MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

# Characterization of the Performance of the MAGIC LIDAR

IMPRS recruiting workshop

15.11.21

Felix Schmuckermaier

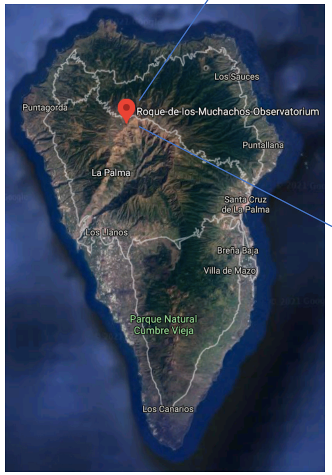
MAX-PLANCK-INSTITUT
FÜR PHYSIK

# Background:

# The MAGIC telescopes & the LIDAR

# The MAGIC telescopes

La Palma:



MAGIC telescopes (Credit: Giovanni Ceribella)

- Indirect gamma-ray detection by detecting atmospheric air showers
- Two IACTs (M1 & M2) with 17 m mirror diameter
- Energy range between ~50 GeV until ~50 TeV

## Main advantages of IACTs:

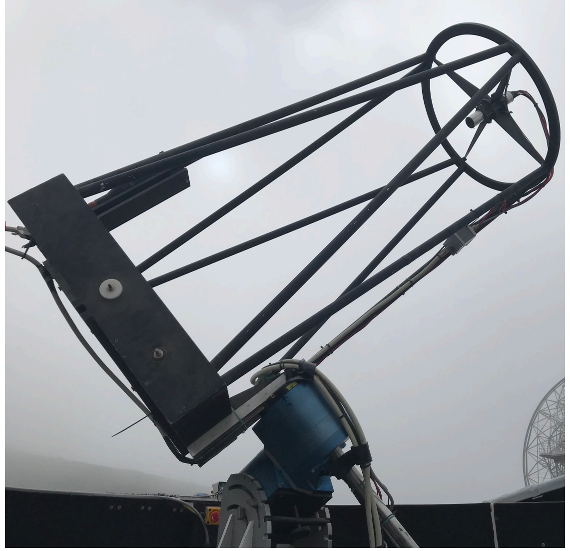
- Using the atmosphere as a calorimeter to achieve large effective areas (~km$^2$)
- Detection of lower photon fluxes compared to satellites

## Challenges:

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

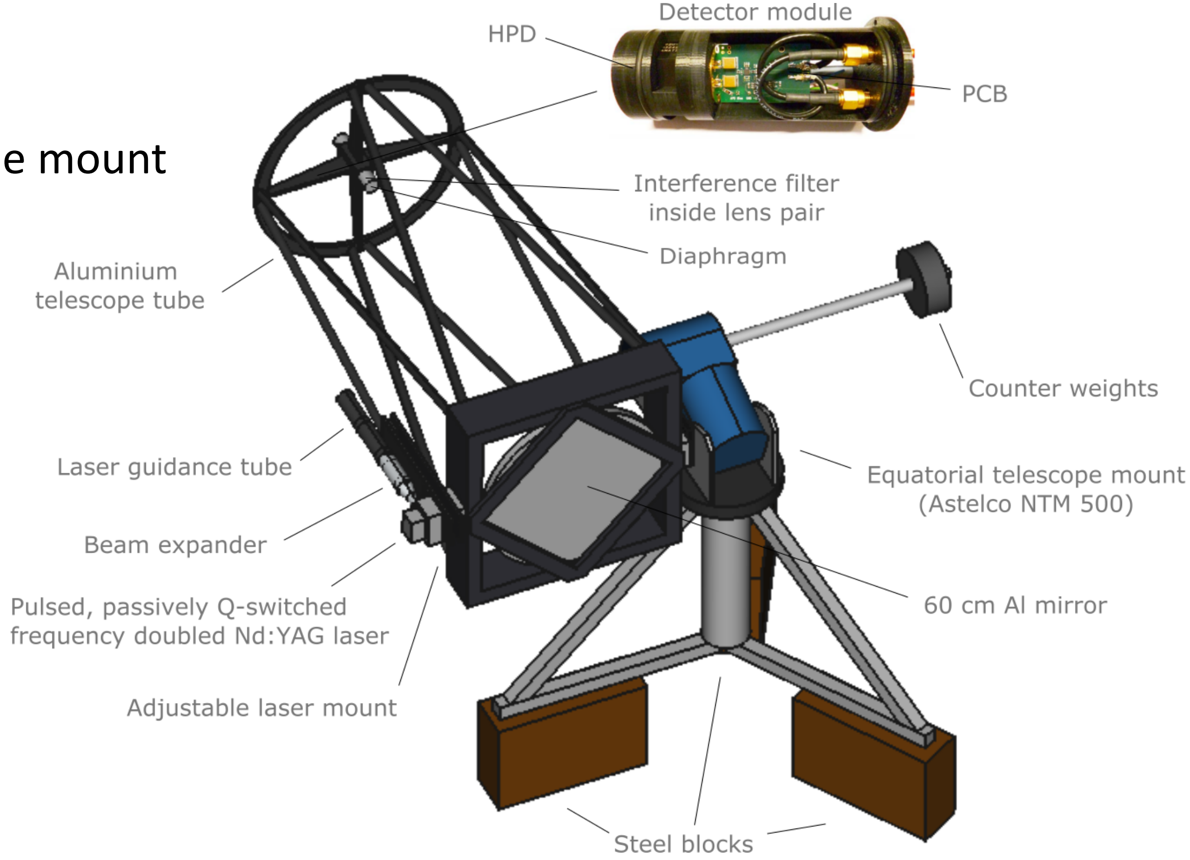
→ Atmospheric monitoring is necessary

# The MAGIC LIDAR system



**Structure:**

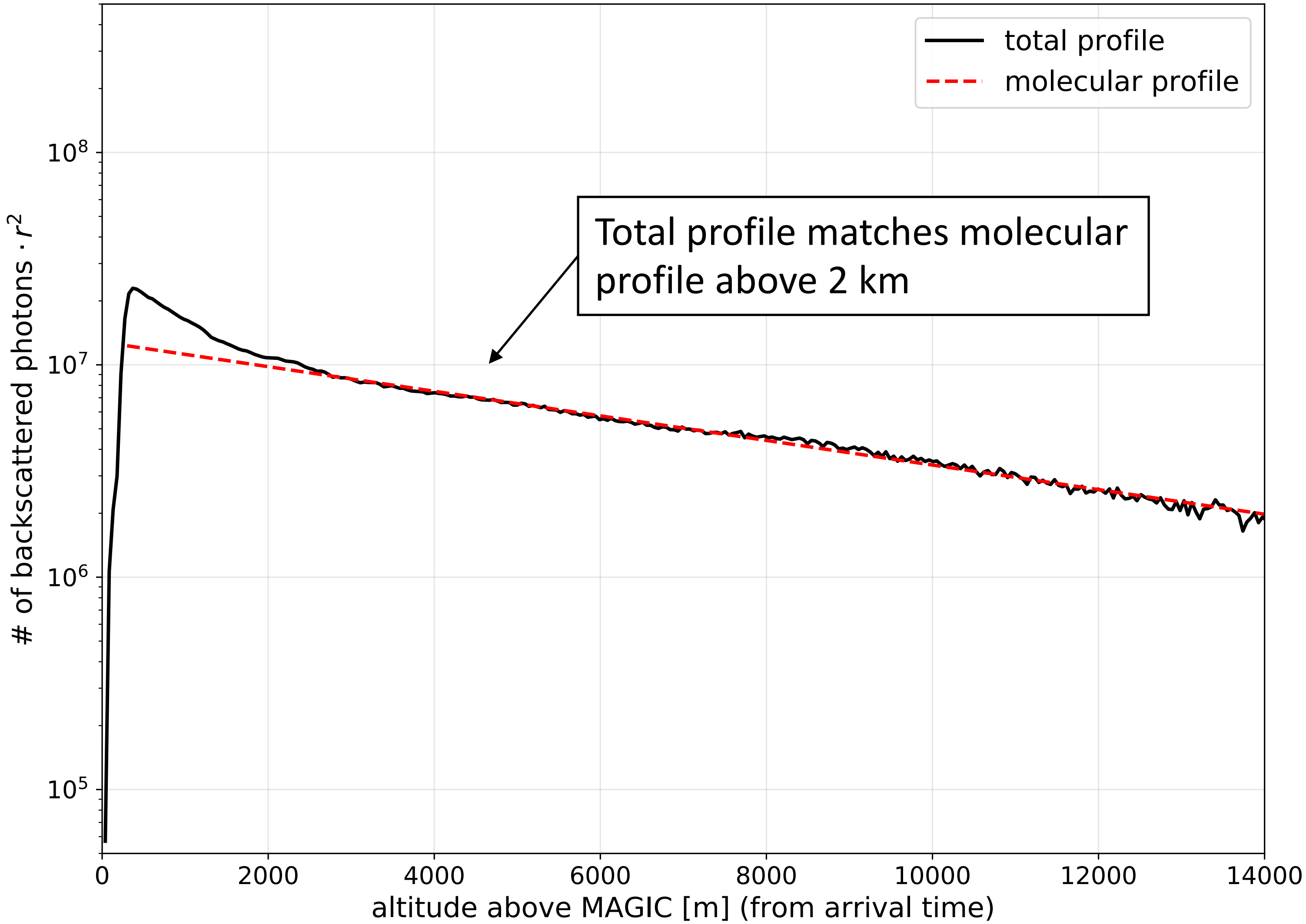
- Aluminum telescope frame controlled by commercial telescope mount
- Nd:YAG laser with 25 $\mu$J at 532 nm
- 60 cm aluminum mirror
- Hybrid photo detector (HPD)



**Goals:**

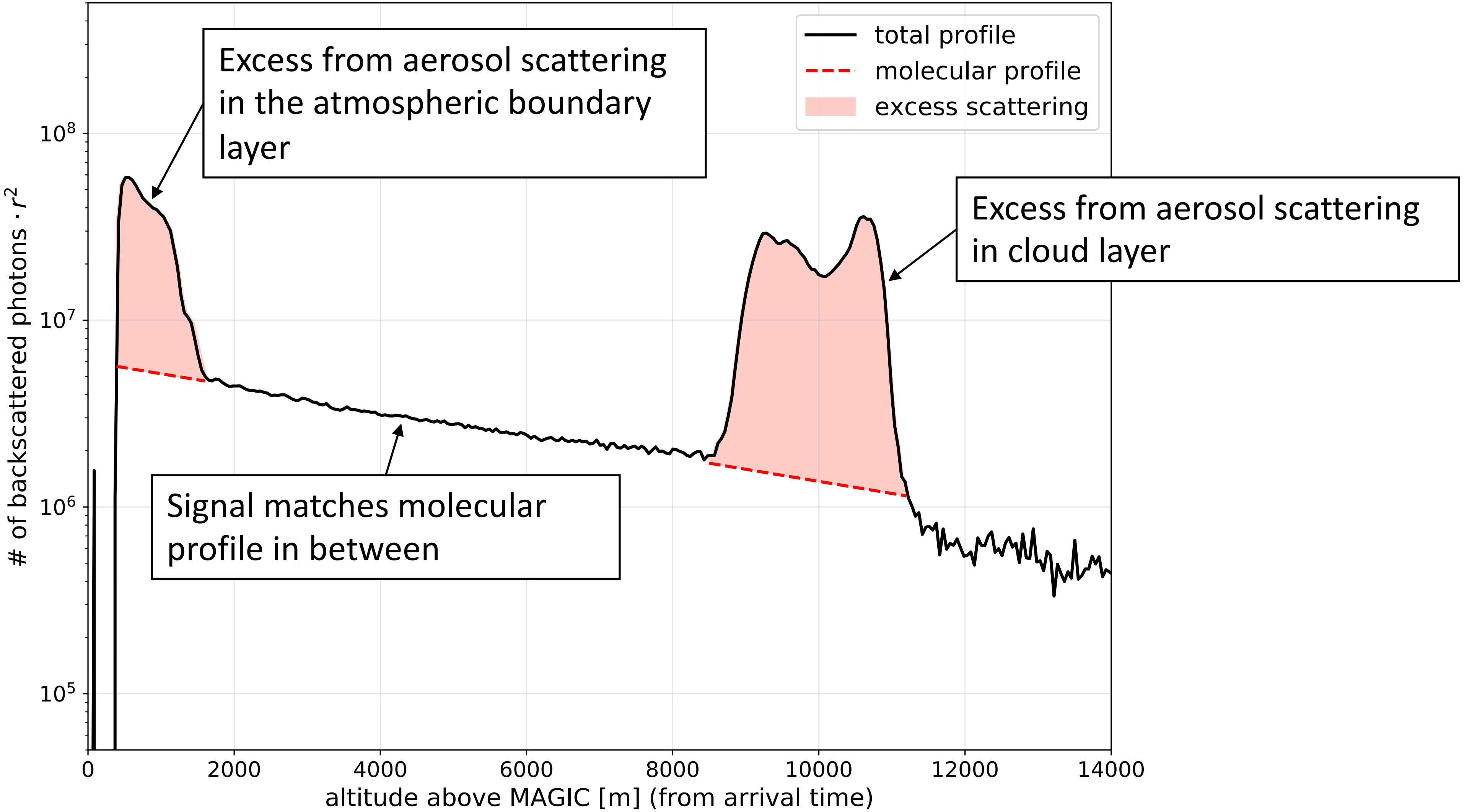
1. Characterize data quality due to atmospheric conditions
2. Corrections of atmospherically impaired data

# LIDAR return signal: clear night



Total profile matches molecular profile above 2 km

# LIDAR return signal: impaired night



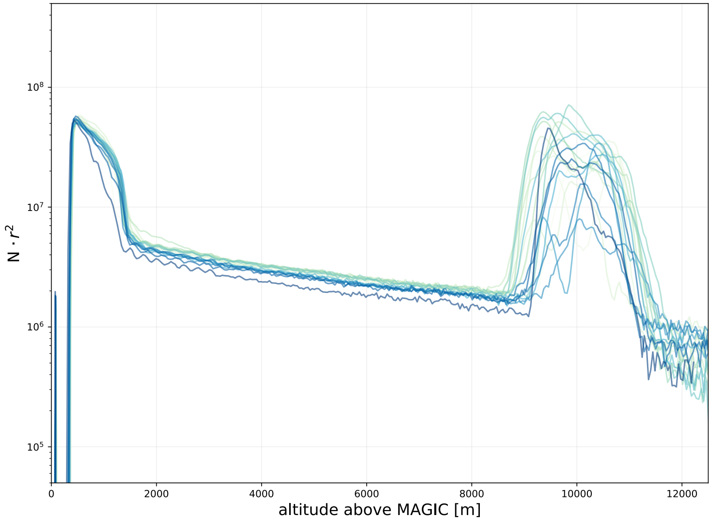
Excess from aerosol scattering in the atmospheric boundary layer

Excess from aerosol scattering in cloud layer

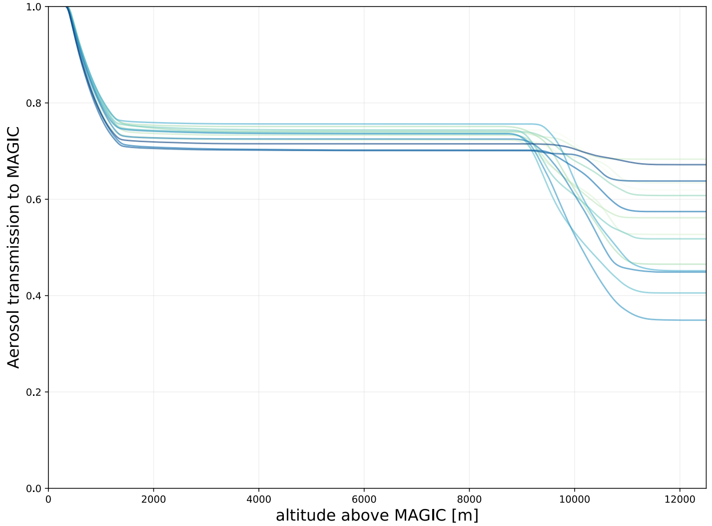
Signal matches molecular profile in between

# Example correction of a Crab spectrum

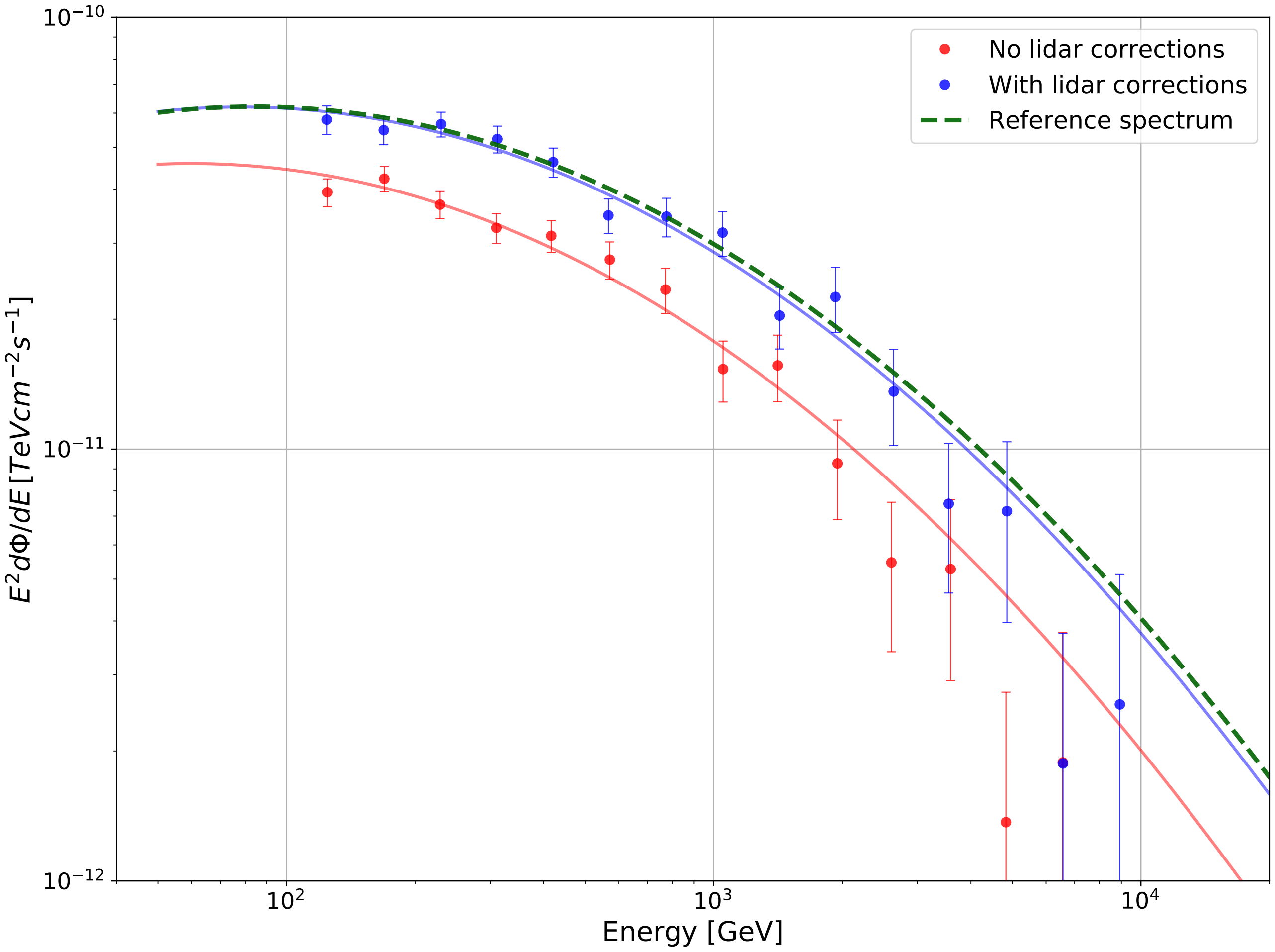
**LIDAR profile:**



**Transmission profile:**



**Uncorrected and corrected spectrum:**



Observation of the Crab Nebula from 13.11.2015

# Characterization of the performance of the LIDAR

# Quantification of the correction

- Using **seven years** of Crab data (2013-2020)
- Divide data into four transmission from 9 km bins:
    - 0.55 to 0.7 (“*low transmission*”)
    - 0.7 to 0.85 (“*medium transmission*”)
    - 0.85 to 0.93 (“*high transmission*”)
    - above 0.93 (“Reference”, perfect atmosphere)
- Fit log-parabola with *b* fixed to value from reference Crab spectrum:

$$\frac{d\phi}{dE} = f \cdot \left(\frac{E}{200\ GeV}\right)^{a - {b_{ref}}^{2} \cdot log_{10}\left(\frac{E}{200\ GeV}\right)}$$

Quantifying deviations of fitted parameters ***f*** and ***a*** in two ways:

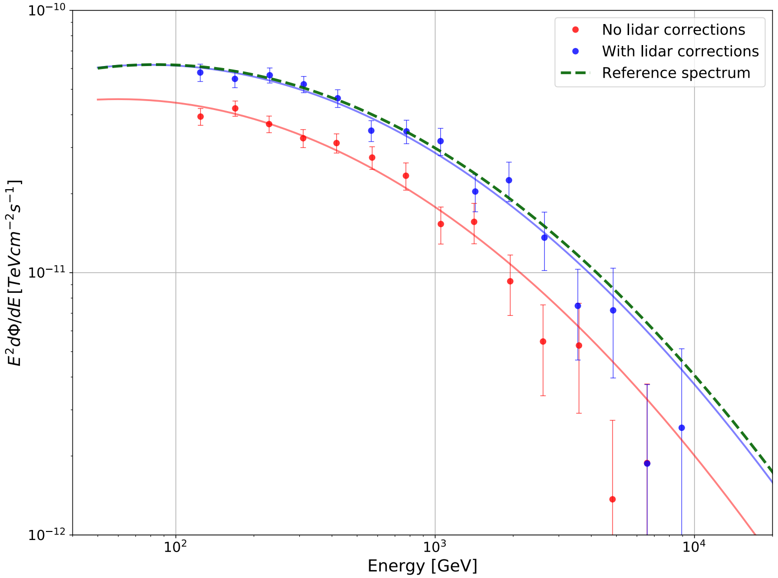
- In percentage: $D_i[\%] = \left|\frac{p_i}{p_{ref}} - 1\right| \cdot 100$
- In terms of $\sigma$: $D_i[\sigma] = \frac{|p_i - p_{ref}|}{\Delta p_i}$

→ Average deviations over all nights

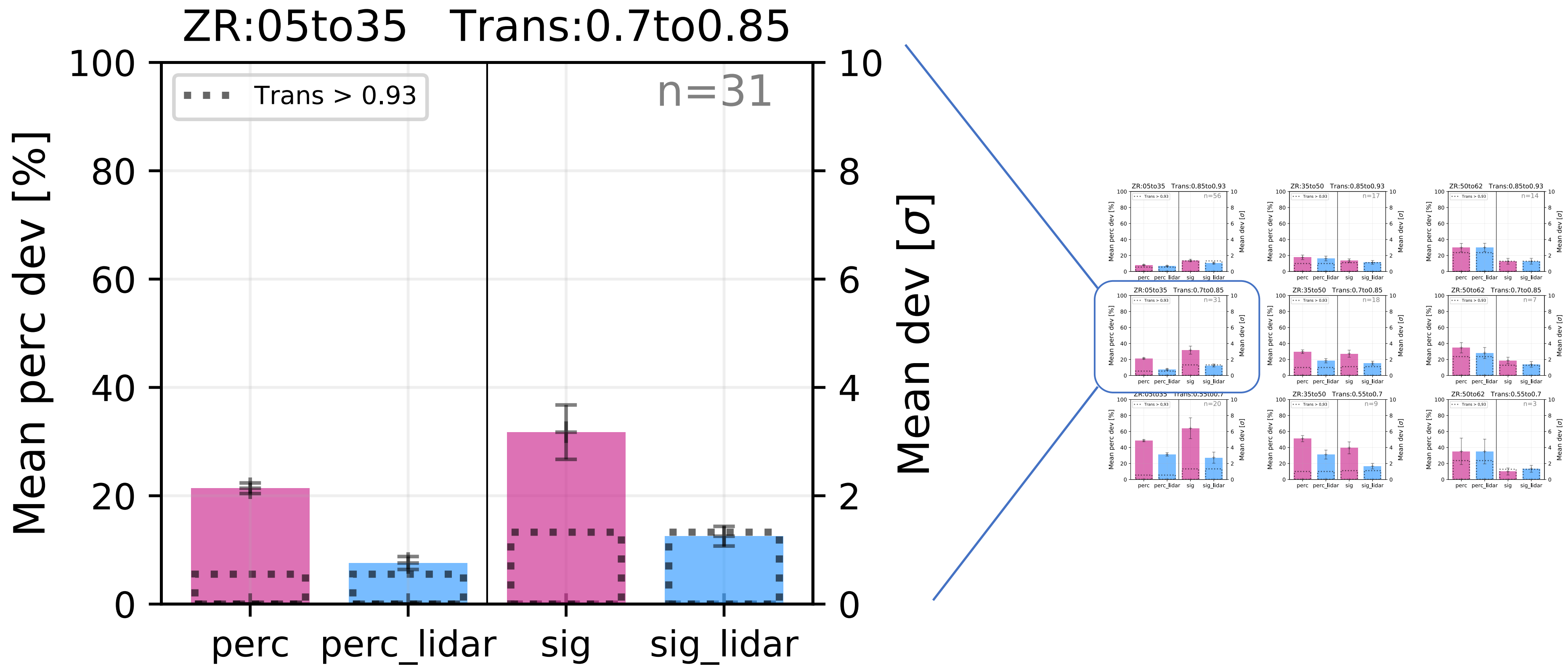
**Crab Nebula:**

Crab Nebula (https://hubblesite.org)

**Example spectrum:**



# Example plot for *f* taken under 5° to 35° with $0.7 < T_{9km} < 0.85$



# Improvements of the parameter *f*:

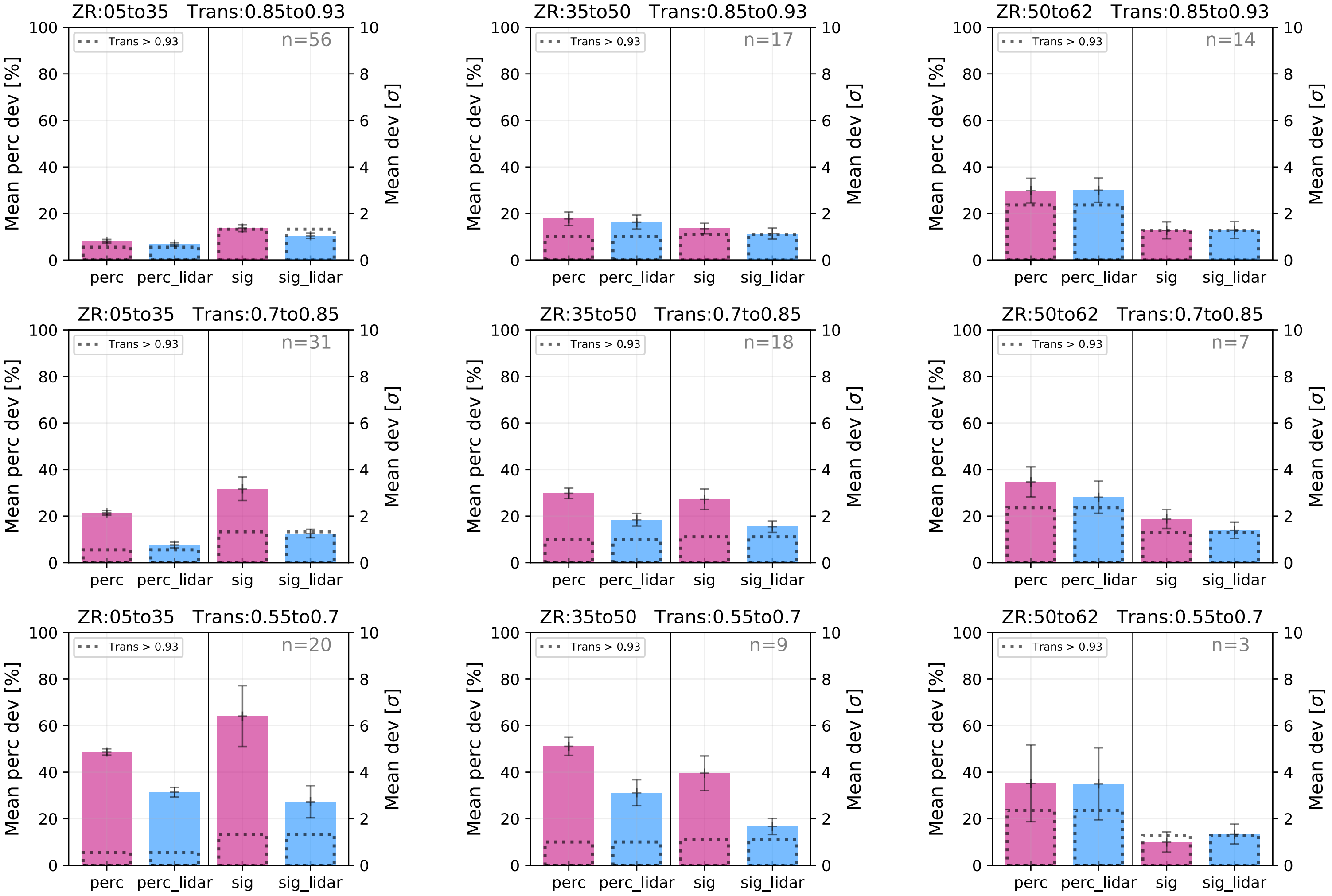
$$\frac{d\phi}{dE} = f \cdot \left(\frac{E}{200\ GeV}\right)^{a - b_{ref}^2 \cdot log_{10}\left(\frac{E}{200\ GeV}\right)}$$

5° - 35°: 35° - 50°: 50° - 62°:

0.85 - 0.93:

0.7 - 0.85:

0.55 - 0.7:



- Only slight improvements
- Data usable without LIDAR corrections

- Full reconstruction after correction
- Data unusable without applying corrections (or with higher systematic uncertainties)

- Strong improvements but insufficient reconstruction
- Data only usable with higher systematic uncertainties

# Improvements of the parameter $a$:

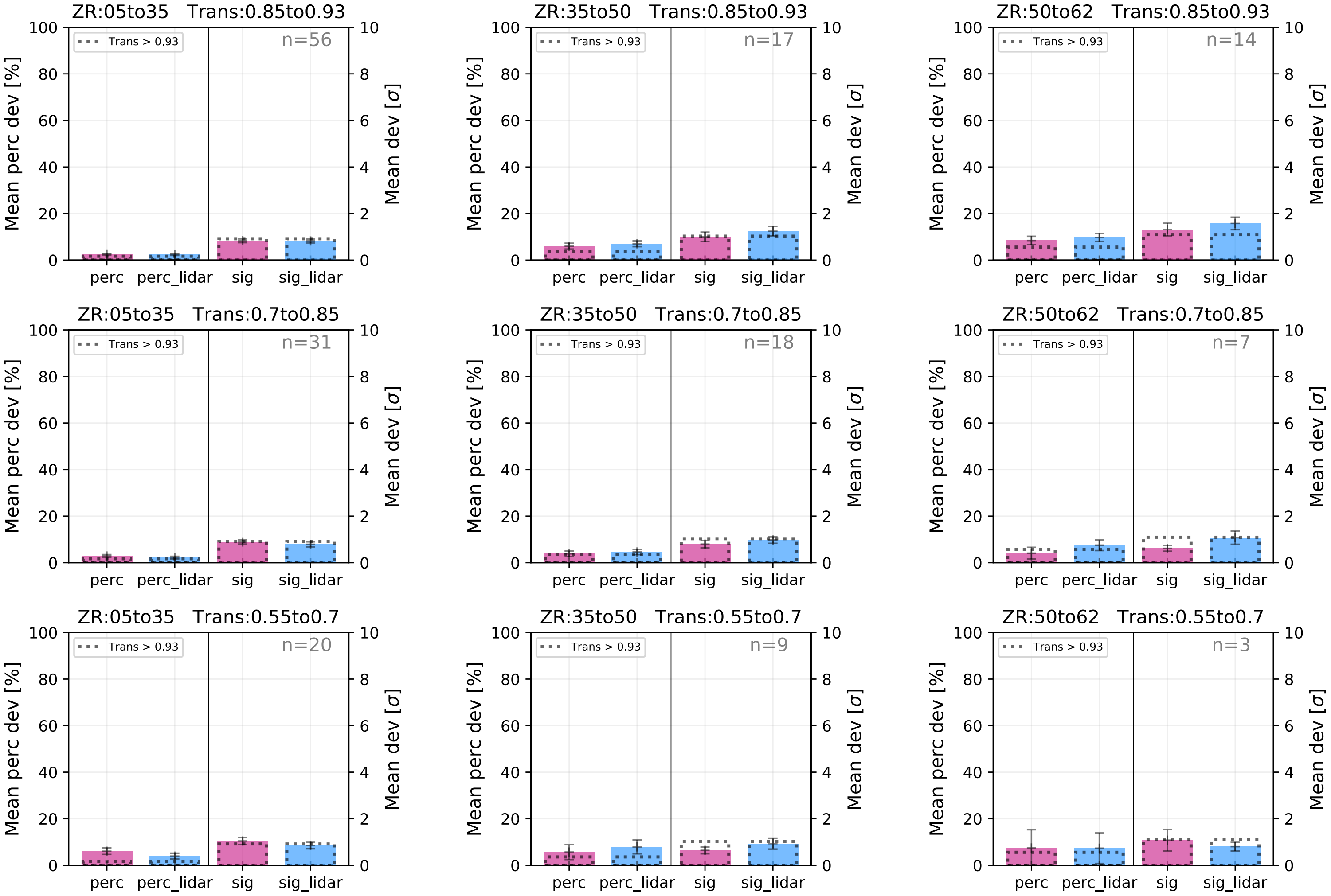
$$\frac{d\phi}{dE} = f \cdot \left(\frac{E}{200\ GeV}\right)^{\boldsymbol{a} - b_{ref}{}^{2} \cdot \log_{10}\left(\frac{E}{200\ GeV}\right)}$$

5° - 35°:    35° - 50°:    50° - 62°:

0.85 - 0.93:

0.7 - 0.85:

0.55 - 0.7:



- No significant improvement
- Spectral shape already accurate on average

# Summary

# Summary

- MAGIC is currently the only IACT using a LIDAR for data correction
- Presented work is part of the first systematic investigation of the correction capabilities of the LIDAR over seven years, from 2013 until 2020
- Results are going to be used as guidelines for analyzers of MAGIC data:
  1) To decide when to accept/reject data
  2) To improve reliability of high-level results (e.g. spectra, light curves)
- Data sample was also used to study different correction algorithms

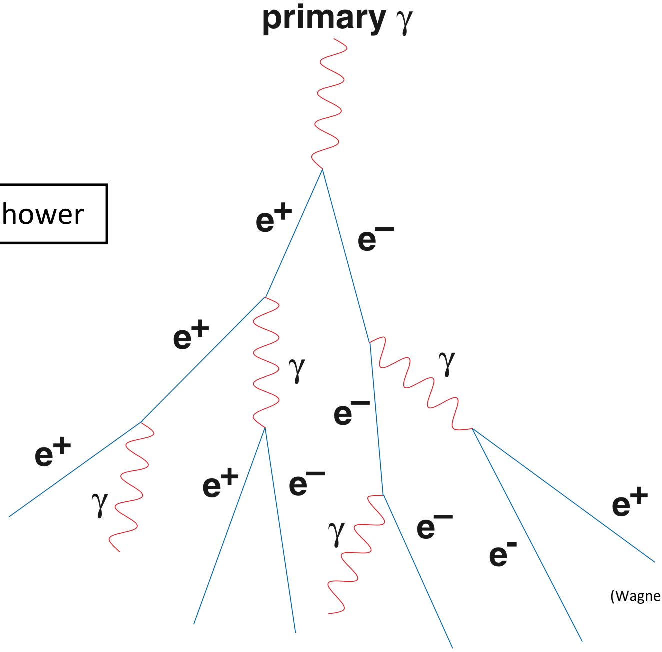
LIDAR at night (Credit: Alexander Hahn)

# Backup

# Ground-based gamma-ray astronomy

## Atmospheric air showers:

Electromagnetic shower

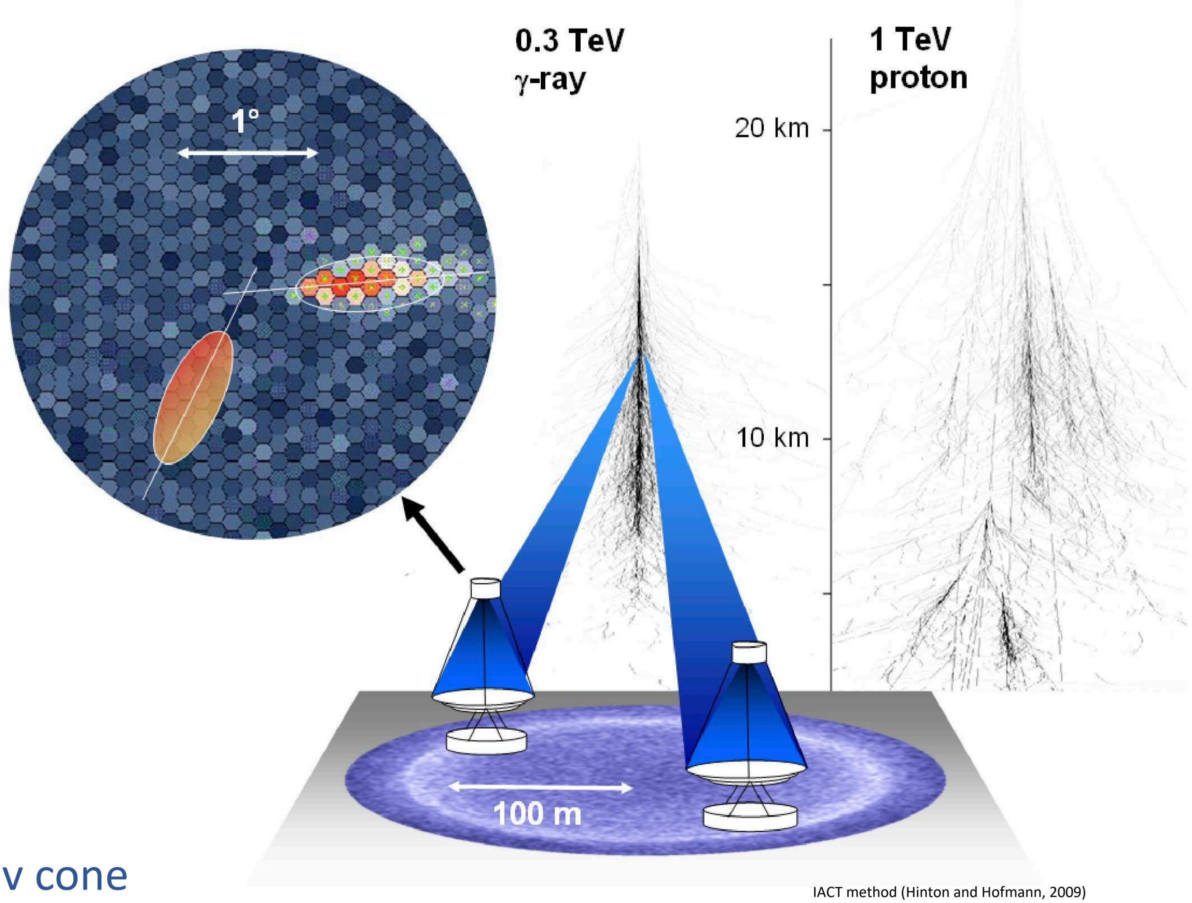


(Wagner, 2006)

→ Emission of Cherenkov light by charged secondary particles

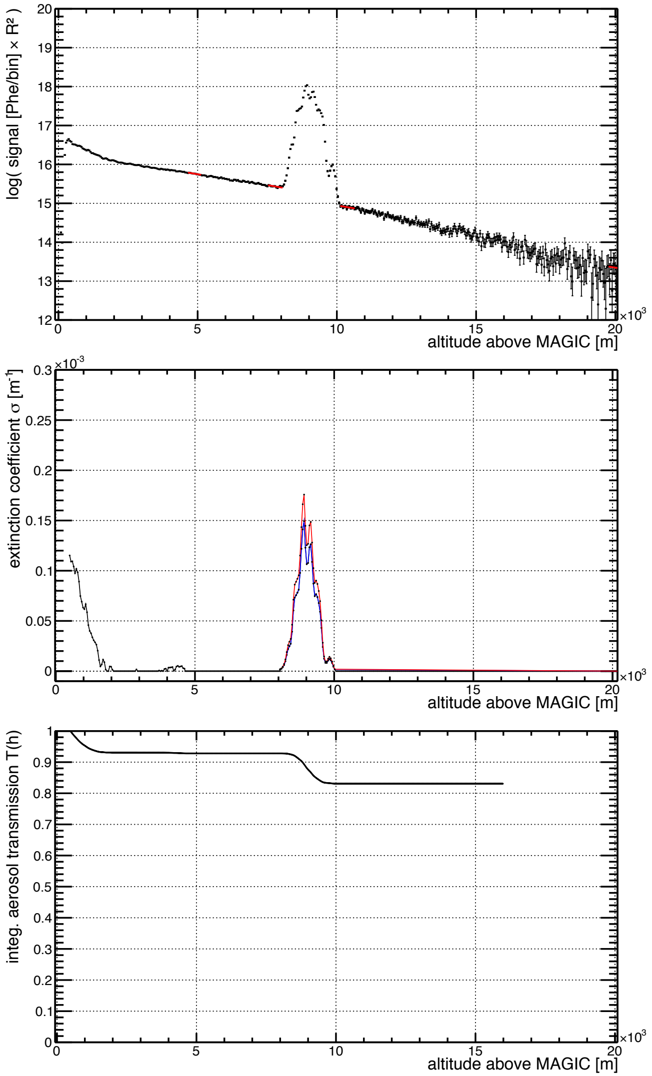
→ Detection of shower through the detection of the Cherenkov cone

## Imaging Atmospheric Cherenkov Telescopes (IACTs):



IACT method (Hinton and Hofmann, 2009)

# 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

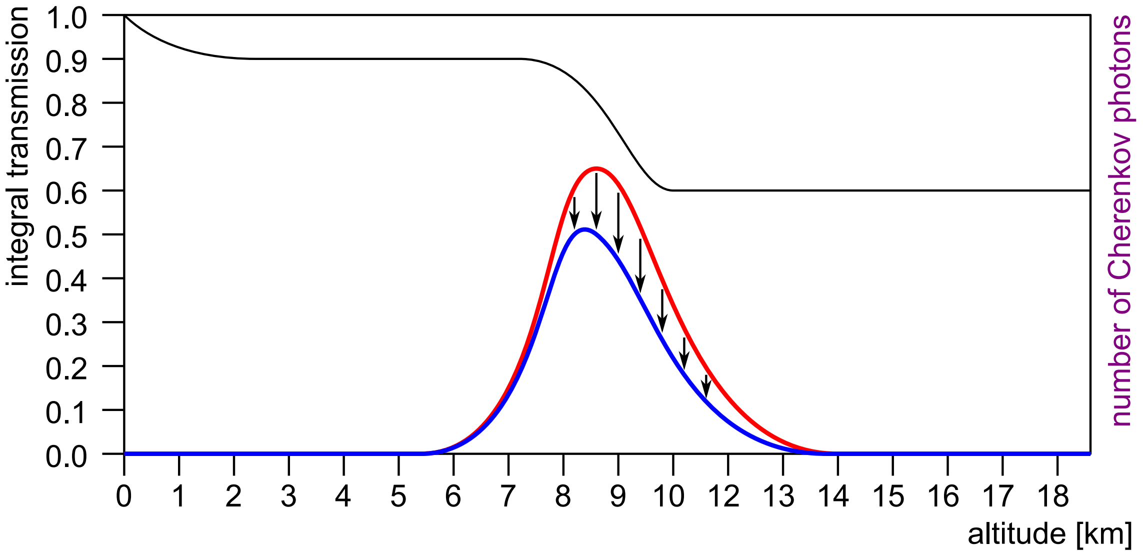
### 3. Generation of the transmission curve

- Resulting integral transmission due to excess aerosols
- Transmission profile allows correction of **energy** and **effective area** of a given gamma-ray event

# Correction of MAGIC data

## Correction of the energy:

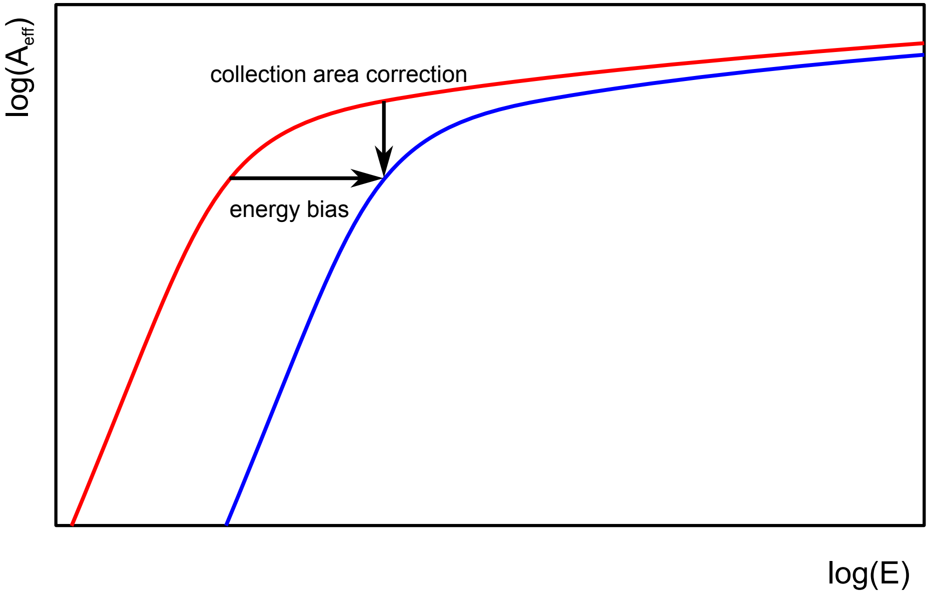
- Number of emitted photons proportional to energy
- Lower transmission results in underestimation of the reconstructed energy
- Transmission profile allows correction of the estimated emission profile



(C. Fruck, 2015)

## Correction of the effective area

- $A_{eff}$ necessary for the computation of fluxes
- Determination of $A_{eff}$ from MC data
- Decreasing of the trigger efficiency due to lower transmission
- Impaired showers resemble shower with lower energy under perfect conditions

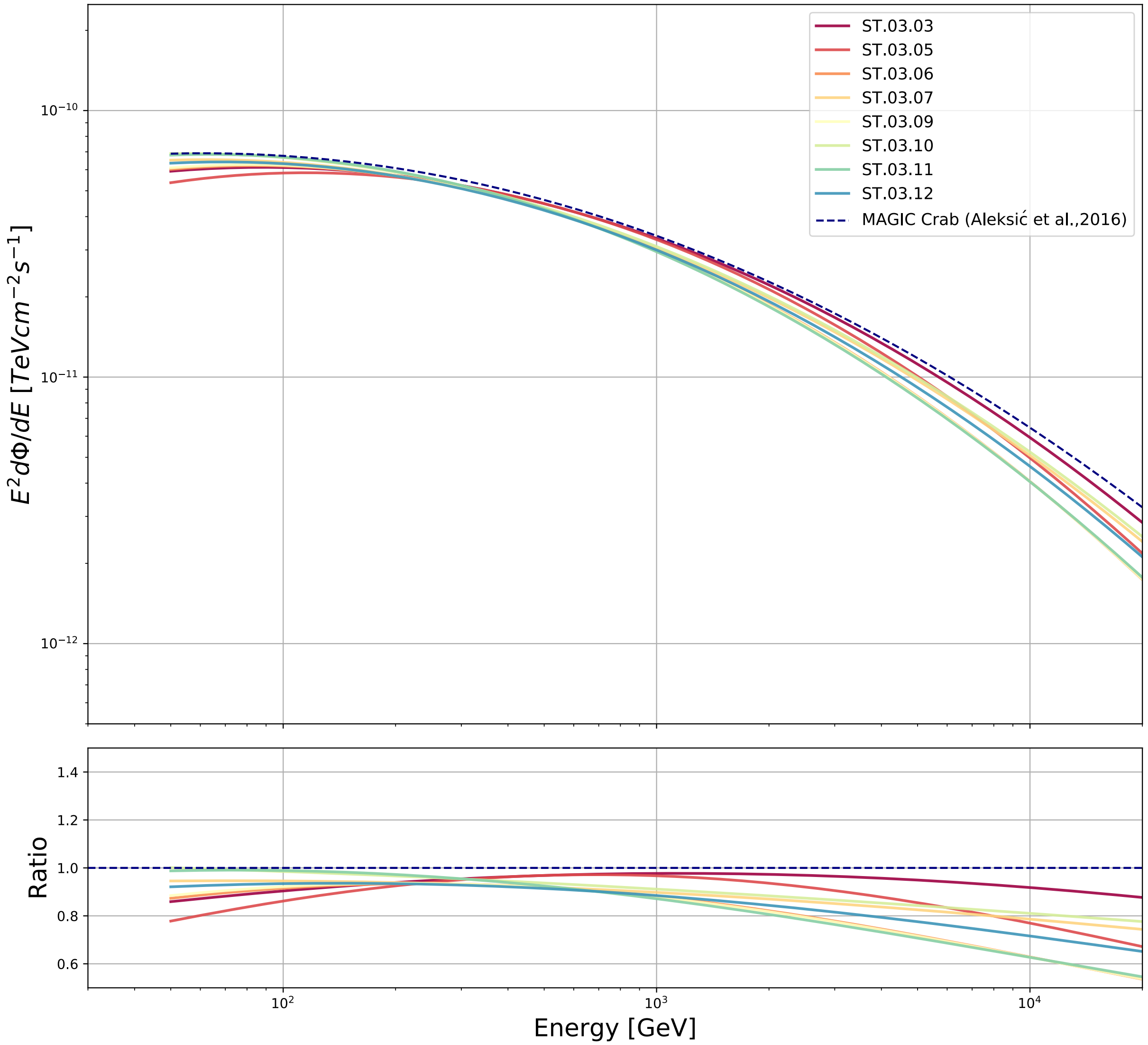


# Construction of the reference spectra

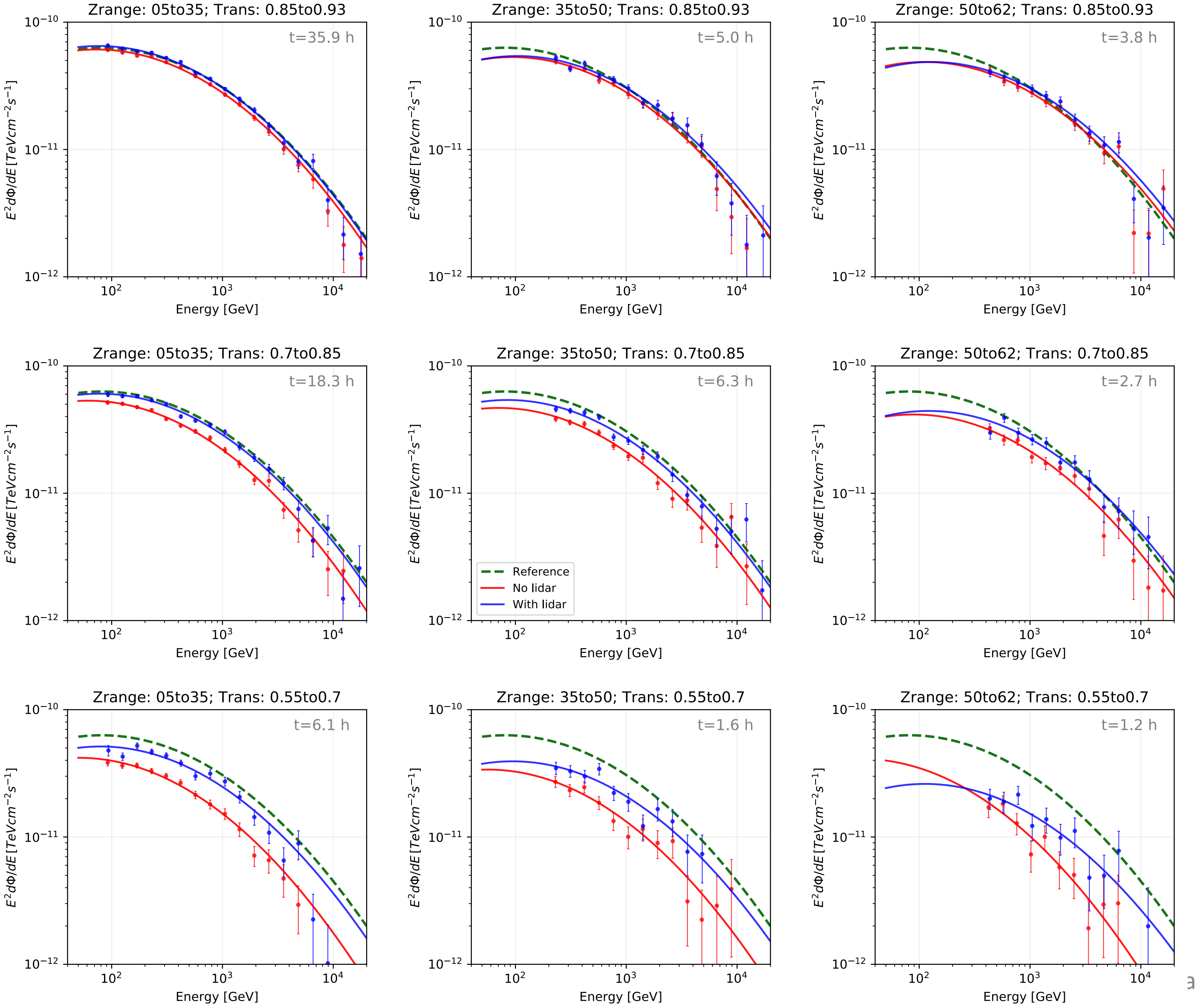
- Crab Nebula chosen as reference source due to bright and stable emission
  → Large amounts of archival data
- Data with $T_{9km} > 0.93$ used to build reference spectra
- Data cover time period from mid 2013 until early 2020
  (Time between start of LIDAR operations until beginning of thesis)
- Period covers eight *analysis periods*
- Each spectrum fitted with a log-parabola function:

$$\frac{d\phi}{dE} = f \cdot \left(\frac{E}{200\ GeV}\right)^{a - b^2 \cdot log_{10}\left(\frac{E}{200\ GeV}\right)}$$

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



# Combined spectra



- Only slight improvements above 0.85
- Data usable without corrections

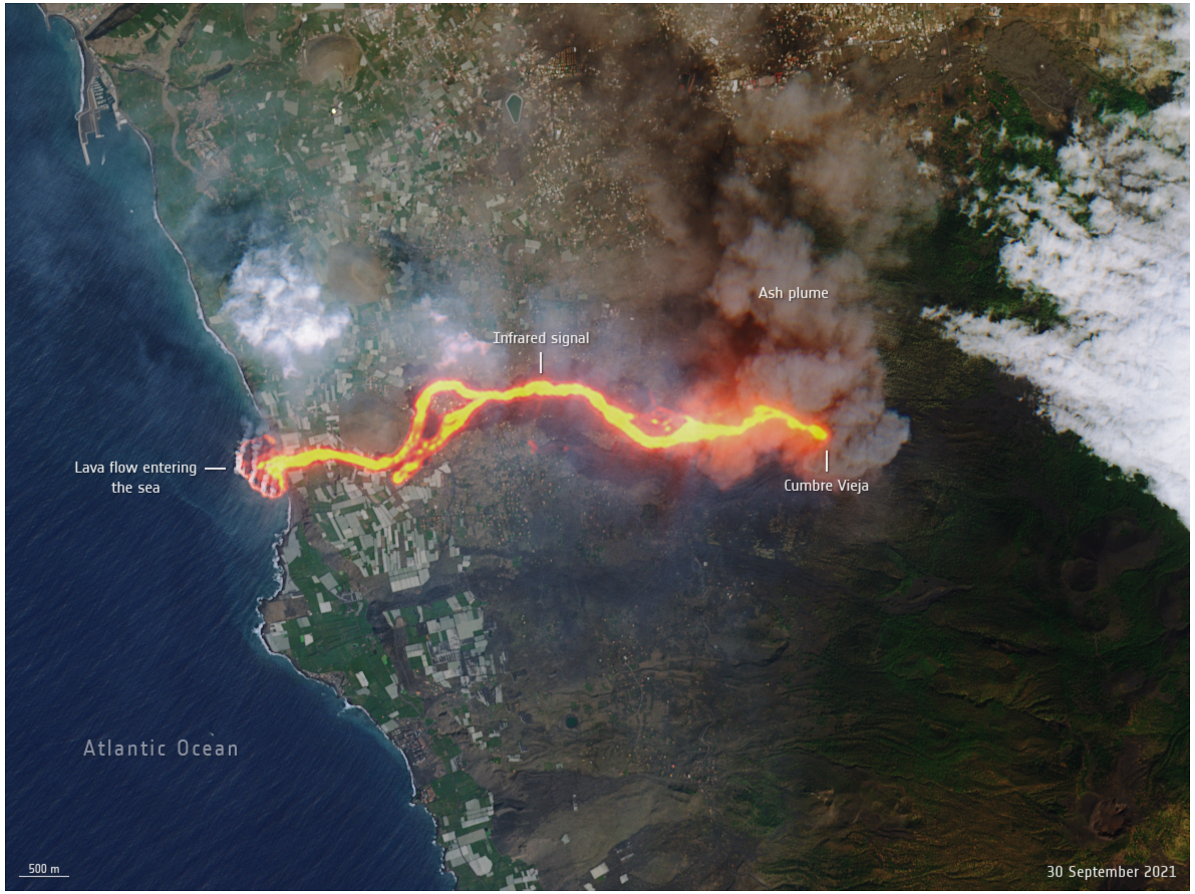
- Full reconstruction for all zenith angles
- Data unusable without applying corrections (or with higher systematic uncertainties)

- Strong improvements but insufficient reconstruction at $T_{9km} < 0.7$
- Data usable with higher systematic uncertainties

# Volcano eruption in 2021

- The volcanic ridge, Cumbre Vieja, started erupting on September 19 and is active to this day
- Caused by earthquake from September 11
- Ash plumes cause higher aerosol content in the atmosphere and ash deposition around the island
- Caused MAGIC to stop operations for the foreseeable future

MAGIC telescopes

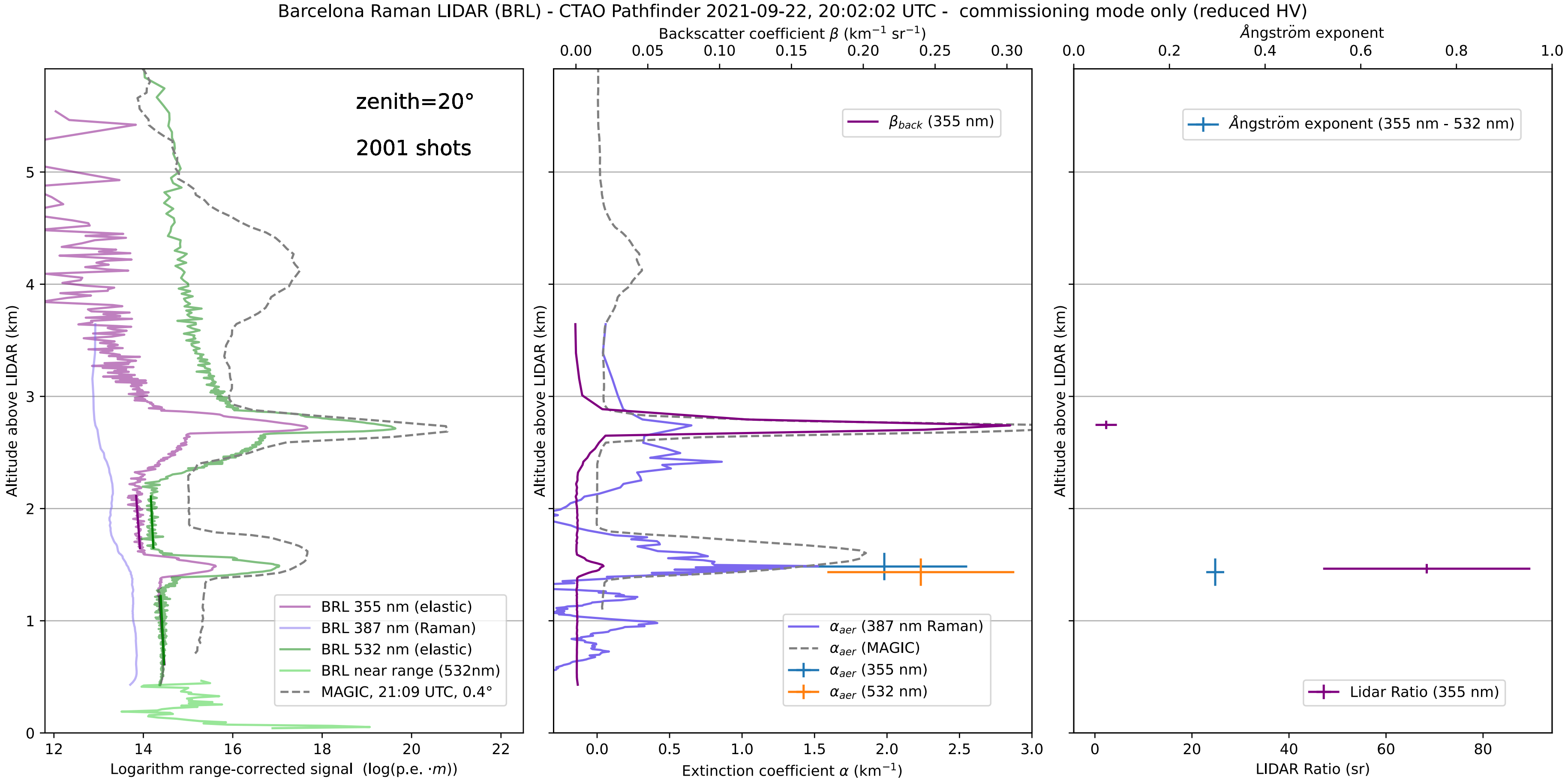


The course of the lava flow between the eruption location and the sea, seen by Copernicus on 1 October.

(Both images from https://en.wikipedia.org/wiki/2021_Cumbre_Vieja_volcanic_eruption)

# LIDAR observations of the volcano eruption

The MAGIC LIDAR as well as the Barcelona Raman LIDAR of CTA took data during September 22:



# LIDAR observations of the volcano eruption

Example observation of the MAGIC LIDAR: