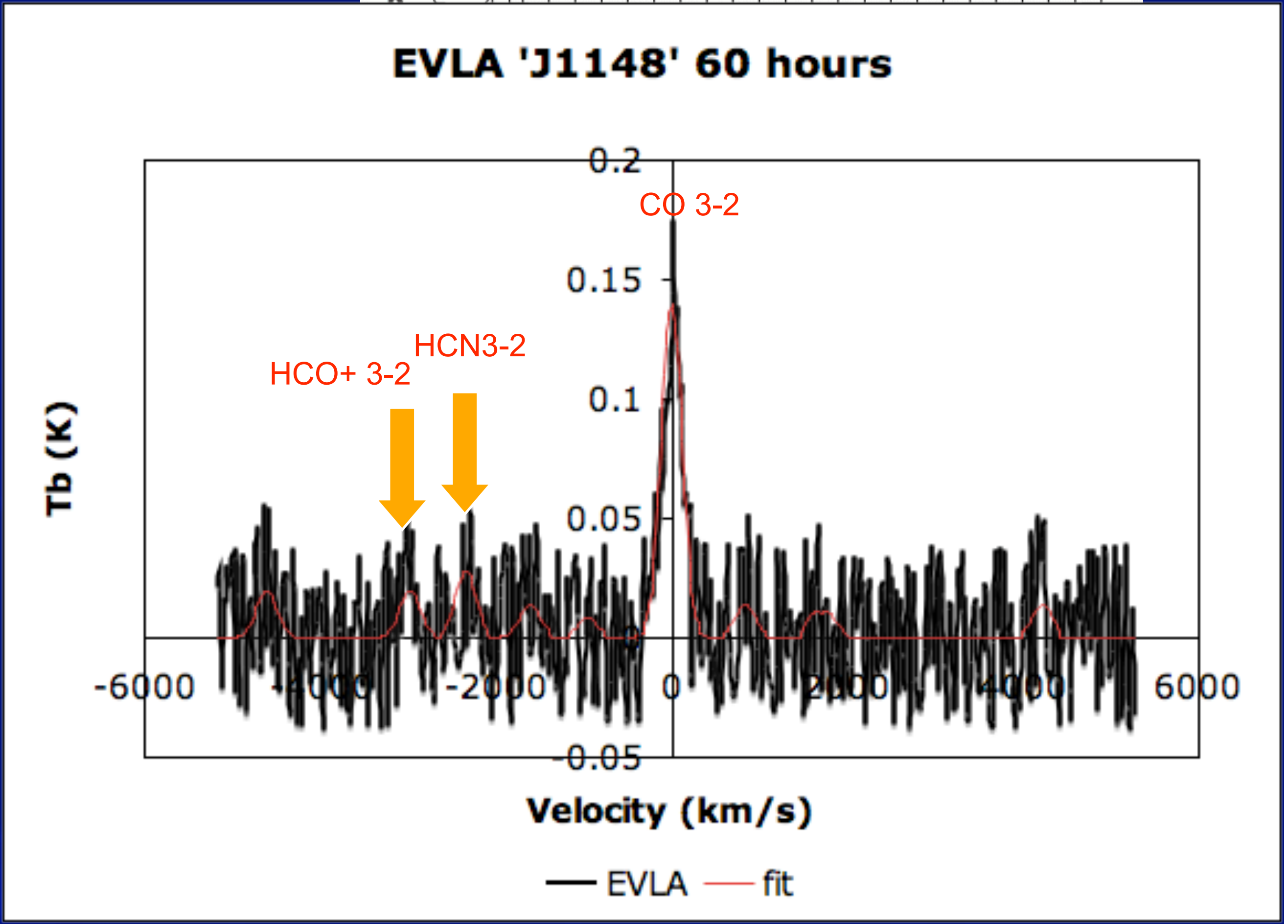
EVLA: A Major New Facility

SKA Demonstrator!

- VLA >20 years old; electronics from the 1970’s
- EVLA: upgrading the electronics of VLA
  - New receivers (1 – 50 GHz)
    - some Mexican contribution
  - 8GHz bandwidths
    - Fiber-optic transmission
  - Very versatile correlator
    - HIA-Penticton, Canadian contribution
- 10-fold increase in sensitivity
- First Science 2010
- Completion in 2012

EVLA: J1148





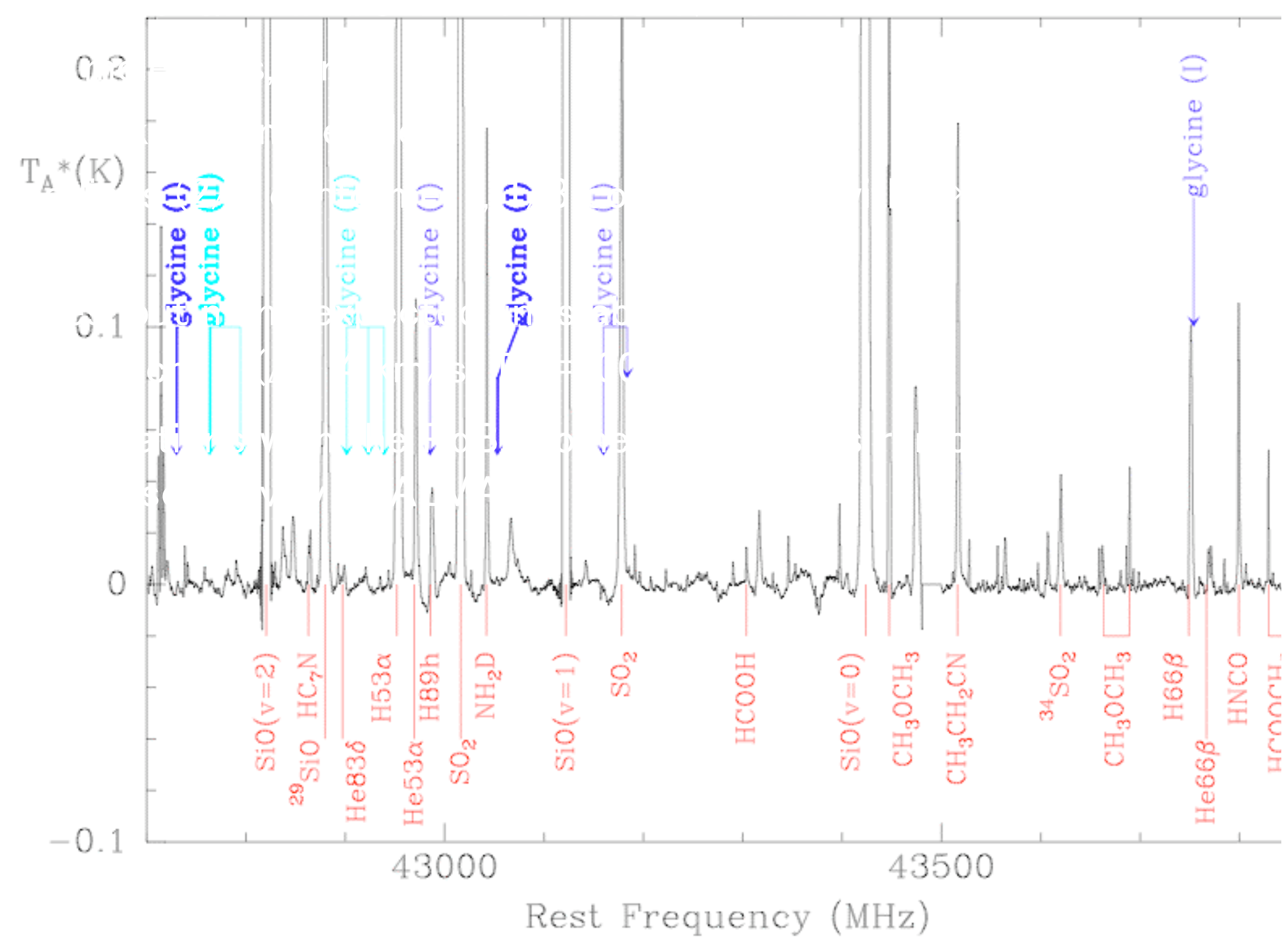
VLA: A Single integration resulted in a two point spectrum, 43 MHz resolution, several needed for line profile (and to discover the correct z!).

EVLA:

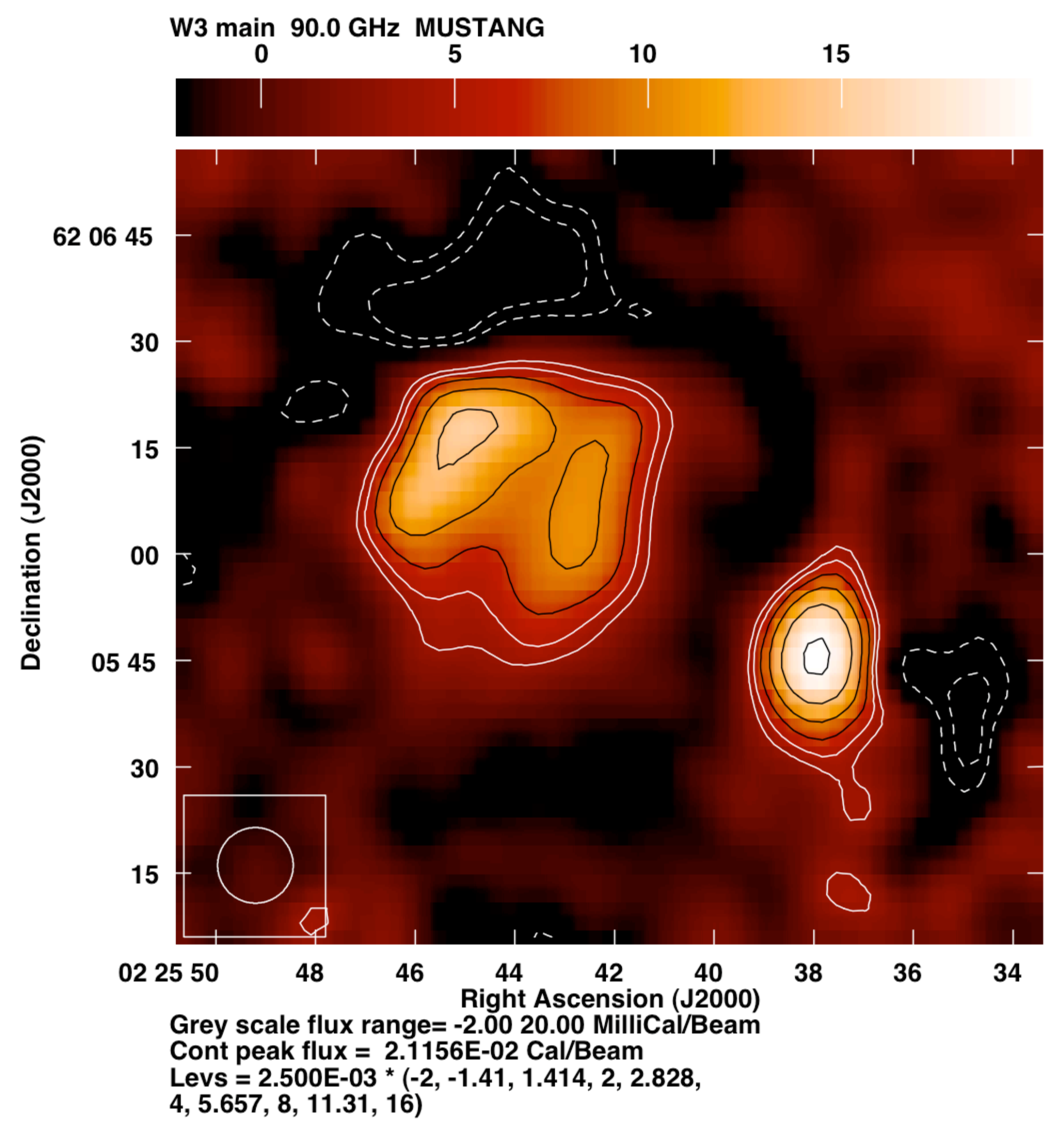
- Single integration covers up to 8 GHz (5.1 GHz shown, 10 MHz resolution)
- Single integration covers the entire 870 micron ‘Band’ as seen from beneath Earth’s atmosphere.
- ***EVLA II (not funded) brings ‘E’ array for short spacings.***

GBT Spectrometer

- 3.2 GHz x 2 polzns, 2.7 km/s @43 GHz, 17” beam, η˜50%
- Glycine searc
  - 70 lines o
  - 20 strong
  - 80 strong
    $E_u/k<500$
  - Some coi
  - $N_{glycine,, I}$
  - In concur
    spatial res



MUSTANG: 90 GHz Imaging Array for the GBT



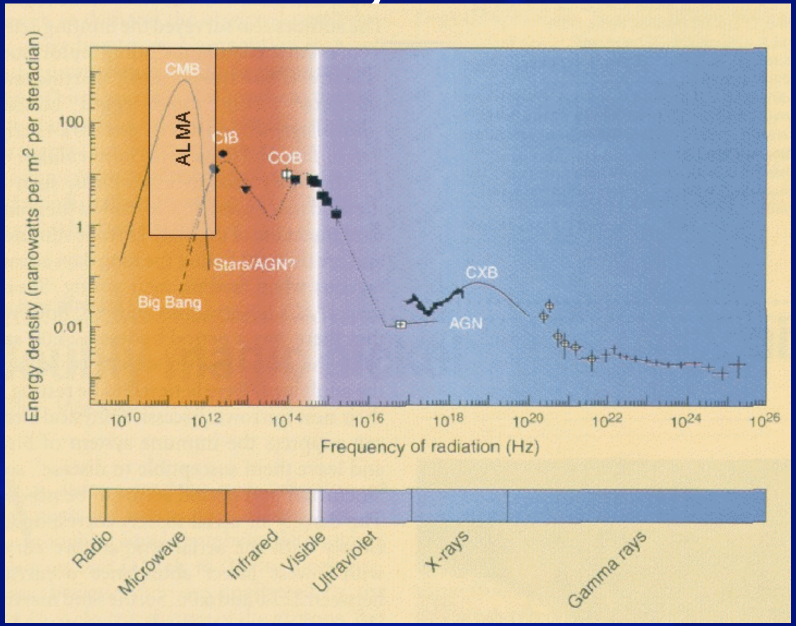
Grey scale flux range= -2.00 20.00 MilliCal/Beam
Cont peak flux = 2.1156E-02 Cal/Beam
Levs = 2.500E-03 * (-2, -1.41, 1.414, 2, 2.828, 4, 5.657, 8, 11.31, 16)

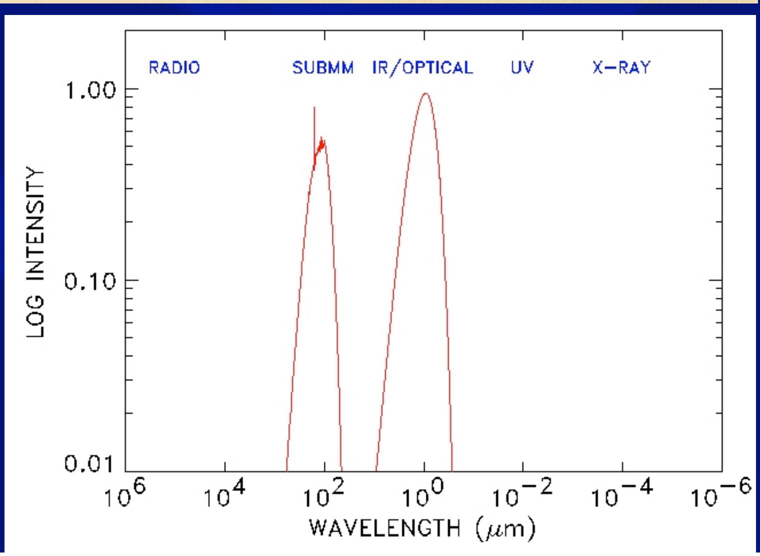
- Upenn: S. Dicker, P. Korngut, M.Devlin (PI)
- GSFC: D.Benford, J.Chervenak, H. Moseley, J. Staguhn, S.Maher,T. Ames, J. Forgione
- NIST: K.Irwin
- NRAO: M.Mello, R.Norrod, S.White, J.Brandt, B.Cotton

Dual beam receiver 67-90 GHz Winter '08

The mm/Submm Spectrum: Focus of ALMA--The Atacama Large Millimeter/submillimeter Array

- 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 submm/FIR 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 the atmosphere of the Earth allows.

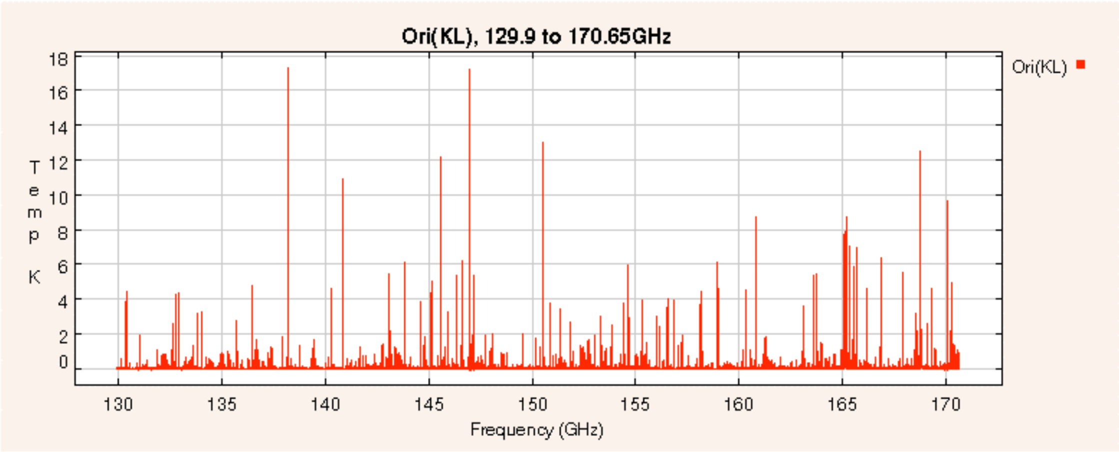


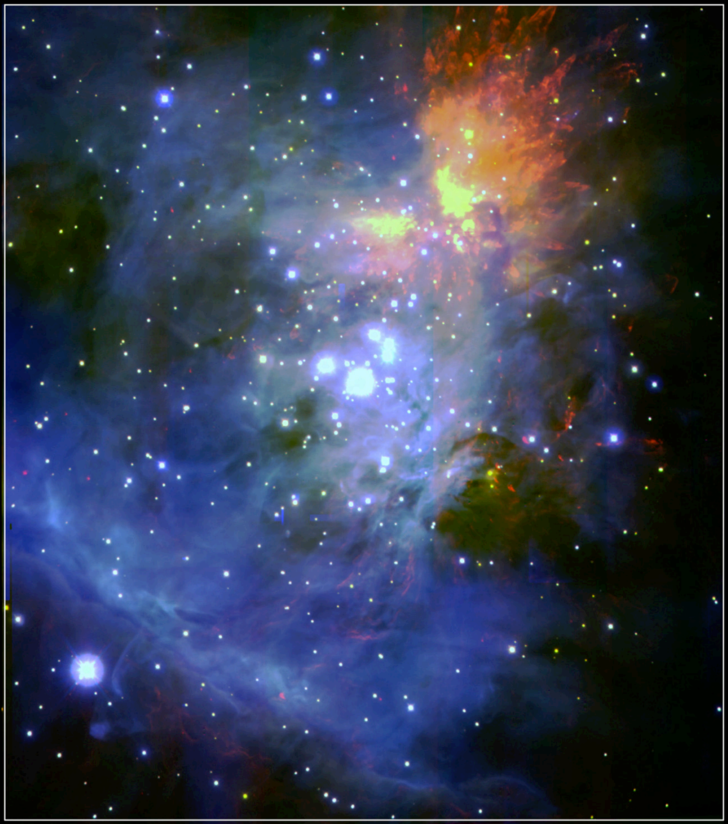


COBE observations

Contributors to the Millimeter Spectrum

Spectrum courtesy B. Turner (NRAO)





Orion Nebula

CISCO (J, K′ & H2 (v=1-0 S(1))

Subaru Telescope, National Astronomical Observatory of Japan

January 28, 1999

- In addition to dominating the spectrum of the distant Universe, millimeter/submillimeter spectral components dominate the spectrum of planets, young stars, many distant galaxies.
- Cool objects tend to be extended, hence ALMA's mandate to image with high sensitivity, recovering all of an object's emitted flux at the frequency of interest.
- Most of the observed transitions of the 142 known interstellar molecules lie in the mm/submm spectral region—here some 17,000 lines are seen in a small portion of the spectrum at 2mm.
- However, molecules in the Earth's atmosphere inhibit our study of many of these molecules. Furthermore, the long wavelength requires large aperture for high resolution, unachievable from space. To explore the submillimeter spectrum, a telescope should be placed at Earth's highest dryest site.

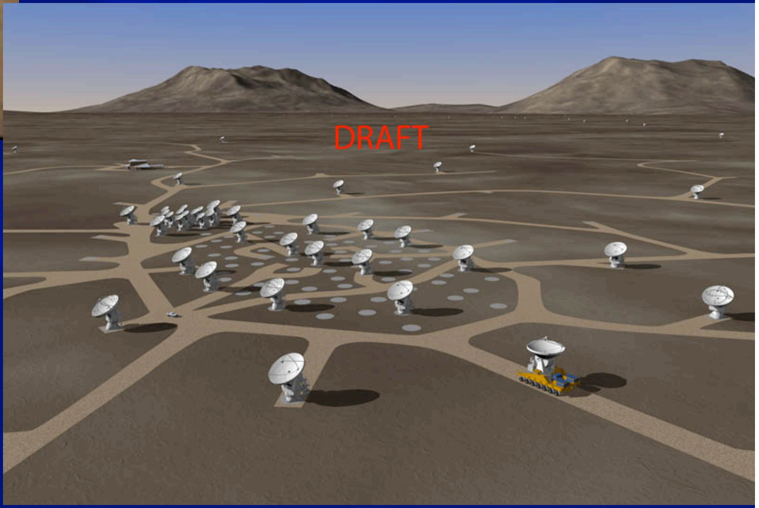
Atacama Large Millimeter/submillimeter Array

Is an international astronomy facility,
a partnership between Europe (32.5%), North America (32.5%) and East Asia (25%),
in cooperation with Chile (10%) through agreements reached in 2003 and updated in 2006.

Llano Chajnantor
Northern Chile
at 5000m elevation

Operational 2012
(Early Science in 2010)

>50 × 12-m telescopes
+
ACA: 12 × 7-m + 4 × 12-m



Al Wootten, ALMA/US Project Scientist

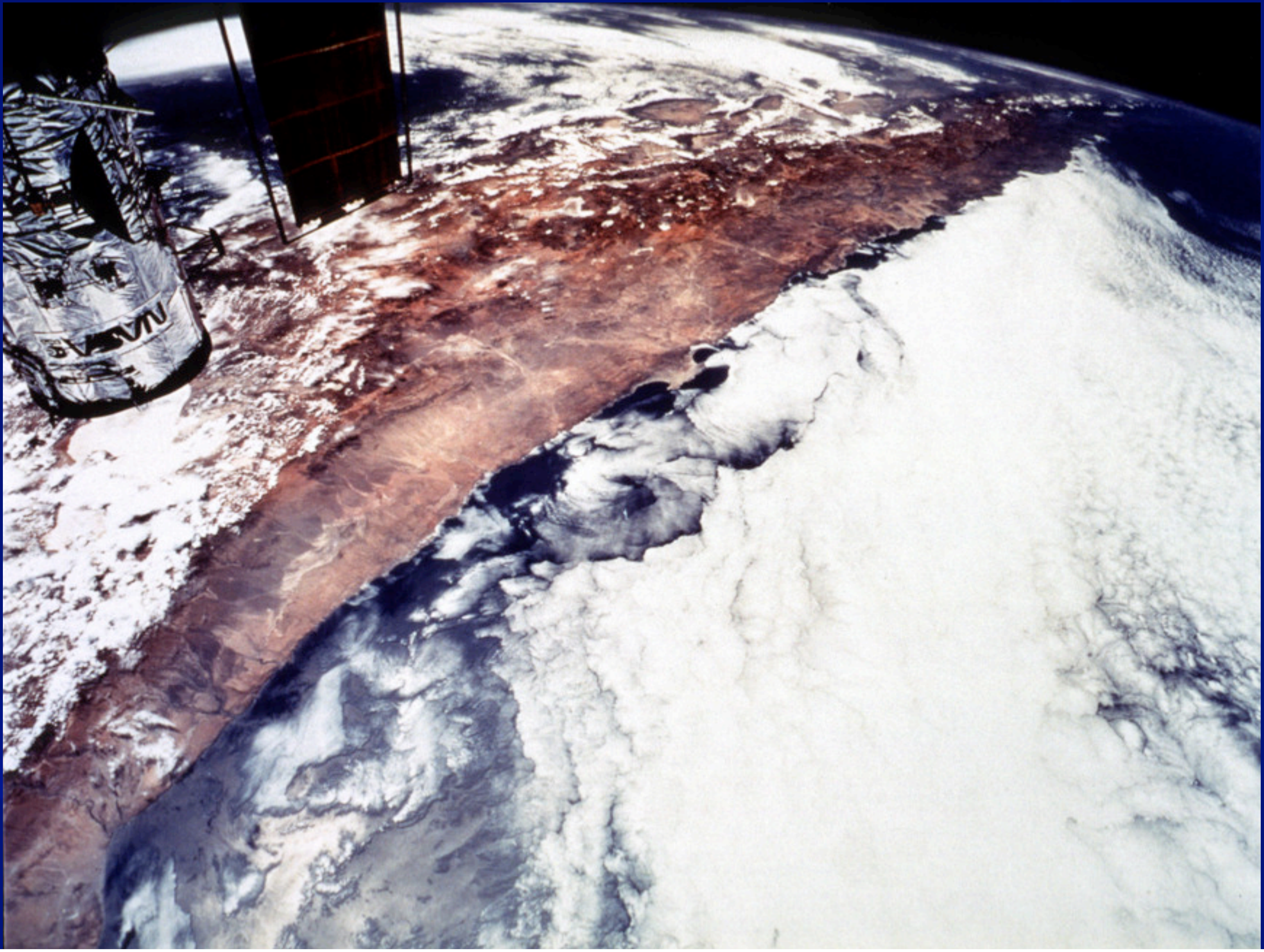
How can I find the ALMA Site?

Paranal

La Serena

Santiago

Where is ALMA?



ALMA - Major Elements

Five antennas now in Chile


Photo H. Heyer (ESO).

- Partners: ESO – US (NSF)+Canada (NRC) – Chile – Japan (NAOJ) …*Taiwan (ASIAA)*

- **Array Operations Site – AOS 5000m**
- **Operations Support Facility – OSF 2900m**
- **Santiago Central Offices – SCO**
- **ALMA Regional Centers – ARCs + ARClets**
- **ALMA Test Facility--Near Very Large Array, NM**

- During full operation, the estimated flow into archive ~ 100 Tbytes per year
- Dataset: proposal, u-v data, a reference image with pipeline processing history, calibration data… modern radioastronomy

ALMA


ALMA Test Facility

- International project to build & operate a large (>66-antenna) millimeter/submm (λ ~0.35-10mm) array at high altitude site (5000m) in northern Chile.
- Project began in 2002; Japan joined in 2004; project redefined/rebaselined 2005; construction, hardware production lines underway, software in development; early science ~2010, full science operations 2012.
- Considerable infrastructure is on site now leading to the arrival of the 6th and 7th antennas by Christmas.
- This talk: Outline high level science goals, technical specifications, ‘tour’ of progress towards meeting those, then details of some specific scientific goals.

Highest Level Science Goals

Bilateral Agreement Annex B:

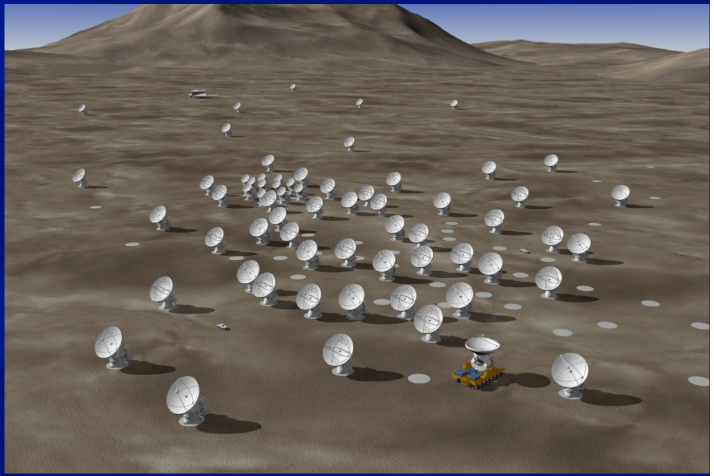
"ALMA has three level-1 science requirements:

- 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 (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), 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". Here the term *precise image* means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees. These requirements drive the technical specifications of ALMA. "

A detailed discussion of them may be found in the ESA publication *Dusty and Molecular Universe* on ALMA and Herschel.

ALMA Science Requirements

- High Fidelity Imaging.
- Precise Imaging at 0.1” Resolution, down to 5mas.
- Routine Sub-mJy Continuum Sensitivity.
- Routine mK Spectral Sensitivity.
- Wideband Frequency Coverage.
- ‘Wide’ Field Imaging Mosaicking.
- Superb submillimeter site.
- Full Polarization Capability.
- System Flexibility.

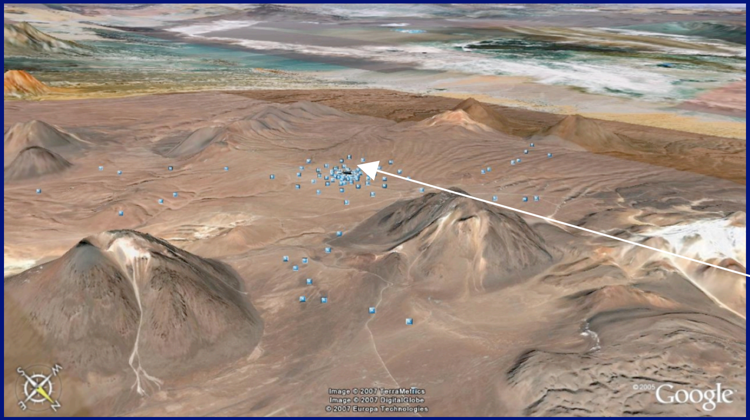


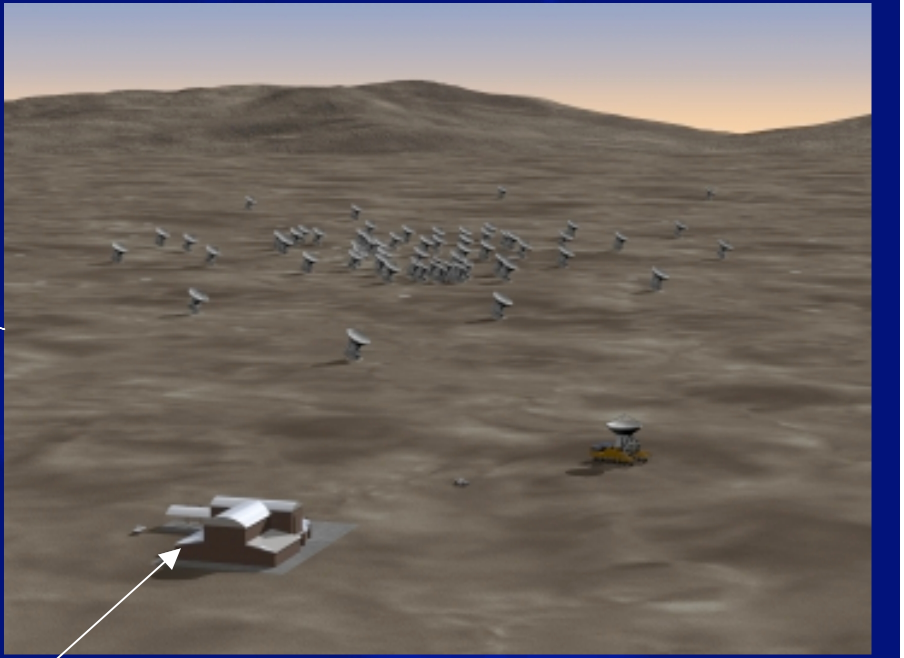
Technical Specifications

- >54 12-m antennas, 12 7-m antennas, at 5000 m altitude site.
- Surface accuracy ±25 μm, 0.6” reference pointing in 9m/s wind, 2” absolute pointing all-sky.
- Array configurations between 150m to ~15 -18km.
- 10 bands in 31-950 GHz + 183 GHz WVR. Initially:
- 84-116 GHz “3”
- 125-169 GHz “4”
- 163-211 GHz “5” 6 rx only, single polzn
- 211-275 GHz “6”
- 275-373 GHz “7”
- 385-500 GHz “8”
- 602-720 GHz “9”
- 787-950 GHz “10” initially partially populated
- 8 GHz BW, dual polarization.
- Flux sensitivity 0.2 mJy in 1 min at 345 GHz (median cond.).
- Interferometry, mosaicing & total-power observing.
- Correlator: 4096 channels/IF (multi-IF), full Stokes.
- Data rate: 6MB/s average; peak 60 MB/s.
- All data archived (raw + images), pipeline processing.

Array Operations Site: 16400 feet

43 km from gate on CH23 on 51ft wide new road





Array Operations Site Technical Building

- Array reconfigurable 150m-14km
- Digitized signals from antenna to TB
    - TB houses Correlator
    - Local oscillator signals
    - Antenna transporter shelter
    - Refuge
    - No one overnight, few during day

Operations Support Facility: 9500 ft altitude

15 km from gate on CH23

OSF TB

- Technical Building
  - Completion Jan ‘08
  - Warehouse
  - Shops, offices, antenna area
- Camps: House, feed and amuse >500 people
  - ALMA
  - Contractors
- Antenna erection areas
  - VertexRSI (NA)
  - Mitsubishi (JP)
  - Alcatel (EU)
- Temporary Offices

ALMA and Contractor Camps

View to the ALMA Camp

- ALMA Camp
  - Housing
  - Offices
  - Dining Hall
  - Recreation Hall
  - Tennis court
  - Temporary technical building
- Future: Residence

ALMA and Contractor Camps

View to the Contractor Camp

- Contractors Camp
  - Housing
  - Offices
  - Dining Hall
  - Recreation Hall

Antenna Vendor Areas

View of AEM, MElCo, VxRSI areas (l-r)

Three nodding Melcos;
No. 1 on right.

Holographic surface measurements on MElCo No 1 confirm better than 25 μm!

VxRSI No 1

Antenna Locomotion

The ALMA Antenna Transporter

ESO Press Photo 45b/07 (5 October 2007)

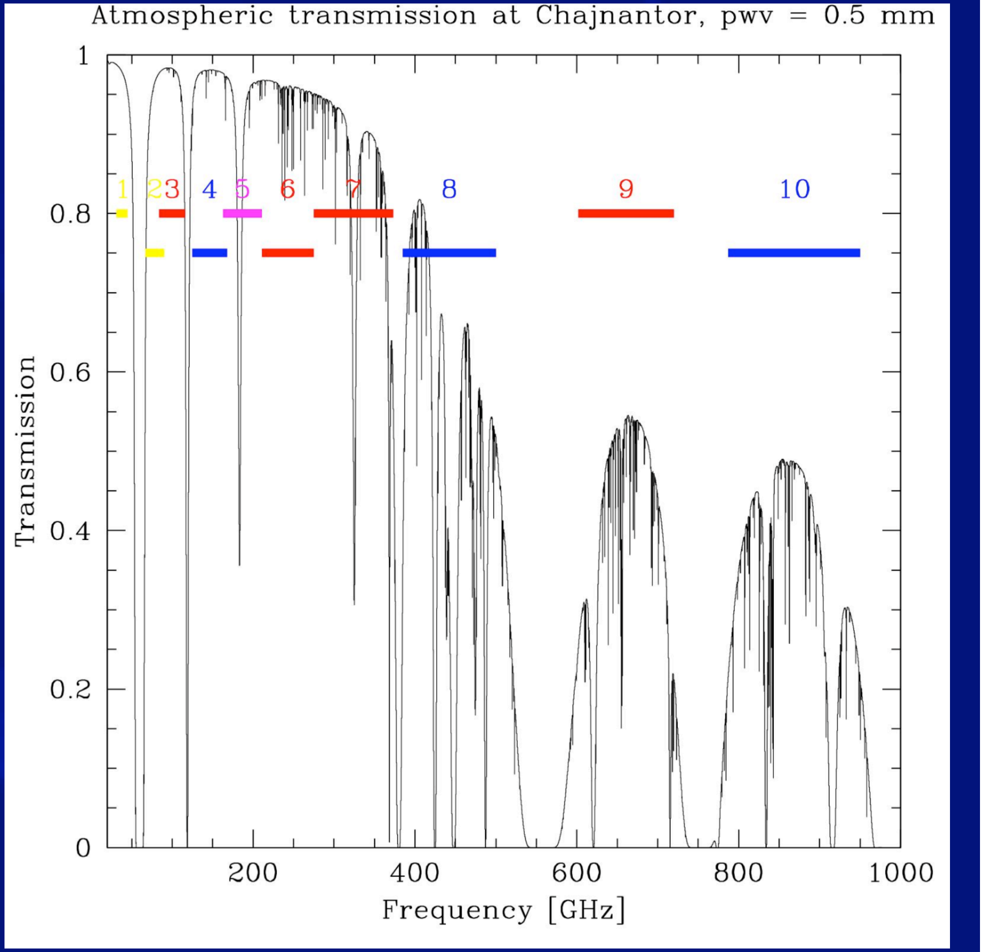
- 10 meters wide, 20 meters long and 6 meters high,
- Will be shipped to Chile 22 Dec.
- The second one will follow in a few weeks.
- Sorry applications for transporter driver are closed.

ALMA Test Facility, New Mexico

- Fringes using ALMA prototype system Mar '07
- Test ALMA software and most hardware prior to installation in Chile summer '08.
- Production 'Front Ends' bypass ATF, go to Chile next month.

Transparent Site Allows Complete Spectral Coverage

- 10 Frequency bands coincident with atmospheric windows have been defined.
- Bands 3 (3mm), 6 (1mm), 7 (.85mm) and 9 (.45mm) will be available from the start.
- Bands 4 (2mm), 8 (.65mm) and, later, some 10 (.35mm), built by Japan, also available.
- Some Band 5 (1.5mm) receivers built with EU funding.
- All process 16 GHz of data
  - 2polzns x 8 GHz (1.3mm=B6)
  - 2 polzns x 2SBs x 4 GHz (3mm=B3, 2mm=B4, .8mm=B7, .6mm=B8, 1.5mm=B5)
  - 2 polzns x DSB x 8 GHz (.45mm=B9, .35mm=B10)



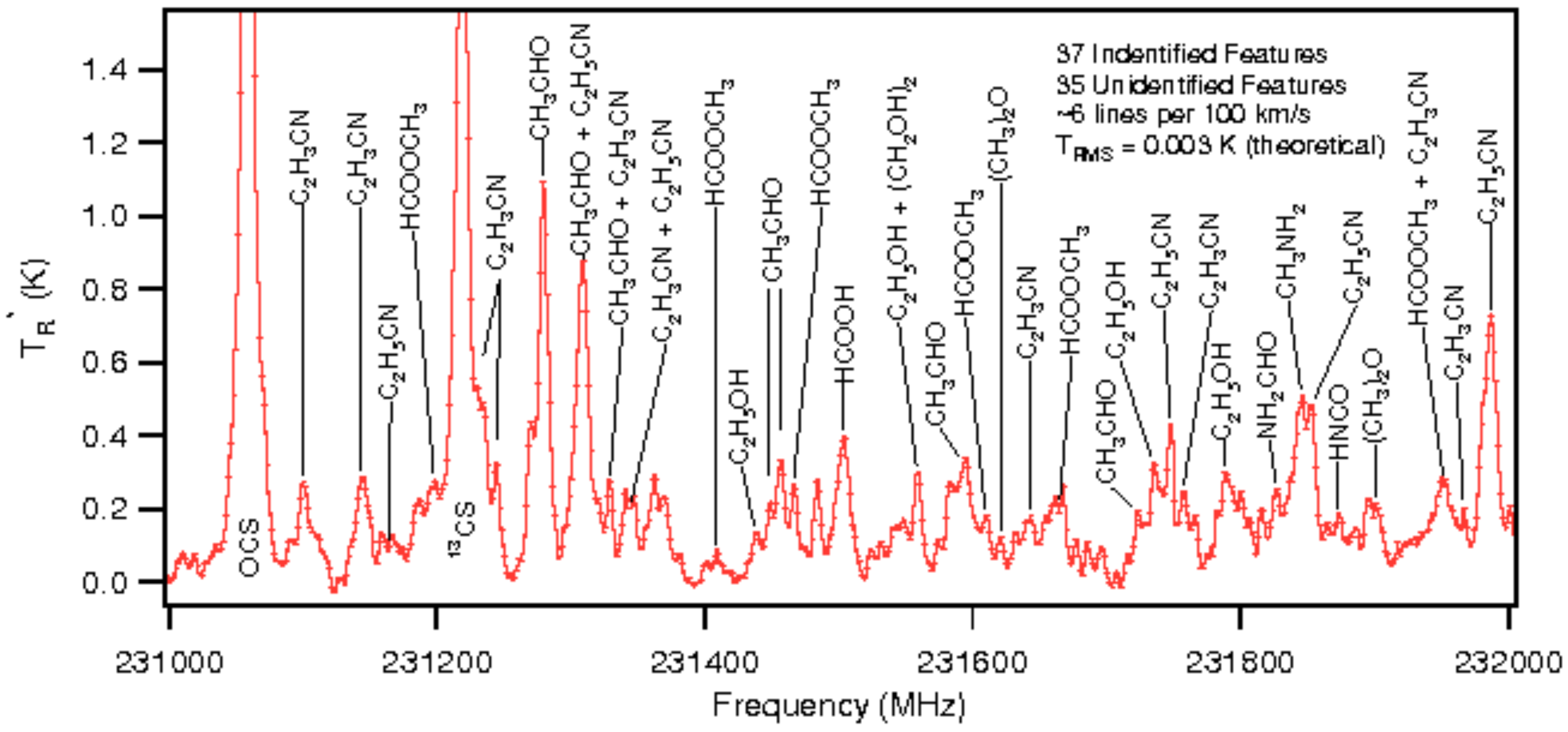
ALMA Receivers/Front Ends

ALMA Band	Frequency Range	Receiver noise temperature		Mixing scheme	Receiver technology	Responsible
		T_{Rx} over 80% of the RF band	T_{Rx} at any RF frequency			
1	31.3 – 45 GHz	17 K	28 K	USB	HEMT	Not assigned
2	67 – 90 GHz	30 K	50 K	LSB	HEMT	Not assigned
3	84 – 116 GHz	37 K (35K)	62 K (50K)	2SB	SIS	HIA
4	125 – 169 GHz	51 K	85 K	2SB	SIS	NAOJ
5	163 - 211 GHz	65 K	108 K	2SB	SIS	6 units EU ?
6	211 – 275 GHz	83 K (40K)	138 K (60K)	2SB	SIS	NRAO
7	275 – 373 GHz*	147 K (80K)	221 K (90K)	2SB	SIS	IRAM
8	385 – 500 GHz	98 K	147 K	2SB	SIS	NAOJ
9	602 – 720 GHz	175 K (120K)	263 K (150K)	DSB	SIS	SRON
10	787 – 950 GHz	230 K	345 K	DSB	SIS	NAOJ ?

- **Dual, linear polarization channels:**
  - **Increased sensitivity**
  - **Measurement of 4 Stokes parameters**

- **183 GHz water vapour radiometer:**
  - **Used for atmospheric path length correction**

Passband taken with ALMA Band 6 mixer at the SMT



Ziurys has shown a SgrB2(N) spectrum at the American Chemical Society meeting in Atlanta, obtained with an ALMA prepreproduction B6 front end on the SMT. This system achieved 107 K system temperature, SSB at 45 deg. elevation at 232 GHz, with > 20 db image rejection, good baselines.

Summary of current status

Frequency	30 to 950 GHz: B3, B6, B7, B9 receivers passed CDR & PAI, preproduction units available, all meet T_{rx} spec, most exceed specs. B6 tested on SMT.
Bandwidth	8 GHz both polzns, fully tunable: All units
Spectral resolution	31.5 kHz (0.01 km/s) at 100 GHz: 1st quadrant built
Angular resolution	30 to 0.016” at 300 GHz: Configuration defined
Dynamic range	10000:1 (spectral); 50000:1 (imaging)
Flux sensitivity	0.2 mJy in 1 min at 345 GHz (median conditions)
Antenna complement	Up to 64 antennas of 12m diameter, plus compact array of 4 x 12m and 12 x 7m antennas (Japan): Contracts for 55 up to 67, three prototype antennas in hand meet all specifications

Brightness Temperature Sensitivity

1 min, AM 1.3, 1.5mm, *0.35 PWV, 1 km/s

Frequency (GHz)	B_{max} 0.2km ΔT_{cont} (K)	B_{max} 0.2km ΔT_{line} (K)	B_{max} 10km ΔT_{cont} (K)	B_{max} 10km ΔT_{line} (K)
35	0.002	0.050	0.48	130
110	0.003	0.049	0.84	120
230	0.0005	0.054	1.3	140
345	0.0014	0.12	3.6	300
409	0.0030	0.23	7.6	580
675*	0.0046	0.28	12	690
850*	0.011	0.58	27	1400

For $\nu<430$ GHz, PWV=1.5mm; $\nu>430$ GHz, PWV=0.35mm

The ALMA Correlators

- NRAO Baseline Correlator (four quadrants for 64 antennas, BW: 8 GHz x 2; 2 bit sampling with limited 3 or 4 bit sampling)
  - First quadrant operating in NRAO NTC, being retrofitted with Tunable Filter Bank enhancement (UBx)
  - Second quadrant being completed at NRAO NTC
  - First installation at AOS TB later this year.
  - Detailed list of Observational Modes in ALMA Memo 556 (available at www.alma.nrao.edu)
- ACA Correlator (NAOJ)
  - Installation at AOS TB later this year.

Baseline Correlator Overview

- Observer may specify a set of disjoint or overlapping spectral regions, each characterized by
  - Bandwidth (31.25 MHz to 2 GHz)
    - Each 2 GHz baseband input (8 available) drives 32 tunable digital filters
  - Frequency (Central or starting)
  - Resolution (number of spectral points)
  - Number of polarization products: 1 (XX or YY), 2 (XX and YY) or 4 (XX, YY, XY, YX cross-polarization products)
  - Improved sensitivity options (4x4 bit correlation, or double Nyquist modes)
  - Temporal resolution depends upon mode (from 16 msec to 512 msec); 1msec autocorrelation
- Simultaneous pseudo-continuum and spectral line operation

Multiple Spectral Line Windows

- Multiple spectral windows
  - Within the 2 GHz IF bandwidth
  - For modes with total bandwidth 125 MHz to 1 GHz
  - Useful for high spectral resolution observations of e.g. several lines within IF bandwidth (examples to be shown)
- Multi-resolution modes
  - Simultaneous high and low resolution
  - Line core and line wings simultaneously
    - Planetary Observations
    - Outflow/Core Observations

- As an ALMA goal is ease of use, the Observing Tool will guide the observer through the maze of spectral line possibilities

Some ALMA Spectroscopic Science

- Solar System
  - Atmospheres and venting on small bodies
  - Atmospheric structure of large bodies
- Star Formation and GMCs in the Milky Way
  - Infall, Outflow and the formation of stars
- Nearby Galaxies
  - Chemistry, organization of structure, evolution
- The Evolution of Galactic Structure
  - The last few billion years
- The Birth of Galaxies and the Early Universe
  - How did all this come to be anyway?

ALMA Design Reference Science Plan (DRSP)

Goal: To provide a prototype suite of high-priority ALMA projects that could be carried out in ~3 yr of full ALMA operations

- DRSP 1.0 finished December 2003;
  - >128 submissions received involving >75 astronomers
  - Review by ASAC members completed; comments included
- (DRSP2.0) updated to include enhancements brought to project by Japan/East Asia.
  - Reviewed by Science Advisory Committees
  - Current version of DRSP on Website at:

http://www.strw.leidenuniv.nl/~alma/drsp.html

New submissions continue to be added.

ALMA: Large Molecules

- Wavelength coverage
- Sensitivity to weak emission

And small molecules

•CF+ detection Neufeld et al. 2006. H_2D^+/ D_2H^+.

•Critical symmetric molecular ions undetectable owing to lack of rotational lines:

H_3^+, CH_3^+, $C_2H_2^+$

•Deuterium substitution asymmetrizes the molecule, giving it a small dipole moment (~0.3D) and hence rotational lines

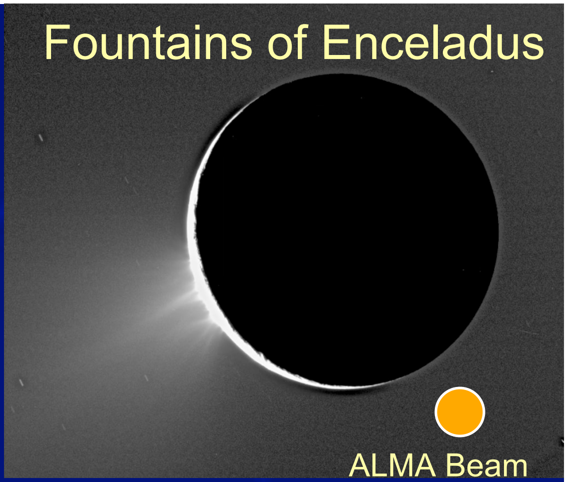
•Although the lines are very weak, ALMA is very sensitive.

•Although the spectra are very sparse, ALMA covers a wide frequency range.

•Line identification through detection of multiple isotopomers:

e.g. H_2D^+/ D_2H^+, CDH_2^+, CD_2H^+

From the Solar System



- From the atmospheres of planets
  - ‘Weather’ on Venus, Mars, Jovian planets
    - ~5km baseline provides 0”.05 at 300 GHz
    - Generally, planets are large with respect to an ALMA beam
      - Advantage of ALMA’s ability to collect complete spatial frequency data
- To that of satellites and smaller bodies
  - Comets
  - Volcanism on Io, Search for Molecules from the Fountains of Enceladus
  - Even UB313 ‘Eris’ with its moon ‘Dysnomia’ easily resolved, Eris could be imaged.

ALMA Observes Other Planetary Systems

- Emphasis has been on optical and infrared wavelengths, as at these wavelengths the Spectral Energy Distributions (SED) of stars and extrasolar planetary systems peak.
- ALMA, reaching long FIR wavelengths with great sensitivity and spatial resolution, will image dust and gas in these systems.
- We consider the ability of ALMA to observe stars and extrasolar planetary systems in various stages of evolution.

Best Frequency for ALMA Continuum?

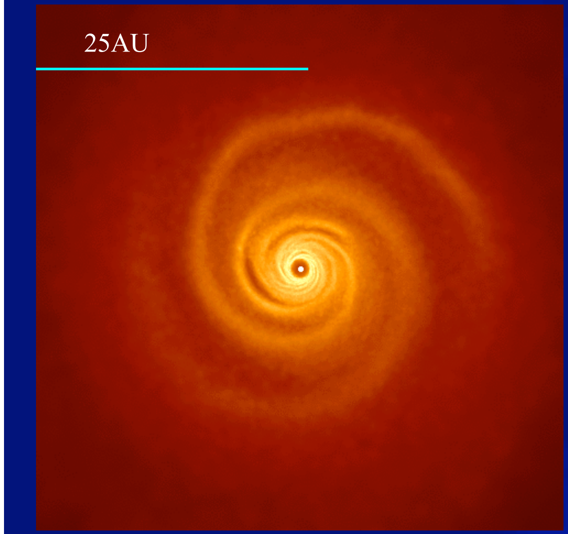
- Define a Figure of Merit
- For observations of any thermal blackbody (with emission which goes like λ^{-2}), the figure of merit that one wants to maximize is $X_\nu = \nu^2/\Delta S$, where ΔS is the noise at frequency ν. We want to maximize X_ν because it is proportional to the SNR obtainable. For $\nu > 350$ GHz, need better weather so use pwv=1.5mm below and 0.5mm above this ν.

Frequency	ΔS (mJy)	X_ν
230	0.07	76
345	0.12	99
675	0.85	54

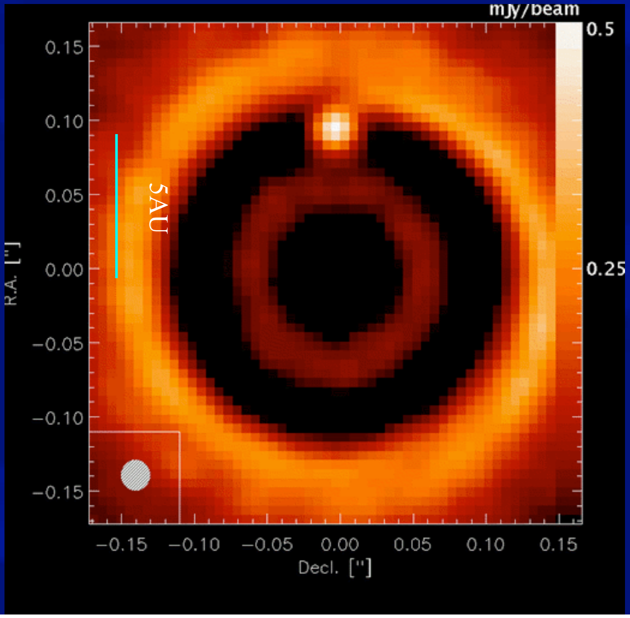
Birth of Stars and Planets

Evolutionary Sequence—
Molecular Cloud Core to Protostar (10^4 yrs) to
Protoplanetary Disk (to ~10^6 yrs) to
Debris Disk (to 10^9 yrs)

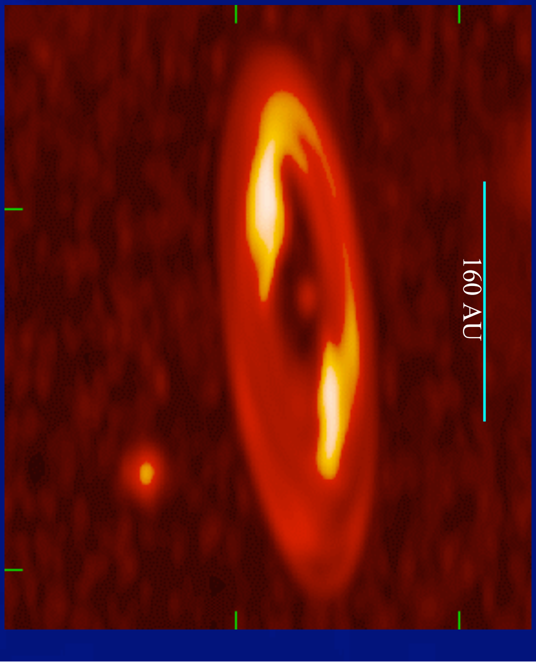
Lodato and Rice 2005



Wolf and D'Angelo 2005



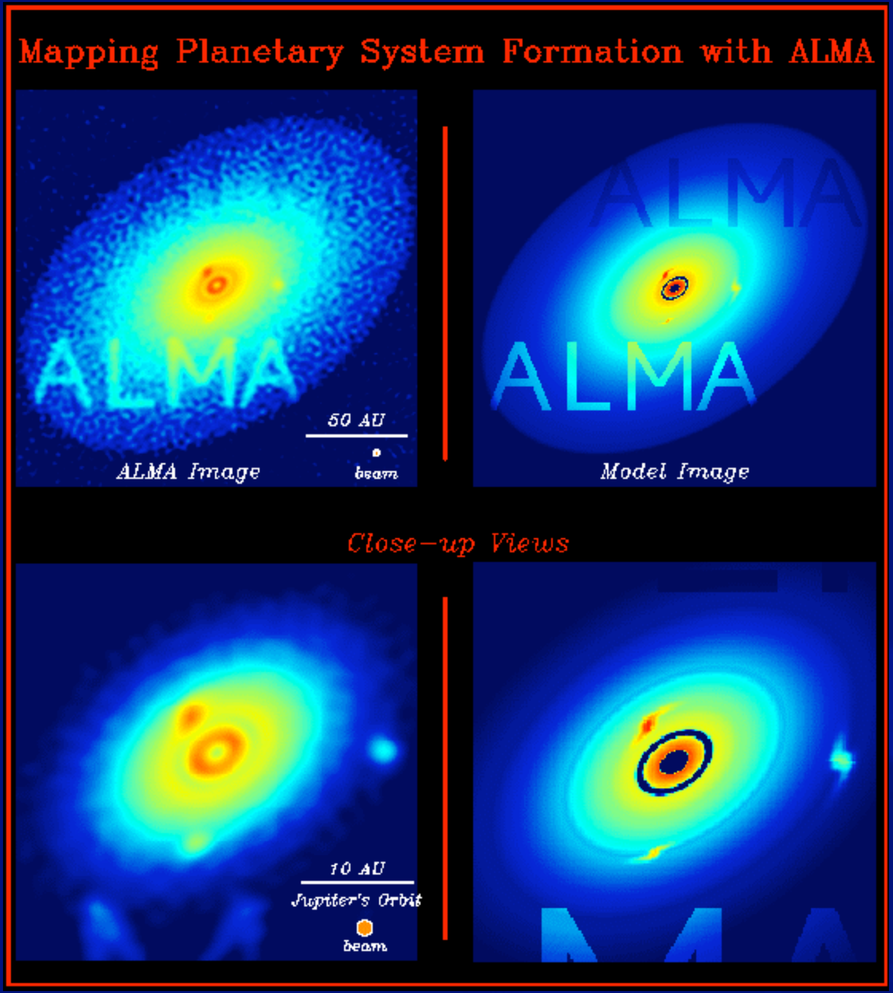
Wilner et al. 2002



Birth of Stars and Planets

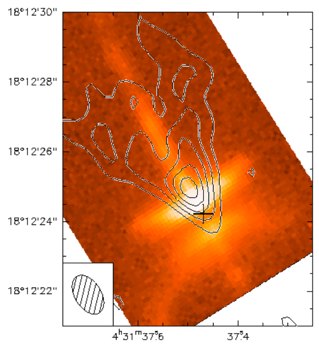
- The nearest Star Formation regions: ~100 pc from the Sun
  - ALMA Beam at 300 GHz (100 pc): 1.5 AU
    - L1457 was once reported to lie at ~80 pc but now seems to be beyond 300 pc.
    - B68 lies at 95 pc (Langer et al.)
    - Rho Oph has parts as close as 120 pc out to 160 pc
    - Taurus has parts as close as 125 pc out to 140 pc
    - Coal Sack and Chameleon and Lupus are about the same.
- The nearest protoplanetary regions lie at ~20 pc from the Sun
  - ALMA Beam at 300 GHz (20 pc): 0.3 AU
    - TW Hya at 56 pc, TW Hya assn is 10 Myr old, not likely to be forming many planets.
    - AU Microscopium, about 14 Myr old, lies only 10 pc from the Sun.
    - Beta Pictoris, 20 Myr old, lies at 17 pc
- The nearest debris disks are even closer—around ~10% of nearby stars.
  - ALMA Beam at 300 GHz (3 pc): 0.05 AU
    - Epsilon Eridani lies a little over 3 pc from the Sun
    - Fomalhaut: 7.7 pc

Protoplanets in formation



- Disks are observed about young stars, but with poor resolution
- ALMA will provide the resolution and the sensitivity to detect condensations, the cores of future giant planets
- As the planets grow, they clear gaps and inner holes in the disks
- On the right are models of this process, and on the left simulations of ALMA’s view showing that condensations, gaps and holes are readily distinguished

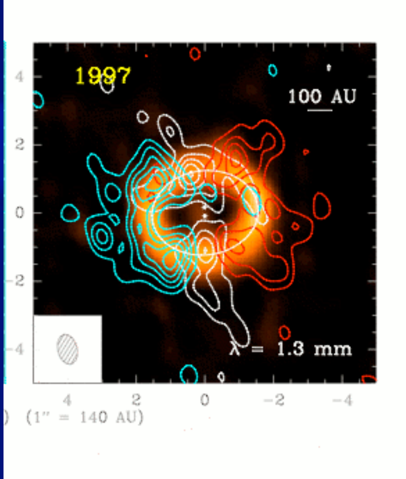
Forming Other Planetary Systems



(1) Infancy. Image the luminous forming stars and planets directly, in emission from stellar photospheres, the gas and dust disk from which the stars formed, and the subsequent assembly of planets from the disk gas and dust.

- Disks are small, <900 AU, requiring high angular resolution (1”~140 AU in nearest star-forming regions)
- Except for the innermost regions, disks are cold (10-30K at R>100 AU) requiring high sensitivity
- Solar-mass stars will have rotation velocities around 2 km/s, turbulence around .2 km/s, requiring high spectral resolution.
- The only way to provide high spectral resolution AND high sensitivity is with large collecting area. ALMA.

Disk Structures

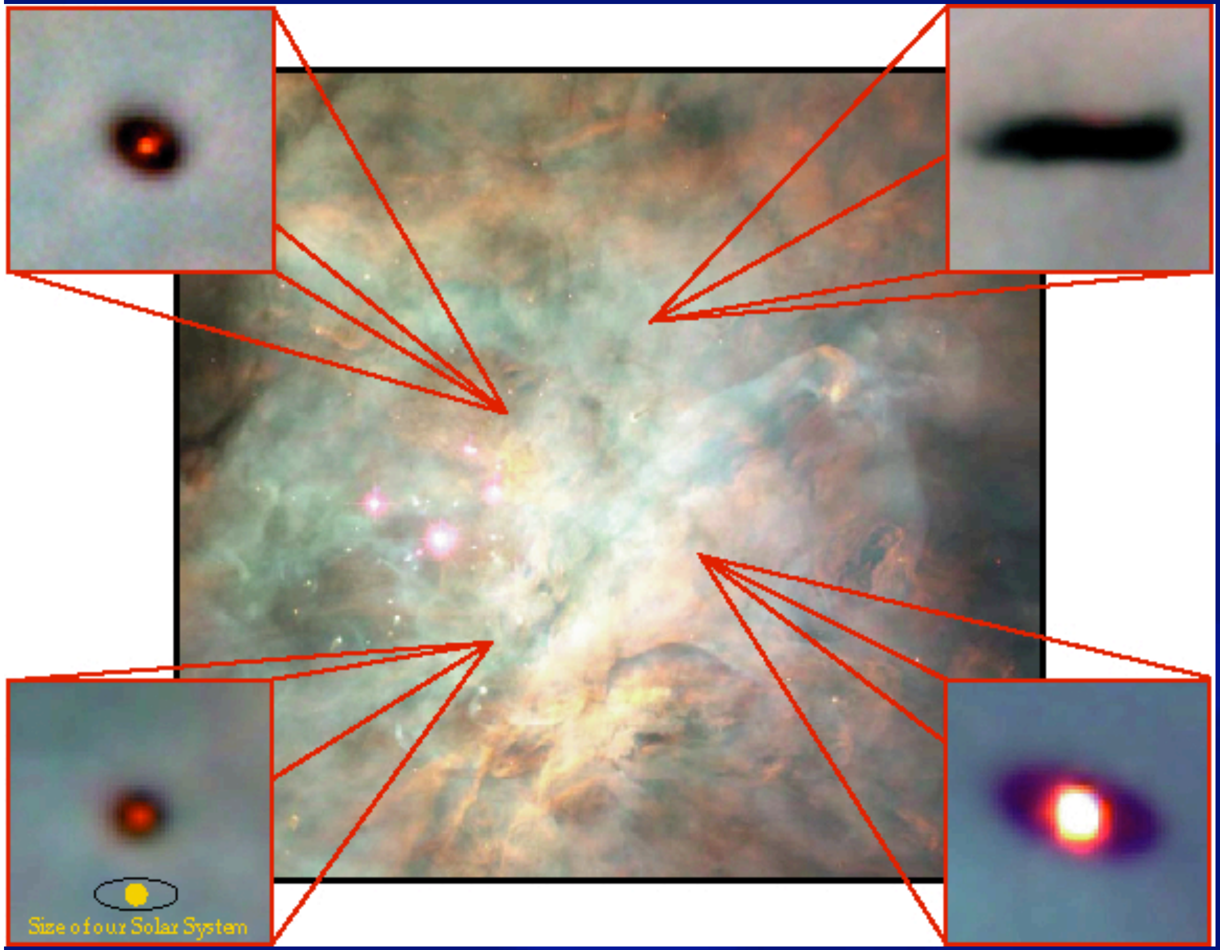


- The partially resolved dust emission probes now the disk at the scale of our solar system, but is not detectable further out with current millimeter array sensitivity.ALMA is sensitive enough to detect the dust emission in the outer optically thin dust disk.
- The CO emission from the outer and from the ~200 AU disk is now detectable. ALMA allows one to map optically thick CO lines at the scale of our Solar System (~ 3 –10 AU), providing information about the gas content and its kinematics; current interferometers do not probe closer in than ~40AU.
- Hence one can compare both dust and gas in the same regions.
- The observations of optically thin lines are still difficult but possible. Long integration times should be used to detect and map molecules rarer than CO in order to investigate the chemistry of protoplanetary disks.

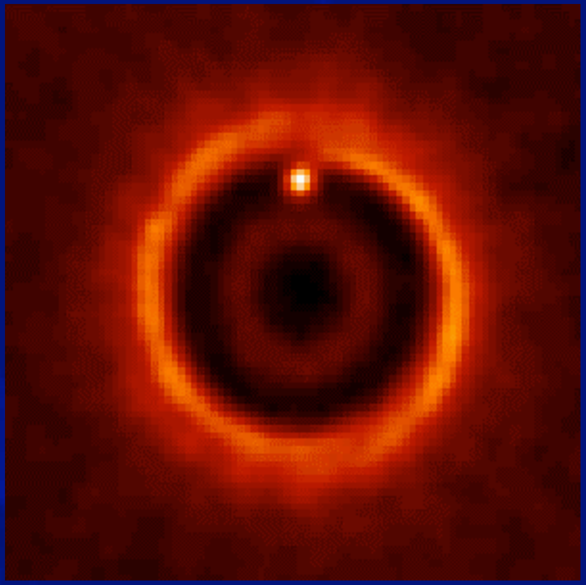
Forming Planets

- (2) Toddler. ALMA will be able to directly detect forming giant planets (‘condensations’) in protoplanetary disks, and the gaps created in these disks as the condensations grow.
- ‘Theoretical investigations show that the planet-disk interaction causes **structures** in circumstellar disks, which are usually **much larger in size than the planet** itself and thus more easily detectable.’ S. Wolf

Formation of Planetary Systems



Wolf and D’Angelo 2005



HST view (left) sees opaque dust projected upon a bright background (if persent). In the ALMA view (above, the dust and the protoplanet appear bright.

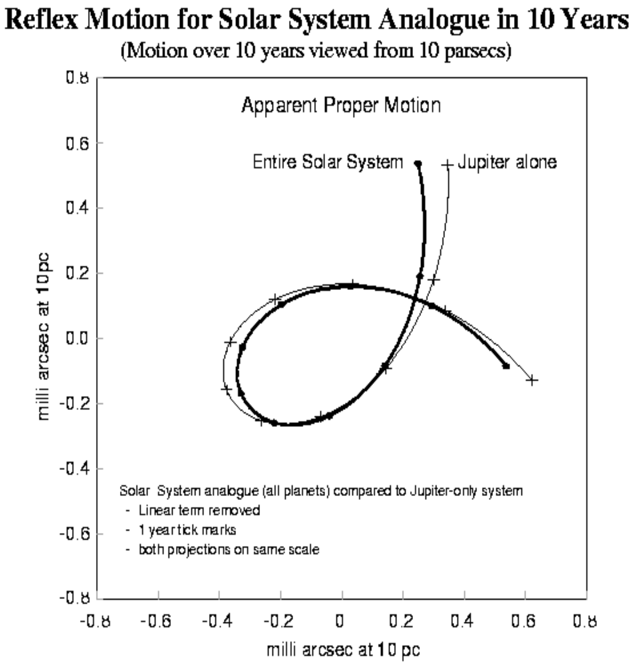
Nearby Planets

- (3) Adolescence. ALMA will be able to directly detect very young giant planets in the nearest star forming regions. Eris, for example, in our own system will be detected in seconds. Integrations times in days for several cases:

Distance (pc)	Jupiter	Gl229B	Proto-Jupiter
1	1.5	0.01	<1hr
5.7	>1yr	12.5	<1hr
10	>1yr	120	<1hr
120	>1yr	>1yr	12.5

Indirect Detection of Mature Planetary Systems

- (4) Adult - ALMA will be able to indirectly detect the presence of giant planets around nearby stars through the use of astrometry. ALMA will also be able to detect and image dust/debris disks around nearby stars (zodiacal analogs).
  - A planet orbiting its central star causes the star to undergo reflexive motion about the barycenter
  - ALMA would measure this motion accurately in its long configuration at submm wavelengths.
  - ALMA could detect photospheres of e.g. 1000 stars well enough to detect a 5Jovian mass planet at 5AU. (10 minute integration).
  - Inclination ambiguities for companions now known could be resolved.
  - All star types, including those suitable for radial velocity searches.



Reflex Motion for Solar System Analogue in 10 Years

(Motion over 10 years viewed from 10 parsecs)

Numerology

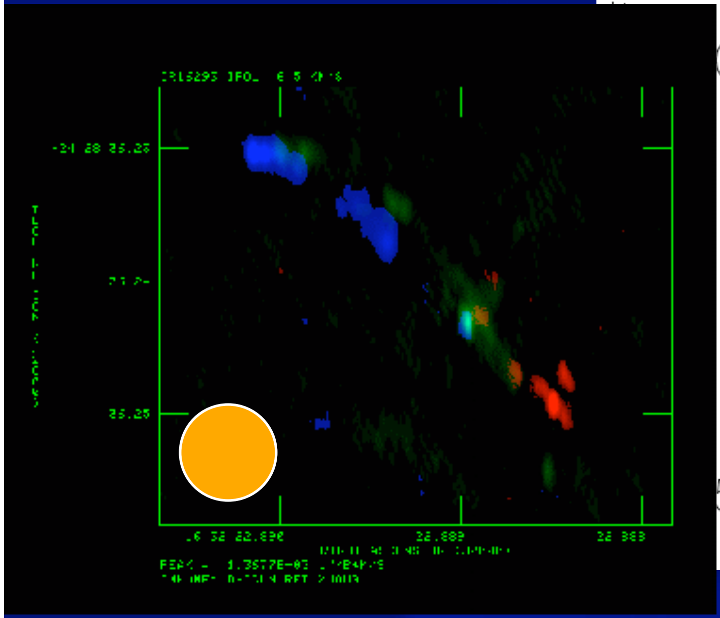
- Assume: 5AU orbit
- Three mass ranges: 5 Jovian, Jovian, Neptunian
- 10 minute integrations, 345 GHz, 1.5mm H_2O

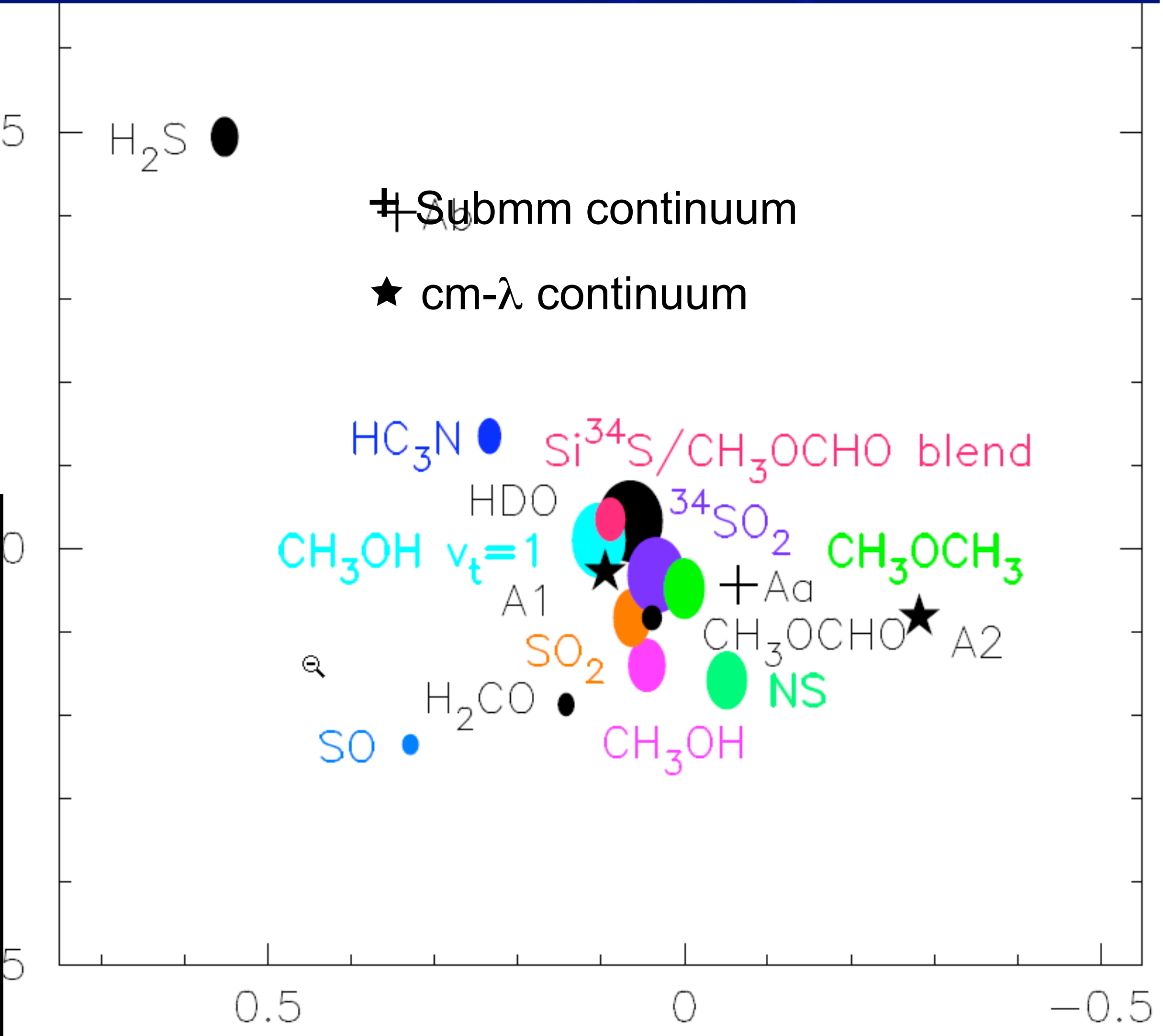
Then:

- 800, 180, 0 Hipparcos stars about which a companion might be detected, virtually none solar type.
- 200, 120, 30 Gliese stars about which a companion might be detected.
  - 100, 30, 0 of these are solar type stars.

To chemically complex star-forming regions such as IRAS16293-2422

Outflow Shock Chemistry





Chandler, Brogan, et al. (2005)

Key features for maser observation enhanced since AMII

- Extensive frequency access--additional frequency bands populated at first light
  - Previous plan: 3mm, 1.3mm, .87mm, .45mm
  - Additions: 2mm (JP), 1.6mm (EU; partial), .61mm (JP), .35mm (JP; partial)
- Large collecting area, high brightness temperature sensitivity
  - Additional antennas (JP), 16 element array ‘Atacama Compact Array’
- Versatile correlator system
  - Tunable filter banks added (EU-Ubx), more flexible system, more channels
  - Additional ACA correlator (JP)
- Southern hemisphere location, but within the tropics.
  - Excellent for Galactic center, Carina arm, Magellanic clouds.

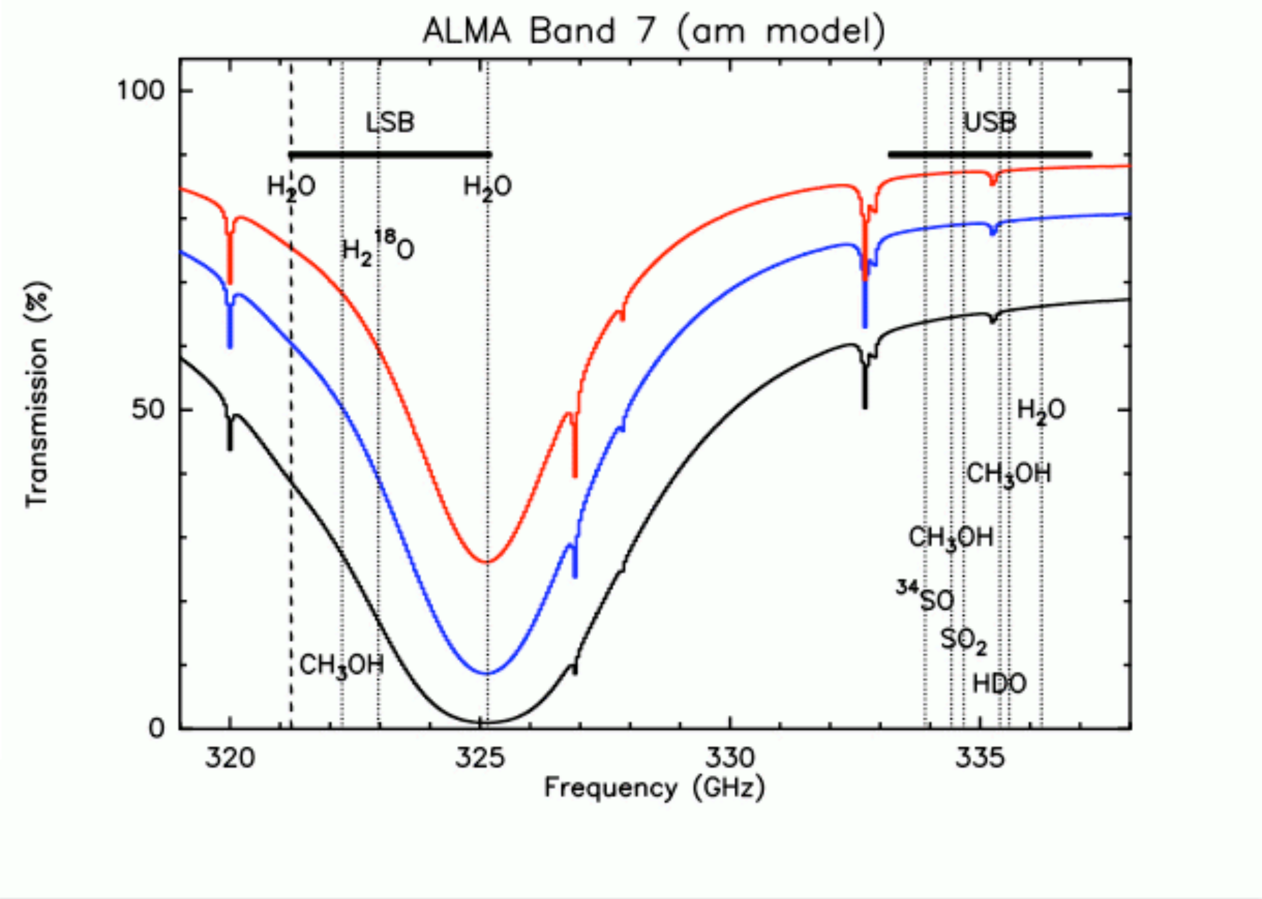
Example multi-transition setup

- Goal: Measure water in five transitions simultaneously, some of which mase.
  - H_2O $J_{Ka,Kc}$ 10_{29} 9_{36} 321.23 GHz ~1800 K ortho
    - E.g. 3-4 Jy SMA; <1” => T_b >? K
  - $H_2{}^{18}O$ $J_{Ka,Kc}$ 5_{15} 4_{22} 322.97 GHz ~500 K para
  - H_2O $J_{Ka,Kc}$ 5_{15} 4_{22} 325.15 GHz ~500 K para
  - H_2O $J_{Ka,Kc}$ 5_{23} 6_{16} $\nu_2=1$ 336.23 GHz ~2939 K ortho
  - HDO $3_{31}-4_{22}$ 335.396
  - Also CH_3OH, SO, SO_2 lines
  - Use B7, LSB on maser lines, largest array
  - Dynamic Scheduler picks superb weather
    - PWV=0.35mm
  - Beamsize = 0”.013; T_b rms~52K 8 hrs, ΔS~0.8mJy
  - 5s ints, data rate~30MB/s, dataset size ~860GB.

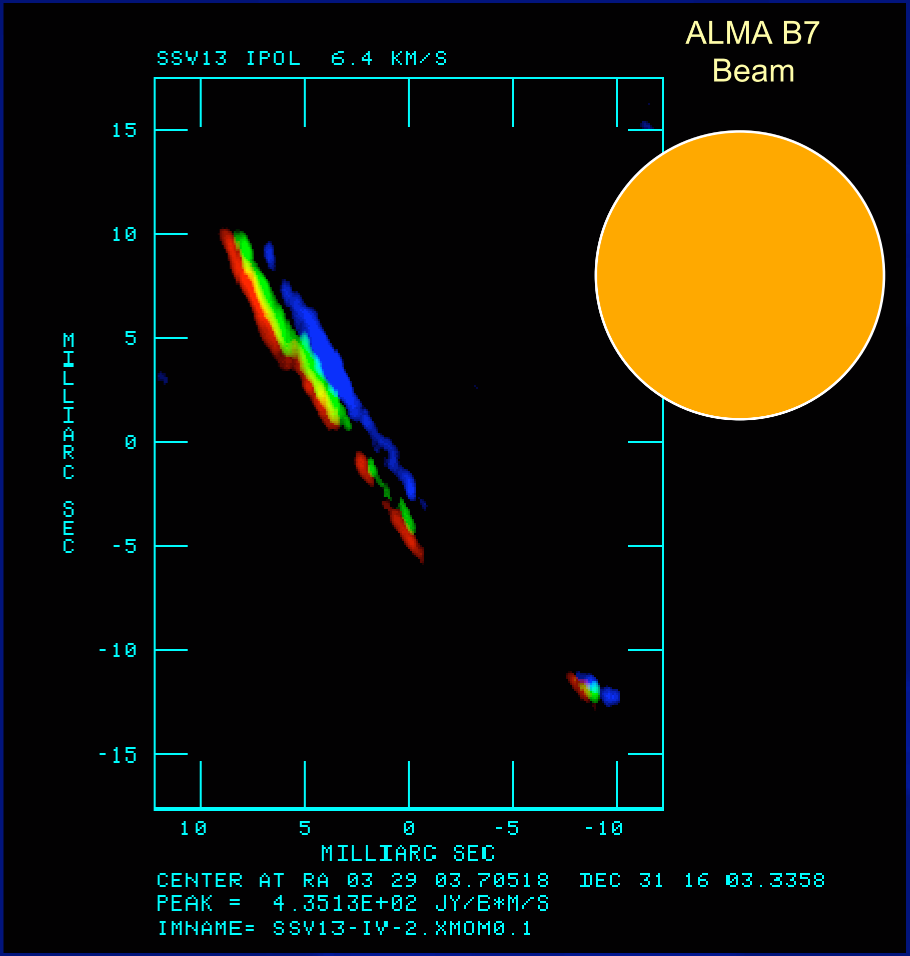
An unfriendly but not obstinate atmosphere…

Chajnantor Atmosphere: 25%=> T_b rms~760K 8 hrs, ΔS~12mJy

Q	τ_{225}	pwv
1	.029	.52
2	.037	.66
3	.048	.86
4	.063	1.13
5	.086	1.54
6	.127	2.26
7	.232	4.14



Proper Motion and Structure of Shocks in Dense Clouds



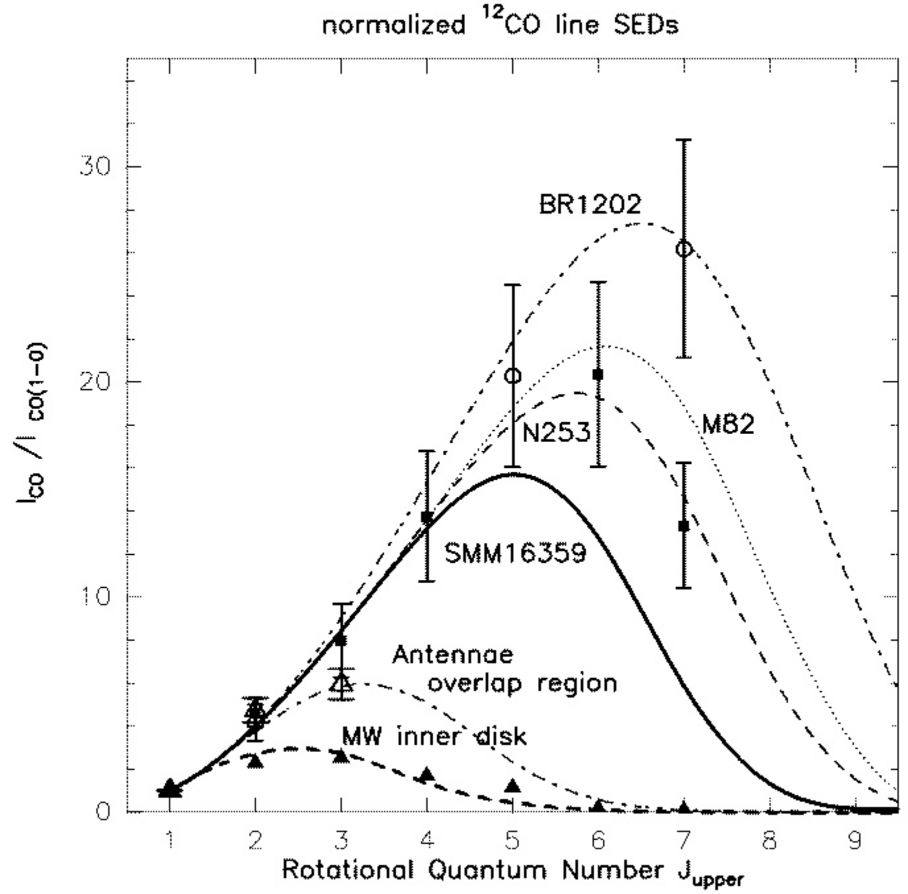
Masers near SVS13; 1mas=0.34AU
Blue Epoch I, Green Epoch III, Blue Epoch IV
Wootten, Marvel, Claussen and Wilking

Water masers observed over four epochs encompassing 50 days (22 GHz, VLBA). Several of the masers define an arc structure about 5AU in length. This consistently moved at a rate of 0.023 mas/day, or 13.6 km/s.

These structures apparently represent water emission from interstellar shocks driven by the outflow from SVS13. ALMA can provide images of chemistry in action in shocks such as this.

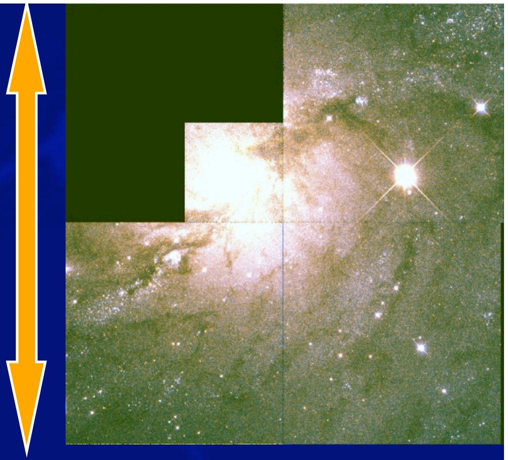
CO rotational transitions (‘ladders’)

Line ratios of CO rotational transitions depend on density and temperature.
In Milky Way type galaxies: low-order transitions are brighter → low densities.
In dense cores of starburst galaxies, higher-order transitions are brighter.
At high z, higher excitation occurs, partly owing to higher CMB.



Weiss et al. astro-ph/0508037

Structure of Nearby Galaxies


2'.7
162 beams

HST

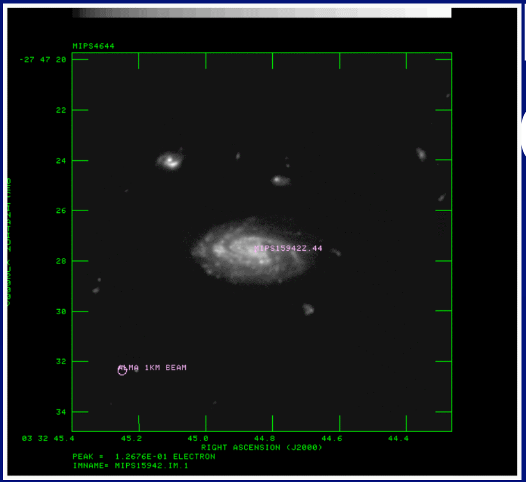
- Example from D. Meier (NRAO) DRSP
  - IC342 ^{12}CO, ^{13}CO, C^{18}O J=2⇒1, HNCO J=10⇒9
  - Image 4'x4' field of view. PB=27″, nyquist=11”
    - 324 pointings
- 10σ sensitivity goal disk emission
  - ➡ B6 (1.3mm) line rms: 0.06 K
    - 2 mins per pointing
    - 11 hours, multiple (~8) mosaics
  - 1mm cont rms: 65 uJy/bm
- Example correlator setup…

Extragalactic CO Setup

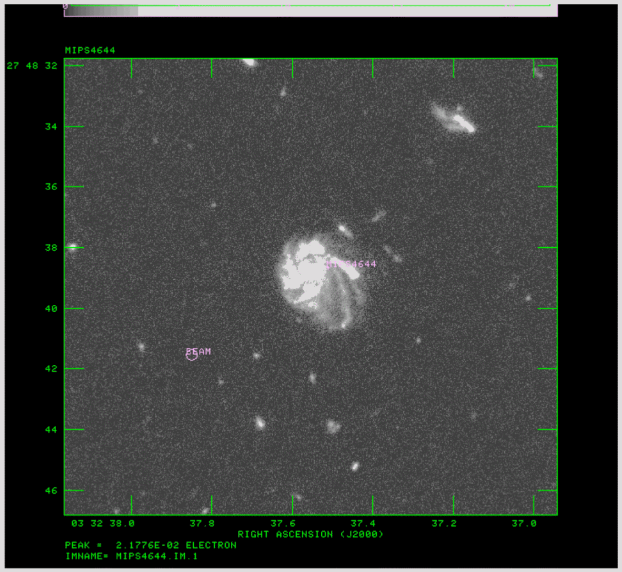
Line	CO	13CO	C18O	HNCO	Cont
Frequency	230.538 USB	220.398 LSB	219.580 LSB	219.798 LSB	4 GHz USB&LSB
Resolution*	0.64 km/s	0.64 km/s	0.64 km/s	0.64 km/s	21 km/s
Window	Q1: 500 MHz	Q2: 500 MHz	Q2: 500 MHz	Q2: 500 MHz	Q3&4: 2 GHz
Channel decimation	To ~5 km/s	To ~5 km/s	To ~5 km/s	To ~5 km/s	Excise lines
Spatial resolution	1” (300m)	1”	1”	1”	1”

LIRGs
0.4<z<1

- MIPS15942, z=0.44



MIPS4644, z=0.67



HST UDF

LIR~5 LIR(MW) so L(CO)2-1~5 L(CO)1-0, MW

Tsys~100K SSB;

Line 1σ reaches 1K/1min 5 km/s;

Continuum 1σ reaches .07 mJy/1min

Could possibly measure CO in ~two dozen MIPS-detected LIRGS in UDF falling in this redshift range, one transit per source

'Age' 7.4-11.3 Gyr; Scale 24-50 kpc/beam

Detecting normal galaxies at z=3

ALMA sensitivity depends on:

Atmospheric transparency:

Chajnantor plateau site at 5000m altitude is superior to existing mm observatories.

Noise performance of receivers: try to approach quantum limit). Also gain √ 2 because ALMA will simultaneously measure both states of polarization.

Collecting area: remaining factor of 7 to 10 can only be gained by increasing collecting area to >7000 m2.

Detecting normal galaxies at z=3

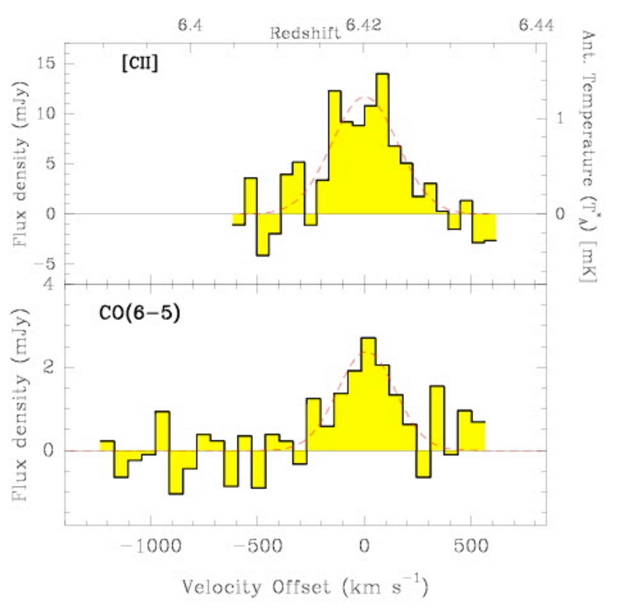
CO emission now detected in >25 z>2 objects, out to z=6.4. [C II] only at z=6.4 (right). To date such line emission is seen only in luminous AGN and/or gravitationally lensed objects. Normal galaxies are 20 to 30 times fainter. Current millimeter interferometers have collecting areas between 500 and 1000 m². ALMA's >7000 m² provides excellent sensitivity.

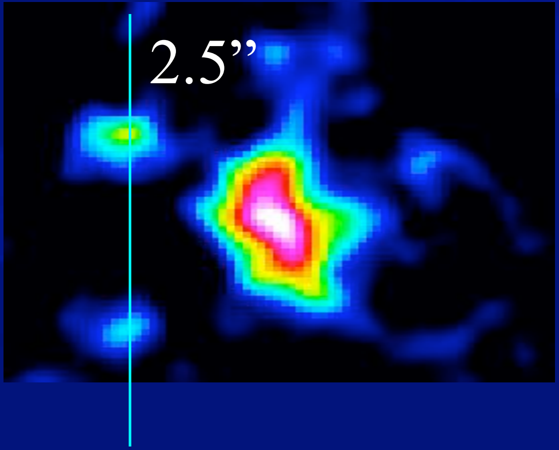
Image at right: 60 hrs VLA, 1.5 hrs ALMA (B3).

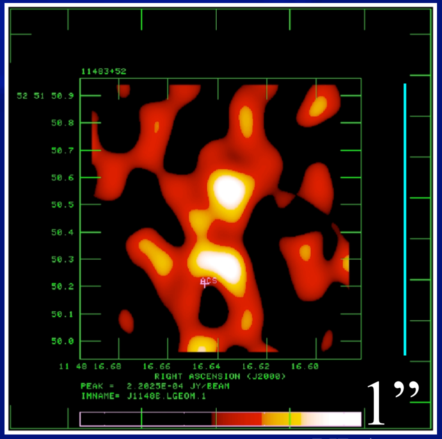
J1148; IRAM

[C II]

[CO]







VLA

[CO 3-2]

Spectrum of a Normal Galaxy

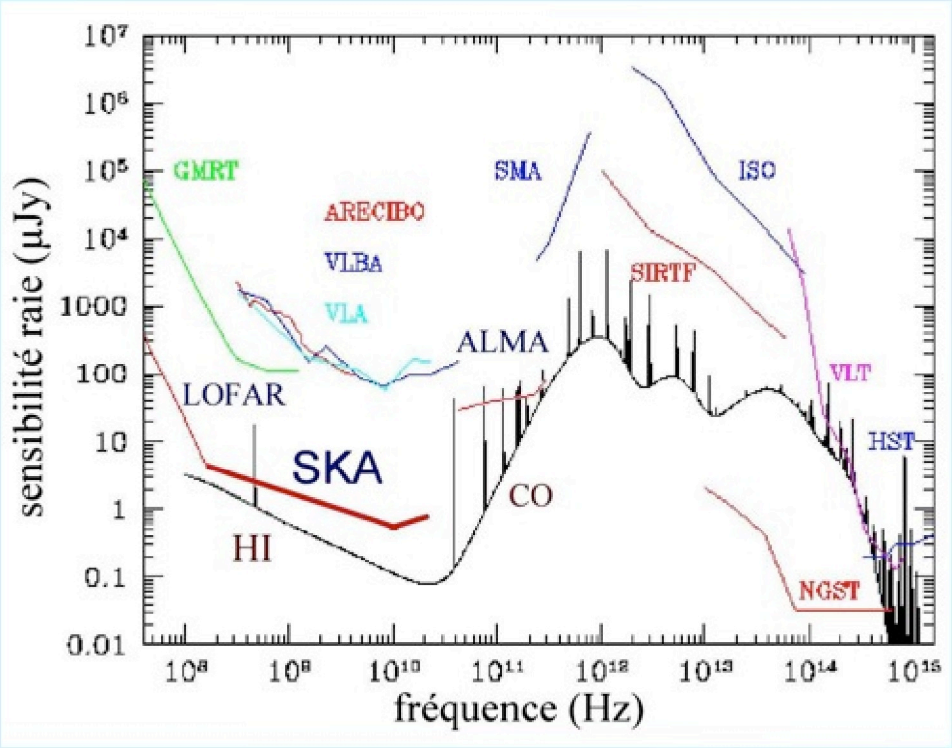
F. Combes

Z=2 in this example

$L(CO)_{1-0}$~$5x10^8$ Kkm/s pc^2 ~$L(CO)_{2-1}$

$S_{CO_{2-1}}$~.1mJy

But when did 'Normal' galaxies evolve?

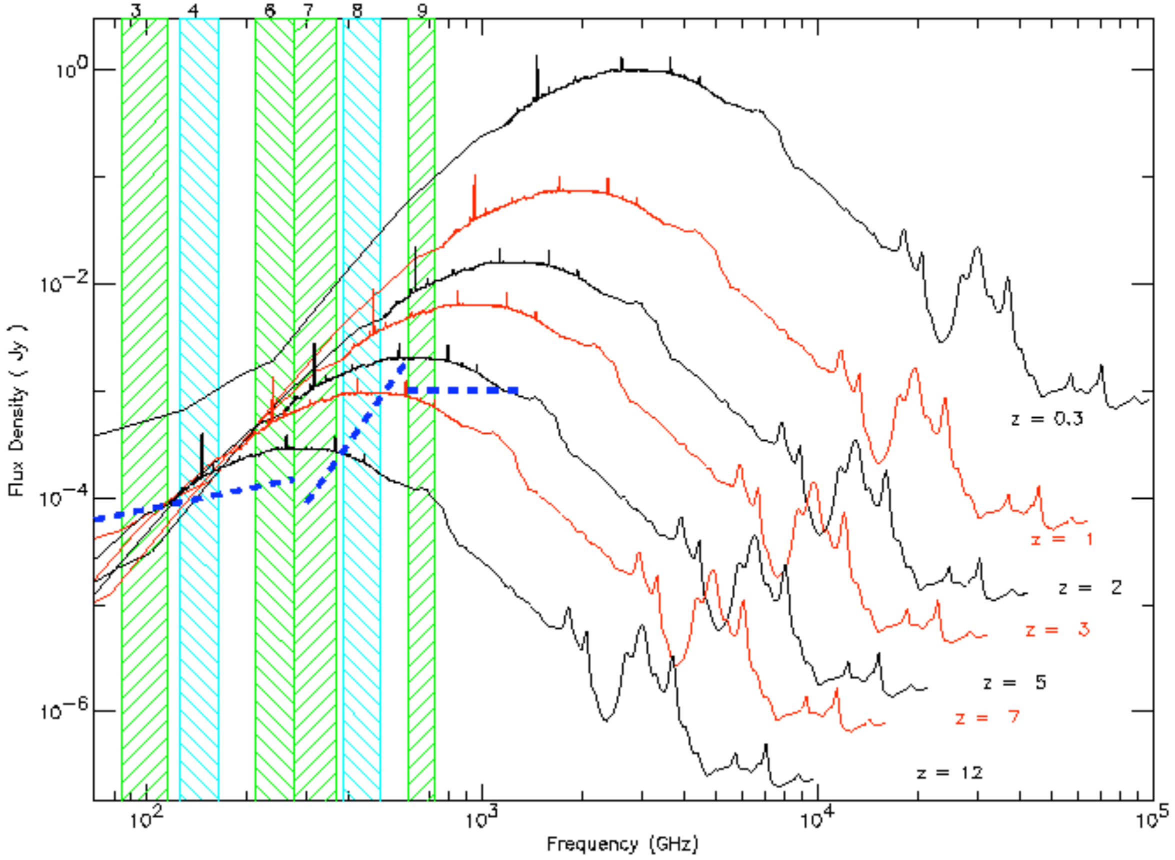


Detection of spectral lines of a 'standard' spiral galaxy at $z = 2$

5σ in 1hour

Infrared Luminous Galaxies

- As galaxies get redshifted into the ALMA bands, dimming due to distance is offset by the brighter part of the spectrum being redshifted in. Hence, galaxies remain at relatively similar brightness out to high distances.



M82 from ISO, Beelen and Cox

Hubble Deep Field

Rich in Nearby Galaxies, Poor in Distant Galaxies

Source: K. Lanzetta, SUNY-SB

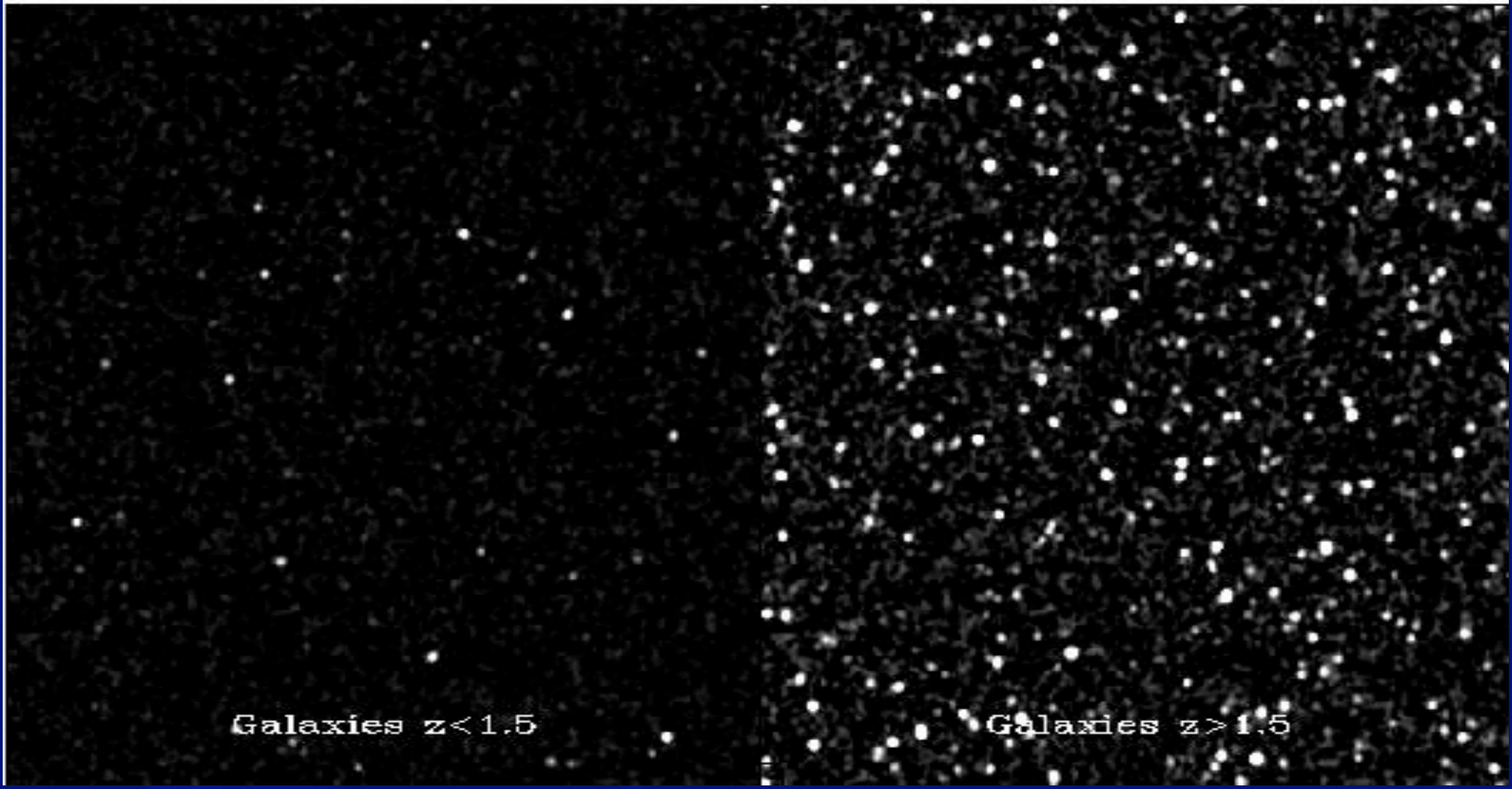
Nearby galaxies in HDF

Distant galaxies in HDF

ALMA Deep Field

Poor in Nearby Galaxies, Rich in Distant Galaxies

Source: Wootten and Gallimore, NRAO

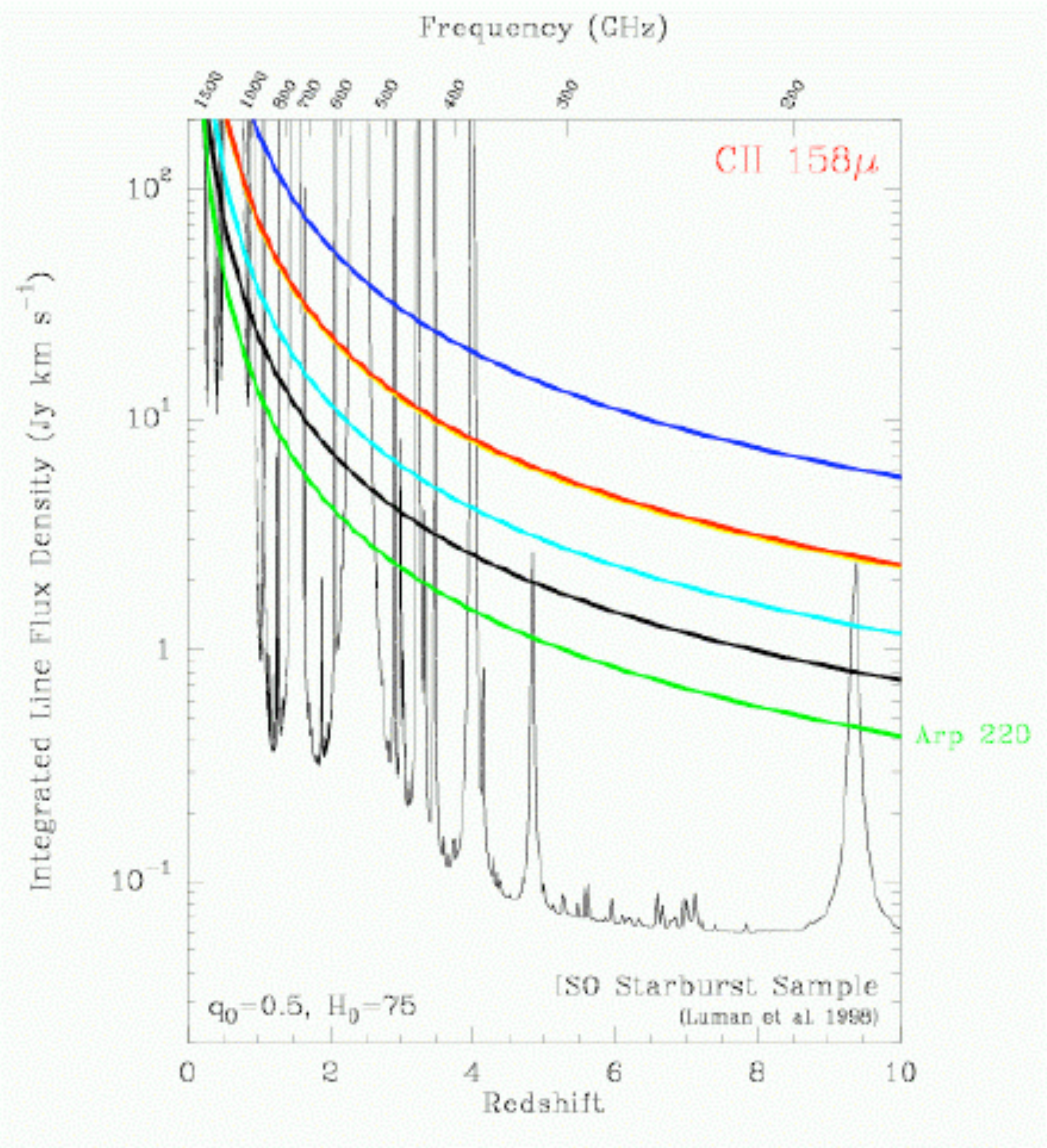


Nearby galaxies in ALMA Deep Field

Distant galaxies in ALMA Deep Field; spectroscopy also!

[C II] Emission from High-z Galaxies

Colored lines track the flux levels seen in a variety of galaxies moved to higher redshift; black is ALMA sensitivity. Note the 'sweet spot' in the 1.3mm band for z>5.

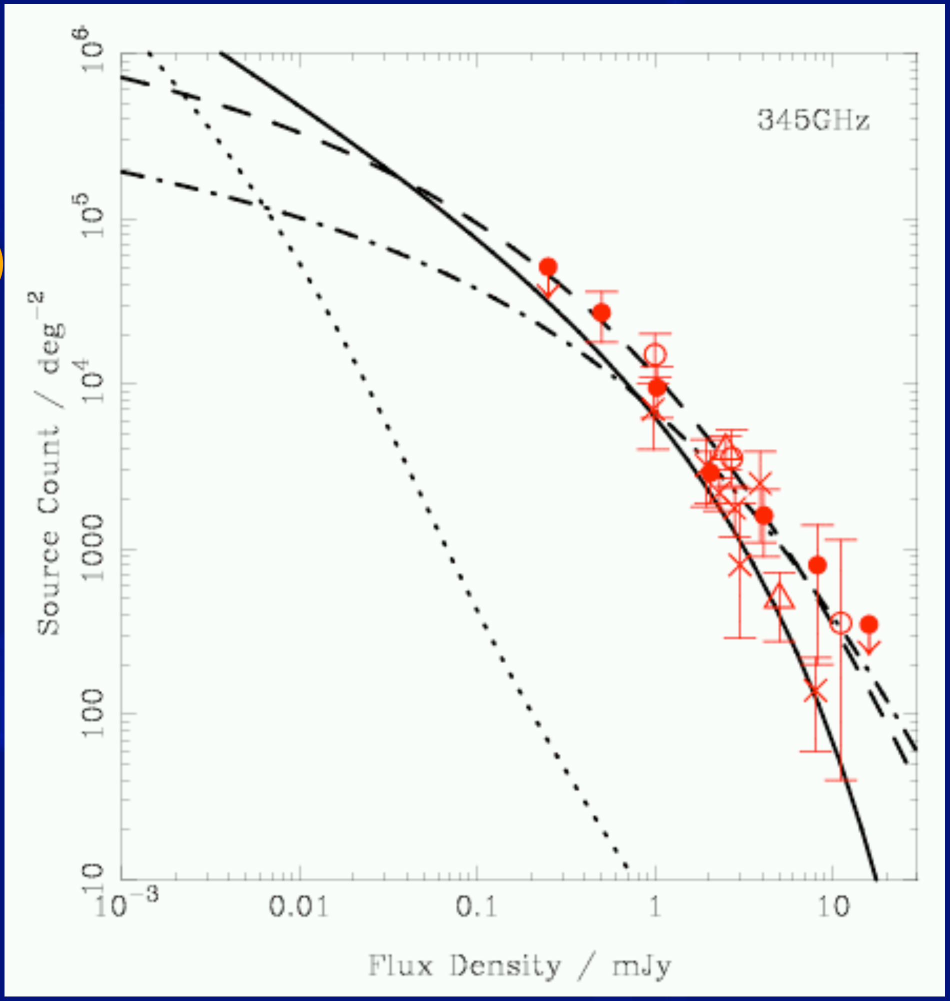


Credit: K. Menten

Example: ALMA Deep Field

Step 1: 300 GHz Continuum Survey

- 4’ x 4’ Field (3000x3000 pixels)
- Sensitivity: 0.1 mJy (5σ)
  - 30 minutes per field
  - 140 pointings
  - A total of 3 days
- 100-300 sources



Determine the contribution of LBGs to the IR background

Example: ALMA Deep Field

Step 2: 100 GHz Spectroscopic Survey

- 4’ x 4’ Field (1000x1000 pixels)
- Sensitivity: 7.5 μJy continuum and 0.02 Jy km/s for a 300 km/s line (5σ)
    - 12 hrs per field
    - 16 pointings (a total of 8 days)
    - 4 tunings
- One CO line for all sources at $z>2$ and two or more at $z>6$ → Obtain spectroscopic redshifts
- Photometric redshifts

Example: ALMA Deep Field

Step 3: 200 GHz Spectroscopic Survey

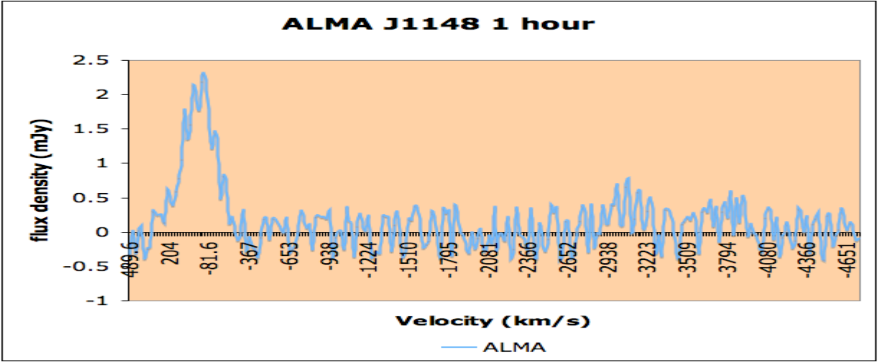
- 4’ x 4’ Field (2000x2000 pixels)
- Sensitivity: 50 μJy continuum (5σ)
  - 1.5 hrs per field
  - 90 pointings (a total of 6 days)
  - 8 tunings
- Along with Step 2, at least one CO line for all redshifts, two CO lines at z>2
- Photometric redshifts

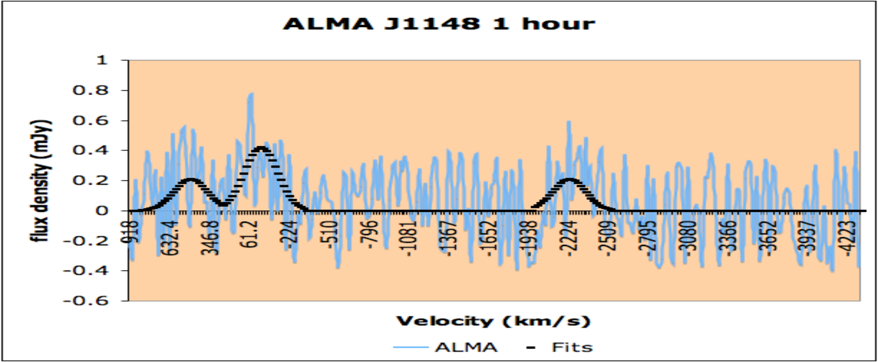
Summary: ALMA Deep Field

J1148+5251: an EoR paradigm with ALMA

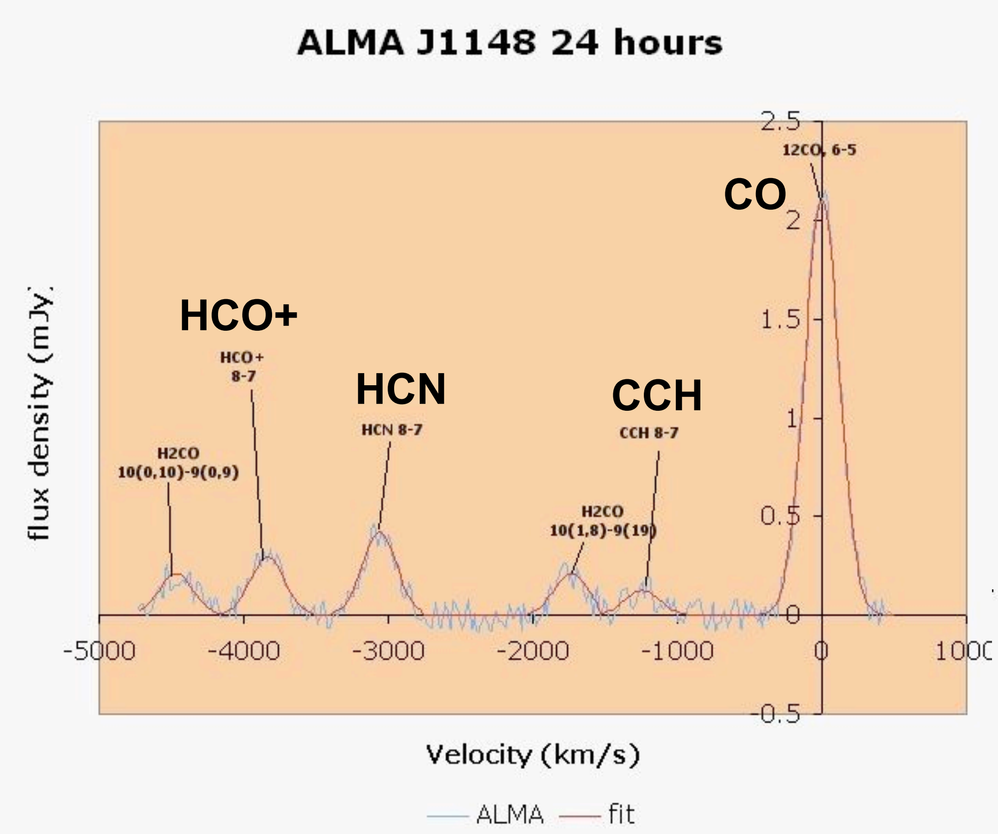
CO J=6-5

Wrong declination (though ideal for Evanston)!
But…
High sensitivity
12hr 1s 0.2mJy
Wide bandwidth
3mm, 2 x 4 GHz IF
Default ‘continuum’ mode
Top: USB, 94.8 GHz
CO 6-5
HCN 8-7
HCO+ 8-7
H2CO lines
Lower: LSB, 86.8 GHz
HNC 7-6
H2CO lines
    C18O 6-5
    H2O 658GHz maser?
Secure redshifts
Molecular astrophysics
ALMA could observe CO-luminous galaxies (e.g. M51) at z~6.





ALMA into the EoR

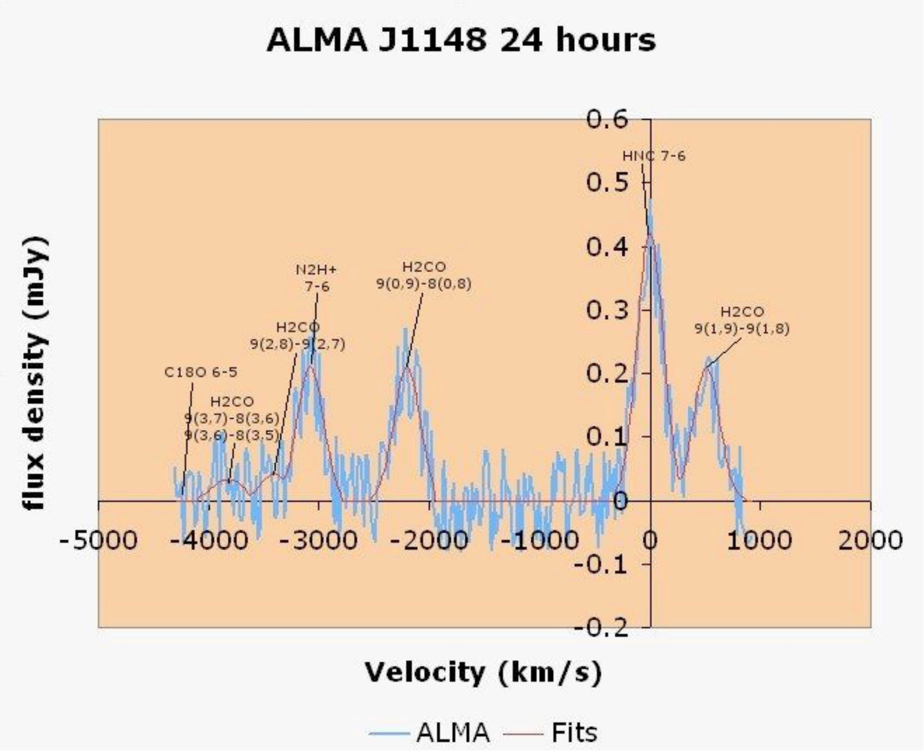


Spectral simulation of J1148+5251

- Detect dust emission in **1sec** (5σ) at 250 GHz
- Detect multiple lines, molecules per band => detailed astrochemistry
- Image dust and gas at sub-kpc resolution – gas dynamics! CO map at 0”.15 resolution in 1.5 hours

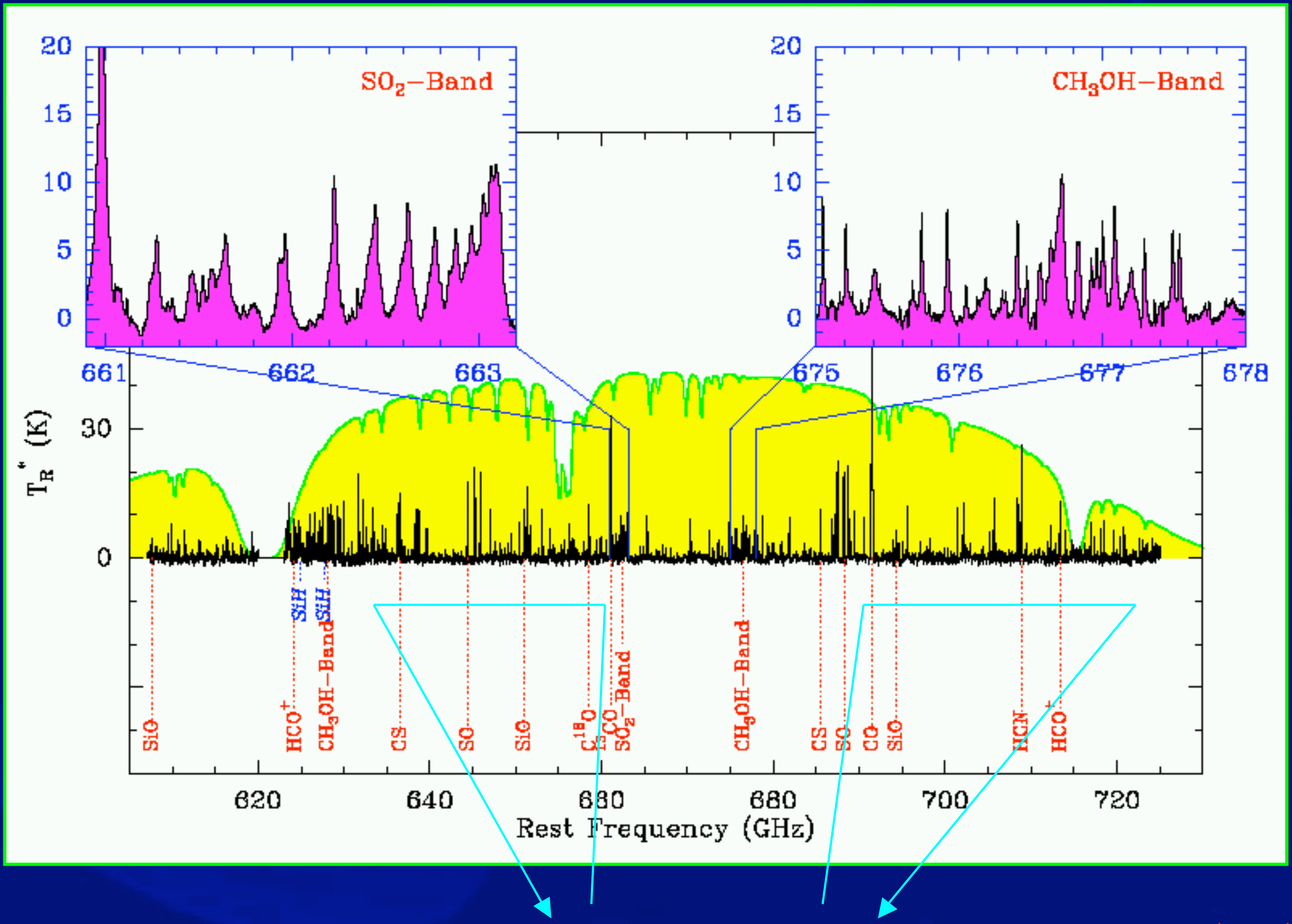
N. B. Atomic line diagnostics

[C II] emission in **60sec** (10σ) at 256 GHz
[O I] 63 μm at 641 GHz
[O I] 145 μm at 277 GHz
[O III] 88 μm at 457 GHz
[N II] 122 μm at 332 GHz
[N II] 205 μm at 197 GHz
HD 112 μm at 361 GHz



Bandwidth Compression

Nearly a whole band scan in one spectrum



LSB

USB

Schilke et al. (2000)

Summary

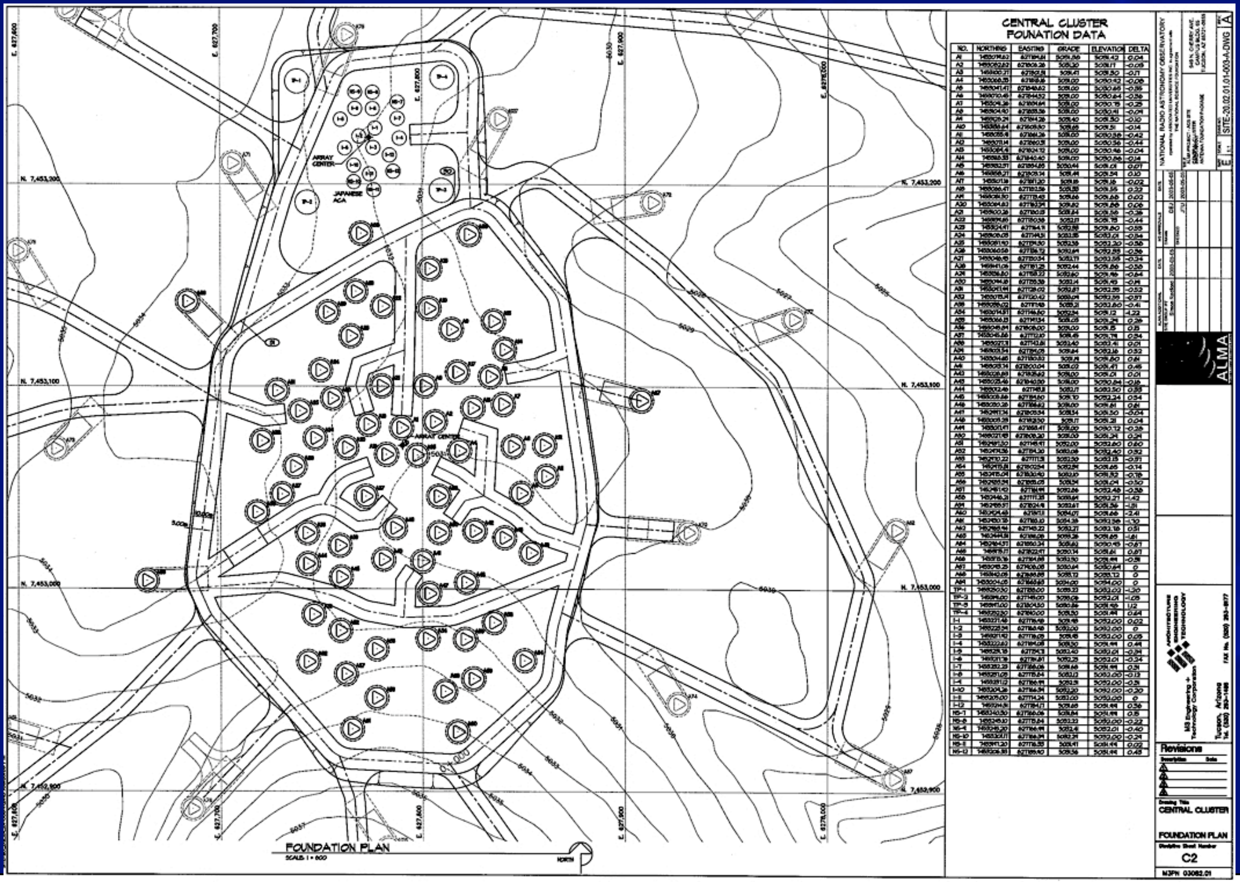
- ALMA provides an increase in sensitivity and resolution over existing facilities in the mm/submm range of nearly two orders of magnitude. Much of the equipment will arrive in Chile by Q4 2008.
- ALMA will begin verification observations mid-2009, call for proposals Q1 2010.
- ALMA provides images to observers in addition to other products (uv datasets, etc)
  - ALMA will be accessible to all astronomers
  - Images will be available via archive
- In North America, the portal to ALMA is the North American ALMA Science Center at NRAO HQ on the University of Virginia grounds in Charlottesville. http://www.cv.nrao.edu/naasc/

ALMA

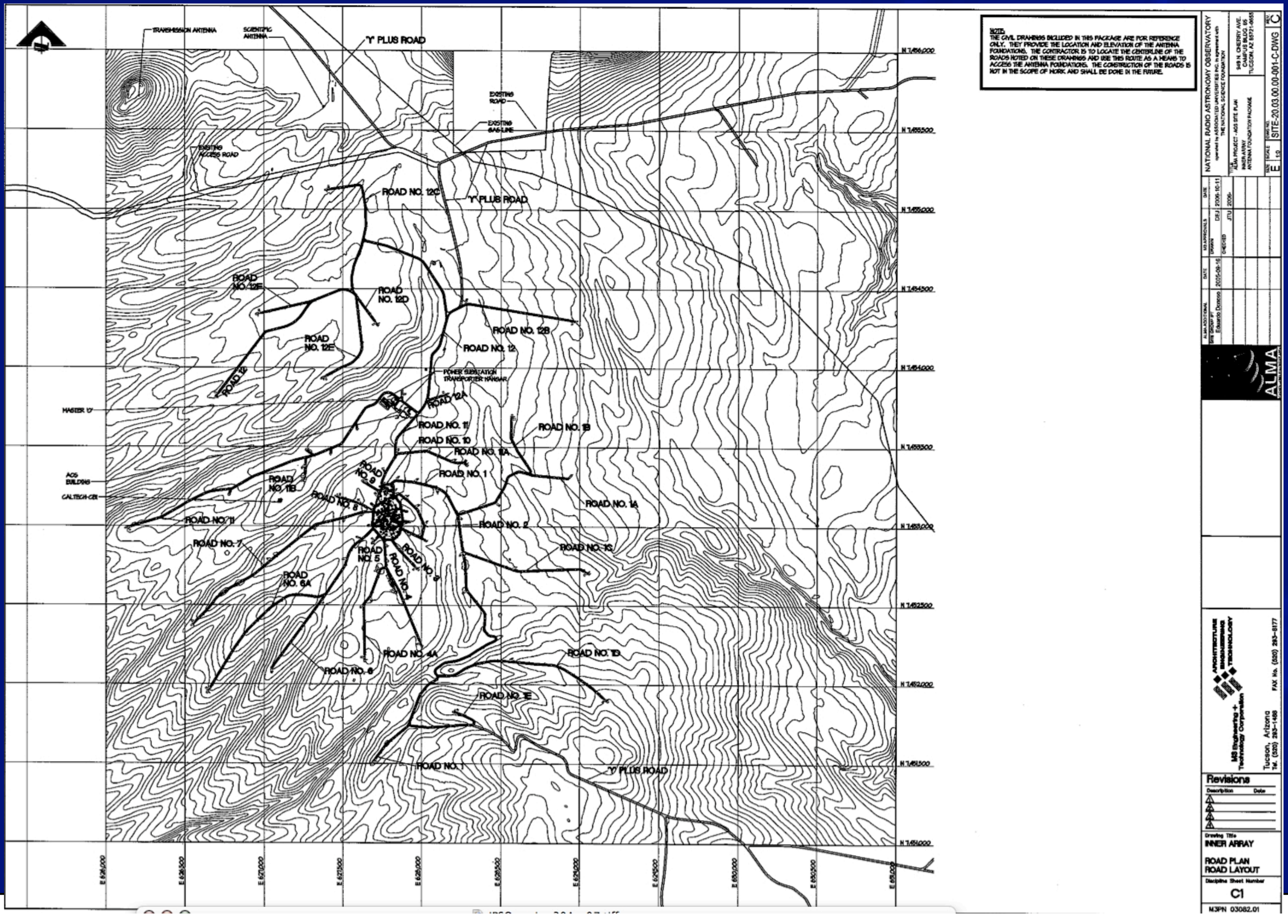
ATACAMA LARGE MILLIMETER ARRAY

Schedule

Central Cluster



Inner Array



NOTE:
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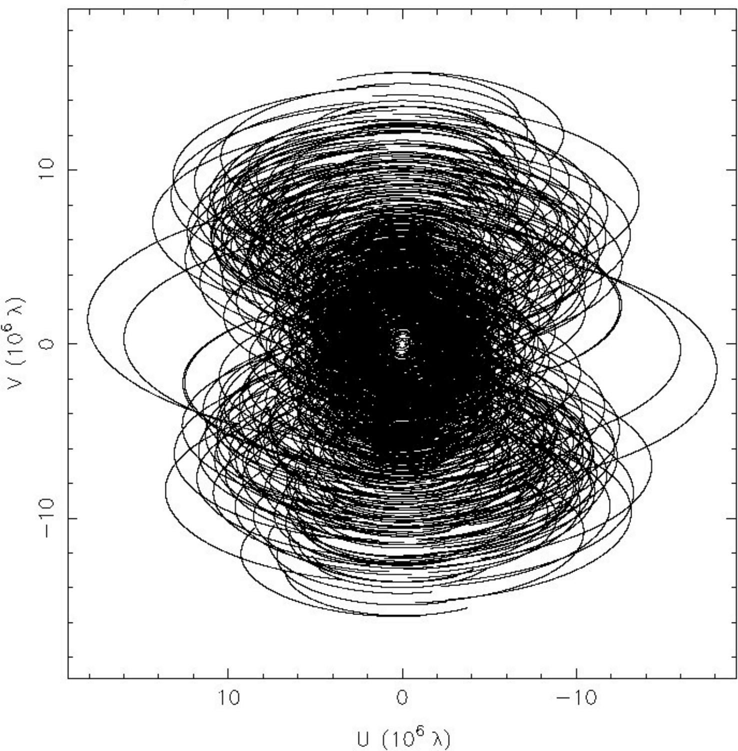
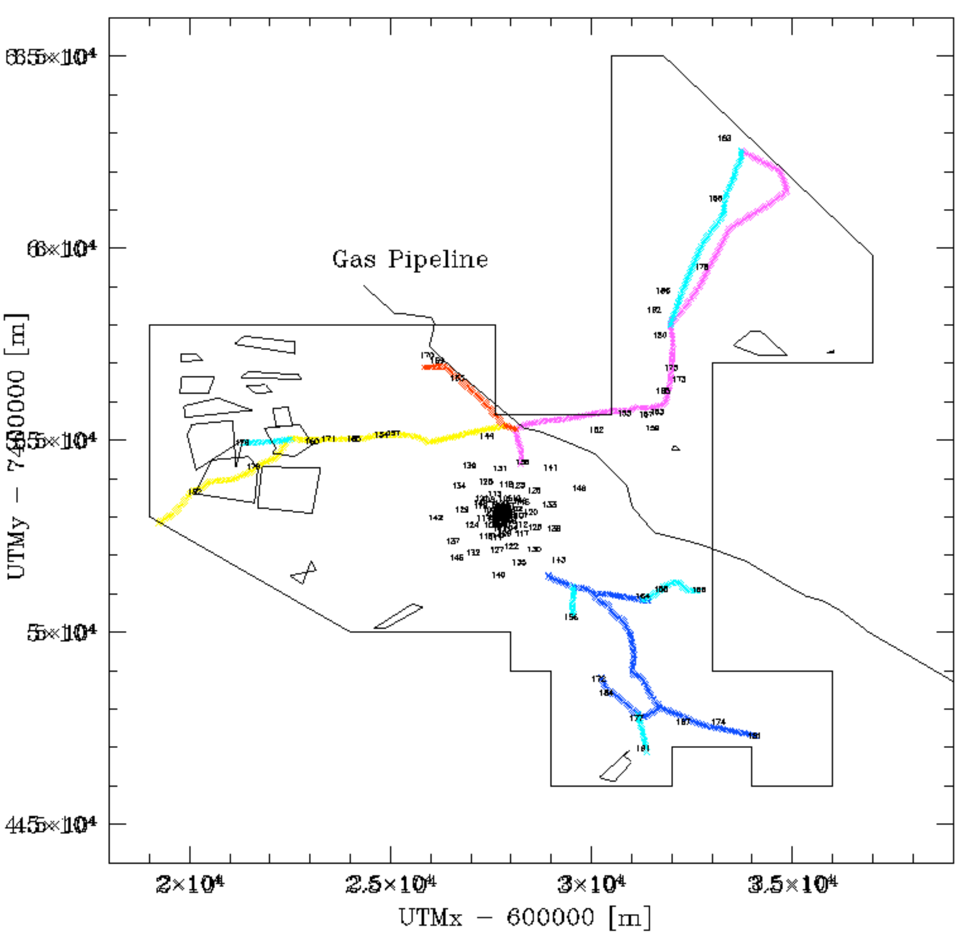
Configuration Characteristics



Uv tracks, from Casa

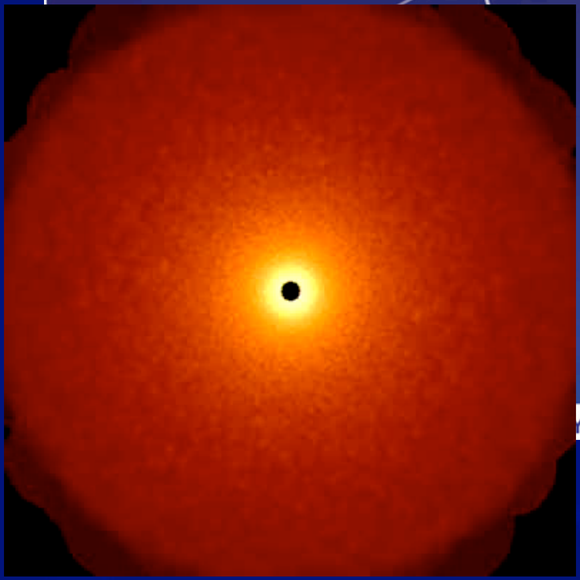


Extended configurations

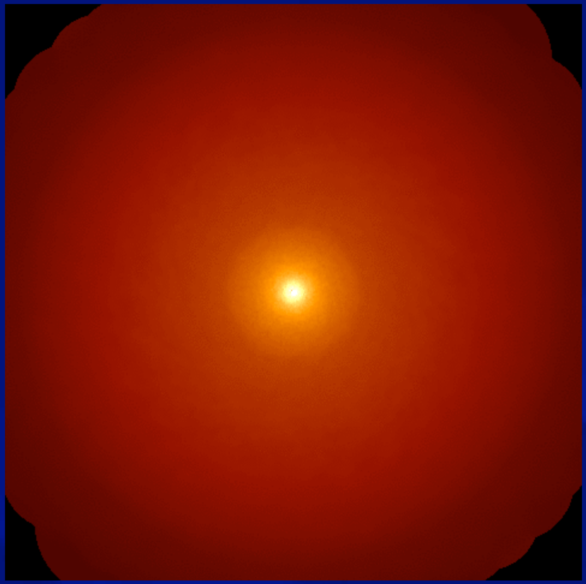
Design Reference Science Plan 2.0

Disk turbulence – impact on outflows

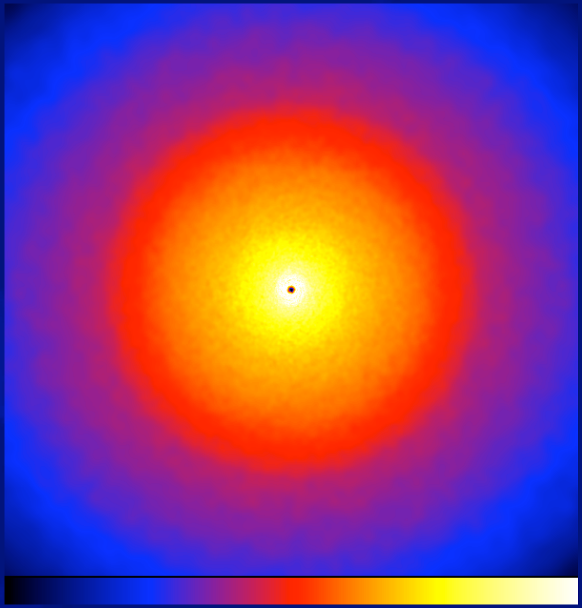
Mass of the disk dramatically changes the characteristics of spiral density waves that can transport angular momentum efficiently. Consider only the disk heating and cooling (no stellar heating, or heating due to ionized outflow or shocks produced by global infall onto the outer disk layers. Then for $M_{disk} = 0.1, 0.5 \,\&\, 1.0\, M_\star$, (Lodato & Rice 2003,2005):



$M_{disk} = 0.1\, M_\star$



$M_{disk} = 0.5\, M_\star$



$M_{disk} = 1.0\, M_\star$

Matzner & Levin (2004) – Low-mass star formation: initial conditions and disk instabilities. Irradiation quenches fragmentation due to local instability because disk temperature is raised above parent cloud temperature. How will increased angular momentum transport affect outflow?

Will $\dot{M}_f / \dot{M}_{acc}$ *decrease with* L_{bol} *(e.g. Shepherd 2003)?*