PIERRE AUGER OBSERVATORY

ICRC2019
Madison, WI, USA

THE ENERGY SCALE OF THE PIERRE AUGER OBSERVATORY

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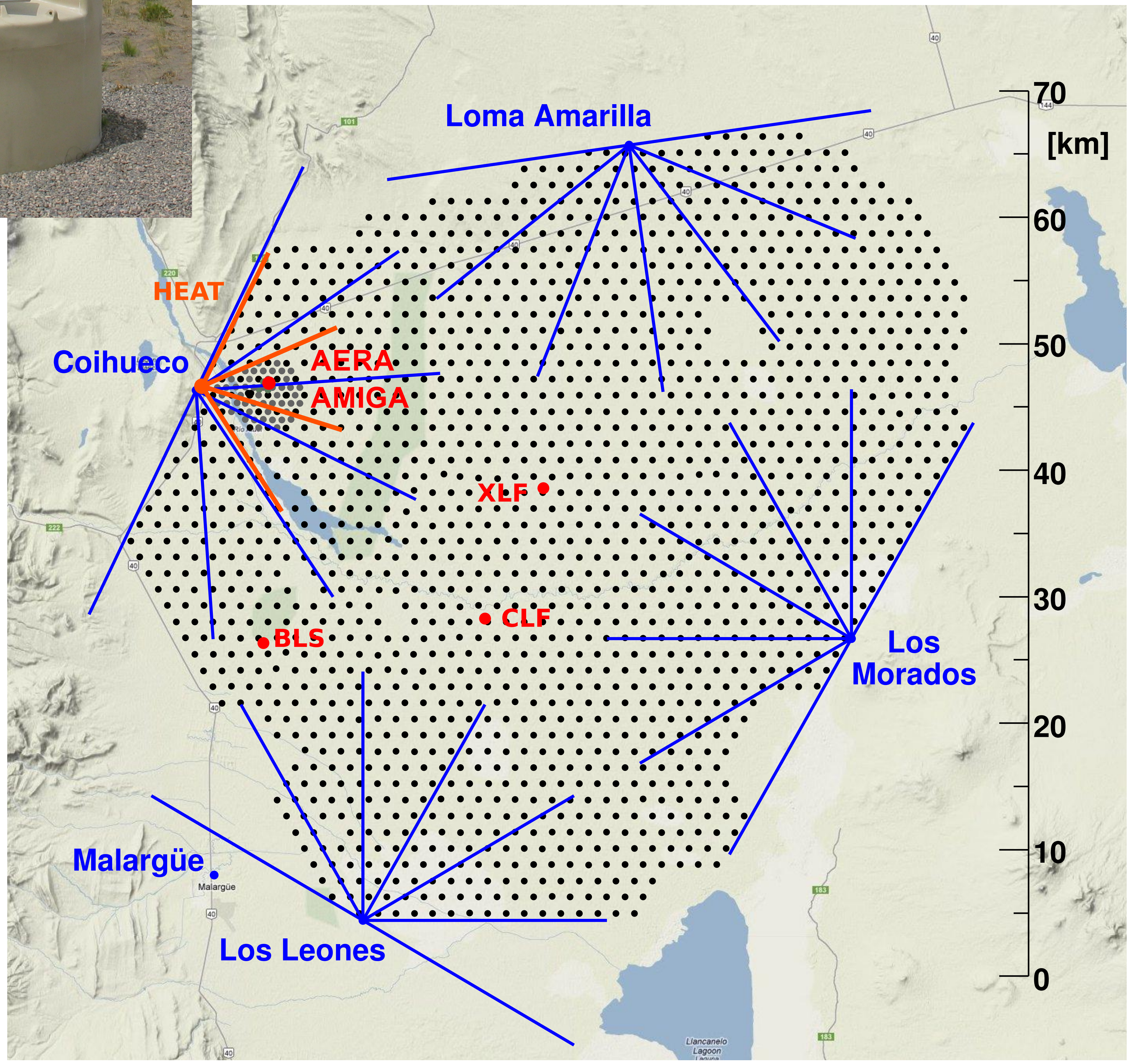
The Pierre Auger Observatory

Water-Cherenkov detector
10 m², 1.2 m deep



3000 km²

1661 water-Cherenkov detectors

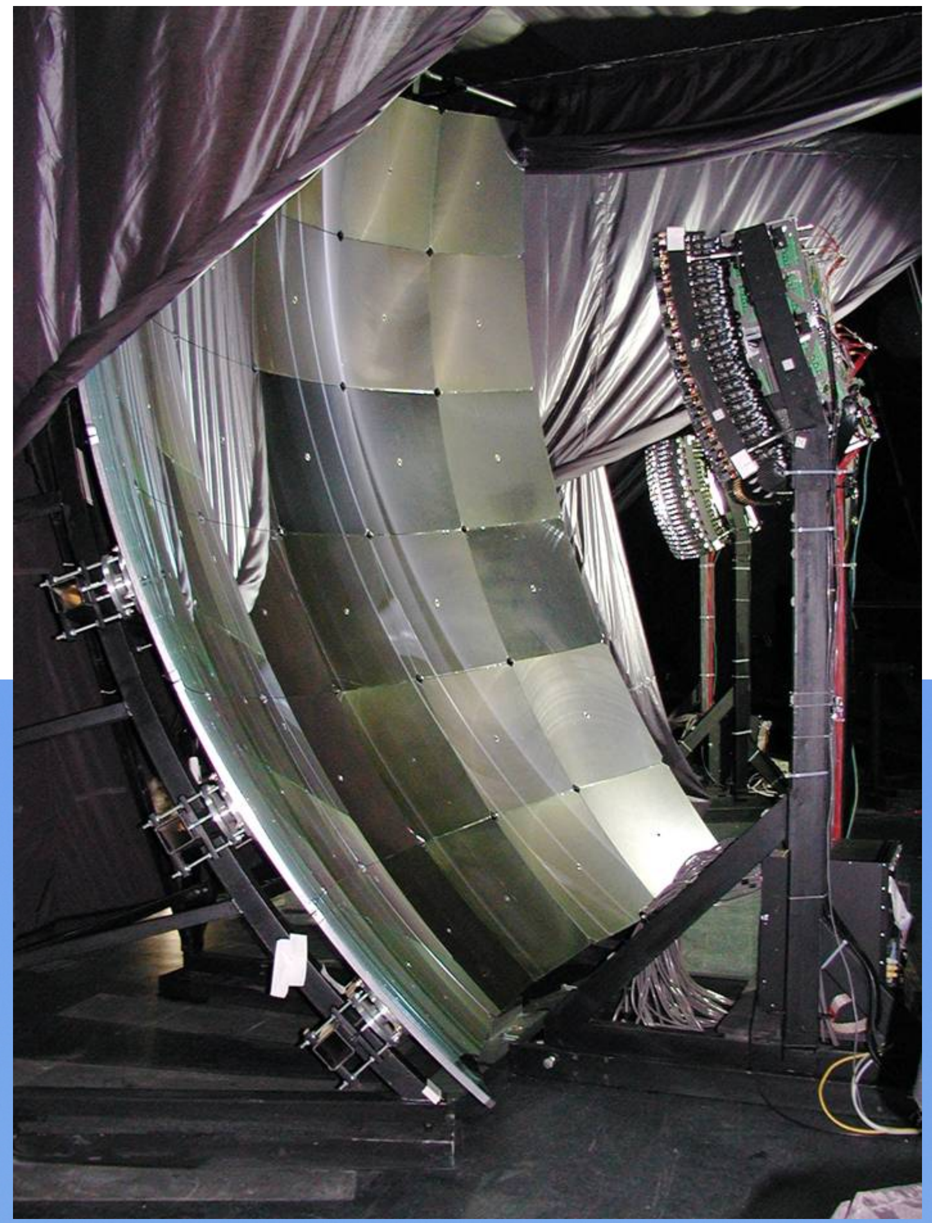
(on 1500 m or 750 m triangular grid)

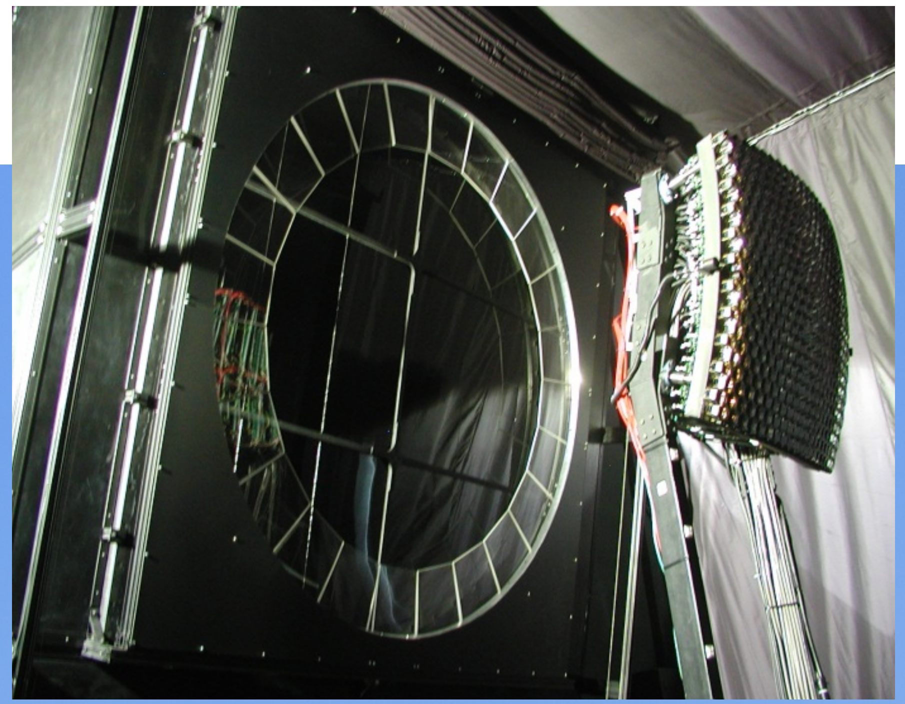
27 fluorescence telescopes (4 sites)

Schmidt telescope

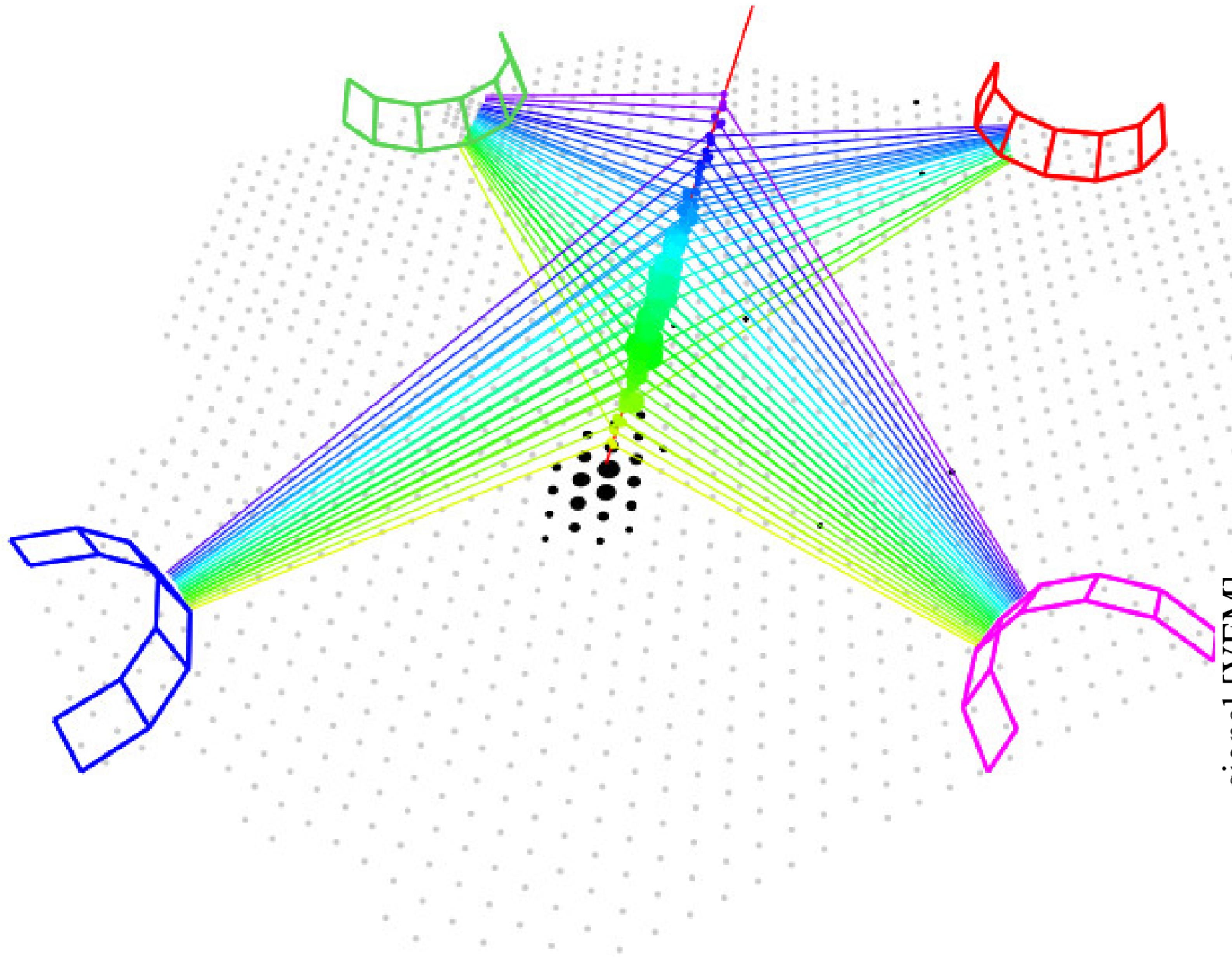
3.4 m diameter mirror
2.2 m diameter aperture

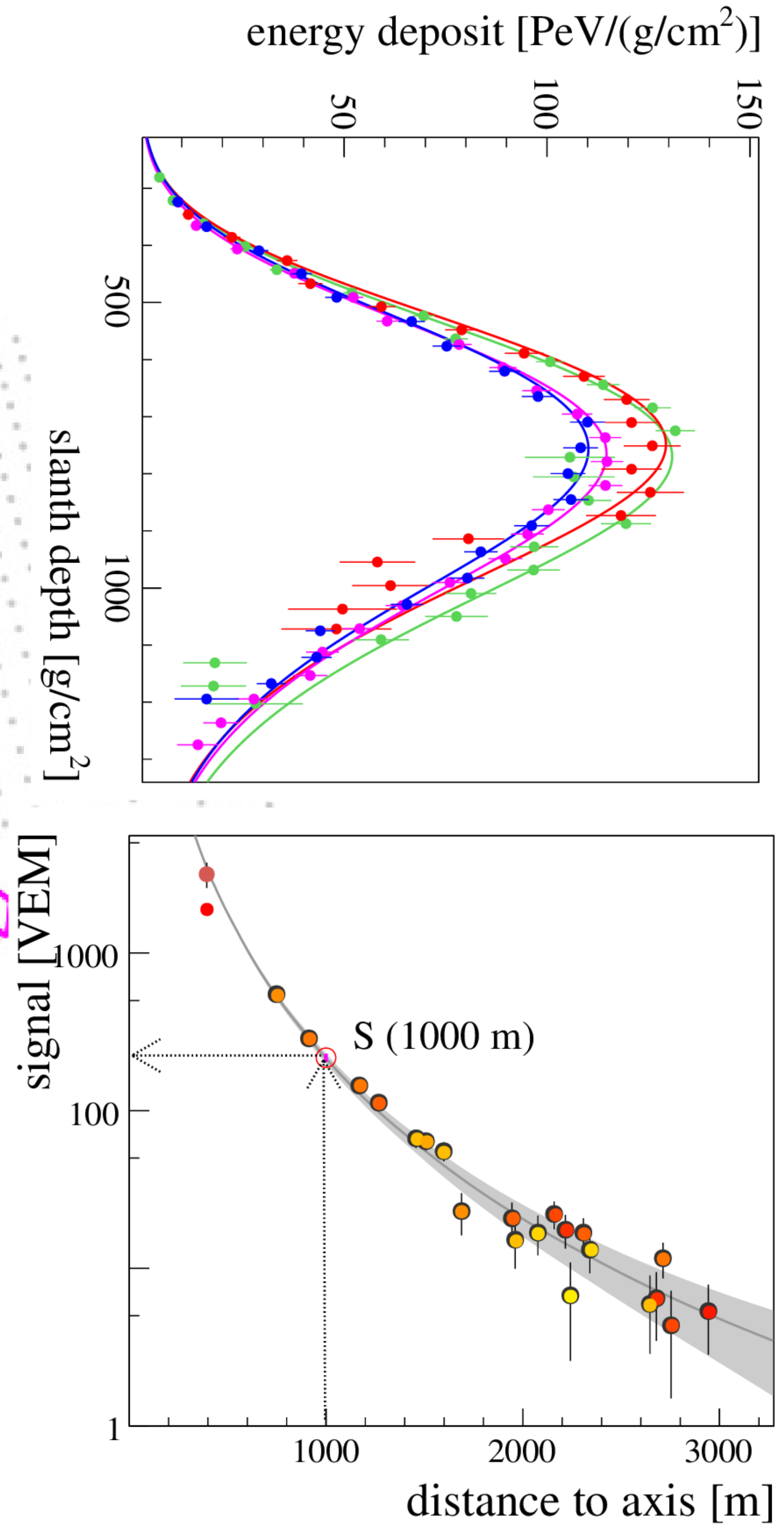
440-pixel camera
UV filter and corrector lenses

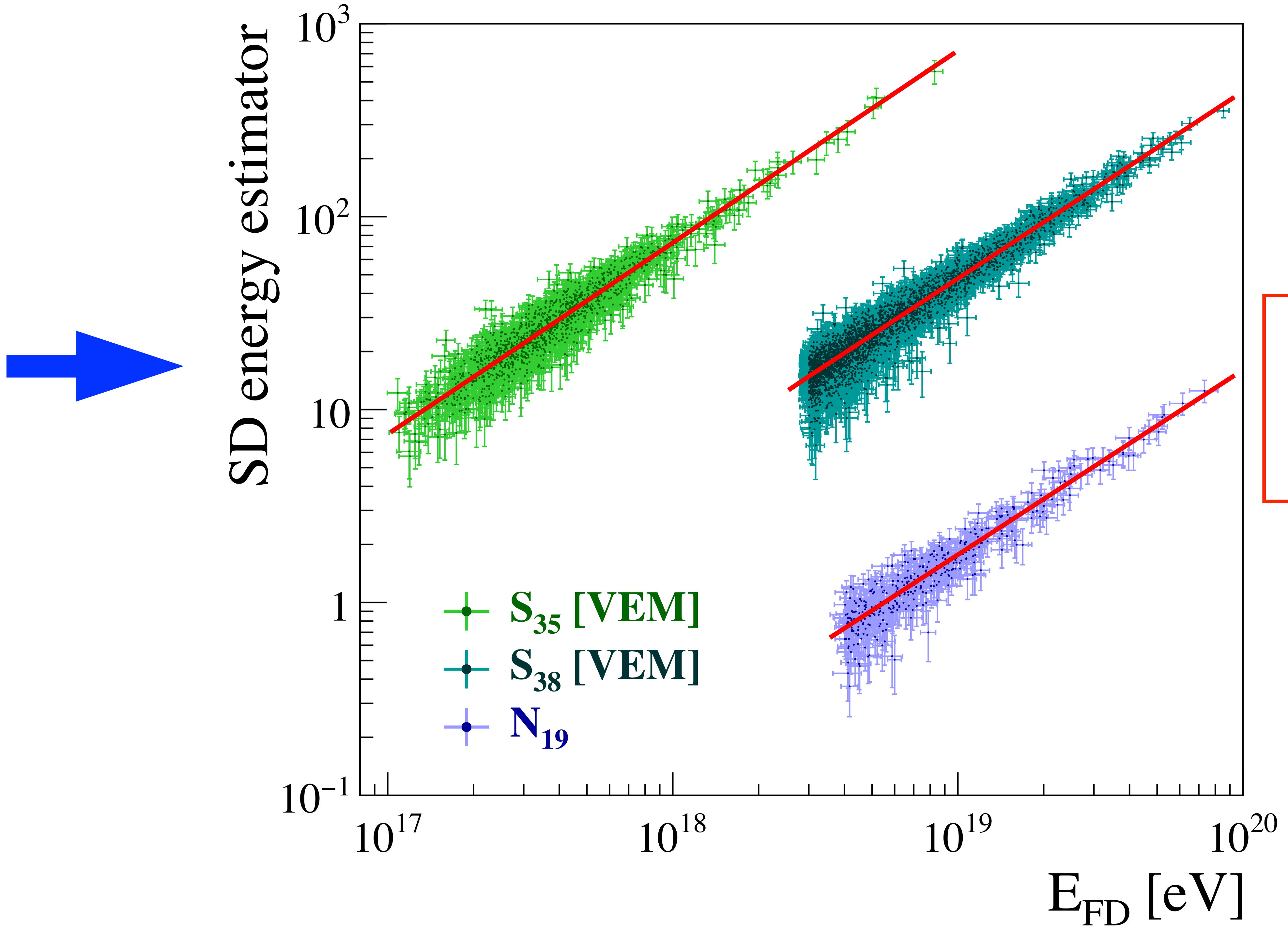




Energy Scale of the Observatory is Based on Fluorescence Measurements







See A. Coleman, V.Verzi, next two talks.

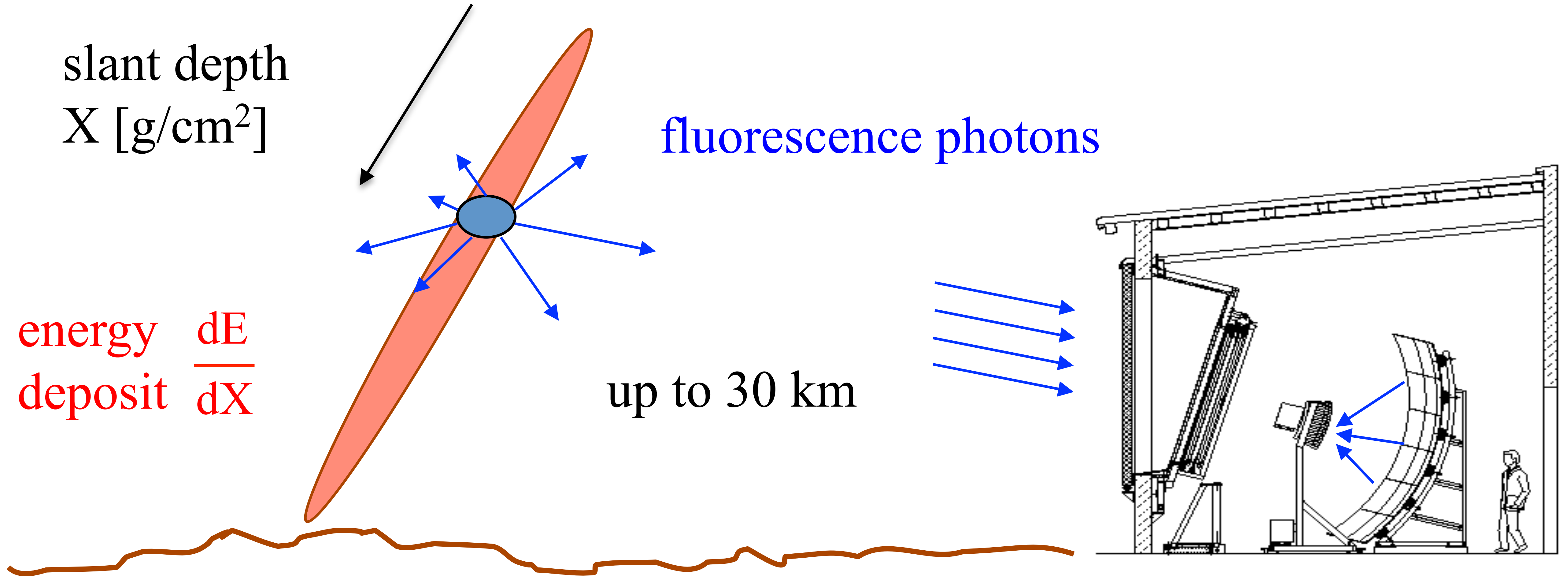
Fluorescence Detector (FD) energy measurements are largely calorimetric.

We transfer this energy scale to the Surface Detector (SD) with hybrid events.

But FD energy measurements are challenging:

- the atmosphere
- calibrations
- reconstruction
- invisible energy

Current Energy Systematics: ICRC 2013



- We report on examples of cross-checks, reduction of model dependence, and small improvements to FD energy determination.
- Overall, changes to FD energies since 2013 are small (later), and there is no significant change to table of systematics.
- later: statistical errors (resolution).

ICRC 2013

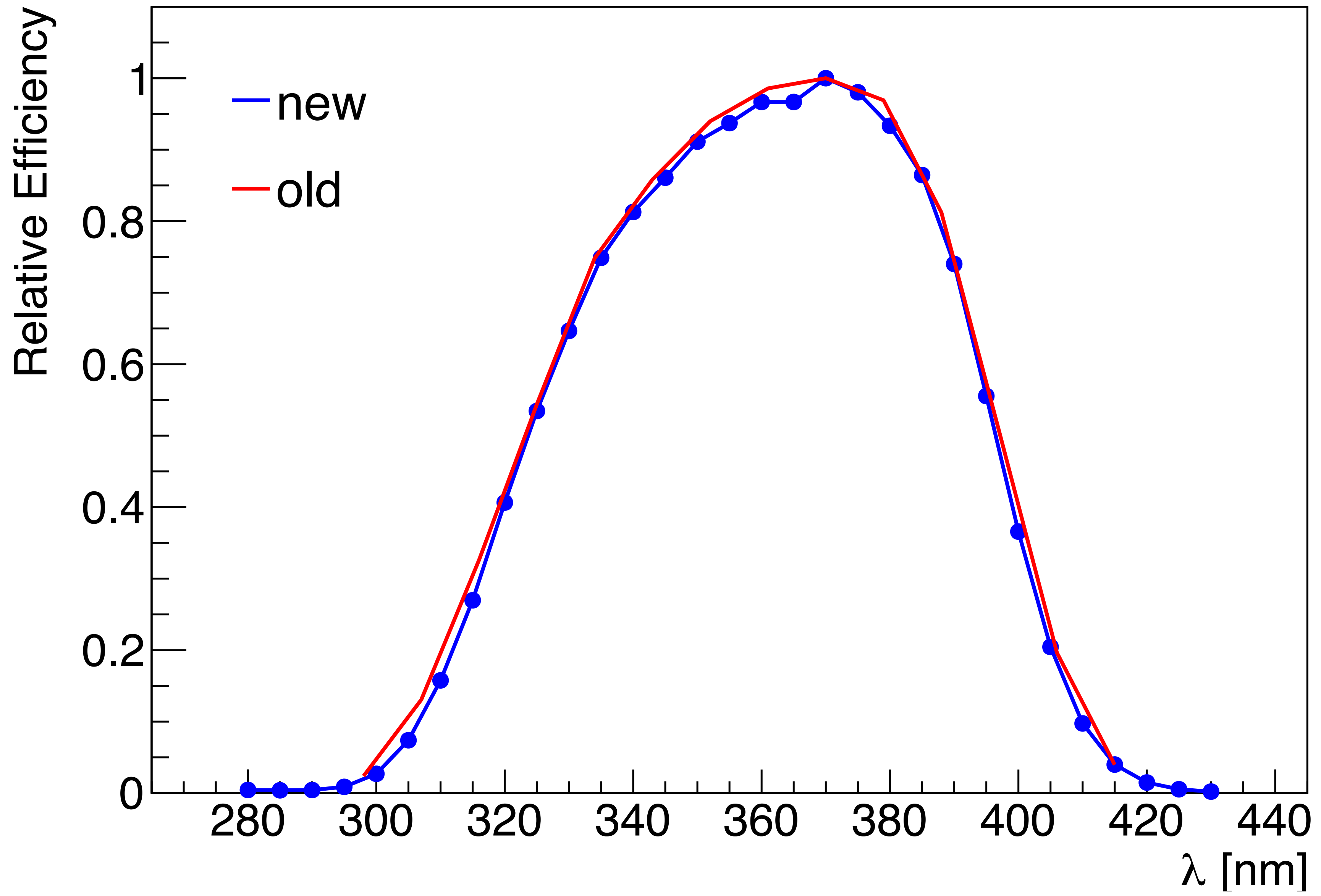
Systematic uncertainty in the energy scale

Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Stability of energy scale	5%
TOTAL	14%

From 3×10^{18} eV to highest energies
- similar at lower energies

Recent cross-checks and improvements: Calibration

New direct measurements of telescope spectral response

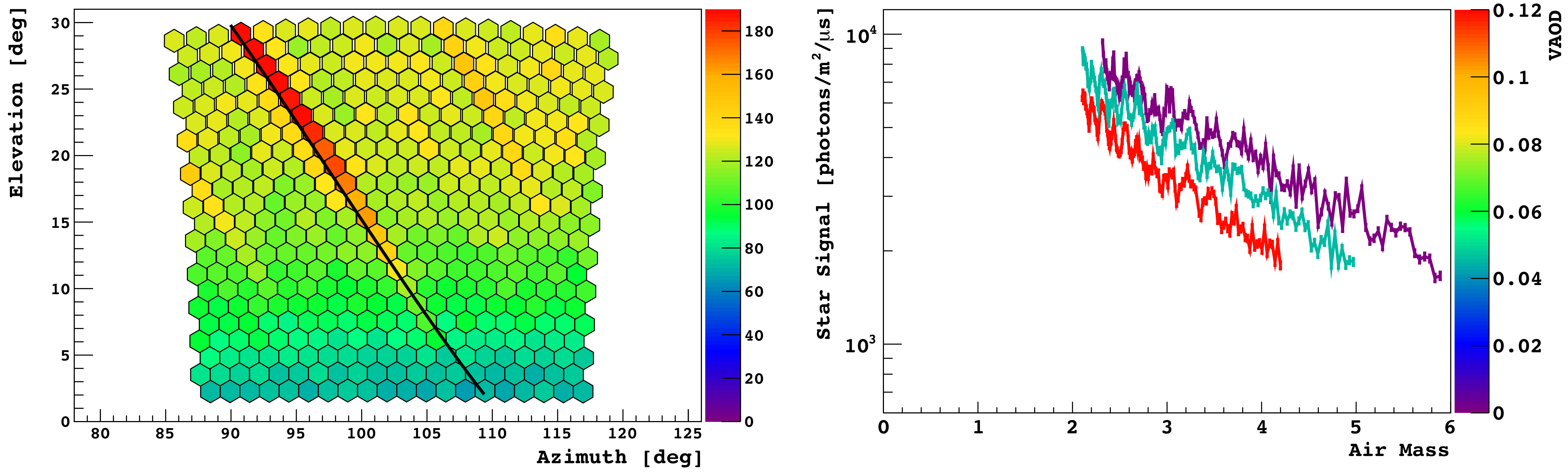


Spectral response of filter, corrector lenses, mirror, PMT (end-to-end)

5 nm steps, 4 telescope types.

Energies increase 0.2% to 2.5%.

Cross-check of absolute calibration - bright UV stars (e.g. Sirius)



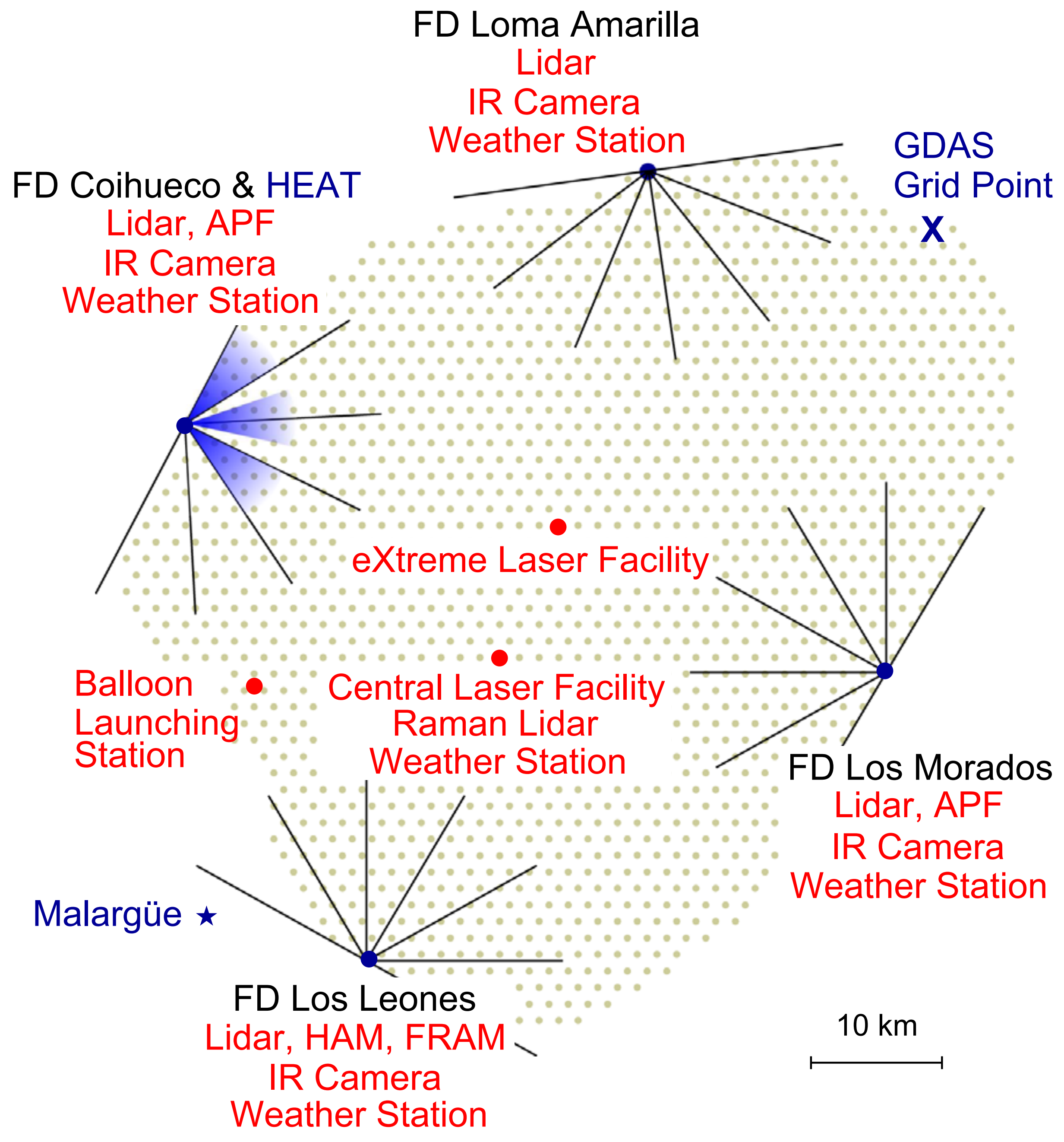
Star measurements

Correct for atmosphere (extinction method).

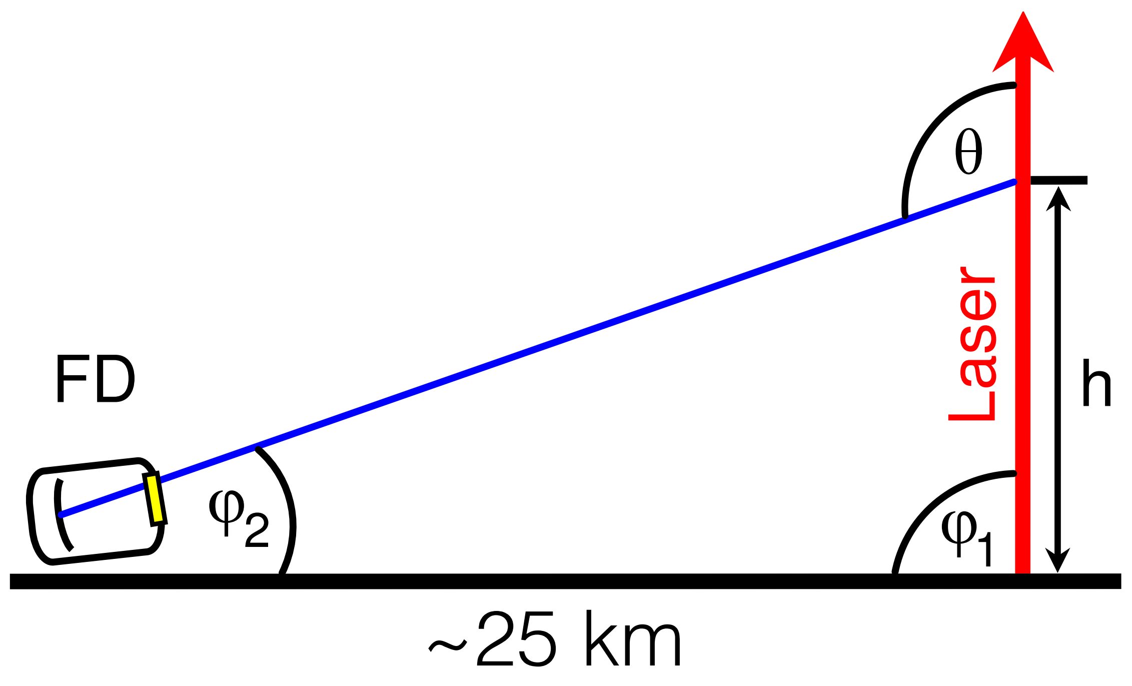
Confirms telescope absolute calibration (within method's 8% systematic uncertainty.)

A. Aab et al. [Pierre Auger Collaboration], Astropart. Phys. **95** (2017) 44.

Recent cross-checks and improvements: Atmosphere

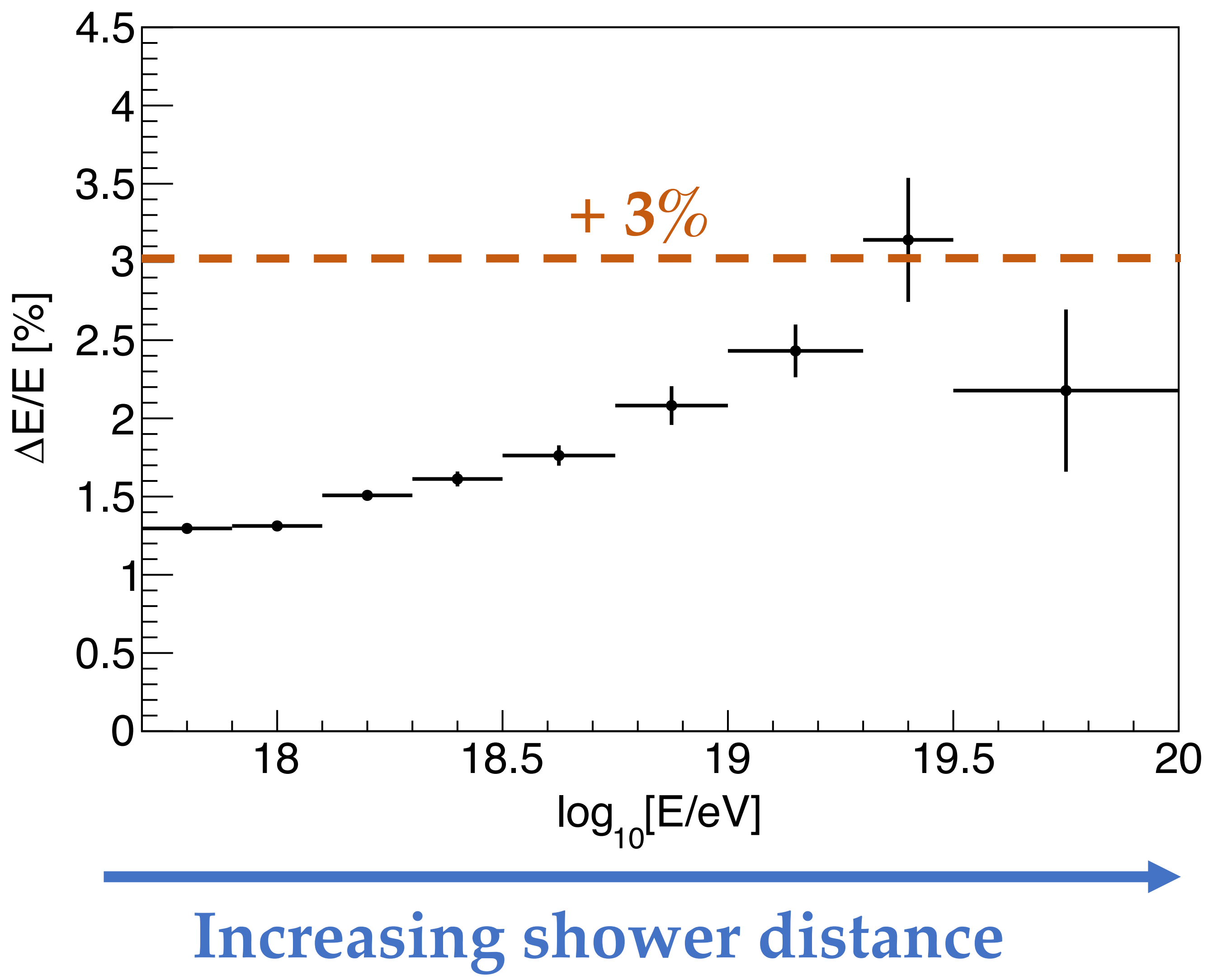


Aerosol measurements using "Data Normalised" method - improvements to algorithm



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

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



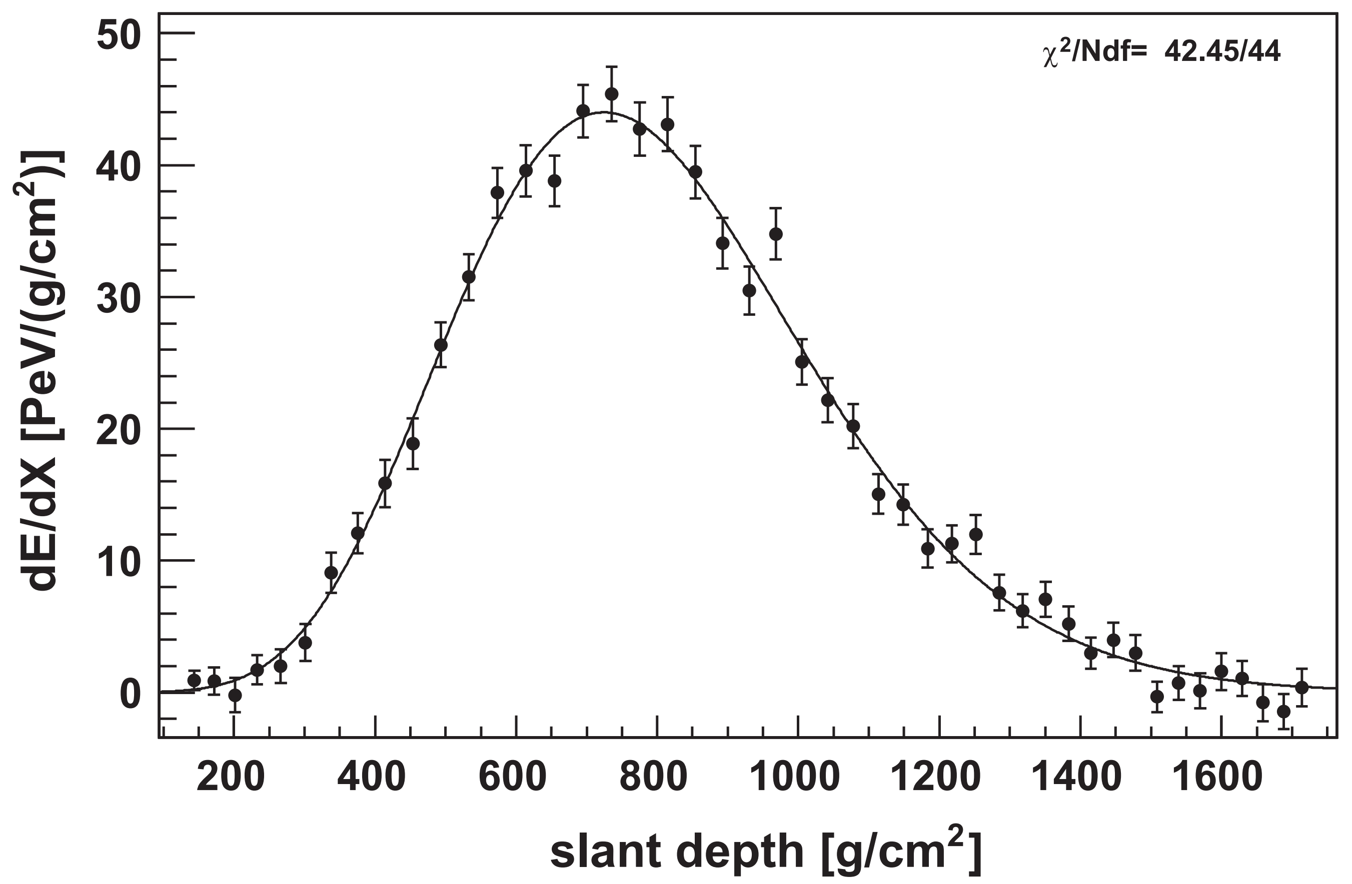
2017: Improved "data normalised" algorithm for aerosols: accounted for multiple scattered light, and that some light is scattered out of laser beam by aerosols (previously ignored).

Shower energies increase by 1.5% to 3%.

2019: Data normalised code completely re-written: all steps checked, uncertainties reviewed.
See V. Harvey (Auger Collab.), this conference, PoS(2019)283.

M. Malacari et al. [Pierre Auger Collaboration], PoS **ICRC2017** (2017) 398.

Recent cross-checks and improvements: Reconstruction



Re-cast of Gaisser-Hillas function for shower development profile

$$f_{\rm GH}(X) = \left(\frac{dE}{dX}\right)_{\rm max} \left(\frac{X - X_0}{X_{\rm max} - X_0}\right)^{\frac{X_{\rm max}-X_0}{\lambda}} \exp\left(\frac{X_{\rm max} - X}{\lambda}\right)$$

$$f'_{\rm GH}(X) = \left(\frac{dE}{dX}\right)_{\rm max} \left(1 + \frac{R}{L}(X - X_{\rm max})\right)^{1/R^2} \exp\left(\frac{X_{\rm max} - X}{RL}\right)$$

$R = \sqrt{\lambda/|X_0 - X_{\rm max}|}$ "asymmetry"

$L = \sqrt{|X_0 - X_{\rm max}|\lambda}$ "width"

New profile function: avoids (intrinsic) correlation between X_0 and λ, and reduces number of constraints.

Reduces reconstructed energies by less than **0.5%.**

Old: fit $X_0,\ \lambda,\ X_{\rm max},\ \left(\frac{dE}{dX}\right)_{\rm max}$ with loose constraints on $X_0,\ \lambda,\ k = \frac{E_{\rm cal}}{(\frac{dE}{dX})_{\rm max}}$

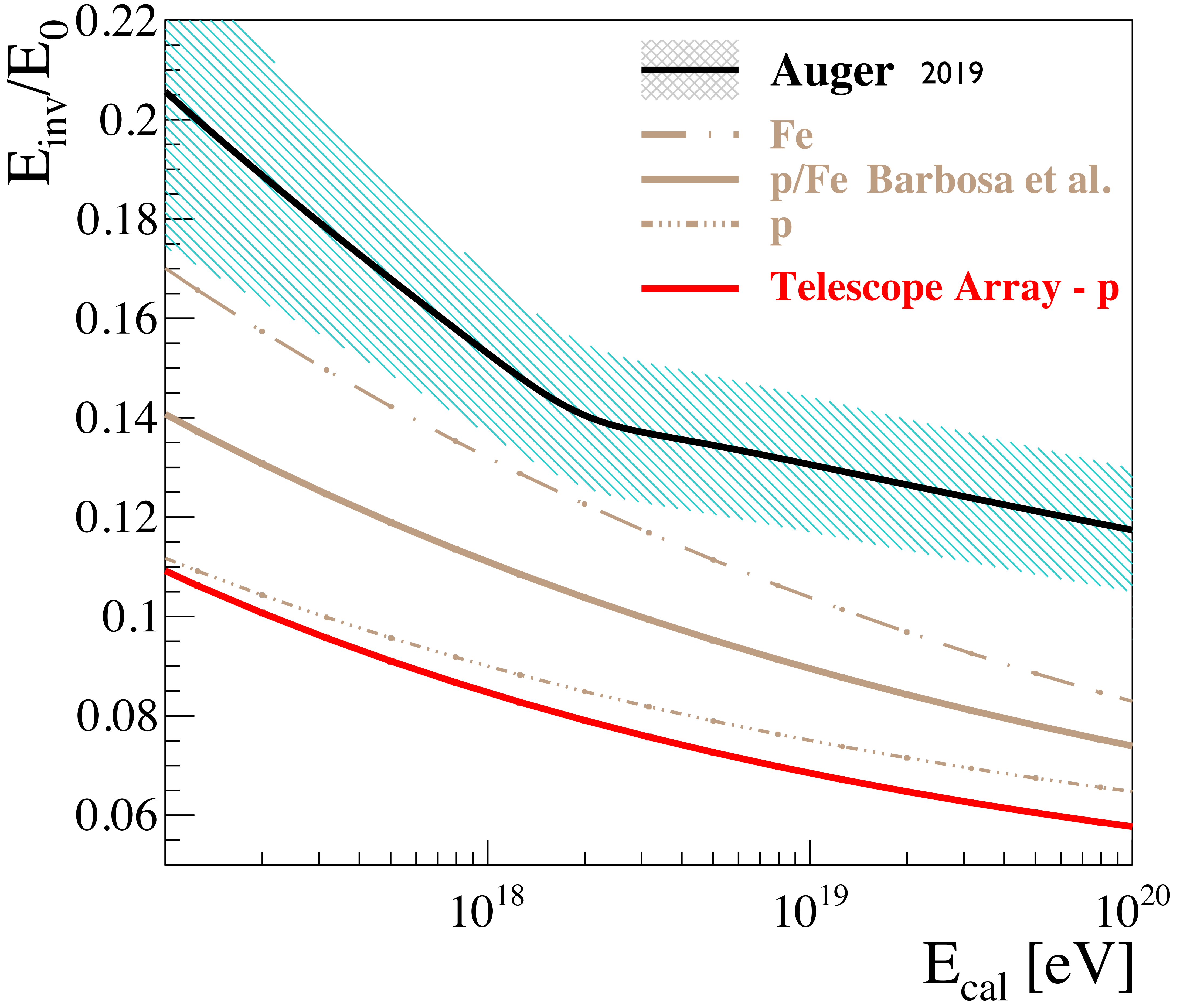
New (ICRC 2019): fit $R,\ L,\ X_{\rm max},\ \left(\frac{dE}{dX}\right)_{\rm max}$ with loose constraints on $R,\ L$

helps shorter profiles, without bias

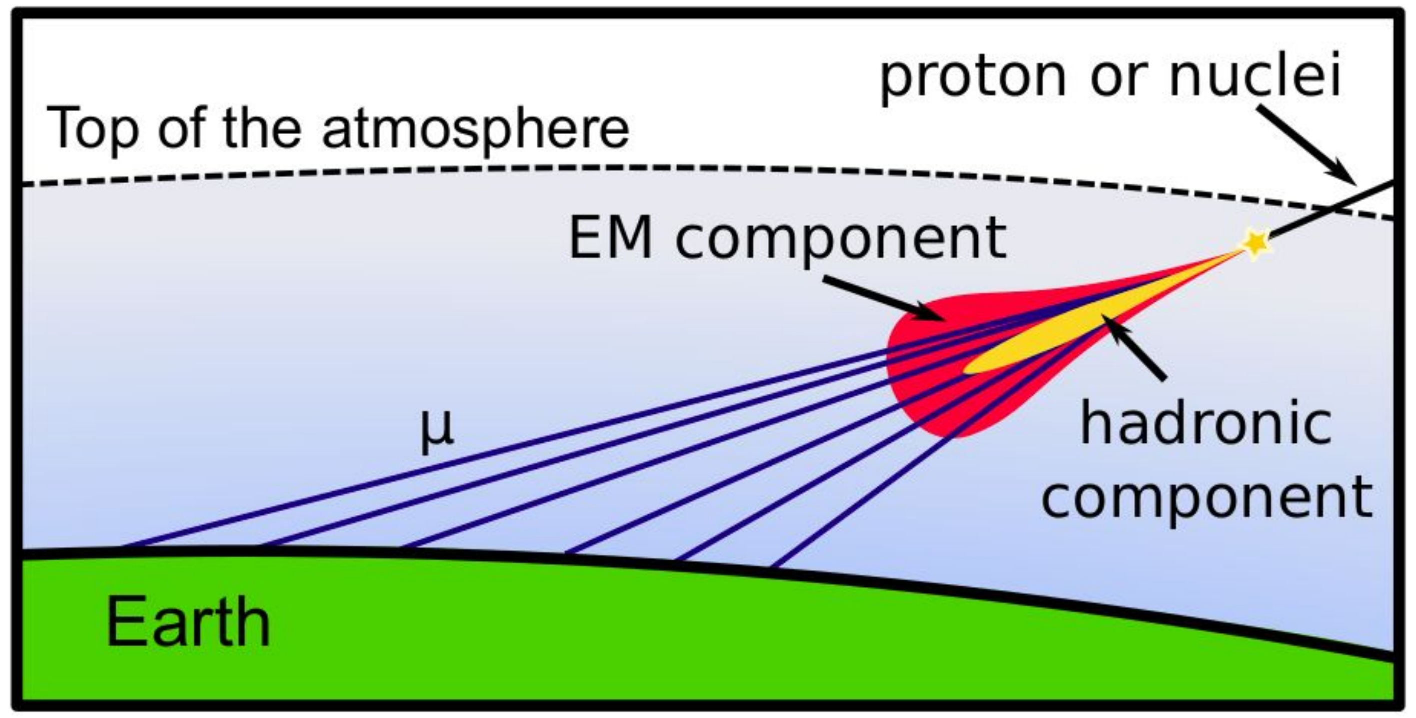
A. Aab et al. [Pierre Auger Collaboration], **JCAP03** (2019) 18.

Recent cross-checks and improvements: Invisible Energy

A. Aab et al. [Pierre Auger Collaboration], "Data-driven estimation of the invisible energy of cosmic ray showers with the Pierre Auger Observatory", Phys. Rev. D (in press) (2019).



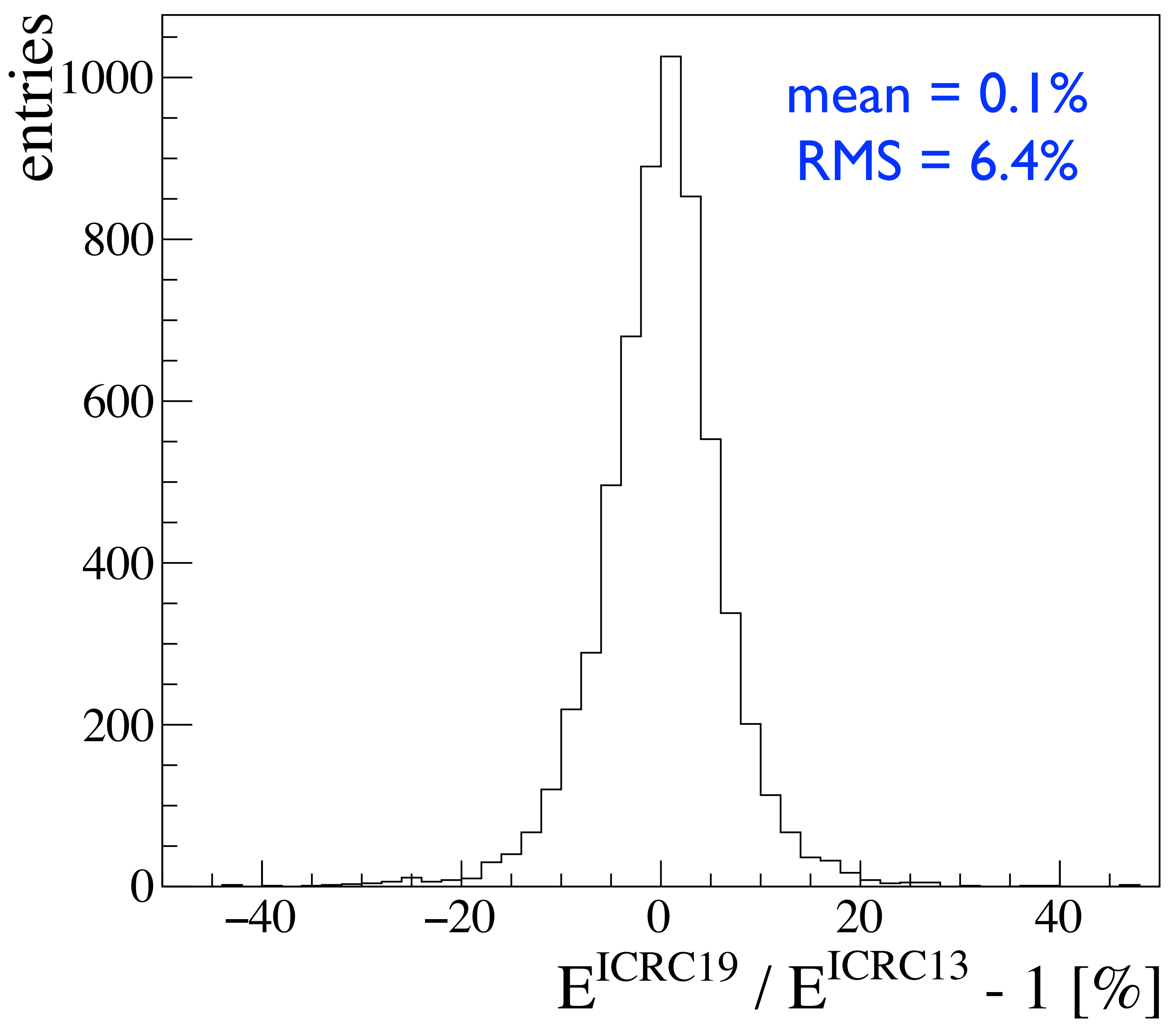
E > 3x10[18] eV : based on direct measurements from inclined showers
E < 3x10[18] eV : extrapolation based on model, and measured X_{max} data

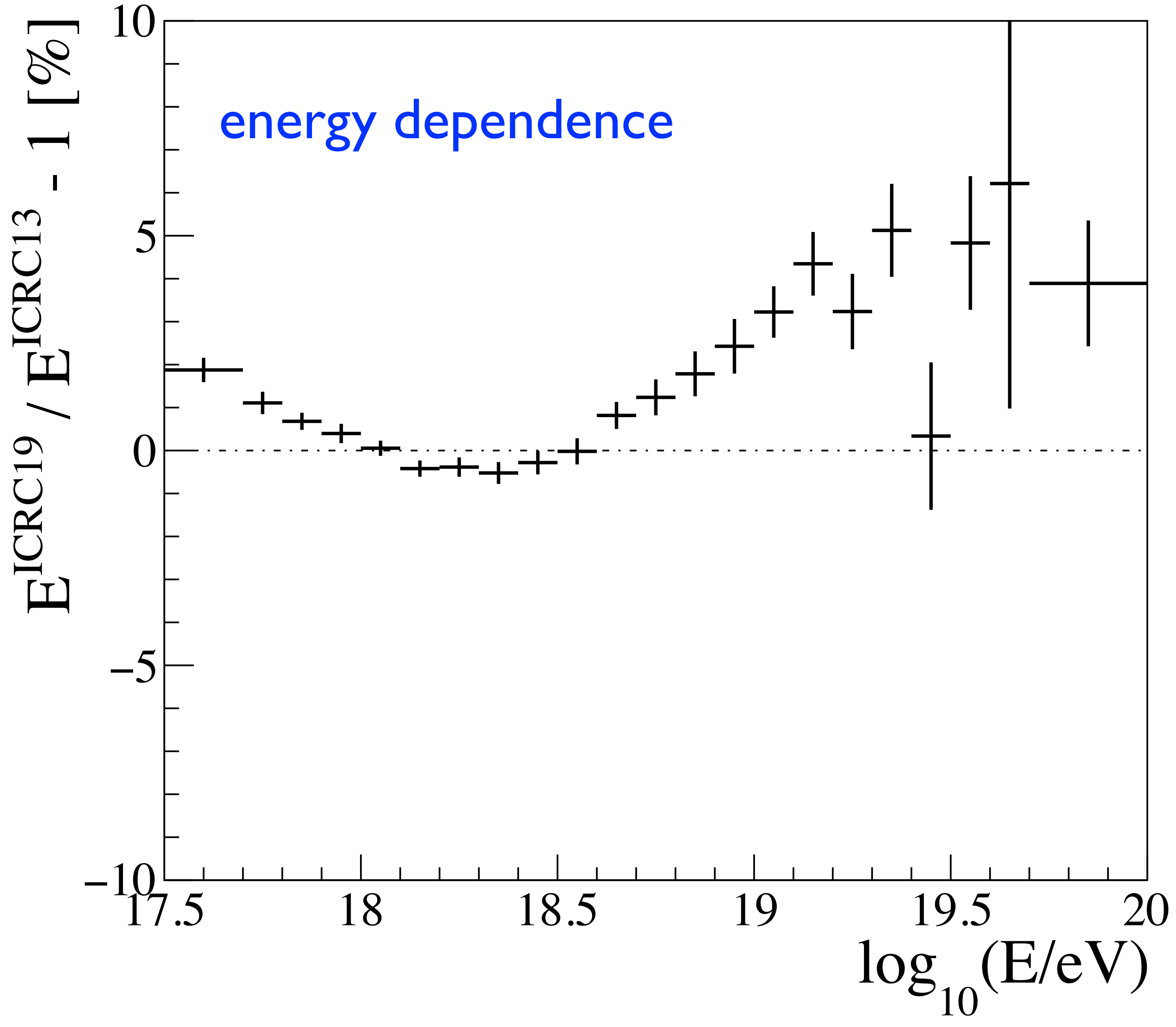


- Takes account of energy in high energy muons and neutrinos that does not appear reflected in fluorescence light.
- New invisible energy analysis: like previous Auger studies (2013, 2017), E_{inv} is derived from data.
- 2019 study based on data from inclined showers $(60^\circ < \theta < 80^\circ)$ dominated by muons.
- including a new extrapolation to lower energies.

Recent cross-checks and improvements: Summary of E changes

- Changes in FD energies for a sample of air showers using ICRC2019 vs ICRC2013 energy scale.
- Includes the effects of improvements in calibration, atmospheric treatment, reconstruction, and invisible energy described earlier.





Re-evaluation of FD energy resolution

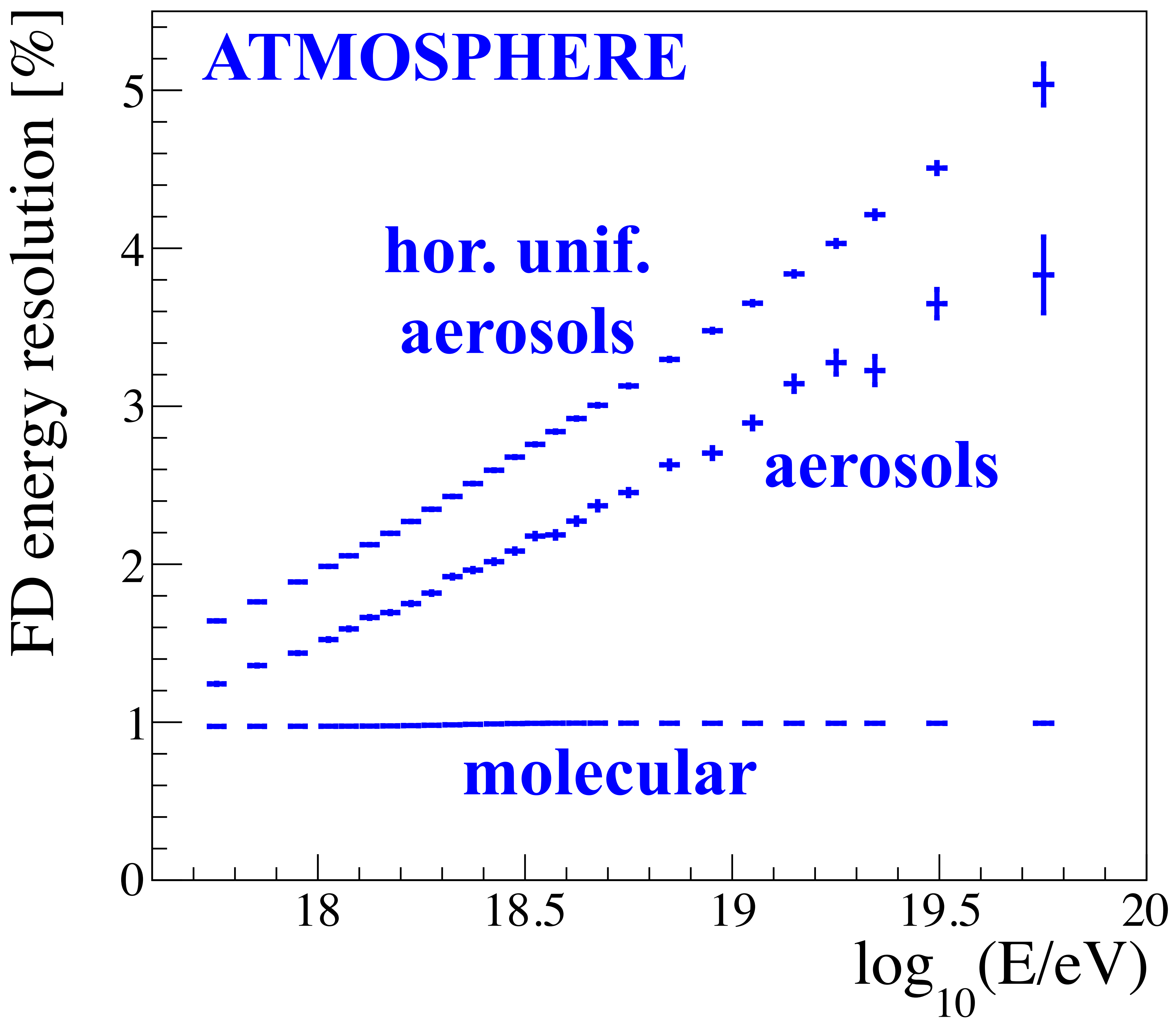
- A new study completed in 2019 has reviewed FD energy resolution.
- Knowing the FD energy resolution allows an evaluation of the SD energy resolution needed to account for resolution effects in SD-based energy spectra.

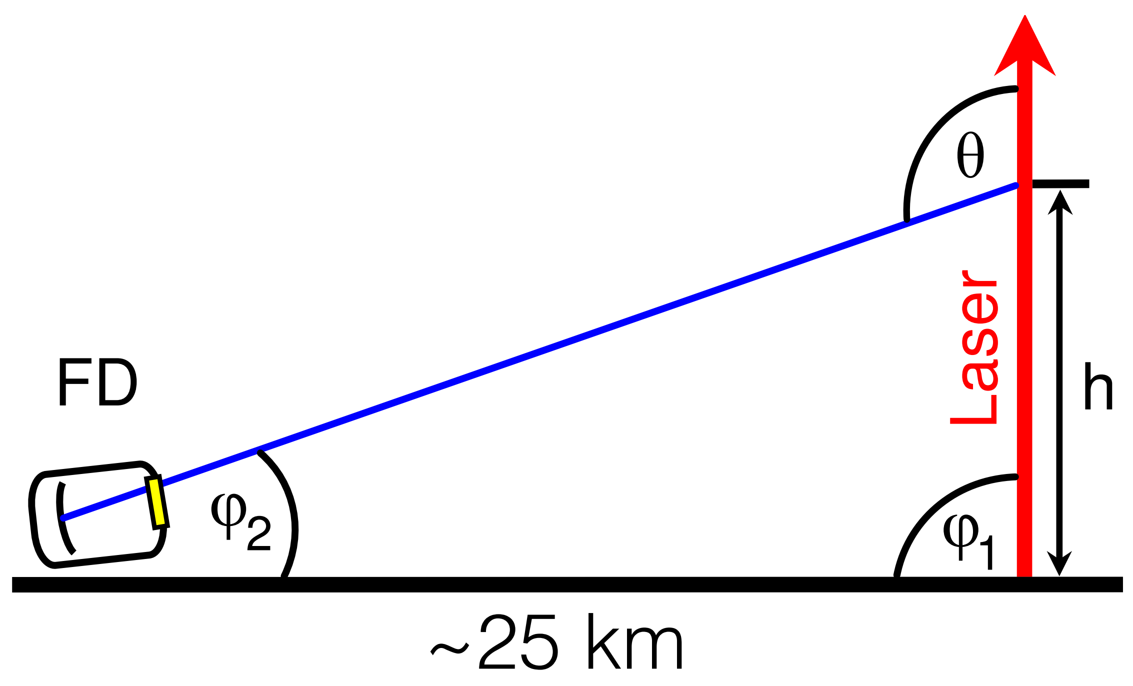
See A. Coleman,
V.Verzi,
next two talks.

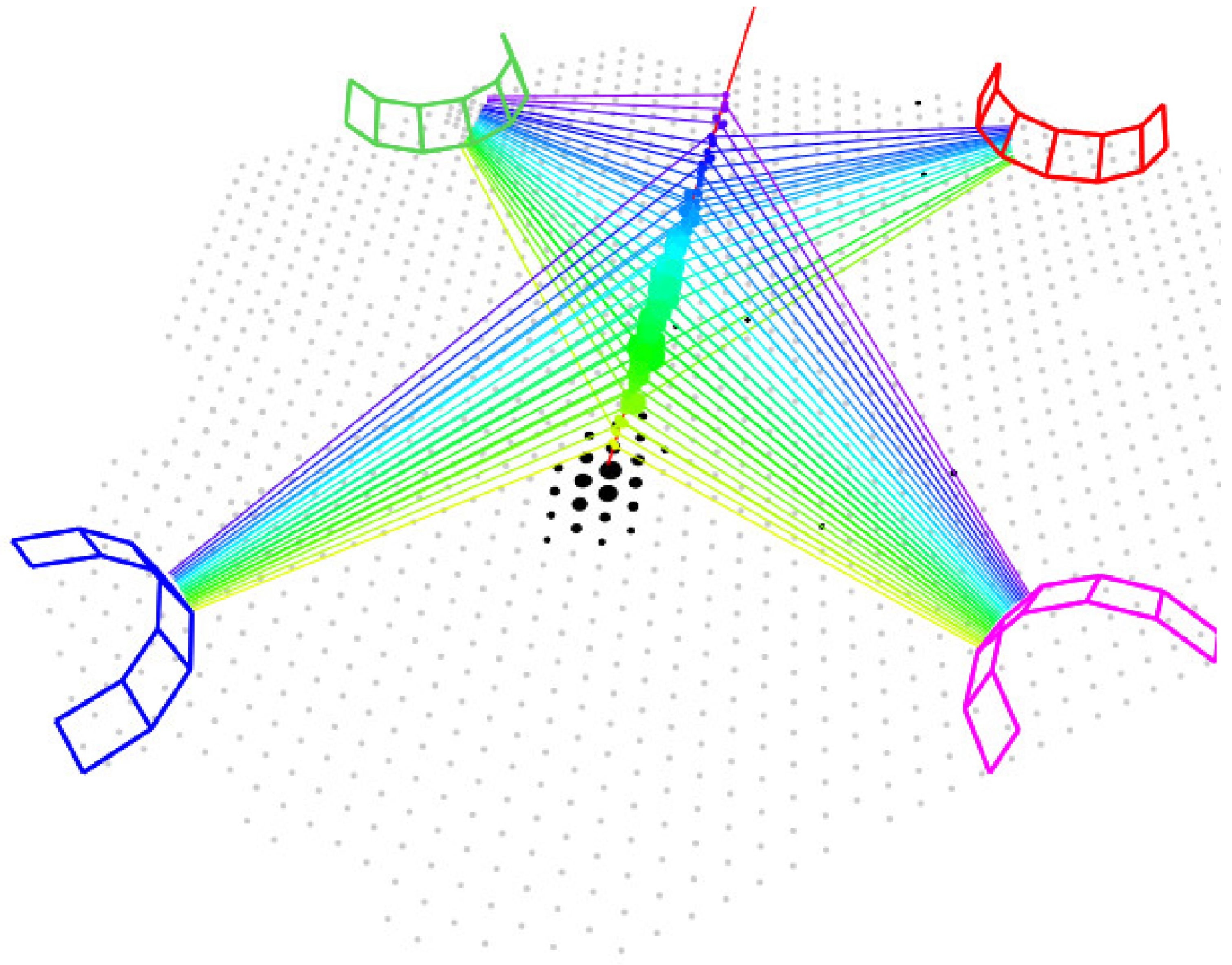
- FD resolution includes contributions from
  - the atmosphere
  - the detector, incl. reconstruction
  - the invisible energy correction.

Re-evaluation of FD energy resolution

The Atmosphere





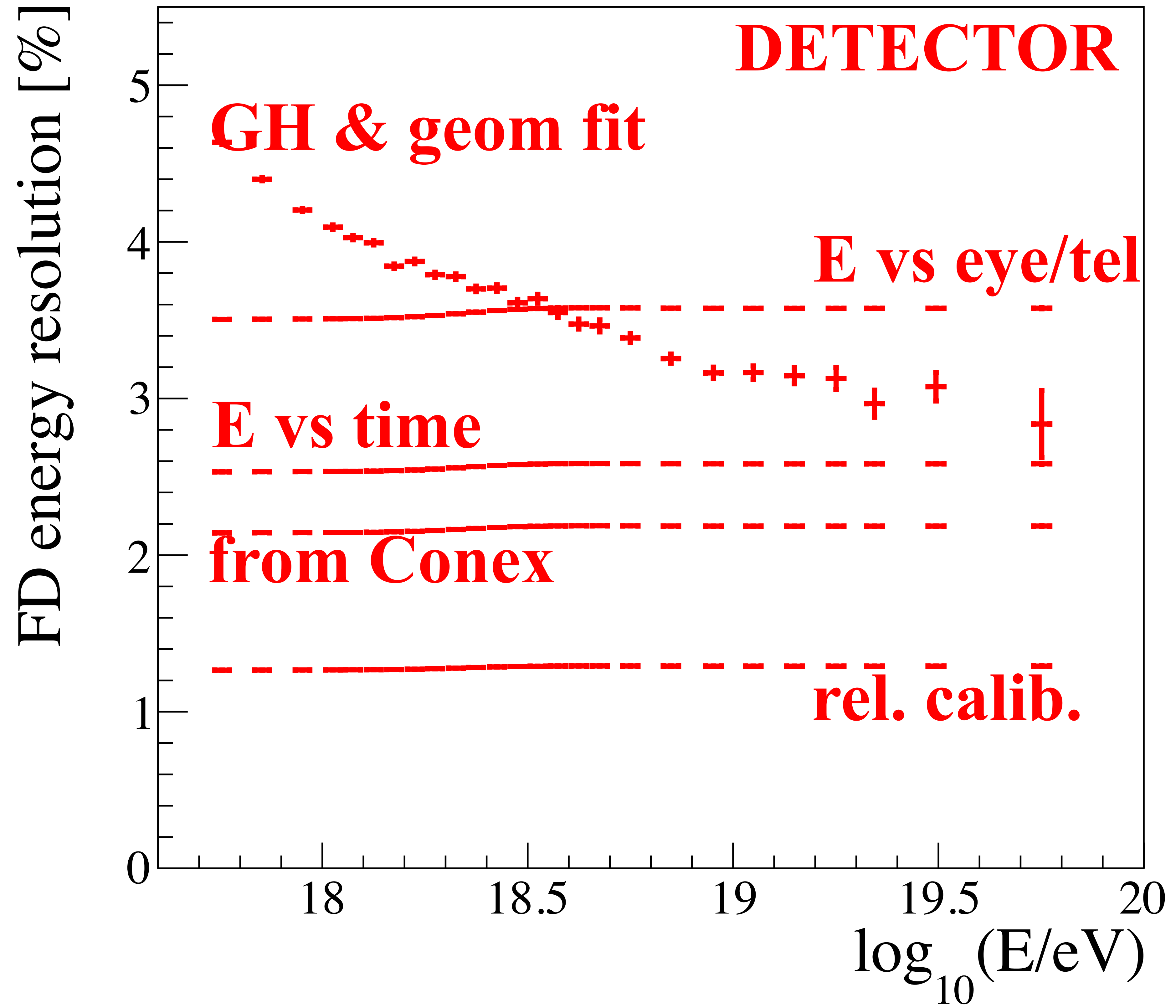


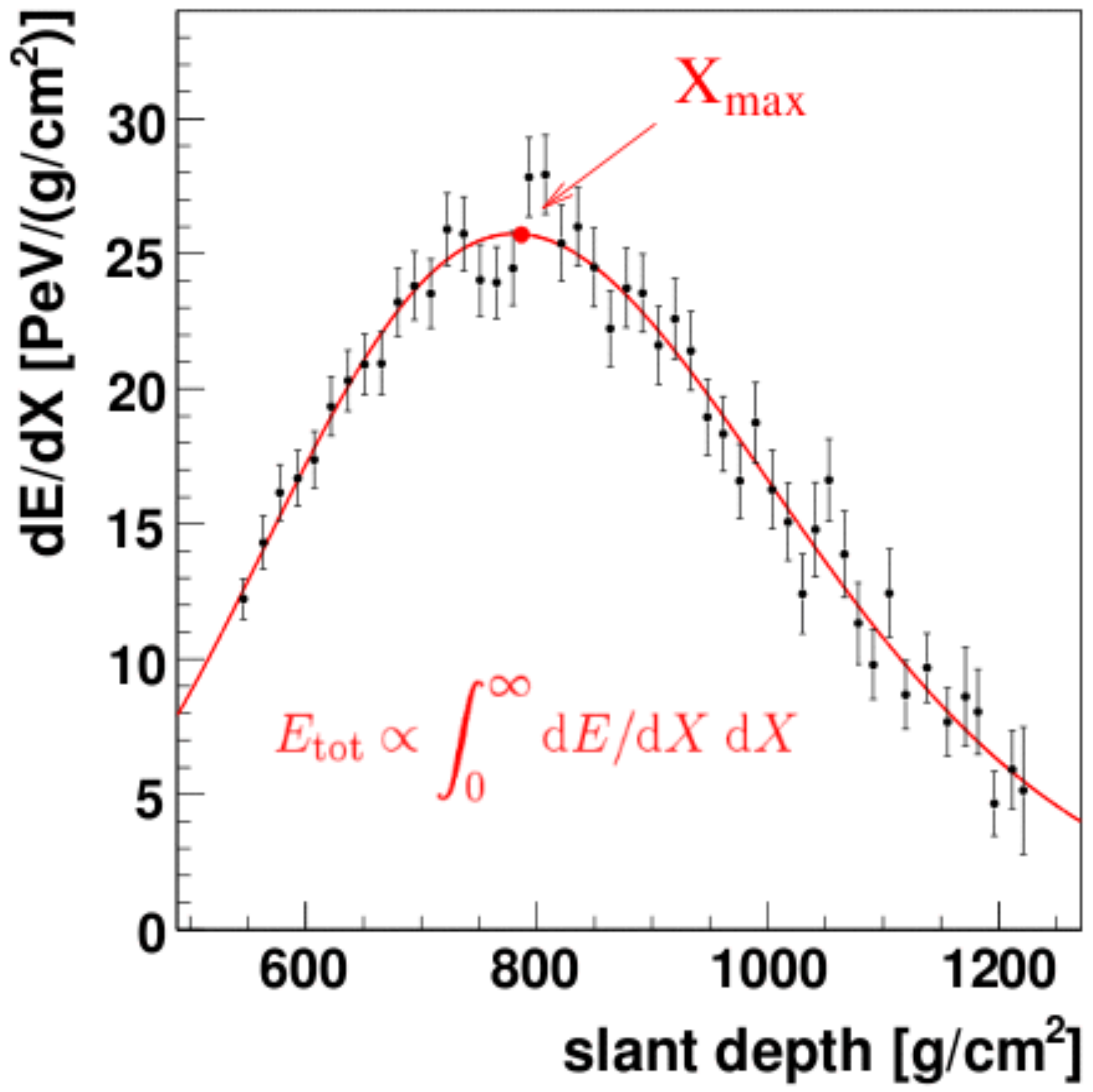
- Aerosol uncertainties dominate.
  - uncertainties in laser energy and FD calibration
  - variation in aerosol content over one hour
  - horizontal uniformity of aerosols (estimated using stereo events)

- Molecular (density) vertical profile (GDAS).

Re-evaluation of FD energy resolution

The Detector/Reconstruction



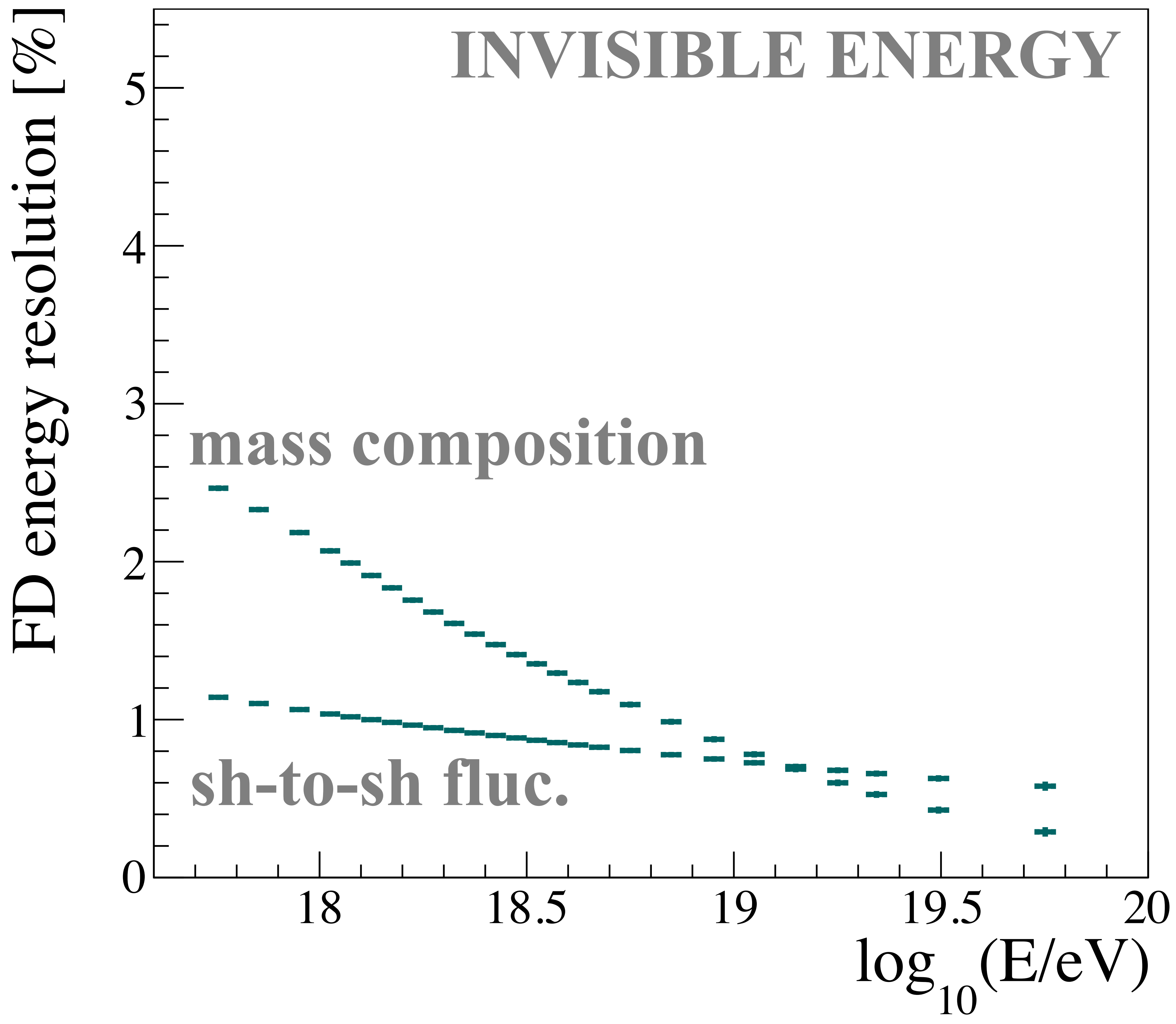


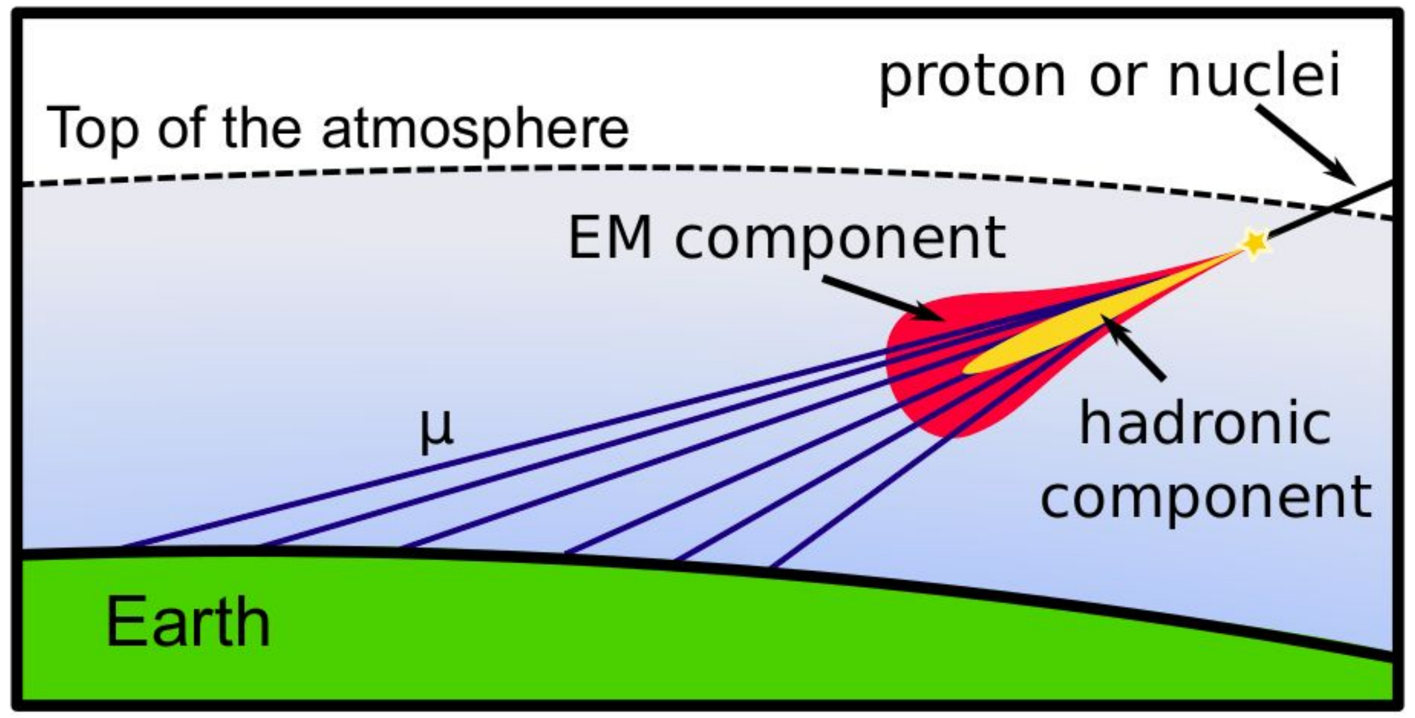
- Geometry and profile fit uncertainties, including extrapolation of profile.

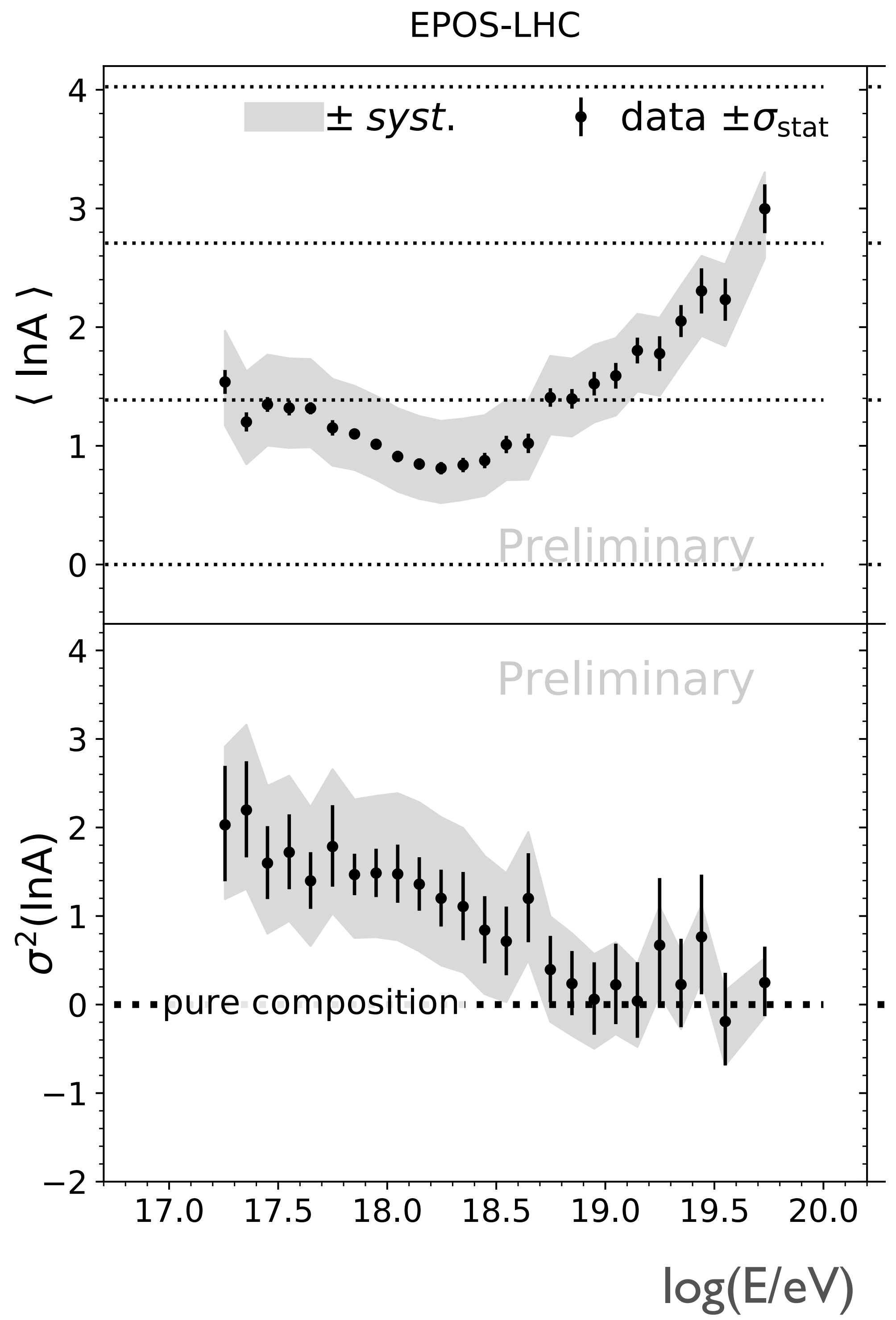
- Nightly relative calibration.
- Telescope to telescope absolute calibrations (via E_{SD}/E_{FD}).
- Long-term stability of calibration.

Re-evaluation of FD energy resolution

Invisible Energy



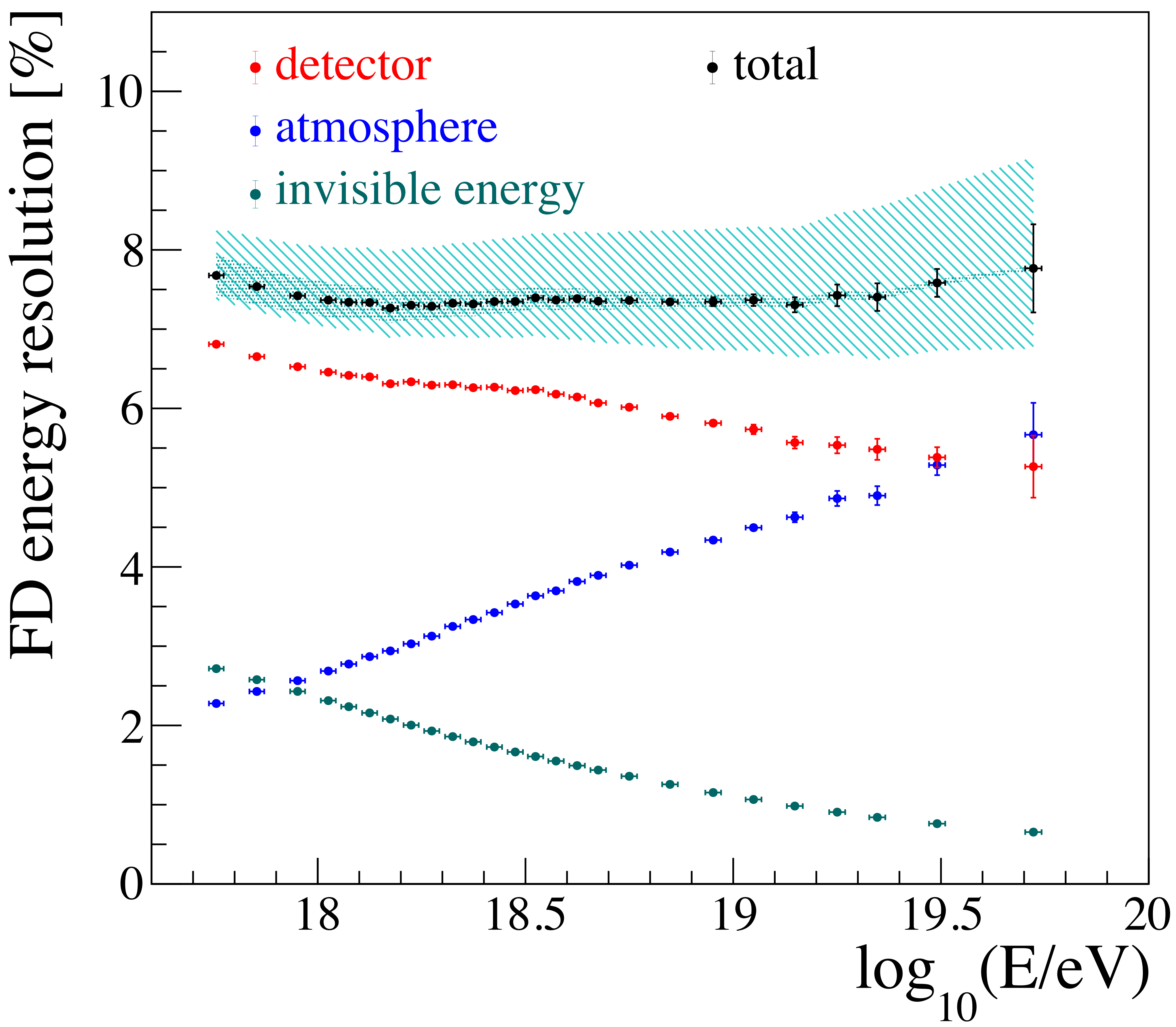




- Statistical uncertainty in corrections from
  - shower-to-shower fluctuations
  - mass variance around the mean at a given energy.

Re-evaluation of FD energy resolution

	FD energy resolution	
atmosphere	Aerosol optical depth	1.2% – 3.8%
	Horiz. uniform. of aerosols	1.6% – 5%
	Molecular atmosphere	1%
detector/ reconstruction	Nightly relative calib.	1.3%
	Time drift of FD energies	2.5%
	Mismatch between telescopes	3.5%
	Stat. error from geom. and GH fit	4.6% – 2.8%
	Extrapolation of profile	2.2%
invisible energy	E_{inv} shower-to-shower fluc.	1.1% – 0.6%
	E_{inv} mass uncertainty	2.4% – 0.3%
	TOTAL	7.6% – 8.6%



Note 1: "total" includes the benefit gained from stereo events above ~10^{19} eV (energies are averaged, improving resolution).

Note 2: total systematic band (cyan shading) is dominated by contributions from detector/atmosphere, but includes contribution from invisible energy (darker shading).

Conclusions

Steven Saffi, University of Adelaide

- We have reviewed the main sources of systematic uncertainty in our FD energies. The 2013 total energy systematic of 14% is still valid.
- We have described new study of FD energy resolution important for evaluating SD energy resolution and the correction of resolution effects in spectra. Energy resolution between 7% and 8%.
- see the next two talks for applications of this work.