



Atacama Large Millimeter/submillimeter Array

# ALMA Construction Status and Science Perspective



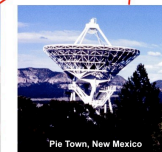
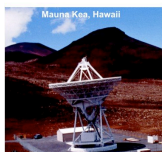
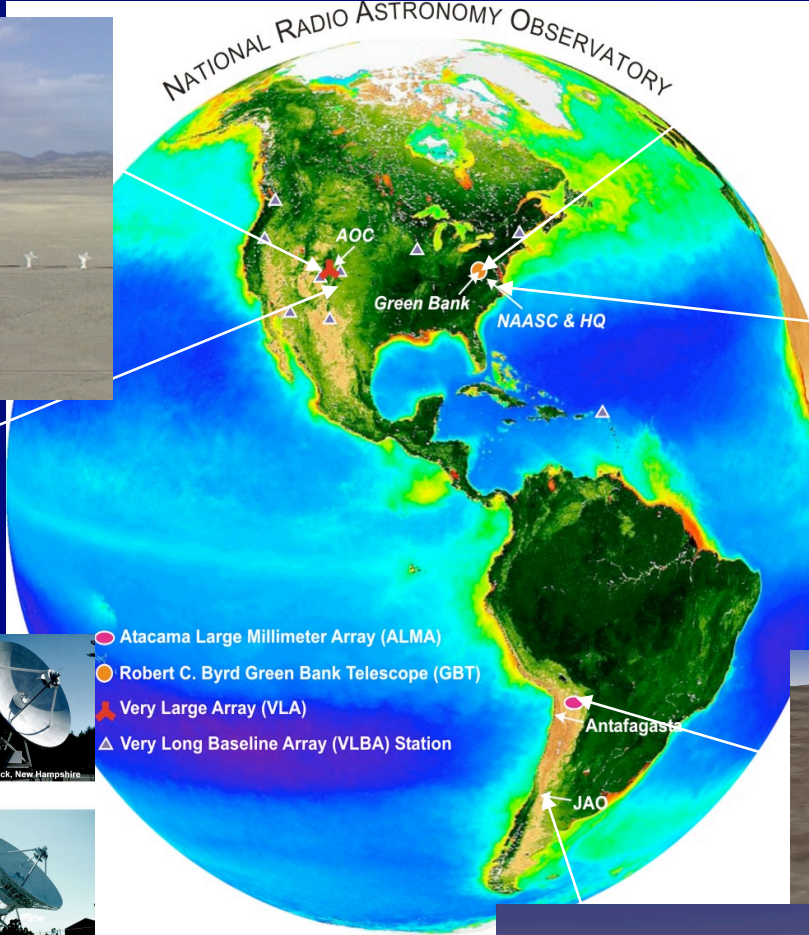
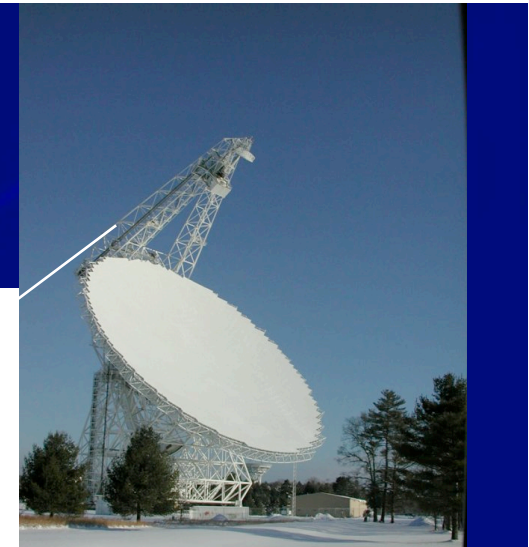
Al Wootten, ALMA/NA Project Scientist

ISSTT 2009

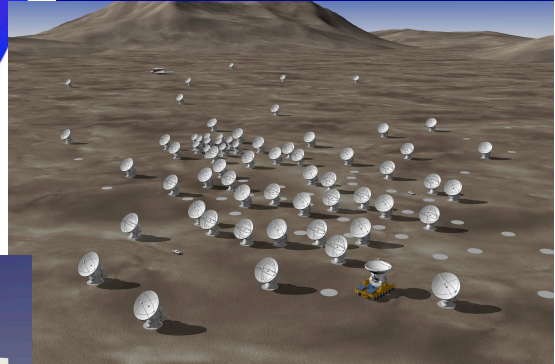
In search of our Cosmic Origins



# NRAO: A System of Complementary Telescopes Under an Open Skies Policy



## ALMA in 2012



## Joint ALMA Obs.





## Atacama Large Millimeter/submillimeter Array

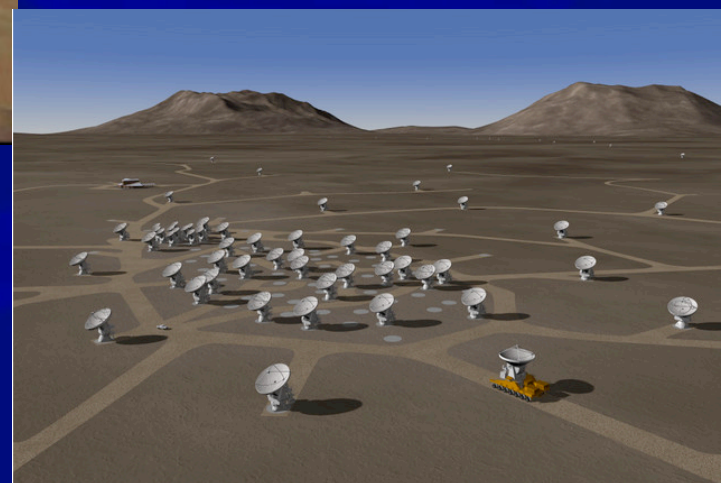
Is an international astronomy facility, a partnership between Europe (32.5%), North America (32.5%) and East Asia (25%), in cooperation with Chile (10%) through agreements reached in 2003 and updated in 2006. ALMA is operated on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) with National Science Foundation funding.



Llano Chajnantor  
Northern Chile  
at 5000m elevation

Inauguration 2012  
(Early Science in 2011)

$>50 \times 12\text{-m}$  telescopes  
+  
ACA:  $12 \times 7\text{-m} + 4 \times 12\text{-m}$





# ALMA – Major Elements

Thirteen antennas now in Chile  
Third ALMA Production Antenna Apr 27



Photo H. Heyer (ESO).

- Partners: US (NSF/NRAO)+Canada (NRC)+Taiwan (ASIAA) – ESO  
Chile – Japan (NINS)+ *Taiwan (ASIAA)*

## Action Sites

- Array Operations Site – AOS 5000m (High Andes)
- Operations Support Facility – OSF 2900m (Upslope Andes)
- Santiago Central Offices – SCO
- ALMA Regional Centers – ARCs + ARC nodes
- ALMA Test Facility--Near Very Large Array, NM closed

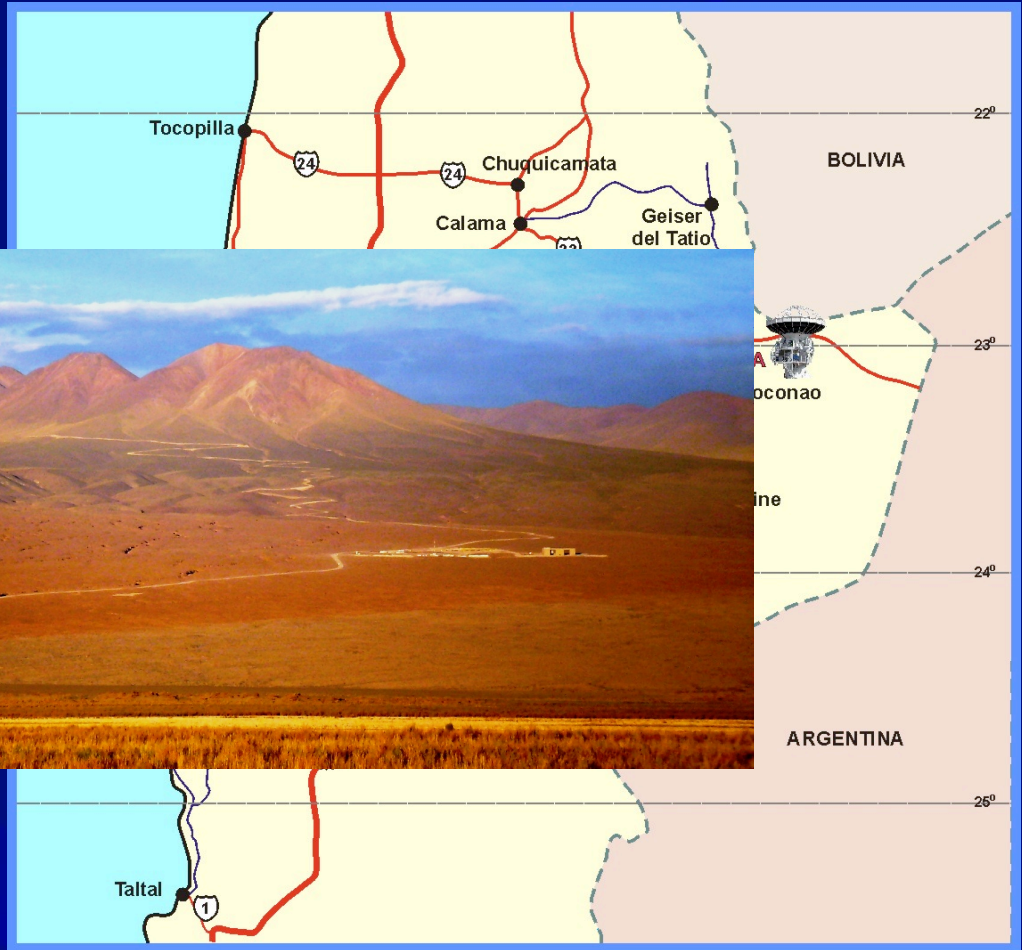


- Astronomers do not travel to telescope (safety!)—data flows to them through SCO and ARCs
- During full operation, the estimated flow into archive ~ 100 Tbytes per year
- Dataset: proposal,  $u$ - $v$  data, a reference image with pipeline processing history, calibration data... modern radioastronomy
- Over the first decade of ALMA we have the opportunity to extend its frequency coverage, collecting area and resolution





# How can I find the ALMA Site?



Paranal

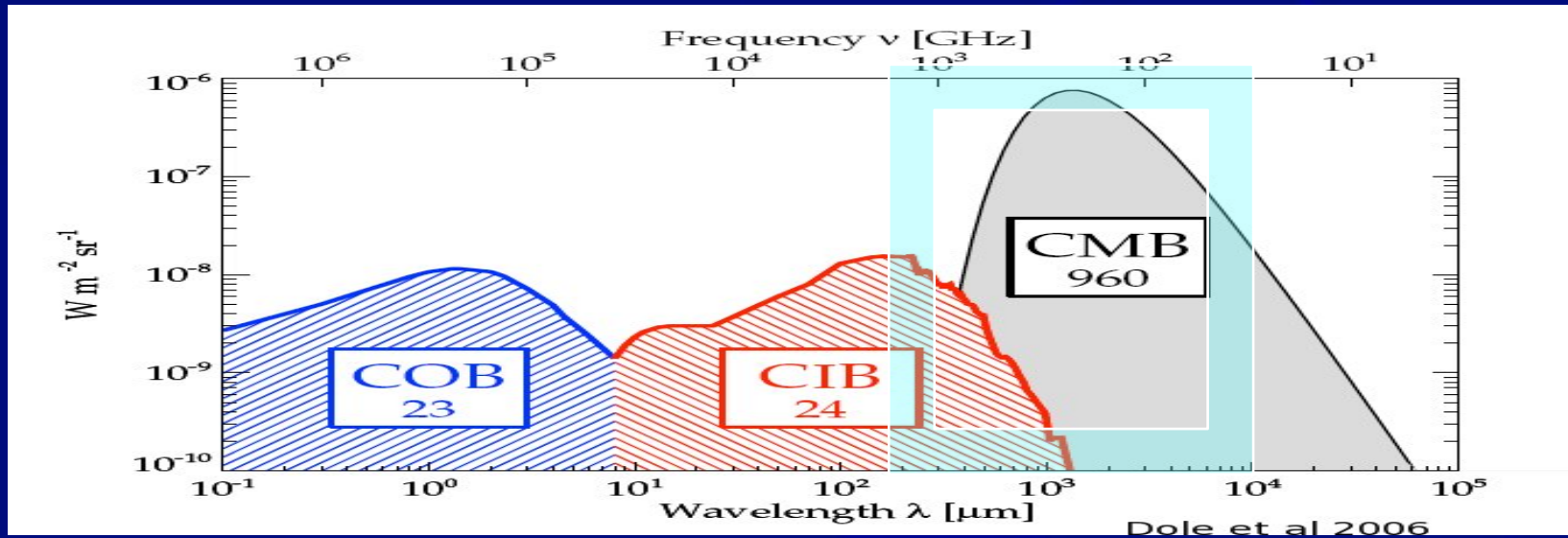
La Serena

Santiago





# The mm/Submm Spectrum: Focus of ALMA

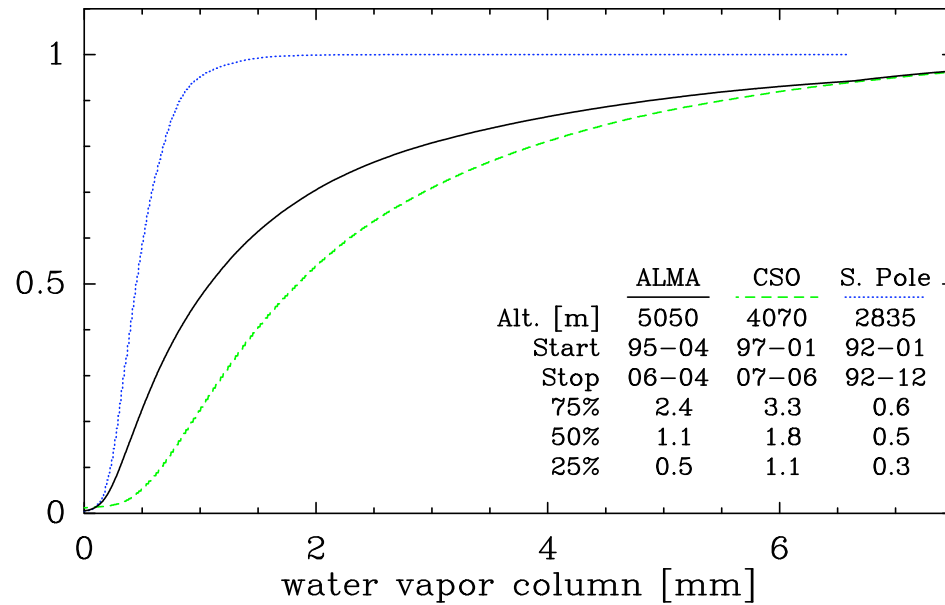


- Millimeter/submillimeter photons are the most abundant photons in the cosmic background, and in the spectrum of the Milky Way and most spiral galaxies.
  - Most important component is the 3K Cosmic Microwave Background (CMB)
  - After the CMB, the strongest component is the CIB/THz component, which 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.
- CIB is a focus of THz astronomy



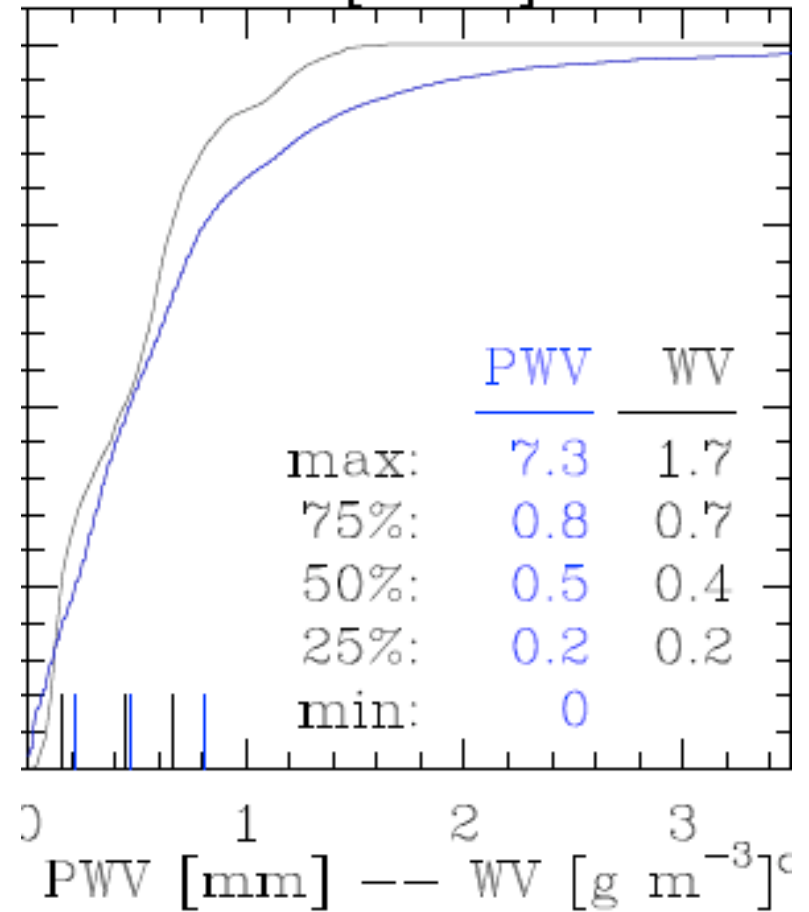
Data courtesy S. Radford

### Eleven Years of Data



PWV < 200  $\mu\text{m}$  for ~10% of time  
Can be better in winter

### APEX July 2008



Chajnantor: An Excellent Site for THz Astronomy



# APEX

- APEX is a slightly modified copy of the ALMA prototype built by Vertex.
- It has operated on the ALMA site since 2005.
- The surface is  $\sim 17 \mu\text{m}$  and has remained stable.
- Observations have been published which were made in the 1.4 THz atmospheric window.



Sooo...

- ALMA has an excellent and proven site for THz astronomy
- ALMA has two prototype antennas; a copy of one is **doing** THz astronomy
  - Bids now being considered for operation
- ALMA has two different Production antennas—how do they compare?
- What are ALMA's science goals and how do they drive development?





# ALMA Science Requirements

Project scientist ensures ALMA meets three “level I” science goals, two of them with THz attributes:

- *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*
- 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).



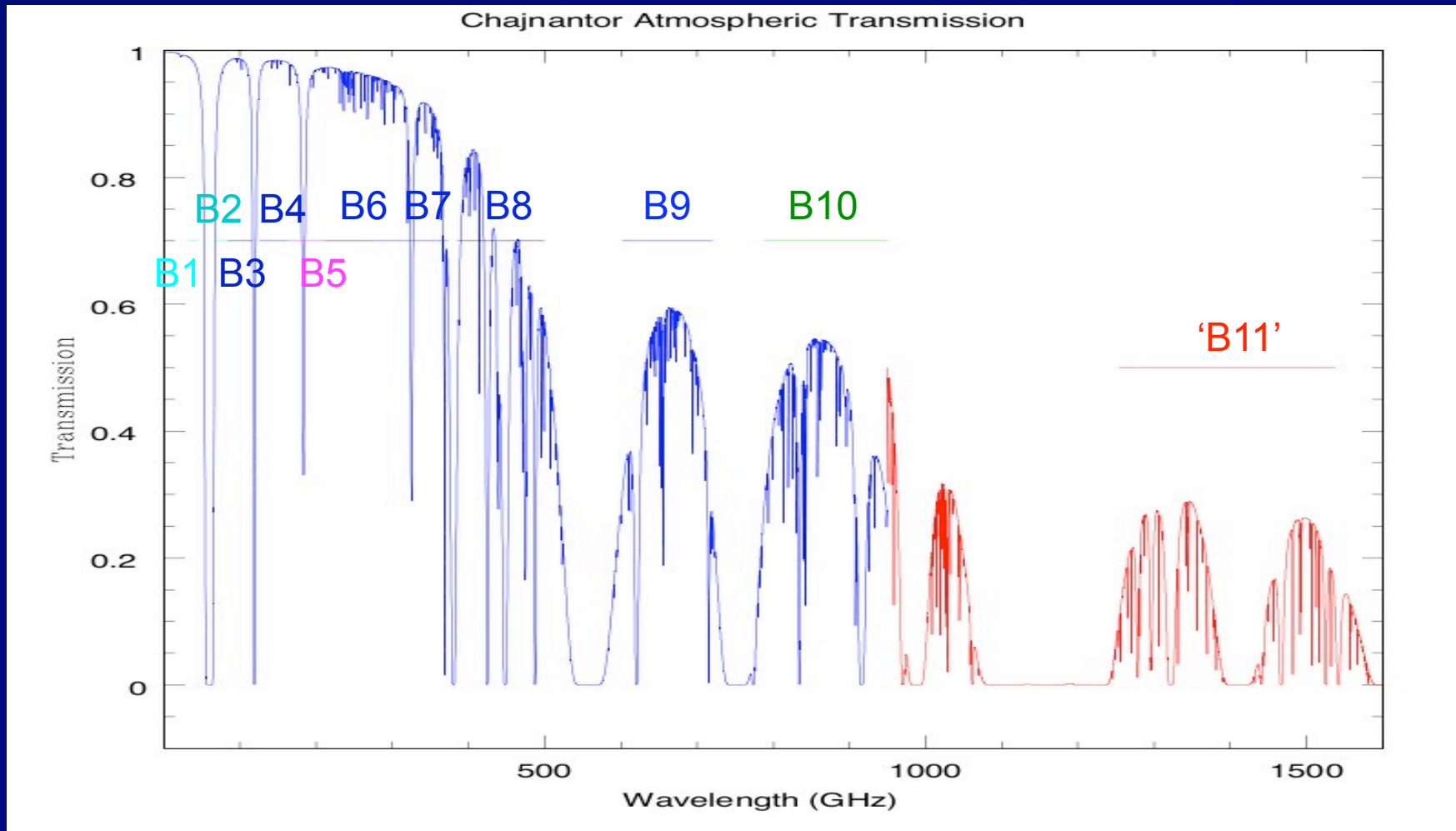
# Technical Specifications

- >54-68 12-m antennas, 12 7-m antennas, at 5000 m altitude site.
- Surface accuracy  $\pm 25 \mu\text{m}$ , 0.6" reference pointing in 9m/s wind, 2" absolute pointing all-sky. First two antennas meet these; accurate to  $< \pm 16 \mu\text{m}$  most conditions
- Array configurations between 150m to  $\sim 15$  -18km.
- 10 bands in 31-950 GHz + 183 GHz WVR. Initially, half are 'THz' bands:
  - 84-116 GHz "3"
  - 125-169 GHz "4"
  - 163-211 GHz "5" 6 rx only, dual 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.





# ALMA Bands and Transparency



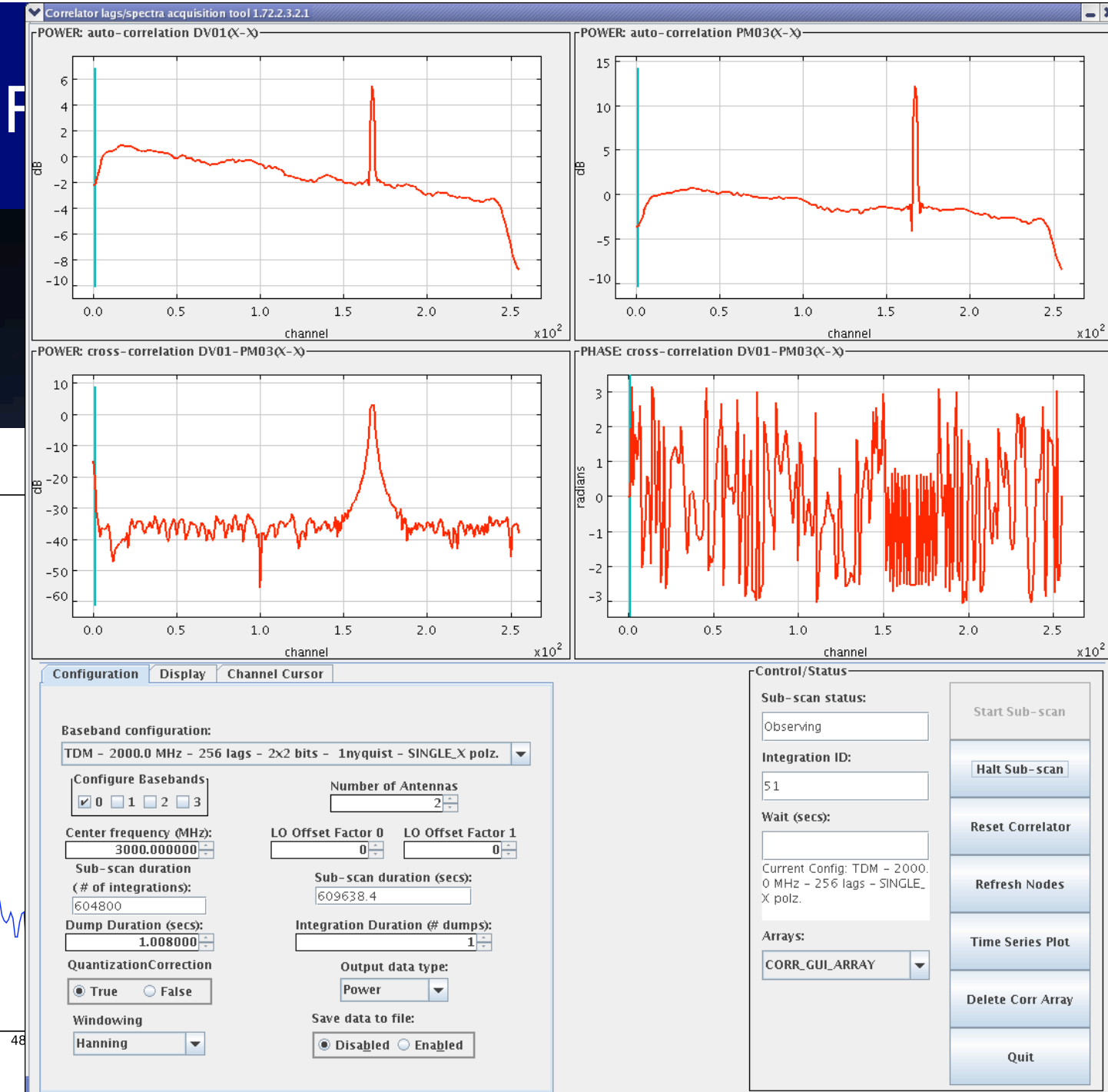
0.5mm PWV  $\nu < 950$  GHz

0.2mm PWV  $\nu > 950$  GHz

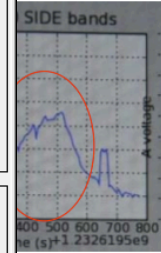


# Specifications Breed Transformational Performance

- With these specifications, ALMA improves
  - Existing sensitivity, by about two orders of magnitude
    - Best accessible site on Earth
    - Highest performance receivers available
    - Enormous collecting area (1.6 acres, or  $>6600 \text{ m}^2$ )
  - 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!



ed !



id 7



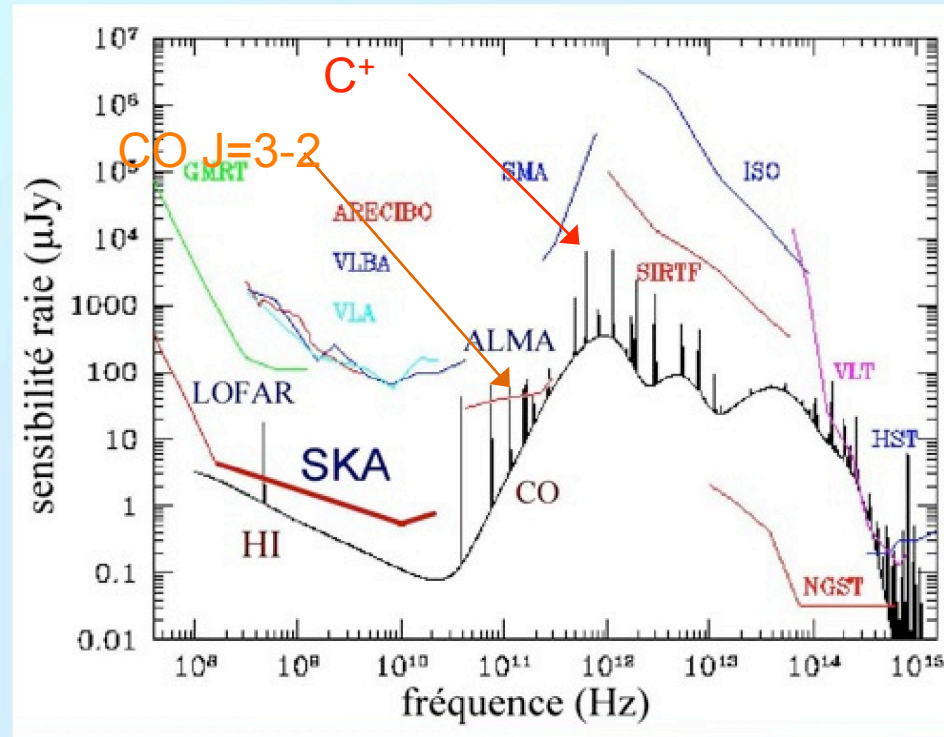




# Science Goal I: Detect CO or C+ in MWG

Combes

- At  $z=2$  this can be done for both lines
- At  $z=3$  this becomes difficult for the CO line
- But notice the 'tail pole' atomic lines in the THz region, including C<sup>+</sup>



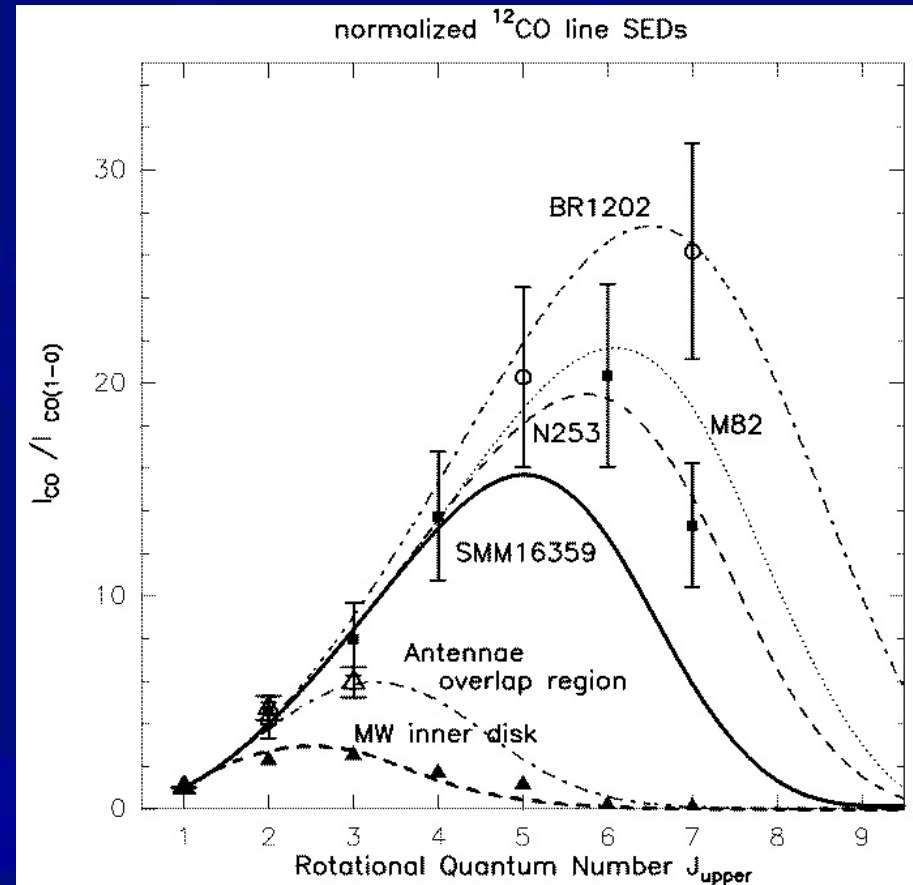
Detection of spectral lines of a 'standard' spiral galaxy at  $z = 2$

5 $\sigma$  in 1 hour



# 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  $\rightarrow$  low densities.  
In dense cores of starburst galaxies, higher-order transitions are brighter.  
At high  $z$ , higher excitation occurs, partly owing to higher CMB.

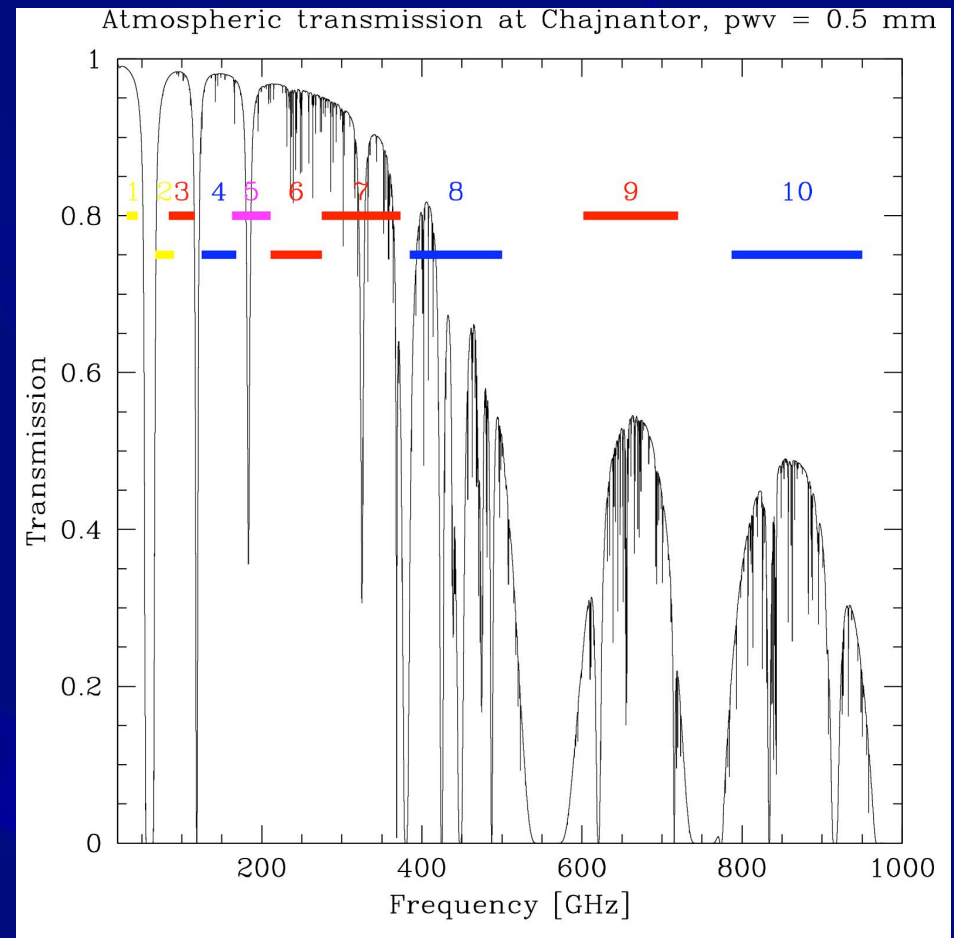


Weiss et al. astro-ph/0508037



# 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
  - ❖ 2 polzns 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)







# Science Goal I: Detect CO or C+ in MWG

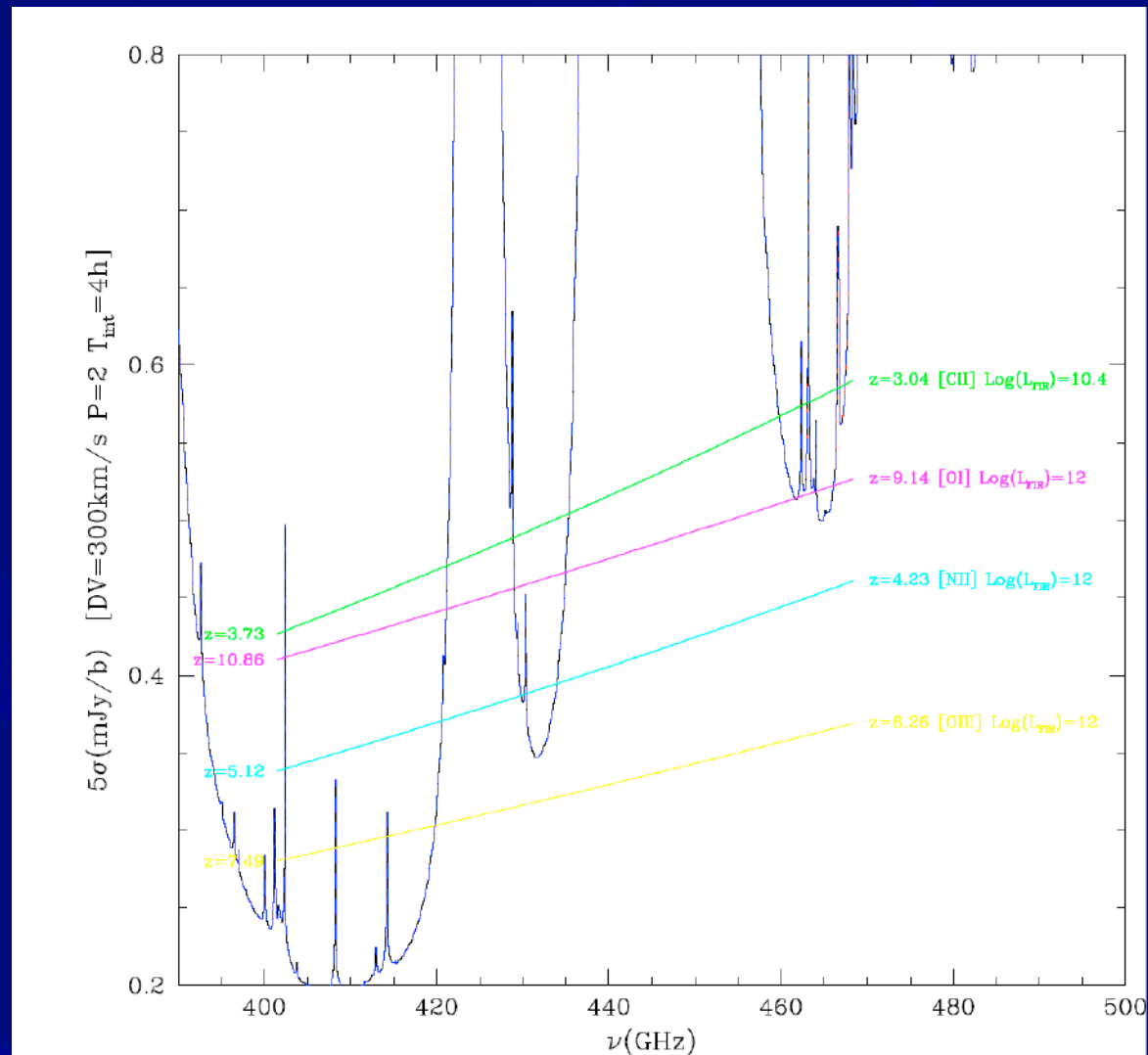
Maiolino and Testi

Viable; depends on exact redshift and transparency window lineup.

For MW galaxy, detection takes a few hours.

Note that other lines on the plot, from luminous galaxies in the local Universe, may be detected, some at very high  $z$ .

ALMA allows us to see the redshifted 'tall pole' THz lines to very high  $z$ .

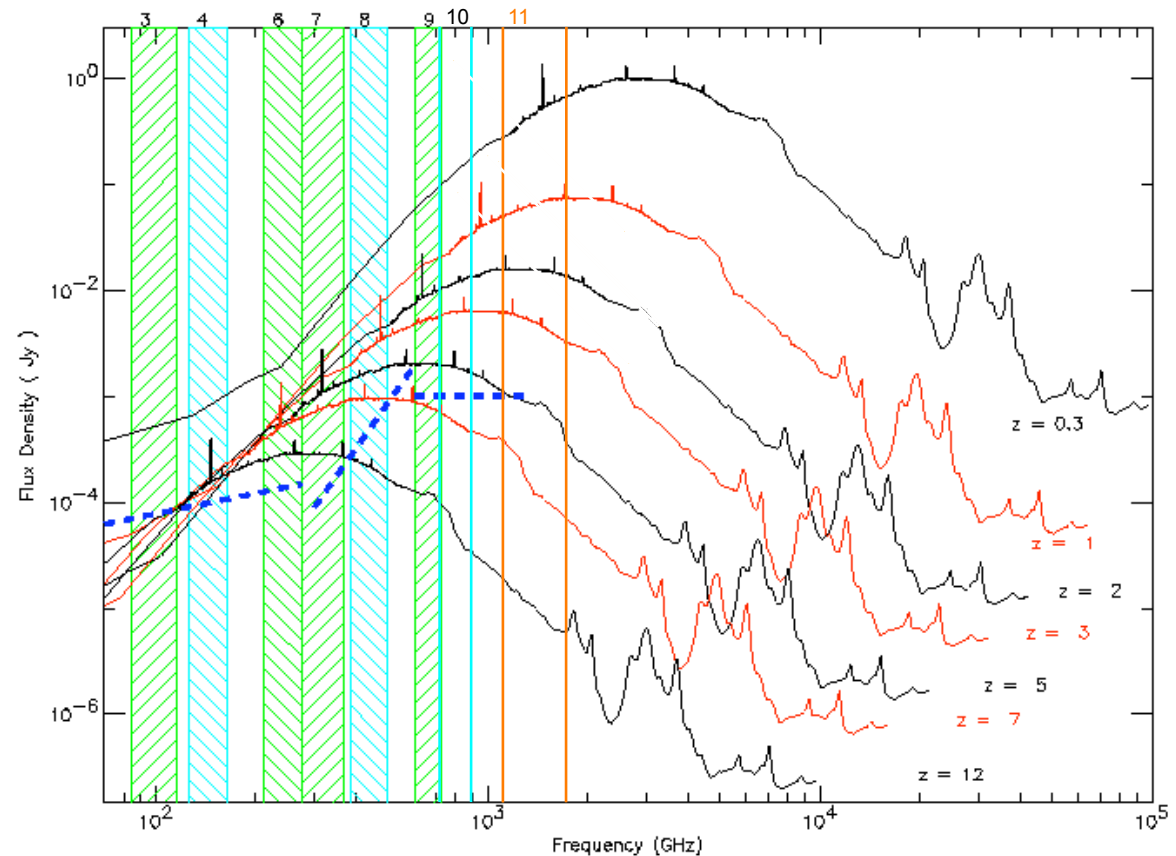




## Inverse K-correction, or magic of the submillimeter

*Super 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.

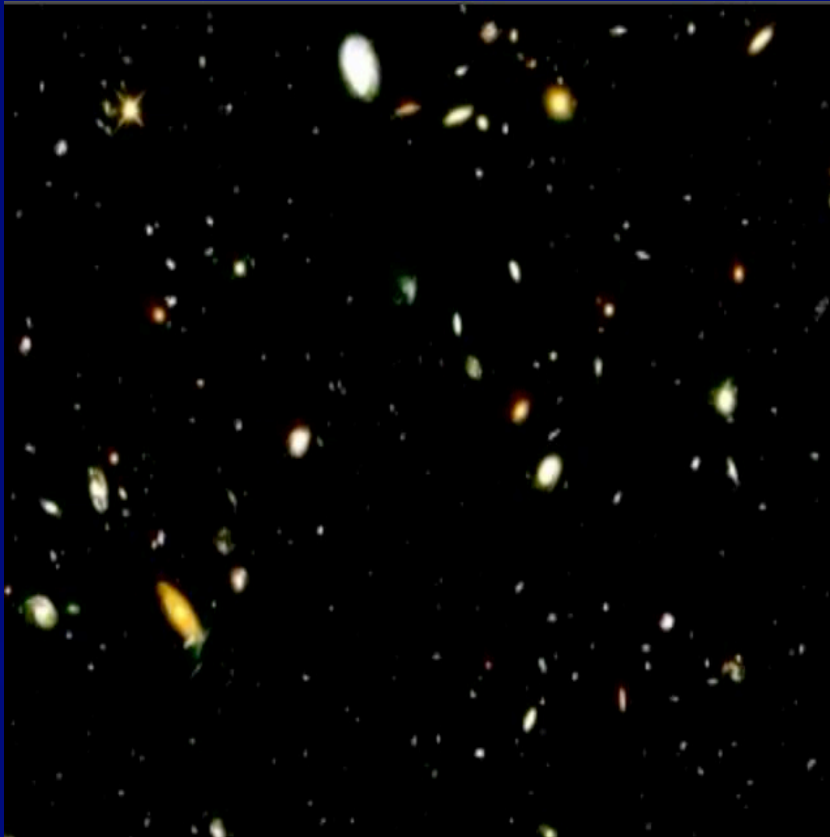




# Hubble Deep Field

Rich in Nearby Galaxies, Poor in Distant Galaxies

Source: K. Lanzetta, SUNY-SB



Nearby galaxies in HDF

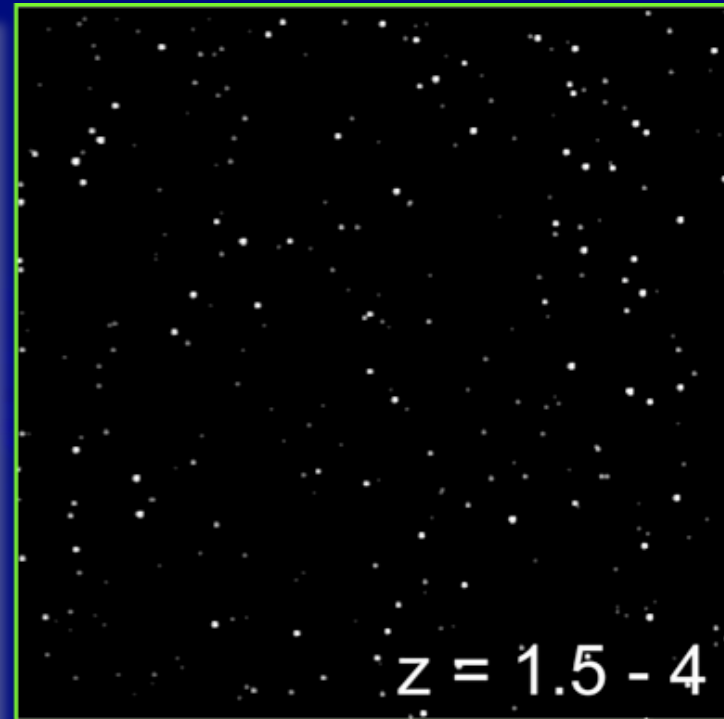


Distant galaxies in HDF





# Submm Sources at High and Low $z$



Wang 2008

Simulation based on:

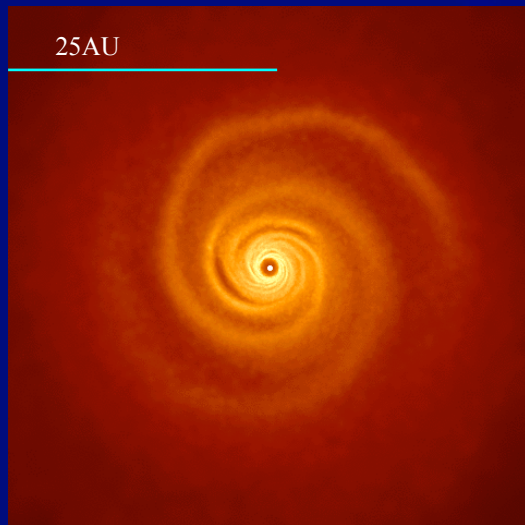
- (1) blank-field bright-end number counts (Wang, Cowie, Barger 2004)
- (2) lensing cluster faint-end number counts (Cowie, Barger, Kneib 2002)
- (3) redshift distribution of the submm EBL (Wang, Cowie, Barger 2004)



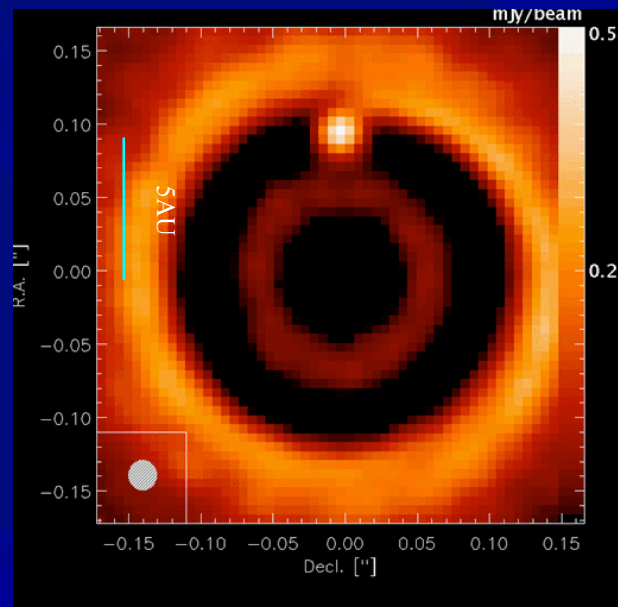
# Birth of Stars and Planets

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

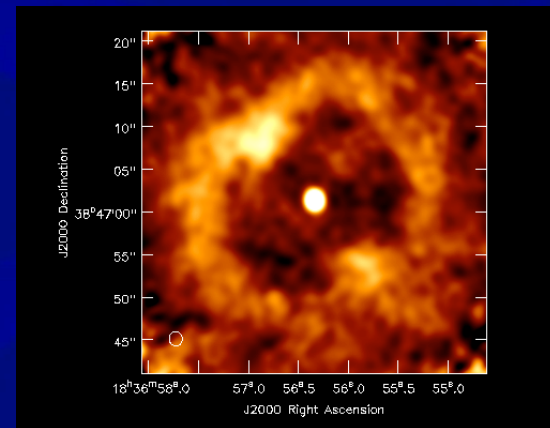
Lodato and Rice 2005



Wolf and D'Angelo 2005



M. Wyatt; R. Reid



Vega Dust Disk



# Birth of Stars and Planets

- The nearest Star Formation regions:  $\sim 100$  pc from the Sun
  - ALMA Beam at 300 GHz (100 pc): 1.5 AU
    - L1457 was once reported to lie at  $\sim 80$  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  $\sim 60$  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  $\sim 10\%$  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





# 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.



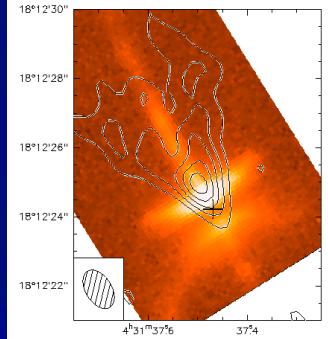
# Best Frequency for ALMA Continuum?

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

Frequency	$\Delta S$ (mJy)	$X_\nu$
230	0.07	76
345	0.12	99
675	0.85	54



# Forming Other Planetary Systems

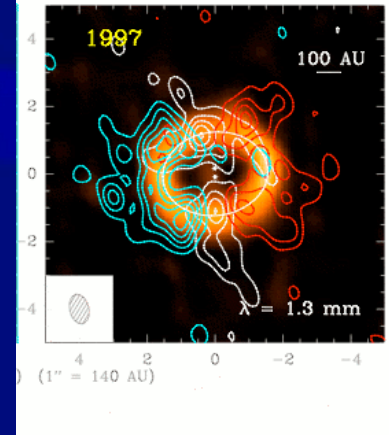


(1) Infancy. Image the luminous forming stars and planets directly, in emission from stellar photospheres, the gas and dust disk from which the stars formed, and the subsequent assembly of planets from the disk gas and dust.

- Disks are small,  $<900$  AU, requiring high angular resolution ( $1'' \sim 140$  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  $\sim 200$  AU disk is now detectable. ALMA allows one to map optically thick CO lines at the scale of our Solar System ( $\sim 3 - 10$  AU), providing information about the gas content and its kinematics; current interferometers do not probe closer in than  $\sim 40$  AU.
- 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

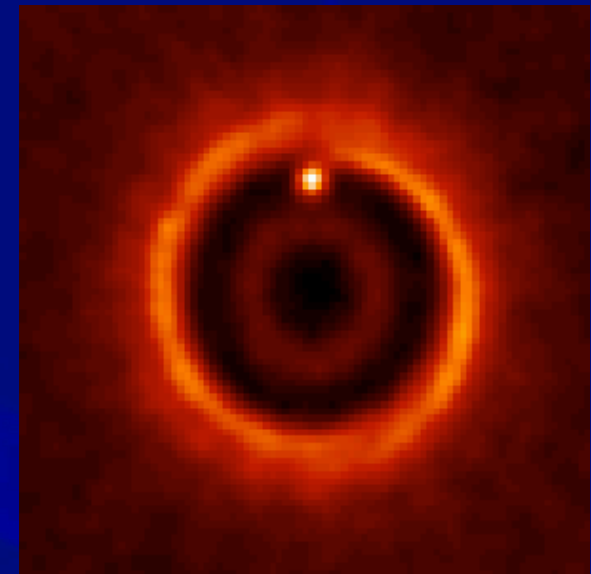
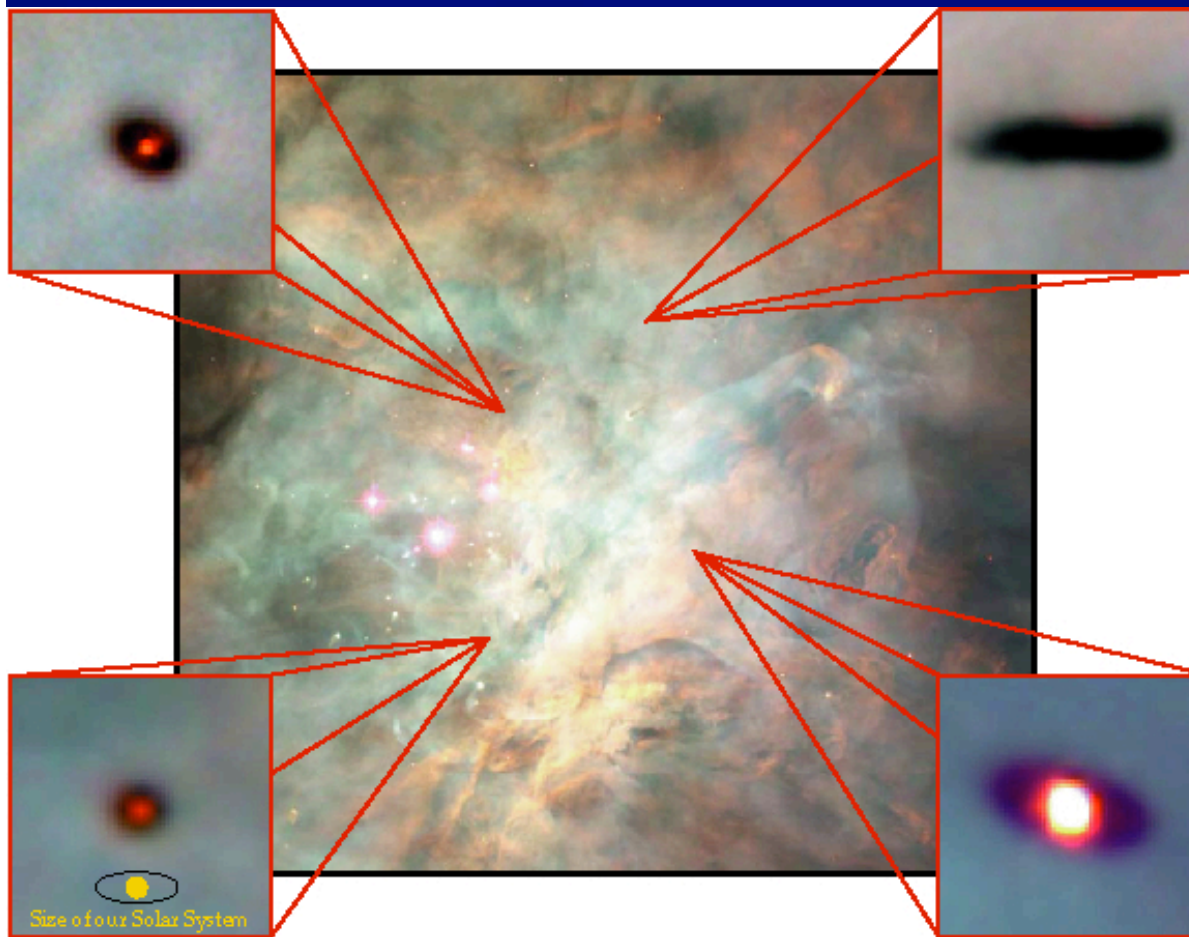
- (2) Toddler. ALMA will be able to directly detect forming giant planets ('condensations') in protoplanetary disks, and the gaps created in these disks as the condensations grow.
- 'Theoretical investigations show that the planet-disk interaction causes **structures** in circumstellar disks, which are 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 present). In the ALMA view (above, the dust and the protoplanet appear bright.



# ALMA's First Ten Years

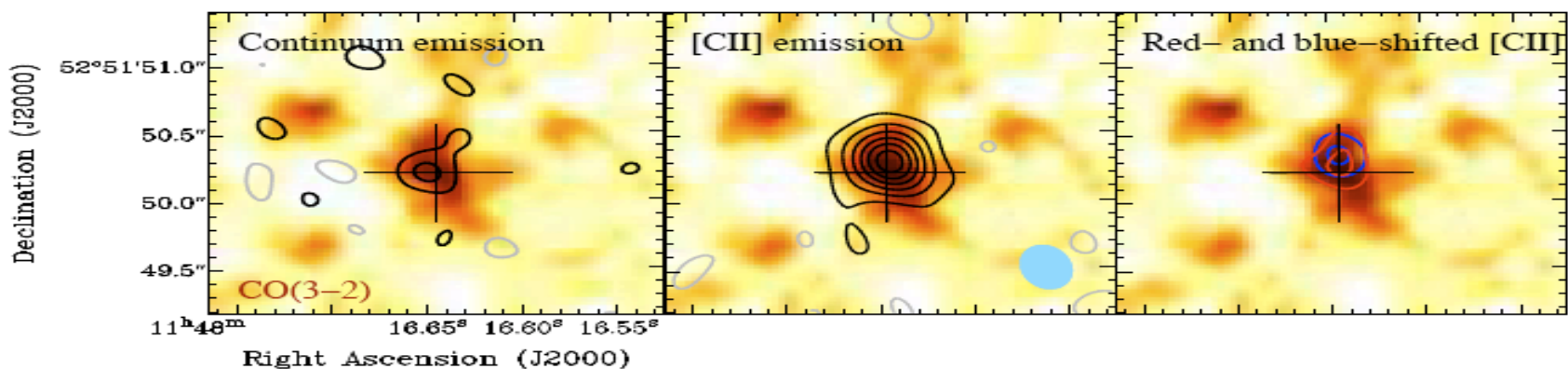
- A feature of ALMA Operations is Development
- Possibilities:
  - Finishing unfinished frequency bands
  - Expand collecting area to recommended 64 x 12m telescopes
  - Expand resolution by adding VLB capability
  - Addition of new bands—more challenging, but a ‘Band 11’ seems unusually promising given the thrust of science, the excellence of the site and the promise of the first antennas



# J1148+52: A Paradigm Distant Monster Galaxy

- An early ( $z=6.42$ ; 0.8Gyr) massive and extended region of tremendous star formation
- $\sim 1000 M_{\text{sun}}/\text{yr}/\text{kpc}^2$
- Region  $\sim 750$  pc radius
- Similar to Arp220 but 100 times larger
- Mass  $\sim 2 \cdot 10^{10} M_{\text{sun}}$

Walter et al 2009





# J1148+5251: an EoR paradigm with ALMA

CO J=6-5

Wrong declination (though ideal for Charlottesville)!

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

H<sub>2</sub>CO lines

Lower: LSB, 86.8 GHz

HNC 7-6

H<sub>2</sub>CO lines

C18O 6-5

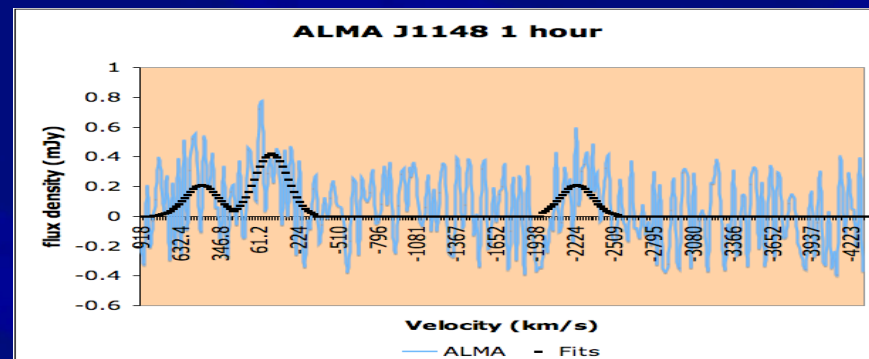
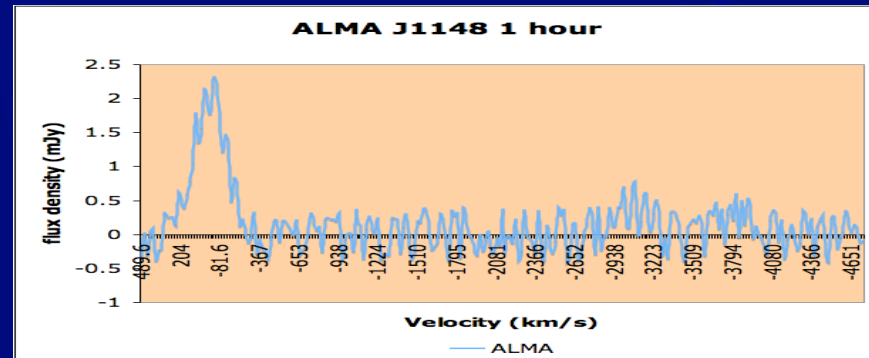
H<sub>2</sub>O 658GHz maser?

Secure redshifts

Molecular astrophysics

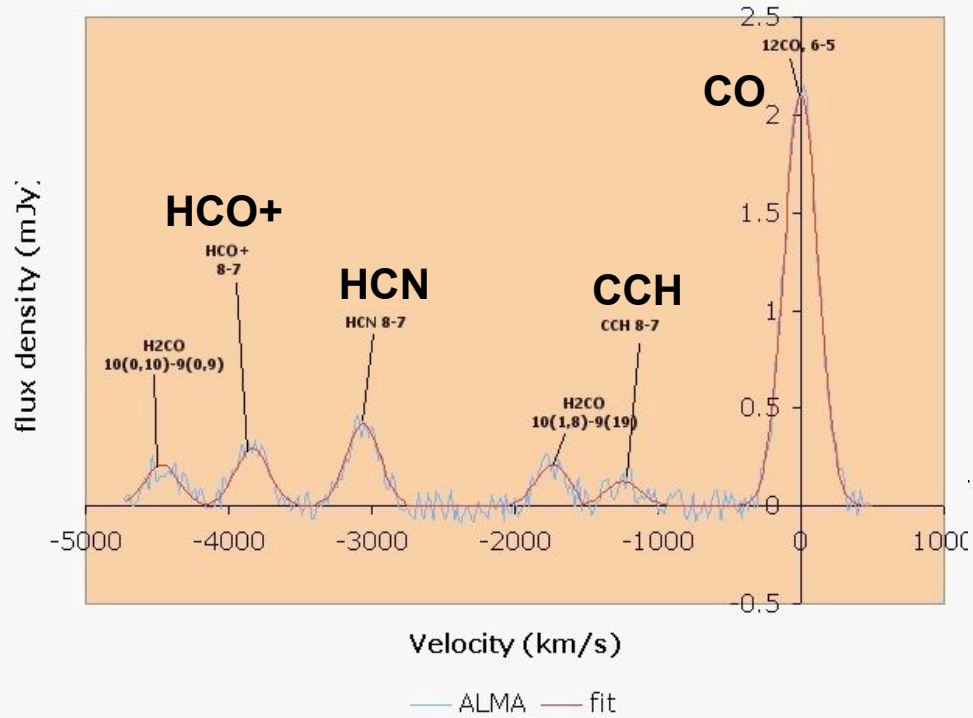
ALMA could observe CO-luminous galaxies (e.g.

M51) at  $z \sim 6$ .



## ALMA into the EoR

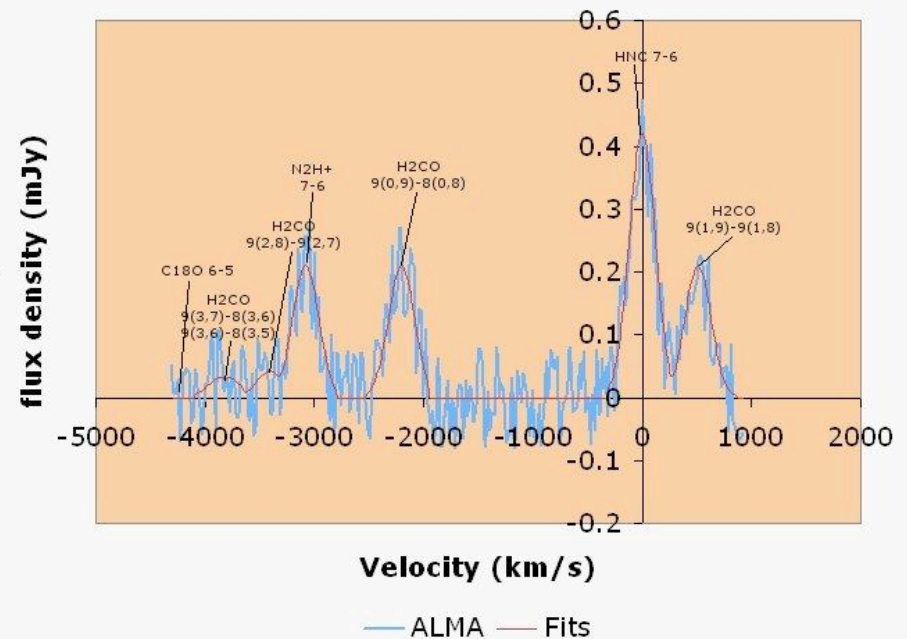
### ALMA J1148 24 hours



## Spectral simulation of J1148+5251

- Detect dust emission in **1sec** ( $5\sigma$ ) 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

### ALMA J1148 24 hours



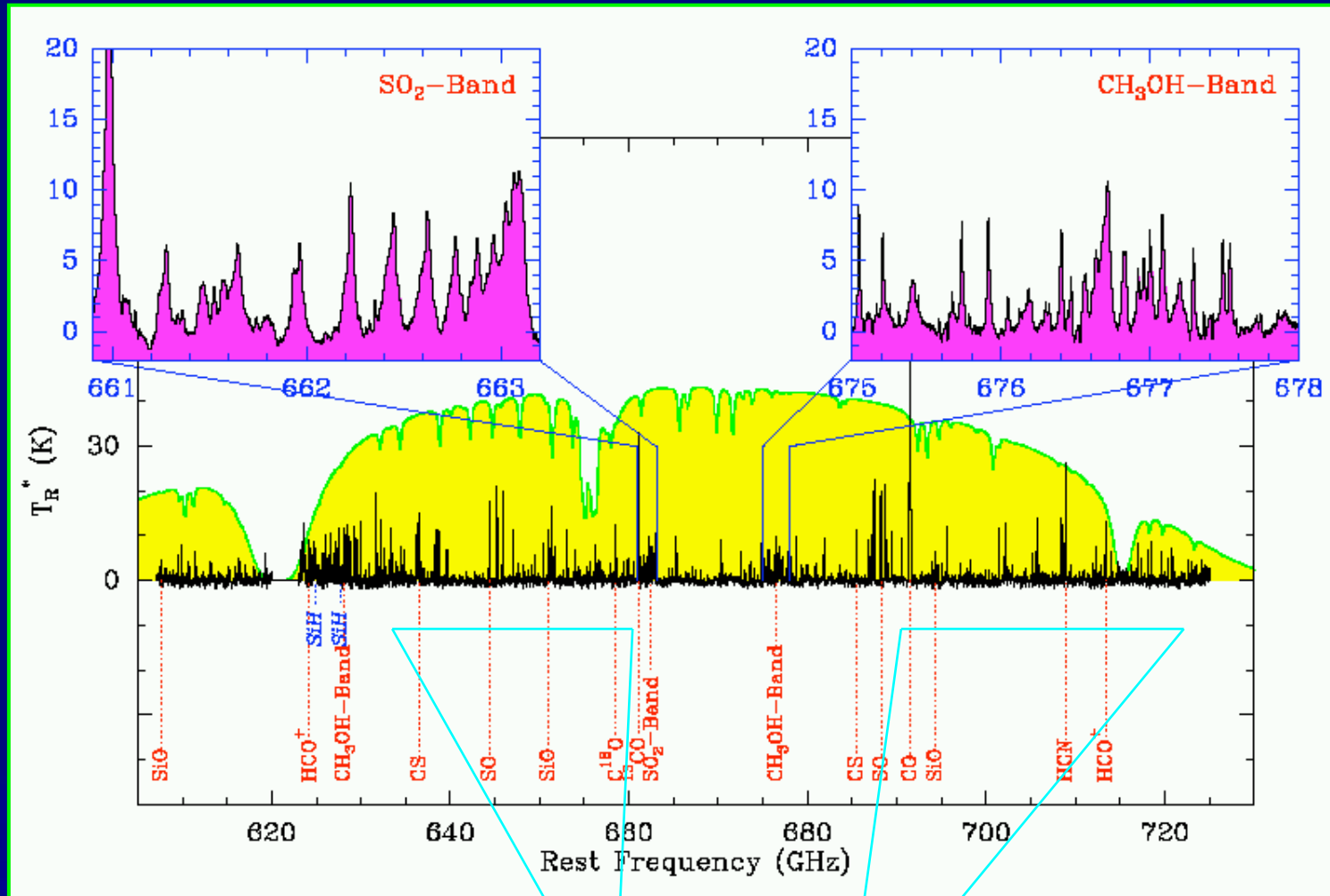
## N. B. Atomic line diagnostics

- [C II] emission in **60sec** ( $10\sigma$ ) at 256 GHz
- [O I] 63  $\mu\text{m}$  at 641 GHz
- [O I] 145  $\mu\text{m}$  at 277 GHz
- [O III] 88  $\mu\text{m}$  at 457 GHz
- [N II] 122  $\mu\text{m}$  at 332 GHz
- [N II] 205  $\mu\text{m}$  at 197 GHz
- HD 112  $\mu\text{m}$  at 361 GHz



# Bandwidth Compression

Nearly a whole band scan in one spectrum



LSB

USB

*Schilke et al. (2000)*

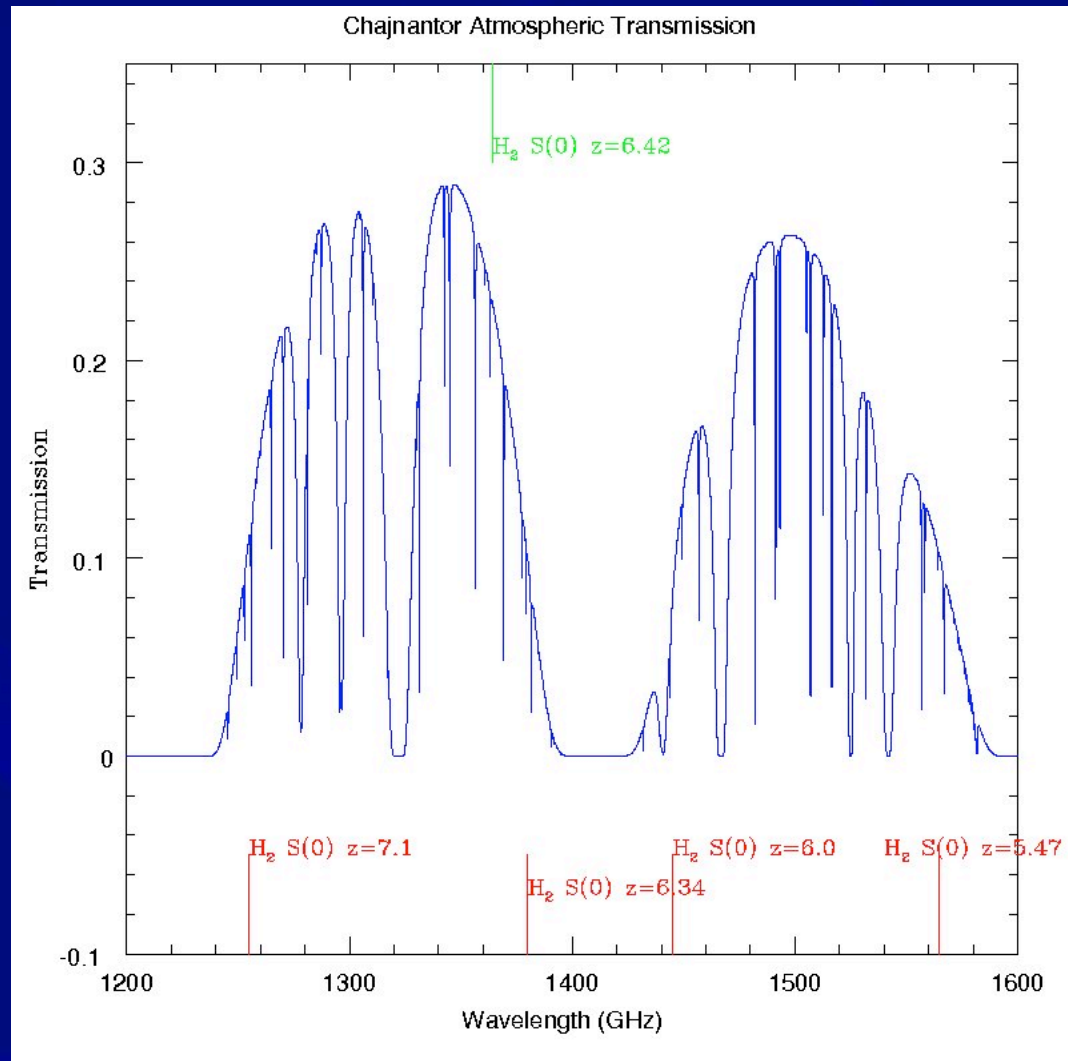


# J1148: A possible (not from Chajnantor!) H<sub>2</sub> observation

An early ( $z=6.42$ ; 0.8Gyr)  
massive and extended  
region of tremendous  
star formation

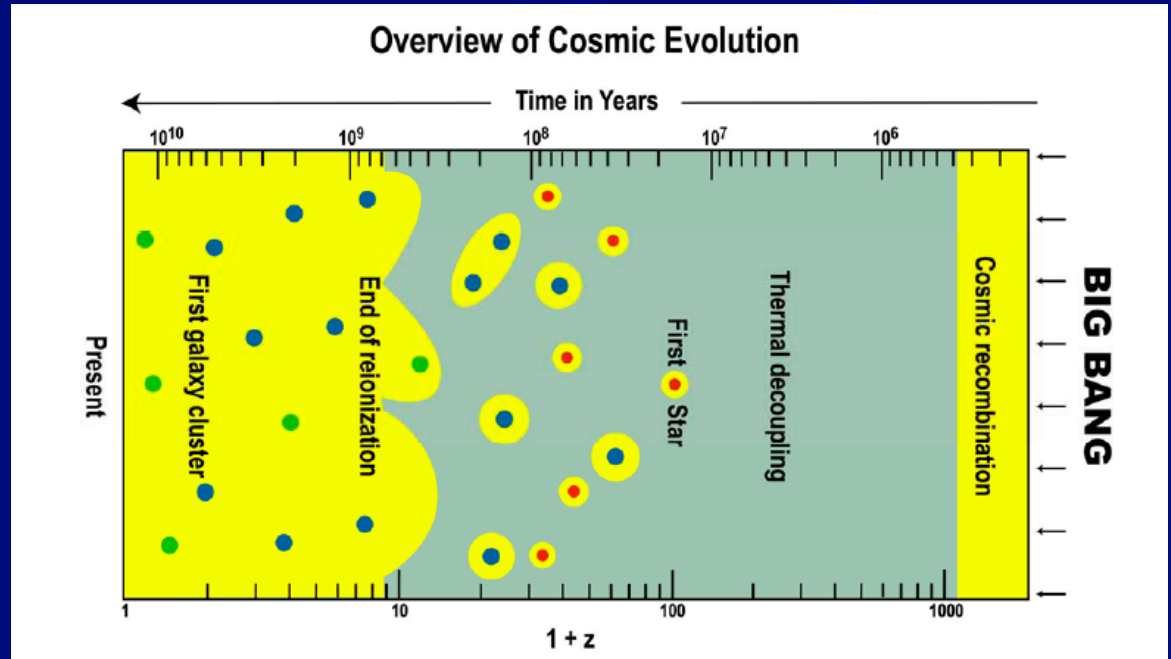
$\sim 1000 M_{\text{sun}}/\text{yr}/\text{kpc}^2$   
Region  $\sim 750$  pc radius  
Similar to Arp220 but 100  
times larger

Mass  $\sim 2 \cdot 10^{10} M_{\text{sun}}$





# Opening Up the Dark Side of Reionization

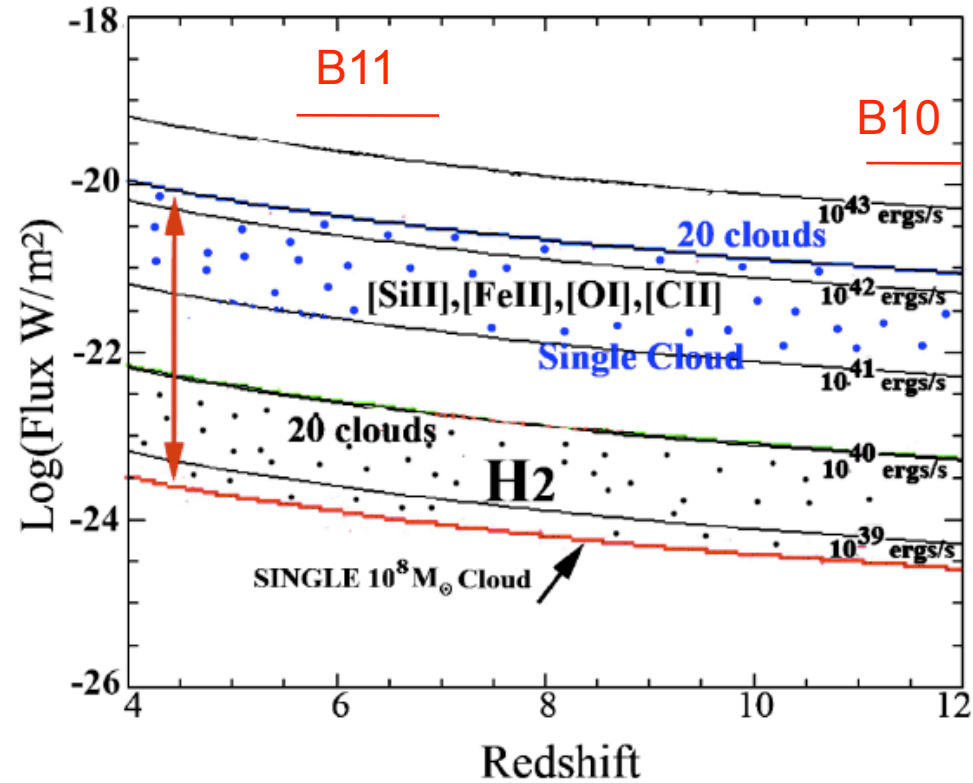


After R. Barkana



# Dark Side of Reionization

ALMA 1 hr,  $5\sigma$ , 300 km/s  
Single to score of clouds of  
 $10^8 M_{\text{sun}}$



After Appleton et al 2009

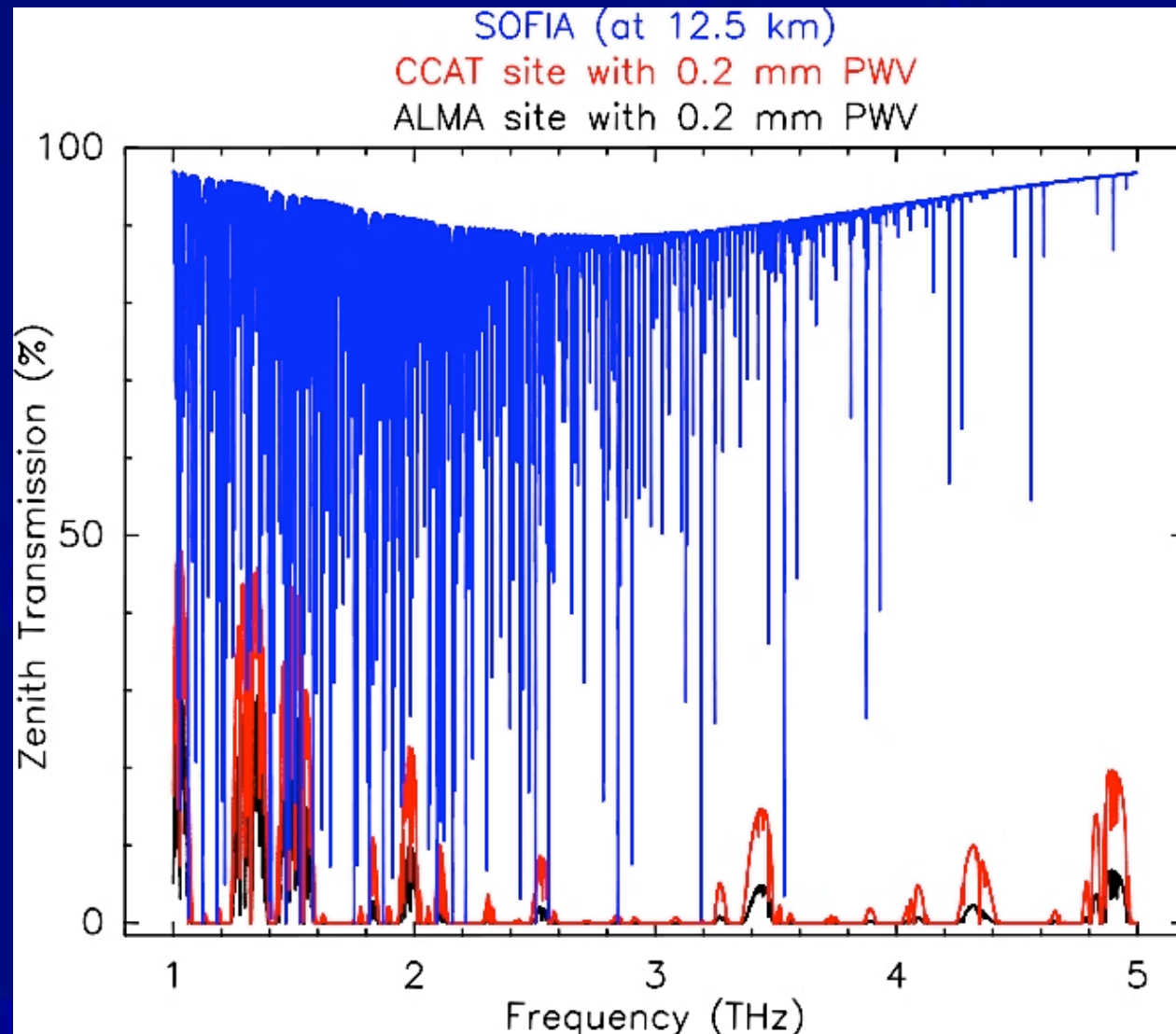


# THz windows

T. Hunter

Next decade's focus:

- Herschel
- SOFIA
- ALMA
- CCAT
- SPICA







# Some Atomic and Light Molecule THz lines

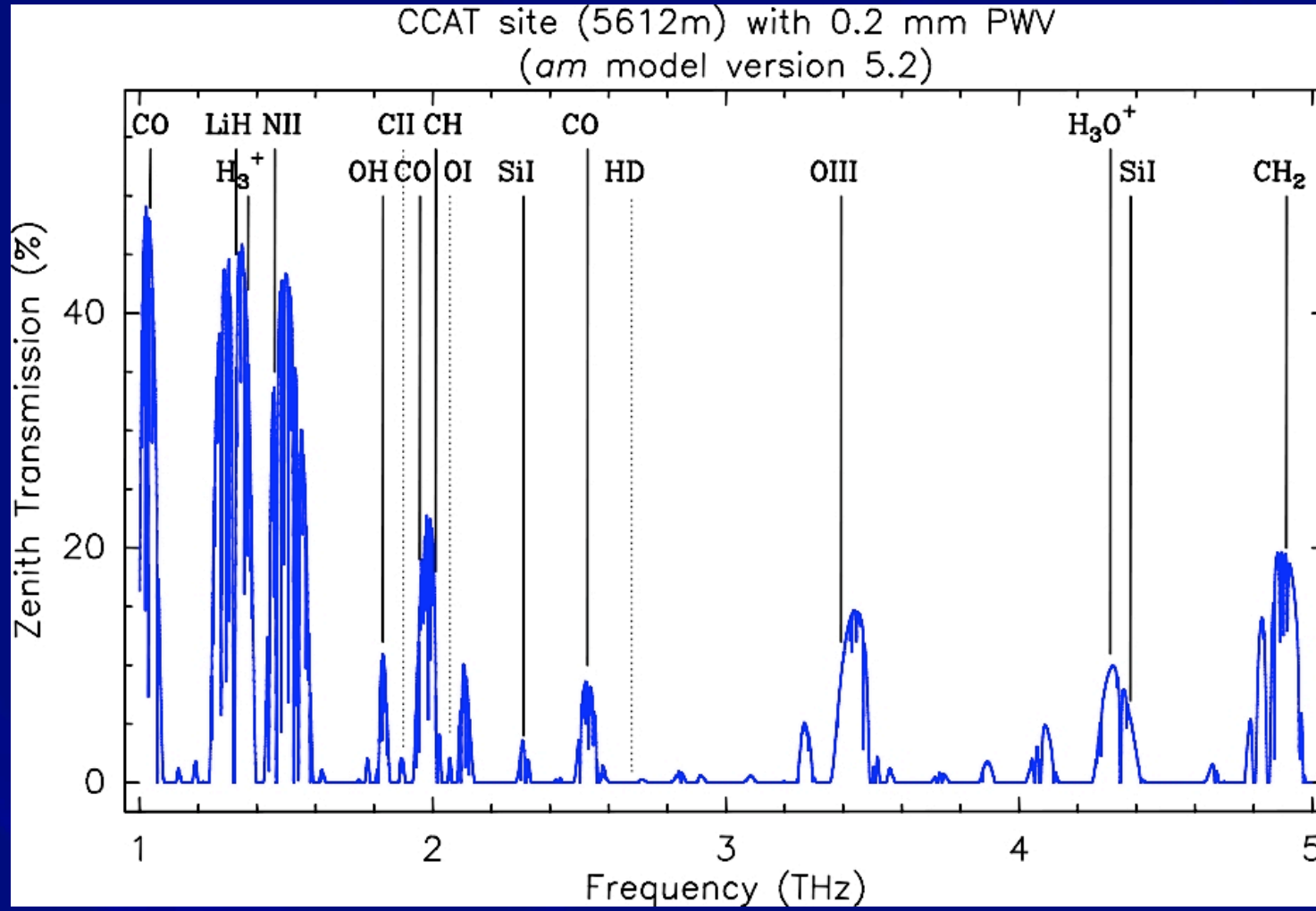
Table 1: Summary of Important Atomic and Molecular Transitions at THz Frequencies

Line	Transition	Frequency (THz) <sup>a</sup>	Approximate Co. Chajnantor	Transmission Antarctica <sup>a</sup> (%)
[OI]	$^3P_1 \rightarrow ^2P_2$	4.74	...	...
[OI]	$^3P_0 \rightarrow ^2P_1$	2.06	2	18
[OIII]	$^3P_2 \rightarrow ^2P_1$	5.79	??	38
[OIII]	$^3P_1 \rightarrow ^2P_0$	3.393	9	60
[CII]	$^2P_{3/2} \rightarrow ^2P_{1/2}$	1.901	1.5	20
[NII]	$^3P_2 \rightarrow ^2P_1$	2.459	...	...
[NII]	$^3P_1 \rightarrow ^2P_0$	1.461	32	??
[SiI]	$^3P_2 \rightarrow ^2P_1$	4.38	5.6	35
[SiI]	$^3P_1 \rightarrow ^2P_0$	2.31	2.7	27
[SI]	$^3P_0 \rightarrow ^2P_1$	5.323	...	...
H <sub>3</sub> <sup>+</sup>	1 <sub>0,1</sub> → 0 <sub>0,0</sub>	1.37 <sup>b</sup>	36	??
HD	1 → 0	2.68	...	..
LiH	3 → 2	1.329	30	??
H <sub>3</sub> O <sup>+</sup>	4 <sub>3</sub> → 3 <sub>3</sub>	4.31	10	??
OH	$^2\Pi_{1/2} J = 3/2^- \rightarrow 1/2^*$	1.83	11	40
CH	$^2\Pi_{3/2} J = 3/2^- \rightarrow ^2\Pi_{1/2} 1/2^*$	2.01	14	59
CH <sub>2</sub>	2 <sub>2,0</sub> → 3 <sub>1,4</sub>	4.93	18	..
CO	17 → 16	1.96	15	..
SiH	$^2\Pi_{1/2} J = 5/2 \rightarrow 3/2$	1.11	...	...
FeH	$^4\Delta_i, J = 9/2 \rightarrow 7/2$	1.41	...	...
MgH	N = 3 → 2	1.03	30	...

<sup>a</sup> Cerro Chajnantor (CCAT) transmission for 0.2mm PWV as shown in plot. Antarctic numbers for 0.1mm PWV from Townes and Melnick, PASP 102, 357 (1990). <sup>b</sup> Molecular Frequencies from <http://www.splatalogue.net> or CDMS



# Spectral lines in THz windows from CCAT



T. Hunter



# THz Region: Key to Chemical Evolution

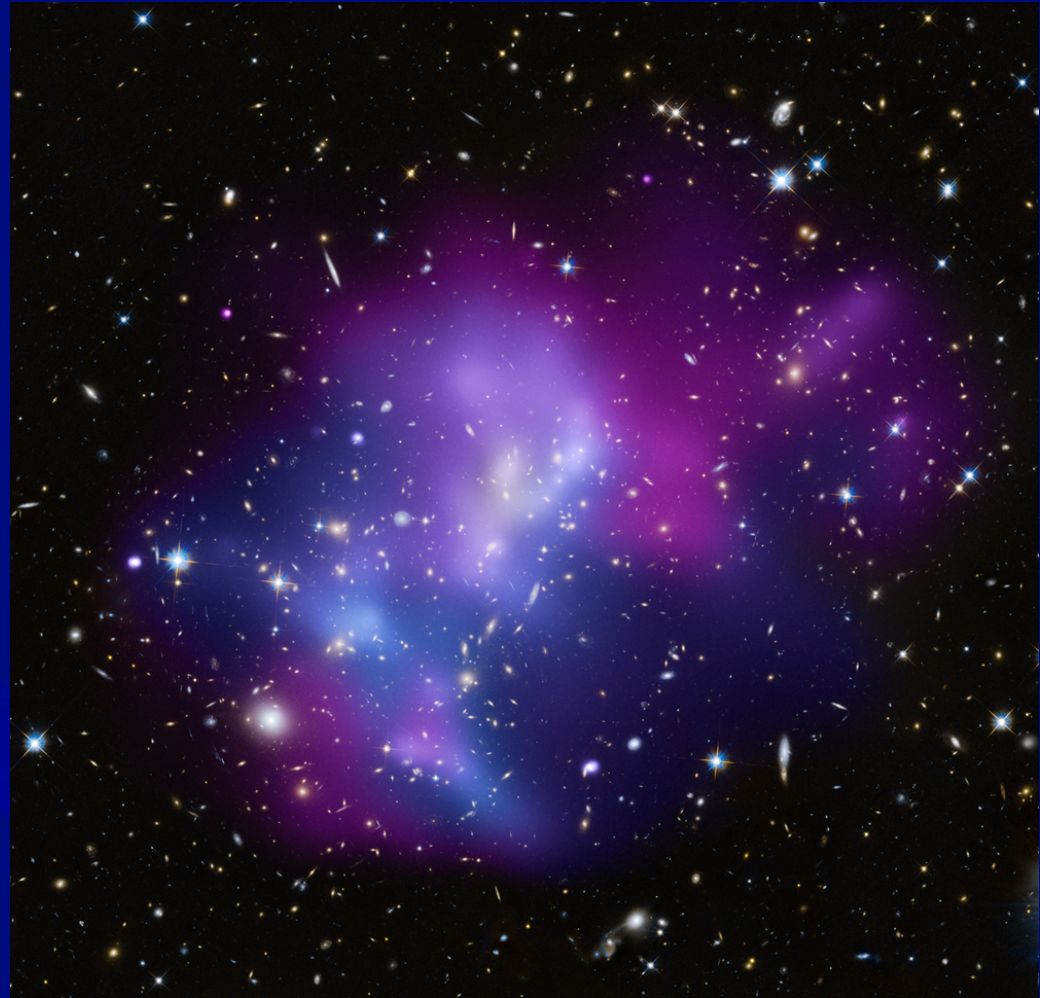
- Molecular Hydrogen cooled the first star-forming regions; at  $z > 6$  lines fall, with breaks, in windows accessible with ALMA
- The first now-abundant atoms were O, C, N, F
  - Atomic and molecular lines of C—CO CH Cl and CII are available for  $z > 1$
  - Atomic and molecular lines of O—OH H<sub>2</sub>O OI and OIII are available for  $z > 4$
  - As these elements were produced, they cooled the gas



# Massive Objects

MACSJ0717.5+3745

Four galaxy clusters collide at  
 $Z=0.55$





[www.alma.info](http://www.alma.info)

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