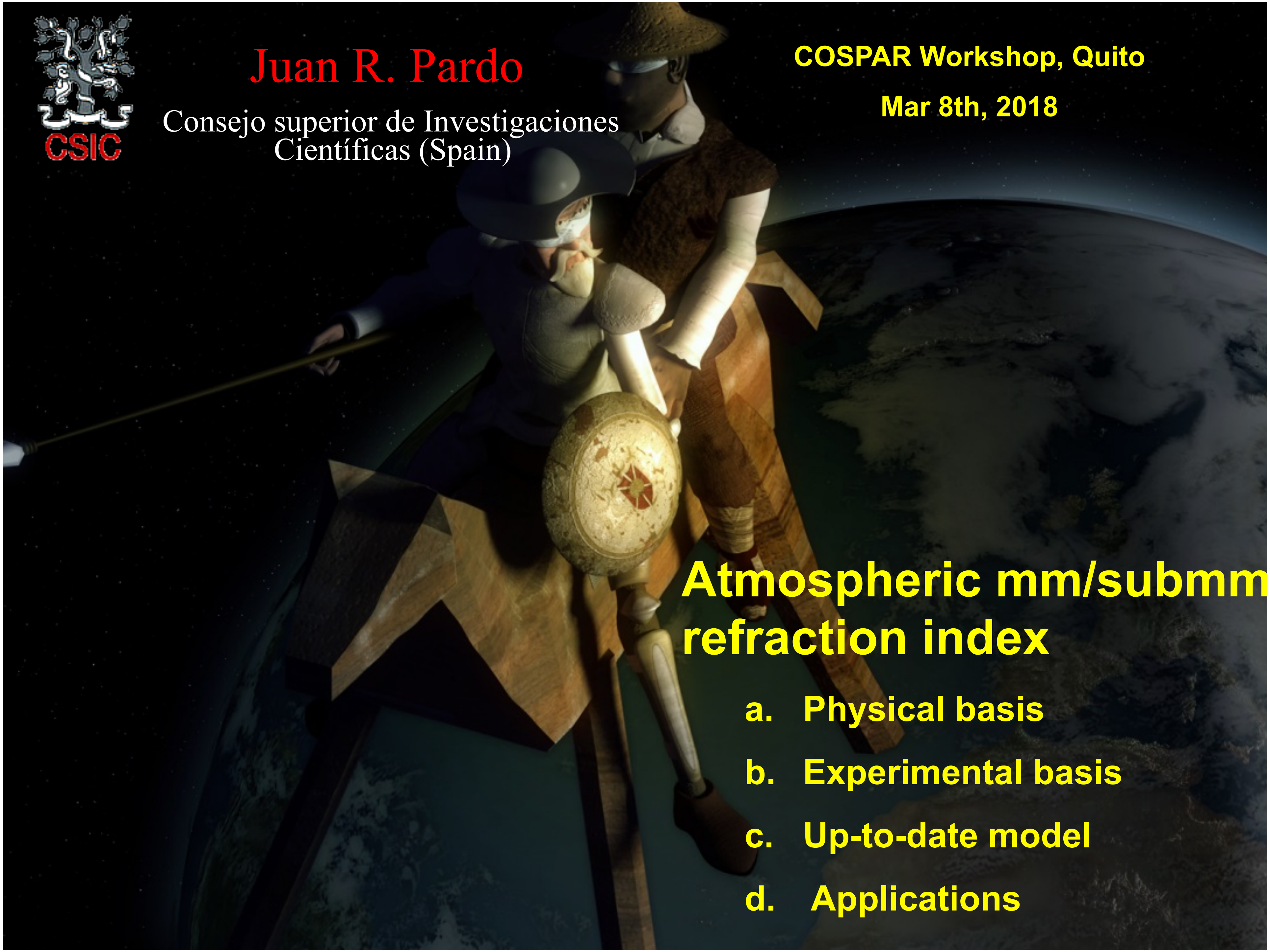


Juan R. Pardo

Consejo superior de Investigaciones Científicas (Spain)

CSIC

COSPAR Workshop, Quito

Mar 8th, 2018

Atmospheric mm/submm refraction index

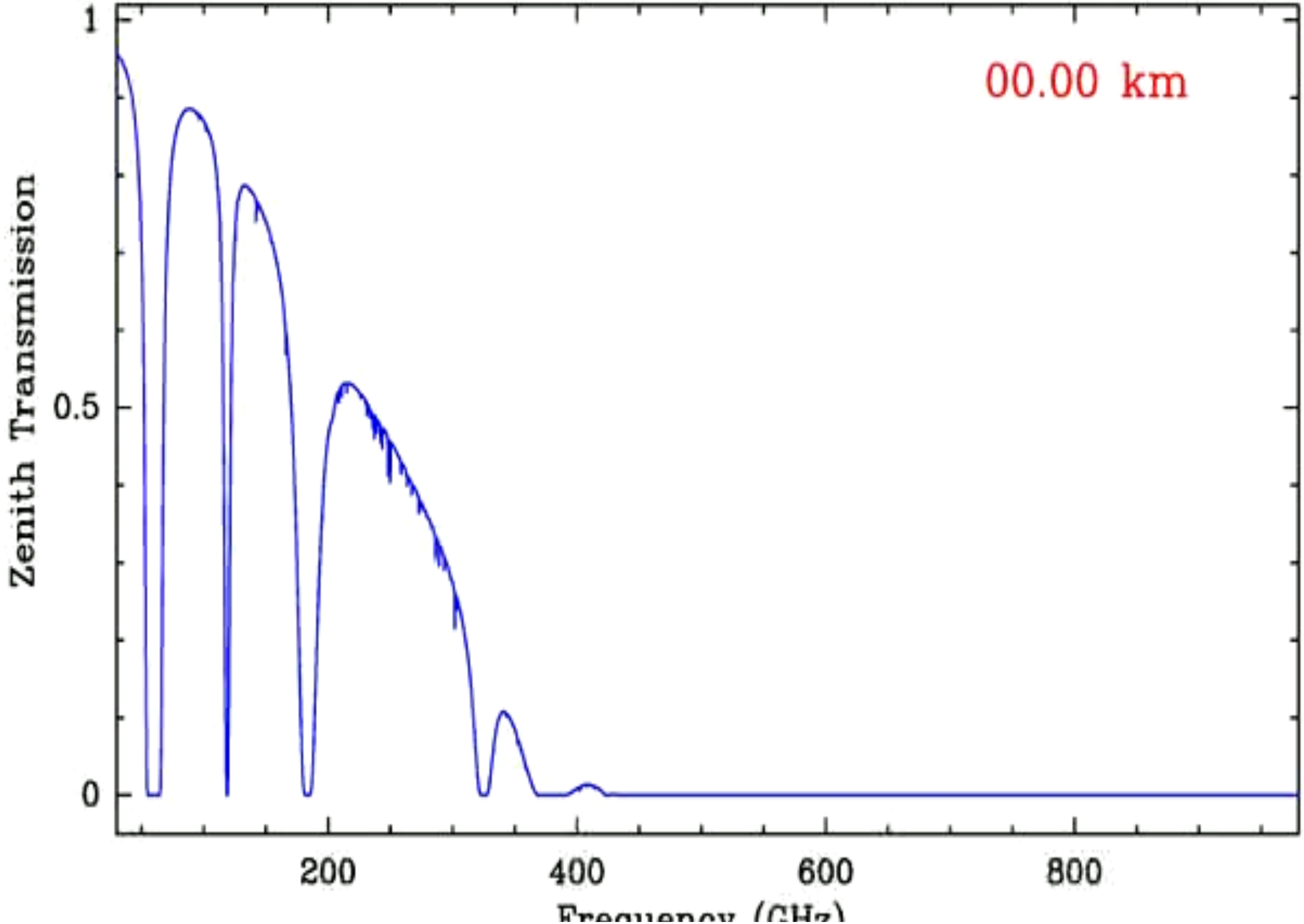
a. Physical basis

b. Experimental basis

c. Up-to-date model

d. Applications

[redacted]



00.00 km
Zenith Transmission
1
0.5
0
200
400
600
800
Frequency (GHz)

General radiative transfer equation (using coordintatates: z, μ=cos(θ), φ)

$$\mu \frac{dI(z,\mu,\varphi)}{dz} = K(z,\mu,\varphi)I(z,\mu,\varphi) -$$

$$- \int_{-1}^{1} d\mu' \int_{0}^{2\pi} d\varphi' Z(z,\mu,\varphi,\mu',\varphi') I(z,\mu',\varphi') - \sigma(z,\mu,\varphi) B[T(z)]$$

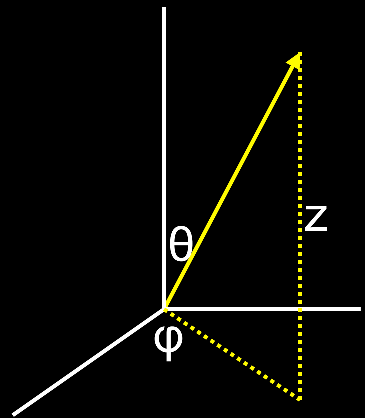
$\mathbf{I}=(I,Q,U,V)^T$ Radiation field (Stokes column vector)

K 4x4 extinction matrix

Z 4x4 phase matrix (describing scattering)

σ 4x1 emission column vector

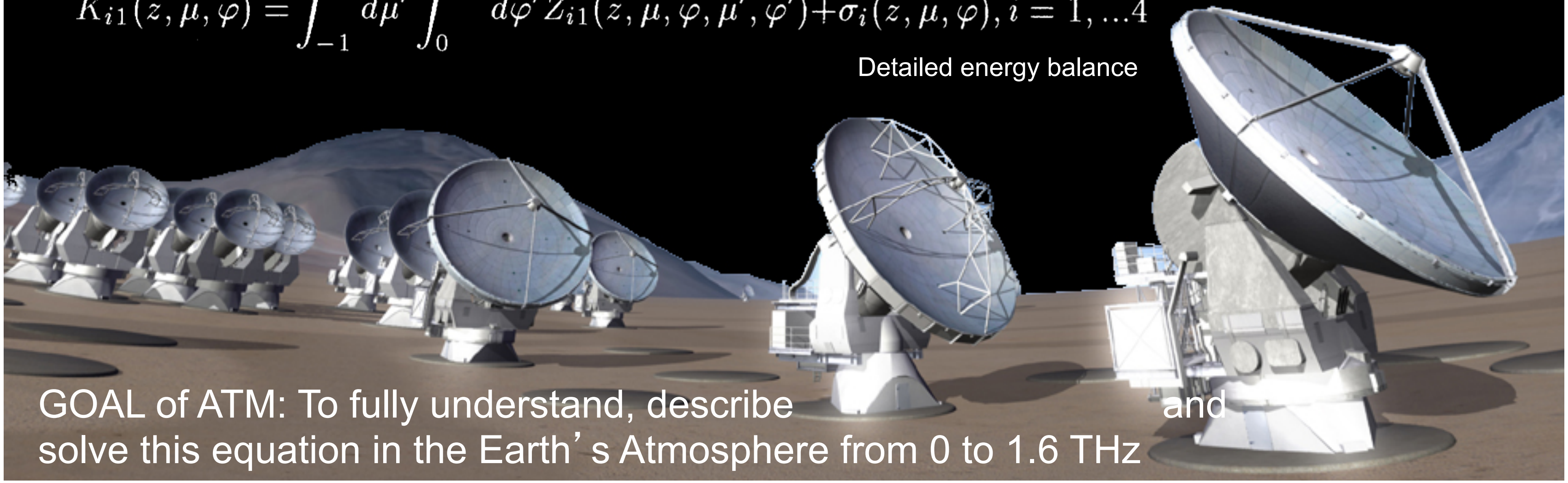
B Blackbody radiance at temperature T (due to LTE)



Frequency dependence is implicit

$$K_{i1}(z,\mu,\varphi) = \int_{-1}^{1} d\mu' \int_{0}^{2\pi} d\varphi' Z_{i1}(z,\mu,\varphi,\mu',\varphi') + \sigma_i(z,\mu,\varphi), i = 1, ...4$$

Detailed energy balance



GOAL of ATM: To fully understand, describe and solve this equation in the Earth's Atmosphere from 0 to 1.6 THz

Clear Atmosphere

$$\frac{dI_\nu(s')}{d\tau_\nu} = -I_\nu(s') + \mathrm{B}_\nu(T[s'])$$

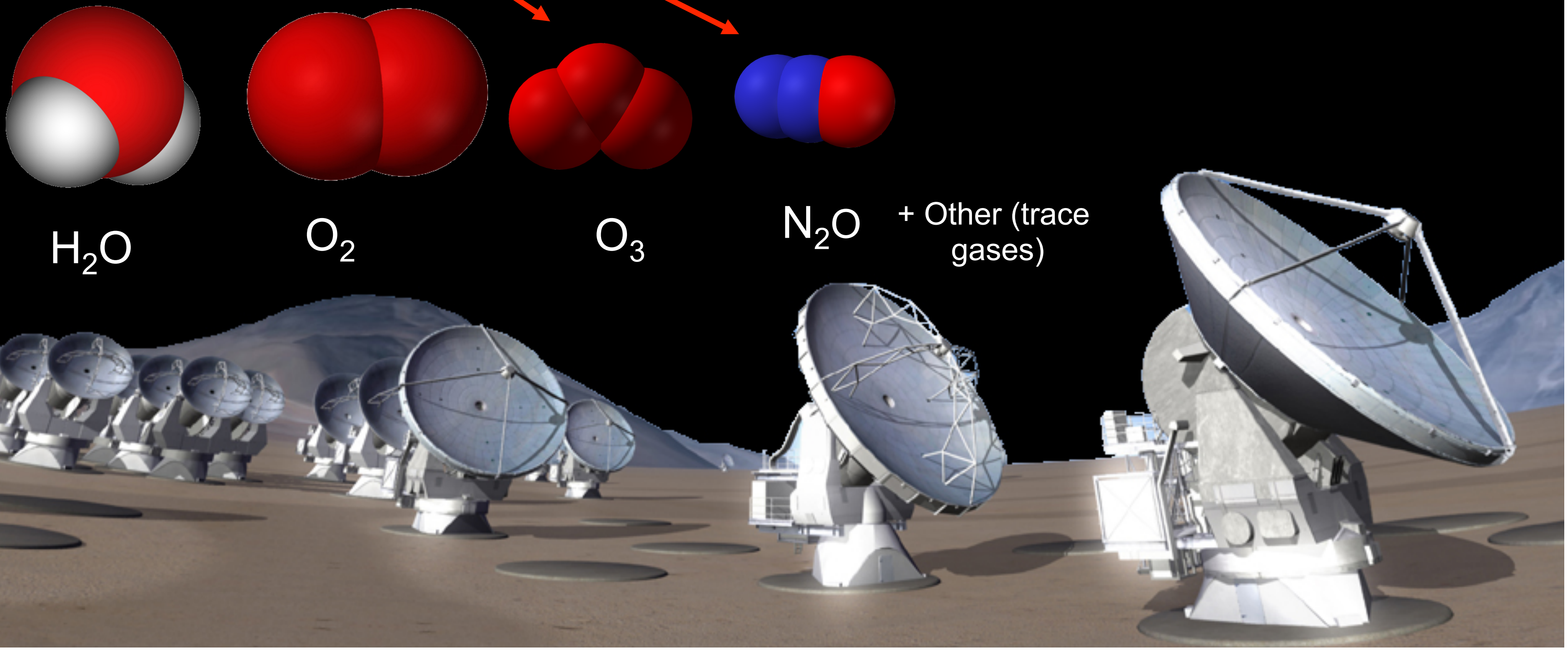
s'	coordinate along the path;
$S_\nu = \epsilon_\nu/\kappa_\nu$	source function;
$d\tau_\nu = \kappa_\nu ds$	differential opacity.

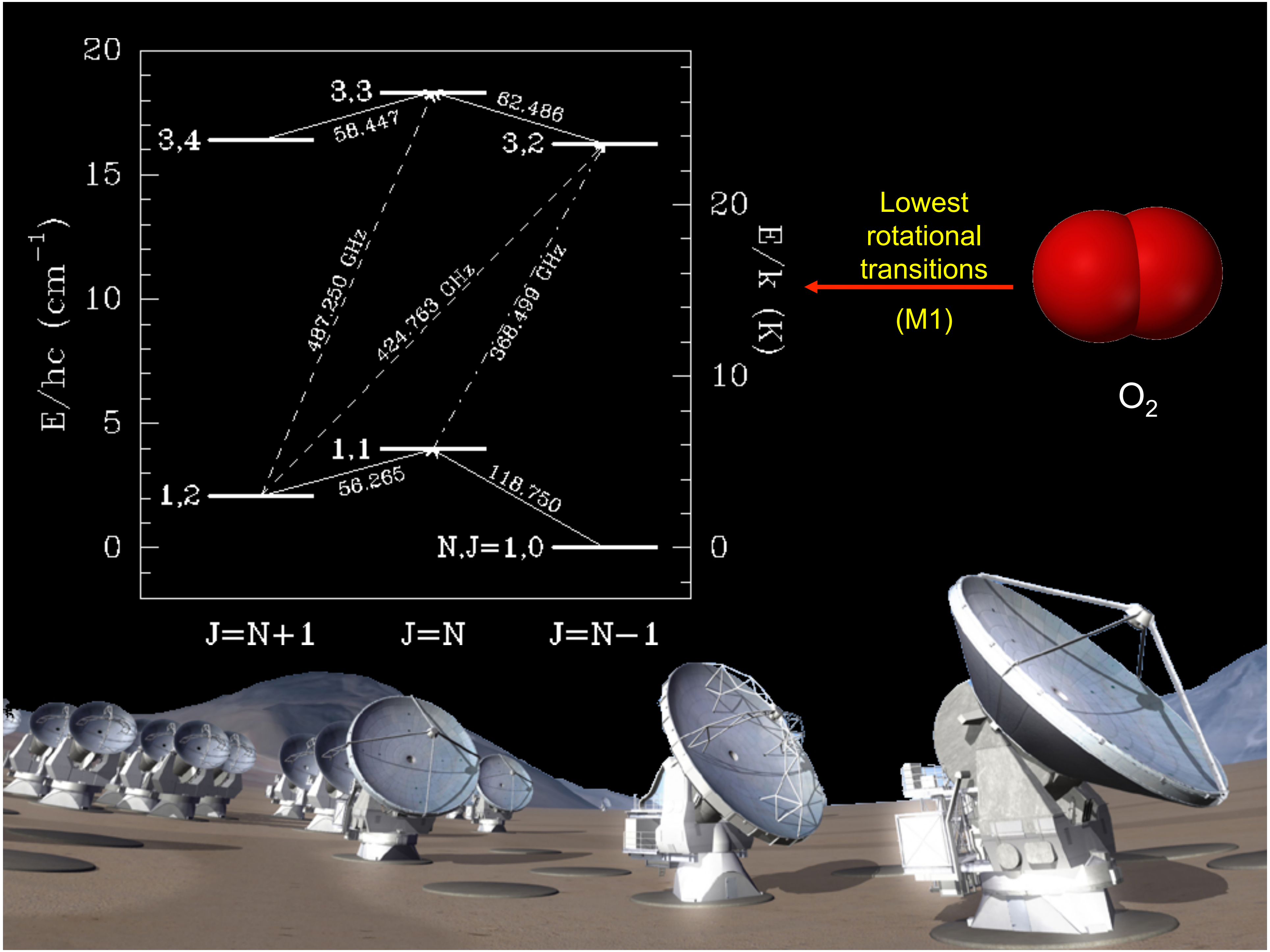
gas-phase κ_ν

$$(\kappa_\nu)_{lu} = \frac{8\pi^3 N\nu}{3hcQ}\left(e^{-E_l/kT} - e^{-E_u/kT}\right) \cdot |< u \mid \mu \mid l >|^2 \; f(\nu, \nu_{l\to u})$$

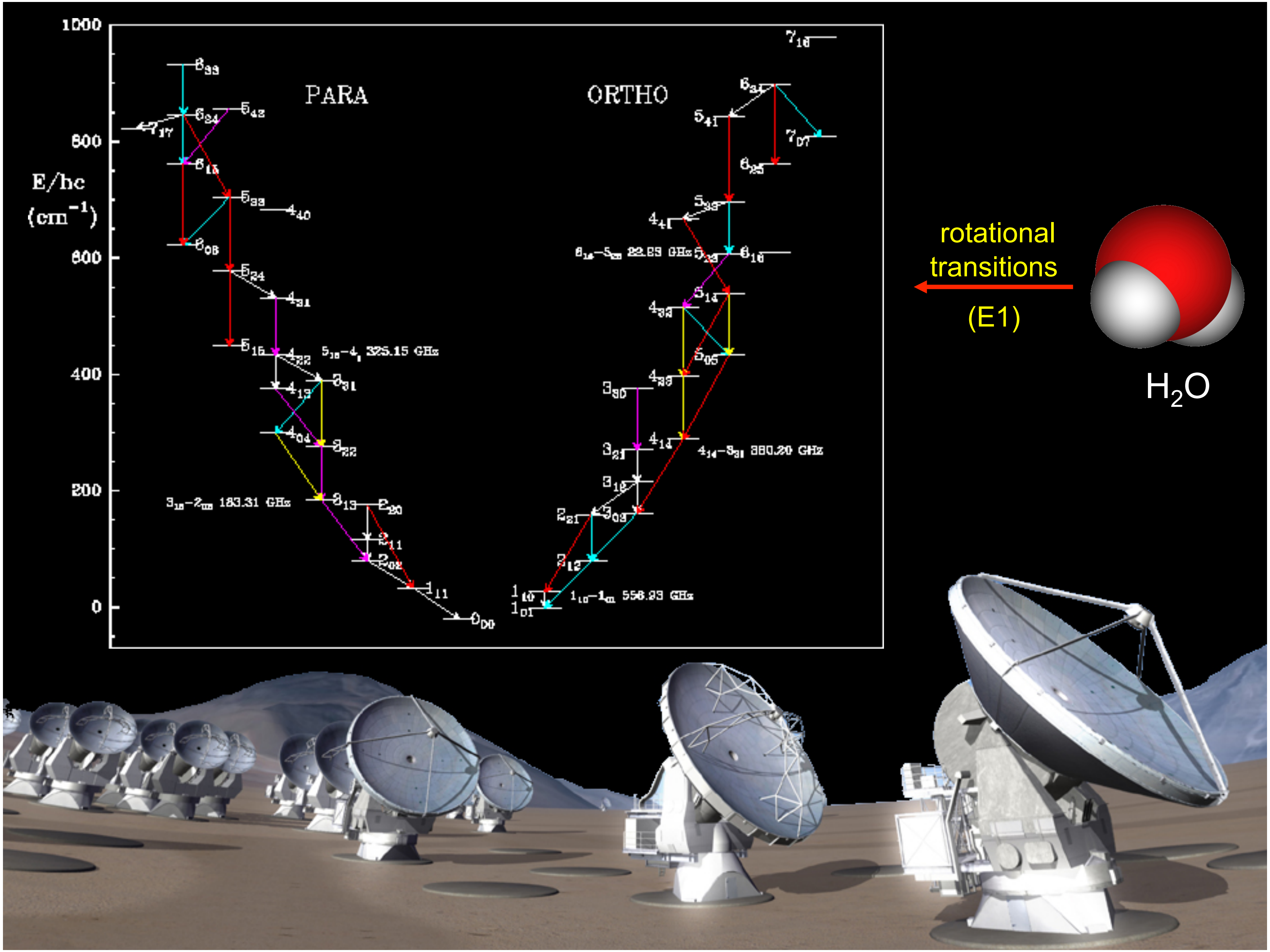
Rotational lines absorption

Continuum-like absorption





20
15
10
5
0
E/hc (cm^-1)
3,3
3,4
3,2
1,1
1,2
N,J=1,0
62.486
58.447
487.250 GHz
424.763 GHz
368.499 GHz
56.265
118.750
20
10
0
E/k (K)
J=N+1
J=N
J=N−1
Lowest
rotational
transitions
(M1)
O2


PARA
ORTHO
E/hc
(cm⁻¹)
1000
800
600
400
200
0
3₁₃–2₂₀ 183.31 GHz
5₁₅–4₂ 325.15 GHz
6₁₆–5₂₃ 22.23 GHz
4₁₄–3₂₁ 380.20 GHz
1₁₀–1₀₁ 556.93 GHz
rotational
transitions
(E1)
H2O

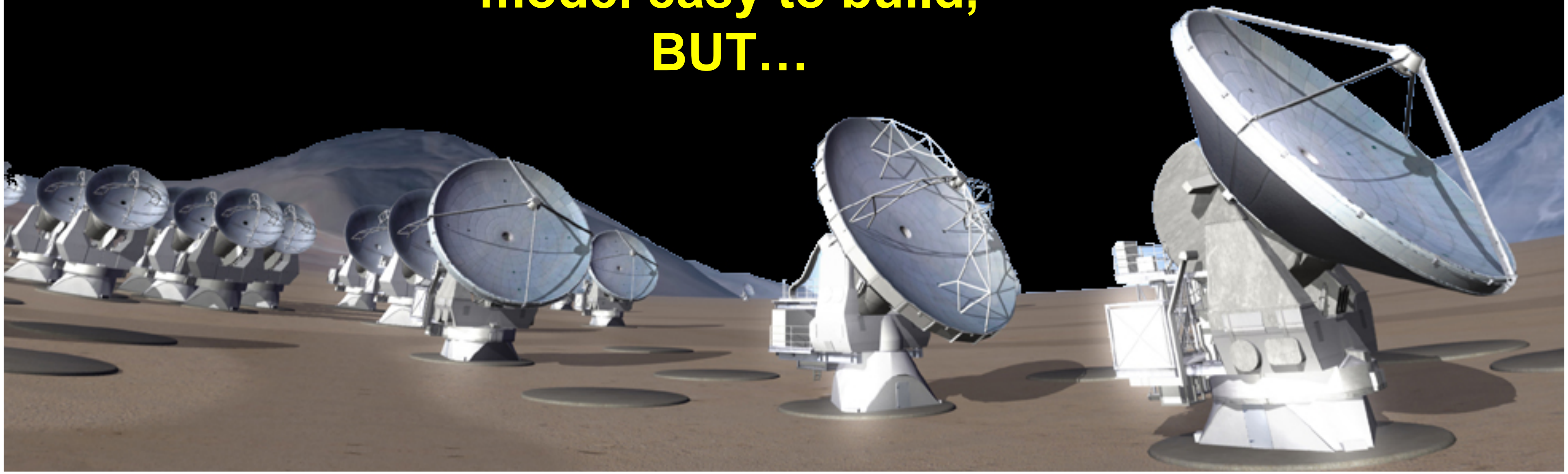
Line strengths from quantum mechanics

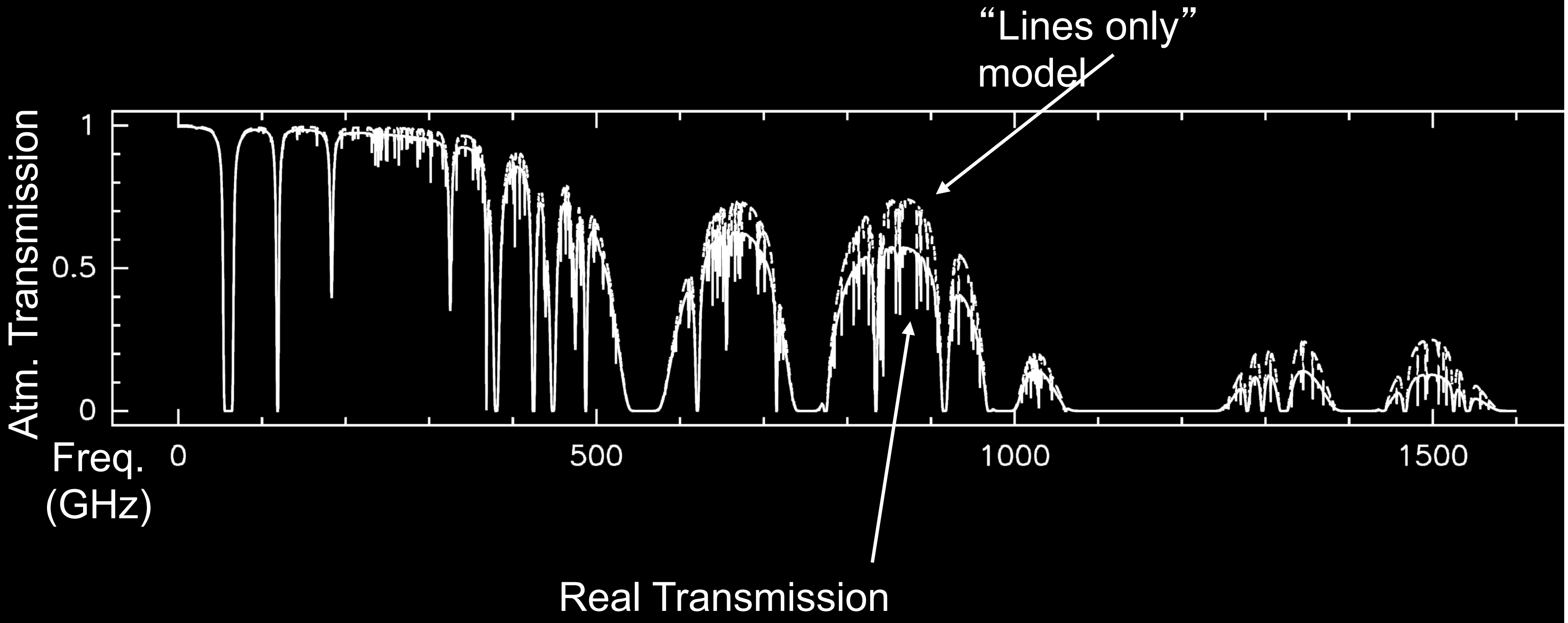
+

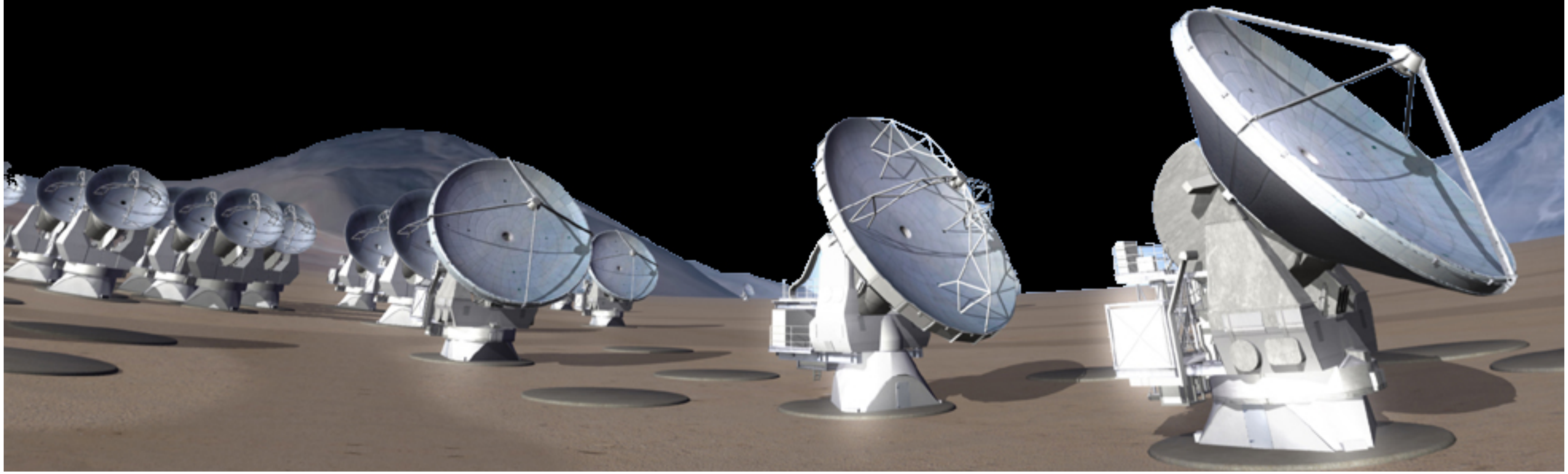
Line profiles (line widths from laboratory)

↓

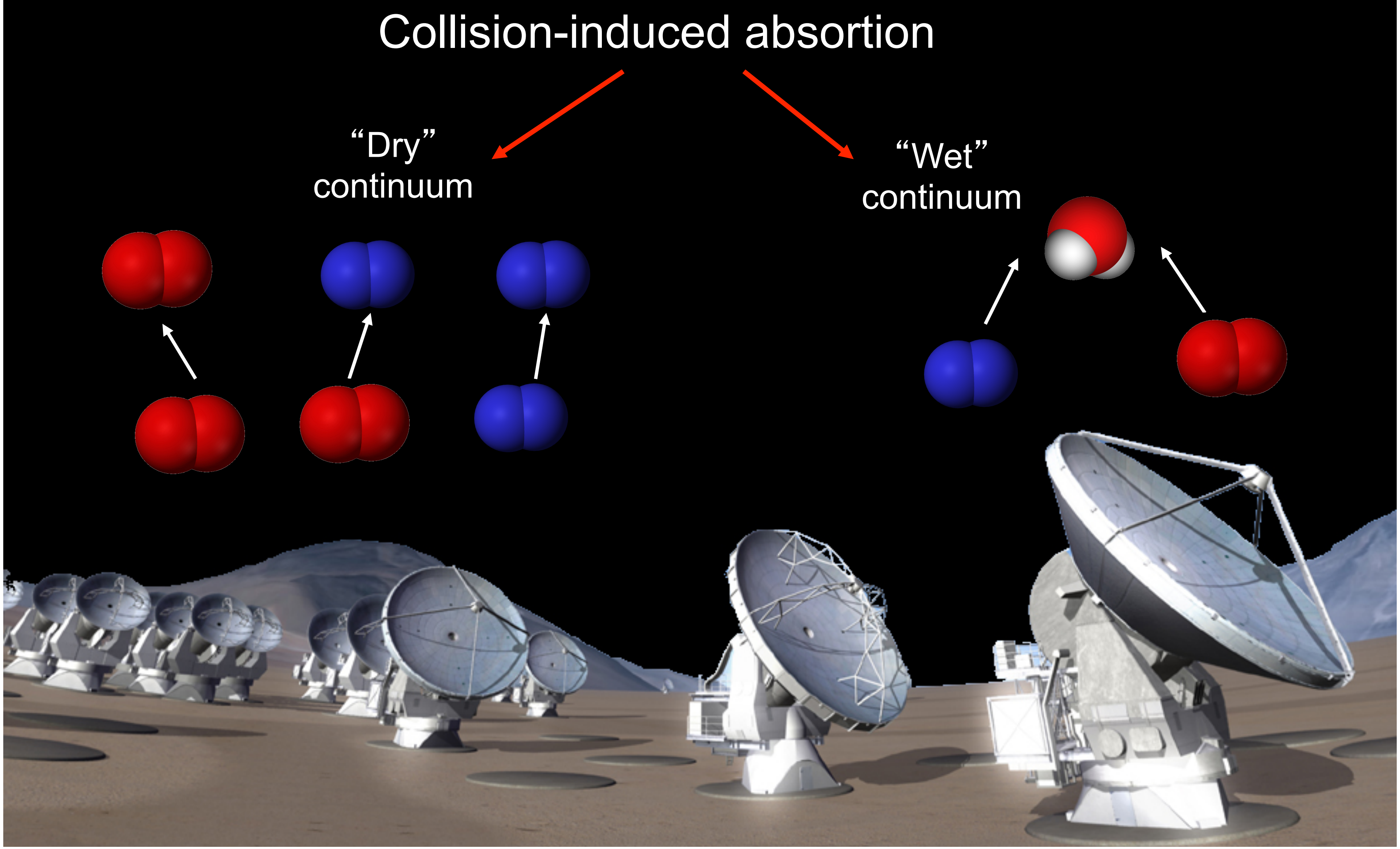
Simple transmission model easy to build, BUT…



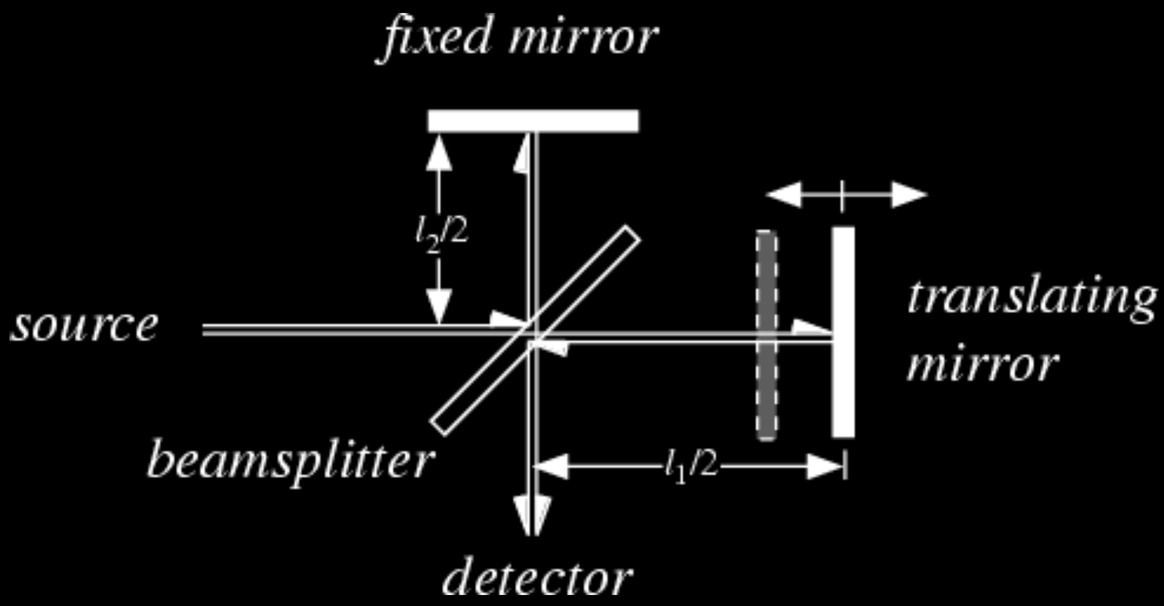

"Lines only"
model
Atm. Transmission
1
0.5
0
Freq.
(GHz)
0
500
1000
1500
Real Transmission



Today we know that the nature of "continuum-like" absorption in clear sky conditions is collision induced absorption involving pairs such as O_2-O_2, N_2-N_2, O_2-N_2, O_2-H_2O and N_2-H_2O

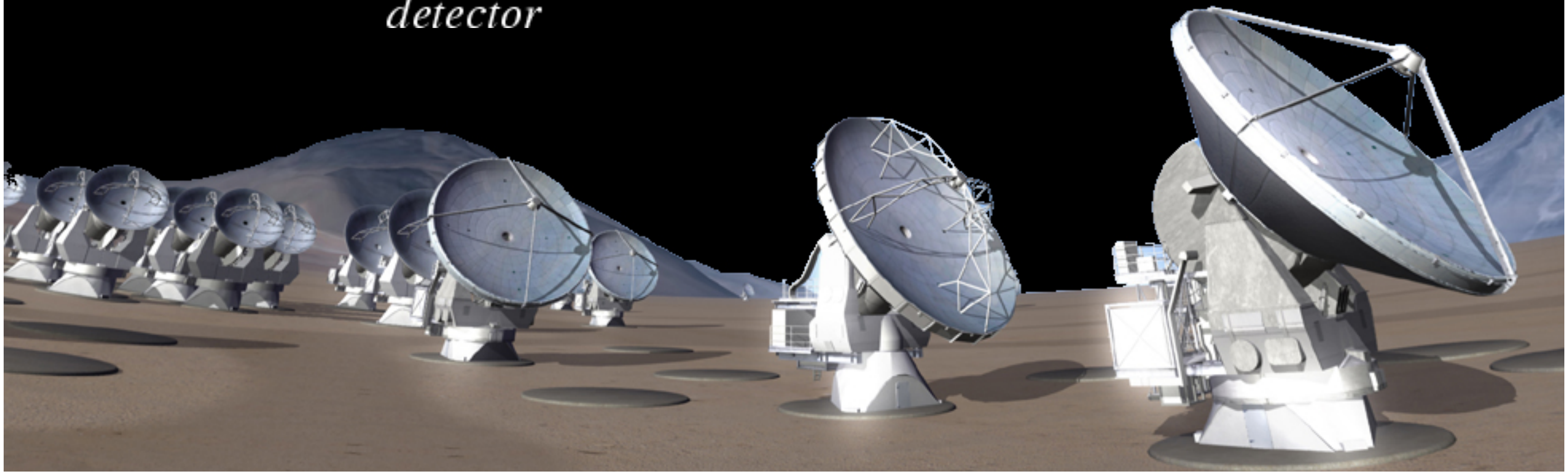


Experimental basis for refined models: Direct measurements with FTS experiments at Mauna Kea, Chajnantor & Sout Pole



Characteristics of CSO-FTS

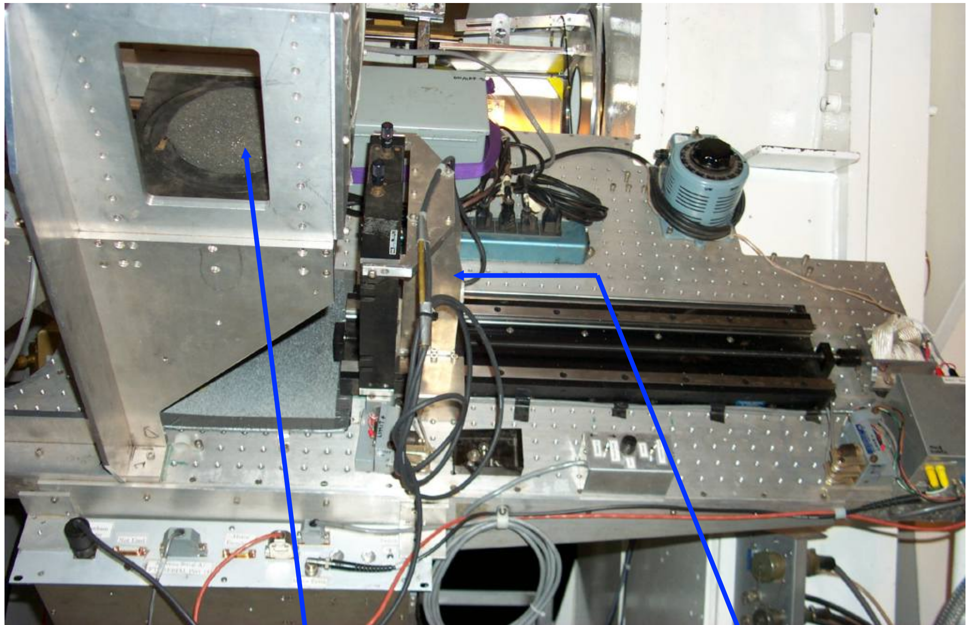
- Mounted on Cassegrain focus of telescope for dedicated obs. runs.
- Detector: ^{3}He cooled Bolometer
- Moving arm: 50 cm
  ~ 200 MHz resolution
- Filters: 7 different (165 to 1600 GHz)

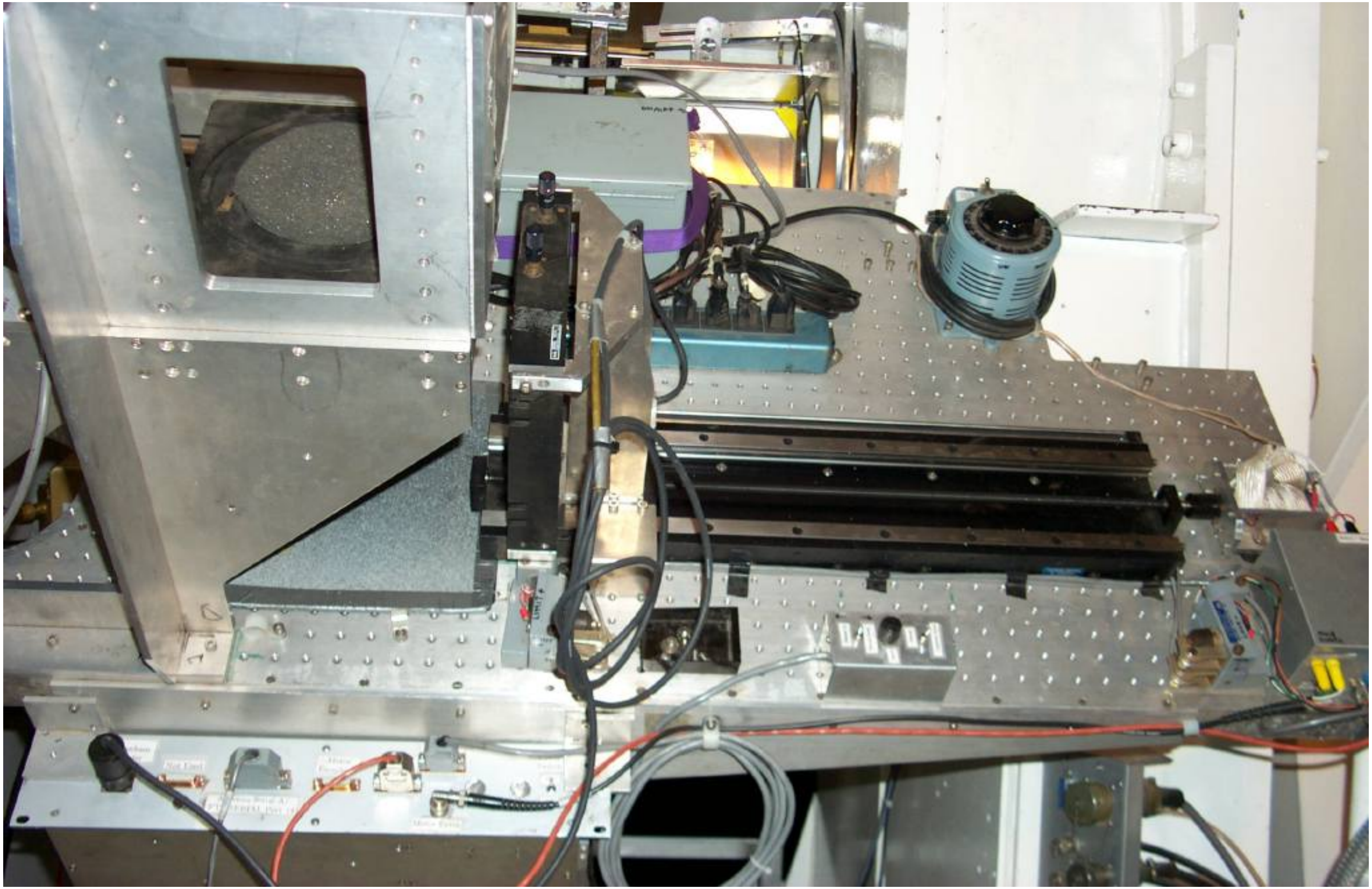



Mauna Kea (4200 m, -5 ºC), Hawai'i
Hapuna Beach (0 m, 25 ºC, Hawai'i)

Caltech Submillimeter Observatory - Fourier Transform Spectrometer (CSO-FTS)

Last mirror and bolometer (cooled to liq. ^{3}He)





CSO-FTS approach to solve the « excess of continuum » problem

Use well calibrated measurements acquired during very dry conditions

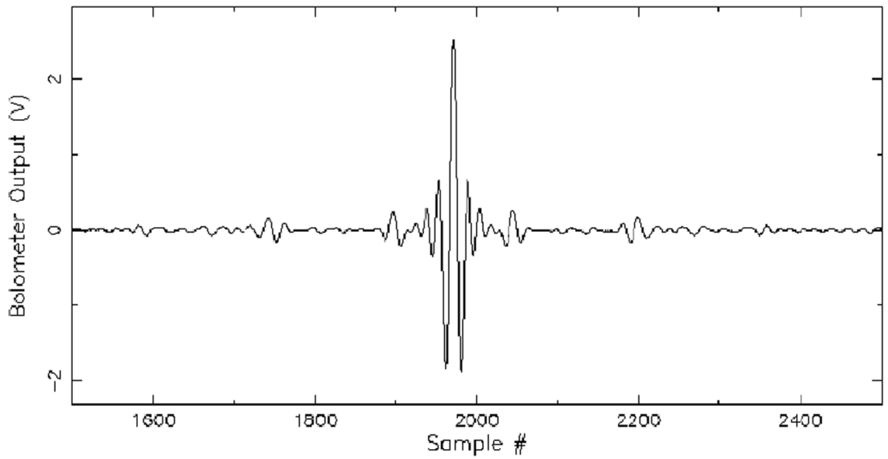
- T_0 ~ 270 ± 3 K
- P ~ 620 ± 1.5 mb at Mauna Kea summit.

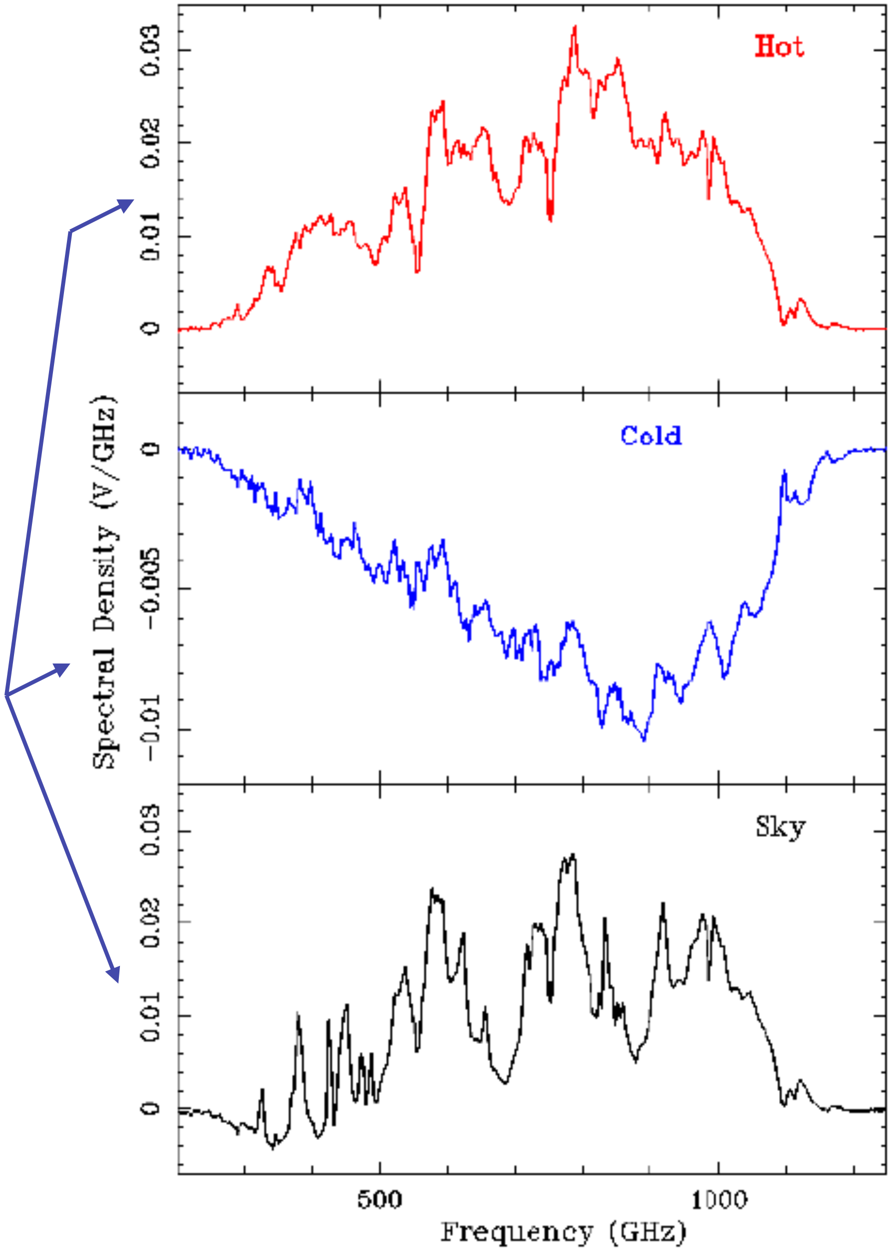
As a consequence: **The"dry" atmospheric absorption is basically the same (within 1-3 %) in the different situations. The remaining opacity is proportional to the PWV**

The water vapor column can be determined very precisely from the near wings of water lines, virtiually independently of the continuum terms.

CSO-FTS. Calibration of atmospheric measurements

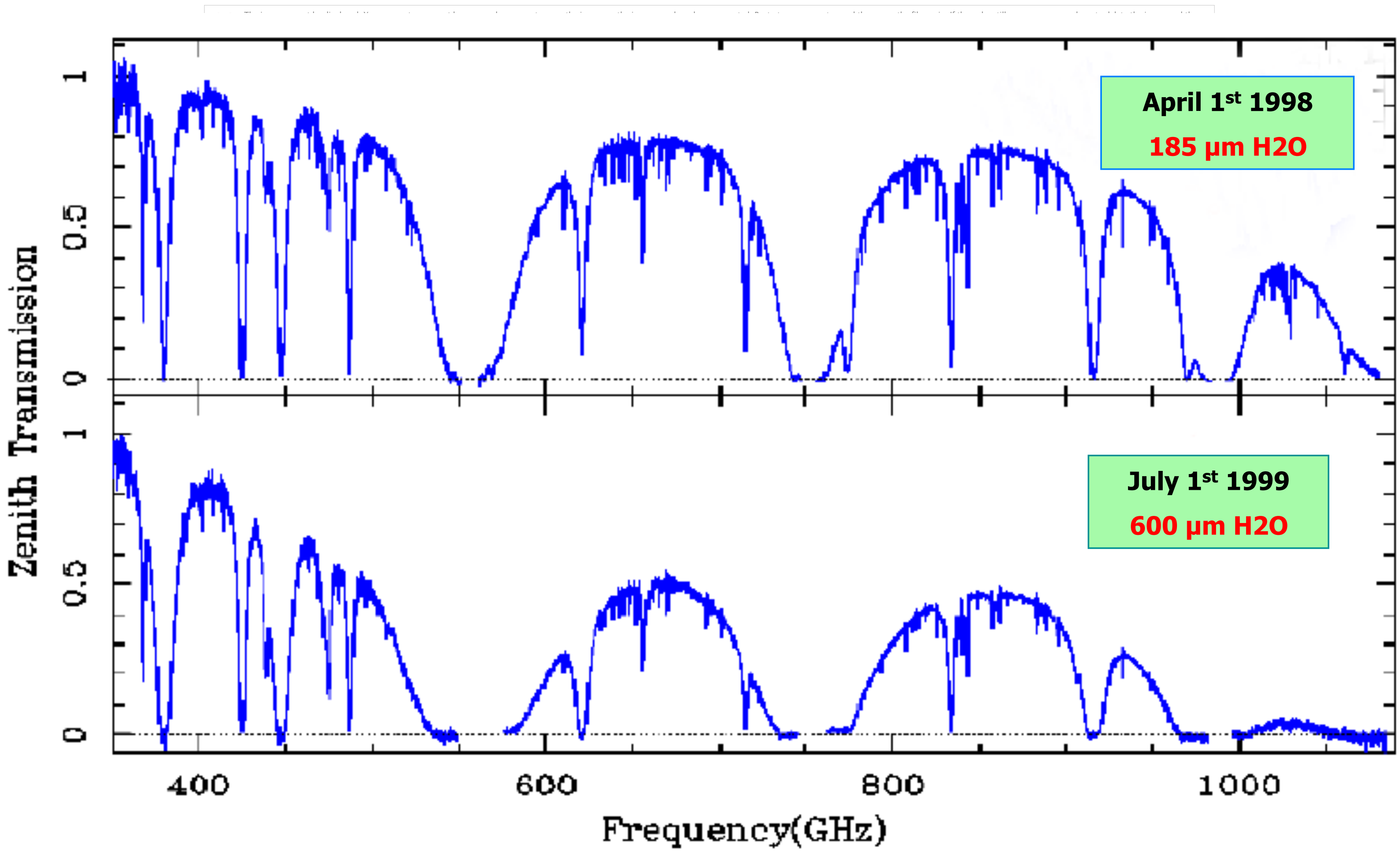
An accurate calibration of the spectra is key to the atmospheric goals of the experiment

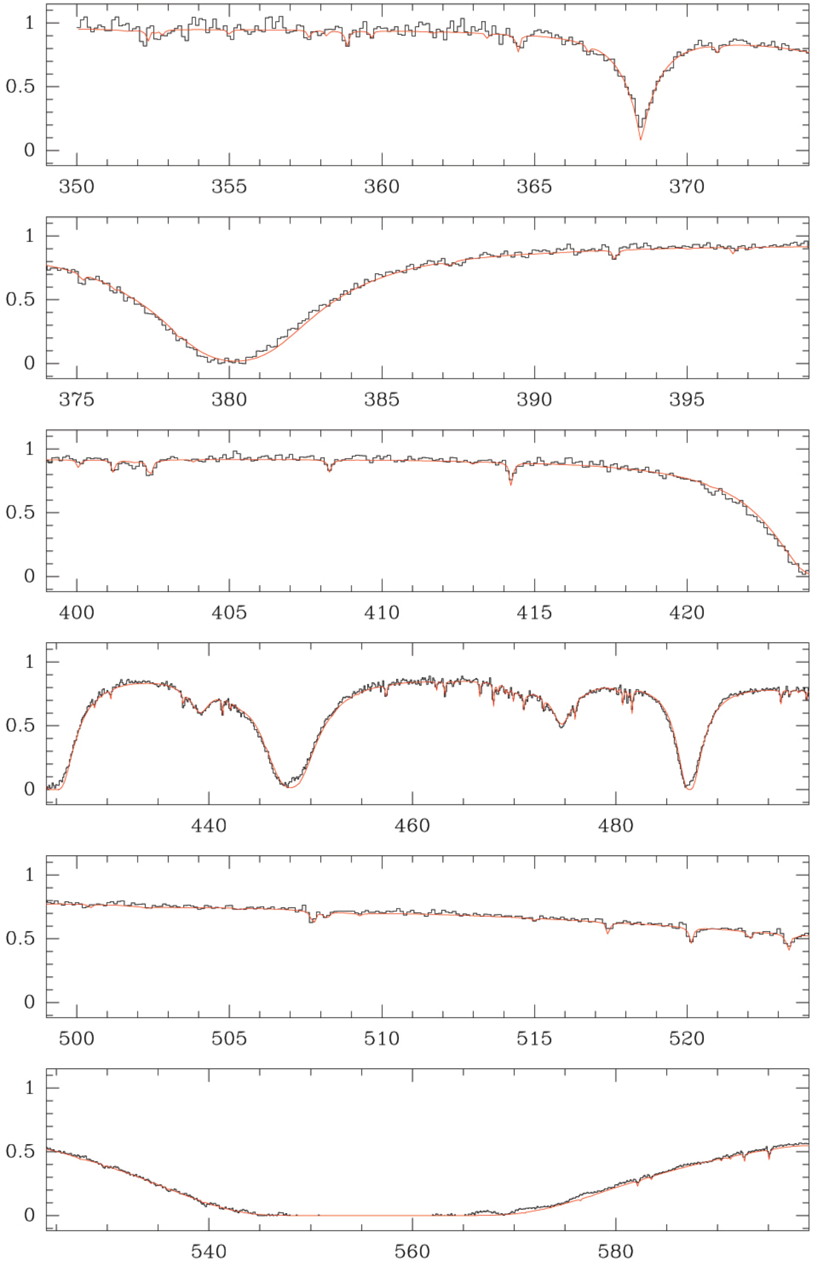


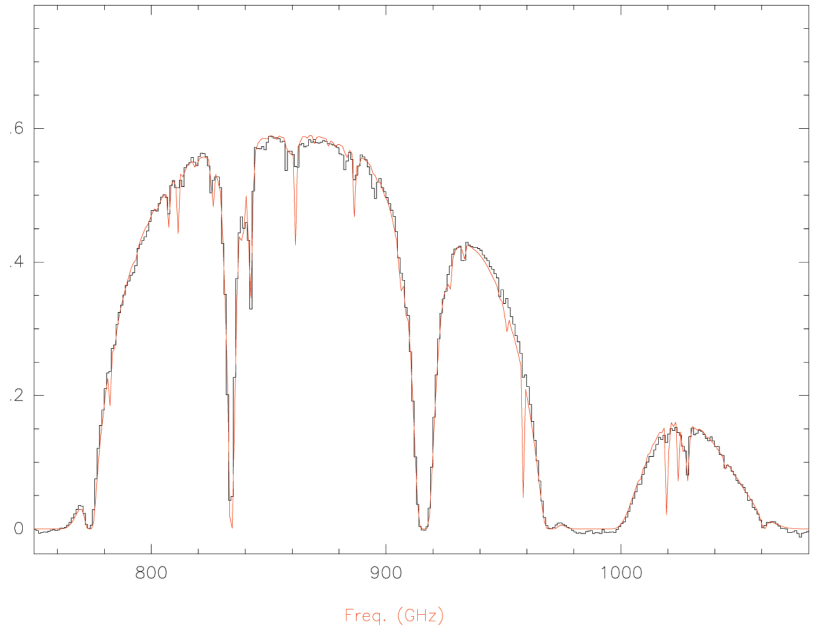


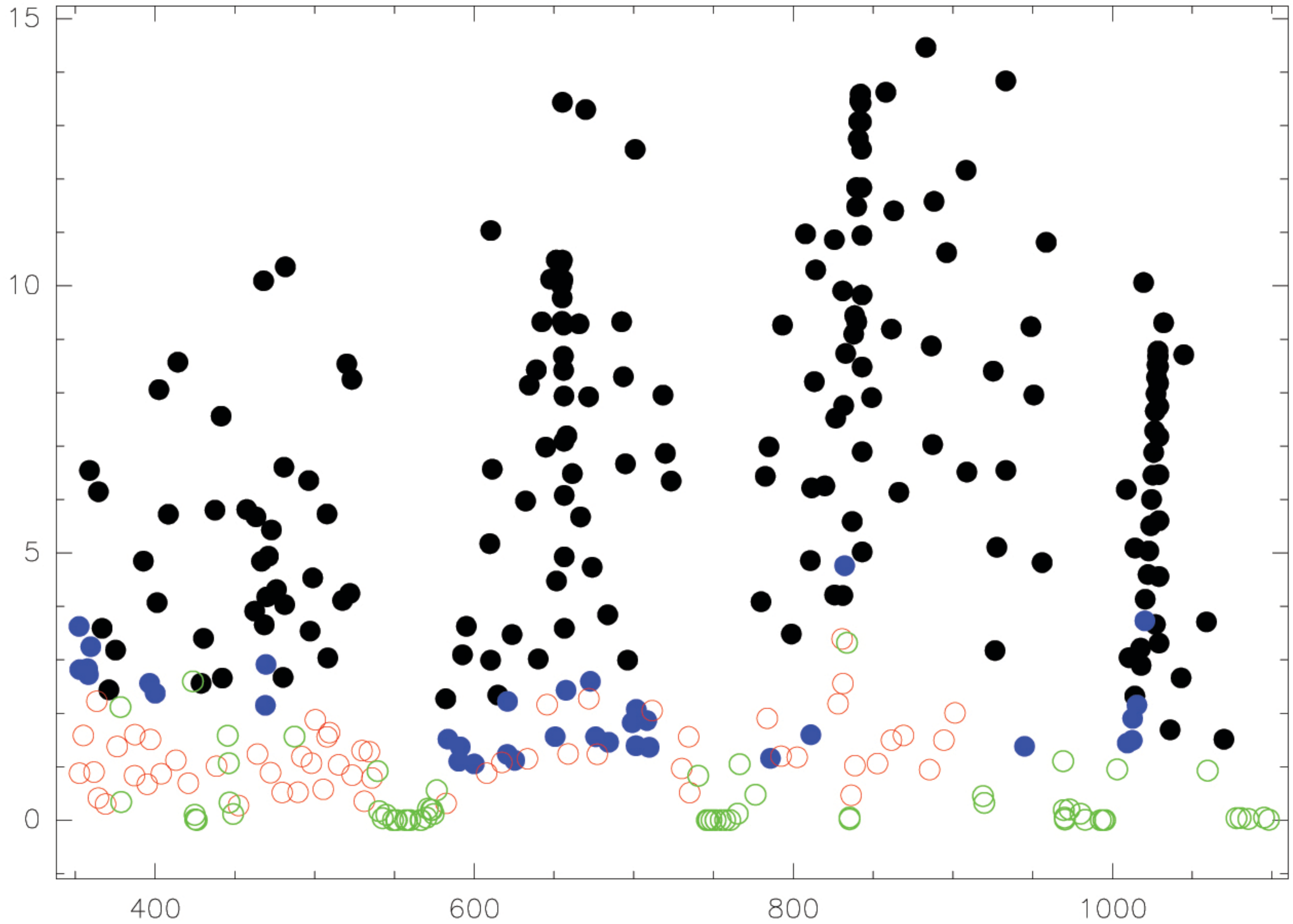
Raw data of CSO- FTS experiment (full resolution two-sided scan takes about 5 minutes to complete)

Relevant results for continuum-like atmospheric absorption below 1 THz



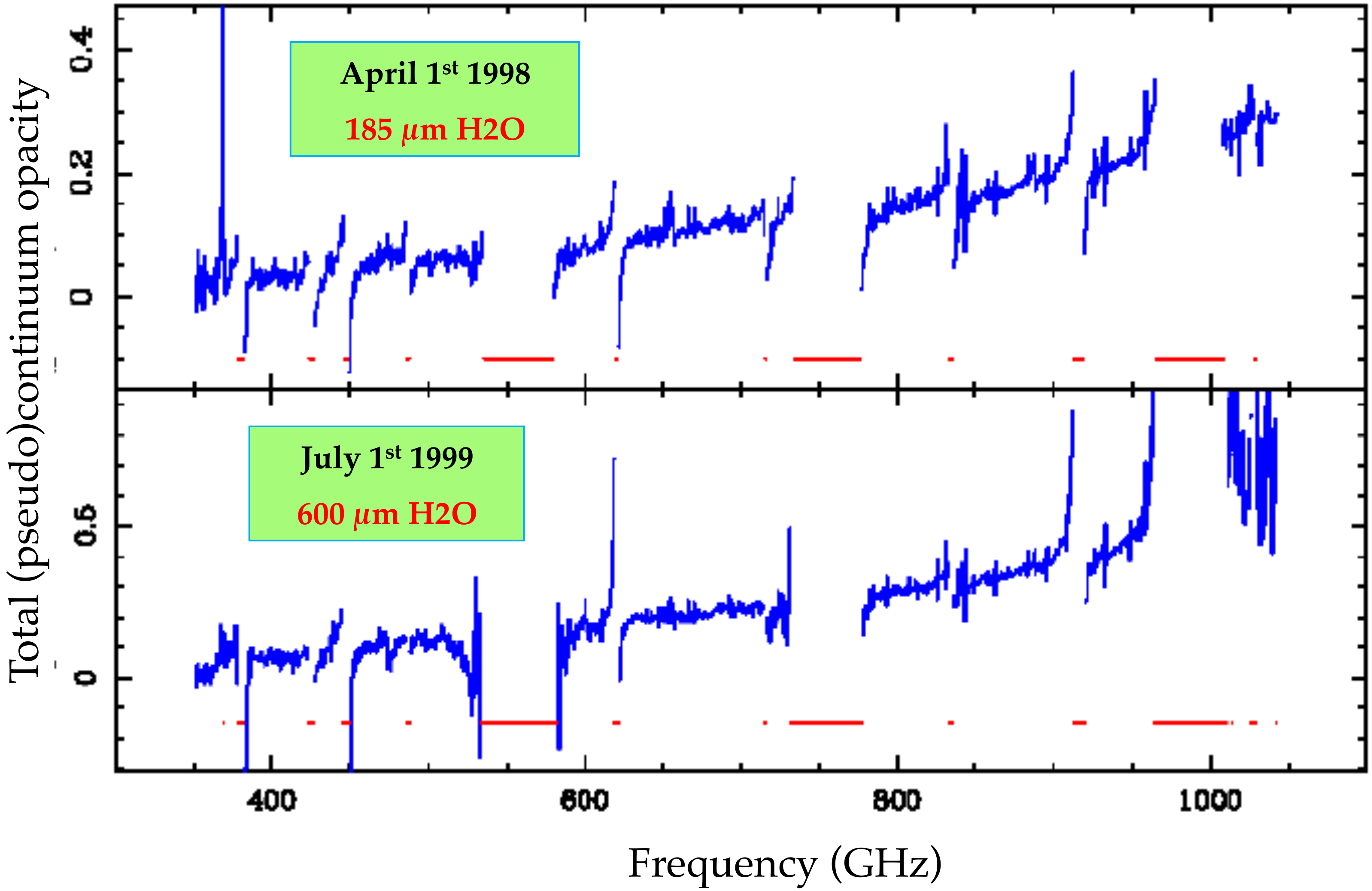

350
355
360
365
370
375
380
385
390
395
400
405
410
415
420
440
460
480
500
505
510
515
520
540
560
580
1
0.5
0

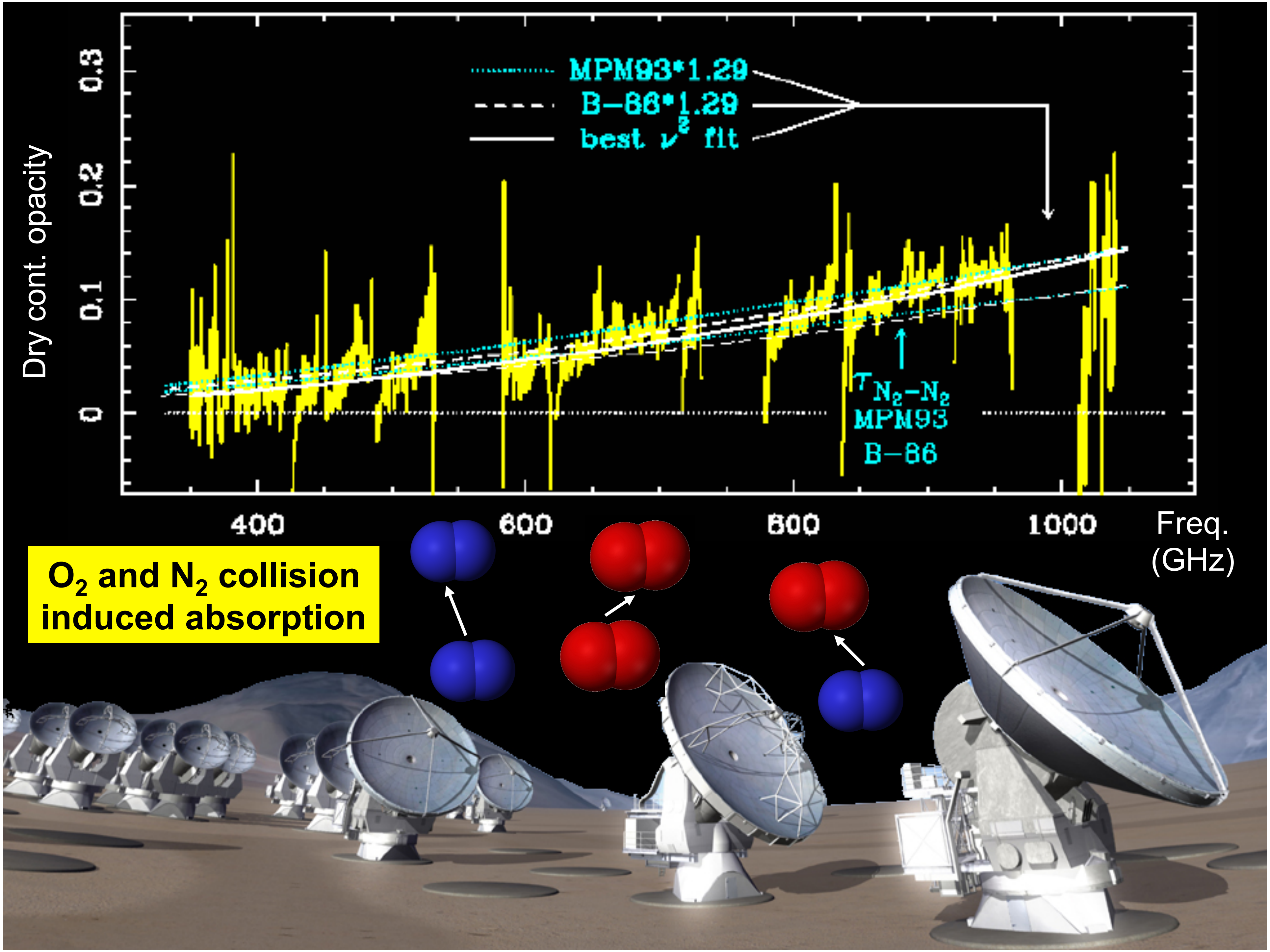

.6
.4
.2
0
800
900
1000
Freq. (GHz)

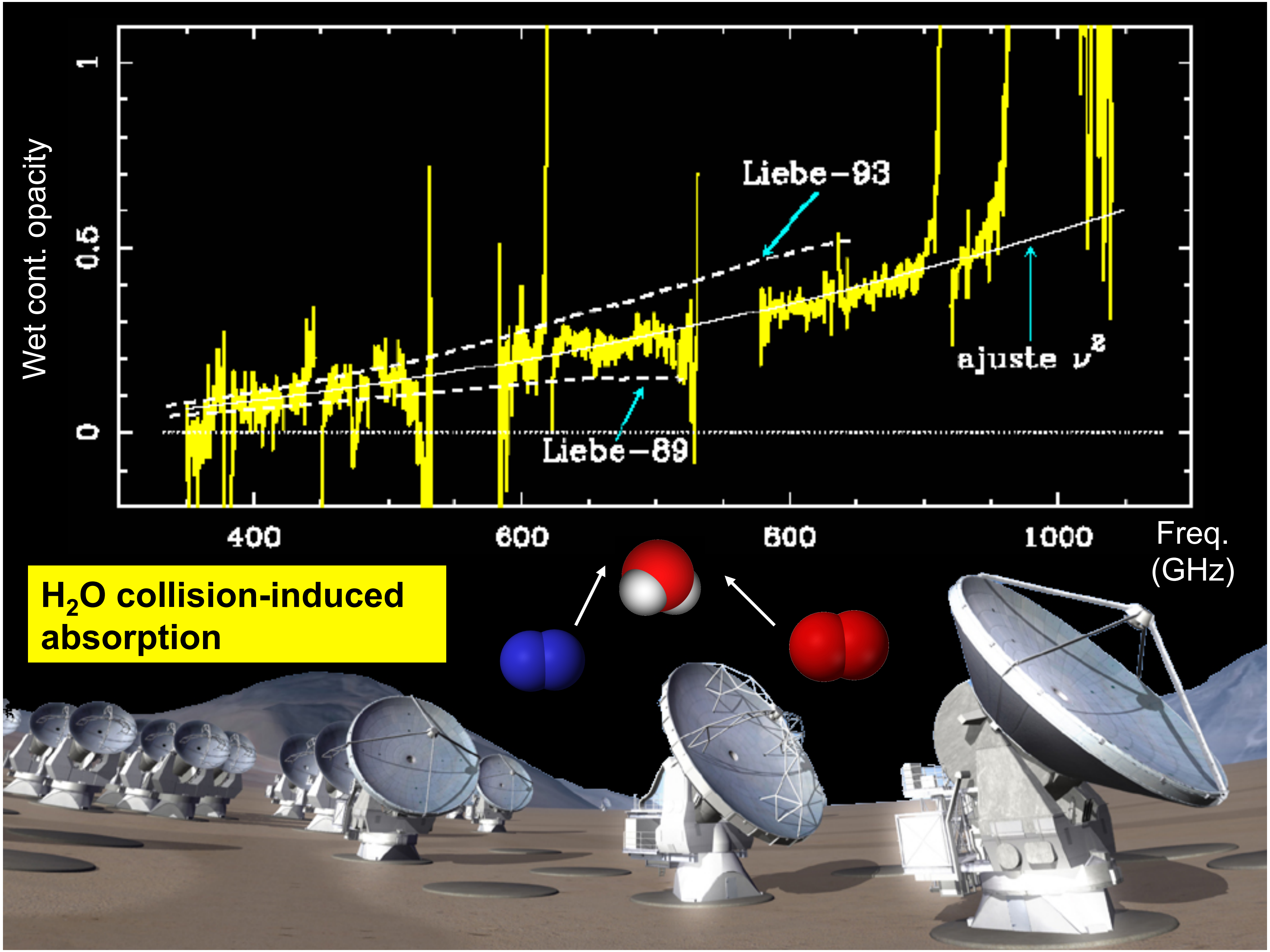

15
10
5
0
400
600
800
1000

Continuum-like terms measured with the FTS

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.




MPM93*1.29
B-86*1.29
best ν^2 fit
Dry cont. opacity
0
0.1
0.2
0.3
$\tau_{N_2-N_2}$
MPM93
B-86
400
600
800
1000
Freq. (GHz)
O_2 and N_2 collision induced absorption



Wet cont. opacity
1
0.5
0
Liebe−93
Liebe−89
ajuste ν²
400
600
800
1000
Freq.
(GHz)
H2O collision-induced
absorption

CSO-FTS approach to solve the « excess of continuum » problem

Use well calibrated measurements acquired during very dry conditions

- $T_0 \sim 270 \pm 3$ K
- P ~ 620 ± 1.5 mb at Mauna Kea summit.

As a consequence: The "dry" atmospheric absorption is basically the same (within 1-3 %) in the different situations. The remaining opacity is proportional to the PWV

The water vapor column can be determined very precisely from the near wings of water lines, virtually independently of the continuum terms.

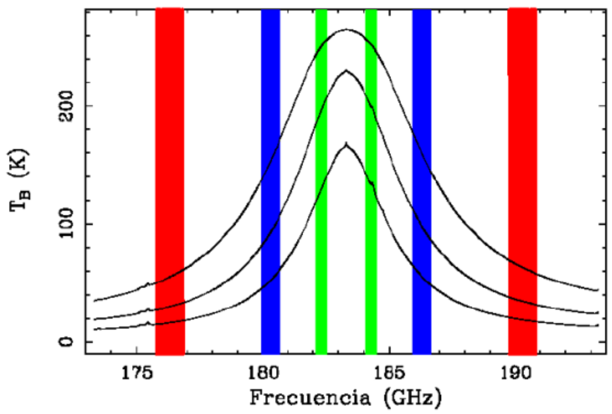
Same approach remains valid for ν > 1THz

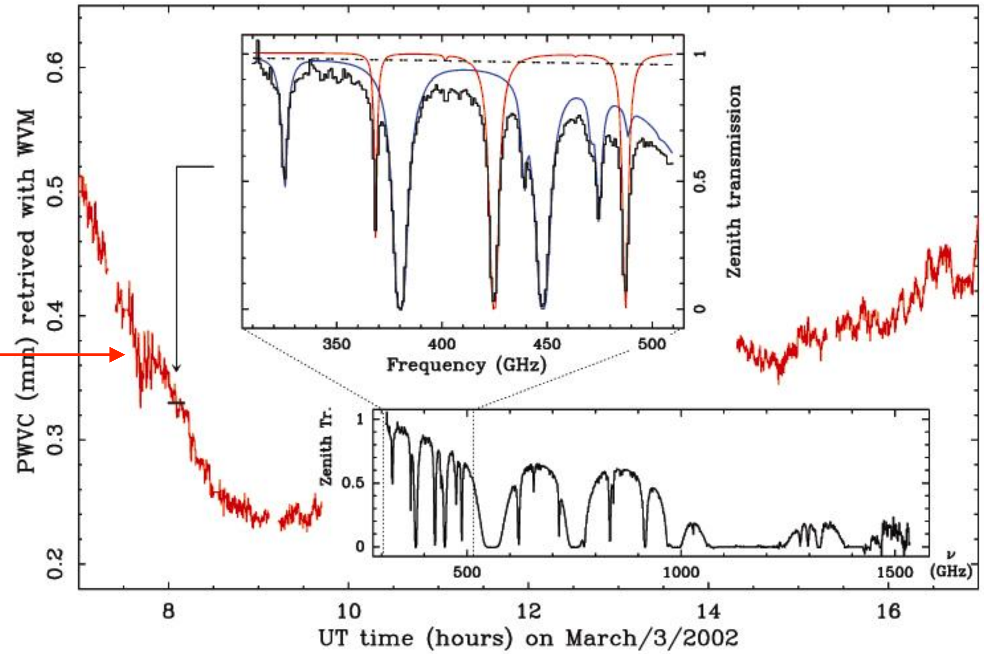
Complementary measurements

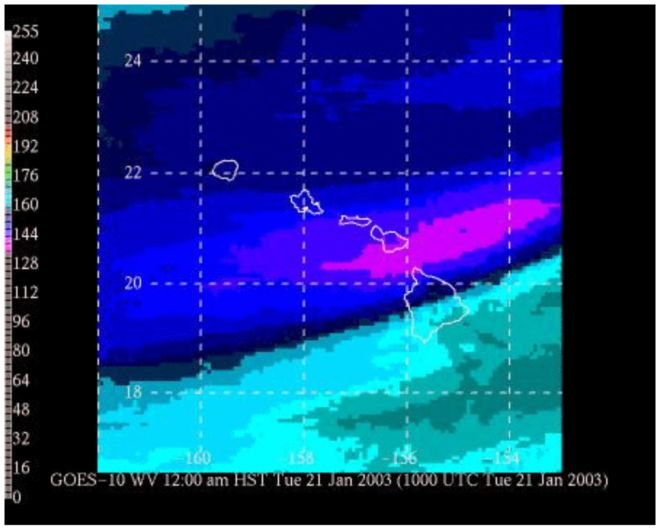
WVM data + FTS data below 500 GHZ + GOES-10 data + Tau_meter data + weather station data: PWV can be determined independently of uncertainties in continuum-like terms and cross-checked

183 GHz WV Monitor - Martina Wiedner

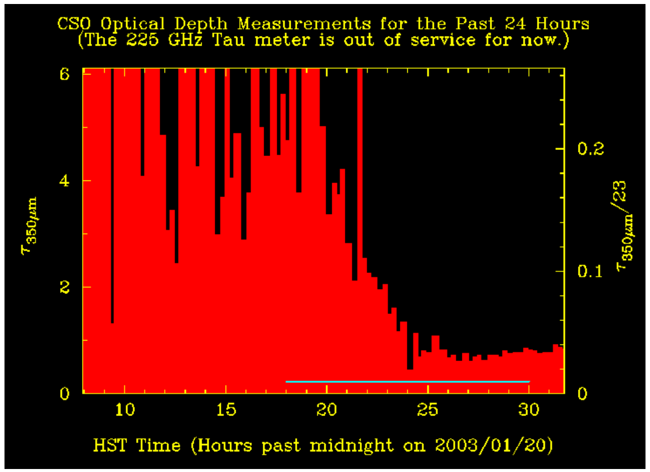
- 3 channels, uncooled T_{sys}=2000-2500K, mounted on telescope, calibration on 300 K and 370 K at 1Hz







GOES-10 Water vapor

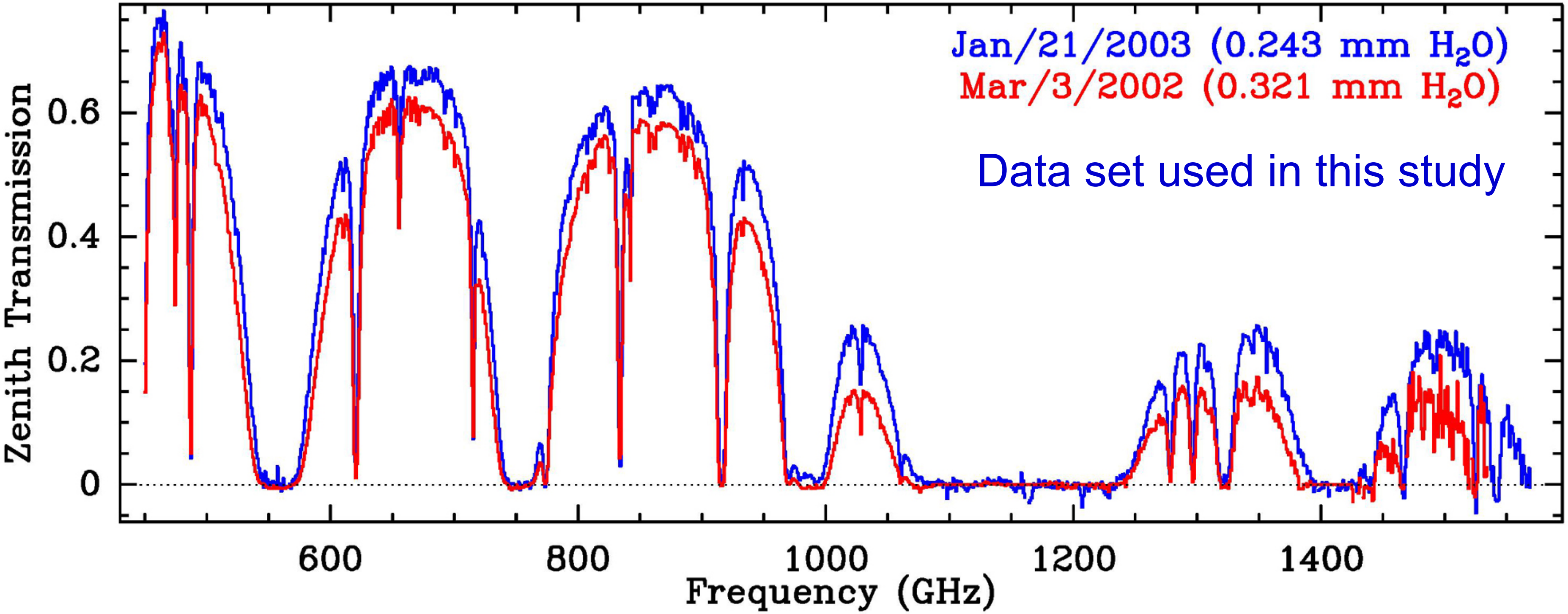


350 μm opacity meter

OTHER:

Hand-held thermo-hygrometer

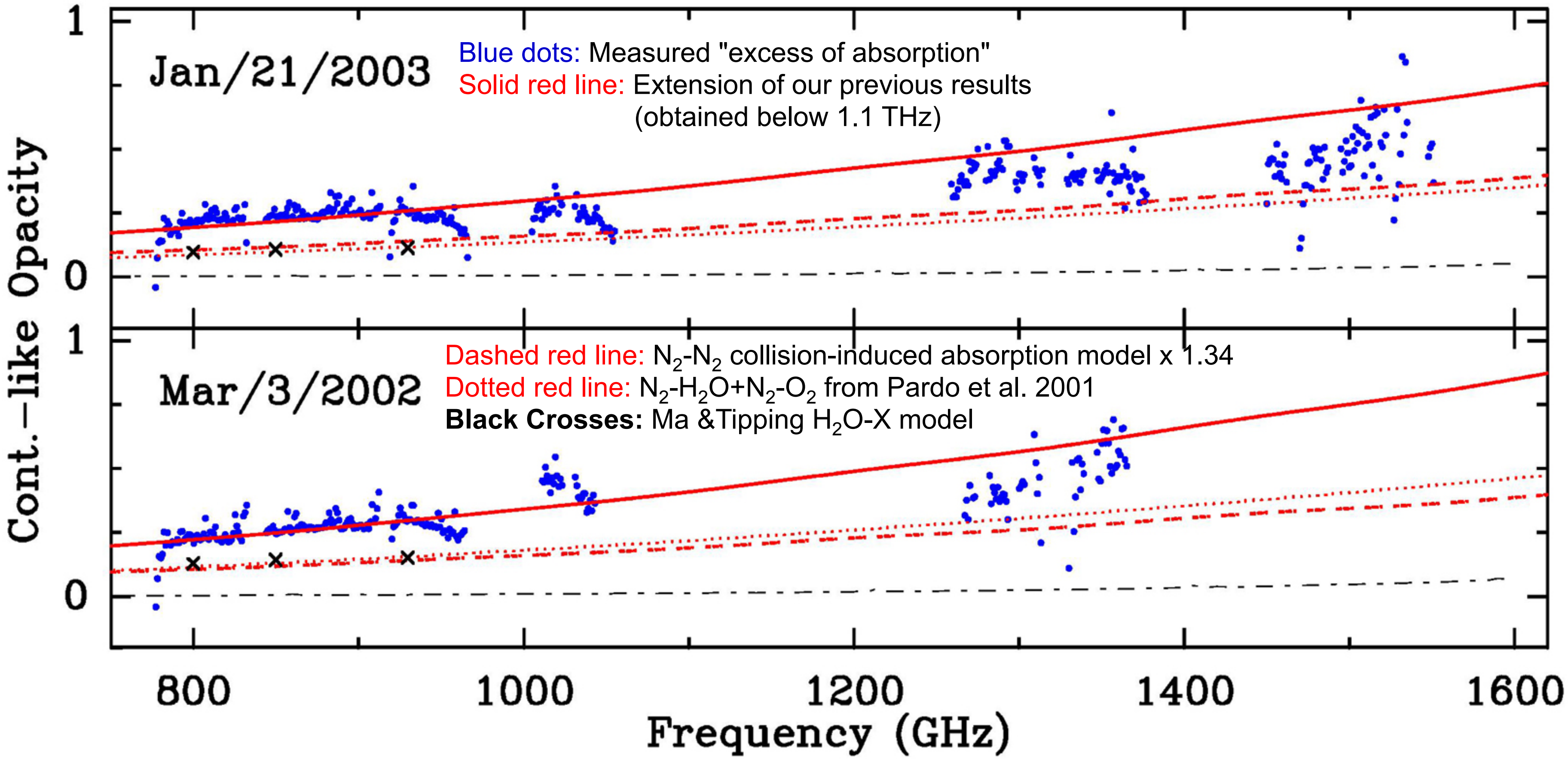
Telescope's weather station



WVM data + FTS data below 500 GHZ:
Allow a Water Vapor Column determination independent of uncertainties in continuum-like terms

GOES-10 data + Tau_meter data + weather station data
Used as extra information to check consistency

Line opacity can be removed considering calculated and/or laboratory line parameters. The remaining absorption is the "excess of opacity"



¿What is the nature of this opacity term?

- Errors in far wings of lines above 2 THz can be ruled out
- Earlier (Pardo et al 2001) collision-induced absorption explanation confirmed below 1.1 THz
- Extension of those results above 1.1 THz results on overestimation
- IF N_2-N_2x1.34 collision induced absorption model (Boissoles et al. 2003) is assumed correct THEN the H_2O-O_2+H_2O-N_2 collision induced absorption calculations (Ma & Tipping 2002) provide very good results below 1 THz and it appears that above that frequency we may start seeing the flattening of this term.

GENERAL CONCLUSIONS

- **An accurate determination of WVC from FTS or WVM data can be done only if the continuum opacity is well know or unimportant (below 0.5 GHz is best).**

- **Below 1.1 THz the continuum-like opacity has been measured and successfully separated into wet and dry parts in Pardo et al. 2001.**

- **Data presented here (both FTS and WVM) have allowed to separate the total continuum from the lines in the range 1.0-1.6 THz.**

Serabyn, Weisstein, Lis & Pardo, Appl. Optics, 37:2185, 1998

Matsushita, Matsuo, Pardo, & Radford, PASJ, 51:603, 1999.

Pardo, Serabyn & Cernicharo, JQSRT, 68:419, 2001

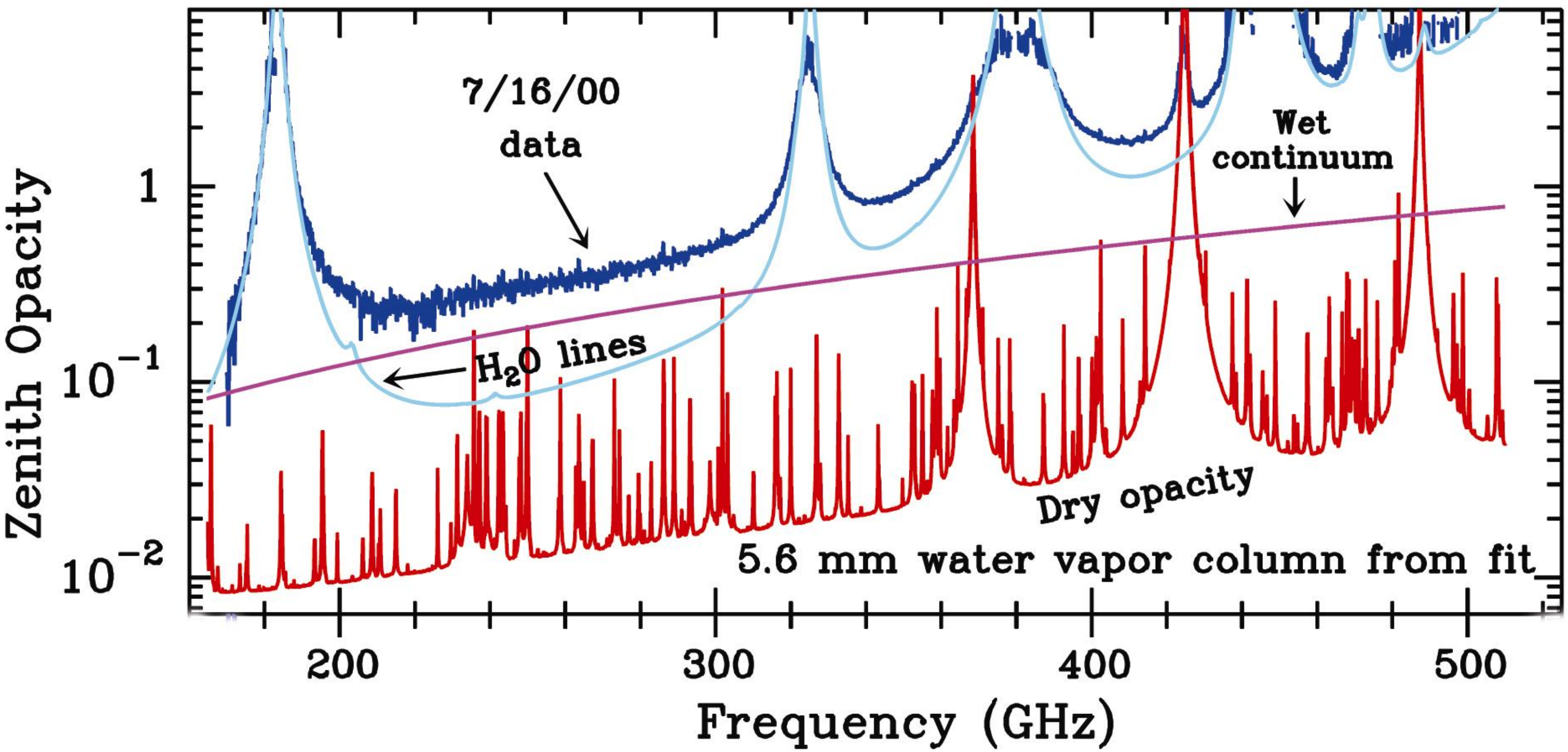
Pardo, Cernicharo & Serabyn, IEEE TAP, 49:1683, 2001

Pardo, Wiedner, Serabyn, Wilson, Cunningham, Hills & Cernicharo, Ap. J. Suppl., 153:363, 2004

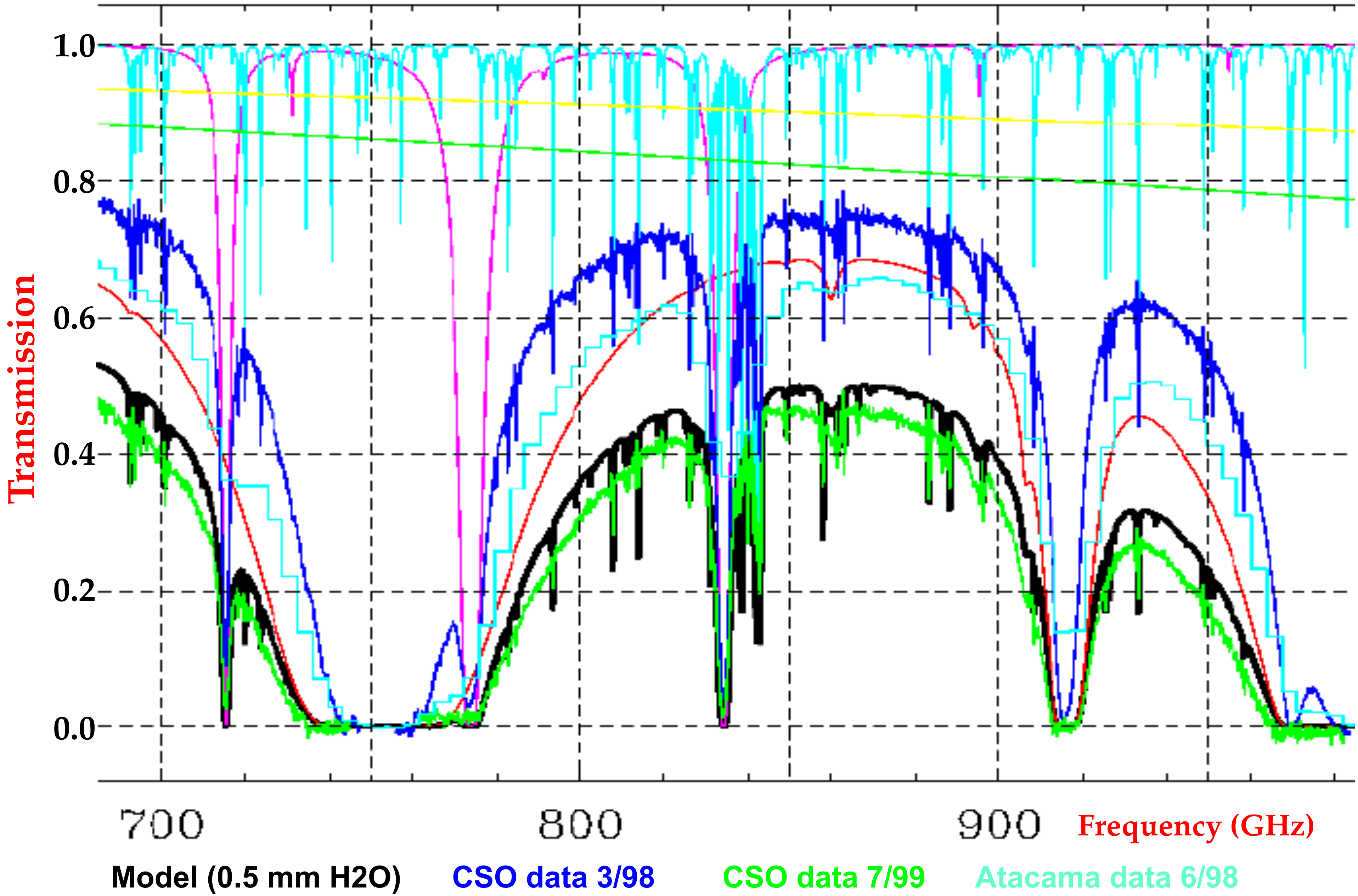
Pardo, Serabyn, Wiedner & Cernicharo, JQSRT, 96:537, 2005

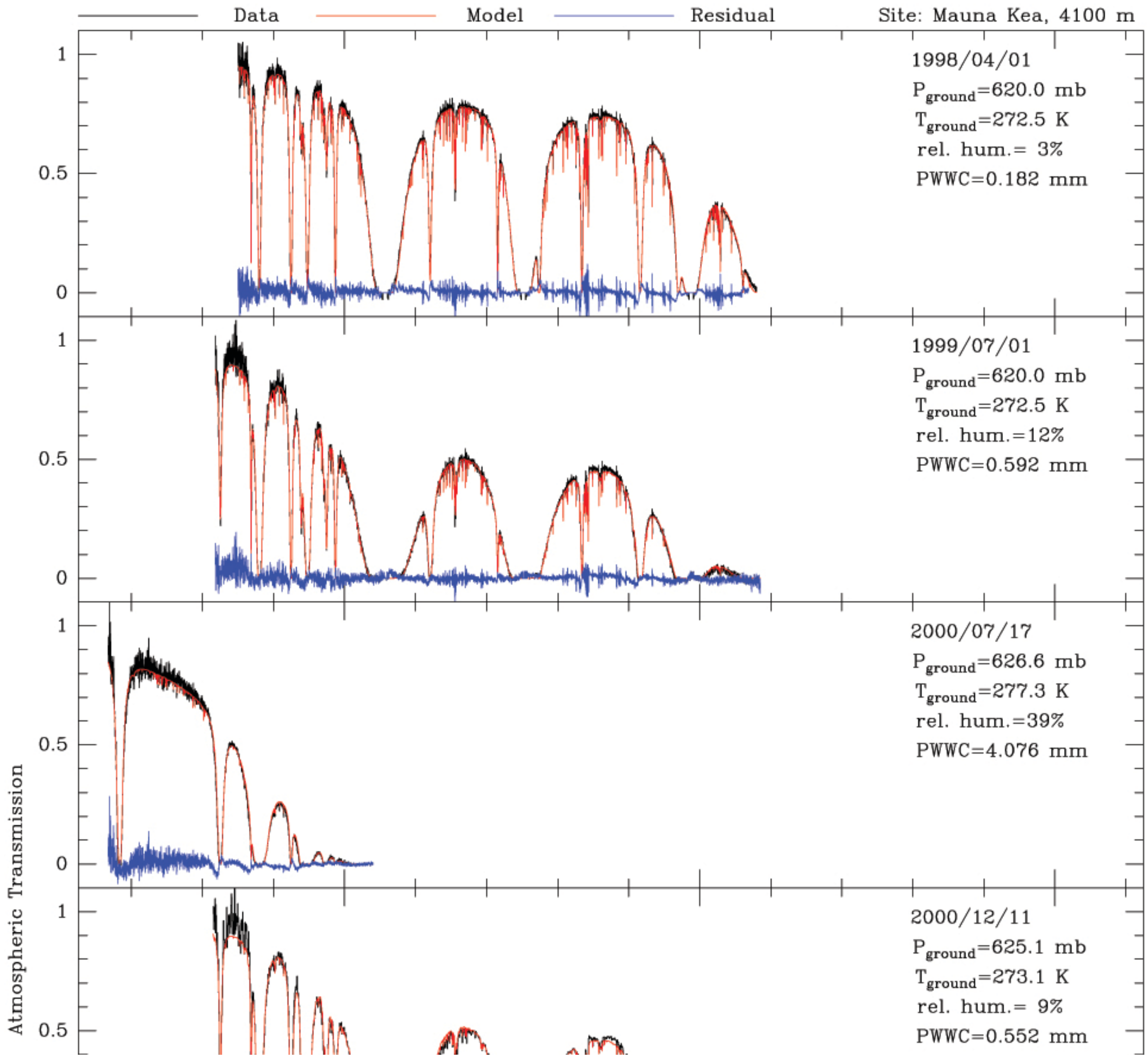
1c. Up-to-date model: ATM

Example 1: Opacity terms in wet atmospheric conditions at Mauna Kea

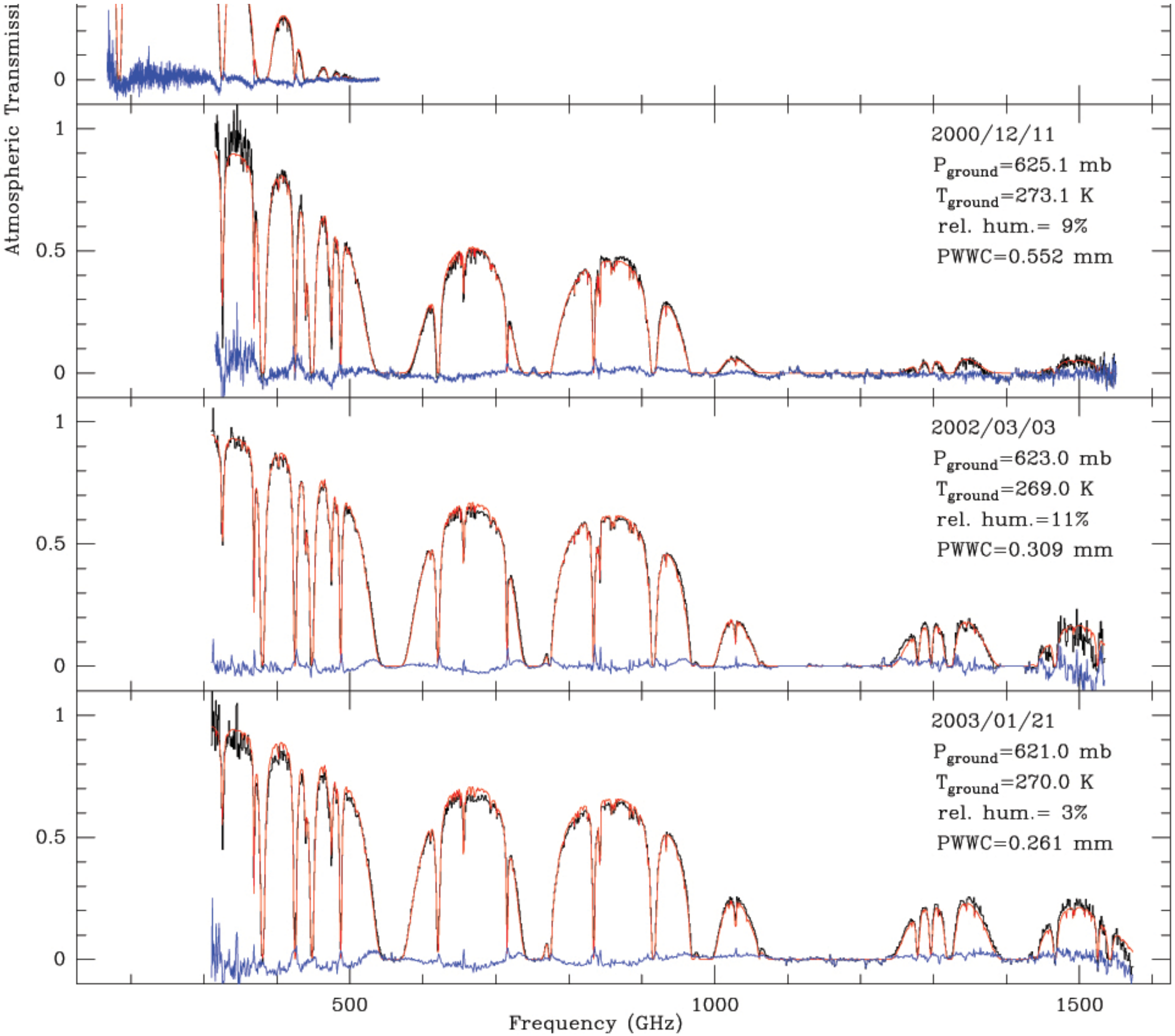


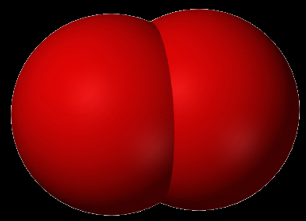
Example 2: Atmospheric transmission at high frequencies in dry Mauna Kea conditions





Data
Model
Residual
Site: Mauna Kea, 4100 m
1998/04/01
Pground=620.0 mb
Tground=272.5 K
rel. hum.= 3%
PWWC=0.182 mm
1999/07/01
Pground=620.0 mb
Tground=272.5 K
rel. hum.=12%
PWWC=0.592 mm
2000/07/17
Pground=626.6 mb
Tground=277.3 K
rel. hum.=39%
PWWC=4.076 mm
2000/12/11
Pground=625.1 mb
Tground=273.1 K
rel. hum.= 9%
PWWC=0.552 mm
Atmospheric Transmission
1
0.5
0

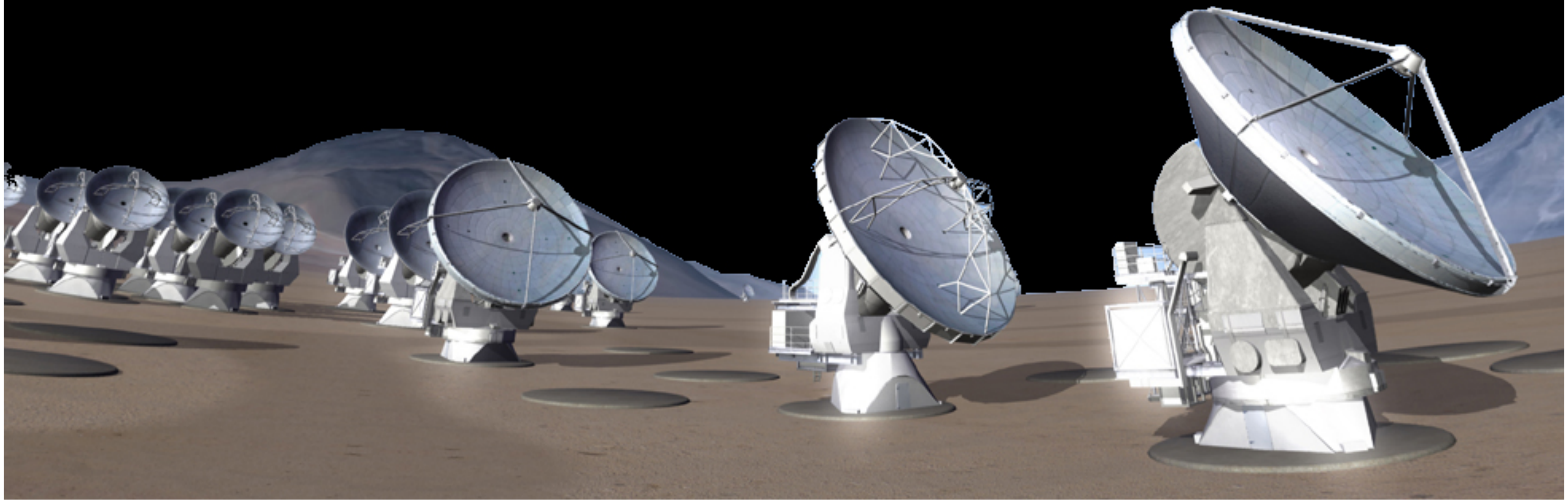

Atmospheric Transmissi
0
1
0.5
2000/12/11
P ground=625.1 mb
T ground=273.1 K
rel. hum.= 9%
PWWC=0.552 mm
2002/03/03
P ground=623.0 mb
T ground=269.0 K
rel. hum.=11%
PWWC=0.309 mm
2003/01/21
P ground=621.0 mb
T ground=270.0 K
rel. hum.= 3%
PWWC=0.261 mm
500
1000
1500
Frequency (GHz)

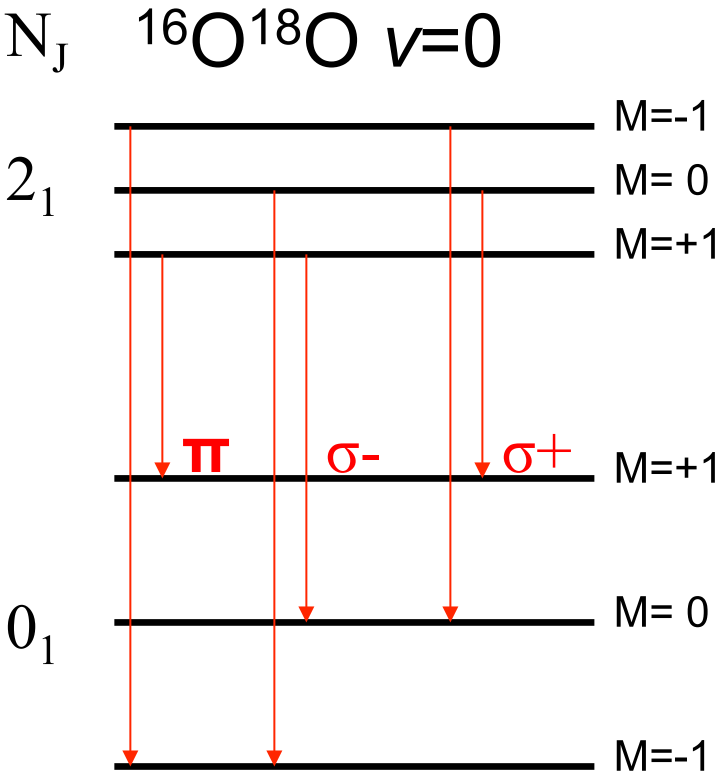


O_2

Paramagnetic molecule: Coupling of its permanent dipole moment with and external magnetic field causes ZEEMAN SPLITTING.

Modeling this effect is rather complex because of anisotropy, polarization, etc…





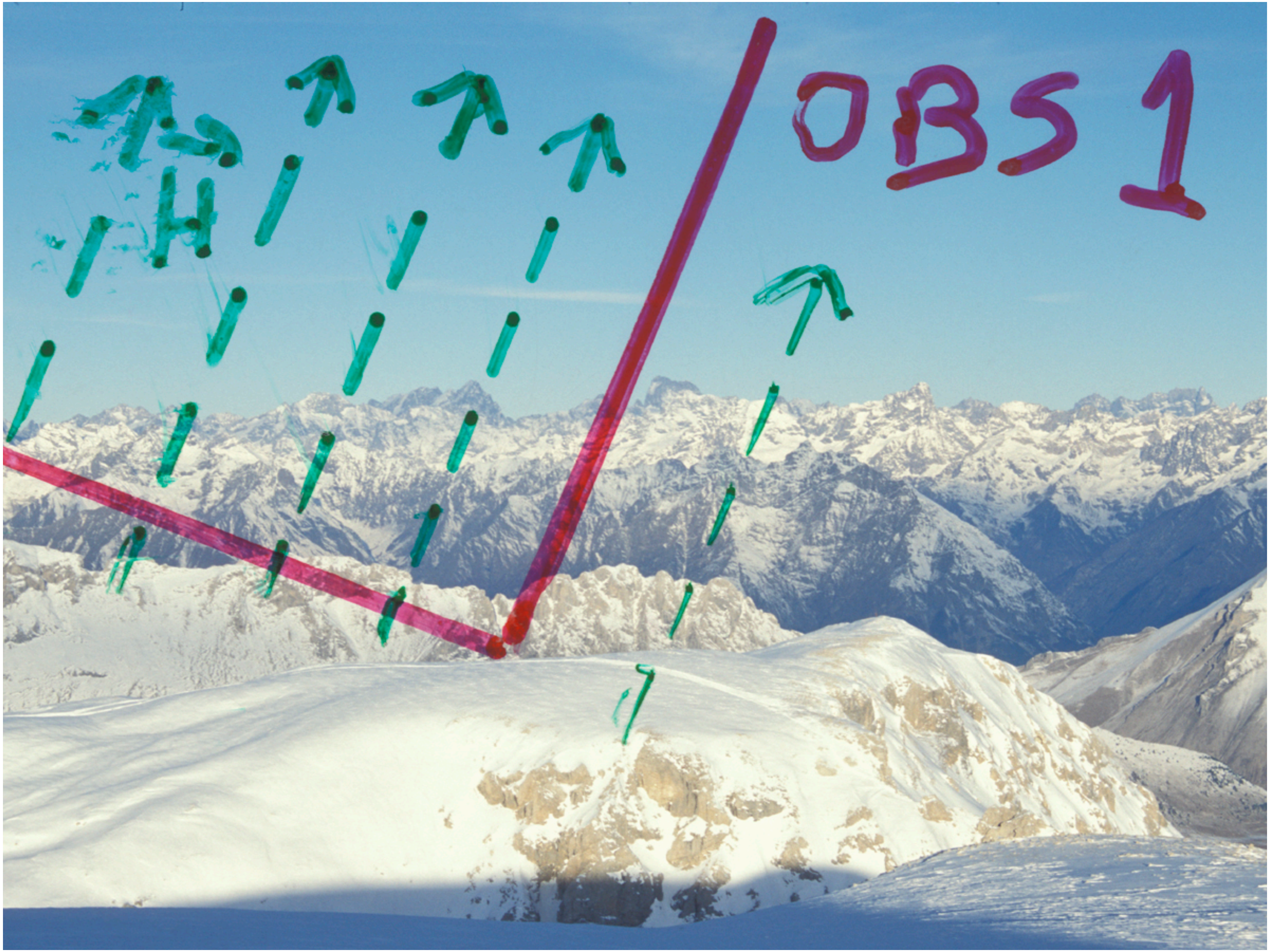
$$\Delta\nu(GHz) = 14.015 \cdot 10^{-6} H_{\mu T}(M_u + 2M_l)$$

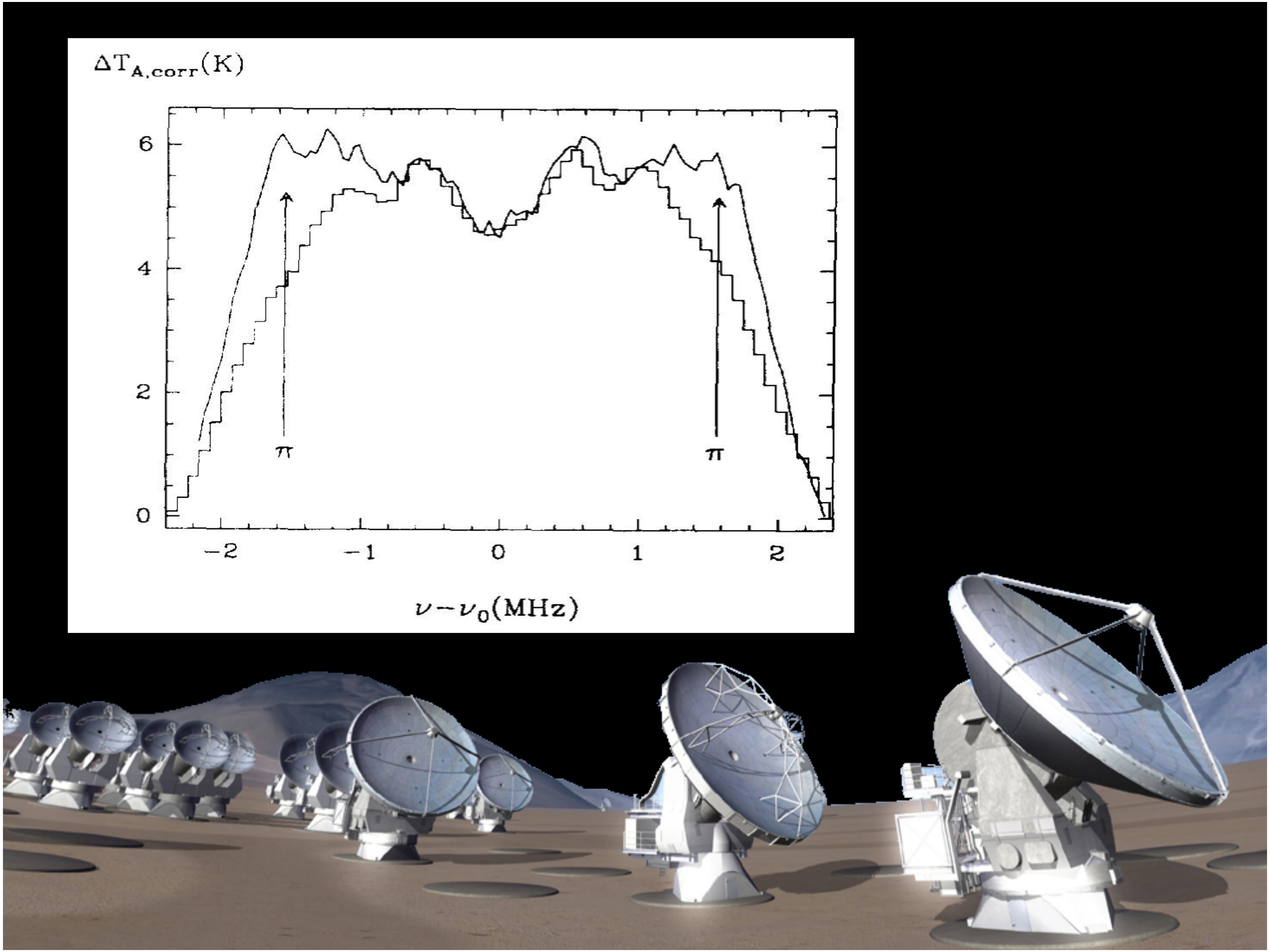
Transitions π (ΔM=0): Radiation linearly polarized in the direction of the geomagnetic field.

Transitions σ (ΔM=±1): Radiation circularly polarized (right-hand or left-hand in the plane perpendicular to the direction of the geomagnetic field.

We should expect differencies in the line profile depending on the line of sight, the type of polarization detected, and the orientation of our detector with the geomagnetic field.

Experiment at POM2. SIS receiver and autocorrelator providing 39 kHz resolution and 4.53 MHz of total band.

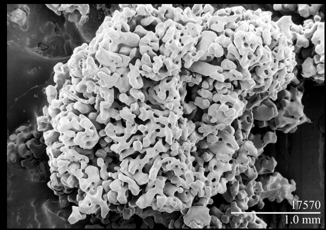

OBS 1



$\Delta T_{A,corr}$(K)
6
4
2
0
−2
−1
0
1
2
π
π
$\nu - \nu_0$(MHz)

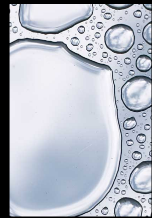
Hydrometeors contribution (absoprtion, scattering, phase…)

aerosols



Wet snow

snow

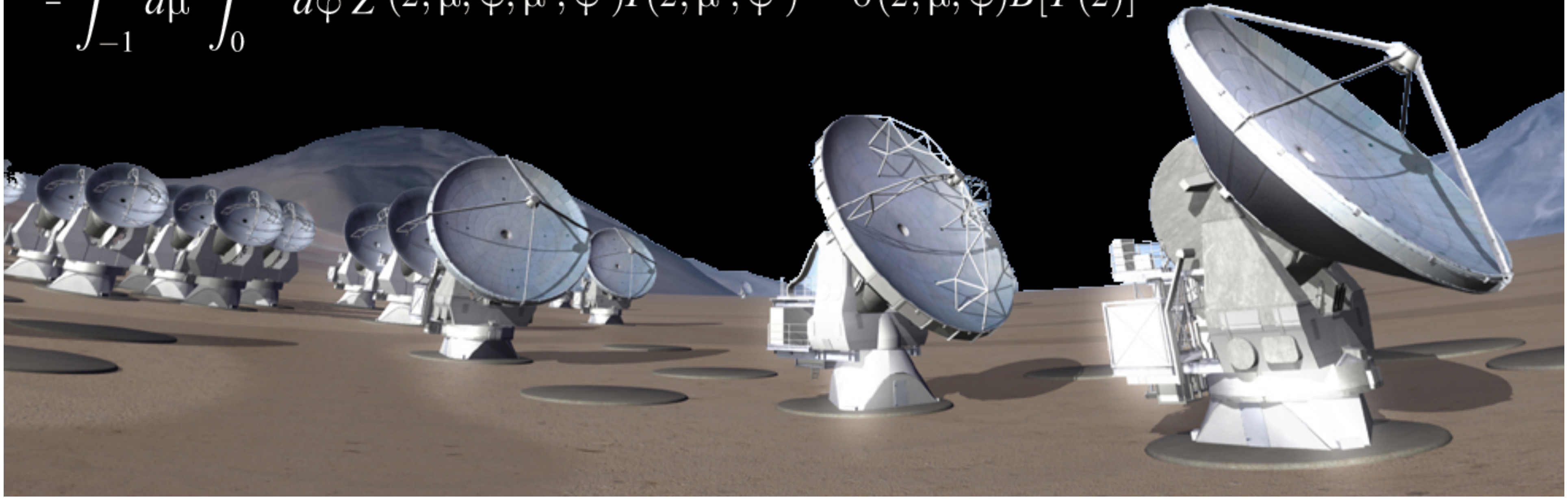


Liquid water

Hale

$$\mu \frac{dI(z,\mu,\varphi)}{dz} = K(z,\mu,\varphi) I(z,\mu,\varphi) -$$

$$- \int_{-1}^{1} d\mu' \int_{0}^{2\pi} d\varphi' Z(z,\mu,\varphi,\mu',\varphi') I(z,\mu',\varphi') - \sigma(z,\mu,\varphi) B[T(z)]$$



In ATM:

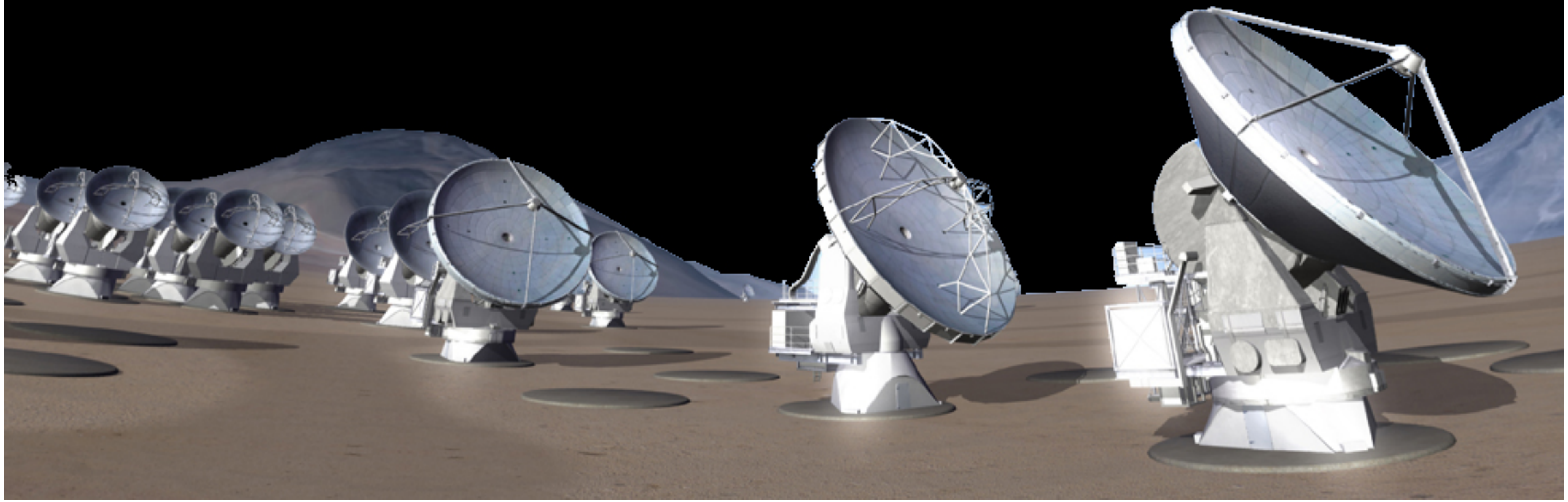
• Phase Matrix calculations from M. I Mishchenko (prolate and oblate spheroids with azimuthaly random distribution, or T-matrix method for spheres.

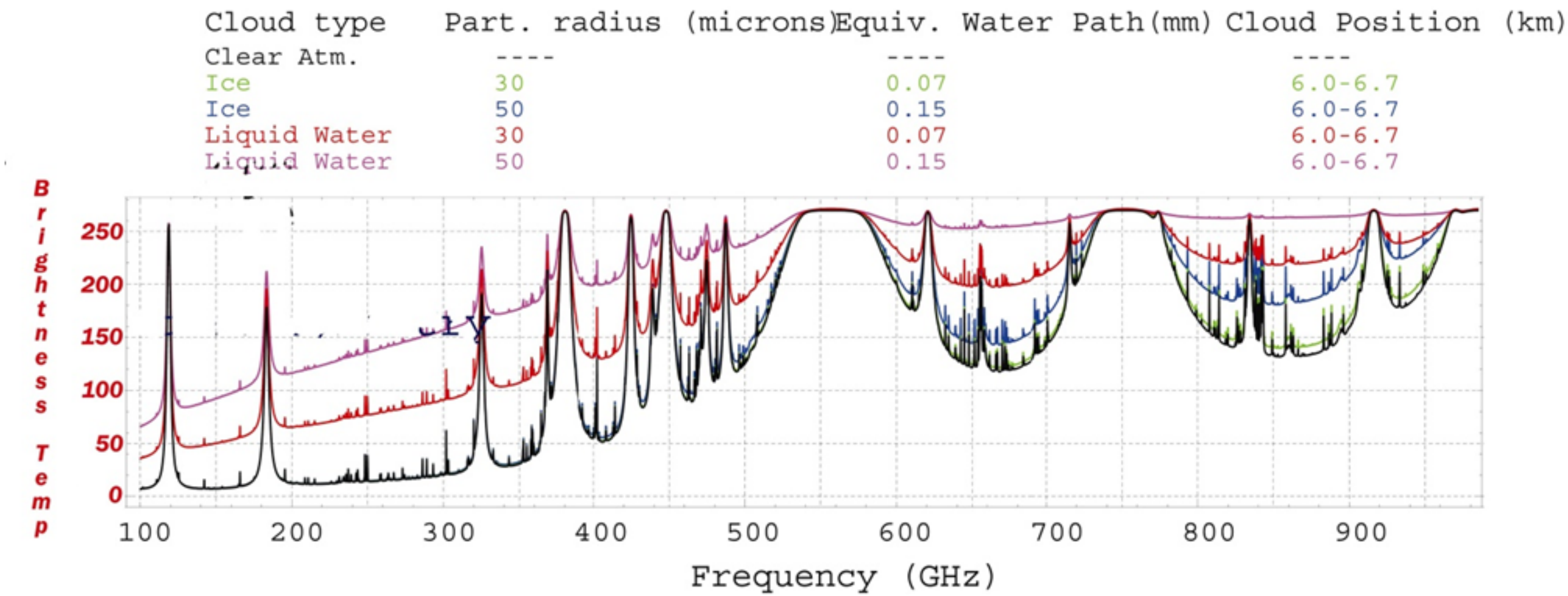
• Refraction indexes from literature.

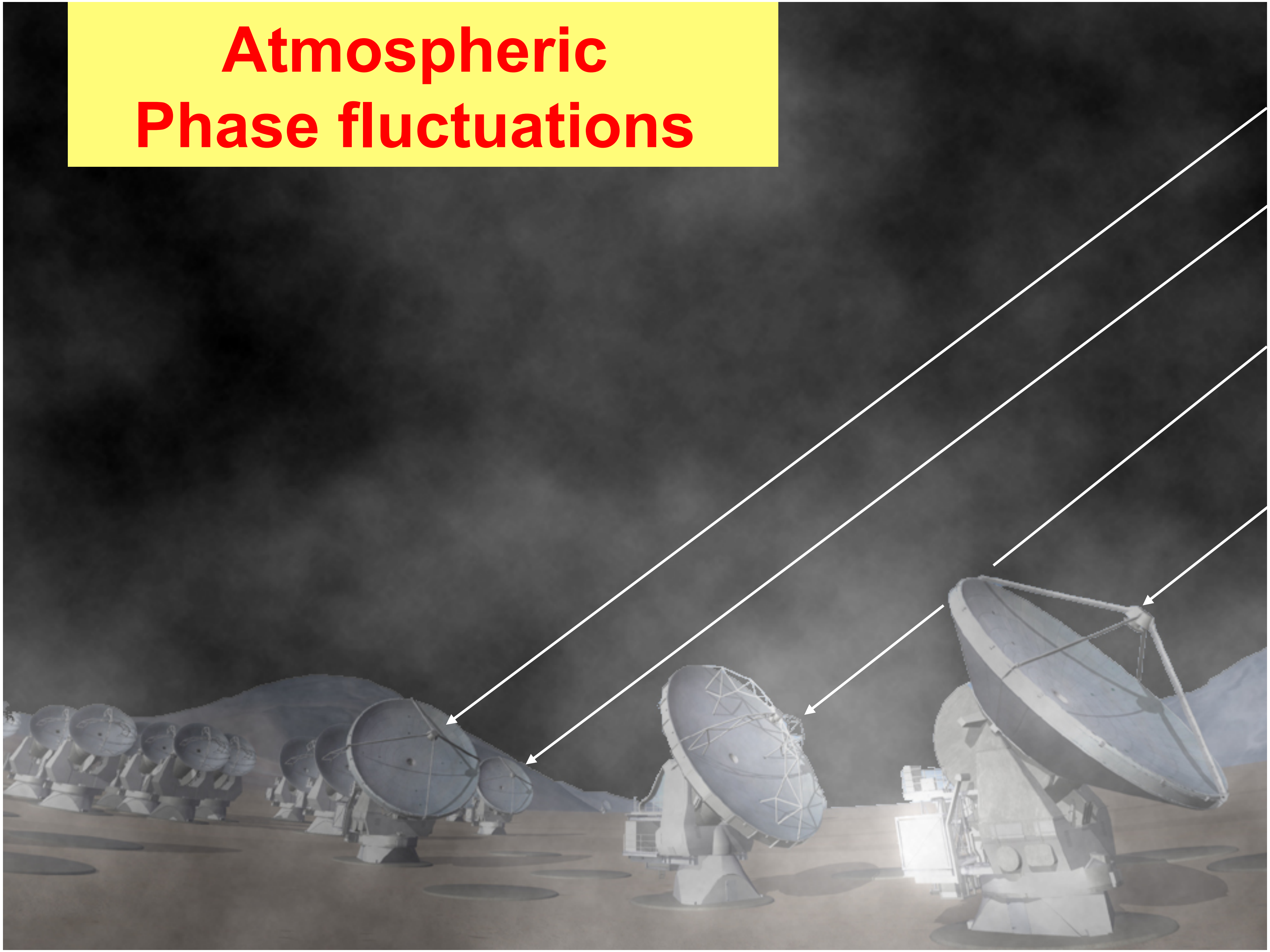
• RT using DDA method from Evans et al.

• Single scattering assumed within each layer.

• Lambertzian, Fresnel and other surface types.




Cloud type Part. radius (microns) Equiv. Water Path (mm) Cloud Position (km)
Clear Atm. ---- ---- ----
Ice 30 0.07 6.0-6.7
Ice 50 0.15 6.0-6.7
Liquid Water 30 0.07 6.0-6.7
Liquid Water 50 0.15 6.0-6.7
Brightness Temp
0
50
100
150
200
250
100
200
300
400
500
600
700
800
900
Frequency (GHz)


Atmospheric
Phase fluctuations

$$(\kappa_\nu)_{lu} = \frac{8\pi^3 N\nu}{3hcQ}\left(e^{-E_l/kT} - e^{-E_u/kT}\right) \cdot |< u \mid \mu \mid l >|^2 f(\nu, \nu_{l\rightarrow u})$$

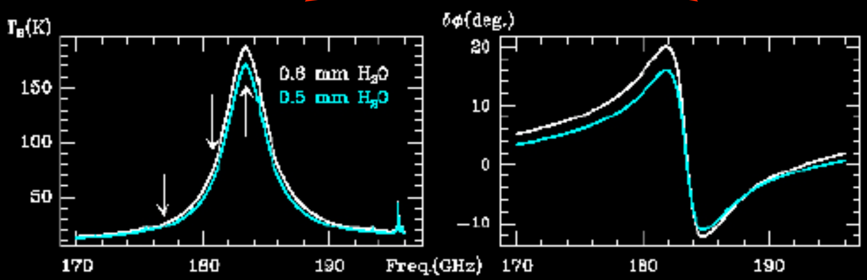
κ_ν Is a complex number

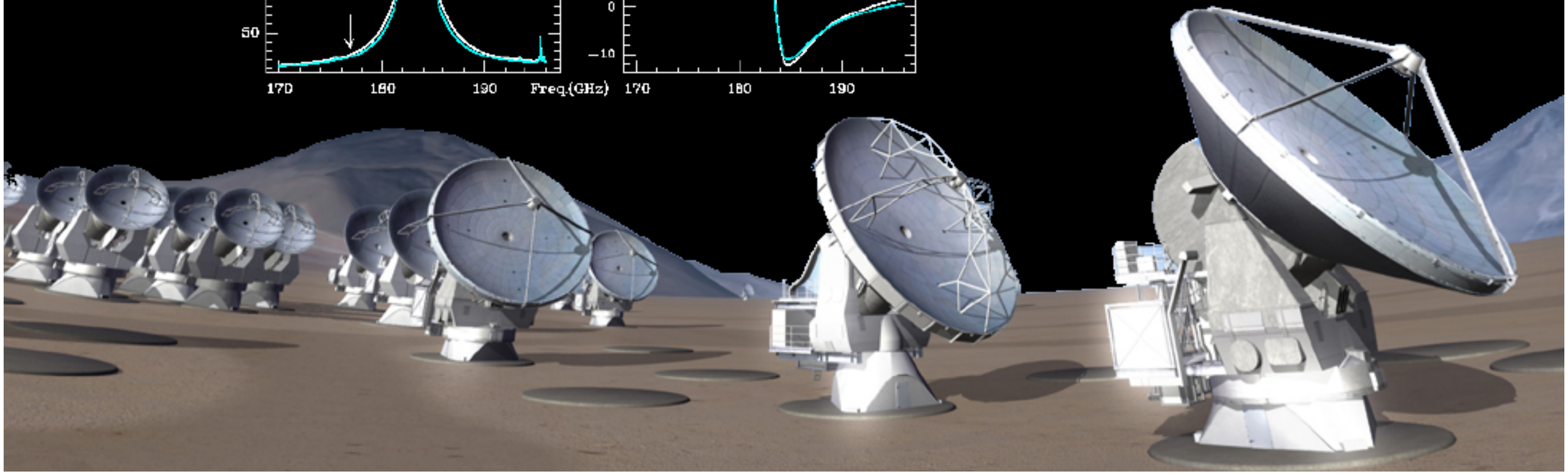
$$\mathcal{F}(\nu, \nu_{u\leftrightarrow l}) = \frac{\nu}{\pi\nu_{u\leftrightarrow l}}\left[\frac{1 - i\delta}{\nu_{u\leftrightarrow l} - \nu - i\Delta\nu} + \right.$$

$$\left. + \frac{1 + i\delta}{\nu_{u\leftrightarrow l} + \nu + \Delta\nu}\right] \quad (1)$$

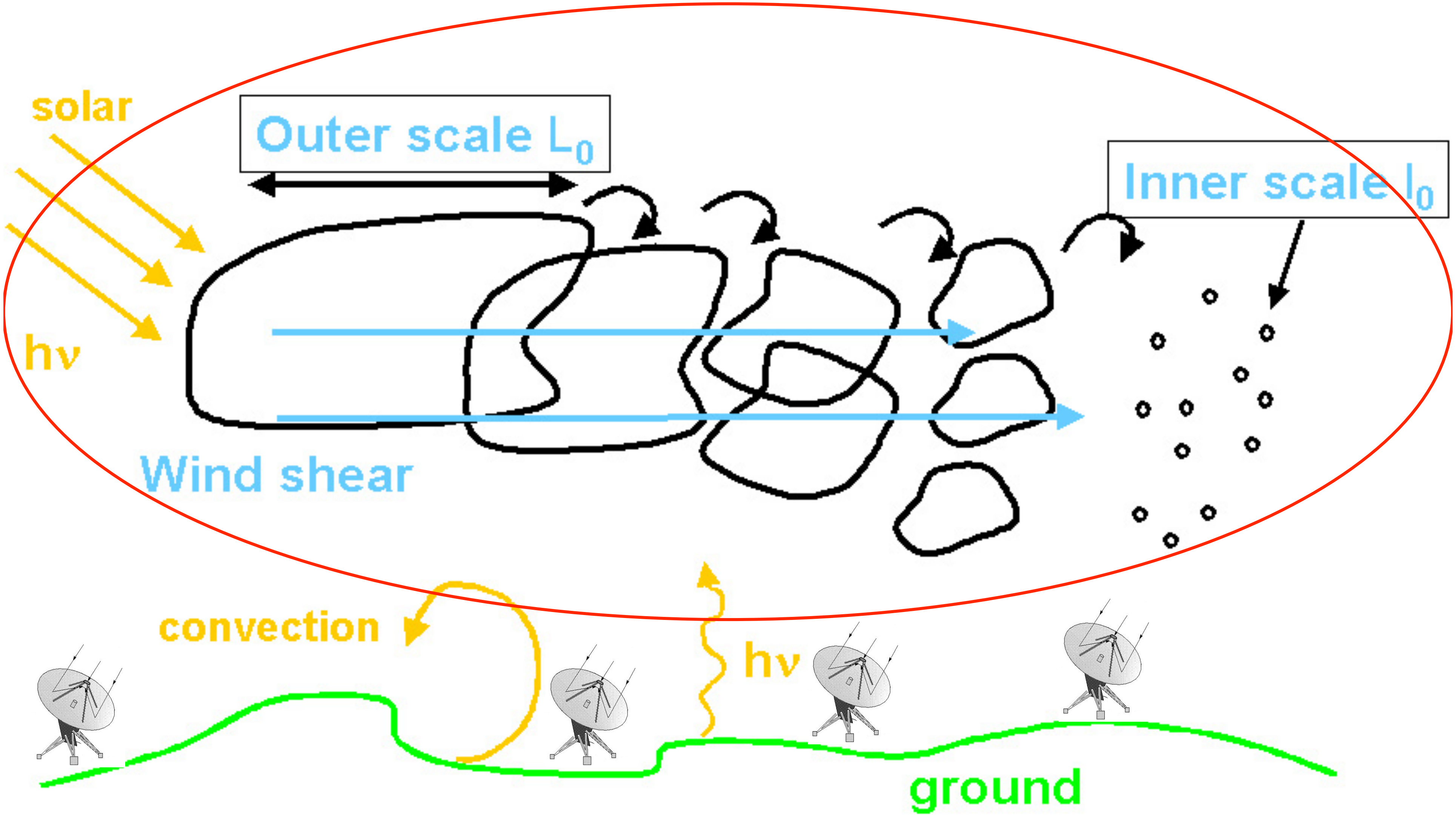
Imaginary part (absorption)

Real part (phase delay or pathlength variation)

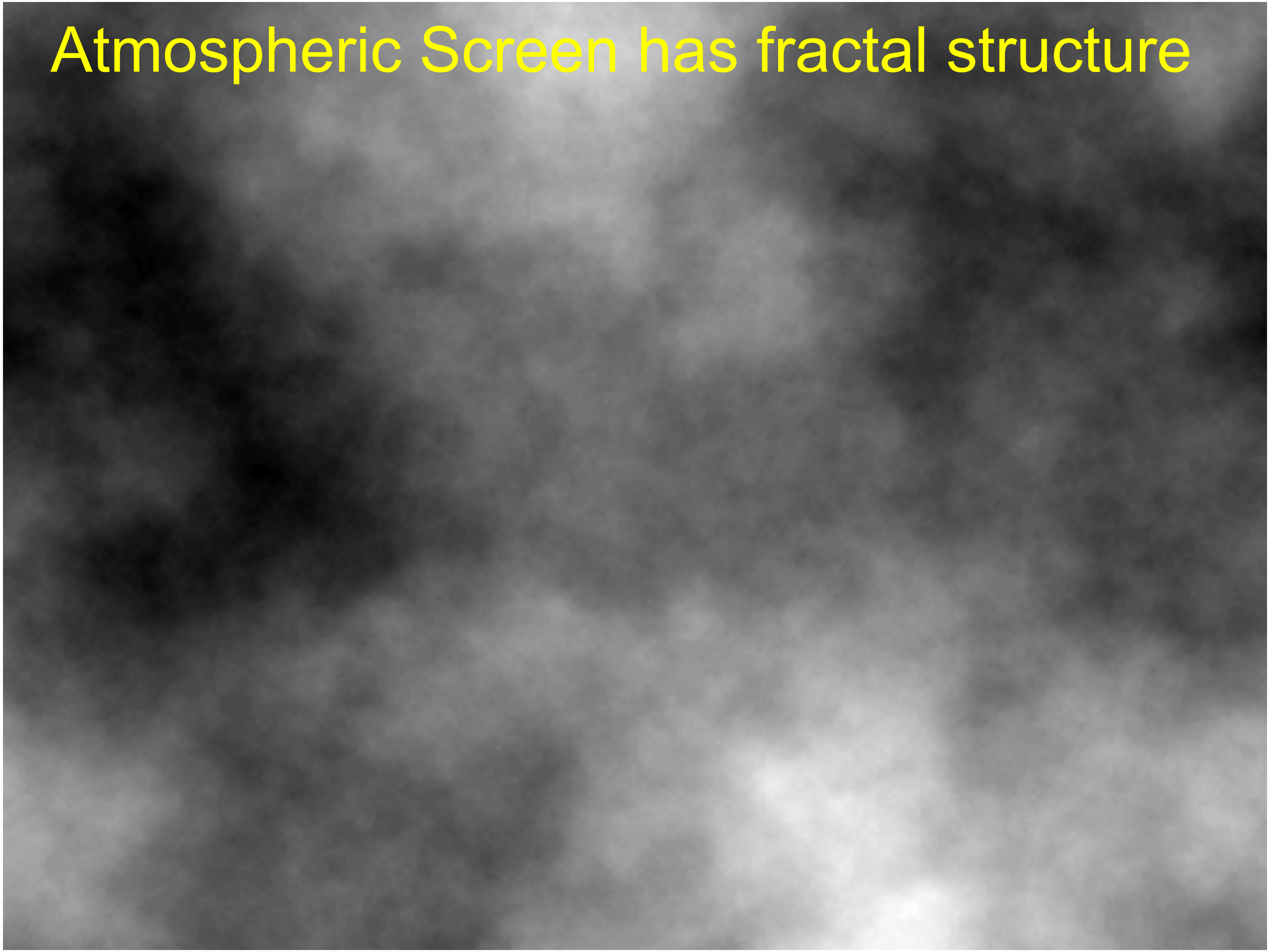




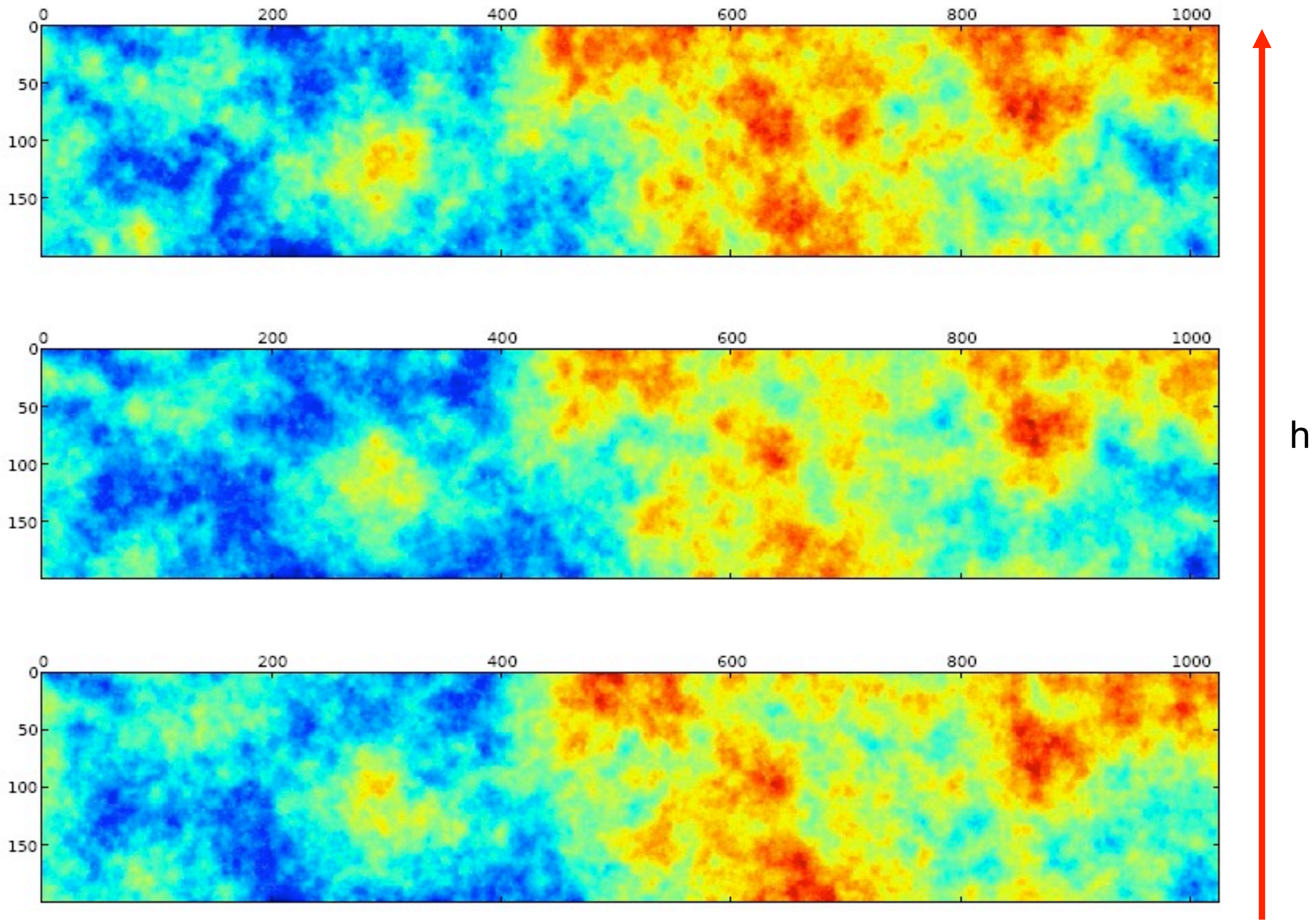
Atmospheric Screen (Wet component moves and evolves in relatively short timescales, ~ 1 sec)



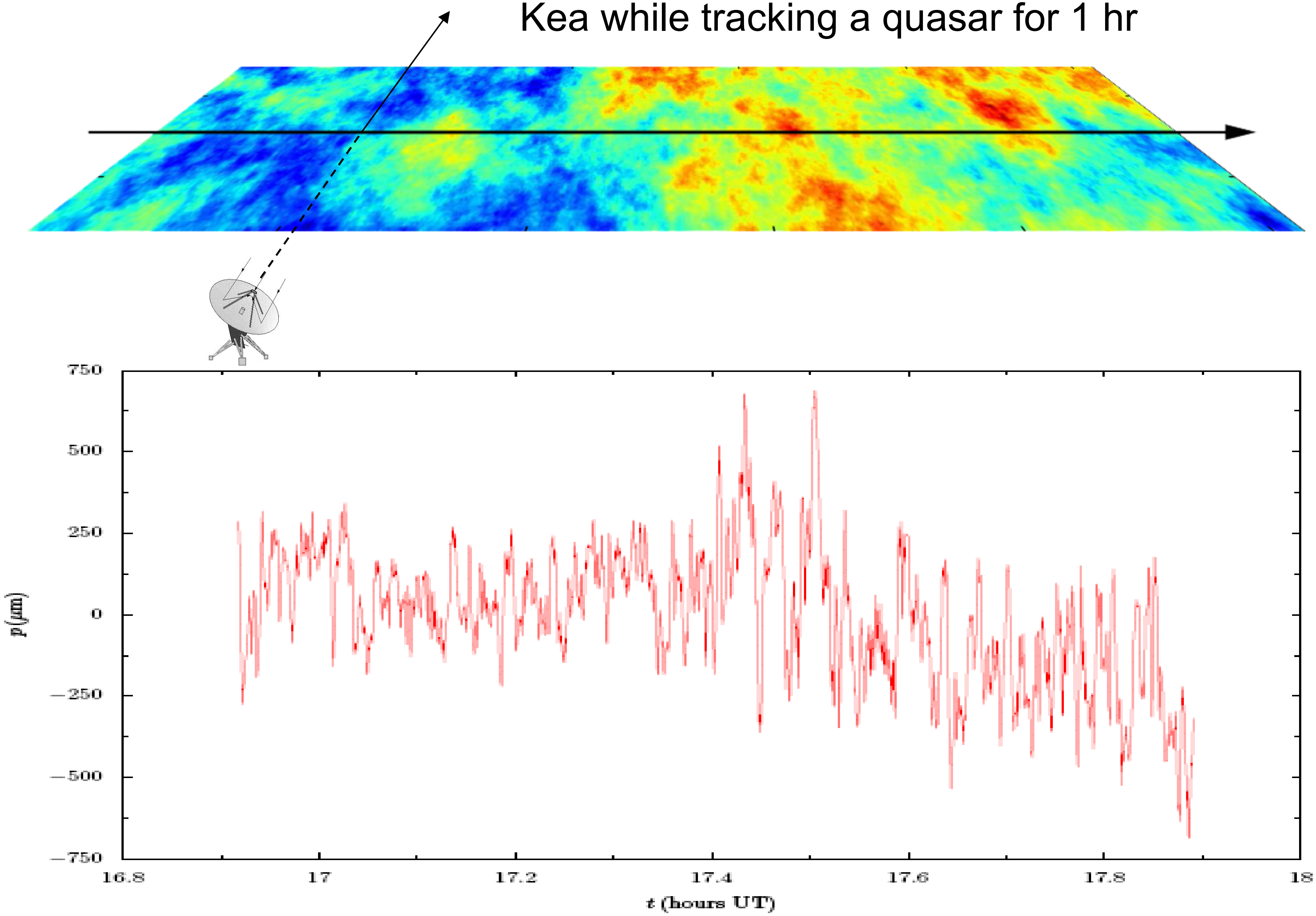
Atmospheric Screen has fractal structure



Atmospheric screen is three-dimensional



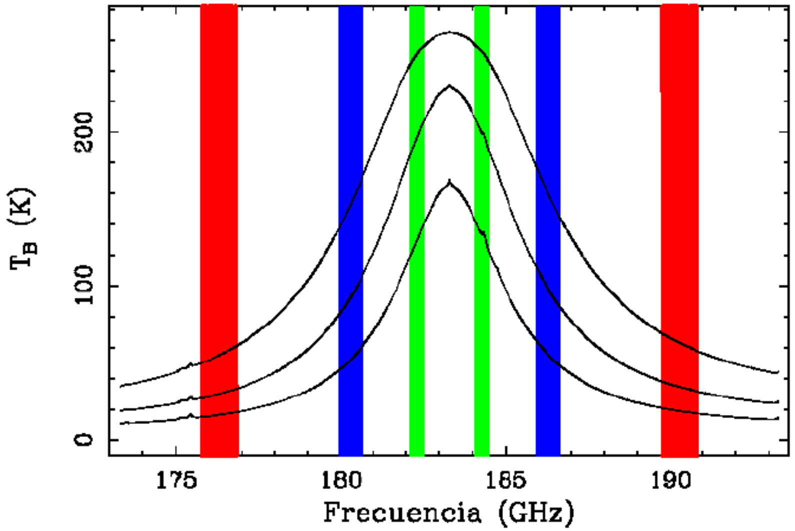
Pathlength fluctuations observed at Mauna Kea while tracking a quasar for 1 hr



Courtesy of B. Nikolic, Cavendish Laboratory,Cambridge

Phase correction can be performed using water vapor radiometry at frequencies sensitive to H_2O

Wavelength (microns)	Pathlength fluctuation factor (microns per micron_H_2O)
612	8.47
482	6.65
312	10.41



Taking an average Precipitable Water Vapor amount of 0.5 mm, we have:

23 mk/μm 60 mk/μm 173 mk/μm

Assuming 0.4 K noise in 1 s in all three channels of the Water Vapor Radiometer

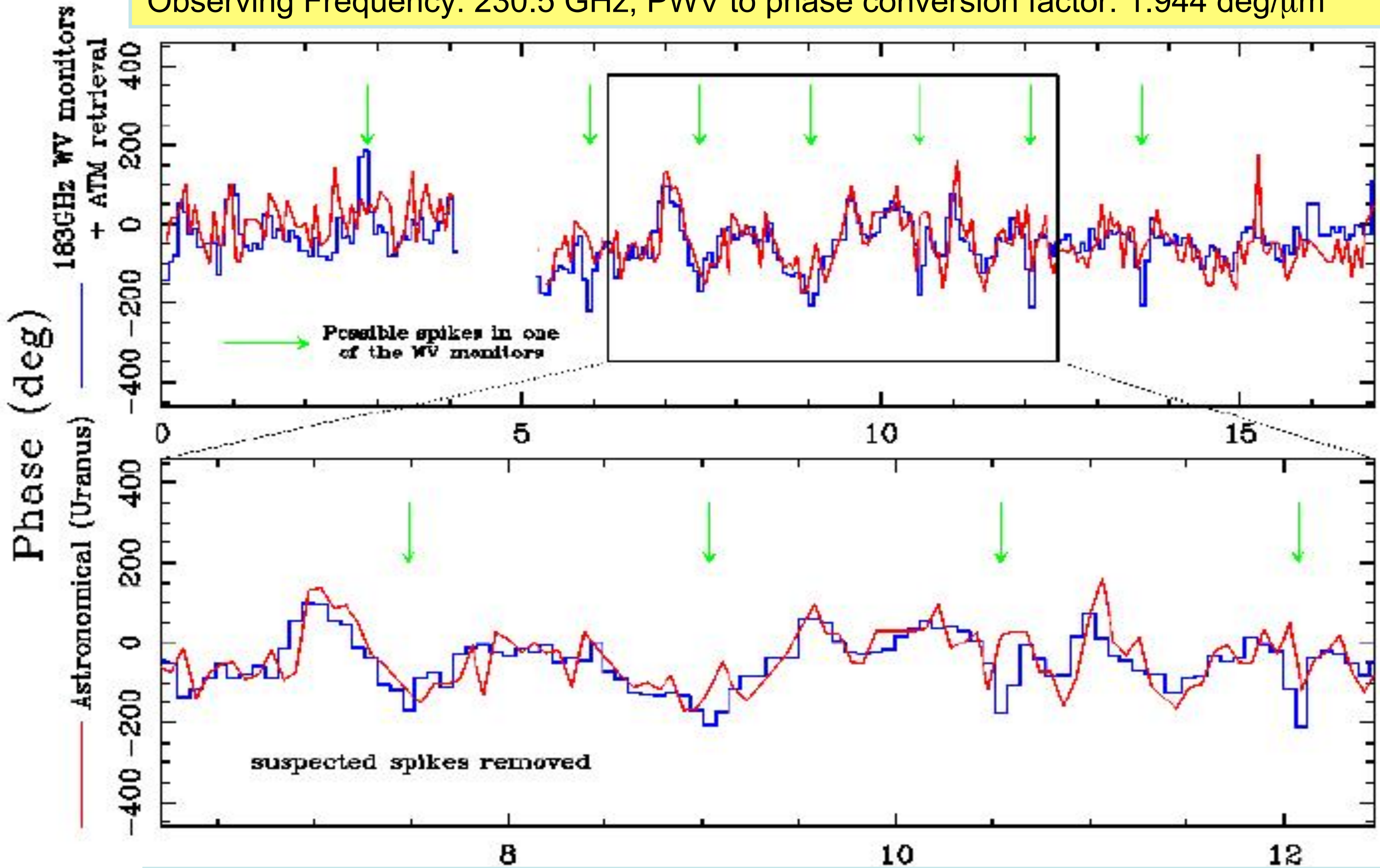
Uncertainty in determining ΔPWV: 2.3 μm

The goal of 15 μm pathlength correction accuracy for ALMA should be reachable with this technique in time scales of the order of 1 s.

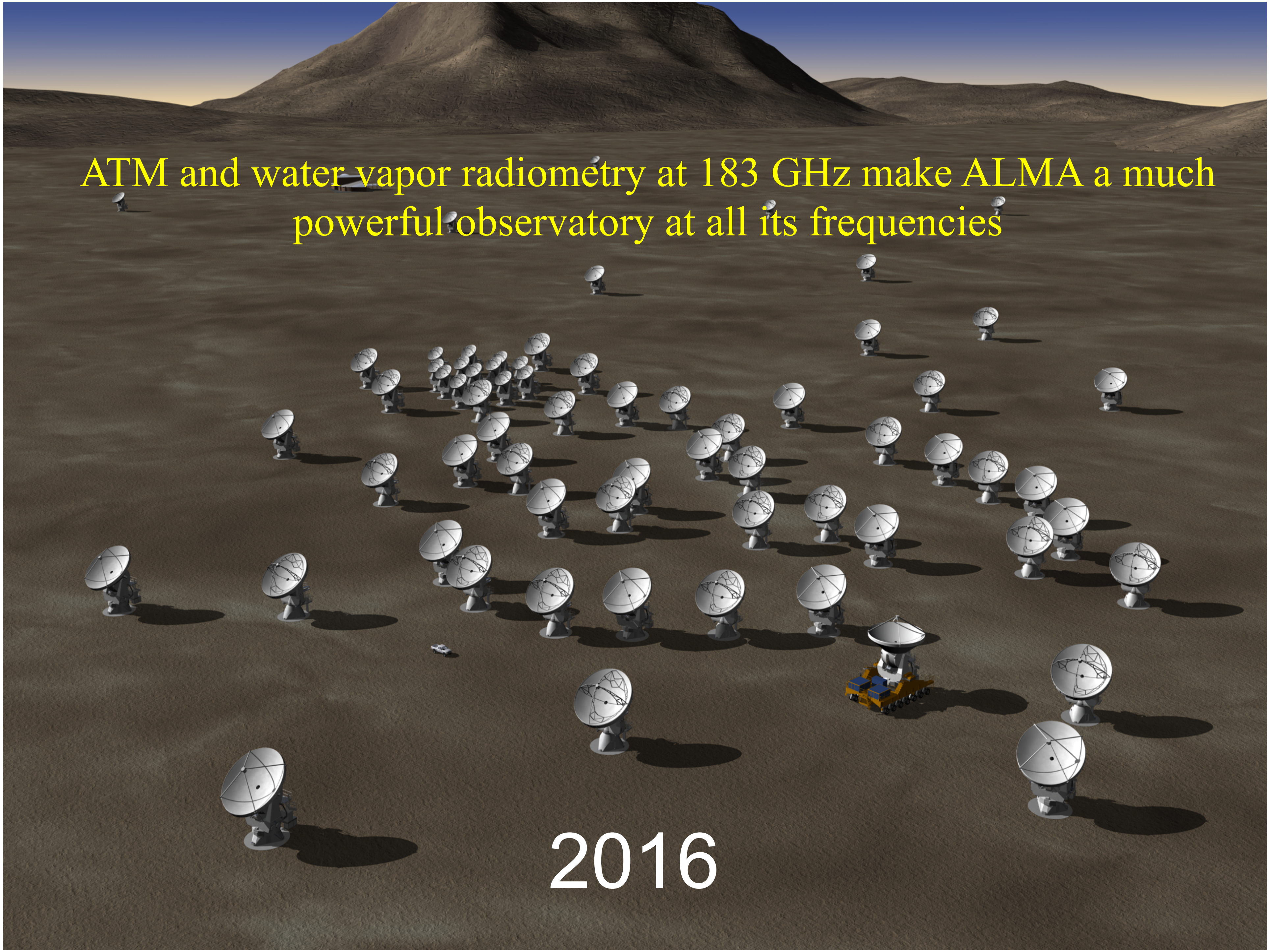
SYSTEM ALREADY DEVELOPED

Phase fluctuations: Correction using 183 GHz water vapor radiometers

Observing Frequency: 230.5 GHz, PWV to phase conversion factor: 1.944 deg/μm



Time since the beginning of the observation (min) on Nov. 25, 2001


ATM and water vapor radiometry at 183 GHz make ALMA a much powerful observatory at all its frequencies
2016