Characterizing the properties of the atmospheric emission in the 10-40 GHz range with QUIJOTE data

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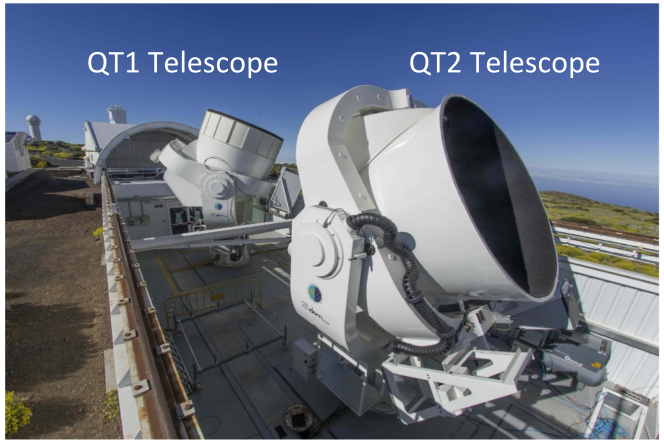
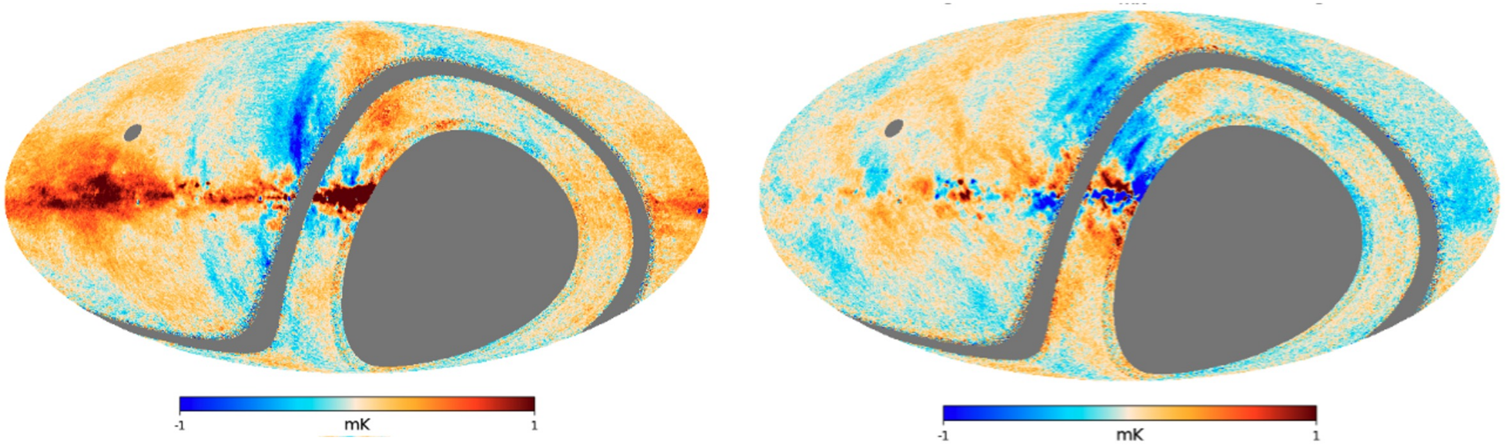
QUIJOTE (Q-U-I JOint TEnerife) CMB Experiment

QUJOTE: Collaboration between Spain and the UK composed of 2 telescopes

QUIJOTE 2 scientific goals:

1. Detect B-modes polarization if they have an amplitude greater/equal to r= 0.03 and put limits on inflation
2. Provide information of the polarization of the astrophysical CMB foreground (synchrotron, anomalous microwave emissions from our Galaxy) at frequencies 10-40 GHz

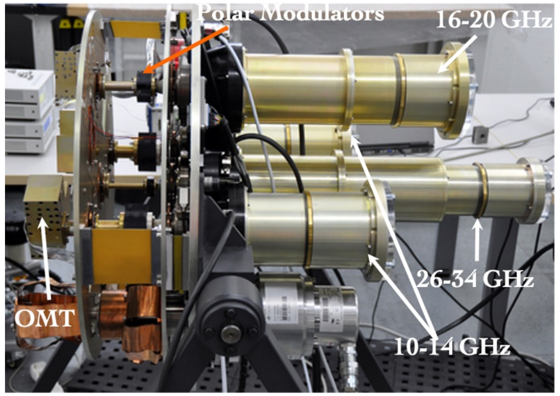




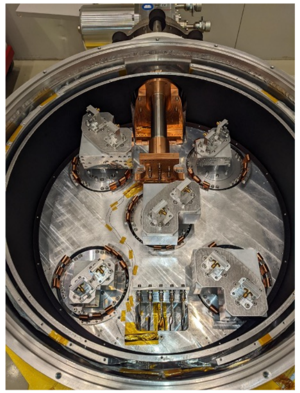
polarization *Q* component - polarization *U* component.
Rubiño-Martín+2023

QUIJOTE's intruments

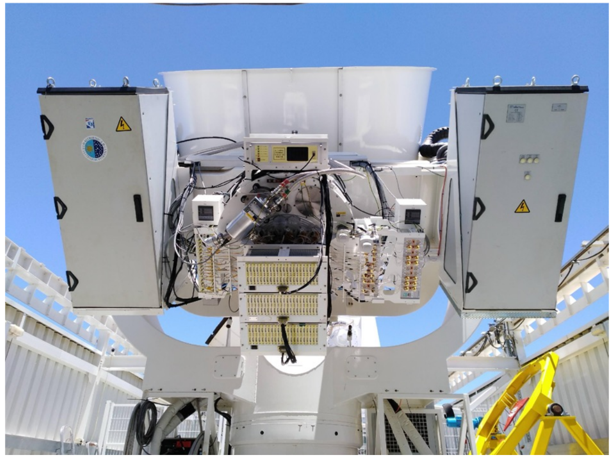
- Multi-Frequency Instrument (MFI) 4 horns:
  - Operated between 2012 and 2018
  - 2 measuring at 17 GHz and 19 GHz
  - 2 measuring at 11 GHz and 13 GHz
  - MFI wide survey: 1223 observations (about 10.000 hours)
- Second Multi-Frequency Instrument (MFI2) 5 horns:
  - Started measuring in the beginning of 2024, 2–3 times more sensitive than the former MFI
  - 3 horns measuring at 10–15 GHz
  - 2 at 15–20 GHz
- Thirty Forty-GHz Instrument (TFGI) 31 horns in the range of 30-40GHz
  - Operates since 2018. Data analysed here uses 7 detectors.



MFI



MFI2



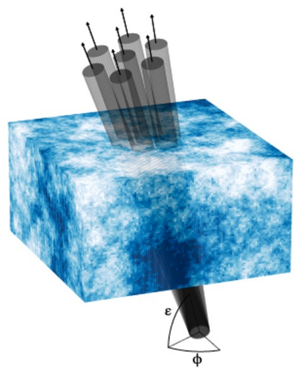
TFGI

Atmospheric contamination

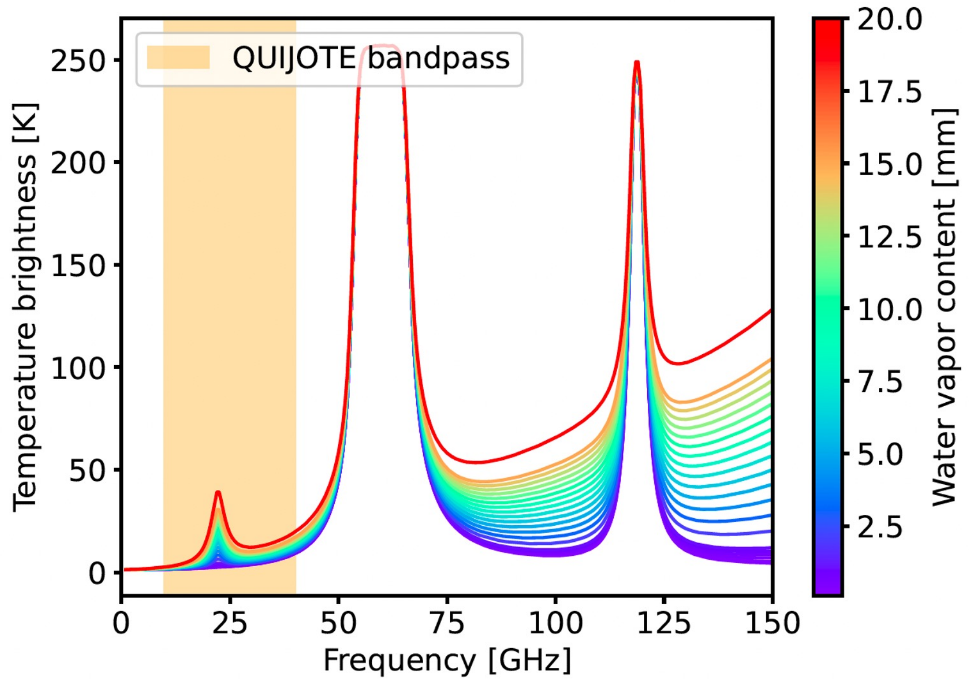
Atmospheric emission: dominant source of noise for CMB ground-based telescopes

- Molecular oxygen at 60 and 120 GHz
- Water lines at 22 and 183 GHz ⇒ the most problematic: has highly variable concentration ⇒ Atmospheric signal varies in time and space

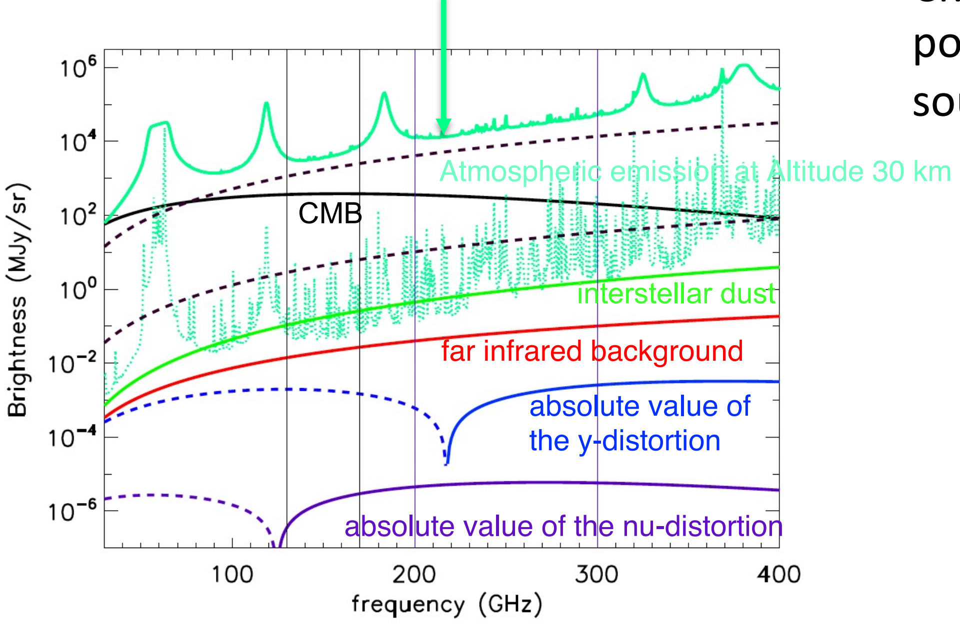
⇒ If these fluctuations can be better modelled and removed ➔ measure larger CMB angular scales from the ground



Morris+2021



Atmospheric contamination



Masi+2021

CMB telescopes measure the **antenna temperature** ⇒ thermal radiation power received by the telescope from the sky, including the CMB and other sources (atmosphere, free-free, synchrotron, AME, …).

Antenna temperature integrating over all the atmosphere:

$$T_A = \frac{1}{\lambda^2} \int_V A_{\mathrm{inst}}(\hat{\boldsymbol{r}}_s, \boldsymbol{r}) \alpha(\boldsymbol{r}) T_{\mathrm{amb}}(\boldsymbol{r}) \frac{\mathrm{d}V}{r^2}$$

Atmospheric absorption coefficient (proportional to water vapor density)

Ambient temperature that is influenced by the atmosphere

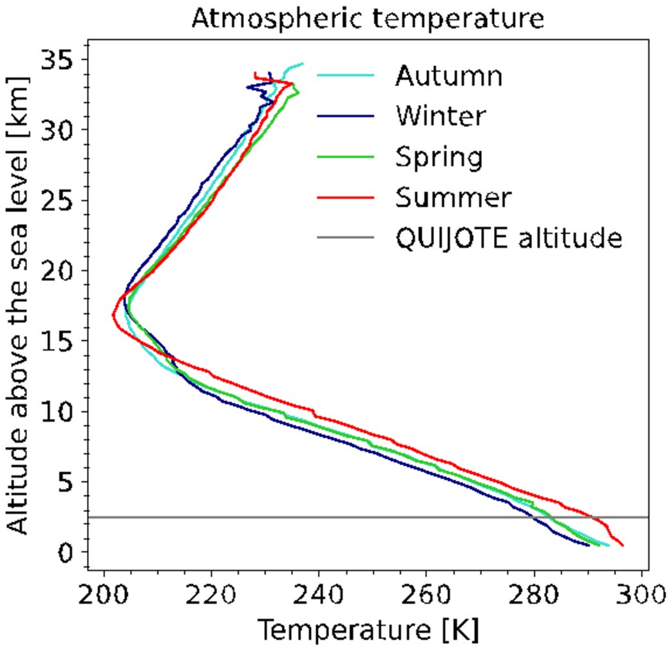
- λ: observed wavelength
- A_{inst}: effective area of the instrument that measures the atmosphere
- α: atmospheric absorption coefficient
- T_{amb}: ambiant temperature
- r_s: pointing direction from a small elemeth through the atmosphere at r

Condition at Teide Observatory

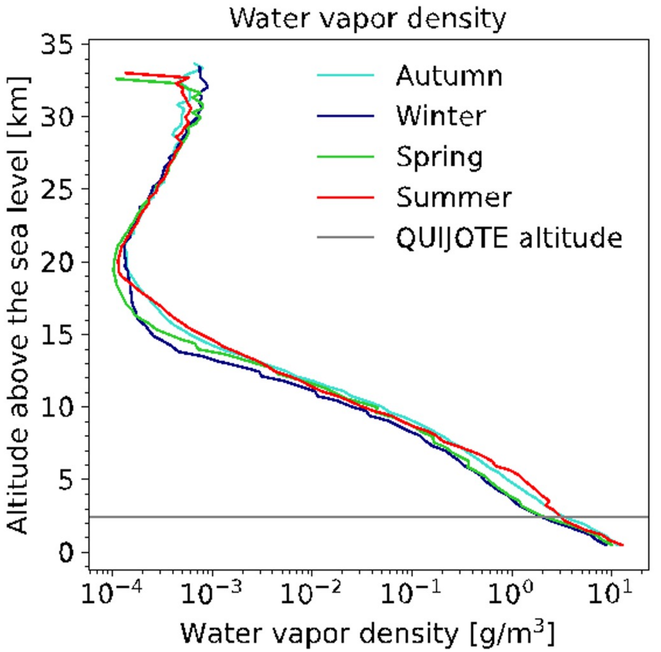
radio sounding by a balloon launched from Tenerife

6 years of data to obtain the **median profiles of the atmospheric parameters** during MFI wide survey (2012-2018, Rubiño-Martin+2023):

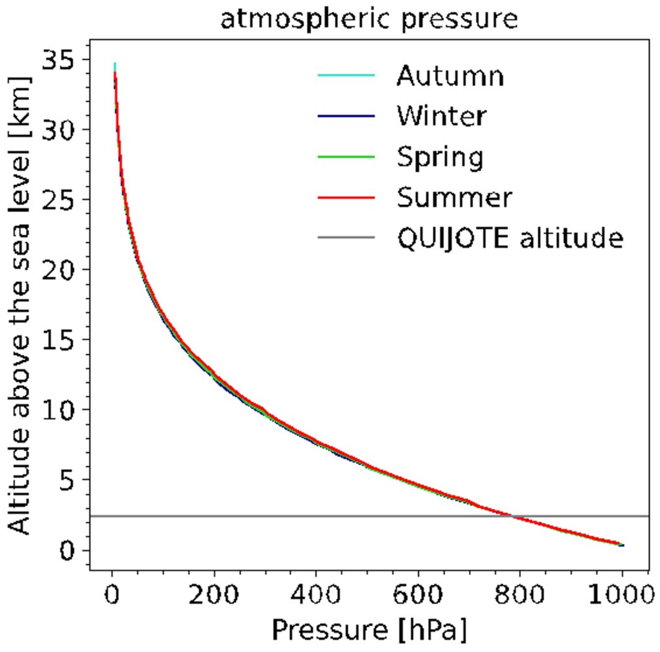
Temperature shows a linear decrease until the tropopause is reached: inversion layer



Water vapor density follows an exponential decay below tropopause



Atmospheric pressure follows an exponential decay



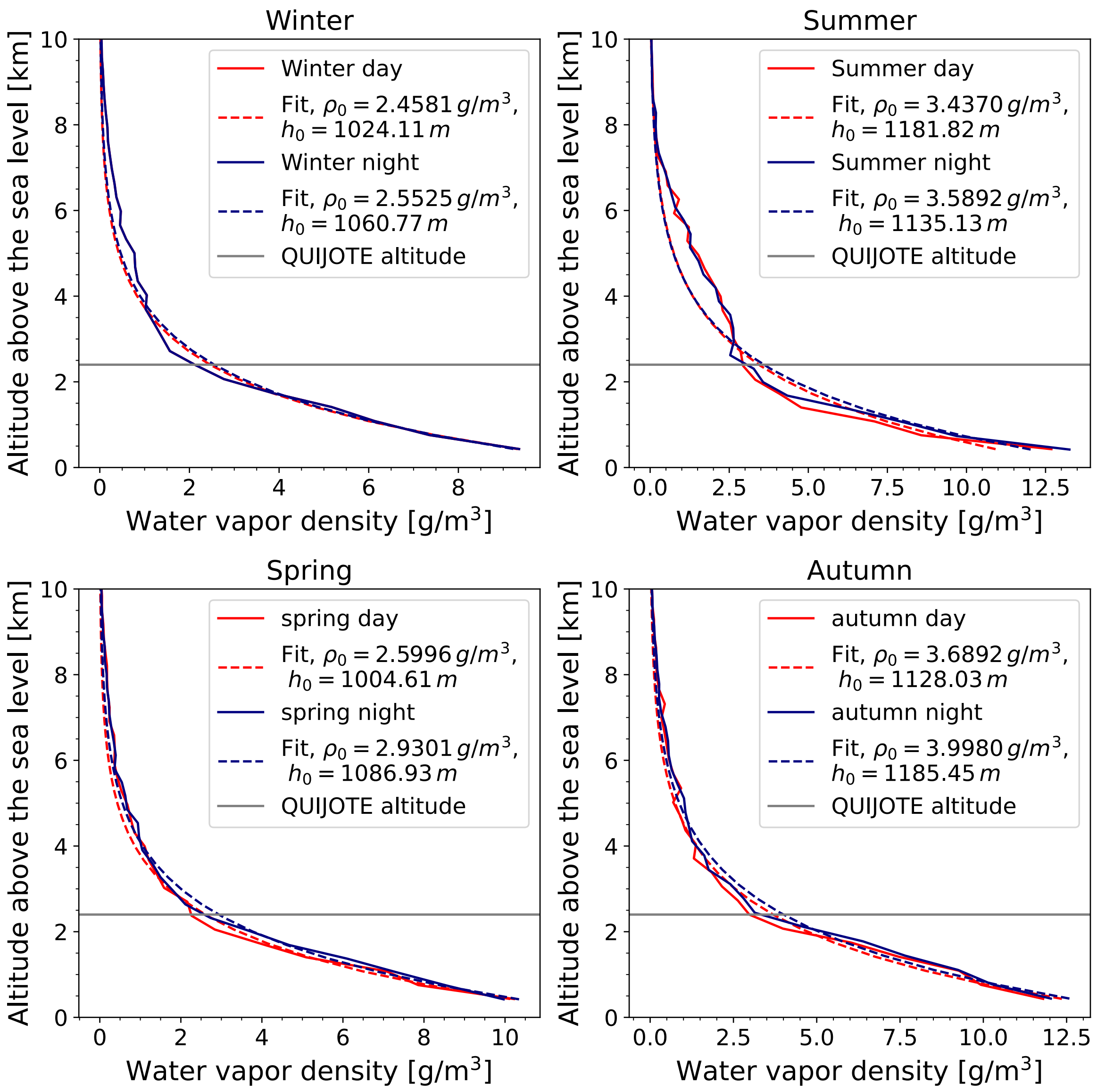
Condition at Teide Observatory

Focus on the water vapor density profiles:

$$\rho(h) = \rho_0 \cdot \exp\left(-\log(2) \cdot \frac{h - 2400\mathrm{m}}{h_0}\right)$$

- h_0: half height i.e. height at which the density falls to half of its initial value
- ρ_0: water vapor density at QUIJOTE altitude
- 2400m: QUIJOTE altitude

➔ Typical h_0 about 1km as for ACT (Morris+2022)
➔ Typical ρ_0 between 2.5g/m^3 and 3.5 g/m^3
➔ The first 2 km of atmosphere account for most of the signal contamination



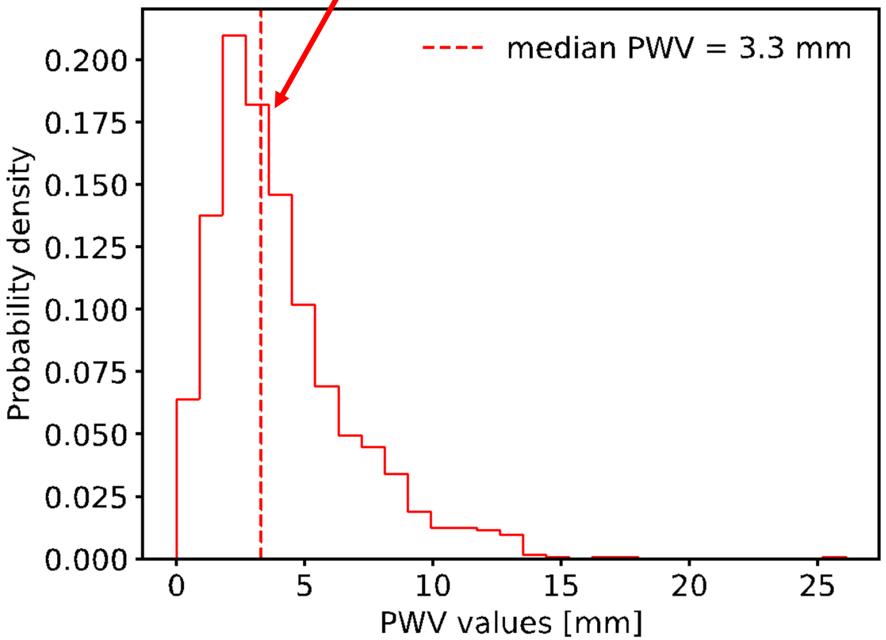
Condition at Teide Observatory

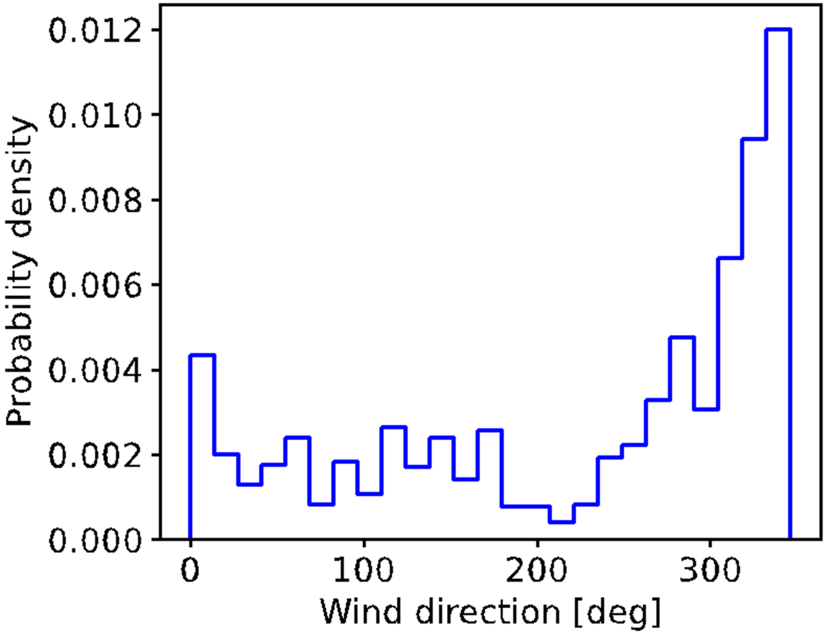
Precipitable Water Vapor:

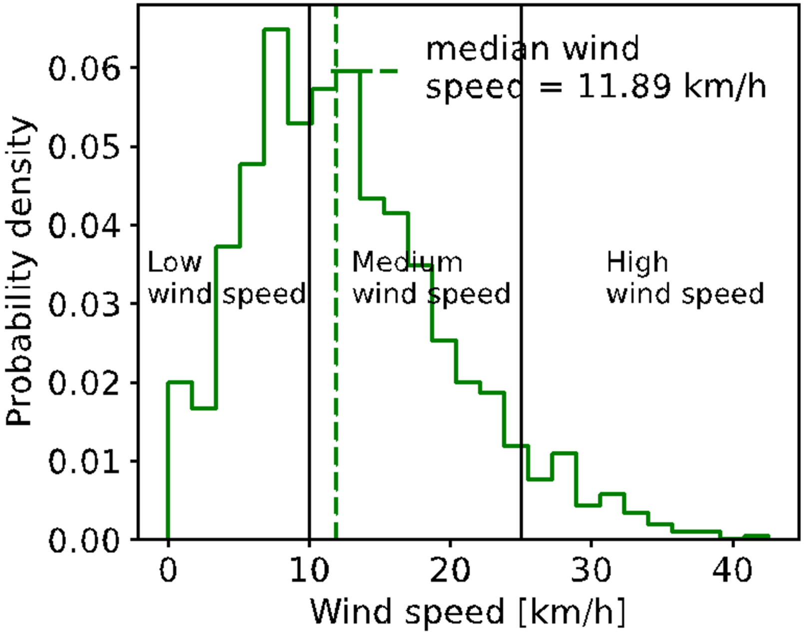
$$PWV = \int_{z_0}^{z_{max}} \rho_{H2O}(z)\mathrm{d}z$$

⇒ Median PWV during MFI wide survey: 3.3mm

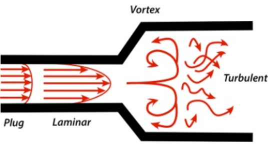
https://izana.aemet.es/







Atmospheric turbulence



Fluid dynamics reminder

- Laminar flow: slow, organized, parallel to vessel walls
- Turbulent flow: disorganized/chaotic, random, with high velocities, different length scales of eddy motion

Atmospheric Turbulence

composed of turbulent eddies of different sizes that transfer their kinetic energy to smaller eddies: energy cascade

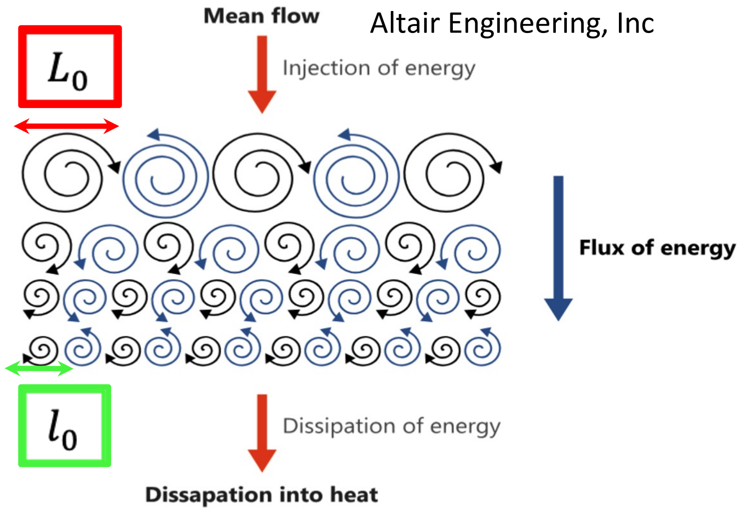
Kolmogorov Theory

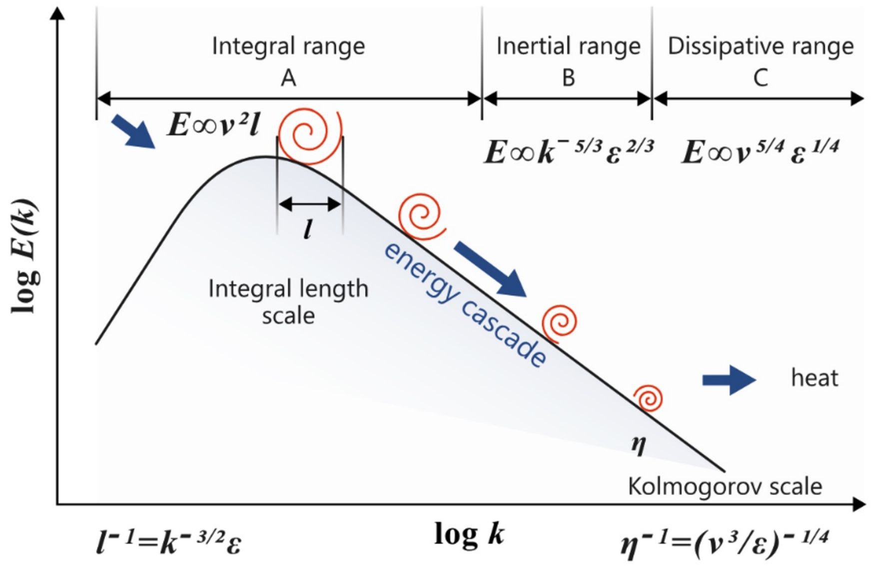
- The atmospheric power spectrum describes energy distribution across turbulence scales.
- Follows a power law in the sub-inertial regime

$$\Phi(\kappa) \propto \kappa^{-8/3}, \quad 1/L_0 < \kappa < 1/l_0$$

- κ: wavenumber of the turbulence
- L_0: the size of the outer scale i.e. the size of the largest turbulence eddies
- l_0: the inner scale i.e. the size of the smallest turbulence eddies

Altair Engineering, Inc





Power spectral density from MFI2 datasets

Goal: verify Kolmogorov theory with QUIJOTE data at 17 GHz, 19 GHz, 30 GHz and 40 GHz

MFI2 data: cross power spectral density of the atmospheric signal of horn 2 and horn 4 at 17 GHz and 19 GHz

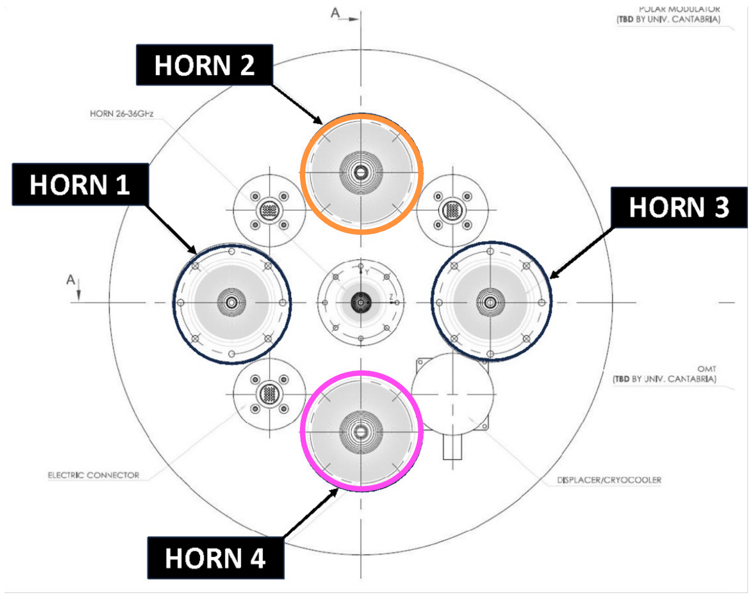
$$P_{h_2h_4} = \frac{\mathcal{F}_{h_2} \cdot (\overline{\mathcal{F}_{h_4}})}{f_s^2}$$

- F_{h_2}: Fourier transform of the time domain signal
- f_s: sampling fequency

Fitted a flat spectrum below some frequency to the data

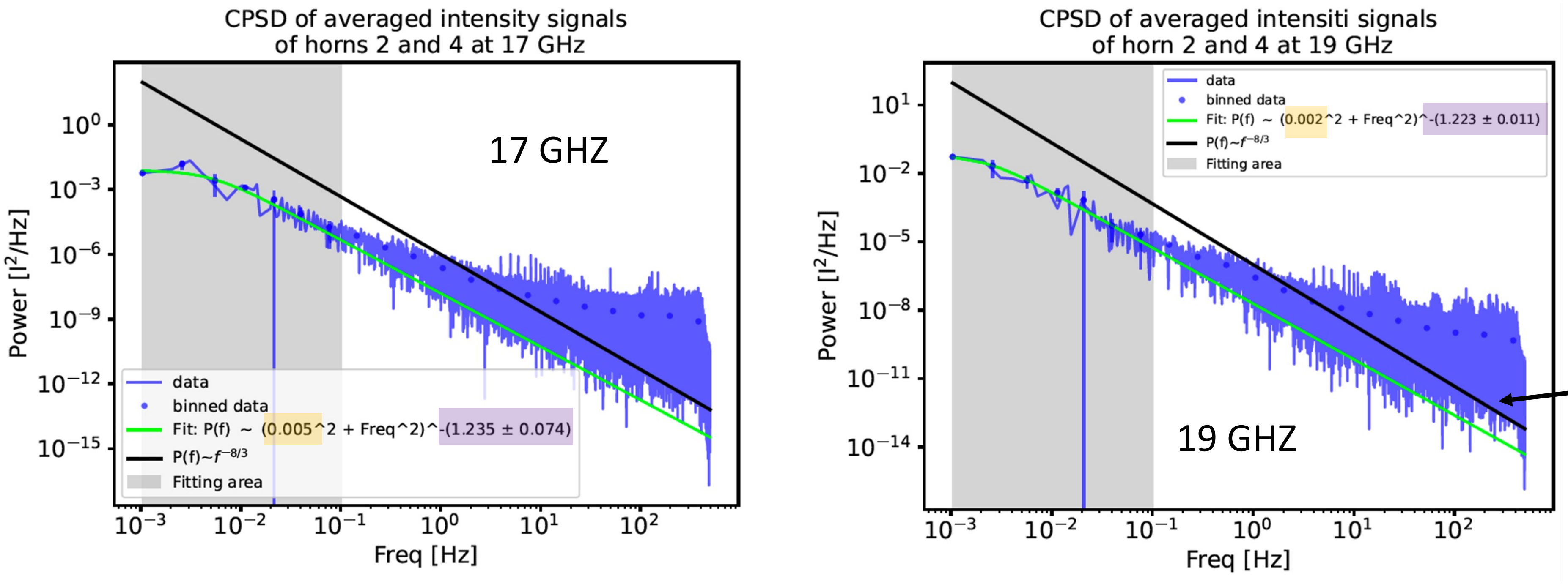
$$\Phi(\boldsymbol{\kappa}) = \Phi(\kappa) = \alpha_0\left(\kappa_0^2 + \kappa^2\right)^{-(\nu+\frac{3}{2})}$$

- α_0: power of the flattening end of the spectrum
- $\kappa_0 = 1/L_0$: frequency of the outer scale regime
- $\nu = -0.17$ for Kolmogorov turbulences in 2D



Hoyland+2012

Power spectral density from MFI2 datasets



$$\Phi(\kappa) \propto \kappa^{-8/3}$$

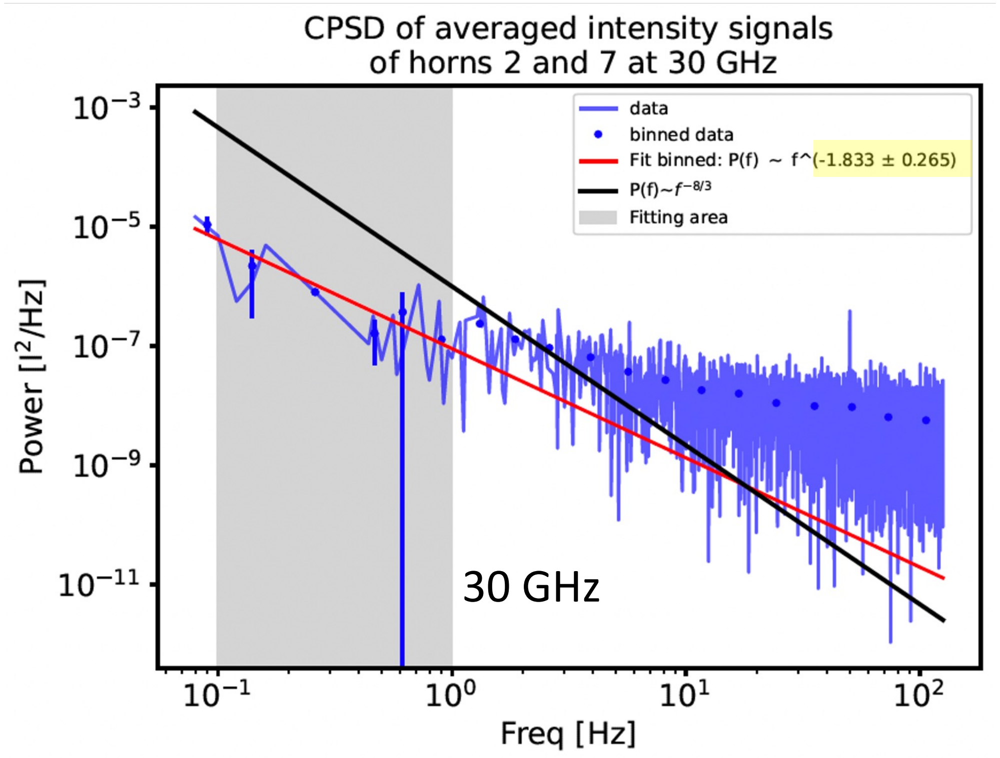
Cross power spectral density of the averaged (20 observations) intensity signal of horns 2 and 4 at 17 GHz and 19 GHz

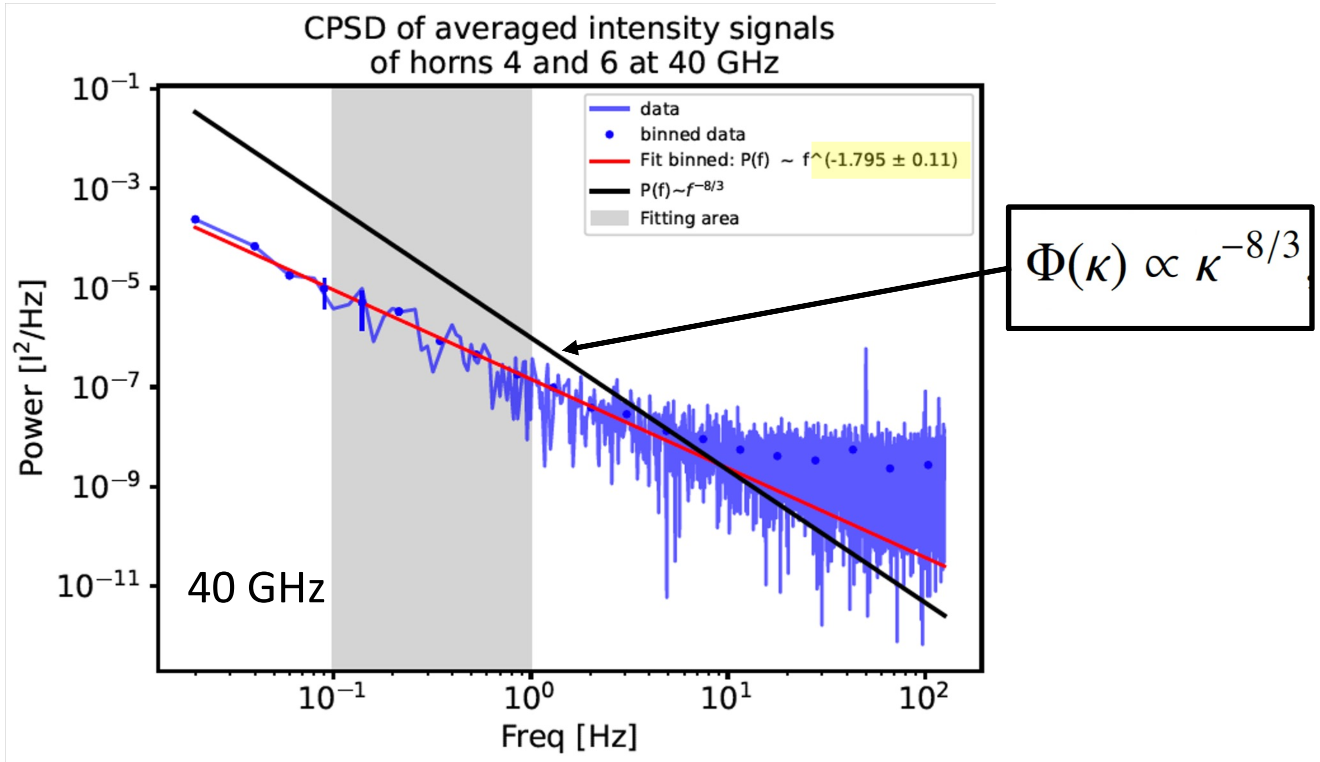
⇒ Atmospheric turbulence **outer scales of the order of 500m** as in Morris+2024

⇒ We obtained a **slightly flattened Kolmogorov spectrum** fitting between $1 \cdot 10^{-3} - 1 \cdot 10^{-1}$ Hz

Power spectral density from TFGI datasets

Same analysis for TFGI datasets at 30 and 40 GHz





Cross power spectral density of the averaged (16 observations) intensity signal of horns at 30 GHz and 40 GHz

⇒ We don't see the atmospheric turbulence outer scale due to short frequency coverage

⇒ We obtain the **flattened Kolmogorov spectrum between 0.1 and 1 Hz** probably due to instrumental effect of dome seeing (ground turbulence)

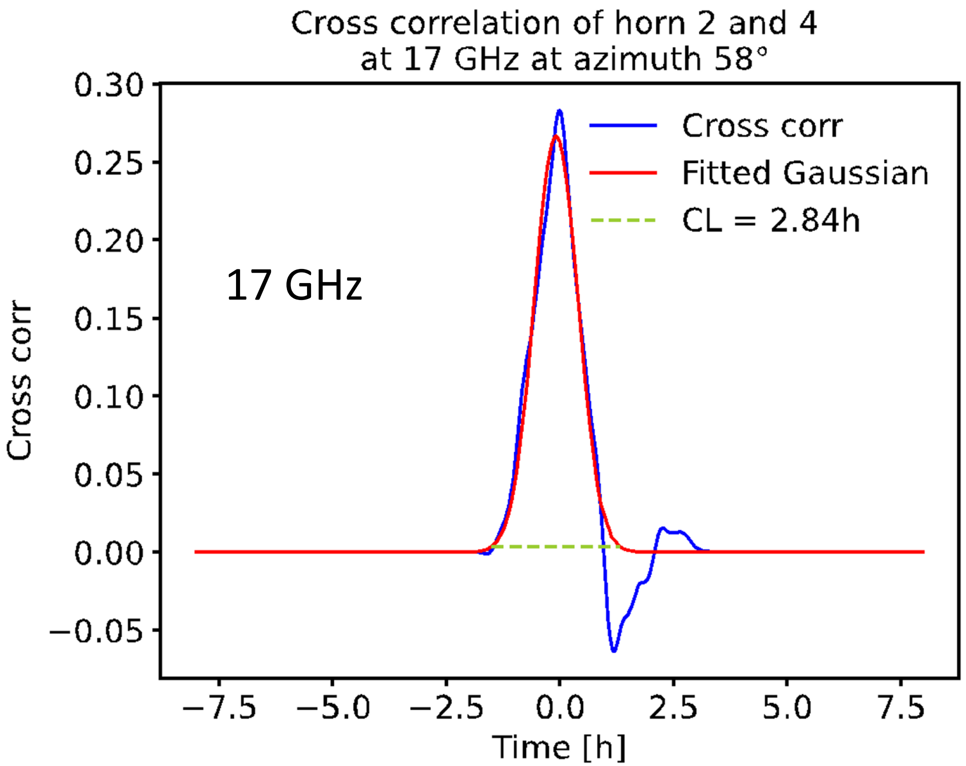
Coherence of the MFI atmospheric signal

Next: verification of the MFI wide survey assumption that the atmospheric signal stays correlated in the scale of 2 hours

Computation of the cross correlation function of signal of horn 2 and horn 4 measuring at the same frequency to spot to commun atmospheric signal

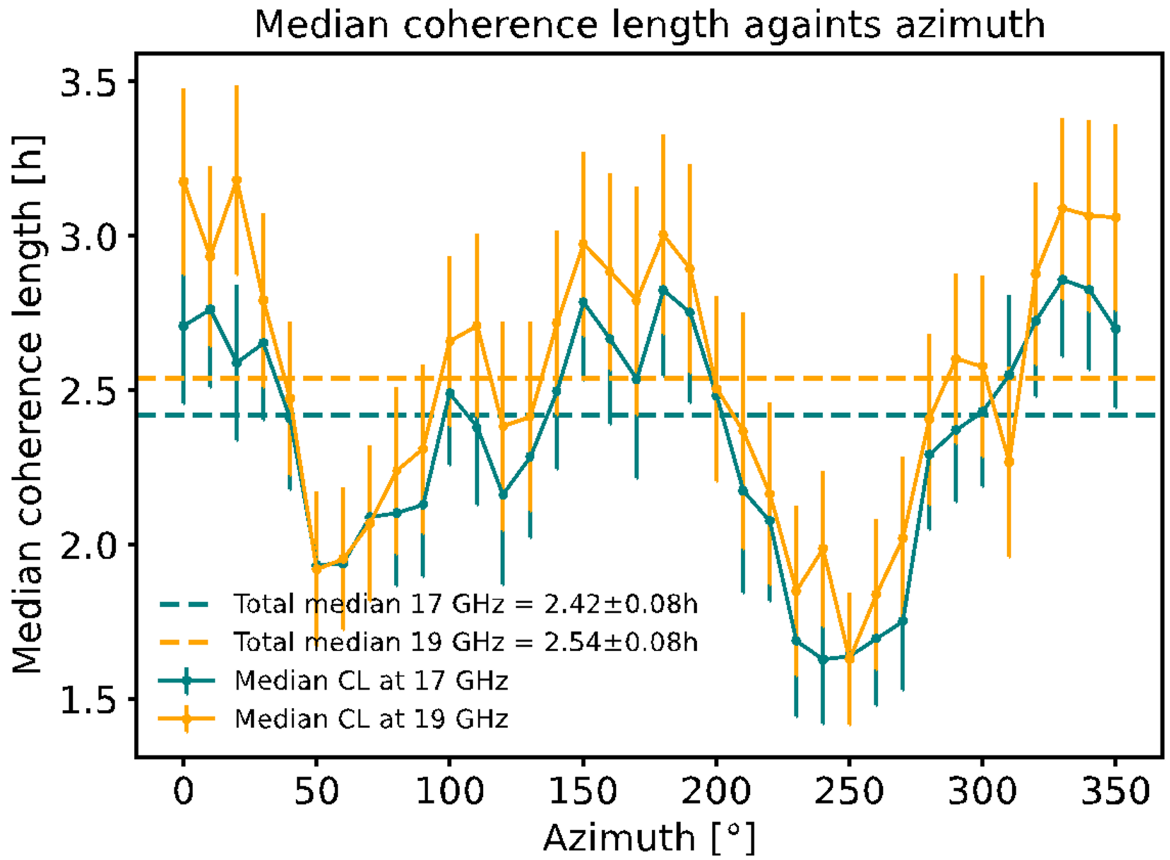
$$C_{h_2h_4}(\tau) = \frac{\sum_{n=0}^{N-1} \overline{h_2(n)} h_4(n+\tau)}{\sqrt{\sigma_{h_2}^2 \cdot \sigma_{h_4}^2}}$$

- $C(\tau)$: cross correlation at lag τ
- N: number of sample in the signal
- $\sigma^2_{f/g}$: variance of the signal (auto-correlation function)



Example of the cross correlation function with Gaussian fit to extract the coherence length for one observation of QUIJOTE wide survey

Coherence of the MFI atmospheric signal



Median coherence length of the cross correlation function as a function of azimuth at 17 and 19 GHz for the 1223 wide survey datasets

⇒ Median coherence length of MFI wide survey atmospheric signal is **between 2 and 3 hours**

⇒ We **confirmed MFI wide survey assumption on the stability of the atmospheric signal**

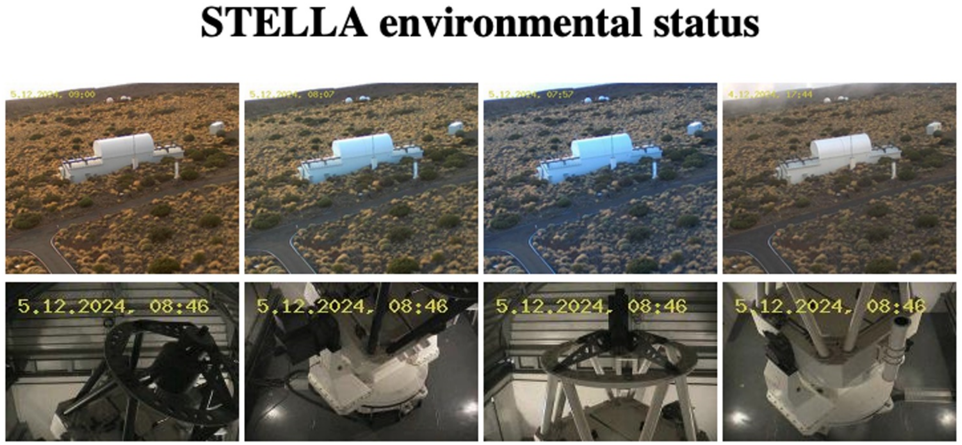
Conclusion

- **The spectrum of MFI2 atmospheric data** is slightly flatter than the Kolmogorov spectrum at 17 GHz and 19 GHz at low frequencies, slopes of the order of -2.5 (theory: -2.67)
- For **TFGI data at 30 GHz and 40 GHz**, we observe slopes of the order of -1.7 in the middle frequency range.
- The **outer scale of turbulence** is approximately **500 meters**, consistent with observations at ACT and Polarbear sites.
- We demonstrate that the atmospheric signal remains correlated on time scales of **2 to 3 hours**.

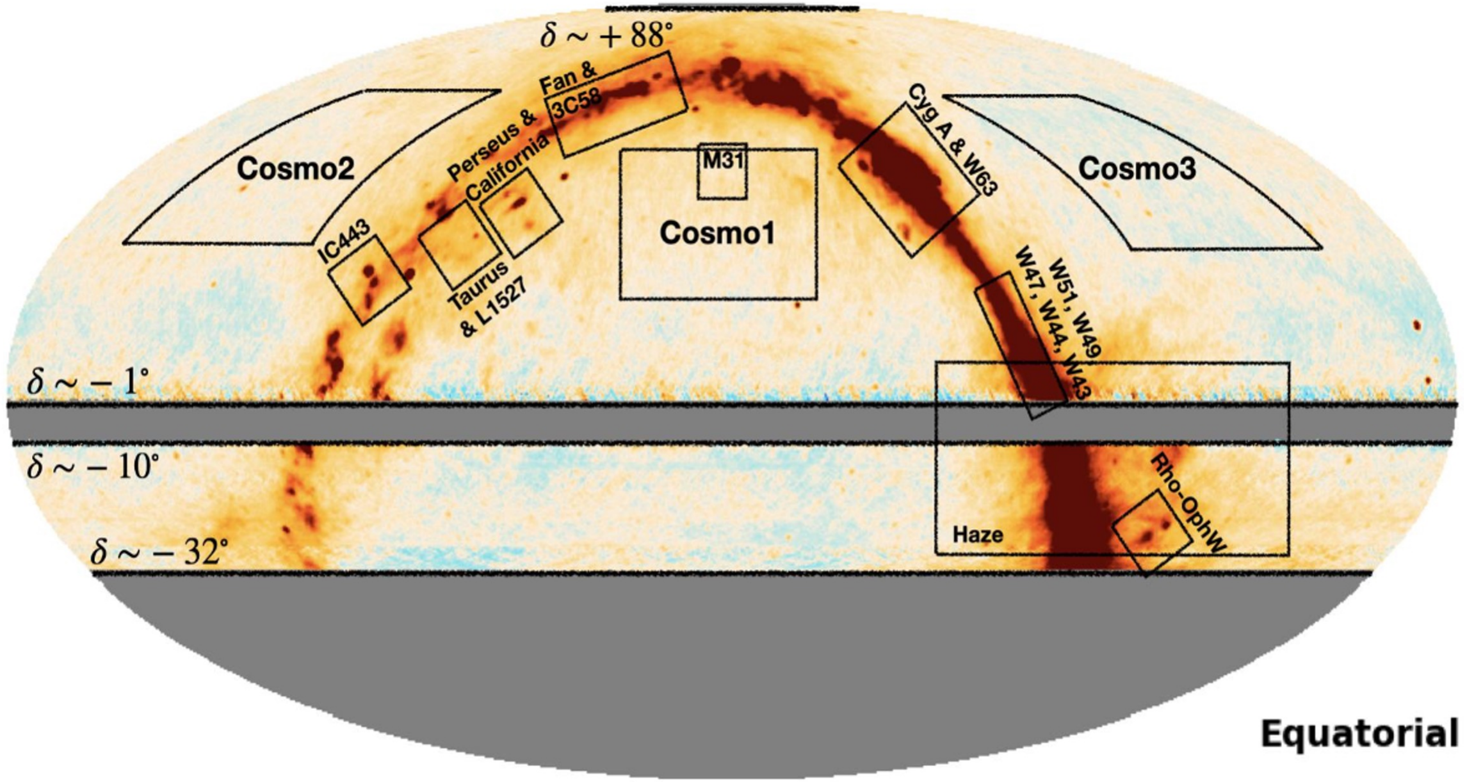

Thank you for your attention
Any questions?

Centro de Investigacion atmosferica de Izana,
located 1400m away from QUIJOTE at an altitude of 2367 m

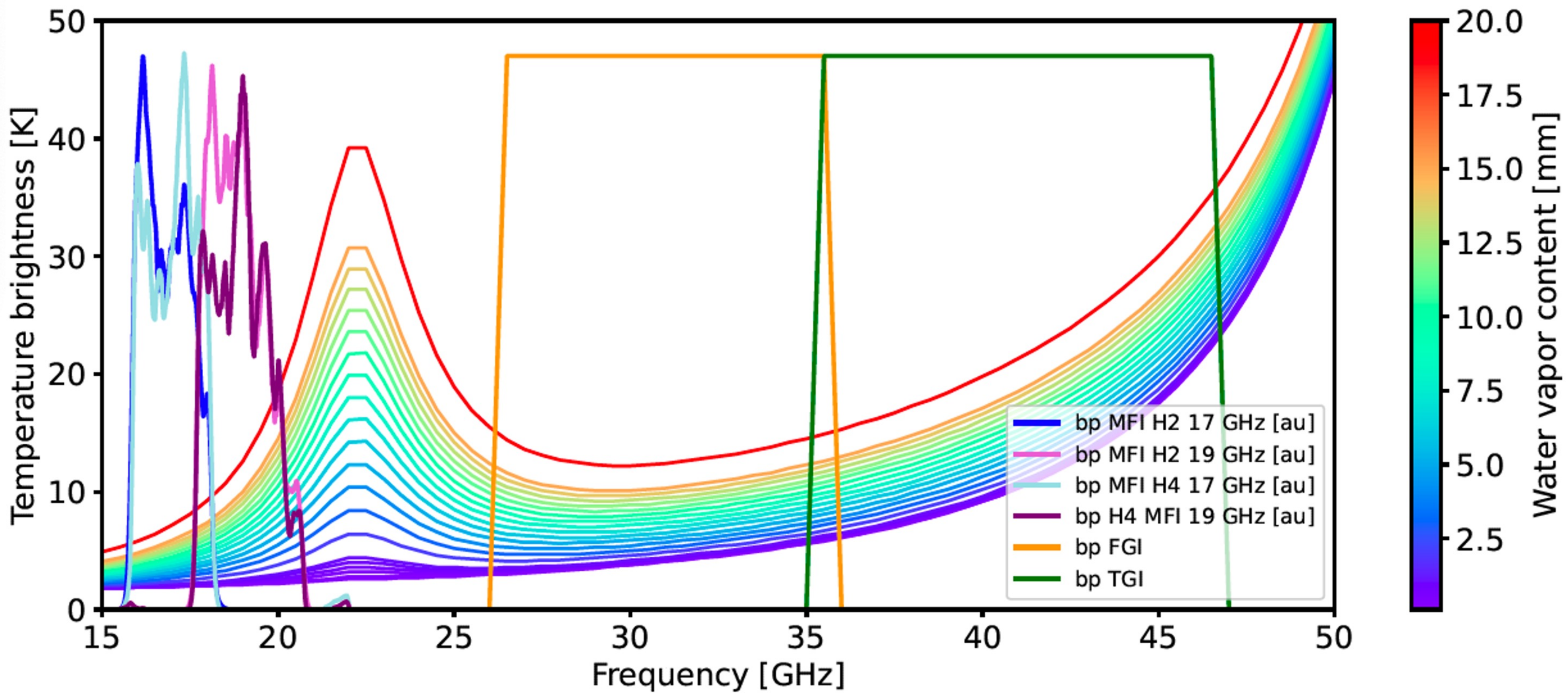
https://izana.aemet.es/



http://stella-archive.aip.de/stella/status/status.php



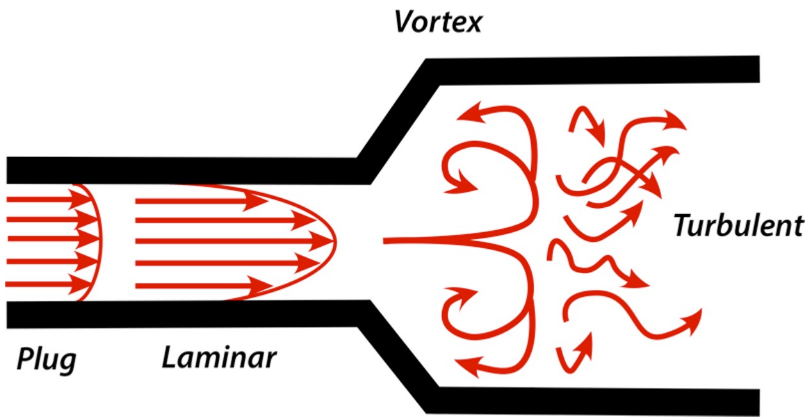
region of interest of the cosmological survey

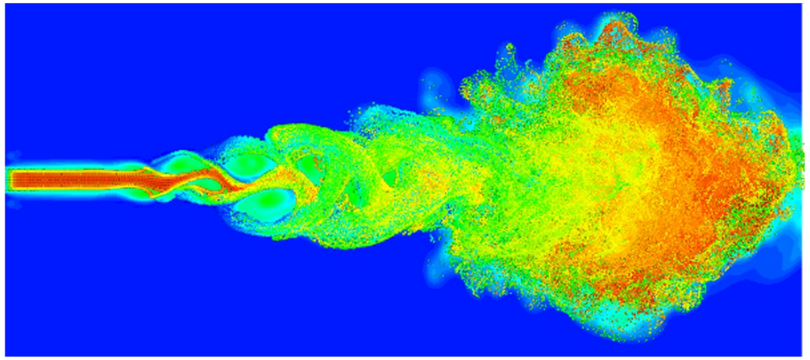


50
40
30
20
10
0
15
20
25
30
35
40
45
50
Temperature brightness [K]
Frequency [GHz]
bp MFI H2 17 GHz [au]
bp MFI H2 19 GHz [au]
bp MFI H4 17 GHz [au]
bp H4 MFI 19 GHz [au]
bp FGI
bp TGI
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
Water vapor content [mm]

Atmospheric turbulence

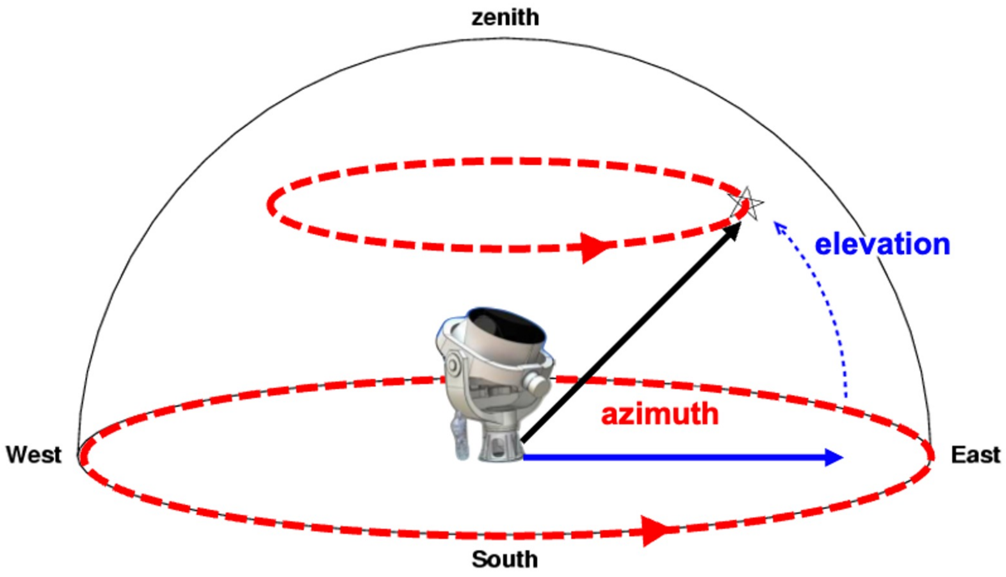
- Fluid dynamics reminder:
  - **Laminar flow:** slow, organized, parallel to vessel walls, parabolic profile
  - **Turbulent flow:** disorganized/chaotic, random, with high velocities, different length scales of eddy motion





Angular correlations from MFI datasets

Next: verify the correlation of the atmospheric signal in real space



Structure Function in Atmospheric Studies:

- Characterizes angular correlation in the atmosphere.
- Quantifies signal fluctuations across angular separations θ
- Highly sensitive to large-scale fluctuations.

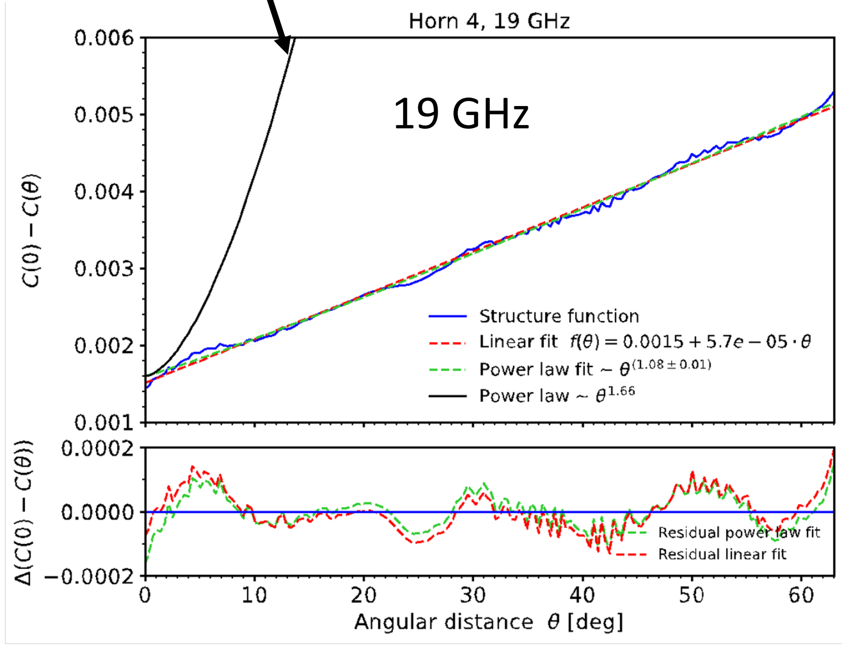
$$\begin{aligned} D(\theta) &= \frac{1}{2}\langle (T(0) - T(\theta))^2 \rangle \\ &= \langle T(0)^2 \rangle - \langle T(0)T(\theta) \rangle \\ &= C(0) - C(\theta), \end{aligned}$$

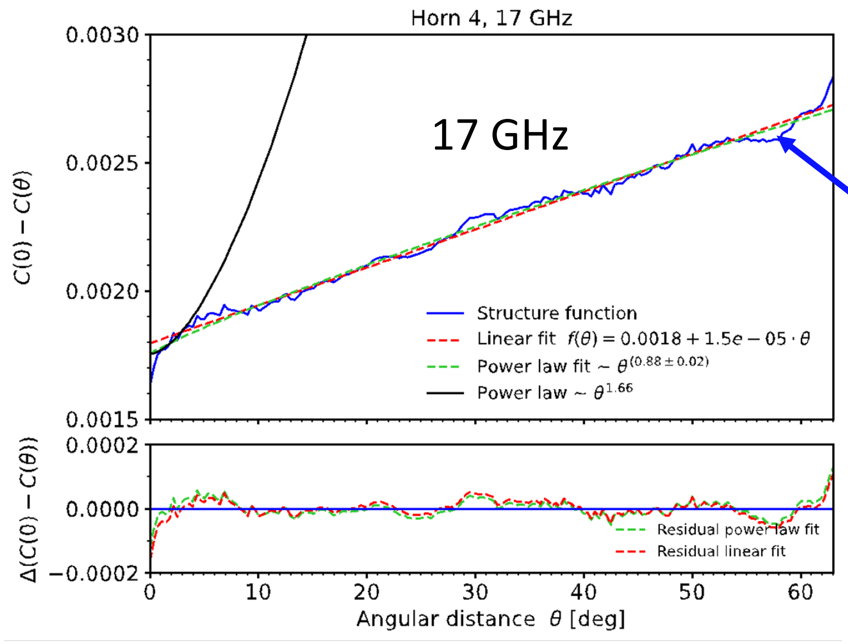
- θ: angular separation between a pair of sample
- $T(0/\theta)$: antenna temperature of sample pair with angular separation 0°/ θ°
- $C(0/\theta)$: correlation function of sample pair with angylar separation 0°/ θ°

Kolmogorov theory: $C(0) - C(\theta) \propto \theta^{5/3 \simeq 1.7}$

Angular correlations from MFI datasets

$$C(0) - C(\theta) \propto \theta^{5/3 \simeq 1.7}$$





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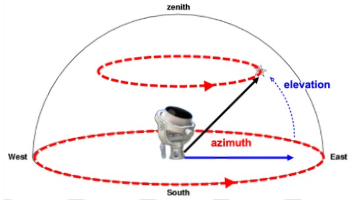

- Median slope of the structure function for MFI wide survey (1223 observations) is about 0.9 whereas Kolmogorov predict 5/3 = 1.67