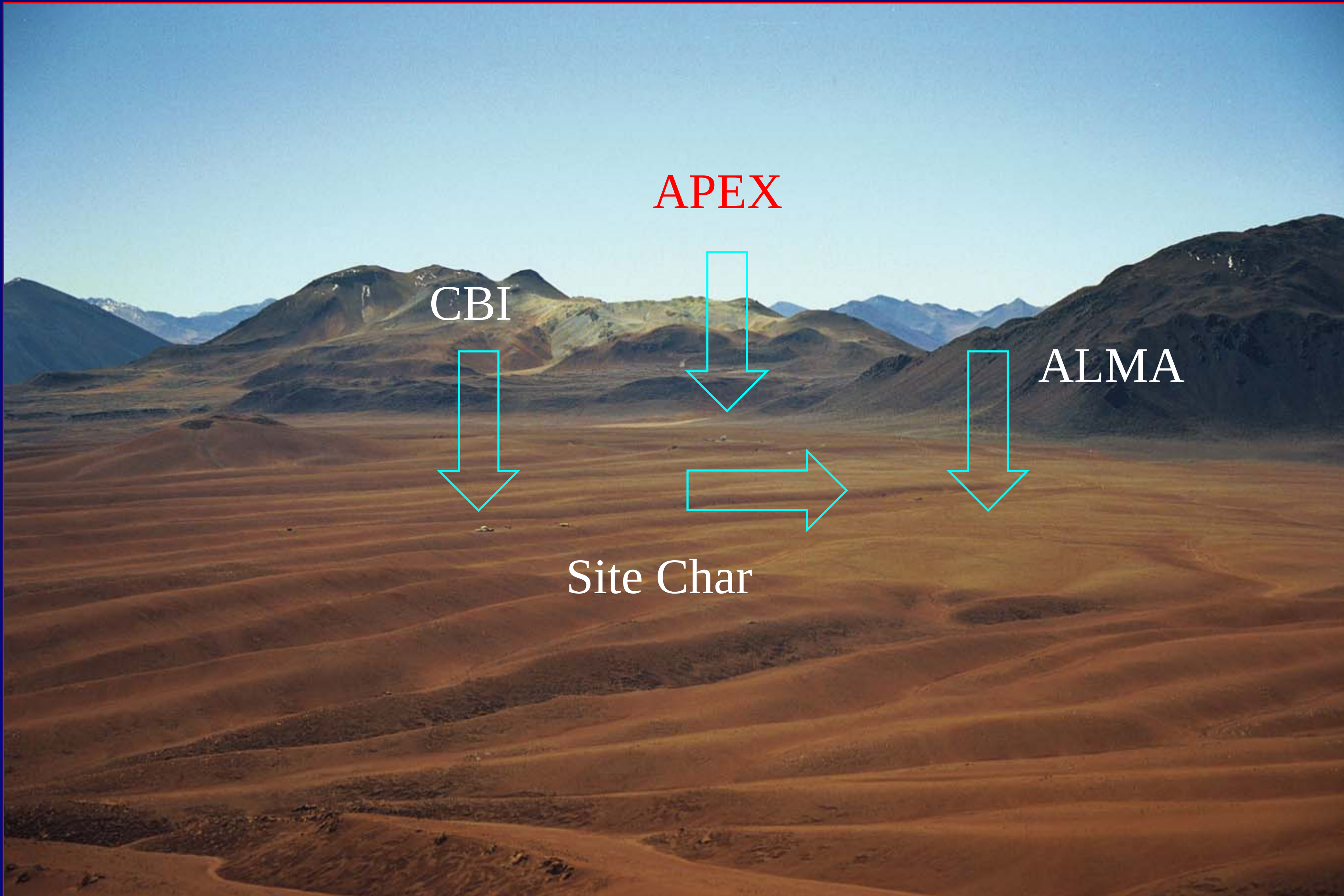
ALMA: Exploring the Outer Limits of Redshift

Al Wootten

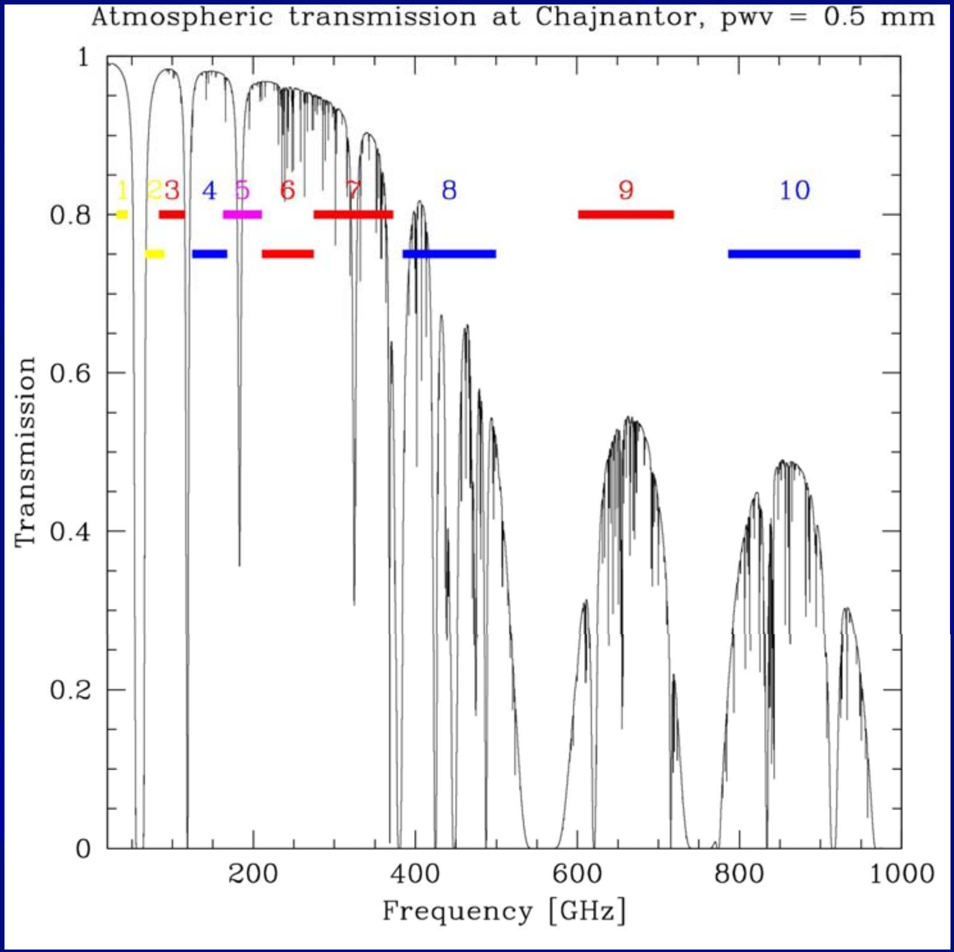
5000m Chajnantor site



Construction Since Town Meeting: Vertex Contractor's Area

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

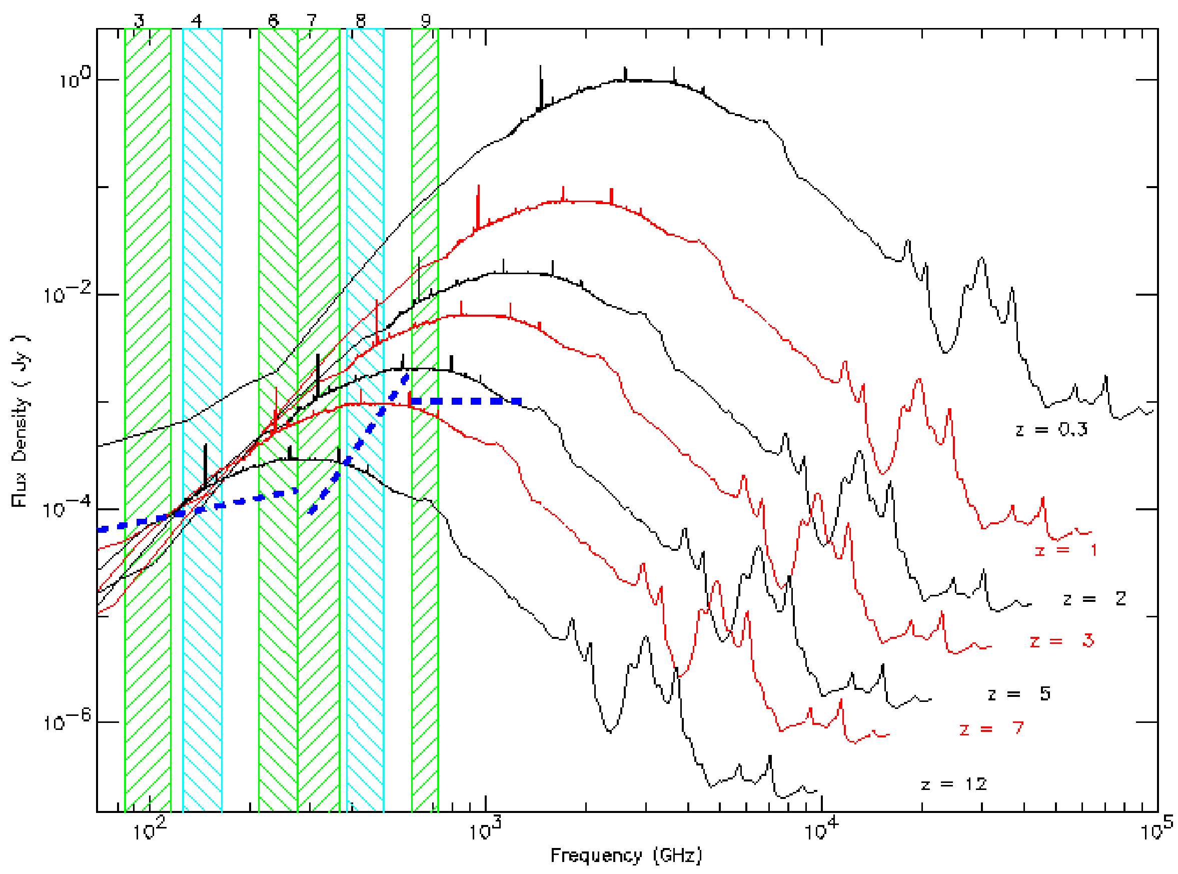
ALMA Band	Frequency Range	Receiver noise temperature		Mixing scheme	Receiver technology
		T_{Rx} over 80% of the RF band	T_{Rx} at any RF frequency		
1	31.3 – 45 GHz	17 K	28 K	USB	HEMT
2	67 – 90 GHz	30 K	50 K	LSB	HEMT
3	84 – 116 GHz	37 K	62 K	2SB	SIS
4	125 – 169 GHz	51 K	85 K	2SB	SIS
5	163 - 211 GHz	65 K	108 K	2SB	SIS
6	211 – 275 GHz	83 K	138 K	2SB	SIS
7	275 – 373 GHz	147 K	221 K	2SB	SIS
8	385 – 500 GHz	98 K	147 K	DSB	SIS
9	602 – 720 GHz	175 K	263 K	DSB	SIS
10	787 – 950 GHz	230 K	345 K	DSB	SIS

- **Dual, linear polarization channels:**
  - **Increased sensitivity**
  - **Measurement of 4 Stokes parameters**
- **183 GHz water vapour radiometer:**
  - **Used for atmospheric path length correction**

Infrared Luminous Galaxies

M82 from ISO, Beelen and Cox

- 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.



Hubble Deep Field

Rich in Nearby Galaxies, Poor in Distant Galaxies

Source: K. Lanzetta, SUNY-SB

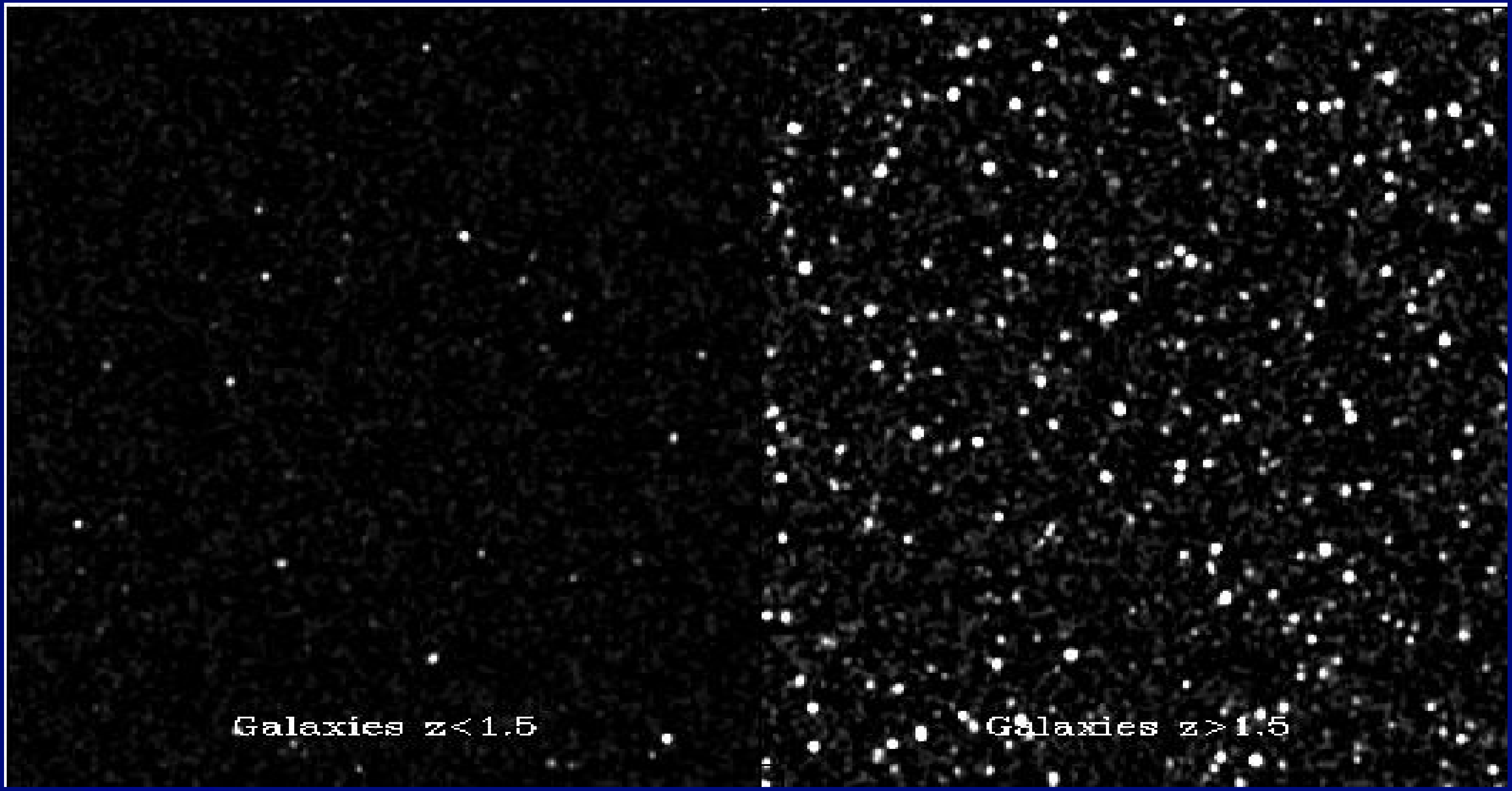
Nearby galaxies in HDF

Distant galaxies in HDF

ALMA Deep Field

Poor in Nearby Galaxies, Rich in Distant Galaxies

Source: Wootten and Gallimore, NRAO

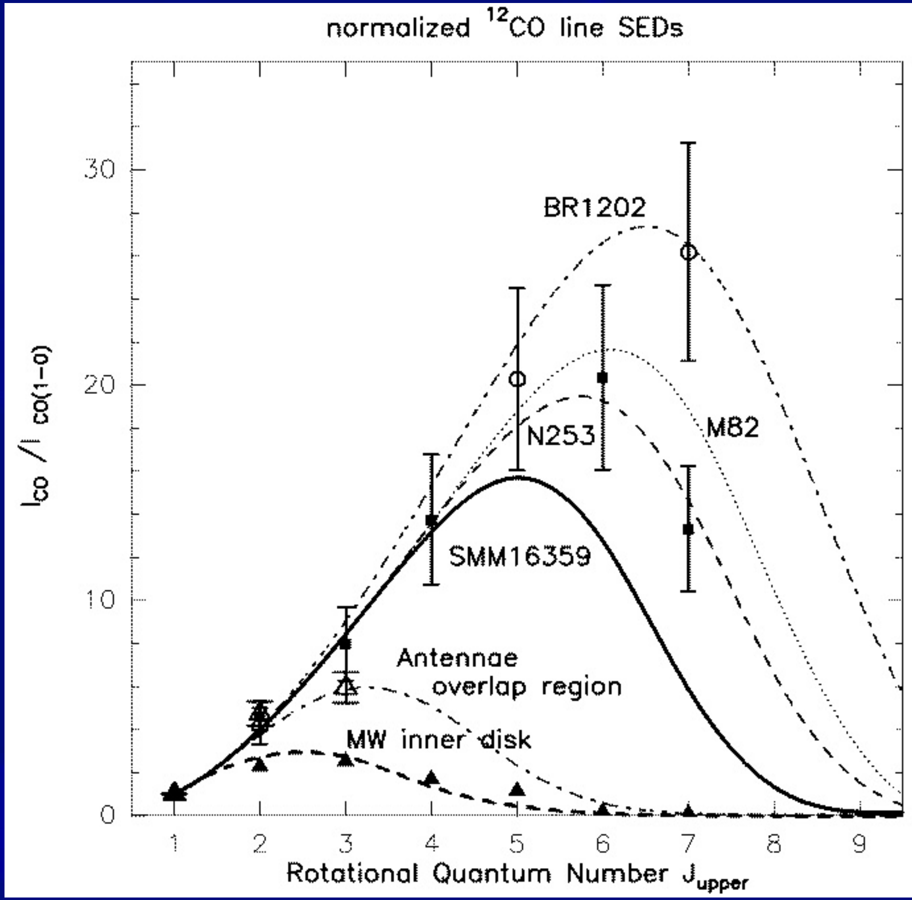


Nearby galaxies in ALMA Deep Field

Distant galaxies in ALMA Deep Field; spectroscopy also!

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

Summary of detailed requirements

Frequency	**30 to 950 GHz (initially only 84-720 GHz fully instrumented)**
Bandwidth	**8 GHz both polzns, fully tunable**
Spectral resolution	**31.5 kHz (0.01 km/s) at 100 GHz**
Angular resolution	**30 to 0.015” at 300 GHz**
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 (Japan)**
Polarization	**All cross products simultaneously**

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.
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.

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.

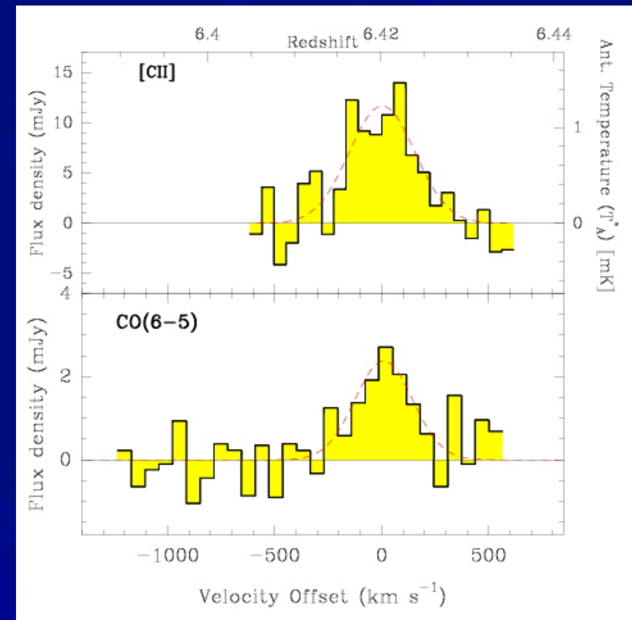
Detecting normal galaxies at z=3

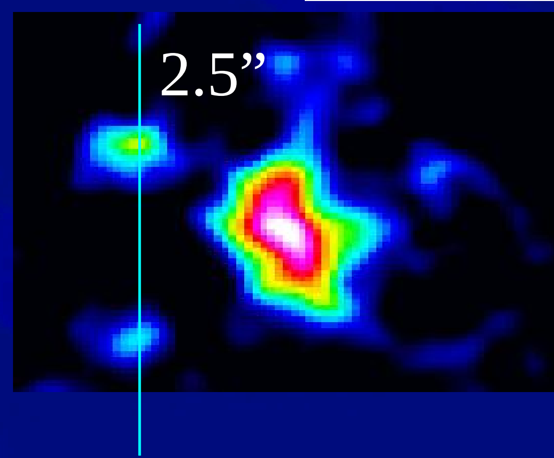
CO emission now detected in >25 z>2 objects, out to z=6.4. [C II] only at z=6.4 (right) To date only in luminous AGN and/or gravitationally lensed. Normal galaxies are 20 to 30 times fainter. Current millimeter interferometers have collecting areas between 500 and 1000 m^2. ALMA's >7000 m^2 provides excellent sensitivity. Image at right: 60 hrs VLA, 1.5 hrs ALMA (B3).

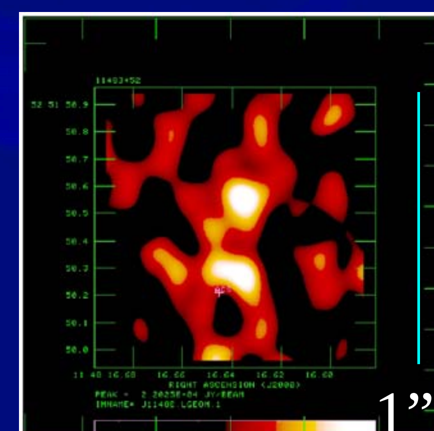
IRAM

[C II]

[CO]







VLA

[CO 3-2]

Detecting normal galaxies at z=3

- At z=3, the 10 kpc molecular disk of the Milky Way will be much smaller than the primary beam → single observation.
- Flux density sensitivity in image from an interferometric array with 2 simultaneously sampled polarizations and 95% quantum efficiency is:

$$\Delta S = \frac{2.6 \times 10^6 T_{\rm sys}}{\epsilon_a N D^2 \sqrt{\Delta\nu \Delta t}} \ \mathrm{mJy}.$$

- Aperture efficiencies $0.45<\varepsilon_a<0.75$ can be achieved (25 µm antenna surface accuracy; ~16 µm achieved on prototypes).
- T_{sys} depends on band, atmosphere, … for 115 GHz, T_{rx} =37 K obtained

Detecting normal galaxies at z=3

- Total CO luminosity of Milky Way: $L'_{CO(1-0)} = 3.7 \times 10^8$ K km $s^{-1} pc^2$ (Solomon & Rivolo 1989).
- COBE found slightly higher luminosities in higher transitions (Bennett et al 1994) → adopt $L'_{CO} = 5 \times 10^8$ K km $s^{-1} pc^2$.
- At z=3 → observe (3-2) or (4-3) transition in the 84-116 GHz atmospheric band → need to correct, but also higher T_{CMB} providing higher background levels for CO excitation.
- Different models predict brighter or fainter higher-order transitions. Few measurements of CO rotational transitions exist for distant quasars and ULIRGs, but these are dominated by central regions.

→ Assume $L'_{CO(3-2)} / L'_{CO(1-0)} = 1$.

Detecting normal galaxies at z=3

- **For ΛCDM cosmology, Δv=300 km/s, the expected peak CO(3-2) flux density is 36 μJy.**
- **Require 5σ detection in 12h on source (16h total time).**

→ ND^2=7300 m^2.

- **Achievable with N=64 antennas of D=12m diameter.** [SCI-100]
- **Achievable with N=50 D=12m antennas with longer integrations, augmentation with the Atacama Compact Array antennas (equivalent to 8 x 12m antennas) or more sensitive receivers.**
- **But--how do we find that distant Milky Way galaxy?**
  - **Medium scale deep field imaging**
  - **Often provides information on redshifts**

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

❖>128 submissions received involving >75 astronomers

❖Review by ASAC members completed; comments included

Current version of DRSP on Website at:

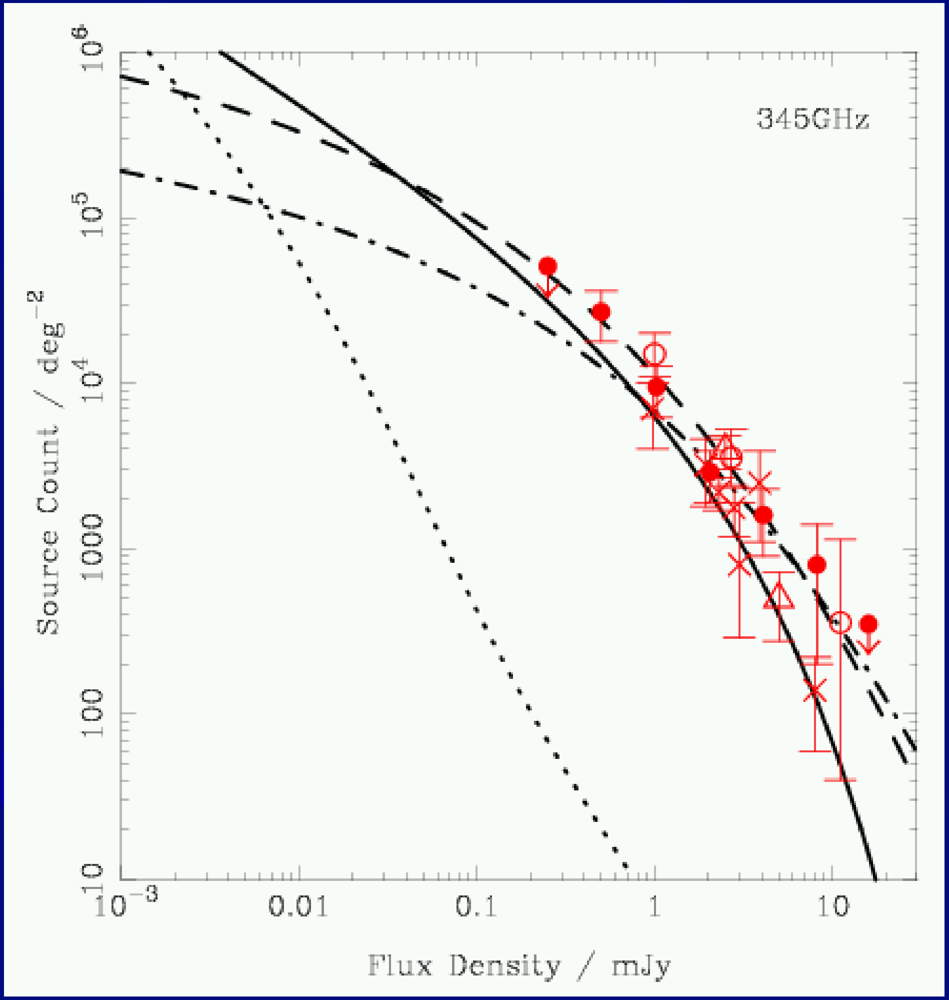
http://www.strw.leidenuniv.nl/~alma/drsp.html

New submissions continue to be added.

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 $\rightarrow$ 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

❖Fully resolve the cosmic IR background into individual sources and determine FIR properties of LBGs and EROs as well as SMGs

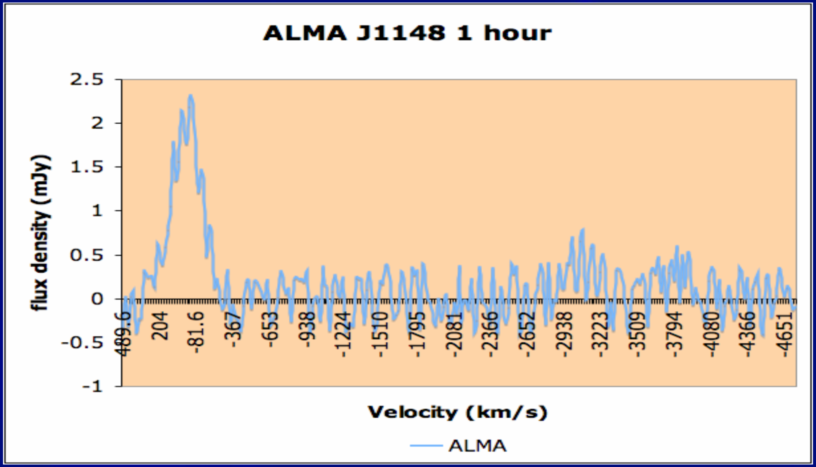
❖Quantify the properties of high-z dusty galaxies (SFRs, gas content, dynamical mass, etc.)

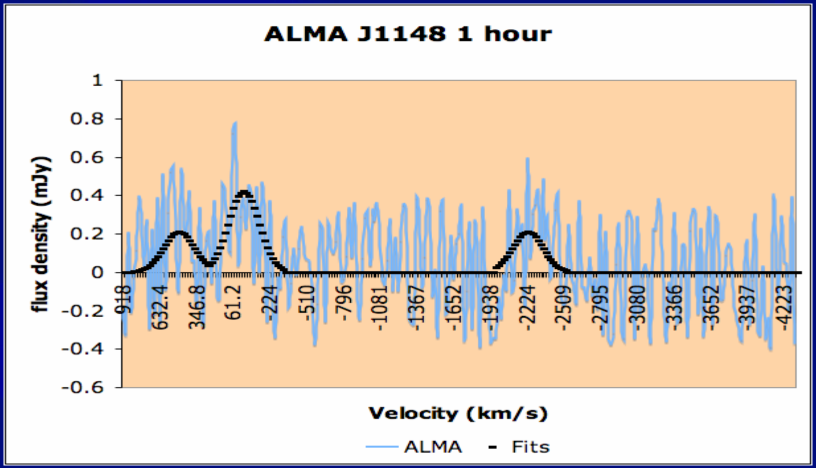
❖Map the cosmic evolution of dusty galaxies and their contribution to the cosmic star formation history

J1148+5251: an EoR paradigm with ALMA

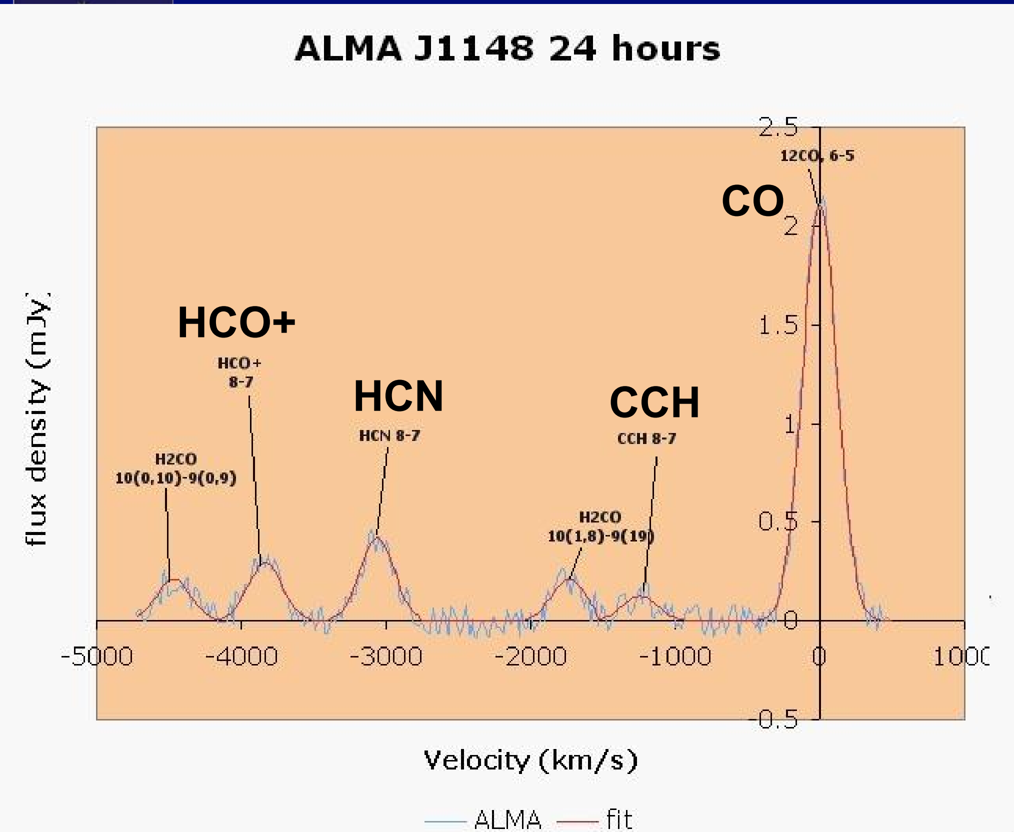
CO J=6-5

- Wrong declination! 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

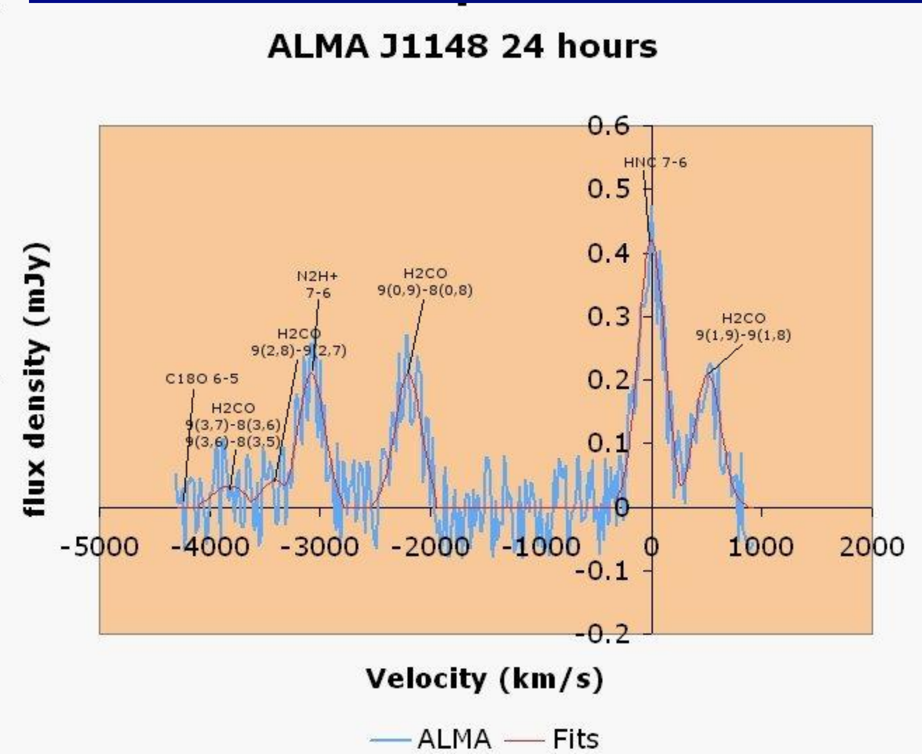


Spectral simulation of J1148+5251

- 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

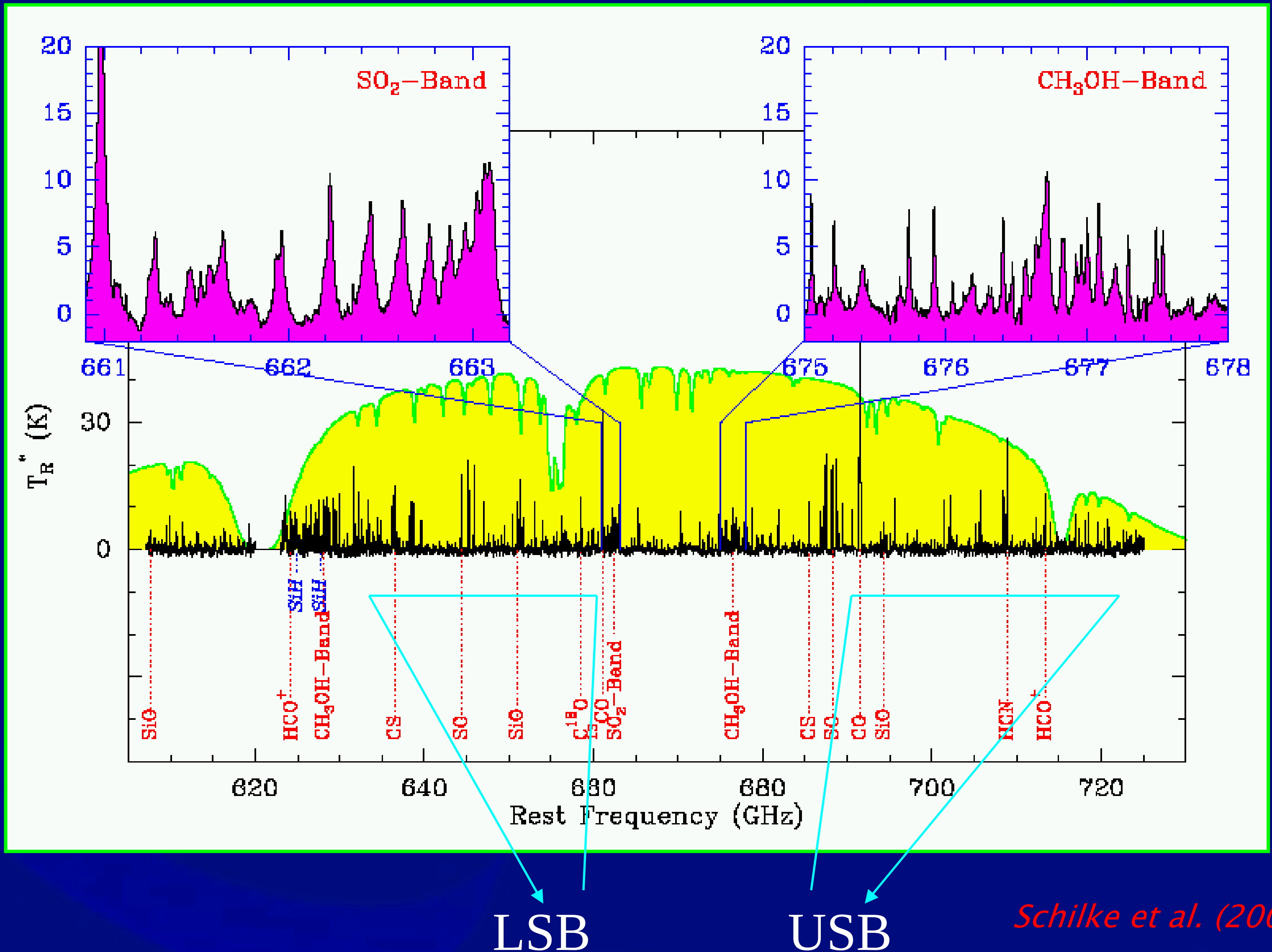
N. B. Atomic line diagnostics

[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)

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
- ALMA shines for deep medium scale surveys
- Targeted investigations of physical conditions
- Atomic lines available for EoR redshifts

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.