Tuna Lunch

June 2, 2009 – Charlottesville, Va.

NRAO and the AS2010

Overview of the ALMA submission to the DS2010 Instrumentation Panel.

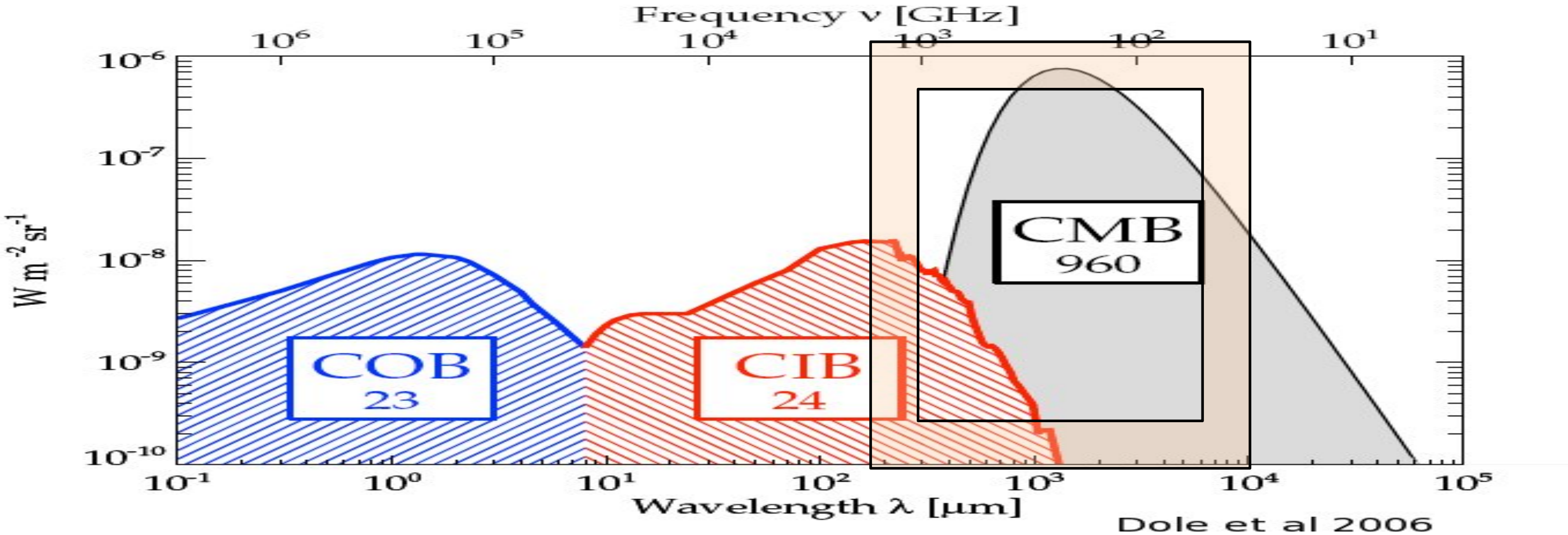
A. Wootten (Project Scientist/NA)

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

The ALMA Partnership

- ALMA is a global partnership in astronomy to deliver a truly transformational instrument
  - North America (US, Canada, Taiwan (NSC))
  - Europe (via ESO)
  - East Asia (Japan, Taiwan (AS))
- Located on the Chajnantor plain of the Chilean Andes at 16500'
- ALMA will be operated as a single Observatory with scientific access via regional centers
  - North American ALMA Science Center (NAASC) is in Charlottesville
- The NSB approved budget for ALMA is $499.3M
  - Total Global Budget ~$1.3B

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. How much power is in spectral lines?

Atacama Large Millimeter/submillimeter Array

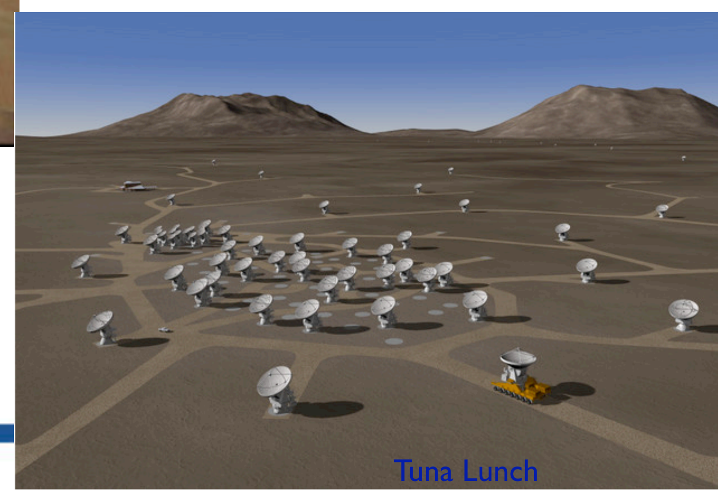
ALMA

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



ALMA – Major Elements

Fifteen+ antennas now in Chile

Fourth ALMA Production Antenna Jun 4

Photo H. Heyer (ESO).

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

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

NRAO

ALMA Phases

- Construction now declining, Operations continuing rampup.
- Continued Development was featured in the Ops Plan, reviewed by Intl Committee and by NSF Committee then adopted by Board.
- No funding agency funds a 'pig in a poke', the character of development must be defined. This is up to the ALMA Board, now pondering.

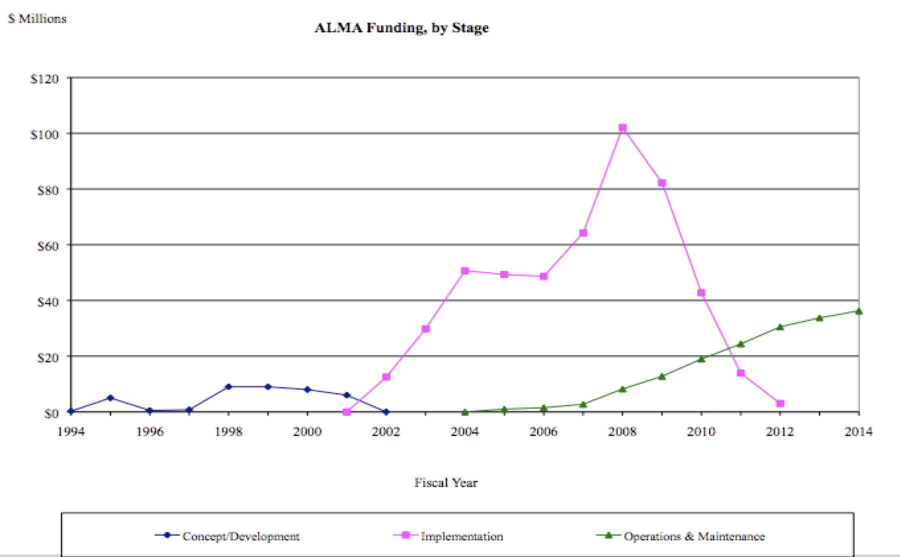
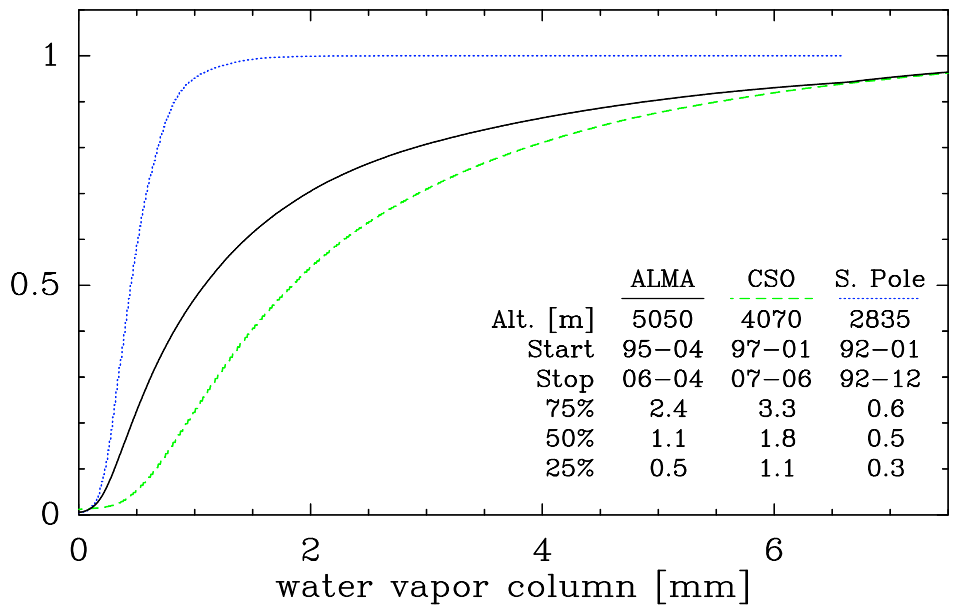


Table 3. Summary of ALMA Development Federal Funding Profile From the operations plan, NSF share, escalated to then-year USD

Fiscal Year	Proposed Development Funding
FY2010:	$ 30k
FY2011:	$ 476k
FY2012:	$1124k
FY2013:	$1995k
FY2014:	$3533k
FY2015:	$5129k

How can I find the ALMA Site?

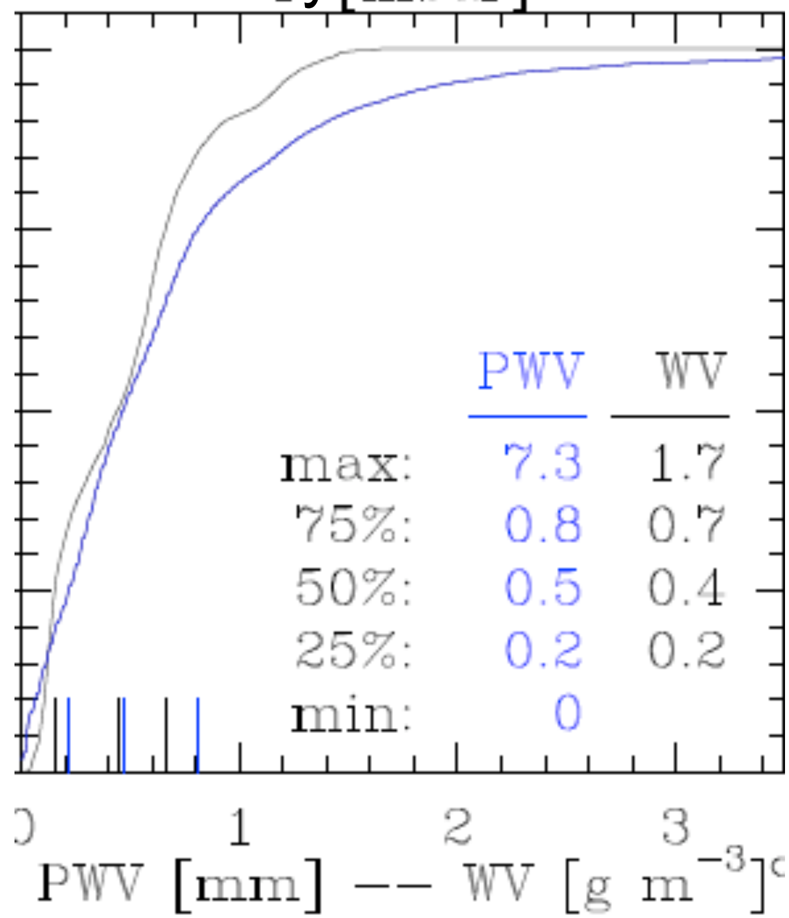
Eleven Years of Data



PWV < 200 µm for ~10% of time

Can be better in winter

APEX July 2008



Chajnantor: An Excellent Site for THz Astronomy

Data courtesy S. Radford

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 ~17 μm and has remained stable.
•Observations have been published which were made in the 1.4 THz atmospheric window.

•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 prototypes!
•What are ALMA's science goals and how do they drive development?

NRAO

ALMA Science Requirements

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

- *Spectral line CO/C^+ in z=3 MWG < 24hrs*
- *resolve ProtoPlanetaryDisks at 150 pc – gas/dust/fields*
- *Precise 0.1" imaging above 0.1% peak*

- 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).

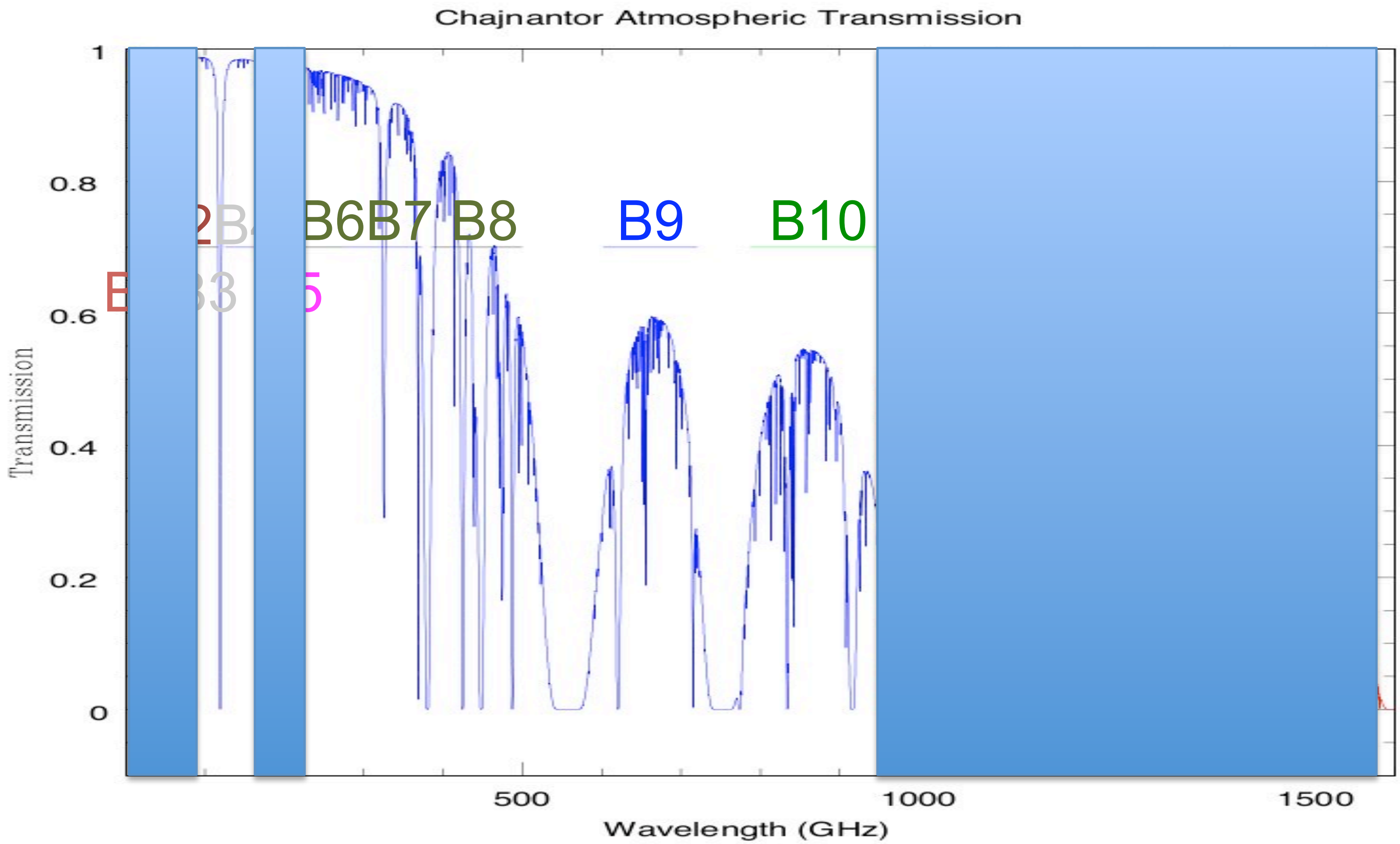
Technical Specifications

ALMA

- 50 12-m antennas, 12 7-m antennas, 4 TP 12m antennas at 5000 m altitude site.
  - 14 antennas 'descoped' during rebaselining. Only ~47 operational at a given time!
- Surface accuracy ±25 μm, 0.6" reference pointing in 9m/s wind, 2" absolute pointing all -sky. First three antennas meet these; accurate to <±16 μm most conditions
- Array configurations between 150m to ~15 -18km.
- 10 bands in 31-950 GHz + 183 GHz WVR. Only 7 included in construction phase.
- 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 but no VLB capability
- 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

7 Bands in Construction Project—3 'descoped'



0.5mm PWV v<950 GHz 0.2mm PWV v>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 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!

Development Items for ALMA 2010-2020

- Science clearly benefits from improving
  - Throughput (collecting area, instantaneous bandwidth, uv coverage)
  - Bandwidth (all accessible frequencies)
  - Resolution
- Proposal: First implement unfunded construction scope
  - Unbuilt antennas (while production line remains open)
  - Unbuilt receivers (and consider bands not contemplated prior)
  - Unimplemented VLB capability
- Many other possibilities
  - ASAC Report
  - Correlator upgrade
  - Longer connected baselines
  - Are any science goals endangered to whose realization development could contribute?

ASAC Recommendations

ALMA

APPENDIX A: Interdependence of development issues

performance to be improved	development item	degree of improvement	speed/technical difficulti	cost	beneficial for
sensitivity	more antenna	add 5 antenna 10%	quick	expensive	all science
	new digital system/2GC	10%	moderate	expensive	all science
	receiver development (lower noise)	10 - 20%?	moderate?	moderate?	all science
angular resolution	longer baseline	a factor of a few	easy/quick but phase stability issues (including atmospheric and LO reference) should be improved as well	expensive?	limited brightest sources
	VLBI	orders of magnitude	easy/quick?	cheap	Sgr A* and very limited bright and compact sources
field of view	multi-beam receiver	a factor of a few?	long/tough? Enhance correlator power is also required?	expensive?	almost all science (but for compact sources)
	under-illuminated feed	a factor of a few	moderate?	moderate	Solar obs only
spectral coverage	band 1		medium-term	moderate	SZ, redshifted lines, protoplanetary disks, solar
	band 2		medium-term	moderate	SZ, redshifted lines, protoplanetary disks, solar
	band 5		medium-term	moderate	redshifted lines, planetary atmosphere
	band 11		long-term	moderate?	redshifted atomic lines, galaxies?
simultaneous frequency coverage	multi-frequency feed	a factor of a few	moderate? Enhance correlator power is also required (for narrow band observations BLC can accommodate?)	moderate?	almost all science?
	receiver development (wider frquency coverage)	a factor of a few?	moderate? Enhance correlator power is also required to cover whole wide freq. range?	moderate?	ISM, galaxies?
	new digital system/2GC	an order of magnitude? (at high spectral resolution mode)	moderate	expensive	ISM, galaxies?
imaging quality	more antenna	add 5 antennas ==> ~13% gain?	quick	expensive	targets with extended structures
	more 7m antenna	?	moderate?	expensive?	targets with extended structures
	software development	??	all	moderate?	all science
accuracy of amplitude	improved calibration device	???	difficult?	??	ISM?
accuracy of phase	improved atmospheric correction	???	difficult?	??	almost all science which requires high angular resolution
accuracy of polarization	improved calibration device	???	difficult?	??	star formation, ISM

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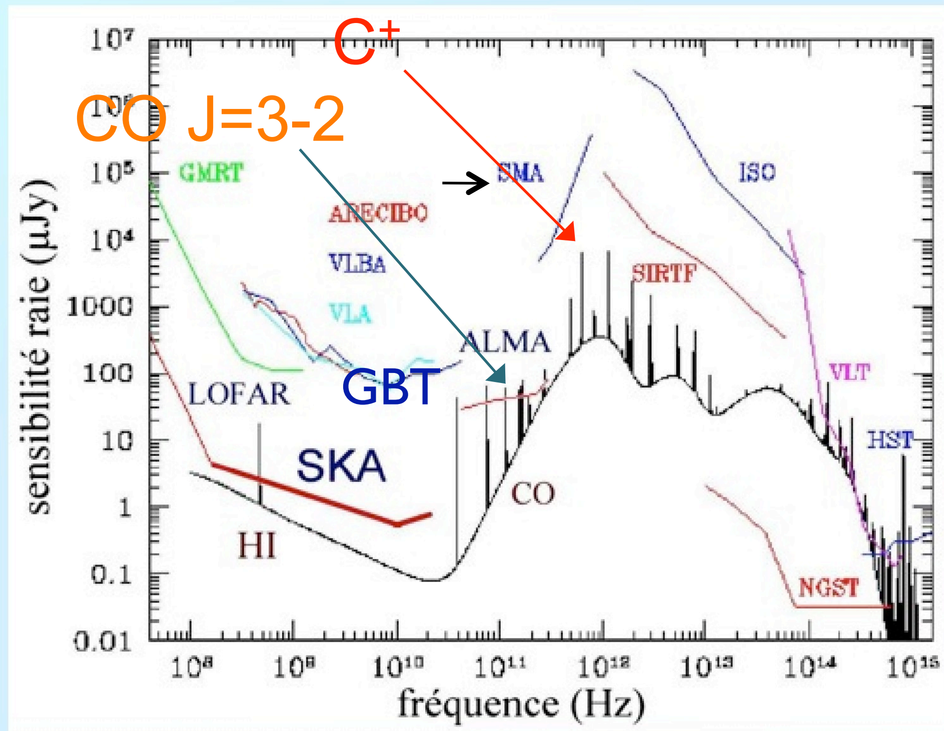
Tuna Lunch

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 'tall pole' atomic lines in the THz region, including C^+

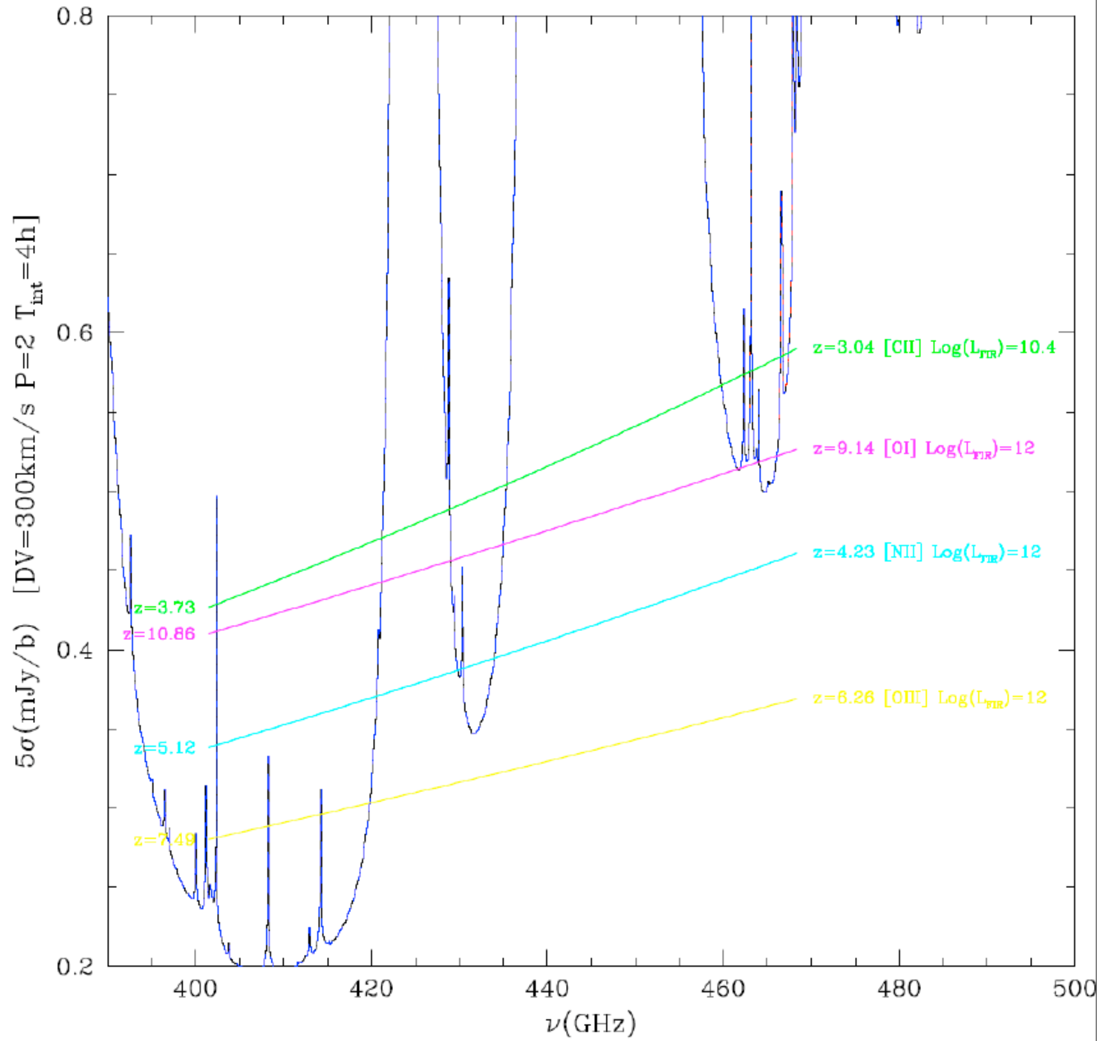


Detection of spectral lines of a 'standard' spiral galaxy at $z = 2$

5σ in 1hour

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.

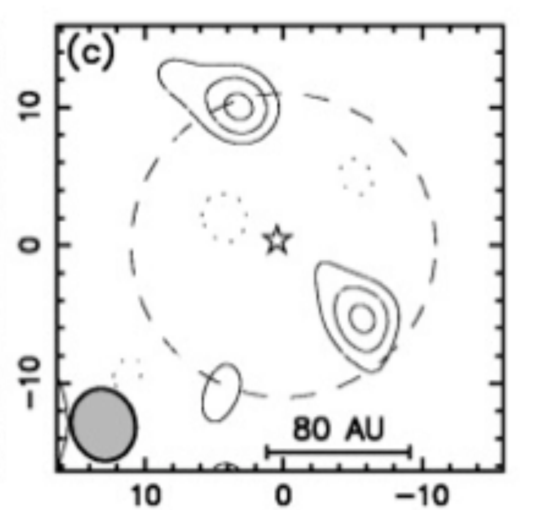
ALMA could track the very creation of the Universe’s ‘metals’.

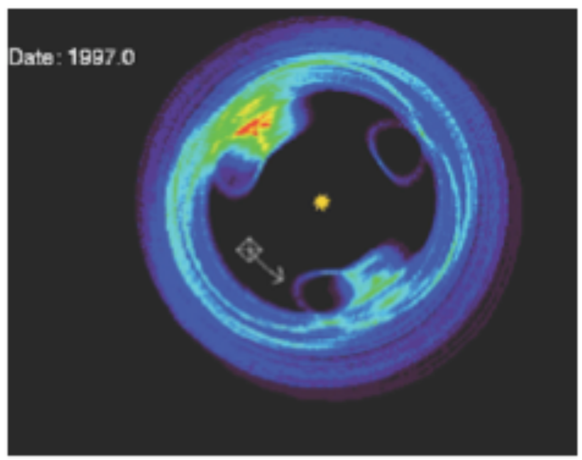
Birth of Stars and Planets

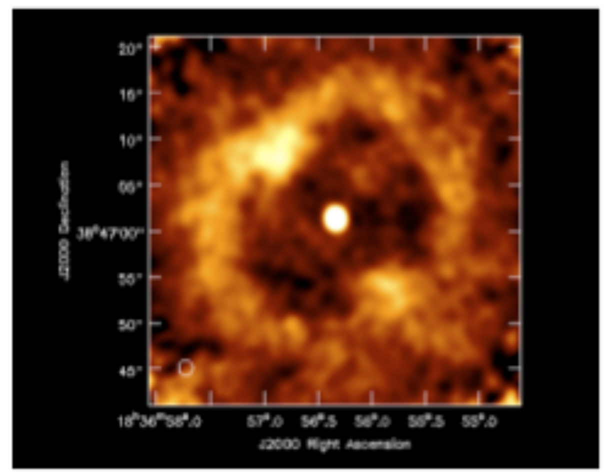
Evolutionary Sequence—
Molecular Cloud Core to Protostar (10^4 yrs) to
Protoplanetary Disk (to ~10^6 yrs) to
Debris Disk (to 10^9 yrs)

Wyatt 2???

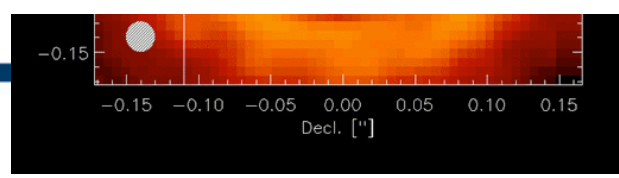
Reid et al 2008







Vega Dust Disk



Highest Level Science Goals

Bilateral Agreement Annex B:

"ALMA's third level-1 science requirement:

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. "

Imaging Ability

- 2005 NRC Panel:
  - "Two of the Level-1 science goals, involving sensitivity and high-contrast imaging of protostellar disks, will not be met with either a 40- or a 50-antenna array. It is not clear if the third requirement, on dynamic range, can be met with a 40-antenna array even if extremely long integrations are allowed for.
  - "Speed, image fidelity, mosaicing ability,2 and point-source sensitivity will all be affected if the ALMA array is descoped. The severest degradation is in image fidelity, which will be reduced by factors of 2 and 3 with descopes to 50 and 40 antennas, respectively.
  - "Despite not achieving the level-1 requirements, a descoped array with 50 or 40 antennas would still be capable of producing transformational results, particularly in advancing understanding of the youngest galaxies in the universe, how the majority of galaxies evolved, and the structure of protoplanetary disks, and would warrant continued support by the United States."
- Holdaway memo 'Image Quality as a Function of the Number of Antennas in ALMA'

H

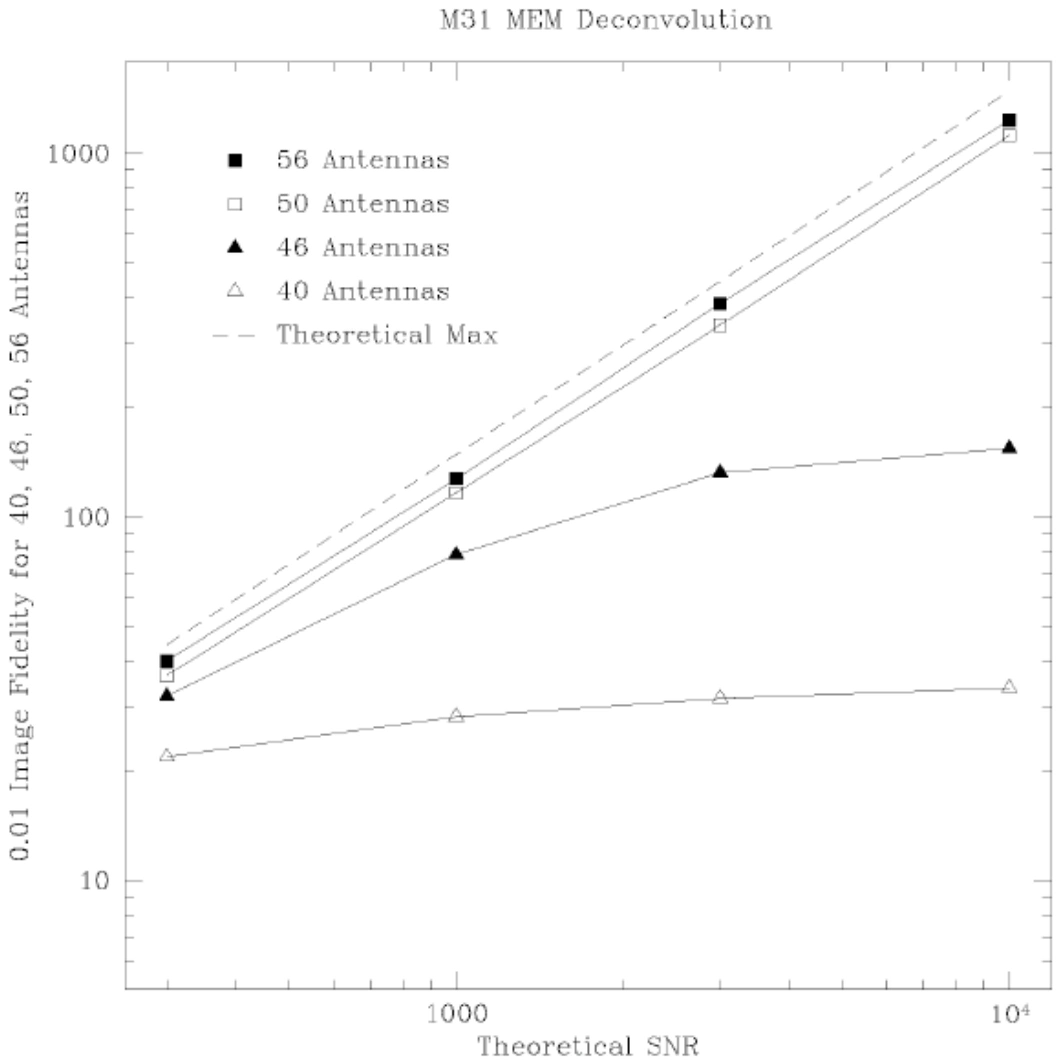


Figure 8: For the M31 model imaged with MEM, the 0.01 image fidelity as a function of SNR for 56, 50, 46, and 40 antenna configurations.

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Summary of Enhanced ALMA2020+

Table 2. Summary of ALMA Receivers

Band[a]	Frequency (GHz)	T^{b}_{SSB} (K)	Configuration of Receiver	Continuum[c] ΔS (mJy[c])	Spectral Line[d] ΔS (mJy)	Beam[e] (arcsec)
1	**31 - 45**	*17*	HEMT	0.03 (0.023)	8.5	0.12
2	**67 - 90**	*30*	HEMT	0.04 (0.032)	8.5	0.06
3	84 - 116	41	2SB	0.040 (0.03)	7.0	0.038
4	125 - 163	51	2SB	0.06 (.046)	7.1	0.030
5	**163 - 211**	*65*	2SB	0.075 (0.059)	4.9	0.021
6	211 - 275	83	2SB	0.10 (0.075)	10.2	0.018
7	275 - 373	147	2SB	0.18 (0.14)	16.3	0.012
8	385 - 500	196	2SB	0.28 (0.02)	22.6	0.010
9	602 - 720	175[f]	DSB	0.62 (0.49)	62.1	0.006
10	787 - 950	230[f]	DSB	1.1 (0.84)	56	0.005
11	**1255 - 1565**	*375*[f]	DSB	*11 (9)*	*450*	0.005

31-45 GHz Astronomy

- Redshifted CO lines
- Sunyaev-Zeldovich Effect
- Excellent probe of very dense dust disks
- debris disks
- chemistry of heavy organic species, carbon-chains, anions
- free-free emission from jets/outflows
- measuring B-field using Zeeman effect (CCS)
- spinning dust grains
- dust chemistry in AGB envelopes
- masers

67-94 GHz Astronomy

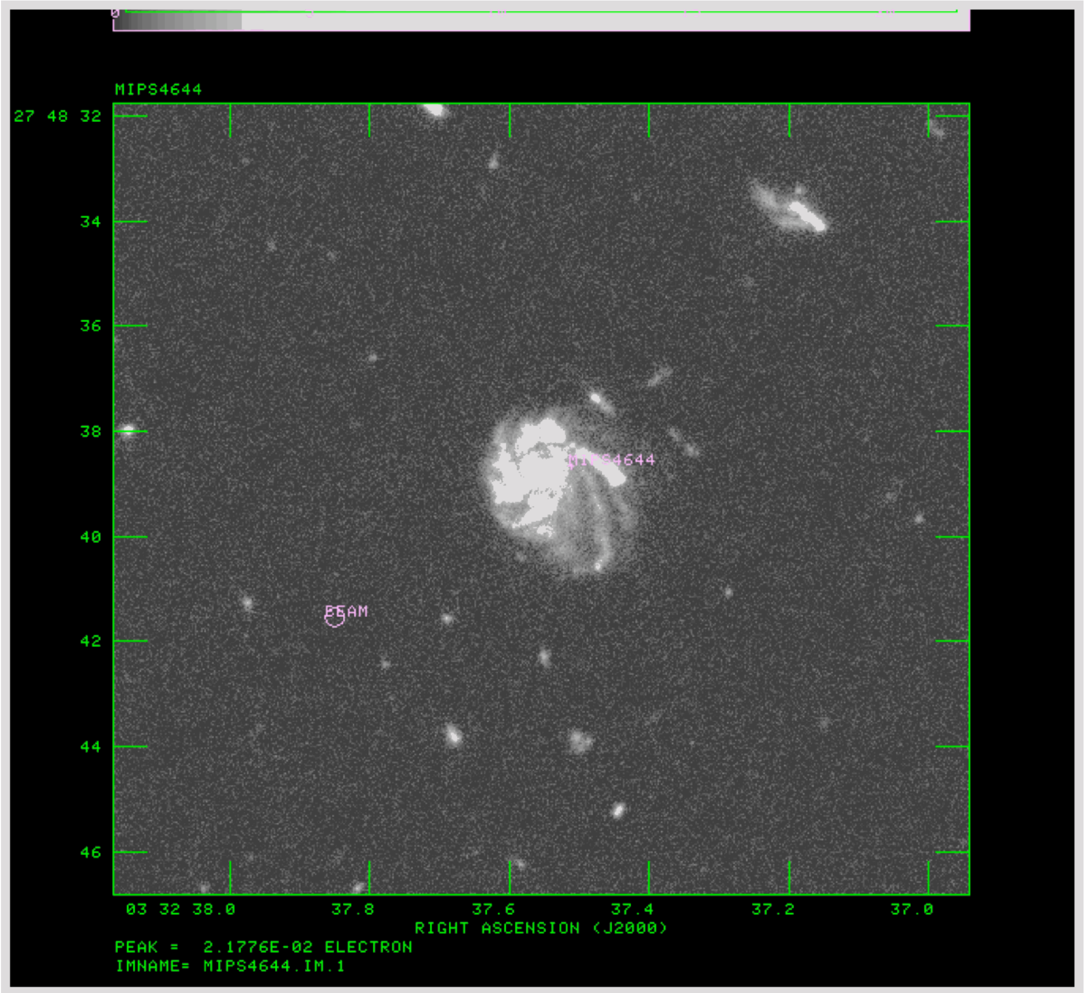
- 67-94 GHz: Resonance lines of abundant molecules
  - HCO^+, HCN, HNC, N_2H^+, H_2CO
- Resonance lines of their deuterium isotopomers
  - DCO^+, DCN, DNC, N_2D^+, NH_2D, NHD_2, HDO, CH_2D^+
- Underutilized band but rx technology straightforward
- Excellent probe of very dense dust disks
- Comets--PD zone often resolved, no missing flux.
- Redshifted CO, near and far

Extragalactic Targets

- Redshifted CO (including Milky Way at z~3)
- LIRGs 0.2<z<0.7
  - L_{IR}~5 L_{IR}(MW) ⇒L(CO)$_{1\text{-}0}$~5 L(CO)$_{1\text{-}0,\,MW}$
  - T_{sys}~250K SSB; Jy/K~0.8
  - 1σ 8 hrs 1mK 75 km/s (10μK km/s)
  - Could probably measure CO in ~two dozen MIPS-detected LIRGS in HDF falling in this redshift range
  - 'Age' 7.4-11.3 Gyr; Scale 24-50 kpc/beam
- Sunyaev-Zeldovich Effect

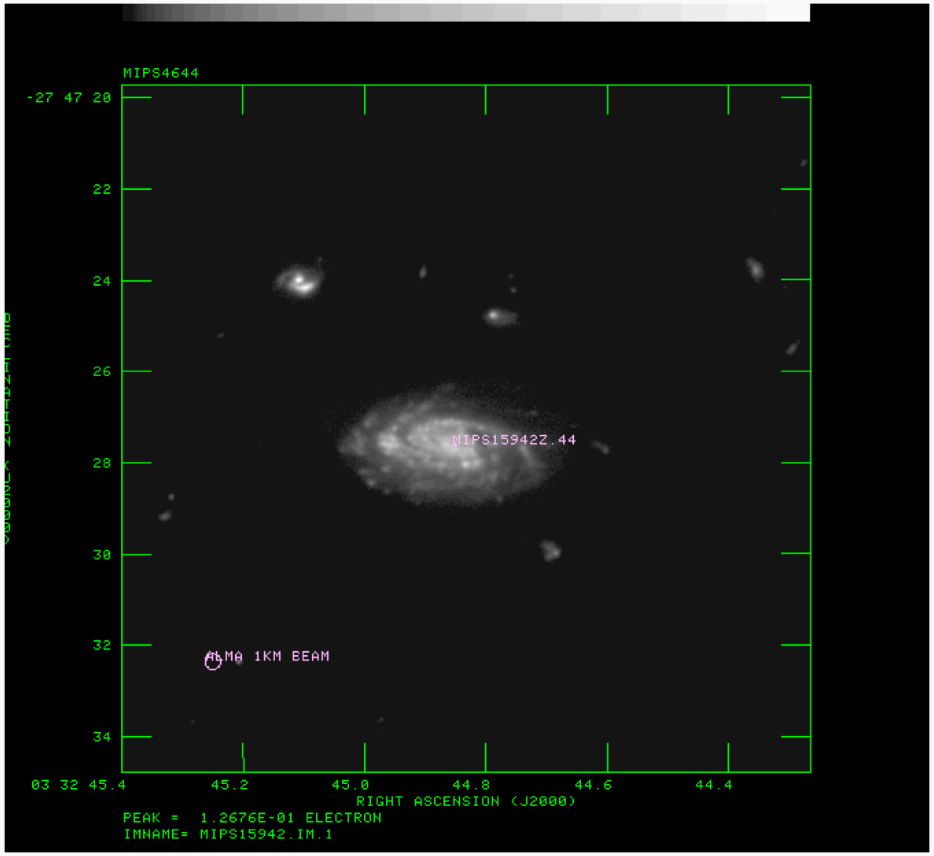
Examples

- MIPS4644, z=0.67
- Note ALMA synthesized beam



Examples

- MIPS15942, z=0.44



ALMA

67-94 GHz Astronomy

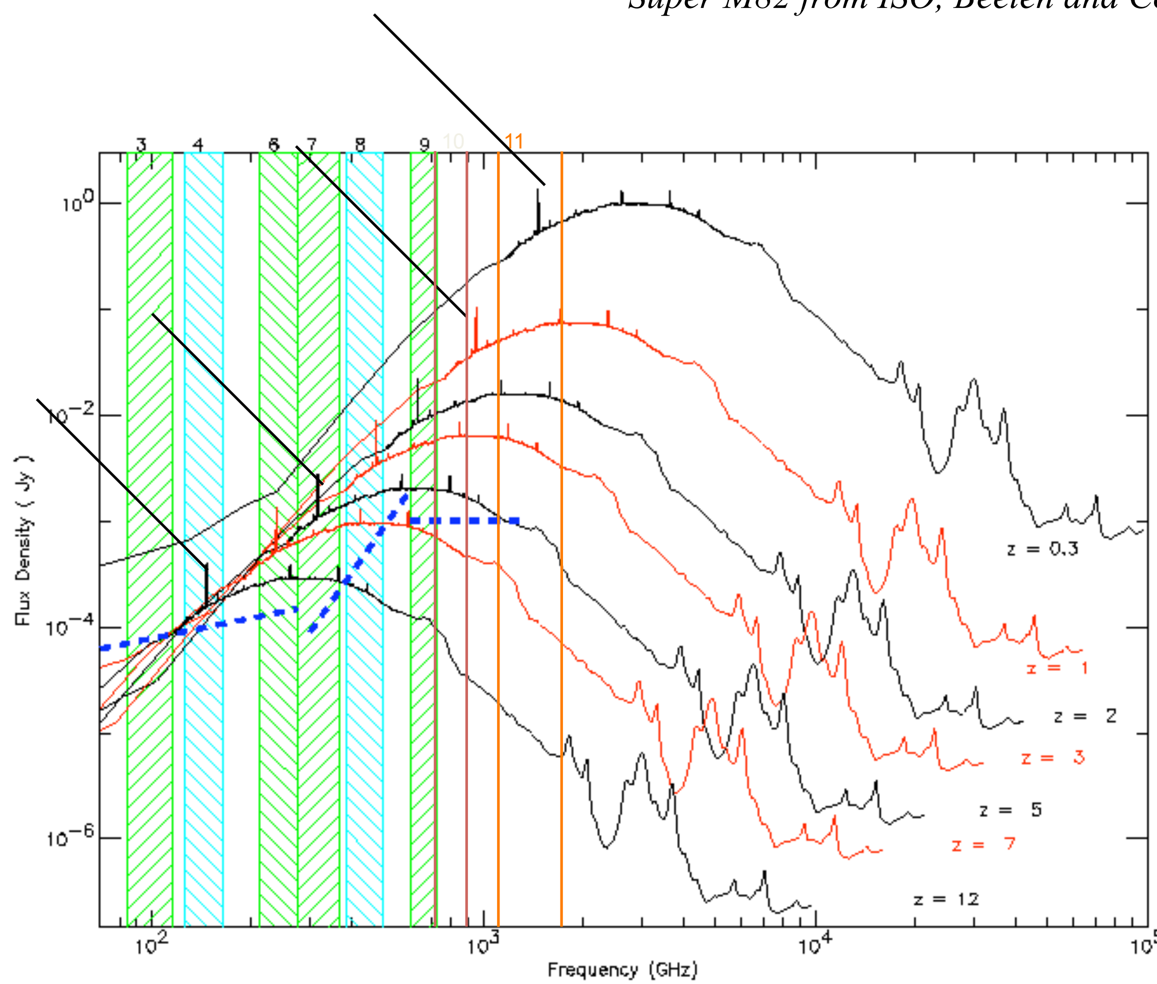
- 67-94 GHz: Resonance lines of abundant molecules
  - HCO^+, HCN, HNC, N_2H^+, H_2CO
- Resonance lines of their deuterium isotopomers
  - DCO^+, DCN, DNC, N_2D^+, NH_2D, NHD_2, HDO, CH_2D^+
- Underutilized band but rx technology straightforward
- Excellent probe of very dense dust disks
- Comets--PD zone often resolved, no missing flux.
- Redshifted CO, near and far

NRAO

Inverse K-correction, or magic of the submillimeter

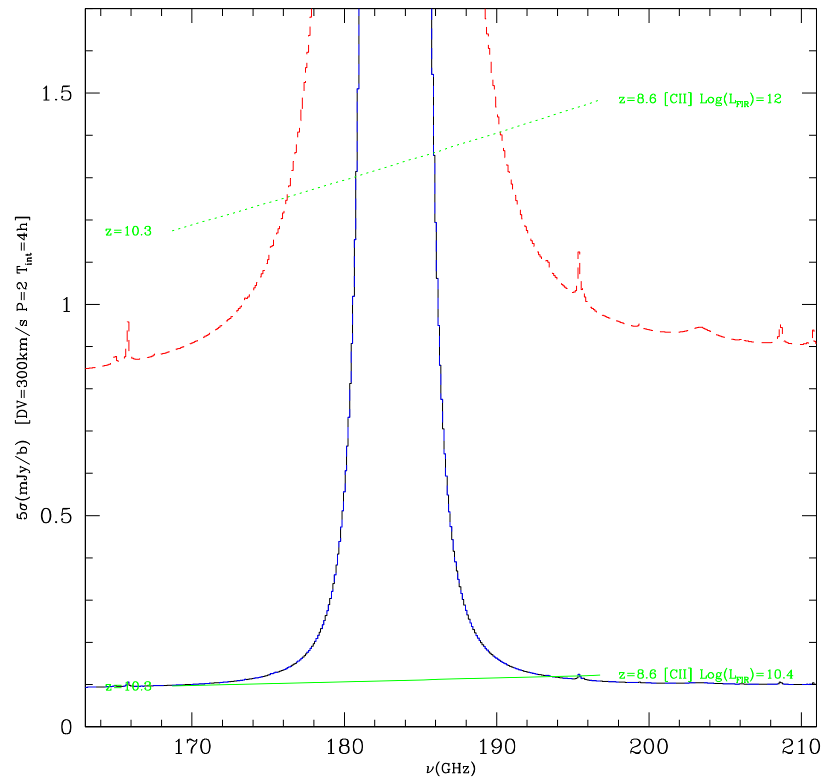
- As galaxies get redshifted into the ALMA bands, dimming due to distance is offset by the brighter part of the spectrum being redshifted in. Hence, galaxies remain at relatively similar brightness out to high distances. But first stars formed z~10… spectra differed.

Super M82 from ISO, Beelen and Cox

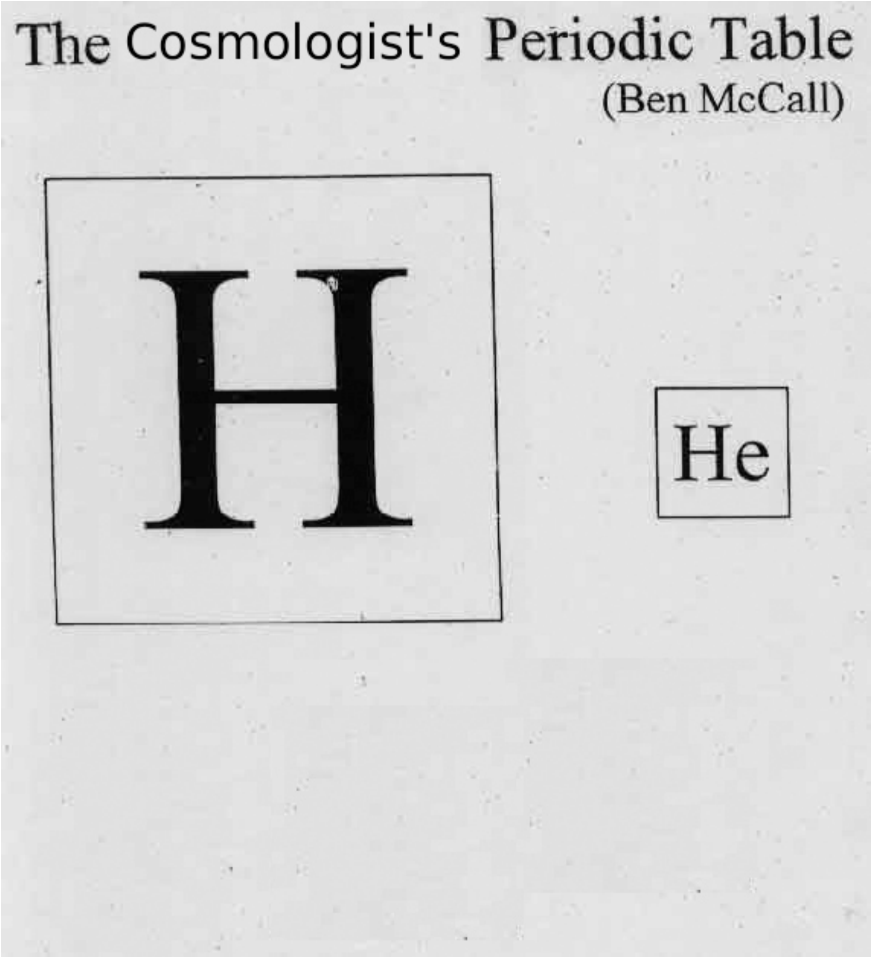


Band 5 (163-211 GHz)

- Water! High resolution Herschel followup
- Redshifted CO and z~10 C^+



'Band 11': Creation of the Metals



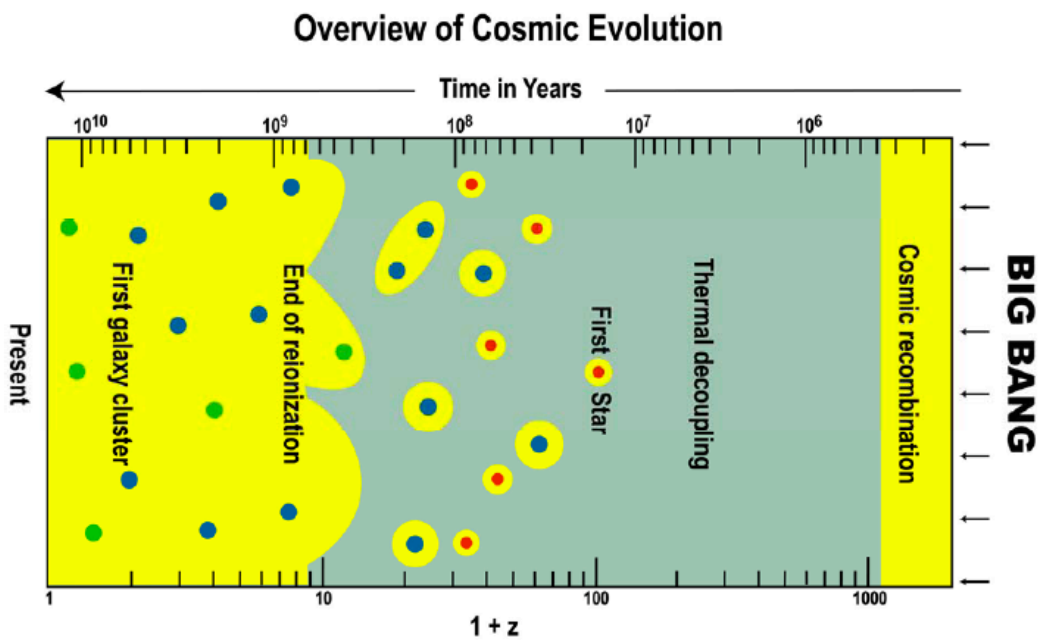
When chemistry got interesting (H_3^+, H_2D^+, H_2, HD notwithstanding)

ALMA should be able to monitor the creation of

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

ALMA

Opening Up the Dark Side of Reionization



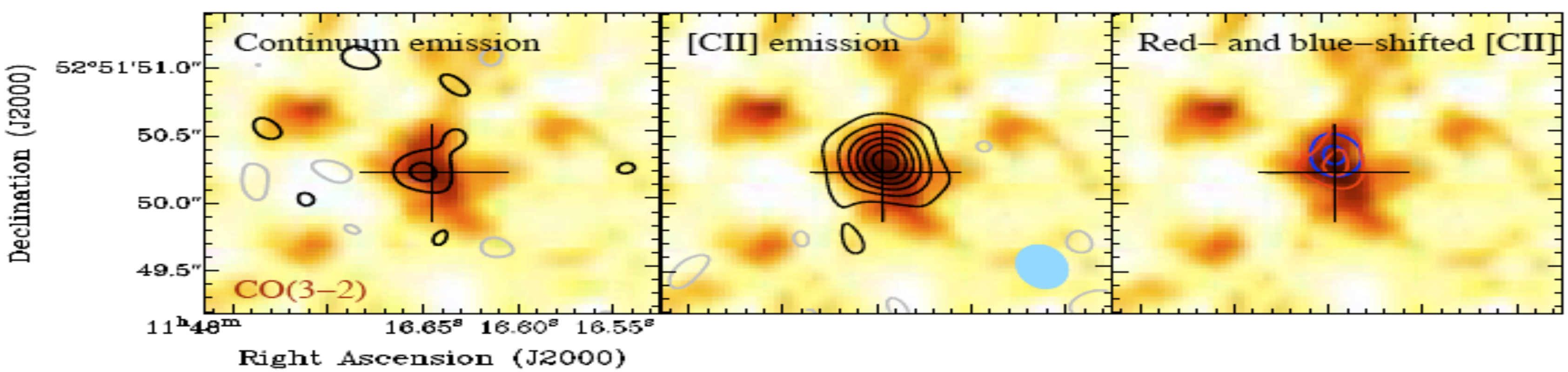
After R. Barkana

J1148+52: A Paradigm Distant Monster Galaxy

ALMA

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

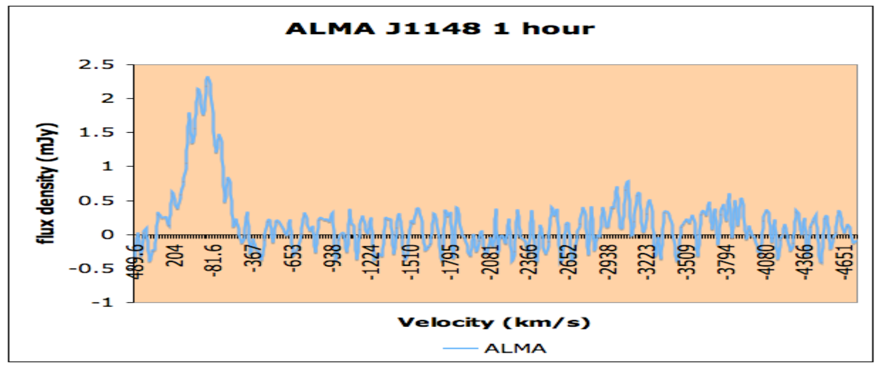
Walter et al 2009

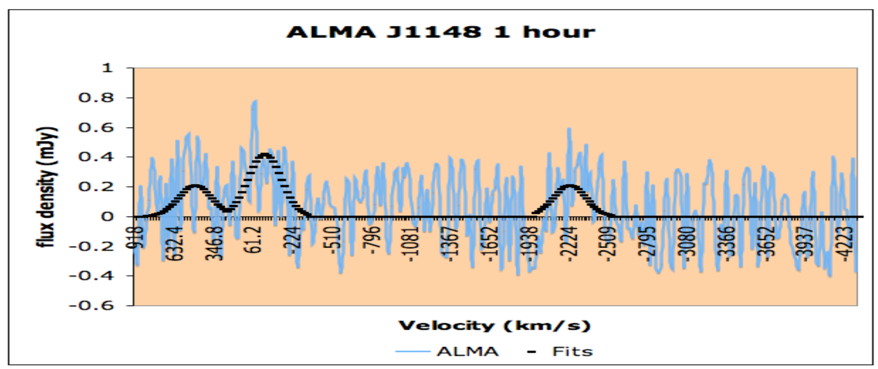


J1148+5251: an EoR paradigm with ALMA

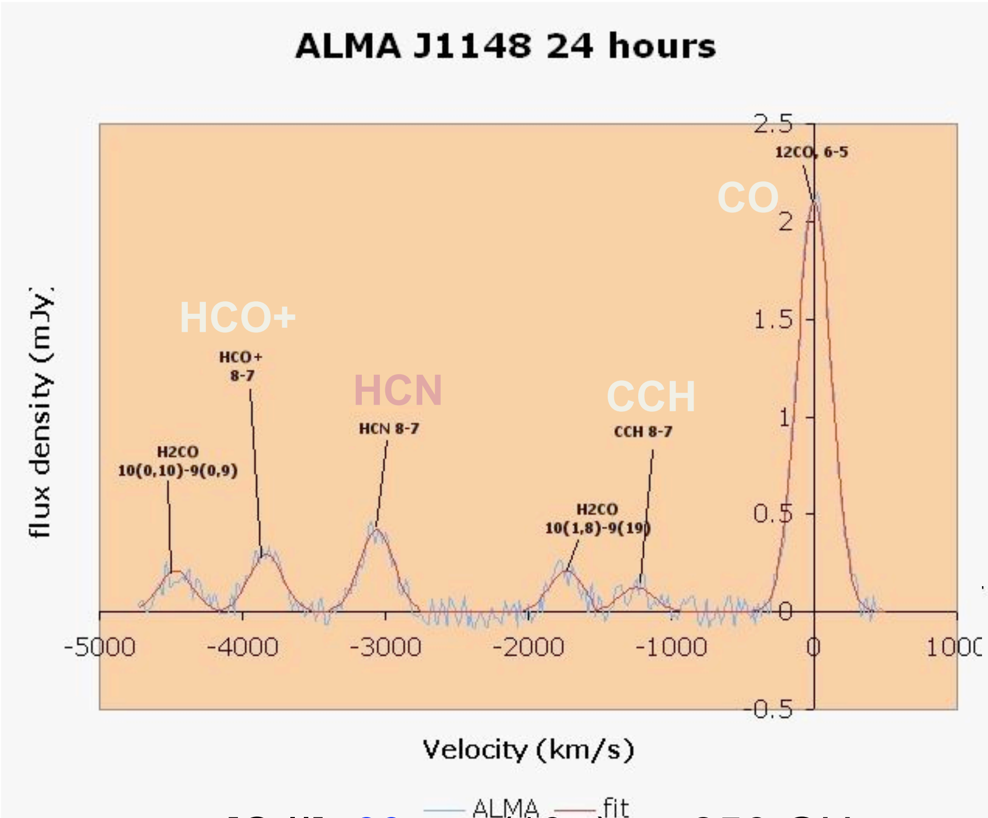
CO J=6-5

Wrong declination (though ideal for Green Bank)!
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_2CO lines
Lower: LSB, 86.8 GHz
HNC 7-6; H_2CO 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.





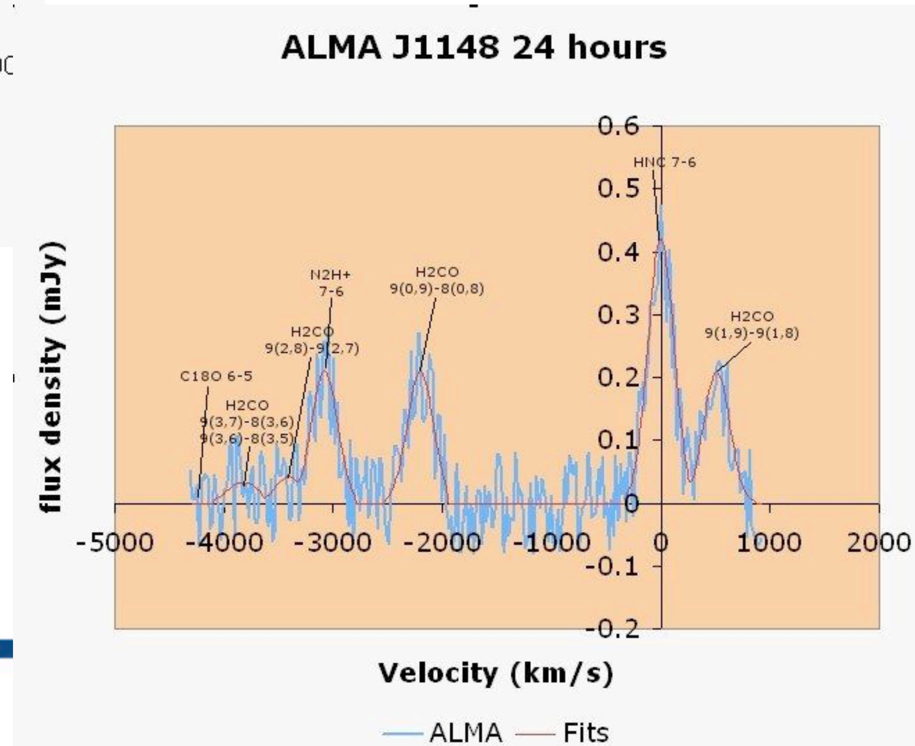
ALMA into the EoR



Spectral simulation of J1148+5251

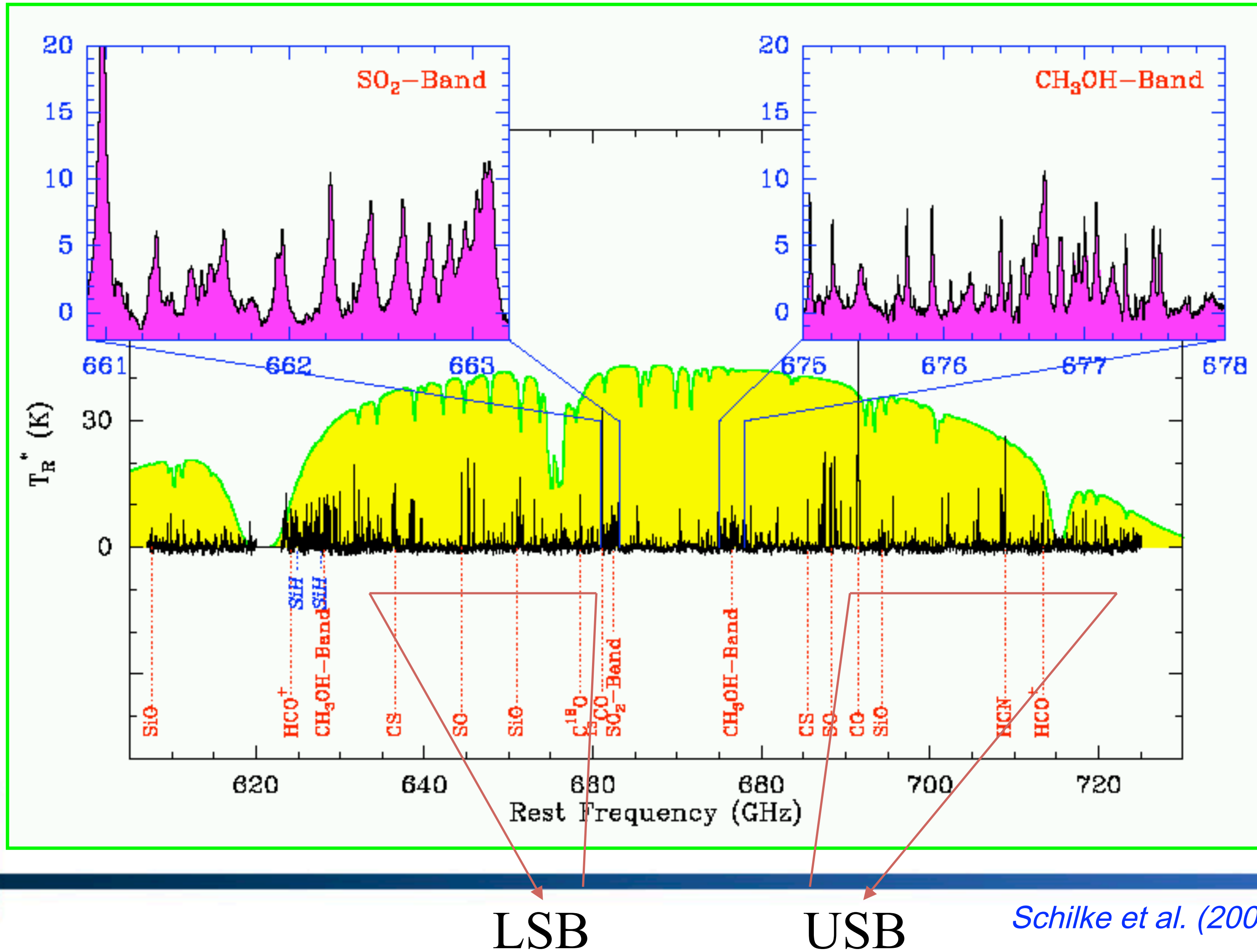
- Detect dust emission in **1sec** (5σ) at 250 GHz
- Detect multiple lines, molecules per band => detailed astrochemistry
- Image dust and gas at sub-kpc resolution – gas dynamics! CO map at 0".15 resolution

[C II]: **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



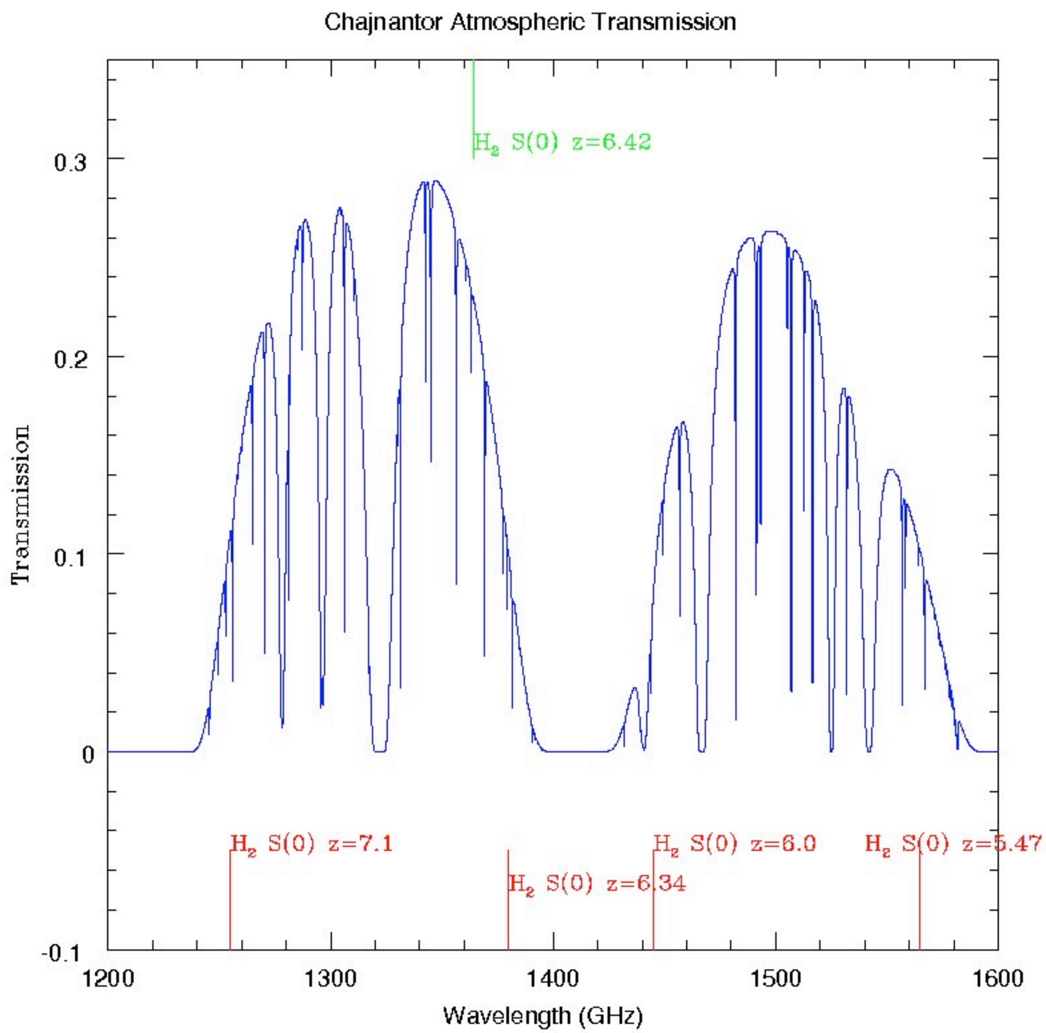
Schilke et al. (2000)

J1148: A possible (not from Chajnantor!) H_2 observation

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

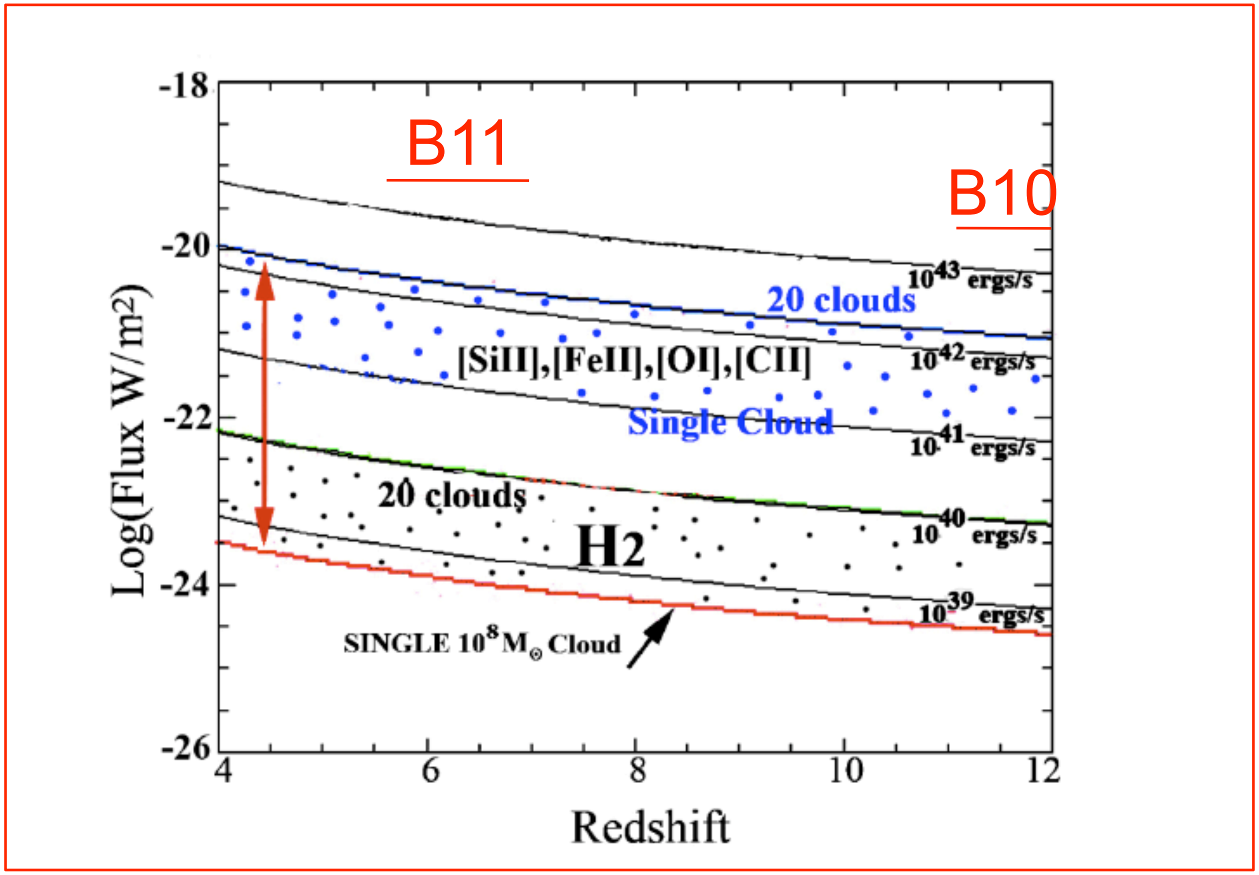
~1000 M_{sun}/yr/kpc^2
Region ~750 pc radius
Similar to Arp220 but 100 times larger

Mass ~2 10^{10} M_{sun}



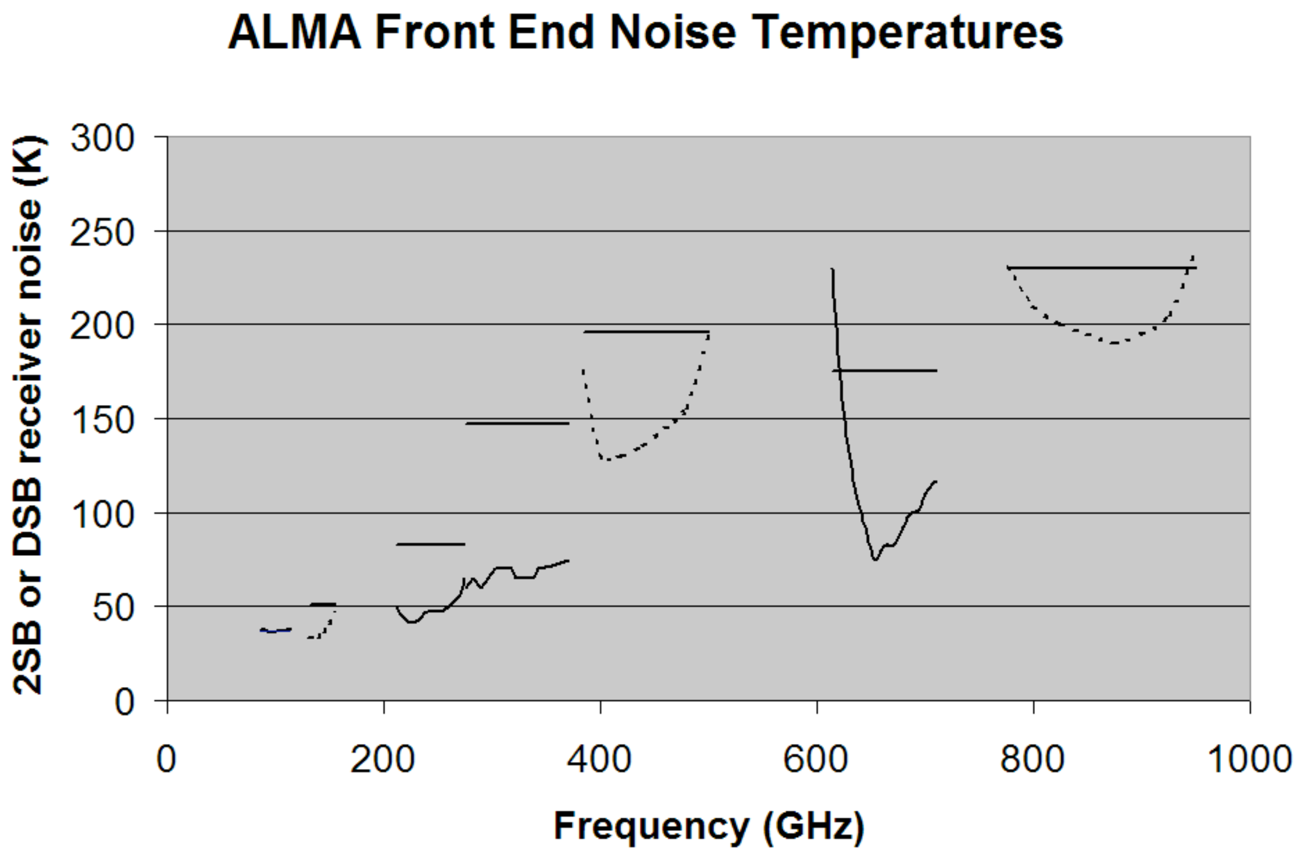
Dark Side of Reionization

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



After Appleton et al 2009

Wh



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  - 7 R … GHz

- *10-100 … resolution compa…*

VLB Capability

- ALMA as a very sensitive node in a breakthrough array could enable:
  - Imaging of the Black Hole at the center of our Galaxy
  - Few 10 microarcsec resolution
  - Include with sensitive elements elsewhere:
    - GBT 3mm and below
    - LMT to 345 GHz
    - CARMA, SMA, JCMT, CSO
- Element of SA Array (~1 milliarcsec resolution)
  - ALMA Prototypes on high Argentine peaks (Brazil-Argentina proposal)
    - Several tens milliarcsec astrometry characterizes exosolar planets
    - Stellar photospheres resolved with beams much below 1 milliarcsec
    - Measure motions of galactic masers
    - High resolution observations of extragalactic megamasers (compare with VLBA project)
  - Resited SMA (Sairecabur?)
  - CCAT (short baseline)

Push to Early Science

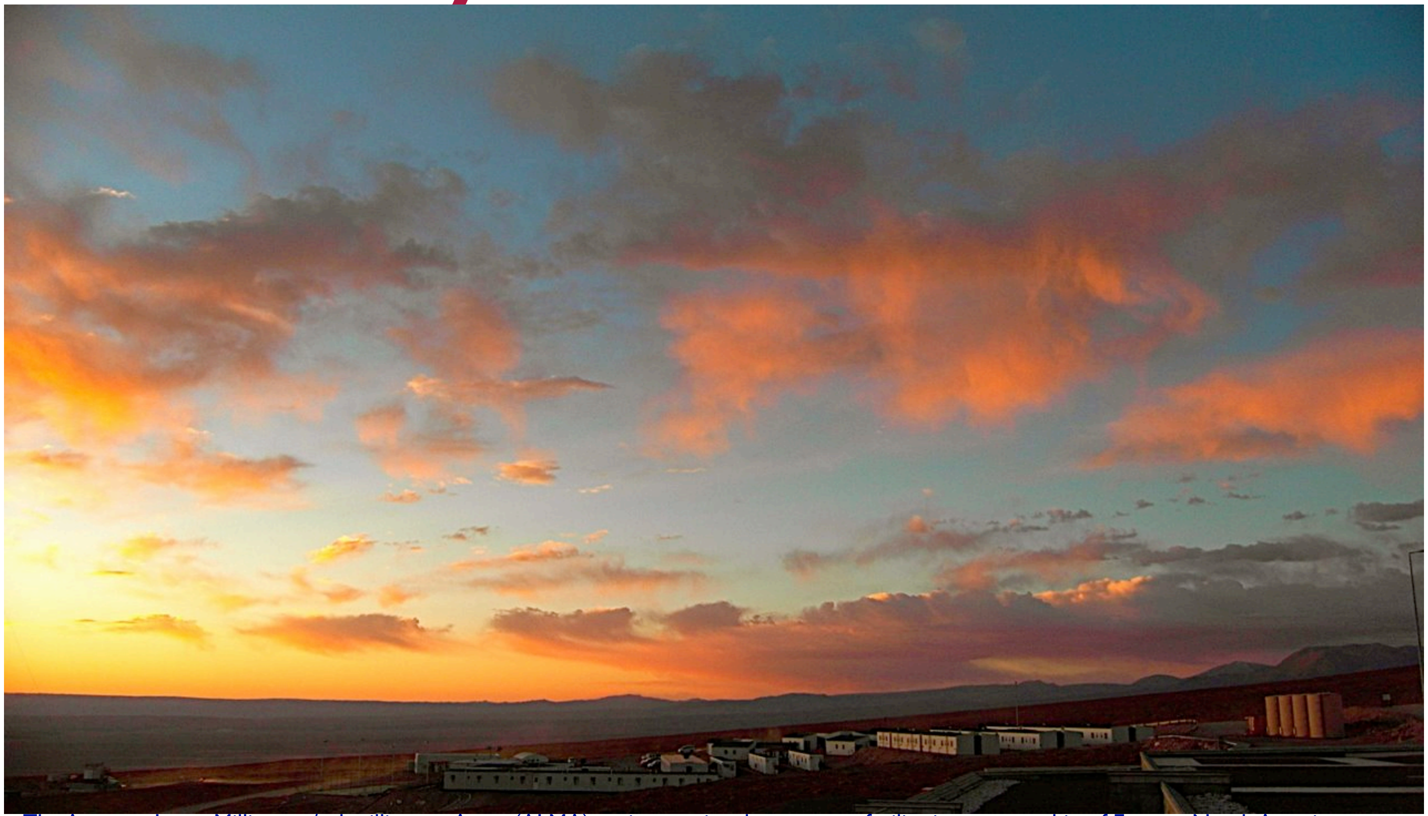
- Interferometry at 2900m June 2009 and onwards
  - Move past accomplishments at the ATF
  - Production equipment, for the most part
  - Still one baseline
- Antennas exiting AIV phases moved to 5000m Aug/Sep 2009
- Interferometry at 5000m Nov/Dec 2009
  - Beginning of Commissioning and Science Verification
  - First use of LO, correlators, B8, B9 and eventually B10
- Call for Early Science Proposals Dec 2010
- Early Science Q4 FY2011

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
- Synergies with GBT
  - Together, they cover the whole sky
  - ALMA's Field of View is limited—*finding* the interesting objects might best be done by arrays on large telescopes—GBT, LMT, CCAT
  - Two unbuilt ALMA bands overlap GBT coverage—prototyping e.g. 67-90GHz B2 ALMA receiver

ALMA is nearly here!

D. Barkats



The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and Eas cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.