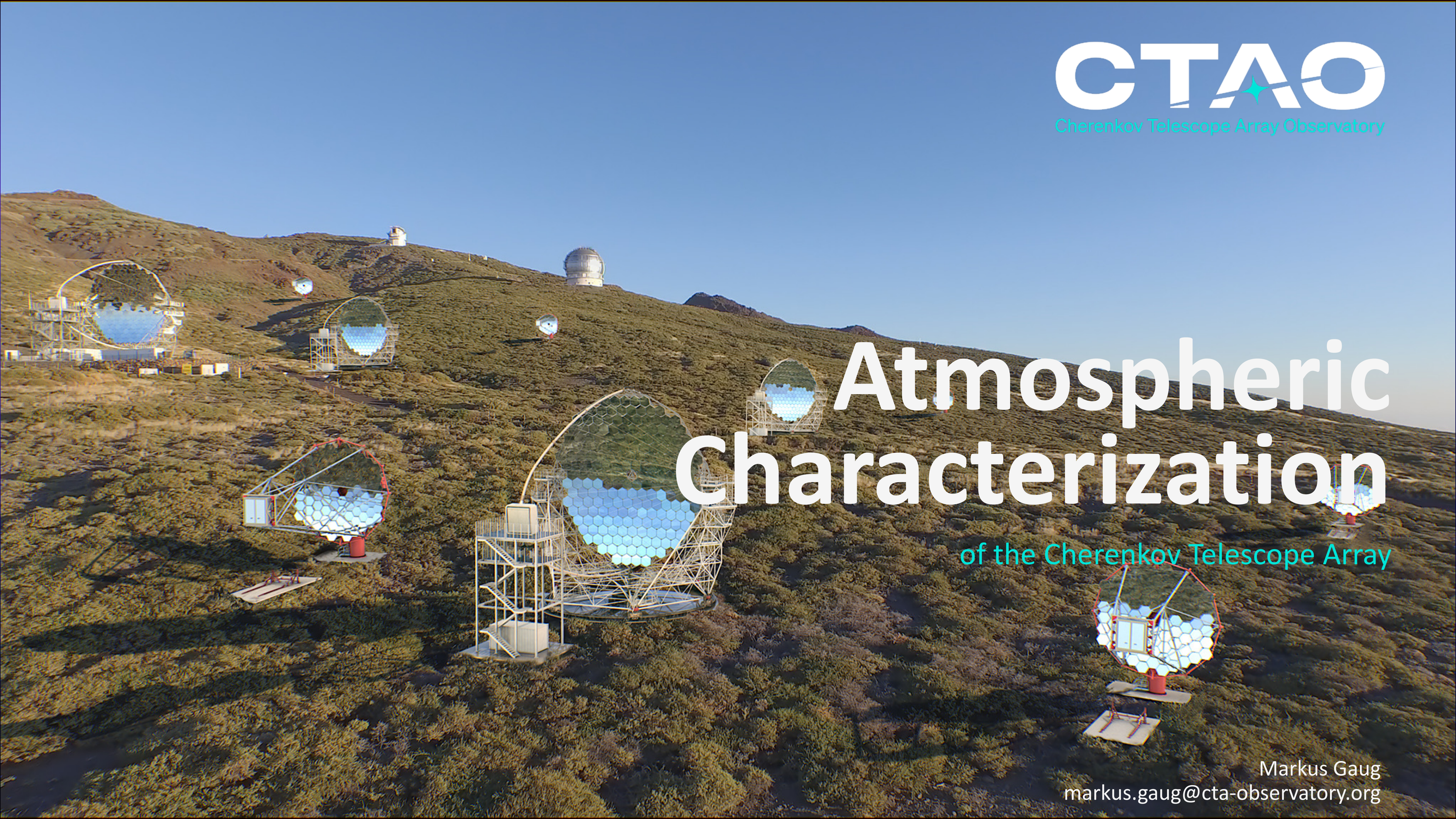
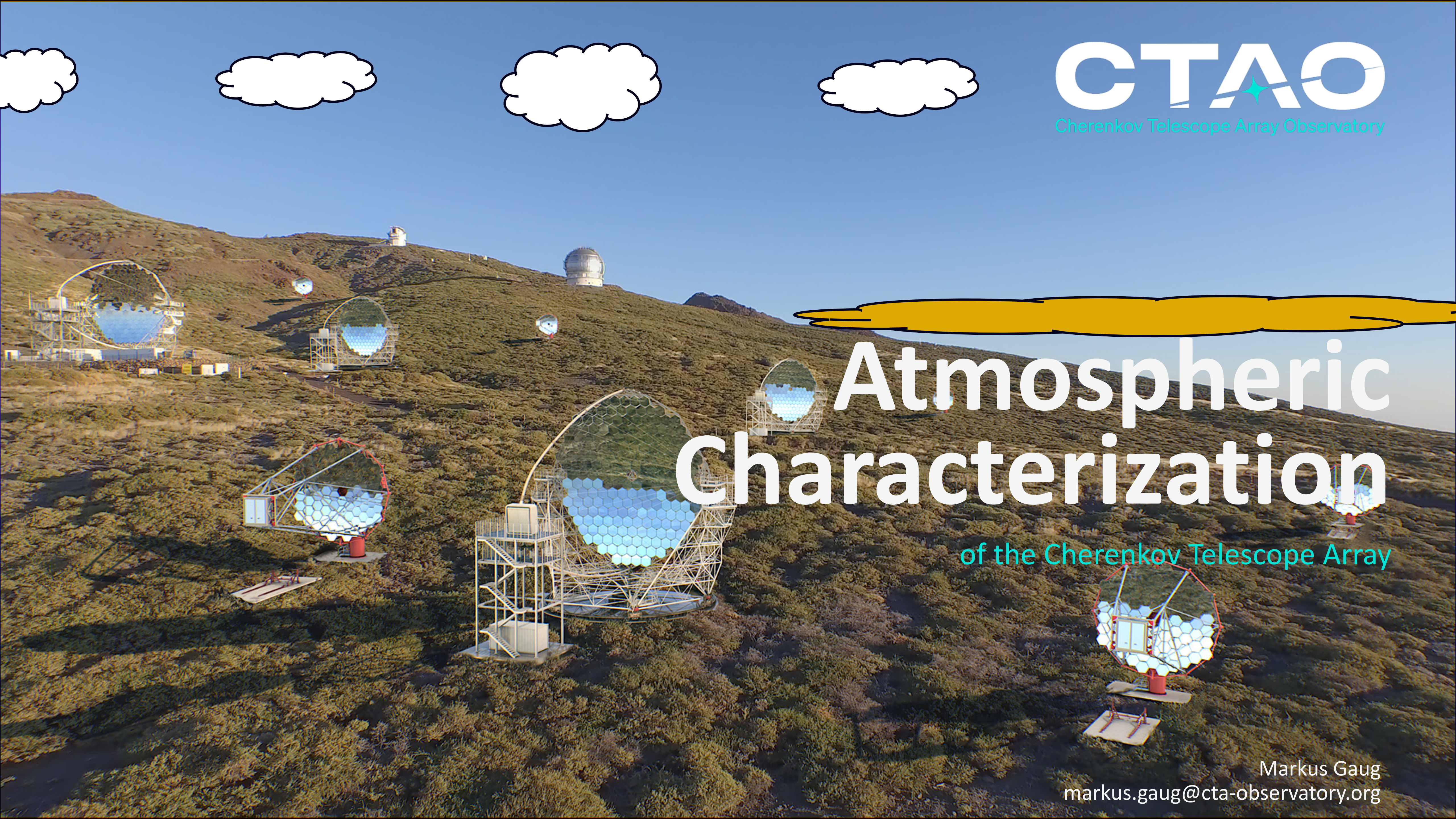


CTAO
Cherenkov Telescope Array Observatory

Atmospheric Characterization

of the Cherenkov Telescope Array

Markus Gaug
markus.gaug@cta-observatory.org



Cherenkov Telescope Array Observatory

Atmospheric Characterization

of the Cherenkov Telescope Array

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1 Intro – Cherenkov light production
2 Intro – Physics of atmosphere
3 Molecular profiles
4 Aerosols and clouds
5 Monitoring instruments
6 Correction strategies

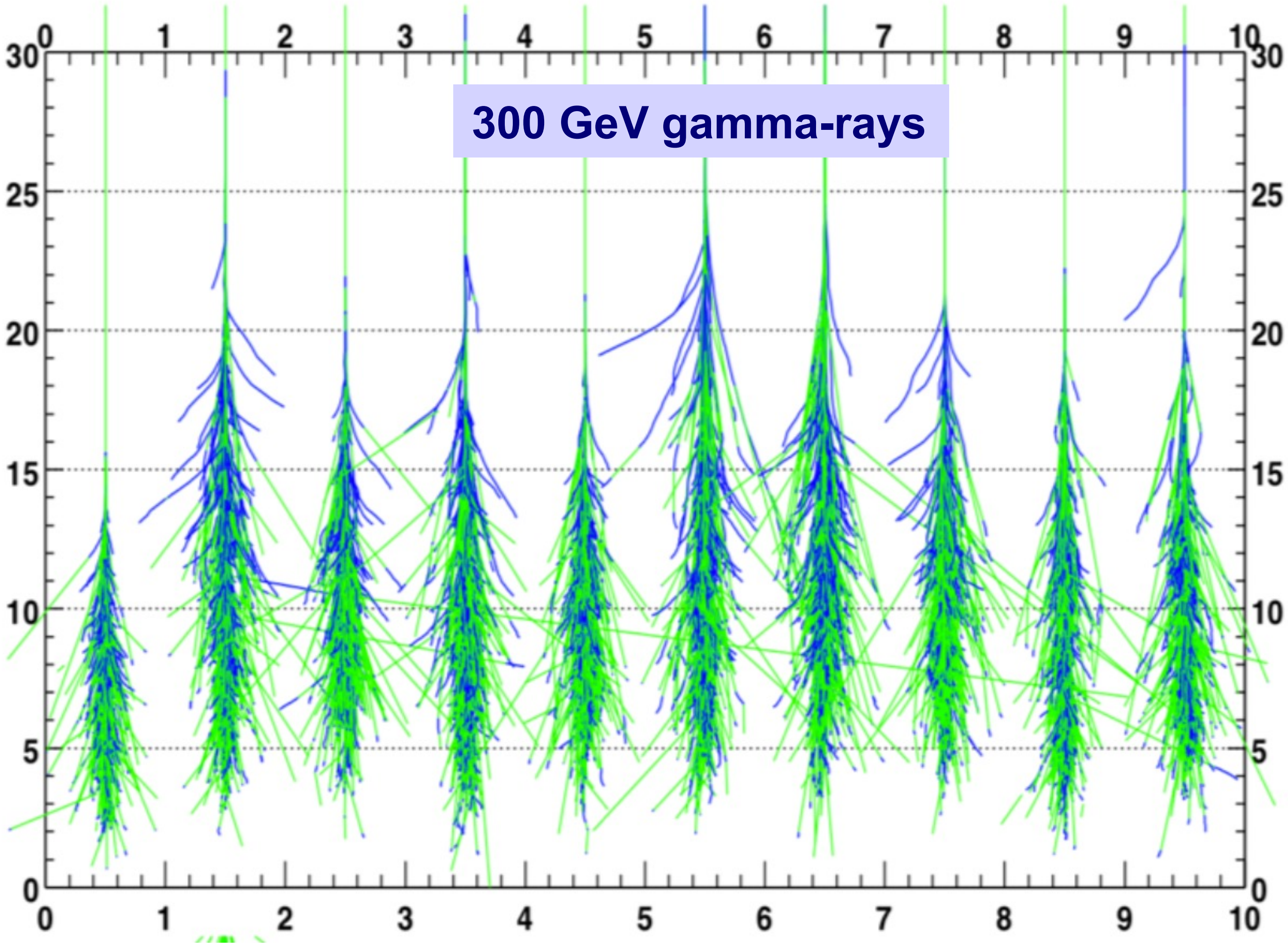
Introduction

Cherenkov light production heights

Gamma-ray showers

Large fluctuations

- Gamma-ray first interaction *stochastic process* (but practically *no energy dependency* on average)
- Particle creation stochastic processes, averaged over many particles, *large energy dependency*

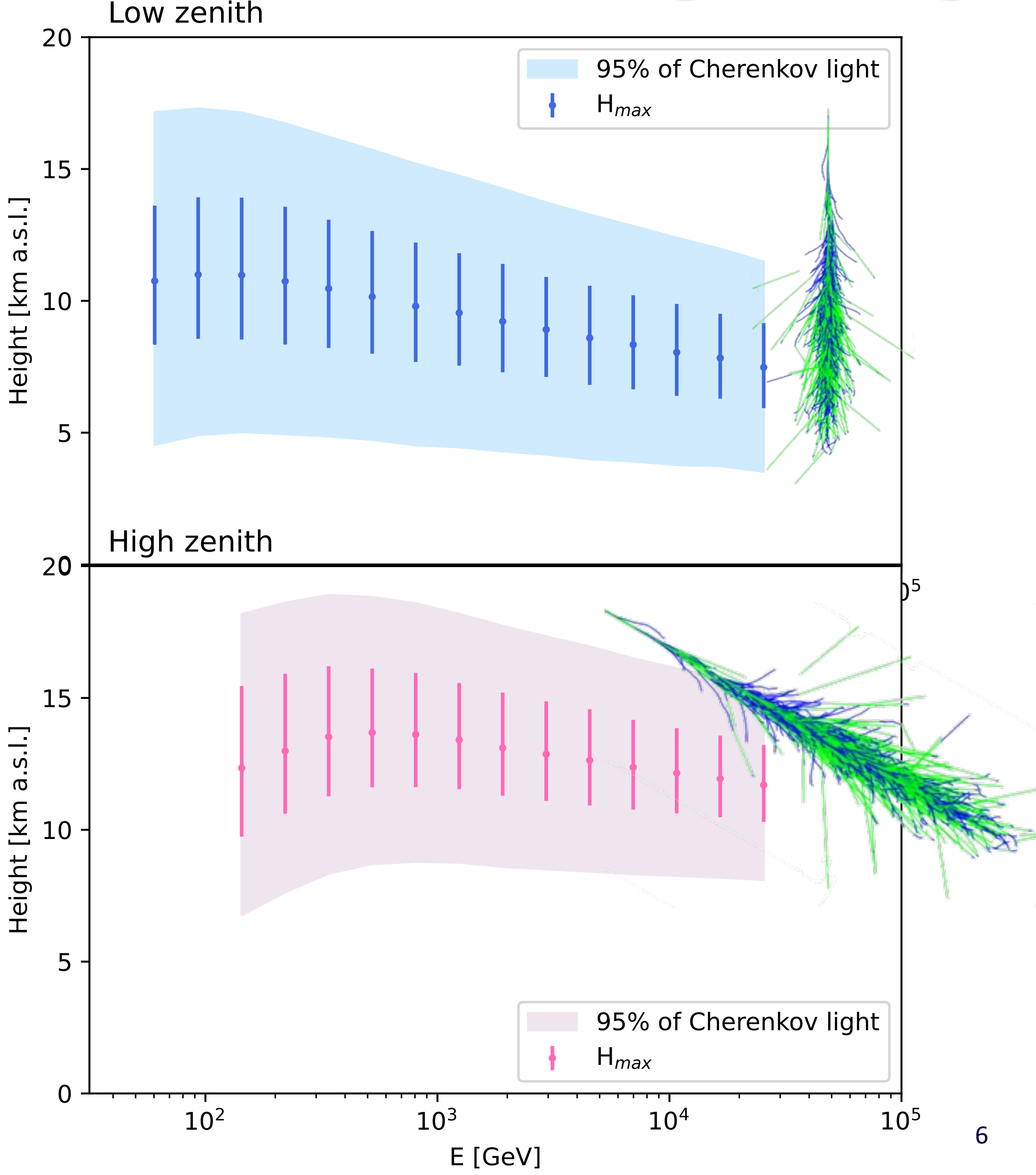


de Naurois M. (2000) Ph.D. thesis, Université Pierre et Marie Curie - Paris V

Cherenkov light production heights

- Only the "visible" Cherenkov light matters (i.e., ending up in the camera image).
- Considerable energy dependency
- Large spread over zenith angles!

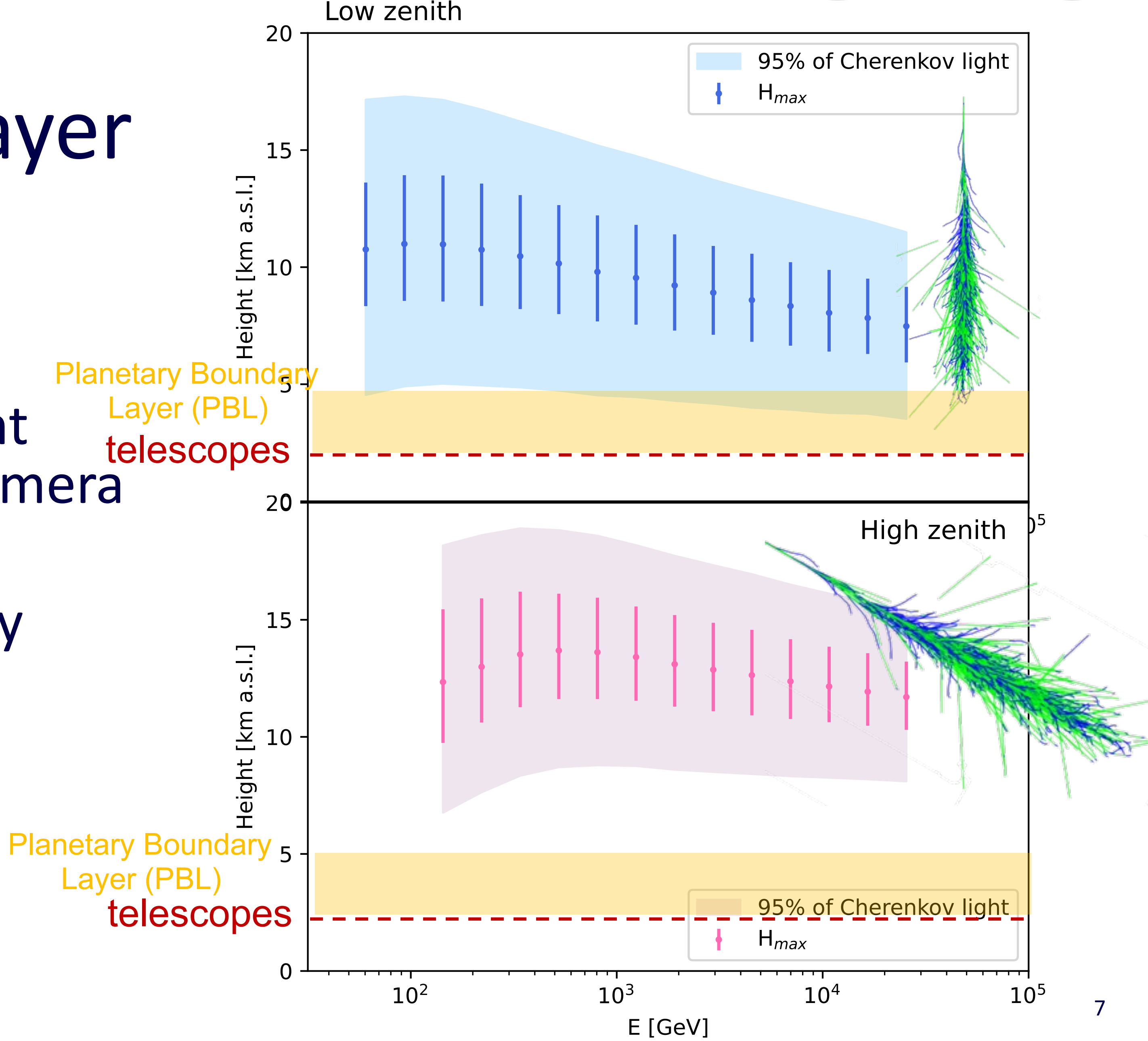
- Where are the "obstacles" ?



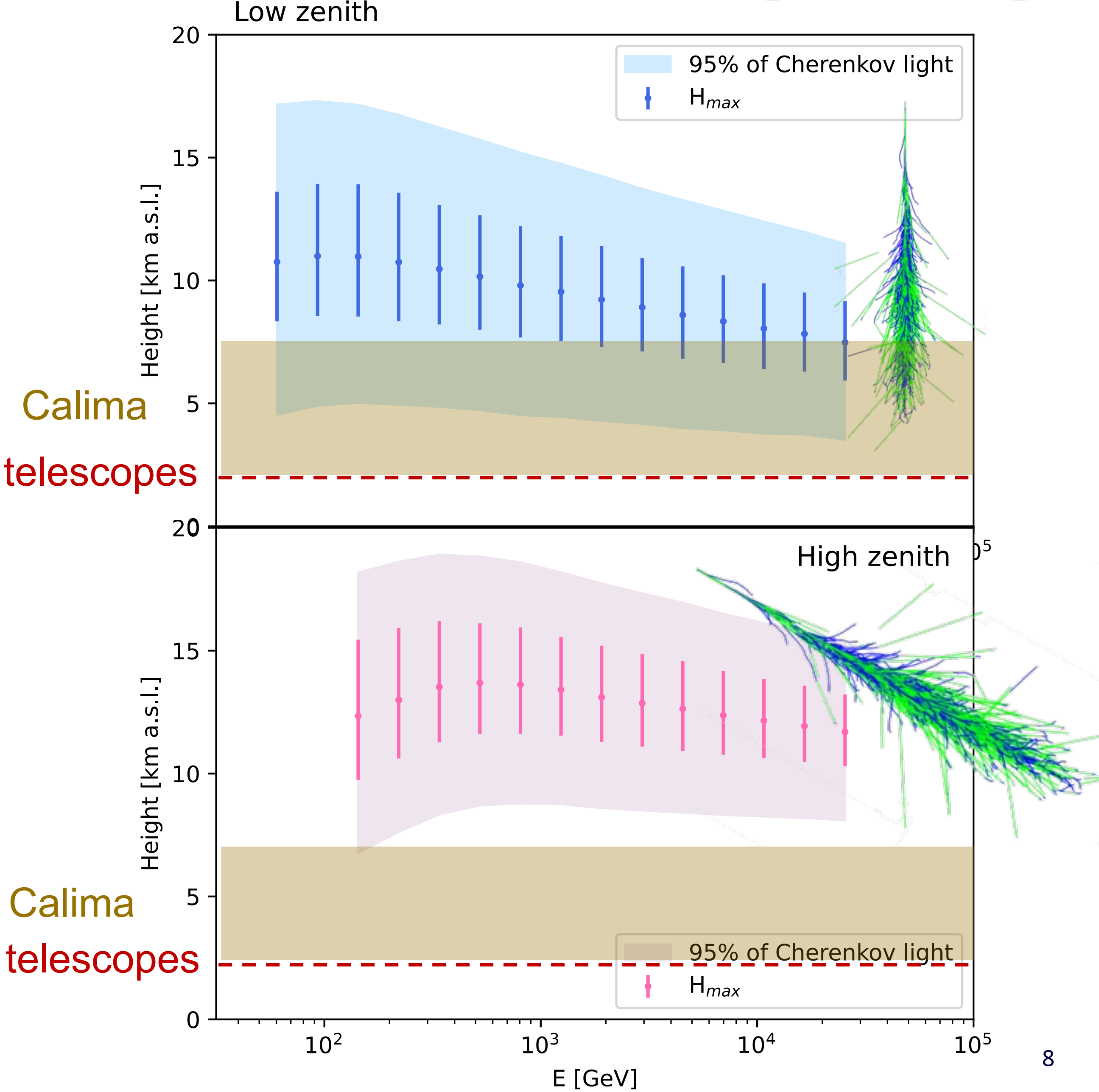
Planetary Boundary Layer (PBL)

- Only the “visible” Cherenkov light matters (i.e., ending up in the camera image).
- Considerable energy dependency
- Large spread over zenith angles!

- Where are the “obstacles” ?



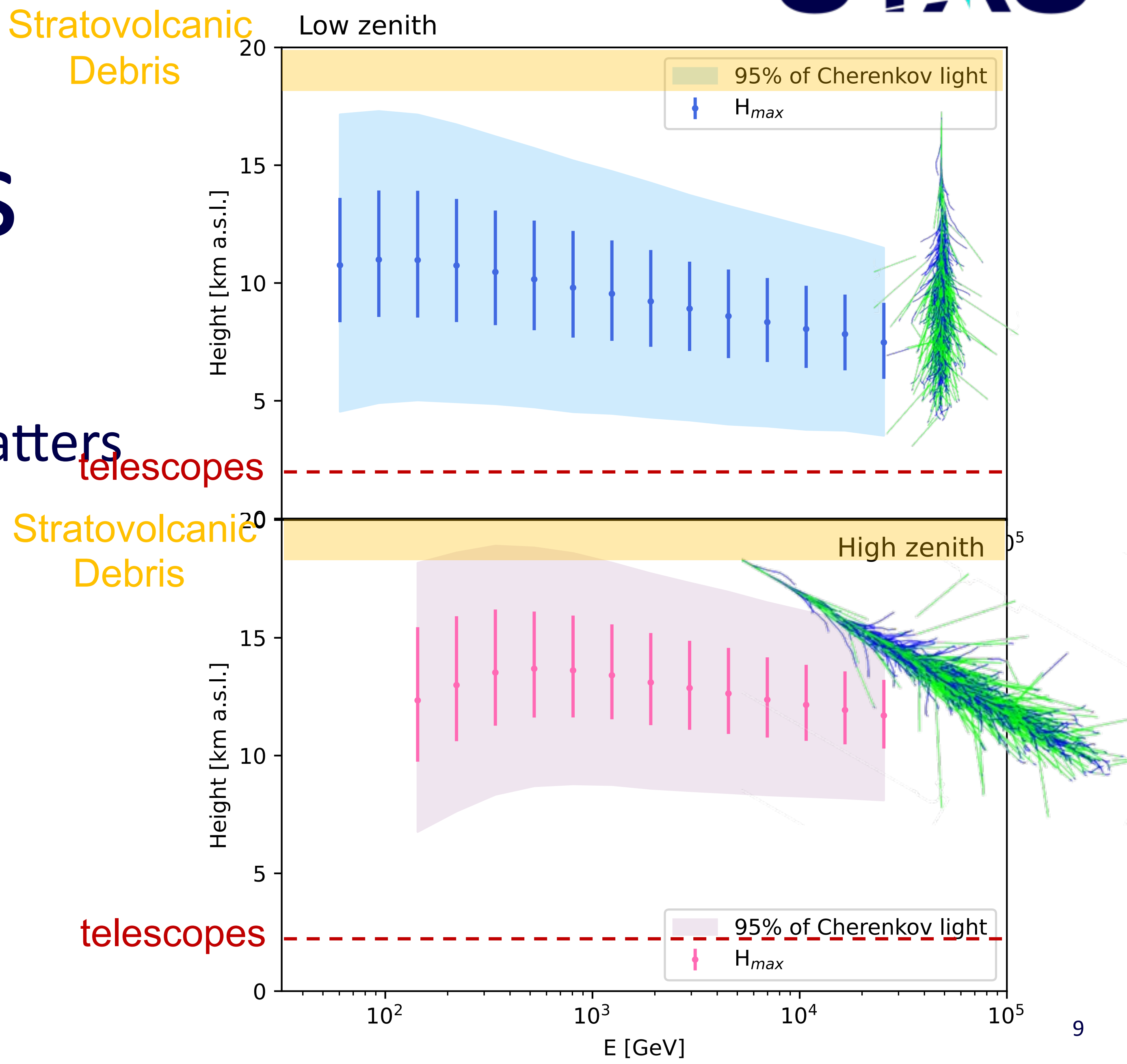
Calima


Low zenith
95% of Cherenkov light
H_{max}
Height [km a.s.l.]
20
15
10
5
Calima
telescopes
High zenith
95% of Cherenkov light
H_{max}
Height [km a.s.l.]
20
15
10
5
0
Calima
telescopes
10^2
10^3
10^4
10^5
E [GeV]

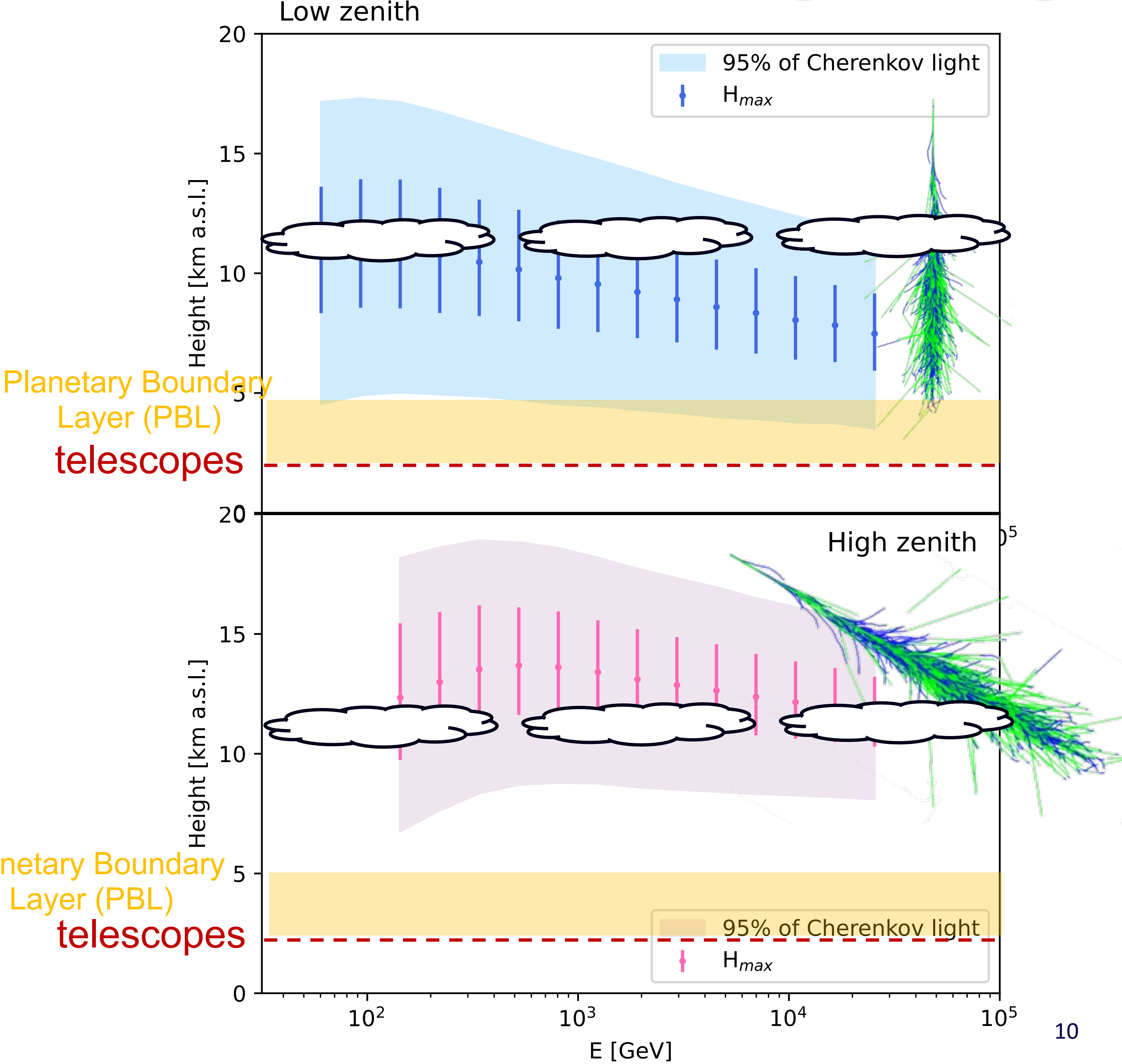
Stratovolcanoes

atters

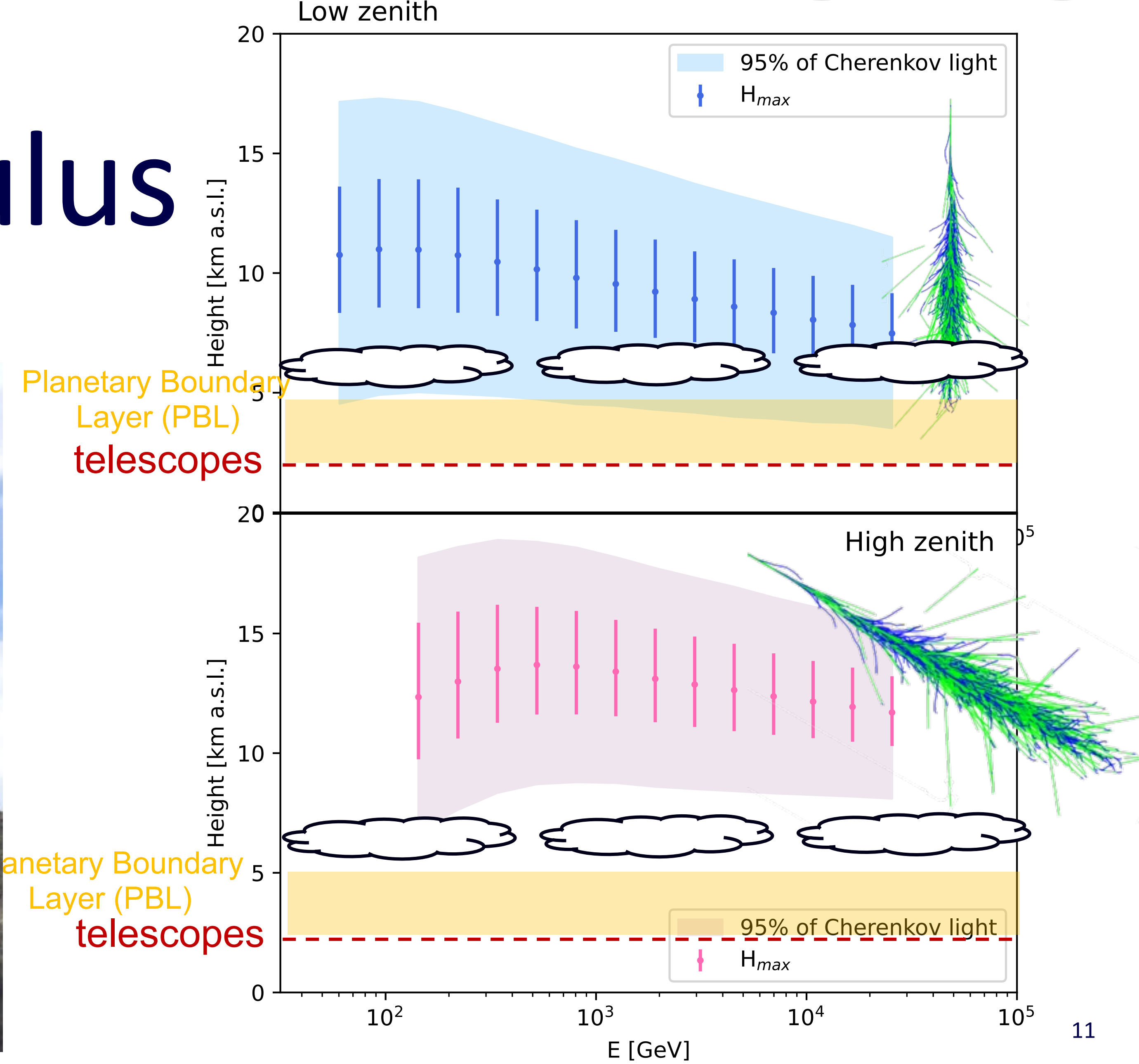
/



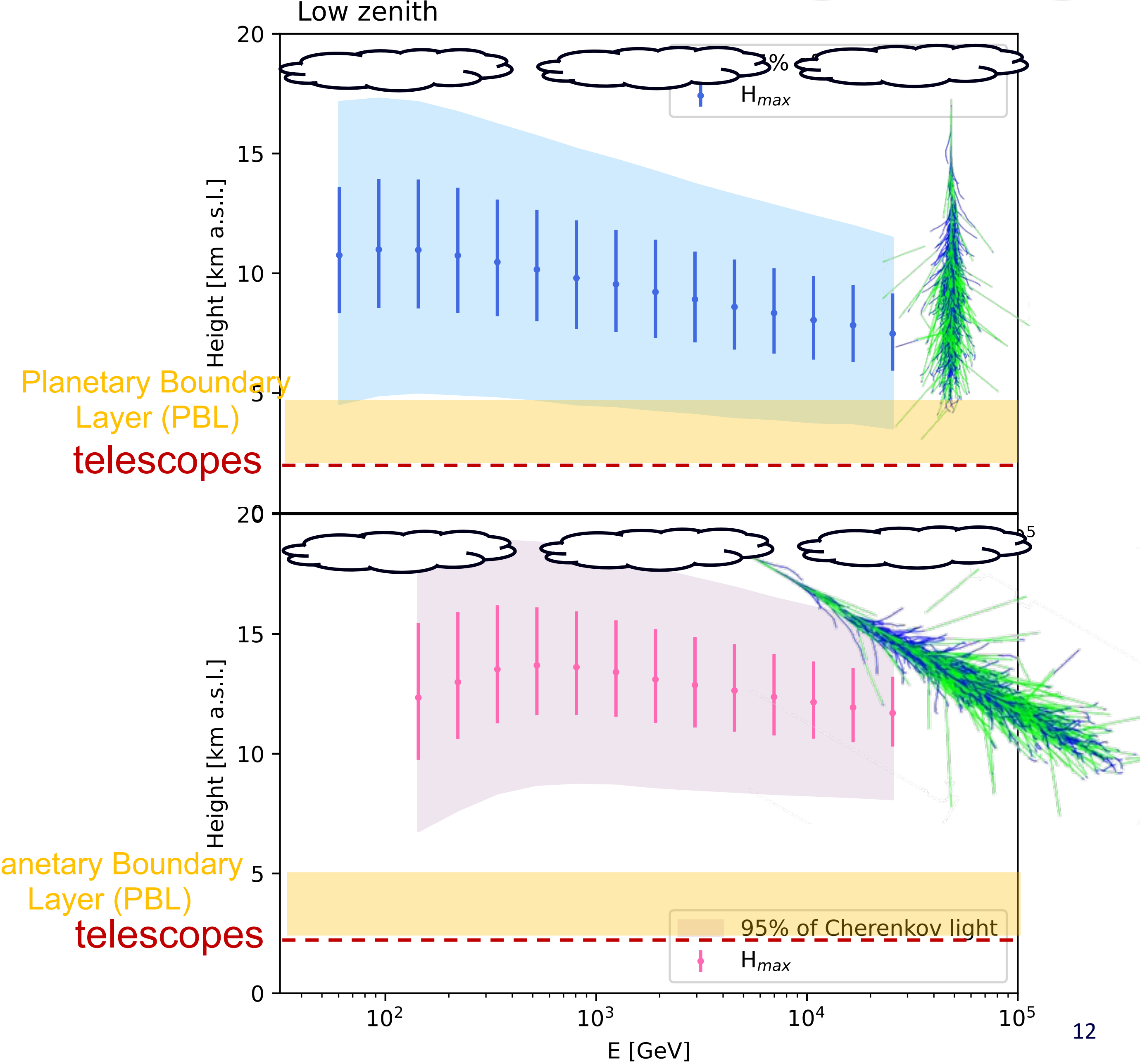
Clouds


Low zenith
95% of Cherenkov light
H$_{max}$
Height [km a.s.l.]
20
15
10
5
Planetary Boundary Layer (PBL)
telescopes
High zenith
20
15
10
5
0
netary Boundary Layer (PBL)
telescopes
95% of Cherenkov light
H$_{max}$
Height [km a.s.l.]
10^2
10^3
10^4
10^5
E [GeV]

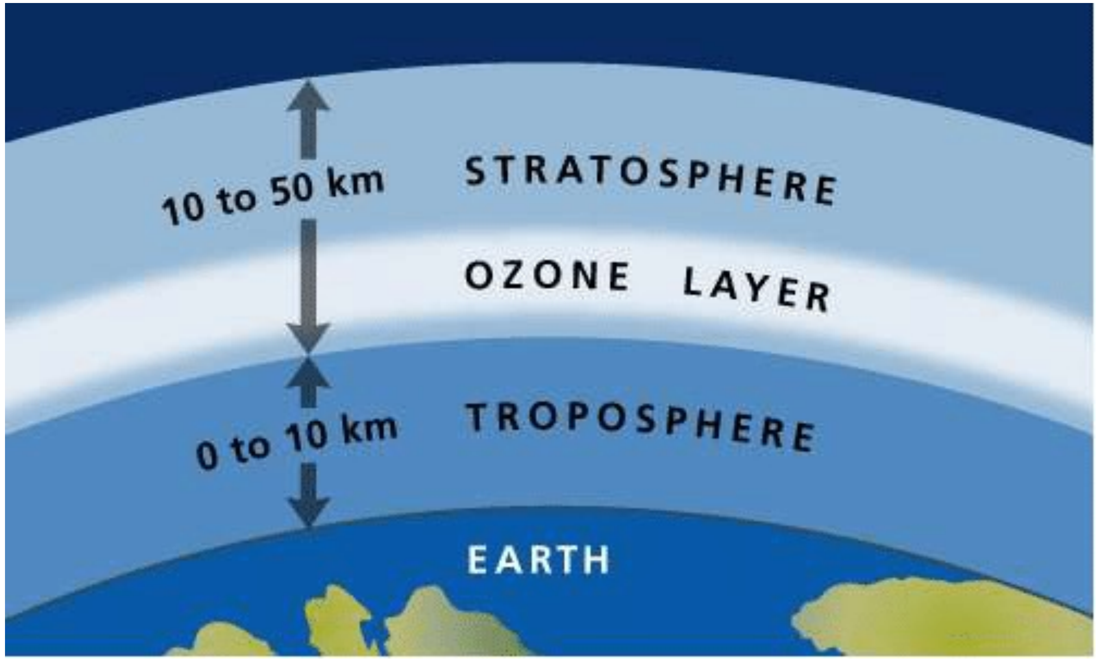
Low stratocumulus

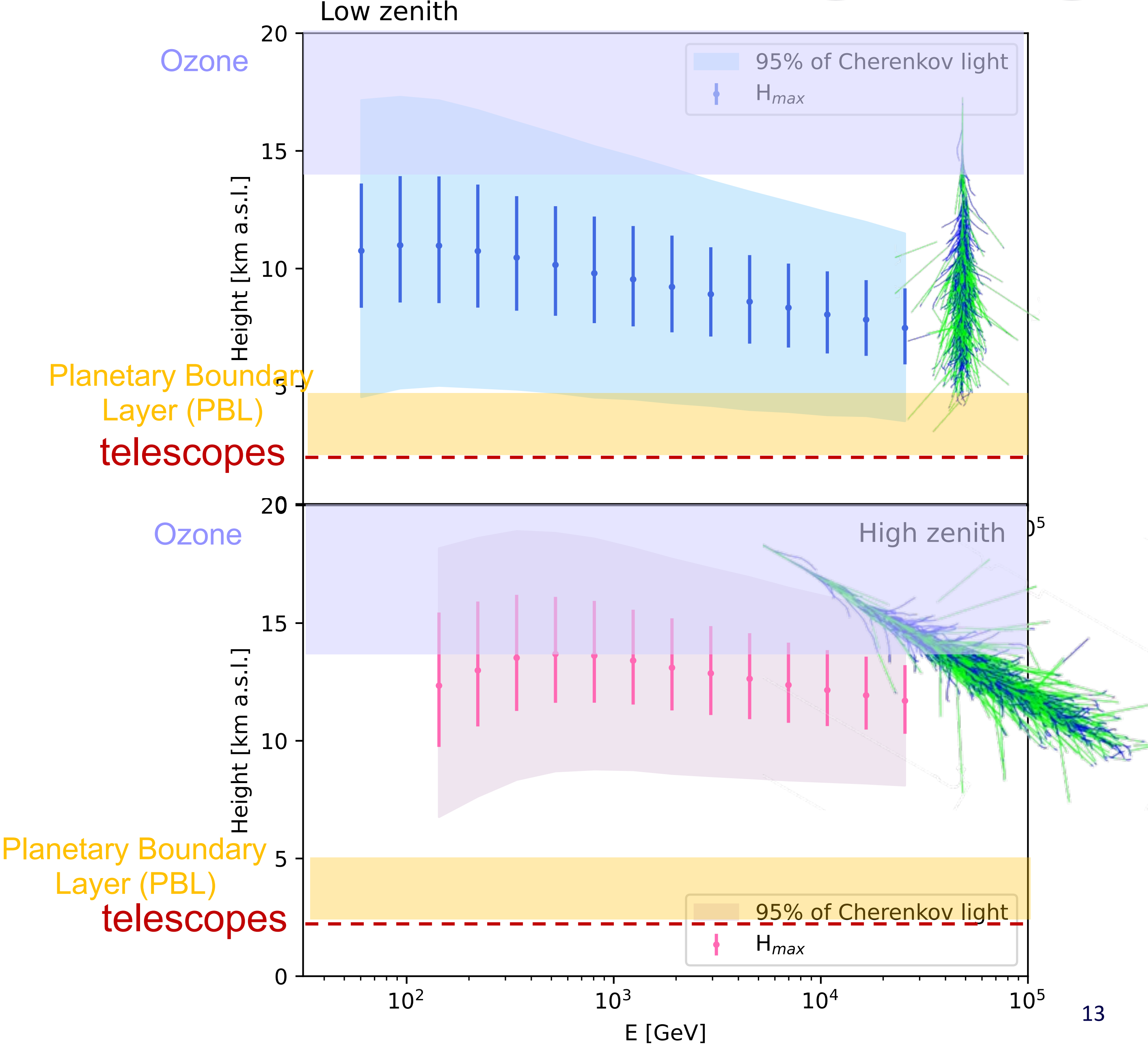


High cirrus


Low zenith
20
15
10
5
0
Height [km a.s.l.]
%
H$_{max}$
Planetary Boundary Layer (PBL)
telescopes
anetary Boundary Layer (PBL)
95% of Cherenkov light
10^2
10^3
10^4
10^5
E [GeV]

Ozone


10 to 50 km
STRATOSPHERE
OZONE LAYER
0 to 10 km
TROPOSPHERE
EARTH


Low zenith
Ozone
Planetary Boundary Layer (PBL)
telescopes
20
15
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Height [km a.s.l.]
95% of Cherenkov light
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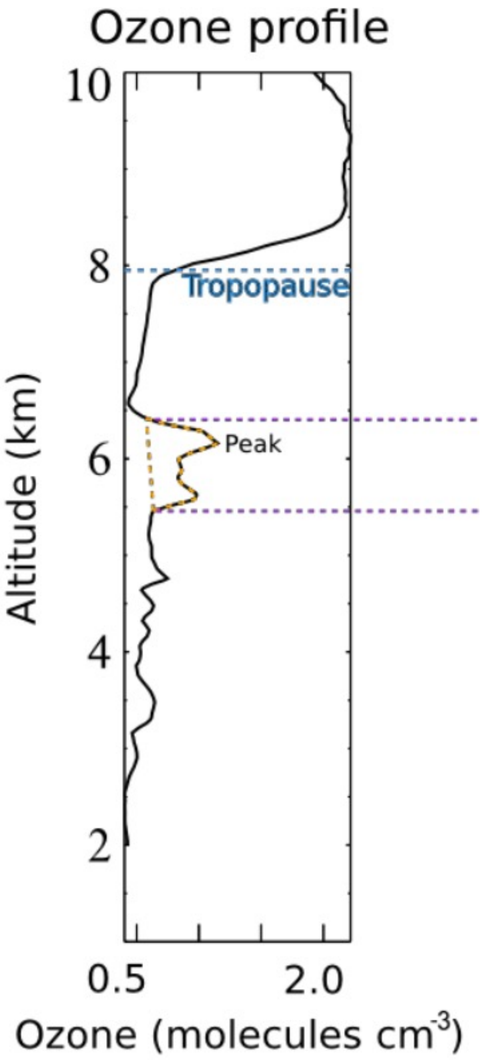
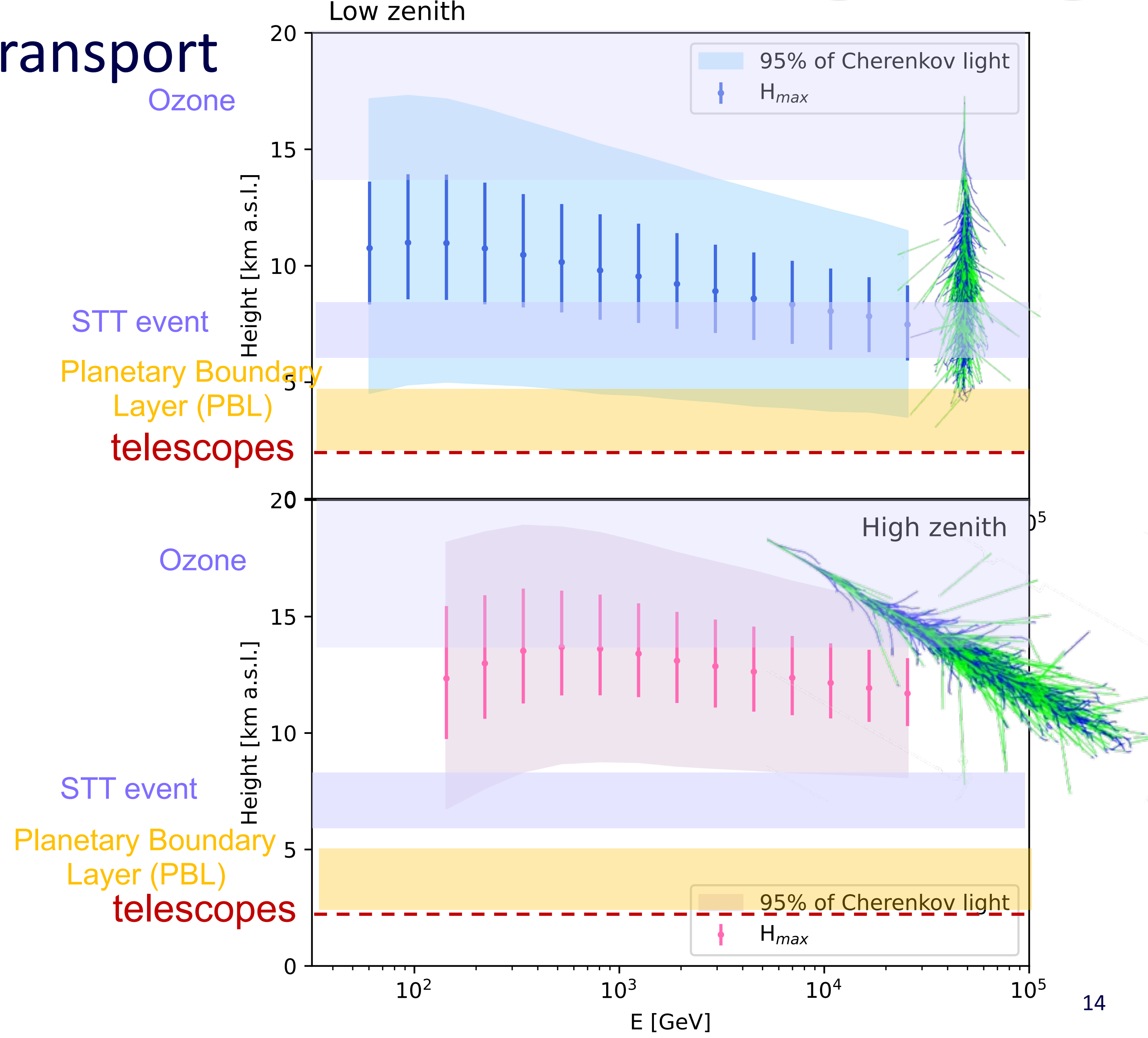
Height [km a.s.l.]
95% of Cherenkov light
H$_{max}$
10^2
10^3
10^4
10^5
E [GeV]

Stratosphere-To-Troposphere Transport

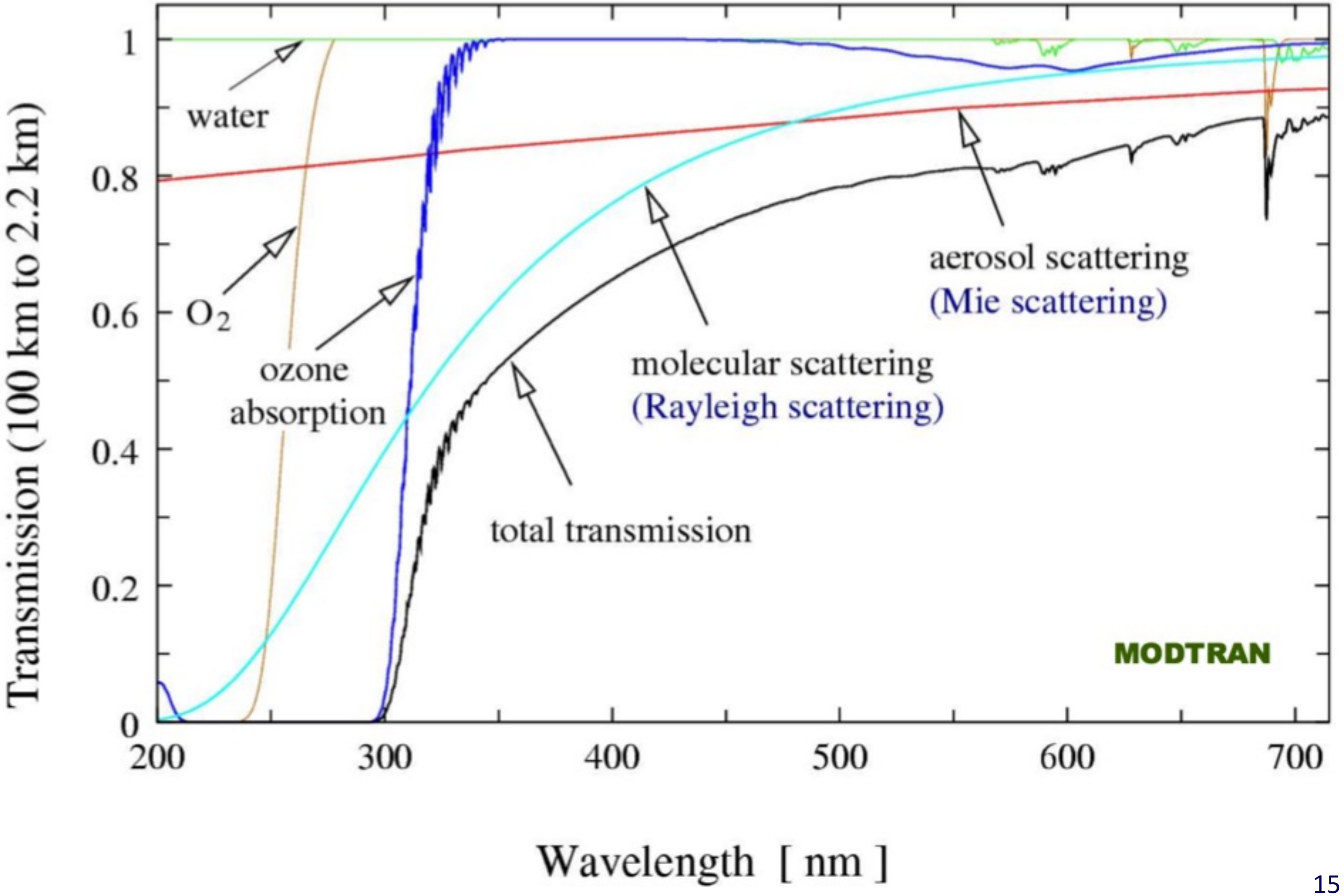


Greeslade J.W. et al., ACP 17 (2017) 10269



Cherenkov light extinction

- Average extinction profile (as function of wavelength) is **dominated by molecular (Rayleigh) scattering**
- However, molecular scattering is the **least variable part.**



Introduction

Physics of the Atmosphere

Structure of Atmosphere

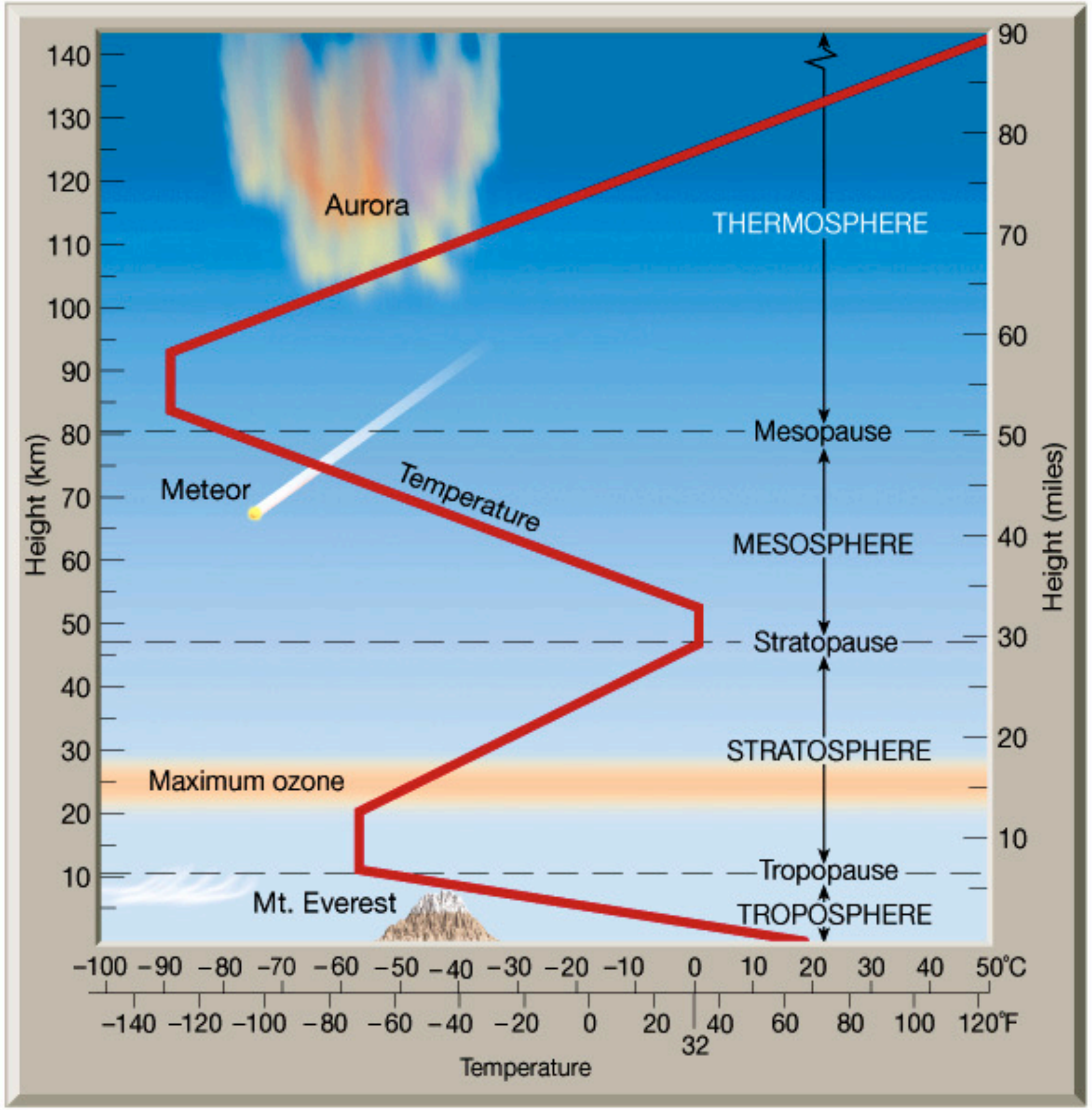
- Pressure follows (roughly) the barometric law:

$$P(h) = P_0 \cdot \left(1 - \frac{L}{T_0}(h - h_0)\right)^{\frac{gM}{RL}} \approx P_0 \cdot e^{-\frac{(h-h_0)}{8.5\ \mathrm{km}}}$$

- Temperature shows (roughly) regions of constant lapse rate:

$$\frac{\mathrm{d}T}{\mathrm{d}h} \approx \text{const.} \cong \quad -6.5°\mathrm{C/km} \quad \textit{(troposphere)}$$

- What about the density profile?



Structure of Atmosphere

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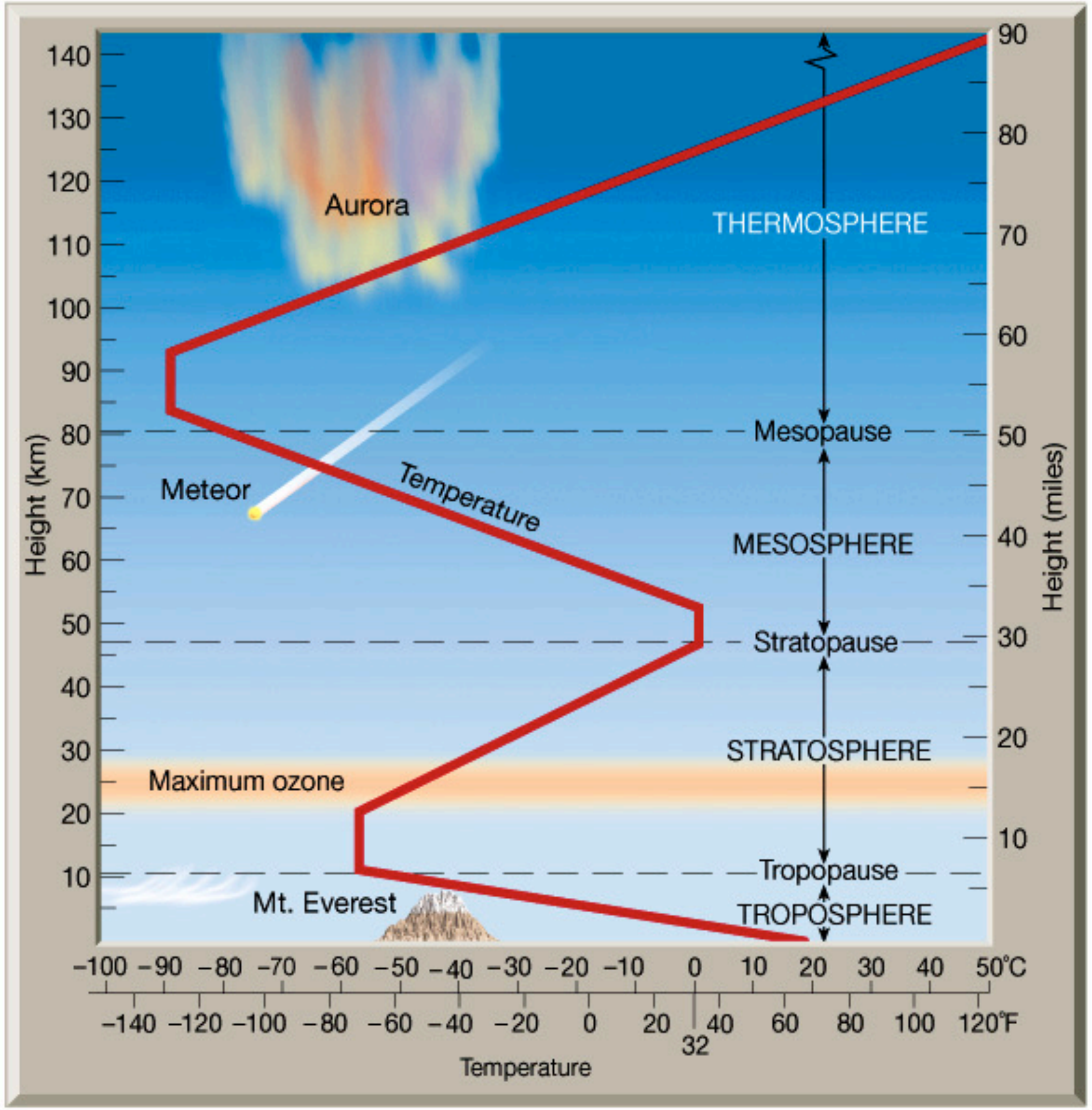
$$\frac{\mathrm{d}T}{\mathrm{d}h} \approx \text{const.} \cong \ -6.5\,°\mathrm{C/km} \quad \textit{(troposphere)}$$

- The density profile:

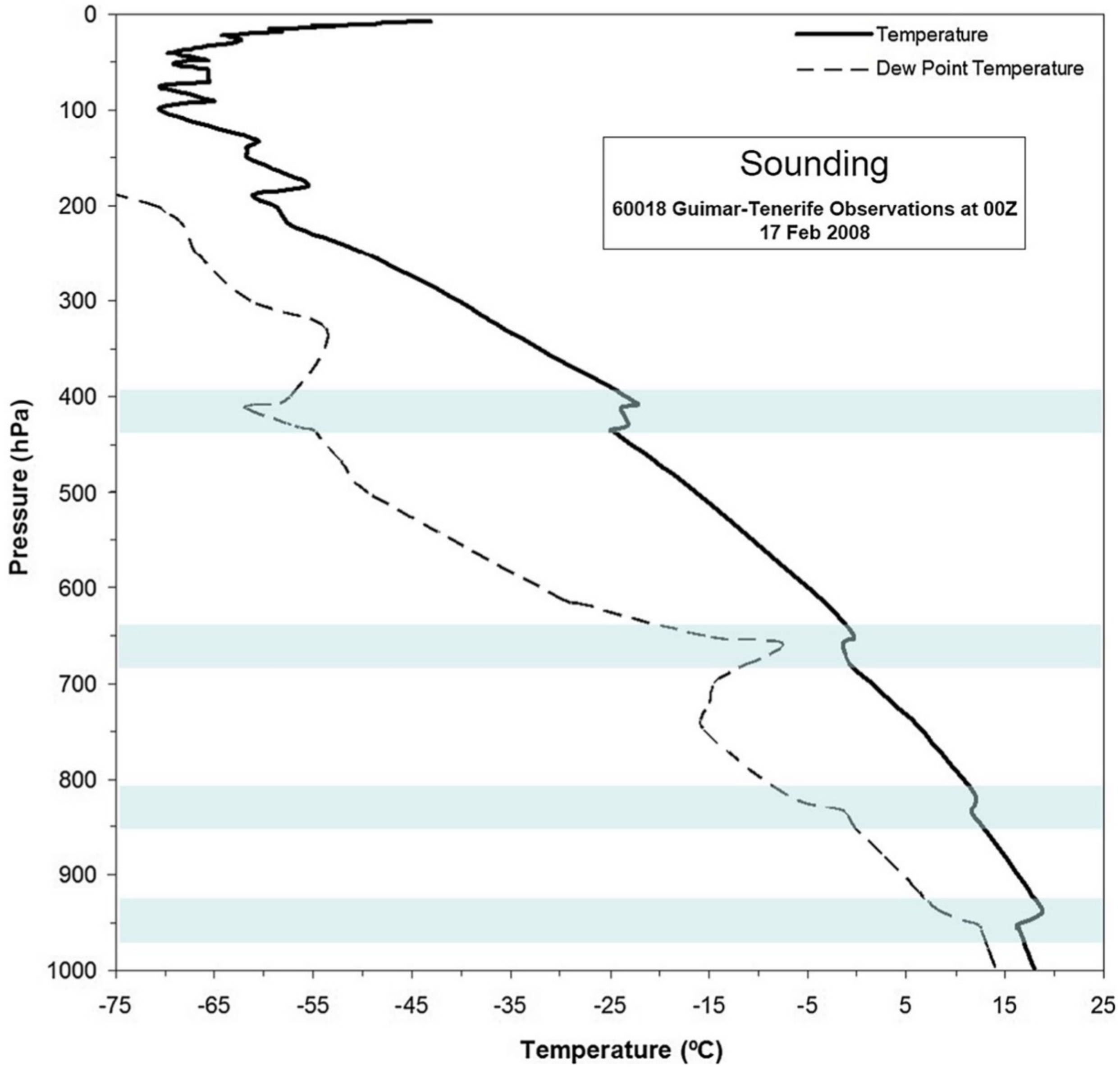
$$\rho(h) = \frac{PM}{RT} = \frac{P_0 M}{RT_0} \cdot \left(1 - \frac{L \cdot h}{T_0}\right)^{\frac{gM}{RL}-1} \approx \rho_0 \cdot e^{-\frac{h}{10.4\ \mathrm{km}}}$$



The truth is …

more complicated!

- Astronomical sites are normally characterized by temperature-inversion layers that "protect" the sites from humidity moving up to the telescopes.
- A closer look reveals more than one inversion layer (at least for La Palma)

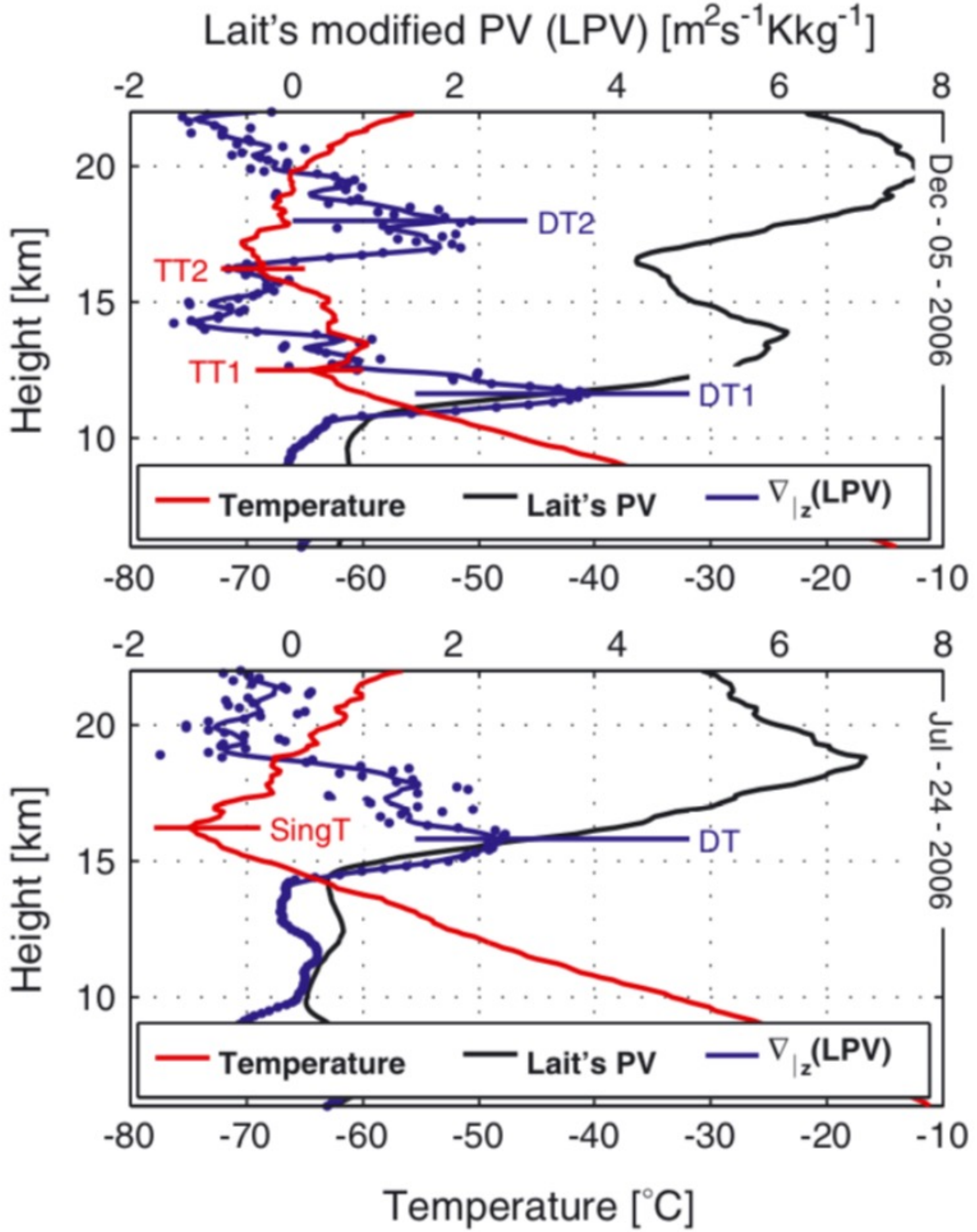


Carrillo J. et al., Boundary-Layer Meteorology 158 (2016) 311

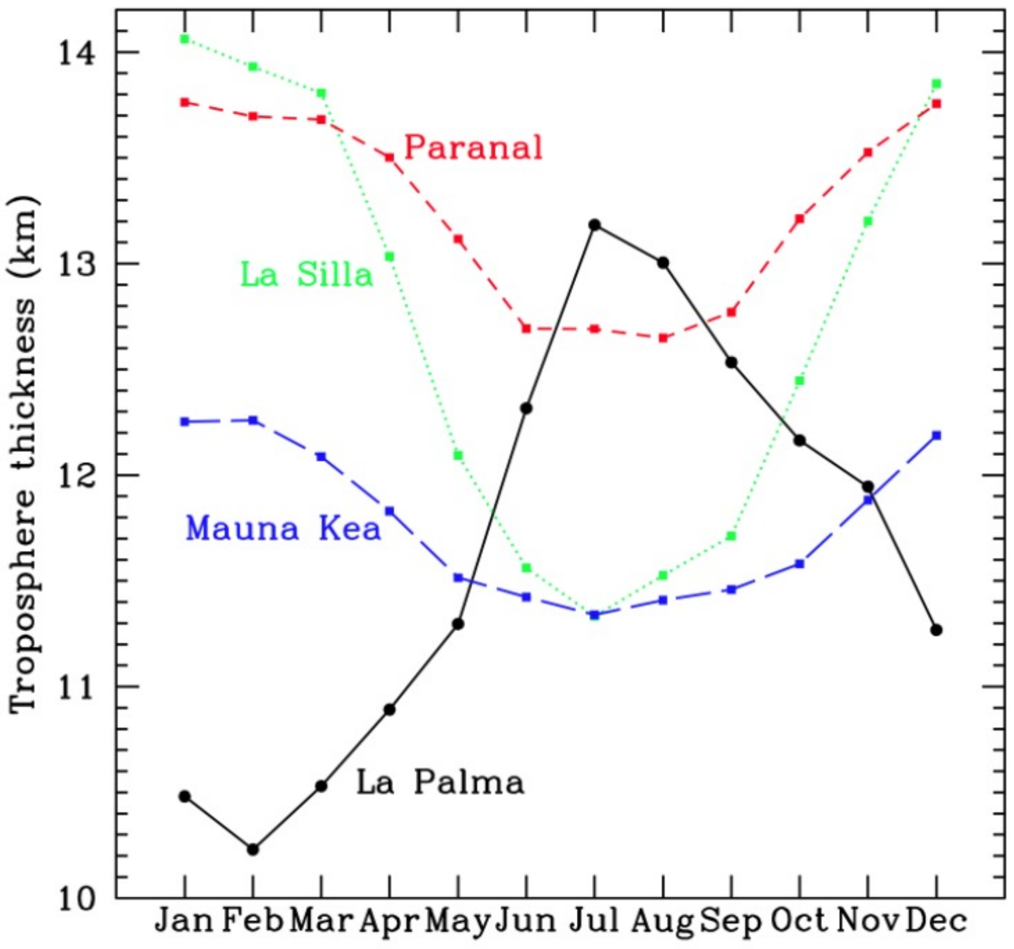
The truth is …

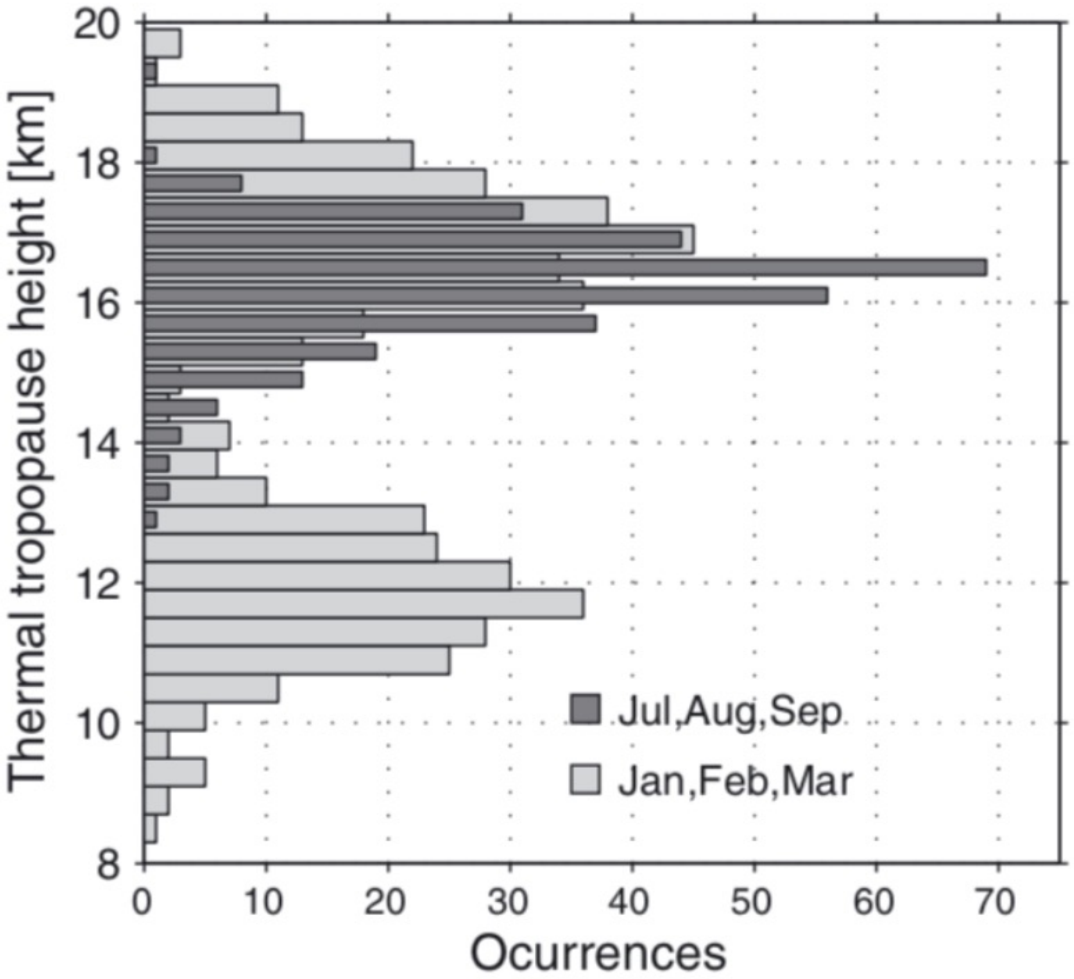
more complicated!

- Also the tropopause is NOT just one huge inversion layer.
- Rodríguez-Franco J.J. et al. (J. Geoph. Res: Atmos. 118 (2013) 10754) find **two or three "tropopauses"** most of the time and a **single tropopause** only during **July and August**.



“Height” of the tropopause





Link to air showers

Molecular scattering cross section depends on the refractive index of air!

$$\frac{\mathrm{d}\sigma(\phi,\theta,\lambda)}{\mathrm{d}\Omega} = \frac{9\pi^2(n^2(\lambda)-1)^2}{\lambda^4 N_s^2(n^2(\lambda)+2)^2}\left(\frac{6+3\rho}{6-7\rho}\right)\left(\frac{2+2\rho}{2+\rho}\right)\left(\sin^2(\phi)+\left(\frac{1-\rho}{1+\rho}\right)\cos^2(\phi)\cos^2(\theta)\right)$$

- Above equation can be simplified: $\rho \approx 0.028 \ll 1, (\mathrm{n}-1)_0 \approx 2.8\times 10^{-4}$

$$9\cdot\frac{\left(n^2-1\right)^2}{(n+2)^2} \approx 4(n-1)^2$$

and: $(n-1) \approx (n-1)_0(\lambda)\cdot N(h) = (n-1)_0(\lambda)\cdot\frac{P(h)}{P_0}\cdot\frac{T_0}{T(h)}$

- $\frac{d\sigma}{d\Omega} \approx \left(\frac{d\sigma}{d\Omega}\right)_0 \cdot \frac{P(h)}{P_0}\cdot\frac{T_0}{T(h)}$, residual dependency on humidity, $CO_2 < 0.5\%$

Tomasi C., et al., AO 44 (2005) 3320

Link to air showers

Cherenkov angle depends on the refractive index of air!

$$\cos\theta_c = \frac{1}{\beta \ \cdot n(h)}$$

- Above equation can be simplified (for $\beta \rightarrow 1$):

$$\theta_c \approx \sqrt{2 \cdot (n-1)} \ \propto \sqrt{2(n-1)_0(\lambda) \cdot \frac{P(h)}{P_0} \cdot \frac{T_0}{T(h)}} \approx 0.024 \cdot \sqrt{\frac{P(h)}{P_0} \cdot \frac{T_0}{T(h)}}$$

- Illuminated area on ground scales as $\theta_c^2 \propto \frac{P(h)}{P_0} \cdot \frac{T_0}{T(h)}$

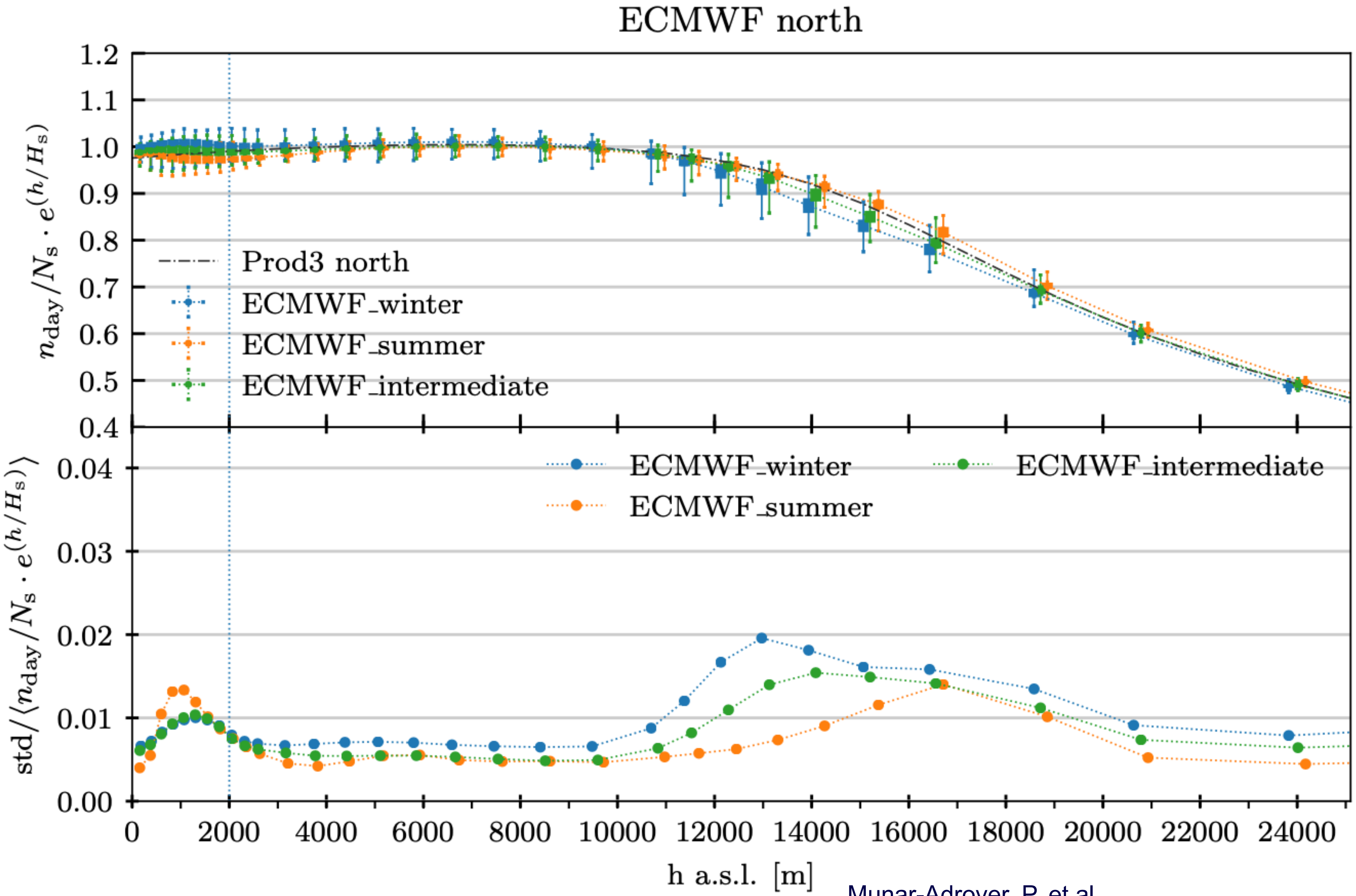
- Amount of Cherenkov light emitted: $\propto \sin{\theta_c}^2 \approx \theta_c^2 \propto \frac{P(h)}{P_0} \cdot \frac{T_0}{T(h)}$

Tomasi C., et al., AO 44 (2005) 3320

Molecular Profiles

Global Data Assimilation Systems

- These (historical) data sets and weather predictions are free!
- American Global Forecast System (GFS)
- European Center for Medium Weather Forecast (ECMWF)



Munar-Adrover, P. et al.,
EPJ Web of Conf. 197 (2019) 01002

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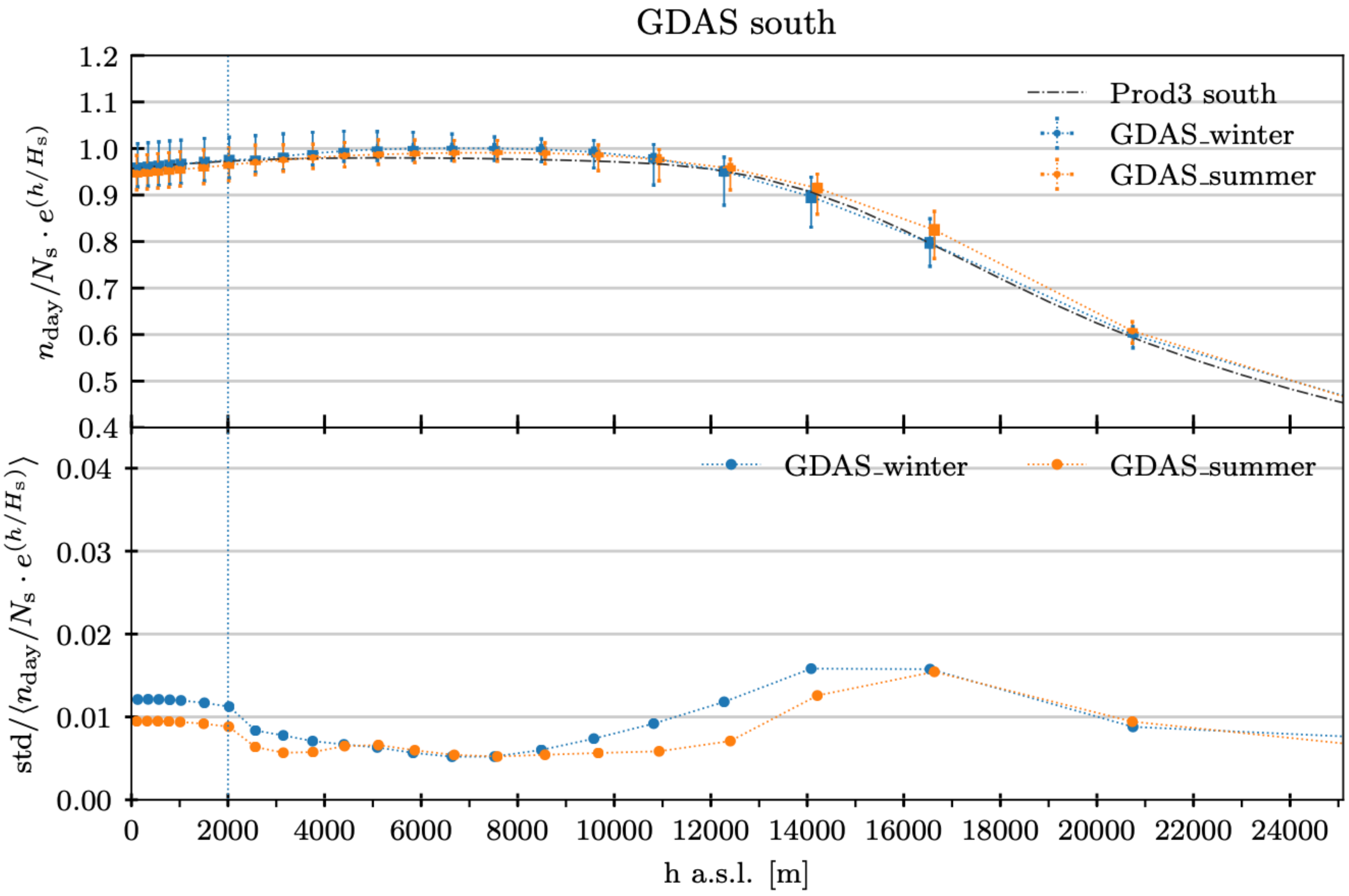
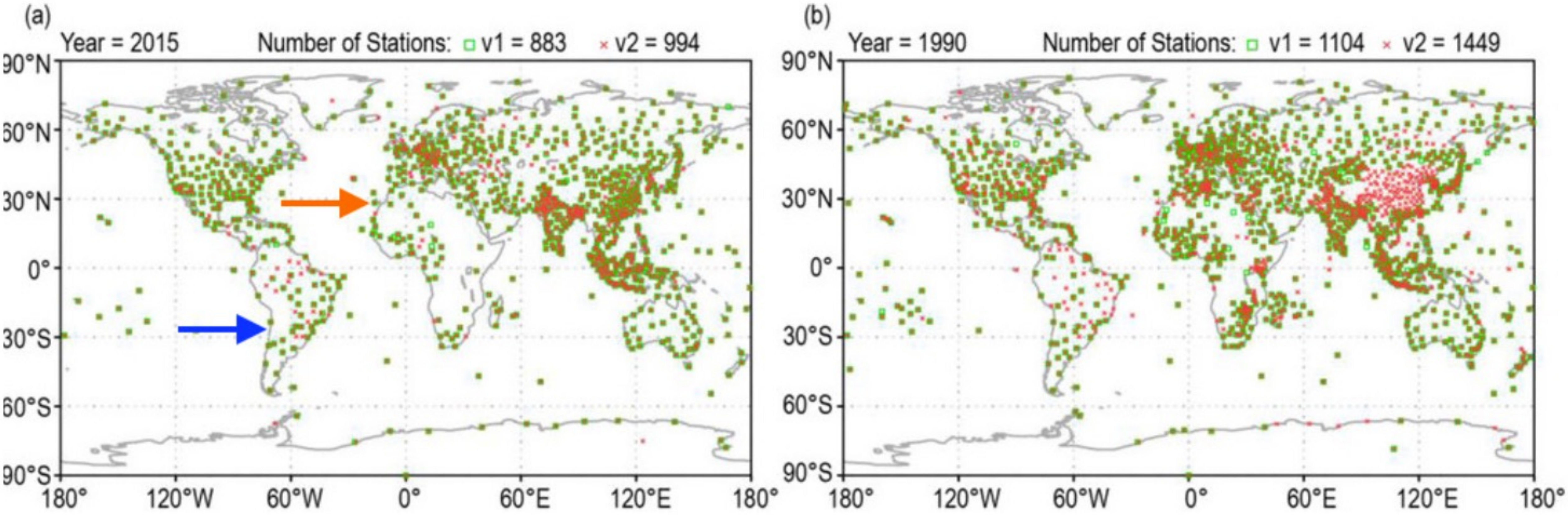


Munar-Adrover, P. et al.,
EPJ Web of Conf. 197 (2019) 01002

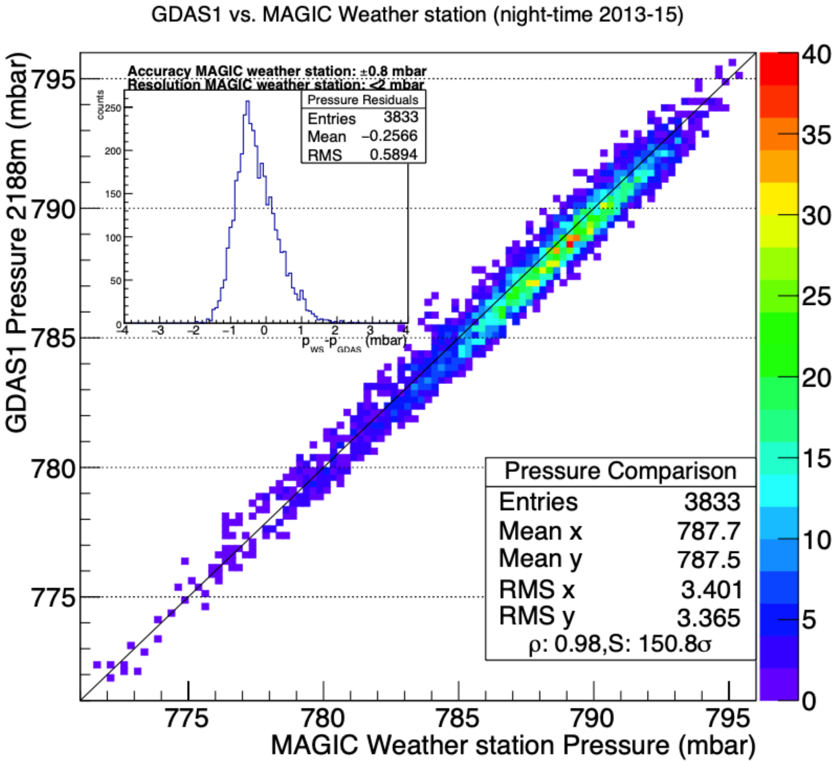
The truth is… more complicated!

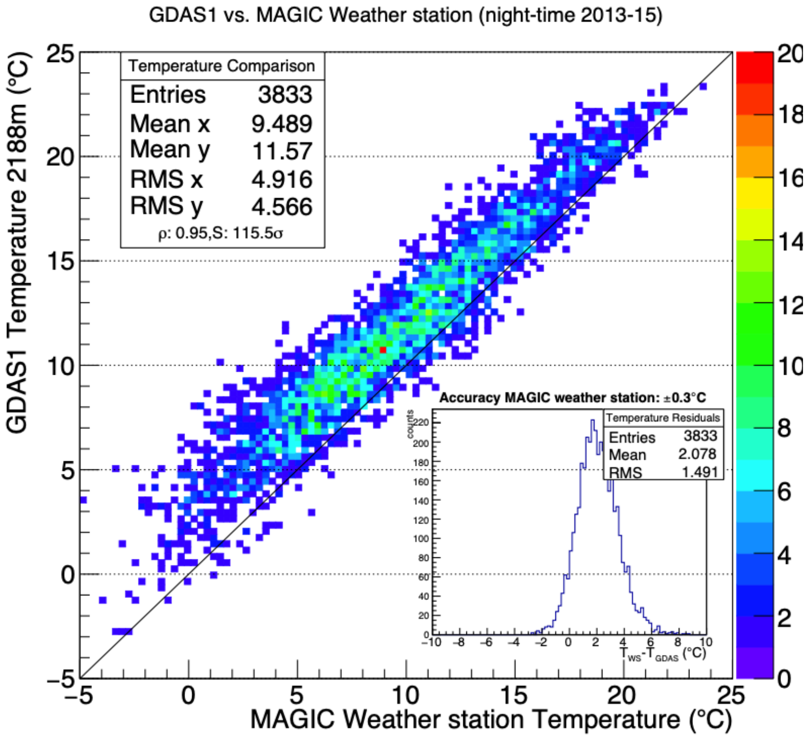


Locations of IGRA 1 (green) and IGRA 2 (red) radio sounding stations during the years of (a) 2015, (b) 1990. A clear trend towards lower sounding coverage over the past years is observed, among other regions, in central South America. The CTAO sites are marked by the green (CTAO-N) and blue (CTAO-S) arrow.

Figures from Durre I., Yin X., Vose R.S. *et al.* (2018). J. Atm. & Oc. Techn. 35, 1753.

The truth is… more complicated!

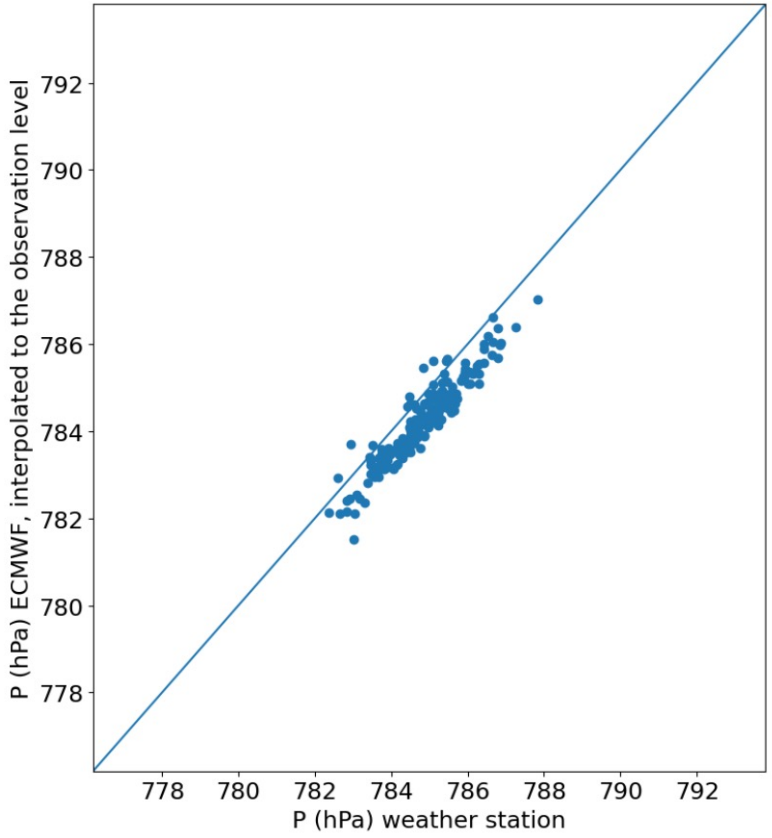


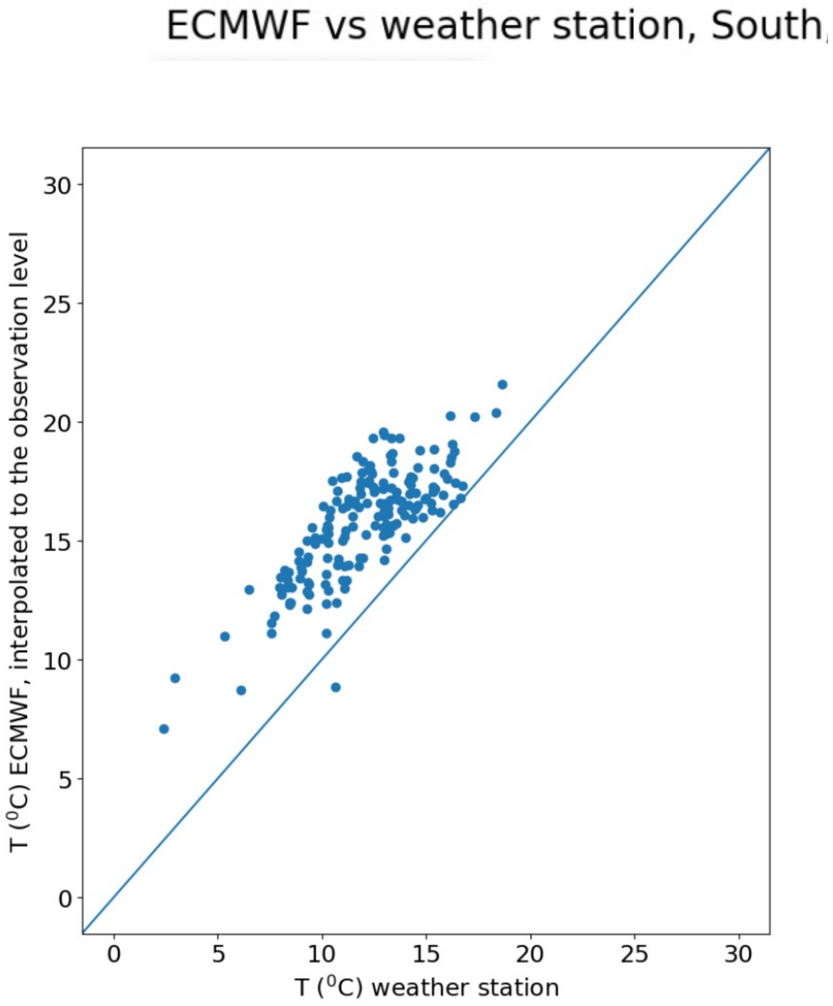


Ground validation of GDAS profiles for CTAO-N

MG et al., EPJ Web of Conf. 144 (2017) 01010

The truth is… more complicated!

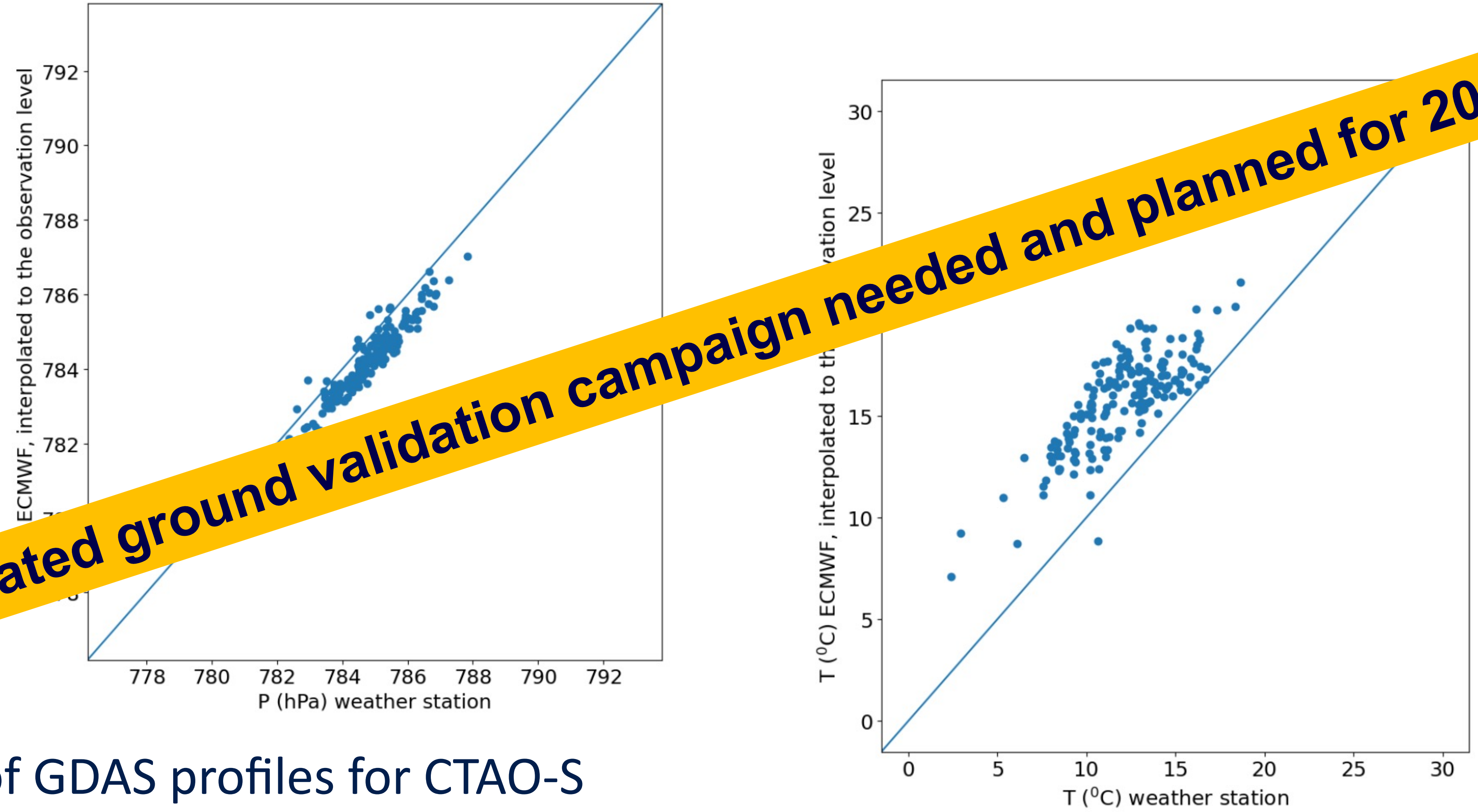




Ground validation of GDAS profiles for CTAO-S

Georgios Voutsinas, priv. comm.

The truth is... more complicated!

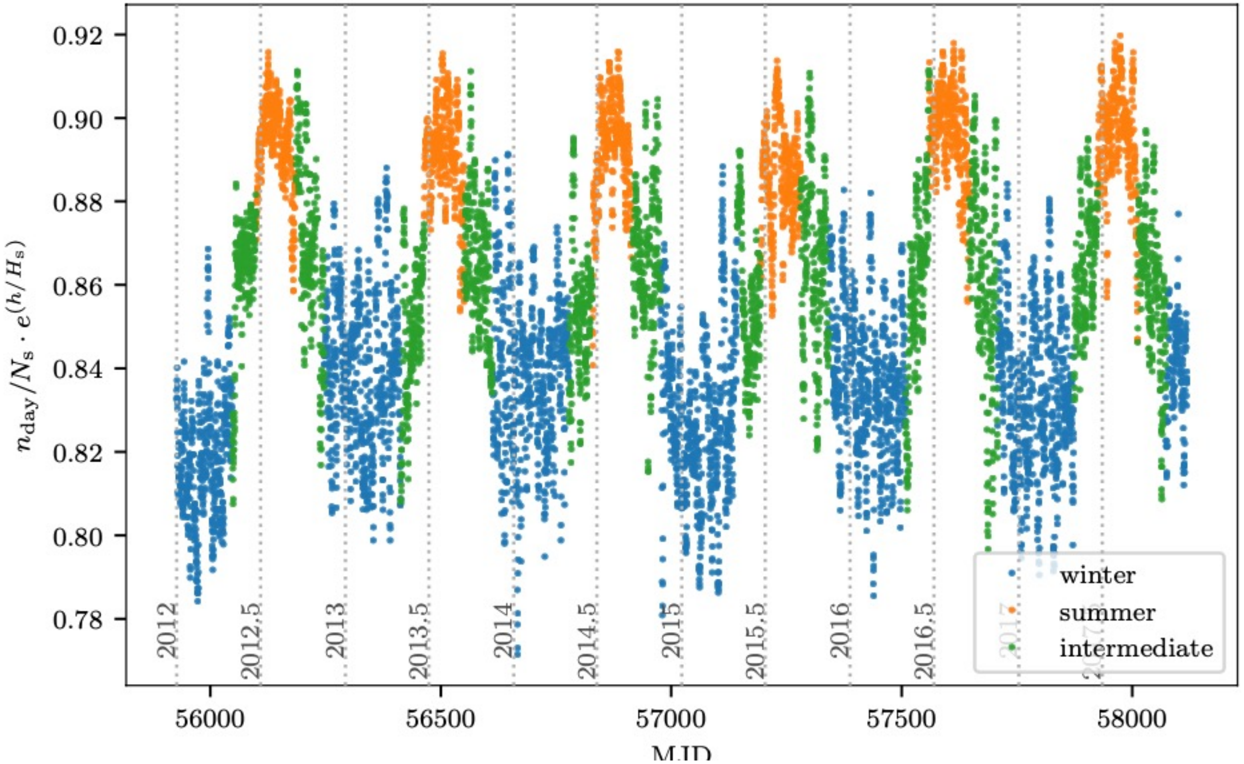


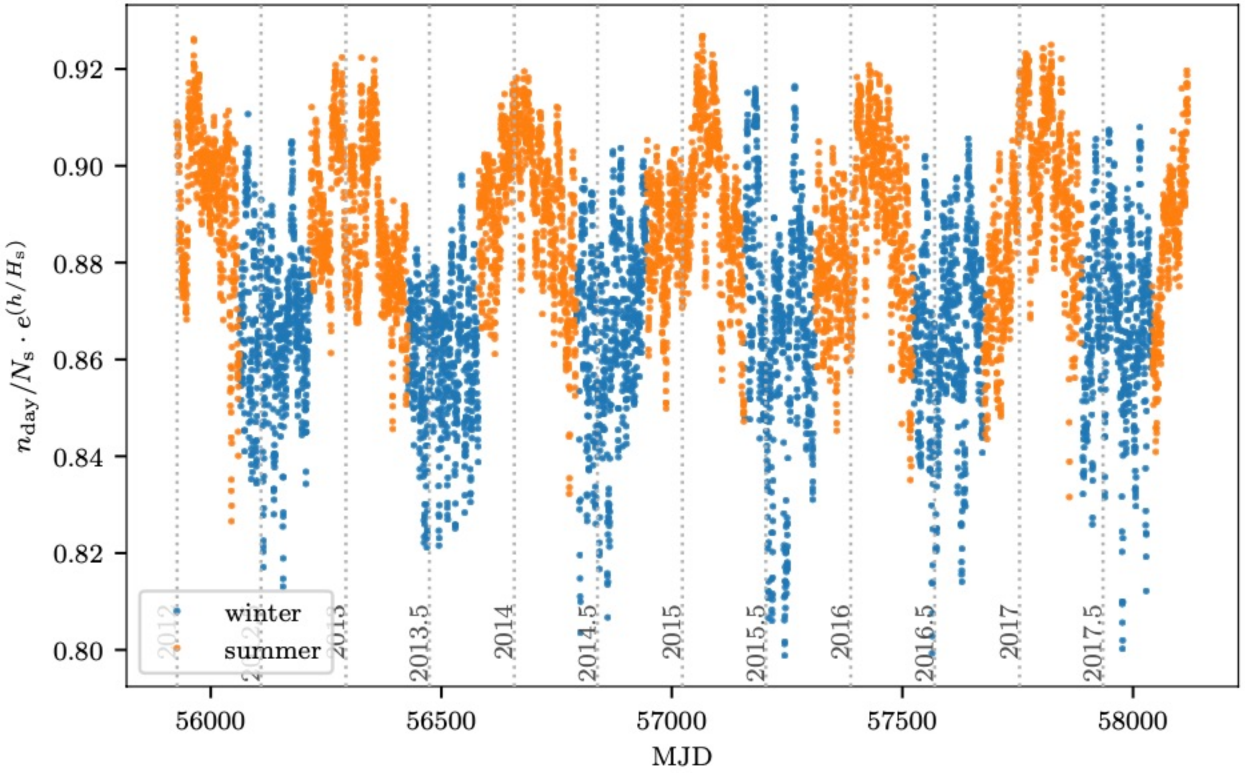
Dedicated ground validation campaign needed and planned for 2025 !

Ground validation of GDAS profiles for CTAO-S

Georgios Voutsinas, priv. comm.

Air density at the tropopause

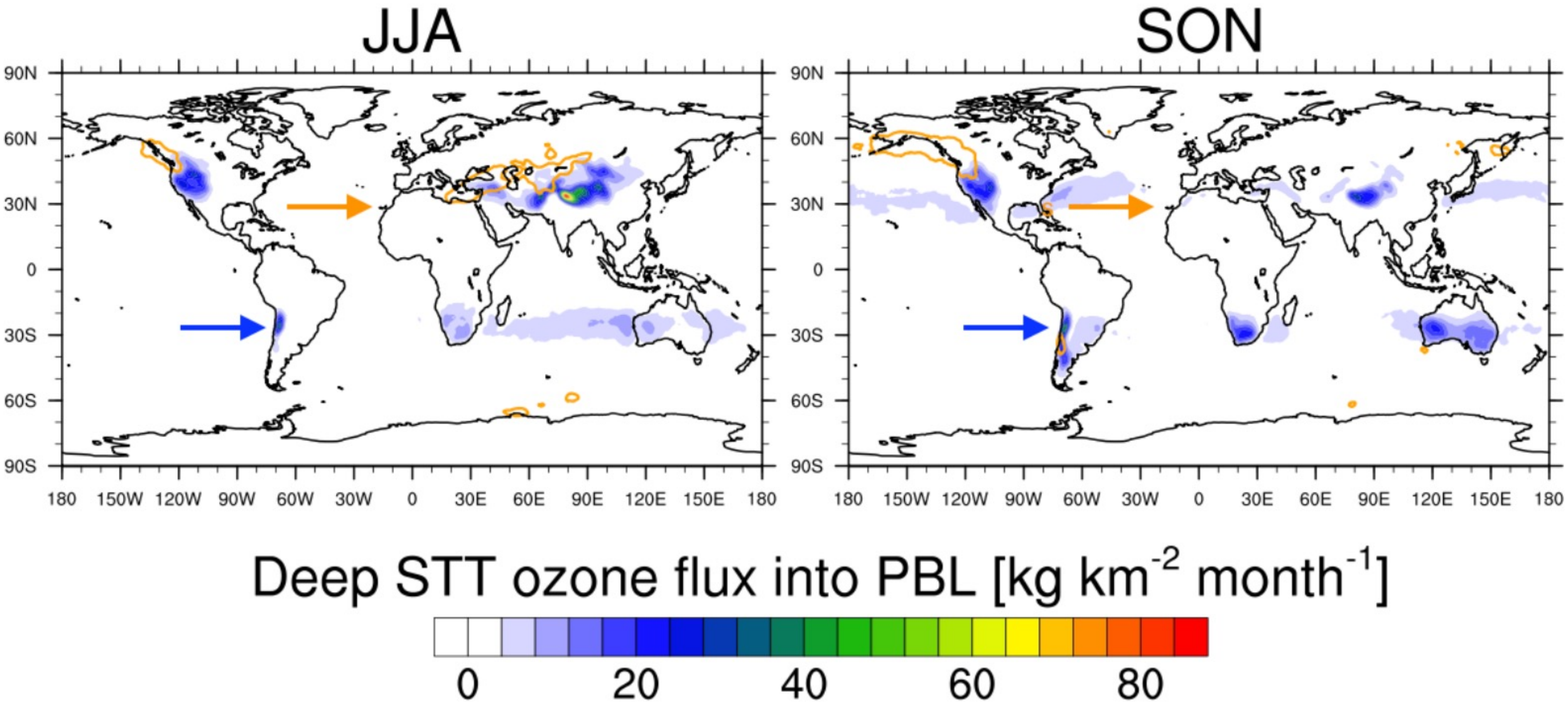




- CTAO will simulate 2 (South) or 3 (North) reference profiles

Munar-Adrover, P. et al.,
EPJ Web of Conf. 197 (2019) 01002

Ozone intrusions into the troposphere



- CTAO-S seems to be a hot spot for stratospheric ozone intrusions into the troposphere. The effect on absorption of Cherenkov light seems to be <2% though.

Skerlak B . et al., Atmos. Chem. Phys. 14 (2014) 913

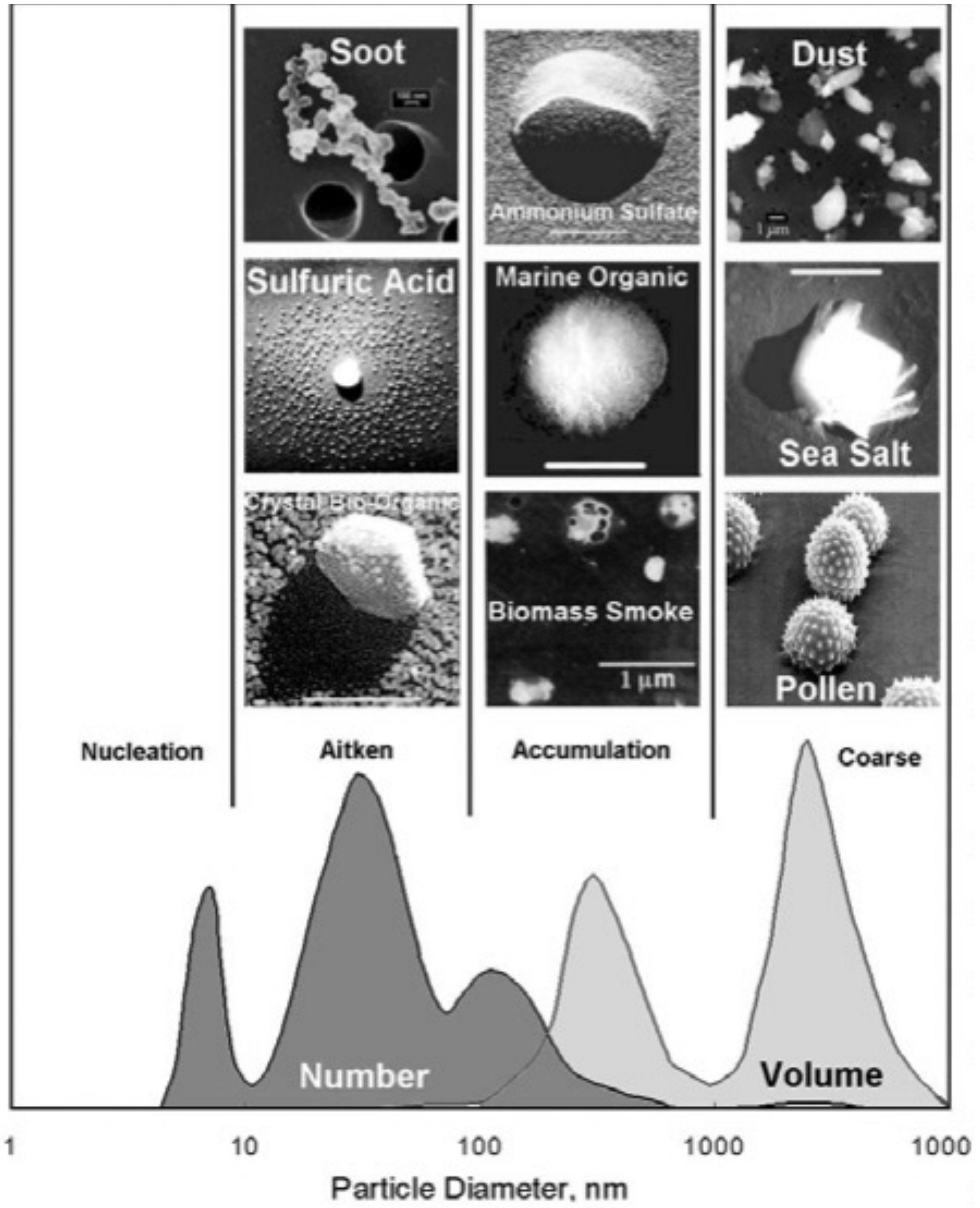
Aerosols and Clouds

Aerosols

Aerosols are any type of particle:

- Larger than molecules
- Suspended in air

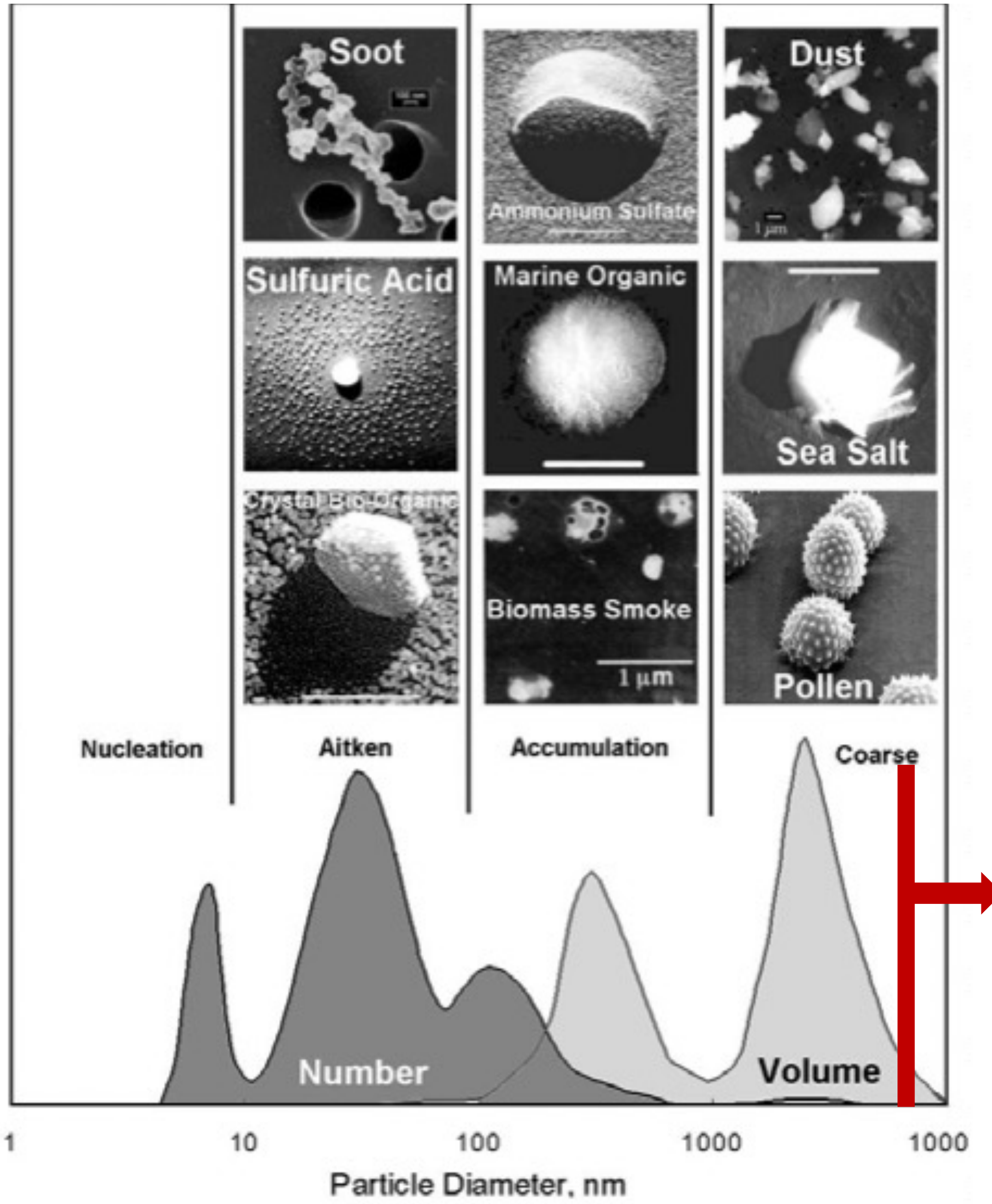
- Normally found close to the ground (in the **planetary boundary layer**)
- Remain in air for up to 20 days



Aerosols

Local aerosols are measured as concentrations of particles exceeding a given diameter:

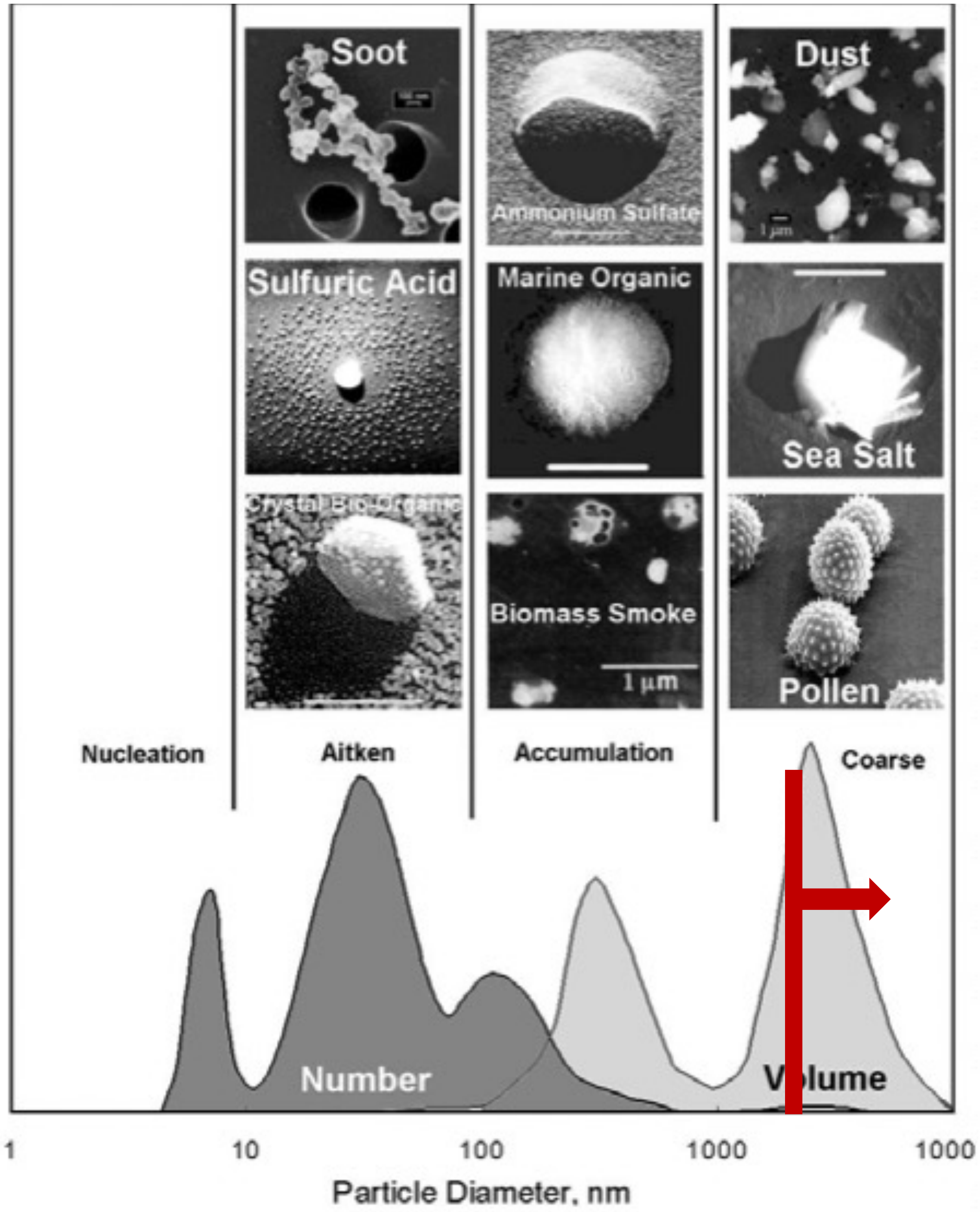
- PM10: Particles larger than 10μm



Aerosols

Local aerosols are measured as concentrations of particles exceeding a given diameter:

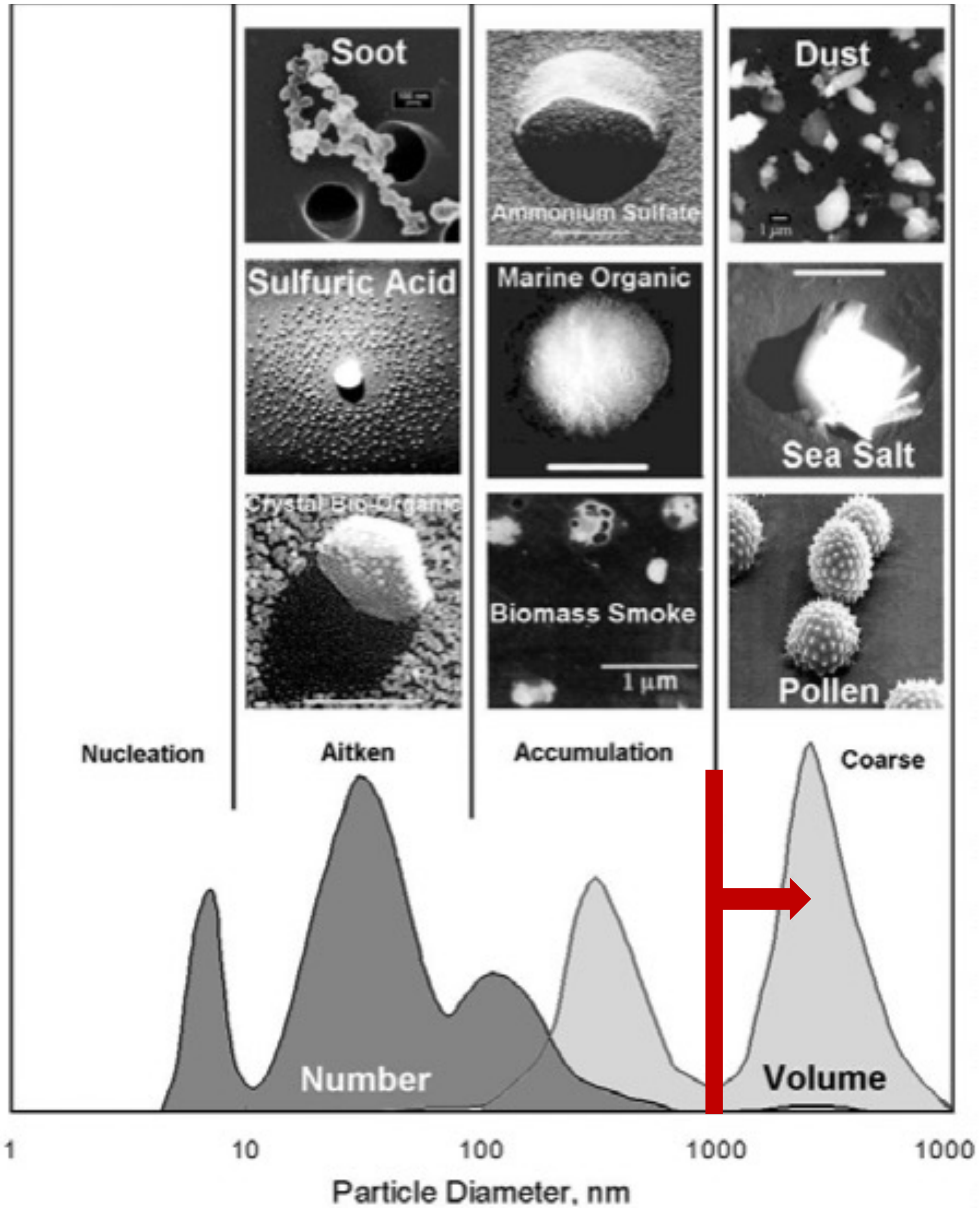
- PM10: Particles larger than 10μm
- PM2.5: Particles larger than 2.5μm



Aerosols

Local aerosols are measured as concentrations of particles exceeding a given diameter:

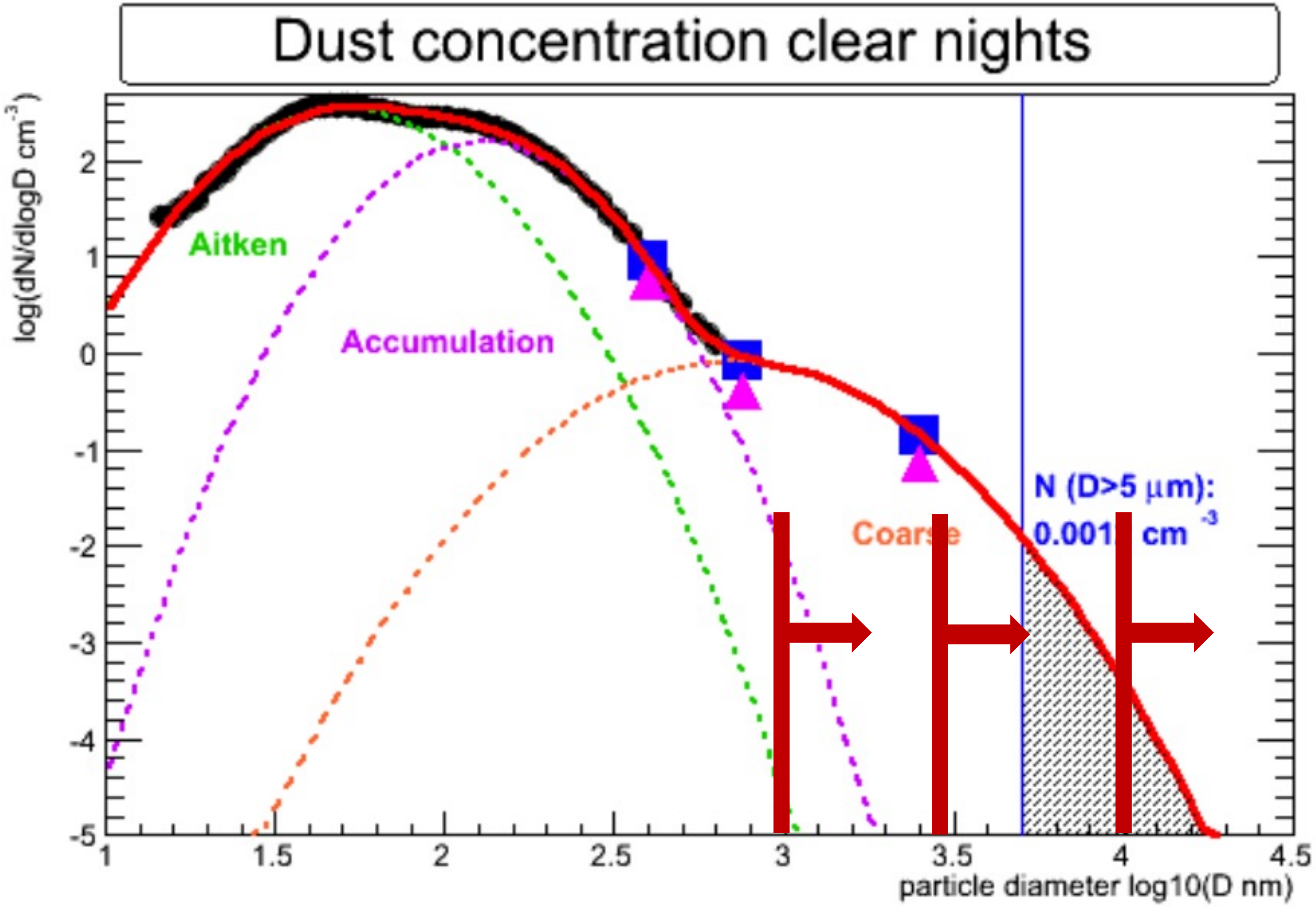
- PM10: Particles larger than 10 μm
- PM2.5: Particles larger than 2.5 μm
- PM1: Particles larger than 1 μm



Aerosols

Local aerosols are measured as concentrations of particles exceeding a given diameter:

- PM10: Particles >10 μm
- PM2.5: Particles >2.5 μm
- PM1: Particles >1 μm

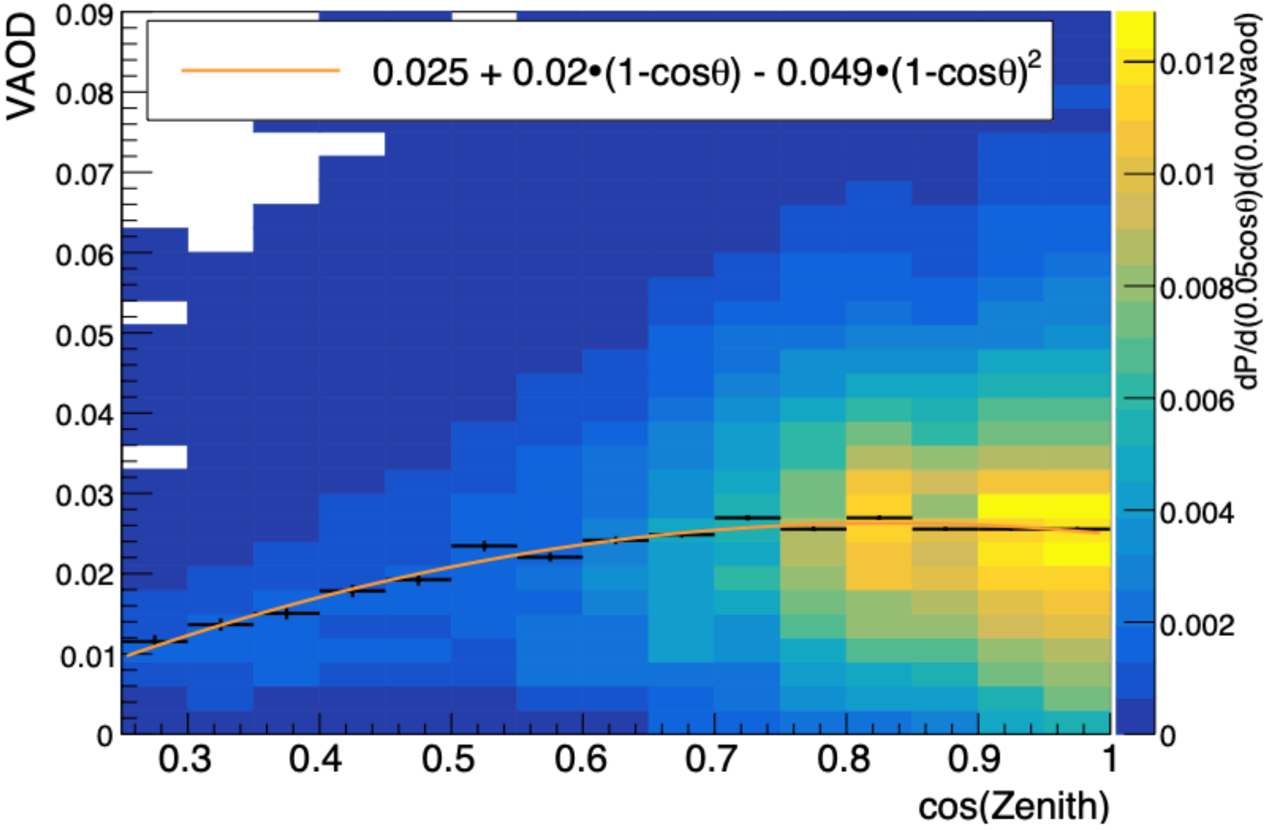


Clear night at ORM

Aerosols

Remote aerosols are measured in terms of **Aerosol Optical Depth (AOD)** or **Vertical Aerosol Optical Depth (VAOD)**

$$T_{\mathrm{aer}} = e^{-\mathrm{AOD}} = e^{-\int_0^h \alpha(h')dh'}$$



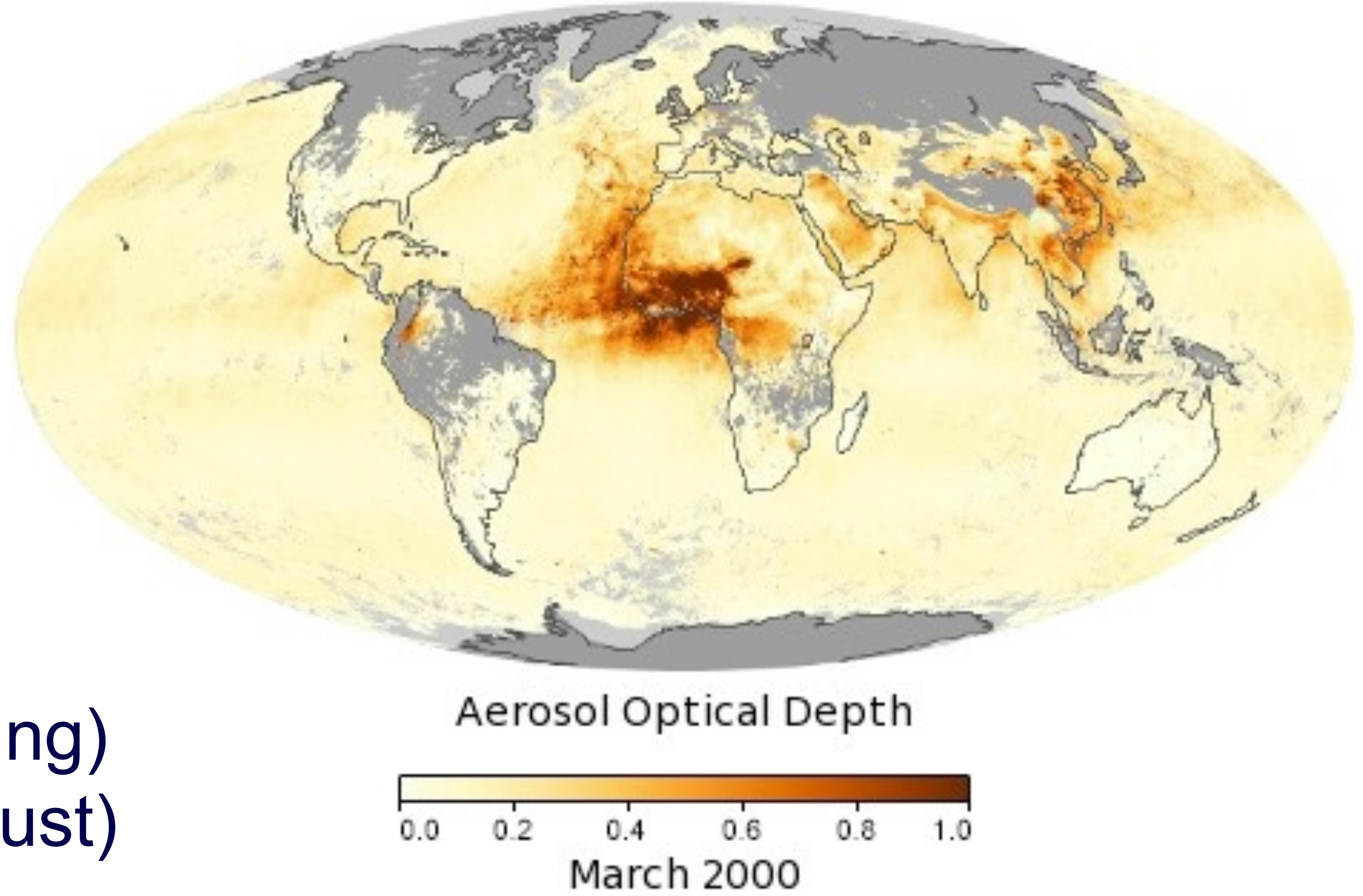
Clear night at ORM

Aerosols

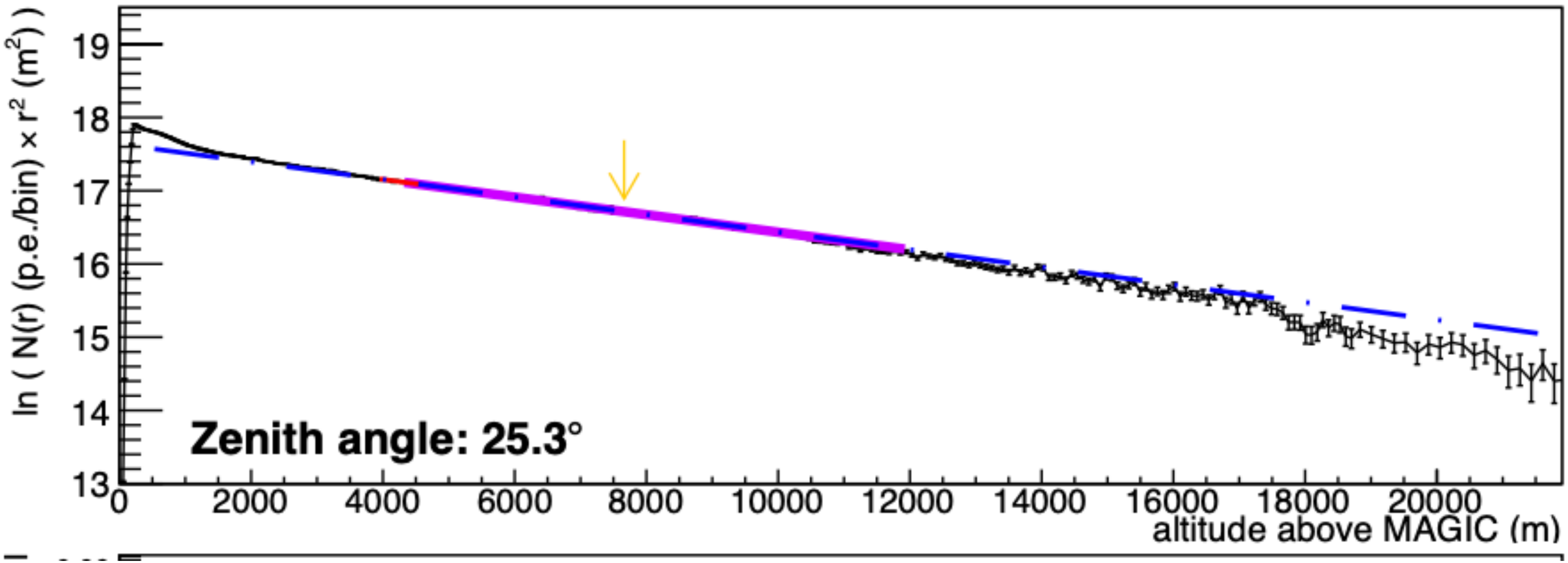
come from:

- Sea (maritime aerosols)
- Volcanic eruptions
- Stratospheric

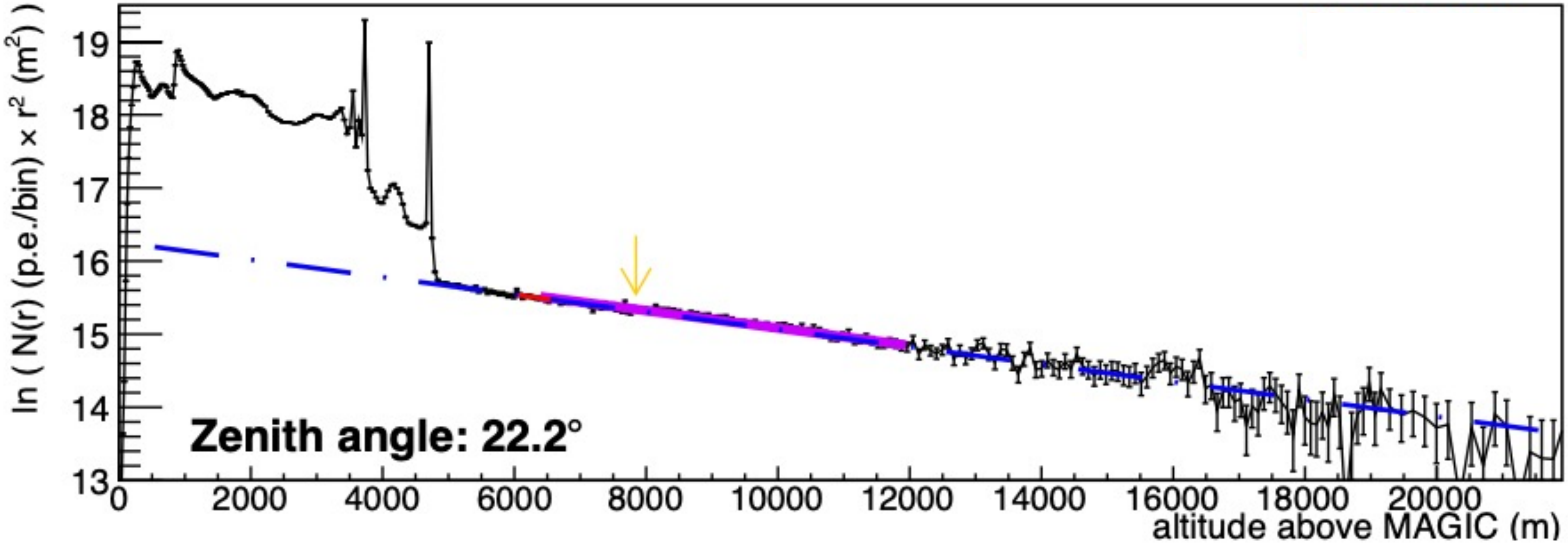
- Deserts
- Wood fires (biomass burning)
- Industrial activities (soot/dust)
- Transport



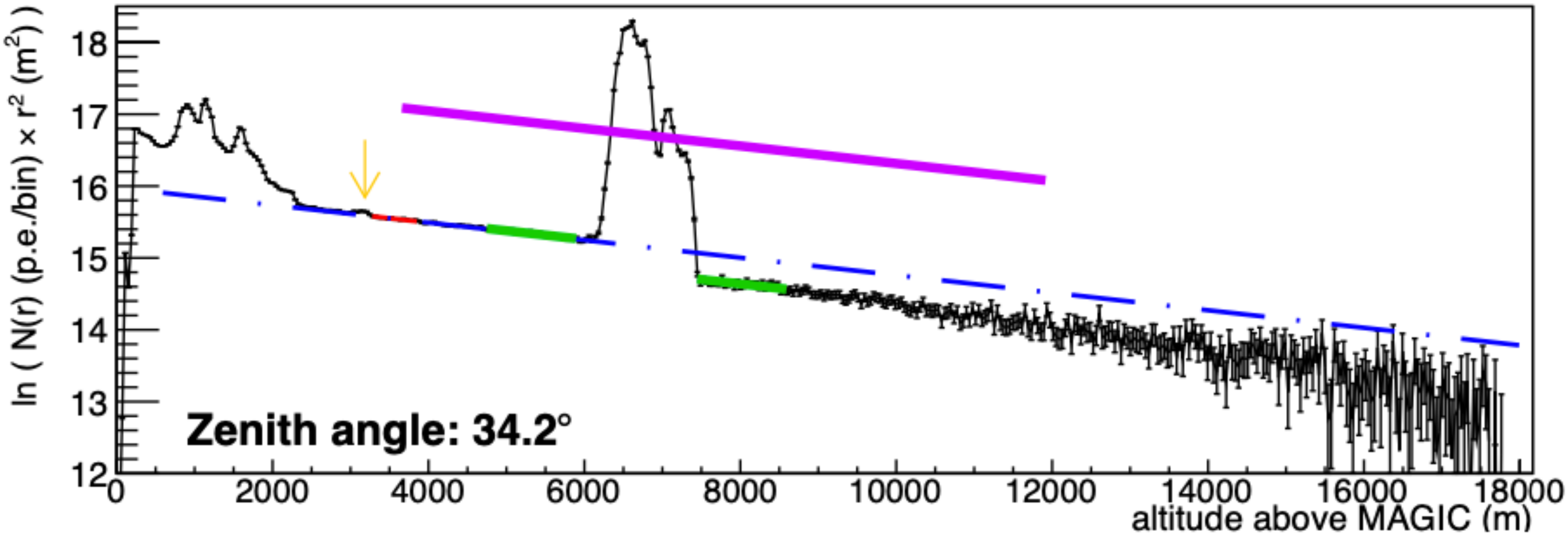
Normally, the atmosphere above both observatories are considered ultra-clean



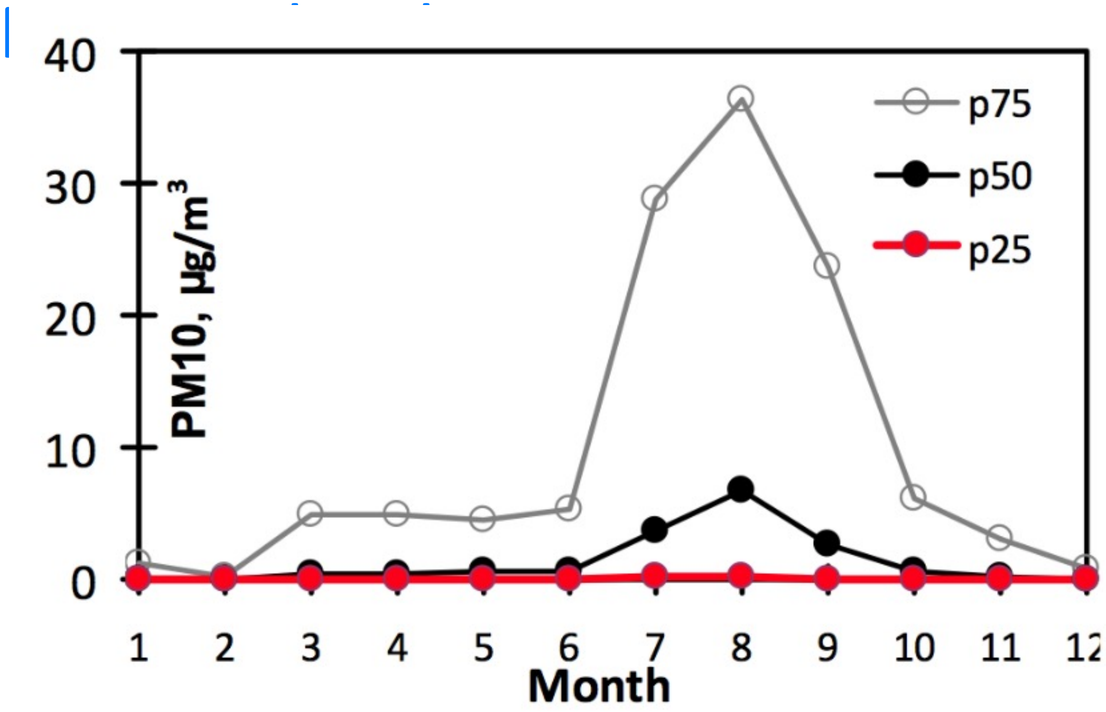
Occasionally, particularly during summer or during February, Saharan dust intrusions may appear.



Dust intrusions may also be accompanied by clouds.

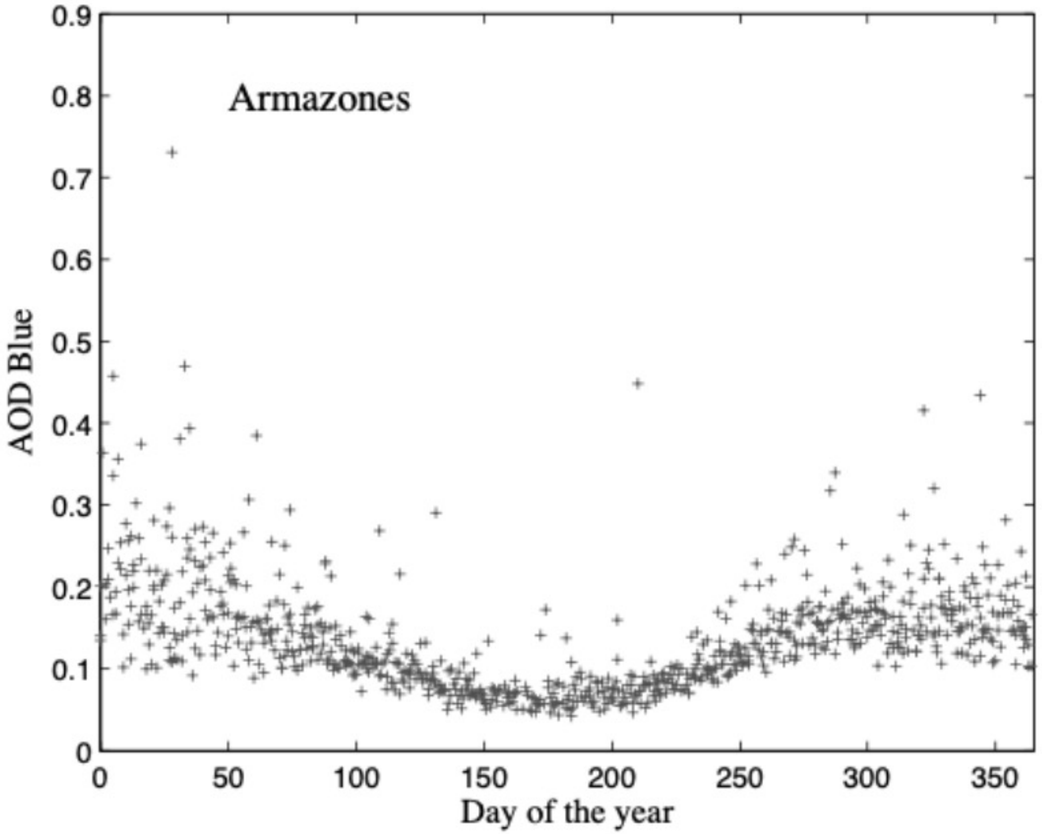


Frequency of dust intrusions

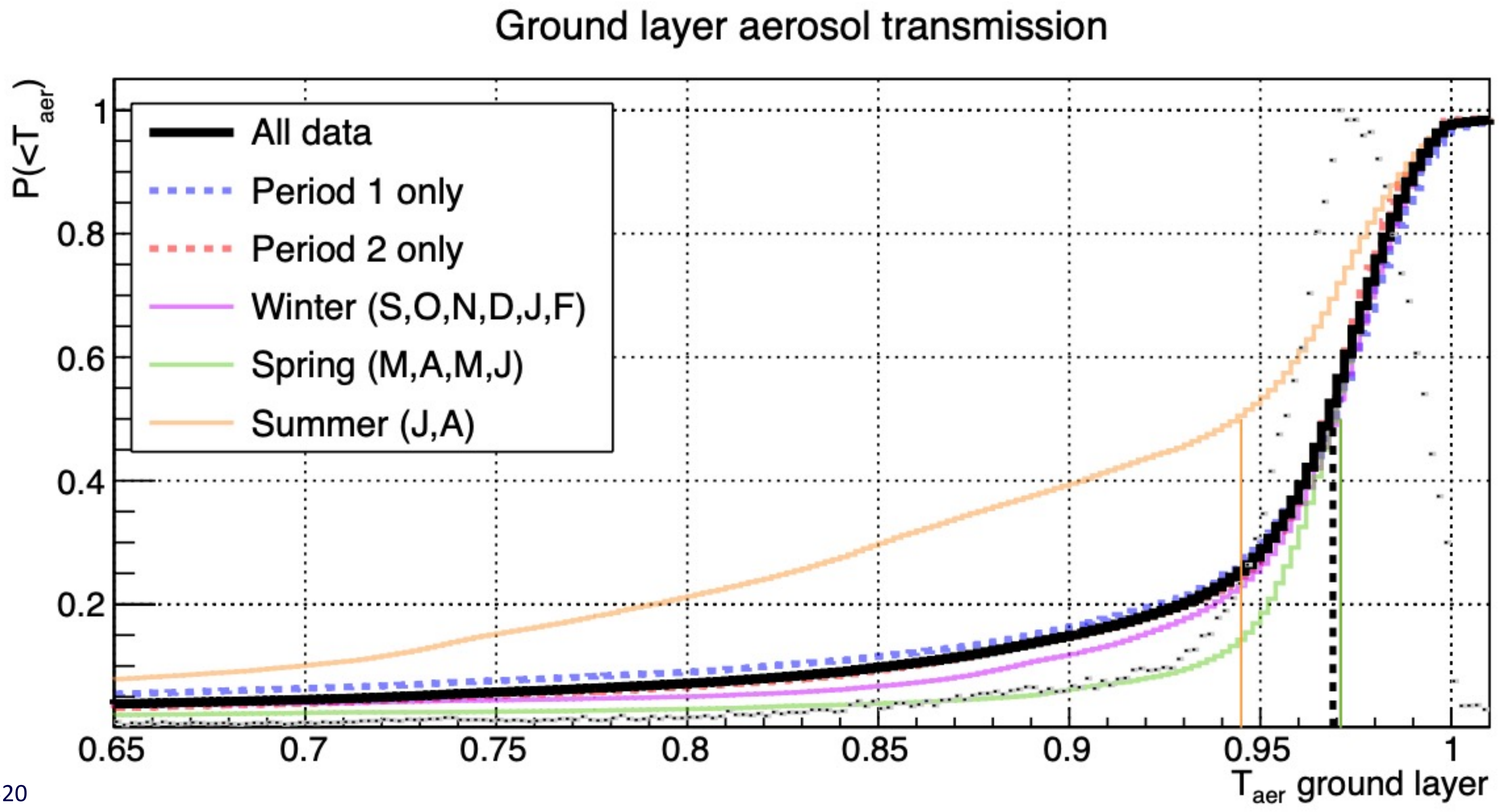


Seasonal variations for the 25th, 50th, 75th percentile of PM10 measured at IZO.

Cuevas E. *Report on the incidence of african dust intrusions at the astronomical observatories of the canary islands: characterization and temporal analysis*

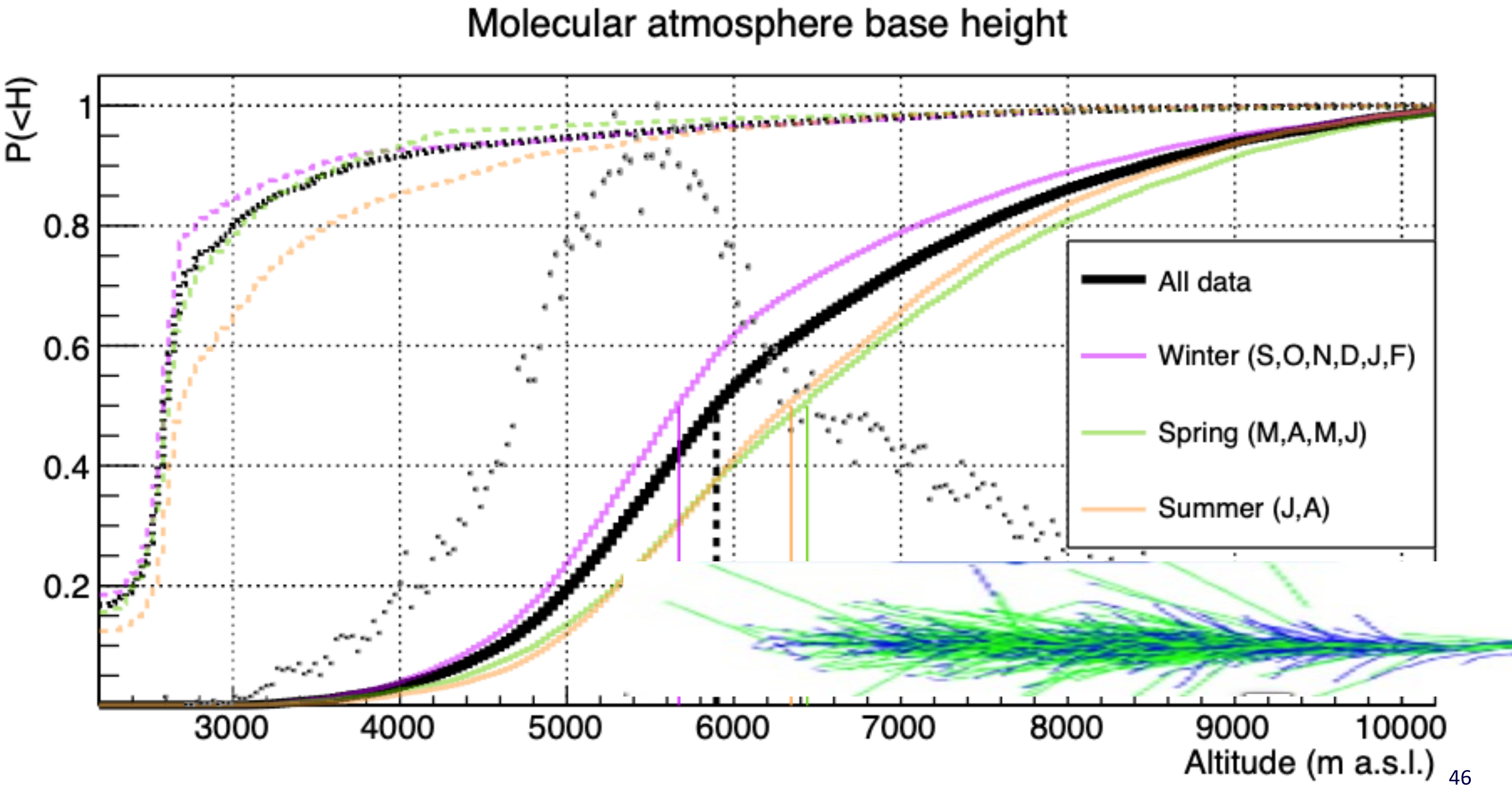


Frequency of dust intrusions



Fruck C. et al., MNRAS 515 (2022) 4520

Height of dust intrusions



Fruck C. et al., MNRAS 515 (2022) 4520

Clouds

Characterization of optical properties

Clouds are measured in terms of **Optical Depth (OD)** or **Vertical Optical Depth (VOD)**

$$T_{\mathrm{aer}} = e^{-\mathrm{OD}} = e^{-\int_{h_{\mathrm{min}}}^{h_{\mathrm{max}}} \alpha(h')dh'}$$

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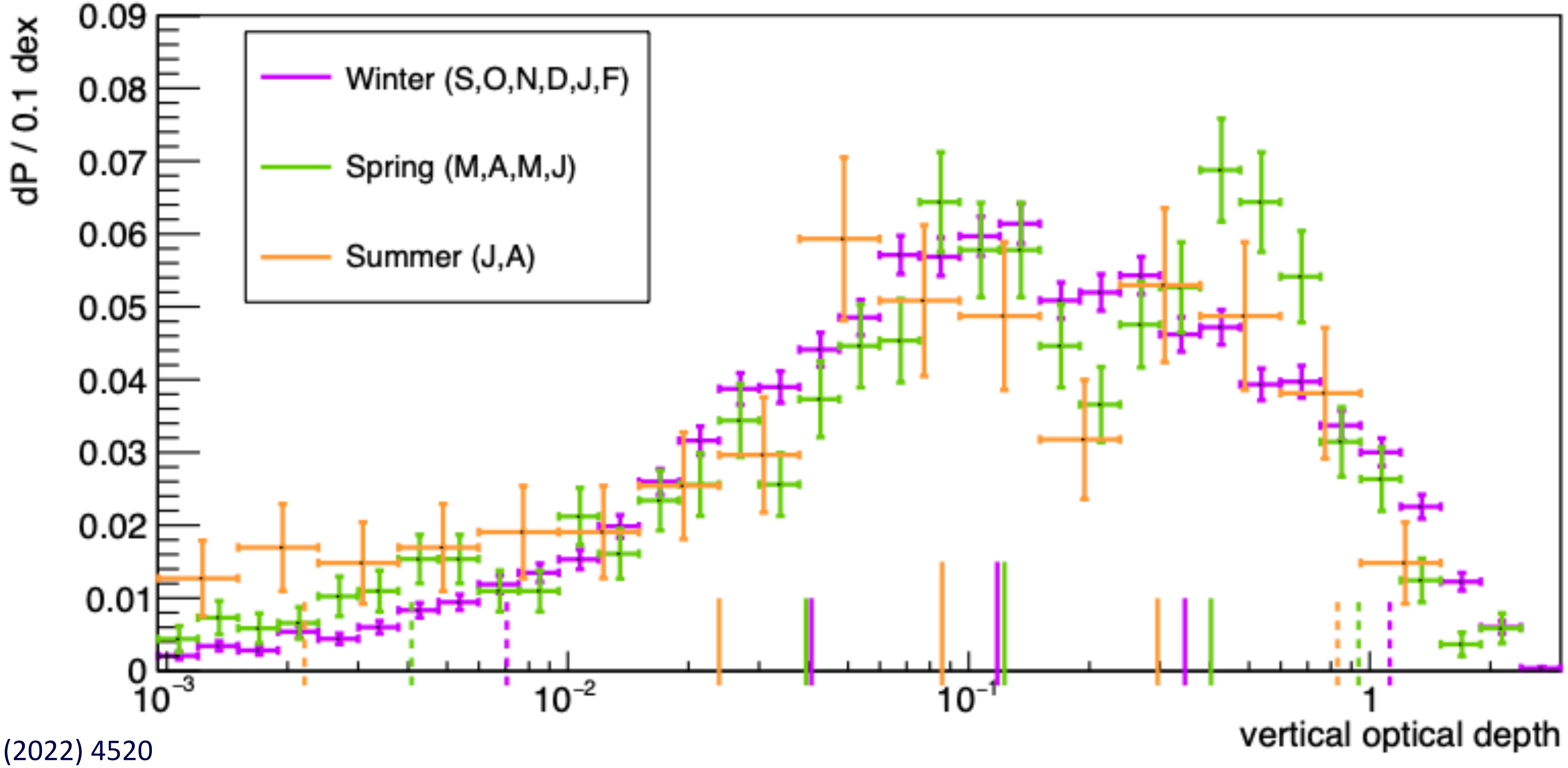
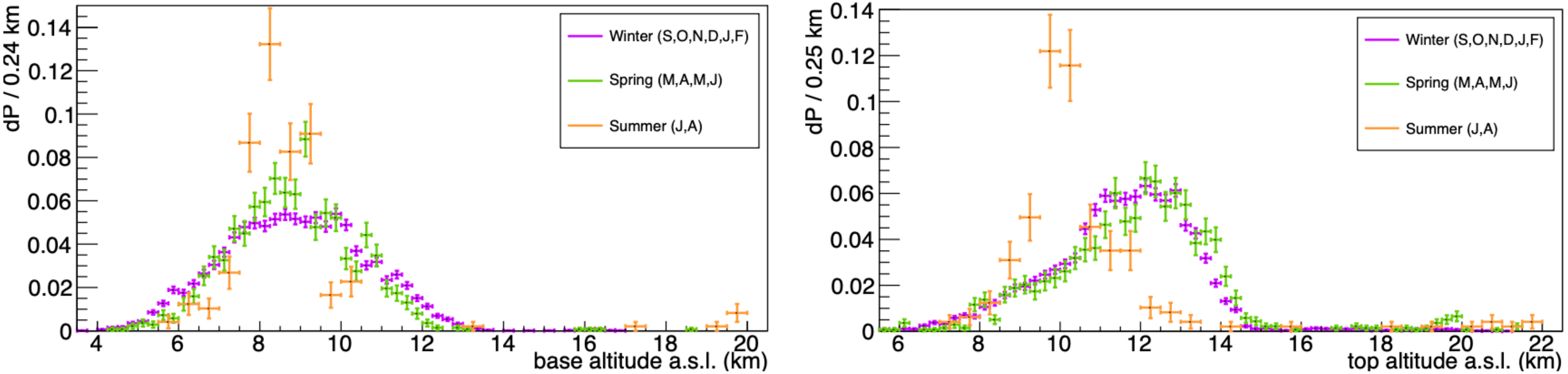


Fruck C. et al., MNRAS 515 (2022) 4520

Clouds

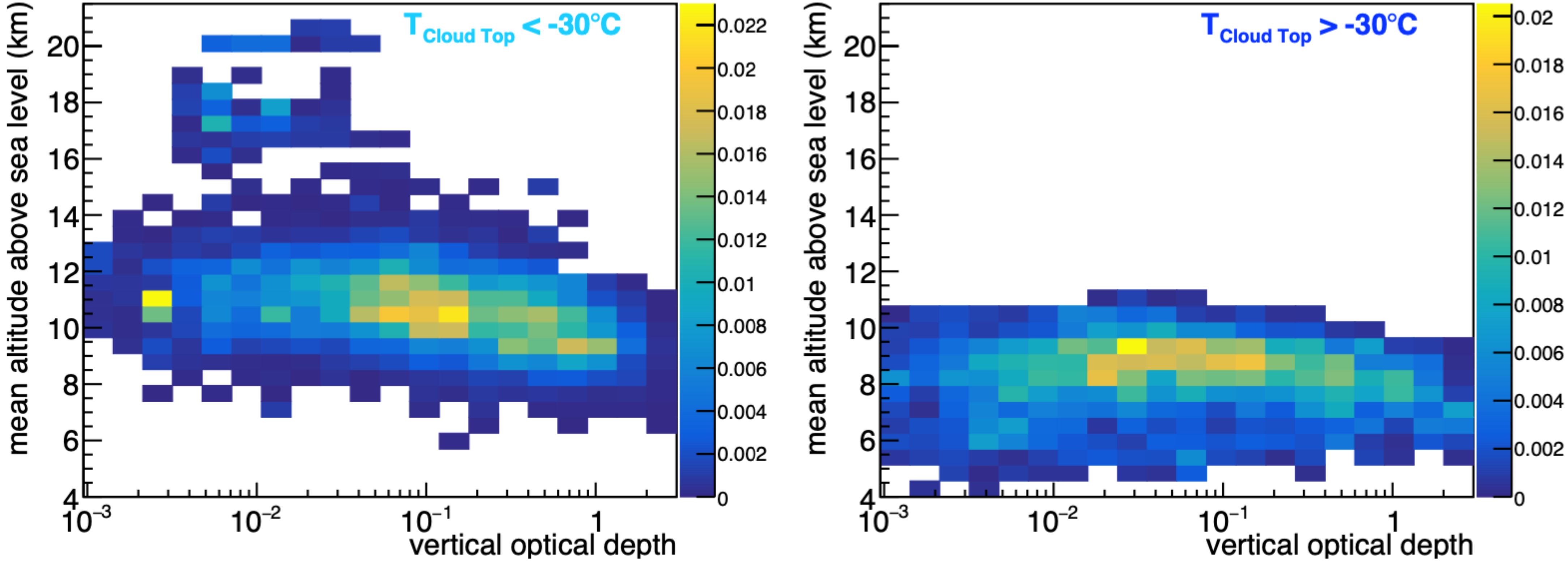
Clouds heights are measured from their base to top



Fruck C. et al., MNRAS 515 (2022) 4520

Clouds

Normally, higher clouds are thinner and less opaque



Fruck C. et al., MNRAS 515 (2022) 4520

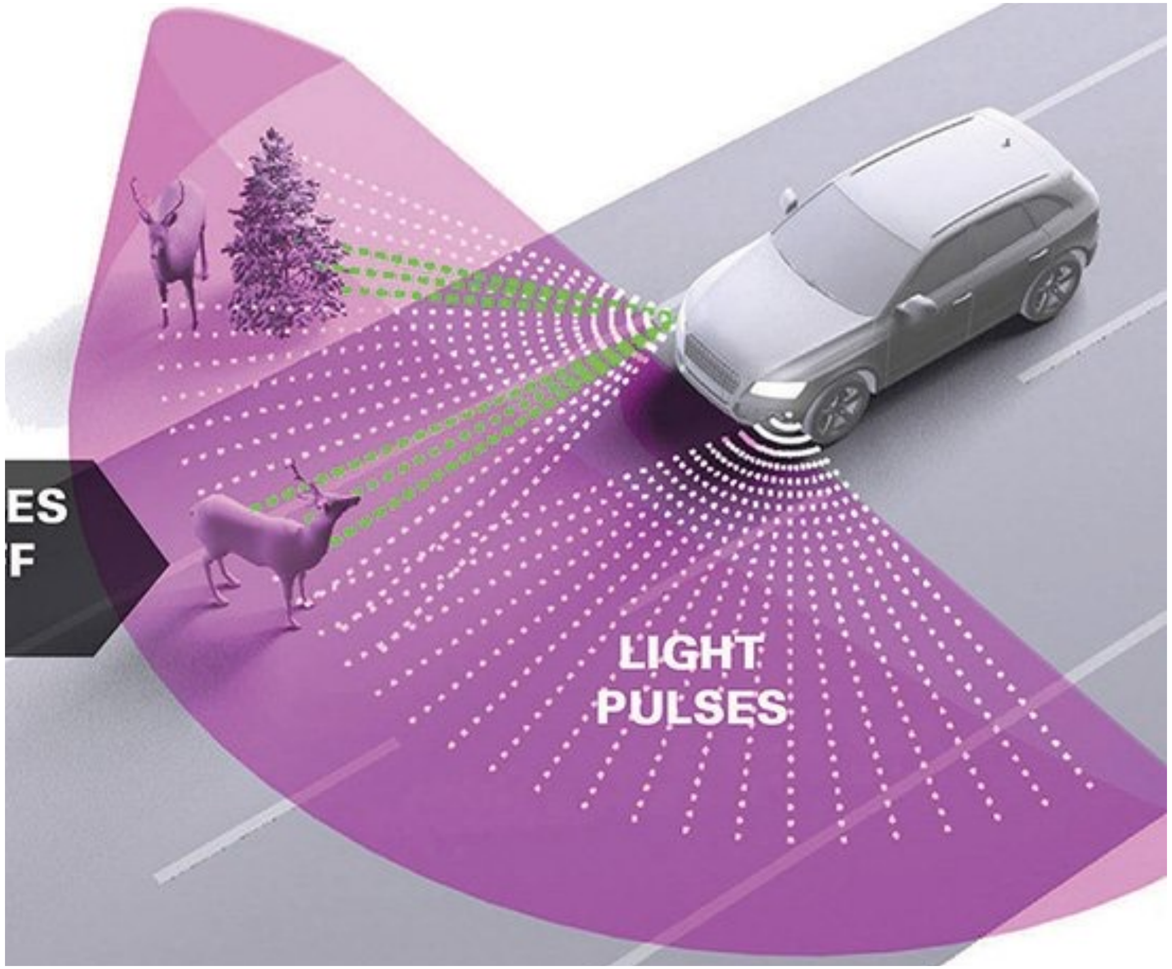
Monitoring Instruments

LIDAR (LIght Detection And Ranging

Operation principles

A LIDAR always consists of a:

- Pulsed Laser
- Light Collector (Telescope)
- Light Detector (PMT)
- DAQ
- Analysis Software



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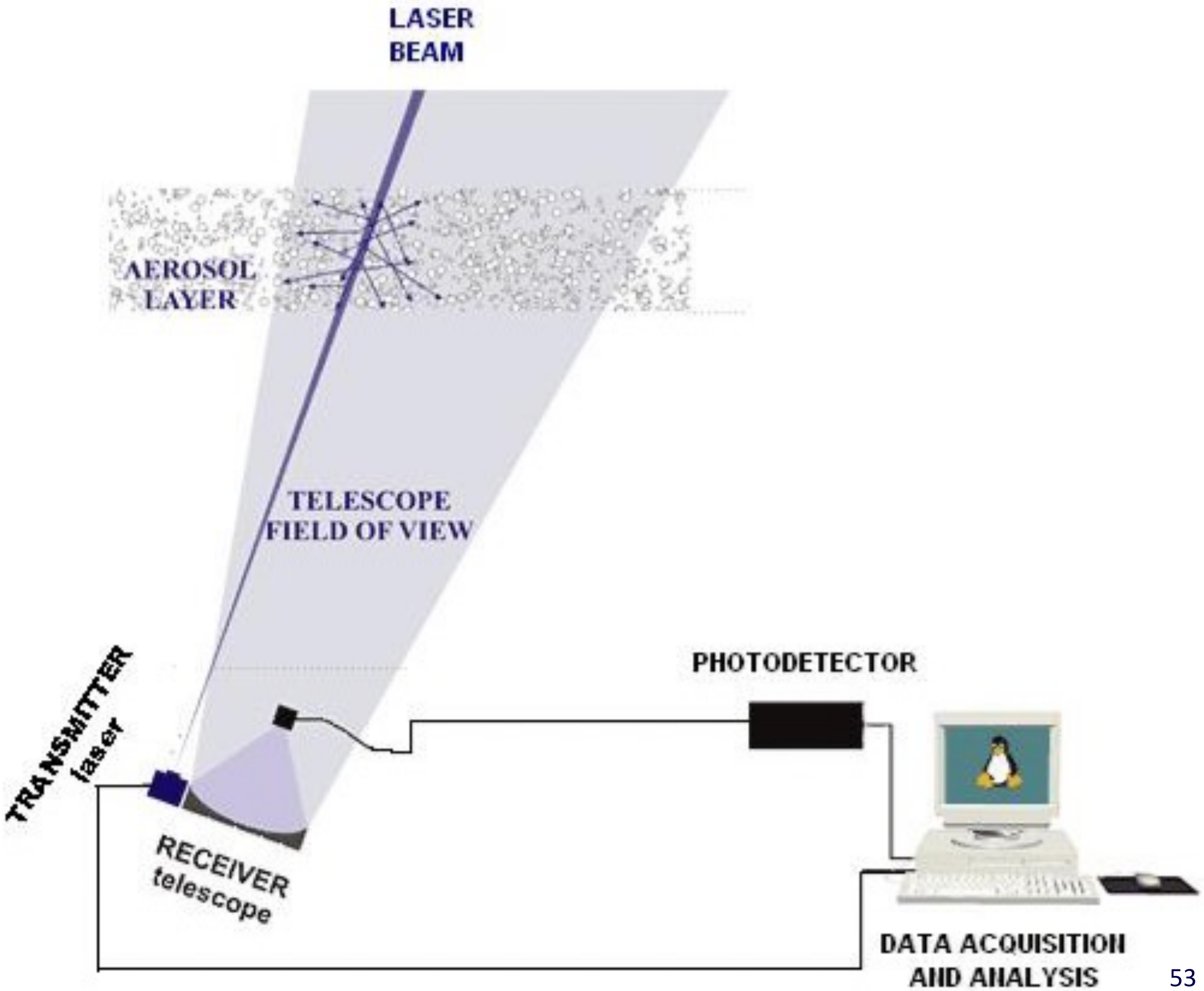
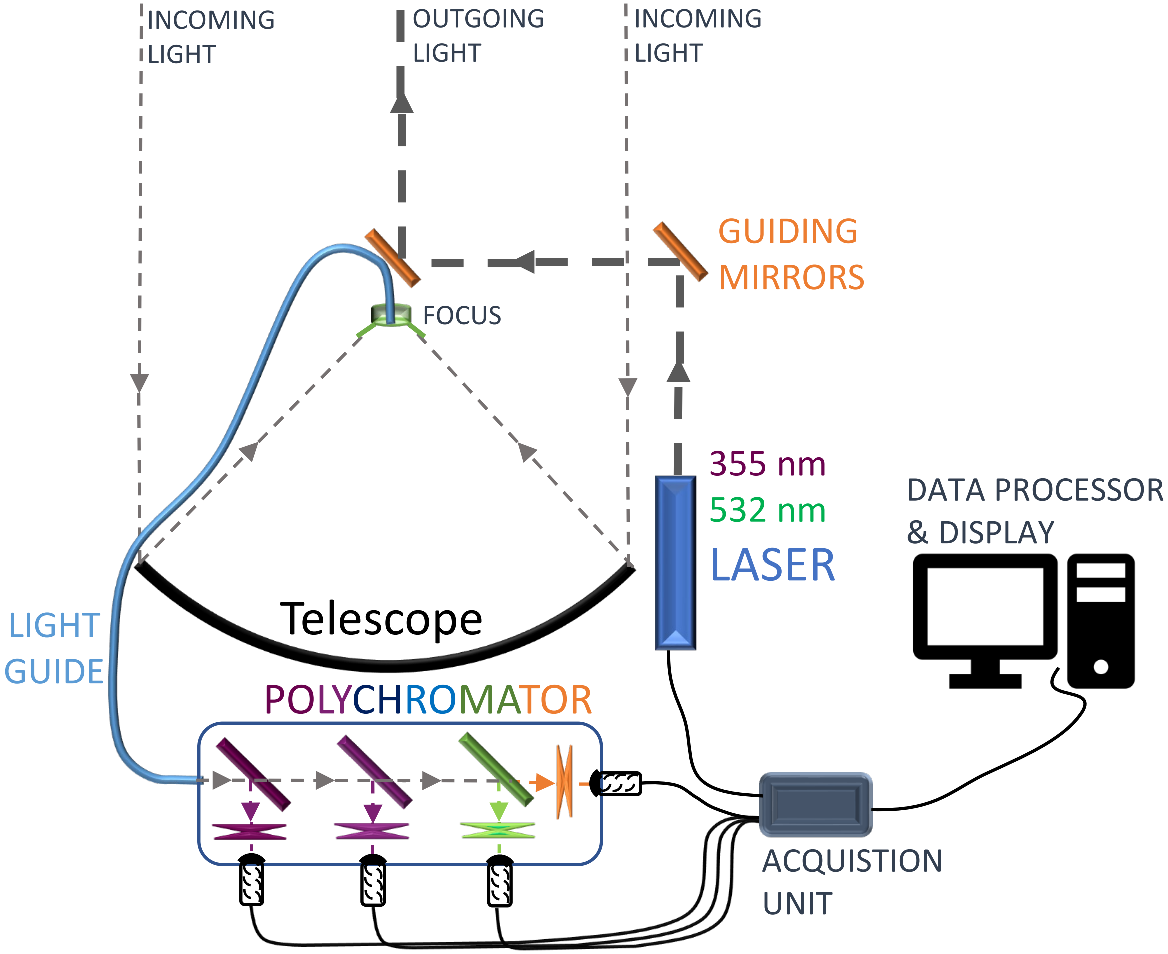


LIDAR (LIght Detection And Ranging

Operation principles

CTAO will use a Raman LIDAR with two laser wavelengths:

- 355 nm
- 532 nm



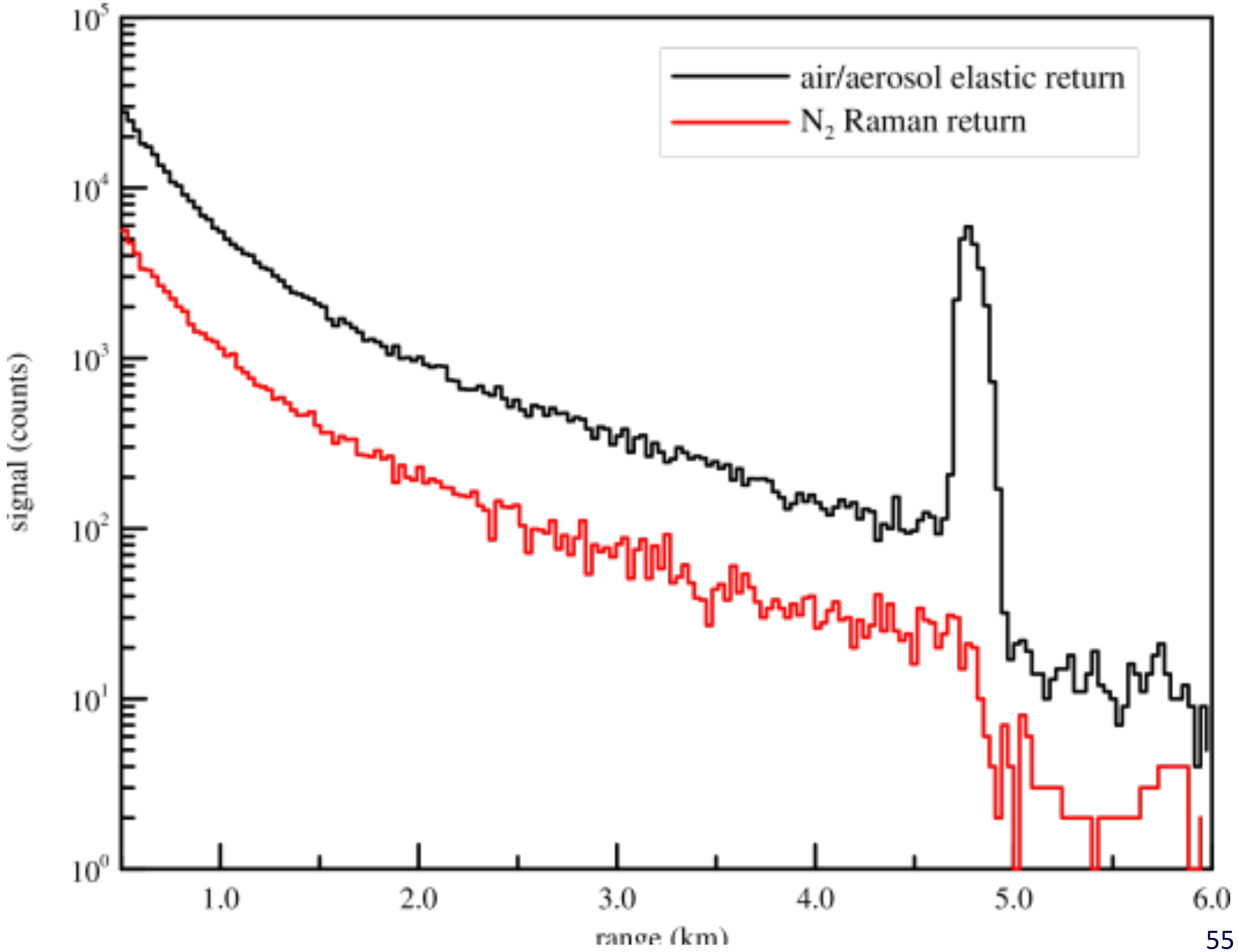
LIDAR (LIght Detection And Ranging

Operation principles

A Raman LIDAR analyses elastically back-scattered light and Raman scattering on N_2:

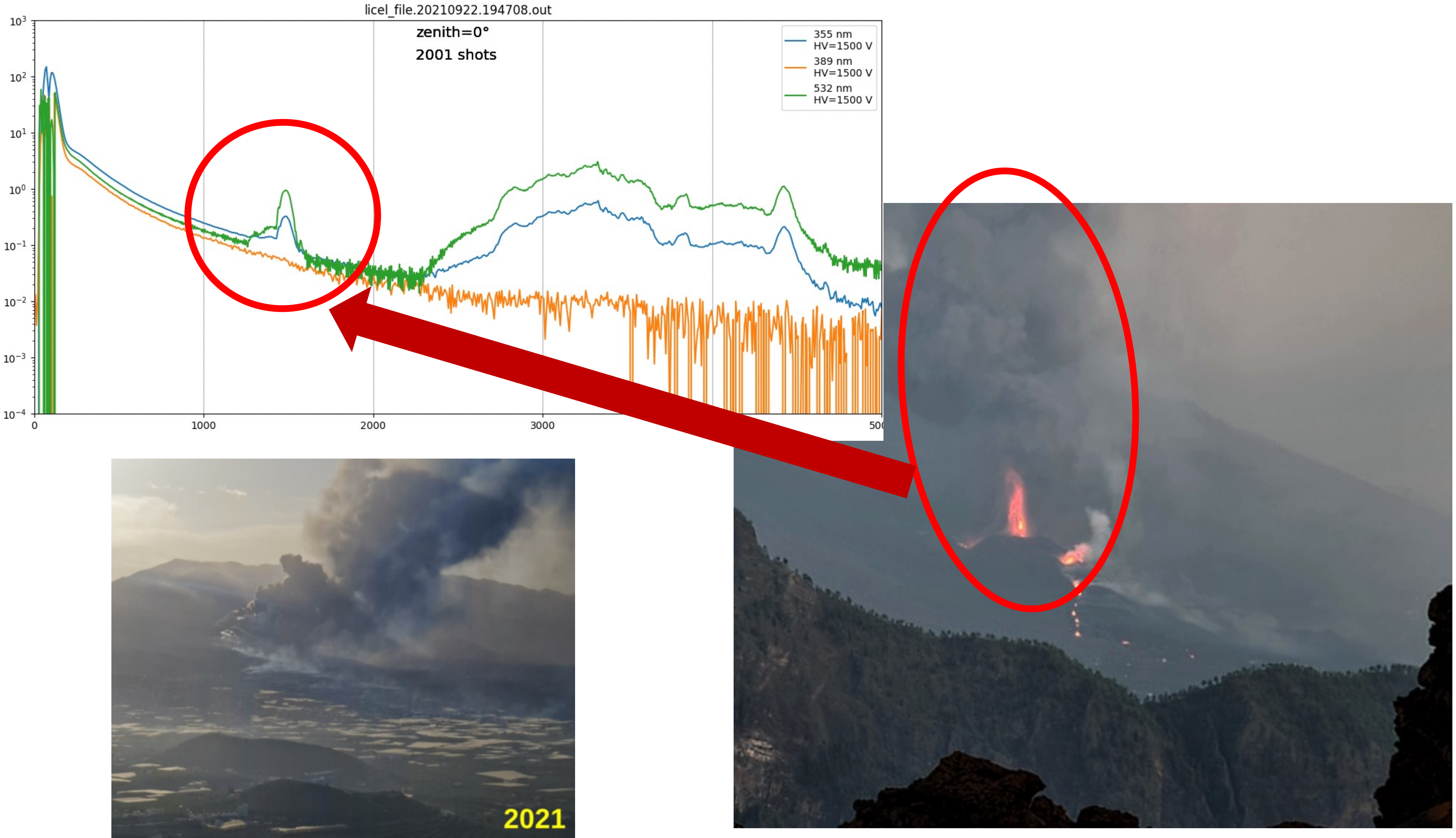
- 355 nm
- 387 nm

Clouds back-scatter light, but do NOT Raman scatter!



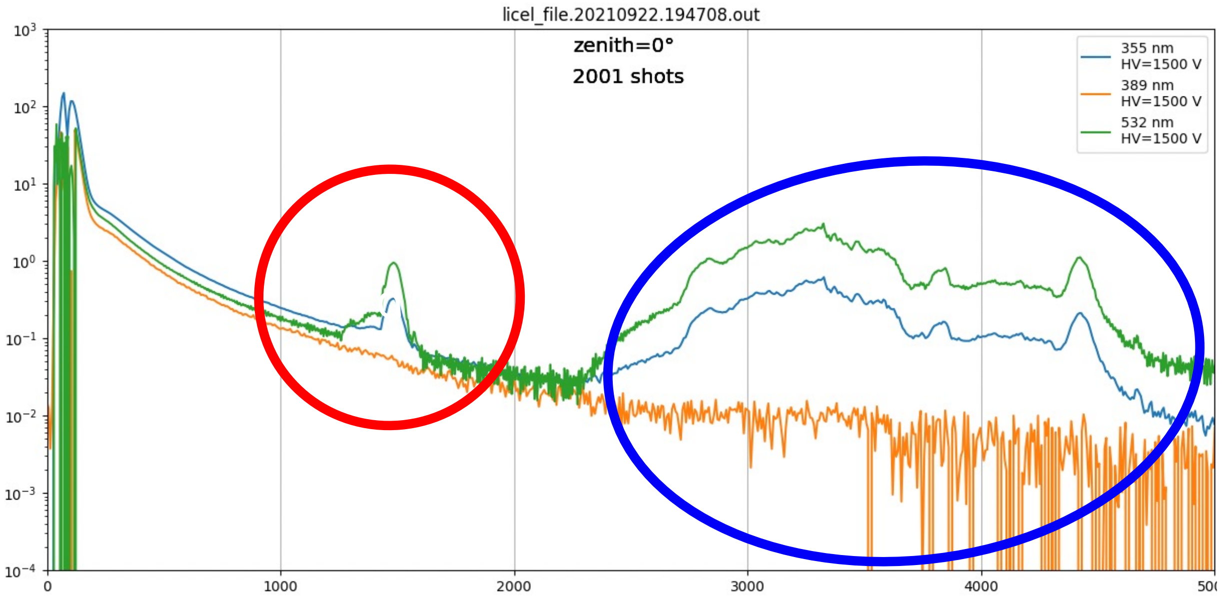
LIDAR (LIght Detection And Ranging

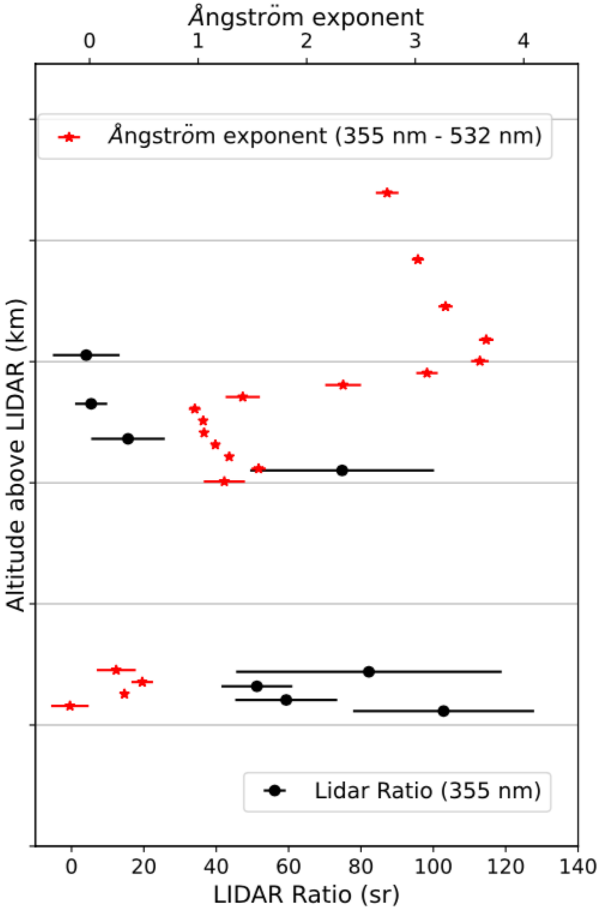
Distinction of aerosol types



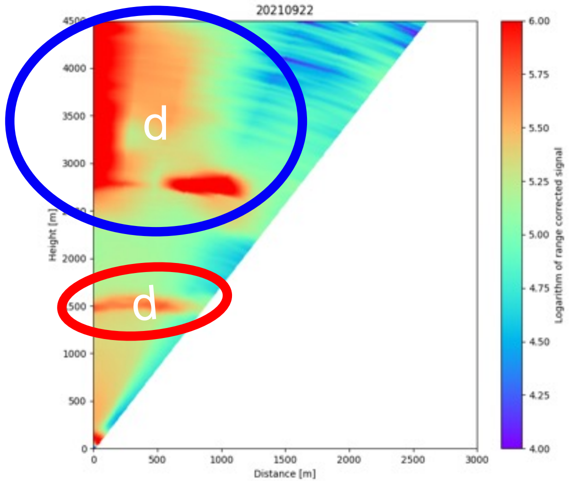
LIDAR (LIght Detection And Ranging

Distinction of aerosol types





- Two distinct features visible:
- Lower steady thin layer of large opaque particles
- Higher variable thick layer of small transparent particles



Stellar Photometry (FRAM)

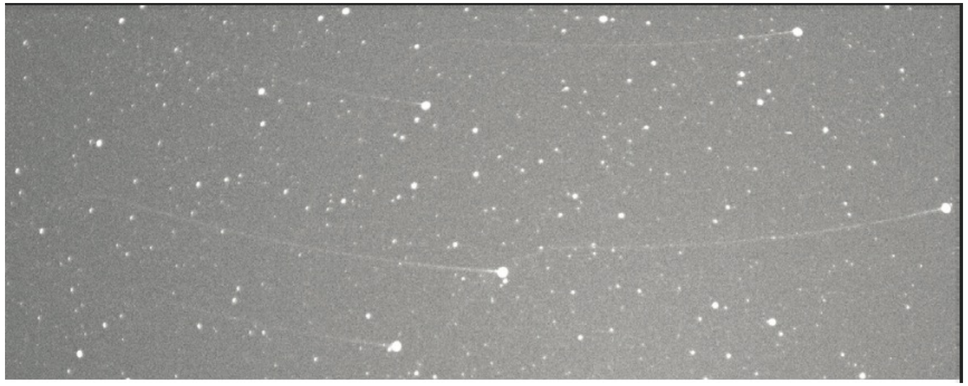
Operation principles

A FRAM always consists of a:

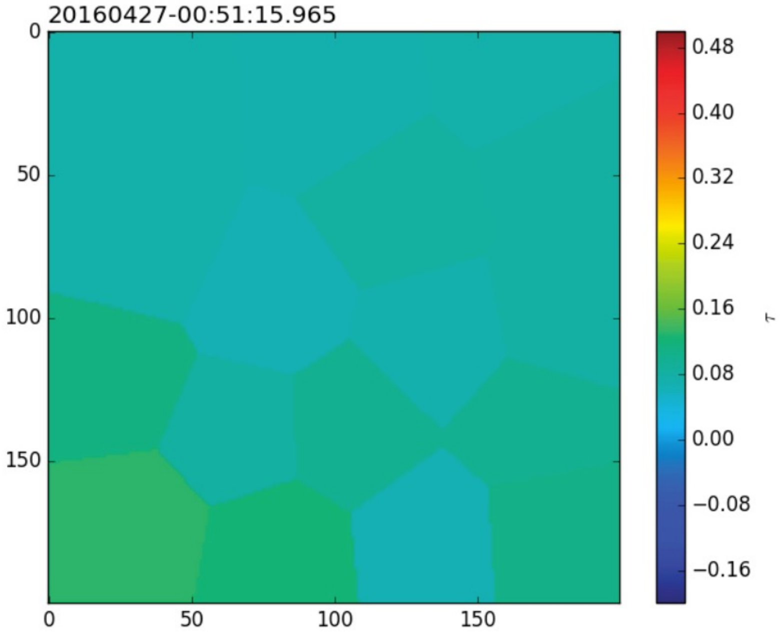
- a lens
- a filter (wheel)
- a CCD
- a mount

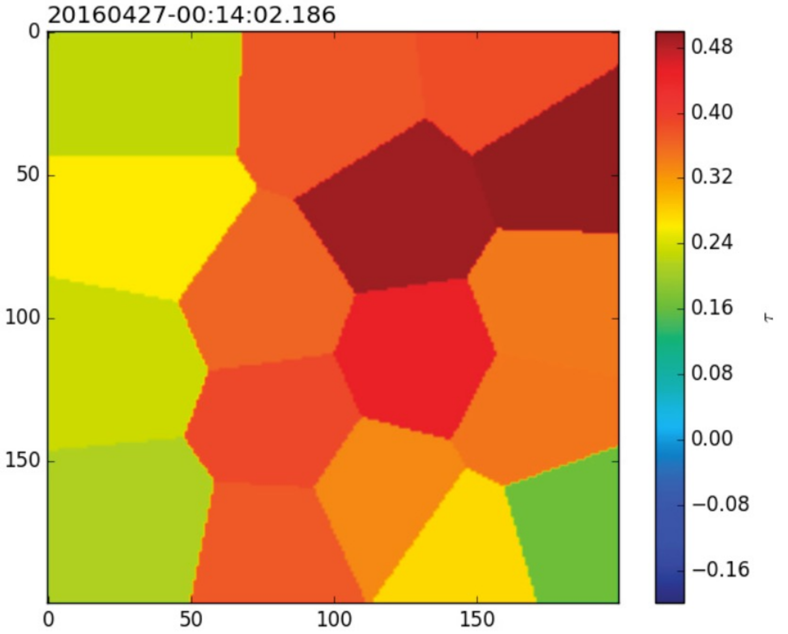
Stellar Photometry (FRAM)

Operation principles



A FRAM compares **stellar brightness** with their **reference from star catalogs** and measures **Vertical Aerosol Optical Depth** across its field-of-view





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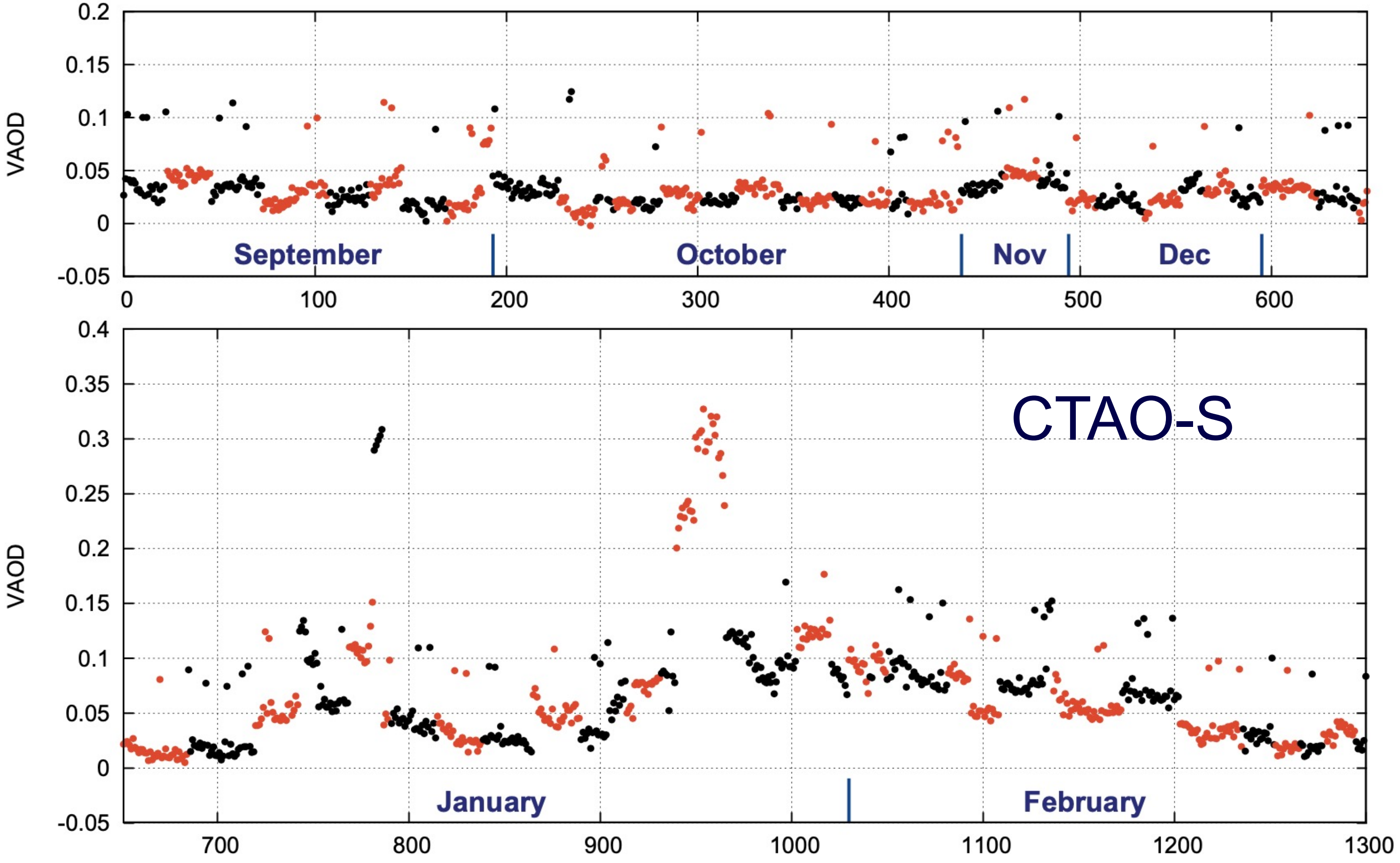
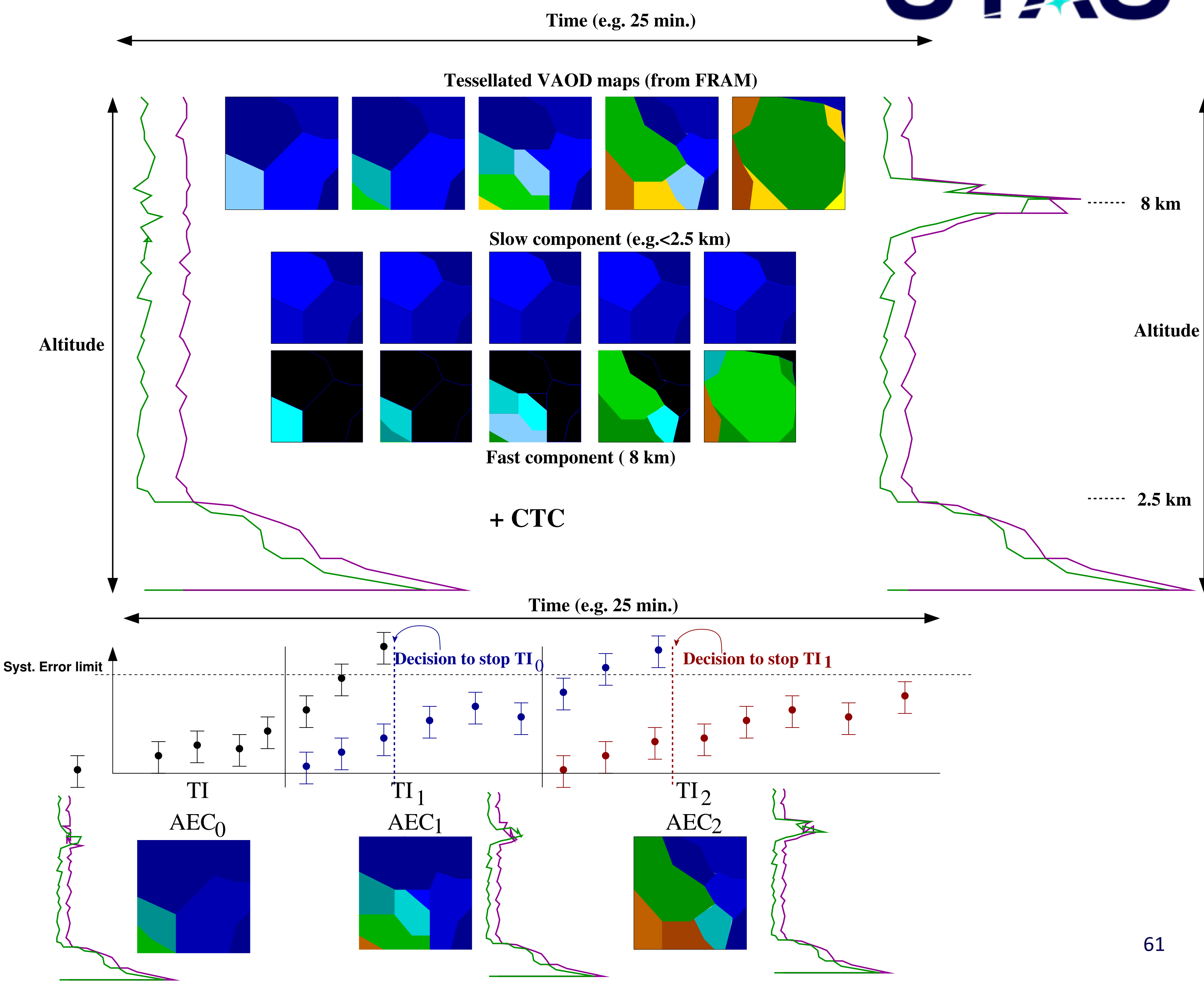


Janecek et al., EPJ Web of Conferences **197** (2019) 02008

Combination of Data from FRAM and LIDAR

- CTAO will generate **Average Extinction Cubes** for each Good Time Interval (**GTI**) and observed **FOV**.
- Systematic errors are guaranteed to lie below a given limit.



Correction Strategies

Correction Strategies for CTAO

Molecular profile and ozone

- CTAO will take care of providing the corresponding atmospheric profiles within the simulations (IRF) provided.
- The IRFs are delivered together with a guarantee for systematic errors to lie below a given limit.

Correction Strategies for CTAO

Aerosols and clouds

Two possibilities:

1. Correct the data
2. Correct the simulations

Which is better 🤔 ???

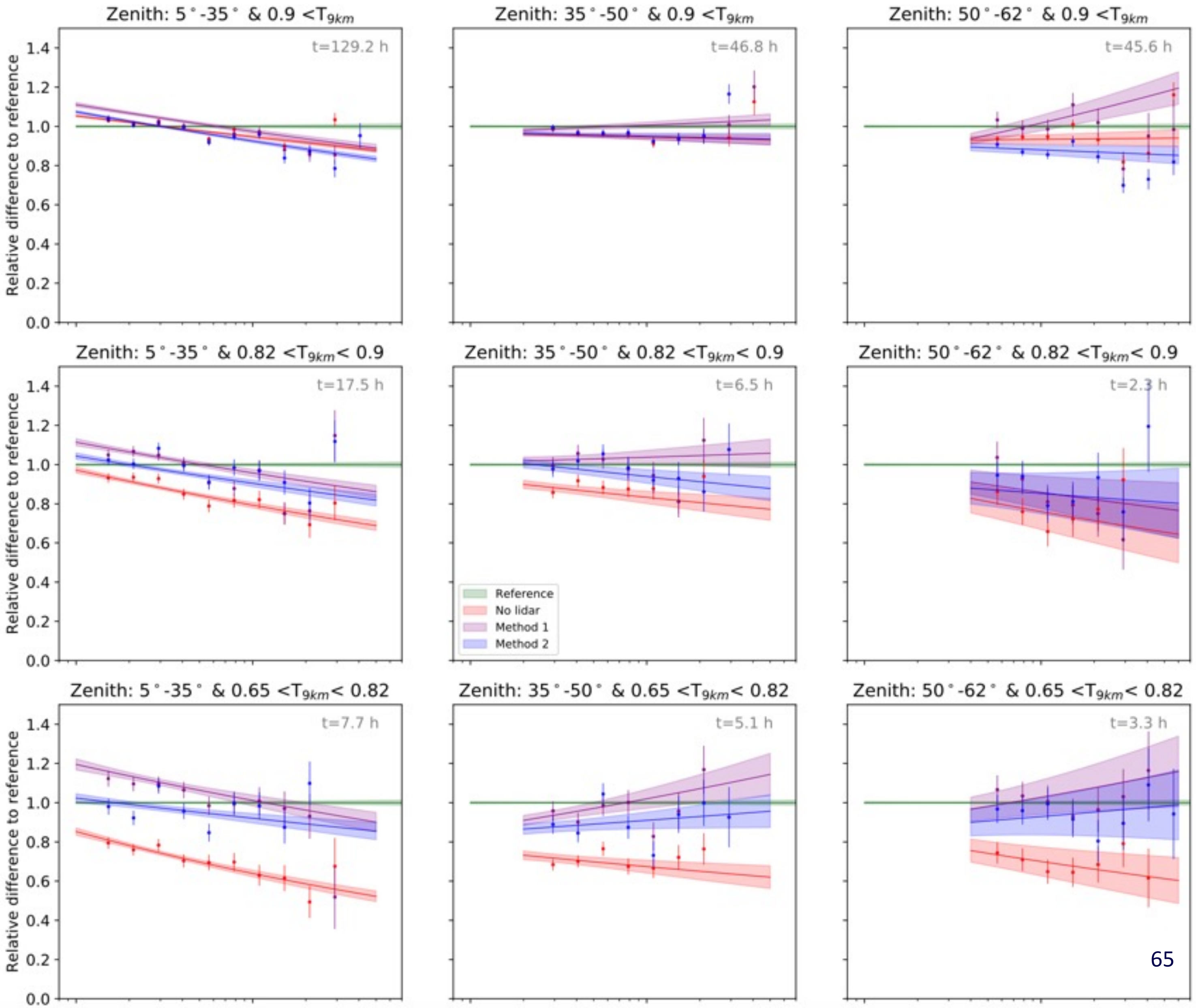
Correction Strategies

Aerosols and clouds

Two possibilities:

1. Correct the data

Schmuckermaier F. et al., A&A 673 (2023) A2 find up to 20% RMSE for Crab Nebula data and VAODs < 0.5



Correction Strategies

Aerosols and clouds

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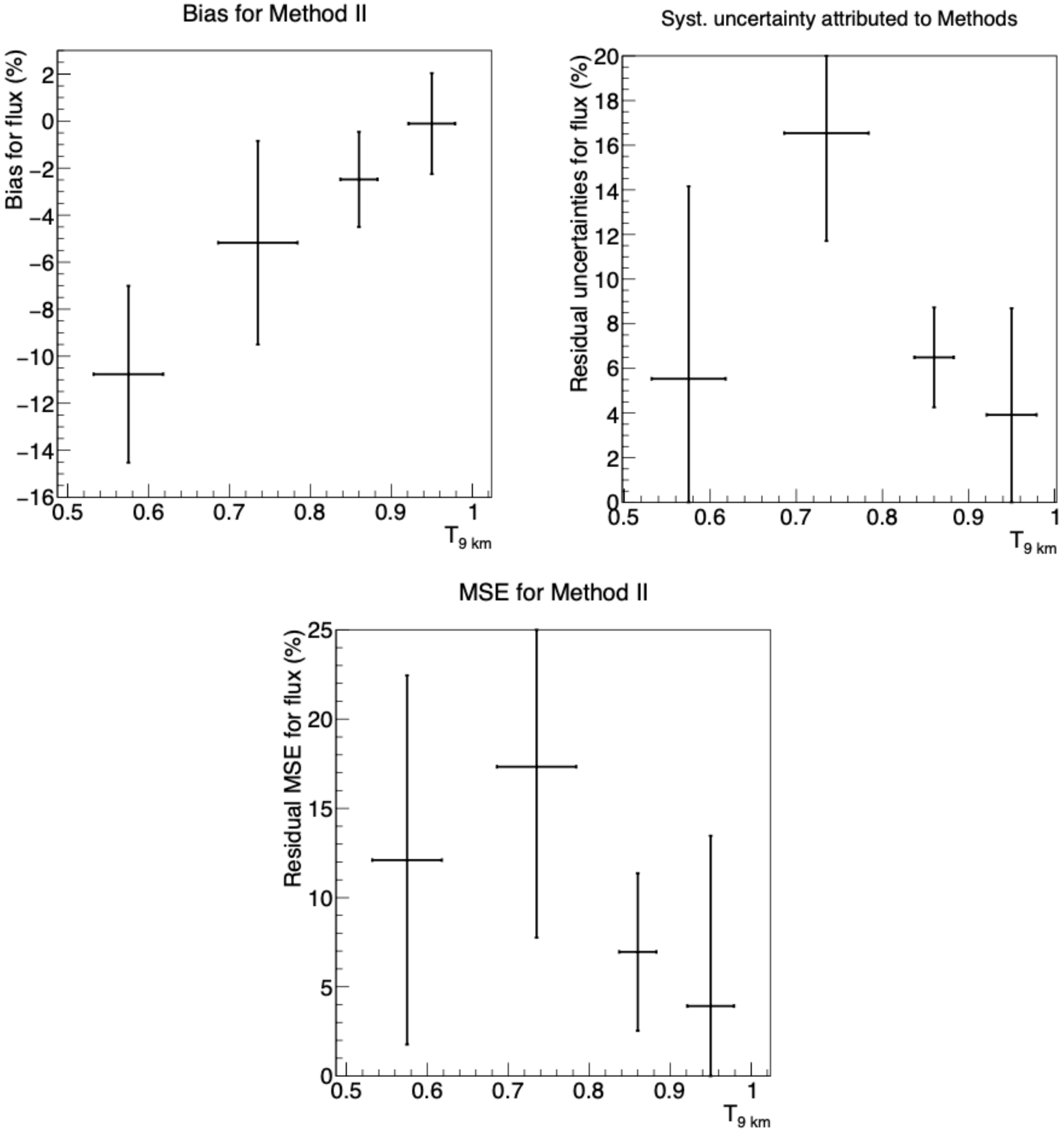


Correction Strategies

Aerosols and clouds

2. Correct the simulations

- Would require **tailored simulations** for each GTI
- Huge amount of computing resources needed
- For the moment, only possible for few sources of high interest

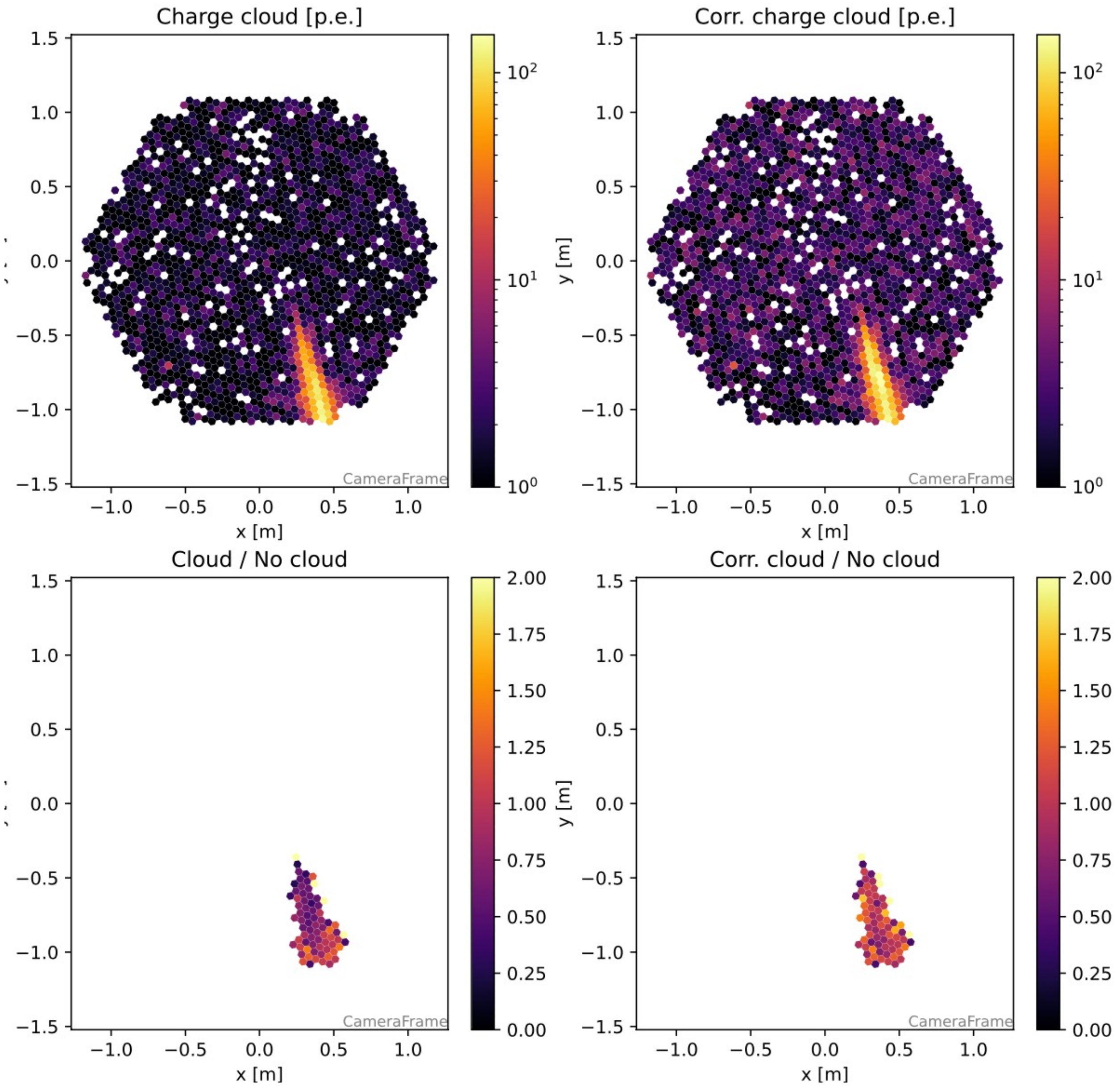
Correction Strategies

Aerosols and clouds

Two possibilities:

1. Correct the data

Zywucka N. et al., A&A 685 (2024) A165 invented a new technique correcting each image directly (instead of IRFs only)



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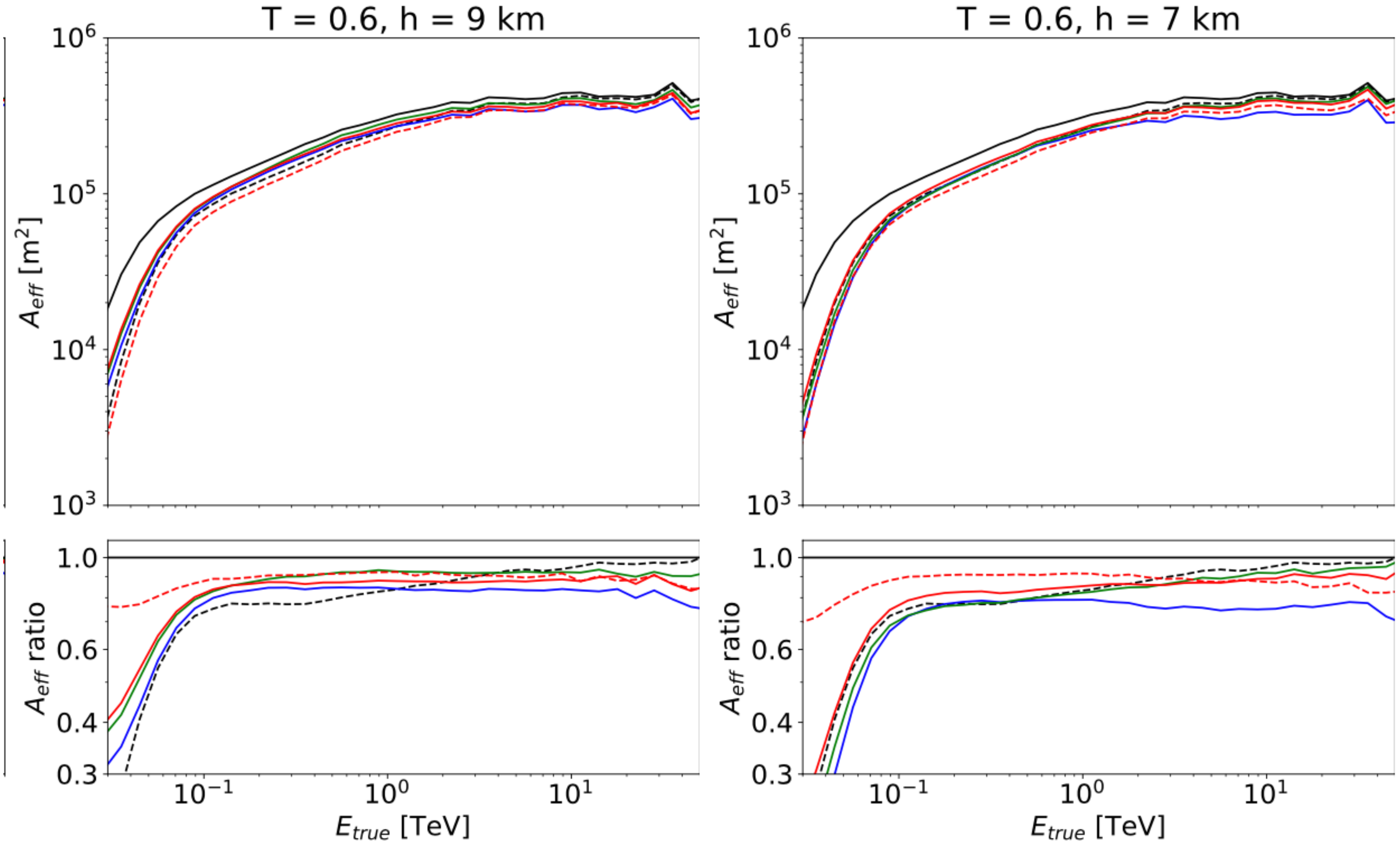

Thank you

CTAO