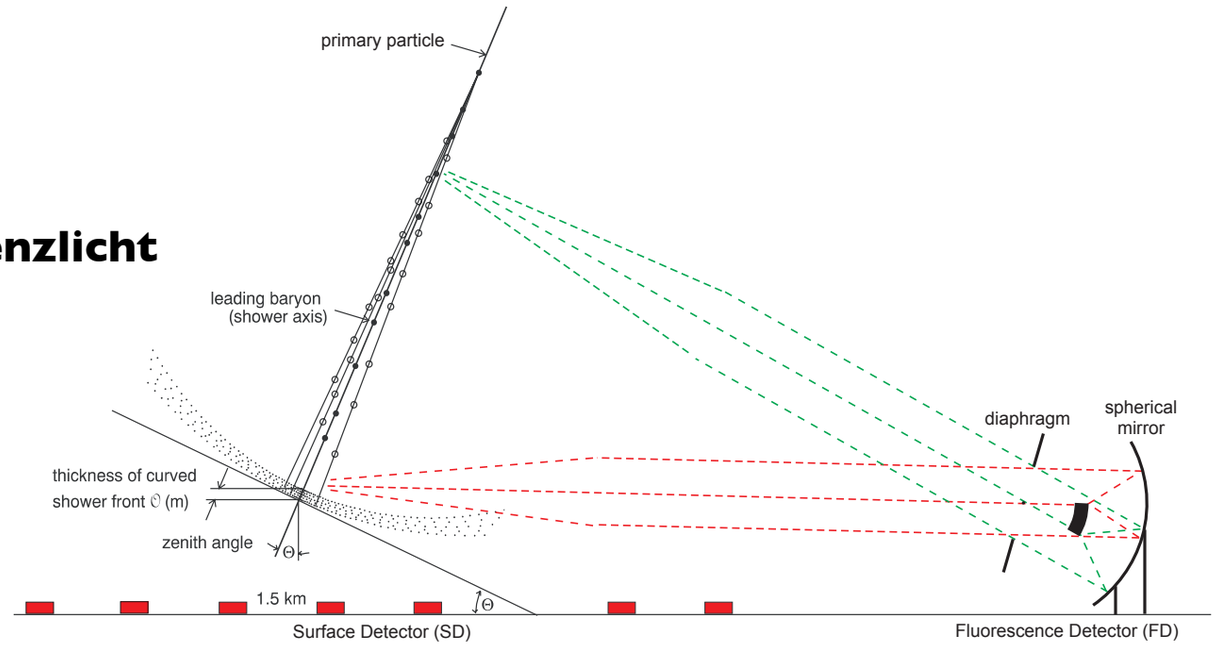
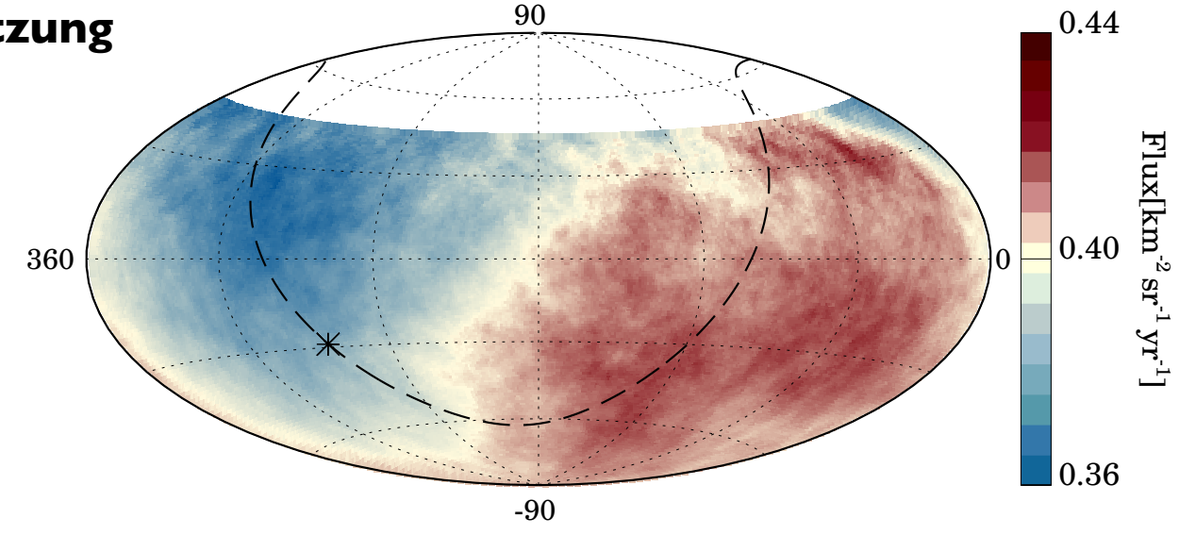
Vorlesung 9:
Abschluss: Indirekte Messung kosmischer Strahlung

Kalorimetrische Messung von Schauern mit Fluoreszenzlicht
- Prozess der Fluoreszenzemission in Luft
- Korrektur für nicht nachgewiesene Energie

Beispiel: das Pierre Auger-Observatorium
- Aufbau und Schauernachweismethoden
- Methode der Hybrid-Messung



Daten zum Primärfluss und der Elementzusammensetzung
- Knöchel (Ankle) im Fluss: Übergang zu extragalaktischen Quellen?
- Tiefe des Schauermaximums und Interpretation
- Anisotropie



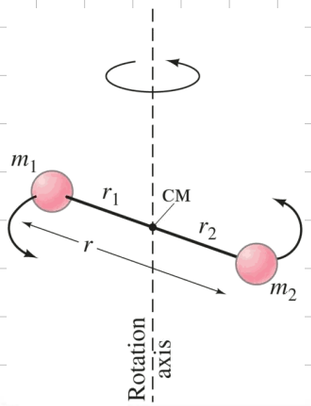
Vorlesung und Übungen : Daten

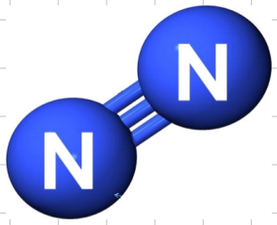
Vorlesung: Dienstags

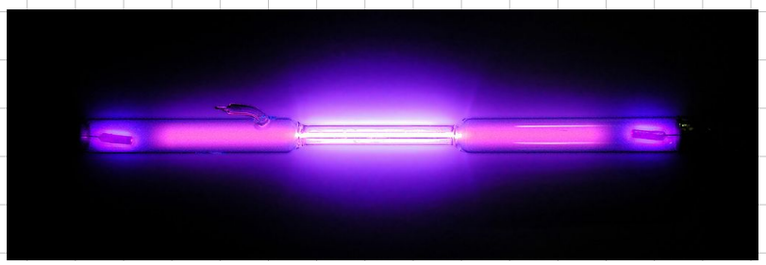
Übungen: Donnerstags
gehalten von Max Stadelmaier

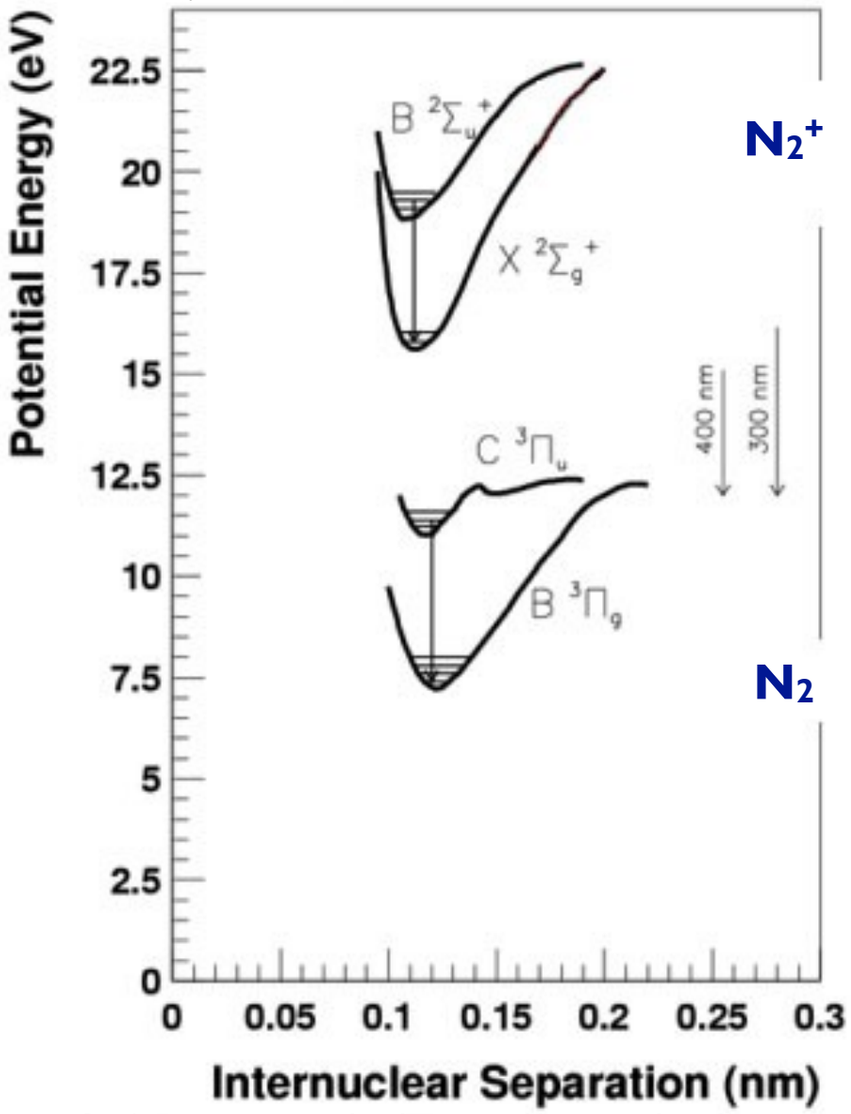
	~~3. Nov. 2020~~	~~19.11.2020 - Blatt 1~~
	~~10. Nov. 2020~~	~~03.12.2020 - Blatt 2~~
	~~17. Nov. 2020~~	~~17.12.2020 - Blatt 3~~
	~~24. Nov. 2020~~	~~14.01.2021 - Blatt 4~~
	~~1. Dez. 2020~~	11.02.2021 - Präsentation (Paul Filip)
	~~8. Dez. 2020~~	18.02.2021 - Blatt 5
	~~15. Dez. 2020~~	
	~~22. Dez. 2020~~	
	~~12. Jan. 2021~~	
	~~*19. Jan. 2021*~~	
	26. Jan. 2021	
	2. Feb. 2021	
Ersatz für 19.1.	4. Feb. 2021	
	9. Feb. 2021	
	16. Feb. 2021	

Fluoreszenzlicht von Stickstoffmolekülen

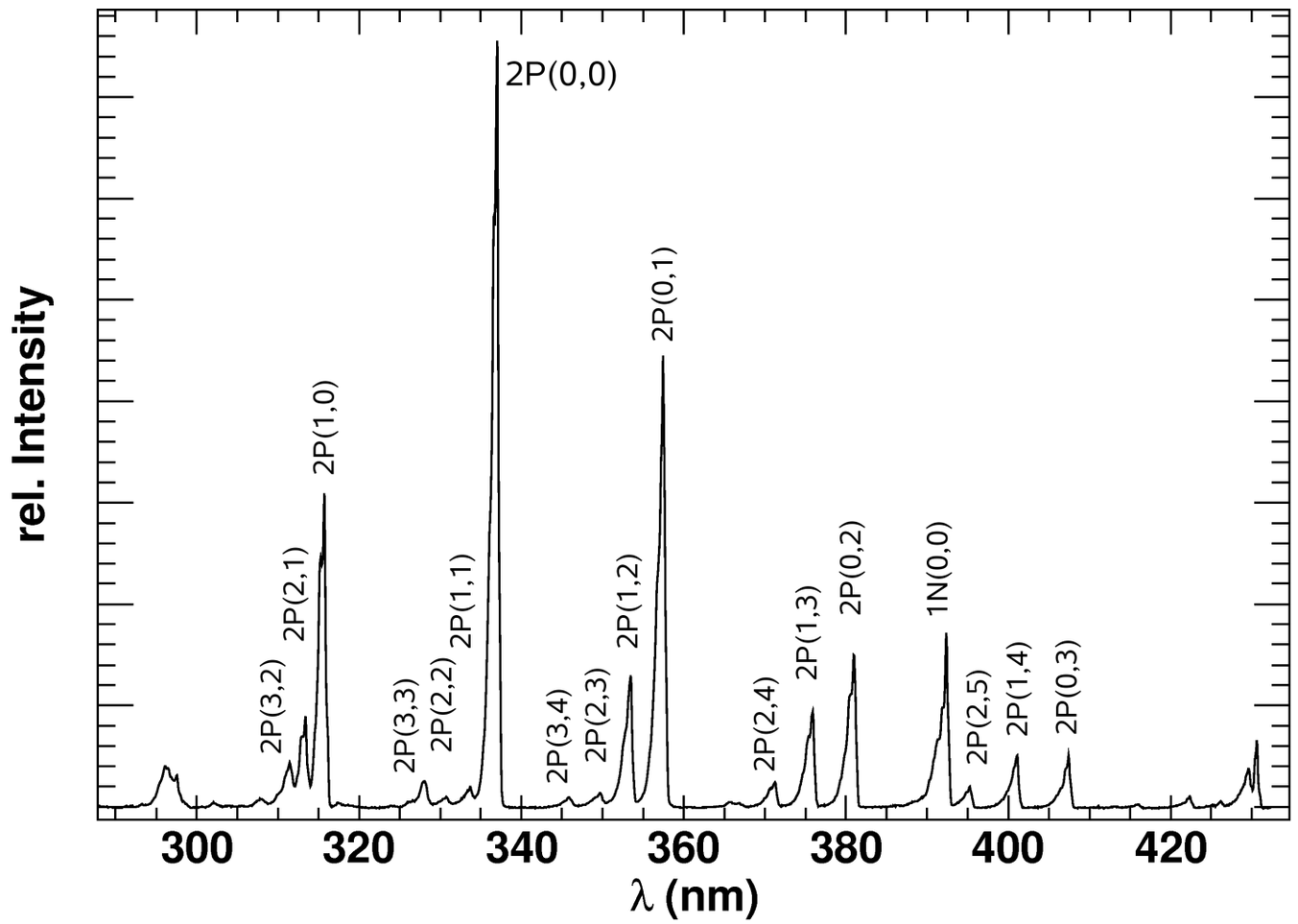






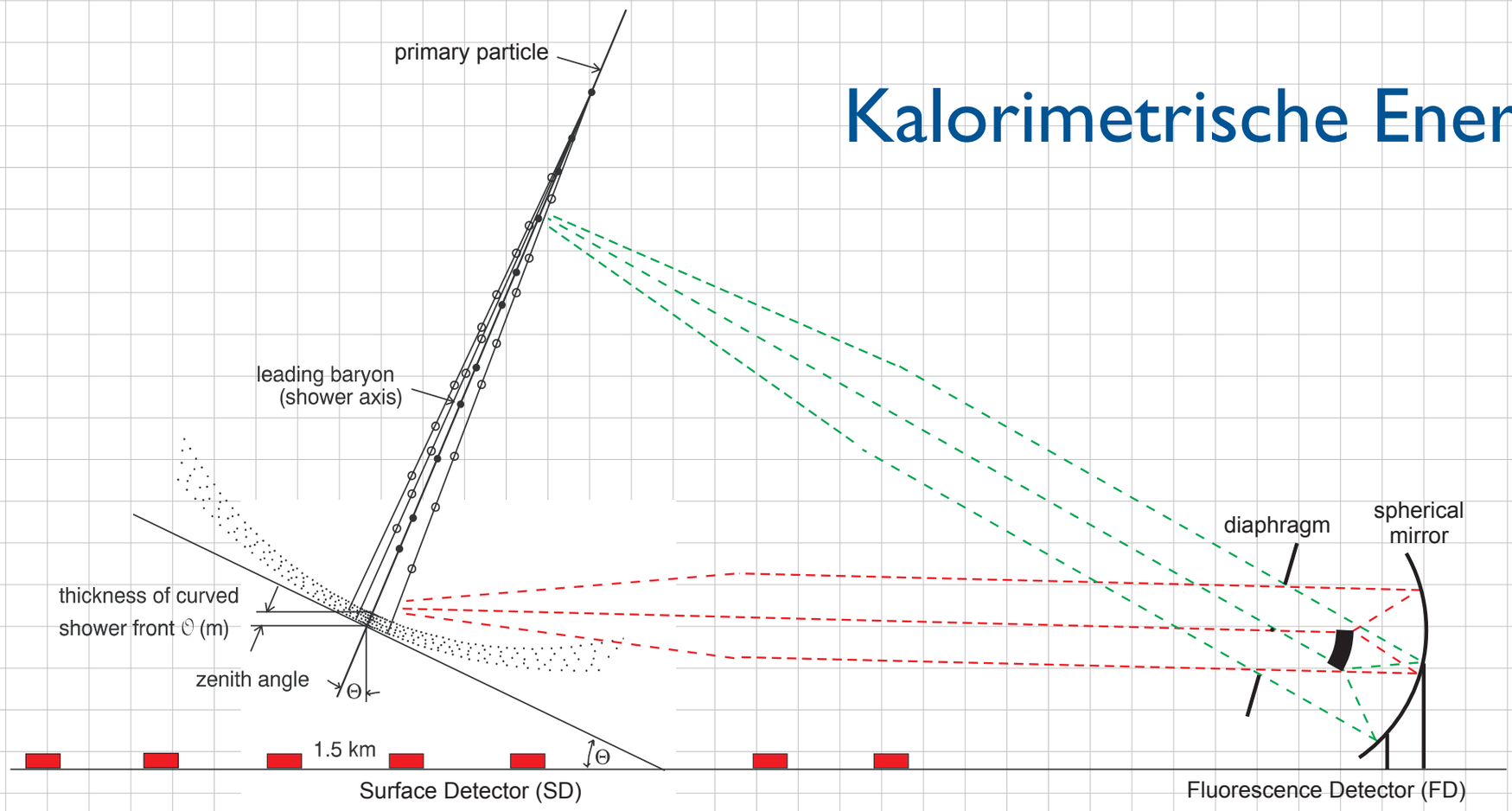


3-4 Photonen/m/Teilchen in 10km Höhe
entspricht einer 30 Watt-Glühbirne

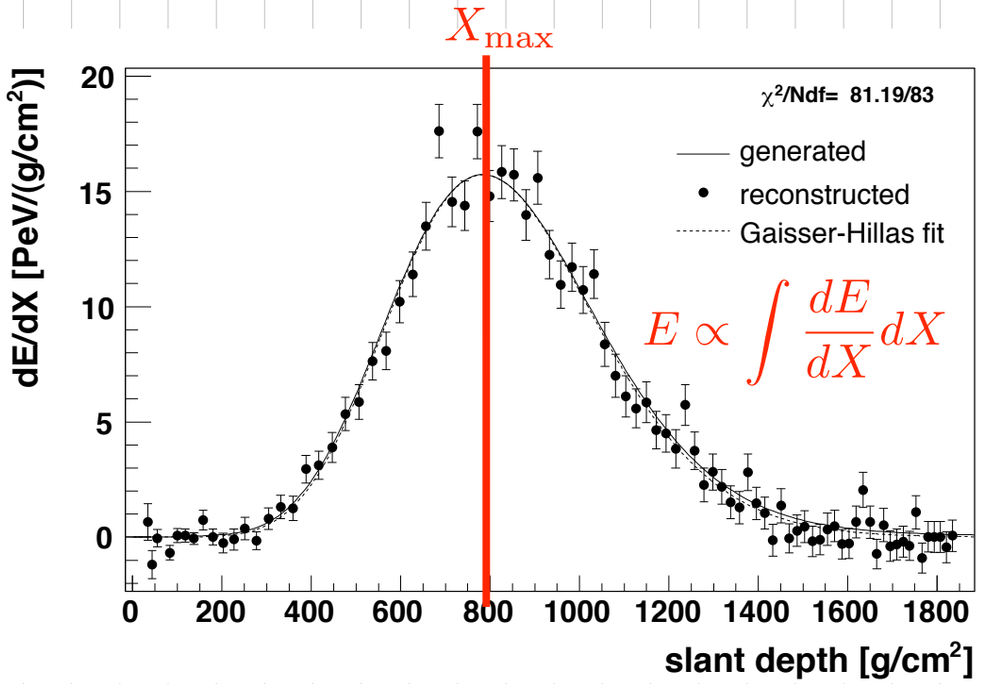


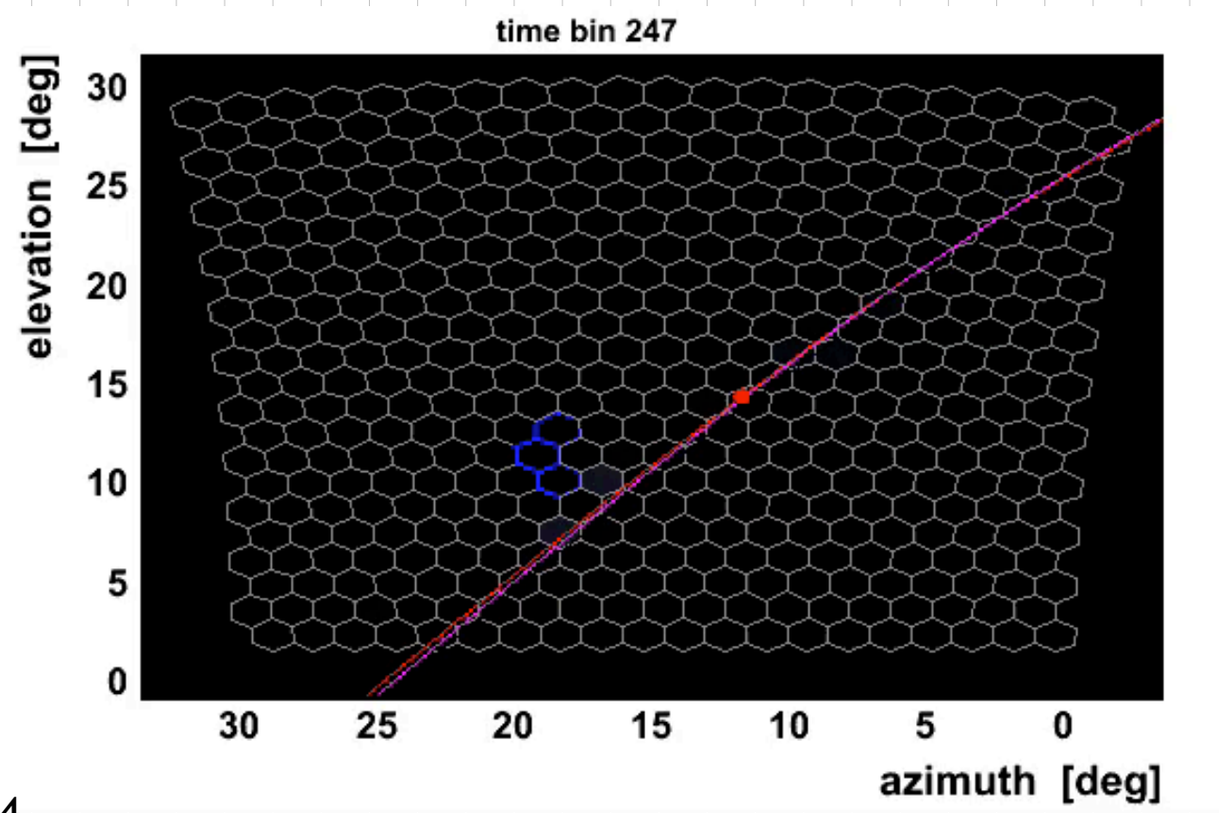
Lebensdauer des angeregten Zustands ~10^{-8} s =10ns
isotrope Emission, hauptsächlich im UV (300 - 400 nm)

Kalorimetrische Energiemessung

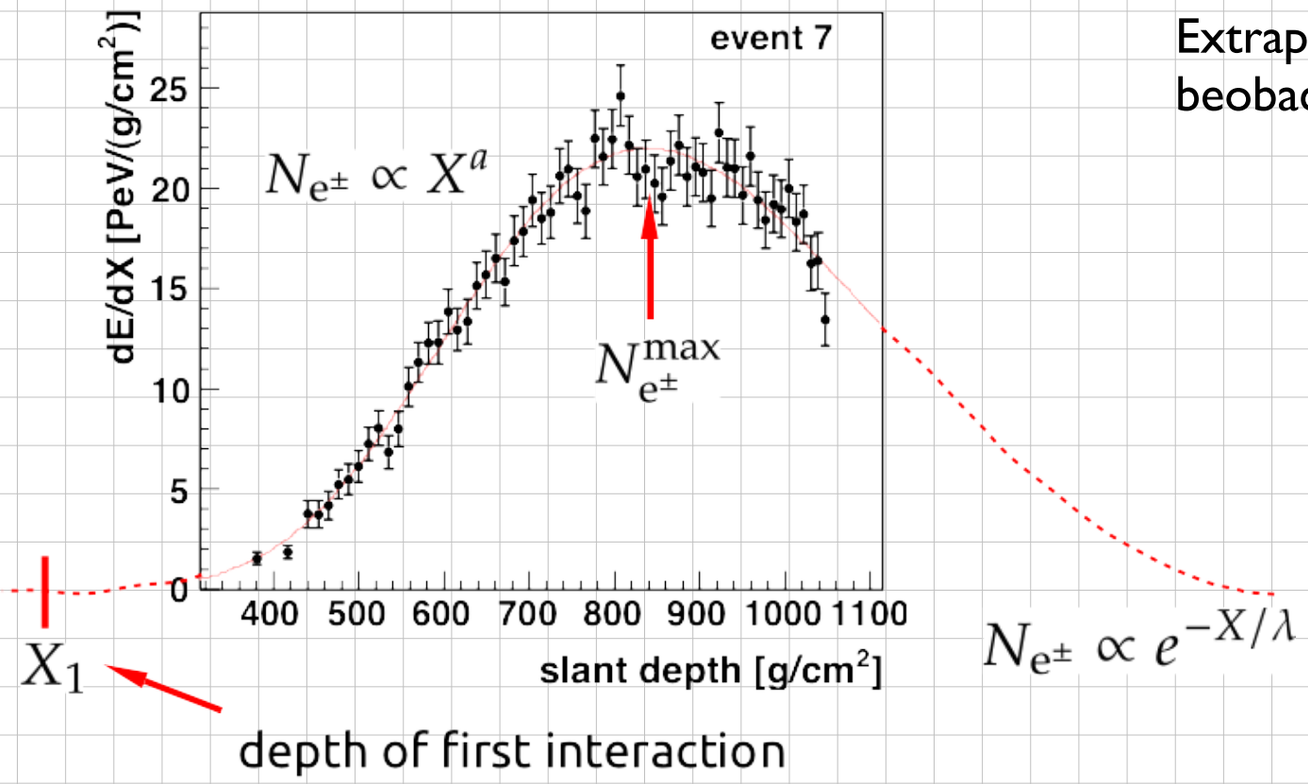


Ionisationsenergieabgabe in Luft





Kalorimetrische Messung der Energie



Extrapolation in nicht direkt beobachtete Bereiche erforderlich

$$E_{\text{cal}} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\text{measured}} dX$$

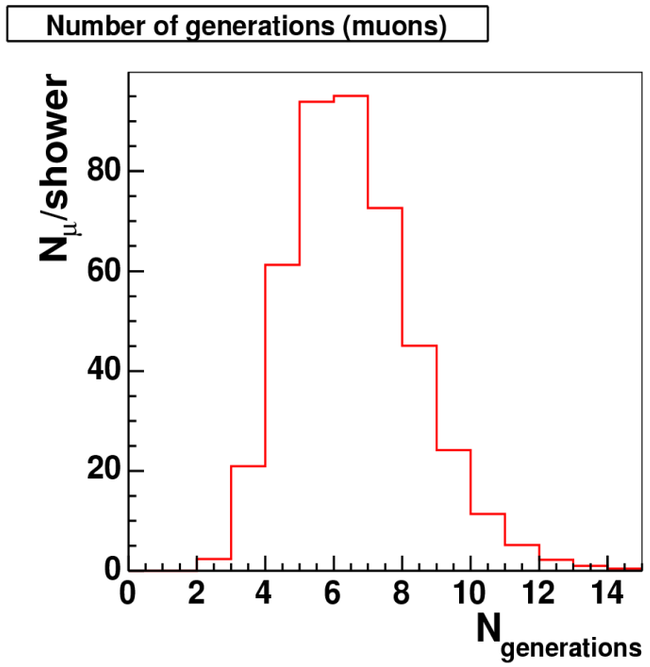
$$\approx \int_0^\infty \langle \alpha_{\text{ion}} \rangle \left(\frac{dN_e}{dX}\right)_{\text{measured}} dX$$

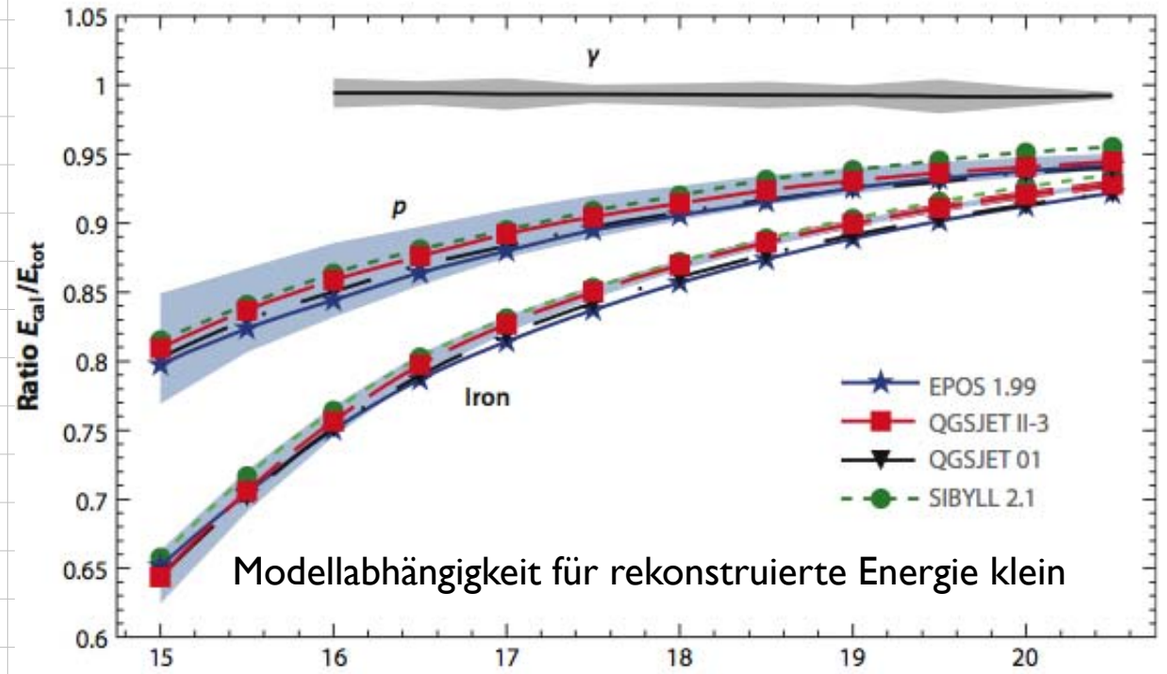
$$N_e(X) = N_{e,\max} \left(\frac{X - X_1}{X_{\max} - X_1}\right)^{\frac{X_{\max} - X_1}{\Lambda}} \exp\left(\frac{X_{\max} - X}{\Lambda}\right)$$

Korrektur der *unsichtbaren Energie*

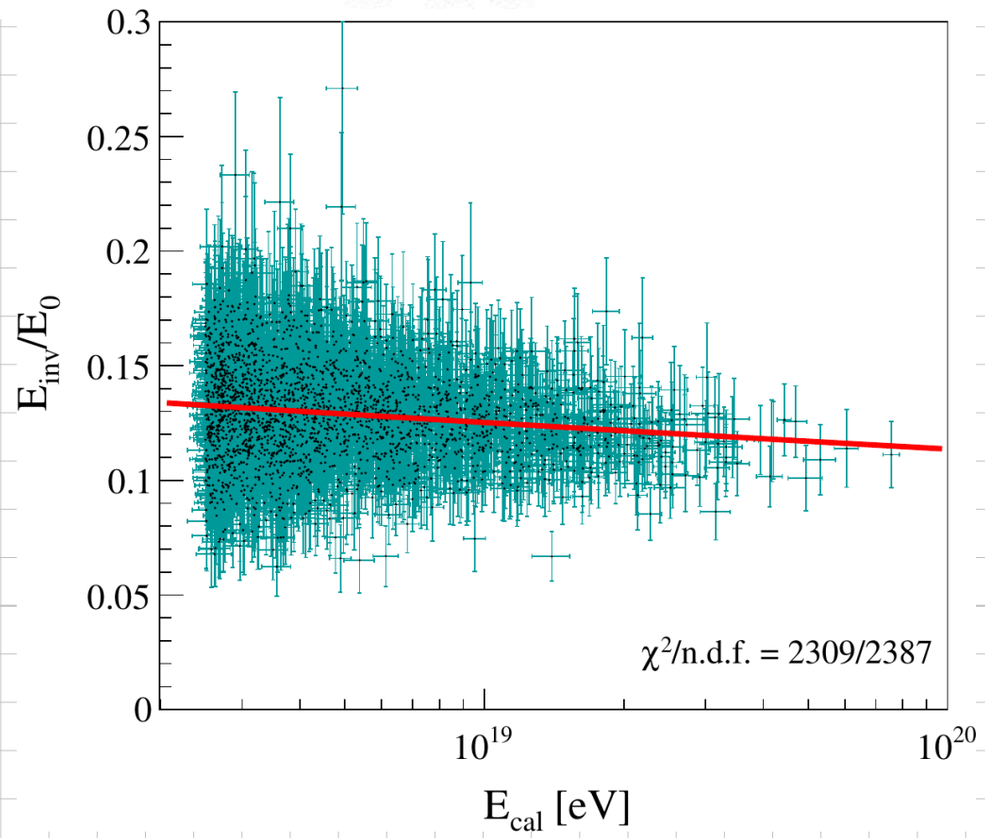
Energiekorrekturfaktor für Fluoreszenzmessungen

Protonschauer, E = 10^{15} eV



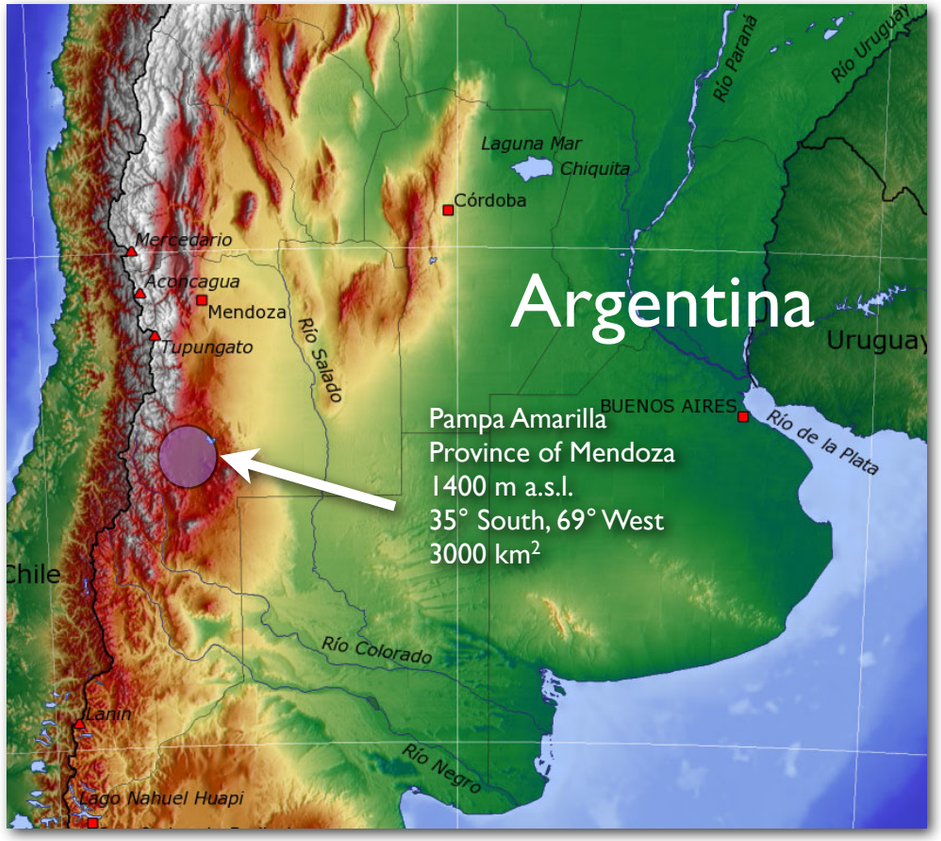


Modellabhängigkeit für rekonstruierte Energie klein



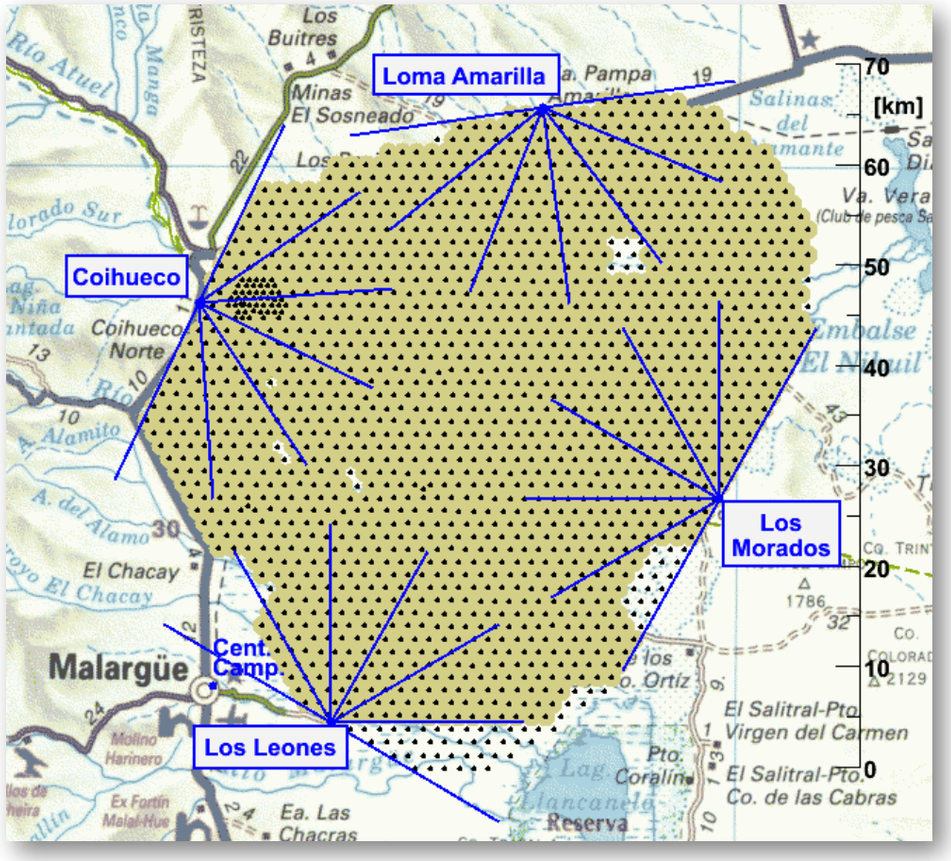
The Pierre Auger Observatory

- Auger: >400 authors from 17 countries
- Southern site:
  Hybrid detector near Malargüe/Argentina



- June 13th 2008 : 1660 tanks deployed
  1637 with water
  1603 totally equipped

- All 4 fluorescence buildings complete
  each with 6 telescopes since February 2007



Ausgedehnte Luftschauer

Primär-
teilchen

Projektilrest

$\pi^\pm$ π^0 γ e^- e^+ ν_μ $\mu^\pm$ ν_e p

Primär
teilchen

Pierre Auger Observatorium:
10^{19} eV < E < 10^{21++} eV

ca 8 km Höhe

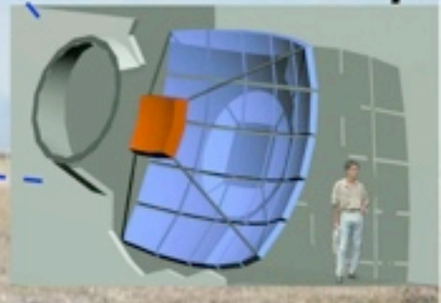
Trajektorie

Fluoreszenz,
Cherenkov Licht

$v \approx c$

1 m Dicke

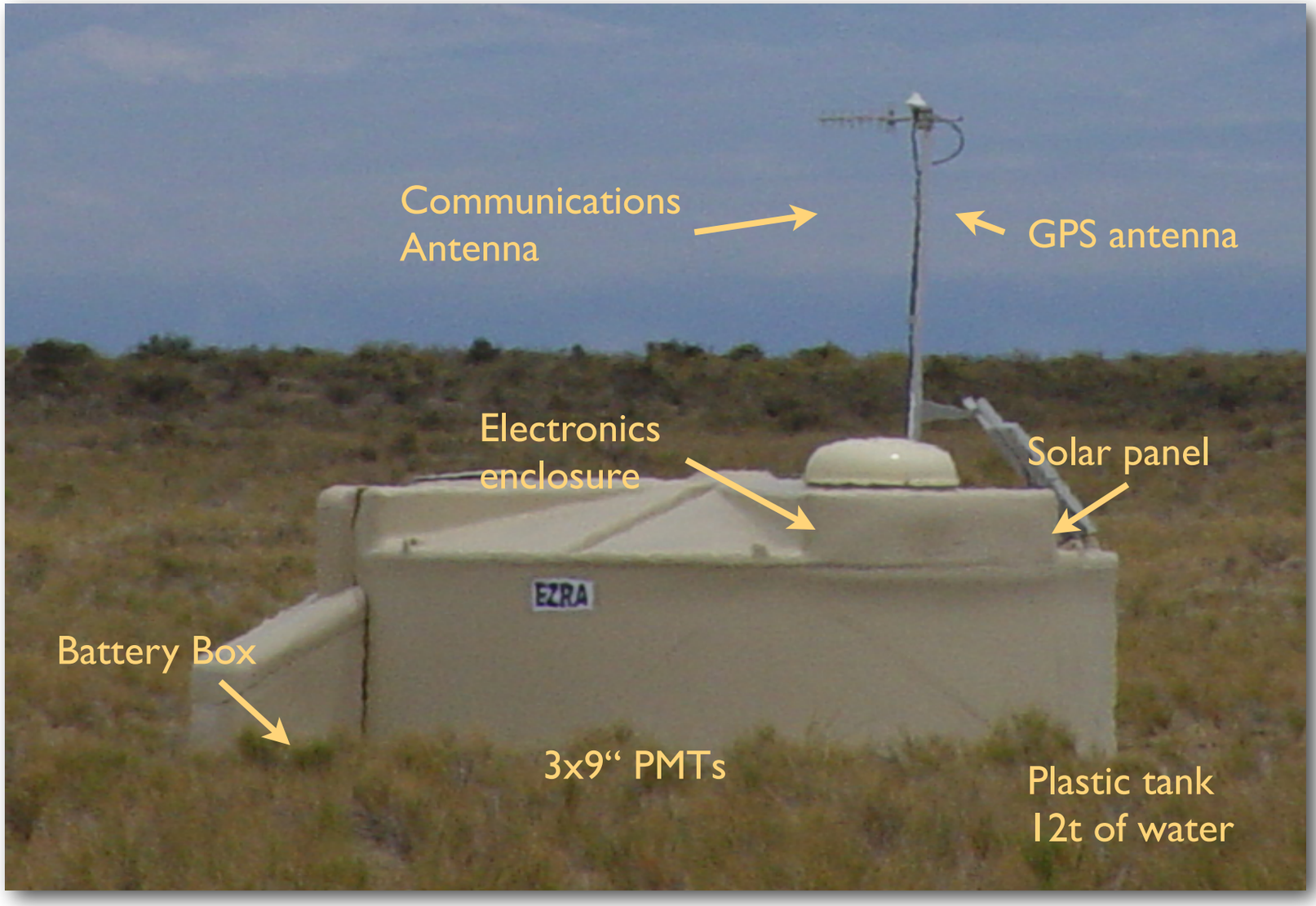
Elektronisches
Schmidt-Teleskop



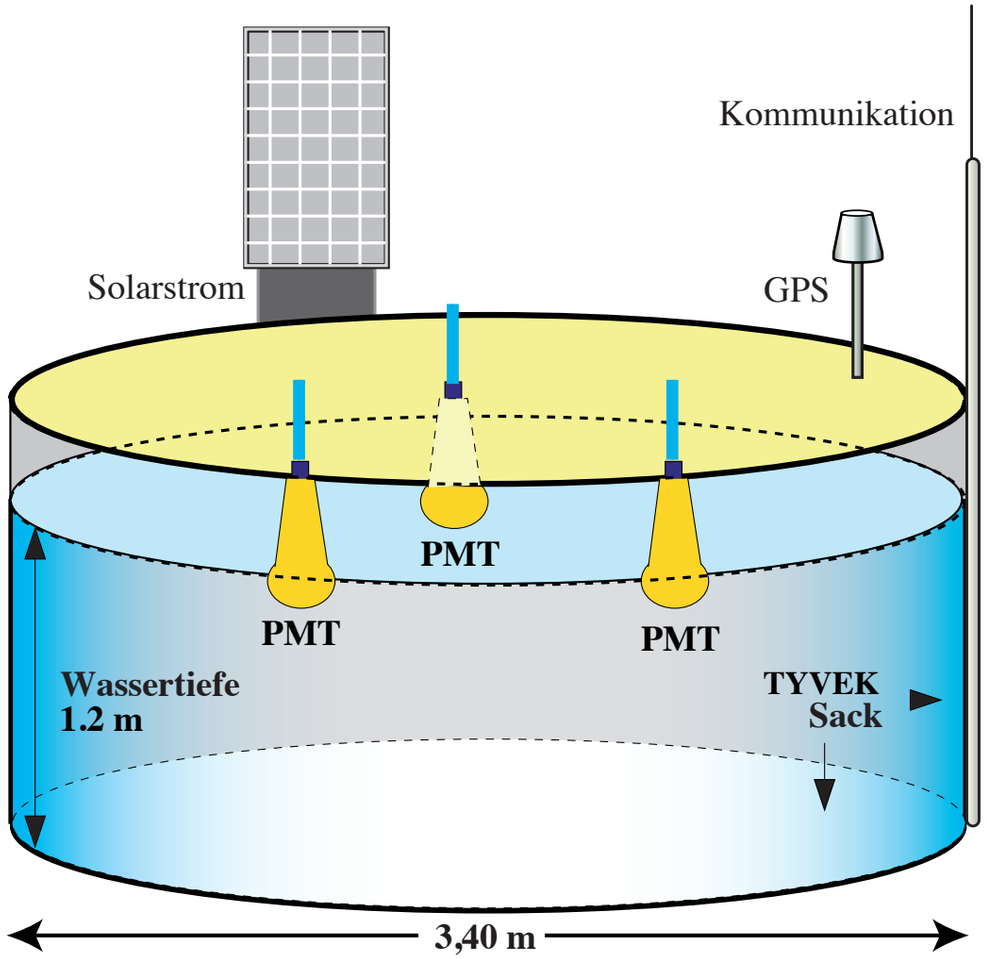
Wasser-
Cherenkovdetektoren

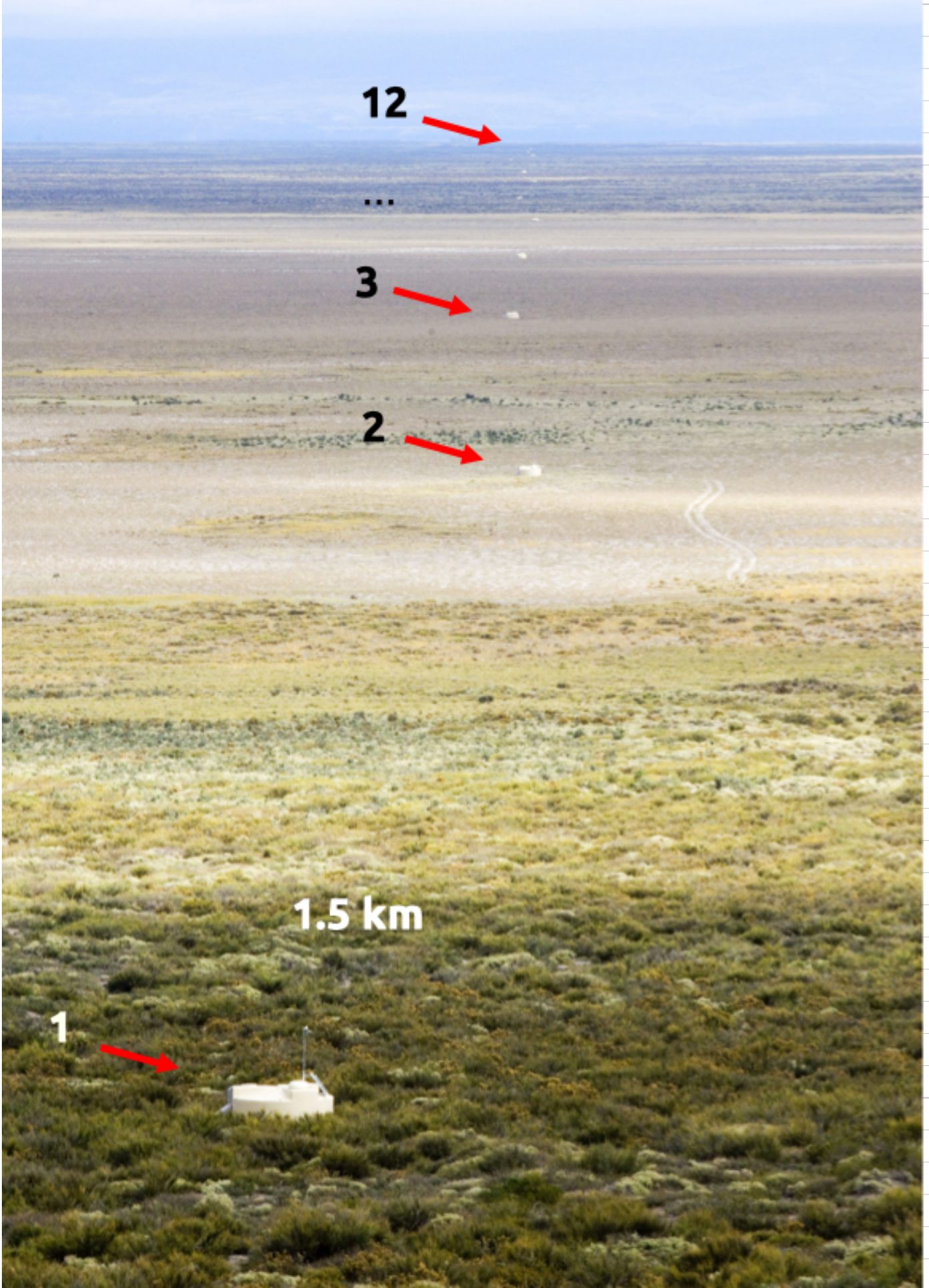
The surface detector

- 1600 Water Cherenkov tanks (1.2 m height, 10 m^2 area)
- 12,000 ltrs of purified Water
- Three 9“ PMTs
- 40 MHz FADCs
- solar powered
- GPS based timing
- micro-wave communication

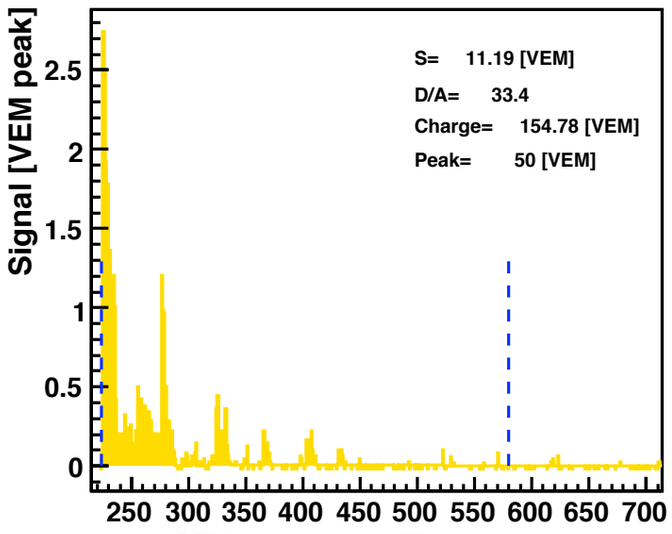


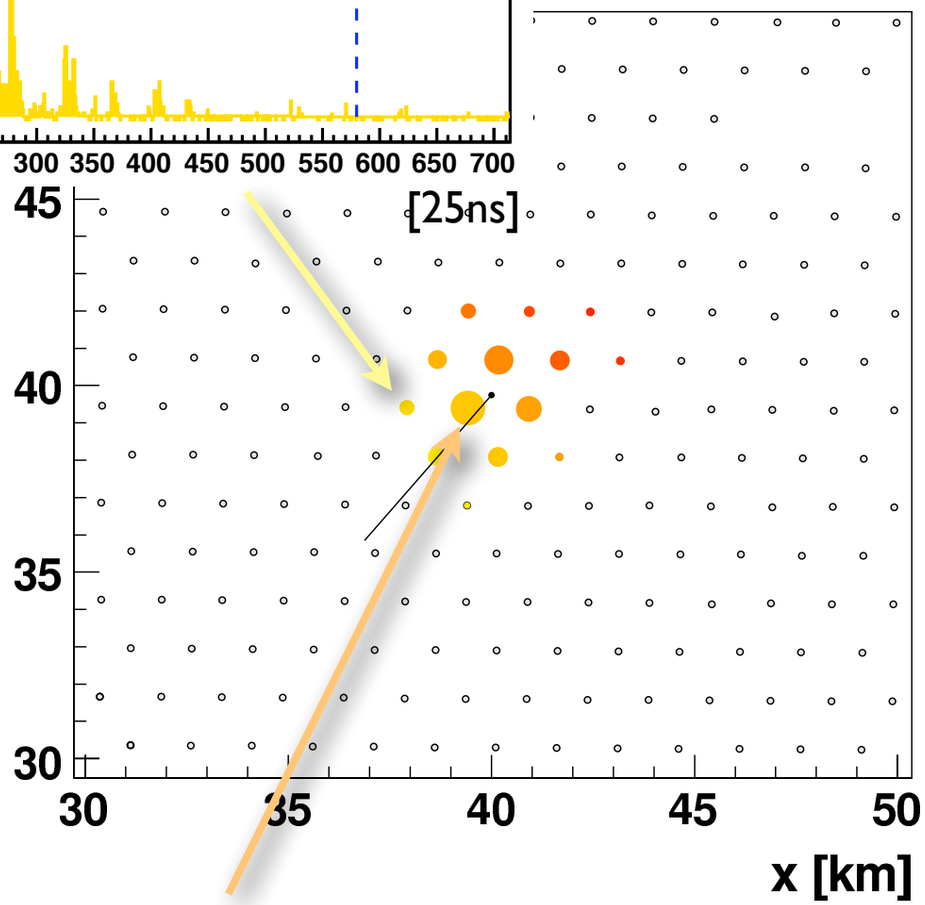
Wasser-Cherenkovdetektor

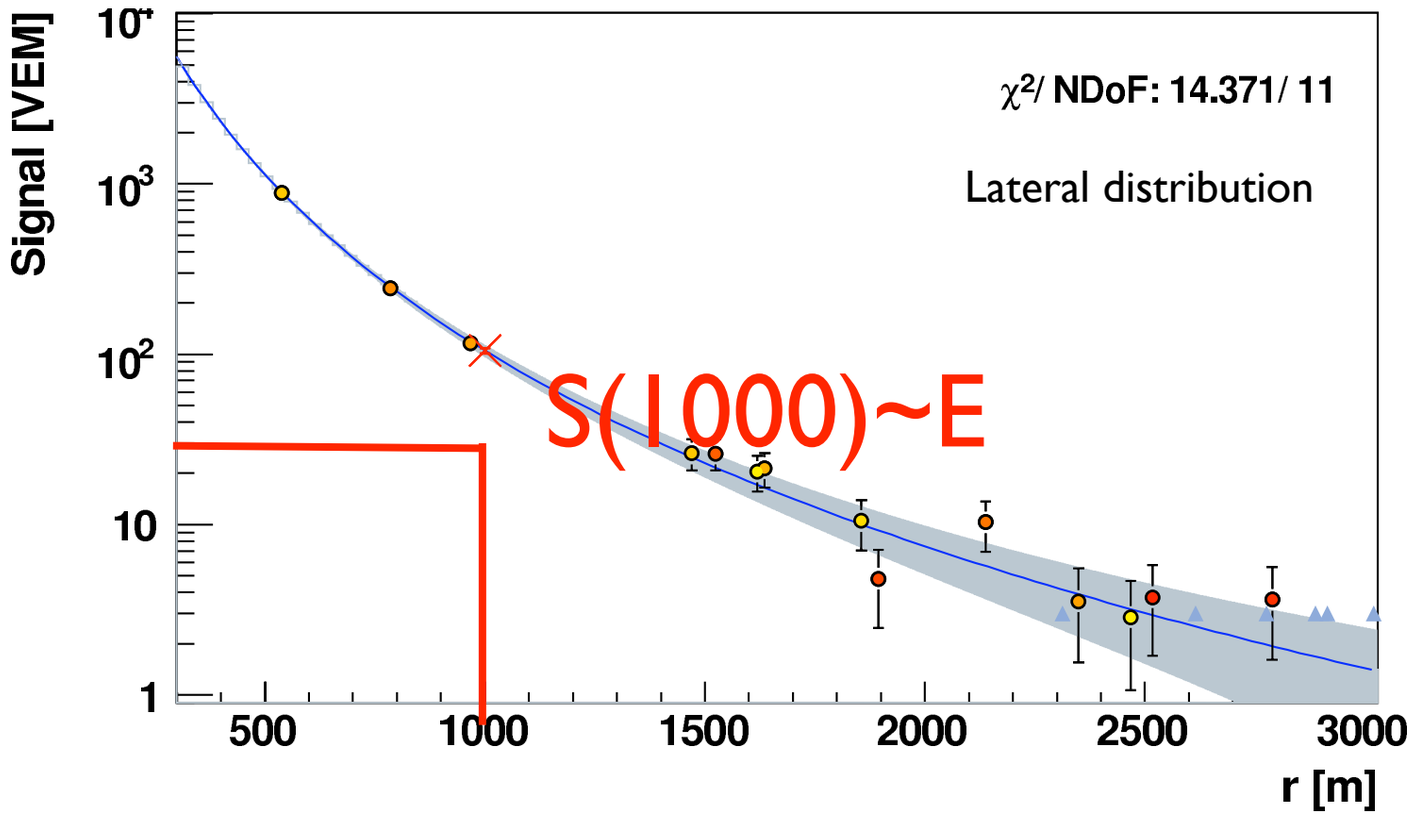


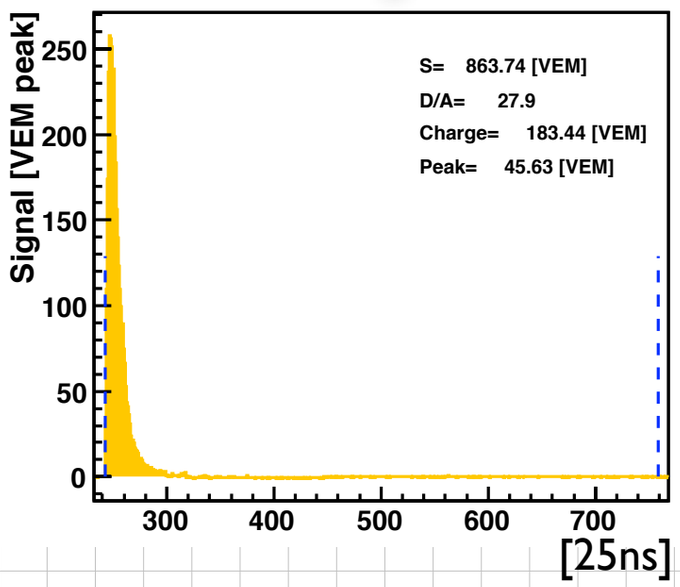

12
...
3
2
1.5 km
1

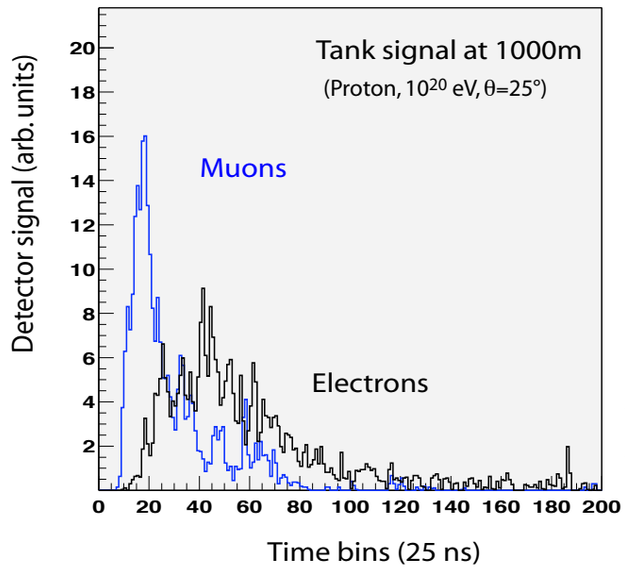
SD reconstruction



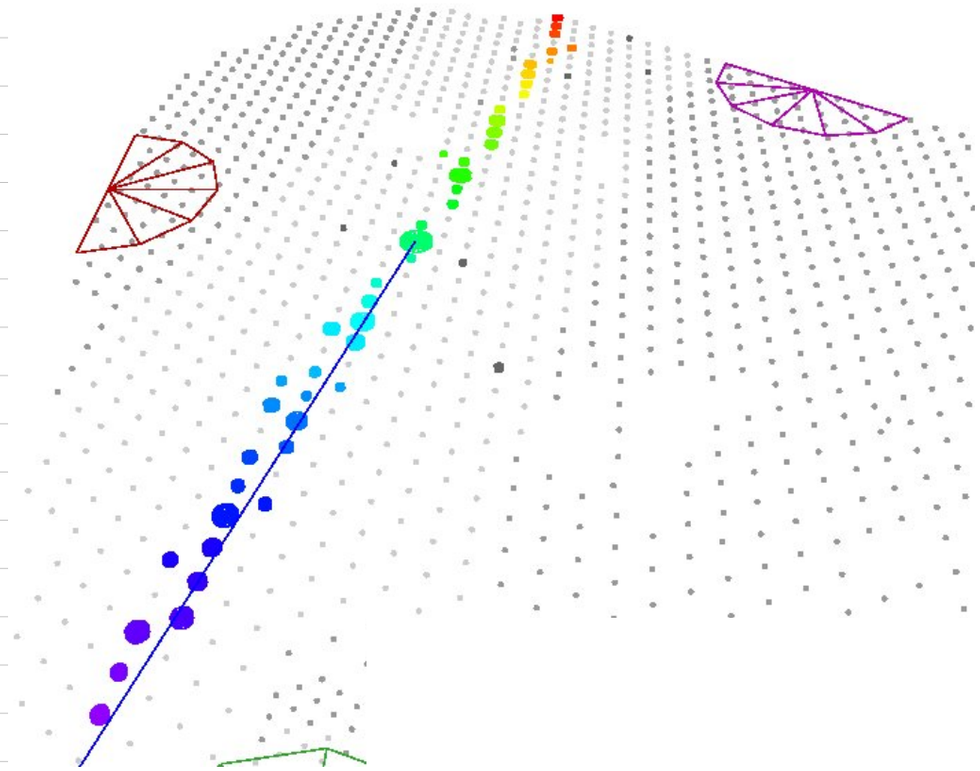




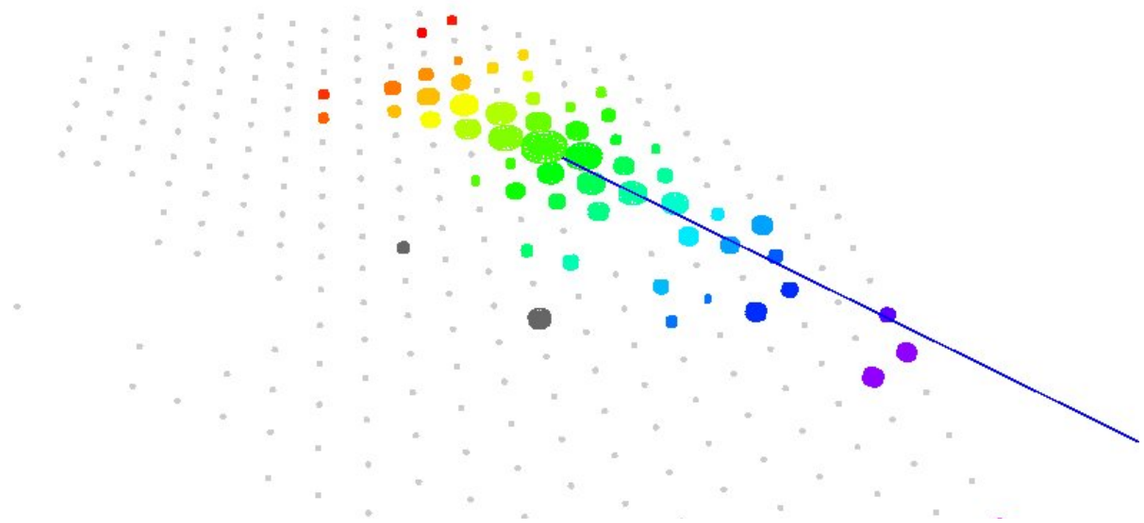




Beispiele sehr schräger Schauer



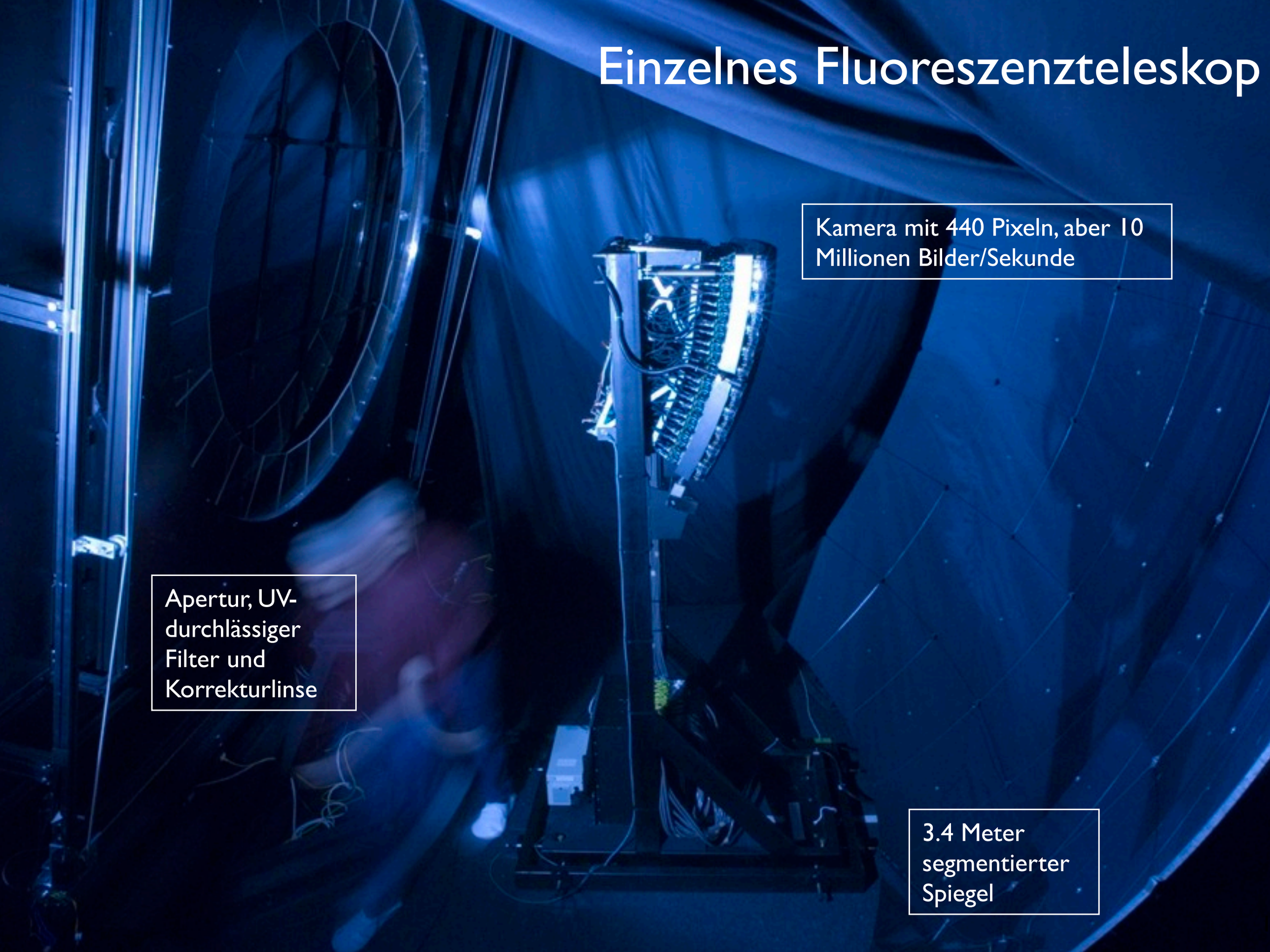
- 14.07.2008
- longest event: 65 km, 45 stations
- zenith: 87 degrees



- 17.08.2008
- highest multiplicity: 54 stations
- zenith: 82 degrees

6 Telescope mit je 30x30 Grad Gesichtsfeld

Einzelnes Fluoreszenzteleskop

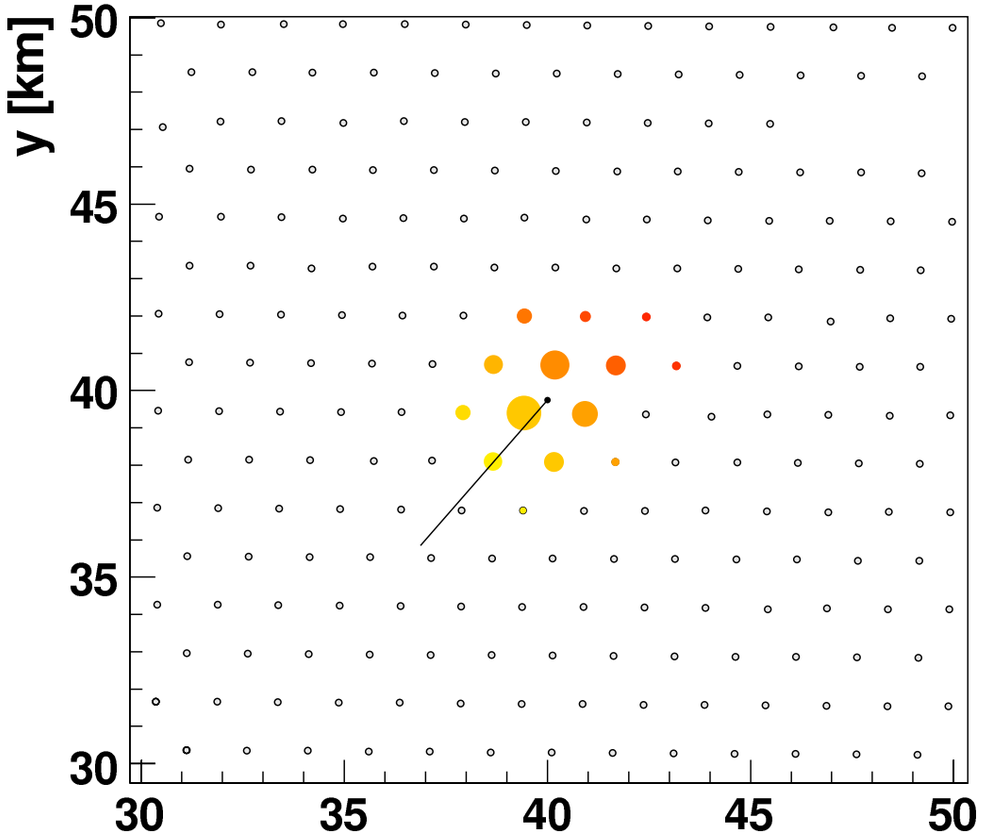


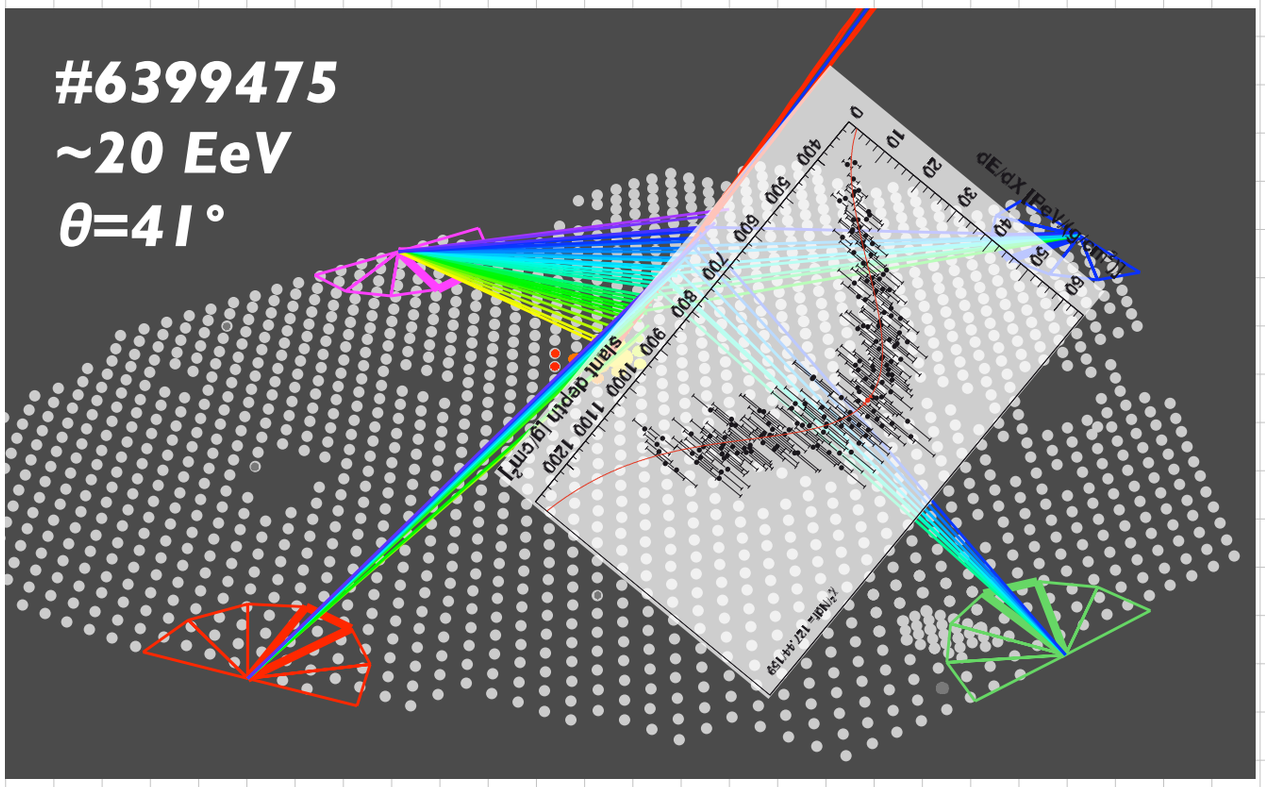
Kamera mit 440 Pixeln, aber 10 Millionen Bilder/Sekunde

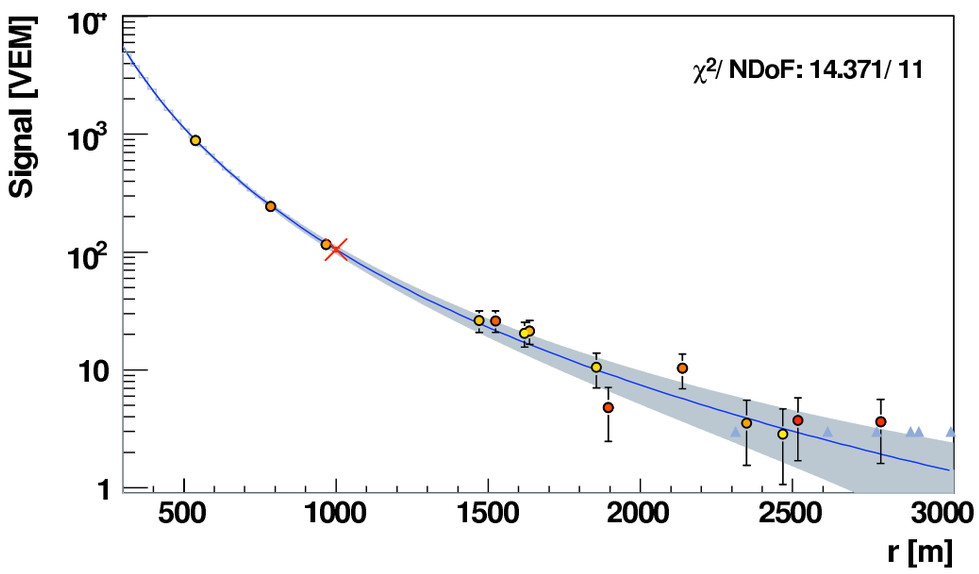
Apertur, UV-durchlässiger Filter und Korrekturlinse

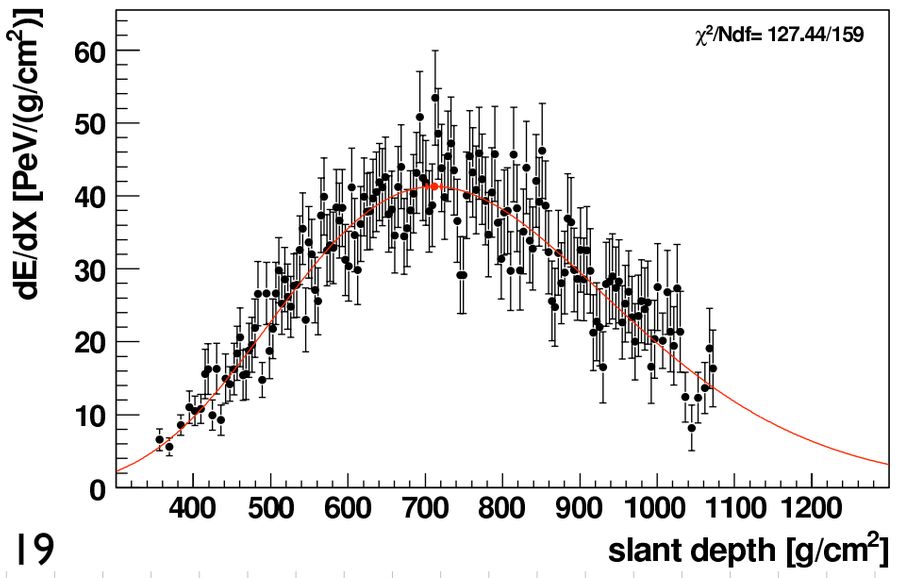
3.4 Meter segmentierter Spiegel

Hybrid-Messung

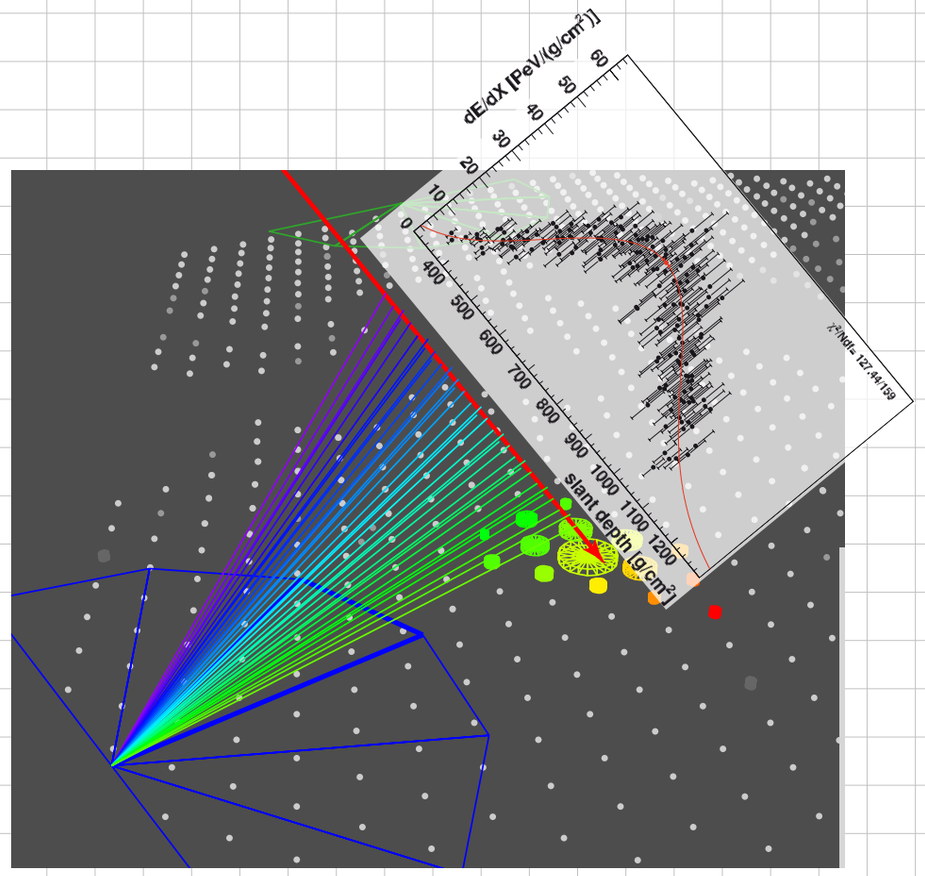




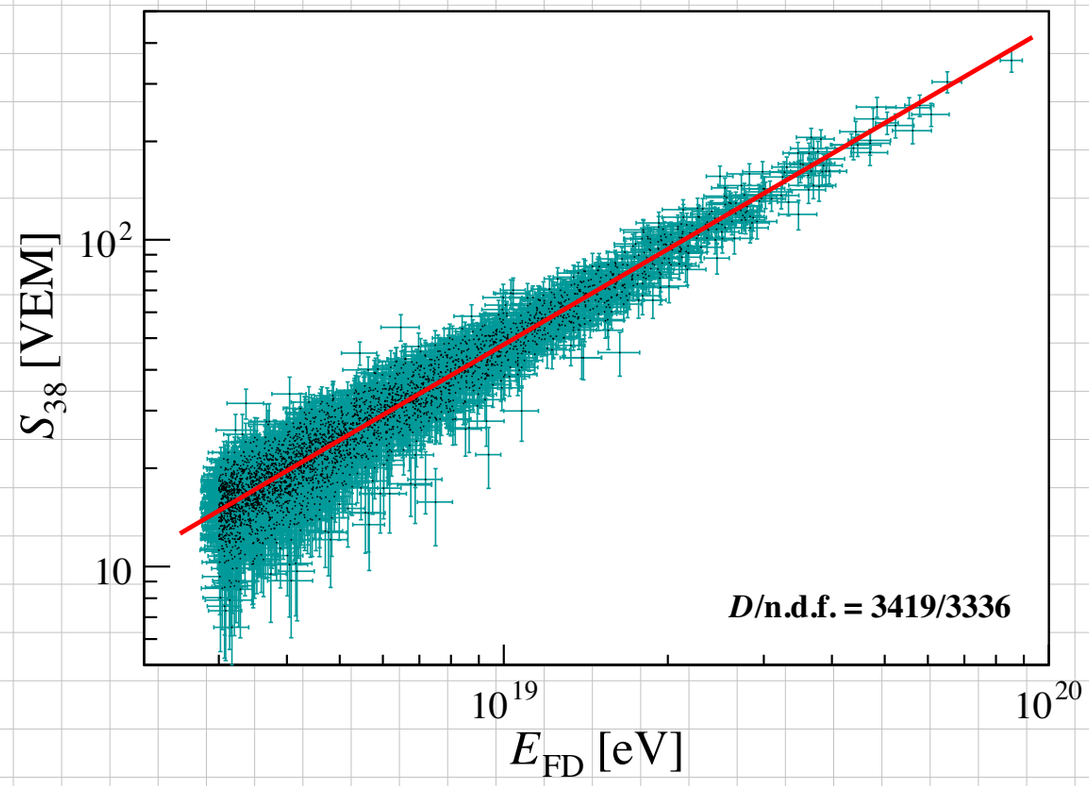




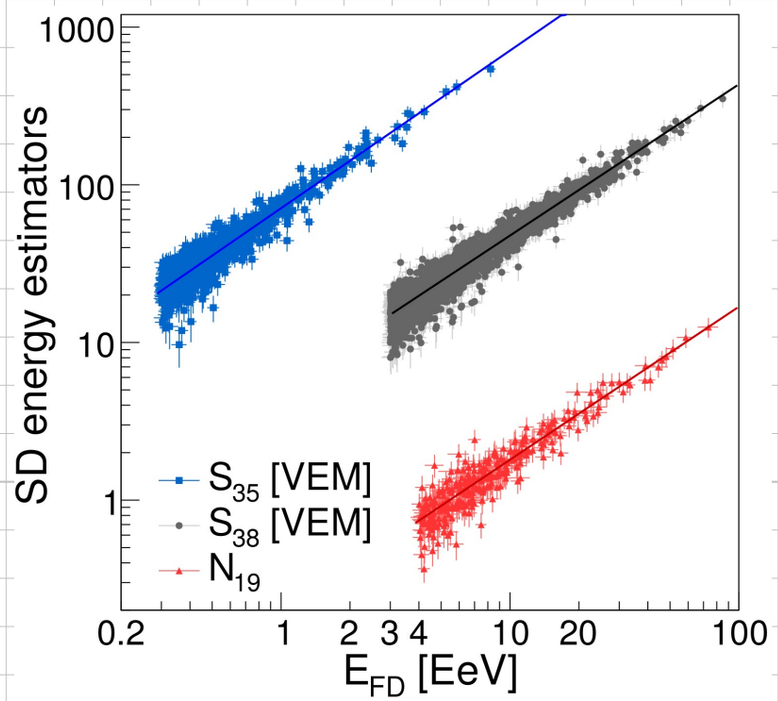
Energiekalibration des Oberflächendetektors

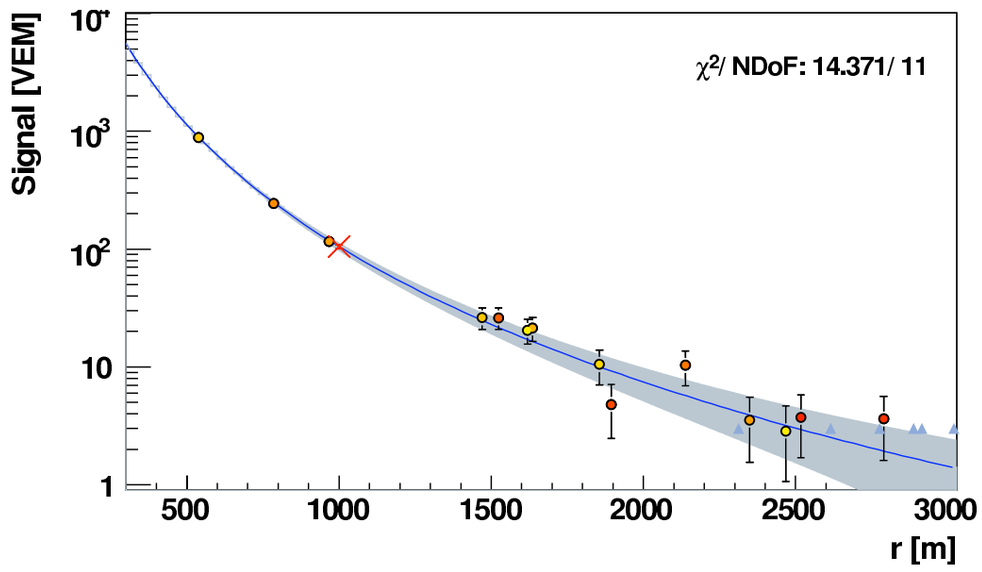


Oberflächensignal bei 1000m, θ=38°

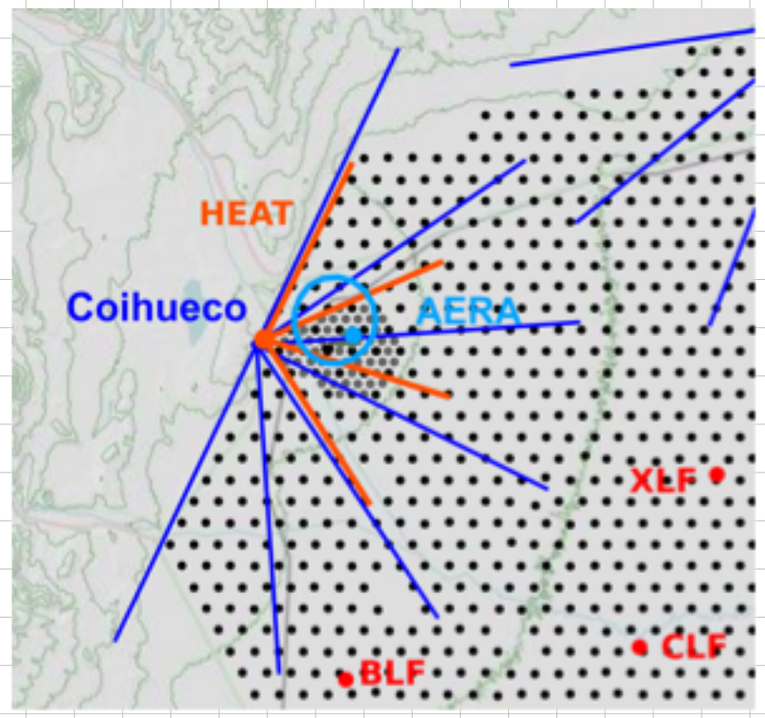


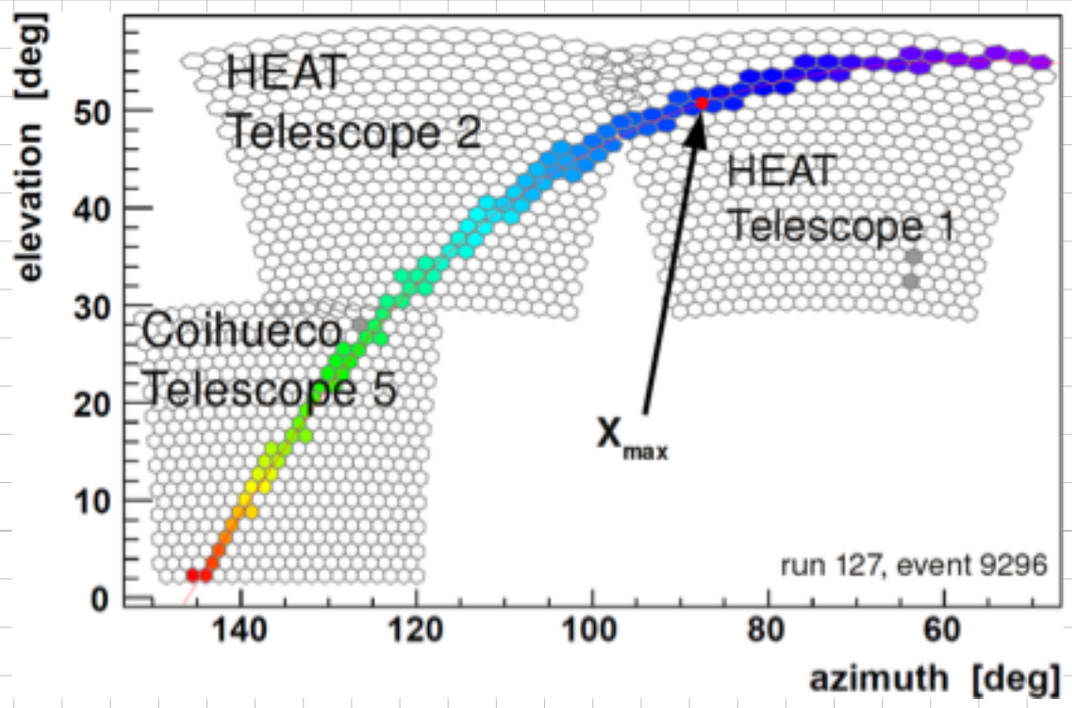
Energie gemessen mit Fluoreszenzdetektor



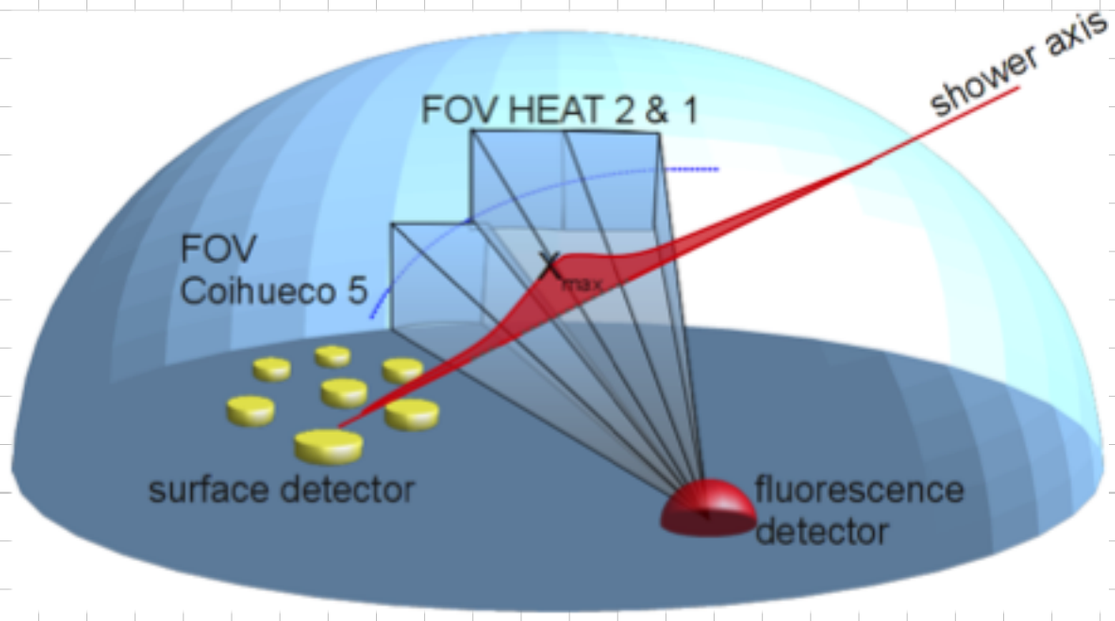


HEAT: FD+Cherenkov

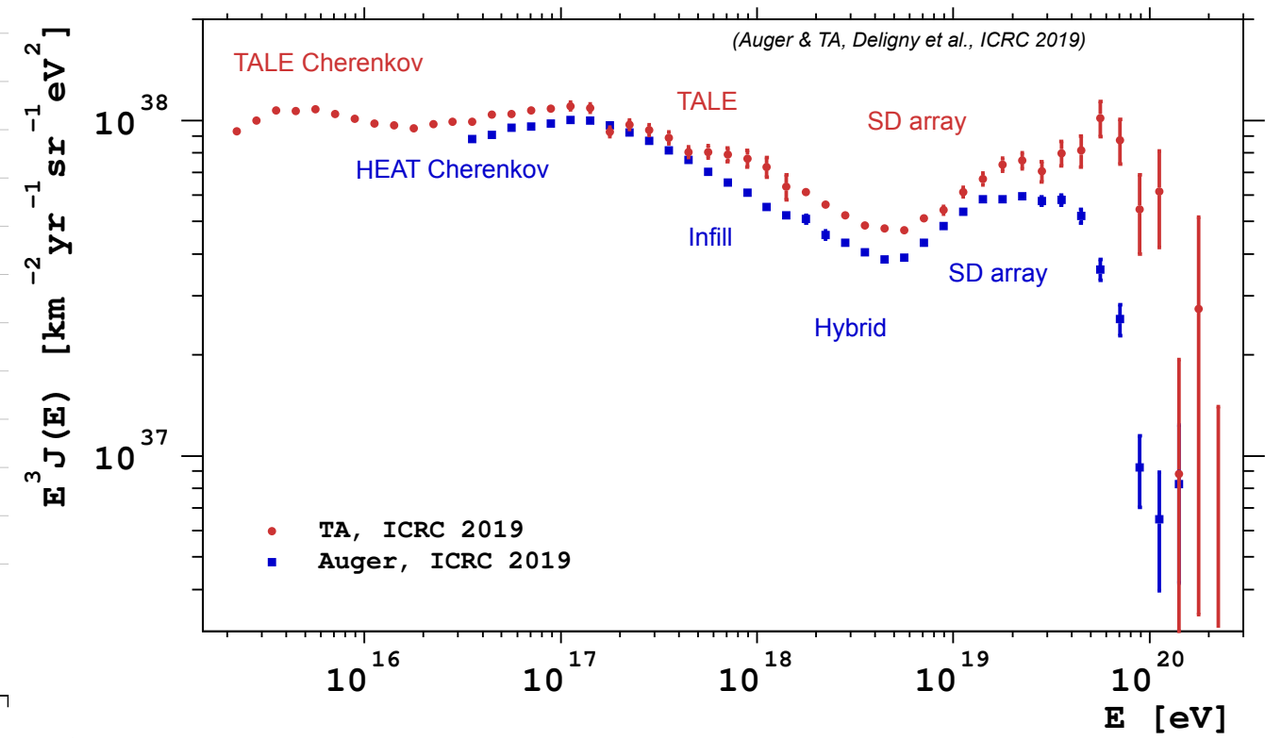


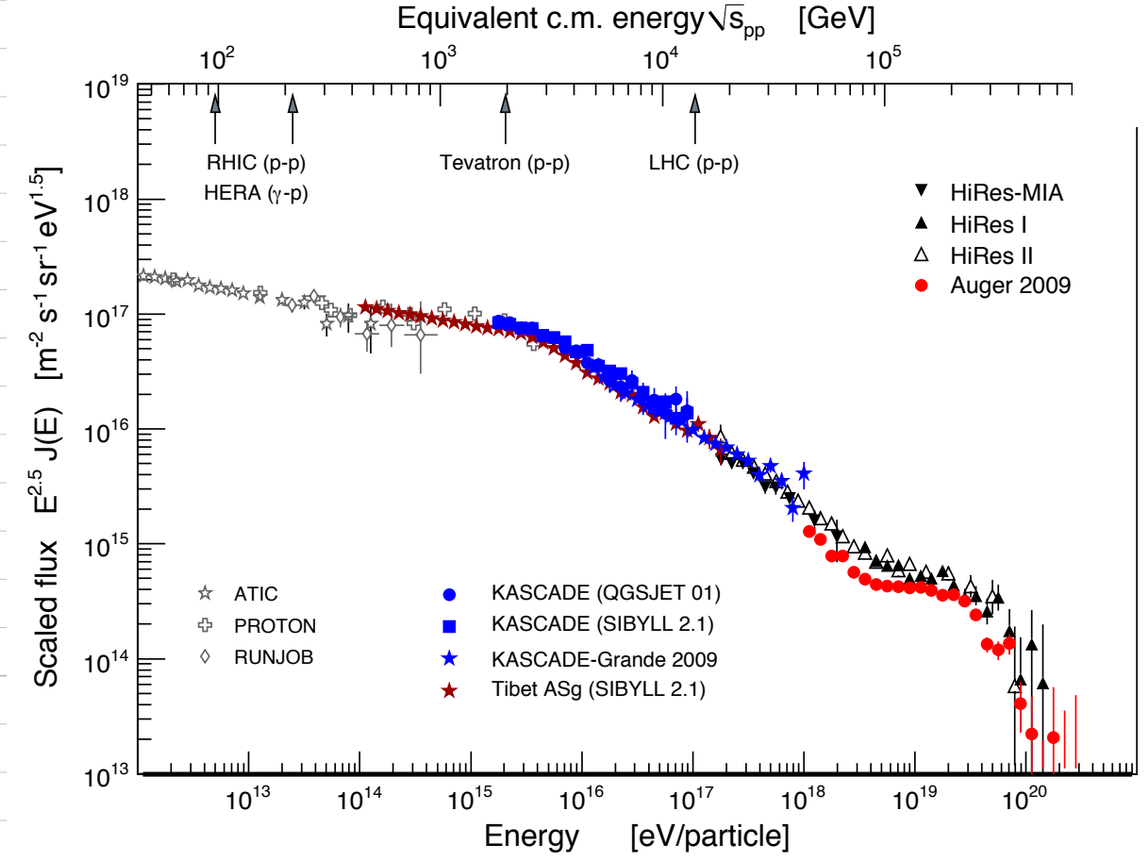


HEAT: High-ElevAtion Telescopes

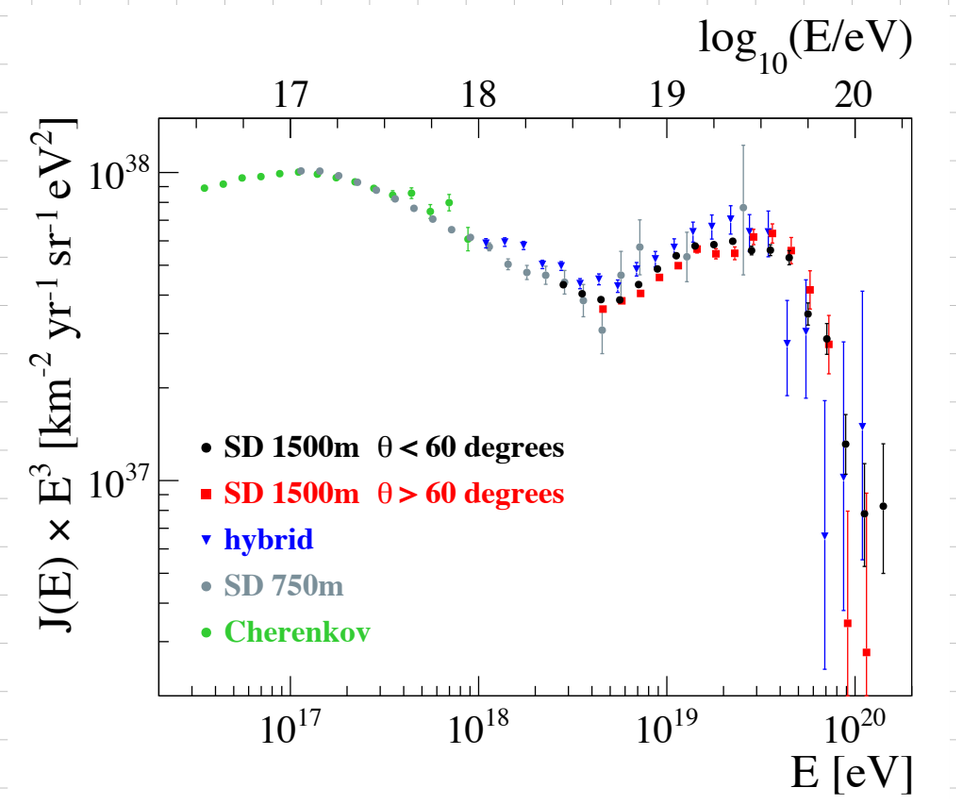


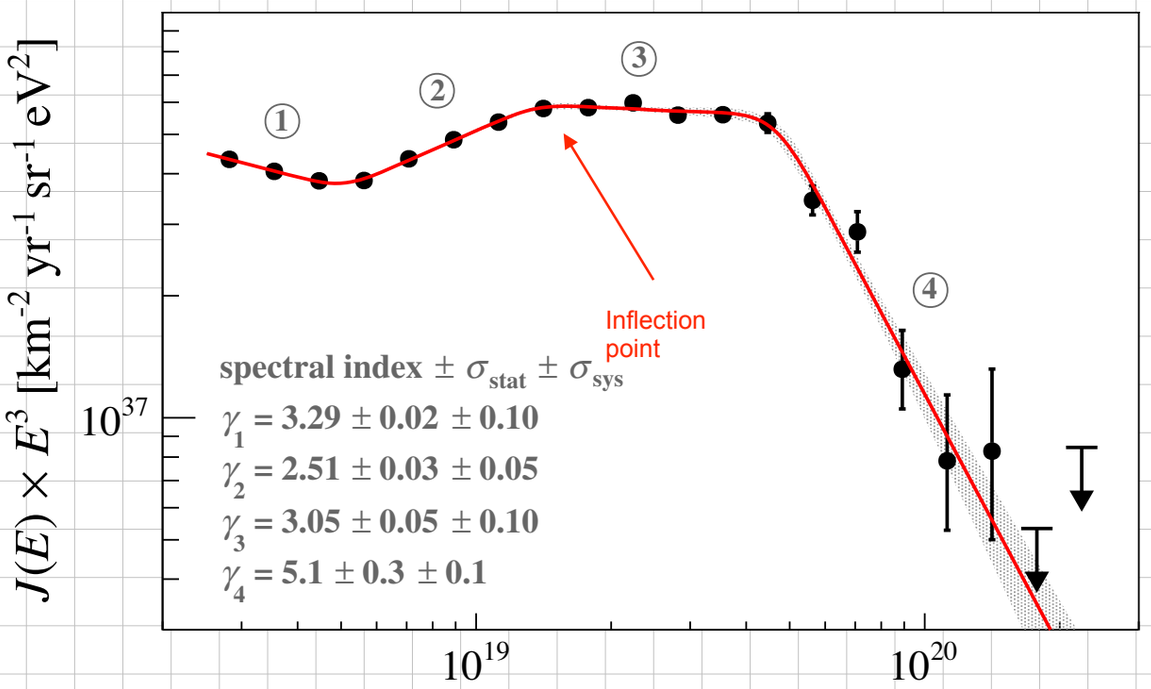
Aktueller Stand der Flussmessungen

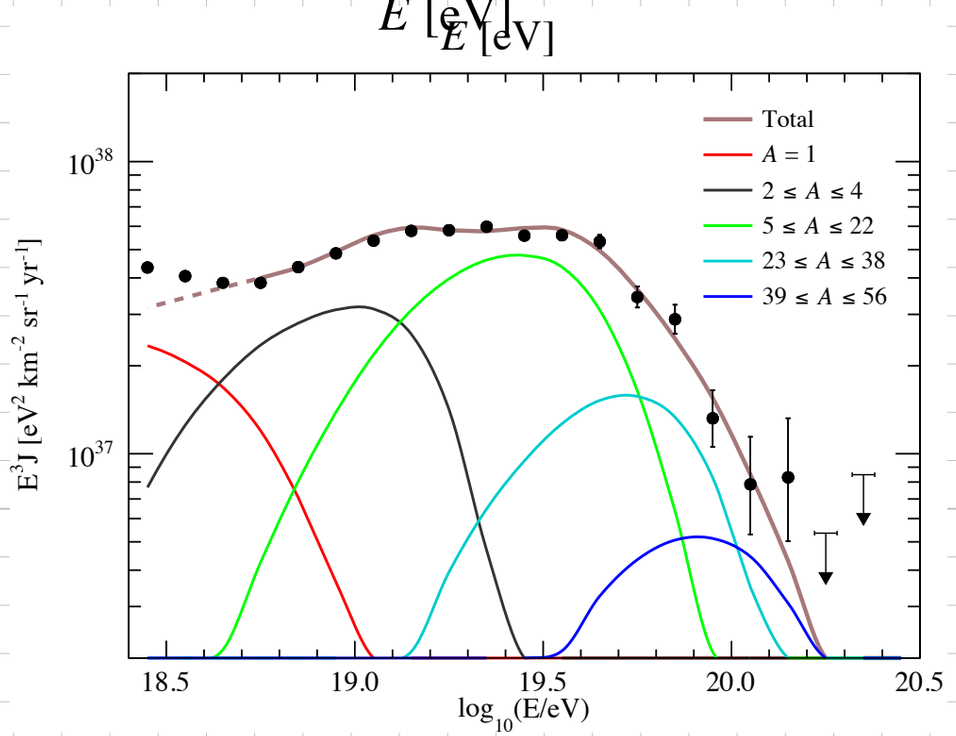




Resultate des Pierre-Auger-Observatoriums

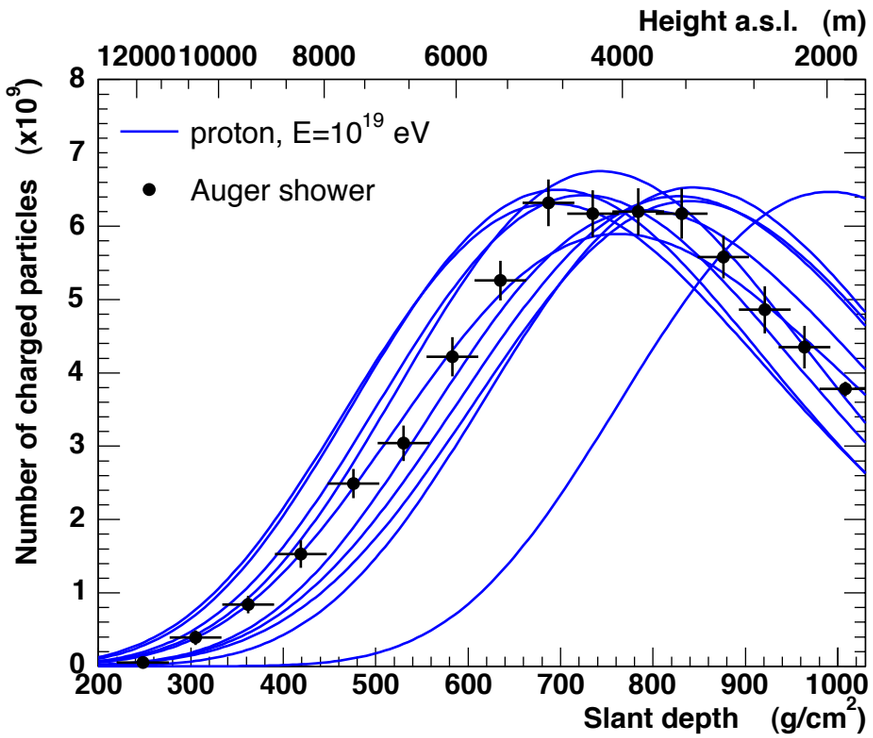


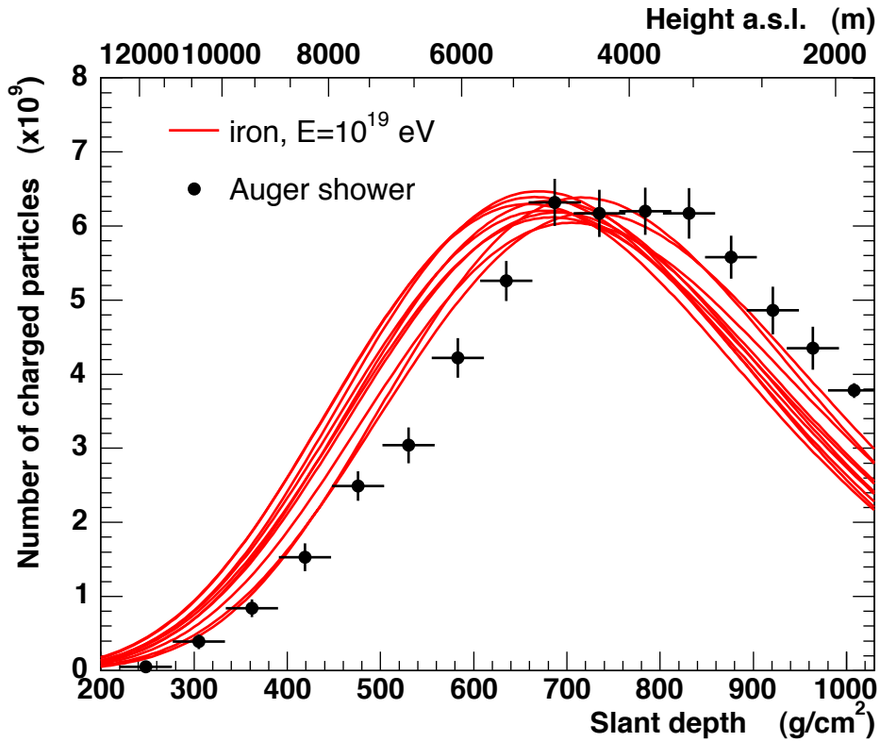


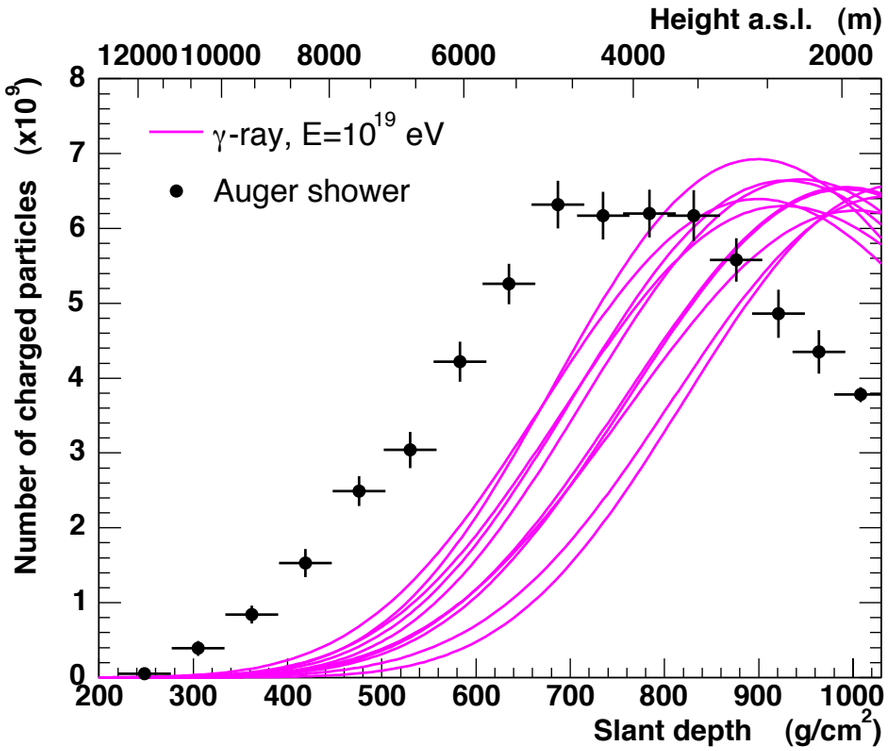


arXiv:1909.09073v1 [astro-ph.HE] 19 Sep 2019

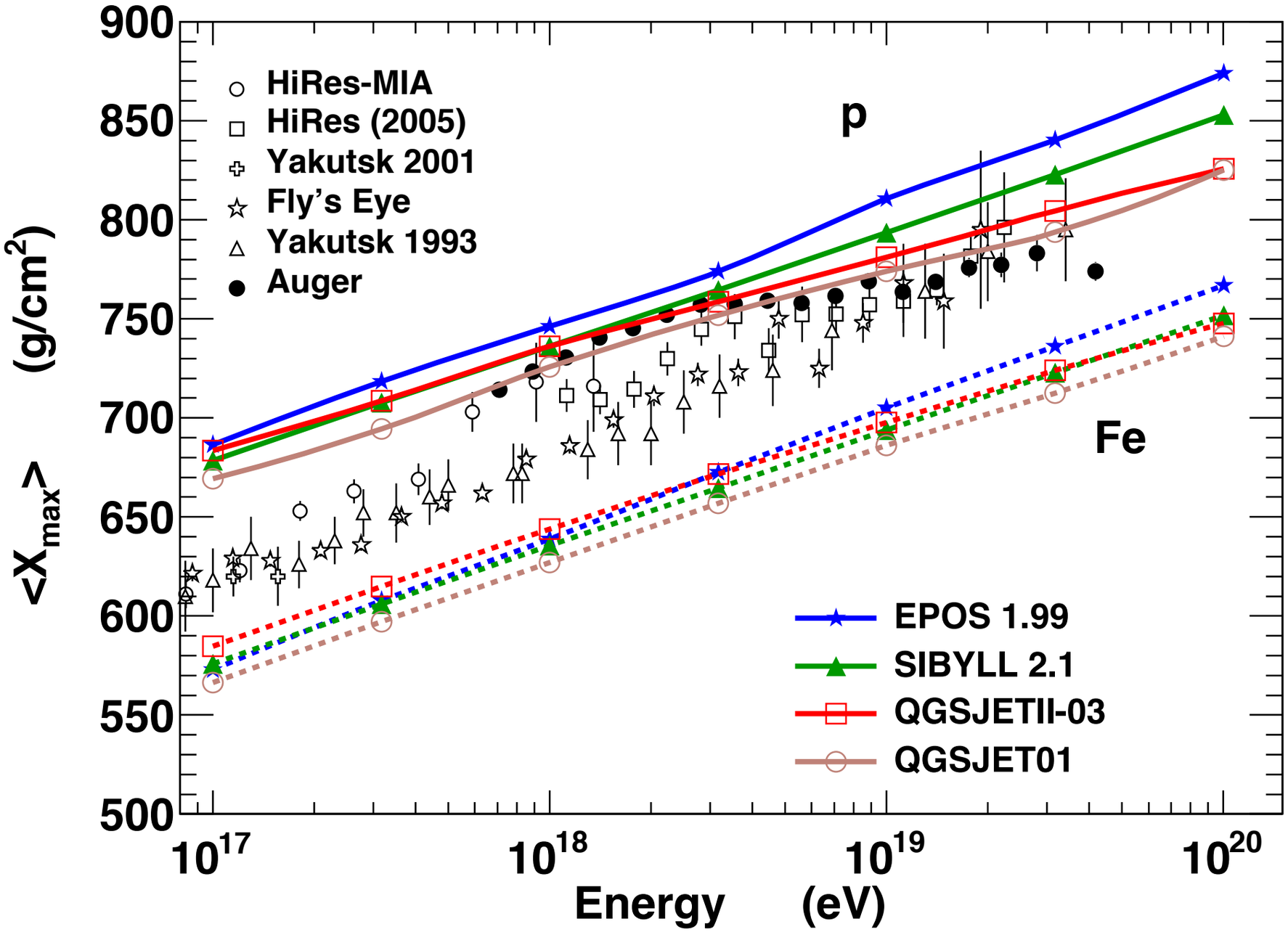
Primärteilchen: Longitudinale Schauerprofile







Mittlere Tiefe des Schauermaximums $\langle X_{max} \rangle$

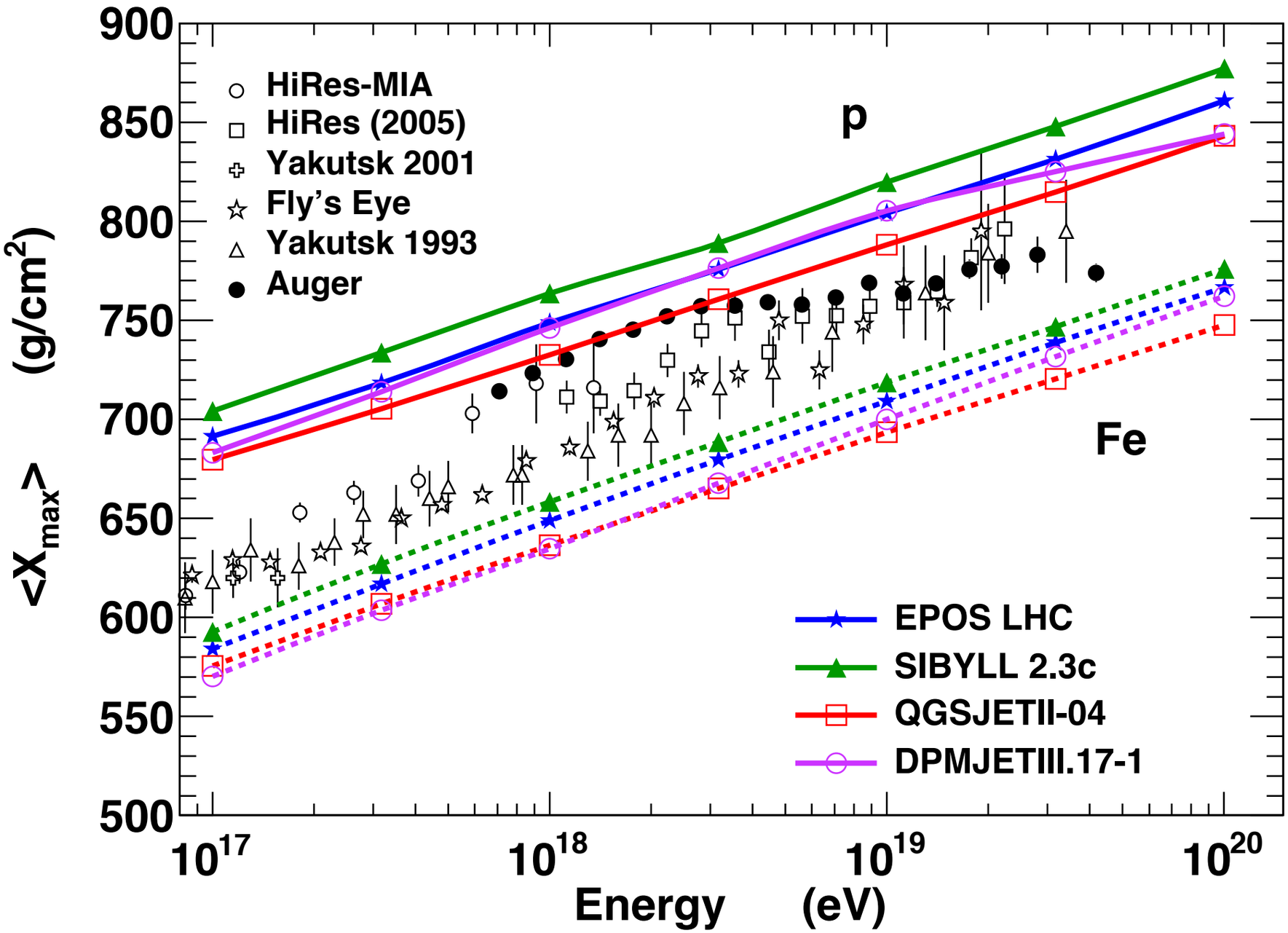


$$X_{\max} \propto D_e \ln(E_0/E_c)$$

$$X^A_{\max} \propto D_e \ln(E_0/A\,E_c)$$

Elongationsrate $D_{10} = \ln(10) D_e$

Mittlere Tiefe des Schauermaximums $\langle X_{max} \rangle$

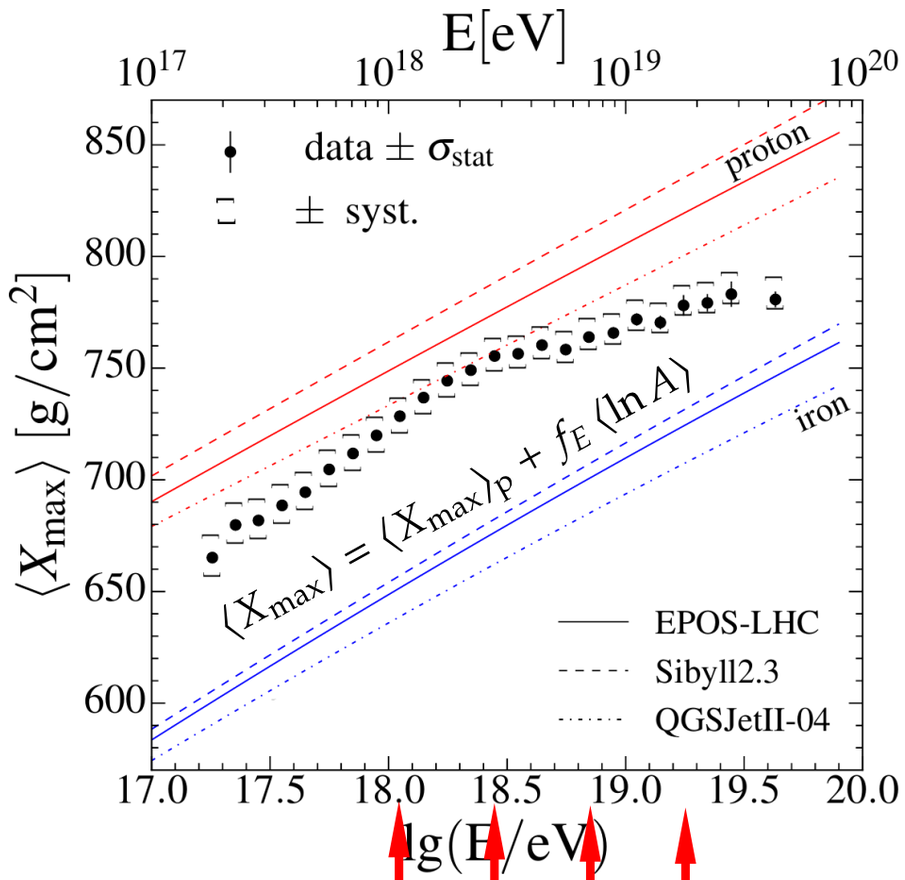


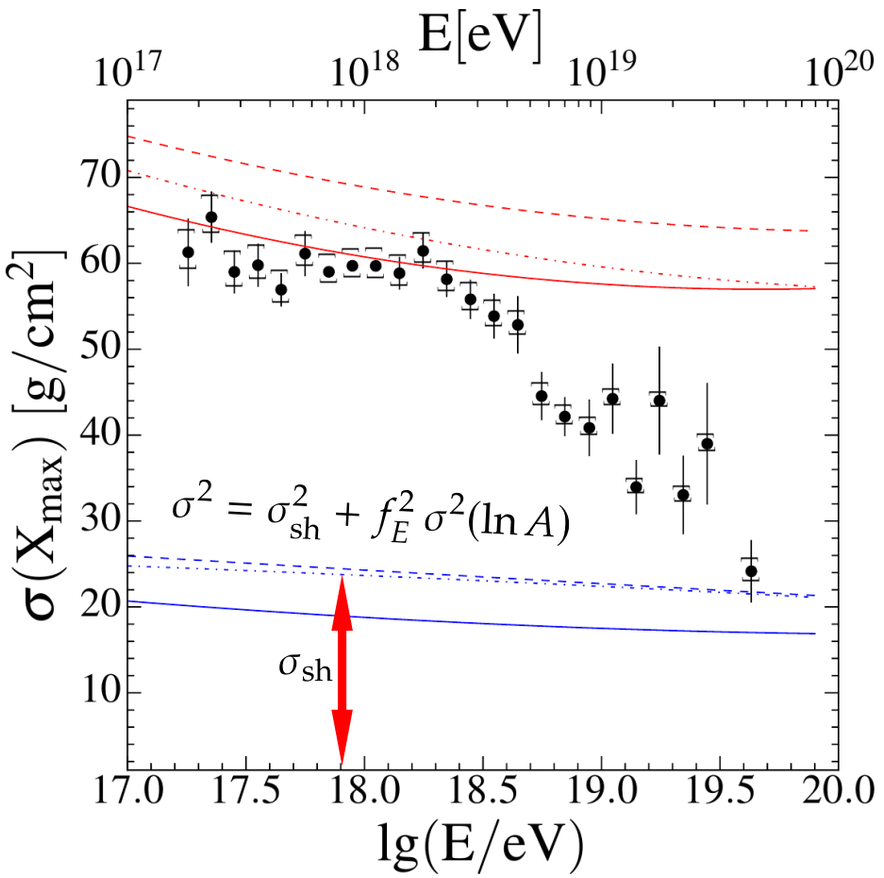
$$X_{\max} \propto D_e \ln(E_0/E_c)$$

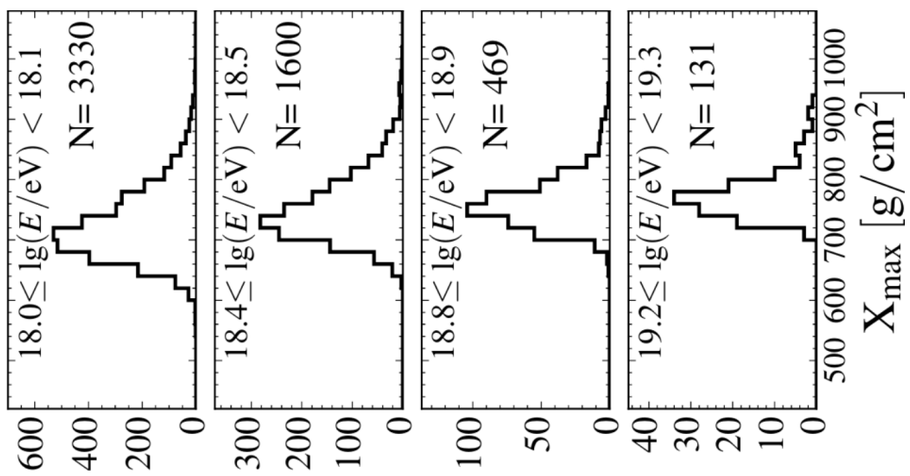
$$X^A_{\max} \propto D_e \ln(E_0/A\,E_c)$$

Elongationsrate $D_{10} = \ln(10) D_e$

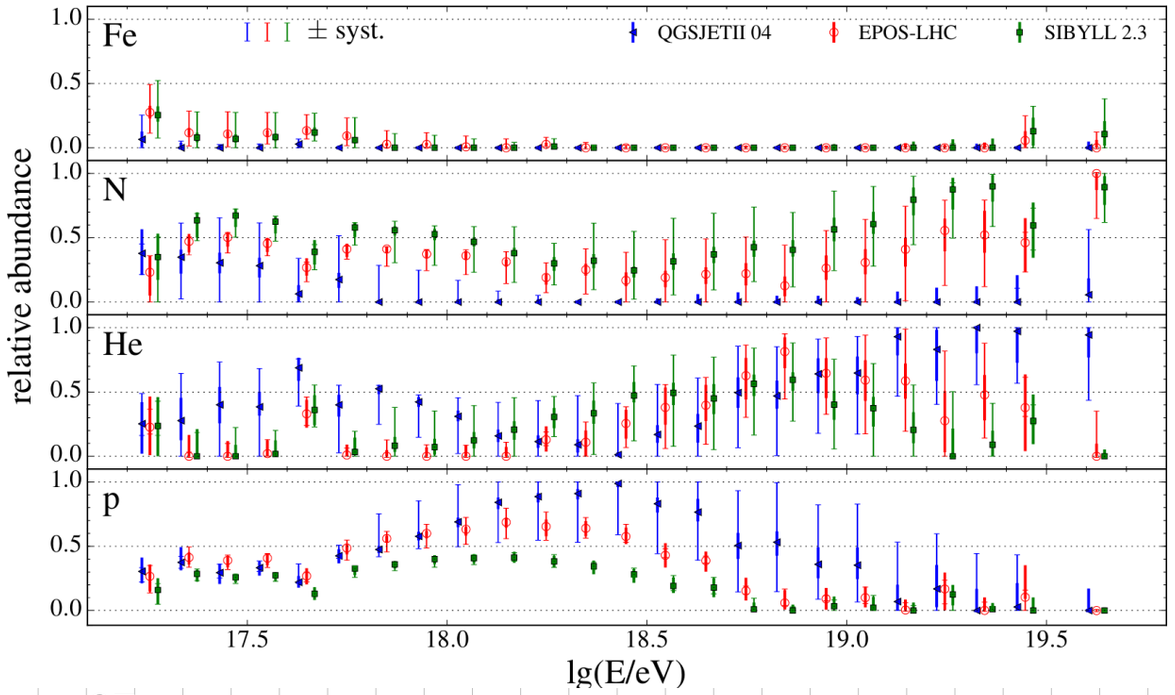
Depth of Shower Maxima



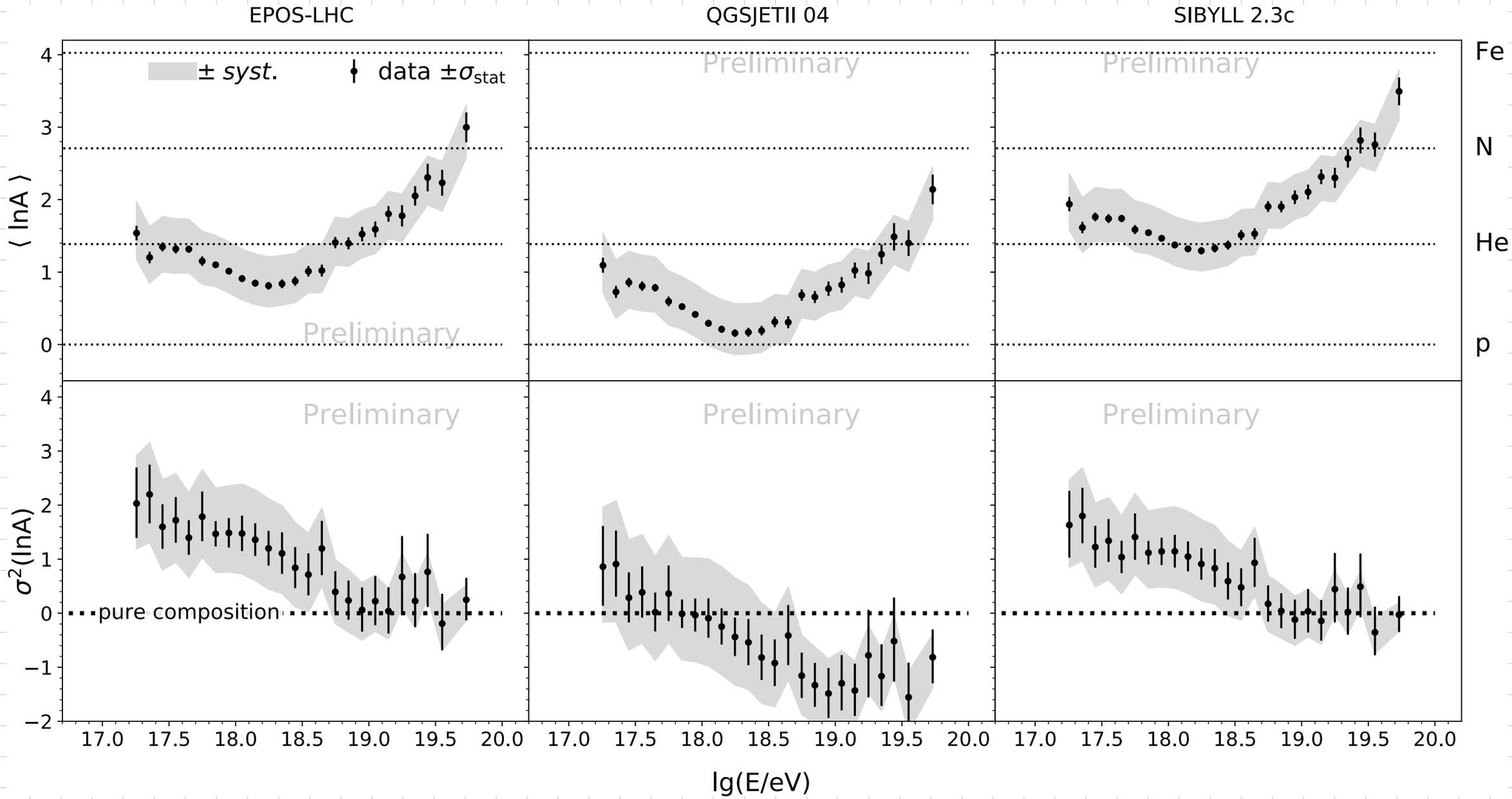




composition from X_{max} distr. fits



Abhängigkeit von hadronischen Wechselwirkungsmodellen



Vorhersagen für das Schauermaximum

Kaskadentheorie: Schauermaximum für elektromagnetischen Schauer exakt bekannt

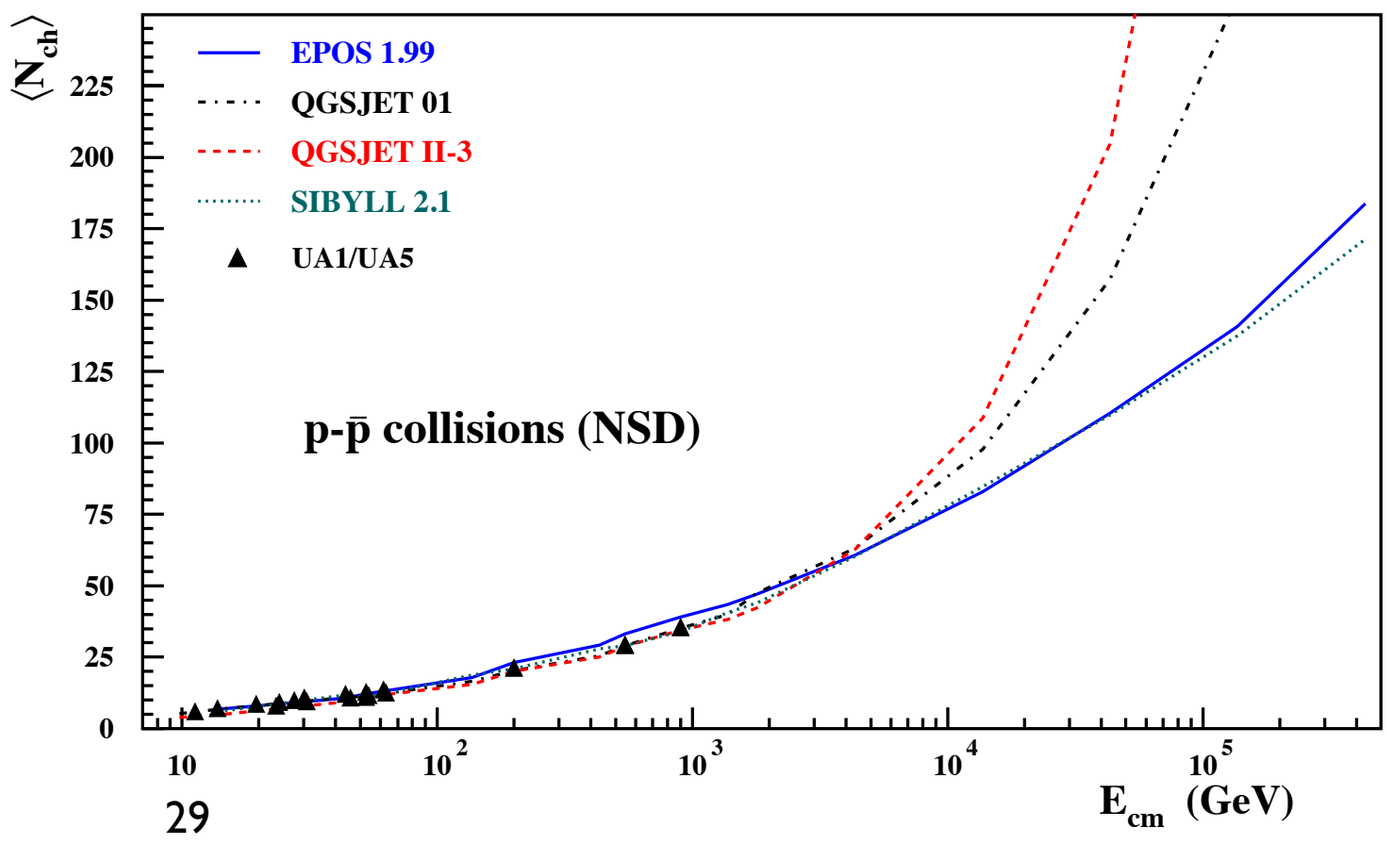
$$X_{\max} = X_0 \ \ln\left(\frac{E_0}{E_c}\right) \ \sim \ D_e^{\mathrm{em}} \ \ln E_0$$

$$B_\lambda = -\frac{1}{X_0}\frac{d\lambda_{\mathrm{int}}}{d\ln E}$$

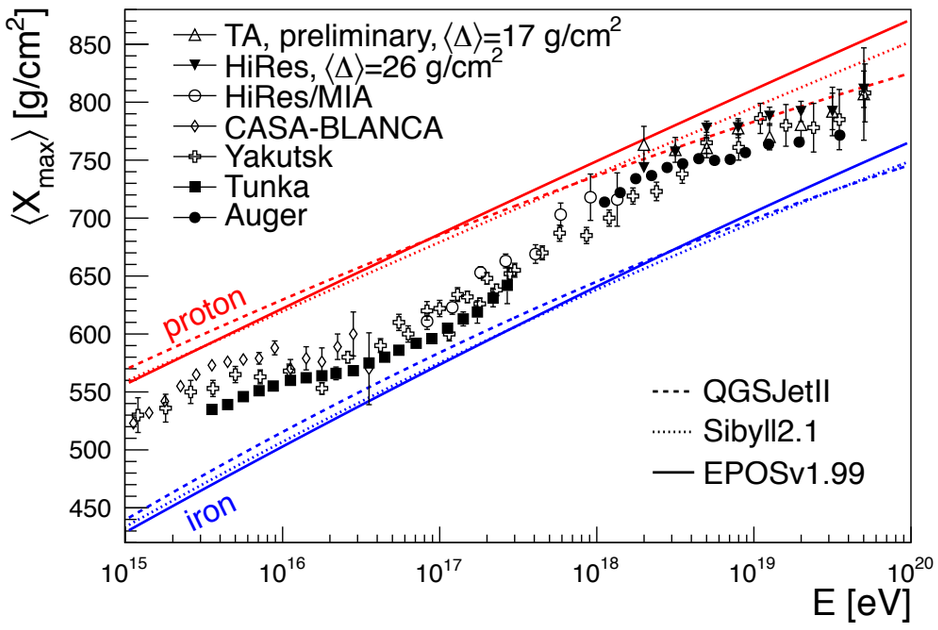
Elongationsratentheorem
(Linsley, Watson PRL46, 1981)

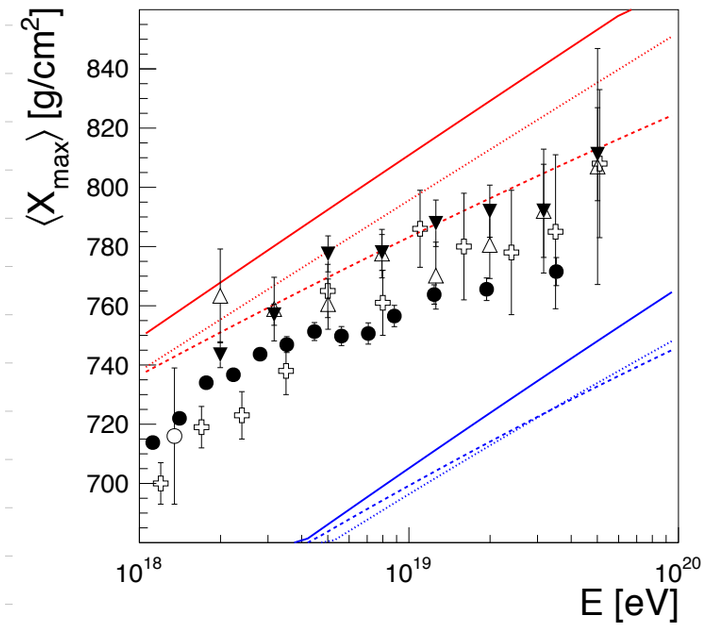
$$D_e^{\mathrm{had}} = X_0(1 - B_\lambda - B_n)$$

$$B_n = \frac{d\ln n_{\mathrm{tot}}}{d\ln E}$$



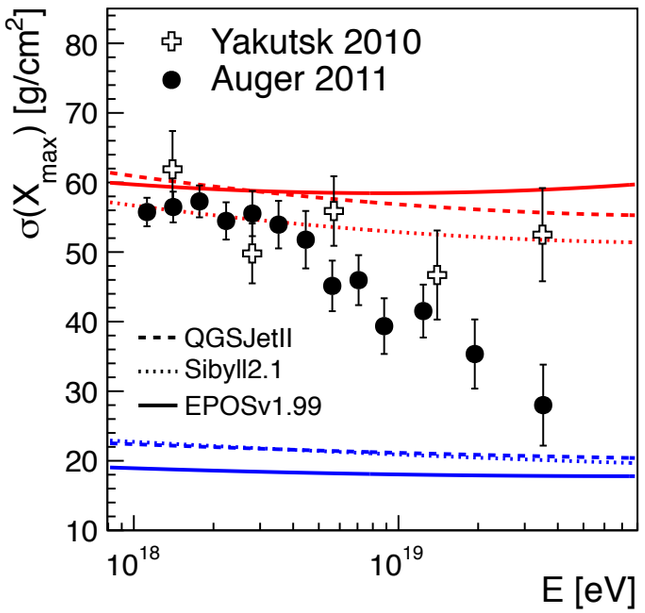
$\langle X_{max} \rangle$ und Streuung

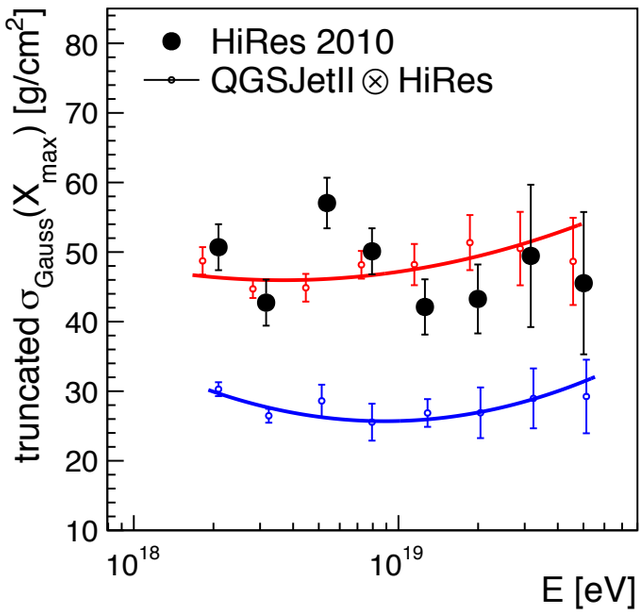


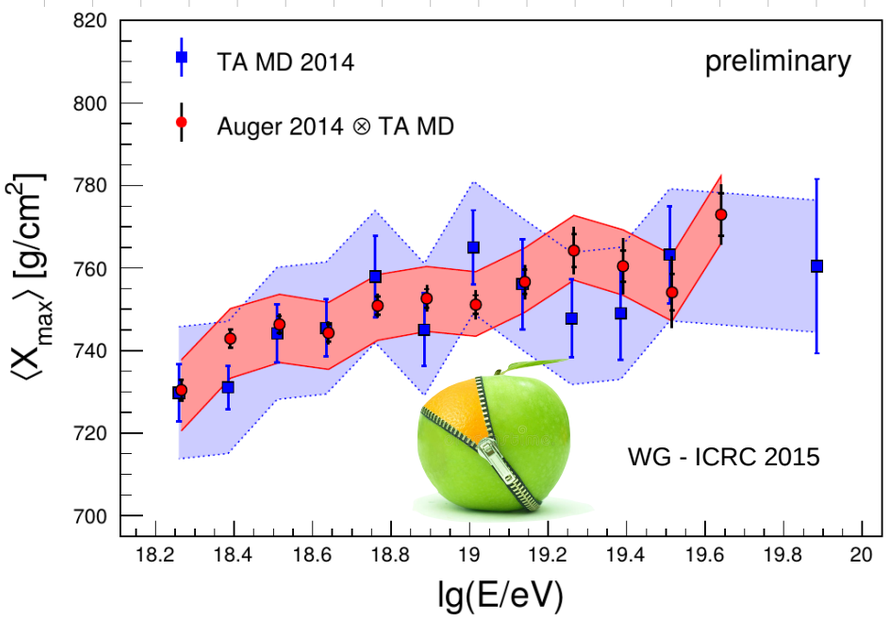


TA: all showers with X_{max} in field of view (bias due to detector acceptance)

Auger: only shower geometries for which all X_{max} values visible

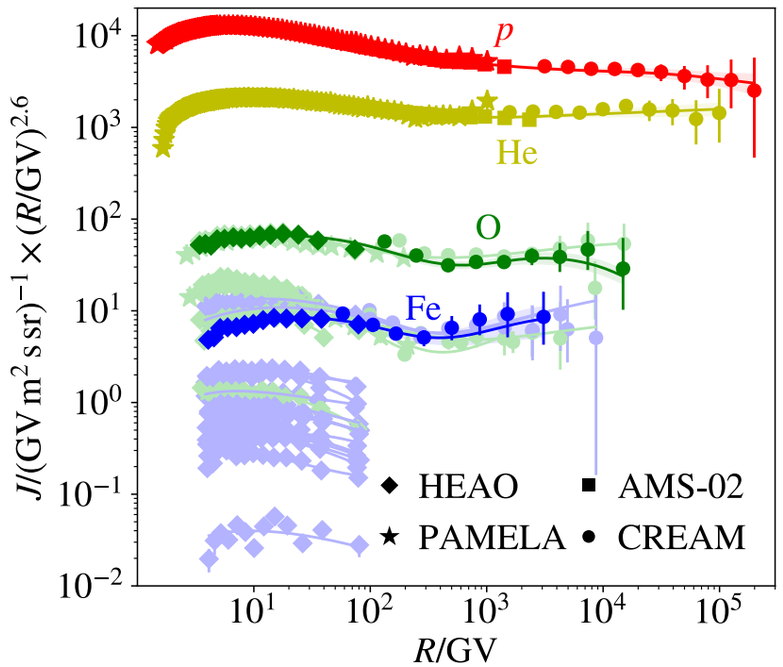


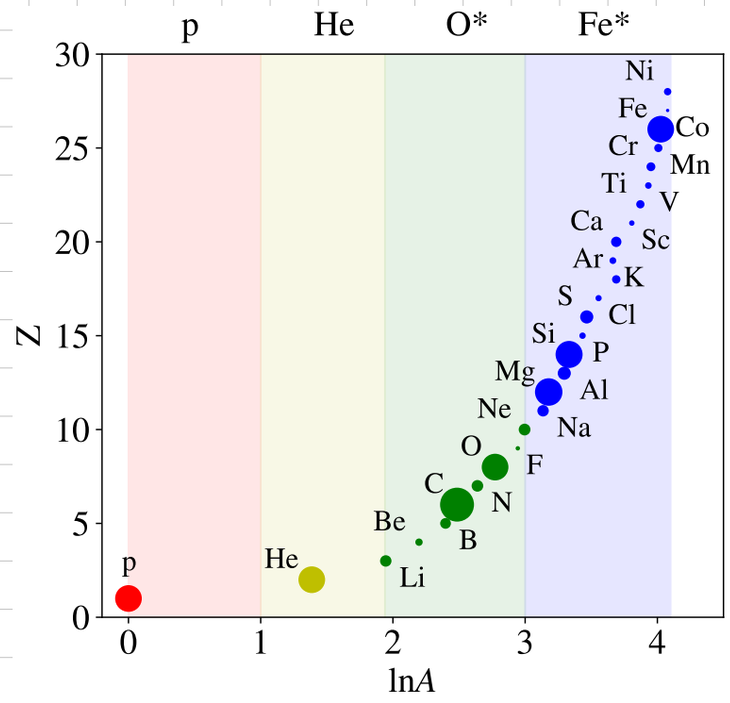


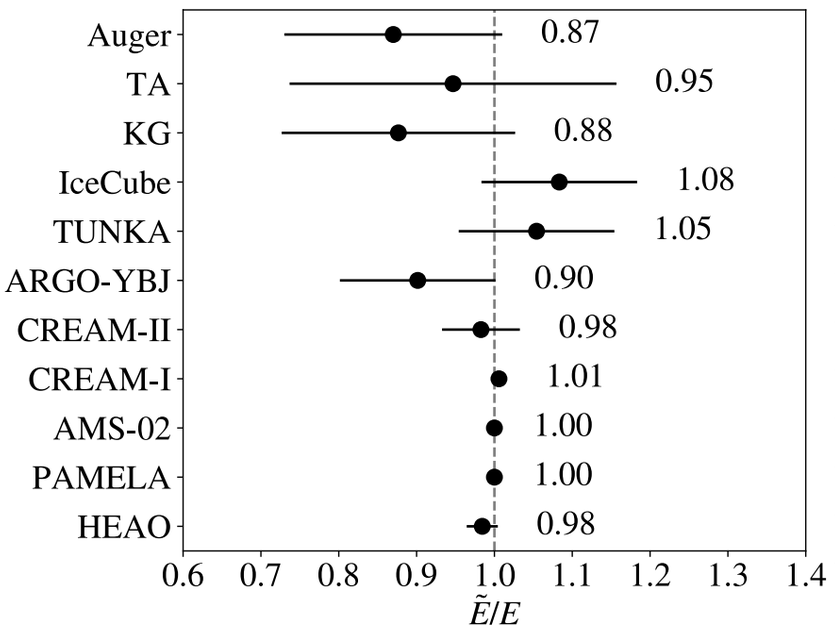


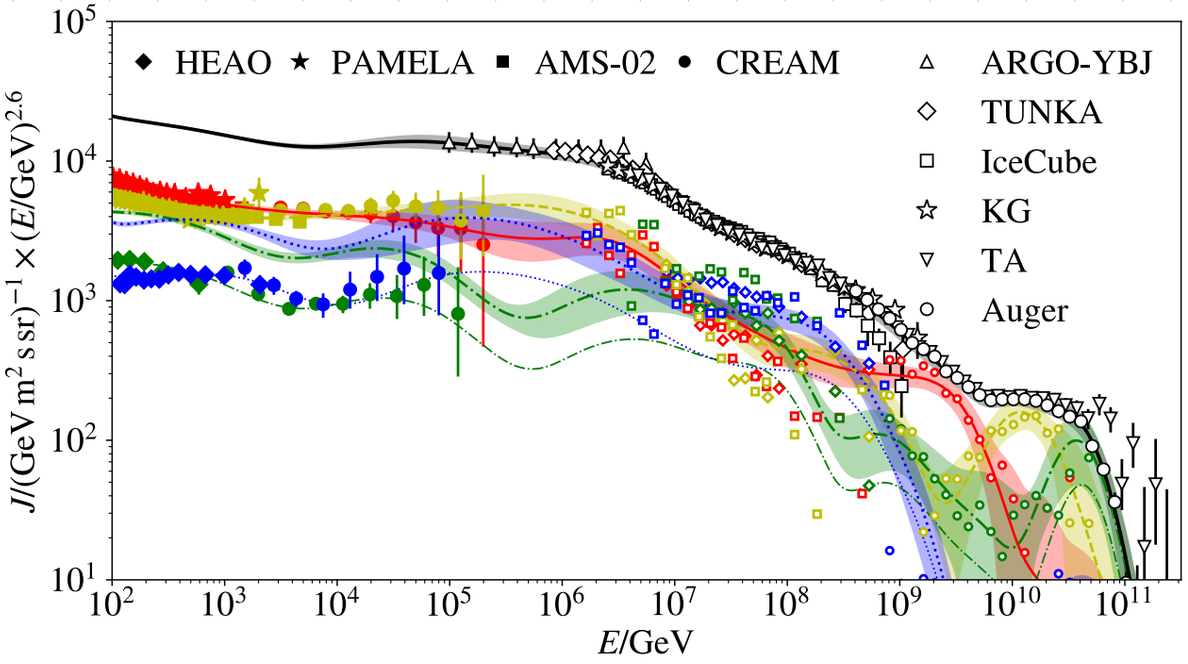
Unsicherheiten durch starke Modellabhängigkeit sehr groß

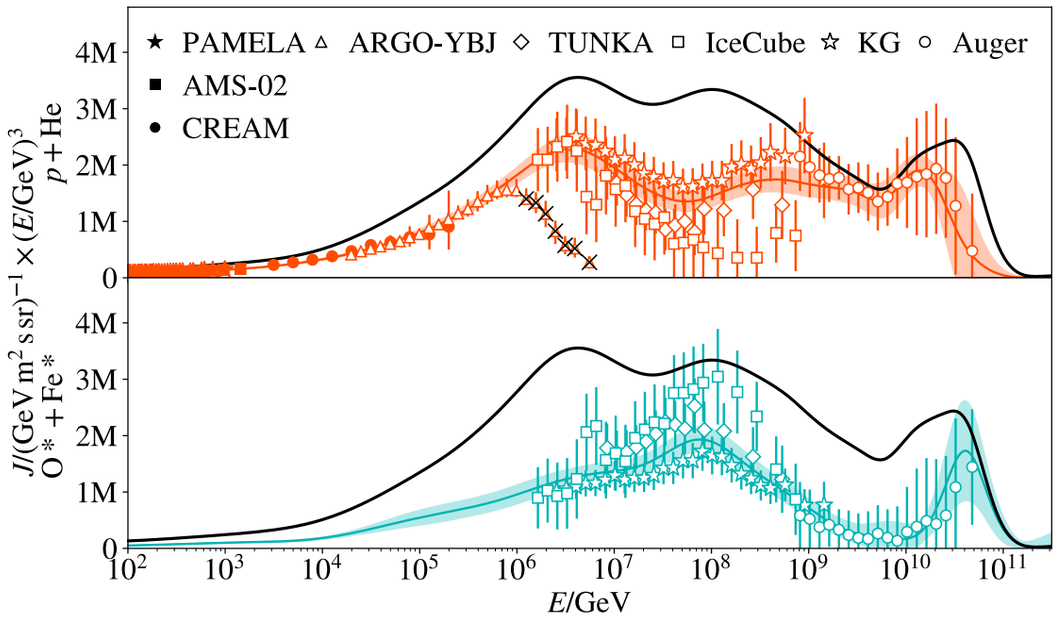
Phänomenologische Beschreibung: Energiespektrum und Elementzusammensetzung











Hans Dembinski et al , ICRC 2017

Dipolstruktur (Auger)

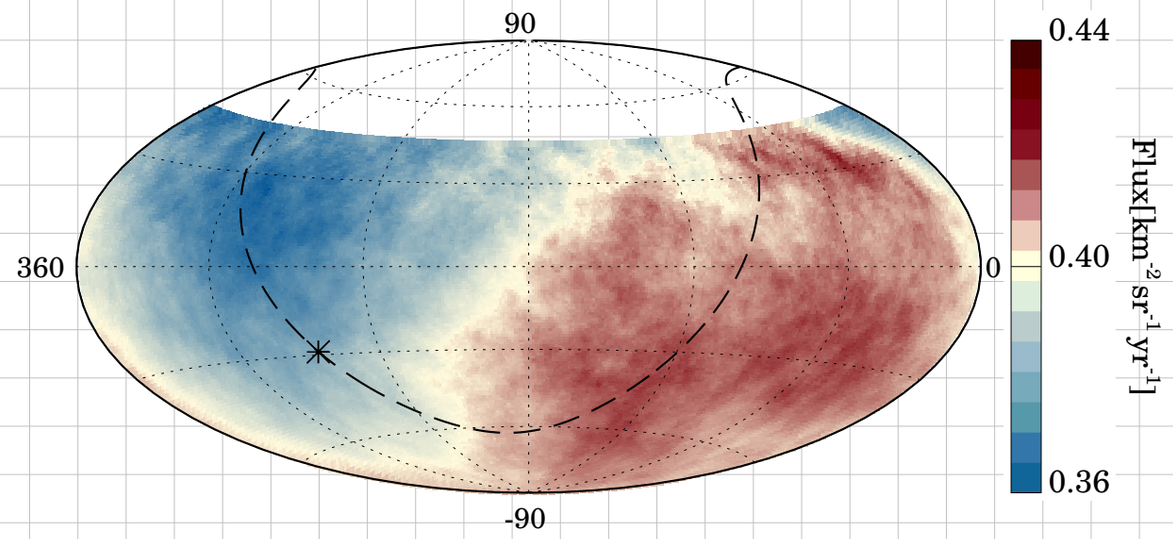


Figure 1: Map in Equatorial coordinates of the CR flux above 8 EeV, averaged on top-hat windows of 45° radius. The location of the Galactic plane is shown with a dashed line, and the Galactic center is indicated with a star.

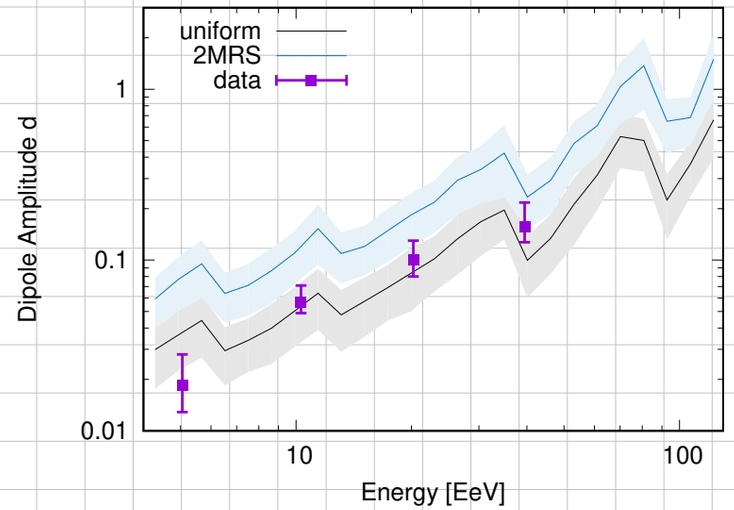


Figure 2: Energy dependence of the dipolar amplitude measured above 4 EeV. Also shown are the predictions from scenarios [12] with extragalactic sources.

Einfluss des galaktischen Magnetfelds auf einen Dipol

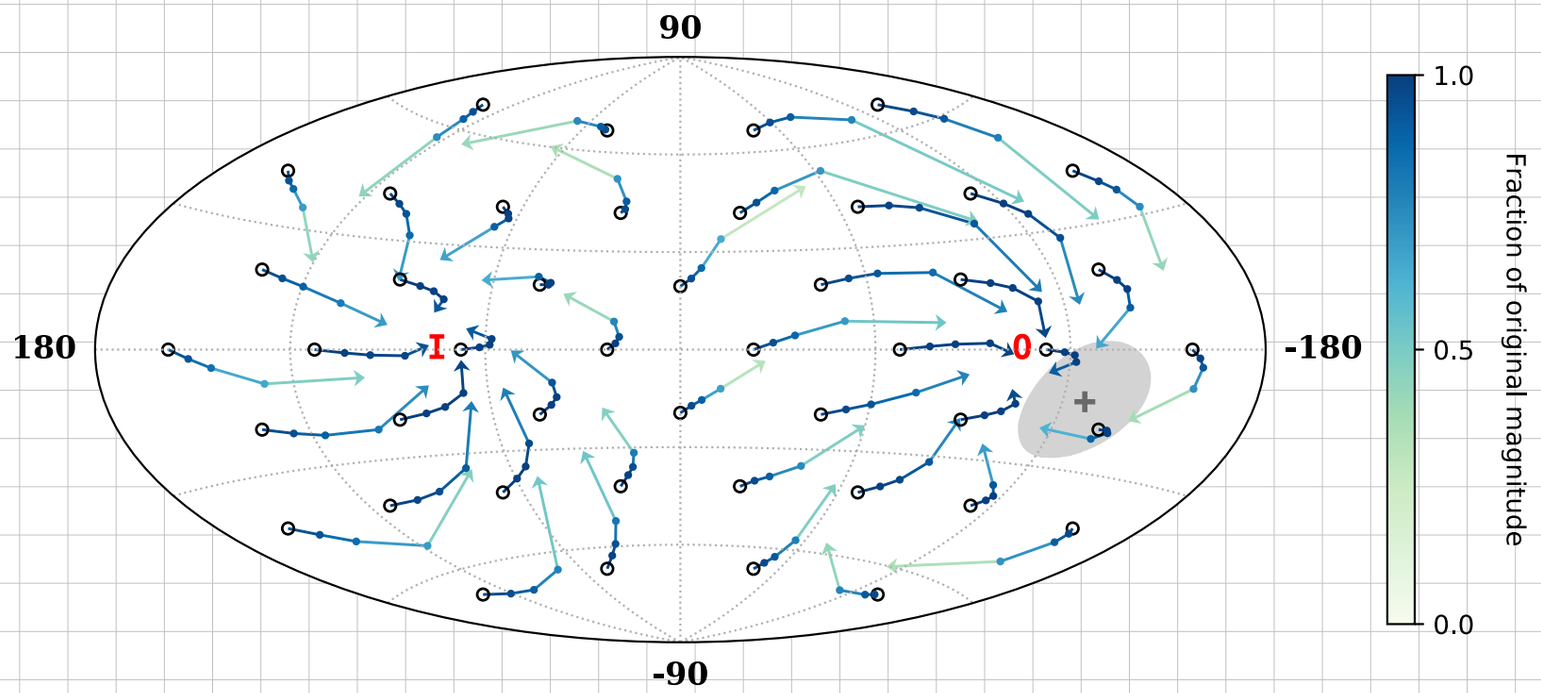


Figure 7. Change of the direction of the dipolar component of an extragalactic flux after traversing the Galactic magnetic field, modeled as in Jansson & Farrar (2012). We consider a grid (black circles) corresponding to the directions of a purely dipolar flux outside the Galaxy. Points along the lines indicate the reconstructed directions for different values of the particle rigidity: 32, 16, and 8 EV, and, at the tip of the arrow, 4 EV. The line color indicates the resulting fractional change of the dipole amplitude. The observed direction of the dipole for energies $E \geqslant 8$ EeV is indicated by the gray plus sign, with the shaded area indicating the 68% CL region. The labels ***I*** and ***O*** indicate the directions toward the inner and outer spiral arms, respectively.

Dipolentwicklung mit Energie

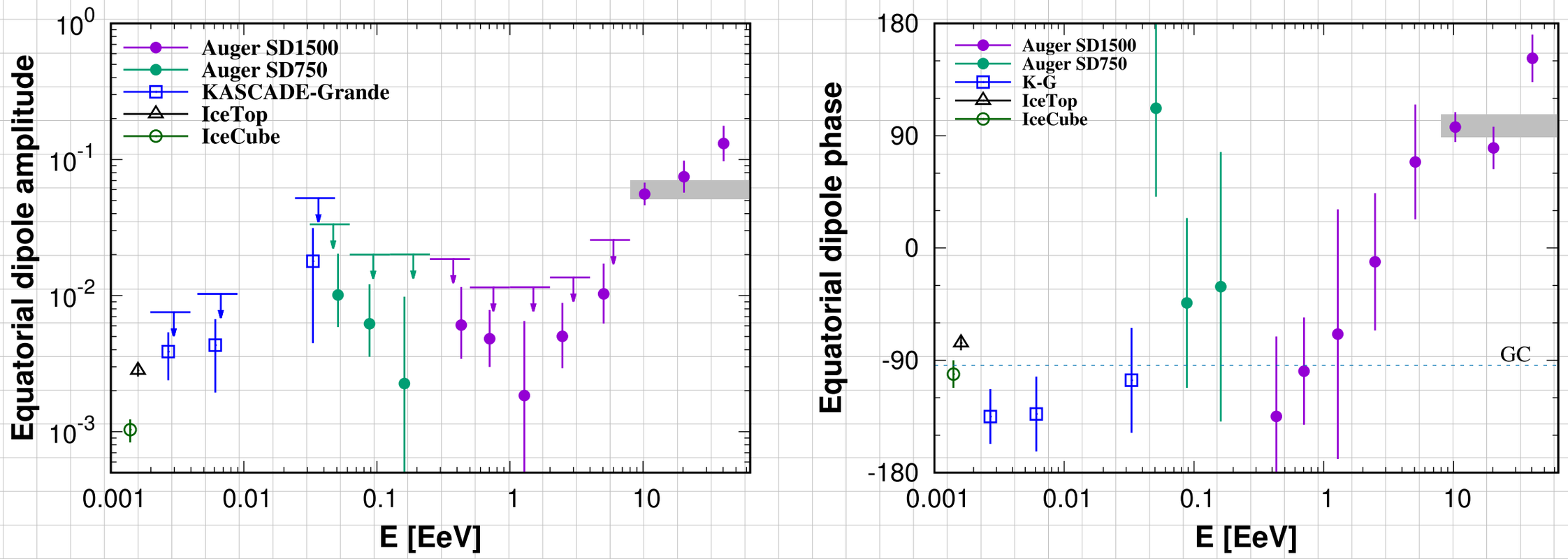
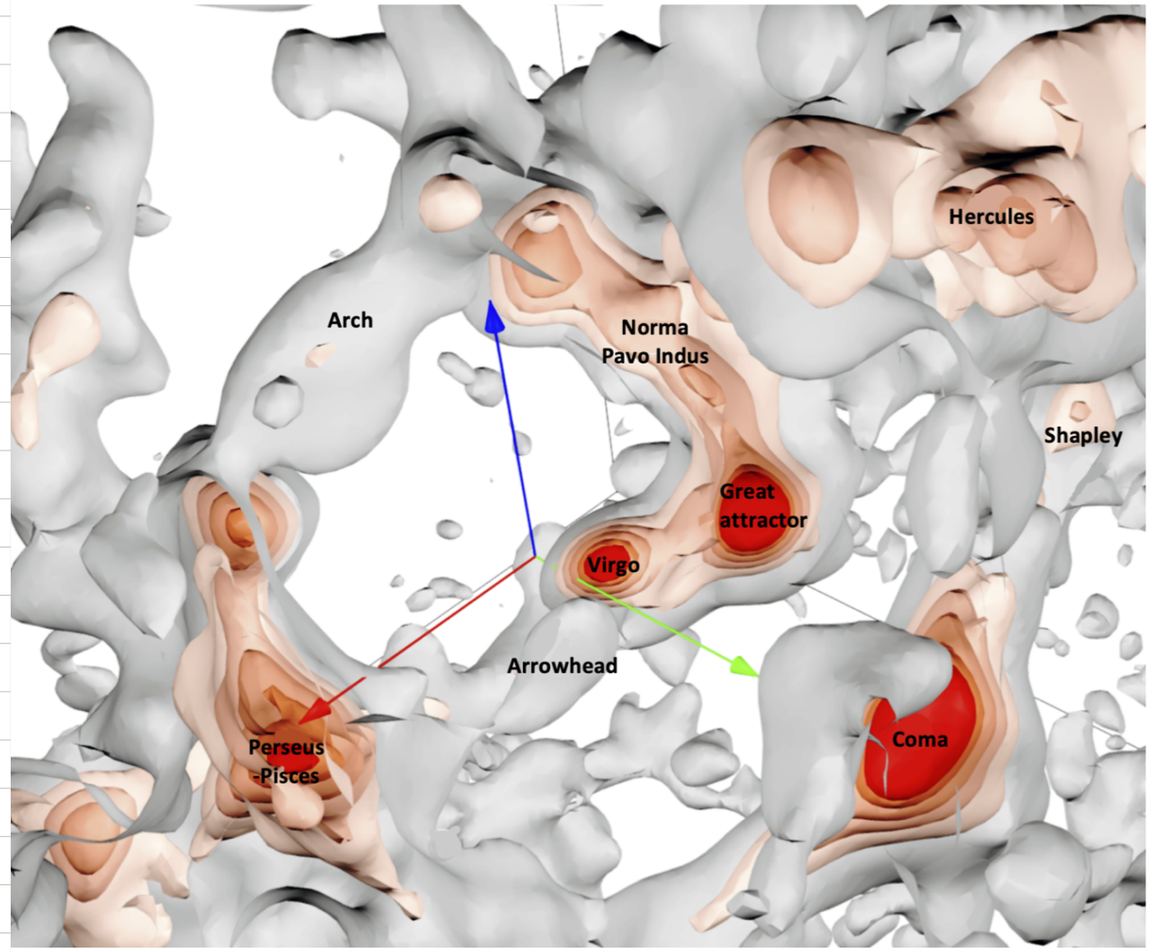


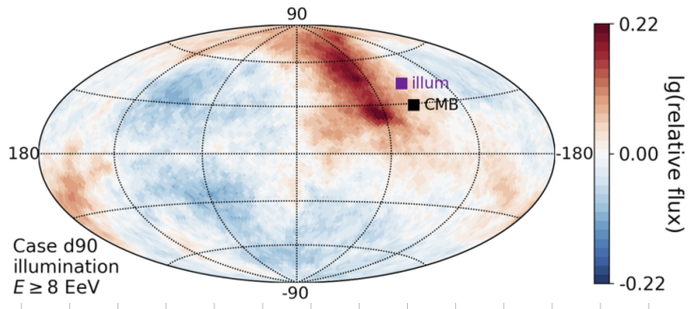
Figure 1. Reconstructed equatorial dipole amplitude (left) and phase (right). The upper limits at 99% CL are shown for all the energy bins in which the measured amplitude has a chance probability greater than 1%. The gray bands indicate the amplitude and phase for the energy bin $E \geqslant 8$ EeV. Results from other experiments are shown for comparison (IceCube Collaboration 2012, 2016; KASCADE-Grande Collaboration 2019).

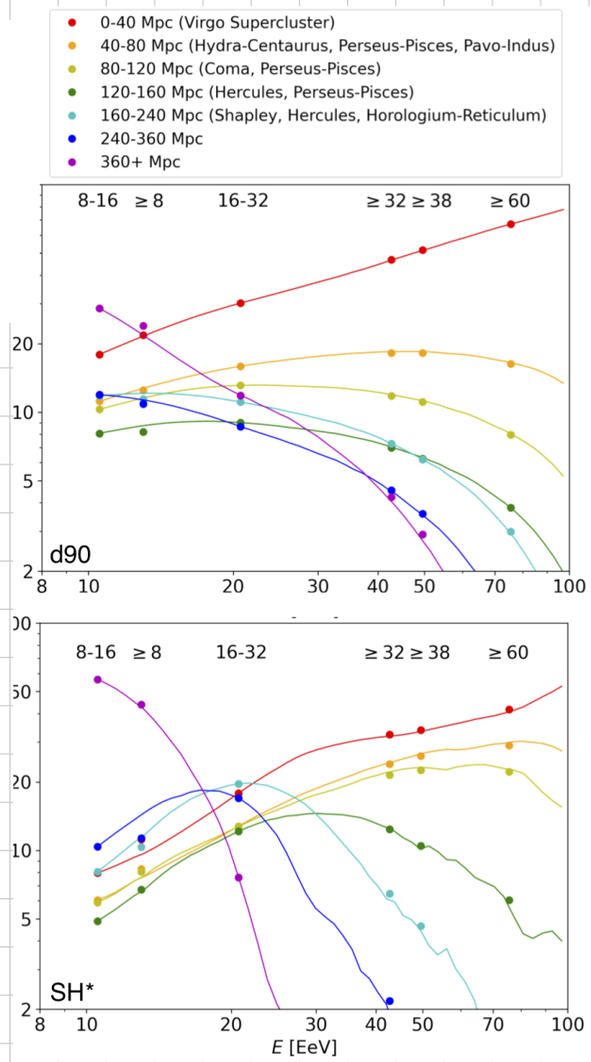
https://doi.org/10.3847/1538-4357/ab7236

The Imprint of Large Scale Structure on the Ultra-High-Energy Cosmic Ray Sky



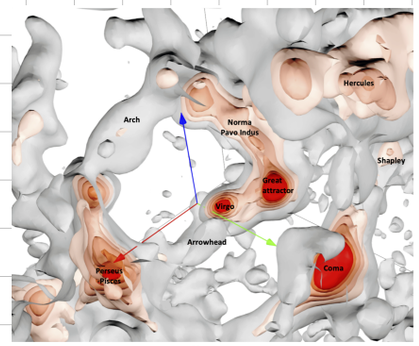
[https://sketchfab.com/3d-models/quasi-linear-construction-of-the-density-field- 91448f58ed5b4a30b5dc270a34fb4352





arXiv:2101.04564v2 [astro-ph.HE] 15 Jan 2021

The Imprint of Large Scale Structure on the Ultra-High-Energy Cosmic Ray Sky



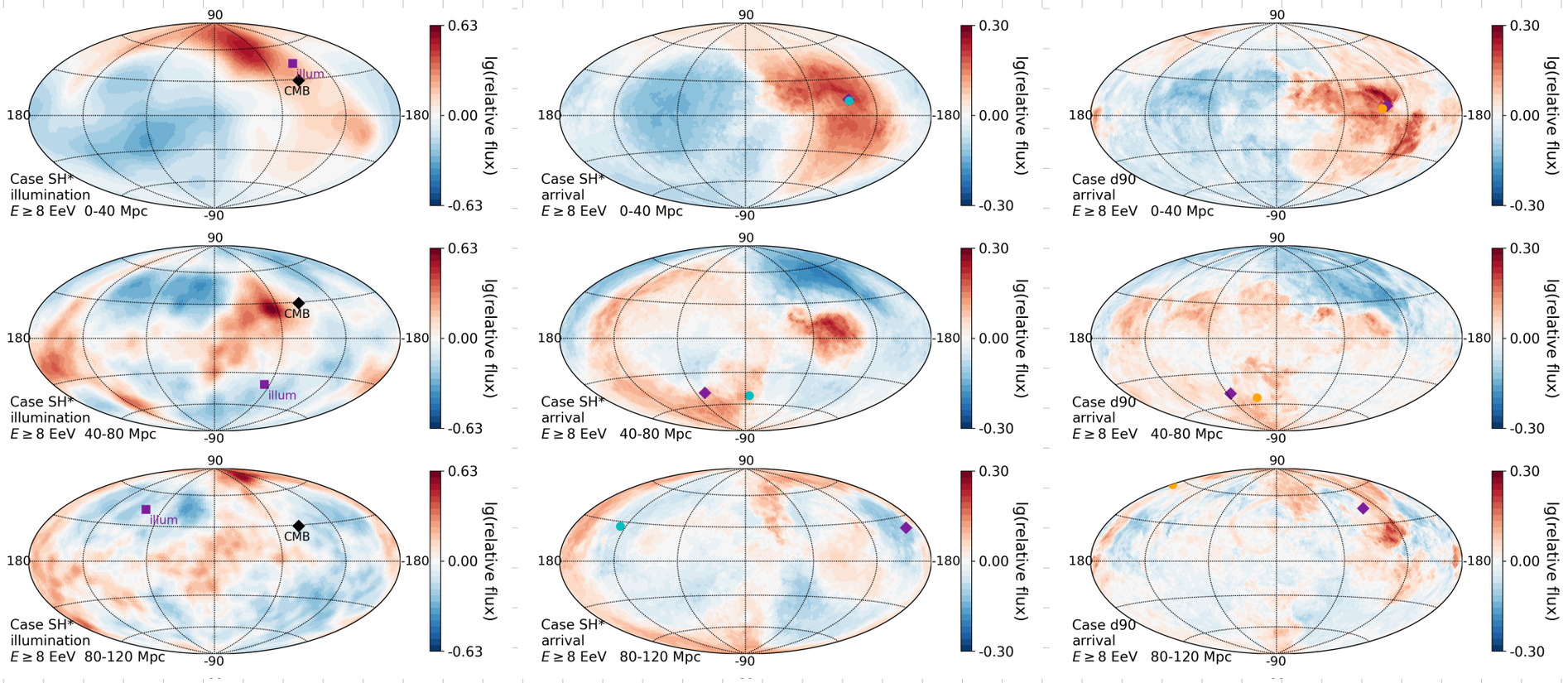


Figure 2. Surface density maps (left column), and arrival maps after propagation in the JF12 Galactic magnetic field model for the SH* (middle) and d90 (right) attenuation models, in LSS shells covering distances (top to bottom): 0-40, 40-80, and 80-120 Mpc. The maps here are for $E \geq 8$ EeV; plots including $E \geq 32$ EeV and a more complete set of distances and models are given in the Appendix Figs. E4– E7.

AugerPrime
Advent of multihybrid data