Physics of ultrahigh-energy cosmic rays

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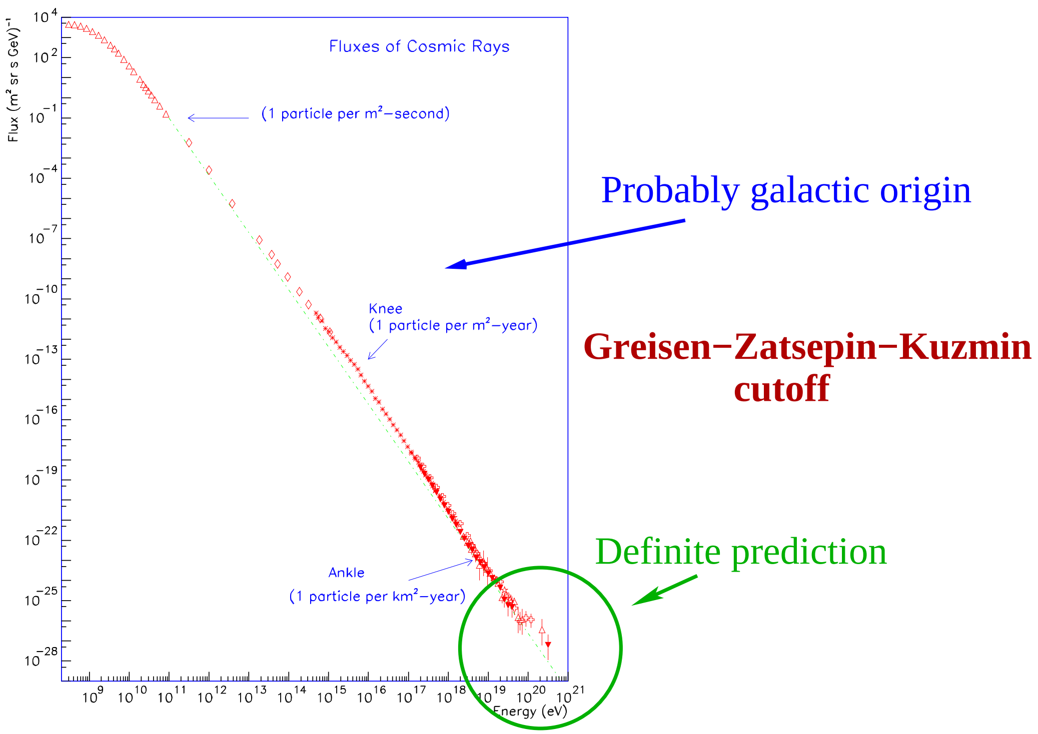
Ultrahigh-energy cosmic rays can teach us about the astrophysics of the most powerful objects in the universe. In addition, they provide an opportunity to study the physics of strong interactions at the extreme values of the center-of-mass energy and for some very small x. Measurements of neutrino-nucleon cross section at $\sqrt{s} \sim 10^5$ GeV can shed light on the small-x behavior of parton distribution functions, as well as new physics.

Spectrum of cosmic rays



Greisen-Zatsepin-Kuzmin cutoff

Cosmic microwave background radiation has temperature $2.7\mathrm{K} = 10^{-4}\mathrm{eV}$
Protons interact with the CMBR and lose energy to pion photoproduction:

$$\boldsymbol{p\gamma \longrightarrow n\pi^+,\ p\pi^0}$$

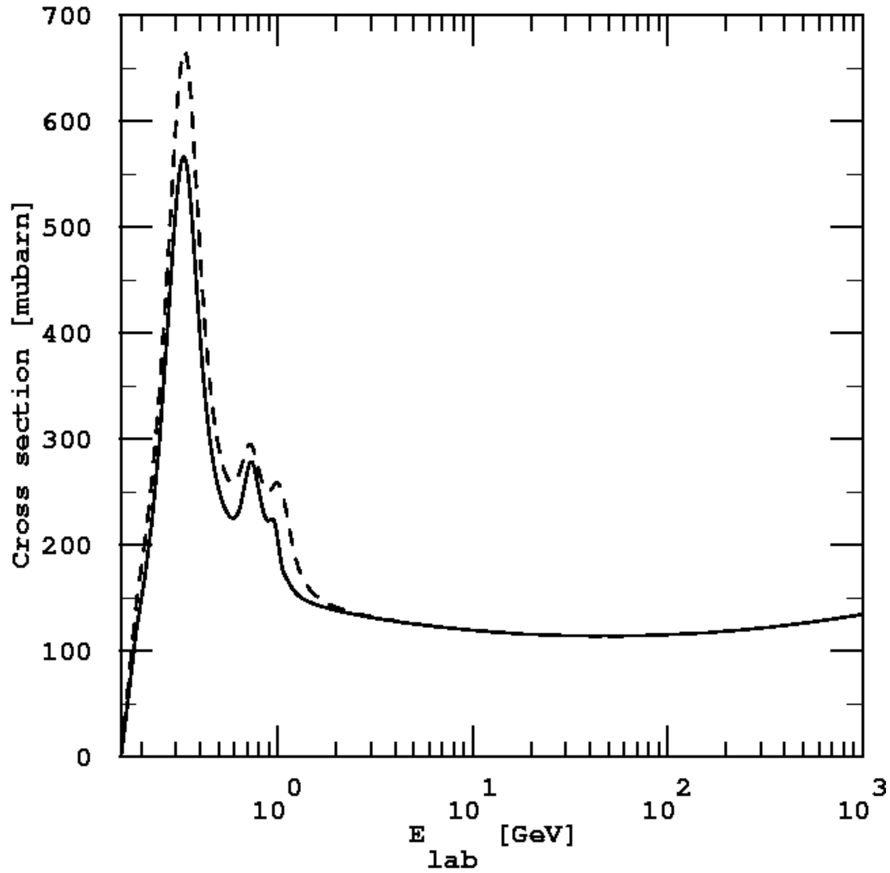
Threshold: $\sqrt{s} = \sqrt{m_p^2 + 2E_\gamma E_p} > m_p + m_\pi$ or

$$\boldsymbol{E_p > 5 \times 10^{19}\,\mathrm{eV}}$$

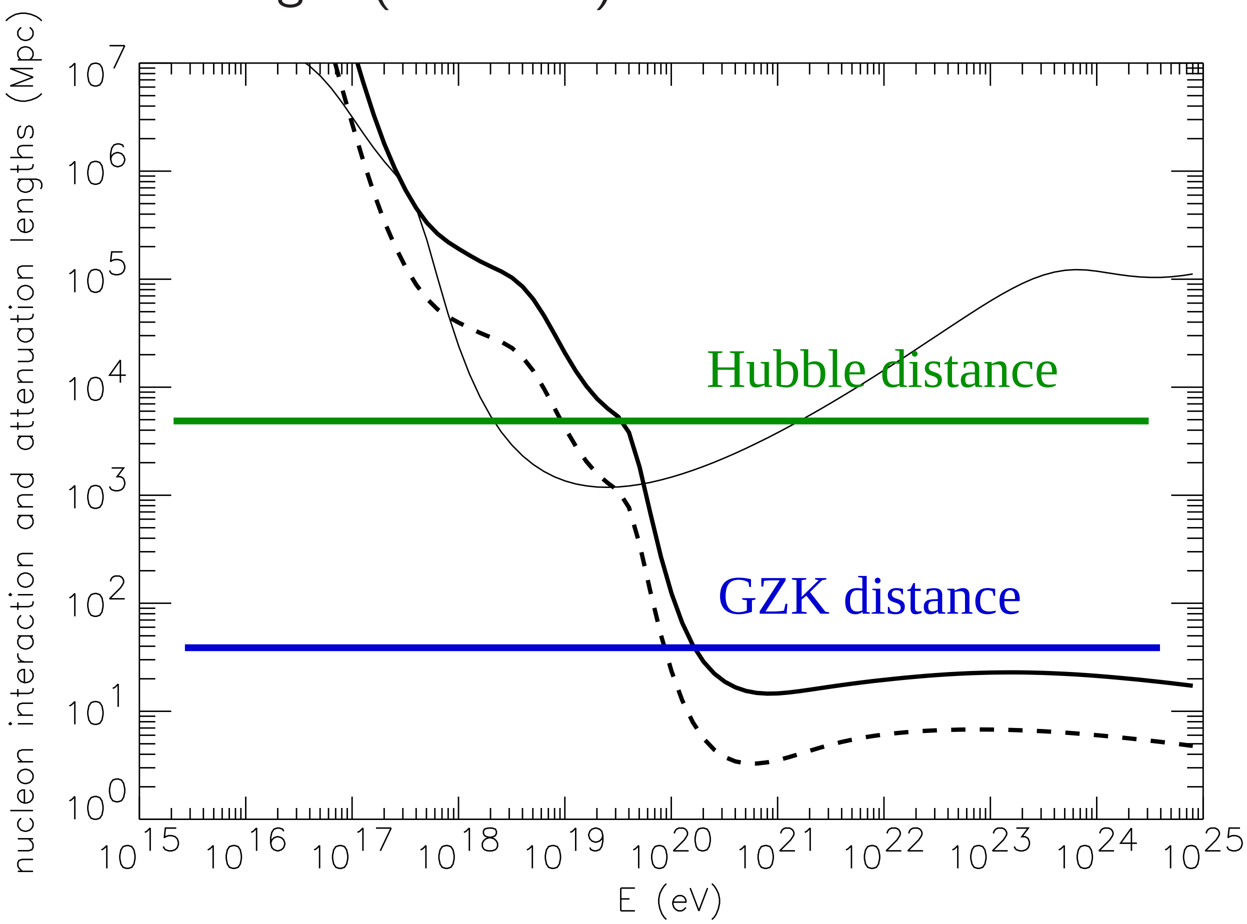
Nucleon loses about 20% of its energy in each interaction Energy attenuation length:

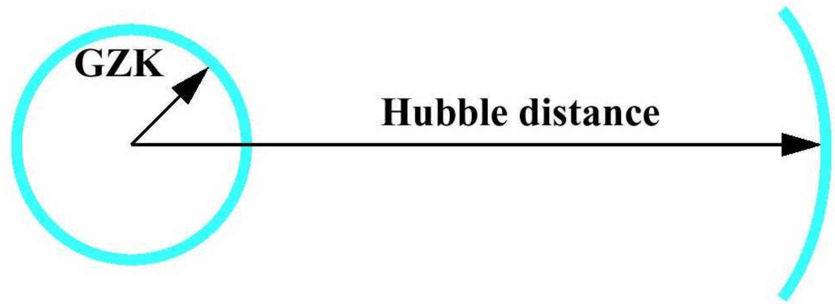
$$\boldsymbol{R_{\mathrm{GZK}} \sim 50\,\mathrm{Mpc}}$$

Cross section of $p\gamma \rightarrow N\pi$ rises rapidly at the Δ resonance



nucleon interaction length (dashed line) and
energy attenuation length (solid line)



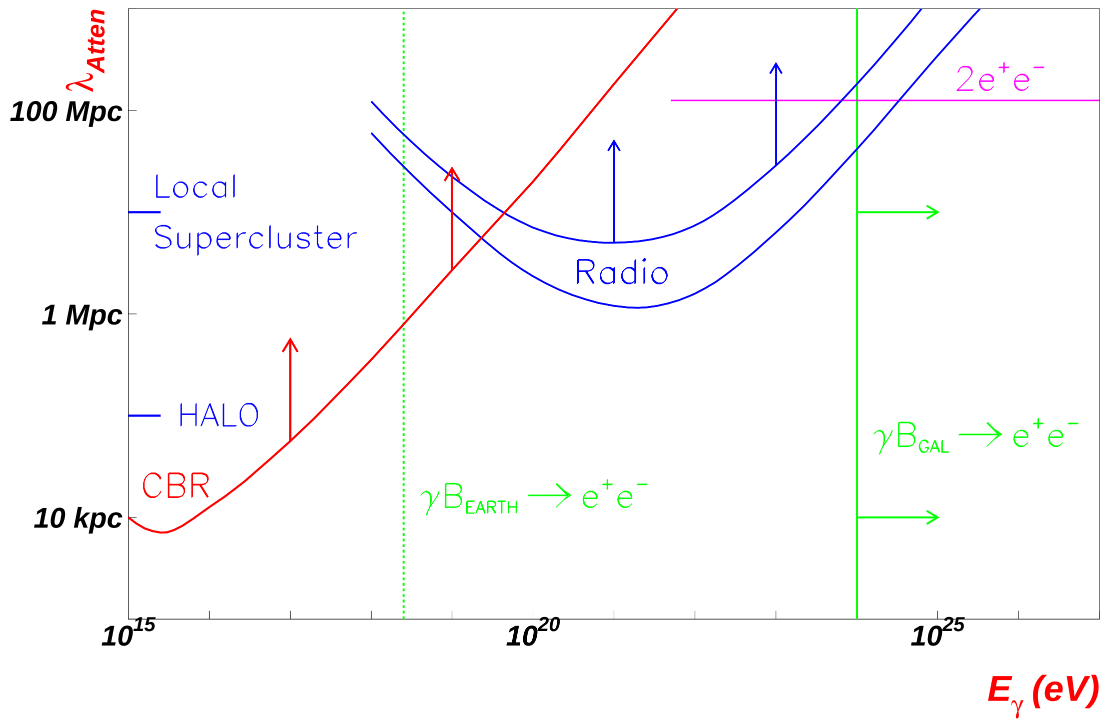


expect a sharp drop in the flux of cosmic rays:

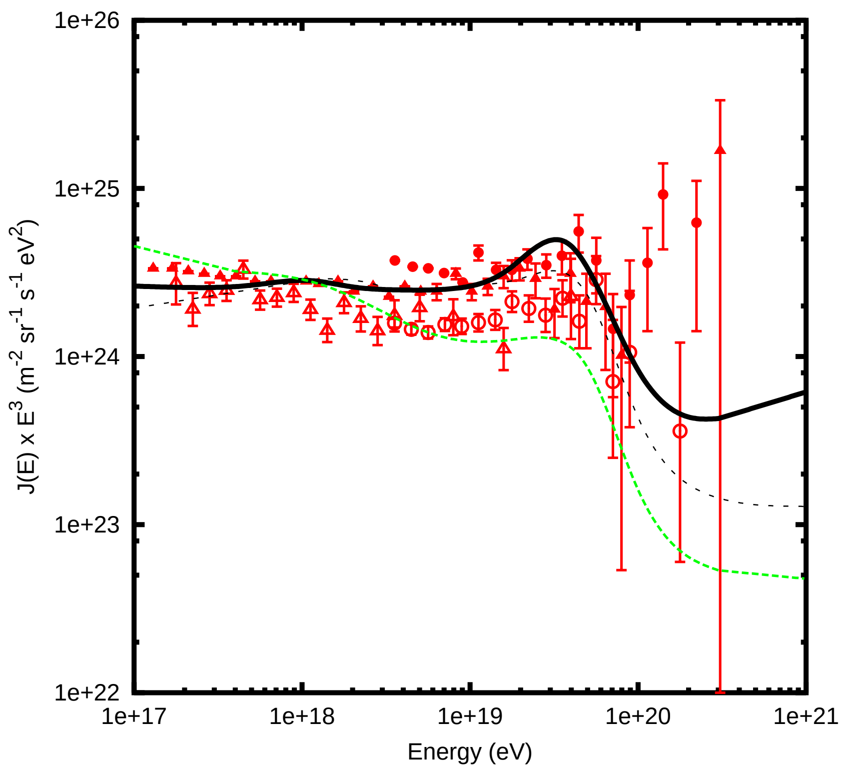
$E < 5 \times 10^{19}\mathrm{eV}$ – should see sources from entire universe

$E > 5 \times 10^{19}\mathrm{eV}$ – should see sources only within 50 Mpc

What about photons?



AGASA, HiRes experiments

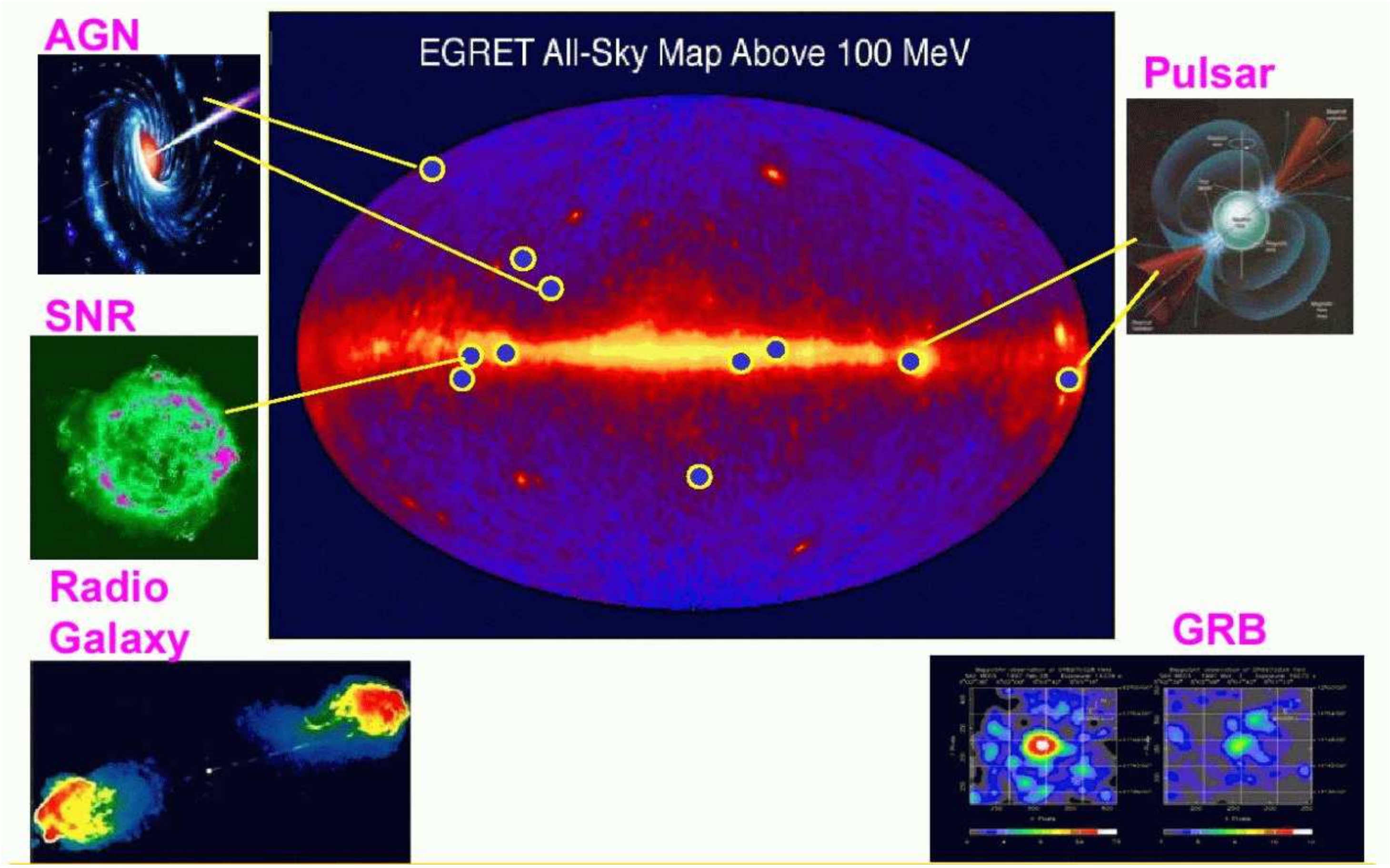


AGASA events beyond the cutoff...

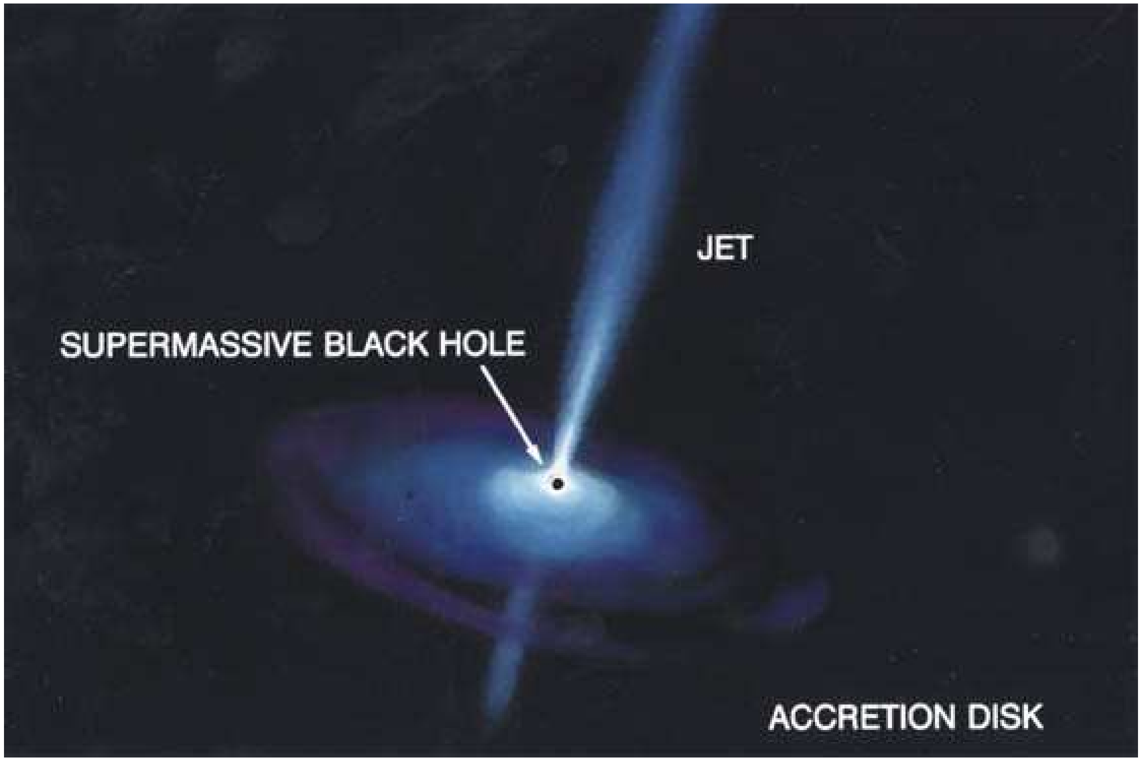
The GZK puzzle is two-fold

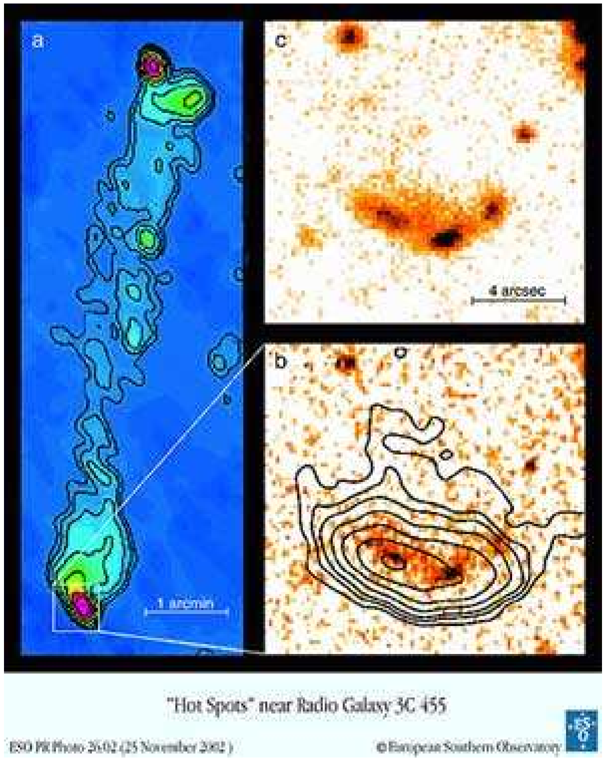
- what are the sources of UHECR?
- Why no GZK cutoff (assuming AGASA results are correct)?

Cosmic accelerators

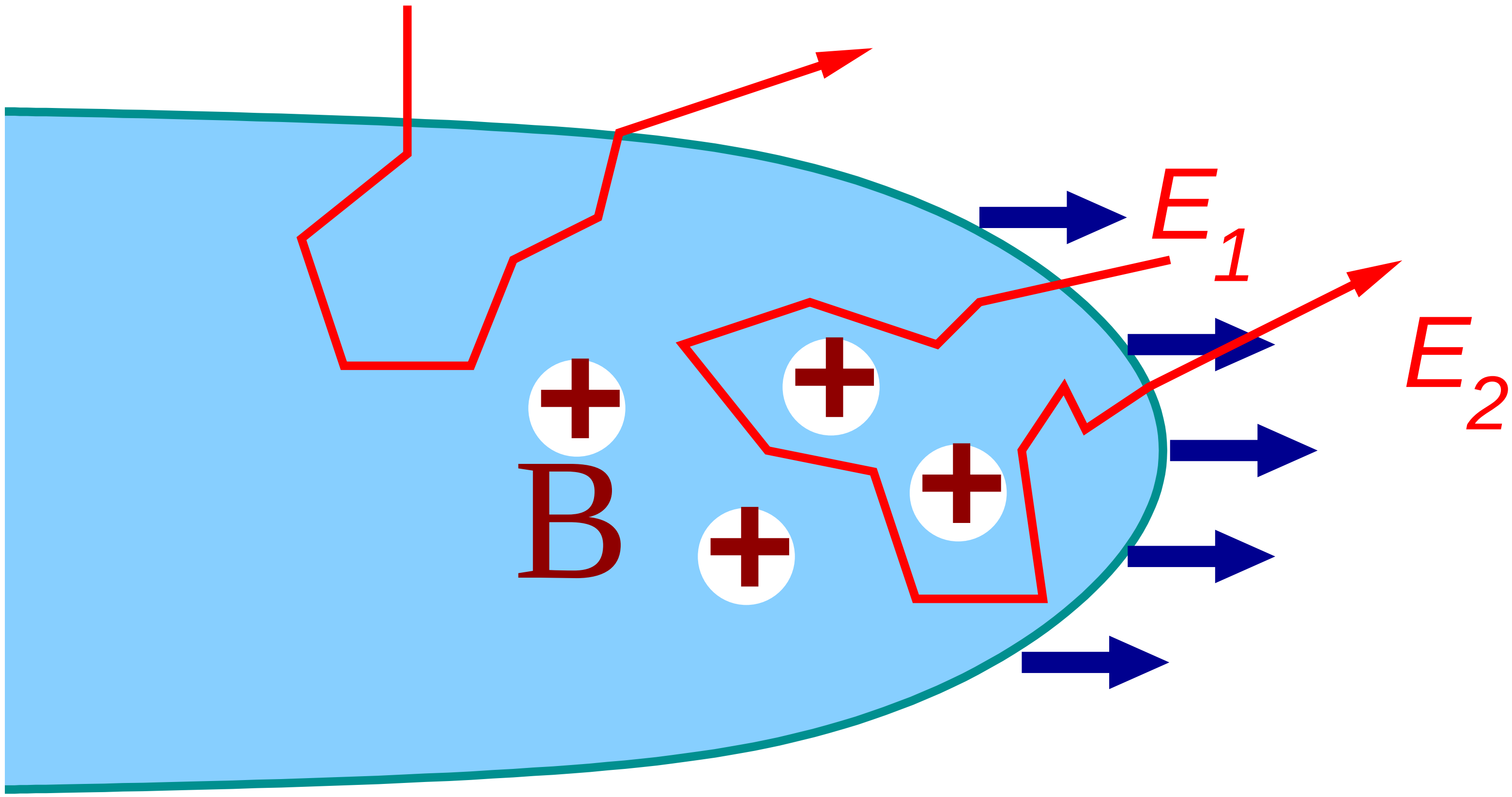


Acceleration in AGN and radio galaxies





Fermi acceleration



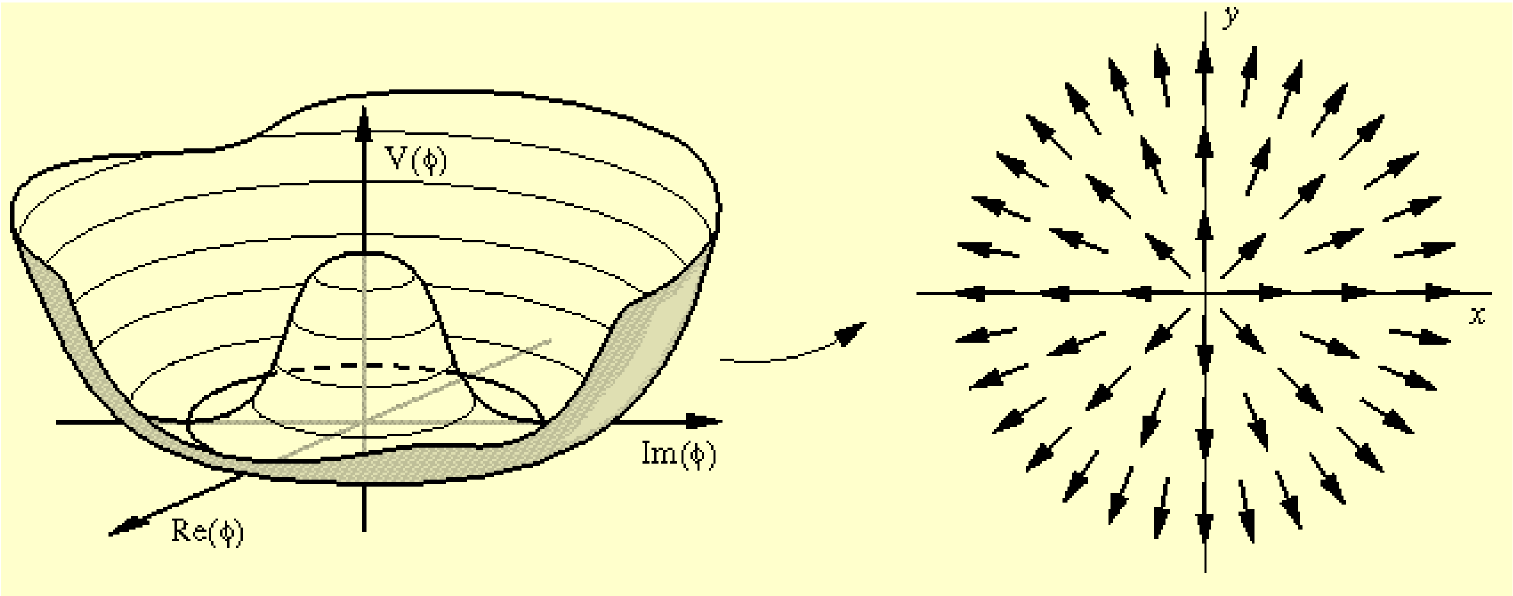
Supermassive relic particles

- Could be copiously produced at the end of inflation, during reheating, from gravity or other interactions at the high scale.
  Can be the dark matter.
- Long lifetime is difficult to explain,
  but models exist [*e.g.*, Kuzmin, Rubakov]

- Decays can produce UHECR in our galactic halo, hence no GZK cutoff

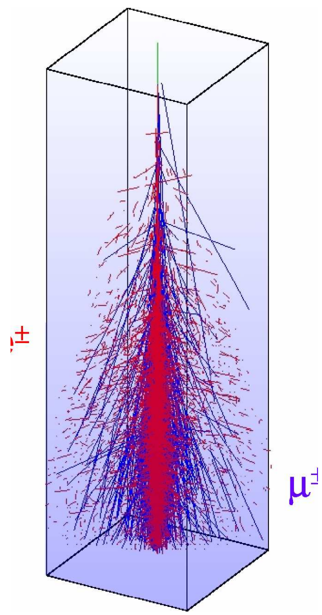
- Signatures: **North-South asymmetry, photons**

Topological defects

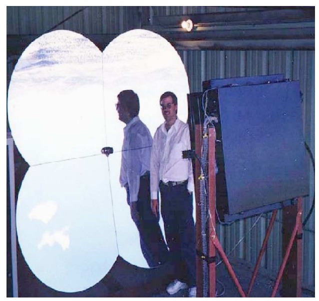


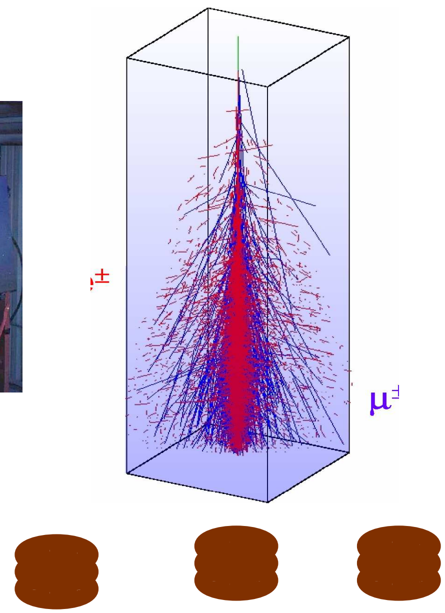
High energy density in the core. Decays can produce high-energy particles. Long lifetimes.

Air showers



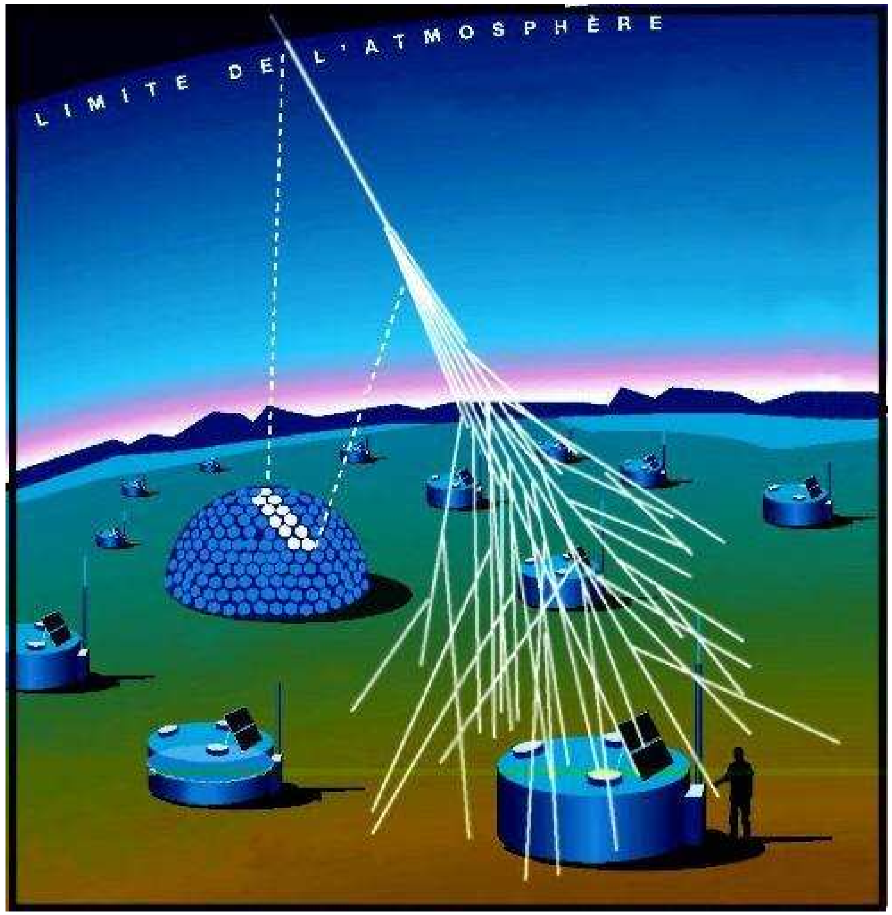
Detection techniques



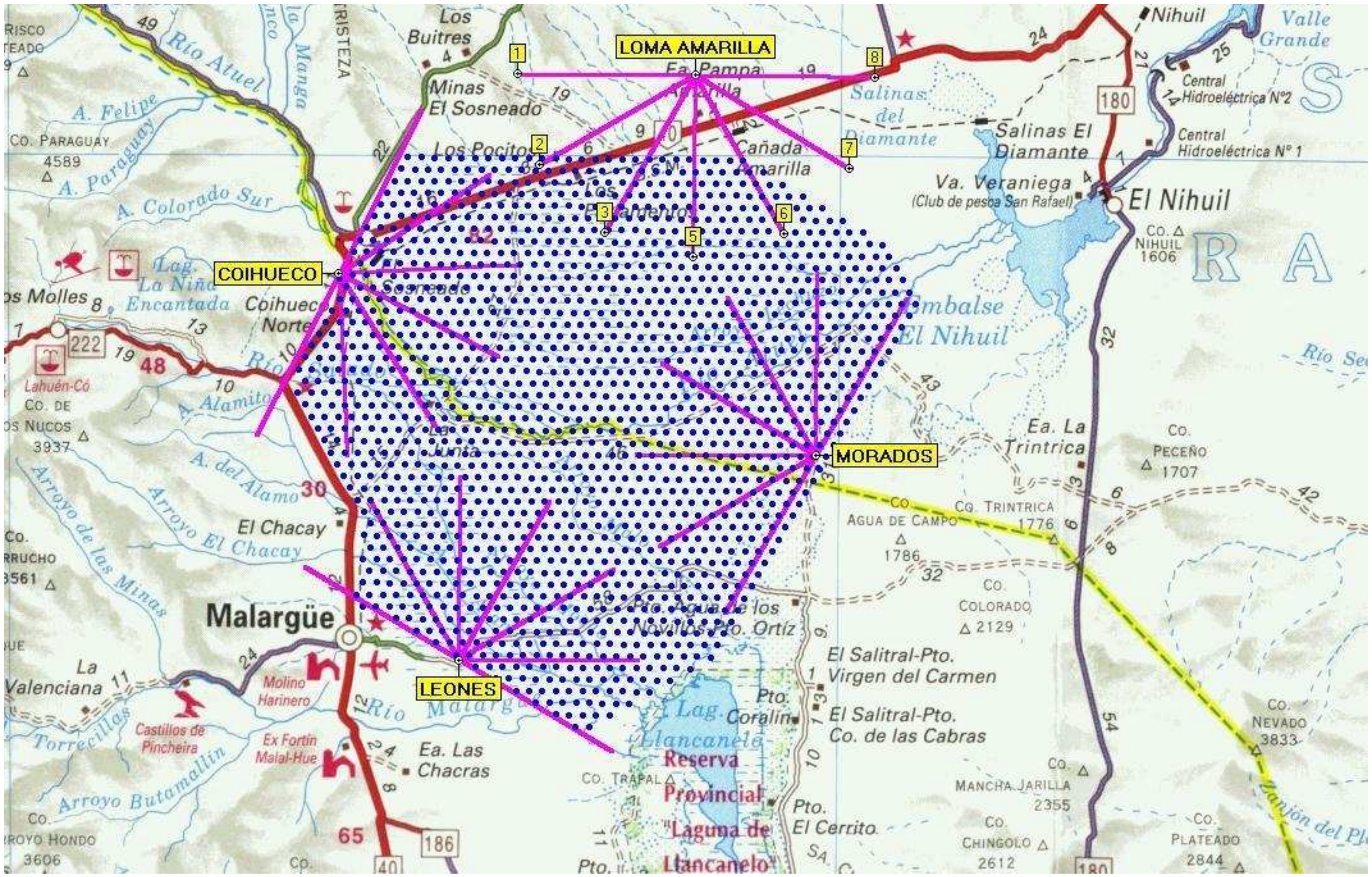


Fluorescent detection: Fly's Eye, Hi Res, EUSO
Surface array: AGASA
Both: Pierre Auger

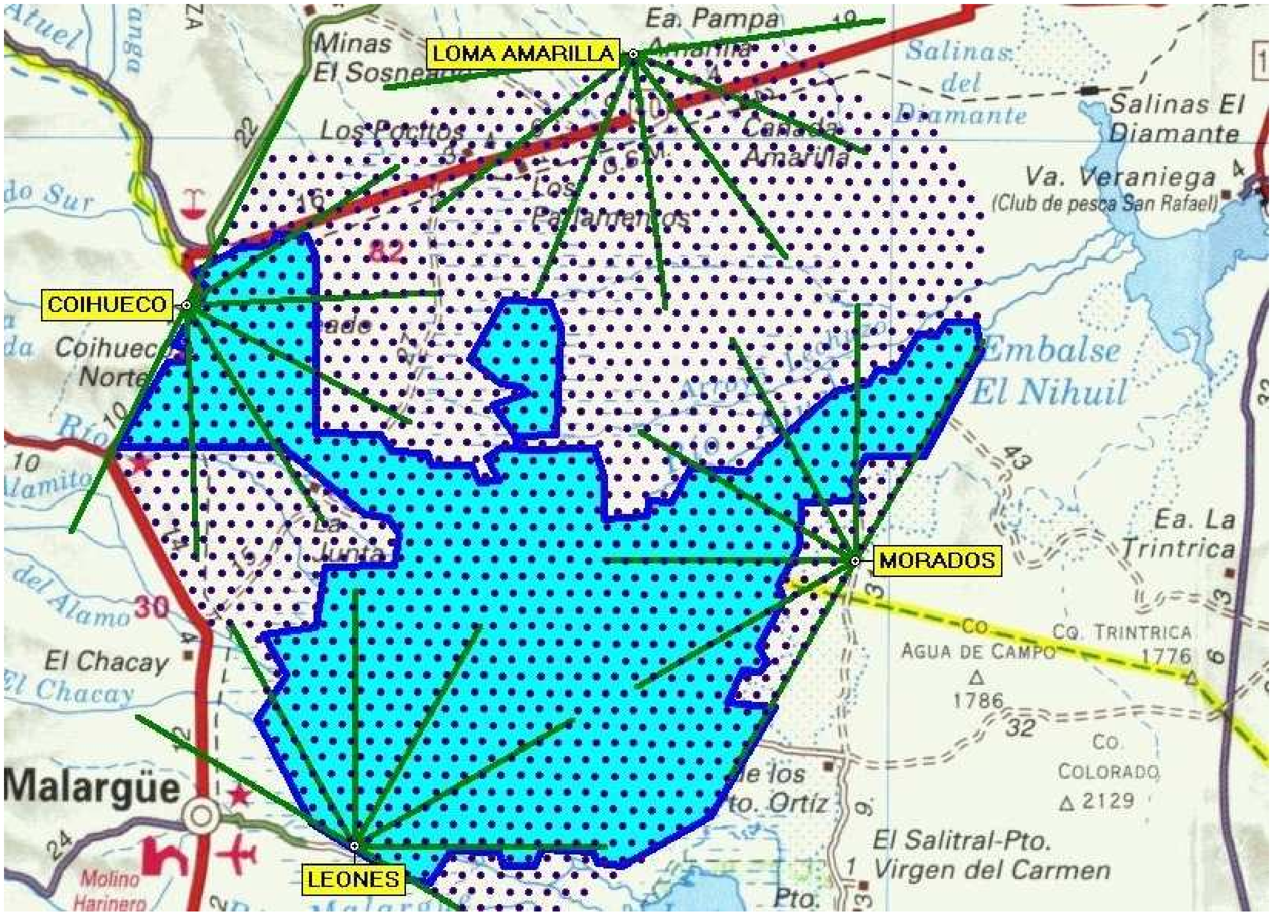
Pierre Auger



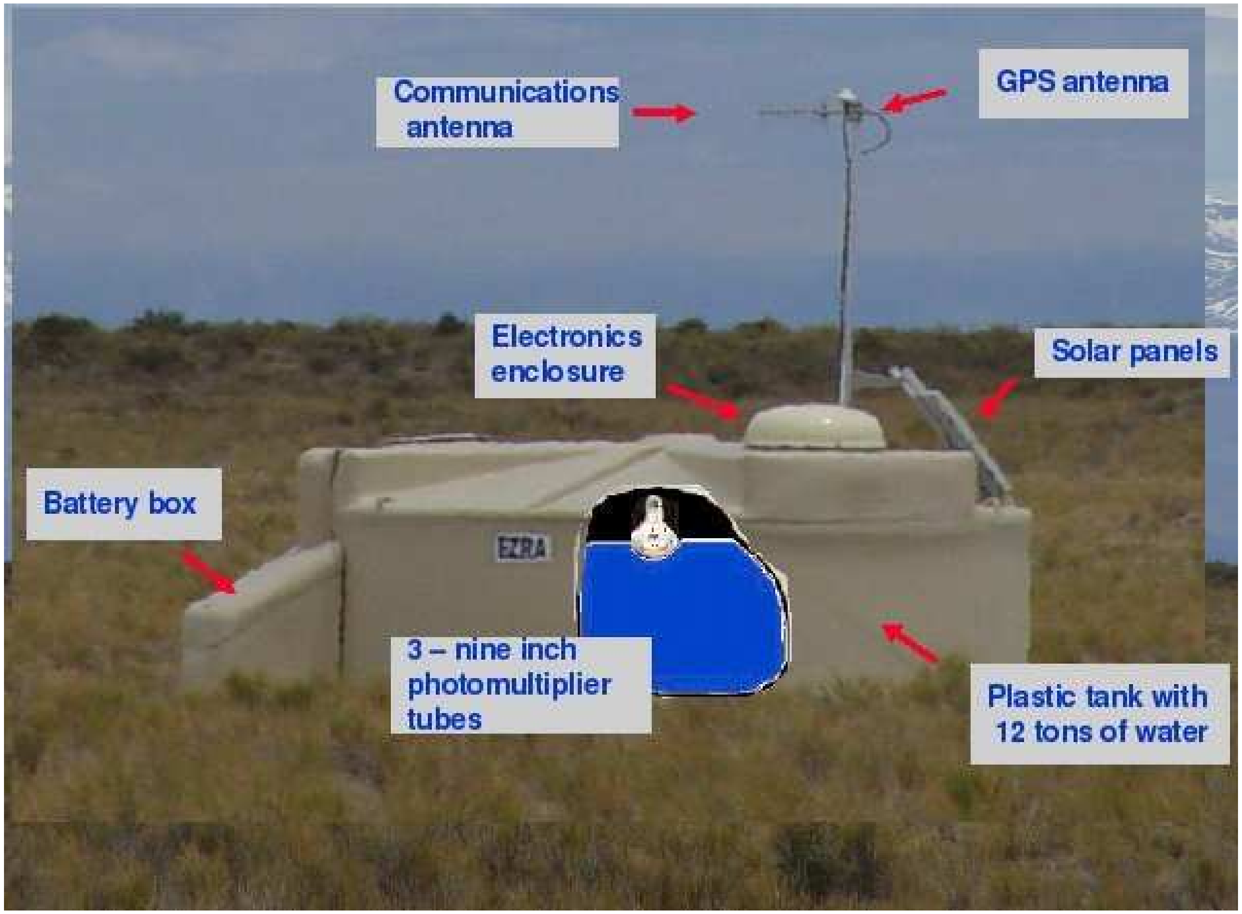
Pierre Auger (South)



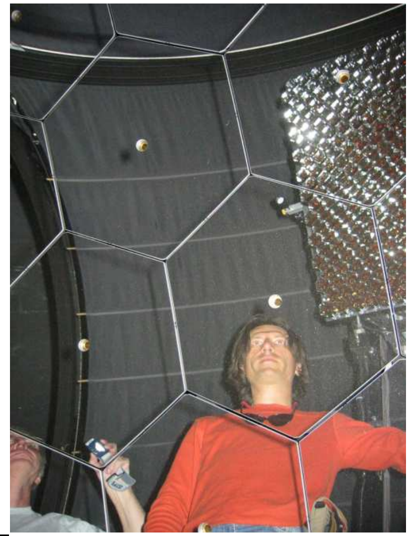
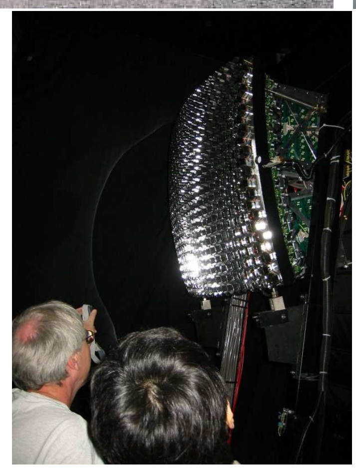
Pierre Auger (South) in 2005



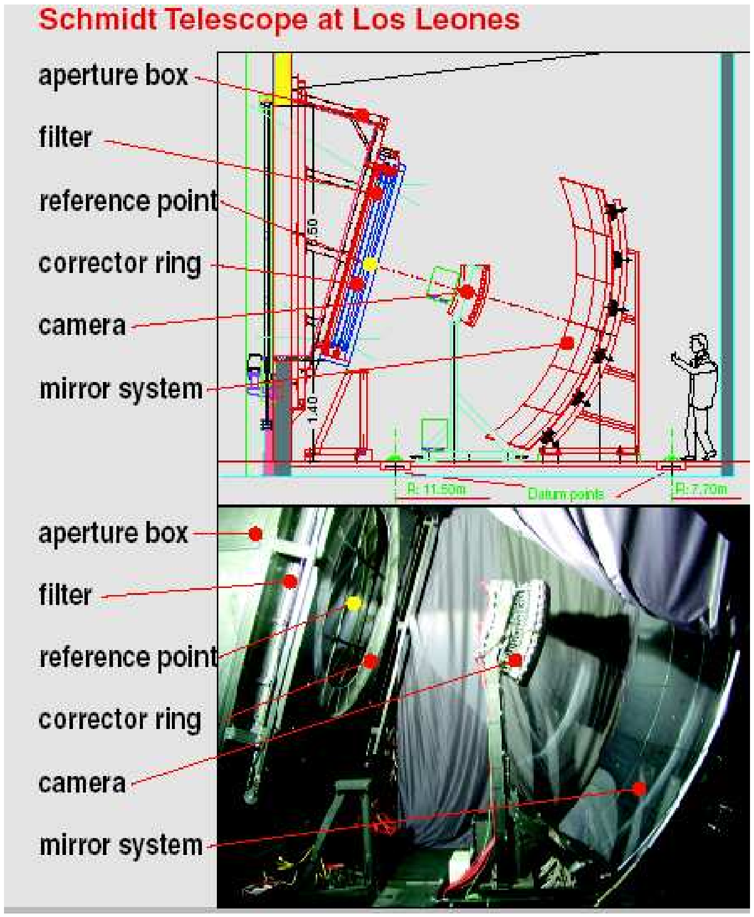
Water tanks


Communications antenna
GPS antenna
Electronics enclosure
Solar panels
Battery box
EZRA
3 – nine inch photomultiplier tubes
Plastic tank with 12 tons of water

Fluorescence detector

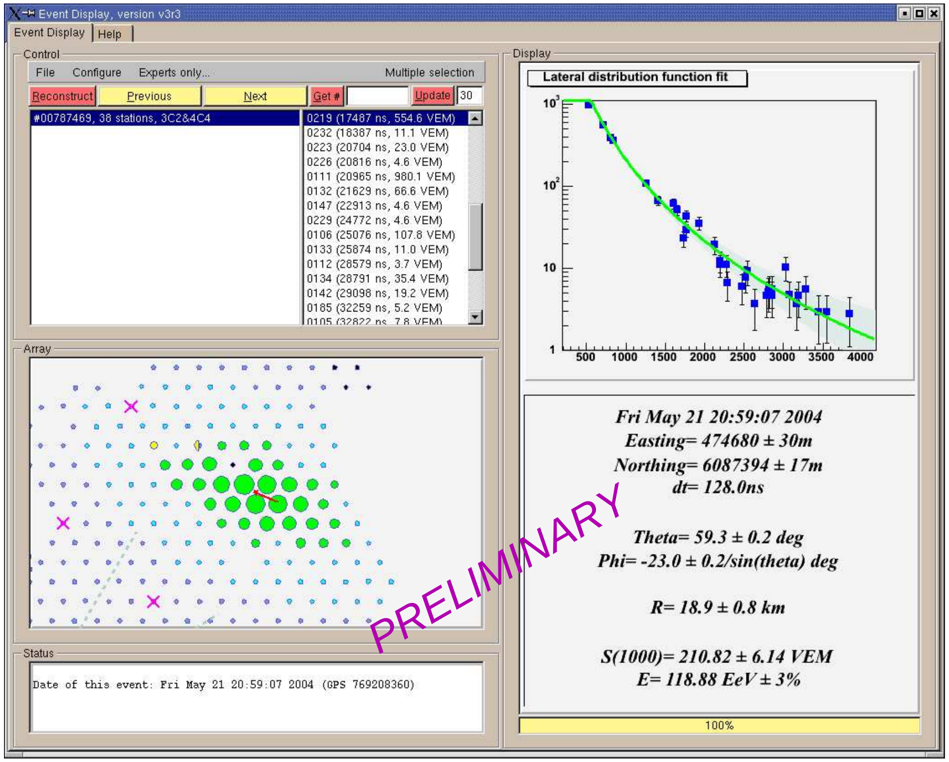




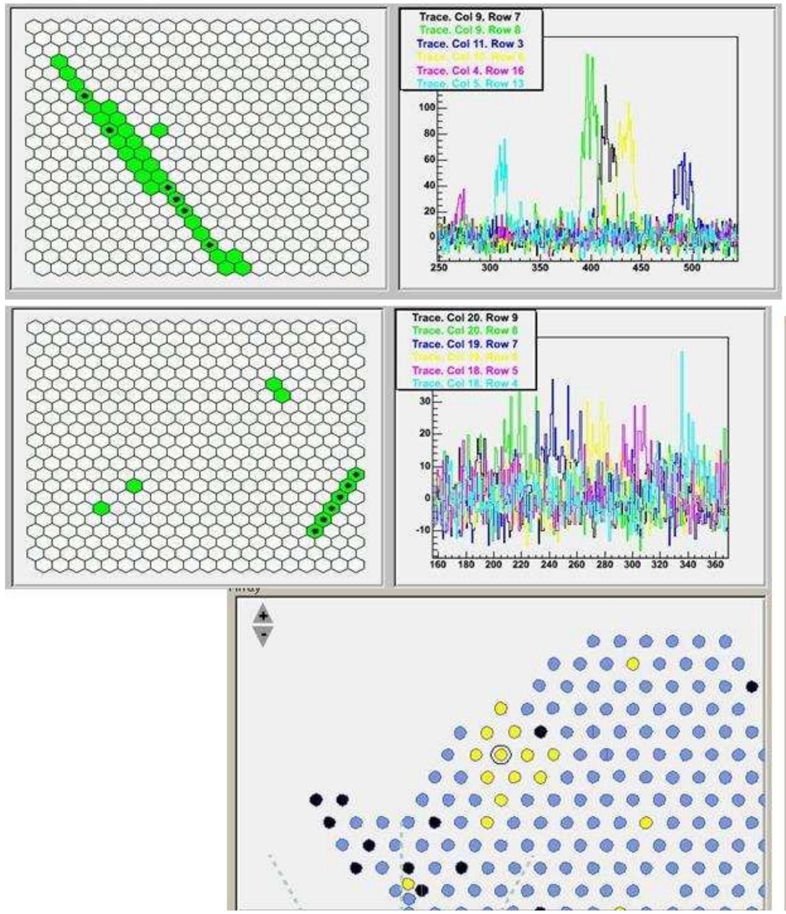
Fluorescence detector



Lidar is used to monitor the atmosphere

Events

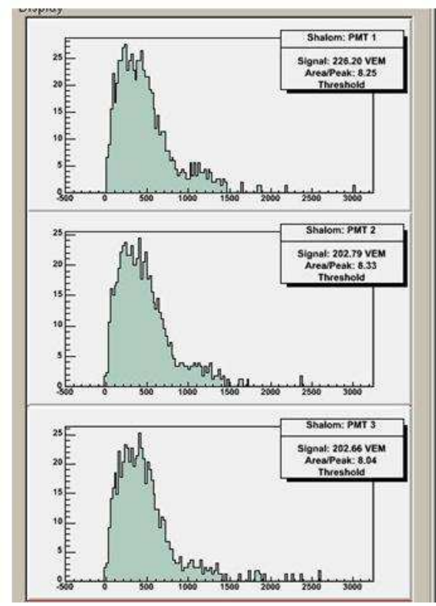

Event Display, version v3r3
Event Display
Help
Control
File
Configure
Experts only...
Multiple selection
Reconstruct
Previous
Next
Get #
Update
30
#00787469, 38 stations, 3C2&4C4
0219 (17487 ns, 554.6 VEM)
0232 (18387 ns, 11.1 VEM)
0223 (20704 ns, 23.0 VEM)
0226 (20816 ns, 4.6 VEM)
0111 (20965 ns, 980.1 VEM)
0132 (21629 ns, 66.6 VEM)
0147 (22913 ns, 4.6 VEM)
0229 (24772 ns, 4.6 VEM)
0106 (25076 ns, 107.8 VEM)
0133 (25874 ns, 11.0 VEM)
0112 (28579 ns, 3.7 VEM)
0134 (28791 ns, 35.4 VEM)
0142 (29098 ns, 19.2 VEM)
0185 (32259 ns, 5.2 VEM)
Array
Status
Date of this event: Fri May 21 20:59:07 2004 (GPS 769208360)
Display
Lateral distribution function fit
Fri May 21 20:59:07 2004
Easting= 474680 ± 30m
Northing= 6087394 ± 17m
dt= 128.0ns
Theta= 59.3 ± 0.2 deg
Phi= -23.0 ± 0.2/sin(theta) deg
R= 18.9 ± 0.8 km
S(1000)= 210.82 ± 6.14 VEM
E= 118.88 EeV ± 3%
100%
PRELIMINARY

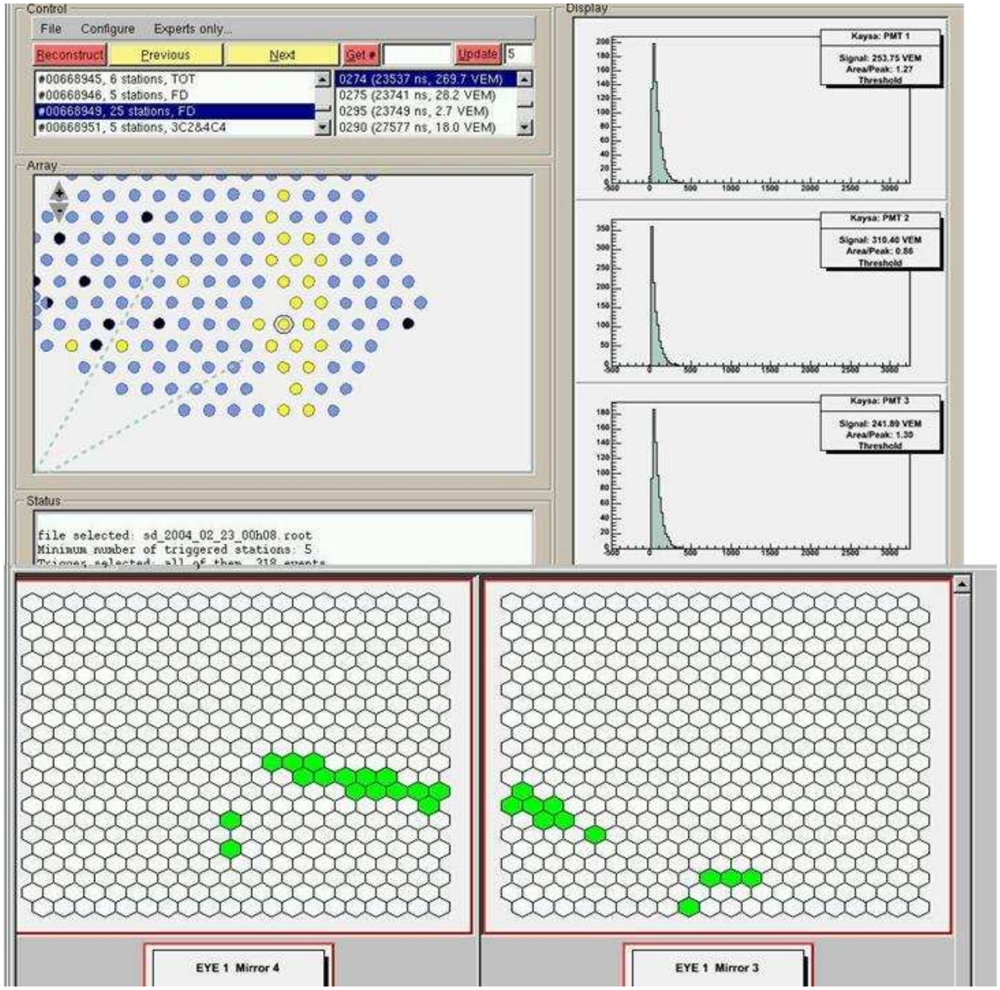


Platinum Event

#673411

(10 tanks in fit)





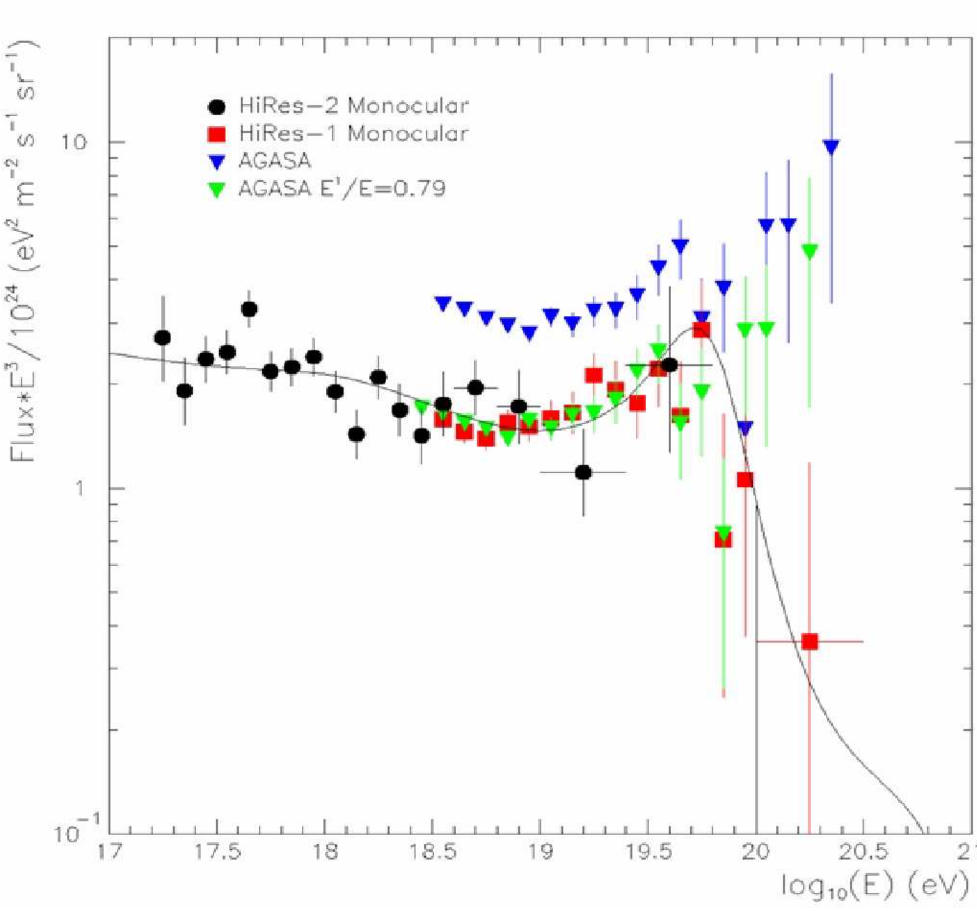
2-Telescope

Golden Hybrid

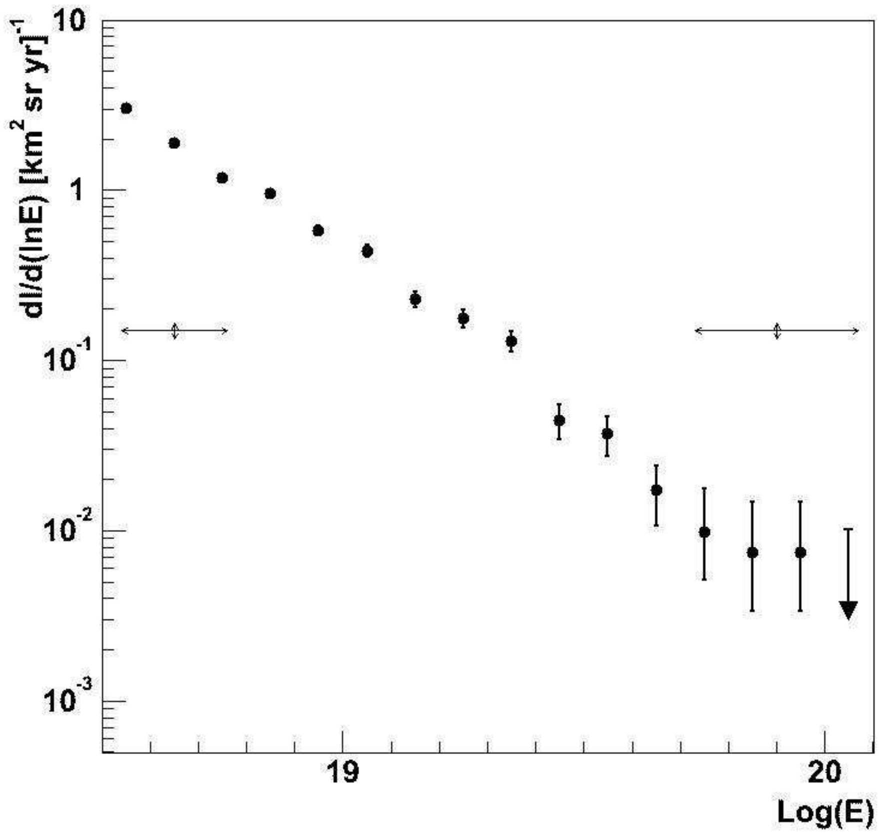
Event #668949

Los Leones

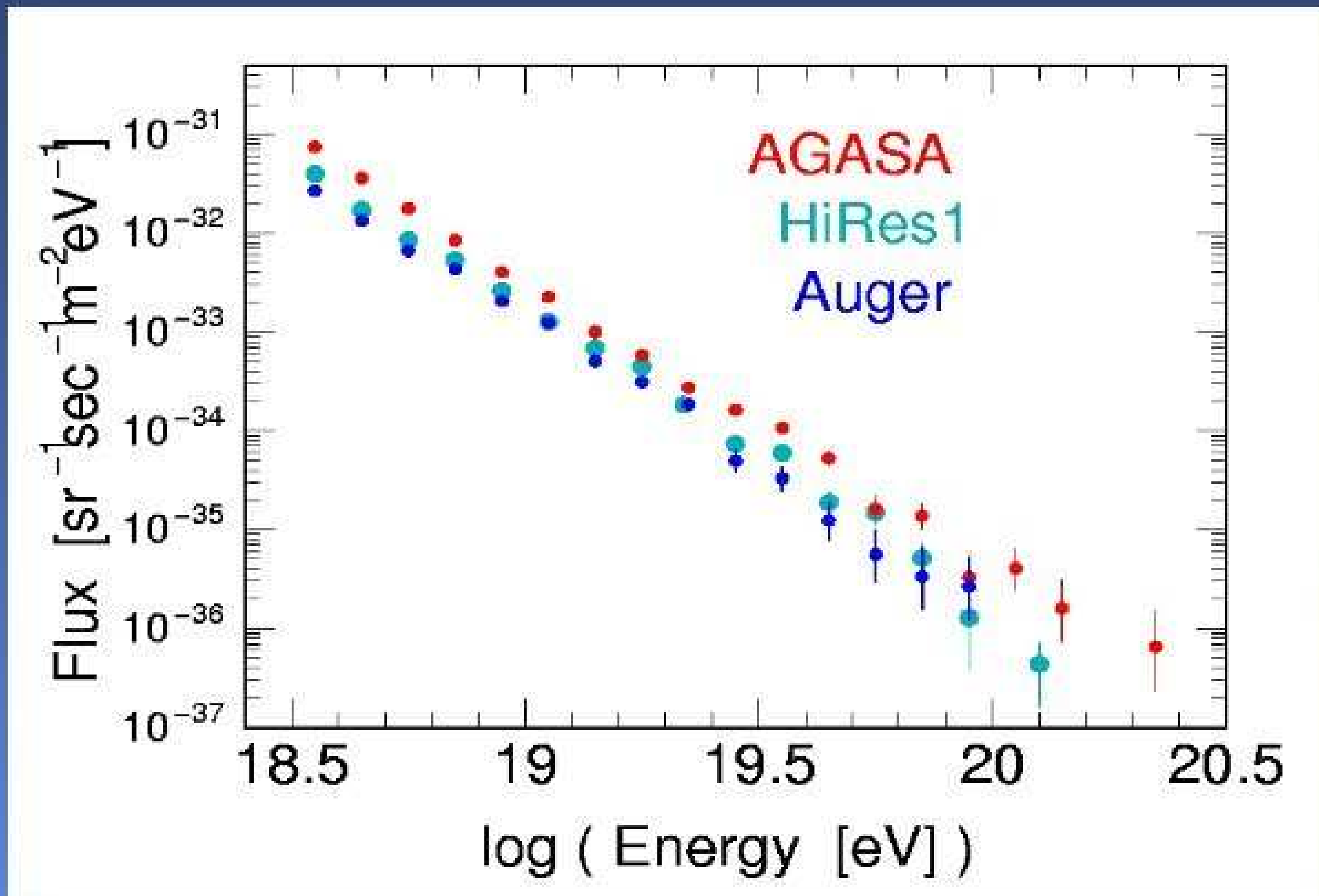
AGASA vs HiRes



Pierre Auger: first results reported at ICRC '05



Comparison with HiRes1, AGASA

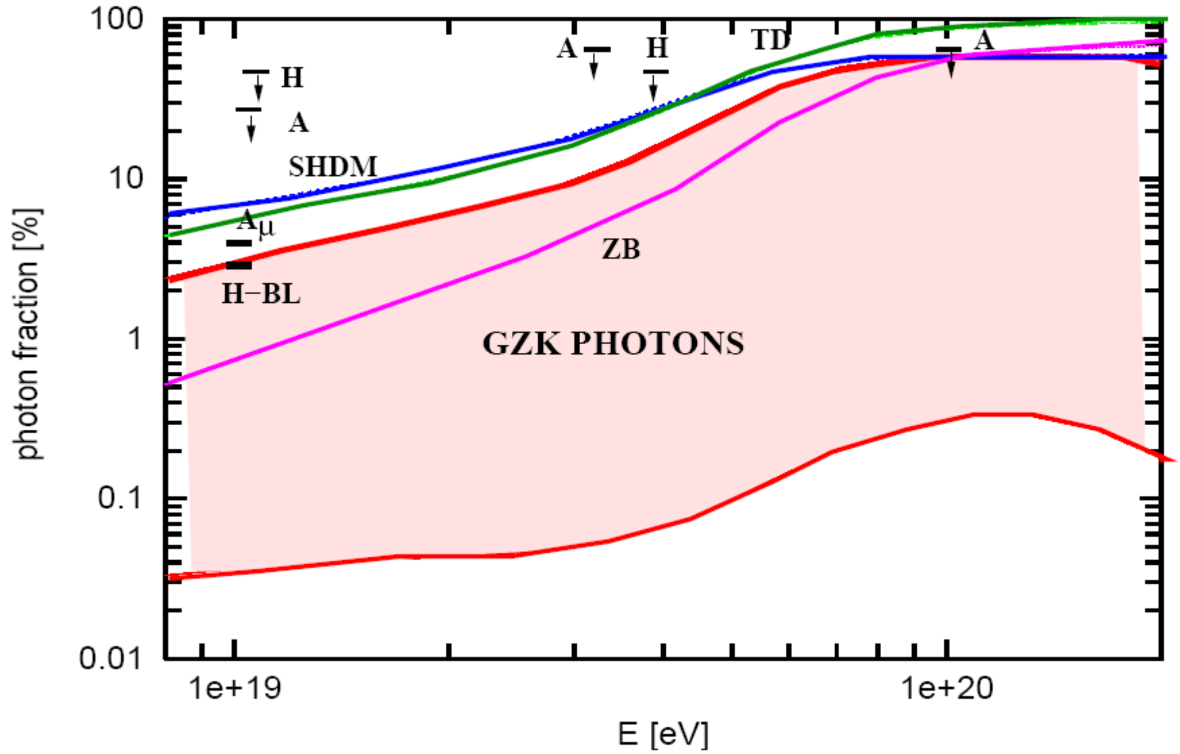


Particle ID

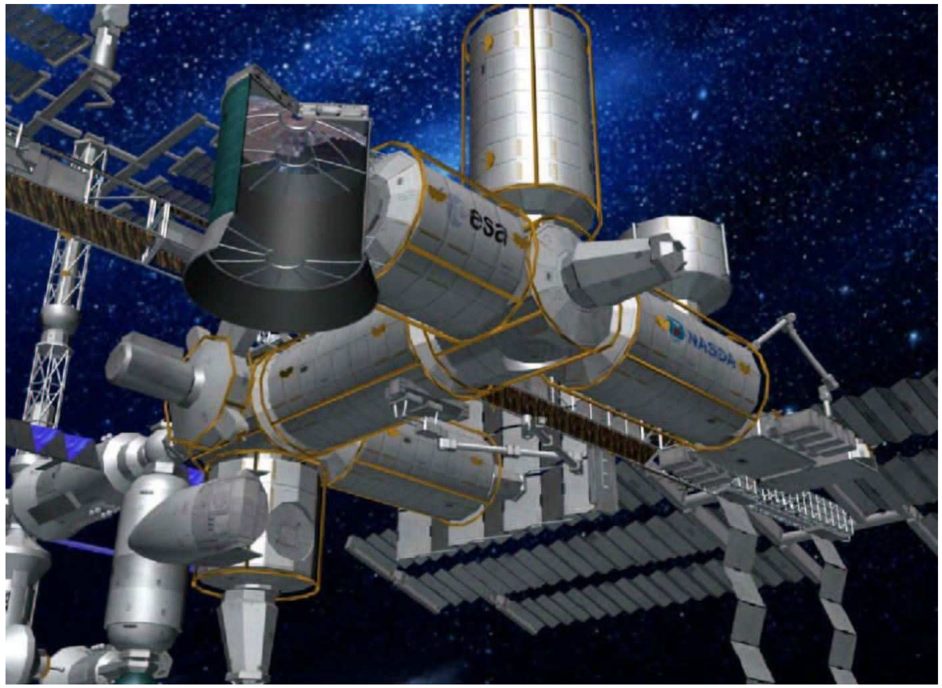
Tools at one's disposal:

- $\boldsymbol{x}_{\mathbf{max}}$, location of EM shower maximum (related to mass and hadronization model)
- $\boldsymbol{N}_{\mathbf{max}}$, the number of e^+e^- at $x_{\mathbf{max}}$ (proportional to energy)
- muon richness, $N^{\mu}_{\mathbf{max}}/N^{e}_{\mathbf{max}}$ (depends on mass, hadronization model, water tank response)
- curvature (from the timing)

Limit on photons



Extreme Universal Space Observatory (EUSO)



EUSO is designed to observe fluorescent air showers initiated by extremely high energy cosmic rays - and neutrinos

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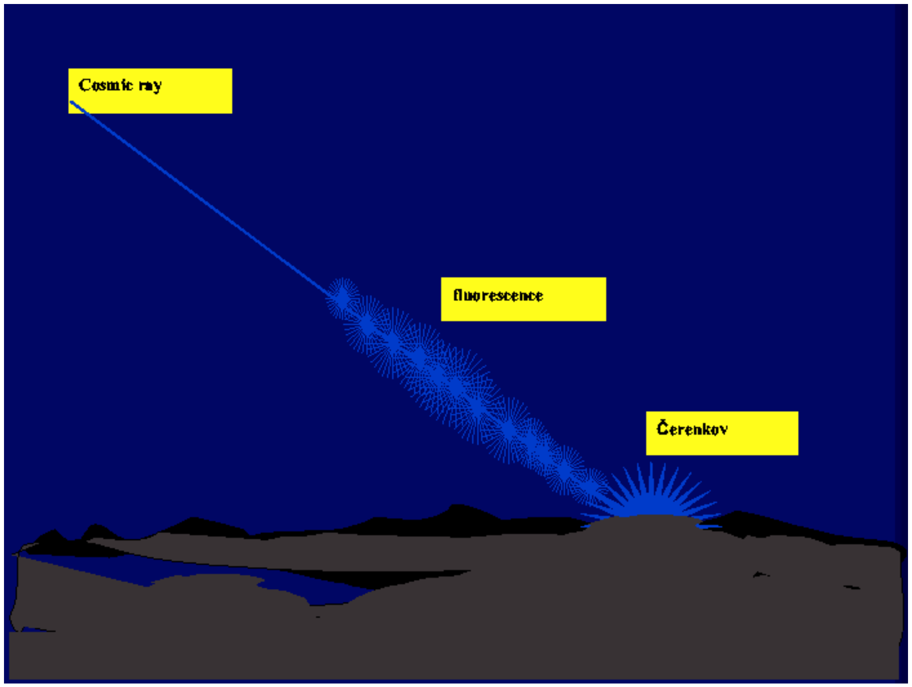
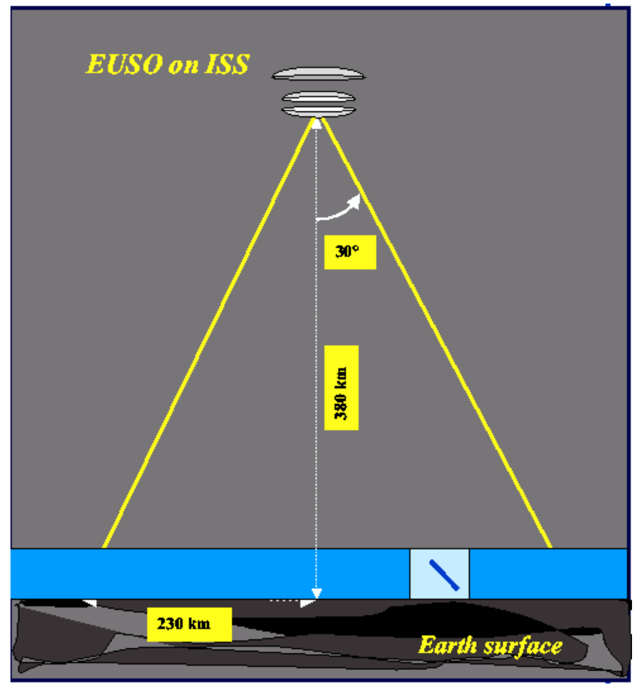


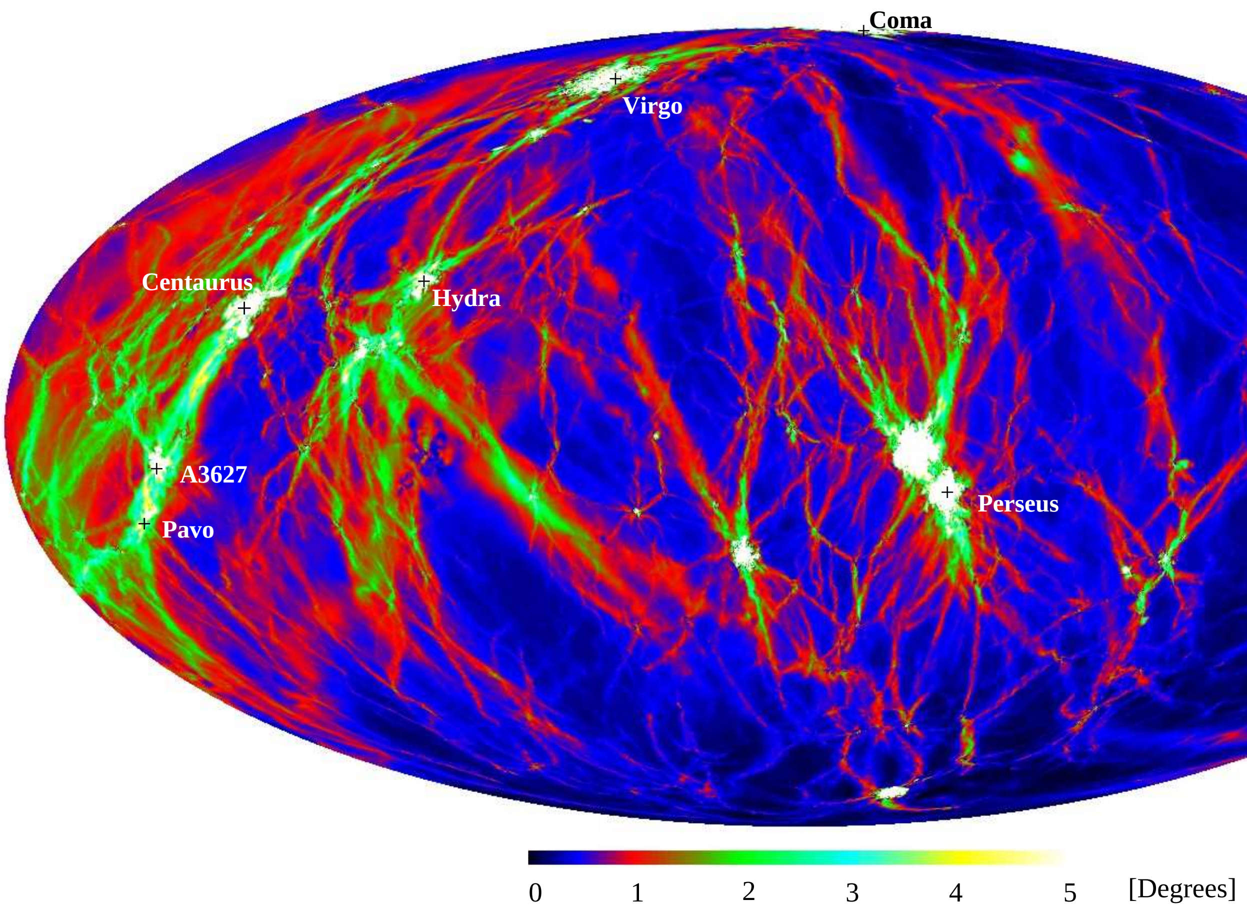


UHE neutrinos are out there!

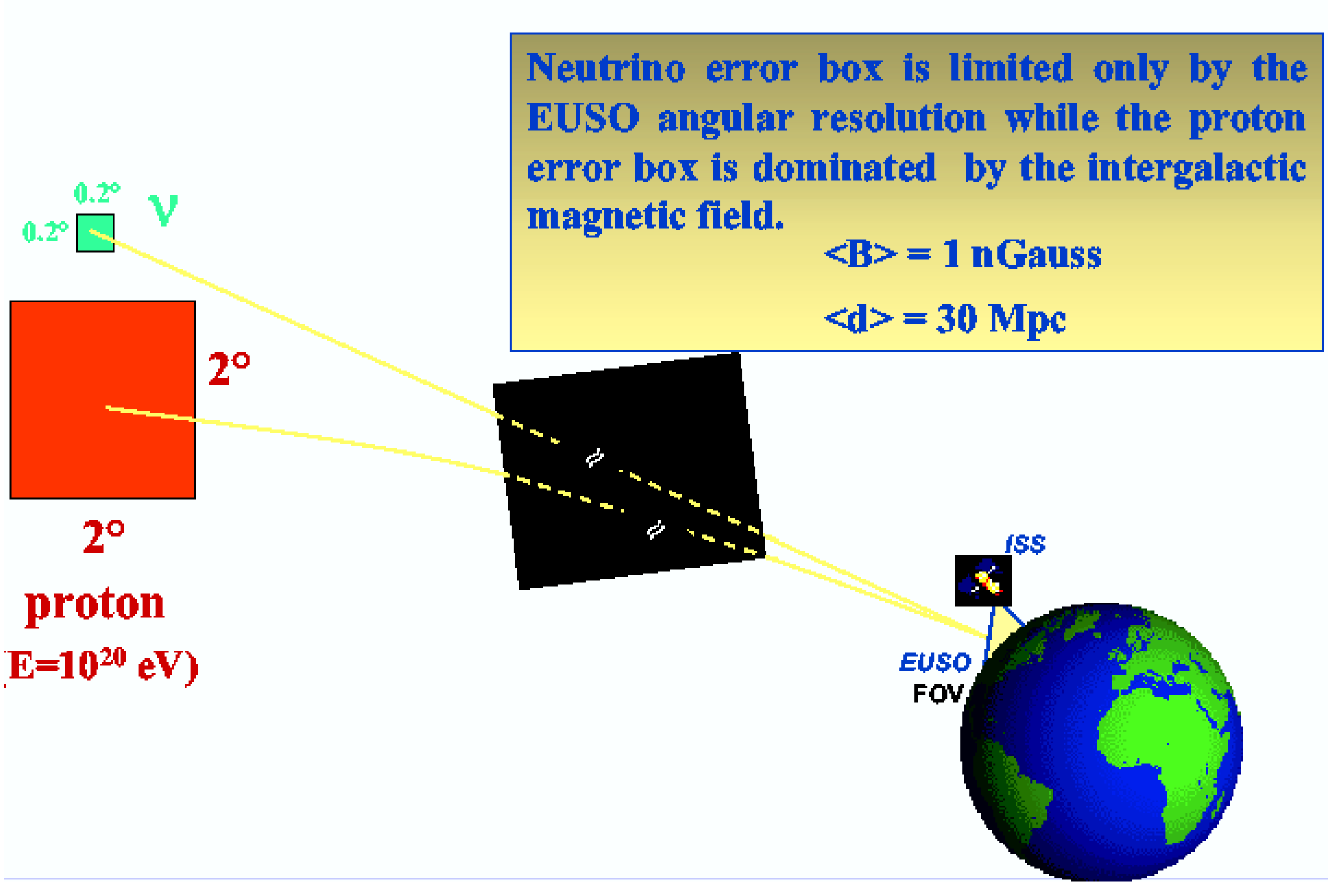
- Astrophysical sources
- $p\gamma$ interactions imply a (predictable) flux of cosmogenic UHE neutrinos.
- Additional sources can provide additional flux. (*e.g.* Z-bursts)

Hopefully, they will be discovered in the near future
Pierre Auger, AMANDA, ANITA, ICE CUBE, EUSO, OWL,...

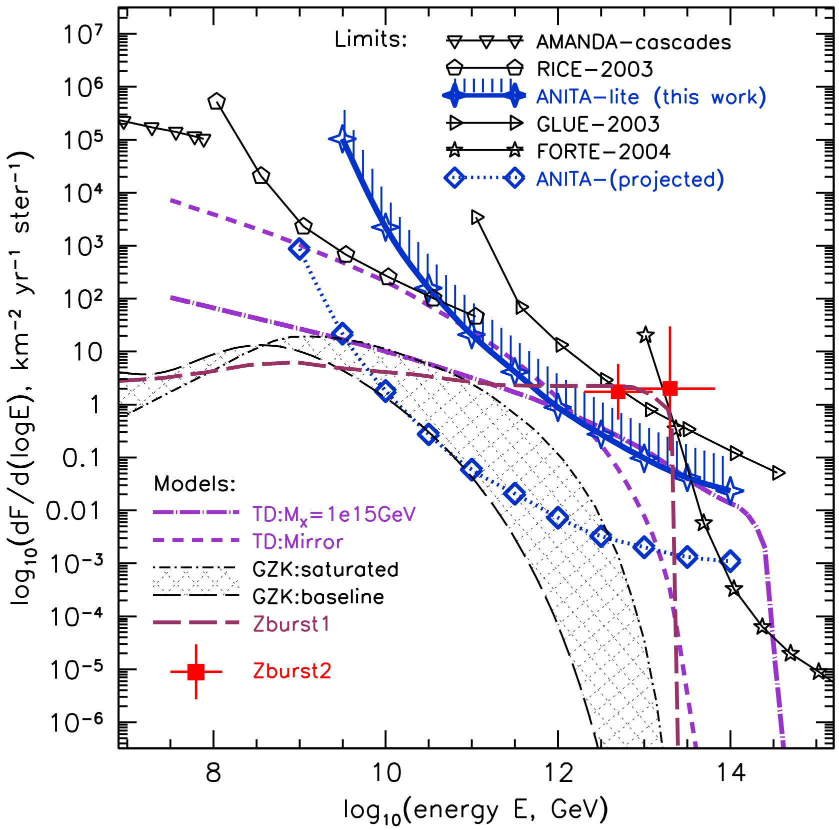
UHECR are deflected by magnetic fields



UHE neutrino astronomy

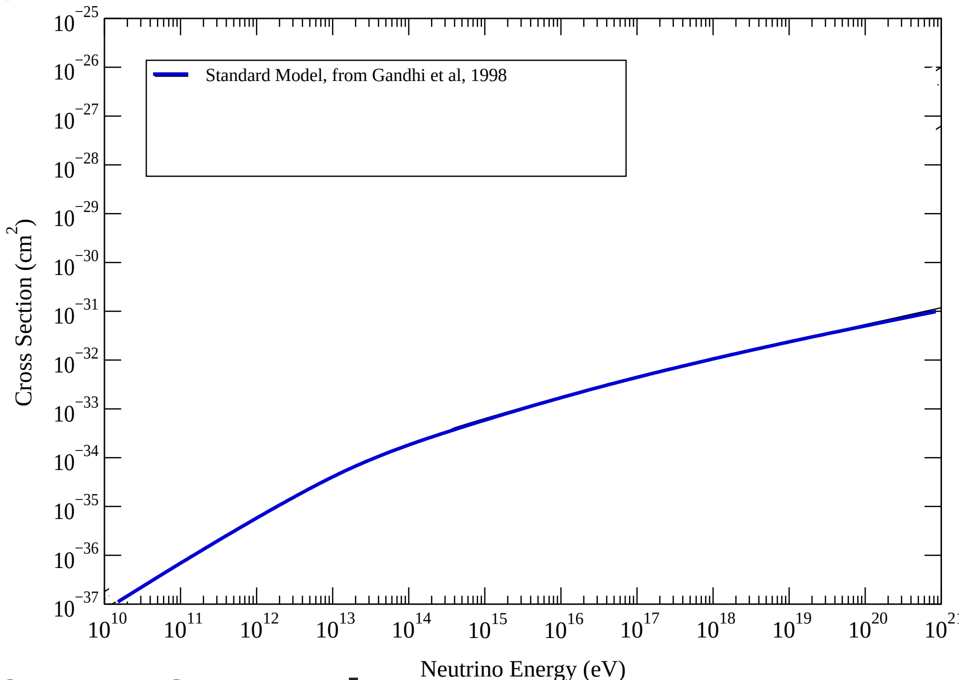


Predictions and limits



Detection strategy relies on the knowledge of the neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.



[Gandhi, Reno, Quigg, Sarcevic]

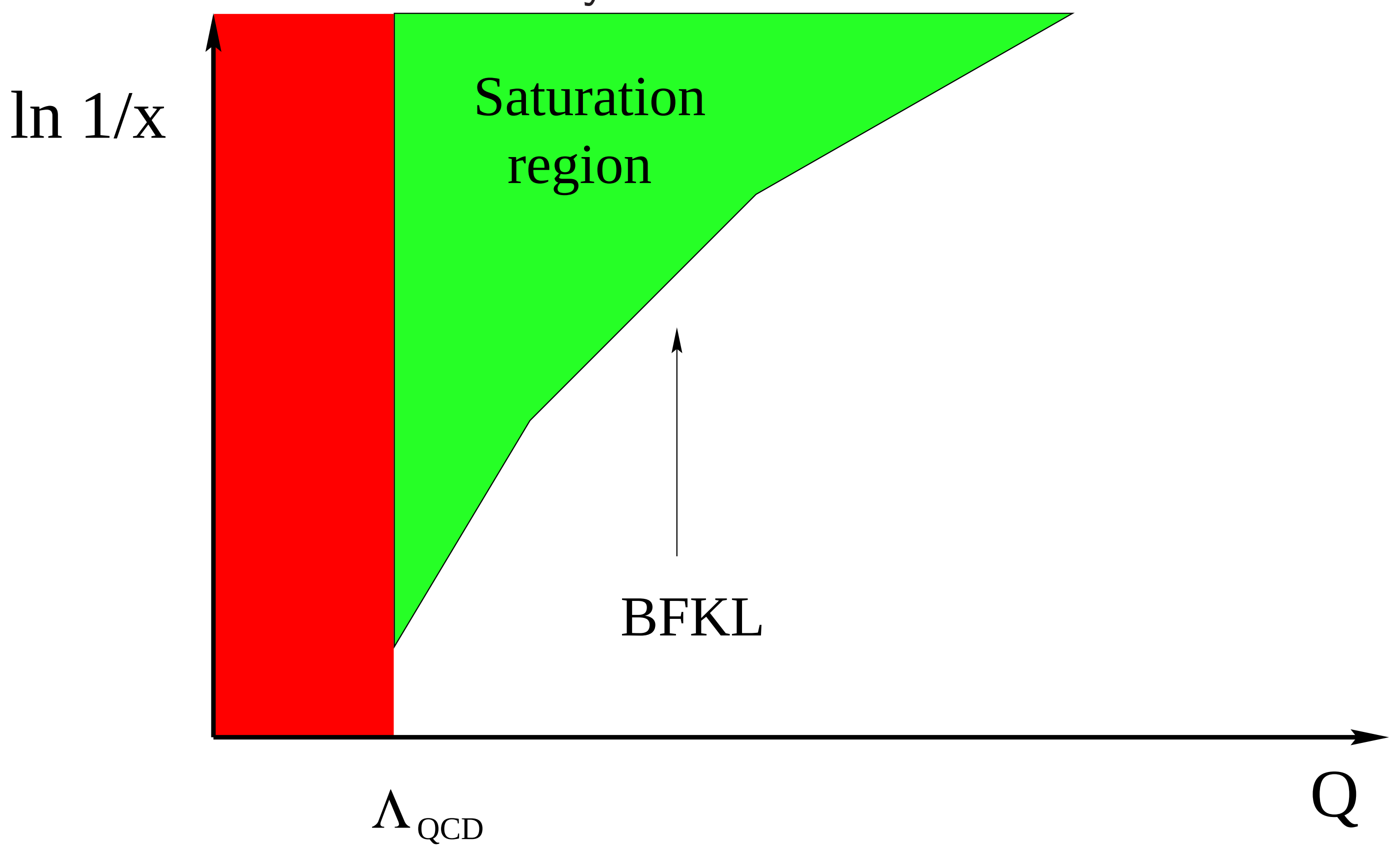
Several approved and proposed experiments plan to **detect UHE neutrinos** by observations of nearly **horizontal air showers**.

Neutrinos are the only particles that interact weakly enough to produce horizontal air showers (assuming the cross section $\sigma_{\nu N} \sim 10^{-31}$cm^2 at 10^{20}eV) Hence, particle ID is straightforward.

How well do we know the neutrino-nucleon cross section? New physics contributions? Can saturation affect the cross section at high energy?

Is it possible to **measure** the neutrino-nucleon cross section at these energies?

LO and saturation effects may affect the cross section



The cross section σ_{ν_N} **decreases** [R. Fiore, L.L. Jenkovszky, A. Kotikov, F. Paccanoni, A. Papa, E. Predazzi]

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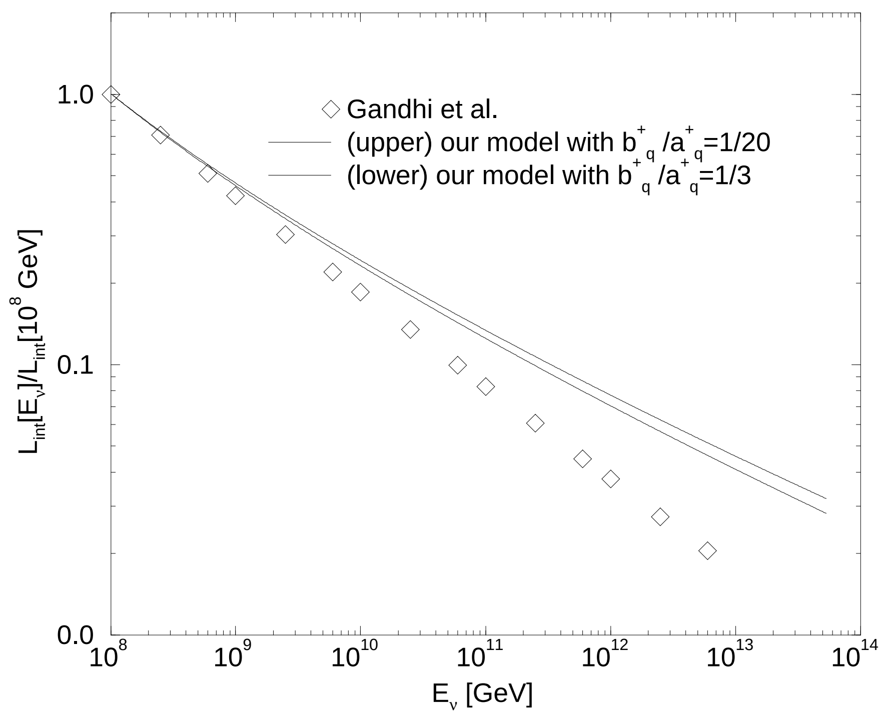
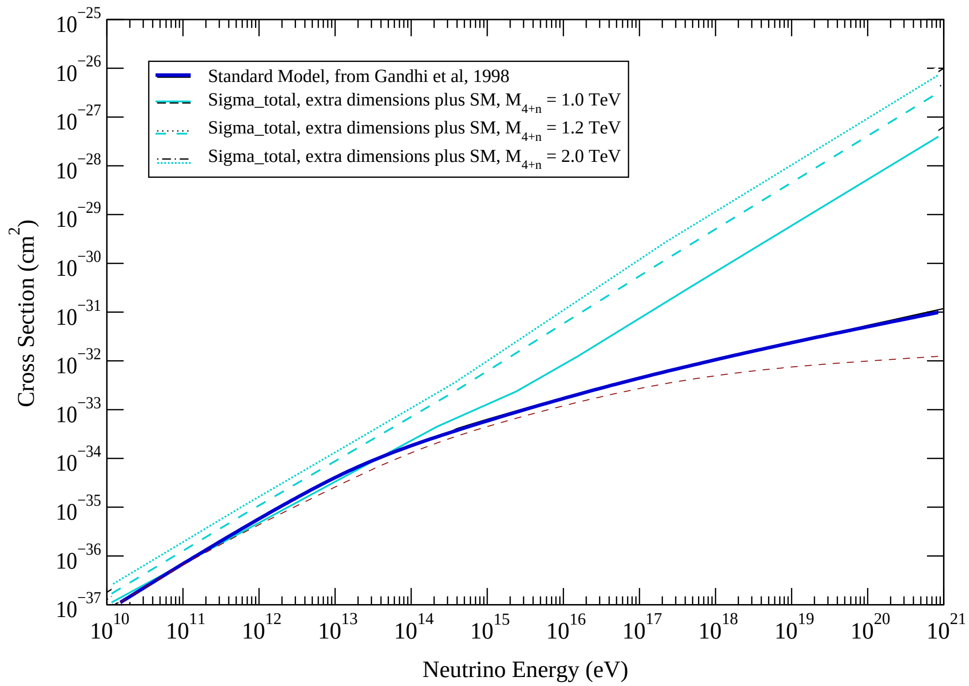


The cross section σ_{ν_N} **decreases** [R. Fiore, L.L. Jenkovszky, A. Kotikov, F. Paccanoni, A. Papa, E. Predazzi]

Neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

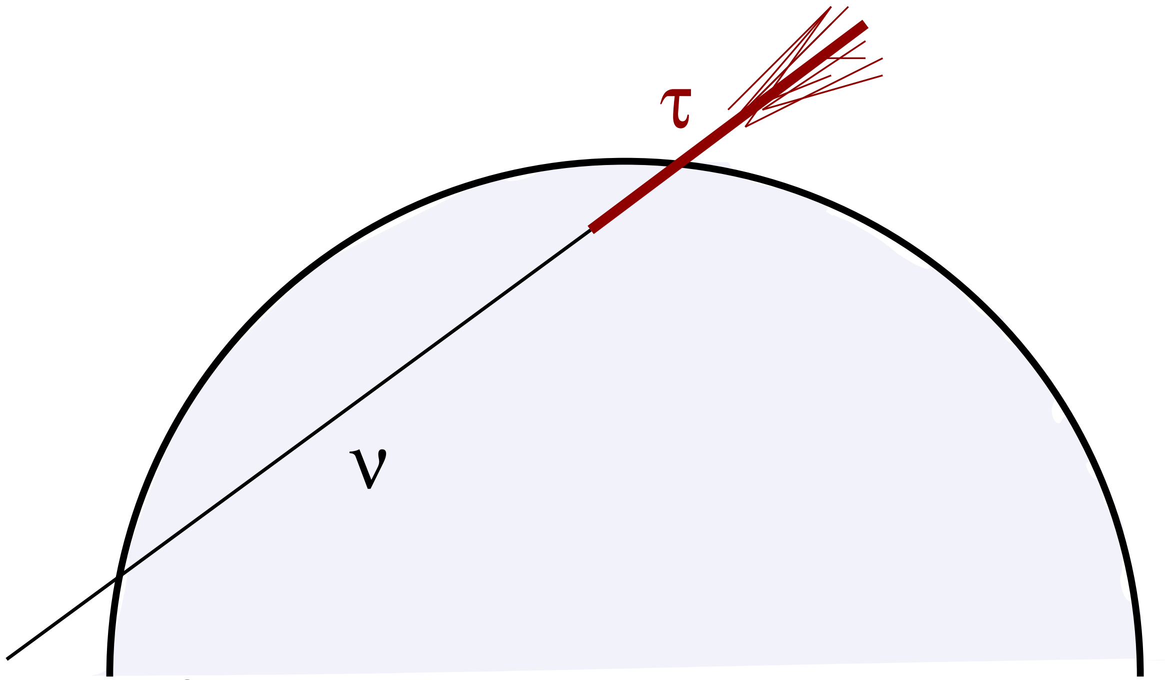
Calculations necessarily use extrapolations of PDF and standard model parameters.



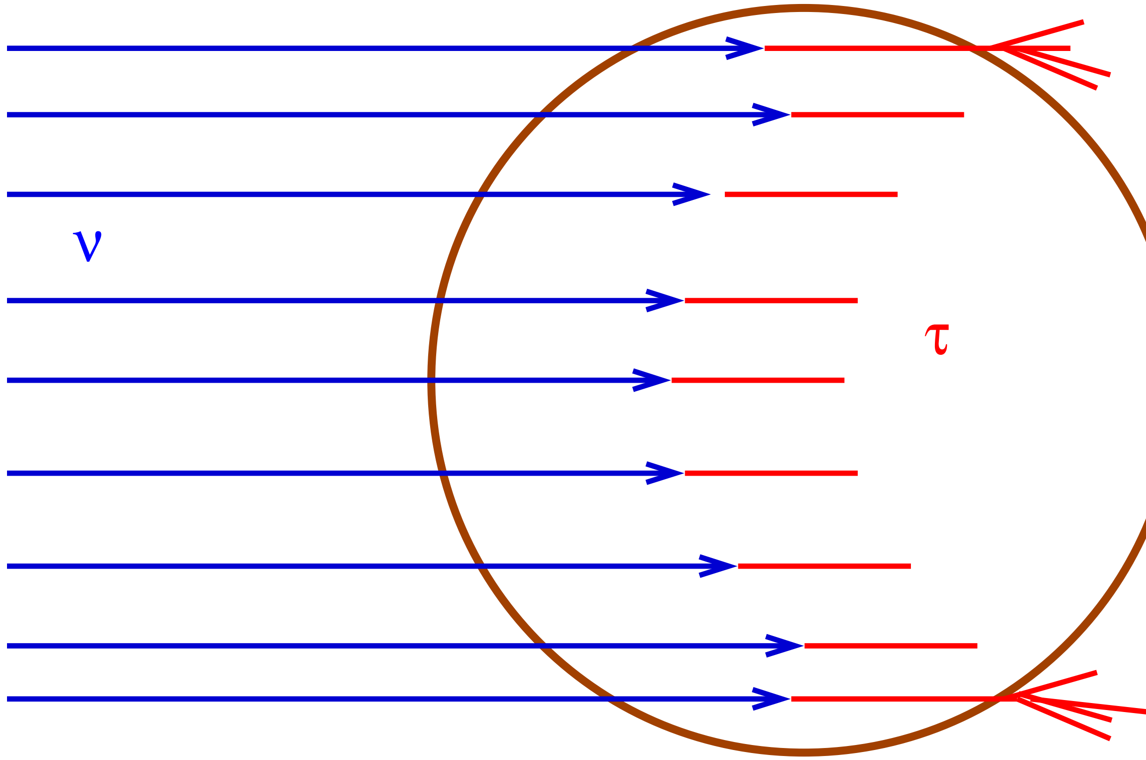
SM calculation [Quigg et al.] is most likely right, but we want to **measure** this cross section.

If the cross section is smaller, the Earth becomes more transparent to neutrinos. More neutrinos can get through the Earth, interact just below the surface and produce a charged lepton that originates an **up-going air shower (UAS)** .

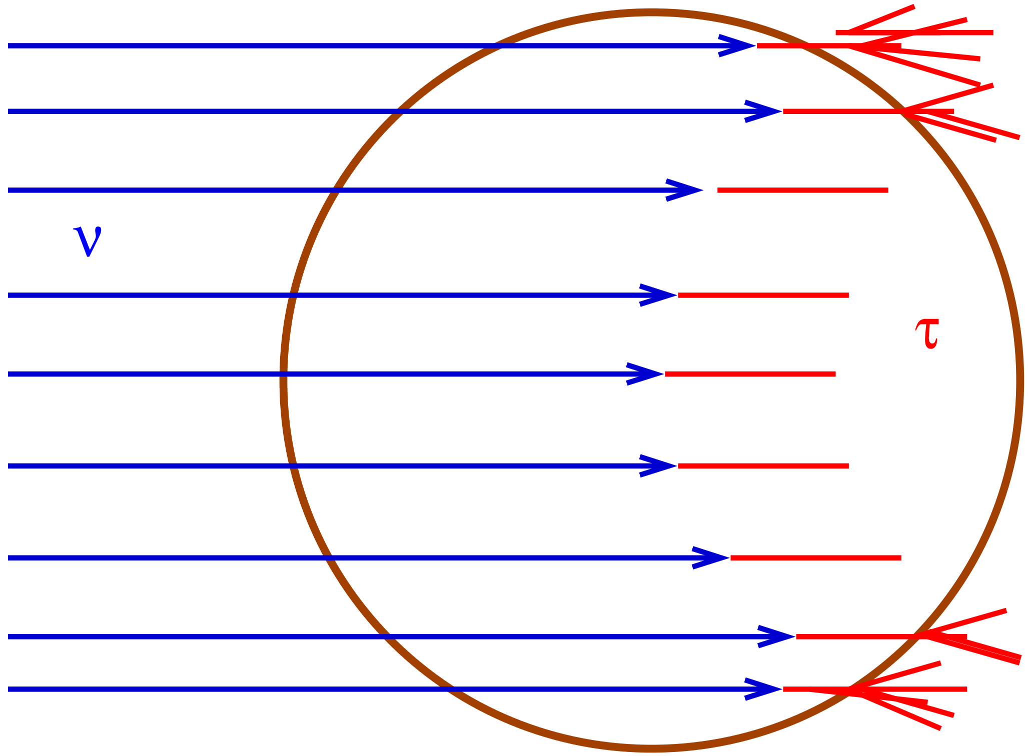
- **The increase in UAS rate compensates for the decrease in HAS.**
- **The comparison of the two rates allows a measurement of the cross section at 10^{11}GeV**
- **Angular distribution of UAS can provide an additional independent information about the cross section**



The probability of a neutrino conversion into an up-going τ grows with the mean free path λ_ν, for $\lambda_\nu < R_\oplus$, because the shadowing by the Earth decreases.

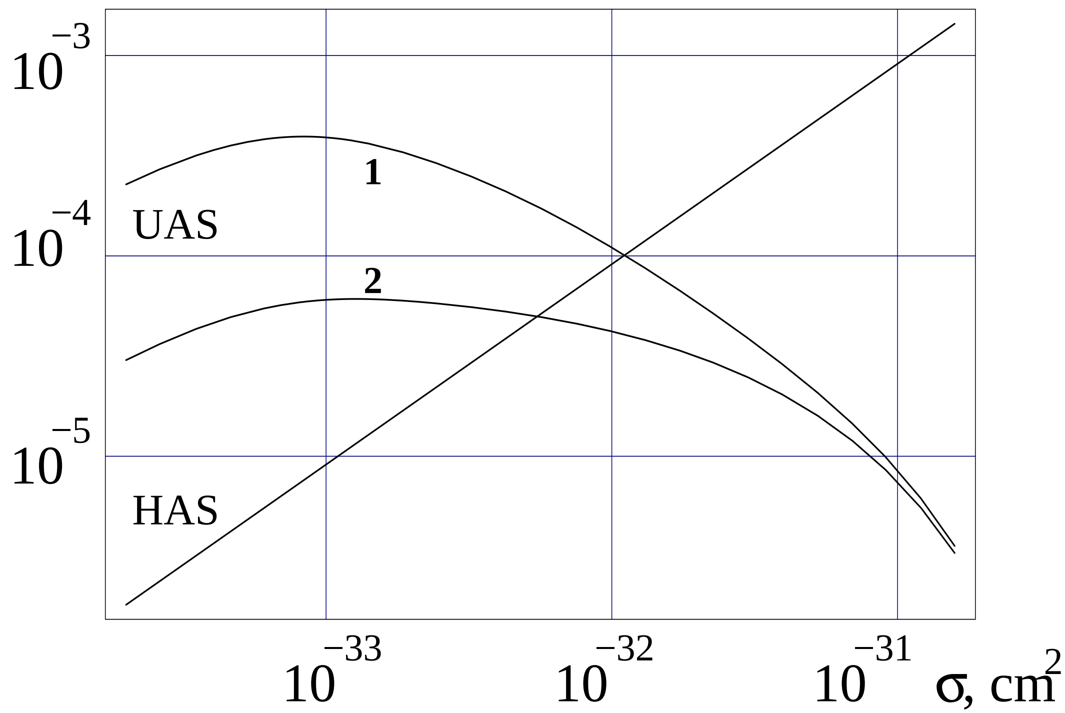


UAS requires a neutrino to interact and produce a τ below the surface.



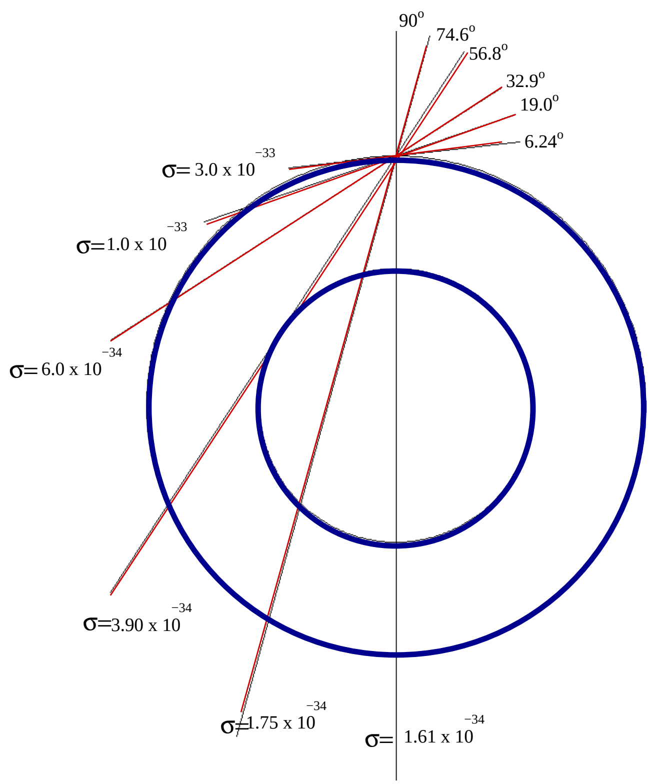
UAS requires a neutrino to interact and produce a τ below the surface. The number of UAS is higher for a smaller cross section.

The shower probability per incident neutrino:



The energy threshold for detection of UAS was assumed $E_{\rm th} = 10^{18}$eV for curve 1 and $E_{\rm th} = 10^{19}$eV for curve 2. Additional UAS events, not included here, can be detected by EUSO or OWL via Cerenkov radiation of tau leptons.

In addition, the angular distributing depends on the cross section.



Most probable UAS corresponds to chord length close to mean free path

Radio detection experiments

- **RICE:** Array of radio antennas at the South Pole, next to Ice Cube detector.
- **GLUE:** Goldstone telescope was pointed at Moon to detect showers in lunar regolith. Completed. No detection; produced limits.
- **FORTE:** Satellite data used to set limits on extremely high energy neutrinos.
- **ANITA:** Radio antennas flown on a balloon over Antarctic ice. Test flights successful. Science run: next winter. Stay tuned.
- **SALSA:** Future experiment in a salt dome.

Conclusion

- Cosmic rays of ultrahigh energies is a rapidly developing field. Pierre Auger experiment has reported the first results. More definitive spectrum, composition, and other results expected soon.

- UHECR and UHE neutrino data have promise for studying nuclear interactions and QCD at high energy

- Need a dialogue between RBRC and Auger.