# ALMA: Current Status and Science Opportunities

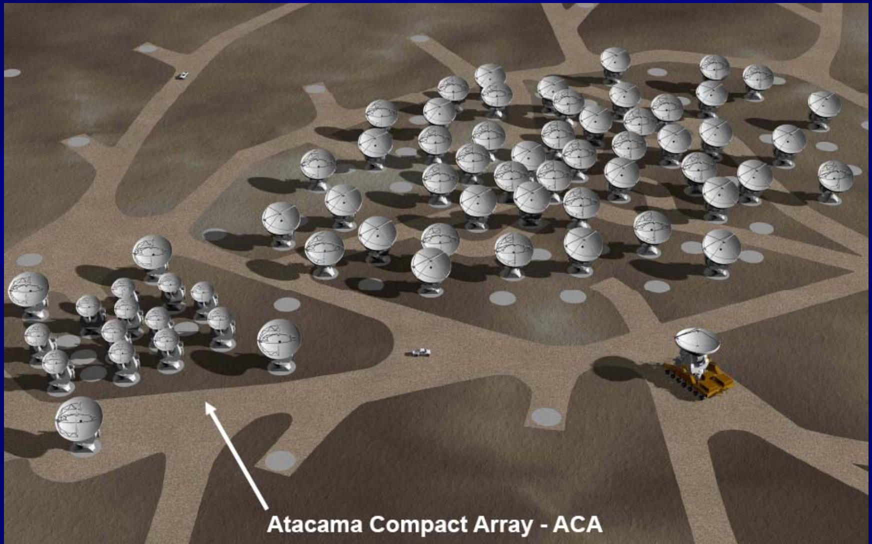
Crystal Brogan (NRAO/NAASC)

Bilateral China-US Astronomy Workshop, April 24, 2008

# What is ALMA?

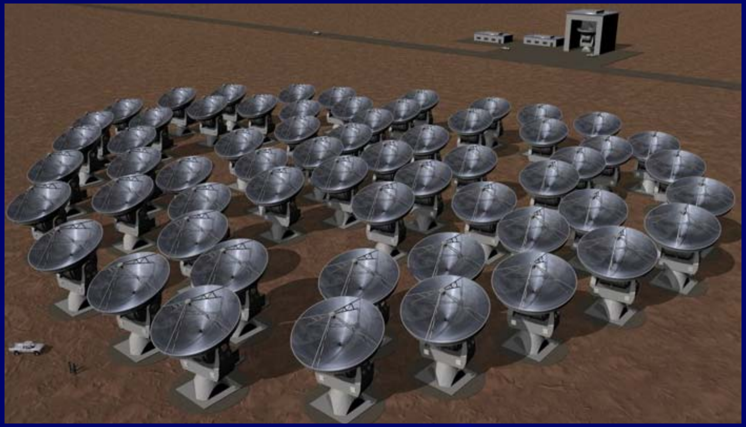
- A global partnership to deliver a transformational millimeter/submillimeter instrument
  - North America (US, Canada)
  - Europe (ESO)
  - East Asia (Japan,Taiwan, China)
- 5000m (16,500 Ft) site in Chilean Atacama desert
- Main Array: 50 x 12m antennas (up to 64 antennas)
  + 4 x 12m (total power)
  + ACA: compact array of 12 x 7m antennas
- Total cost ~1.3 Billion ($US)

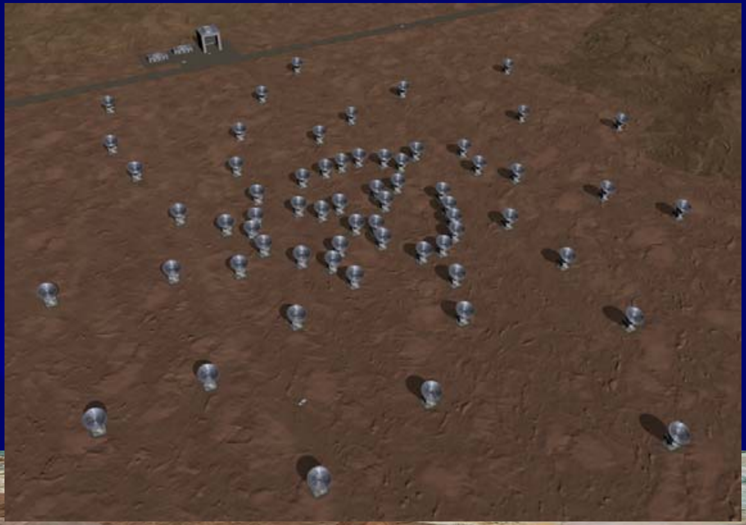
*10-100 times more sensitive and 10-100 times better angular resolution compared to current mm/submm telescopes*

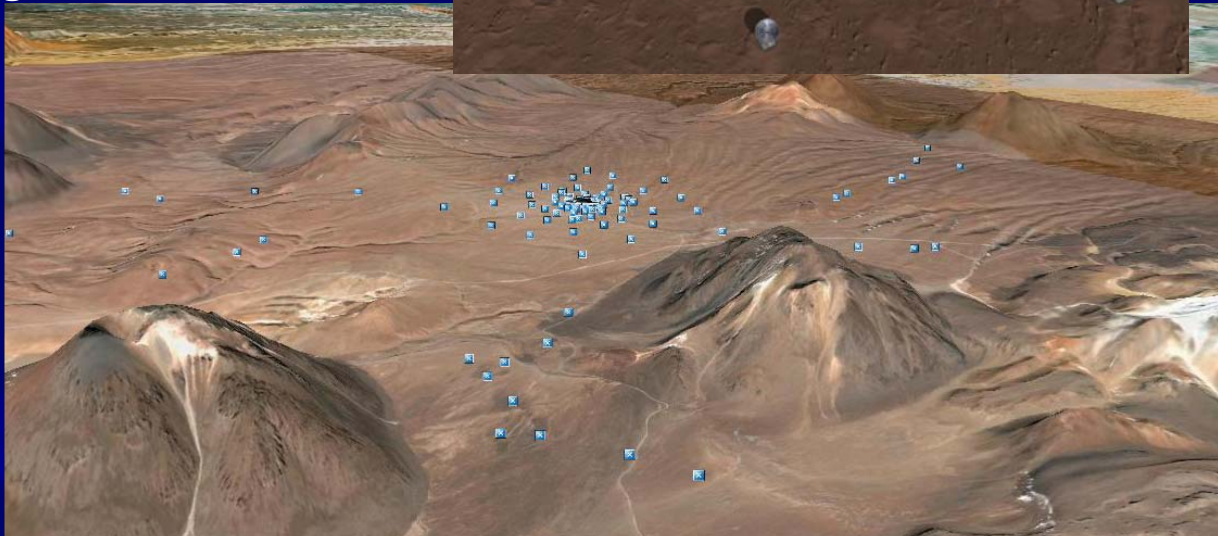


# What is ALMA?

- Baselines up to 15 km (0.015” at 300 GHz) in “zoom lens” configurations
- Sensitive, precision imaging between 30 to 950 GHz (7 mm to 350 μm)
- Receivers: low-noise, wide-band (8 GHz)
- Flexible correlator with high spectral resolution at wide bandwith
- Full polarization capabilities
- A resource for ALL astronomers including pipeline products and regional science centers







# Where is ALMA?

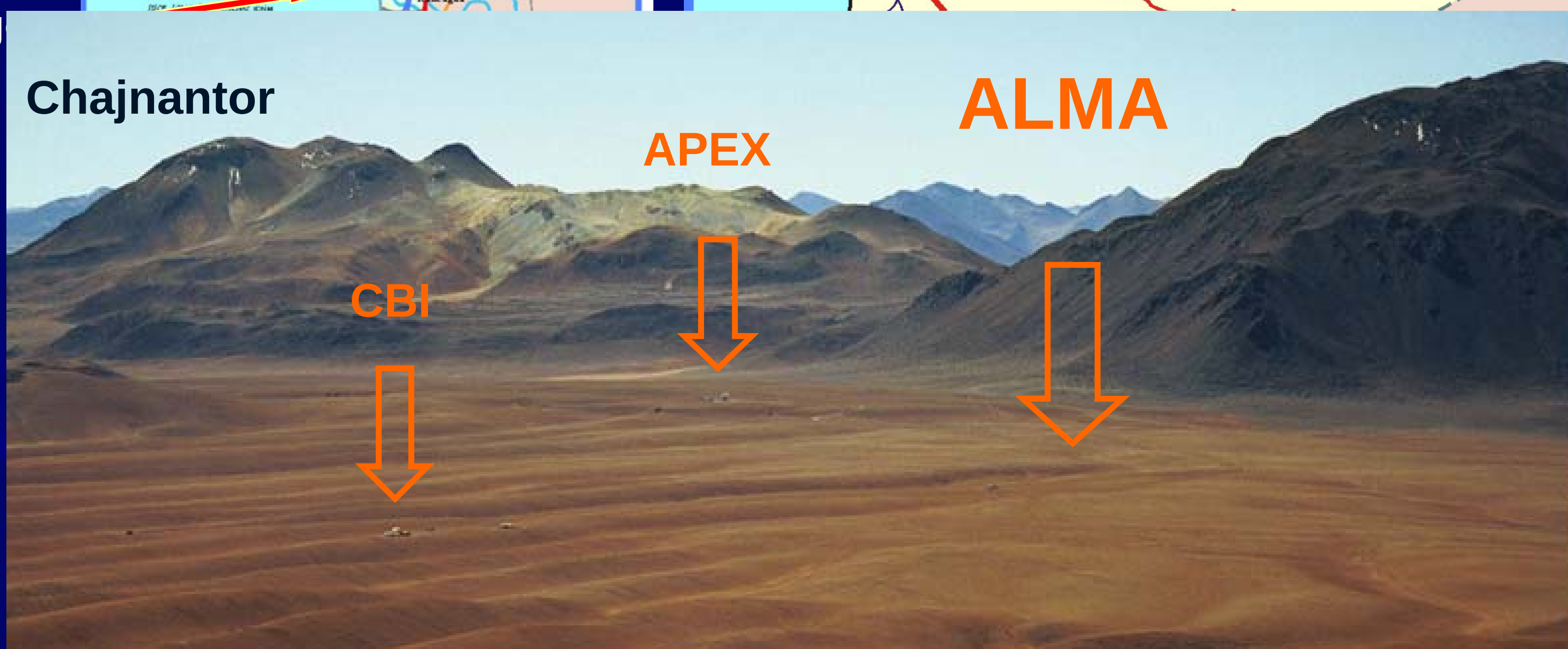
ALMA

Paranal

La Serena

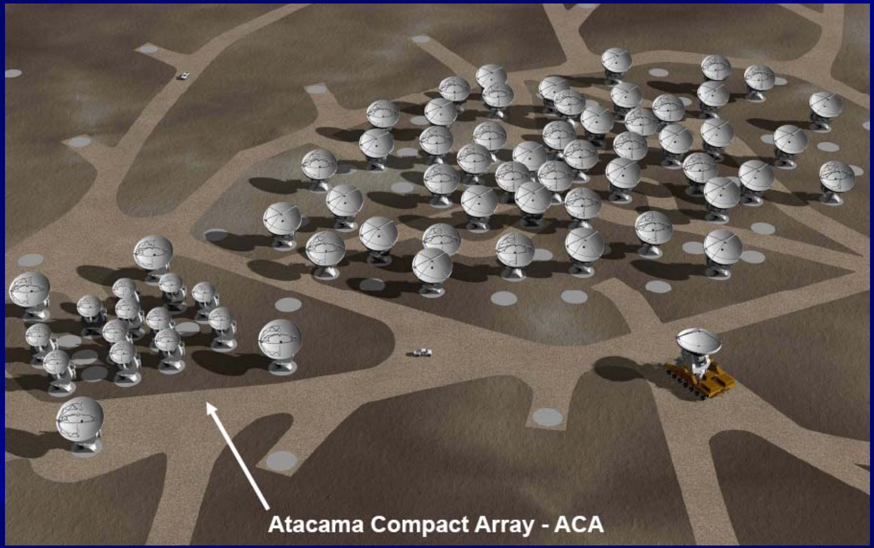
Santiago





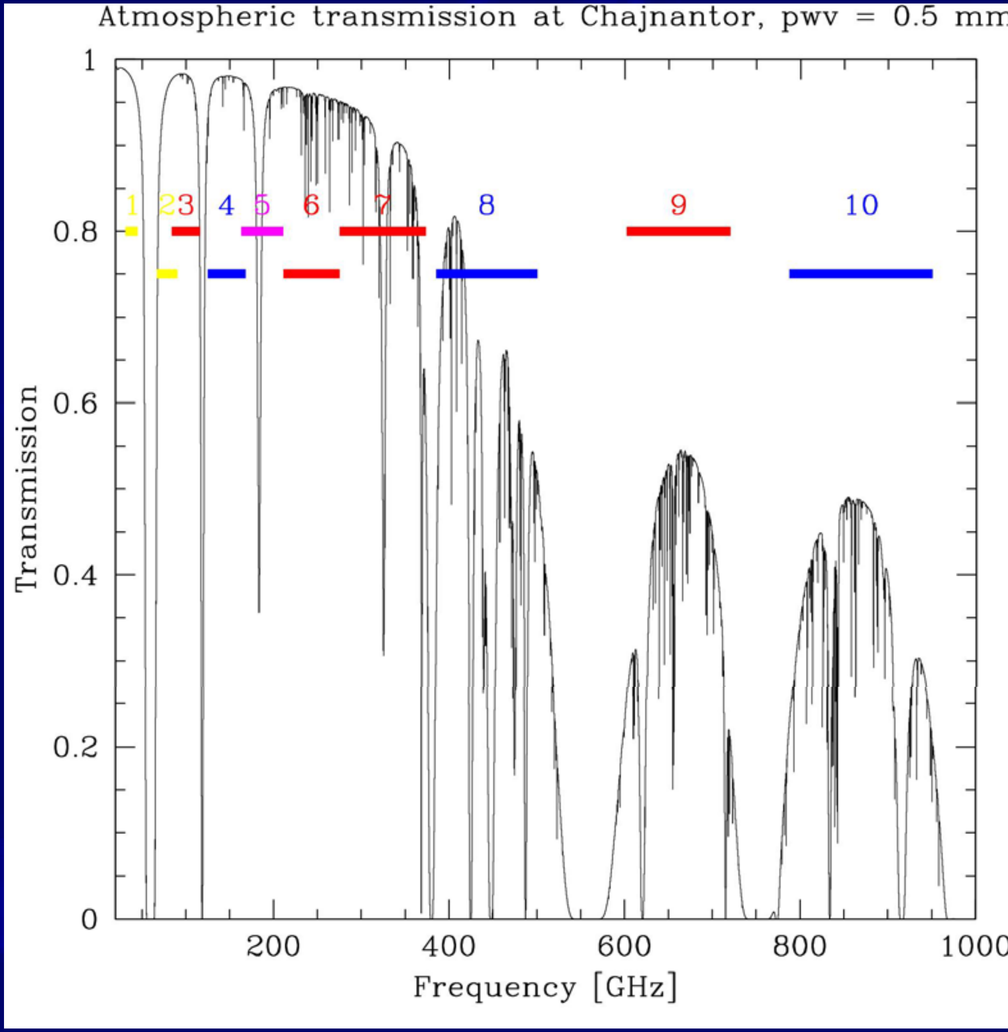
# Existing and future mm/sub-mm arrays

| Telescope | altitude (feet) | diam. (m) | No. dishes | A ($m^2$) | $\nu_{max}$ (GHz) |
|---|---|---|---|---|---|
| NMA | 2,000 | 10 | 6 | 470 | 250 |
| CARMA | 7,300 | 3.5/6/10 | 23 | 800 | 250 |
| IRAM PdBI | 8,000 | 15 | 6 | 1060 | 250 |
| SMA | 13,600 | 6 | 8 | 230 | 690 |
| eSMA | 13,600 | 6/10/15 | 10 | 490 | 690 |
| ALMA | 16,400 | 12 | 50 | 5700 | 950 |
| ACA | 16,400 | 7 | 12 | 460 | 950 |



# Transparent Site Allows Complete Spectral Coverage

- ❖ **10 Frequency bands**
- ❖ **Bands available from start: B3 (3mm, 100 GHz), B6 (1mm, 230 GHz), B7 (.85mm; 345 GHz) and B9 (.45mm, 650 GHz)**
- ❖ **Some B4 (2mm, 150 GHz), B8 (.65mm, 450 GHz) and later B10 (.35mm, 850 GHz), built by Japan**
- ❖ **A few B5 (1.5mm, 183 GHz) receivers built with EU funding**
- ❖ **B1 and B2 have not yet been assigned**
- ❖ **All process 16 GHz of data**
  - **Dual pol x 2SBs x 5.5 GHz (B6)**
  - **Dual pol x 2SBs x 4 GHz (B3, B4, B5, B7, B8)**
  - **Dual pol x DSB x 8 GHz (B9, B10)**

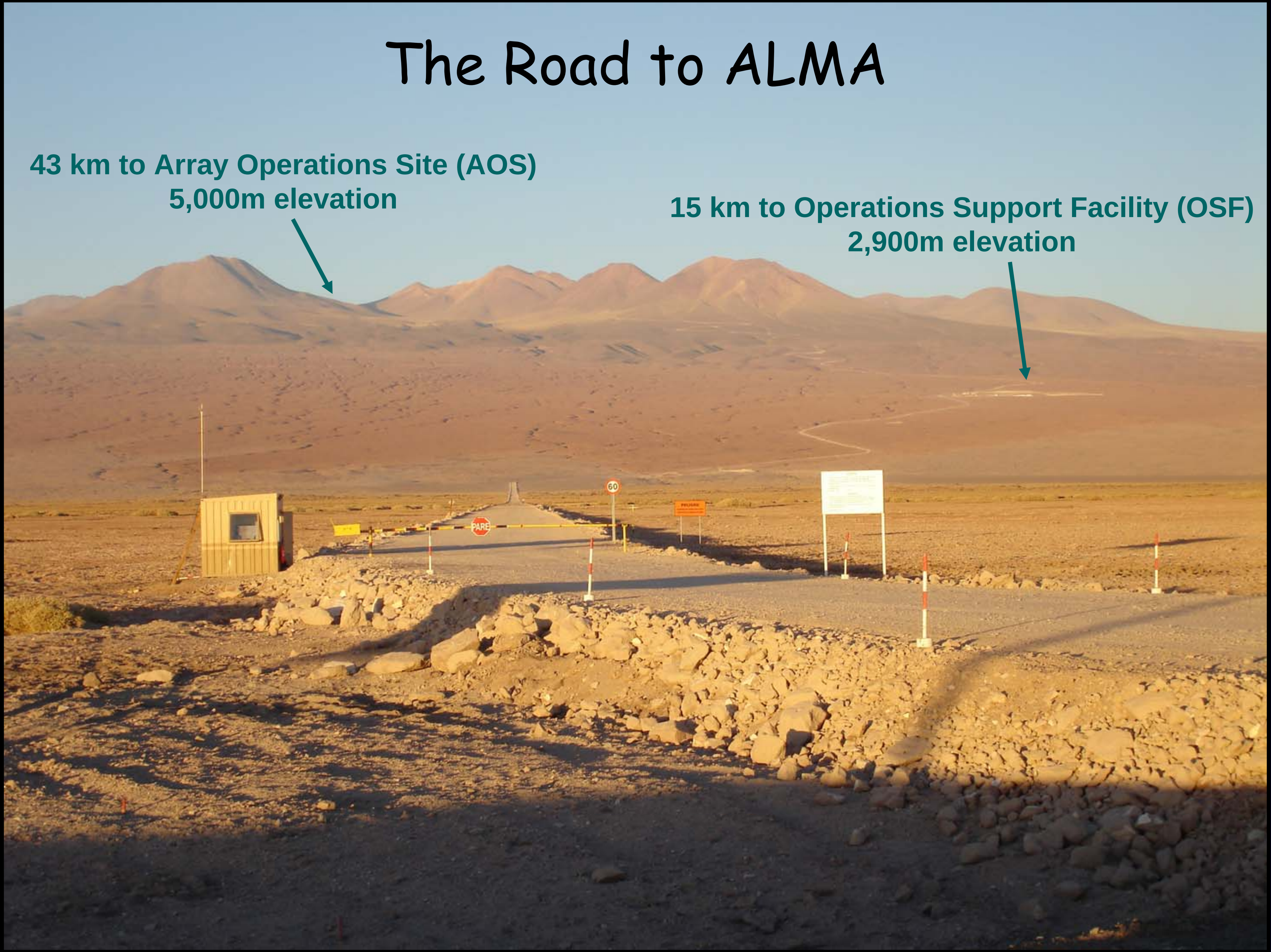


# ALMA Median Sensitivity

(1 minute; 75% Quartile opacities $\lambda$>1mm, 25% $\lambda$ <1mm)

| Frequency (GHz) | Continuum (mJy) | Line 1 km $s^{-1}$ (mJy) | Line 25 km $s^{-1}$ (mJy) |
|---|---|---|---|
| 35 | 0.02 | 5.1 | 1.03 |
| 110 | 0.027 | 4.4 | 0.89 |
| 140 | 0.039 | 5.1 | 1.01 |
| 230 | 0.071 | 7.2 | 1.44 |
| 345 | 0.12 | 10 | 1.99 |
| 675 | 0.85 | 51 | 10.2 |
| 950 | 1.26 | 66 | 13.3 |

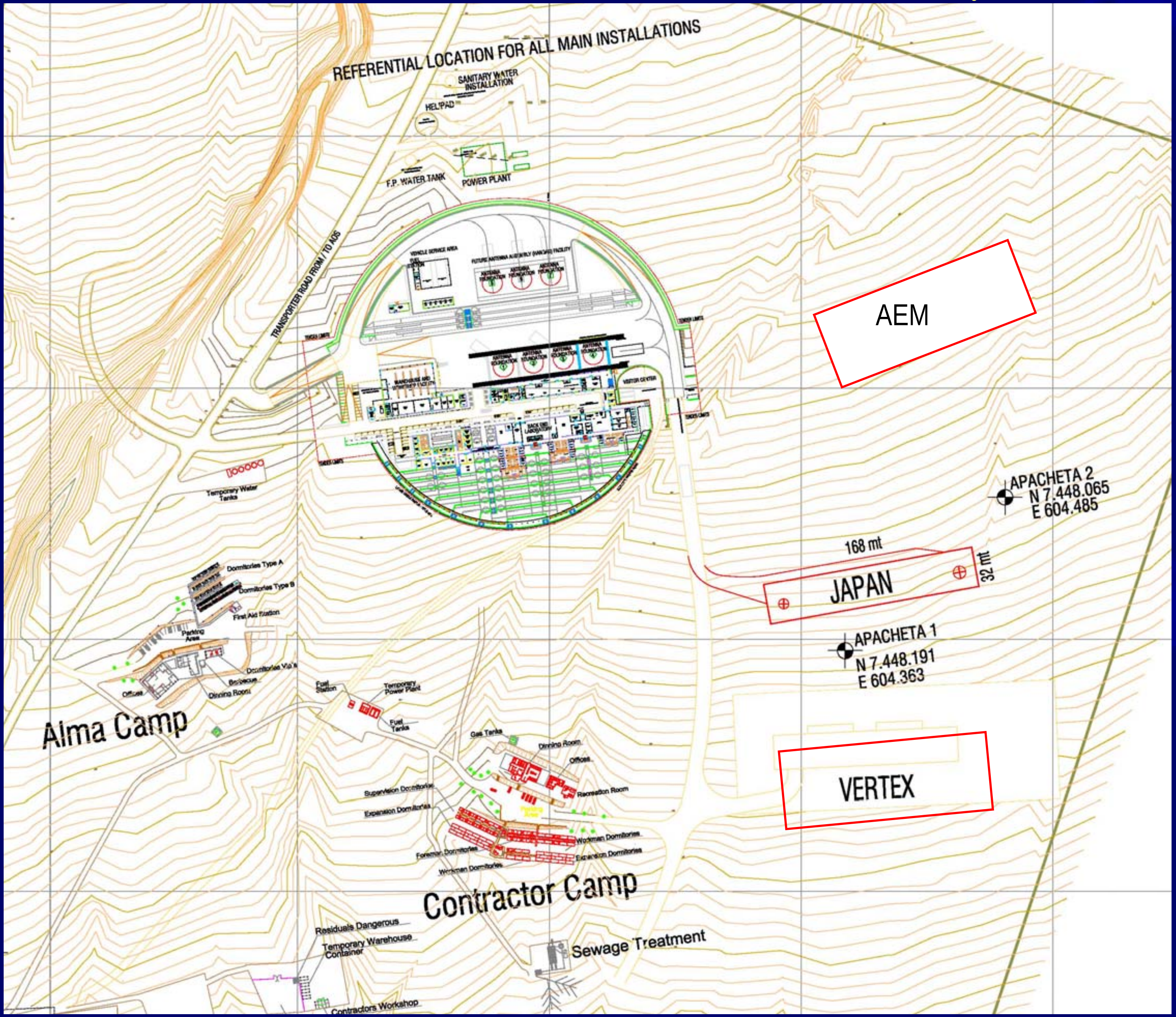
# The Road to ALMA



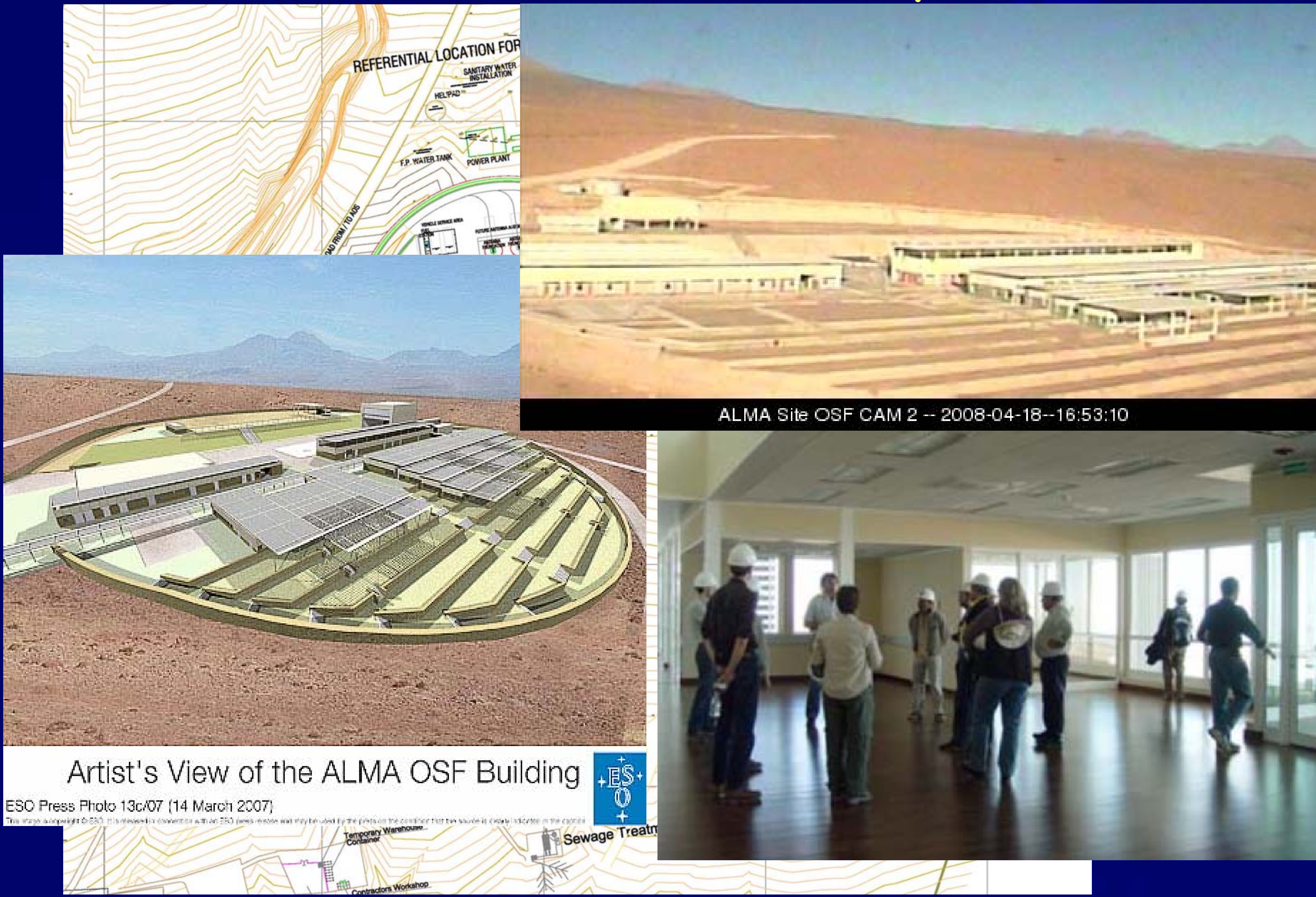
# AOS and Transporter Hangar Construction

Houses the ALMA and ACA correlators

# OSF Construction Completed



# OSF Construction Completed



# ALMA Camp - OSF

AIV Lab

Offices and cantina

Tennis court

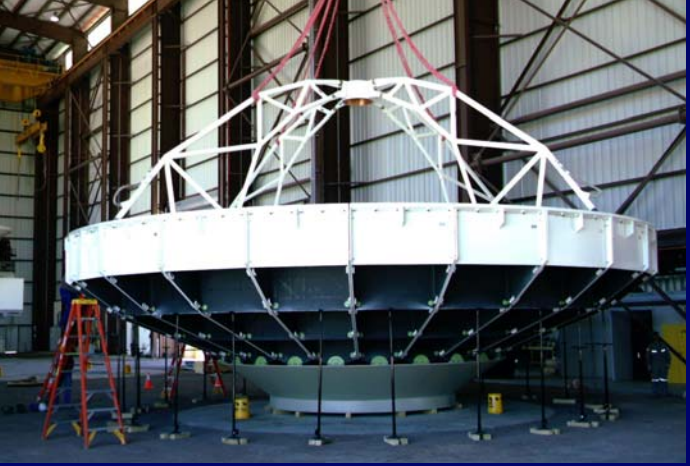
First dorms

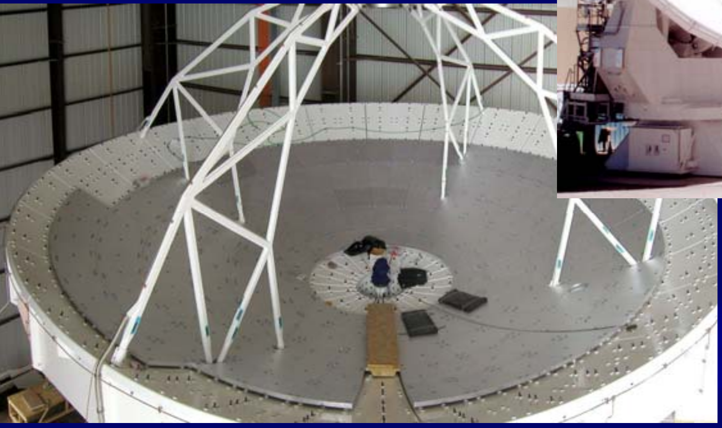
New dorms


Much nicer!

# Transporter

# Antenna Assembly and Testing



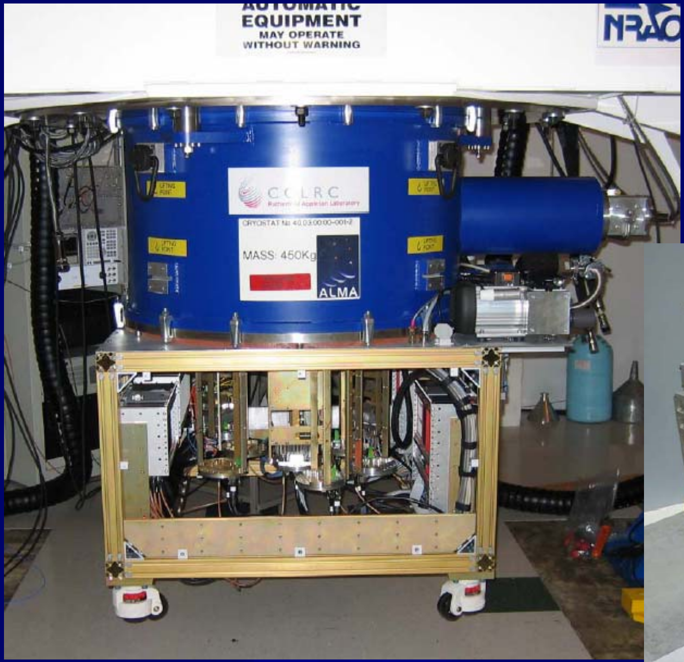


Surfaces better than 15 µm!

Currently 3 Vertex and all 4 Melco 12m (ACA)

# Hardware Arriving in Chile

1st quadrant of ALMA correlator

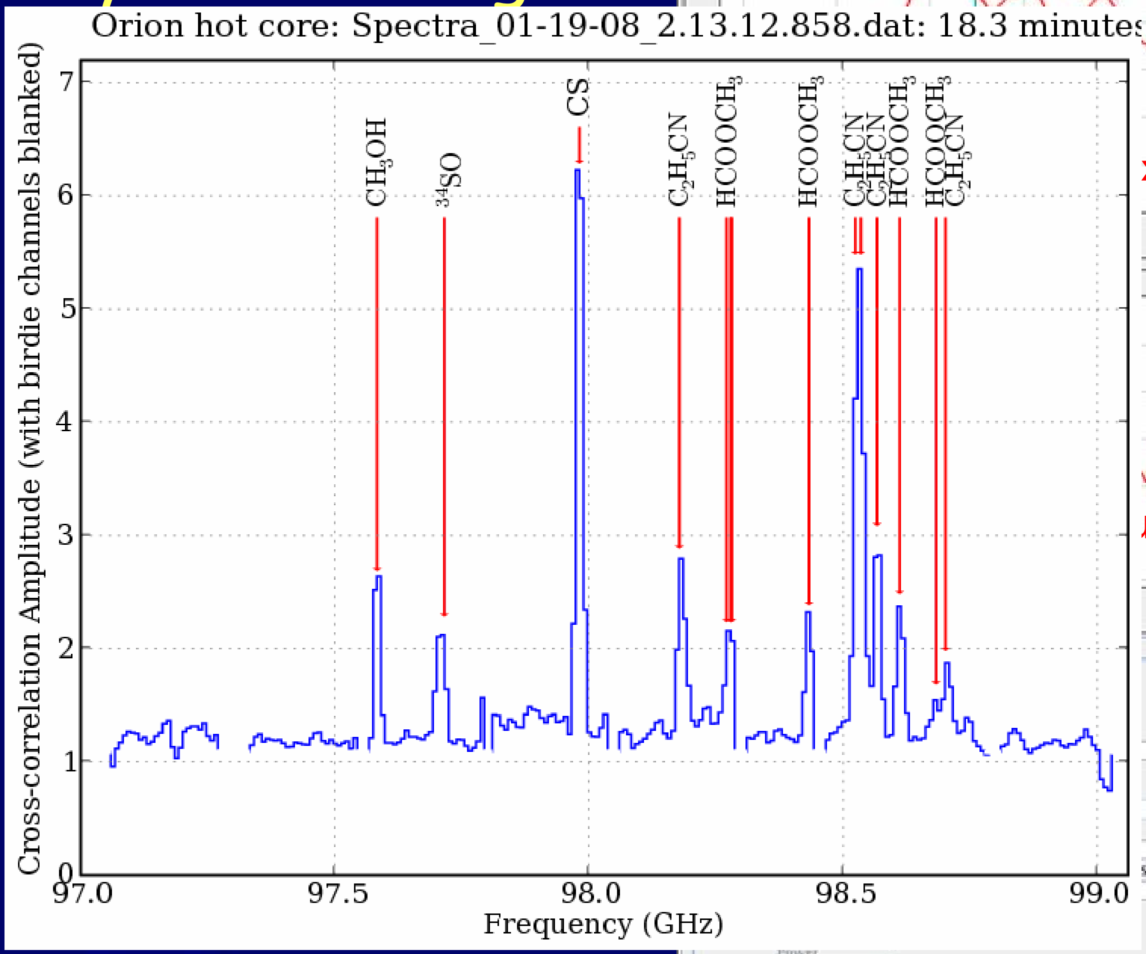



ALMA Front End and band 6 cartridges

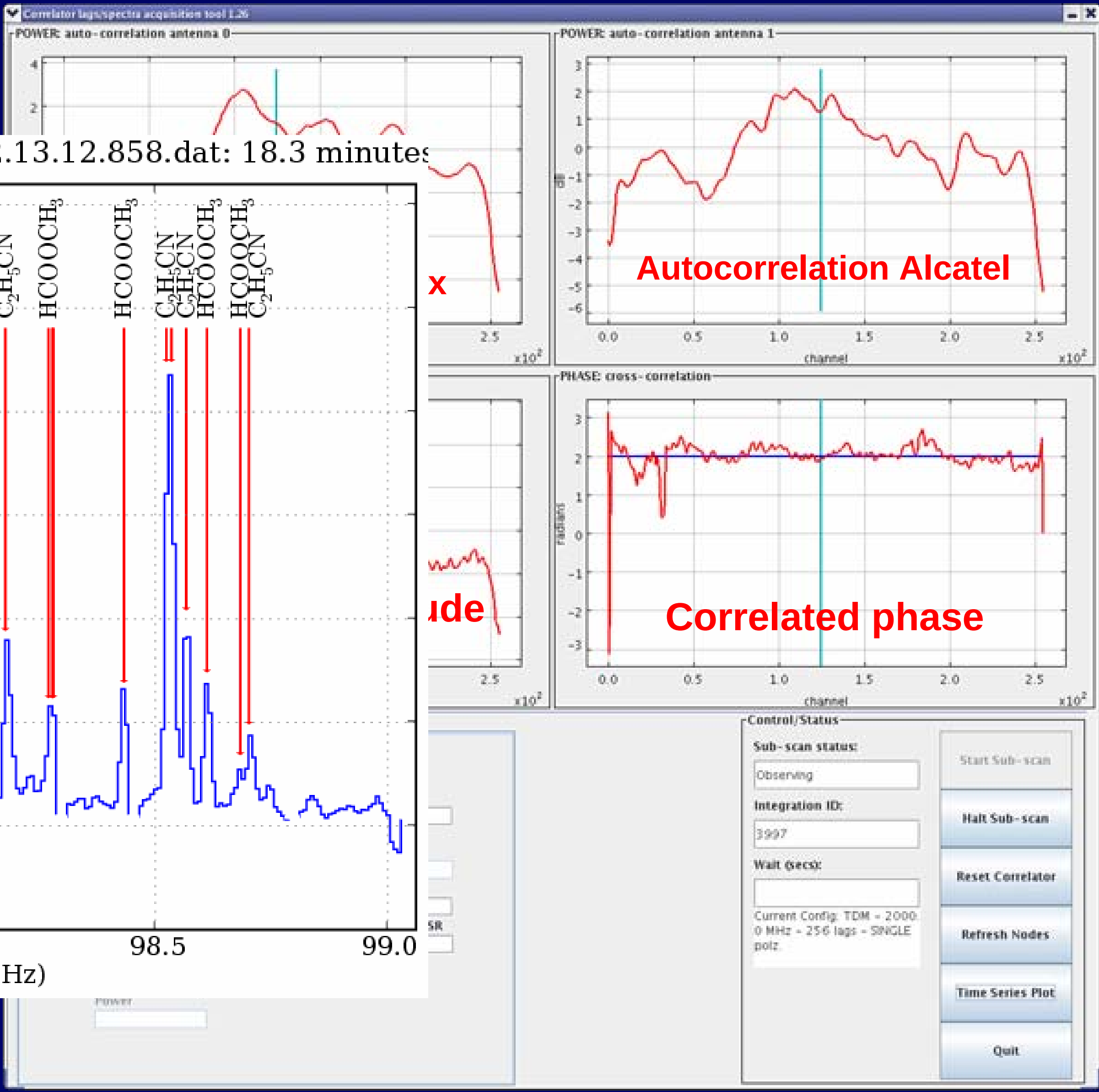
ACA correlator being installed at AOS


15

# ALMA Test Facility: Dynamic Fringes




- First interferometric spectrum on Orion Hot Core at 98 GHz




Dynamic Fringes on 3C279.

# Highest Level-1 Science Drivers

***Bilateral Agreement Annex B:***

- 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), 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 detect spectral line emission from CO or CII in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.

- 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.

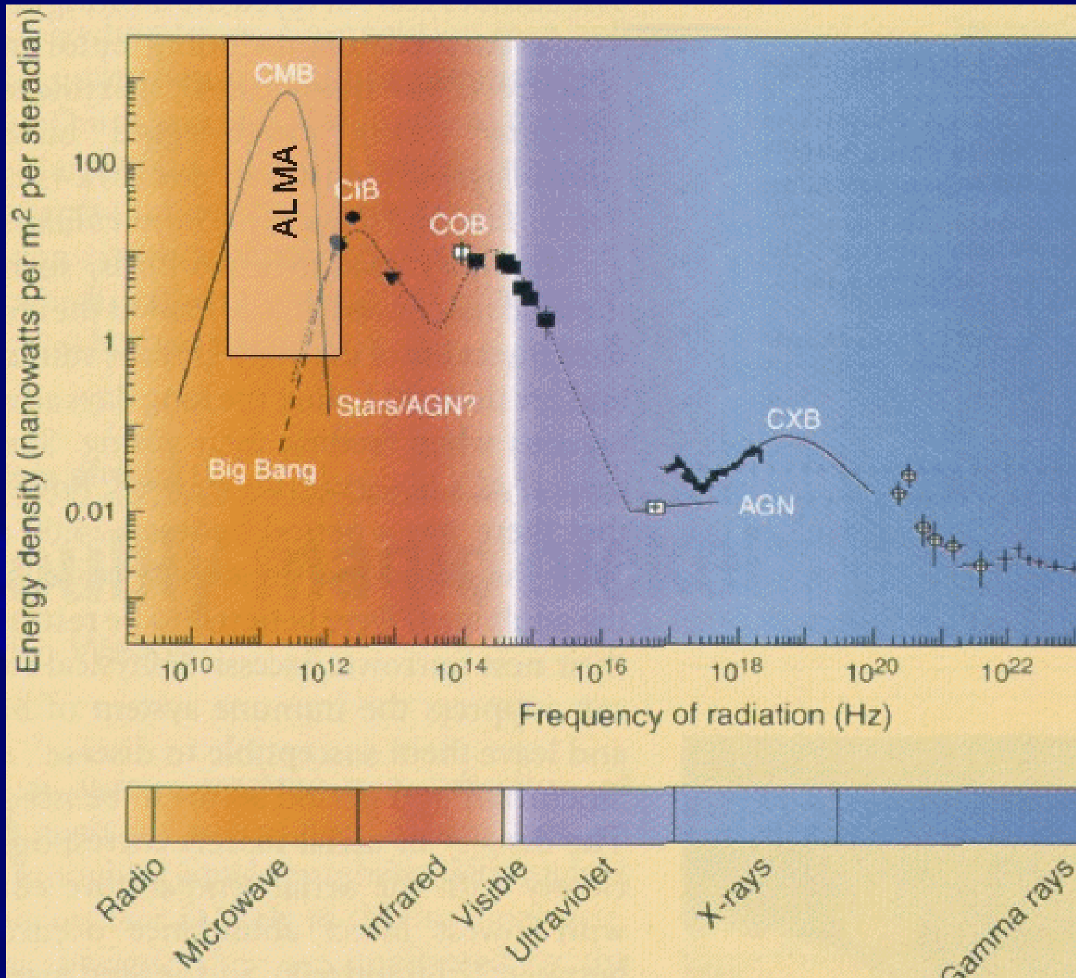
These goals drive the technical specifications of ALMA.

# Why Do We Care About mm/submm?

- After the 3K cosmic background radiation, mm/submm photons carry most of the radiative energy in the Universe:
  - 40% of Milky Way photons are in mm/submm

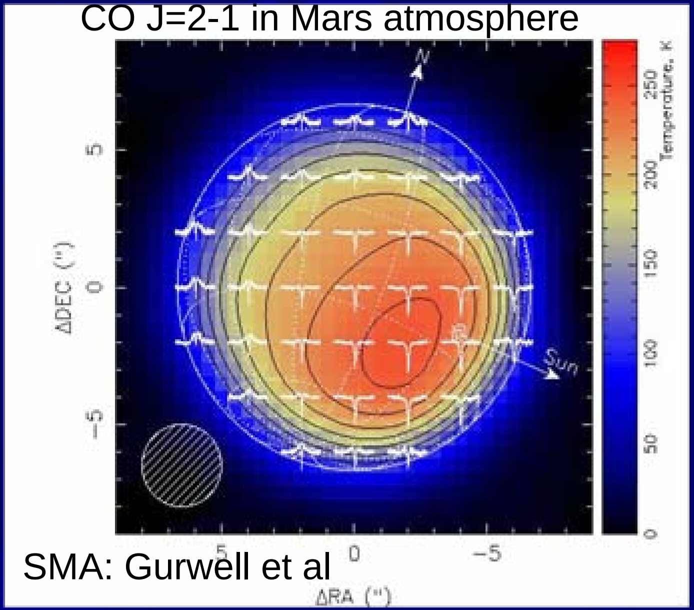
- Unique science because of the sensitivity to thermal emission from dust and molecular lines:
  $S_\nu \propto \nu^4$; $T_B \propto \nu^2$

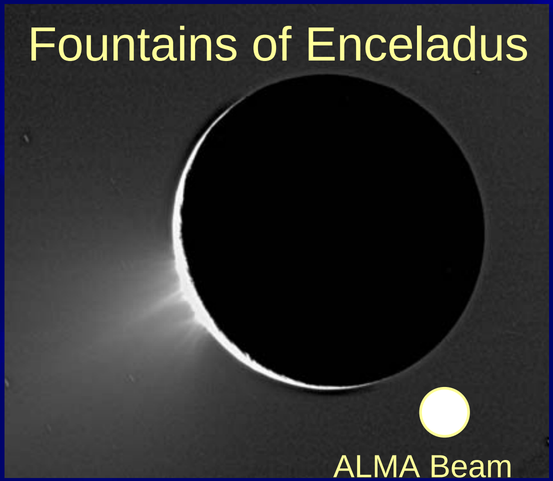
- Probe of cool gas and dust

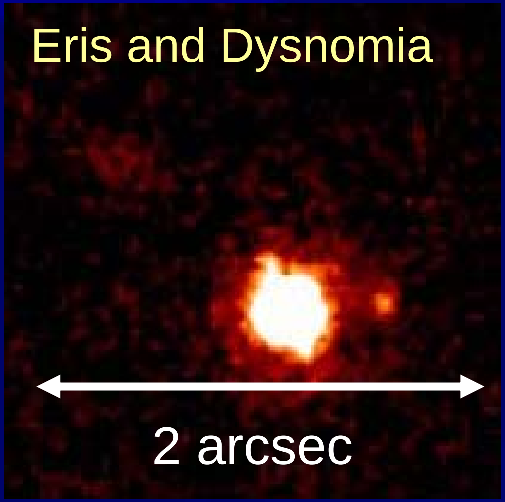


# Exploration of the Solar System

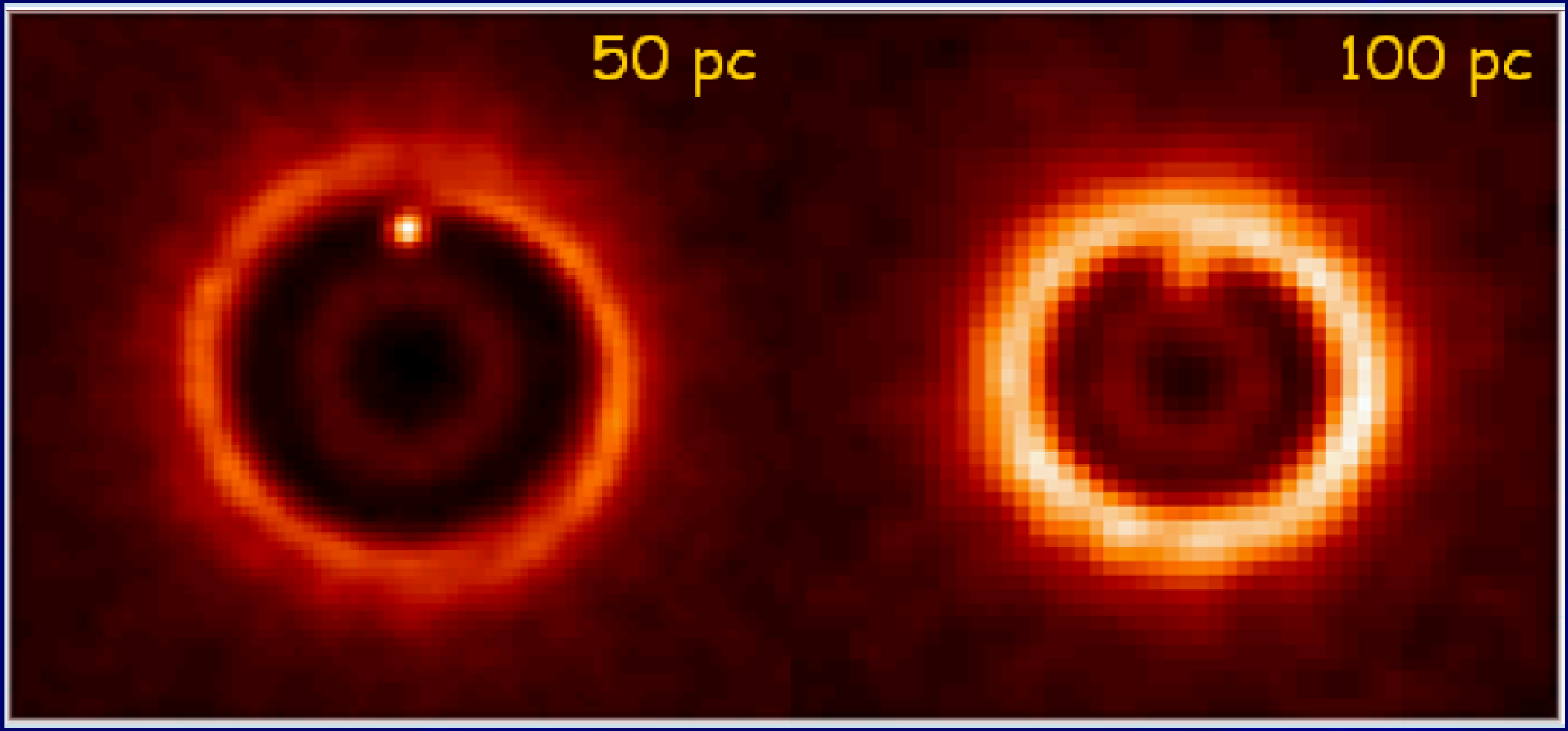
- 'Weather' on Venus, Mars, Jovian planets
- Comets
- Volcanism on Io
- Search for Molecules from the "Fountains of Enceladus"
- Minor planet 'Eris' with its moon 'Dysnomia' easily resolved, Eris could be imaged.



# Searching for "dust gaps" in Nearby Low Mass Protoplanetary Disks




Simulation of the 950 GHz dust emission from a 1 Jupiter Mass planet around a 0.5 Solar mass star (orbital radius 5 AU)

- The disk mass was set to that of the Butterfly star in Taurus
- Integration time 8 hours; 10 km baselines; 30 degrees phase noise

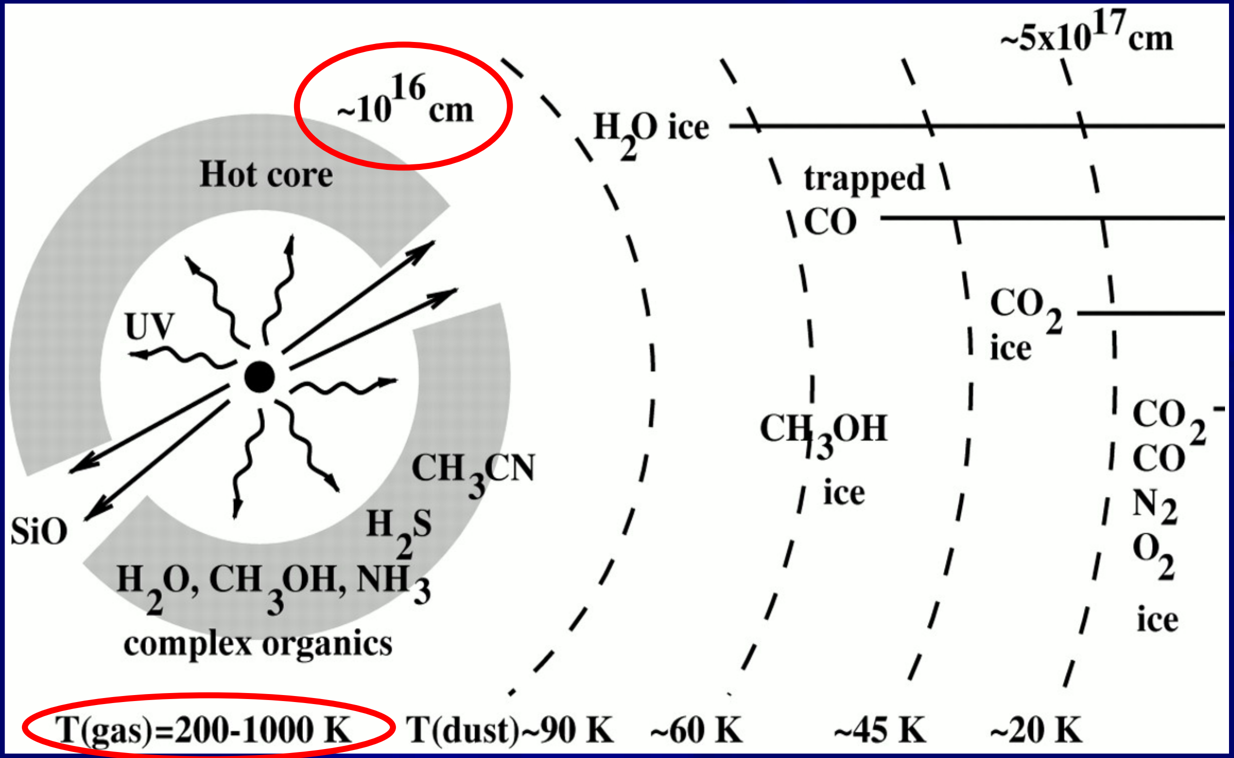
Wolf & D'Angelo (2005)

# How Do Massive Stars Form?


Although massive stars dominate our view of galaxies through heating, turbulence, and ionization, we do not understand how they form even in our own Galaxy

The “Hot Cores” that form around massive protostars are excellent probes of the earliest stages

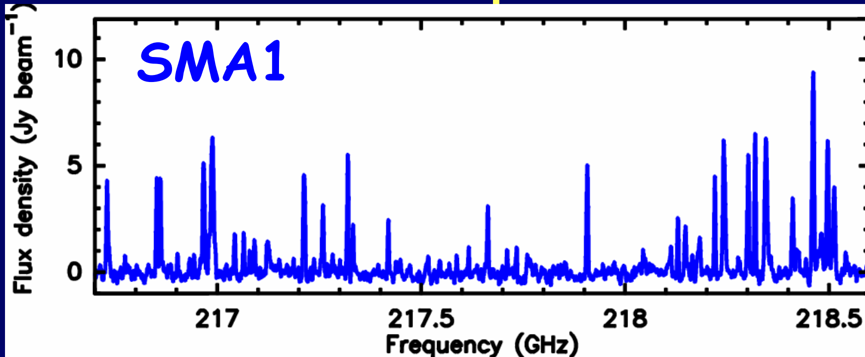
Van Dishoeck & Blake (1998)

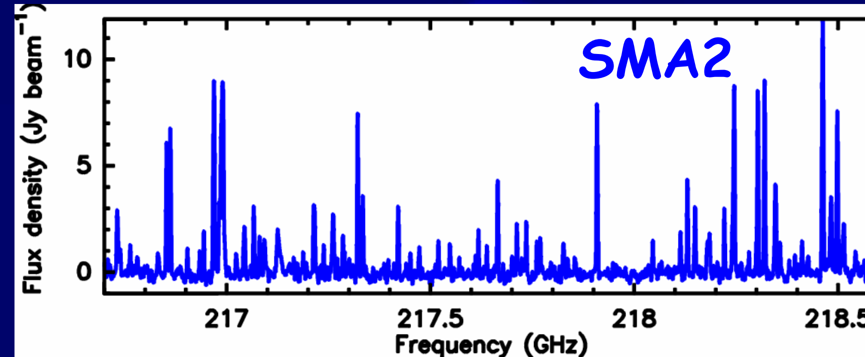



2” = $10^{16}$ cm (2,000 AU) at 1kpc

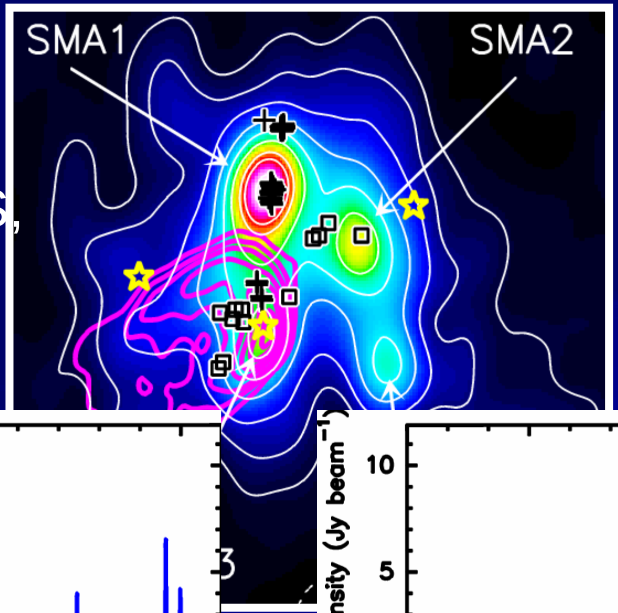
- High temperatures combined with newly liberated atoms and molecules drive copious organic chemistry
- Can only be observed at high angular resolution (beam dilution)

# SMA 1.3 mm Spectra of Massive Protostars in NGC6334I

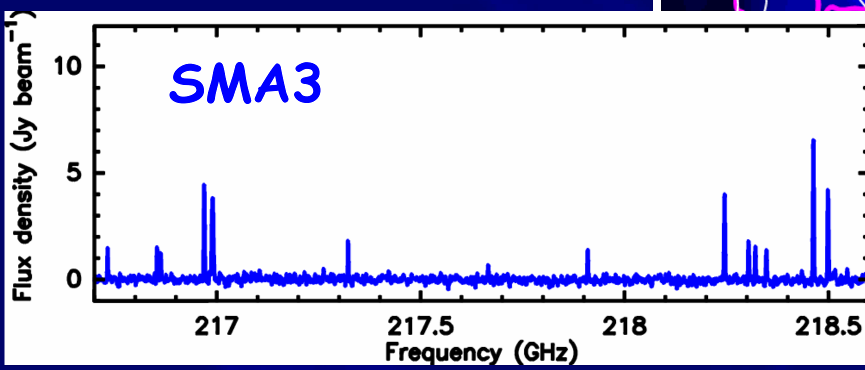


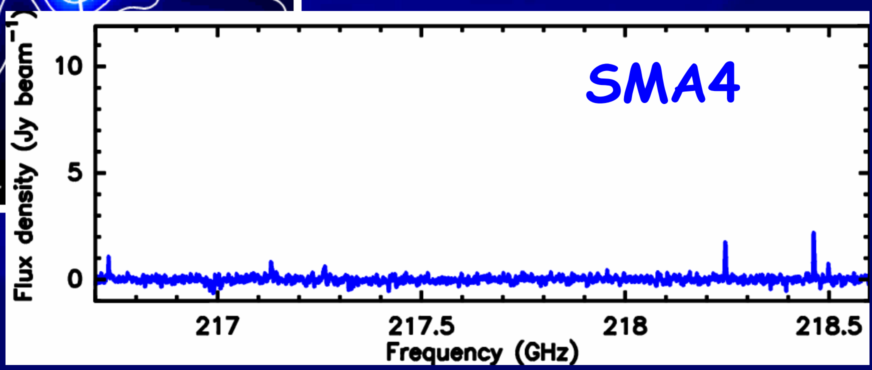




CO, $^{13}CO$, $C^{17}O$, $C^{18}O$, $^{34}CS$, SO, $SO_2$, $^{34}SO_2$, $H_2S$, NS, SiO, $H_2CO$, $CH_3OH$, $^{13}CH_3OH$, $H^{13}CO^+$




DCN, $HC_3N$, $HC_5N$, $CH_3CN$, $C_2H_5CN$, $NH_2CH$, $CH_3OCH_3$, $CH_3OCHO$ + many more + unidentified

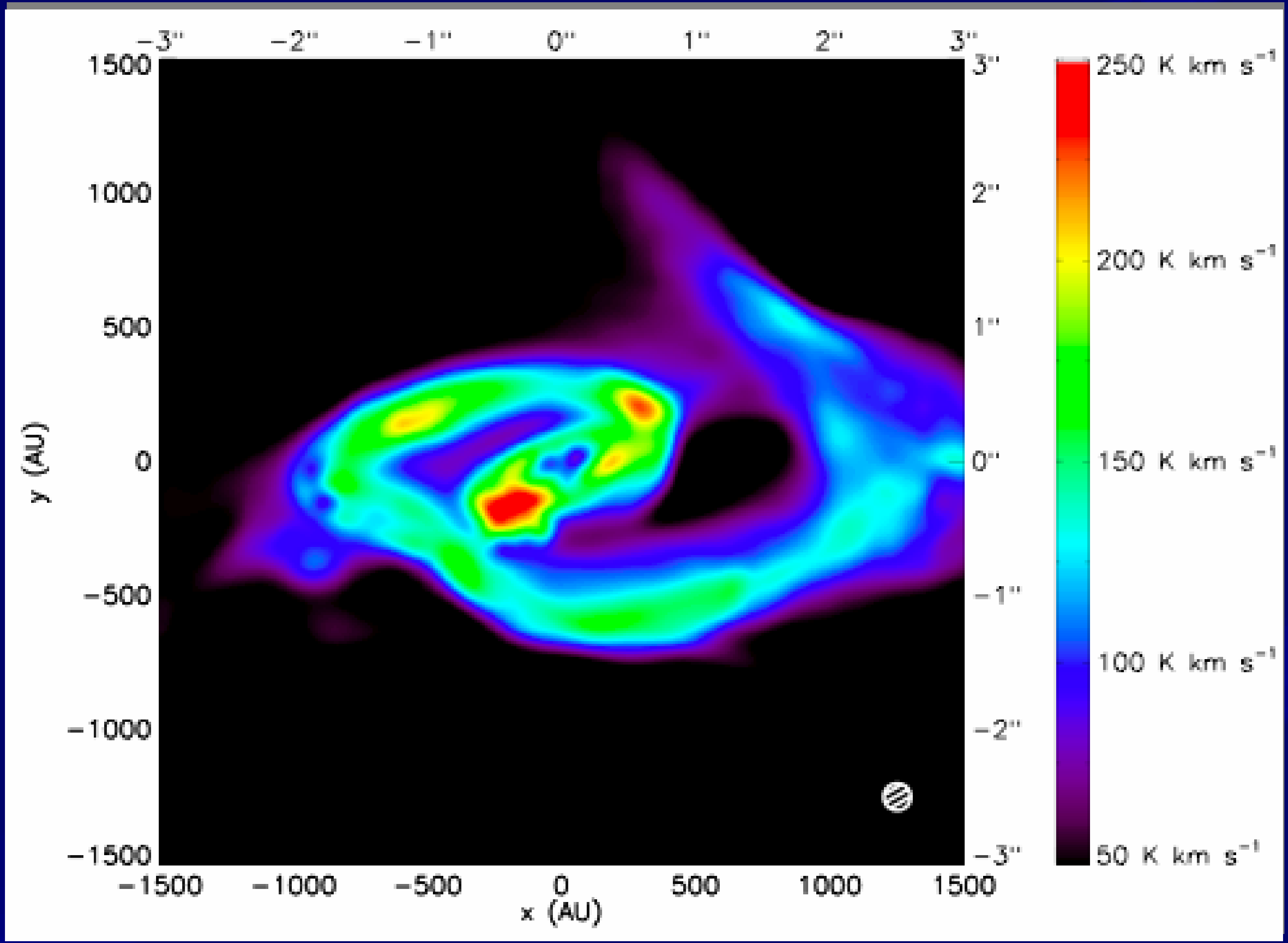



ALMA will improve resolution and spectral line sensitivity by more than a factor of 25!

Brogan, Hunter et al. in prep

# ALMA Simulation: Rotating m = 1 Spiral

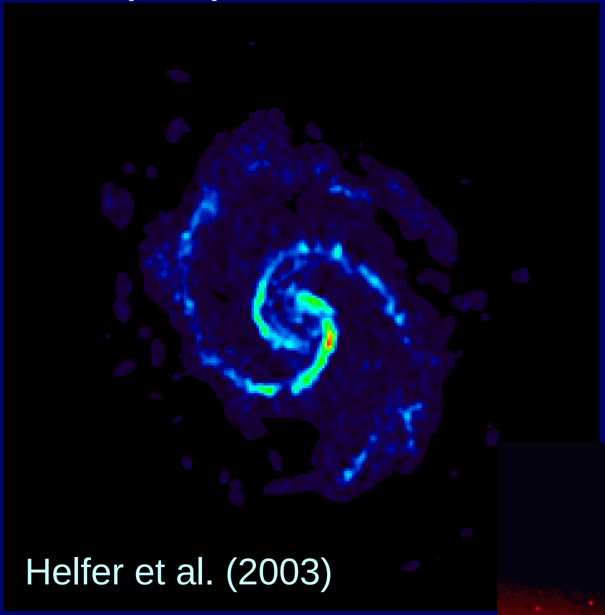



17 minutes observation of disk at 0.5 kpc in $CH_3CN$ transition at 220.747 GHz, $T_{upper}$ = 69 K

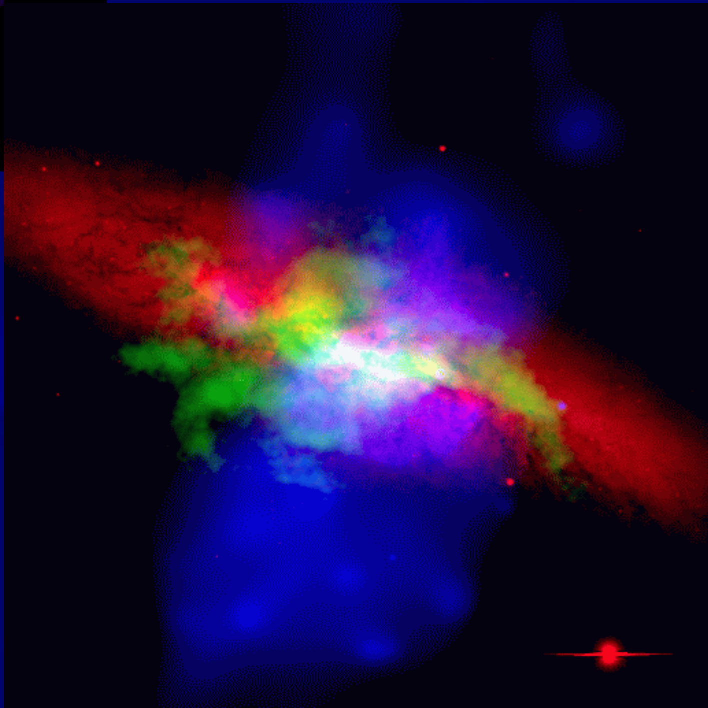
(Krumholtz, Klein, & McKee 2007)

# Galaxy Structure and Evolution


CO(1-0) BIMA-SONG



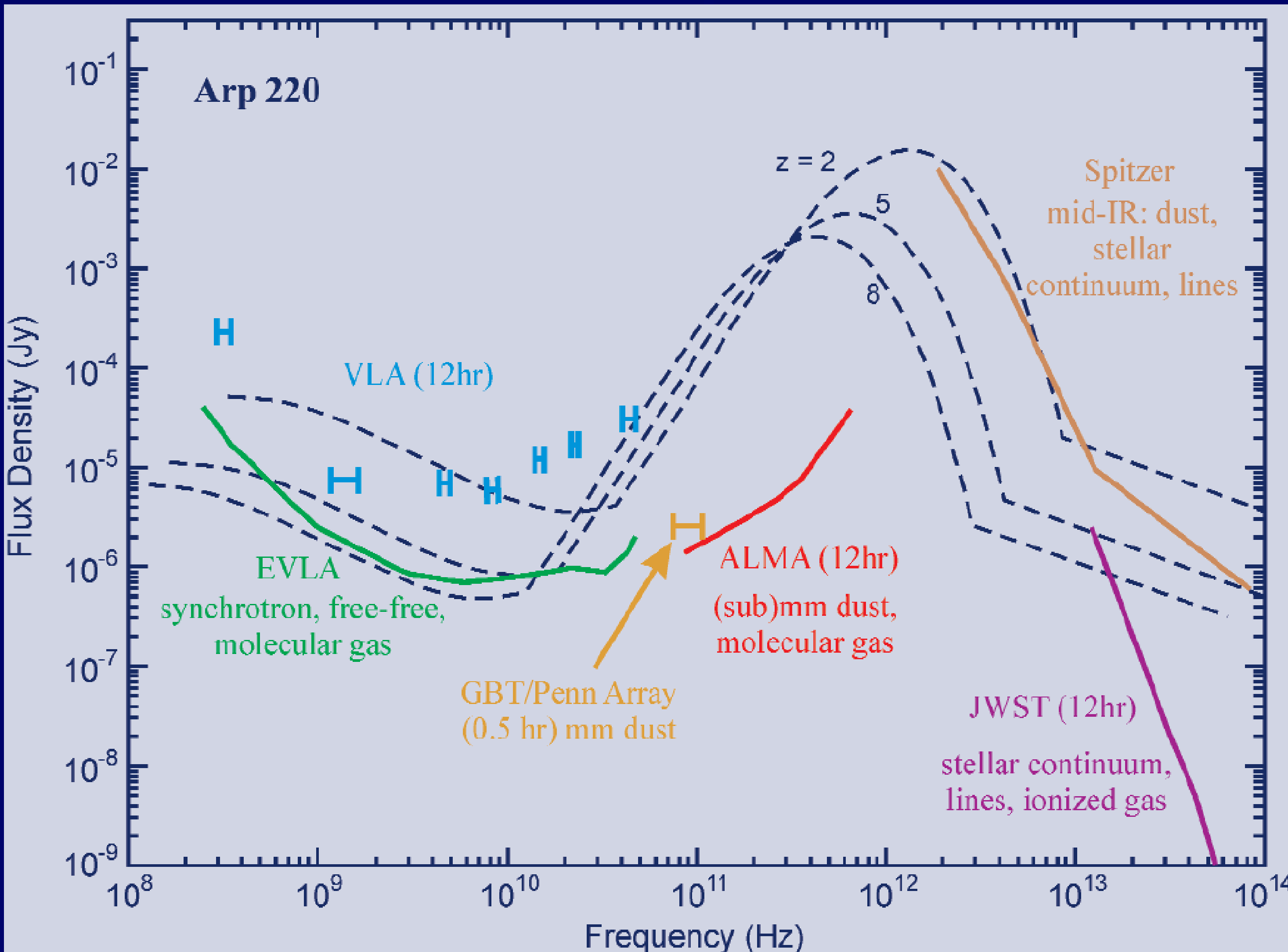

Ability to trace chemical composition of galaxies to z=3 in less than 24 hours

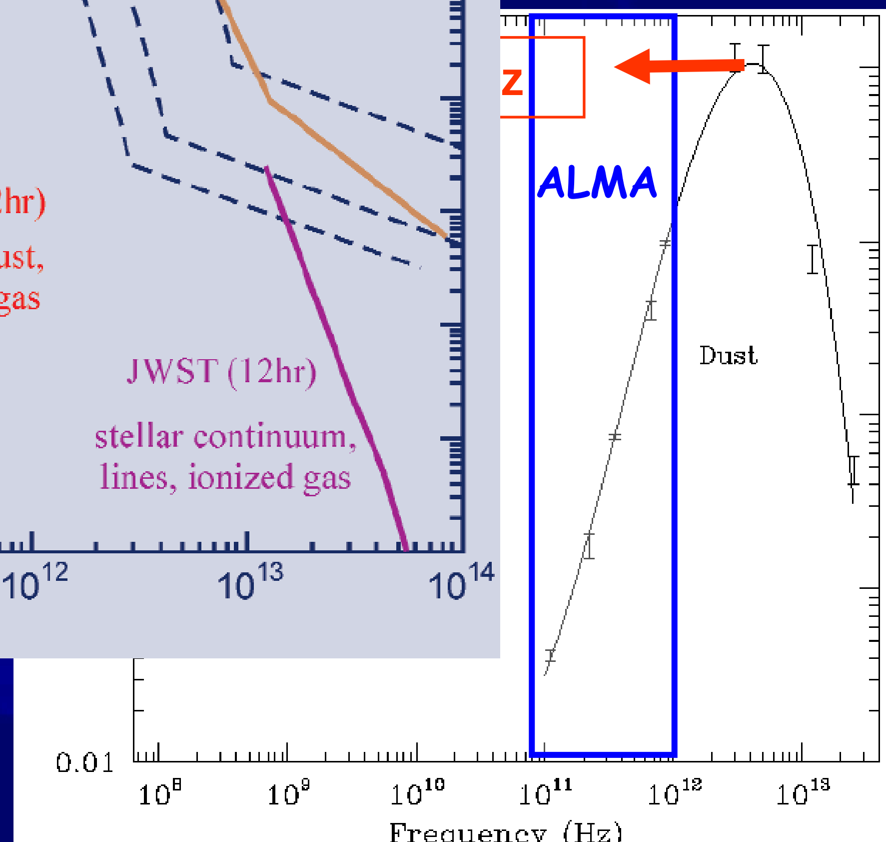


M82 starburst
Red: optical emission
Blue: x-ray emission
Green: OVRO $^{12}CO(J=1-0)$
*(Walter, Weiss, Scoville 2003)*

# ighest z

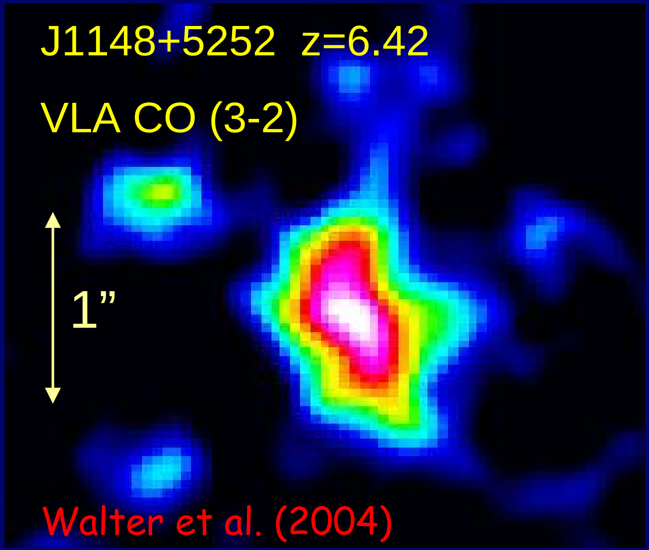
eep submm
racts inverse
ng




Detect high-z galaxies as easily as those at z~0.5

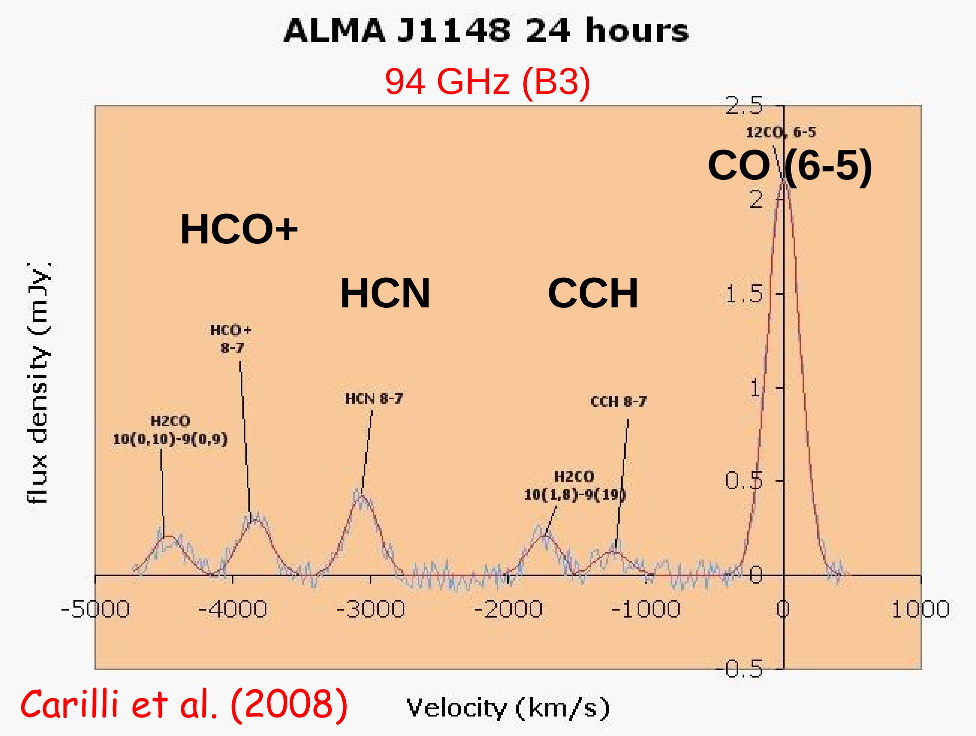
# ALMA: study of 'first light' during cosmic reionization




Current State-of-art: Tens of hours to detect rare, systems (FIR ~$1 \times 10^{13}$ L⊙)

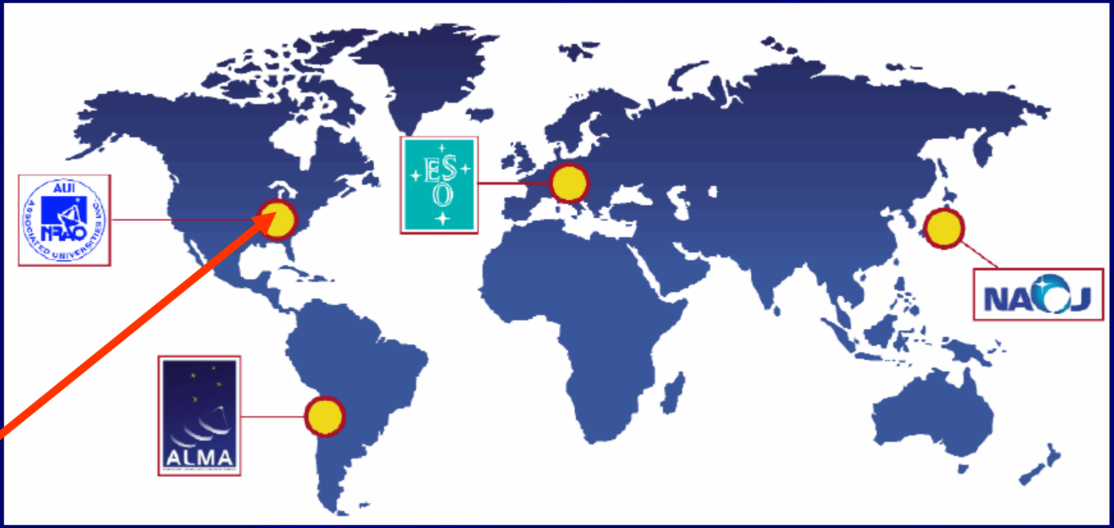
**Spectral simulation of J1148+5251**

- Detect dust emission in **1sec** (5σ)
- Detect multiple lines => detailed astrochemistry
- Image dust and gas at sub-kpc resolution – gas dynamics!
- Detect continuum of 'normal' galaxies in ~1hr



# The Tri-Partner ALMA Project – Service community through ALMA Regional Centers (ARC)

The North American ARC is a partnership between the US and Canada (7.25%)





One-stop shopping for:

- Proposals
- Observing scripts
- Data archive and reduction

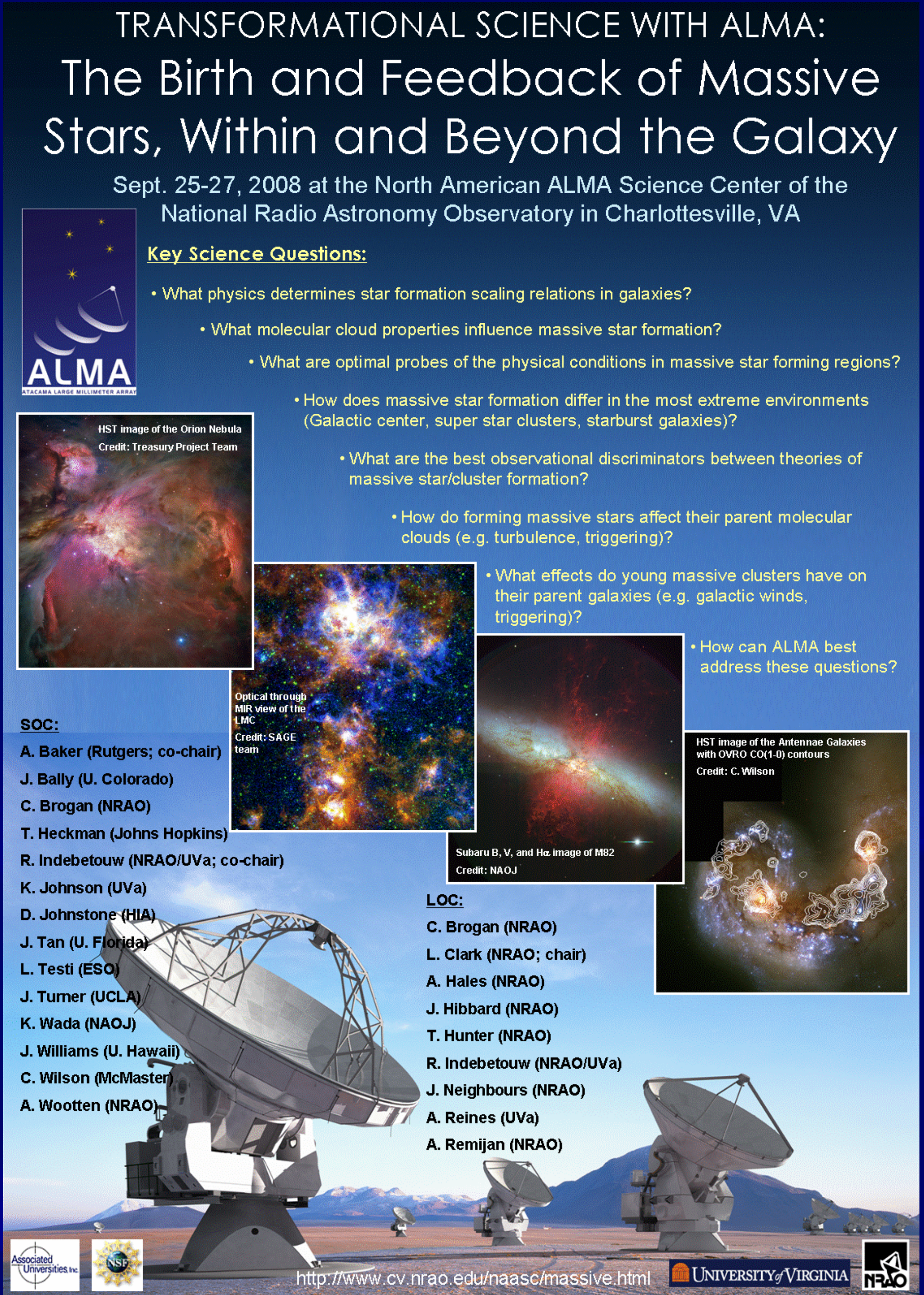
NAASC: North America ALMA Science Center, Charlottesville, VA

# Activities of the NAASC:

Make full power of ALMA user friendly at all levels of experience

- End to end proposal submission
  - US ALMA time allocation will follow “open skies” policy
- Pipeline and off-line data reduction software (CASA) maintenance and advanced algorithm development
  - Pipeline will produce science-ready images for basic ALMA observing modes (off-line data reduction in early years)
- North America hardware maintenance and development
  - NA deliverables like Band 3 & 6 Receivers
- Maintain close connection to ALMA operations through Astronomer on Duty, scheduling block verification, QA, and proposal review
- Education and Public Outreach
- Student Pre-doc and Post-doctoral Fellowship programs
- Summer schools and science workshops

# 3rd Annual ALMA/ NAASC workshop



# Current Projected Timeline

| | |
|---|---|
| Mid 2008 | Testing at ATF continues |
| Fall 2008 | Commissioning Begins at OSF |
| Mid 2009 | Commissioning Begins with 3-element array |
| Mid 2010 | Call for Early Science Proposals |
| | * 24+ antennas, 2+ bands, continuum & spectral line, 1km baselines |
| Early 2011 | Start Early Science |
| | * Off line data reduction |
| Mid 2012 | Pipeline images for standard modes |
| Early 2013 | Baseline ALMA Construction Complete |

# ALMA News

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.

# 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 – 163 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 | 2SB | SIS |
| 9 | 602 – 720 GHz | 175 K | 263 K | DSB | SIS |
| 10 | 787 – 950 GHz | 230 K | 345 K | DSB | SIS |

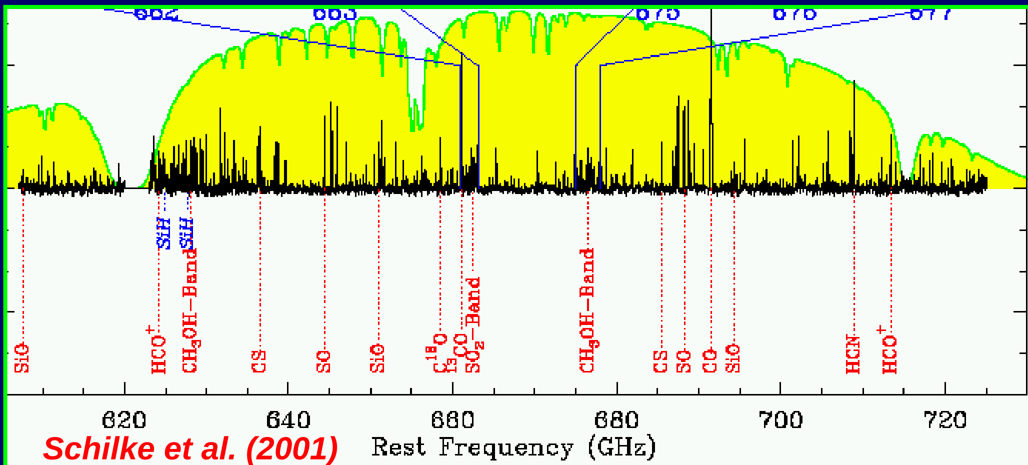
**Dual, linear polarization channels:**

- Increased sensitivity
- Measurement of 4 Stokes parameters

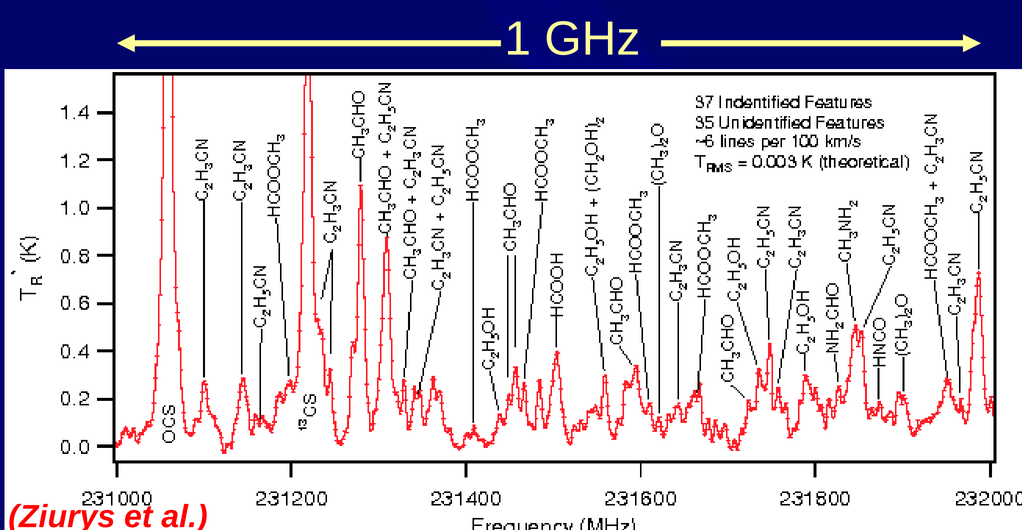
**183 GHz water vapour radiometer:**

- Used for atmospheric path length correction

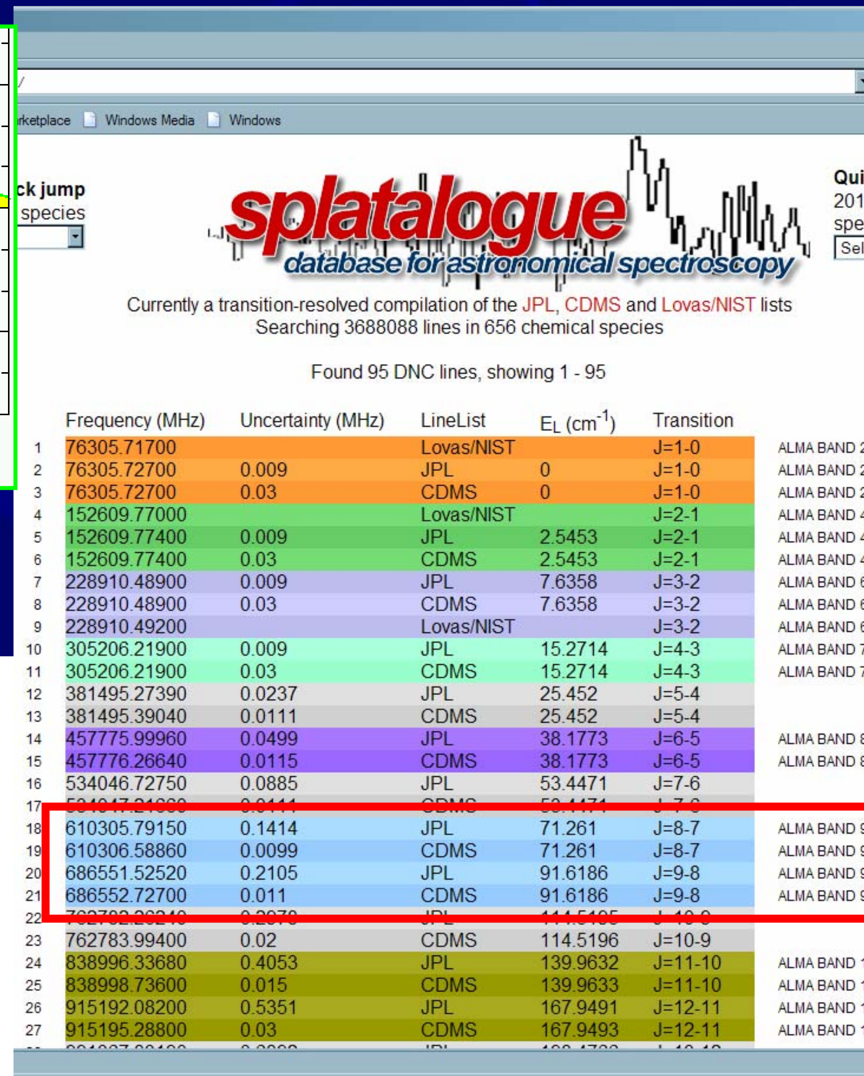
# Spectral Line catalogs and tools needed to deal with tremendous spectral complexity




Lines visible in Band 9 (CSO)




SgrB2(N) spectrum using Band 6 mixer at the SMT




| | Frequency (MHz) | Uncertainty (MHz) | LineList | $E_L$ ($cm^{-1}$) | Transition | |
|---|---|---|---|---|---|---|
| 1 | 76305.71700 | | Lovas/NIST | | J=1-0 | ALMA BAND 2 |
| 2 | 76305.72700 | 0.009 | JPL | 0 | J=1-0 | ALMA BAND 2 |
| 3 | 76305.72700 | 0.03 | CDMS | 0 | J=1-0 | ALMA BAND 2 |
| 4 | 152609.77000 | | Lovas/NIST | | J=2-1 | ALMA BAND 4 |
| 5 | 152609.77400 | 0.009 | JPL | 2.5453 | J=2-1 | ALMA BAND 4 |
| 6 | 152609.77400 | 0.03 | CDMS | 2.5453 | J=2-1 | ALMA BAND 4 |
| 7 | 228910.48900 | 0.009 | JPL | 7.6358 | J=3-2 | ALMA BAND 6 |
| 8 | 228910.48900 | 0.03 | CDMS | 7.6358 | J=3-2 | ALMA BAND 6 |
| 9 | 228910.49200 | | Lovas/NIST | | J=3-2 | ALMA BAND 6 |
| 10 | 305206.21900 | 0.009 | JPL | 15.2714 | J=4-3 | ALMA BAND 7 |
| 11 | 305206.21900 | 0.03 | CDMS | 15.2714 | J=4-3 | ALMA BAND 7 |
| 12 | 381495.27390 | 0.0237 | JPL | 25.452 | J=5-4 | |
| 13 | 381495.39040 | 0.0111 | CDMS | 25.452 | J=5-4 | |
| 14 | 457775.99960 | 0.0499 | JPL | 38.1773 | J=6-5 | ALMA BAND 8 |
| 15 | 457776.26640 | 0.0115 | CDMS | 38.1773 | J=6-5 | ALMA BAND 8 |
| 16 | 534046.72750 | 0.0885 | JPL | 53.4471 | J=7-6 | |
| 17 | | | | | | |
| 18 | 610305.79150 | 0.1414 | JPL | 71.261 | J=8-7 | ALMA BAND 9 |
| 19 | 610306.58860 | 0.0099 | CDMS | 71.261 | J=8-7 | ALMA BAND 9 |
| 20 | 686551.52520 | 0.2105 | JPL | 91.6186 | J=9-8 | ALMA BAND 9 |
| 21 | 686552.72700 | 0.011 | CDMS | 91.6186 | J=9-8 | ALMA BAND 9 |
| 22 | | | | | | |
| 23 | 762783.99400 | 0.02 | CDMS | 114.5196 | J=10-9 | |
| 24 | 838996.33680 | 0.4053 | JPL | 139.9632 | J=11-10 | ALMA BAND 10 |
| 25 | 838998.73600 | 0.015 | CDMS | 139.9633 | J=11-10 | ALMA BAND 10 |
| 26 | 915192.08200 | 0.5351 | JPL | 167.9491 | J=12-11 | ALMA BAND 10 |
| 27 | 915195.28800 | 0.03 | CDMS | 167.9493 | J=12-11 | ALMA BAND 10 |
| 28 | | | | | | |

Unified spectral line database (to be used in observing tool)