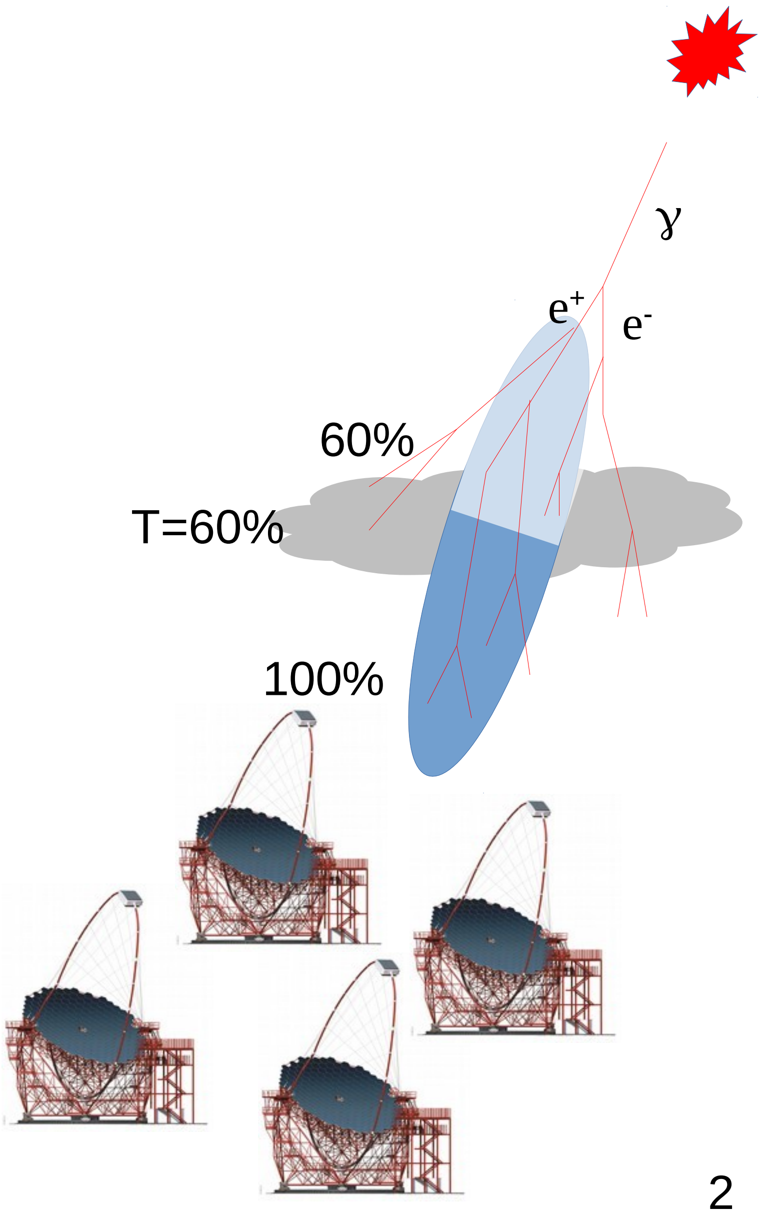
Proton LIDAR - direct measurement of atmospheric transmission profile with Cherenkov telescopes

J. Sitarek, M. Pecimotika, N. Żywucka,
D. Sobczyńska, A. Moralejo, D. Hrupec

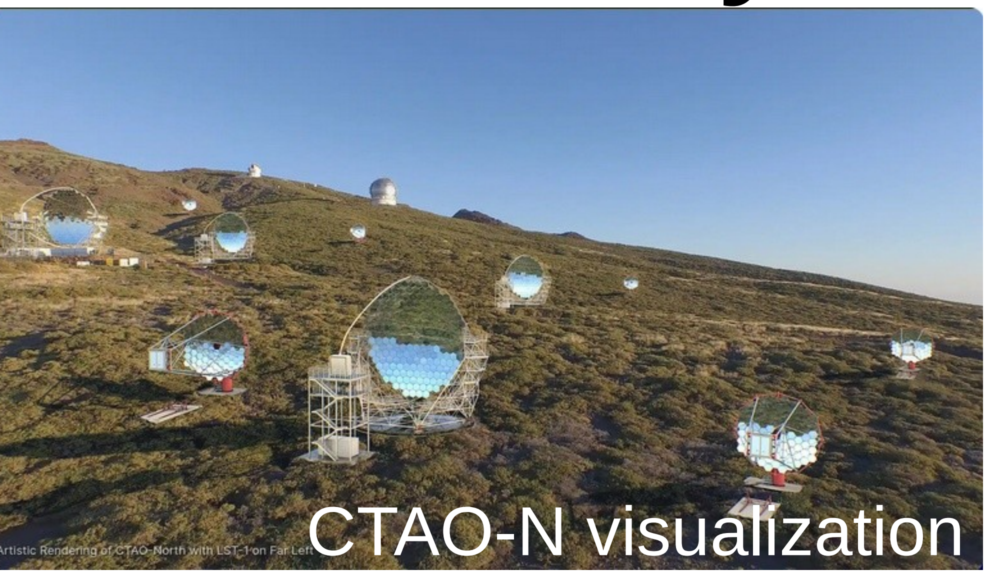
2024.09, Milano, 8th Heidelberg International Symposium on
High-Energy Gamma-Ray Astronomy

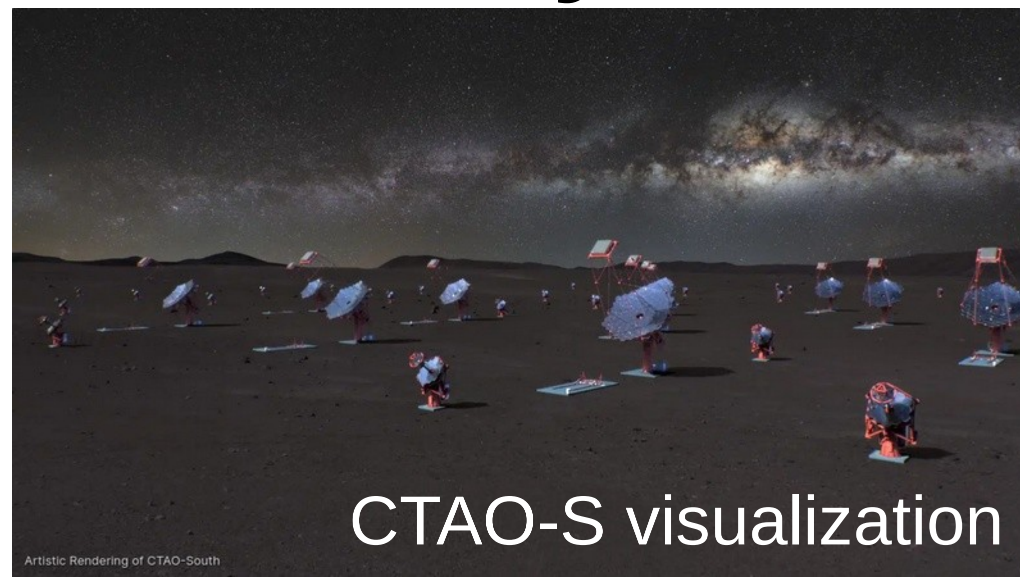
Cherenkov telescopes and clouds

- 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

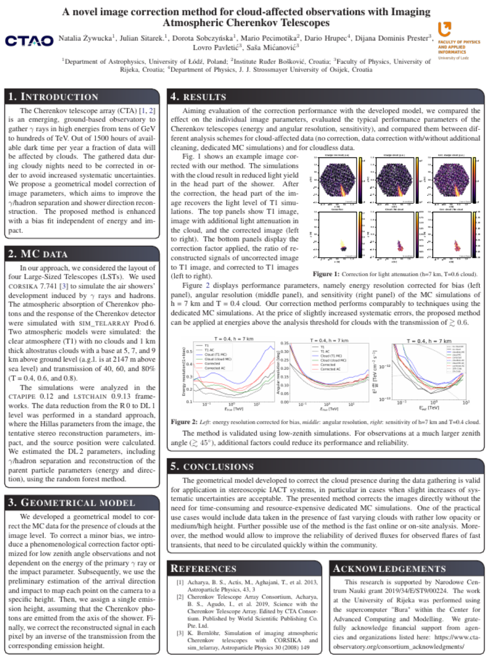




https://www.ctao.org/emission-to-discovery/array-sites/

- 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 <~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

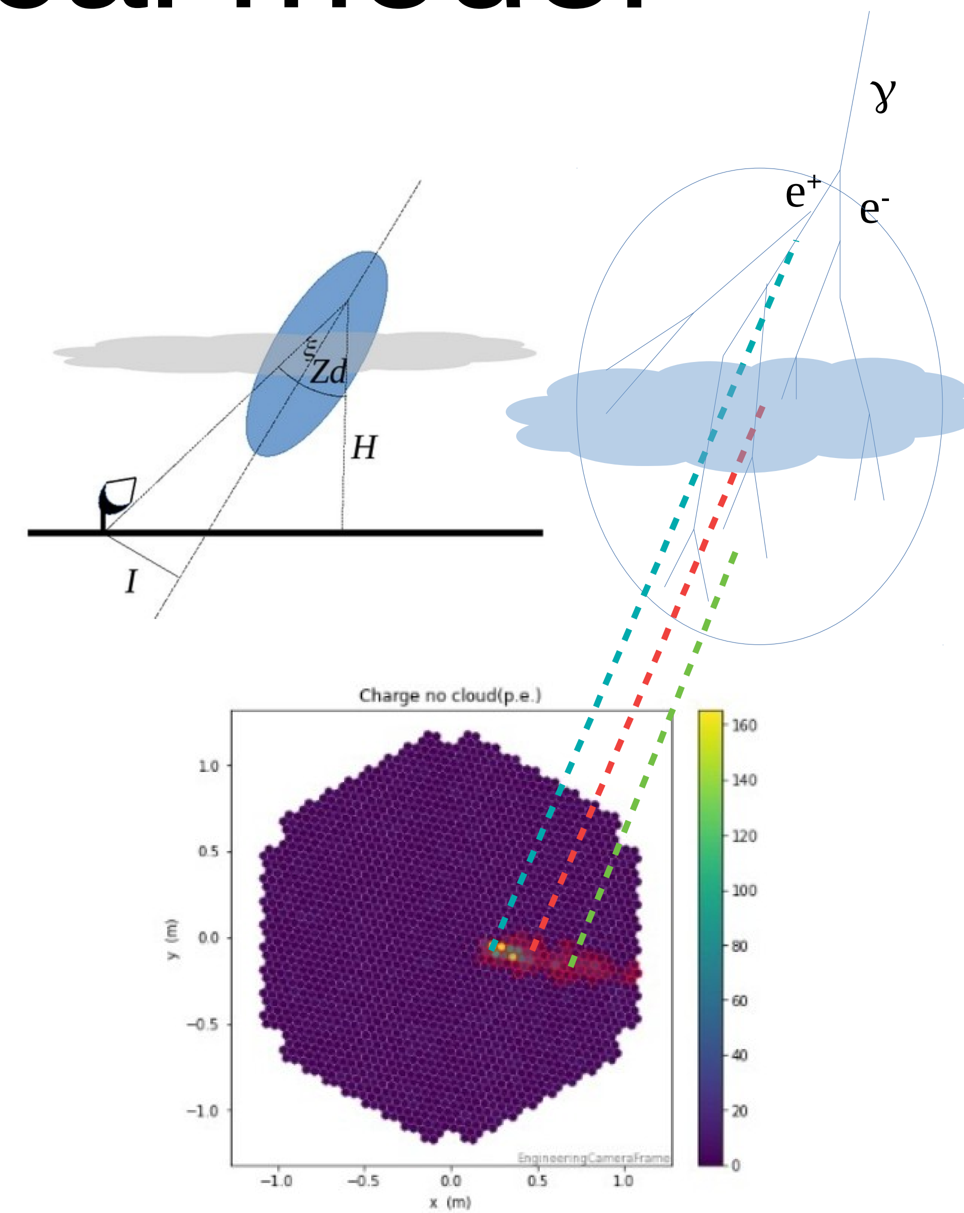
MAGIC LIDAR
(Fruck et al 2022)

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

Geometrical model

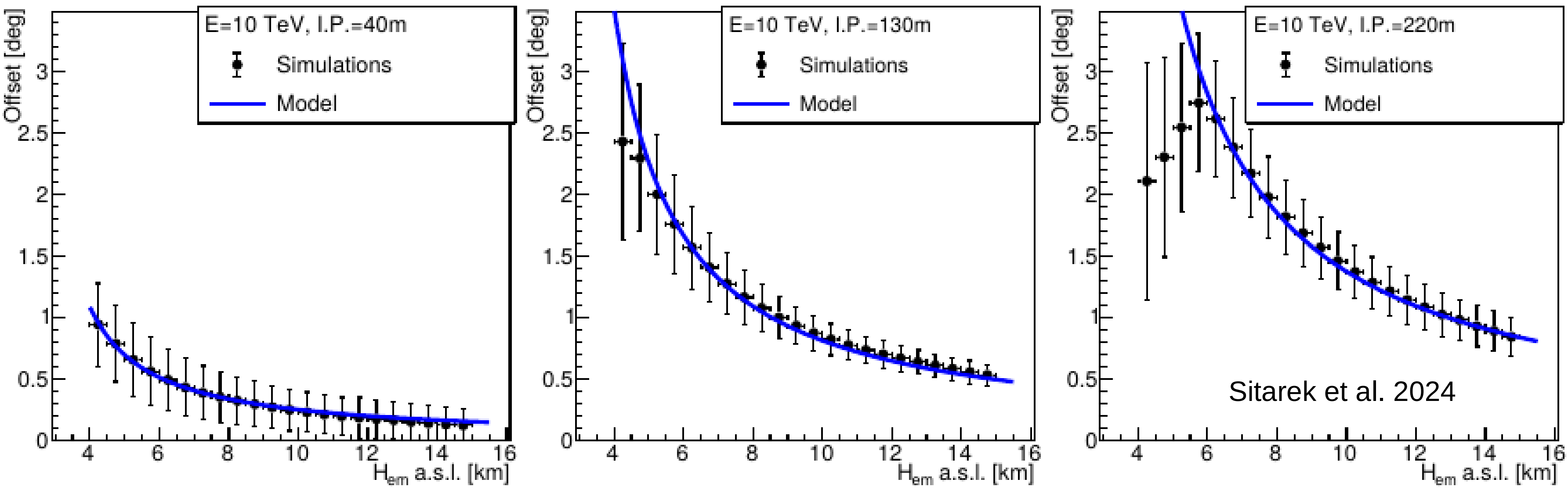
- We assume that the whole light is generated along the shower axis
- With tentative estimation of the shower direction and impact each pixel on the camera can be mapped to an emission height

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



Check N. Żywucka poster for details

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

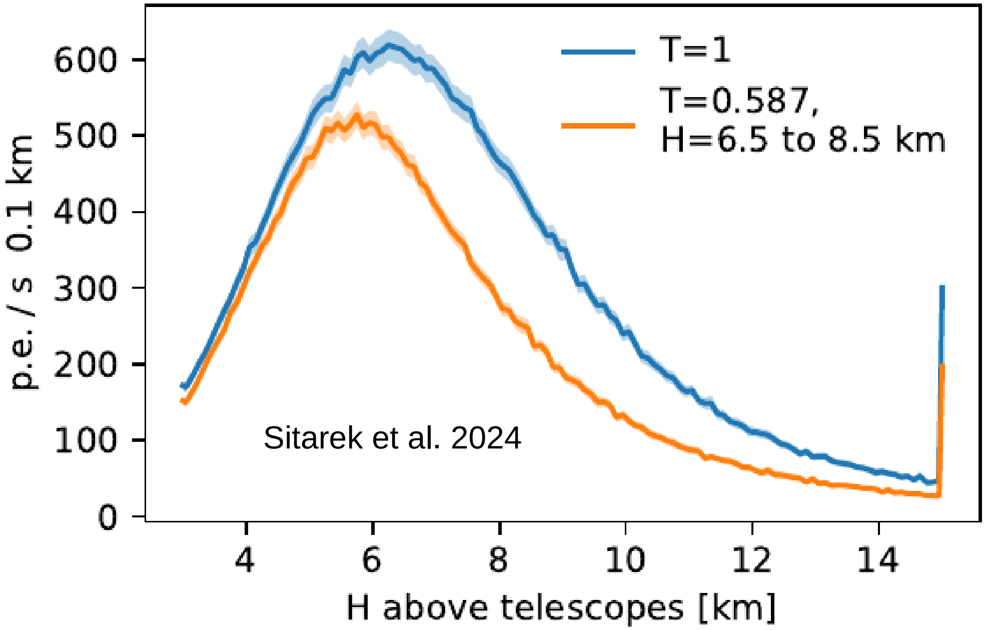
Transmission	Base height [km]	Thickness [km]
0.388	6.5 a.g.l.	2
0.587	5.5	2
0.587	**6.5**	**2**
0.587	6.0	3
0.587	5.5	4
0.587	7.0	1
0.587	7.5	2
0.800	6.5	2
1	–	–

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

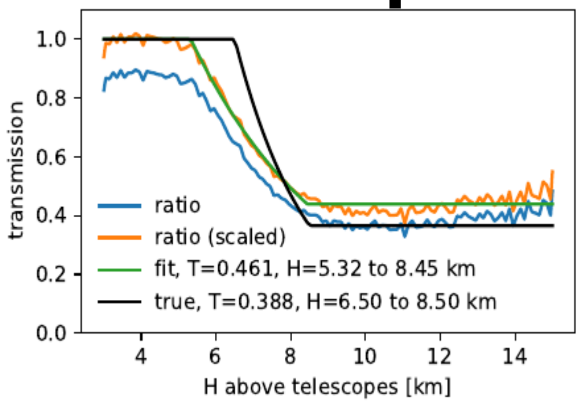
(Aggregated) longitudinal distribution of shower light

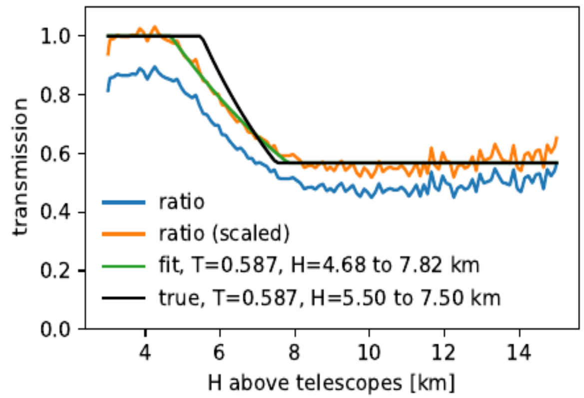
- For each event we can sum up all the pixel signals assigned to a particular emission height
- We obtain a longitudinal distribution of the registered Cherenkov light
- Weighting the events to CR proton spectrum and summing them up
- There is a clear difference between the Cherenkov profile – ratio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

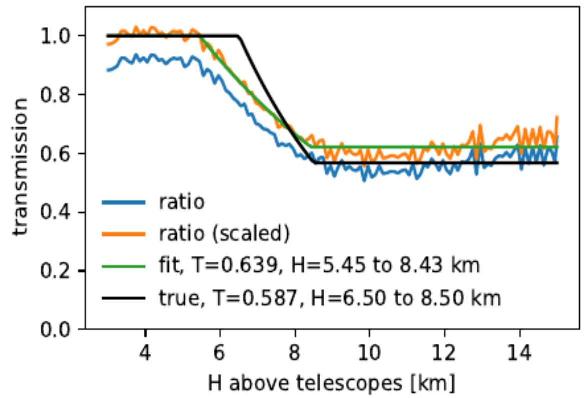


Shaded region represents uncertainties for 5 min long observations of 4 x LST

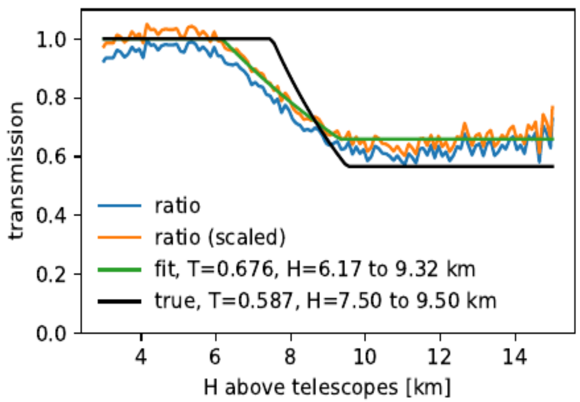
Comparisons for different clouds

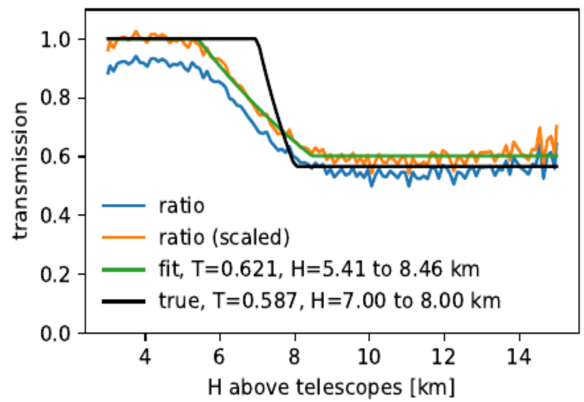


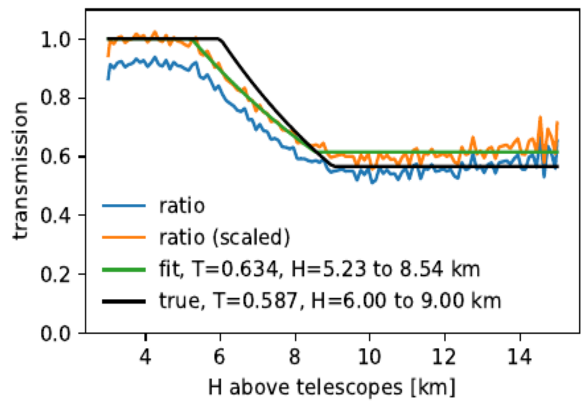


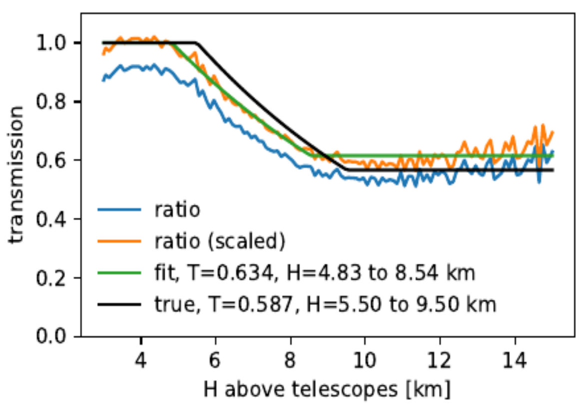


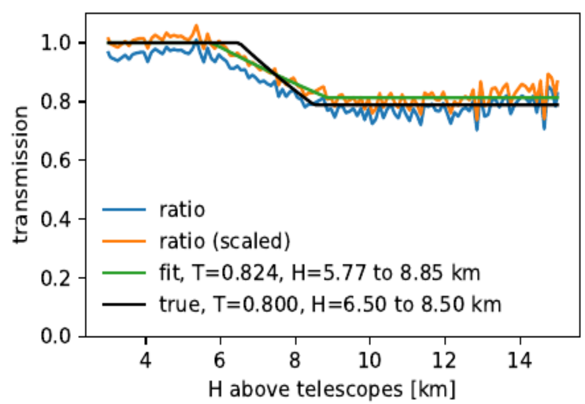
Sitarek et al. 2024





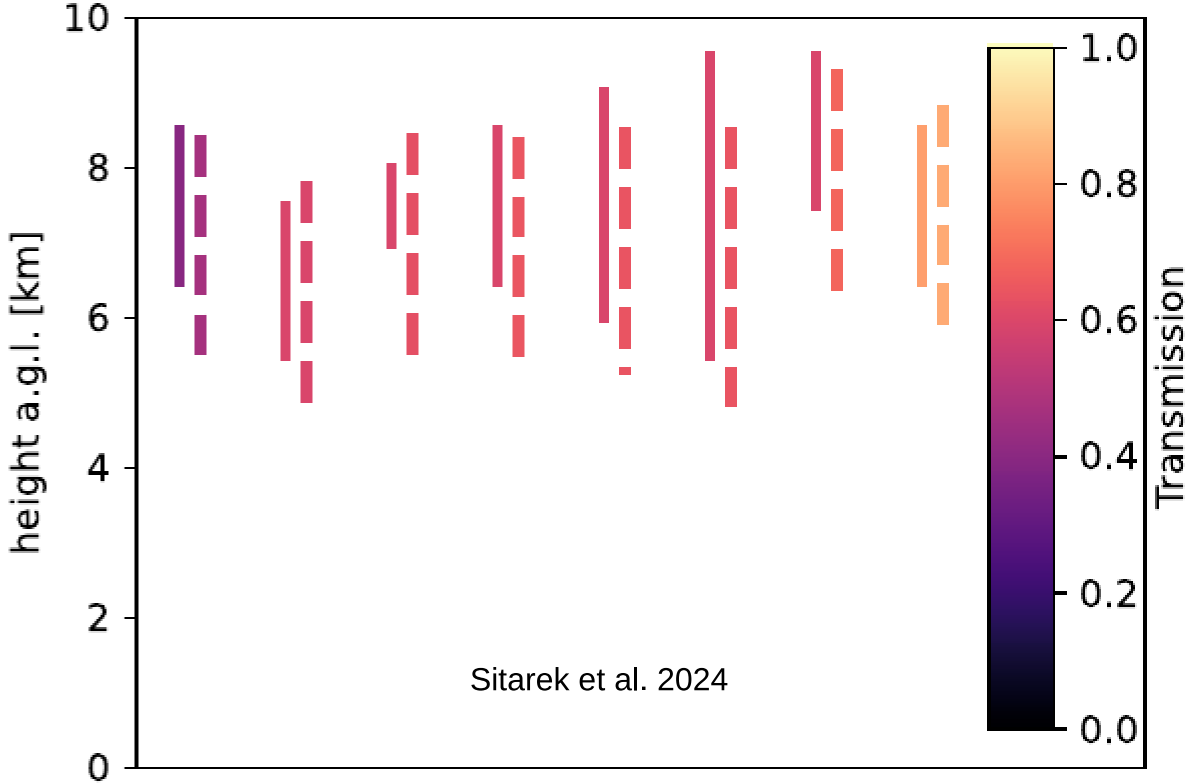






The residual bias due to lost events requires normalization of the curve at low heights (3-4 km)

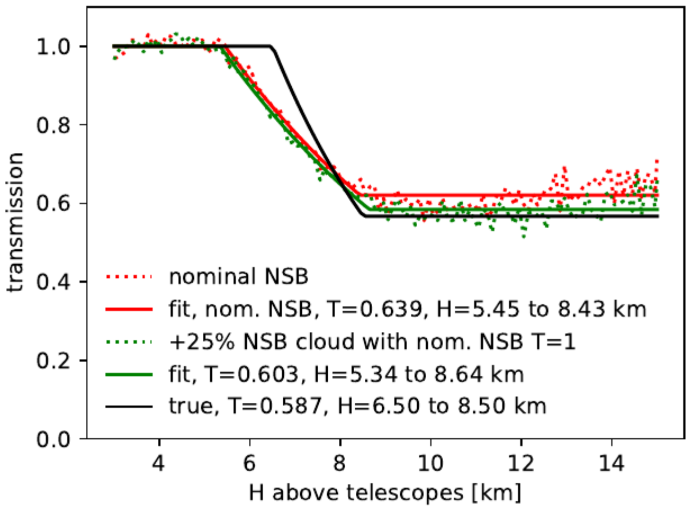
Comparisons for different clouds

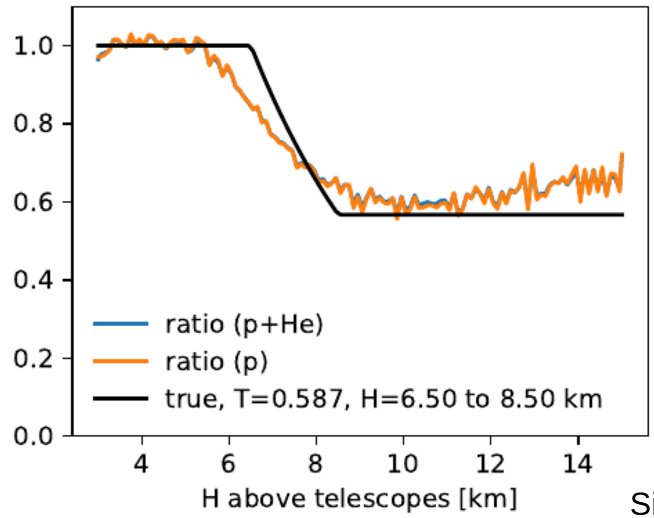


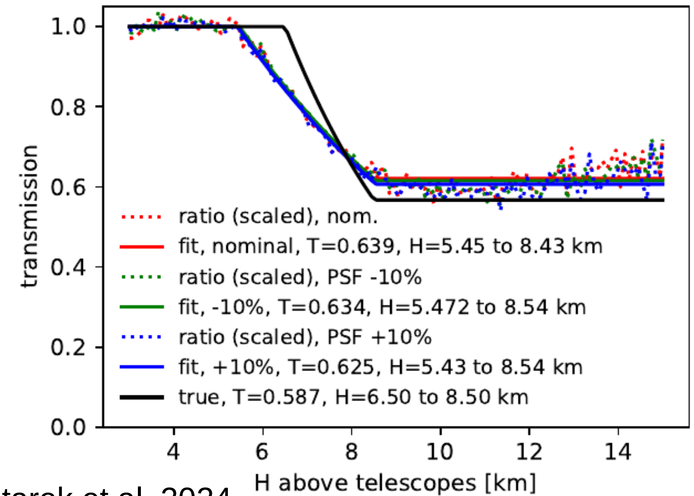
The method reproduces well the total transmission of the cloud and partially reconstructs the profile (broadening it for narrow clouds)

Solid line: simulated cloud
dashed line: reconstructed cloud

Systematic uncertainties

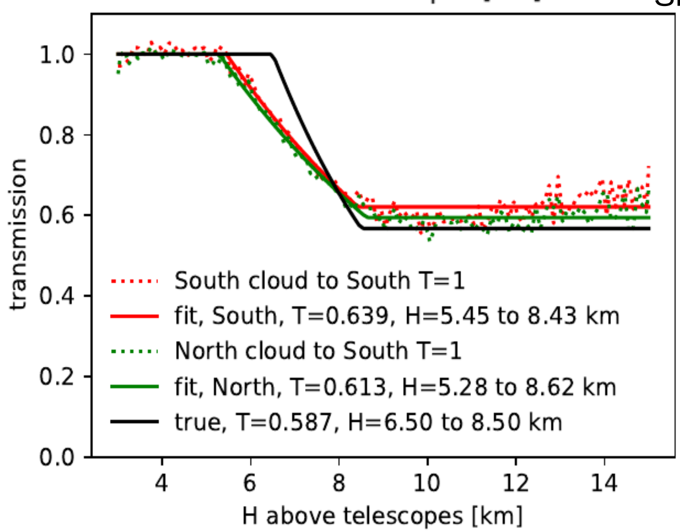


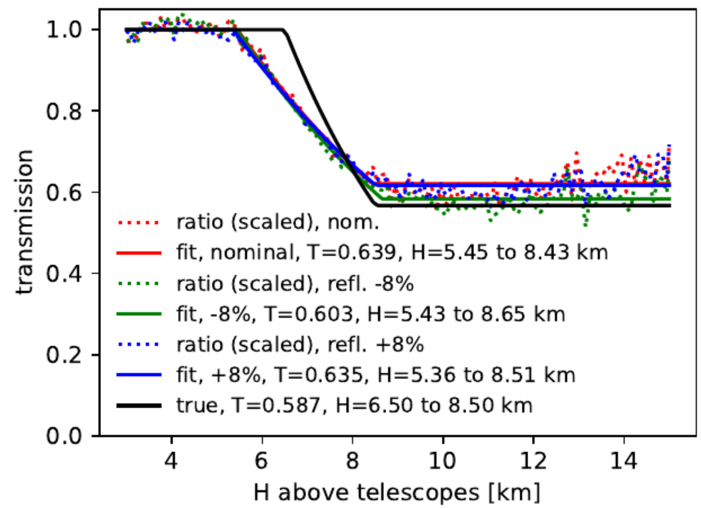




Sitarek et al. 2024

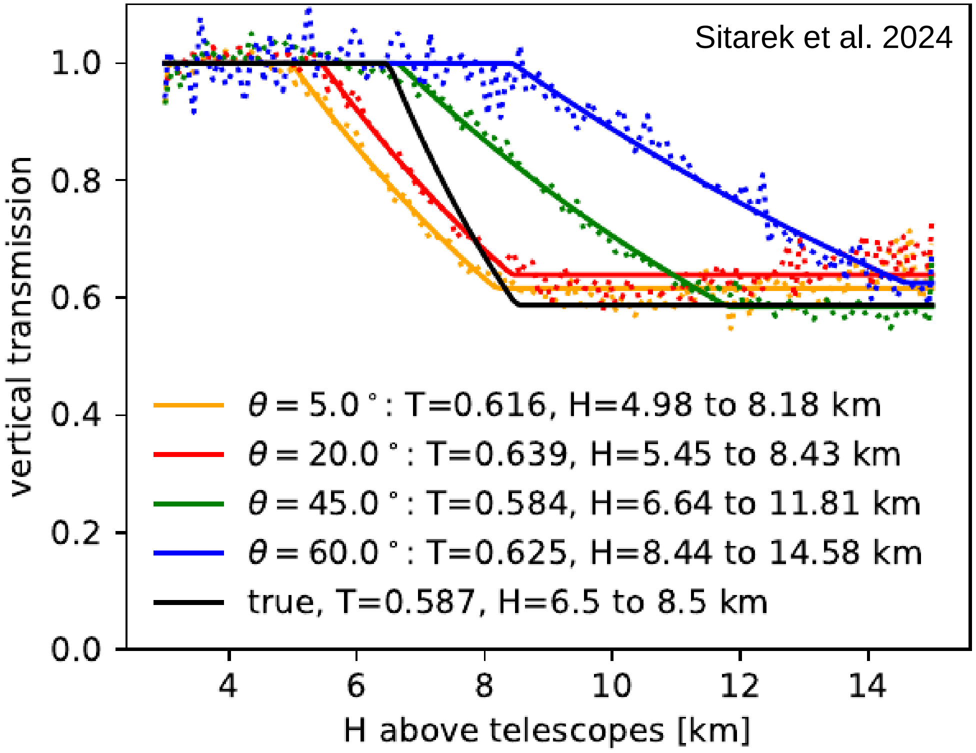
Higher elements, geomagnetic field as well as small changes in the optical performance of the telescopes and NSB level do not affect the method significantly





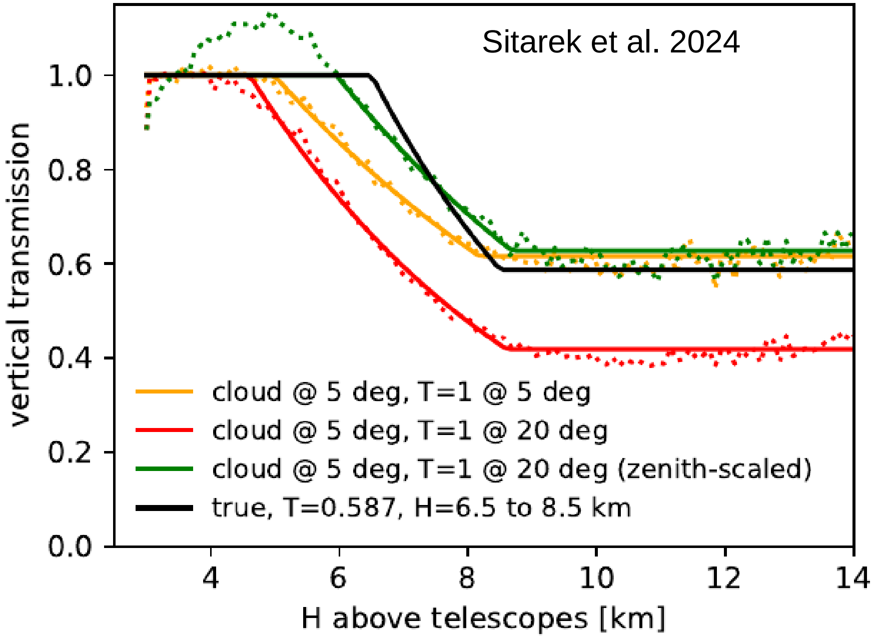
Zenith distance dependence

- 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



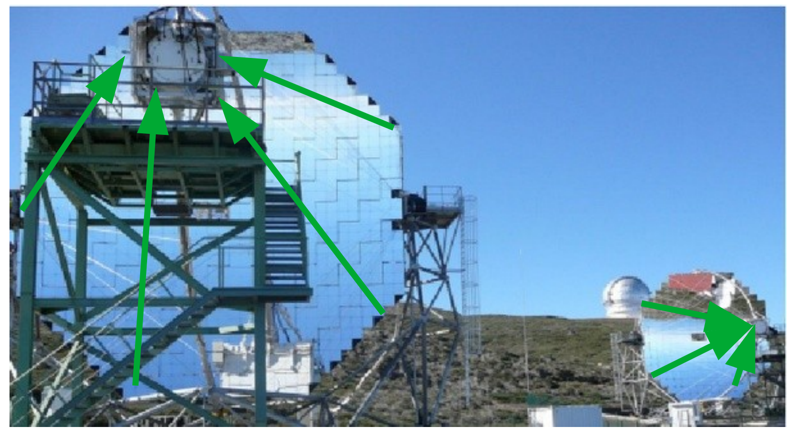
Summary

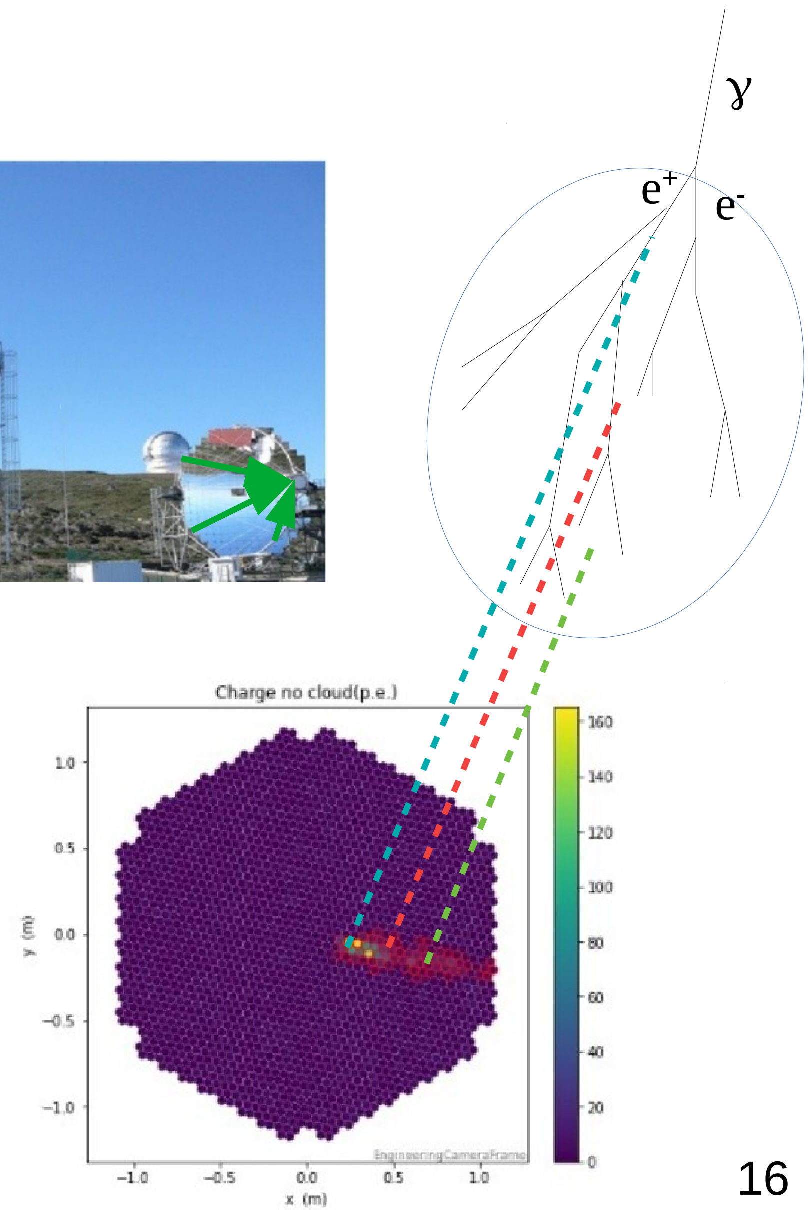
- Clouds can have an important effect on IACT observations, and different correction methods require knowledge of atmospheric transmission profile
- We propose a novel method that allows to estimate the atmospheric transmission profile directly with IACT data. It allow us to obtain **independent, always 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 >~3km**
- The method is very resilient against typical systematic uncertainties related to IACT observations, however looses performance for higher zenith distance observations

Backup

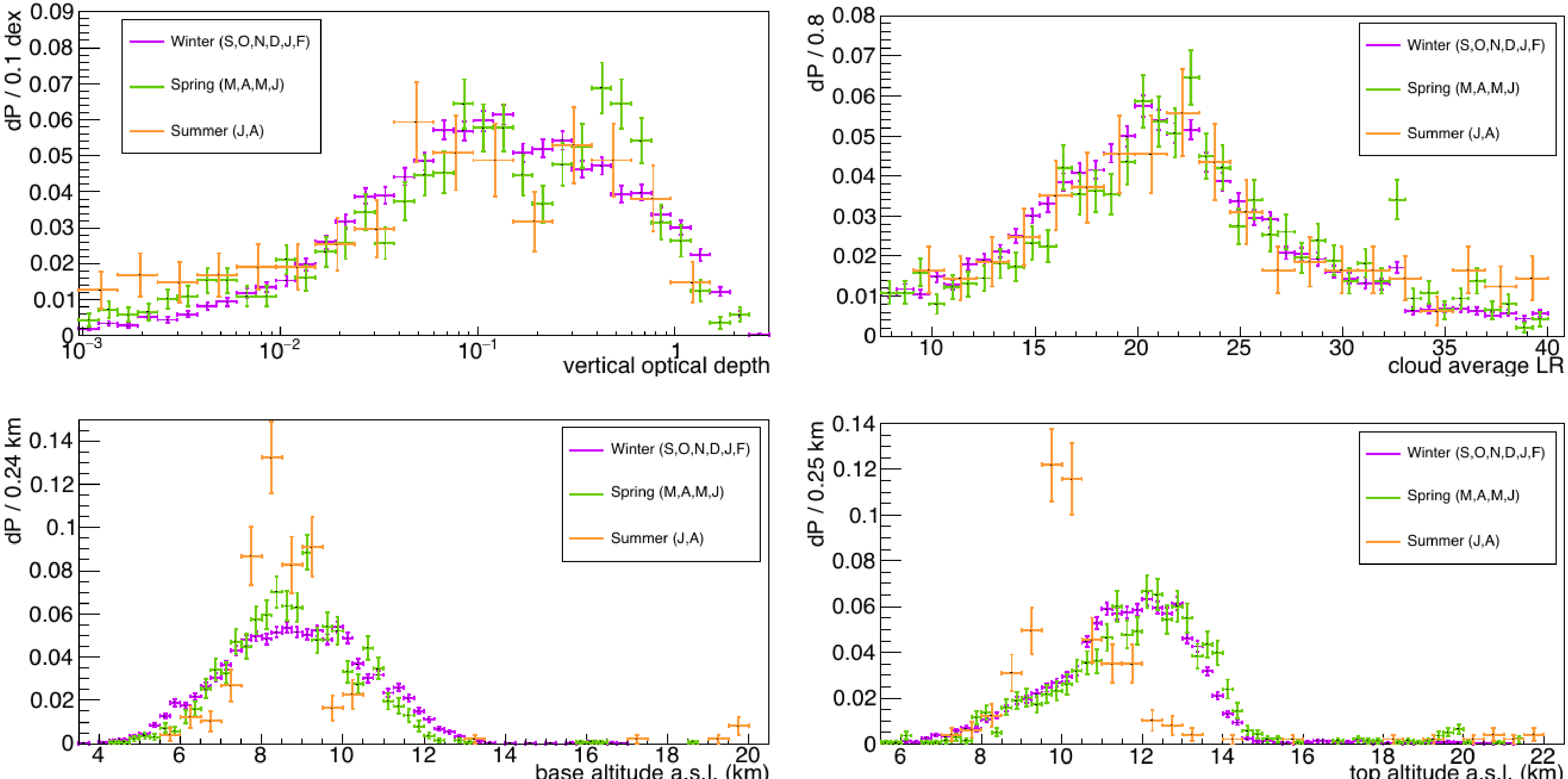
Catching Cherenkov light

- 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





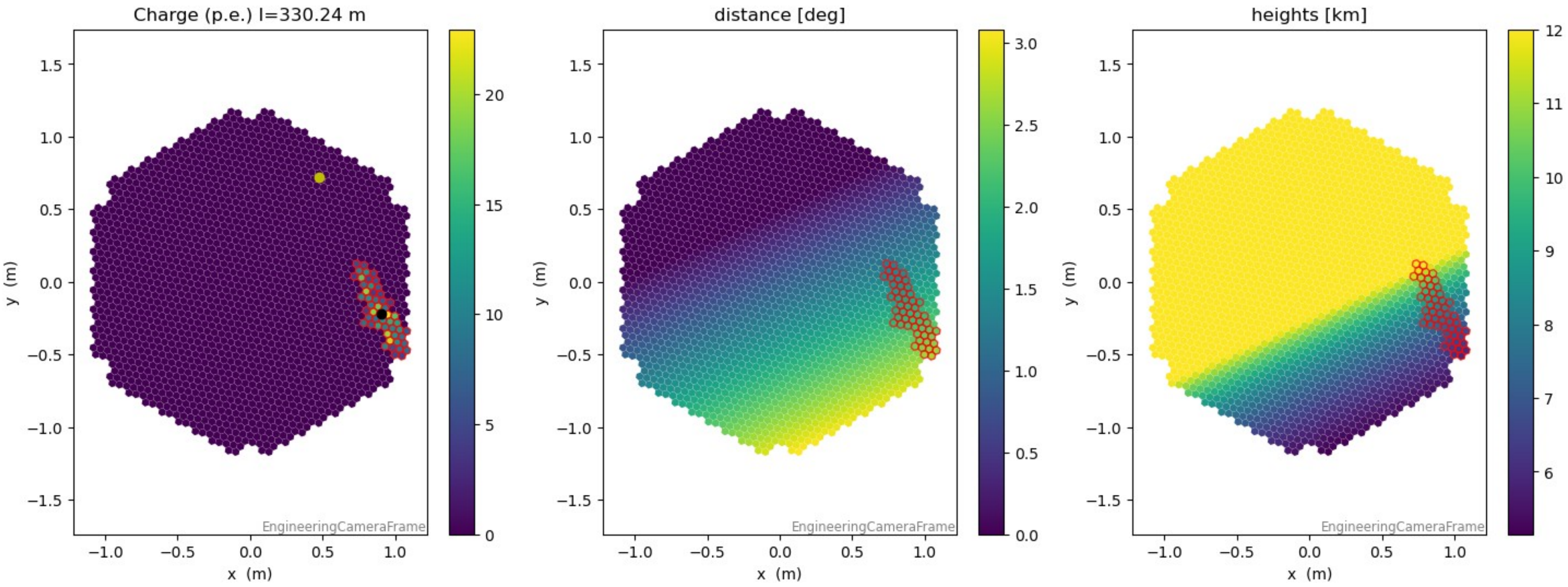
Clouds over La Palma



Fruck et al. 2022

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
  - |Time gradient | > 1 ns/m – to avoid single muons
  - concentration_cog > 0.001

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

- Then keep events with
  - 5 ns/m<|Time gradient | < 15 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