Correcting MAGIC Telescope data taken under non-optimal atmospheric conditions with an elastic LIDAR

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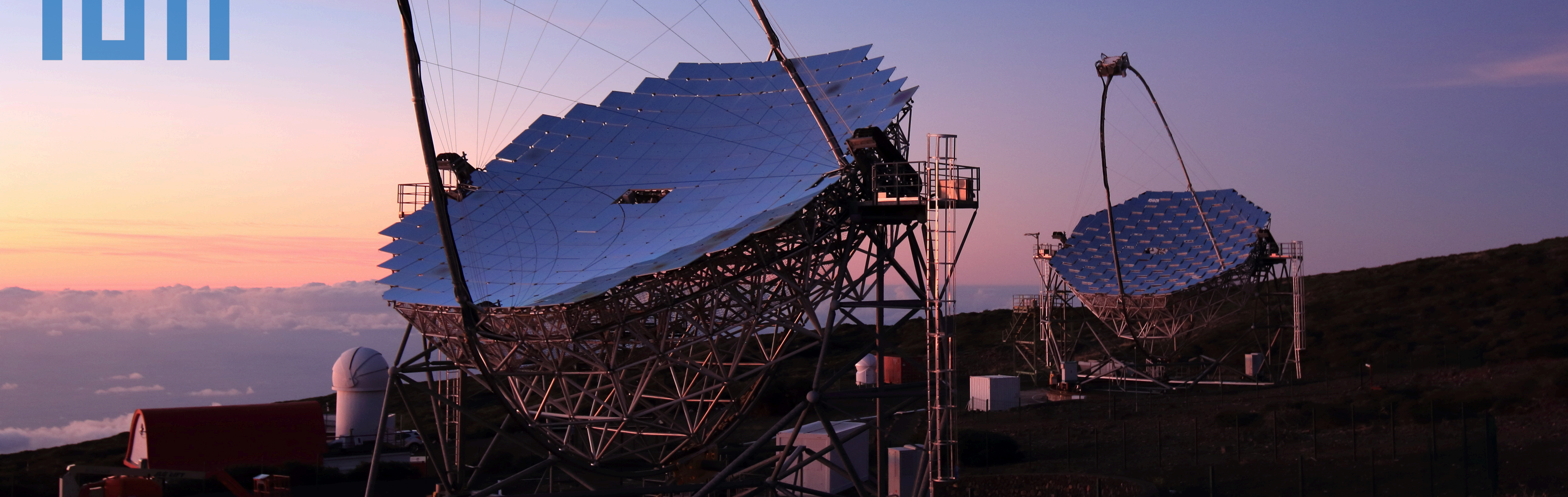


Image: Giovanni Ceribella

1. Correcting MAGIC Telescope data

The MAGIC telescopes

La Palma:

MAGIC telescopes (Credit: Giovanni Ceribella)

- Two IACTs (M1 & M2) with 17 m mirror diameter
- Located at 2200m at the Roque de Los Muchachos Observatory
- Operating since 2003 (mono) and 2009 (stereo)
- Energy range between ~50 GeV until ~50 TeV

Main advantages of IACTs:

- Using the atmosphere as a calorimeter to achieve large effective areas (~km^2)
- Detection of lower photon fluxes compared to satellites

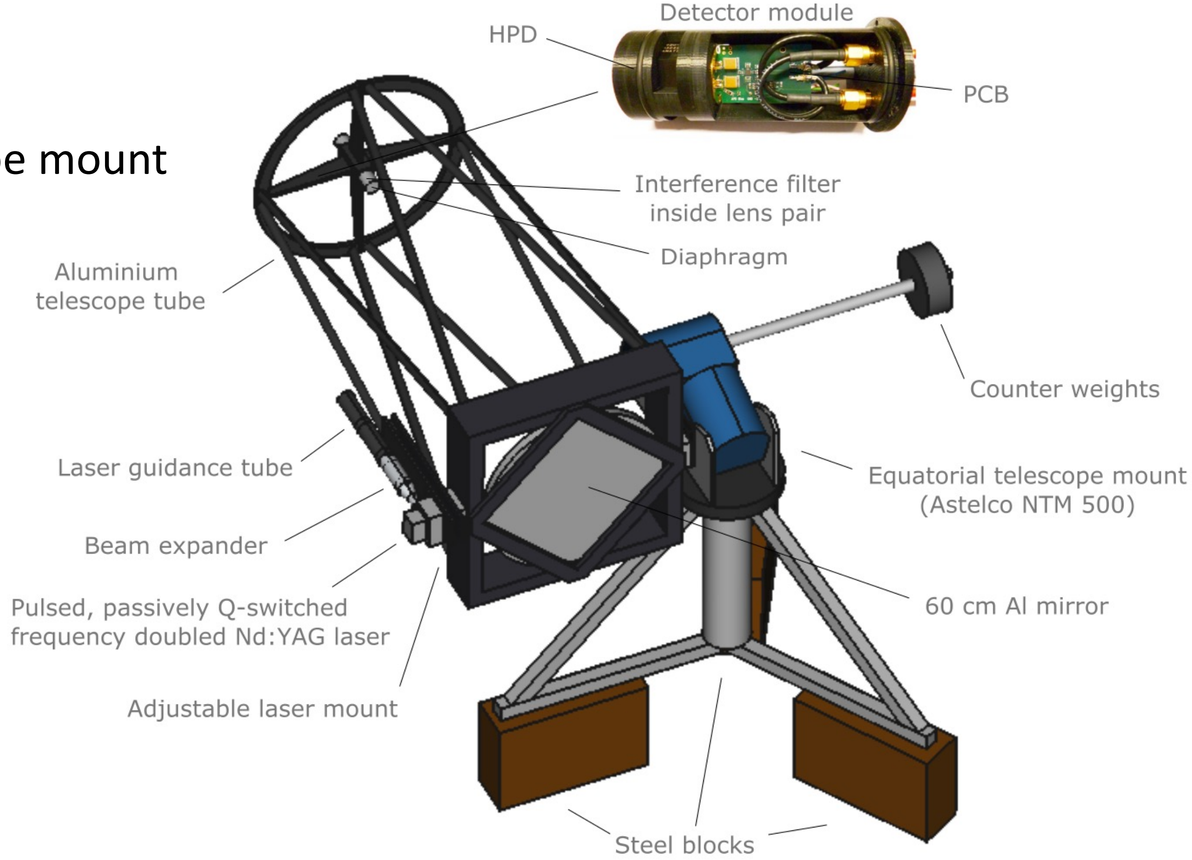
Challenges:

- Atmosphere is part of the detector
- Variable down to minutes
- Sub-optimal atmospheric conditions impair reconstruction of air showers

→ Atmospheric monitoring is necessary

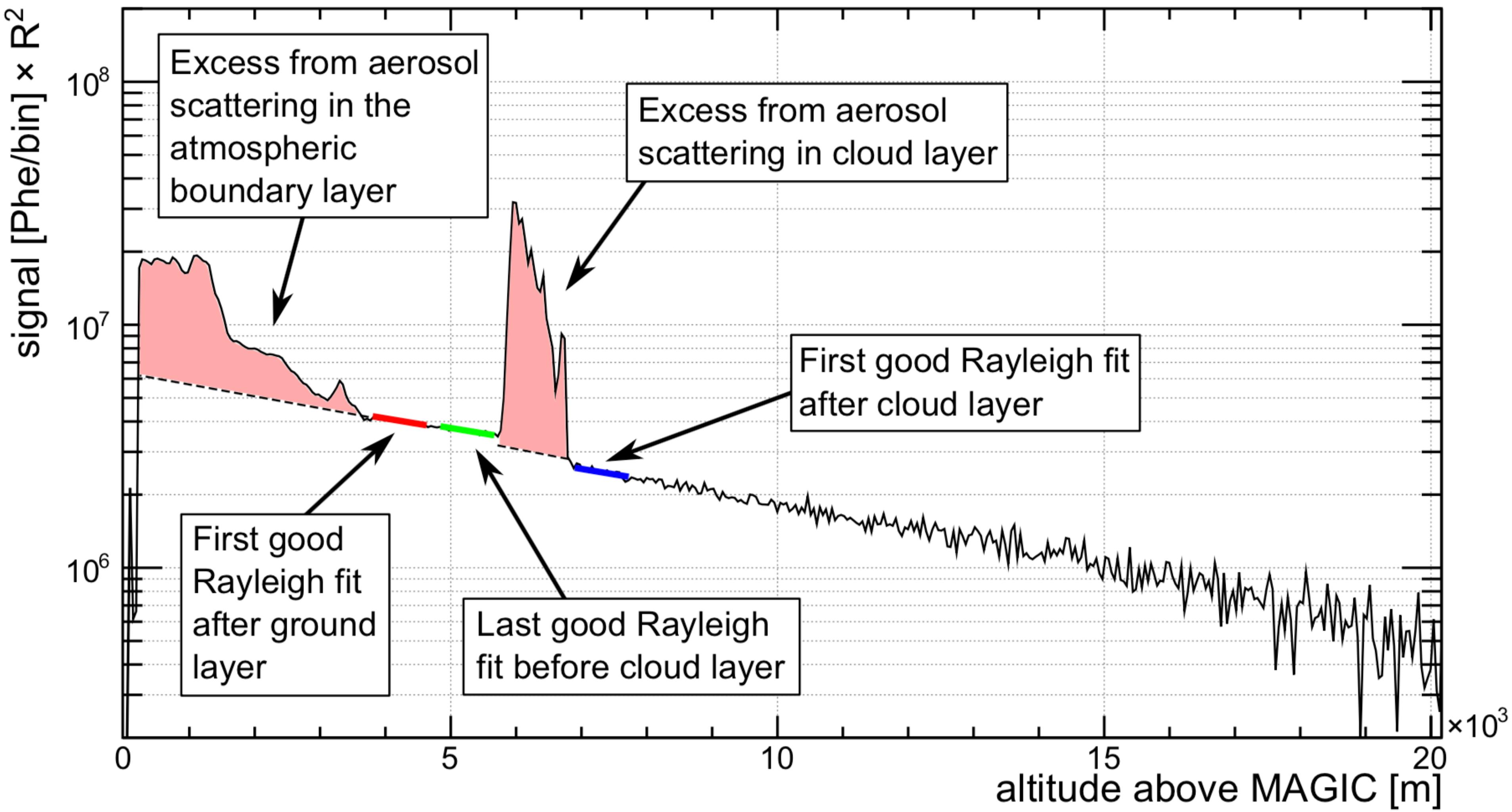
The MAGIC LIDAR system

Structure:
- Aluminum telescope frame controlled by commercial telescope mount
- Nd:YAG laser with 25 μJ at 532 nm
- 61 cm borosilicate mirror
- Hybrid photo detector (HPD)



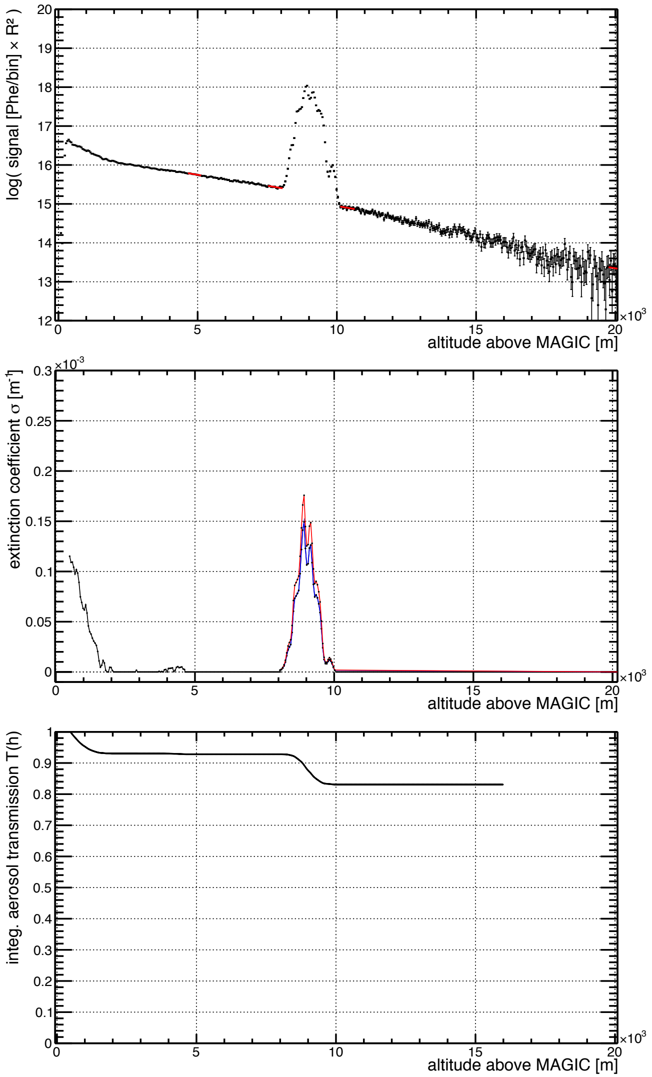
Goals:
1. Characterize data quality due to atmospheric conditions
2. Corrections of atmospherically impaired data

LIDAR return signal



(C. Fruck, 2015)

Analysis of LIDAR data



(C. Fruck, 2015)

1. Detection of the return signal

- Number of backscattered photons as a function of height above the MAGIC telescopes

2. Extraction of the extinction profile

- Backscattered photons reveal the extinction due to excess aerosols (e.g. clouds, Calima,…) in the atmosphere

3. Generation of the transmission curve

- Resulting integral transmission due to excess aerosols

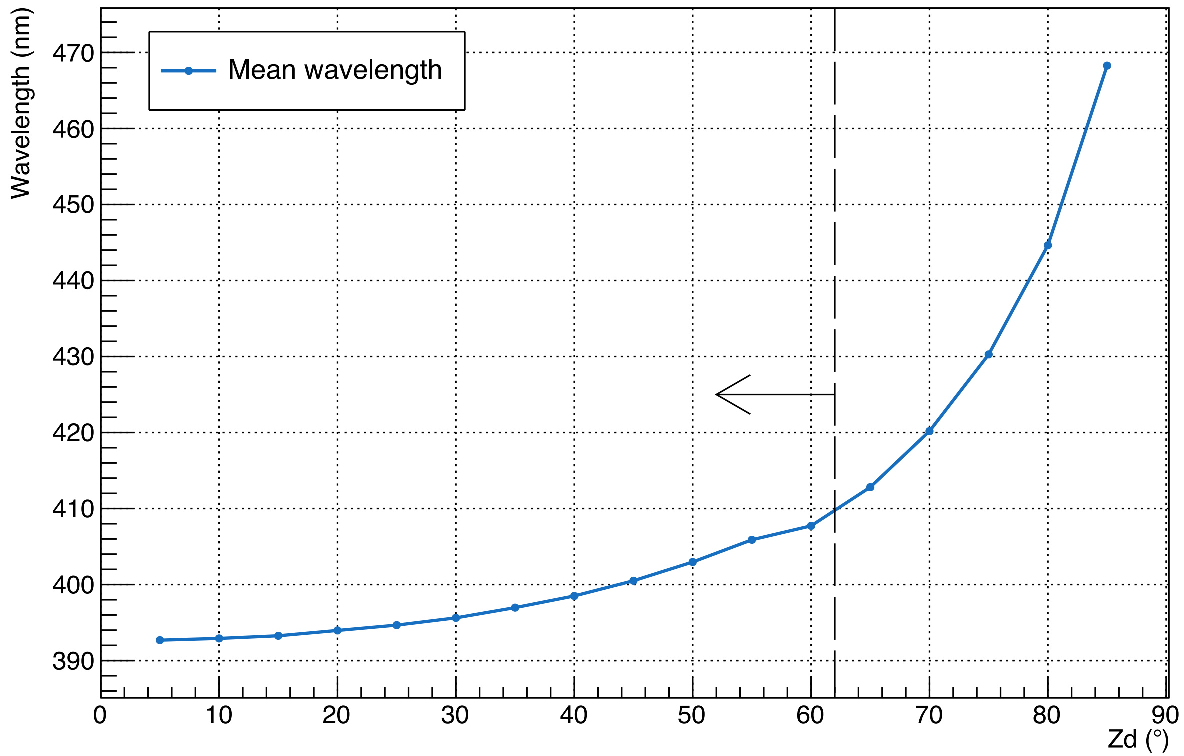
Wavelength correction

- LIDAR fires at 532 nm
- Characterizes the aerosol extinction at 532 nm

- Average Cherenkov light *detected* by MAGIC camera ranges from 390 to 410 nm (Zd < 62°)

  → Mean at 400 nm

- Aerosol extinction is higher at shorter wavelengths!



Average Cherenkov wavelength of air showers at given zenith angles detected by the MAGIC I

Adjusting the aerosol extinction

$$\alpha_{\bar{\lambda}_{\mathrm{Cher}}} = \alpha_{\mathrm{LIDAR}} \cdot \left(\frac{\bar{\lambda}_{\mathrm{Cher}}}{532\ \mathrm{nm}} \right)^{-\mathring{A}}$$

Ångstrom exponent:
Values taken from literature

Non-dusty periods ($T_{\text{ground-layer}} > 0.93$):

$$\alpha_{\bar{\lambda}_{\mathrm{Cher}},\mathrm{non-dusty}} = \alpha_{\mathrm{LIDAR}} \cdot \left(\frac{400\ \mathrm{nm}}{532\ \mathrm{nm}} \right)^{-(1.2\pm0.4)} = \alpha_{\mathrm{LIDAR}} \cdot (1.41 \pm 0.16)$$

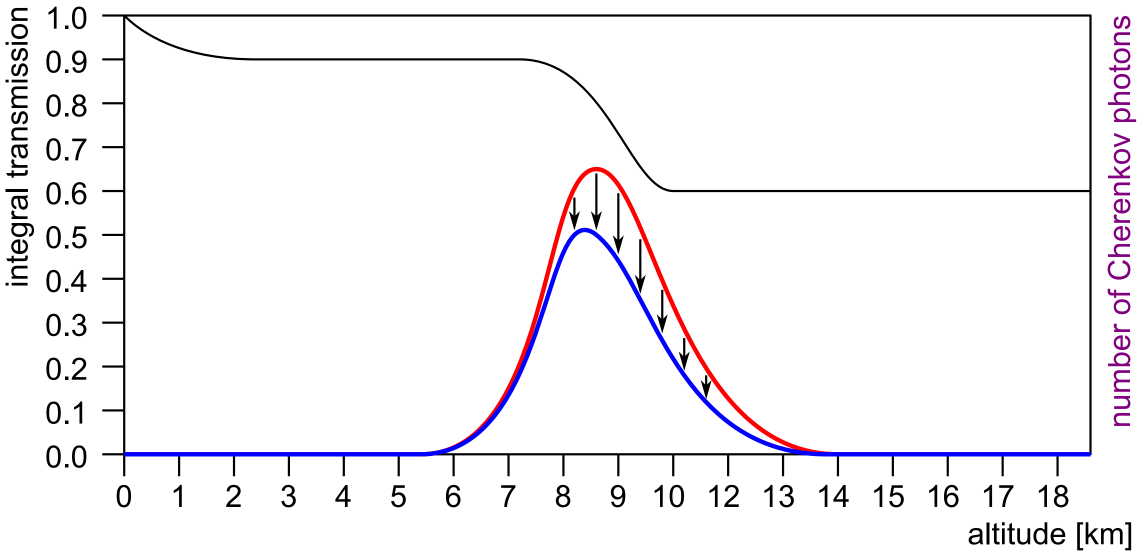
Dusty periods / Calima:

$$\alpha_{\bar{\lambda}_{\mathrm{Cher}},\mathrm{calima}} = \alpha_{\mathrm{LIDAR}} \cdot \left(\frac{400\ \mathrm{nm}}{532\ \mathrm{nm}} \right)^{-(0.6\pm0.3)} = \alpha_{\mathrm{LIDAR}} \cdot (1.19 \pm 0.10)$$

Correction of MAGIC data

Correction of the energy:

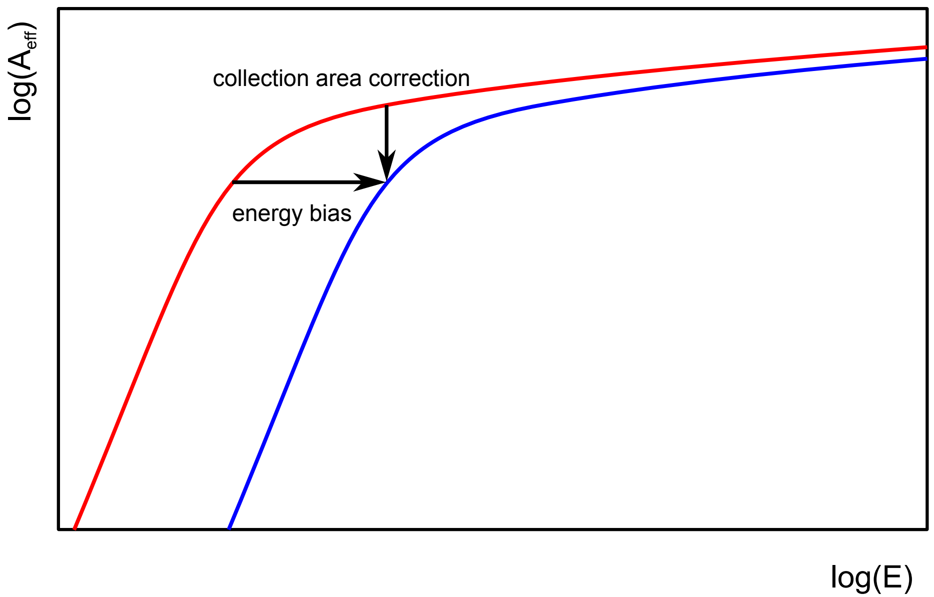
- Number of emitted photons proportional to energy
- Lower transmission results in underestimation of the reconstructed energy
- Transmission profile allows correction of the estimated emission profile



(C. Fruck, 2015)

Correction of the effective area:

- A_{eff} necessary for the computation of fluxes
- Decrease of the trigger efficiency due to lower transmission
- Impaired showers resemble shower with lower energy under perfect conditions



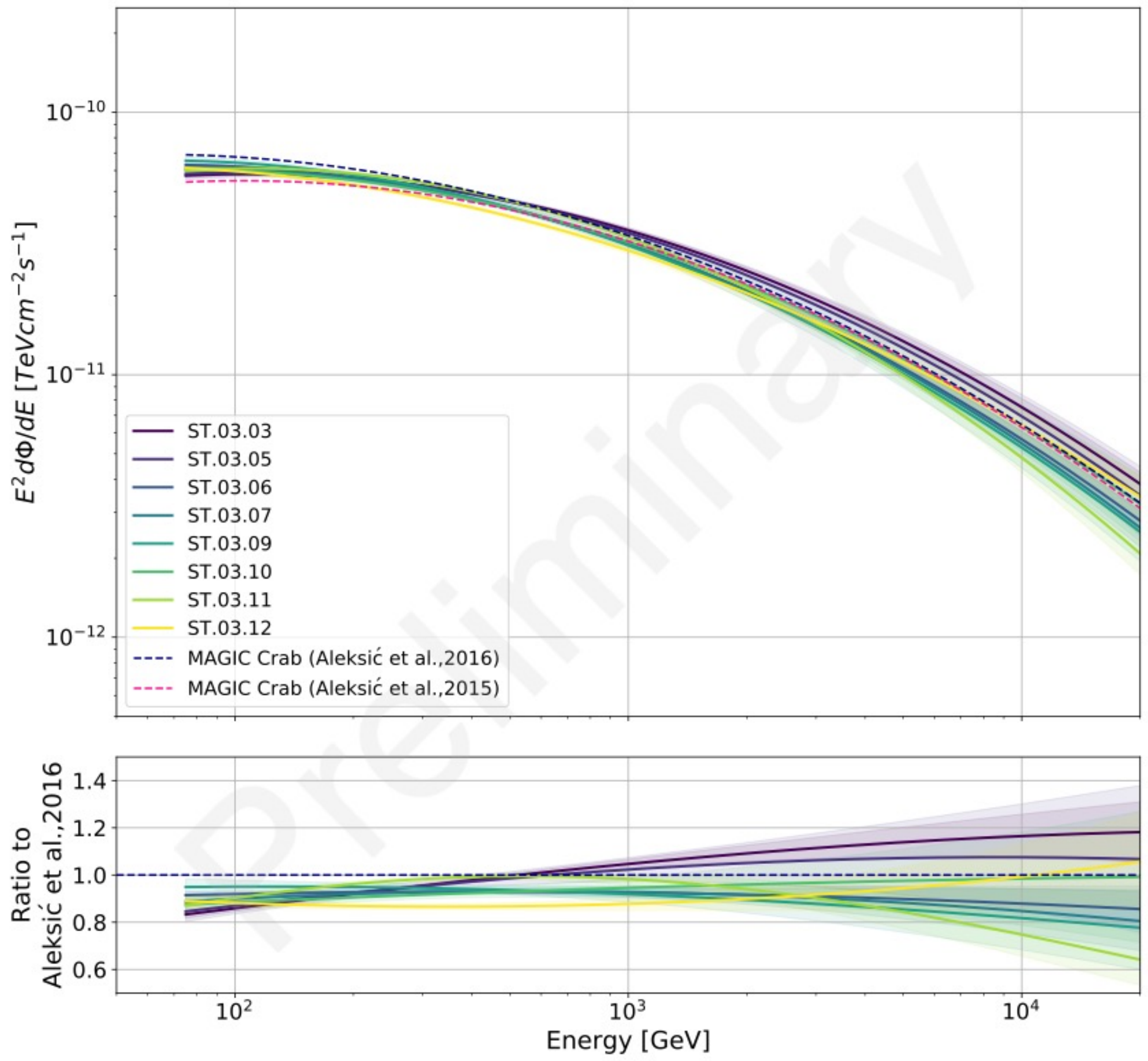
2. Characterization of the performance of the LIDAR

Construction of the reference spectra

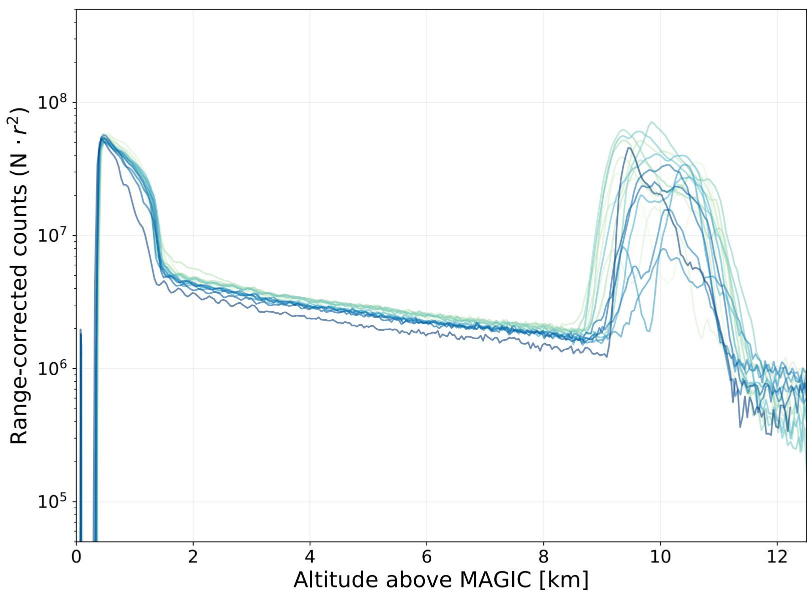
- Crab Nebula chosen as reference source due to bright and stable emission
  → Large amount of archival data
- Data with $T_{9km} > 0.95$ used to build reference spectra
- Data cover time period from mid 2013 until early 2020
- Period covers eight *analysis periods*
- Each spectrum fitted with a log-parabola function:

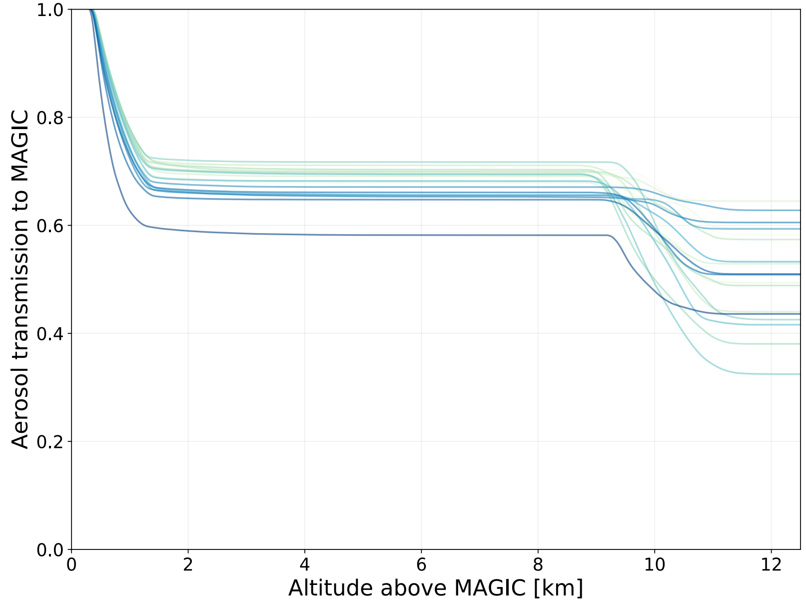
$$\frac{d\phi}{dE} = f \cdot \left(\frac{E}{275\ GeV}\right)^{a - b^2 \cdot log_{10}\left(\frac{E}{275\ GeV}\right)}$$

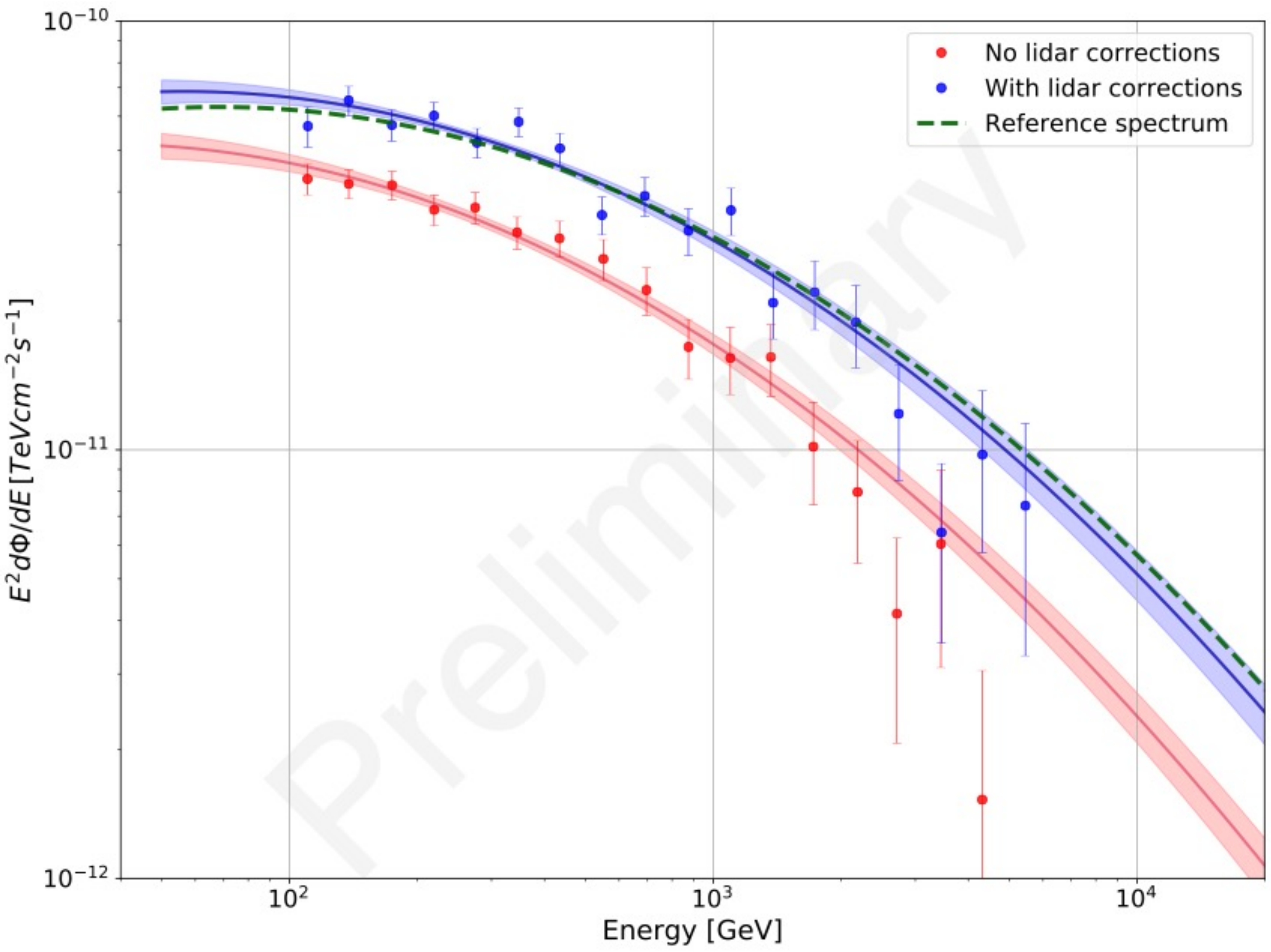
- **Obtained eight reference spectra to compare uncorrected and corrected impaired data taken under non-perfect atmospheric conditions**



Correction of an example spectrum



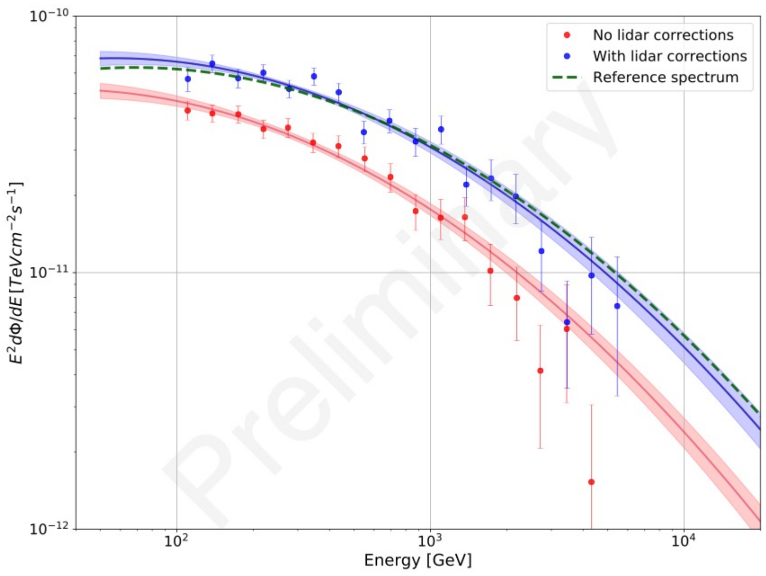




Quantification of the correction

- Divide data into three transmission bins:
  - 0.5 to 0.65 (*“low transmission”*)
  - 0.65 to 0.82 (*“medium transmission”*)
  - 0.82 to 0.9 (*“high transmission”*)
- Fit log-parabola with *b* fixed to value from reference Crab spectrum:

$$\frac{d\phi}{dE} = f \cdot \left(\frac{E}{275\ GeV}\right)^{a - {b_{ref}}^{2} \cdot log_{10}\left(\frac{E}{275\ GeV}\right)}$$



Quantifying deviations of fitted parameters in two ways:

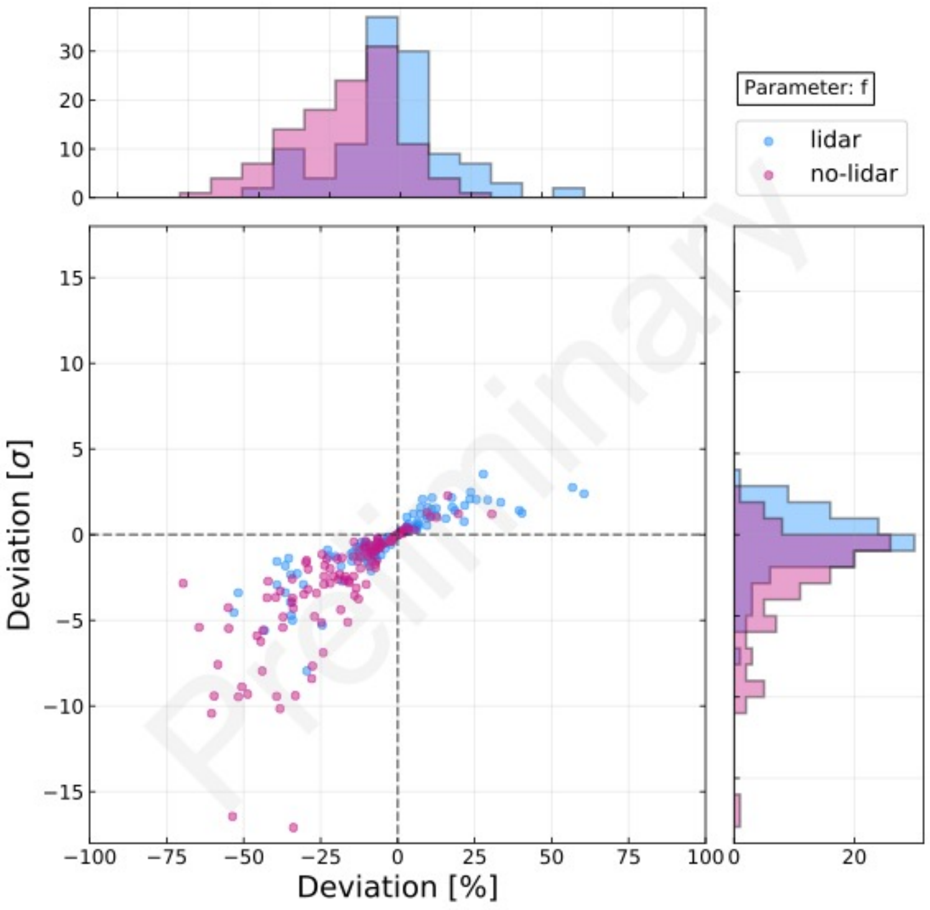
- In terms of percentage: $D_{\%} = \left(\frac{q_i}{q_{ref}} - 1\right) \cdot 100$
- In terms of stdv: $D_{\sigma} = \frac{q_i - q_{ref}}{\Delta q}$ with $\Delta q(q_i, q_{ref})$

→ Average deviations over all nights

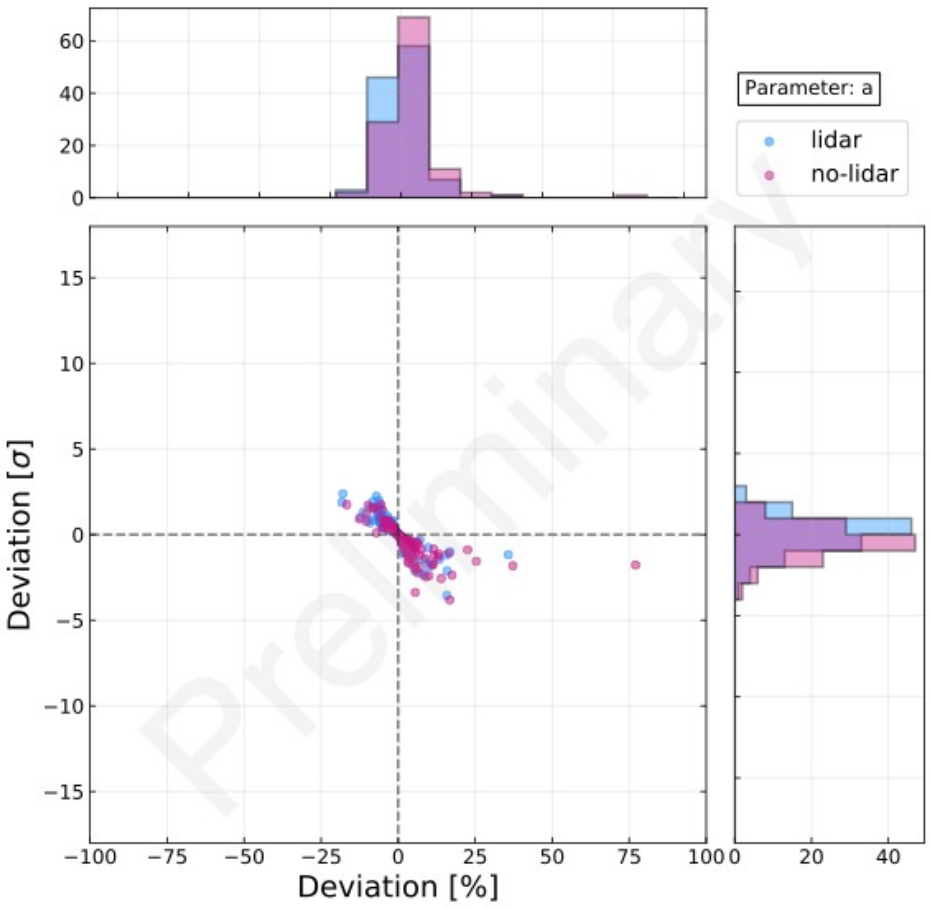
Parameter reconstruction:

All transmission (0.5-0.9) bins mixed

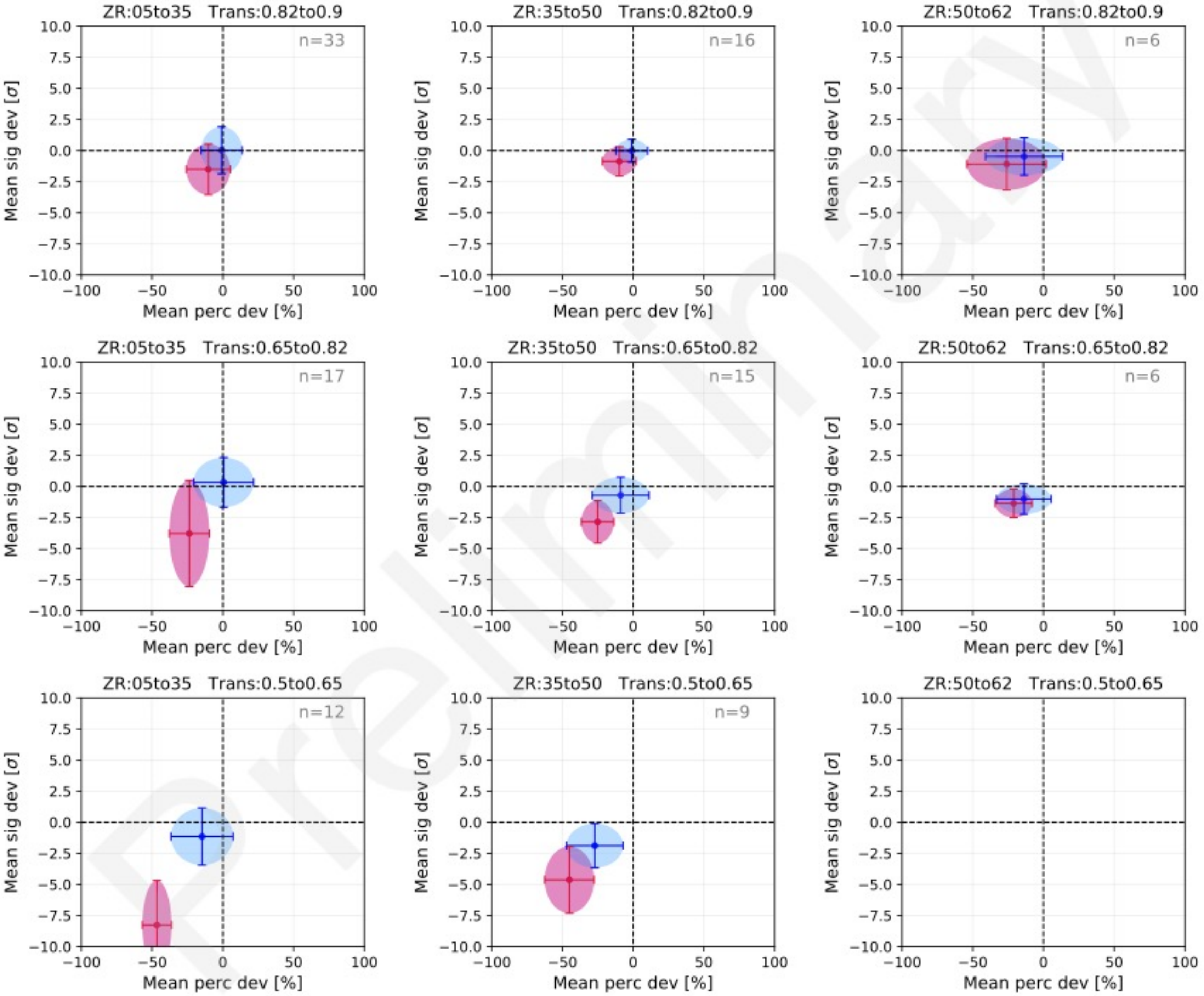
Amplitude, *f*



Index, *a*



Parameter reconstruction, Amplitude, f:



Zenith: 5° 62° columns

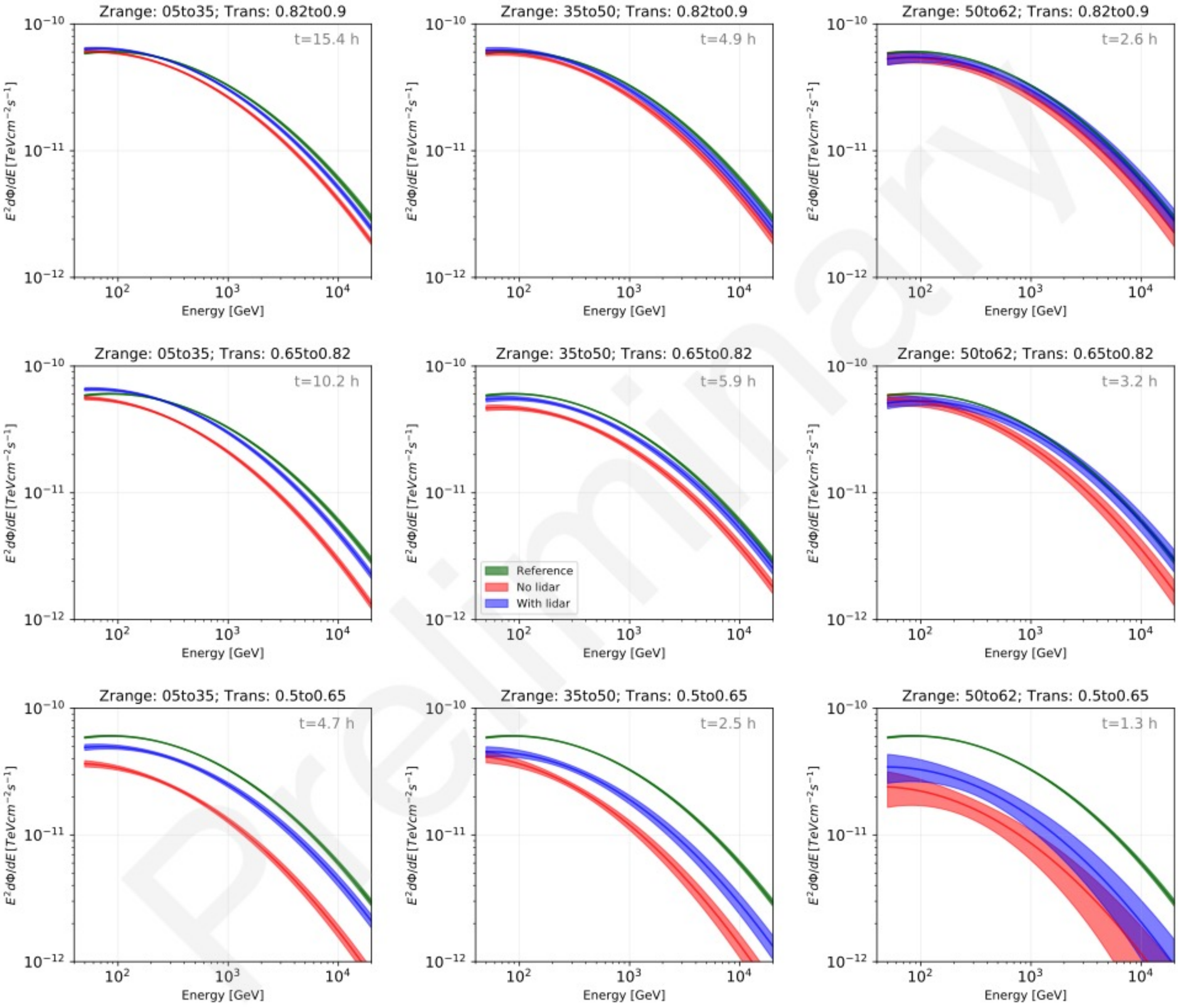
Transmission: 0.9 0.5 rows

Long-term SEDs

- Alternative approach: Combine data over whole observation time
- Results in SEDs with maximum statistics

Zenith: 5° → 62° (columns)

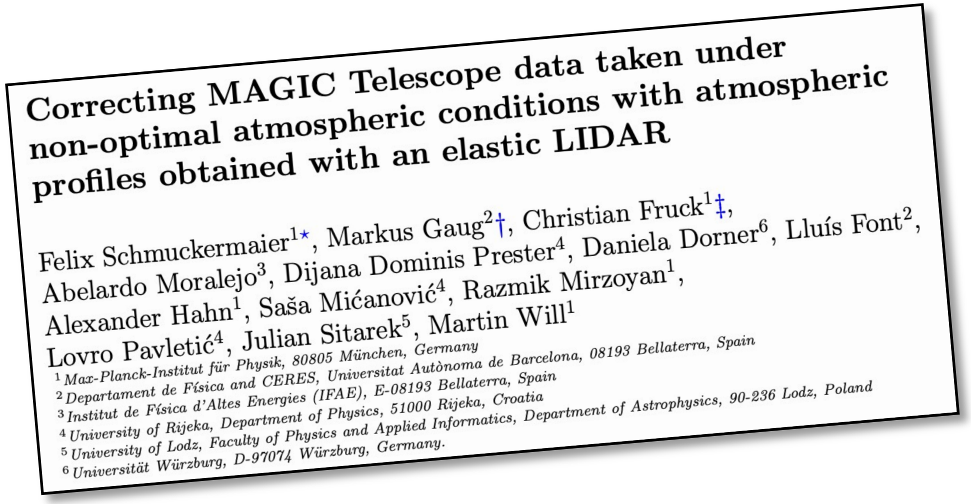
Transmission: 0.5 → 0.9 (rows)



3. Summary & Outlook

Summary & Outlook

- Presented work contains the first systematic investigation of the correction capabilities of the MAGIC LIDAR over seven years, from 2013 until 2020
- Performance of LIDAR corrections were investigated for several transmission and zenith regions
- Results will be part of a forthcoming publication:



Correcting MAGIC Telescope data taken under non-optimal atmospheric conditions with atmospheric profiles obtained with an elastic LIDAR

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LIDAR at night (Credit: Alexander Hahn)