# Atmospheric Monitoring for Astroparticle Physics Observatories

B. Keilhauer

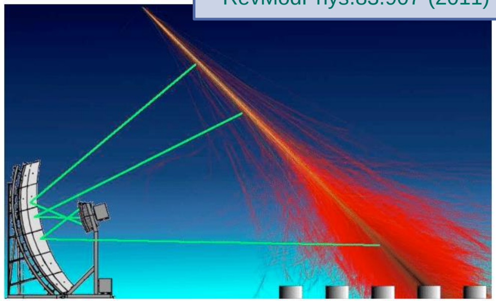
# Overview

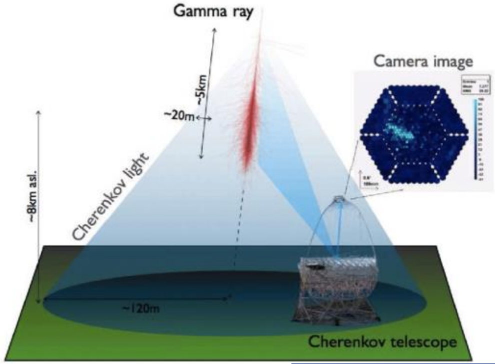
- Detector techniques and their atmospheric dependences
- Instruments for Atmospheric Monitoring
- Interdisciplinary Spin-offs

# Detection Techniques in Astroparticle Physics

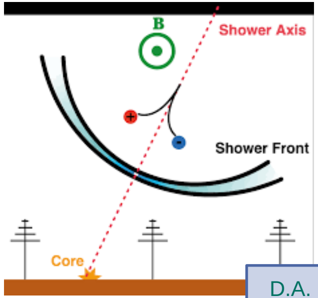
- Particle detectors at ground (scintillator or water-Cherenkov)
- Fluorescence telescopes
- Cherenkov telescopes
- Radio antennas

RevModPhys.83.907 (2011)






O. Blanch Bigas, PhD (2014)




D.A. Butler, PhD (2020)

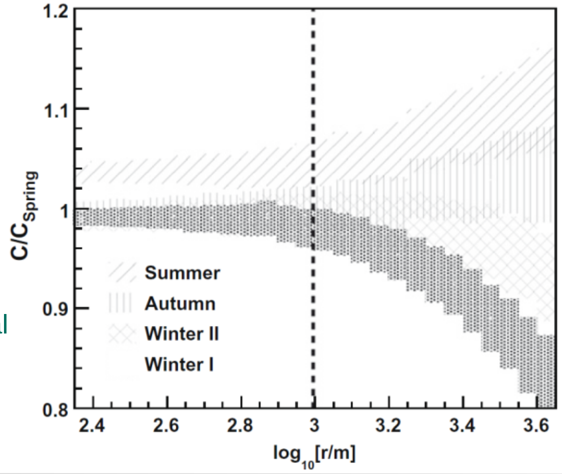
# Detection Techniques in Astroparticle Physics

- Particle detectors at ground (scintillator or water-Cherenkov)

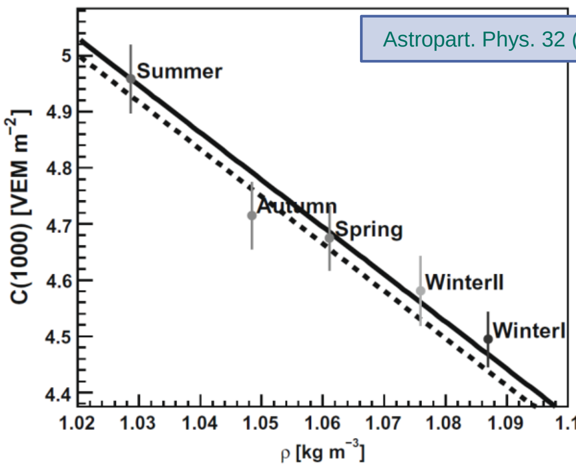


# Detection Techniques in Astroparticle Physics

- Particle detectors at ground (scintillator or water-Cherenkov)
  - Measuring secondary particles of extensive air showers at ground level
  - **Atmospheric conditions** vary longitudinal shower development
  - $P$, $T$, $\rho$ affect em and muonic component in the signals at ground and the event rate



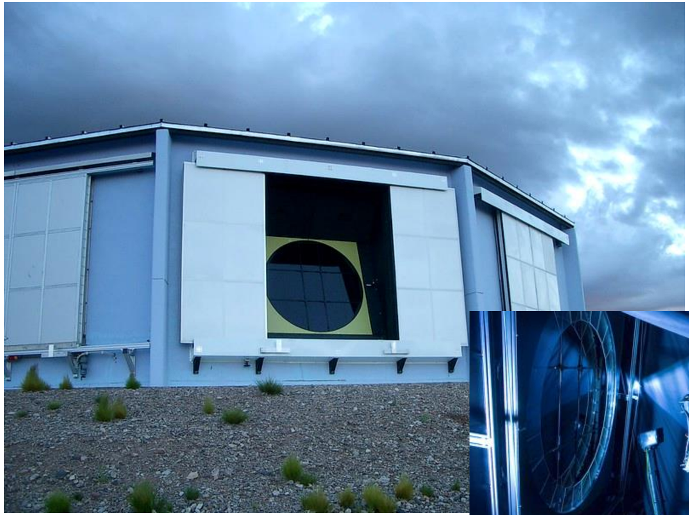

Simulated Cherenkov signal perpendicular to shower axis, normalised to Spring, p, $10^{19}$ eV, $\theta = 18°$

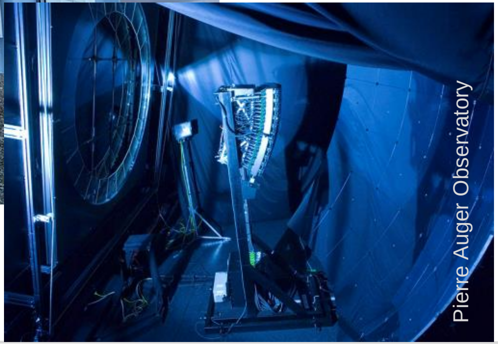



Cherenkov signal at 1000 m from shower core,
- - - $P$ = 856 hPa
— $P$ = 862 hPa

# Detection Techniques in Astroparticle Physics

- Fluorescence telescopes



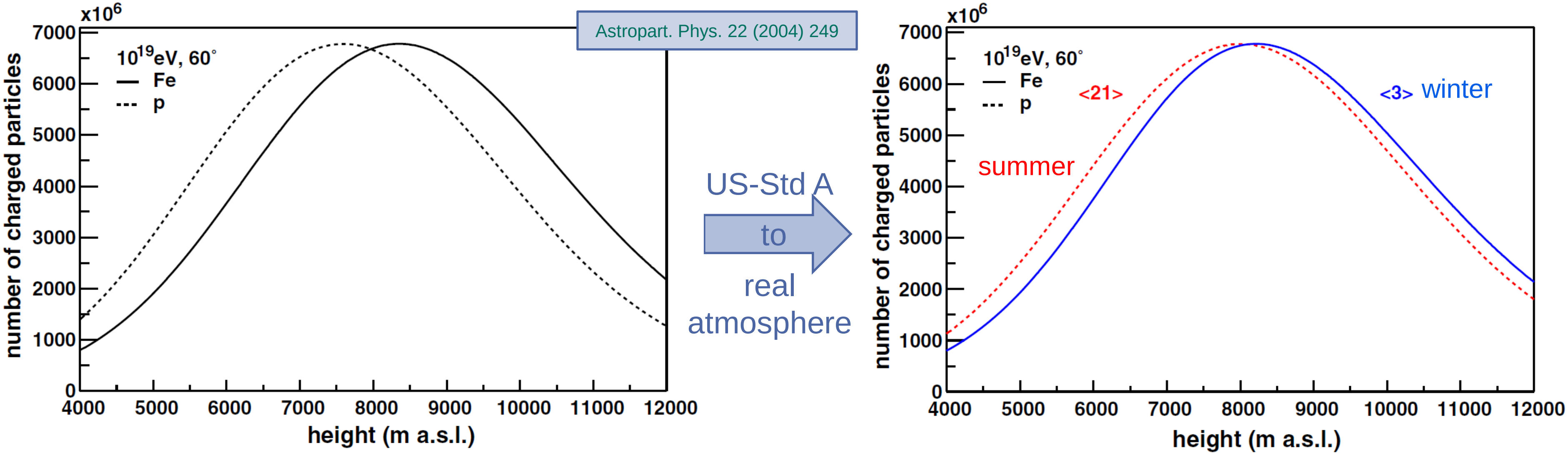



# Detection Techniques in Astroparticle Physics

- Fluorescence telescopes
  - Measuring fluorescence light induced by extensive air showers in the atmosphere
  - **Atmospheric conditions** vary
    - longitudinal shower development
    - fluorescence light emission
    - light transmission towards telescopes
    - clouds in FOV

# Longitudinal Shower Development

- Fluorescence emission depends on the energy an EAS deposits in the atmosphere
- Seasonal variations can obscure primary particle identification




Simulated Fe- and p-induced EAS, $10^{19}$ eV, $\theta = 60°$, measured atmospheric profiles at the Auger Observatory

# Fluorescence Light Emission

EPJ WoC 53, 01010 (2013);
Y. Tsunesada et al. ICRC2013

$$Y_{\mathrm{air}}(\lambda, p, T) = Y_{\mathrm{air}}(337\mathrm{nm}, p_0, T_0) \cdot I_\lambda / I_{337}(p_0, T_0) \cdot \frac{1 + \frac{p_0}{p'_{\mathrm{air}}(\lambda, T_0)}}{1 + \frac{p}{p'_{\mathrm{air}}(\lambda, T_0) \cdot \sqrt{\frac{T}{T_0}} \cdot \frac{H_\lambda(T_0)}{H_\lambda(T)}}}$$

EPJ WoC 53, 01010 (2013);
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# Fluorescence Light Emission

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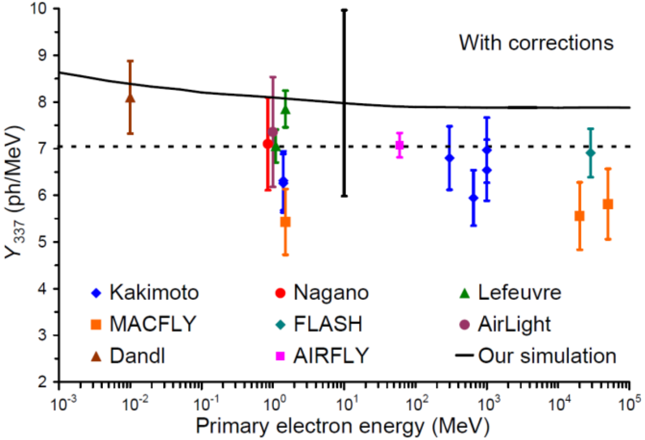
a) b)

a) absolute yield value of a reference transmission

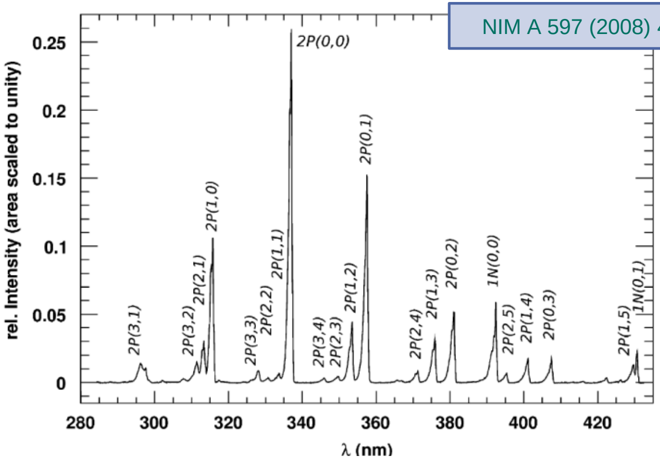
b) Wavelengths-dependent spectrum

Astropart. Phys. 55 (2014) 51




FY measurements normalized to common conditions (337 nm band in air at 800 hPa and 293 K). Dashed line represents the average FY determined in that paper.

NIM A 597 (2008) 41




Air fluorescence spectrum excited by 3 MeV electrons at 800 hPa. Labels indicate 21 major transitions.

# Fluorescence Light Emission

EPJ WoC 53, 01010 (2013);
Y. Tsunesada et al. ICRC2013

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a) absolute yield value of a reference transmission
b) Wavelengths-dependent spectrum
c) Pressure dependence in dry air

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a) absolute yield value of a reference transmission
b) Wavelengths-dependent spectrum
c) Pressure dependence in dry air
d) Humidity quenching

$$\frac{1}{p'_{\text{air}}} \longrightarrow \frac{1}{p'_{\text{air}}} \left(1 - \frac{p_h}{p}\right) + \frac{1}{p'_{H_2O}} \frac{e}{p}$$

# Fluorescence Light Emission

EPJ WoC 53, 01010 (2013);
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a) absolute yield value of a reference transmission
b) Wavelengths-dependent spectrum
c) Pressure dependence in dry air
d) Humidity quenching
e) Temperature-dependent collisional cross section

$$\frac{H_\lambda(T)}{H_\lambda(T_0)} = \left(\frac{T}{T_0}\right)^{\alpha_\lambda}$$

$\alpha_\lambda$-exponent of the power law describing the T-dependent collisional cross section for each $\lambda$

EPJ WoC 53, 01010 (2013);
Y. Tsunesada et al. ICRC2013

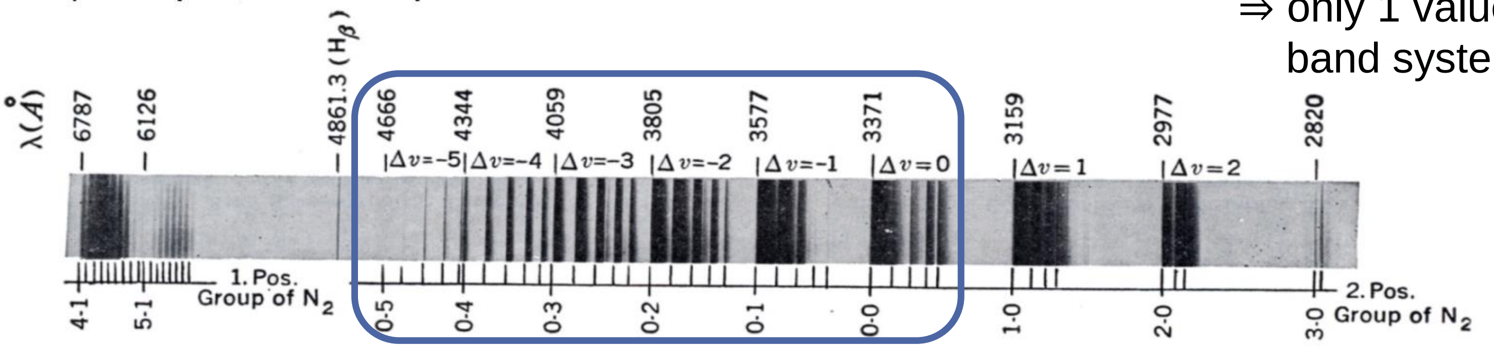
# Fluorescence Light Emission

$$Y_{\text{air}}(\lambda, p, T) = Y_{\text{air}}(337\text{nm}, p_0, T_0) \cdot I_\lambda / I_{337}(p_0, T_0) \cdot \frac{1 + \frac{p_0}{p'_{\text{air}}(\lambda, T_0)}}{1 + \frac{p}{p'_{\text{air}}(\lambda, T_0) \cdot \sqrt{\frac{T}{T_0} \cdot \frac{H_\lambda(T_0)}{H_\lambda(T)}}}}$$

a) absolute yield value of a reference transmission
b) Wavelengths-dependent spectrum
c) Pressure dependence in dry air
d) Humidity quenching
e) Temperature-dependent collisional cross section

Non-radiative de-excitation of excited nitrogen molecules

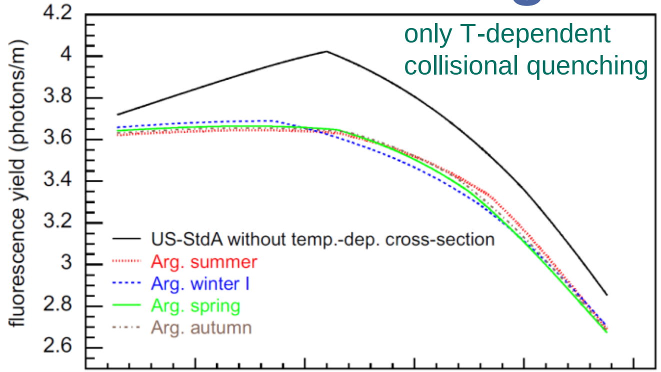
⇒ only 1 value for each band system, e.g. 2P $v=0$

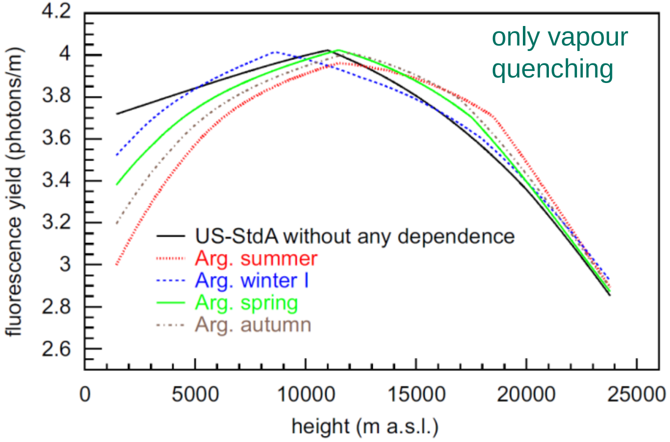


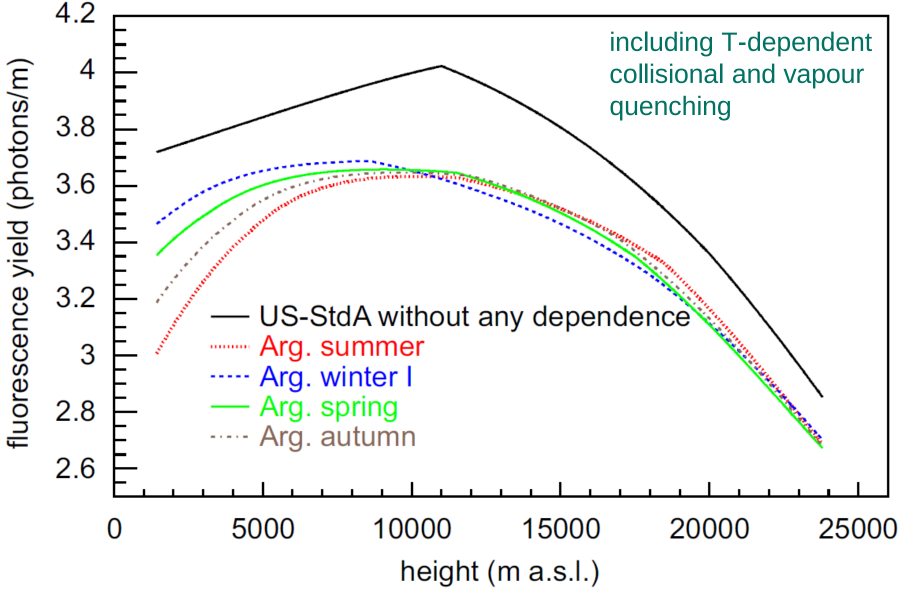
# Fluorescence Light Emission

NIM A 597 (2008) 94

FY for a 0.85 MeV $e^-$



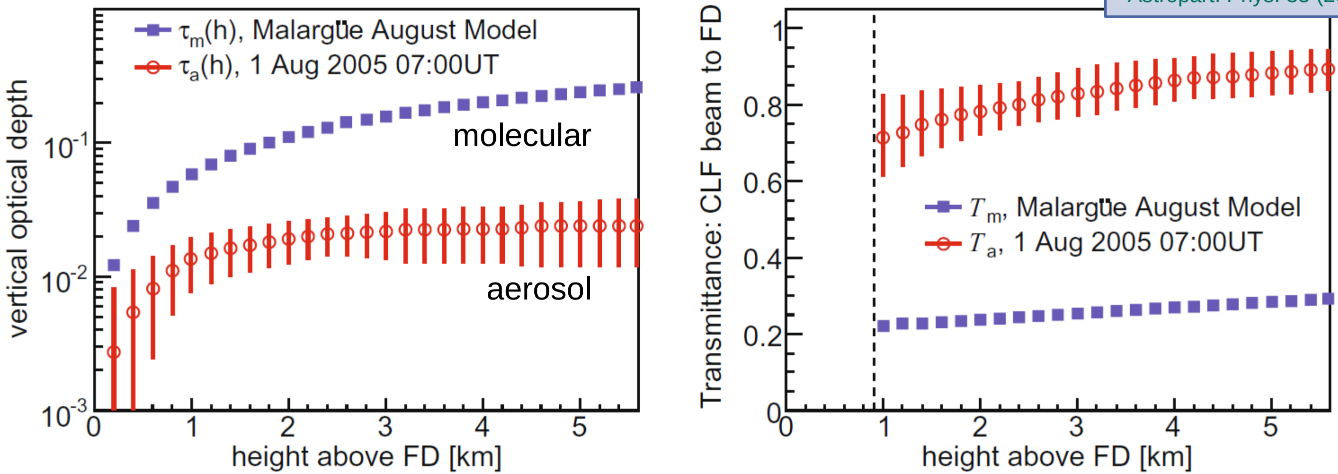



# Light Transmission towards Telescopes

- Fluorescence photons (approx. 300 – 400 nm) are mainly scattered by air molecules (Rayleigh sc.) and aerosols (Mie sc.)

- Absorption, e.g. by Ozone, plays only a minor role

Astropart. Phys. 33 (2010) 108

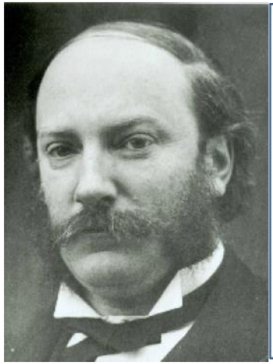



Laser shots, 355 nm, at a distance of 26 km from the Fluorescence Telescope

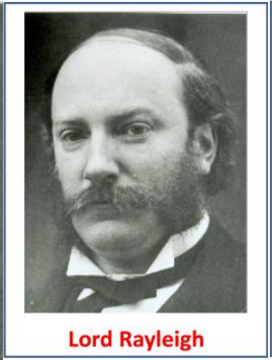
# Light Transmission towards Telescopes

- Lord Rayleigh suffering from aerosols

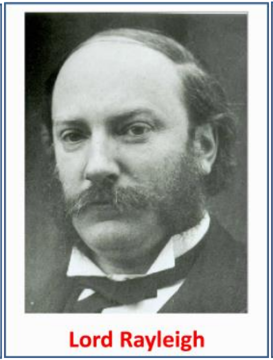
V. Rizi, presentation at AtmoHEAD 2022



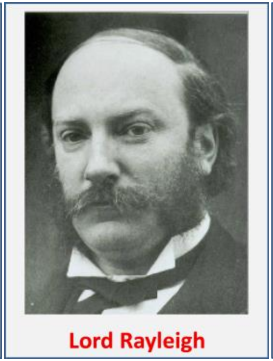
Pure „Rayleigh night“ = without aerosols



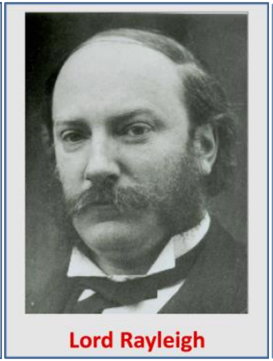

VAOD ≈ 0.005



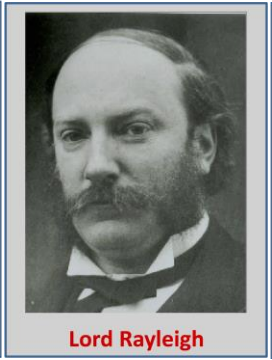

VAOD ≈ 0.01



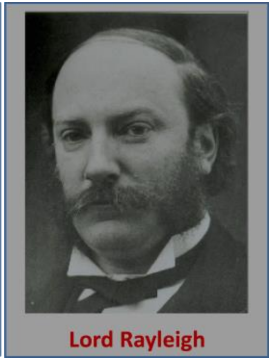

VAOD ≈ 0.05




VAOD ≈ 0.1




VAOD ≈ 0.2

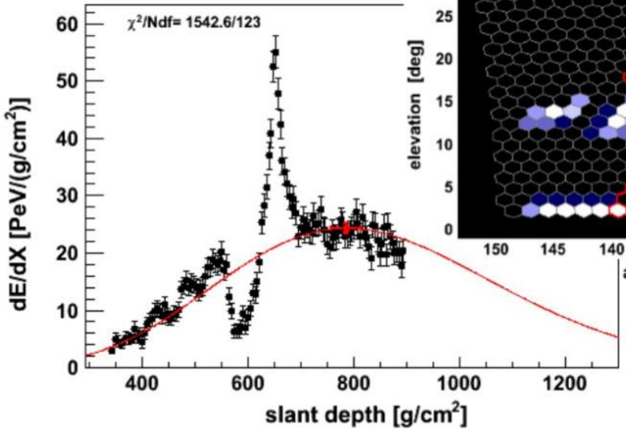



VAOD ≈ 0.5

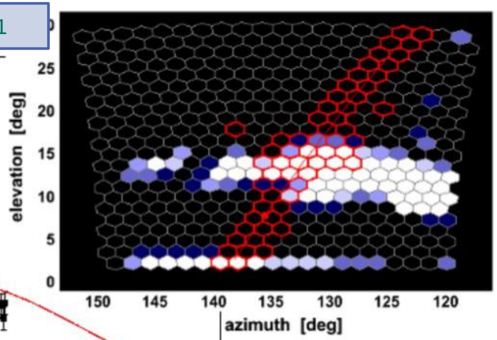
# Clouds in FOV

- Clouds obscure (parts of) the longitudinal light profiles
- Scattering might enhance light in different parts of the profile

A. Puyleart, presentation at ICRC 2021

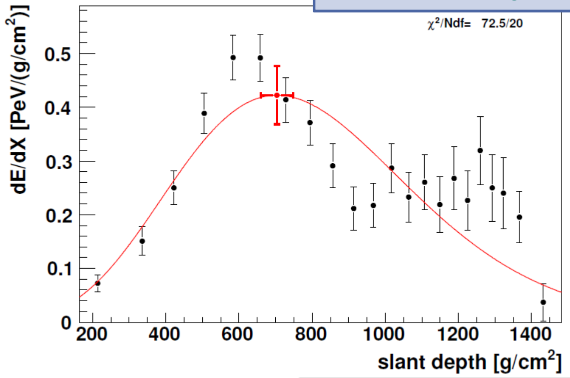


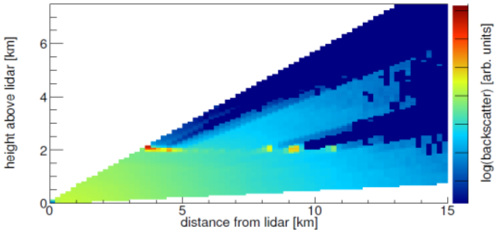

profile of energy deposit seen by a fluorescence camera




Light track at fluorescence camera indicated by red pixels, overlaid with colored pixels marked as „cloudy“

C. Baus, Auger GAPnote 2011



# Detection Techniques in Astroparticle Physics

- Cherenkov telescopes



# Detection Techniques in Astroparticle Physics

- Cherenkov telescopes
  - Measuring Cherenkov light induced by gamma rays in the atmosphere
  - **Atmospheric conditions** vary
    - longitudinal shower development
    - Cherenkov light emission
    - light transmission towards telescopes
    - clouds in FOV

# Longitudinal Shower Development and Cherenkov light emission

Astropart. Phys. 12 (2000) 255

- Cherenkov emission depends on the charged particles of an EAS induced by gamma rays in the atmosphere

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{(\beta n(\lambda))^2}\right) \frac{1}{\lambda^2}\, d\lambda$$

with a refractive index $n$, dependent on wavelength, $p$, $T$, and water vapor

$$(n-1)_{Tp} = (n-1)_s \cdot \frac{p \cdot [1 + p(61.3 - T) \cdot 10^{-10}]}{96095.4 \cdot (1 + 0.003661 \cdot T)}$$

empirical formulas from different textbooks

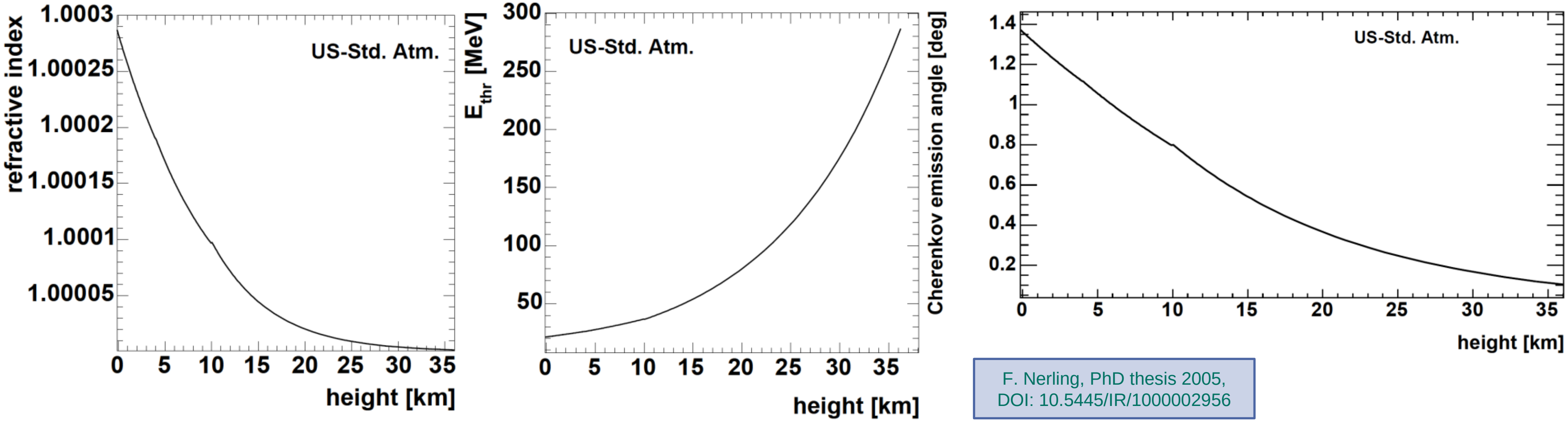
$$(n_{air} - 1) \cdot 10^8 = 8059.20 + \frac{2480588}{132.274 - \lambda^{-2}} + \frac{17452.9}{39.32957 - \lambda^{-2}}$$

$$(n_{CO_2} - 1) \cdot 10^8 = 22822.1 + 117.8 \cdot \lambda^{-2} + \frac{2406030}{130 - \lambda^{-2}} + \frac{15997}{38.9 - \lambda^{-2}}$$

$$(n_{vapour} - 1) \cdot 10^8 = 295.235 + 2.6422 \cdot \lambda^{-2} - 0.03238 \cdot \lambda^{-4} + 0.004028 \cdot \lambda^{-6}$$

# Longitudinal Shower Development and Cherenkov light emission

- Atmospheric effects on the Cherenkov emission – simplyfied approach with density dependence only and without wavelengths dependence

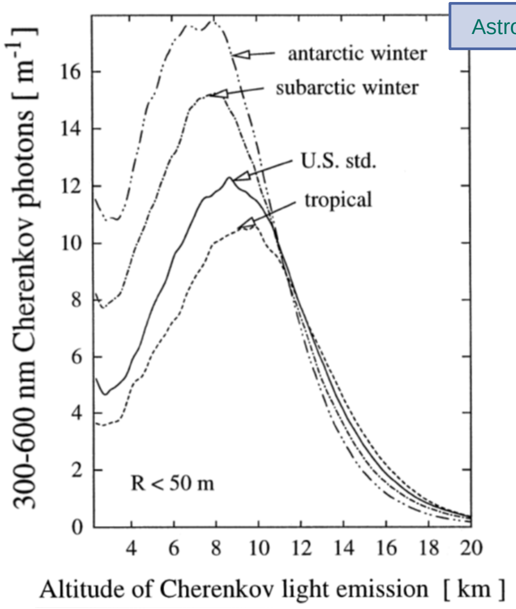



F. Nerling, PhD thesis 2005, DOI: 10.5445/IR/1000002956

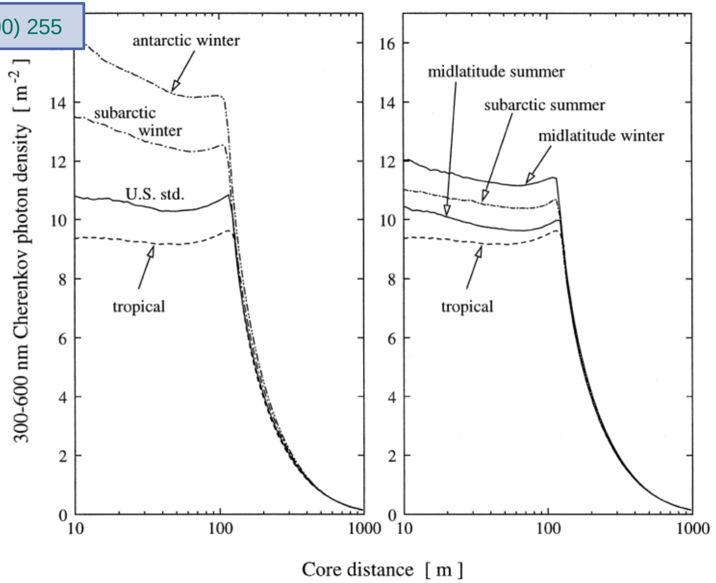
# Longitudinal Shower Development and Cherenkov light emission

- Cherenkov emission with all dependences

Astropart. Phys. 12 (2000) 255



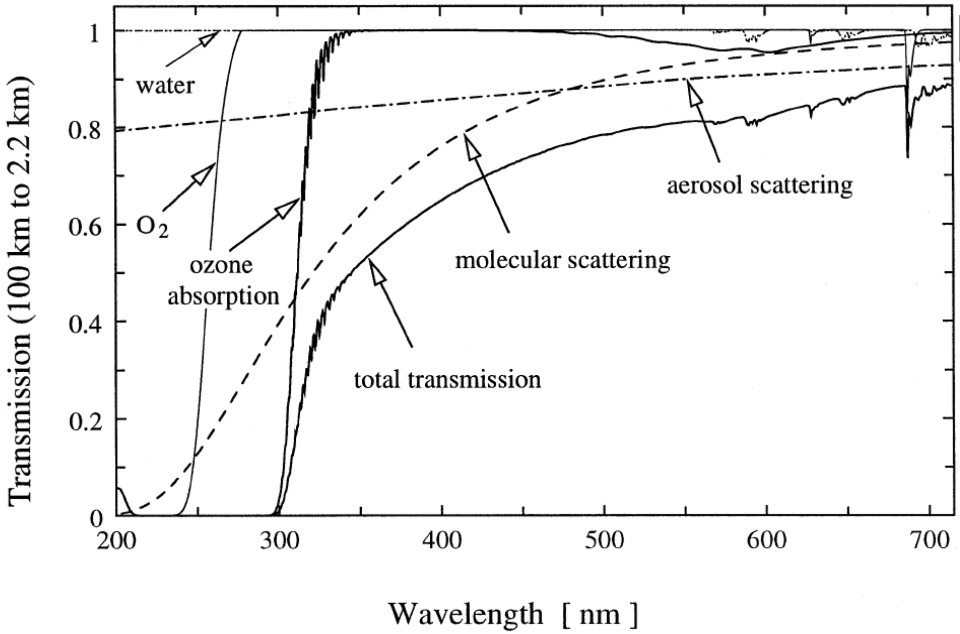

Average Cherenkov light emission along the shower axis for vertical 100 GeV gamma-rays with different atmospheric profiles; observation level at 2200 m.




Lateral distribution of Cherenkov photons.

# Light Transmission towards Telescopes

- Cherenkov photons (approx. 300 – 600 nm range at Cherenkov telescopes) are mainly scattered by air molecules (Rayleigh sc.) and aerosols (Mie sc.)

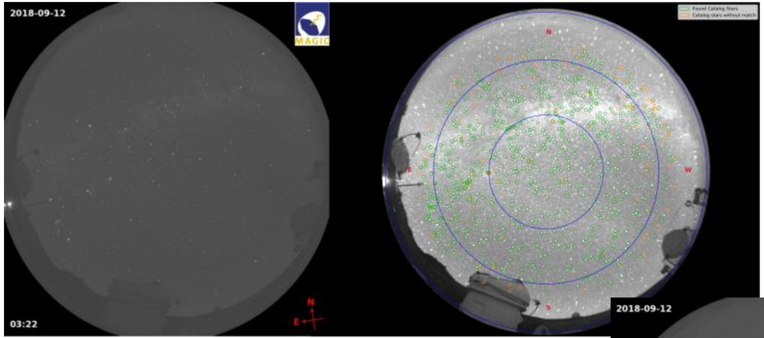



Astropart. Phys. 12 (2000) 255

# Clouds in FOV

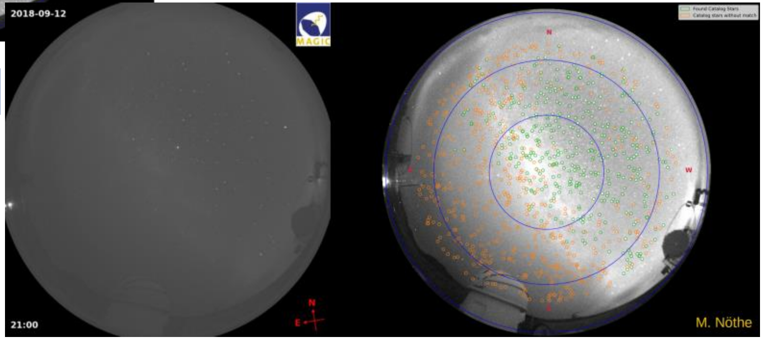
- Aim for adaptive scheduling of the telescopes

Compare observed with expected stars




Clear sky

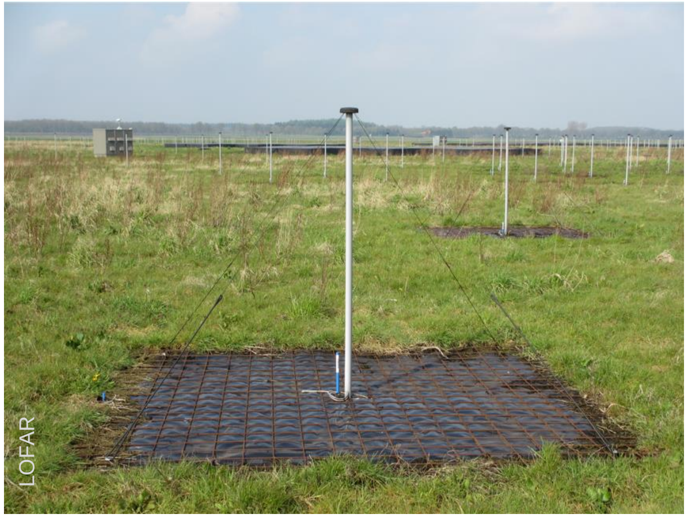
Clouds at the left half of FOV




M. Will, presentation at AtmoHEAD 2018

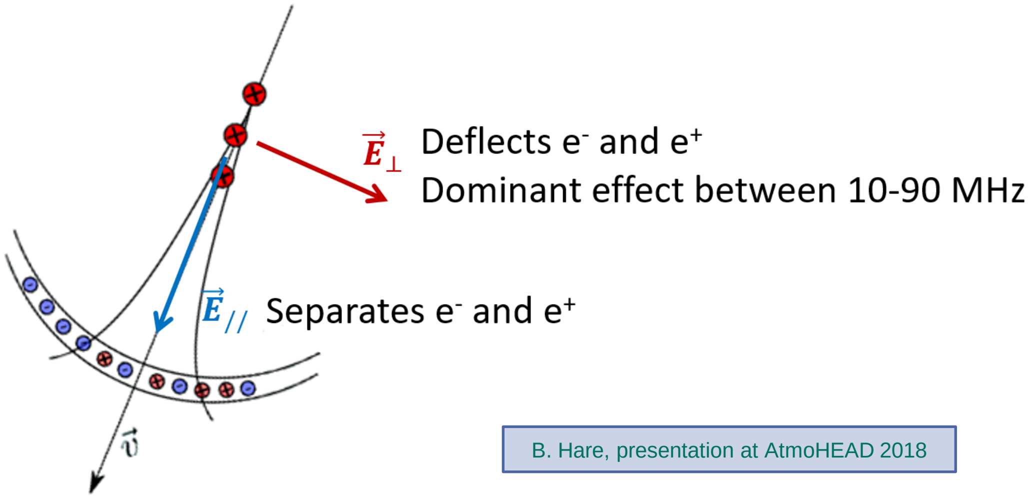
# Detection Techniques in Astroparticle Physics

- Radio antennas




# Detection Techniques in Astroparticle Physics

- Radio antennas
  - Measuring radio emission by extensive air showers in the atmosphere
  - Typical frequency range 30 – 80 MHz
  - **Atmospheric conditions** vary
    - Electron-positron separation

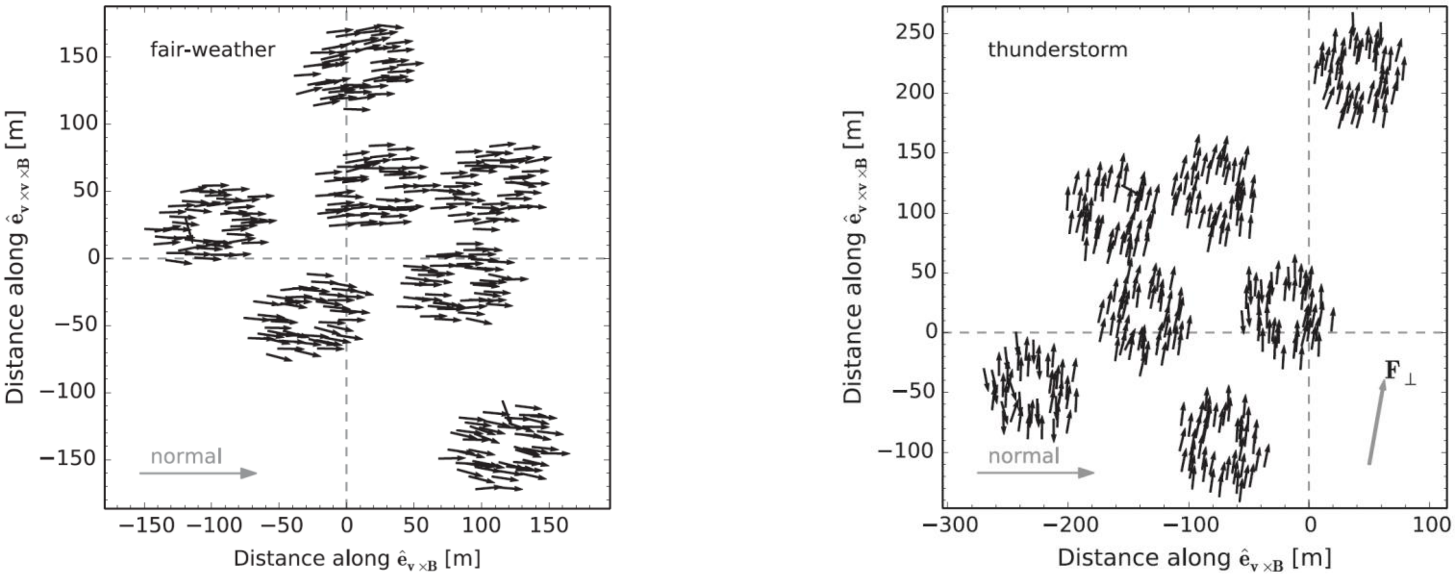



B. Hare, presentation at AtmoHEAD 2018

# Detection Techniques in Astroparticle Physics

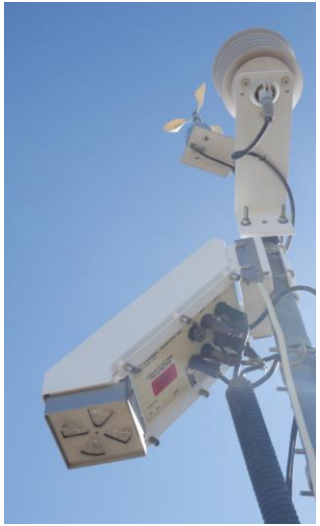
- Radio antennas
  - Polarization pattern of radio signals

PRL 114 (2015) 165001



# Overview

- Detector techniques and their atmospheric dependences
- Instruments for Atmospheric Monitoring
- Interdisciplinary Spin-offs

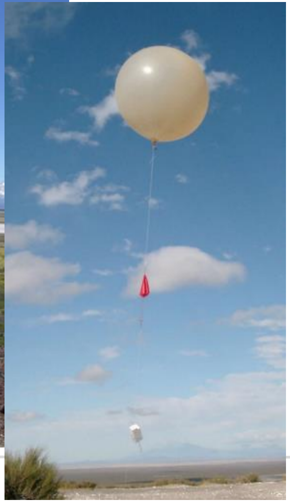


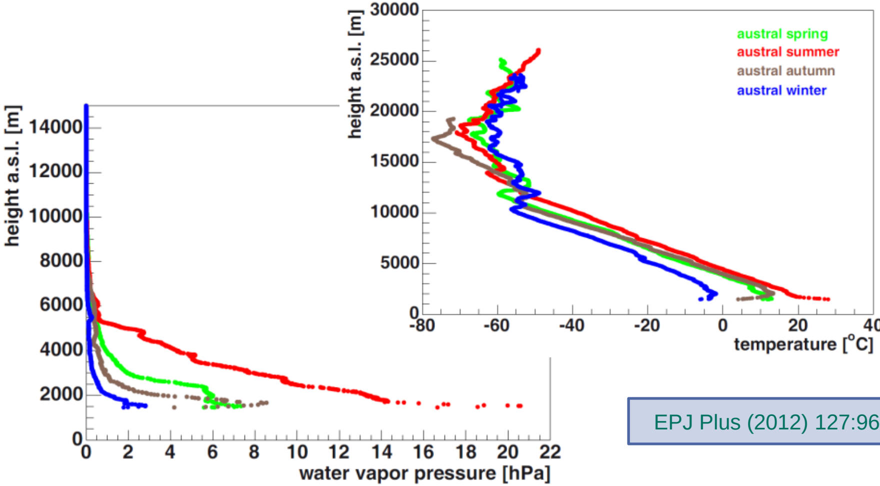
# Instruments for Atmospheric Monitoring

| | molecular atmosphere / state variables (*P*, *T*, *u* → *ρ*, *X* ), refractive index *n*, Rayleigh scattering | aerosols / Mie scattering | clouds | electric field, lightning | slow control / safety of observatory instruments |
|---|---|---|---|---|---|
| weather station | x | | | | x |
| meteorological radio sounding / atmospheric models | x | | | | |
| wind sensor | | | | | x |
| electric field mill | | | | x | x |
| dust monitor | | | | | x |
| elastic lidar | | x | x | | |
| bistatic elastic lidar / laser facility | | x | x | | |
| Raman lidar | x | x | x | | |
| FRAM | | x | x | | |
| photometer | | x | x | | |
| cloud camera | | | x | | |

# Instruments for Atmospheric Monitoring

| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **weather station** | X | | | | X |
| **meteorological radio sounding / atmospheric models** | X | | | | |
| **wind sensor** | | | | | X |

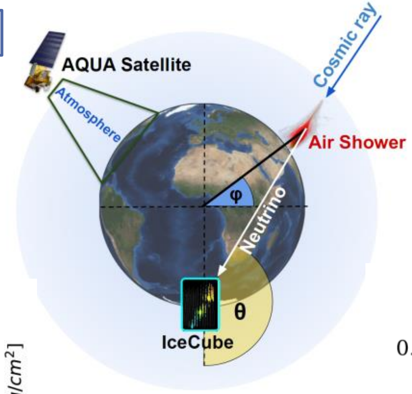




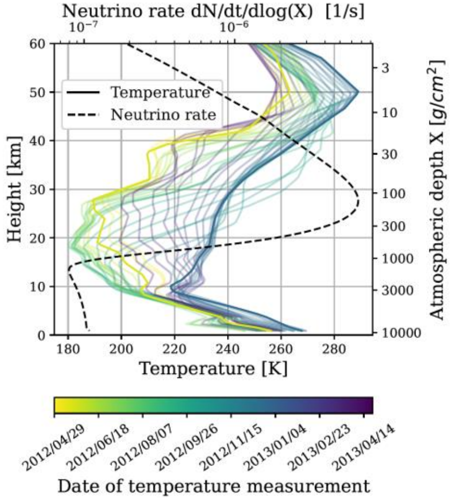

EPJ Plus (2012) 127:96

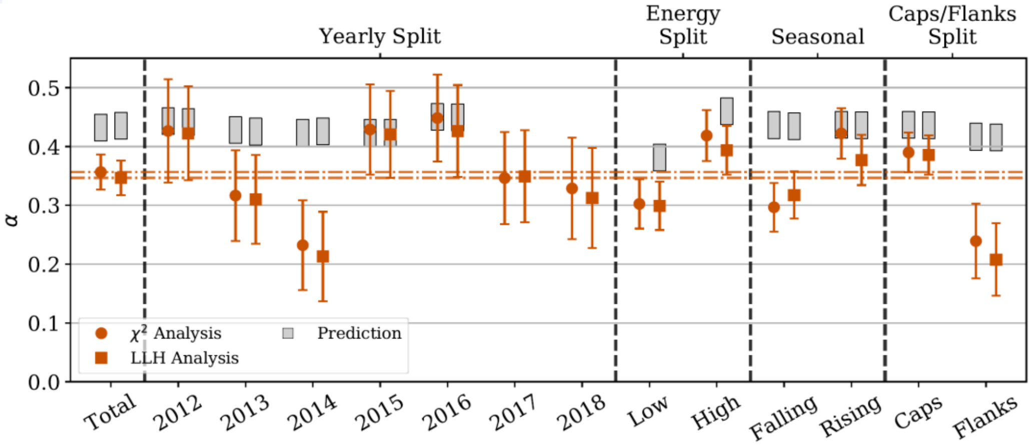
# Local Measurements and Global Models

https://doi.org/10.48550/arXiv.2303.04682




- 3.5% highly significant seasonal variation for the rate of high-energy atm. neutrinos is observed for 10% variation of $T_{eff}$
- Tension with prediction
- Production of atm. $\nu_\mu$ might not be fully understood



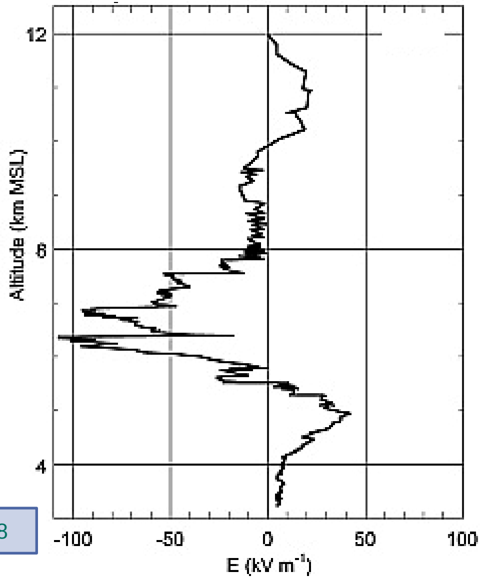

α is strength of the correlation between the atmospheric temperatures and the measured atmospheric $\nu_\mu$ rates

# Instruments for Atmospheric Monitoring

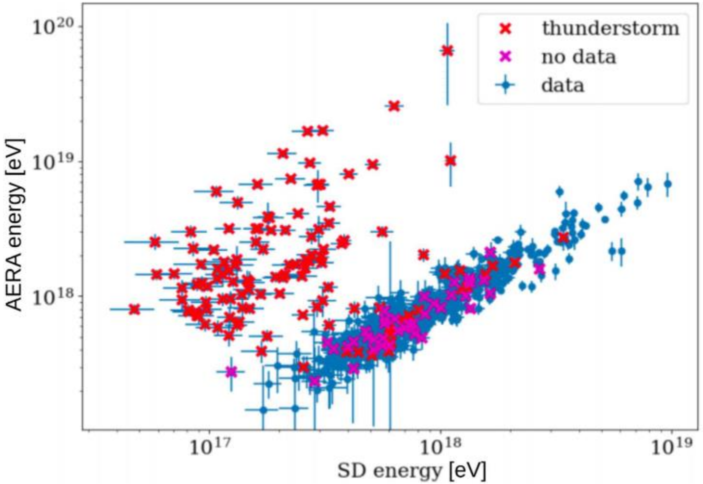
| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **electric field mill** | | | | X | X |

B. Hare, presentation at AtmoHEAD 2018

E-field in thunderstorm




EAS energy estimate from radio antenna vs. particle det.

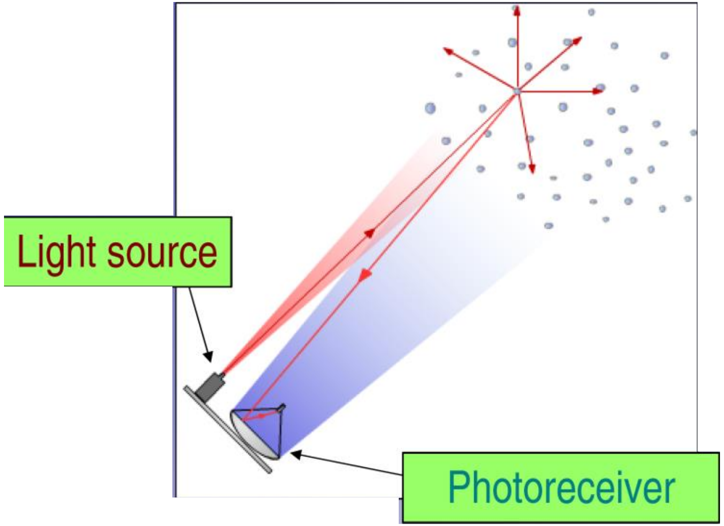



M. Büsken, presentation at AtmoHEAD 2022

# Instruments for Atmospheric Monitoring

| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **elastic lidar** | | X | X | | |

Elastic lidar principle

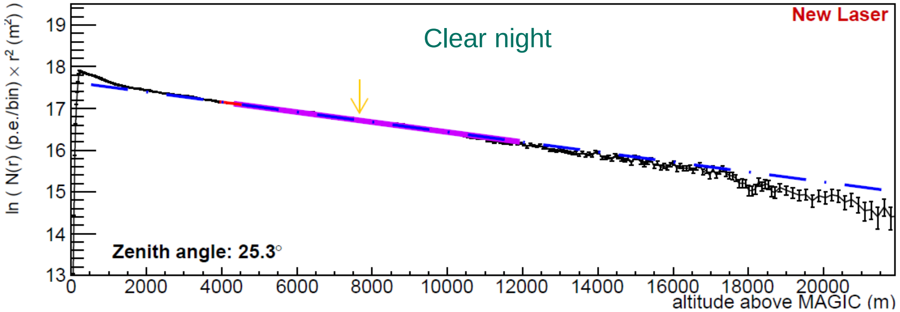


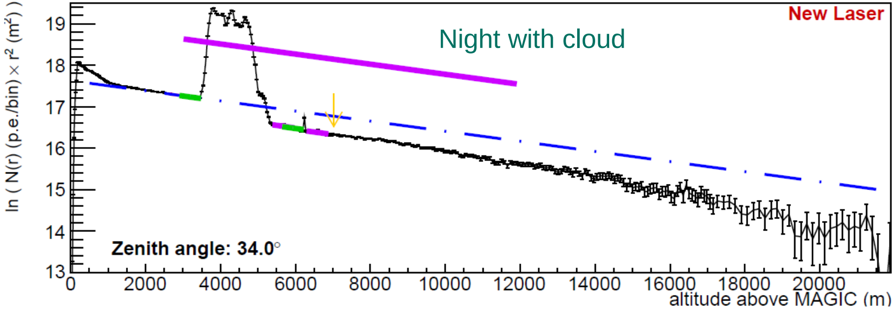

R. Mussa, presentation at Arequipa School 2008

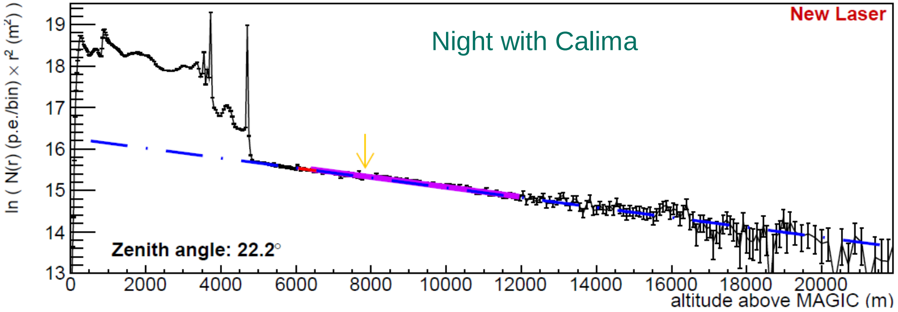

# Instruments for Atmospheric Monitoring

| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **elastic lidar** | | X | X | | |

MNRAS 515 (2022) 4520



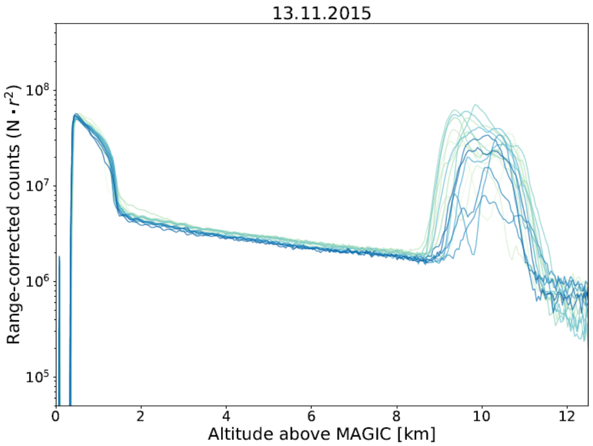



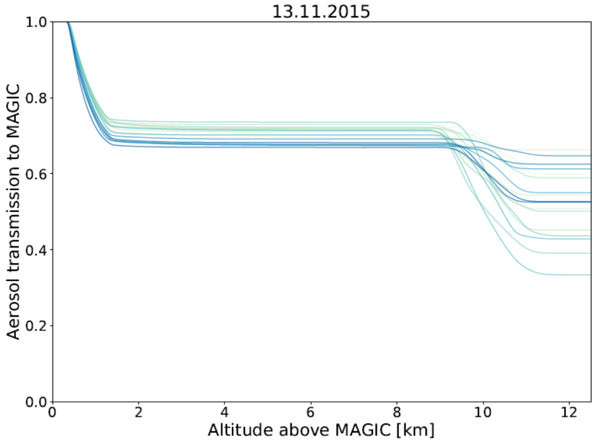

Lidar signals taken at MAGIC in 2019

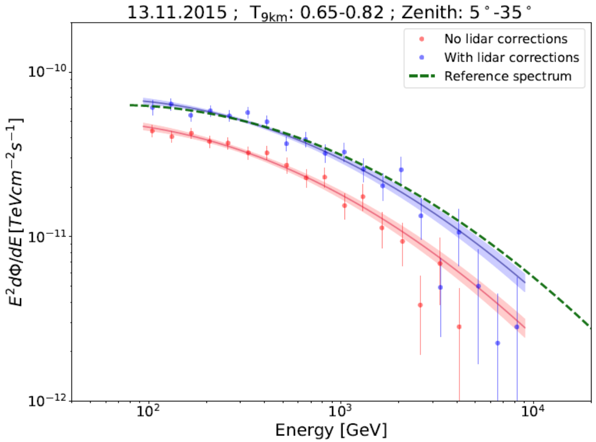
# Instruments for Atmospheric Monitoring

| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **elastic lidar** | | X | X | | |

A&A 673 (2023) A2



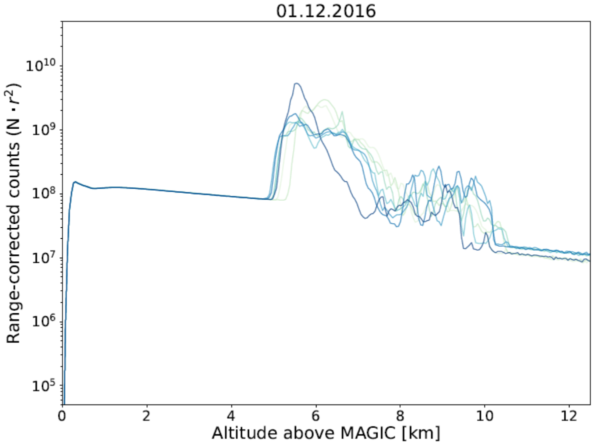



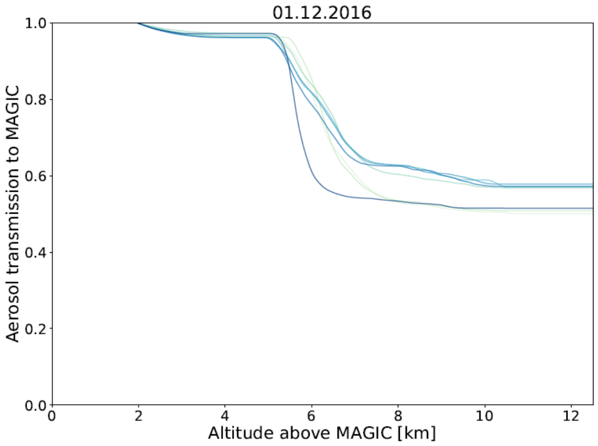

Spectral energy distribution of concurrent observation of the Crab Nebula

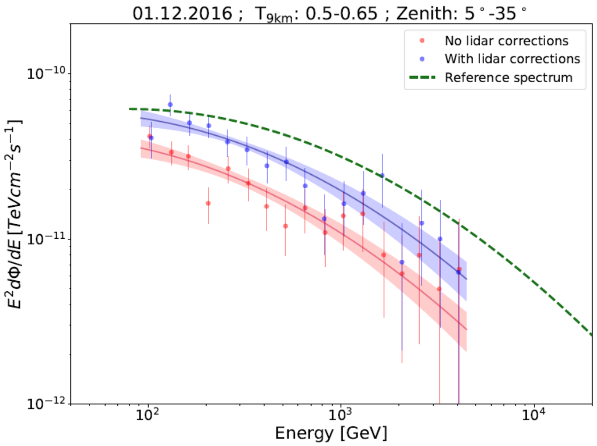
# Instruments for Atmospheric Monitoring

| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **elastic lidar** | | X | X | | |

A&A 673 (2023) A2



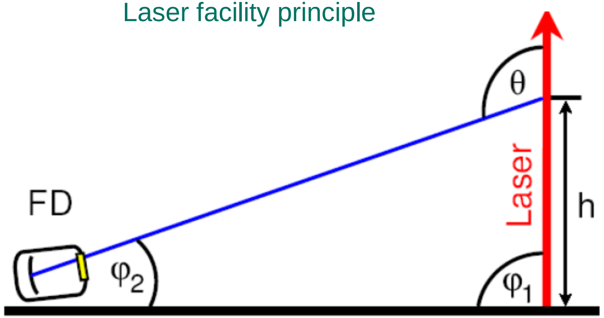




Spectral energy distribution of concurrent observation of the Crab Nebula

# Instruments for Atmospheric Monitoring

| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **bistatic elastic lidar / laser facility** | | X | X | | |

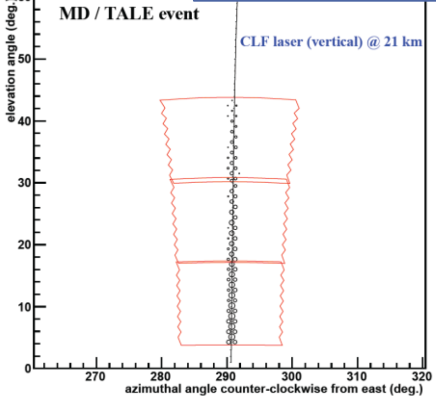
Laser facility principle





L. Valore, presentation at AtmoHEAD 2018

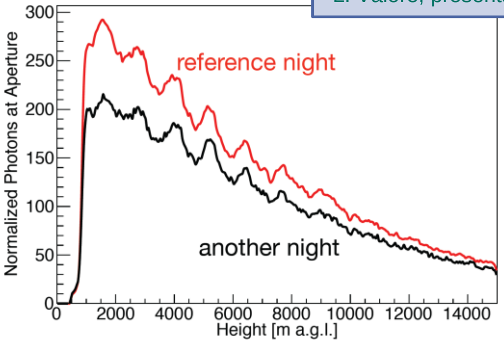
EPJ 197 (2019) 01003



# Instruments for Atmospheric Monitoring

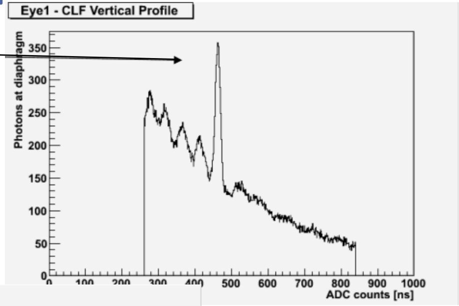
| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **bistatic elastic lidar / laser facility** | | X | X | | |

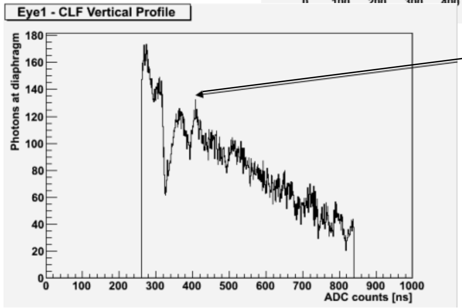
L. Valore, presentation at AtmoHEAD 2018



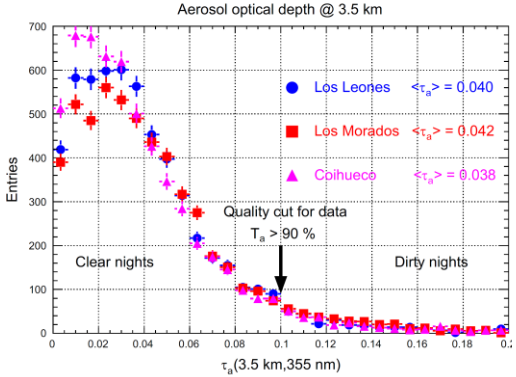

Cloud detection

Peak: cloud above laser beam

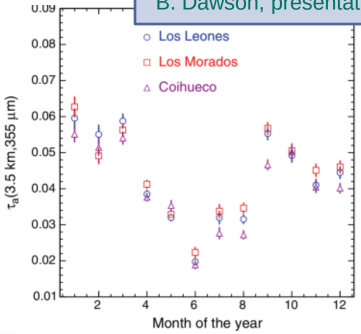



Dip: cloud between laser beam and telescope



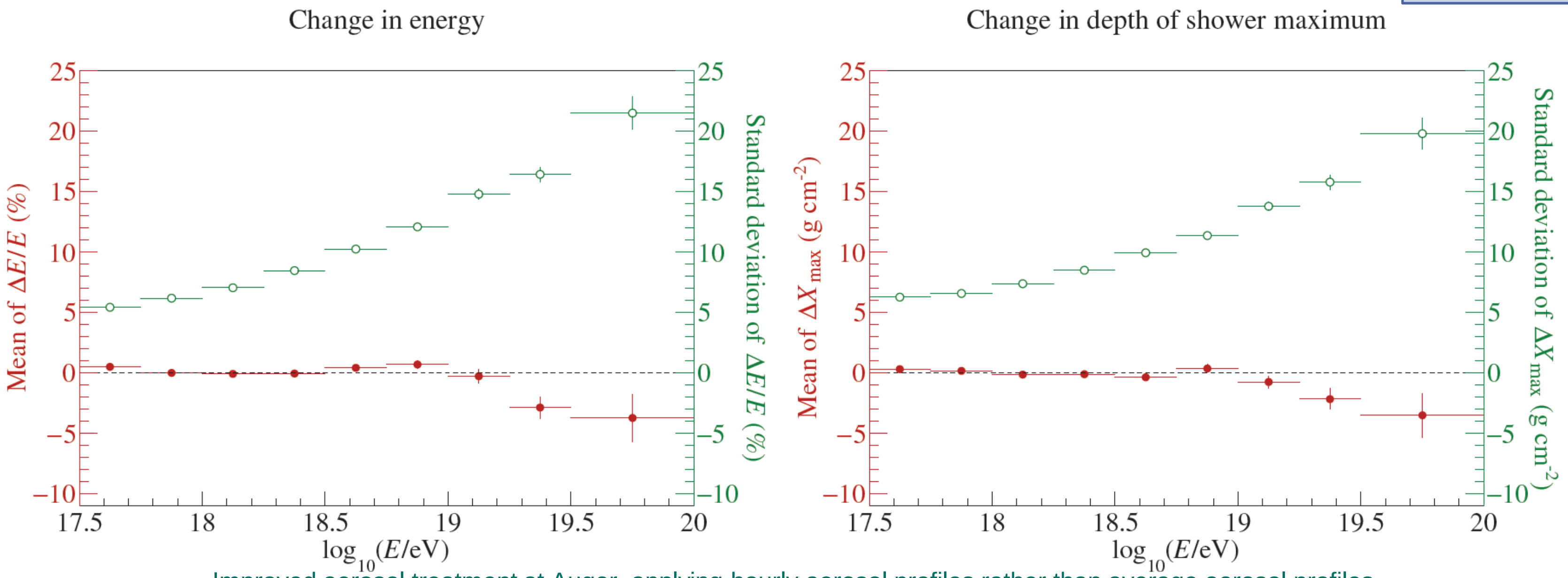

B. Dawson, presentation at AtmoHEAD 2018



# Instruments for Atmospheric Monitoring

| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **bistatic elastic lidar / laser facility** | | X | X | | |

PoS (ICRC2019) 283

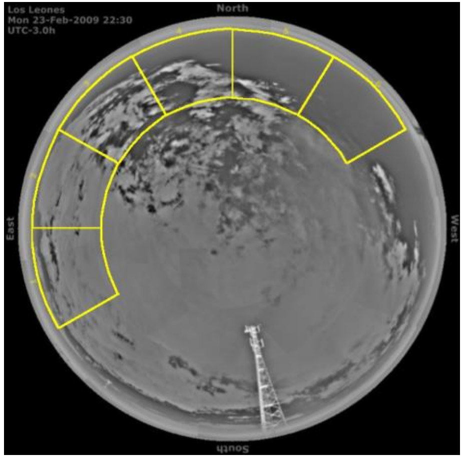


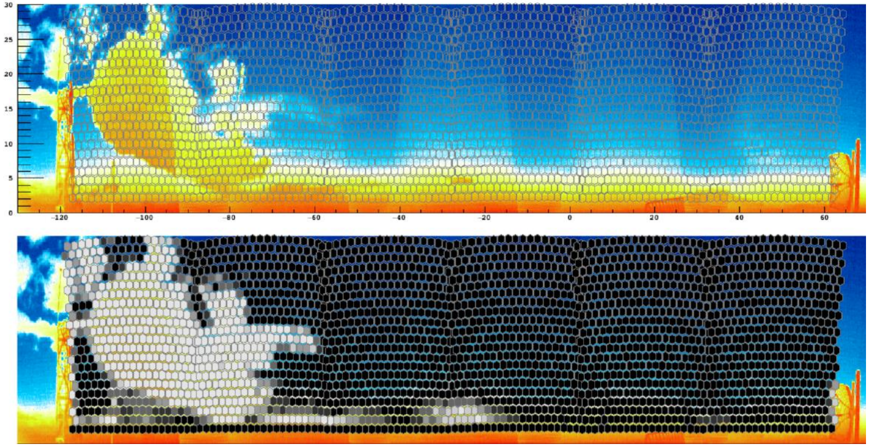

Improved aerosol treatment at Auger, applying hourly aerosol profiles rather than average aerosol profiles

# Instruments for Atmospheric Monitoring

| | molecular atmosphere | aerosols | clouds | electric field | slow control |
|---|---|---|---|---|---|
| **cloud camera** | | | X | | |

J. Chirinos Diaz, poster at ICRC 2013



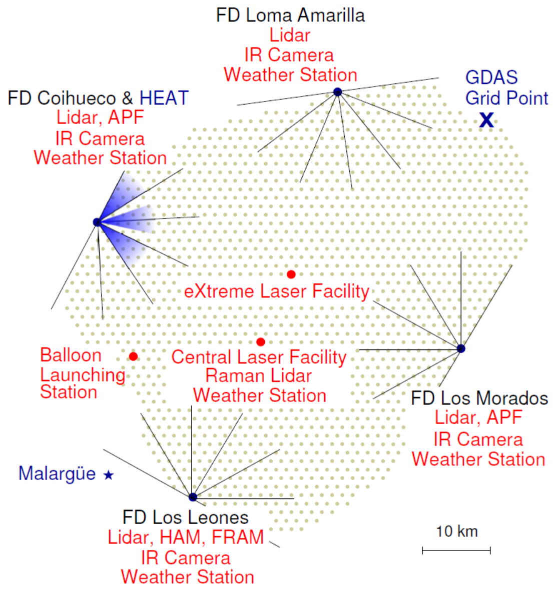



IR camera skymap and cloud mask of each pixel of a fluorescence telescope

# Instruments for Atmospheric Monitoring

- Most of the observatories operate a set of instruments on site and apply meteorological data

NIM A 798 (2015) 17



# Overview

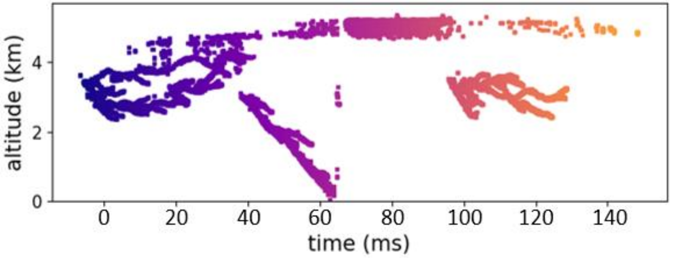
- Detector techniques and their atmospheric dependences
- Instruments for Atmospheric Monitoring
- Interdisciplinary Spin-offs

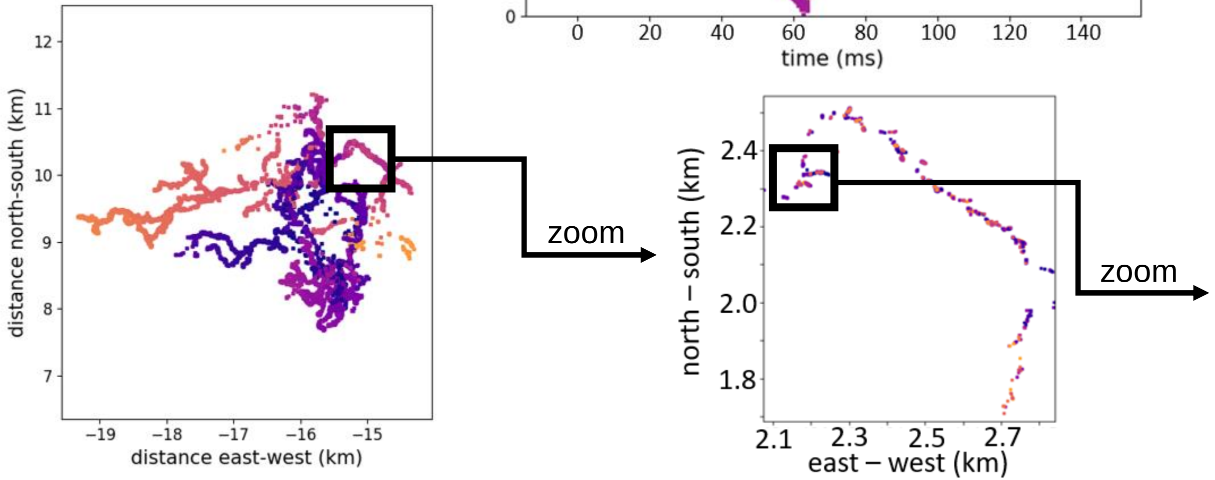
# Interdisciplinary Spin-offs

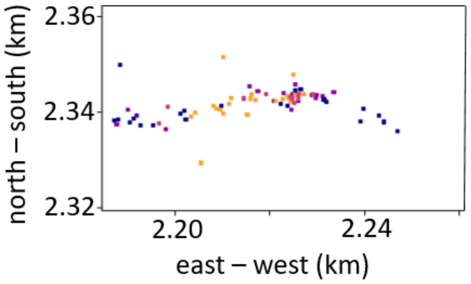
B. Hare, presentation at AtmoHEAD 2022

- Lightining Mapping

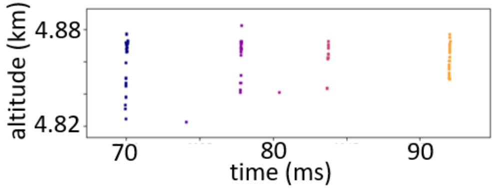
3D lightning records at LOFAR




➢ Needles on Leader Branch
  - 30 – 100 m long
  - Each needle can re-excite
  - Occur all along leader channel

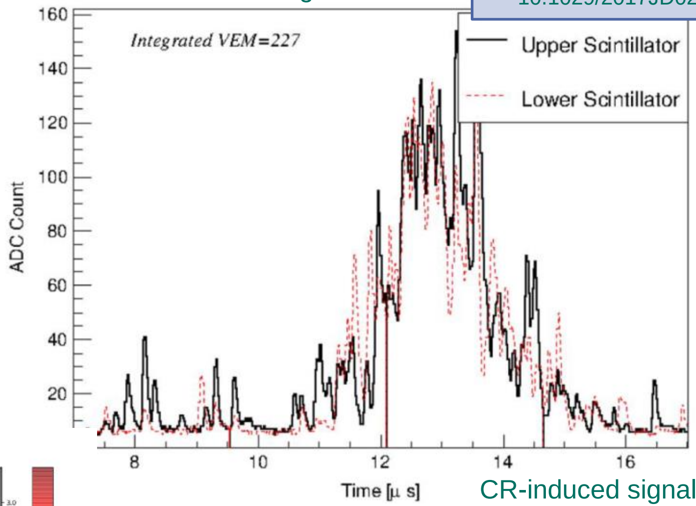


# Interdisciplinary Spin-offs

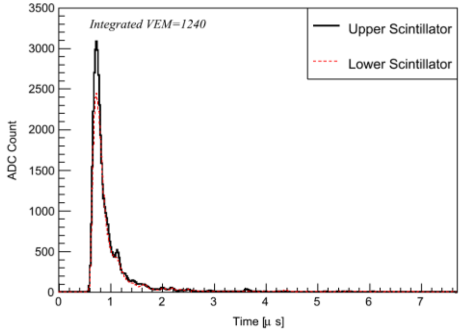
- Terrestrial Gamma Ray Flashes
  - ➢ Burst of consecutive TASD triggers
  - ➢ occurred within the first or second millisecond of a negative cloud-to-ground flash
  - ➢ Setup a local lightning mapping array (9 stations)
  - ➢ High-speed video camera

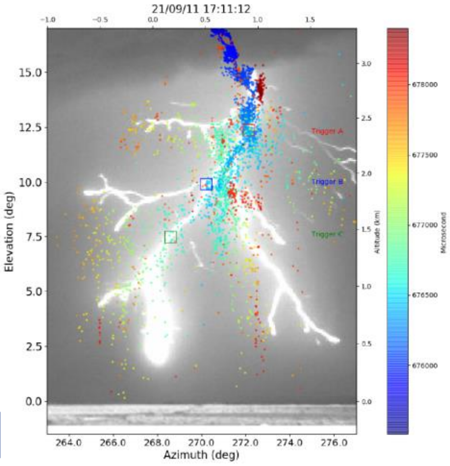
TGF-induced signal at TA

10.1029/2017JD027931




CR-induced signal



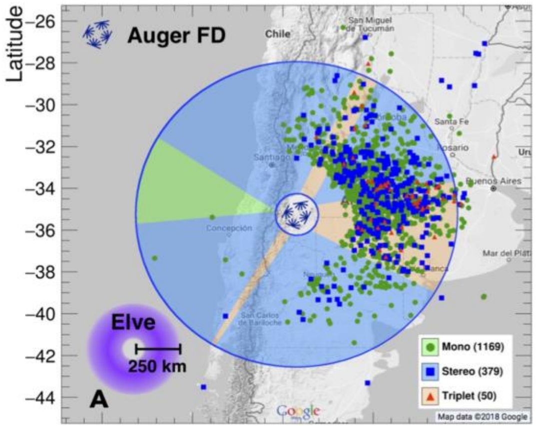




https://doi.org/10.48550/arXiv.2205.05115

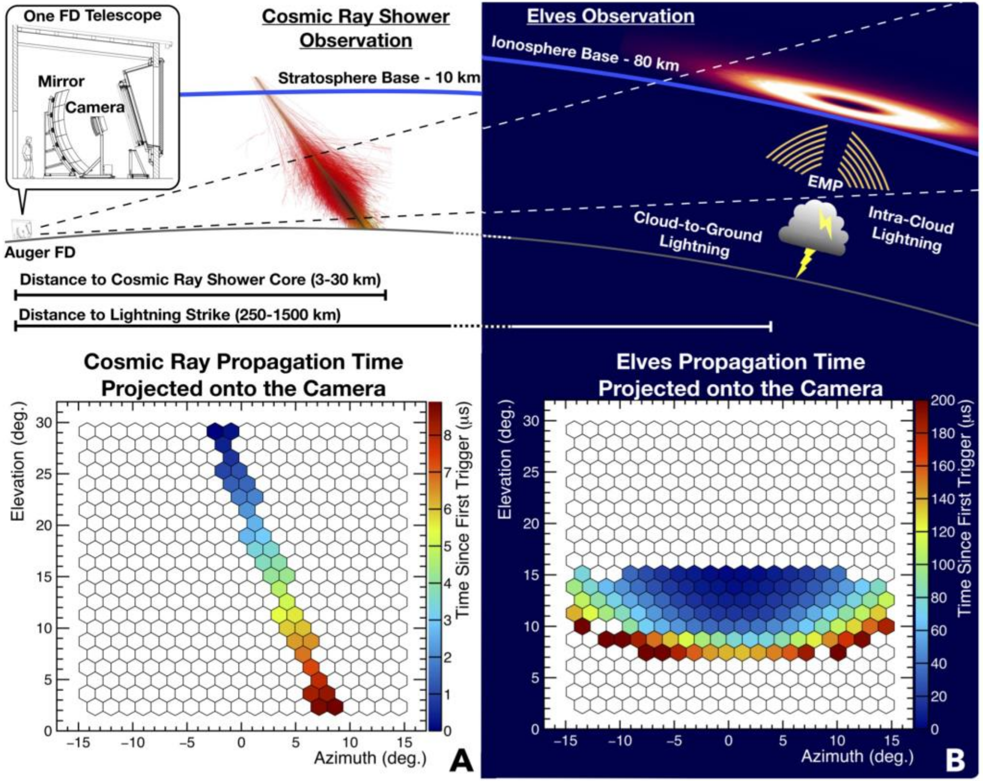
# Interdisciplinary Spin-offs

Earth Space Sci. 7 (2020) 4

- ELVES
  (Emission of Light and Very Low Frequency perturbations due to Electromagnetic Pulse Sources)



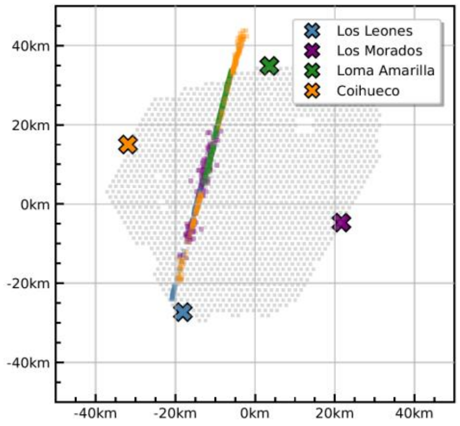

Reconstructed lightning strike location from Auger elves (data 2014 - 2016) and the number of FD sites contributing to each observation. The overlap ofthe FoV of each FD sites is shown in the shaded regions.



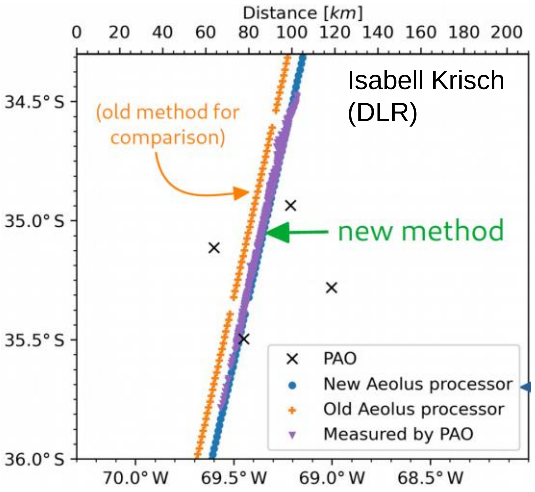
# Interdisciplinary Spin-offs

- Measurements of the laser of the AEOLUS satellite
  - ➢ first satellite mission to acquire profiles of Earth’s wind
  - ➢ Equipped with a lidar (355 nm)
  - ➢ Like a “moving” central laser facility

Optica 11 (2024) 263




Measured AEOLUS laser at the Auger Obervatory



# Summary

- **Atmospheric monitoring is essential for most observatories**
- **Atmospheric monitoring is a very active and interdisciplinary field**
- **Many thanks to the colleagues from MAGIC, CTA, H.E.S.S., IceCube, TA and Pierre Auger Observatory**
- **…and the organizers and participants of the AtmoHEAD workshops**
  **(ATmospheric MOnitoring for High Energy Astroparticle Detectors))**

AtmoHEAD

Next AtmoHEAD in Ischia,
15-17 July 2024