Millimeter Interferometry and ALMA

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(NRAO)

Eleventh Synthesis Imaging Workshop

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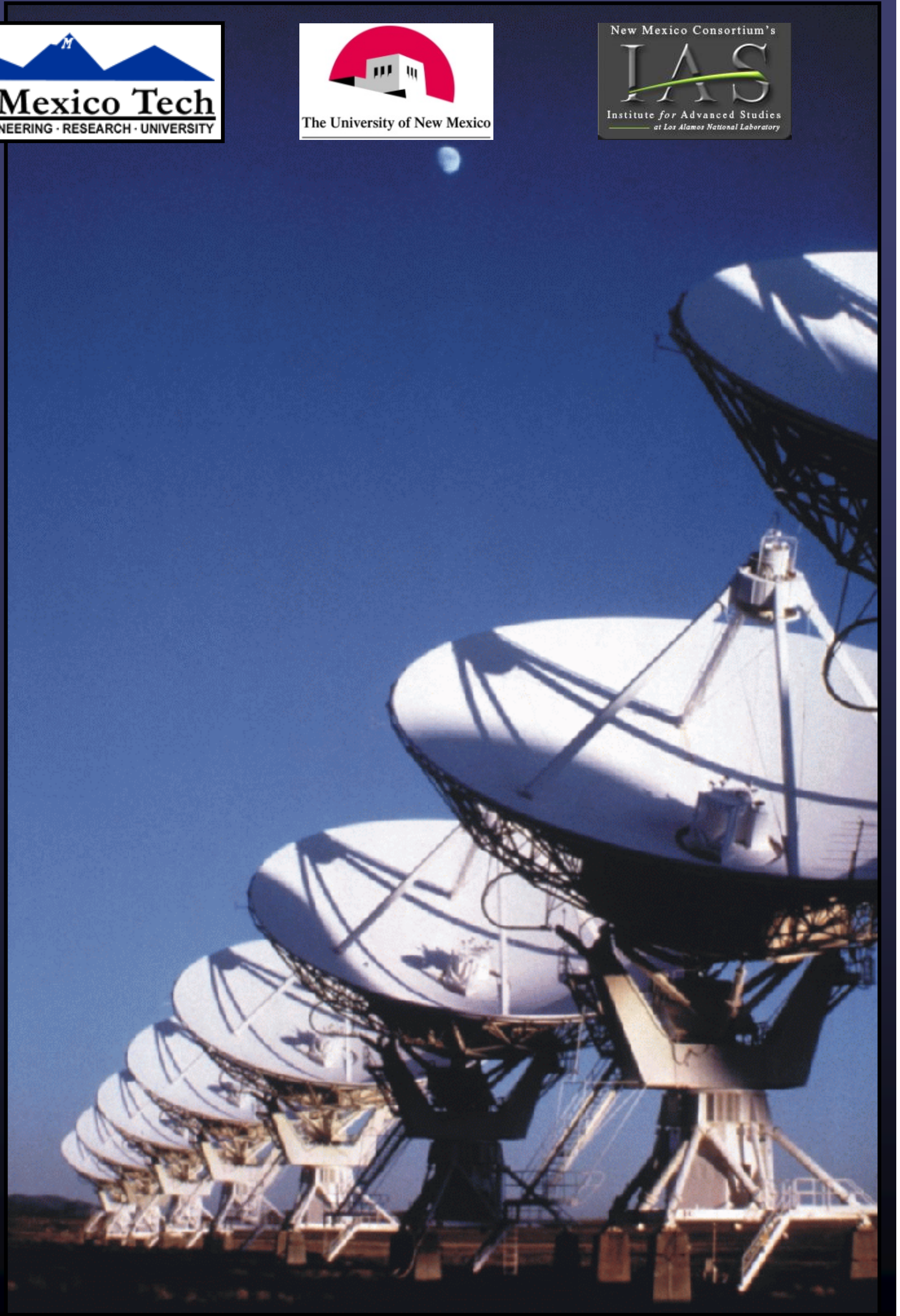
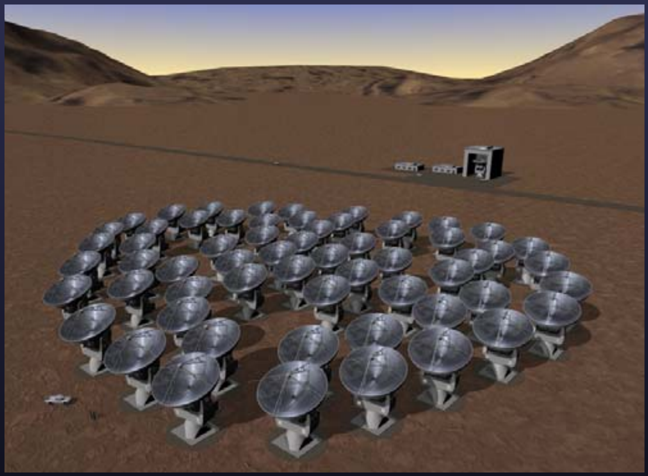


Outline



- The ALMA project and status

- Unique science at mm & sub-mm wavelengths
- Problems unique to mm/sub-mm observations
  - Atmospheric opacity
  - Absolute gain calibration
  - Tracking atmospheric phase fluctuations
  - Antenna and instrument constraints



- Summary
- Practical aspects of observing at high frequency with the VLA

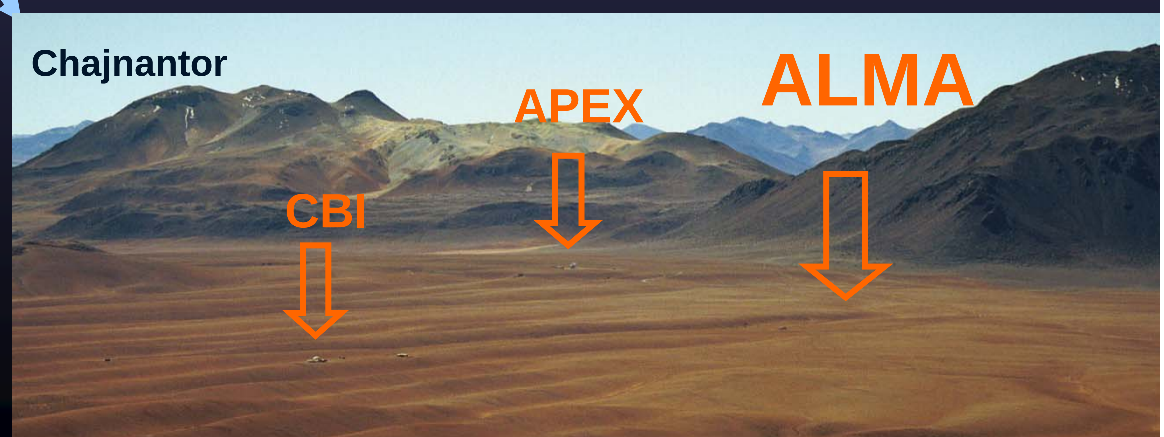
What is ALMA?

- A global partnership to deliver a transformational millimeter/submillimeter instrument
  - North America (US, Canada)
  - Europe (ESO)
  - East Asia (Japan,Taiwan)

- 5000m (16,500 Ft) site in Chilean Atacama desert

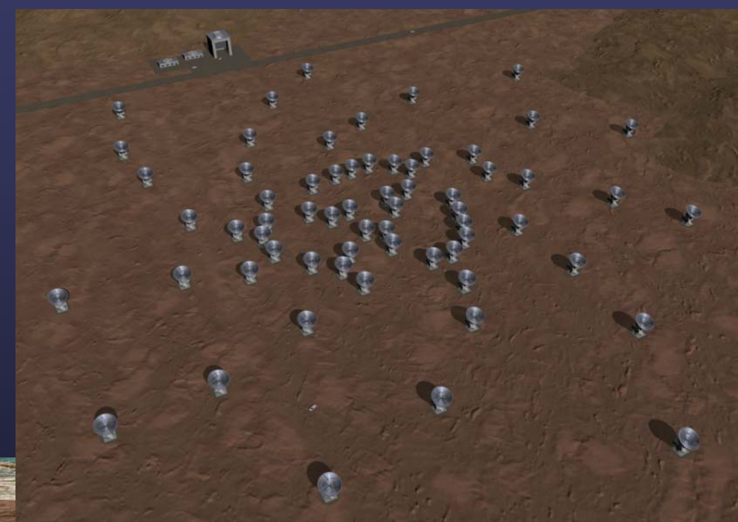
- Main Array: 50 x 12m antennas (up to 64 antennas)
  - + 4 x 12m (total power)
  - + ACA: compact array of 12 x 7m antennas

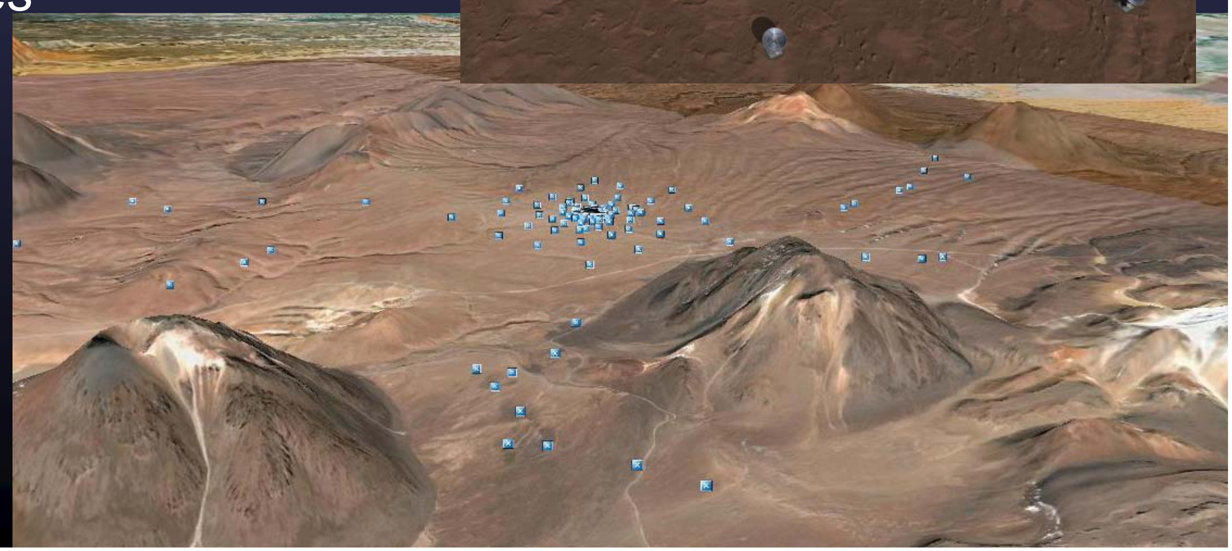
- Total cost ~1.3 Billion ($US)



ALMA

- Baselines up to 15 km (0.015” at 300 GHz) in “zoom lens” configurations
- Sensitive, precision imaging between 30 to 950 GHz (10 mm to 350 μm)
- Receivers: low-noise, wide-band (8 GHz)
- Flexible correlator with high spectral resolution at wide bandwidth
- Full polarization capabilities
- A resource for ALL astronomers including pipeline products and regional science centers



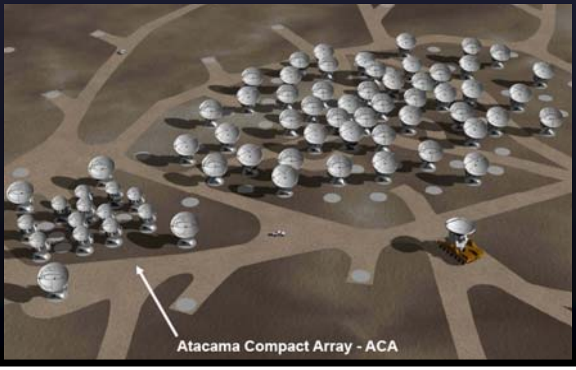


Summary of Existing and Future mm/sub-mm Arrays

Telescope	altitude (feet)	diam. (m)	No. dishes	A (m^2)	ν_{max} (GHz)
NMA	2,000	10	6	470	250
EVLA	7,050	25	27	13250	43
CARMA	7,300	3.5/6/10	23	800	250
IRAM PdB	8,000	15	6	1060	250
SMA	13,600	6	8	230	650
eSMA	13,600	6/10/15	10	490	345
ALMA[1]	16,400	12	50	5700	950
ACA	16,400	7	12	490	950

[1] First call for early science proposals expected in Q2 2010

ALMA will be 10-100 times more sensitive and have 10-100 times better angular resolution compared to current millimeter interferometers



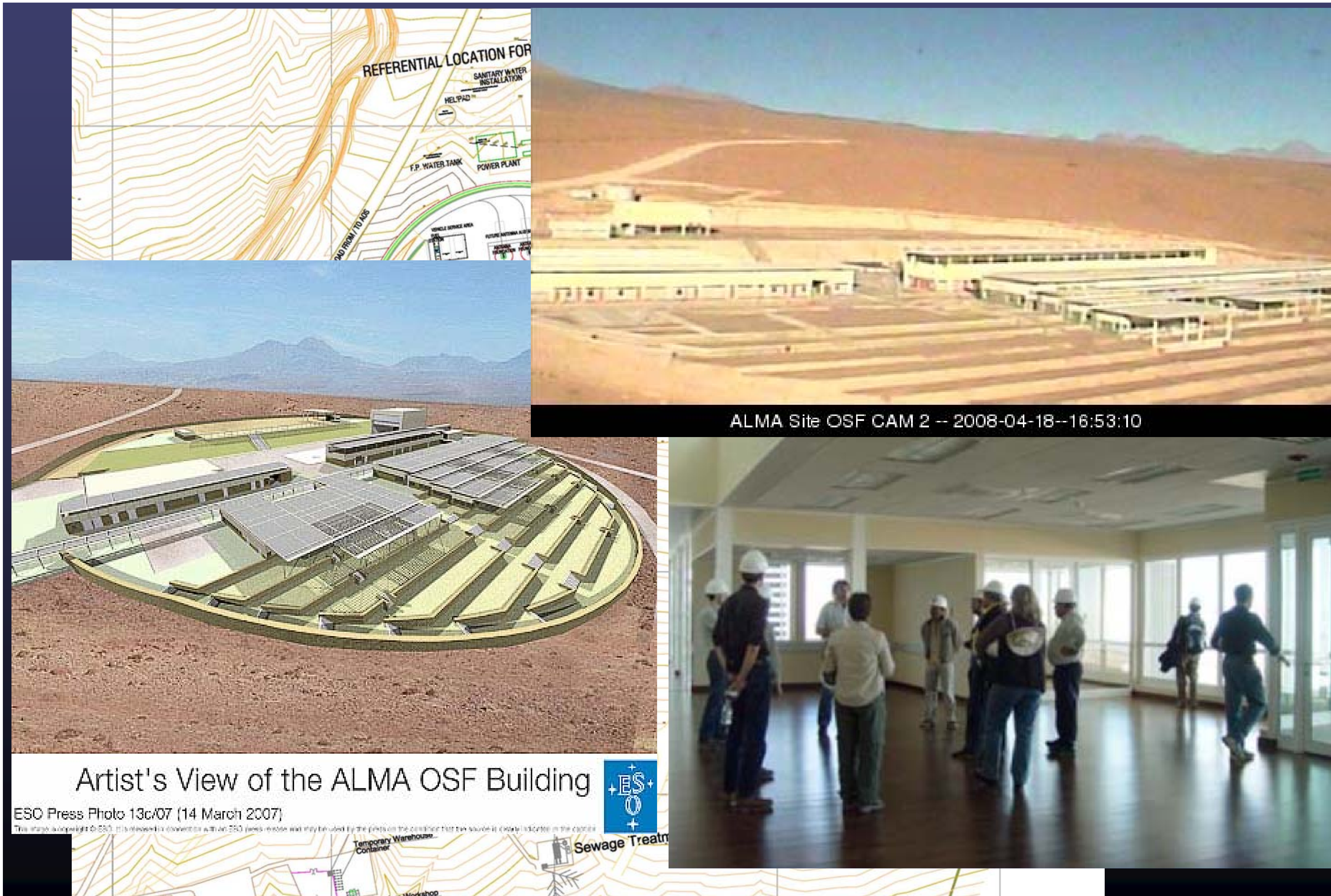
The Road to ALMA

AOS (High Site) Completed

Houses the ALMA and ACA correlators

ACA correlator being installed at AOS

OSF (mid-level) Construction Completed



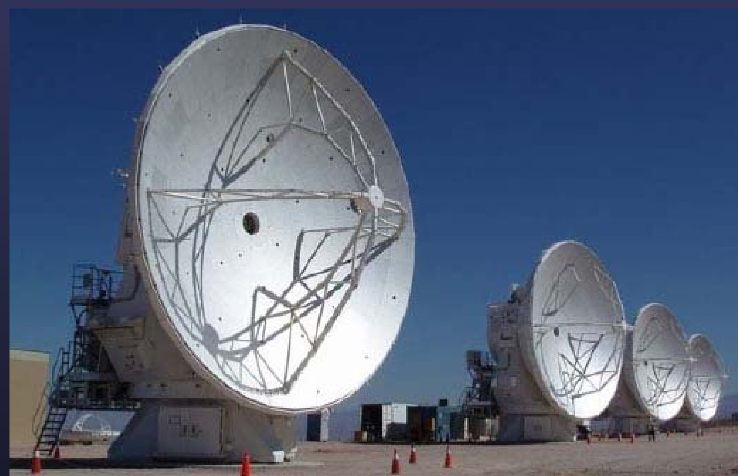
Artist's View of the ALMA OSF Building

ESO Press Photo 13c/07 (14 March 2007)

ALMA Site OSF CAM 2 -- 2008-04-18--16:53:10

Hardware arriving in Chile

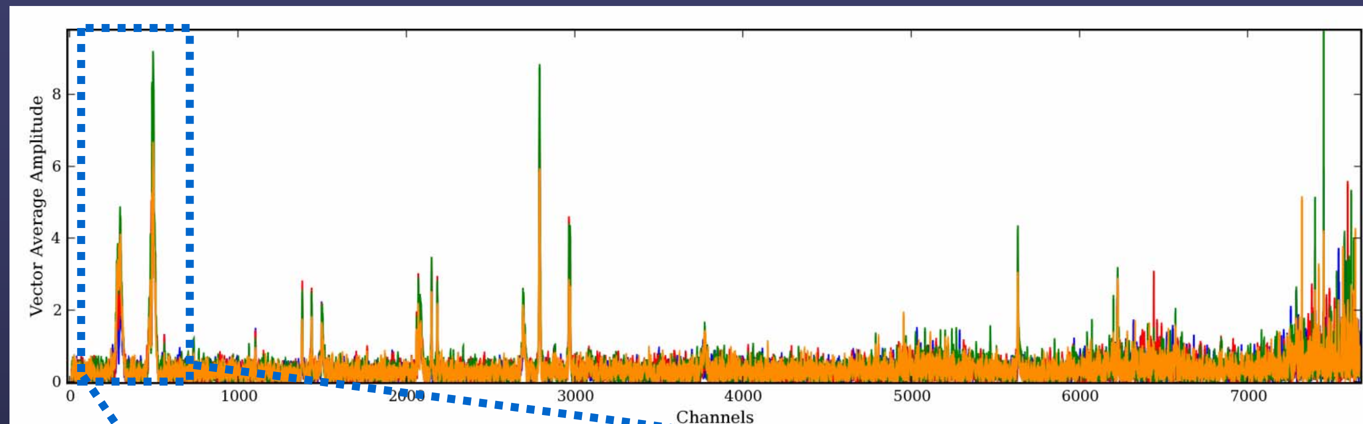
1st quadrant of ALMA correlator



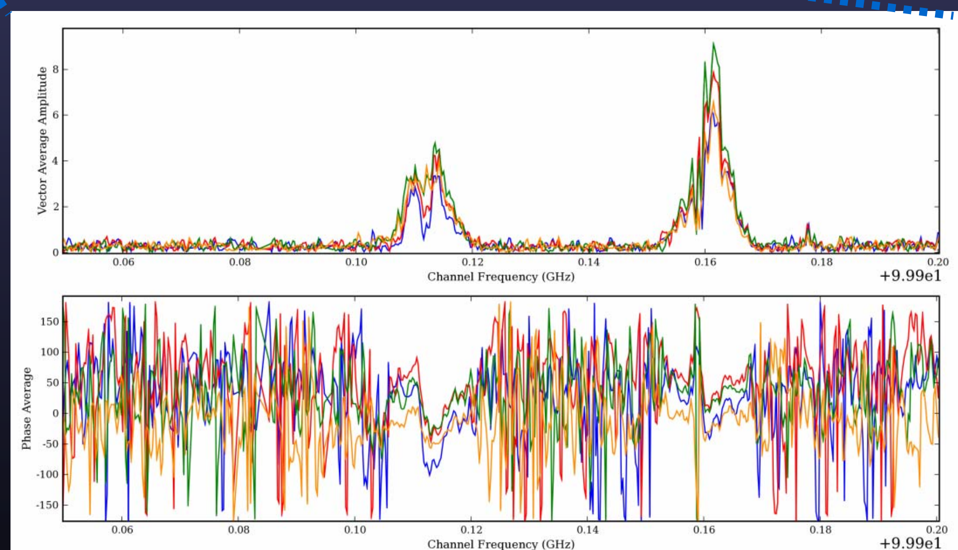
- Surfaces better than 15 μm!
- Pointing accuracy 2” absolute, 0.6” offset
- Fast switching (1.5 deg in 1.5 sec)
- Currently 4 Vertex and all 4 Melco 12m (total power)

An Important ALMA Milestone: Spectrum from ALMA Test Facility

ATF Orion spectrum (four datasets) edited and calibrated in CASA



- “Real” ALMA scheduling blocks are being run routinely at the ATF
- ALMA data format ASDM ⇨ CASA filler completed
- CASA routinely being used to reduce data at the ALMA Test Facility at VLA



Zoom in on amplitude and phase showing good agreement between 4 datasets

Current Projected Timeline

Mid 2008 Testing at ATF continues

Fall 2008 Commissioning Begins at OSF

Mid 2009 Commissioning Begins with 3-element array at AOS

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

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

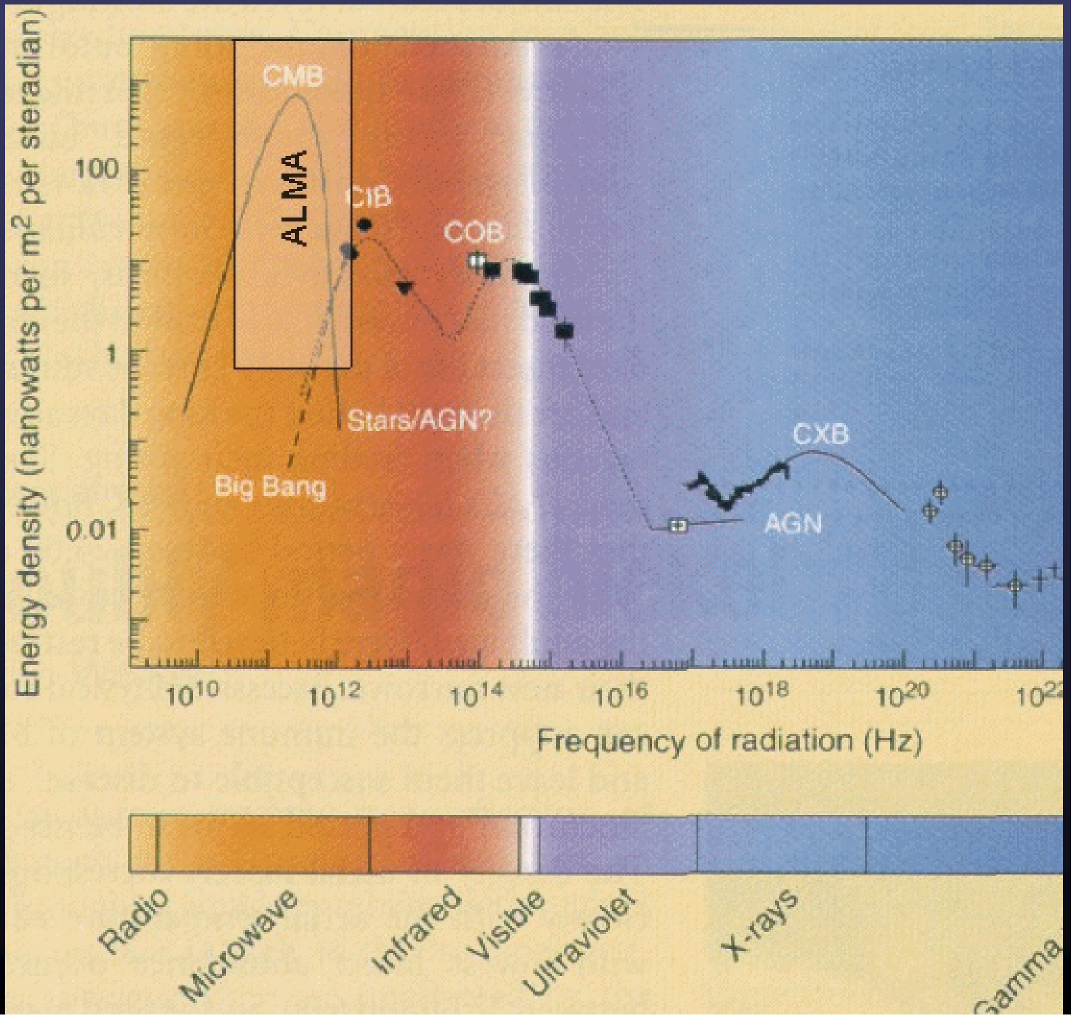
- Unique science because of the sensitivity to thermal emission from dust and molecular lines:

In Rayleigh-Jeans regime, $h\nu \ll kT$,

$$S_\nu = \frac{2kT\nu^2\tau_\nu\Omega}{c^2} \quad \mathrm{Wm^{-2}\,Hz^{-1}}$$

for optically-thin emission $\tau_\nu \propto \nu^2$,

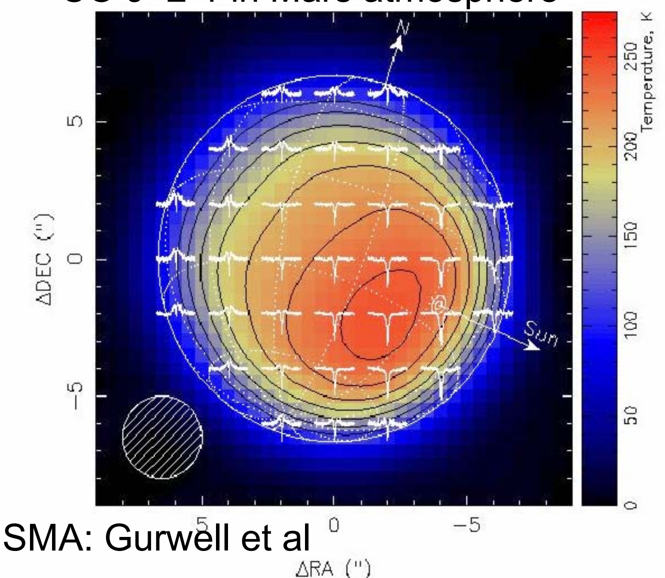
flux density: $S_\nu \propto \nu^4$



Exploration of the Solar System

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

CO J=2-1 in Mars atmosphere

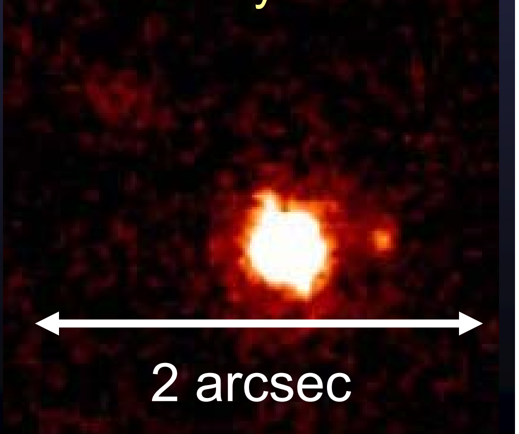


SMA: Gurwell et al

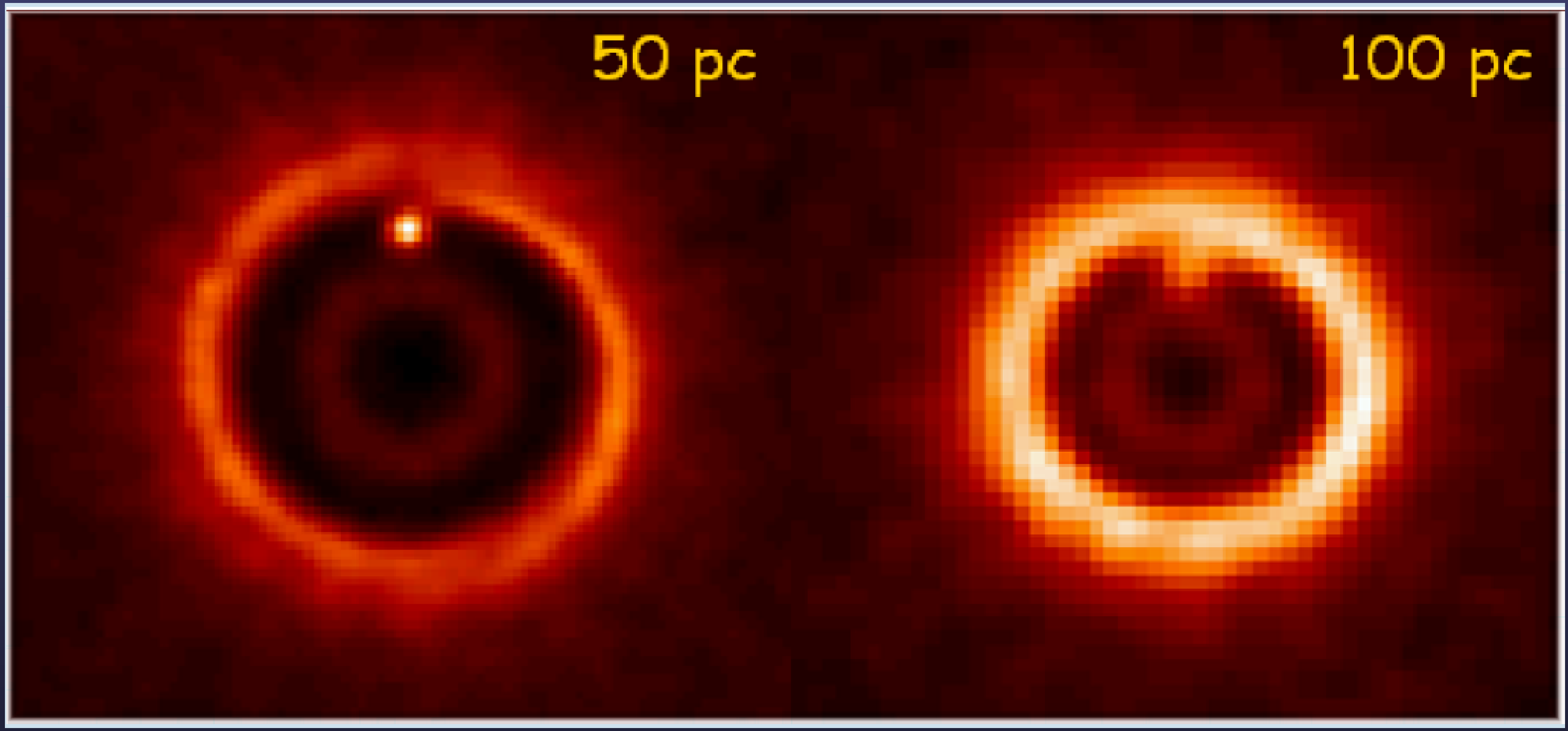
Fountains of Enceladus

ALMA Beam

Eris and Dysnomia



Searching for “dust gaps” in Nearby Low Mass Protoplanetary Disks

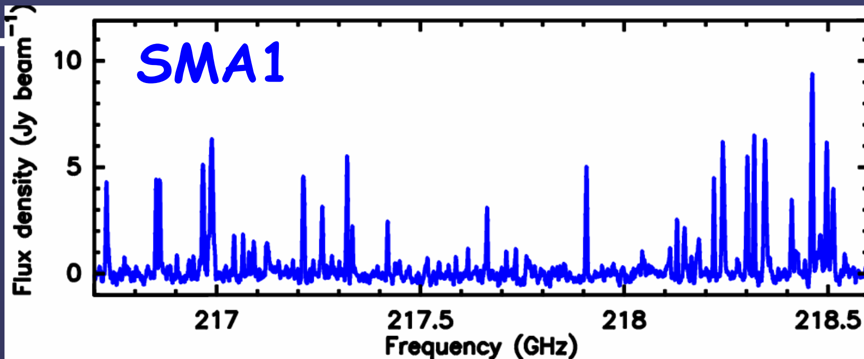


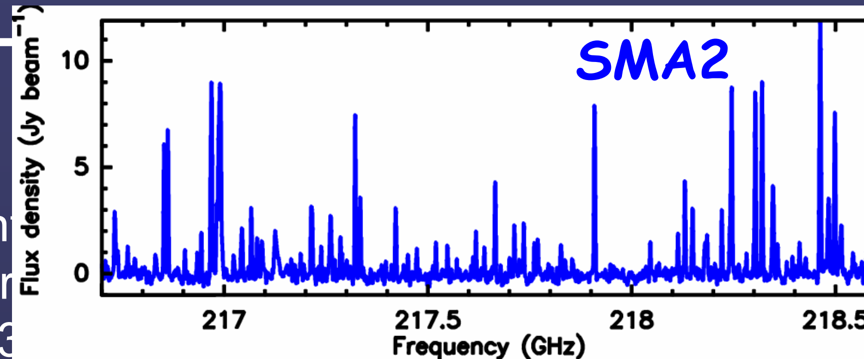
Simulation of the 950 GHz dust emission from a 1 Jupiter Mass planet around a 0.5 Solar mass star (orbital radius 5 AU)

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

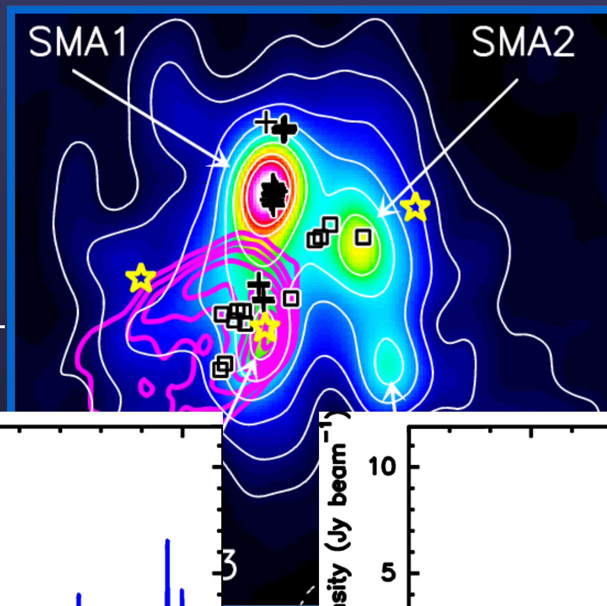
Wolf & D’Angelo (2005)

Understanding how Massive Stars form though Hot Core Line Emission

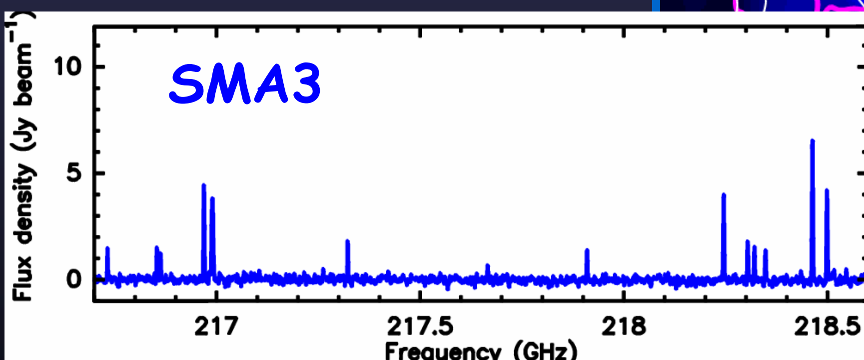


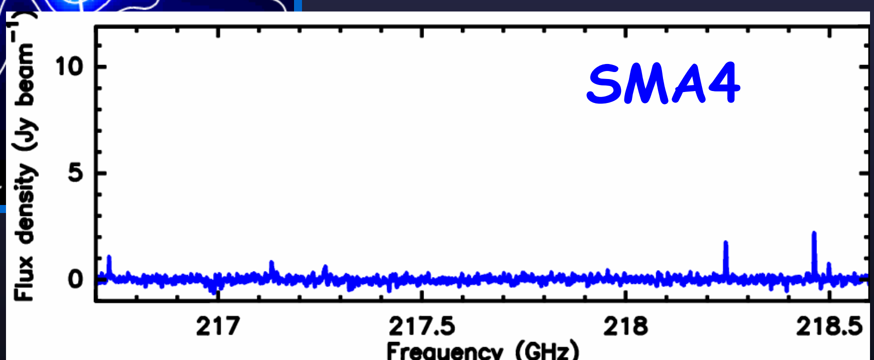


CO, ^{13}CO, $C^{17}O$, $C^{18}O$, ^{34}CS, SO, SO_2, $^{34}SO_2$, H_2S, NS, SiO, H_2CO, CH_3OH, $^{13}CH_3OH$, $H^{13}CO^+$



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

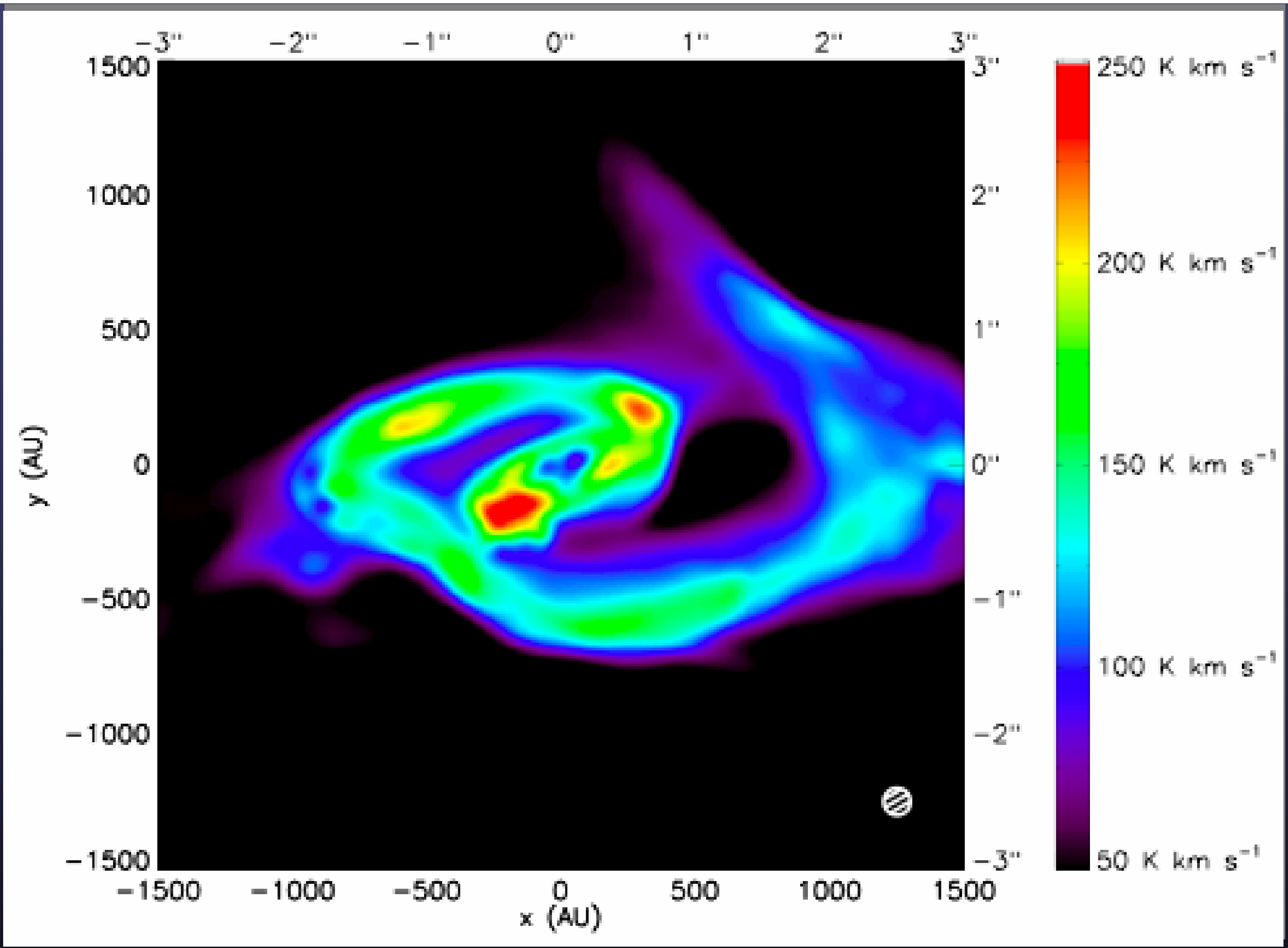




ALMA will improve resolution and spectral line sensitivity by more than a factor of 25!

Brogan, Hunter et al. in prep

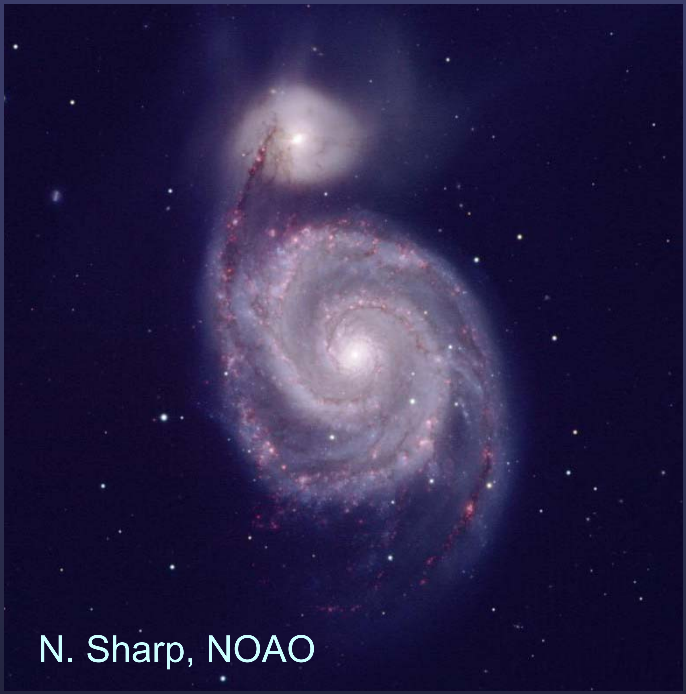
ALMA Simulation: Rotating m = 1 Spiral



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

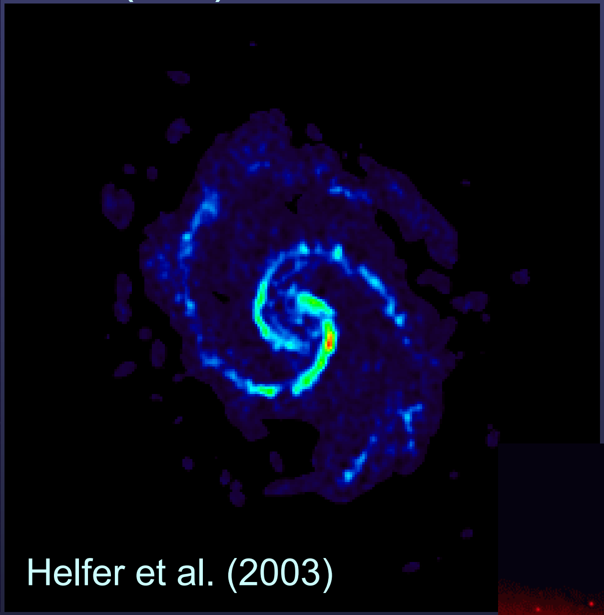
(Krumholtz, Klein, & McKee 2007)

Galaxy Structure and Evolution



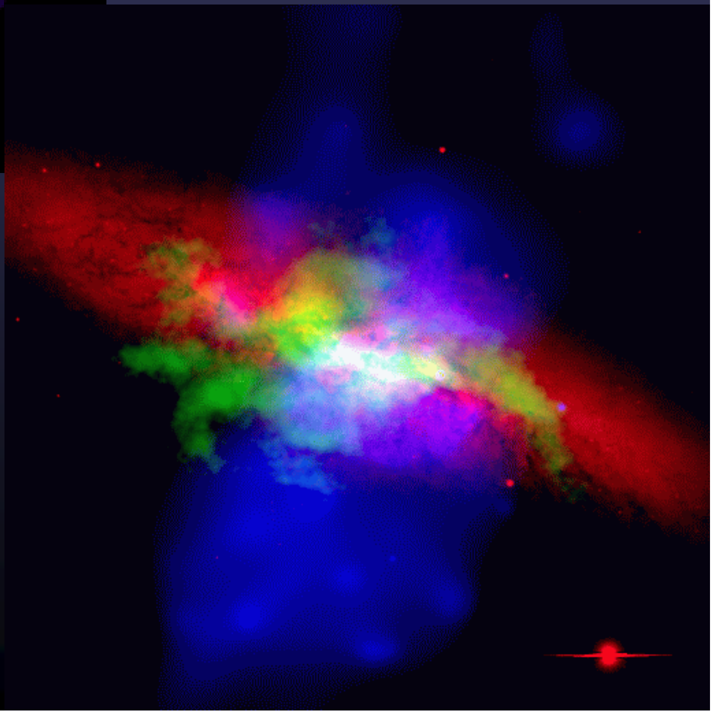
N. Sharp, NOAO

CO(1-0) BIMA-SONG



Helfer et al. (2003)

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)

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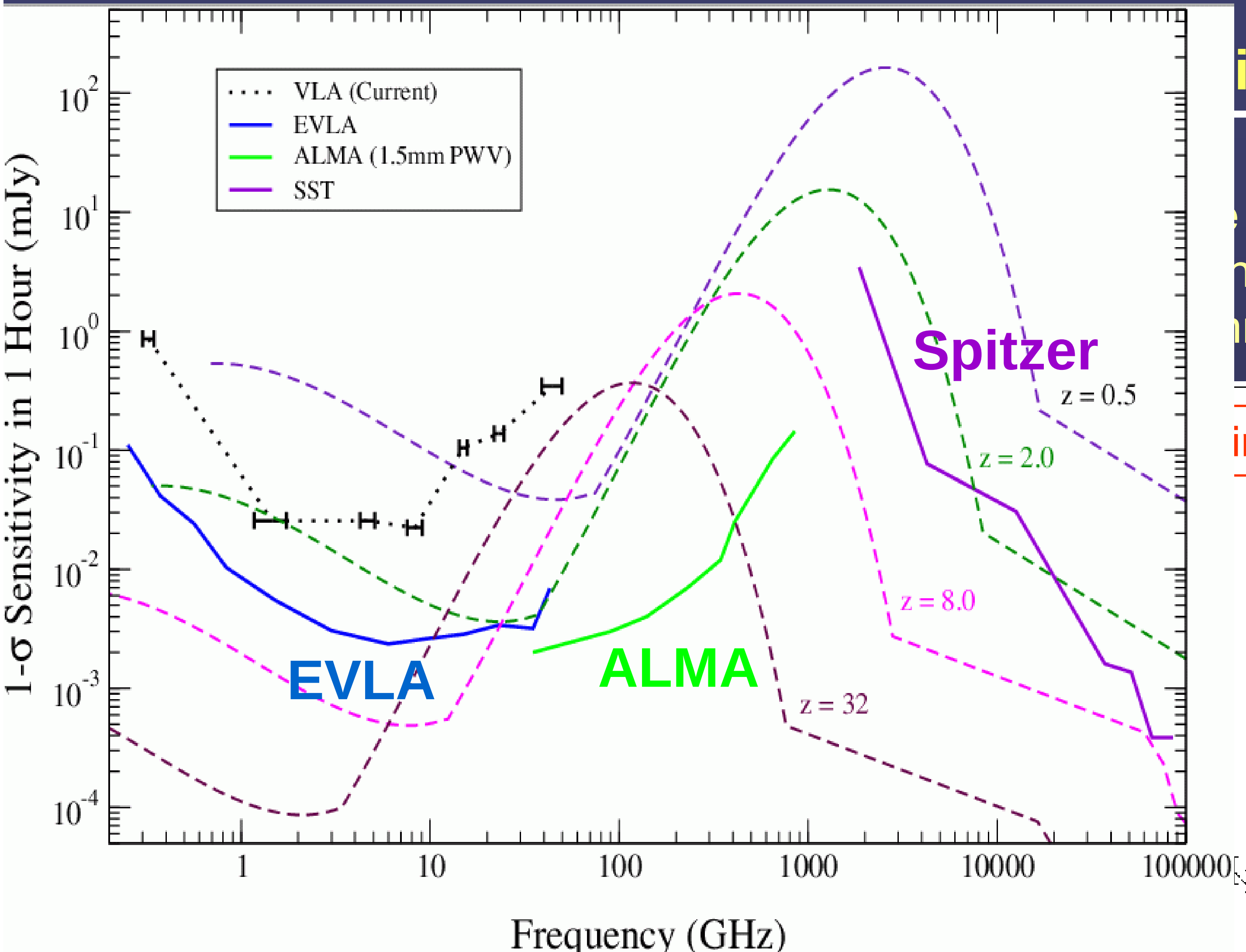
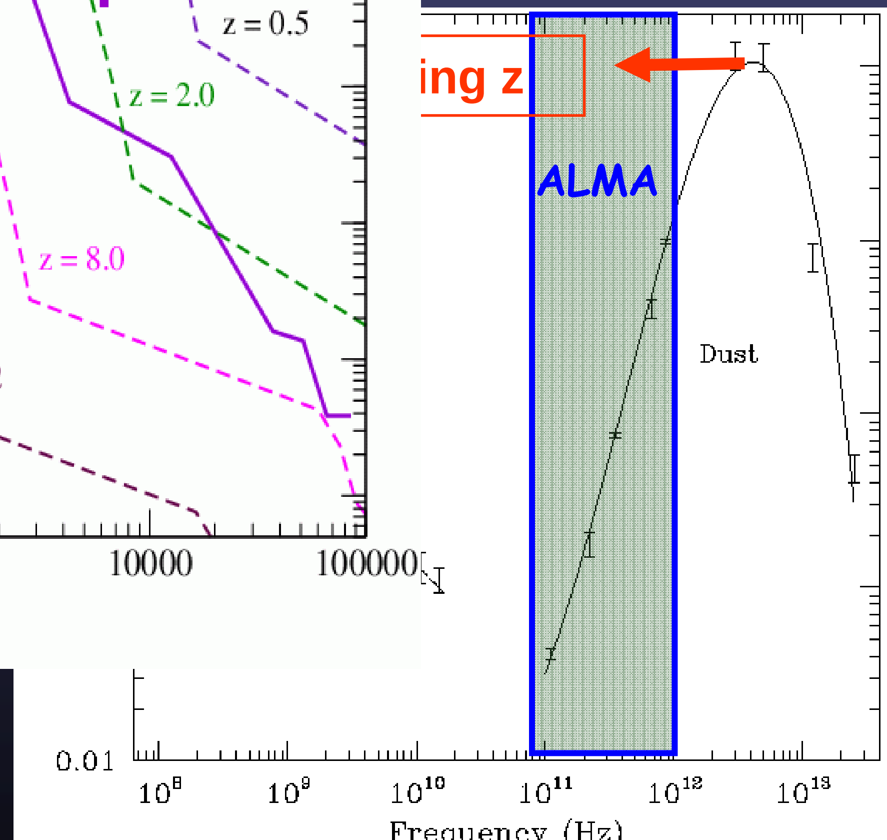
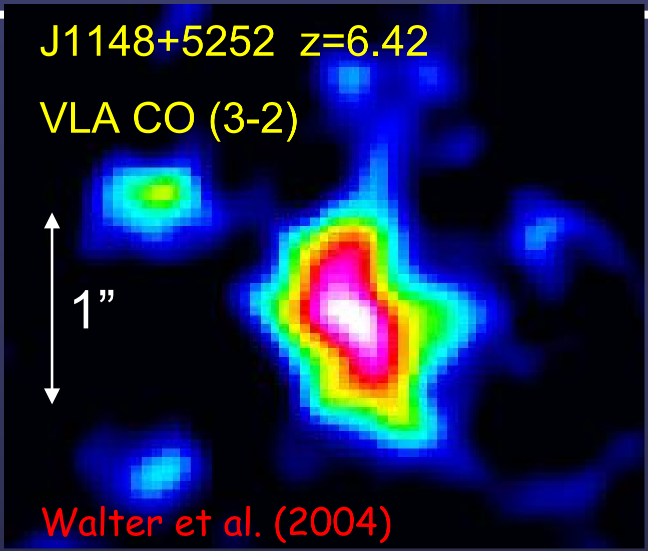
mming





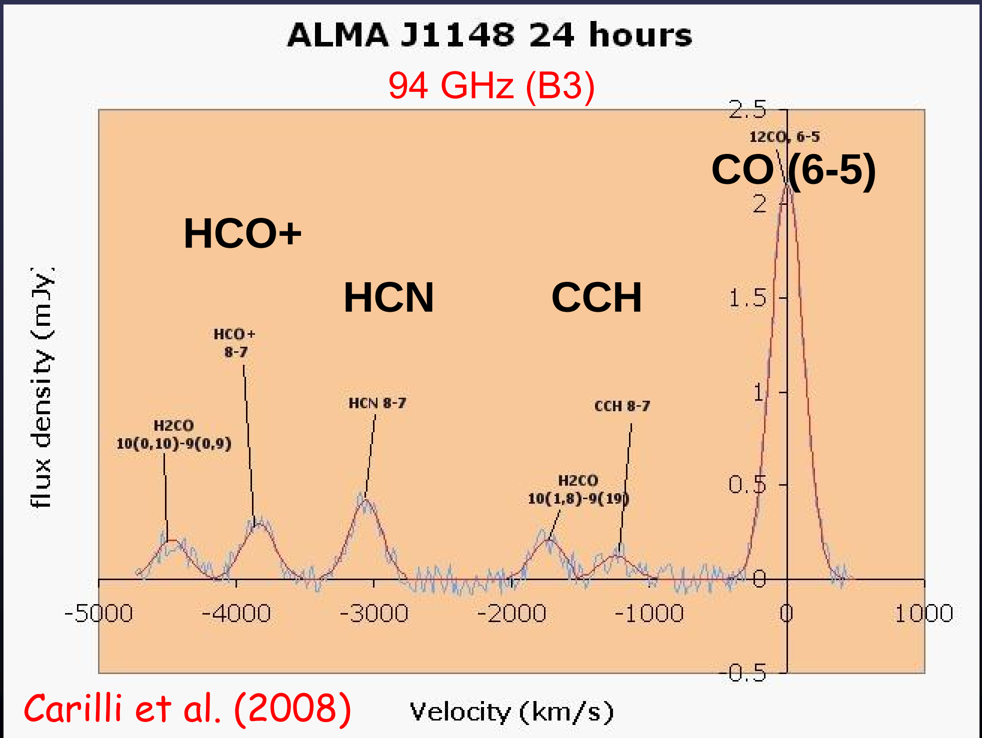
Detect high-z galaxies as easily as those at z~0.5

Study of 'first light' During Cosmic Reionization



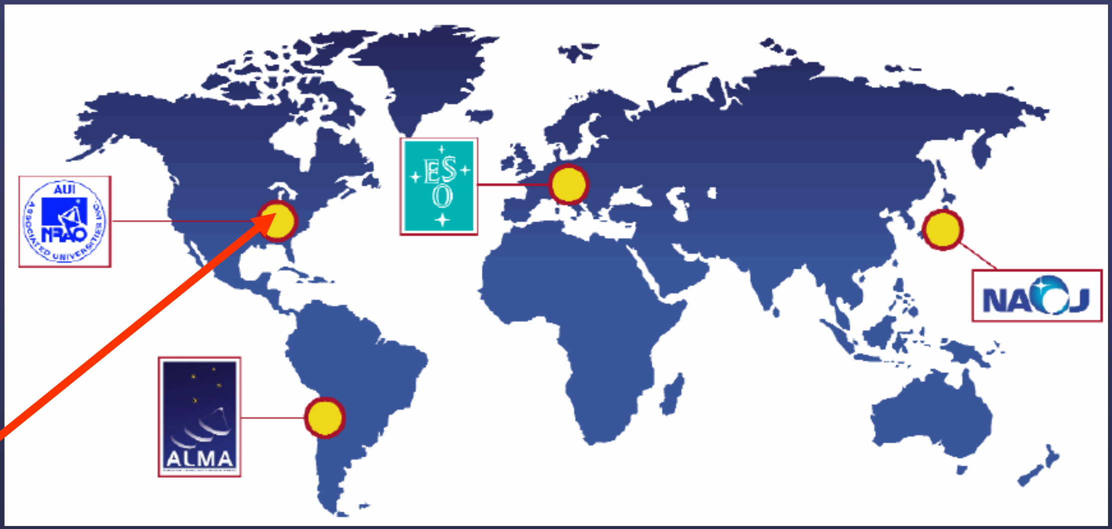
Current State-of-art: Tens of hours to detect rare, systems (FIR ~1×10^{13} L$_\odot$)

- Brightest submm galaxies detect dust emission in **1sec** (5σ)
- Detect multiple lines in 24 hours => detailed astrochemistry
- Image dust and gas at sub-kpc resolution – gas dynamics!



ALMA Science Support

- Three regional ALMA science centers: ARCs
- The North American ARC is a partnership between the US and Canada (7.25%)
- One international proposal review committee is envisioned. Details TBD



NAASC: North America ALMA Science Center, Charlottesville, VA

One-stop shopping for:

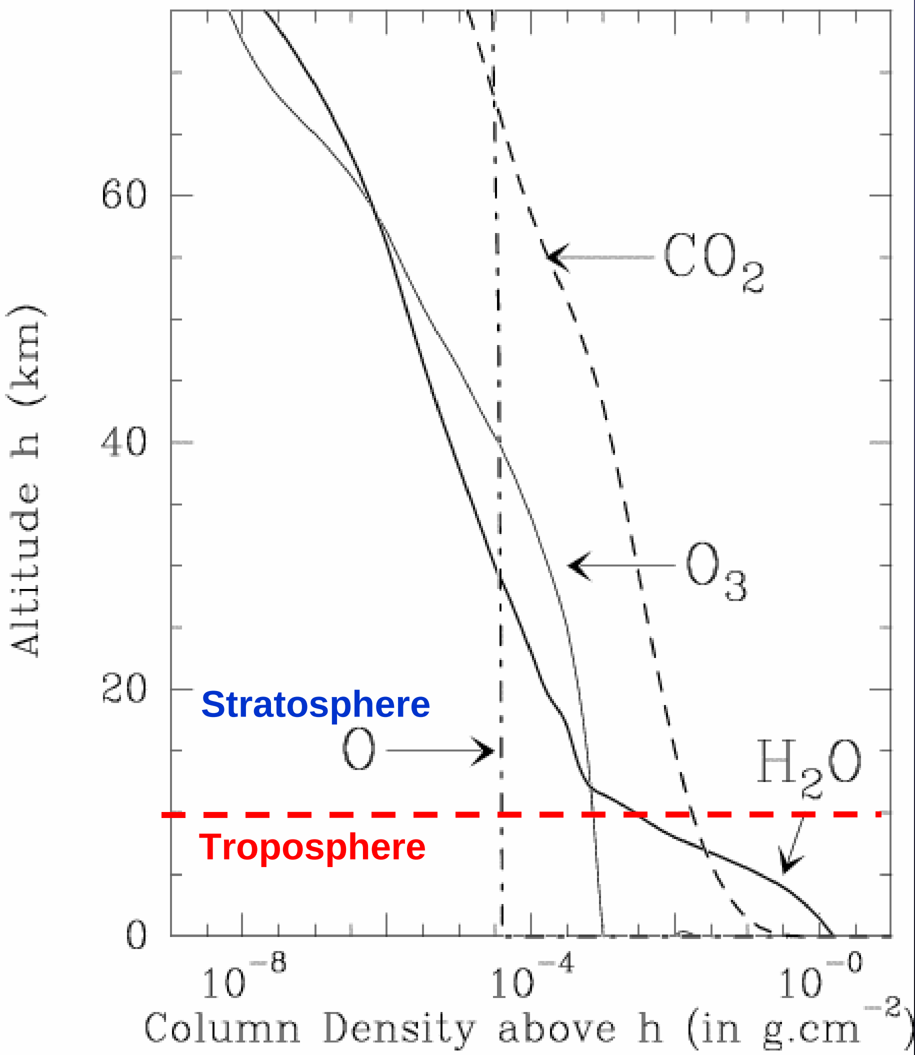
- Proposals
- Observing scripts
- Data archive and reduction
- Astronomer outreach (summer schools, tutorials, workshops)

Problems unique to the mm/submm

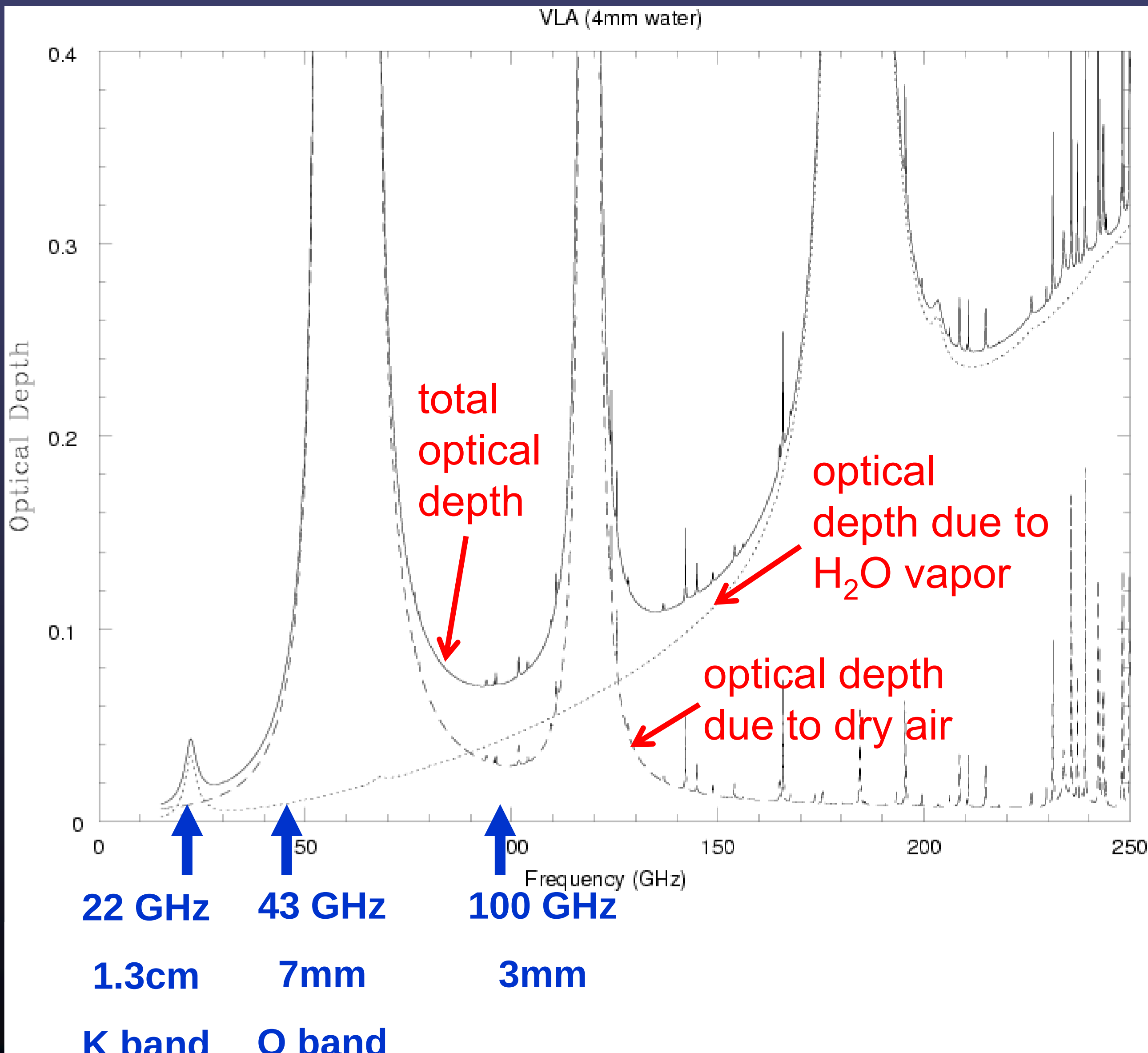
Constituents of Atmospheric Opacity

- Due to the troposphere (lowest layer of atmosphere): h < 10 km
- Temperature ↓ with ↑ altitude: clouds & convection can be significant
- Dry Constituents of the troposphere:, O_2, O_3, CO_2, Ne, He, Ar, Kr, CH_4, N_2, H_2
- H_2O: abundance is highly variable but is < 1% in mass, mostly in the form of water vapor
- "Hydrosols" (i.e. water droplets in the form of clouds and fog) also add a considerable contribution when present

Column Density as a Function of Altitude

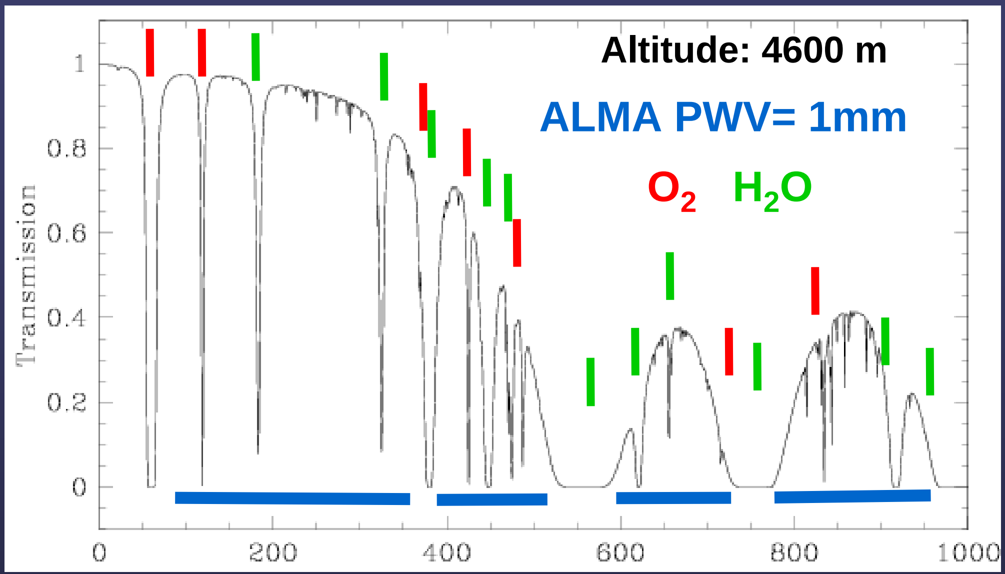


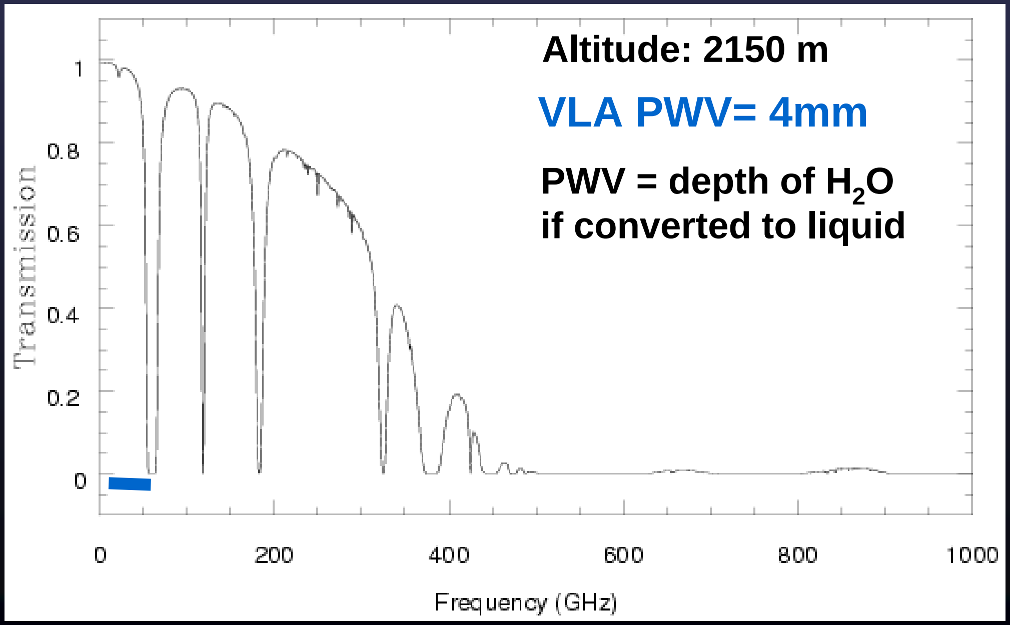
Optical Depth as a Function of Frequency



- At 1.3cm most opacity comes from H_2O vapor
- At 7mm biggest contribution from dry constituents
- At 3mm both components are significant
- “hydrosols” i.e. water droplets (not shown) can also add significantly to the opacity

Troposphere opacity increases with frequency:





Models of atmospheric transmission from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

$\Rightarrow$ Atmosphere transmission not a problem for λ > cm (most VLA bands)

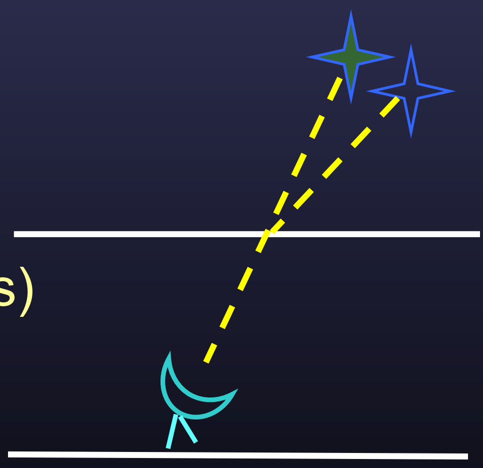
Mean Effect of Atmosphere on Phase

- Since the refractive index of the atmosphere ≠1, an electromagnetic wave propagating through it will experience a phase change (i.e. Snell's law)
- The phase change is related to the refractive index of the air, *n*, and the distance traveled, *D*, by

$$\phi_e = (2\pi/\lambda) \times n \times D$$

For water vapor $n \propto \frac{w}{DT_{atm}}$ *w*=precipitable water vapor (PWV) column

so $$\phi_e \approx \frac{12.6\pi}{\lambda} \times w \quad \text{for } T_{atm} = 270\text{ K}$$



This refraction causes:

- Pointing off-sets, $\Delta\theta \approx 2.5x10^{-4}\ x\ tan(i)$ (radians)
  @ elevation 45° typical offset~1'
- Delay (time of arrival) off-sets

⇨ These "mean" errors are generally removed by the online system

Sensitivity: System noise temperature

In addition to receiver noise, at millimeter wavelengths the atmosphere has a significant brightness temperature (T_{sky}):

For a perfect antenna, ignoring spillover and efficiencies

$$T_{noise} \approx T_{rx} + T_{sky}$$

$$\text{where } T_{sky} = T_{atm}\,(1 - e^{-\tau}) + T_{bg} e^{-\tau}$$

$$\text{so } \boxed{T_{noise} \approx T_{rx} + T_{atm}(1 - e^{-\tau})}$$

Receiver temperature — Emission from atmosphere

T_{atm} = temperature of the atmosphere ≈ 300 K

T_{bg} = 3 K cosmic background

Before entering atmosphere the source signal $S = T_{source}$

After attenuation by atmosphere the signal becomes $S = T_{source}\, e^{-\tau}$

Consider the signal-to-noise ratio:

$$S / N = (T_{source}\, e^{-\tau}) / T_{noise} = T_{source} / (T_{noise}\, e^{\tau})$$

$$\boxed{T_{sys} = T_{noise}\, e^{\tau} \approx T_{atm}(e^{\tau} - 1) + T_{rx} e^{\tau}}$$

⇨ The system sensitivity drops rapidly (exponentially) as opacity increases

Atmospheric opacity, continued

Typical optical depth for 345 GHz observing at the SMA:

at zenith τ_{225} = 0.08 = 1.5 mm PWV, at elevation = 30° $\Rightarrow$ τ_{225} = 0.16

Conversion from 225 GHz to 345 GHz ⇨ $\tau_{345} \approx 0.05 + (2.25\,\tau_{225}) \approx 0.41$

assume T_{atm} = 300 K and T_{rx}=100 K

$T_{sys}(DSB) = T_{sys}\, e^{\tau} = e^{\tau}\,(T_{atm}(1-e^{-\tau}) + T_{rx}) = 1.5(101 + 100) \approx 300$ K

⇨ Atmosphere adds considerably to T_{sys} and since the opacity can change rapidly, T_{sys} must be measured often

Many MM/Submm receivers are double sideband, thus the effective T_{sys} for spectral lines (which are inherently single sideband) is doubled:

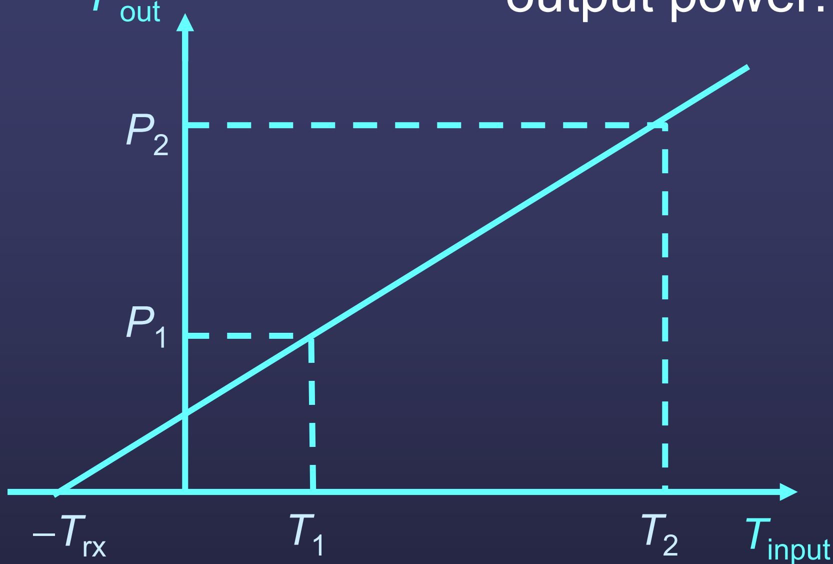
$$T_{sys}(SSB) = 2\, T_{sys}\,(DSB) \sim 600\ K$$

Sensitivity: Receiver noise temperature

- Good receiver systems have a linear response:

output power: $P_{out} = G \times (T_{input} + T_{rx})$

Unknown slope (G) — Calibrated 'load' (T_{input}) — Receiver temperature (T_{rx})



In order to measure T_{rx}, you need to make measurements of two calibrated 'loads':

T_1 = 77 K liquid nitrogen load

$T_2 = T_{load}$ room temperature load

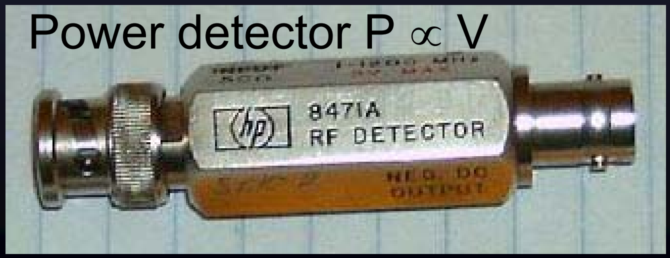
$$T_{rx} = \frac{(T_2 - T_1)\,P_1}{(P_2 - P_1)} - T_1$$

T_{rx} is not constant in time or frequency, especially for mm/submm receivers which are difficult to tune to ideal performance.

Let $Y = P_2/P_1$ (Y-factor)

$$T_{rx} = \frac{(T_2 - Y T_1)}{(Y - 1)}$$

Power(ν) ⇨



⇨ Voltage = $G * (T_{input} + T_{rx})$

So $Y = V_2/V_1$

Interferometric MM Measurement of T_{sys}

- How do we measure $T_{sys} = T_{atm}(e^{\tau} - 1) + T_{rx}e^{\tau}$ without constantly measuring T_{rx} and the opacity?
- T_{sys} is obtained by the "chopper wheel" method i.e. putting an ambient temperature load (T_{load}) in front of the receiver and measuring the resulting power compared to power when observing sky (Penzias & Burrus 1973).

Load in: $V_{in} = G\ T_{in} = [T_{rx} + T_{load}]$

Load out: $V_{out} = G\ T_{out} = [T_{rx} + T_{atm}(1 - e^{-\tau}) + T_{bg}e^{-\tau} + T_{source}e^{-\tau}\ ]$

$$assume\ T_{atm} \approx T_{load}$$

Comparing in and out: $$\frac{V_{in} - V_{out}}{V_{out}} = \frac{T_{load}}{T_{sys}}$$

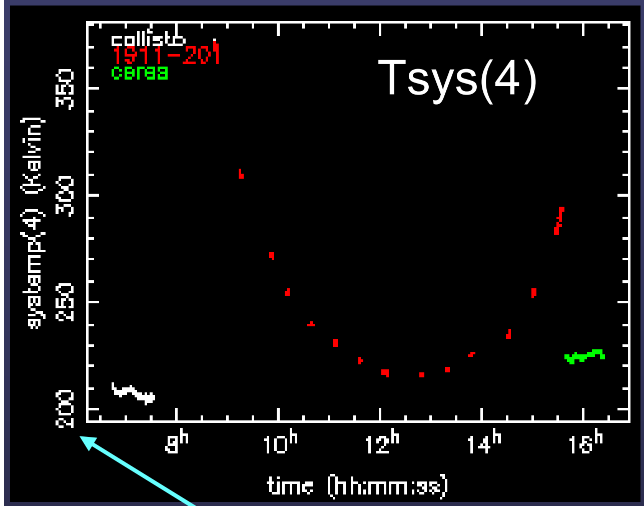
$$T_{sys} = T_{load} * T_{out} / (T_{in} - T_{out})$$

Power is really observed but is $\propto$ T in the R-J limit

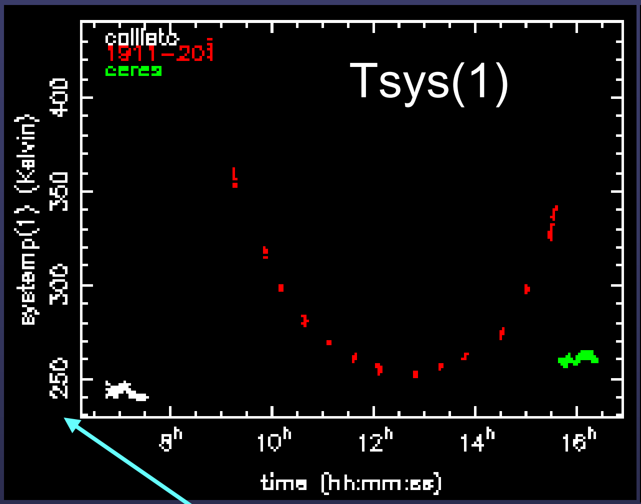
- IF $T_{atm} \approx T_{load}$, and T_{sys} is measured often, changes in mean atmospheric absorption are corrected. ALMA will have a two temperature load system which does not require assuming $T_{atm} \approx T_{load}$

SMA calibration load swings in and out of beam

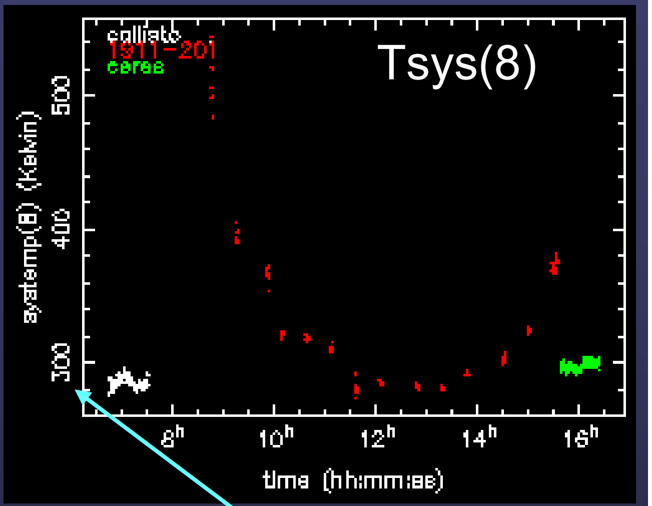
Example SMA 345 GHz T_{sys} Measurements



Good



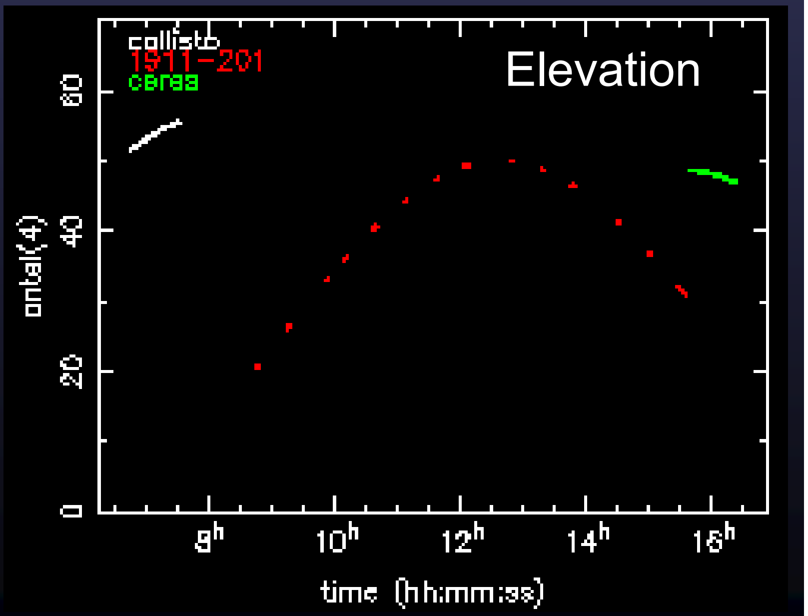
Medium



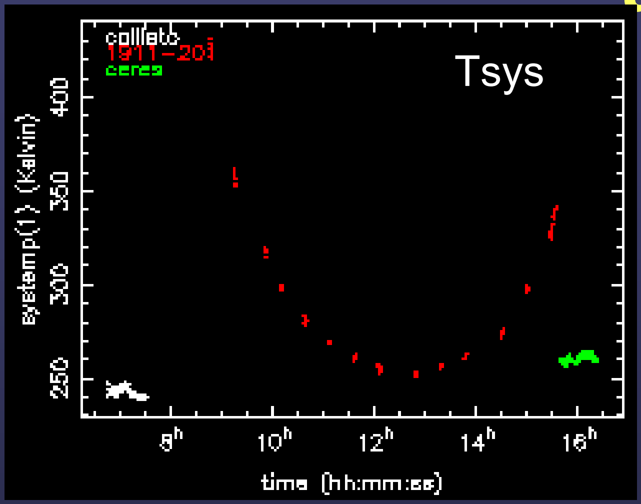
Poor

For calibration and imaging,

visibility “sensitivity” weight is $\propto 1/[T_{sys}(i) * T_{sys}(j)]$



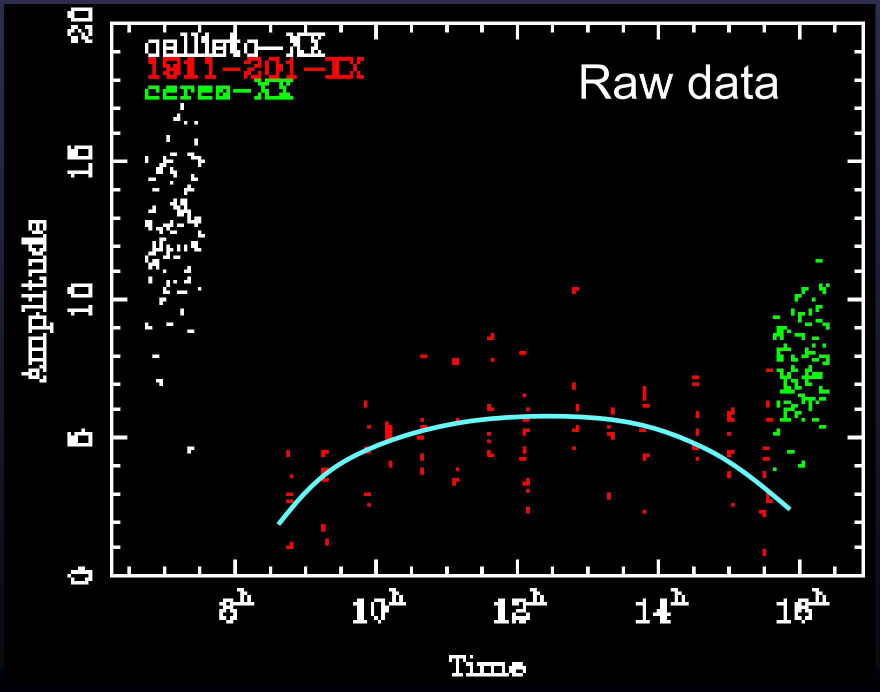
SMA Example of Correcting for T_{sys} and conversion to a Jy Scale

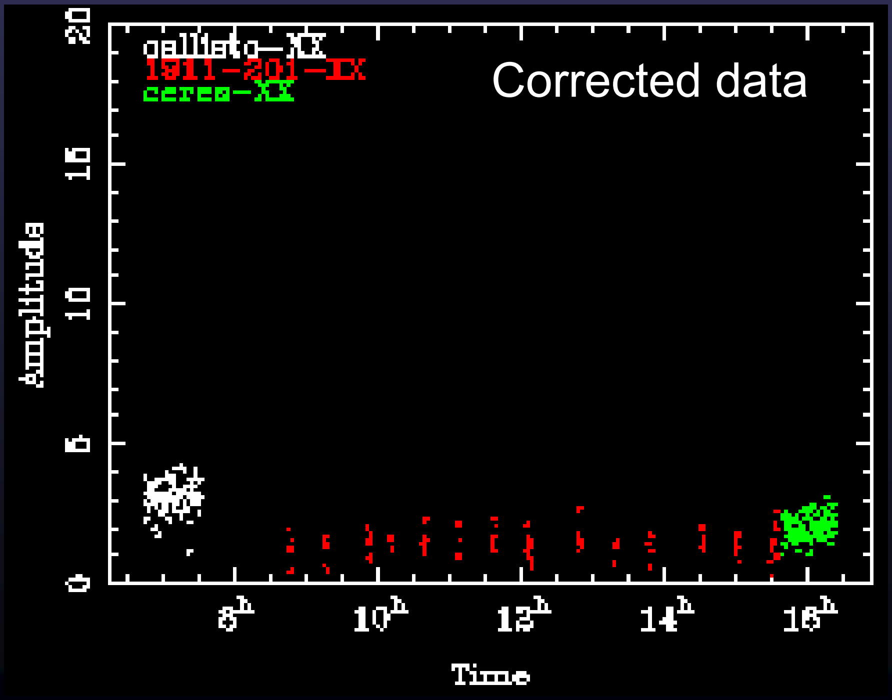


$$S = S_o * [T_{sys}(1) * T_{sys}(2)]^{0.5} * 130 \text{ Jy/K} * 5 \times 10^{-6} \text{ Jy}$$

SMA gain for 6m dish and 75% efficiency

Correlator unit conversion factor





Absolute gain calibration

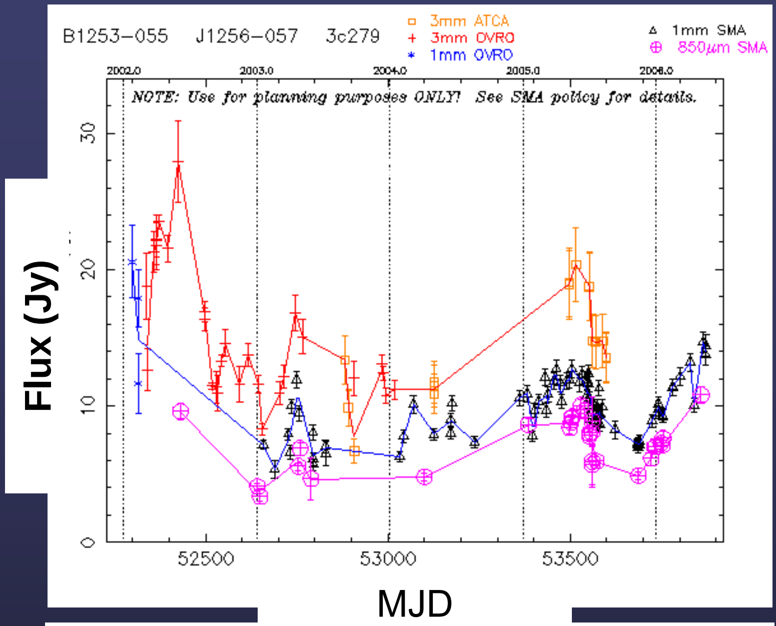
There are no non-variable quasars in the mm/sub-mm for setting the absolute flux scale

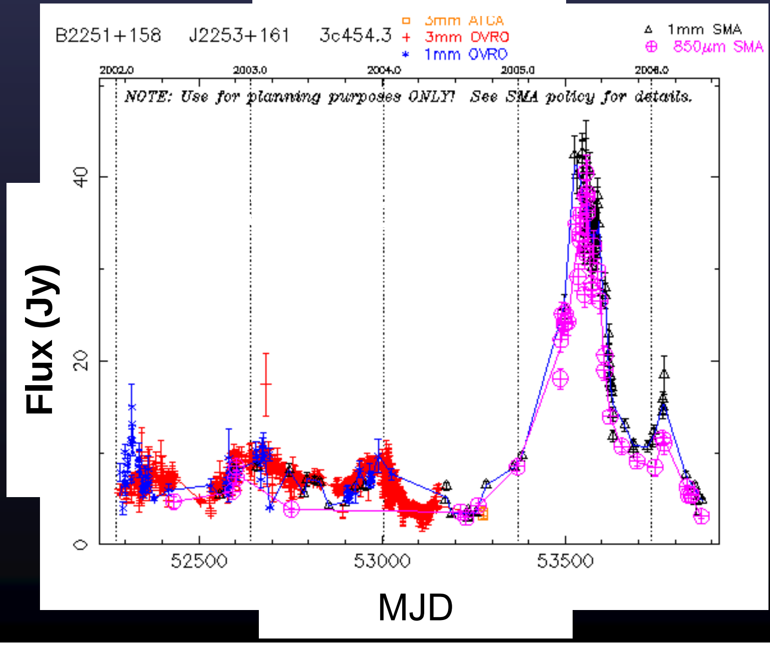
Instead, planets and moons are typically used: roughly black bodies of known size and temperature:

Uranus @ 230 GHz: S_ν ~ 37 Jy, θ ~ 4″

Callisto @ 230 GHz: S_ν ~ 7.2 Jy, θ ~ 1.4″

- S_ν is derived from models, and can be uncertain by ~ 10%
- If the planet is resolved, you need to use visibility model for each baseline
- If larger than primary beam it shouldn't be used (can be used for bandpass)





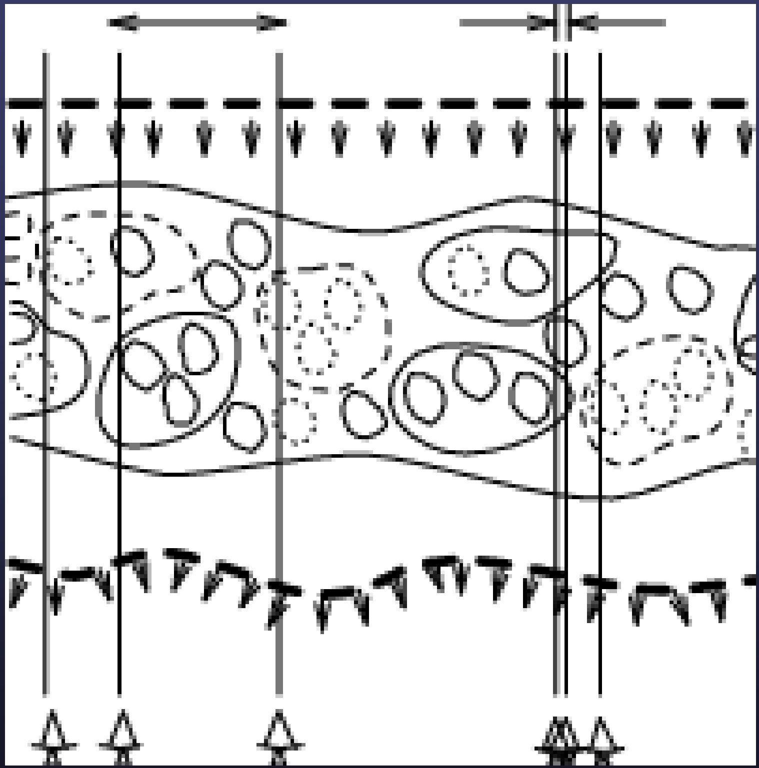
Atmospheric phase fluctuations

- Variations in the amount of precipitable water vapor (PWV) cause phase fluctuations, which are worse at shorter wavelengths, and result in
  - Low coherence (loss of sensitivity)
  - Radio “seeing”, typically 1″- 3″ at 1 mm
  - Anomalous pointing offsets
  - Anomalous delay offsets

Simplifying assumption:

The timescale for changes in the water vapor distribution is long compared to time for wind to carry features over the array

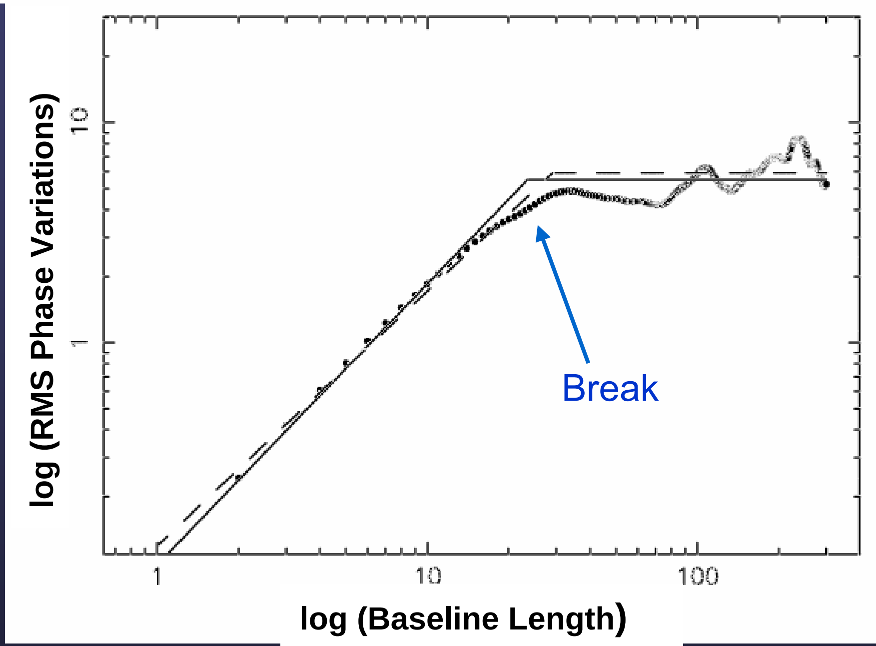
V_w~10 m/s



Patches of air with different water vapor content (and hence index of refraction) affect the incoming wave front differently.

Atmospheric phase fluctuations, continued…

Phase noise as function of baseline length



- "Root phase structure function" (Butler & Desai 1999)
- RMS phase fluctuations grow as a function of increasing baseline length until break when baseline length ≈ thickness of turbulent layer
- The position of the break and the maximum noise are weather and wavelength dependent

RMS phase of fluctuations given by Kolmogorov turbulence theory

$$\phi_{rms} = K\, b^{\alpha} / \lambda \text{ [deg]}$$

b = baseline length (km)

α = 1/3 to 5/6

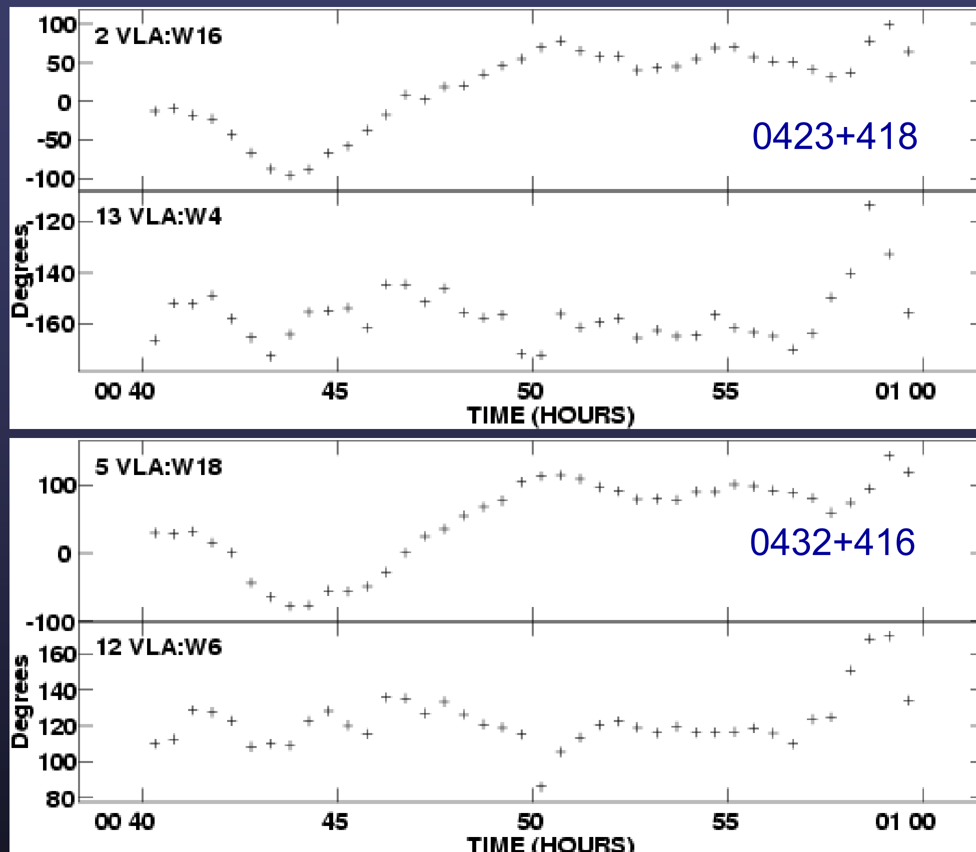
λ= wavelength (mm)

K = constant (~100 for ALMA, 300 for VLA)

Atmospheric phase fluctuations, continued…

22 GHz VLA observations of 2 sources observed simultaneously

Antennas 12 & 13 are adjacent, phases track each other closely



Antennas 2 & 5 are adjacent, phases track each other closely

Self-cal applied using a reference antenna within 200 m of W4 and W6, but 1000 m from W16 and W18:

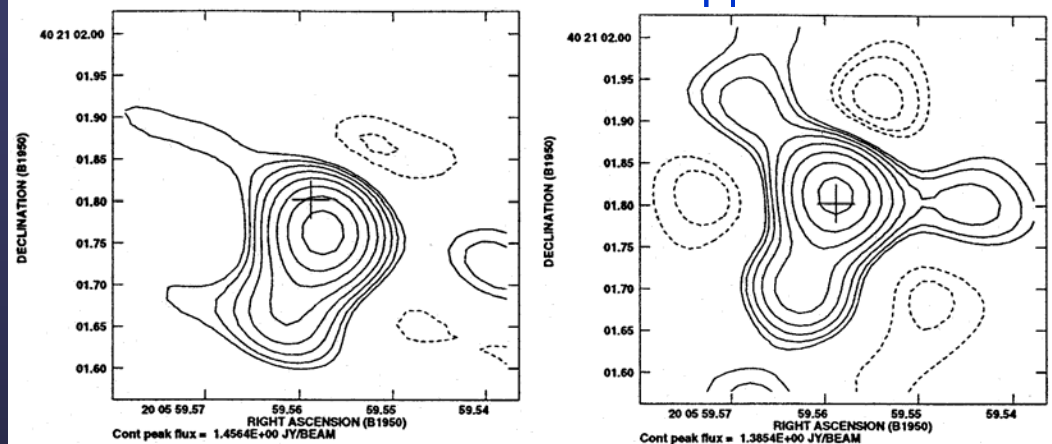
- ⇨Long baselines have large amplitude, short baselines smaller amplitude
- ⇨ Nearby antennas show correlated fluctuations, distant ones do not

VLA observations of the calibrator 2007+404

at 22 GHz with a resolution of 0.1″ (Max baseline 30 km):

Position offsets due to large scale structures that are correlated ⇨ phase gradient across array

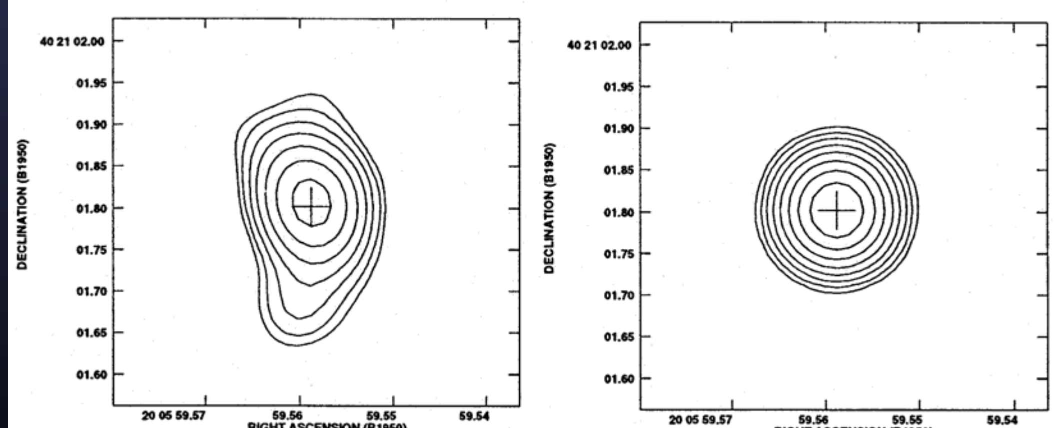
one-minute snapshots at t = 0 and t = 59 min with 30min self-cal applied



Sidelobe pattern shows signature of antenna based phase errors ⇨ small scale variations that are not correlated

Reduction in peak flux (decorrelation) and smearing due to phase fluctuations over 60 min

self-cal with t = 30min: self-cal with t = 30sec:

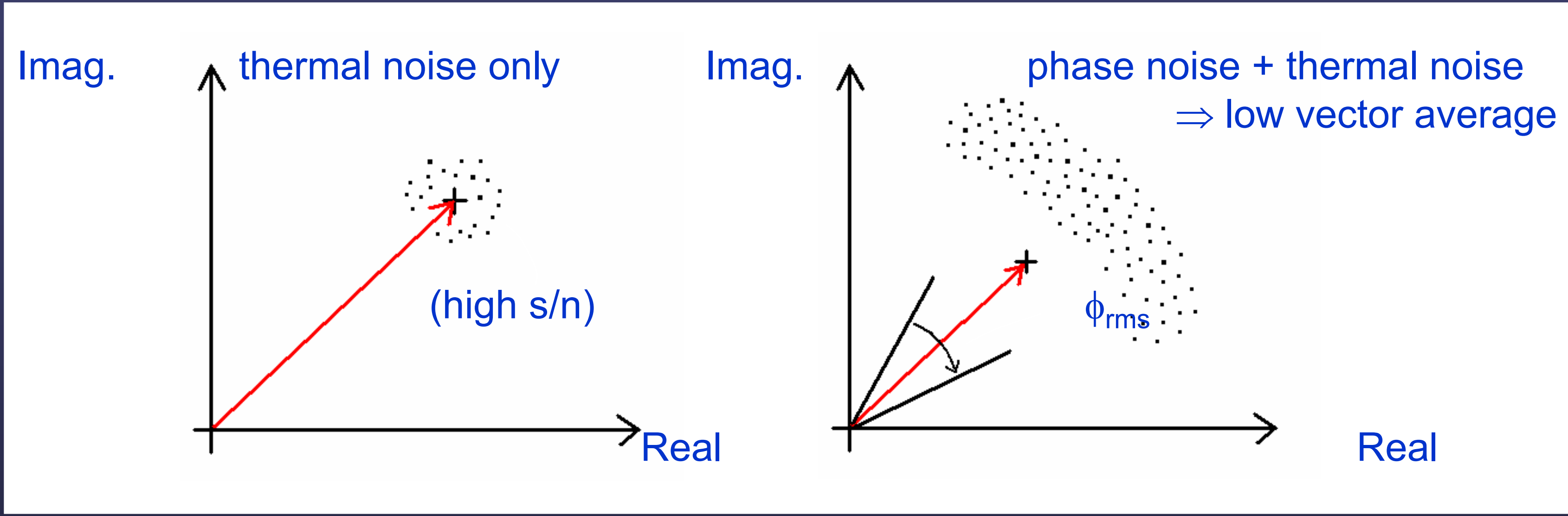


No sign of phase fluctuations with timescale ~ 30 s

⇨ Uncorrelated phase variations degrades and decorrelates image

⇨ Correlated phase offsets = position shift

Phase fluctuations: loss of coherence



Coherence = (vector average/true visibility amplitude) = $\langle V\rangle / V_0$

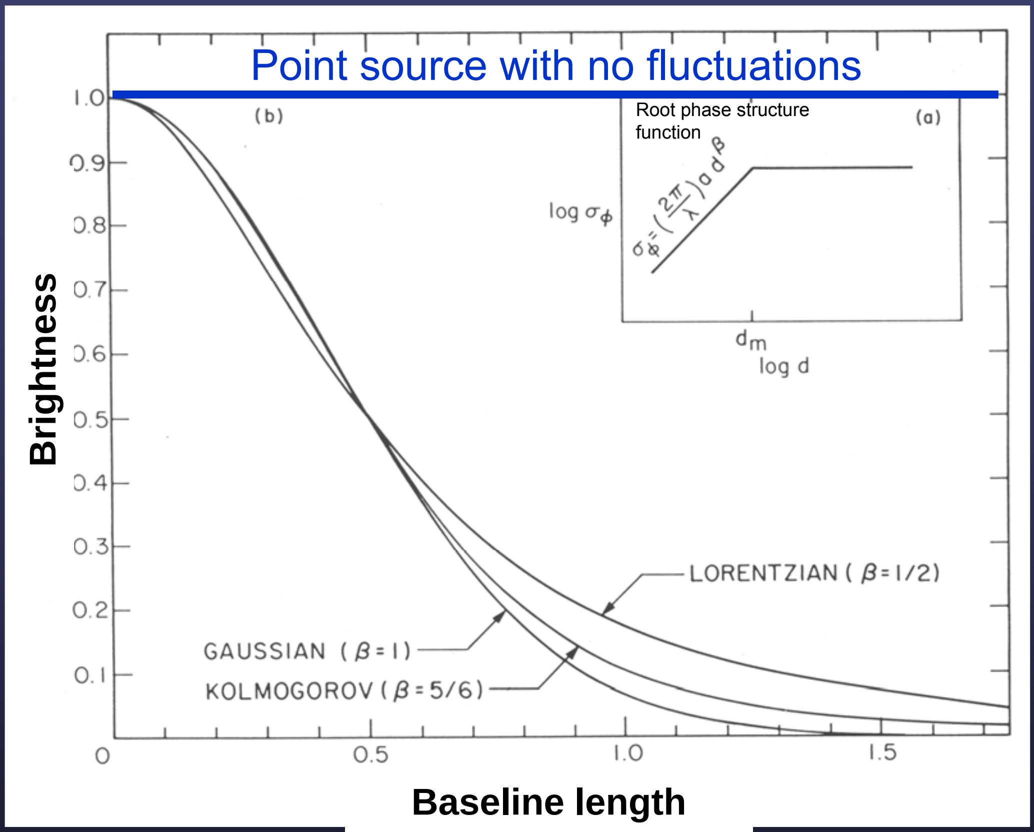
Where, $V = V_0 e^{i\phi}$

The effect of phase noise, ϕ_{rms}, on the measured visibility amplitude in a given averaging time:

$$\langle V\rangle = V_0 \times \langle e^{i\phi}\rangle = V_0 \times e^{-\phi^2_{rms}/2} \text{ (Gaussian phase fluctuations)}$$

Example: if ϕ_{rms} = 1 radian (~60 deg), coherence = $\frac{\langle V\rangle}{V_0}$ = 0.60

Phase fluctuations: radio "seeing"



Phase variations lead to decorrelation that worsens as a function of baseline length

Point-source response function for various power-law models of the rms phase fluctuations (Thompson, Moran, & Swenson 1986)

$\langle V\rangle/V_0 = \exp(-\phi^2_{rms}/2) = \exp(-[K' b^\alpha / \lambda]^2/2)$ [Kolmogorov with K'=K *pi/180]

- Measured visibility decreases with baseline length, *b,* (until break in root phase structure function)
- Source appears resolved, convolved with "seeing" function

⇨ Without corrections diffraction limited seeing is precluded for baselines longer than 1 km at ALMA site!

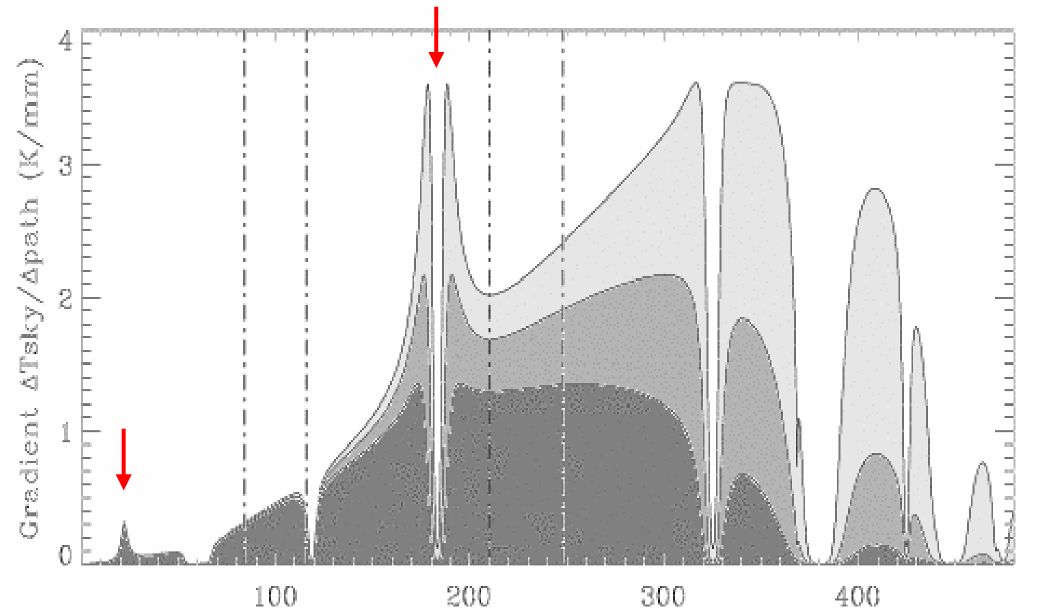
⇒ Phase fluctuations severe at mm/submm wavelengths, correction methods are needed

- Self-calibration: OK for bright sources that can be detected in a few seconds.
- Fast switching: used at the VLA for high frequencies and will be used at CARMA and ALMA. Choose fast switching cycle time, $t_{\mathbf{cyc}}$, short enough to reduce $\phi_{\mathbf{rms}}$ to an acceptable level. Calibrate in the normal way.
- Phase transfer: simultaneously observe low and high frequencies, and transfer scaled phase solutions from low to high frequency
- Paired array calibration: divide array into two separate arrays, one for observing the source, and another for observing a nearby calibrator.
  - Will not remove fluctuations caused by electronic phase noise
  - Only works for arrays with large numbers of antennas (e.g., VLA, ALMA)

Phase correction methods (continued):

- Radiometry: measure fluctuations in T_B^{atm} with a radiometer, use these to derive changes in water vapor column (w) and convert this into a phase correction using

$$\phi_e \approx \frac{12.6\pi \times w}{\lambda}$$



(Bremer et al. 1997)

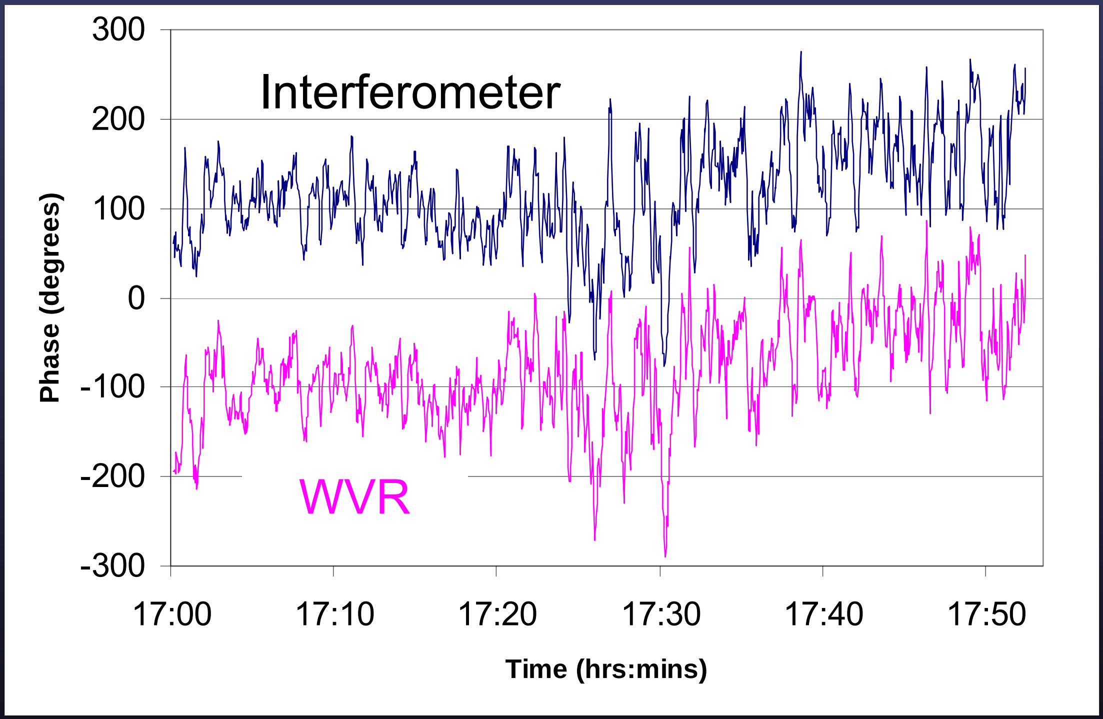
Monitor: 22 GHz H_2O line (CARMA, VLA)

183 GHz H_2O line (CSO-JCMT, SMA, ALMA)

total power (IRAM, BIMA)

ALMA: Radiometer Phase Correction

183 GHz Water Vapor Radiometers, tested at SMA



Mike Reid et al, 2006

Antenna requirements

- **Pointing:** for a 10 m antenna operating at 350 GHz the primary beam is ~ 20″

  a 3″ error ⇒ Δ(Gain) at pointing center = 5%

  Δ(Gain) at half power point = 22%

  ⇒ need pointing accurate to ~1″

  ⇒ ALMA pointing accuracy goal 0.6″

- **Aperture efficiency, η:** Ruze formula gives

  $$\eta = \exp(-[4\pi\sigma_{\mathbf{rms}}/\lambda]^2)$$

  ⇒ for η = 80% at 350 GHz, need a surface accuracy, σ_{rms}, of 30μm

  ⇒ ALMA surface accuracy goal of 15 μm

Antenna requirements, continued…

- **Baseline determination:** phase errors due to errors in the positions of the telescopes are given by

$$\Delta\phi = \frac{2\pi}{\lambda} \times \Delta b \times \Delta\theta$$

$\Delta\theta$ = angular separation between source & calibrator

Δb = baseline error

Note: $\Delta\theta$ = angular separation between source and calibrator, can be > 20° in mm/sub-mm

$\Rightarrow$ to keep $\Delta\phi < \Delta\theta$ need $\Delta b < \lambda/2\pi$

e.g., for λ = 1.3 mm need Δb < 0.2 mm

Problems, continued…

- Instrument stability
  - Must increase linearly with frequency (delay lines, oscillators, etc…)
- Millimeter/sub-mm receivers
  - SIS mixers needed to achieve low noise characteristics
  - Cryogenics cool receivers to a few K
  - IF bandwidth
- Correlators
  - Need high speed (high bandwidth) for spectral lines:
    $\Delta V = 300$ km s^{-1} → 1.4 MHz @ 1.4 GHz; 230 MHz @ 230 GHz
  - Broad bandwidth also needed for sensitivity to thermal continuum and phase calibration
- Limitations of existing and future arrays
  - Small FoV ⇨ mosaicing: FWHM of 12 m antenna @ 230 GHz is ~ 30”
  - Limited *uv*-coverage, small number of elements (improved with CARMA, remedied with ALMA)

Summary

- ALMA construction is well underway and the science opportunities are astounding
- Atmospheric emission can dominate the system temperature
  - Calibration of T_{sys} is different from that at cm wavelengths
- Tropospheric water vapor causes significant phase fluctuations
  - Need to calibrate more often than at cm wavelengths
  - Phase correction techniques are under development at all mm/sub-mm observatories around the world
  - Observing strategies should include measurements to quantify the effect of the phase fluctuations
- Instrumentation is more difficult at mm/sub-mm wavelengths
  - Observing strategies must include pointing measurements to avoid loss of sensitivity
  - Need to calibrate instrumental effects on timescales of 10s of mins, or more often when the temperature is changing rapidly

Extra Slides

Practical aspects of observing at high frequencies with the VLA

Note: details may be found at
http://www.aoc.nrao.edu/vla/html/highfreq/

- Observing strategy: depends on the strength of your source
  - Strong ($\geq$ 0.1 Jy on the longest baseline for continuum observations, stronger for spectral line): can apply self-calibration, use short integration times; no need for fast switching
  - Weak: external phase calibrator needed, use short integration times and fast switching, especially in A & B configurations
  - If strong maser in bandpass: monitor the atmospheric phase fluctuations using the maser, and apply the derived phase corrections; use short integration times, calibrate the instrumental phase offsets between IFs every 30 mins or so

Practical aspects, continued…

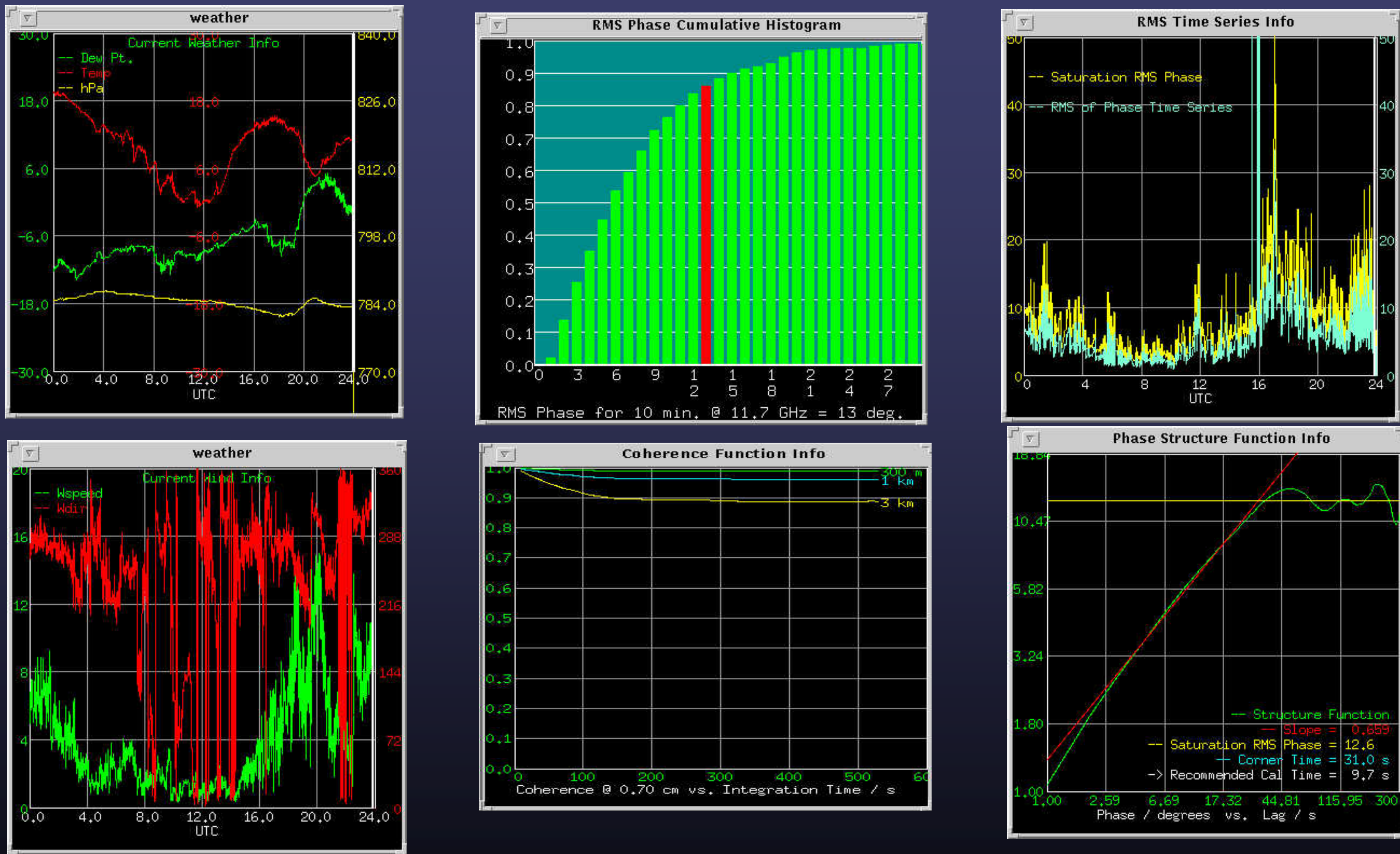
- Referenced pointing: pointing errors can be a significant fraction of a beam at 43 GHz
  - Point on a nearby source at 8 GHz every 45-60 mins, more often when the az/el is changing rapidly. Pointing sources should be compact with $F_{8GHz} \geq 0.5$ Jy

- Calibrators at 22 and 43 GHz
  - Phase calibration: the spatial structure of water vapor in the troposphere requires that you find a phase calibrator $< 3^\circ$ from your source, if at all possible; for phase calibrators weaker than 0.5 Jy you will need a separate, stronger source to track amplitude variations
  - Absolute Flux calibrators: 3C48/3C138/3C147/3C286. All are extended, but there are good models available for 22 and 43 GHz

Practical aspects, continued…

- If you have to use fast switching
  - Quantify the effects of atmospheric phase fluctuations (both temporal and spatial) on the resolution and sensitivity of your observations by including measurements of a nearby point source with the same fast-switching settings: cycle time, distance to calibrator, strength of calibrator (weak/strong)
  - If you do not include such a "check source" the temporal (but not spatial) effects can be estimated by imaging your phase calibrator using a long averaging time in the calibration
- During the data reduction
  - Always correct bandpass before phase and amplitude calibration
  - Apply phase-only gain corrections first, to avoid de-correlation of amplitudes by the atmospheric phase fluctuations

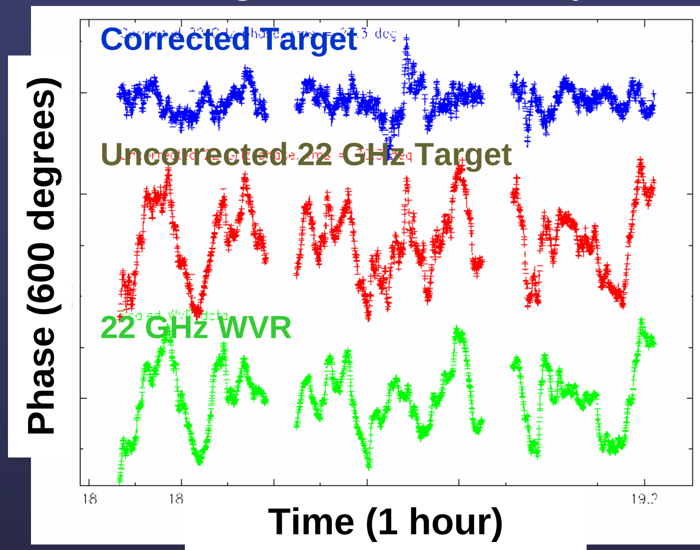
The Atmospheric Phase Interferometer at the VLA

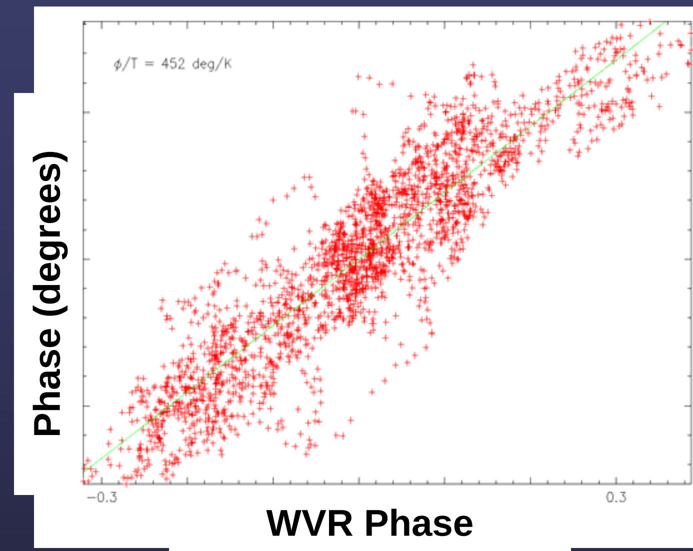


Accessible from http://www.vla.nrao.edu/astro/guides/api

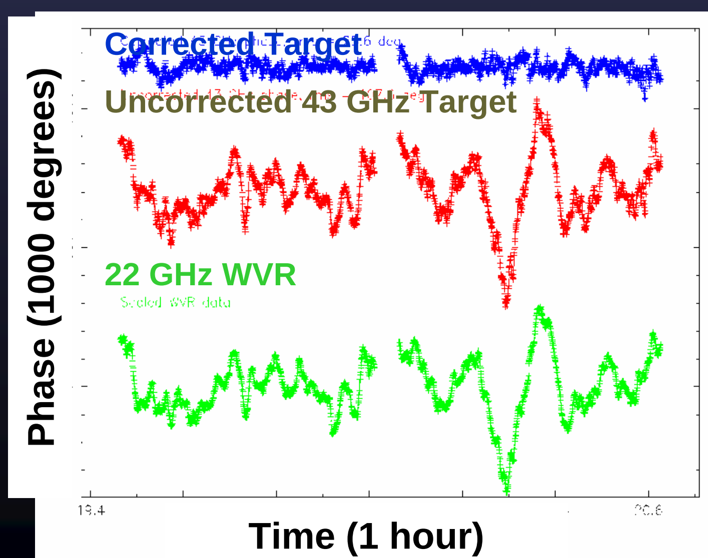
Results from VLA 22 GHz Water Vapor Radiometry

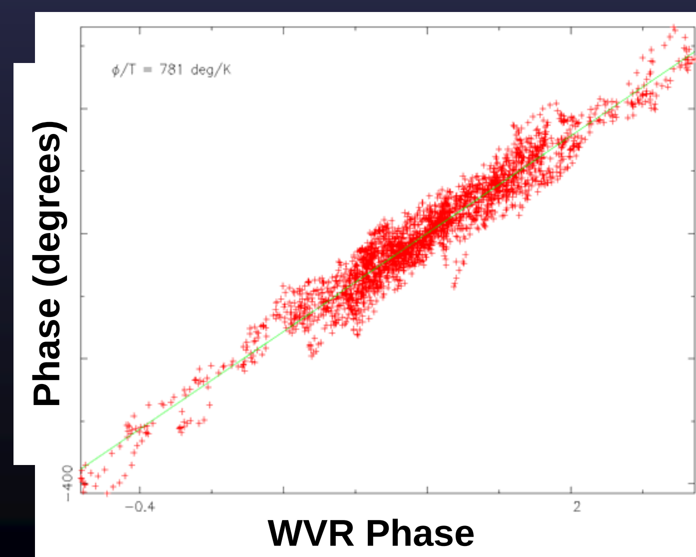
Baseline length = 2.5 km, sky cover 50-75%, forming cumulous, n=22 GHz





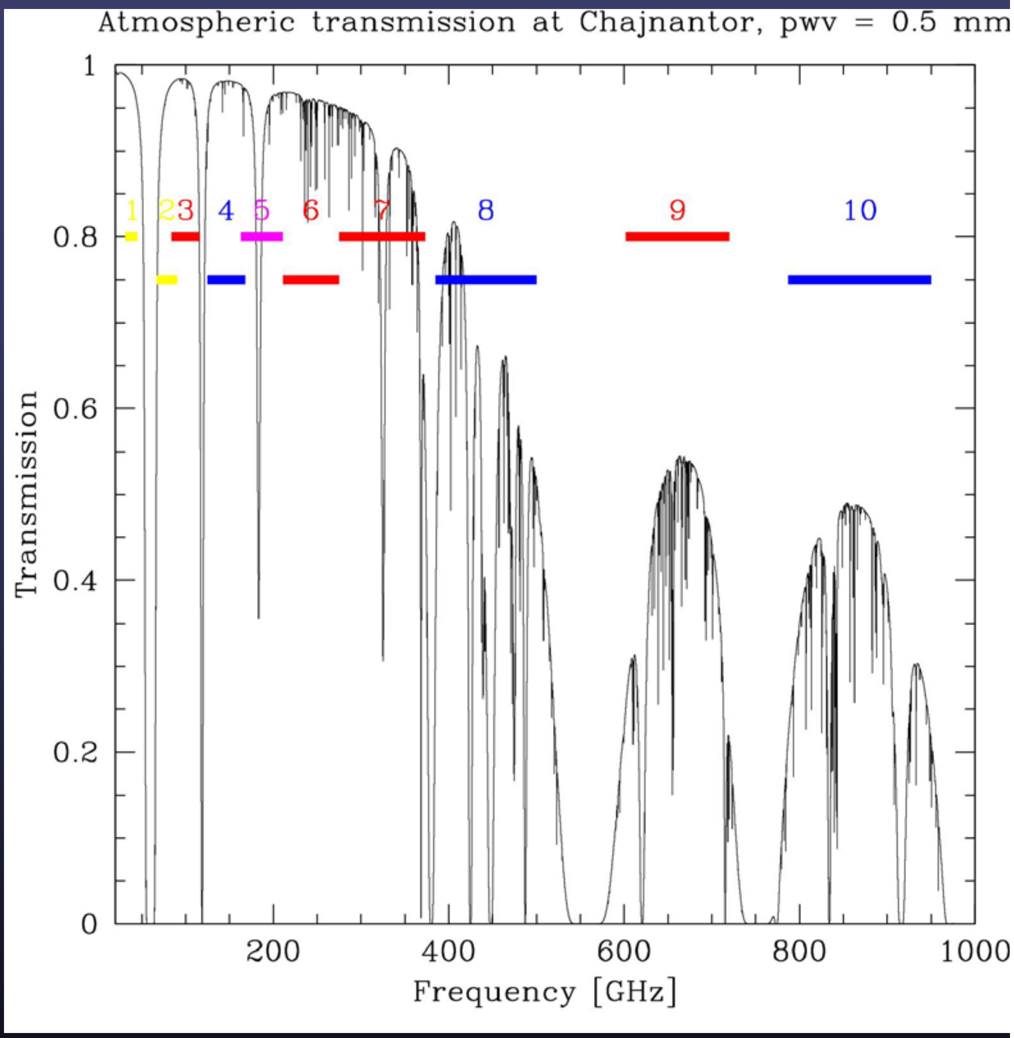
Baseline length = 6 km, sky clear, n=43 GHz





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 Band	Frequency Range	Receiver noise temp: T_{Rx} over 80% of the RF band	Receiver noise temp: T_{Rx} at any RF frequency	Mixing scheme	Receiver technology
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

ALMA Median Sensitivity

(1 minute; 75% Quartile opacities λ>1mm, 25% λ <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