The Pierre Auger Observatory
and the highest-energy particles in the Universe

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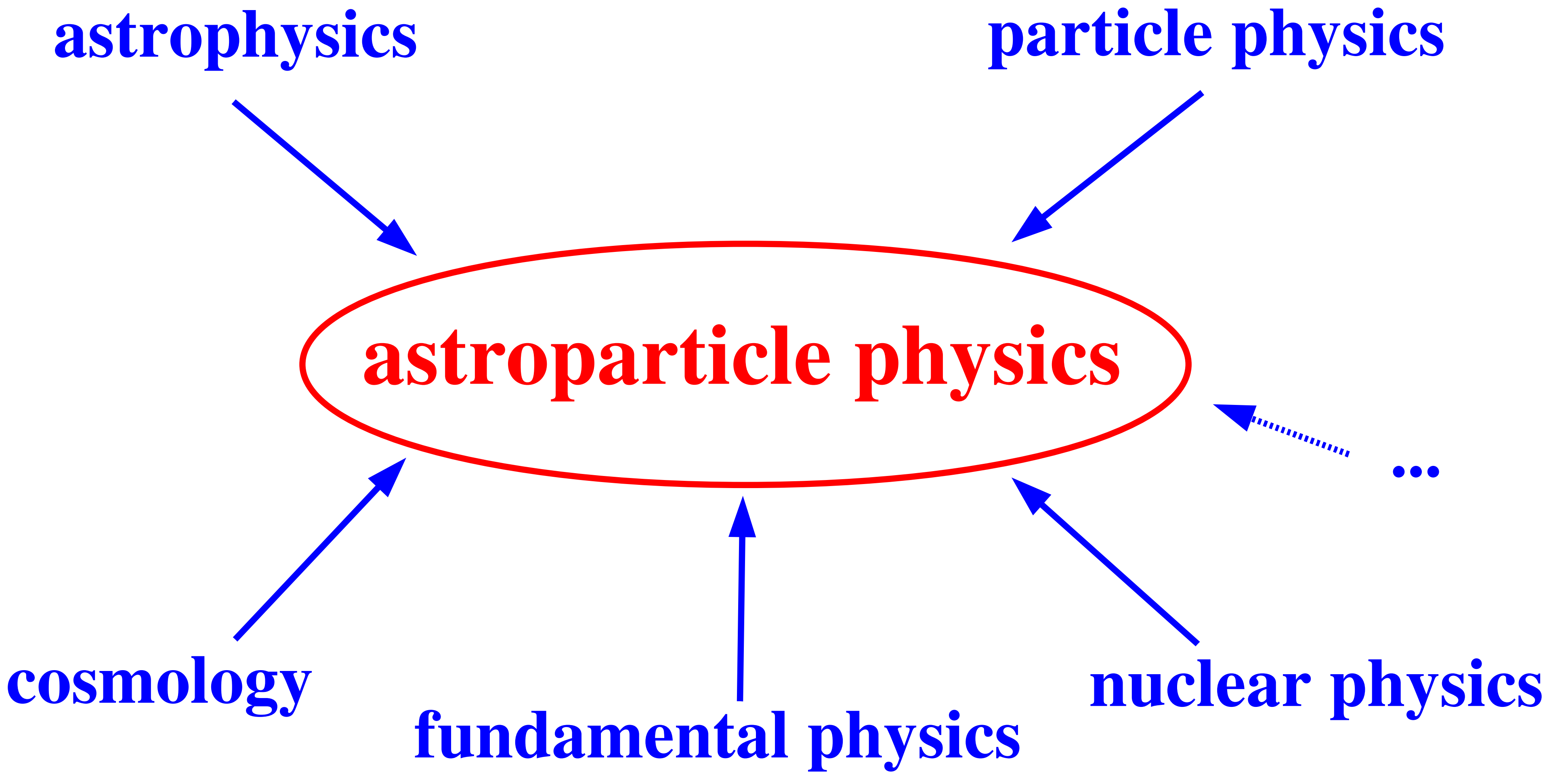
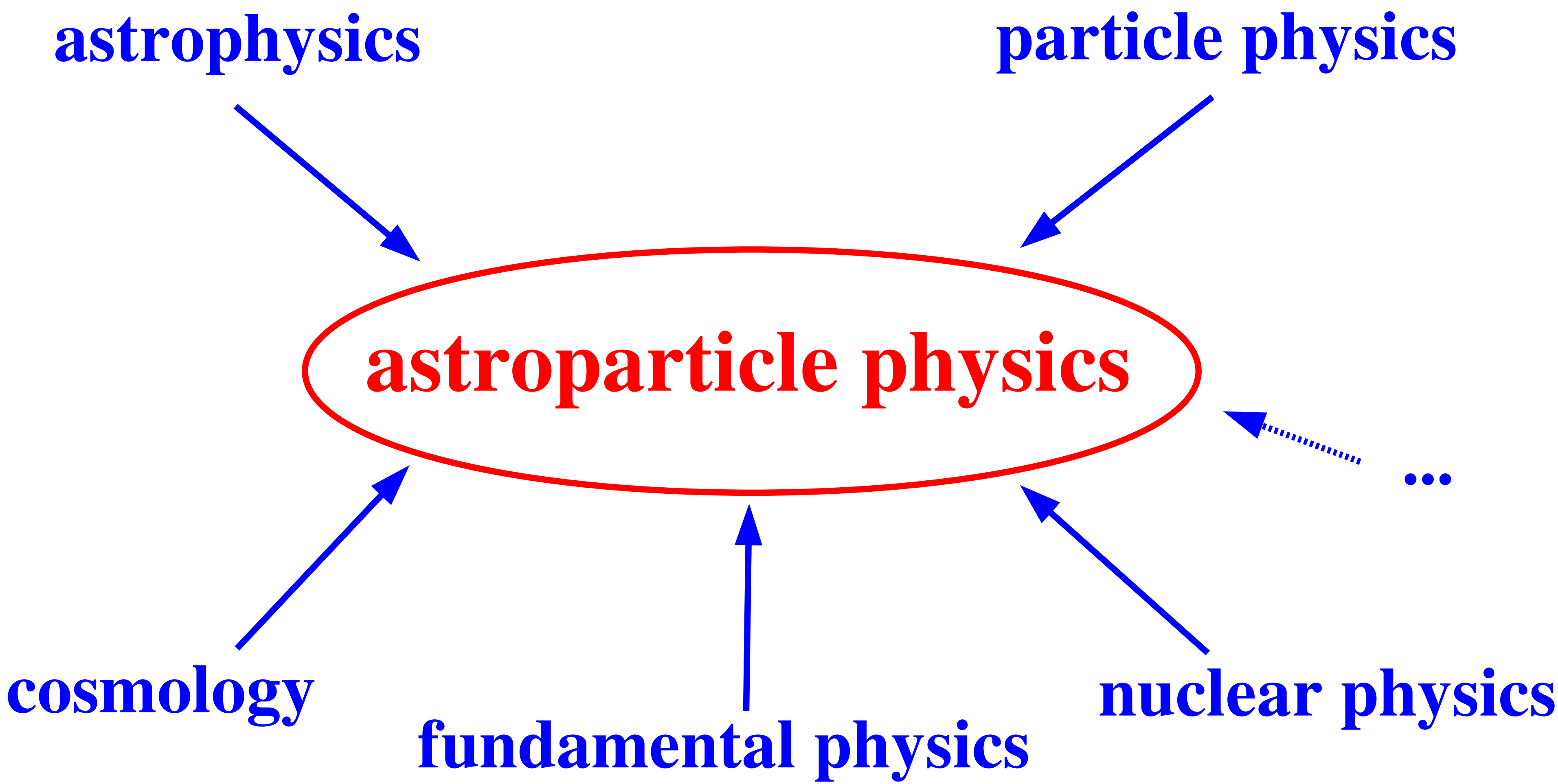
6. Schule für Astroteilchenphysik
Obertrubach-Bärnfels, October 7-15, 2009

- **A first overview**
- **History** ***and inserts: air showers, GZK effect***
- **Pierre Auger Observatory** ***(how, what)***
- **Future**

PIERRE AUGER OBSERVATORY

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung


astrophysics
particle physics
astroparticle physics
...
cosmology
fundamental physics
nuclear physics



astroparticle physics = *"physics using astroparticles"*

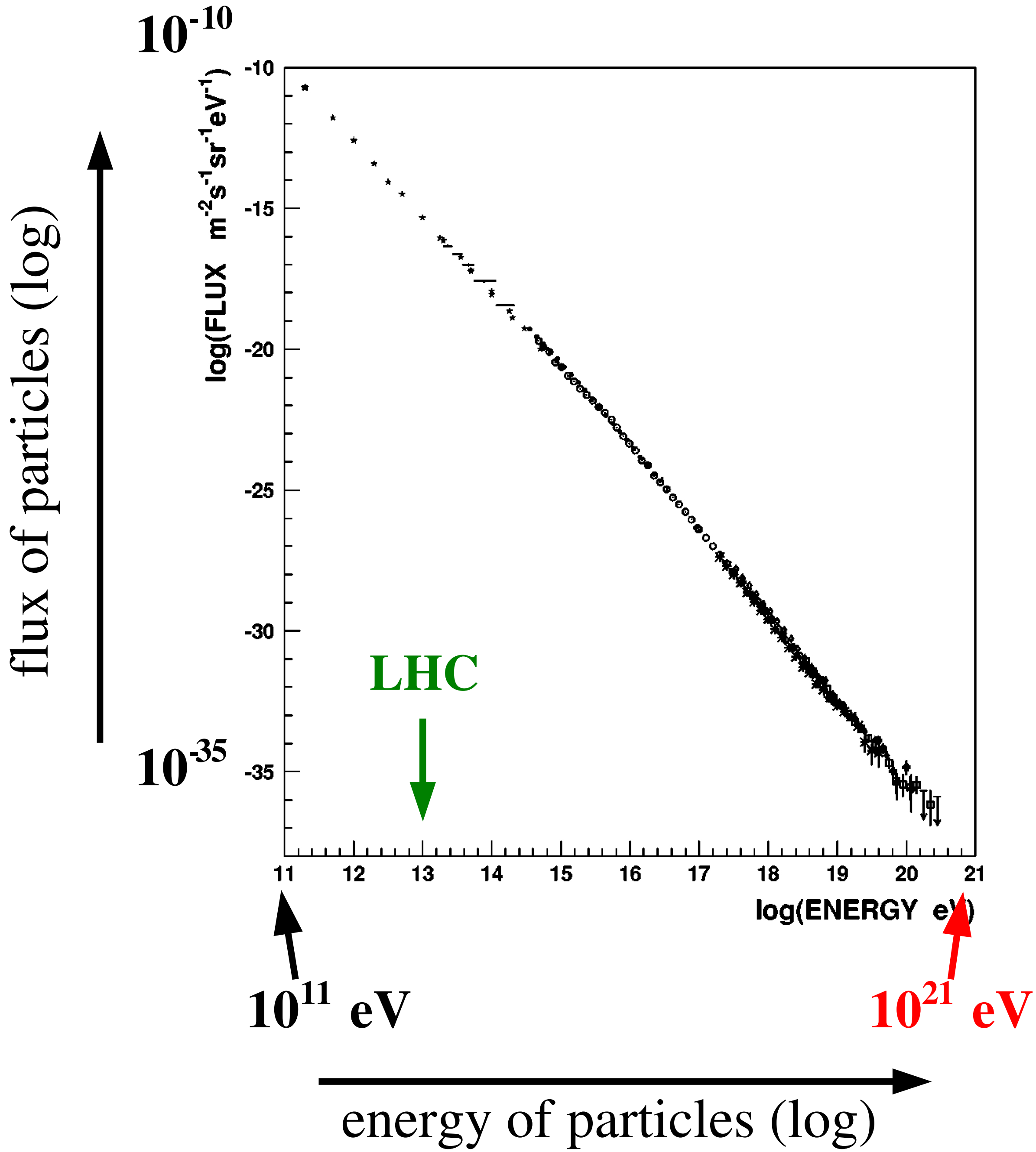
-> cosmic rays ...

Cosmic rays

magnetic fields
scramble paths

- **particles** with almost speed-of-light (= very high energy) entering the atmosphere
- what particles? (mostly) **atomic nuclei**
- ***How often?*** *Depends on energy …*

Cosmic rays: how often ?



unit of energy "**electron volt**" (eV):

visible light ~1 eV

particles in sun ~1000 eV

LHC (CERN) ~10^{13} eV

here up to ~10^{21} eV

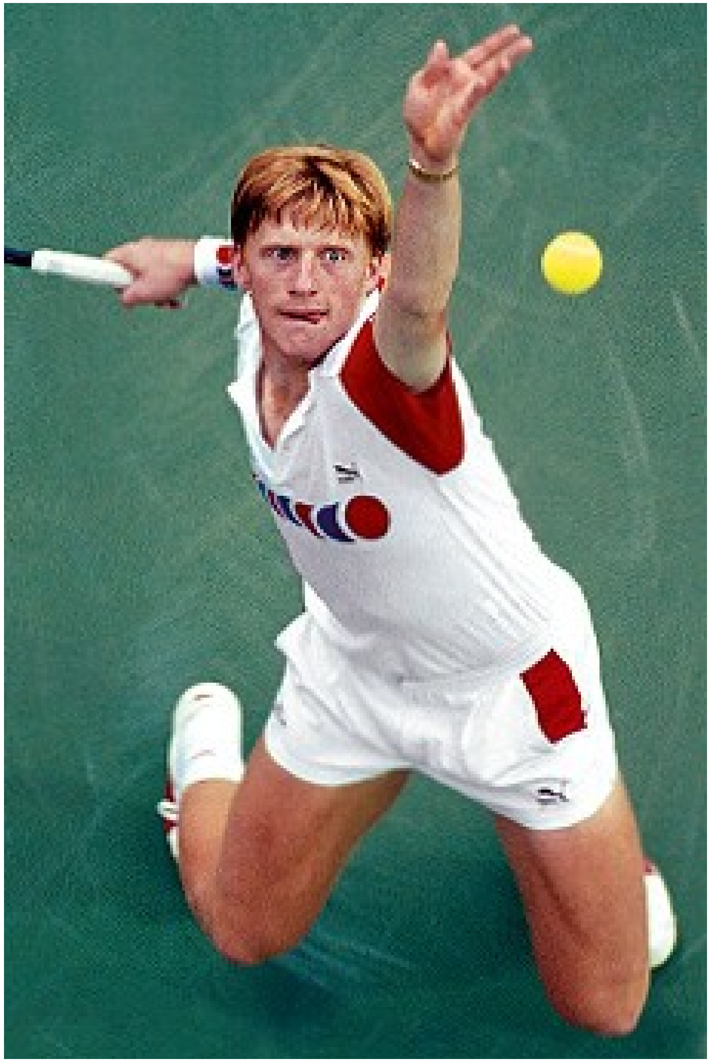
1000000000000000000000 eV

"highest-energy particles in the Universe"

... for comparison:

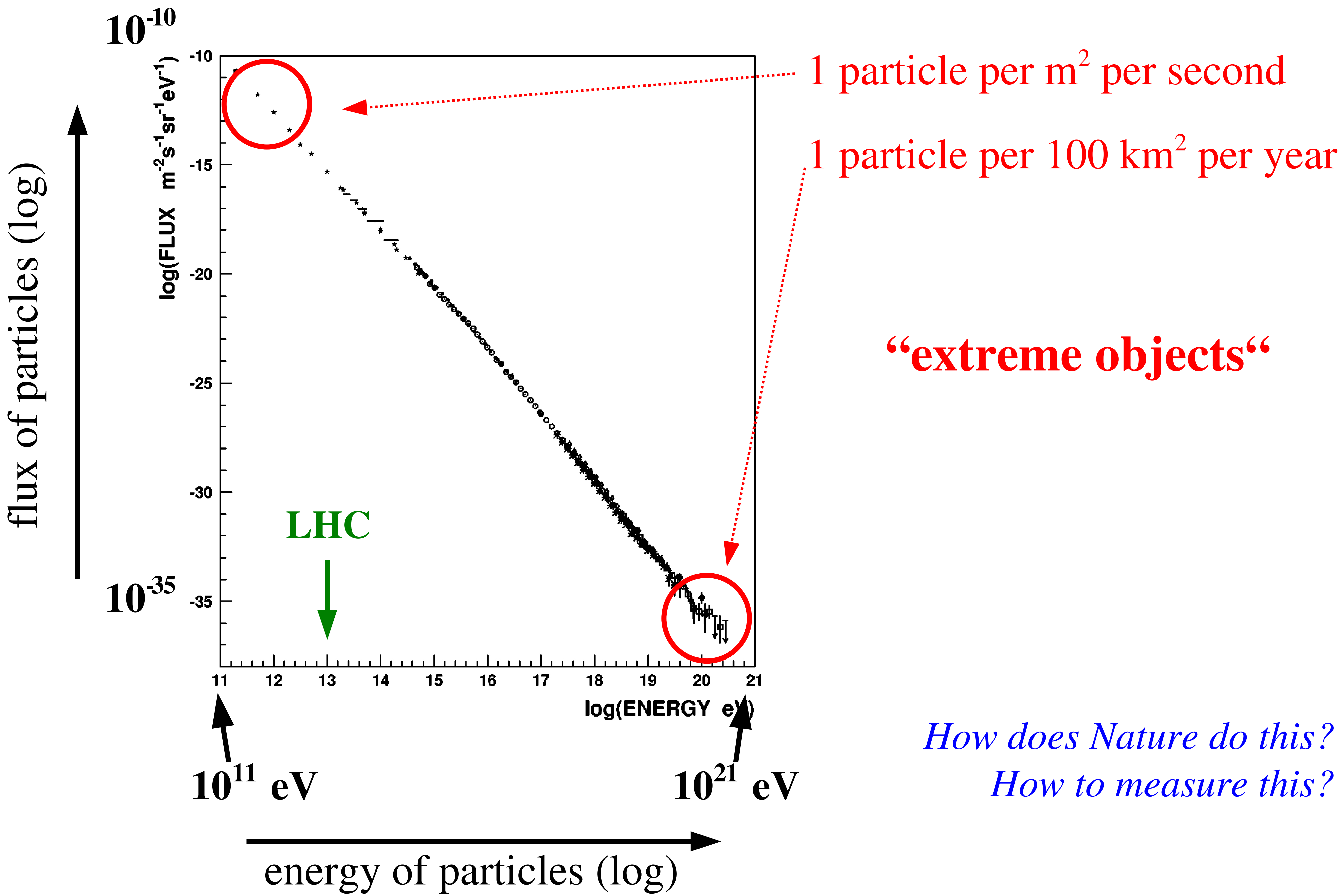
~ kinetic energy of ...

... first service
of Boris !



note: energy carried
by ~10^{24} particles
instead of 1 cosmic ray

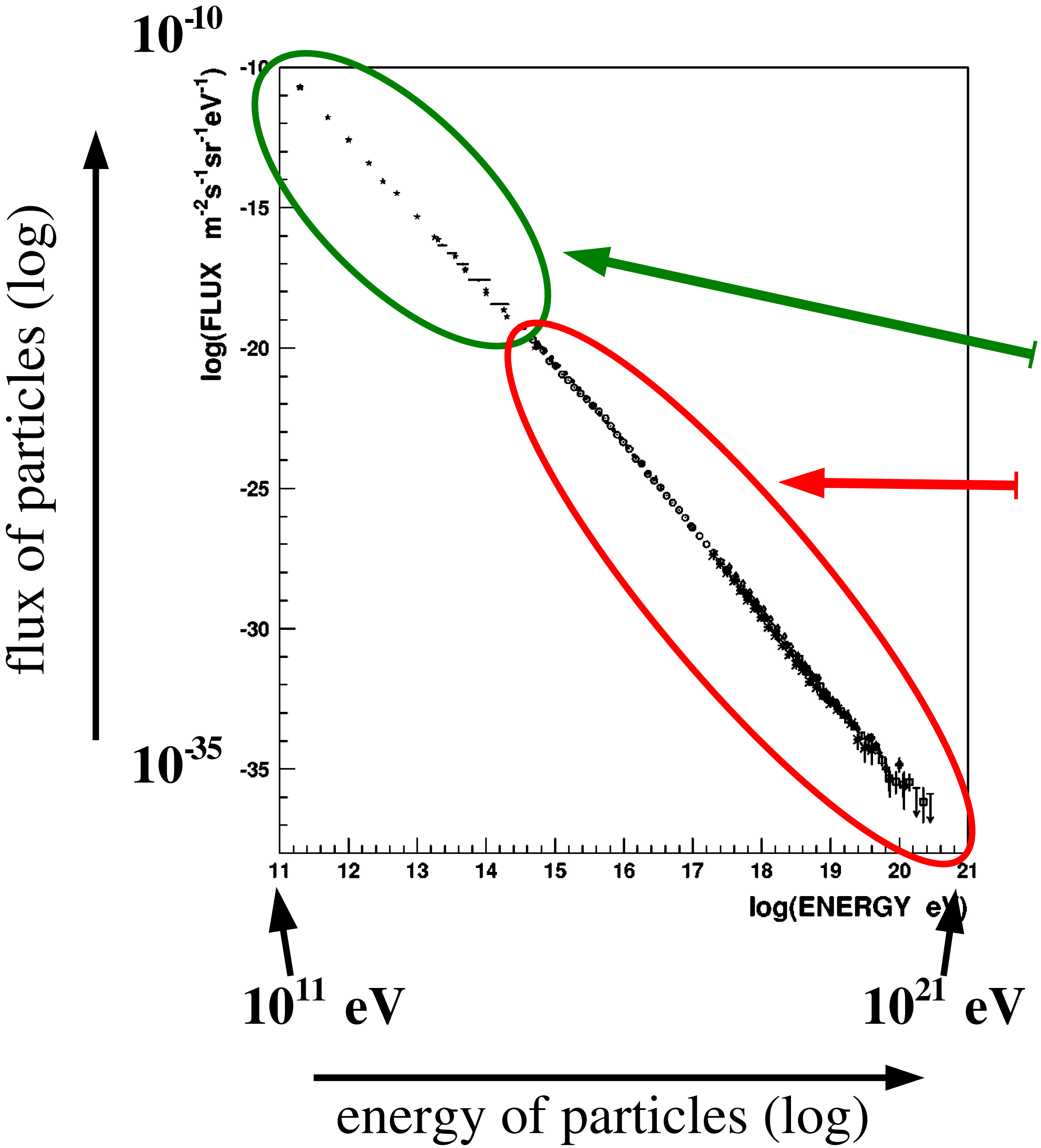
Cosmic rays: how often ?

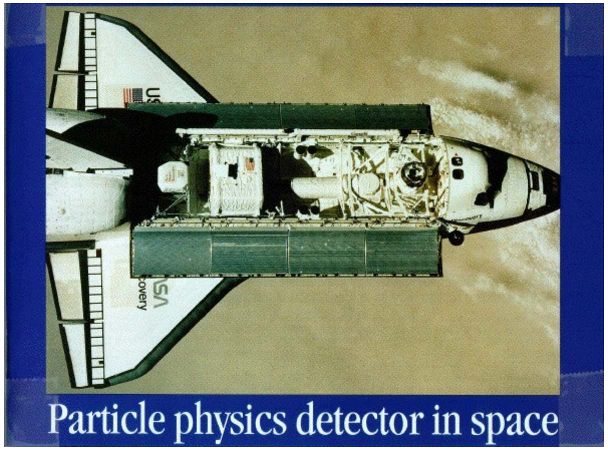


"extreme objects"

How does Nature do this?
How to measure this?

How to measure ?





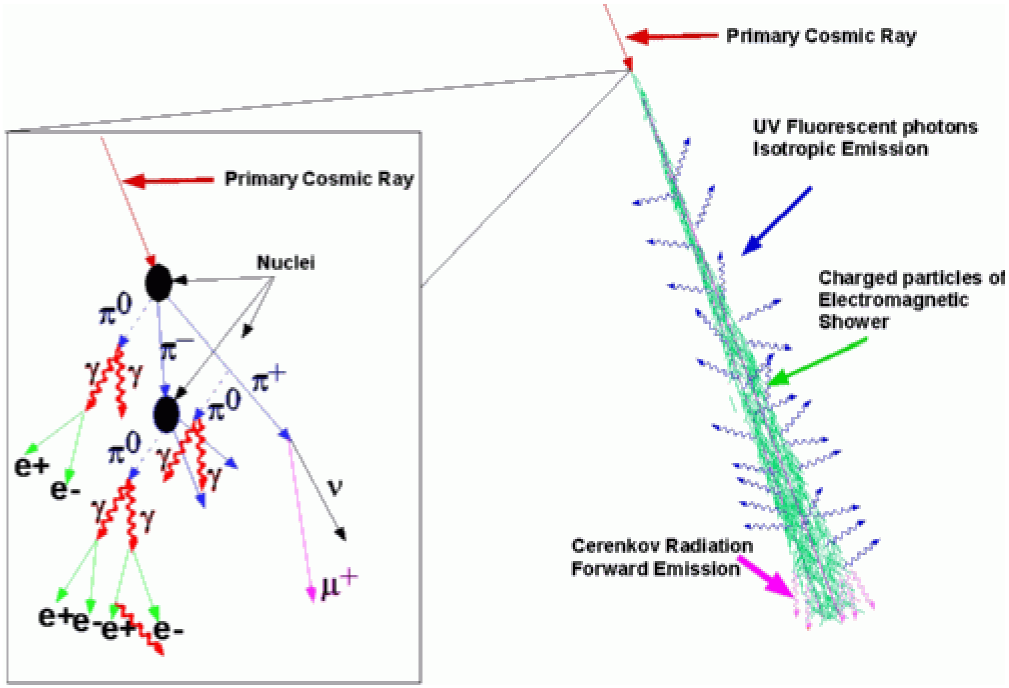
direct: satellites, balloons

here: flux too small !?

but: *nature helps* ...

Indirect measurement using air showers !

later more !

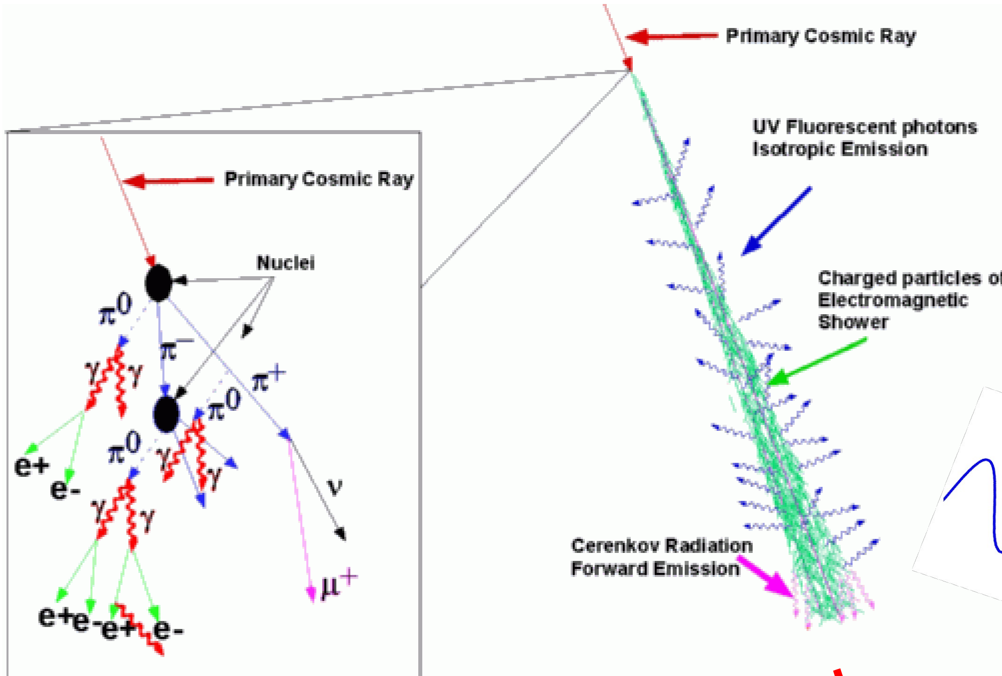


- **collisions** in atmosphere

➔ particle **cascade**: “air shower“

Indirect measurement using air showers !

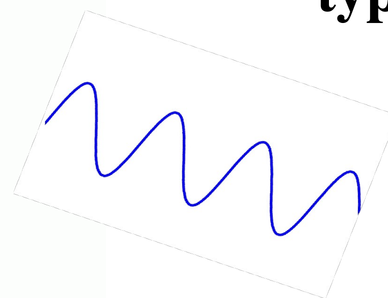
later more !



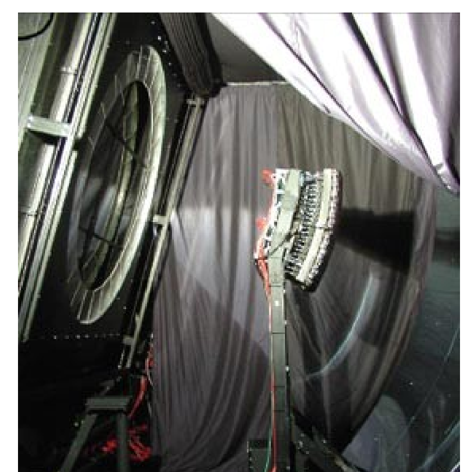
- **collisions** in atmosphere

➔ particle **cascade**: "air shower"

=> **direction** (~1°), **energy** (25%),
type (tricky; using simulations)



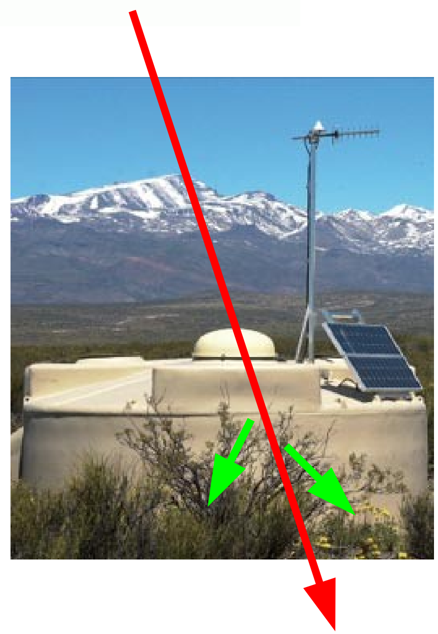
fluorescence light



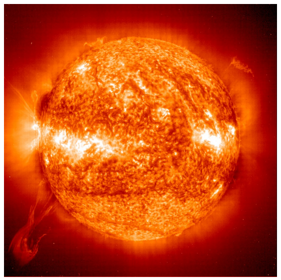
only in clear nights

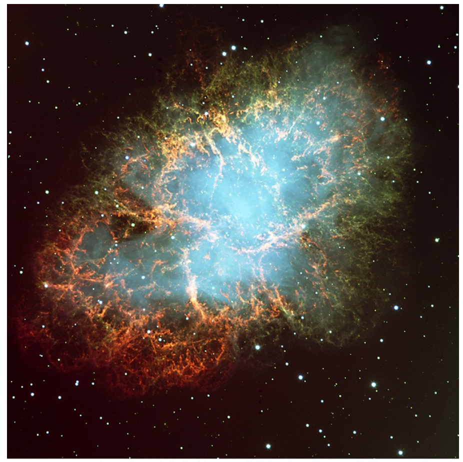
particles on ground

water detectors =>
cherenkov light

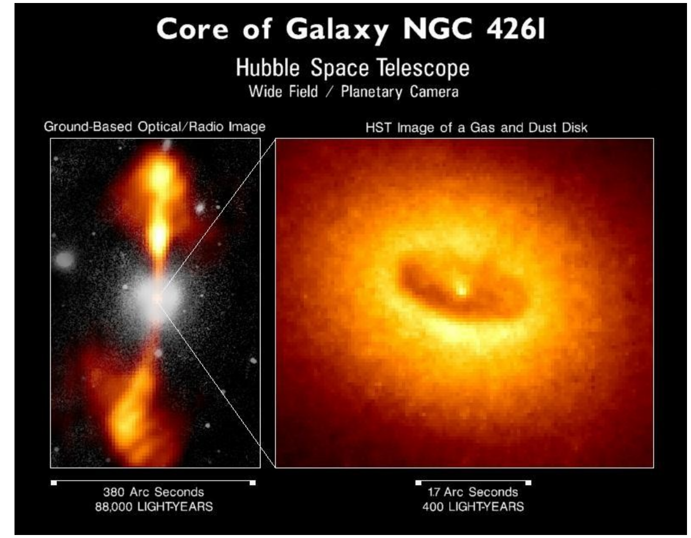


Cosmic rays: sources ?

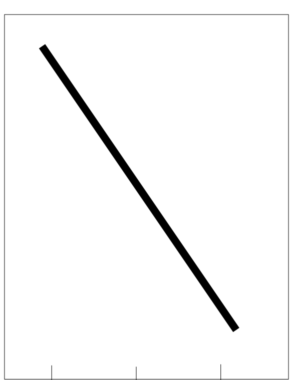


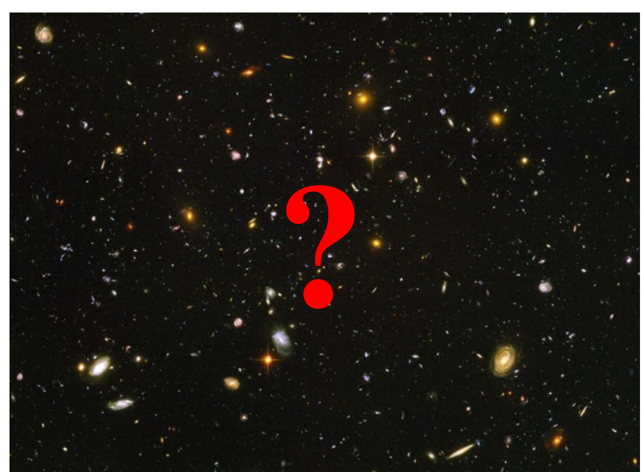


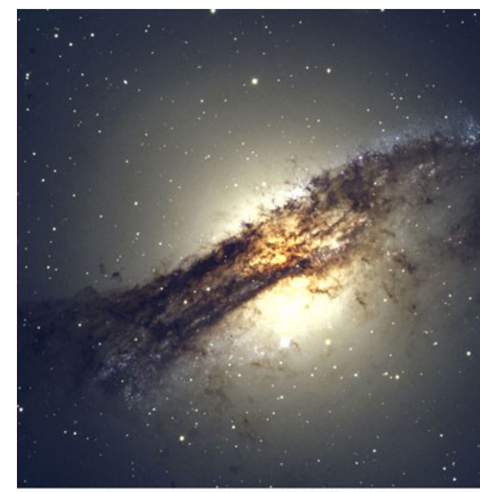
The Crab Nebula in Taurus (VLT KUEYEN + FORS2)



- small energy: **sun !**
- medium energy: **supernovae (?)**
- highest energy: **???**





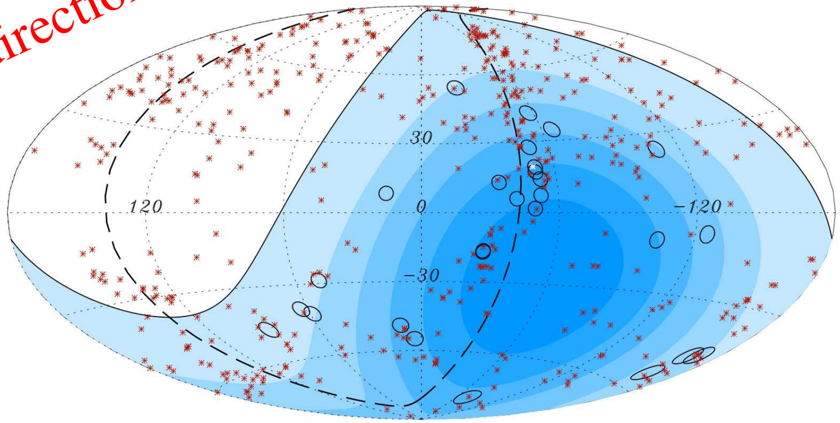


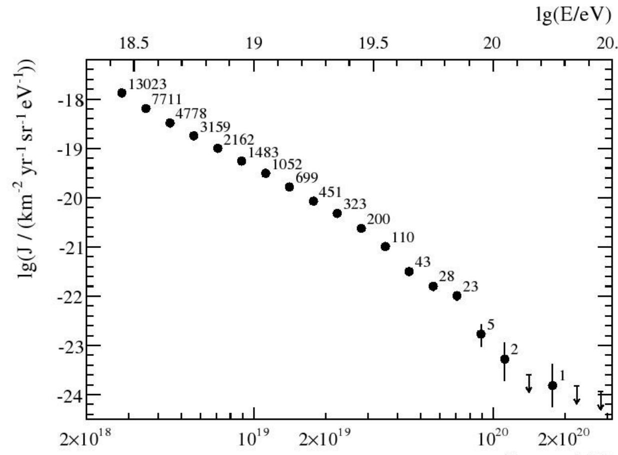
Centaurus A Radio Galaxy (VLT KUEYEN + FORS2)

extreme astrophysics or „new physics“ ?

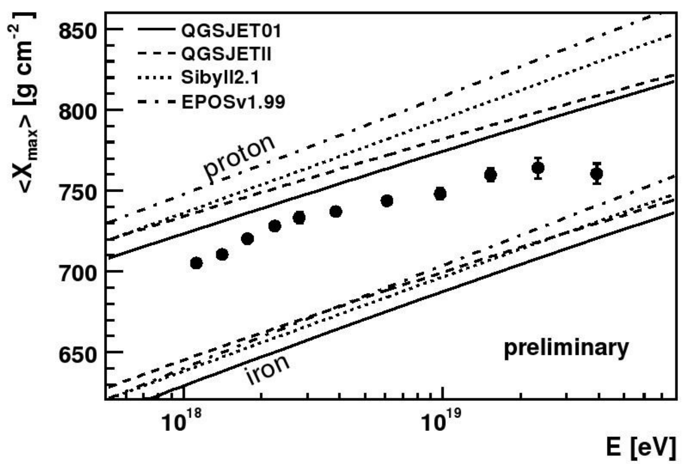
"Auger - News"

direction

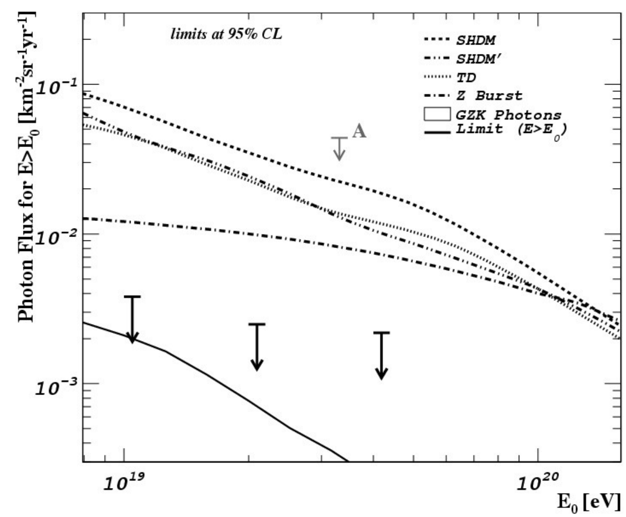




energy



type



Visit of Prussian King Friedrich Wilhelm IV. at the new observatory in Bonn (1845):

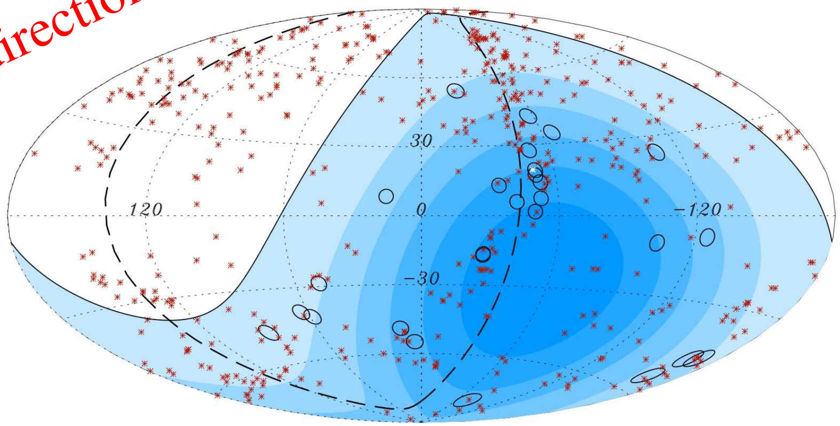
Friedrich Wilhelm IV.: **„Na, Argelander, was gibt es Neues am Himmel?"**

F.W.A. Argelander:

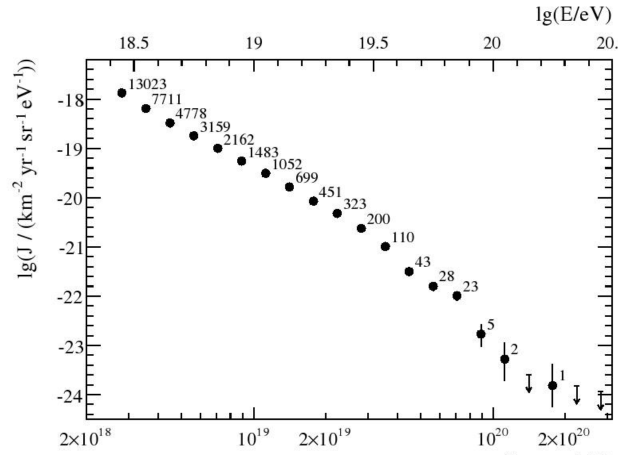
[cf. Mayer-Kuckuk, Kernphysik, 5. Auflage 1992]

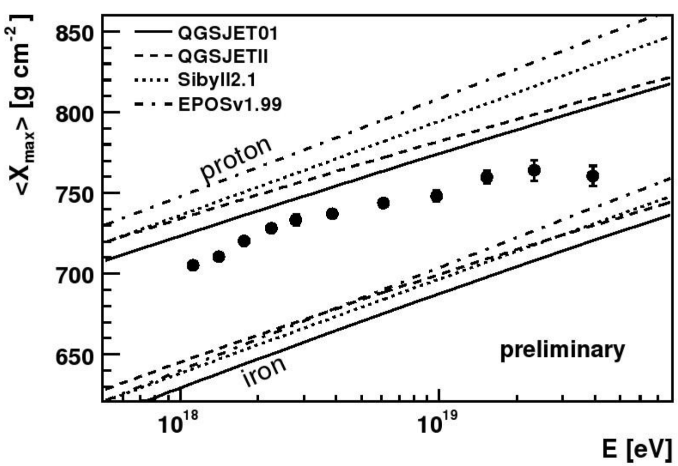
"Auger - News"

direction

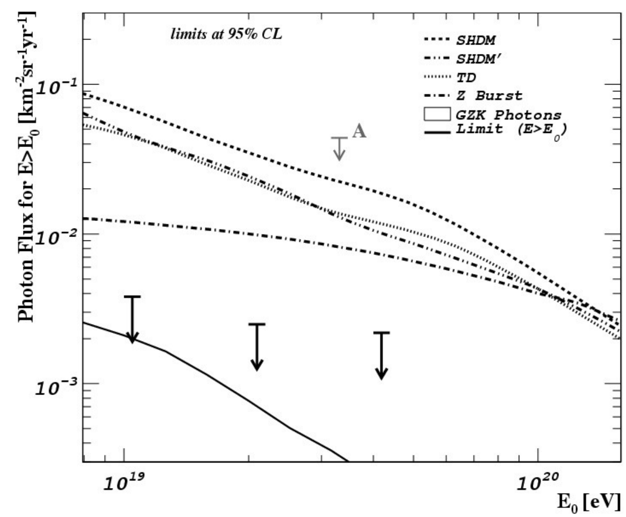


energy





type



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F.W.A. Argelander: **„Eine Menge, aber kennen Majestät schon das Alte?“**

[cf. Mayer-Kuckuk, Kernphysik, 5. Auflage 1992]

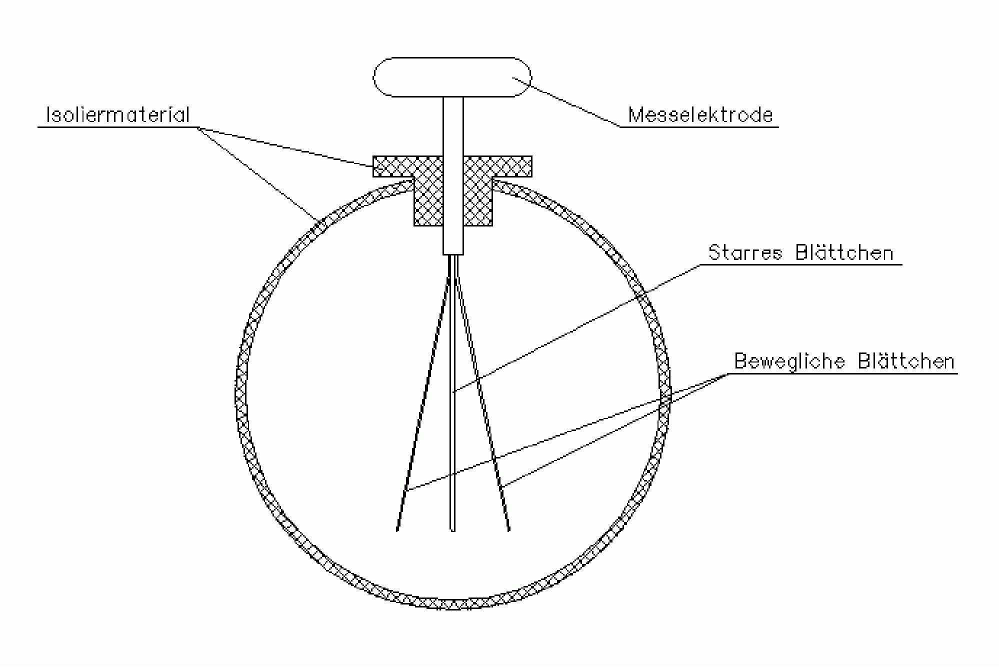
A short history of the cosmic-ray century

Discovery of cosmic rays: electroscopes

1910: Theodor Wulf (SJ):

- constructed the best electroscopes!
- measures ***ionisation of air*** (by discharging)
- observation: electroscopes discharge with time

➔ origin: terrestrial radio activity. ***Or ... ?***



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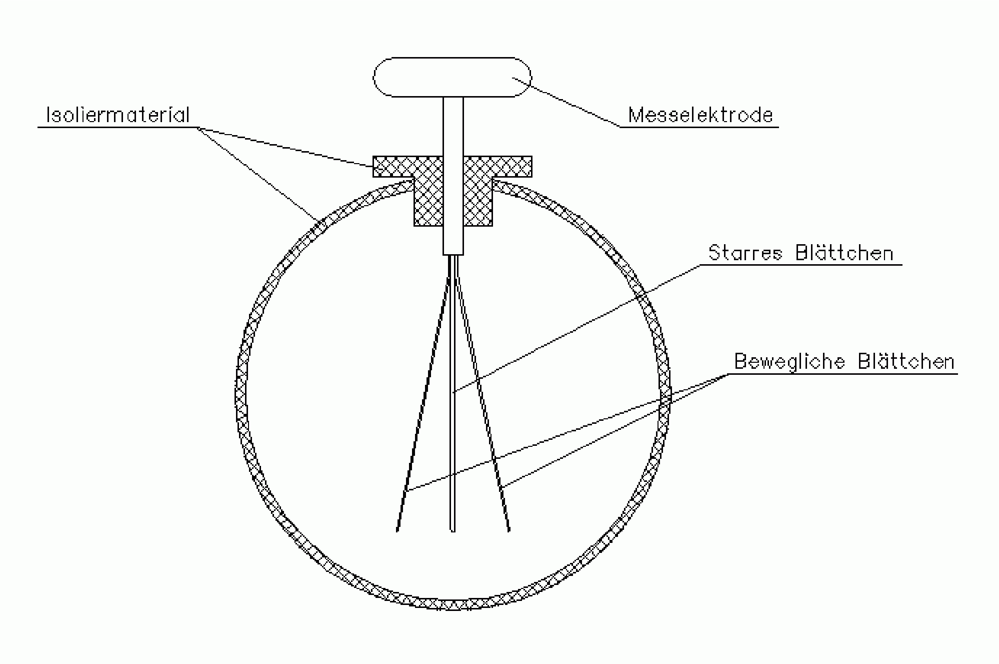


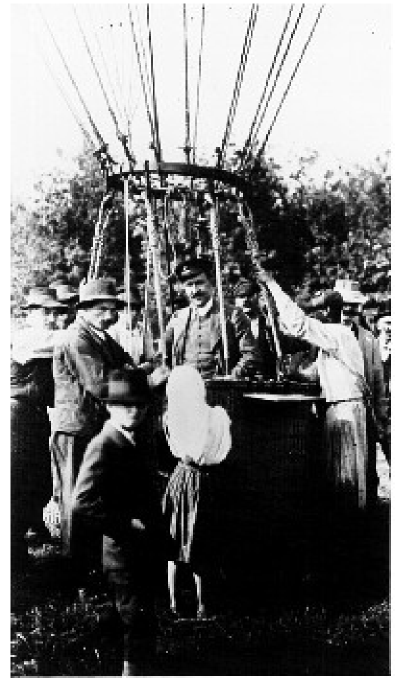
- **Wulf:** ionisation on Eiffel tower (330 m) decreases only to **~64%** (expected: **10%**)

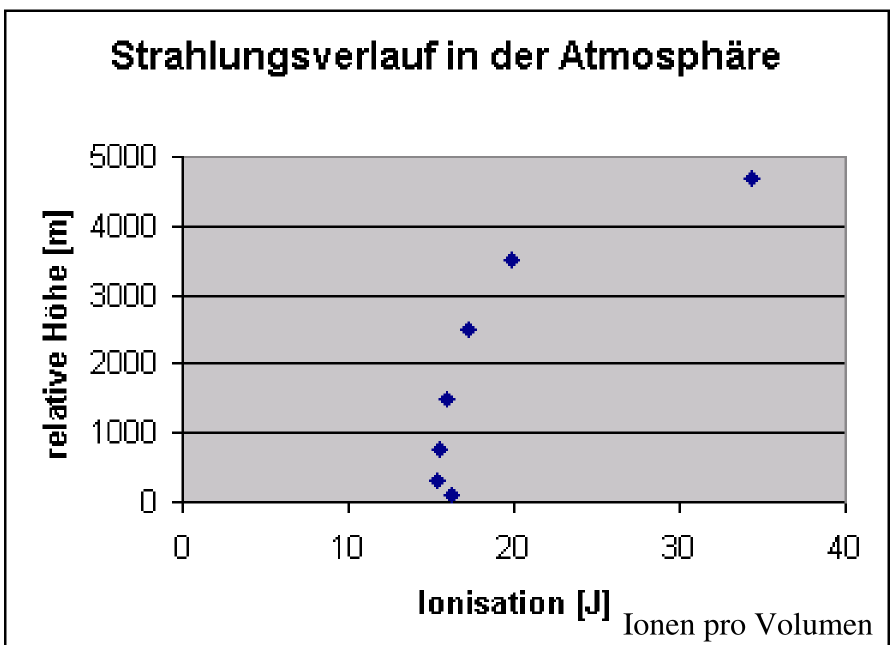
➔ source not Earth, but radiation from sky ?

➔ *need data at much larger altitudes !*

(constructed 1887-1889)

Discovery of cosmic rays: balloons





V. Hess, 7. August 1912:
~200 km, up to 5350 m altitude

→ ionisation increases !
- radiation from above !
- „Höhenstrahlung“ (cosmic rays)

Discovering new particles with the cosmic radiation

start of particle physics !

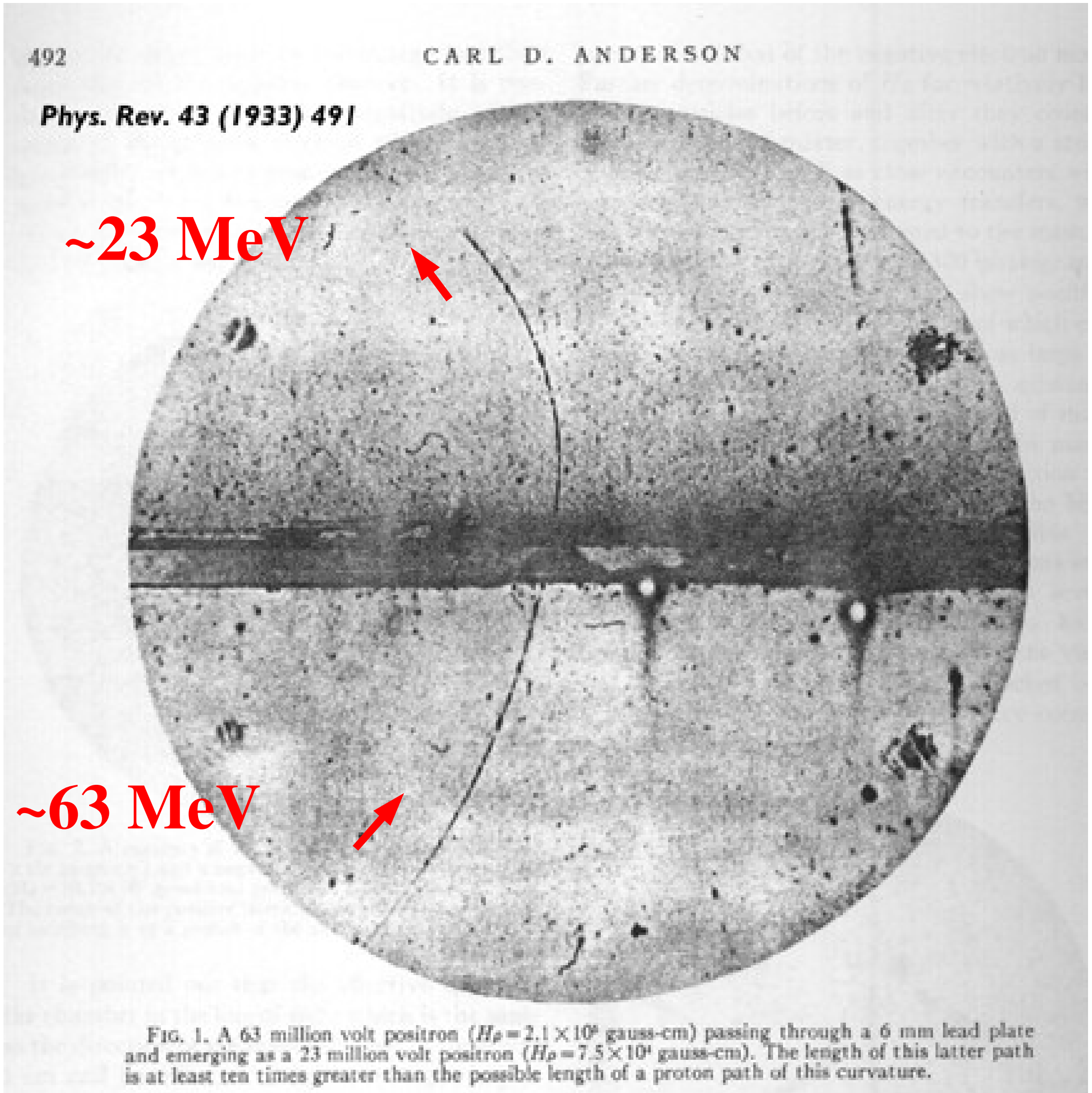
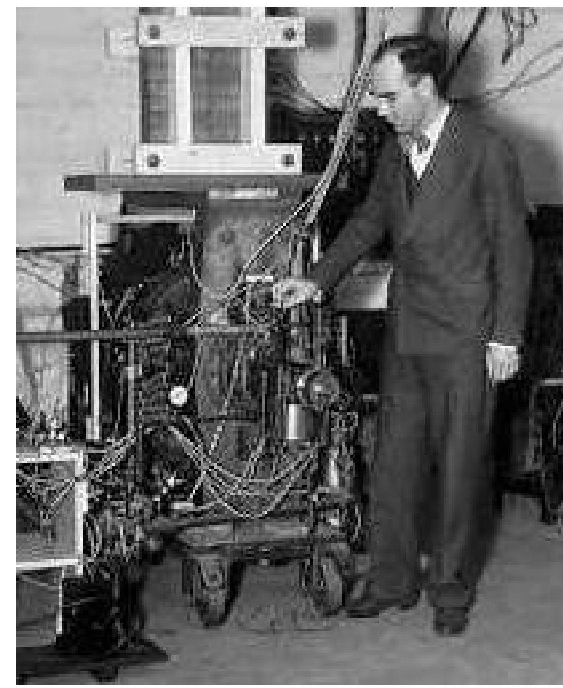


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.



Positron (~1932, C.D. Anderson): cloud chamber, magnet, 6mm lead

- like electron, but opposite charge !

Discovery of air showers

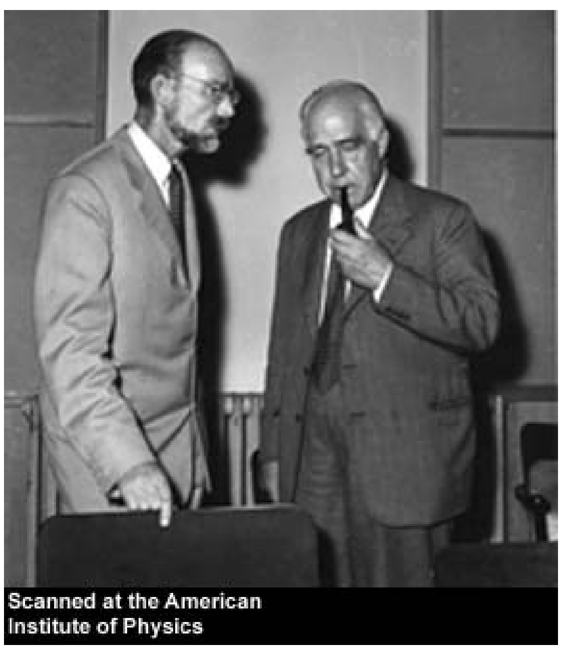
1938: Pierre Auger, coincidence measurements

➔ coincident even for ~300 m distance

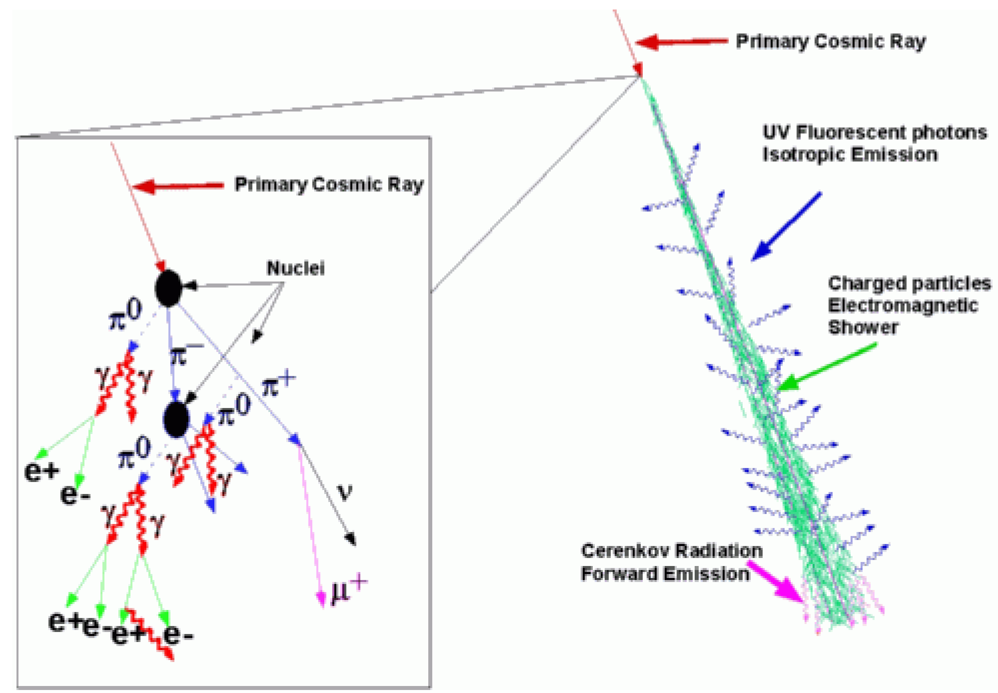
➔ **seconderies** from one high-energy particle!

2 Geiger counters

➔ ~10^6 particles (of ~1 GeV) over 300 m => **~10^{15} eV**



P. Auger, N. Bohr

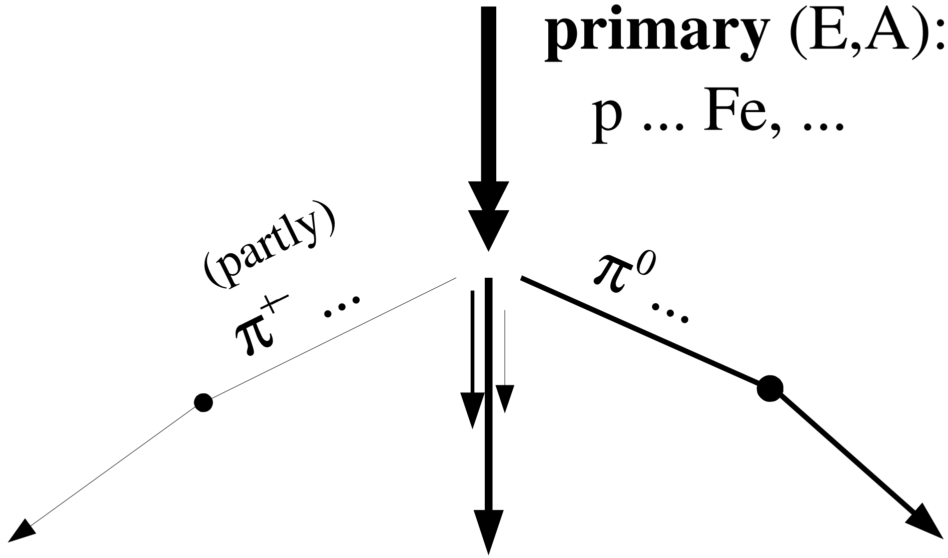


Insert:

Extensive Air Showers (EAS)

Extensive Air Shower, EAS: schematic

primary (E,A):
p ... Fe, ...



muon, **neutrino** | **hadron** | **elmagn**

-> *large* λ | -> *feeding* | -> *cascading*

inelasticity k:
energy fraction
into secondaries

-> ≈**1/3 k** into
elmagn channel
per hadr. interact.

<k> ≈ 0.6 => **20%**

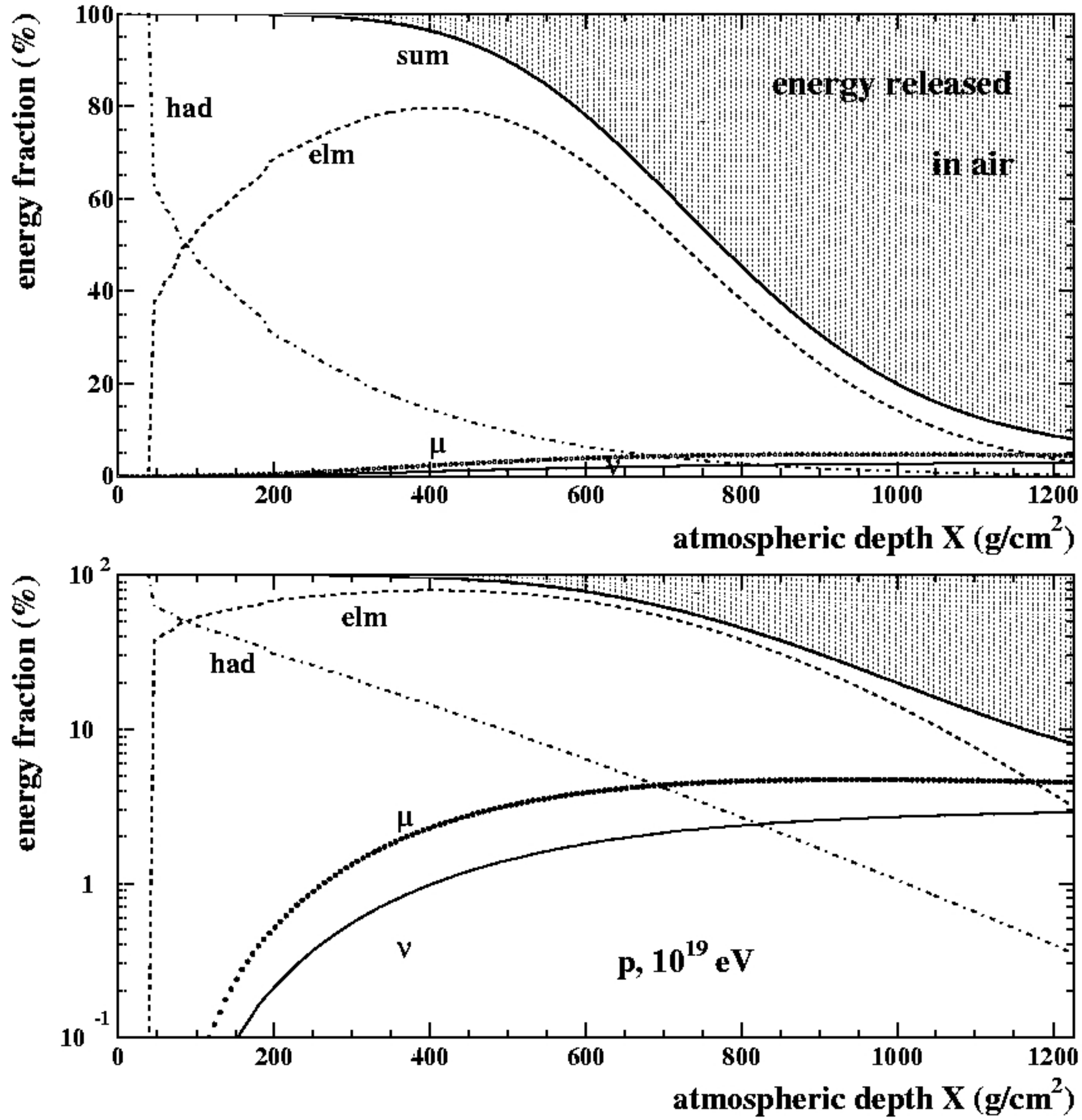
detection: muons - hadrons - elmagn **Č** **fluorescence** **...**

particles on ground *opt --- UV*

Energy flow in EAS: how much energy in which component?

linear

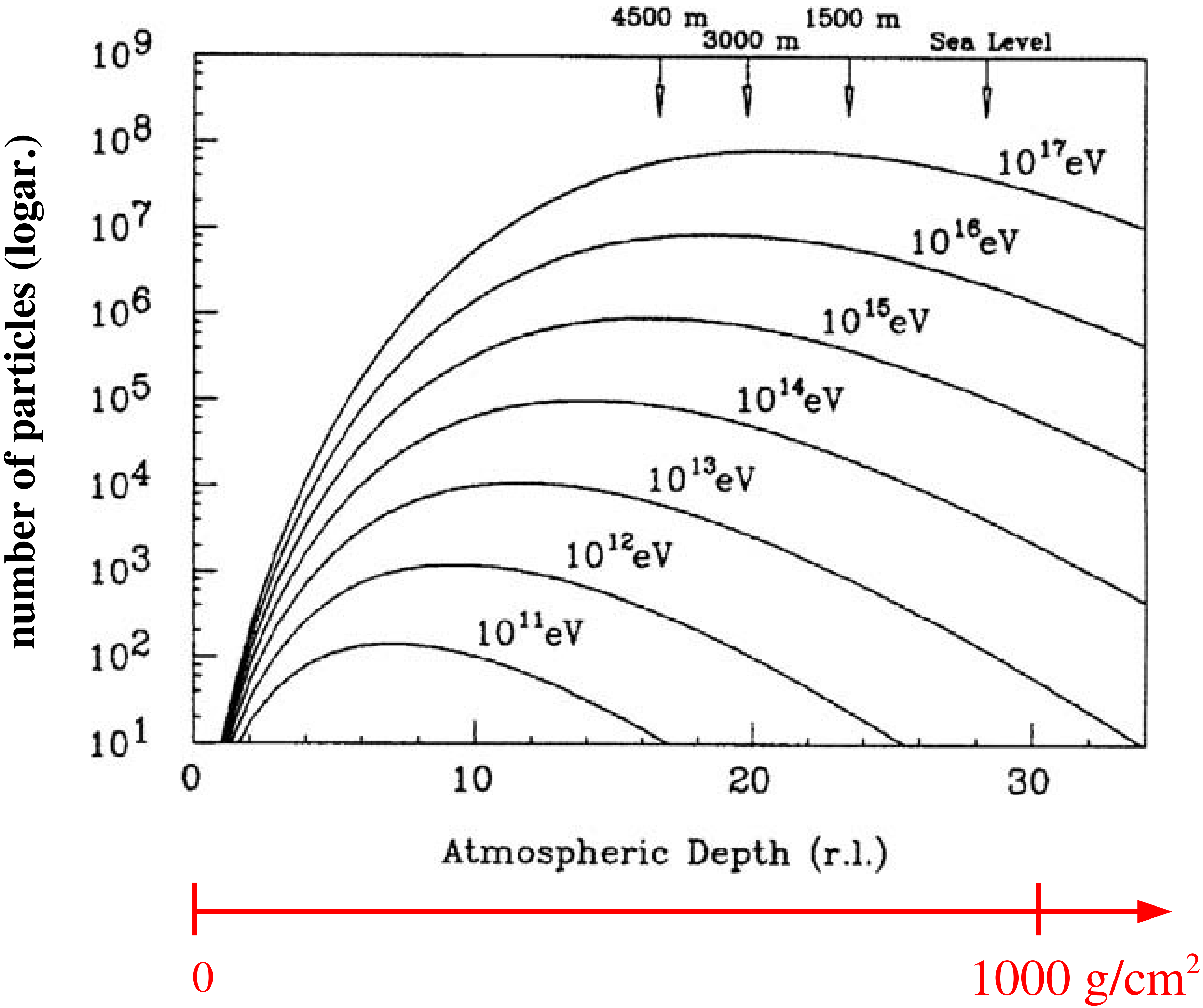
logar.



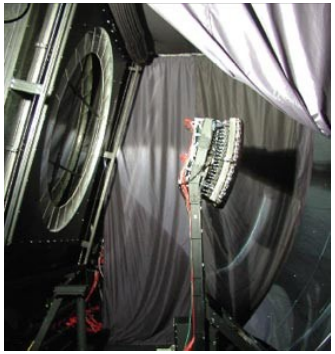
... finally, most energy dumped into air!

Example: proton, 10^{19} eV; CORSIKA simulations

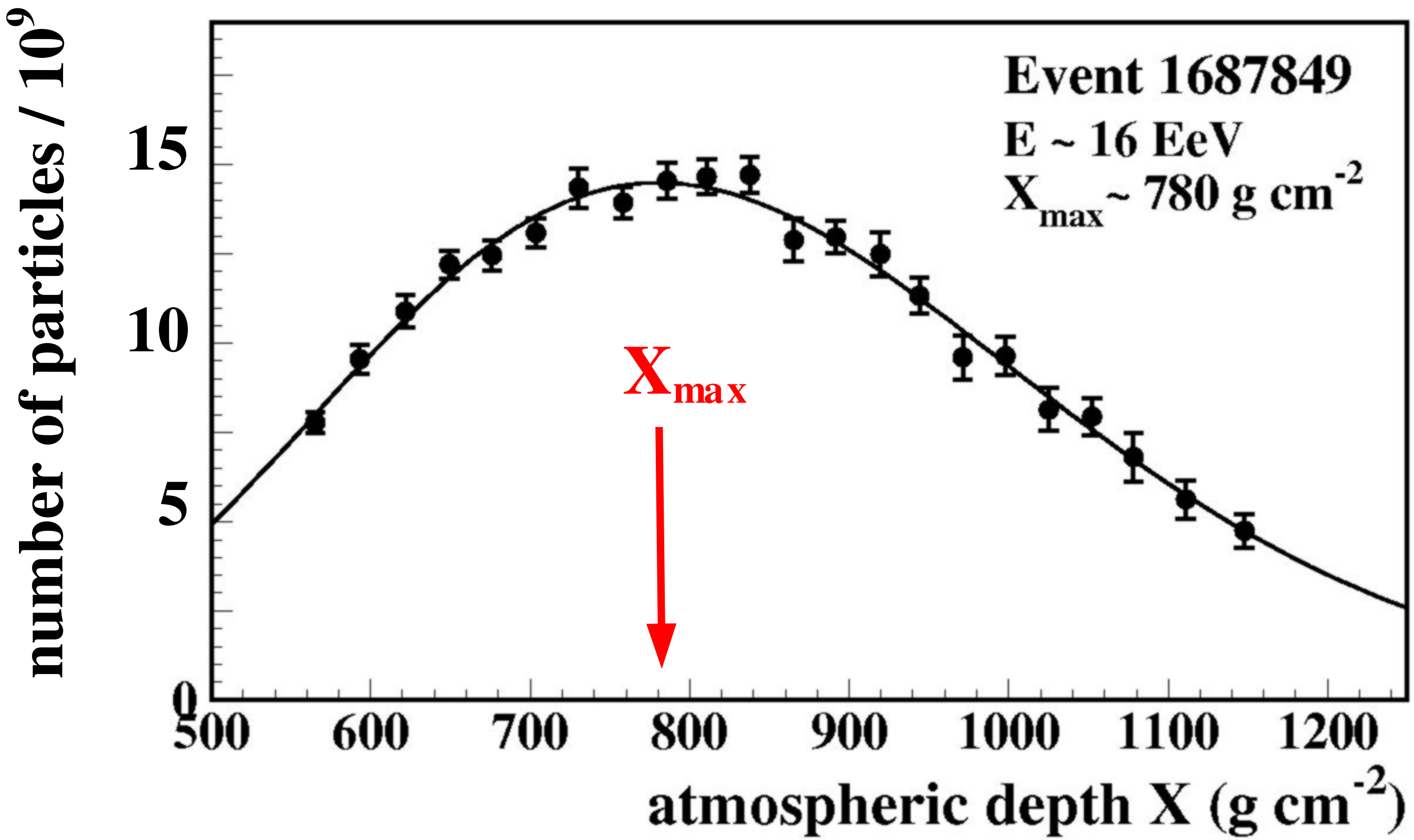
(MR 2004)


4500 m
3000 m
1500 m
Sea Level
number of particles (logar.)
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^{17}eV
10^{16}eV
10^{15}eV
10^{14}eV
10^{13}eV
10^{12}eV
10^{11}eV
0
10
20
30
Atmospheric Depth (r.l.)
0
1000 g/cm^2

Example: longitudinal shower profile

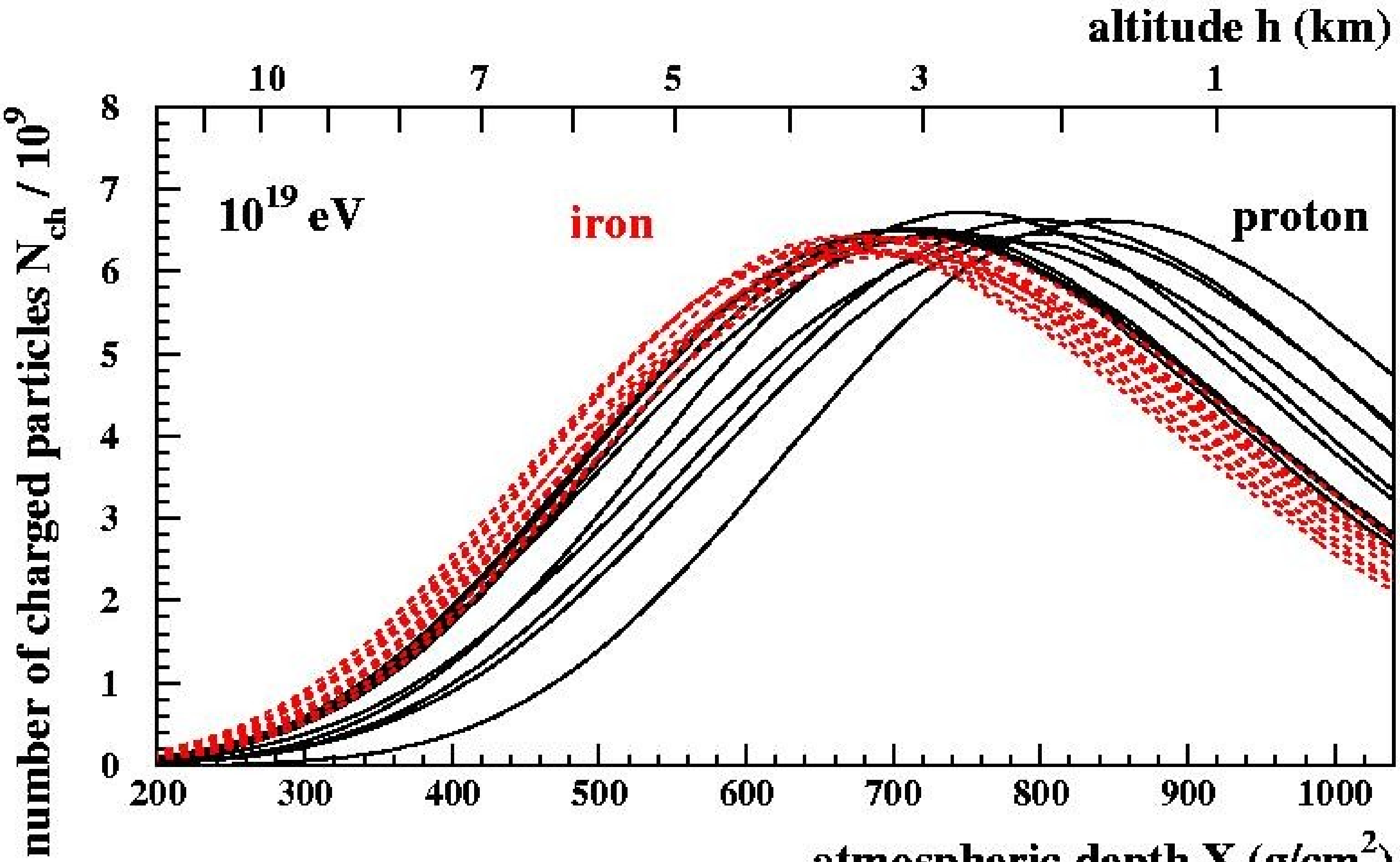


event measured by Auger



- integral => energy (here: $1.6*10^{19}$ eV)
- X_{max} : **type of primary !**

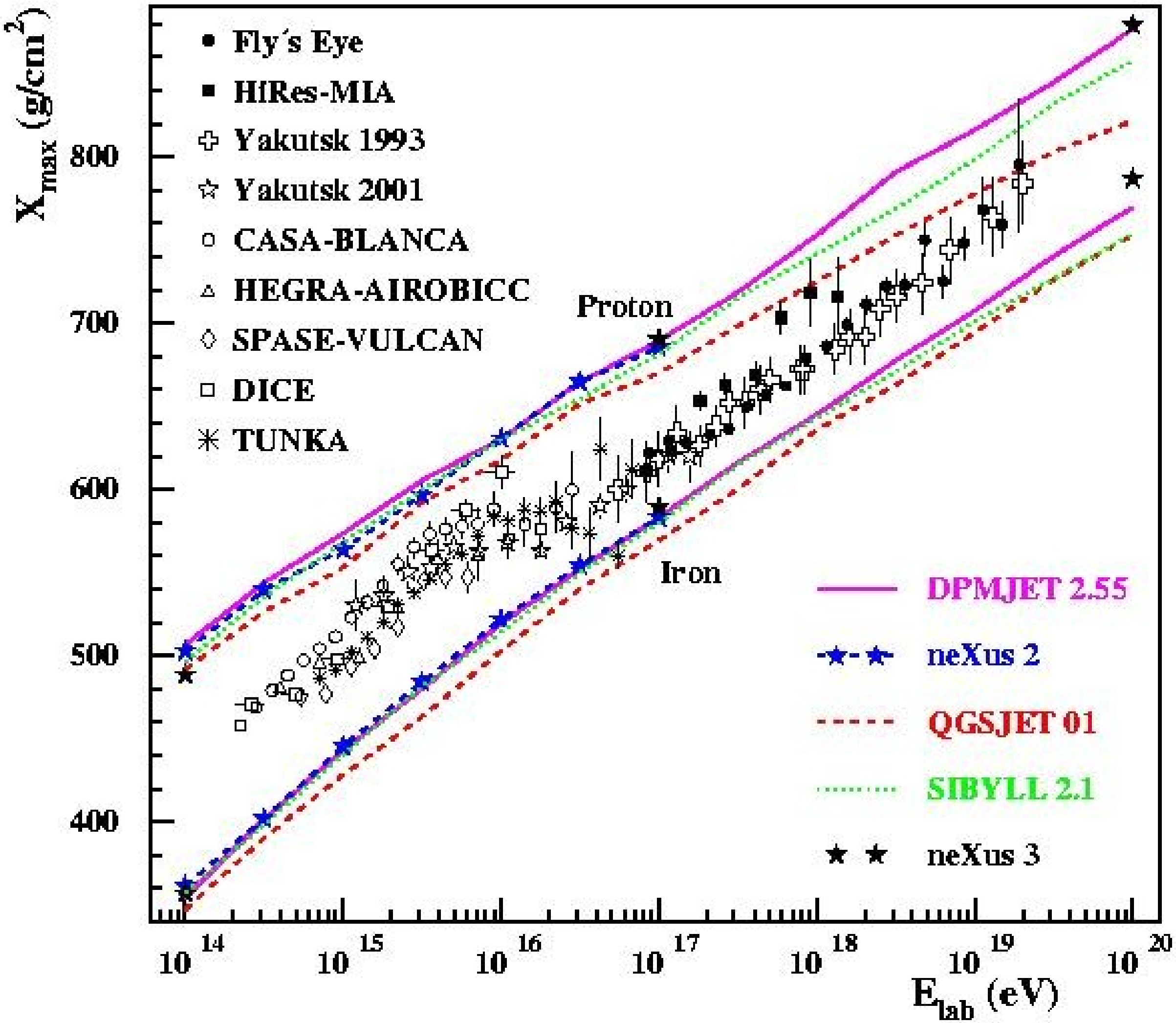
Profiles from different primaries



- **protons deeper !** (X_{max} <-> type of primary)
- **shower fluctuations!** (event-by-event identif. difficult; -> *MC sims*)

Primary mass separation: X_{max}

$< X_{max} >$



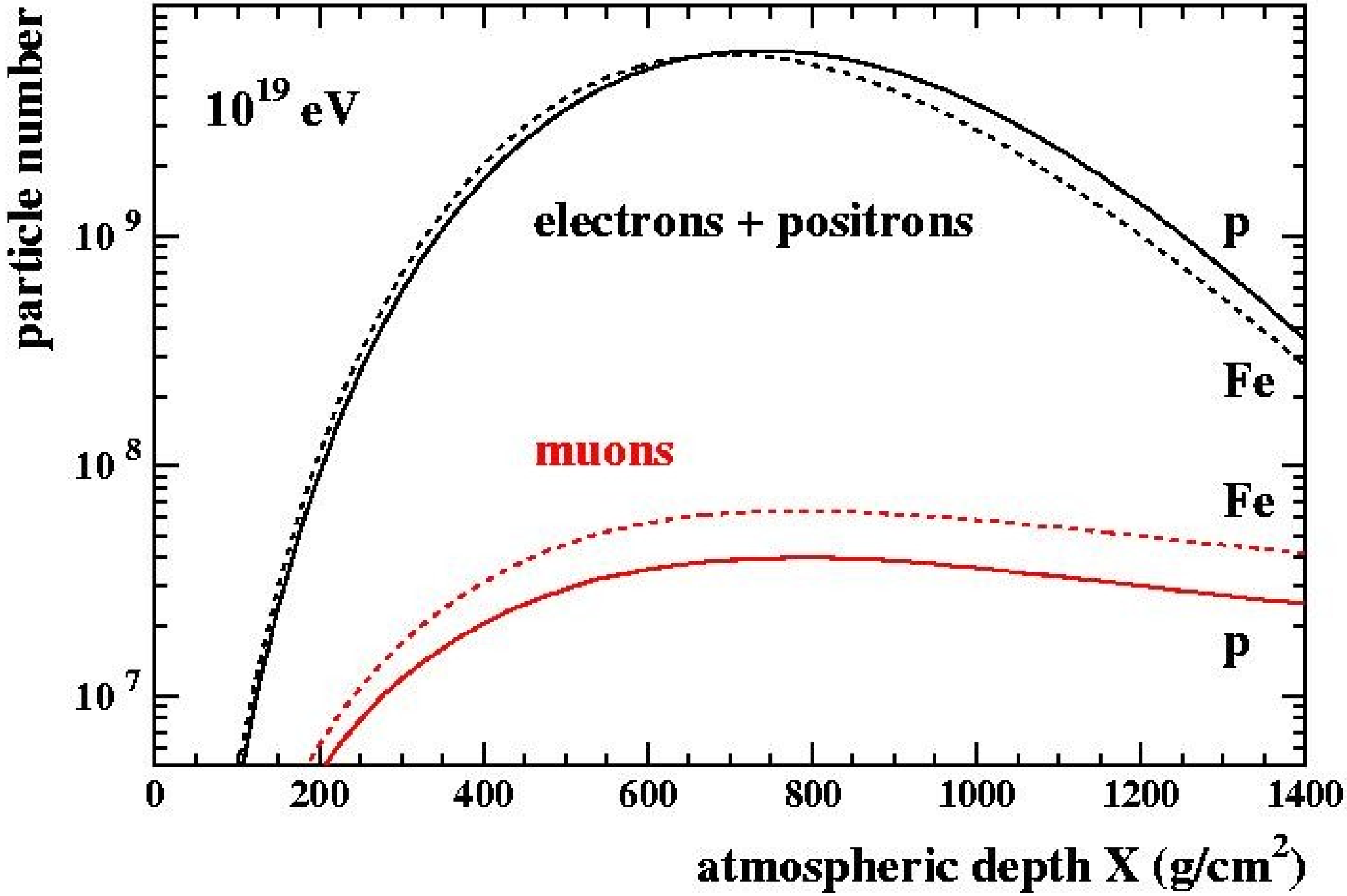
$<X_{max}> \sim \ln(E)$

$X_{max}(Fe) < X_{max}(p)$

- sensitivity on **primary mass**
- *note: comparison to* ***model predictions ...***

Shower muons

(logarithmic scale !)



note different development of N_e and N_μ

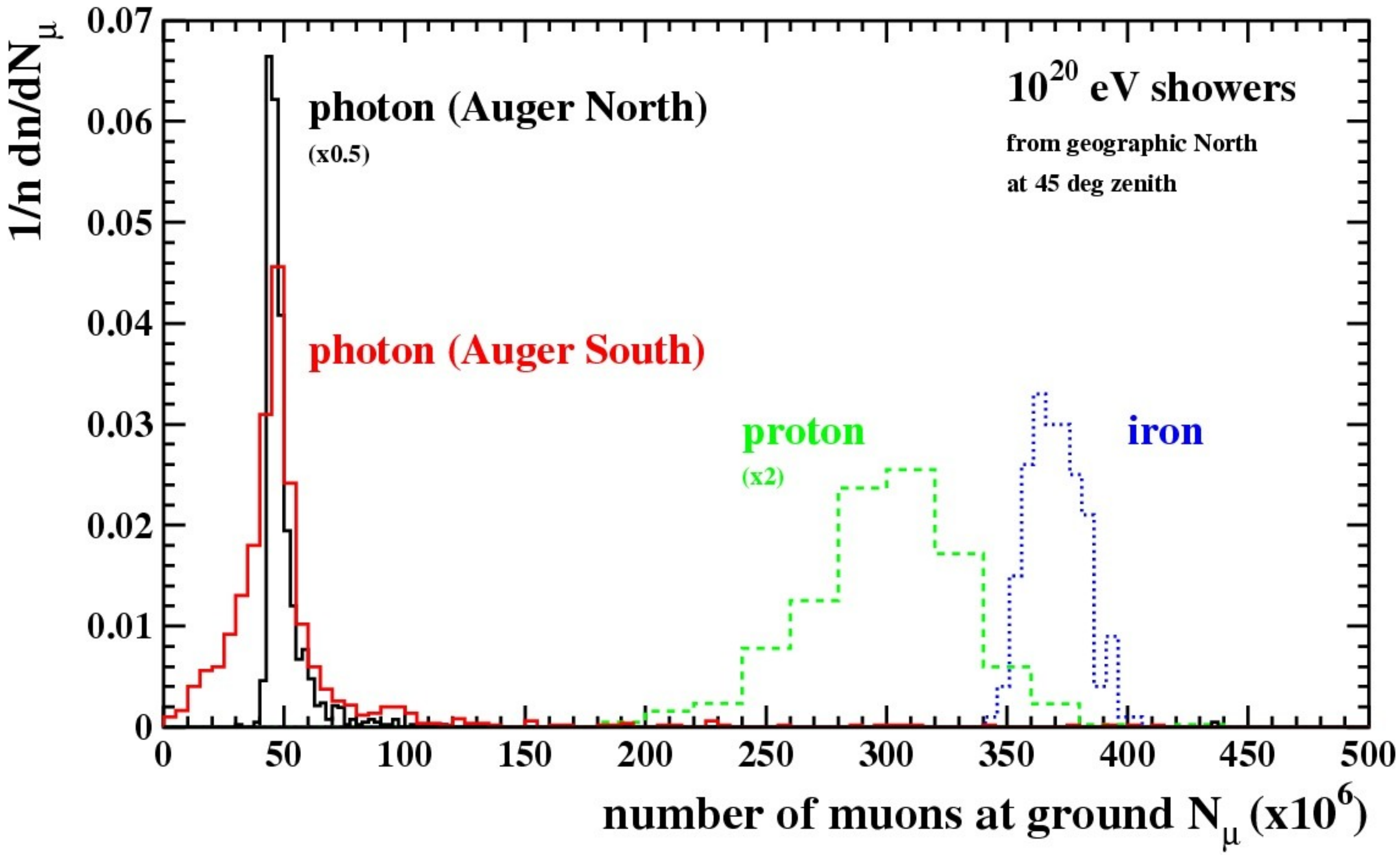
- **Fe: more muons** (total number) *-> primary mass sensitivity*

✓ smaller E_0/A -> π^{+-} less energetic

✓ higher altitude -> smaller ρ

} decay favoured

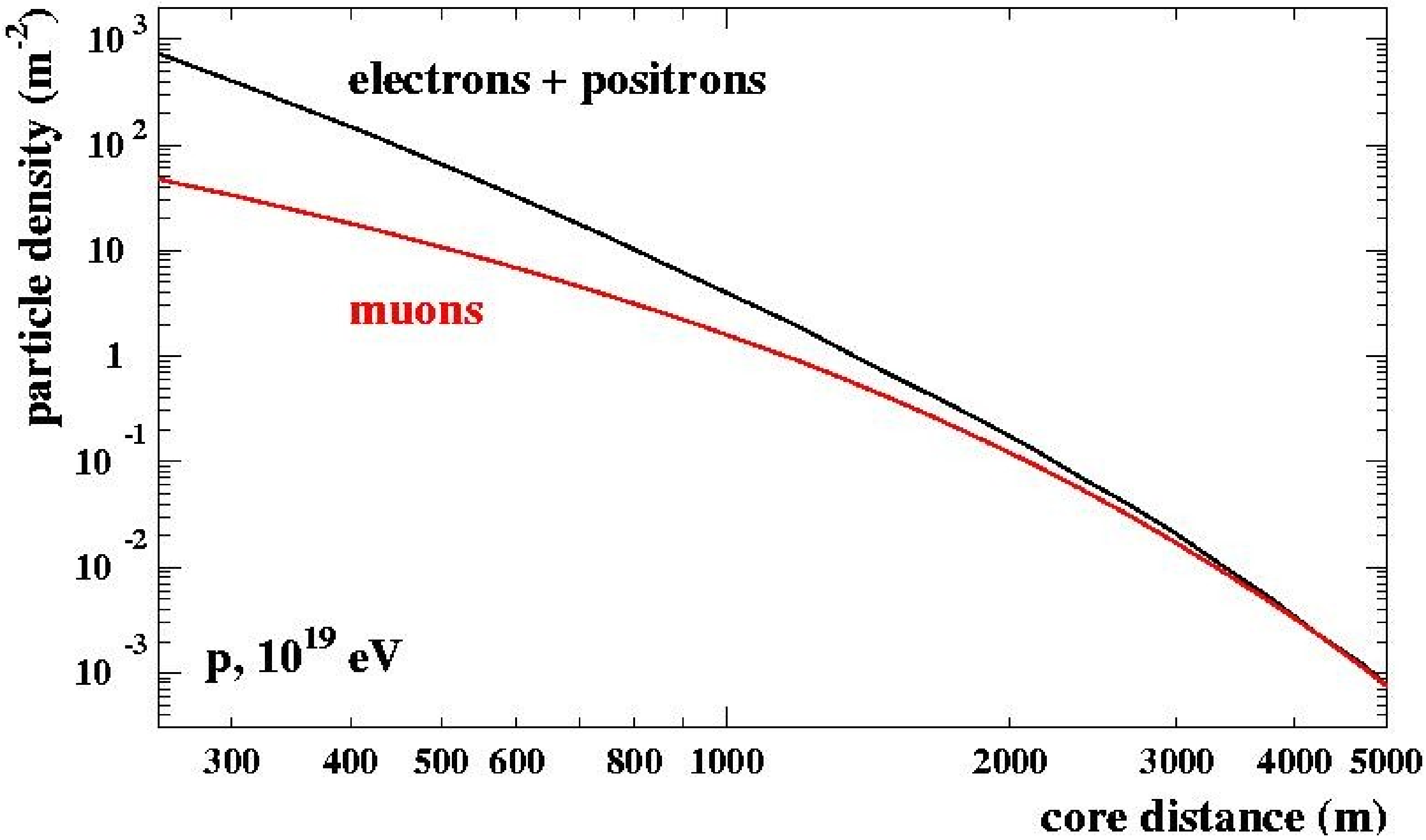
Shower muons at ground



simulations:
same energy and direction,
different primaries

iron > proton (>> photon)

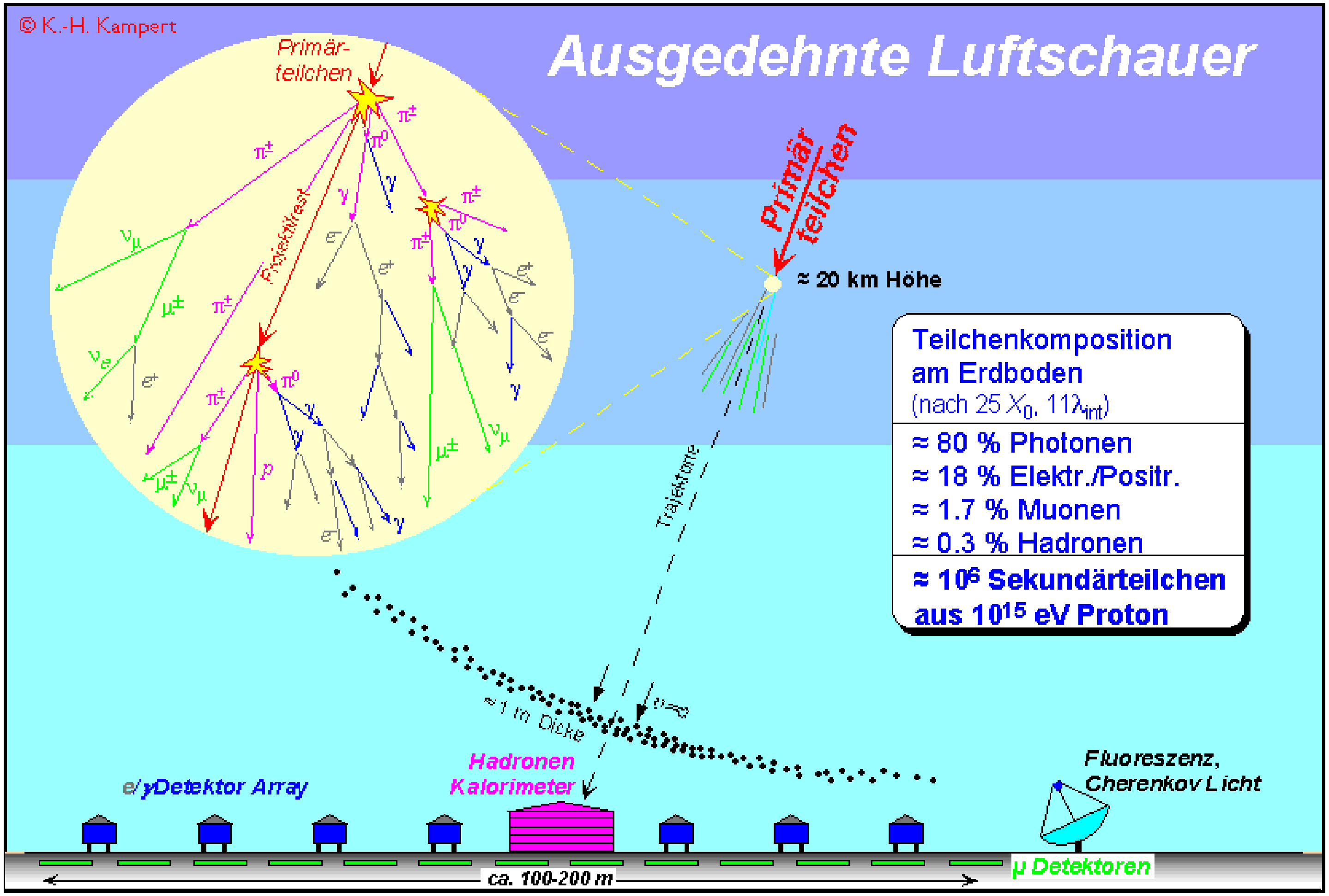
Lateral distribution of particles on ground



- ➔ different characteristics of shower components:

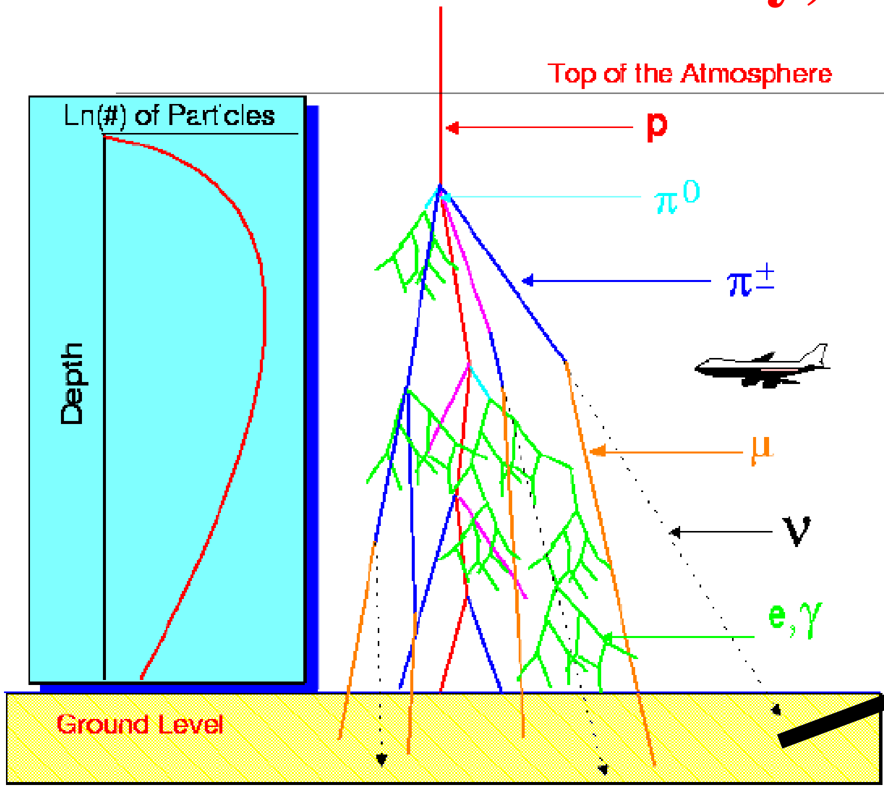
muon lat. dist. flatter (from larger altitudes)

Indirect measurement of cosmic rays with air shower experiments



(traditionally) **2 techniques: (1) ground detectors, (2) telescopes**

1961: Linsley, towards highest energies



Extensive Air Showers

measured by ground array

Linsley, Scarsi, Rossi, PRL 1961:

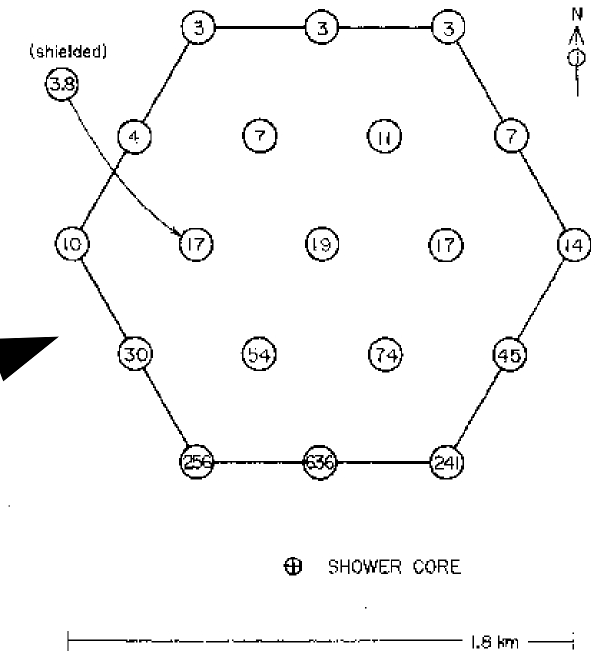


FIG. 1. Diagram of the Volcano Ranch 2-km^2 array, showing the location of the shower axis and measured densities in particles/m^2 for this event, No. 39 565. The shielded detector was located very near the indicated main detector.

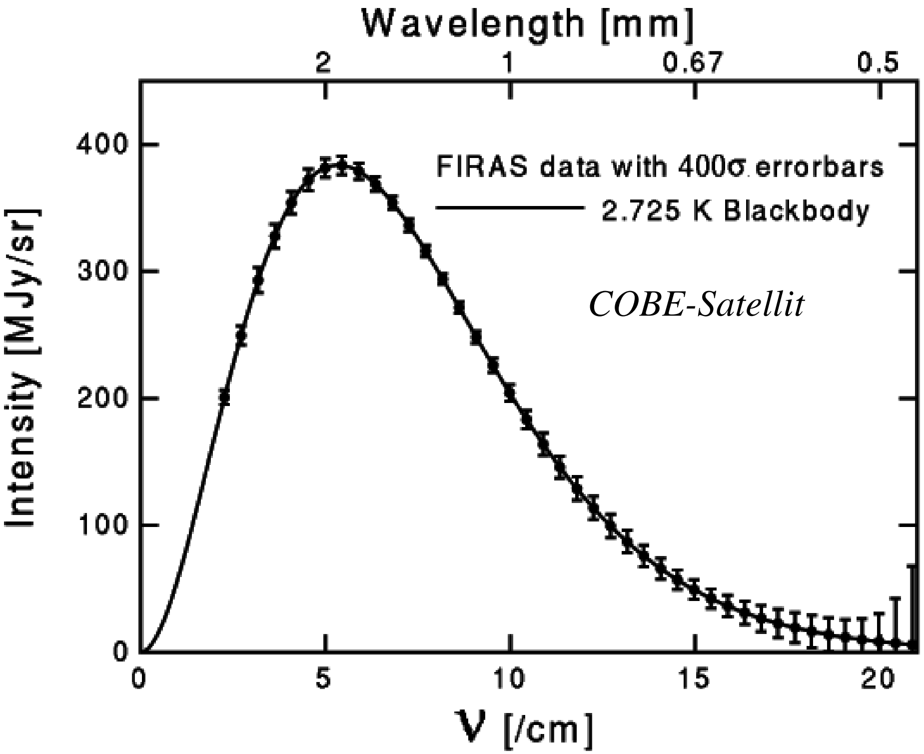
Linsley (checking for rattlesnakes)

- 19 scintillation counter (~3 m^2) on ~2 km²
- **N > 5x10^9 => E > 10^{19} eV**

➔ extragalactic origin likely !

1965: CMB

Wilson Penzias



COBE-Satellit

➔ *the universe is filled with photons ...*

Insert:

GZK effect, particle propagation

GZK effect (or GZK suppression)

- **G**reisen; **Z**atsepin, **K**uzmin, 1966:
  protons >6*10^{19} eV interact with CMB

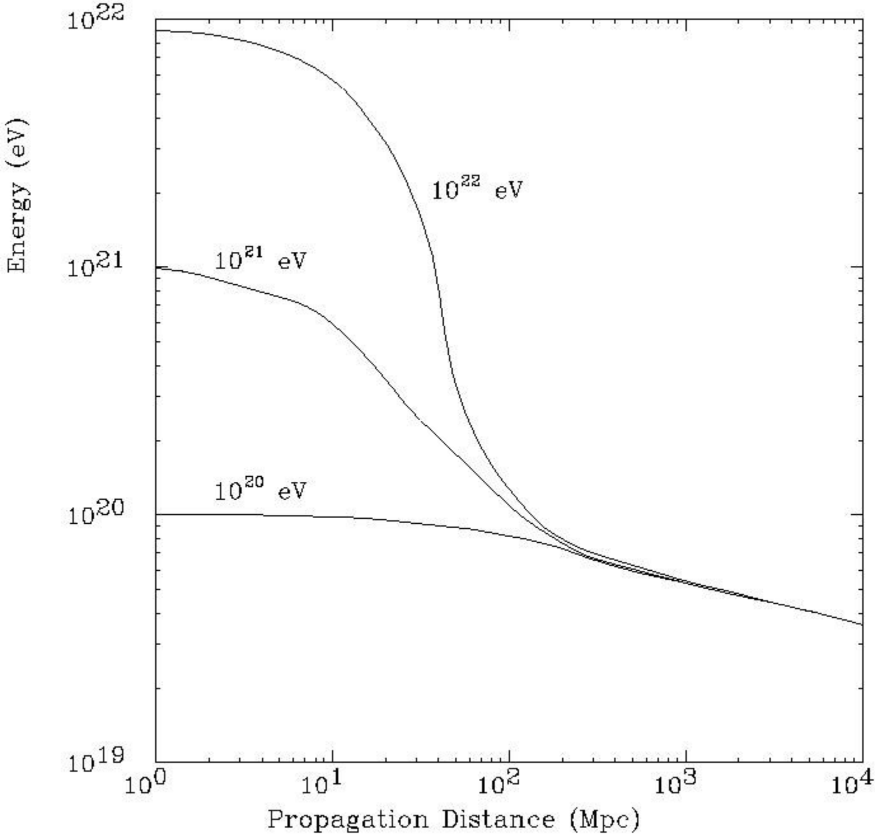
$$p\,\gamma_{2.7} \rightarrow \Delta^{+} \rightarrow p\,\pi^{0}$$

$$\rightarrow n\,\pi^{+}$$

- *energy loss length ~20 Mpc*
- *flux suppression for distant sources!*

→ known from lab data + *Lorentz invariance*

→ *GZK photons & neutrinos* from pion decay

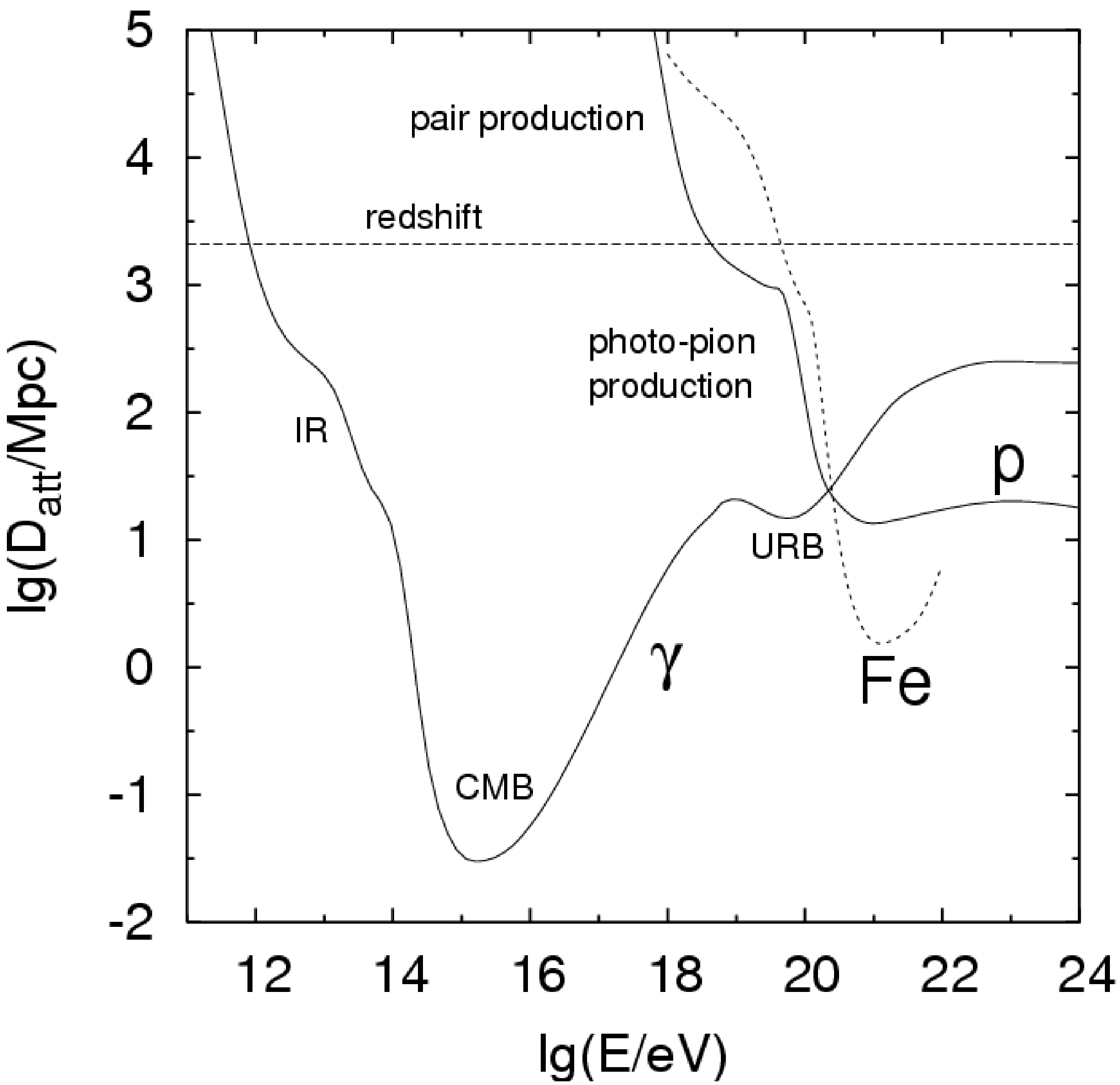


(Cronin)

=> is there a GZK suppression in the spectrum at ~6*10^{19} eV ?

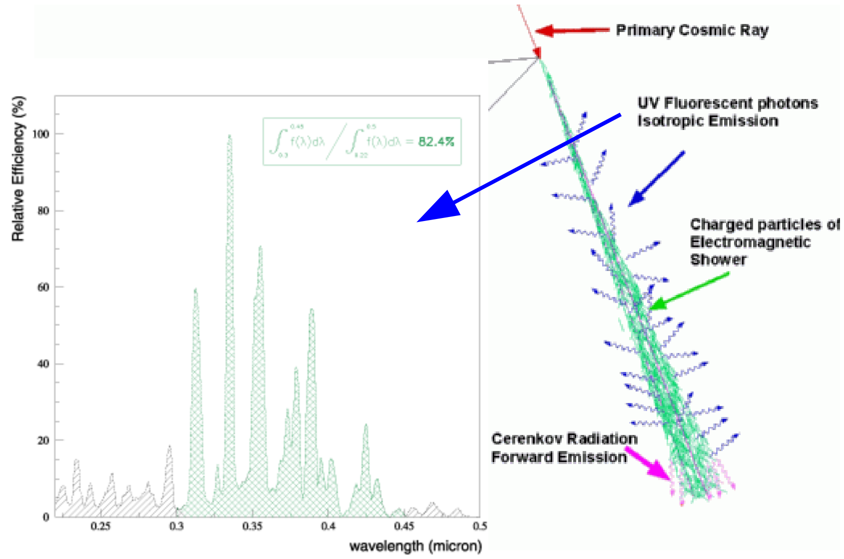
Extragalactic propagation: energy loss lengths

energy
loss
length



uncertainties exist for the Radio Background URB and for IR

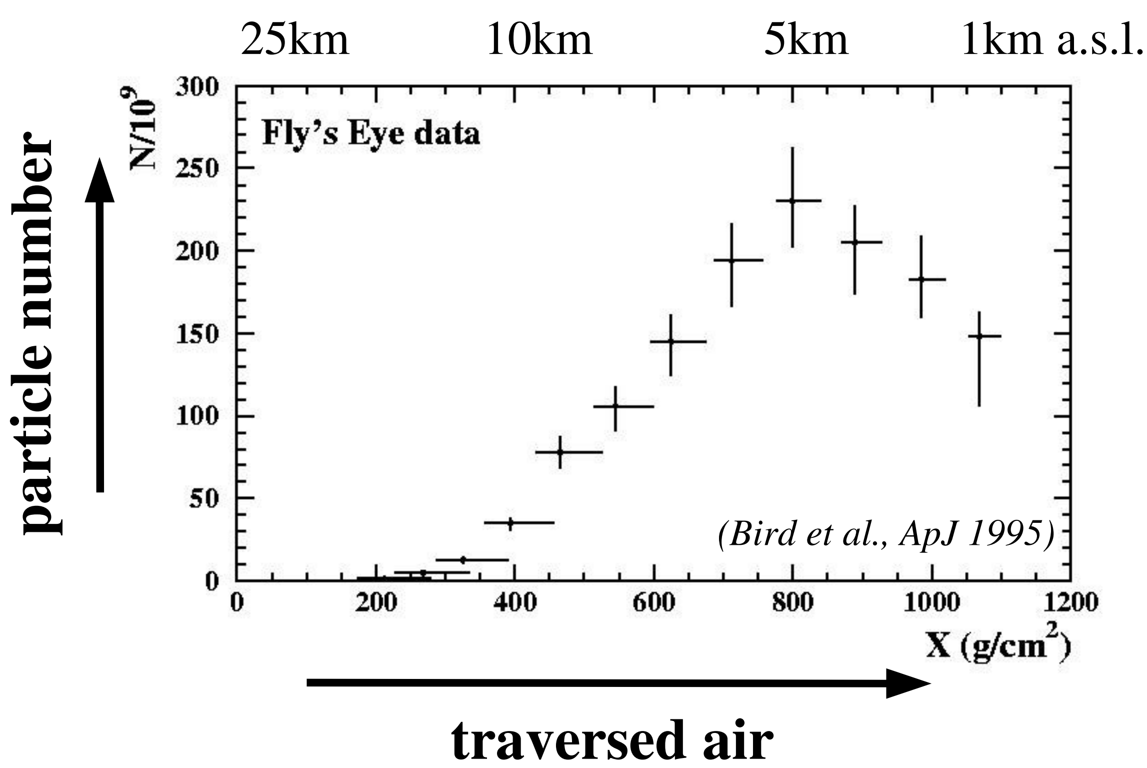
15 Oct 1991: Fly's Eye event

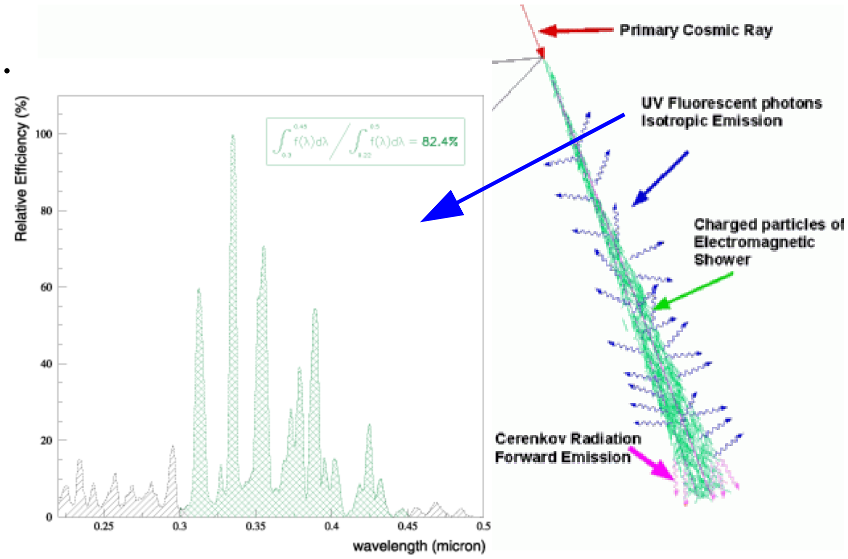


– UV fluorescence light ~ N_{ch}
– observation of shower profile (in clear nights)

Fly's Eye, Utah (successor: HiRes)

15 Oct 1991: Fly's Eye event





- UV fluorescence light ~ N_{ch}
- observation of shower profile (in clear nights)

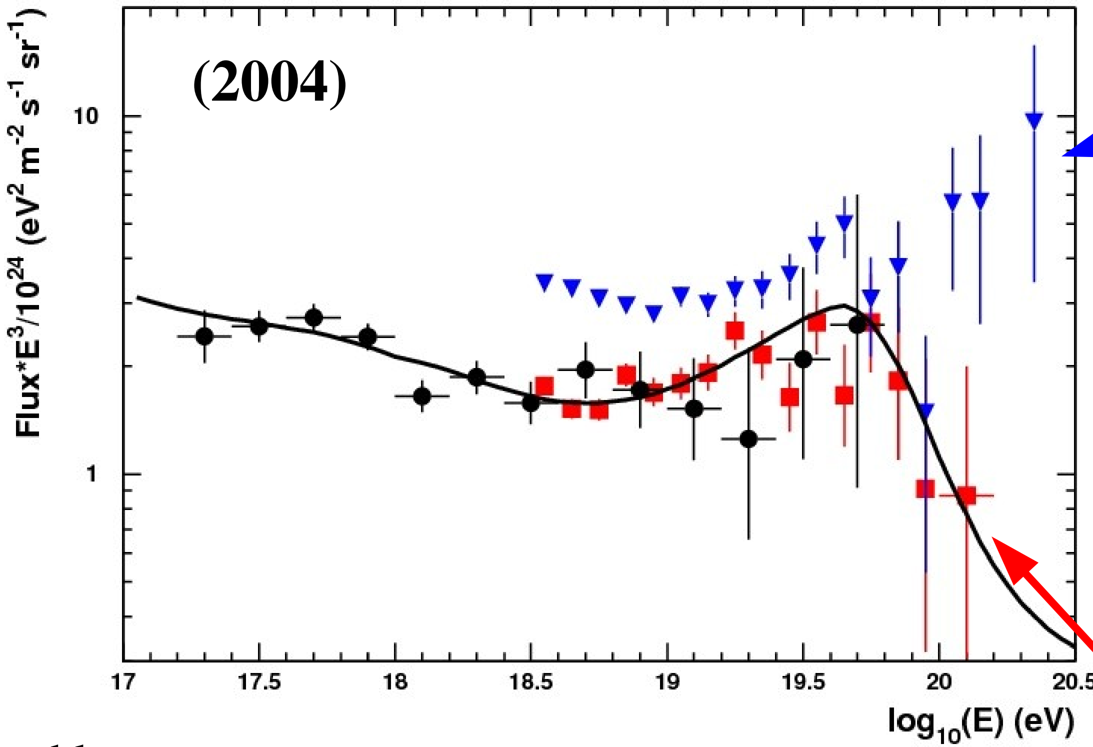
- >200 billion particles at maximum !!
- integration => $E \sim (3.2 \pm 0.9)\ 10^{20}$ eV
- $X_{max} \sim 815 \pm 60$ g cm^{-2} => type? *anything ...*

→ **there are „super-GZK“ events!**

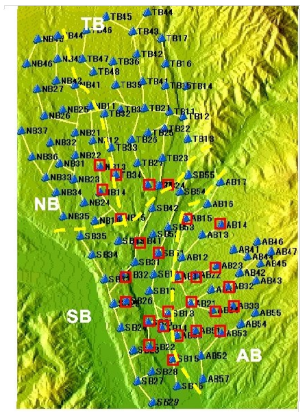
Fly's Eye, Utah (successor: HiRes)

2004: suppression at highest energies ?

flux scaled by E^3 !



No !
(AGASA, 100 km^2)

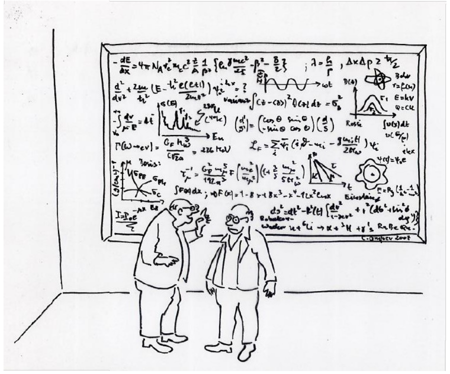


Akeno Observatory
35.7°N 138.5°E 900m asl. 920g/cm²

Yes !
(HiRes)

- problems:
  - **statistics** (~17 events >100 EeV)
  - **systematics** (array vs telescopes)
- **experimental status 2004: unclear**
  - incl. type and possible directional correlations

→ *needed: **"big & both"** => Auger Observatory*

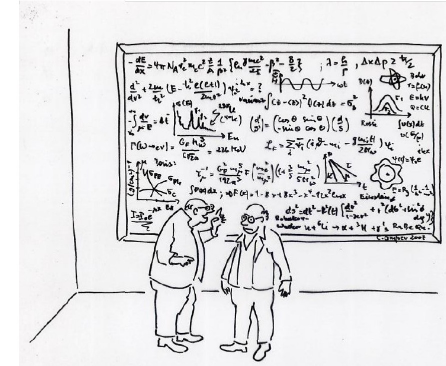


Theoretical status (2004)

- **bottom-up models (astrophysics):**
  - active galactic nuclei, gamma-ray bursts, jets in radio galaxies, pulsars, ...
  - ➔ *not easy to accelerate particles to $>10^{20}$ eV*
  - ➔ *arrival directions ~isotropic, no obvious correlations*

- **top-down models (particle physics):**
  - super-heavy dark matter, topological defects; monopoles, strings, necklaces, WIMPZILLAS, cryptons ...
  - ➔ *hypothetical massive objects produce normal particles*

Theoretical status (2004)



- **bottom-up models (astrophysics):**
  - active galactic nuclei, gamma-ray bursts, jets in radio galaxies, pulsars, ...
  - ➔ *not easy to accelerate particles to $>10^{20}$ eV*
  - ➔ *arrival directions ~isotropic, no obvious correlations*

photon fractions < ~1 %

smoking gun !

- **top-down models (particle physics):**
  - super-heavy dark matter, topological defects; monopoles, strings, necklaces, WIMPZILLAS, cryptons ...
  - ➔ *hypothetical massive objects produce normal particles*

photon fractions > ~10 %

To Do:

Flux suppression at highest energies ??

Large photon fluxes ? (More general:) **Particle type ?**

Directional correlation (anisotropy) ?

.....

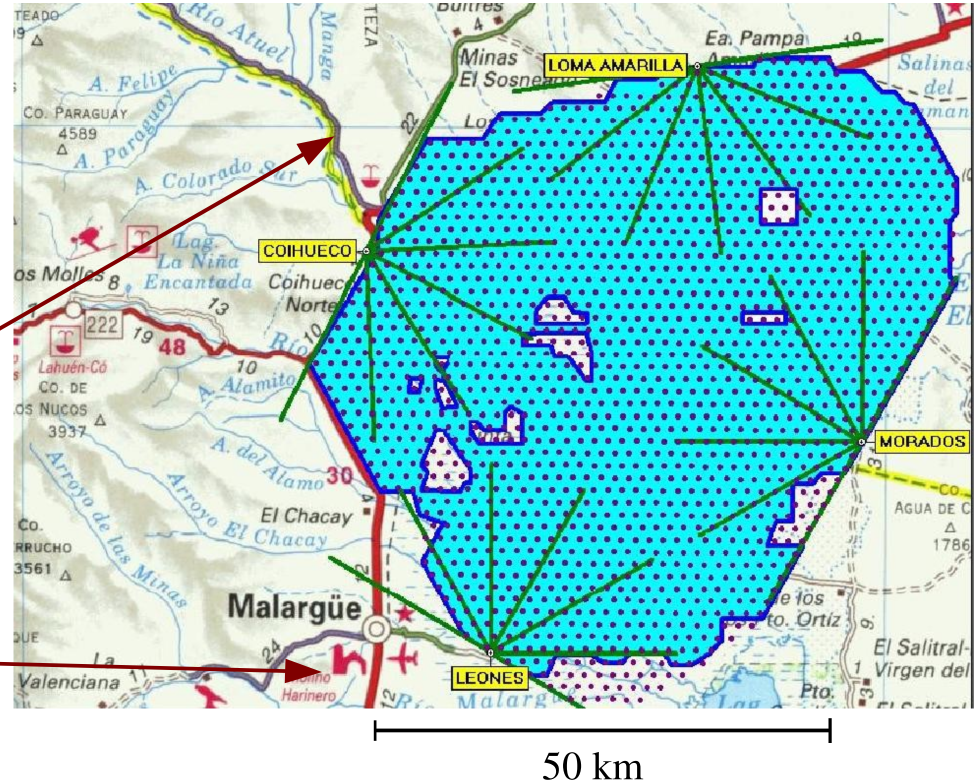
The Pierre Auger Observatory

Pierre Auger Collaboration

>400 scientists from 17 countries

strong German participation !

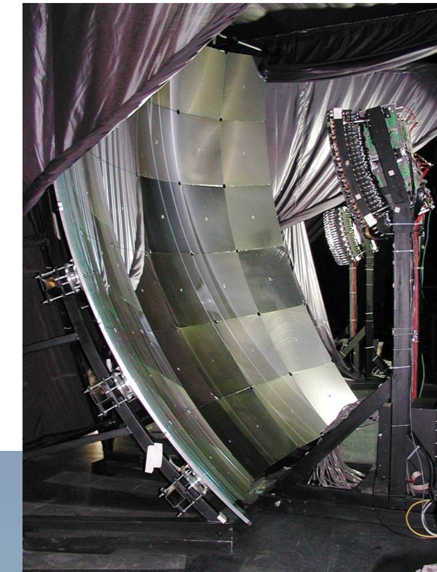
Pierre Auger Observatory (South)

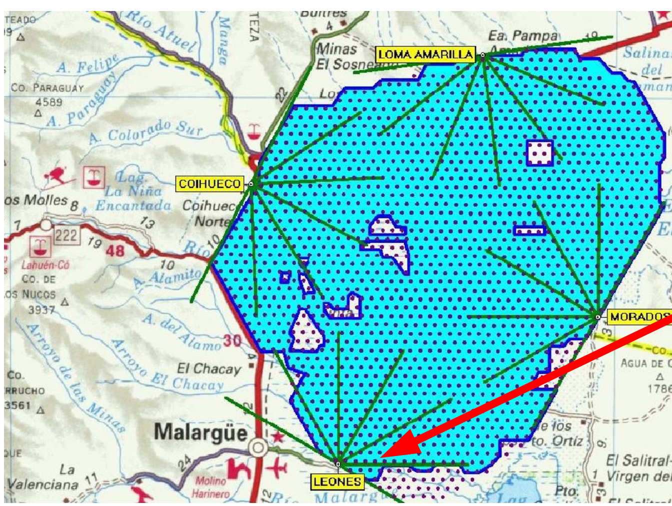


Pampa Amarilla *(Malargüe, province of Mendoza)*

- 1600 **water detectors** (1.5 km distance each) => **3000 km^2** (predecessor: 100 km^2)
- 4 stations with 6 (fluorescence) **telescopes**
- **data since 2004**, inauguration November 2008

Auger: *impressions ...*





preparing ...

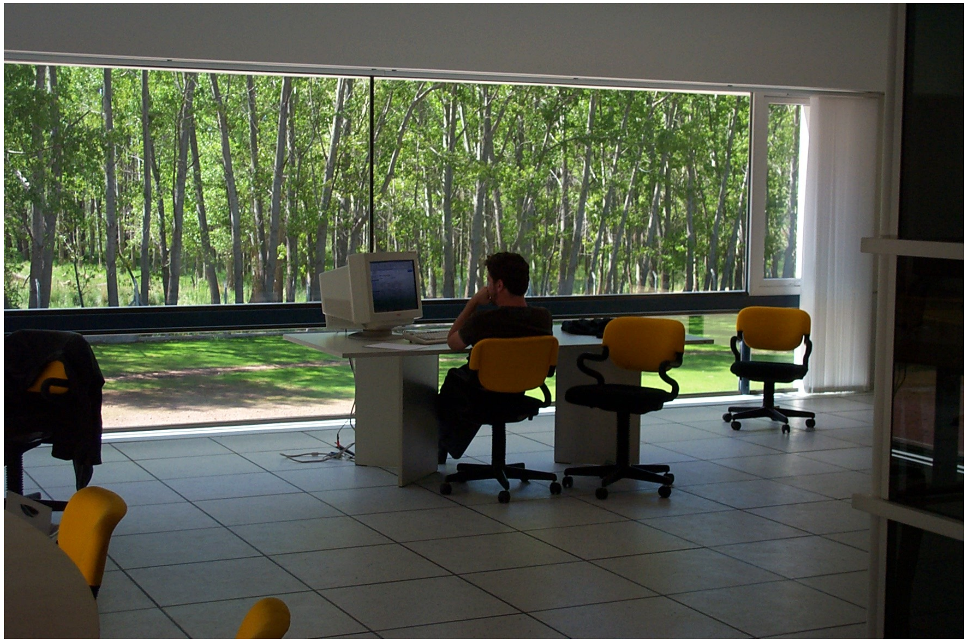
... out to the Pampa ...

Water !

Water ?!

Water tank 1600 – June 2008

critical detector check



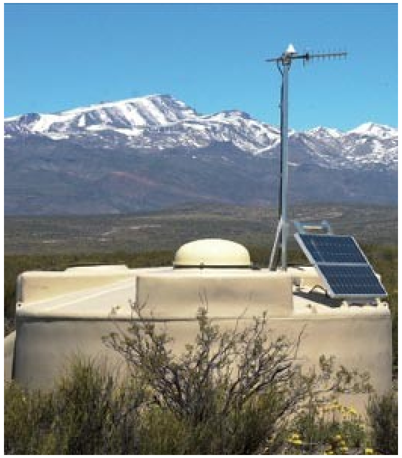
Data transfer and analysis

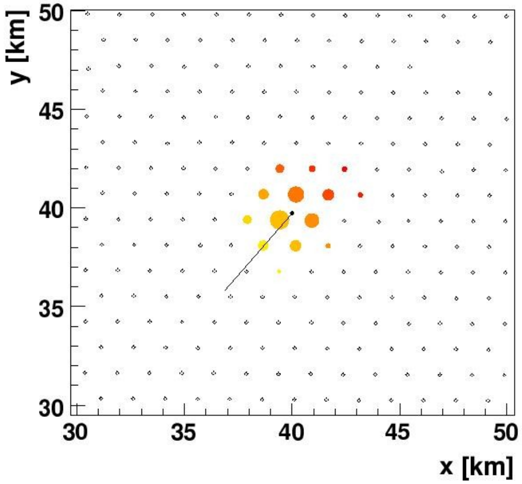
Beyond science ...

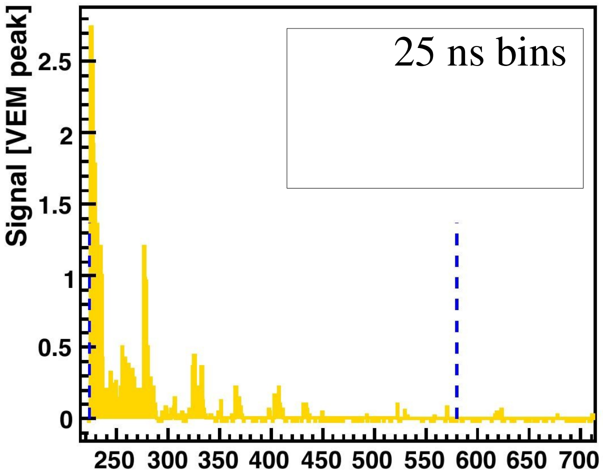
Test your eyes ...

Ground detector array

tank signal
= s(r,t)



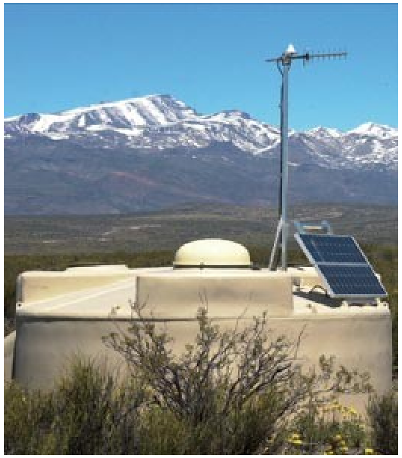


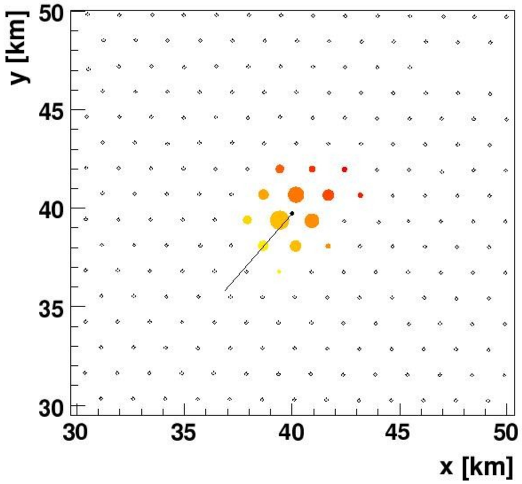


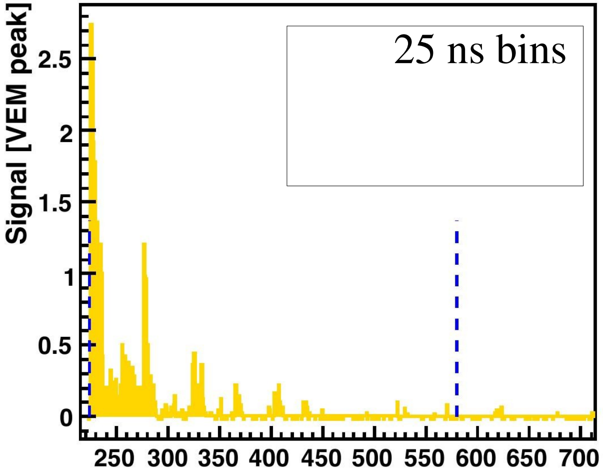
- **geometry**: timing of triggered tanks

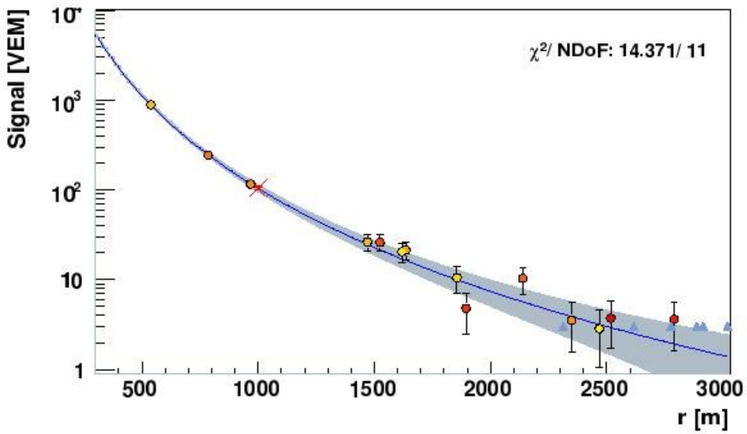
Ground detector array

tank signal
= s(r,t)



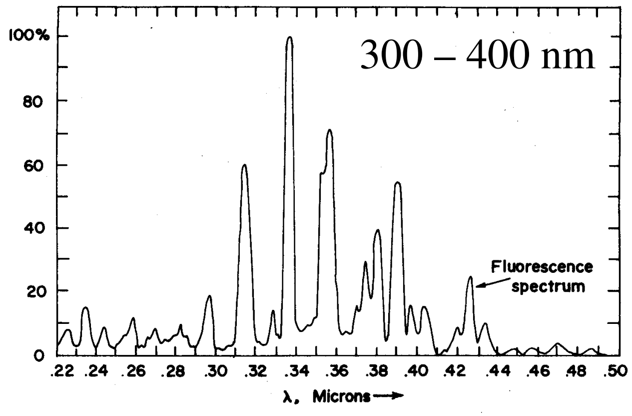


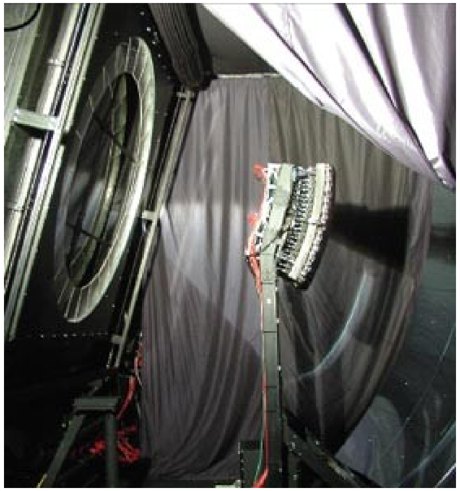




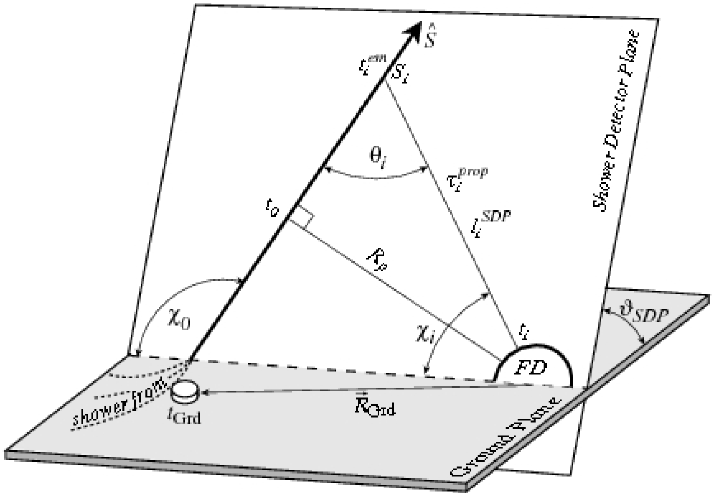
- **geometry**: timing of triggered tanks
- e.g. **S(1000)** (<-> energy), or signal **risetime** (<-> primary type)

Fluorescence telescopes



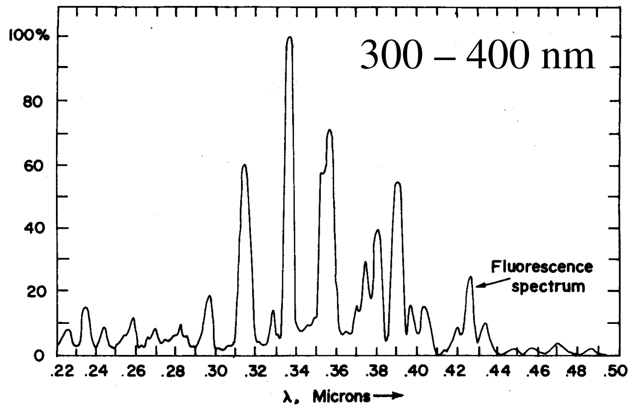


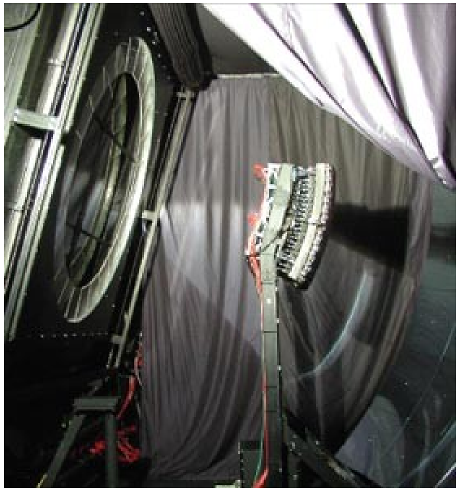
PMT signal
= f(dir,t)



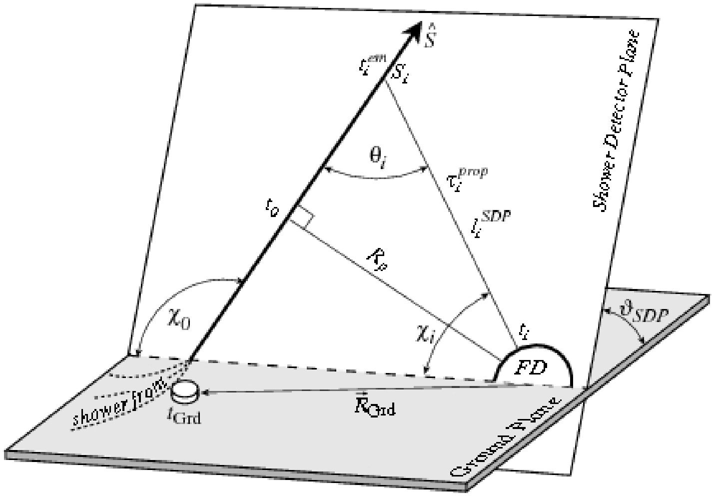
- **geometry**: angular-time correlation of triggered PMTs

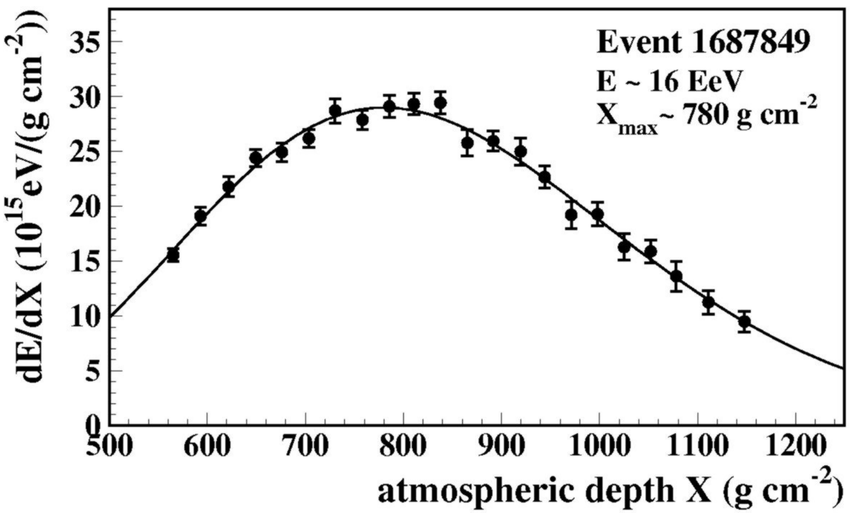
Fluorescence telescopes





PMT signal
= f(dir,t)





- **geometry**: angular-time correlation of triggered PMTs
- **profile**: PMT signal -> light at aperture -> light at shower -> dE/dX at shower
- $\mathbf{X_{max}}$ and **energy** (integrating dE/dX plus missing energy correction)

Two types of data

Array

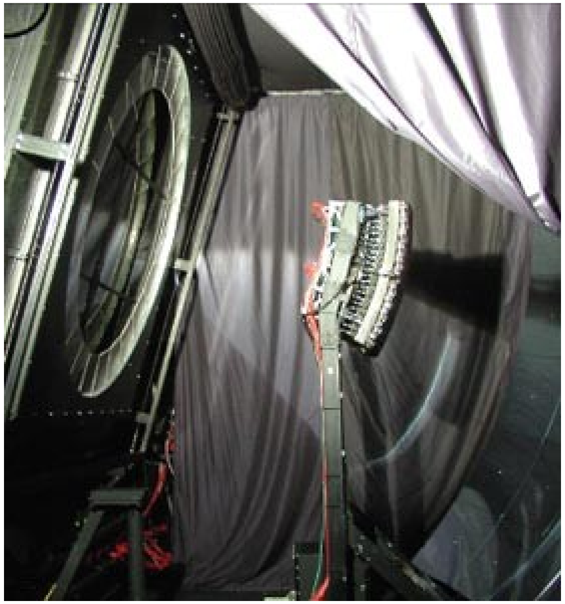
100% duty cycle

s(r,t) of ground particles

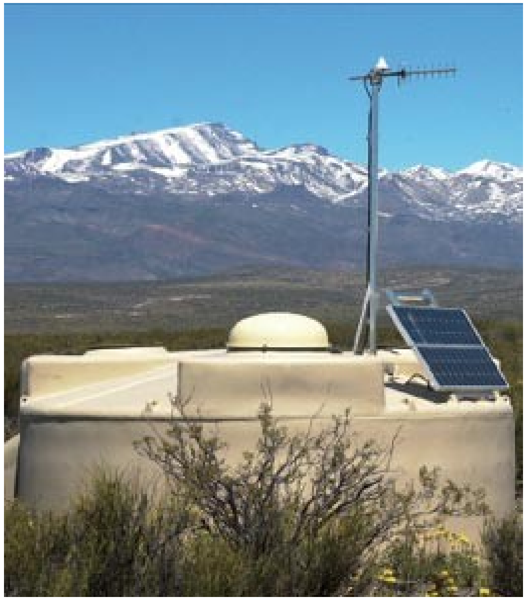
***Hybrid* =**

10% duty cycle

f(dir,t) -> longit. profile



+

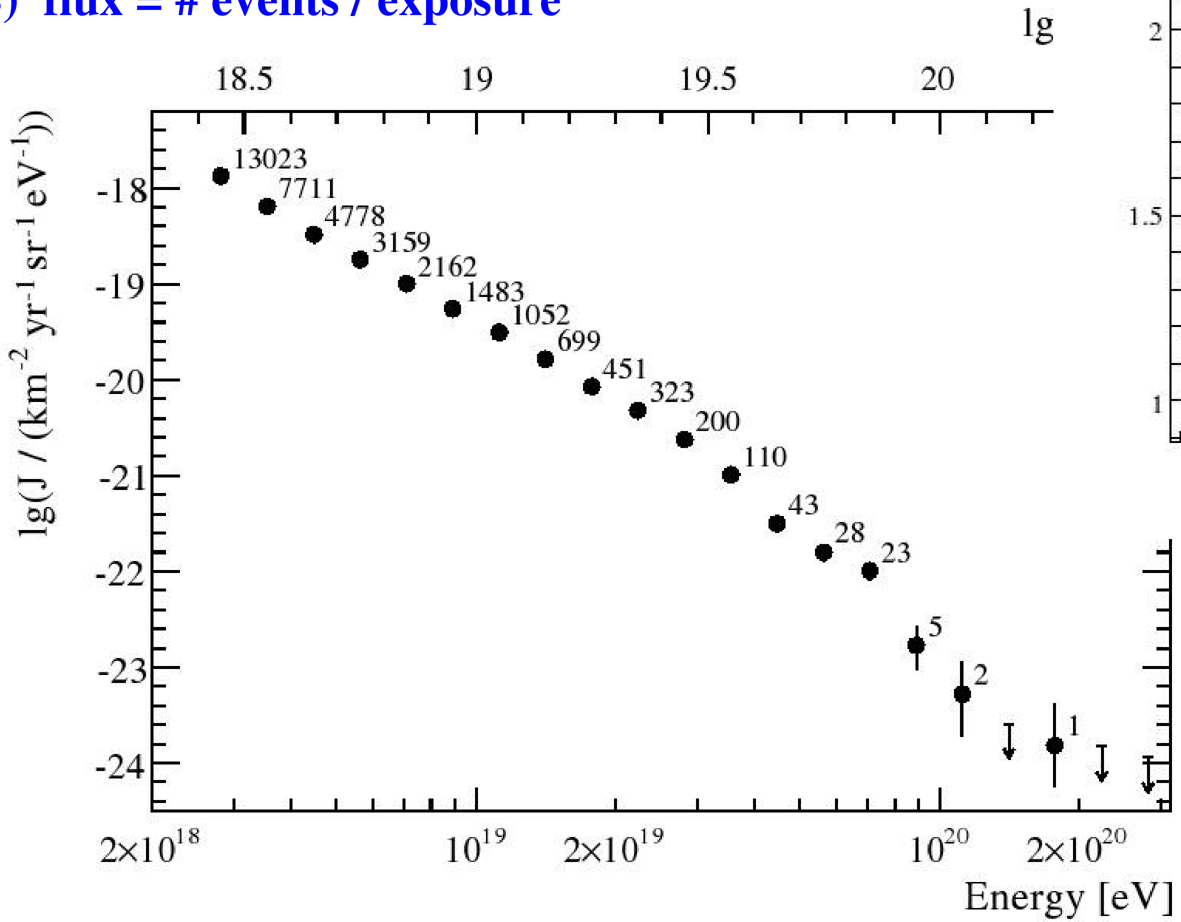


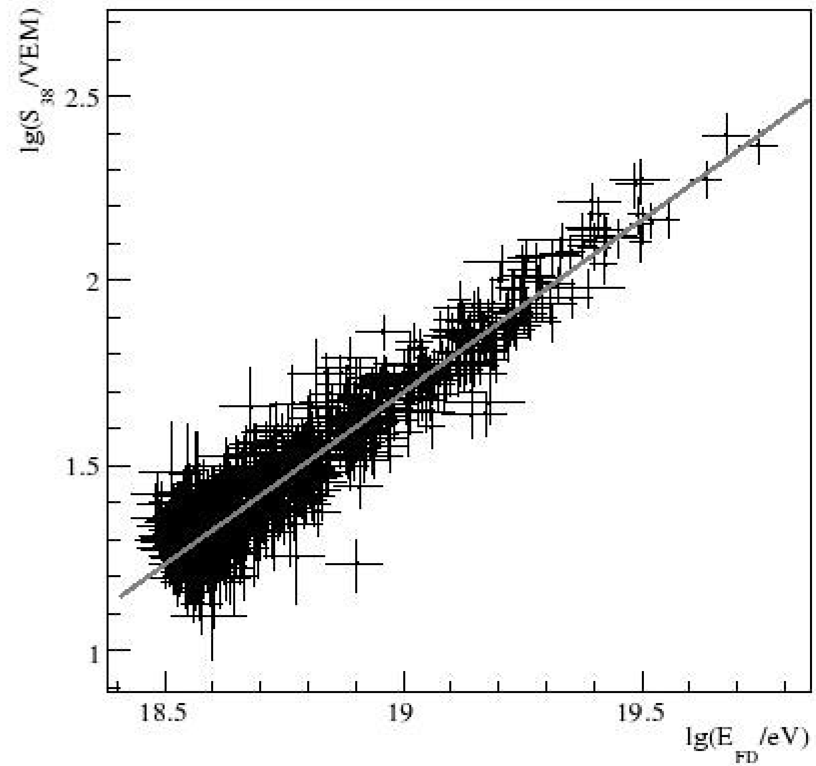
First results on:

- ***energy spectrum*** *(suppression?)*
- ***primary type*** *(top-down models: photons!)*
- ***arrival directions*** *(correlations?)*

Flux at highest energies

(B) flux = # events / exposure





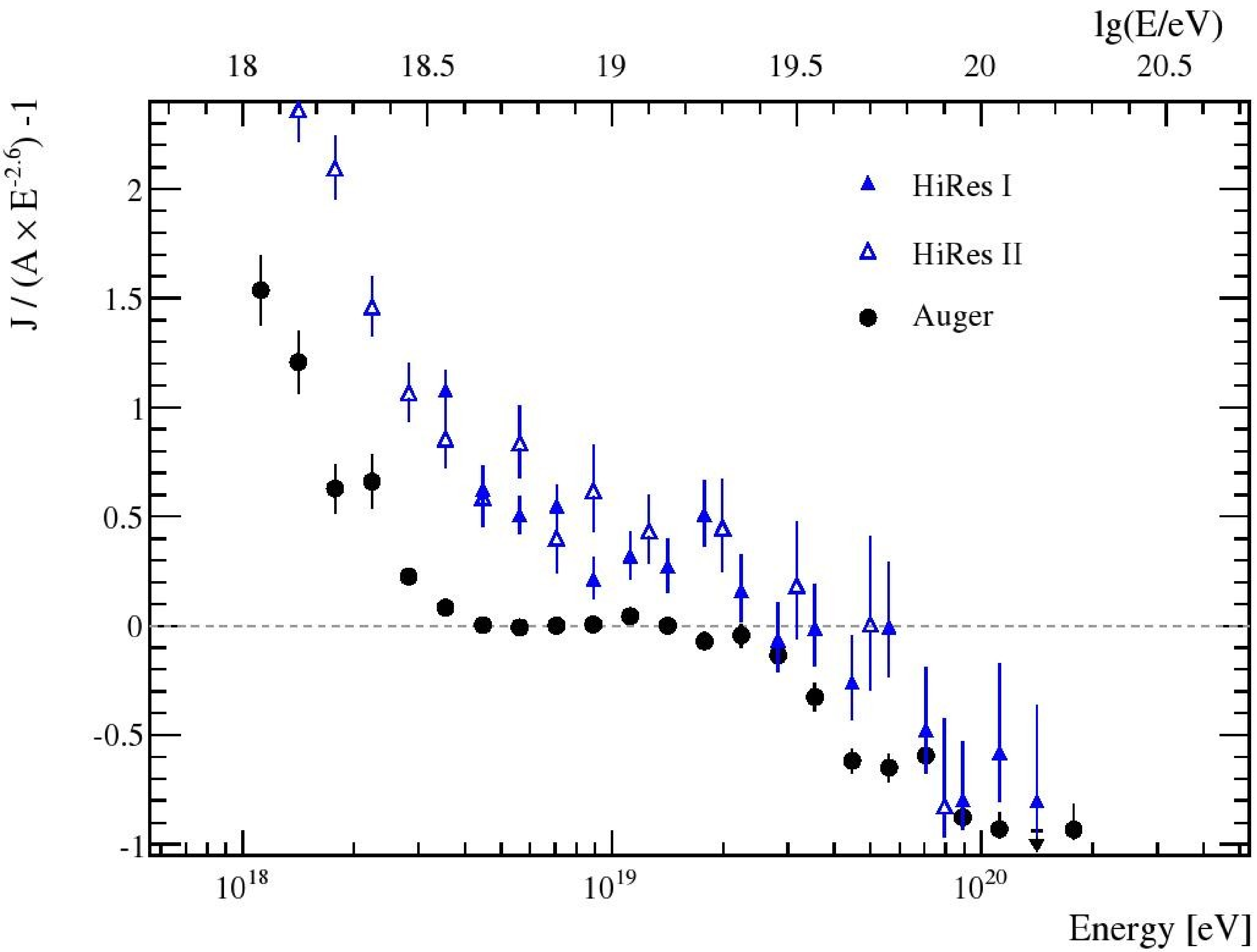
(A) calibration with telescopes using hybrid events:

***S38**: S1000 norm. to 38 deg zenith*

Figure 5: Energy spectrum derived from surface detector data calibrated with fluorescence measurements. Only statistical uncertainties are shown. The upper limits correspond to 84% CL.

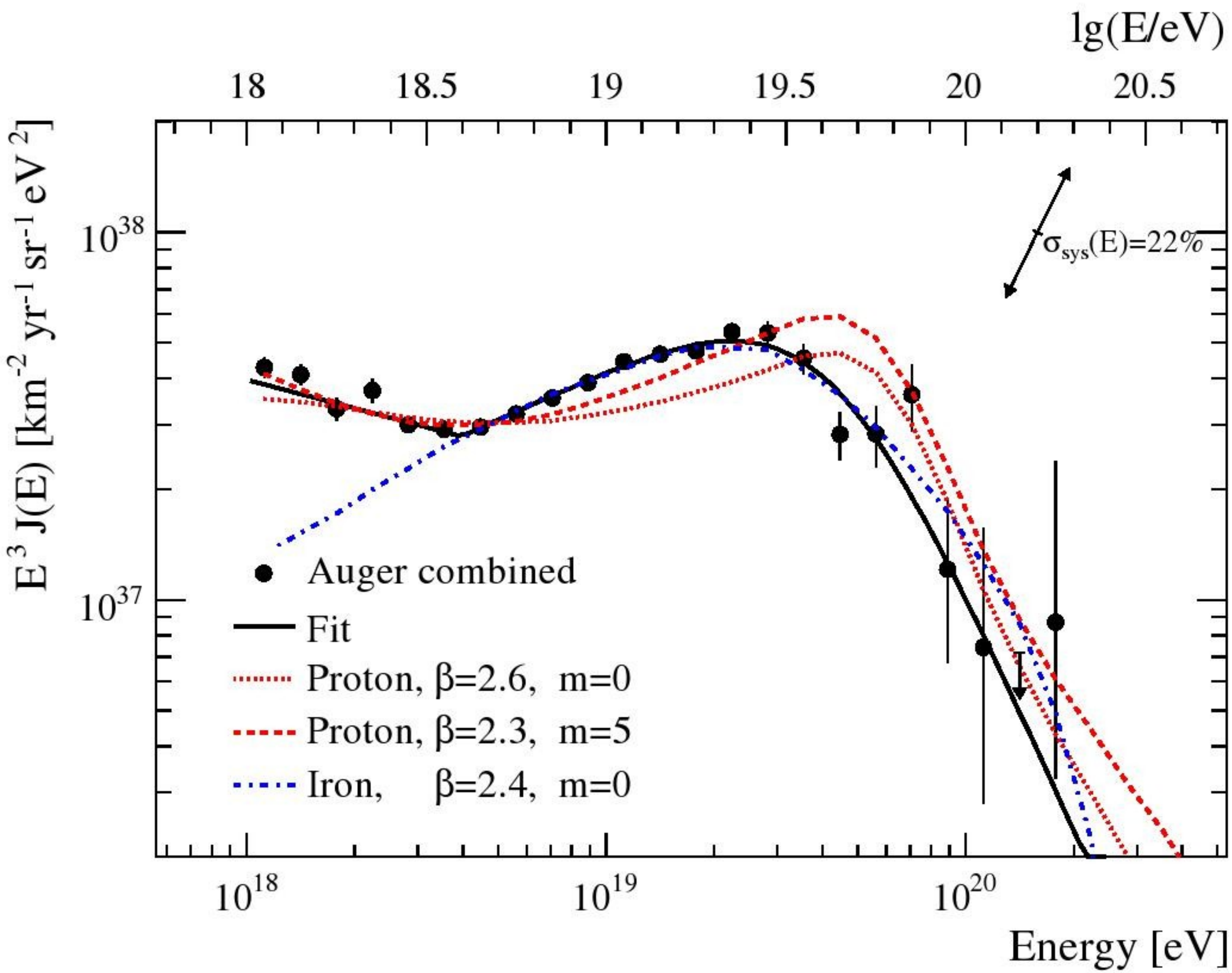
(Auger Collab., PRL 2008)

Flux at highest energies



→ *2 features:* ***“ankle“*** *@ ~4*10*^{18} *eV,* ***suppression*** *@ ~4*10*^{19} *eV*

Flux at highest energies, data vs source scenarios

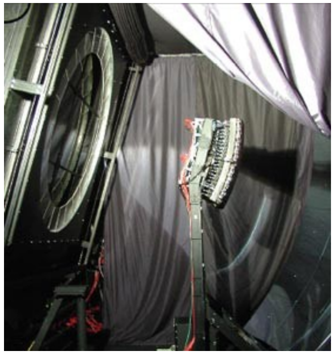


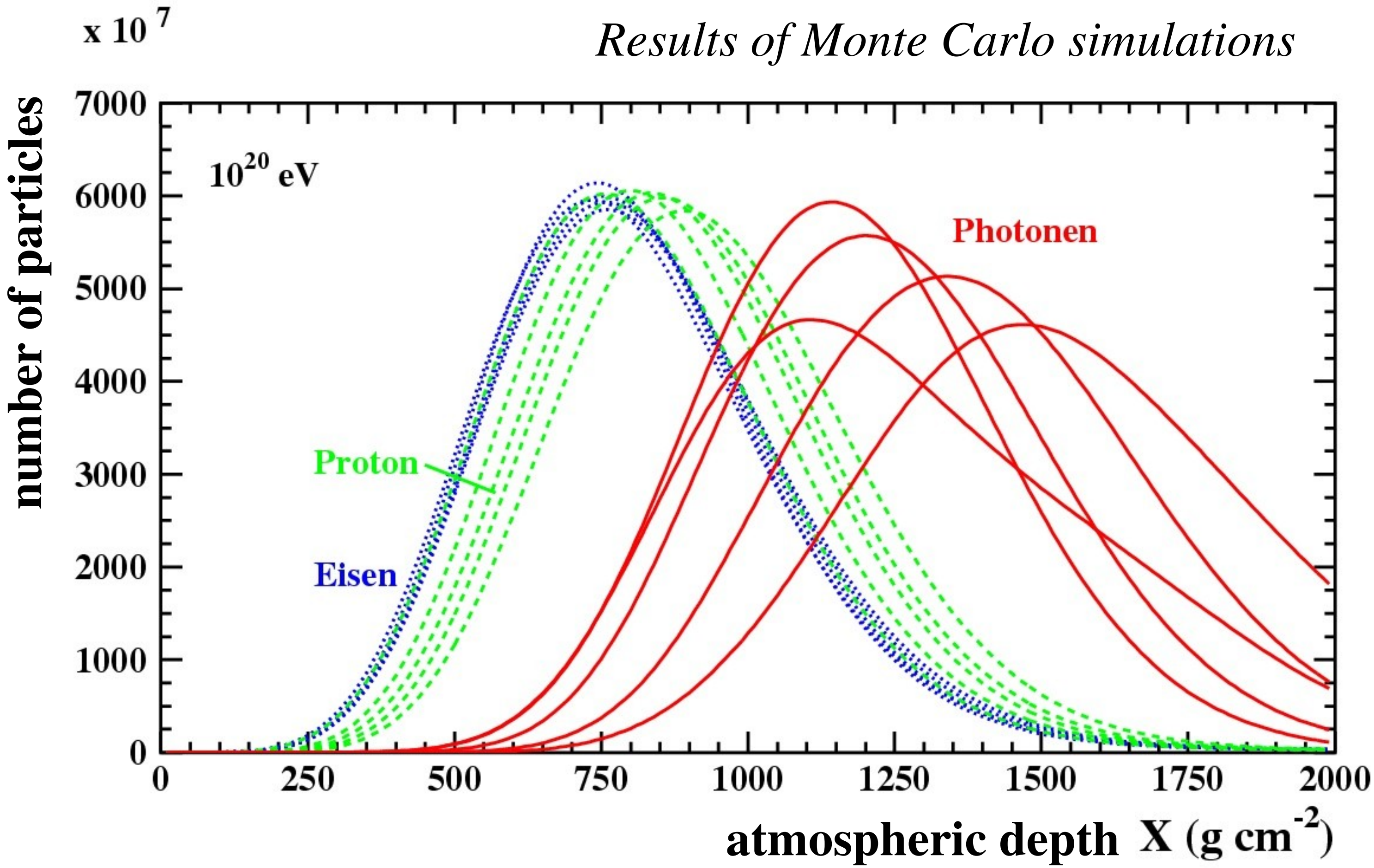
… start to test specific source scenarios

First results on:

- ***energy spectrum: suppression!***
- ***primary type*** *(top-down models: photons!)*
- ***arrival directions*** *(correlations?)*

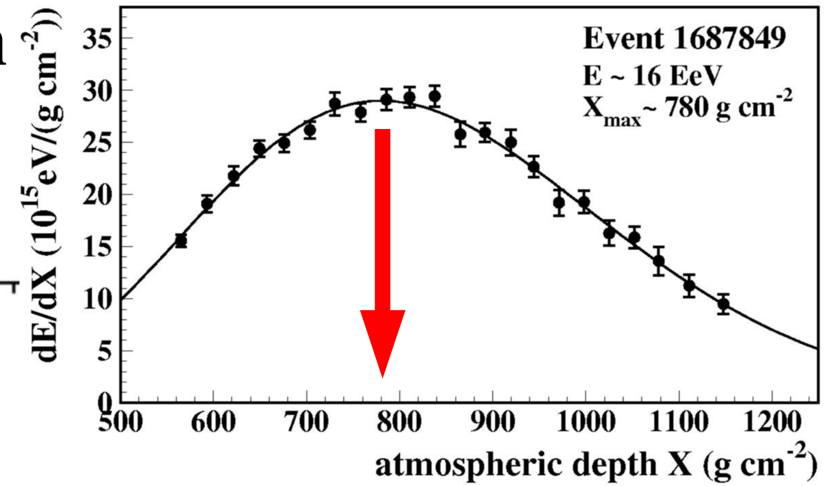
Photon shower go deeper (= larger X_{max}) !



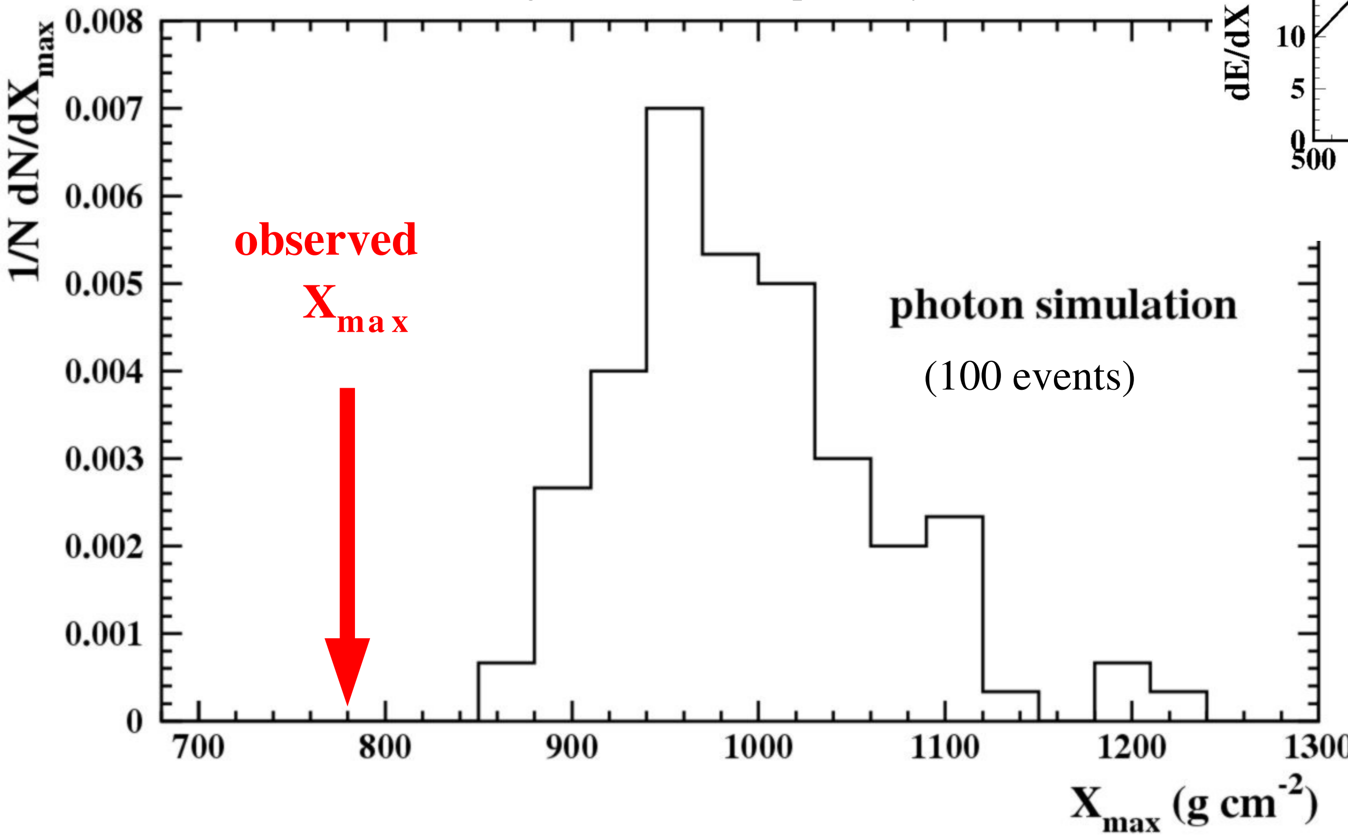


➔ *does observation “fit“ to photons ?*

Comparison observation / expectation



Auger Collab., Astropart. Phys. 2007 + 2009



observed:
X_{max} = 780 ± 28 (stat) ± 23 (syst) g cm^{-2}

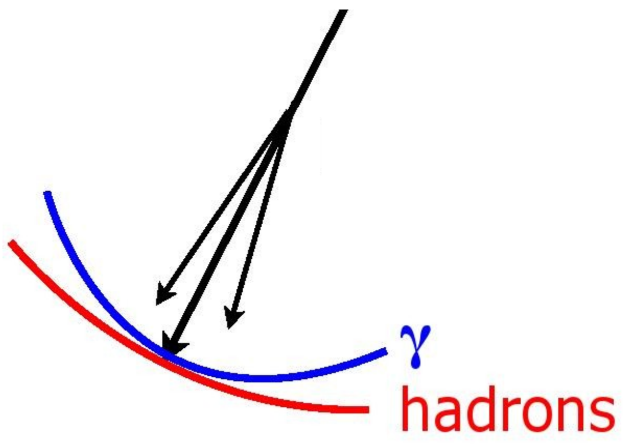
photon simulations:
$\langle X_{max} \rangle$ = 1000 g cm^{-2} , rms = 71 g cm^{-2}

- **observed X_{max} well below photon expectation !**
- total 29 events ***=> upper limit to photon fraction in cosmic-ray flux***

UHE photons and water tanks

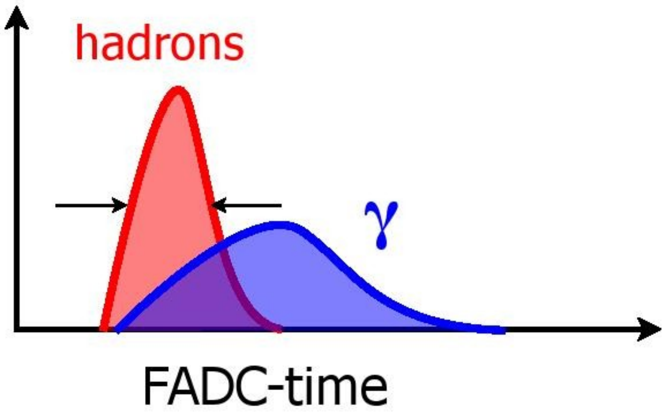
- larger $\mathbf{X}_{\mathbf{max}}$

→ smaller **radius of curvature** of shower front



- smaller **number of muons**

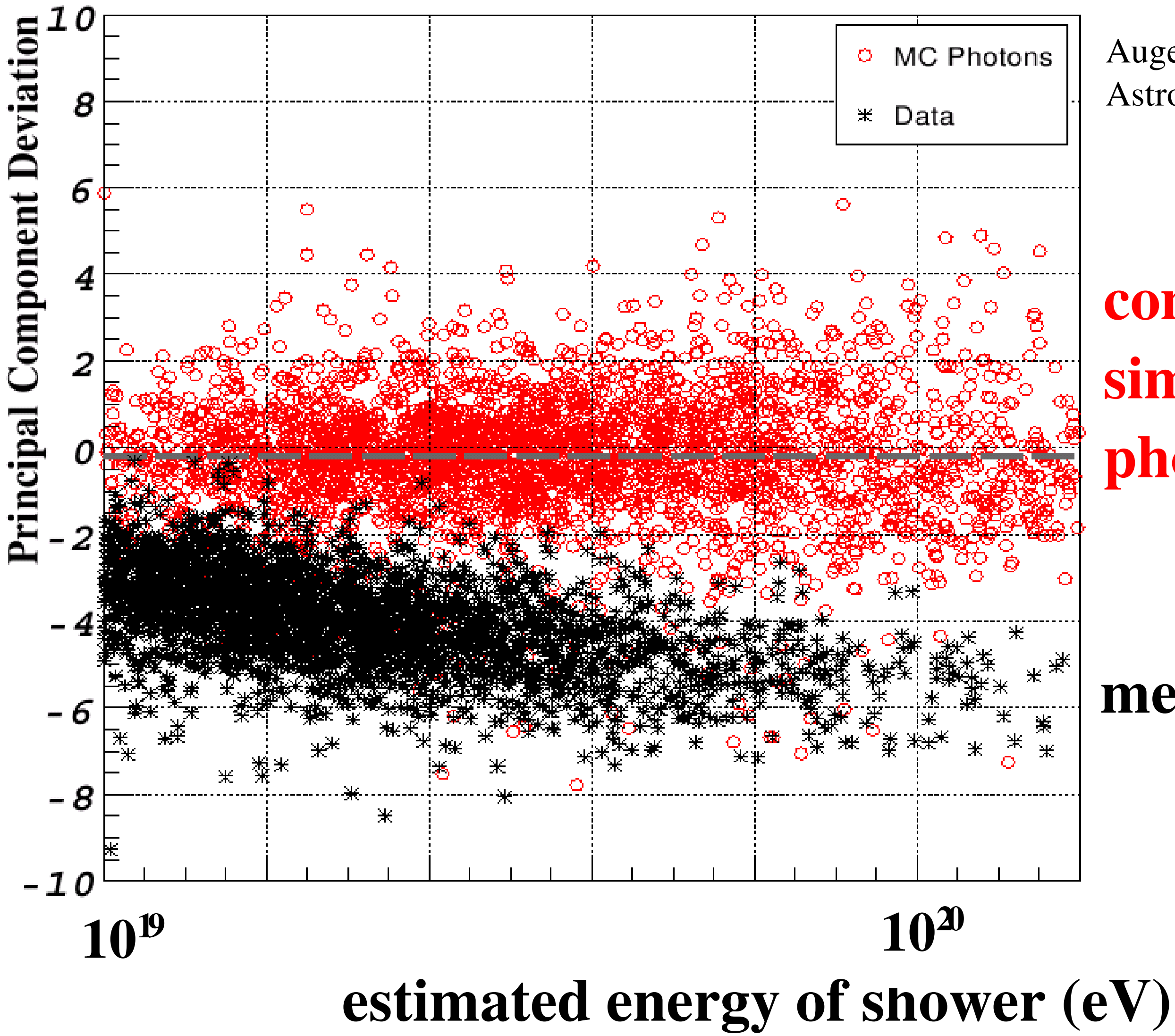
→ larger **signal rise time** in the detector



-> *combination ...*

photon limit with ground array

combination of measured risetime and curvature



Auger Collaboration Astropart. Phys. 2008

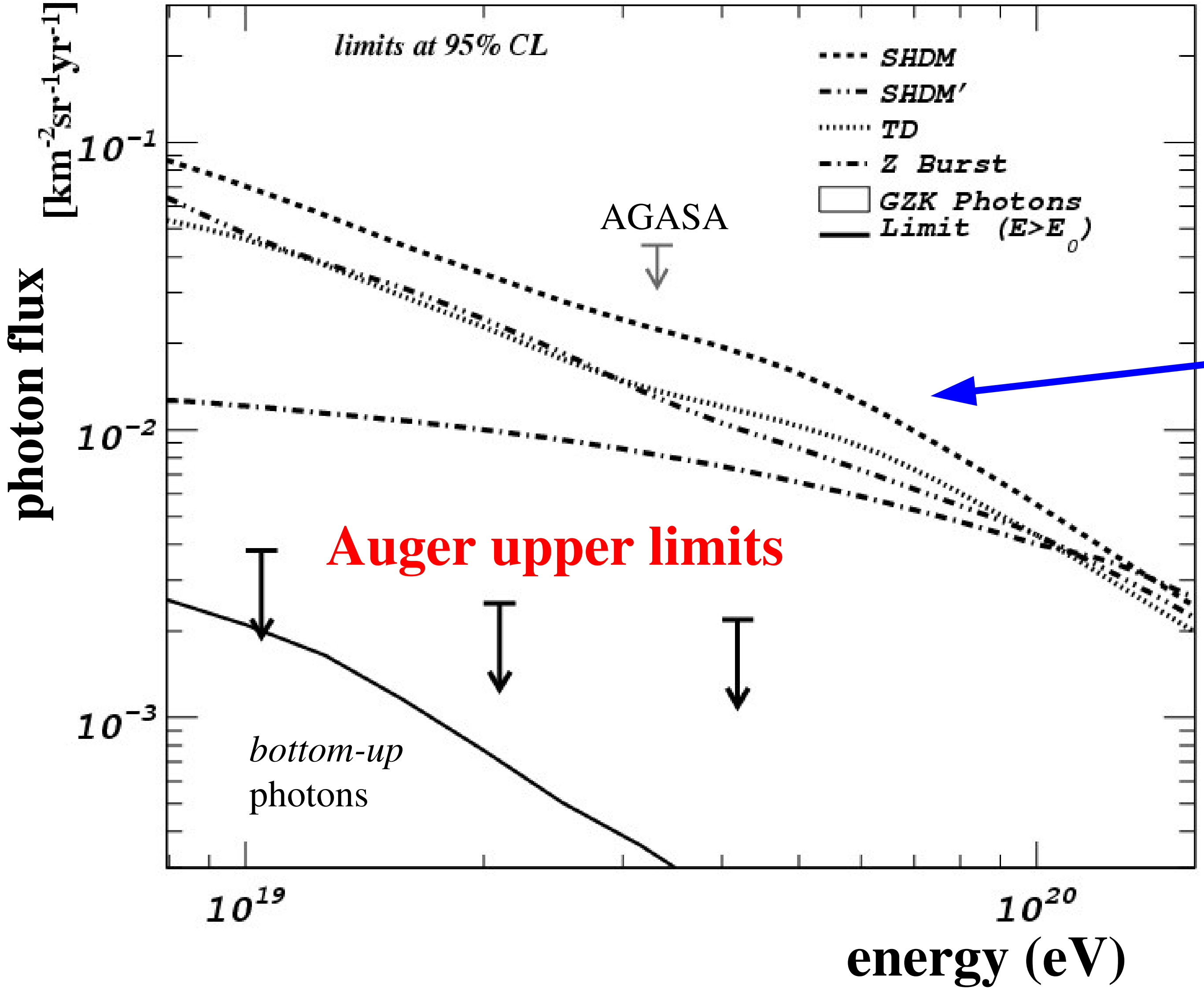
computer simulations of photon showers

measurement

- **photons don't fit well the mesurement**

→ ***upper limit to photon flux in cosmic rays ...***

Upper limit to photon flux



Auger Collaboration, Astropart. Phys. 2008

top-down
predictions

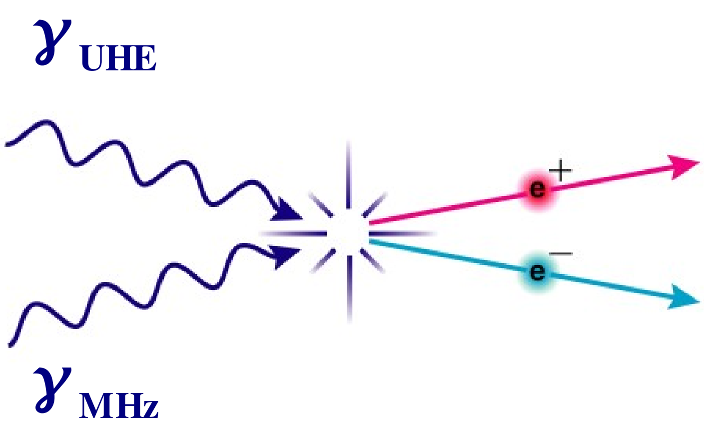
=> cosmic rays not from *top-down* !

so … ***top-down***  ***bottom-up*** 

so … ***top-down***  ***bottom-up*** 

bottom-up: UHE photons ~0.1% (pair production; scale ~few Mpc)

$$p + \gamma_{CMB} \to \Delta \to p + \pi^0$$
$$\hookrightarrow \gamma\gamma \not\to e^+e^-$$

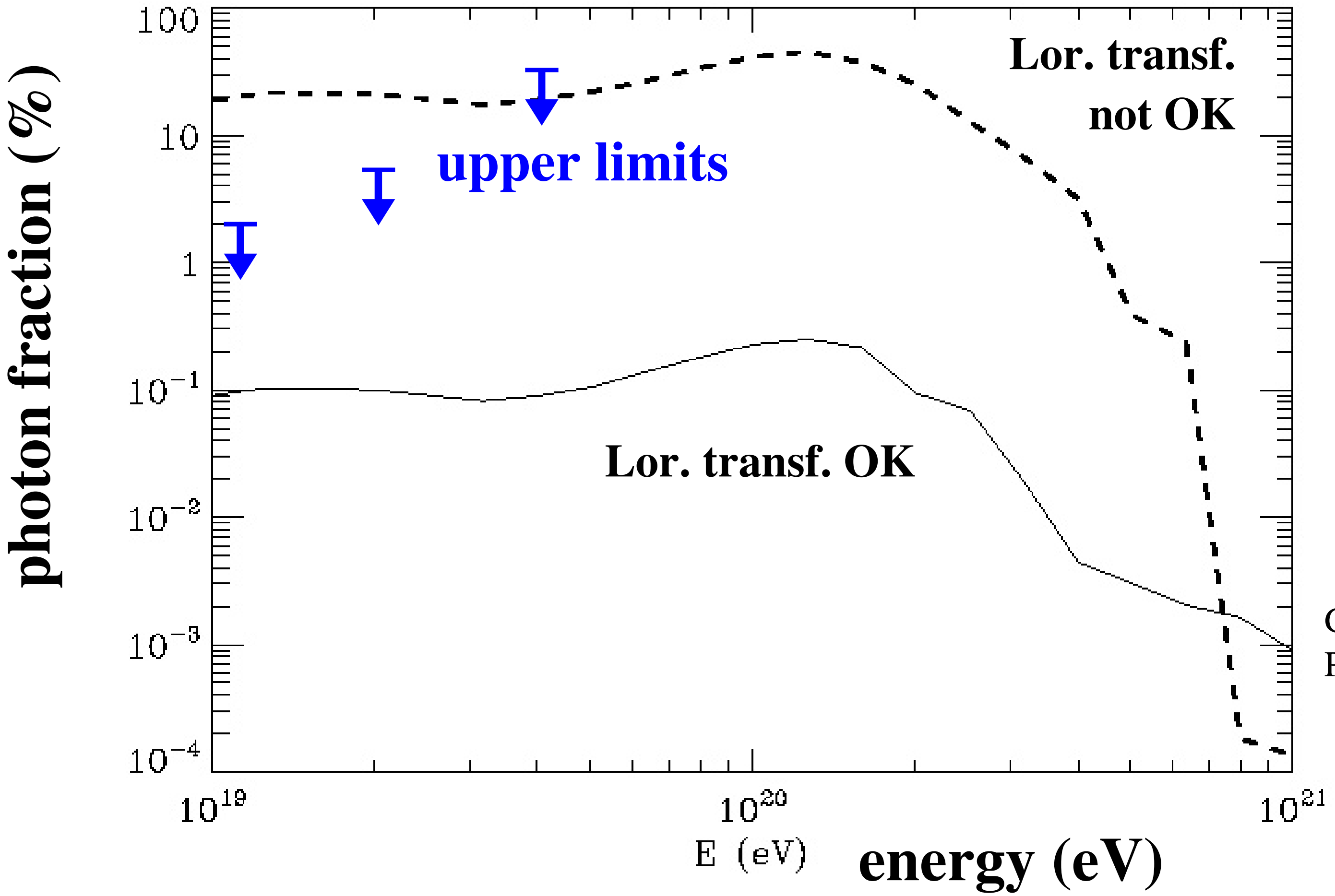


but:

if Lorentz transformation not OK => larger UHE photon flux possible !

Lorentz transformation OK ?

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0$$
$$\hookrightarrow \gamma\gamma \not\rightarrow e^+e^-$$



Galaverni & Sigl, PRL 100, 021102 (2008)

if not OK: ***20% expected,***

but <2% observed !

UHE photons =>
Lorentz transformation OK !

condition: there are nucleons > $6*10^{19}$ eV

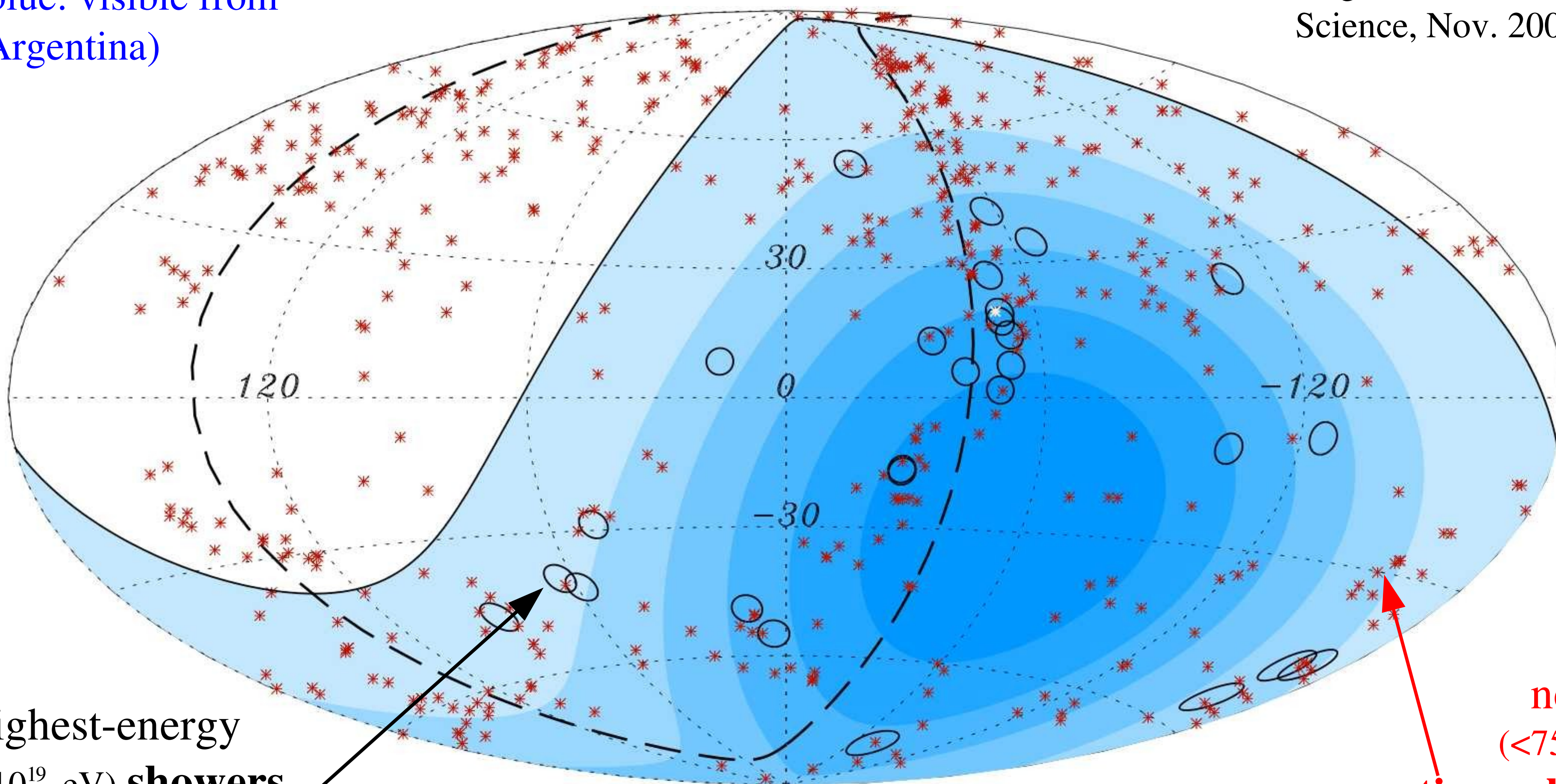
First results on:

- ***energy spectrum: suppression !***
- ***primary type: no photons (so far) !***
- ***arrival directions*** *(correlations?)*

Sky map: from where ?

(blue: visible from Argentina)

Auger Collaboration, Science, Nov. 2007



27 highest-energy ($> 6*10^{19}$ eV) **showers** (as 3.2 deg circles)

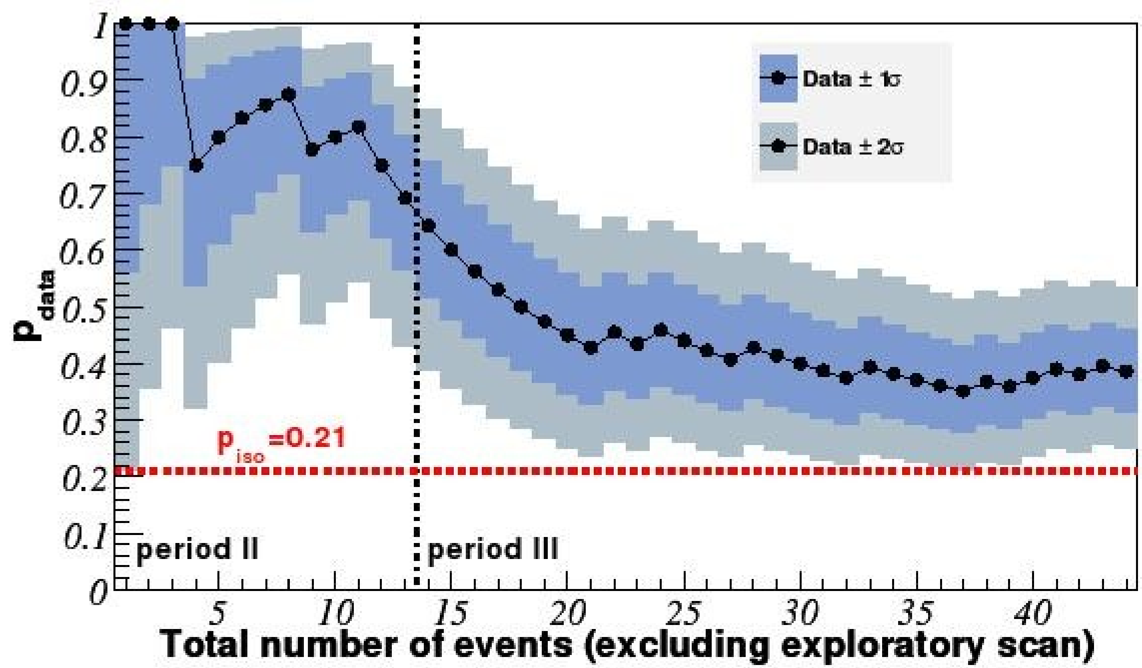
nearby (<75 Mpc) **active galaxies**

Do directions match each other?

-> 20 matches out of 27 events (5.6 random matches expected)

=> directional correlation with active galaxies ! (99% CL)

Time evolution of anisotropy signal



fraction of correlating events: $P_{data} = k / N$

	Period	Exposure	GP	N	k	k_{iso}	P
scan (01/2004 – 05/2006)	I	4390	unmasked	14	9	2.9	
			masked	10	8	2.5	
test (=> publication) (- 08/2007)	II	4500	unmasked	13	9	2.7	2×10^{-4}
			masked	11	9	2.8	1×10^{-4}
after publication (- 03/2009)	III	8150	unmasked	31	8	6.5	0.33
			masked	24	8	6.0	0.22
anisotropy @ 99% cl	II+III	12650	**unmasked**	**44**	**17**	**9.2**	6×10^{-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	

First results on:

- ***energy spectrum: suppression !***
- ***primary type: no photons (so far) !***
- ***arrival directions: correlation (nearby AGN) !***

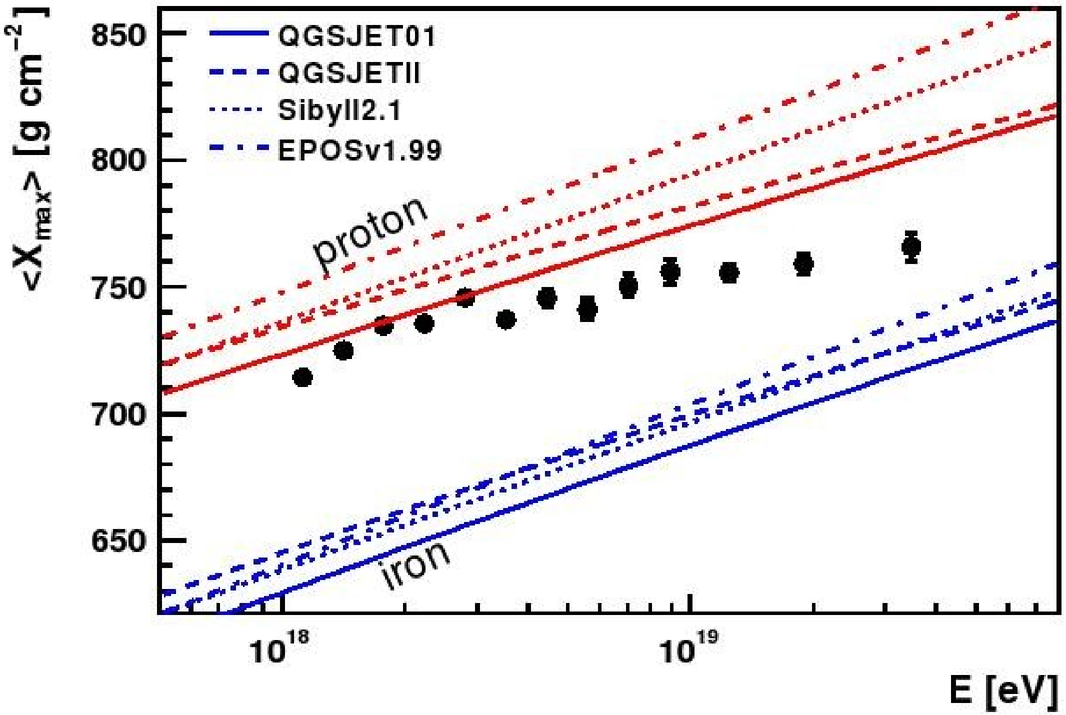
..... what type ... ?

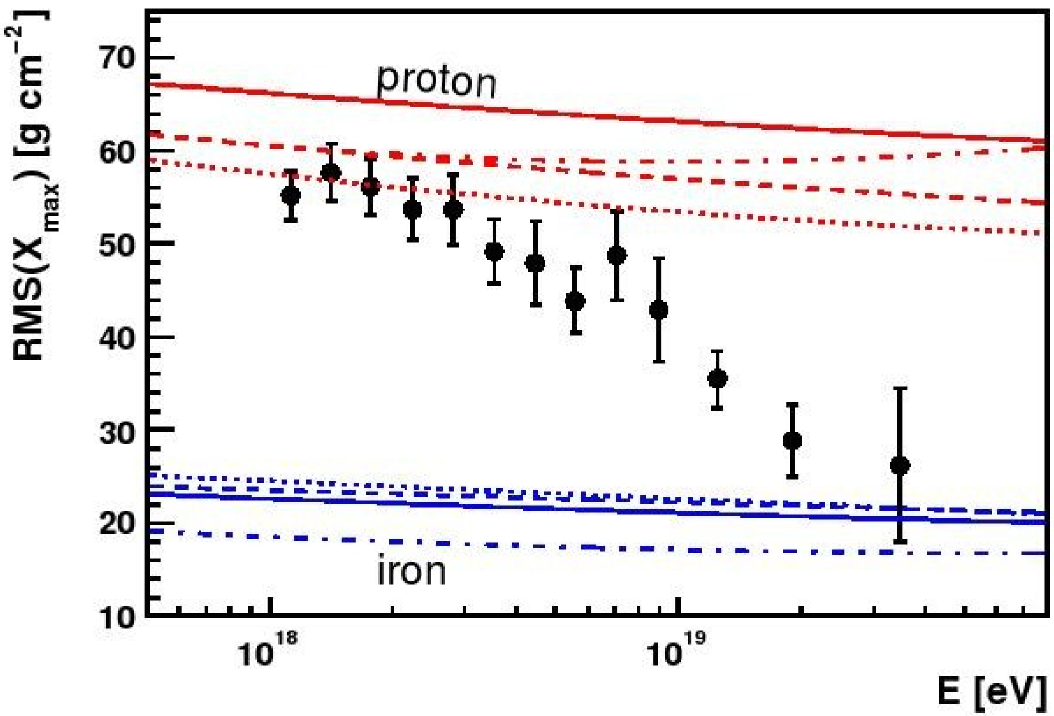
Primary type

from (rather) light towards (more) heavy ?

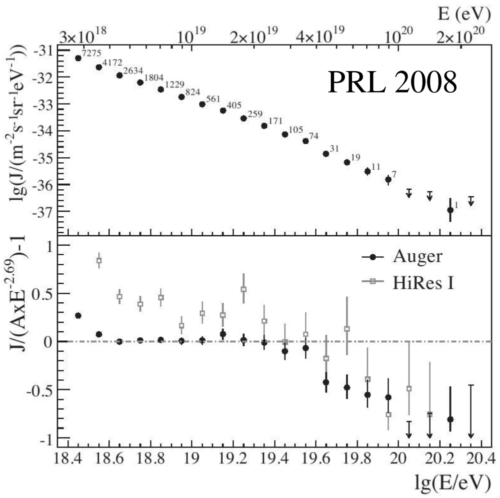
transition more pronounced in RMS ?

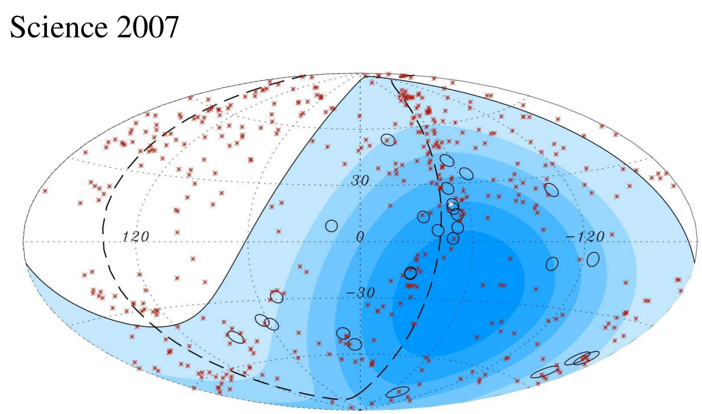
how reliable are hadronic models anyway ... ?

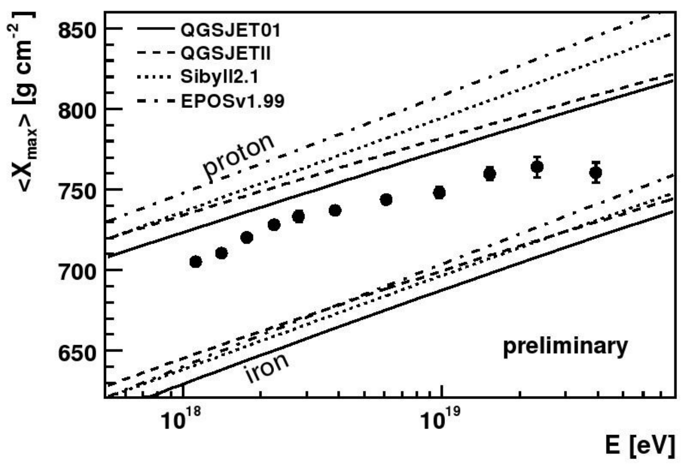




Status & (some) open questions







suppression: GZK effect,
or sources "tired" ?

correlation: small Z
or extremely small B ?

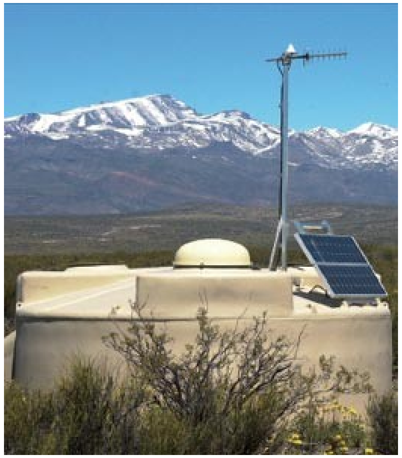
type: larger Z
or "bad" models ?

Some approaches …

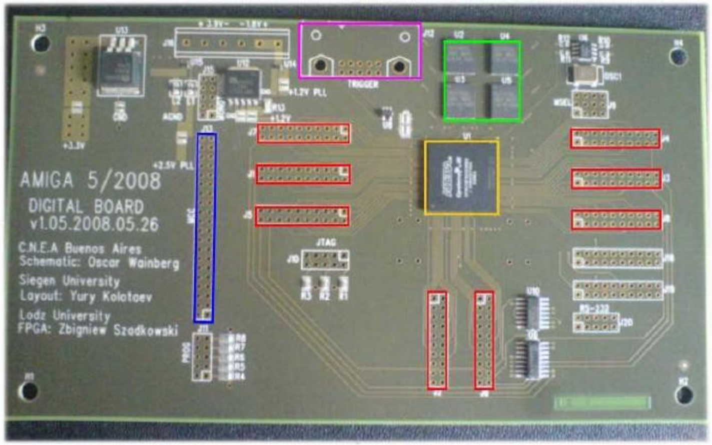
- ✔ *learn more about particle type*
- ✔ *any photons (neutrinos) as expected in GZK scenarios ?*
- ✔ *correlations with specific AGNs, or at low energy with galactic objects, or … ?*
- ✔ *any further fine structure in spectrum ?*
- ✔ …

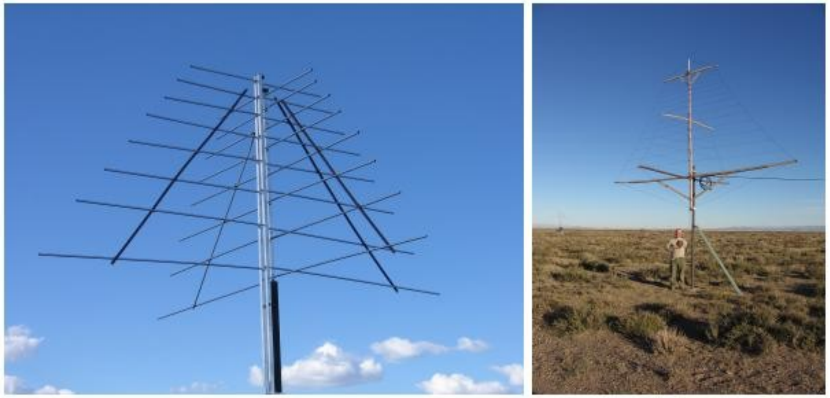
➔ ***creativity required !***

Enhancements Auger South: AMIGA, HEAT, AERA



AMIGA: dedicated muon detectors





HEAT:

better observation of profiles at low energy

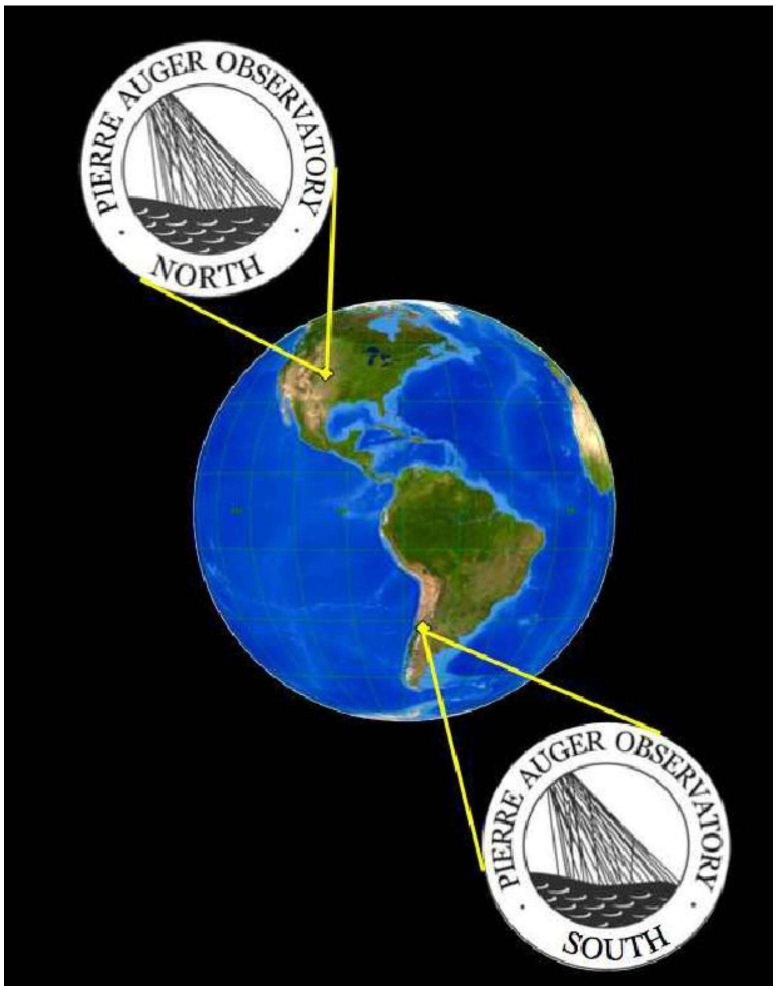
R&D **- Radio:**

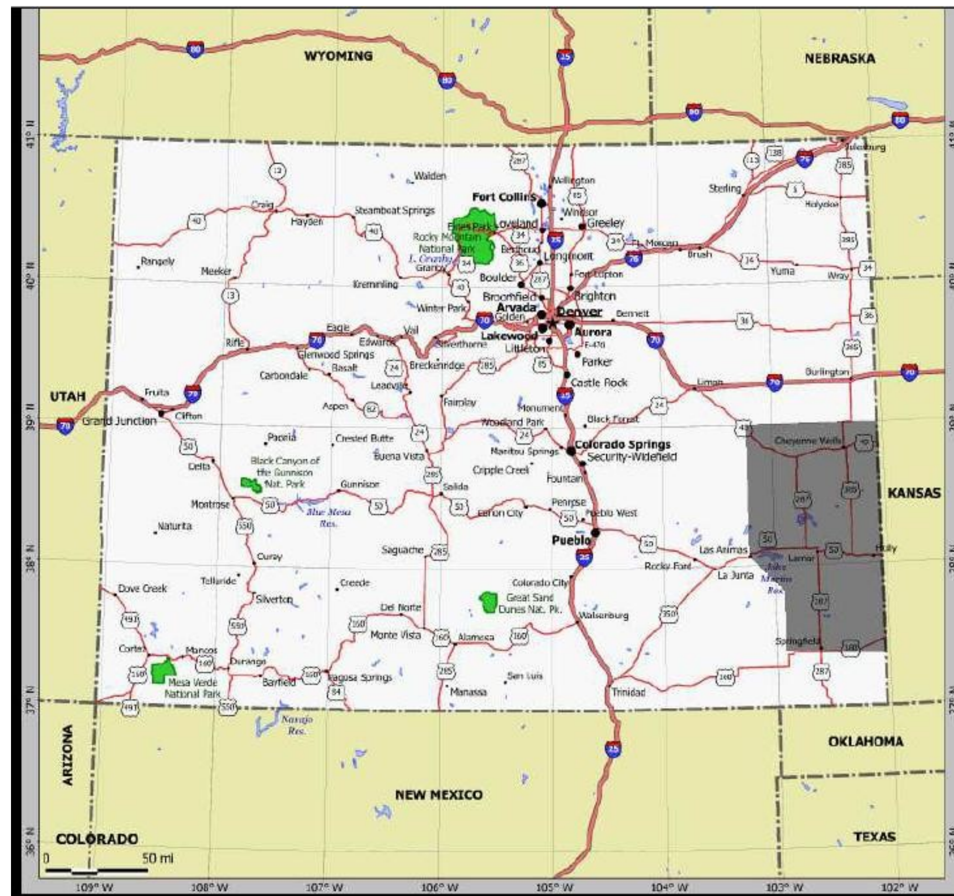
profiles with 100% duty cyce?

Auger plans: South & North

Auger South: continue ~10 yrs !

Auger North: planned (Colorado) !





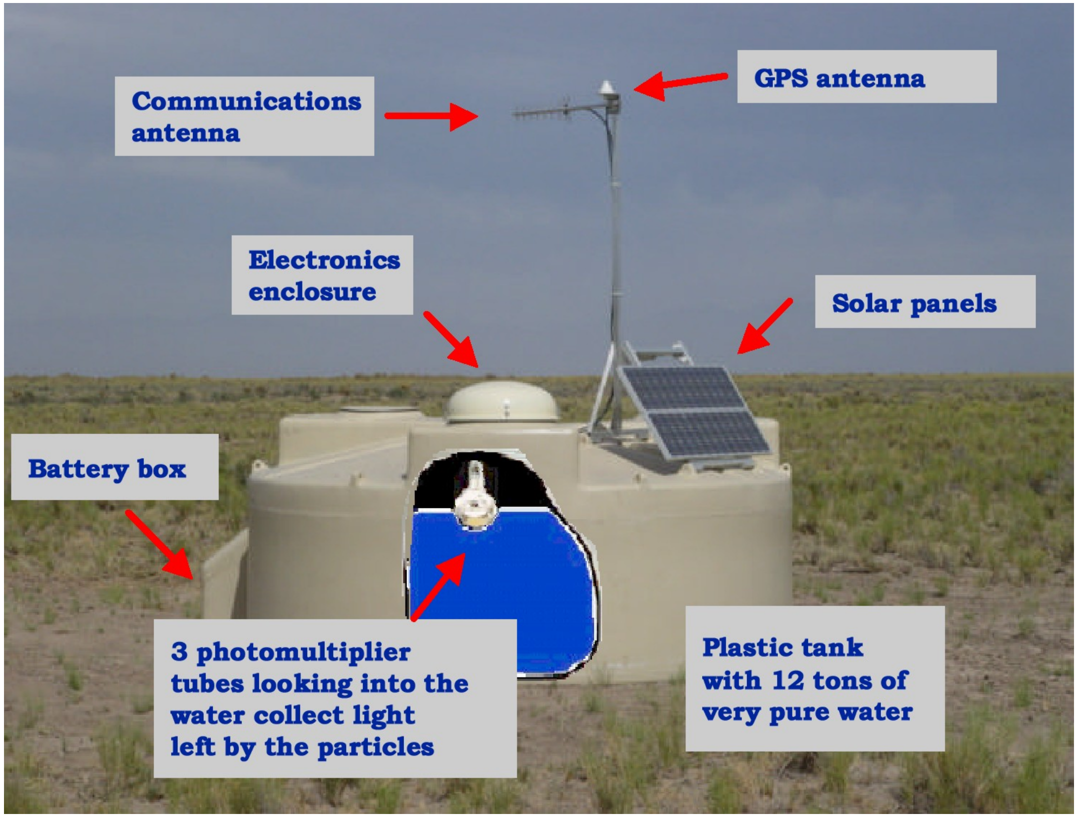
... full sky coverage !

North ~20000 km² = 7x South !

The Pierre Auger Observatory
and the highest-energy particles in the Universe

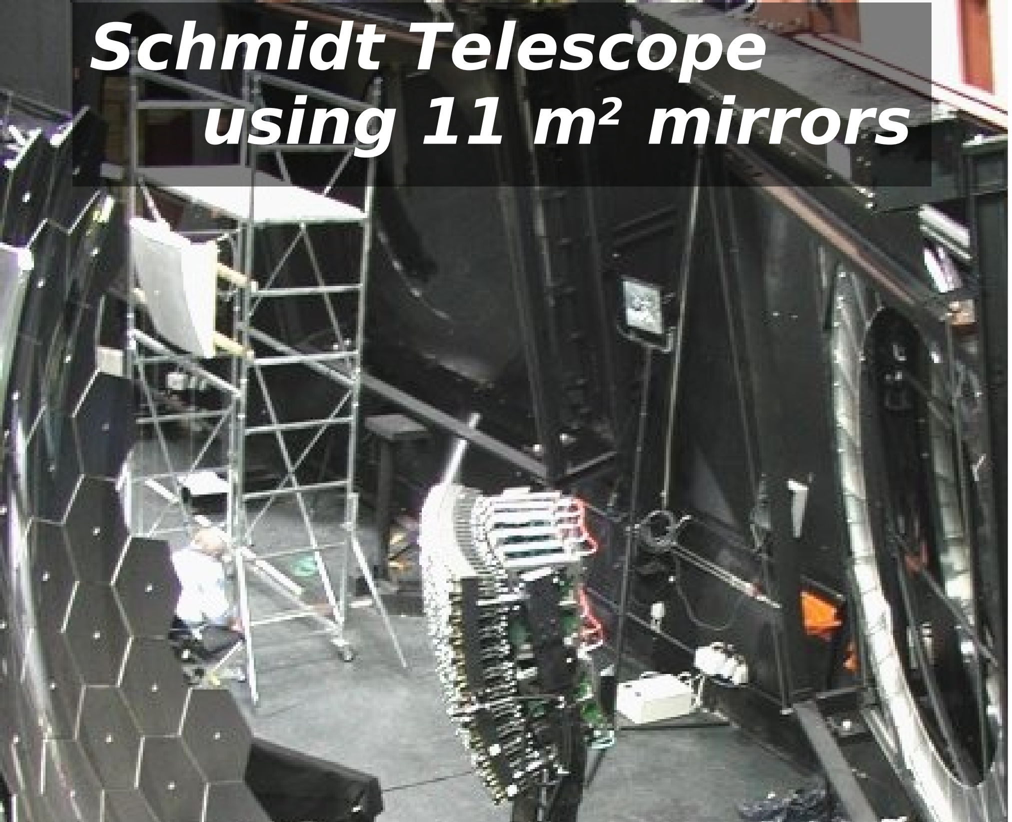
- **Nature produces extreme energies !**
- **Auger: exciting times …**
  - **first results !**
  - **continue data taking !**
  - **extend Auger South and complement it in the North !**

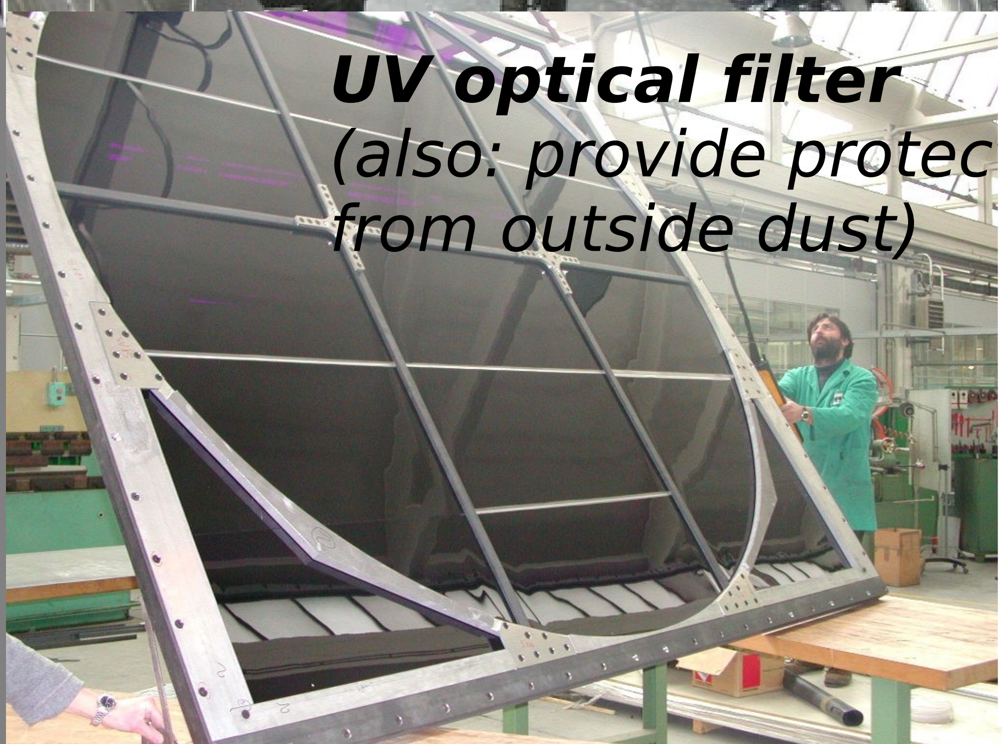
→ ***stay tuned ....***

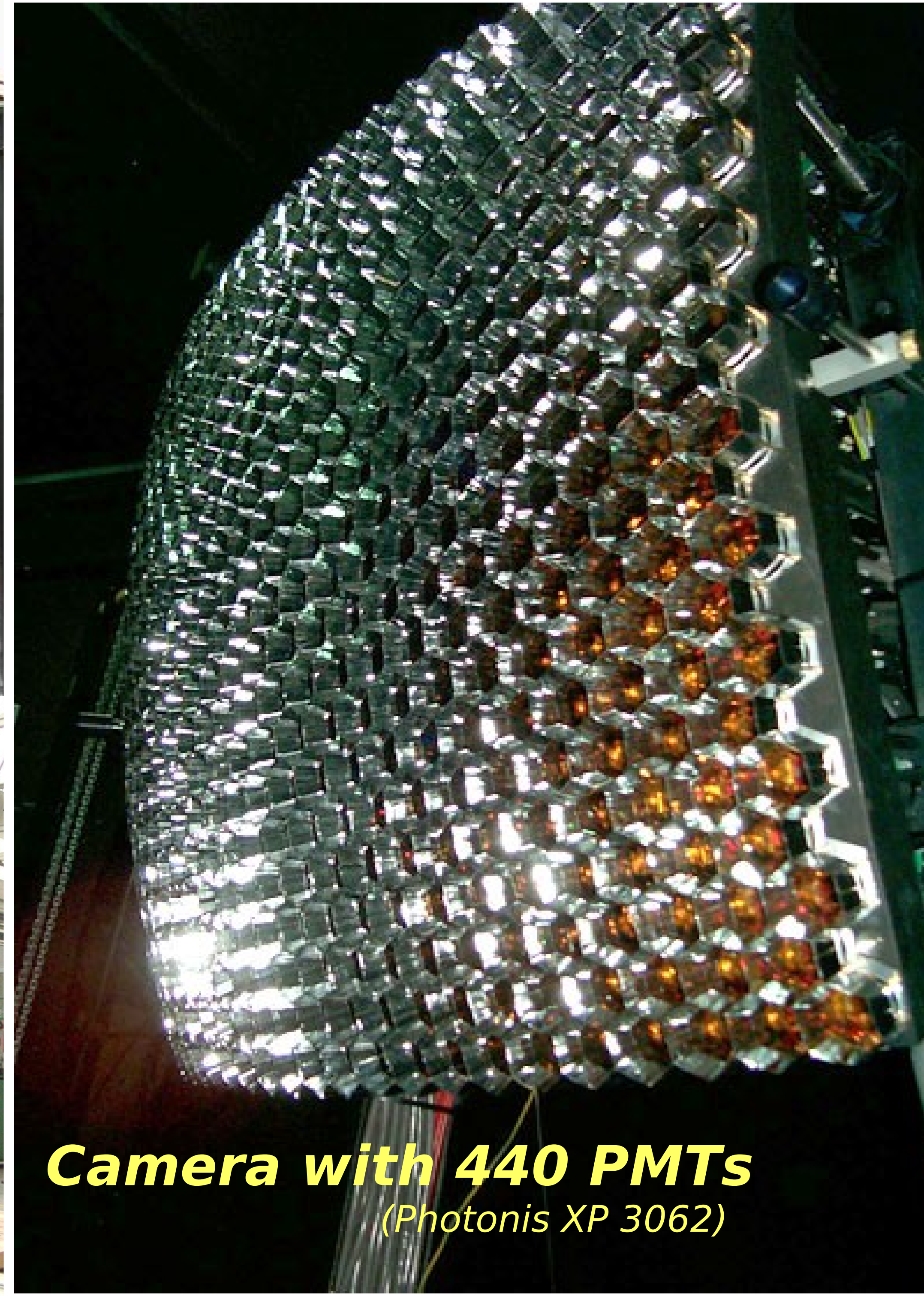


ground detector

➔ measure secondary shower particles reaching ground


Schmidt Telescope
using 11 m² mirrors


UV optical filter
(also: provide protec
from outside dust)


Camera with 440 PMTs
(Photonis XP 3062)

Testing hadronic models with muons

4 methods for muon content

-> overlap region exists !

-> suggests increase of energy scale by 25-30 %

-> more muons than expected?

-> ~OK with iron, but then contradiction to profile observations

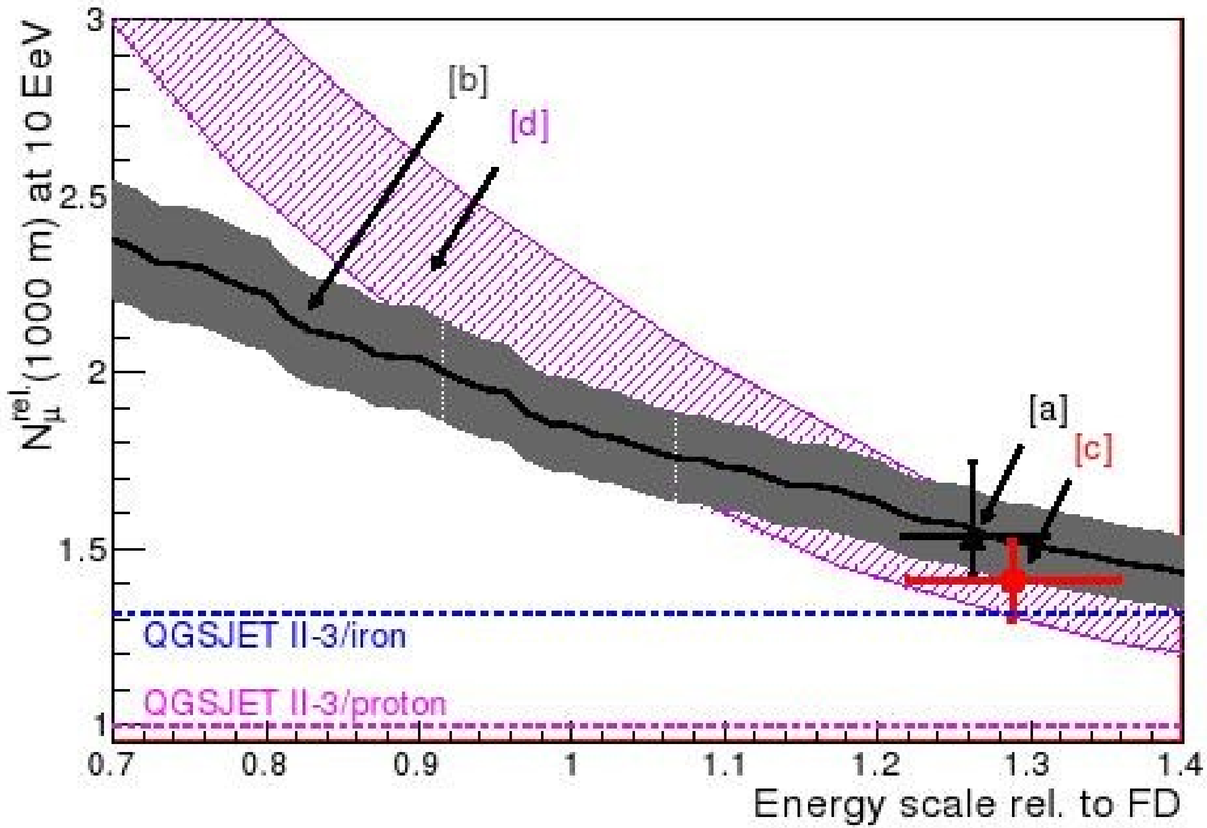


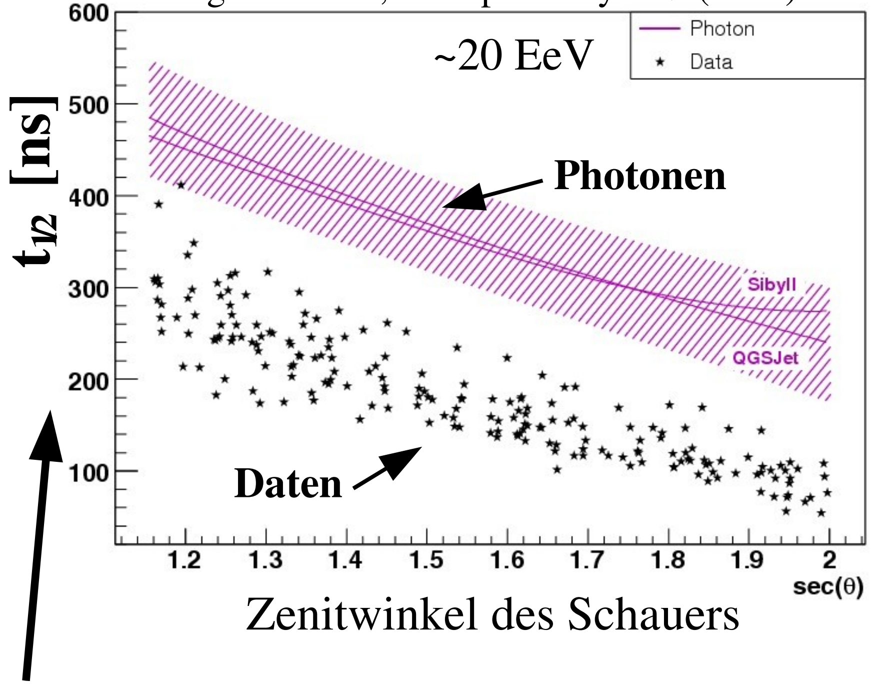
Fig. 6: Number of muons at 1000 m relative to QGSJET-II/proton vs. the energy scale from [a] the universality method (triangle); [b] the jump method (filled area); [c] the smoothing method (circle); [d] the golden hybrid analysis (dashed area). The events have been selected for $\log_{10}(E/\mathrm{eV}) = 19.0 \pm 0.02$ and $\theta \leq 50°$. According to the tested model, Iron primaries give a number of muons 1.32 times bigger than that from protons (horizontal lines in the figure).

References of Figures

auger.org , astronomy2009.org , wikipedia , NASA , Wikipedia Commons , Weblo.com , C. Grupen (Siegen) , toonpool.com

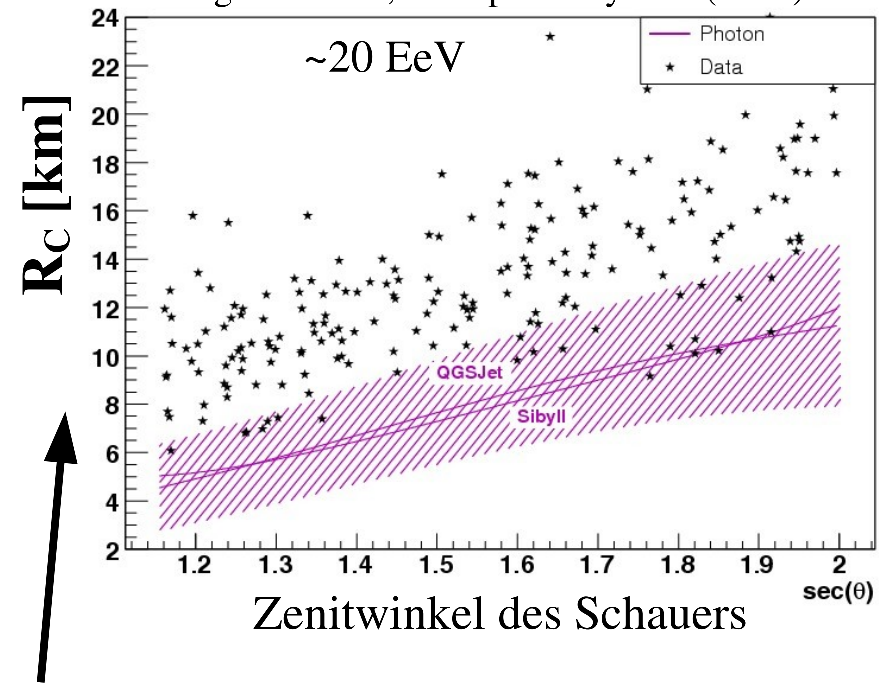
Array (Faktor ~10 mehr Daten!): Observablen

Auger-Kollab., Astropart. Phys. 29 (2008) 243

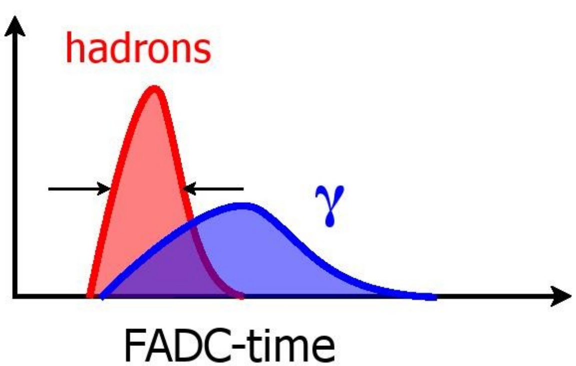


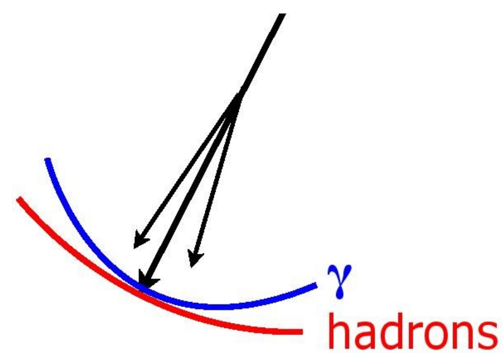
Signalanstiegszeit im Detektor (bei r = 1 km)

Auger-Kollab., Astropart. Phys. 29 (2008) 243



Krümmungsradius der Schauerfront

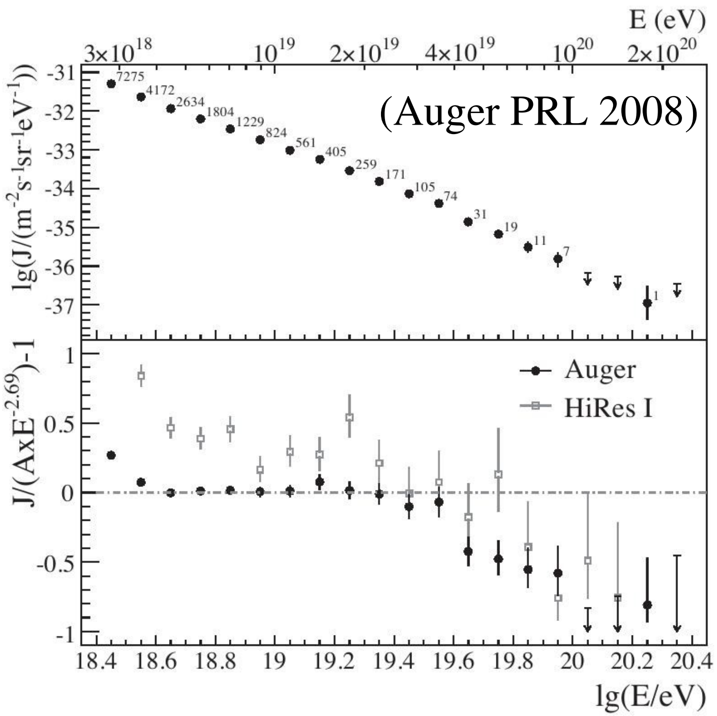




Photonen: groß (wenig Myonen, ...)

Photonen: klein (tiefes X_{max} , ...)

Question: doesn't the spectrum suppression anyway rule out top-down models?

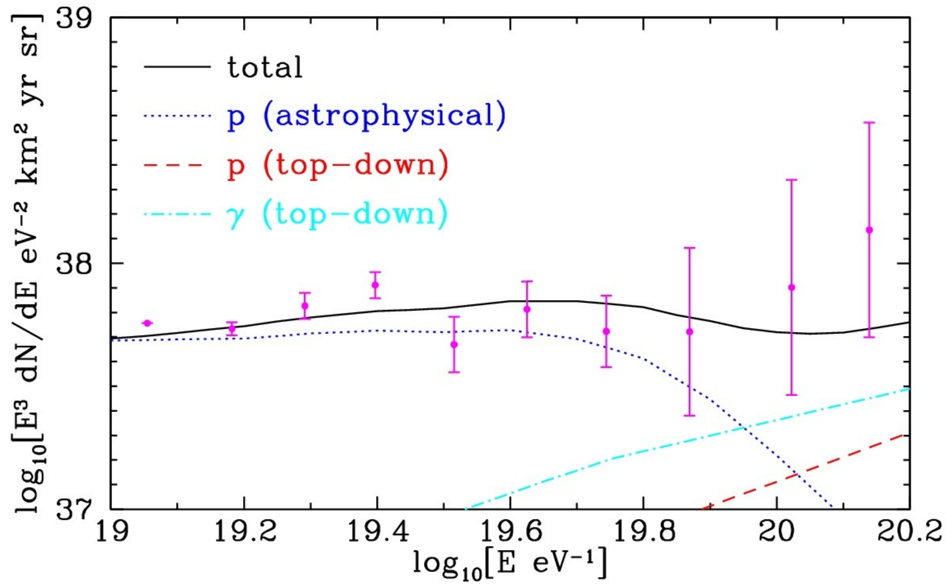


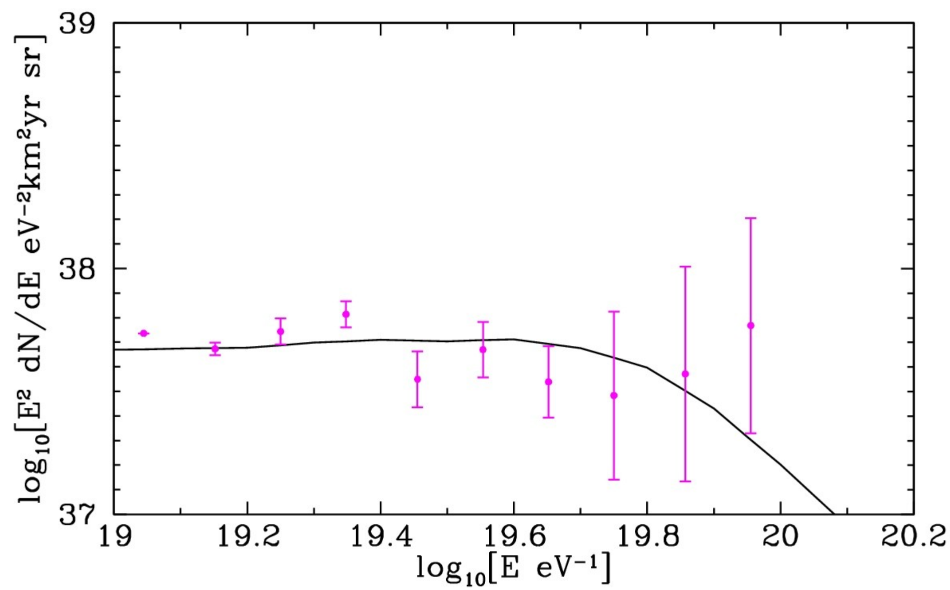
Caveat: photons shifted to smaller energy !

S(1000) factor 2-3 smaller for photons (less muons!)

spectrum with excess but increasing photon fraction appears to have a flux suppression

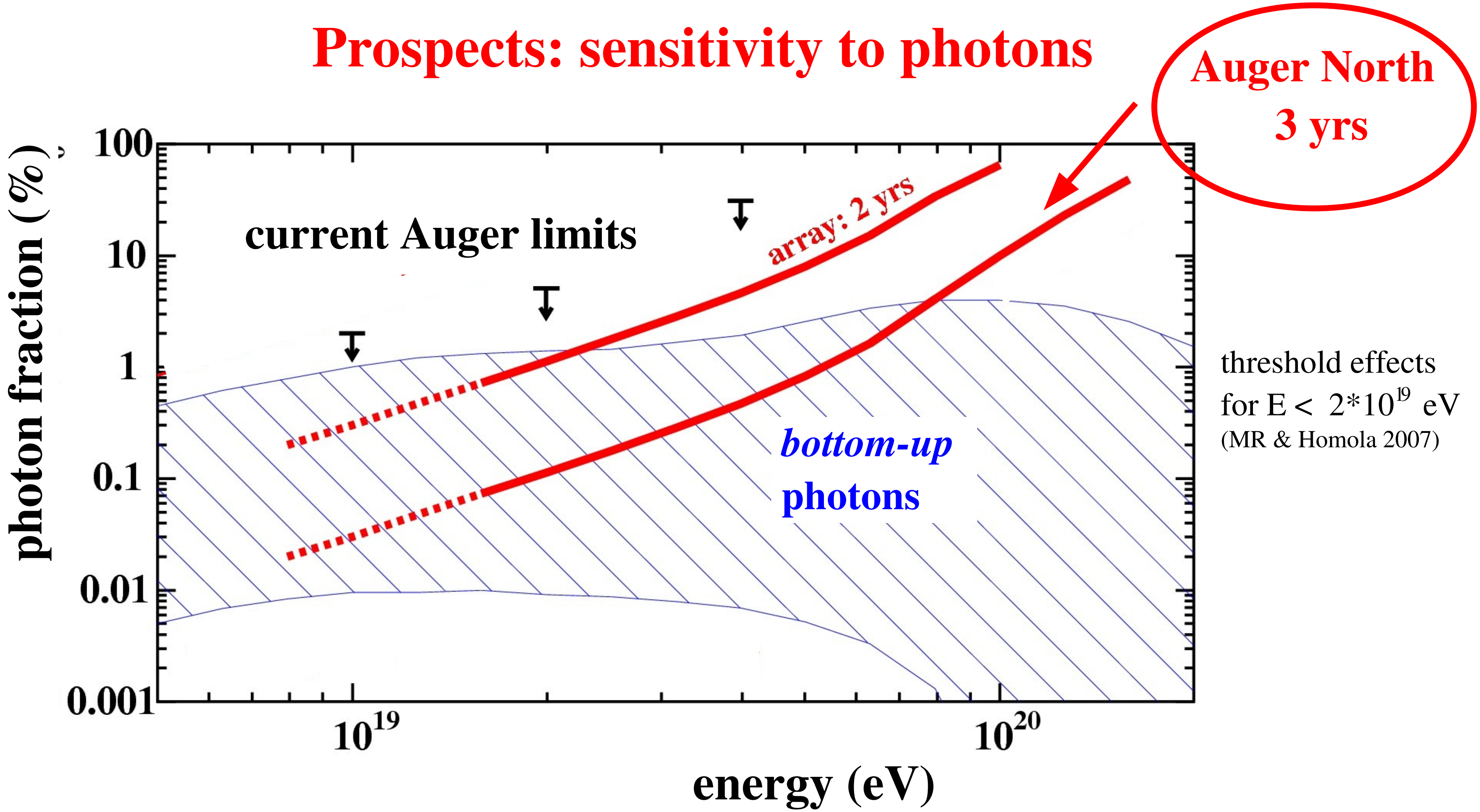
➔ **photon limits reduce spectrum syst.**





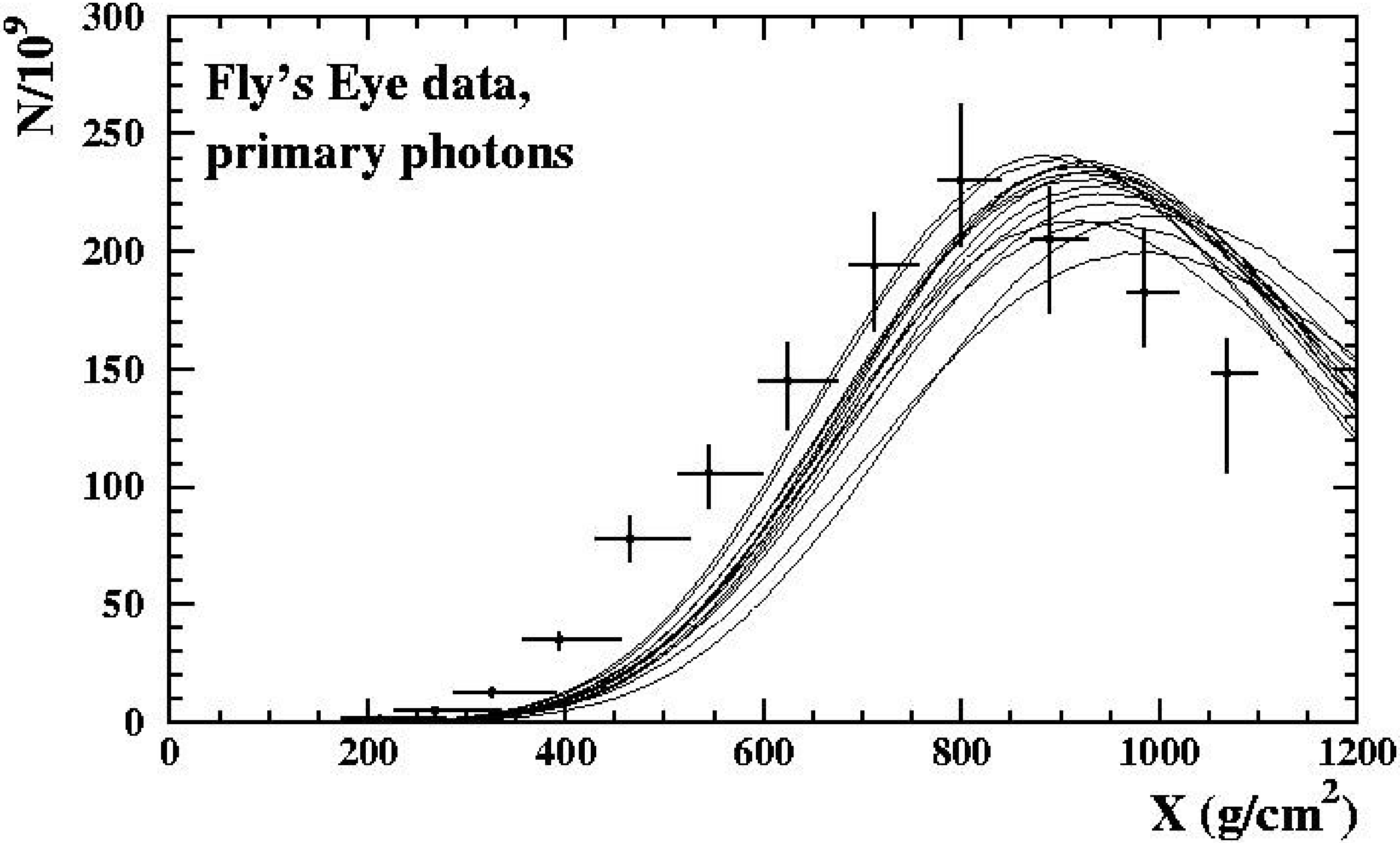
(Busca et al. 2006)

Prospects: sensitivity to photons



threshold effects
for E < $2*10^{19}$ eV
(MR & Homola 2007)

Fly's Eye event & photons



note: X errors correlated !!!
(common geometry fit)

(MR et al., 2004)

- calculate probability of primary photon hypothesis

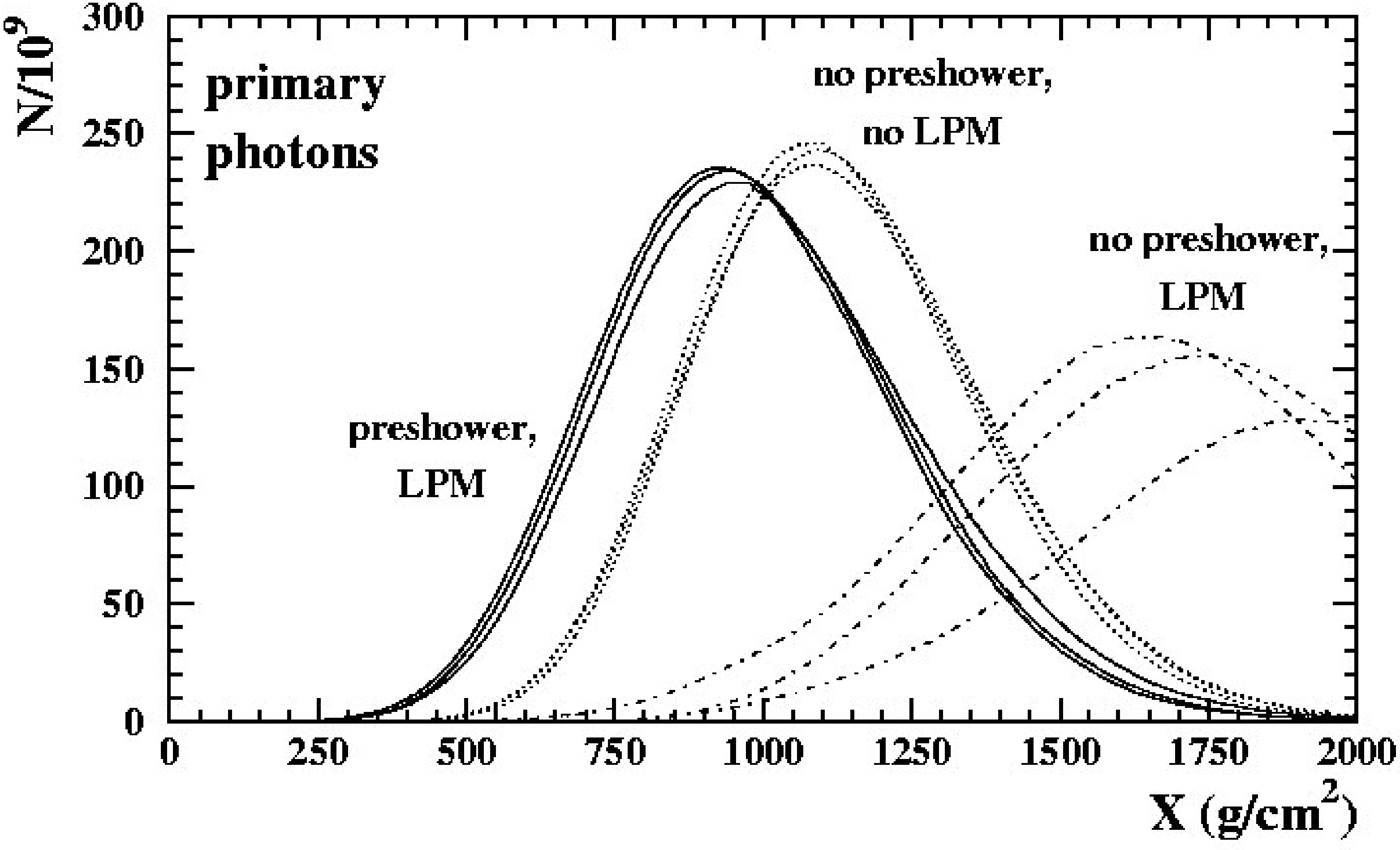
→ **photon: 1.5 sigma (13% probability)**

→ **a photon origin of the 320 EeV event is not excluded !**

- hadrons fit better, though ...

Einfluß von LPM- und Preshower-Effekt auf Profil

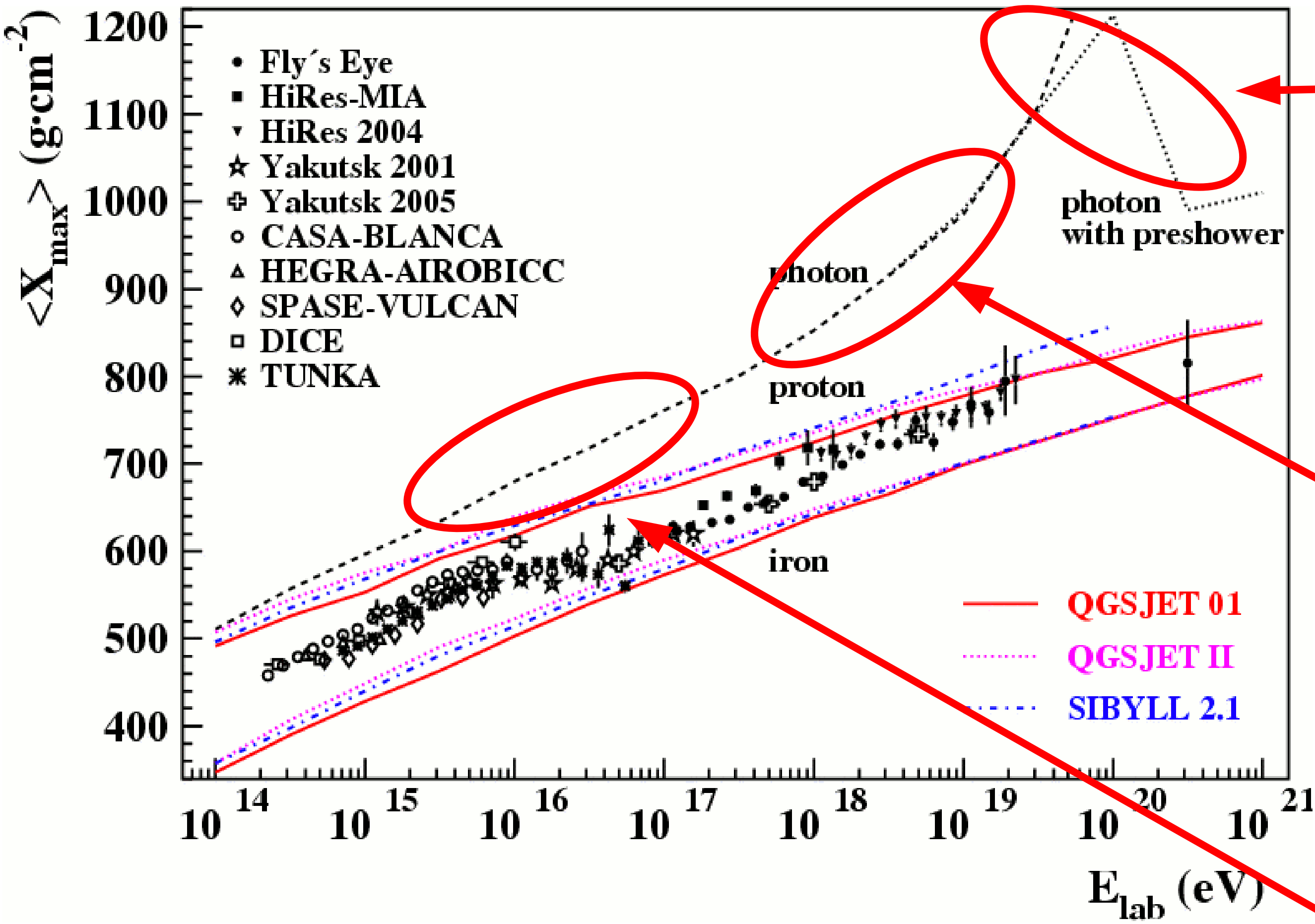
MR et al., ApP 2004



Simulationen für 320 EeV-Photonen („Fly's Eye-Event“)

- **Konkurrenz von LPM und Preshower !**

Photon-Luftschauer: neue UHE Effekte



Preshower

Photonkonversion im Erdmagnetfeld
-> Wahrschlkt. = *f(E,Richtung)*

LPM Landau-Pomeranchuk-Migdal

destruktive Interferenz in Materie
-> Wq reduziert ~$1/sqrt(\rho E)$

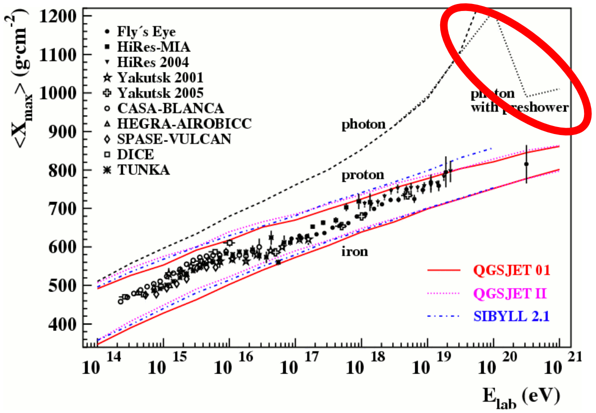
„Standard“

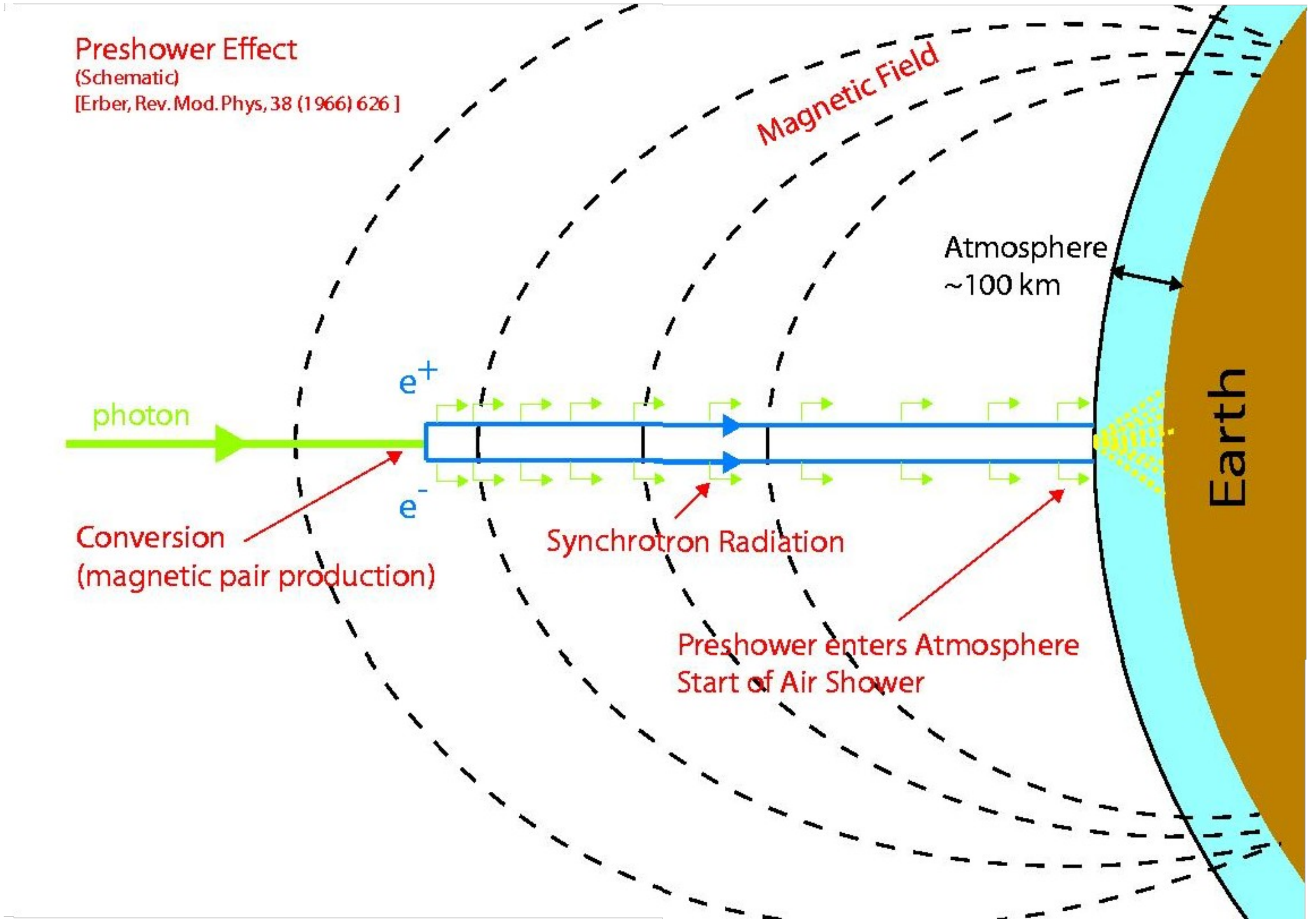
Steigung ~ 85 g cm^{-2} pro Dekade
-> Multiplizität = 2 in elmagn. WW

UHE Photonen: Preshower-Effekt

- Kaskade im Erdmagnetfeld vor “normalem“ Luftschauer
- hängt ab von **Energie** und **transv. *B*** (<-> Richtung!)

  -> PRESHOWER-Code: Homola et al. 2005





Preshower probability: sky plots

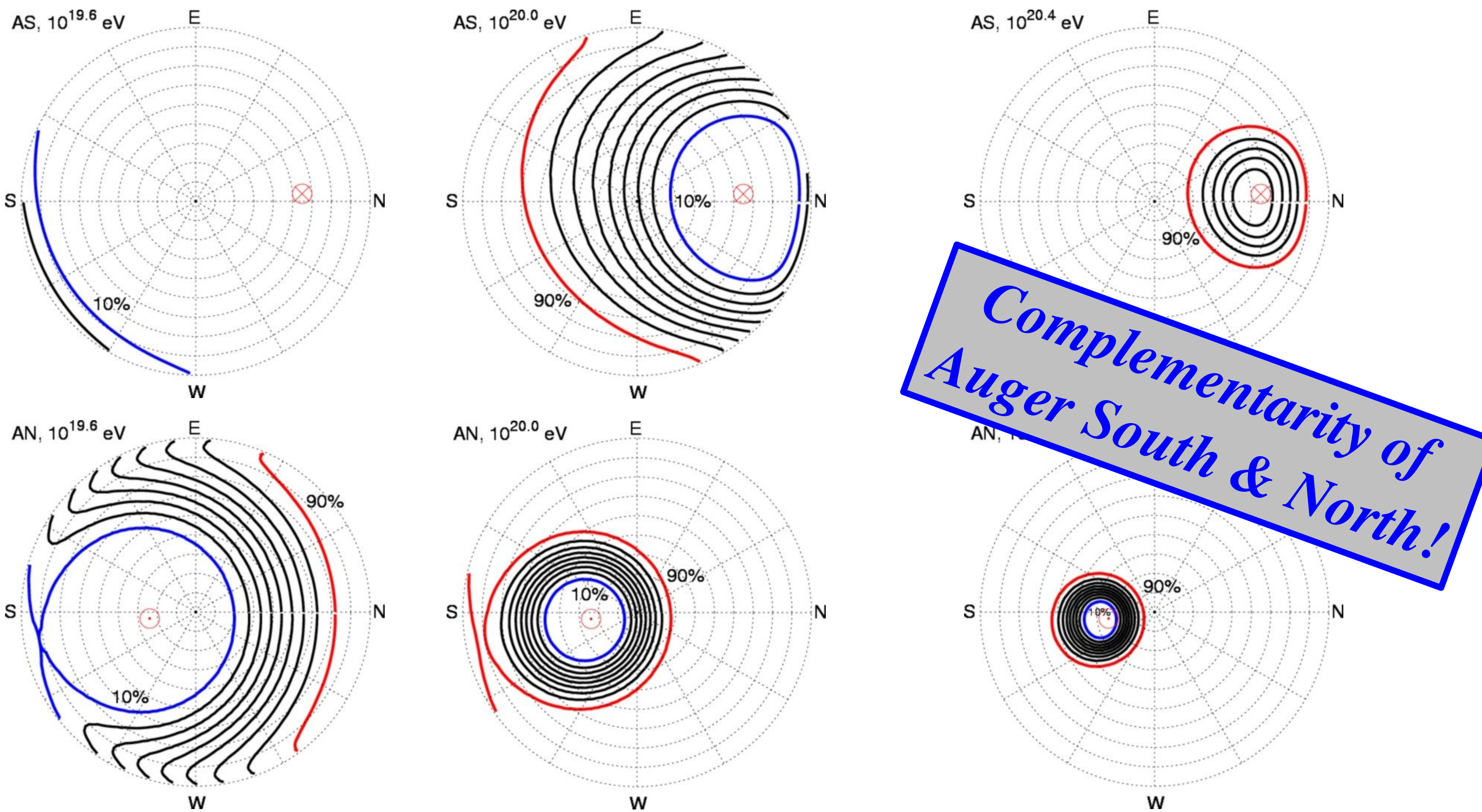
Homola et al. 2007

probability for preshower from UHE photons at ...

40 EeV **100 EeV** **250 EeV**

Auger South

Auger North



Complementarity of Auger South & North!

preshower at North ...

“starts“ at smaller energy
(factor 2 stronger field)

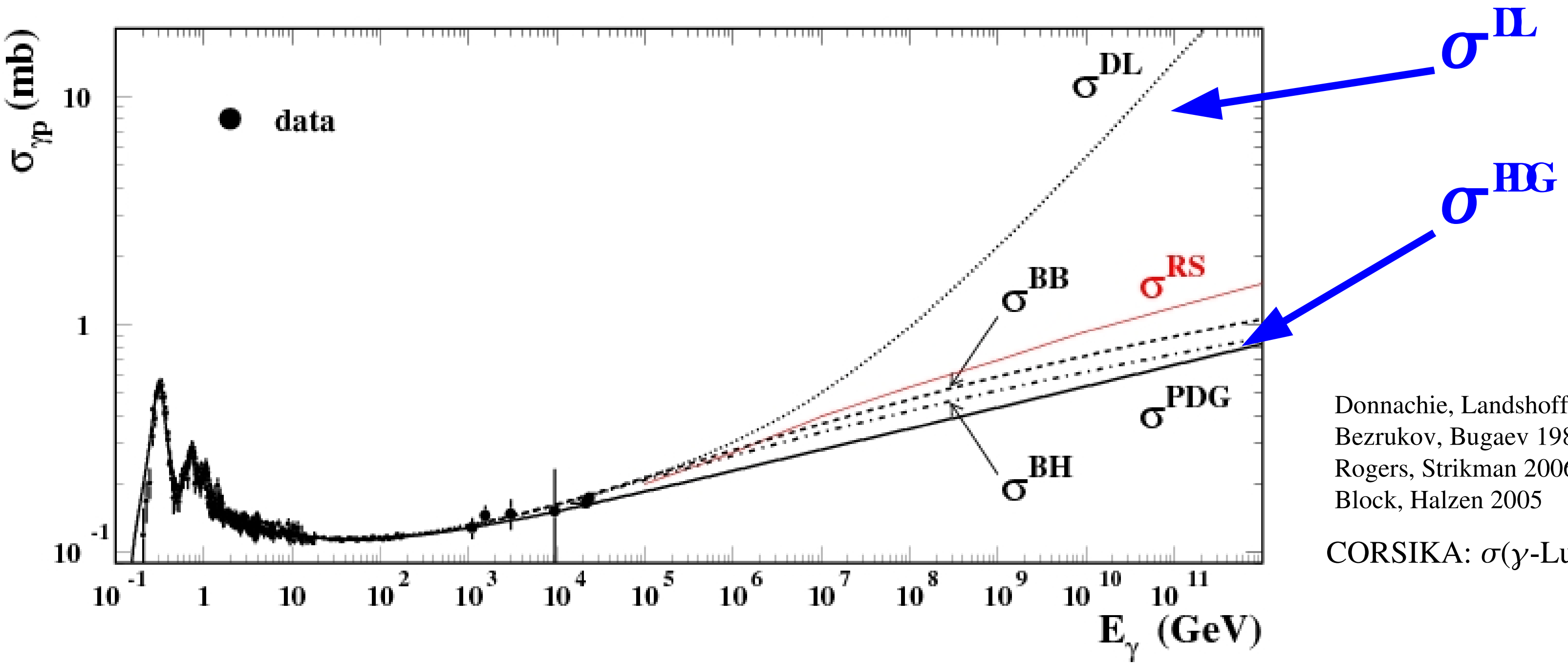
shift of sky pattern
(different field direction)

“ends“ at higher energy
(field line less curved)

Was wäre wenn ? (Physikaussichten - 2)

Beobachtung von **UHE Photon-Luftschauern**

➔ **teste QED** und **QCD** (Photoproduktion) **@ UHE**



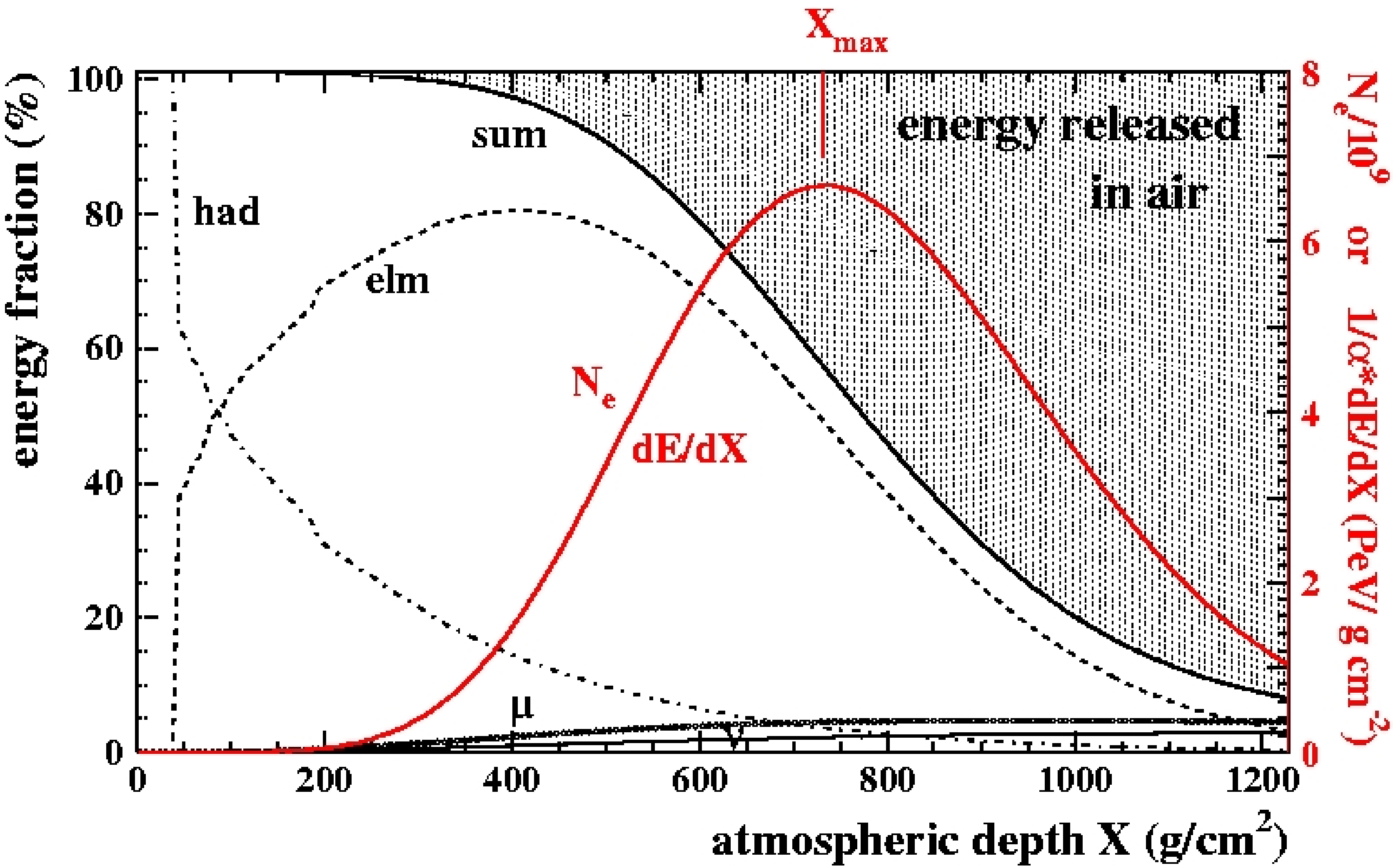
Donnachie, Landshoff 2001
Bezrukov, Bugaev 1981
Rogers, Strikman 2006
Block, Halzen 2005

CORSIKA: $\sigma(\gamma\text{-Luft})=11.44\ \sigma^{PDG}(\gamma p)$

- **σ^{PDG} -> σ^{DL} => Myonzahl x2, X_{max} -100 g cm^{-2}** *(MR et al. 2005)*
  - Theorie: σ^{DL} exotisch (=> Maximum: σ^{RS} !) *(Rogers & Strikman 2006)*

➔ falls Photonschauer „wie erwartet“ => **exp. Obergrenze auf σ**

Energy Flow in EAS: how much energy in which component?



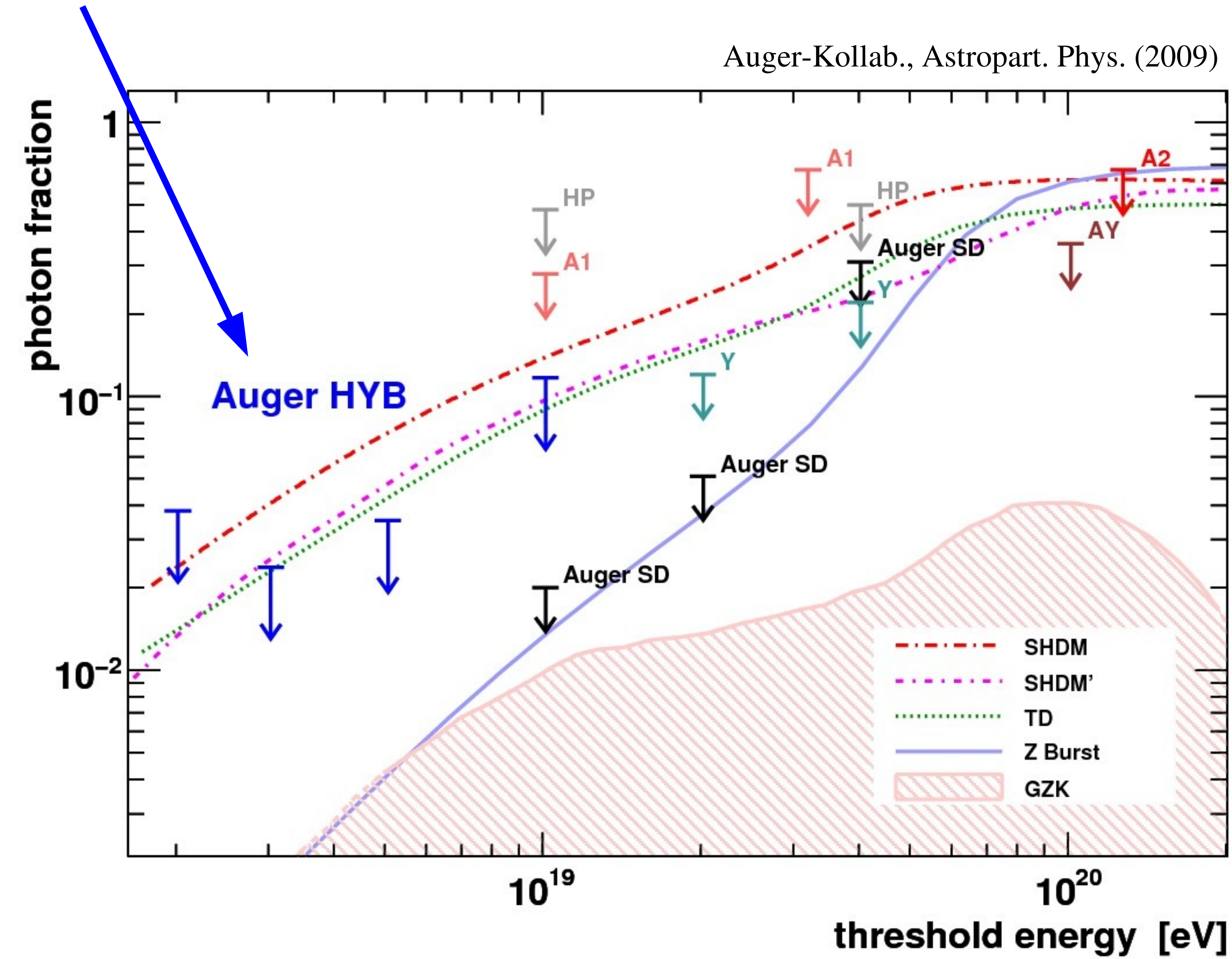
energy maximum in elm. not equal to X_{max} !

Example: proton, 10^{19} eV; CORSIKA simulations

M. Risse, Acta Phys. Polon. 2004

NEU!! Hybrid-Daten => erstes Limit im EeV-Bereich !

Auger-Kollab., Astropart. Phys. (2009)

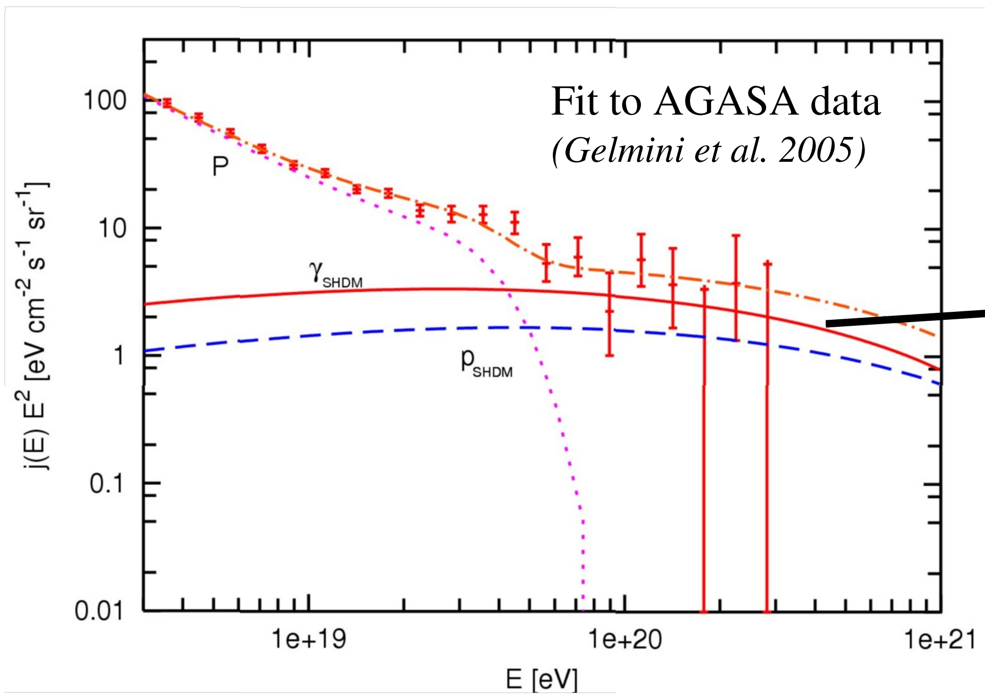


- bestätigen Einschränkungen auf *top-down*-Modelle

Super Heavy Dark Matter (SHDM)

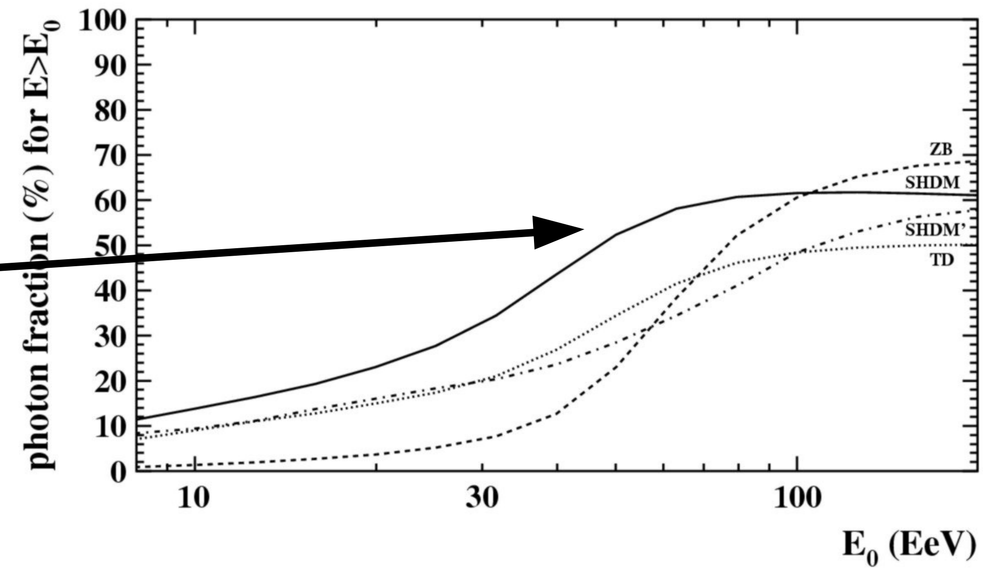
- produced during inflation; $\mathbf{M_x \sim 10^{23}}$ **eV**, clumped in **galactic halo** (overdensity $\sim 10^5$)
- lifetime $\sim 10^{20}$ y: **decay** (SUSY-QCD) => pions => **UHE photons** (and neutrinos)

➔ little processing during propagation: **decay spectrum** at Earth



(Berezinsky et al. 1997, ...)

(integral photon fraction)



➔ **photons dominate >50-80 EeV**

➔ similar shapes for ZB *(Weiler 1982, ...)* and TD *(Hill 1983, ...)* models

➔ **signature for new physics !**