

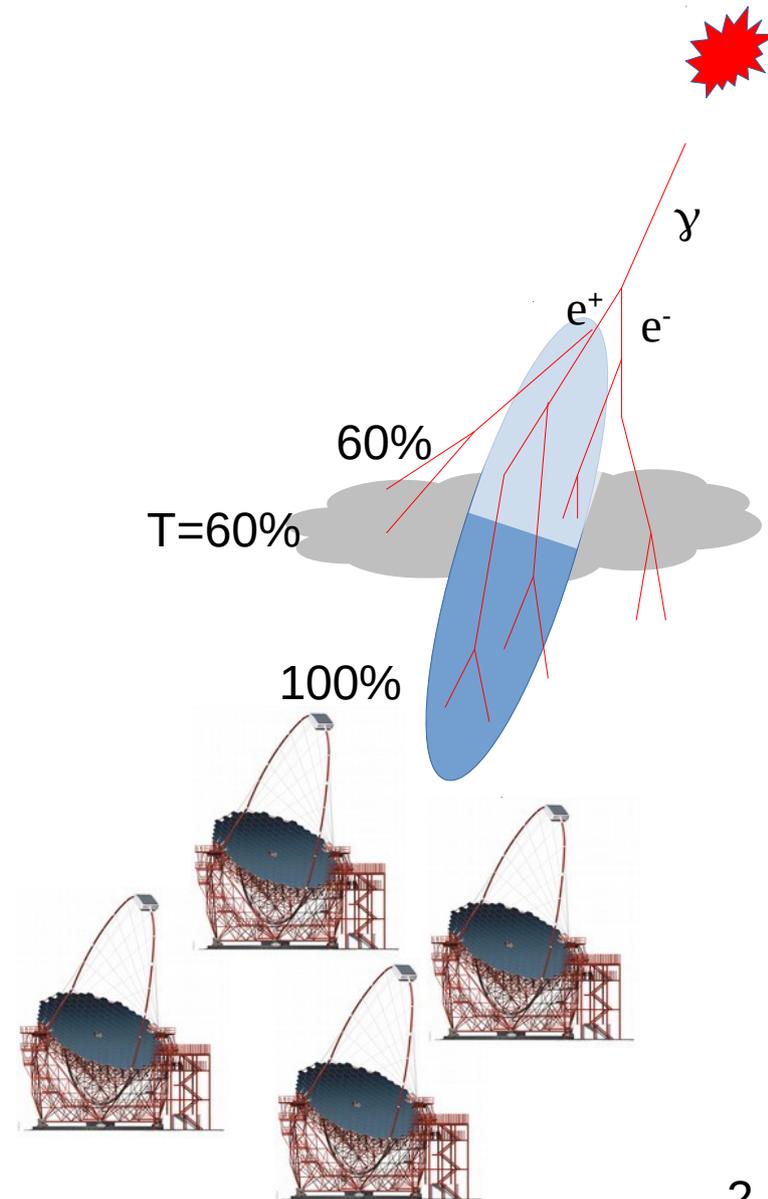
# Proton LIDAR - direct measurement of atmospheric transmission profile with Cherenkov telescopes

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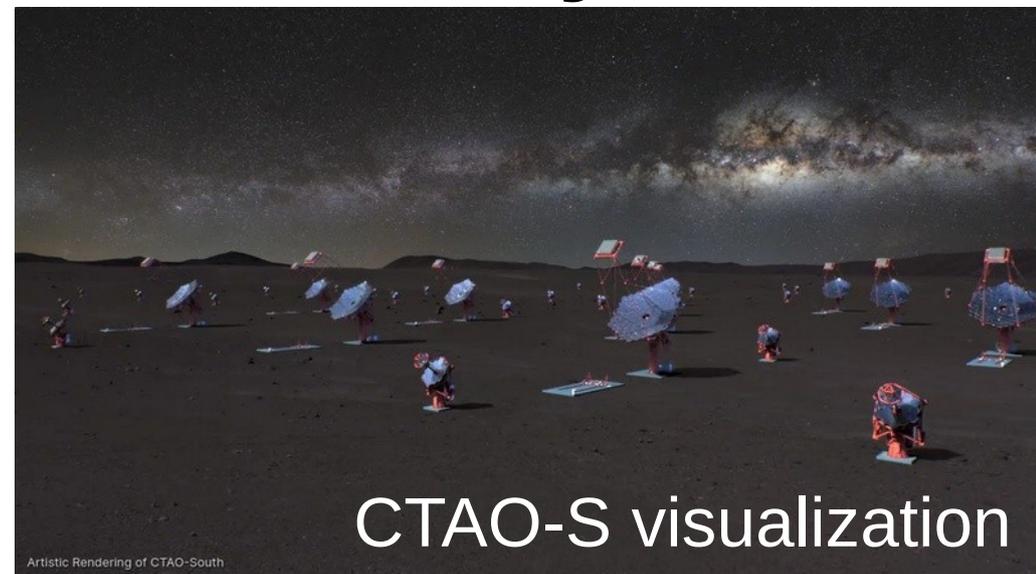
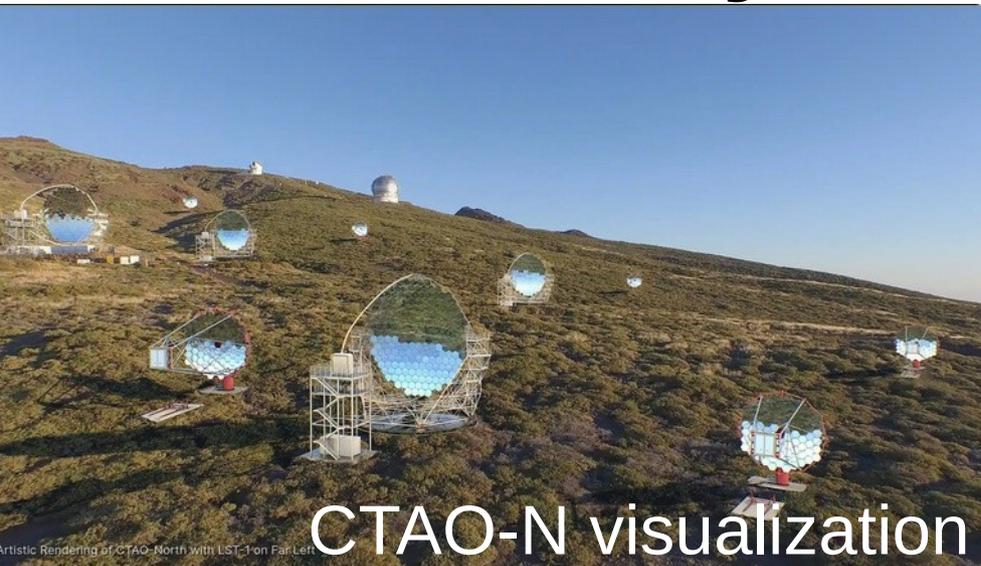
2024.09, Milano, 8<sup>th</sup> Heidelberg International Symposium on  
High-Energy Gamma-Ray Astronomy

# Cherenkov telescopes and clouds

- IACTs exploit observation of UV-optical emission induced by a shower to reconstruct gamma-ray events reaching Earth
- The light is affected by absorption in the atmosphere, including clouds
- Some of the light will be generated above the cloud, some within and some below the cloud with different absorption
- **To take this into account it is essential to know absorption profile of the cloud** (height dependent transmission)



# Cherenkov Telescope Array Observatory



<https://www.ctao.org/emission-to-discovery/array-sites/>

- Planned observatory located in two sites and composed of telescopes of 3 different kinds (LST, MST and SST)
- LSTs are the largest type of telescopes – focused on energies  $< \sim 100$  GeV
- Four LSTs are planned in the CTAO-North site

# Rationale

- IACTs are sensitive instruments, but their duty cycle is only ~10%, limited by dark time and weather – **each hour is precious**
- Some data are taken under presence of clouds – there is a number of methods to correct them if we know the transmission profile of the cloud. **See the poster of N. Żywucka for the novel correction method**
- Clouds can be characterized with the usage of LIDAR, but powerful laser can interfere with observations, clouds can vary in between LIDAR measurements, ...

Good data \* cloud transmission = Cloud data

PHYSICS

Good data = Cloud data / cloud transmission

CORRECTION

Cloud transmission = Cloud data / Good data ??

MEASURE  
ATMOSPHERE

Can we use inverted correction method to measure atmosphere transmission profile with IACT data?

A novel image correction method for cloud-affected observations with Imaging Atmospheric Cherenkov Telescopes

CTAO

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### 1. INTRODUCTION

The Cherenkov telescope array (CTA) [1, 2] is an emerging ground-based observatory that gathers  $\gamma$  rays in high energies from tens of GeV to hundreds of TeV. Out of 1500 hours of available dark time per year a fraction of data will be affected by clouds. The gathered data during cloudy nights need to be corrected in order to avoid increased systematic uncertainties. We propose a geometrical model correction of image parameters, which aims to improve the shadow separation and shower direction reconstruction. The proposed method is enhanced with a bias fit independent of energy and impact.

### 2. MC DATA

In our approach, we considered the layout of four Large-Sized Telescopes (LSTs). We used CORSIKA 7.741 [3] to simulate the air shower's development induced by  $\gamma$  rays and hadrons. The atmospheric absorption of Cherenkov photons and the response of the Cherenkov detector were simulated with the TELEARX Python. Two atmospheric models were simulated: the clear atmosphere (T1) with no clouds and 1 km thick altocumulus clouds with a base of 5.7, and 9 km above ground level (e.g., in a 2147 m above sea level) and transmission of 0.0, 0.6, and 0.9. The simulations were analyzed in the CTAFIT 0.12 and LSTCHAIN 0.9.13 frameworks. The data reduction from the F0 to DL1 level was performed in a standard approach, where the Hillas parameters from the image, the transverse stress reconstruction parameters, impact, and the source position were calculated. We simulated the MC2 parameters, including shadow separation and reconstruction of the parent particle parameters (energy and direction), using the random forest method.

### 3. GEOMETRICAL MODEL

We developed a geometrical model to correct the MC data for the presence of clouds at the image level. To correct a source bias, we introduce a phenomenological correction factor optimized for low zenith angle observations and not dependent on the energy of the primary  $\gamma$  ray or the impact parameter. Subsequently, we use the preliminary estimation of the arrival direction and impact to map each point on the camera to a specific height. Then, we assign a single emission height, assuming that the Cherenkov photons are emitted from the axis of the shower. Finally, we correct the reconstructed signal at each pixel by an inverse of the transmission from the corresponding emission height.

### 4. RESULTS

During evaluation of the correction performance with the developed model, we compared the effect on the individual image parameters, evaluated the typical performance parameters of the Cherenkov telescopes (energy and angular resolution, sensitivity), and compared them between different analysis schemes for cloud-affected data (no correction, data correction with/without additional shower MC simulations) and for cloudless data. Fig. 1 shows an example image corrected with our method. The simulations with the cloud result in reduced light yield in the head part of the shower. After the correction, the head part of the image recovers the light level of T1 simulations. The top panels show T1 image, image with additional light attenuation in the cloud, and the corrected image (left to right). The bottom panels display the correction factor applied, the ratio of reconstructed signals of uncorrected image to T1 image, and corrected to T1 images (left to right).

### 5. CONCLUSIONS

The geometrical model developed to correct the cloud presence during the data gathering is valid for application in stereoscopic IACT systems, in particular in cases when slight increases of systematic uncertainties are acceptable. The presented method corrects the images directly without the need for time-consuming and resource-intensive dedicated MC simulations. One of the practical use cases would include data taken in the presence of fast varying clouds with rather low opacity or medium-high height. Further possible use of the method is the fast online or on-site analysis. Moreover, the method would allow to improve the reliability of derived fluxes for observed flares of fast transients, that need to be circled quickly within the community.

### REFERENCES

- [1] Adriani, O., S. Alois, M. Aglietta, T. et al. 2013, *Astroparticle Physics* 38, 1.
- [2] Cherenkov Telescope Array Consortium, Adriani, O., S. Alois, L. et al. 2019, *arXiv:1907.01571*, <https://arxiv.org/abs/1907.01571>.
- [3] R. Brunetti, *Simulation of imaging atmospheric Cherenkov telescopes with CORSIKA*, and [www.corsika.de](http://www.corsika.de).

### ACKNOWLEDGEMENTS

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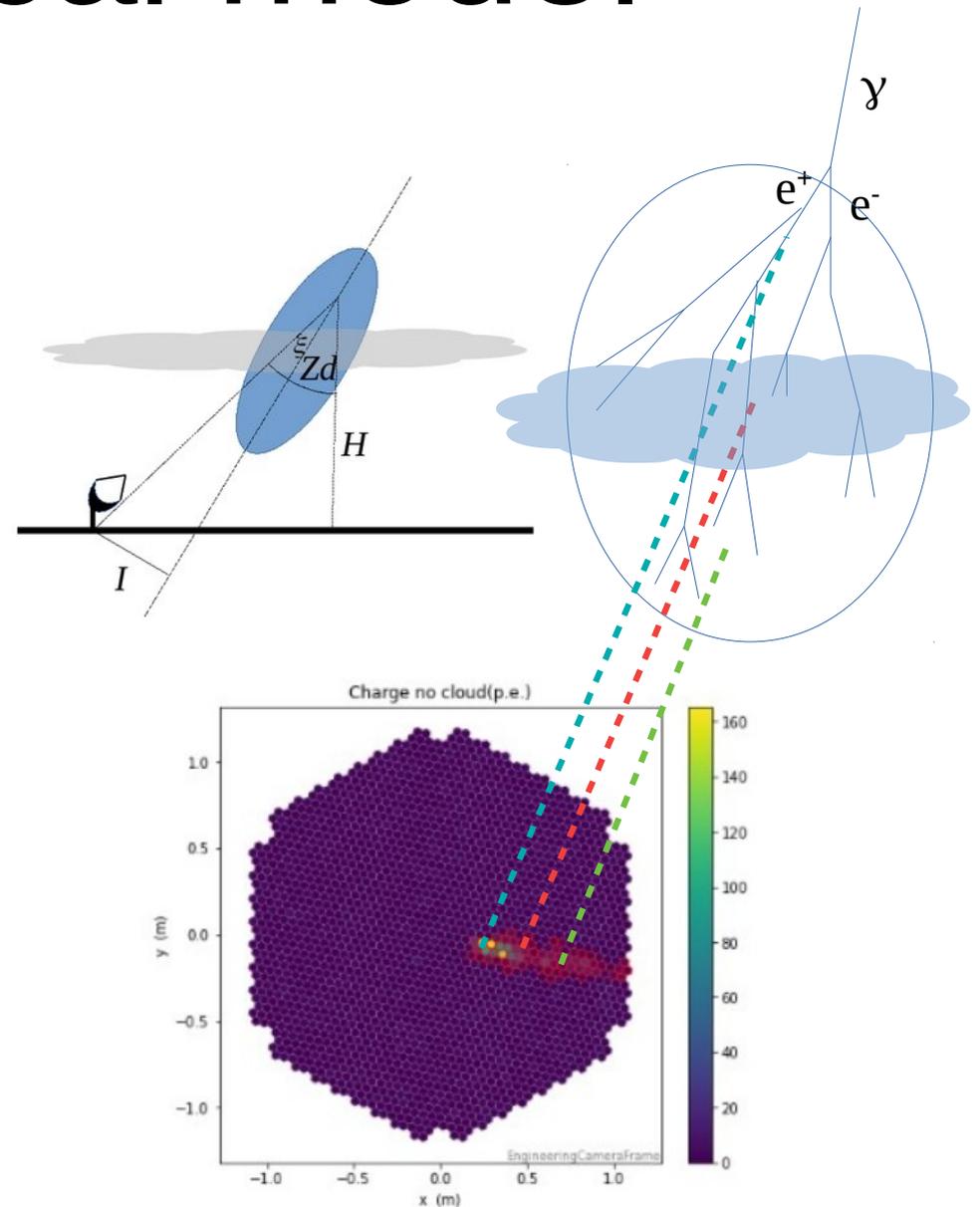


MAGIC LIDAR (Fruck et al 2022)

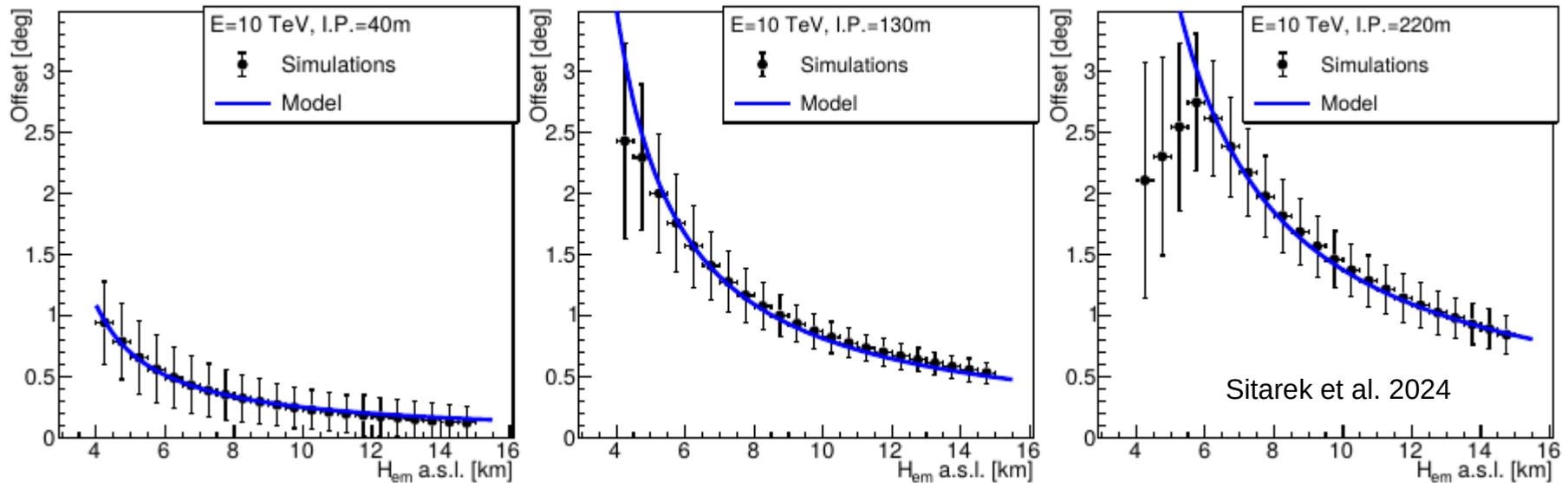
# Geometrical model

- We assume that the whole light is generated along the shower axis
- With tentative estimation of the shower direction and impact each pixel on the camera can be mapped to an emission height

$$\xi = \arctan\left(\frac{I \cos Z_d}{H}\right)$$



# Validation of geometrical model



- Protons at different energies and impacts were simulated to check the emission (with simple atmospheric absorption) at different heights
- Generic simplified simulations (no telescope simulation, generic atmospheric absorption)
- Subsequently, the mean position of the emission from a given height was checked and compared with the model

- With simple phenomenological correction factor (independent of impact or energy) the model accurately describes mean offset as a function of emission height  $\xi' = \frac{0.85}{\cos \theta} \cdot \xi$

- **The resolution depends on impact and energy, but +/- 1.5 km is achievable with protons**

# Simulations

- 4 x LST using current LST-1 settings
- Simulations:
  - Clear atmosphere
  - Cloud:
    - baseline
    - higher/lower
    - (geometrically) thinner/thicker
    - more/less opaque

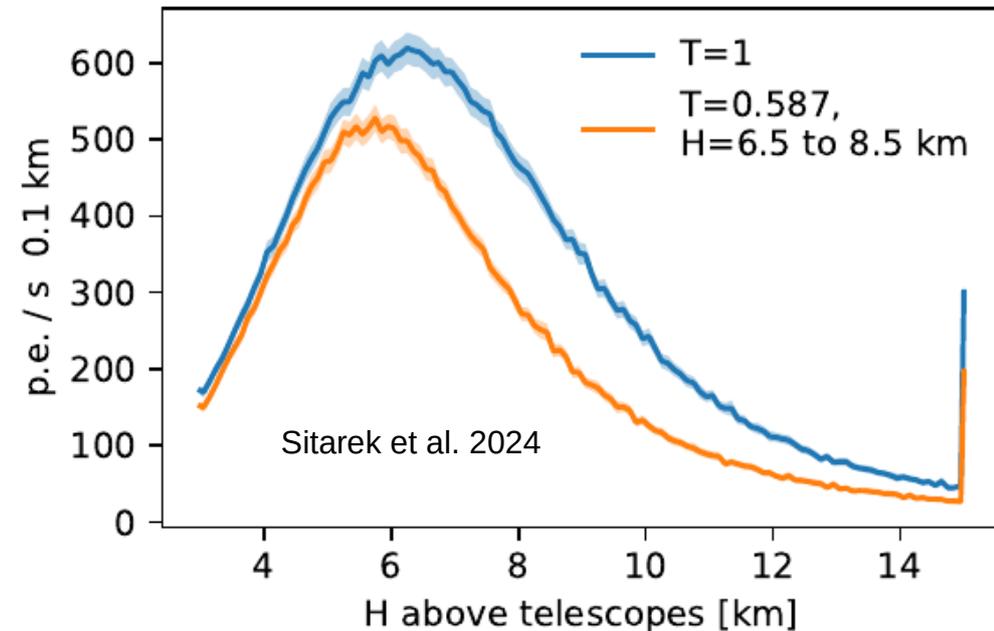
Transmission	Base height [km]	Thickness [km]
0.388	6.5 a.g.l.	2
0.587	5.5	2
<b>0.587</b>	<b>6.5</b>	<b>2</b>
0.587	6.0	3
0.587	5.5	4
0.587	7.0	1
0.587	7.5	2
0.800	6.5	2
1	–	–

Clouds (simulated with MODTRAN 5.2.2.) are quasi-gray and for simplicity homogeneous

The results of the simulations are weighted to the observed proton spectrum

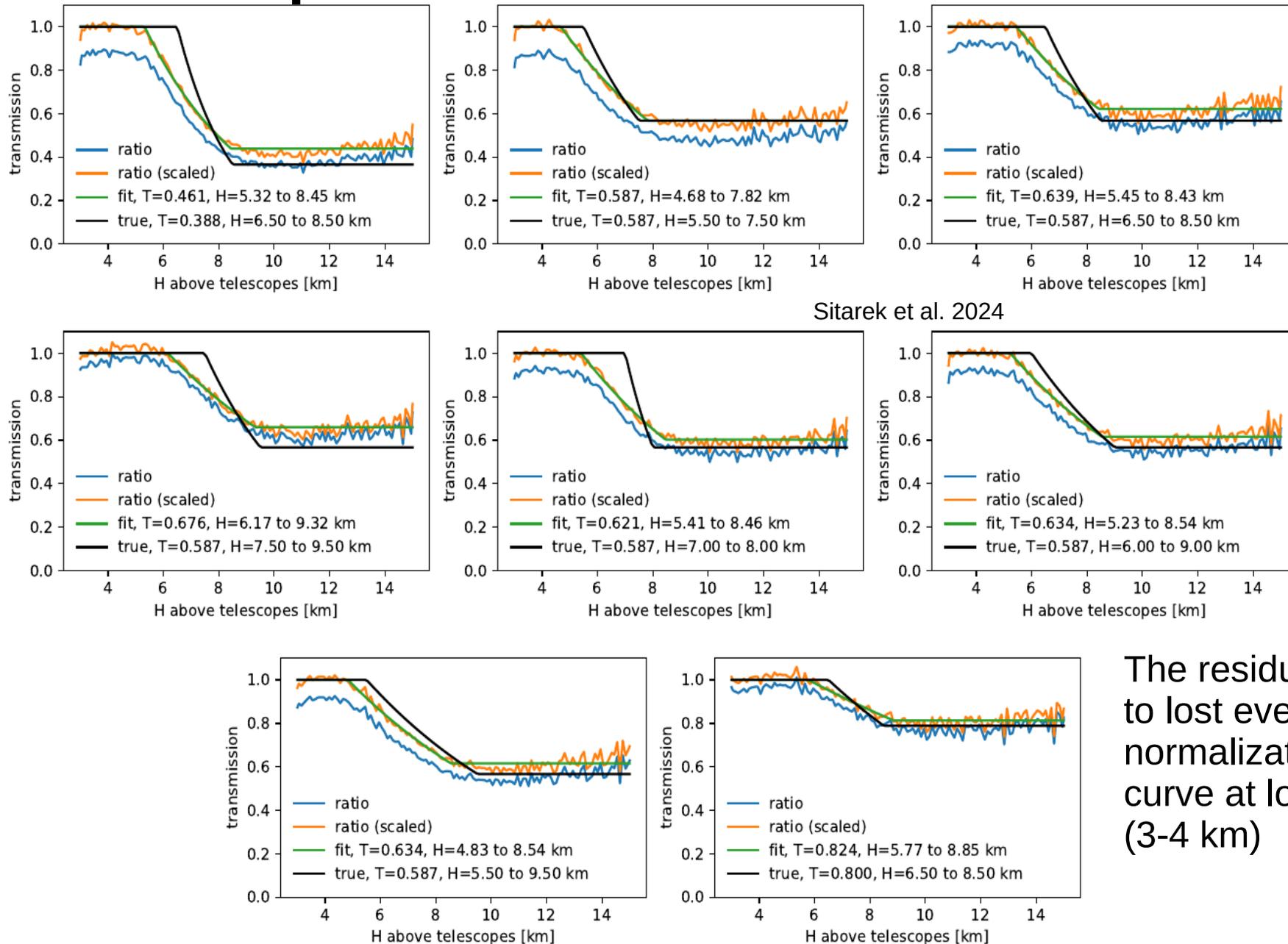
# (Aggregated) longitudinal distribution of shower light

- For each event we can sum up all the pixel signals assigned to a particular emission height
- We obtain a longitudinal distribution of the registered Cherenkov light
- Weighting the events to CR proton spectrum and summing them up
- There is a clear difference between the Cherenkov profile – ratio of the two can be directly interpreted as height-dependent cloud transmission



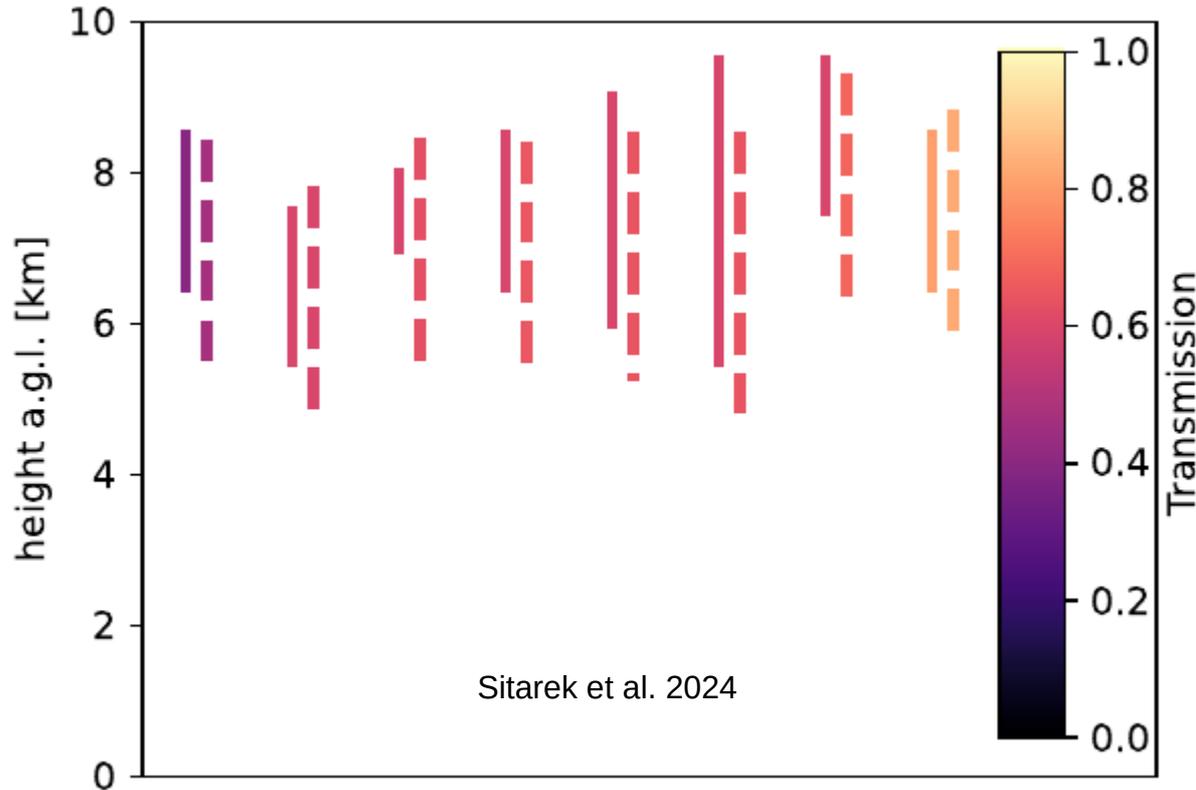
Shaded region represents uncertainties for 5 min long observations of 4 x LST

# Comparisons for different clouds



The residual bias due to lost events requires normalization of the curve at low heights (3-4 km)

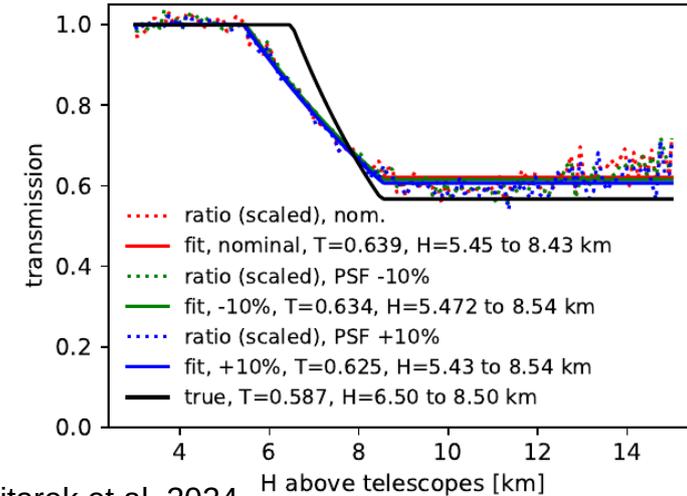
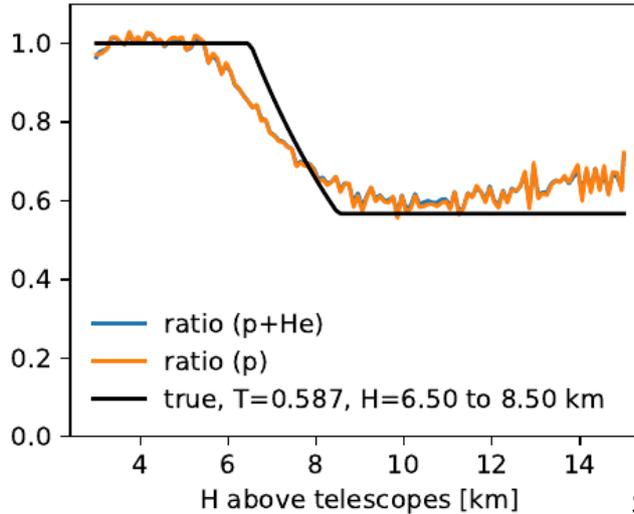
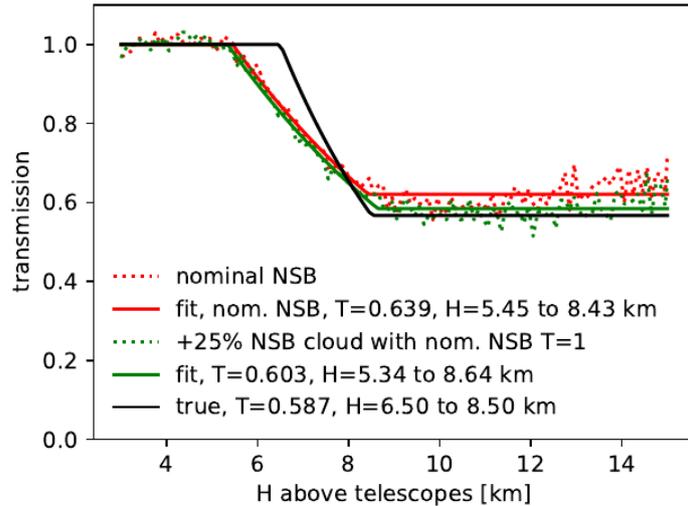
# Comparisons for different clouds



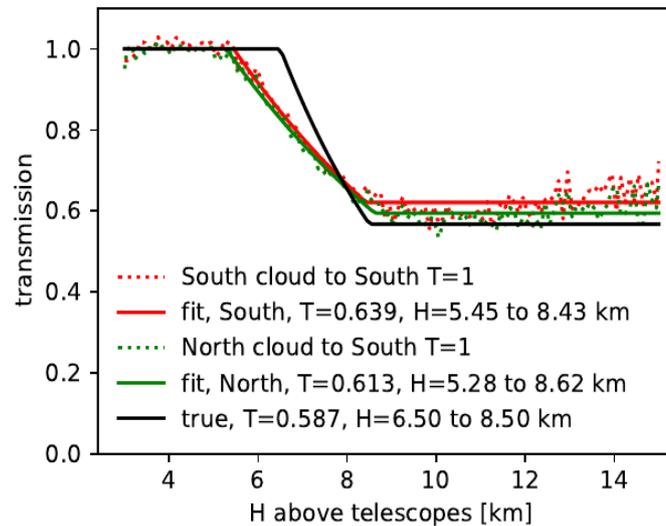
The method reproduces well the total transmission of the cloud and partially reconstructs the profile (broadening it for narrow clouds)

Solid line: simulated cloud  
dashed line: reconstructed cloud

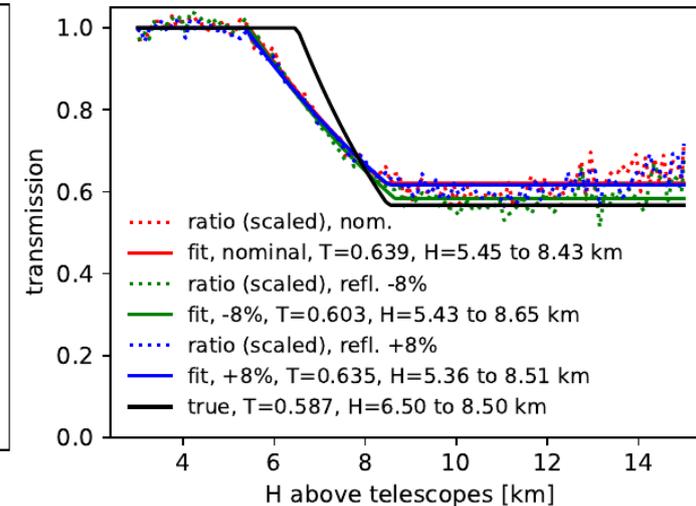
# Systematic uncertainties



Higher elements, geomagnetic field as well as small changes in the optical performance of the telescopes and NSB level do not affect the method significantly

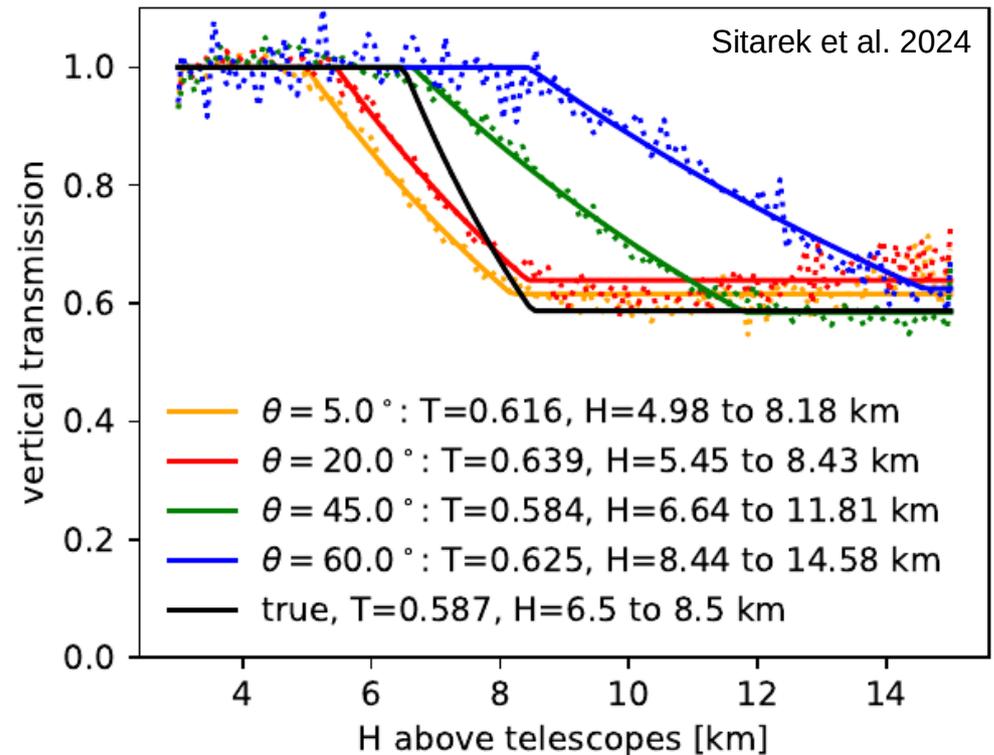


Sitarek et al. 2024



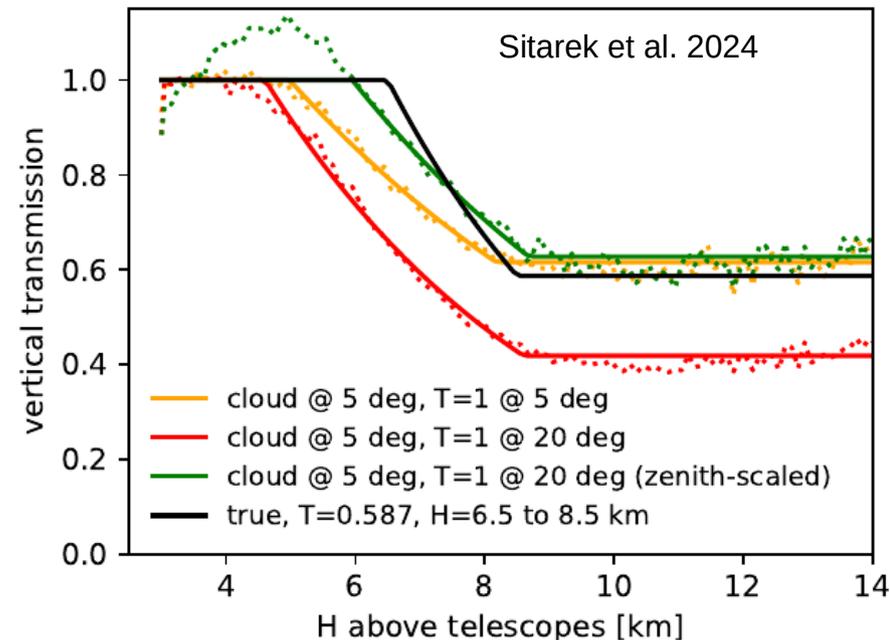
# Zenith distance dependence

- The method however quickly loses performance for observations with higher zenith distance:
  - the transmission is properly estimated but the geometrical extend of the cloud is overestimated



# How will the method be applied to the observations?

- A reference night with good weather conditions is needed to be compared with a given observations
- The largest systematic uncertainty is related to the zenith distance of the observations. The data optimally should be matched in zenith to a reference sample
- MC study comparing the data at different zenith angles show that alternatively rescaling (with zenith-dependent atmospheric thickness) can be applied



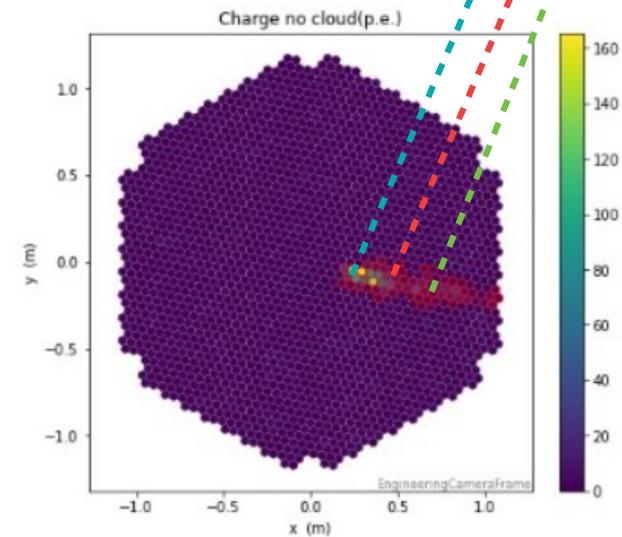
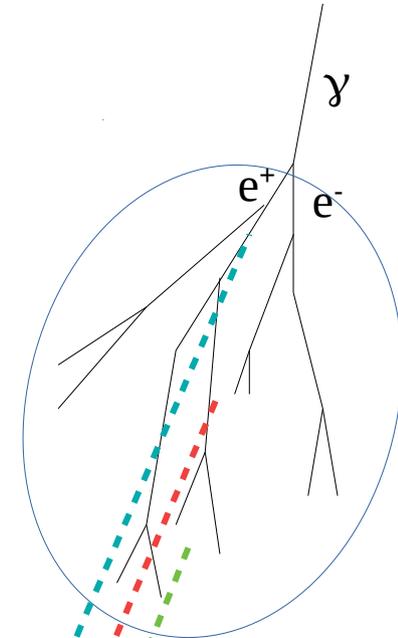
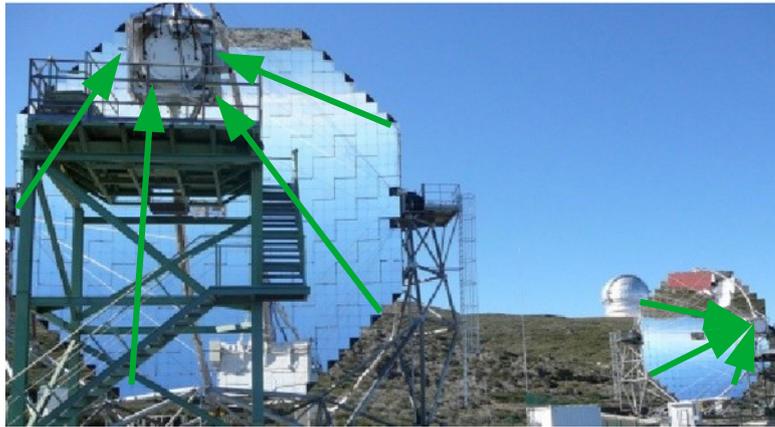
# Summary

- Clouds can have an important effect on IACT observations, and different correction methods require knowledge of atmospheric transmission profile
- We propose a novel method that allows to estimate the atmospheric transmission profile directly with IACT data. It allow us to obtain **independent, always present and non-invasive** measurement of possible cloud transmission profile
- The method applied to an array of 4 LST can reproduce the simulated transmission of the cloud down to a **few per cent level and allows to reconstruct its geometrical thickness if  $>\sim 3\text{km}$**
- The method is very resilient against typical systematic uncertainties related to IACT observations, however loses performance for higher zenith distance observations

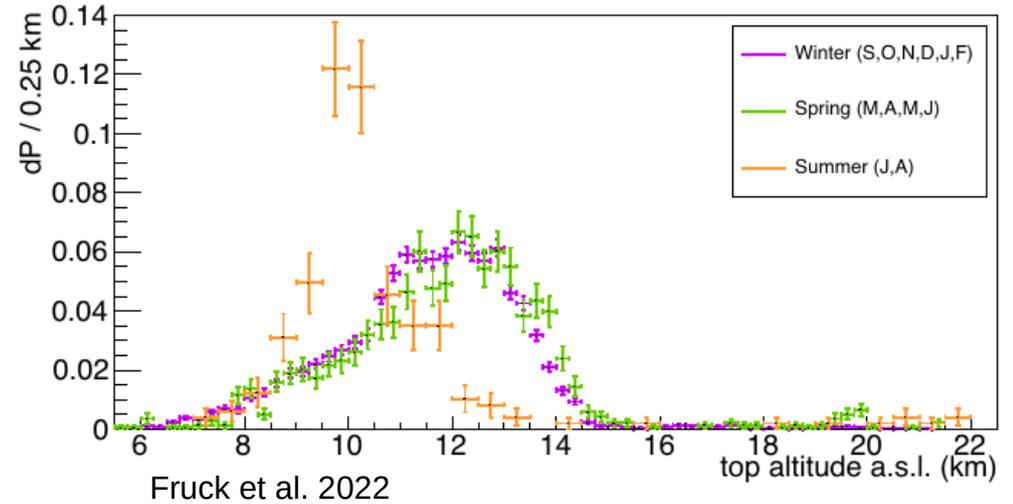
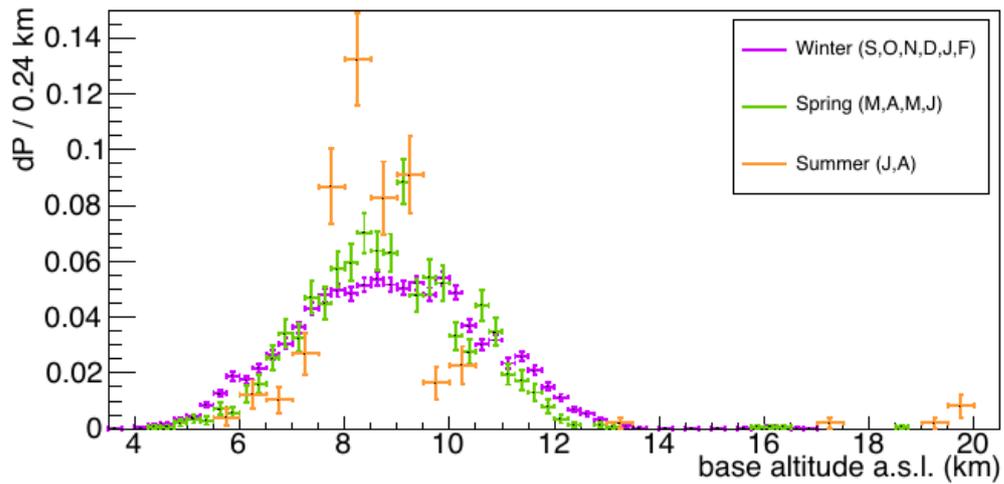
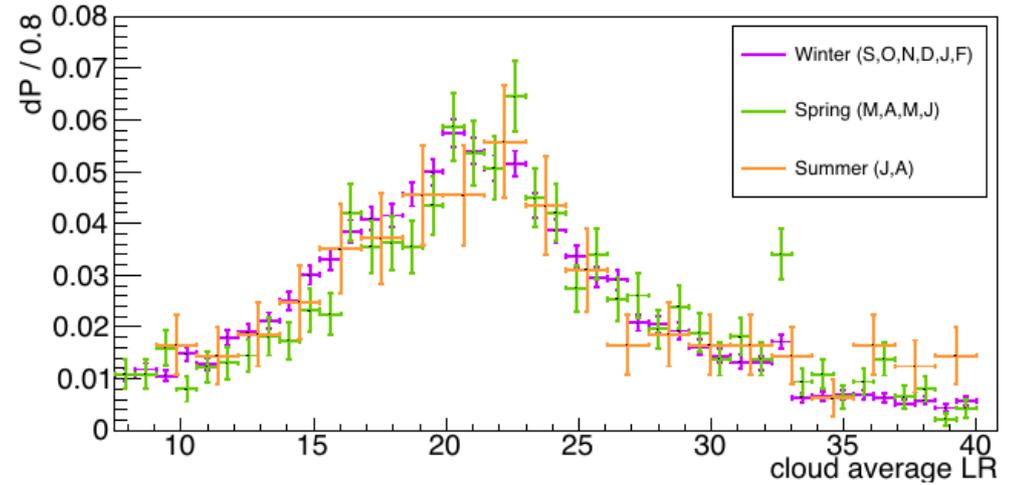
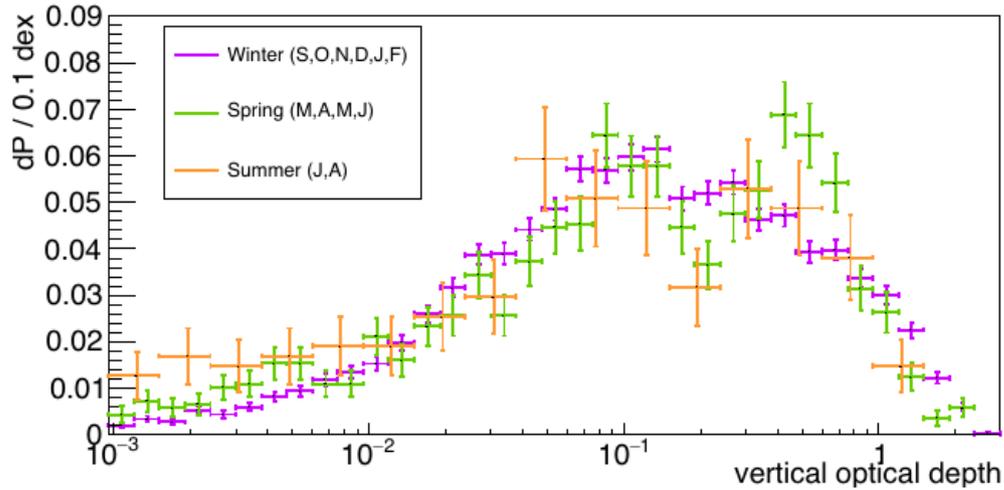
# Backup

# Catching Cherenkov light

- Cherenkov light is gathered by large mirror size and detected by fast and sensitive photodetectors
- Each pixel in the camera gathers light from a particular direction in the sky (we measure angular distribution of the Cherenkov light)
- Different parts of the image can be associated to different parts of the shower

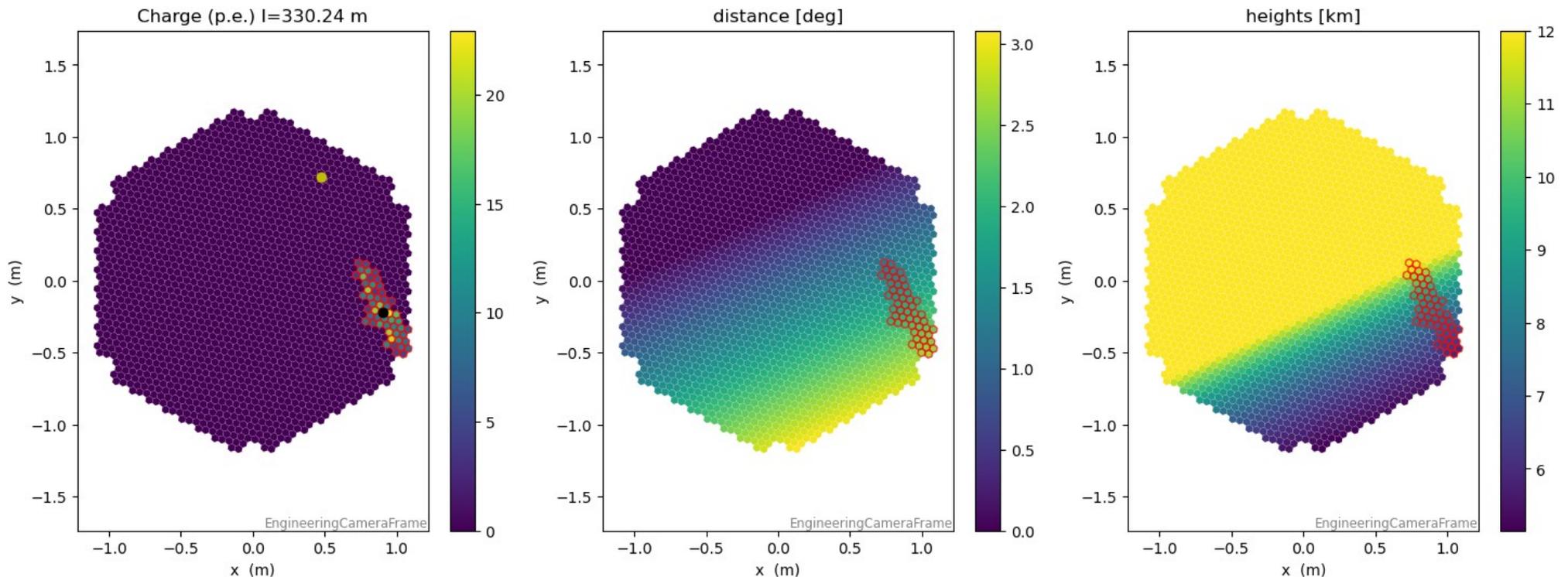


# Clouds over La Palma



# Geometrical model

- Distance of each pixel from the reconstructed source position (projected at the line joining it to image COG) is computed and converted to high
- Only light up to 0.2 deg from the main axis of the image is considered



# Quality cuts

- We select only images with
  - At least 20 pixels (large, better reconstructed images), Intensity should not be used directly, because it gets strongly affected by the cloud
  - Only one island
  - $|\text{Time gradient}| > 1 \text{ ns/m}$  – to avoid single muons
  - $\text{concentration\_cog} > 0.001$

and make stereo analysis with them (requiring at least 2 LST telescopes)

- Then keep events with
  - $5 \text{ ns/m} < |\text{Time gradient}| < 15 \text{ ns/m}$  (excludes large impact images that are more problematic)

and calculate summed up (not average) longitudinal profile of Cherenkov light

- Depending on the cloud this results in 30-60 Hz of selected images – high statistics even on minutes time scale