Latest Results from the Pierre Auger Cosmic Ray Observatory

Outline

- Energy spectrum
- Composition
  - charged particles
  - neutrinos/photons
- Anisotropy

ISAPP summer school
Karlsruhe
27 July 2009

Markus Roth
Karlsruhe Institute of Technology

Cosmic rays at highest energies

Goal:

Understand the mechanism that produces UHECR particles

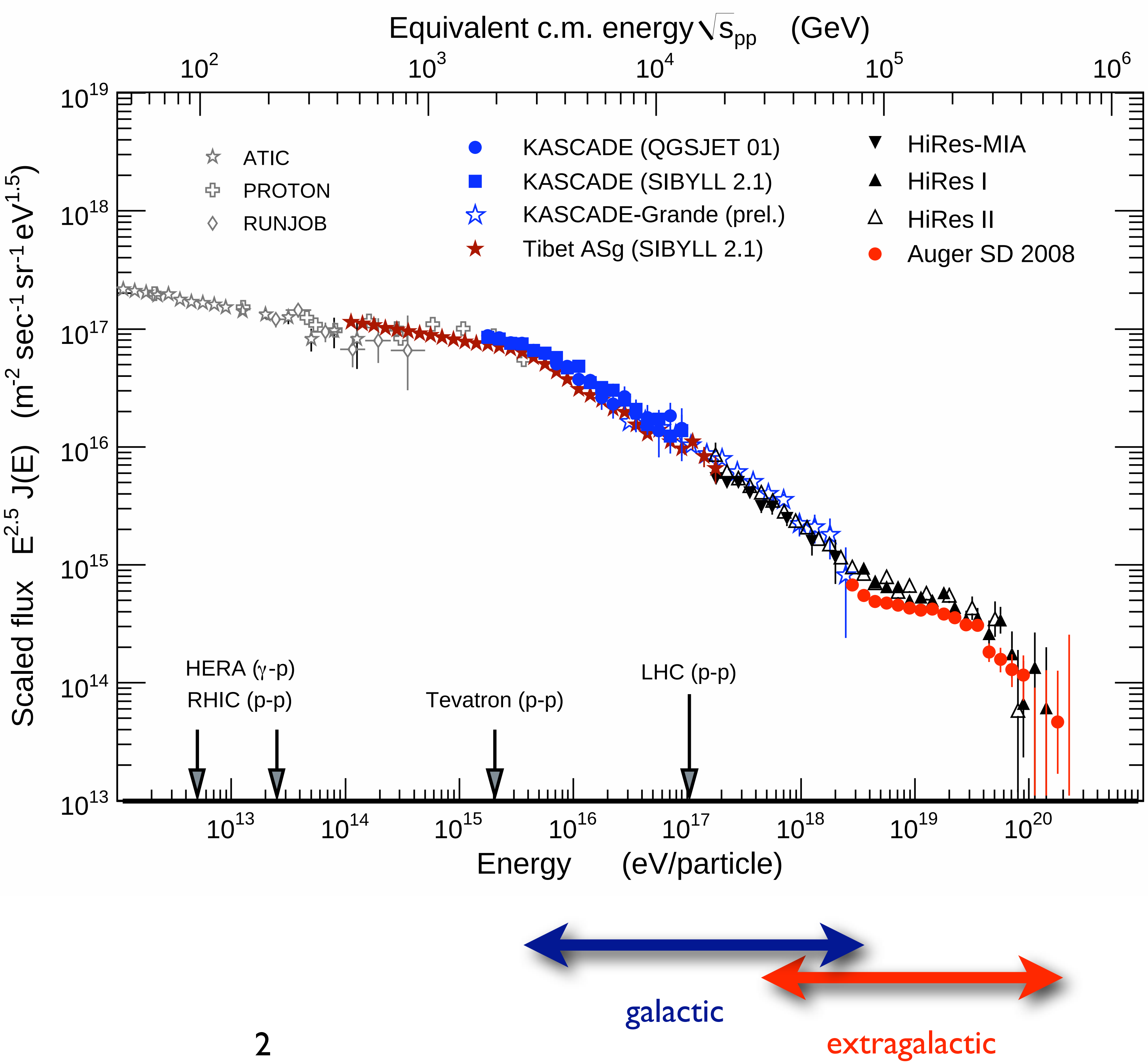
- What and where are the sources?
- How do they work?

We need to measure:

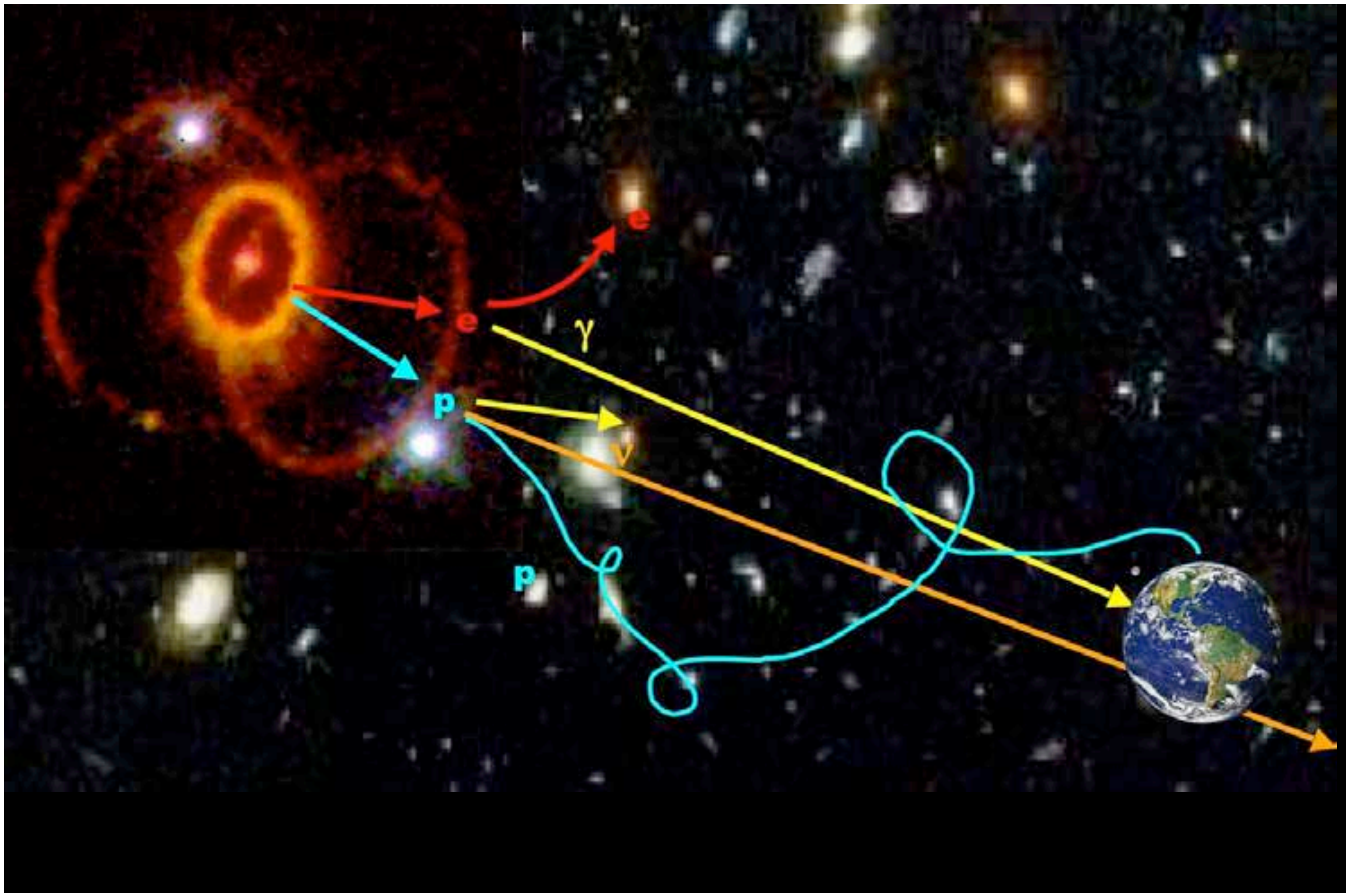
- direction
- energy
- particle-type

To determine

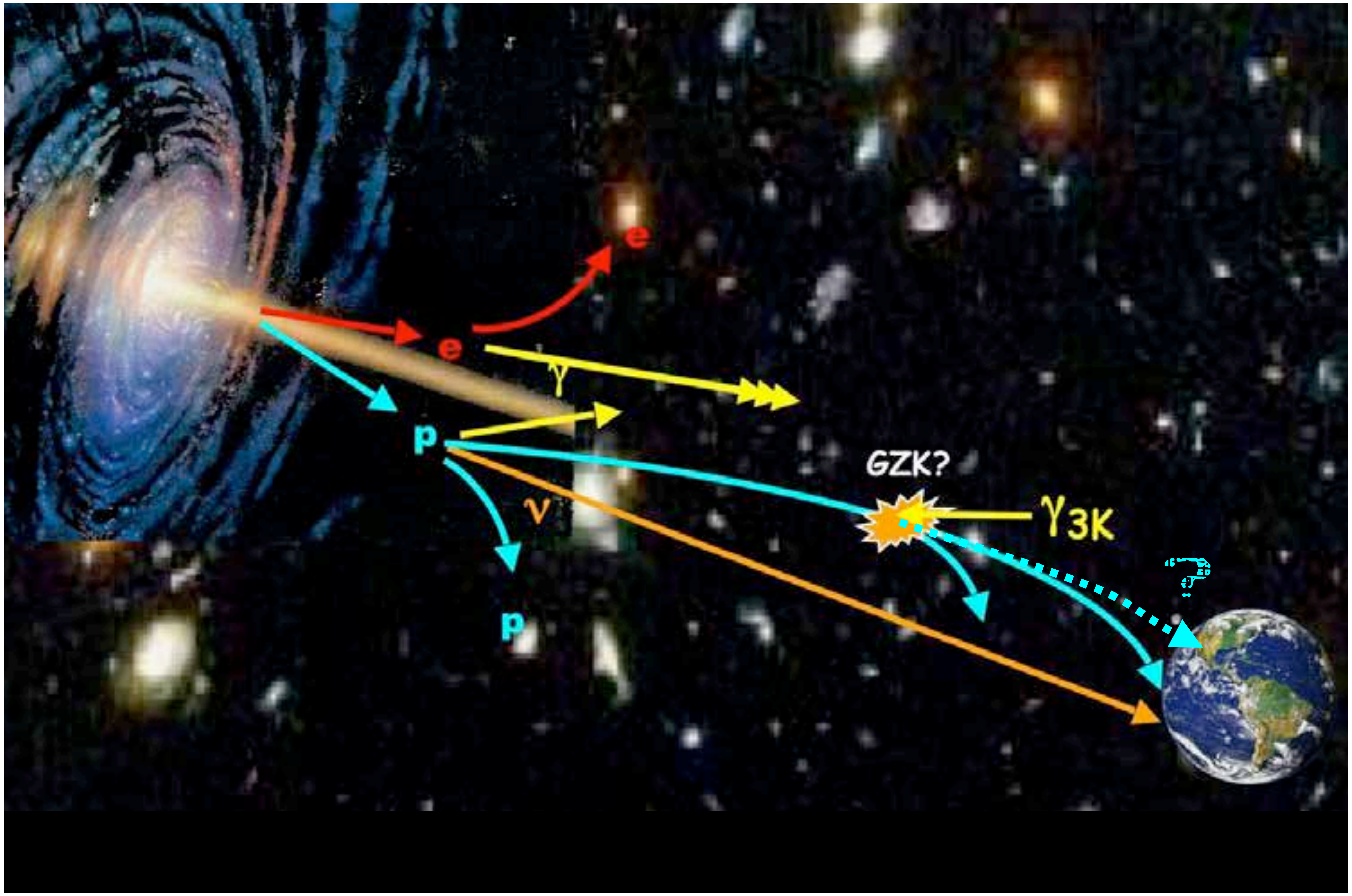
- Spectral features
  - knee
  - (second knee ??)
  - ankle
- Chemical composition
- Anisotropy



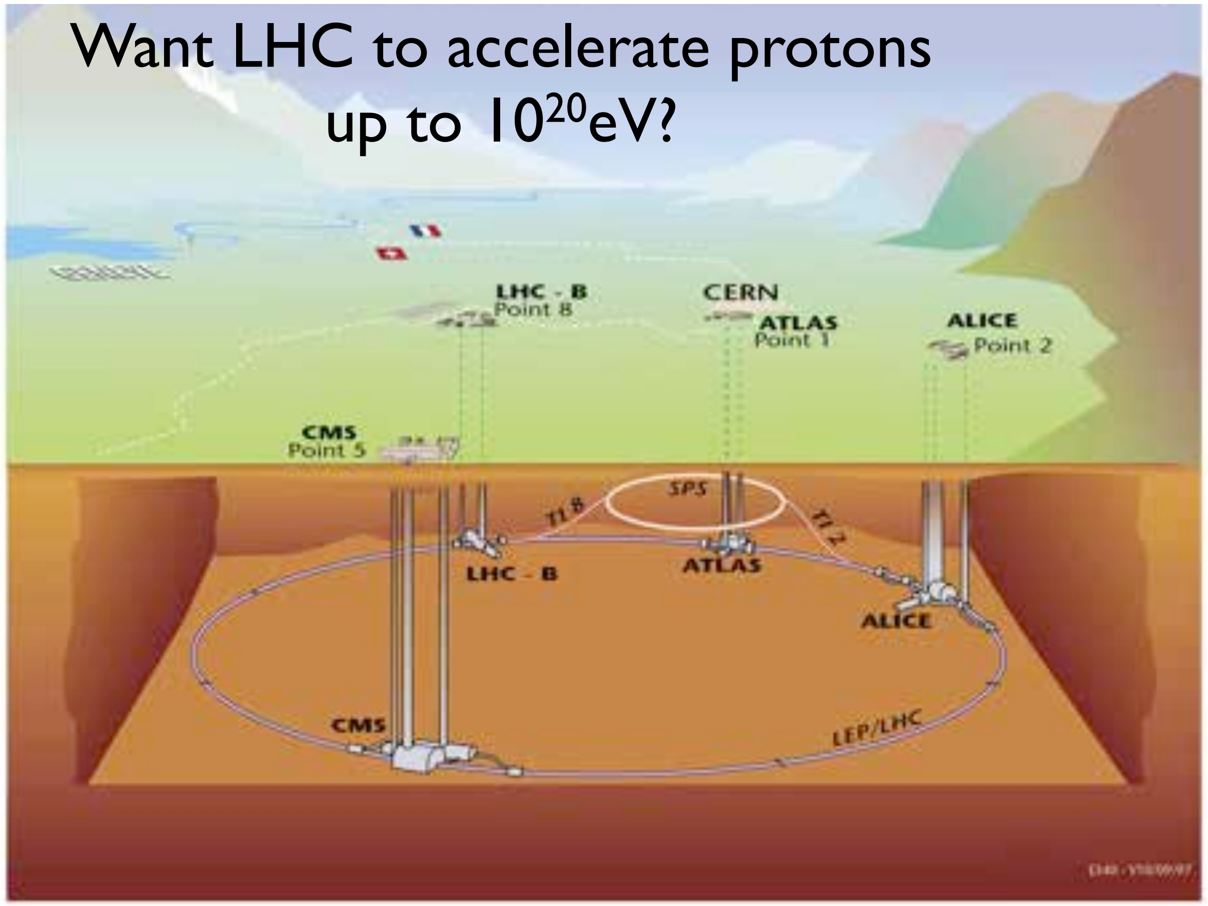
Galactic cosmic rays



Extragalactic cosmic rays? A guess



Accelerators for 10^{20}eV protons



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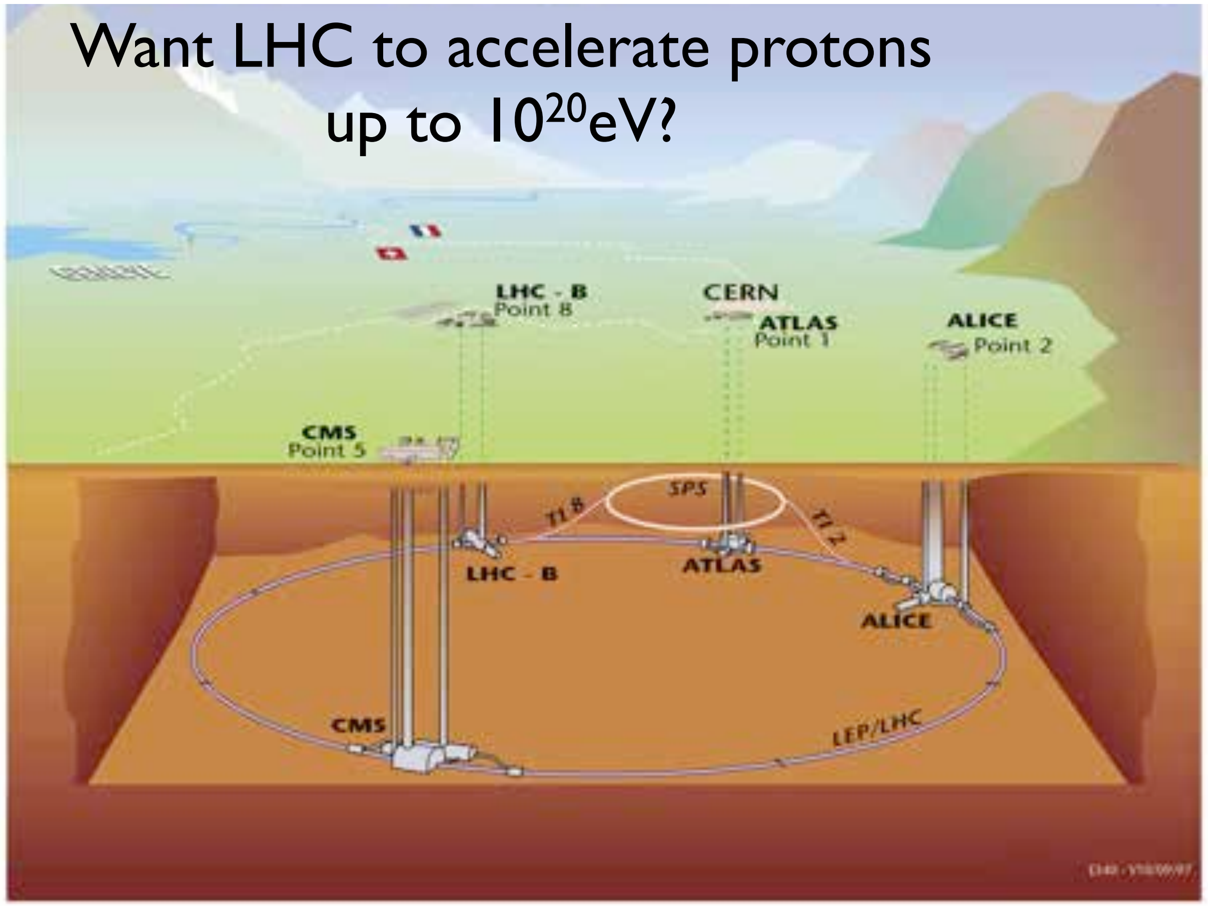
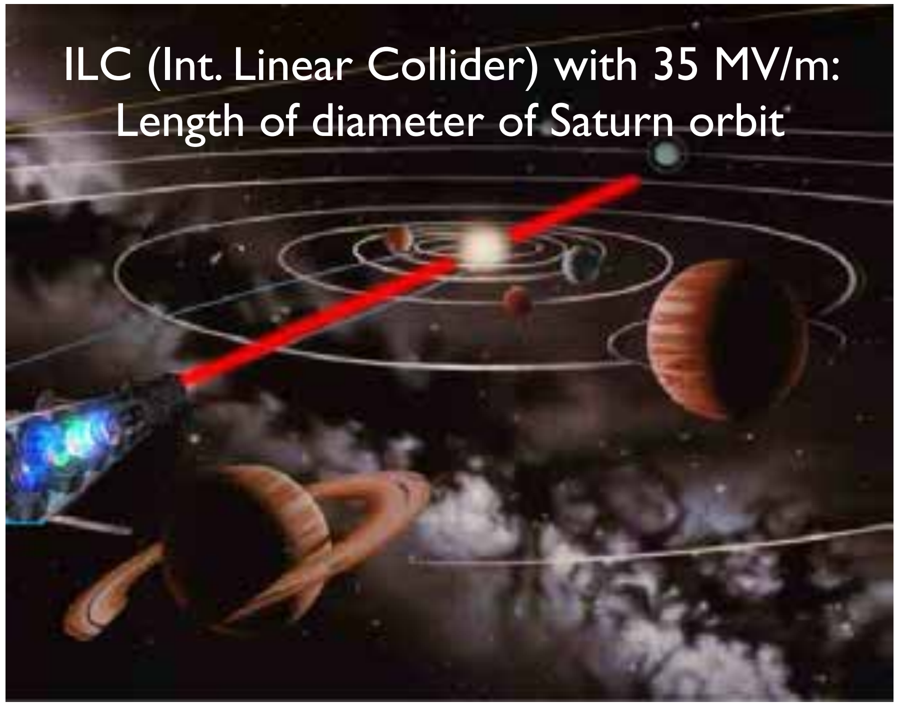
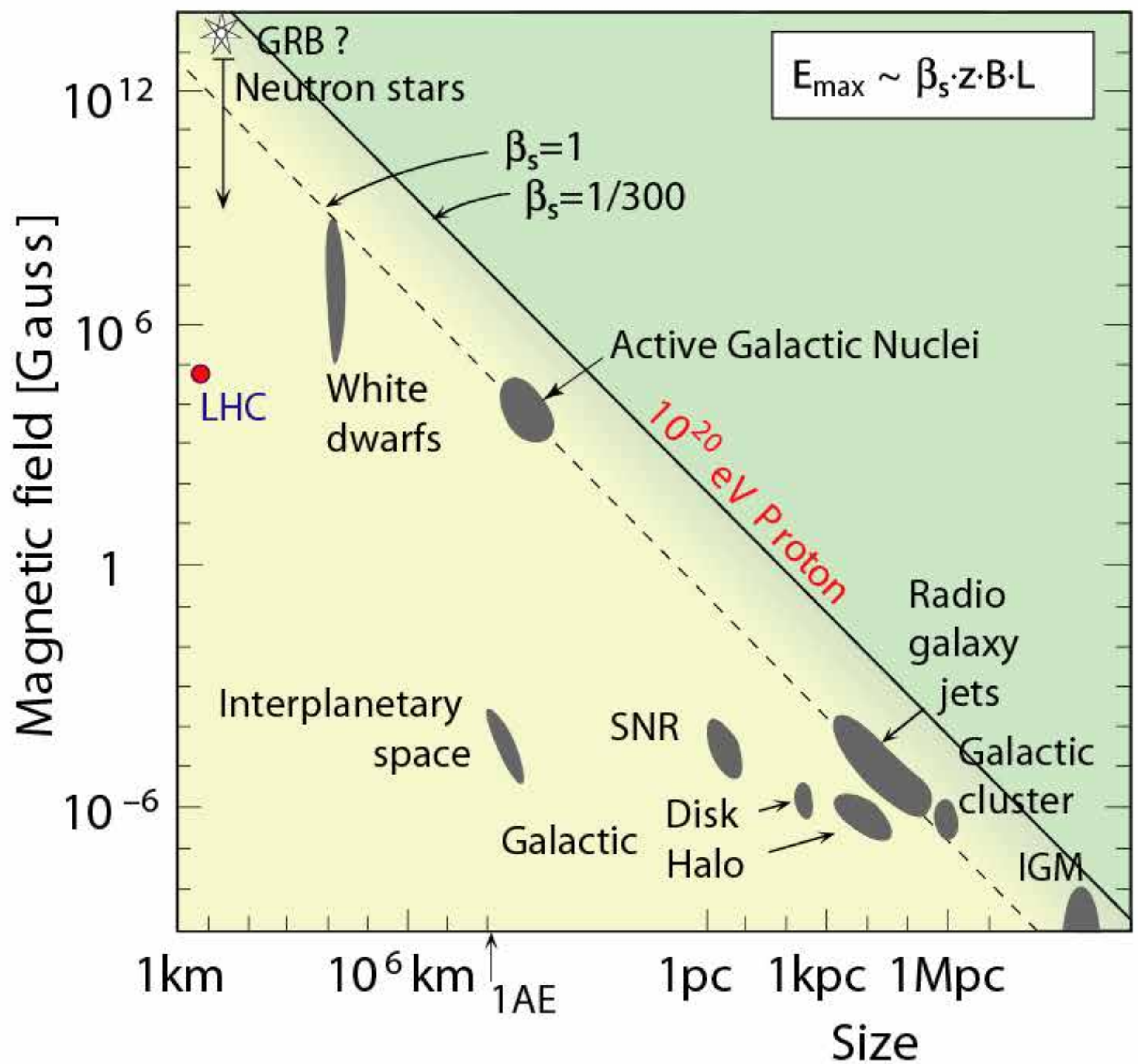




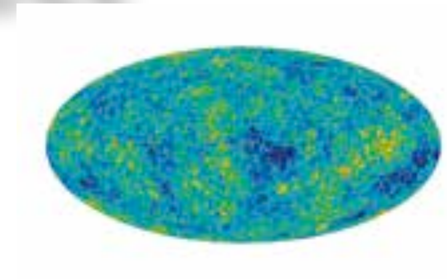
Astrophysical candidates

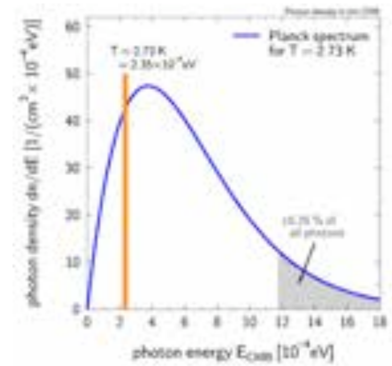
$$E_{\max} \propto Z\beta_s BL$$

Z: charge of the CR
ß: shock velocity
B: magnetic field strength
L: size of the accel. region



Particle horizon / Greisen-Zatsepin-Kuzmin effect

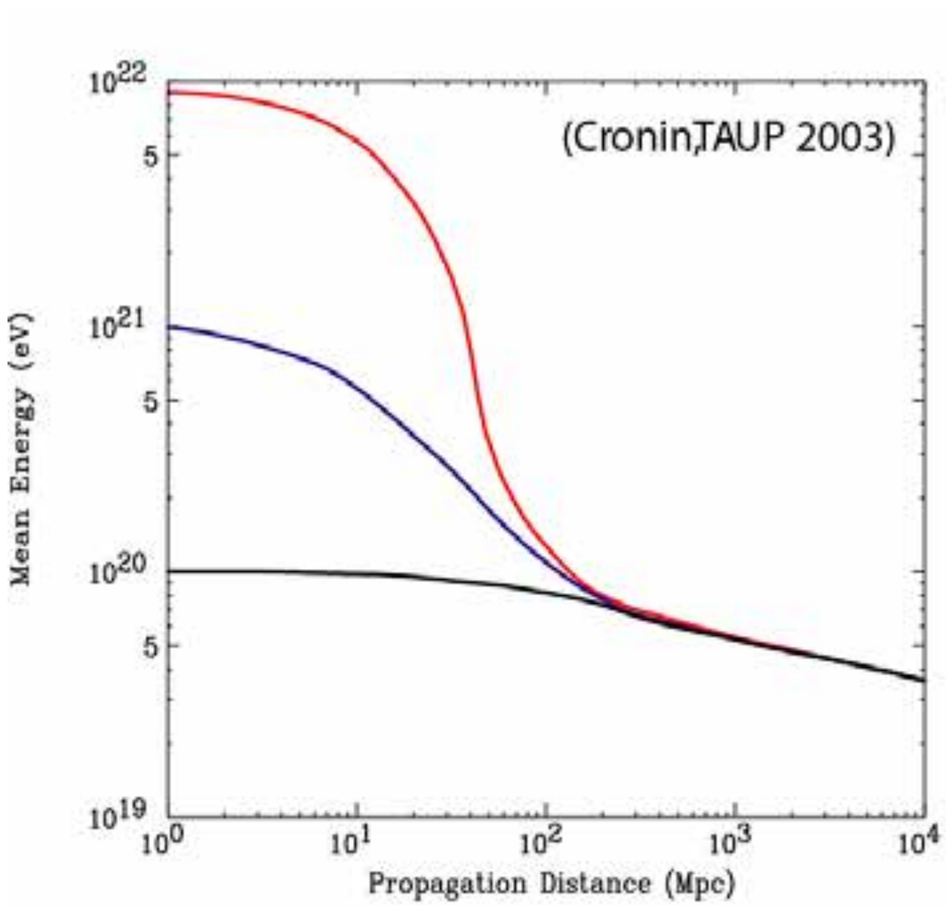


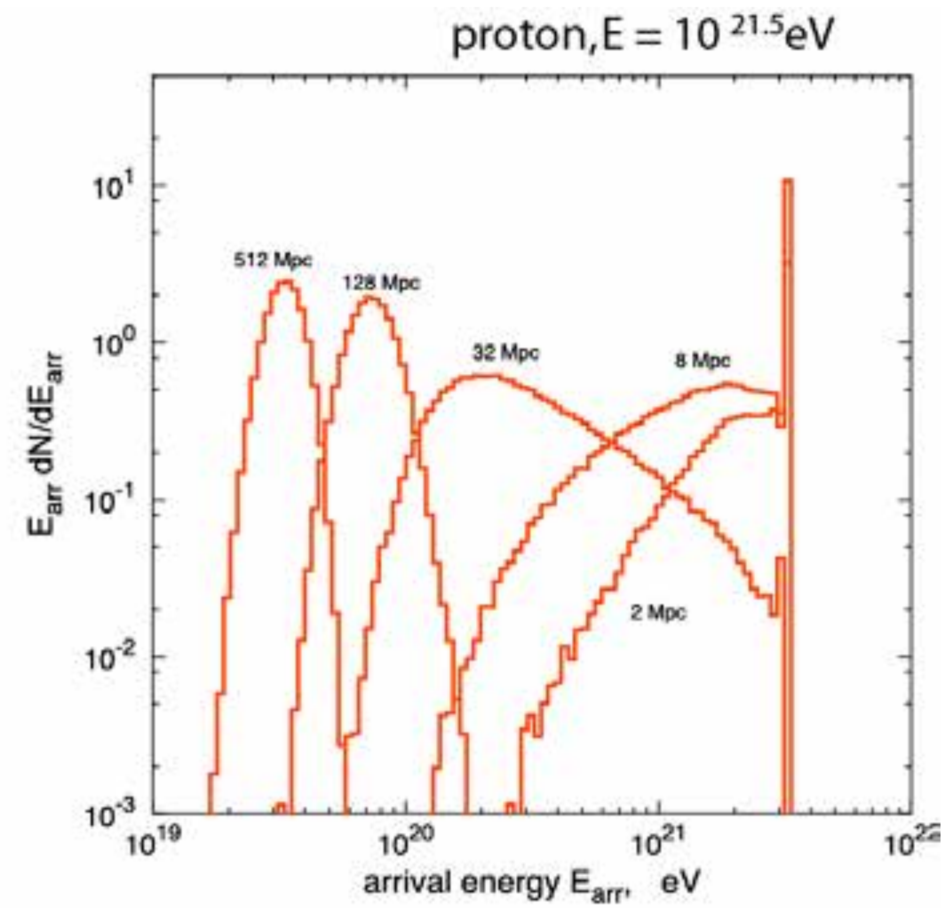


Pion photo production (E_p > 5×10^{19}eV due to CMB) :

$$p + \gamma \quad \rightarrow \quad \Delta^+ \rightarrow p + \pi^0$$
$$p + \gamma \quad \rightarrow \quad \Delta^+ \rightarrow n + \pi^+$$

Interaction length ~ 6 Mpc
Energy loss ~ 20% / interaction



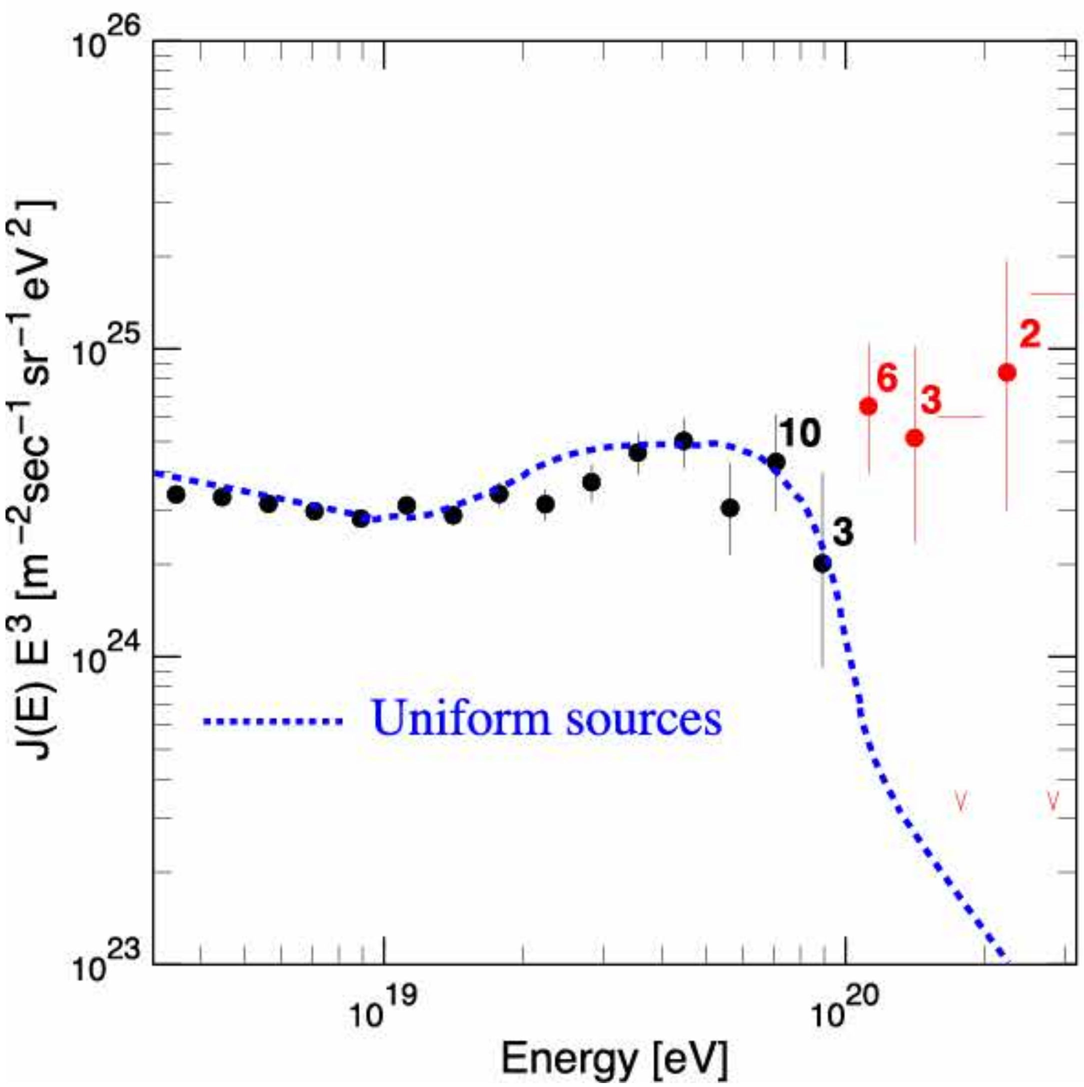


➜ Nearby sources (<50 Mpc)

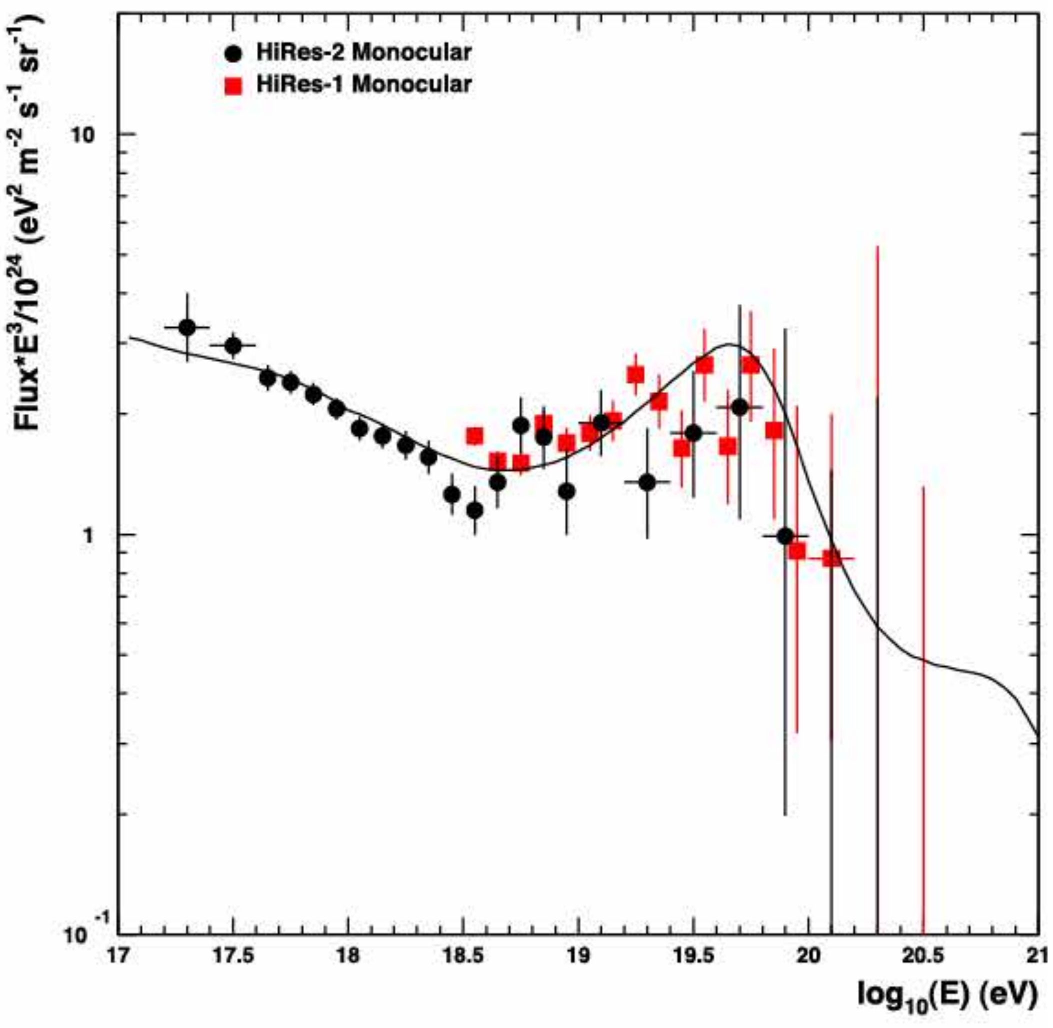
1 lyr = 9.46×10^{15} m
1 pc = 3.26 lyr ~ π lyr

Pre Auger data

(AGASA, PRL 81, 1998 & ICRC 2003)



(HiRes mono, PRL 92, 2004)



Inconsistent with GZK ??

Consistent with GZK ??

The Pierre Auger Collaboration

- ✦ Argentina
- ✦ Australia
- ✦ Brasil
- ✦ Bolivia*
- ✦ Czech Republic
- ✦ France
- ✦ Germany
- ✦ Italy
- ✦ Mexico
- ✦ Netherlands
- ✦ Poland
- ✦ Portugal
- ✦ Slovenia
- ✦ Spain
- ✦ United Kingdom
- ✦ USA
- ✦ Vietnam*

- 300 PhD scientists from ~70 Institutions and 17 countries

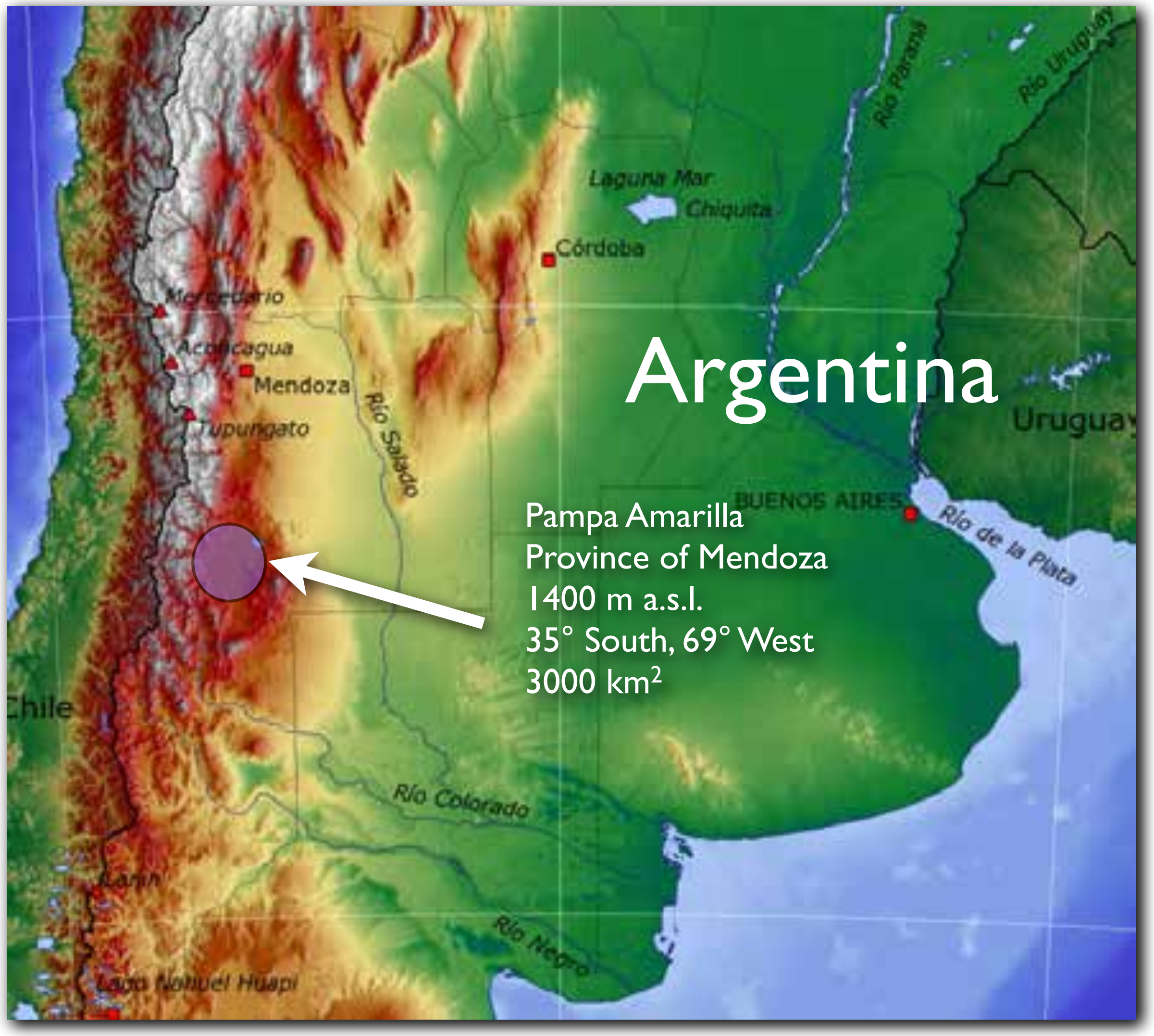
  *Associate Countries

The Pierre Auger Observatory

- *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



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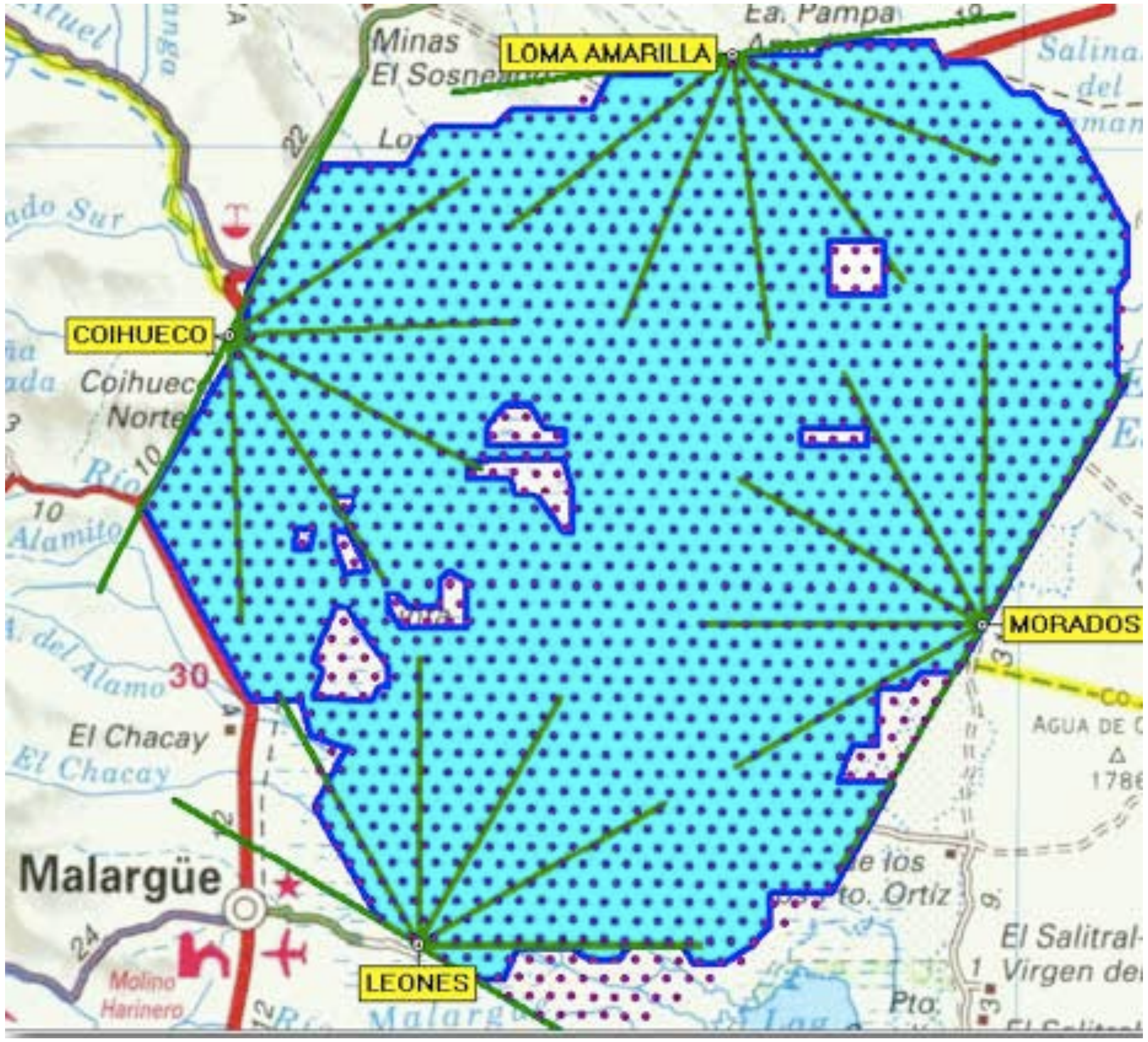
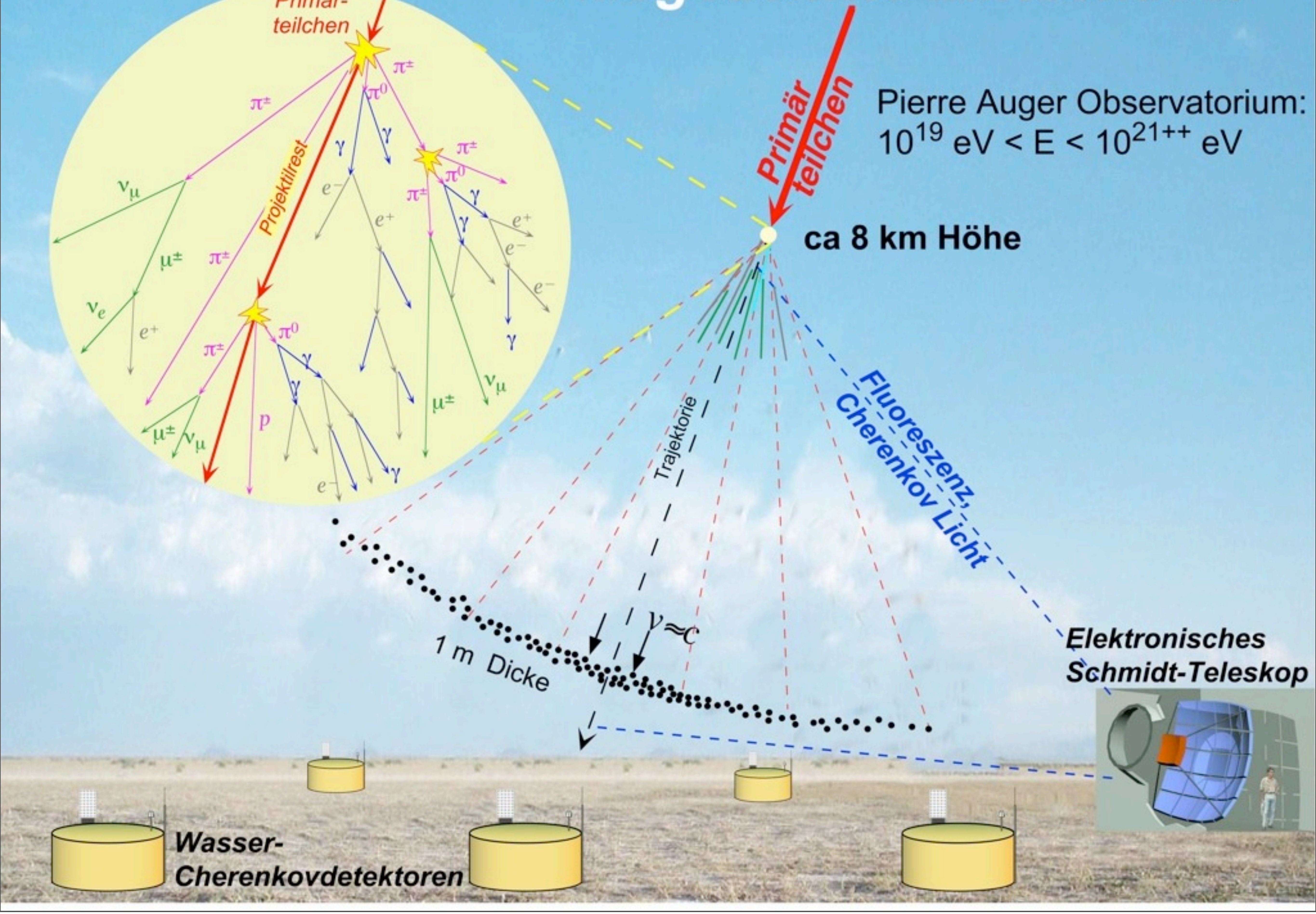
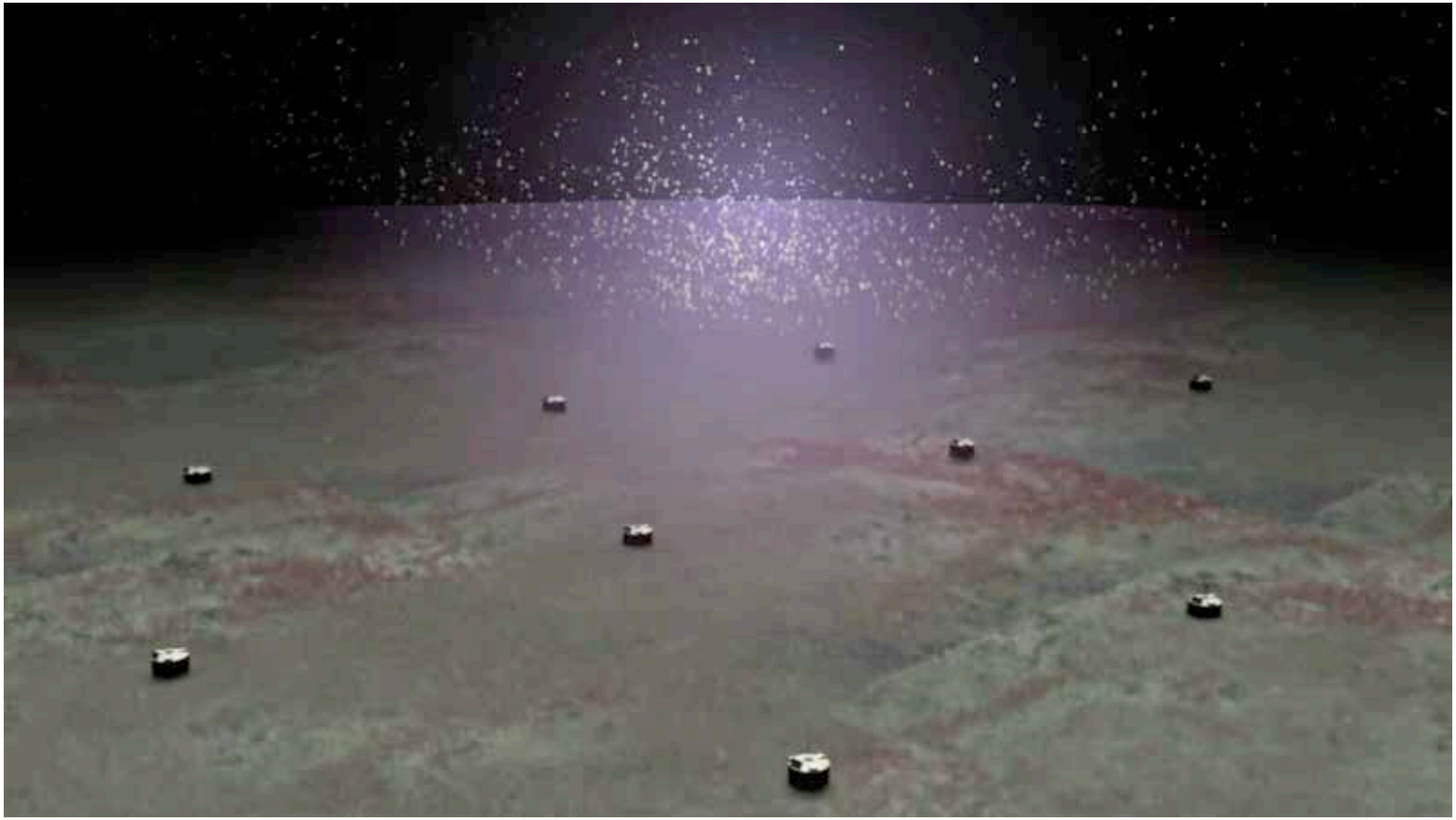


Ausgedehnte Luftschauer



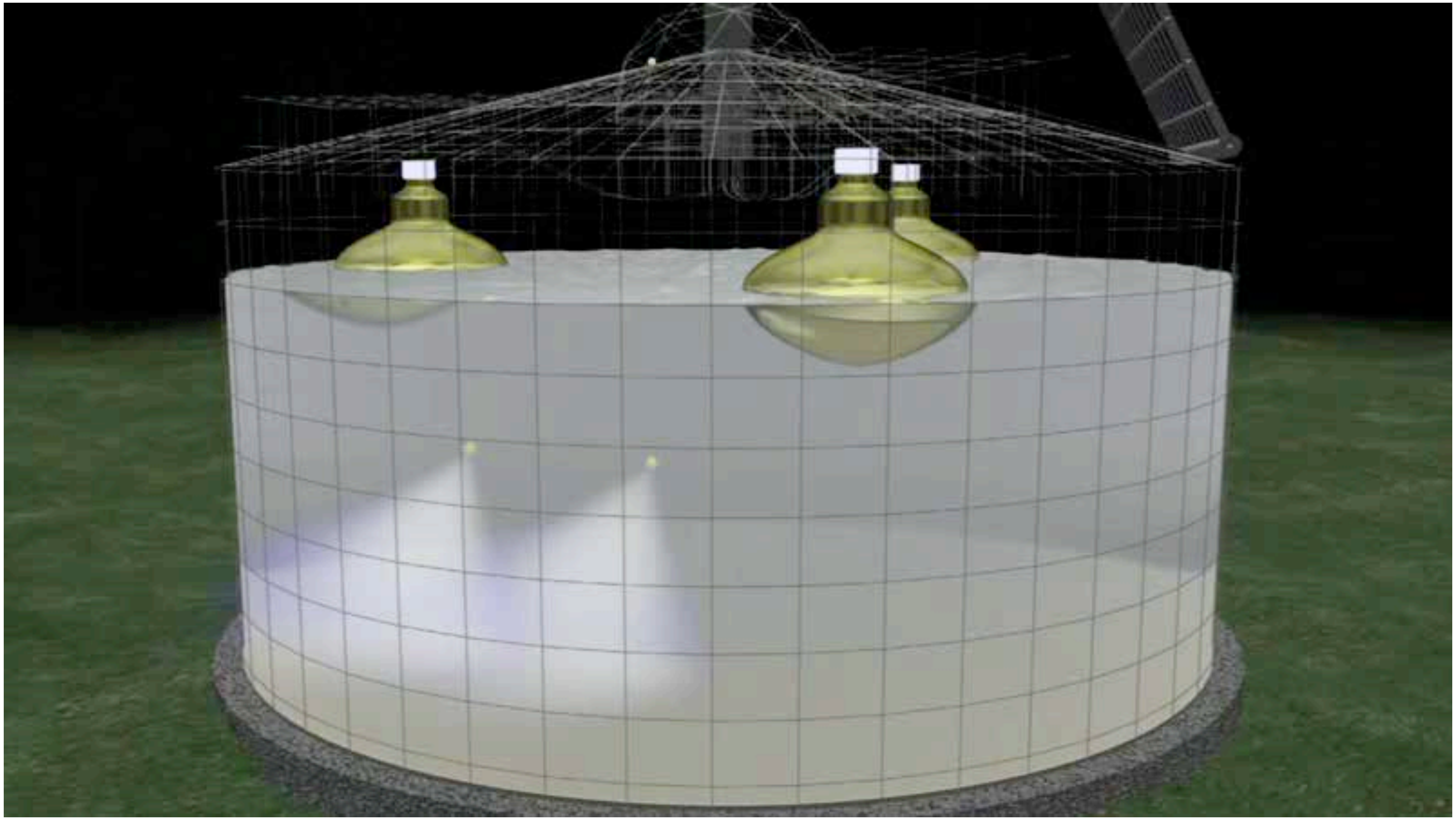
The Southern Observatory

The Southern Observatory



A surface detector station

A surface detector station



A fluorescence telescope

A fluorescence telescope

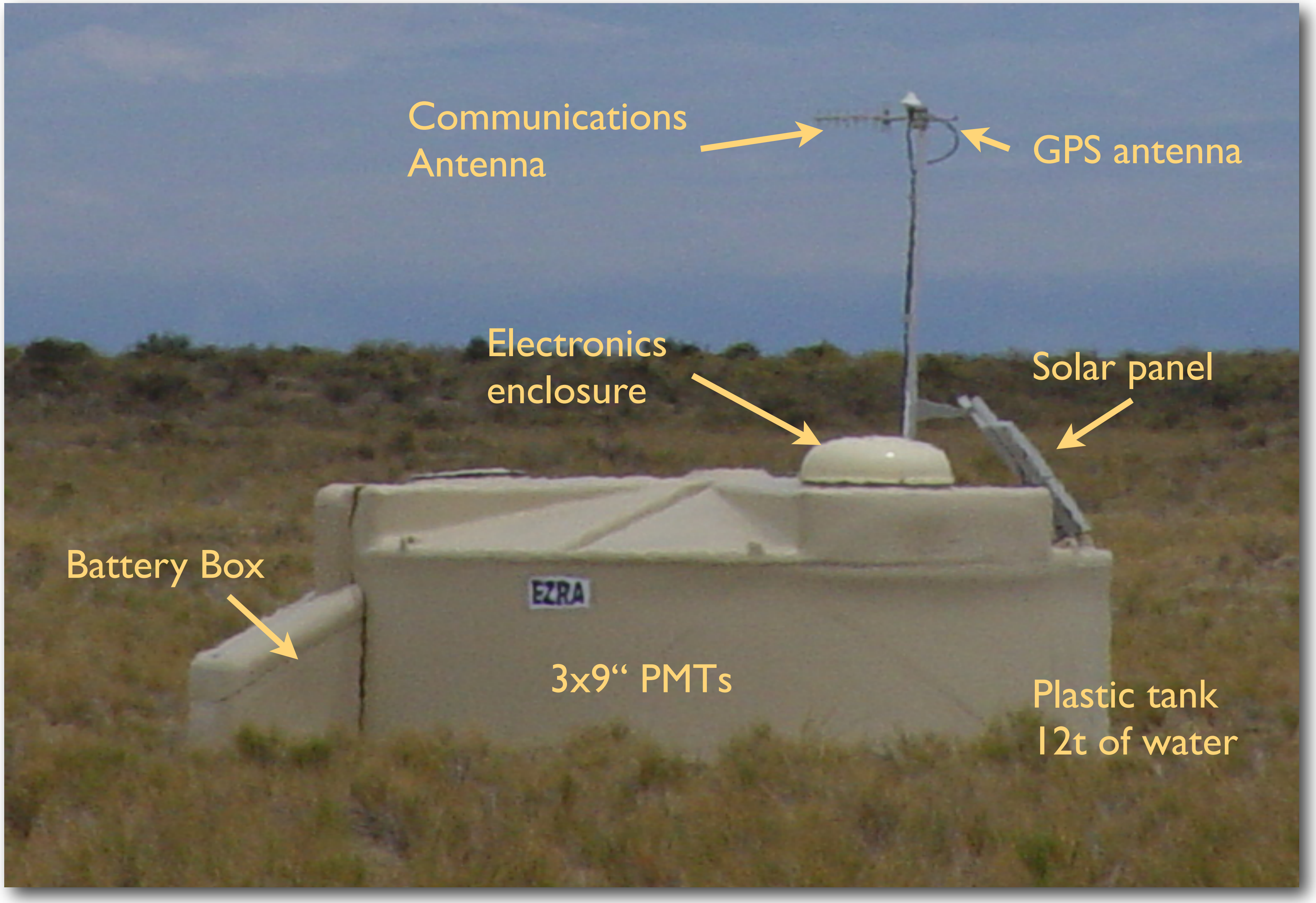
The hybrid nature of Auger

The surface detector

The surface detector

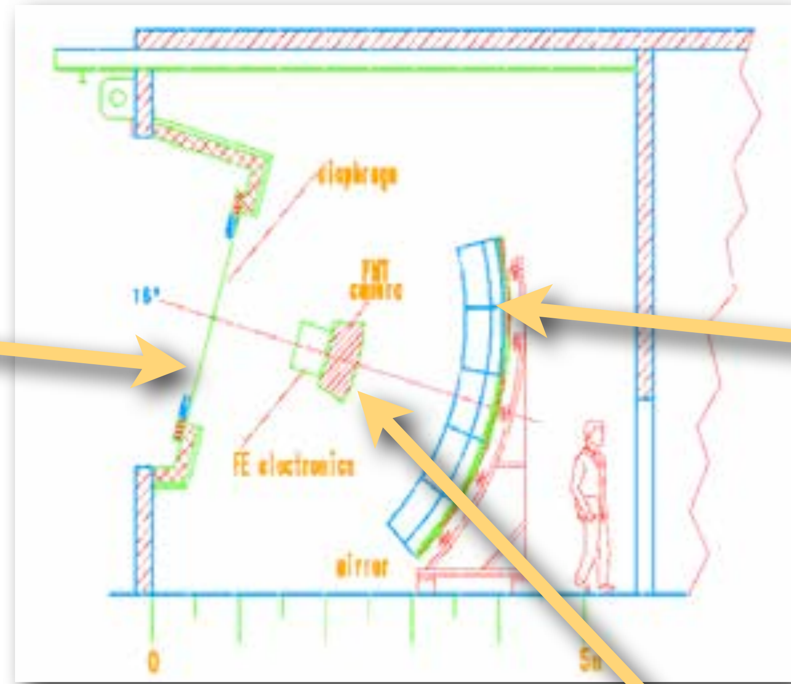
The surface detector

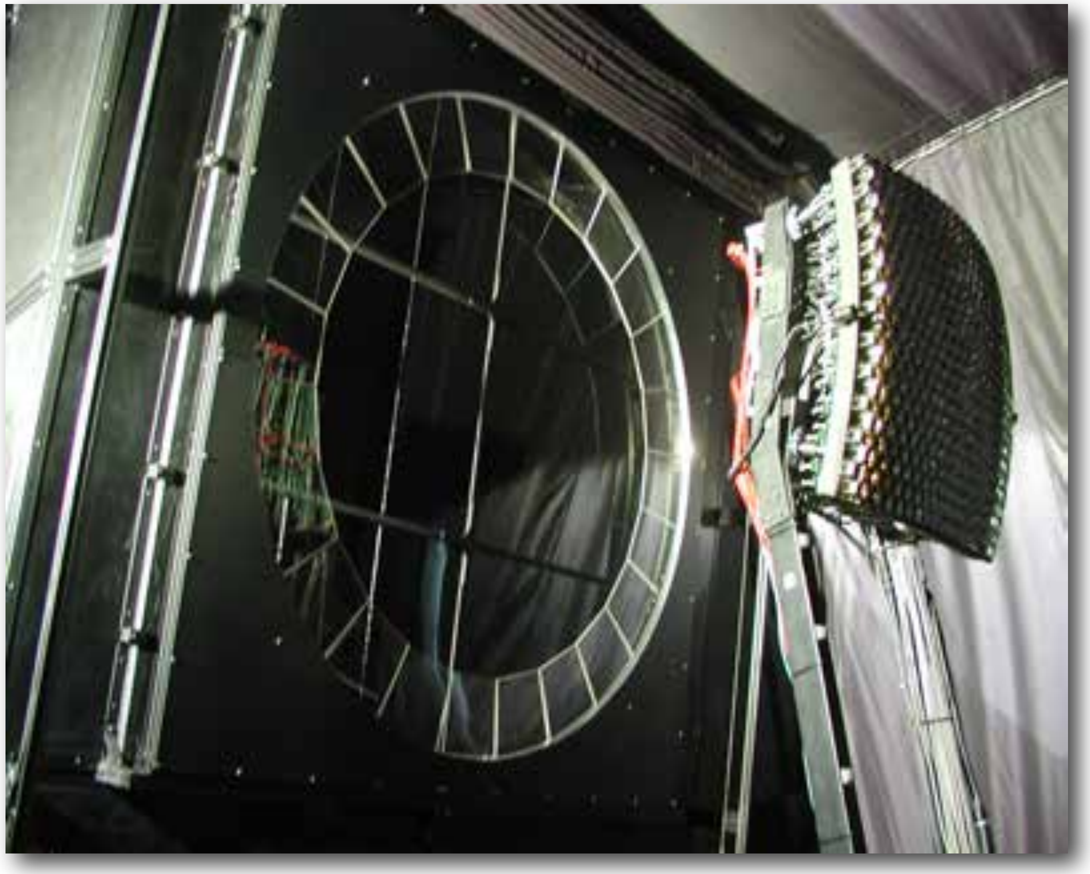
- 1600 Water Cherenkov tanks (1.2 m height, 10 m^2 area)
- 12,000 ltrs of purified Water
- Three 9" PMTs
- 40 MHz FADCs
- solar powered
- GPS based timing
- micro-wave communication

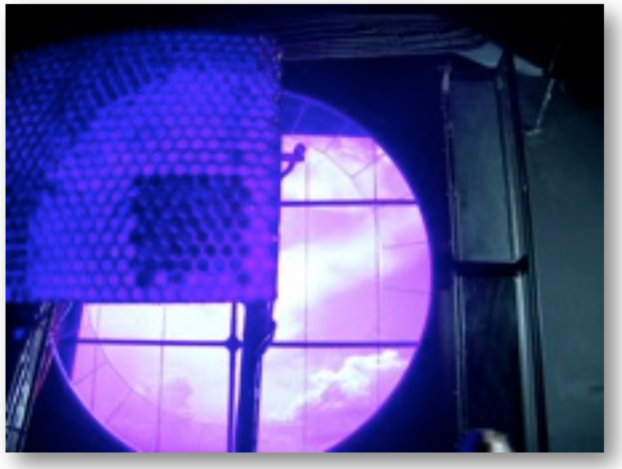


The fluorescence detector

The fluorescence detector



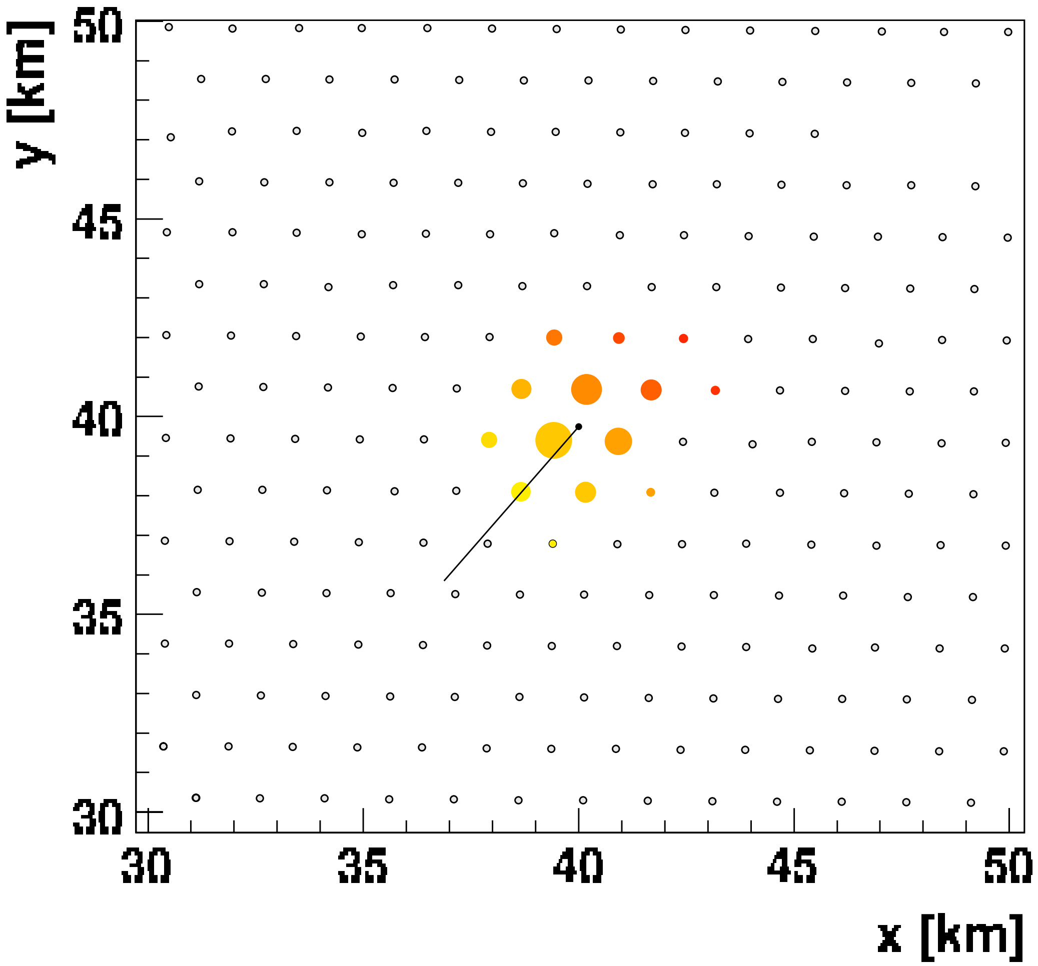


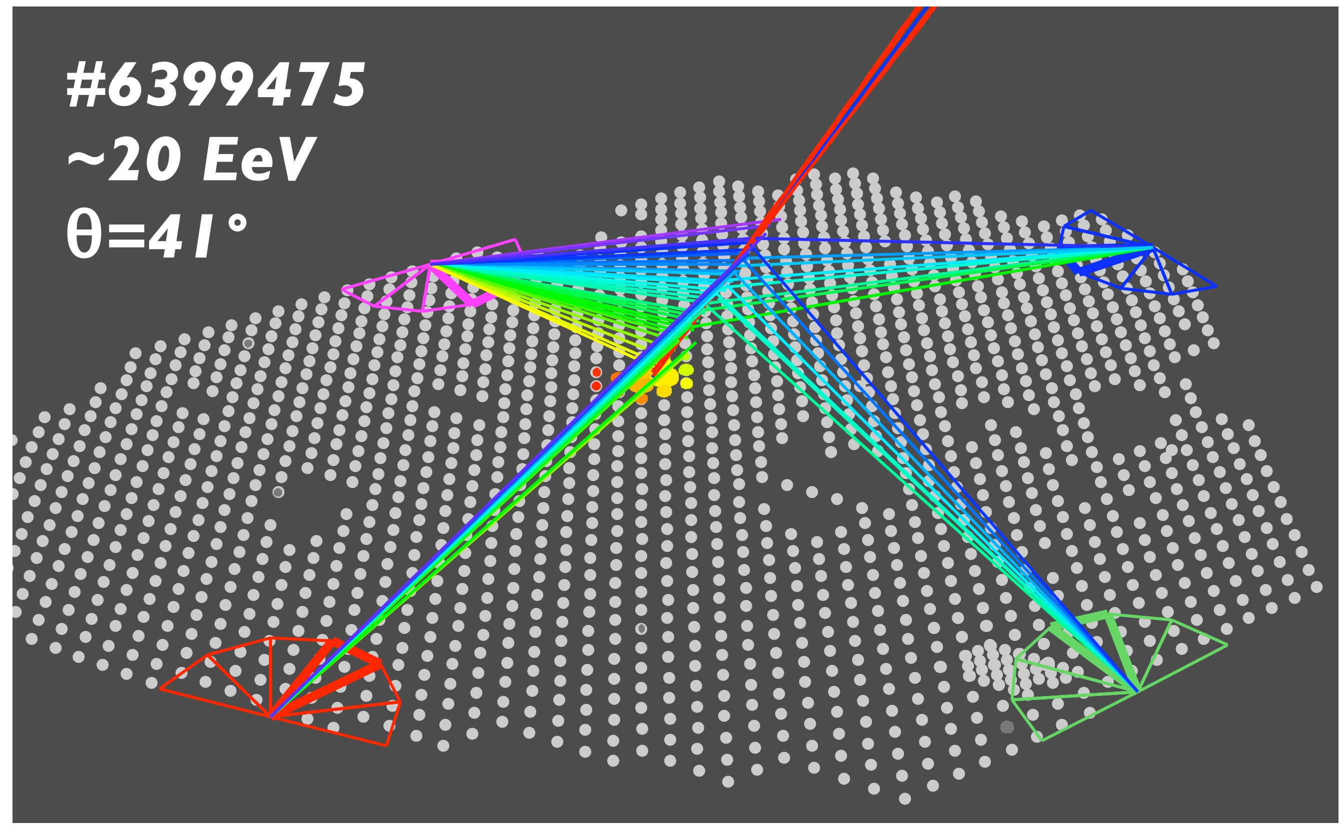


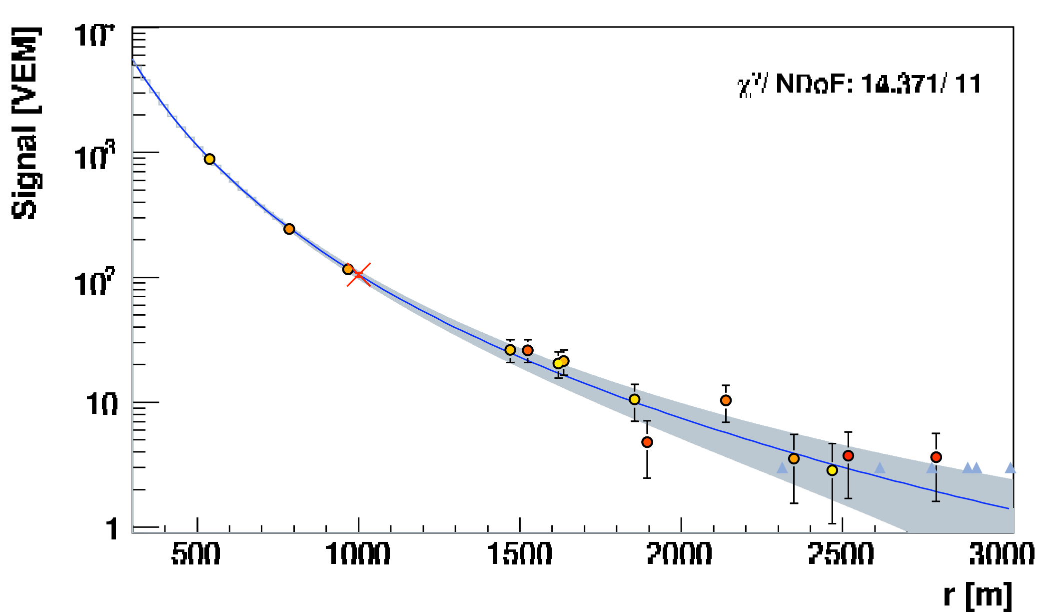
The hybrid era

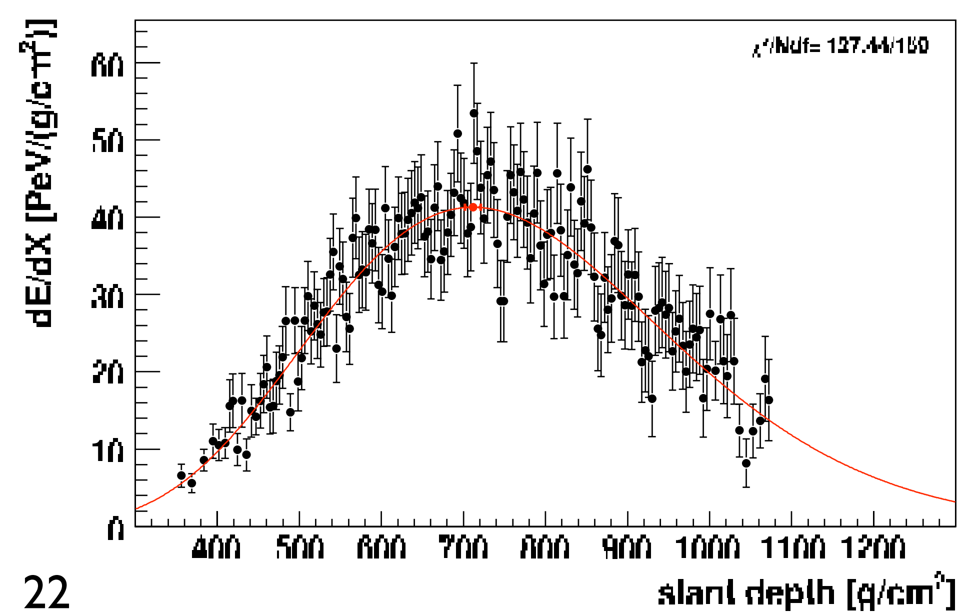
	FD-mono	SD-only	FD+SD (Hybrid)	SD (Hyb calib)
Angular resolution	~3-5°	~1-2°	~0.5°	~1-2°
Aperture	dependent on detector MC and atmosph. cond.	purely geometric, A and model free	dependent on detector MC and atmosph. cond.	purely geometric, A and model free
Energy	approx. A and model free	A and model dependent	approx. A and model free	approx. A and model free
Duty cycle	~13%	~100%	~13%	100%
Experiment	Fly's Eye, HiRes I, Hires II	AGASA, Haverah Park	Auger	Auger

4-fold event


y [km]
x [km]
30
35
40
45
50


#6399475
~20 EeV
θ=41°

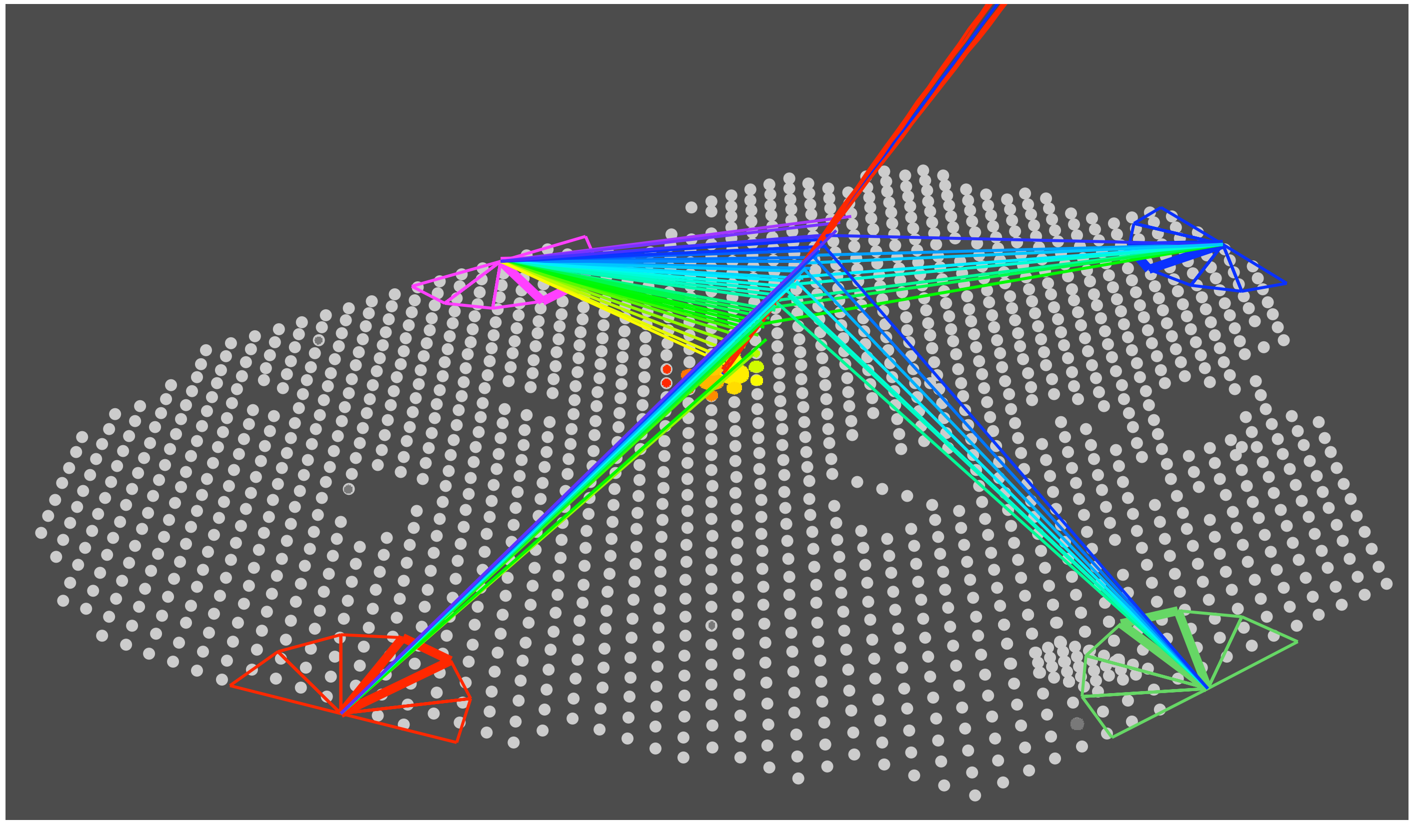

Signal [VEM]
χ²/ NDoF: 14.371/ 11
r [m]
500
1000
1500
2000
2500
3000


dE/dX [PeV/(g/cm²)]
χ²/Ndf= 127.44/150
slant depth [g/cm²]

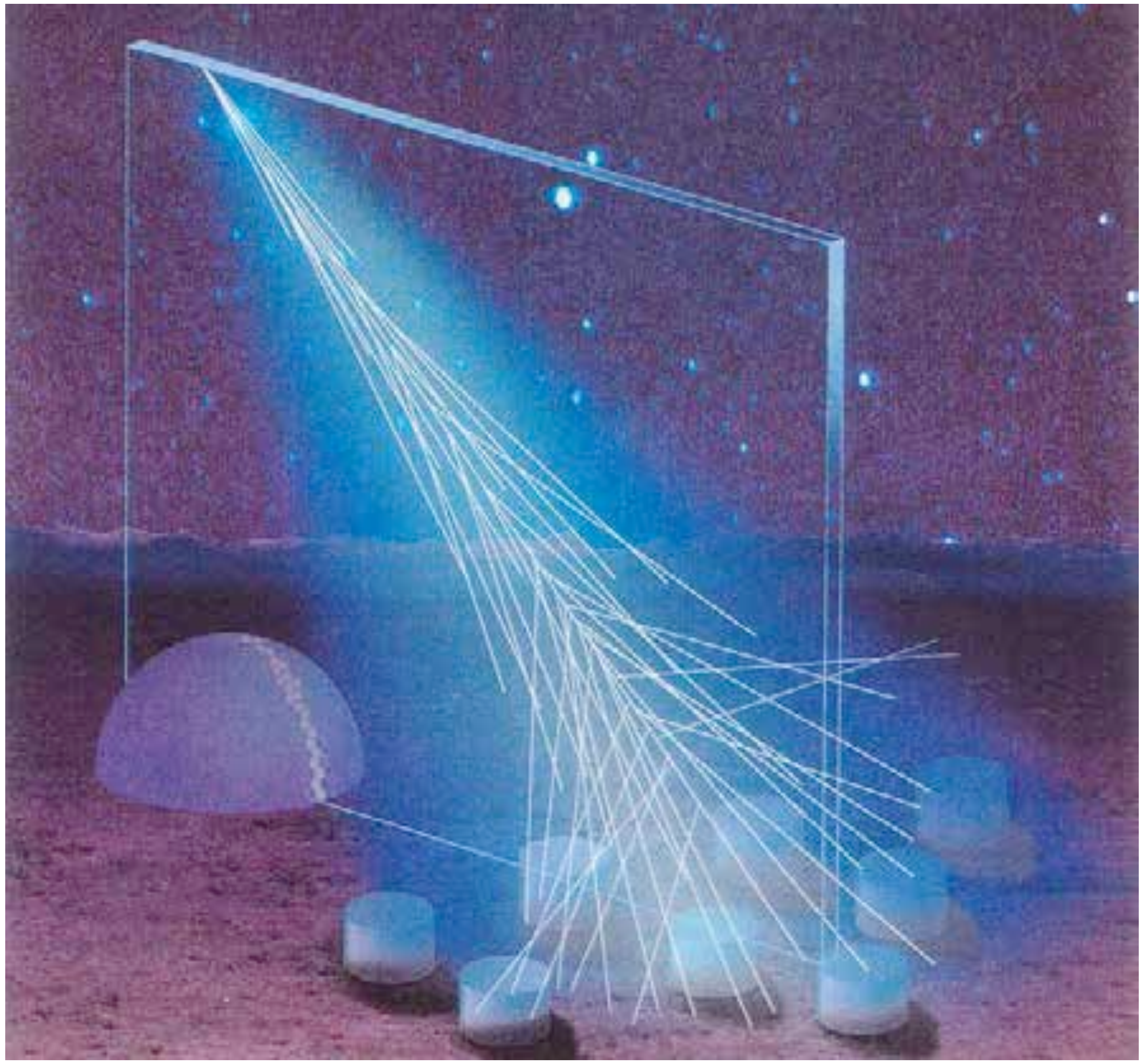
Energy spectrum

- Hybrid spectrum (FD & SD)
- Surface detector spectrum
- Auger spectrum (i.e. combined)
- (Horizontal EAS spectrum)

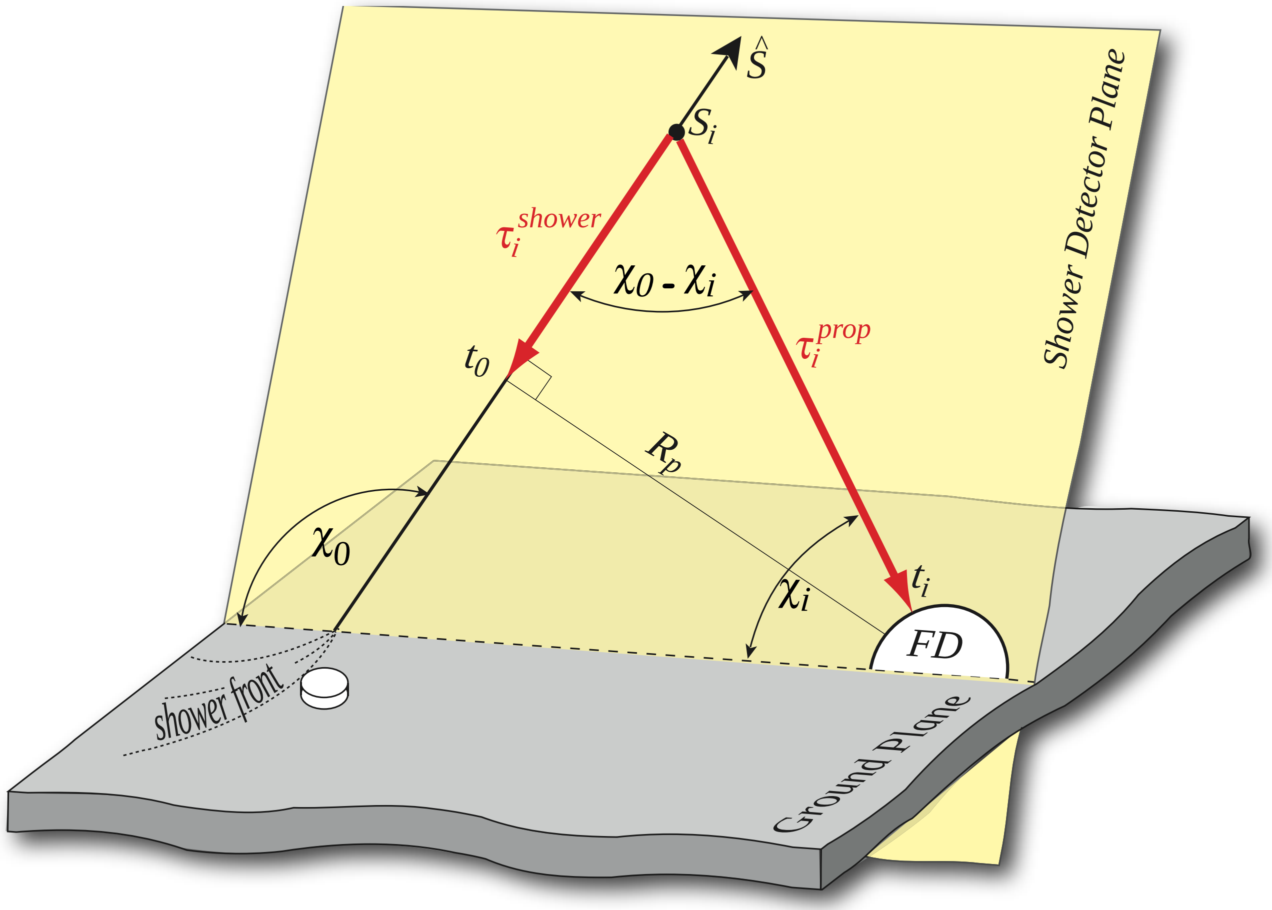
Hybrid spectrum



Geometrical reconstruction



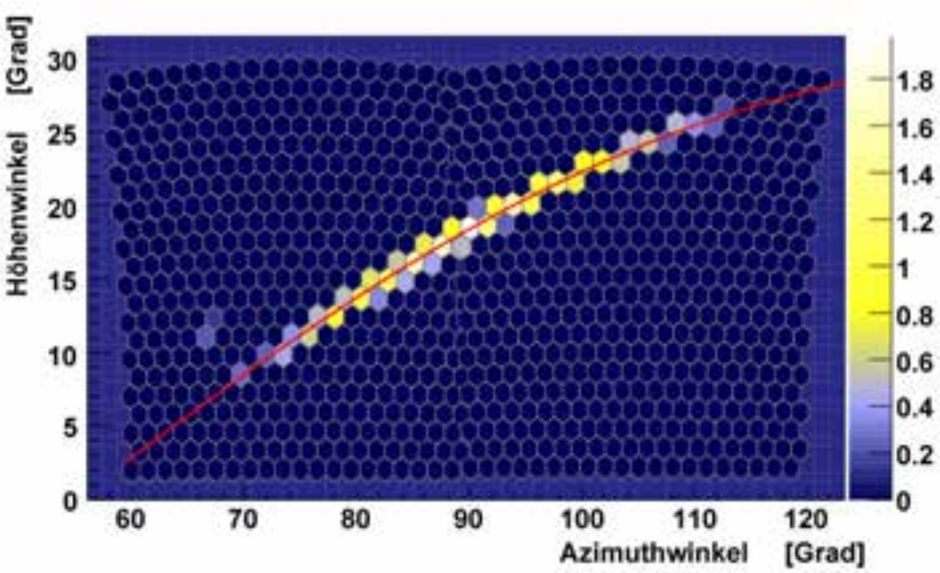
Precise shower geometry
from breaking degeneracy using SD timing

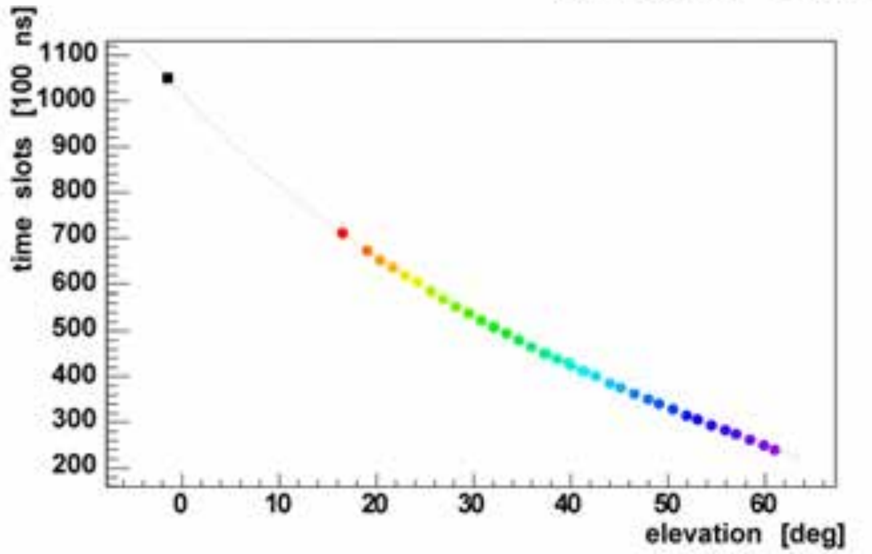


times, t_i, at angles χ_i, are key to finding R_p

$$t_i = t_0 + \frac{R_p}{c} \cdot \tan\left(\frac{\chi_0 - \chi_i}{2}\right)$$

Geometrical reconstruction





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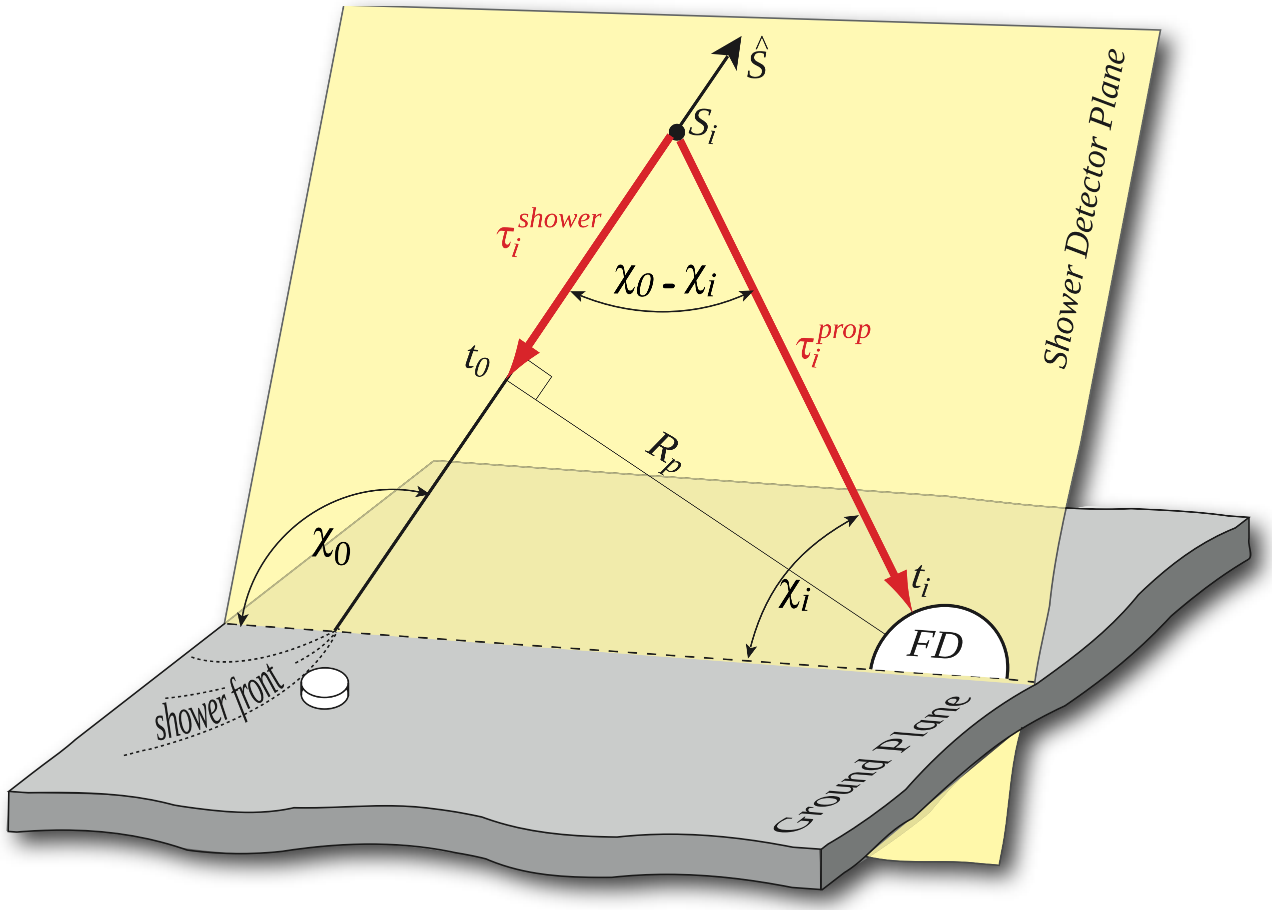

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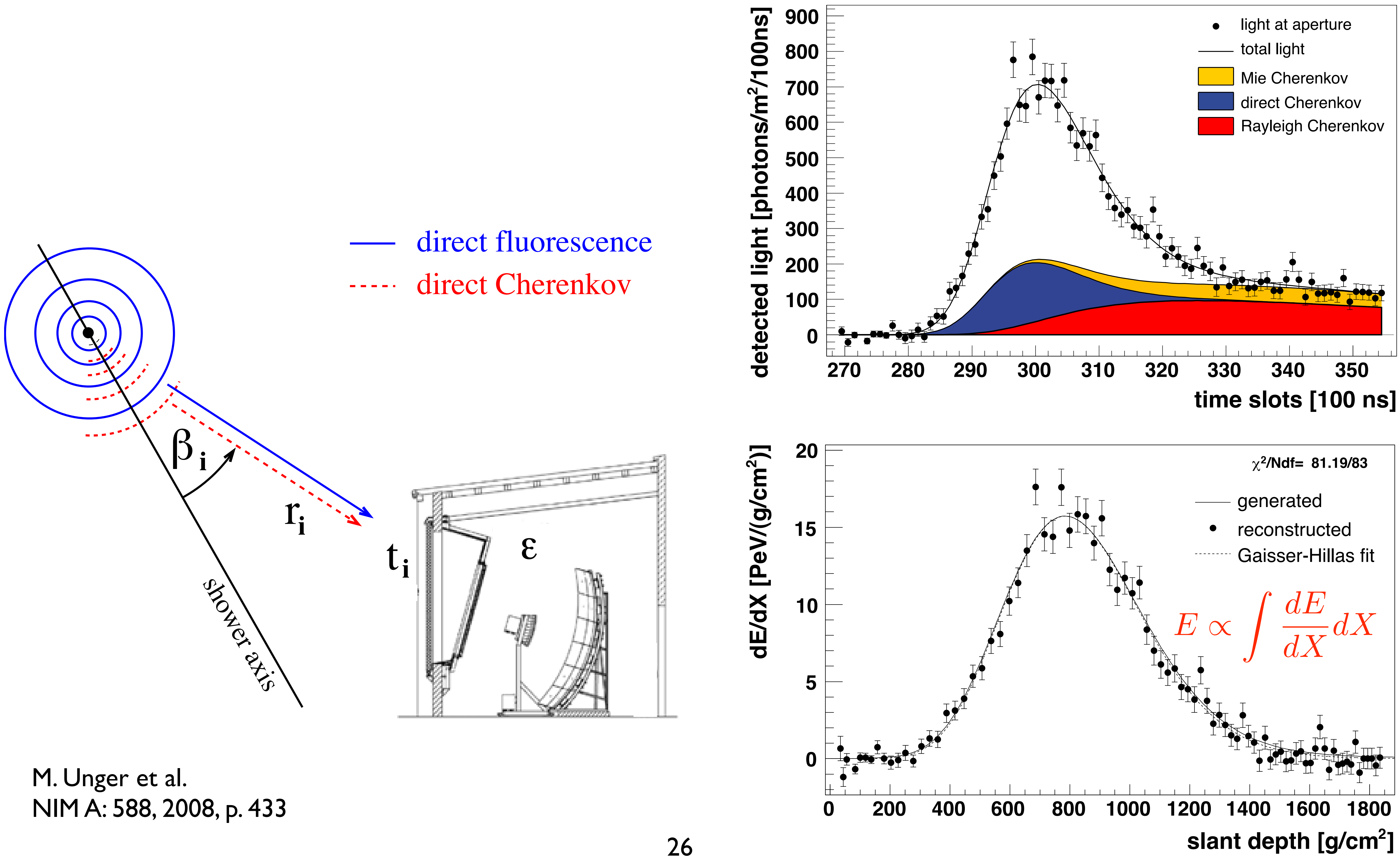
FD energy calibration



M. Unger et al.
NIM A: 588, 2008, p. 433

How to determine the hybrid spectrum

Aim: Flux measurement $$J(E) = \frac{d^4 N}{dE\, dS\, d\Omega\, dt} \simeq \frac{1}{\Delta E} \frac{\Delta N(E)}{\mathcal{E}(E)}$$

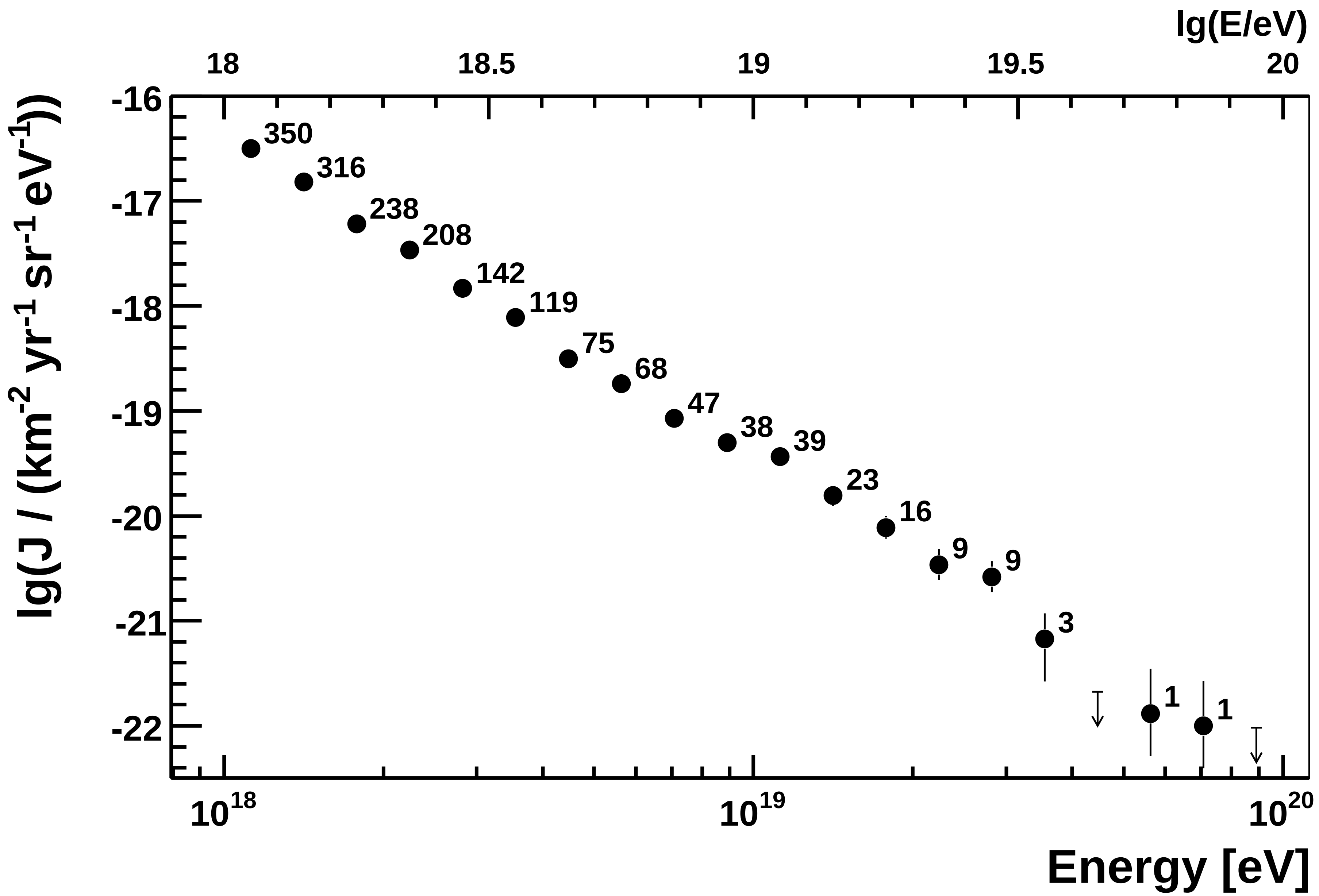
Event selection of high quality events:

- Geometrical reconstruction
  - Zenith < 60°
  - Station within 1500m from shower axis
  - Energy dependent distance between core and FD site (Astropart. Phys. 27, 2007)
  - Energy dependent filed of view (Unger, ICRC Merida 2007)
- Profile reconstruction
  - Gaisser-Hillas fit with χ^2/ndof <2.5
  - X_{max} contained in the observed depth range
  - Cherenkov light < 50%
  - $\sigma(E)$<20%
- Atmospheric conditions
  - Measurement of atmospheric parameters available
  - Cloud coverage from Lidar measurements < 25%

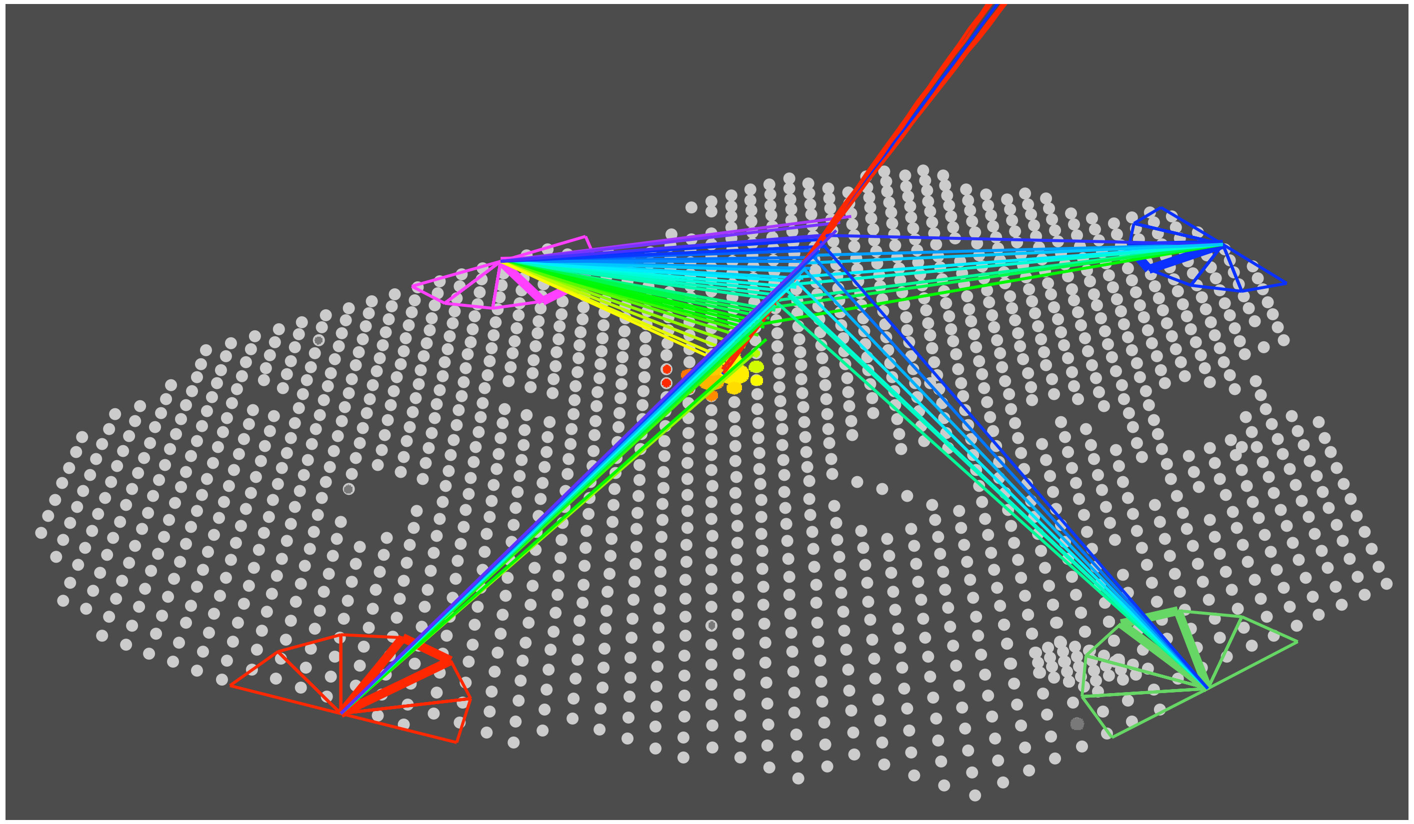
Hybrid spectrum

Energy resolution<6%
Overall syst. uncert. (exposure):

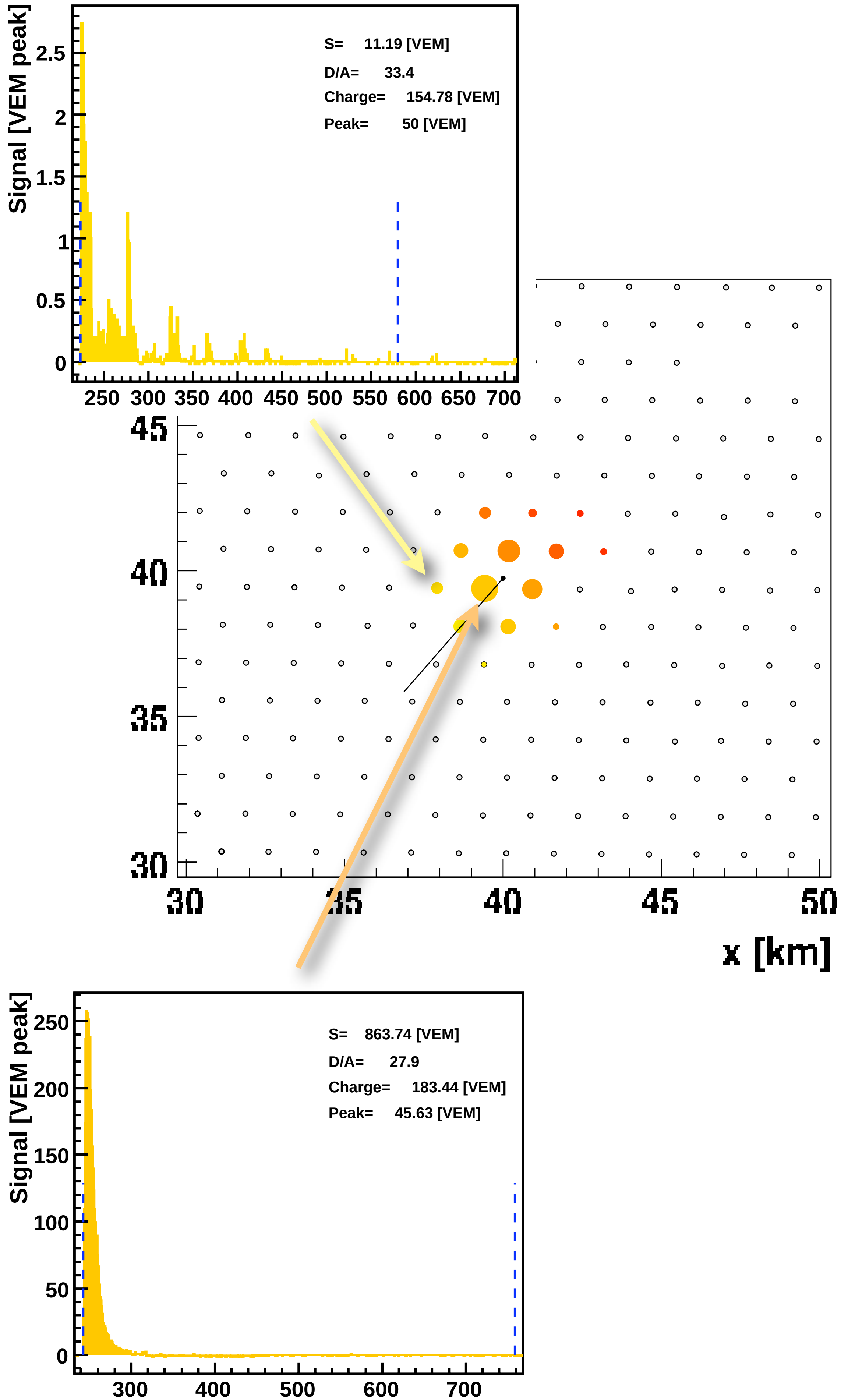
- 10% @ 10^{18}eV
- 6% @ 10^{19}eV

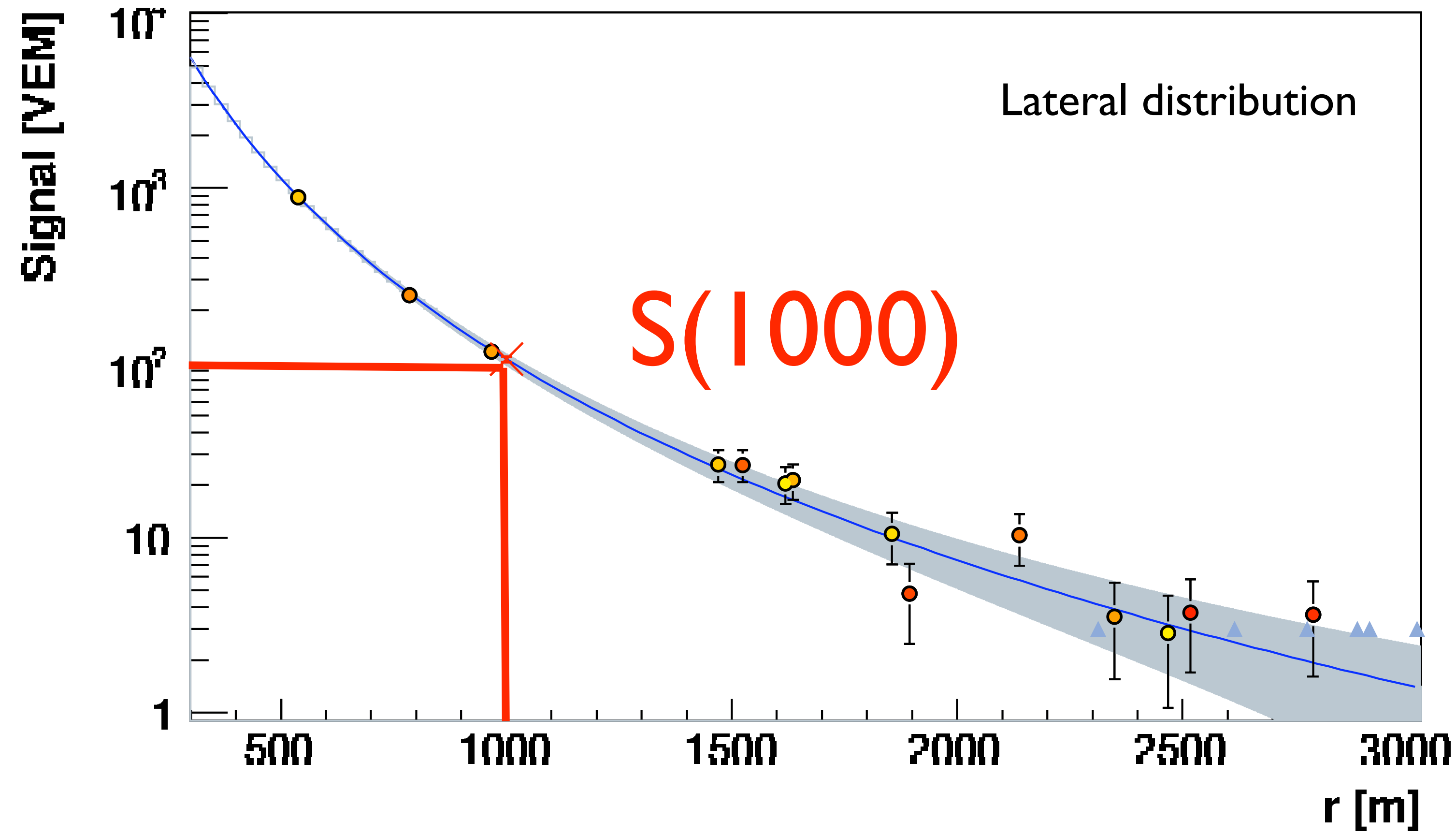


SD-array spectrum (<60°)



4-fold event (SD part)





Detector signal at 1000 m from shower core

- S(1000)
- determined for each surface detector event

S(1000) ~ E

Energy calibration with the fluorescence detector

Energy uncertainty from calibration curve:

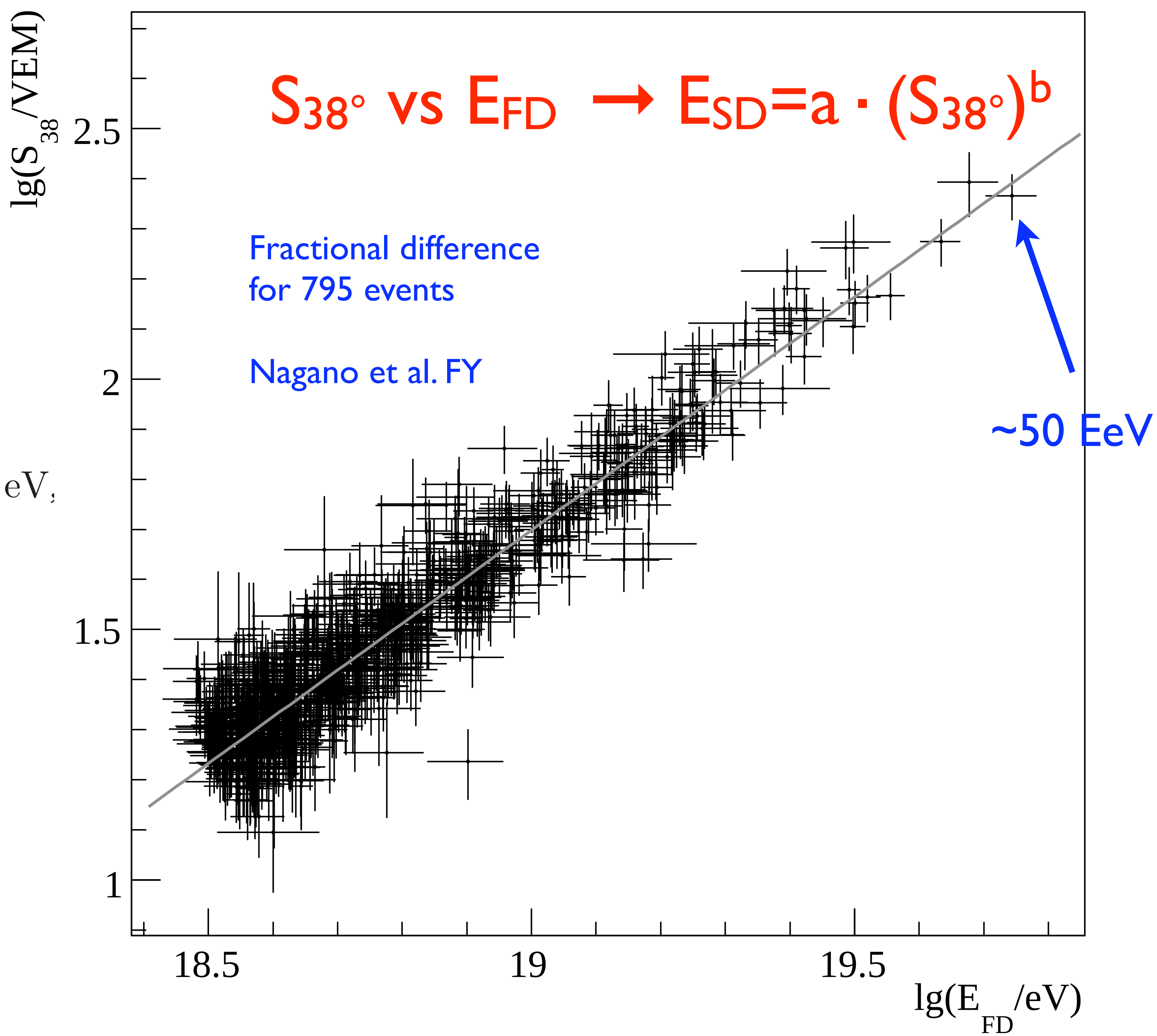
- 7% at 10 EeV
- 15% at 100 EeV

Improves with increased hybrid statistics

$$a = (1.51 \pm 0.06(stat) \pm 0.12(syst)) \times 10^{17}\,\mathrm{eV},$$
$$b = 1.07 \pm 0.01(stat) \pm 0.04(syst),$$

Note:

Both S_{38° and E_{SD} are determined experimentally. We do not rely on shower simulation.



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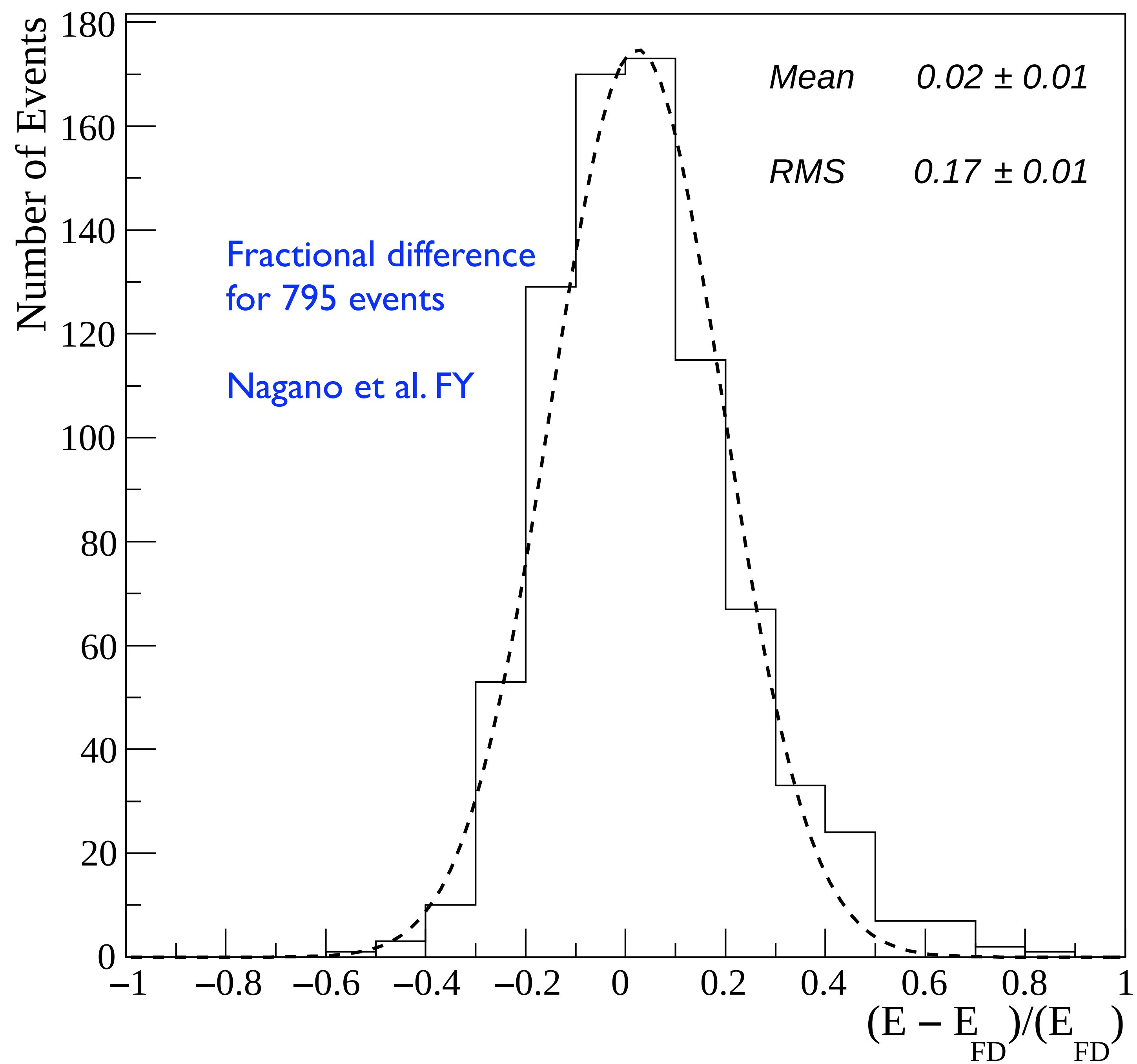
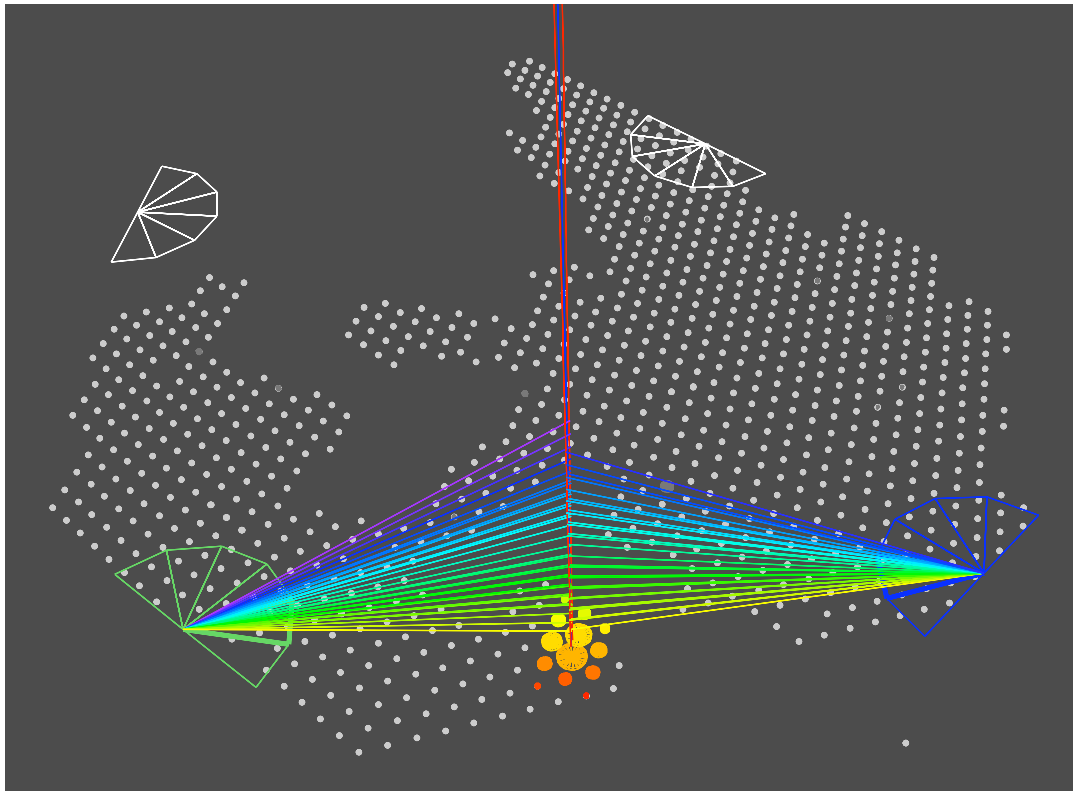


Energy determination with FD



Source	Systematic uncertainty	Comment
Fluorescence yield	14%	Nagano + AIRFLY
P,T and humidity effects on yield	7%	
Calibration	9.5%	Calib. source, laser
Atmosphere	4%	
Reconstruction	10%	Optical spot, Lat. Ch. dist.
Invisible energy	4%	Model dependence
Total	22%	

FD energy: statistical uncertainty <6%
determined with
- detector simulation
- validated by stereo events

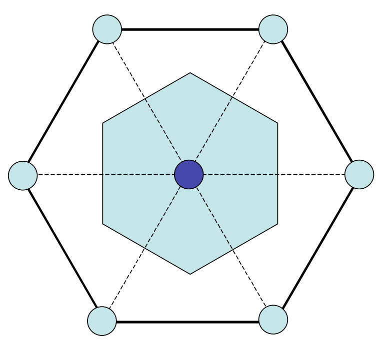
FD energy: systematic uncertainty ~22%

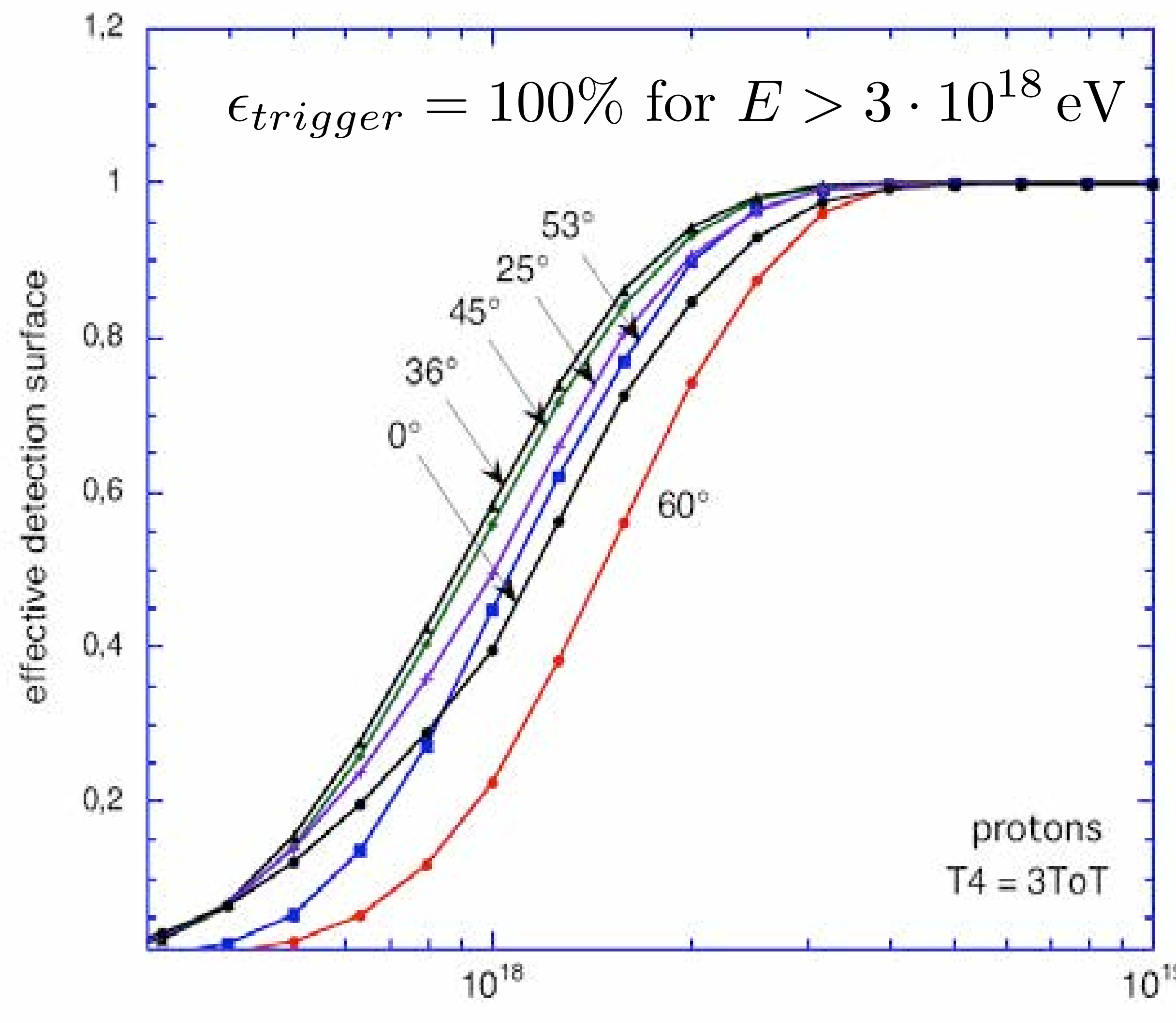
Exposure

Data period:
1 Jan 2004 - 31 Dec 2008
154 Tanks - >1600 Tanks

$$\text{Exposure} = \int \epsilon_{trigger} \times A(t)dt$$

A(t) = sum of areas of all active hexagons



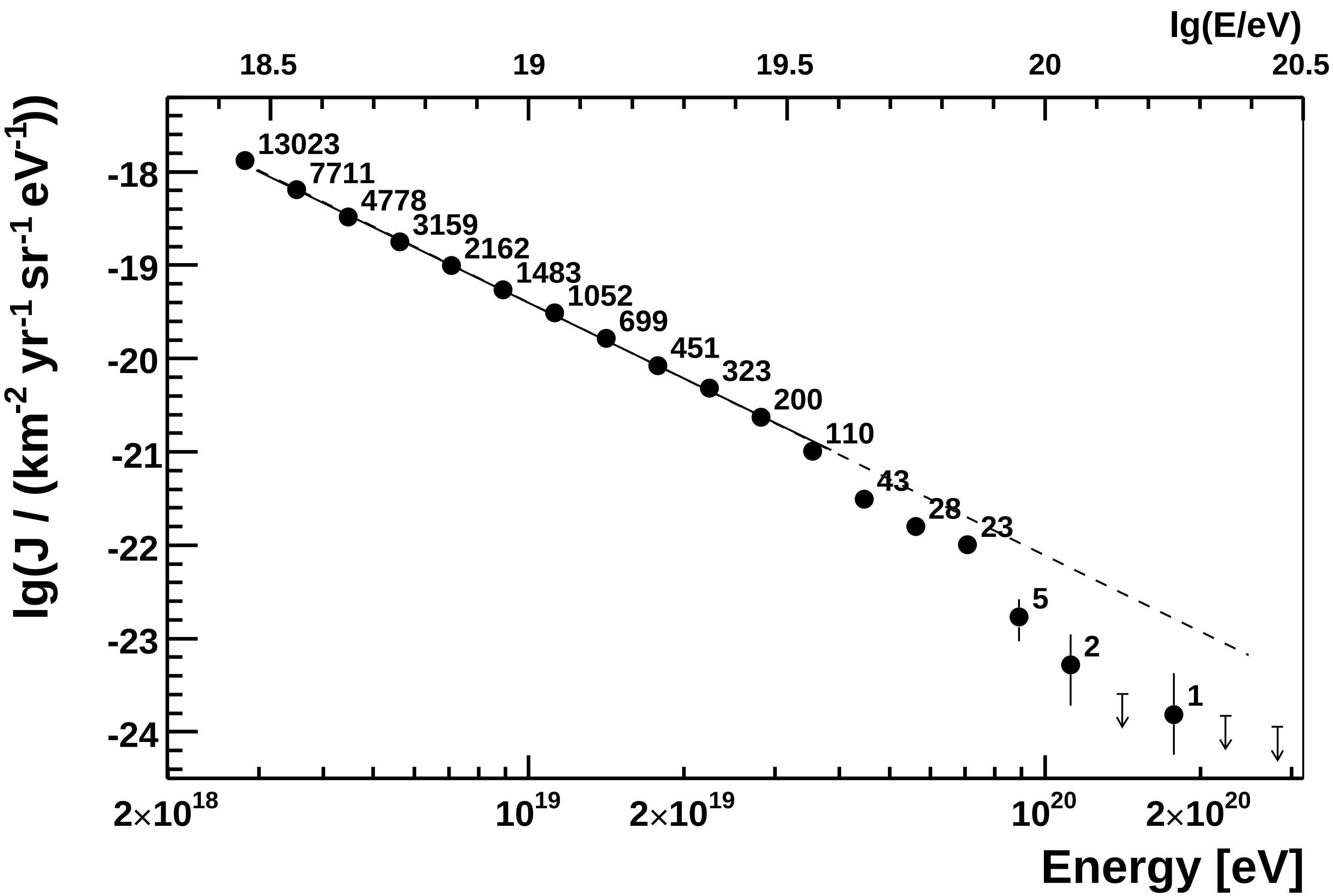


Integrated exposure: 12,790 km^2 sr year

SD energy spectrum

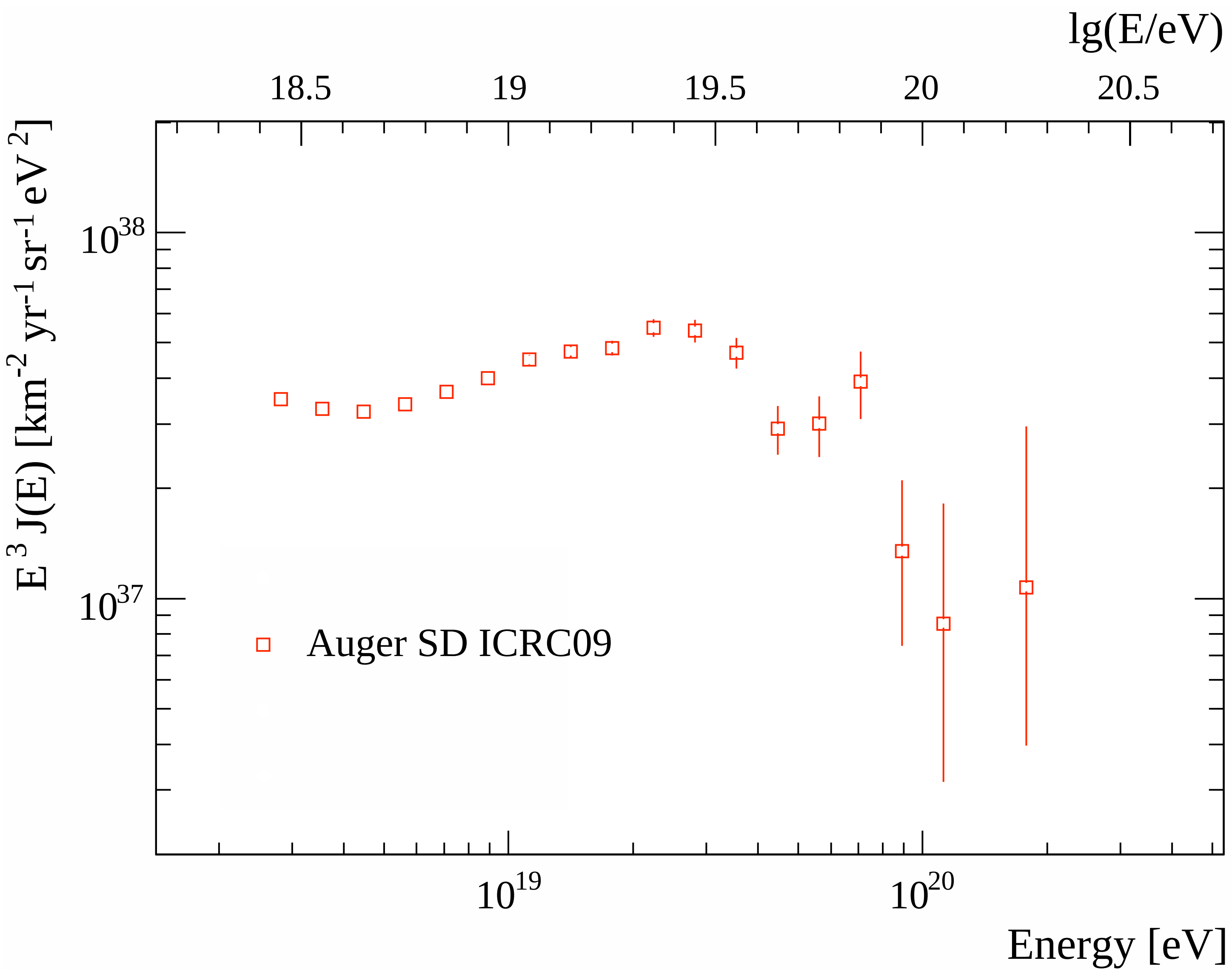
35,250 SD events
with E > $3 \cdot 10^{18}$ eV

Corrected for energy resolution by a forward folding procedure
- energy dependent
- less than 20% over the full range

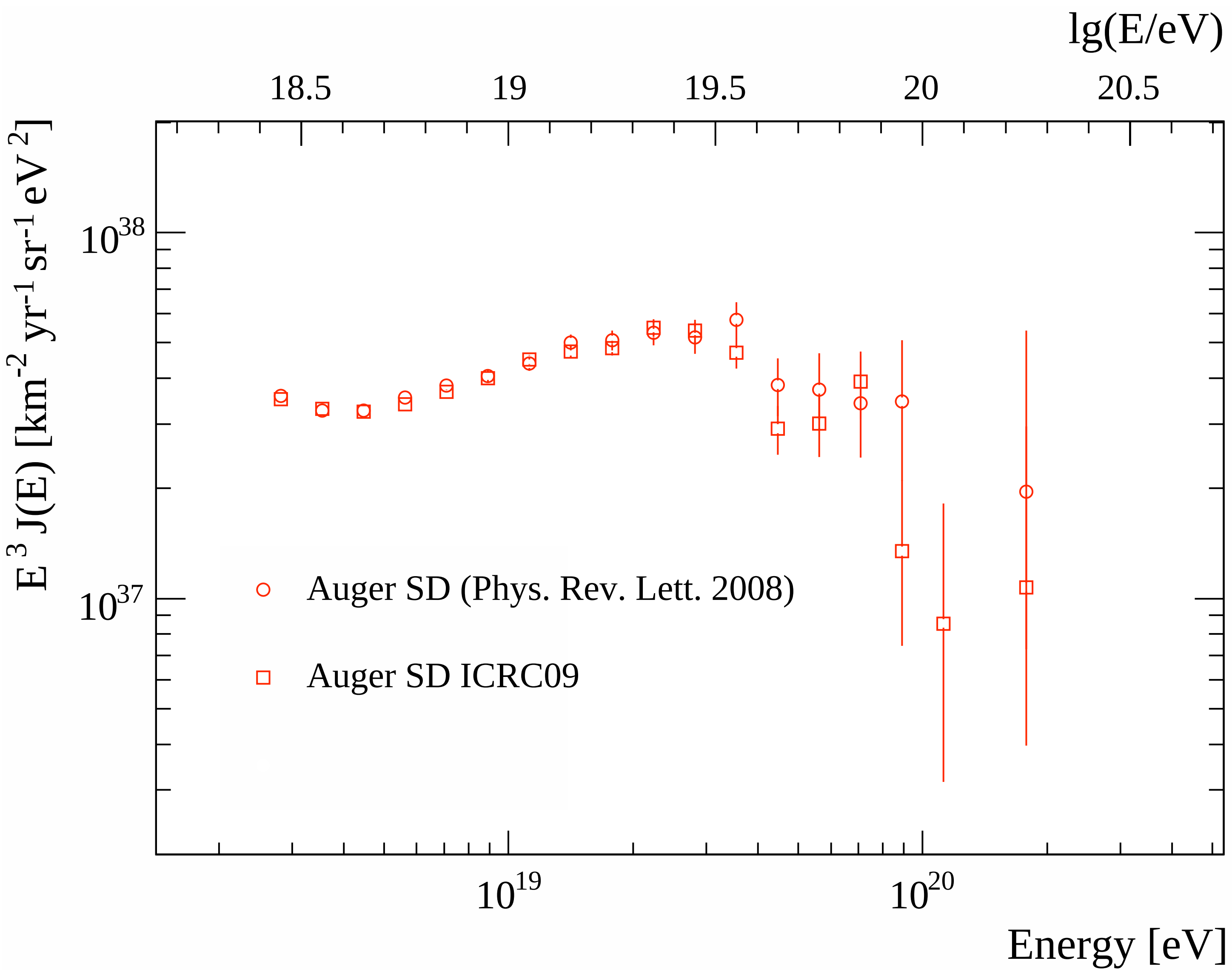


Update of PRL 101, 061101 (2008)

SD energy spectrum



SD energy spectrum



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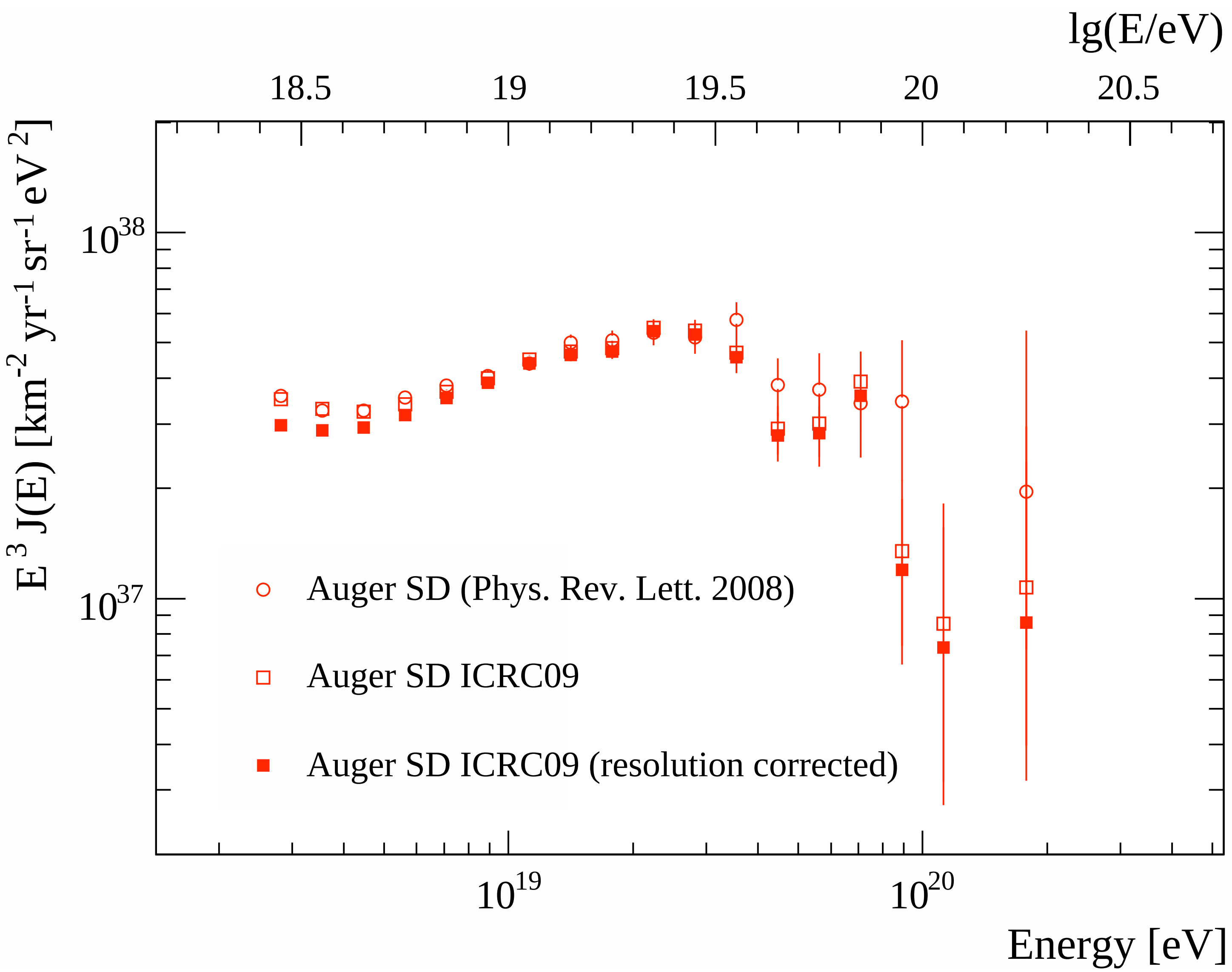
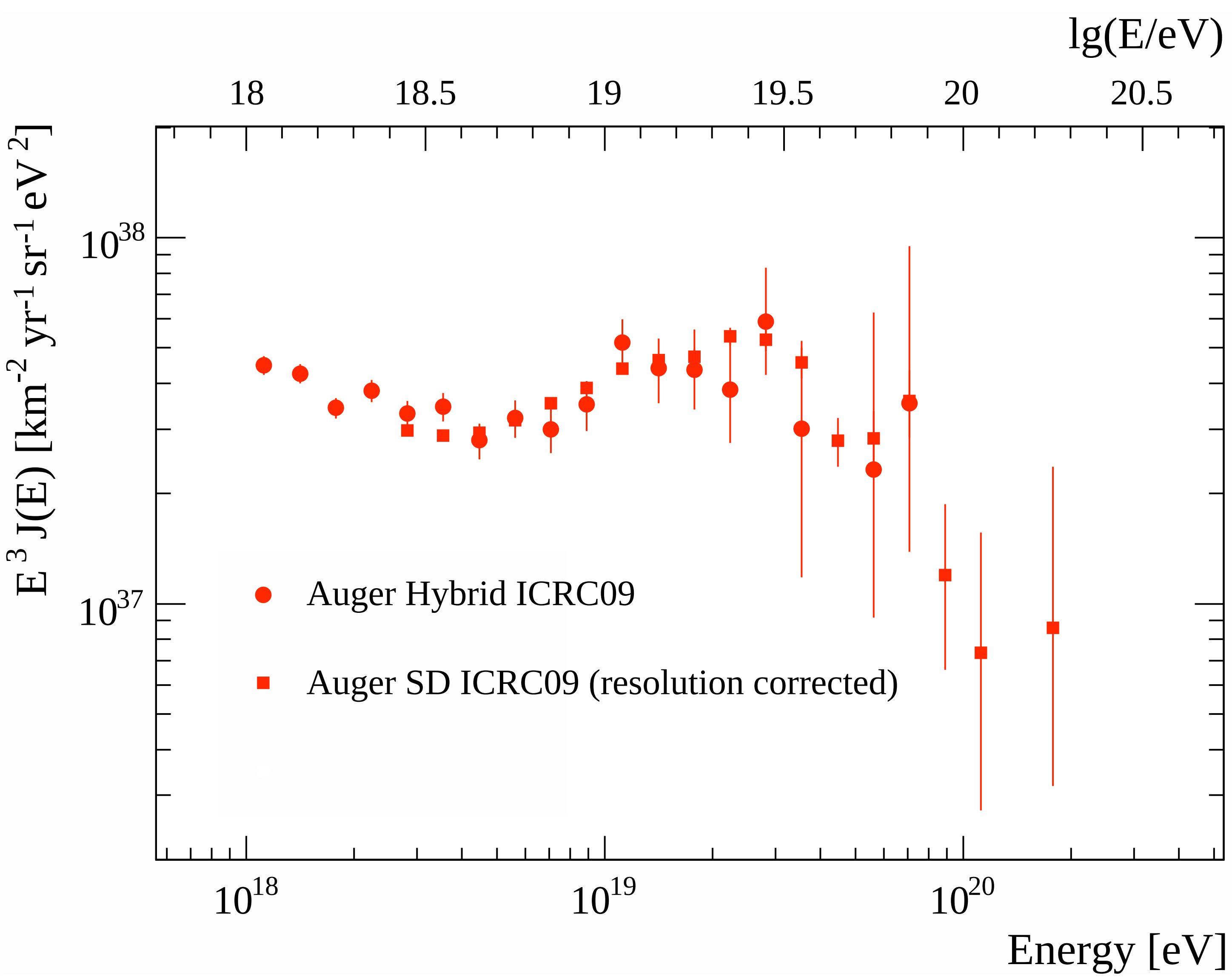
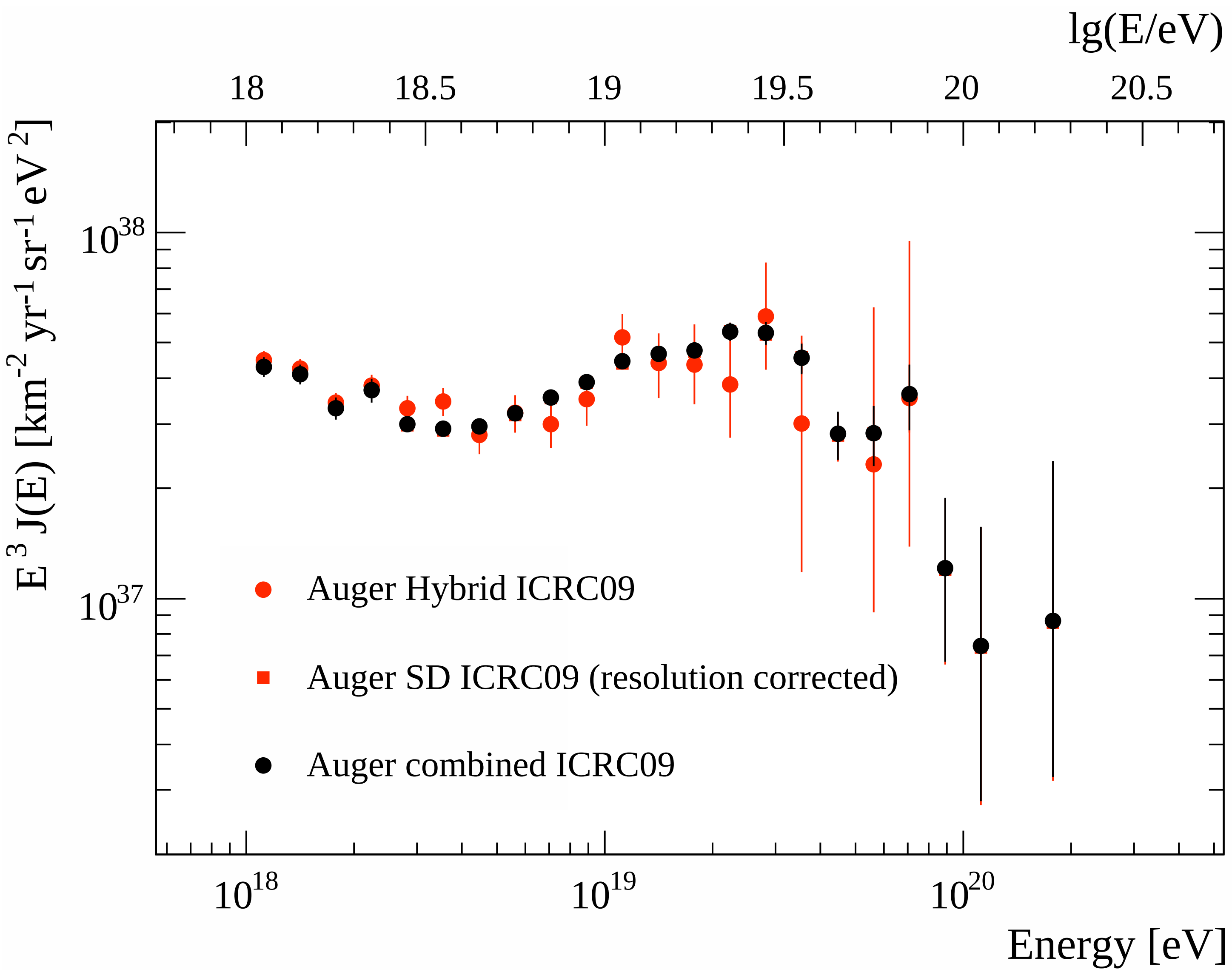


The Auger spectrum



The Auger spectrum

Syst. uncertainty on flux <4%

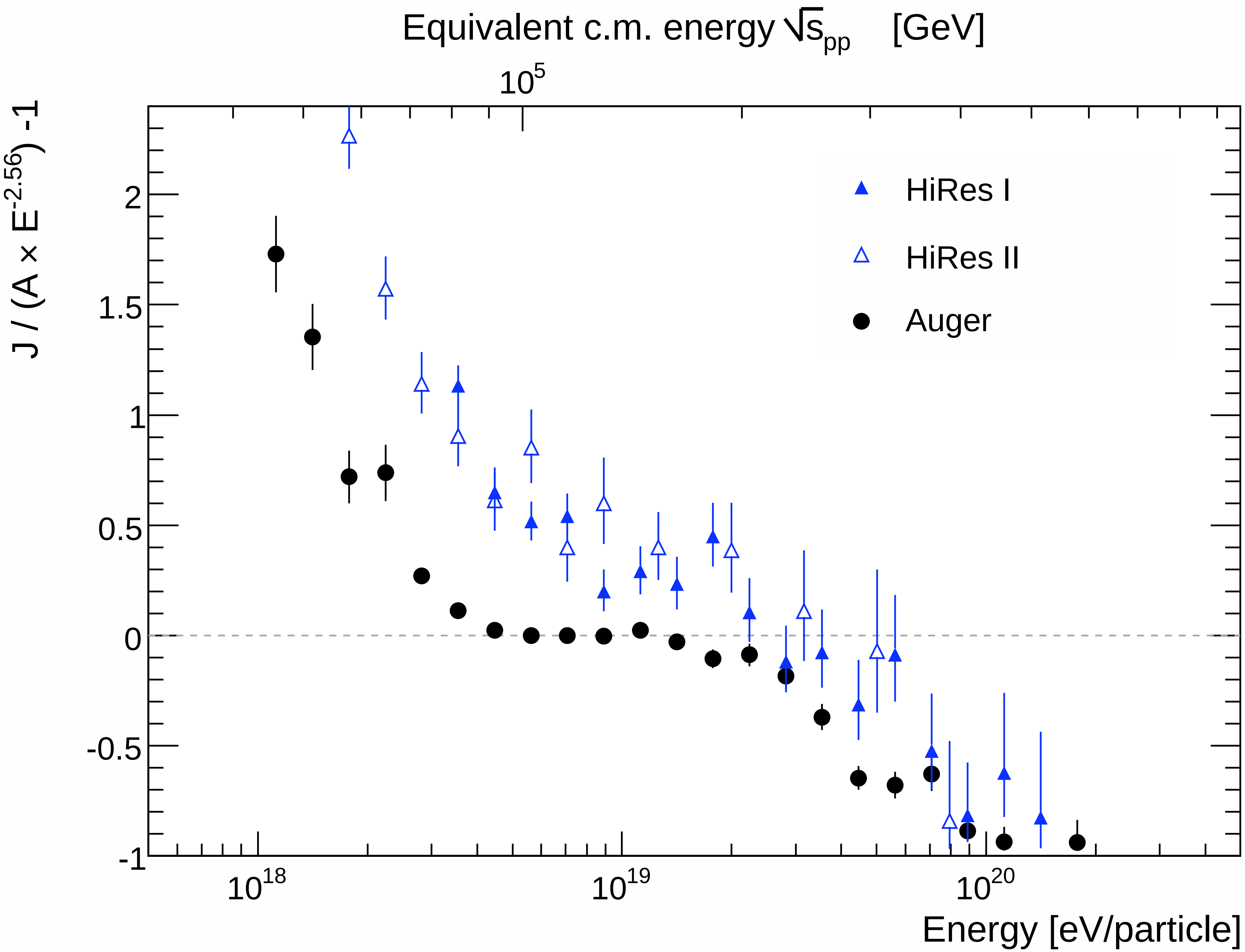


Likelihood method to combine the spectra incl. stat. and syst. uncertainties

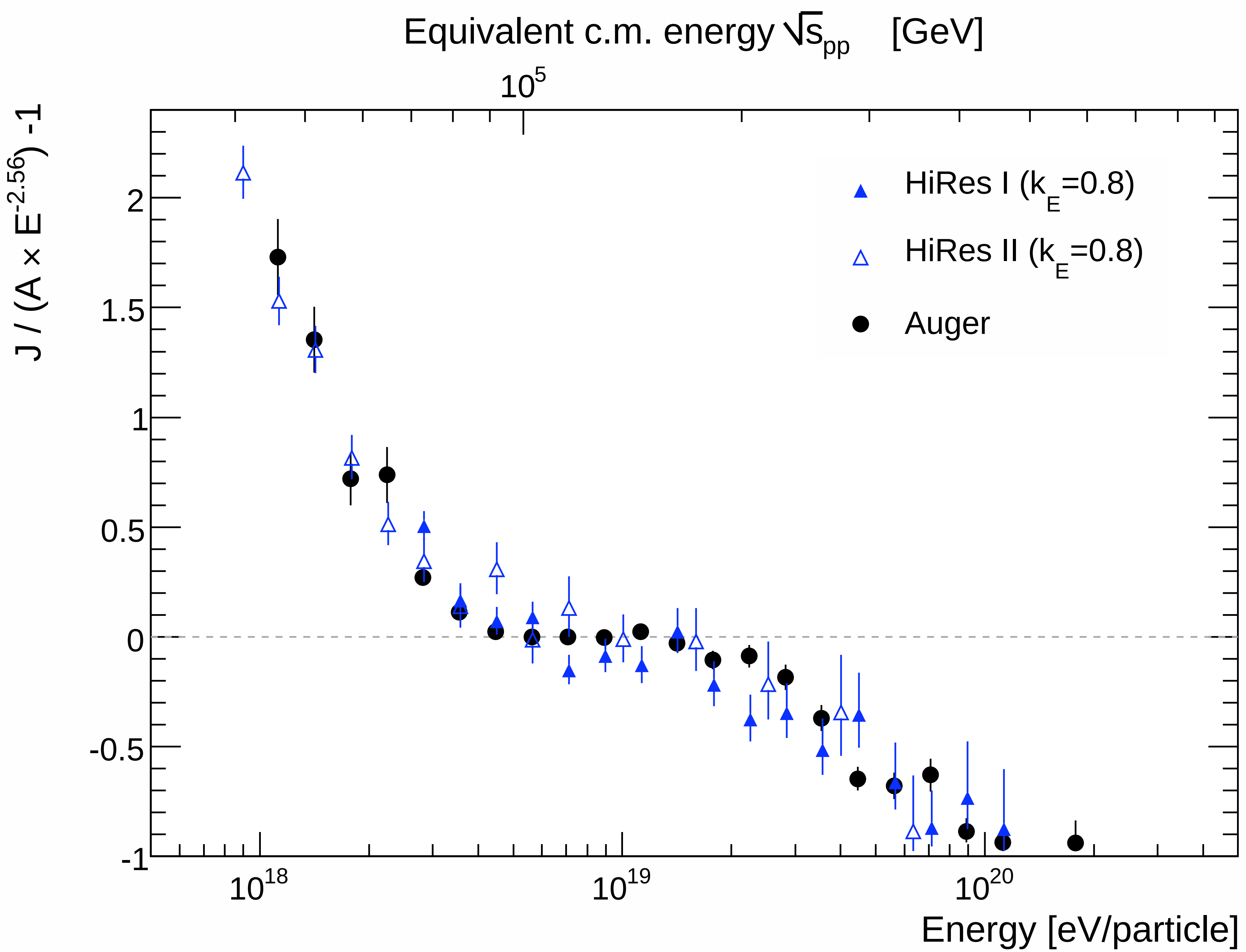
k_{sd} =1.01

k_{hyb}=0.99

The Auger spectrum



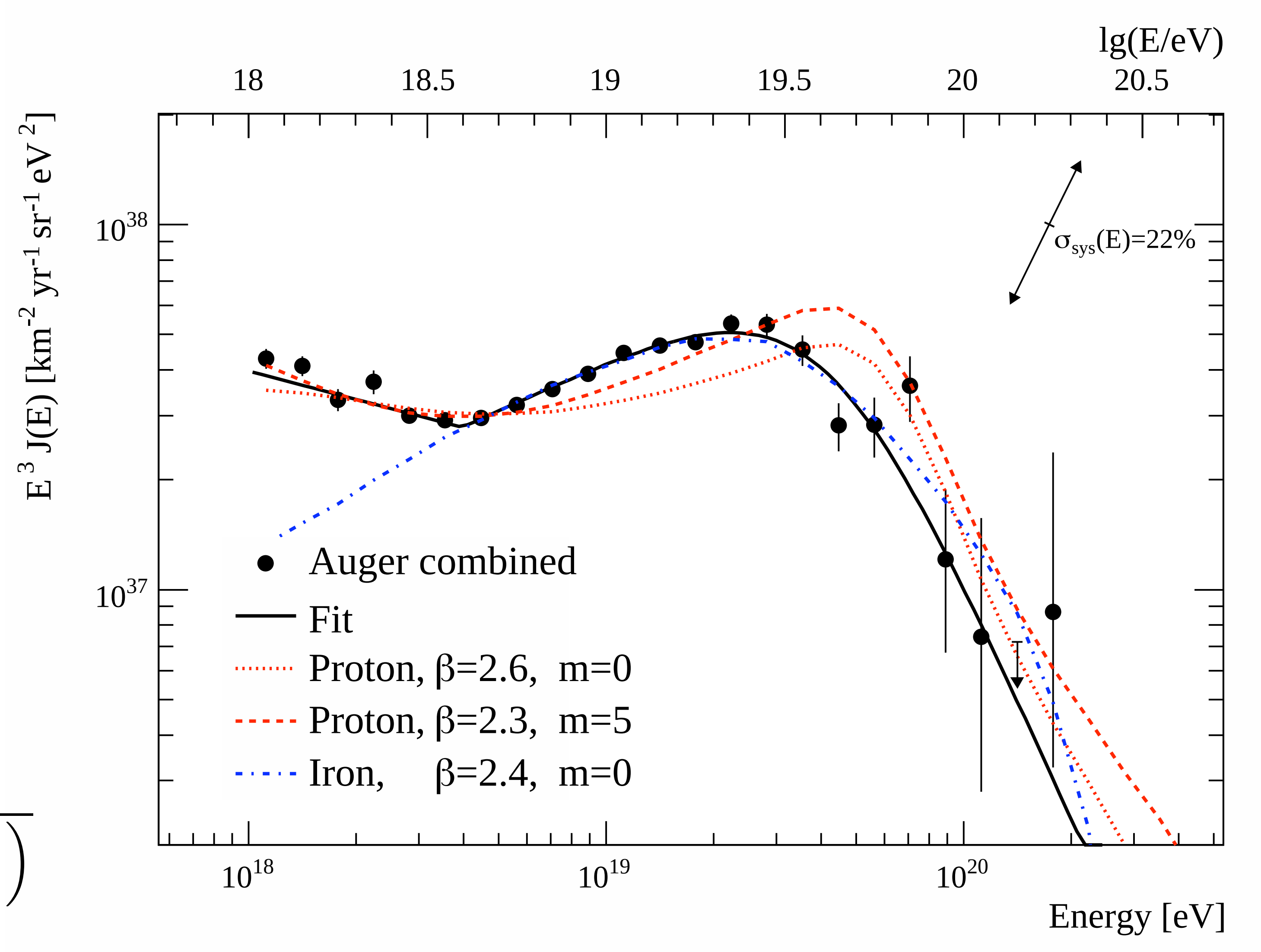
The Auger spectrum



The Auger spectrum

parameter	broken power laws	power laws + smooth function
$\gamma_1(E < E_{\rm ankle})$	3.26 ± 0.04	3.26 ± 0.04
$\lg(E_{\rm ankle}/{\rm eV})$	18.61 ± 0.01	18.60 ± 0.01
$\gamma_2(E > E_{\rm ankle})$	2.59 ± 0.02	2.55 ± 0.04
$\lg(E_{\rm break}/{\rm eV})$	19.46 ± 0.03	
$\gamma_3(E > E_{\rm break})$	4.3 ± 0.2	
$\lg(E_{1/2}/{\rm eV})$		19.61 ± 0.03
$\lg(W_{\rm c}/{\rm eV})$		0.16 ± 0.03

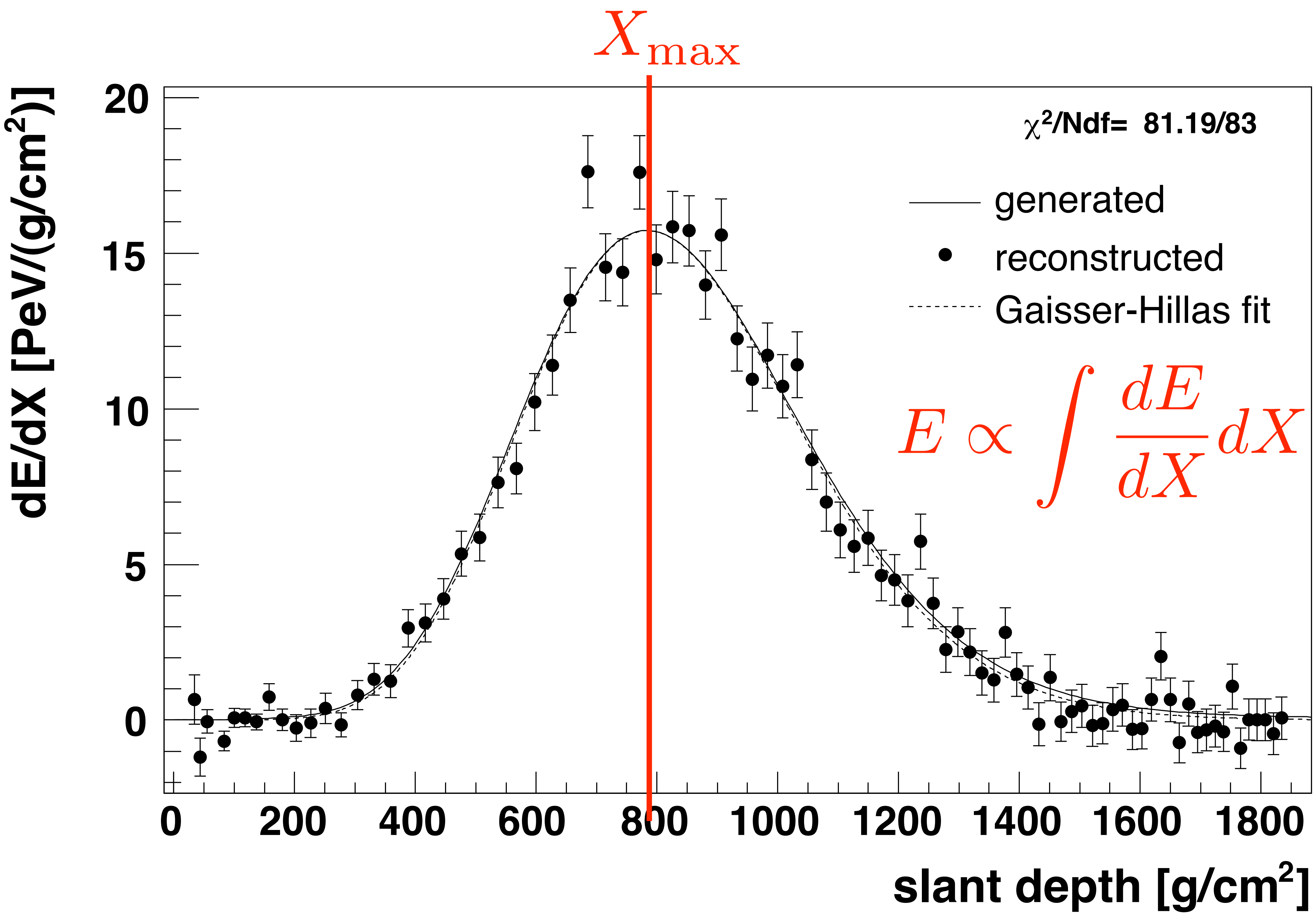
$$J(E; E > E_{\rm ankle}) \propto E^{-\gamma_2} \frac{1}{1 + \exp\left(\frac{\lg E - \lg E_{1/2}}{\lg W_c}\right)}$$



With a cosmological evolution of the source luminosity of $(z+1)^m$

Elemental composition
- Charged particles

FD: Longitudinal Shower Profiles



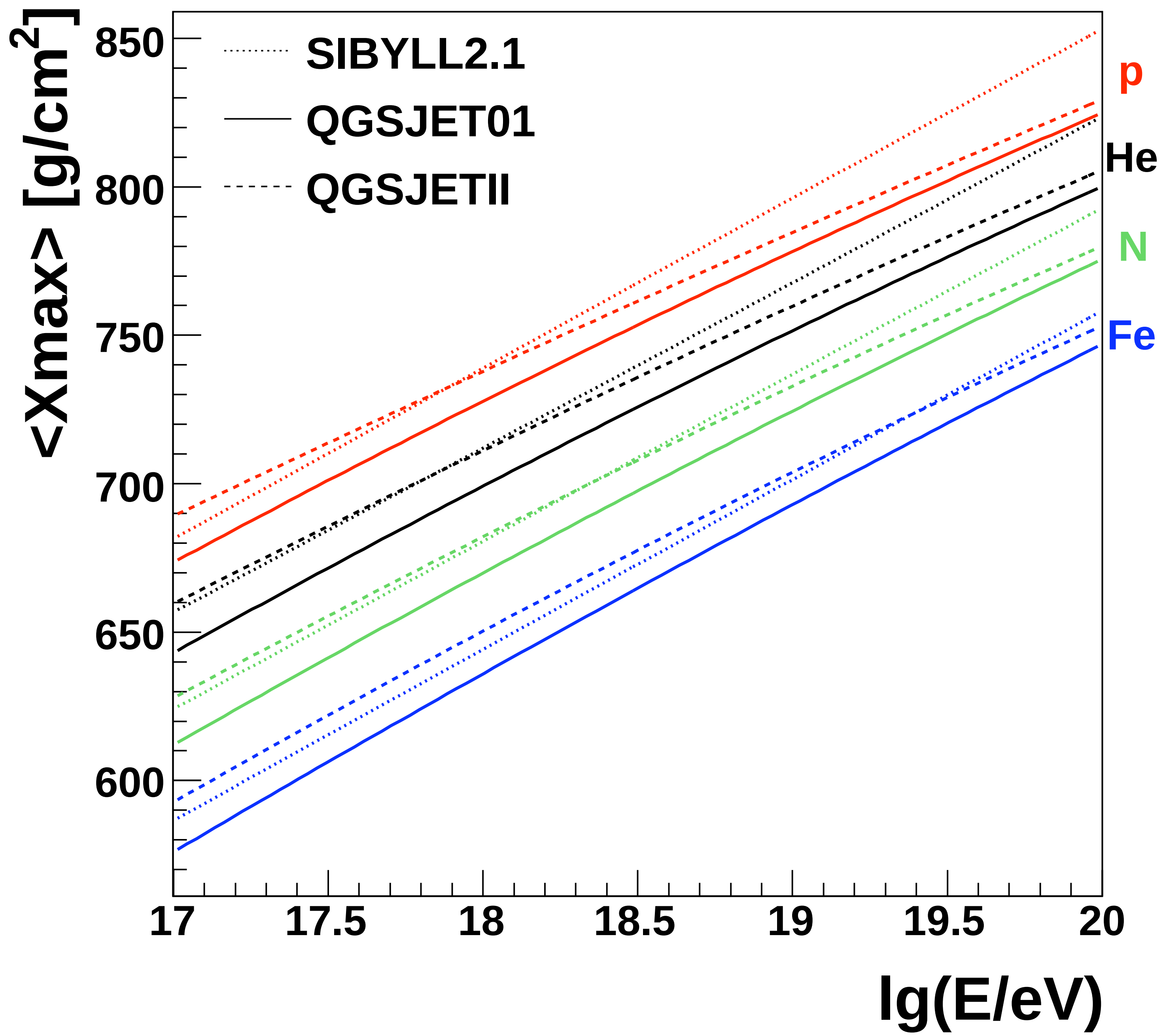
Average shower maximum X_{max}

Primary protons:

$$\langle X_{max} \rangle = D_{10} \lg(E) + \text{const}$$

Superposition model:

$$\langle X_{max} \rangle = D_{10} \lg(E/A) + \text{const}$$



Shower to shower fluctuations

Primary protons:

$RMS(X_{max})^2 = \lambda_p + V(shower)$

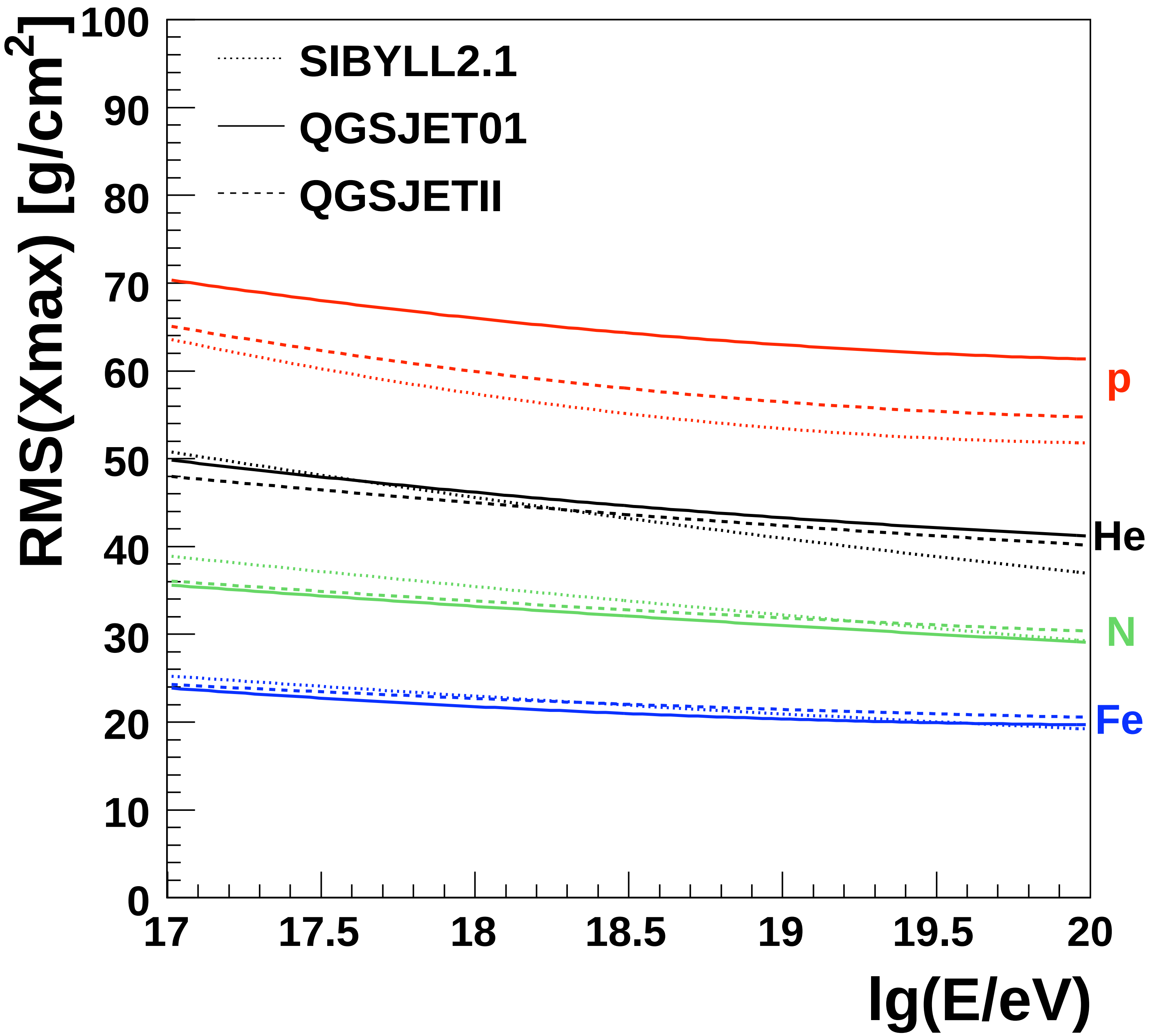
Superposition model ...

$RMS(A) = RMS(p)/\sqrt{A}$

... does not work here (fragmentation), but qualitatively

$RMS(A_1) < RMS(A_2)$

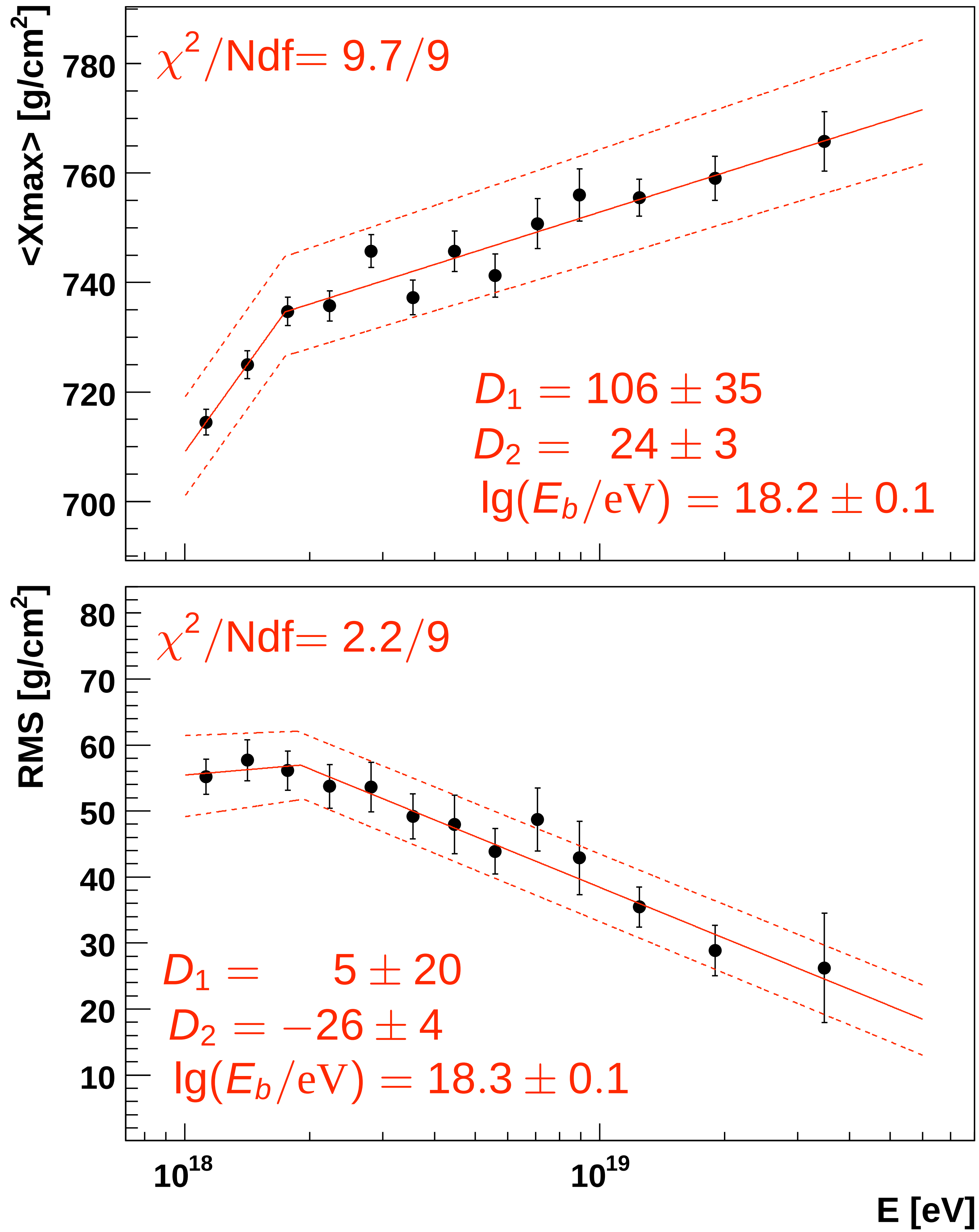
for $A_1 > A_2$



FD results

$\langle X_{max} \rangle$ and RMS vs E

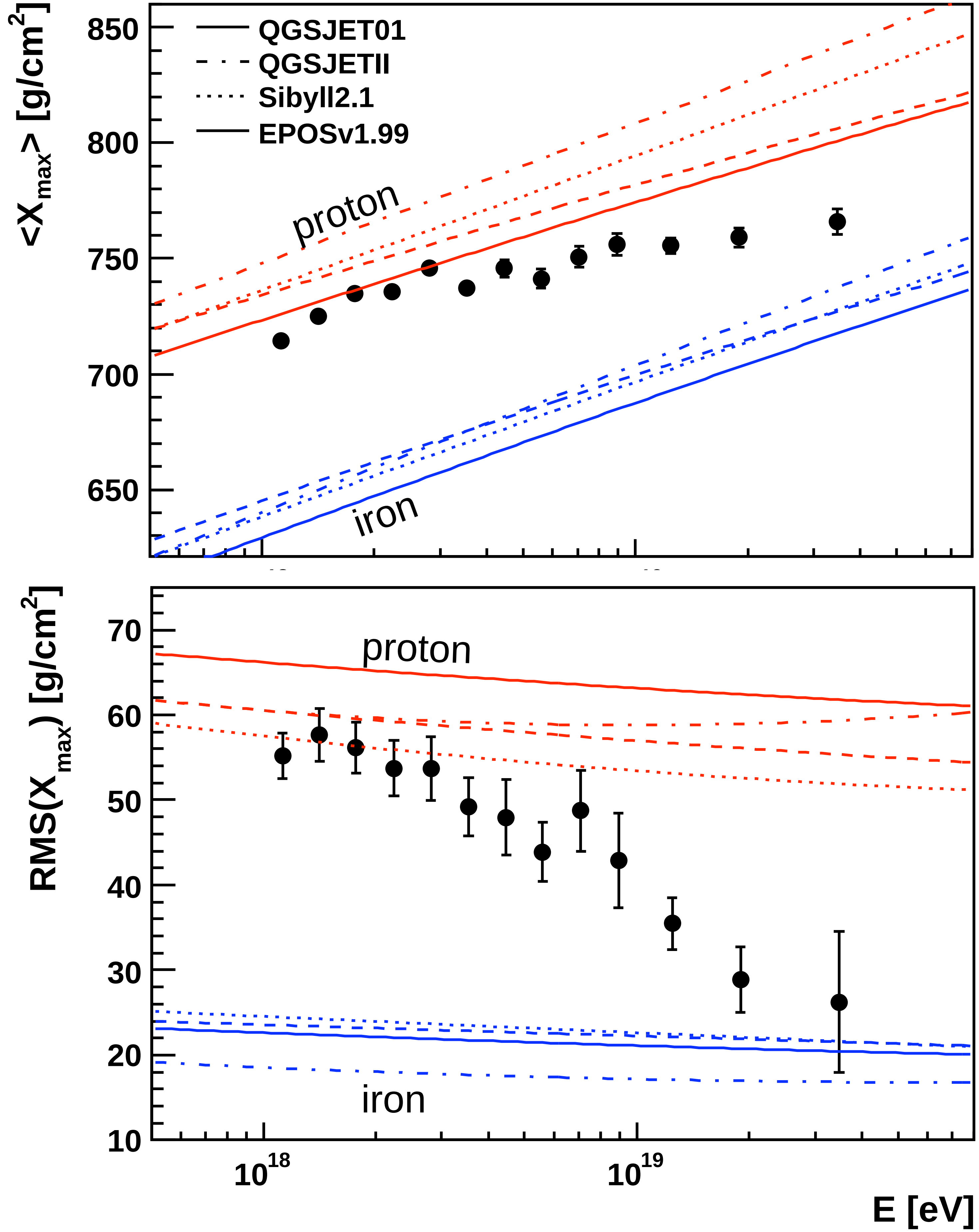
Broken line fit:
Slopes D [g/cm²/decade]



FD results

$\langle X_{max} \rangle$ and RMS vs E

Clear trend to heavier elements

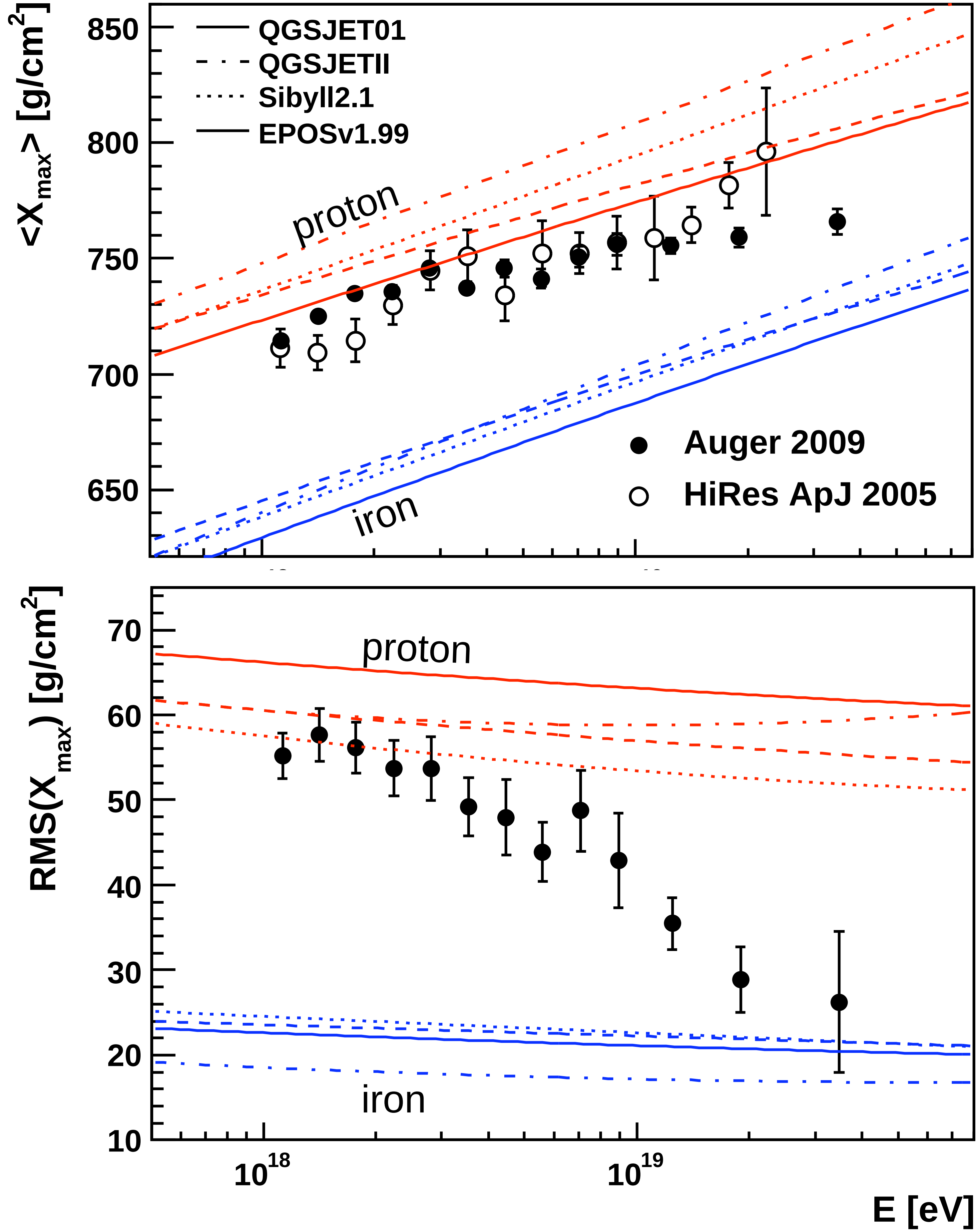


FD results

⟨X_{max}⟩ and RMS vs E

- vs simulations
- vs published HiRes data

Clear trend to heavier elements



Elemental composition
- Neutrinos

Generation & Detection

Pion decay at source a/o propa.:

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_\mu$$

$$\hookrightarrow \quad \mu^{\pm} \longrightarrow e^{\pm} + \nu_e + \nu_\mu$$

Flavour counting $2\nu_\mu + \nu_e$

Neutrino oscillation $1\nu_e + 1\nu_\mu + 1\nu_\tau$

$$\tau \longrightarrow \mu + \nu_\mu + \nu_\tau$$

→ track ☹

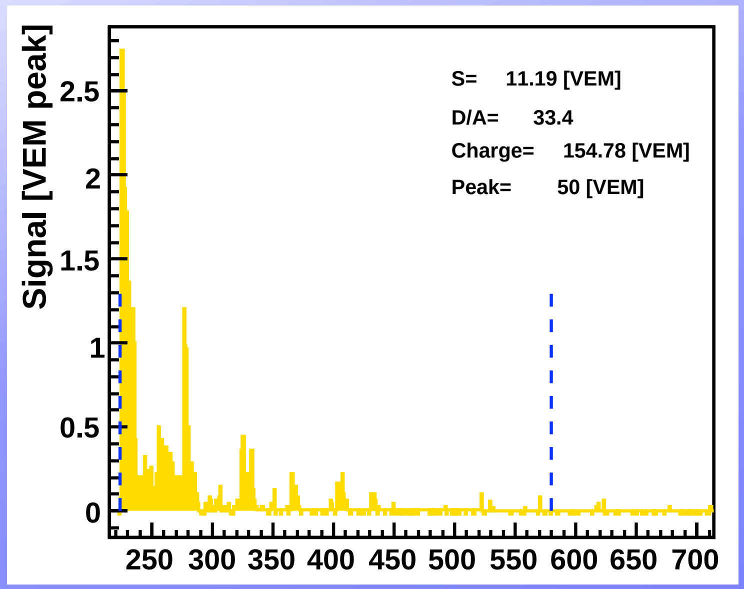
$$\tau \longrightarrow e + \nu_e + \nu_\tau$$

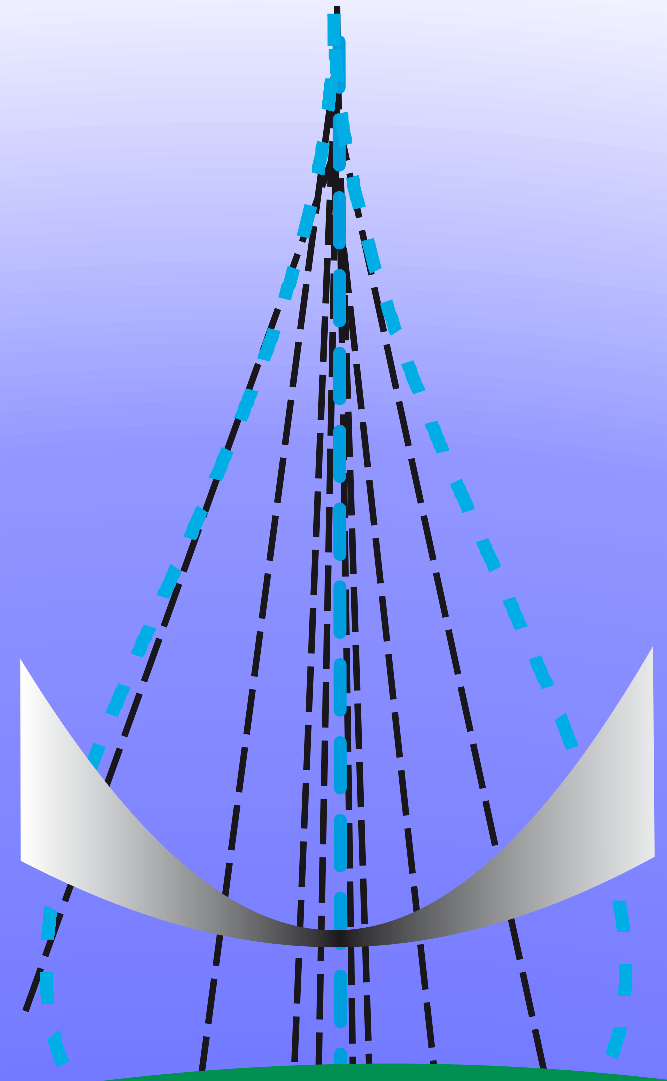
→ shower ☻

$$\tau \longrightarrow hh + \nu_\tau$$

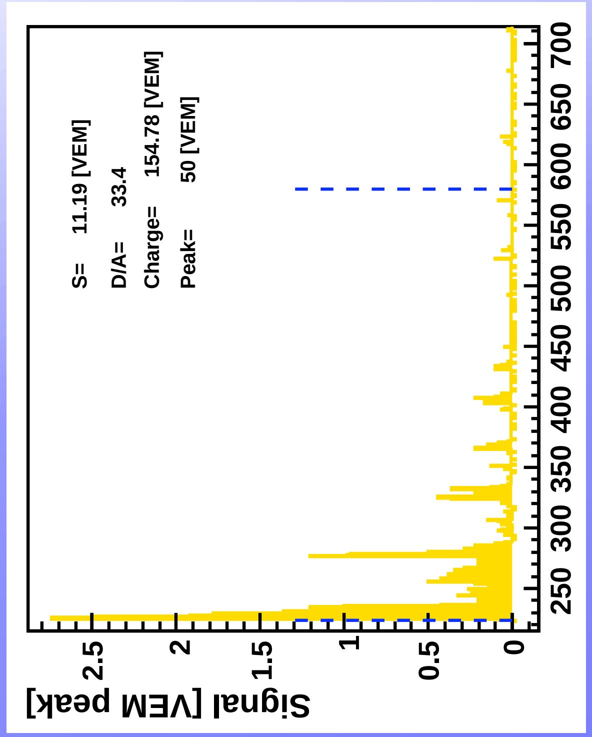
→ shower ☻

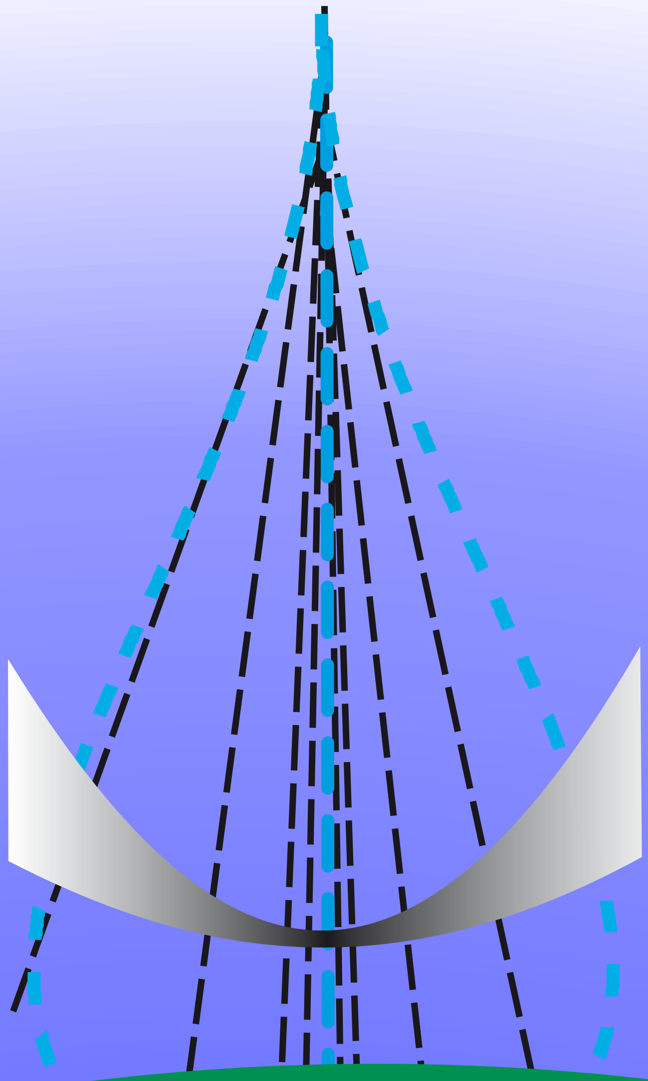
A vertical shower



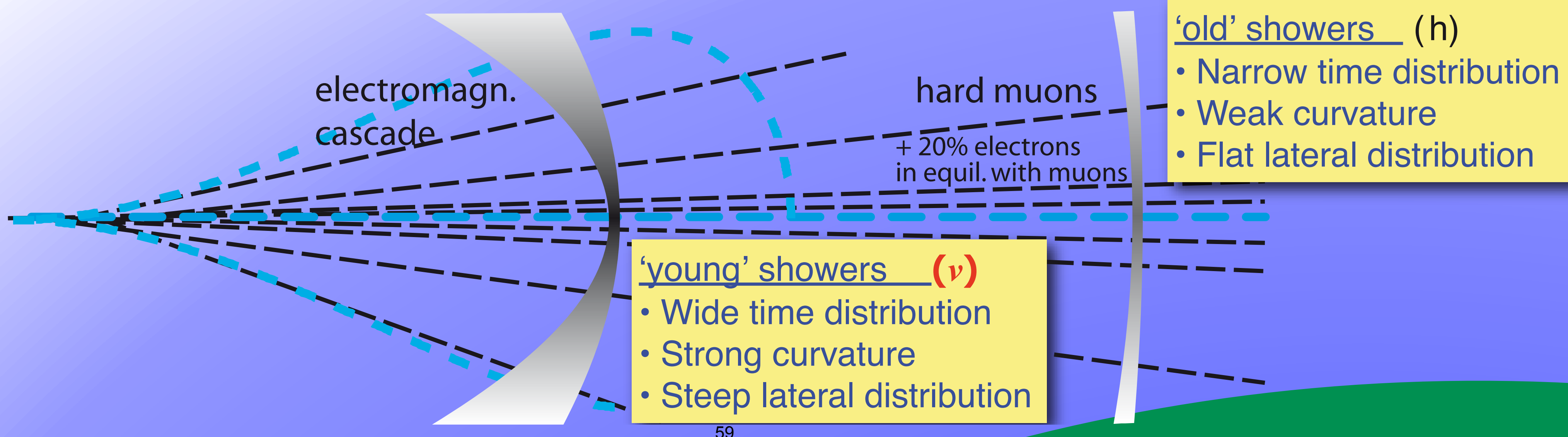


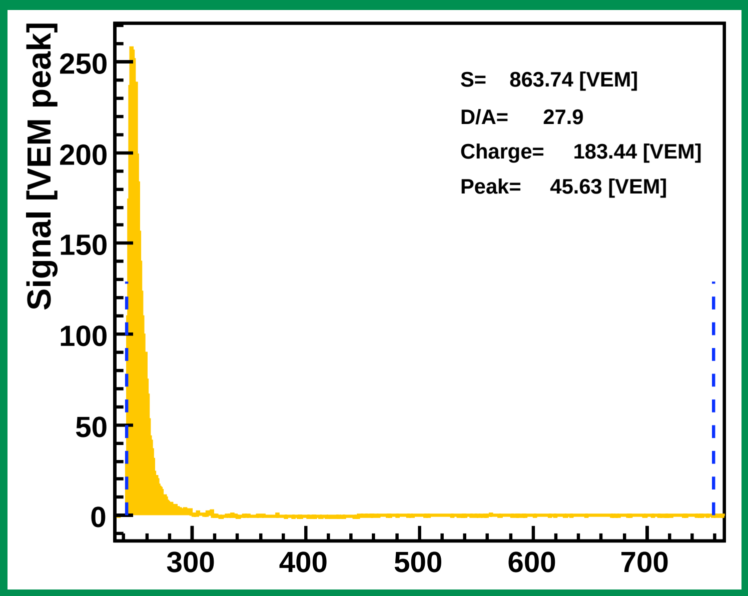
A vertical shower





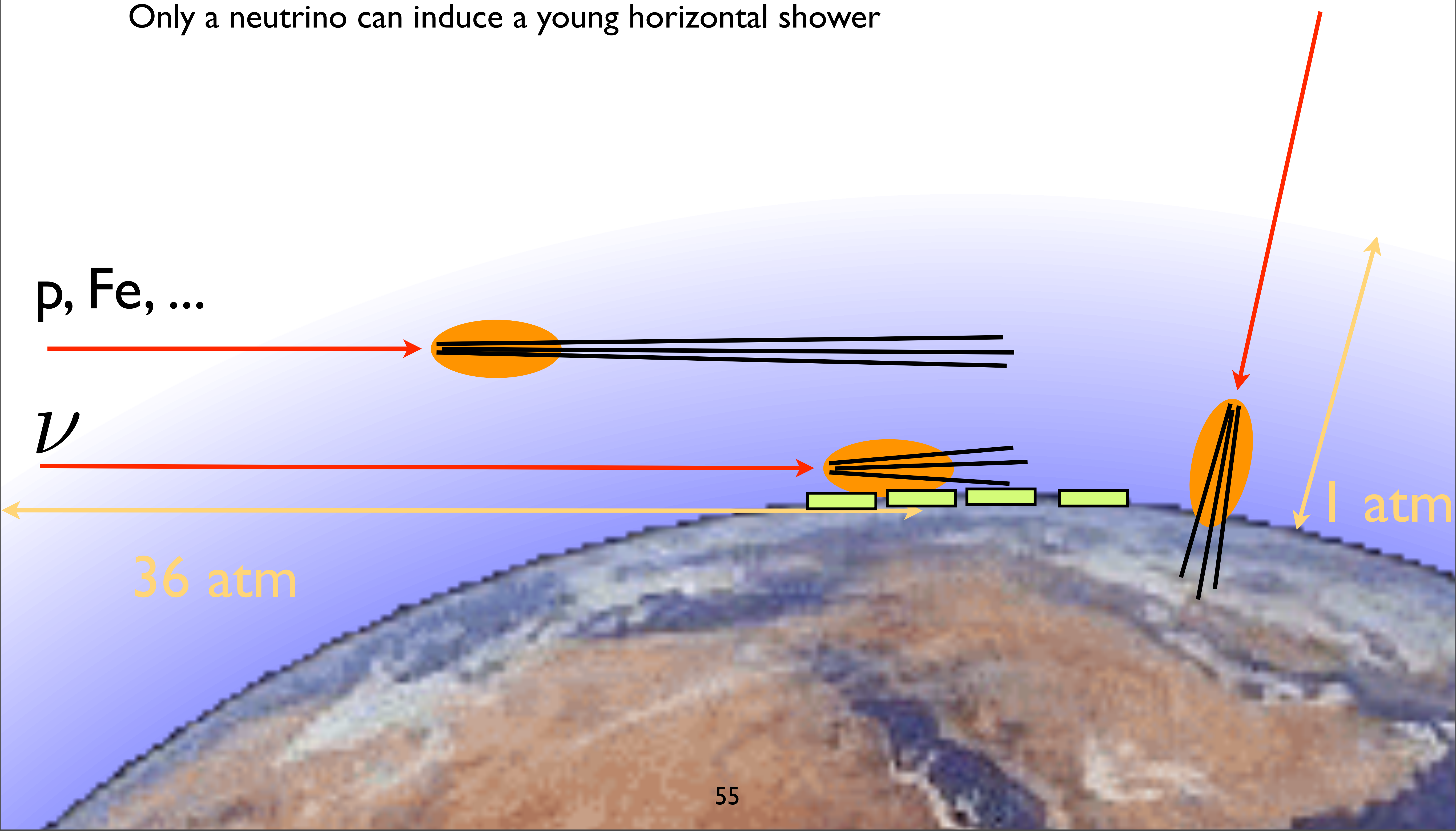
«Young» vs «old» showers



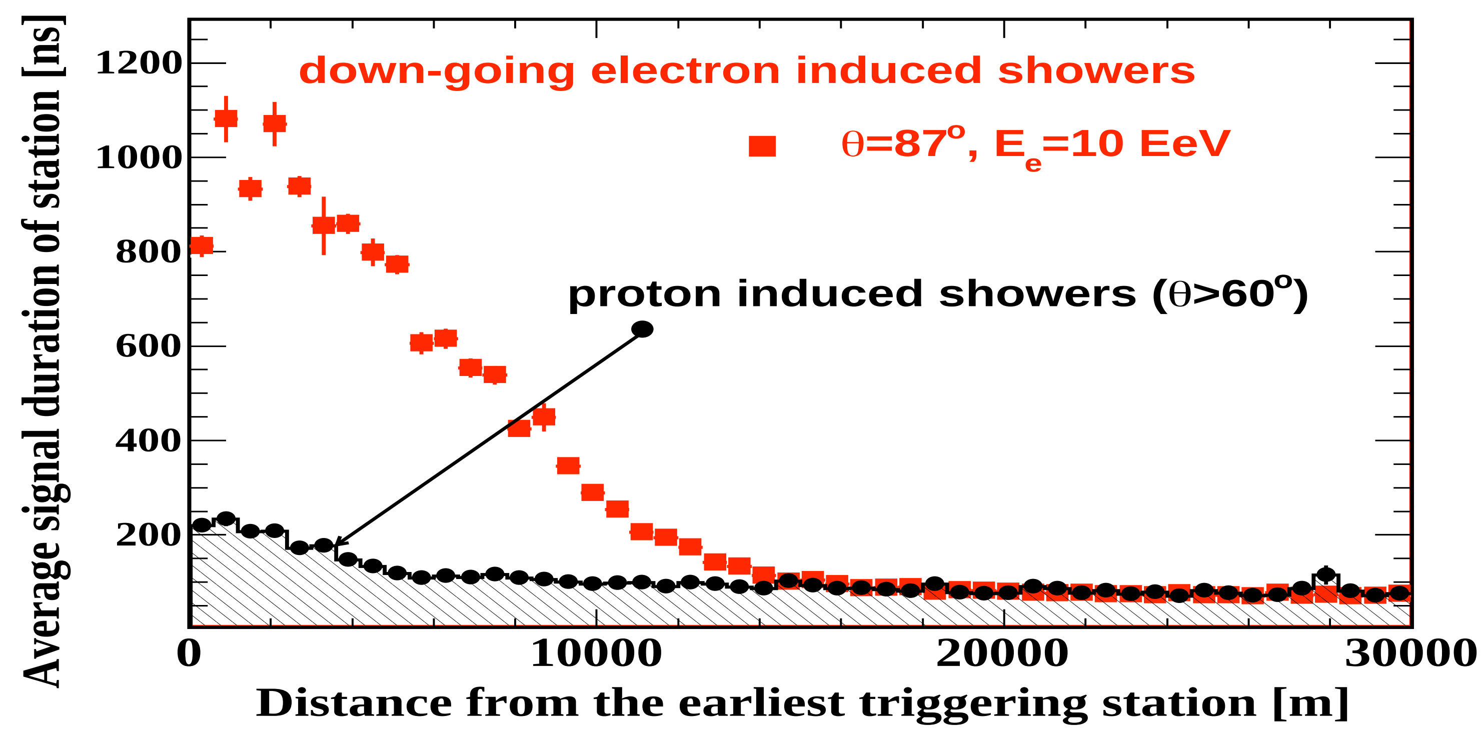


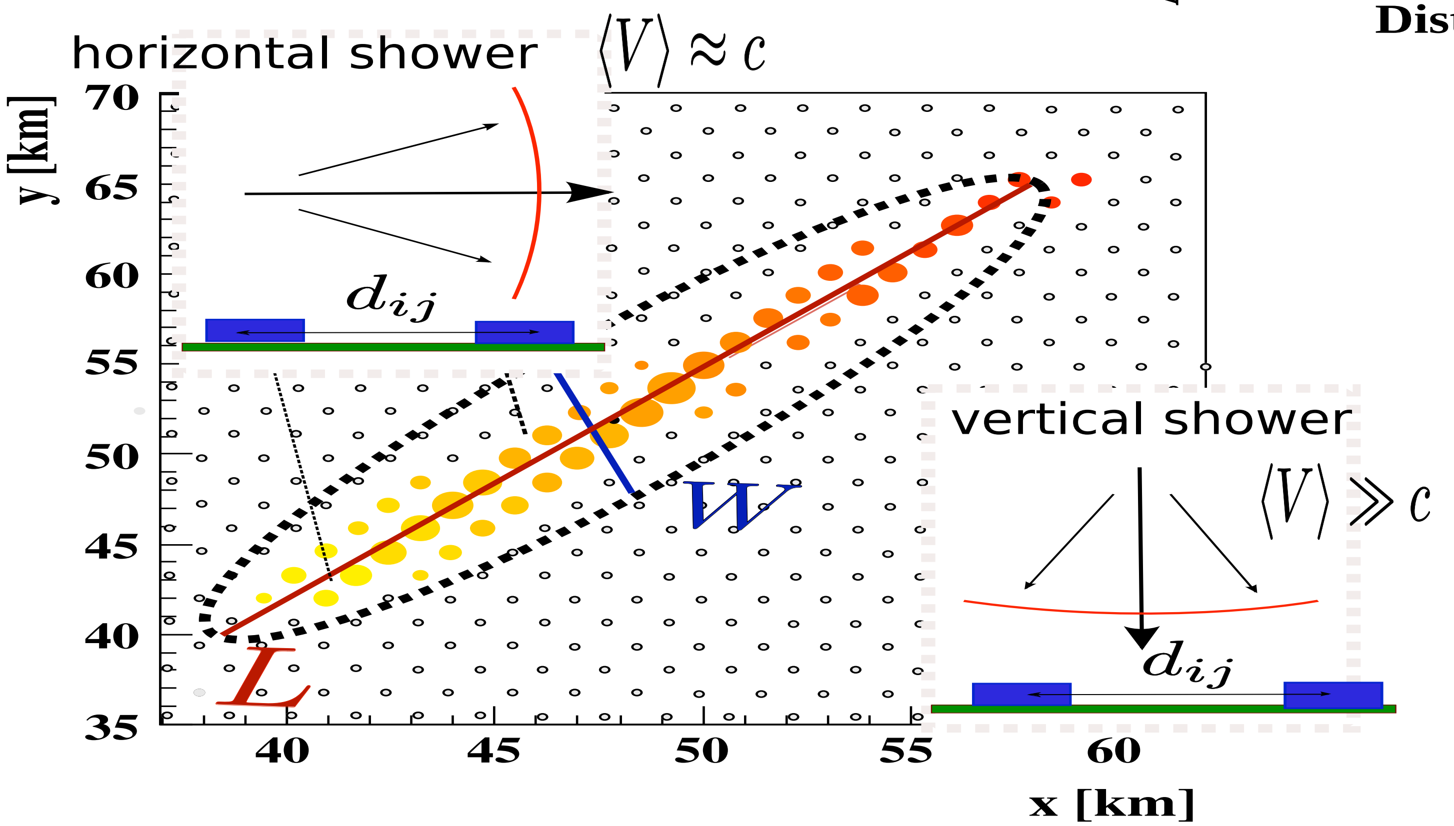
Neutrinos vs hadronic showers

Only a neutrino can induce a young horizontal shower

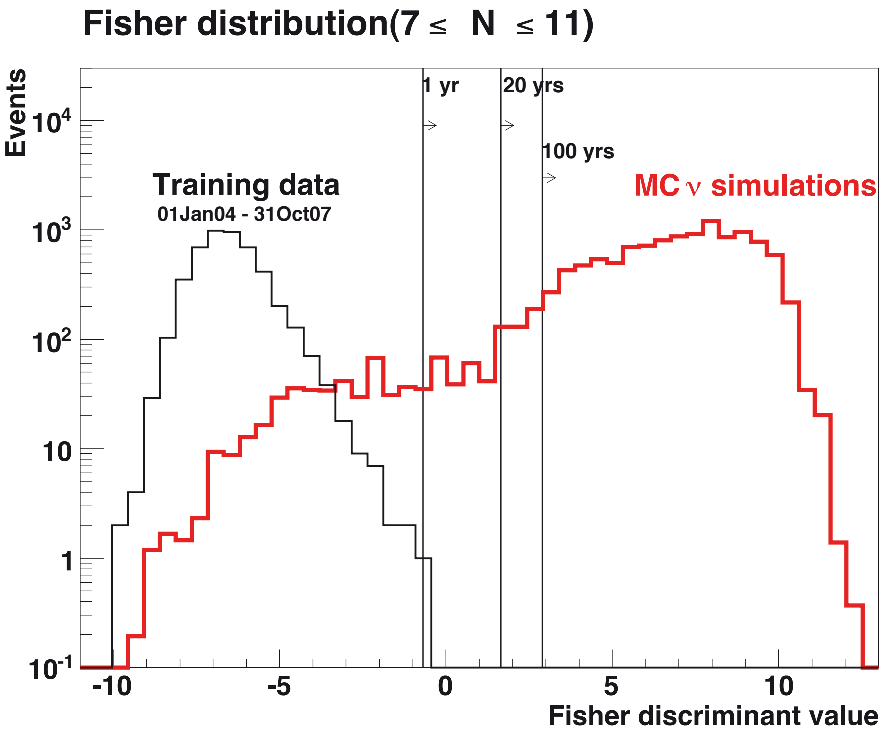


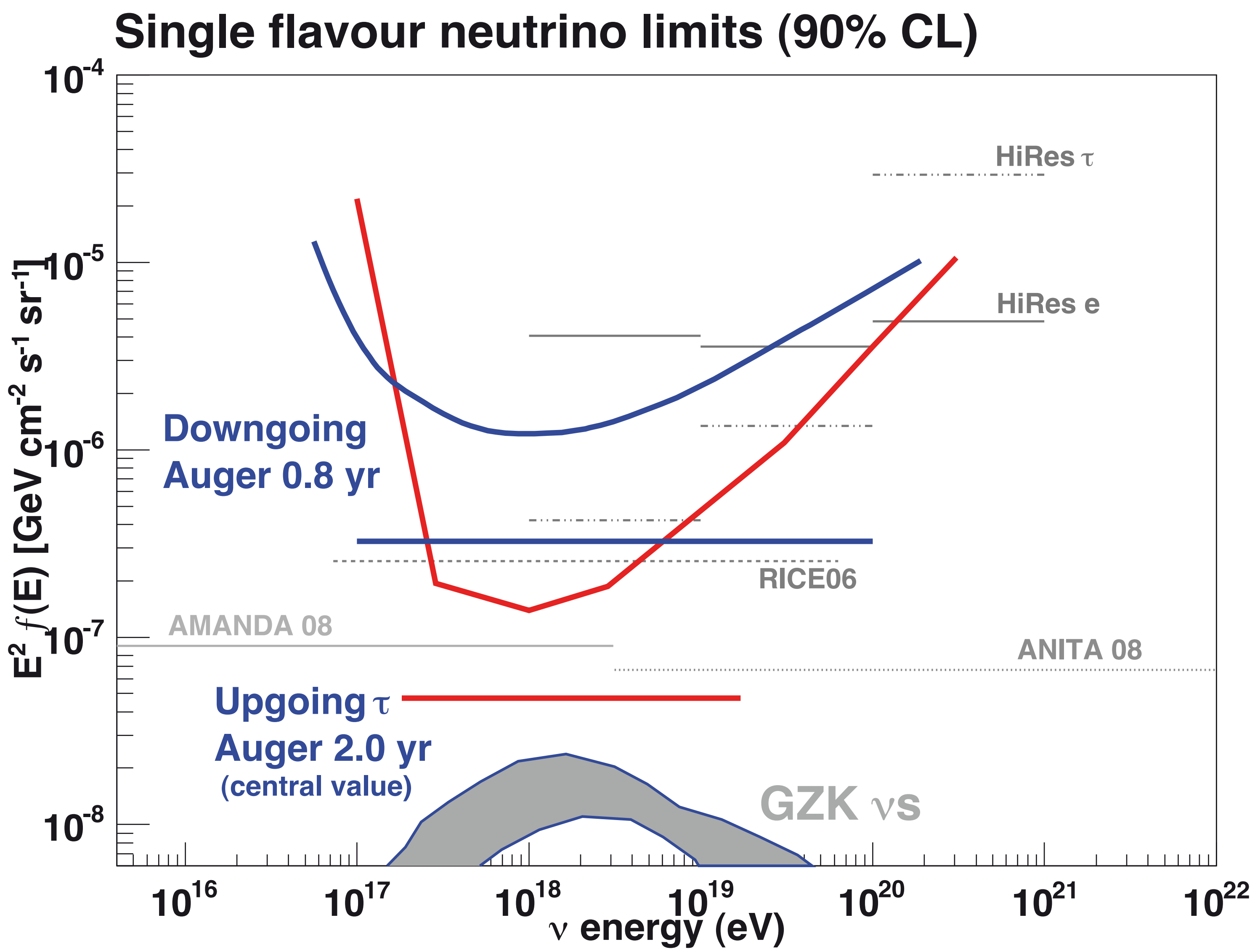
Neutrino signatures



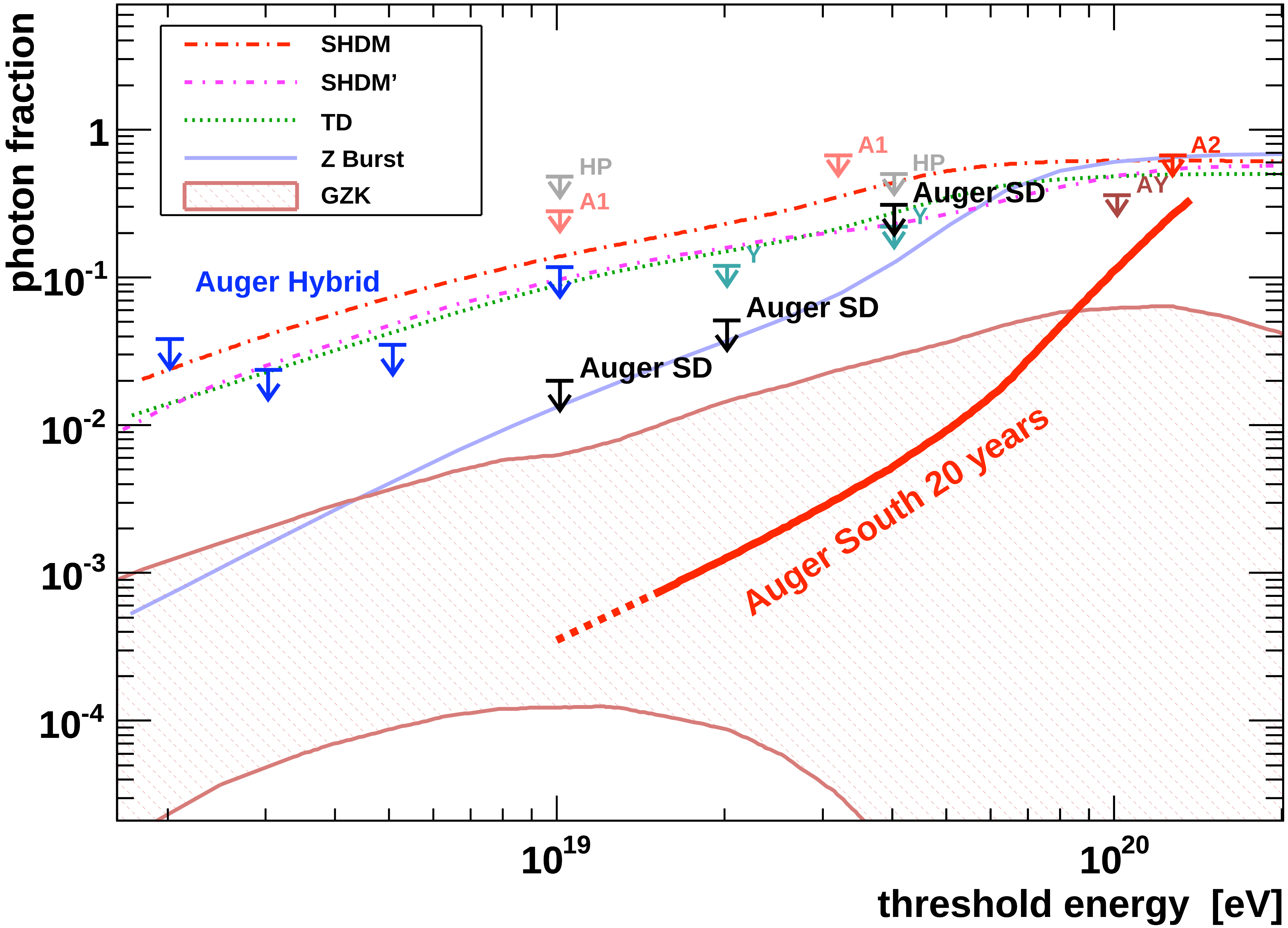


Neutrino flux limits





Photon flux limit

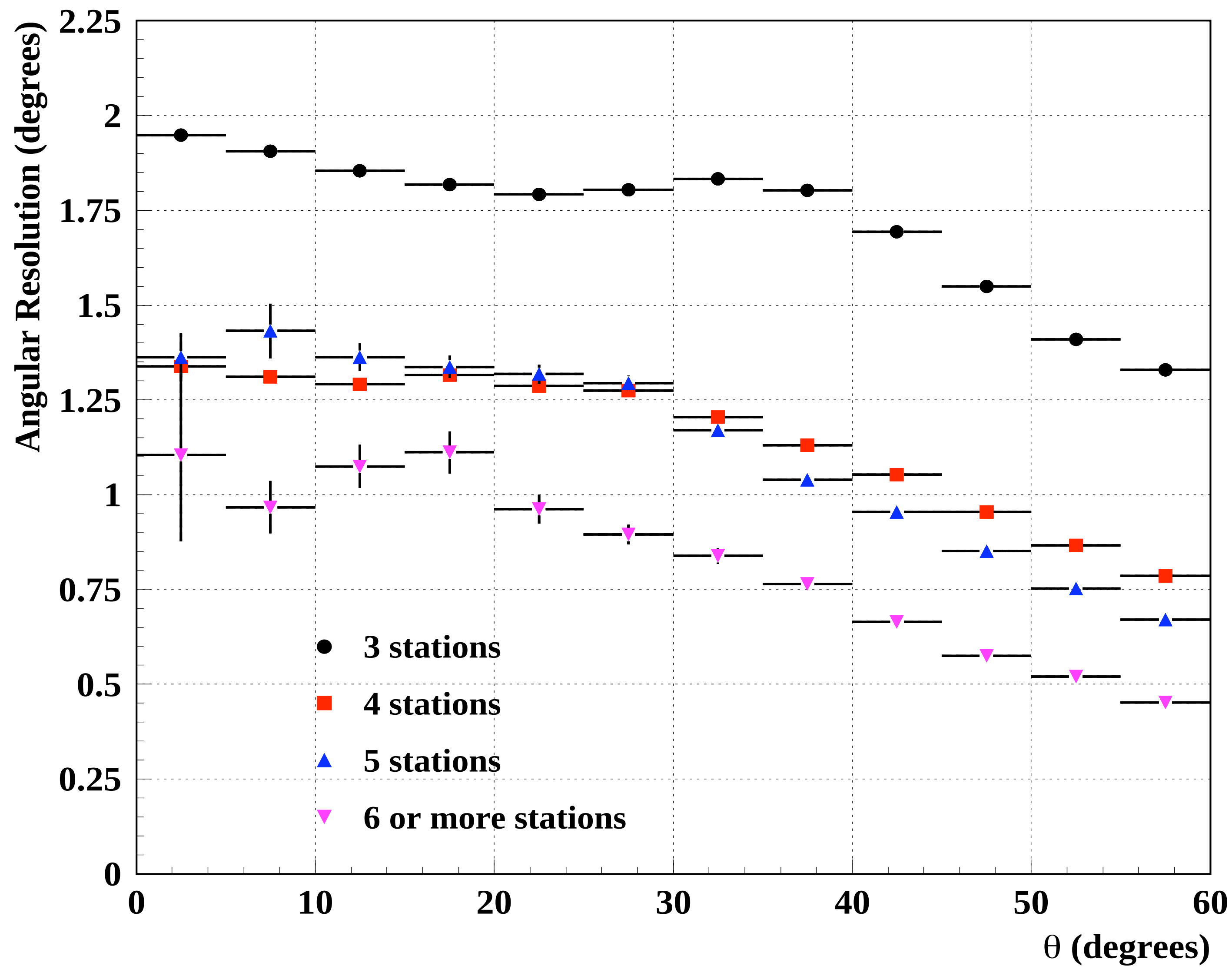


Anisotropy

Angular resolution

Angular accuracy depends on station multiplicity

9 stations ~10^{19} eV



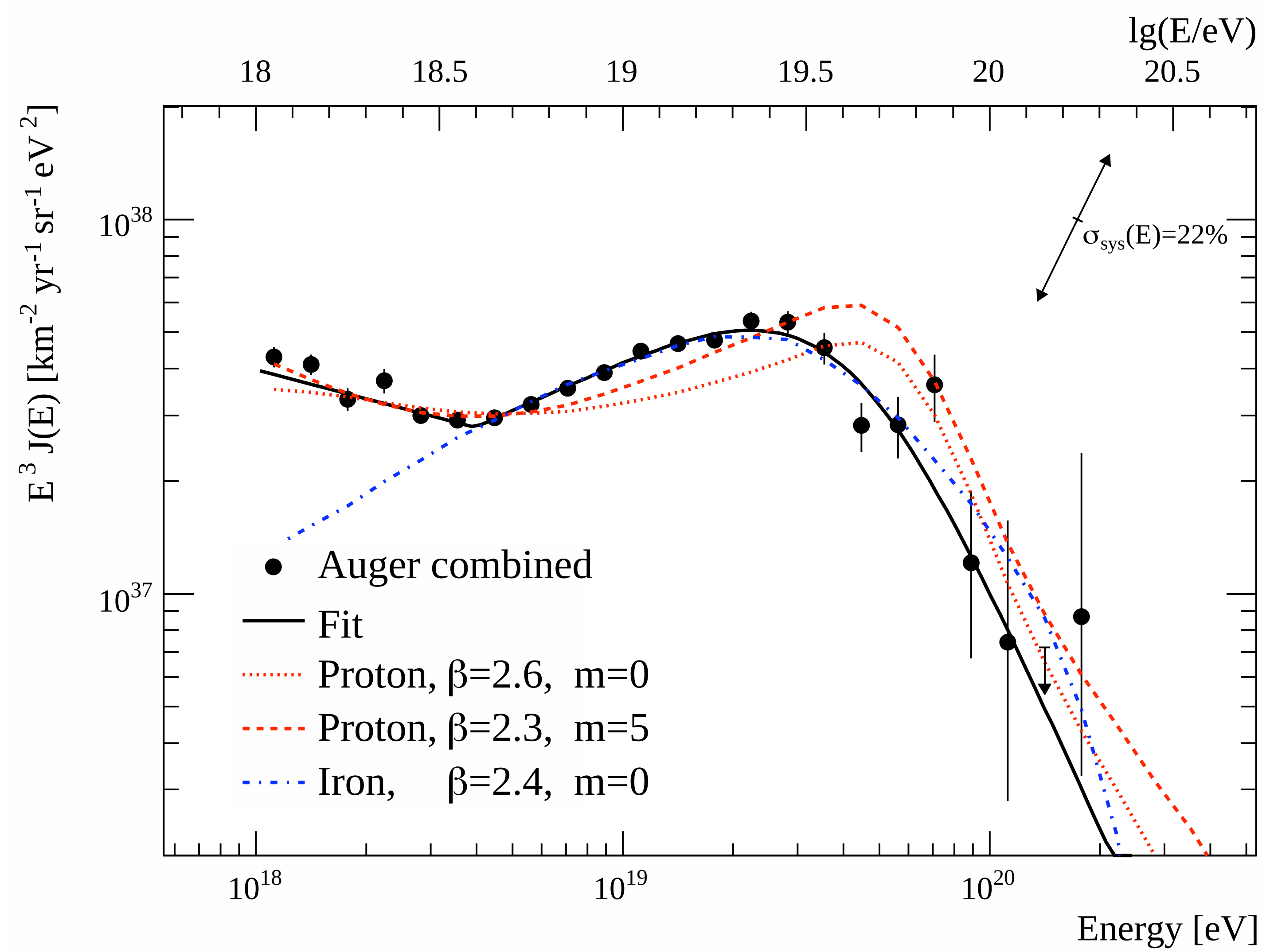
Search for large scale anisotropy at EeV energies

Are EeV CRs of galactic or extra-galactic origin?

2 possible scenarios

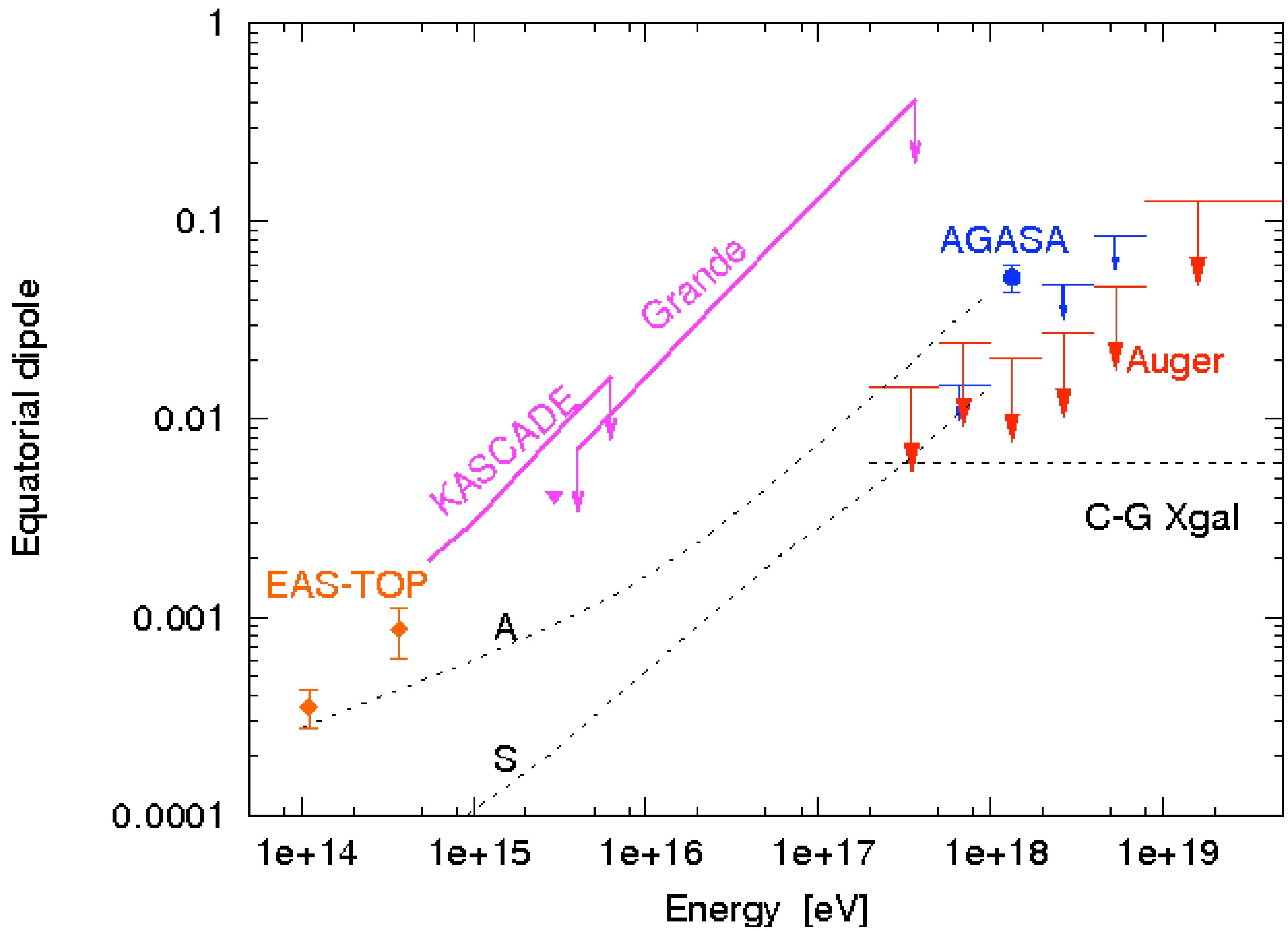
- Transition occuring at the ankle:
  amplitude of dipol pattern steadily increasing with energy up to the ankle (very model-dependent)

- Transition at lower energy:
  relative motion of the observer wrt the frame of the sources influences the large scale distribution of CRs

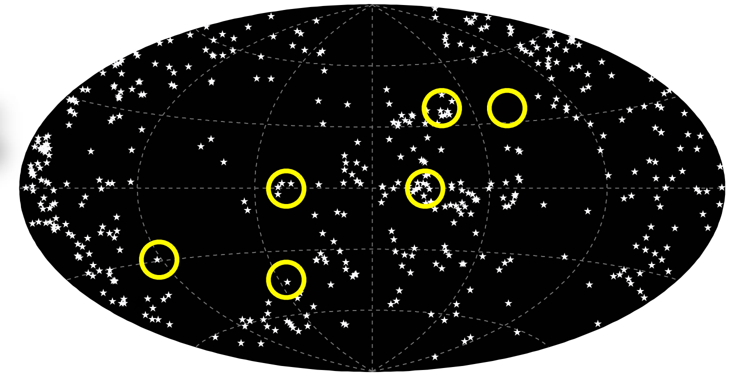


Measuring the large scale anisotropy vs energy is one of the main tools for discriminating between the 2 scenarios

Upper limit


1
0.1
0.01
0.001
0.0001
Equatorial dipole
1e+14
1e+15
1e+16
1e+17
1e+18
1e+19
Energy [eV]
KASCADE
Grande
AGASA
Auger
EAS-TOP
A
S
C-G Xgal

Anisotropy at highest energies

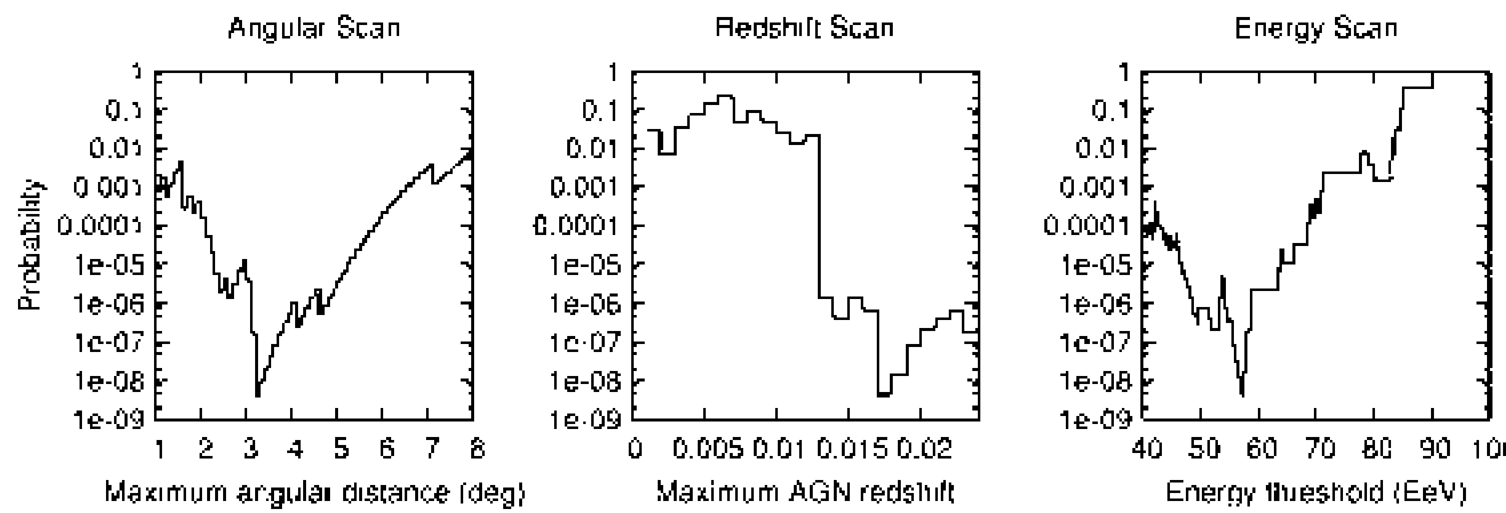


Take CR source candidates from some catalog, e.g. VCV (Veron-Cetty and Veron)

Define probability to find a single event of an isotropic distr. within a certain opening angle from a source: $p = p(\psi, n_{sources}) = p(\psi, z_{max})$

Exploratory scan < 26 May 2006:

Scan $P = \sum_{j=k}^{N} \binom{N}{j} p^j (1-p)^{N-j}$



for 3 free parameters

- z_{max}: Number of sources
- Ψ: Allowed angular separation
- E_{Thr}: Energy threshold

Minimum of P, i.e. largest deviation from isotropy found for

z_{max} = 0.018 (d_{max} = 75 Mpc)
Ψ = 3.1°
E_{Thr} = 56 EeV

Result: 12 among 15 measured events correlate with at least one source
3.2 expected if flux was isotropic (p=0.21) and exposure was accounted for

Running prescription (27.5.06- ...)

Verify a posteriori result by applying these correlation parameters to new data instead of using penalty factors to account for # of searches

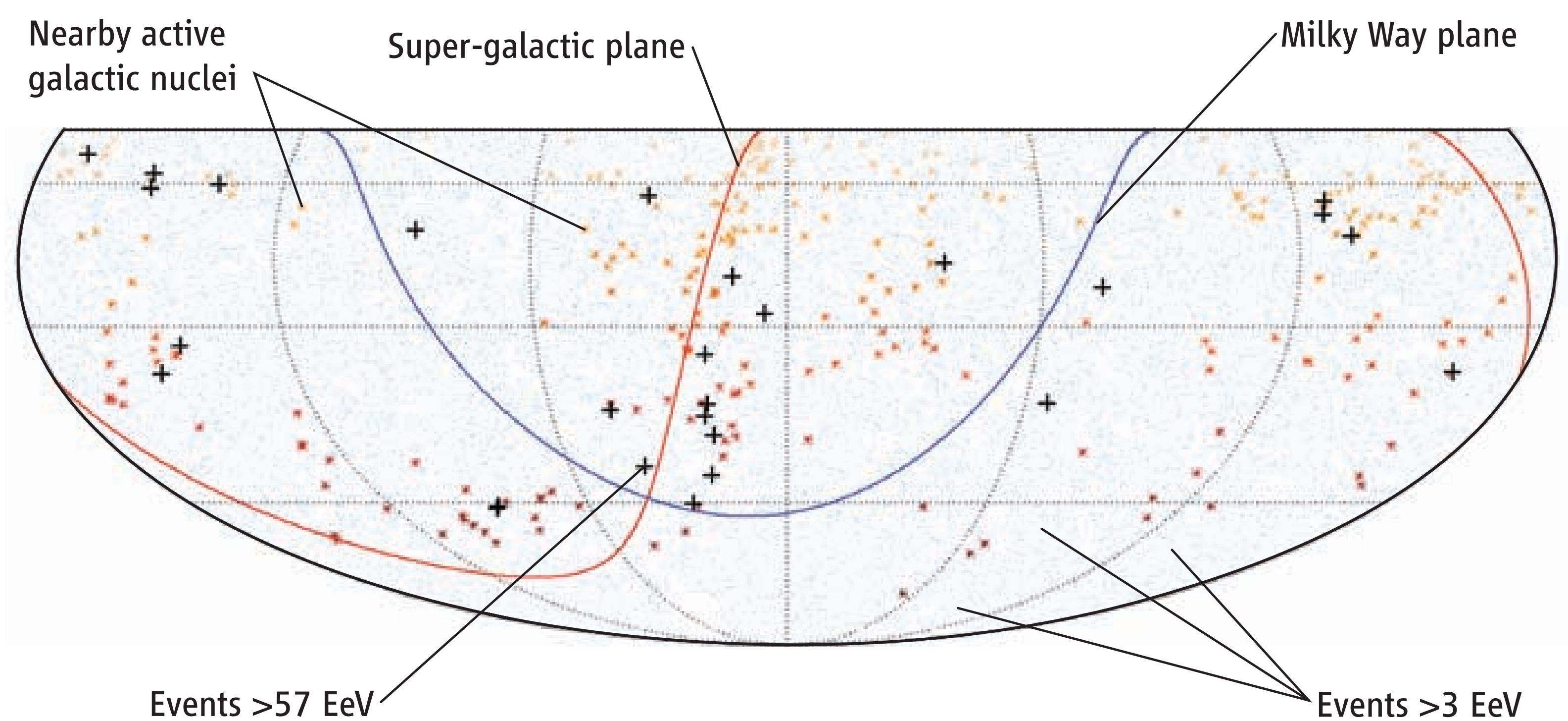
Goal: confirm results from exploratory scan by new data set
(a priory search)

Base Hypothesis: Isotropic Flux
Predefined stopping rule:
a) incorrectly reject isotropy hypothesis < 1% ($\equiv\alpha$) (i.e. $p<1\%$)
b) incorrectly accept isotropy hypothesis < 5% ($\equiv\beta$)

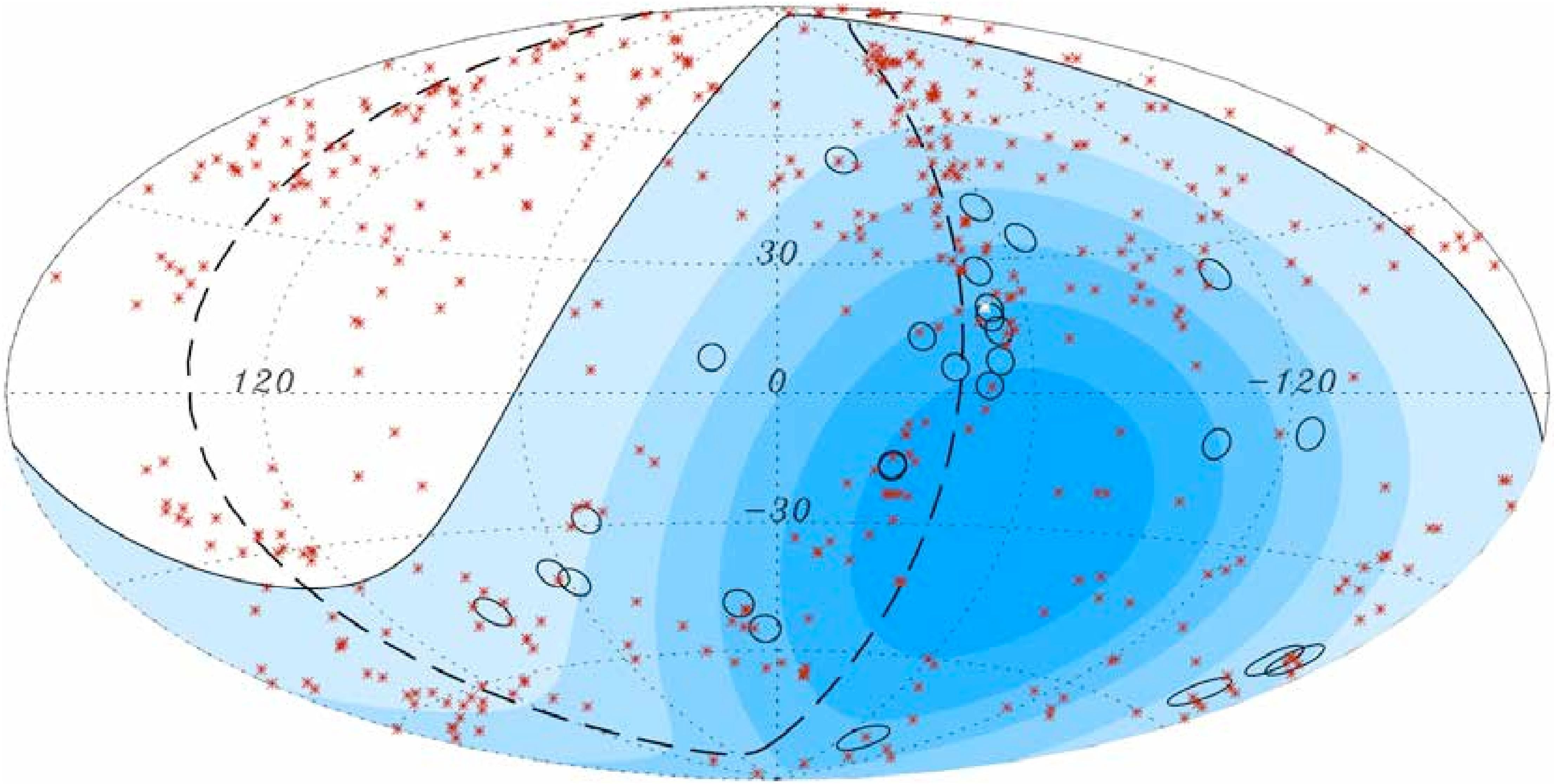
VCV:
472 AGNs
$z\leq0.018$
318 in fov

25 May 2007:
The prescription passed
(chance probability <= 1%)

20/27 events correlated



The correlation plot



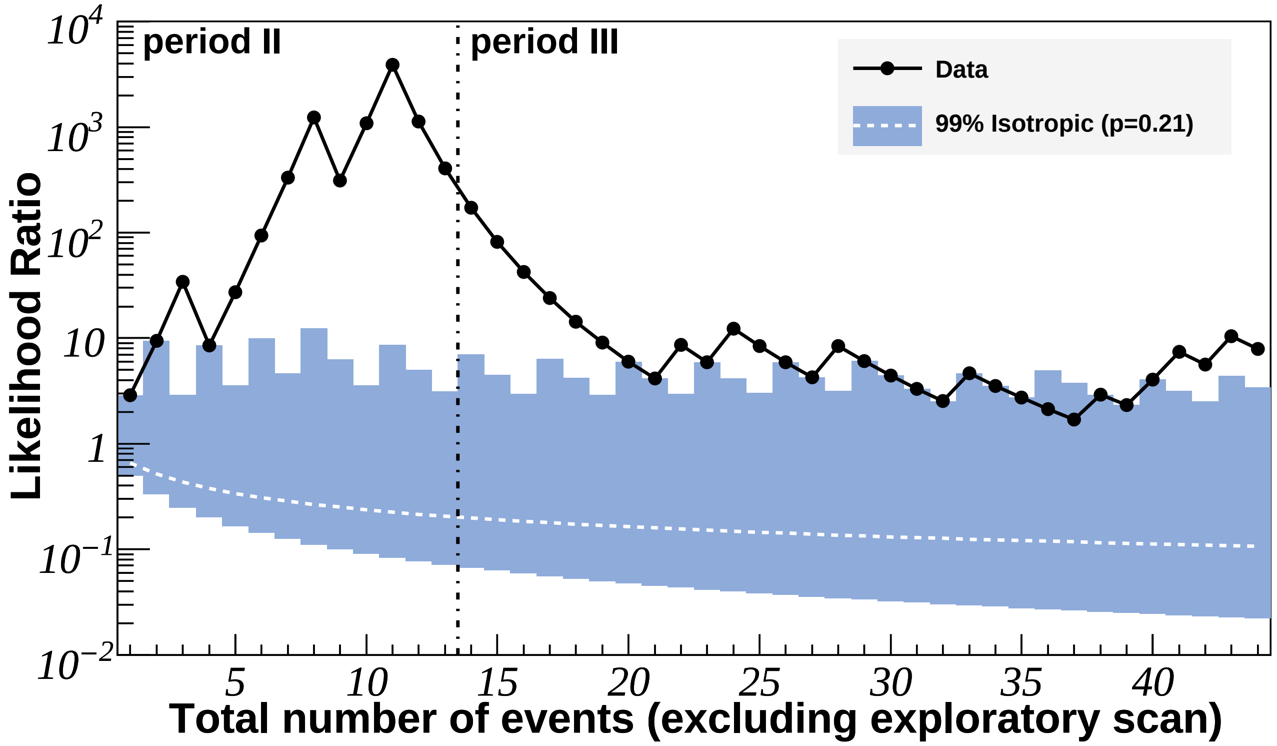
Current status

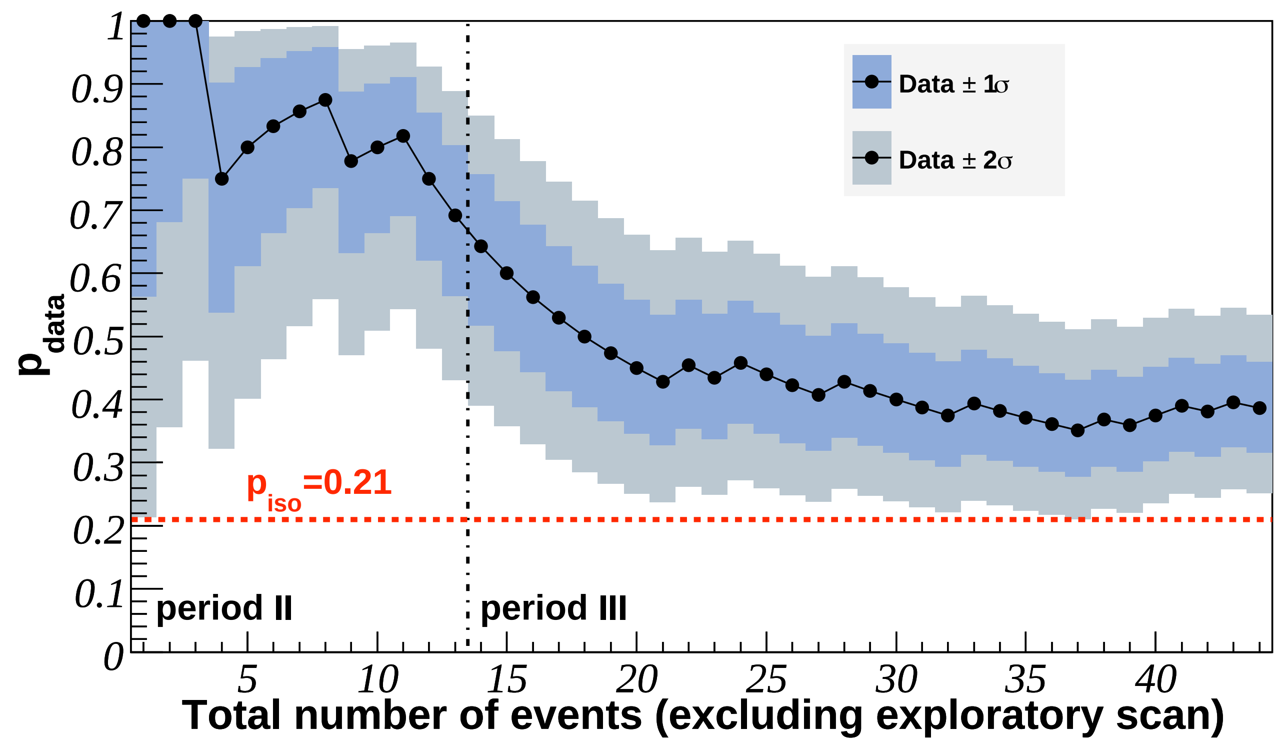
$$R = \frac{\int_{p_{\rm iso}}^{1} p^k (1-p)^{N-k}\ dp}{{p_{\rm iso}}^k (1-p_{\rm iso})^{N-k+1}}$$

$p_{iso} < p < 1$

$p = p_{iso}$

Reject iso. hyp. if $R > \frac{1-\beta}{\alpha} \equiv 95$





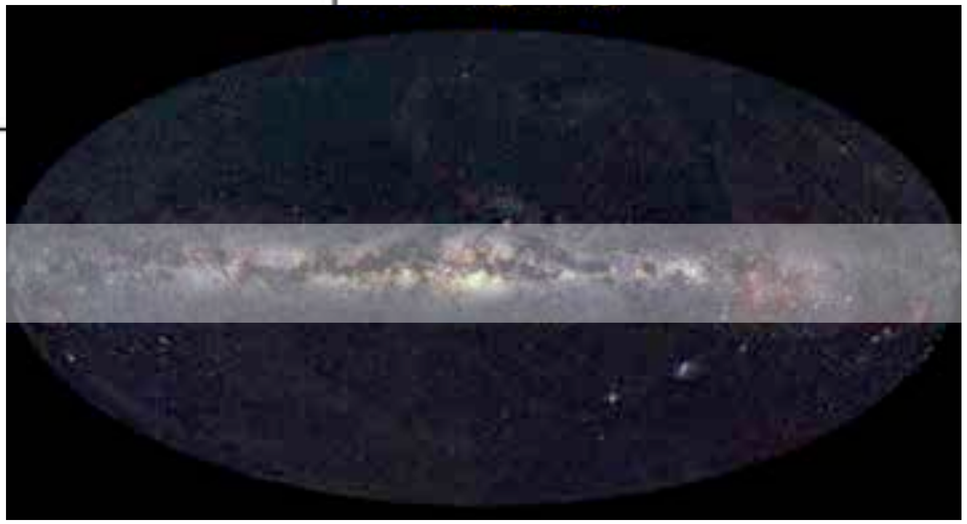
17/44 events in correlation (P=0.006)

p=17/44=0.38 more than 2 s.d. from isotropy

The degree of correlation has decreased, but still provides evidence for anisotropy of UHECRs >55 EeV at > 99% C.L.

Table of Results with full data set

Period	Exposure	GP	N	k	$k_{\rm iso}$	P
I	4390	unmasked	14	9	2.9	
		masked	10	8	2.5	
II	4500	unmasked	13	9	2.7	2×10^{-4}
		masked	11	9	2.8	1×10^{-4}
III	8150	unmasked	31	8	6.5	0.33
		masked	24	8	6.0	0.22
II+III	12650	**unmasked**	**44**	**17**	**9.2**	$\mathbf{6 \times 10^{-3}}$
		masked	35	17	8.8	2×10^{-3}
I+II	8890	unmasked	27	18	5.7	
		masked	21	17	5.3	
I+II+III	17040	unmasked	58	26	12.2	
		masked	45	25	11.3	

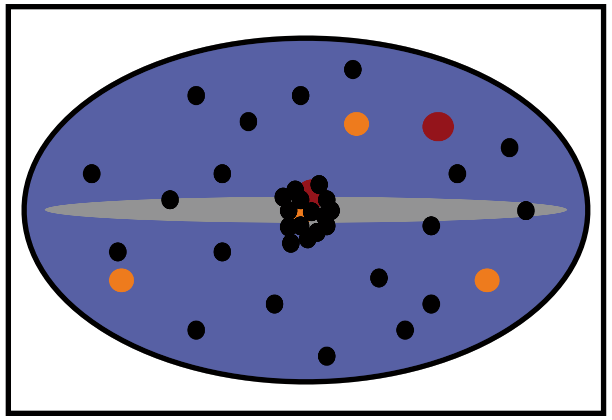


Anisotropy searches

$E_1 < E_2 < E_3$

Galactic centre

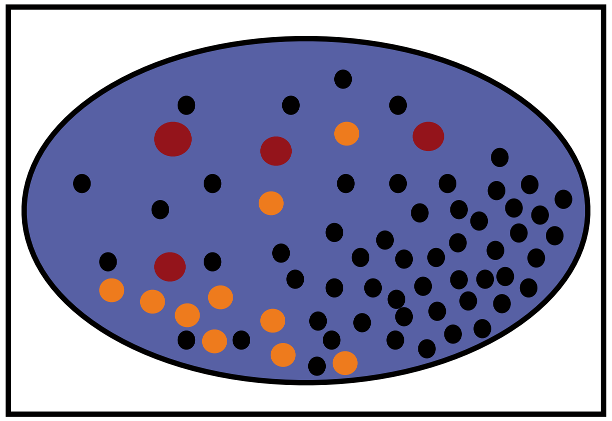
AGASA & SUGAR: yes



Auger not at this level

Multipole search

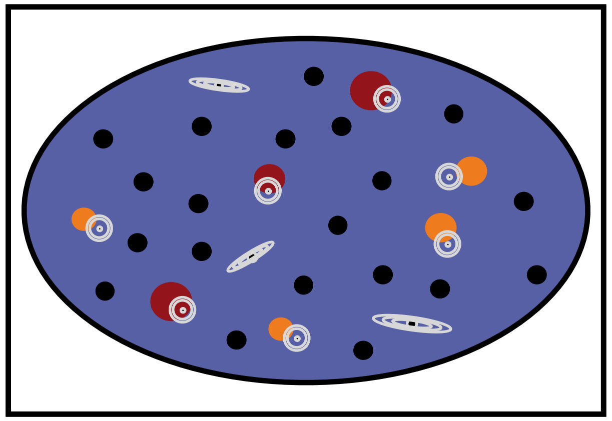
(Large scale anisotropy)



No evidence yet

Point sources

VCV catalog Auger: yes

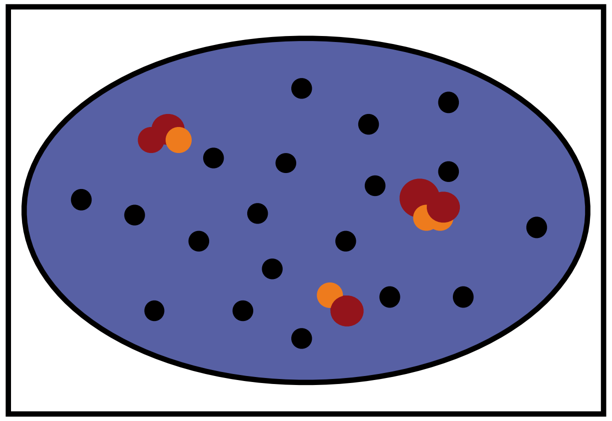


Hires: No

Cluster search

(Autocorrelation)

AGASA: yes

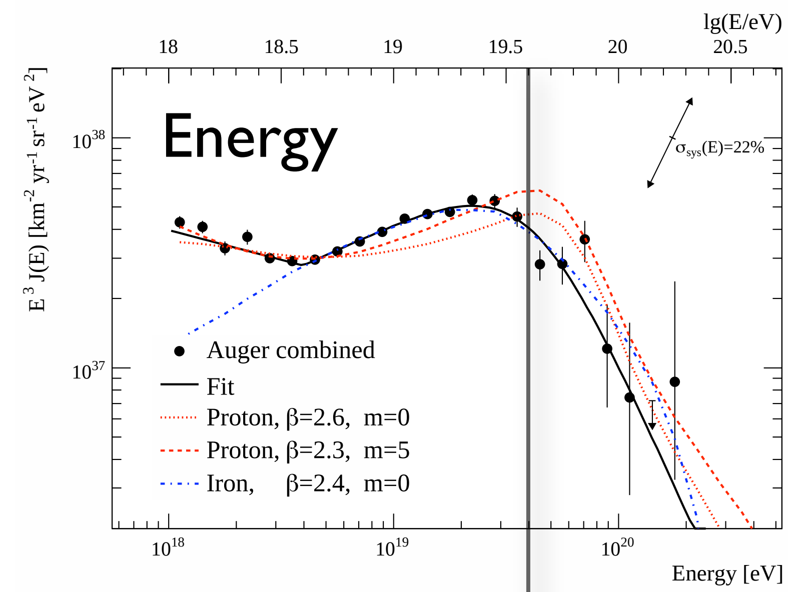


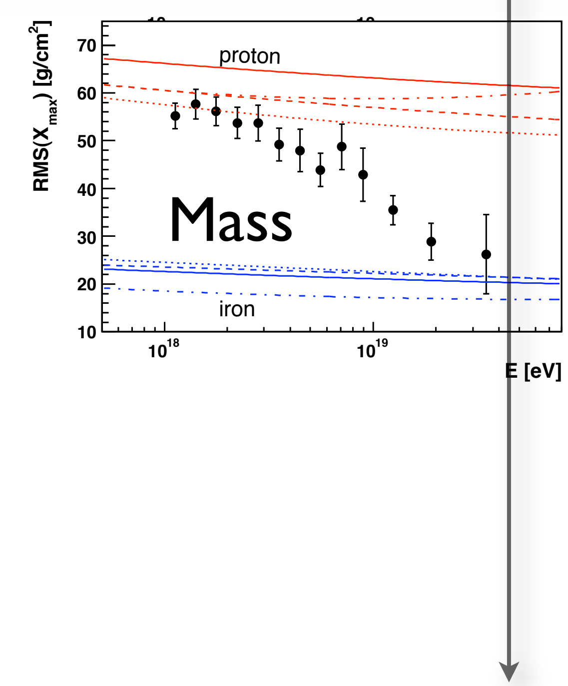
Hires: No

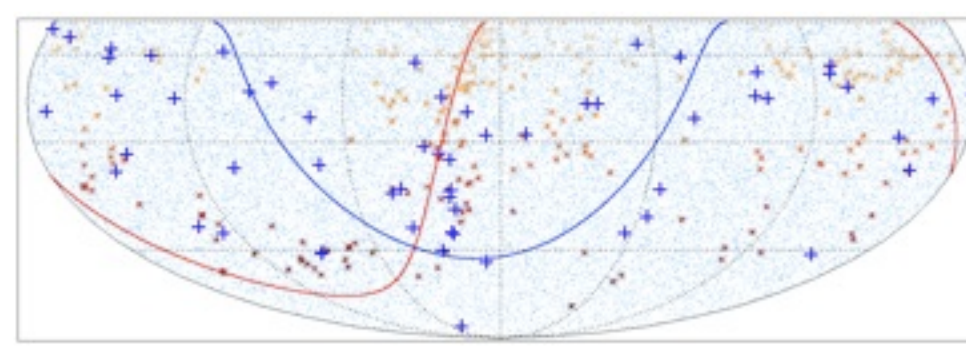
Auger: not at this scale

Summary and outlook

- Spectrum measurement is fundamental to solve the UHECR puzzle, but in addition
- Deducing the mass is crucial incl. photons and neutrinos
  - p/Fe at highest energy? Neutrinos and photons?
  - Composition around 10^{18} eV will sheet light on the origin too:
    Extensions of the southern site;
    - HEAT (3 FD telescopes; elevation of 30-60°)
    - AMIGA; Muon counting,
- Anisotropy may ultimately pin point the sources
  We need more statistics
    - Auger North

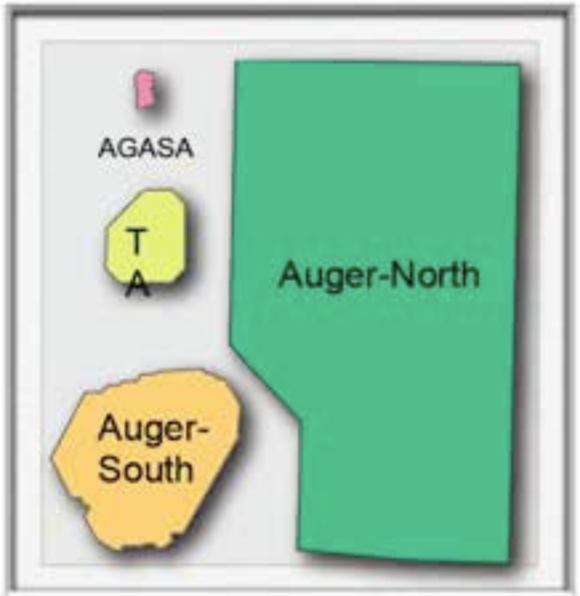


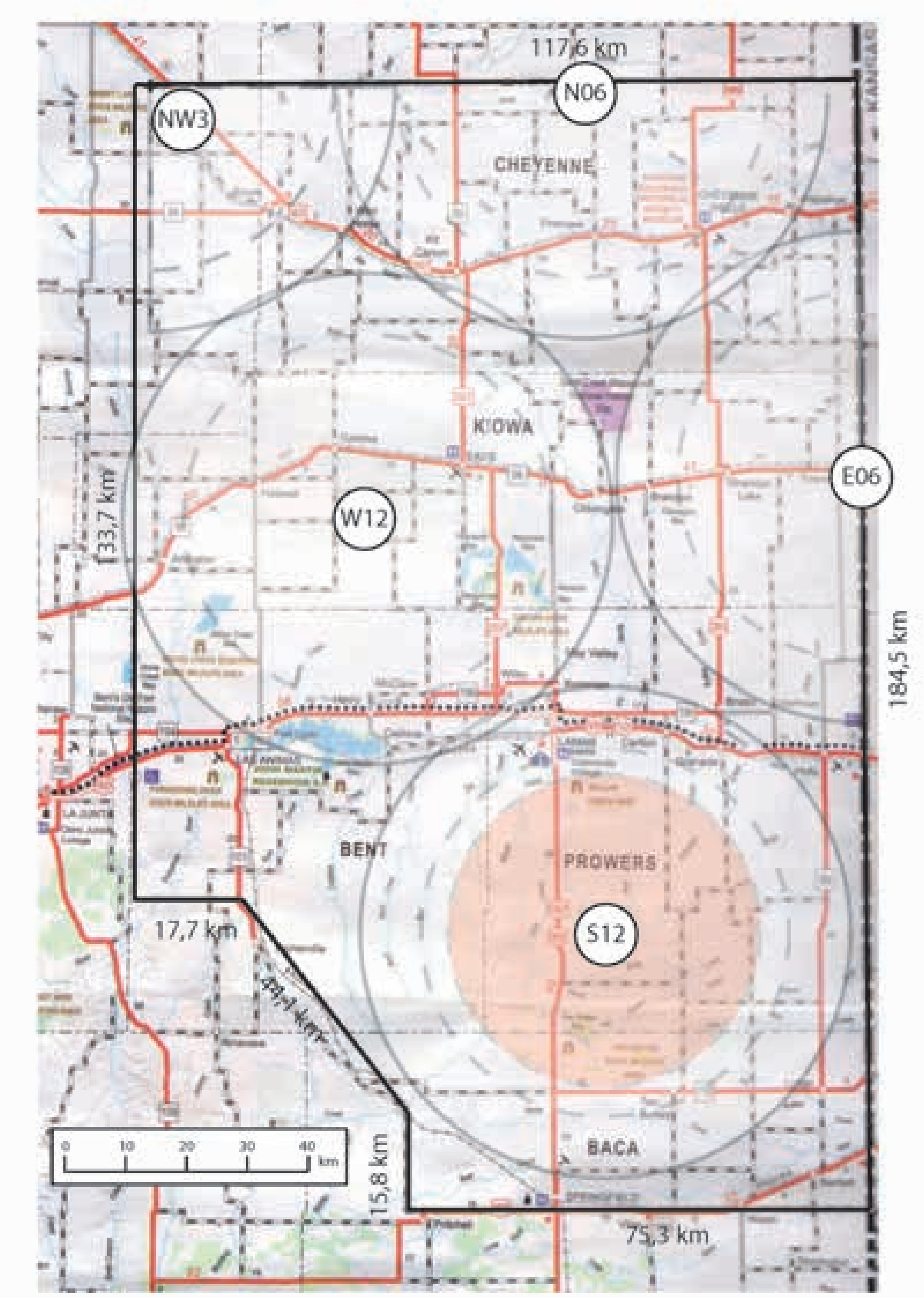




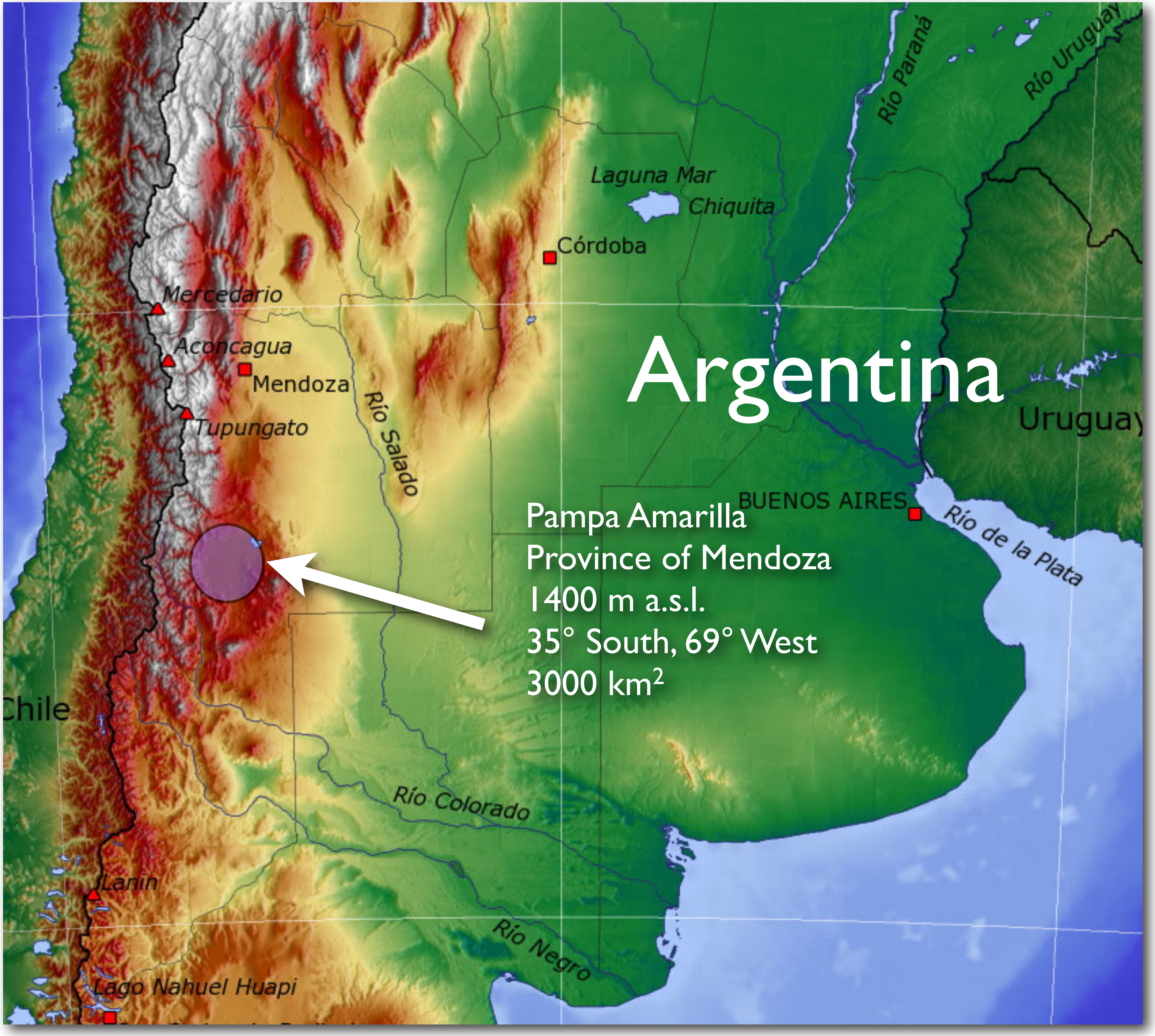
Northern Observatory in Colorado/USA

- 20,000 square kilometer
- ~40 FD telescopes
- > 4000 SD stations
- SD energy threshold of > 10^{19}eV

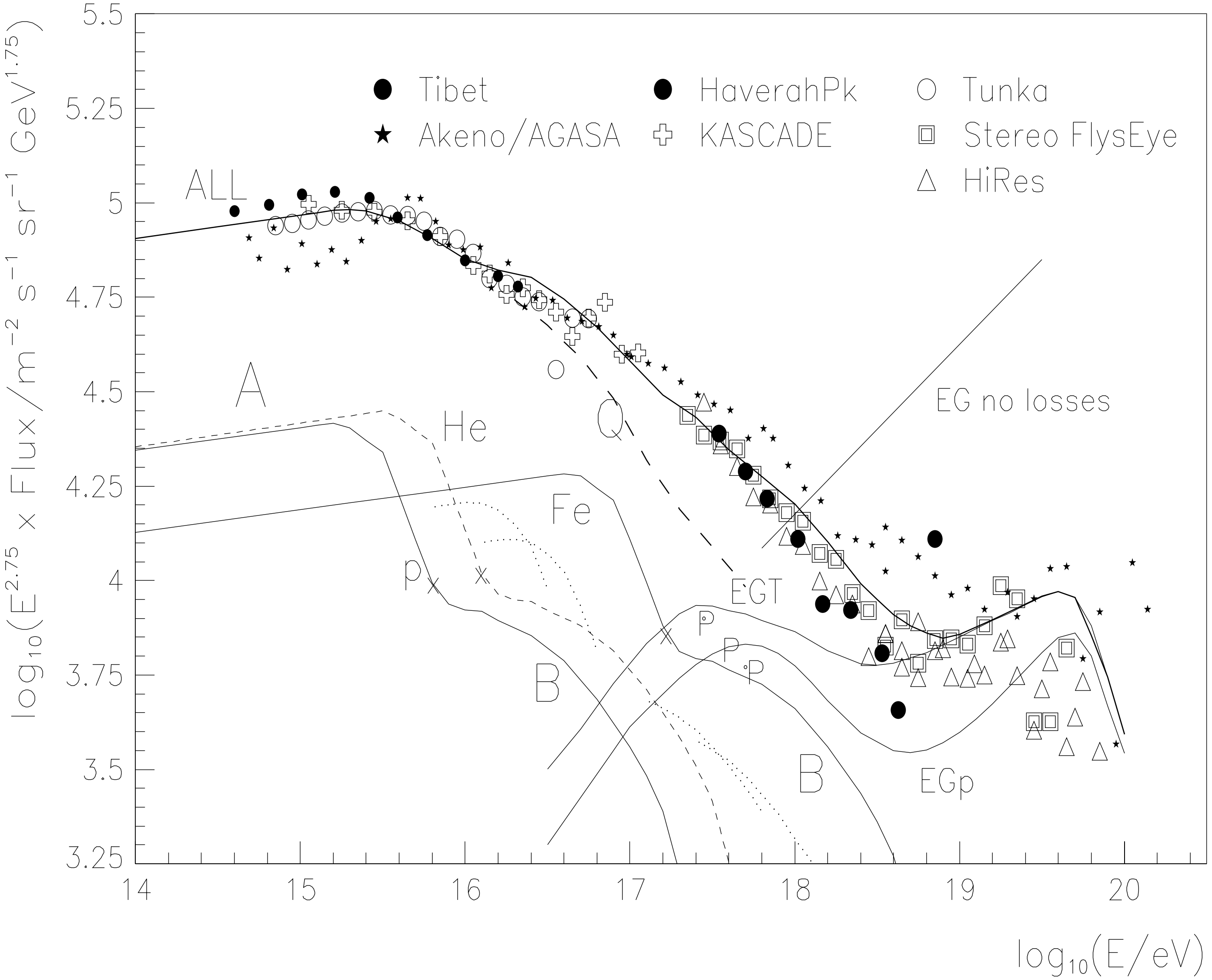




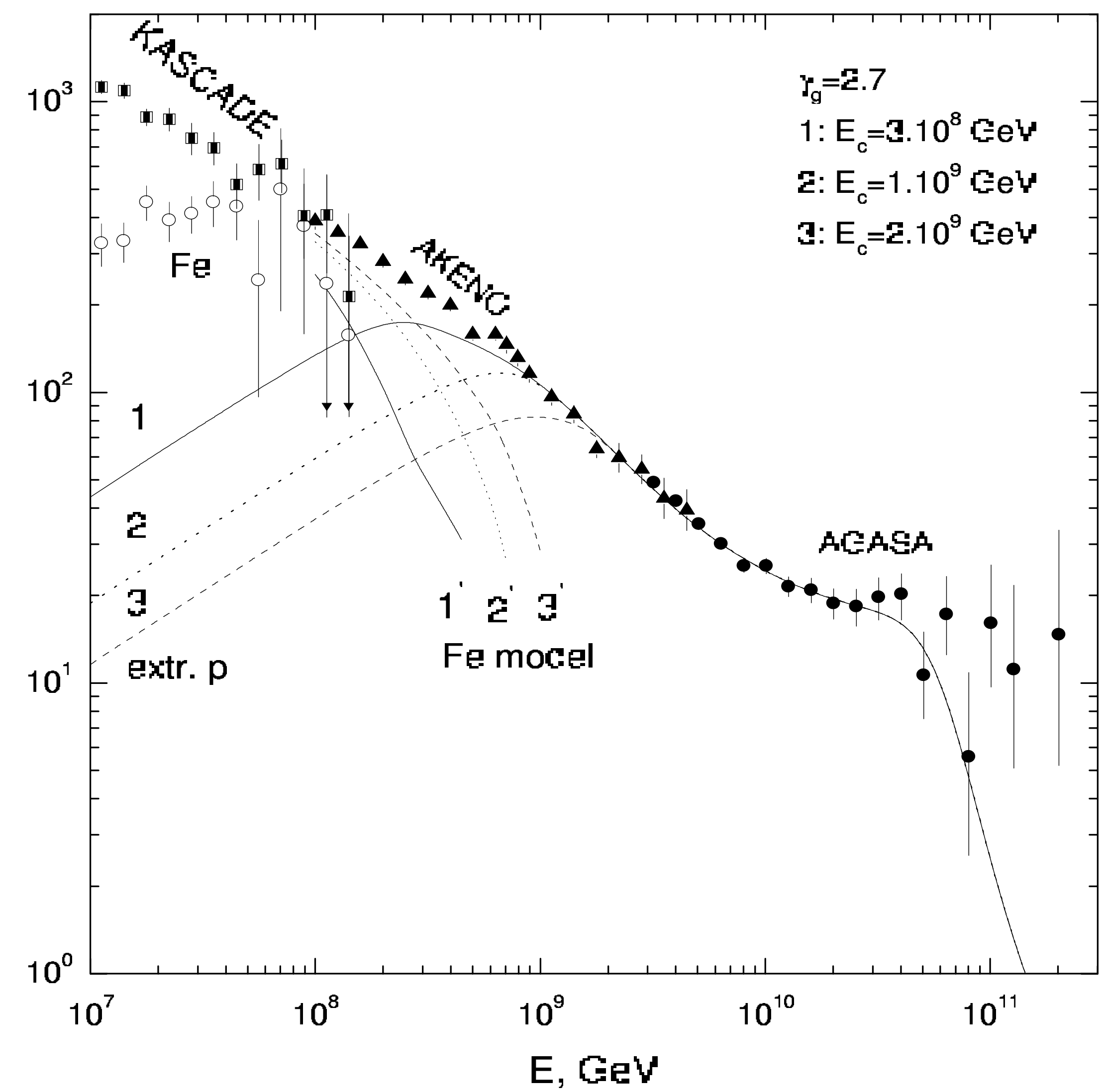
END


Argentina
Pampa Amarilla
Province of Mendoza
1400 m a.s.l.
35° South, 69° West
3000 km²
Laguna Mar
Chiquita
Córdoba
Mercedario
Aconcagua
Mendoza
Tupungato
Río Salado
Río Paraná
Río Uruguay
Uruguay
BUENOS AIRES
Río de la Plata
Chile
Río Colorado
Río Negro
Lanin
Lago Nahuel Huapi

Hillas model

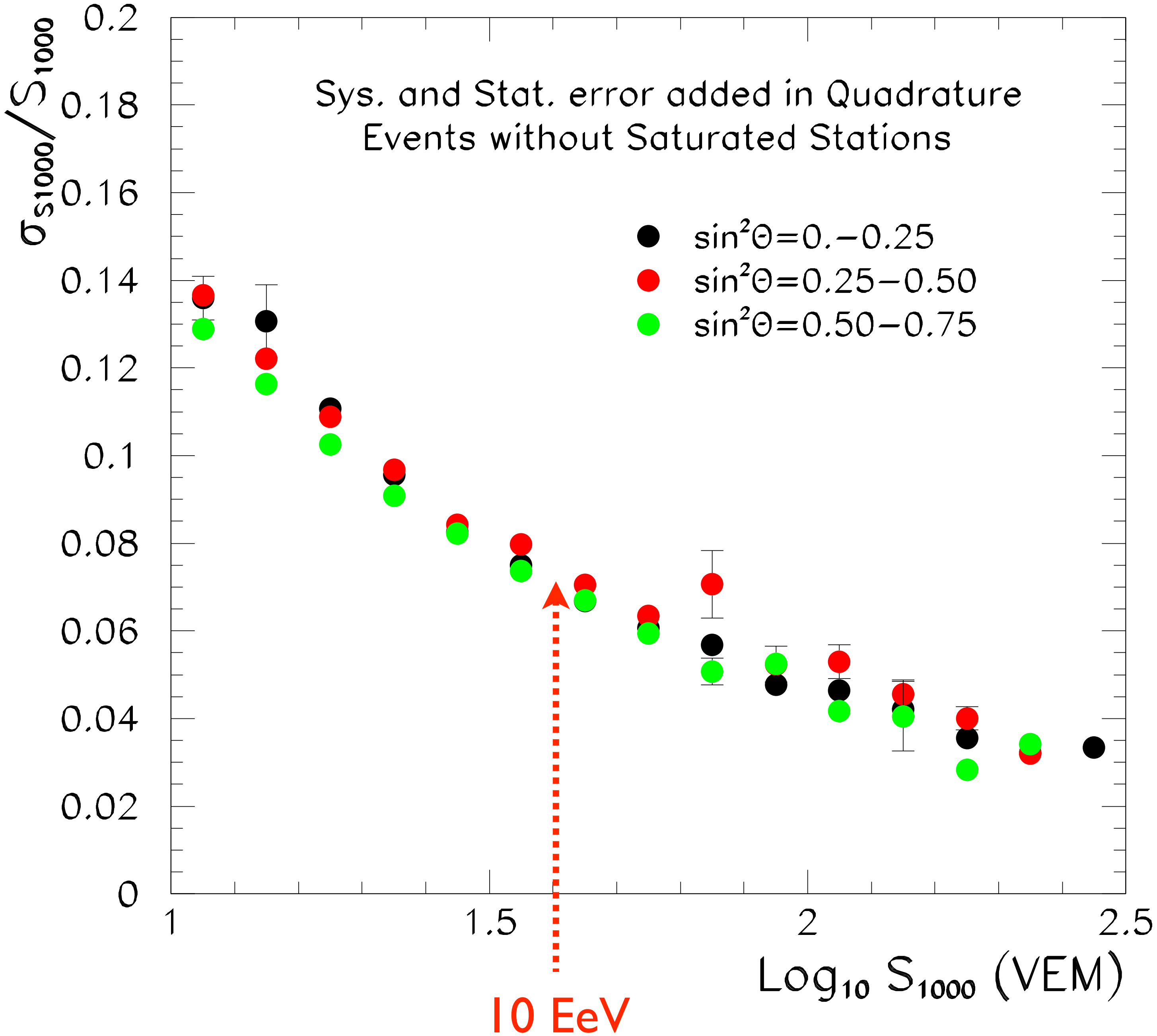


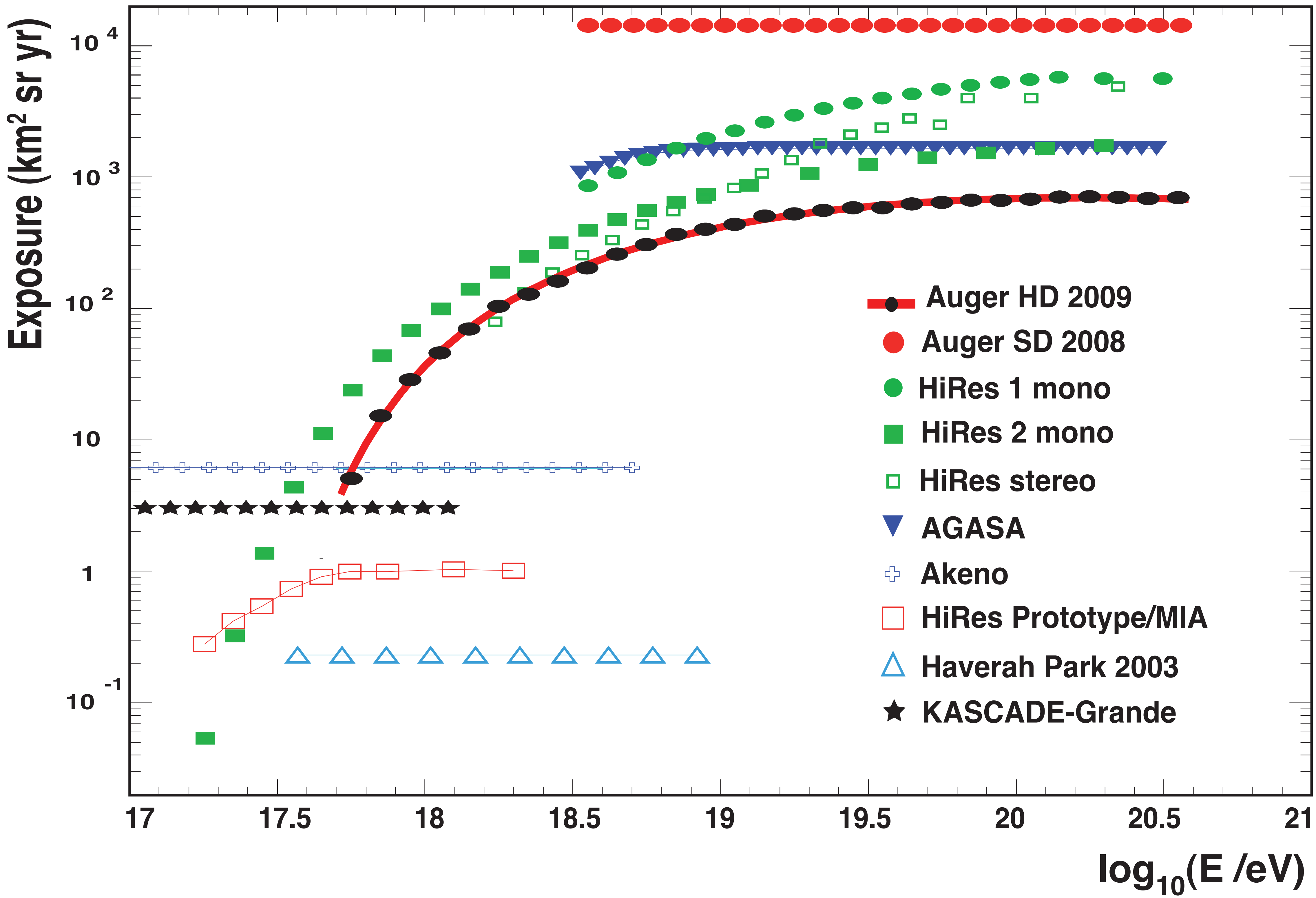
Bereszinsky model



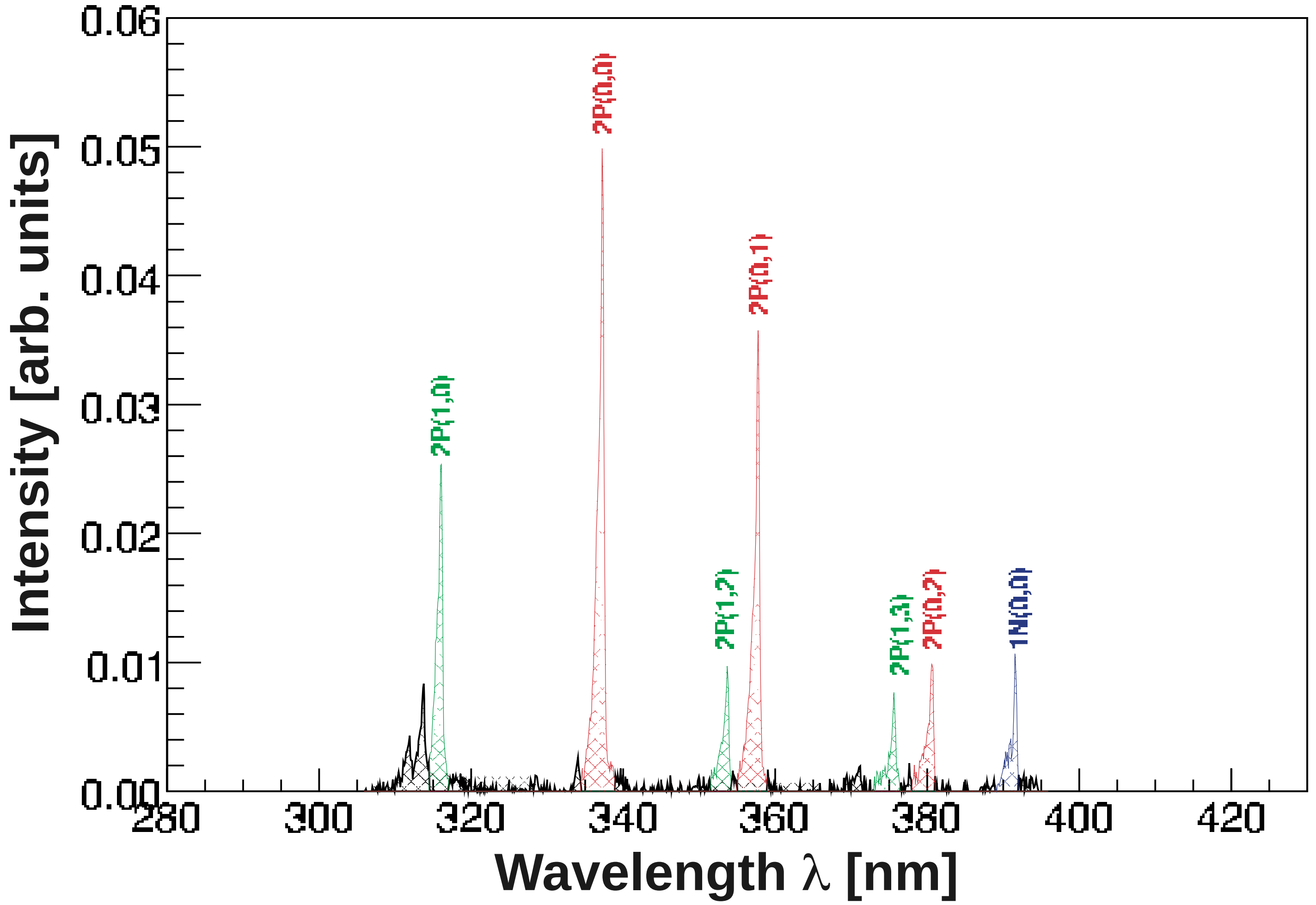
Uncertainty of S(1000)

Precision of S(1000) improves as energy increases





Montag, 27. Juli 2009



Intensity [arb. units]
0.06
0.05
0.04
0.03
0.02
0.01
0.00
280
300
320
340
360
380
400
420
Wavelength λ [nm]
2P(1,0)
2P(0,0)
2P(1,2)
2P(0,1)
2P(1,3)
2P(0,2)
1N(0,0)