The use of aerosol data in Auger Fluorescence Detector analysis

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Photo: Steven Saffi, University of Adelaide

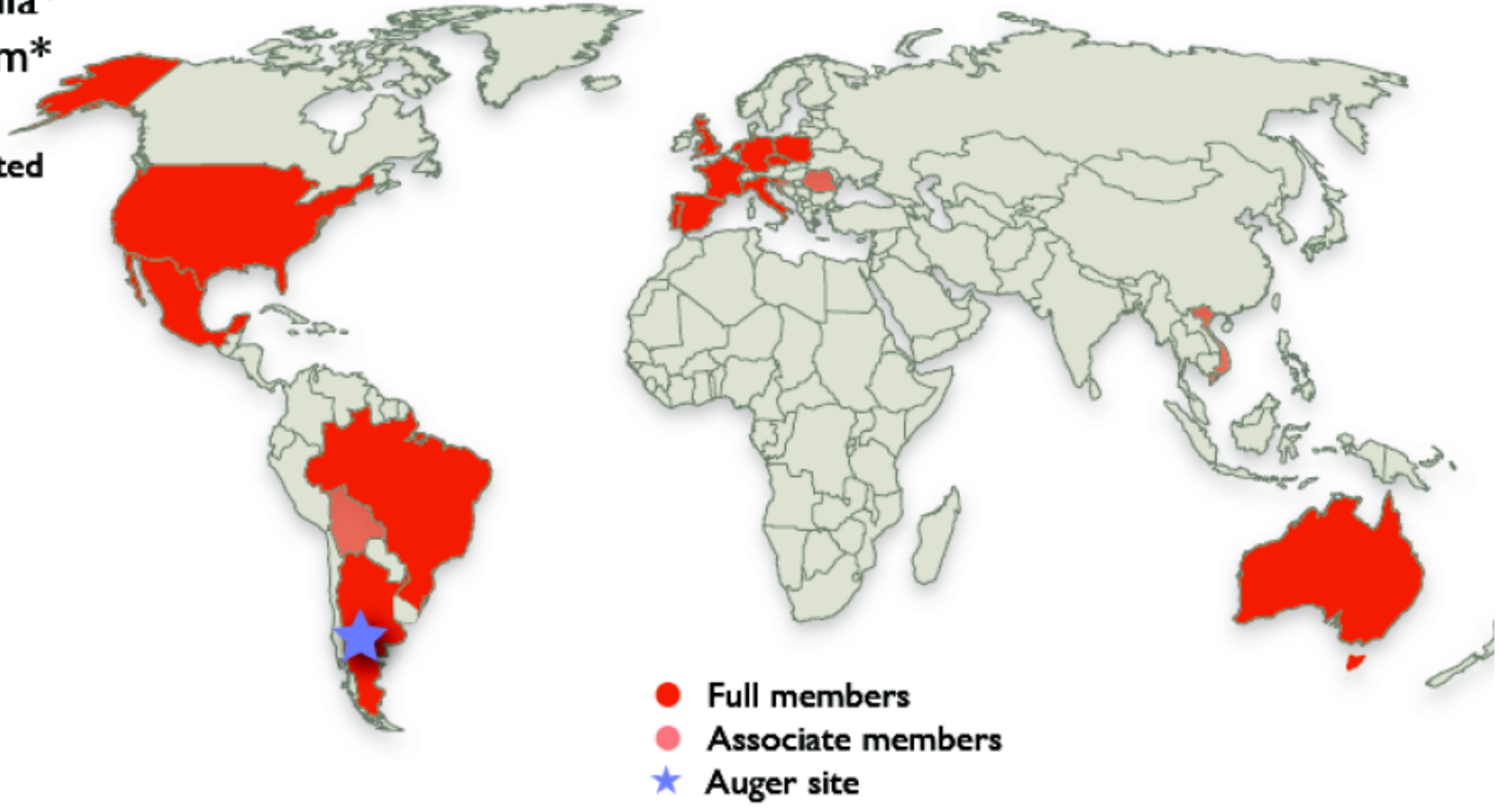
Pierre Auger Collaboration

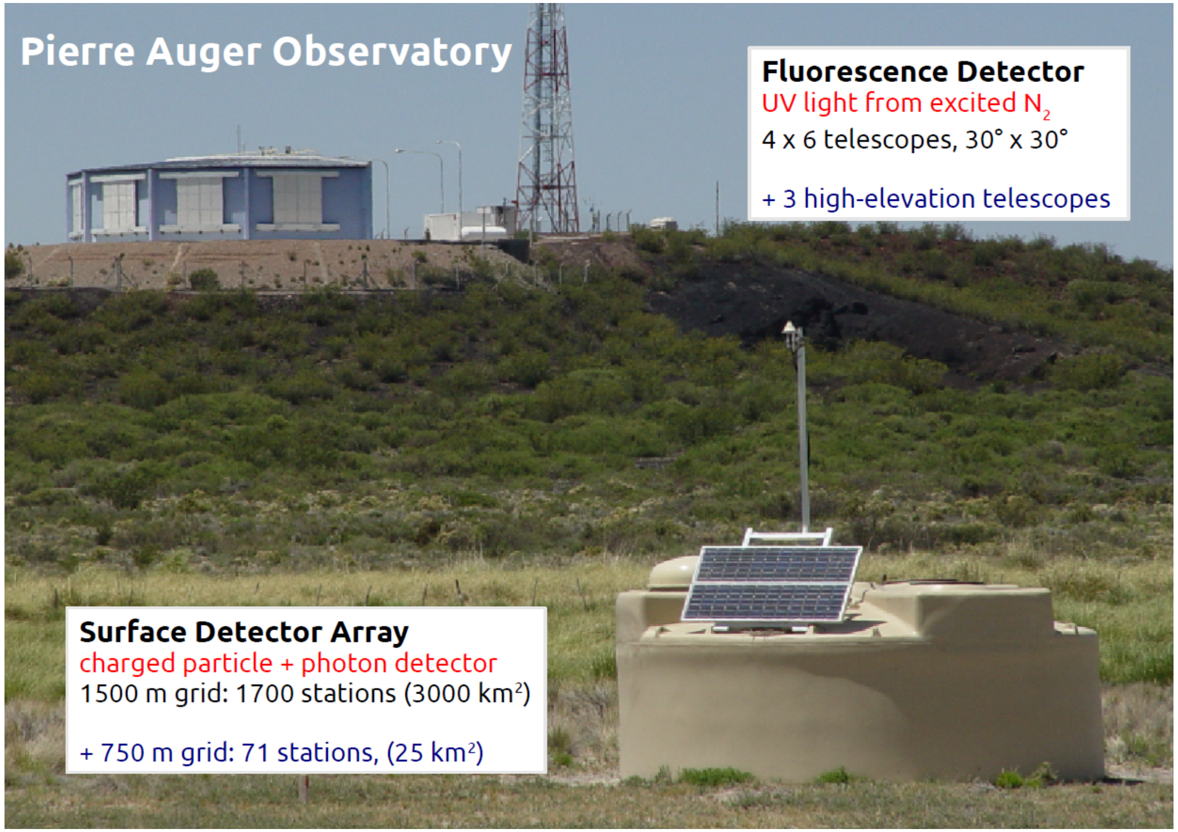
About 500 members from 19 countries

- Argentina
- Australia
- Brazil
- Croatia
- Czech Republic
- France
- Germany
- Italy
- Mexico
- Netherlands
- Poland
- Portugal
- Slovenia
- Spain
- United Kingdom
- USA

- Bolivia*
- Romania*
- Vietnam*

*Associated





Pierre Auger Observatory

Fluorescence Detector

UV light from excited N_2

4 x 6 telescopes, 30° x 30°

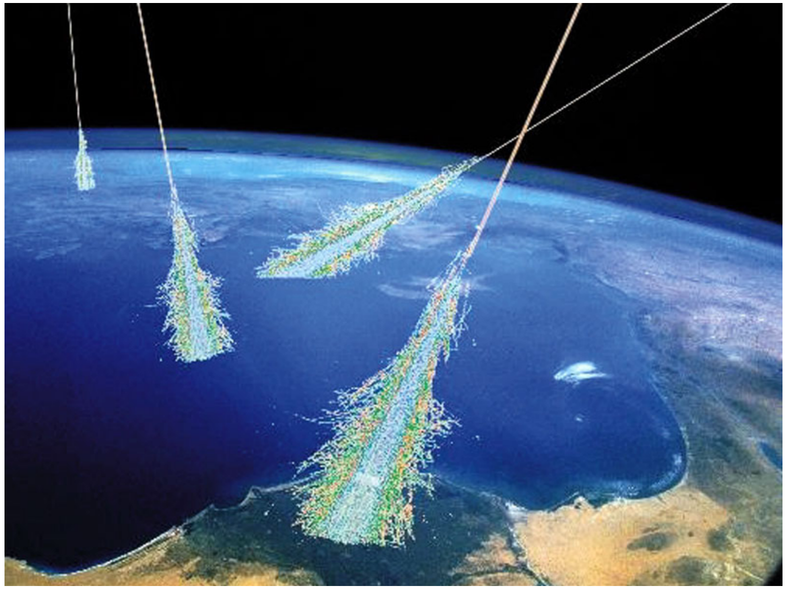
+ 3 high-elevation telescopes

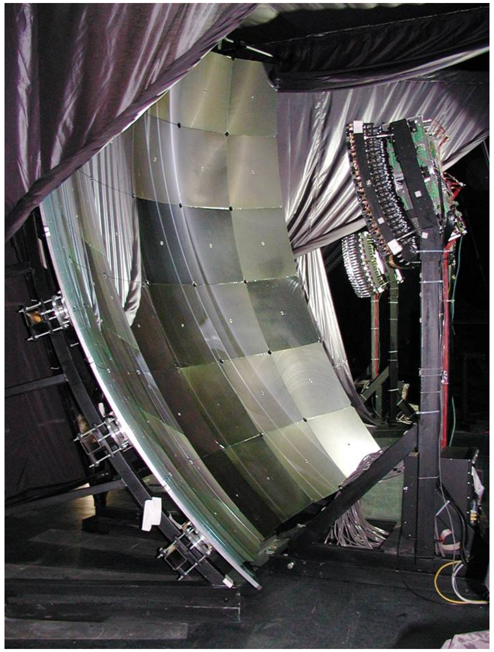
Surface Detector Array

charged particle + photon detector

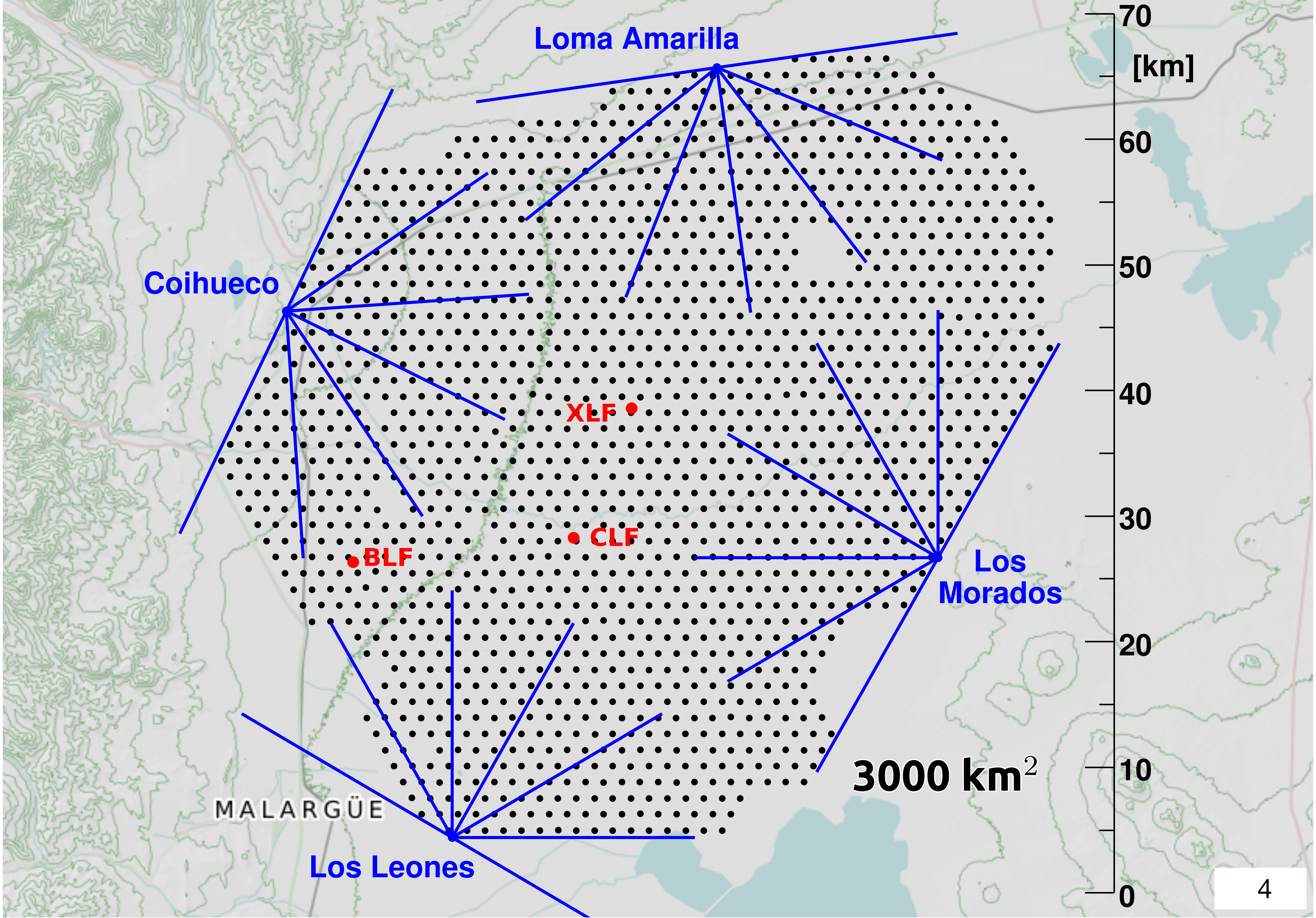
1500 m grid: 1700 stations (3000 km^2)

+ 750 m grid: 71 stations, (25 km^2)

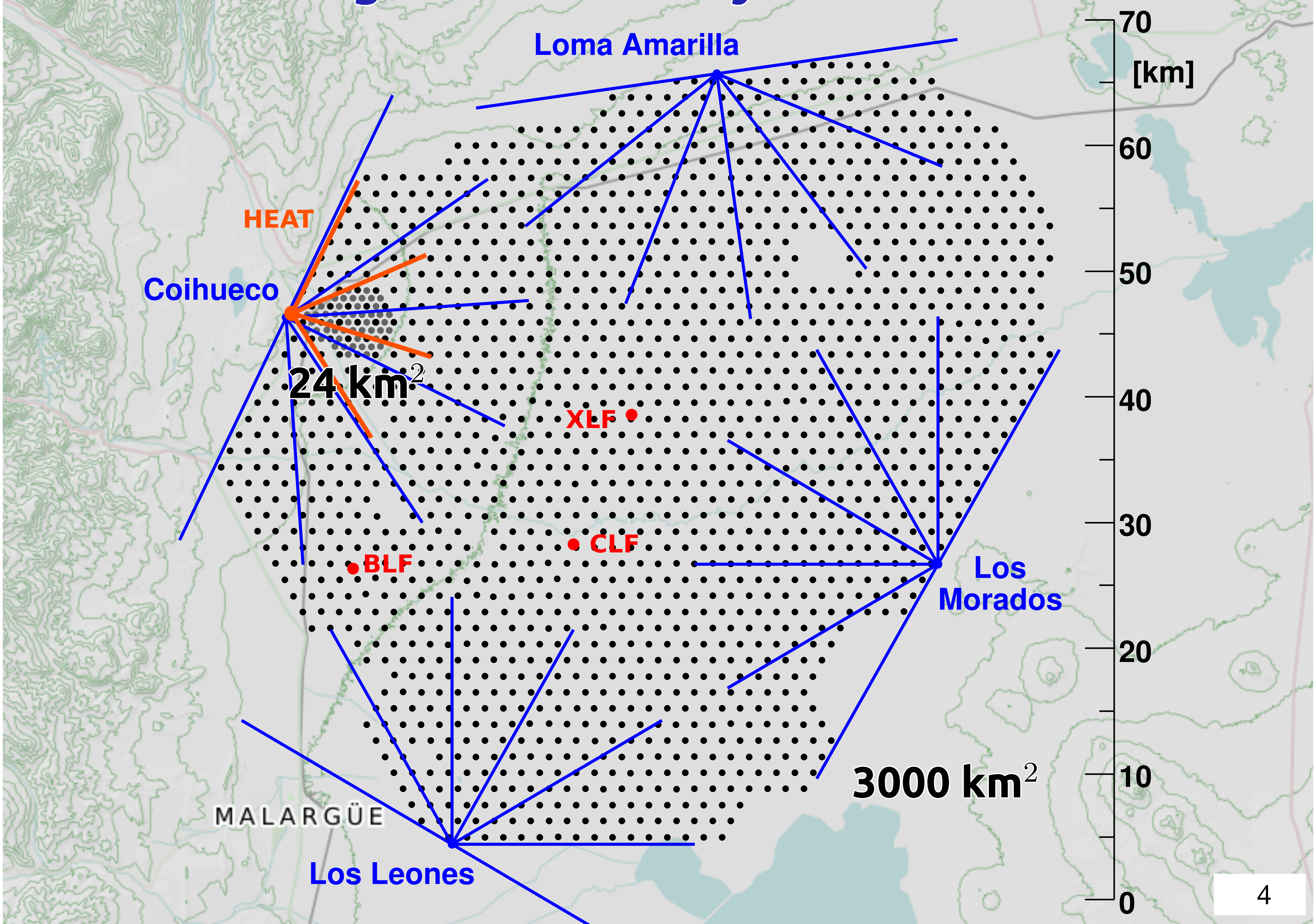




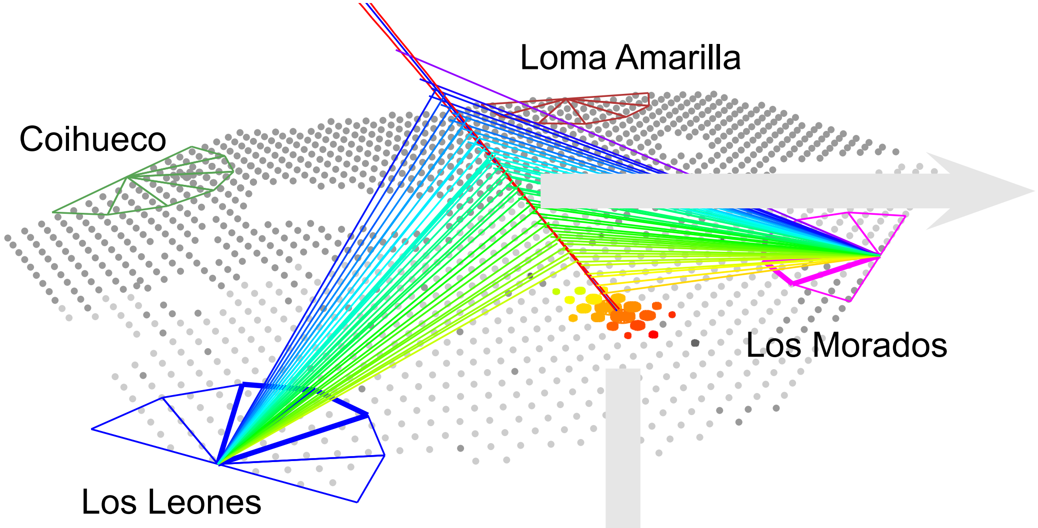
The Pierre Auger Observatory

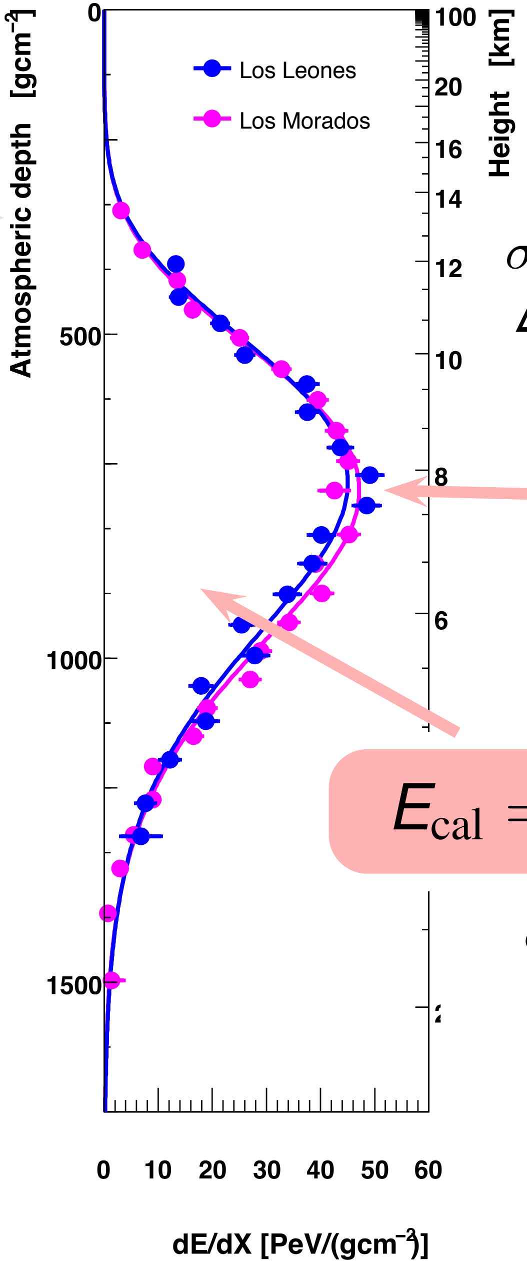


The Pierre Auger Observatory



Auger is a Hybrid detector - FD calibrates SD energy scale



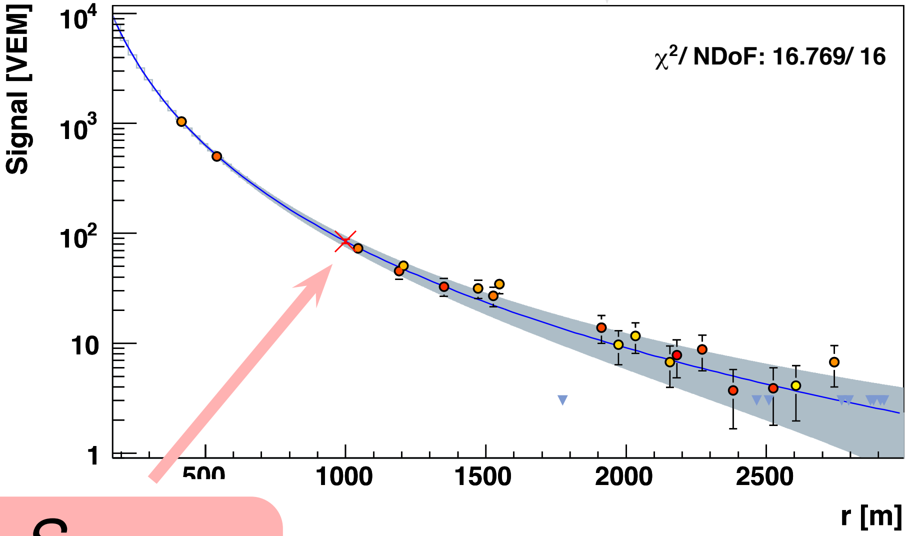


$$\sigma_{X_{\max}} \leq 20\,\mathrm{g/cm^2}$$
$$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$$

$X_{\max}$

$$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$$

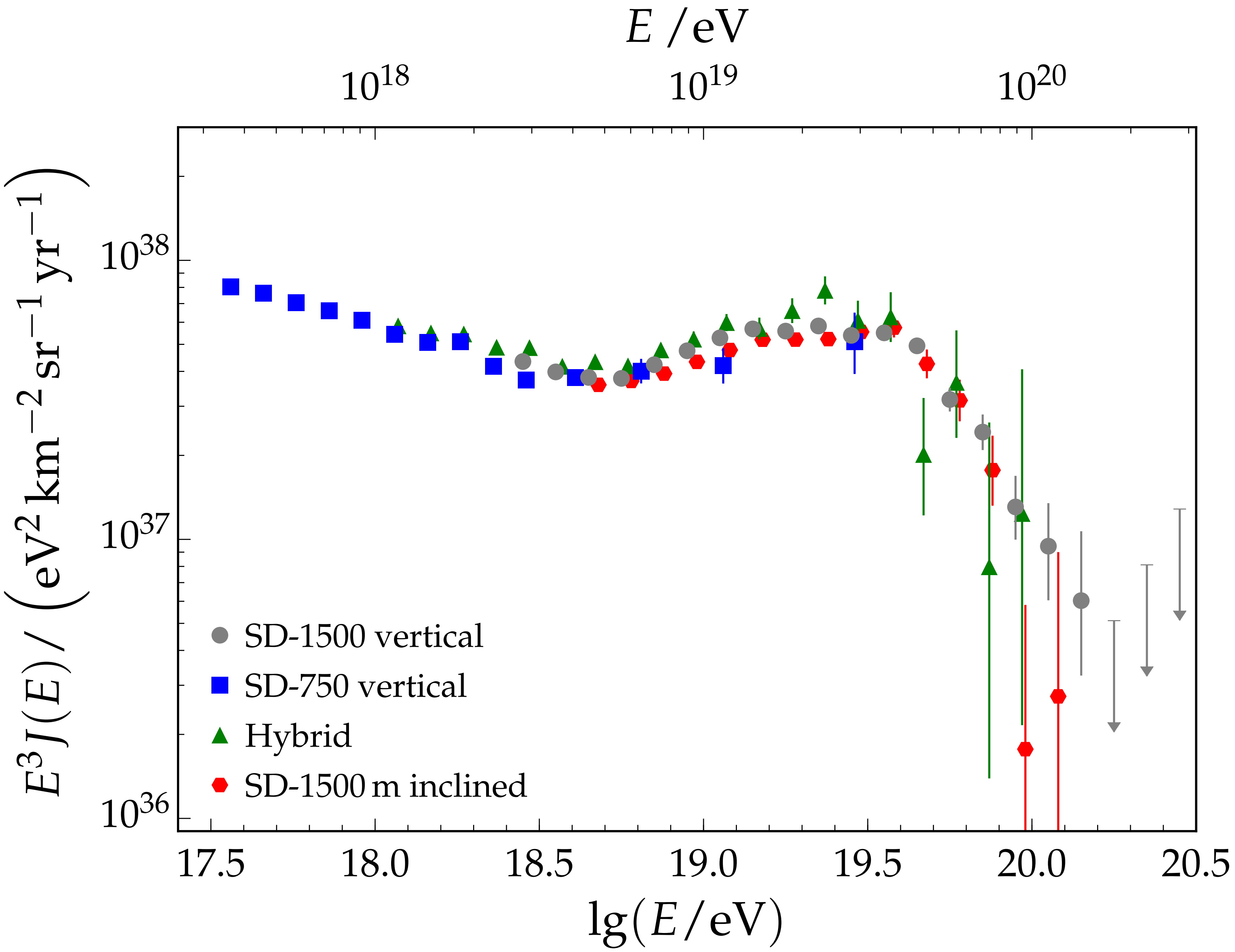
$$\sigma_E/E \sim 8\,\%$$
$$\Delta_{\mathrm{sys}} \approx 15\,\%$$



S_{1000}

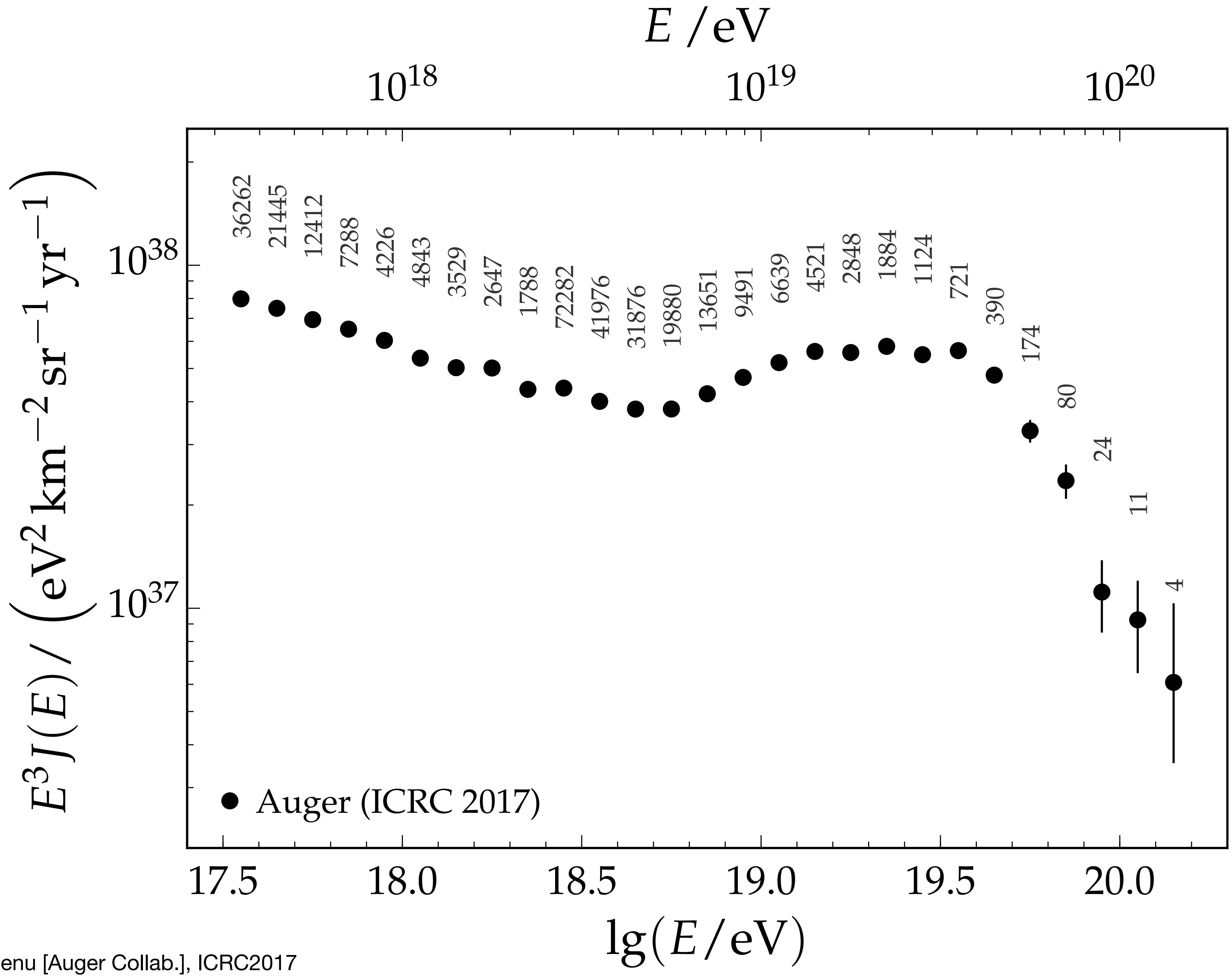
$$E_{\mathrm{surface}} = f(S_{1000},\,\theta)$$

Energy Spectrum



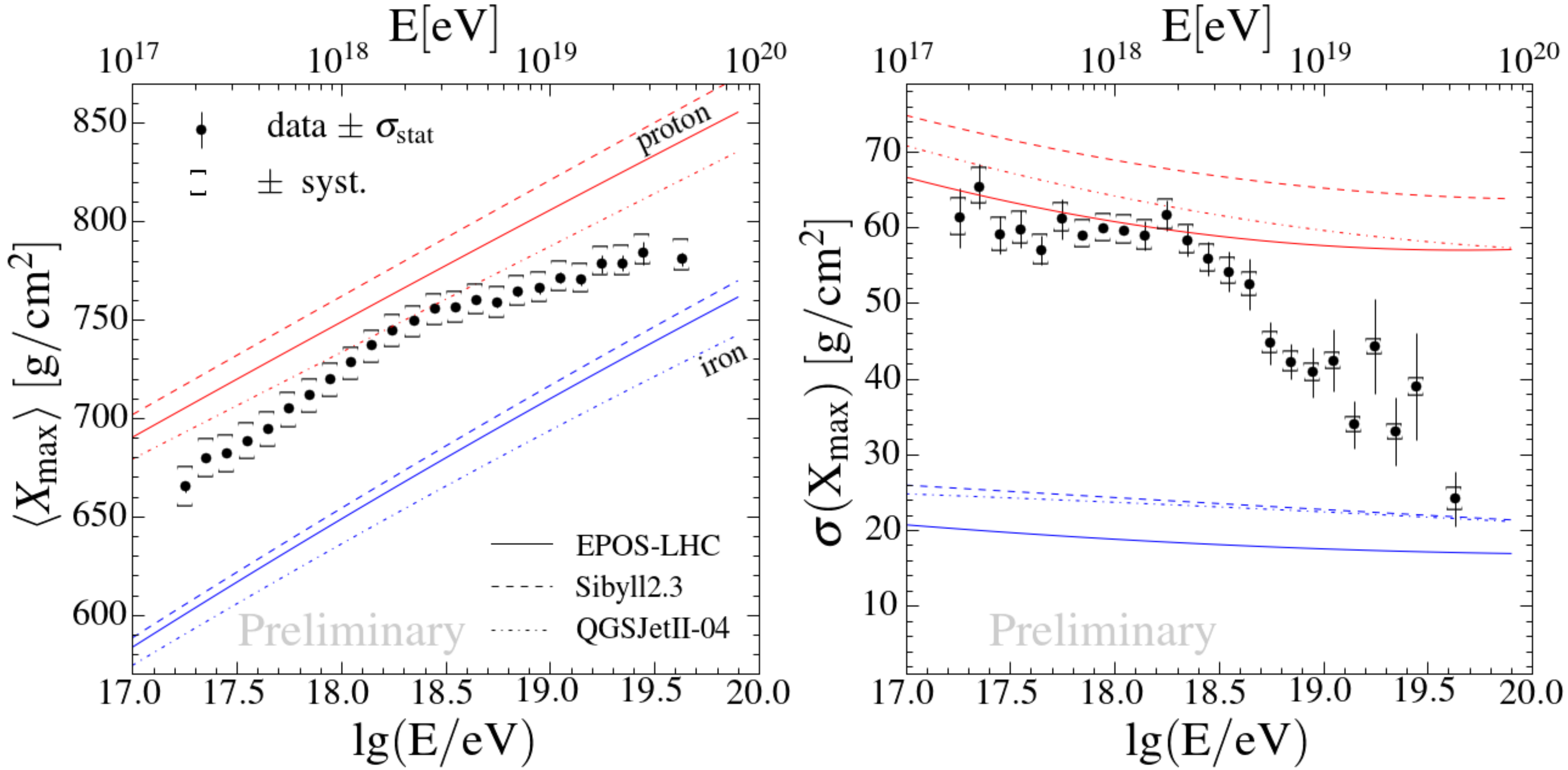
F. Fenu [Auger Collab.], ICRC2017

Combined Energy Spectrum



F. Fenu [Auger Collab.], ICRC2017

Mean X_{max} and fluctuations in X_{max}

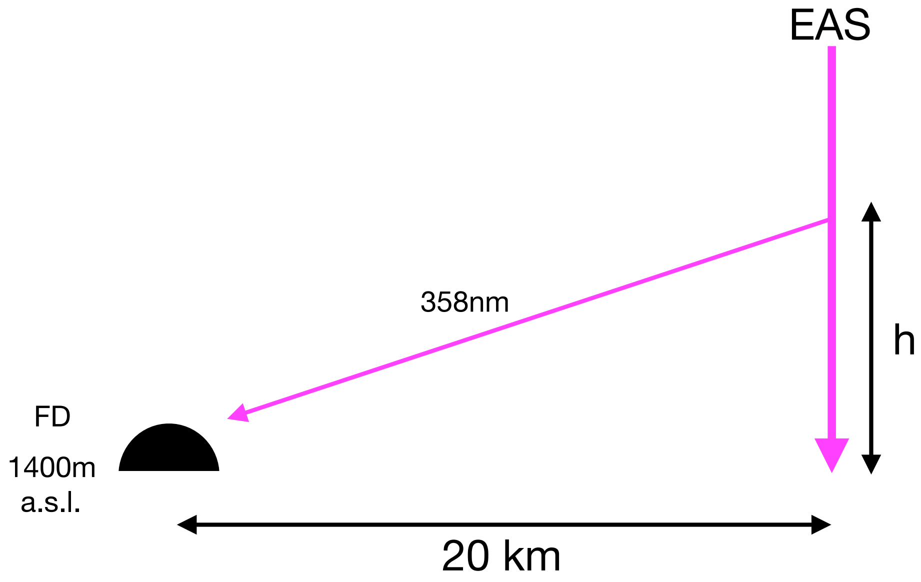


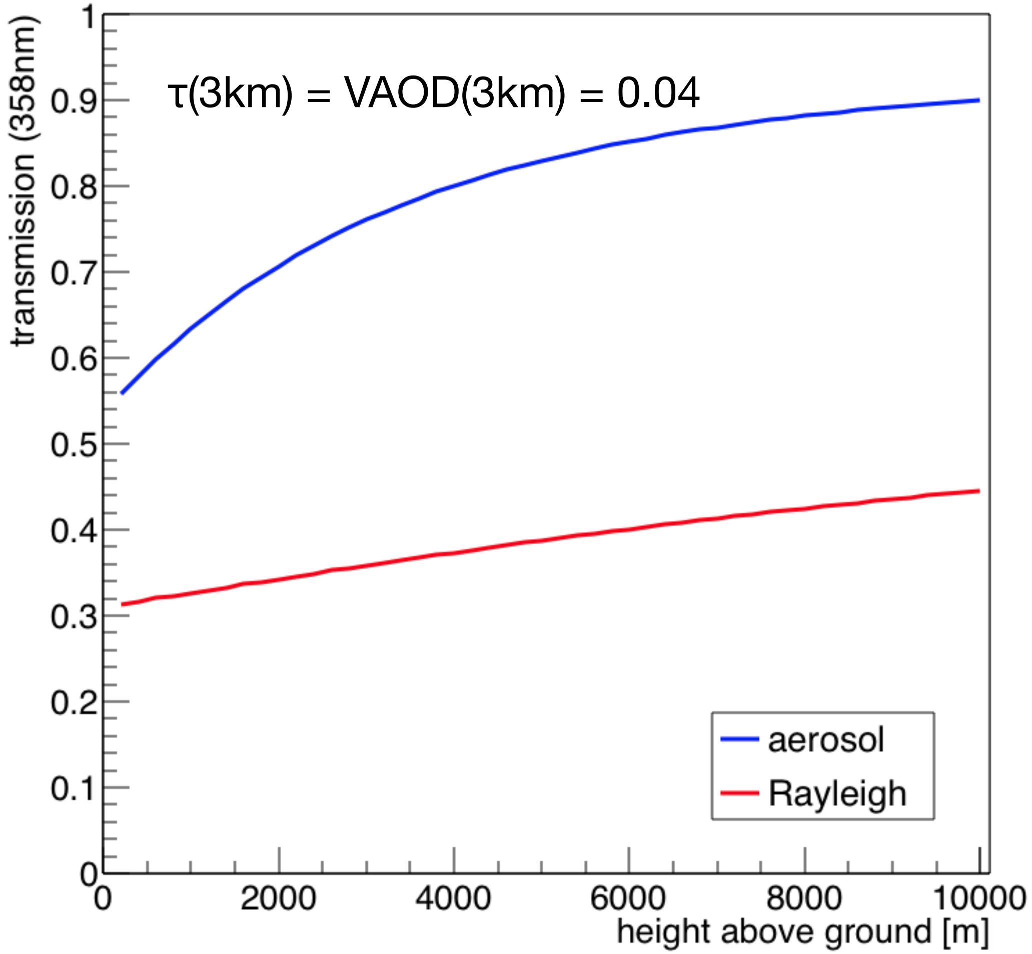
Coloured lines: post-LHC hadronic models

J. Bellido [Auger Collab.], ICRC2017

Aerosols

- Shower light transmission to the FD (sensitivity <u>300-400nm</u>):
  - no major *absorption* (though we account for O_3)
  - scattering (Rayleigh and aerosol) determines transmission

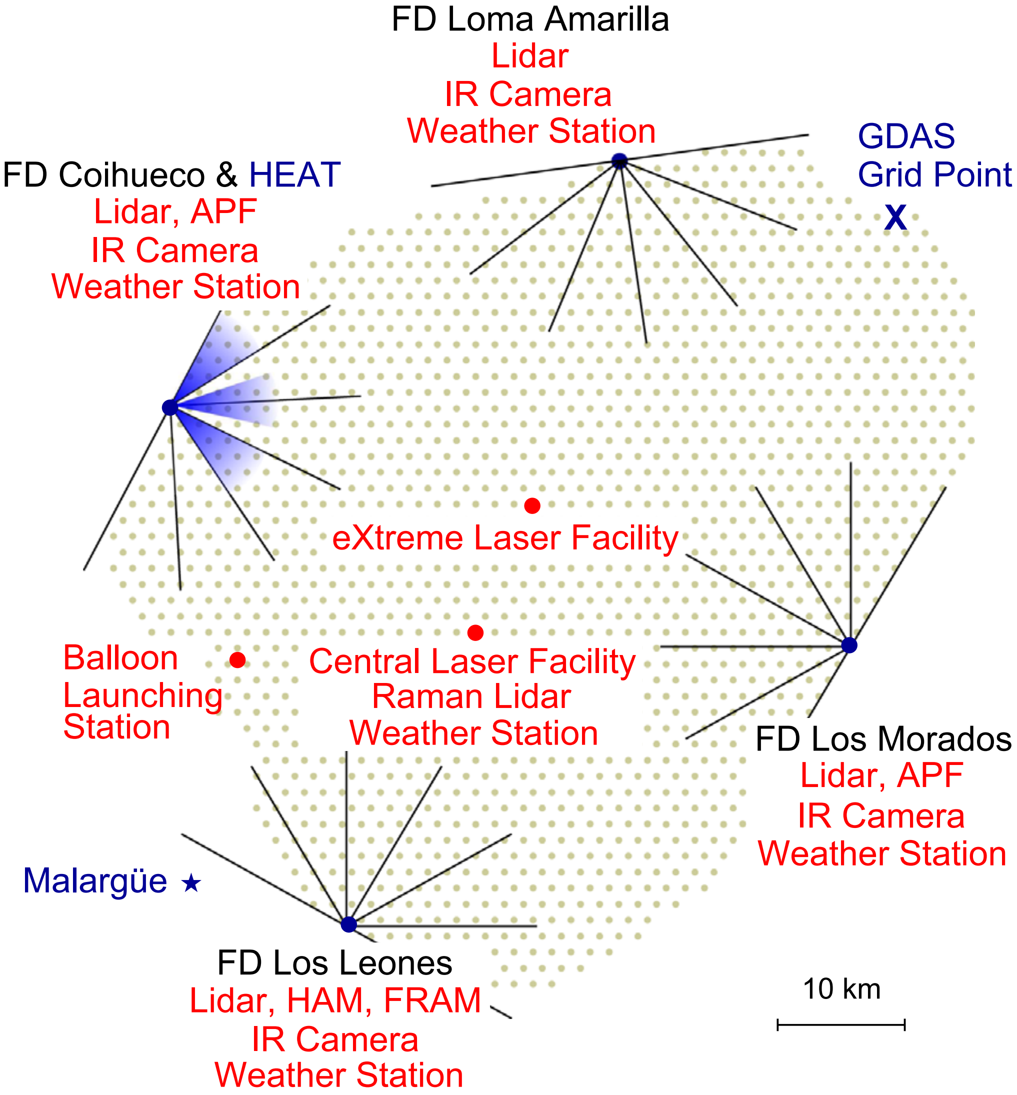




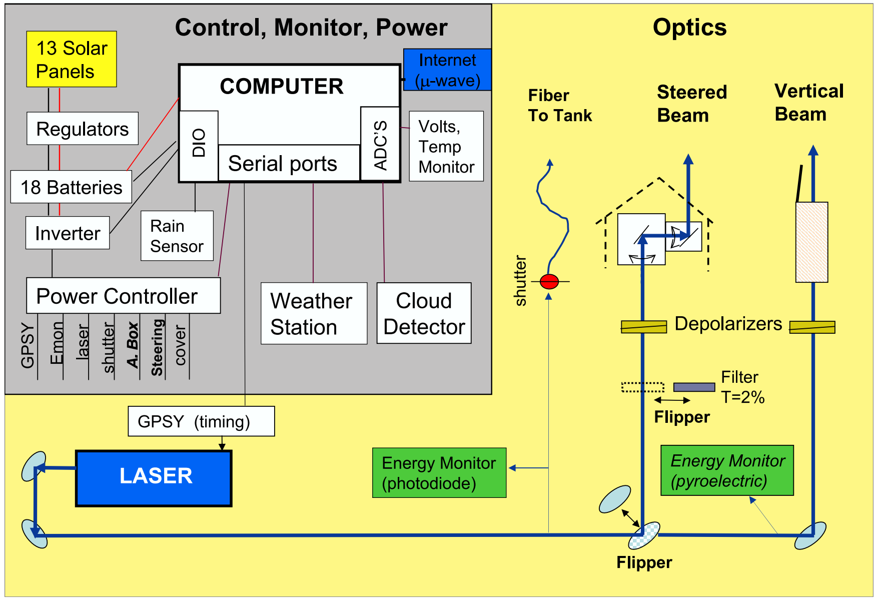
Measuring Aerosols

See talks at this meeting about these instruments and analysis!

B. Keilhauer, L. Valore, V. Rizi, J. Ebr, P. Janecek



Central Laser Facility (CLF)



Laser: 355nm, 6.5 mJ per pulse to sky

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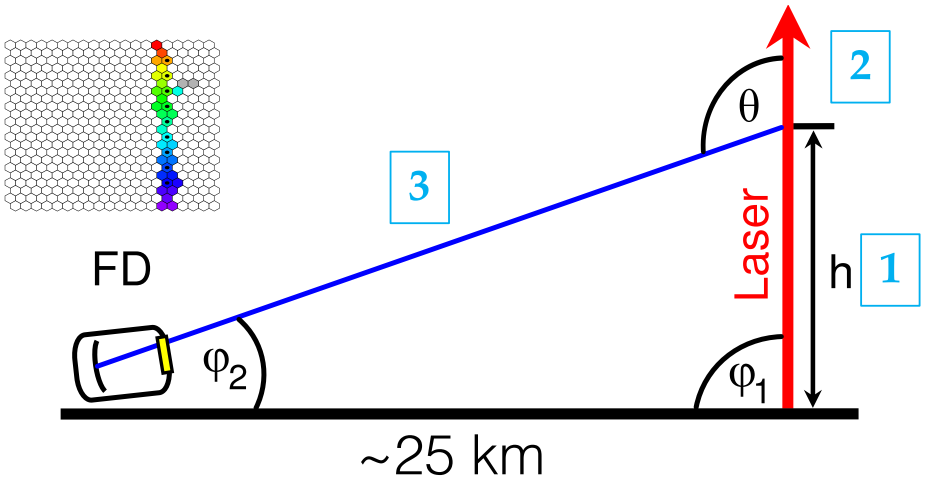
Measuring Aerosols   Data normalised (DN) method

Our standard method: bi-static lidar

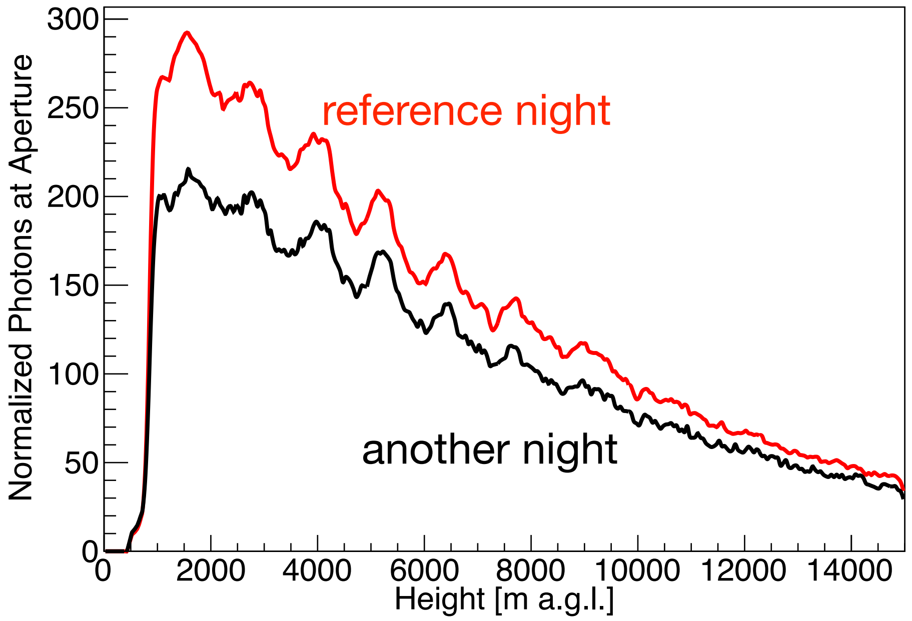
(currently cross-checked with Raman lidar, FRAM…)

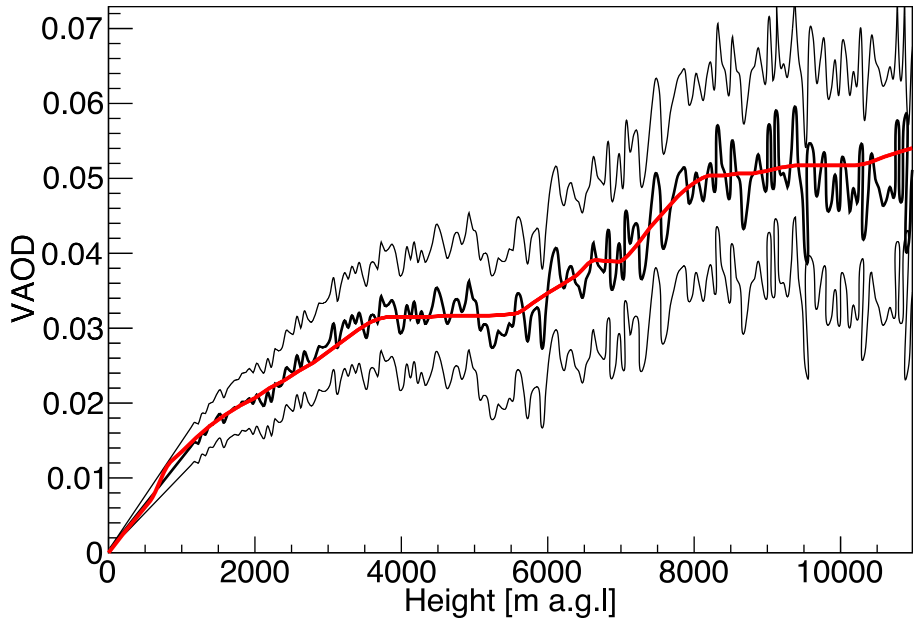


$$\mathrm{VAOD}(h) = \frac{-1}{1+1/\sin\phi_2}\ln\left(\frac{N_\mathrm{aer}}{N_\mathrm{ref}}\right)$$

Measured light flux relative to that on a nominally aerosol free **reference night**

Note: VAOD often denoted by τ





M. Malacari [Auger Collab.], ICRC2017

Measuring Aerosols - example light profiles

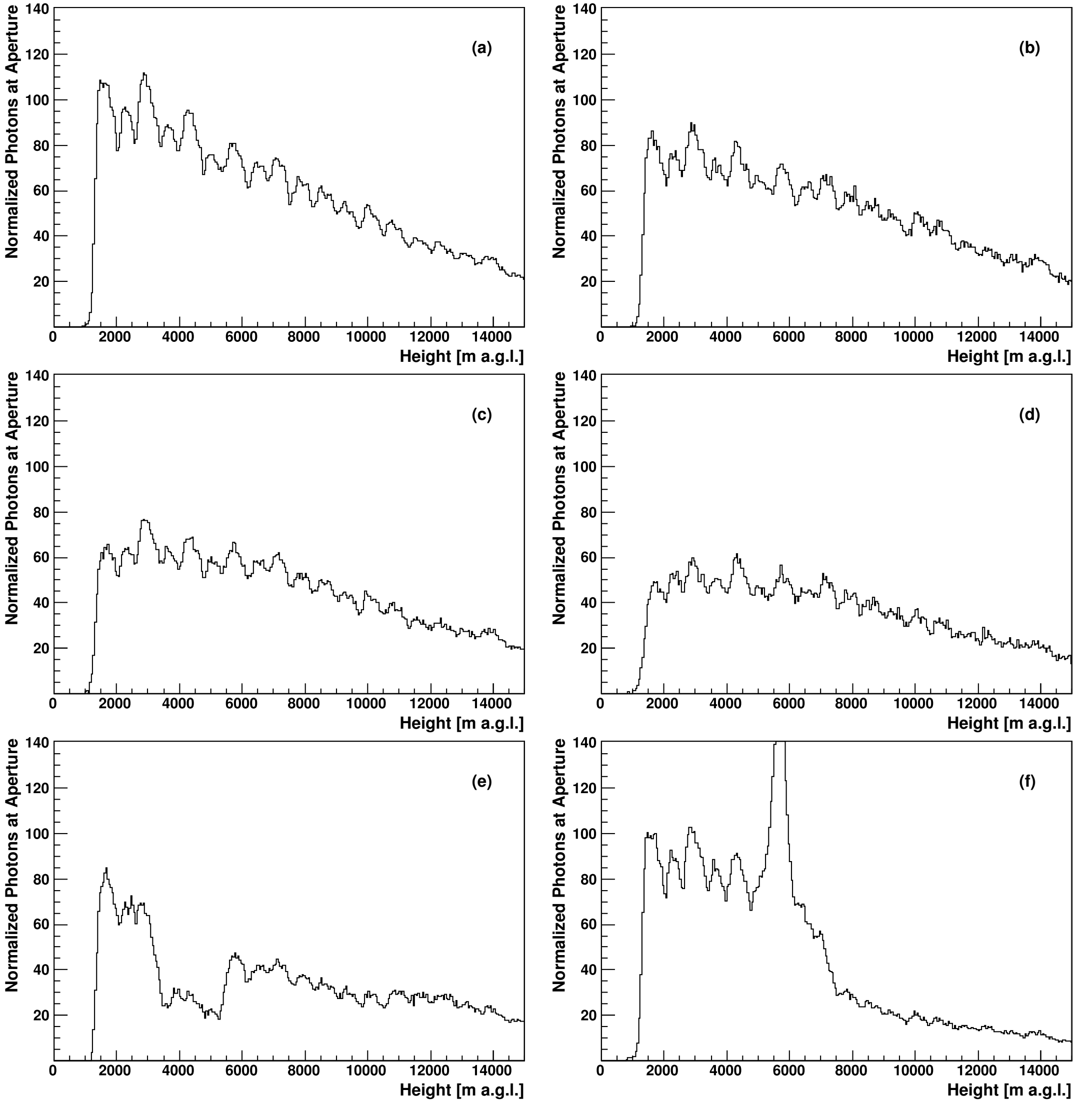
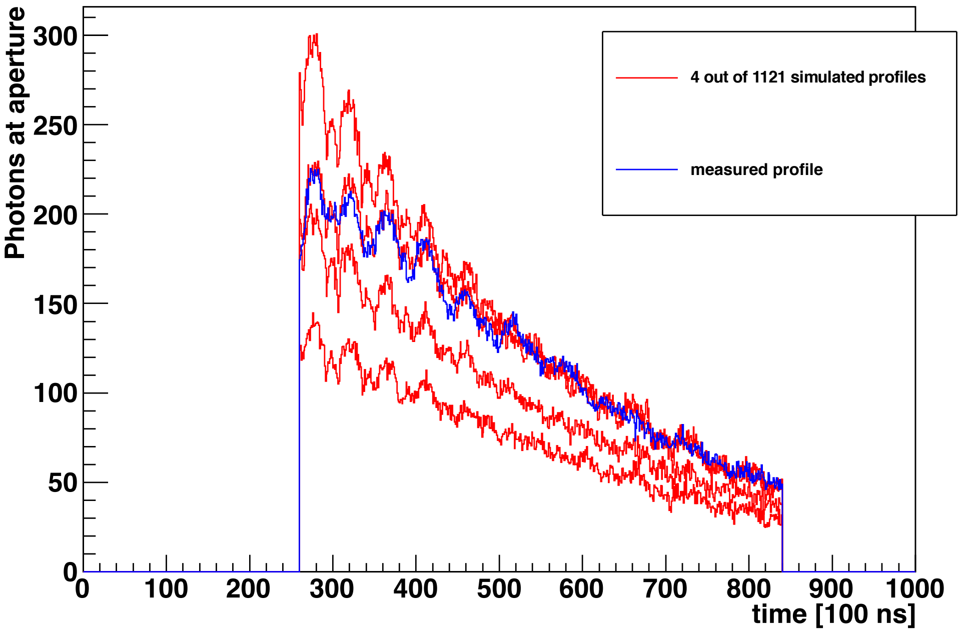
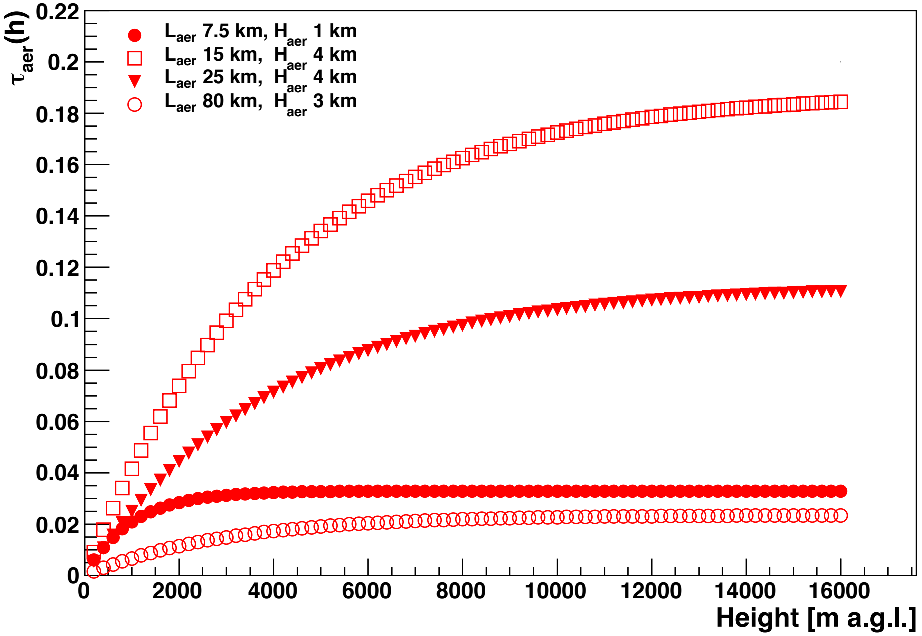


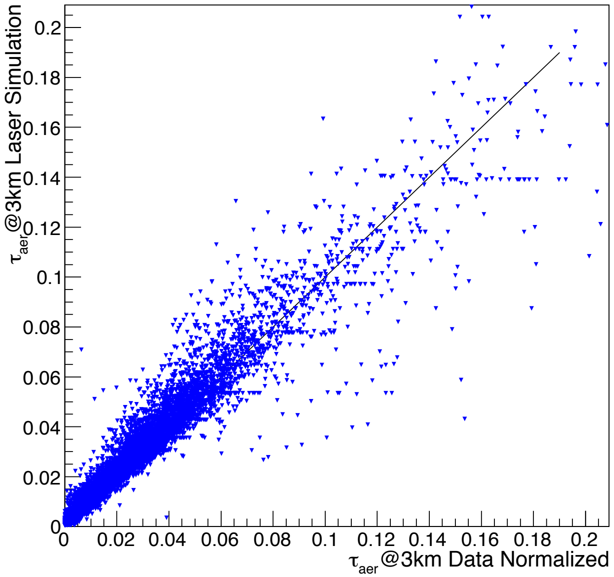
Figure 8: Examples of light profiles measured with the FD at Coihueco under various atmospheric conditions. The height is given above the FD. The number of photons at the aperture of the FD is normalized per mJ of laser energy. Shown are a reference clear night (a); low (b), average (c) and high aerosol attenuation (d); cloud between FD and laser (e); laser beam passing through cloud (f).

Pierre Auger Collaboration, JINST 8, P04009 (2013)

Measuring Aerosols Laser Simulation (LS) method







Pierre Auger Collaboration, JINST 8, P04009 (2013)

Measuring Aerosols scattering angular distributions

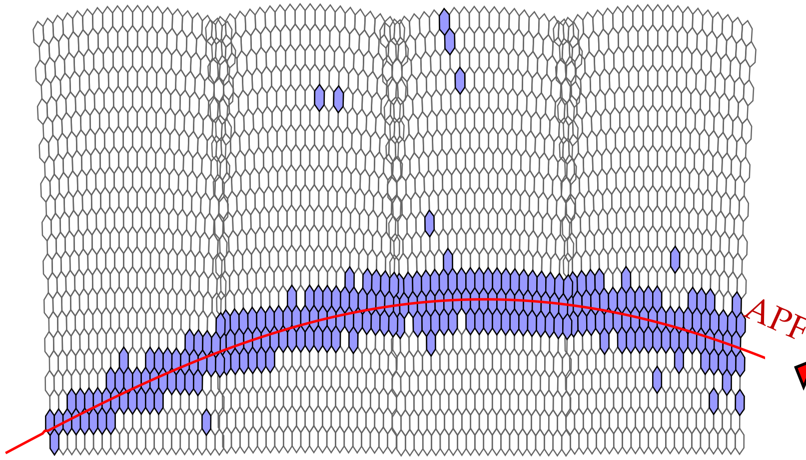
Modified
Henyey-Greenstein phase function

For aerosols:

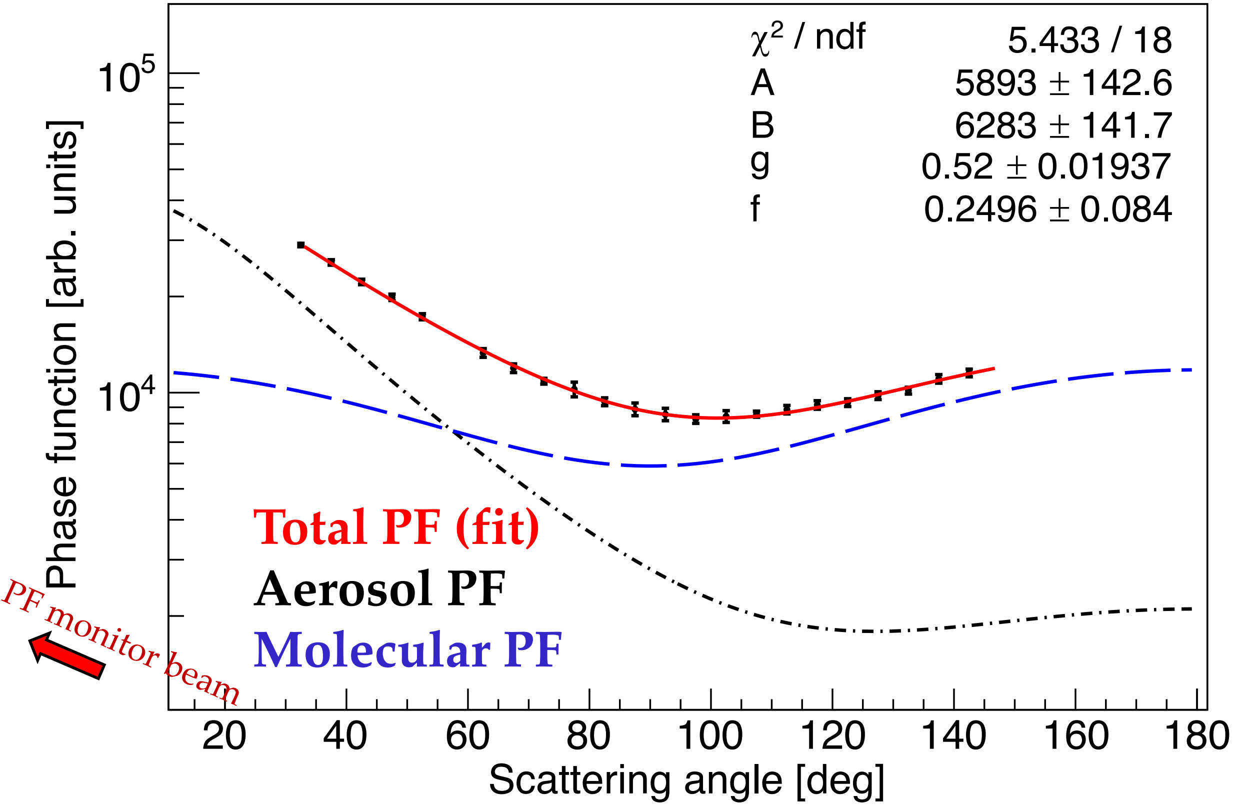
$$\left(\frac{1}{\sigma}\frac{d\sigma}{d\Omega}\right)_{\mathrm{A}} = \frac{1-g^2}{4\pi}\left(\frac{1}{(1+g^2-2g\cos\theta)^{3/2}} + f\,\frac{3\cos^2\theta-1}{2(1+g^2)^{3/2}}\right)$$

g **– asymmetry parameter**

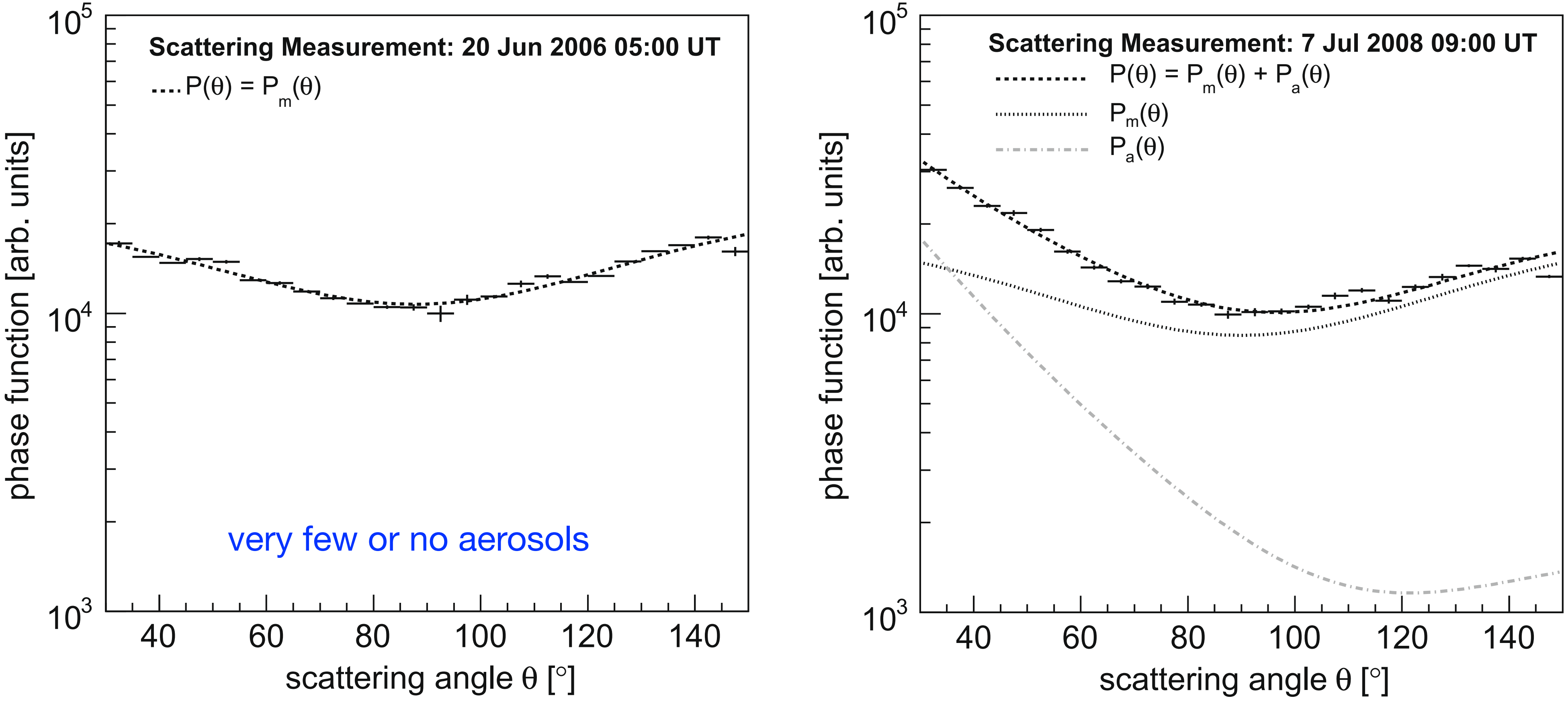
f **– backscattering parameter**



[S.Y. BenZvi et al., Astropart. Phys. 28 (2007) 312-320]

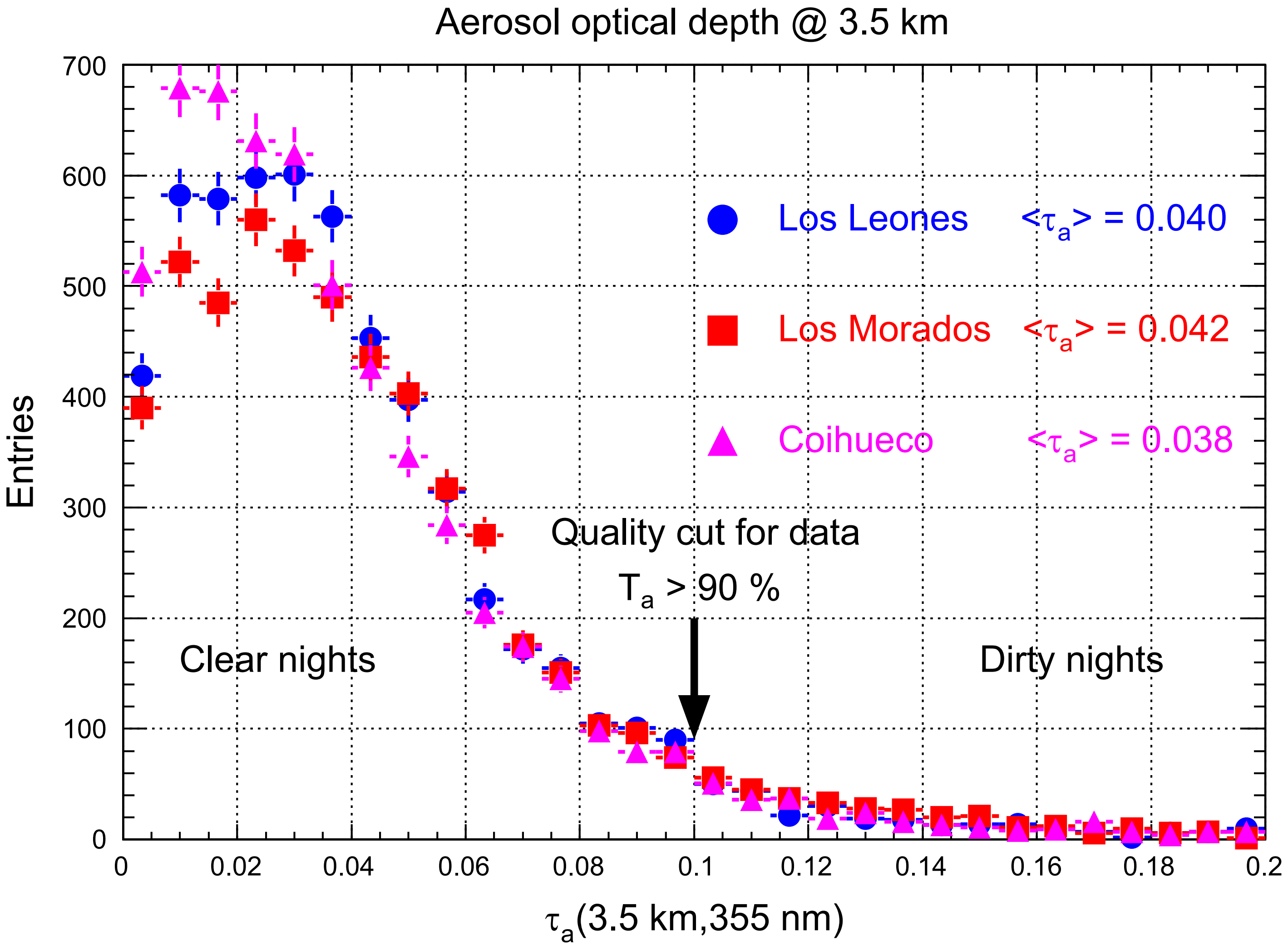


Measuring Aerosols scattering angular distributions



M. Malacari [Auger Collab.], ICRC2017

Characteristics of Aerosols at Auger - VAOD(3.5km)



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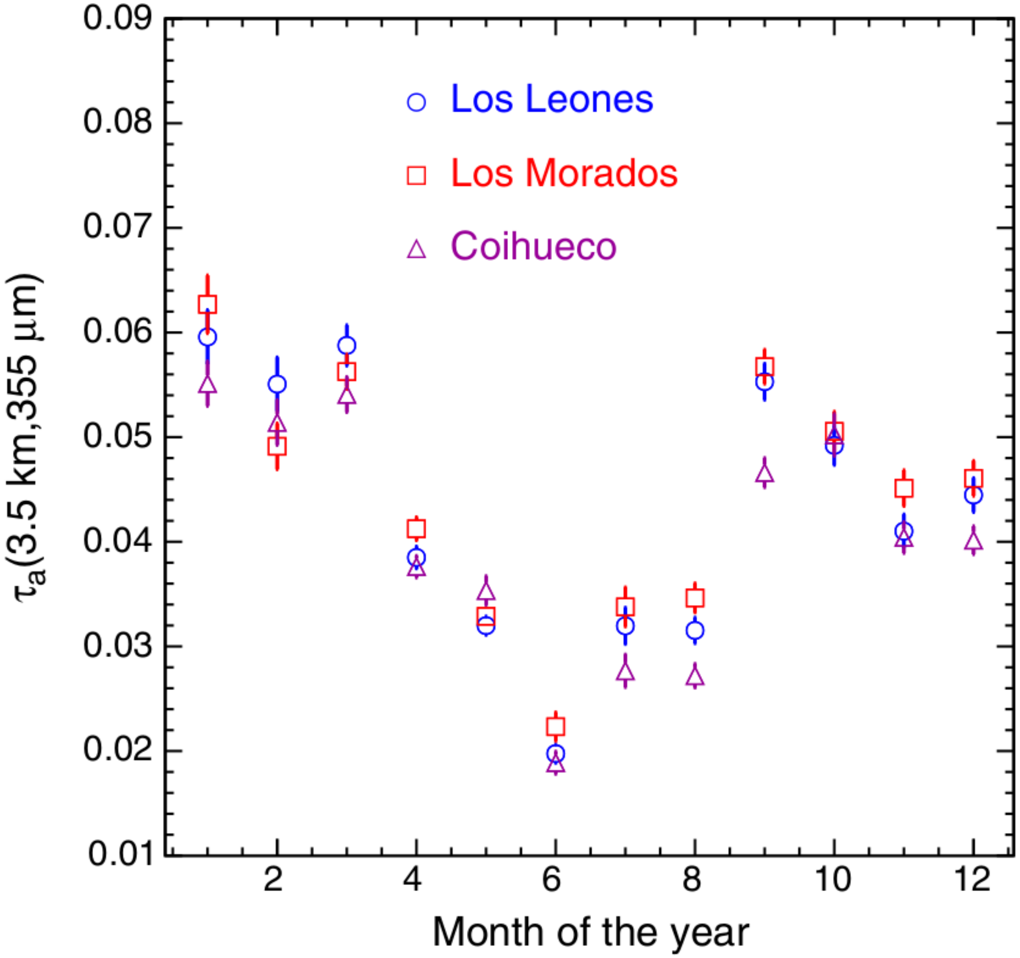
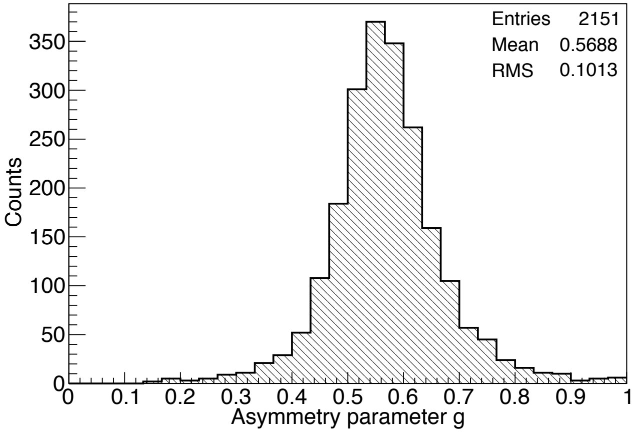
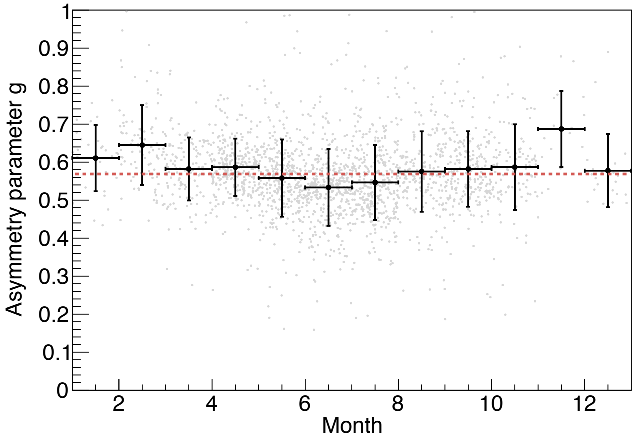
Characteristics of Aerosols at Auger - seasonal dep.



[The Pierre Auger Collaboration, Atmos. Res. 149 (2014) 120-135]

Characteristics of Aerosols at Auger - phase function

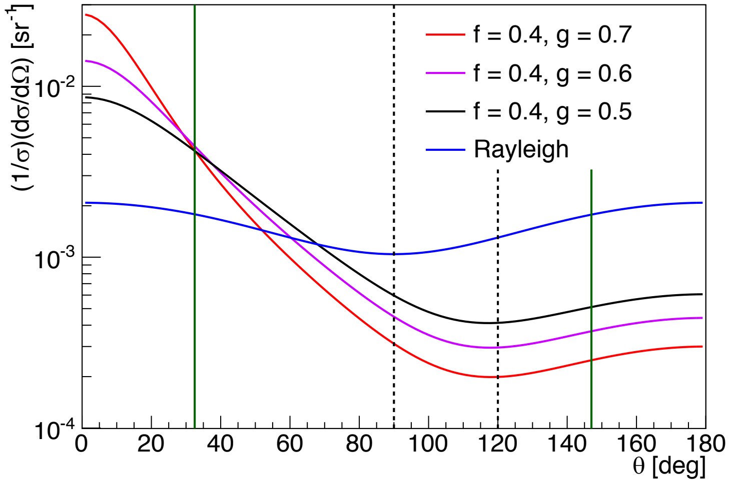




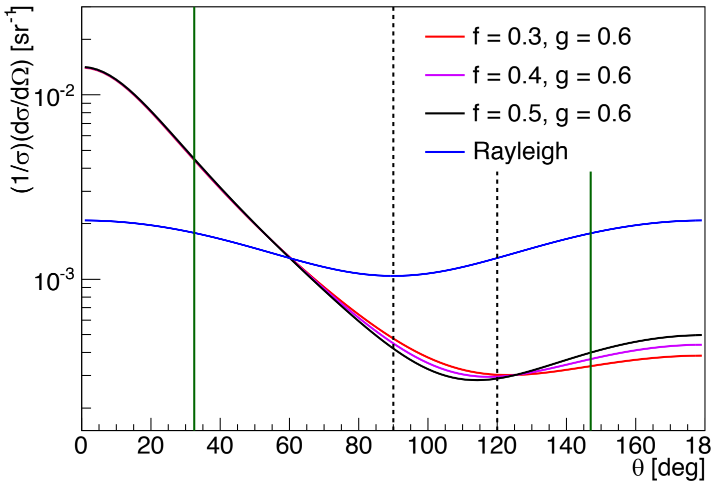
5-year dataset

$$\left(\frac{1}{\sigma}\frac{d\sigma}{d\Omega}\right)_{\mathrm{A}} = \frac{1-g^2}{4\pi}\left(\frac{1}{(1+g^2-2g\cos\theta)^{3/2}} + f\,\frac{3\cos^2\theta-1}{2(1+g^2)^{3/2}}\right)$$

Varying the asymmetry parameter (g)



Varying the backscattering parameter (f)



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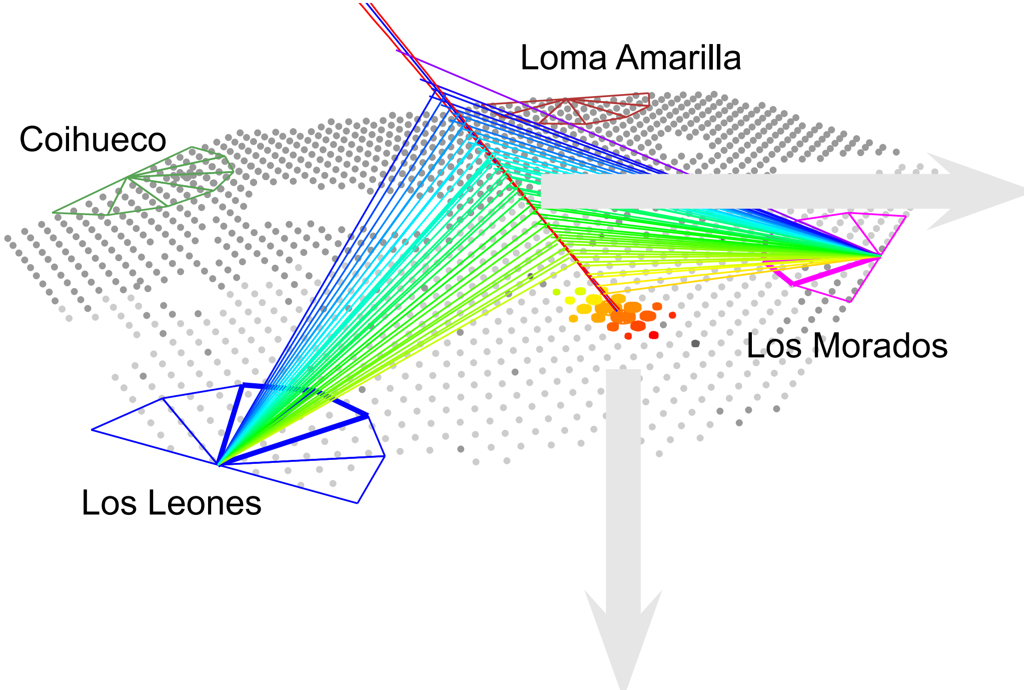
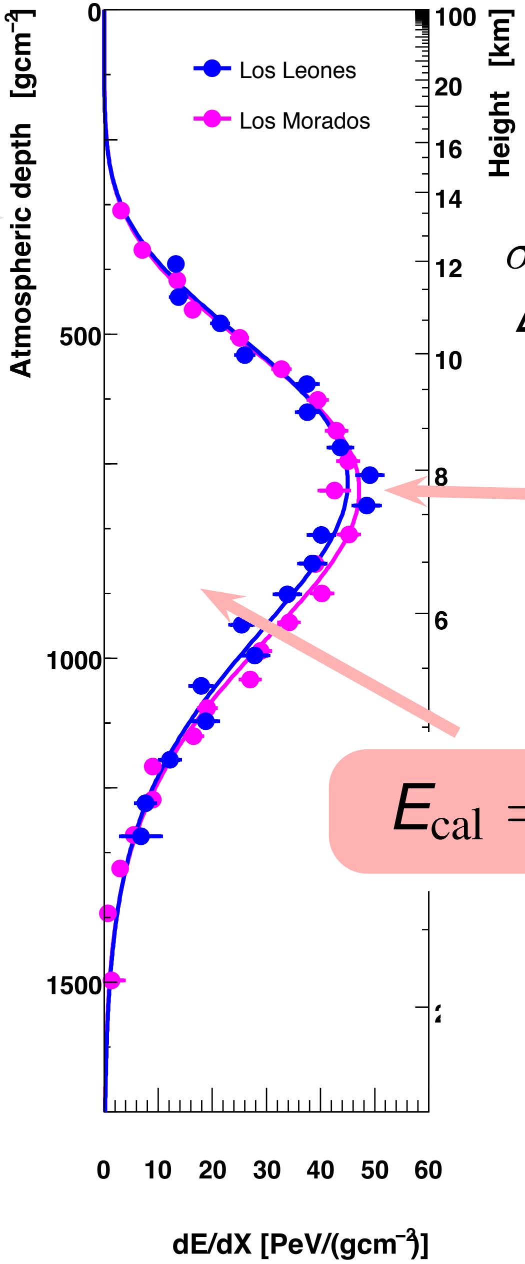
Reconstructing the energy and Xmax of an air shower



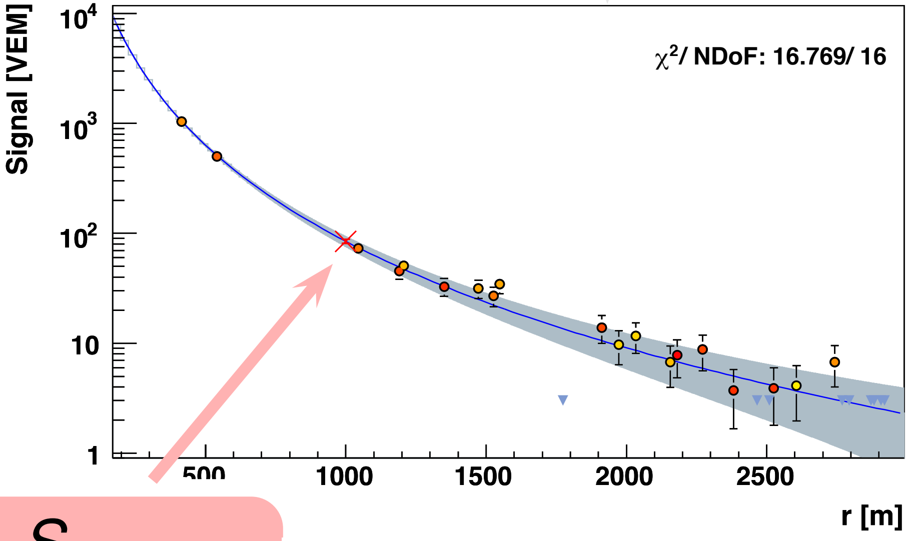


$\sigma_{X_{\mathrm{max}}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

X_{max}

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

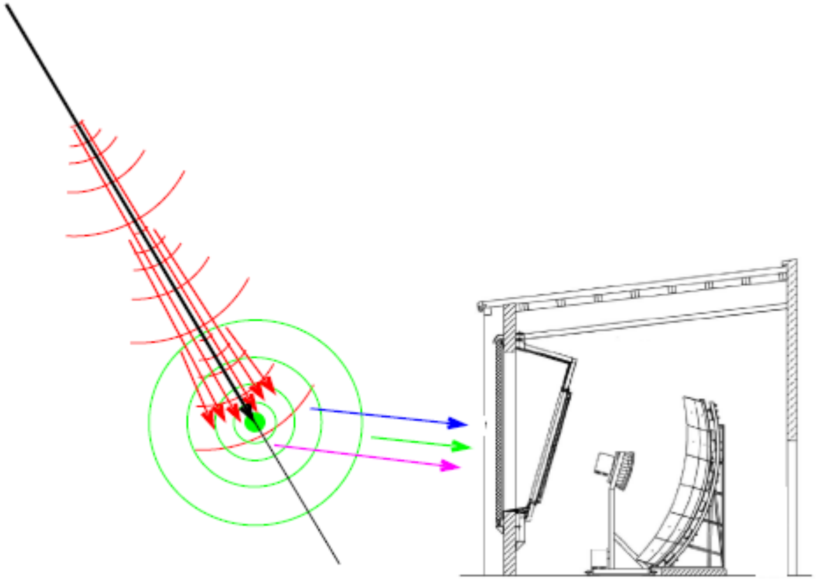


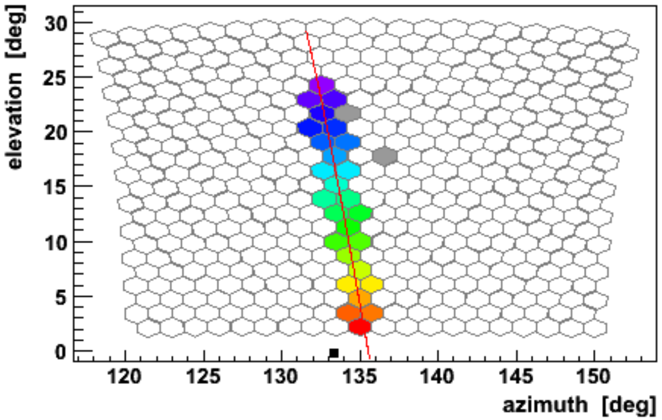
S_{1000}

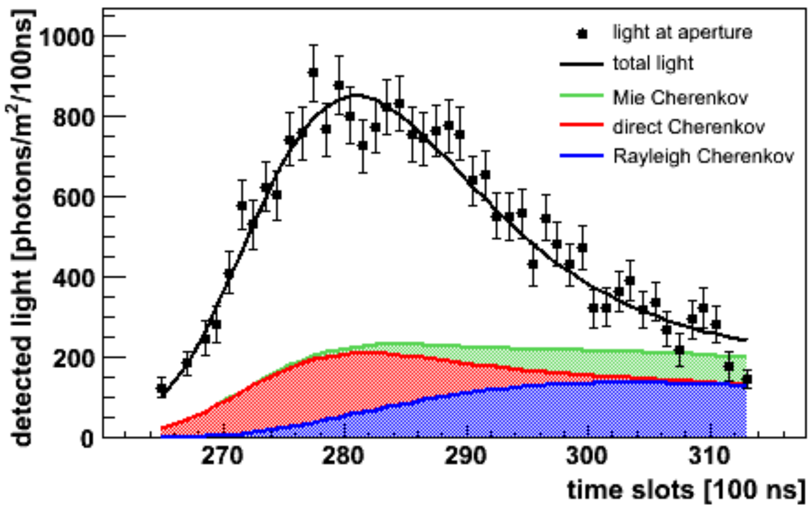
$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$

Reconstructing the energy and Xmax of an air shower

- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light







Unger, Dawson, Engel, Schuessler & Ulrich NIM A588 (2008) 443

Reconstructing the energy and Xmax of an air shower

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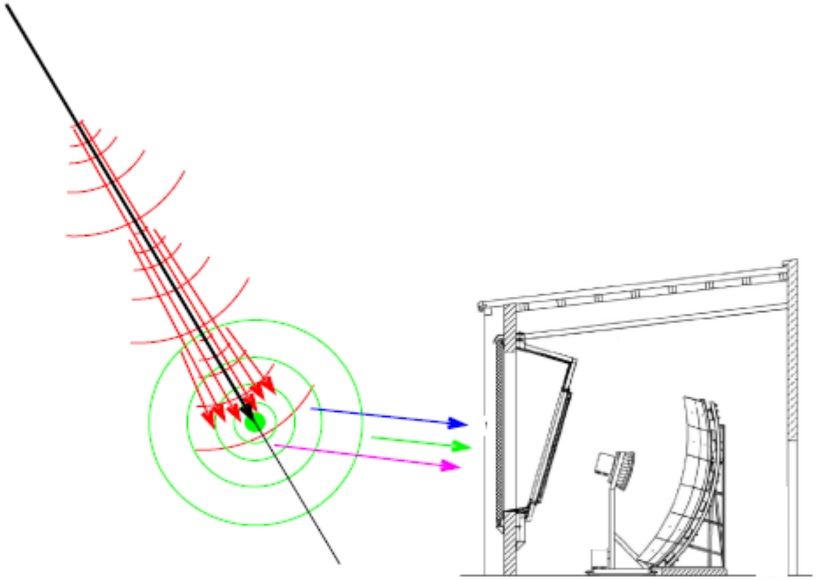

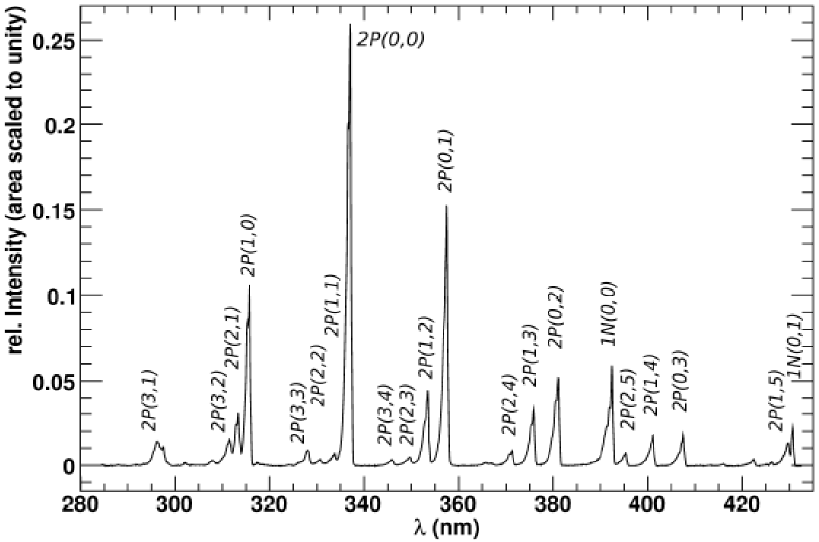

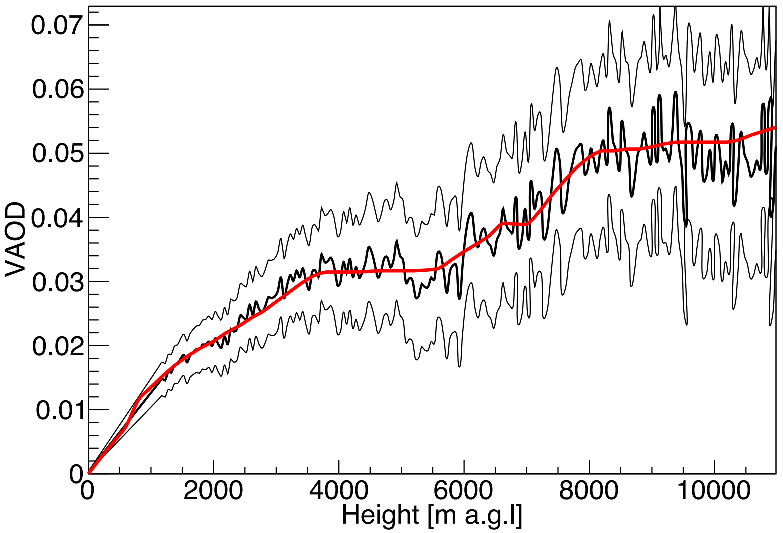

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Reconstructing the energy and Xmax of an air shower

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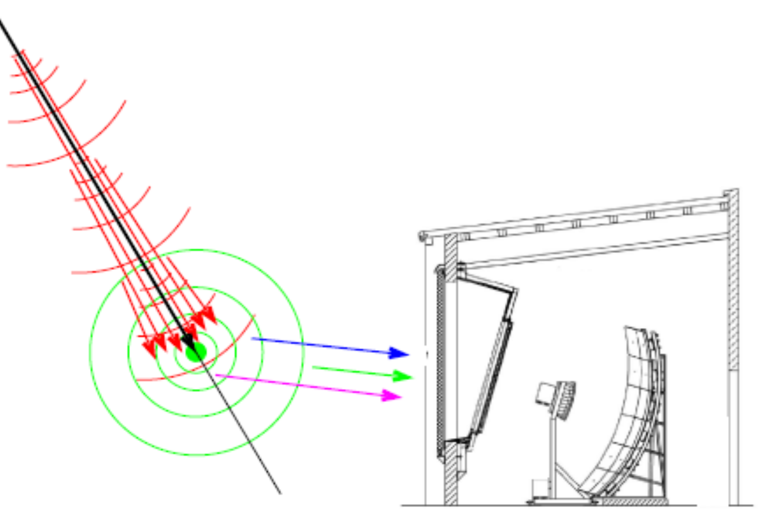
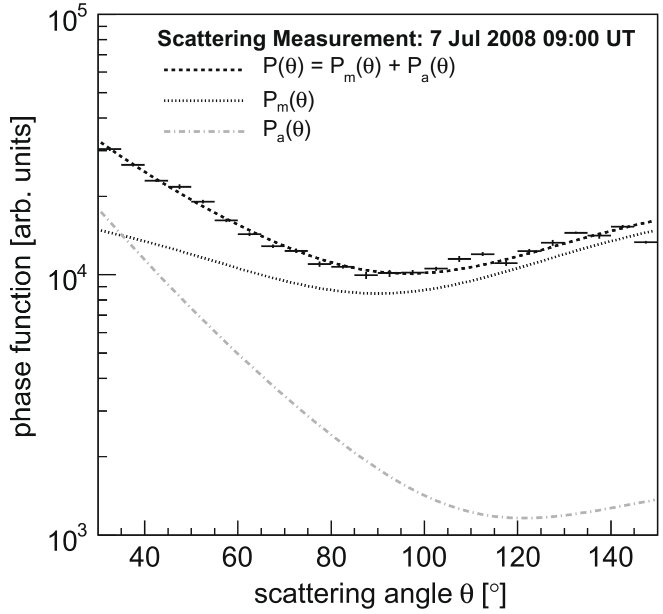
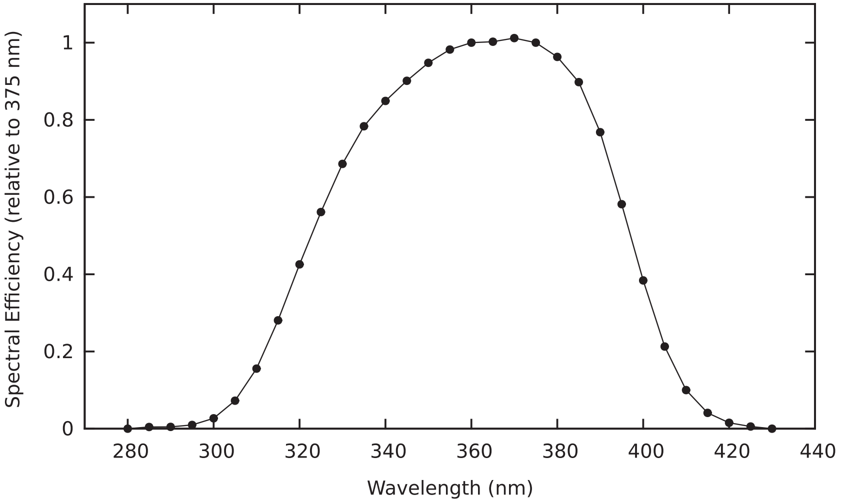






Unger, Dawson, Engel, Schuessler & Ulrich NIM A588 (2008) 443

Cherenkov light is also signal

- reconstruct $w = dE/dX$ profile by matrix method

Production at the shower

$$N_\gamma^{\mathrm{f}}(X_i) = Y_i^{\mathrm{f}} w_i \Delta X_i.$$

$$N_\gamma^{\mathrm{C}}(X_i) = Y_i^{\mathrm{C}} N_i^{\mathrm{e}} \Delta X_i$$

$$w_i = N_i^{\mathrm{e}} \int_0^\infty f_{\mathrm{e}}(E, X_i) w_{\mathrm{e}}(E)\, \mathrm{d}E$$

$$= dE/dX(X_i)$$

Light at the FD

$$y_i^{\mathrm{f}} = d_i Y_i^{\mathrm{f}} w_i \Delta X_i$$

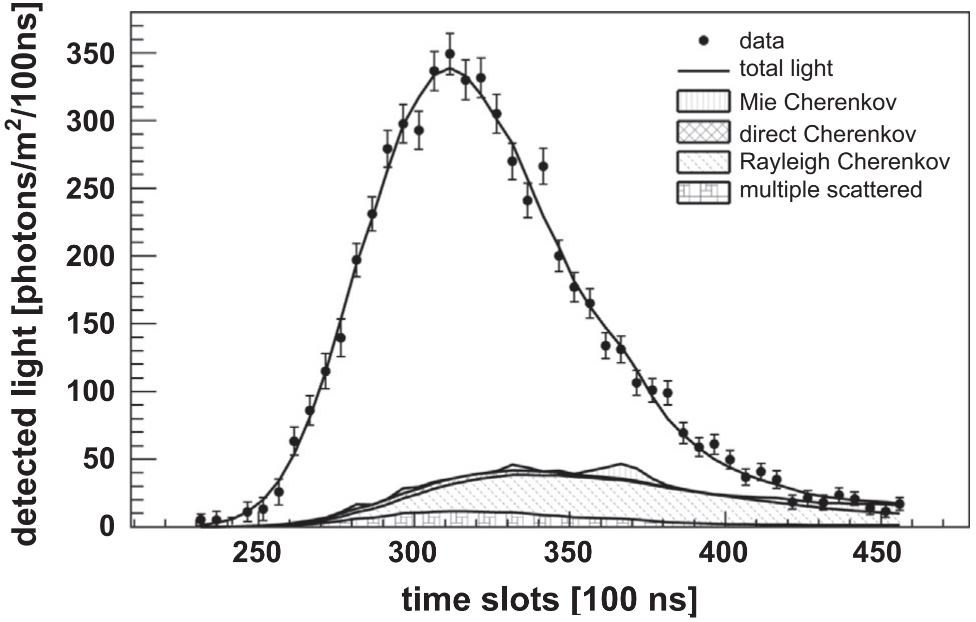
$$y_i^{\mathrm{Cd}} = d_i f_{\mathrm{C}}(\beta_i) Y_i^{\mathrm{C}} \Delta X_i N_i^{\mathrm{e}}.$$

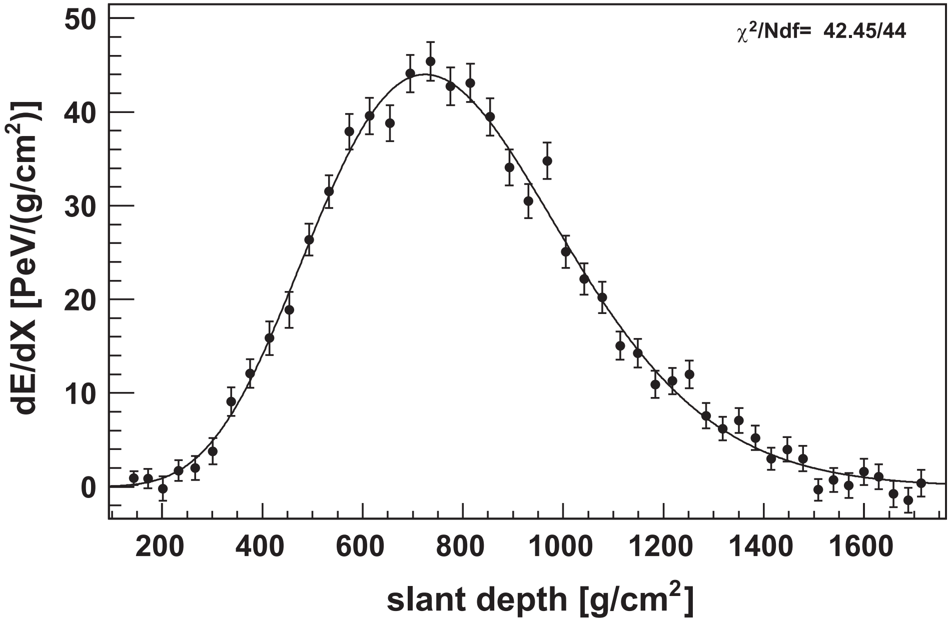
$$y_i^{\mathrm{Cs}} = d_i f_{\mathrm{s}}(\beta_i) \sum_{j=0}^{i} \mathscr{T}_{ji} Y_j^{\mathrm{C}} \Delta X_j N_j^{\mathrm{e}}.$$

$$y_i = y_i^{\mathrm{f}} + y_i^{\mathrm{Cd}} + y_i^{\mathrm{Cs}}.$$

Matrix inversion

$$\widehat{\mathbf{w}} = \mathbf{C}^{-1}\mathbf{y}$$





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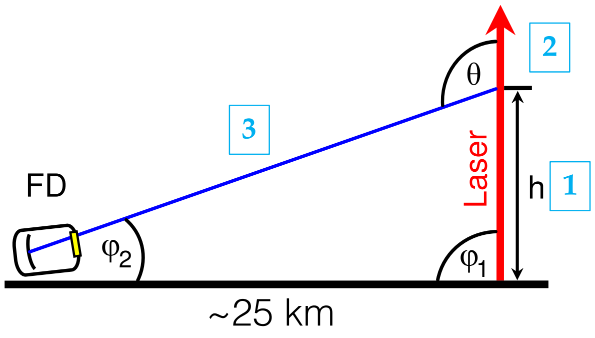
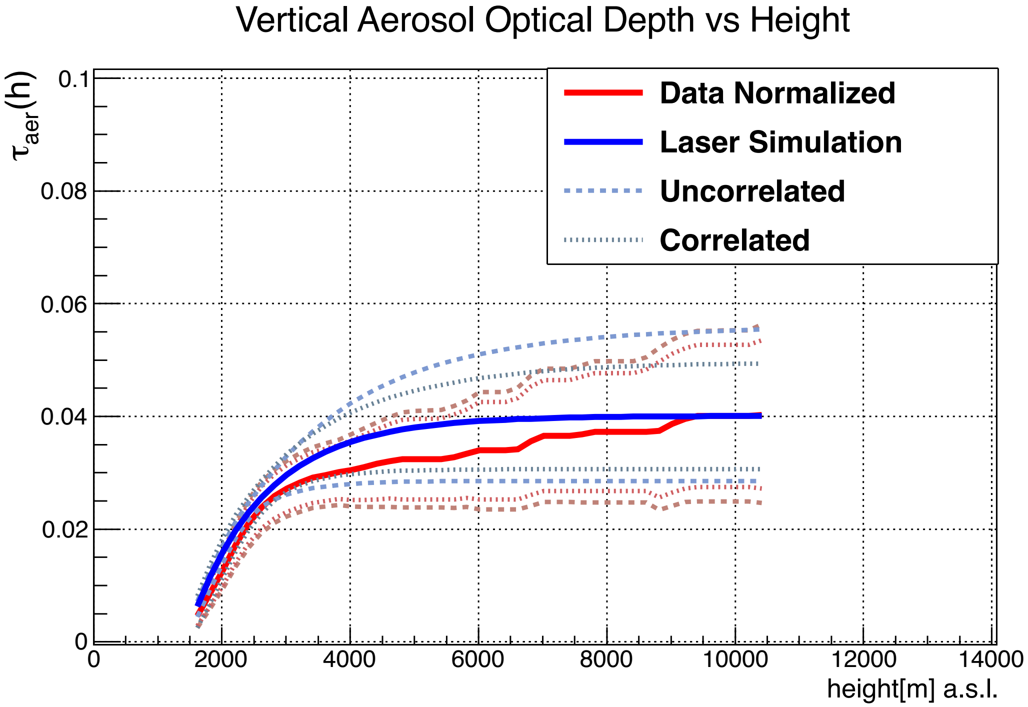
Uncertainties in aerosol measurements



Example from a typical hour



Correlated errors: are correlated across a period of time

e.g. due to drift in *relative calibration* of FD or laser since the reference night

Uncorrelated errors: change from hour to hour

e.g. statistical error on light profiles, and variation within a given hour

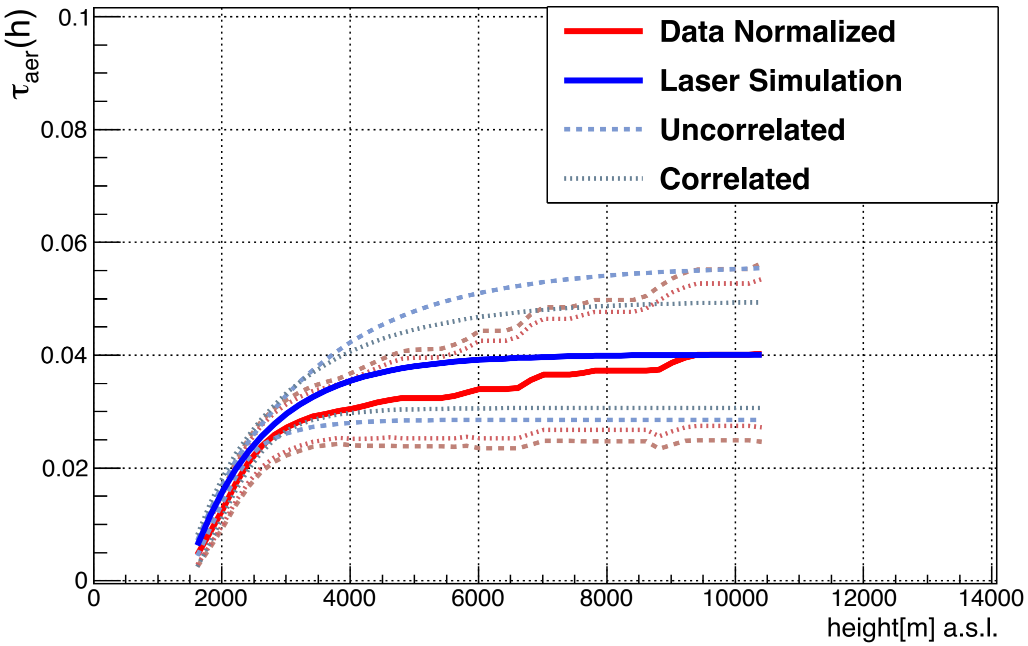
Uncertainties in aerosol measurements

	Correlated	Uncorrelated
Relative FD calibration	2%	4%
Relative laser energy (CLF)	1 – 2.5%	2%
Relative laser energy (XLF)	1%	2%
Reference clean night	3%	-
Atmospheric variations	-	~ 3%

Table 1. Errors relevant to the calculation of VAOD from CLF/XLF laser profiles at the FD. See text and [14] for details.

Example from a typical hour

Vertical Aerosol Optical Depth vs Height



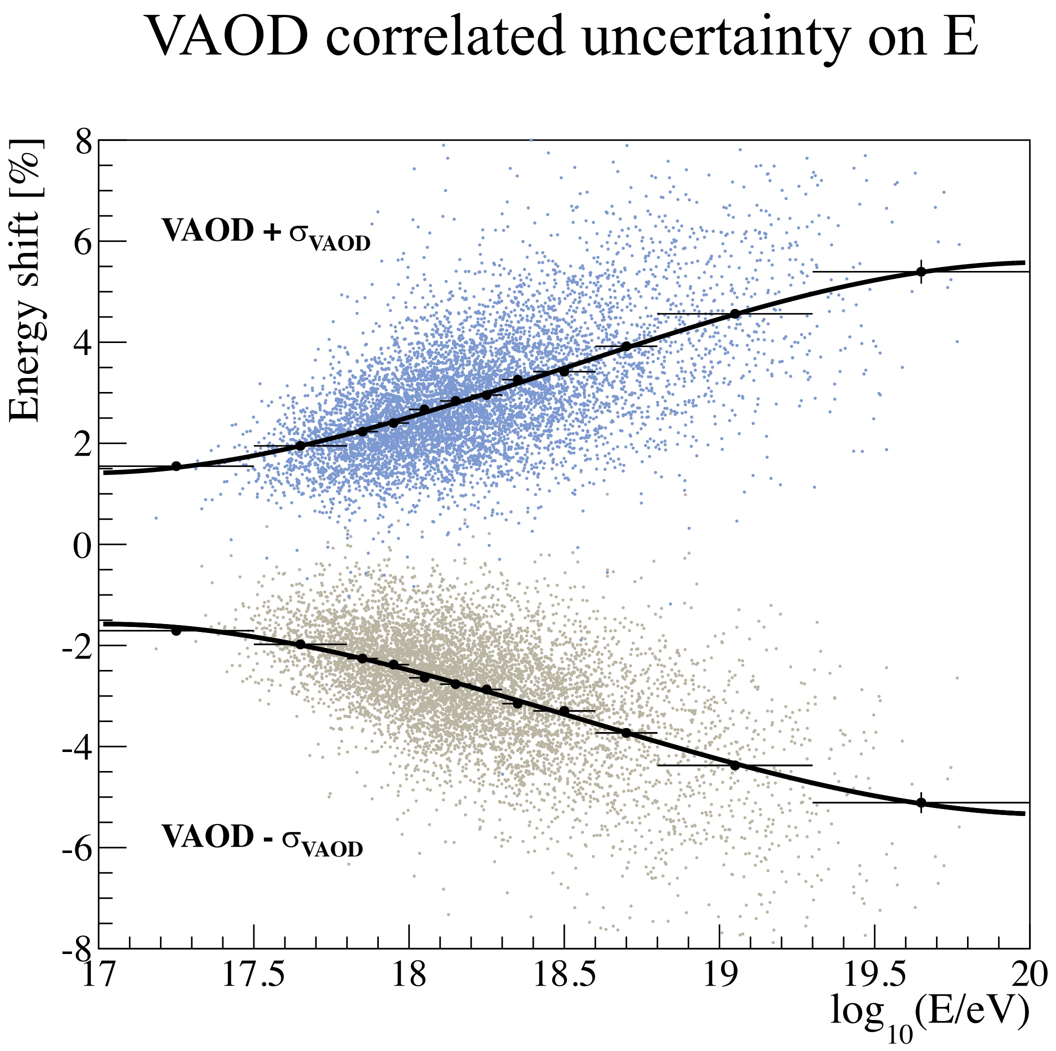
Correlated errors: are correlated across a period of time

e.g. due to drift in FD or laser relative calibration since reference night

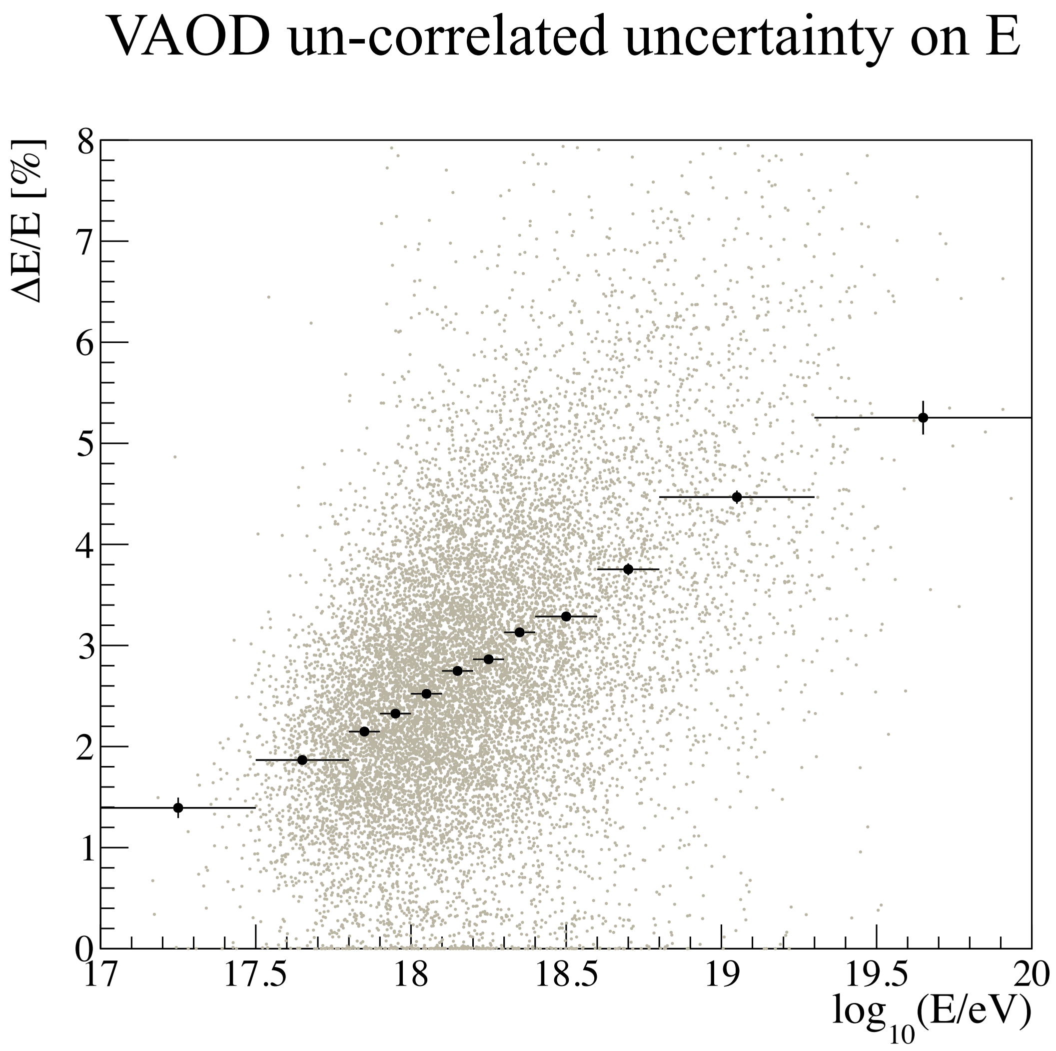
Uncorrelated errors: change from hour to hour

e.g. statistical error on light profiles, variation within a given hour

VAOD uncertainty propagated to EAS energy

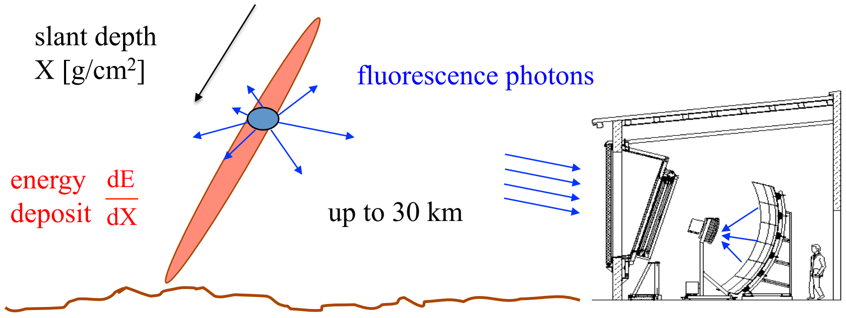


VAOD uncertainty propagated to EAS energy



Similar method used for uncertainties in shower maximum, X_{max}

Contribution to total uncertainties - energy



Uncorrelated errors on shower energy

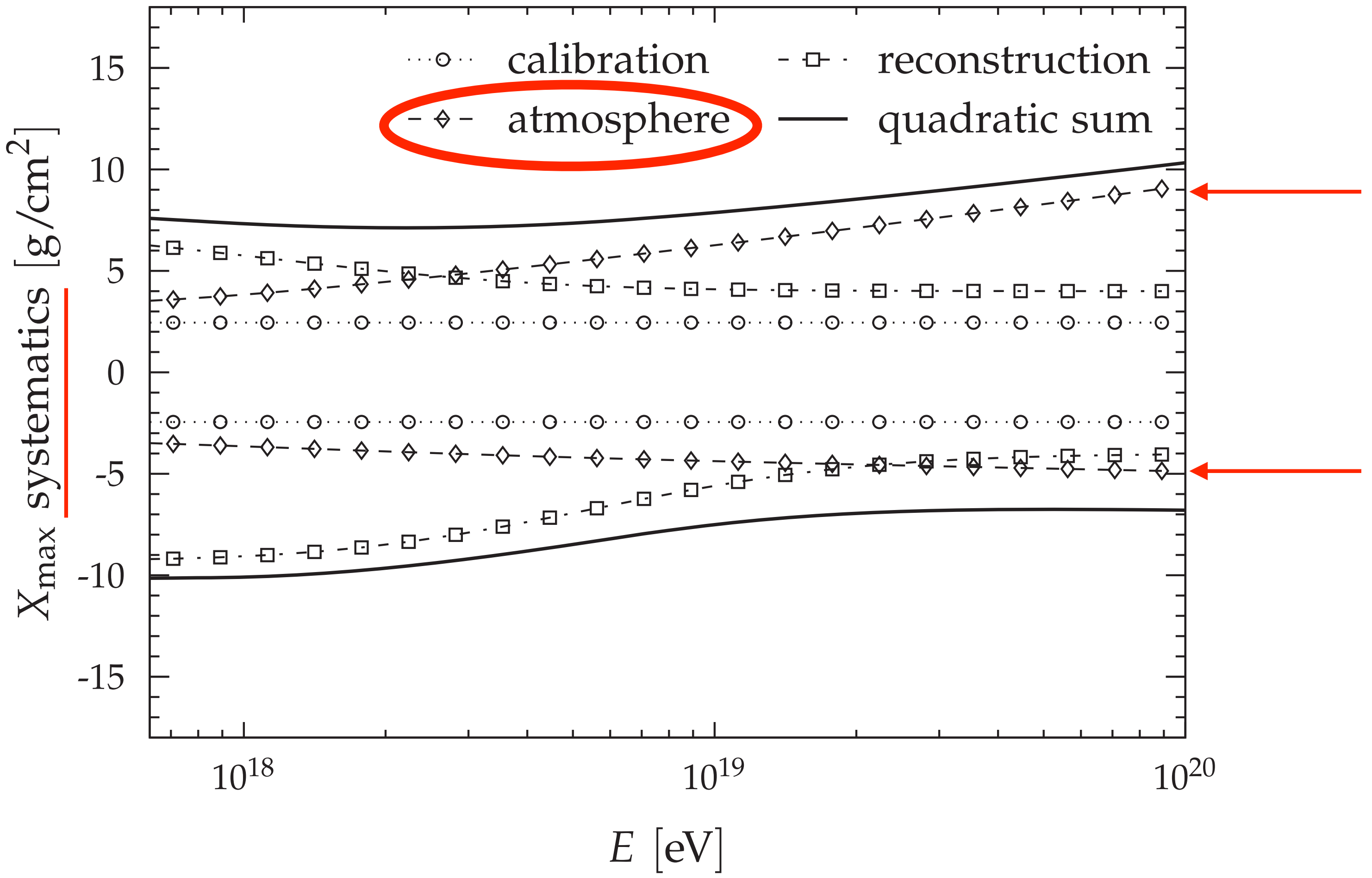
Aerosol optical depth	3%÷6%
Horizontal uniformity	1%
Atmosphere variability	1%
Nightly relative calibration	3%
Statistical error of the profile fit	5%÷3%
Uncertainty in shower geometry	1.5%
Invis. energy (shower-to-shower fluc.)	1.5%
FD energy resolution	**7% ÷ 8%**

Correlated errors on shower energy

Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere - sec. 3)	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration - sec. 4)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec. - sec. 5)	**6.5% ÷5.6%**
Invisible energy (sec. 6)	**3%÷1.5%**
Stat. error of the SD calib. fit (sec. 7)	**0.7%÷1.8%**
Stability of the energy scale (sec. 7)	**5%**
Total	**14%**

V. Verzi [Auger Collab.], ICRC2013

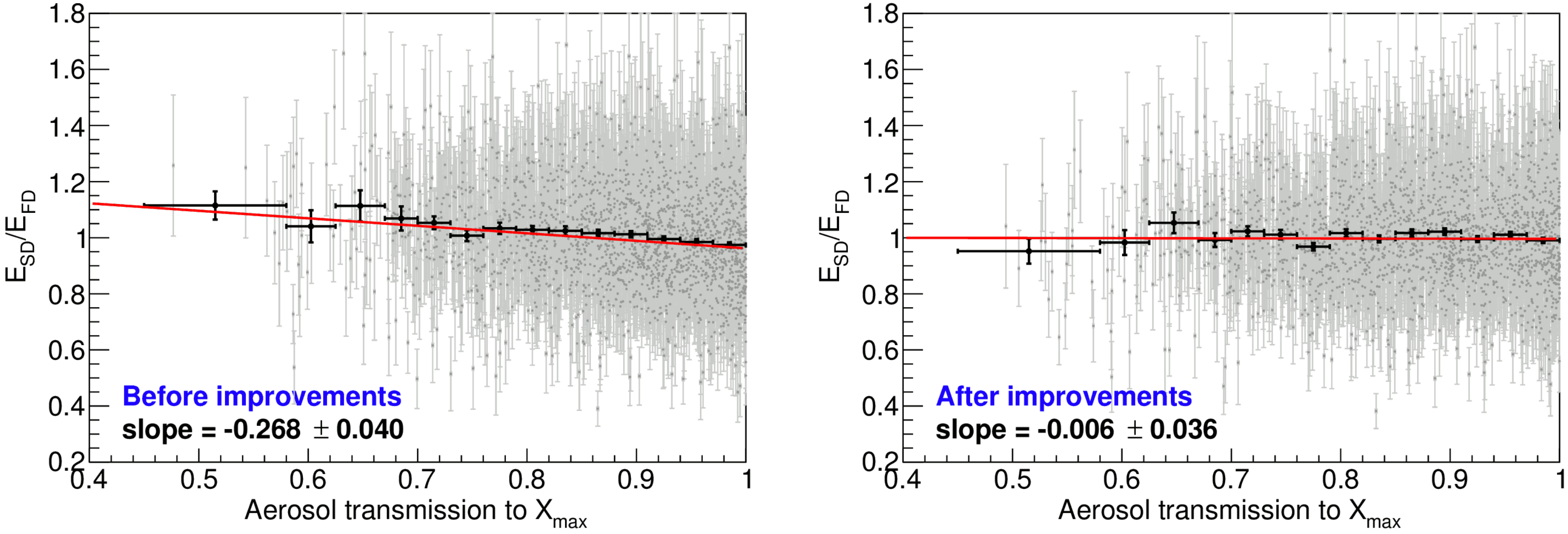
Contribution to total uncertainties - X_{max}



X_{max} statistical error (resolution): atmosphere contributes up to 10 g/cm^2 at highest energies (the major contribution to the total uncertainty there, 15 g/cm^2)

A. Aab et al. [Pierre Auger Collab.], Phys. Rev. D 90, 122005 (2014)

Cross-check on aerosol corrections



(a) (b)

Figure 5: Ratio of the reconstructed SD to FD energy as a function of the aerosol transmission to the depth of shower maximum. (a) Before the improvements made to aerosol extinction measurements. The negative slope indicates that the aerosol content of the atmosphere has been underestimated. (b) Following the improvements made to aerosol extinction measurements. The slope is fully compatible with zero, demonstrating internal consistency within the data.

M. Malacari [Auger Collab.], ICRC2017

Conclusions

Steven Saffi, University of Adelaide

- The measurement and treatment of aerosols in Auger’s shower analysis pipeline is well developed and stable.
- However we continue fine tuning and cross checks, and we are in the process of tuning the assignment of uncertainties.
- For more detail on Auger’s atmospheric measurements and analysis, see talks by my colleagues!