ALMA
-
Interferometry @ mm

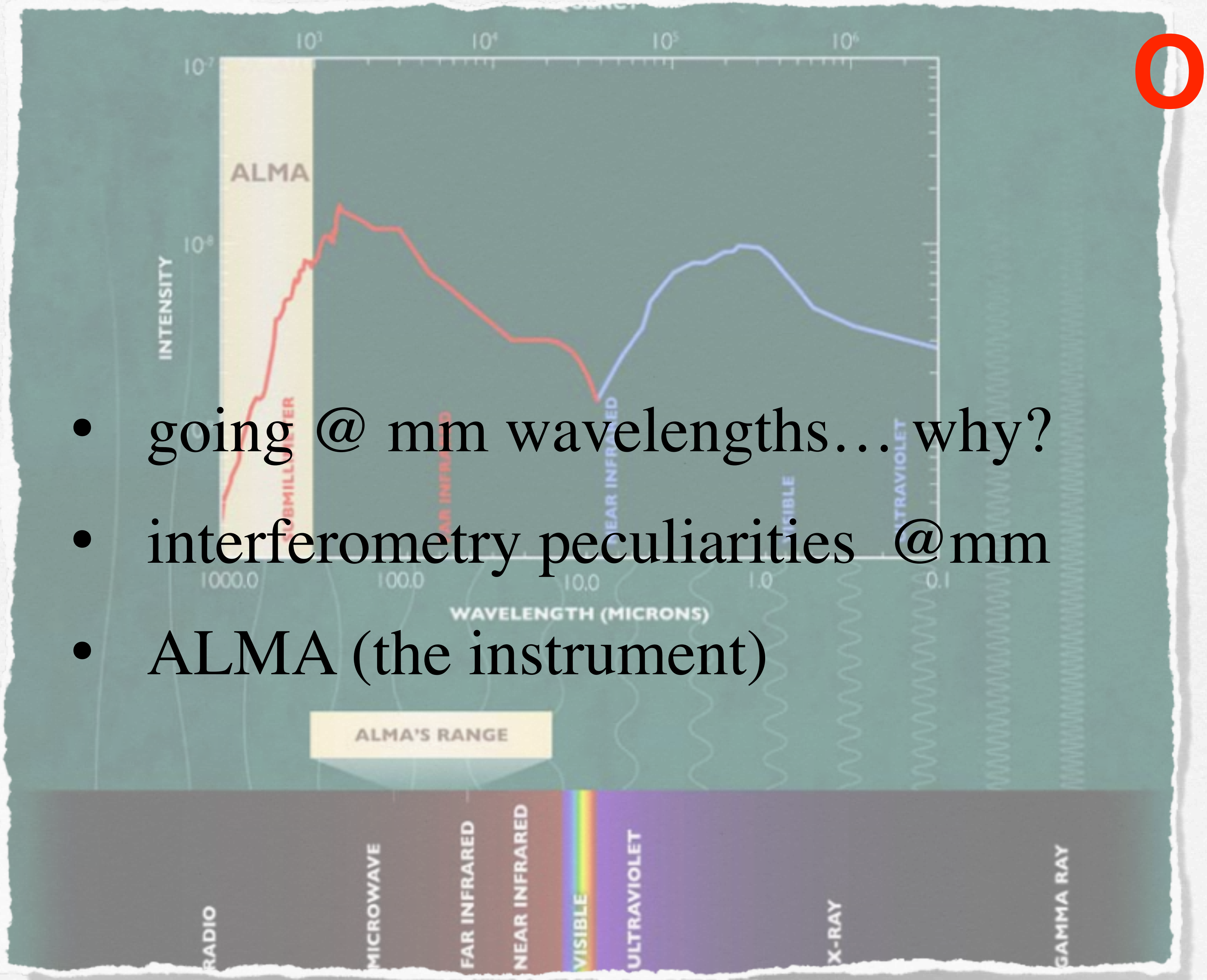
Arturo Mignano + Rosita Paladino
(It-ARC)

EUROPEAN ARC
ALMA Regional Centre || Italian

remarks

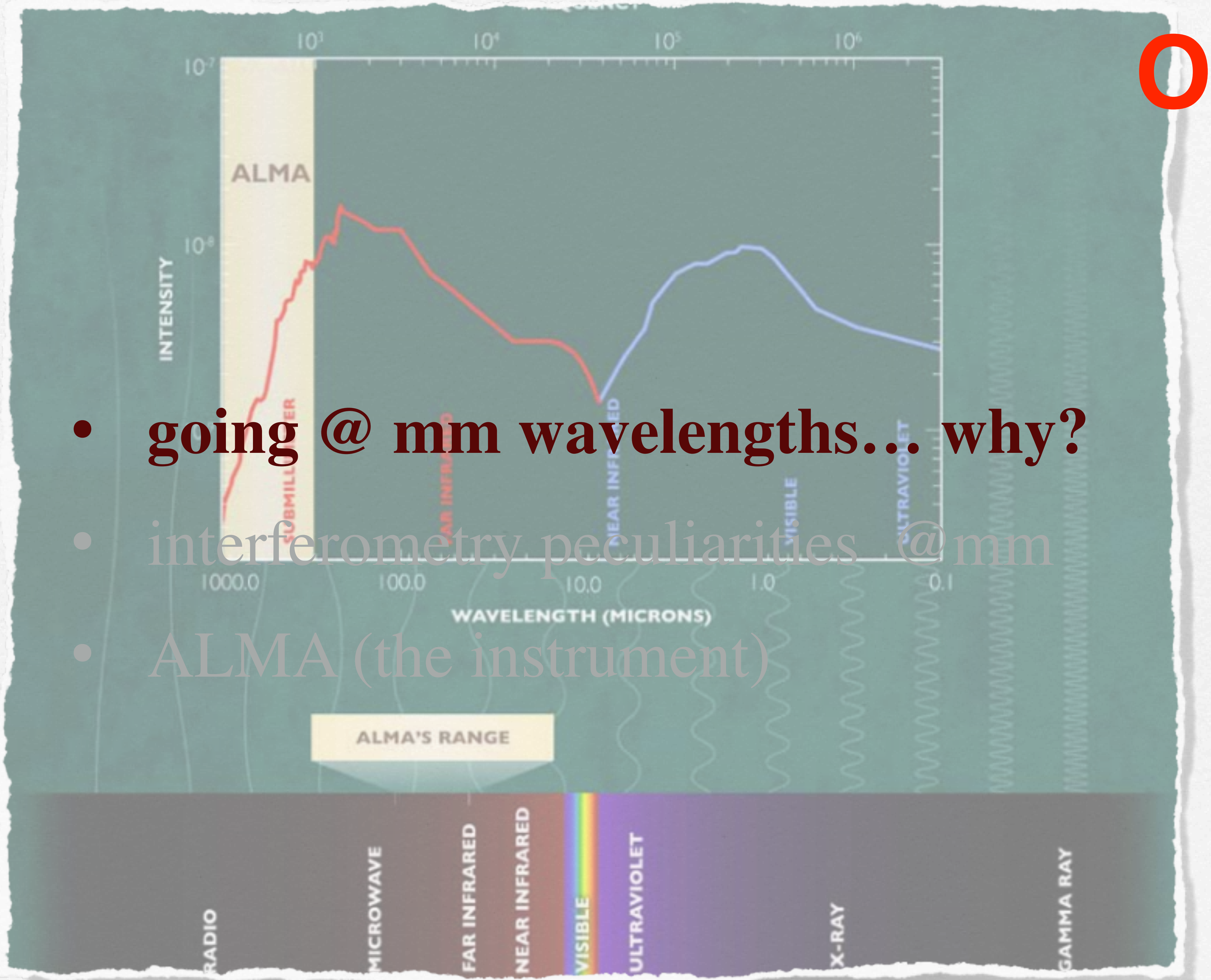
- gruppi?
- date lab: 2 settimane --> dal 12 al 23 ottobre … tutti i giorni
- lun-mar-mer: solo mattina
    - gio-ven: tutta la giornata
- laptop ssh con finestra pittorica (molto meglio aver installato linux/affini!)

Outline



- going @ mm wavelengths… why?
- interferometry peculiarities @mm
- ALMA (the instrument)

Outline



- **going @ mm wavelengths… why?**
- interferometry peculiarities @mm
- ALMA (the instrument)

why build a mm interferometer?

- molecular spectroscopy
    - $T_{excitation}$ low (10’s K) —> probe dense cooler regions of ISM (dark clouds)
- study of thermal objects
    - negative k correction, flux is z independent
    - SFR at z>2 unobscured by dust

why build a mm interferometer?

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? …

why build a mm interferometer?

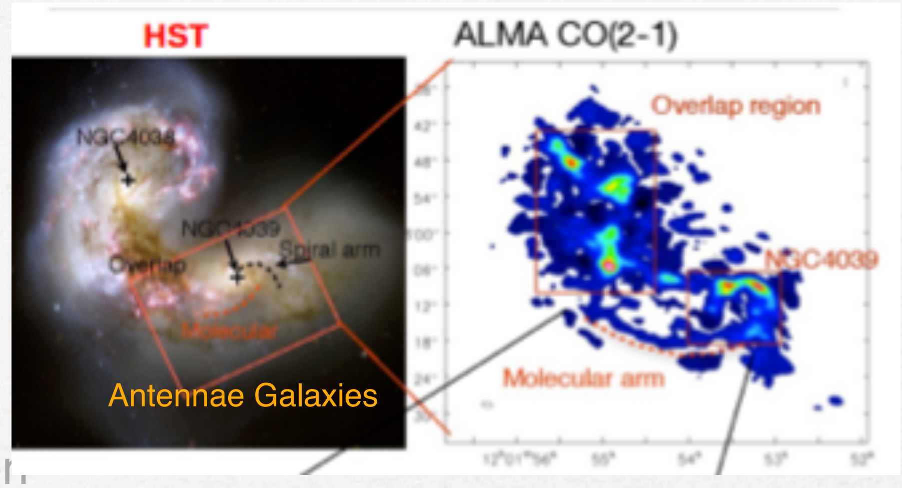
Dark clouds are of interest because:

- 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? …

why build a mm interferometer?

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? …

why build a mm interferometer?

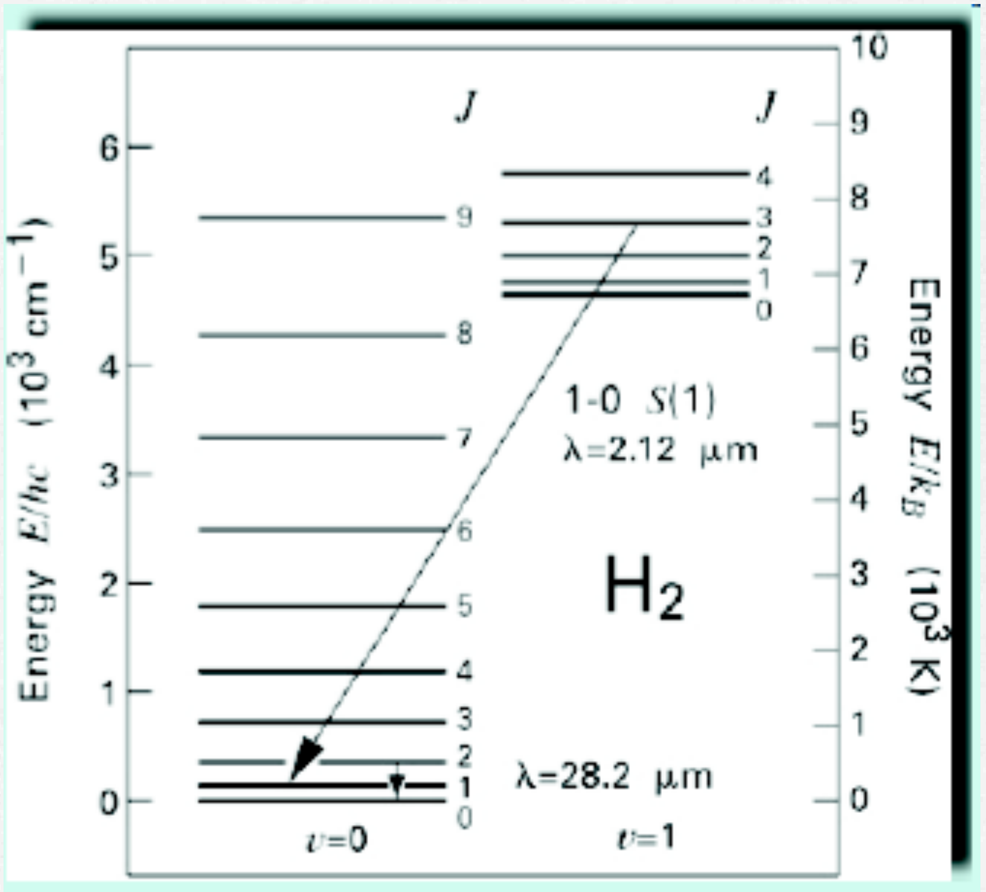
The first obvious approach: look for molecular Hydrogen…. BUT!

H2 is a symmetric molecule with a very low angular momentum —> lot of energy to excite:

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

H2 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 …

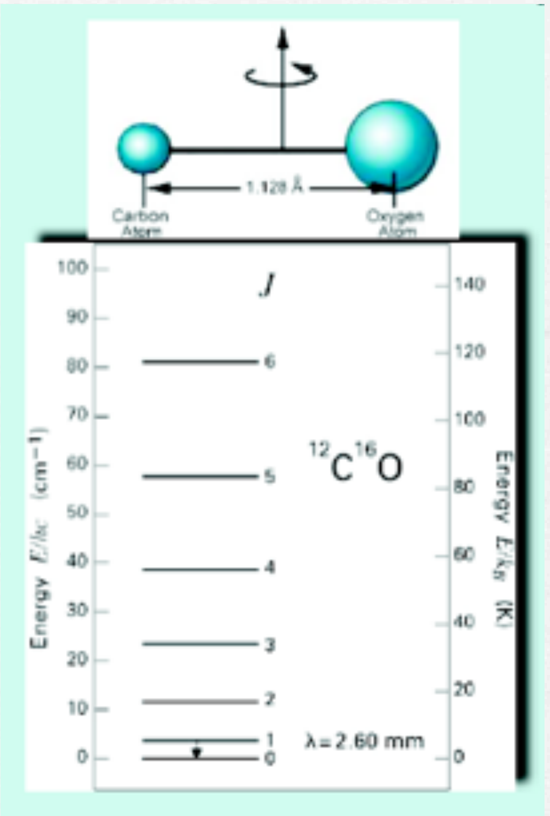
why build a mm interferometer?

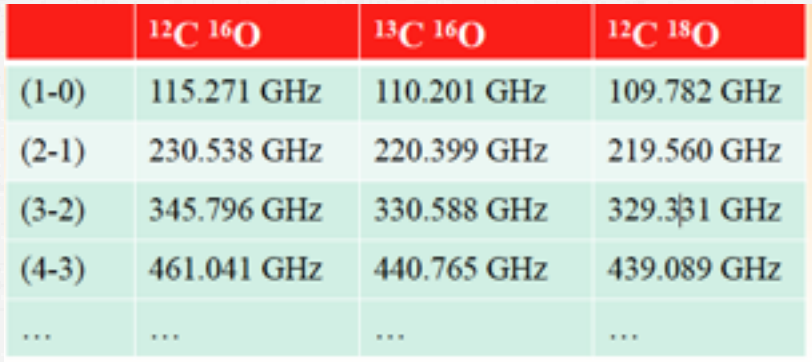
Next choice: Carbon monoxide (CO)

- 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}
- 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
…	…	…	…

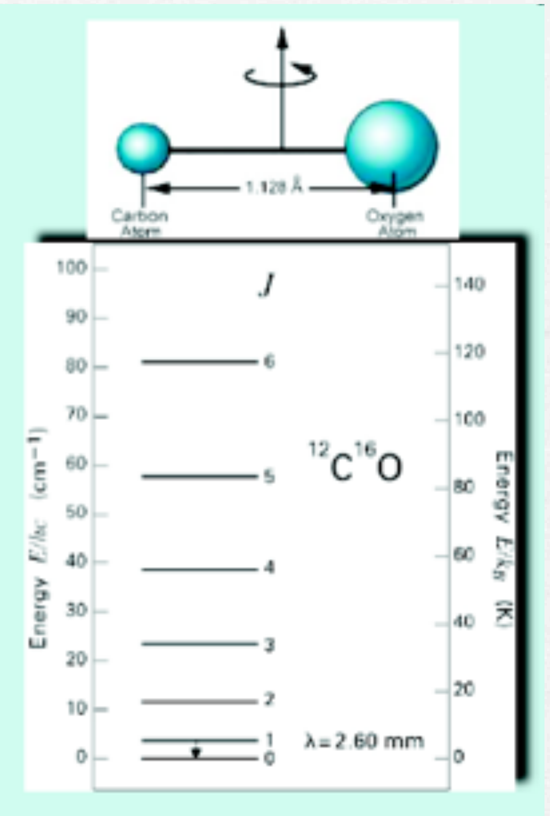
why build a mm interferometer?

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}
- 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

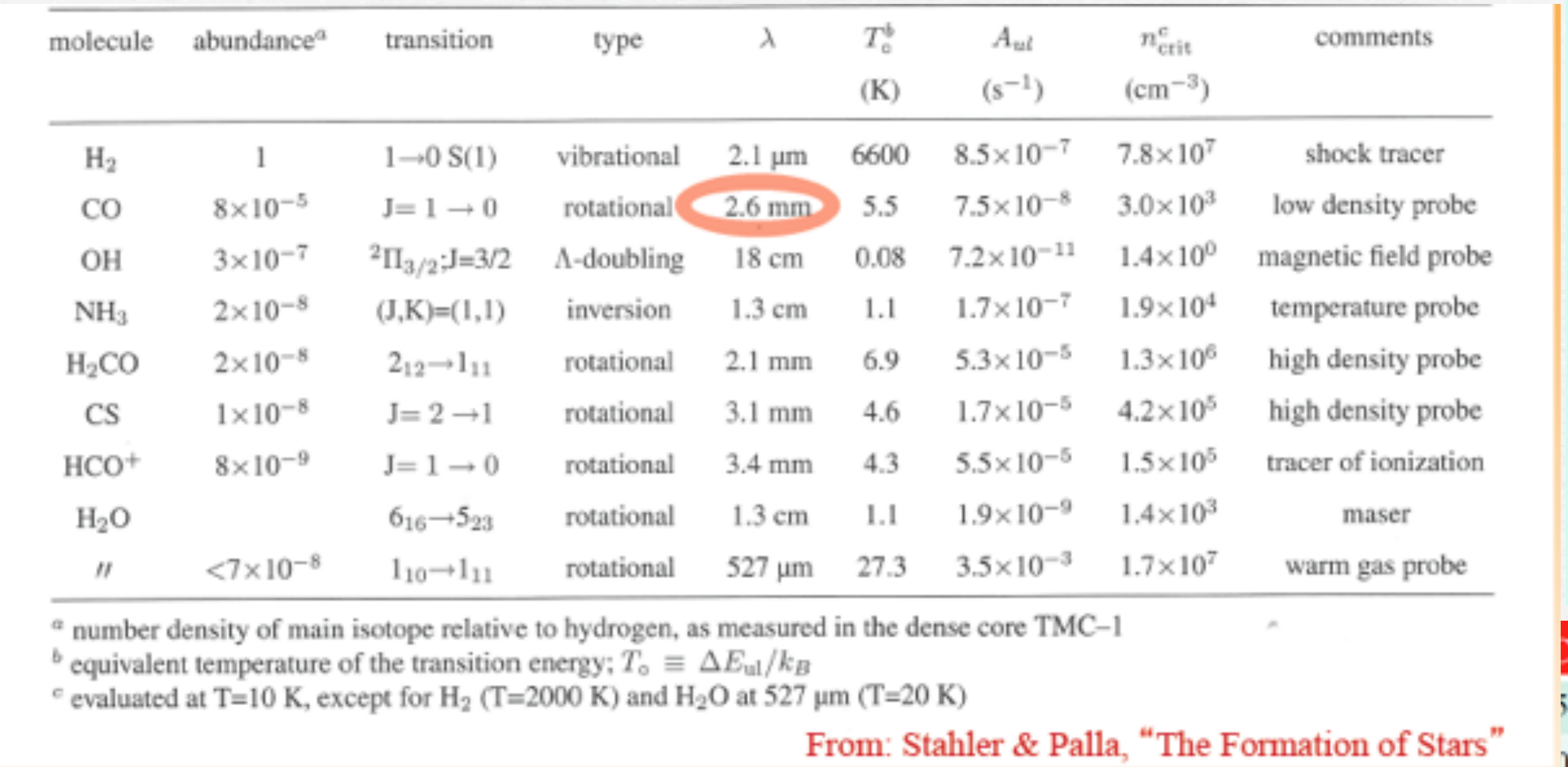


	$^{12}C\ ^{16}O$	$^{13}C\ ^{16}O$	$^{12}C\ ^{18}O$
(1-0)	115.271 GHz	110.201 GHz	109.782 GHz
(2-1)	230.538 GHz	220.399 GHz	219.560 GHz
(3-2)	345.796 GHz	330.588 GHz	329.331 GHz
(4-3)	461.041 GHz	440.765 GHz	439.089 GHz
…	…	…	…

CO, the main driver to build instruments beyond 100GHz

why build a mm interferometer?

Next choice: Carbon monoxide (CO)



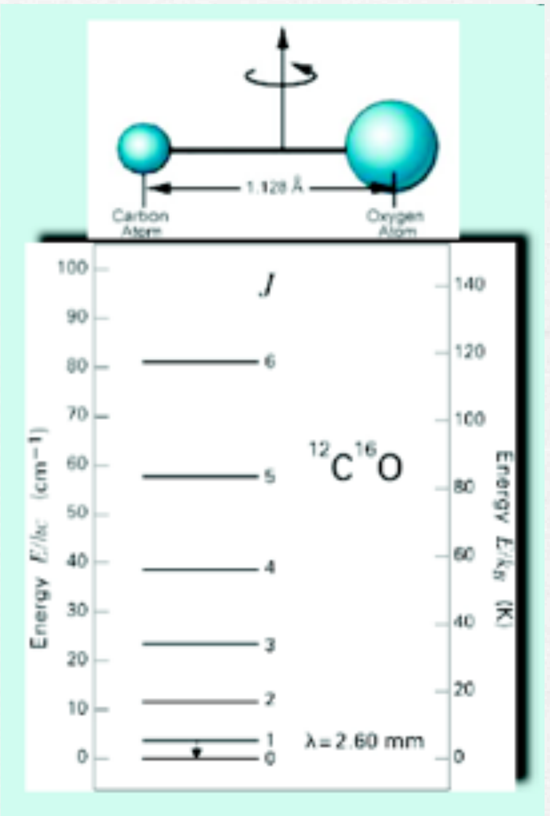
molecule	abundance[a]	transition	type	λ	$T_\circ^b$ (K)	A_{ul} (s^{-1})	n^c_{crit} (cm^{-3})	comments
H_2	1	1→0 S(1)	vibrational	2.1 μm	6600	8.5×10^{-7}	7.8×10^{7}	shock tracer
CO	8×10^{-5}	J= 1 → 0	rotational	2.6 mm	5.5	7.5×10^{-8}	3.0×10^{3}	low density probe
OH	3×10^{-7}	$^2\Pi_{3/2}$;J=3/2	Λ-doubling	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 →1	rotational	3.1 mm	4.6	1.7×10^{-5}	4.2×10^{5}	high density probe
HCO^+	8×10^{-9}	J= 1 → 0	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"

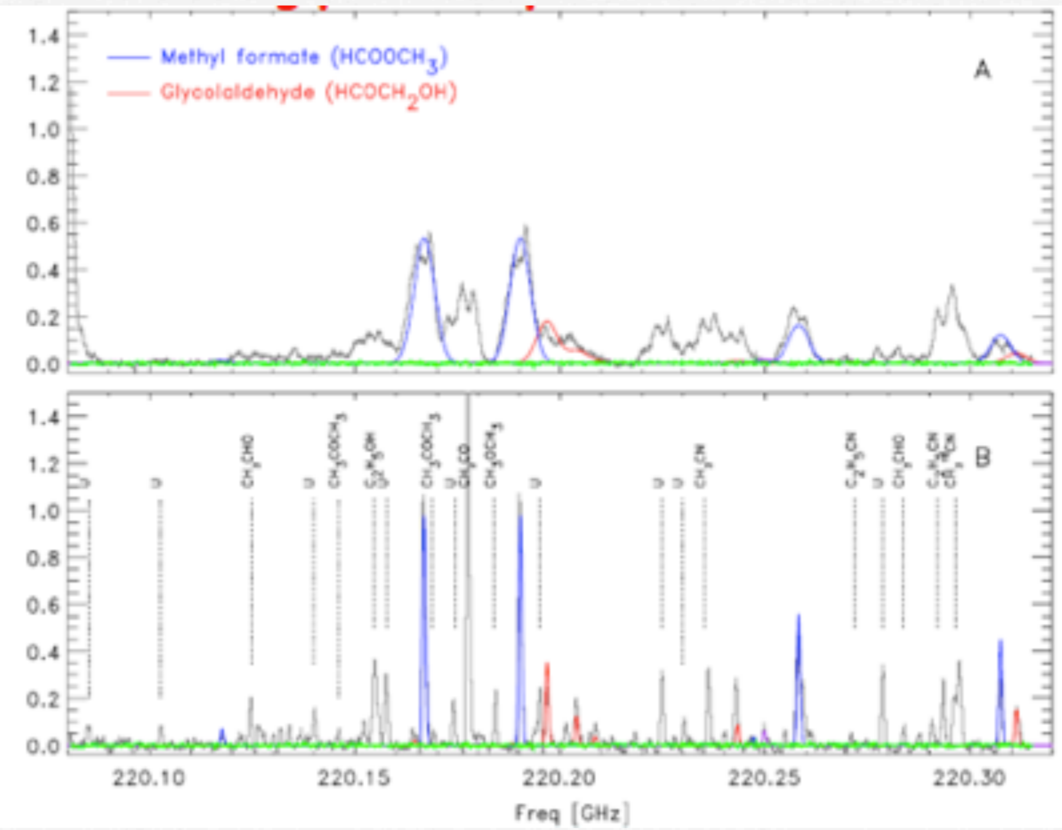


	C ^{16}O	^{13}C ^{16}O	^{12}C ^{18}O
	5.271 GHz	110.201 GHz	109.782 GHz
(2-1)	0.538 GHz	220.399 GHz	219.560 GHz
(3-2)	345.796 GHz	330.588 GHz	329.331 GHz
(4-3)	461.041 GHz	440.765 GHz	439.089 GHz
	…	…	…

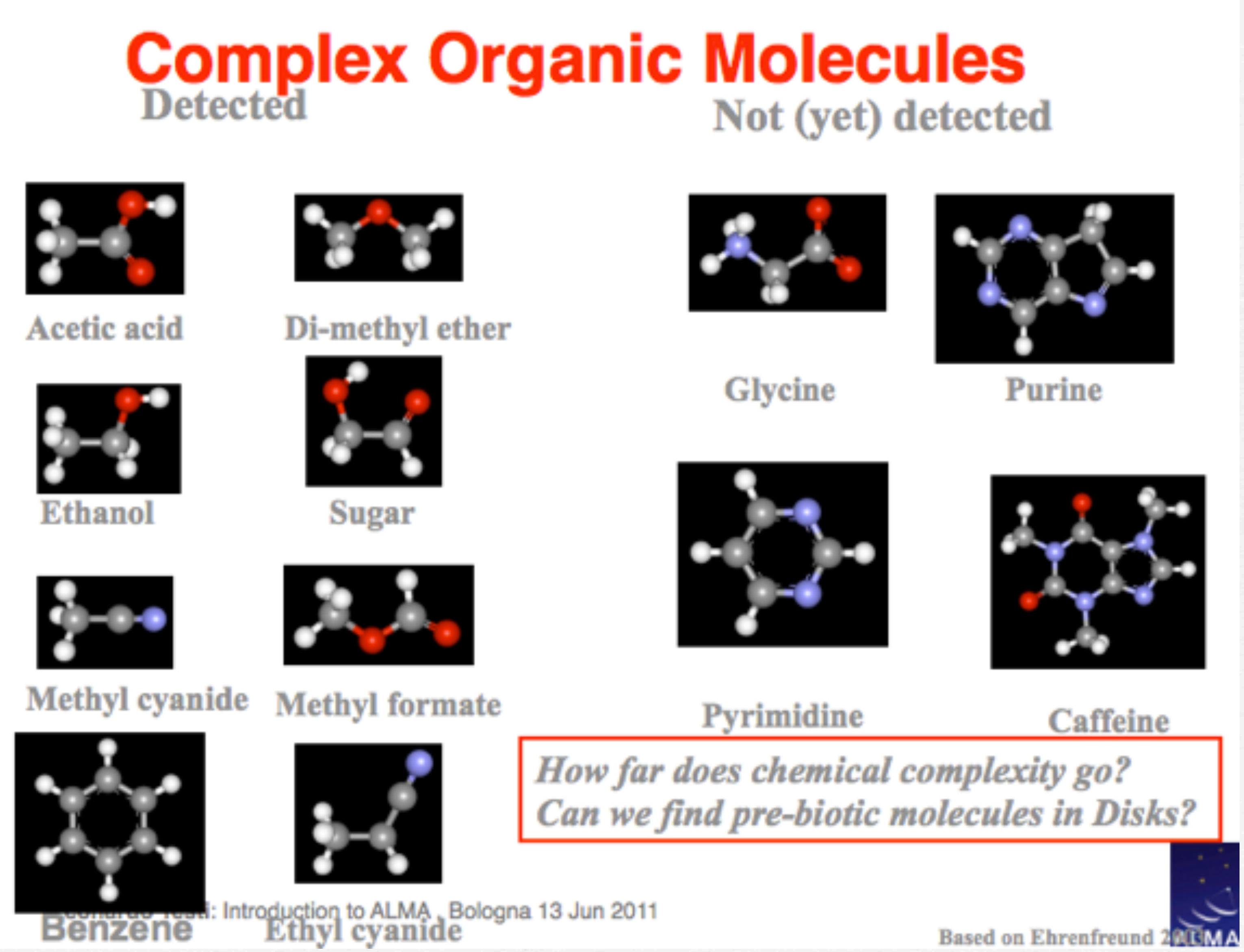
CO, the main driver to build instruments beyond 100GHz

why build a mm interferometer?

not only CO! large variety of molecules in ISM



@ALMA: glycolaldehyde detection in IRAS 16293-2422



Complex Organic Molecules

Detected

Not (yet) detected

How far does chemical complexity go?
Can we find pre-biotic molecules in Disks?

Based on Ehrenfreund 2

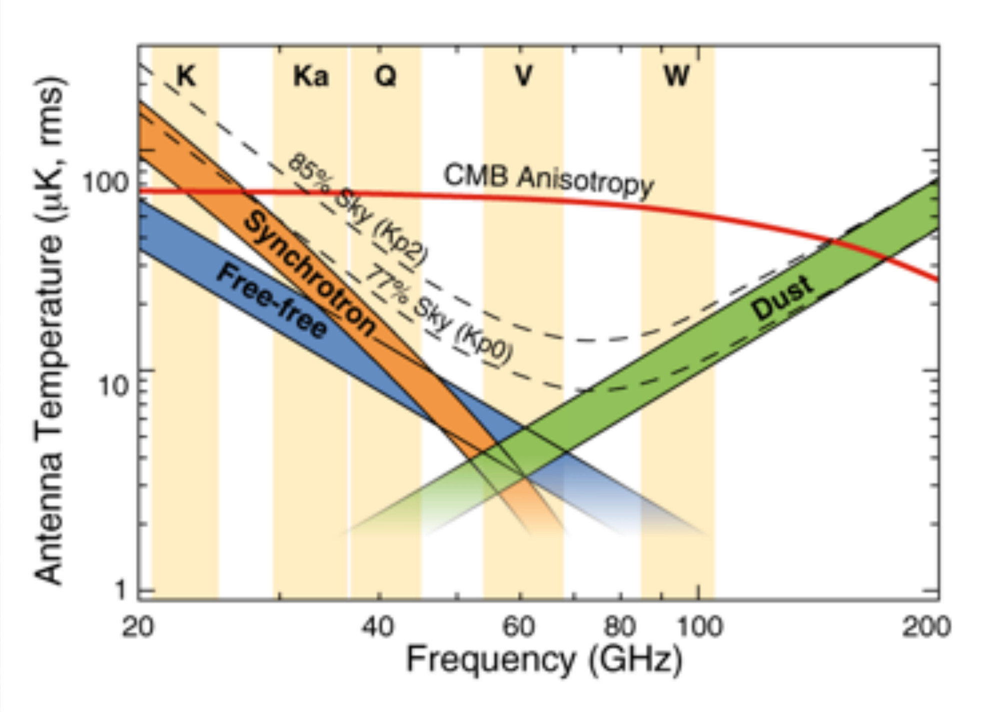
: Introduction to ALMA , Bologna 13 Jun 2011

why build a mm interferometer?

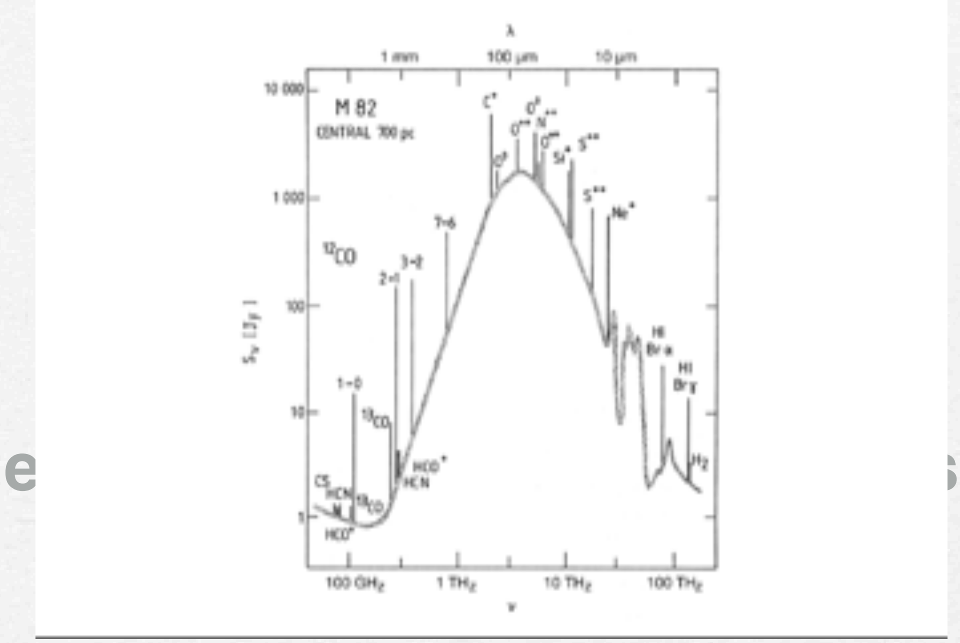
- molecular spectroscopy
    - $T_{excitation}$ low (10’s K) —> probe dense cooler regions of ISM (dark clouds)
- study of thermal objects
    - negative k correction, flux is z independent
    - SFR at z>2 unobscured by dust

in Rayleigh Jeans regime
hν<<kT

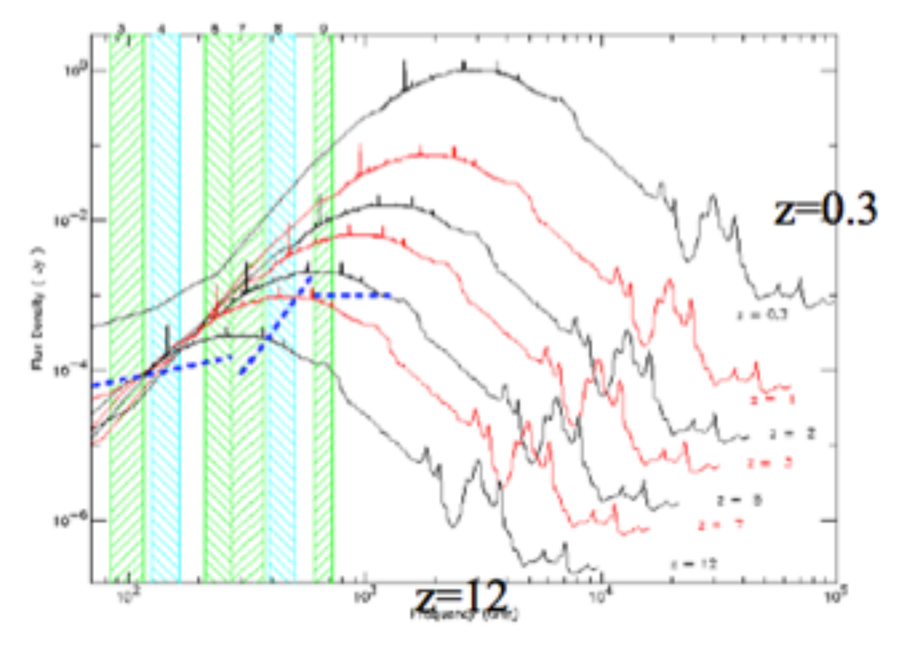
$$\boxed{B_\nu = \frac{2kT\nu^2}{c^2}}$$



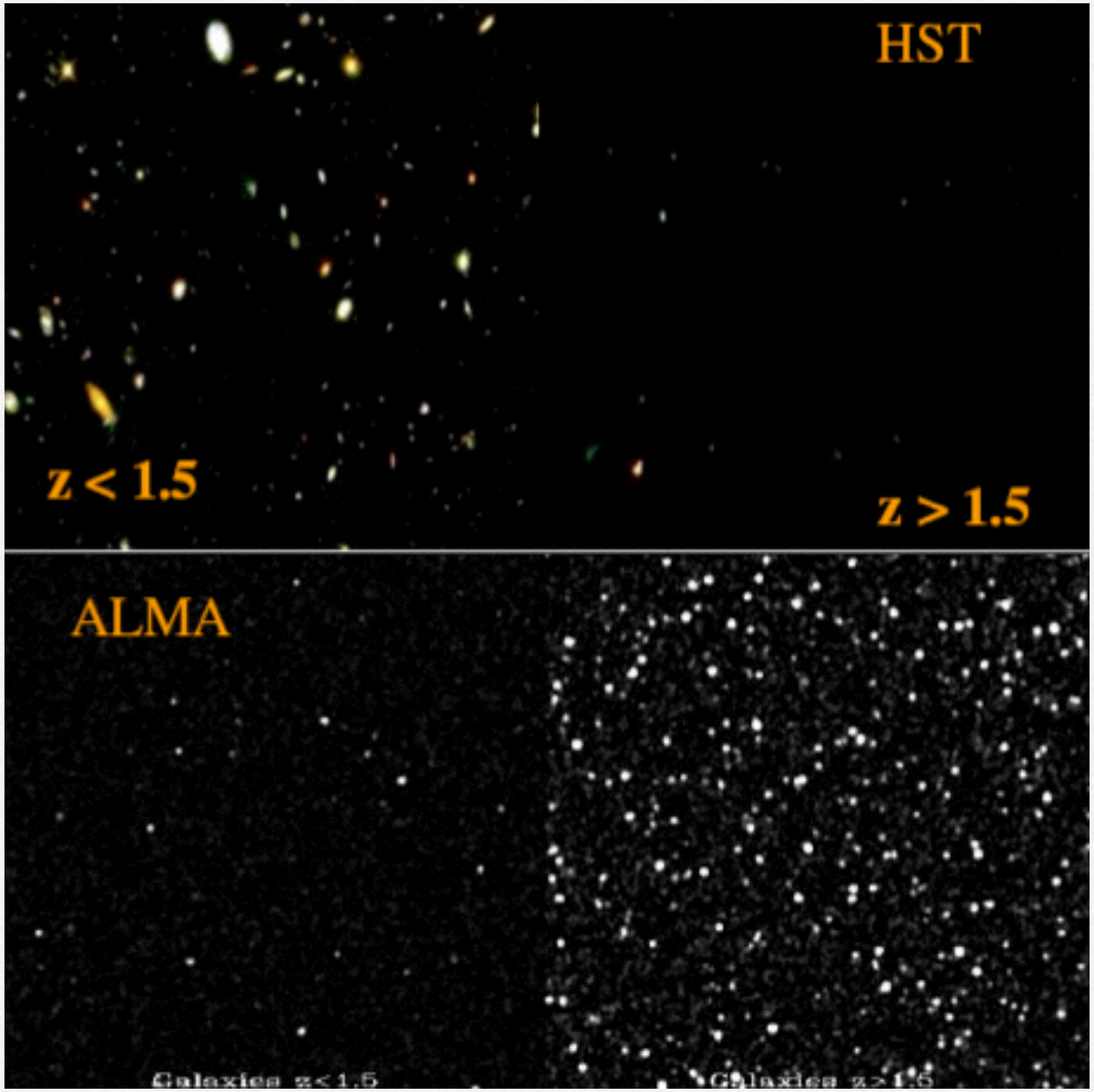
why build a mm interferometer?



- molecular spectroscopy
    - $T_{\text{excitation}}$ low (10's K) —> probe dense coole s)
- **study of thermal objects**
    - **negative k correction, flux is z independent**
    - **SFR at z>2 unobscured by dust**



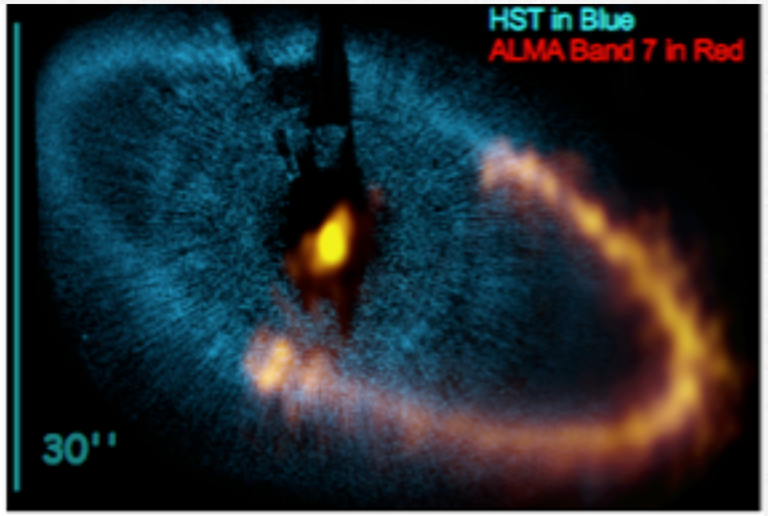
why build a mm interferometer?

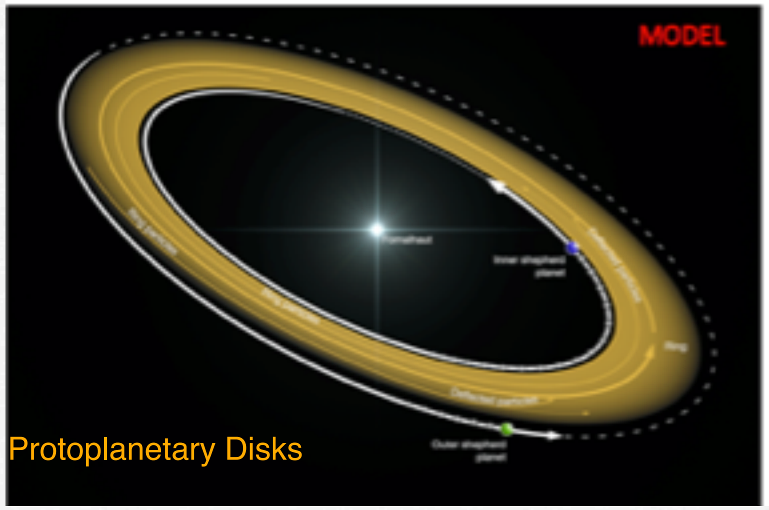


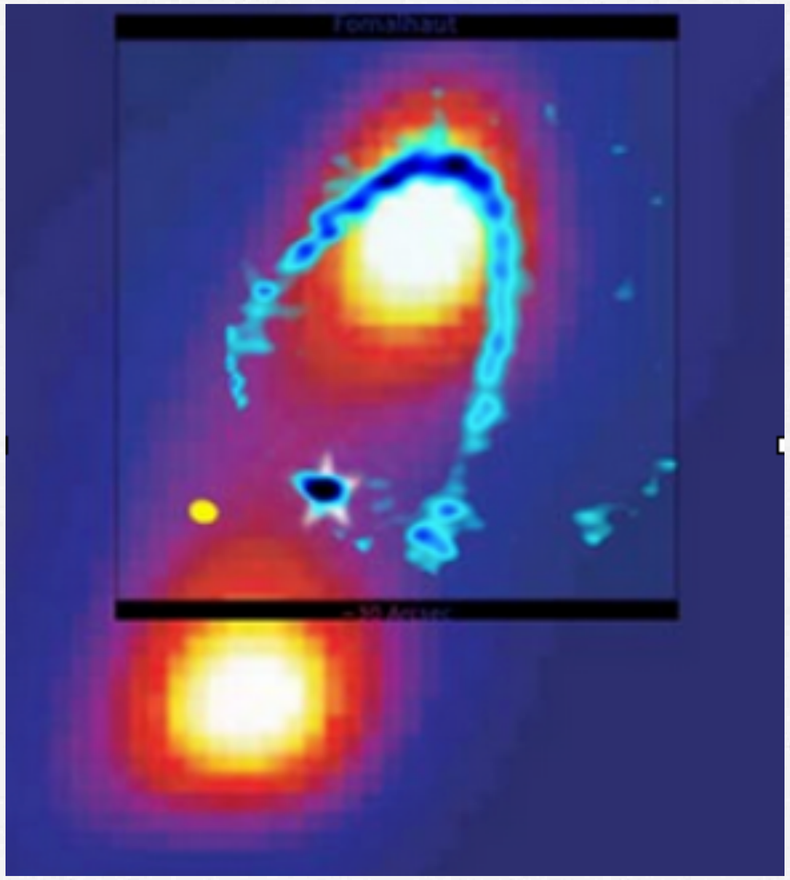
why build a mm interferometer?

- ☐ **angular resolution**
- ☐ sensitivity

cycle 0ALMA observations!



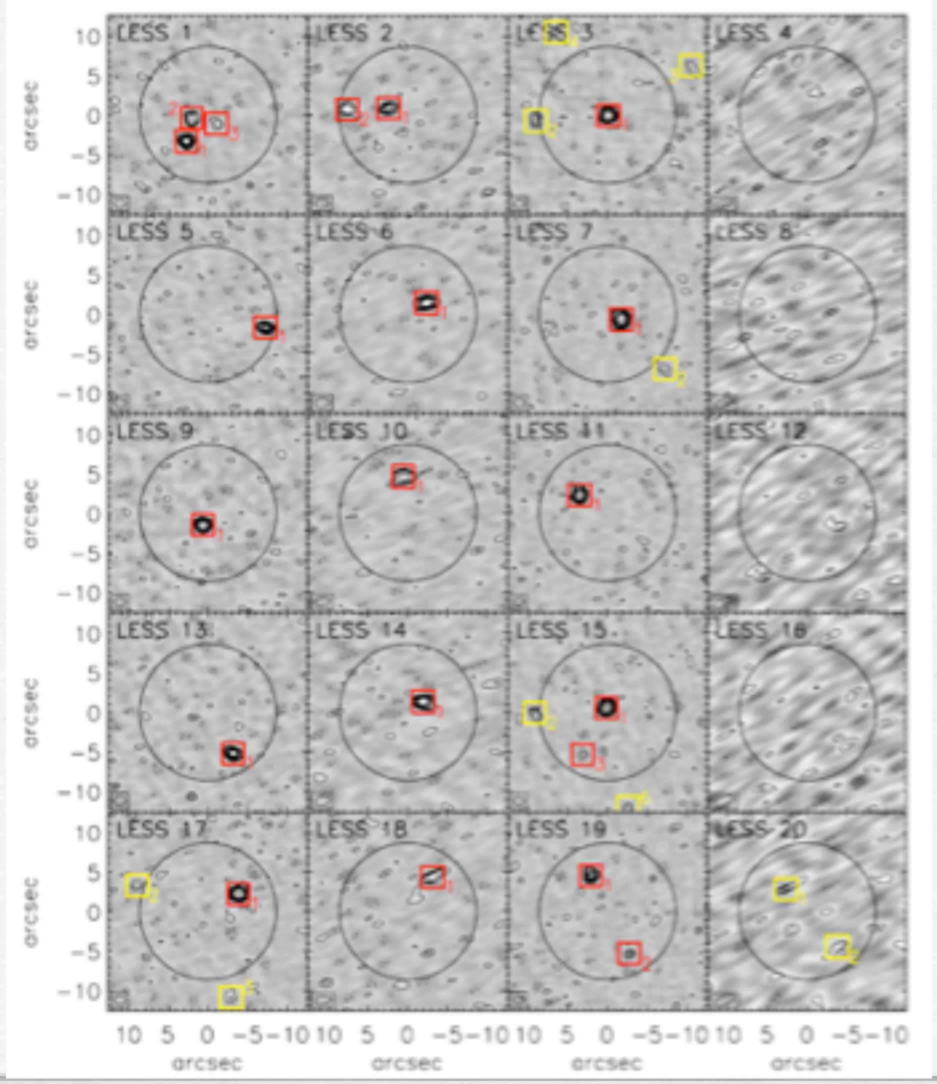




why build a mm interferometer?

- **angular resolution**
- **sensitivity**

cycle 0ALMA observations!

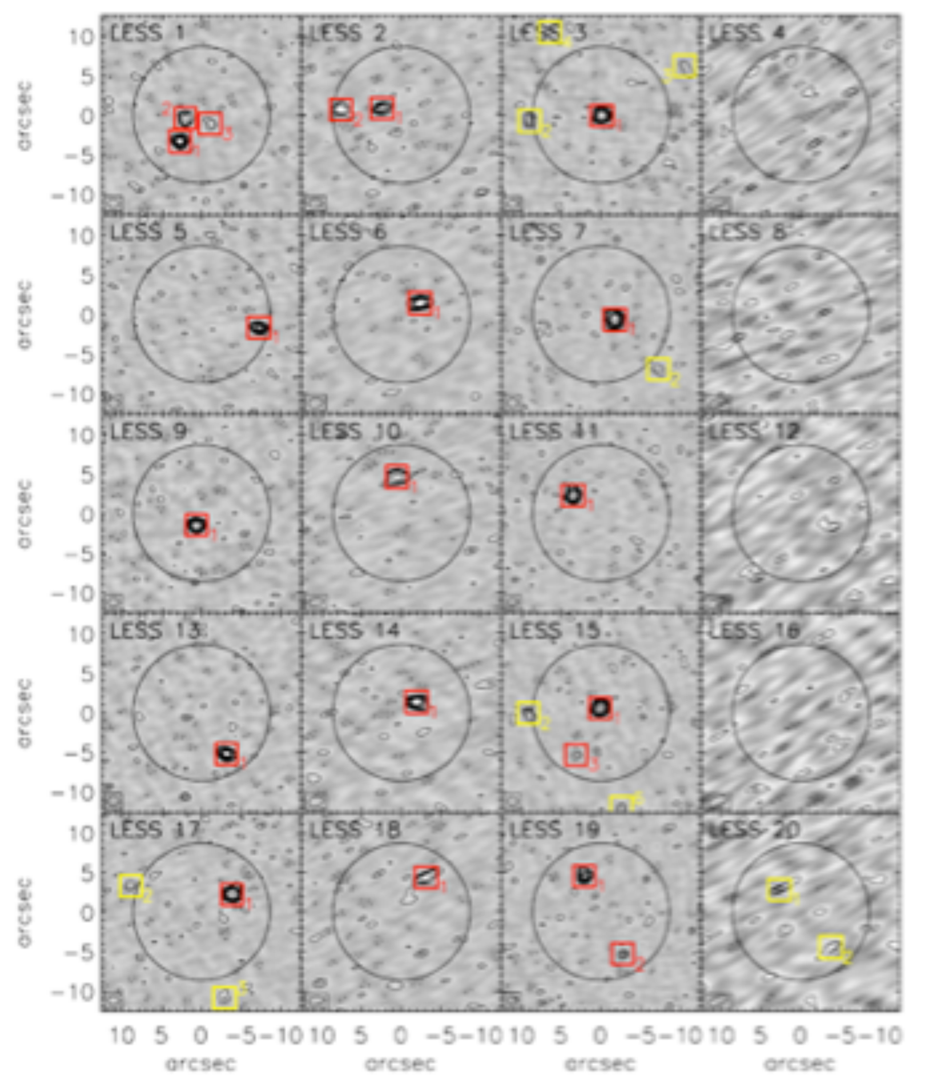


why build a mm interferometer?

- **angular resolution**
- **sensitivity**

cycle 0ALMA observations!

Band7 Alma survey of submm galaxies in Extended Chandra Deep Field South



why build a mm interferometer?

R sculptoris

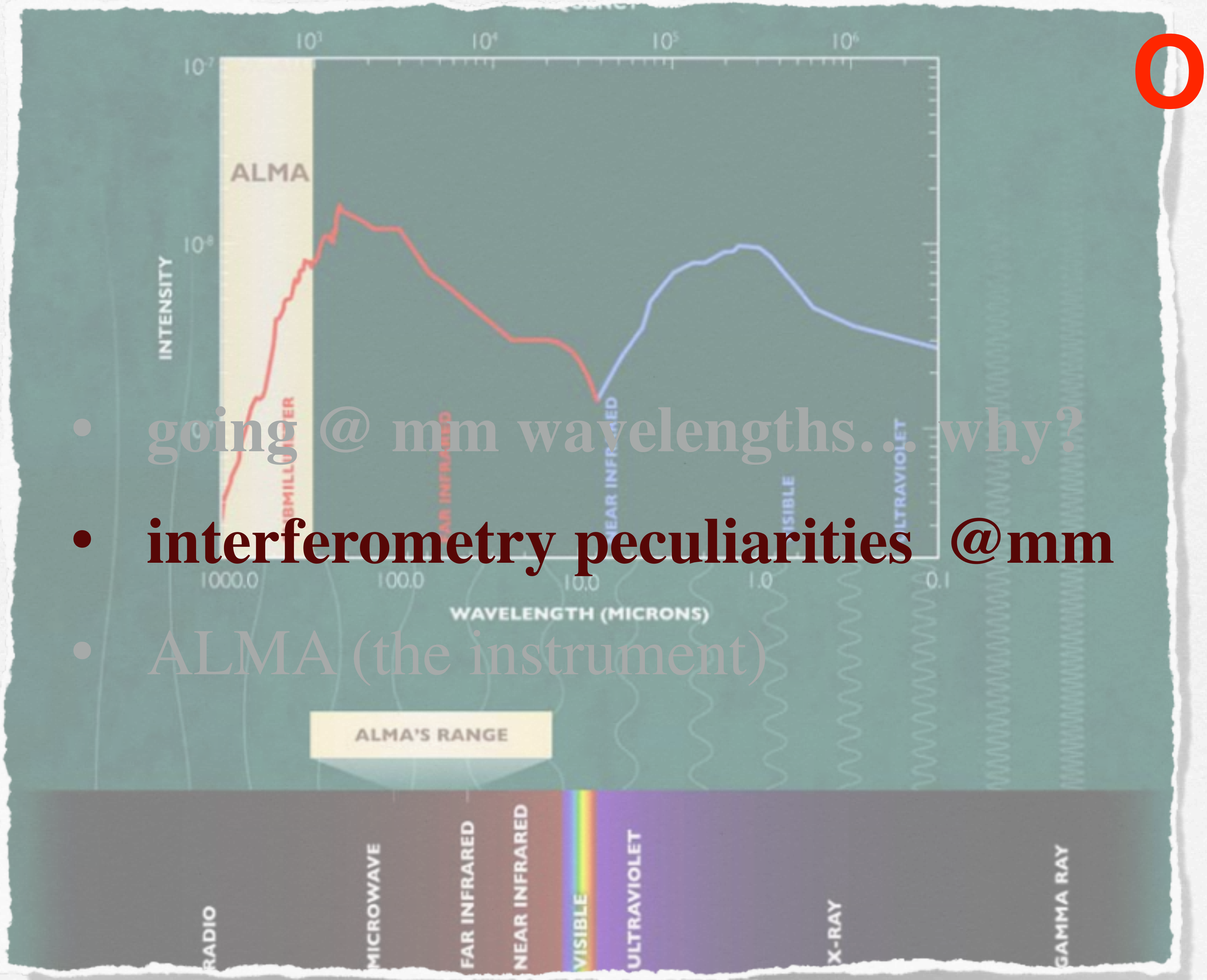
www.eso.org

why build a mm interferometer?

R sculptoris

www.eso.org

Outline

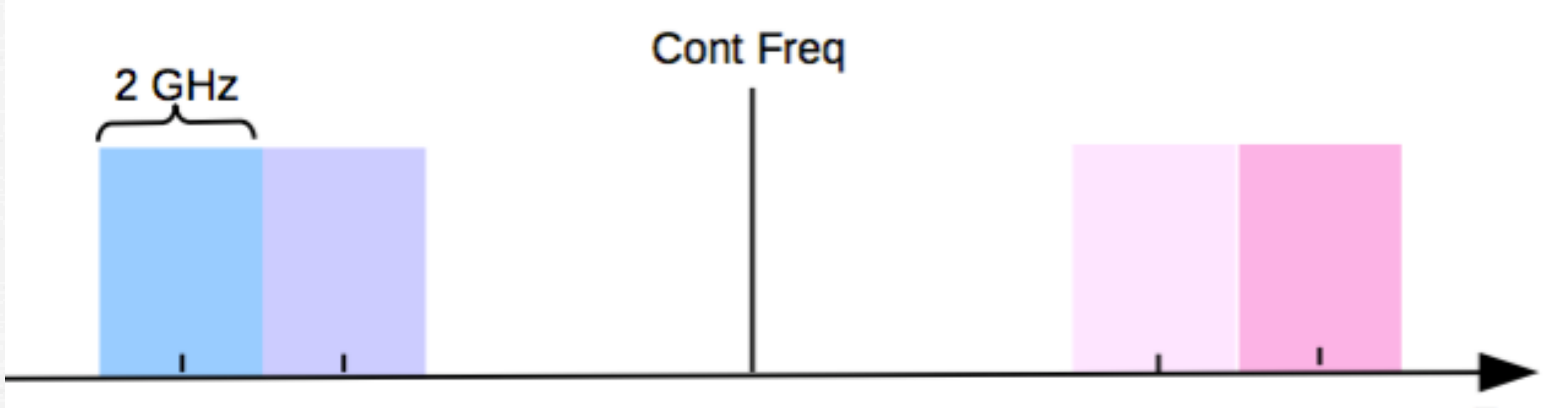


- going @ mm wavelengths… why?
- **interferometry peculiarities @mm**
- ALMA (the instrument)

Interferometric peculiarities @ mm

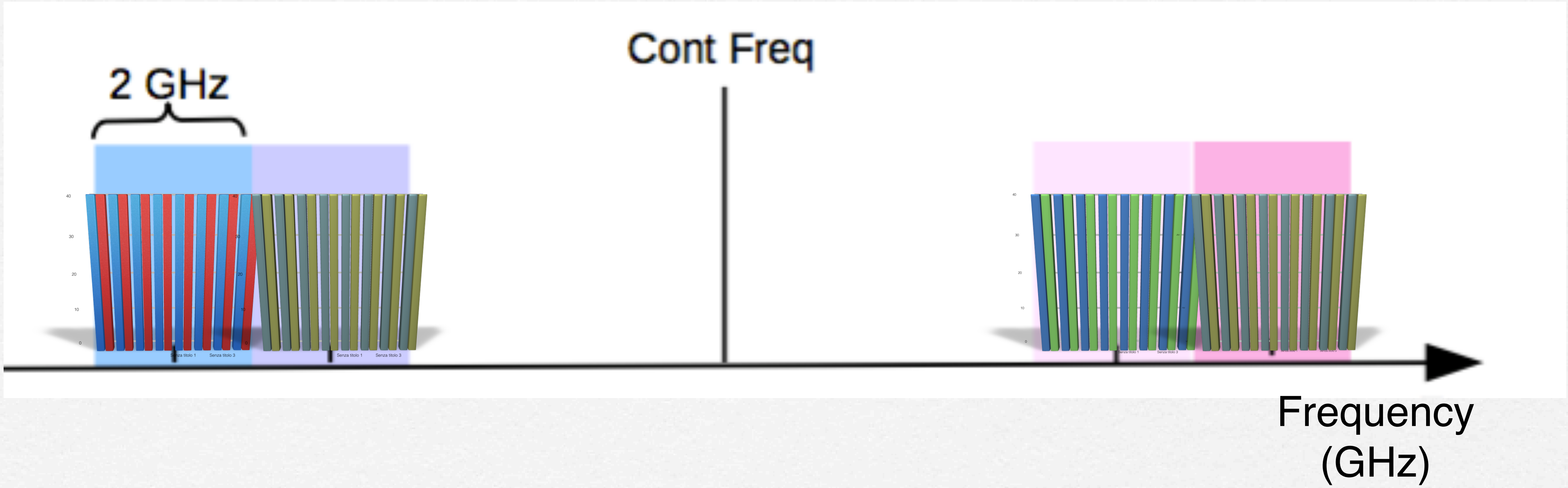
(ALMA) data format—> the cube

- @mm wavelengths molecular spectroscopy
  - wide spectral range (~8GHz)
  - each spw divided into several channels



Interferometric peculiarities @ mm

(ALMA) data format—> the cube

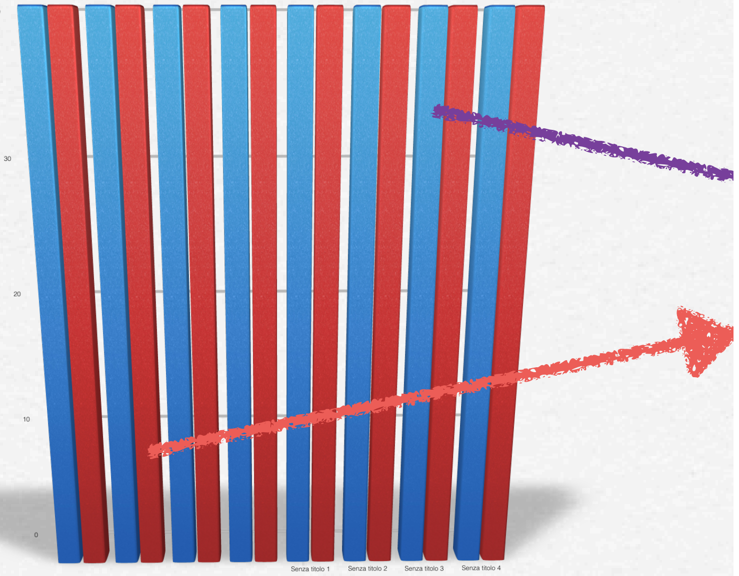


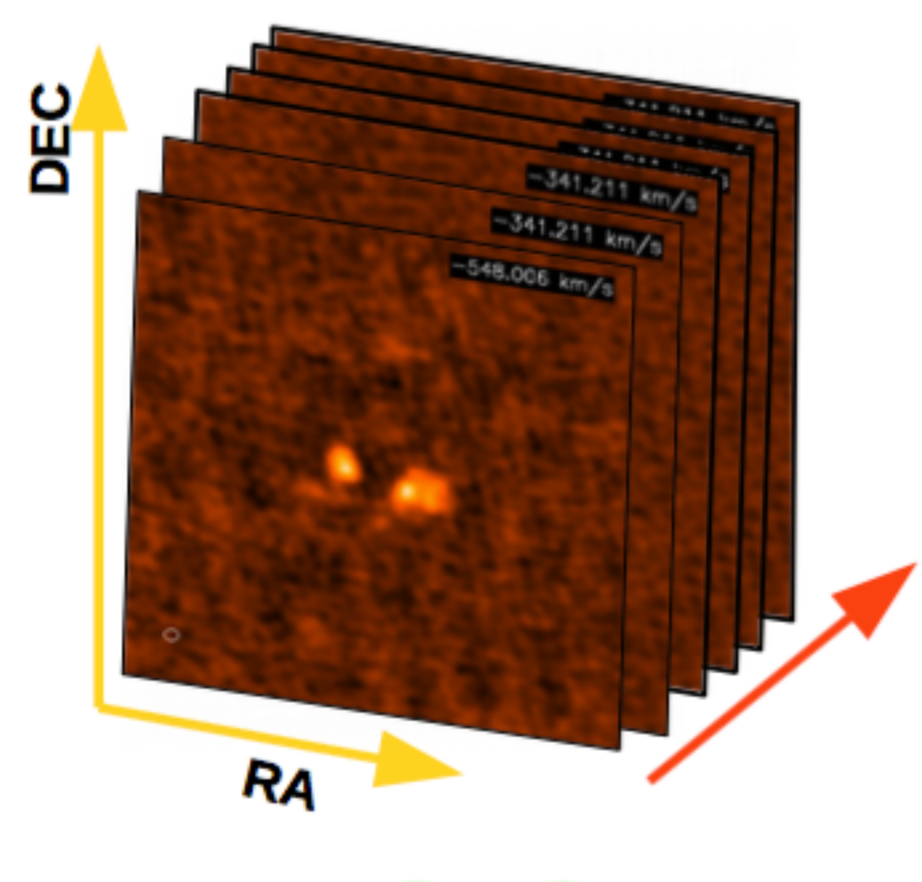
Interferometric peculiarities @ mm

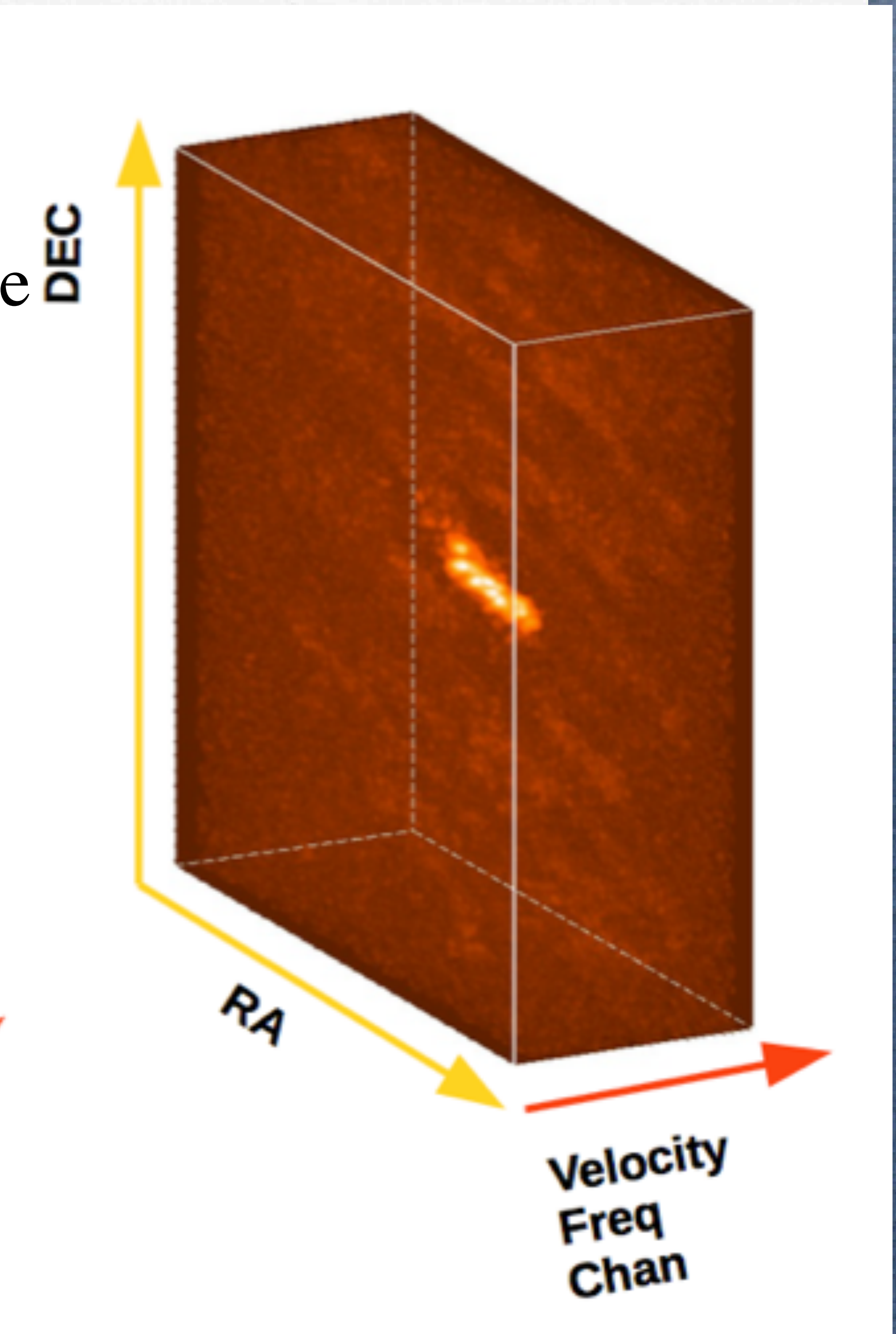
(ALMA) data format—> the cube

From each channel, one uv-plane/image is produced

Spectral line observations have up to 3840 channels. The highest spectral resolution achieavable is 30 kHz.



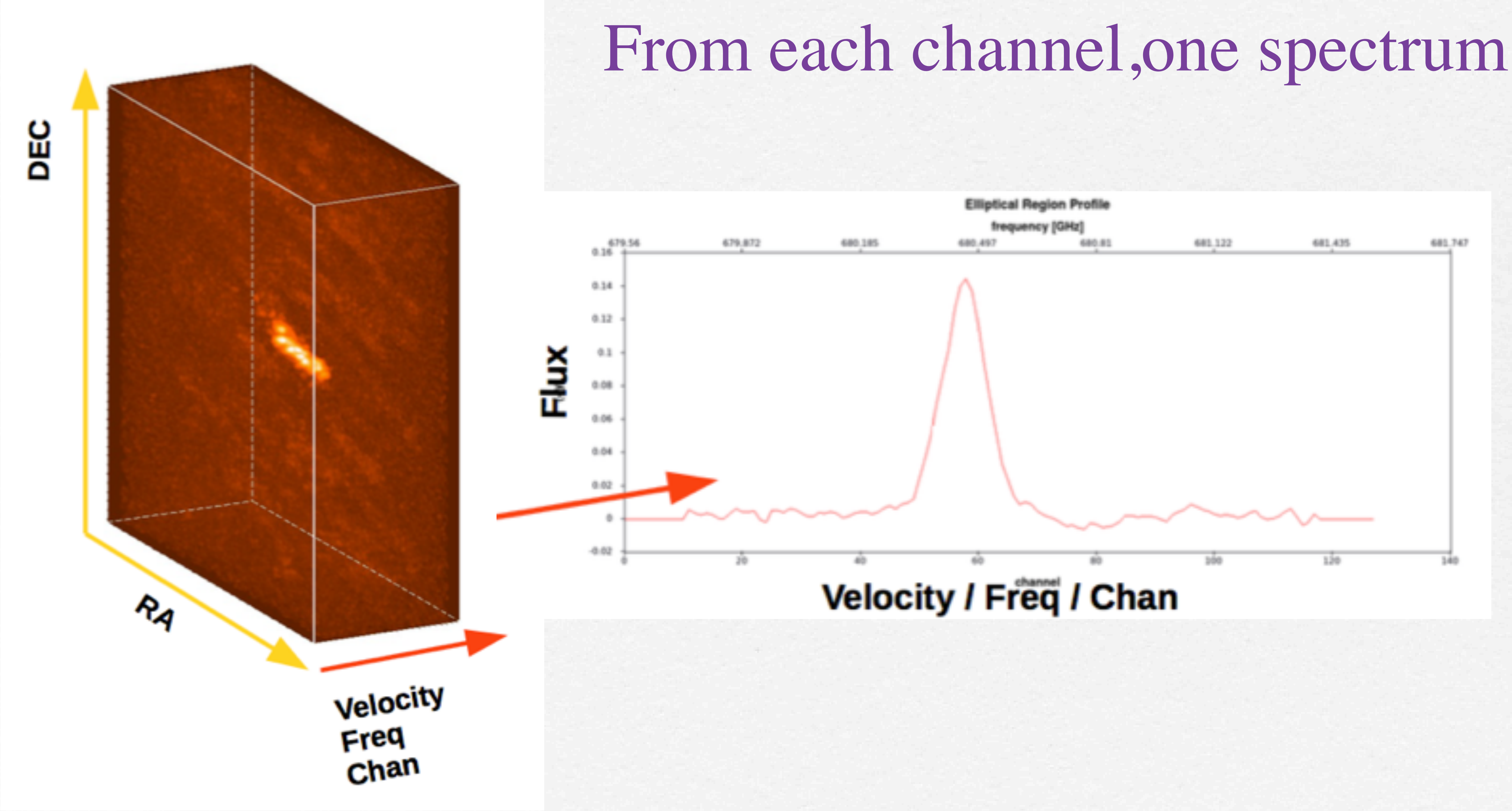




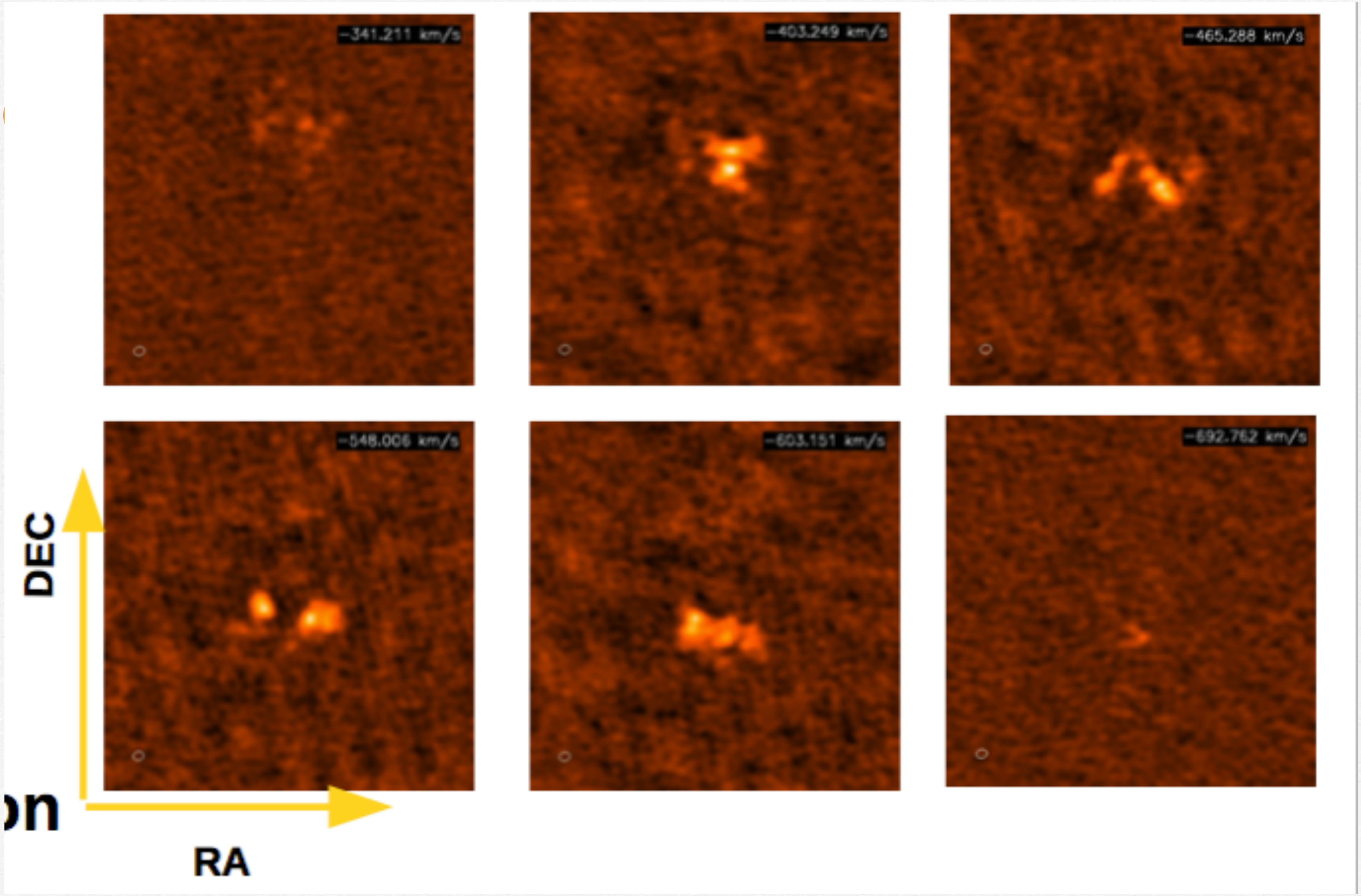
Interferometric peculiarities @ mm

(ALMA) data format —> the cube

From each channel,one spectrum!



Interferometric peculiarities @ mm

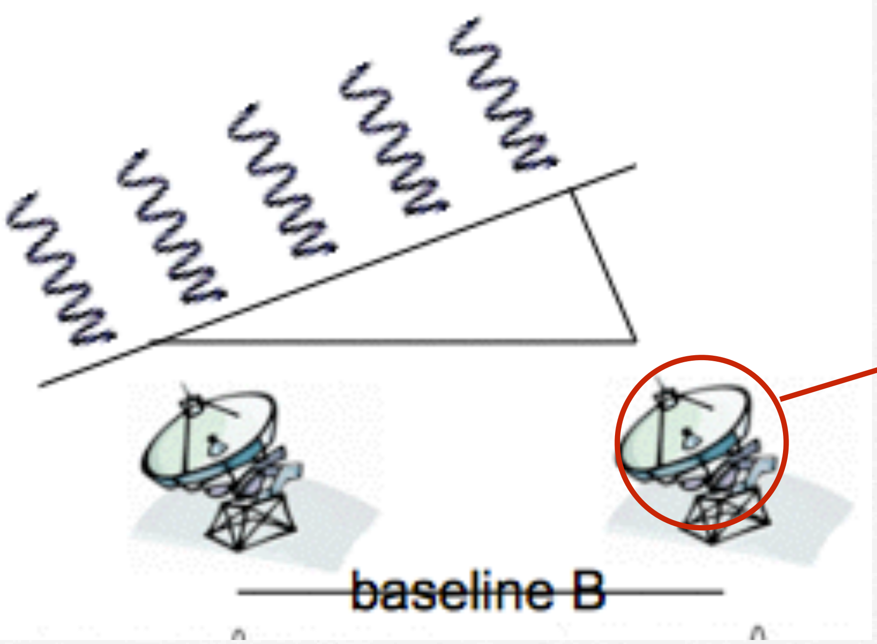


A brief (very brief) intro to interferometry

you should already know that….

A brief (very brief) intro to interferometry

- Field of View: depends on the single dish diameter

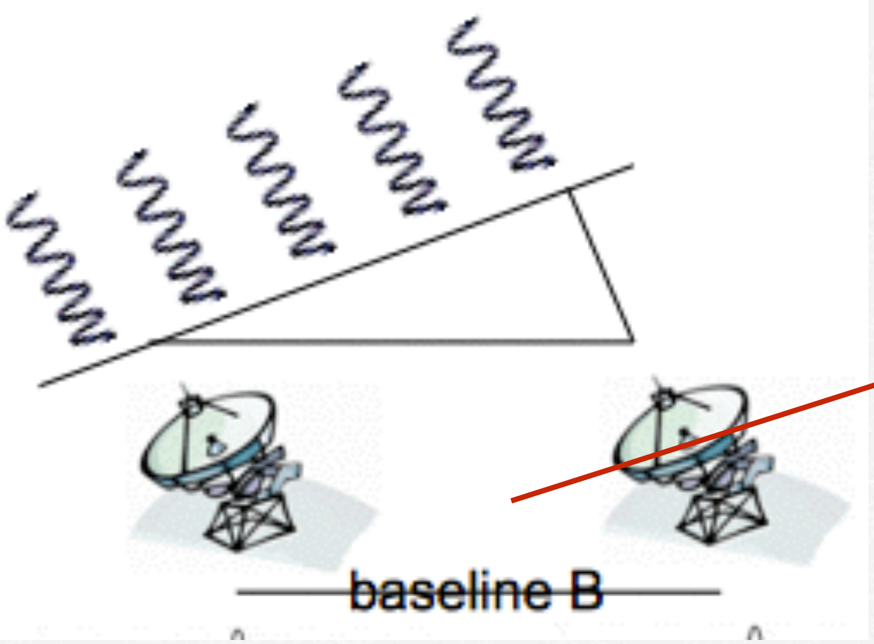


FOV = λ/D

smaller dish —> larger FOV

A brief (very brief) intro to interferometry

- Angular resolution: depends on maximum distance between antennas

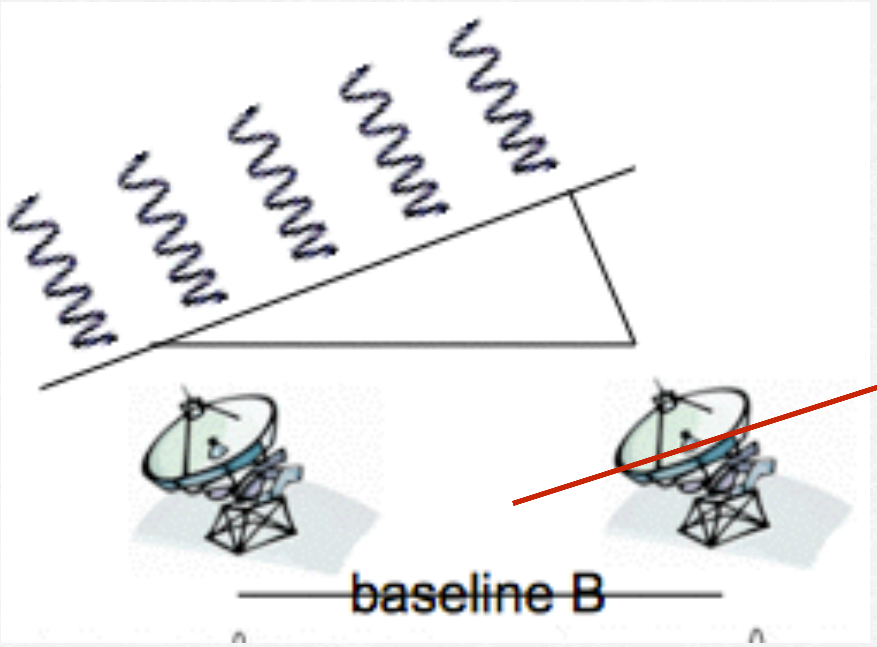


$$\theta_{max} = \lambda/D_{max}$$

- more distant —> more resolution (image details)

A brief (very brief) intro to interferometry

- Largest Angular scale: depends on minimum distance between antennas

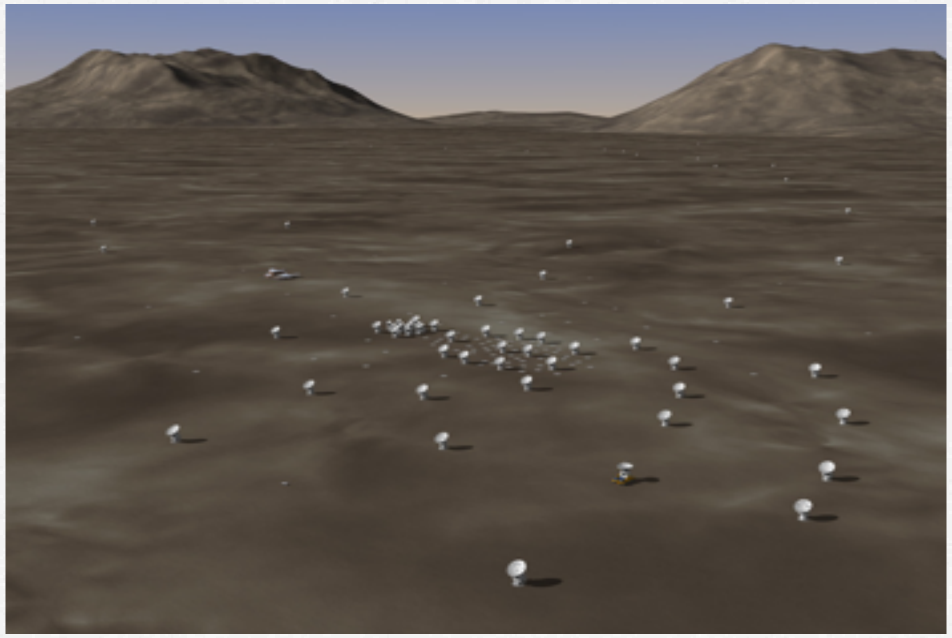


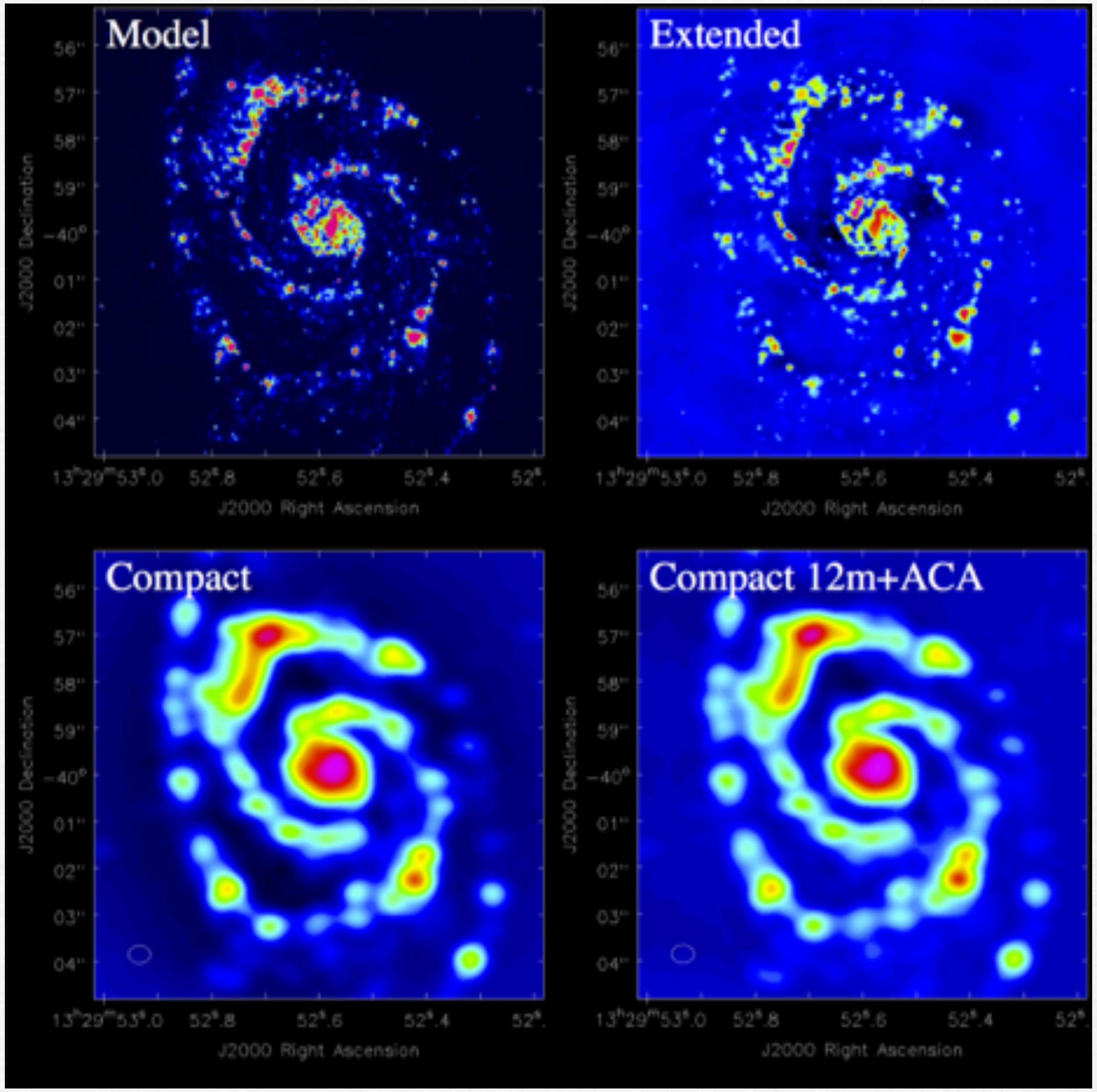
LAS = λ / D_{min}

- more compact —> sensitive to extended sources

so what?

- Largest scale: depends on minimum distance between antennas





- more compact —> sensitive to extended sources

A brief (very brief) intro to interferometry

- Sensitivity: depends on … a lot of things

$$\Delta S_\nu = 2\,k\,\frac{T_{\mathrm{sys}}}{A_{\mathrm{e}}\sqrt{2t\,\Delta\nu}}$$

The rms noise in the signal (sensitivity):

Tsys is the brightness temperature equivalent to the flux received from the antenna

source, atmosphere, instrumental noise….

Sensitivity can be improved by:

- getting **lower Tsys** (sites with low water vapour levels)
- increasing the **collecting area**
- increasing the **bandwidth** and/or the **integration time**

Interferometric peculiarities @ mm

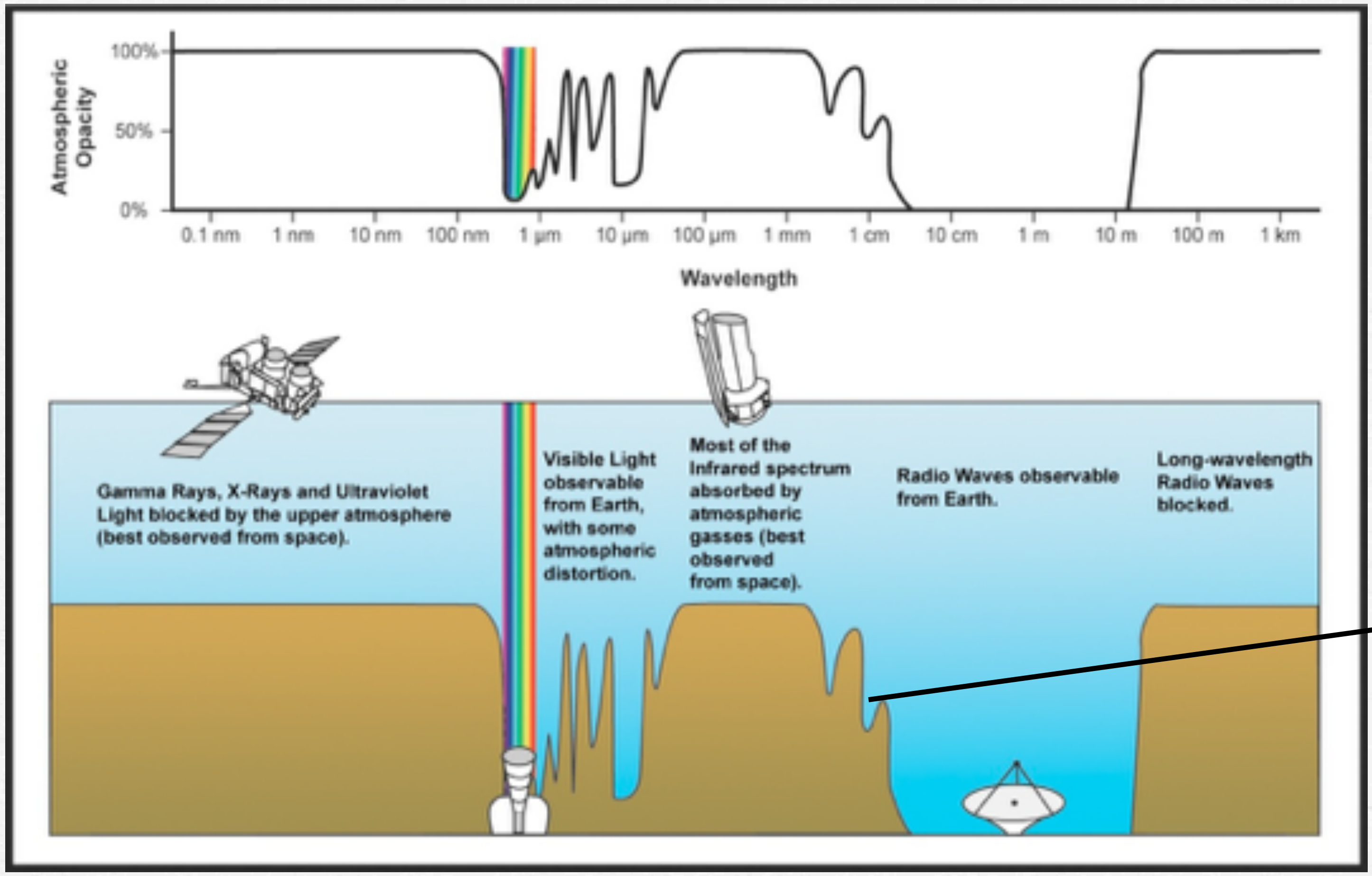
what changes for observer between cm and mm waves?

… with increasing frequency

- non-thermal sources become weaker, but thermal sources are not strong yet
- no external human interference in the data
- 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….)

Interferometric peculiarities @ mm

The atmospheric transmission windows



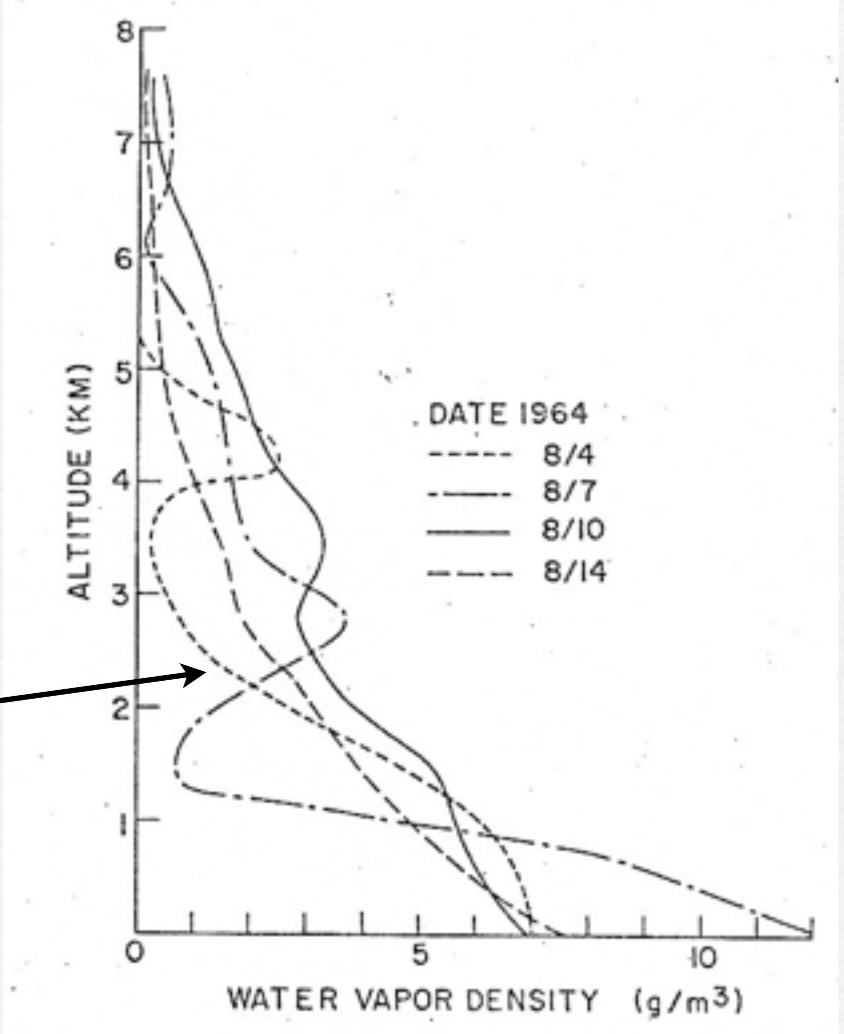


Fig. 3. Atmospheric water vapor profiles measured by radiosondes.

From: Staelin, 1966
(method: radiosondes)

Main absorber:

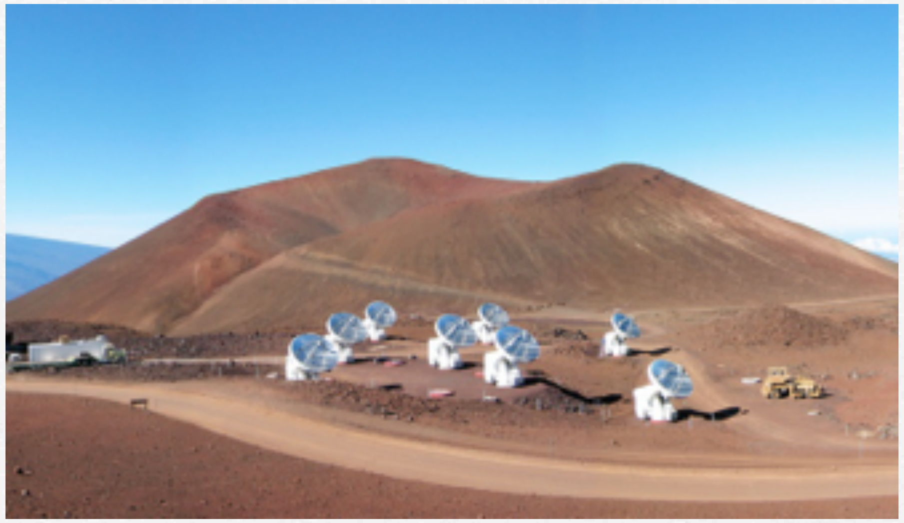
H_20

Co_2

Interferometric peculiarities @ mm

ALMA: 5000m

SMA: 4100m



PdBI: 2550m

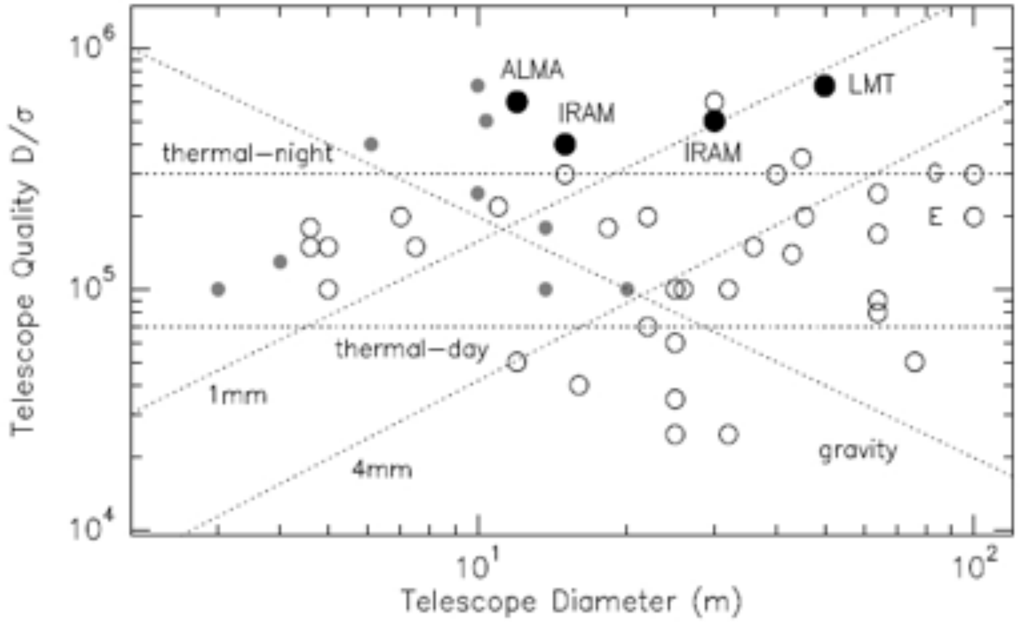
CARMA: 2440m

ATCA: 208m

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

Interferometric peculiarities @ mm

mm Telescopes - Properties



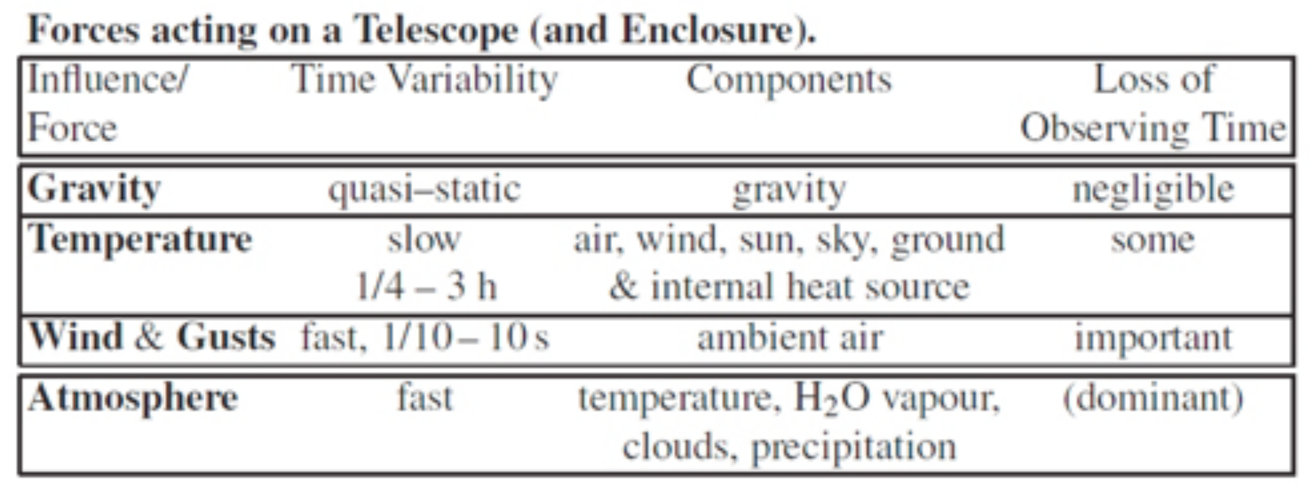
Von Hoerner–diagram. Telescope quality D/σ (D = reflector diameter, σ = surface precision, rms value) and natural limits of gravity and thermal effects, for mm – wavelength (•) and cm–wavelength telescopes (○). The lines labelled 1 mm and 4 mm show the relation $\lambda_{\min} = 16\,\sigma$. For the 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)

Interferometric peculiarities @ mm

mm Telescopes - Properties

Von Hoerner–dia
rms value) and na
wavelength telesc
the limiting relatio
Effelsberg telescop

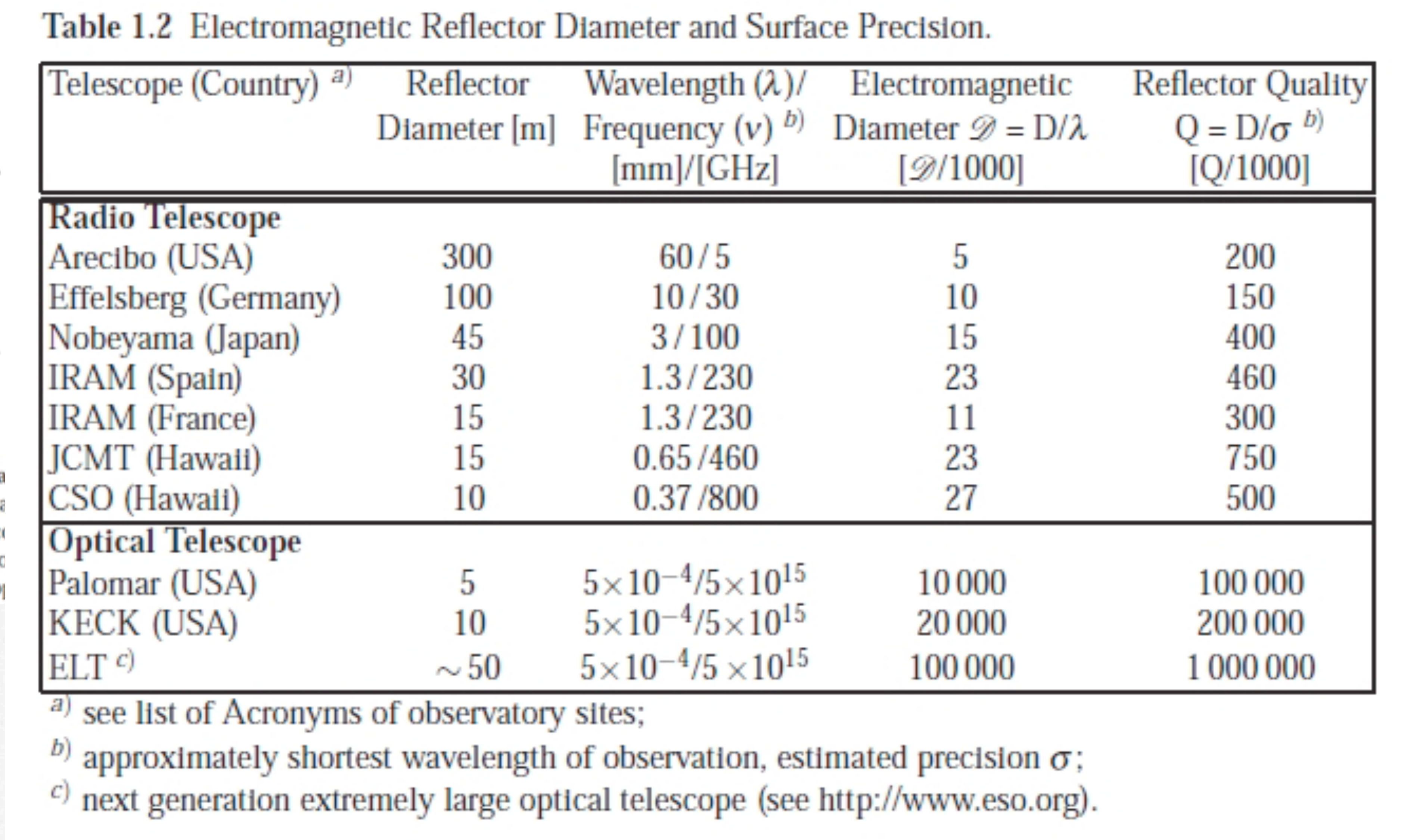


Table 1.2 Electromagnetic Reflector Diameter and Surface Precision.

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]	~50	$5\times10^{-4}/5\times10^{15}$	100 000	1 000 000

[a] see list of Acronyms of observatory sites;

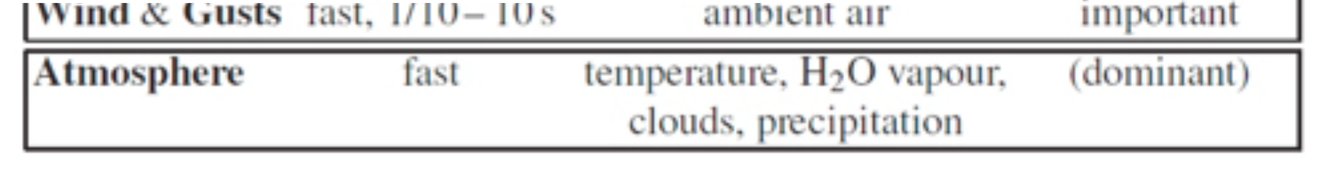
[b] approximately shortest wavelength of observation, estimated precision σ;

[c] next generation extremely large optical telescope (see http://www.eso.org).

Problems:

hest frequency,

ng weather



			Loss of serving Time
			negligible
			some
Wind & Gusts	fast, 1/10 – 10 s	ambient air	important
Atmosphere	fast	temperature, H_2O vapour, clouds, precipitation	(dominant)

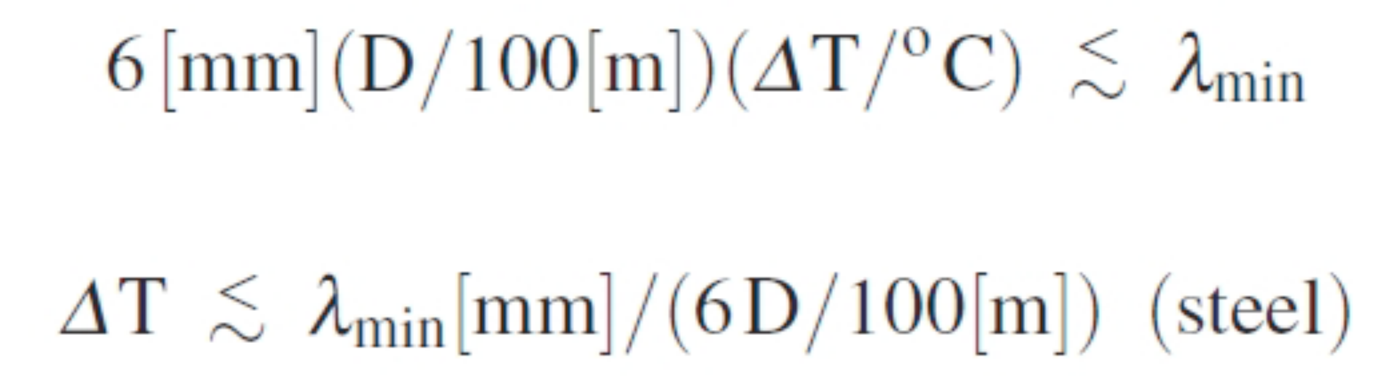
weather conditions really important!!!

mm Telescopes - Properties

Temperature variation and telescope geometry

Two approches to get the desired millimeter performance:

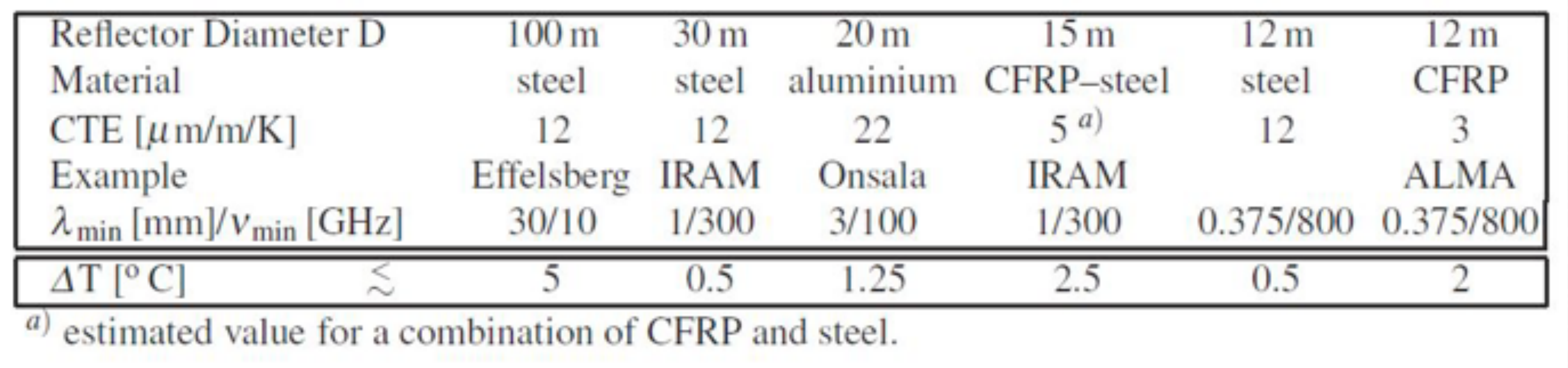
- choose material with compatible constant of thermal expansion
- control the reflector temperature



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

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

Von Hoerner (1967, 1975)



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 [$^{\circ}$C] $\lesssim$	5	0.5	1.25	2.5	0.5	2

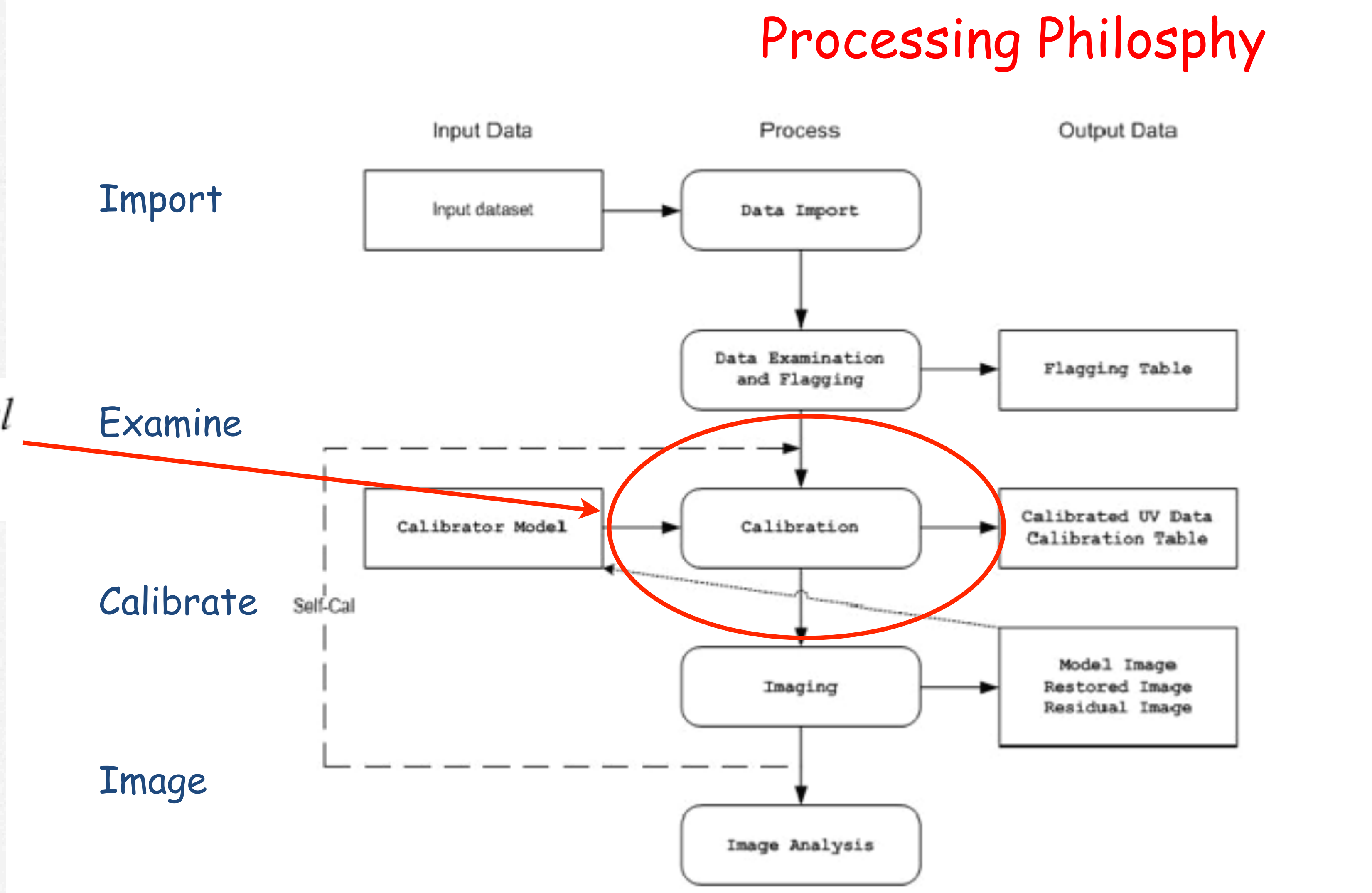
[a] estimated value for a combination of CFRP and steel.

Interferometric peculiarities @ mm

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

Input Data
Process
Output Data

Import
Input dataset
Data Import

Examine
Data Examination and Flagging
Flagging Table

Calibrate
Self-Cal
Calibrator Model
Calibration
Calibrated UV Data
Calibration Table

Image
Imaging
Model Image
Restored Image
Residual Image
Image Analysis

Data Reduction (Calibration)

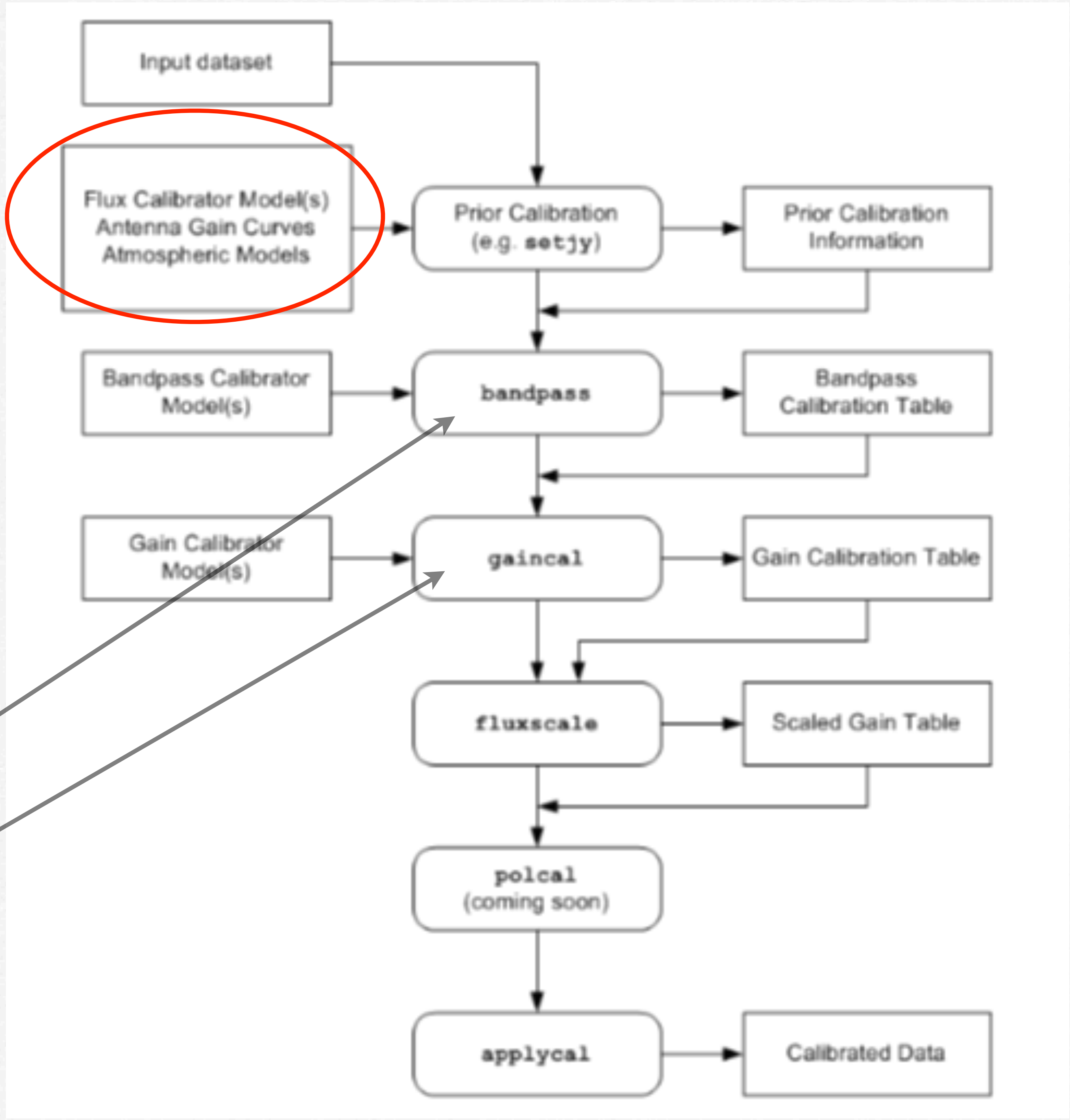
Measurement Equation

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

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



Input dataset

Flux Calibrator Model(s)
Antenna Gain Curves
Atmospheric Models

Prior Calibration
(e.g. `setjy`)

Prior Calibration Information

Bandpass Calibrator Model(s)

`bandpass`

Bandpass Calibration Table

Gain Calibrator Model(s)

`gaincal`

Gain Calibration Table

`fluxscale`

Scaled Gain Table

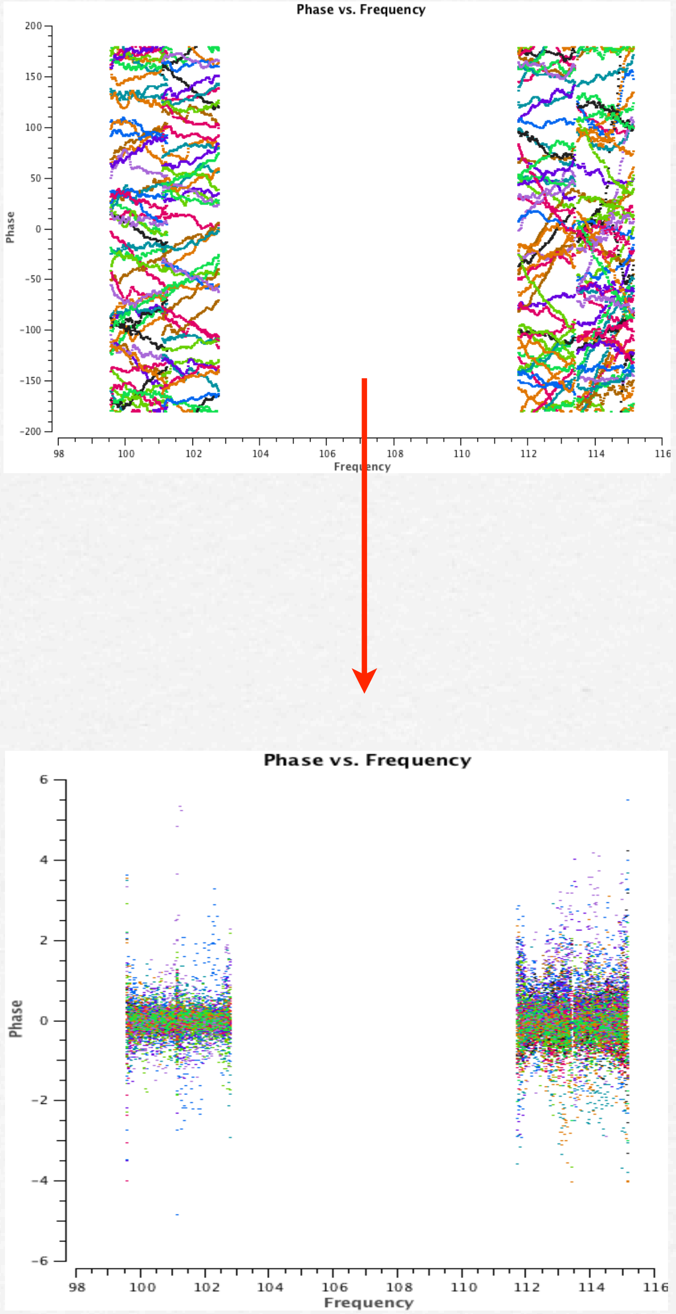
`polcal`
(coming soon)

`applycal`

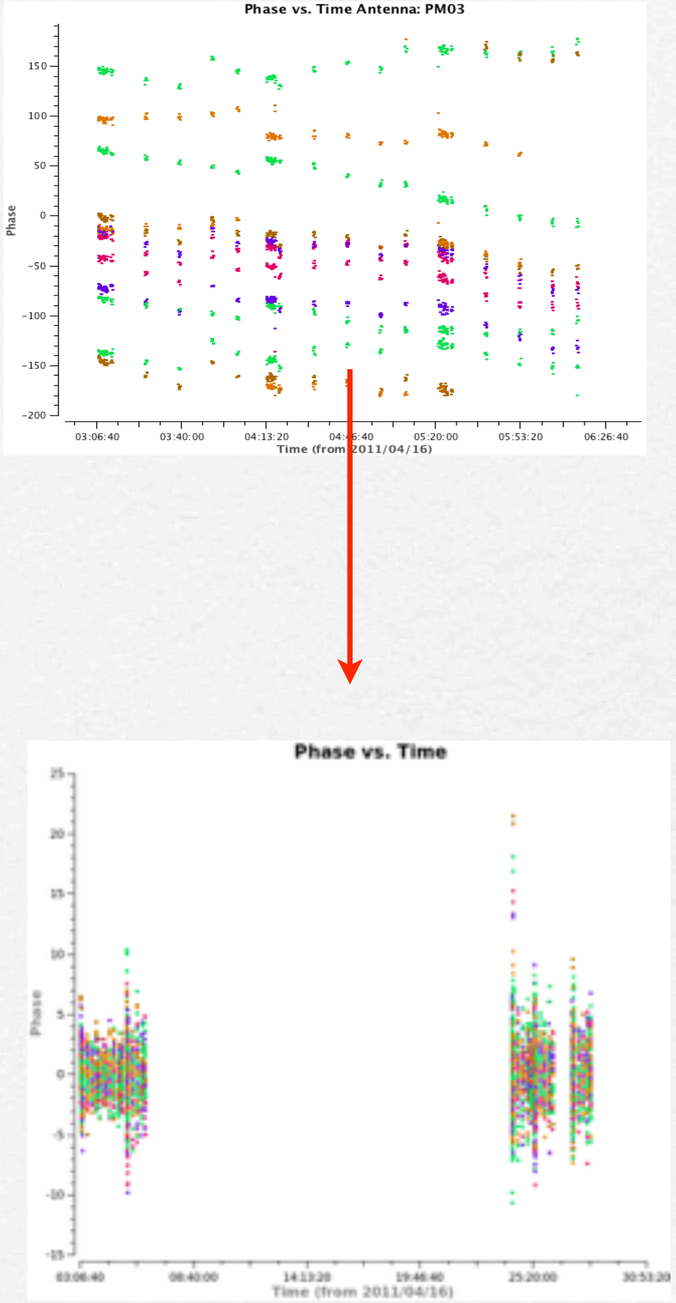
Calibrated Data

Data Reduction (Calibration): why so important?

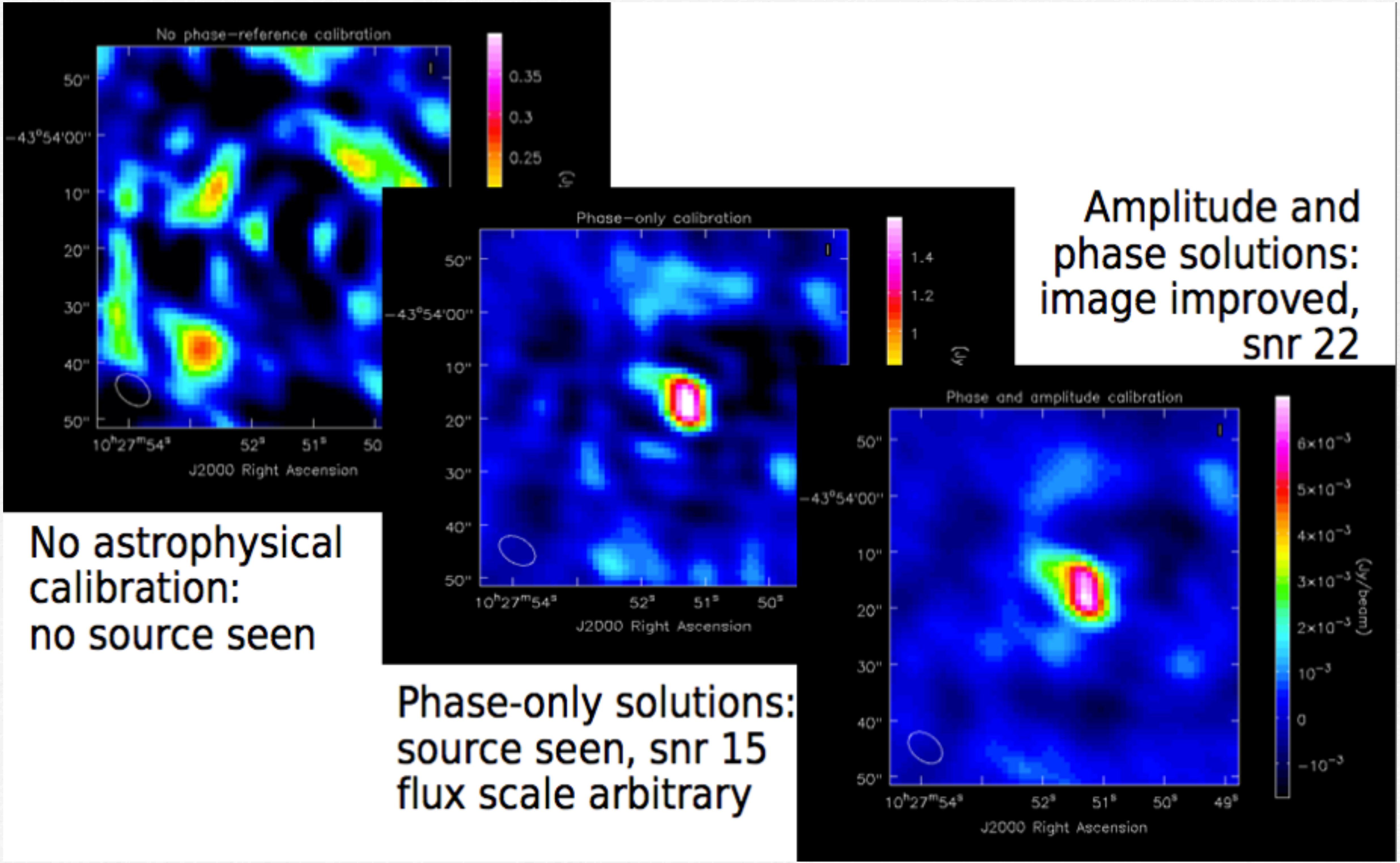
Frequency dependent



Time dependent



Data Reduction (Calibration)



No astrophysical calibration:
no source seen

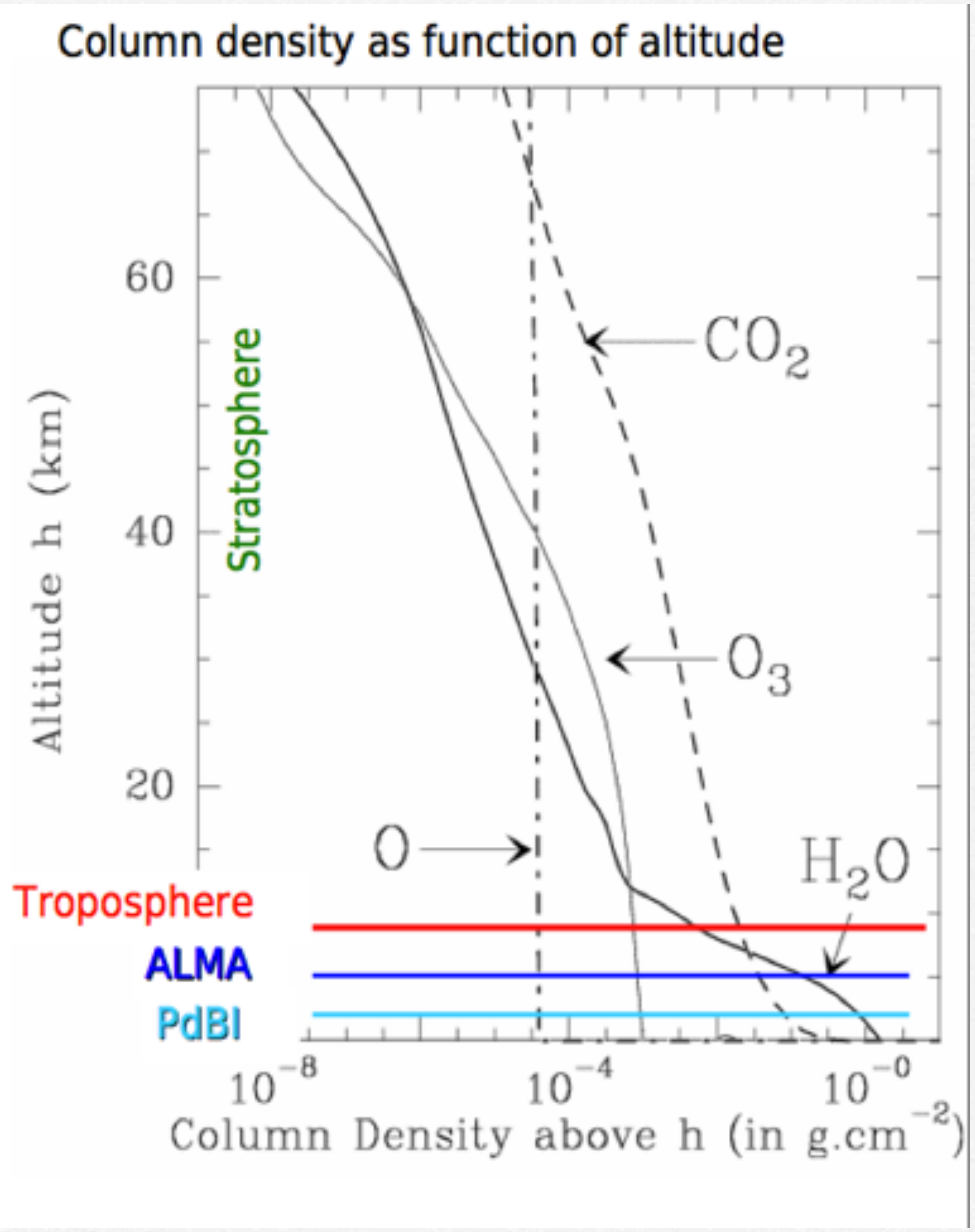
Phase-only solutions:
source seen, snr 15
flux scale arbitrary

Amplitude and
phase solutions:
image improved,
snr 22

Interferometric peculiarities @ mm

The role of troposphere

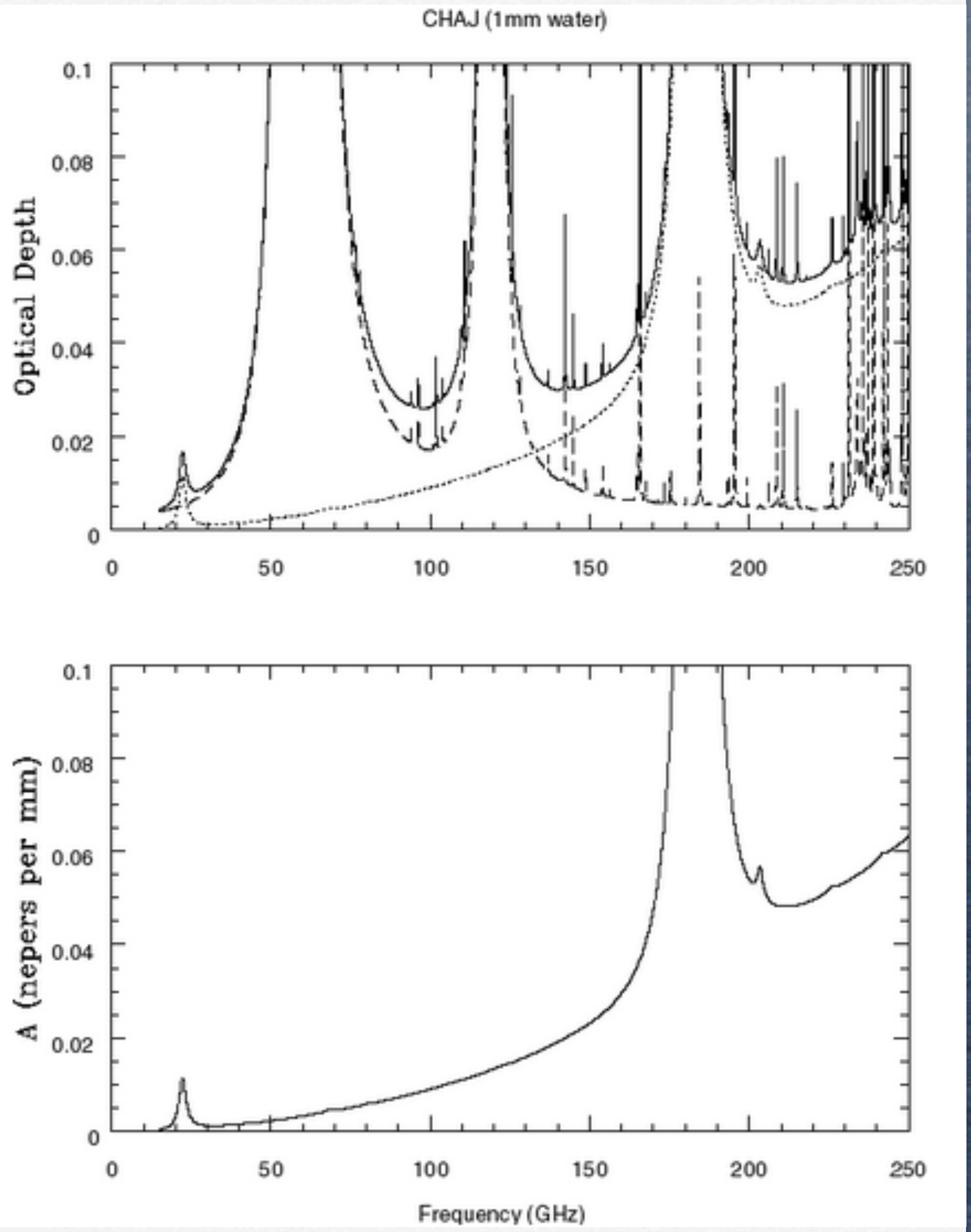
- 'Dry' component:
  - Worst O_2, O_3
- 'Wet' component:
  - H_2O vapour/clouds
  - Highly turbulent layer
    - Measure PWV = precipitable water vapour
- Atmospheric depth increases at lower elevation

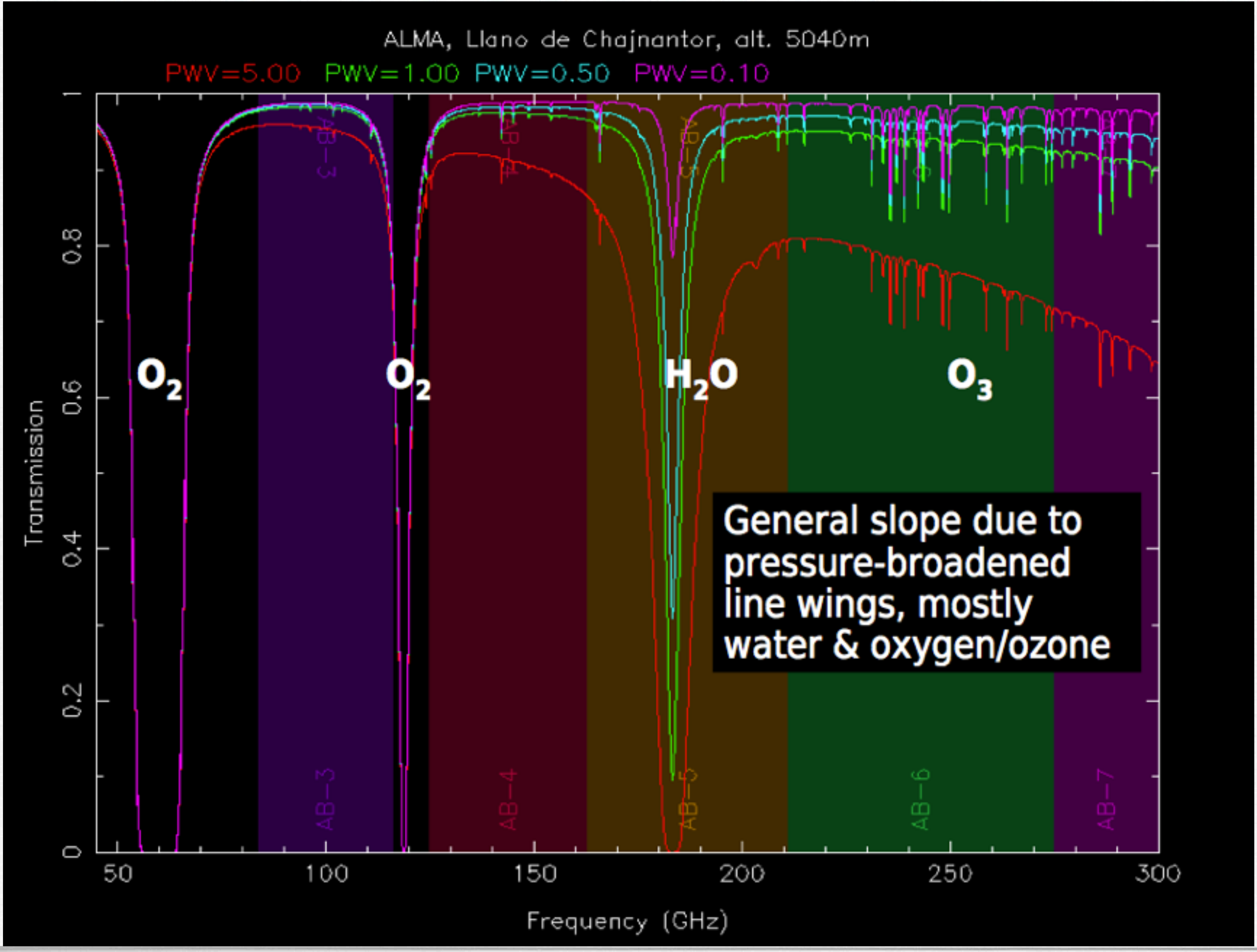


Interferometric peculiarities @ mm

The role of troposphere

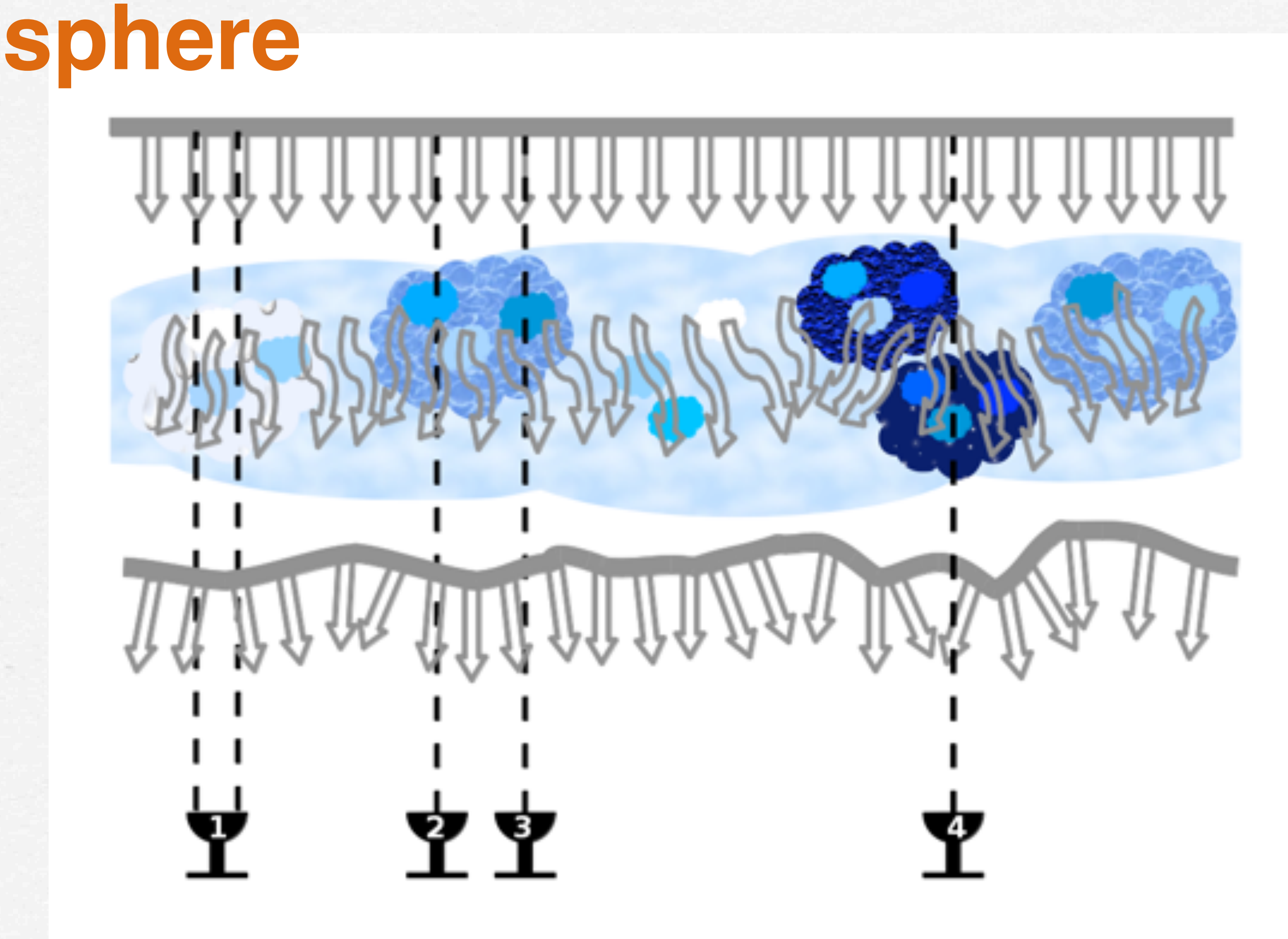
- ‘Dry’ component:
  - Worst O_2, O_3
- ‘Wet’ component:
  - H_2O vapour/clouds
  - Highly turbulent layer
    - Measure PWV = precipitable water vapour
- Atmospheric depth increases at lower elevation





General slope due to pressure-broadened line wings, mostly water & oxygen/ozone

The role of troposphere



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

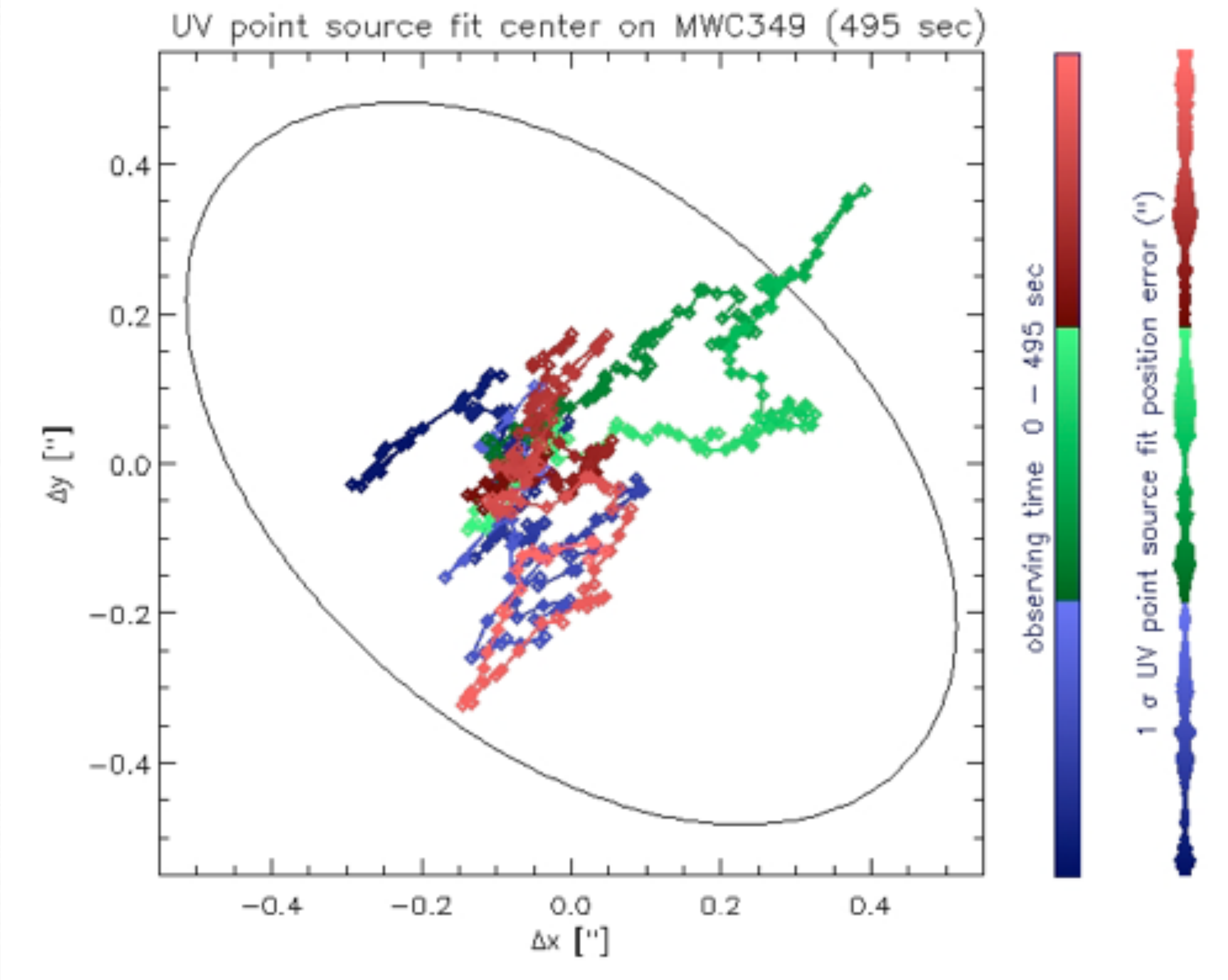
The role of troposphere: the phase noise

Three impacts on observation:

a) source “moves”

why???

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



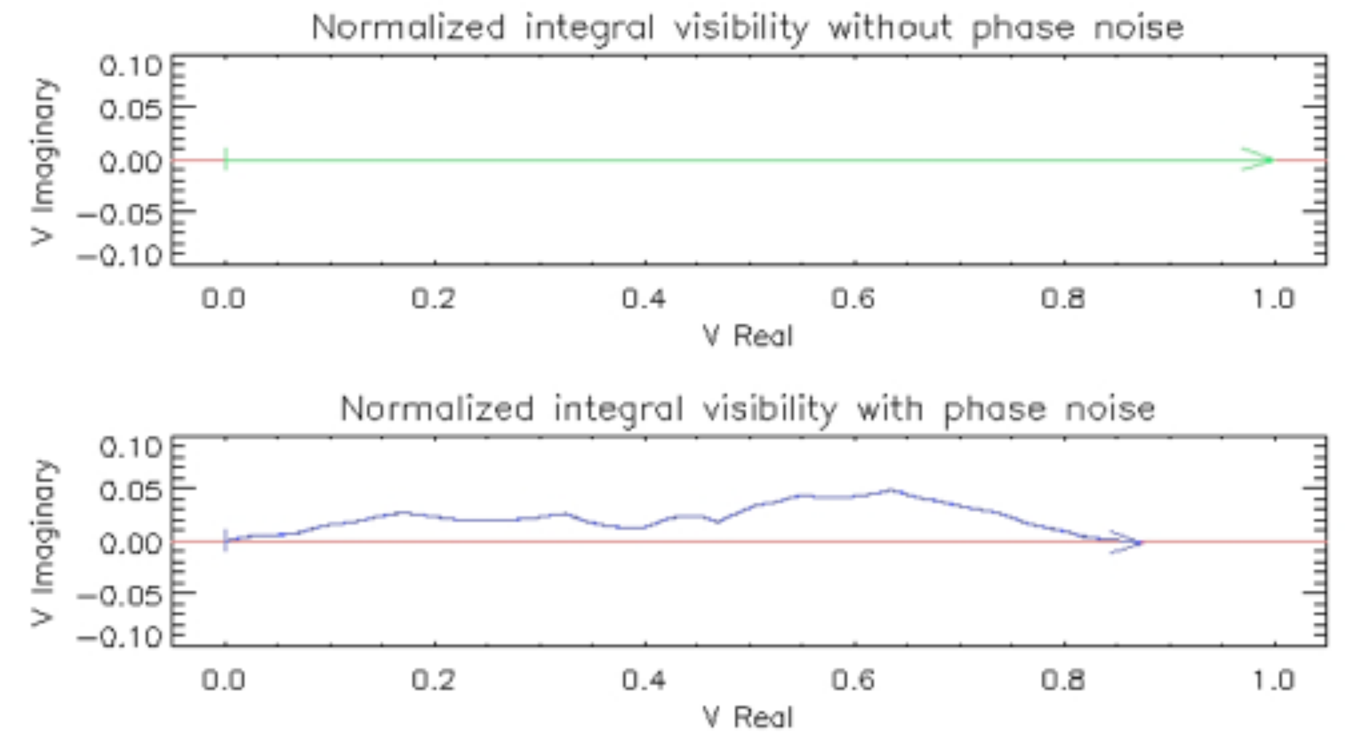
The role of troposphere: the phase noise

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

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

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

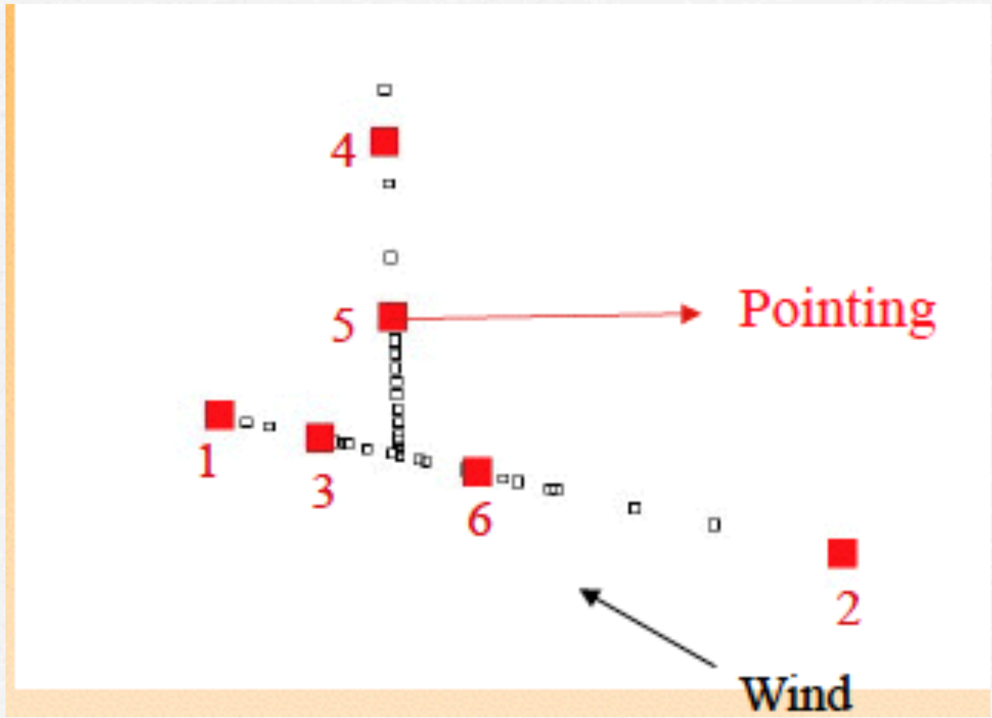
- with phase noise ϕ in radian.

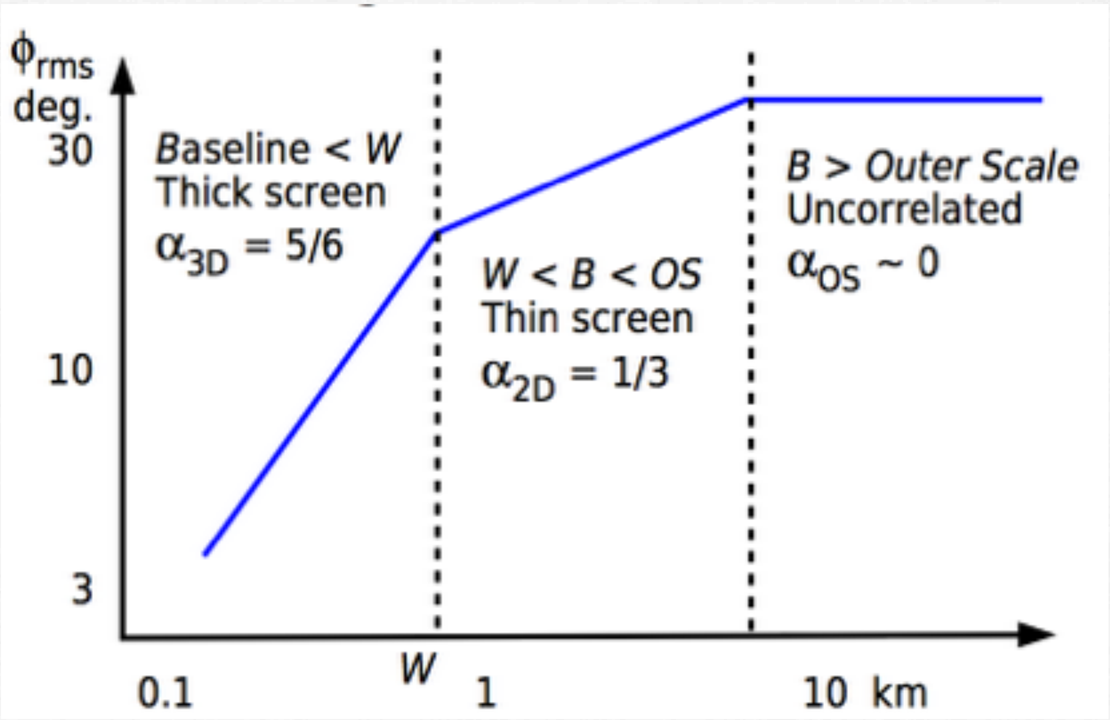


Observations were at 89 GHz and average phase noise 30º: 12.5% loss. If we would have used a frequency 2 or 3 times higher: 42% or 71% loss …

The role of troposphere: the phase noise

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





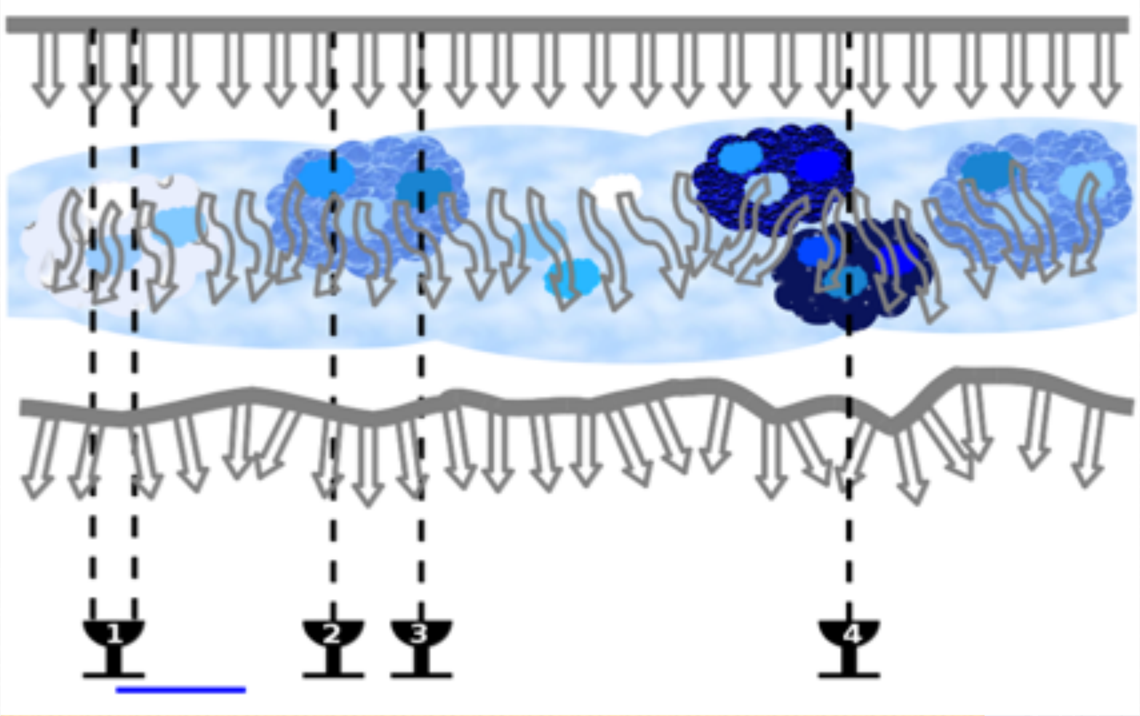
$$\varphi_{rms} = \frac{K}{\lambda} B^{\alpha}$$

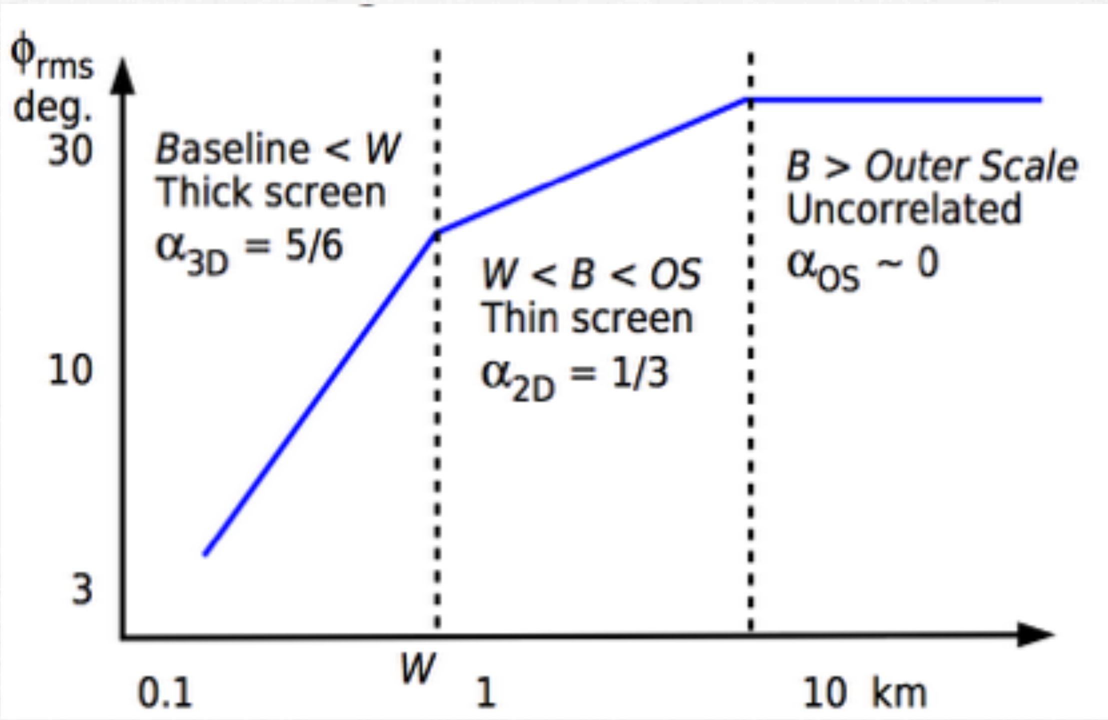
- Atmospheric phase noise is worst on the longest baselines. (Coulman '90)
    - k=100 at ALMA for λ in mm

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

The role of troposphere: the phase noise

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





- Atmospheric phase noise is worst on the longest baselines. (Coulman '90)
  - k=100 at ALMA for λ in mm
  - Antennas 1, 2, 3 see slightly different disturbances

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

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

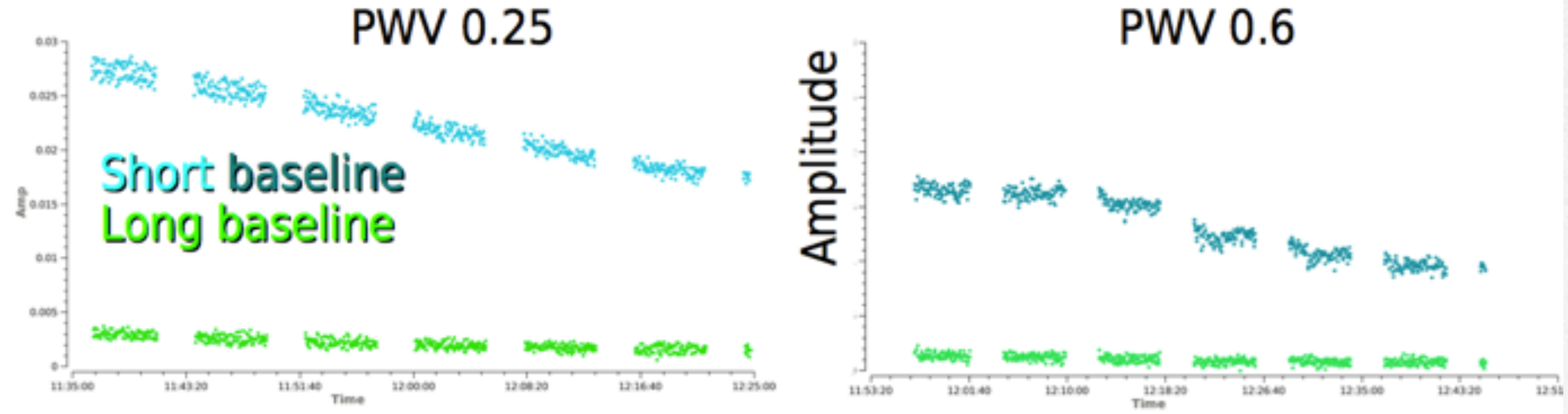
The role of troposphere: absorption and emission

- 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



Possible Solution: The radiometer

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

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

- Norma/PdBi measures PWV at 22 GHz

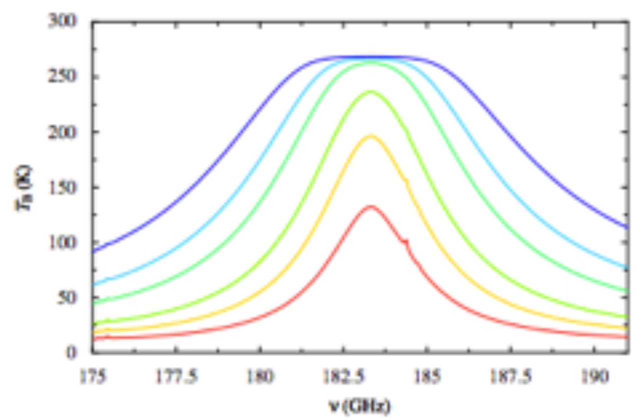
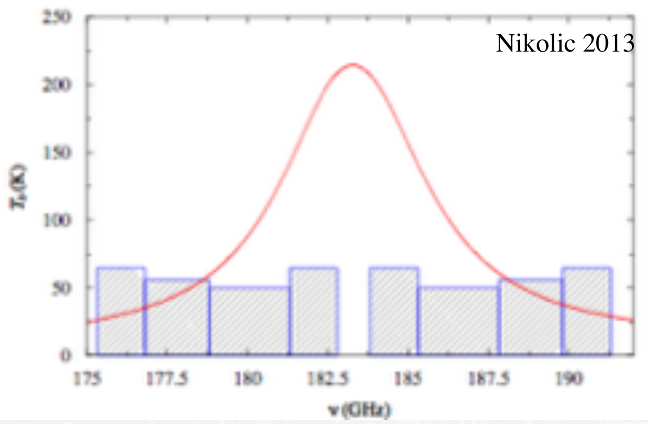


Fig. 2. Model brightness of the atmosphere at frequencies around the 183 GHz water vapour line for six values of PWV along the line of sight: 0.3, 0.6, 1, 2, 3 and 5 mm (from lowest red line to highest blue line). The model was computed using the ATM program by Pardo et al. (2001), using the source code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

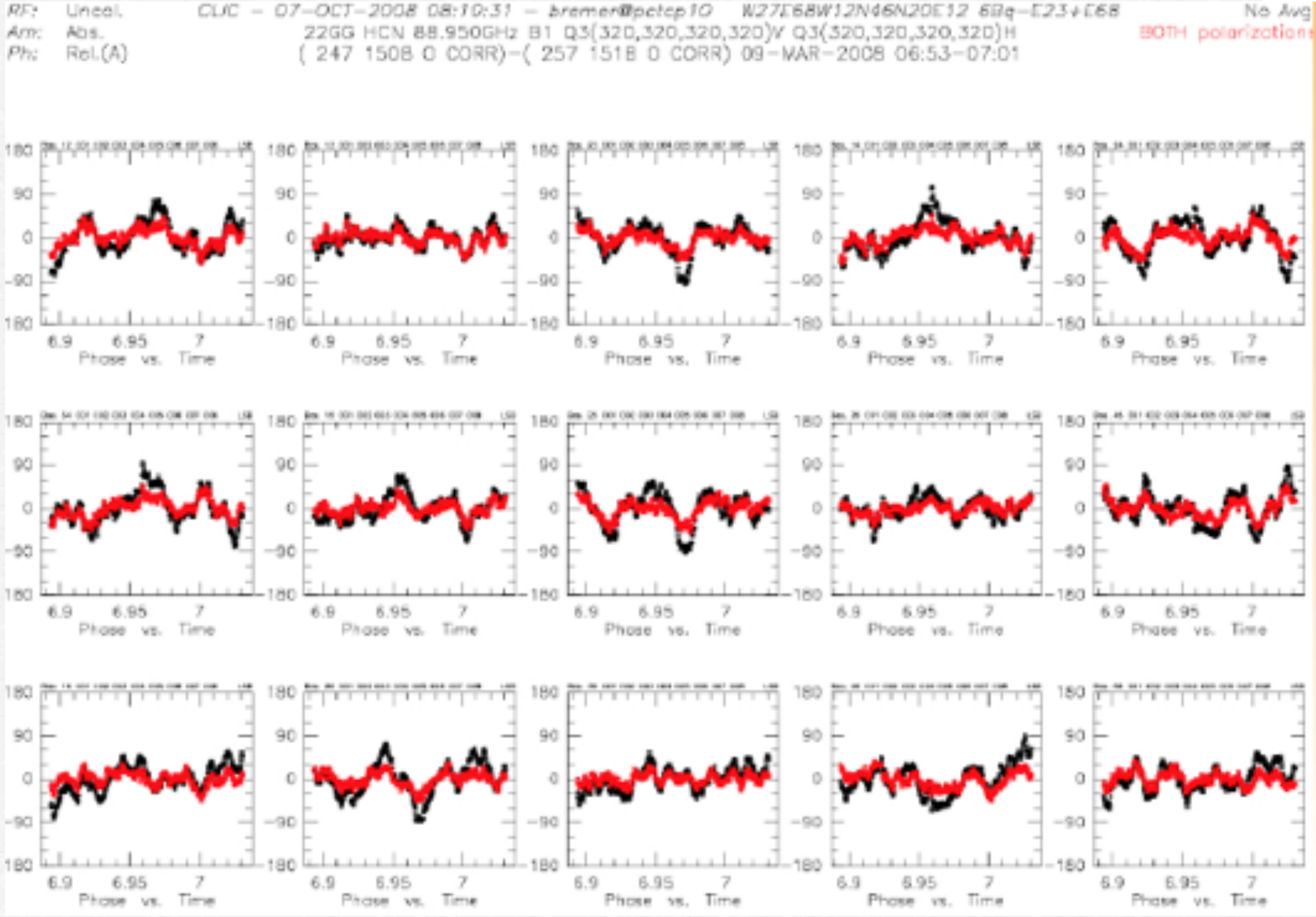
The 183 GHz Water Vapour Line

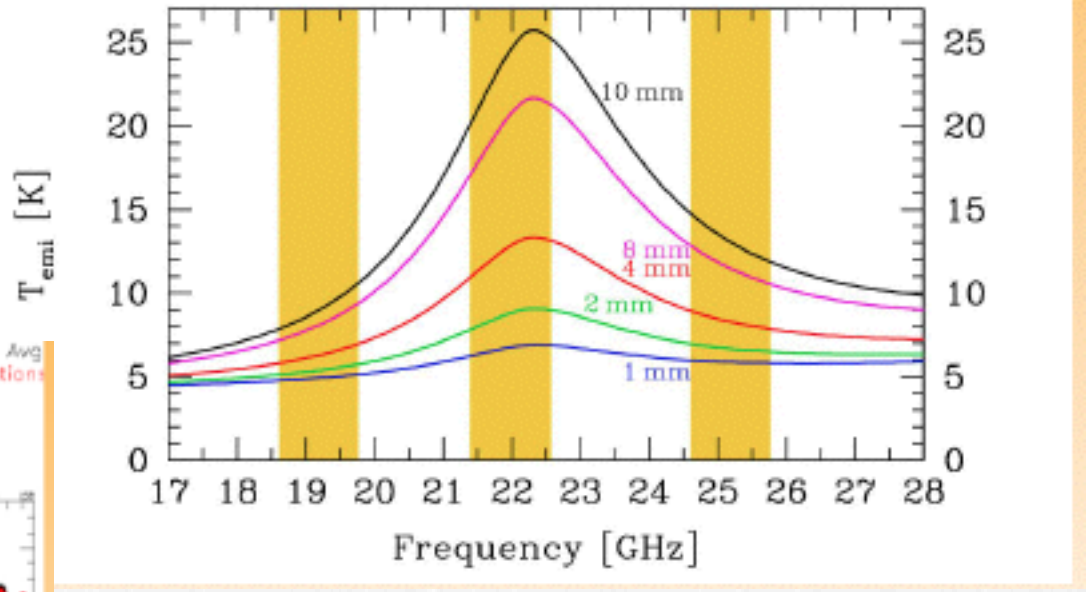
Blue rectangles are the production WVR filters

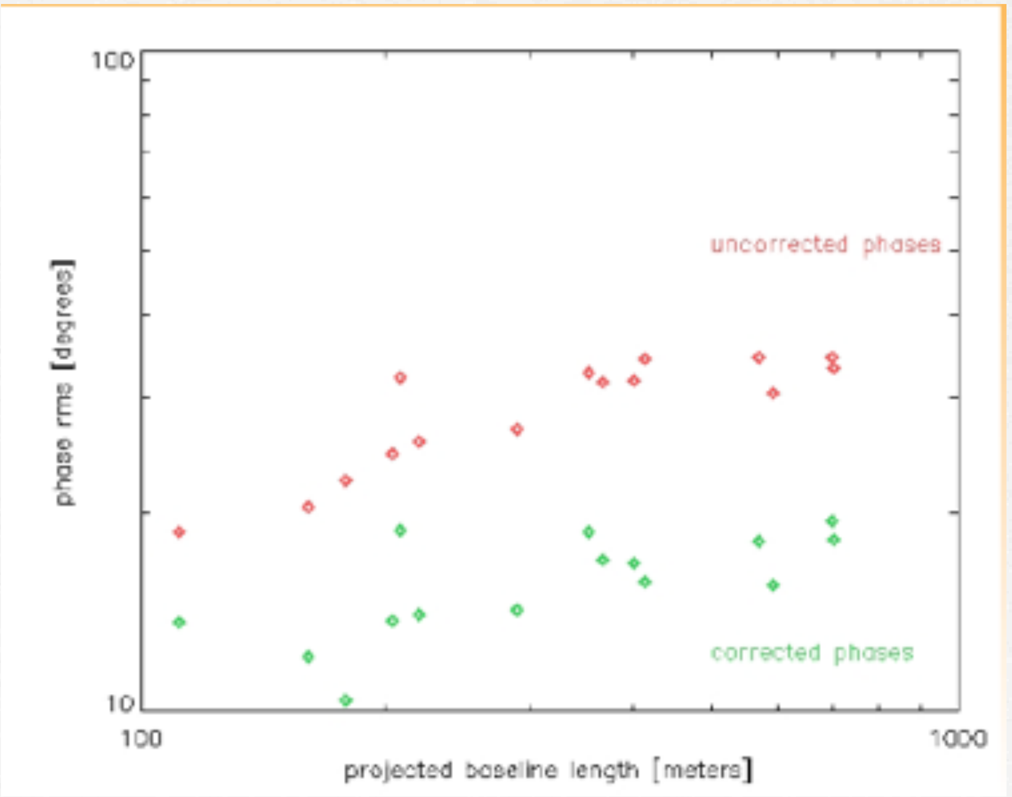


Nikolic 2013

PdBI 22 GHz radiometer





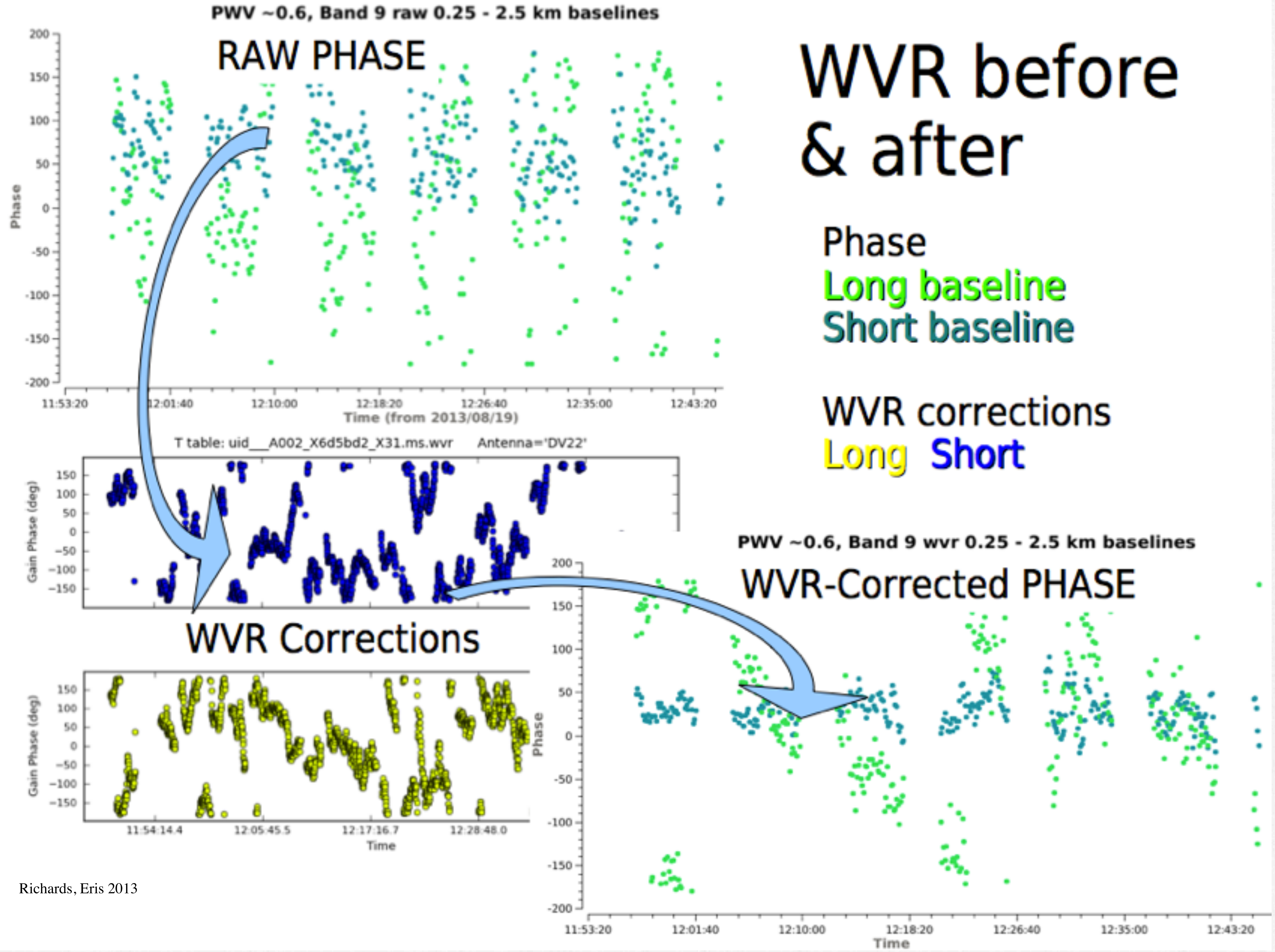


Bremer, Eris 2013

WVR before & after

Phase
Long baseline
Short baseline

WVR corrections
Long Short



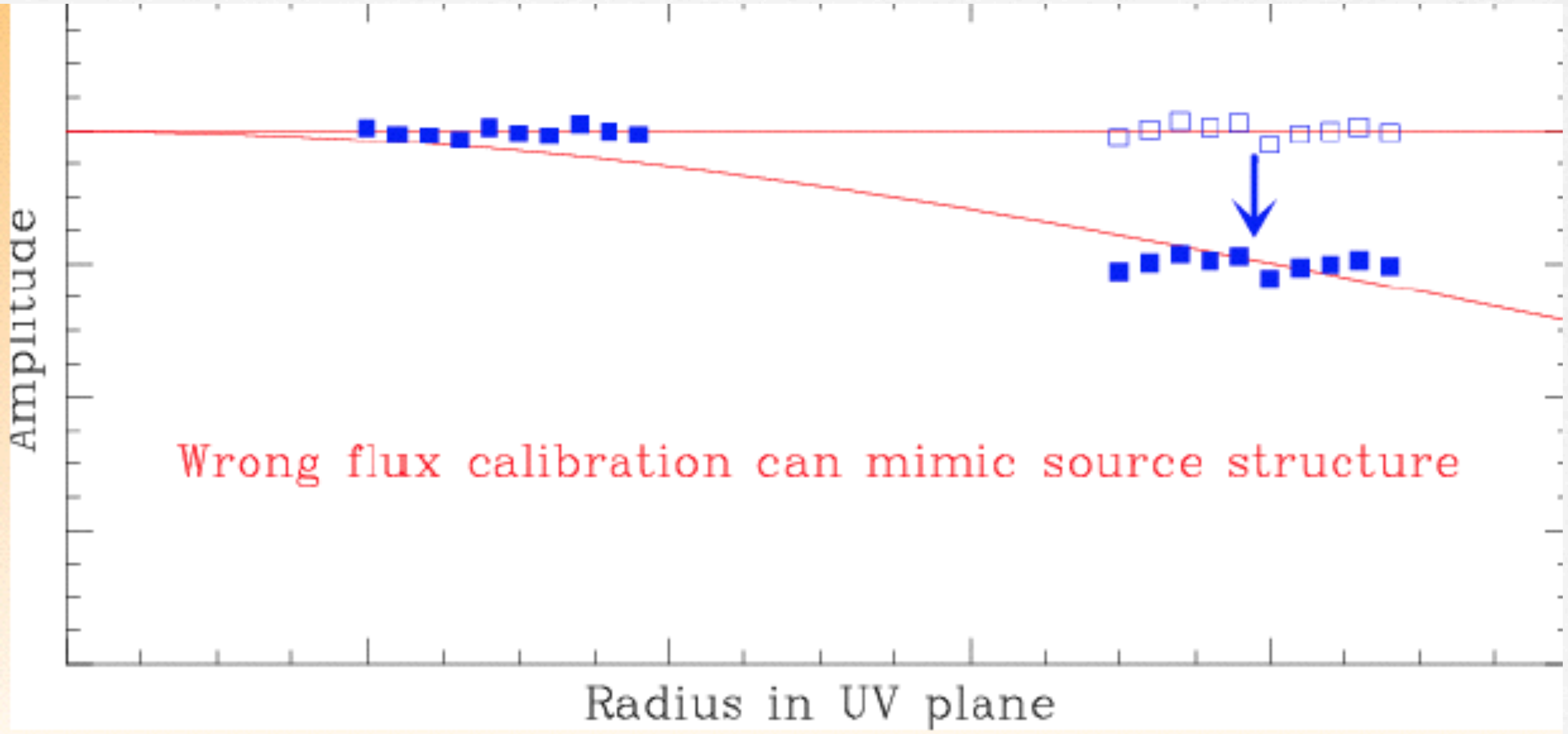
Richards, Eris 2013

Interferometric peculiarities @ mm

Flux calibration

Very important!!!

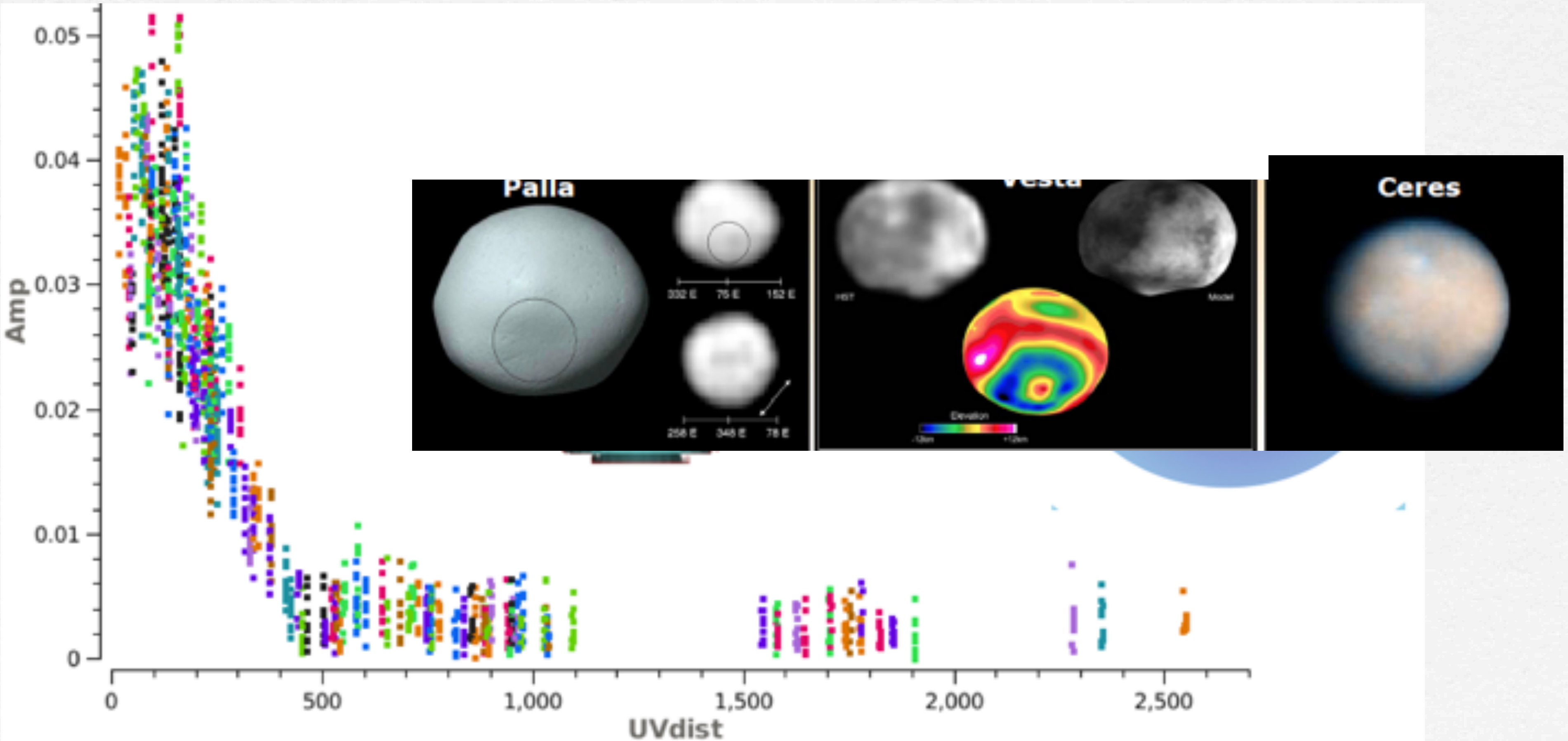
- apply the correct flux-scale
- combine observations at different times and configuration



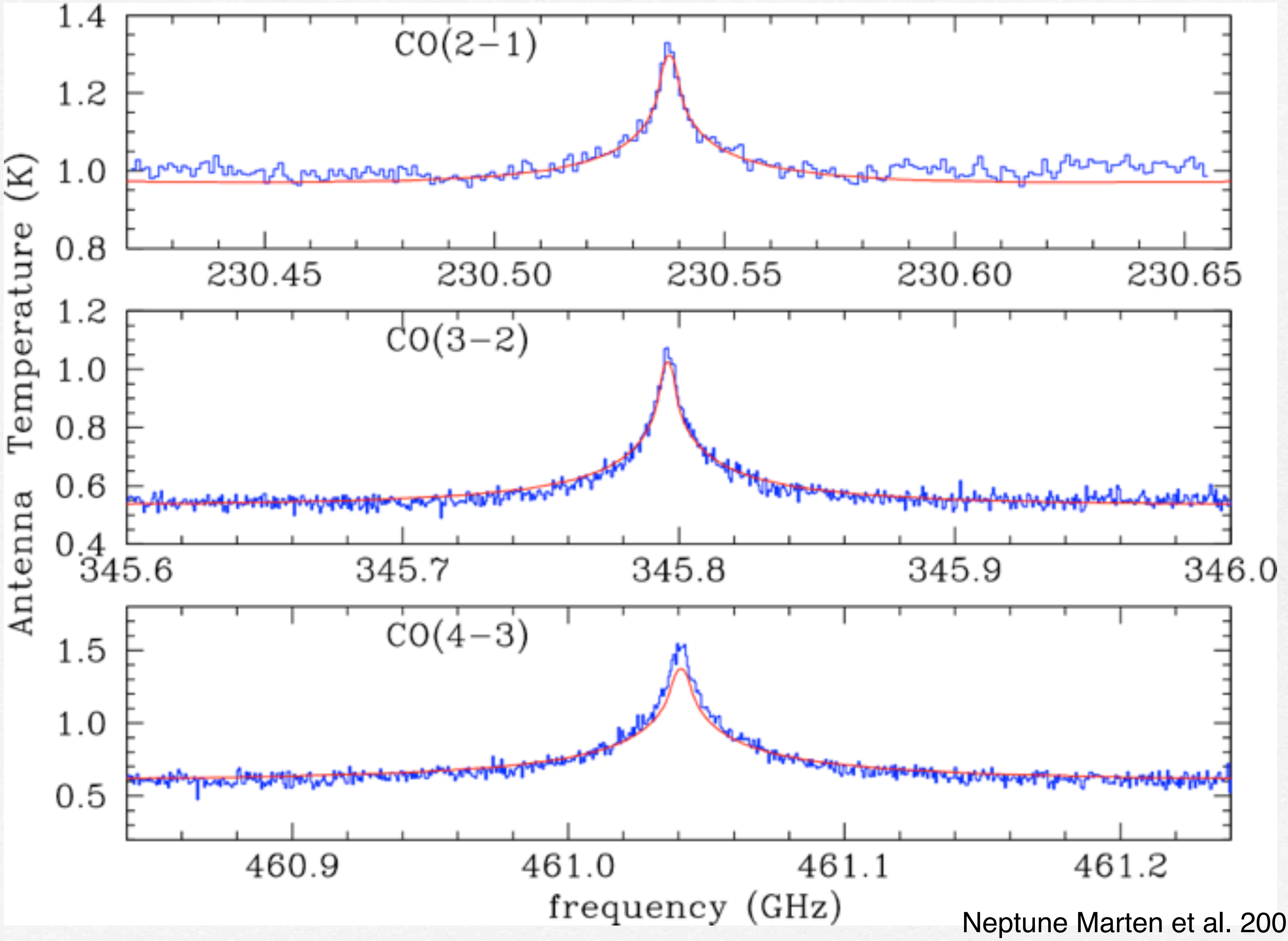
Flux calibration

Flux calibrators: Planets, Moons, Asteroids… BUT!

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

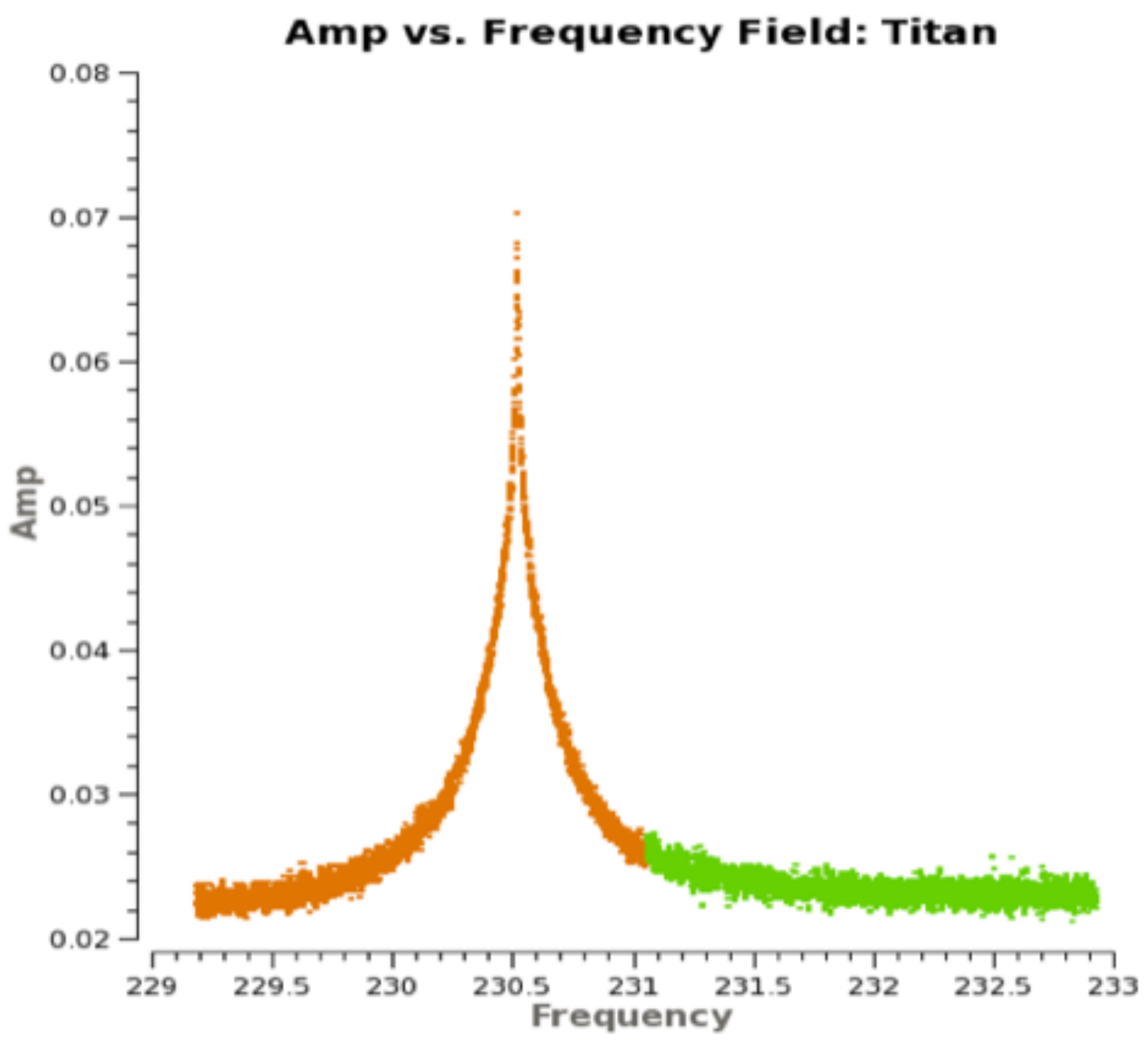


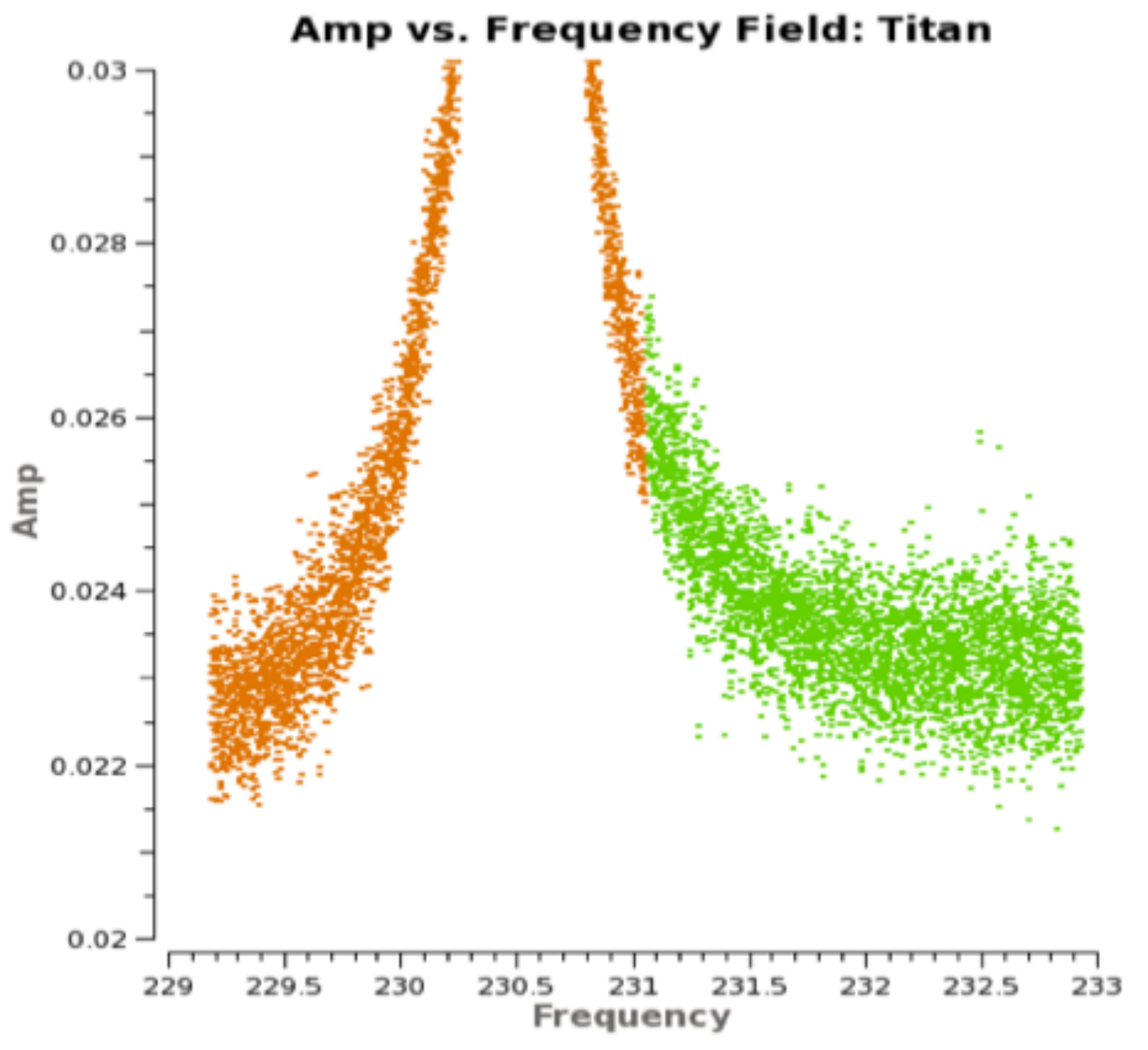
Atmospheric lines in Neptune (model? … work in progress!)

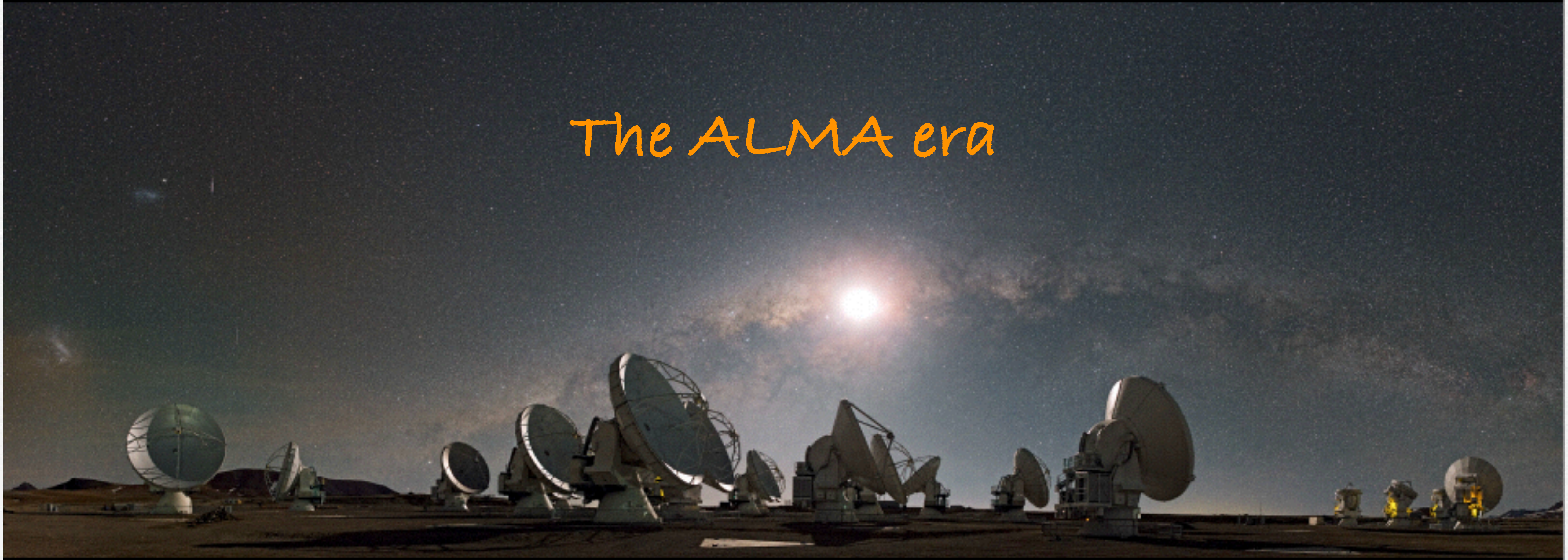


Neptune Marten et al. 2005

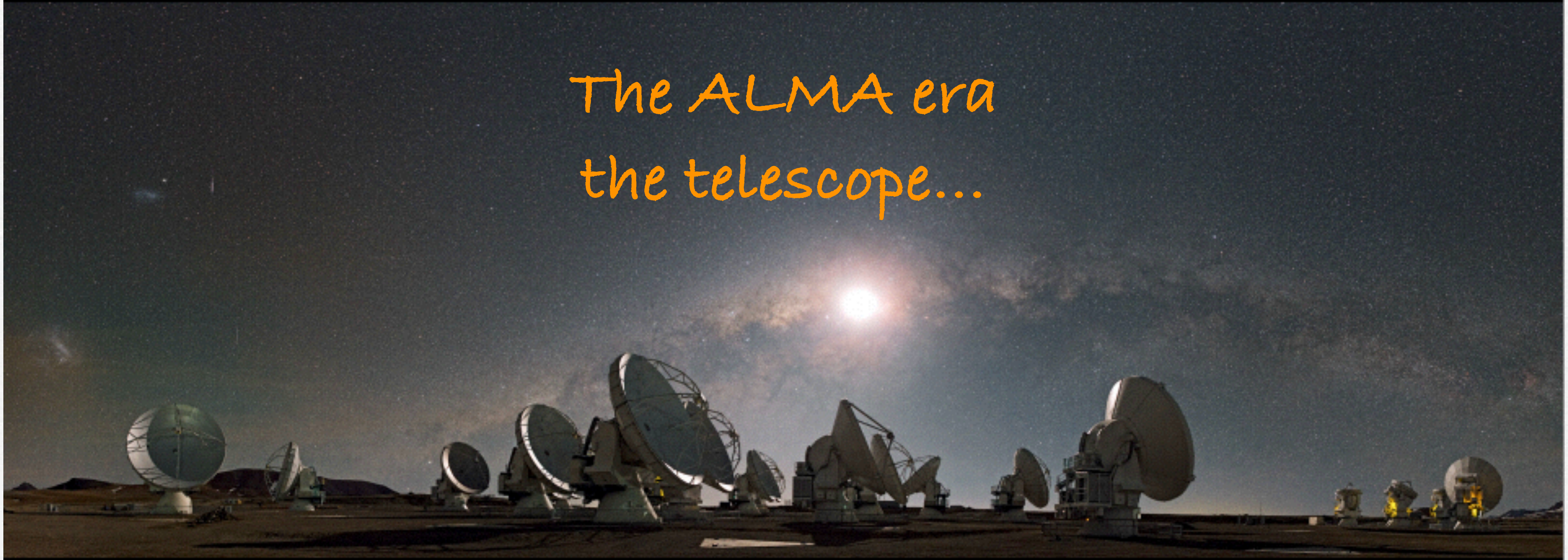
to handle carefully…(the case of Titan)







The ALMA era



The ALMA era

the telescope...

... a movie

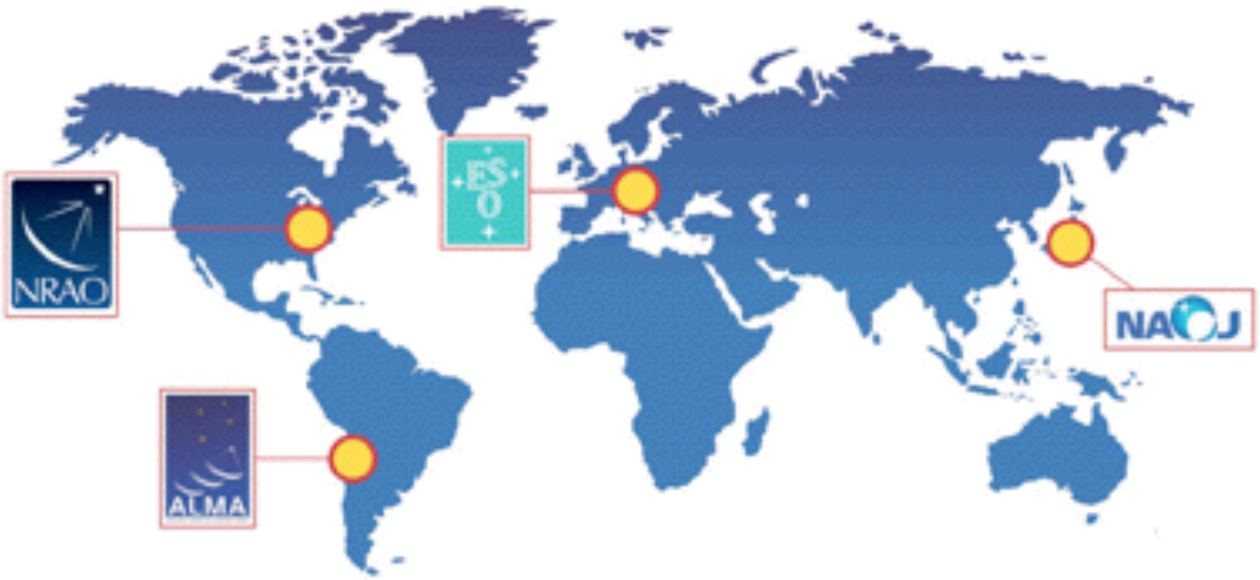
... a movie

The ALMA organization

World wide collaboration

- Europe: **ESO** (14 countries)
- North America: **NRAO** (USA, Canada)
- East Asia: **NAOJ** (Japan, Taiwan)
- Chile

Contributors share the observing time



3 Sites in Chile

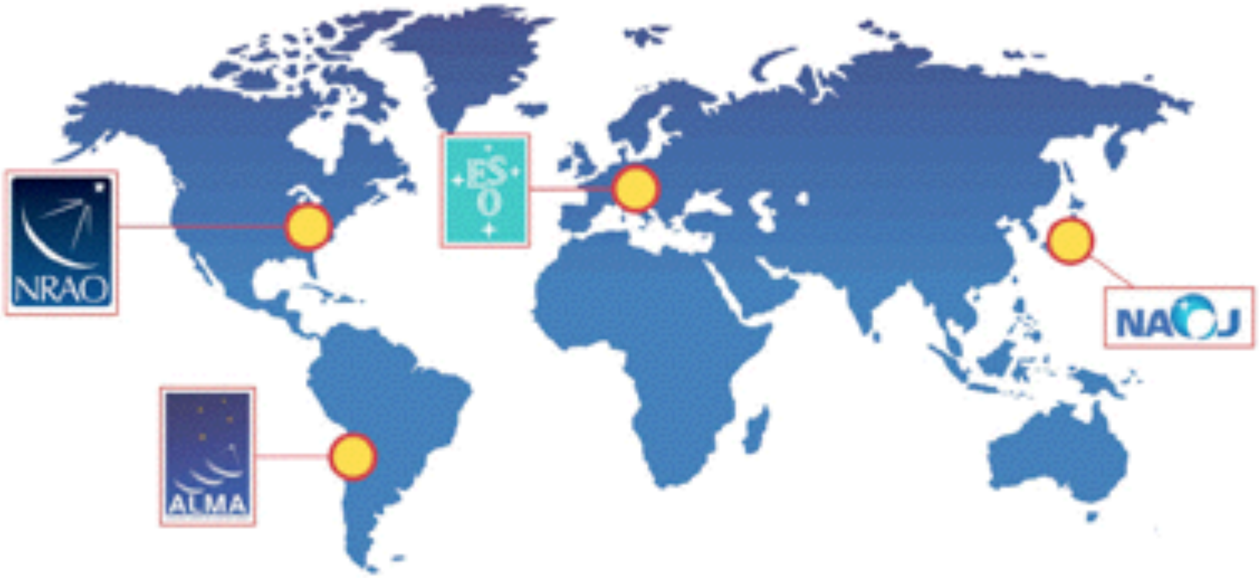
- **AOS**: ALMA Operations Site (5000m): Antennas, Correlator
- **OSF**: Operations Support Facility (3000m): Labs, Antenna Assembly & Maintenance Operators, Astronomers
- **SCO**: Santiago Central Office:
  - ✓ JAO (Joint ALMA observatory)
    - Call for Proposals
    - Running ALMA
    - Data Reduction Pipeline
    - Quality Assessment
  - ✓ Archive

The ALMA organization

World wide collaboration

- Europe: **ESO** (14 countries)
- North America: **NRAO** (USA, Canada)
- East Asia: **NAOJ** (Japan, Taiwan)
- Chile

Contributors share the observing time



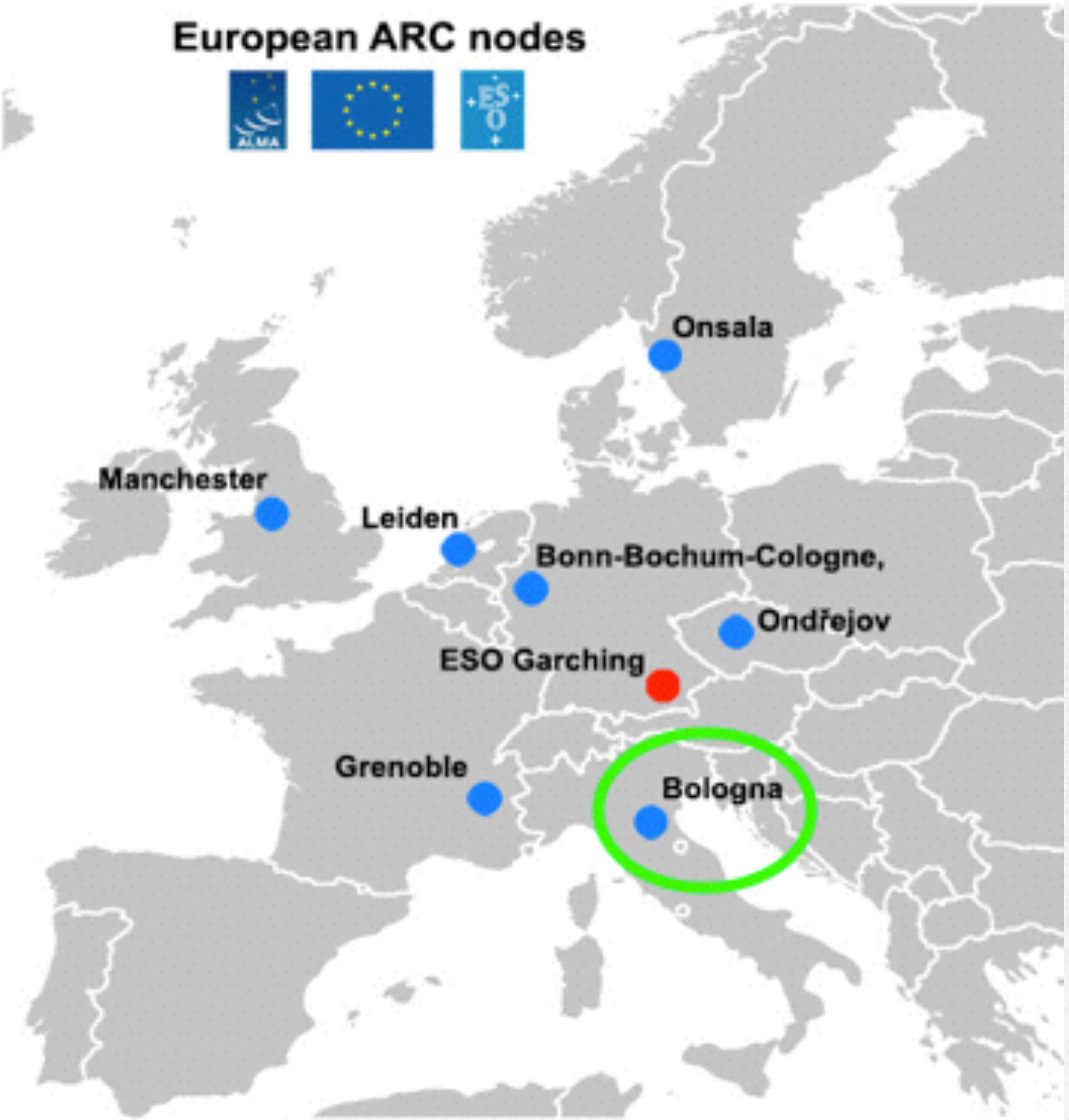
3 Sites in Chile

- **AOS**: ALMA Operations Site (5000m): Antennas, Correlator
- **OSF**: Operations Support Facility (3000m): Labs, Antenna Assembly & Maintenance Operators, Astronomers
- **SCO**: Santiago Central Office:
  - JAO (Joint ALMA observatory)
    - Call for Proposals
    - Running ALMA
    - Data Reduction Pipeline
    - Quality Assessment
  - Archive

1.3 bilions $

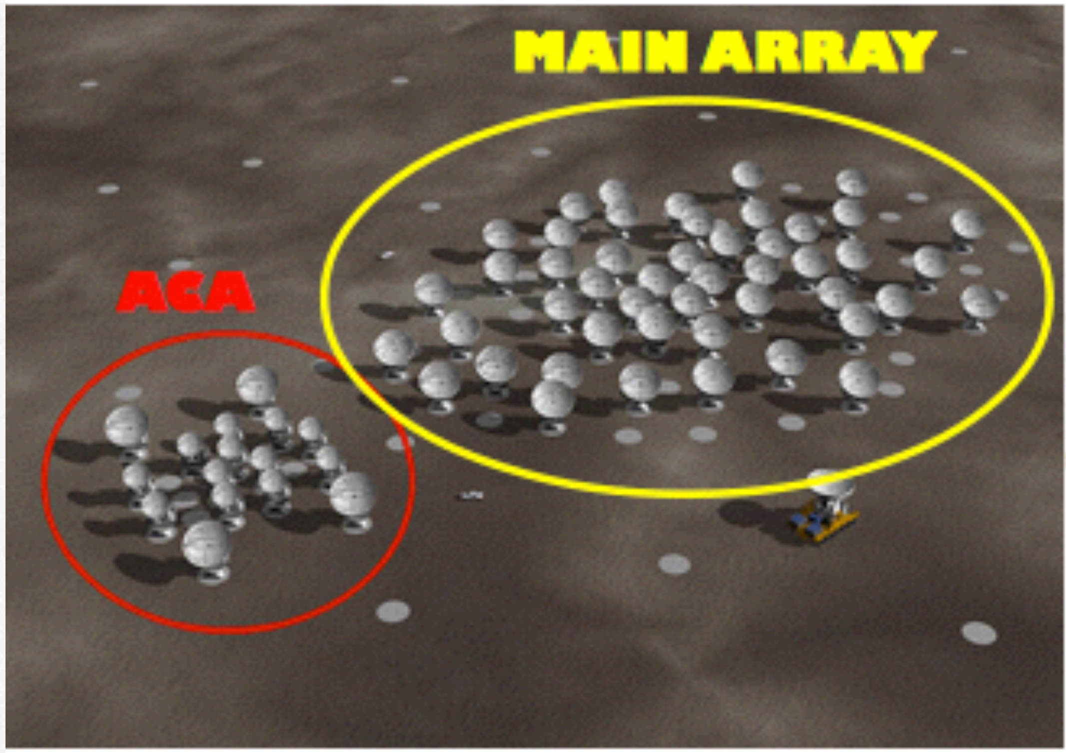
The ALMA Regional Centers (ARCs)

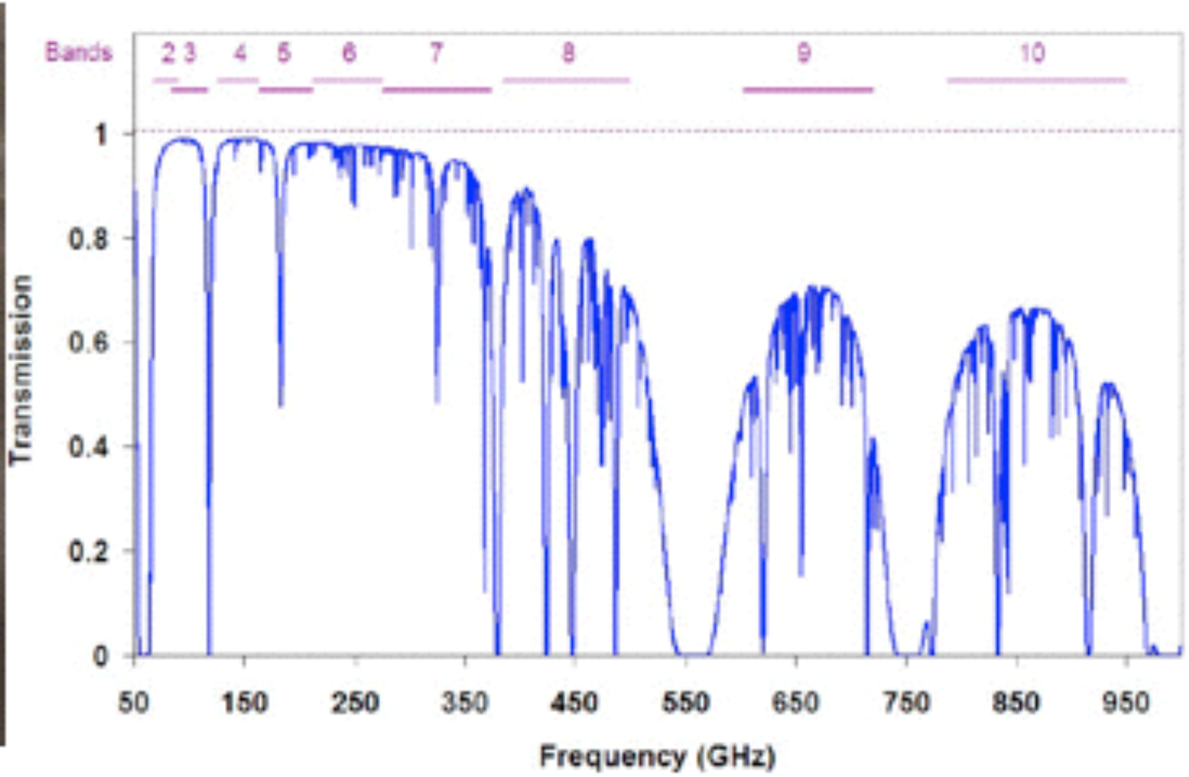
- **Interface between JAO and users**
- 1 ARC per Partner:
  - NRAO for North America
  - NAOJ for East Asia
  - ESO for Europe (split in 7 nodes)
- Operation support
  - Archive replication
  - Astronomer on duty
  - Software tools
- User support
  - Community formation and outreach (schools, workshops, tutorials, ...)
  - Phase 1 (proposal preparation)
  - Phase 2 (scheduling block preparation)
  - Data analysis, Archive mining
  - F2F user support, Helpdesk



ALMA: Atacama Large Millimeter/Submillimeter Array

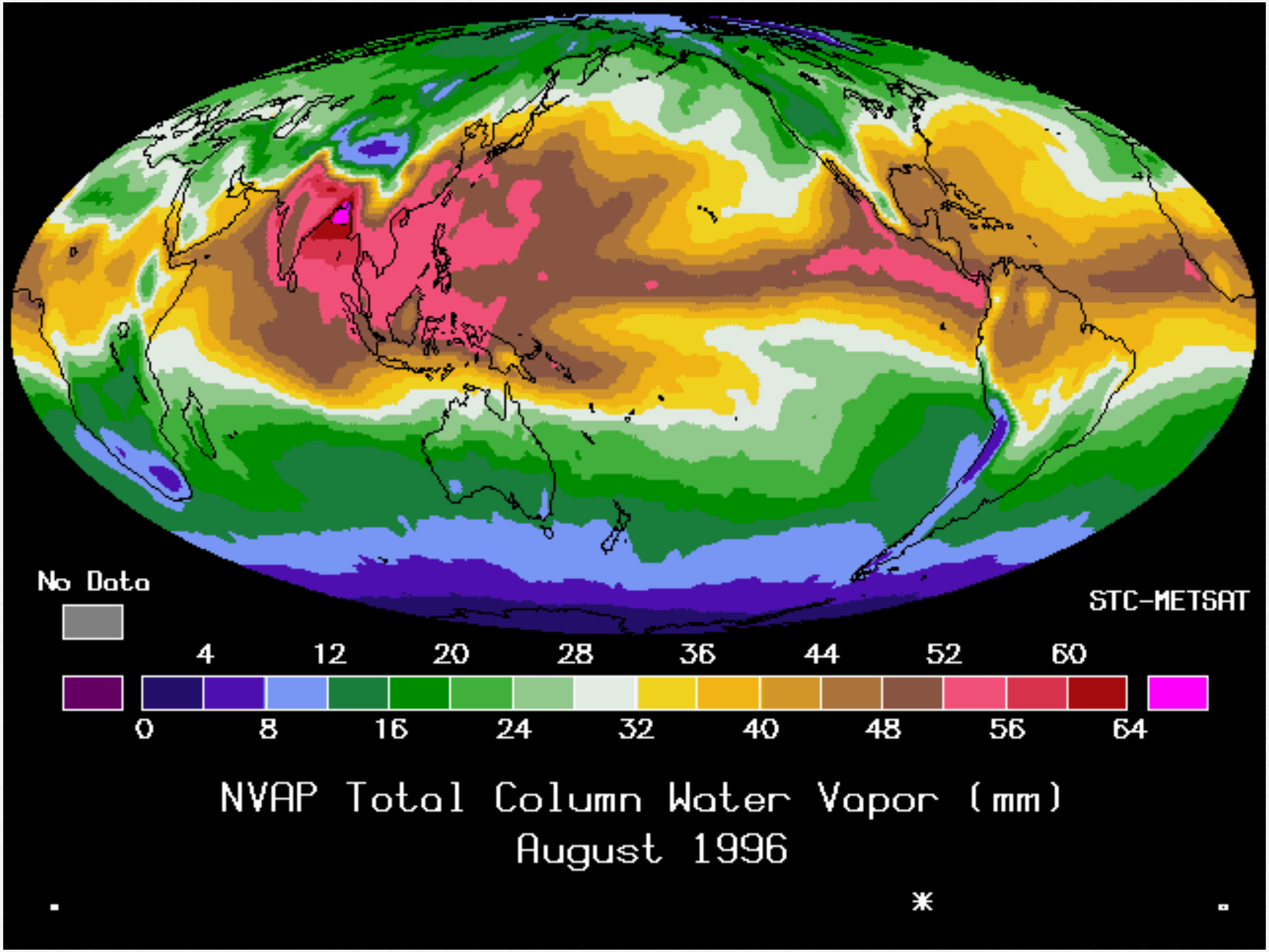
- Inaugurated on March 2013 on the Chajinantor plain (**5000m**, Chile, latitude -23°): dry site, low precipitable water vapour, low Tsys, high sensitivity
- Antennas: **50x12m** main array + (**12x7m + 4x12m**) Atacama Compact Array (ACA)
- ACA for short-spacings and Total Power observations
- Frequency range: **10 bands between 30-950 GHz** (0.3-10 mm)
- Baselines length: **MAIN ARRAY: 15m → 150m-16km; ACA: 9m → 50m**



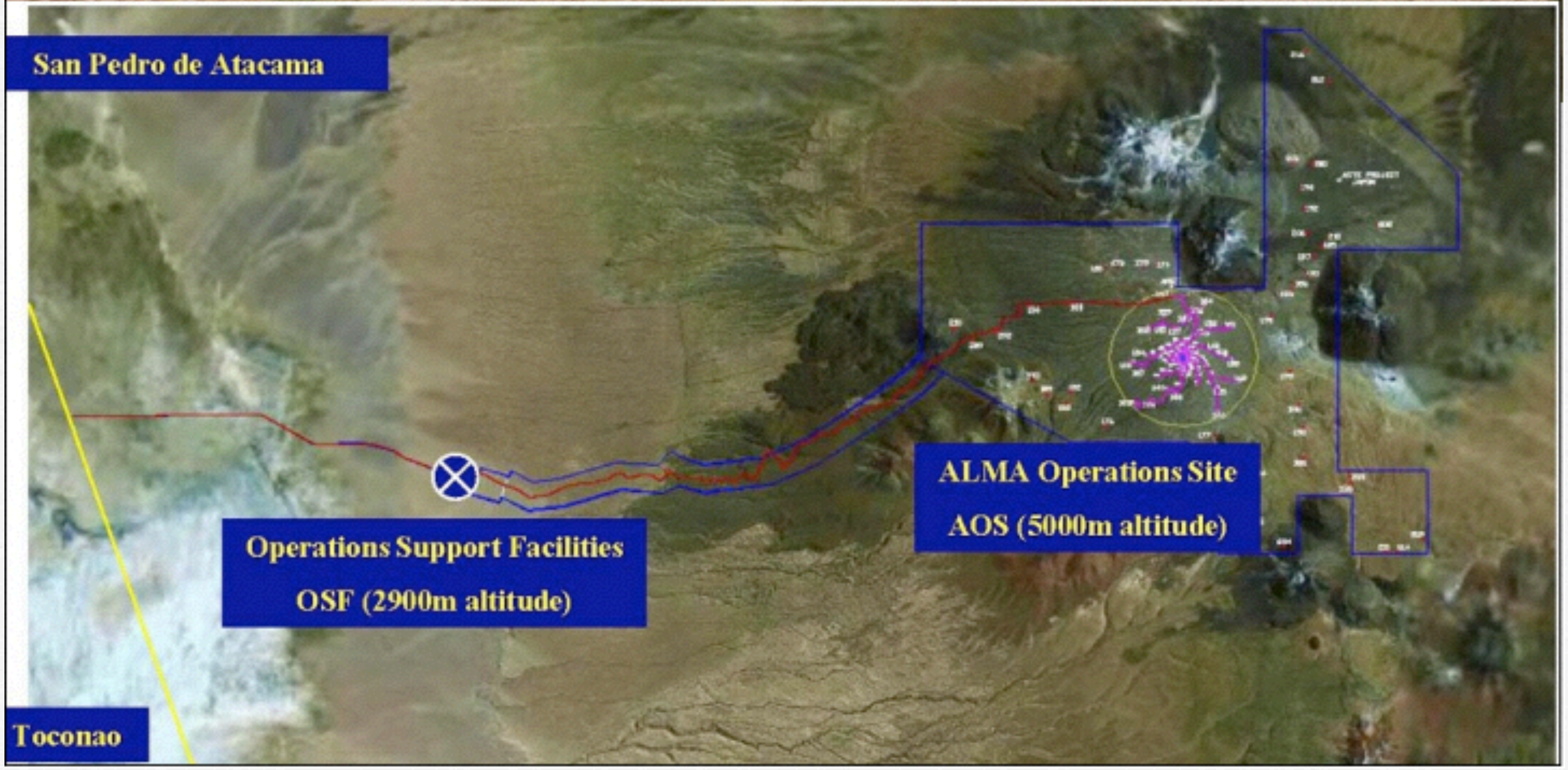


Alma map

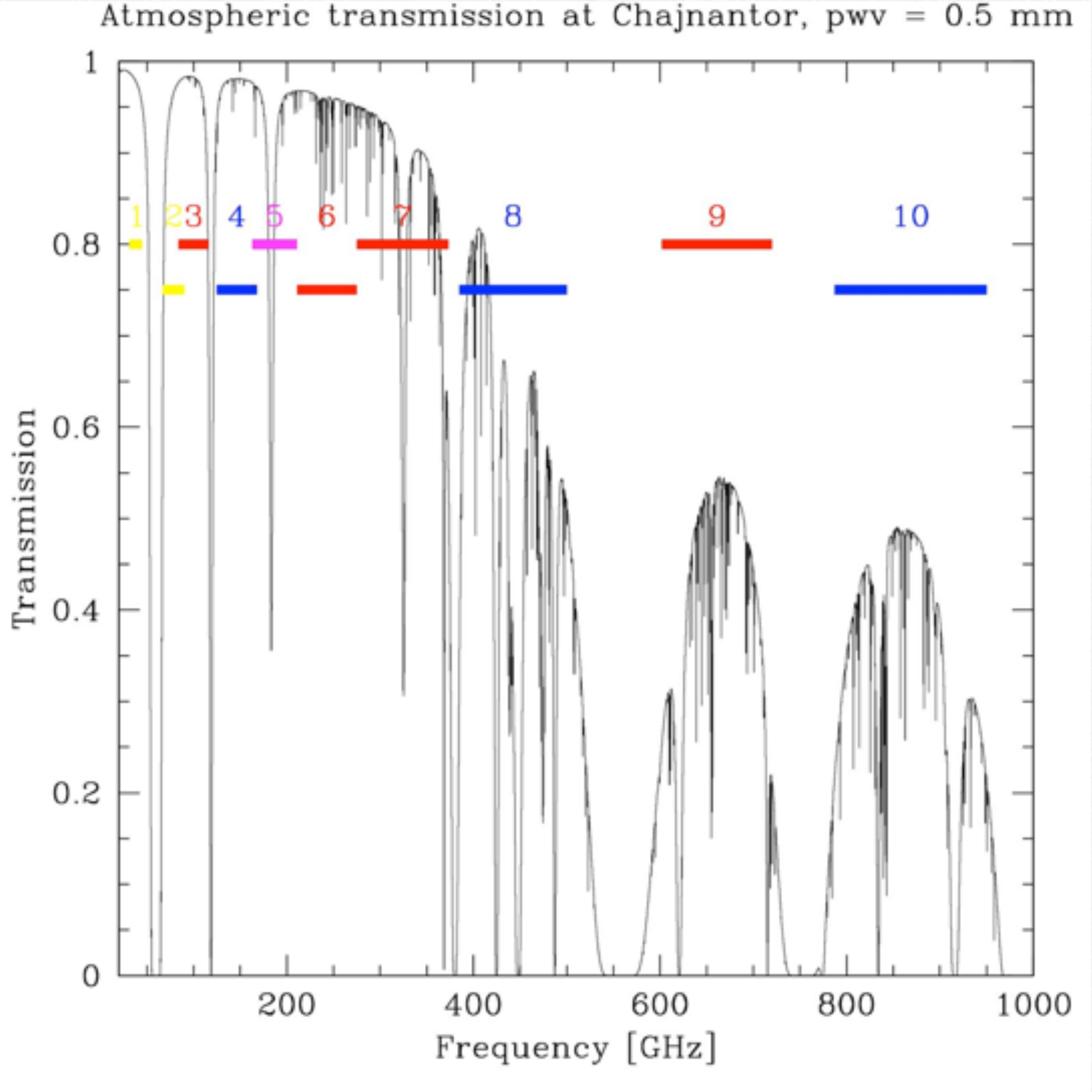

Tocopilla
24
Chuquicamata
Calama
23
Geiser del Tatio
BOLIVIA
22°
Mejillones
1
5
25
San Pedro de Atacama
ALMA
Toconao
23°
Baquedano
Salar de Atacama
Antofagasta
Peine
24°
Mina Escondida
Paranal
ARGENTINA
25°
Taltal
Peru
Brazil
ma
La Paz
Bolivia
Paraguay
Asunción
Chile
Uruguay



NVAP Total Column Water Vapor (mm)
August 1996


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

(sub-)mm windows & ALMA bands

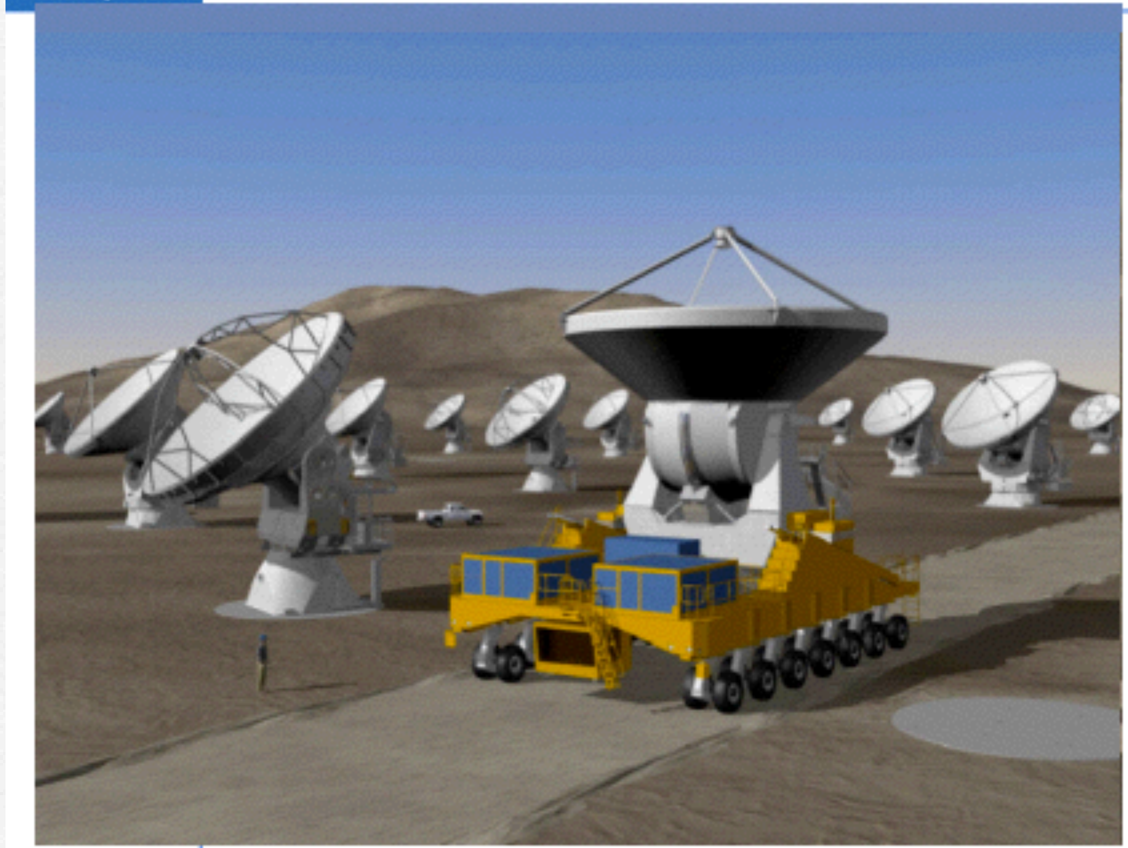


ALMA: Atacama Large Millimeter/Submillimeter Array

- Angular Resolution: **0.2'' x (300/freq_GHz)x(1km/max_baseline)**
  40 mas @ 100 GHz, 5 mas @ 950 GHz
- Velocity resolution: **As narrow as 0.008 × (Freq/300GHz) km/s**
  ~0.003 km/s @ 100 GHz, ~0.03 km/s @ 950 GHz

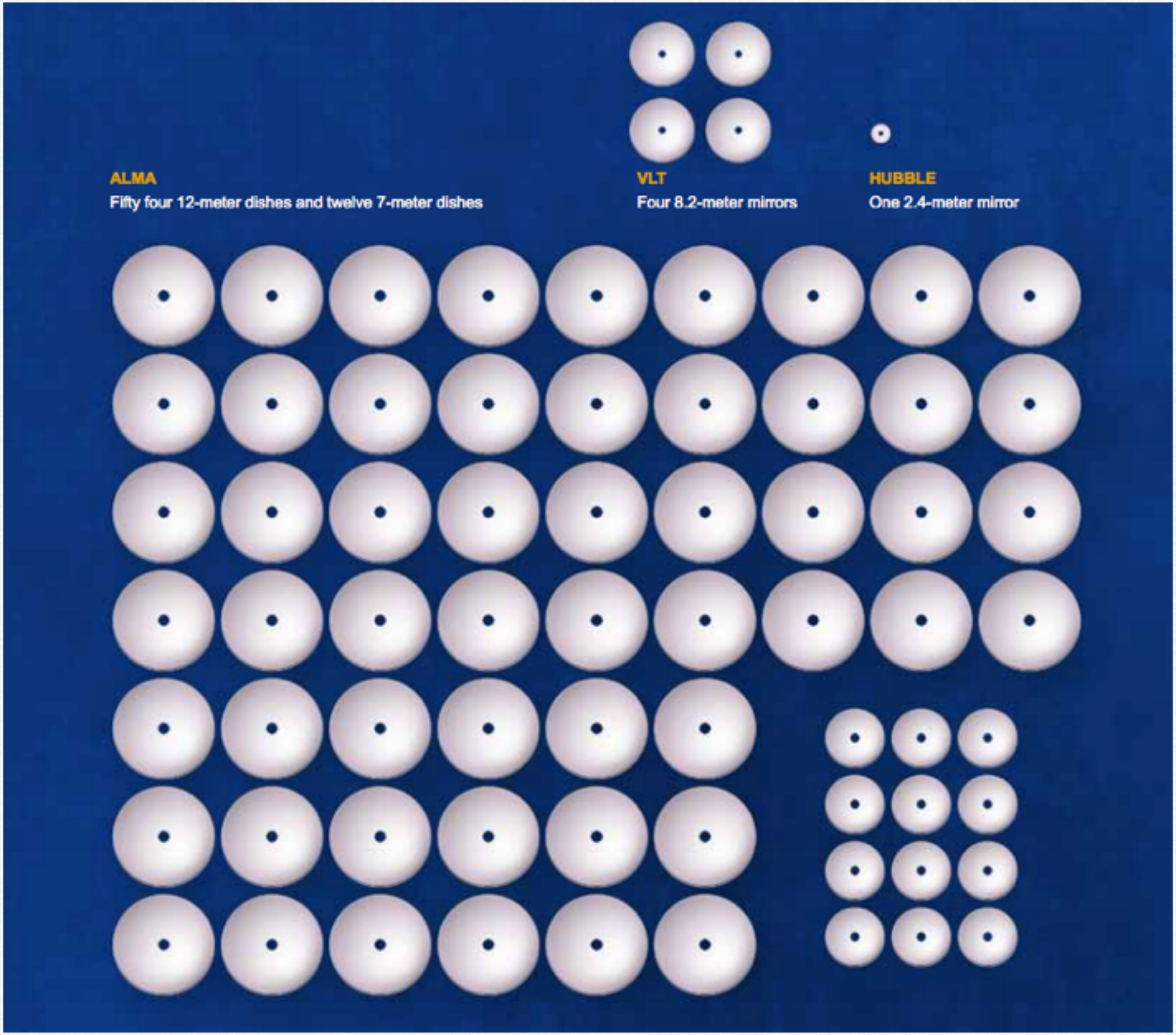
- FOV 12m array: **20.3''/(300/freq_GHz)**
- Bandwidth: **2 GHz x 4 basebands for each of 2 polarizations**
  sensitivity <0.05 mJy @100 GHz in 1 hr
- Polarimetry: Full Stokes polarization capability

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)

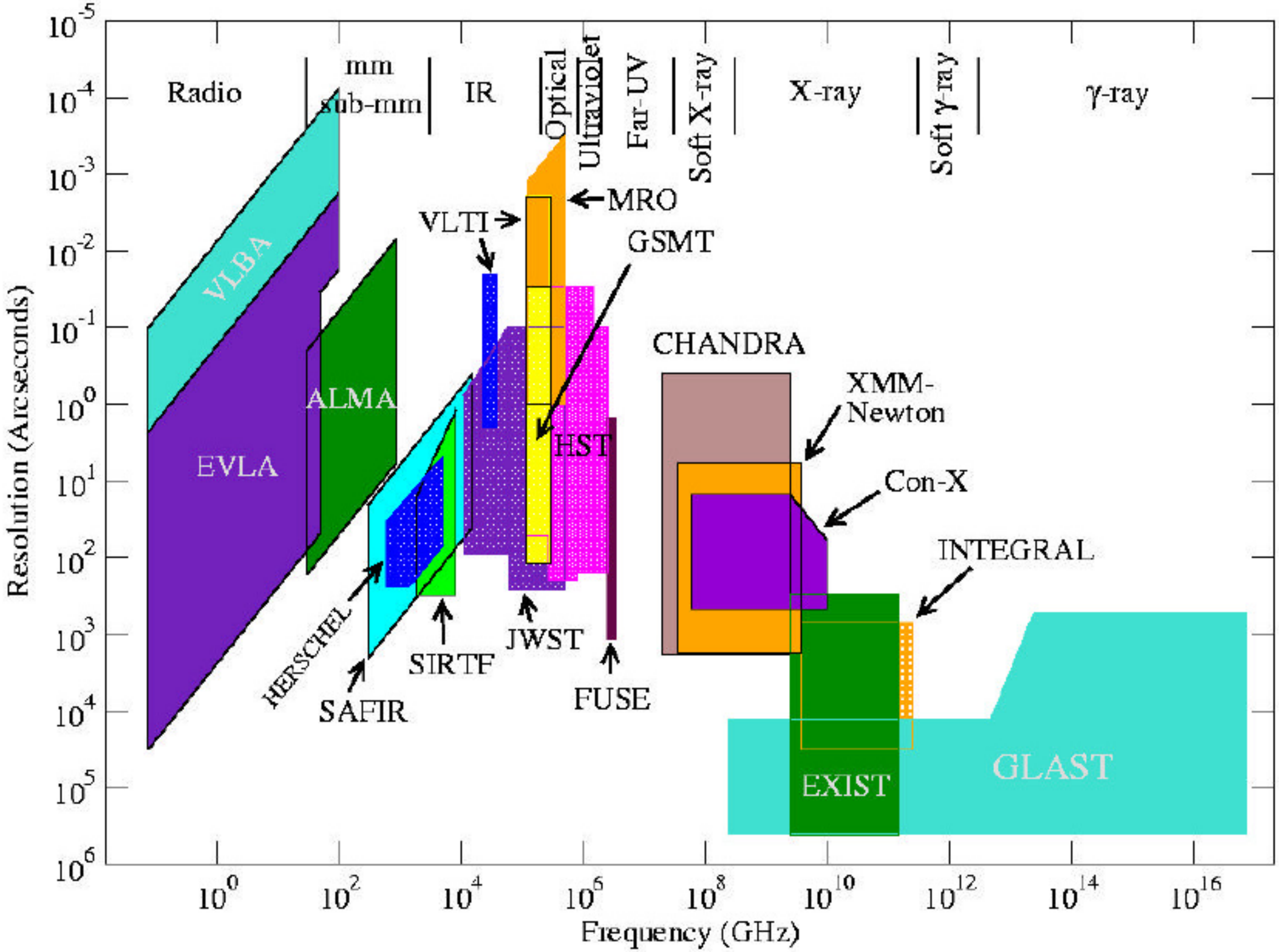
1. Detect and map CO and [C II] in a Milky Way galaxy at z=3 in less than 24 hours of observation
2. Map dust emission and gas kinematics in protoplanetary disks
3. Provide high fidelity imaging in the (sub)millimeter at 0.1 arcsec resolution



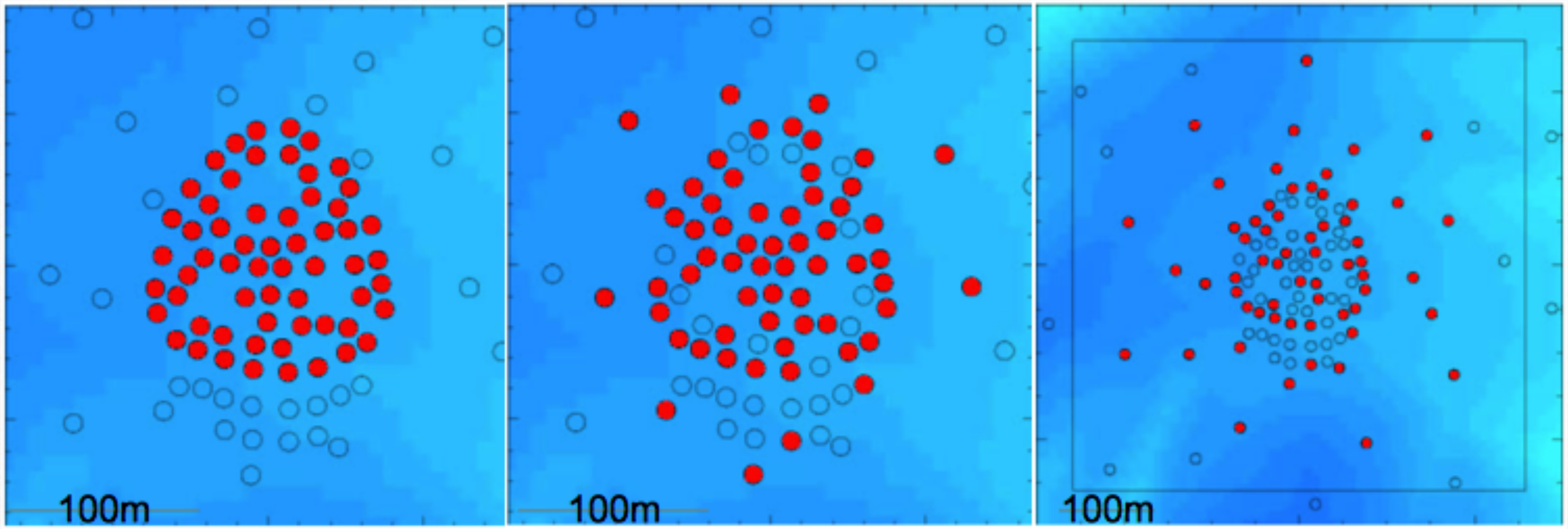
ALMA
Fifty four 12-meter dishes and twelve 7-meter dishes

VLT
Four 8.2-meter mirrors

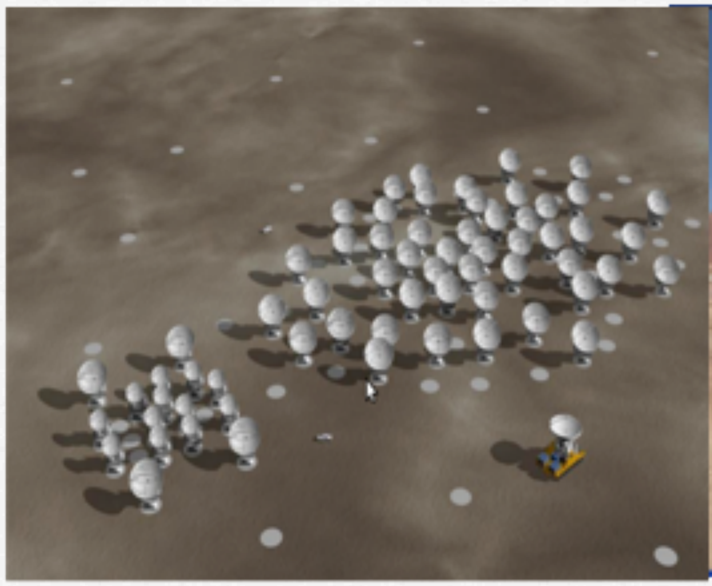
HUBBLE
One 2.4-meter mirror


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
HERSCHEL
SAFIR
SIRTF
JWST
FUSE
CHANDRA
XMM-Newton
Con-X
INTEGRAL
EXIST
GLAST
Resolution (Arcseconds)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
Frequency (GHz)

ALMA reconfiguration

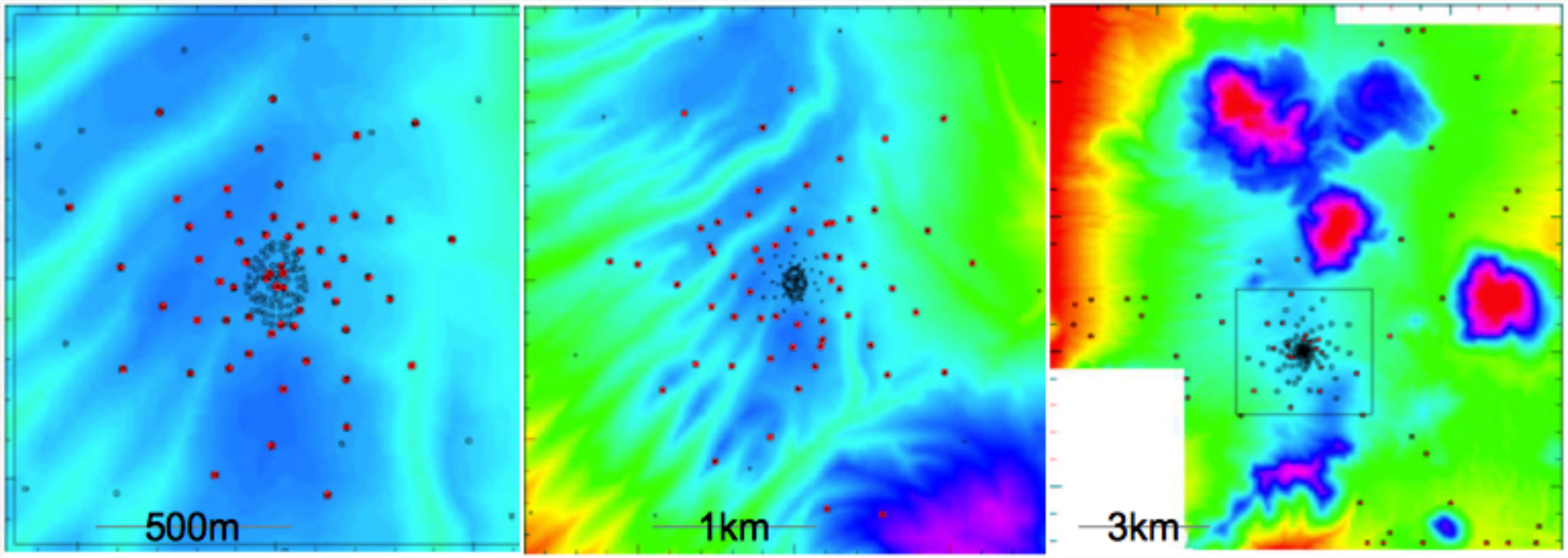


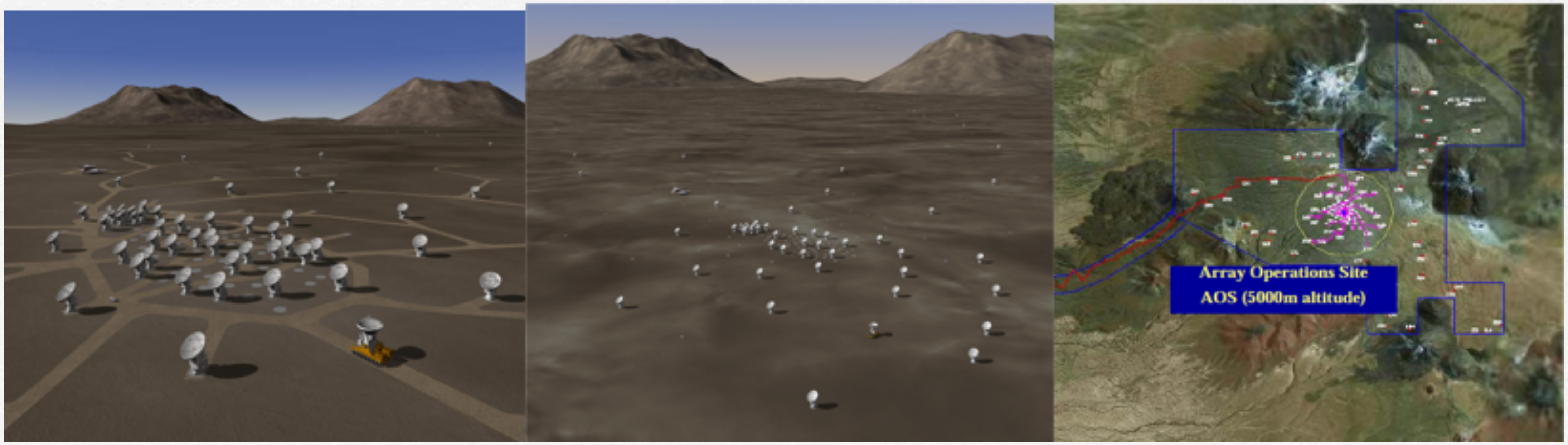

Antenna transporter




Antenna stations at 5000m

ALMA reconfiguration





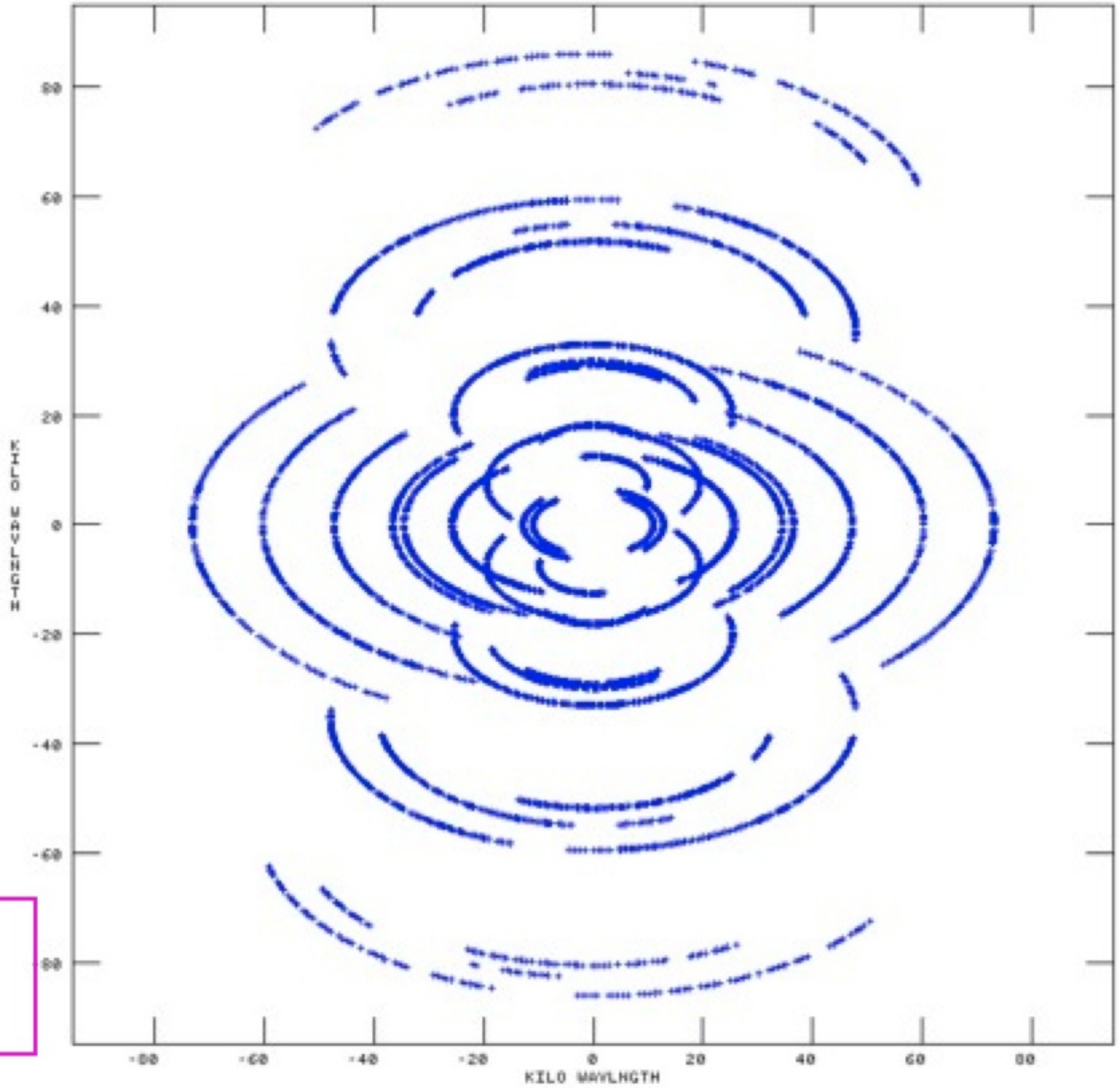
mm Interferometers (u,v) coverage

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



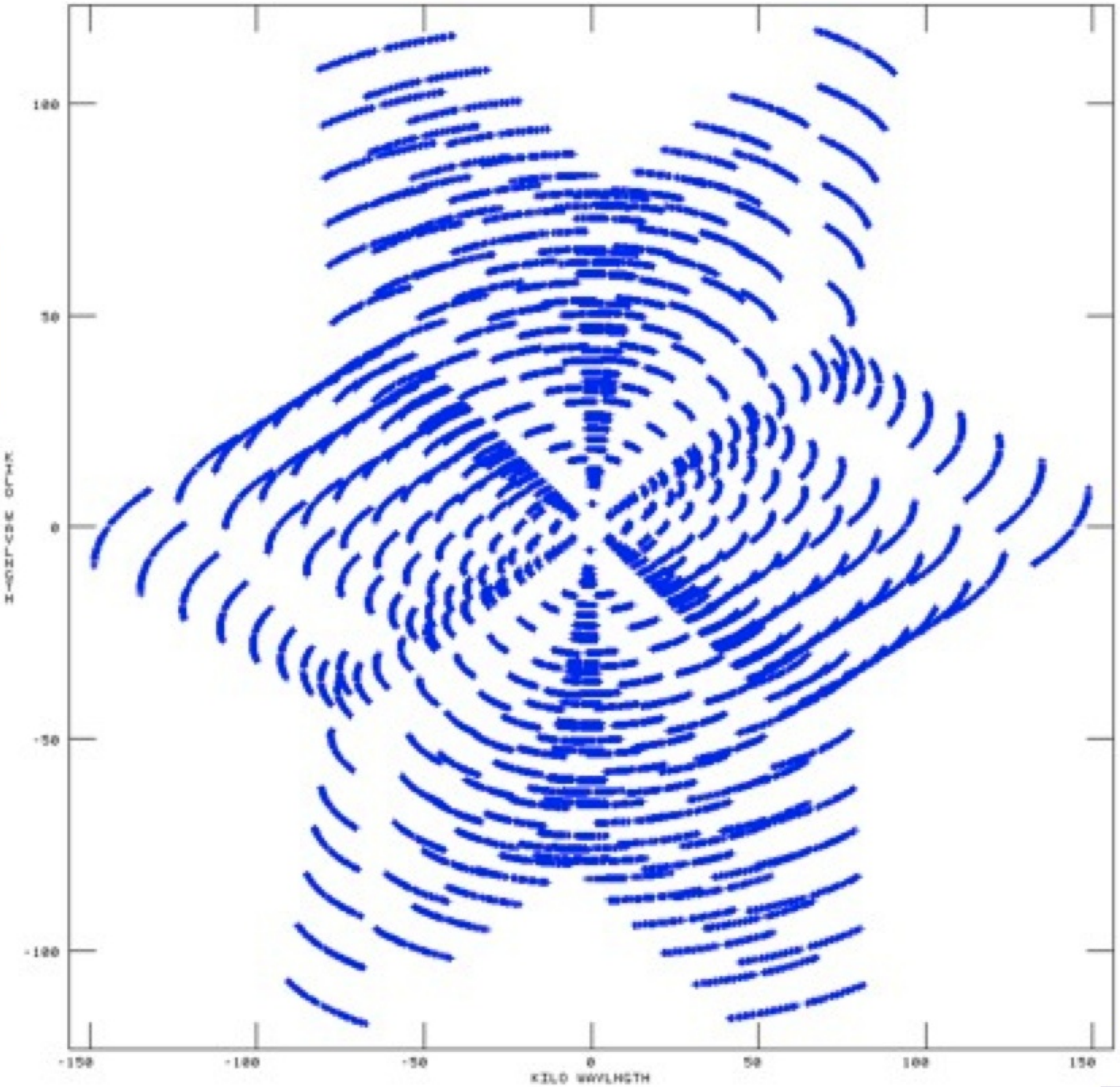
N.B. (u,v) coverage
is not uniform

mm Interferometers (u,v) coverage

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

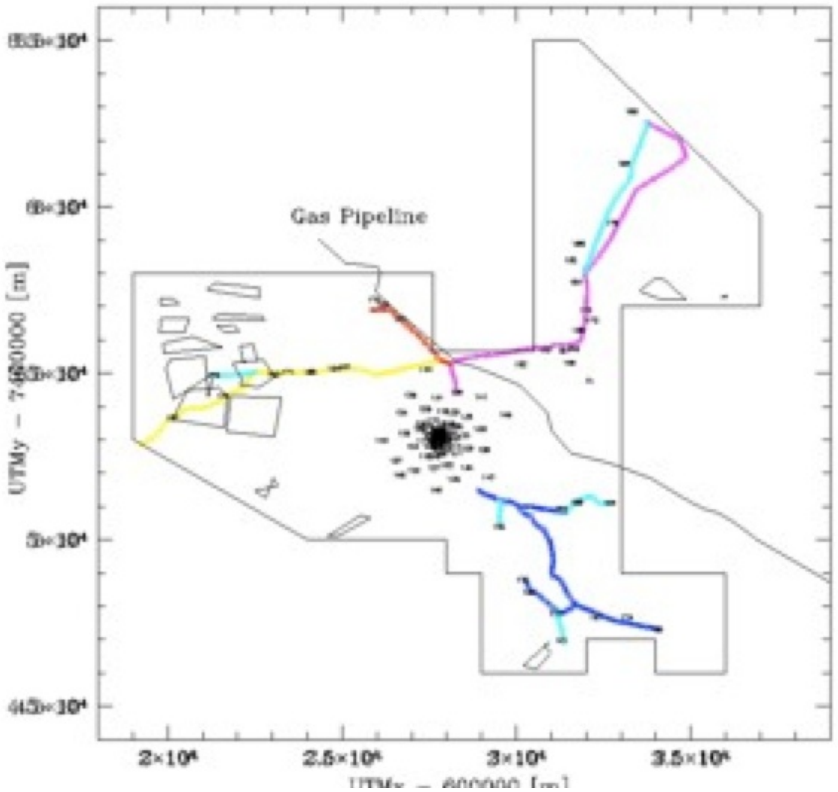
<u>N.B.</u> (u,v) coverage is still not uniform.

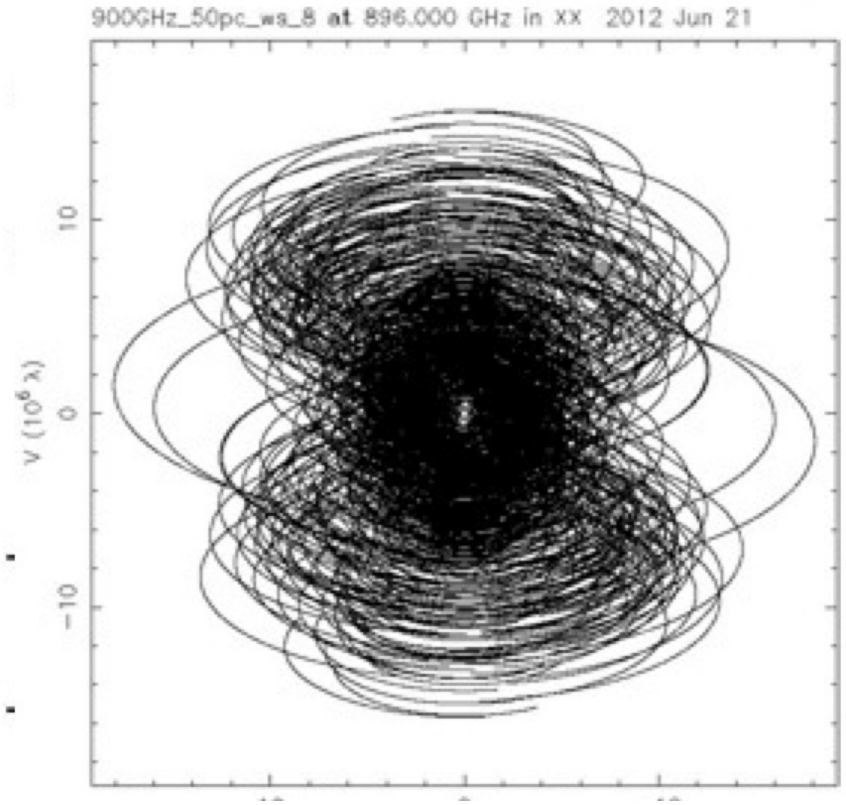
Critical parameters:
- Long baselines
- Short baselines
- Number of (u,v) points
- (u,v) coverage distribution



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





- websites: www.alma.inaf.it
  www.almaobservatory.com

- mail: amignano@ira.inaf.it

…. grazie!