Millimeter Interferometry: ALMA & EVLA

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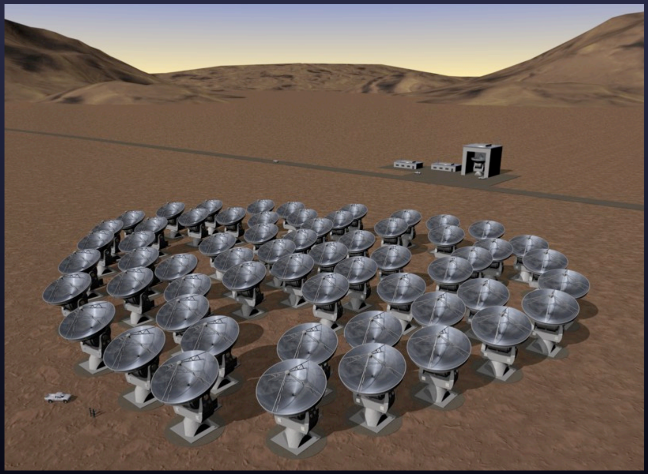
Twelfth Synthesis Imaging Workshop

Socorro, June 8-15, 2010

Outline



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

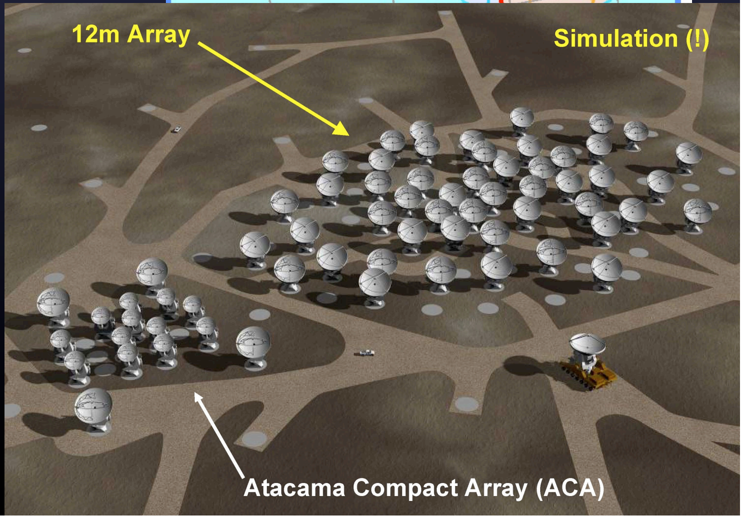
The Atacama Large MM/Submm Array : ALMA

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

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

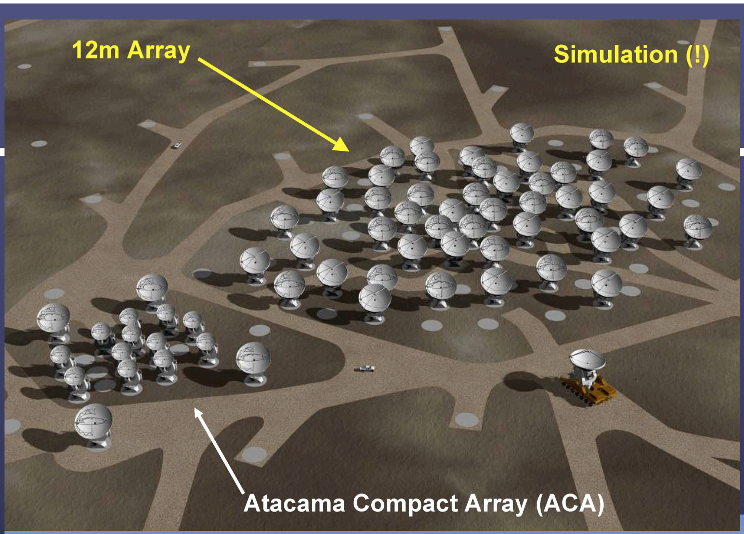
- Main Array: 50 x 12m antennas (up to 64)
  + 4 x 12m (total power)
  + ACA: compact array of 12 x 7m antennas

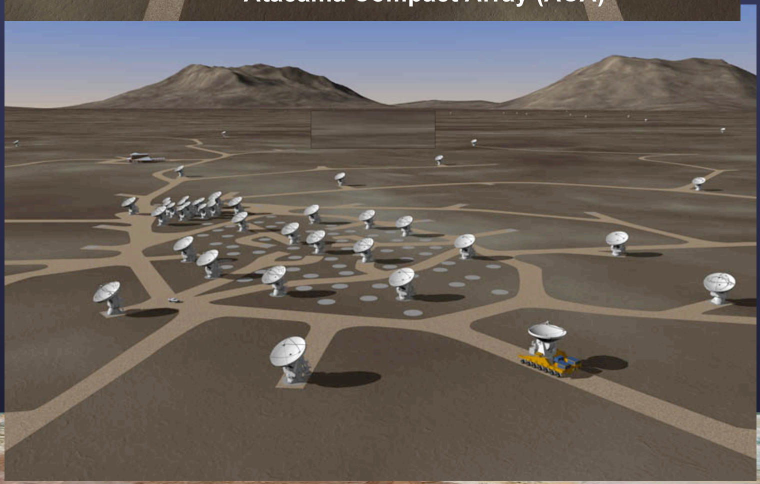
- Total shared cost ~1.3 Billion ($US)

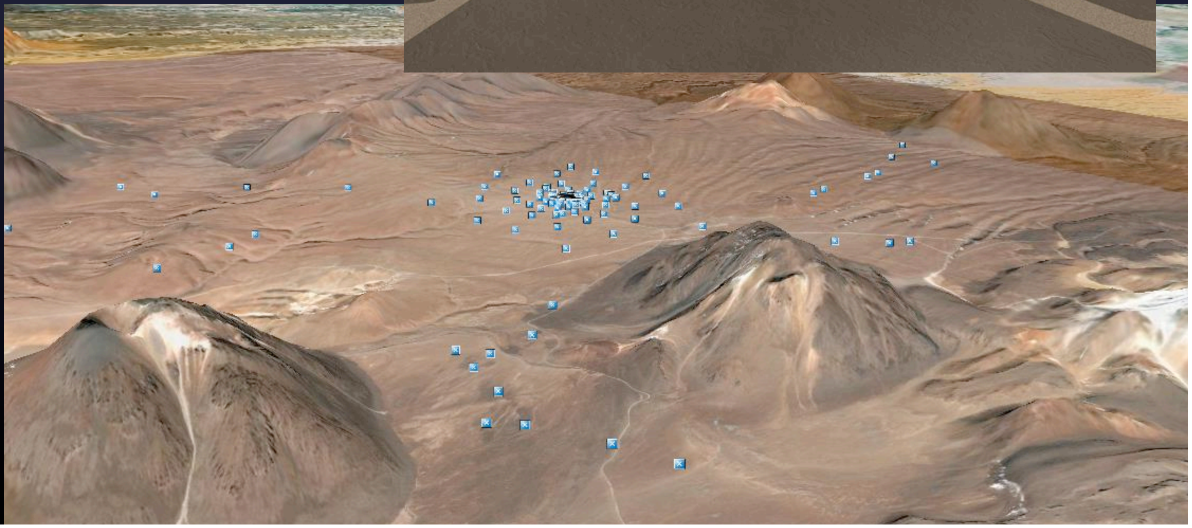


ALMA

- Baselines up to 15 km (0.015” at 300 GHz) in “zoom lens” configurations
- Sensitive, precision imaging between 84 to 950 GHz (3 mm to 350 μm)
- Receivers: low-noise, wide-band (8 GHz)
- Flexible correlator with high spectral resolution at wide bandwidth
- Full polarization capabilities
- Data rate: 6Mb/s average; peak 64 Mb/s; estimate 1 TB per day to be archived
- A resource for ALL astronomers





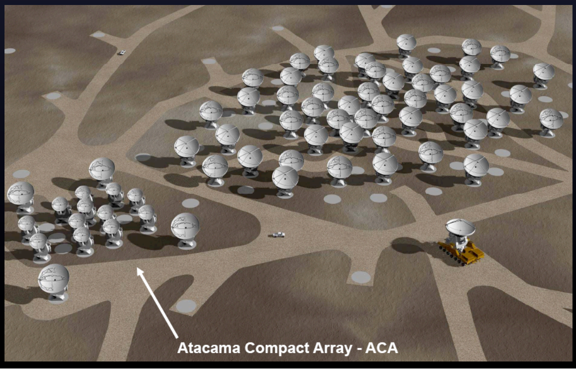


Summary of Existing and Future mm/sub-mm Arrays

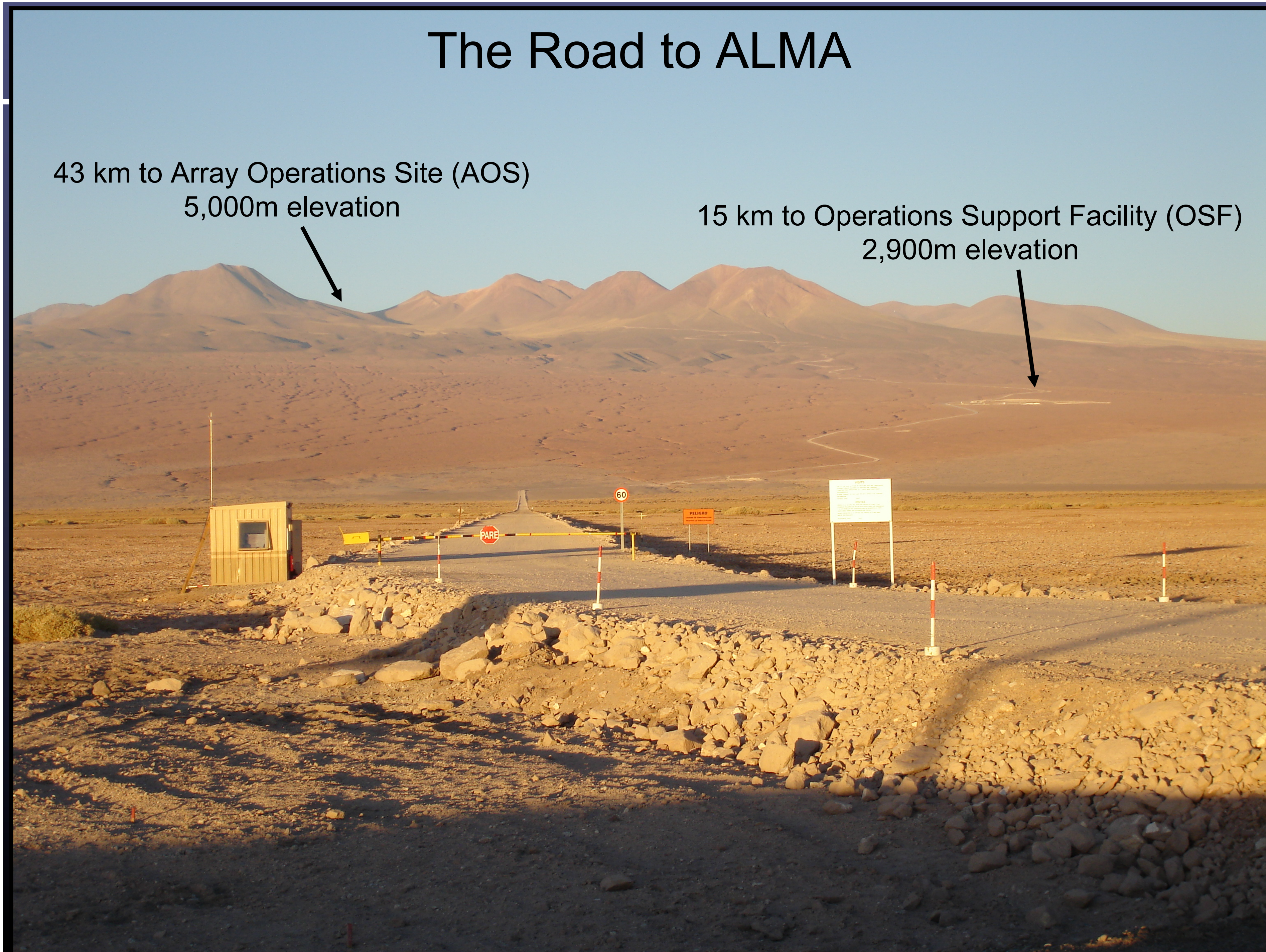
Telescope	altitude (feet)	diam. (m)	No. dishes	A (m^2)	ν_{max} (GHz)
NMA	2,000	10	6	470	250
EVLA	7,050	25	27	13250	43
CARMA	7,300	3.5/6/10	23	800	250
IRAM PdB	8,000	15	6	1060	250
SMA	13,600	6	8	230	650
eSMA	13,600	6/10/15	10	490	345
ALMA	16,400	12	54	6100	950
ACA	16,400	7	12	490	950

Sensitivity is proportional to collecting area A (among other things)

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



OSF (3000m level) Construction Completed

Melco and Vertex antenna assemble
There are now >20 antennas in various stages of completion

Operations Support Facility

AOS Technical Building at 5000m

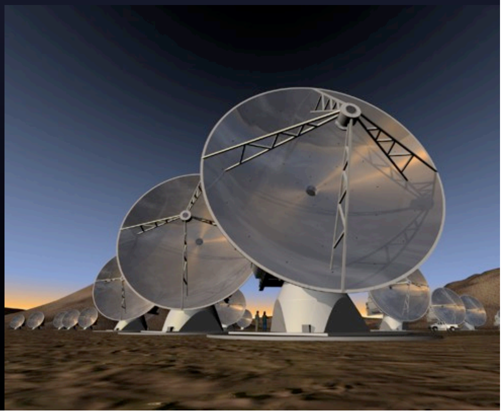
AOS Technical Building - completed 2008

Home of the ALMA and AC correlators

Current Projected Timeline

Early 2009	First Light on ALMA antenna at OSF
Late 2009	Commissioning Began with 3-element array at AOS
All 2010	Commissioning and Science Verification
Early 2011	Call for Early Science Proposals * 16+ antennas, 2+ bands, continuum & spectral line, +0.3 km baselines
Mid 2011	Start Early Science Observing * Off line data reduction
Mid 2012	Pipeline images for standard modes
Mid 2013	Baseline ALMA Construction Complete

Come to the ALMA/NAASC reception tonight : 18:30 – 20:30 on 3rd floor of the Fidel Center to learn more about ALMA, NAASC, and Early Science



A Few Examples of Unique and Exciting MM/Submm Science

Why Do We Care About mm/submm?

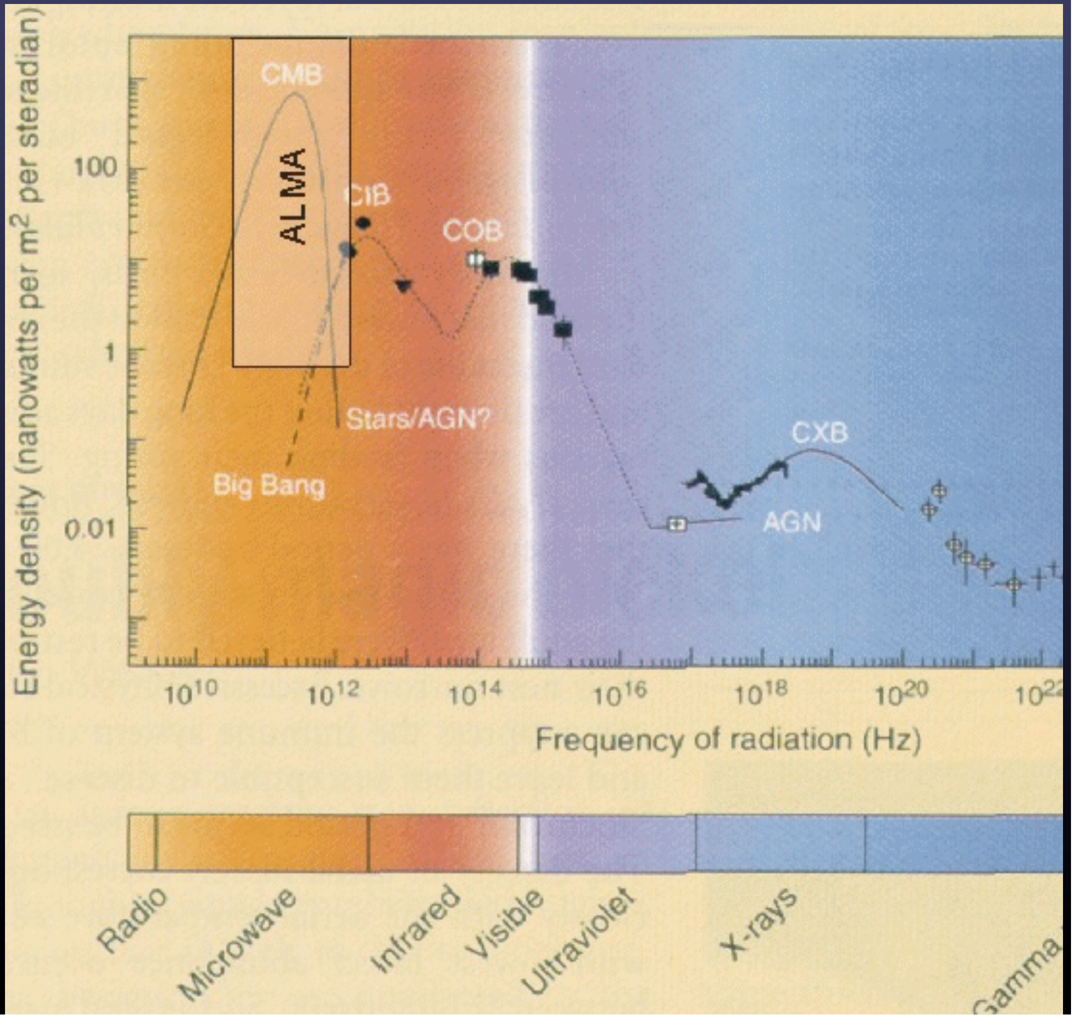
- After the 3K cosmic background radiation, mm/submm photons carry most of the radiative energy in the Universe:
  - 40% of Milky Way photons are in mm/submm

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

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

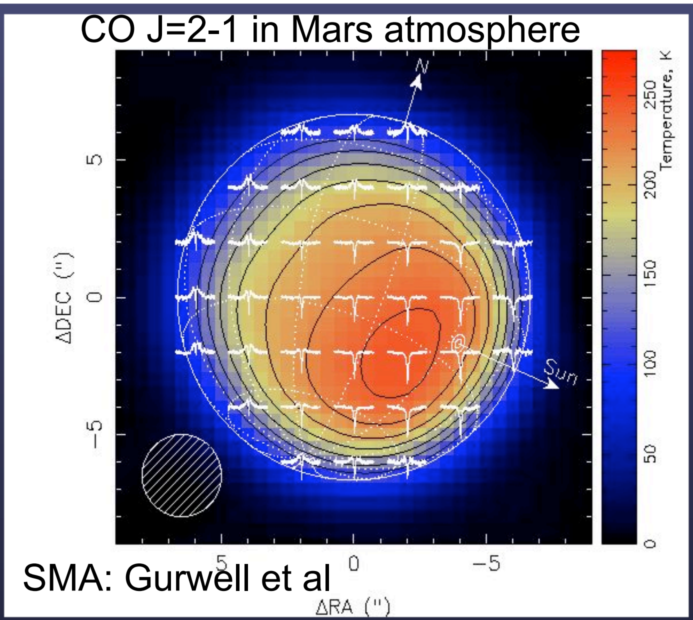
$$S_\nu = \frac{2kT\nu^2\tau_\nu\Omega}{c^2} \quad \mathrm{Wm^{-2}\,Hz^{-1}}$$

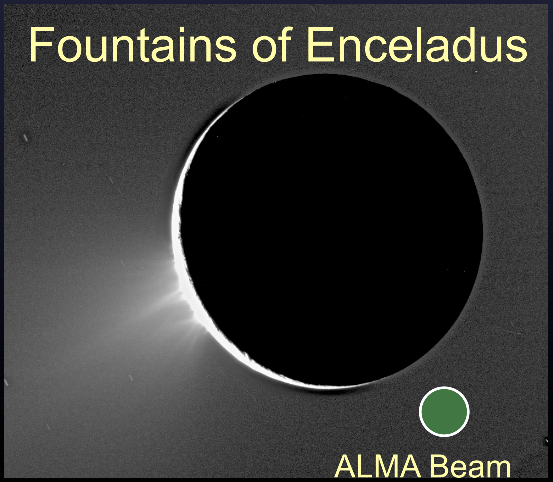
for optically-thin emission $\tau_\nu \propto \nu^2$,
flux density: $S_\nu \propto \nu^4$

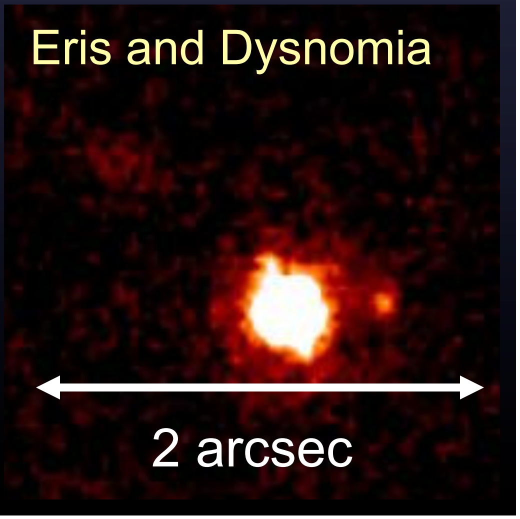


Exploration of the Solar System

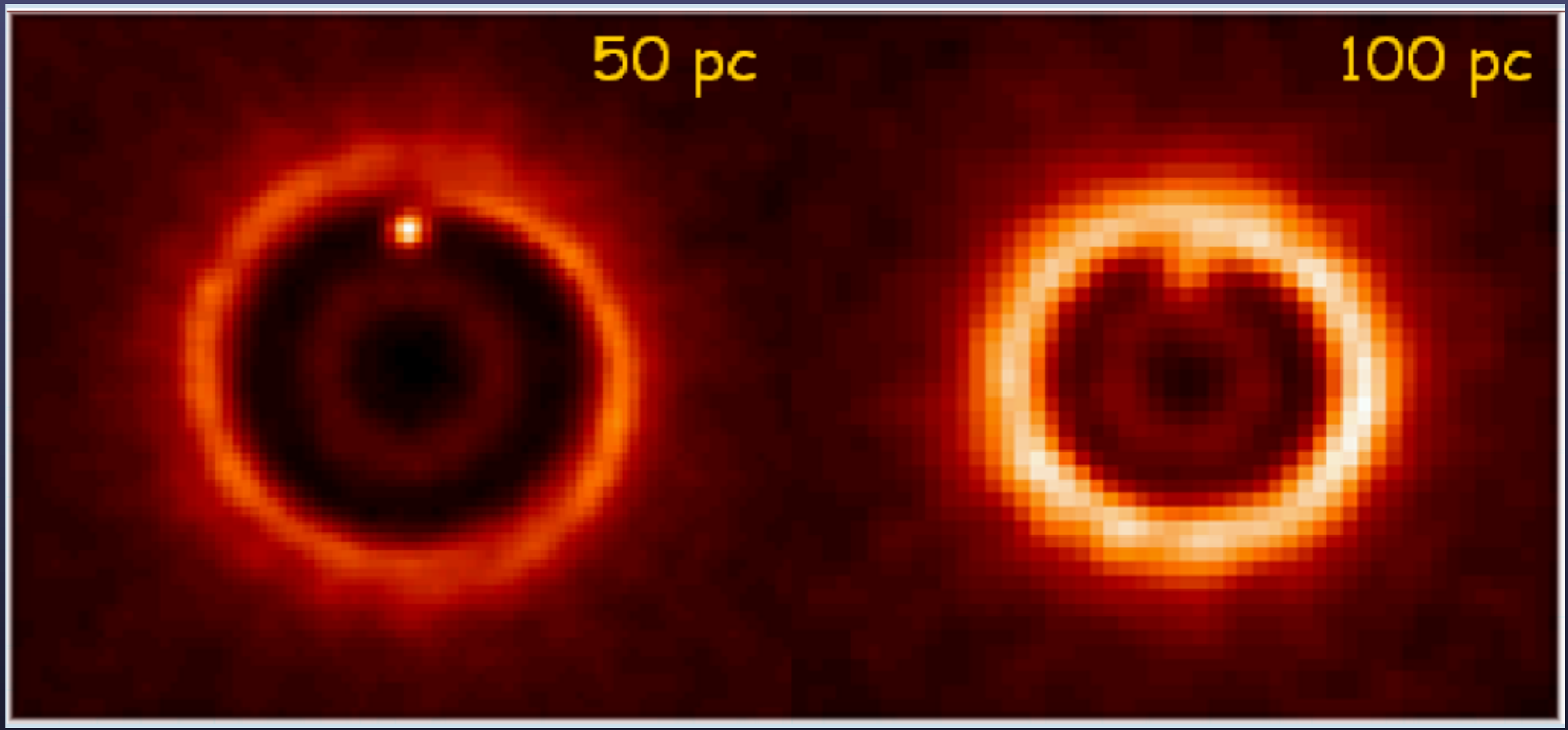
- ‘Weather’ on Venus, Mars, Jovian planets
- Comets
- Volcanism on Io
- Search for Molecules from the “Fountains of Enceladus”
- Better understand Minor Planets. For examle: ‘Eris’ with its moon ‘Dysnomia’ easily resolved, Eris could be imaged.







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

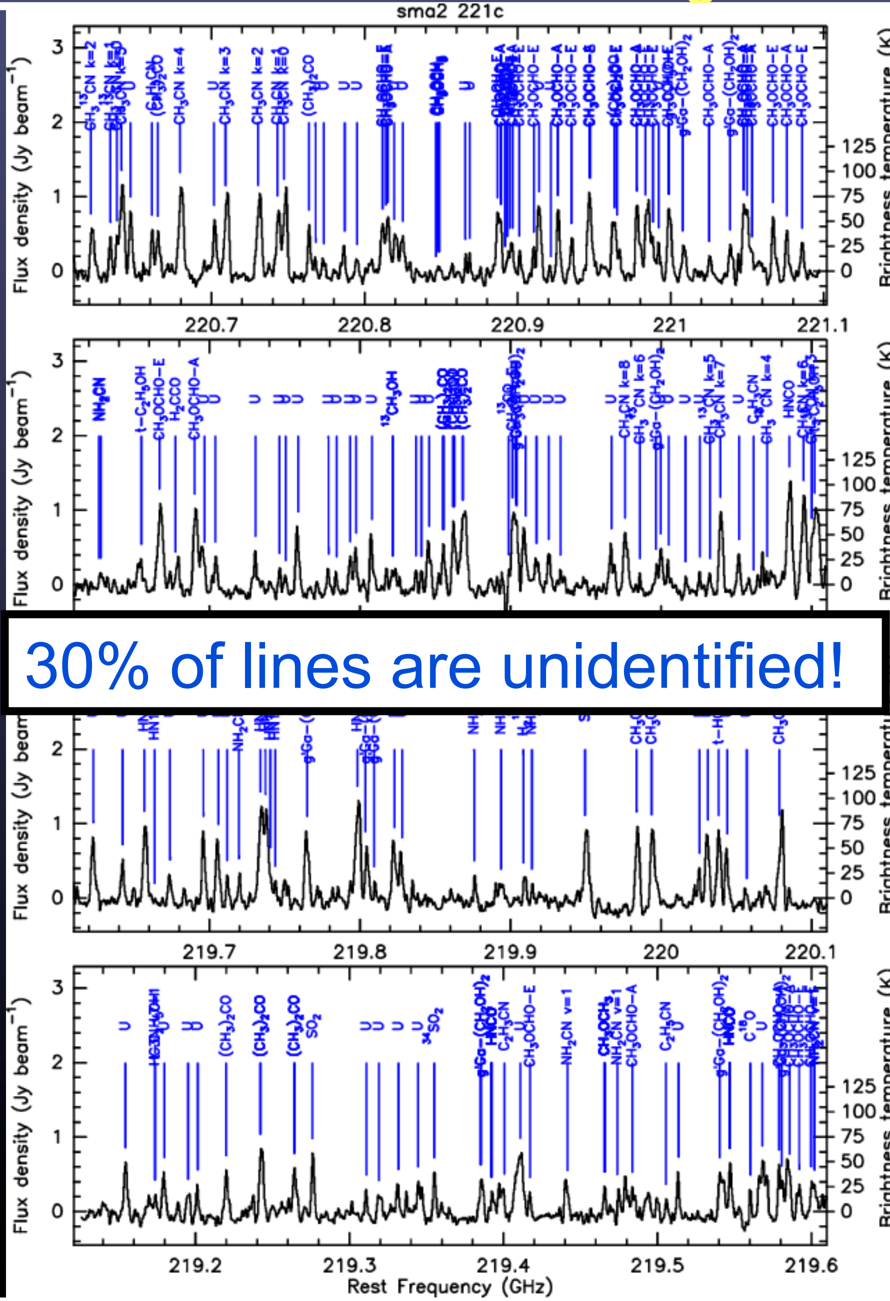


Simulation of the 950 GHz dust emission from a 1 Jupiter Mass planet around a 0.5 Solar mass star (orbital radius 5 AU)

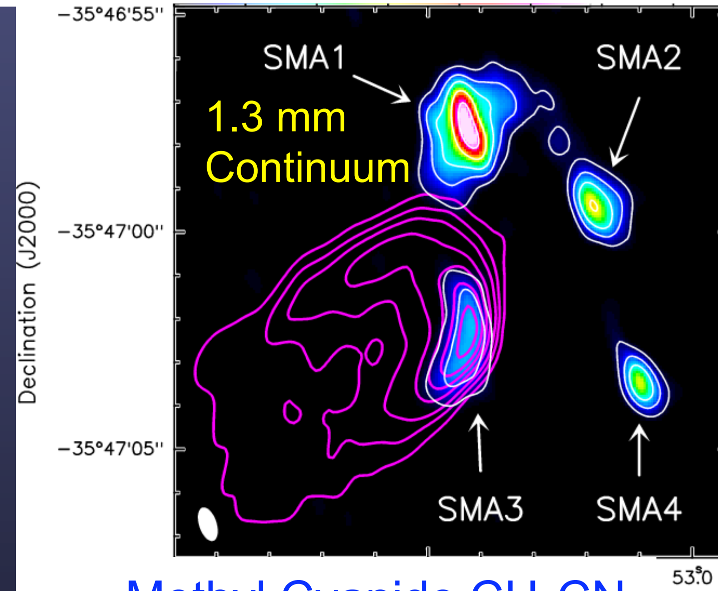
- The disk mass was set to that of the Butterfly star in Taurus
- Integration time 8 hours; 10 km baselines; 30 degrees phase noise

Wolf & D'Angelo (2005)

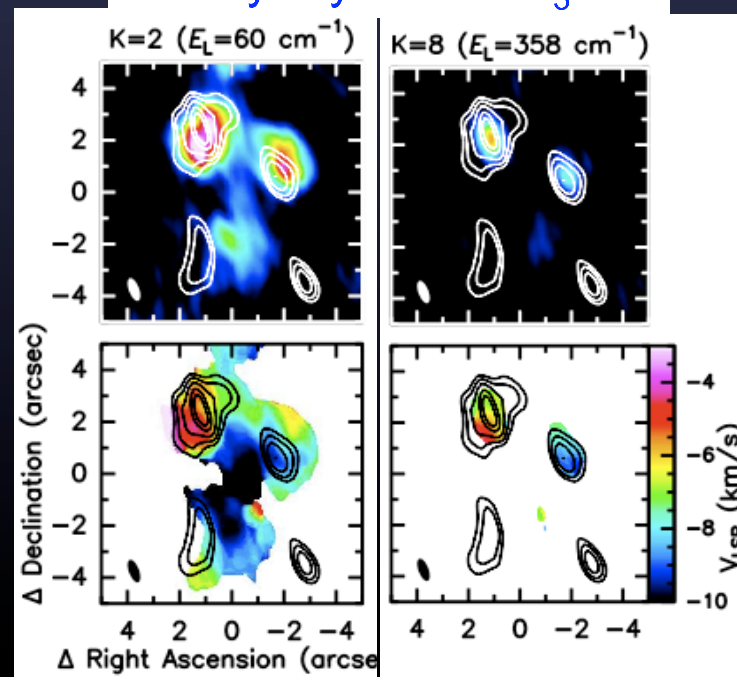
SMA Observations of NGC6334I: Hot Core Emission from a forming Massive Protocluster



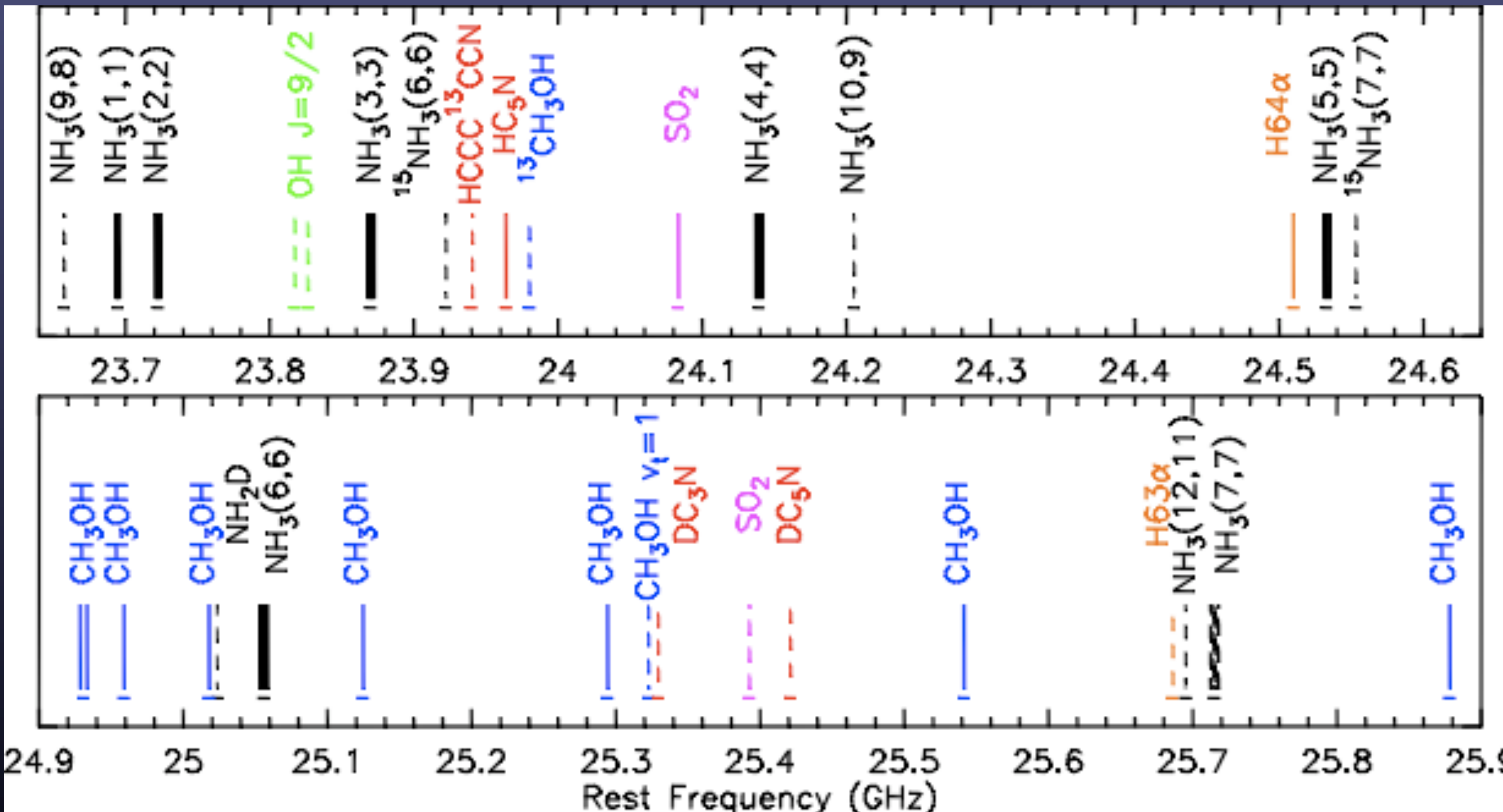
30% of lines are unidentified!



Methyl Cyanide CH_3CN



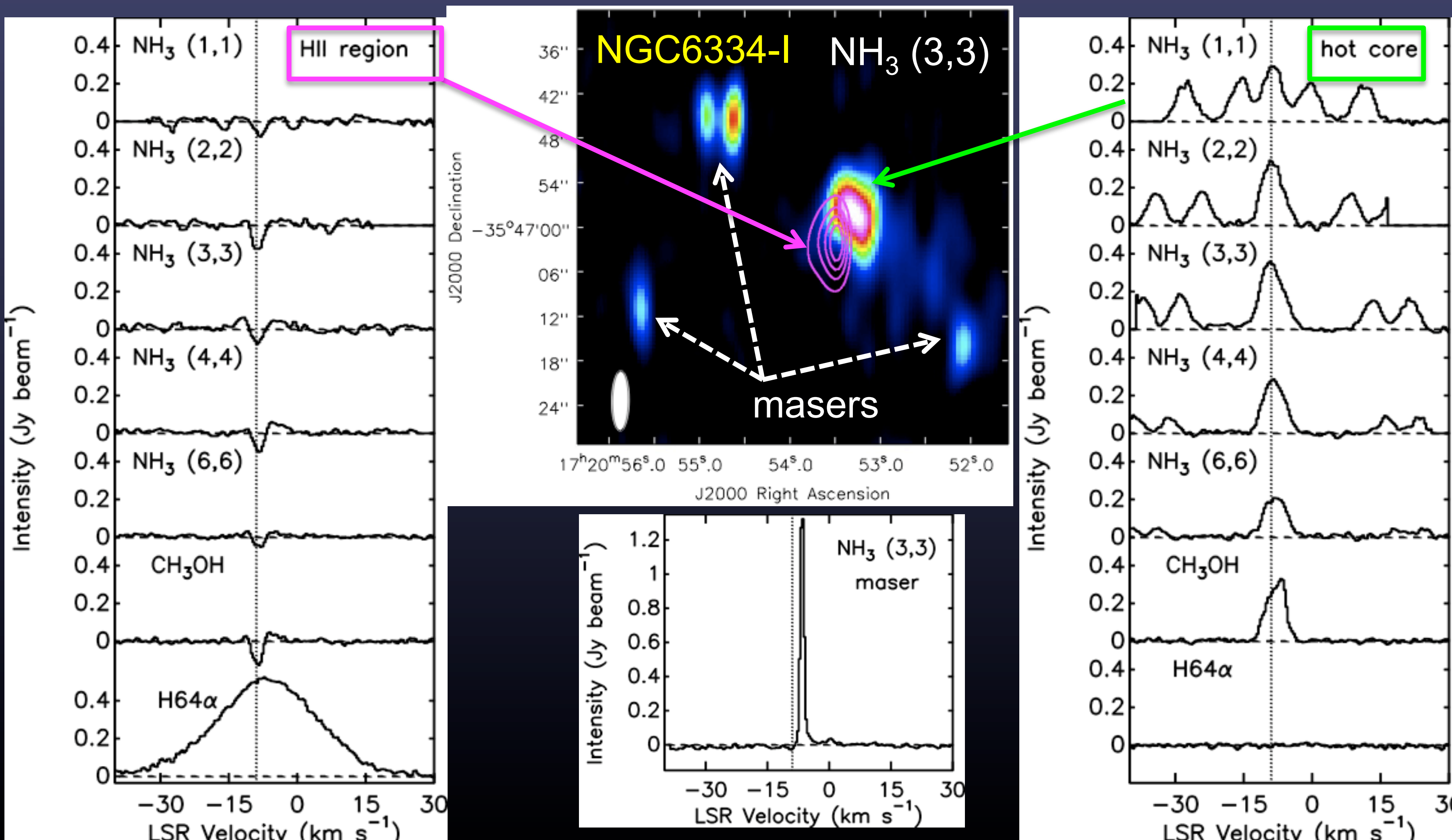
The Power of EVLA WIDAR: RSRO (AB1346): A Diagnostic K-band Survey of 30 Massive Protostellar Objects



- Ammonia 1,1 to 7,7
- Radio Recombination Lines
- Hot Core Lines (methanol, SO_2)
- Rare diagnostic lines including deuterated species

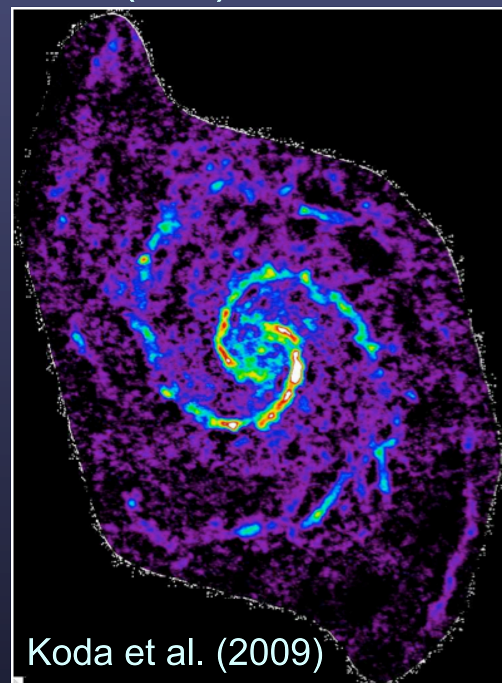
EVLA K-band Observations of massive young stellar objects in NGC6334-I

- 8 x 8 MHz subbands with 256 channels RR only; referenced pointing: 10 minutes on source!!!!
- Test for RSRO project AB1346



Galaxy Structure and Evolution

CO(1-0) CARMA



Key ALMA Science goal: Ability to trace chemical composition of galaxies to z=3 in less than 24 hours

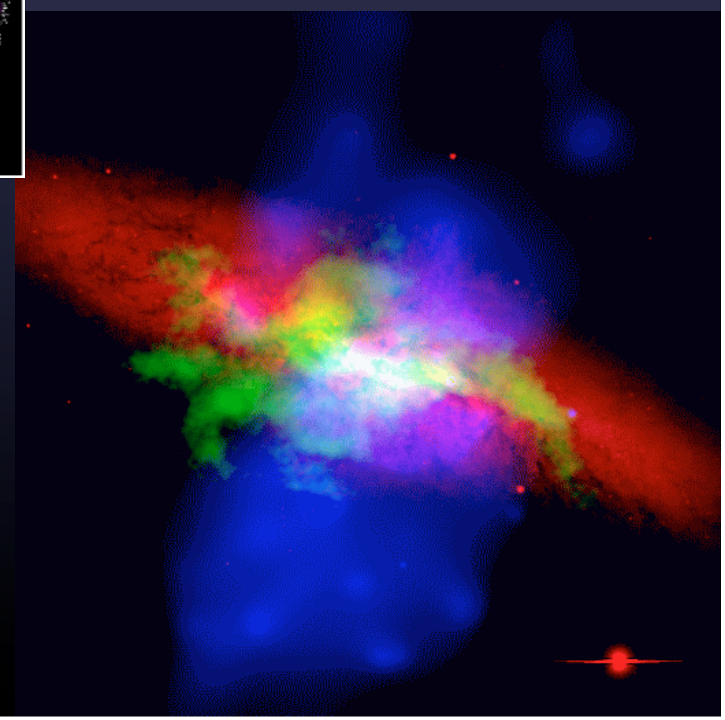
M82 starburst

Red: optical emission

Blue: x-ray emission

Green: OVRO $^{12}CO(J=1-0)$

(Walter, Weiss, Scoville 2003)



highest z

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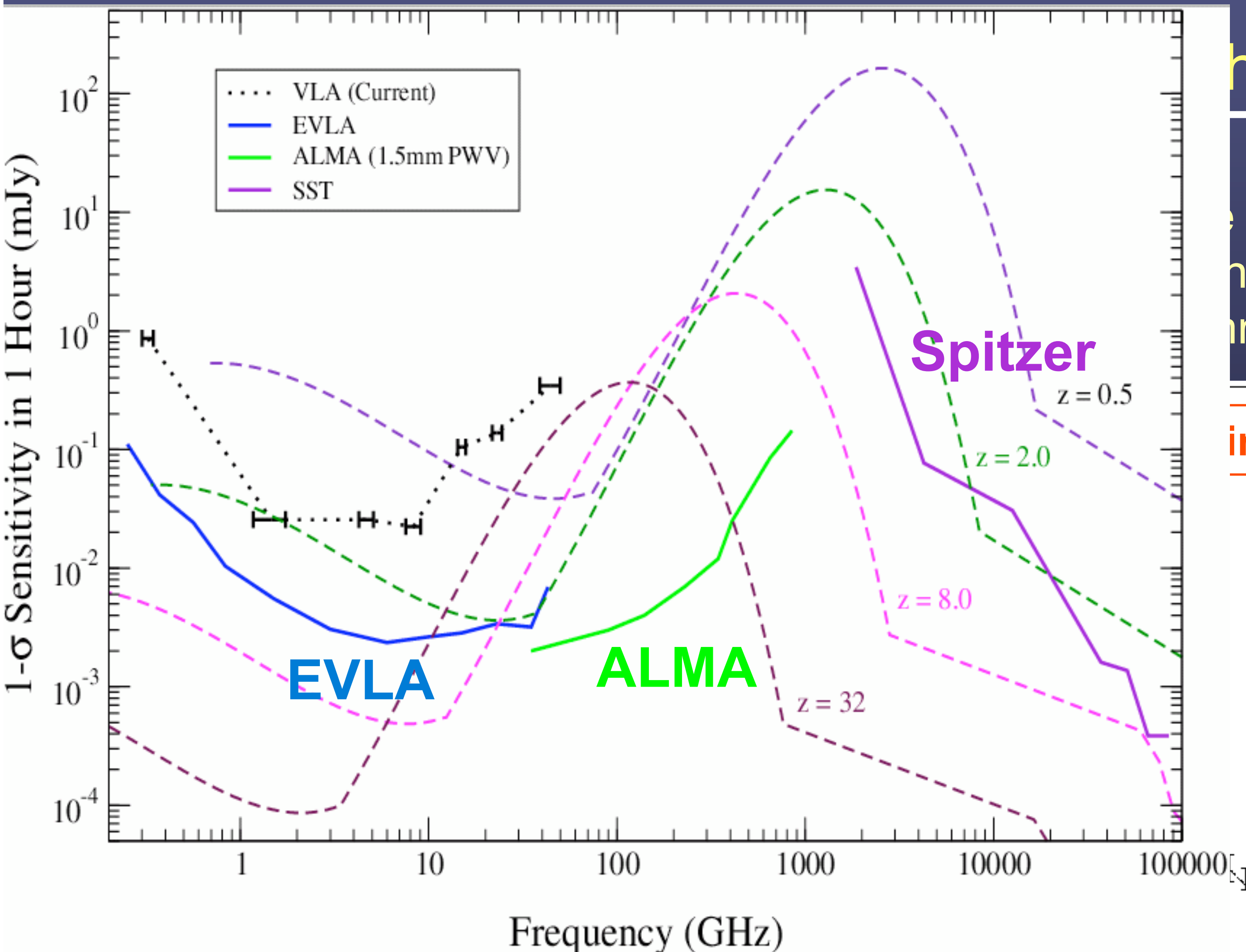
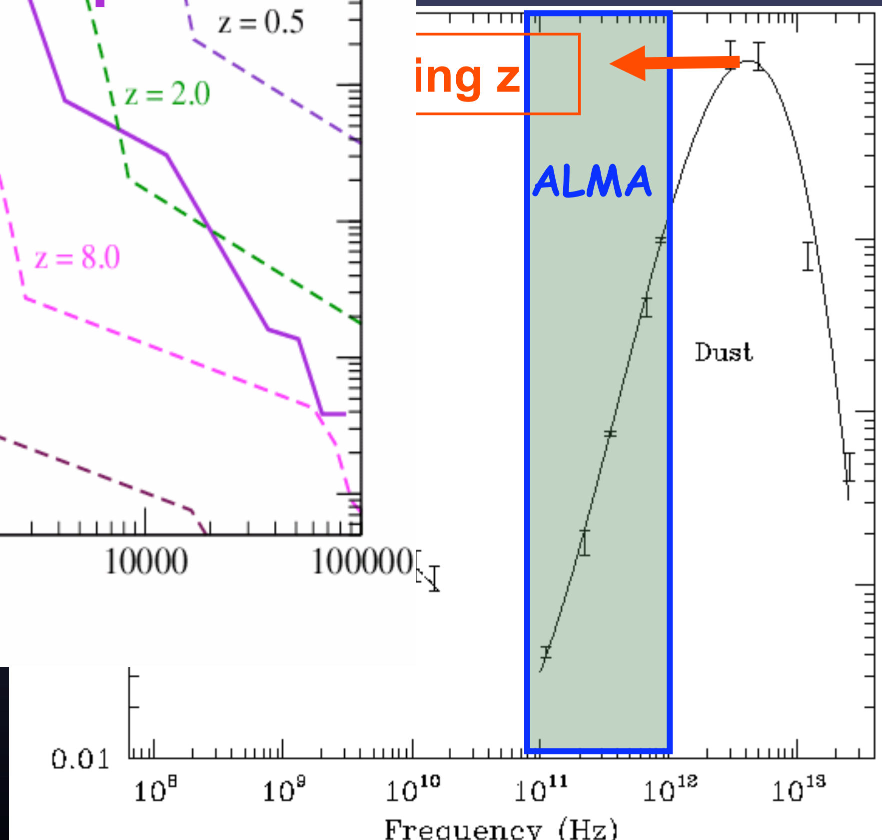
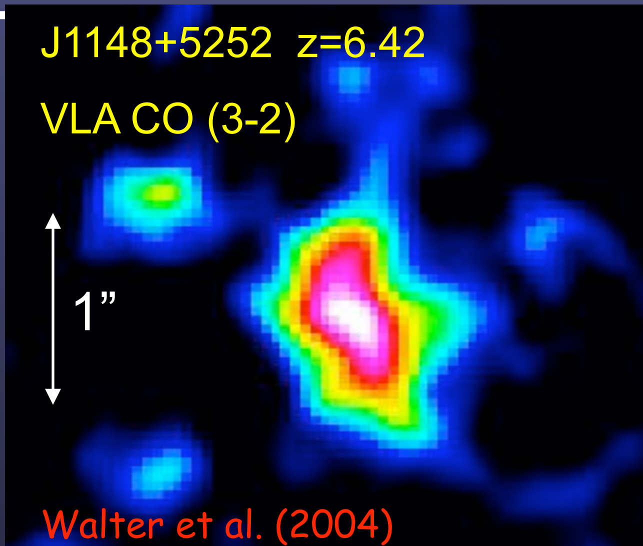




Detect high-z galaxies as easily as those at z~0.5

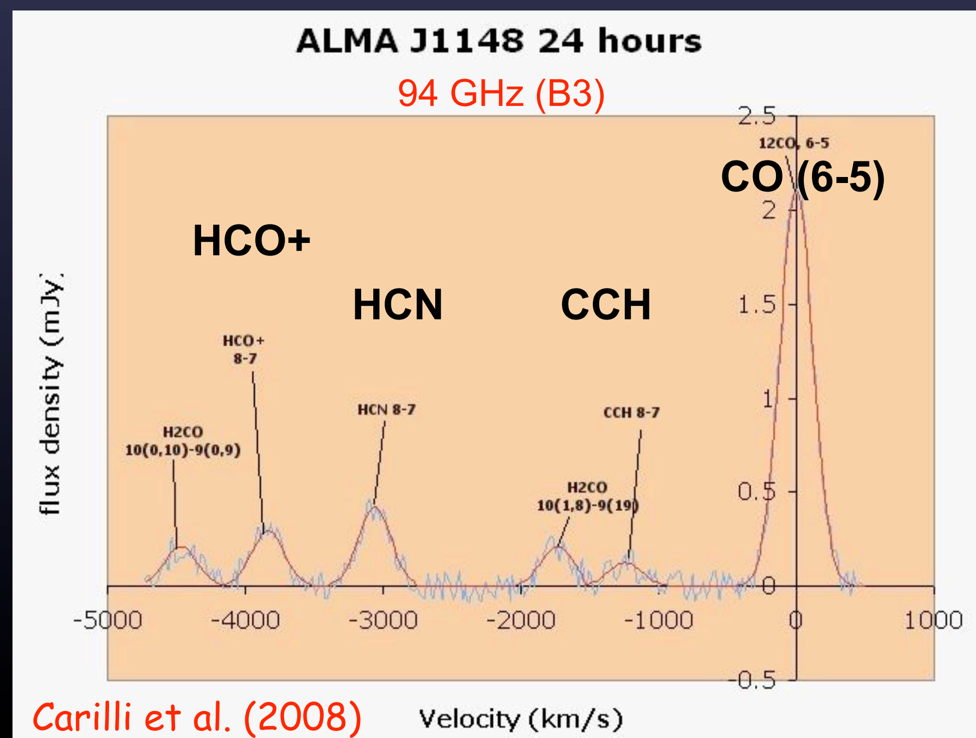
Study of 'first light' During Cosmic Reionization



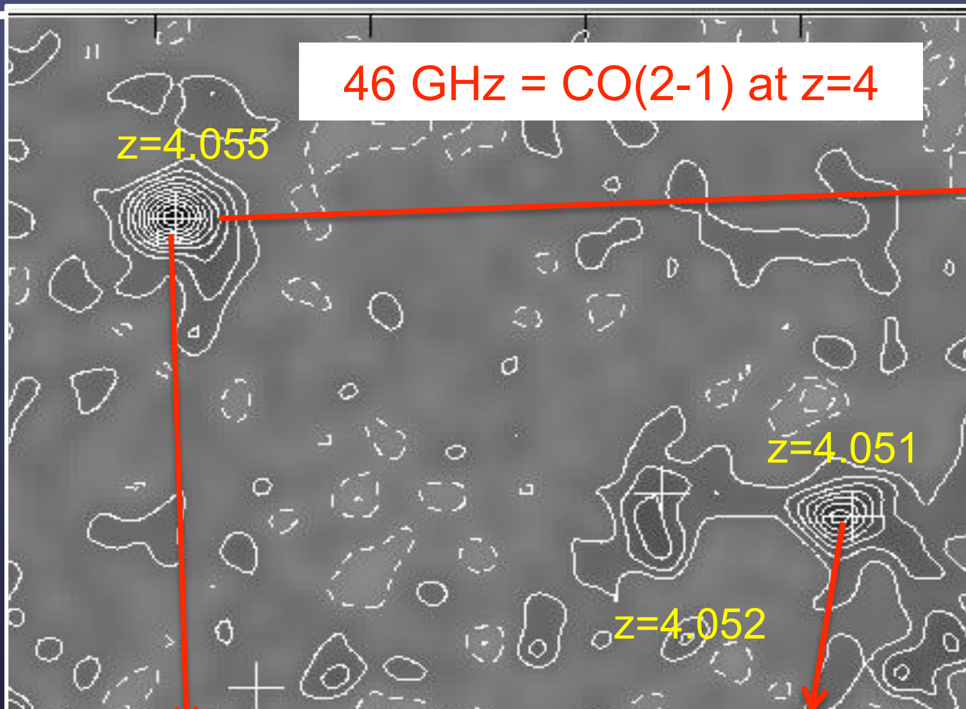
Low J molecular transitions ➔ EVLA

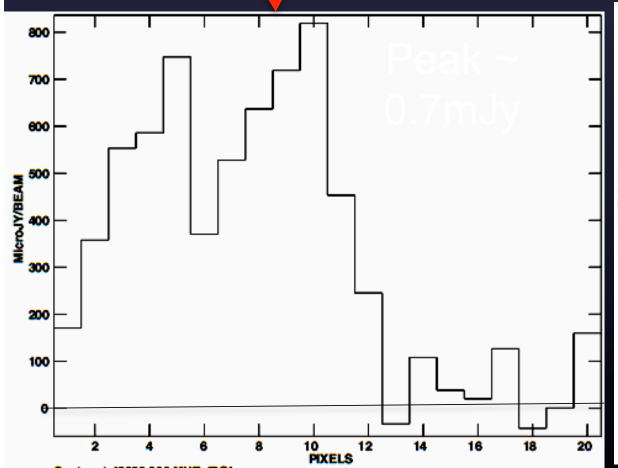
High J molecular transitions and fine structure lines ➔ ALMA

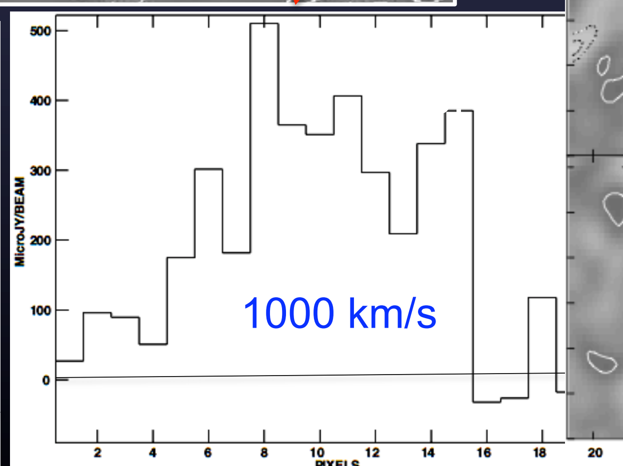
- Brightest submm galaxies detect dust emission in **1sec** (5σ)
- Detect multiple lines in 24 hours => detailed astrochemistry
- Image dust and gas at sub-kpc resolution – gas dynamics!

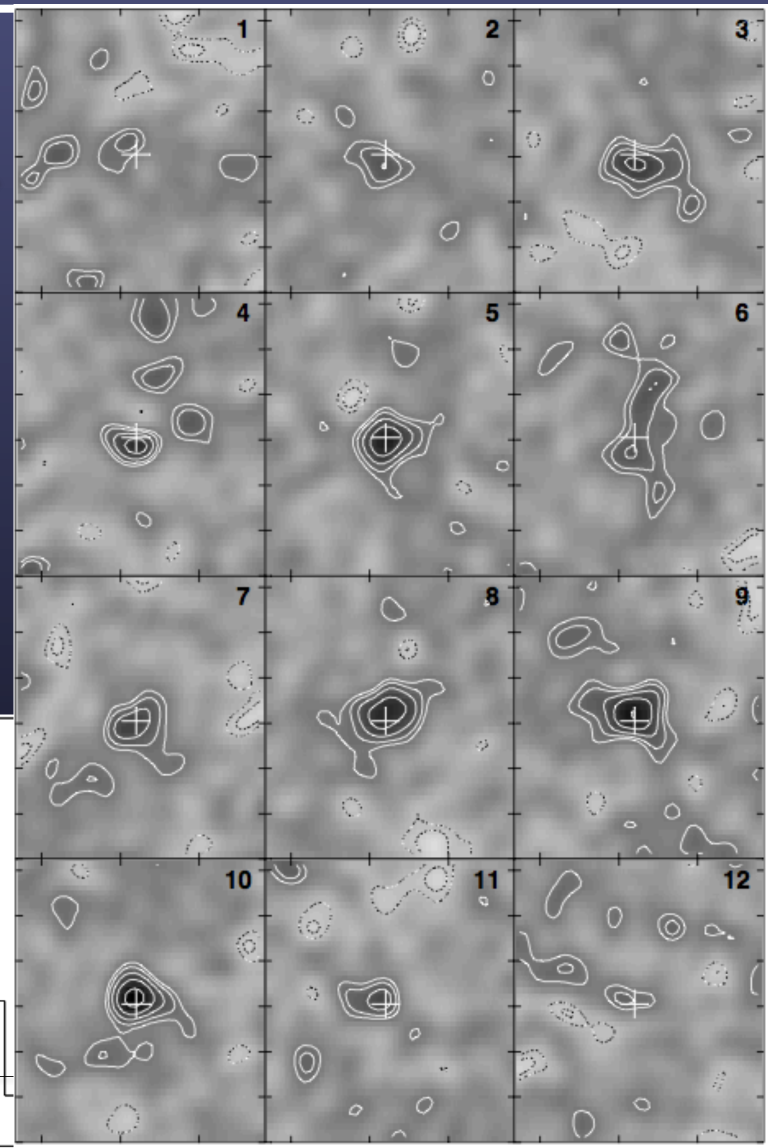


EVLA Early Science CO results for High Redshift Galaxies: GN20





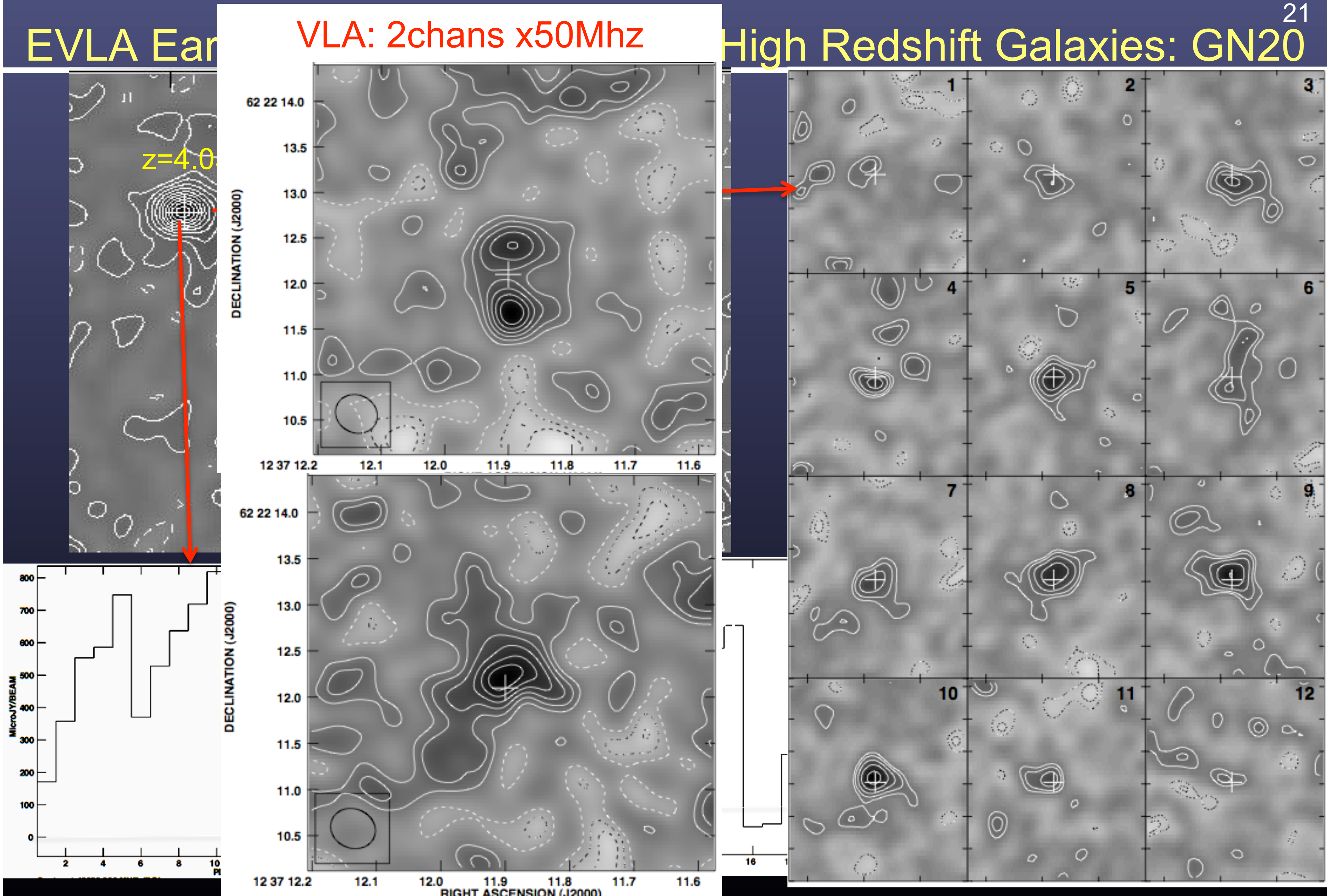




Carilli et al. in prep

Spatially resolved velocity fields at z=4!

EVLA Ear High Redshift Galaxies: GN20



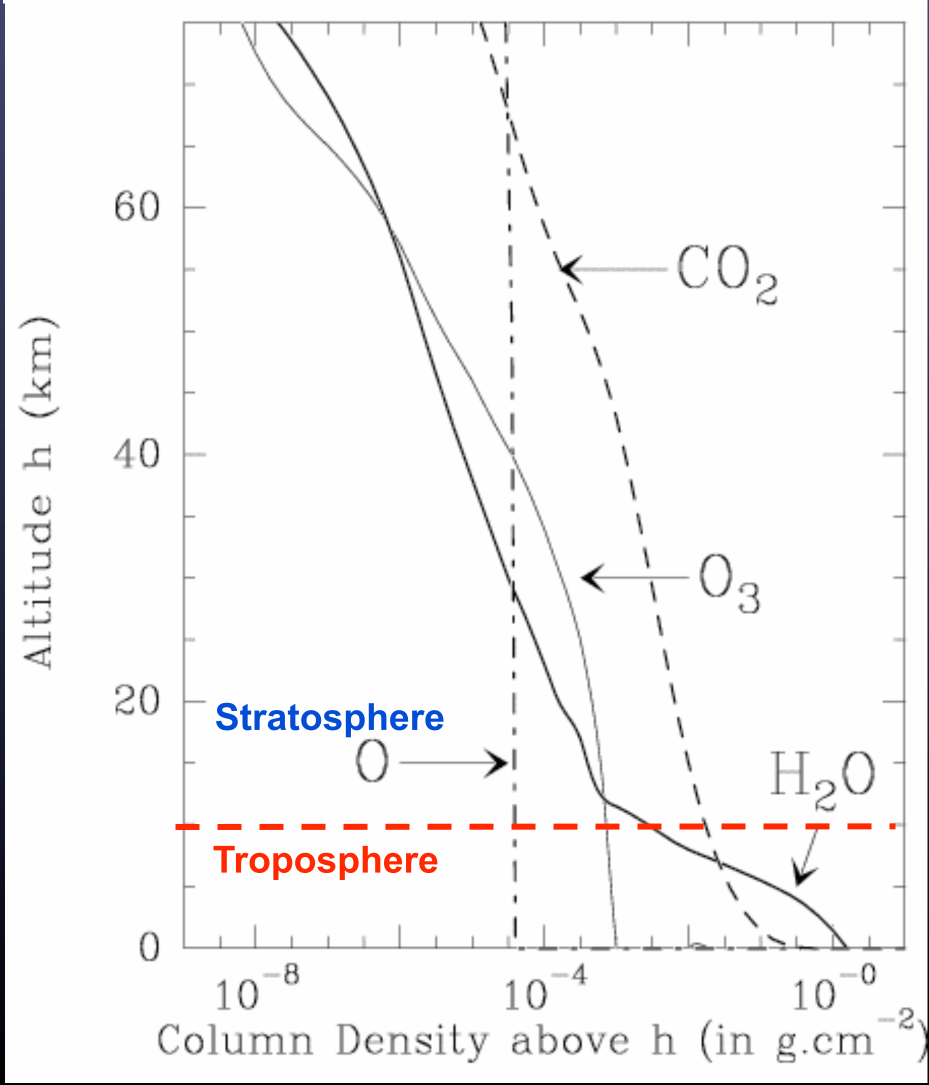
Spatially resolved velocity fields at z=4!

Problems unique to the mm/ submm

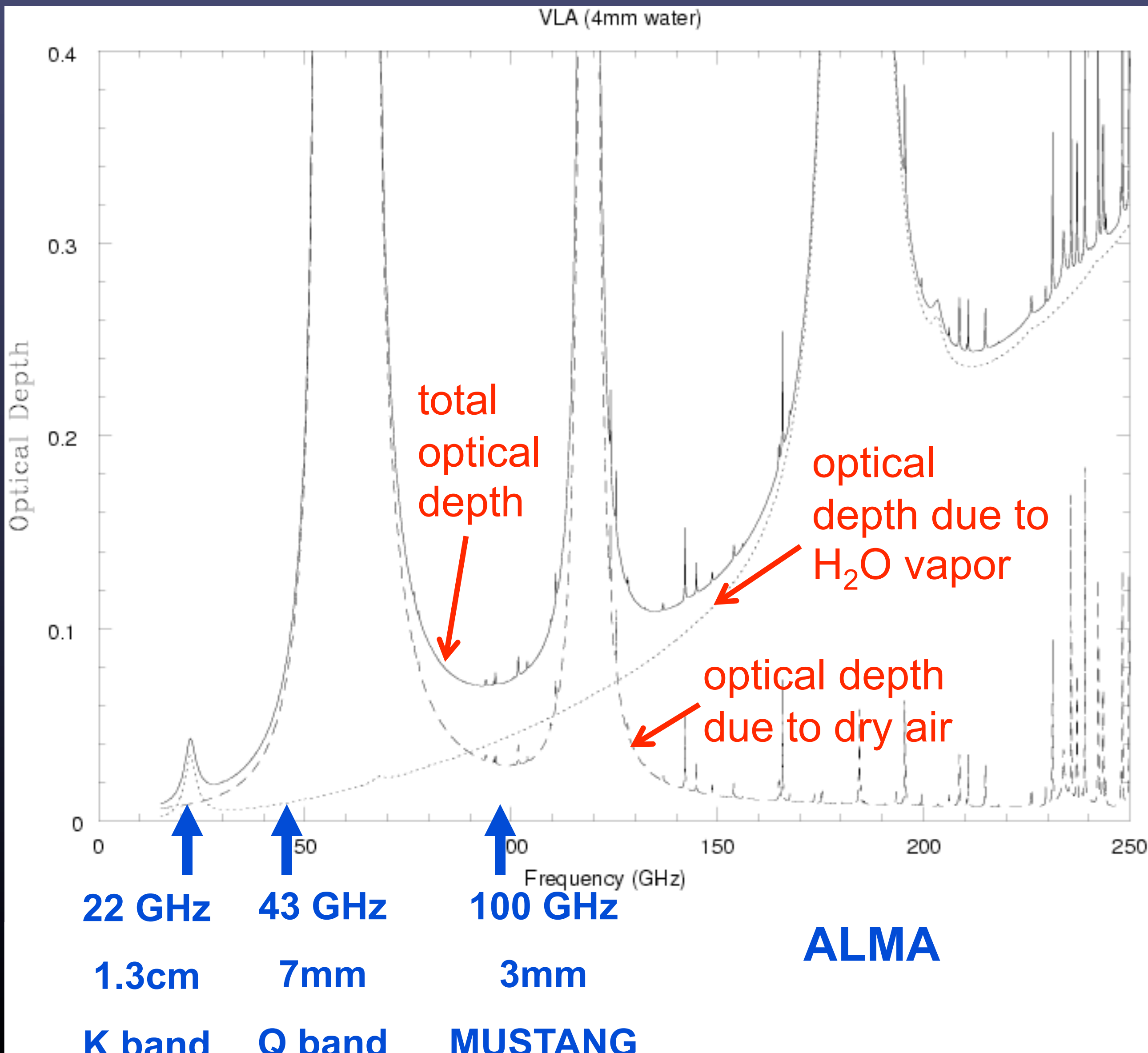
Constituents of Atmospheric Opacity

- 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

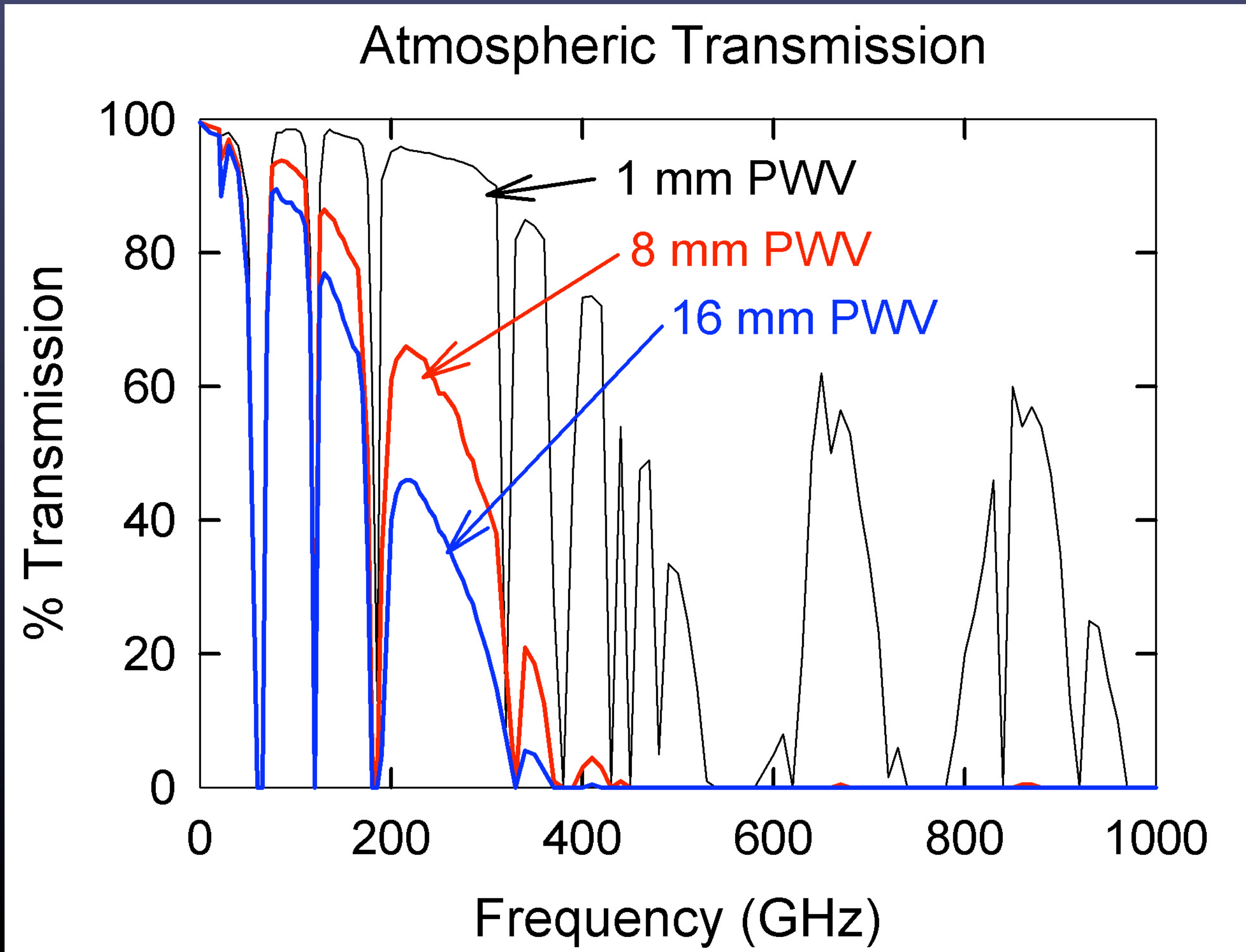


Optical Depth as a Function of Frequency

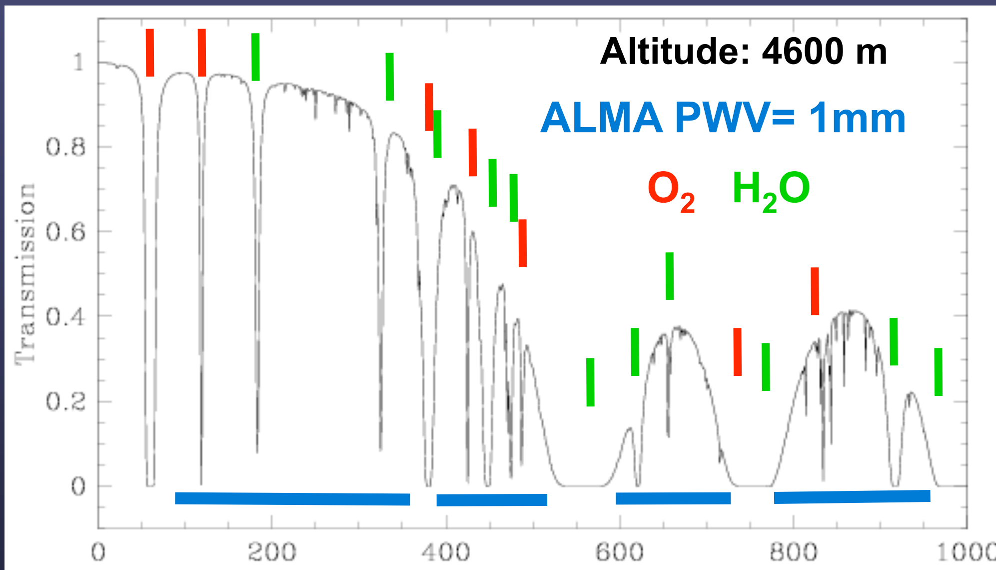


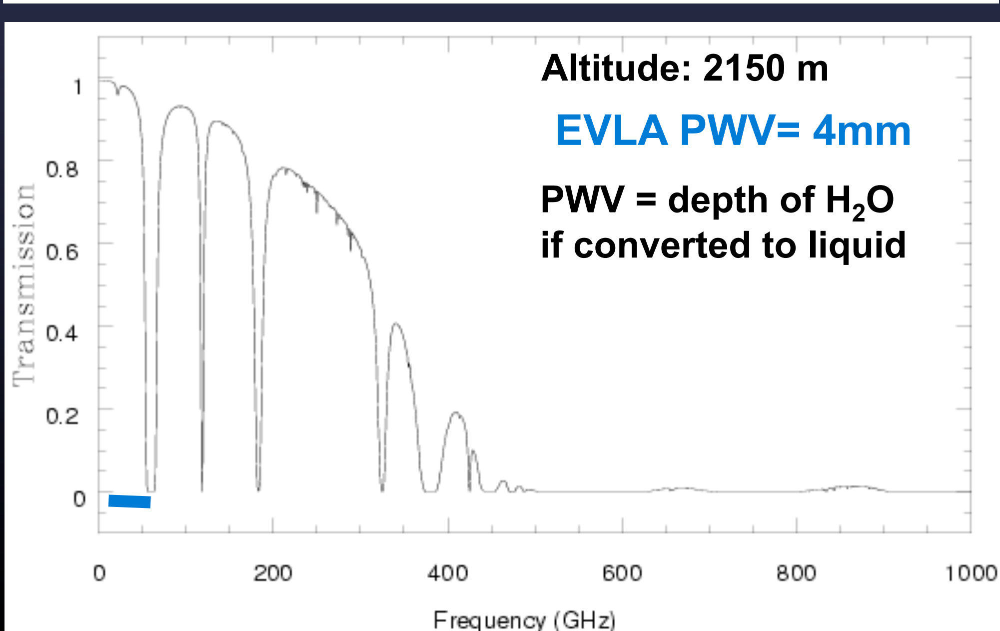
- At 1.3cm most opacity comes from H_2O vapor
- At 7mm biggest contribution from dry constituents
- At 3mm both components are significant
- "hydrosols" i.e. water droplets (not shown) can also add significantly to the opacity

Opacity as a Function of PWV (PWV=Precipitable Water Vapor)



Troposphere Opacity Depends on Altitude:





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 $n \propto \dfrac{w}{D T_{atm}}$

w=precipitable water vapor (PWV) column

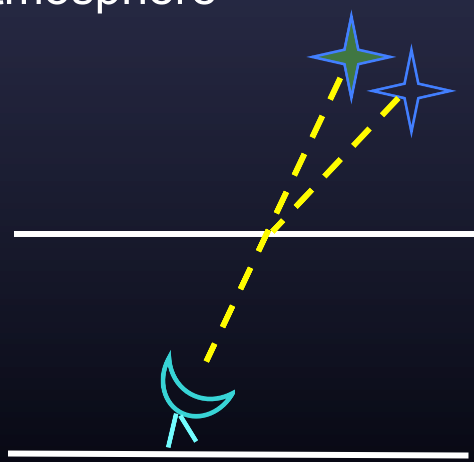
T_{atm} = Temperature of atmosphere

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

This refraction causes:

- Pointing off-sets, $\Delta\theta \approx 2.5\mathrm{x}10^{-4} \times \tan(i)$ (radians)
  @ elevation 45^o 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

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

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

so $\boxed{T_{noise} \approx \underbrace{T_{rx}}_{\text{Receiver temperature}} + \underbrace{T_{atm}(1-e^{-\tau})}_{\text{Emission from atmosphere}}}$

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:

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

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

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

Atmospheric opacity, continued

Typical optical depth for 230 GHz observing at the CSO:

at zenith τ_{225} = 0.15 = 3 mm PWV, at elevation = 30° $\Rightarrow \tau_{225}$ = 0.3

$$T_{sys}^*(DSB) = e^{\tau}(T_{atm}(1-e^{-\tau}) + T_{rx}) = 1.35(77 + 75) \sim 200\ K$$

assuming T_{atm} = 300 K

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

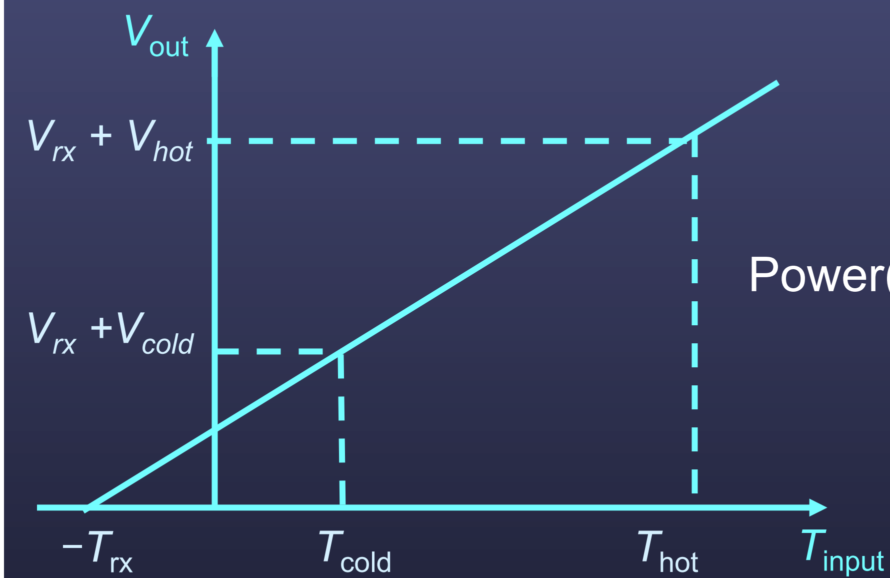
Many MM/Submm receivers are double sideband (ALMA Bands 9 and 10 for example) , thus the effective T_{sys} for spectral lines (which are inherently single sideband) is doubled

$$T_{sys}^*(SSB) = 2\ T_{sys}\ (DSB) \sim 400\ K$$

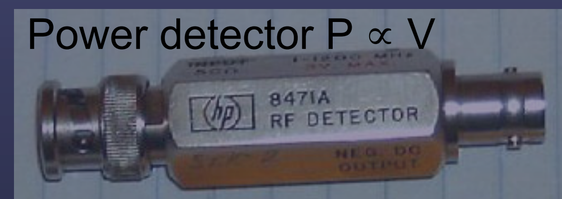
Determining the T_{rx} and the Temperature Scale

Good receiver systems have a linear response: $P_{out} \propto V_{out} = G * (T_{input} + T_{rx})$

Unknown slope — Calibrated 'load' — Receiver temperature



Power(ν) ⇨



⇨ Voltage

To measure T_{rx}, you need measurements of two calibrated 'loads':

$T_{\mathbf{cold}}$ = 77 K liquid nitrogen load

$T_{\mathbf{hot}}$ = Room temperature load

Starting from $y = mx + b$

$$T_{RX} = \frac{T_{HOT} - YT_{COLD}}{Y - 1}$$

And letting, the "Y" factor

$$Y = \frac{V_{RX} + V_{HOT}}{V_{RX} + V_{COLD}}$$

$$G[Volt/Kelvins] = \frac{[V_{RX} + V_{HOT}] - [V_{RX} + V_{COLD}]}{T_{HOT} - T_{COLD}}$$

However, T_{rx} is not a constant, especially for mm/submm receivers which are more difficult to tune to ideal performance ➔ best approach is to measure it often

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?

- The "chopper wheel" method: putting an ambient temperature load (T_{load}) in front of the receiver and measuring the resulting power compared to power when observing sky T_{atm} (Penzias & Burrus 1973).

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

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

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

Comparing in and out $\quad \dfrac{V_{in} - V_{out}}{V_{out}} = \dfrac{T_{load}}{T_{sys}}$

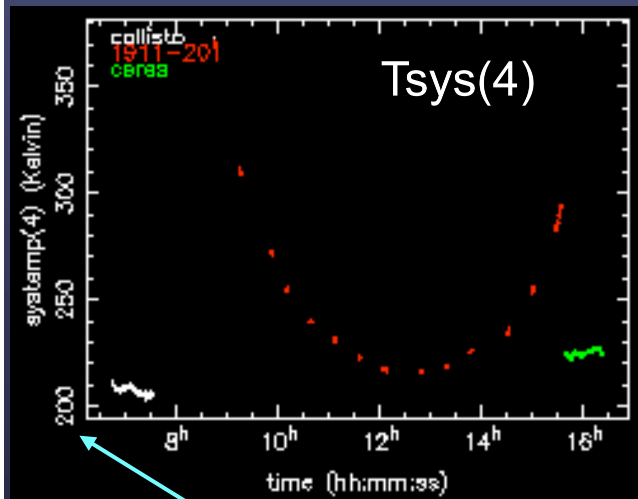
$$\boxed{T_{sys} = T_{load} * T_{out} / (T_{in} - T_{out})}$$

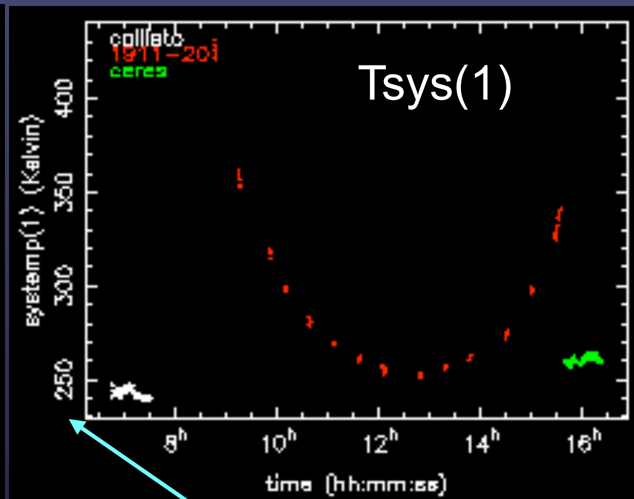
Power is really observed but is $\propto$ T in the R-J limit

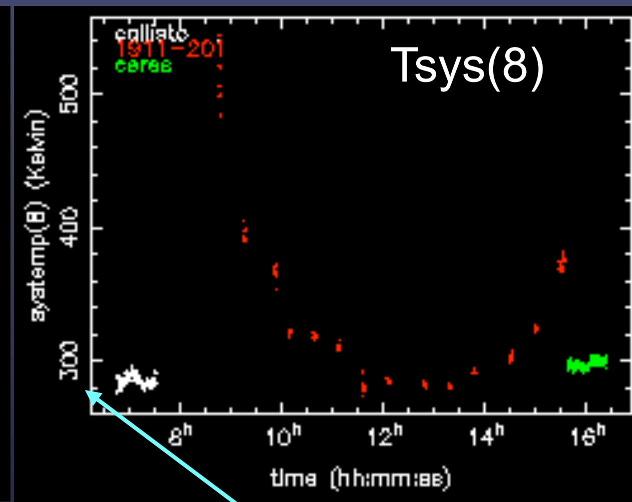
- IF $T_{atm} \approx T_{load}$, and T_{sys} is measured often, changes in mean atmospheric absorption are corrected. ALMA will have a two temperature load system which allows independent measure of T_{rx}

SMA calibration load swings in and out of beam

Example SMA 345 GHz T_{sys} Measurements







Good

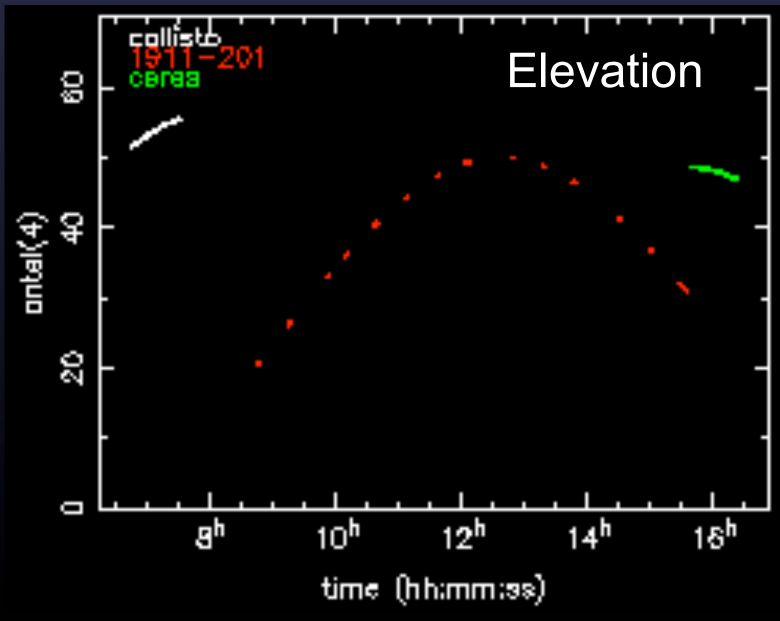
Medium

Poor

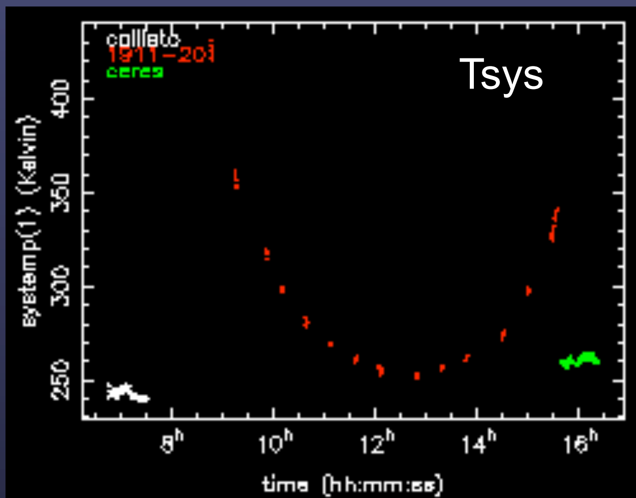
Note sharp rise in T_{sys} at low elevations

For calibration and imaging

$$VisibilityWeight \propto \frac{1}{T_{sys}(i)T_{sys}(j)}$$



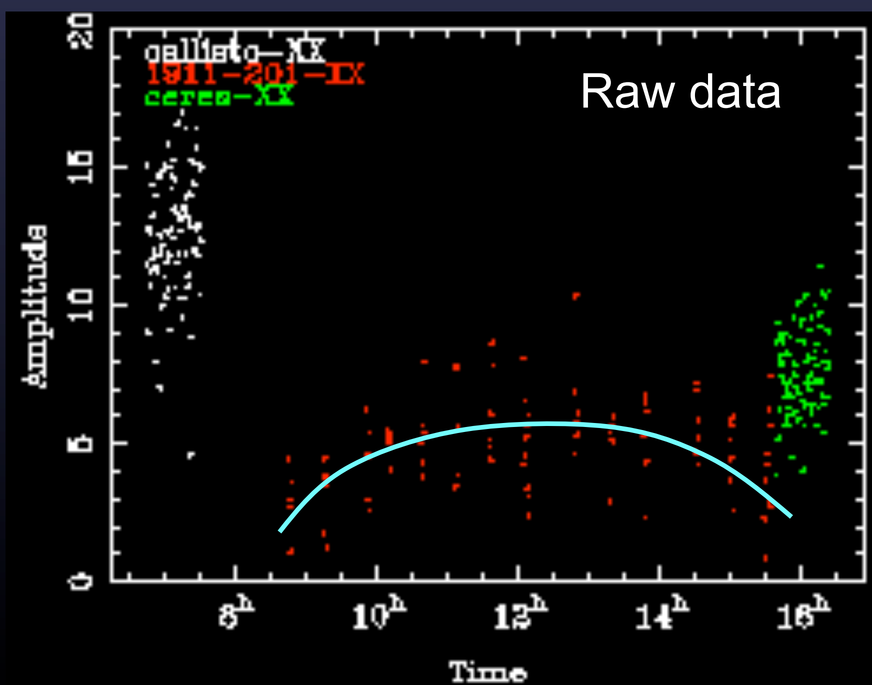
SMA Example of Correcting for T_{sys} and conversion to a Jy Scale

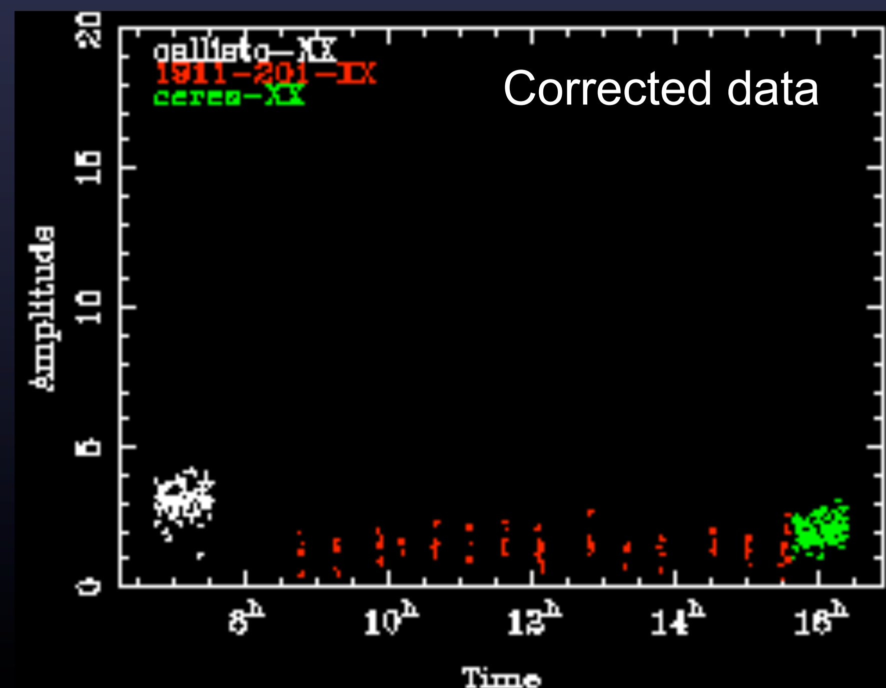


$$S = S_o * [T_{sys}(1) * T_{sys}(2)]^{0.5} * 130\ \text{Jy/K} * 5 \times 10^{-6}\ \text{Jy}$$

SMA gain for 6m dish and 75% efficiency

Correlator unit conversion factor

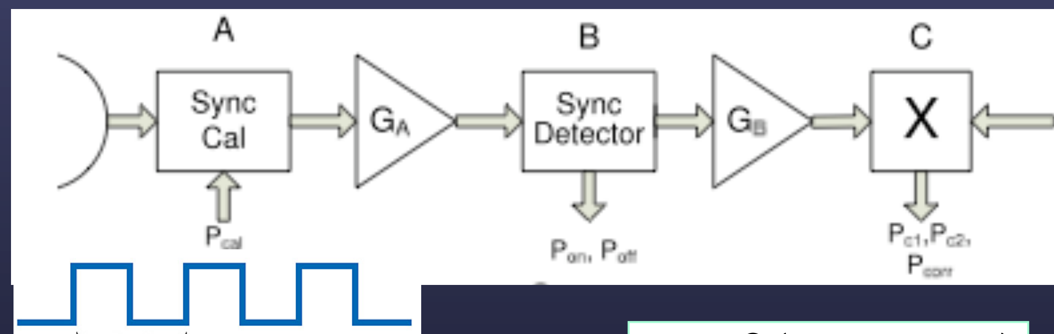




EVLA Switched Power

Alternative to a mechanical load system is a switched "calibration diode"

- Broad band, stable noise (Tcal~3K) is injected into receiver at ~20 Hz
- Synchronous detector downstream of gives sum & difference powers



$$R = \frac{2(P_{on} - P_{off})}{P_{on} + P_{off}}$$

$$T_{sys} = \frac{T_{cal}}{R}$$

$$VisibilityWeight \propto \frac{1}{T_{sys}(i)T_{sys}(j)}$$

Advantages

- Removes all gain variations due to the analog electronics between A and B
- Puts data on absolute temperature scale

Caveats:

- Does not account for opacity effects
- Does not account for antenna gain curve

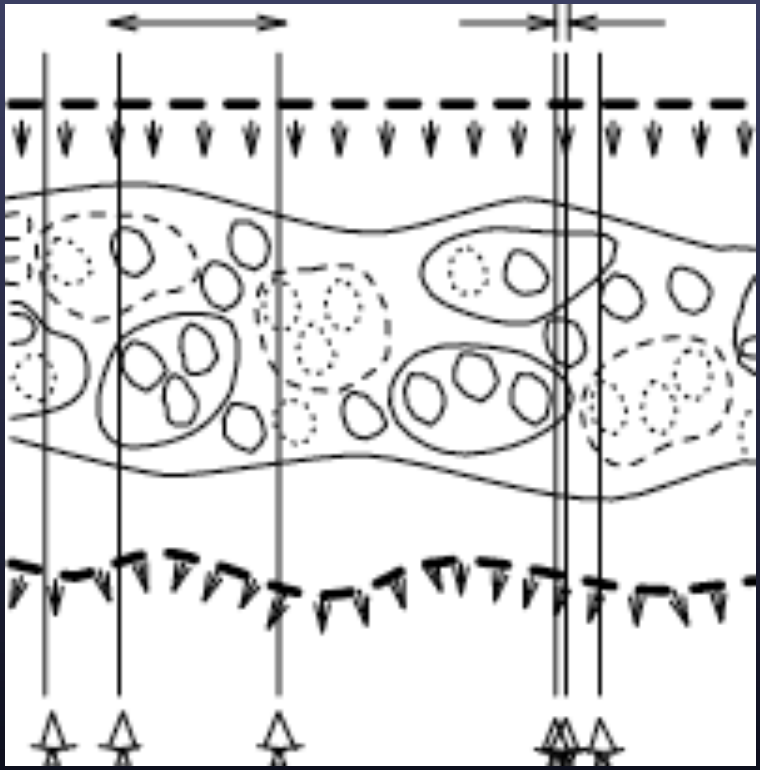
Atmospheric phase fluctuations

- Variations in the amount of precipitable water vapor (PWV) cause phase fluctuations, which are worse at shorter wavelengths (higher frequencies), 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

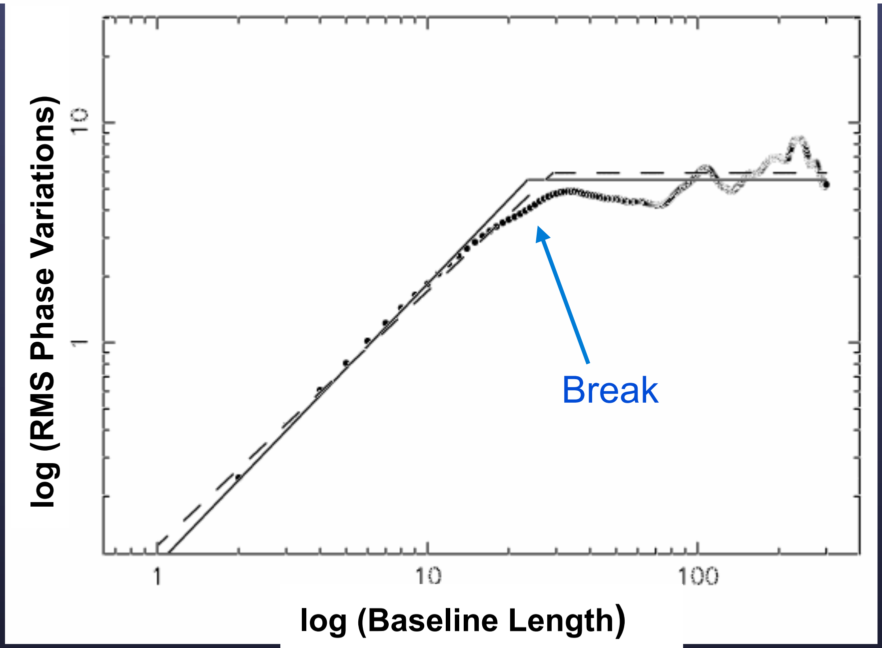
V_w~10 m/s



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)

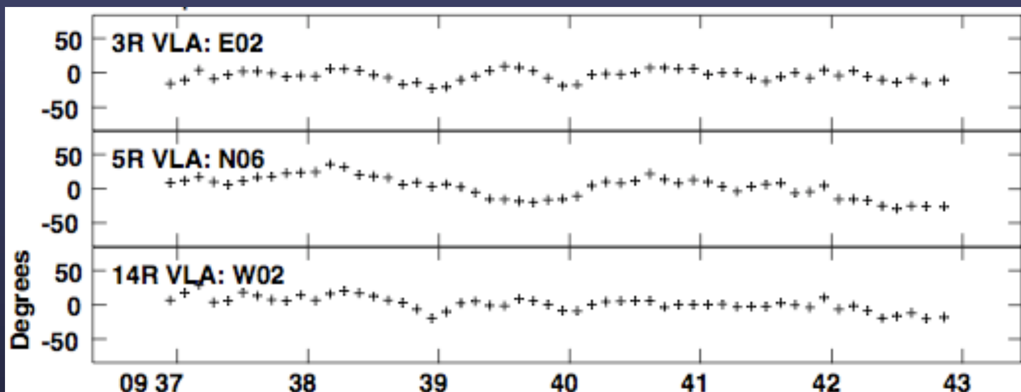
α = 1/3 to 5/6

λ= wavelength (mm)

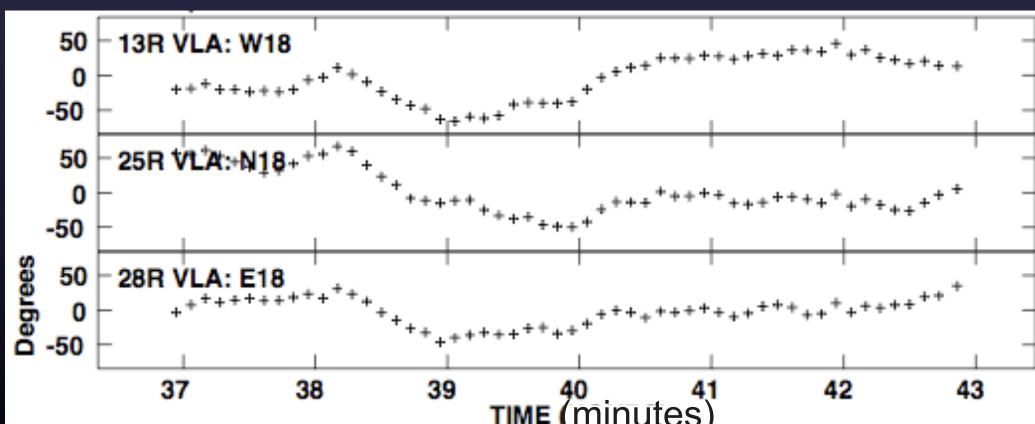
K = constant (~100 for ALMA, 300 for VLA)

Residual Phase and Decorrelation

Q-band (7mm) VLA C-config. data from "good" day
An average phase has been removed from absolute flux calibrator 3C286



Short baselines



Long baselines

⇨ Residual phase on long baselines have larger amplitude, than short baselines

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 :

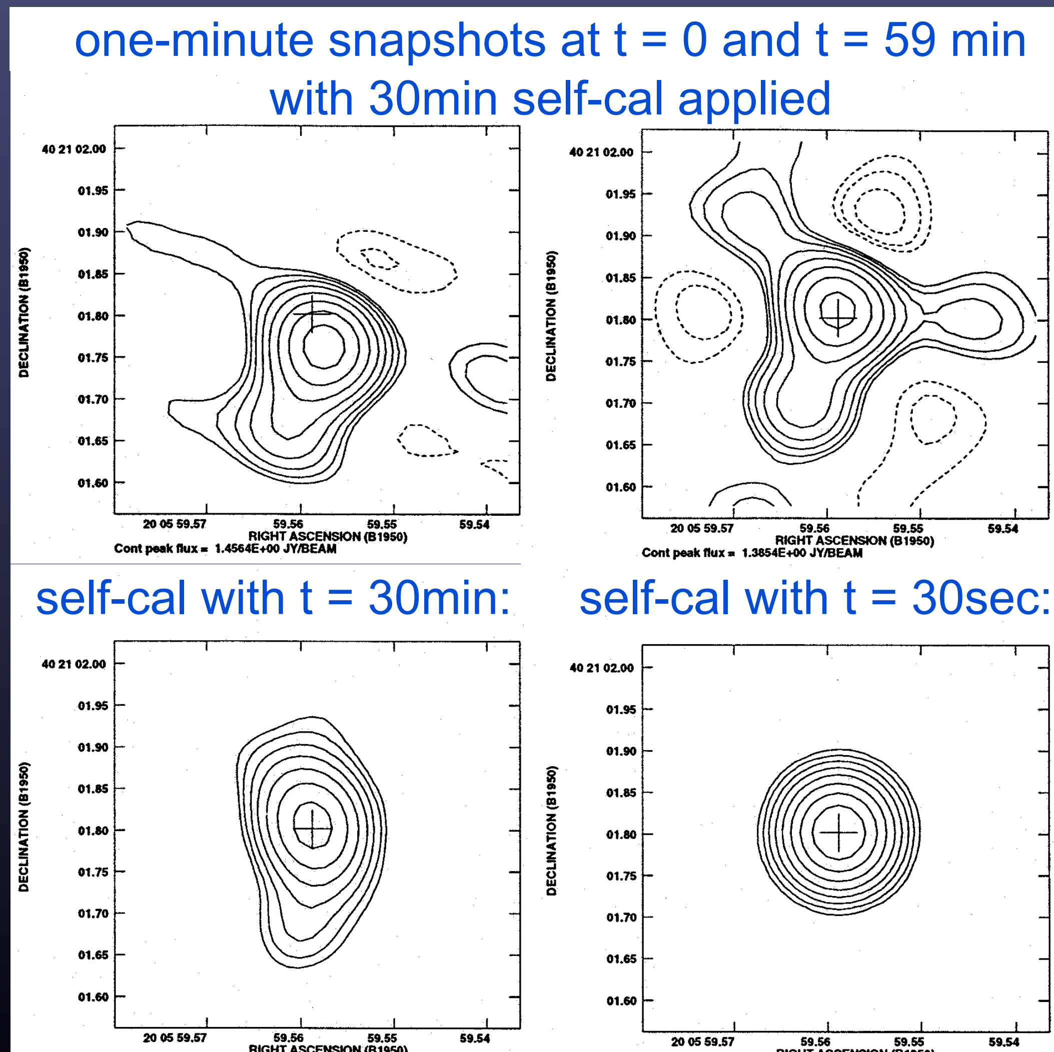
$\langle V \rangle = V_0 \times \langle e^{i\phi} \rangle = V_0 \times e^{-\phi^2_{rms}/2}$
(Gaussian phase fluctuations)

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

For these data, the residual rms phase (5-20 degrees) from applying an average phase solution produces a 7% error in the flux scale

VLA observations of the calibrator 2007+404 at 22 GHz (13 mm) with a resolution of 0.1″ (Max baseline 30 km)

Position offsets due to large scale structures that are <u>correlated</u> ⇨ phase gradient across array



Sidelobe pattern shows signature of antenna based phase errors ⇨ small scale variations that are <u>uncorrelated</u>

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

No sign of phase fluctuations with timescale ~ 30 s

⇨ Uncorrelated phase variations degrades and decorrelates image

⇨ Correlated phase offsets = position shift

⇒ 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 EVLA for high frequencies and will be used at ALMA. Choose fast switching cycle time, t_{cyc}, short enough to reduce ϕ_{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. Can be tricky, requires well characterized system due to differing electronics at the frequencies of interest.

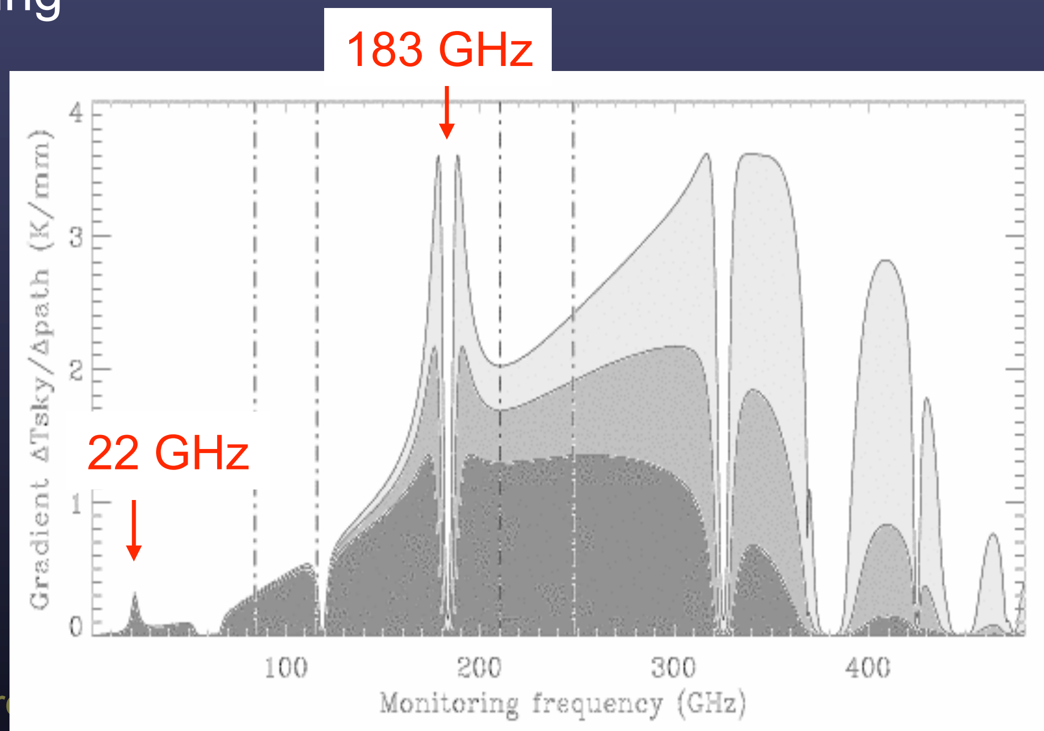
- Paired array calibration: divide array into two separate arrays, one for observing the source, and another for observing a nearby calibrator.
  - Will not remove fluctuations caused by electronic phase noise
  - Only works for arrays with large numbers of antennas (e.g., CARMA, EVLA, ALMA)

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

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

w=precipitable water vapor (PWV) column



(Br

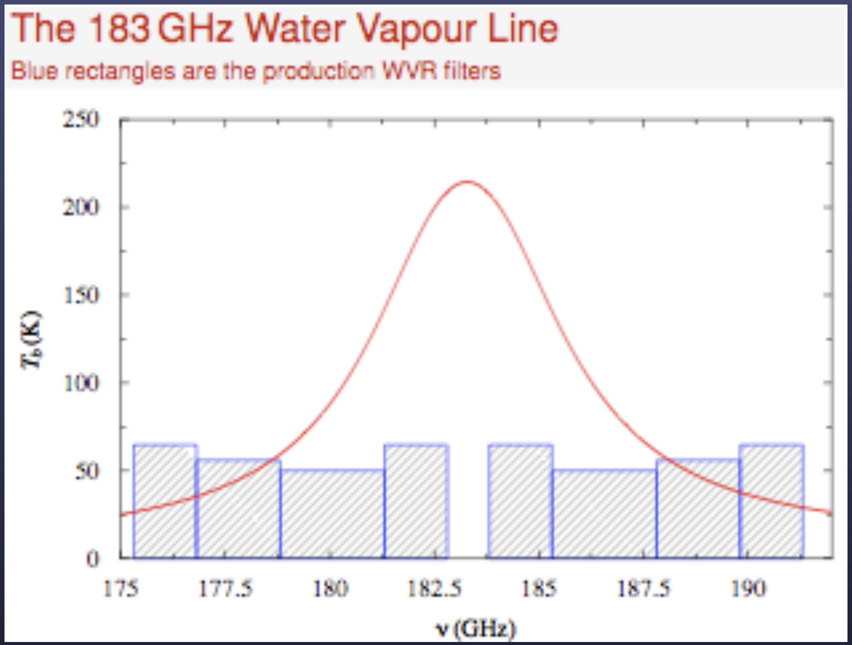
Monitor: 22 GHz H_2O line (CARMA, VLA)

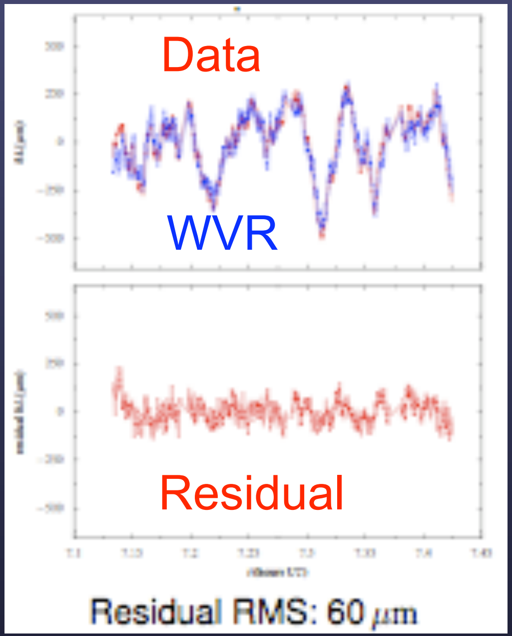
183 GHz H_2O line (CSO-JCMT, SMA, ALMA)

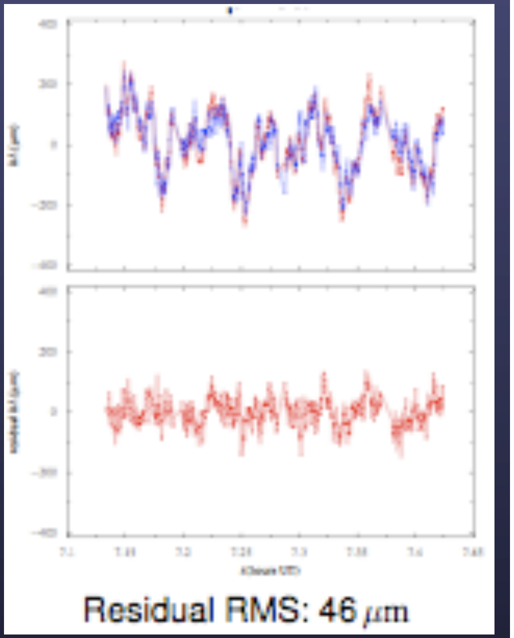
total power (IRAM, BIMA)

Testing of ALMA WVR Correction

Two different baselines Jan 4, 2010







There are 4 “channels” flanking the peak of the 183 GHz line

- Matching data from opposite sides are averaged
- The four channels allow flexibility for avoiding saturation
- Next challenges are to perfect models for relating the WVR data to the correction for the data to reduce residual

Absolute gain calibration

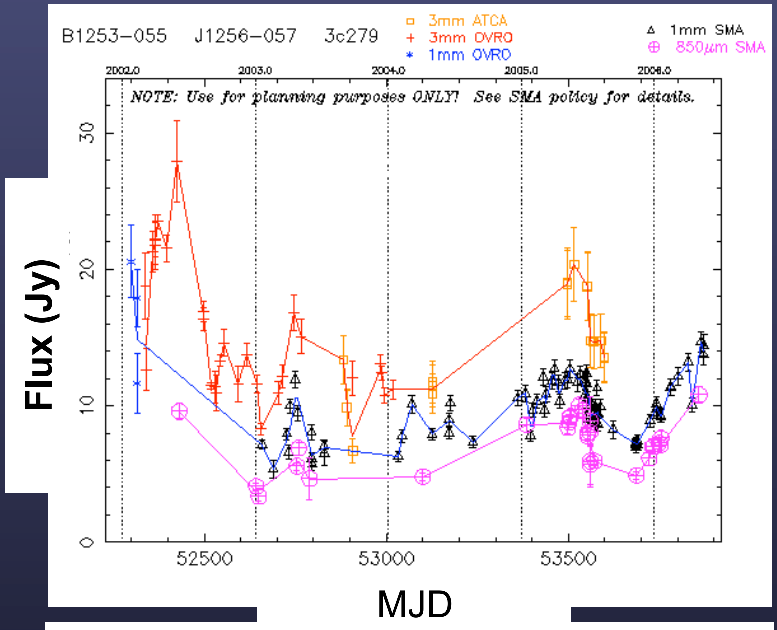
There are no non-variable quasars in the mm/sub-mm for setting the absolute flux scale

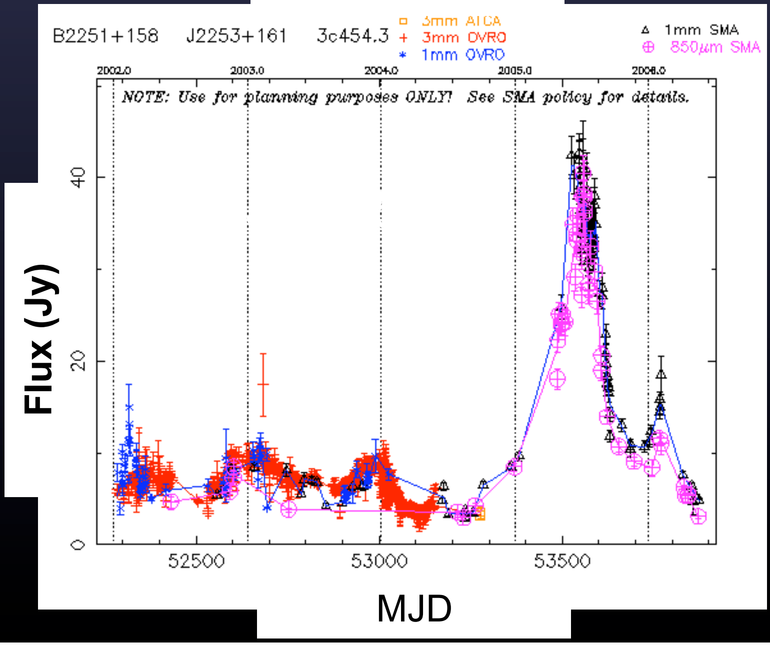
Instead, planets and moons are typically used: roughly black bodies of known size and temperature:

Uranus @ 230 GHz: $S_\nu \sim 37$ Jy, $\theta \sim 4''$

Callisto @ 230 GHz: $S_\nu \sim 7.2$ Jy, $\theta \sim 1.4''$

- 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 at all





Antenna requirements

- **Pointing:** 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

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

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

  ⇒ ALMA surface accuracy goal of 25 μm

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

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

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

  e.g., for λ = 1.3 mm need Δb < 0.2 mm

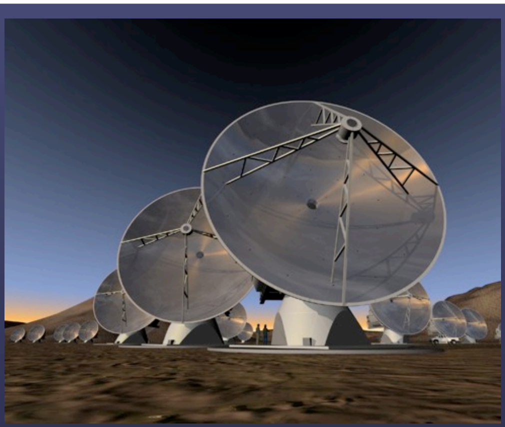
  $\Delta\theta$ = angular separation between source & calibrator, can be large in mm/sub-mm

  Δb = baseline error

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 broad bandwidth) for spectral lines: For line extent ΔV = 300km 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

ALMA Preparation: Early Science is Almost Here!

ALMA First call for Early Science proposals with 16+ antennas expected in Jan. 2011

June 2010 FIVE antennas at the high site!

On Tuesday June 15: ALMA Preparation Activities will include:

- CARMA CO(1-0) spectral line mosaic data reduction tutorial (CASA)
- Simulated ALMA observation tutorial (CASA)
- Demonstrations of the ALMA Observation Preparation Tool (OT)
- Demonstrations of Splatalogue spectral line database for observation preparation and analysis

If you didn't sign up for the CARMA tutorial on Tuesday (which includes all the activities above) and this sounds interesting feel free to change on the signup sheets in the lobby