mm/sub-mm interferometry

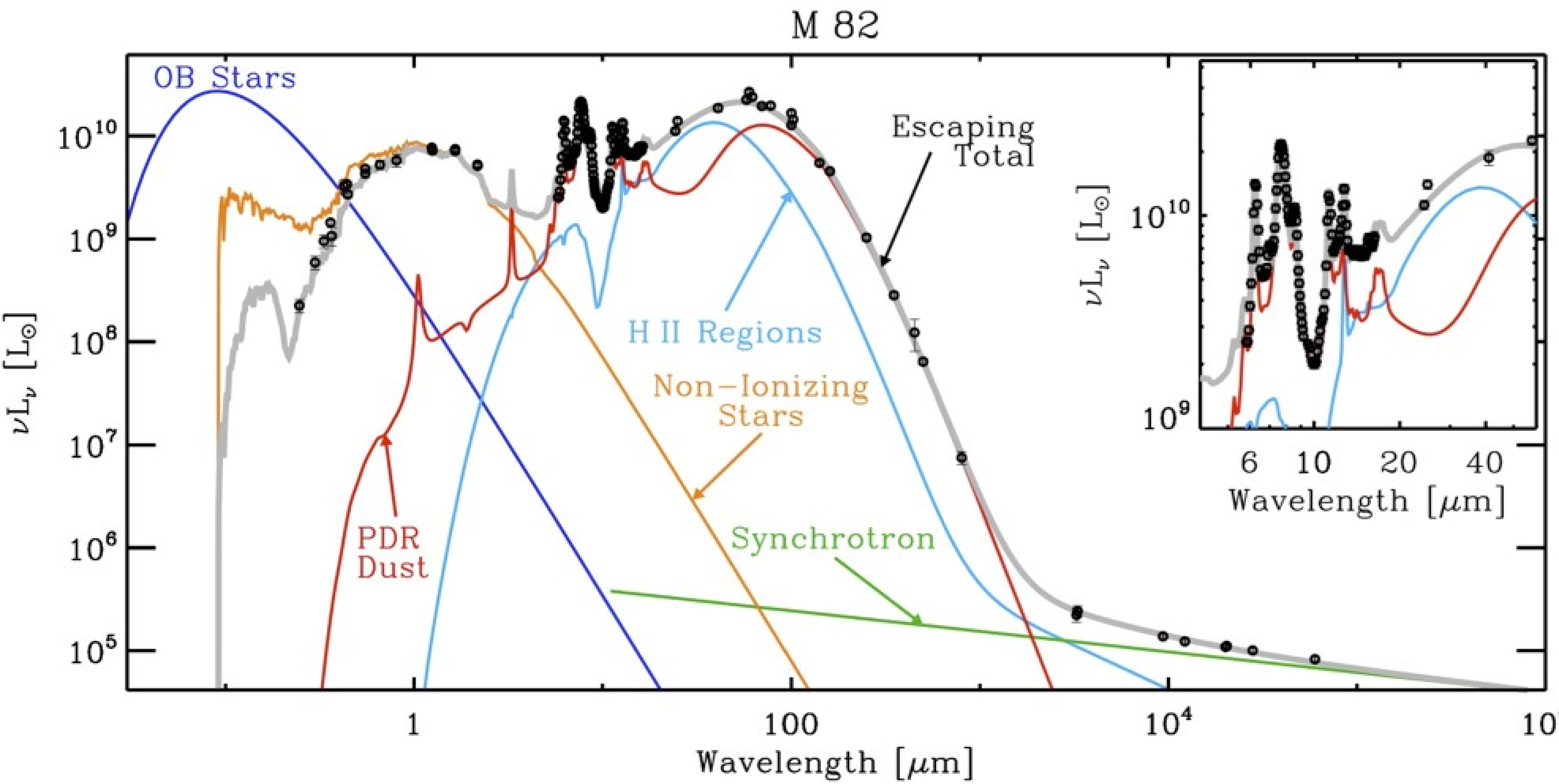
Vincent Piétu
IRAM

This presentation has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]

Outline

- Sub-millimeter science:
  - Why observing in the mm/sub-mm domain
- Specificities:
  - Atmosphere.
  - Hardware.
- Spectrum management:
  - Regulatory environment.
  - Threats
- Sub-mm interferometers
  - ALMA.
  - NOEMA.
- *Slides from M. Krips, M. Bremer, F. Gueth, R. Neri, S. Corder, T. Tzioumis, H. van der Marel, T. Hezareh*

Emission mechanisms



From dustpedia, SED fitting Galliano et al.

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{-\frac{h\nu}{kT}} - 1}$$

Rotational molecular lines

THE ASTROPHYSICAL JOURNAL, 161:L43–L44, July 1970

CARBON MONOXIDE IN THE ORION NEBULA

R. W. WILSON, K. B. JEFFERTS, AND A. A. PENZIAS
Bell Telephone Laboratories, Inc., Holmdel, New Jersey, and
Crawford Hill Laboratory, Murray Hill, New Jersey
Received 1970 June 5

ABSTRACT

We have found intense 2.6-mm line radiation from nine galactic sources which we attribute to carbon monoxide.

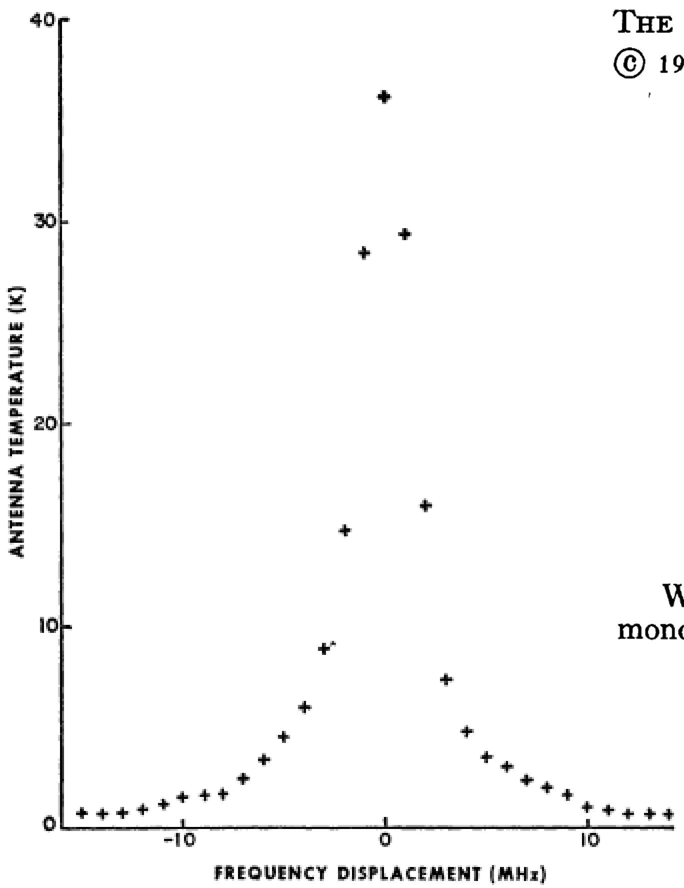


FIG. 1

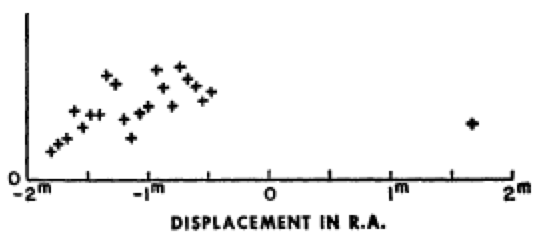


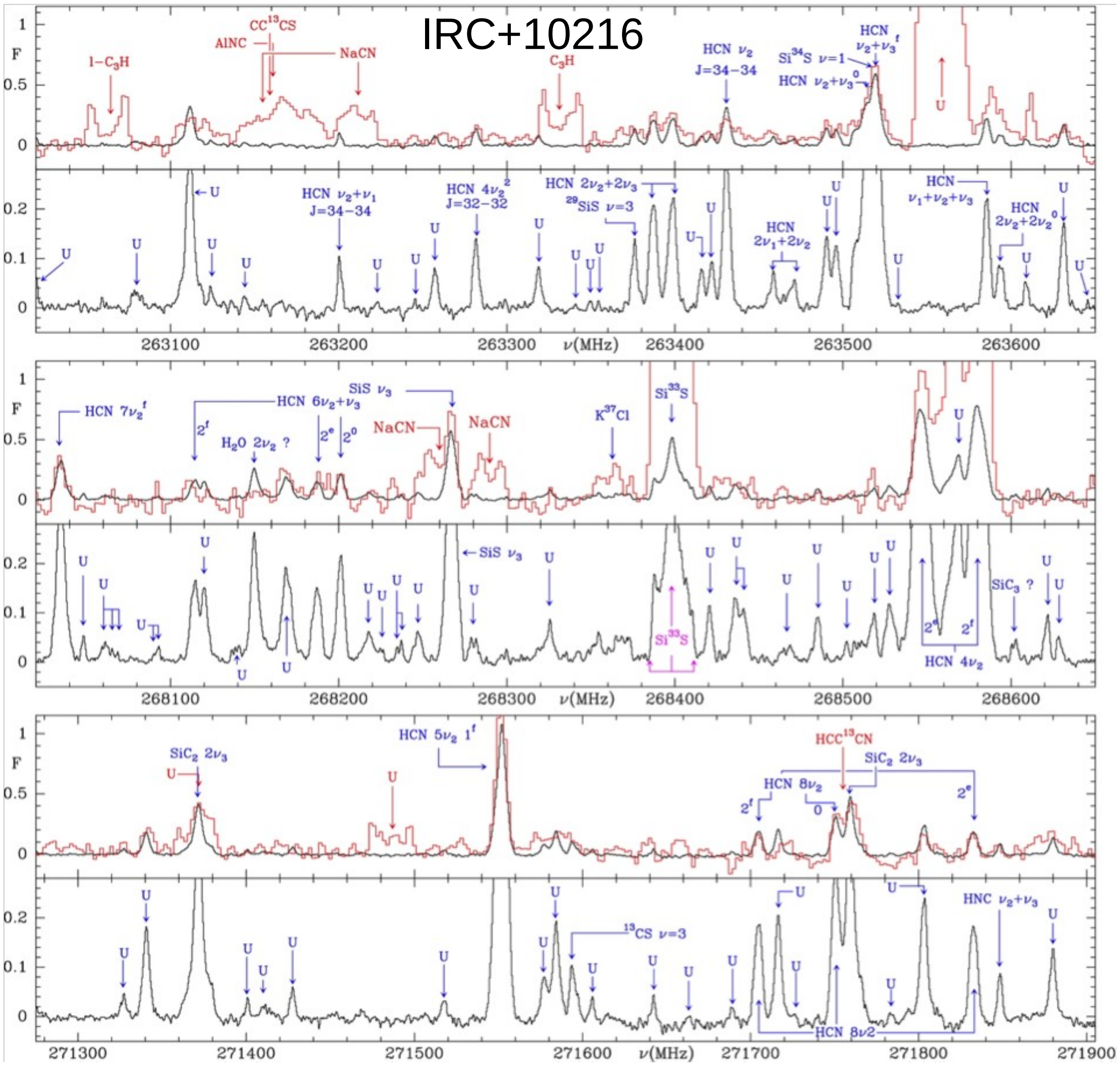
FIG. 2

FIG. 1.—Spectrum of CO radiation in the Orion Nebula made with the NRAO forty-channel line receiver. The center frequency is 115, 267.2 MHz.

FIG. 2.—Distribution in right ascension of the peak antenna temperature of CO radiation at a declination of −5°24′21″.

netry

Rotation lines

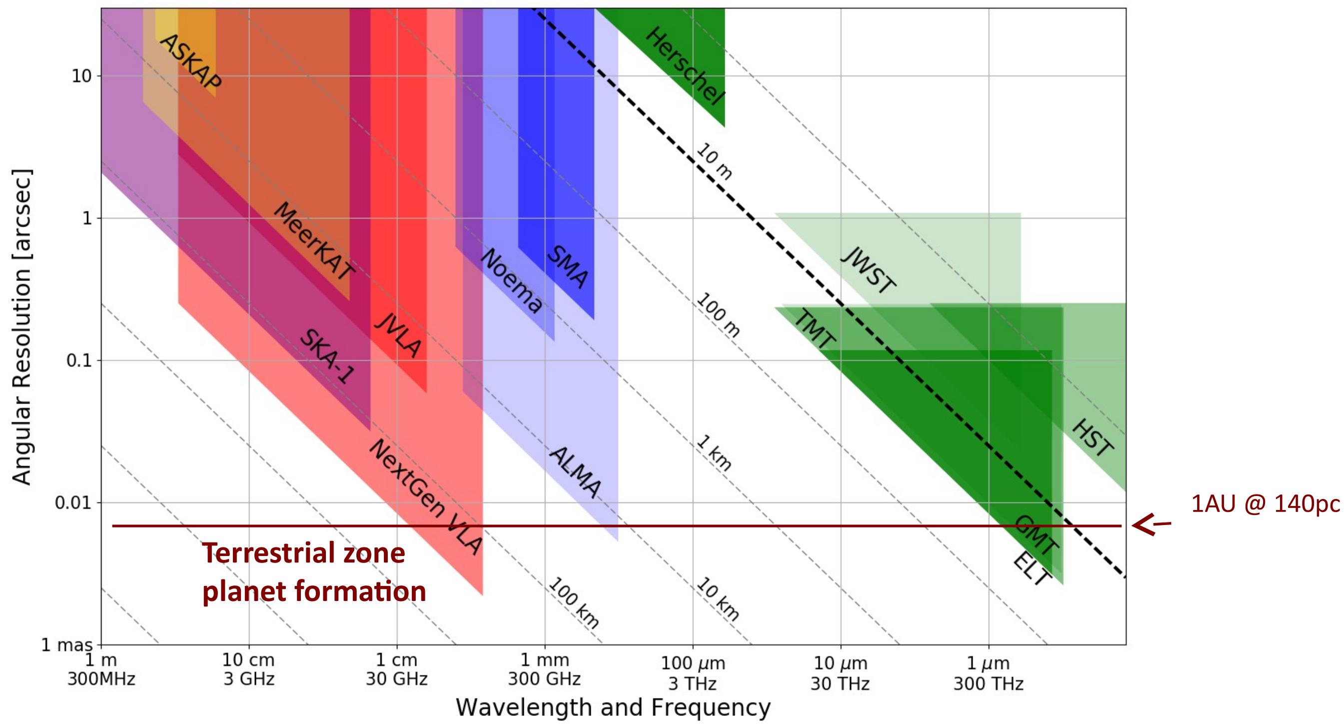


- mm spectrum full of molecular lines.
- Already many are unidentified (U)
- Interferometer helps beating the spectral confusion by resolving out emission from different regions (in red single dish, in black ALMA).

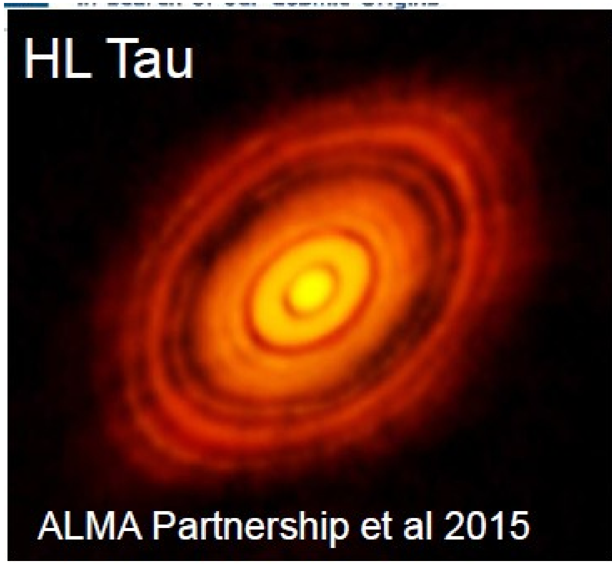
Cernicharo et al. 2013

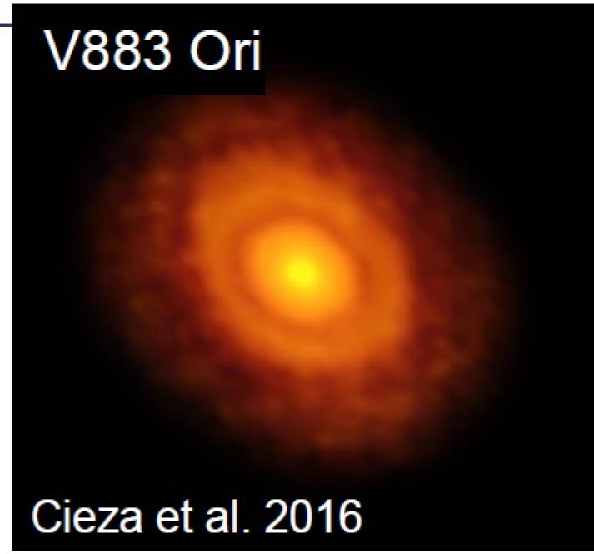
Angular resolution

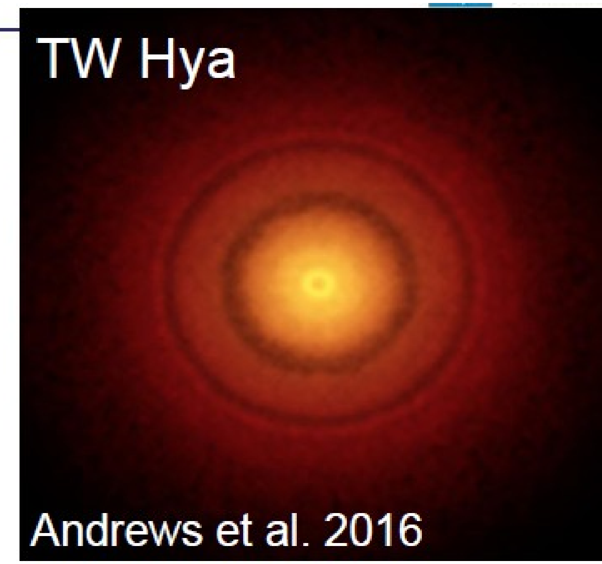
- Sub-mm range, shorter wavelengths, higher angular-resolution for a given baseline length.
- Matching if not surpassing angular resolution in the optical/IR domain.
- To realize it fully, needs decent brightness temperature sensitivity, i.e. large collecting area/wide bandwidth.
- As an aside, reason why EHT is done at mm/sub-mm wavelengths

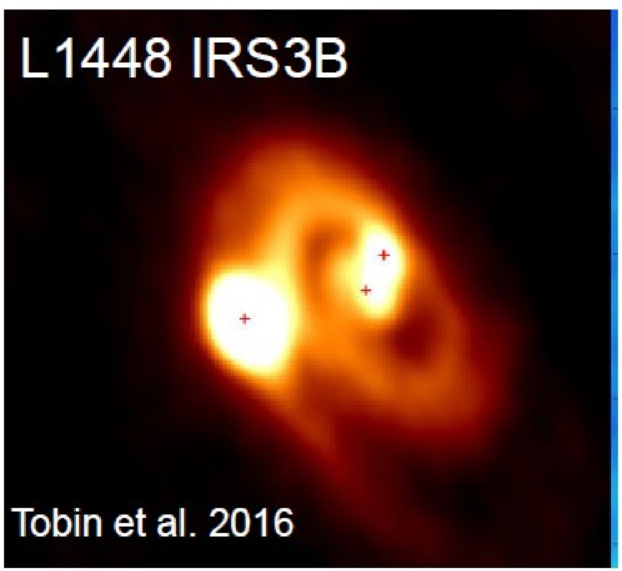


ALMA long baselines: dust



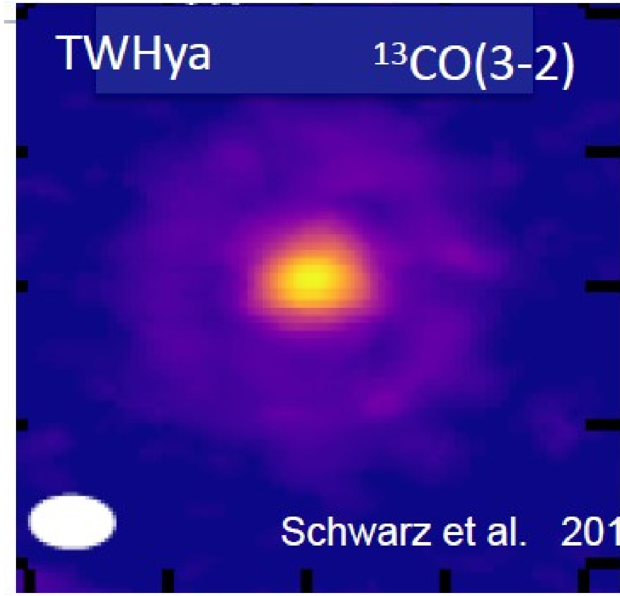


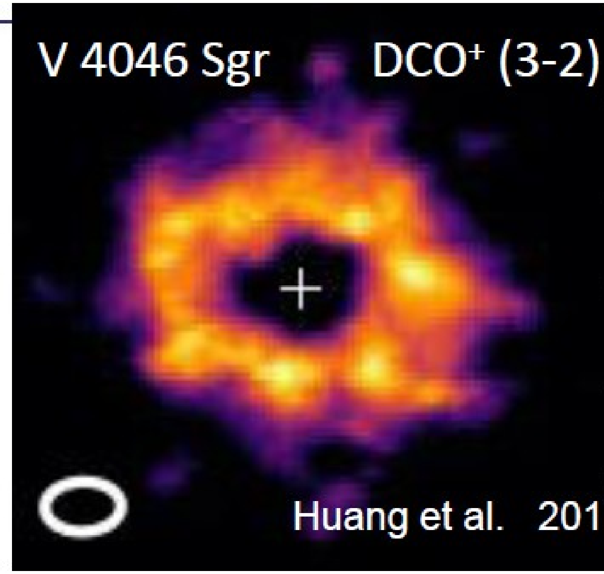


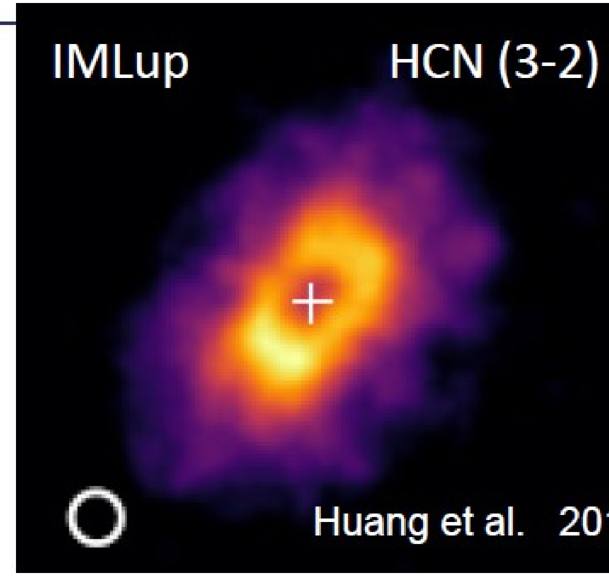


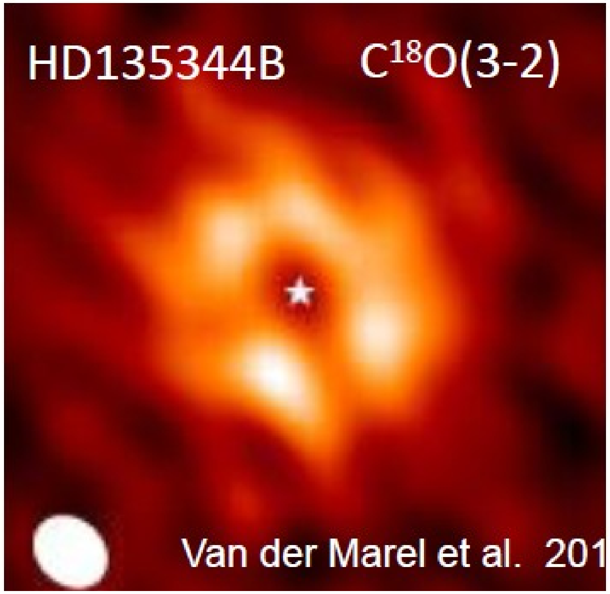
ALMA long baselines: molecules

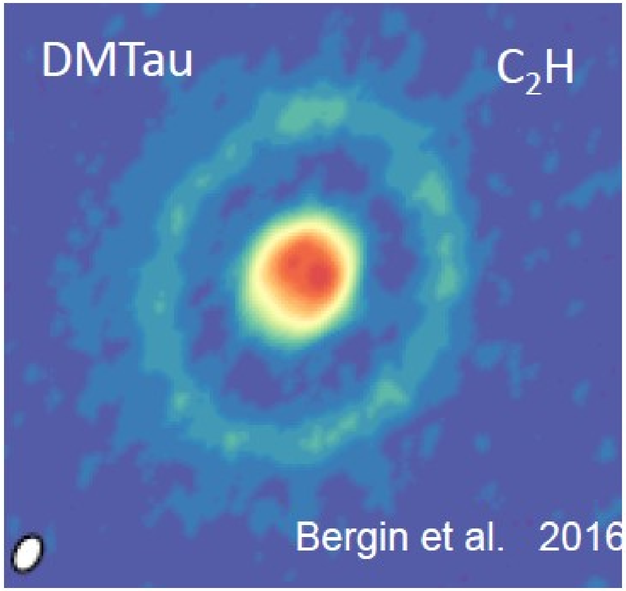
iram
Institut de
Radioastronomie
Millimétrique

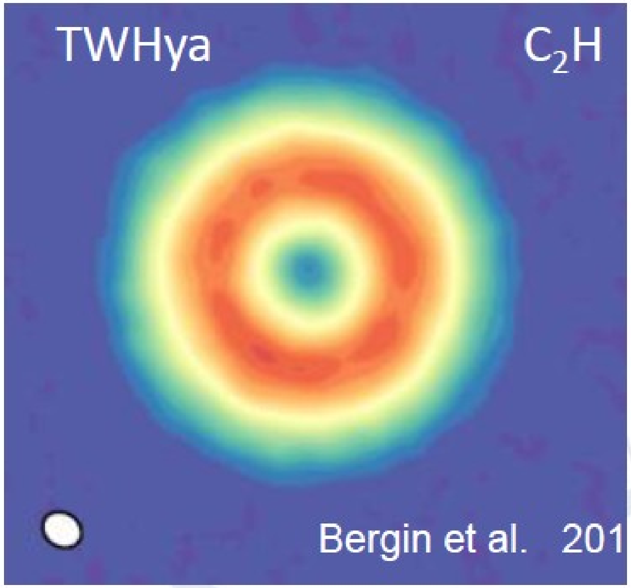






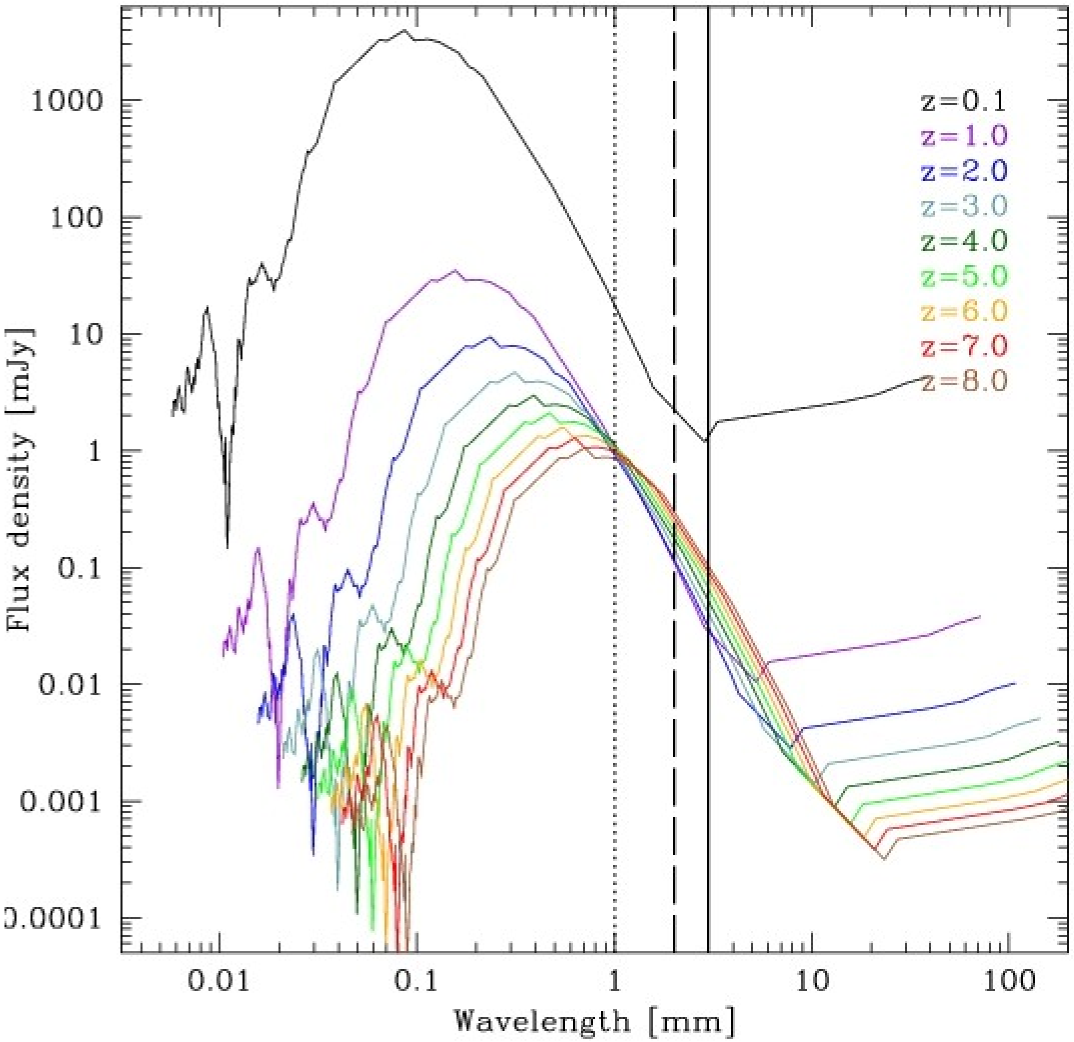






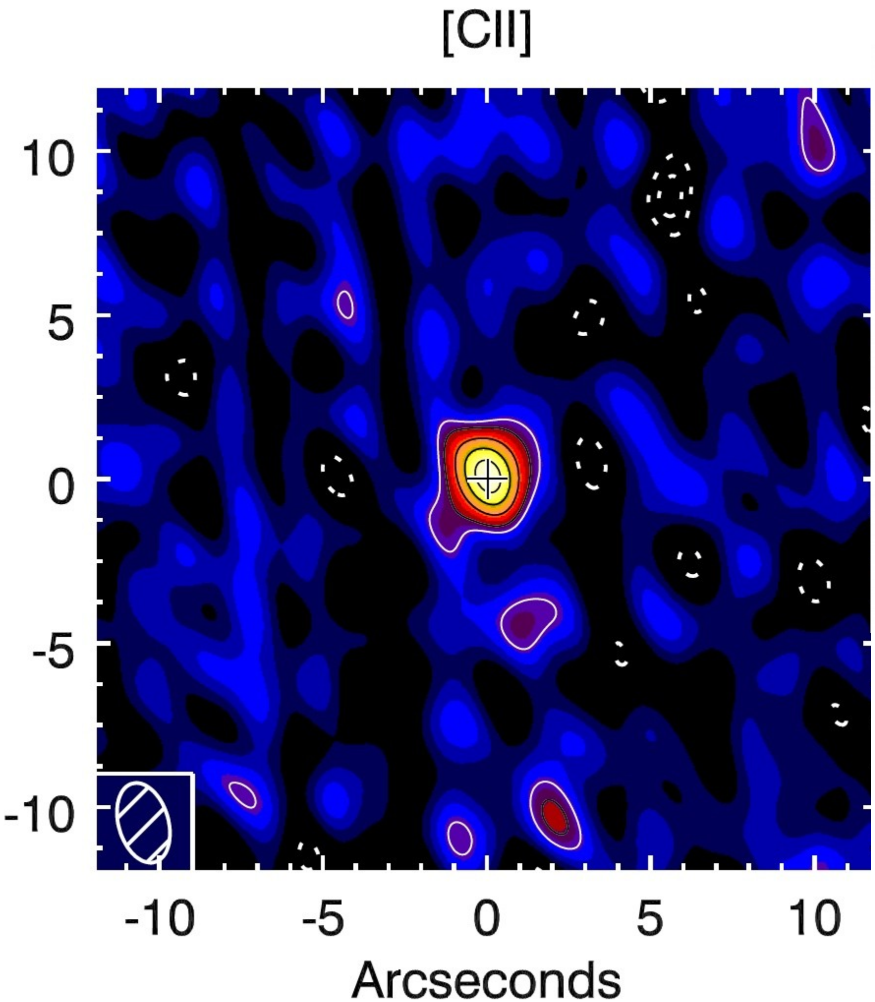
High-redshift universe

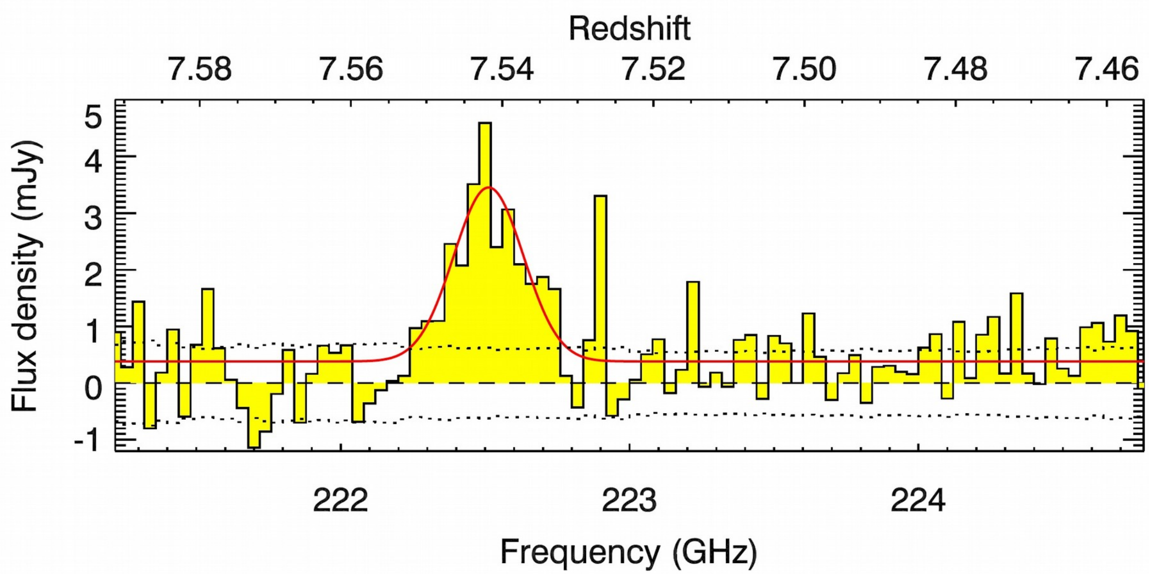
- The farther away, the dimmer are galaxies, but the whole spectrum also shifts towards lower frequencies.
- Peak of dust emission shifts towards sub-mm wavelengths: negative k-correction.
- Sub-mm astronomy is an ideal tool to study the high-redshift universe
- Study the cosmic star formation history.



Arp 220 redshifted, MPIA

The most distant quasar with confirmed redshift (z=7.54) NOEMA 8 Ants





Venemans et al in prep.

- ~10% younger than J1120+0641
- dust ~10^8 $M_\odot$, [CII] ~ 10^7 $M_\odot$
- SFR ~ 300 $M_\odot$/yr

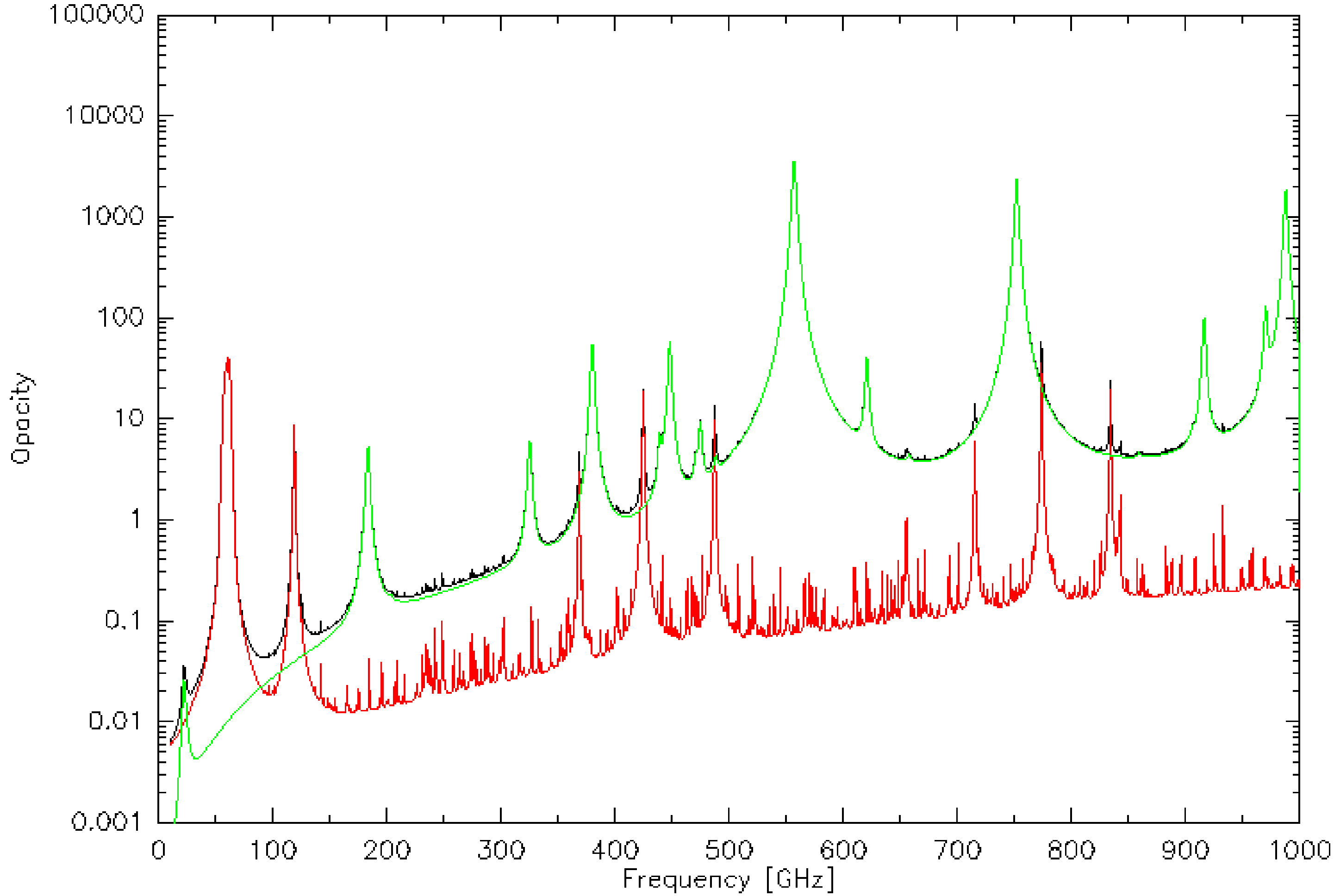
Sub-millimeter specifities

The sub-mm interforemeter

- A sub-mm interferometer is not different from a radio-interferometer
  - Antennas
  - Receiver
  - Correlator
  - Lots of cable, electronics, frequency generator and software
- However a number of effects have to be dealt with:
  - Atmosphere: emits/absorbs.
  - Atmosphere: wet/dry delays → atmospheric phases.
  - Antenna: needs precise surface/pointing.
  - Receiver: needs cryo-cooling

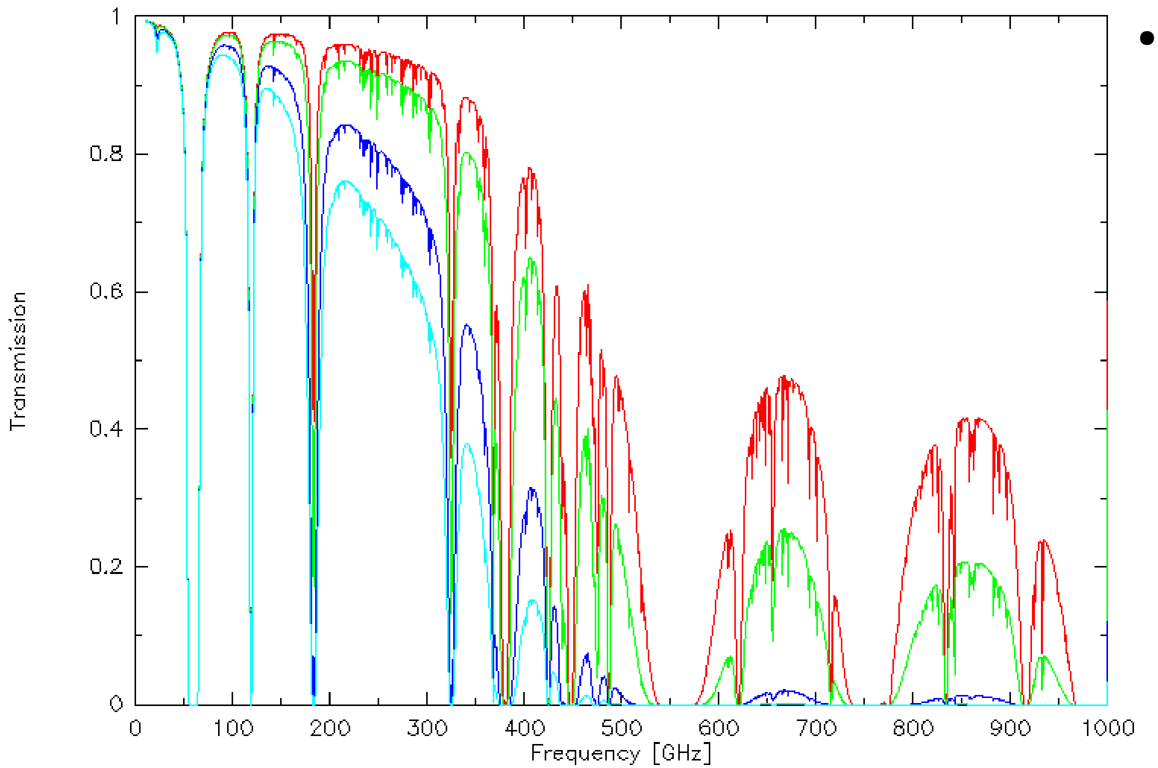
Atmosphere

- Atmospheric lines: mainly H2O, O2, O3 in the mm/sub-mm range



Atmospheric model ATM (Pardo et al.)

Atmospheric “windows”



0.5, 1, 3 and 5 mm of zenith precipitable water vapor.

- Atmosphere defines “windows” where observations are possible from the ground.
  - mm windows reasonnably accessible.
  - sub-mm windows only in the driest places.

Solution: get rid of water vapor

- Atmospheric scale height:
  - Dry air: 8.4 km
  - Water vapor: 2 km

- Solution: go to a dry high altitude site:
  - ALMA: Chajnantor (5000 m)
  - SMA: Mauna Kea (4000 m)
  - NOEMA: (2500 m)

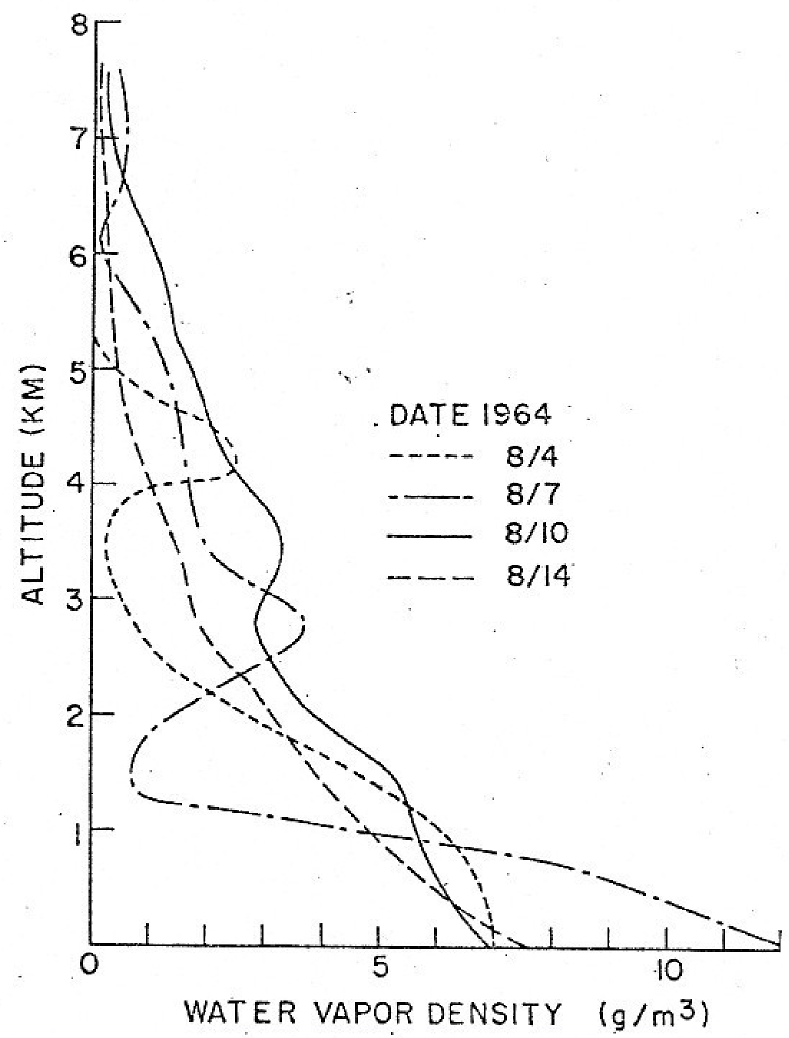


Fig. 3. Atmospheric water vapor profiles measured by radiosondes.

System temperature

$$
\begin{aligned}
T_{ant} &= T_{bg} \\
&+ T_{sky} \sim \eta_f (1 - \exp(-\tau_{atm}) T_{atm} \\
&+ T_{spill} \sim (1 - \eta_f - \eta_{loss}) T_{ground} \\
&+ T_{loss} \sim \eta_{loss} T_{cabin} \\
&+ T_{rec}
\end{aligned}
$$

- At mm wavelength, we are dominated by the atmosphere.
- 35K < Trec < 100 K
- Taking into account receiver rejection and refering to a perfect antenna outside atmosphere, one gets:

$$T_{sys} = (1 + g) \frac{\exp(\tau_{atm})}{\eta_f} T_{ant}$$

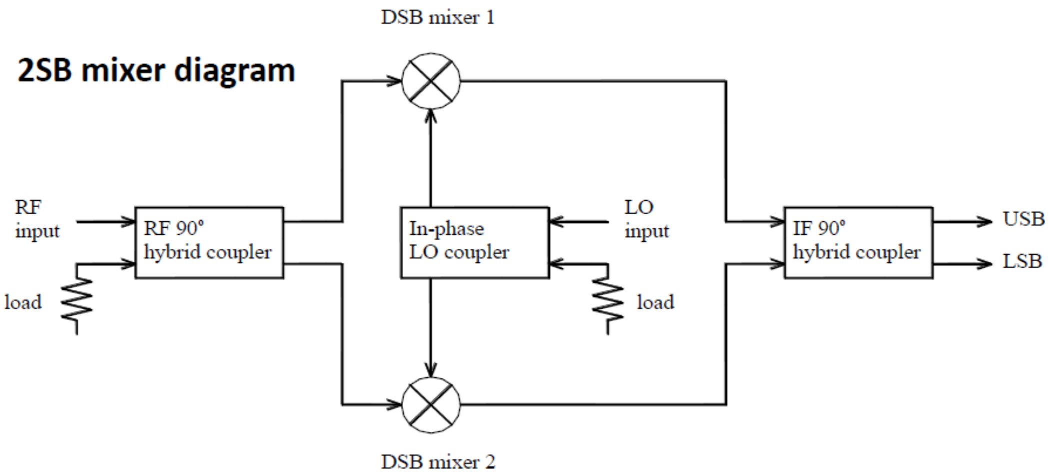
- Opacity correction allows to have sources on a scale proportional to their intensities (no more elevation dependant)

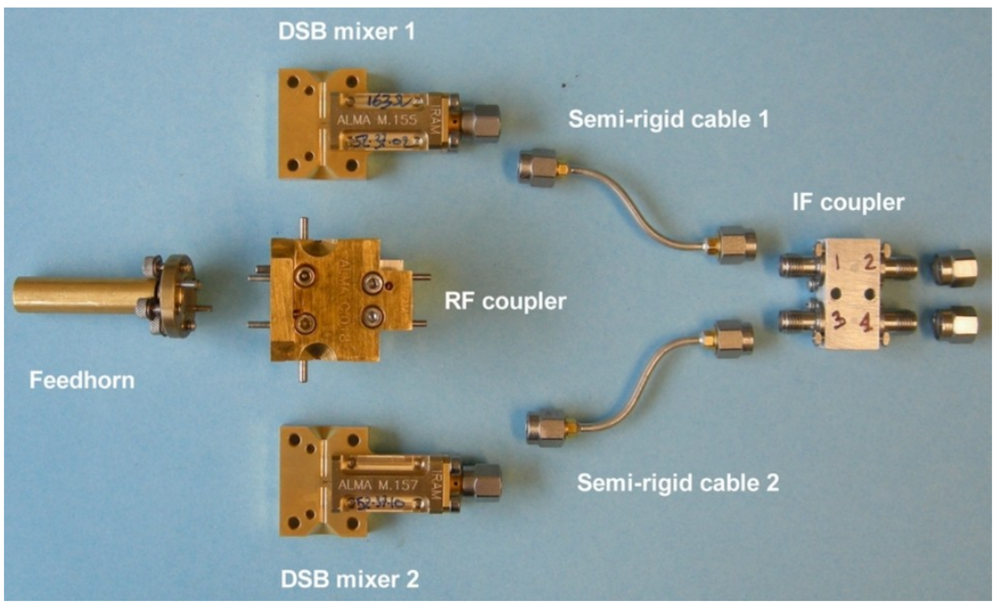
Receiver

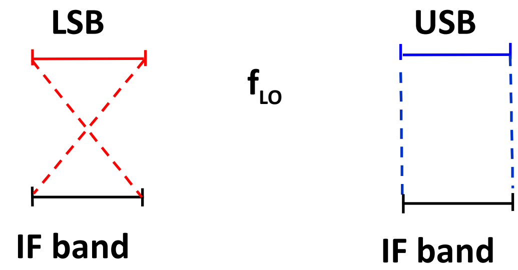
- High frequencies are not suited for a direct processing: needs a (frequency) down-conversion
  - Cm: amplify then down-convert
  - Mm: down-convert then amplify
- Technologies:
  - SIS mixers: needs a 4 K cooling, 2 times 8 GHz bandwidth
  - HEMT: direct amplification, 15 K sufficient. Bw up to 30%
  - HEB: 4 K cooling, up to Thz frequencies, 4 GHz bandwidth

Sideband

2SB mixer diagram







- DSB: both sidebands superimposed after downconversion
- SSB: one sideband is suppressed
- 2SB: sidebands are separated

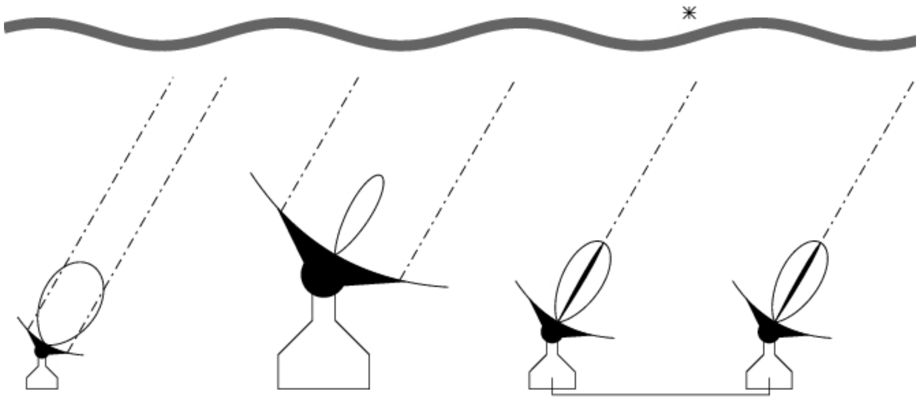
- SSB have typically a factor of 2 lower system temperatures.
- In interferometry, phase control allows separation (walsh switching)/suppression (LO offseting) of signal from image sideband

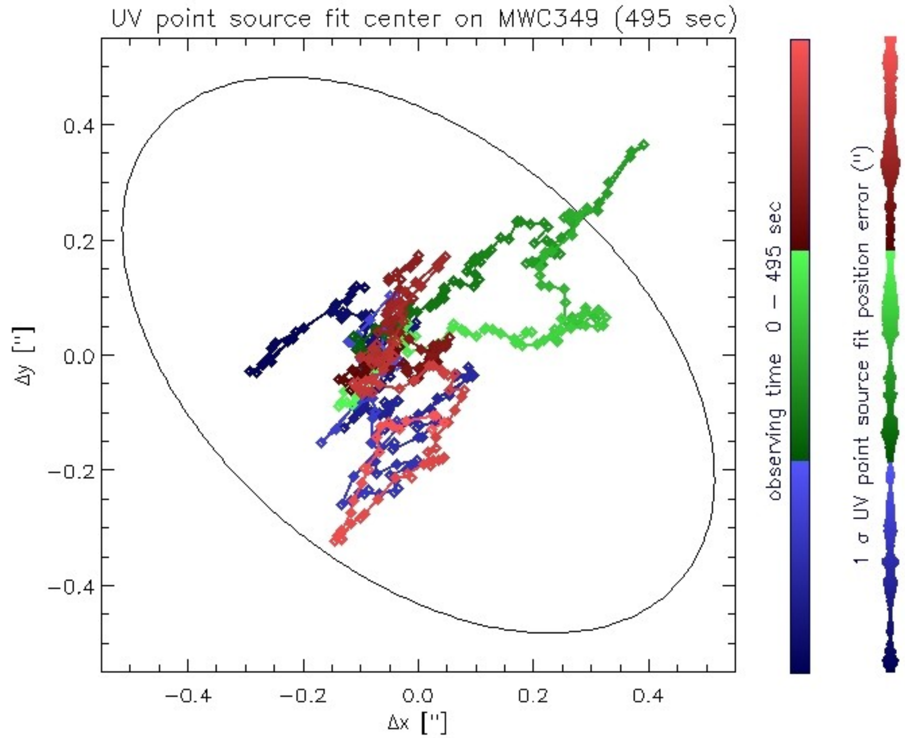
Tropospheric phase noise

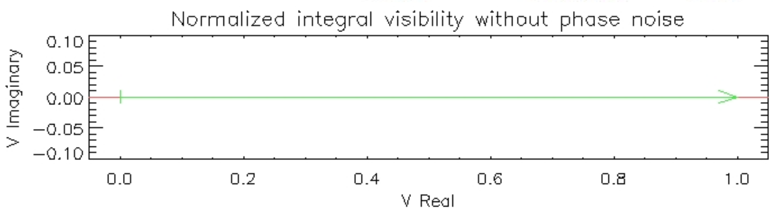
- Water vapor along the line of sight adds a phase:

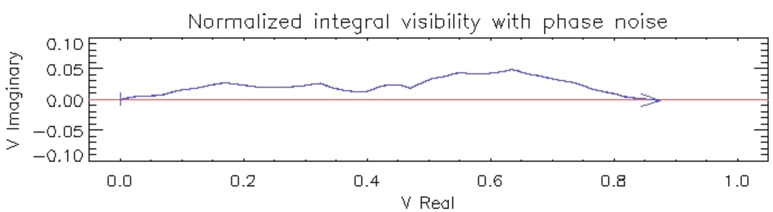
$$\phi \simeq \frac{12.6\pi}{\lambda} \times w$$

- And the air does not mix well
- Point source appears to move:
- We lose integrated flux due to phase jitter: $V_{obs} = V_{ideal}\exp(-\phi^2$



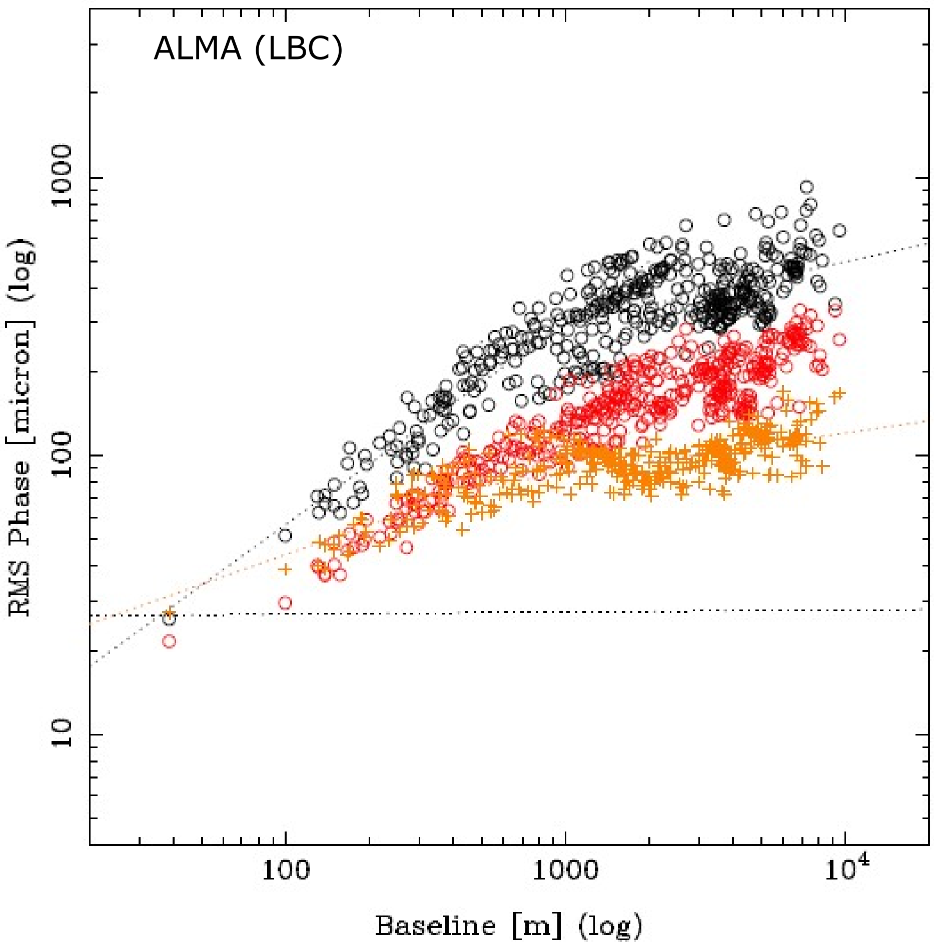


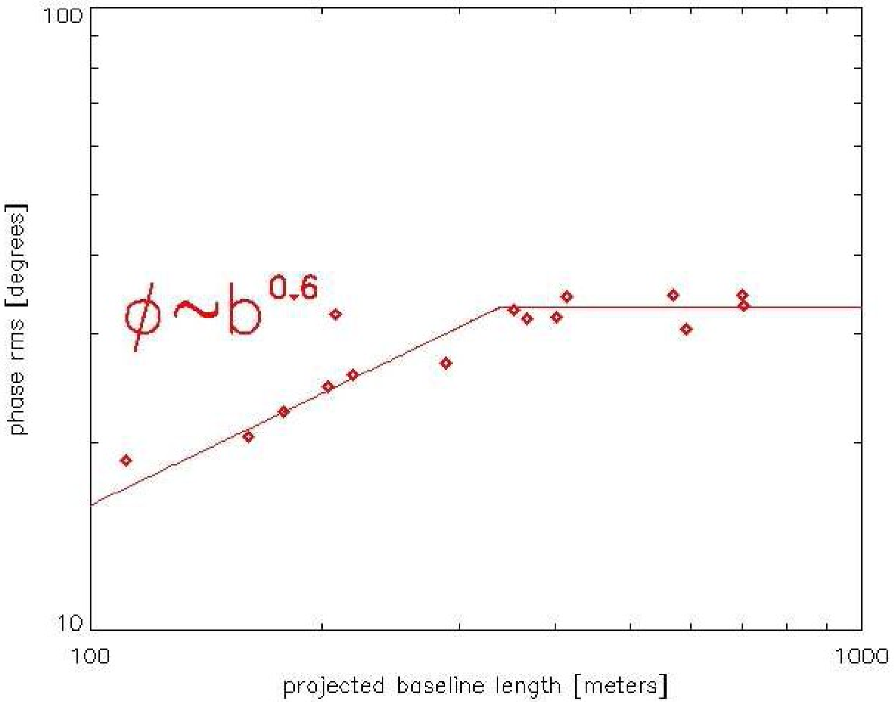




Structure function of the atmosphere

Following Kolmogorov turbulence theory, phase rms increases up to an outer scale

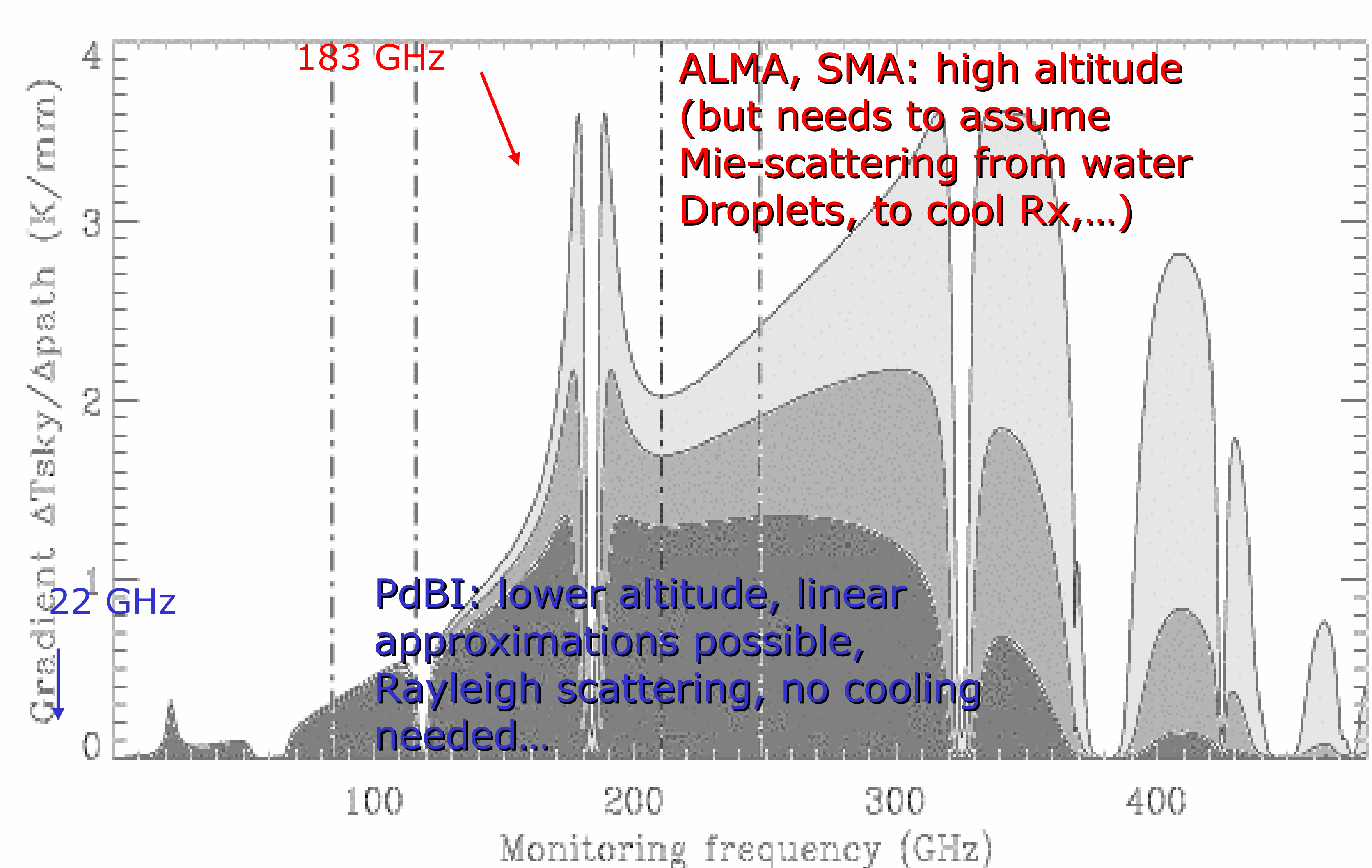




PdBI (*Bremer 2010*)

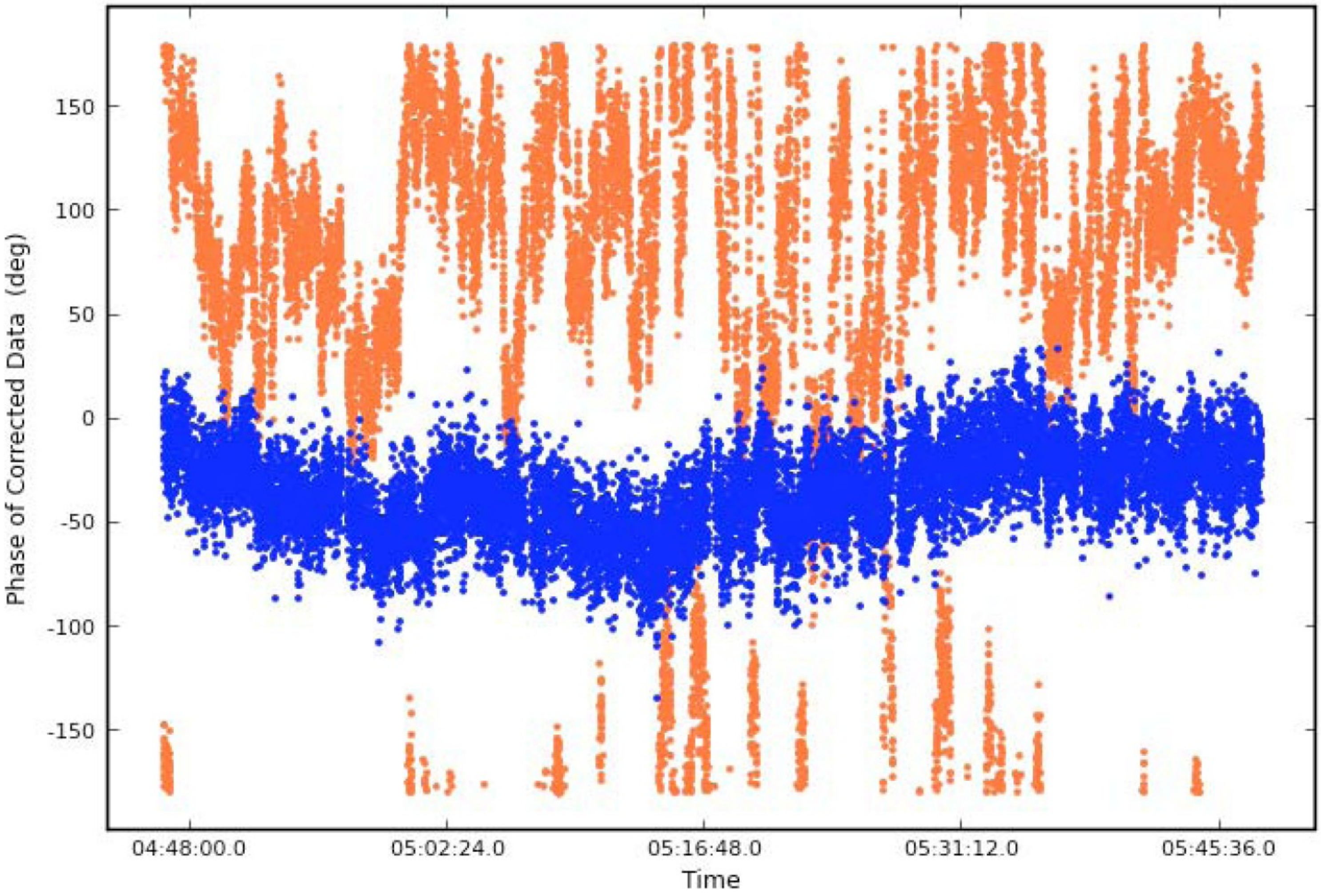
Radiometers

(Un)fortunately, water vapor has emission lines.



(Bremer et al. 1997)

Applying radiometric correction

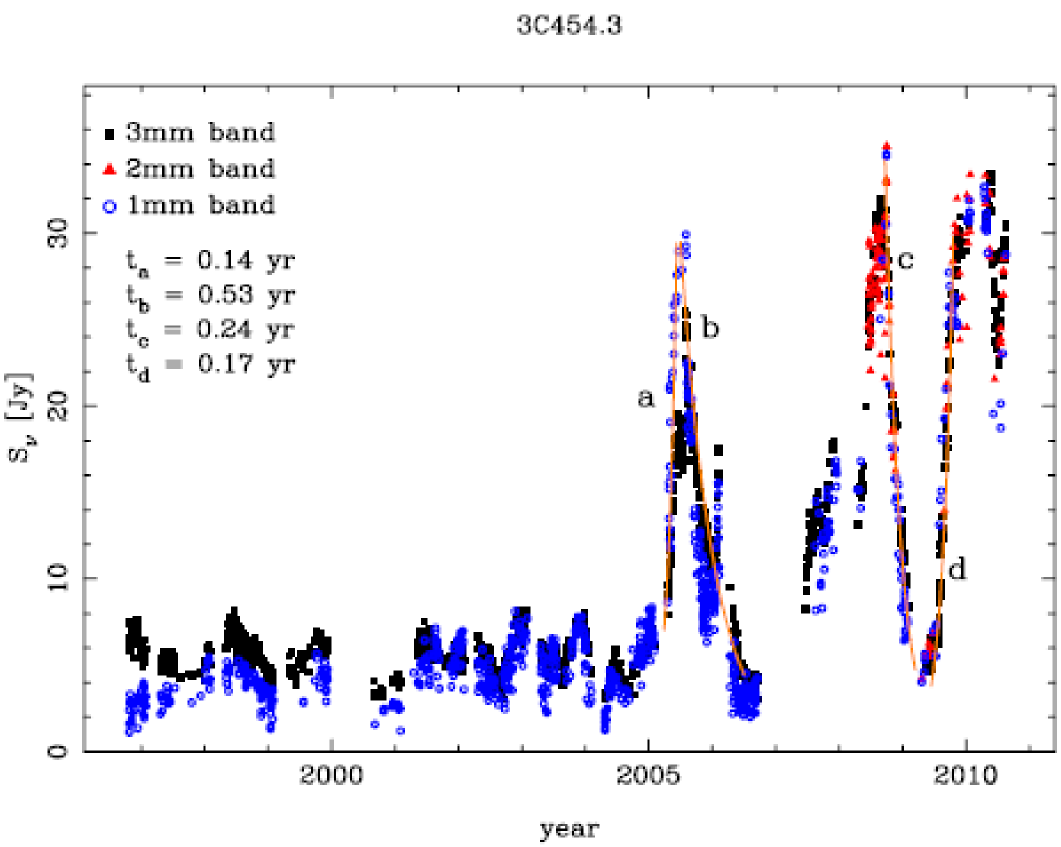


Antenna

- Field of view inversely proportional to observing frequency for a given antenna size. As a consequence, the field of view is quite smaller than at radio-wavelength (of the order of the minute of arc at mm wavelength). This also imposes stricter requirements on the antenna pointing and tracking accuracy.
- Feed arrays are considered (even if not yet ready) for improving mapping speed at (sub)mm wavelenghts.
- The filtering nature of the interferometer is more acute at (sub)mm wavelengths. Need short and/or zero spacings more often than at radio-wavelengths.
- Ruze formula requires a surface r.m.s. a 20th of the observing wavelength. Need to overcome gravity and thermal limits on antenna deformations (homological design, low thermal expansion back-up structure).

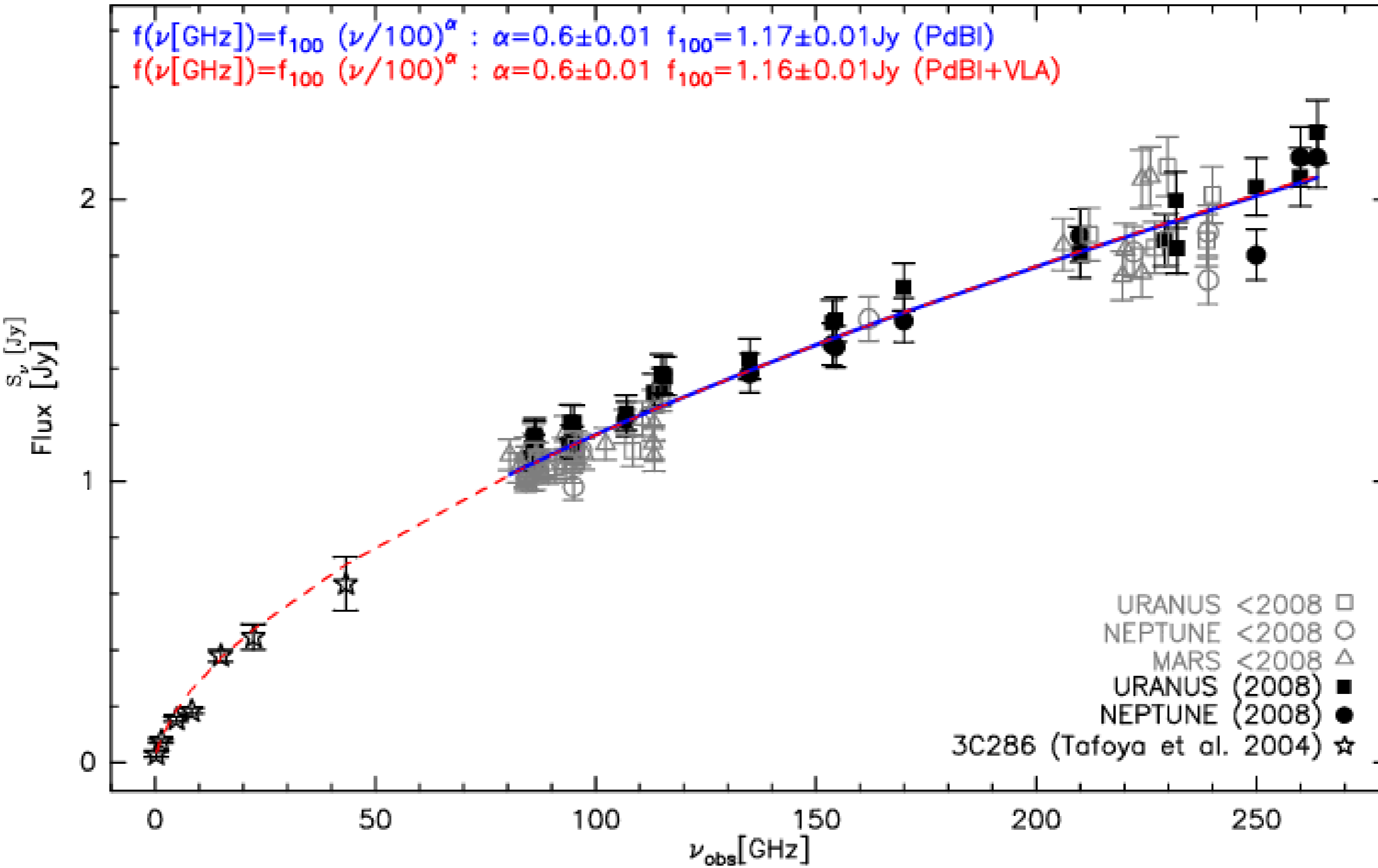
$$\eta_a = \eta_0 \exp(-(4\pi\sigma/\lambda)^2)$$

Quasars are variable



- Use primary calibrators to set the flux scale
  - Planets, but can be resolved out depending on frequency and configuration. Can have absorption line.
  - Satellites
    - Take care that it is not too close from planet
  - Solar system small bodies, but need a good model.
  - Radio-stars. At NOEMA, MWC349 is used as a flux reference
- In the sub-mm quasars get fainter

Quasars are variable



o set

esolved
uency
n have

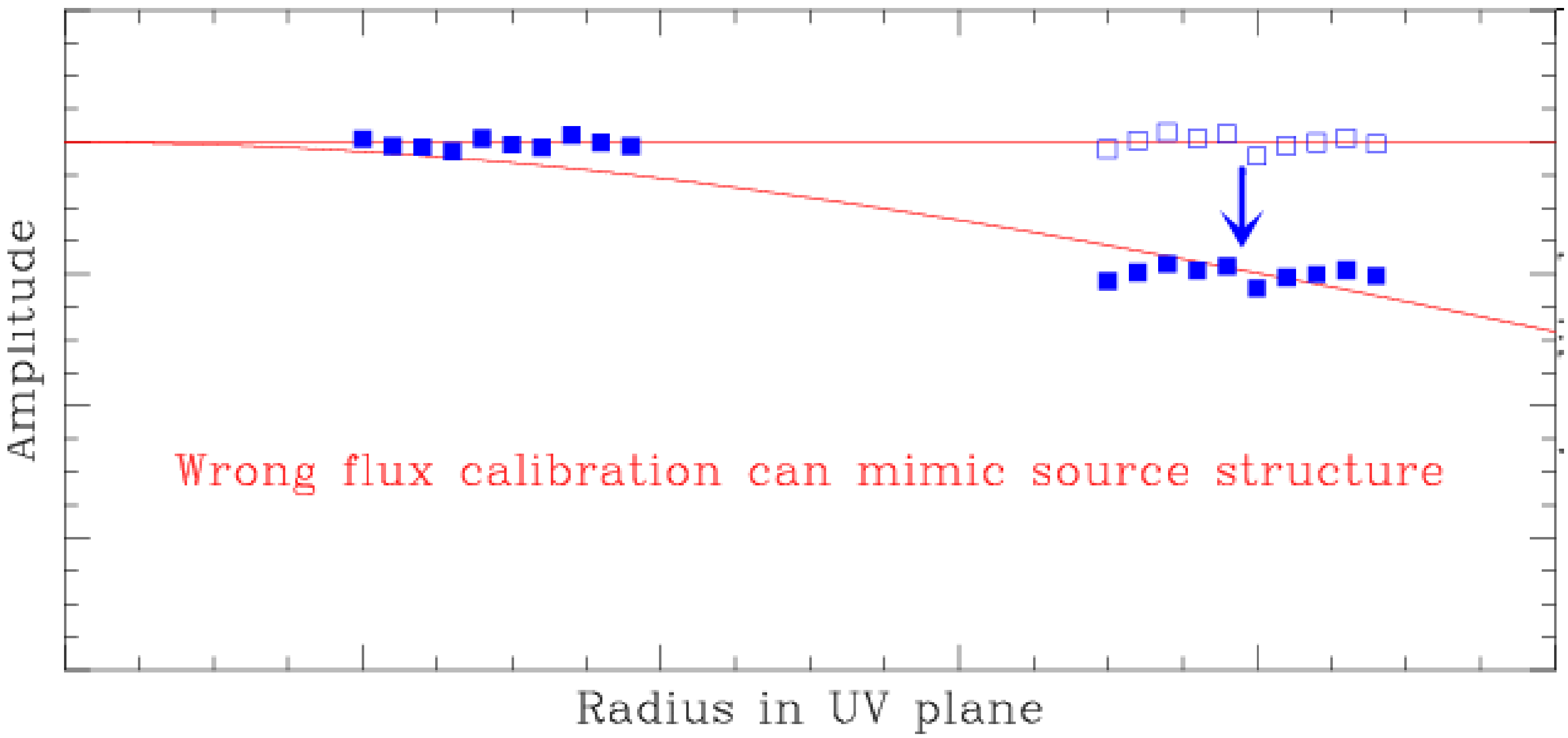
not
net

odies,
el.

A,
a flux

Why flux scale matters

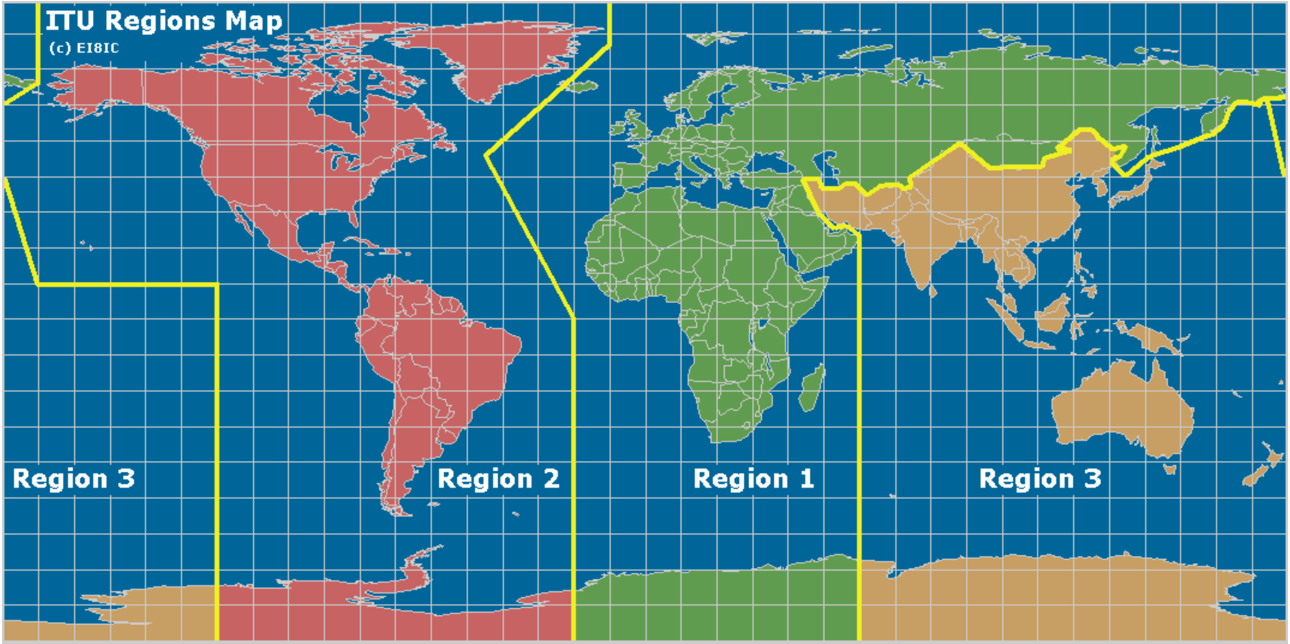
- Direct error on temperature or surface density.
- When observing with multi configurations:



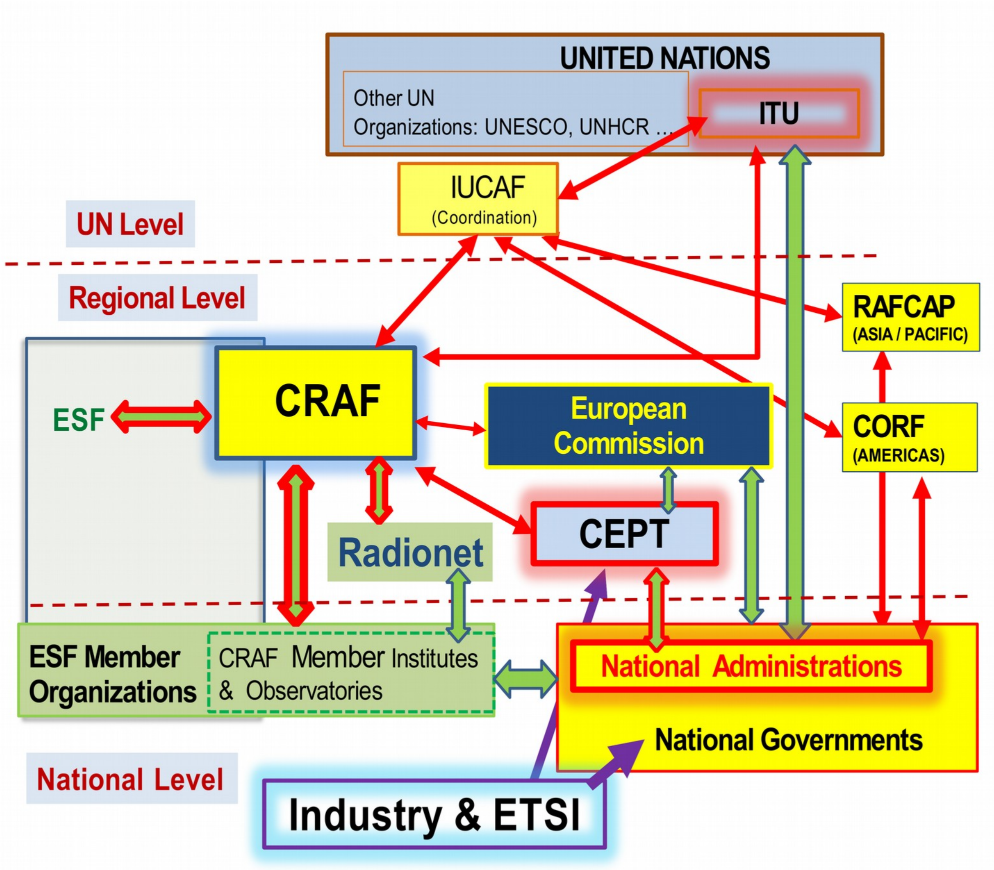
Radio-Astronomy Frequencies Protection and spectrum management

ITU and WRC

- ITU (International Telecommunication Union).
- Agency of the UN
- Edit the Radio Regulations
- Contain the spectrum allocation (assigment by national administrations).
- Deal with services:
  - Radionastromy is one of them (RAS).
- Organize World Radio Conferences (hundred of admistrations, 3000 attendees):
  - Last: WRC15
  - Next: WRC19



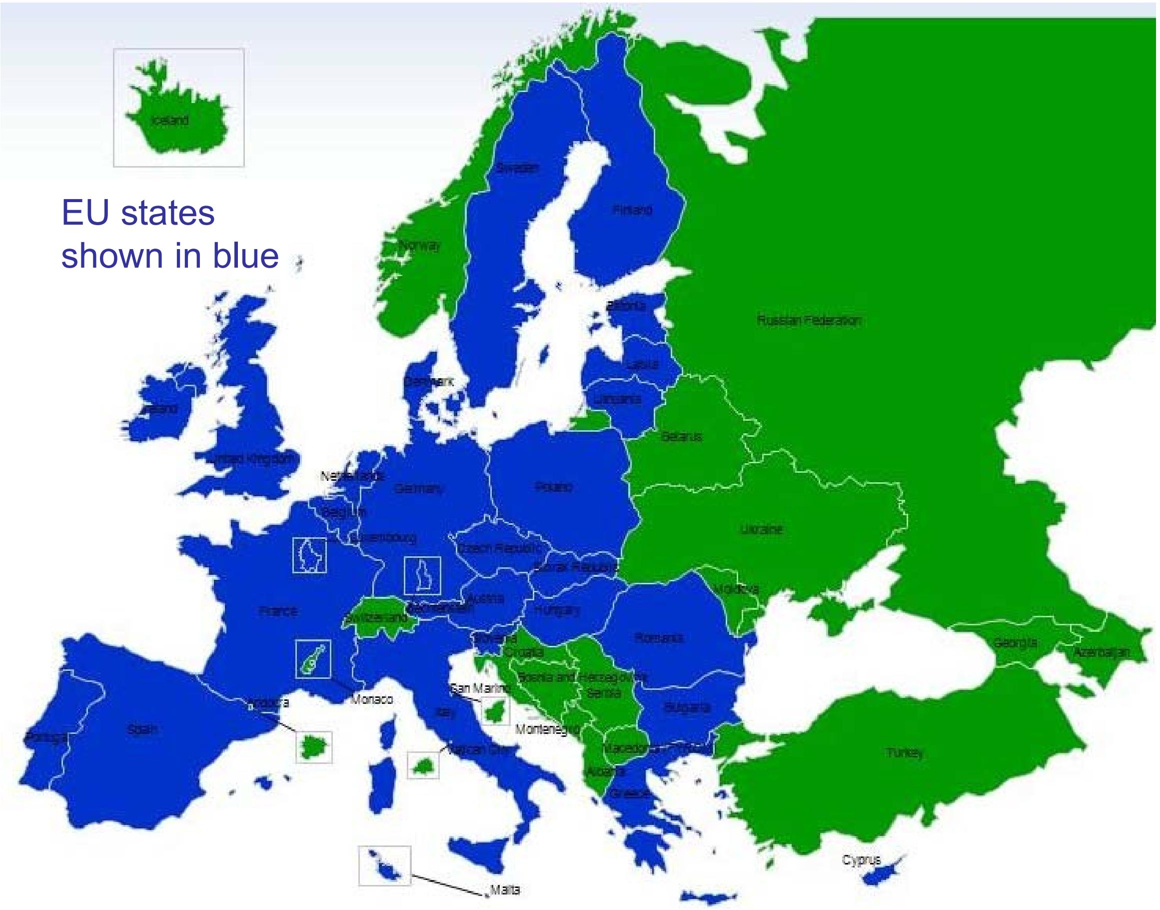
Regulatory environment



- Astronomers interact through:
  - IUCAF
  - CRAF (Europe)
  - CORF (Americas)
  - RAFCAP (ASIA/PACIFIC)
- Very important to have close contacts with national administrations.
- Spectrum ownership is of national sovereignty.

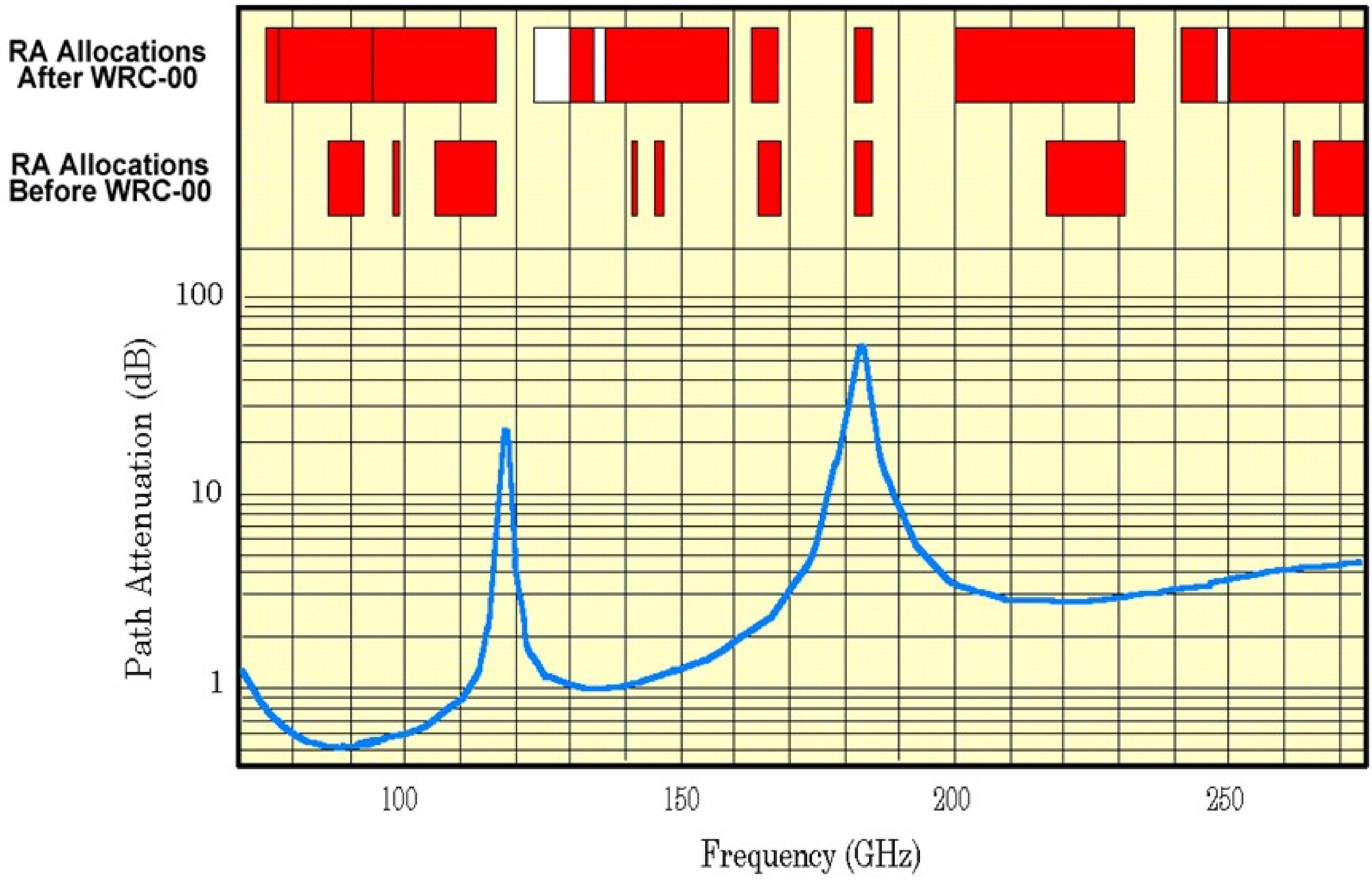
Spectrum management in Europe

- In europe:
  - 28 EU countries
  - 48 CEPT (Conference Europeenne des Postes et Telecommunications) countries
- EC is implementing its digital agenda.
  - IoT: Internet of Things
  - 5G mobile
- Role of ETSI (European Telecommunication Standard Institute).
- CRAF (Comittee on Radio-Astronomical Frequencies):
  - Employ a full-time frequency manager (T. Hezareh).



Radio allocation summary

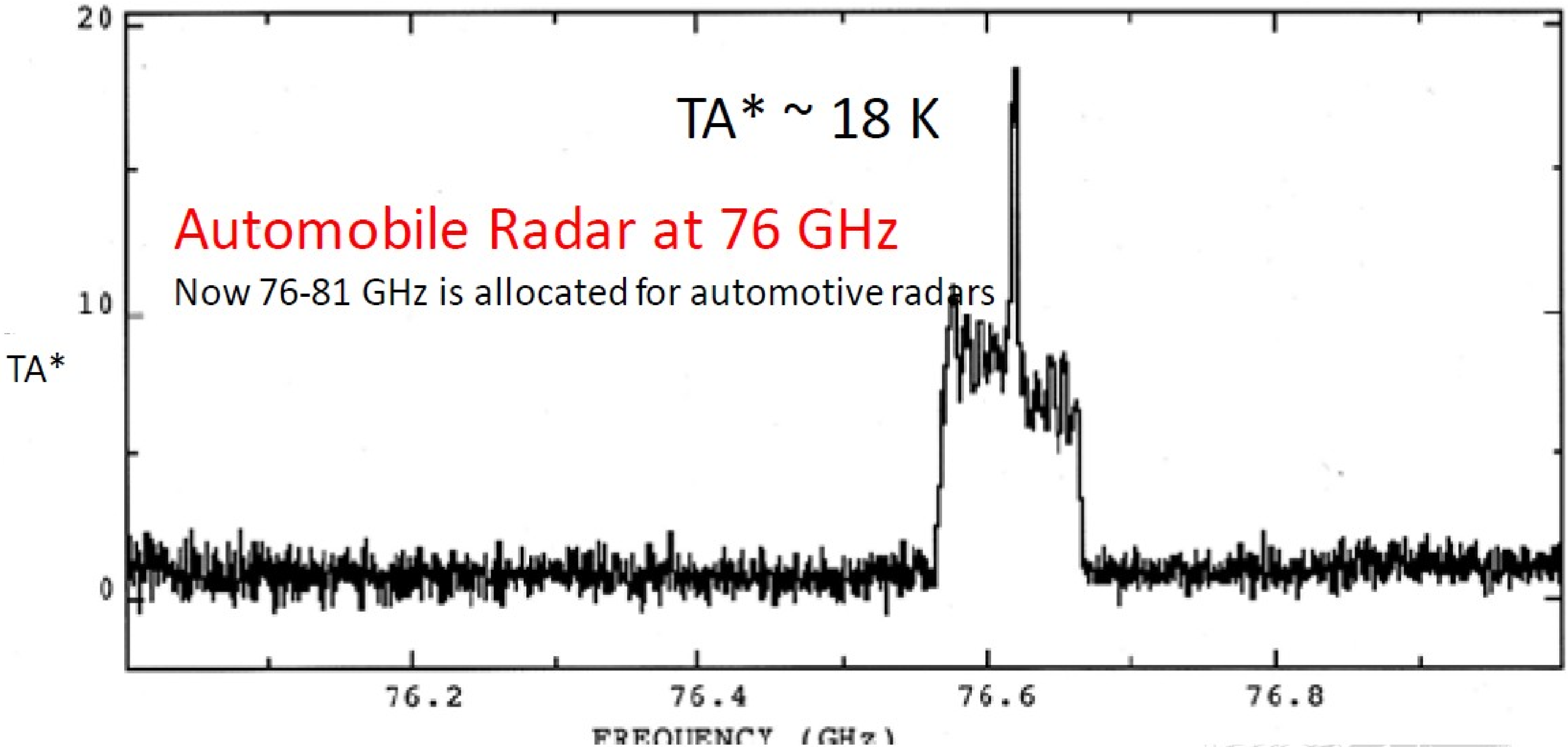
- **< 30 GHz:**
  - 1.3% primary exclusive for passive frequency use
  - 1.2% primary shared allocations
  - 0.5% secondary allocations
- **30 - 275 GHz:**
  - 16.8% primary exclusive for passive frequency use
  - 38.3% primary shared allocations
  - 5.1% secondary allocations
- **> 275 GHz:**
  - No allocation yet


RA Allocations
After WRC-00
RA Allocations
Before WRC-00
100
10
1
Path Attenuation (dB)
100
150
200
250
Frequency (GHz)

Current agenda (not exhaustive)

- From WRC15:
  - Car (and helicopter) radars (76-77 GHz, 76-81 GHz)
- WRC19 agenda items:
  - 1.13: MS number of bands above 24 GHz are considered (including 31.8-33.4, 40.5-43.5, 81-86 GHz !). 3400-3800 MHz and 24.5-26.7 GHz in Europe.
  - 1:14: HAPS (High Altitude Platforms Service). 38-39.5 GHz (21.4-22 GHz and 24.25-27.5 in the Americas).
  - 1.15: Identification of bands for mobile and fixed service in 275-400 GHz range.
  - 1.8: GMDSS: Iridium attempting to be a safety of life service (free-pass for interferences).
  - 1.7: NGSO spectrum needs. Impact on 150.05-153.0 MHz and 406.1-410.0 MHz ?
- Iridium-next going to space: measurement campaign at the Leeheim satellite-tracking station on-going. Interference in the 1610 MHz band.
- NGSO OneWeb and SpaceX in the 10 and 14 GHz bands
- Wind turbines (LOFAR).

New Discovery?



Masao Saito, Nobeyama observatory

What you can do

- Register your telescopes in the ITU/national database (no protection otherwise).
- You do not need to know all the details, but to be aware of spectrum management.
- Report RFI to the observatory:
  - Need to have documented evidence with calibrated spectra.
- Please answer when asked about band usage
  - Need to consider actual but also possible future usage. When a band is “lost”, it is usually lost forever.
  - At the time when you are hit, decisions have been taken 5-10 years before.
- Argue within your institutes for the need of radio-frequencies protection and support your colleagues in charge ot it.

(sub)-mm interferometers

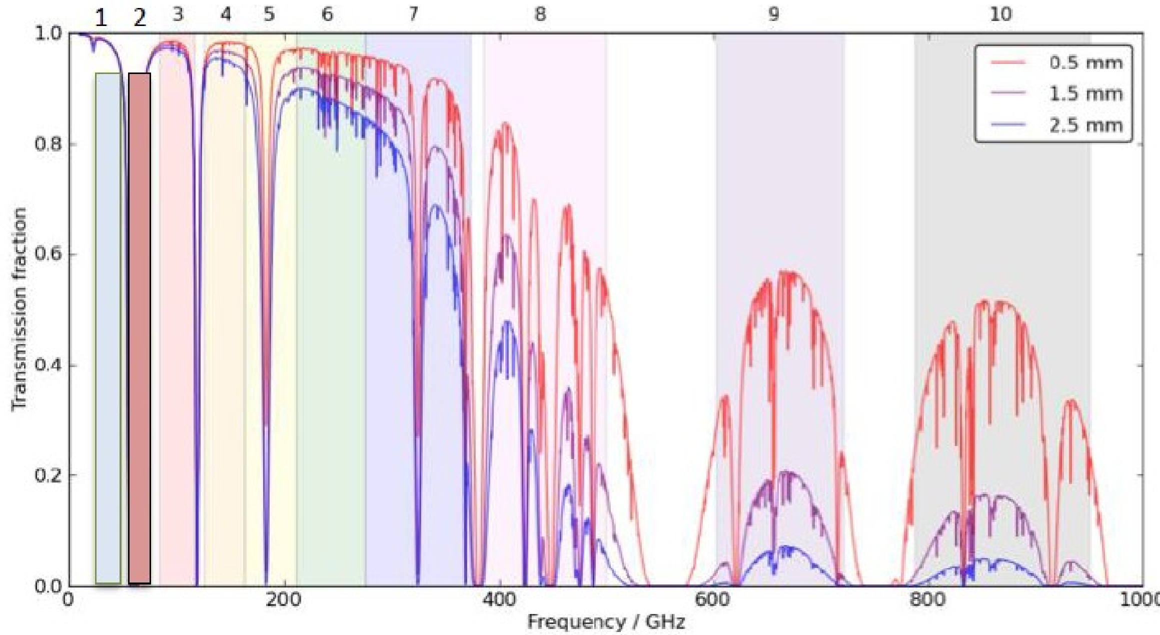
ALMA

- Collaboration between, NRAO, ESO, NAOJ, NINS and Chile.
- 50 12-meters antennas + 12 7-meters antennas (Morita Array or ACA) + 4 12-meters antennas (total power) for short/zero spacings.
- Baselines up to 16 kilometers.

ALMA receiver

Receiver Bands currently (being) installed on all antennas, in construction and under study:

- Band 1: 6 mm (35-52 GHz)
- Band 2: 4 mm (65-90+ GHz)
- Band 3: 3 mm (84-116 GHz)
- Band 4: 2 mm (125-163 GHz)
- Band 5: 1.5 mm (163-211 GHz)
- Band 6: 1 mm (211-275 GHz)
- Band 7: 850 µm (275-370 GHz)
- Band 8: 650 µm (385-500 GHz)
- Band 9: 450 µm (602-720 GHz)
- Band 10: 350 µm (787-950 GHz)



ALMA

- Sub-mm interferometer:
  - Antenna surface < 25 microns
  - Complex delay server to account for wet and dry components, difference in the altitude of the antennas, possibly different partial pressure of oxygen.
  - Covers all the sub-mm/mm windows.
- ALMA has already transformed pretty much all of the scientific fields with a huge impact and achieved the initial top scientific goals.
- ALMA is heavily oversubscribed (5 to 10, worst in Europe).
- ALMA has a ambitous development program (13.5 M$/yr):
  - Has been used to restore capabilities that were descoped during rebaselining.
  - Is now turning into plans to double the bandwidth (needs new receivers, digitizers, correlator ….)
  - Contempting adding new antennas, developing longer baselines.

NOEMA

- NOEMA is a transformational upgrade of the PdB interferometer in order to achieve ALMA-like sensitivities, high fidelity, high resolution imaging.
- It consist of:
  - Doubling the number of antennas from 6 to 12.
  - Doubling the maximal baseline length to 1.6 km.
  - Quadrupling the RF bandwith to 32 GHz (2SB x 2 pol x 8 GHz).
  - Enabling dual-band observing, bringing the bandwidth to 64 GHz.
  - Total budget of 53 Meuros in two phases.
- Phase I:
  - 4 new antennas
  - New receivers in all 10 antennas
  - Correlator able to process to up to 12 antennas

iram
Institut de
Radioastronomie
Millimétrique

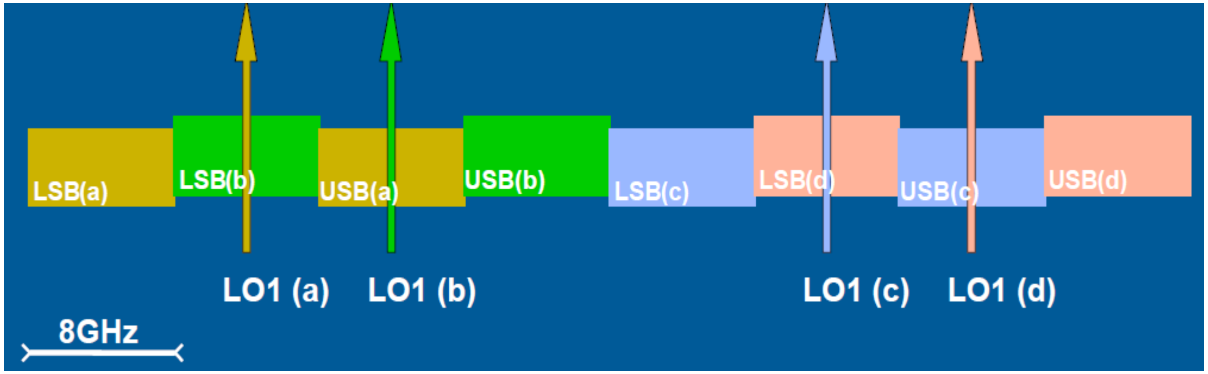

Feb 2015


May 2016

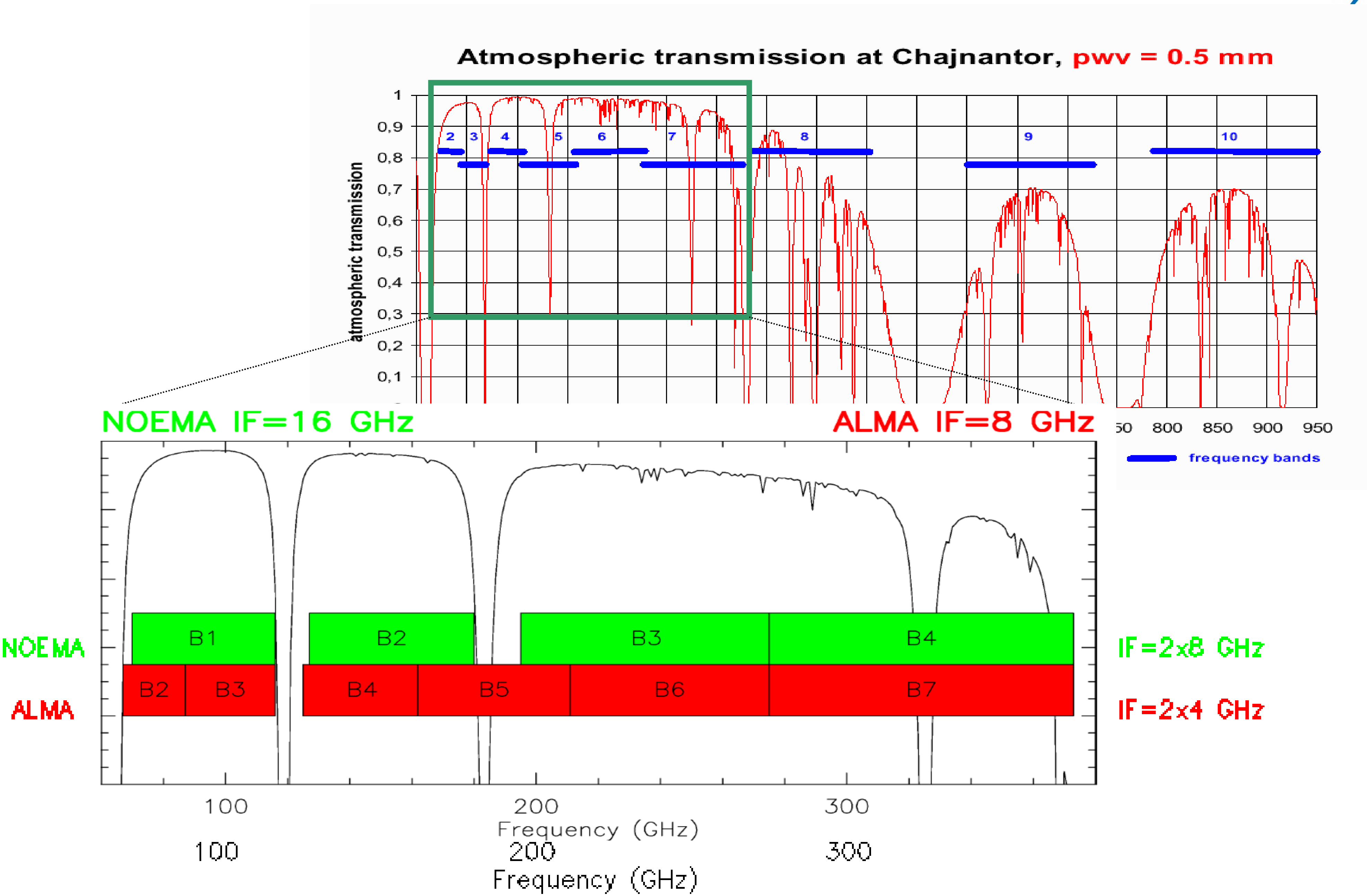

May 2017

NOEMA Phase I

- 3 new antennas assembled and commissioned.
- 9 antennas equiped with new receivers (32 GHz).



NOEMA receivers



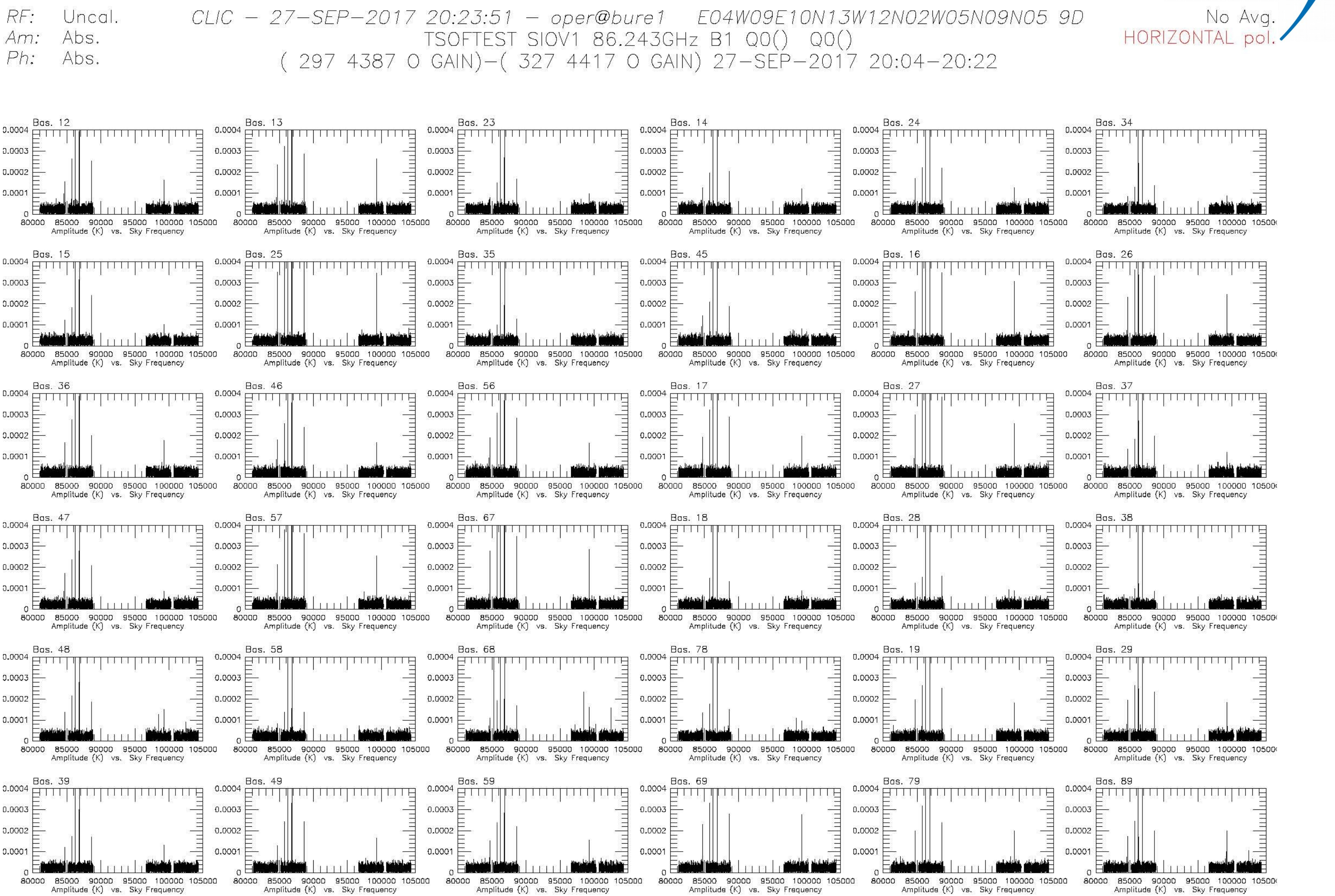
NOEMA Phase I

iram
Institut de
Radioastronomie
Millimétrique

- Polyfix installed last month (last half two weeks ago).

complete 16 GHz coverage in each polarization with 2 MHz channels
AND
128 windows of 64 MHz (= 8 GHz coverage) with 62.5 kHz channels, each window tunable individually in steps of 64 MHz within 16 GHz
complete 16 GHz coverage in each polarization with 250 kHz channels
same as mode 1, but with 64/32/16 windows of 64 MHz with 32/15/8 kHz channels

Polyfix first fringes



NOEMA Phase II

- Phase II includes:
  - Two new antennas (not yet funded).
  - Extension of the baselines (funded by MPG).
  - Enabling dual band observations with a retrofit a receivers and a second Polyfix correlator (funded by MPG).
  - Develop phasing capabilities and enable mm-VLBI (funded by ERC Black Hole Camera).

Summary

- Unique science: thermal dust emission and rotational lines.
- Mm/sub-mm interferometry is similar in many aspects with lower frequency interferometry
  - You can use all the generic background of this school
- Smaller field of view, demanding on antenna performances.
  - To increase mapping speed, use focal arrays ?
- Needs cryo-cooled receivers
- Some specificies:
  - Atmosphere:
    - Absorbing incident radiation and emitting (noise)
    - Corrupting the astronomical phases
    - But one can use radiometers
- Not so much RFI so far, but this may (will ?) change