Development of the Atmospheric Transmission at Microwaves model (ATM)

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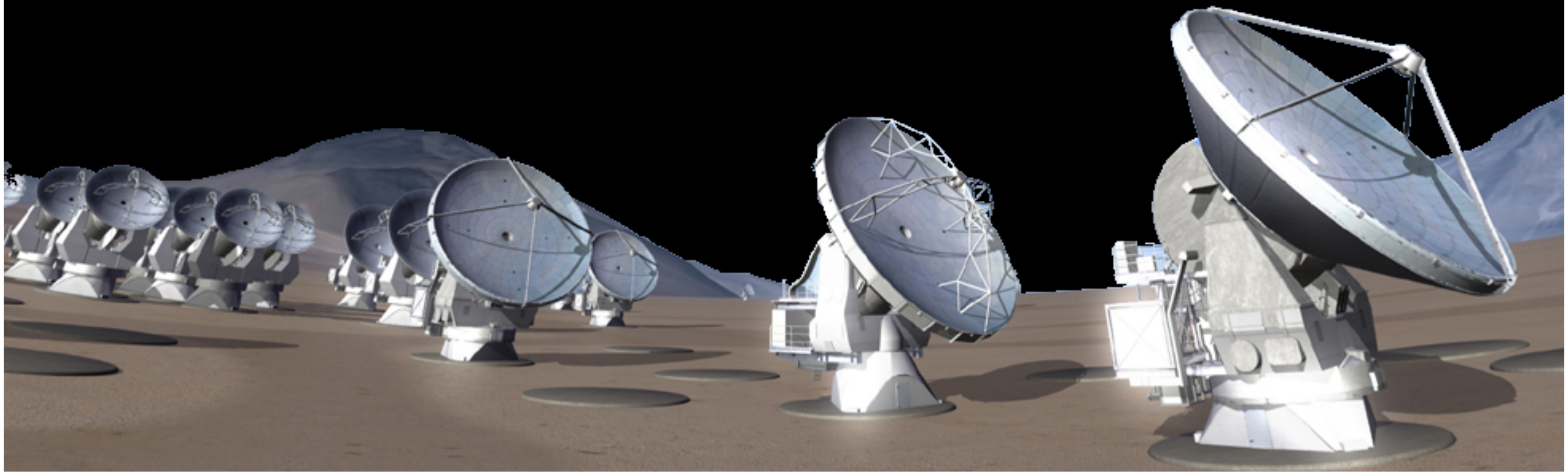
* Developer of ATM for the ALMA TelCal Subsystem under an ESO contract

ISMAR Workshop
September 29, 2015

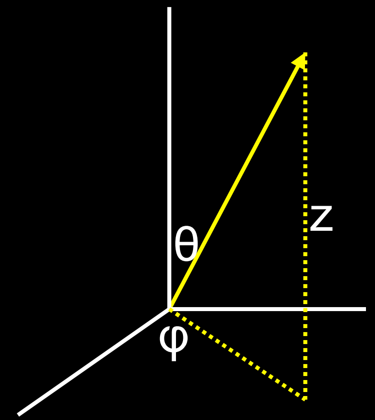


General radiative transfer equation (using coordintates: z, μ=cos(θ), φ)

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

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

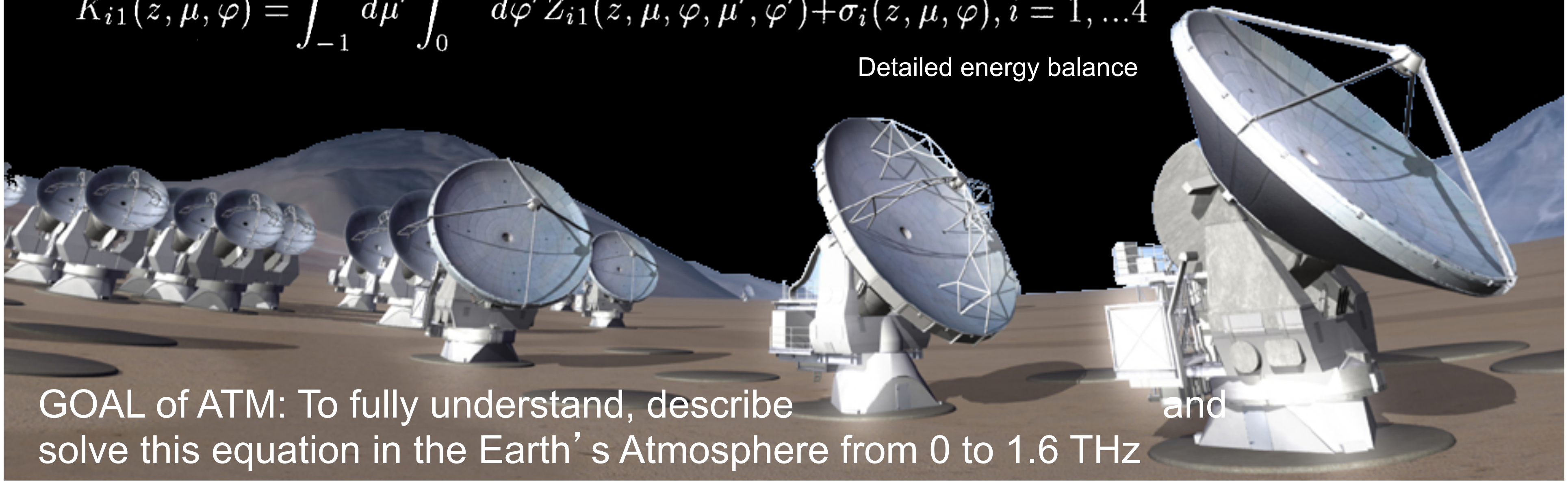
$\mathbf{I}=(I,Q,U,V)^T$ Radiation field (Stokes column vector)
K 4x4 extinction matrix
Z 4x4 phase matrix (describing scattering)
σ 4x1 emission column vector
B Blackbody radiance at temperature T (due to LTE)



Frequency dependence is implicit

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

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

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

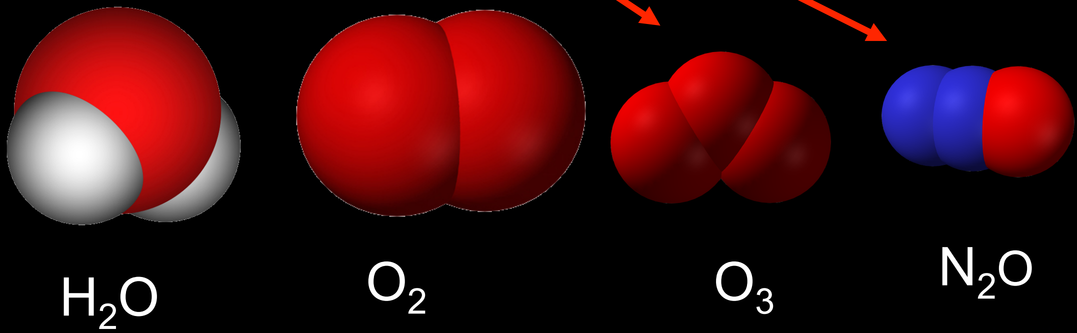
s'	coordinate along the path;
$S_\nu = \epsilon_\nu / \kappa_\nu$	source function;
$d\tau_\nu = \kappa_\nu ds$	differential opacity.

gas-phase κ_ν

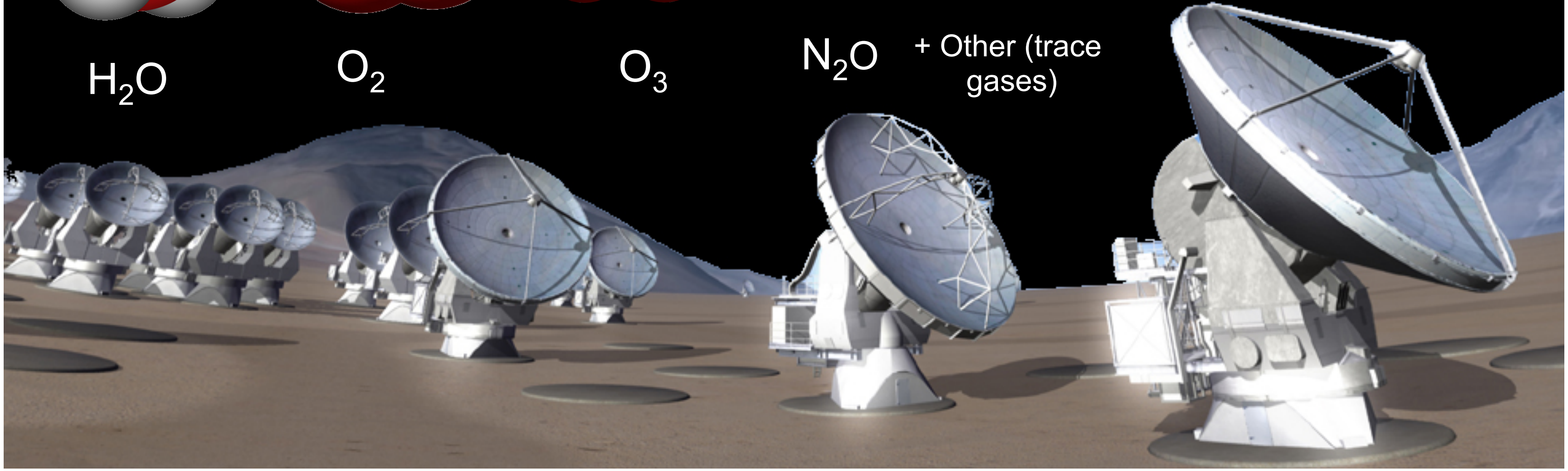
$$(\kappa_\nu)_{lu} = \frac{8\pi^3 N \nu}{3hcQ} \left(e^{-E_l/kT} - e^{-E_u/kT} \right) \cdot |< u \mid \mu \mid l >|^2 \, f(\nu, \nu_{l \to u})$$

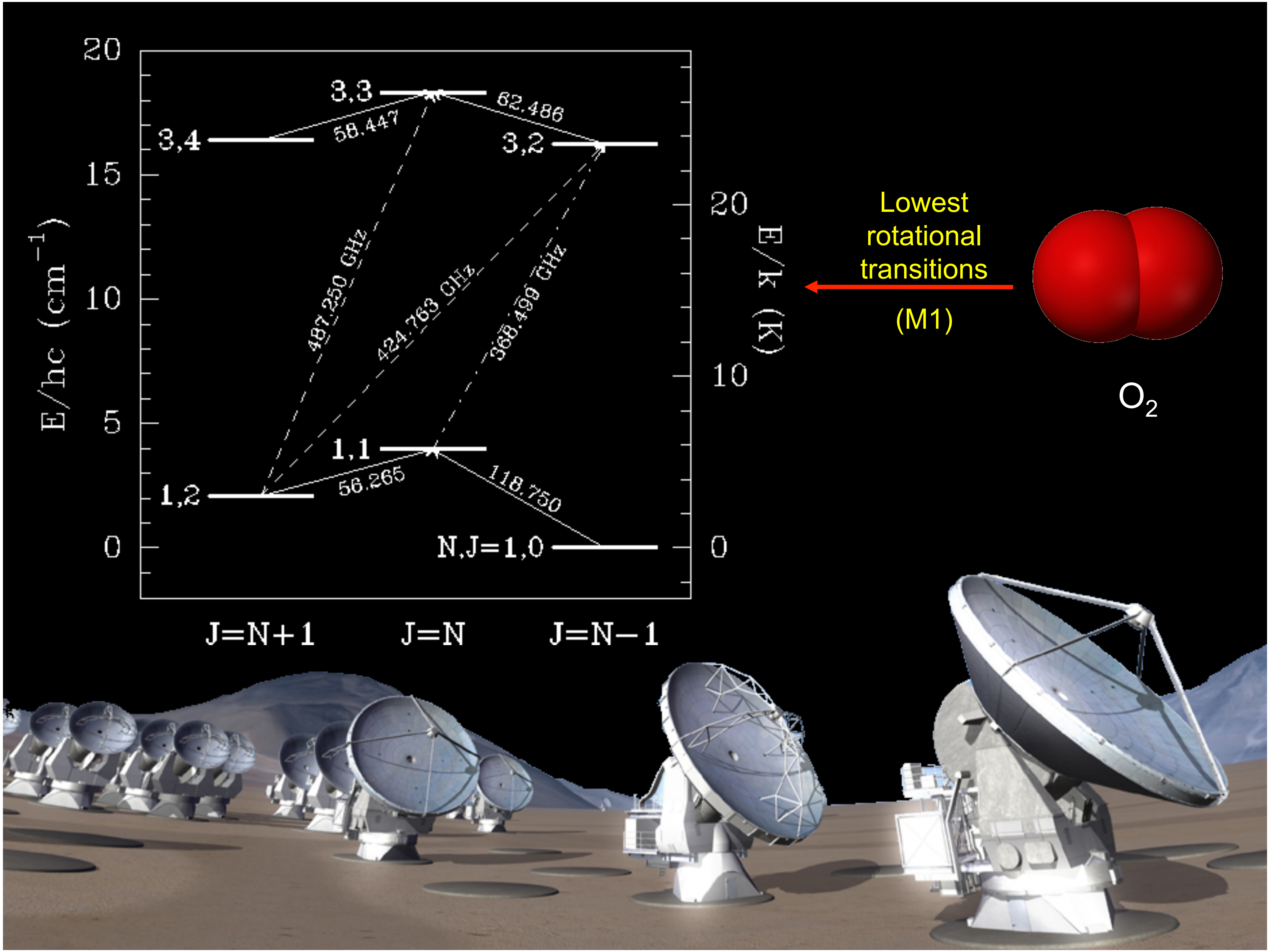
Continuum-like absorption

Rotational lines absorption

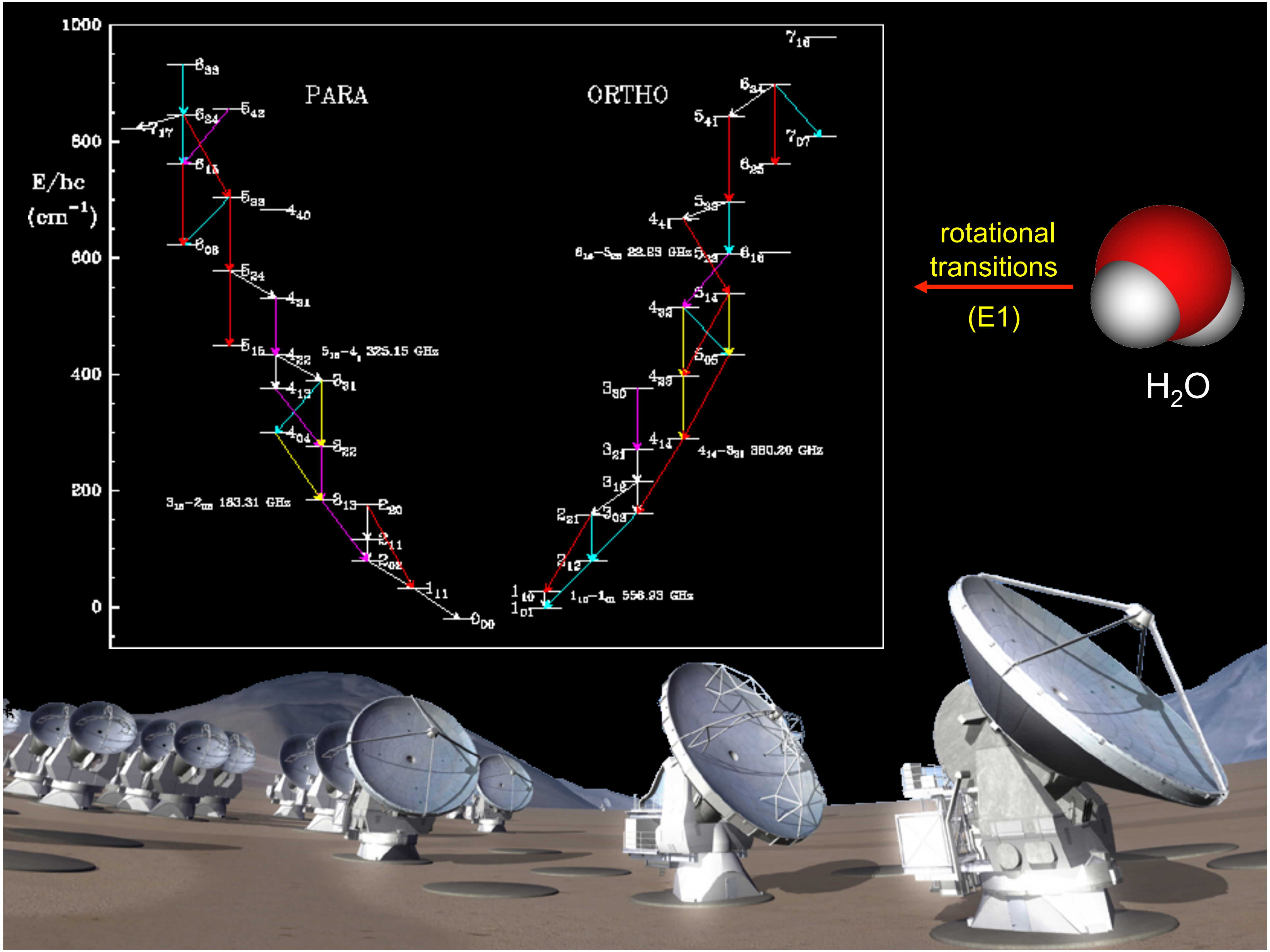


+ Other (trace gases)





E/hc (cm^{-1})
E/k (K)
3,3
3,4
3,2
1,1
1,2
N,J=1,0
58.447
62.486
56.265
118.750
487.250 GHz
424.763 GHz
368.499 GHz
J=N+1
J=N
J=N−1
Lowest rotational transitions
(M1)
O_2



PARA
ORTHO
E/hc (cm^{-1})
1000
800
600
400
200
0
3_{13}–2_{20} 183.31 GHz
5_{15}–4_{22} 325.15 GHz
6_{16}–5_{23} 22.23 GHz
4_{14}–3_{21} 380.20 GHz
1_{10}–1_{01} 556.93 GHz
rotational transitions
(E1)
H_2O

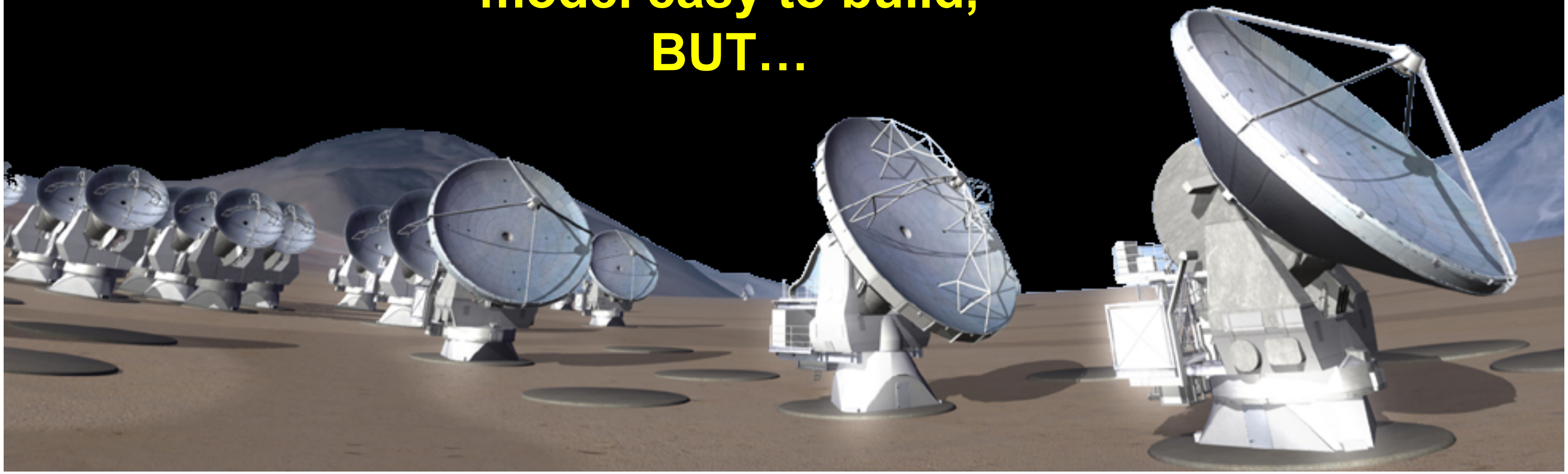
Line strengths from quantum mechanics

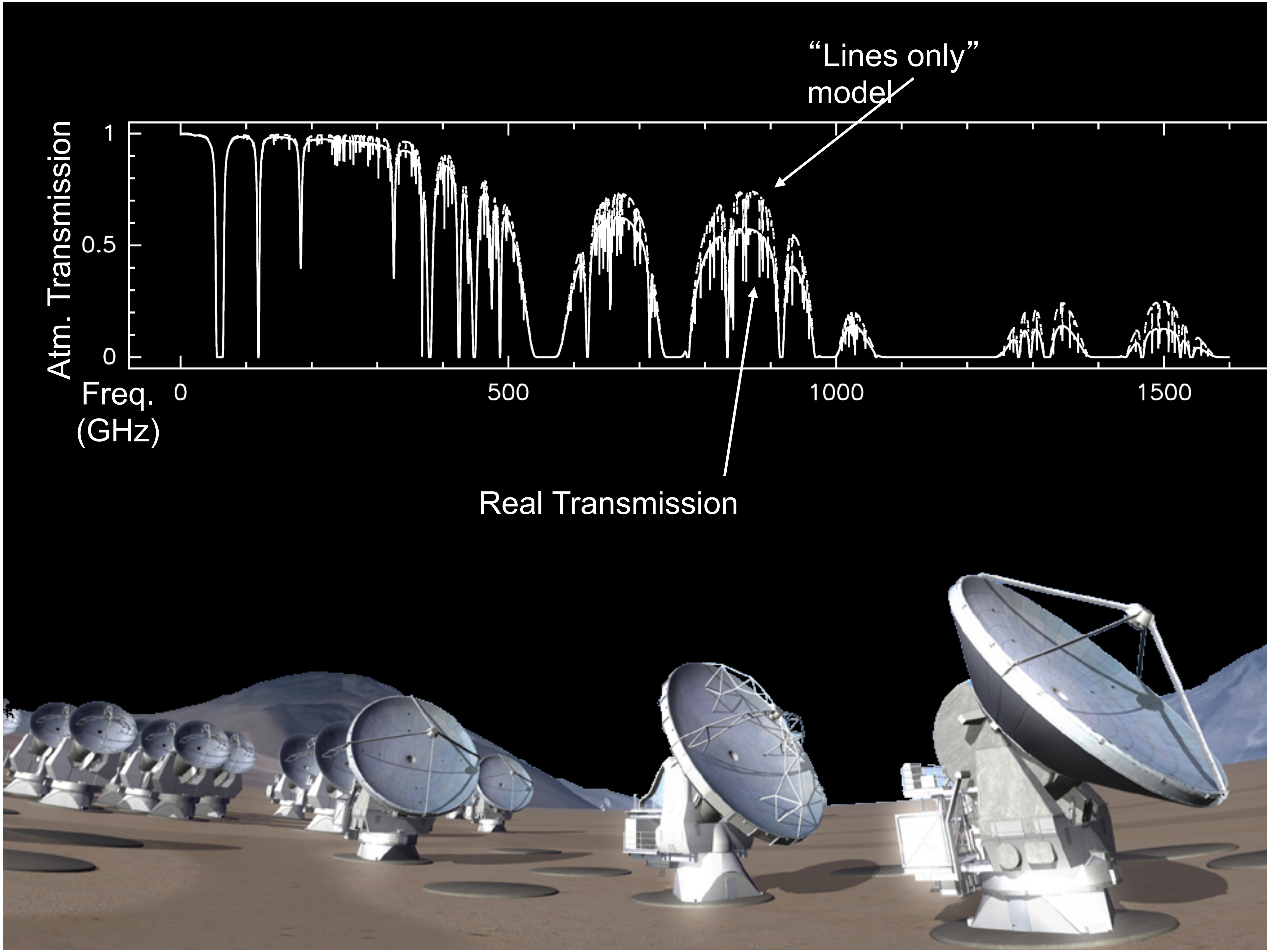
\+

Line profiles (line widths from laboratory)

↓

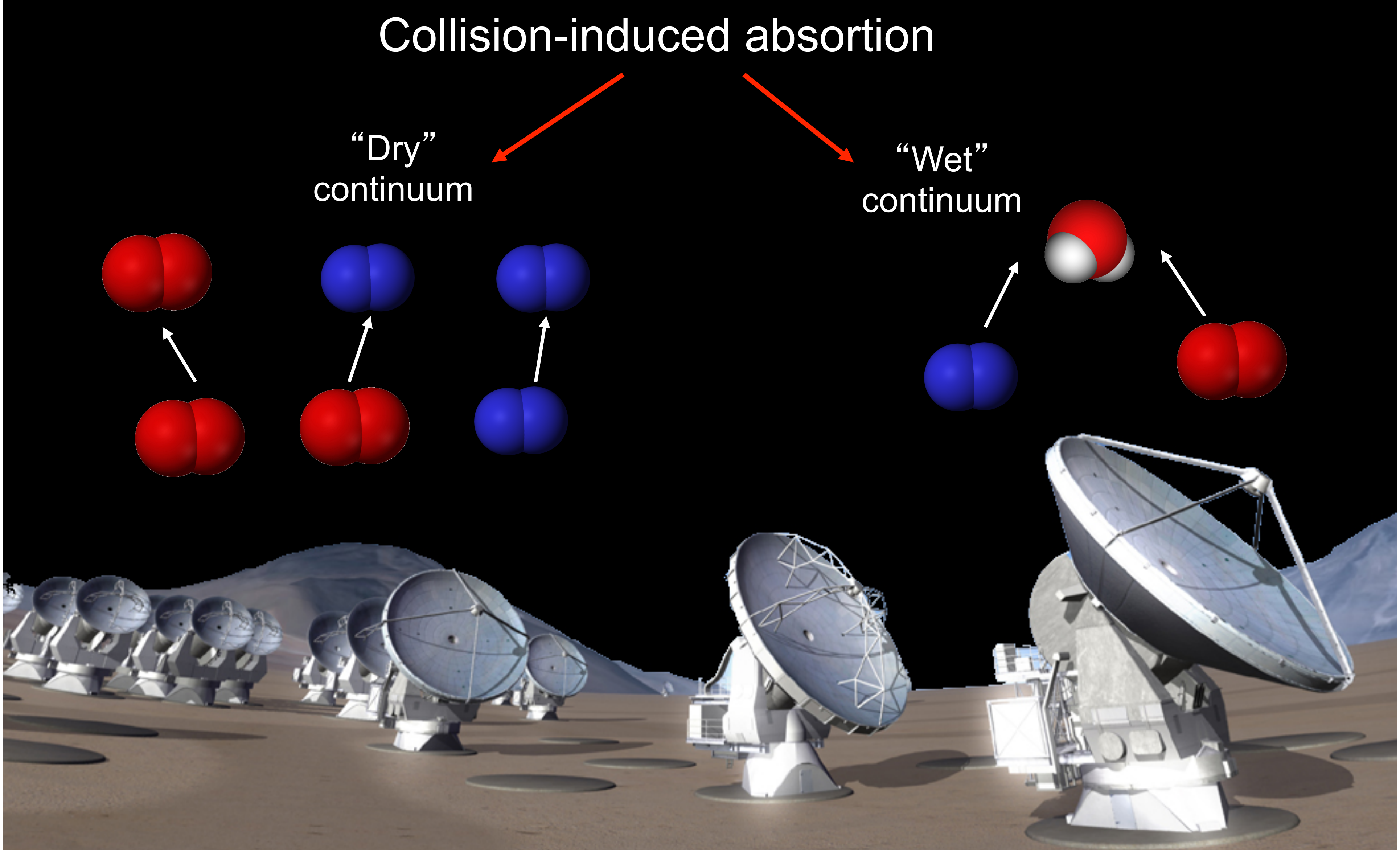
Simple transmission model easy to build, BUT…



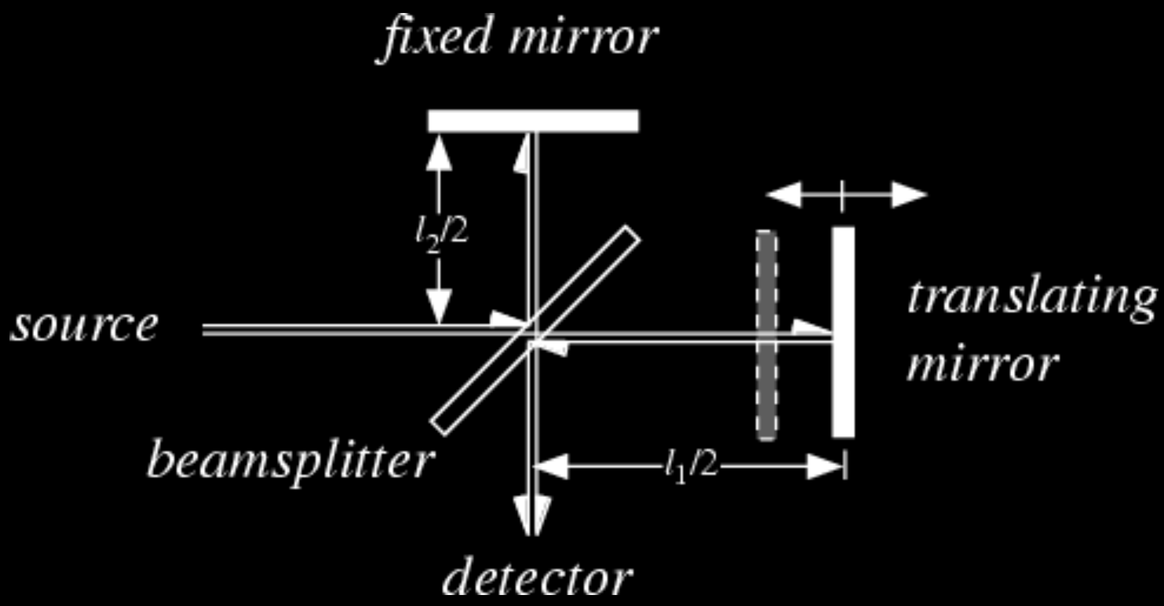


"Lines only" model
Atm. Transmission
1
0.5
0
Freq. (GHz)
0
500
1000
1500
Real Transmission

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

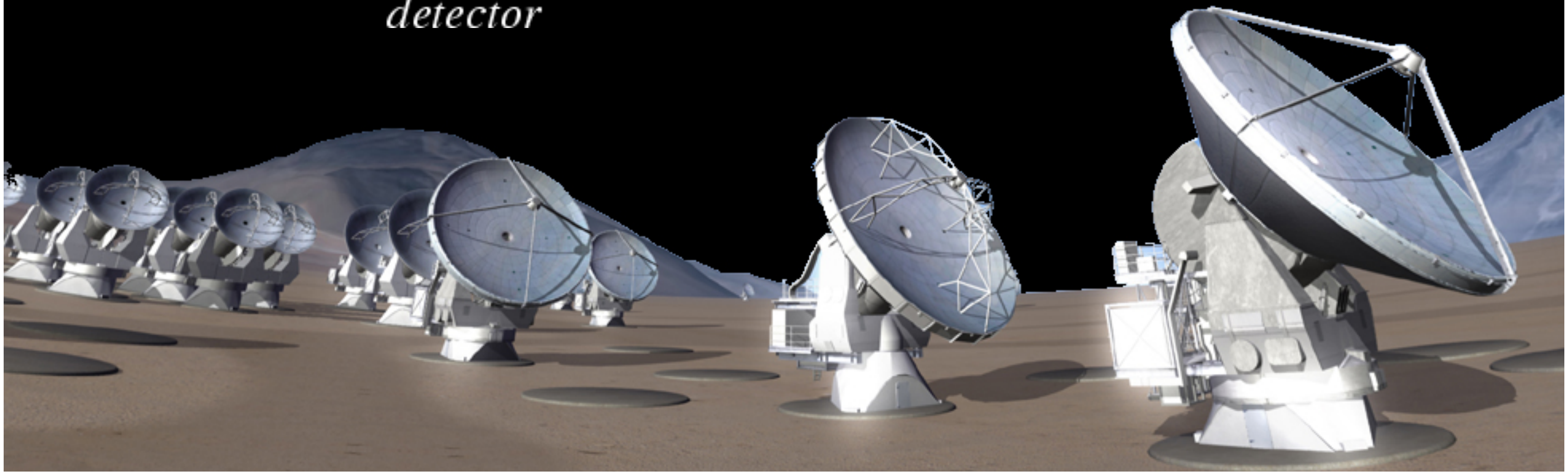


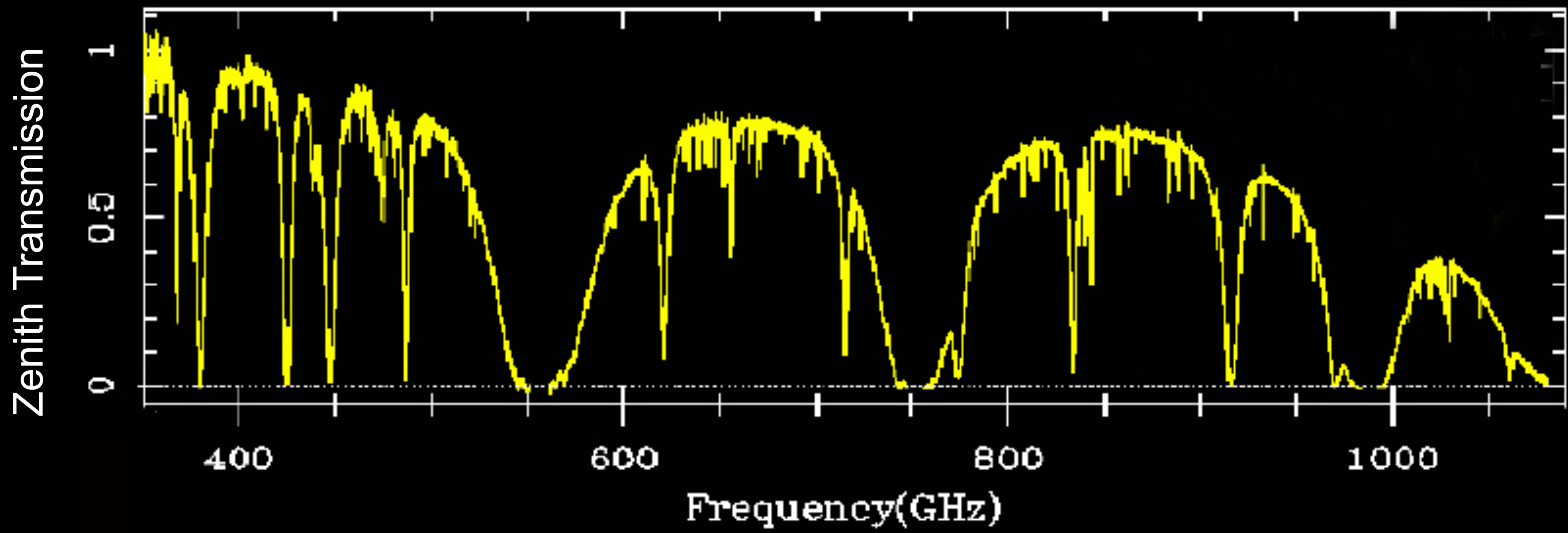
Experimental basis for refined models: Direct measurements with FTS experiments at Mauna Kea, Chajnantor & Sout Pole



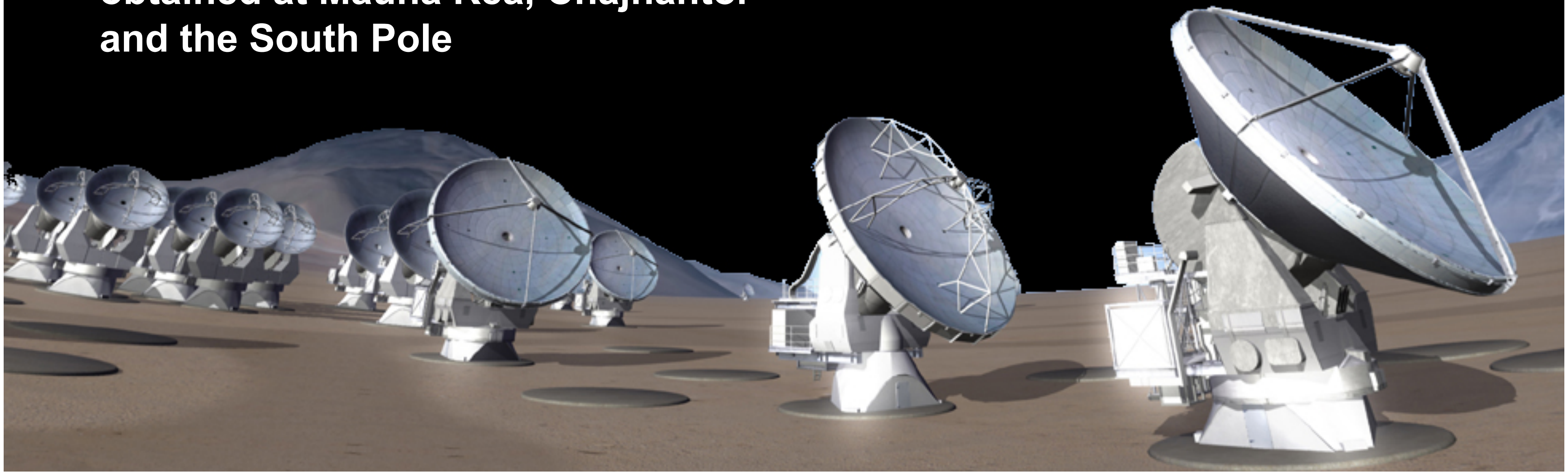
Characteristics of CSO-FTS

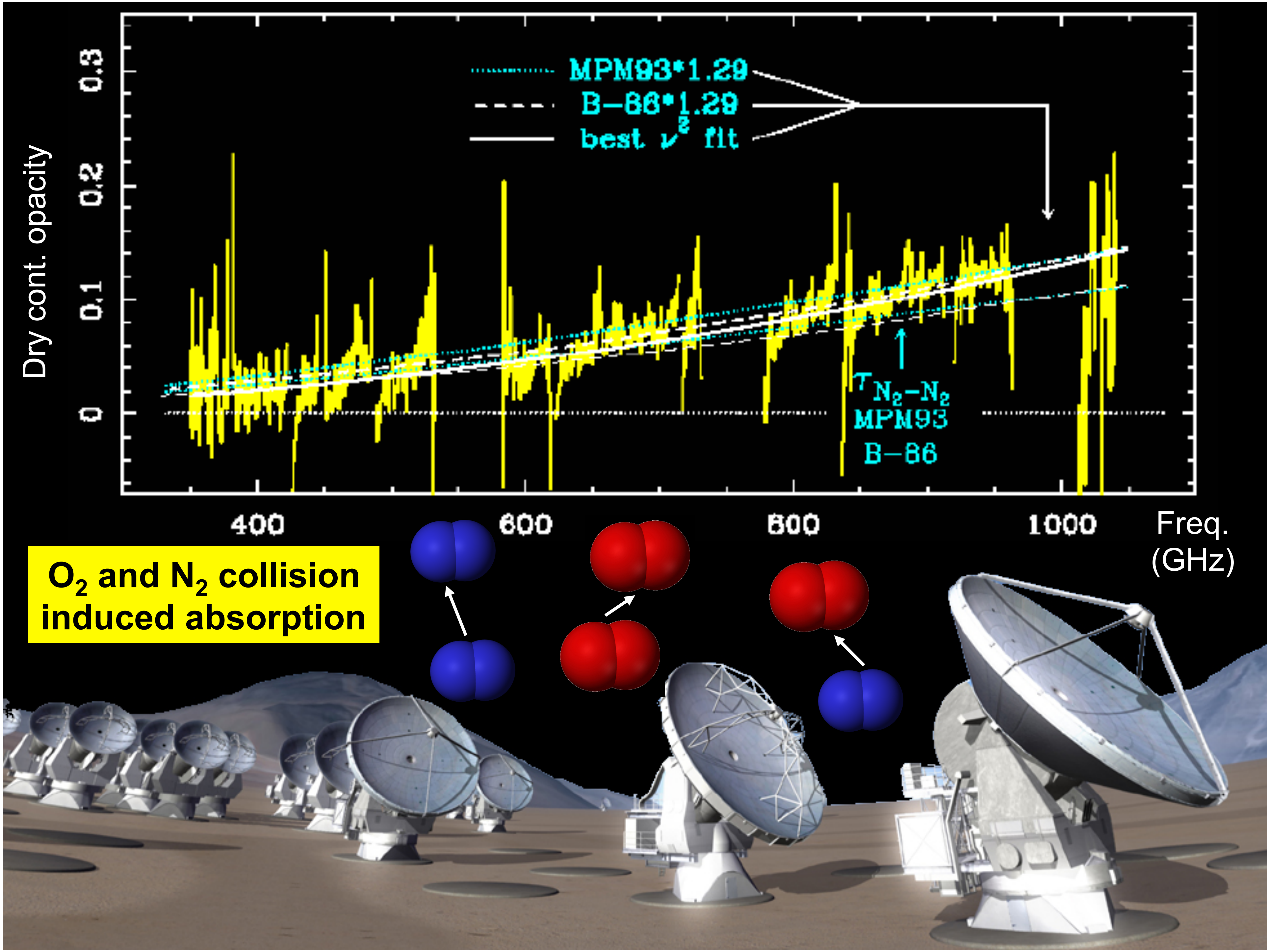
- Mounted on Cassegrain focus of telescope for dedicated obs. runs.
- Detector: ^{3}He cooled Bolometer
- Moving arm: 50 cm ~ 200 MHz resolution
- Filters: 7 different (165 to 1600 GHz)



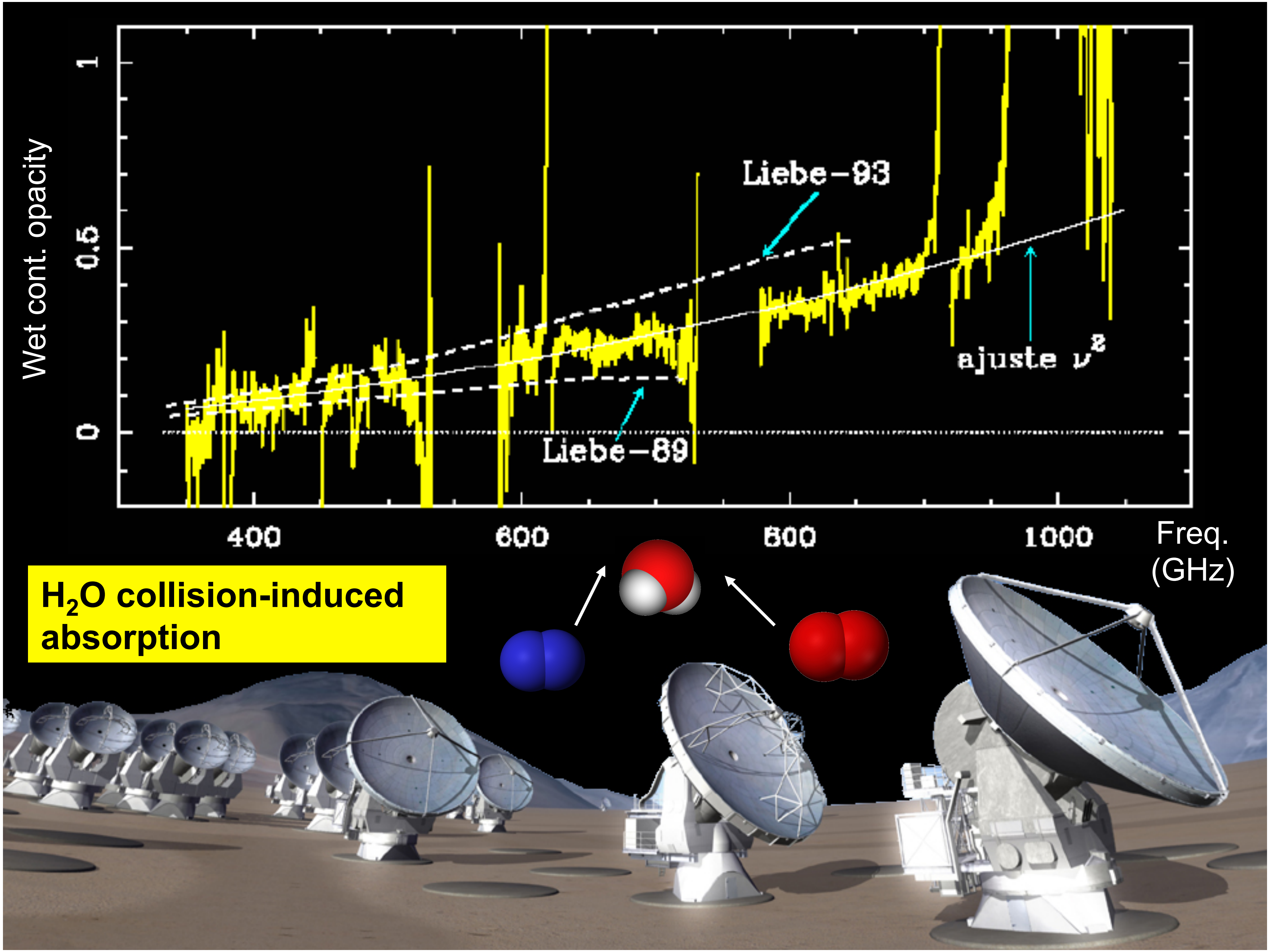


A wide set of these spectra was obtained at Mauna Kea, Chajnantor and the South Pole

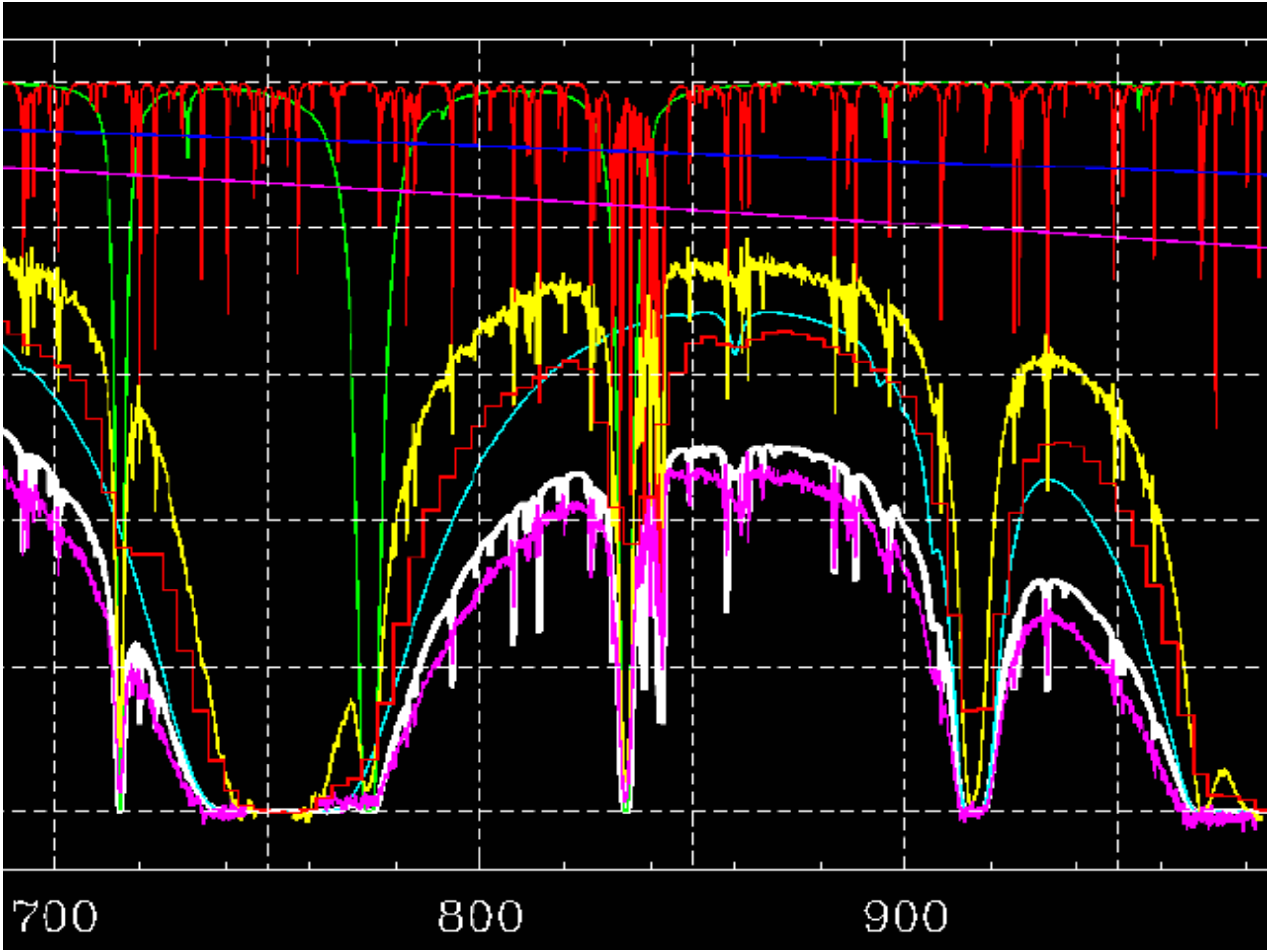


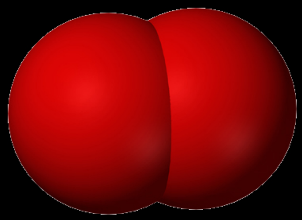


MPM93*1.29
B-86*1.29
best ν² fit
Dry cont. opacity
0
0.1
0.2
0.3
400
600
800
1000
Freq. (GHz)
τ N2-N2 MPM93 B-86
O2 and N2 collision induced absorption



Wet cont. opacity
1
0.5
0
Liebe−93
Liebe−89
ajuste ν^2
400
600
800
1000
Freq. (GHz)
H_2O collision-induced absorption

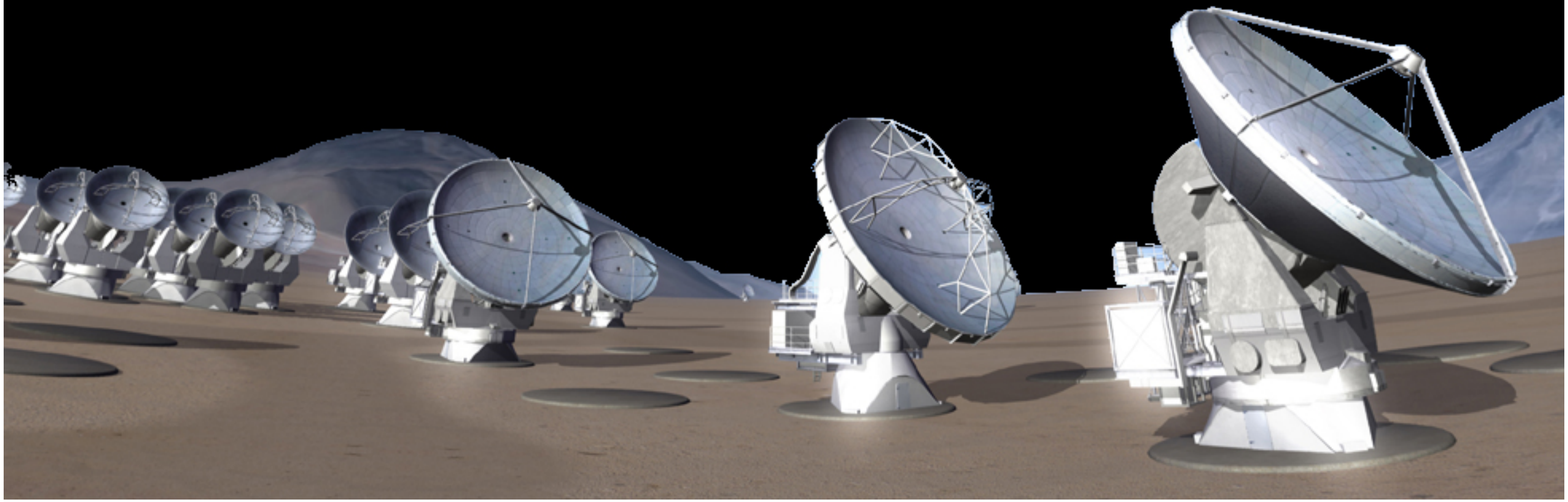

700
800
900

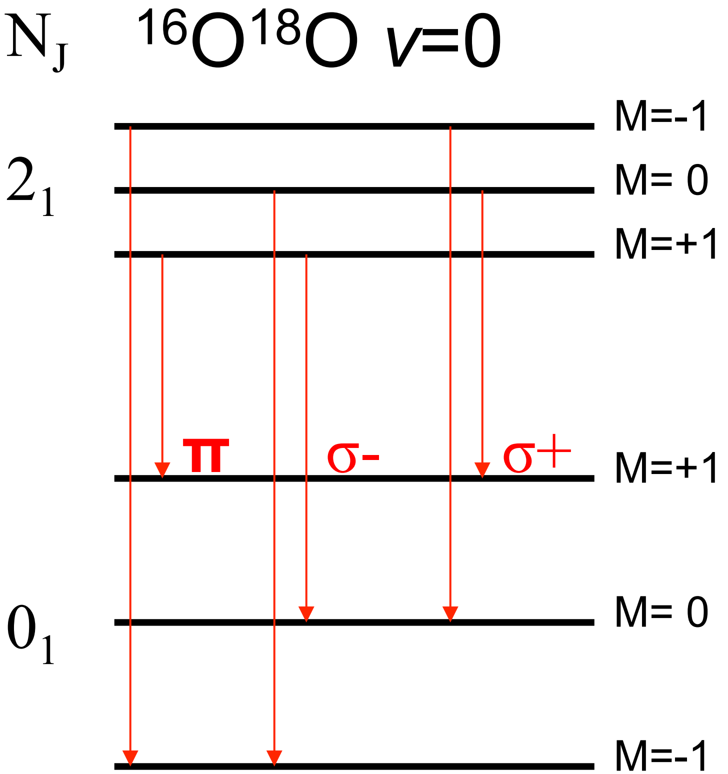


O_2

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…





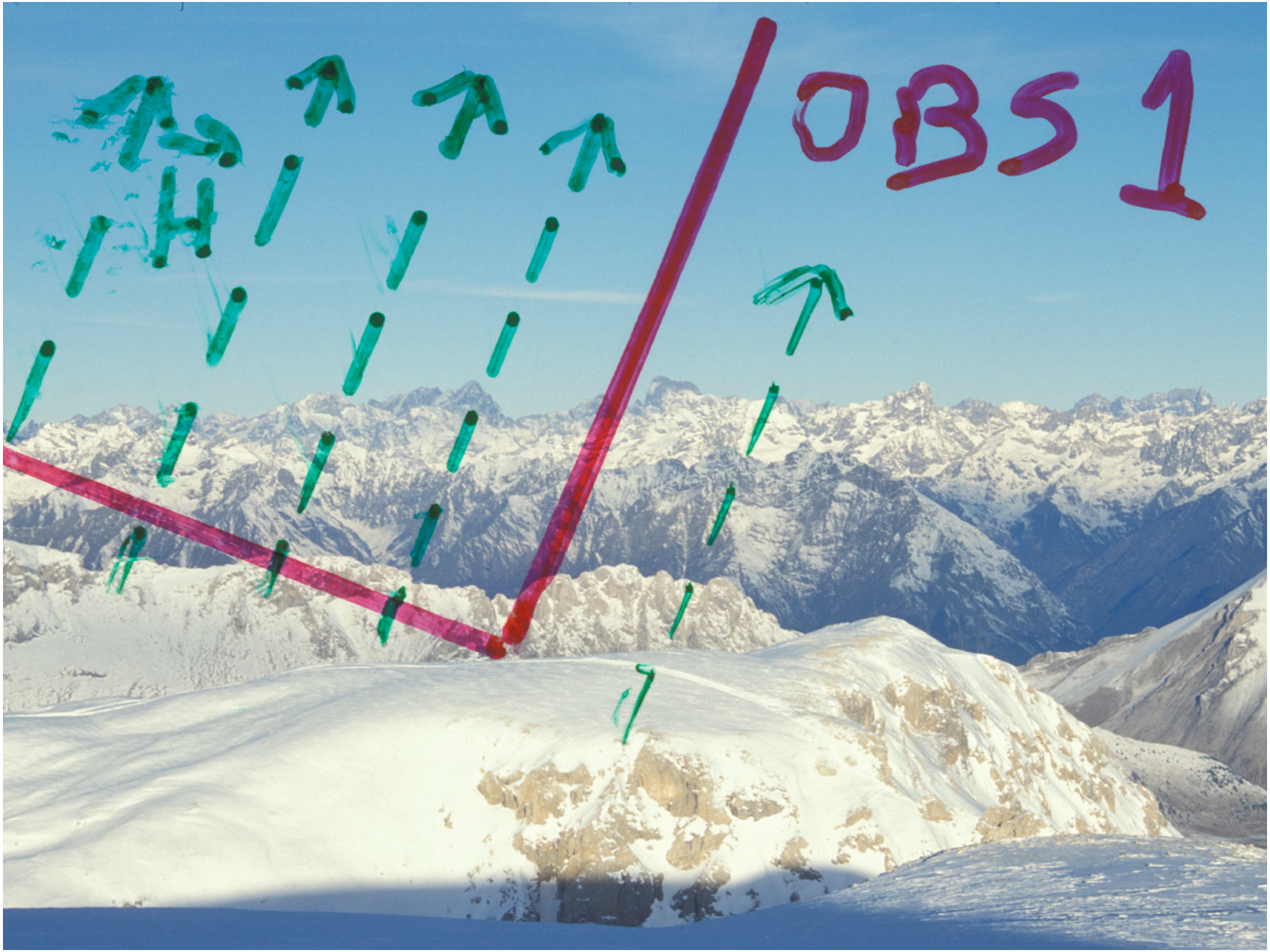
$$\Delta\nu(GHz) = 14.015 \cdot 10^{-6}\, H_{\mu T}(M_u + 2M_l)$$

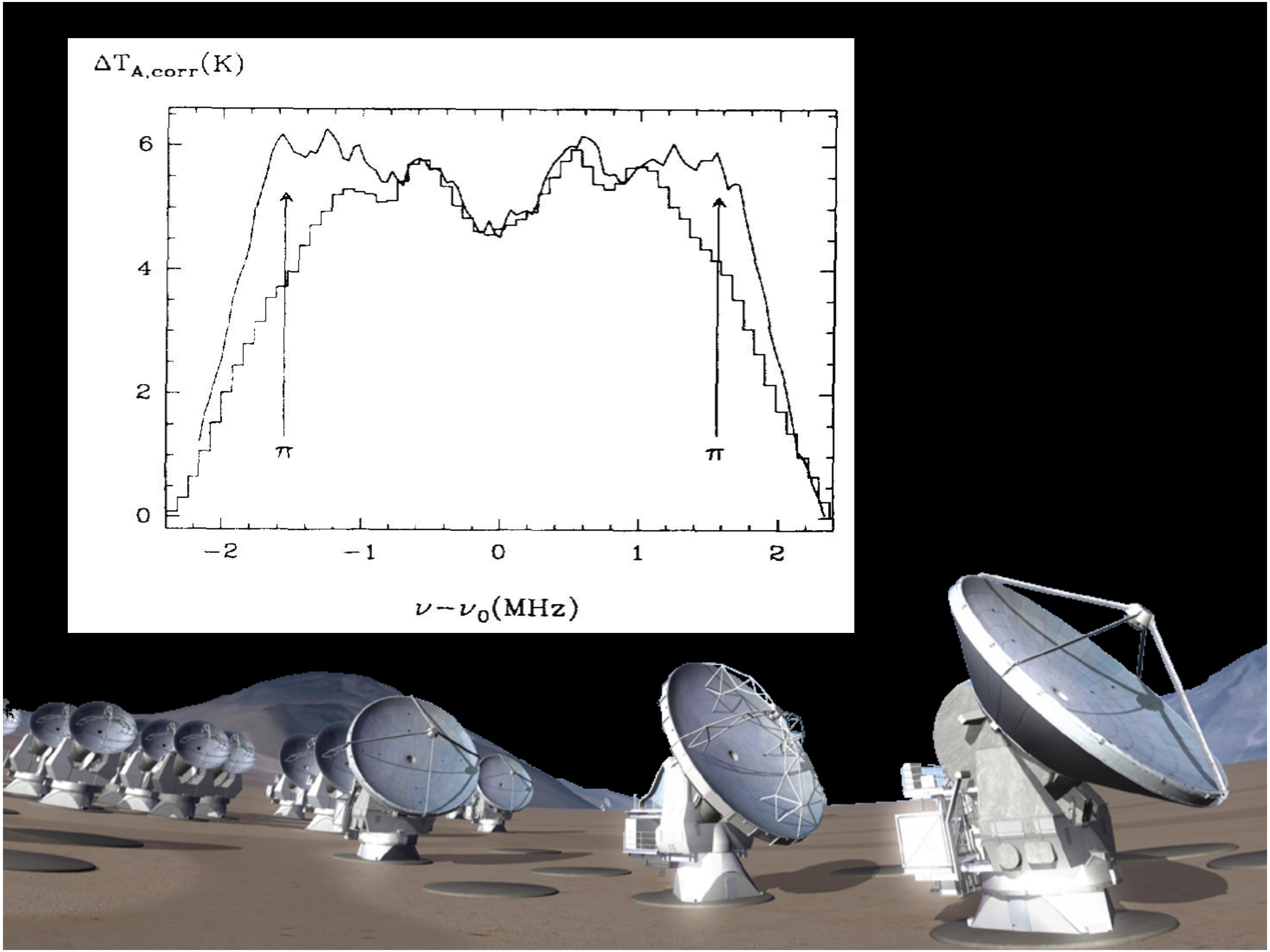
Transitions π (ΔM=0): Radiation linearly polarized in the direction of the geomagnetic field.

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.

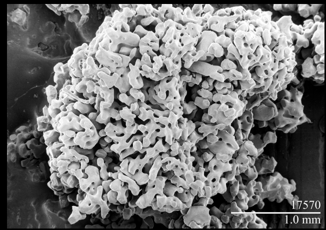

OBS 1
H



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

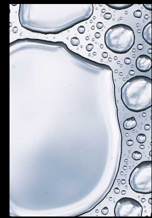
Hydrometeors contribution (absoprtion, scattering, phase…)

aerosols



Wet snow

snow

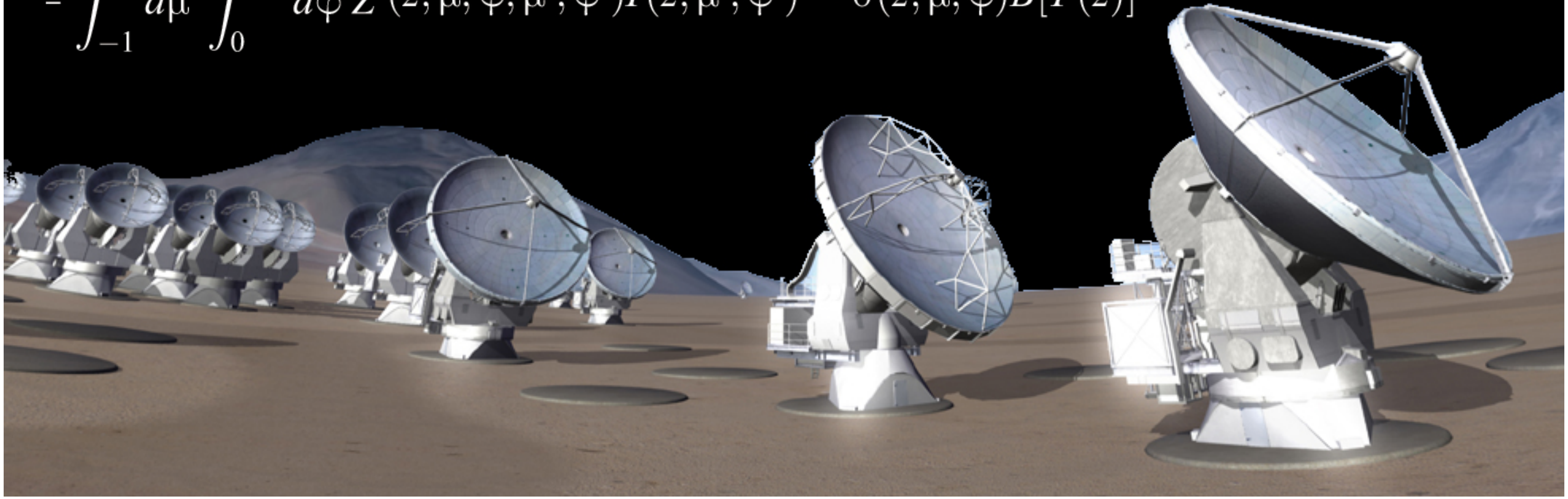


Liquid water

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:

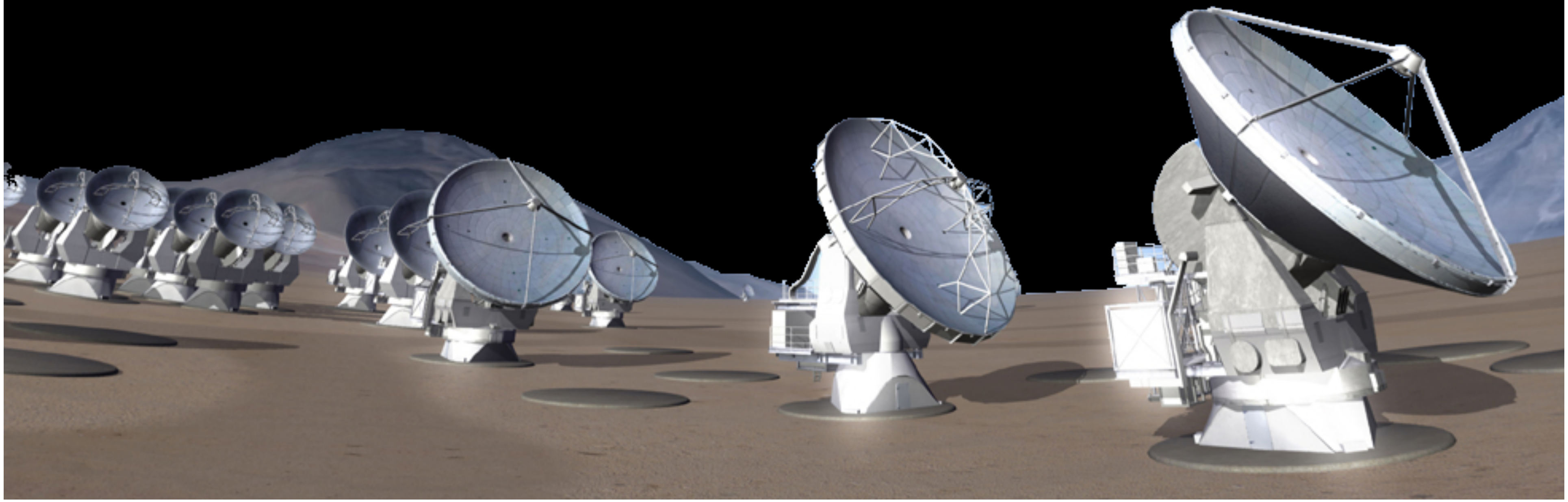
• Phase Matrix calculations from M. I Mishchenko (prolate and oblate spheroids with azimuthaly random distribution, or T-matrix method for spheres.

• Refraction indexes from literature.

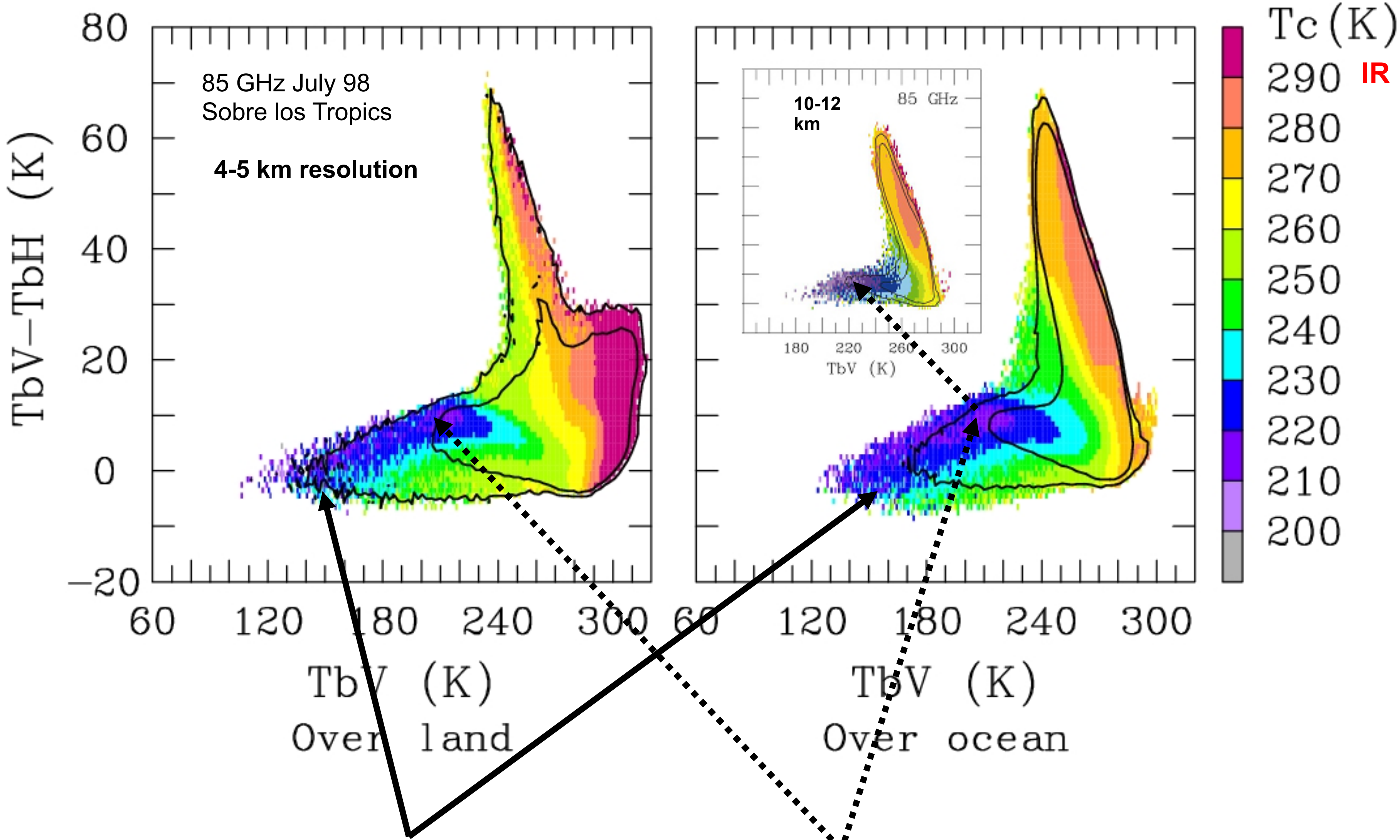
• RT using DDA method from Evans et al.

• Single scattering assumed within each layer.

• Lambertzian, Fresnel and other surface types.



¿Is it possible that T_BV-T_BH (K)<0?



$T_BV<T_BH$ **$T_BV>T_BH$**

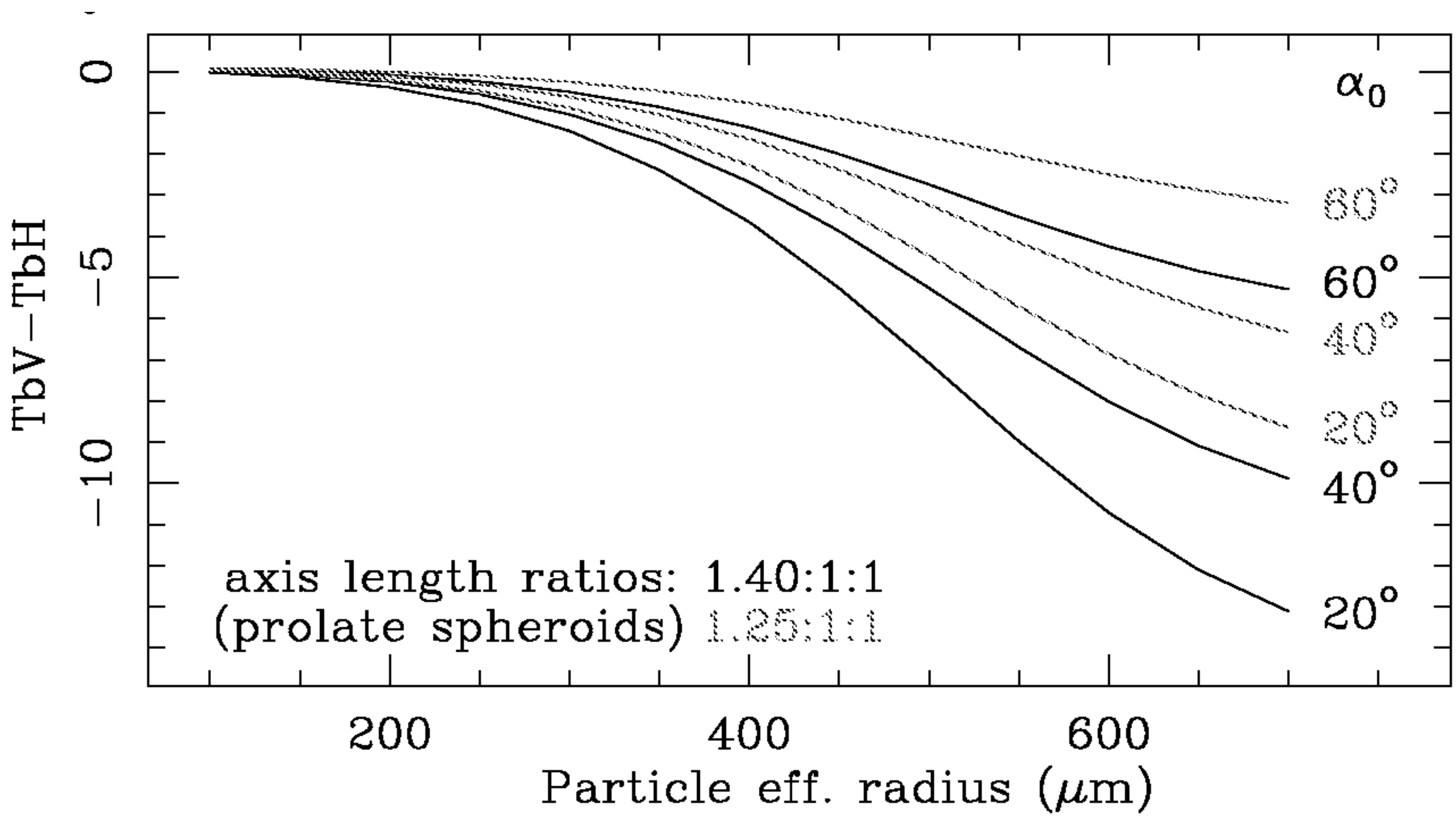
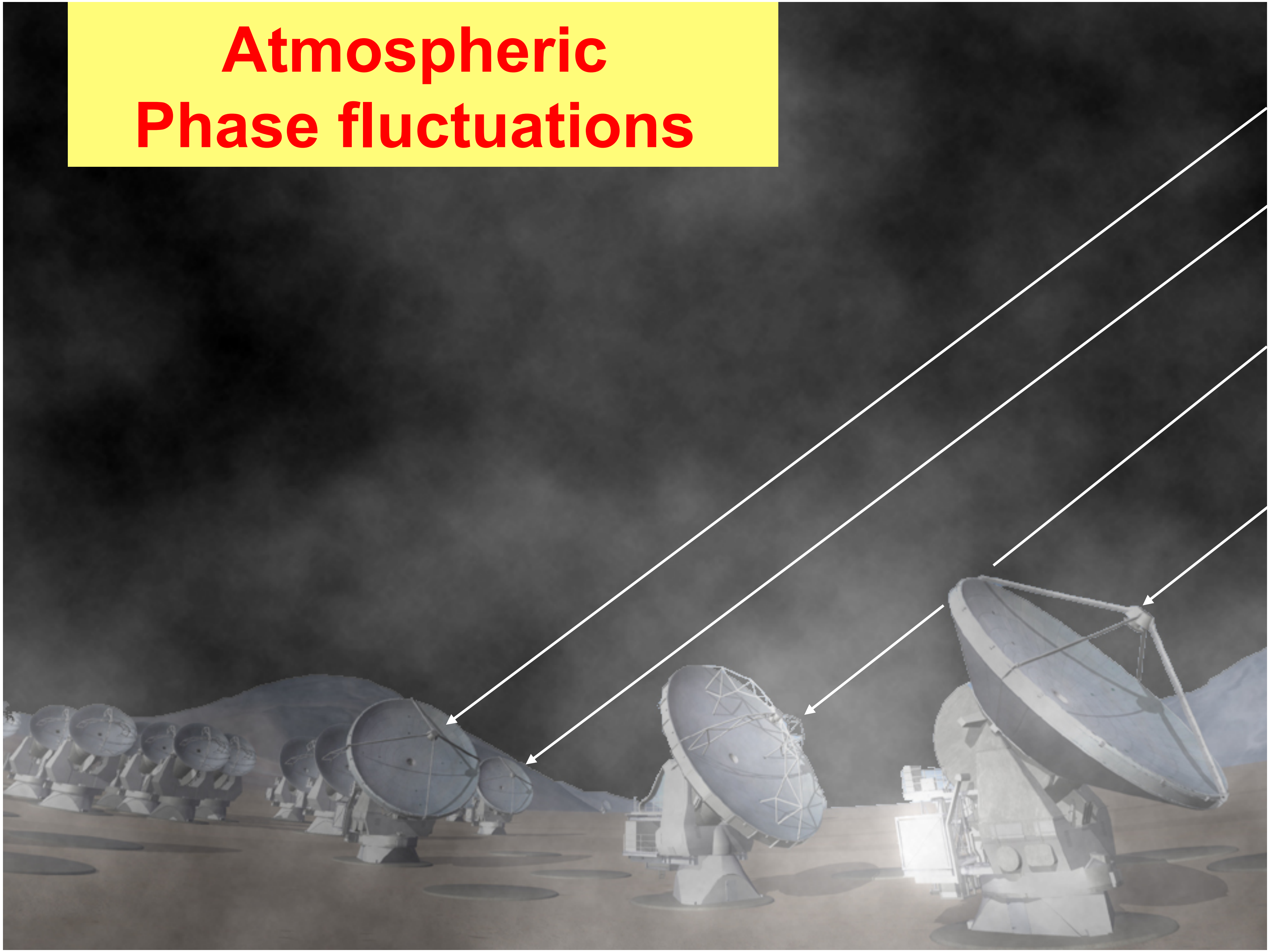


Figure 2. Sensitivity of the 85 GHz polarization difference to the orientation of the non-spherical ice particles as a function of particle size. The orientation of the particles is random within α_0 from the vertical axis.

Atmospheric Phase fluctuations



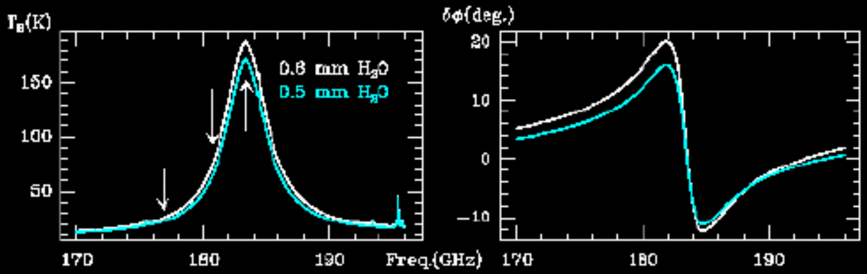
$$(\kappa_\nu)_{lu} = \frac{8\pi^3 N\nu}{3hcQ}\left(e^{-E_l/kT} - e^{-E_u/kT}\right) \cdot |< u \mid \mu \mid l >|^2 f(\nu, \nu_{l\to u})$$

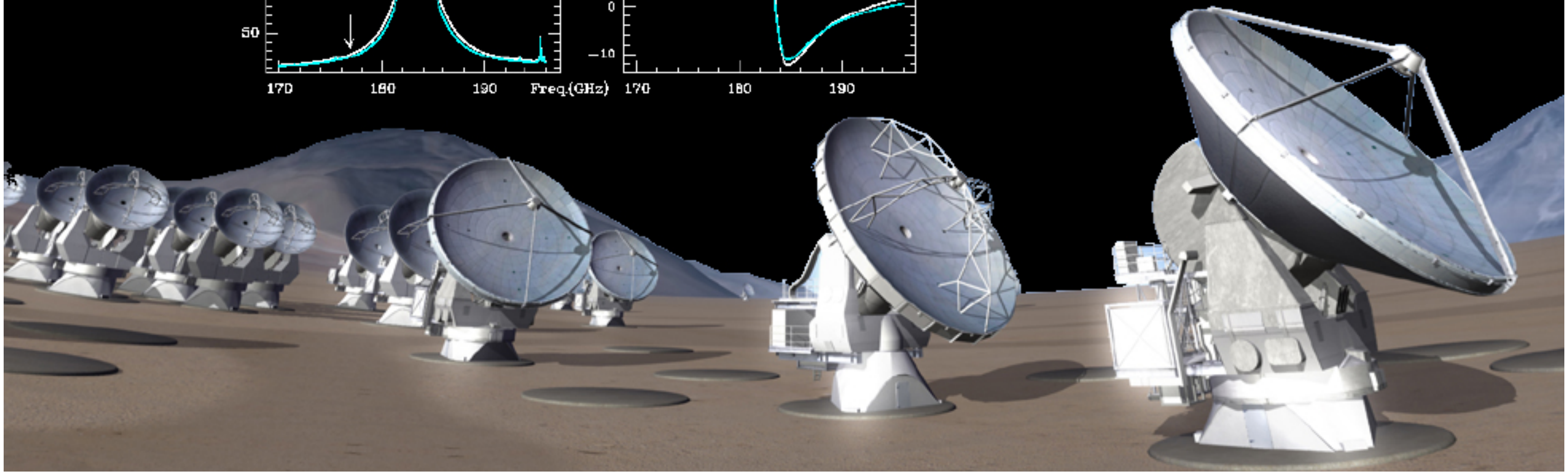
κ_ν Is a complex number

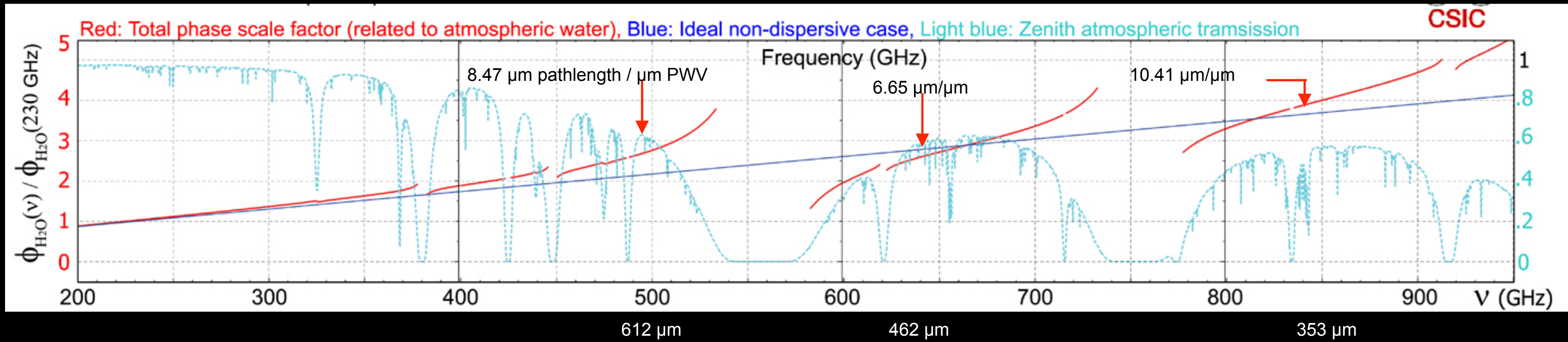
$$\mathcal{F}(\nu, \nu_{u\leftrightarrow l}) = \frac{\nu}{\pi\nu_{u\leftrightarrow l}}\left[\frac{1 - i\delta}{\nu_{u\leftrightarrow l} - \nu - i\Delta\nu} + \frac{1 + i\delta}{\nu_{u\leftrightarrow l} + \nu + \Delta\nu}\right] \qquad (1)$$

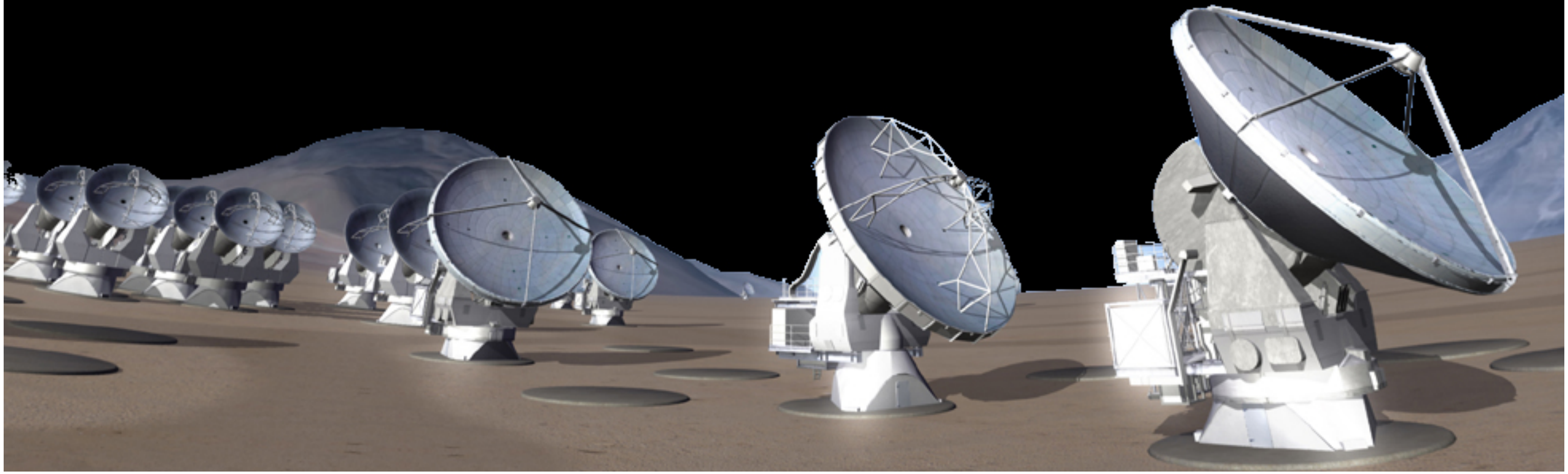
Imaginary part (absorption)

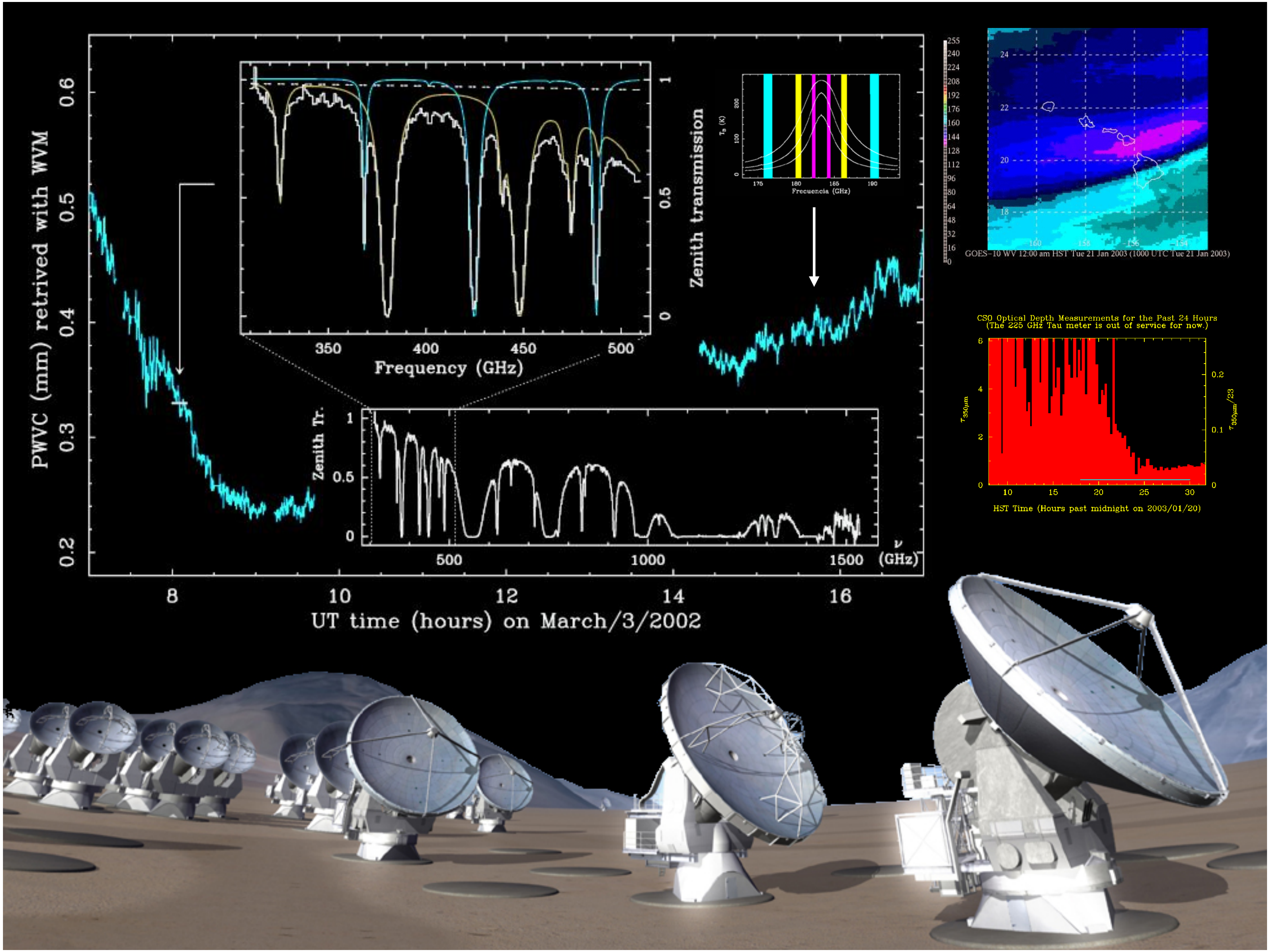
Real part (phase delay or pathlength variation)





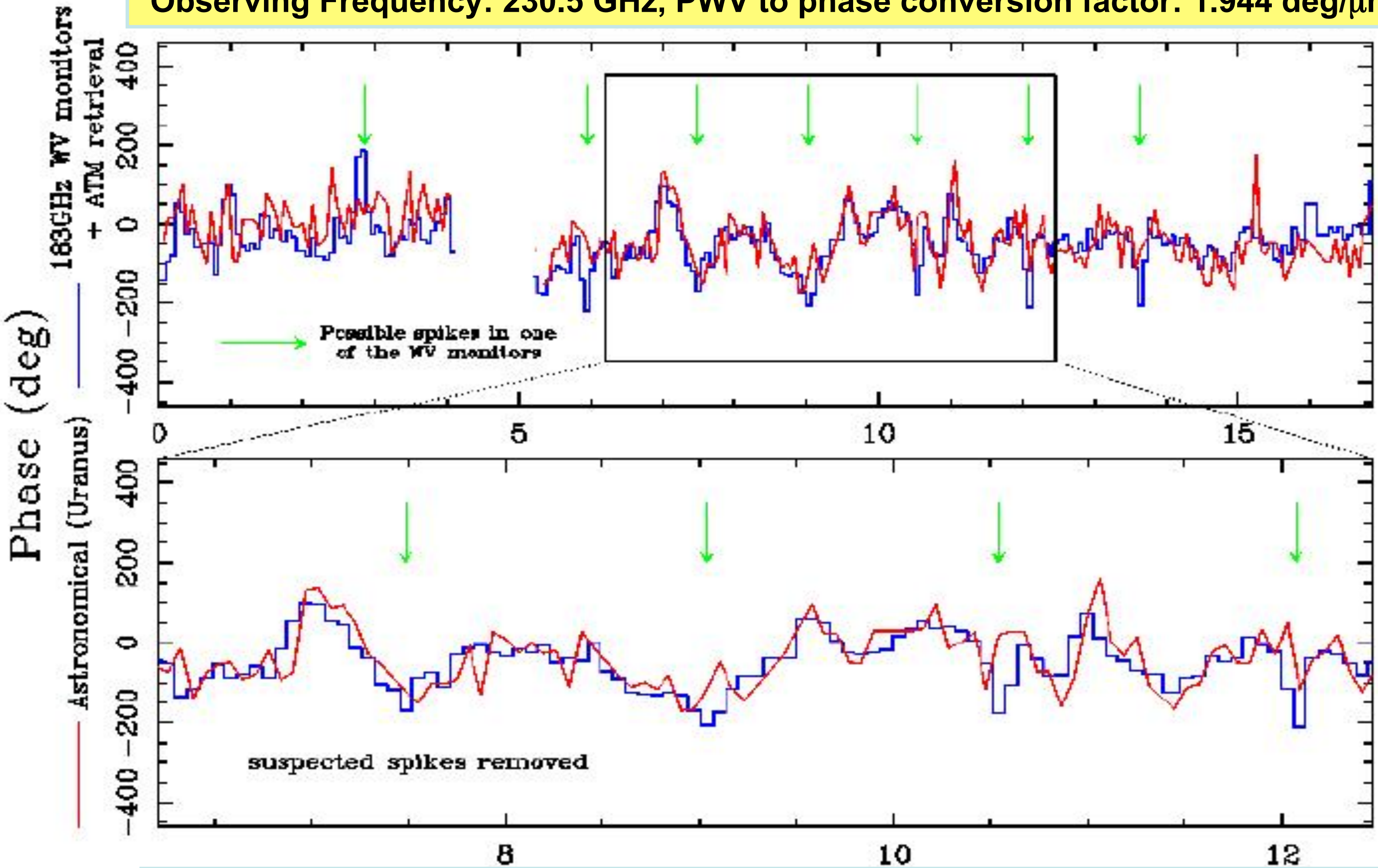

Red: Total phase scale factor (related to atmospheric water), Blue: Ideal non-dispersive case, Light blue: Zenith atmospheric tramsission
CSIC
Frequency (GHz)
8.47 µm pathlength / µm PWV
6.65 µm/µm
10.41 µm/µm
$\phi_{H_2O}(\nu) / \phi_{H_2O}(230\ GHz)$
ν (GHz)
200
300
400
500
600
700
800
900
612 µm
462 µm
353 µm



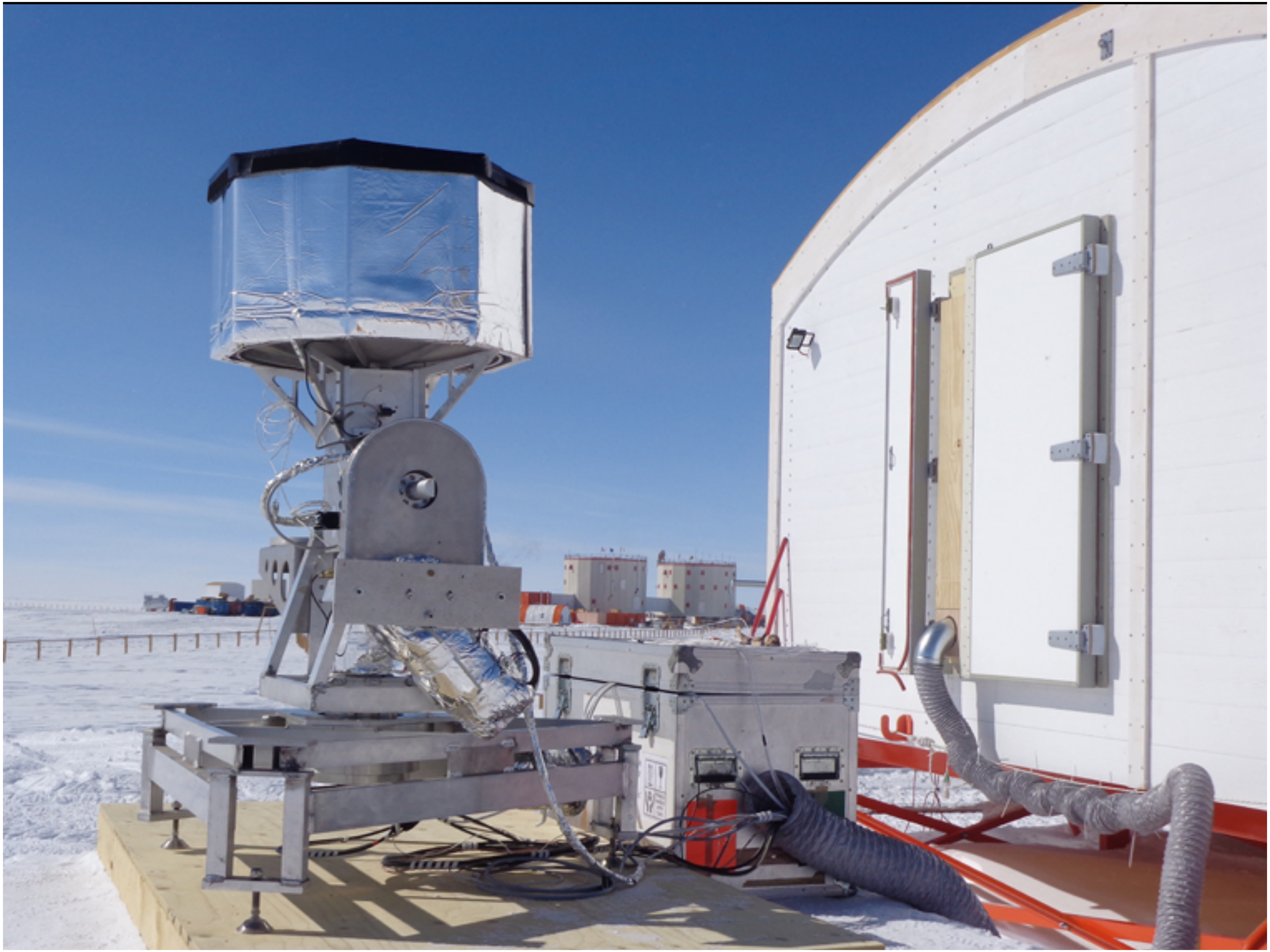

PWVC (mm) retrived with WVM
UT time (hours) on March/3/2002
Zenith transmission
Frequency (GHz)
Zenith Tr.
ν (GHz)
Frecuencia (GHz)
GOES-10 WV 12:00 am HST Tue 21 Jan 2003 (1000 UTC Tue 21 Jan 2003)
CSO Optical Depth Measurements for the Past 24 Hours
(The 225 GHz Tau meter is out of service for now.)
HST Time (Hours past midnight on 2003/01/20)

Phase fluctuations: Correction using 183 GHz water vapor radiometers

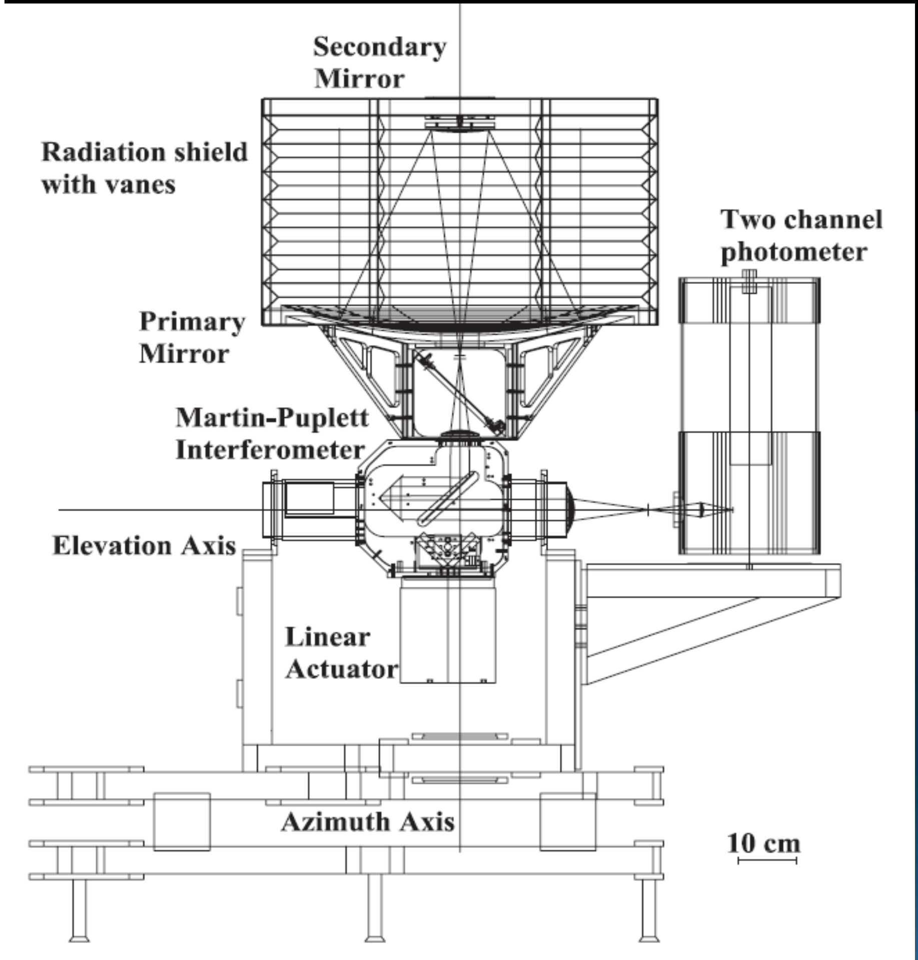
Observing Frequency: 230.5 GHz, PWV to phase conversion factor: 1.944 deg/μm

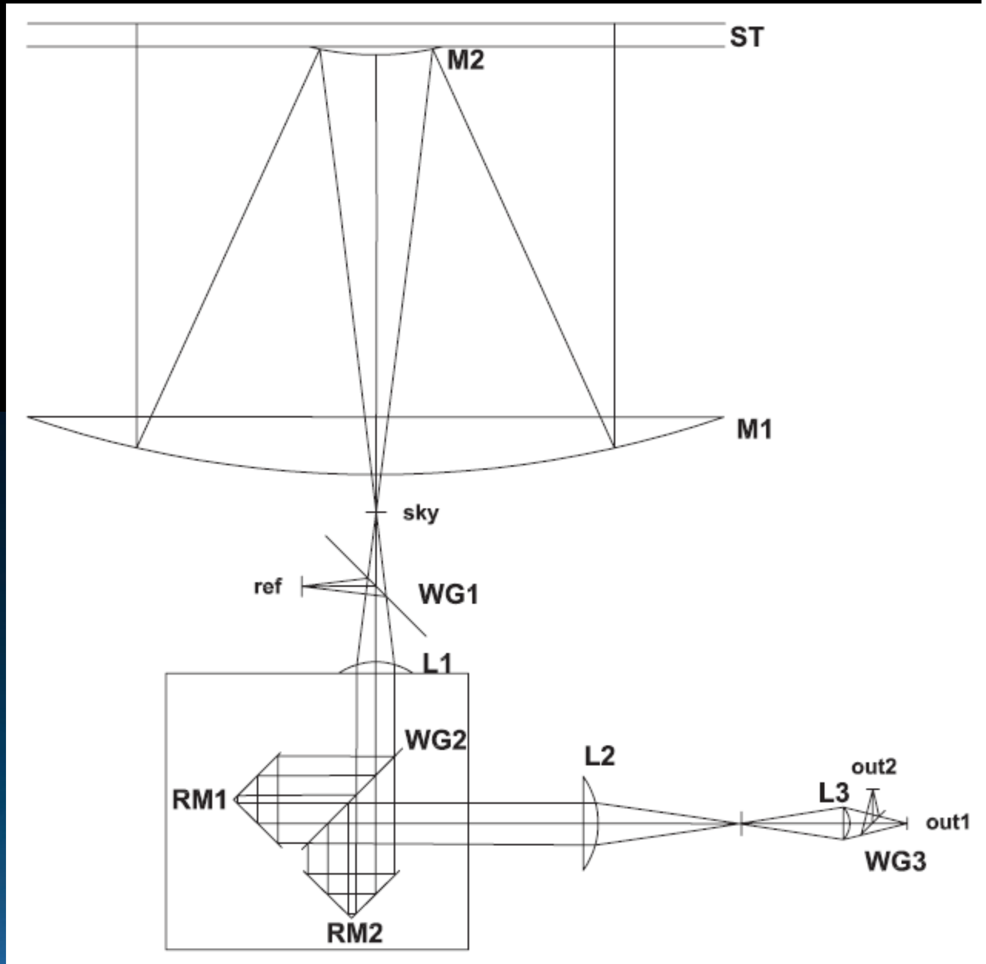


Time since the beginning of the observation (min) on Nov. 25, 2001



Latest ATM work: CASPER experiment at **Concordia Station**, Antarctica (2015)





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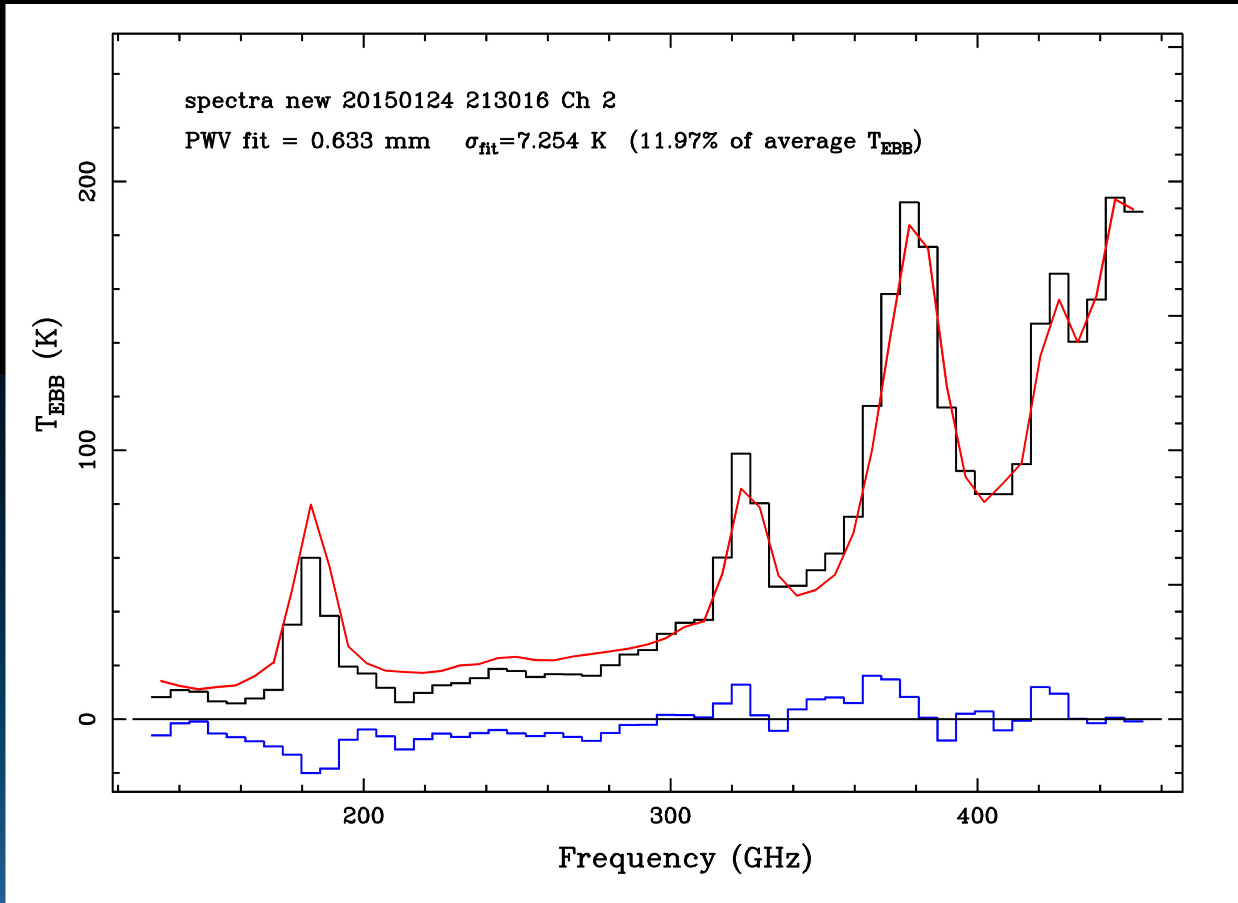

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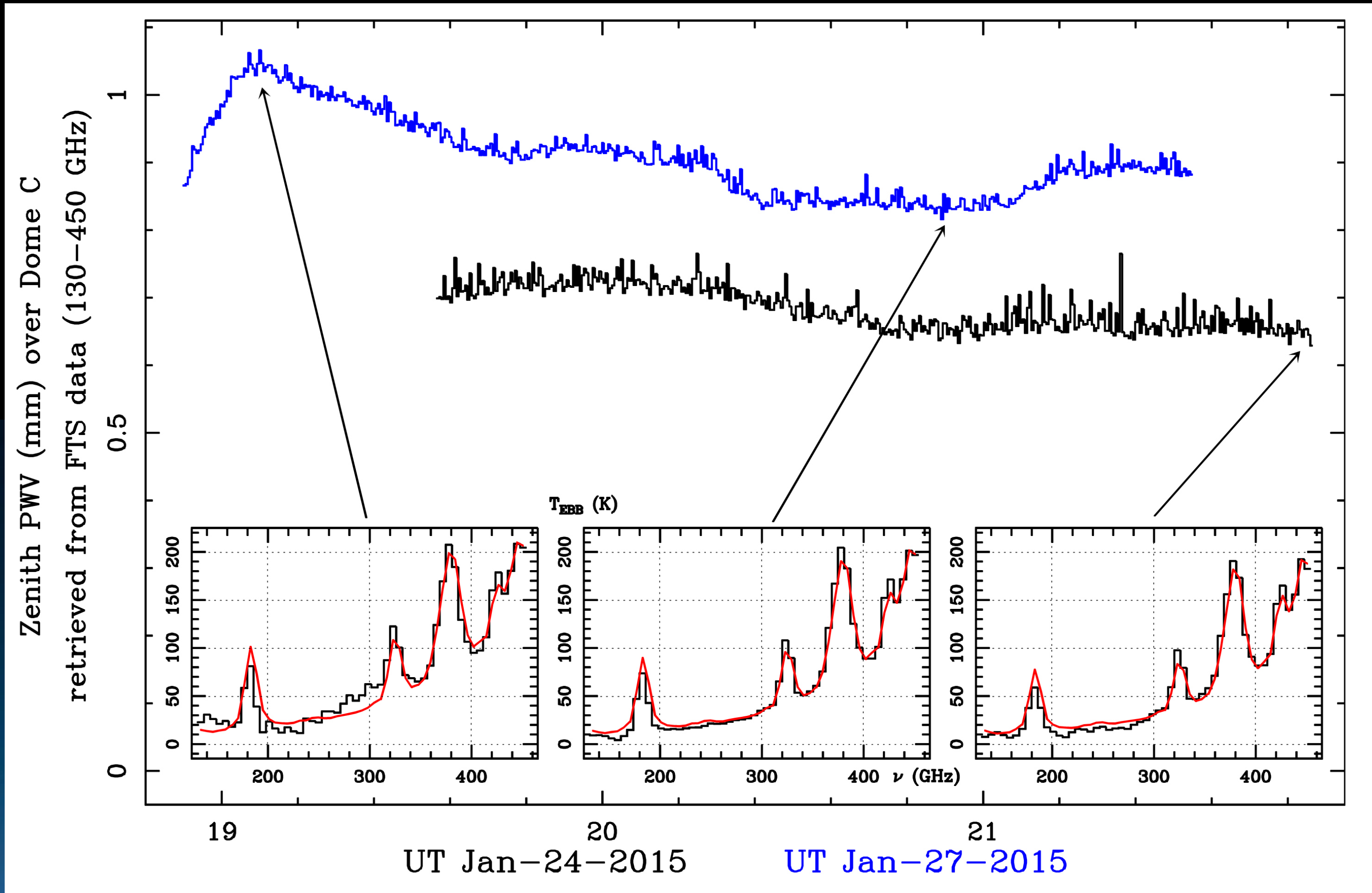
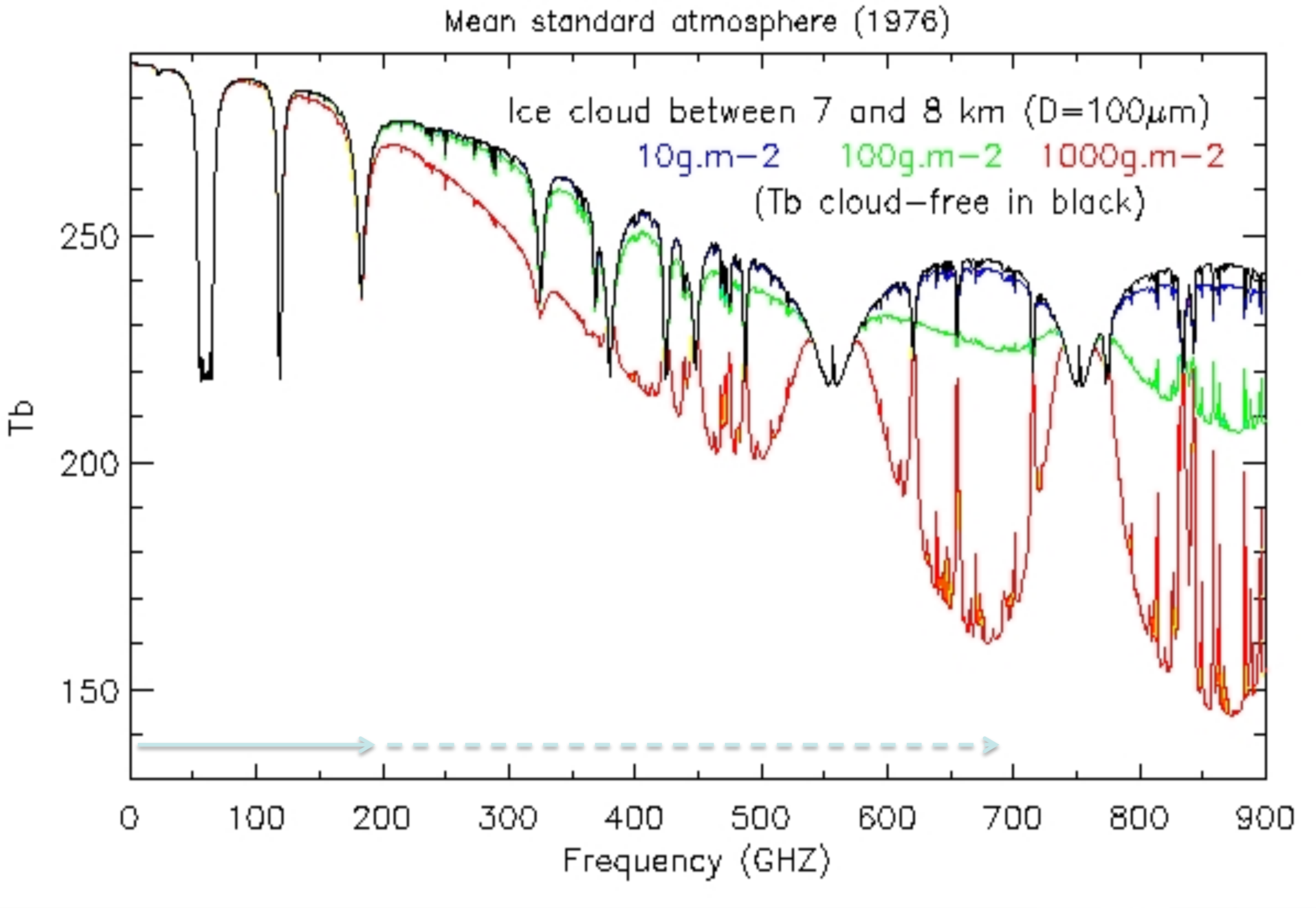


Next: We are going to make cross-comparisons with WVR and F-IR experiments on site.


Mean standard atmosphere (1976)
Ice cloud between 7 and 8 km (D=100μm)
10g.m−2
100g.m−2
1000g.m−2
(Tb cloud−free in black)
Tb
250
200
150
0
100
200
300
400
500
600
700
800
900
Frequency (GHZ)