ALMA's Window on Molecular Emission: Small Ions to Complex Prebiotics

Al Wootten

Boom Time for IS Spectroscopy

1000 year anniversary of SN1006 this week!

- Correlator technology: Huge increases in data processing ability produce a flood of new data
- Telescopes: GBT combines collecting area with powerful correlator capacity: 8 new molecules in the past 2 yrs.
- All-sky: AT, ASTE, NANTEN II, APEX in the S. hemisphere, soon to be followed by ALMA
- Multibeaming: NRO 45M, FCRAO, JCMT, APEX, LMT
- Interferometers: No longer limited in spectroscopic capability, new and upgraded instruments improve sensitivity

New Arrival on the World MM Stage

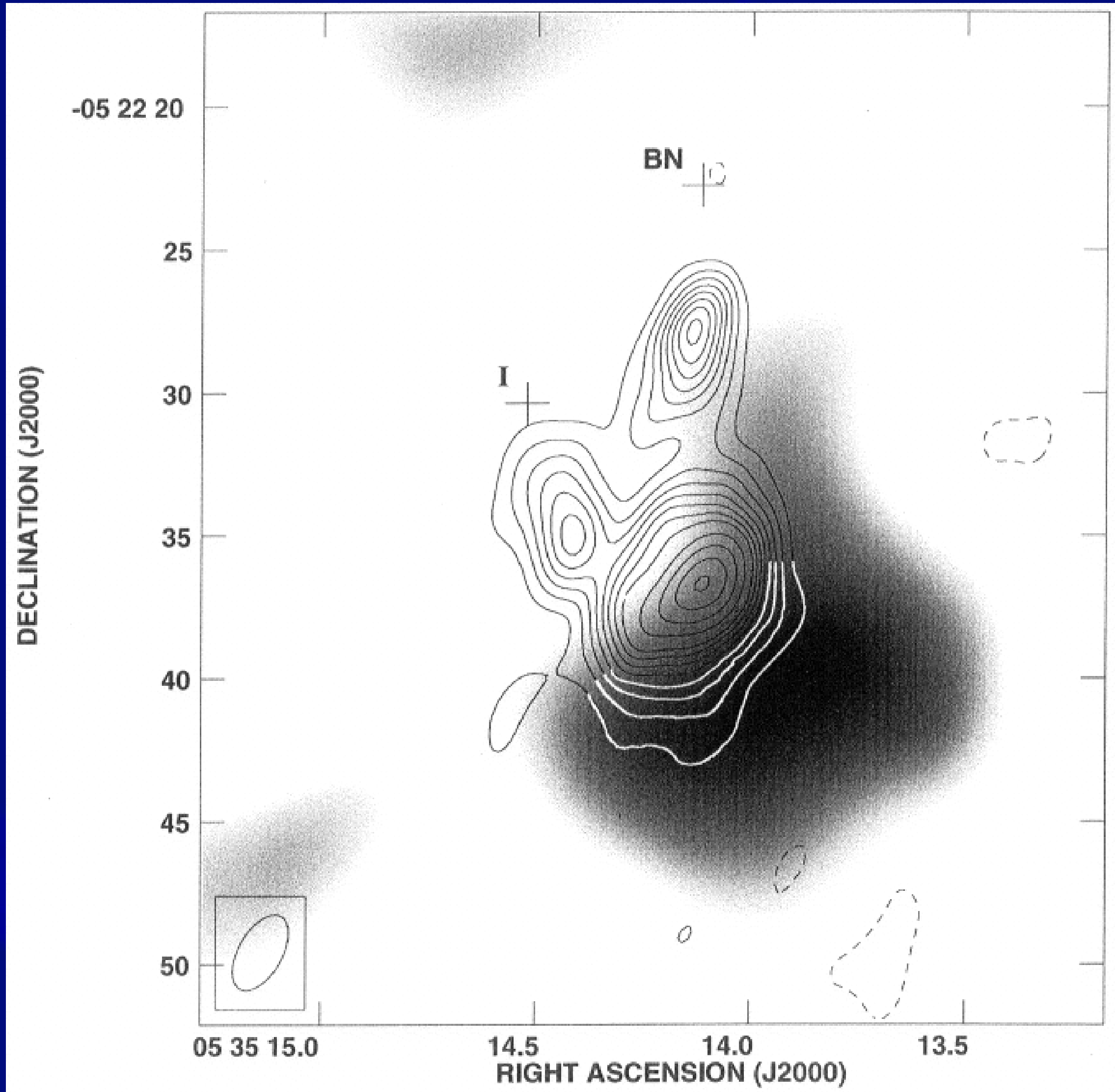
CARMA has achieved fringes on all 15 antennas
Future: Correlator covers 4 GHz

VLA Array Observations – HCOOH toward Orion KL

Observations of HCOOH and $HCOOCH_3$ at 43 GHz have shown much the same morphology as is seen at 1 mm with BIMA

Hollis et al. 2003 showed the distribution of HCOOH (greyscale) at 7 cm was very similar to the distribution to the HCOOH distribution at 1 mm…thus evidence of HCOOH tracing a shock region.

EVLA promises far better results, mostly owing to the improved correlator.



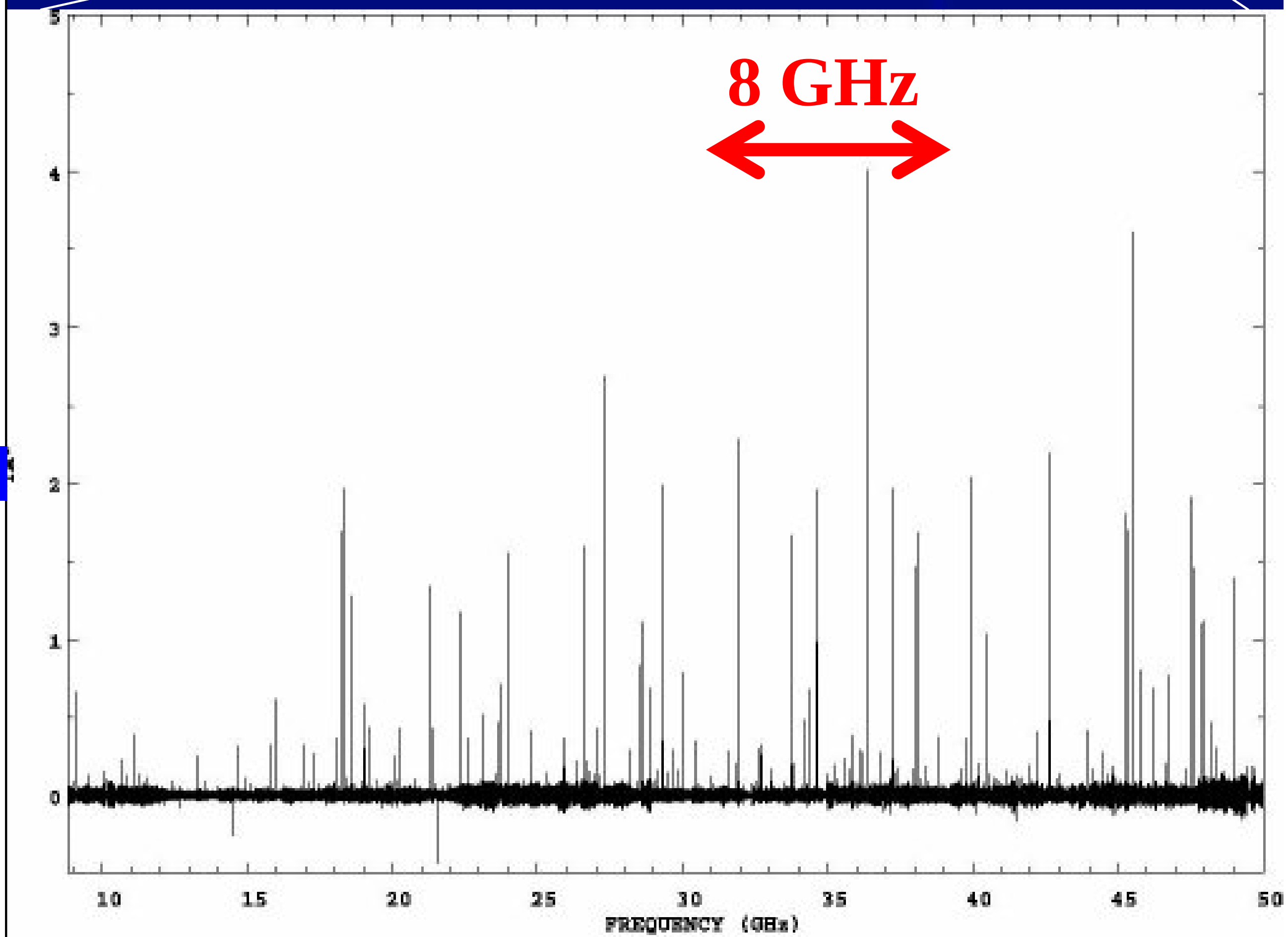
Remijan 2006

Hundreds of Spectral Lines

- Kaifu, et al., TMC-1, 2004.
- Nobeyama spectral scan.
- 414 lines (8 to 50 GHz)
- 38 species.
- Some likely to show Zeeman splitting.
- “D-array” EVLA
  - Resolution,
  - Spectral baseline stability,
  - Imaging.
- EVLA can observe 8 GHz at one time – an average of 80 lines --- at 1 km/s velocity res’n (30 GHz)
- EVLA Correlator can “target” many (~60) lines at once.

Sky Frequency Bands

1-2	2-4	4-8	8-12	12-18	18-27	27-40	40-50	GHz
L	S	C	X	U	K	Ka	Q	



EVLA

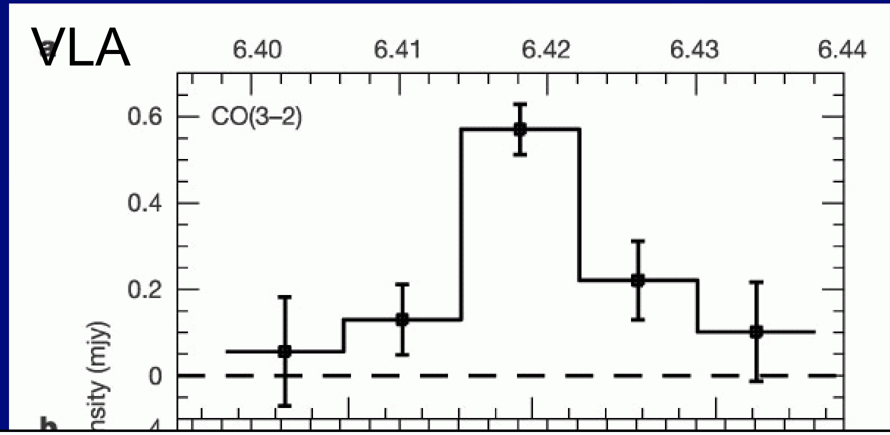
VLA: A Single integration resulted in a two point spectrum, 43 MHz resolution, several needed for line profile (and to discover the correct z!).

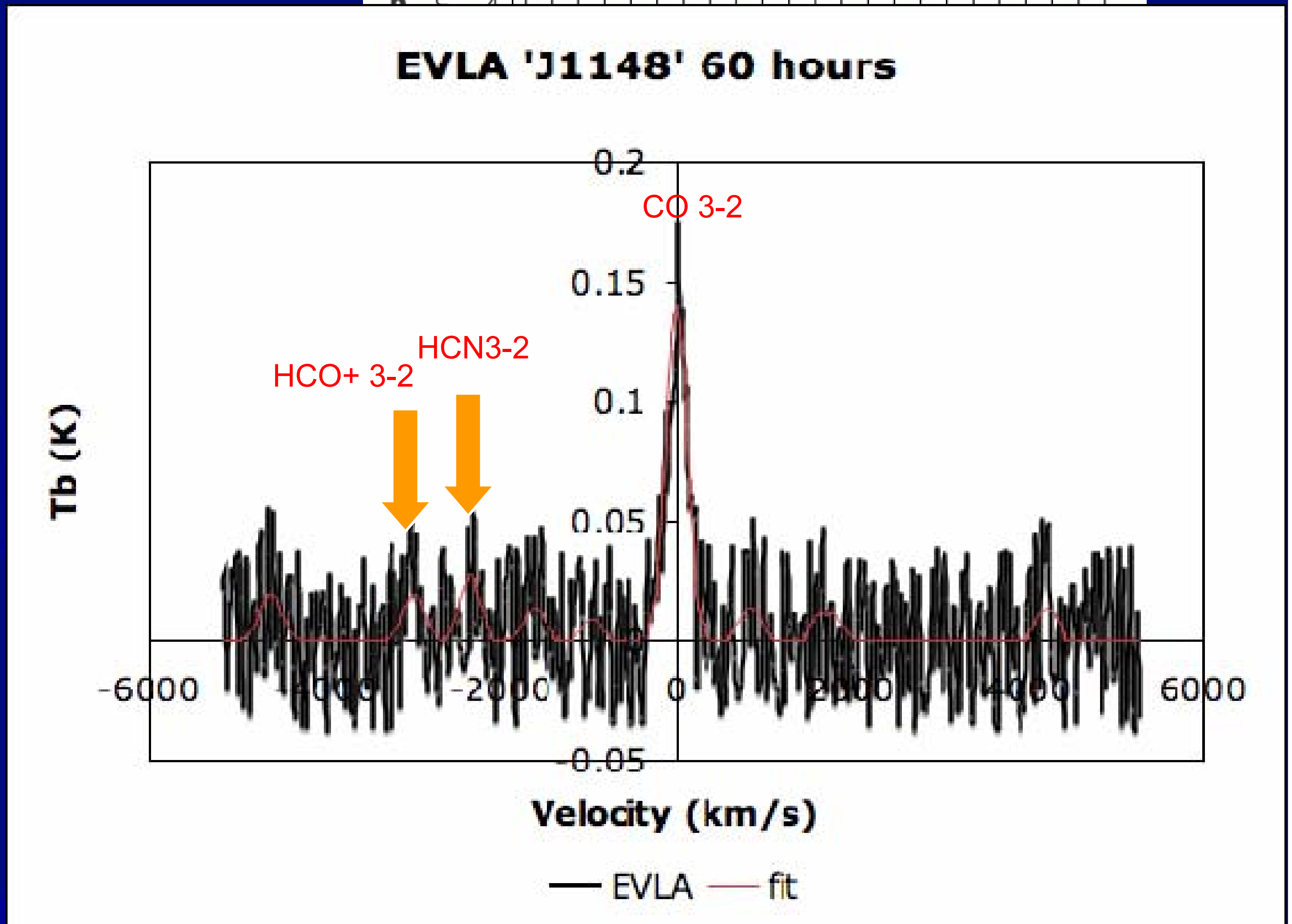
EVLA:

•Single integration covers up to 8 GHz (5.1 GHz shown, 10 MHz resolution)

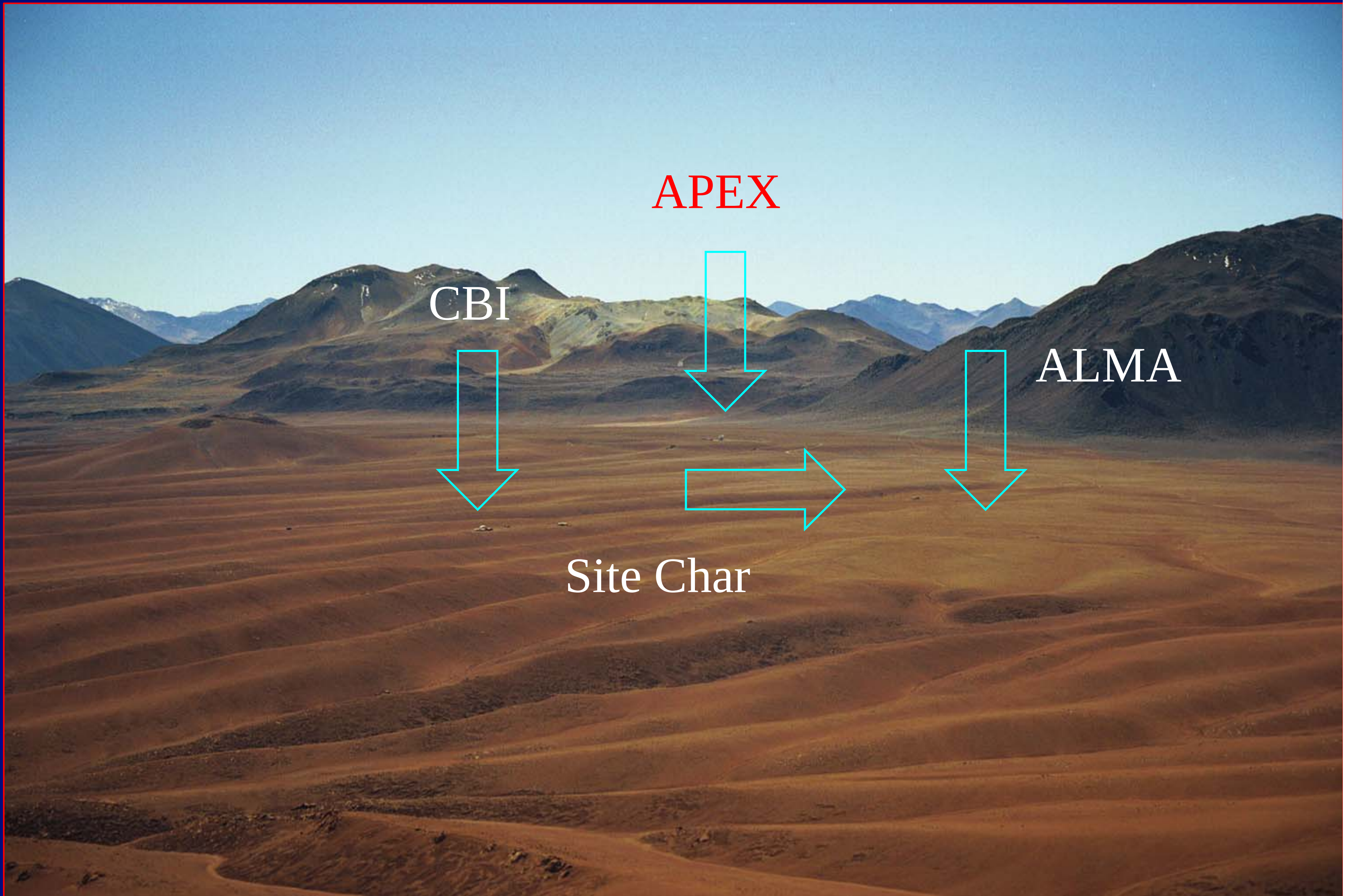
•Single integration covers the entire 870 micron 'Band' as seen from beneath Earth's atmosphere.

•EVLA II (not funded) brings 'E' array for short spacings.





ALMA: Coming Now to its 5000m Chajnantor site



43km Road From CH23 to AOS Complete

43km Road From CH23 to AOS Complete

Array Operations Center Technical Building Shell Complete April 2006

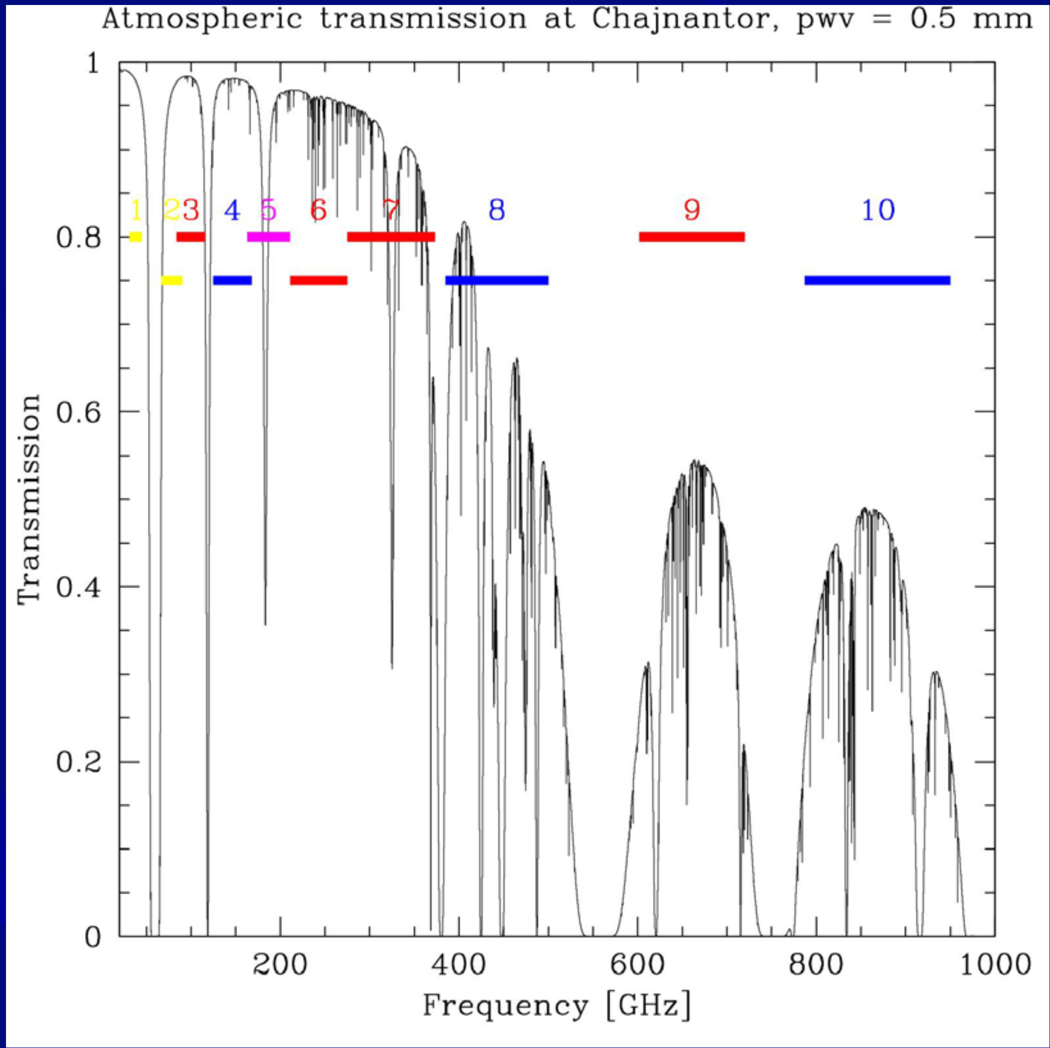
ALMA Camp Complete for 1.5 years

Summary of detailed requirements

Frequency	30 to 950 GHz (initially only 84-720 GHz fully instrumented)
Bandwidth	8 GHz both polzns, fully tunable but tunerless
Spectral resolution	31.5 kHz (0.01 km/s at 100 GHz)
Angular resolution	30 to 0.015” at 300 GHz--more than 20 configurations: beam matching for different lines
Dynamic range	10000:1 (spectral); 50000:1 (imaging)
Flux sensitivity	0.2 mJy in 1 min at 345 GHz (median conditions); total power flux recovered.
Antenna complement	Up to 64 antennas of 12m diameter, plus compact array of 4 x 12m and 12 x 7m antennas
Polarization	All cross products simultaneously

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, 1.5mm=B5)
- ❖2 polzns x DSB x 8 GHz (.6mm=B8, .45mm=B9, .35mm=B10)

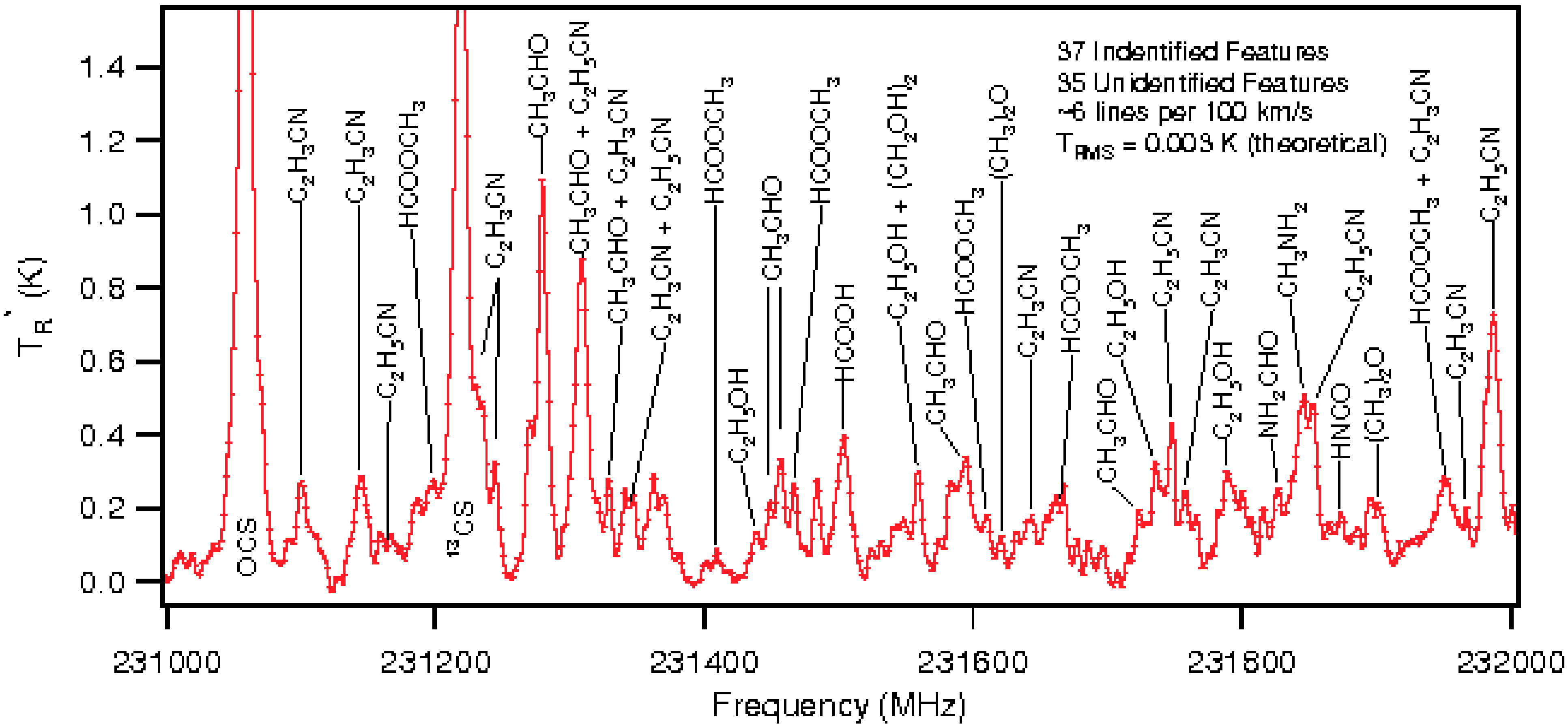


Receivers/Front Ends

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	DSB	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, B4, B6, B7, B8, B9 receivers passed CDR, 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 0.015" 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 53 up to 67, three antennas in hand meet all specifications

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 new ESA publication *Dusty and Molecular Universe* on ALMA and Herschel.

General Science Requirements

General Science Requirements, from ALMA Project Plan v2.0:

“ALMA should provide astronomers with a general purpose telescope which they can use to study at a range of angular resolutions millimeter and submillimeter wavelength emission from all kinds of astronomical sources. ALMA will be an appropriate successor to the present generation of millimeter wave interferometric arrays and will allow astronomers to:

Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z=10;

Trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies throughout the history of the Universe;

Reveal the kinematics of obscured galactic nuclei and Quasi-Stellar Objects on spatial scales smaller than 300 light years;

Image gas rich, heavily obscured regions that are spawning protostars, protoplanets and pre-planetary disks;

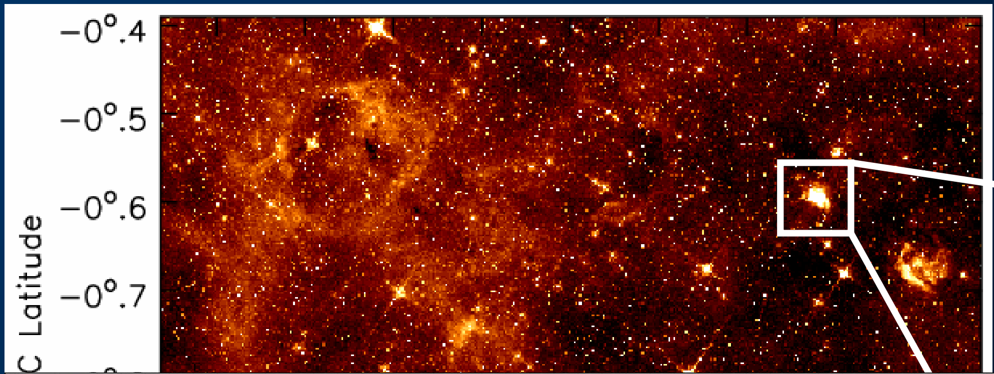
Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;

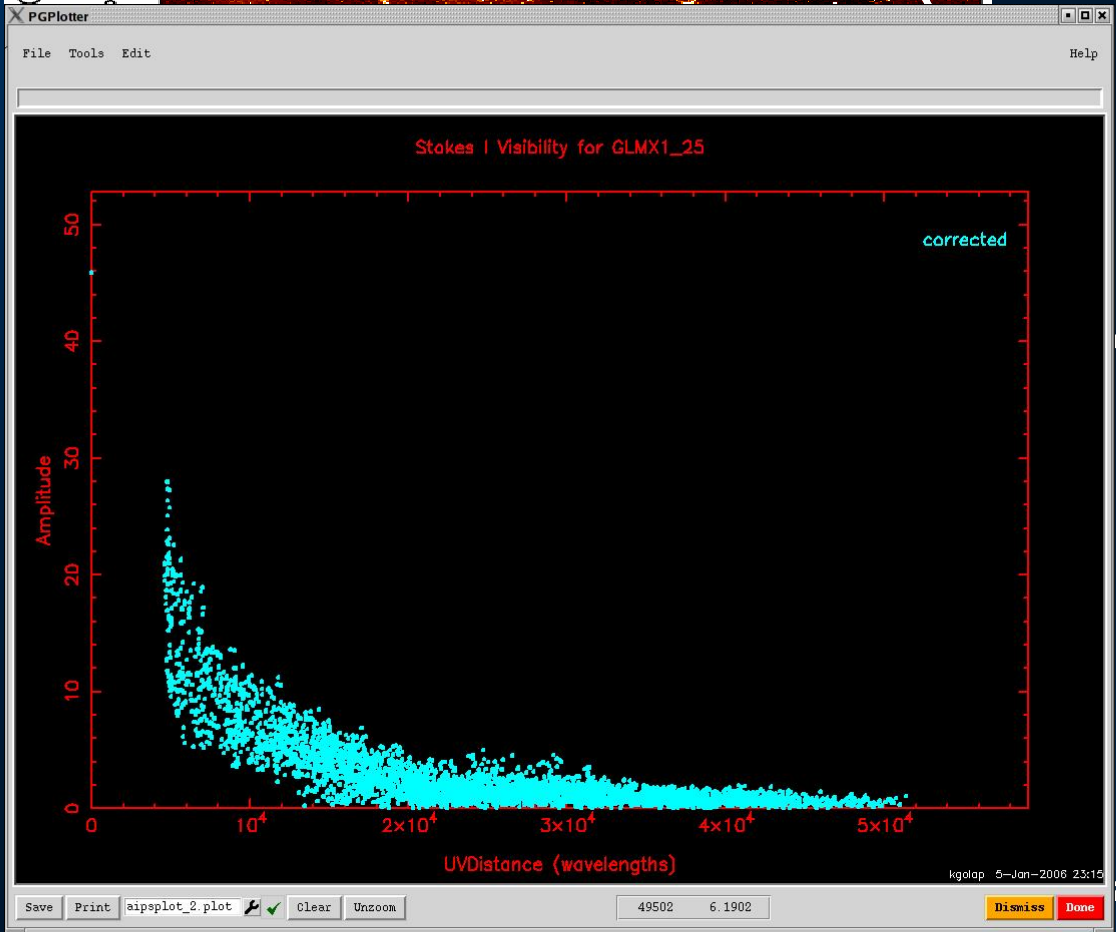
Obtain unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper Belt Objects in the solar system along with images of the planets and their satellites;

Image solar active regions and investigate the physics of particle acceleration on the surface of the sun.

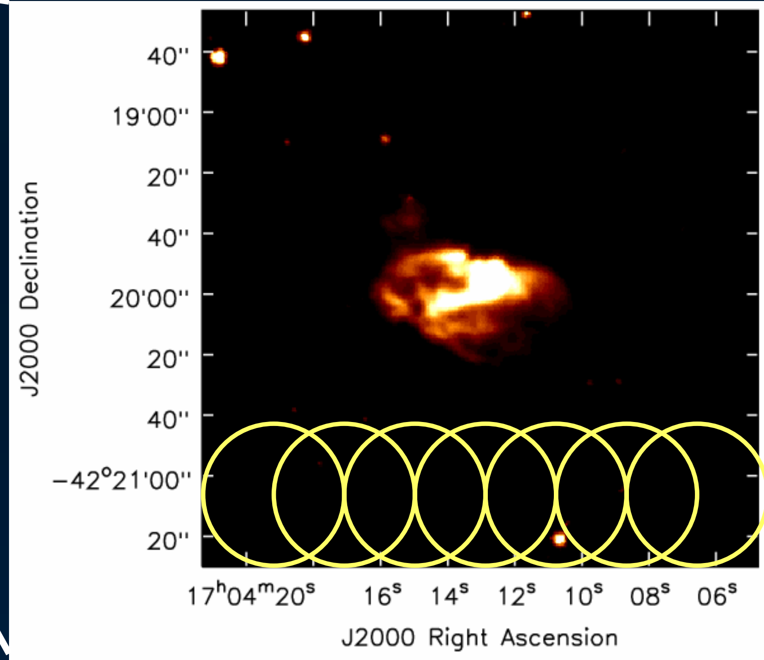
No instrument, other than ALMA, existing or planned, has the combination of angular resolution, sensitivity and frequency coverage necessary to address adequately these science objectives.“

Model Image



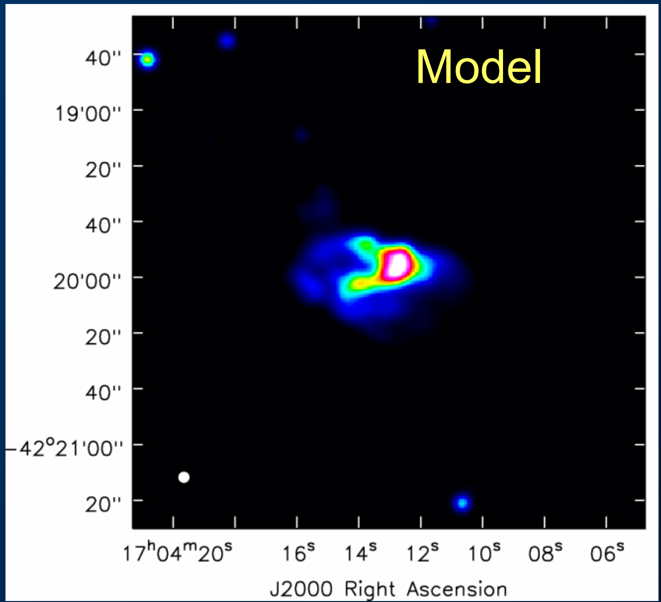


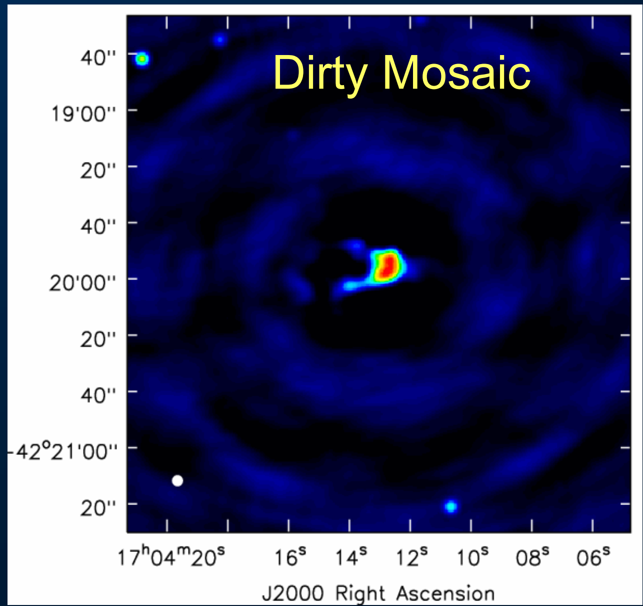
Spitzer GLIMPSE 5.8 μm image

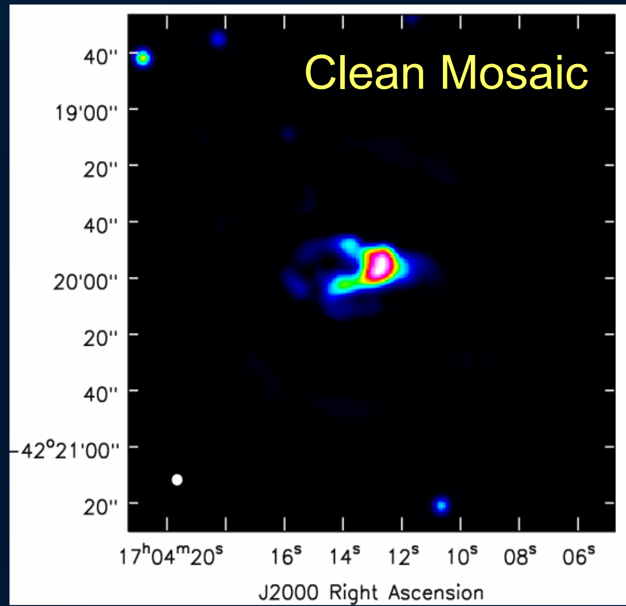


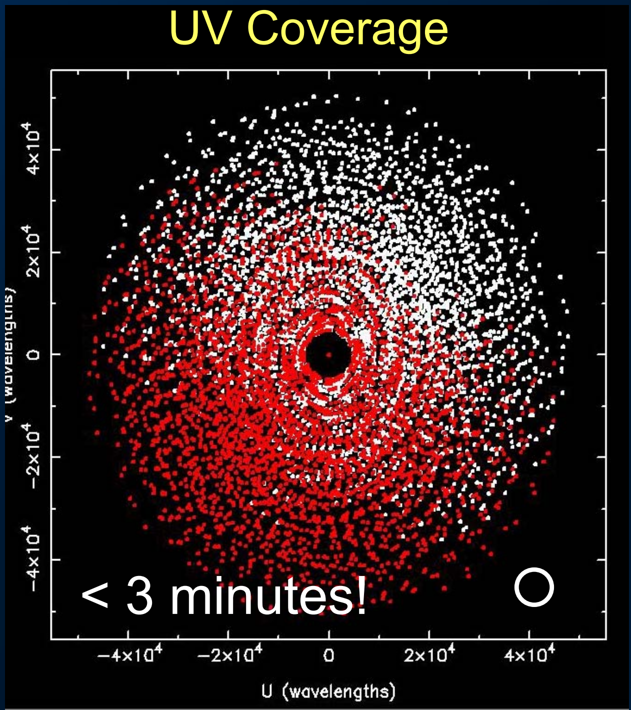
- Aips++/CASA simulation of ALMA with 50 antennas in the compact configuration (< 150 m)
- 100 GHz 7 x 7 pointing mosaic
- +/- 2hrs

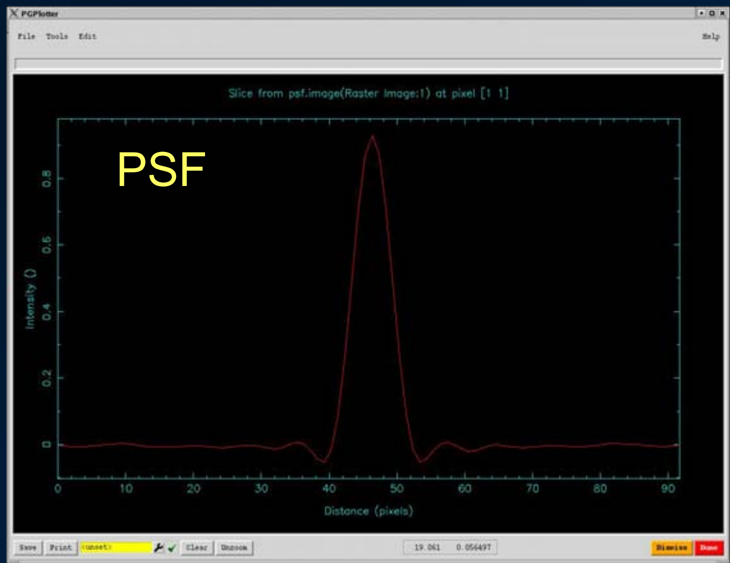
50 Antenna ALMA CLEAN results

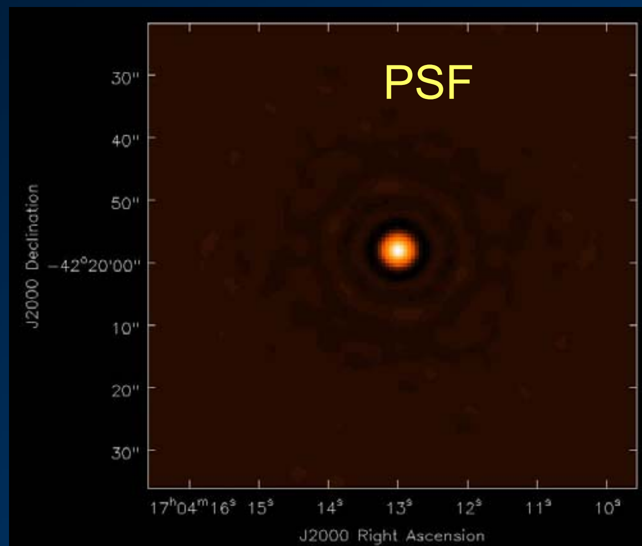












Missing Short Spacings

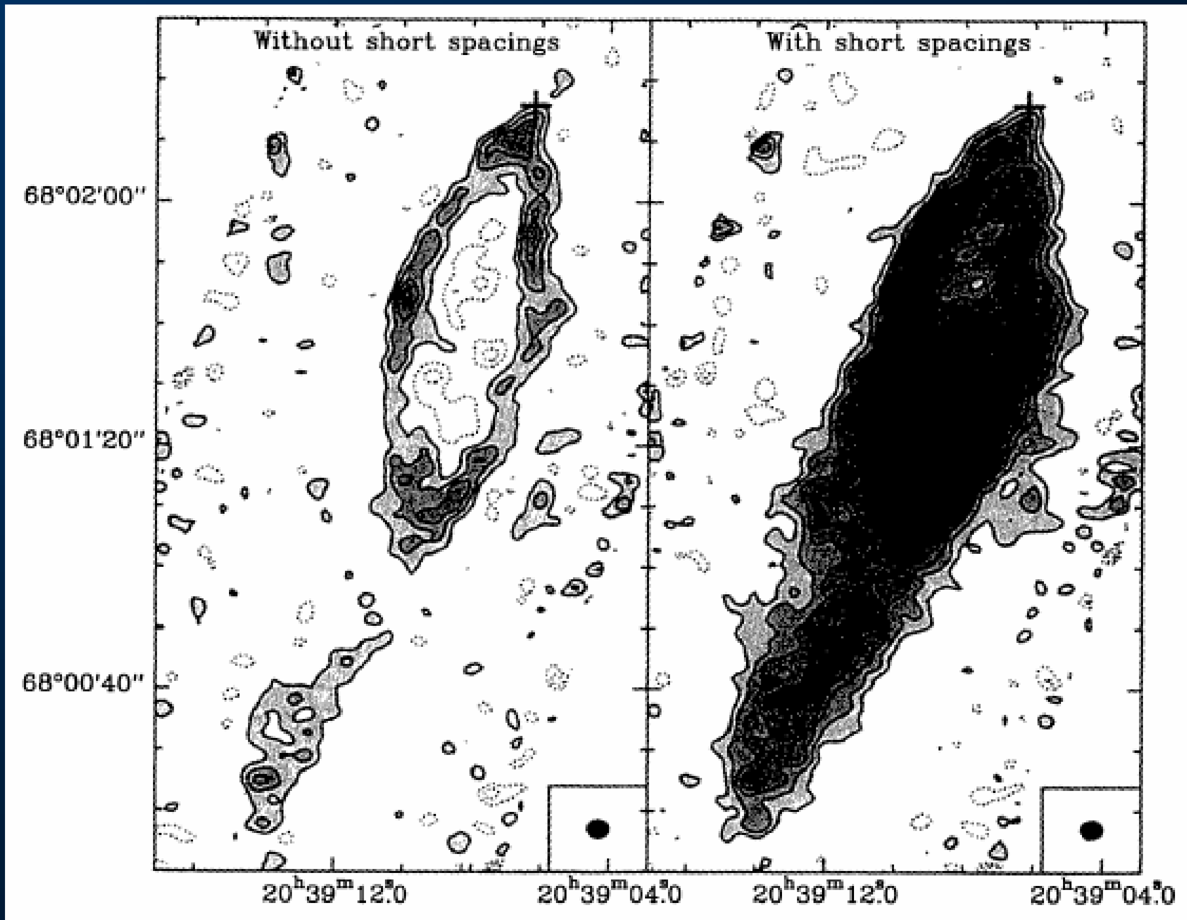
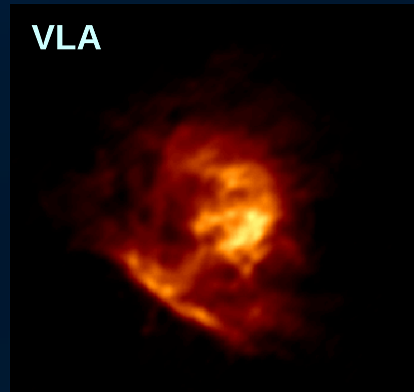
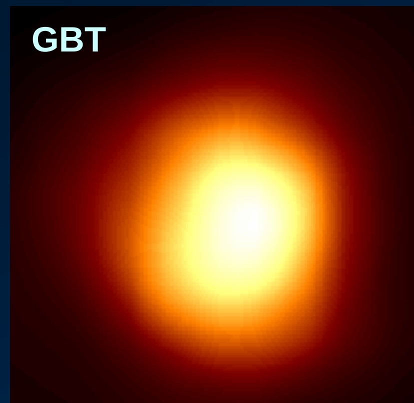
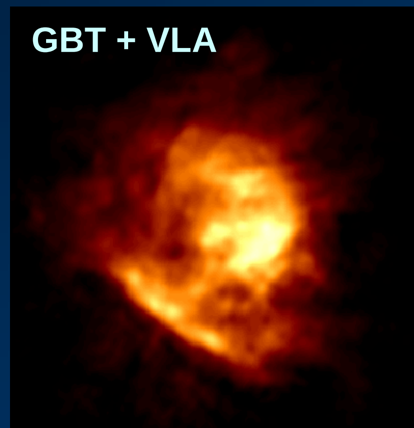


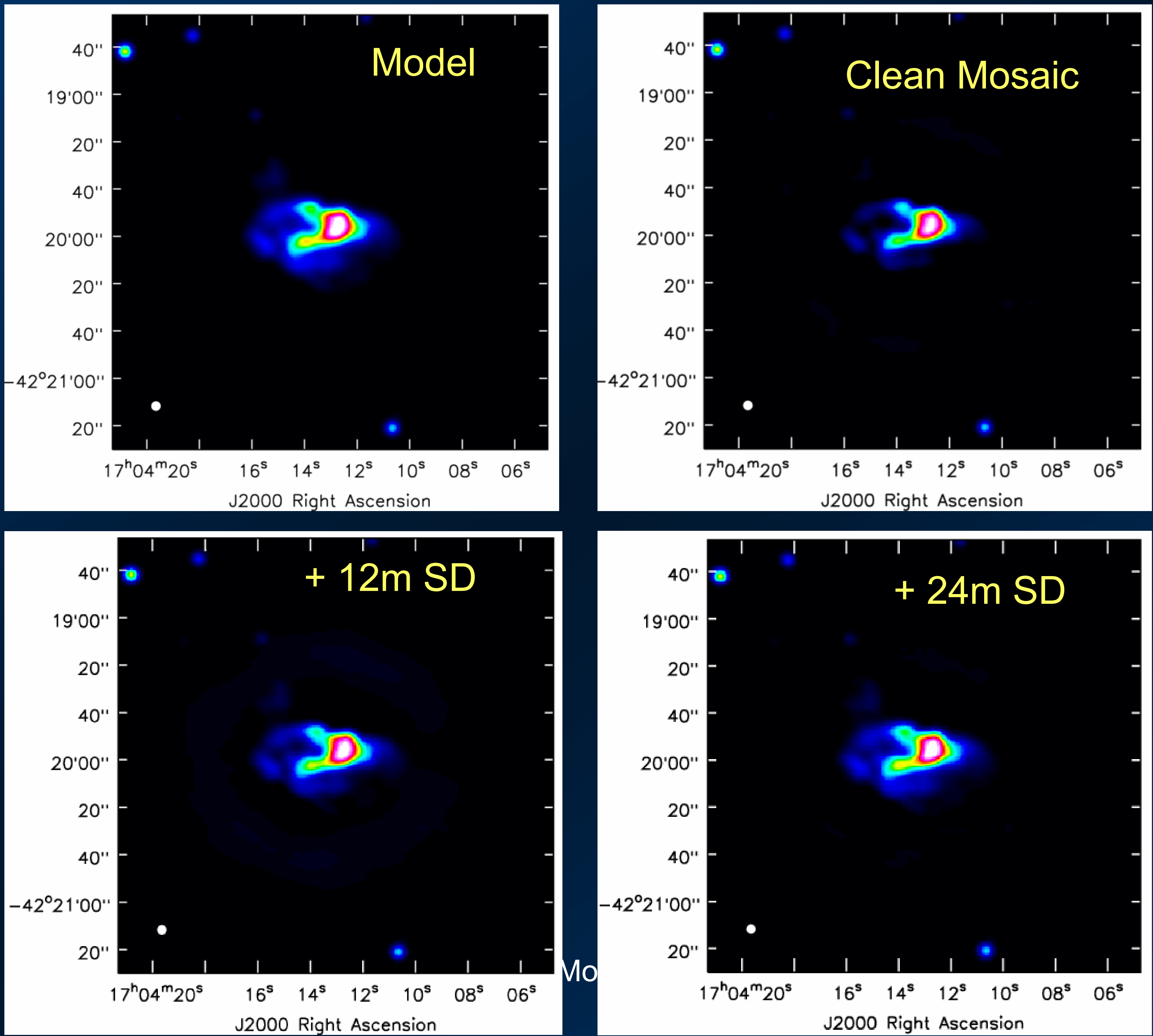
Figure 3. 10 field mosaic of the CO J = 1 → 0 emission in the southern lobe of the L 1157 molecular outflow. The two panels represent





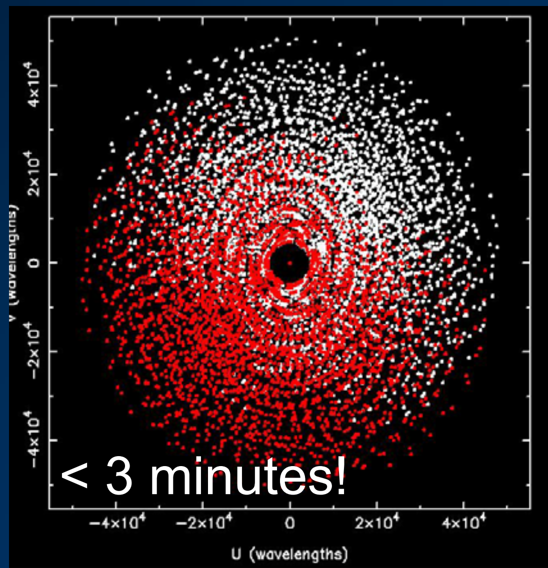


50 antenna + SD ALMA Clean results



Mosaicing Considerations

- ❖ Each pointing ideally should have similar U-V coverage and hence synthesized beams – similar S/N is more important
- ❖ Nyquist sampling of pointings
  - ➢ On-the-fly mosaicing can be more efficient at lower frequencies
- ❖ Small beams imply many pointings
- ❖ At higher frequencies weather conditions can change rapidly
  - ➢ Push to have very good instantaneous snapshot U-V coverage
- ❖ Polarimetry even more demanding for control of systematics due to rotation of polarization beam on sky
- ❖ Accurate primary beam characterization
  - ➢ Account for heterogeneous array properties



Total Power Considerations

- Getting Single Dish (SD) zero-spacing tricky because it requires
  - Large degree of overlap in order to calibrate with interferometric data
  - Excellent pointing accuracy which is more difficult with increasing dish size
  - On-the-fly mapping requires rapid telescope movement
  - SD Continuum calibration – stable, accurate, large throws

Solution:
The Atacama Compact Array

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

❖Started planning late April 2003; outline + teams complete early July; submitted December 2003; updated periodically (another update period imminent)

❖>128 submissions received involving >75 astronomers

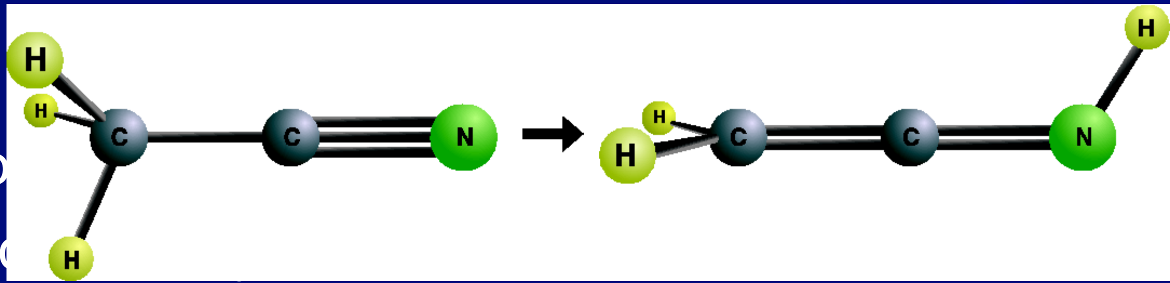
❖Review by ASAC members completed; comments included

Current version of DRSP on Website at:

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

New submissions continue to be added.

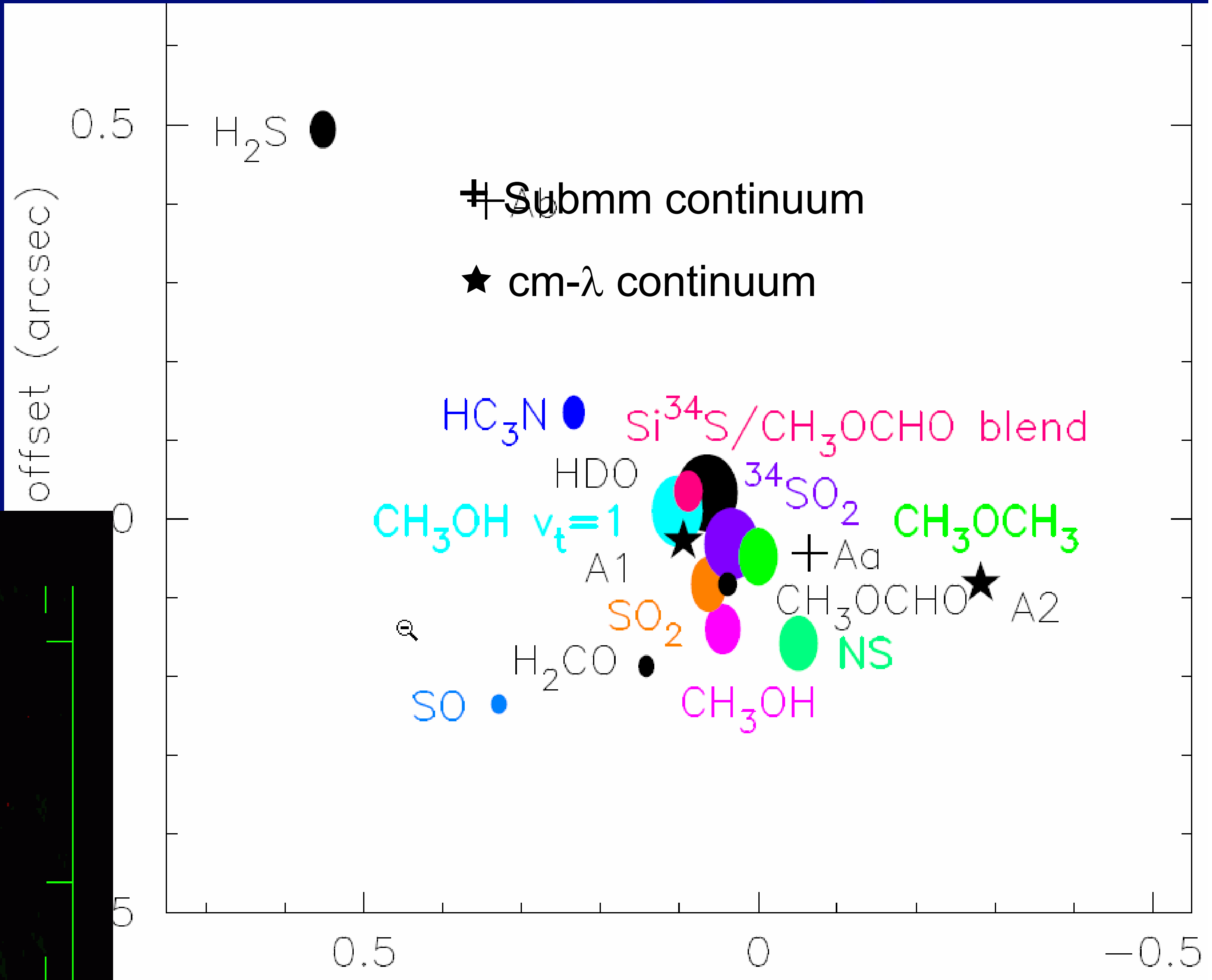
DRSPs with Astrochemical Focus

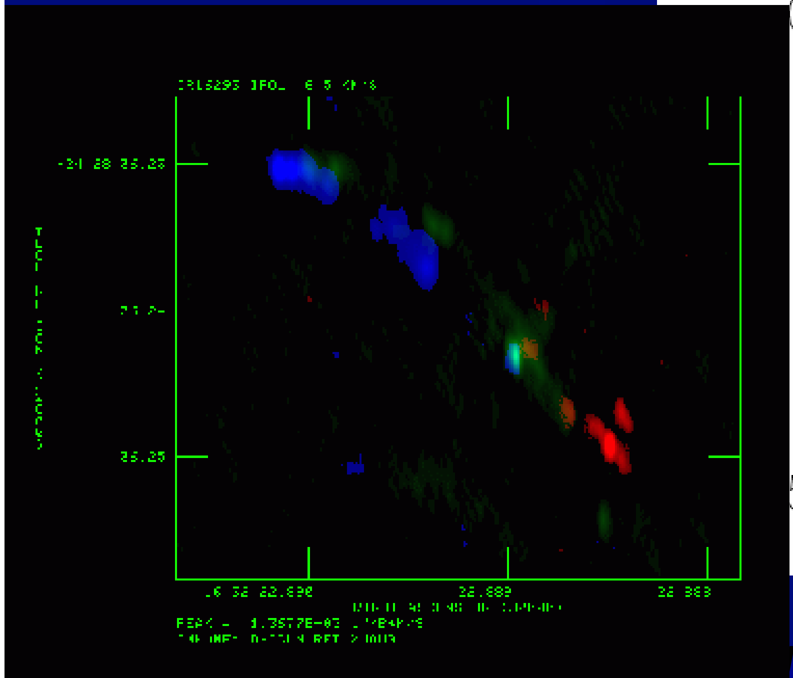


2.3 Chemistry o

- 2.3.1 Chemi van Dishoeck 585
- 2.3.2 Depletion of molecules in low-mass cores Tatematsu 216
- 2.3.3 Chemical differentiation in sf-regions Wright 134
- 2.3.4 Unbiased line surveys of high mass star forming regions Schilke 612
- 2.3.5 Low freq. spectral survey aimed at complex organics Turner 35
- 2.3.6 Survey of HCO+ absorption in diffuse clouds Lucas 80
- 2.3.7 Absorption line survey Lucas 57
- 2.3.8 Chemical Enhancements in Outflows Plume 16
- 1.7.1 The Chemical Anatomy of Nearby Galaxies Meier/Turner 144

IRAS16293-2422





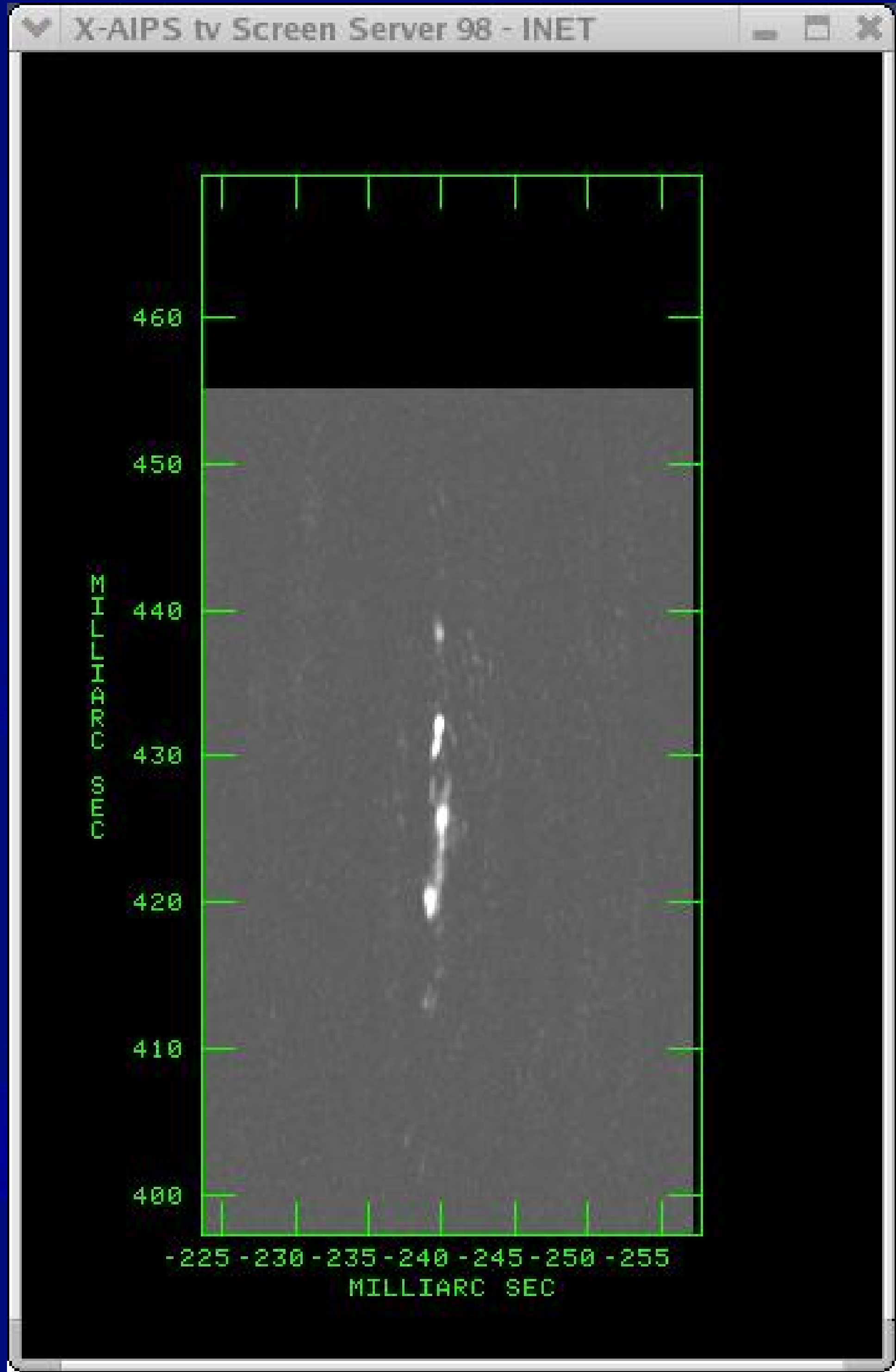
...ler, Brogan, et al. (2005)

It Moves!

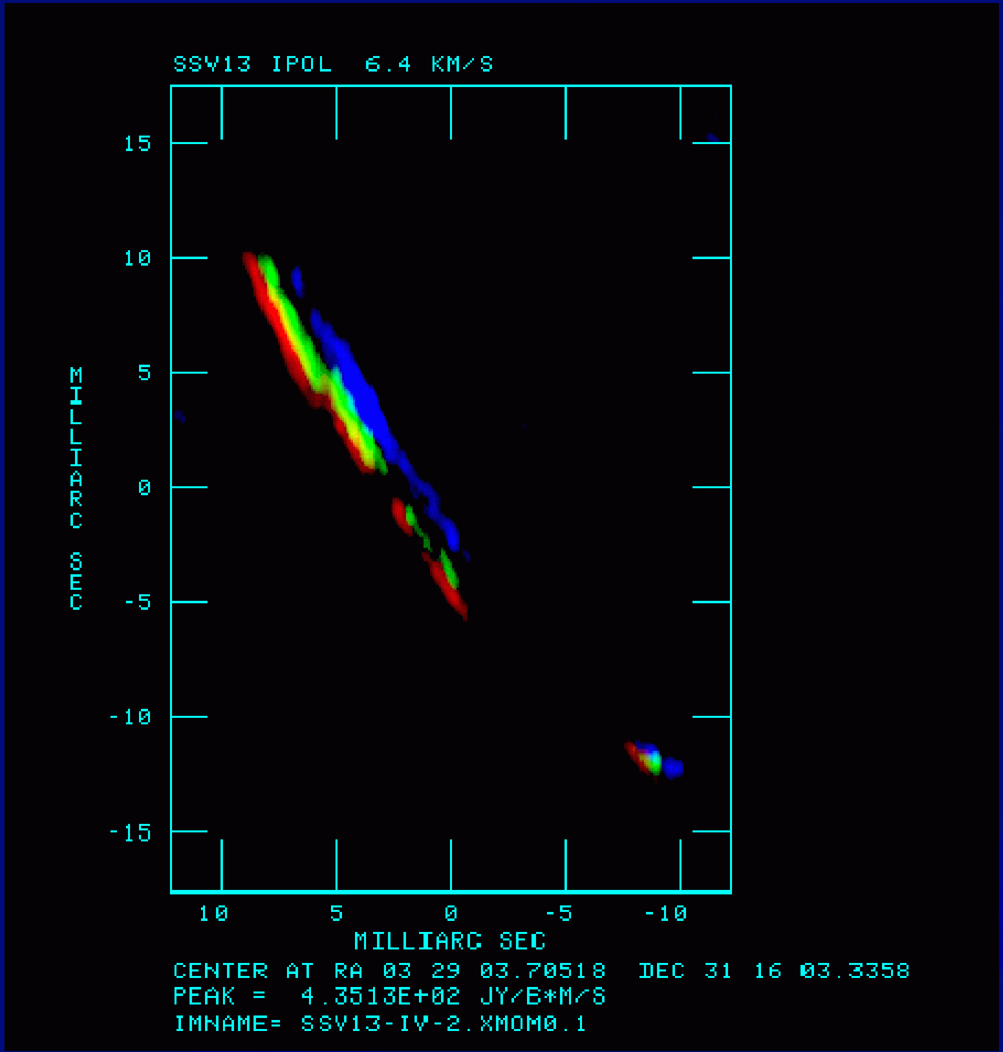
Water masers in NGC1333 4B (north):

A flow in motion

- Each shock lasts <2 months
- Any parcel of gas must be exposed to a succession of shocks
- ALMA will reveal the complex chemical evolution of these shocks.
- Excellent brightness temperature sensitivity
- Excellent, near-VLBI, resolution.



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. 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.

Including the radial velocity offset, a space velocity of 13.7 km/s is calculated at an inclination of 6 degrees from the plane of the sky.

These structures apparently represent water emission from interstellar shocks driven by the outflow from SVS13.

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:

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^+

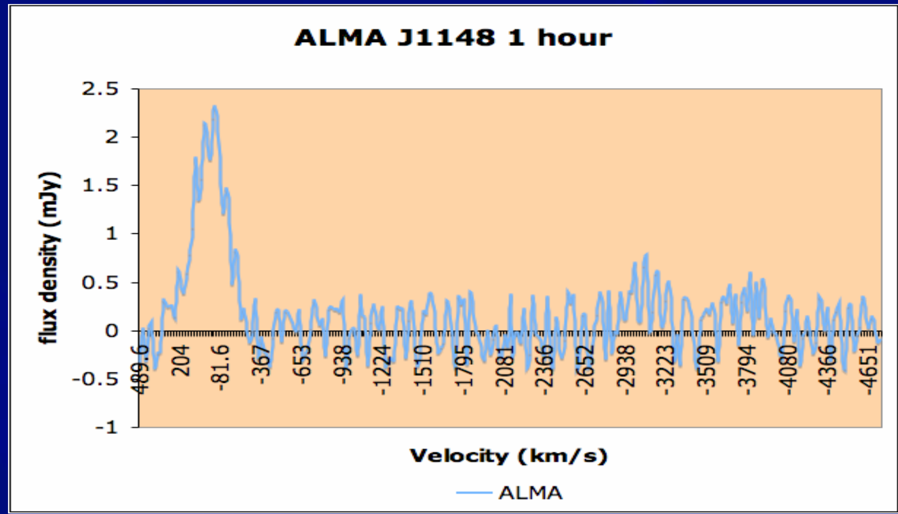
Brightness Temperature Sensitivity

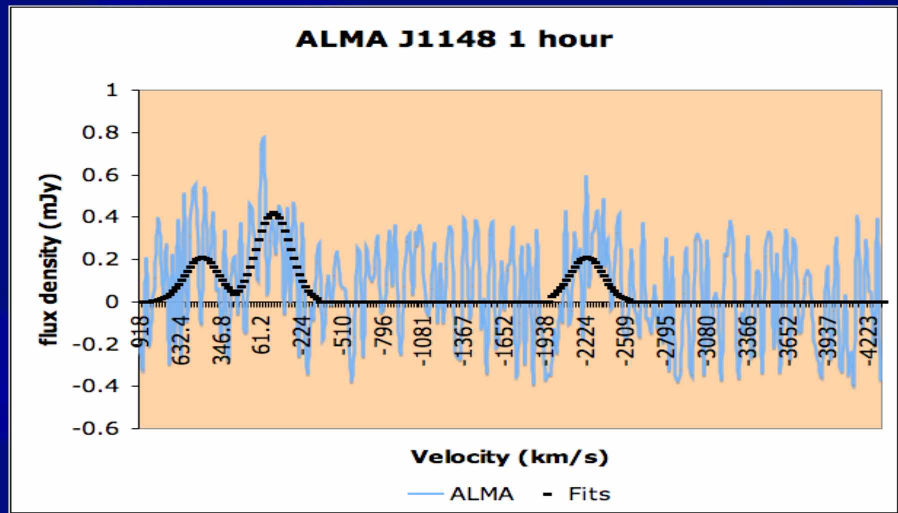
1 min, AM 1.3, 1.5mm, *0.35 PWV, 1 km/s

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
1500*	1.4	57	3600	140000

J1148+5251: an EoR paradigm with ALMA

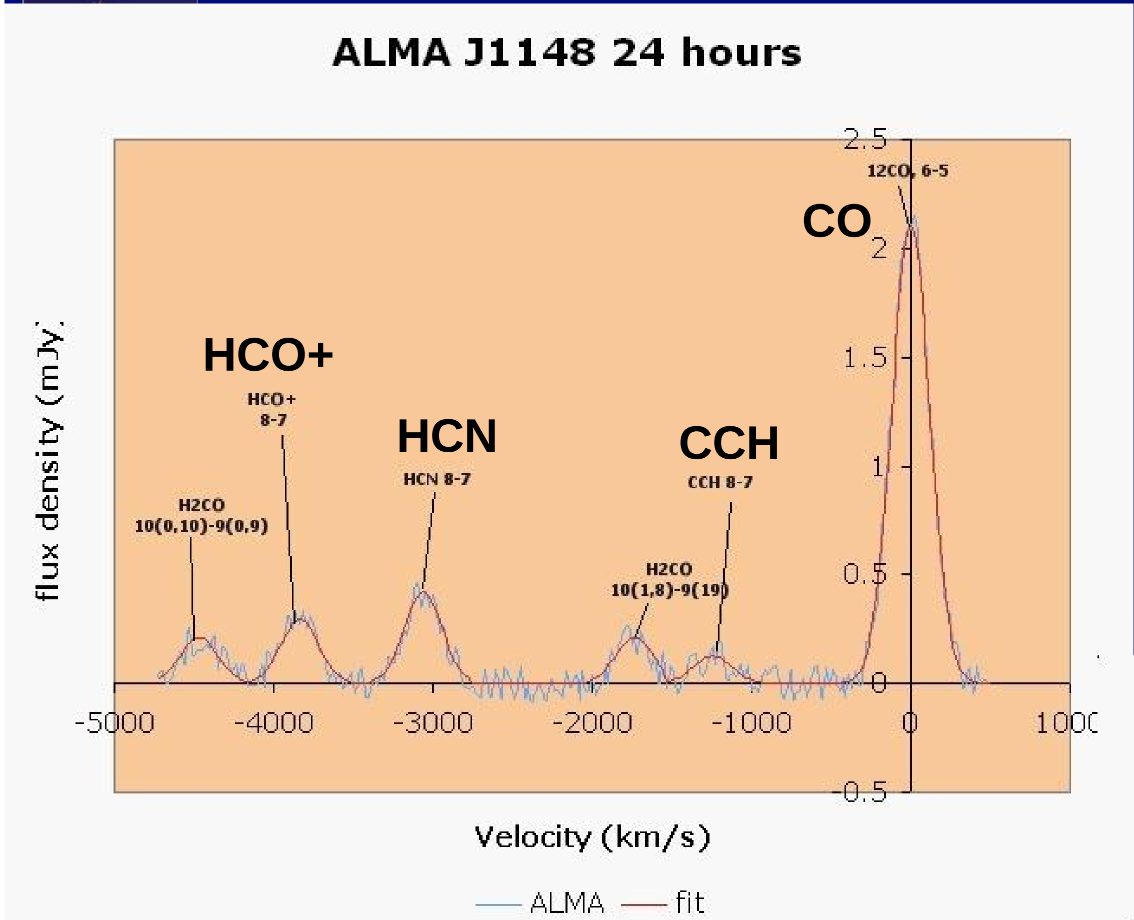
CO J=6-5





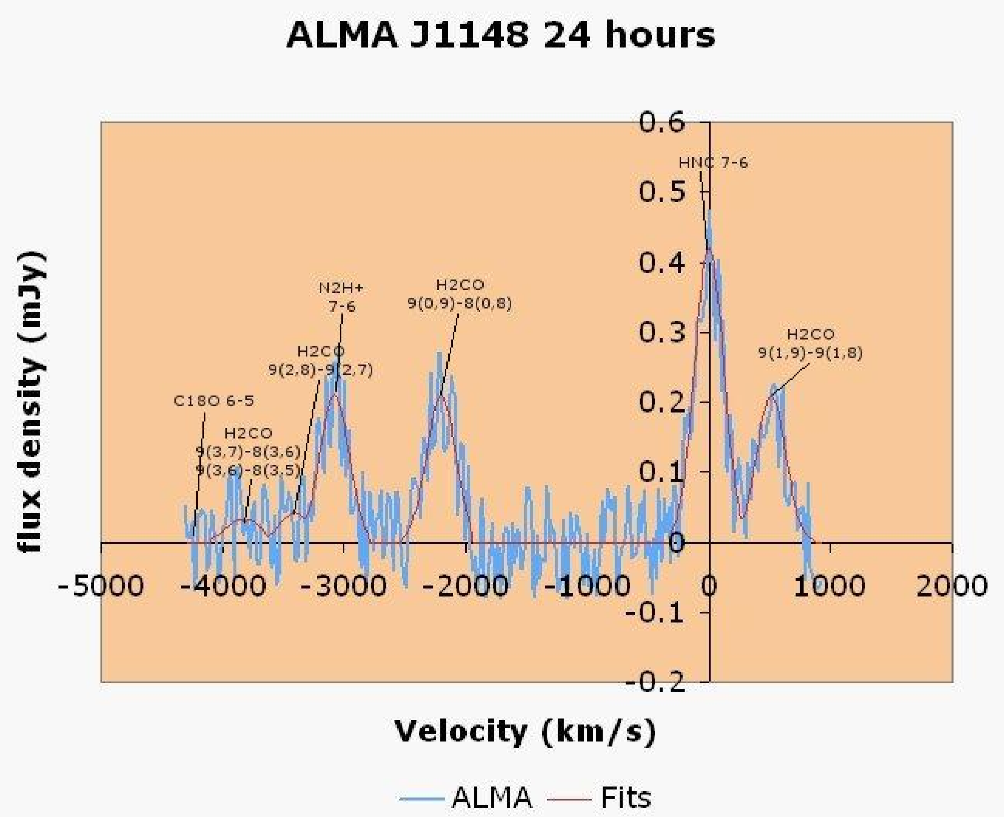
- Wrong declination (though ideal for Aarhus)!
- But…
- High sensitivity
  - 12hr 1σ 0.2mJy
- Wide bandwidth
  - 3mm, 2 x 4 GHz IF
  - Default 'continuum' mode
  - Top: USB, 94.8 GHz
    - CO 6-5
    - HCN 8-7
    - HCO+ 8-7
    - H2CO lines
  - Lower: LSB, 86.8 GHz
    - HNC 7-6
    - H2CO lines
    - $C^{18}O$ 6-5
    - H_2O 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

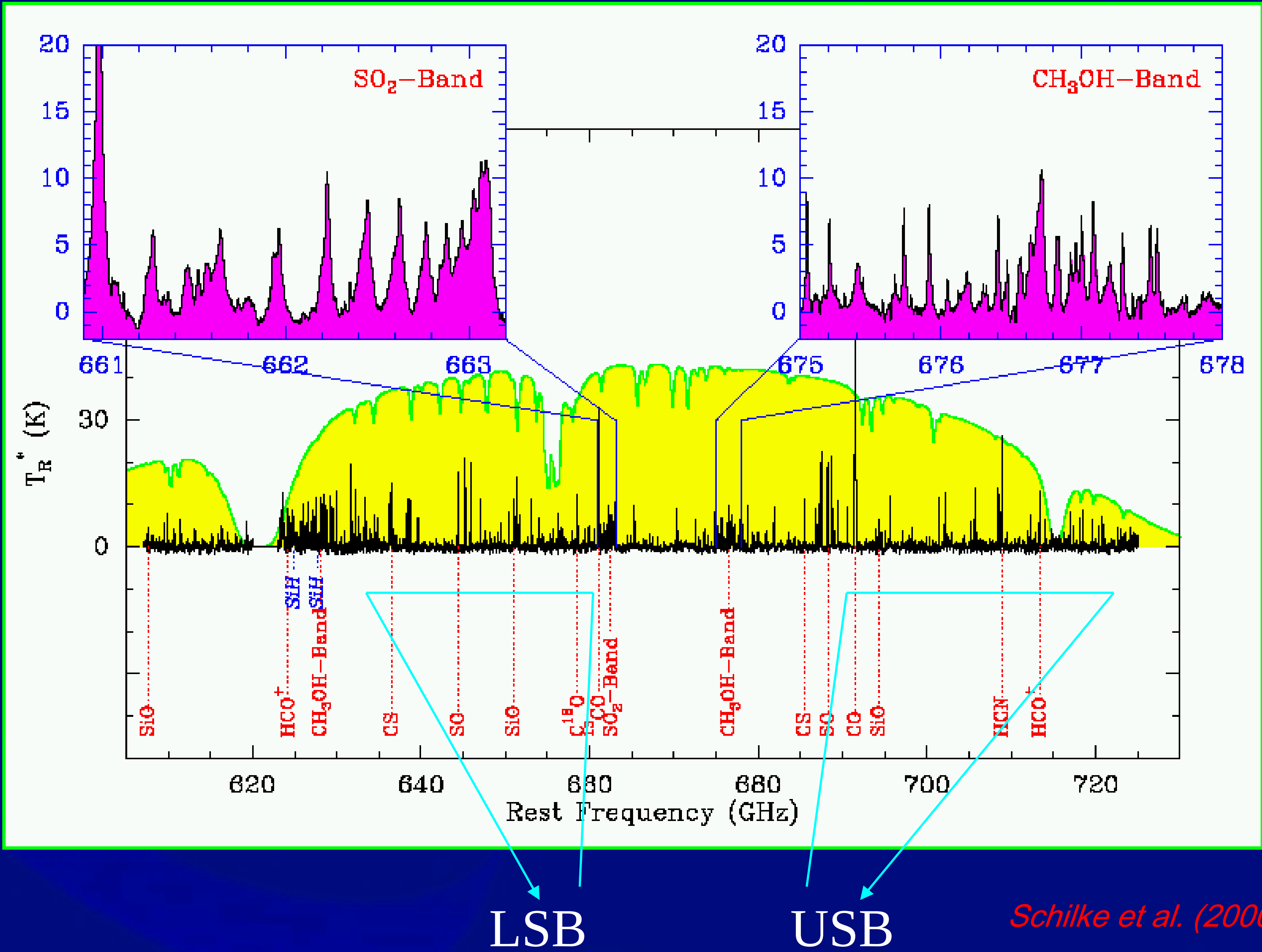


N. B. Atomic line diagnostics

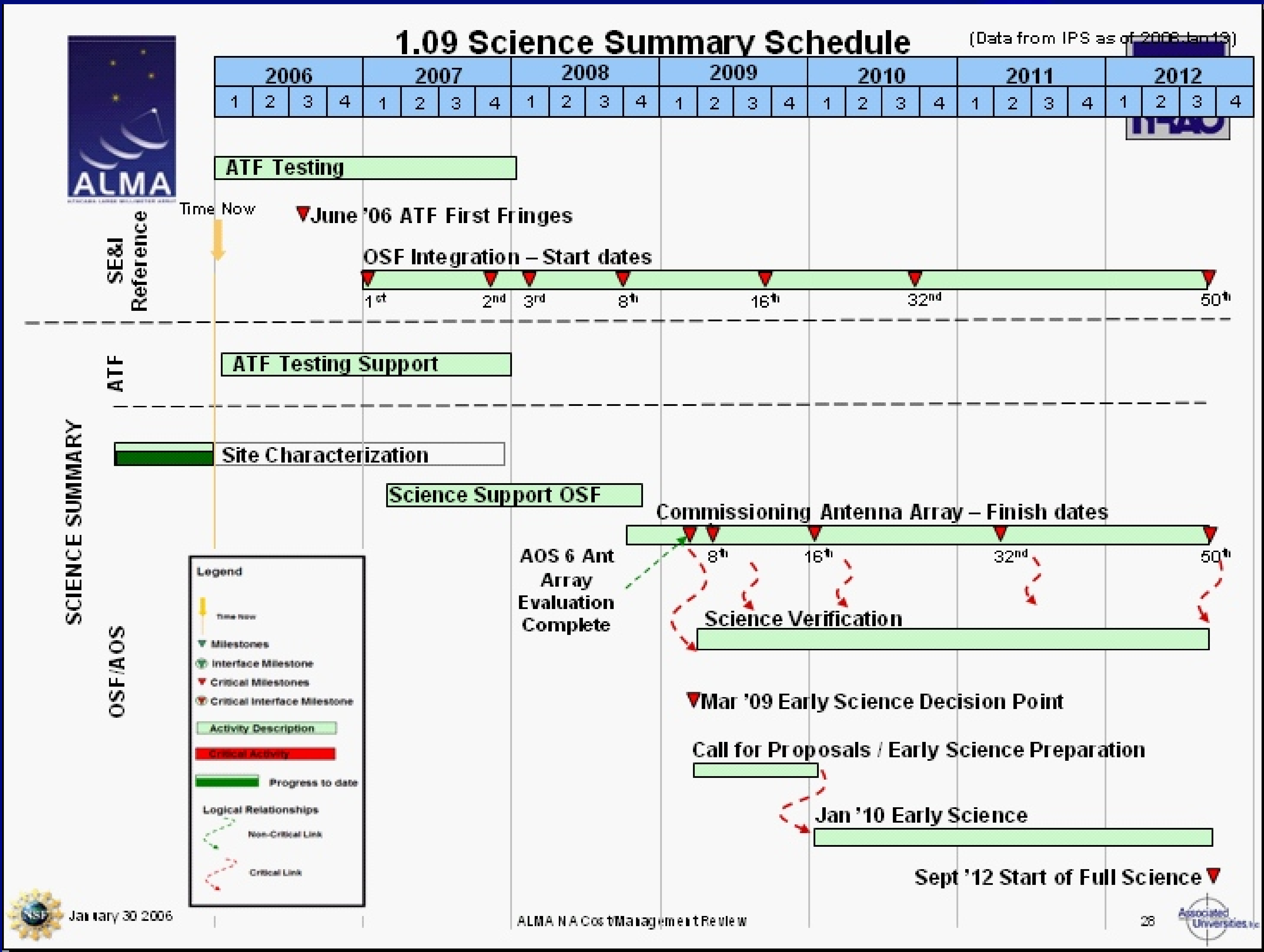
[C II] emission in **60sec** (10σ) at 256 GHz
[O I] 63 μm at 641 GHz
[O I] 145 μm at 277 GHz
[O III] 88 μm at 457 GHz
[N II] 122 μm at 332 GHz
[N II] 205 μm at 197 GHz
HD 112 μm at 361 GHz

Bandwidth Compression

Nearly a whole band scan in one spectrum



Schilke et al. (2000)



1.09 Science Summary Schedule
(Data from IPS as of 2006 Jan 13)
2006
2007
2008
2009
2010
2011
2012
1 2 3 4
SE&I Reference
ATF Testing
Time Now
June '06 ATF First Fringes
OSF Integration – Start dates
1st
2nd
3rd
8th
16th
32nd
50th
SCIENCE SUMMARY
ATF
ATF Testing Support
OSF/AOS
Site Characterization
Science Support OSF
Commissioning Antenna Array – Finish dates
AOS 6 Ant Array Evaluation Complete
8th
16th
32nd
50th
Science Verification
Mar '09 Early Science Decision Point
Call for Proposals / Early Science Preparation
Jan '10 Early Science
Sept '12 Start of Full Science
Legend
Time Now
Milestones
Interface Milestone
Critical Milestones
Critical Interface Milestone
Activity Description
Critical Activity
Progress to date
Logical Relationships
Non-Critical Link
Critical Link
January 30 2006
ALMA NA Cost/Management Review
28

Summary

- First antenna in Chile within a year
- Site, electronics and collecting area provide sensitivity
- Wide bandwidths combined with a flexible correlator provide spectral coverage
- Multiple spectral lines quickly accessible
  - Large surveys possible (but large area surveys relatively slow)
  - Robust excitation, abundance analyses possible
  - Imaging of emission regions provides dynamical information

European ALMA News (www.eso.org),
ALMA/NA Biweekly Calendar (www.cv.nrao.edu/~awootten/mmaimcal/ALMACalendars.html)

ALMA
ATACAMA LARGE MILLIMETER ARRAY

www.alma.info

The Atacama Large Millimeter Array (ALMA) is an international astronomy facility. ALMA is a partnership between Europe, North America and Japan, in cooperation with the Republic of Chile. ALMA is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC), in Europe by the European Southern Observatory (ESO) and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), on behalf of Europe by ESO, and on behalf of Japan by the National Astronomical Observatory of Japan.