ALMA

-

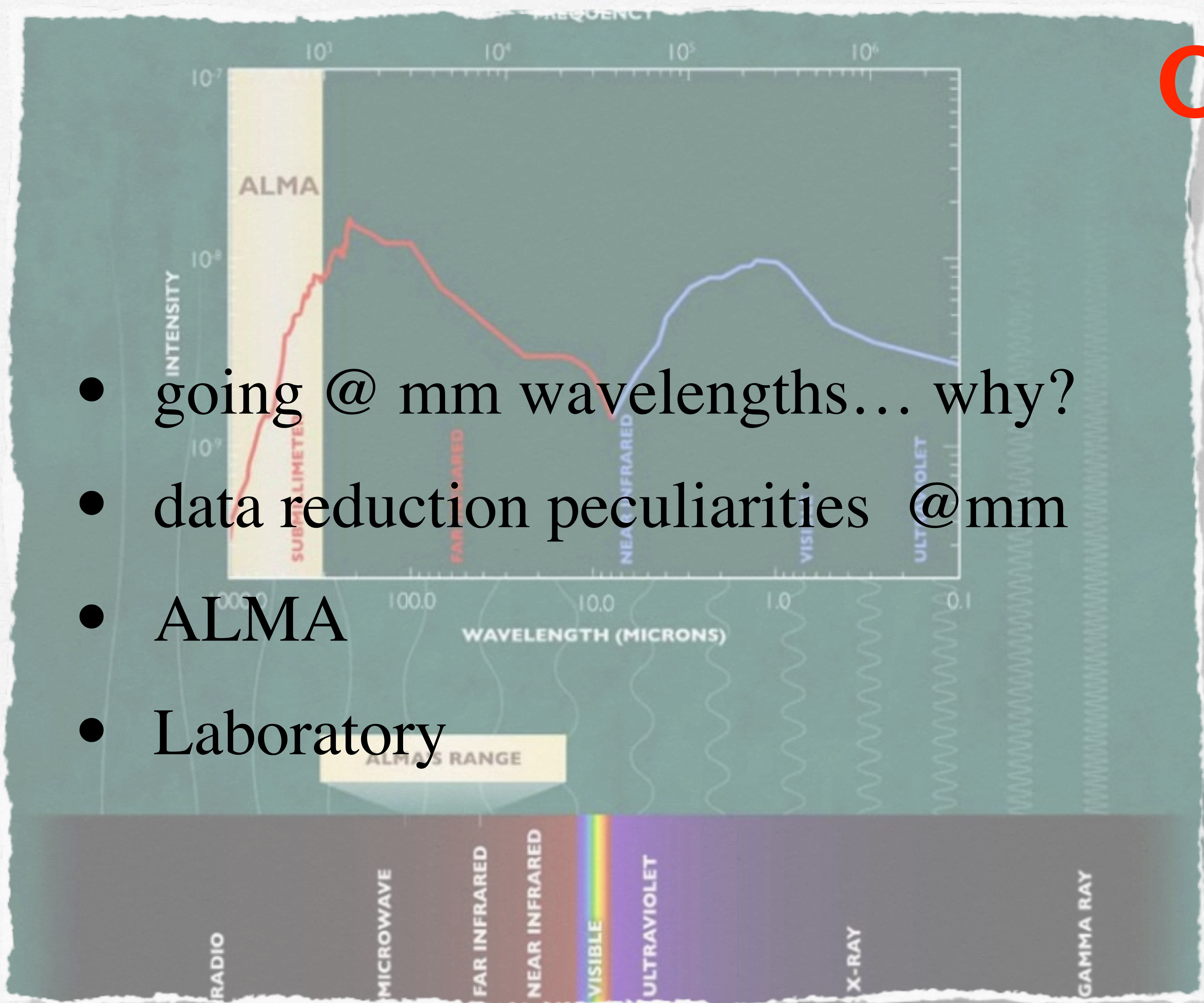
Interferometry @ mm

Arturo Mignano + many others...
Italian Arc

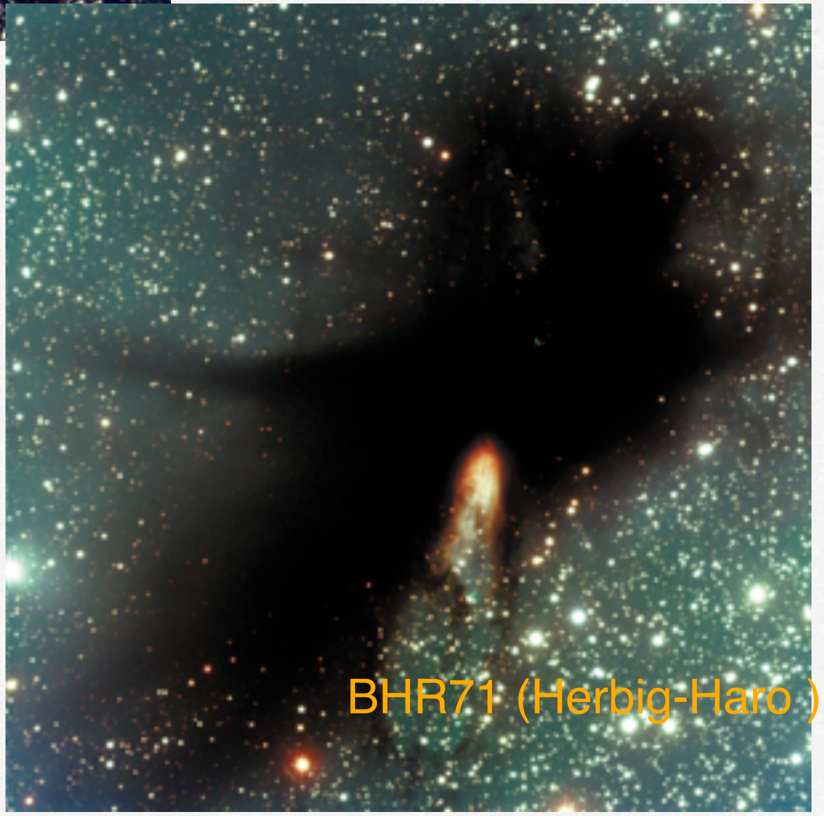
EUROPEAN ARC
ALMA Regional Centre || Italian

Outline

- going @ mm wavelengths… why?
- data reduction peculiarities @mm
- ALMA
- Laboratory



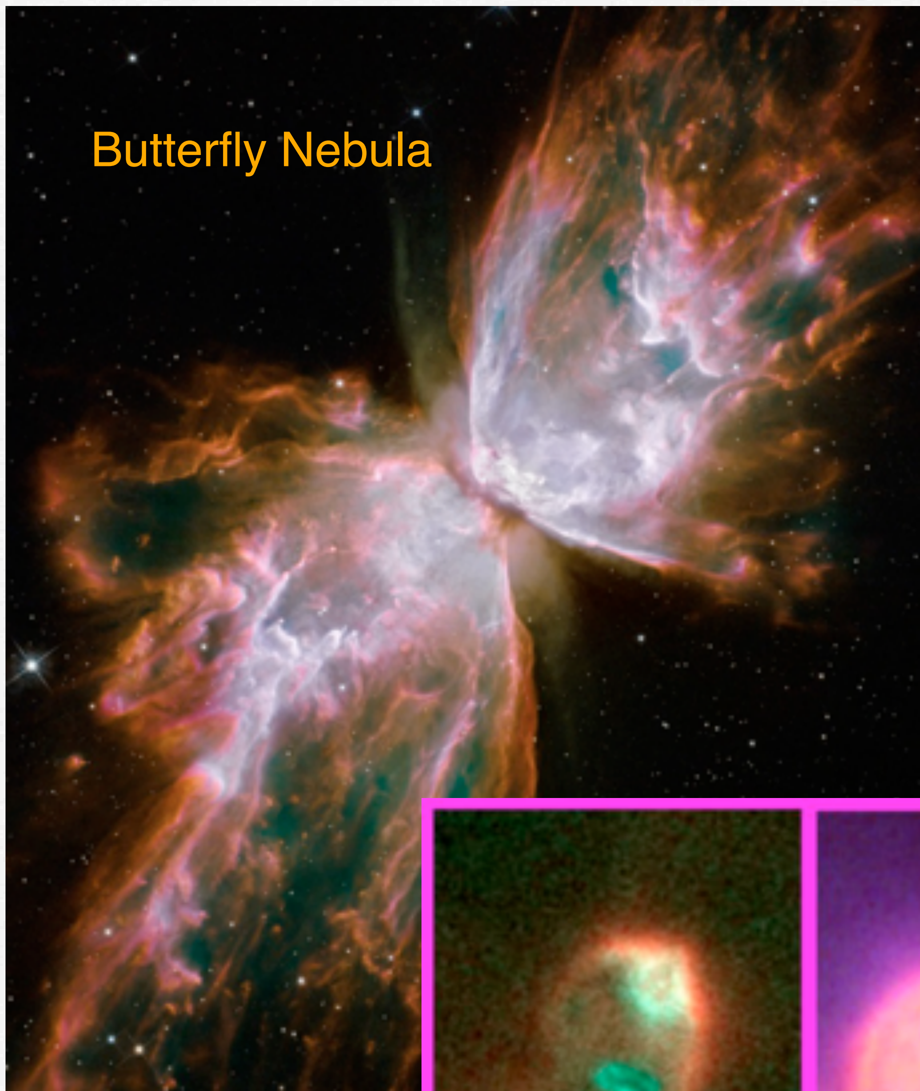
Motivation: Dark Clouds in Space

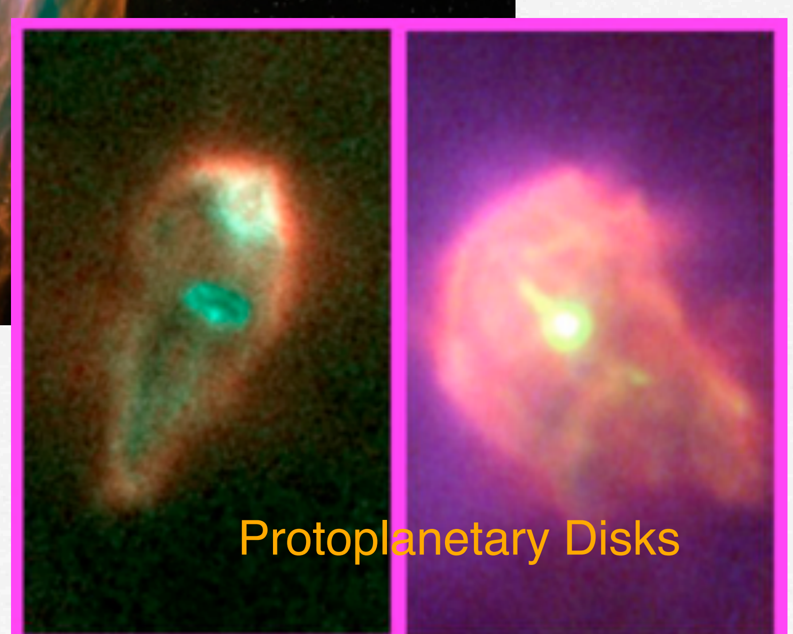


http://www.youtube.com/watch?v=zvJss-EI4KE

www.eso.org

Motivation: more dark clouds in Space





Dark clouds are of interest because:

- The formation of stars takes place in dark clouds,
- the late Red Giant phases of the life of a “medium mass” star involve heavy mass loss by stellar winds that hide the star in a cold, dusty cocoon
- Many galaxies show large-scale structures of dark clouds in their morphology.

This part of the stellar and galactic life cycle is completely inaccessible for optical astronomy!
Dynamics? Masses? Composition? Chemistry? …

The first obvious approach: look for molecular Hydrogen

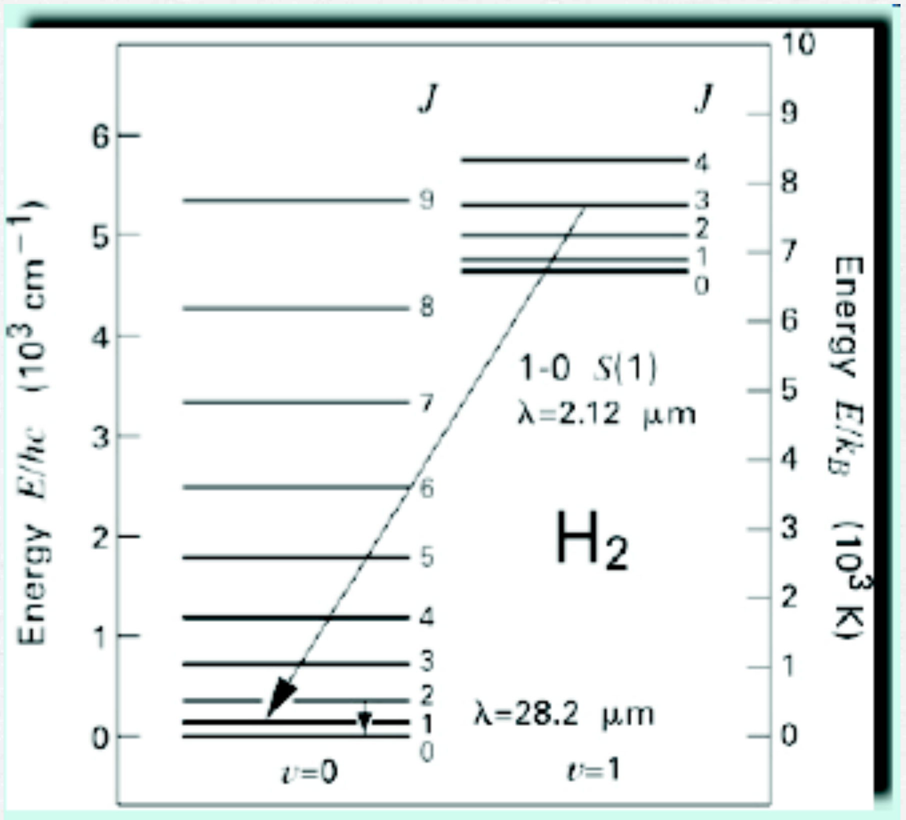
- H_2 is a symmetric molecule

- Unfortunately it has a very low angular momentum, which requires a lot of energy to excite:

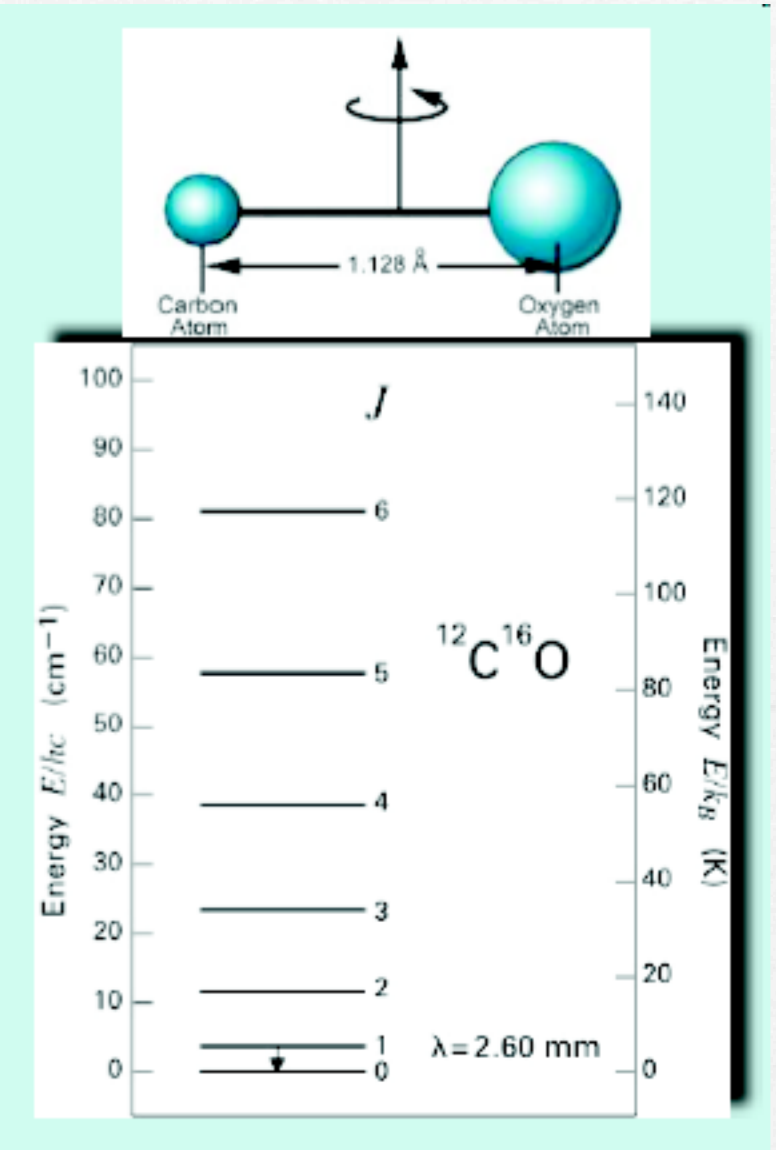
  $E_{rot} = \hbar^2/(2\Theta)\, J^*(J+1)$

- Consequence: H_2 has transitions from the IR to the UV, but its emission traces only hot or shocked gas.
- Abundant in cold, dark clouds, but it does not emit!

We need another molecule …



Next choice: Carbon monoxide (CO)



- Asymmetric molecule, easy to excite even in cold clouds.
- UV radiation above 11.09 eV required to break it up
- Most abundant molecule after H_2 , ~ 10^{-4}
- CO can self-shield in dark clouds (see e.g.Visser et al, A&A 503, 323)
- Line frequencies for dominant isotopes:
  see http://spec.jpl.nasa.gov/ftp/pub/catalog/catform.html
  or http://physics.nist.gov/cgi-bin/micro/table5/start.pl

	$^{12}C\ ^{16}O$	$^{13}C\ ^{16}O$	$^{12}C\ ^{18}O$
(1-0)	115.271 GHz	110.201 GHz	109.782 GHz
(2-1)	230.538 GHz	220.399 GHz	219.560 GHz
(3-2)	345.796 GHz	330.588 GHz	329.331 GHz
(4-3)	461.041 GHz	440.765 GHz	439.089 GHz
…	…	…	…

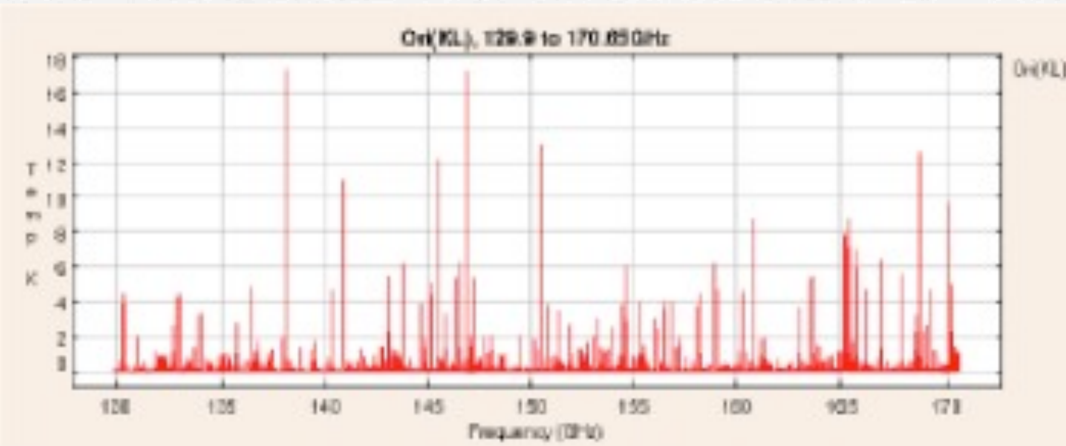
some useful molecules

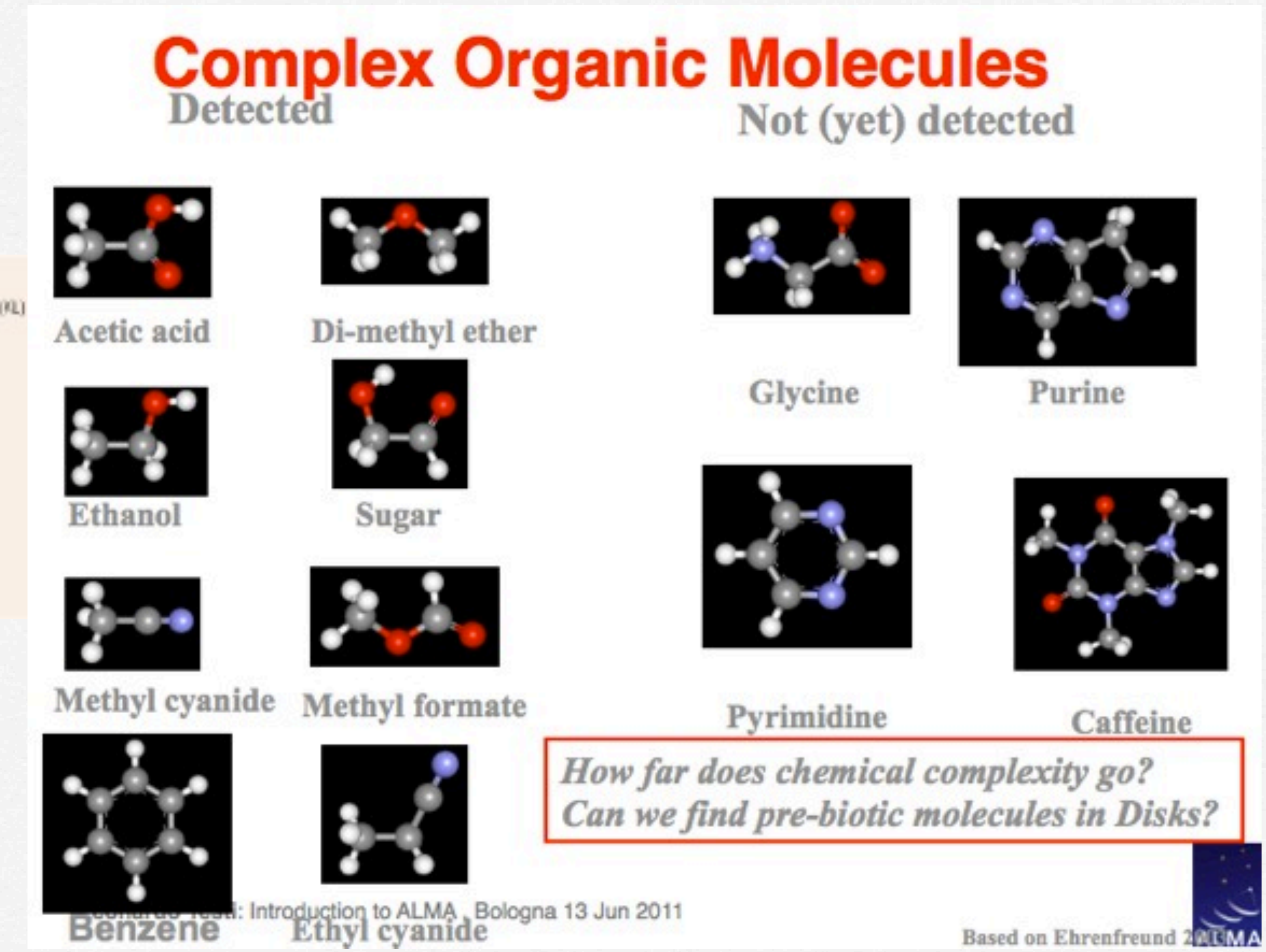
molecule	abundance[a]	transition	type	λ	$T_\circ^b$ (K)	A_{ul} (s^{-1})	n_{crit}^c (cm^{-3})	comments
H_2	1	$1 \rightarrow 0$ S(1)	vibrational	2.1 μm	6600	8.5×10^{-7}	7.8×10^{7}	shock tracer
CO	8×10^{-5}	$J=1\rightarrow0$	rotational	2.6 mm	5.5	7.5×10^{-8}	3.0×10^{3}	low density probe
OH	3×10^{-7}	$^2\Pi_{3/2}$;J=3/2	Λ-doubling	18 cm	0.08	7.2×10^{-11}	1.4×10^{0}	magnetic field probe
NH_3	2×10^{-8}	(J,K)=(1,1)	inversion	1.3 cm	1.1	1.7×10^{-7}	1.9×10^{4}	temperature probe
H_2CO	2×10^{-8}	$2_{12}\rightarrow1_{11}$	rotational	2.1 mm	6.9	5.3×10^{-5}	1.3×10^{6}	high density probe
CS	1×10^{-8}	$J=2\rightarrow1$	rotational	3.1 mm	4.6	1.7×10^{-5}	4.2×10^{5}	high density probe
HCO^+	8×10^{-9}	$J=1\rightarrow0$	rotational	3.4 mm	4.3	5.5×10^{-5}	1.5×10^{5}	tracer of ionization
H_2O		$6_{16}\rightarrow5_{23}$	rotational	1.3 cm	1.1	1.9×10^{-9}	1.4×10^{3}	maser
"	$<7\times10^{-8}$	$1_{10}\rightarrow1_{11}$	rotational	527 μm	27.3	3.5×10^{-3}	1.7×10^{7}	warm gas probe

[a] number density of main isotope relative to hydrogen, as measured in the dense core TMC–1
[b] equivalent temperature of the transition energy; $T_\circ \equiv \Delta E_{ul}/k_B$
[c] evaluated at T=10 K, except for H_2 (T=2000 K) and H_2O at 527 μm (T=20 K)

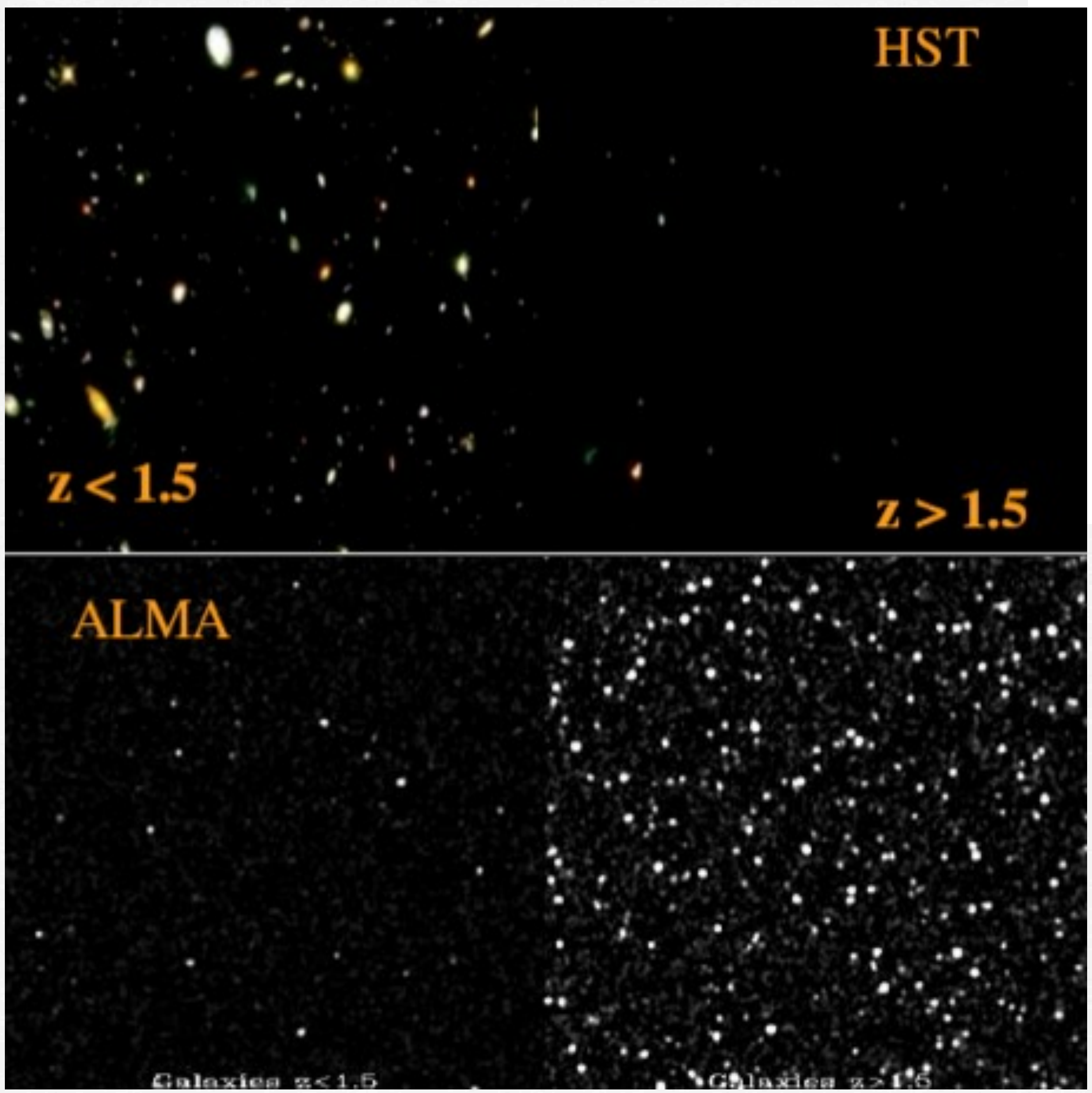
From: Stahler & Palla, "The Formation of Stars"

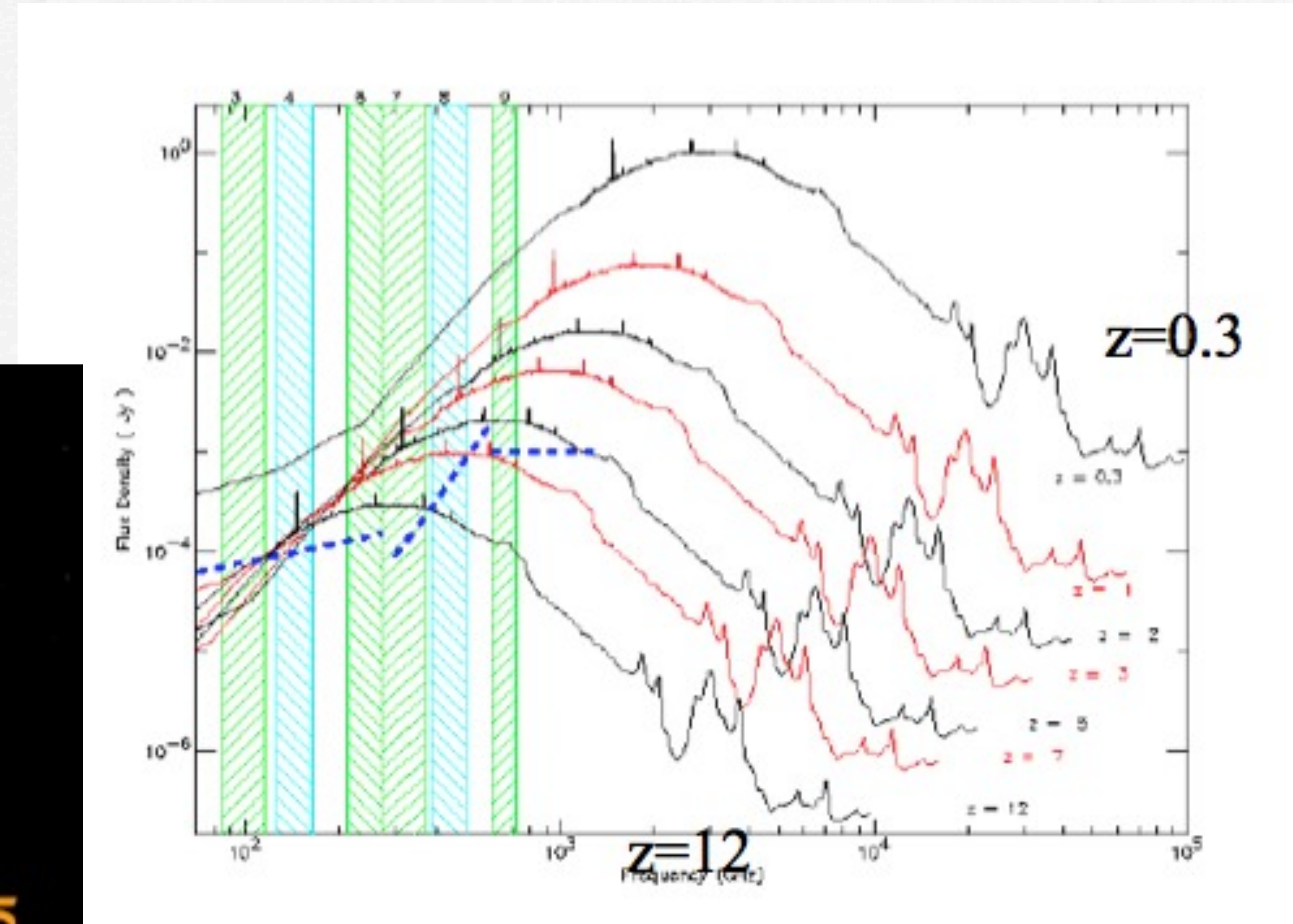
CO, the main driver to build instruments beyond 100GHz not only CO! large variety of molecules in ISM



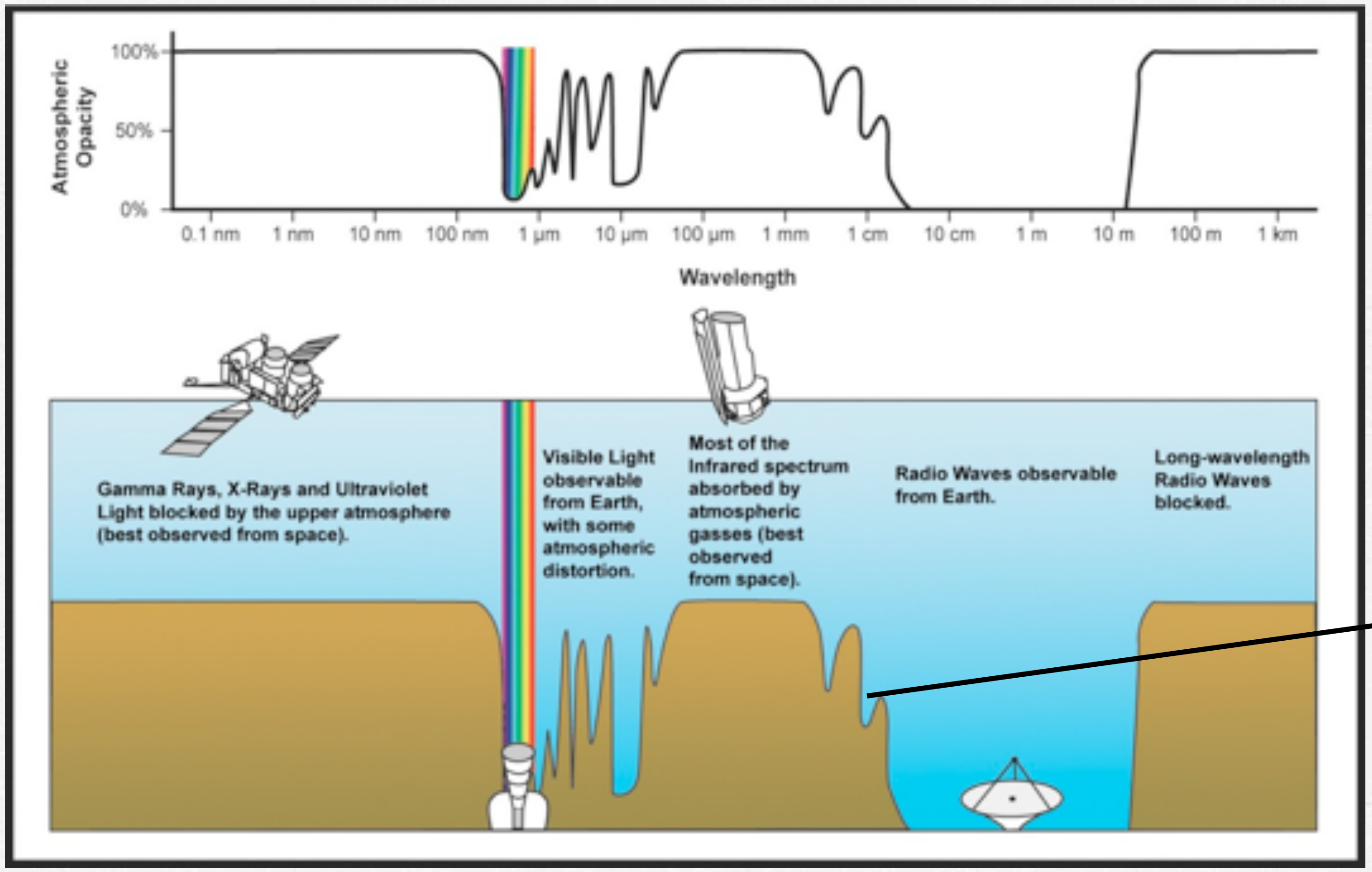


Probing history of galaxies





The atmospheric transmission windows



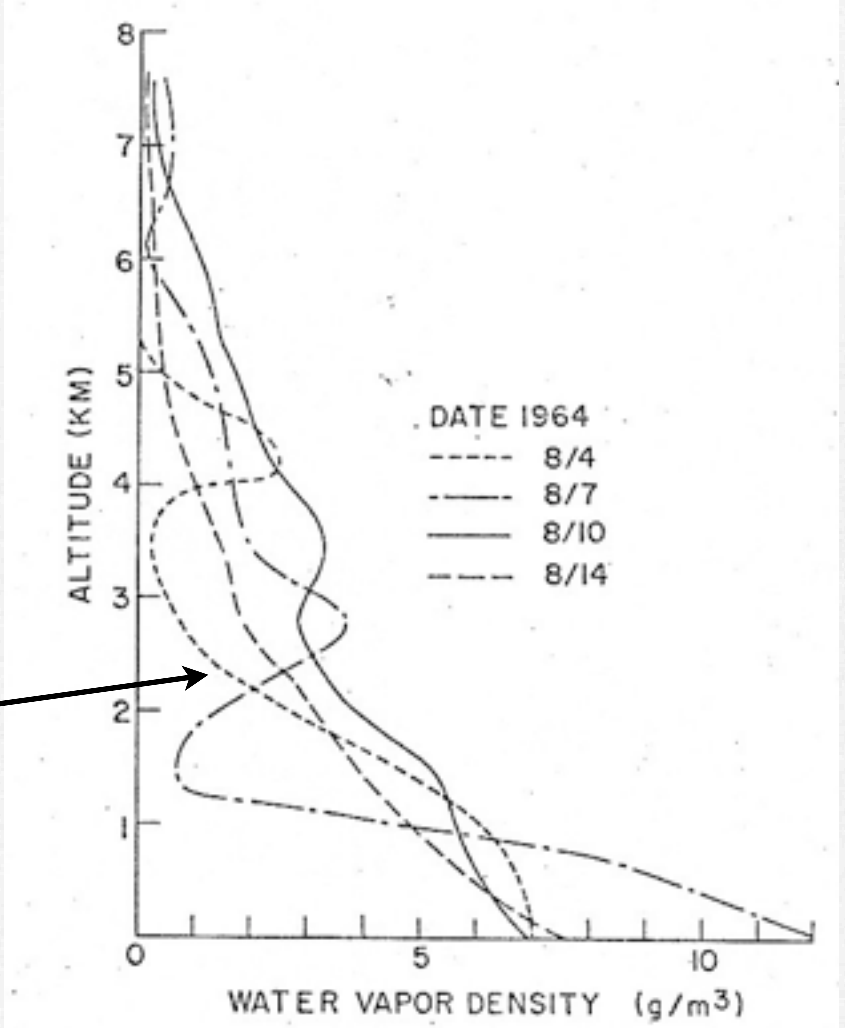


Fig. 3. Atmospheric water vapor profiles measured by radiosondes.

From: Staelin, 1966
(method: radiosondes)

Main absorber:

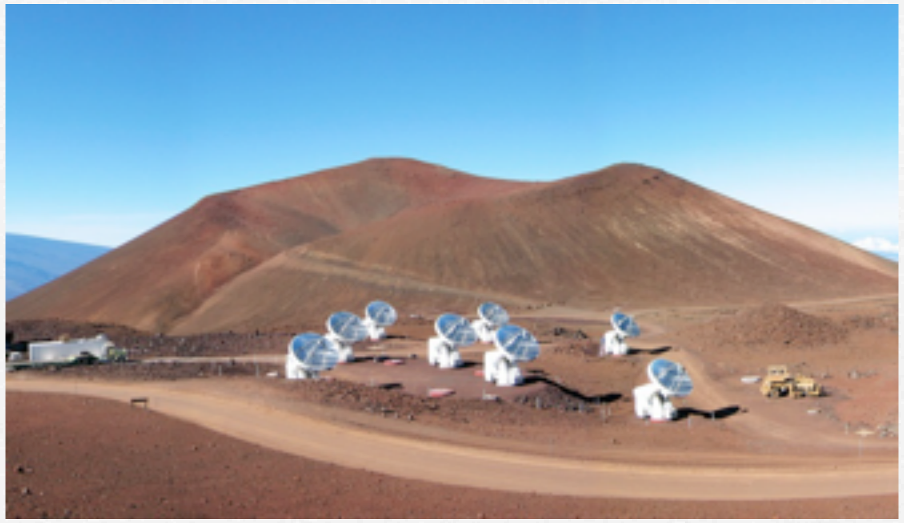
H_20

Co_2

Getting rid of water vapour by going high and/or dry

ALMA: 5000m

SMA: 4100m



PdBI: 2550m

CARMA: 2440m

ATCA: 208m

mm Telescopes - Properties (1)

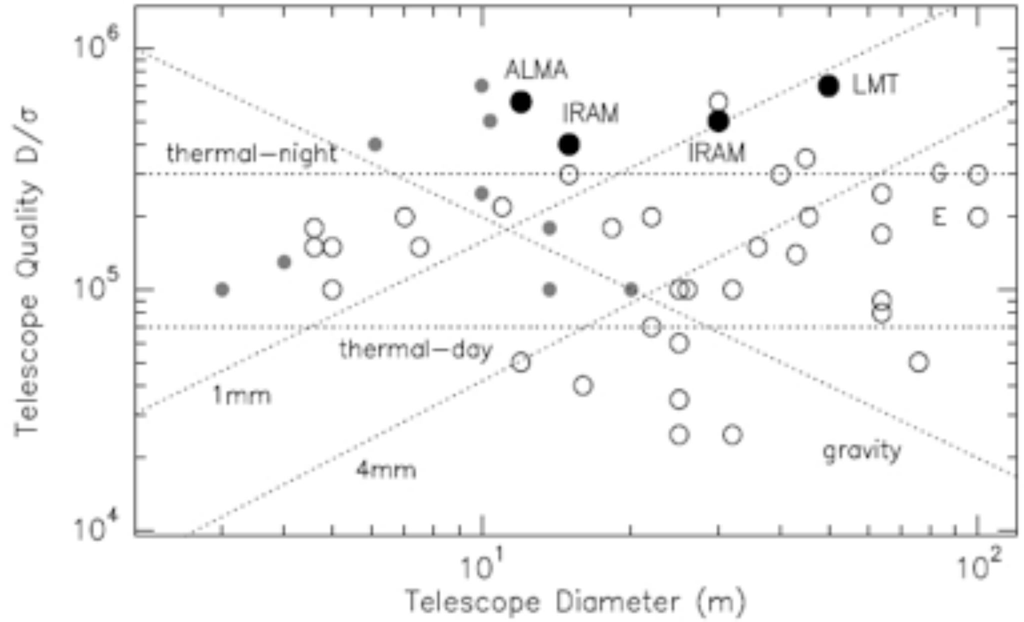
Table 1.2 Electromagnetic Reflector Diameter and Surface Precision.

Telescope (Country) [a]	Reflector Diameter [m]	Wavelength (λ)/ Frequency (ν) [b] [mm]/[GHz]	Electromagnetic Diameter $\mathscr{D} = D/\lambda$ [$\mathscr{D}$/1000]	Reflector Quality $Q = D/\sigma$ [b] [Q/1000]
Radio Telescope				
Arecibo (USA)	300	60 / 5	5	200
Effelsberg (Germany)	100	10 / 30	10	150
Nobeyama (Japan)	45	3 / 100	15	400
IRAM (Spain)	30	1.3 / 230	23	460
IRAM (France)	15	1.3 / 230	11	300
JCMT (Hawaii)	15	0.65 /460	23	750
CSO (Hawaii)	10	0.37 /800	27	500
Optical Telescope				
Palomar (USA)	5	$5\times10^{-4}/5\times10^{15}$	10 000	100 000
KECK (USA)	10	$5\times10^{-4}/5\times10^{15}$	20 000	200 000
ELT [c]	$\sim$50	$5\times10^{-4}/5\times10^{15}$	100 000	1 000 000

[a] see list of Acronyms of observatory sites;
[b] approximately shortest wavelength of observation, estimated precision σ;
[c] next generation extremely large optical telescope (see http://www.eso.org).

check reflector quality

mm Telescopes - Properties (2)



Von Hoerner–diagram. Telescope quality D/σ (D = reflector diameter, σ = surface precision, rms value) and natural limits of gravity and thermal effects, for mm – wavelength (•) and cm–wavelength telescopes (○). The lines labelled 1 mm and 4 mm show the relation $\lambda_{min} = 16\,\sigma$. For the limiting relations see von Hoerner [1967 a, 1977 a] and Baars [2007]. G = GBT telescope, E = Effelsberg telescope.

Problems:

- must be precise enough for your highest frequency,
- with a large collecting area,
- in a place where you have encouraging weather statistics,
- and stay within budget.

$\sigma = \lambda_{min}/16$

weather conditions really important!!!

Forces acting on a Telescope (and Enclosure).

Influence/ Force	Time Variability	Components	Loss of Observing Time
Gravity	quasi–static	gravity	negligible
Temperature	slow 1/4 – 3 h	air, wind, sun, sky, ground & internal heat source	some
Wind & Gusts	fast, 1/10 – 10 s	ambient air	important
Atmosphere	fast	temperature, H_2O vapour, clouds, precipitation	(dominant)

Temperature variation and telescope geometry

Two approches to get the desired millimeter performance:

- choose material with compatible constant of thermal expansion
- control the reflector temperature

$$6\,[\mathrm{mm}](\mathrm{D}/100[\mathrm{m}])(\Delta\mathrm{T}/^{\circ}\mathrm{C}) \lesssim \lambda_{\min}$$

Von Hoerner (1967, 1975)

$$\Delta\mathrm{T} \lesssim \lambda_{\min}[\mathrm{mm}]/(6\,\mathrm{D}/100[\mathrm{m}]) \quad (\mathrm{steel})$$

Reflector Diameter D		100 m	30 m	20 m	15 m	12 m	12 m
Material		steel	steel	aluminium	CFRP–steel	steel	CFRP
CTE [μm/m/K]		12	12	22	5 [a)]	12	3
Example		Effelsberg	IRAM	Onsala	IRAM		ALMA
$\lambda_{\min}$ [mm]/$\nu_{\min}$ [GHz]		30/10	1/300	3/100	1/300	0.375/800	0.375/800
ΔT [^{o} C]	$\lesssim$	5	0.5	1.25	2.5	0.5	2

[a)] estimated value for a combination of CFRP and steel.

what changes for observer between cm and mm waves?

with increasing frequency...

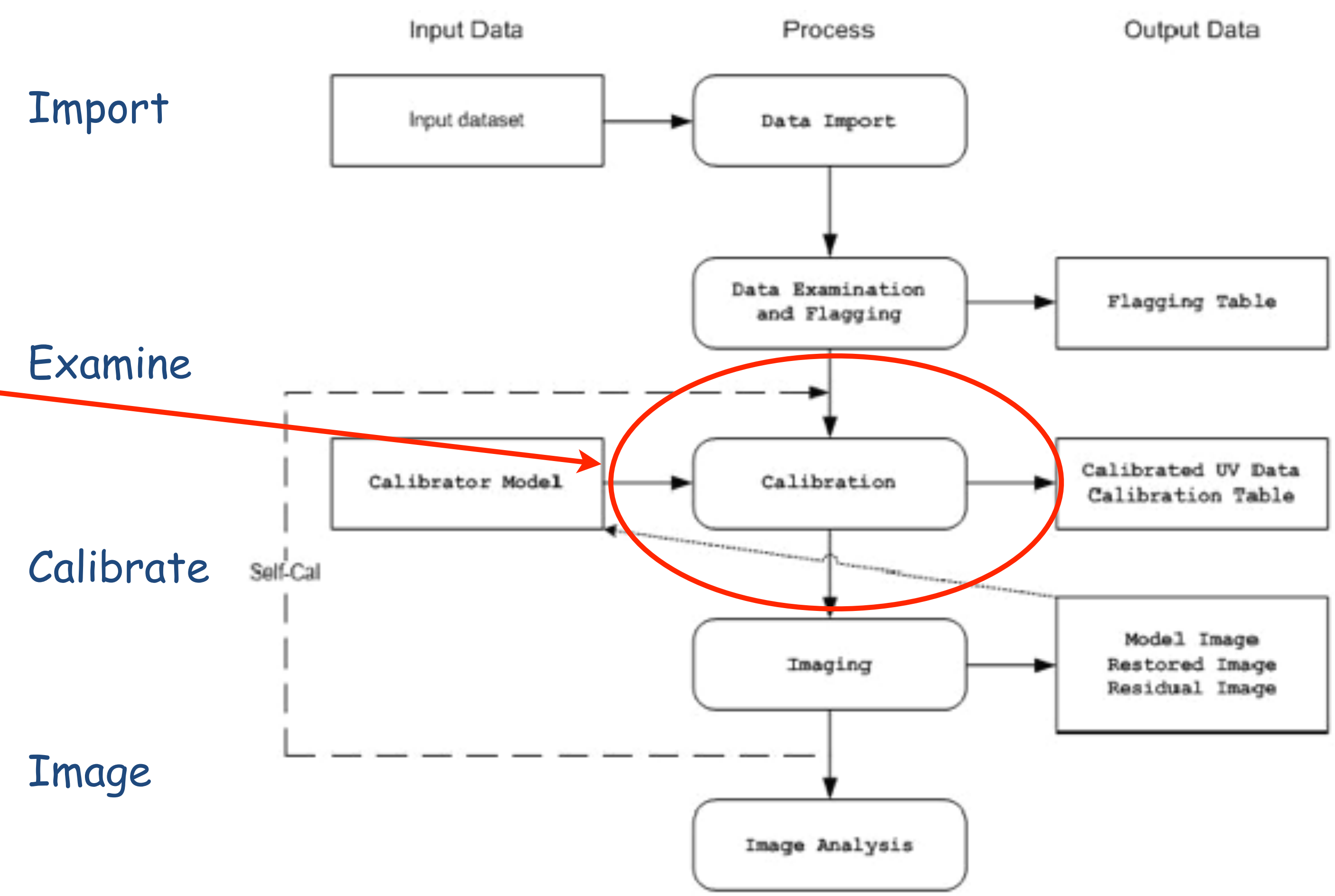
- no external human interference in the data
- non-thermal sources become weaker, but thermal sources are not strong yet
- atm water vapour and clouds become more absorbent, therefore:
    - stronger weather dependency of observations
    - T_{sys} of low elevation observation a lot worse
- the time variability of qso increases (Flux calibration….)

Data Reduction (Calibration)

Measurement Equation

$$\vec{V}_{ij}^{obs} = \overleftrightarrow{B}_{ij}\overleftrightarrow{G}_{ij}\overleftrightarrow{D}_{ij}\overleftrightarrow{P}_{ij}\overleftrightarrow{T}_{ij}\overleftrightarrow{F}_{ij}\vec{V}_{ij}^{ideal}$$

Processing Philosphy



Data Reduction (Calibration)

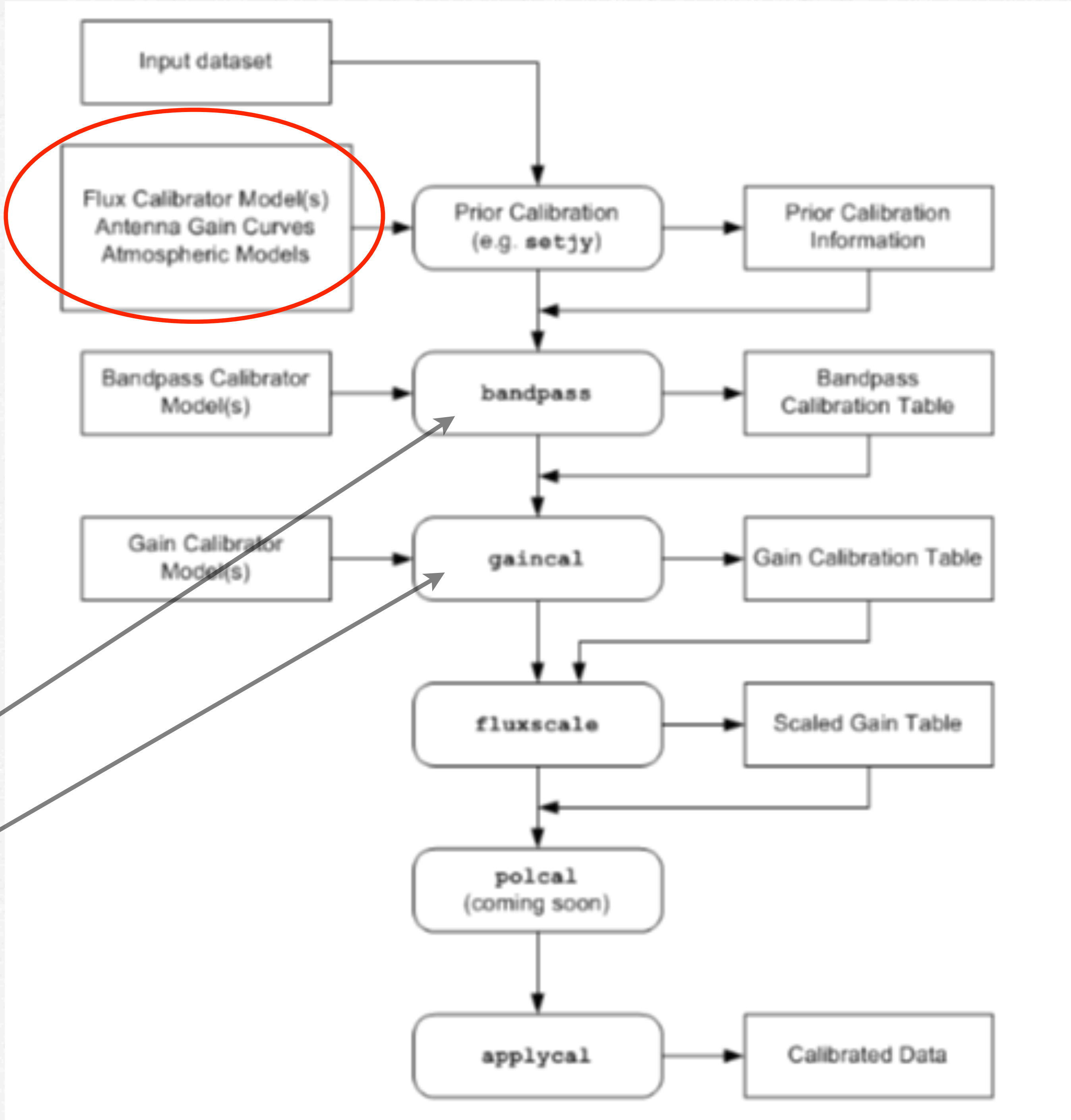
Measurement Equation

$$\vec{V}_{ij}^{obs} = \overleftrightarrow{B}_{ij}\overleftrightarrow{G}_{ij}\overleftrightarrow{D}_{ij}\overleftrightarrow{P}_{ij}\overleftrightarrow{T}_{ij}\overleftrightarrow{F}_{ij}\vec{V}_{ij}^{ideal}$$

Calibration steps

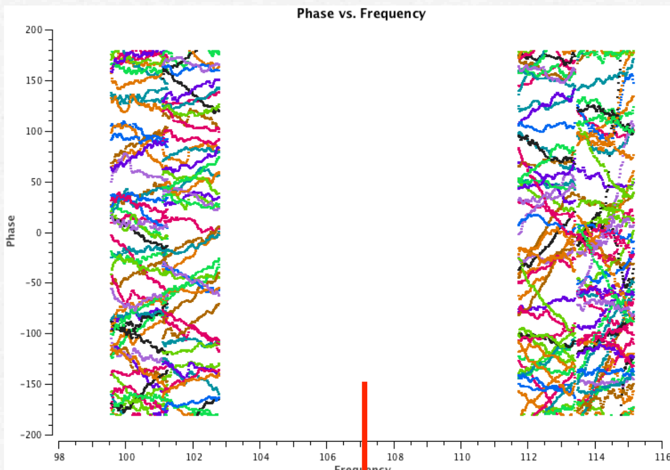
Opacity correction: observe (every 20 minutes or more often) hot load, cold load, sky and determine T_{sys}, T_{rec} and receiver gain

- BPass calibration on a strong qso
- Phase calibration on point-like qso
- Real-time phase correction
- Flux calibration

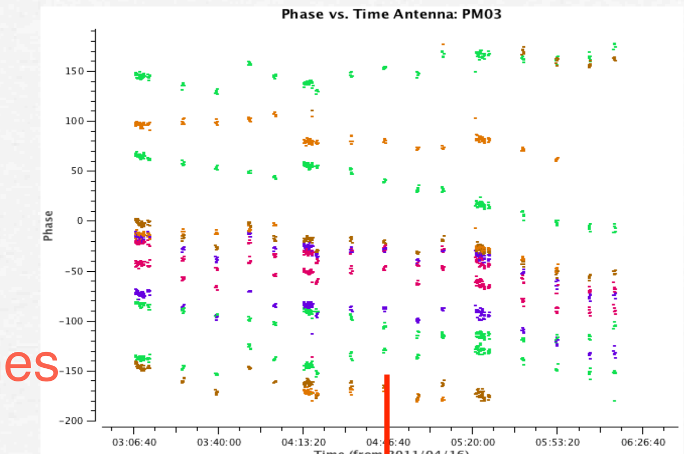


Data Reduction (Calibration): why so important?

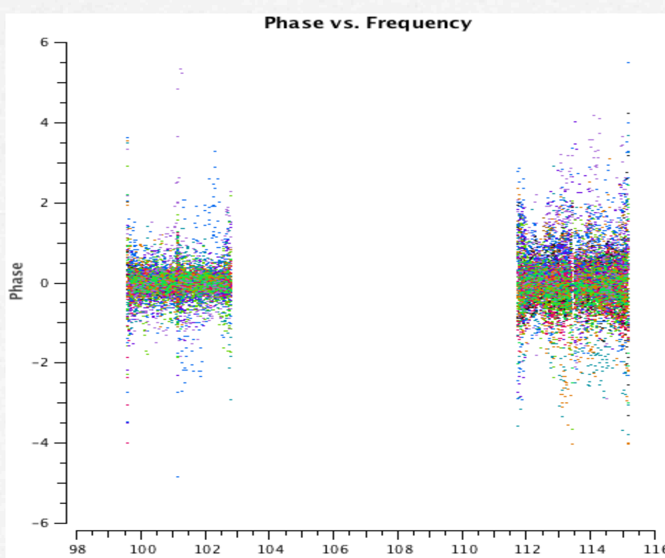
Frequency dependent

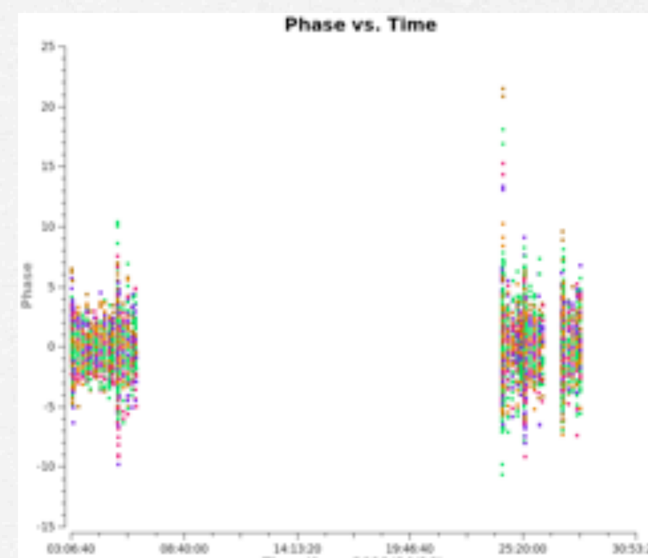


different colors,
different baselines

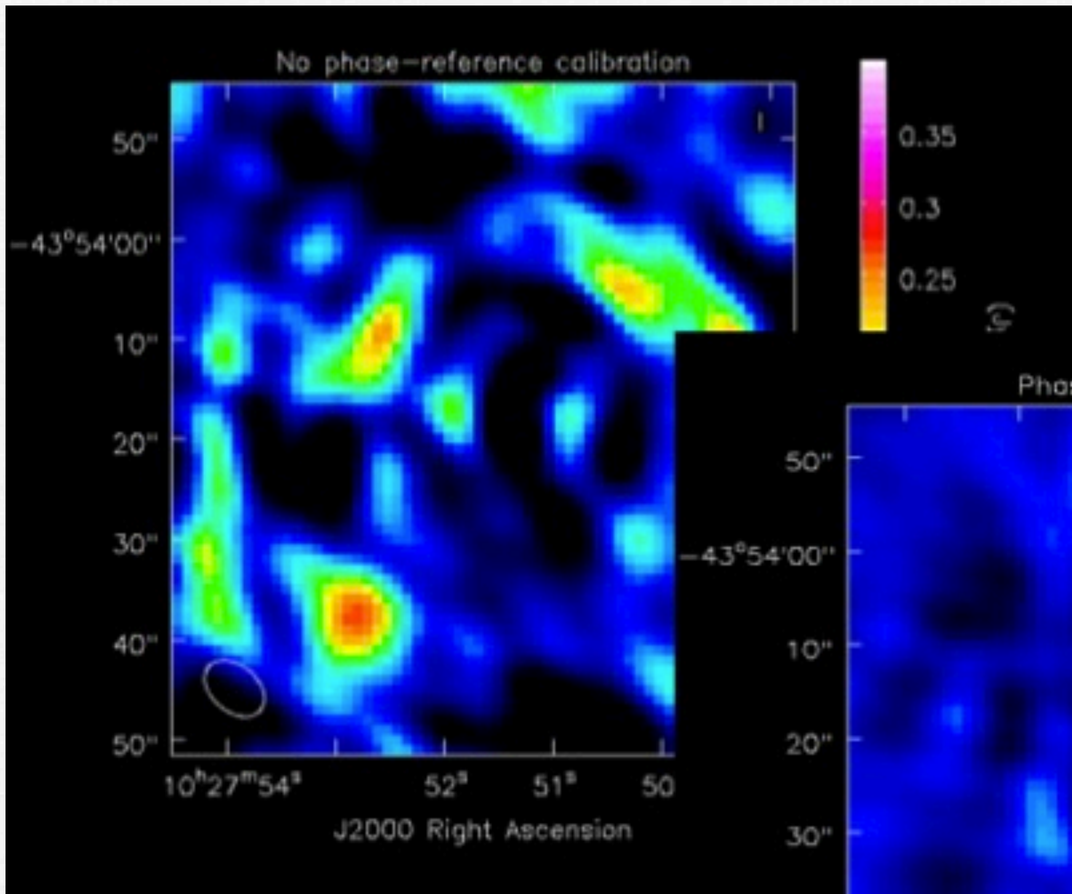


Time dependent

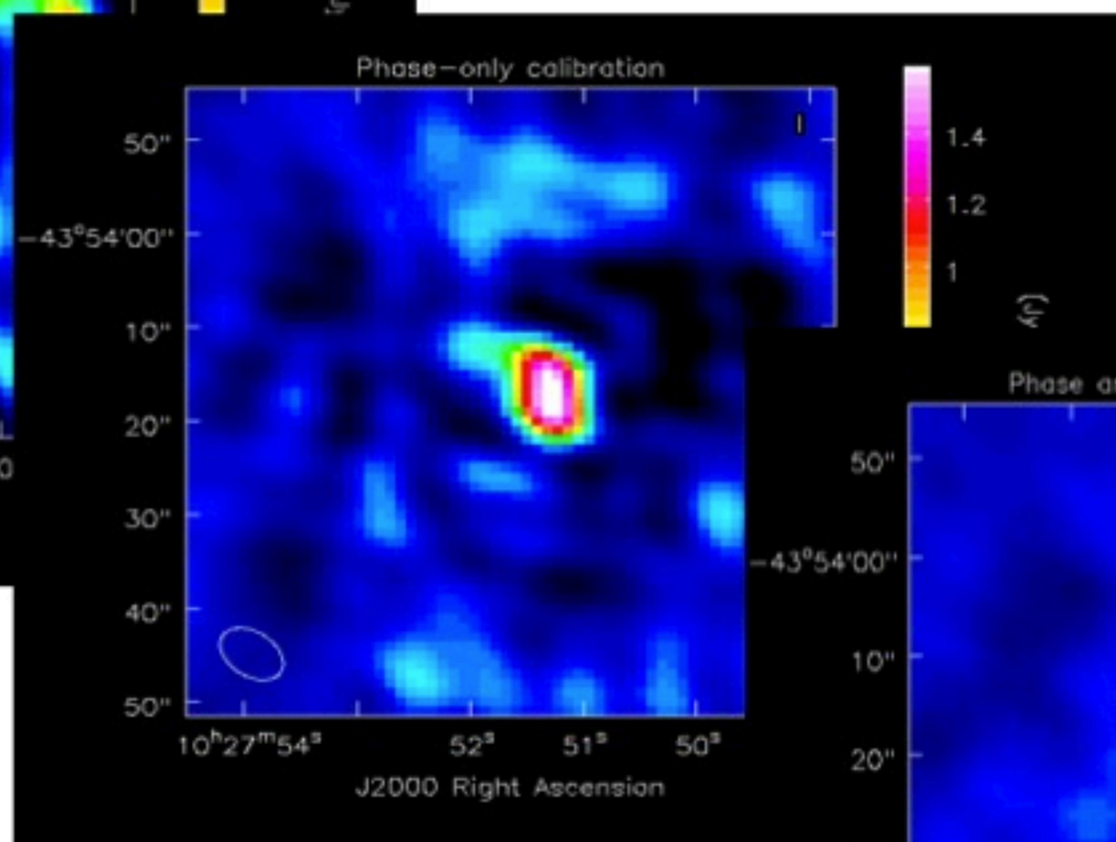




Data Reduction (Calibration): why so important?

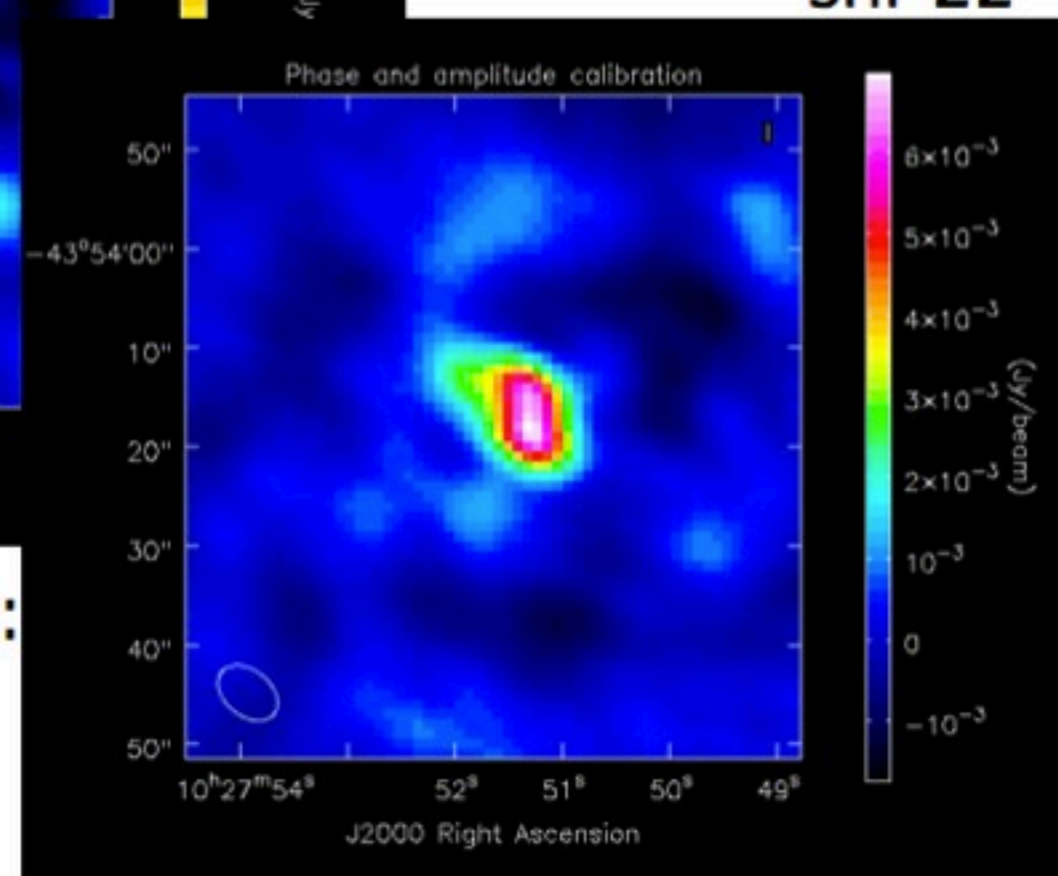


No astrophysical calibration:
no source seen



Phase-only solutions:
source seen, snr 15
flux scale arbitrary

Amplitude and
phase solutions:
image improved,
snr 22

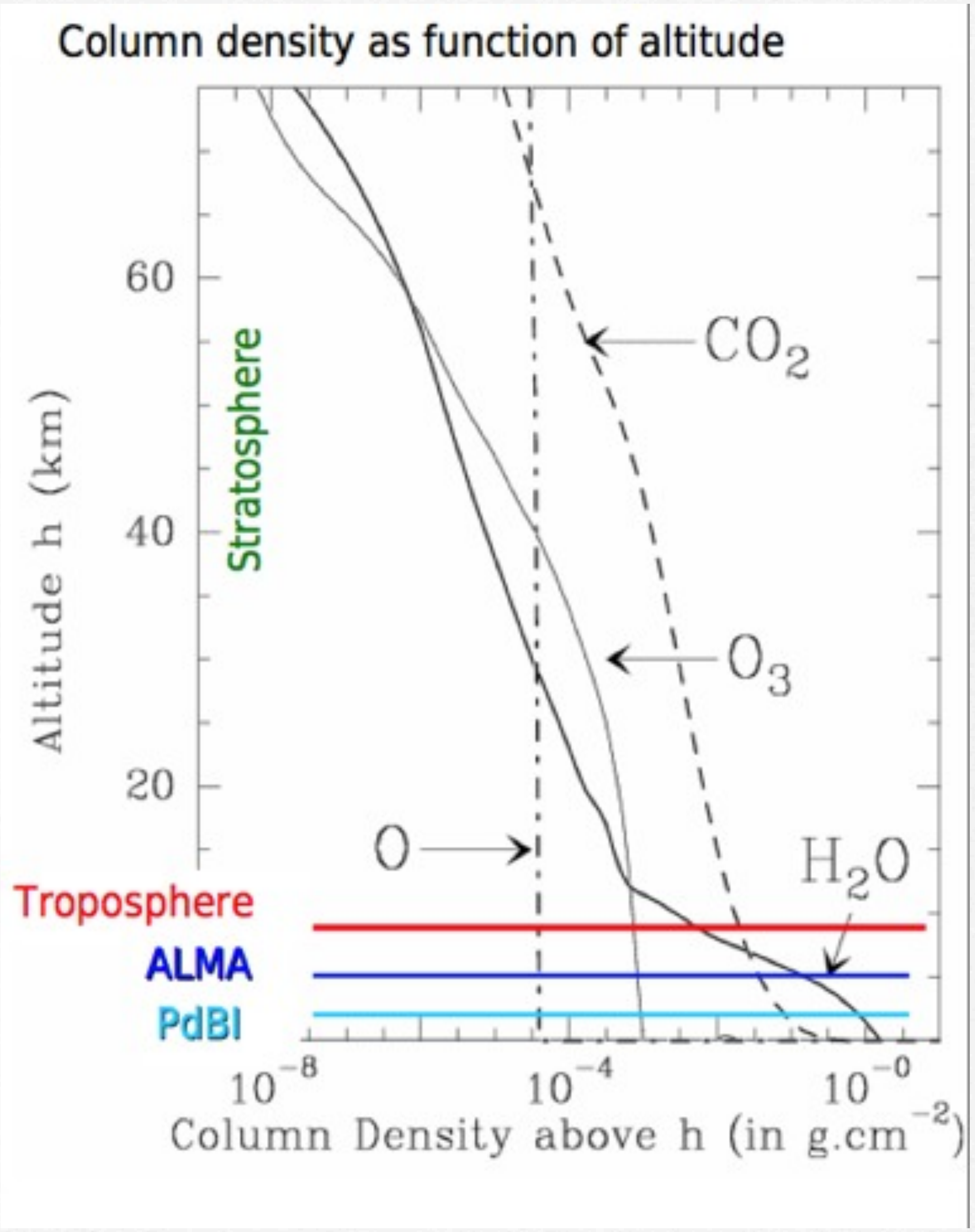


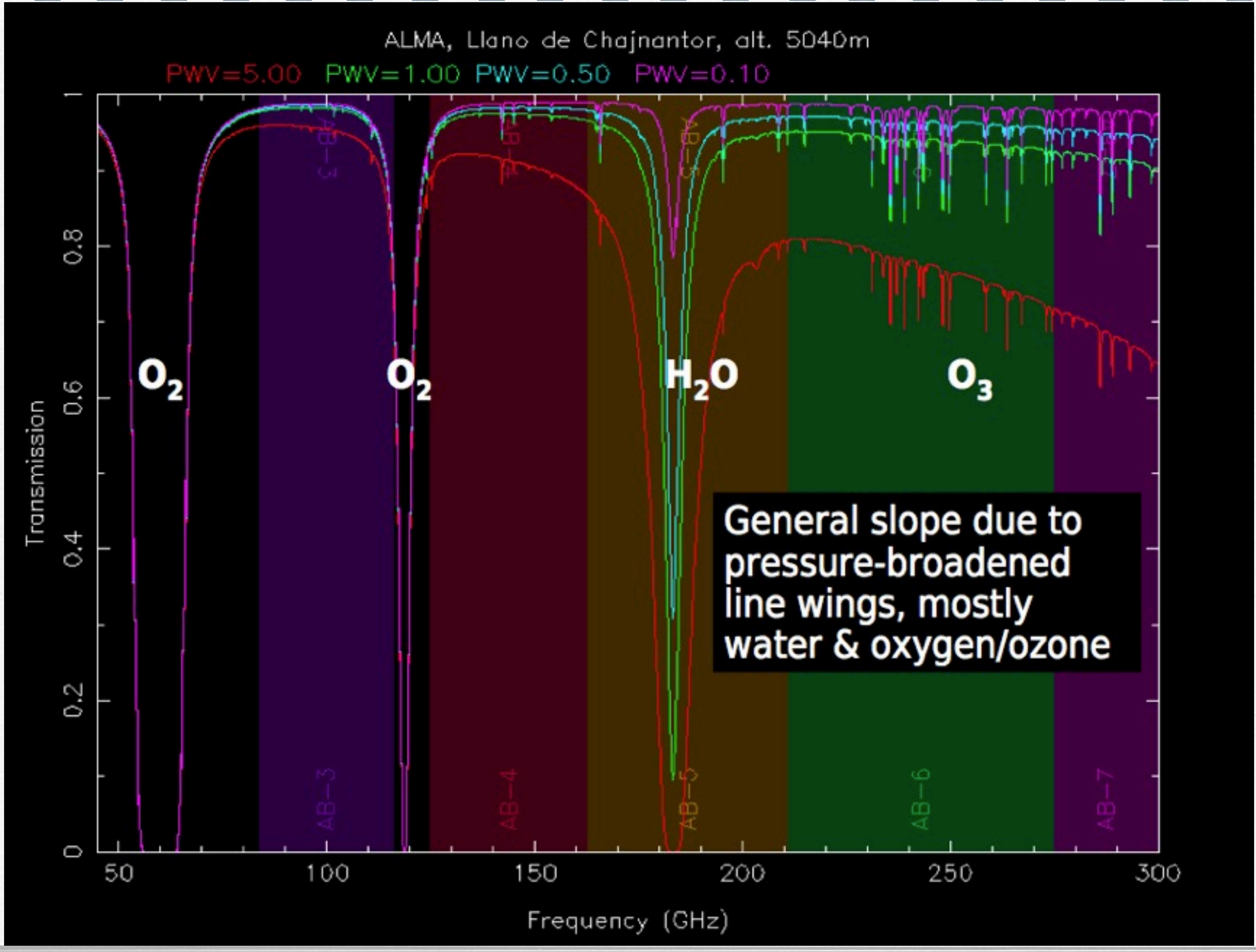
The impact of atmosphere

- 'Dry' component:
  - Worst O_2, O_3

- 'Wet' component:
  - H_2O vapour/clouds
  - Highly turbulent layer
    - Measure PWV = precipitable water vapour

- Atmospheric depth increases at lower elevation



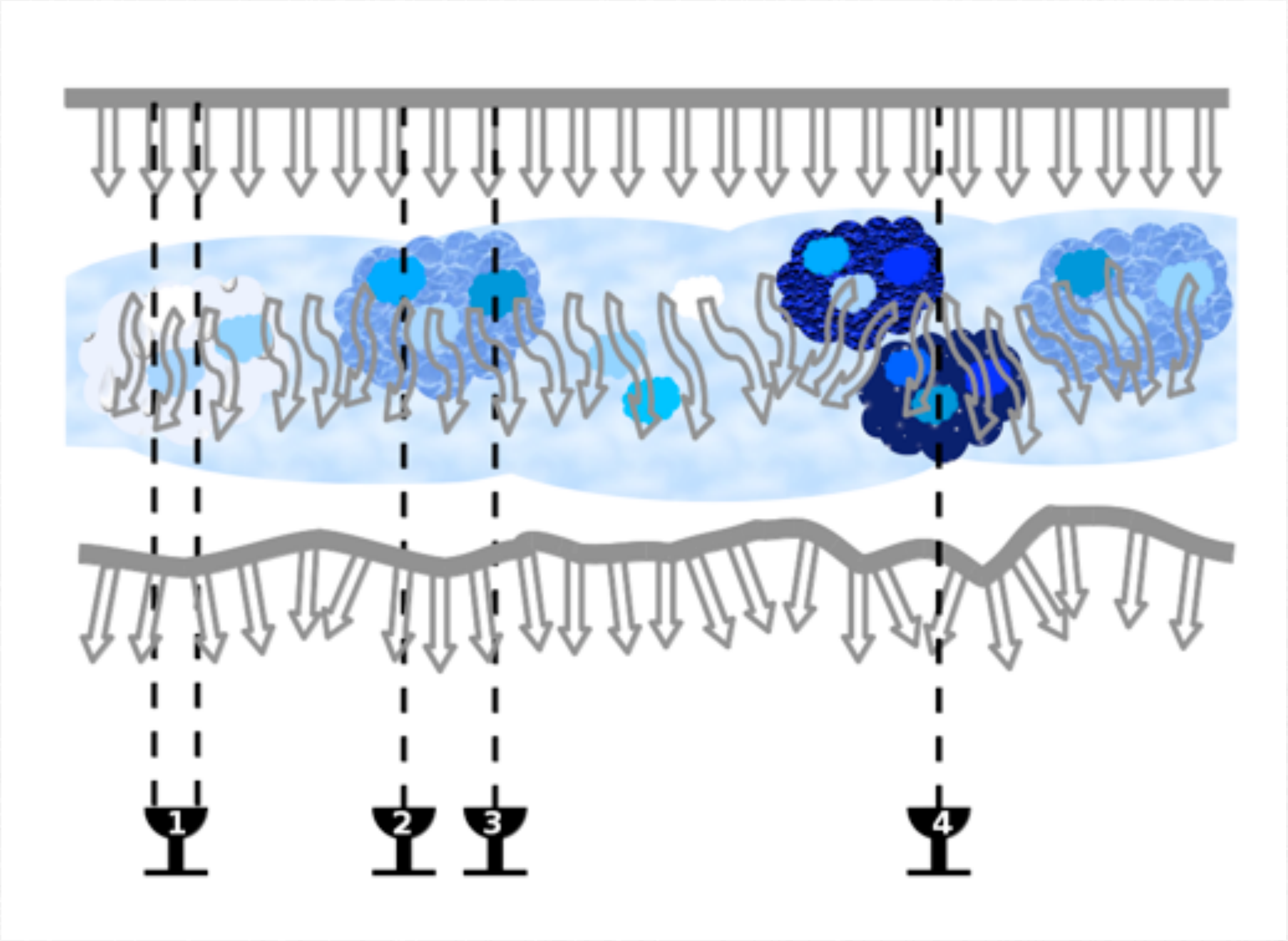


ALMA, Llano de Chajnantor, alt. 5040m
PWV=5.00 PWV=1.00 PWV=0.50 PWV=0.10
Transmission
Frequency (GHz)
AB-3
AB-4
AB-5
AB-6
AB-7
O2
O2
H2O
O3
General slope due to pressure-broadened line wings, mostly water & oxygen/ozone

Troposphere variability scales

Width of turbulent layer, W ~ 800m

Wind
75 km/hr
~ 21 m/s



- Isoplanatic patch > sky area above single mm antenna
- Antennas 1, 2, 3 see slightly different disturbances
- Sky above antenna 4 very different, varies independently

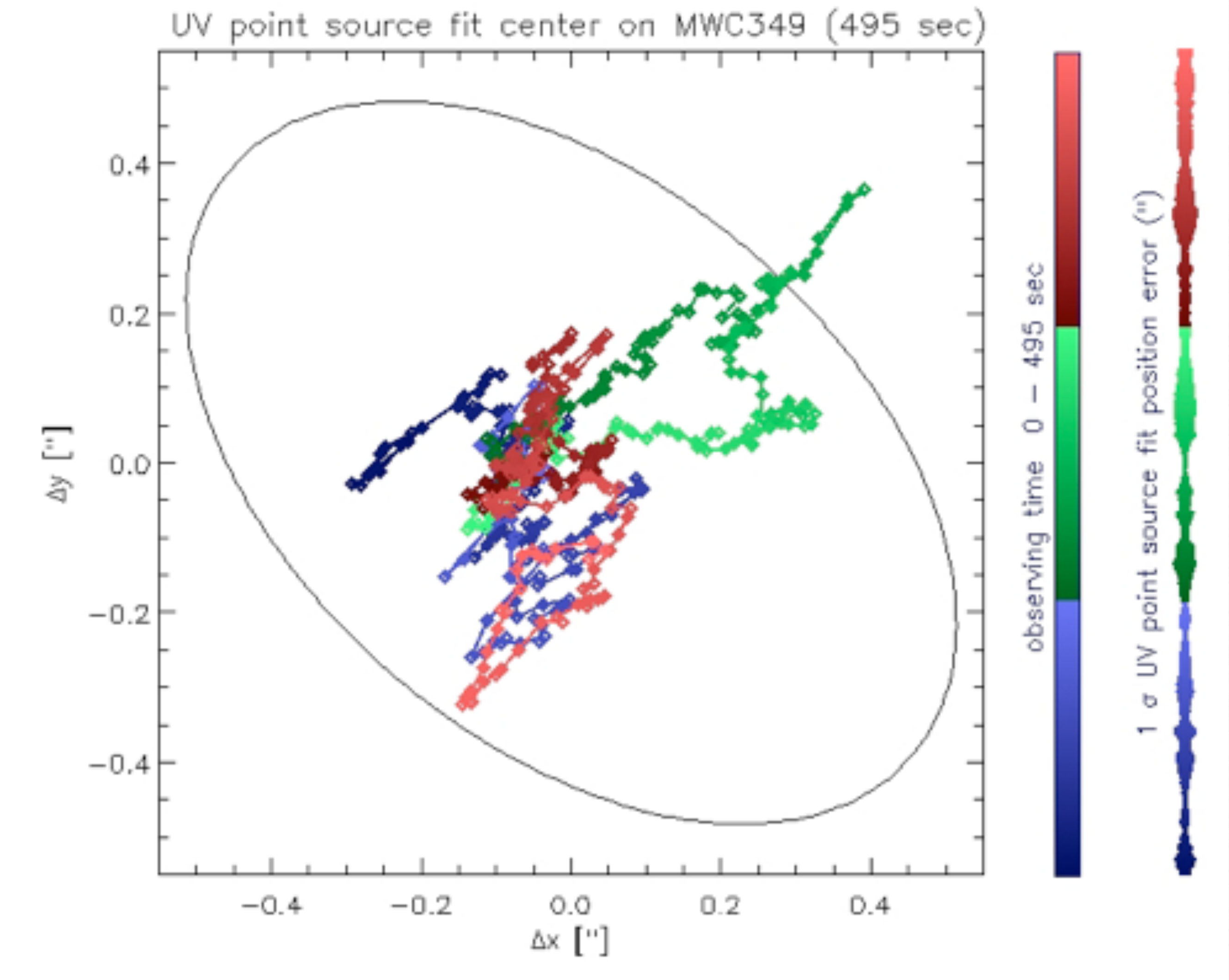
Tropospheric phase noise

Three impacts on observation:

a) source "moves"

why???

$$d\theta = \frac{10^6 \lambda}{\left(1.2 \frac{\lambda}{180/\pi \;\; K}\right)^{(1/\alpha)}} \quad \text{rad}$$



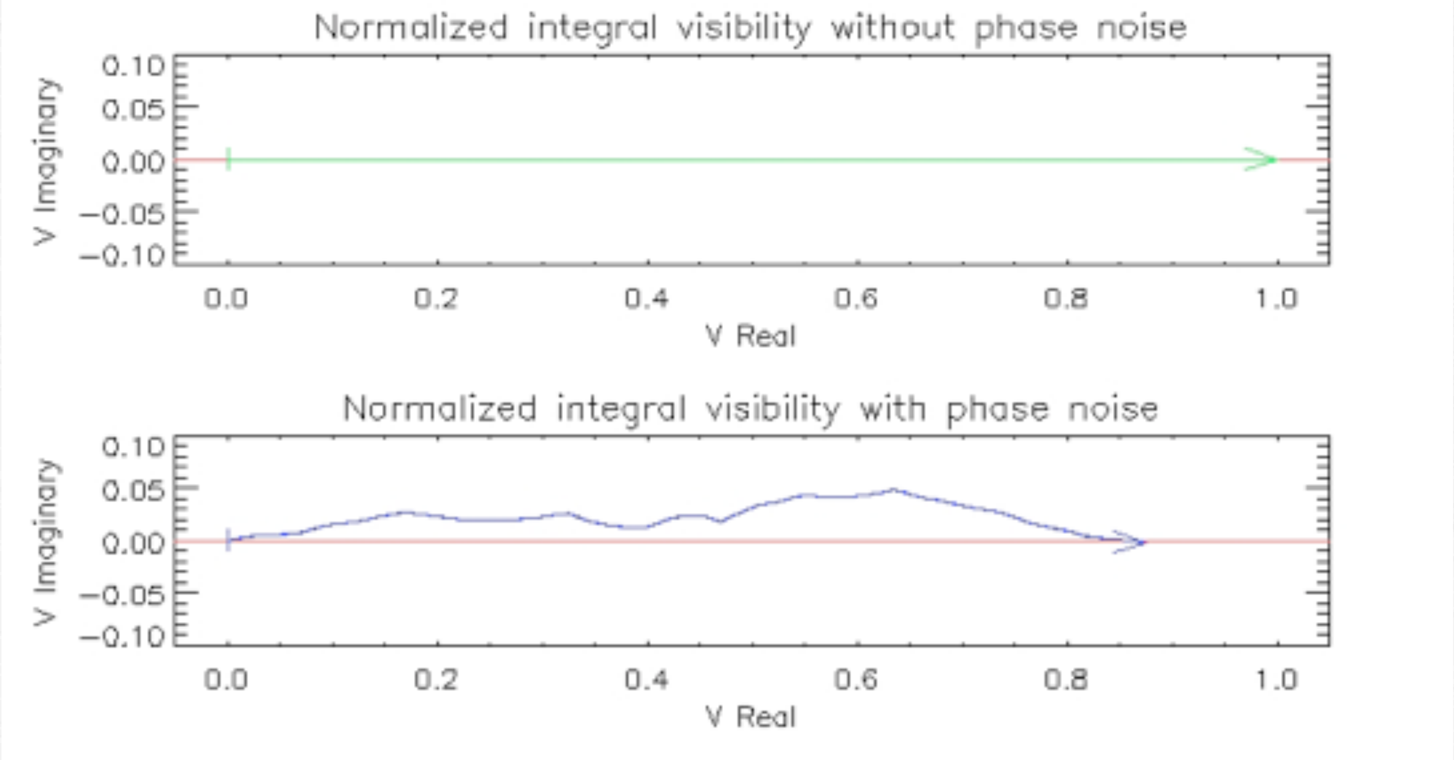
Tropospheric phase noise

b) we loose integrated flux because visibility vectors partly cancel out. Formula:

$$V = V_o e^{i\phi}$$

$$\langle V \rangle = V_o \langle e^{i\varphi} \rangle = V_o e^{-(\varphi_{rms}^2)/2}$$

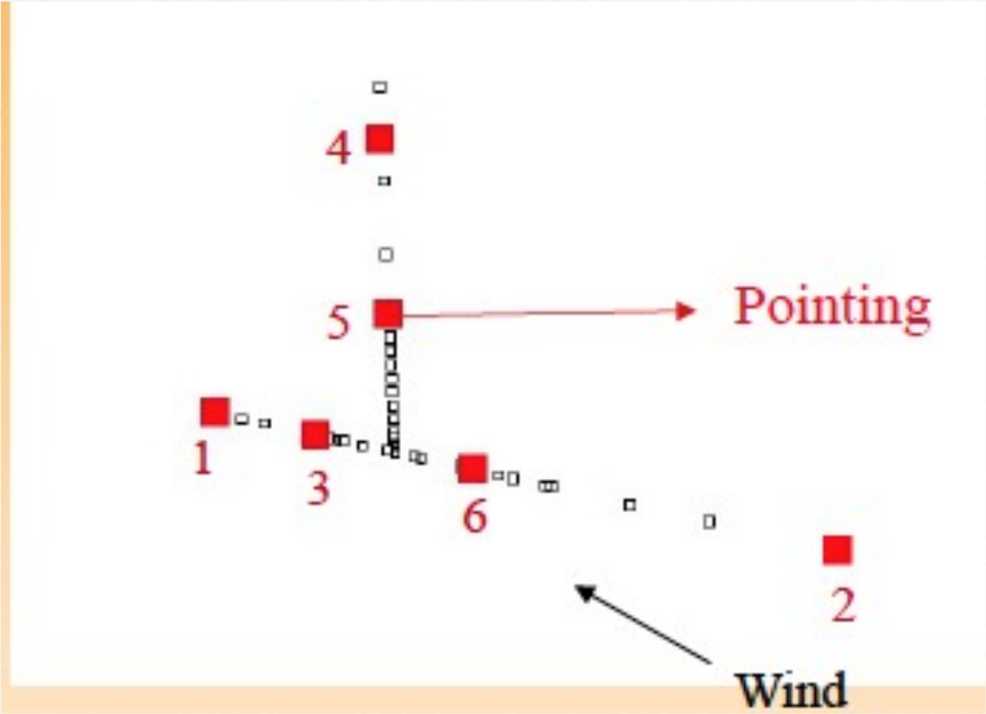
- with phase noise ϕ in radian.

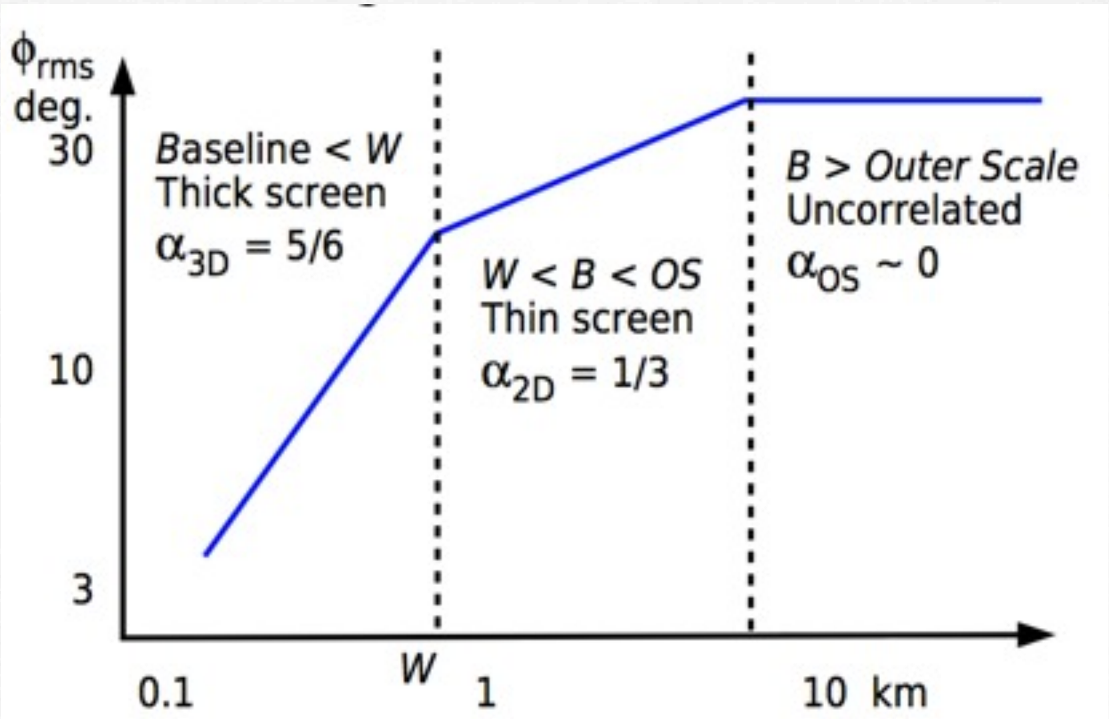


Observations were at 89 GHz and average phase noise 30º: 12.5% loss. If we would have used a frequency 2 or 3 times higher: 42% or 71% loss …

Tropospheric phase noise

c) and we loose more signal on the longest baselines (kolmogorov turbolence).





$$\varphi_{rms} = \frac{K}{\lambda} B^{\alpha}$$

- Atmospheric phase noise is worst on the longest baselines. (Coulman '90)
  - k=100 at ALMA for λ in mm

- The power-law break is weather dependent, and can be at several km.

Tropospheric phase noise

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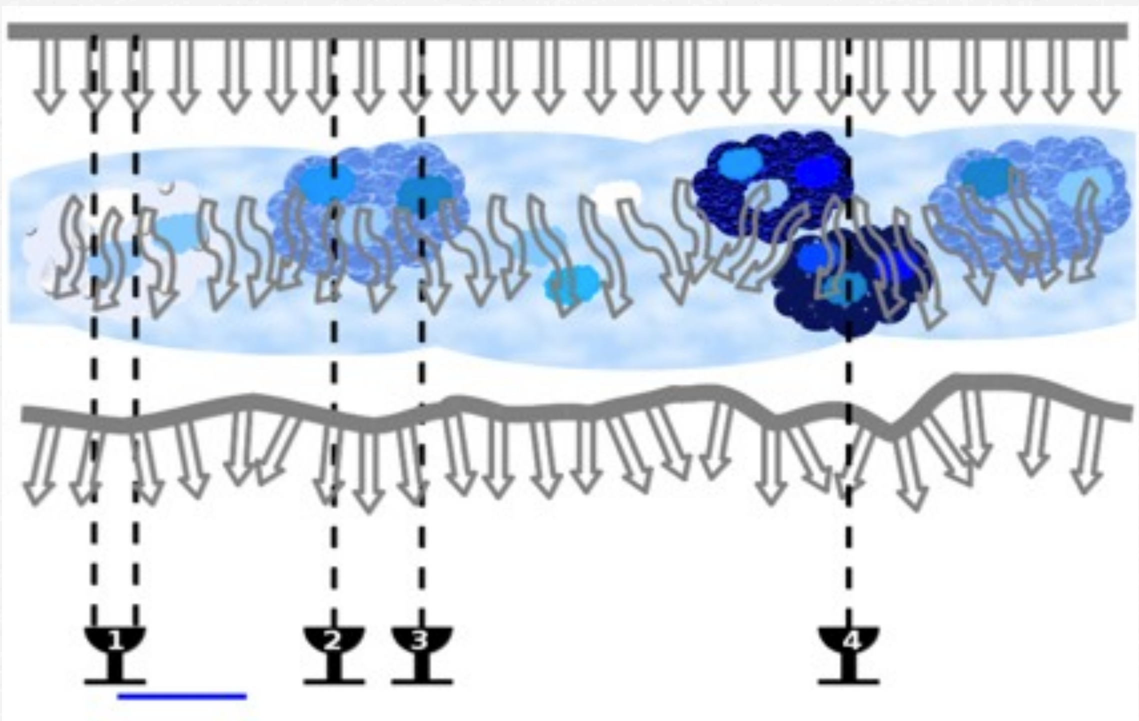

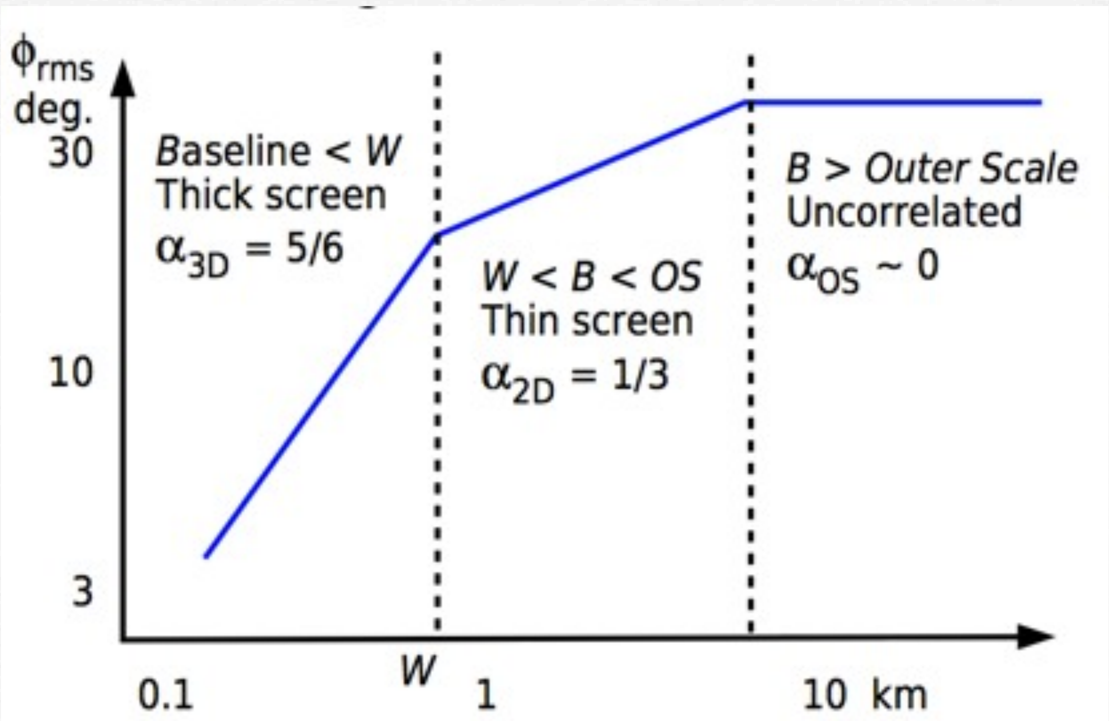

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  - Antennas 1, 2, 3 see slightly different disturbances

- The power-law break is weather dependent, and can be at several km.

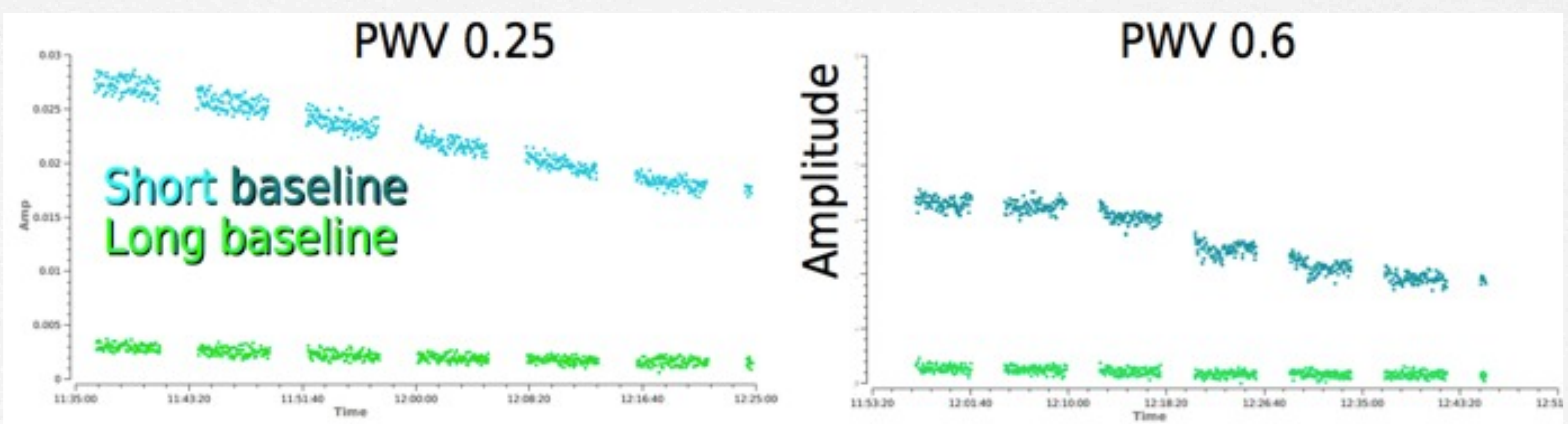
Absorption and Emission

- The atmosphere both absorbs the astrophysical signal, and adds noise

$$T_{received} = T_{source} e^{\tau_{atm}/\cos z} + T_{atm}\left(1 - e^{\tau_{atm}/\cos z}\right)$$

where the source would provide temperature *T* if measured above the atmosphere and z is the zenith distance

- Same source, same baselines. Raw amplitudes significantly lower at higher PWV



Water Vapour Radiomettry

- Each ALMA 12-m has water vapour radiometer (@183GHz~1 sec integrations)
- ALMA scales (and "will apply in real time") phase correction per band:

$$\Phi_e \propto (2\pi/\lambda)\ \mathrm{PWV}$$

- PdBI measures PWV at 22 GHz

.

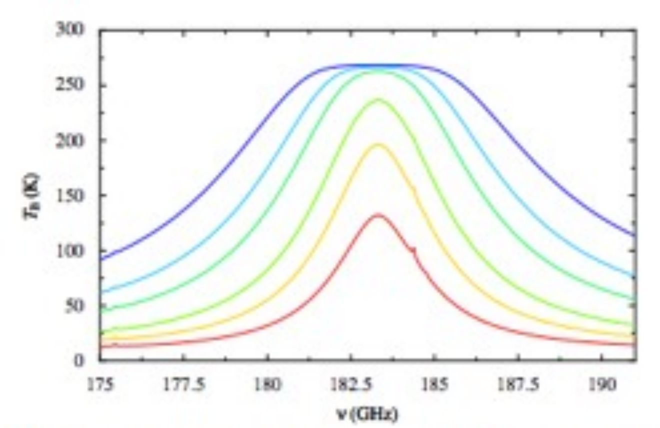
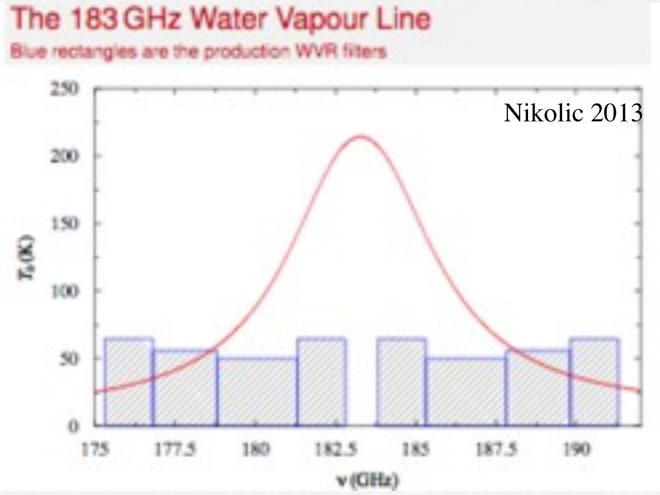
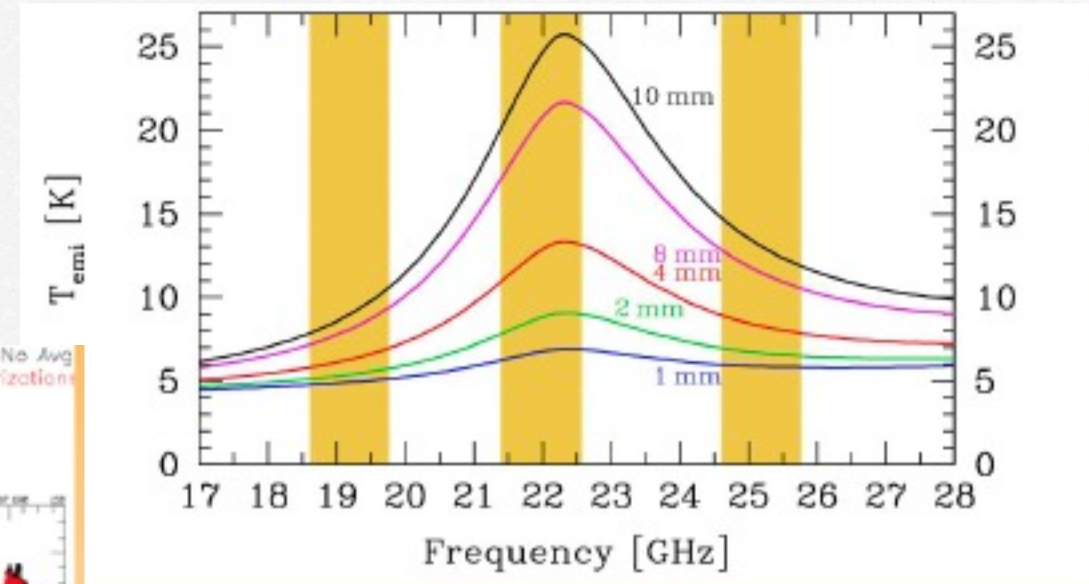
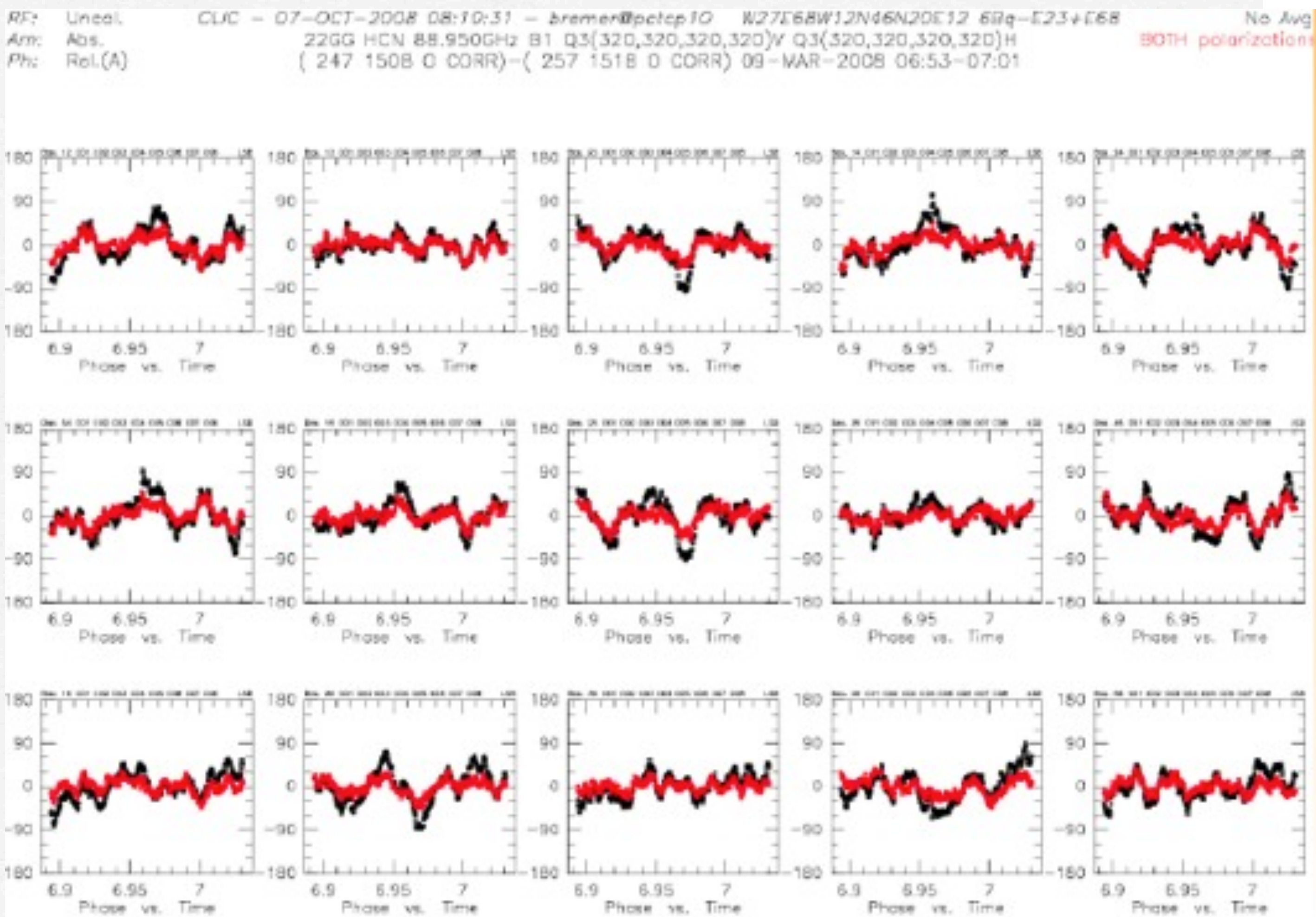


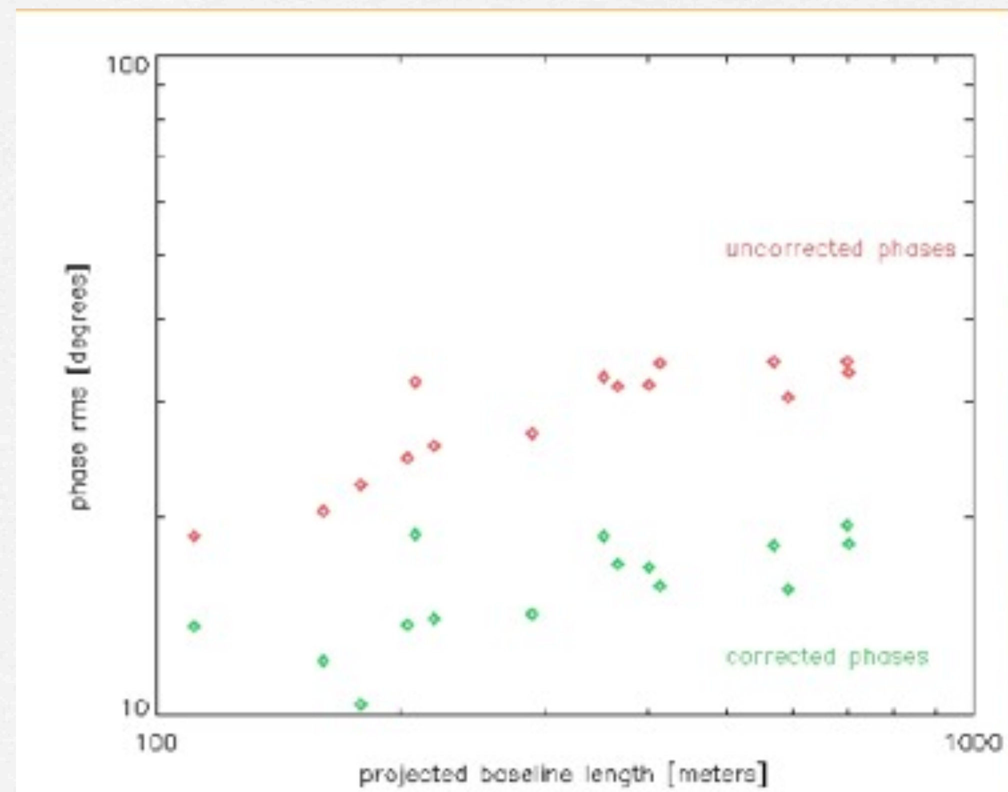
Fig. 2. Model brightness of the atmosphere at frequencies around the 183 GHz water vapour line for six values of PWV along the line of sight: 0.3, 0.6, 1, 2, 3 and 5 mm (from lowest red line to highest blue line). The model was computed using the ATM program by Pardo et al. (2001), using the source code the model as used by ALMA (this is available for public download at http://www.mrao.cam.ac.uk/~bn204/alma/atmomodel.html).



PdBI 22 GHz radiometer

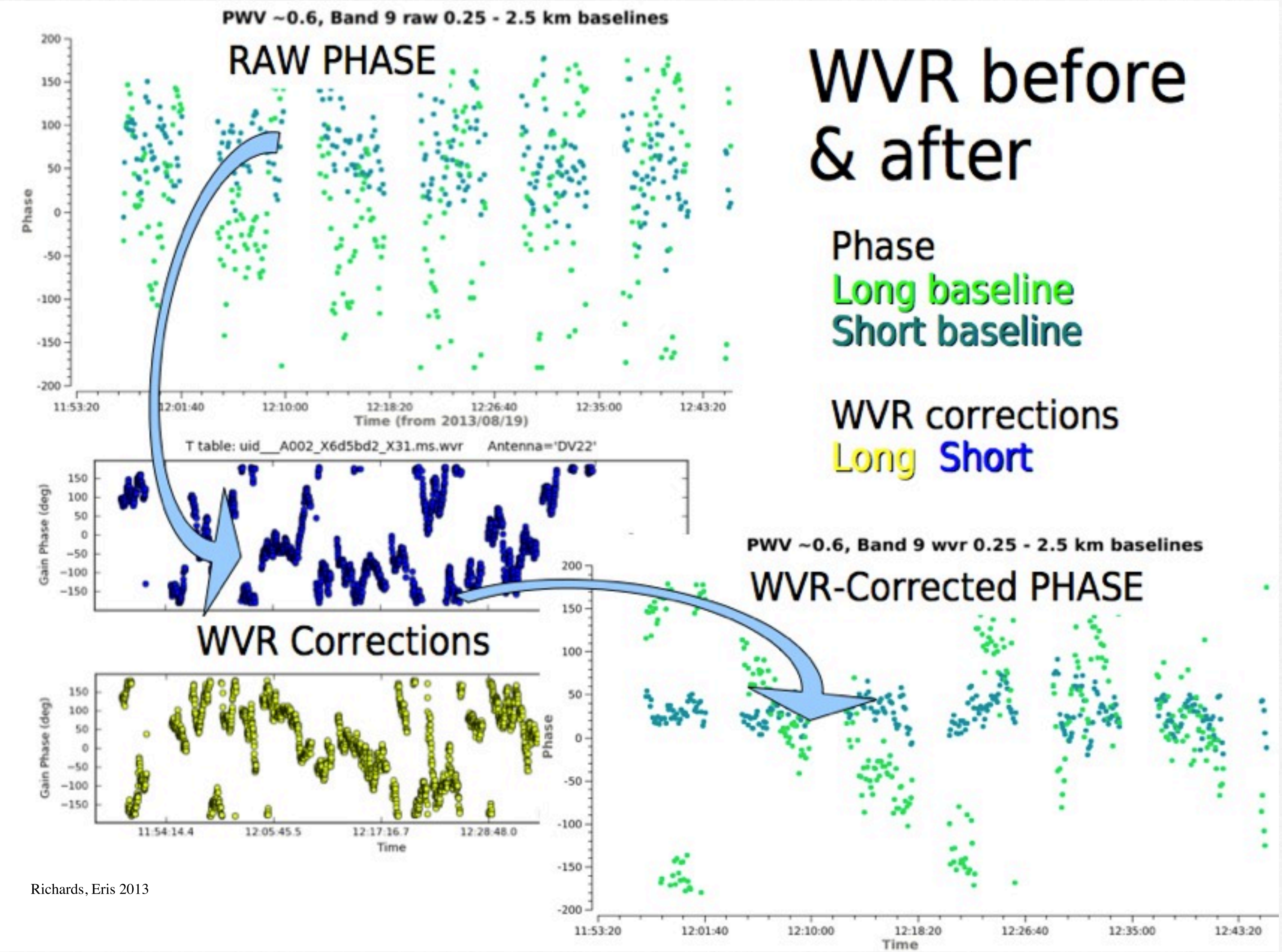






Bremer, Eris 2013

WVR before & after

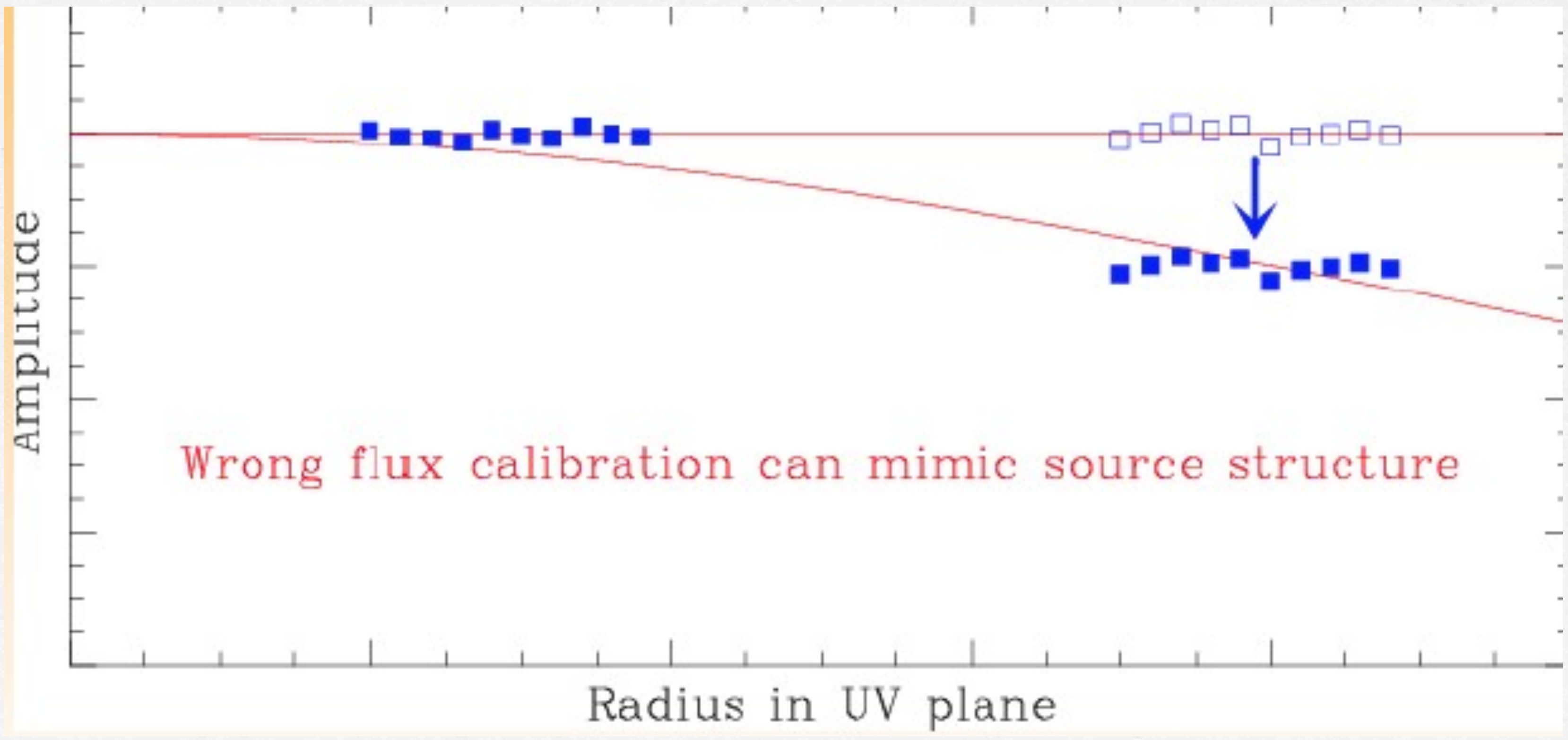


Richards, Eris 2013

Flux Calibration

Very important!!!

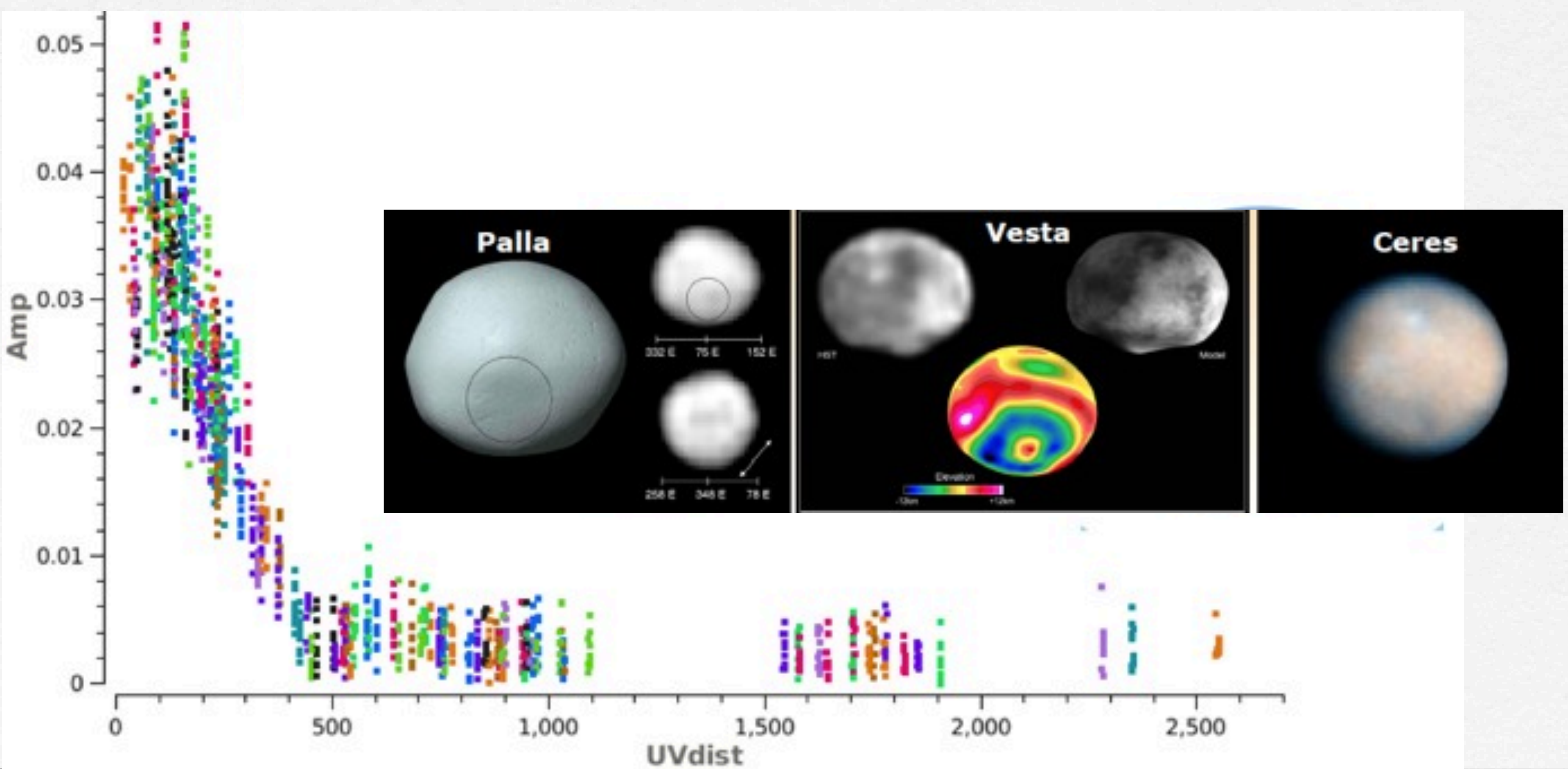
- apply the correct flux-scale
- combine observations at different times and configuration



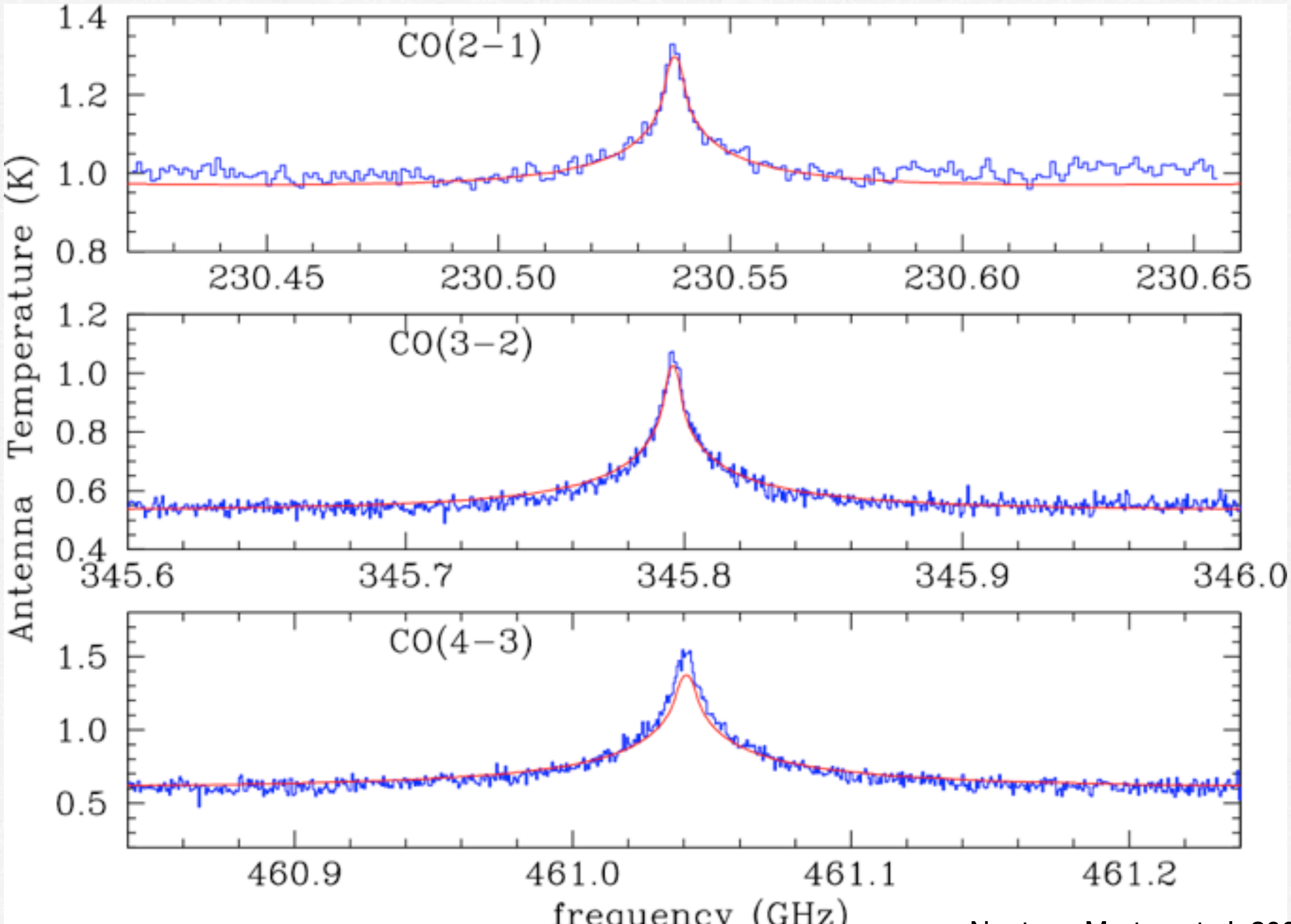
Flux Calibration (Sources)

Flux calibrators: Planets, Moons, Asteroids… BUT!

- already resolved @3mm (planets...), models required!
- Objects Confusions (Moons) --> d>3PB
- Atmospheric Lines

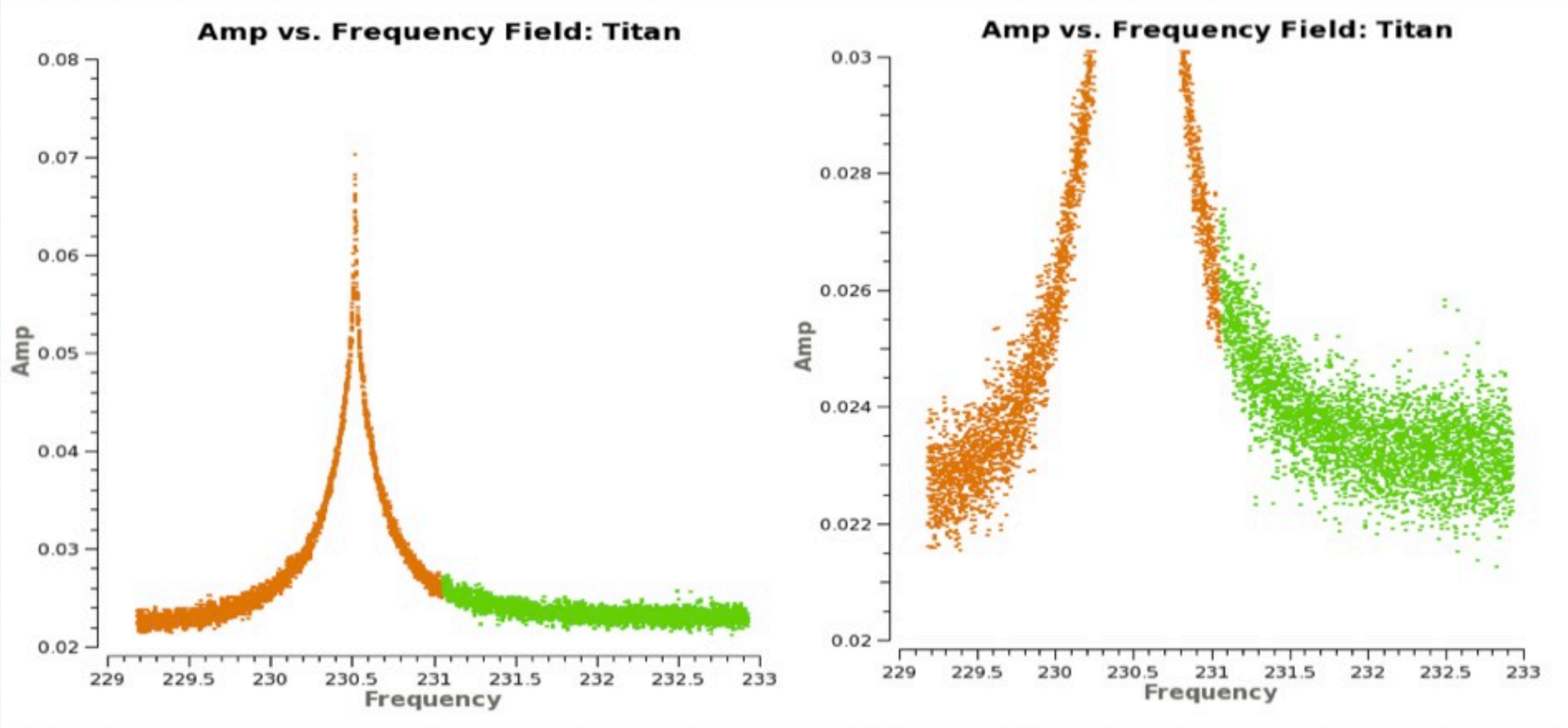


Atmospheric lines in Neptune (model? … work in progress!)

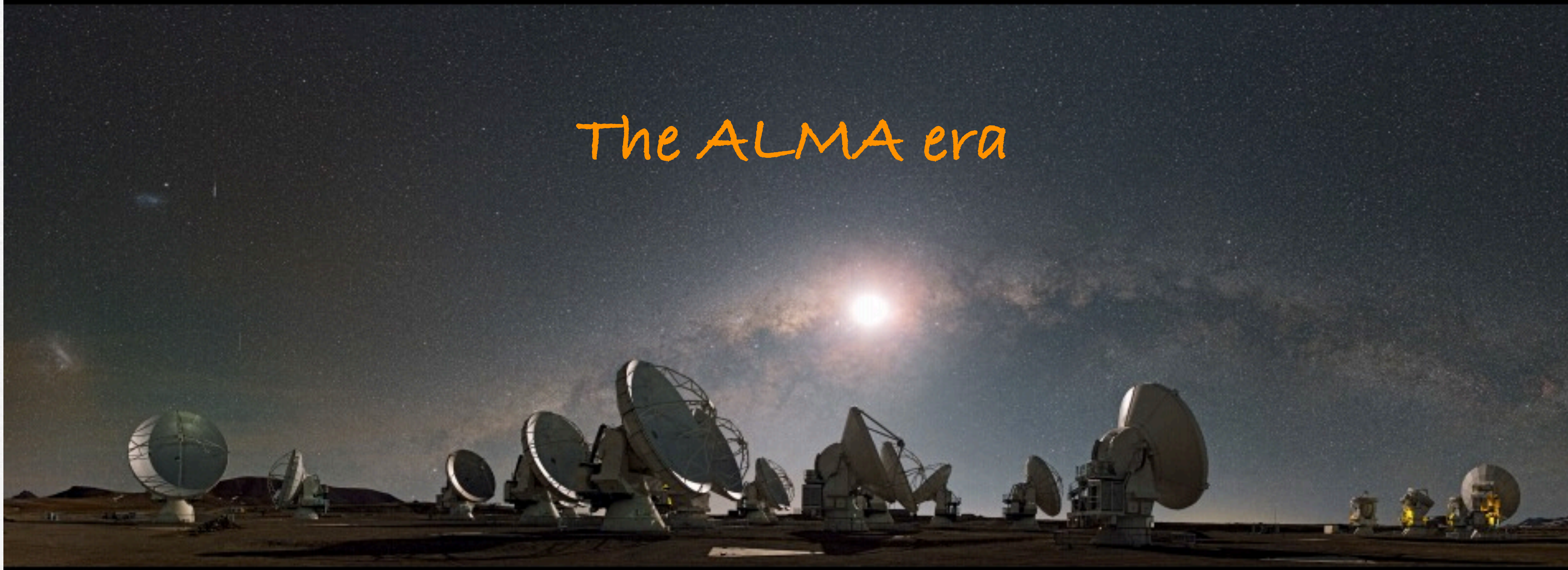


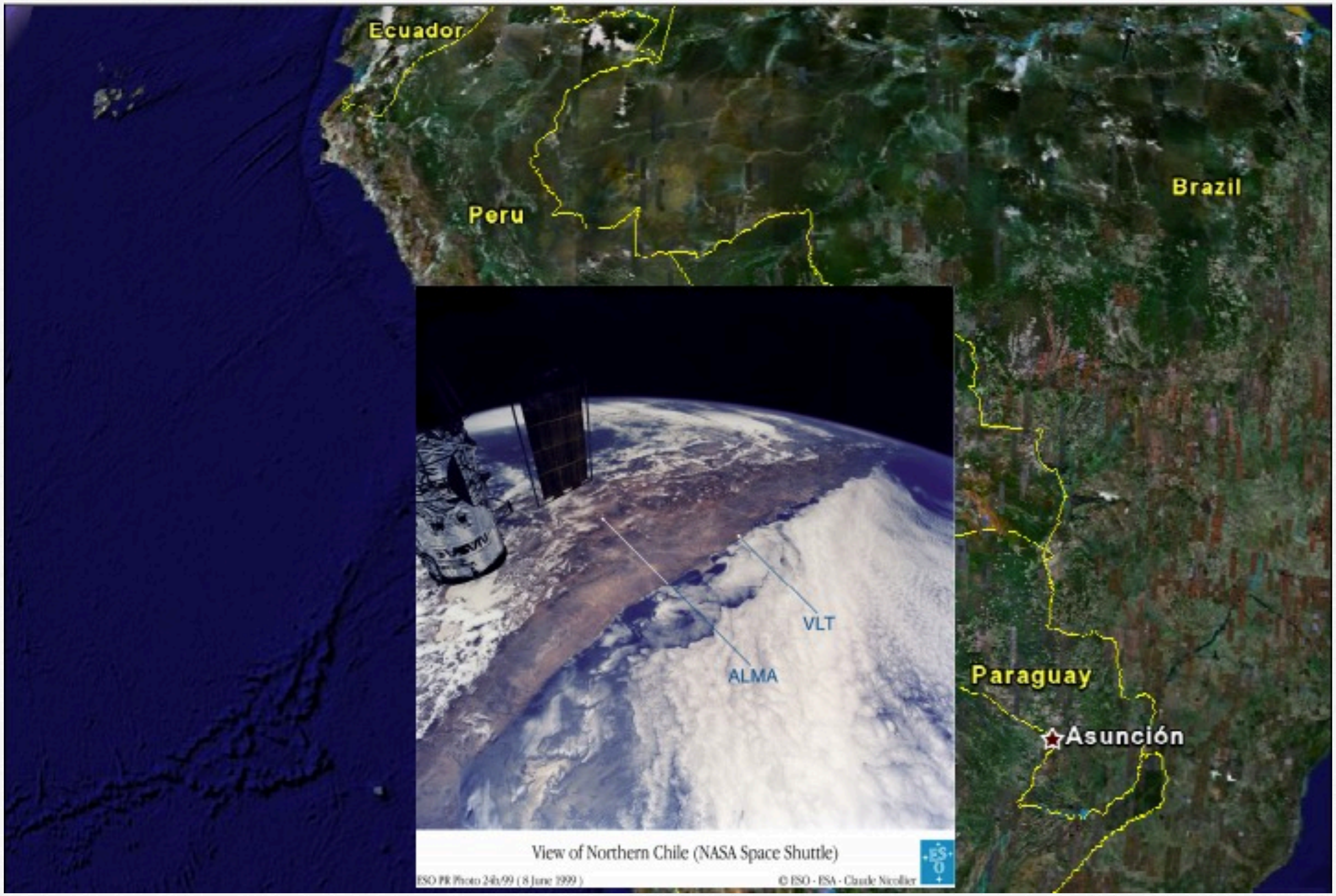
Neptune Marten et al. 2005

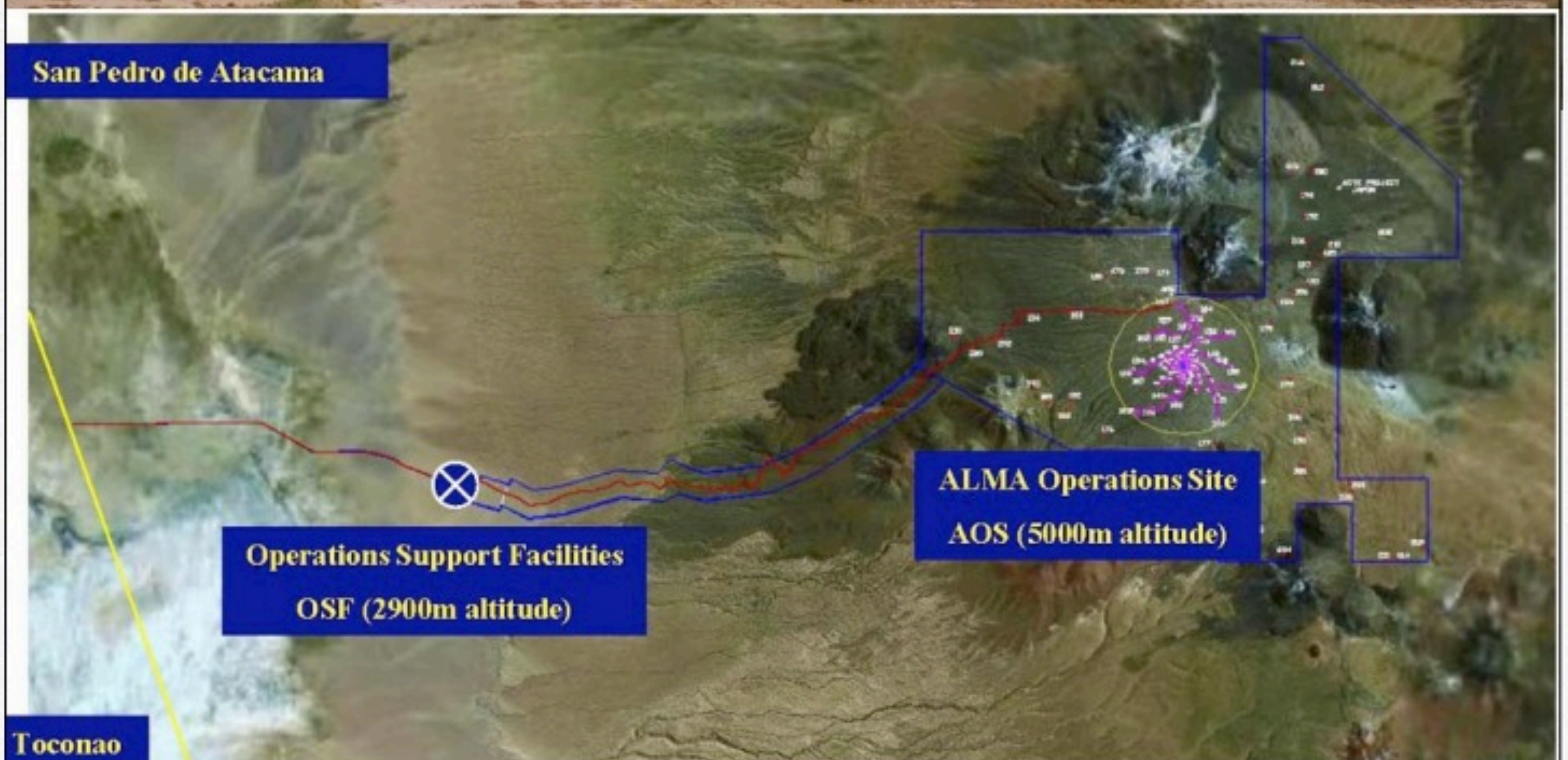
to handle carefully…(the case of Titan)



The ALMA era

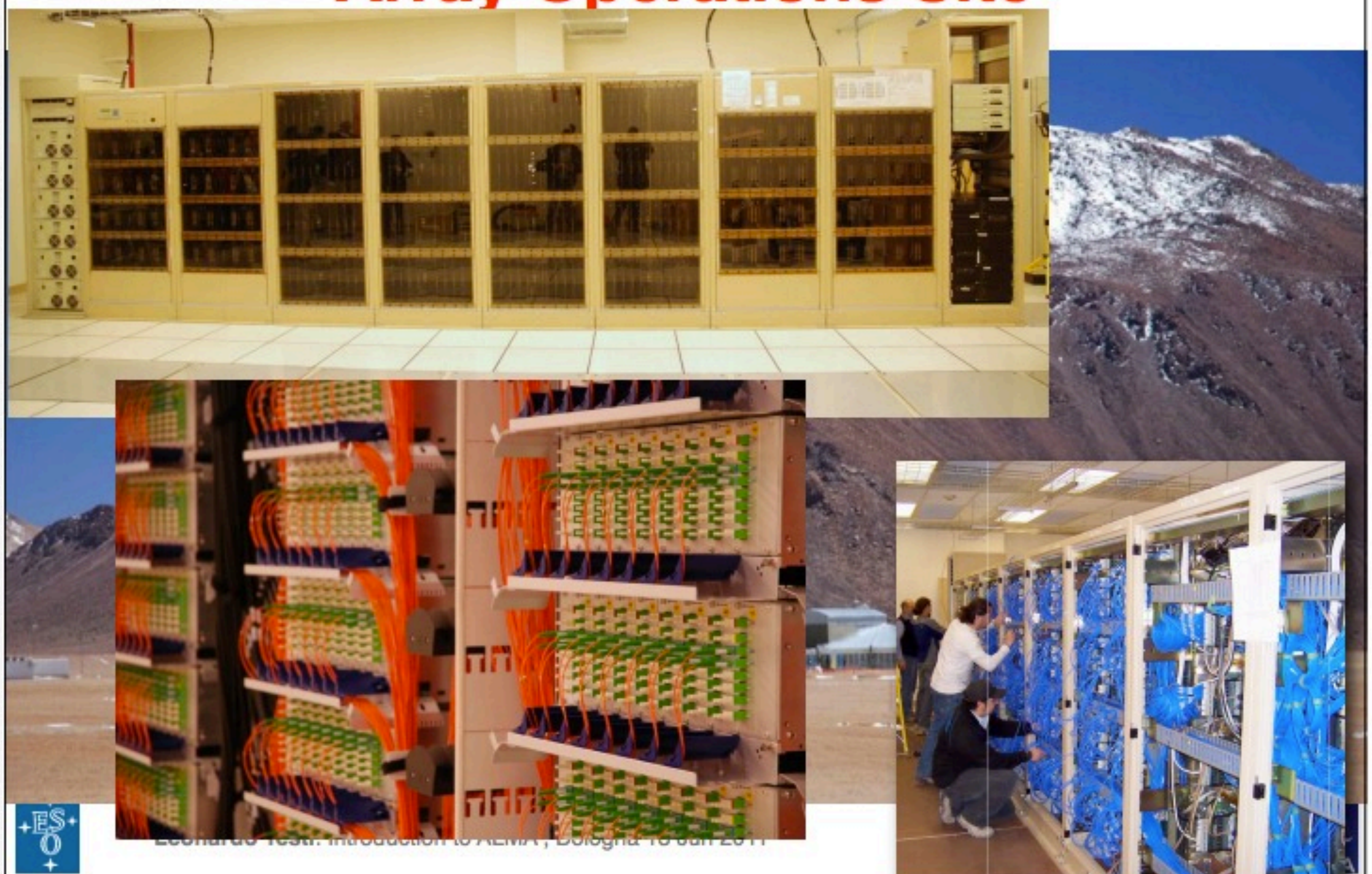



Ecuador
Peru
Brazil
Paraguay
Asunción
VLT
ALMA
View of Northern Chile (NASA Space Shuttle)
ESO PR Photo 24b/99 (8 June 1999)
© ESO - ESA - Claude Nicollier

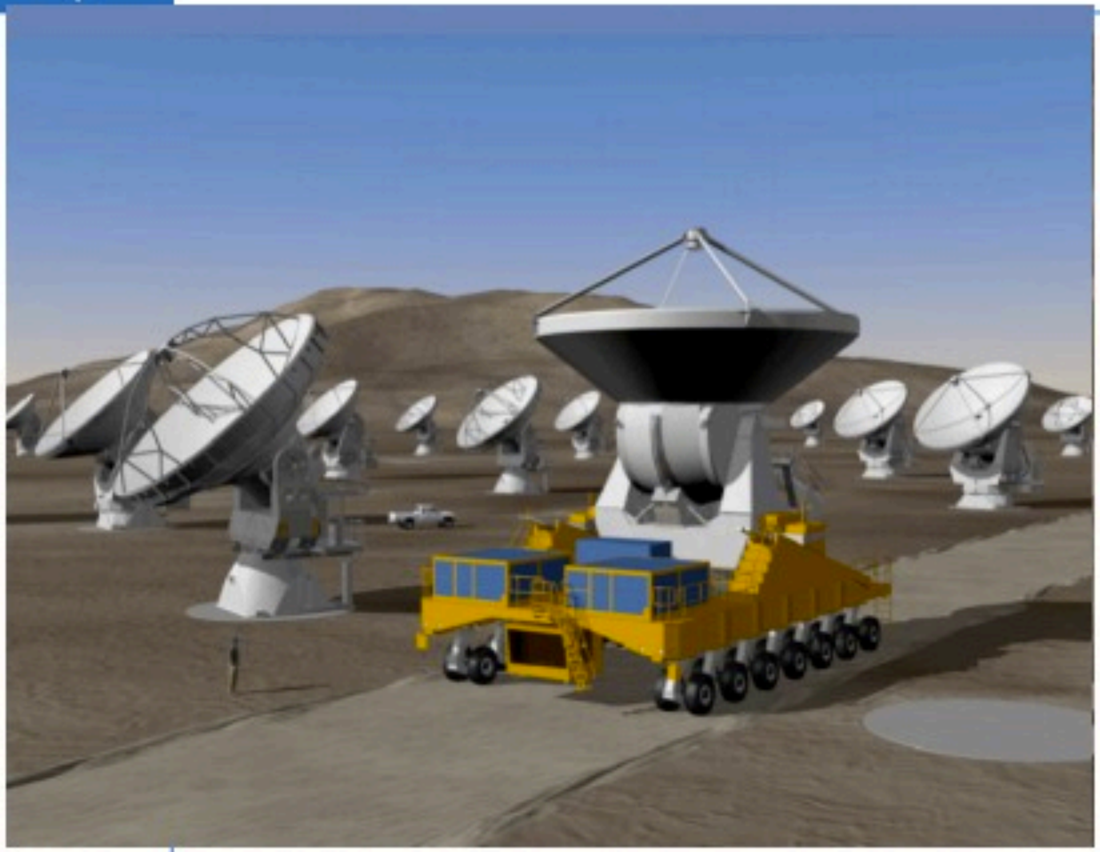

San Pedro de Atacama
Operations Support Facilities
OSF (2900m altitude)
ALMA Operations Site
AOS (5000m altitude)
Toconao

Operations Support Facility - 2900m

Array Operations Site

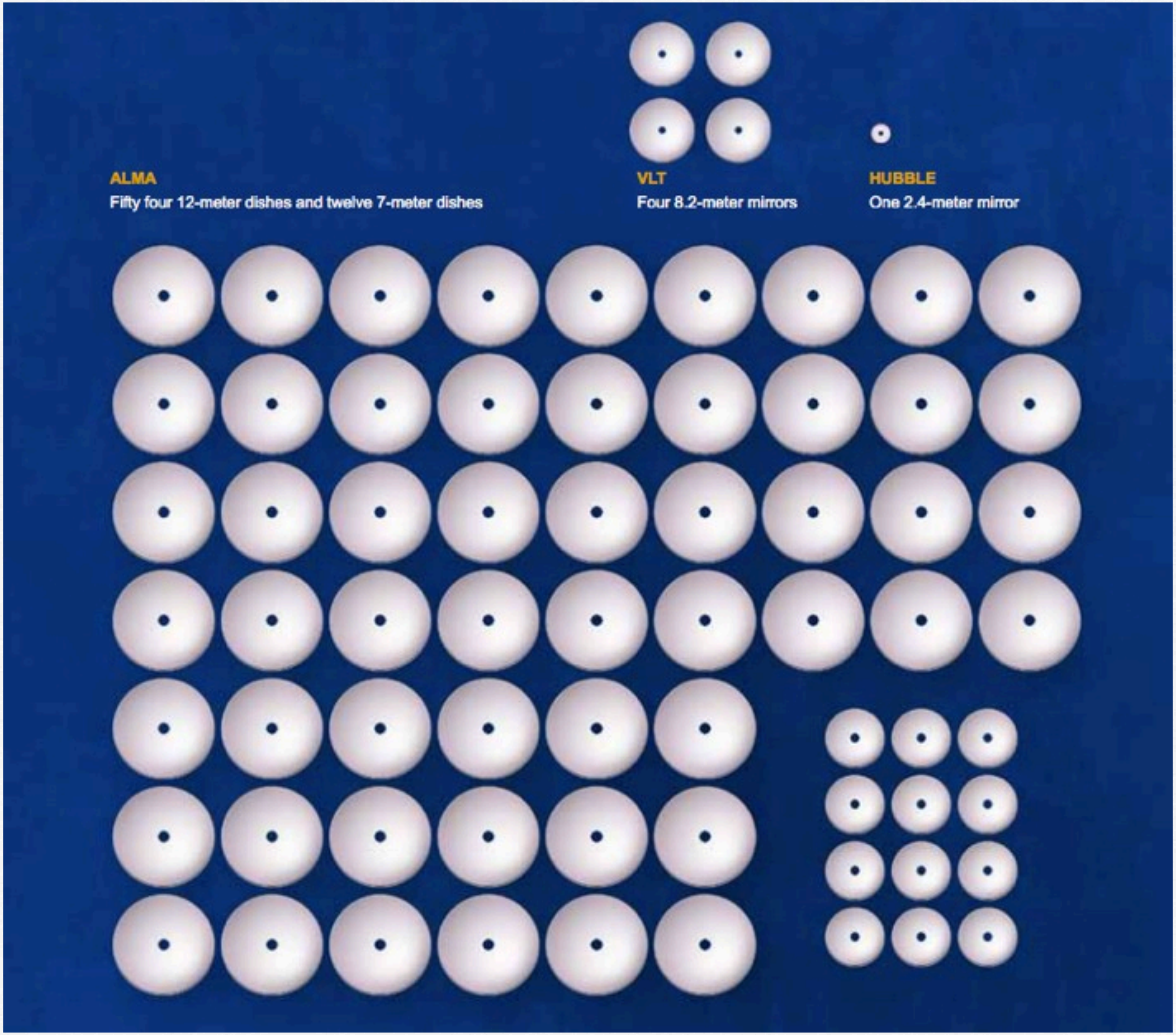


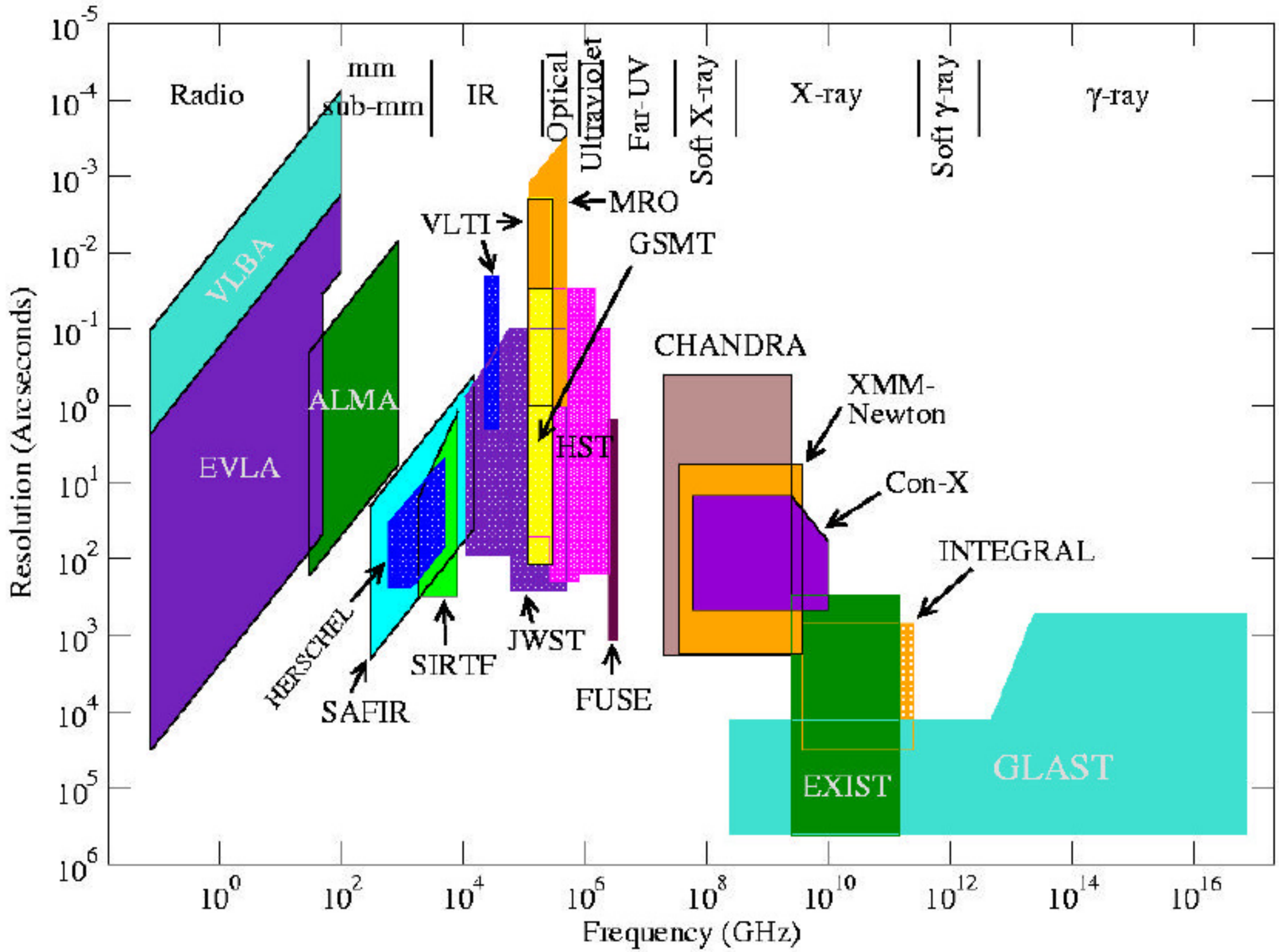
Atacama Large Millimeter Array



- At least 50x12m Antennas
- Frequency range 30-1000 GHz (0.3-10mm)
- 16km max baseline (<10mas)
- ALMA Compact Array (4x12m and 12x7m)

1. Detect and map CO and [C II] in a Milky Way galaxy at z=3 in less than 24 hours of observation
2. Map dust emission and gas kinematics in protoplanetary disks
3. Provide high fidelity imaging in the (sub)millimeter at 0.1 arcsec resolution


ALMA
Fifty four 12-meter dishes and twelve 7-meter dishes
VLT
Four 8.2-meter mirrors
HUBBLE
One 2.4-meter mirror

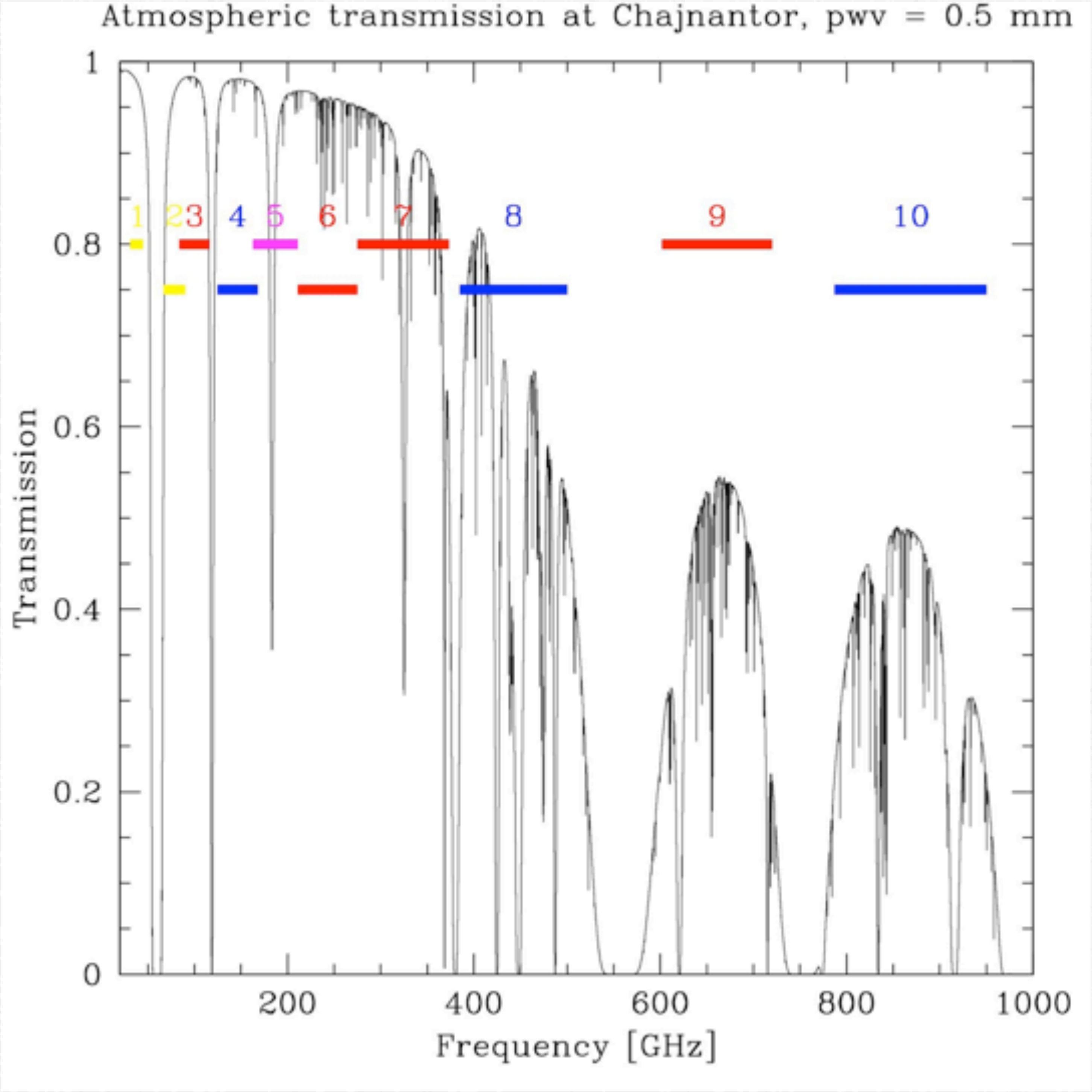


Radio
mm
sub-mm
IR
Optical
Ultraviolet
Far-UV
Soft X-ray
X-ray
Soft γ-ray
γ-ray
VLBA
EVLA
ALMA
VLTI
MRO
GSMT
HST
CHANDRA
XMM-
Newton
Con-X
INTEGRAL
GLAST
EXIST
HERSCHEL
SAFIR
SIRTF
JWST
FUSE
Resolution (Arcseconds)
Frequency (GHz)

Technical Specifications

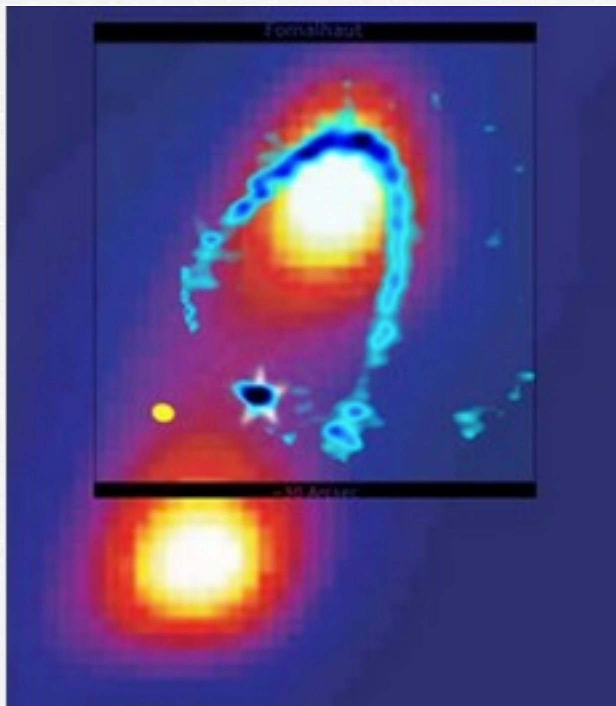
- 54 12-m antennas, 12 7-m antennas, at 5000 m site
- Surface accuracy ±25 μm, 0.6" reference pointing in 9m/s wind, 2" absolute pointing all-sky.
- Array configurations between 150m to ~16km.
- 10 bands in 31-950 GHz + 183 GHz WVR.
- 8 GHz BW, dual polarization.
- Flux sens. 0.2 mJy in 1 min at 345 GHz (median cond.).
- Interferometry, mosaicing & total-power observing.
- Correlator: 4096 channels/IF (multi-IF), full Stokes.
- Data rate: 6MB/s average; peak 60-150 MB/s.
- All data archived (raw + images), pipeline processing.

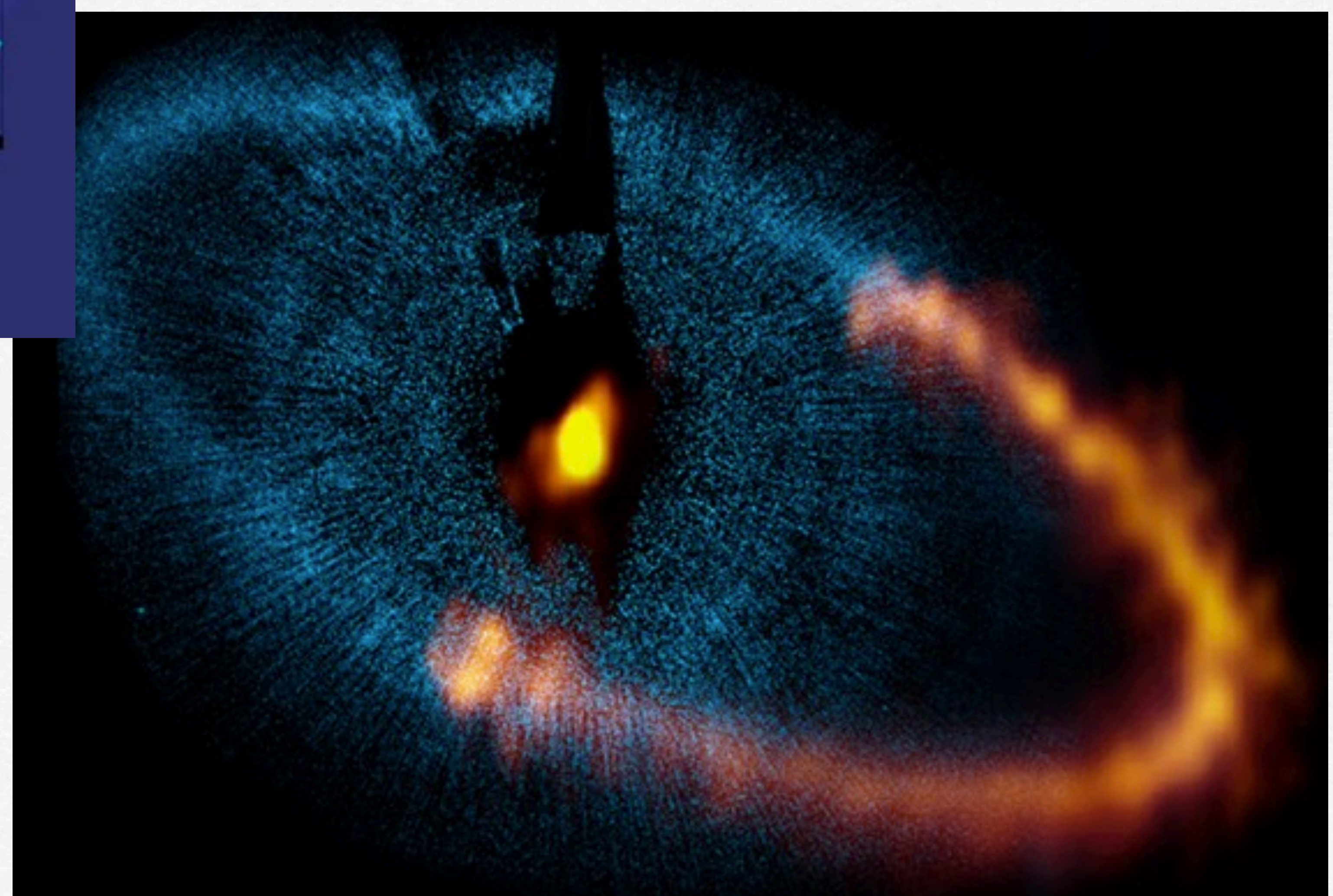
(sub-)mm windows & ALMA bands



Hardware	Specification
Number of Antennas	*At least 50×12 m, plus 12×7 m & 4×12 m total power antennas*
Maximum Baseline Lengths	*0.15 - 16 km*
Angular Resolution (")	*0.2" × (300/ν GHz) × (1 km / max. baseline)*
12m Primary beam (")	*20.3" × (300/ν GHz)*
Number of Baselines	*Up to 2016 (ALMA correlator can handle up to 64 antennas)*
Effective Bandwidth	*16 GHz (2 polarizations × 4 basebands × 2 GHz/baseband)*
Velocity Resolution	*As narrow as 0.008 × (ν/300GHz) km/s*
Polarimetry	*Full Stokes parameters*

High Spatial Resolution: The Fomalhaut Disk





						Compact		Most Extended	
Band	Frequency (GHz)	Wave-length (mm)	Primary Beam (FOV; ")	Ap-prox. Largest Scale (")	Contin-uum Sensi-tivity (mJy/beam)	Angular Resolu-tion (")	ΔT_{line} (K)	Angular Resolution (")	ΔT_{line} (K)
1‡	31.3-45	6.7-9.5	145-135	93	‡	13-9	‡	0.14-0.1	‡
2‡	67-90	3.3-4.5	91-68	53	‡	6-4.5	‡	0.07-0.05	‡
3	84-116	2.6-3.6	72-52	37	0.05	4.9-3.6	0.07	0.05-0.038	482
4	125-163	1.8-2.4	49-37	32	0.06	3.3-2.5	0.071	0.035-0.027	495
5	163-211	1.4-1.8	37-29	23	*	*	*	*	*
6	211-275	1.1-1.4	29-22	18	0.10	2.0-1.5	0.104	0.021-0.016	709
7	275-373	0.8-1.1	22-16	12	0.20	1.5-1.1	0.29	0.016-0.012	1128
8	385-500	0.6-0.8	16-12	9	0.40	1.07-0.82	0.234	0.011-0.009	1569
9	602-720	0.4-0.5	10-8.5	6	0.64	0.68-0.57	0.641	0.007-0.006	4305
10	787-950	0.3-0.4	7.7-6.4	5	1.2	0.52-0.43	0.940	0.006-0.005	—

‡To be developed in the future. *Available on a limited number of antennas

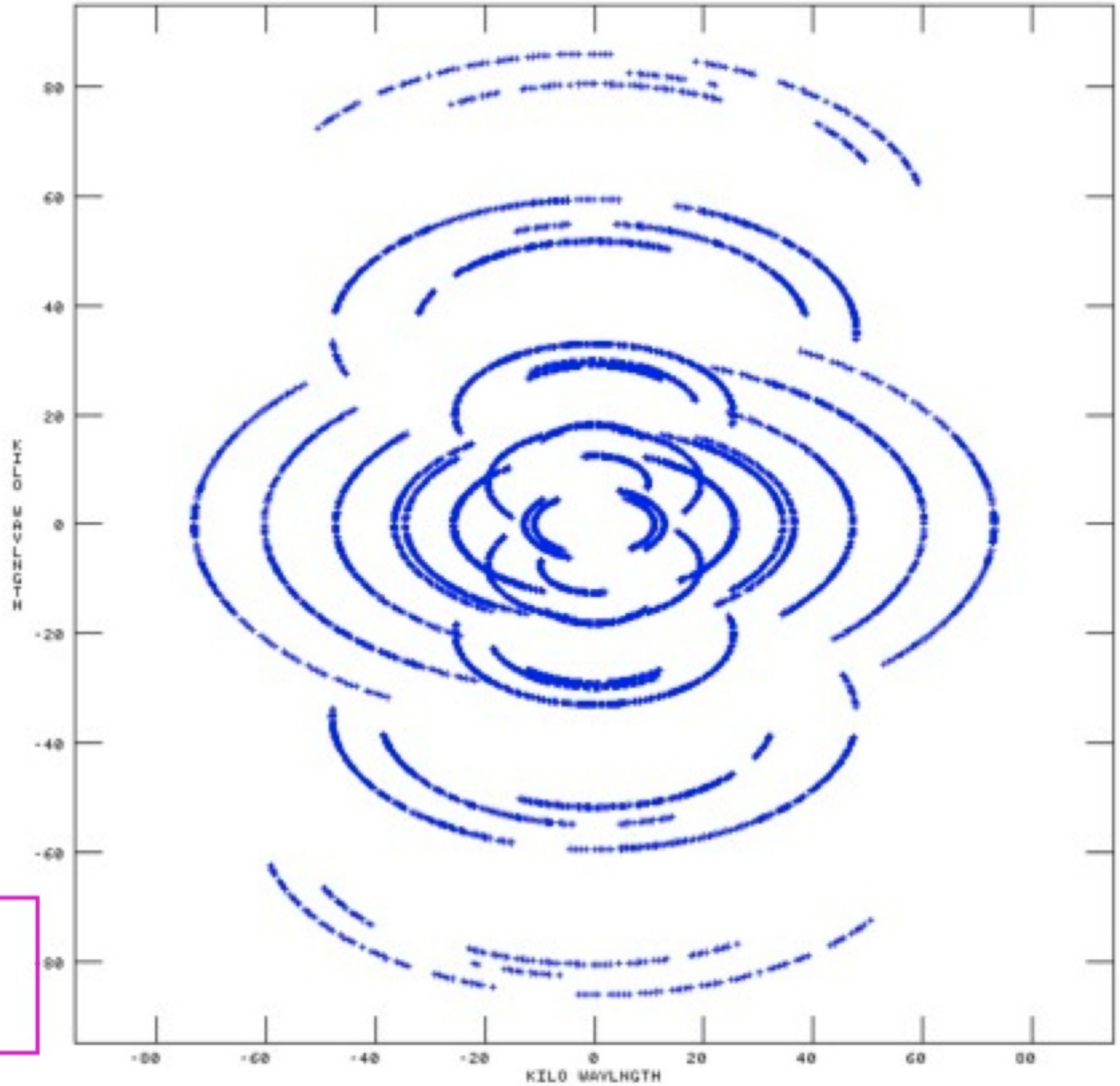
mm Interferometers (u,v) coverage

OVRO mm Array,
6 Antennas

L-configuration
single integration

L-Configuration few
hrs of observations

Final coverage: a
few hrs in both the L
and H configurations



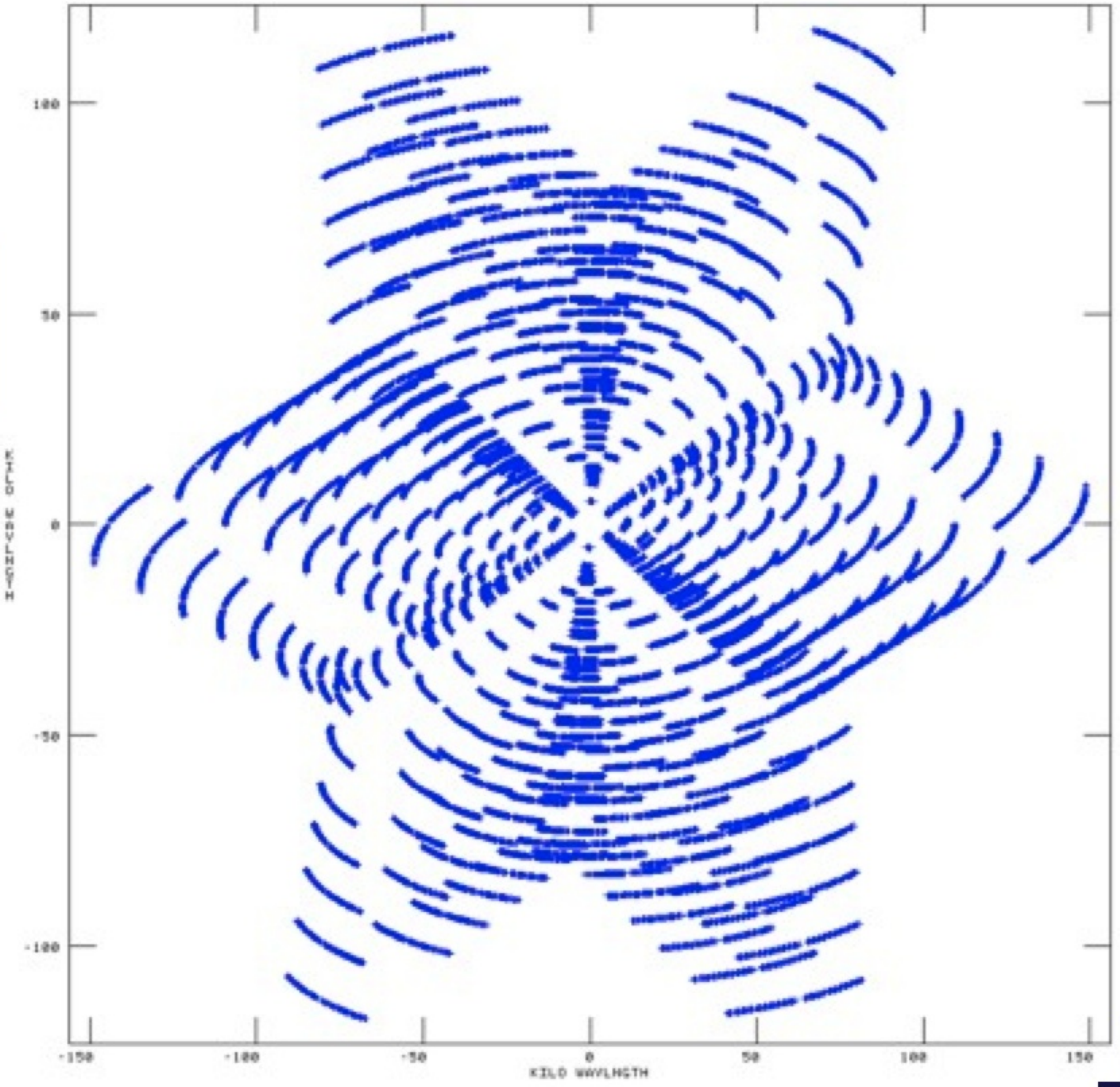
N.B. (u,v) coverage
is not uniform

mm Interferometers (u,v) coverage

Very Large Array,
27 Antennas,
1.5h of observing time!

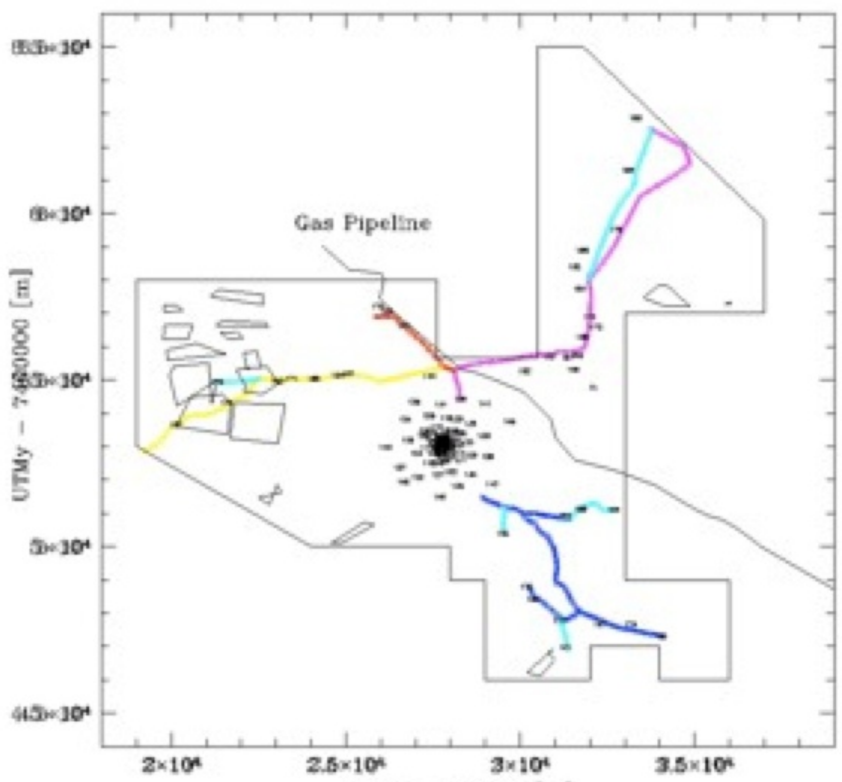
N.B. (u,v) coverage is still not uniform.

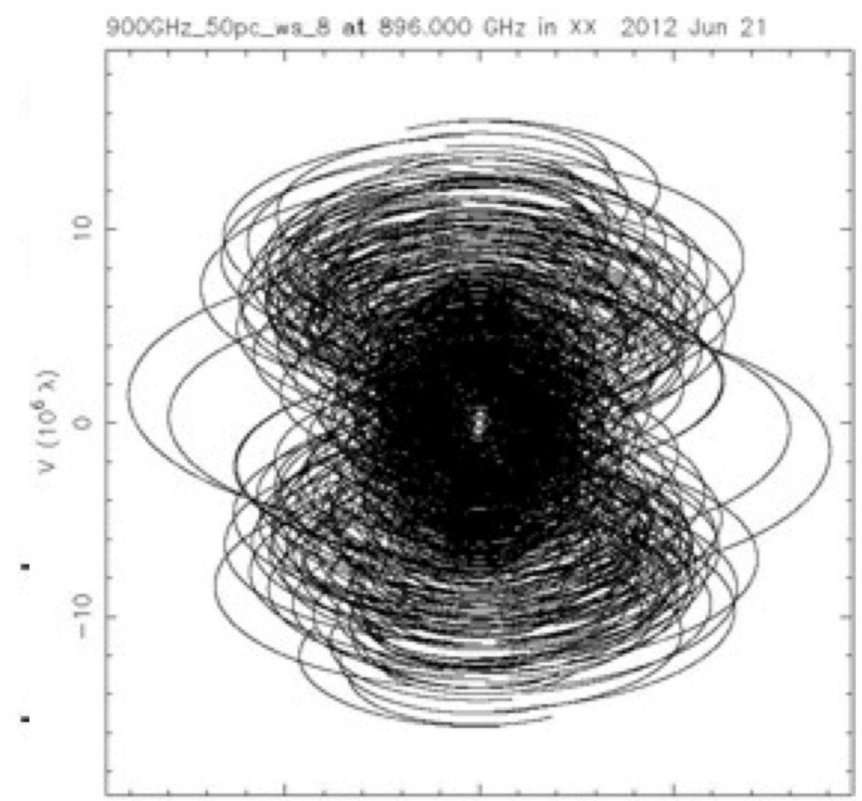
Critical parameters:
- Long baselines
- Short baselines
- Number of (u,v) points
- (u,v) coverage distribution



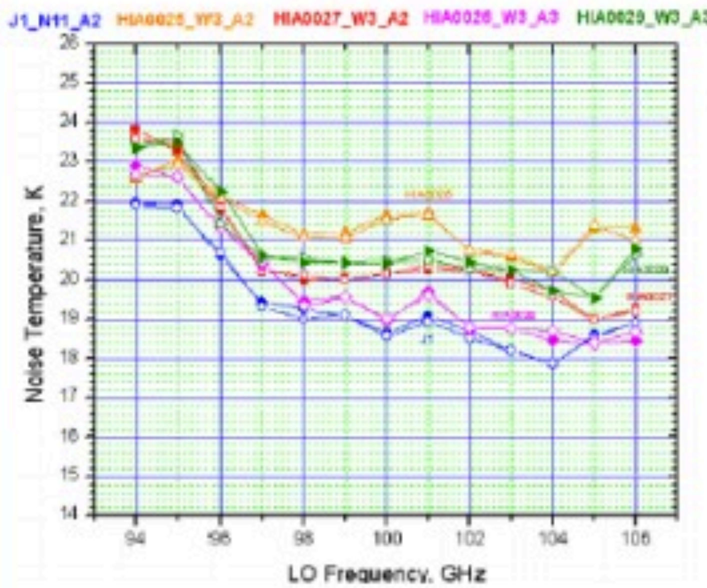
mm Interferometers (u,v) coverage

- Current mm interferometers offer typically ~10^4 visibility measurements in several hours, the VLA delivers ~10^5 visibilities per hour
- ALMA will improve by almost two orders of magnitude

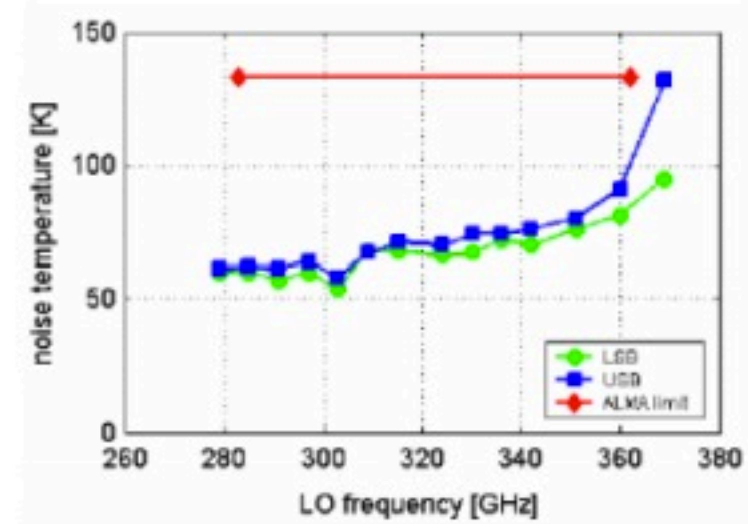




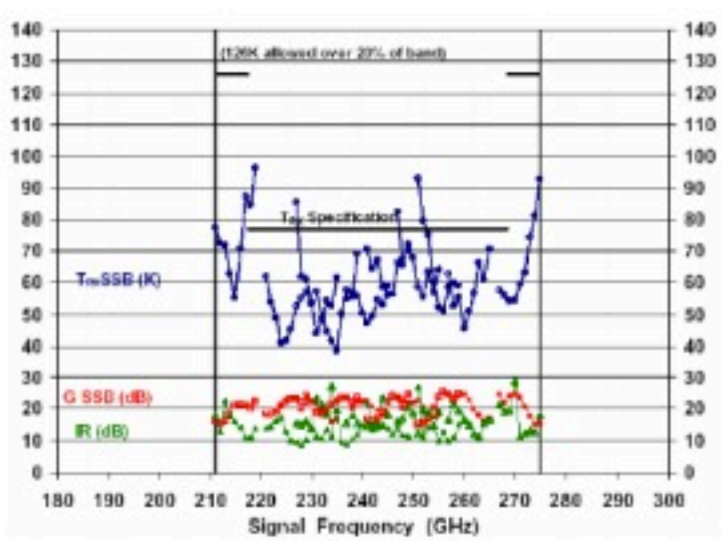
ALMA Receivers

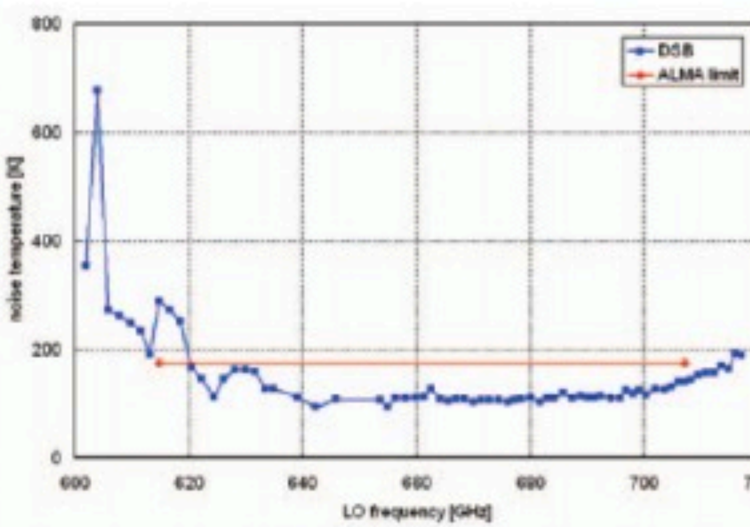
Band 3 ("3mm")

Band 7 ("850μm")

Band 6 ("1mm")

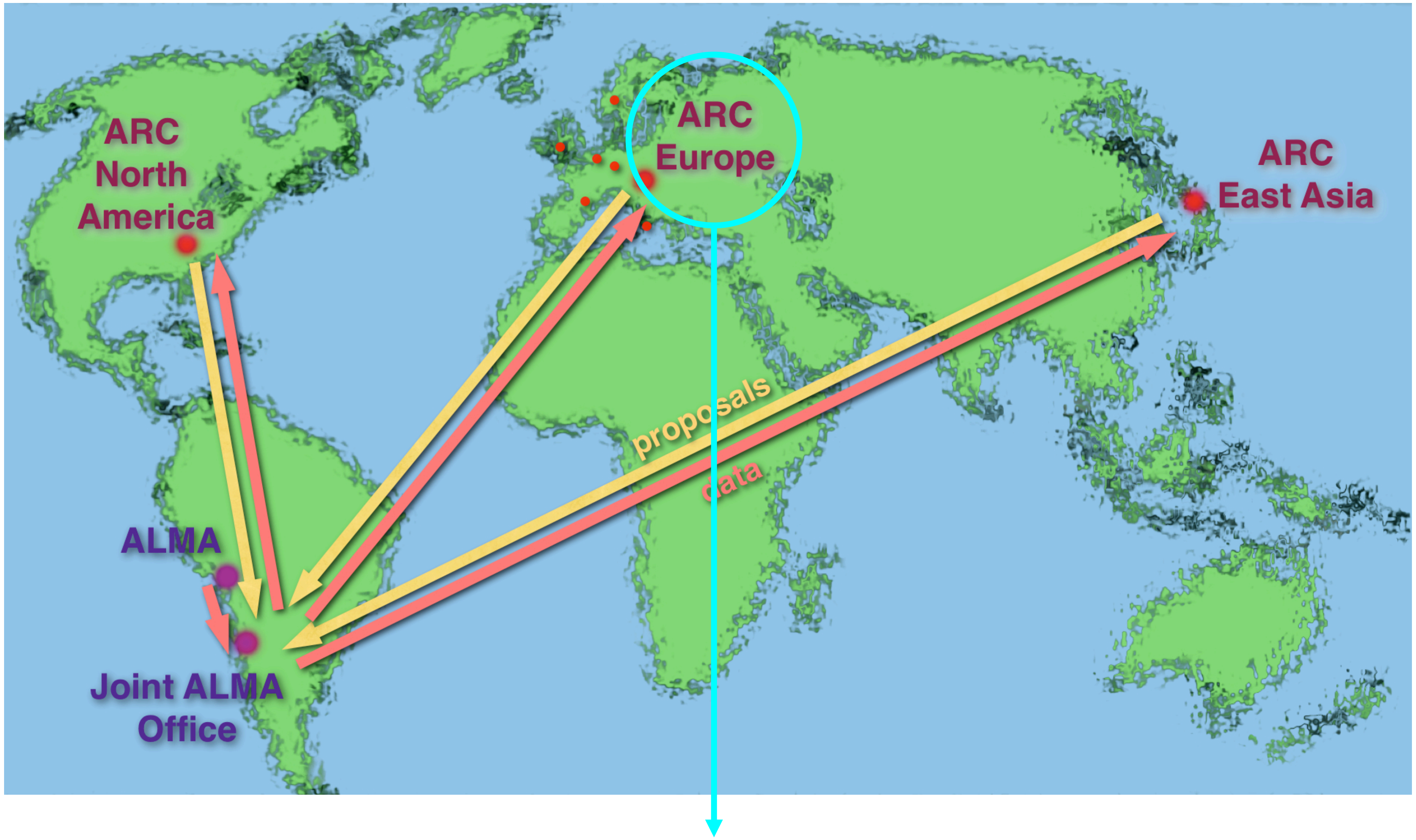



Band 9 ("450μm")

ALMA Early Science

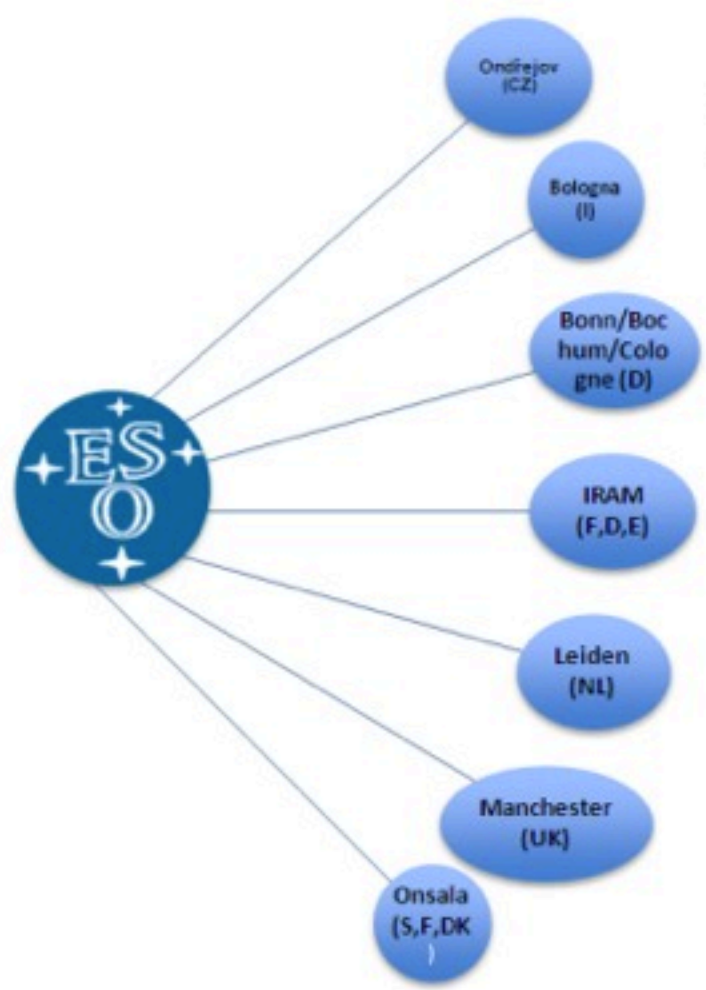
- ALMA Early Science C0 & C1
  - 30-70% of the total number of antennas
  - Maximum separation 1km (6% of final ALMA)
  - Already the most powerful submm observatory
- Enormous pressure to use ALMA worldwide
  - Requests for 9 times the available time
  - Top 8% science projects selected (ESO)

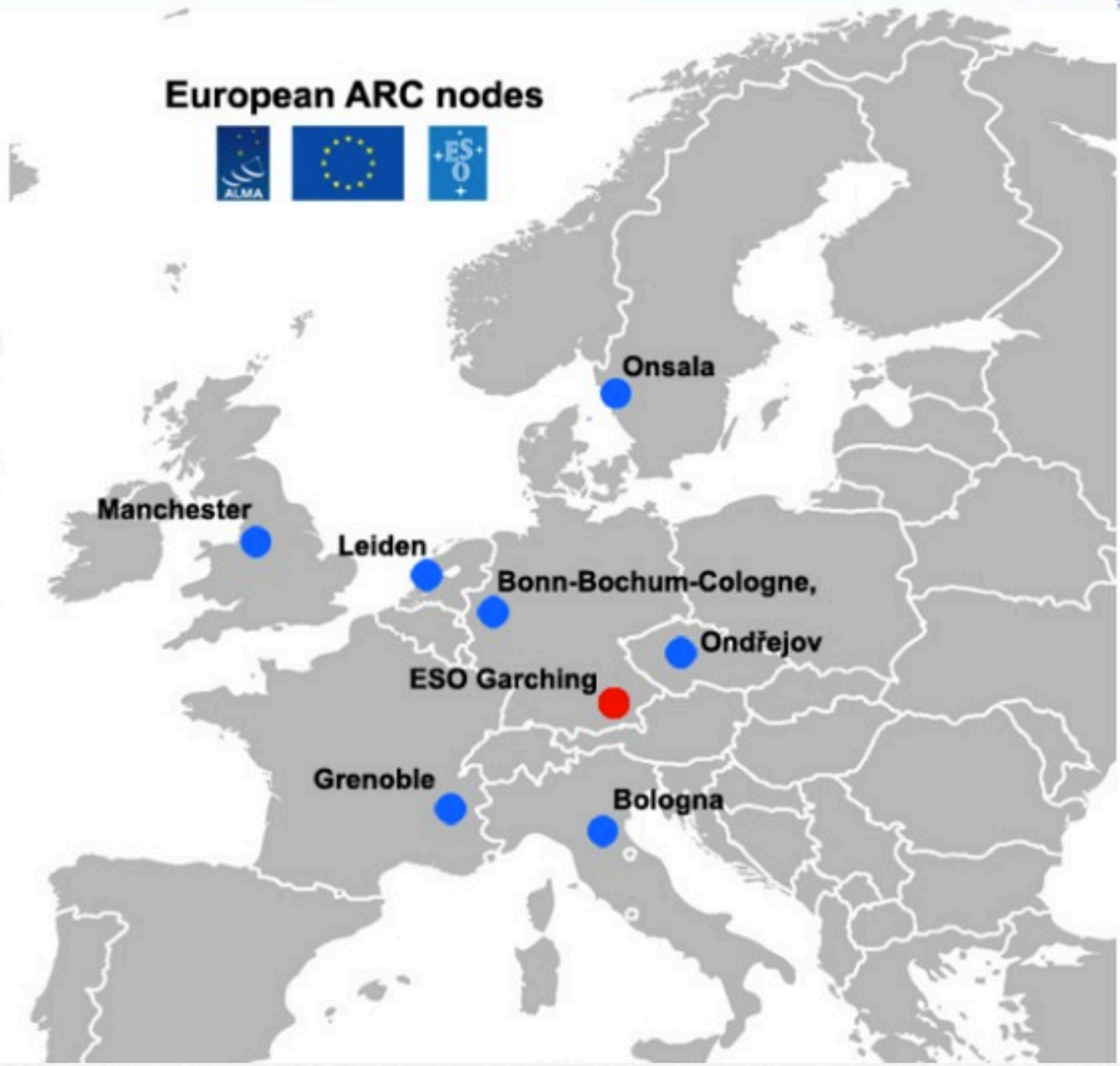
ALMA World-wide organisational structure



Central node (ESO) + Network of regional nodes

ALMA Regional Centre Nodes





remarks

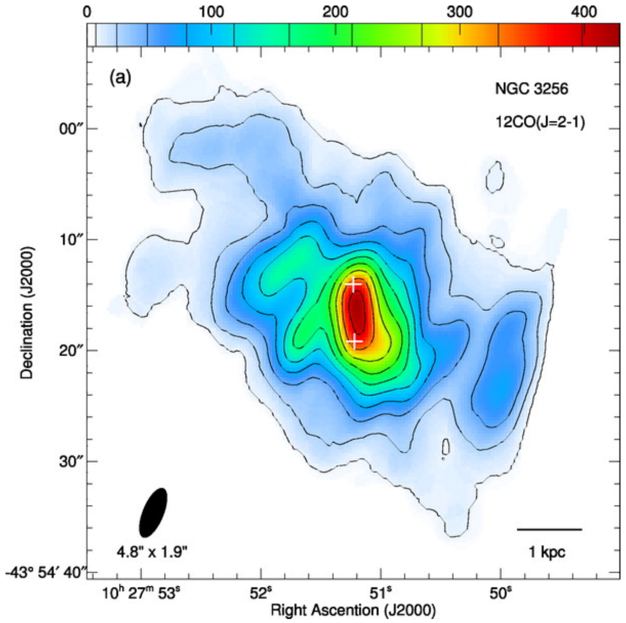
- 24/11 coffee talk all’IRA su primi risultati scientifici di ALMA
- date lab: 3 settimane --> 24/25/30-10; 6/7/8 -11
- laptop ssh con finestra pittorica

The Case of NGC3256

ALMA Science Verification Data (April, 16-17 2011)

- CO (1-0) Band 3
- spectral resolution 15.625 MHz (40 kms-1)
- Angular resolution 6.5″ (8 antennas)

HST image of NGC3256 (credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA)-ESA/ Hubble Collaboration and A. Evans



SMA map of CO (2–1) emission in the center of NGC 3256 (Sakamoto, Ho & Peck, 2006)

USEFUL WEB PAGES

Latest News:
http://www.almaobservatory.org/

General ALMA pages at ESO:
http://www.eso.org/sci/facilities/alma/

Possible Science Projects (DRSP):
http://www.eso.org/sci/facilities/alma/science/drsp/

ESO-ARC pages:
http://www.eso.org/sci/facilities/alma/arc/

Italian ARC-pages:
http://www.alma.inaf.it/

Check for job offers.