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# Estimation of the atmospheric transmission profile with the IACT background data

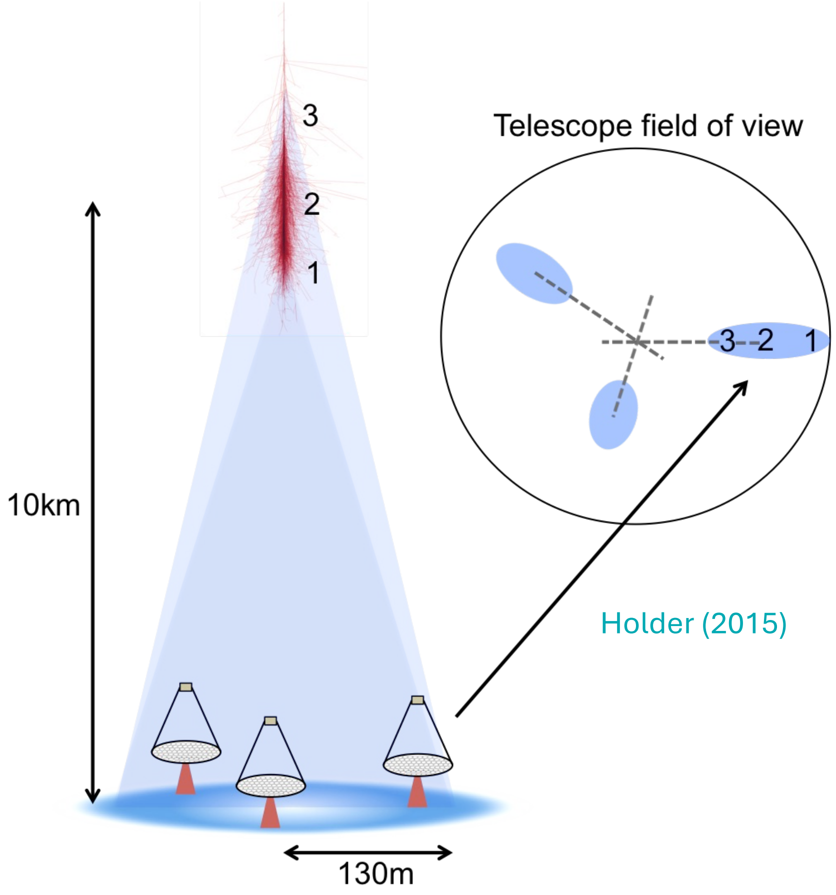

Mario Pecimotika*, Julian Sitarek, Natalia Żywucka, Dorota Sobczyńska, Abelardo Moralejo, Dario Hrupec

* Ruđer Bošković Institute, Zagreb, Croatia

mario.pecimotika@cta-consortium.org

# Imaging Atmospheric Cherenkov Technique

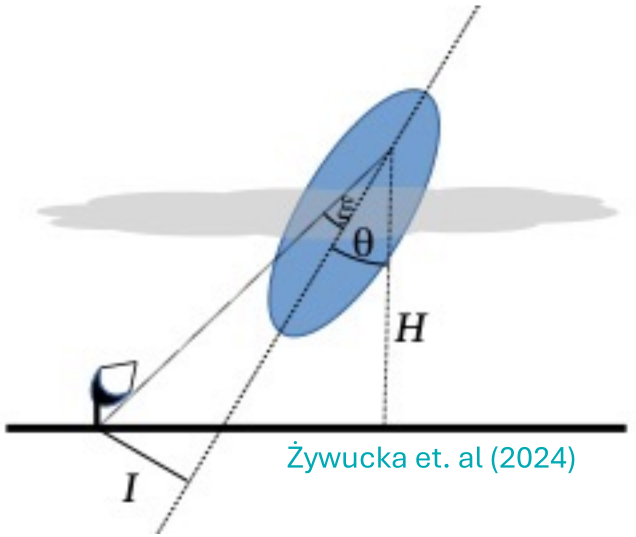
- IACT – indirect observations of gamma-ray sources by the detection of Cherenkov light generated in a cascade of secondary particles.
- The atmosphere acts as a medium in which the Cherenkov light is both generated and propagated → Continuous atmospheric monitoring.
- LIDARs require calibration and additional assumptions, while very powerful LIDARs can only be used in the time between telescope repositioning.
- Can we get the transmission profile from the IACT data itself?




Holder (2015)

# Methodology: Derivation of the atmo. profile

- The method is very similar to that previously presented by Natalia (cf. Żywucka et al. 2024).
- Sitarek et. al (2024) *JHEAP* 42, 87-95
- It involves construction of a sum of the longitudinal distributions of the observed Cherenkov light.
- By comparing these distributions between cloudy and clear atmosphere, it is possible to obtain the transmission of the cloud.



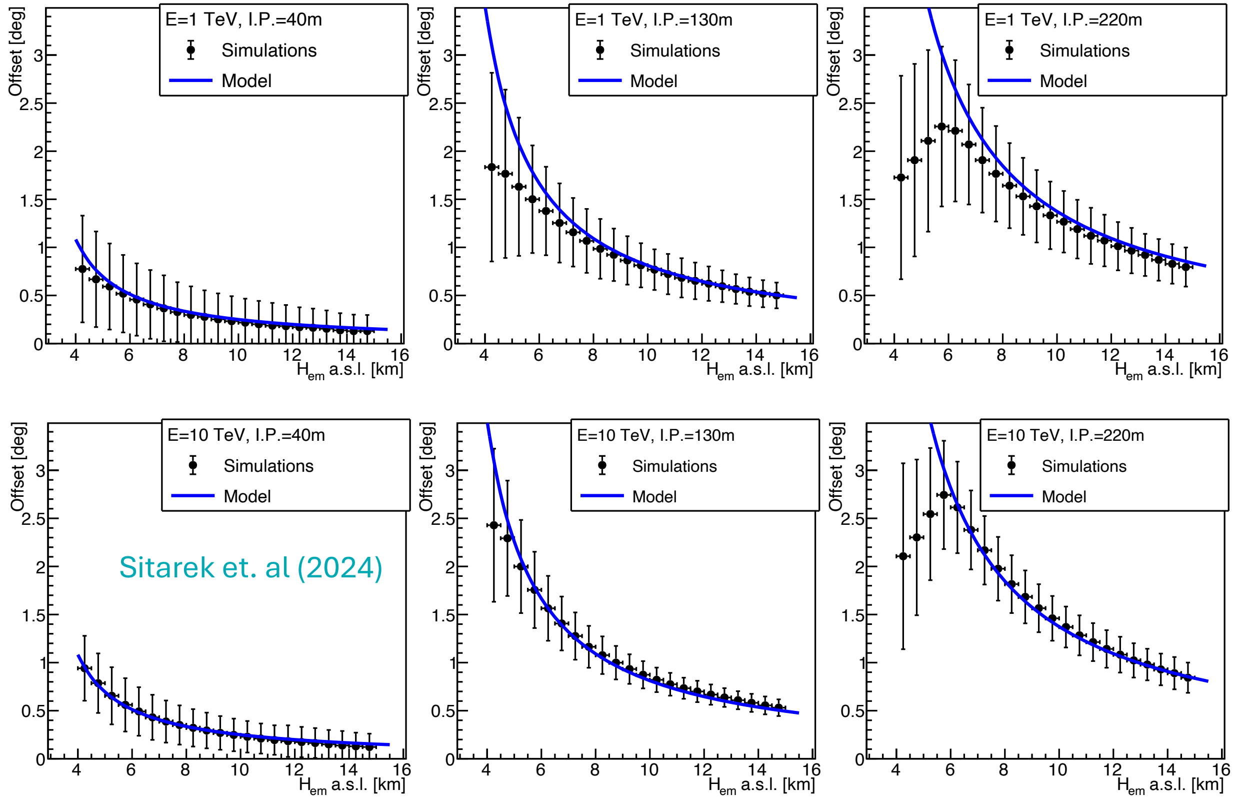

Żywucka et. al (2024)

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

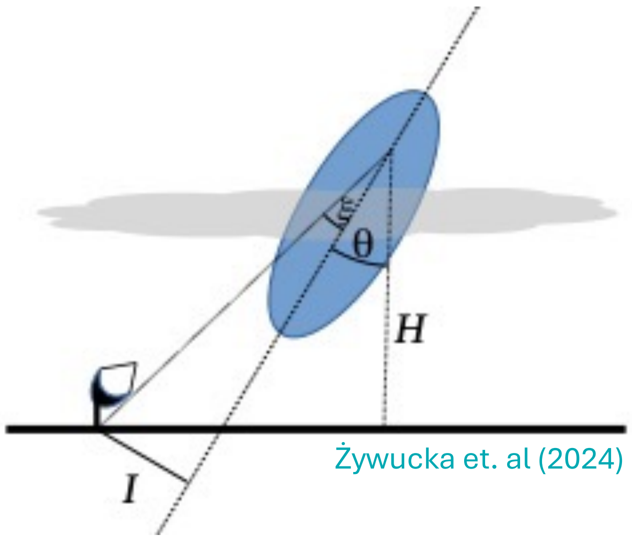
$\xi$ - ang. dist. from the primary particle direction
$I$ - (preliminary reconstructed) impact parameter
$H$ - Cherenkov photons emission height
$\theta$ - Zenith angle of observations

# Methodology: Derivation of the atmo. profile

- We have calculated the mean angular offset (and its std. dev.) for the light emitted at a certain height and compared it with the geometric model.




Sitarek et. al (2024)

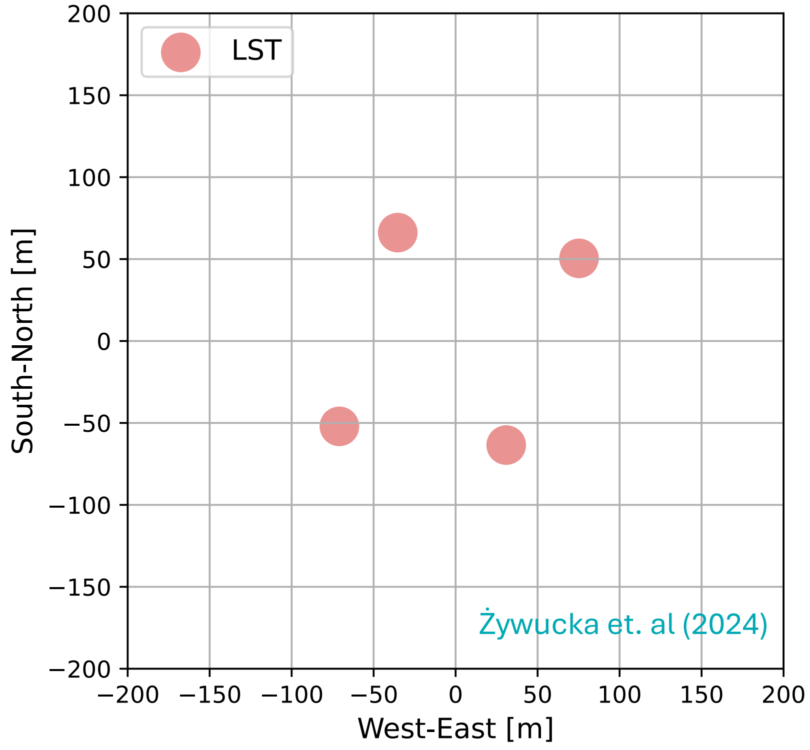



Żywucka et. al (2024)

$$\xi = \frac{0.85}{\cos\theta} \cdot \arctan\left(\frac{I\cos\theta}{H}\right)$$

# Methodology: Simulations

- COsmic Ray SImulations for KAscade (CORSIKA) + sim_telarray
- Proton-induced air shower, Zenith: 20 deg, Azimuth: 180 deg
- Atmospheric profiles modelling: MODerate resolution atmospheric TRANsmission (MODTRAN) band model
- Baseline cloud: $T = 0.587$ , $H_{\mathrm{base}} = 6.5$ km a.g.l., 2 km thick
- We have also tested method for other clouds with different transmissions, base heights and thicknesses, cf. Table 1 in Sitarek et. al (2024)

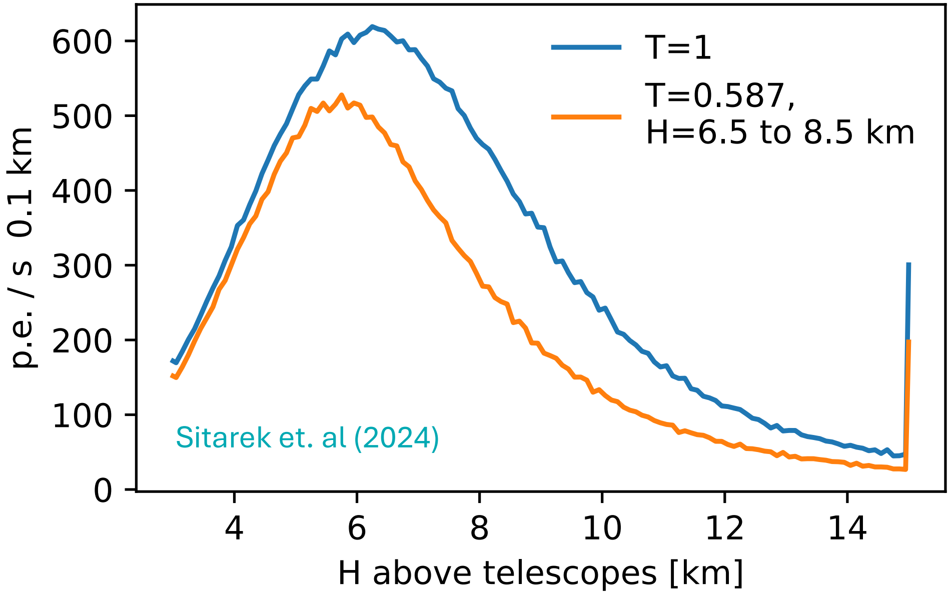


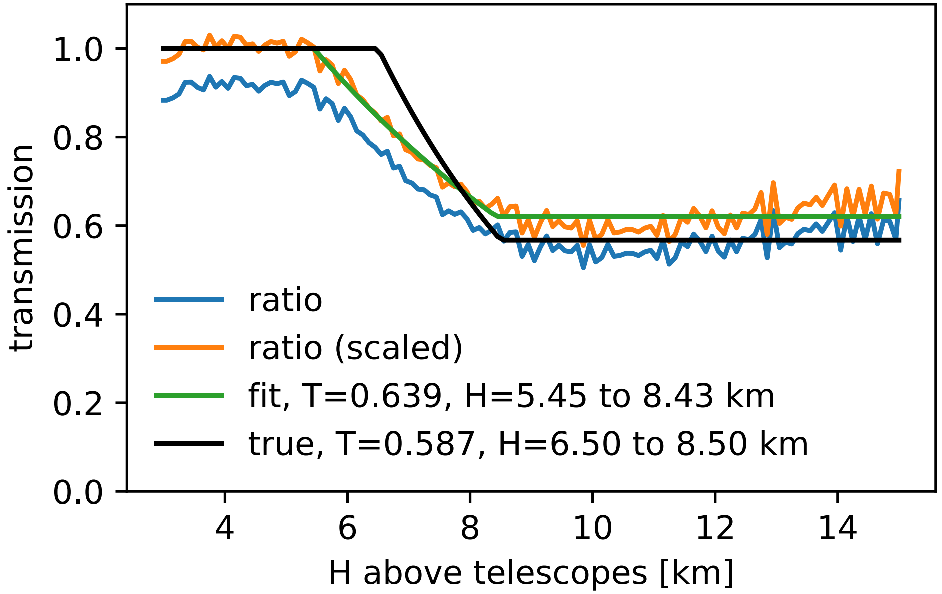
# Methodology: Analysis

- ctapipe[1] + lstchain[2]
- Selection criteria applied at the stereoscopic reconstruction level:
  - images with at least 20 pixels and only one island,
  - |Time gradient | > 1 ns/m to avoid single muons,
  - exclude events with the centre of gravity outside of the cleaned image.
- Second set of selection criteria:
  - 5 ns/m < |Time gradient | < 15 ns/m.
- These images were used to calculate the longitudinal Cherenkov light profile.

[1] https://github.com/cta-observatory/ctapipe
[2] https://github.com/cta-observatory/cta-lstchain

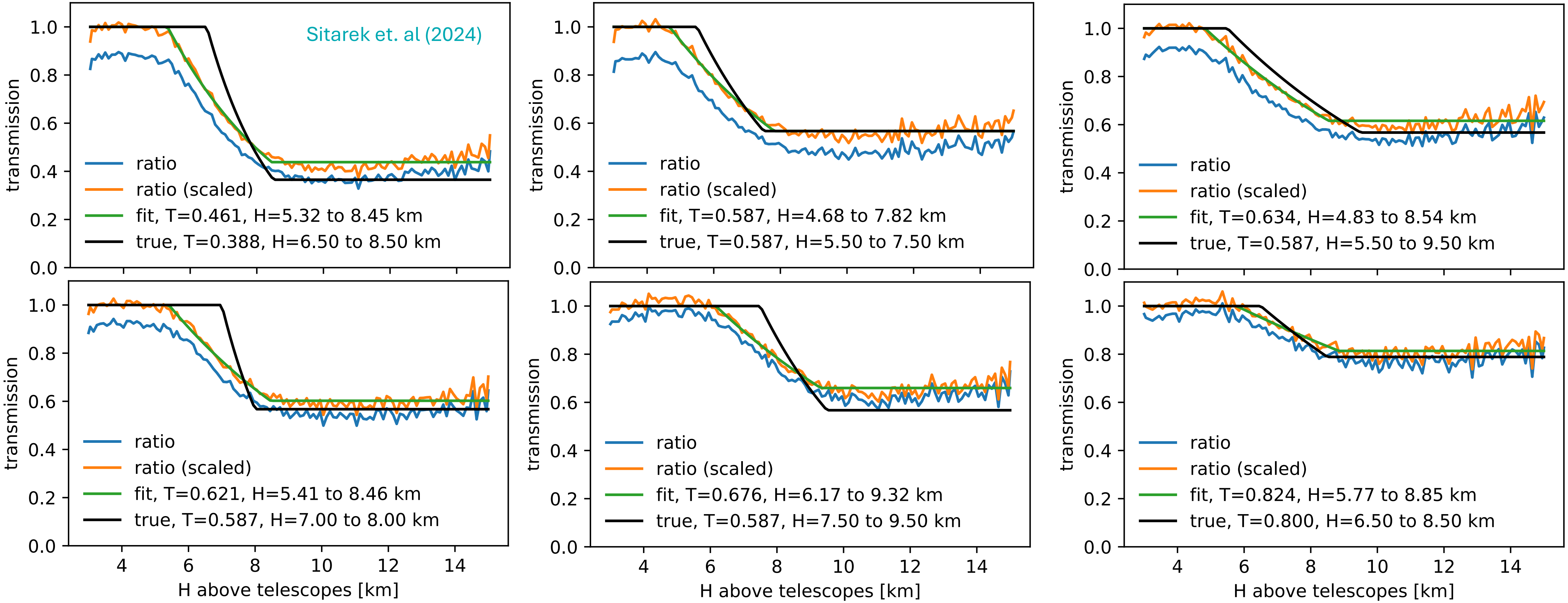
# Performance of the method




- The relative difference in the reconstructed transmission is on the order of 10%, while the thickness of the cloud is overestimated by $\approx$ 1 km. Geometrical centre of the cloud was reconstructed with ~ 0.5 km bias.

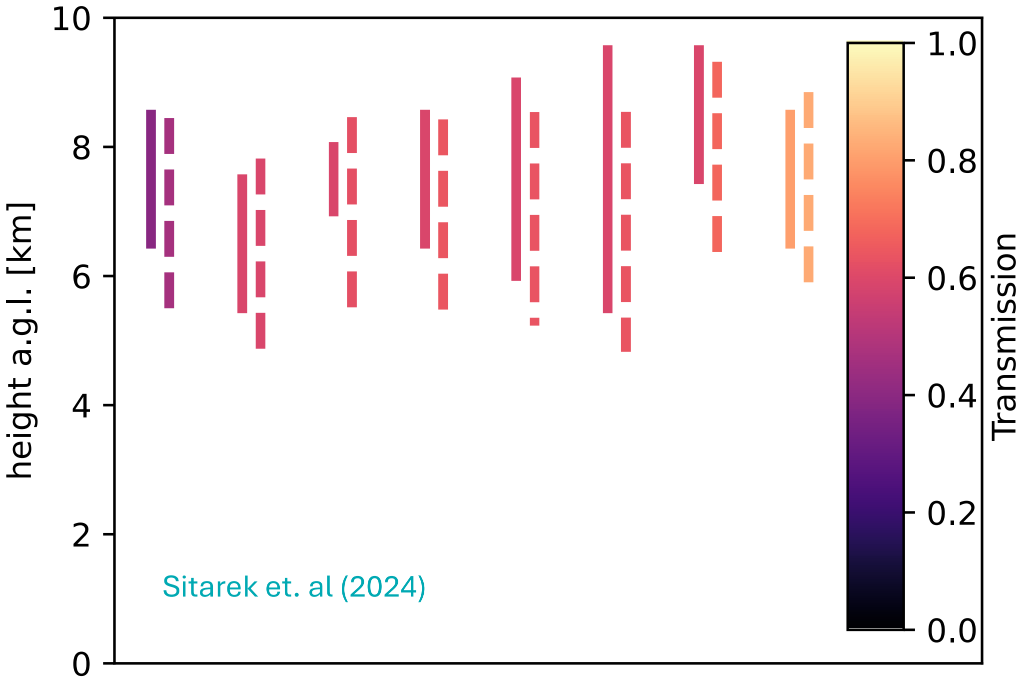
# Performance of the method



# Performance of the method

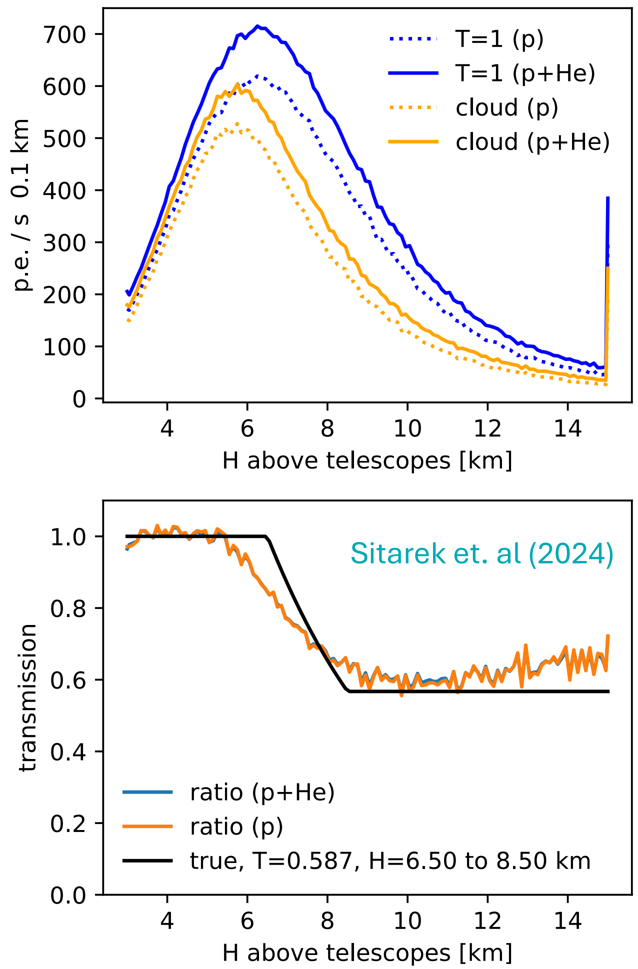
- The transmission is reconstructed within a few per cent of absolute accuracy.
- In all the simulated cases there is a bias underestimating the height of the cloud → reconstructing the cloud base at lower heights.
- Broadness of the angular offset distribution at a given emission height → cloud structures narrower than ~ 3 km have overestimated geometrical thickness.

Solid lines – Simulated
Dashed lines - Reconstructed



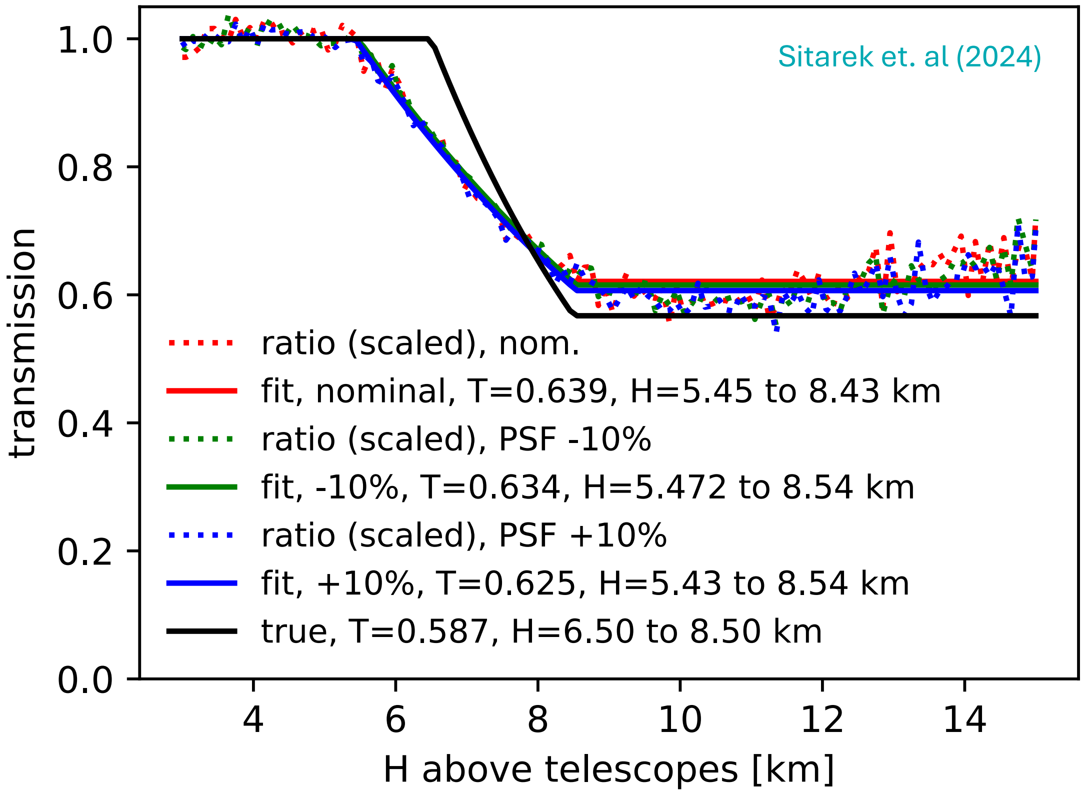
# Systematics: Other background sources

- Protons are not the only source of background in IACT, but also helium and higher nuclei.
- To test their influence on the proposed method, we created a data set of helium-induced air showers in the presence of clouds.
- The addition of helium nuclei in the data sample had no siginifcant effect on the obtained longitudinal distribution of the observed Cherenkov light and the reconstructed transmission profile.



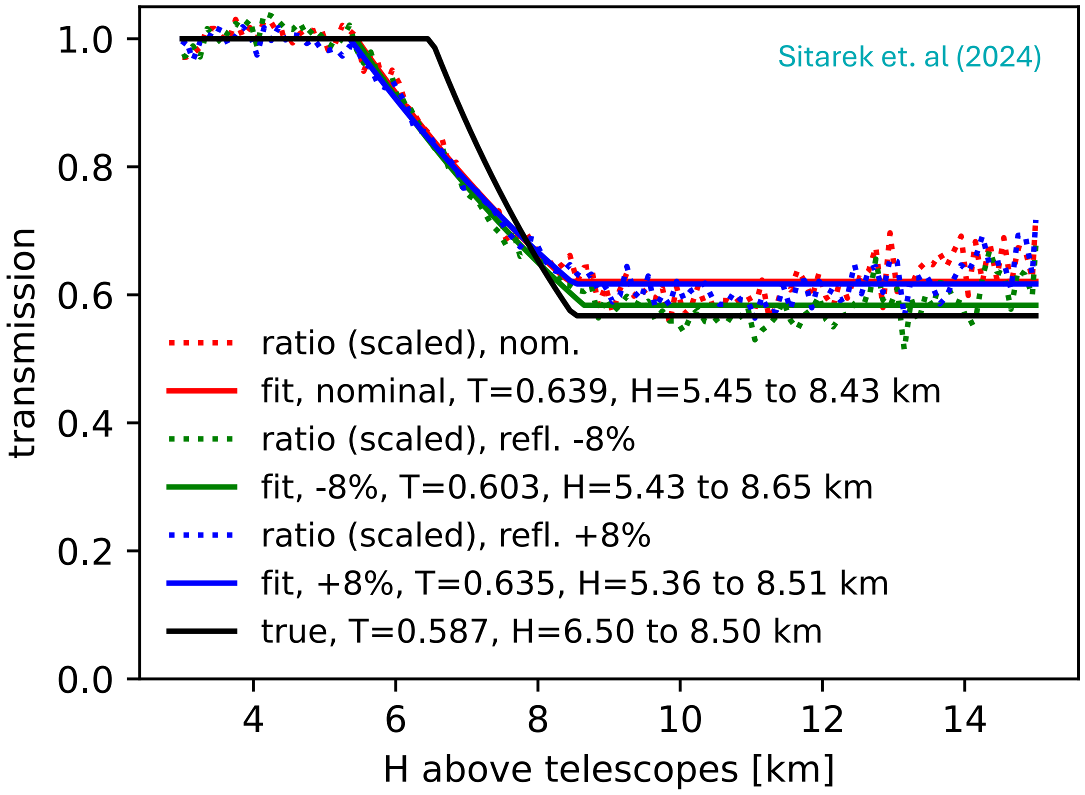
# Systematics: Changes in the optical PSF

- To investigate the effects of telescope agening, we simulated cloud-affected data sets for cases where the optical point spread function (PSF) of the Cherenkov telescope is changed by $\pm$ 10%.
- The calculated rate of the images changes by less than 1% compared to the nominal rate.
- The relative difference in the reconstructed transmission is $<$ 2%.



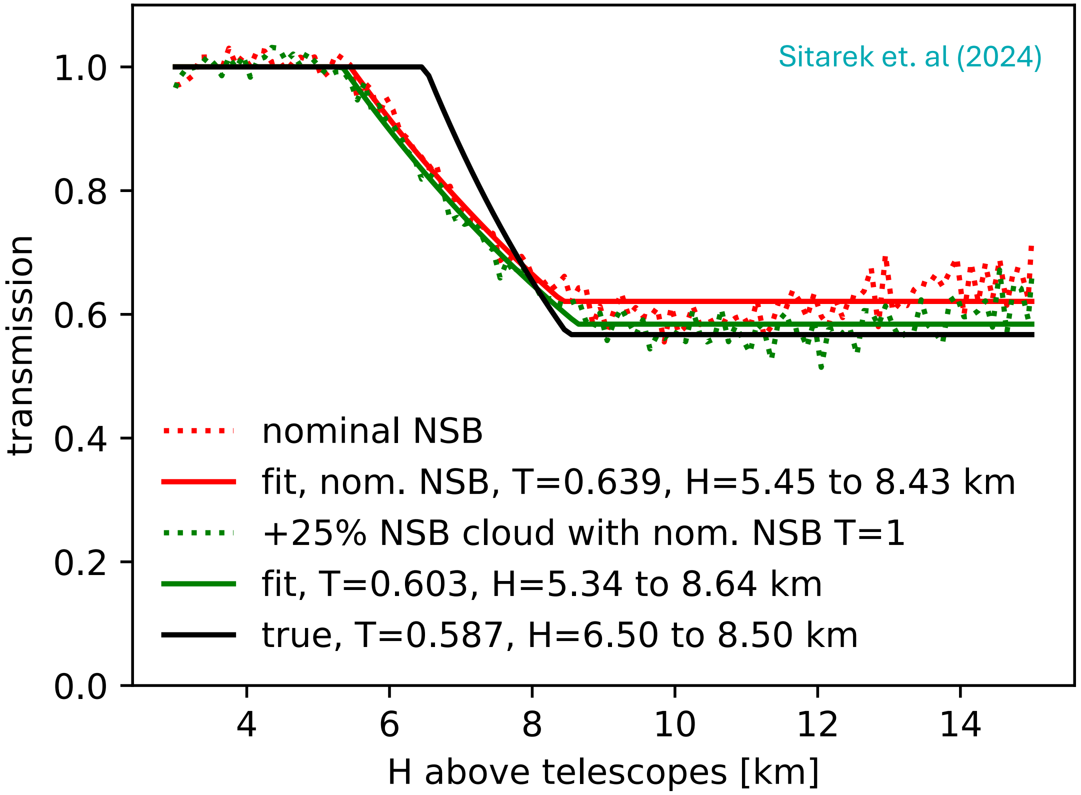
# Systematics: Changes in the mirror reflectivity

- We also simulated additional cloud-affected data sets for which the mirror reflectivity is changed by ± 8% compared to the nominal one.
- The calculated rate of the images changes by ≈ 8% compared to the nominal rate.
- The relative difference in the reconstructed transmission is on the order of 6%.



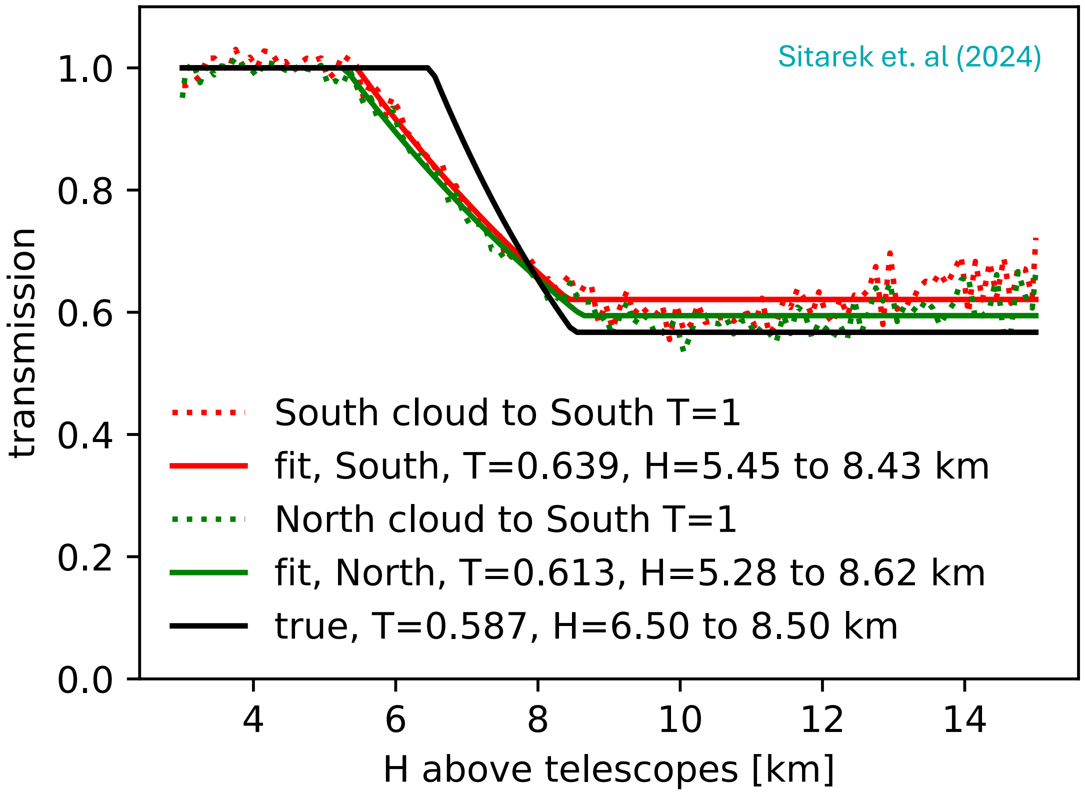
# Systematics: Increased night sky background

- Cloudless and cloud-affected data may not cover the same field of view, i.e. they may be exposed to different levels of night sky background (NSB).
- We also simulated an additional cloud-affected data set for which NSB was increased by 25%.
- Increasing the NSB by 25% does not lead to any significant changes in the transmission value obtained - an absolute difference of ≤ 4%.



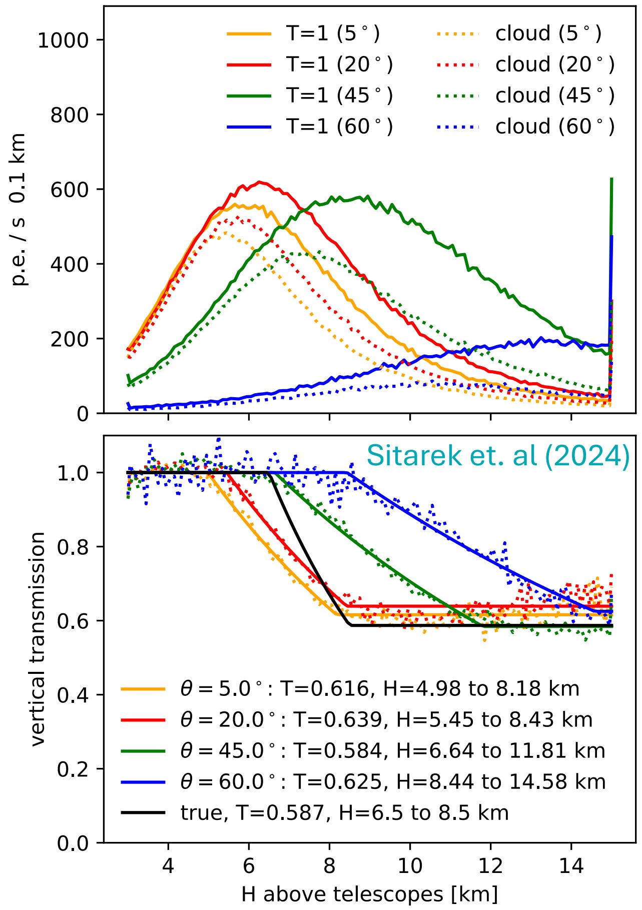
# Systematics: Pointing direction (Azimuth)

- We investigated the impact of pointing direction on the performance of our method.
- The study demonstrated that data taken at different azimuth angles can be reliably used.
- Comparing cloud-affected south-pointing data with reference cloudless north-pointing data introduced an absolute difference in reconstructed cloud transmission of only 3%.



# Systematics: Pointing direction (Zenith)

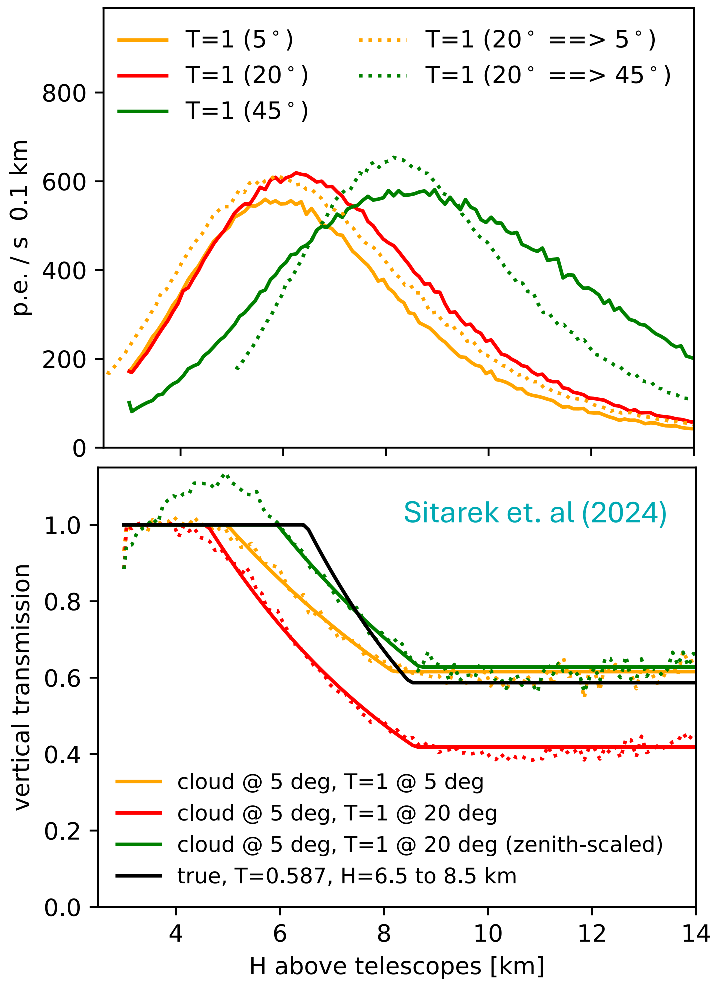
- We also generated proton-induced air shower in cloudless and cloud-affected observation for three additional zenith angles: 5°, 45° and 60°.
- Reconstructed distribution of the emission height shows a strong dependence on the zenith angle.
- For higher zenith angles, the geometrical thickness of the cloud and its centre are overestimated.



# Systematics: Pointing direction (Zenith)

- When zenith angles do not match, we propose to use the scaling method.
- Assuming reference observations at zenith $\theta_0$ with height distribution $M(h_o;\theta_0)$, the goal is to scale this distribution to the zenith $\theta_c$ at which cloud-affected data were taken, resulting in the height distribution $M'(h_c;\theta_c)$:

$$M'(h_c;\theta_c) = M(h_o;\theta_0) \cdot \frac{\Delta h_0}{\Delta h_c}$$



# Summary and conclusions

- Estimation of the transmission profile from IACTs based on the summation of the longitudinal distributions of the observed Cherenkov light from isotropic background events (proton-induced air showers).
- Helium and heavier nuclei, minor changes in mirror reflectivity or optical PSF due to telescope ageing, azimuth dependence, and increased NSB have negligible effects on the performance of the method.
- The main limitation of the method is the zenith angle - a scaling method to mitigate the bias caused by different zenith distributions is proposed for cases where no cloudless reference dataset with the same zenith exists.

NARODOWE CENTRUM NAUKI

HRZZ Croatian Science Foundation

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# Backup slides

# Parameters of the simulated clouds

| Transmission | Base height [km] | Thickness [km] |
| --- | --- | --- |
| 0.388 | 6.5 | 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 | -- | -- |

Sitarek et. al (2024) *JHEAP* 42, 87-95

# Nominal Monte Carlo simulations parameters

- Proton-induced air showers
  - Spectral index = -2
  - Energy range: [0.02, 300] TeV
  - Zenith: 20 deg, Azimuth: 180 deg, VIEWCONE = [0, 10] deg
  - NSCAT = 20, CSCAT = 1400 M, NSHOW (total) = $10^9$
- Helium-induced air showers
  - Spectral index = -2
  - Energy range: [0.04, 1200] TeV
  - Zenith: 20 deg, Azimuth: 180 deg, VIEWCONE = [0, 10] deg
  - NSCAT = 20, CSCAT = 1400 M, NSHOW (total) = $10^9$