



The Highest-Energy Cosmic Rays

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Cosmic Ray Discovery

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Victor Hess after his 1912 balloon flight, during which he discovered cosmic rays from space. (National Geographic)



Extended Air Showers

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P.Auger and R.Maze, C.R.Acad.Sci.Ser. **B 207** 228 (1938)

P.Auger, P.Ehrenfest, R.Maze, J.Daudin, and R.A.Fron, Rev.Mod.Phys. **11** 288-291 (1939)



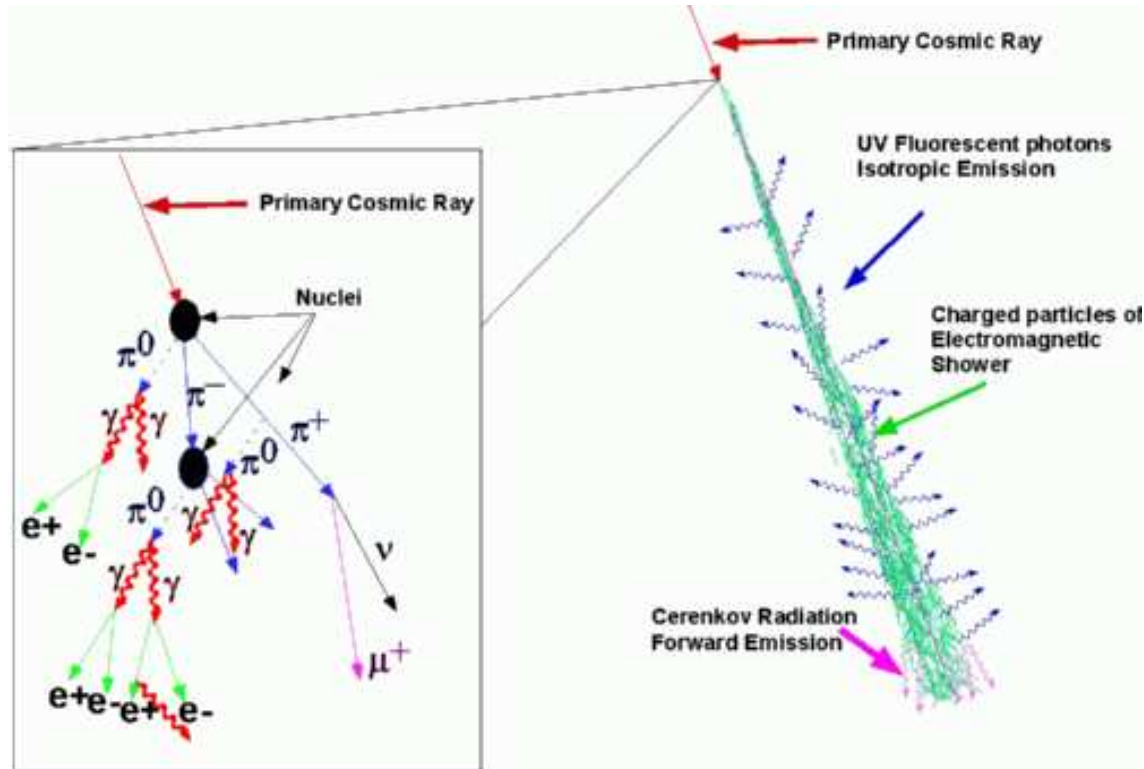
Pierre Auger, discoverer of cosmic ray air showers. (CERN)

“One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} eV is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energies along electric fields of a very great extension.”



Extended Air Showers

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Depth of atmosphere is $800 - 1200 \text{ g}\cdot\text{cm}^{-2}$.

Proton of energy $E > 10 \text{ EeV}$ interacts within $80 \text{ g}\cdot\text{cm}^{-2}$.

CMS energy $> 500 \text{ TeV}$.

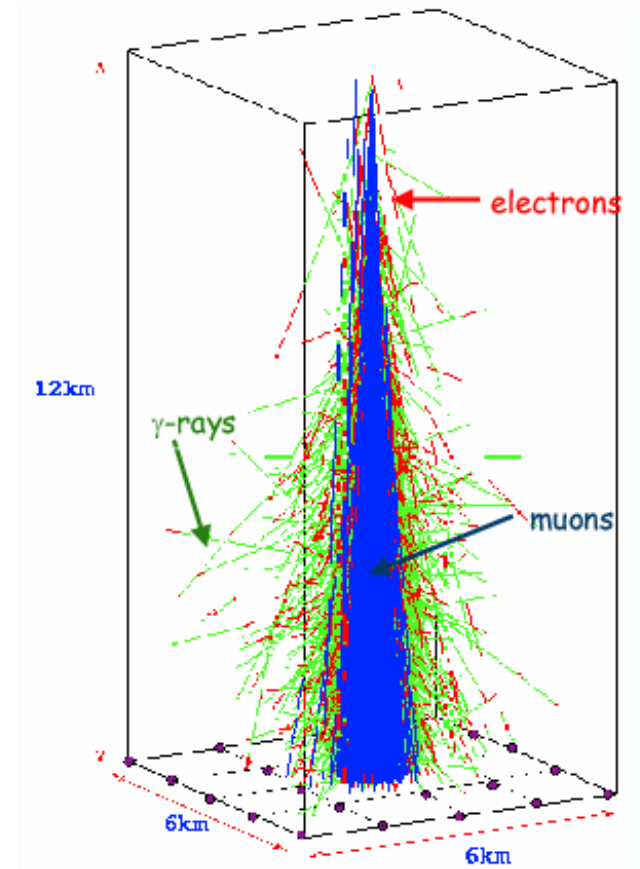
Shower develops with final number of more than 10^{10} low energy particles.



Detection of Extensive Air Showers

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Ground array – footprint of the showers – γ, e^\pm, μ^\pm .
Typically more than 10^{10} γ in area $10 - 50 \text{ km}^2$.
Number of low energy particles \rightarrow primary energy.
Space-time signal \rightarrow arrival direction.
Number of e^\pm/μ^\pm \rightarrow type of primary particle.





Detection of Extensive Air Showers

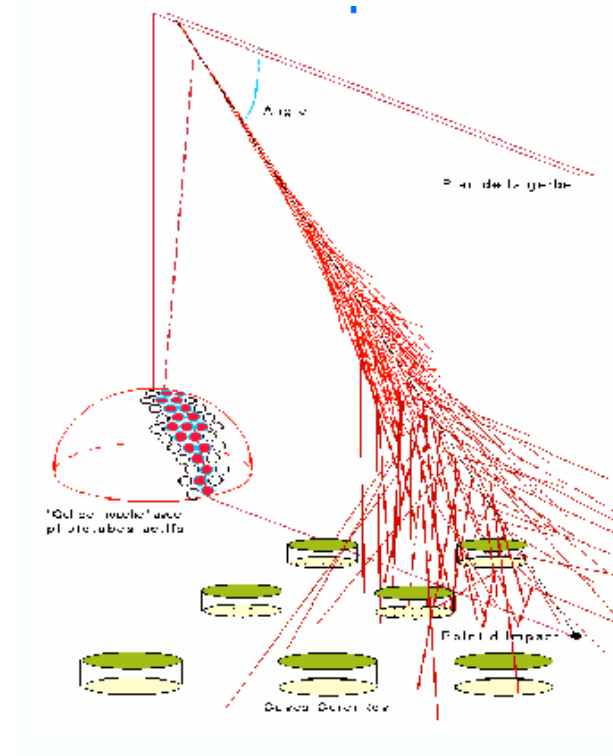
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Fluorescence technique – N_2 light along shower.

Total amount of light \rightarrow primary energy.

Shape of shower \rightarrow primary particle.

Time structure of signal \rightarrow arrival direction.





Experiments

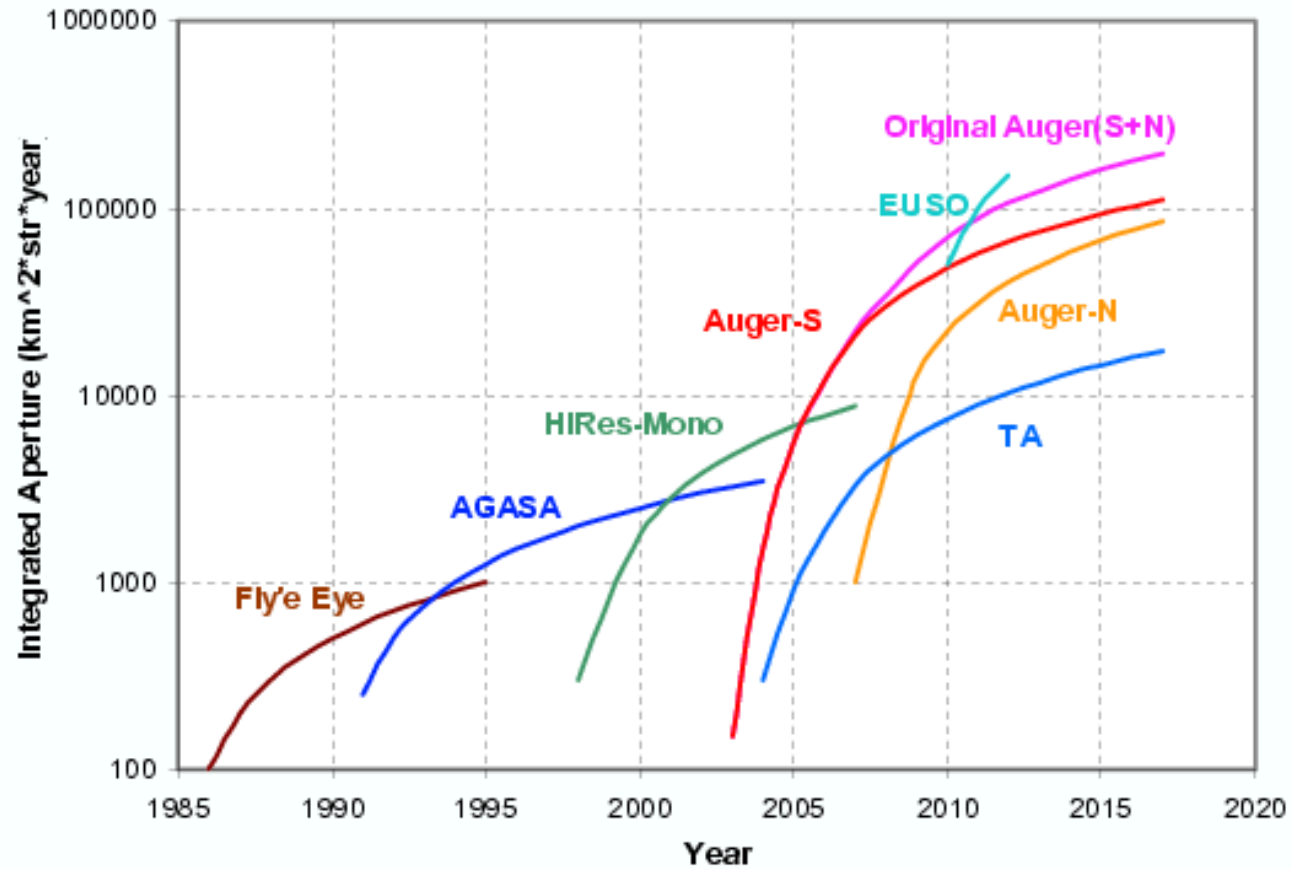
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Experiment	Operation	Latitude	Longitude	Altitude [m]	Depth [g·cm ⁻²]	Area [km ²]	Detection	Events > 40 EeV
Volcano Ranch	1959-63	35°09' N	106°47' W	1770	843	8	SC	8
SUGAR	1968-79	30°32' S	149°43' E	250	1015	60	SC	80
Haverah Park	1968-87	53°58' N	1°38' W	200	1016	12	WČ	26
Yakutsk	1974-	61°36' N	129°24' E	105	1020	18/10	SC/AČ	9
Fly's Eye	1981-93	40° N	113° W		869		F	> 1
HiRes	1998-	40.3°N	112.5° W		869		F	(27)
AGASA	1990-04	35°47' N	138°30' E	900	920	100	SC	72
AUGER S	2004-	35°20' S	69°20' E	1400	870	3000	F/WČ	



Experiments - Exposure

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at $E = 100 \text{ EeV}$



Experiments

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First detection of $E \geq 100$ EeV primary: John Linsley, Phys.Rev.Lett. **10**, 146-148 (1963)
20 tanks, $5 \cdot 10^{10}$ particles

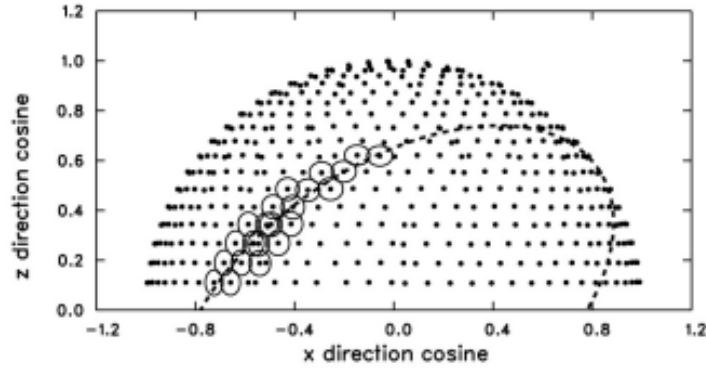


John Linsley checking for rattlesnakes in the straw covering his detectors, at the Volcano Ranch array in New Mexico.

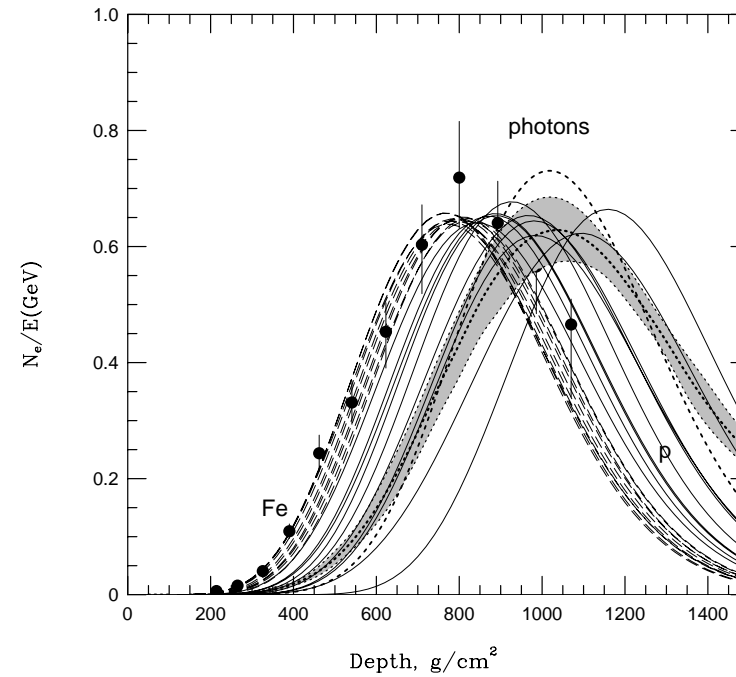
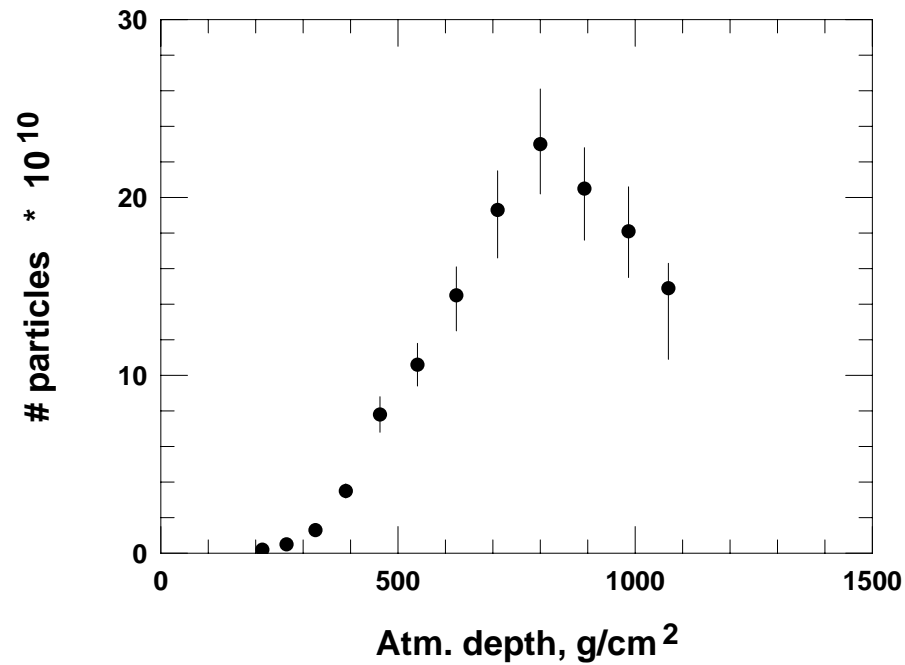


Highest Energy Event - Fly's Eye

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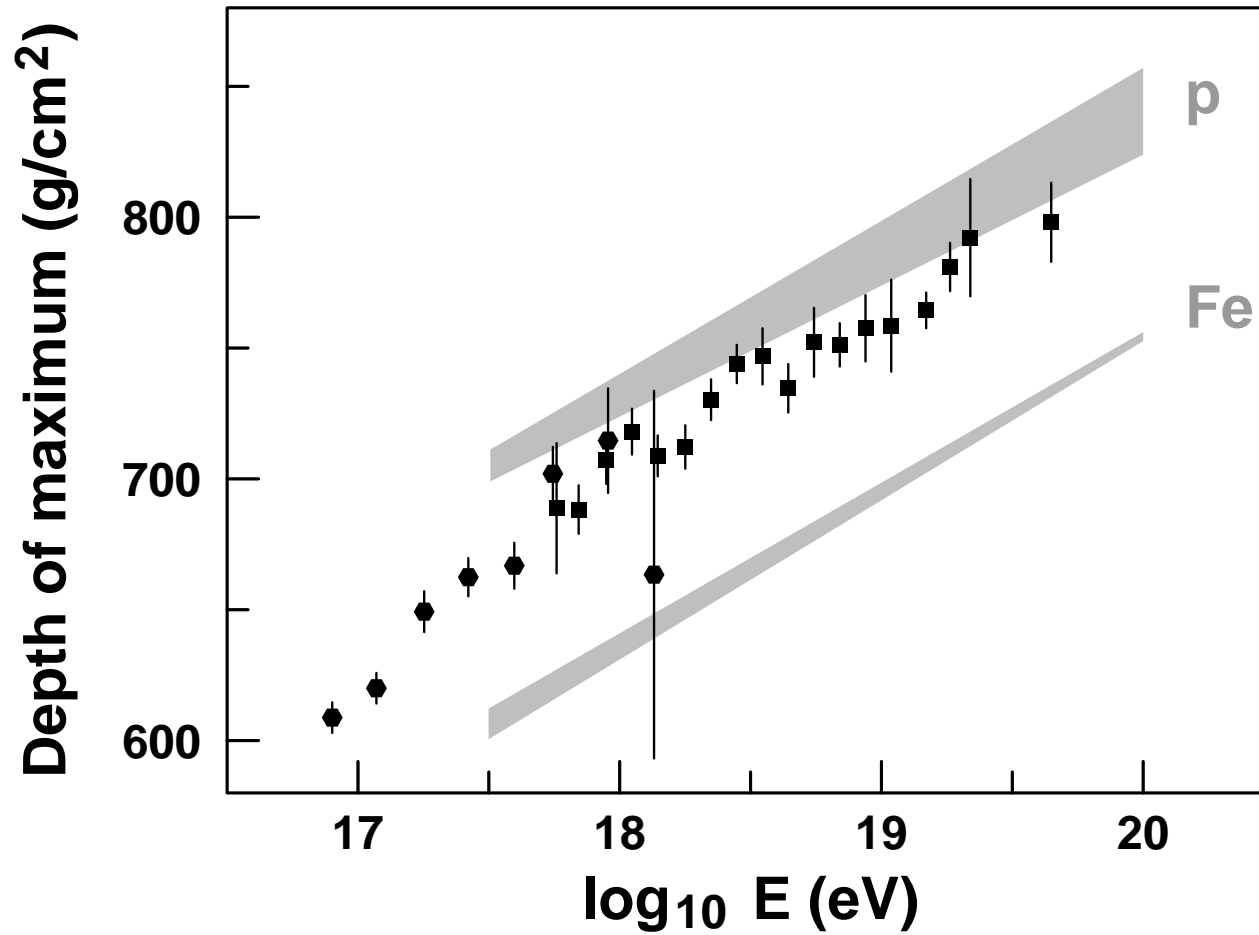
November 1991
 $E \approx 320 \text{ EeV} (50 \text{ J})$ $5 \times$ GZK limit
FE1 detector
 $X_{max} \approx 800 \text{ g} \cdot \text{cm}^{-2}$
hadron-initiated air shower





Composition - HiRes

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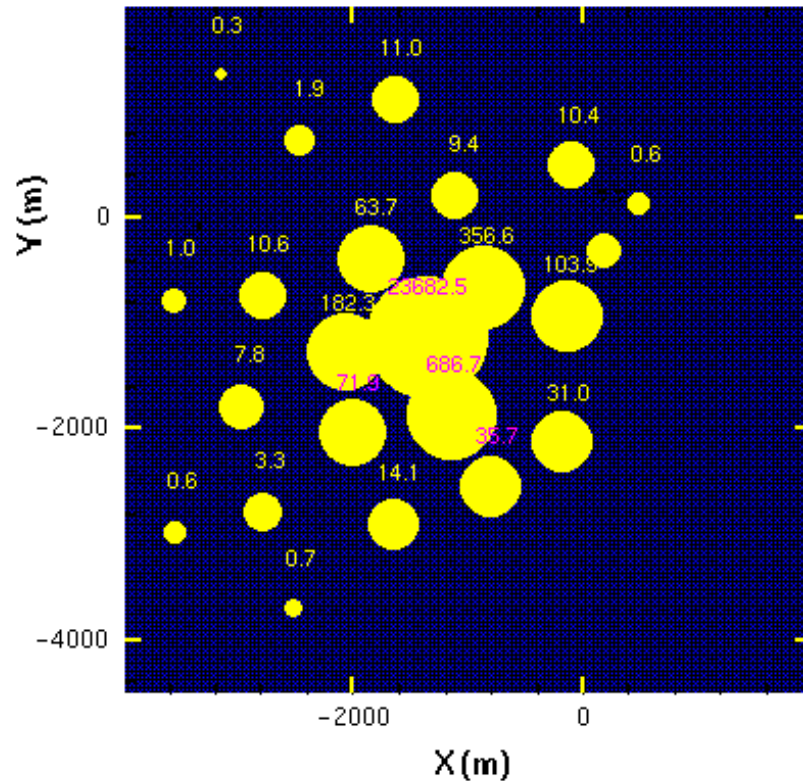


HiRes Collaboration, *Astrophys.J.* 622 (2005) 910-926, astro-ph/0407622



Highest Energy Event - AGASA

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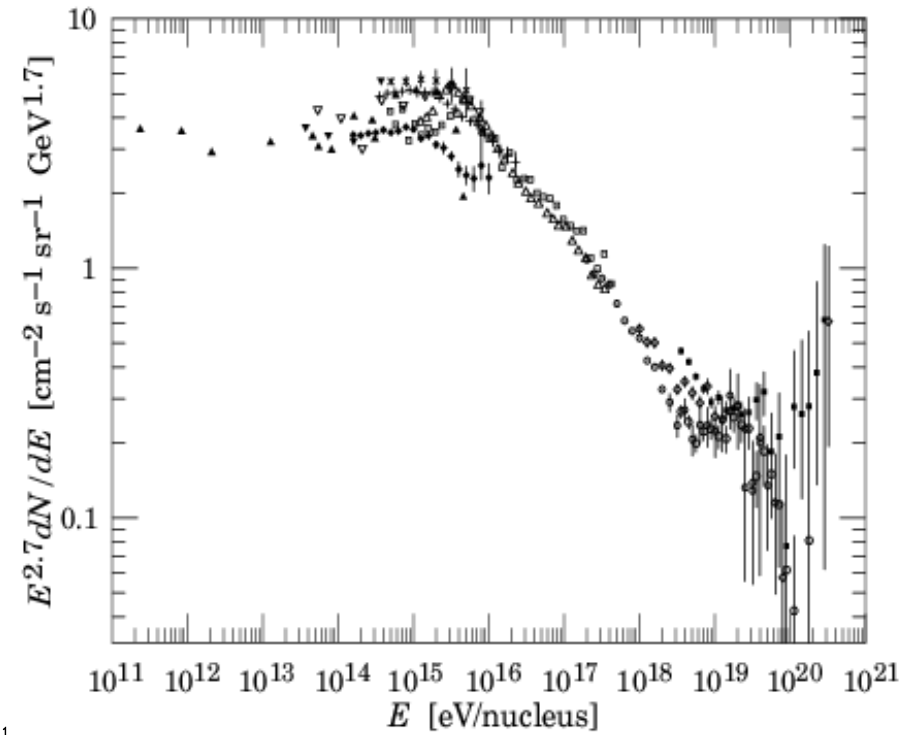
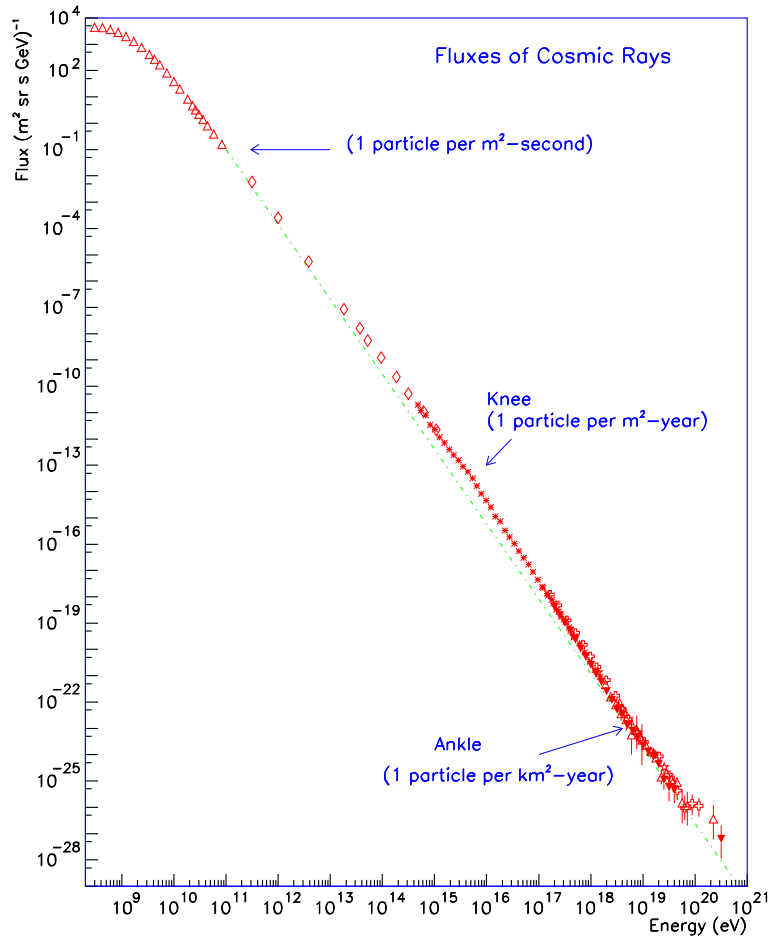


December 3, 1993
 $E \approx 200 \text{ EeV}$

Shown is a map of the particle density distribution of this superbig event. The radius of each circle represents the logarithm of the density at each detector location. The associated particles spread over a 6km x 6km area.



CR spectrum





Greisen–Zatsepin–Kuzmin cutoff

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K.Greisen, Phys.Rev.Lett. **16** (1966) 748
“End to the cosmic-ray spectrum?”

G.T.Zatsepin, V.A.Kuzmin, Sov.Phys.JETP **4** (1966) 78
“O verchnej granice spektra kosmiceskich lucej”



Georgi Zatsepin, with a cable around his neck, prepares the Pamir air shower experiment in Russia in 1946.



Greisen–Zatsepin–Kuzmin cutoff

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CMB photon: $E_0 = \frac{\pi^4}{30\zeta(3)}kT_{\gamma,0} \approx 0.636 \cdot 10^{-3} \text{ eV}$, ($T_{\gamma,0} = 2.73 \text{ K}$)

$$p + \gamma_{\text{CMB}} \longrightarrow p + \pi^0, n + \pi^+, \quad E_{\text{th}} = \frac{(2m_p + m_\pi)m_\pi}{4E_0} \approx 100 \text{ EeV}, \quad \frac{\Delta E}{E_{\text{th}}} = \frac{m_\pi}{m_p + m_\pi} \approx 0.126$$

$$p + \gamma_{\text{CMB}} \longrightarrow p + e^- + e^+, \quad E_{\text{th}} = \frac{(m_p + m_e)m_e}{E_0} \approx 0.8 \text{ EeV}, \quad \frac{\Delta E}{E_{\text{th}}} = \frac{2m_e}{m_p + m_e} \approx 10^{-3},$$

$$A + \gamma_{\text{CMB}} \longrightarrow A + e^- + e^+, \quad E_{\text{th}} \approx \frac{Am_N m_e}{E_0}, \quad \frac{\Delta E}{E_{\text{th}}} \approx \frac{2m_e}{Am_N}$$

$$A + \gamma_{\text{CMB}} \longrightarrow (A - k) + kN, \quad k = 1, 2, \quad E_{\text{GDR}} \approx \text{MeV}$$

$$\gamma + \gamma_{\text{CMB}} \longrightarrow e^- + e^+, \quad E_{\text{th}} = \frac{m_e^2}{E_0} \approx 0.4 \text{ PeV}$$

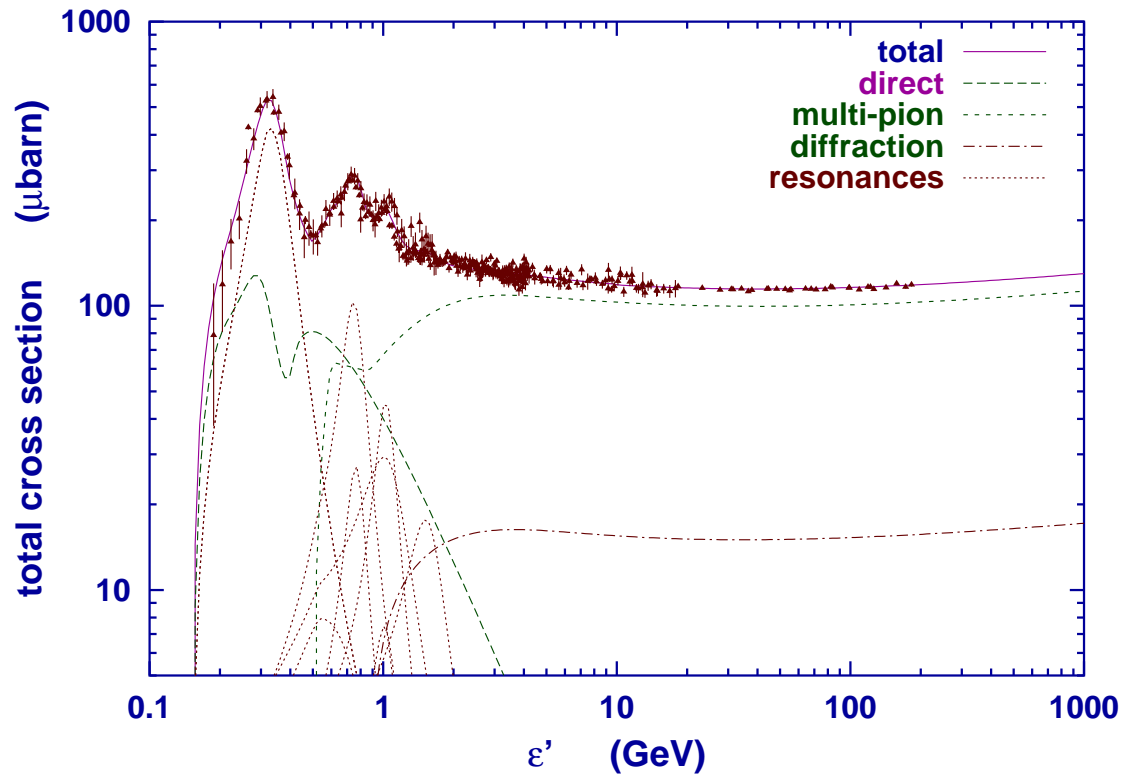
Proton, photon and neutrino fluxes are connected by a well-defined way.

$$N + \gamma_{\text{CMB}} \rightarrow N + \sum \pi, \quad \pi^0 \rightarrow 2\gamma, \quad \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \quad \mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$



Cross section

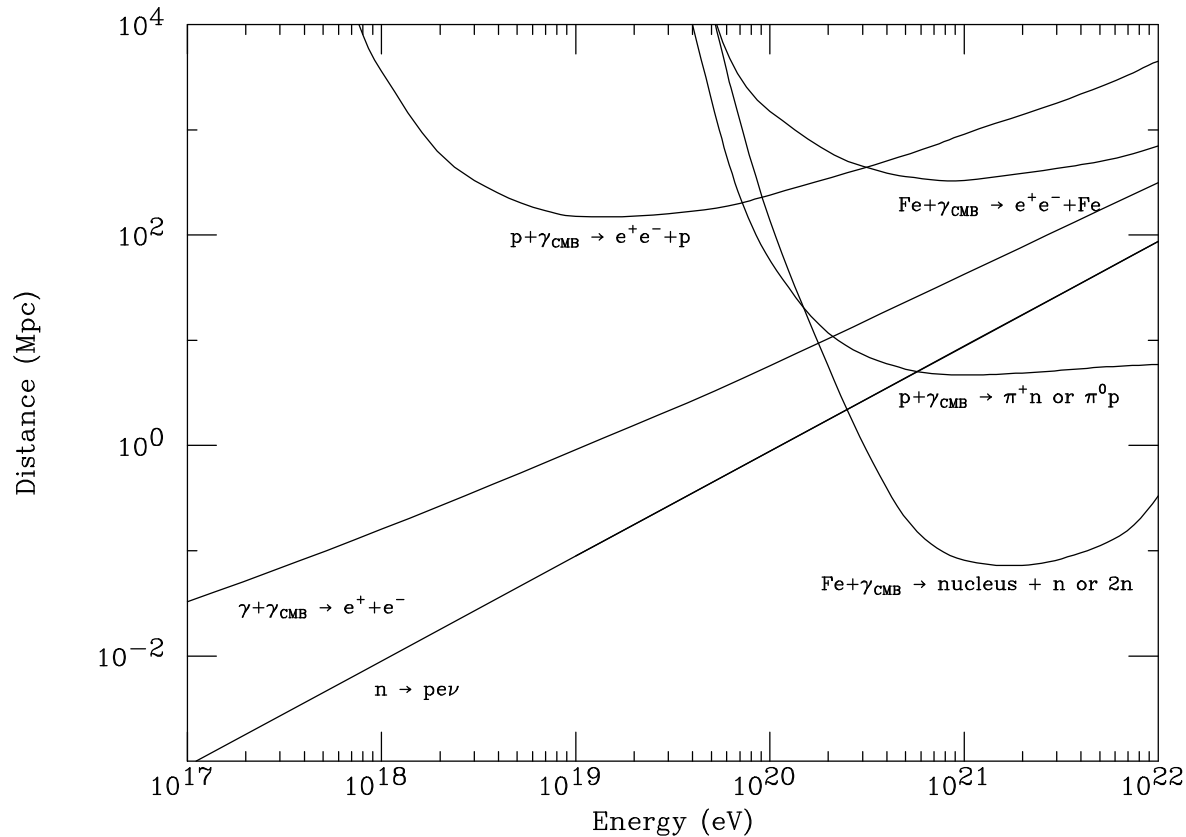
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Photoproduction cross section as a function of the photon energy for stationary proton targets.



CR propagation



Panorama of the interactions of possible cosmic primaries with the CMB.
(J.Cronin, astro-ph/0402487)

$p + \gamma_{\text{CMB}} \rightarrow e^+e^- + p$, $\text{Fe} + \gamma_{\text{CMB}} \rightarrow e^+e^- + \text{Fe}$... energy loss lengths

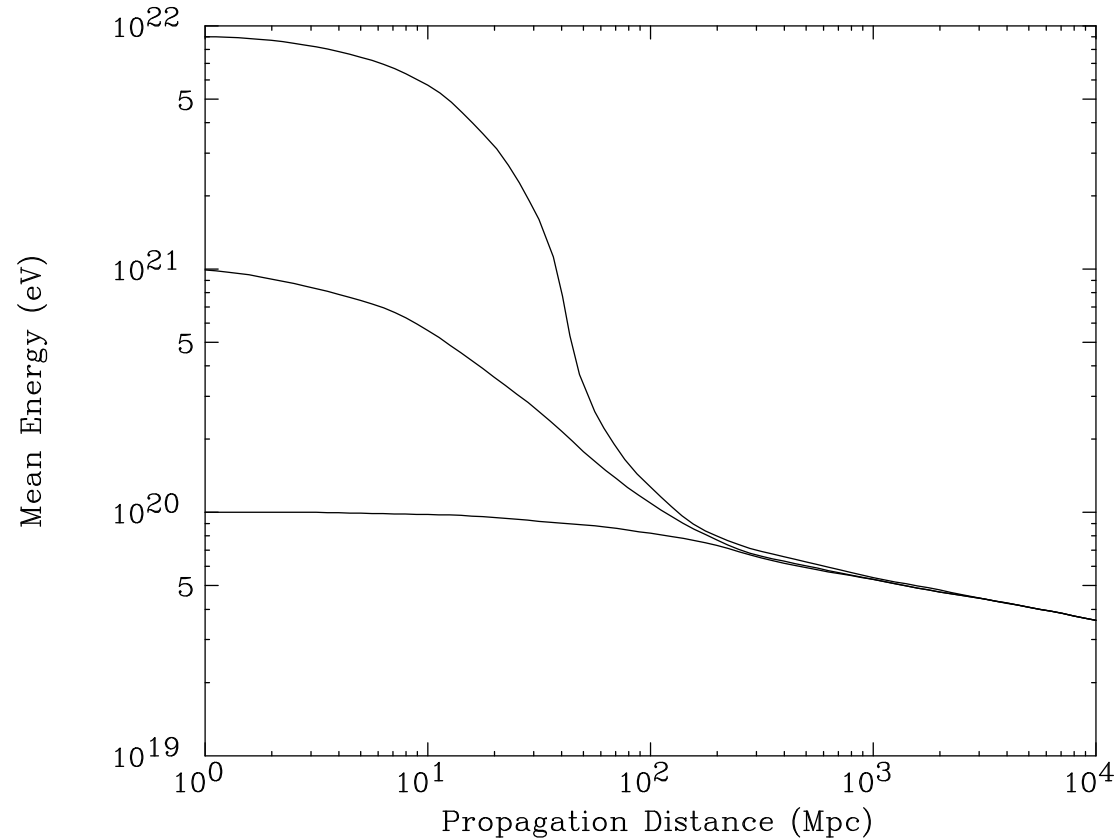
$p + \gamma_{\text{CMB}} \rightarrow \pi^+n$, π^0p , $\text{Fe} + \gamma_{\text{CMB}} \rightarrow \text{nucleus} + n$ or $2n$, $\gamma + \gamma_{\text{CMB}} \rightarrow e^+e^-$... mean free path

$n \rightarrow pe\nu$... mean decay length for a neutron



CR propagation

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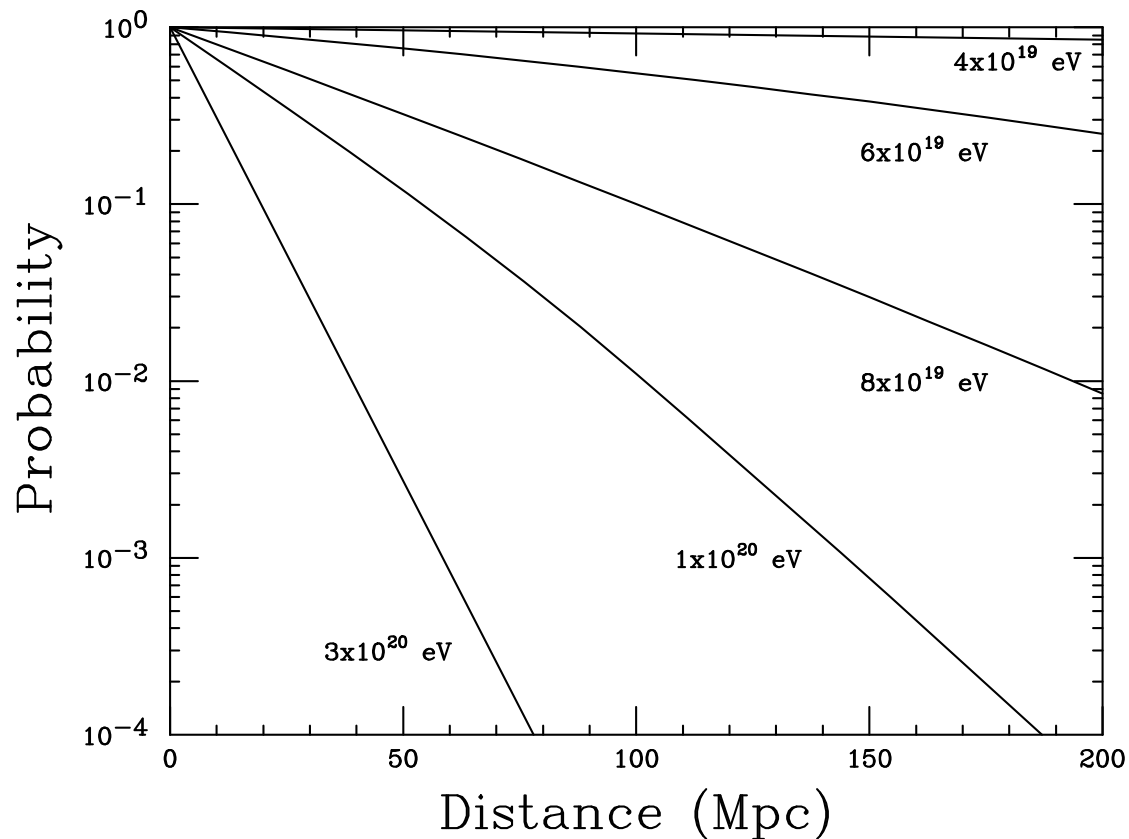
The mean energy of a nucleon as a function of propagation distance through the CMB.

(J.Cronin, astro-ph/0402487)

Significant energy loss, stochastic interaction. The anisotropic distribution of possible sources < 100 Mpc \rightarrow not simple estimation of post-GZK spectrum \rightarrow entire sky.



CR propagation



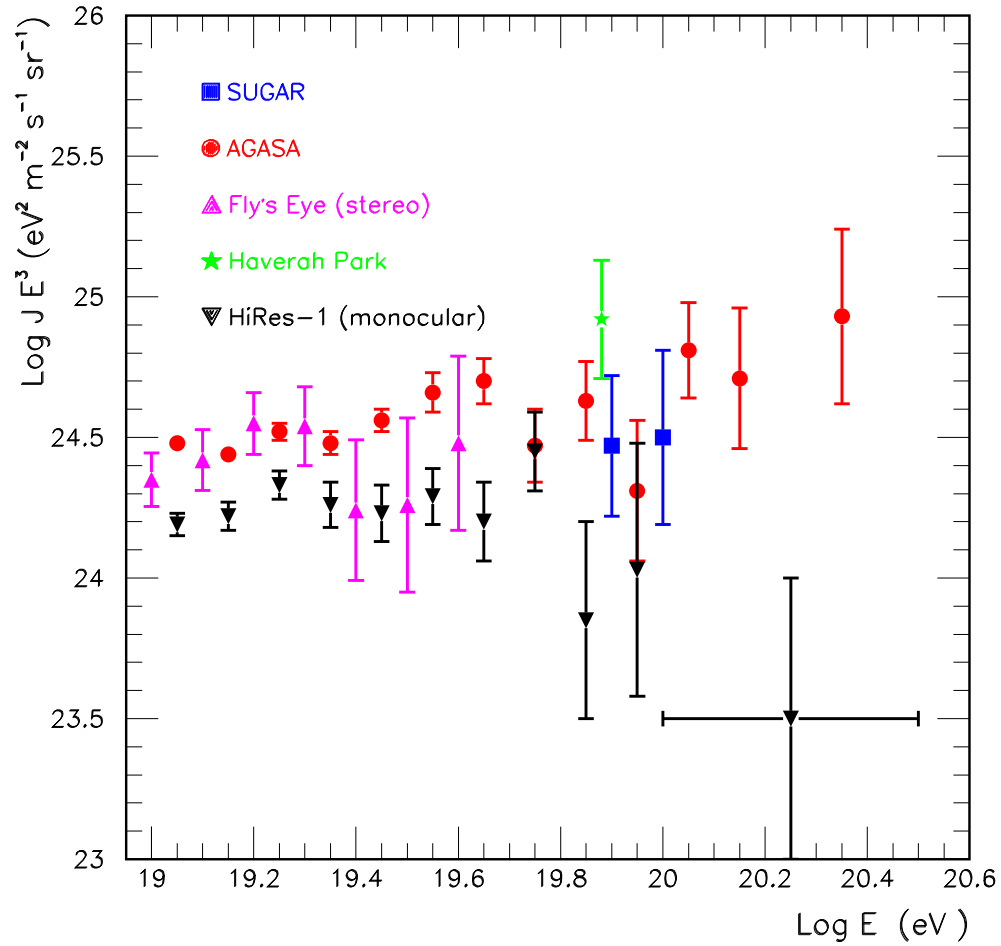
The probability that the proton came from a distance greater than a specified amount with an assumed source spectrum of $E^{-2.5}$. (J.Cronin, astro-ph/0402487)

GZK interaction significant for $E > 80$ EeV, $P < 10\%$ for $l > 100$ Mpc, HiRes single event $E \approx 320$ EeV – 0.1% chance of having traveled more than 50 Mpc.



GZK and experiment

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Systematic errors 20 – 30%
All see super-GZK events
Above GZK - disagreement



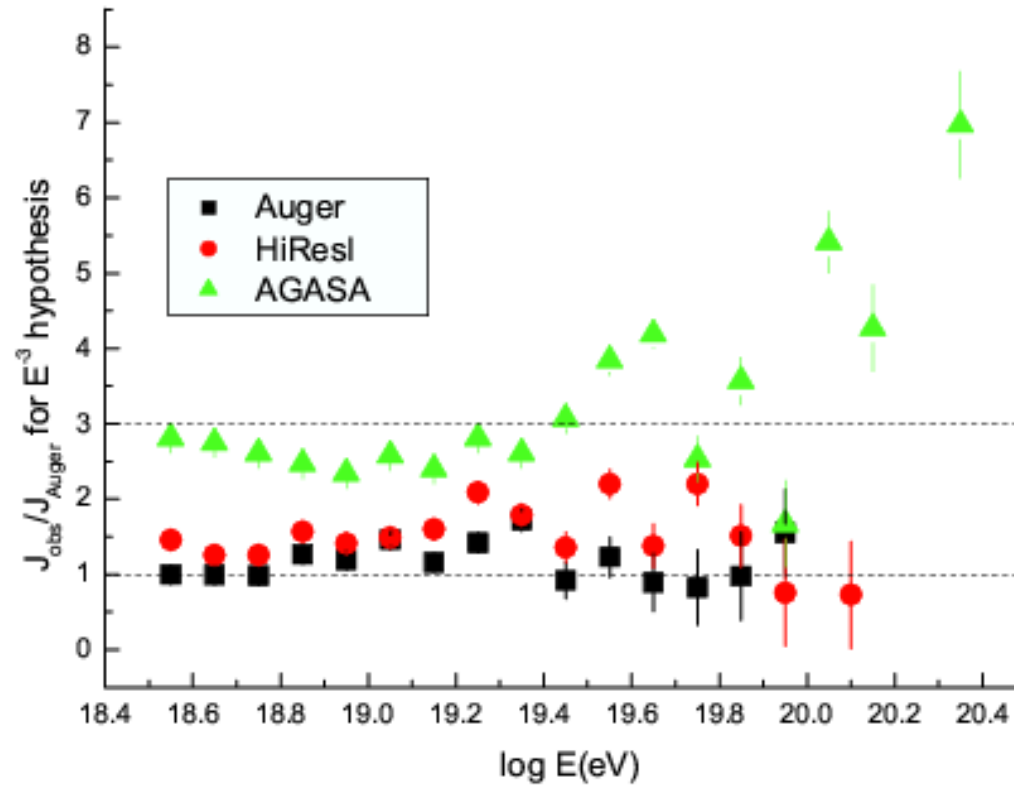
GZK and experiment

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Experiment	2003				2005		
	Exposure [km ² sr y]	Events $E > 10,$	40,	100 EeV	Exposure [km ² sr y]	Events > 10 EeV	Rate [(km ² sr y) ⁻¹]
Volcano Ranch	60	6	1				
Haverah Park	230	106	27	4			
Yakutsk	420	130	12	1	≈900	171	0.19
Fly's Eye mono	820	297	22	1			
Fly's Eye stereo	140	67	2	0			
HiRes I mono					≈ 5000	403	0.08
HiRes stereo					≈ 2500	≈500	≈0.20
AGASA	1200	775	59	8	1600	827	0.52
AUGER					1750	444	0.25



GZK and AUGER

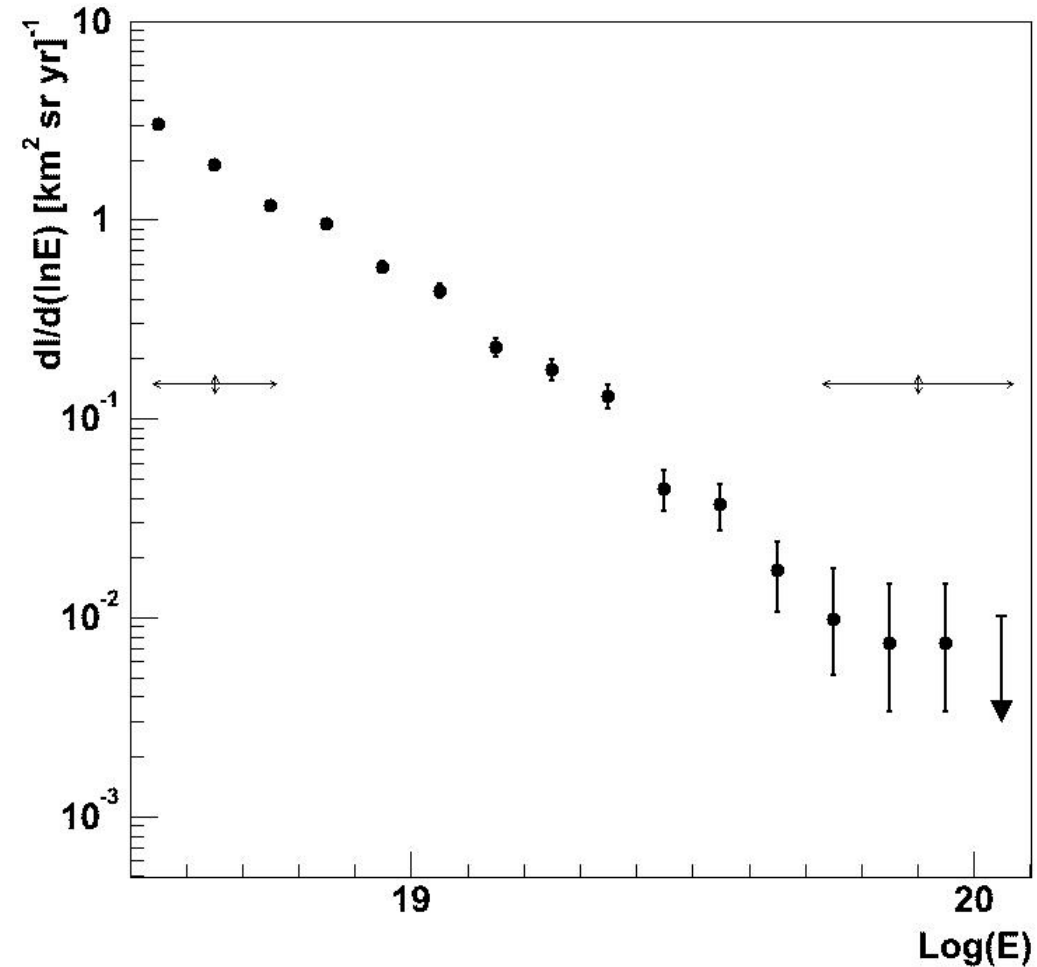


Differences between different measurements. The ratio of the value of each point with respect to a fit of E^{-3} to the first point of the Auger spectrum at $E = 3.55$ EeV contains 1216 events. (A.Watson, astro-ph/0511800)



CR spectrum – AUGER

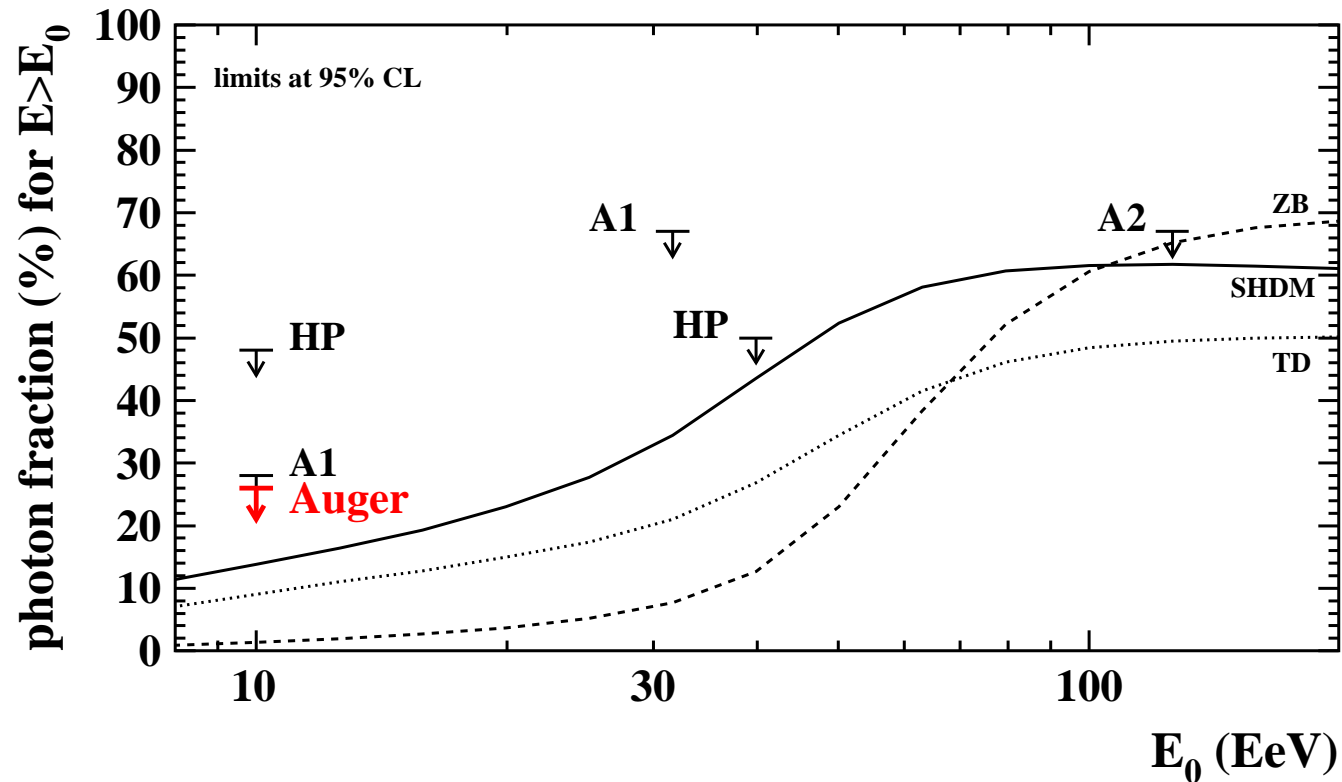
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P.Sommers for The Pierre Auger Collaboration, ICRC 2005, usa-sommers-P-abs1-he14-oral
systematic uncertainties in energy 30 – 50% at 3 – 100 EeV and 10% in exposure



Photon limit – AUGER



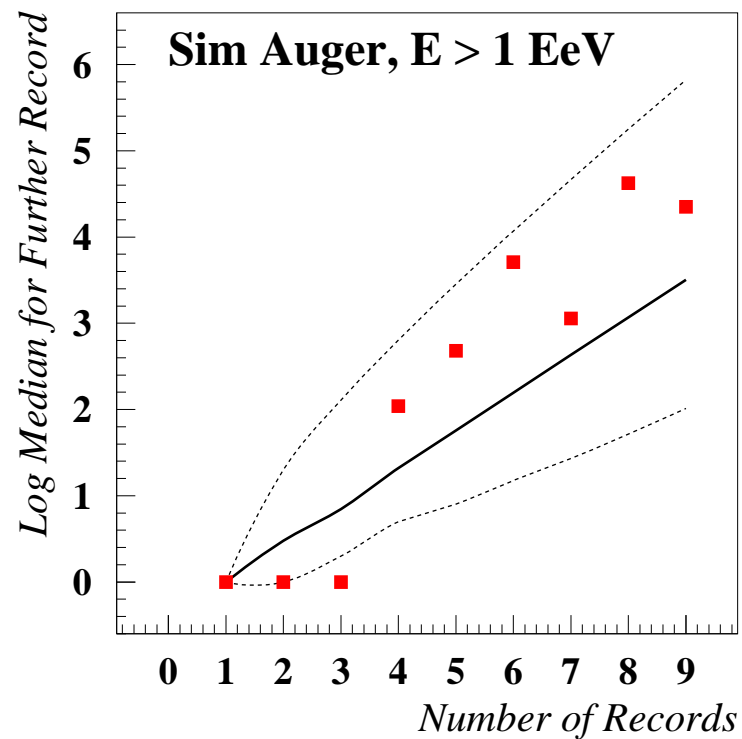
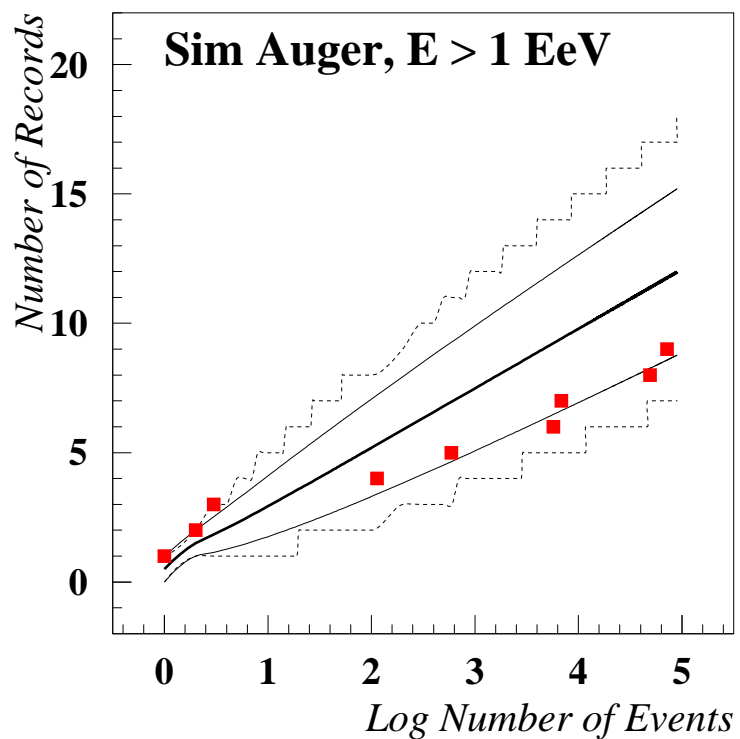
Upper limits (95% CL) on cosmic-ray photon fraction derived in the present analysis (Auger) and previously from AGASA (A1), (A2) and Haverah Park (HP) data compared to some estimates based on non-acceleration models. $\gamma < 26\%$ at 10 EeV.

M.Risse and The Pierre Auger Collaboration, ICRC 2005, ger-risse-M-abs2-he14-oral



Energy Best - AUGER

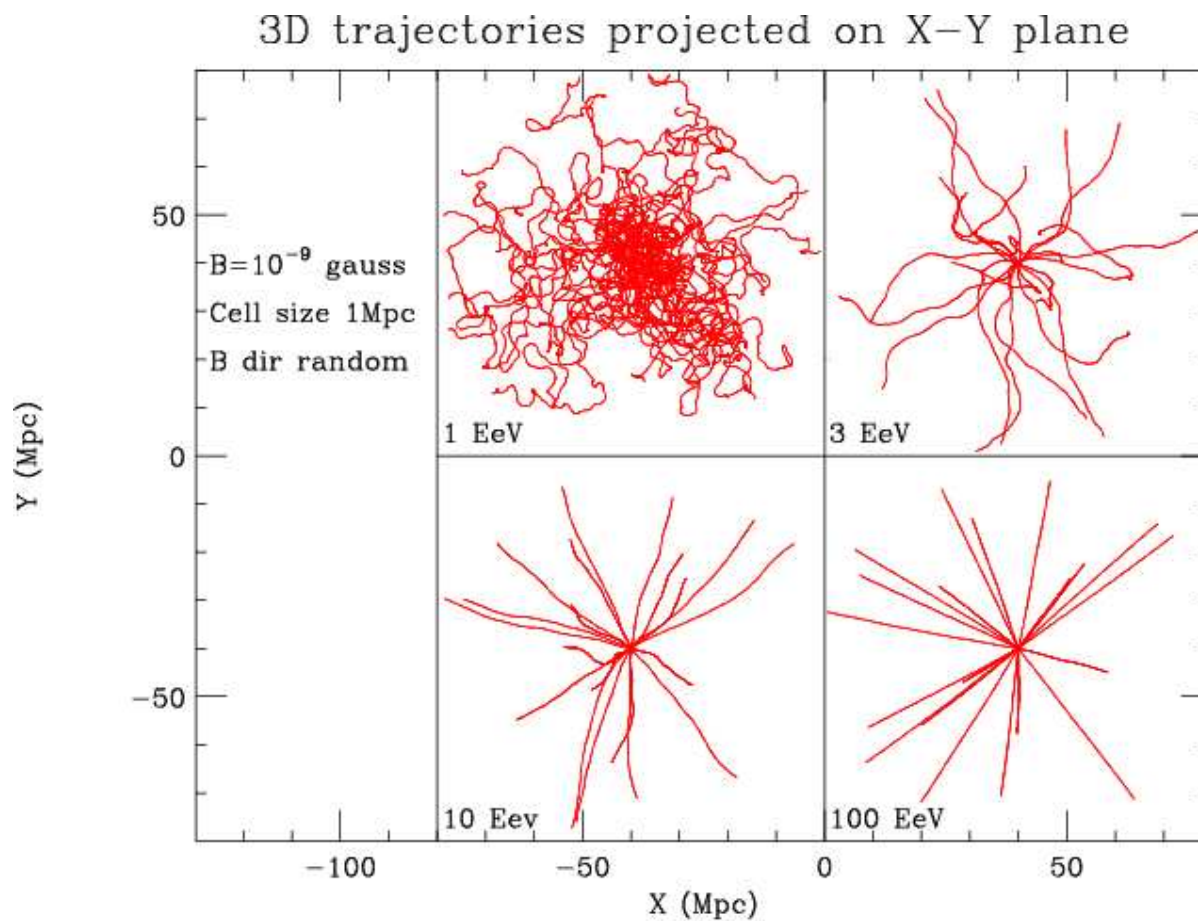
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CR propagation - magnetic field

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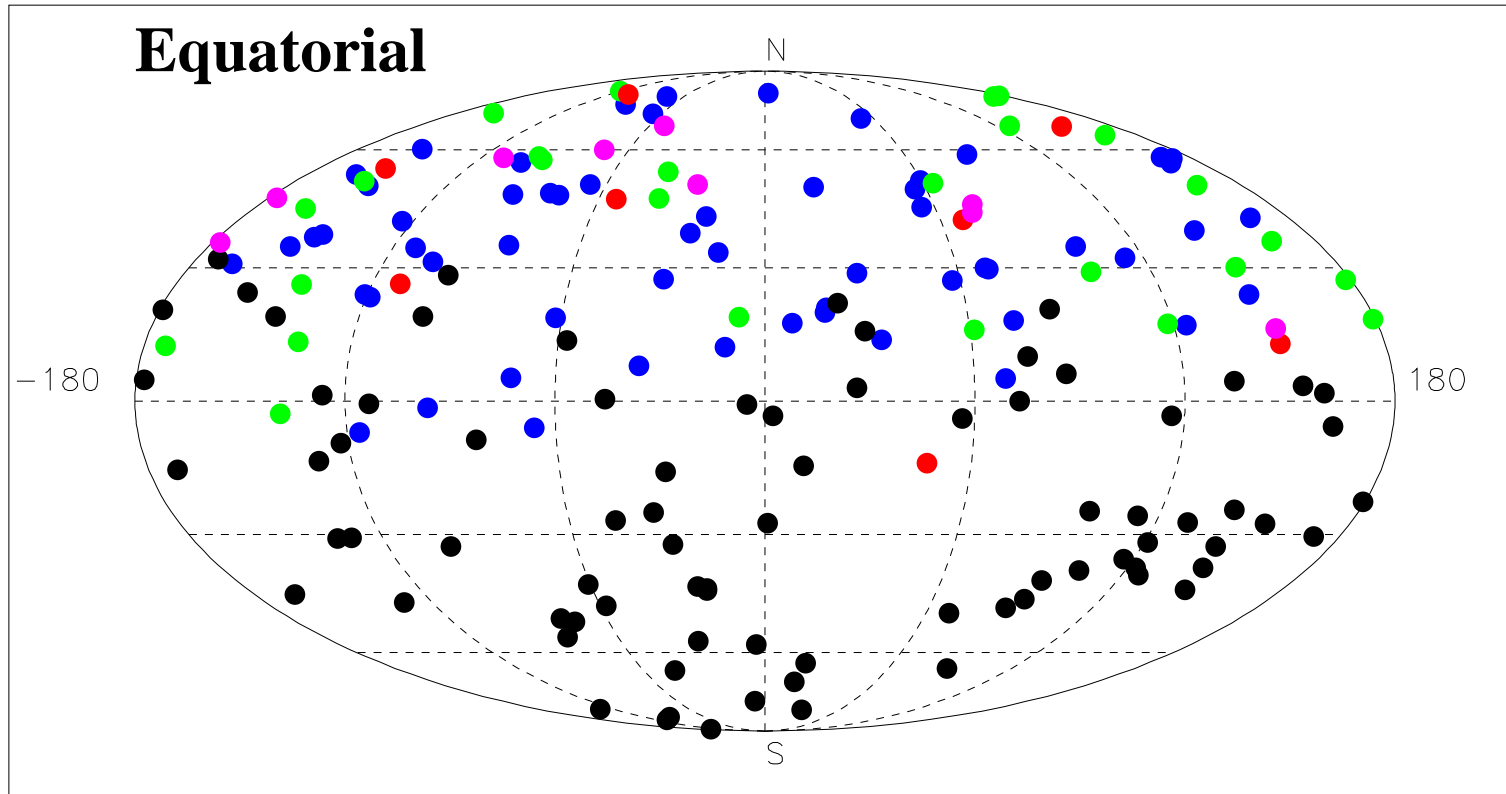


(J.Cronin, astro-ph/0402487)



CR Astronomy

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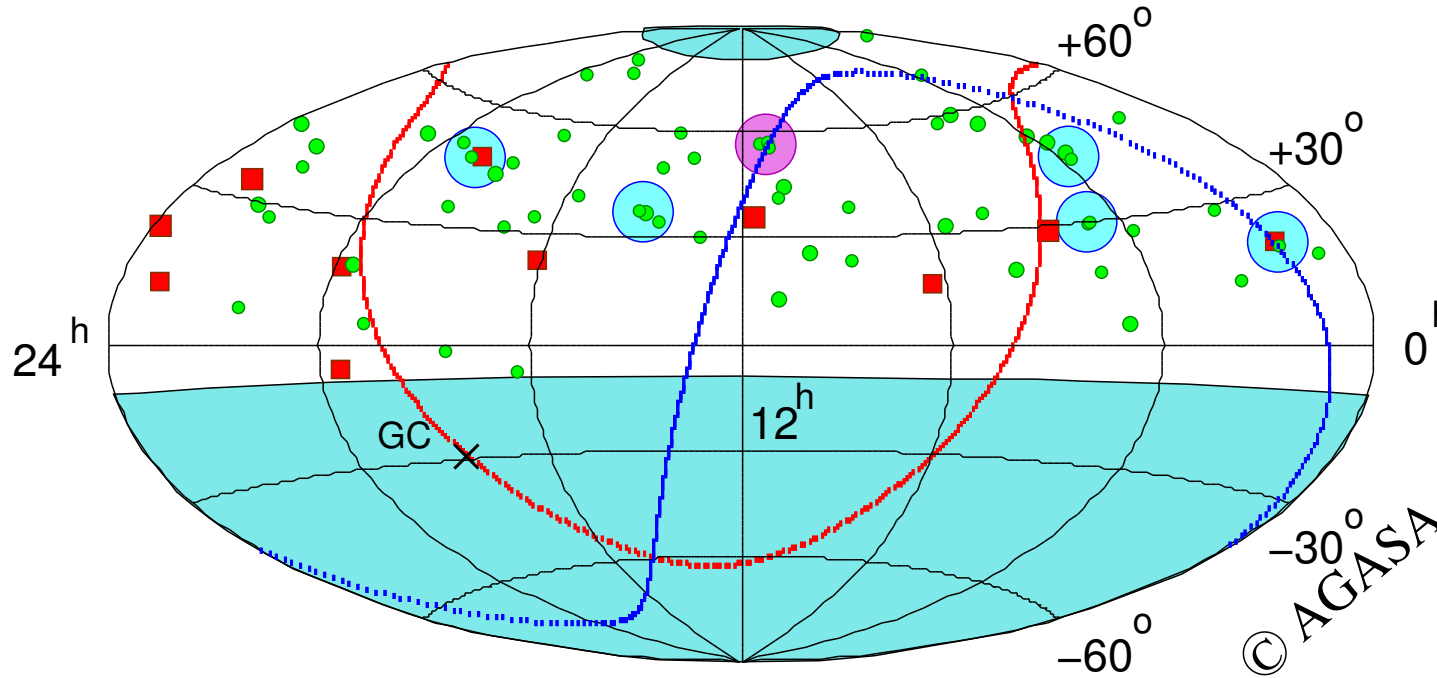
$E > 40 \text{ EeV}$

Blue ... AGASA (58), Black ... SUGAR (80), Red ... Volcano Ranch (8),
Green ... Haverah Park (26), Magenta ... Yakutsk (9)



Small scale anisotropy AGASA

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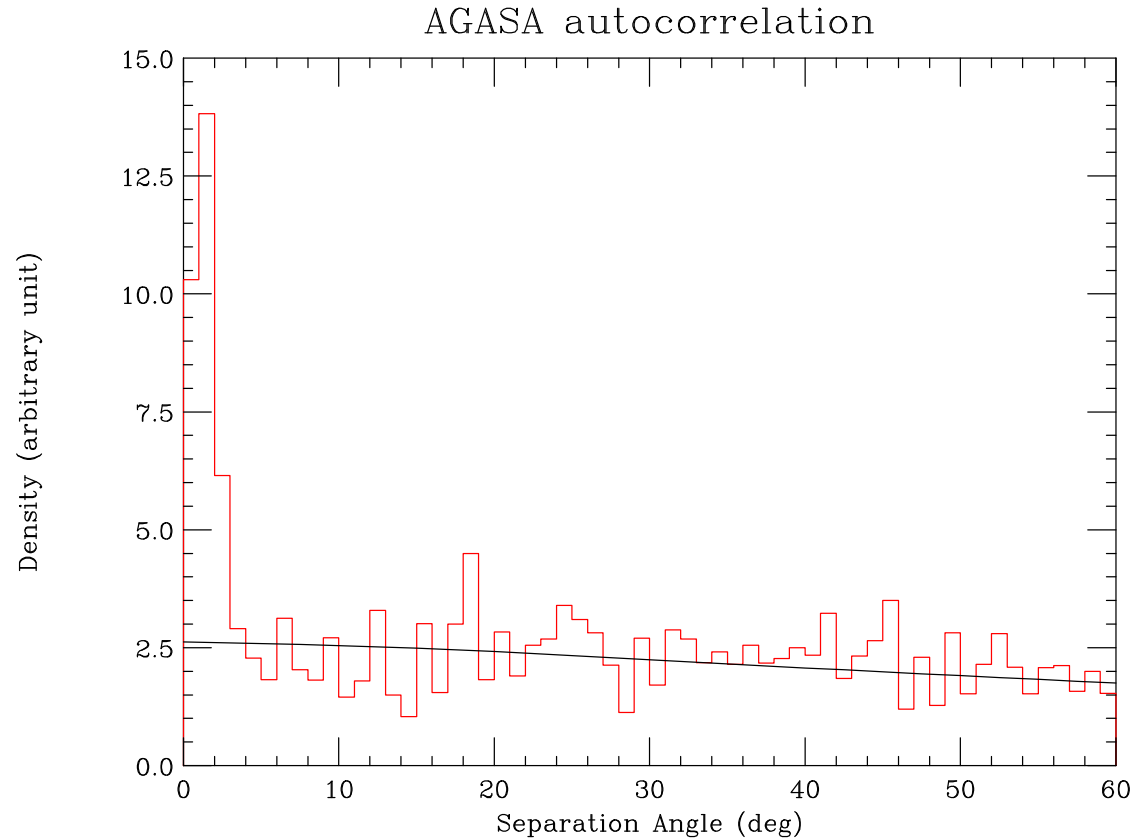


Arrival directions of cosmic rays with energies above 40 EeV. Red squares $E > 100$ EeV, green circles $E = 40 - 100$ EeV. Shaded circles indicate event clustering within 2.5° . At (11h 20m, 57°), three 40 EeV cosmic rays are observed against expected 0.06 events. The chance probability of observing such triplet under an isotropic distribution is only 0.9%.



Small scale anisotropy AGASA

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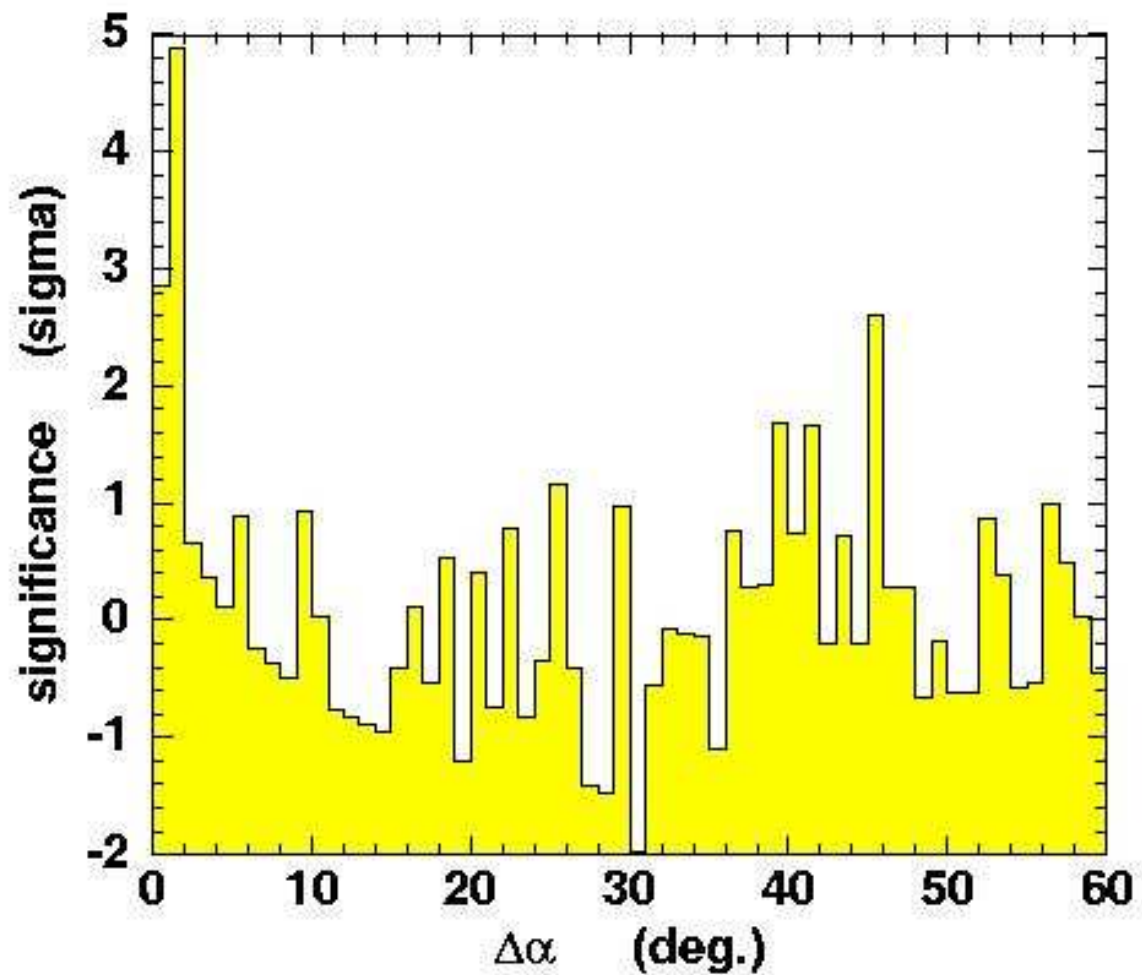


Distribution of angular distances between pairs of 59 AGASA events with energy ≥ 40 EeV weighted by the inverse of the solid angle of the angular bin. The solid line is the distribution expected for random arrival directions. (J.Cronin, astro-ph/0402487)



Small scale anisotropy AGASA

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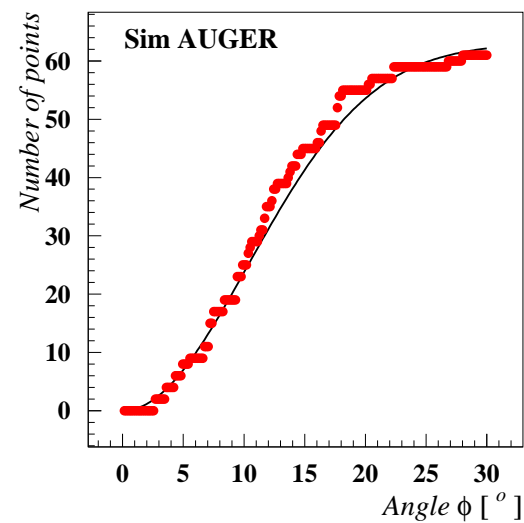
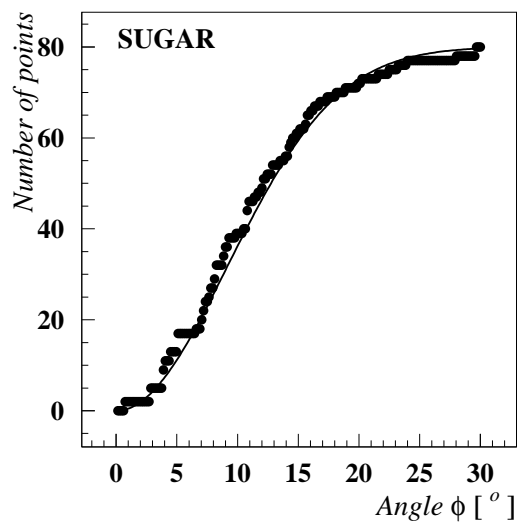
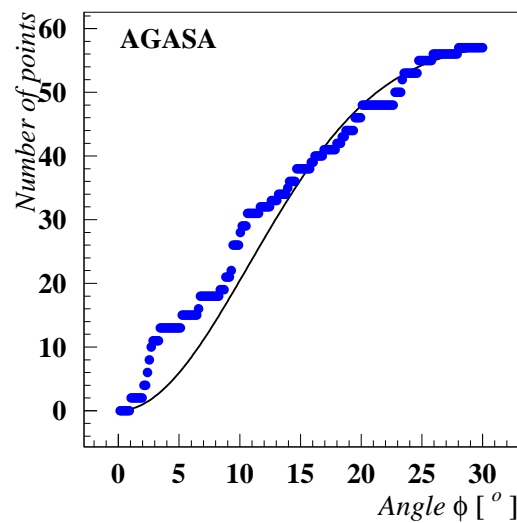
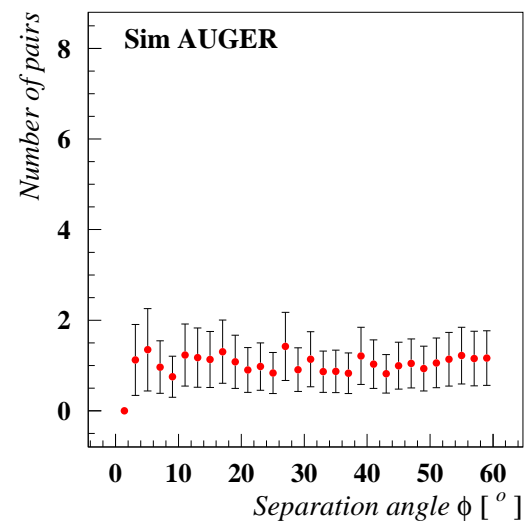
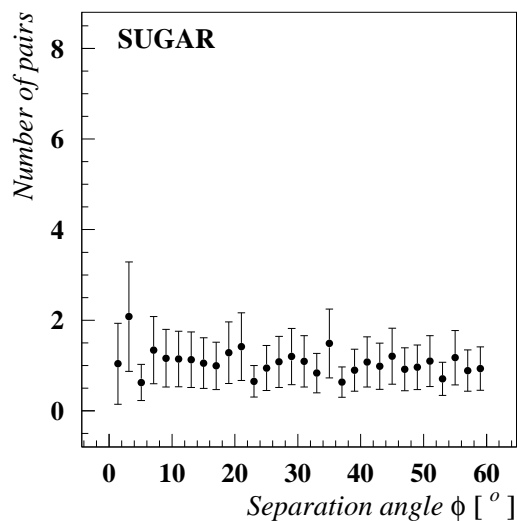
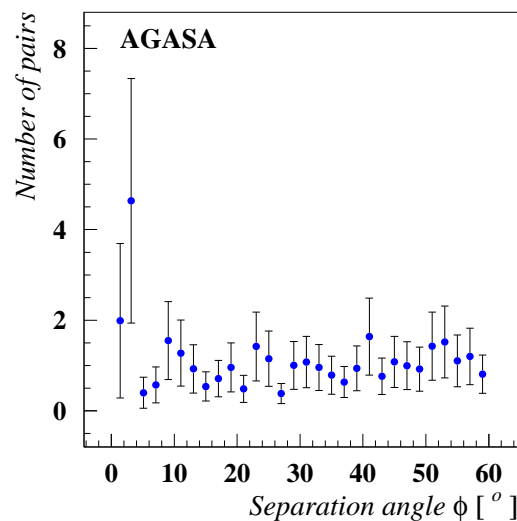


M.Takeda and AGASA Collaboration, ICRC 2001



Small scale anisotropy

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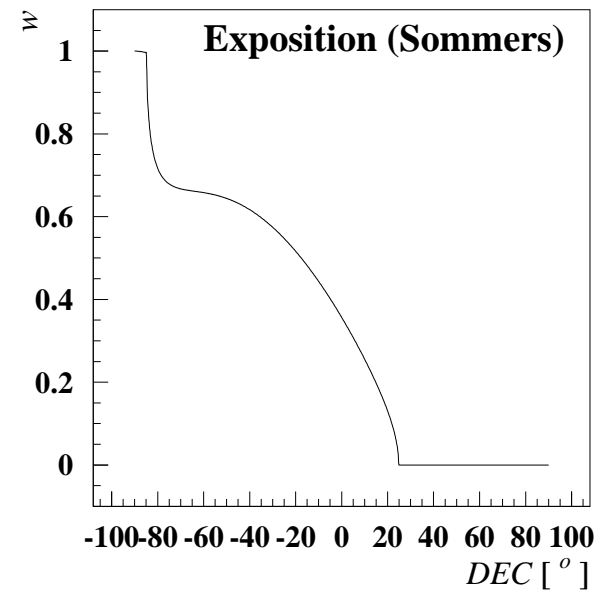
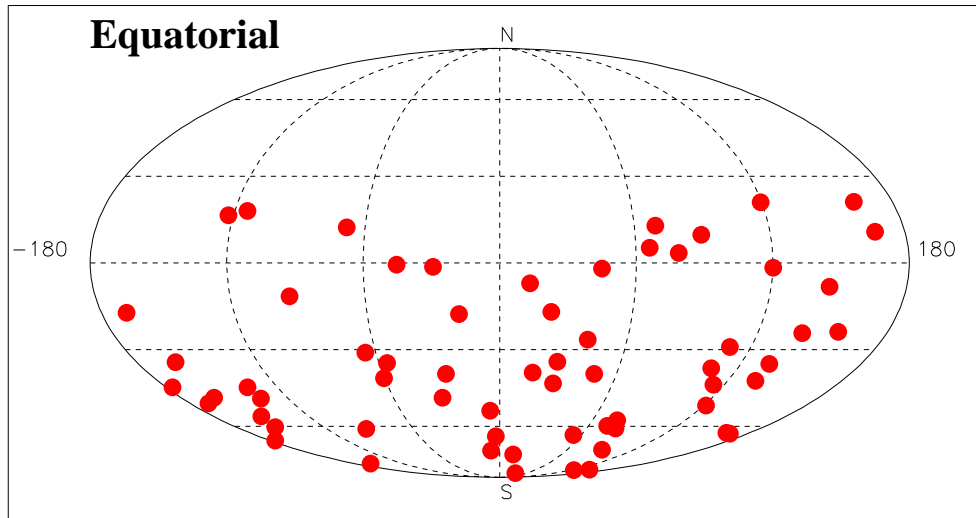




Arrival directions AUGER

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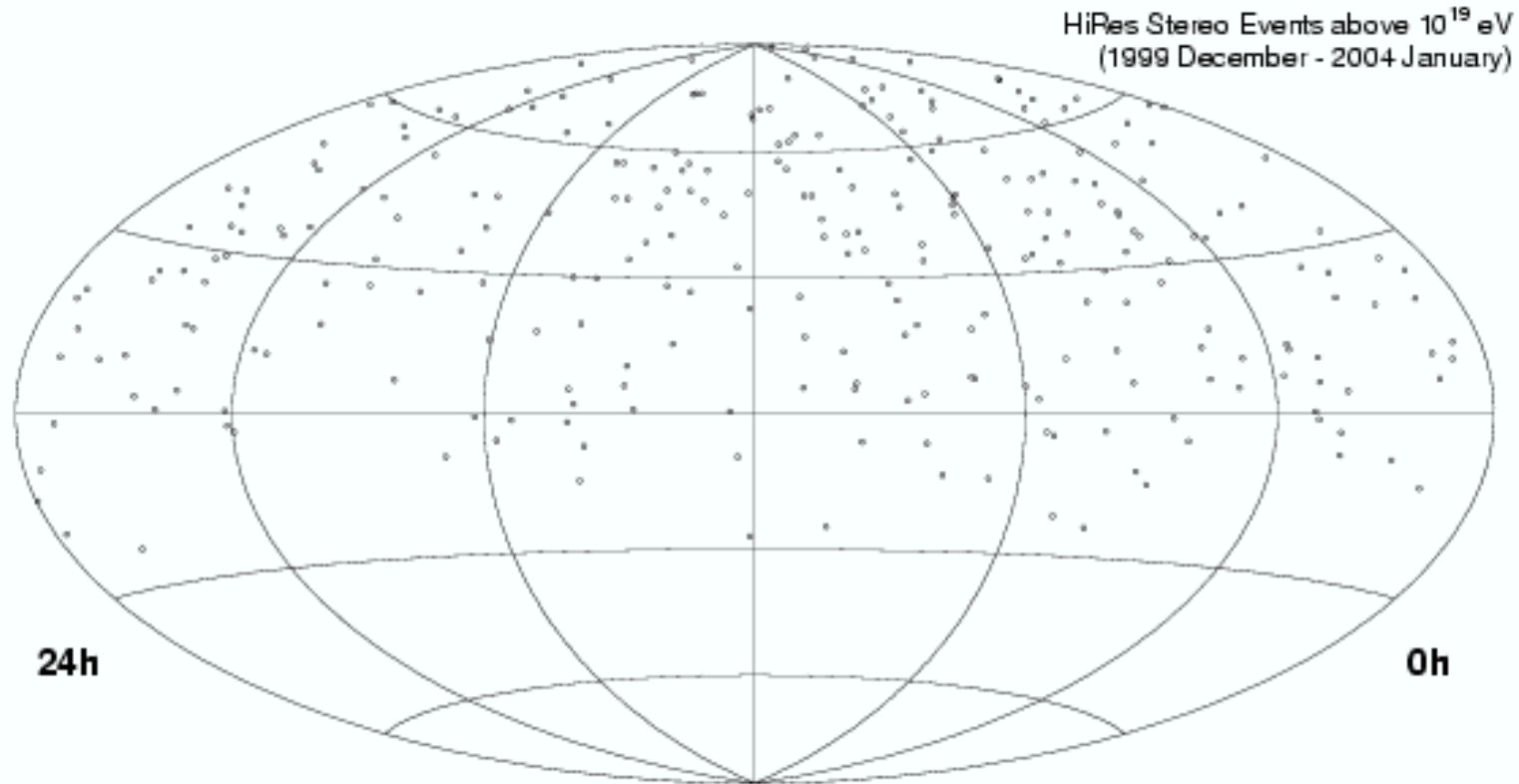
$E > 40 \text{ EeV}$, $\approx 75\,000 \rightarrow 63$ events





Arrival directions HiRes

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HiRes Collaboration, ApJ **610** L73 (2004), astro-ph/0404137

Analysis of 271 events above 10 EeV – Isotropic arrival up to 5° (CL = 52%)

HiRes Collaboration, ApJ **623** 164 (2005)

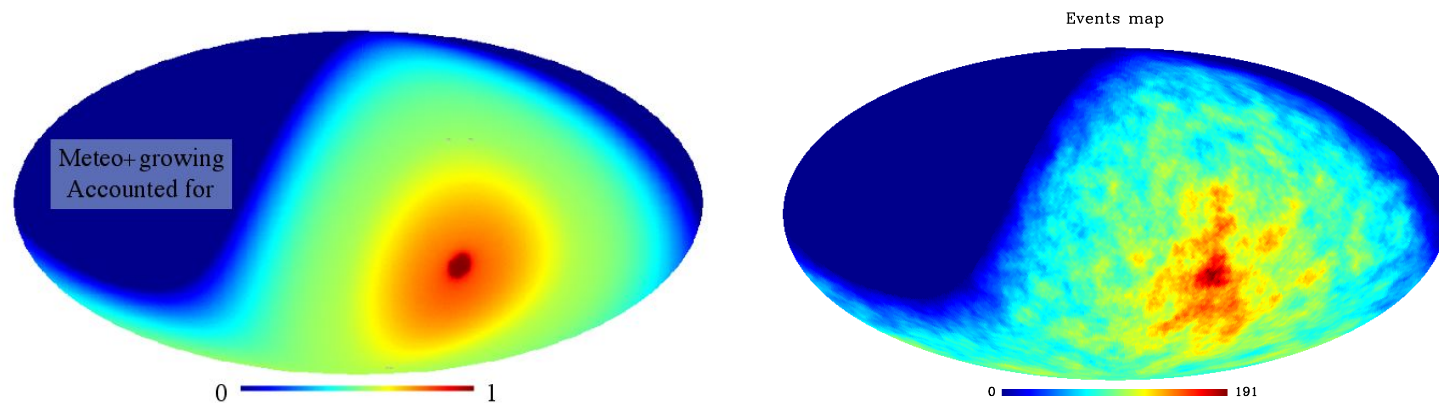
AGASA (57) and HiRes (27) data above 40 EeV - No point sources



Coverage and events map AUGER

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Relative coverage map obtained with the semi-analytical method accounting for acceptance variations due to weather effects and growing of the array.
Galactic coordinates, Mollweide projection.



Blind source search / Prescribed target – no excess

Pierre Auger Collaboration, ICRC 2005, fra-revenu-B-abs1-he14-oral

J.-Ch.Hamilton for the Pierre Auger Collaboration, ICRC 2005, fra-hamilton-JC-abs1-he14-oral



What is observed/should be solved?

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	AGASA		HiRes	AUGER
Super-GZK events	many	X	a few	likely
GZK cutoff observed	no	X	yes	?
Large scale isotropy	yes		yes	?
Small scale isotropy	no	X	yes	?
Composition changing	3 EeV	X	1 EeV	?

What should be solved for CR primaries

- Origin/Acceleration of charged particles to highest energies
- Propagation from sources to the Earth and their interaction with atmosphere
- Arrival directions – Isotropy? Point sources?
- Composition of high-energy species
- High-energy γ and ν fluxes



AUGER Globus

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