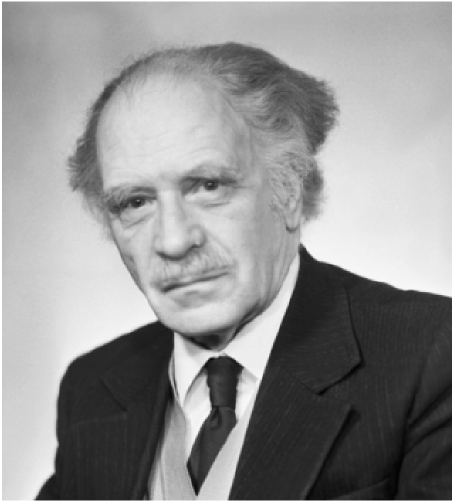
The highest energy cosmic rays: observations and search for new physics

Grigory I. Rubtsov

QFTHEP'2010, Golitsyno
September 10, 2010

Institute for Nuclear Research of the Russian Academy of Sciences

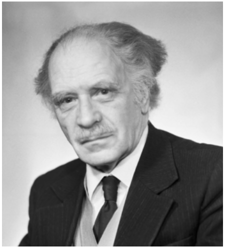
In memory of S.N.Vernov



Sergey Nikolaevich Vernov
1910–1982

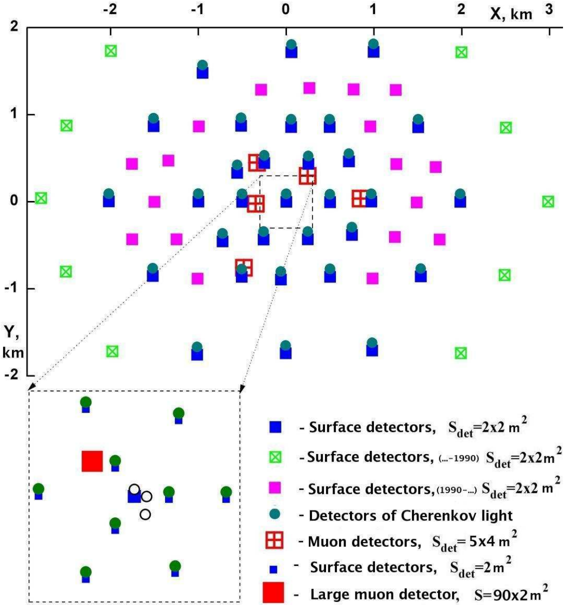
S.N.Vernov's work related to UHECRs

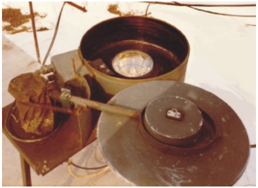
- 1957, MSU Extensive Air Shower array
  - 1958, Knee discovery, $E \sim 3 \cdot 10^{15}$ eV
    Kulikov, Kristiansen, ZhETF 35 (1958) 635
- 1963, S.N. Vernov proposed to build large scale array for highest energy CR
  - 1973, Yakutsk EAS Array is built using experimental facilities of SINP MSU



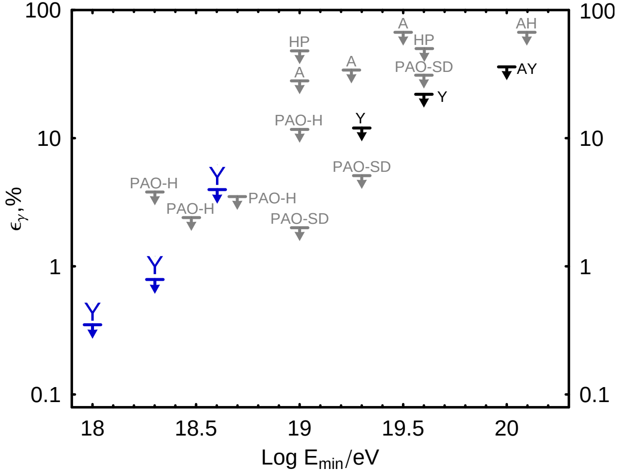
Yakutsk Array is the first experiment capable to target the whole UHECR physics. It's designed ahead of it's time and still competitive today, although size advantage of new setups.

Yakutsk EAS Array





Yakutsk recent photon limit for $E > 10^{18}$ eV

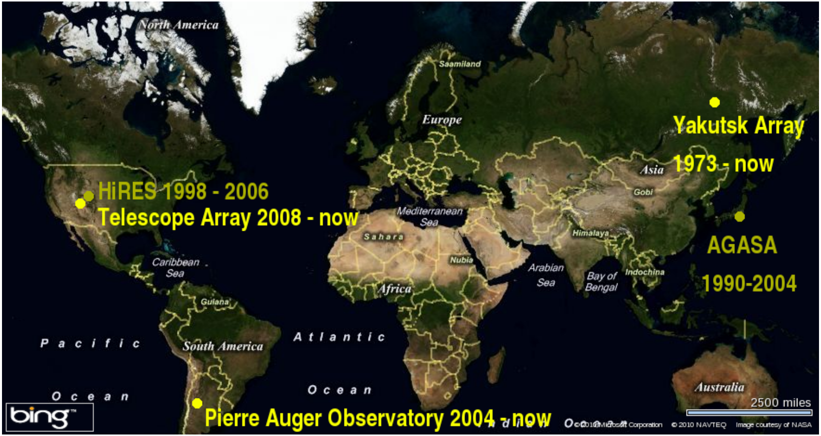


Glushkov et al., Phys. Rev. D 82, 041101 (2010)

Outline

- UHECR ($E \gtrsim 10^{18}$ eV) experiments today
- The highest energy physics
  - Spectrum and GZK cut-off
  - Composition
  - Sources
  - Photons and neutrino
  - Search for new physics
- Conclusions and outlook

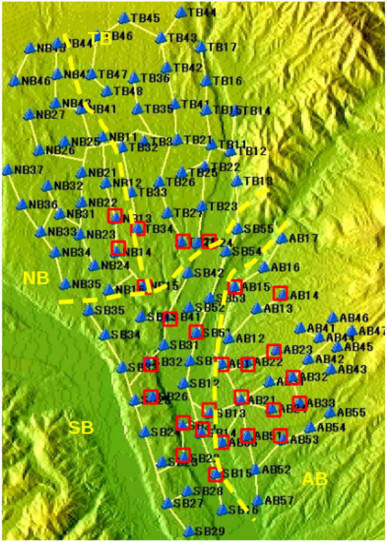
UHECR experiments today



AGASA

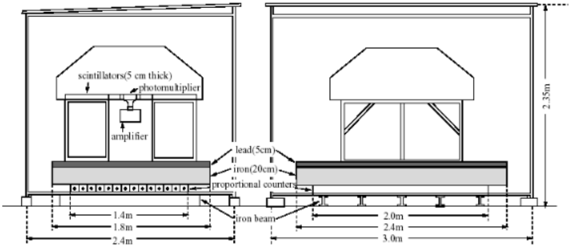
AGASA (Akeno Giant Air Shower Array)

- **Detector station**
  - 111 surface detectors
    - Effective area ~100km²
    - Optical fibre cable connection to observatory
  - 27 muon detectors
    - Southern region ~30km² coverage



- **Operation**
  - Feb. 1990–Dec.1995
    4 separate-array operation
  - Dec. 1995–Jan.2004
    Unified operation

AGASA surface detector



- **Surface detector**
  - 5cm thick scintillator
  - Hamamatsu 5” R1512 PMT

- **Muon detectors** (2.8–10m^2;south region)
  - 14–20 Proportional counters
  - Shielded by 30cm Fe or 1m concrete
    - Threshold energy: 0.5GeVxsecθ
  - Triggered by accompanying surface detector

The High-Resolution Fly's Eye (HiRes)

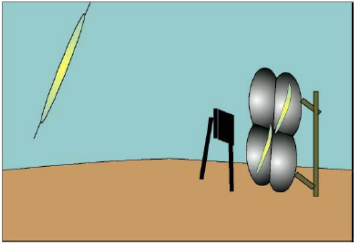
Two HiRes Detectors

HiRes-I:

- 21 mirrors, 1 ring, 3º < elev < 17º
- Readout pulse height and time

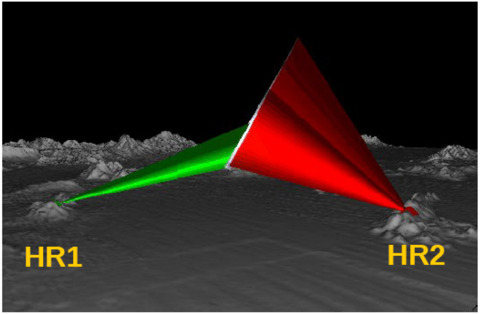
HiRes-II:

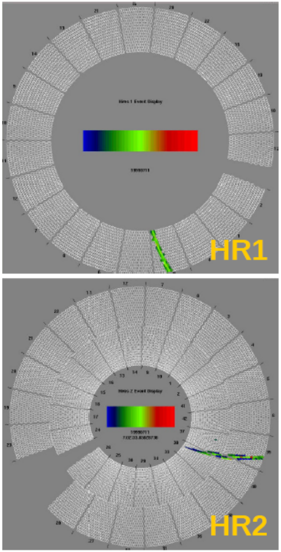
- 12.6 km SW of HiRes-I
- 42 mirrors, 2 rings, 3º < elev < 31º
- Electronics stores pulse shape vs time w/ 100 ns sampling



Observe nitrogen fluorescence from airshowers

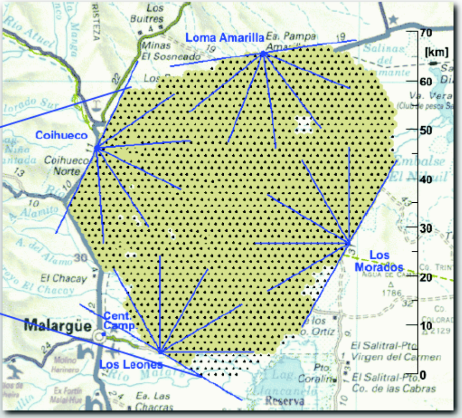
Event Reconstruction: Geometry





Obtain pointing directions for anisotropy searches...

Pierre Auger Observatory in Argentina



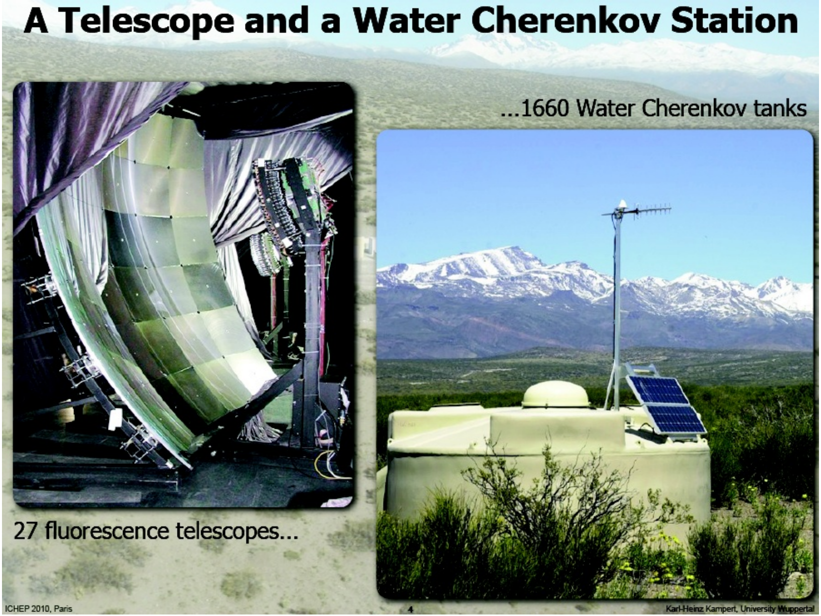
3000 km² area on a plateau 1450 m a.s.l.

1660 Detector Stations +

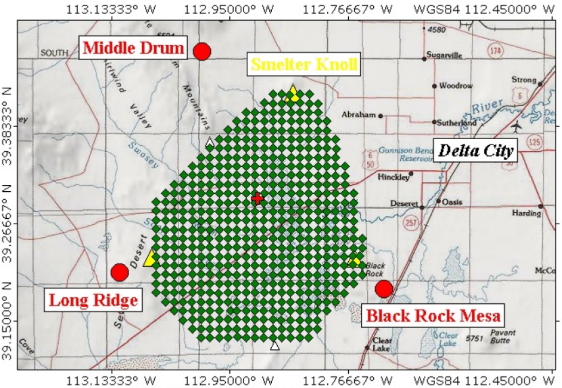
27 FD Telescopes at periphery

K. Kampert, ICHEP'10, Paris

Auger fluorescence and surface detector



Telescope Array experiment



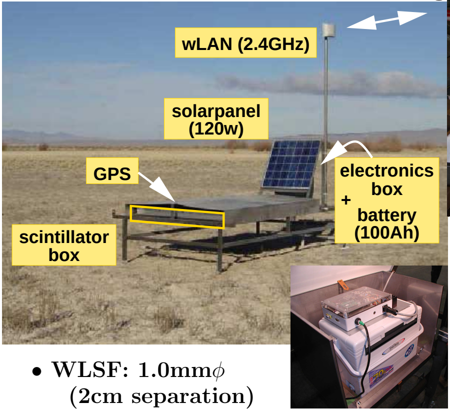
Map created with TOPO!® ©2002 National Geographic (www.nationalgeographic.com/topo)

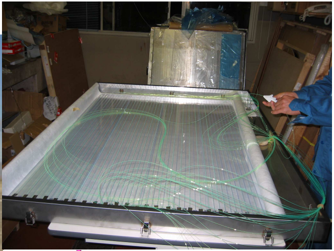
- Utah, 2hr drive from SLC
- 507 SD's, $S = 3m^2$, 1.2 km spacing
- 3 FD's

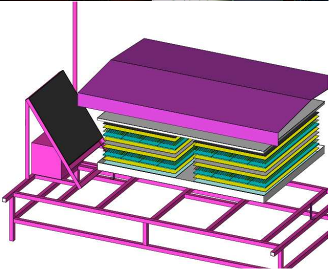
TA surface detector

< Surface Detector >

∼200kg







- WLSF: 1.0mmϕ
  (2cm separation)
- PMTs: ET 9123SA $\times$ 2
- 3m^2 (12mm $\times$ 2 layers)

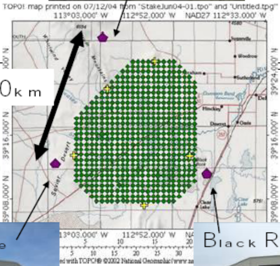
TA Fluorescence Detectors

Refurbished from HiRes

Observation started Dec. 2007

Middle Drum

14 cameras/station
256 PMTs/camera



Observation started Nov. 2007

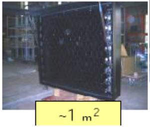
Long Ridge

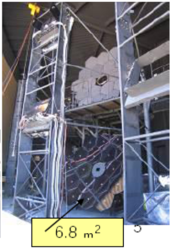
Observation started Jun. 2007

Black Rock Mesa

New FDs

256 PMTs/camera
HAMAMATSU R9508
FOV~15x18deg
12 cameras/station

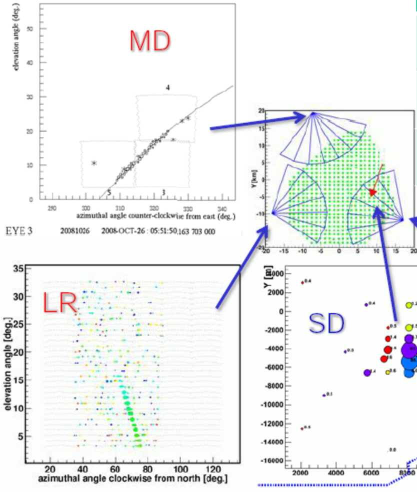


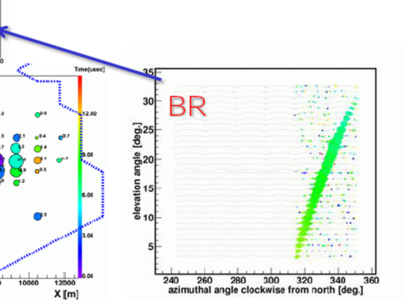


TA hybrid event example

Triple FD Event (2008-10-26)

	θ[deg]	φ[deg]	X[km]	Y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88





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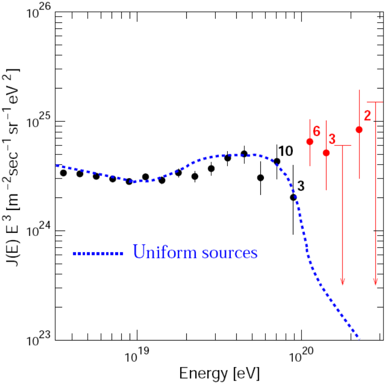
Greisen, 1966; Zatsepin, Kuzmin, 1966

Cut-off predicted for $E \gtrsim 10^{19.7}$ eV.

$$p + \gamma_{2.7K} \rightarrow n + \pi^+$$
$$\rightarrow p + \pi^0$$

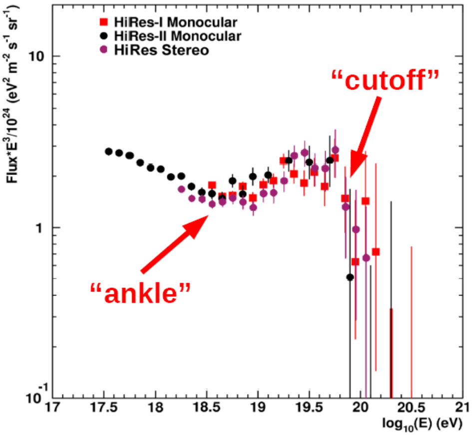


AGASA spectrum, 2003

Takeda, M. et al., Astropart. Phys 19(2003)

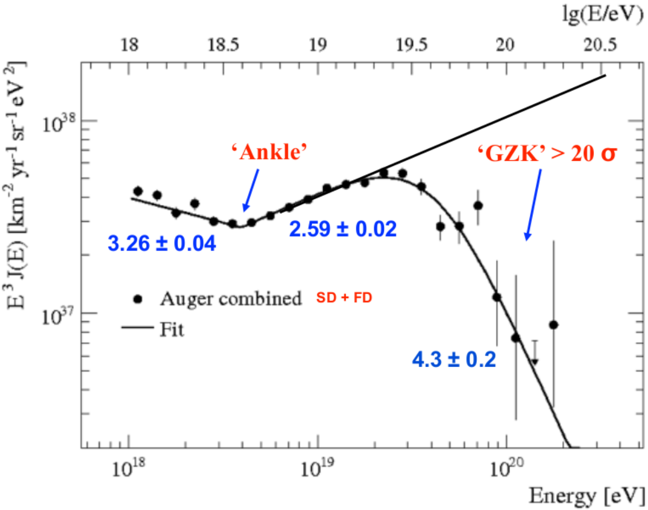
- Expected 1.9 event
- Observed 11 events above 10^{20} eV

Cut-off observation by HiRES



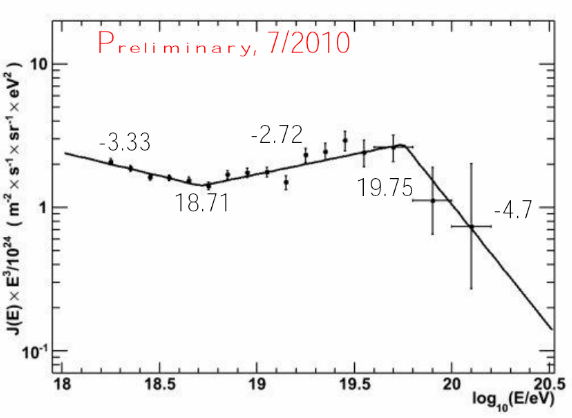
Monocular: Quarks'06; PRL 100 (2008)
Stereo: Astropart. Phys. 32 (2010)

Pierre Auger spectrum



PRL 101 (2008) & Phys. Lett. B 685 (2010)

Telescope Array surface detector spectrum



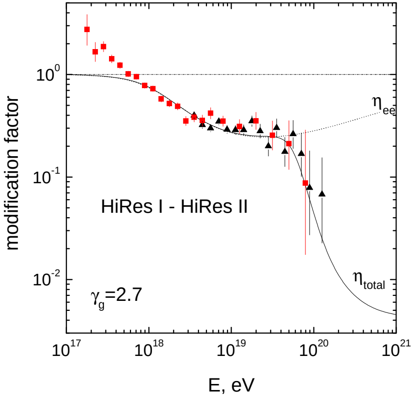
GZK confirmed by plastic scintillator SD (AGASA-like)

Cut-off significance 3.5σ *G.Thomson, ICHEP'10, Paris*

Pair production “dip” in the spectrum

$$p + \gamma_{2.7K} \to p + e^+ + e^-$$

Berezinsky, Grigorieva, Astron. Astoph. 1 (1988)



Aloisio et al., Astropart. Phys. 27 (2007)

Spectrum summary

- Cut-off is observed in 3 independent experiments with good significance
- GZK process in not questioned, but it's contribution to cut-off is unknown due to unknown spectrum and composition at the sources
- One may probe $E > 10^{20}$ eV physics by looking at GZK secondaries: photons and neutrinos

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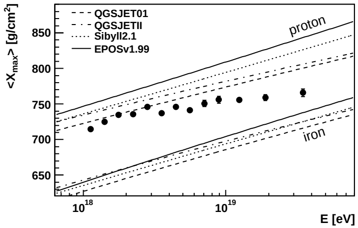
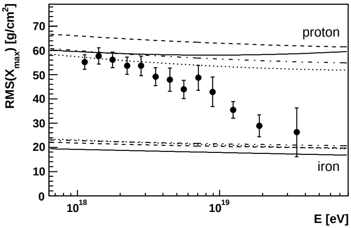
Composition from the depth of the shower maximum

Auger

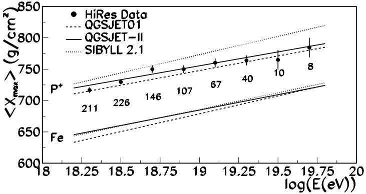
Phys.Rev.Lett.104.091101

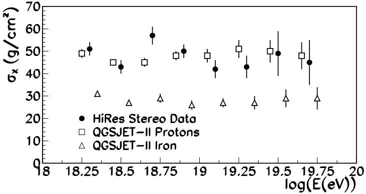




HiRES

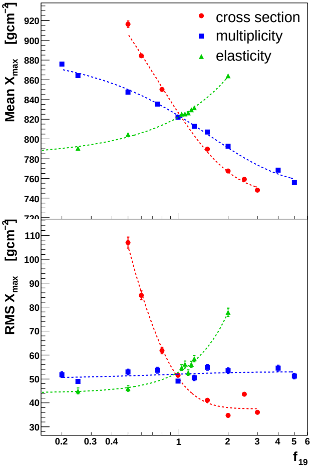
Phys.Rev.Lett.104.161101



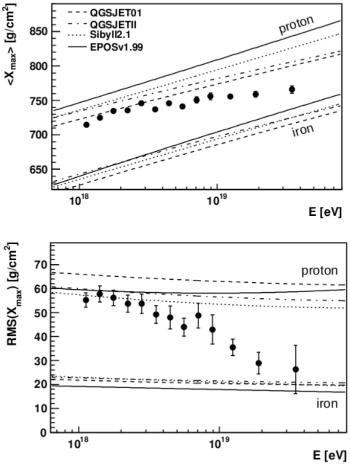


Another interpretation of Auger result

R. Engel, 31th ICRC, arXiv:0906.0418v1



Auger, Phys.Rev.Lett.104.091101



protons + growth of cross-section at high energies

Auger/HiRES XMAX results

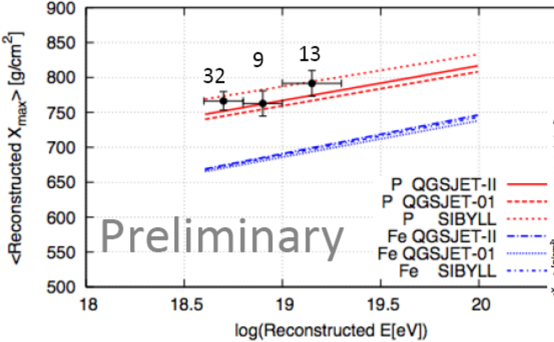
Auger:

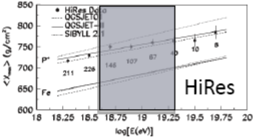
- Southern hemisphere
- Heavy nuclei or cross-section growth

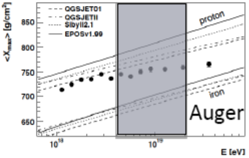
HiRES:

- Northern hemisphere
- Protons dominate

?







TA data favor **protons for $E \sim 10^{19}$ eV**
data collection is in progress

Y. Tameda, JPS meeting March 2010; G.Thomson, ICHEP'10, Paris

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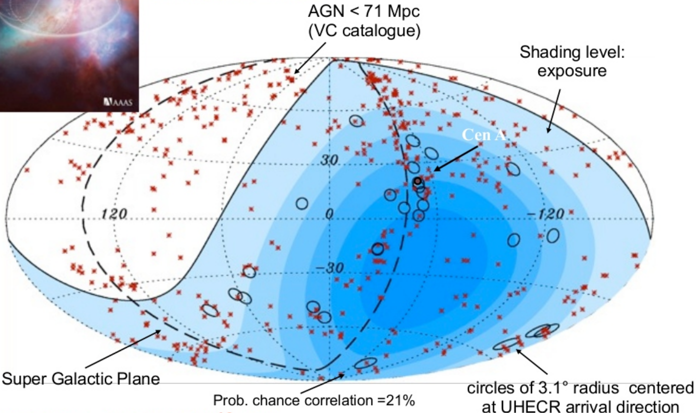
Pierre Auger AGN claim

November 9, 2007

"Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects"

Anisotropy of the UHECR sky



27 events E> $5.7 \cdot 10^{19}$ eV

Angular resolution < 1°

Auger claim discussion

- HiRES doesn't see correlations with AGN (2 of 13, bg: 3)

  Astropart.Phys.30,2008

- Comment by Gorbunov,Tinyakov,Tkachev,Troitsky
  - Events do not follow prediction of AGN hypothesis. E.g. nothing comes from Virgo, while it contains significant fraction of nearby AGNs
  - Cen A may be a single source with correlation angle about 20°

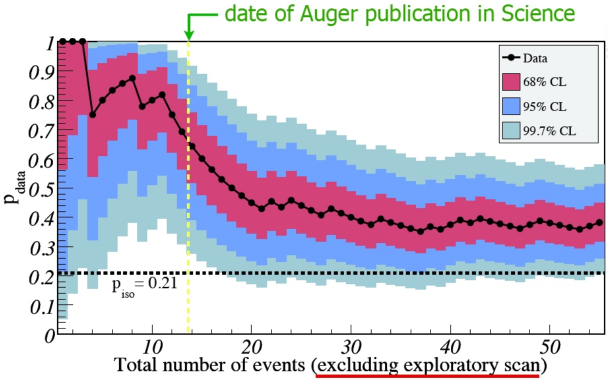
  JETP Lett.87,2008

- AGN correlation requires proton primaries; contradicts with Auger composition results due to large deflection of nuclei in Galactic magnetic field

- TA doesn't see correlations with AGN (3 of 13, bg: 3)

  G.Thomson, ICHEP'10, Paris

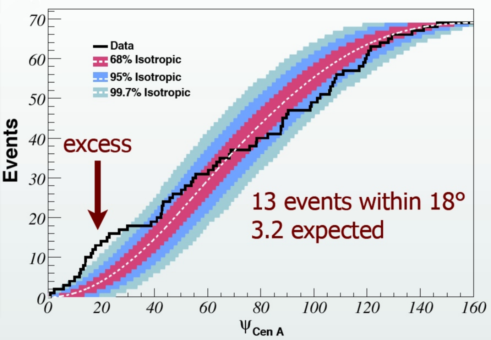
Auger AGN correlation update



K. Kampert, ICHEP'10, Paris

Before publication date: 9/13 correlate. Background: 2.7 ± 1.6
After publication date: 12/42 correlate. Background: 8.9 ± 3.0

Auger Centaurus A update



K. Kampert, ICHEP'10, Paris

- Cen A may be a source
- Unfortunately out of field of view of HiRES and TA

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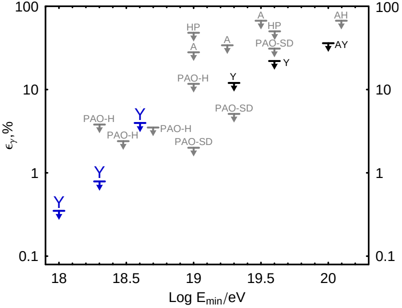
Photon search techniques

Photon-sensitive parameter:

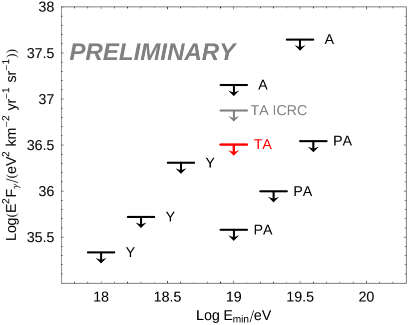
AGASA, Yakutsk	muon density (strongest discrimination)
Pierre Auger SD	shower front curvature and thinkness
Pierre Auger hybrid	XMAX
Telescope Array	shower front curvature

Photon fraction and flux limits

Fraction limits

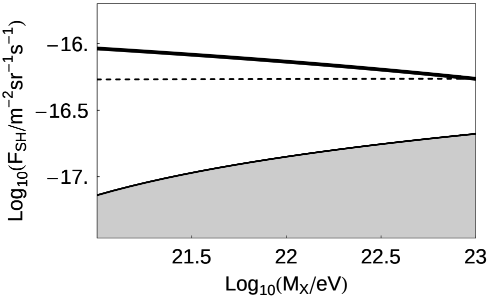


Flux limits



- GZK prediction: $\epsilon_\gamma < 1\%$ for $E > 10^{19}$ eV
- Photons may be detected in the near future (depends on the sources parameters)

Constraints on parameters of Superheavy dark matter



F_{SH} – flux of SHDM-produced cosmic rays $E > 10^{20}$ eV
above thick line – excluded by spectral fits
shaded area – allowed by spectrum and γ limits
$\Rightarrow$ SHDM decay may not be the source of all UHECRs

Kalashev, Rubtsov, Troitsky, Phys.Rev.D80,2009

Lorentz invariance violation tests 1/2

- LIV is proposed by Coleman & Glashow to suppress GZK process *Phys.Rev.D59,1999*
- If LI is broken, threshold of GZK reaction may be upshifted $p + \gamma_{2.7K} \rightarrow \Delta(1232)$
- If we can prove that GZK reaction takes place, we have a constraint on LIV parameters
- One approach to confirm GZK reaction is to observe secondary photons
- These tests are strongest due to huge Lorentz factors.

Lorentz invariance violation tests 2/2

- If LI is broken for photons in form

$$\omega^2 = k^2 + \xi_n k^2 (k/M_{Pl})^n$$

pair production on CMB

$$\gamma + \gamma_{CMB} \to e^+ + e^-$$

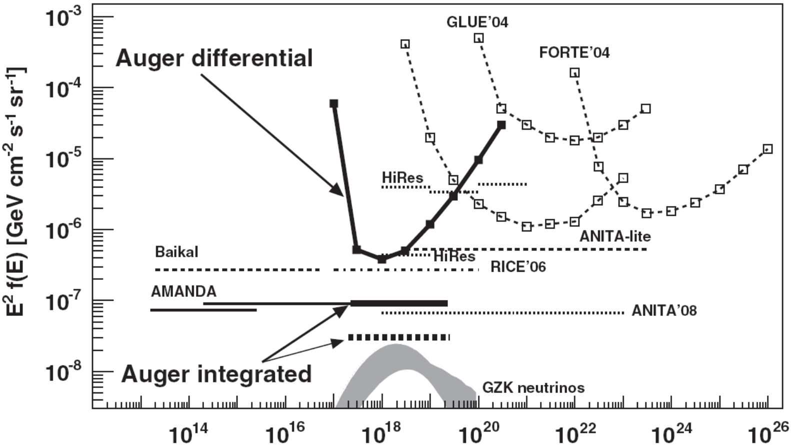
may be suppressed by kinematics and photons will propagate through large distances.

- Observed photon flux will contradict existing photon limits if $|\xi_1| \gtrsim 10^{-14}$ or $\xi_2 \lesssim -10^{-6}$.

Galaverni, Sigl, Phys.Rev.Lett.100, 2008

- Drawback: conclusion depends on the primary composition

UHE neutrino limits



Being optimistic: detection of GZK-neutrino is possible

Good task for space-air detectors: TUS, KLPVE, JEM-EUSO

TeV gravity tests

- If there is a TeV gravity, UHE neutrino will produce black holes interacting in the atmosphere. BH decay producing a shower.

  see, e.g. Gora, Haag, Roth, arXiv:0906.2650, ICRC'09

- BH production cross-section may be higher than SM cross-section.

- Nonobservation of UHE neutrino may constrain TeV gravity

- Both flux and cross-section of ν may be measured independently by considering two techniques:
  - Down going ν, int. probability $\ll 1$
  - Earth skimming ν, int. probability $\gtrsim 1$

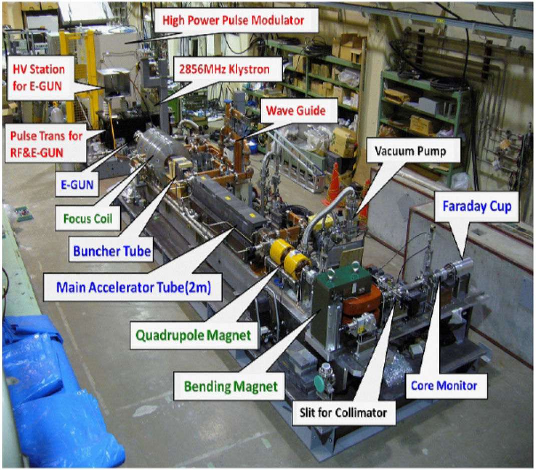
Drawback: To be conclusive detect neutrino of photon

Conclusions

- GZK cut-off is observed
- Composition is unclear: North and South may be different
- Sources are not yet discovered
- Good chance to detect GZK photons in the near future (3 - 5 years)
- Photon discovery will highlight the highest energy processes
- Some probability to catch neutrino with existing setups

UHECR + Accelerator =

- Electron accelerator 100 m from TA FD
- Rate 0.5 Hz
- Energy $\sim$ 40 MeV
- Current $10 - 250 pC/pulse$



J.N.Matthews, Quarks'10

Running schedule: this summer