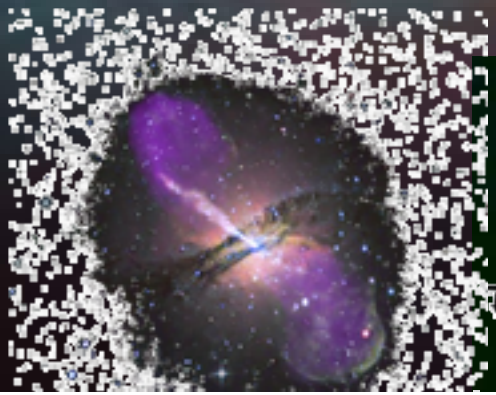
Results from the Pierre Auger Observatory

Paul Sommers, Penn State

August 7, 2008, SSI

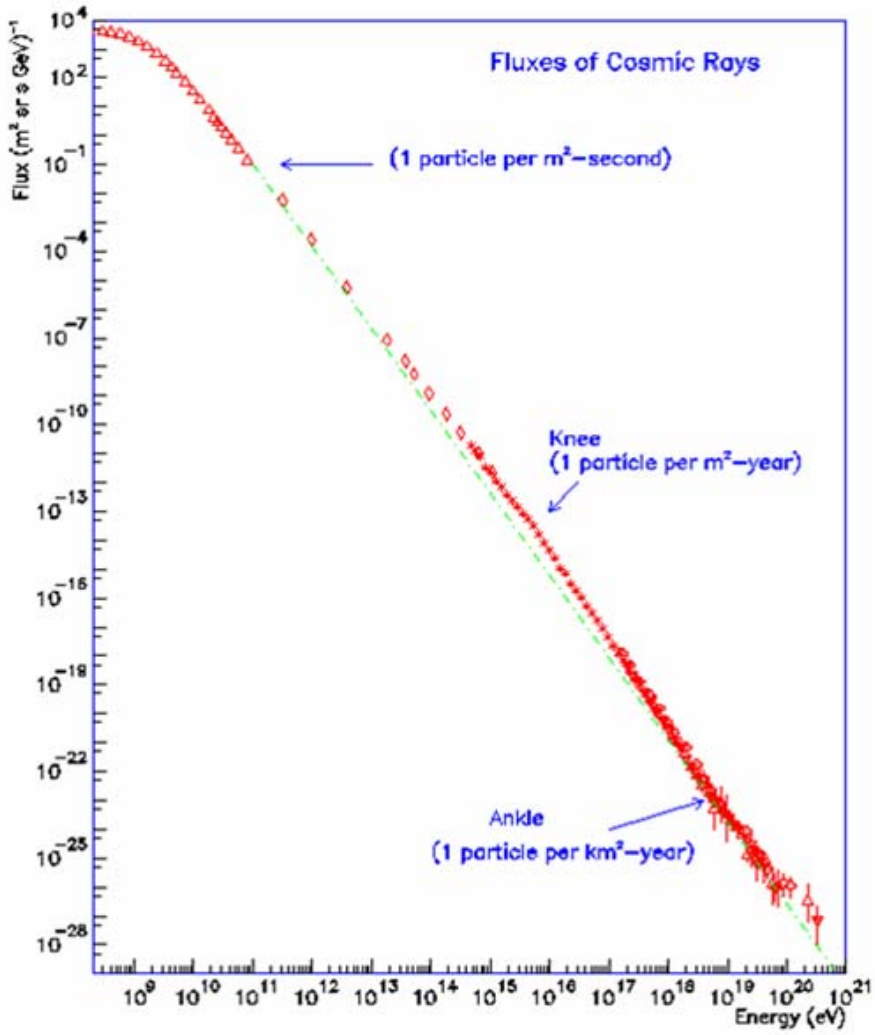


Beijing 2008

COSMIC Accelerators

The Cosmic Ray Energy Spectrum

Non-thermal, approximate power law, up to about 3×10^{20} eV (possibly higher)



1 EeV = 10^{18} eV

6 EeV ≈ 1 Joule

[Simon Swordy]

Primary objectives

Where do UHE cosmic rays originate?

UHE here means E > ~10^{18} eV (1 EeV)

How does Nature endow them with Joules of energy?

Indirect measurements via air shower cascades

Following discovery by Pierre Auger in 1938

Atmosphere is transducer and amplifier

Secondaries are sampled at ground level or measured by air fluorescence

Present observatories (Auger, TA) are hybrid (using both methods)

Customary measurement objectives

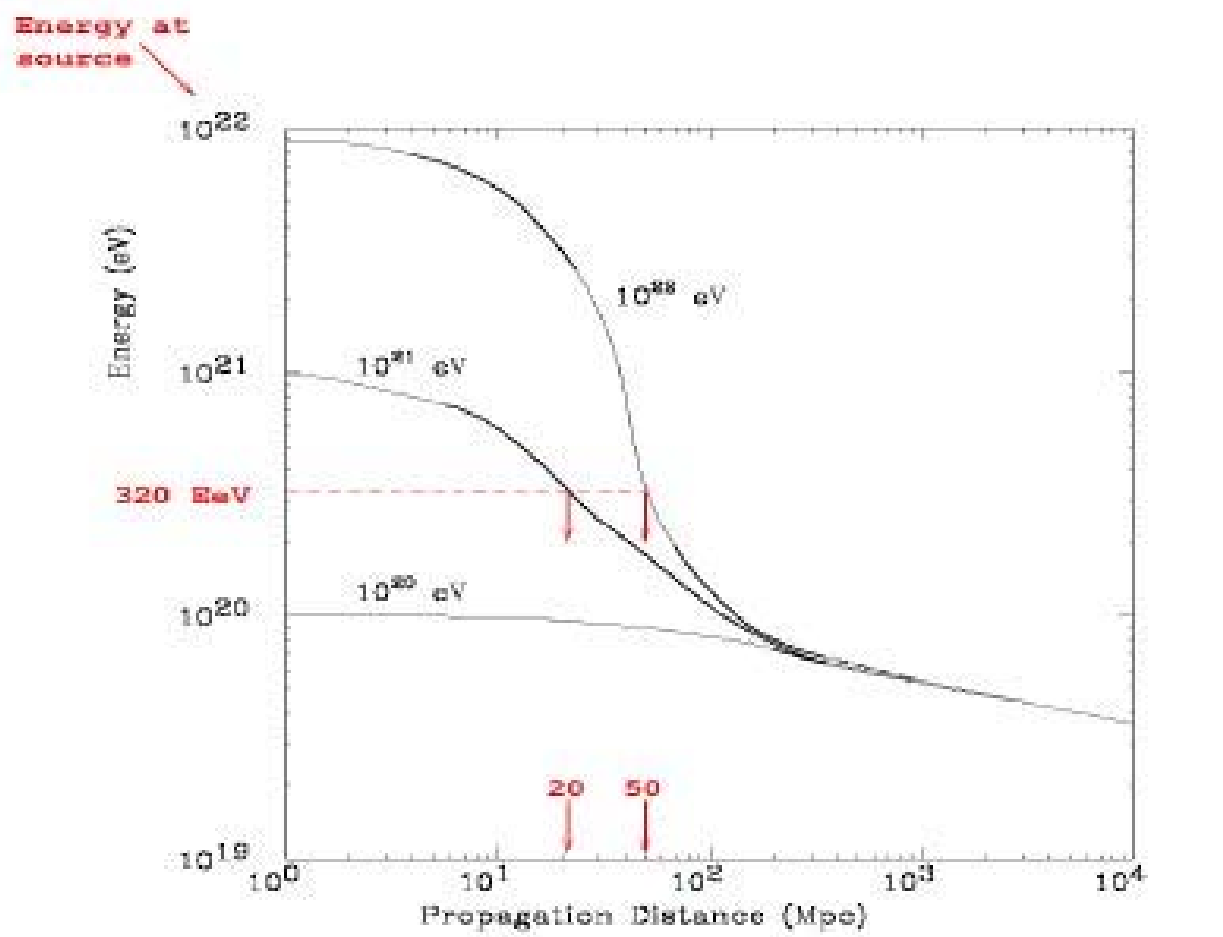
Cosmic ray energy for energy spectrum

Arrival direction for anisotropy studies

Observable(s) which correlate with cosmic ray nuclear mass

[See the talk by Angela Olinto on air shower measurements next week!]

Charged particle astronomy is plausible above the GZK energy threshold because the isotropic background from distant sources is eliminated.

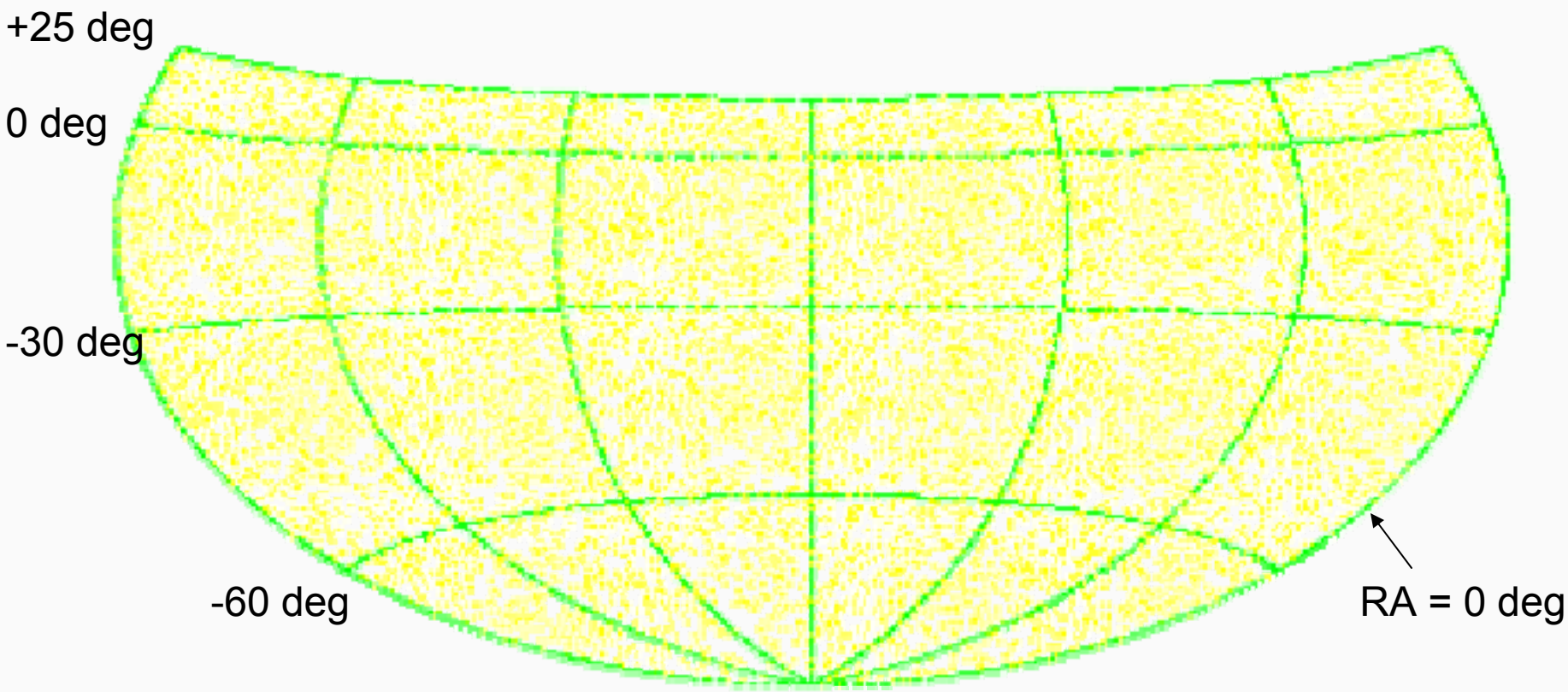


Energy attenuation of protons

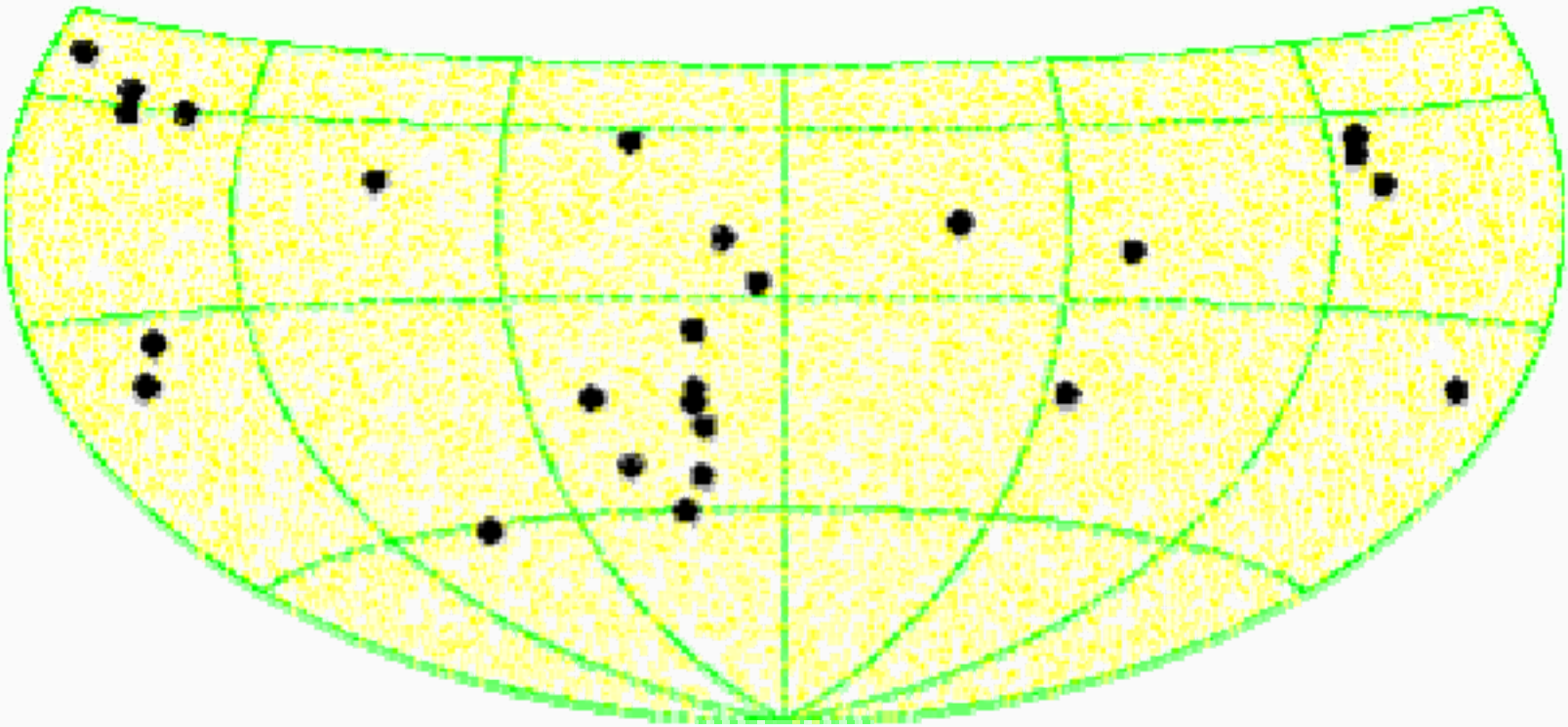
[Cronin]

Equal Exposure Plot

Arrival Directions for E>3 EeV



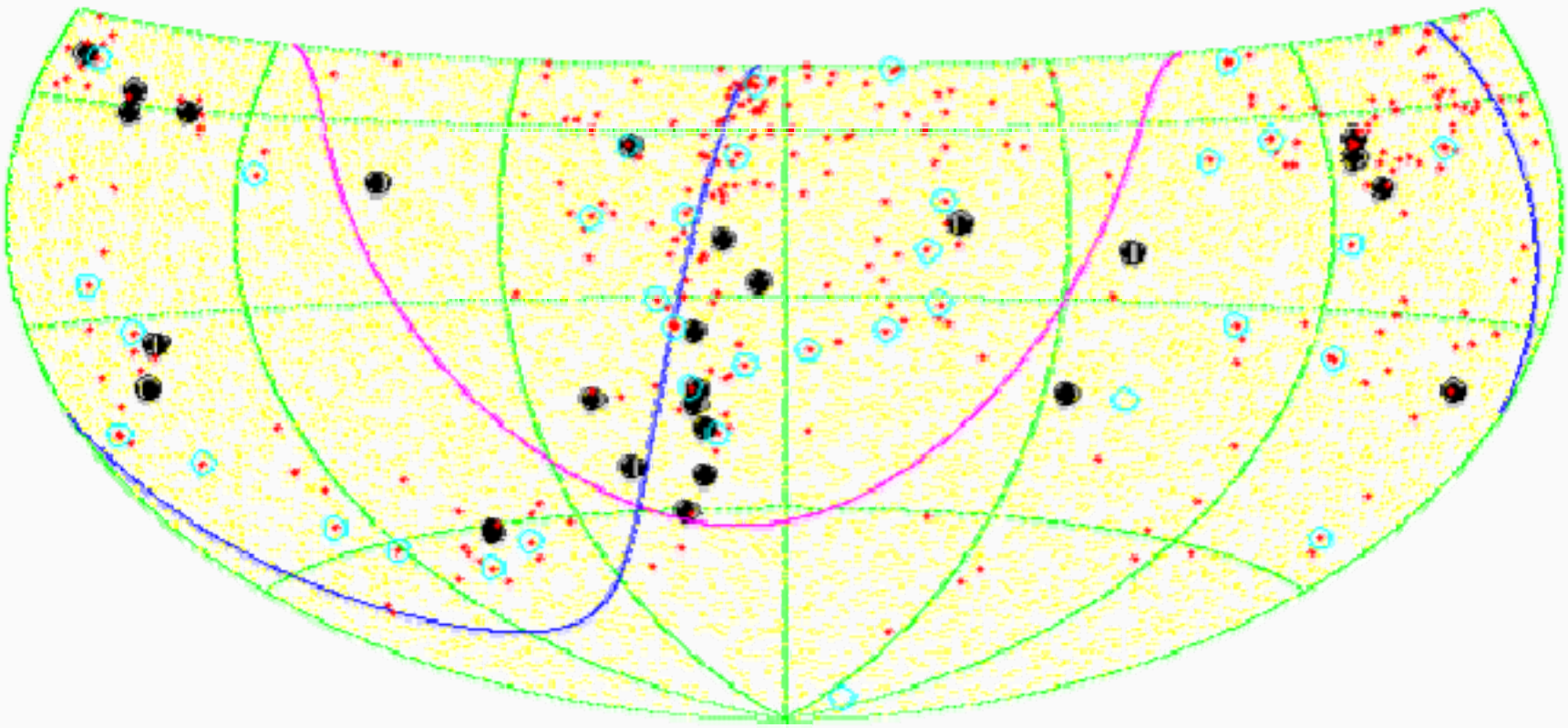
Arrival directions of the 27 highest energy events



Veron-Cetty AGNs (red dots)

Supergalactic Plane (blue line)

Swift x-ray galactic black holes (blue circles)



Full-Sky Aitoff Projection

(Observatory exposure shaded)

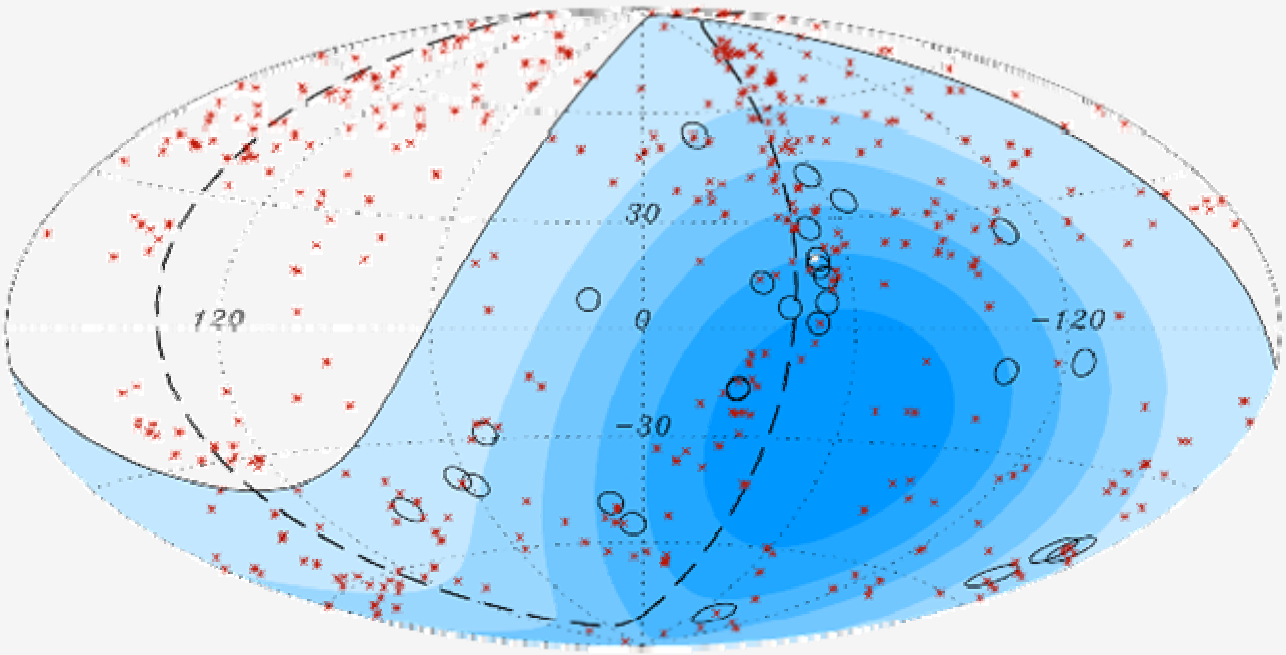
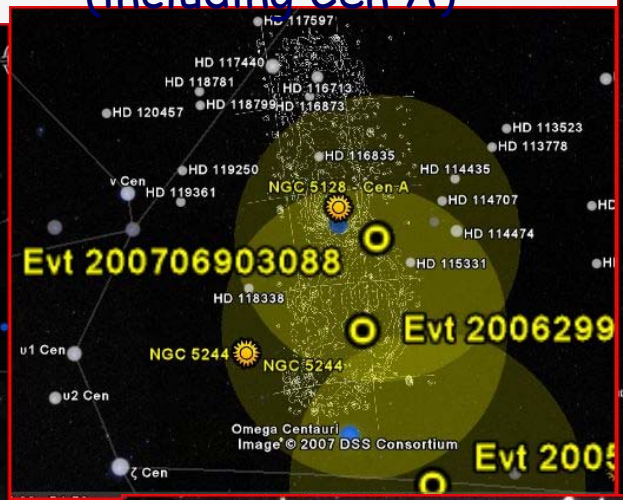
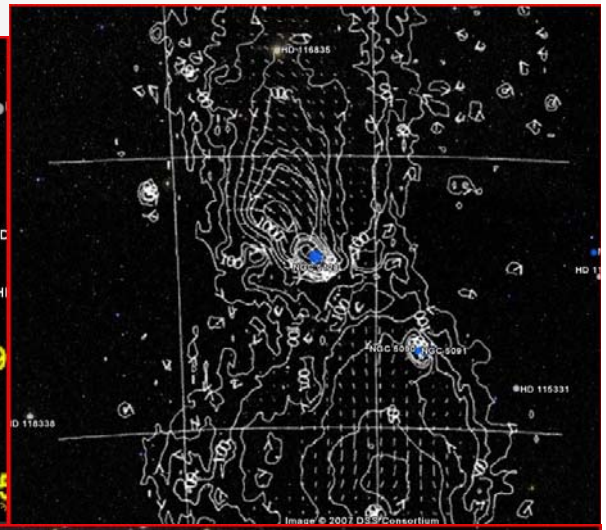


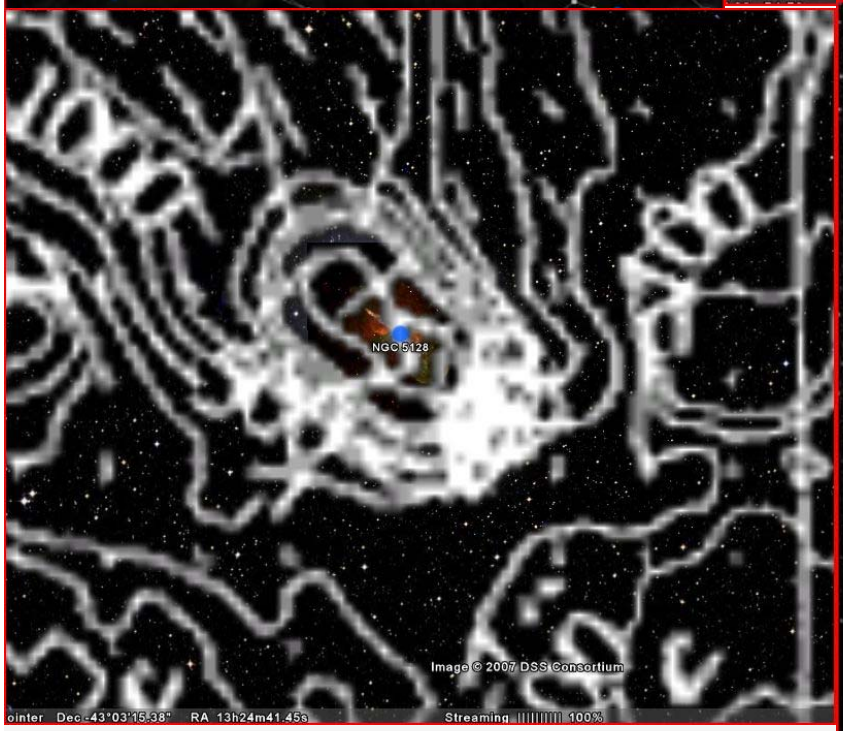
Figure 2: Aitoff projection of the celestial sphere in galactic coordinates with circles of radius 3.1° centered at the arrival directions of the 27 cosmic rays with highest energy detected by the Pierre Auger Observatory. The positions of the 472 AGN (318 in the field of view of the Observatory) with redshift $z \leq 0.018$ ($D < 75$ Mpc) from the 12th edition of the catalog of quasars and active nuclei (*12*) are indicated by red asterisks. The solid line draws the border of the field of view (zenith angles smaller than 60°). Darker color indicates larger relative exposure. Each colored band has equal integrated exposure. The dashed line is, for reference, the super-galactic plane. Centaurus A, one of our closest AGN, is marked in white.

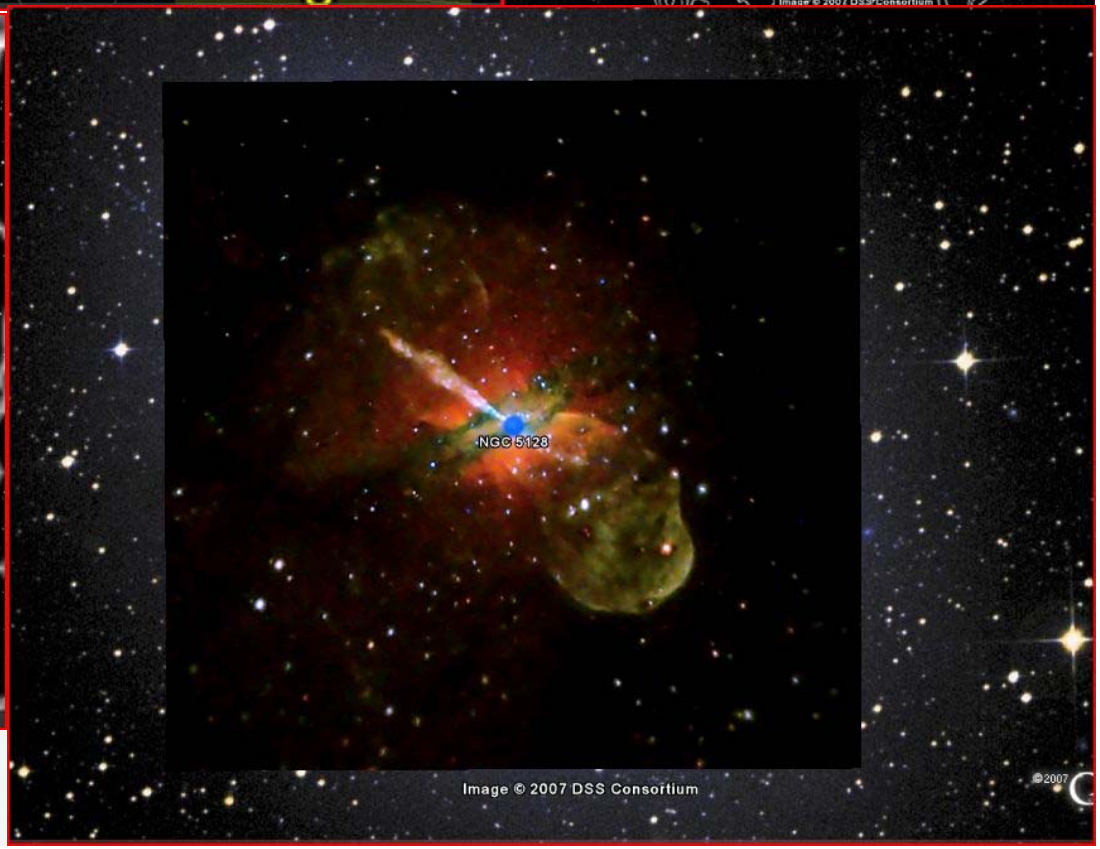
Google Sky view of 7 arrival directions clustered in the Centaurus region (including Cen A)

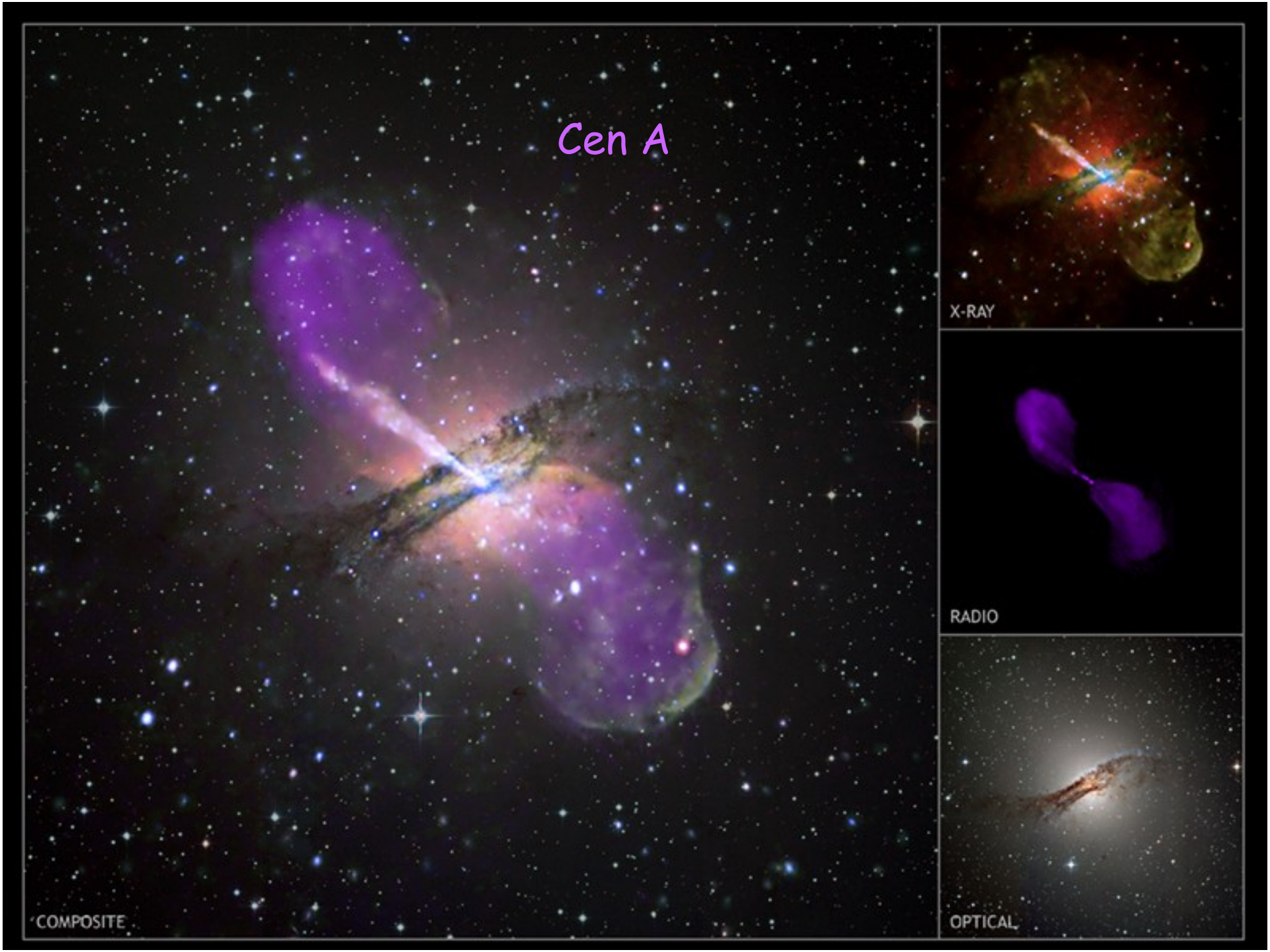
Inner part of Cen A



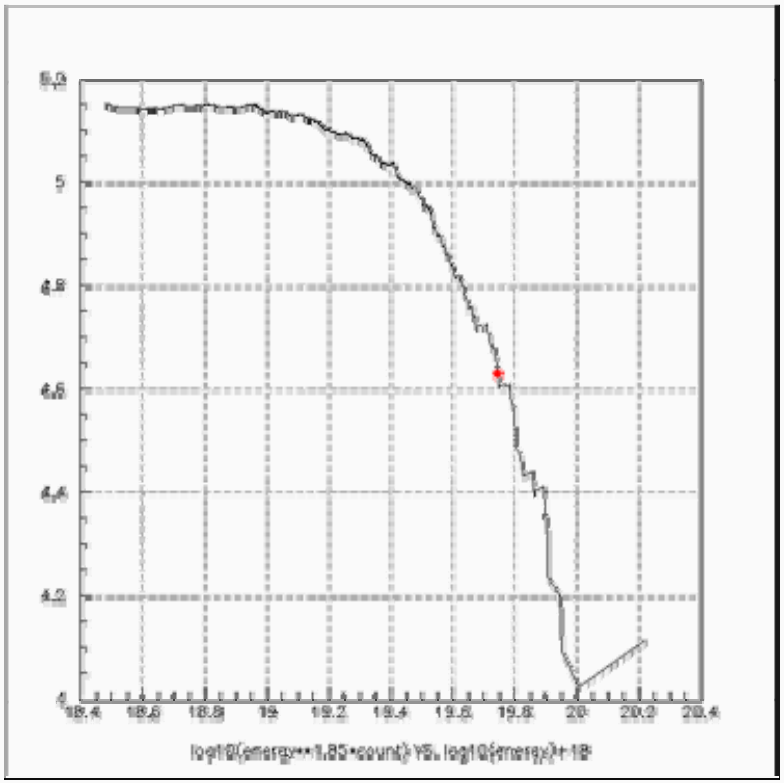


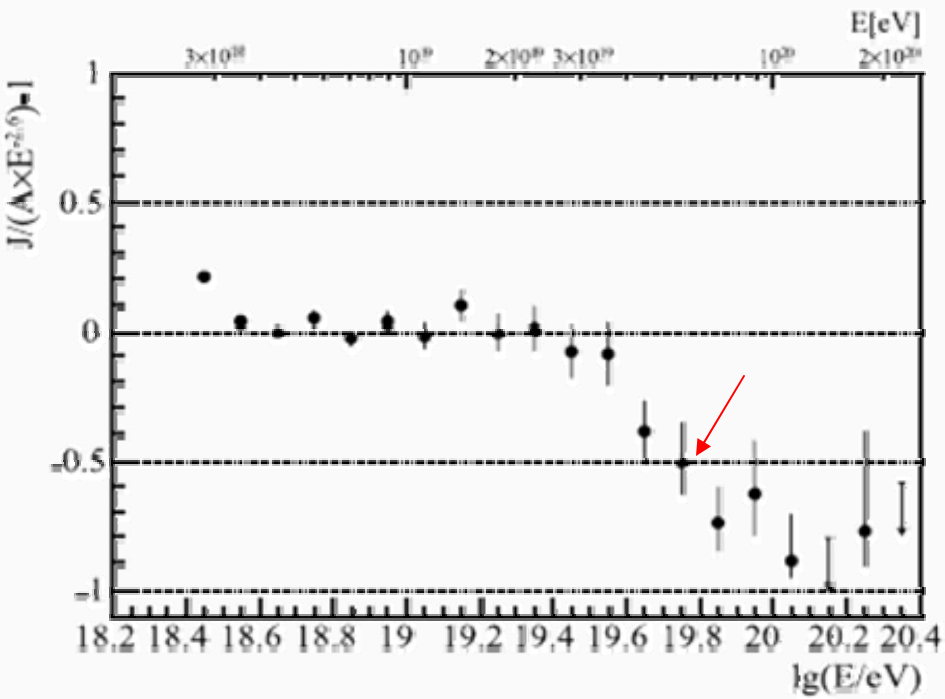


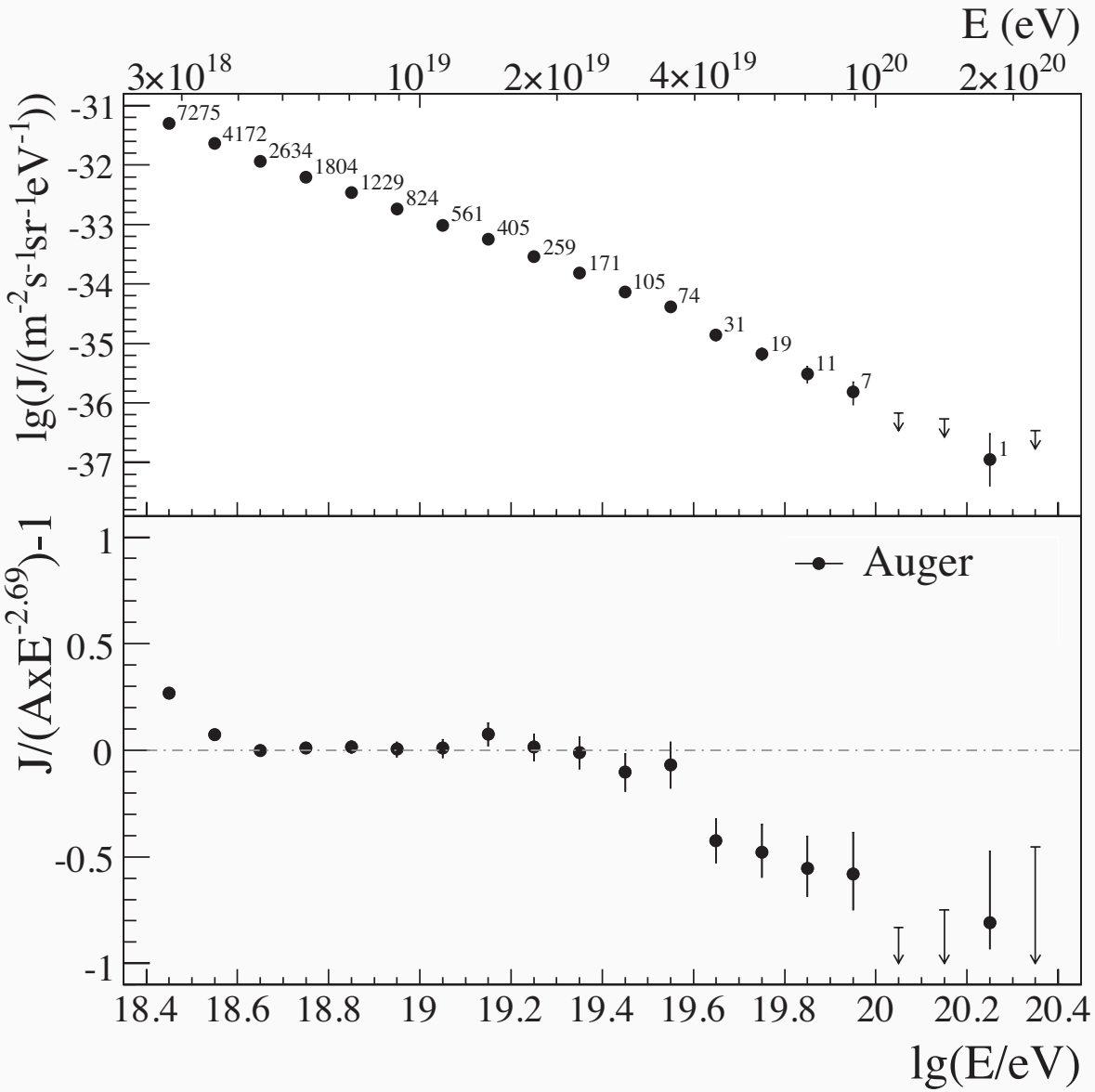



Cen A
COMPOSITE
X-RAY
RADIO
OPTICAL

The GZK-related energy threshold for anisotropy
is where the spectrum falls rapidly







The spectrum <u>does</u> steepen at the GZK threshold energy.
The AGN correlation confirms that it is a propagation effect:
It is <u>not</u> due to the sources "running out of steam" at that energy.

Firm Conclusions

Cosmic rays do not arrive isotropically. *(99% confidence based on single trial test)*

The arrival pattern proves that sources are extragalactic.

The GZK effect is confirmed. [Spectral steepening is not due simply to "sources running out of steam." We see structure for D<75 Mpc without confusion from more distant sources.]

Extragalactic B-fields are weak enough to allow the correlation.

B-fields in the halo of the Galaxy do not destroy the correlation either.

Potential Implications

Discrete sources out to ~75 Mpc are being detected.

Charged particle astronomy will be possible with very large exposure.

Halo B-fields are weak. (Point sources smeared less than about 3.2 degrees.)

Intergalactic B-fields are interestingly weak.

The highest energy cosmic rays are protons.

Cosmic ray acceleration occurs where supermassive black holes are accreting matter.

There are two reasons why charged particle astronomy is plausible only at the highest energies:

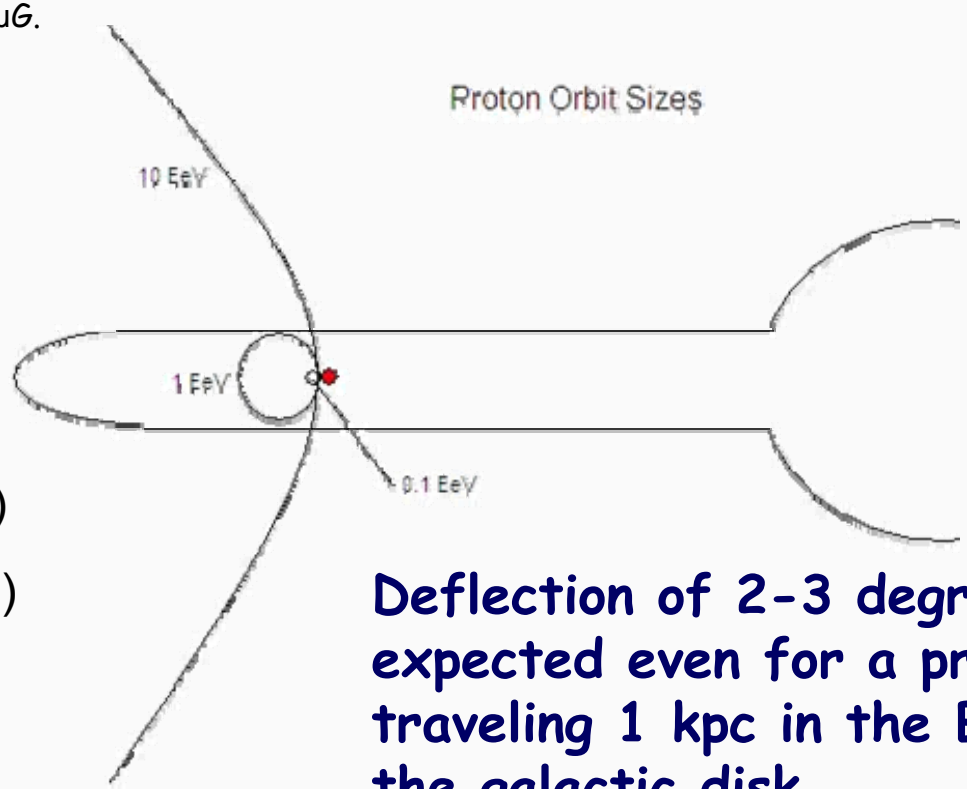
The GZK effect eliminates the isotropic background due to distant sources.

Magnetic deflections, even from just the B-field in the disk of the Galaxy, are severe. But that deflection shrinks from roughly 12 degrees to roughly 2 degrees in going from 10 to 60 EeV (for protons).

It is a coincidence that magnetic smearing becomes tolerable at just the energy range where the background disappears. The two effects are completely unrelated.

Cosmic ray astronomy above the GZK threshold is a crucial tool for high energy astrophysics. The electromagnetic window closes for extragalactic astronomy at 10^{14} eV. Neutrinos might be able to fill in part of the 6-order energy gap, but cosmic ray astronomy is the best way to test models of particle acceleration to UHE energies.

For 60-EeV protons, deflection is $\theta \sim L_{kpc} B_{\mu G}$ (in degrees) for a path length L_{kpc} through a regular transverse field $B_{\mu G}$.



Larmor radius:

$$R_{kpc} \approx E_{EeV} / (Z\, B_{\mu G})$$

$$R_{Mpc} \approx E_{EeV} / (Z\, B_{nG})$$

Deflection of 2-3 degrees expected even for a proton traveling 1 kpc in the B-field of the galactic disk.

High-Z nuclei could not correlate.

Light nuclei photodisintegrate too rapidly to get here.

Tentative conclusion: Trans-GZK cosmic rays are protons!

The Auger Collaboration

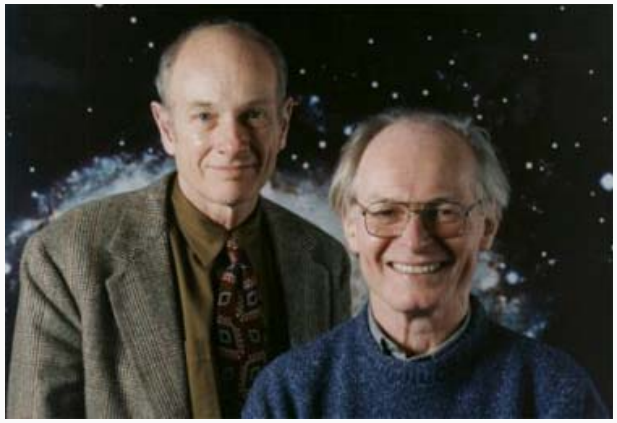
Argentina
Australia
Bolivia
Brazil
Czech Republic
France

Germany
Italy
Mexico
Netherlands
Poland

Portugal
Slovenia
Spain
United Kingdom
United States
Vietnam

Jim Cronin

Alan Watson

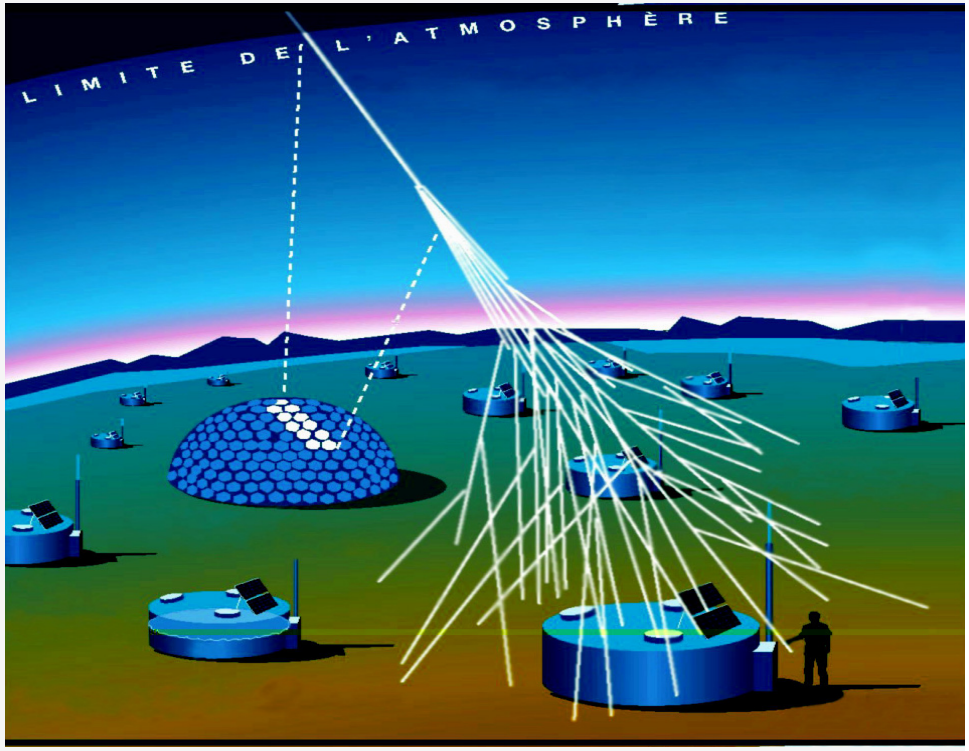


The Auger Observatory

The Auger Observatory was designed with sites in the northern and southern hemispheres in order to observe the entire sky.

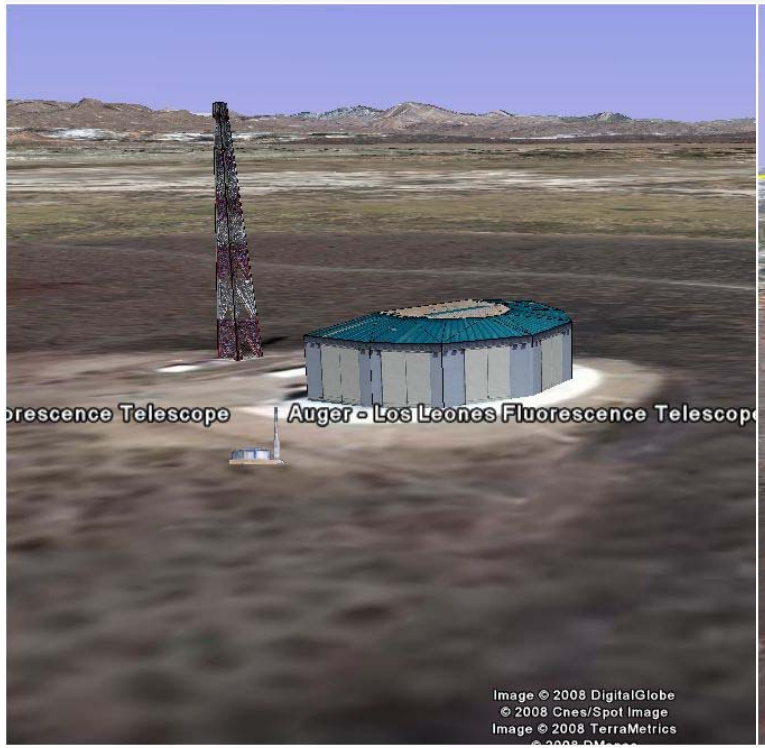
The southern site in Argentina is now complete, and approval to build a northern site in southeast Colorado will be sought by the same international collaboration.

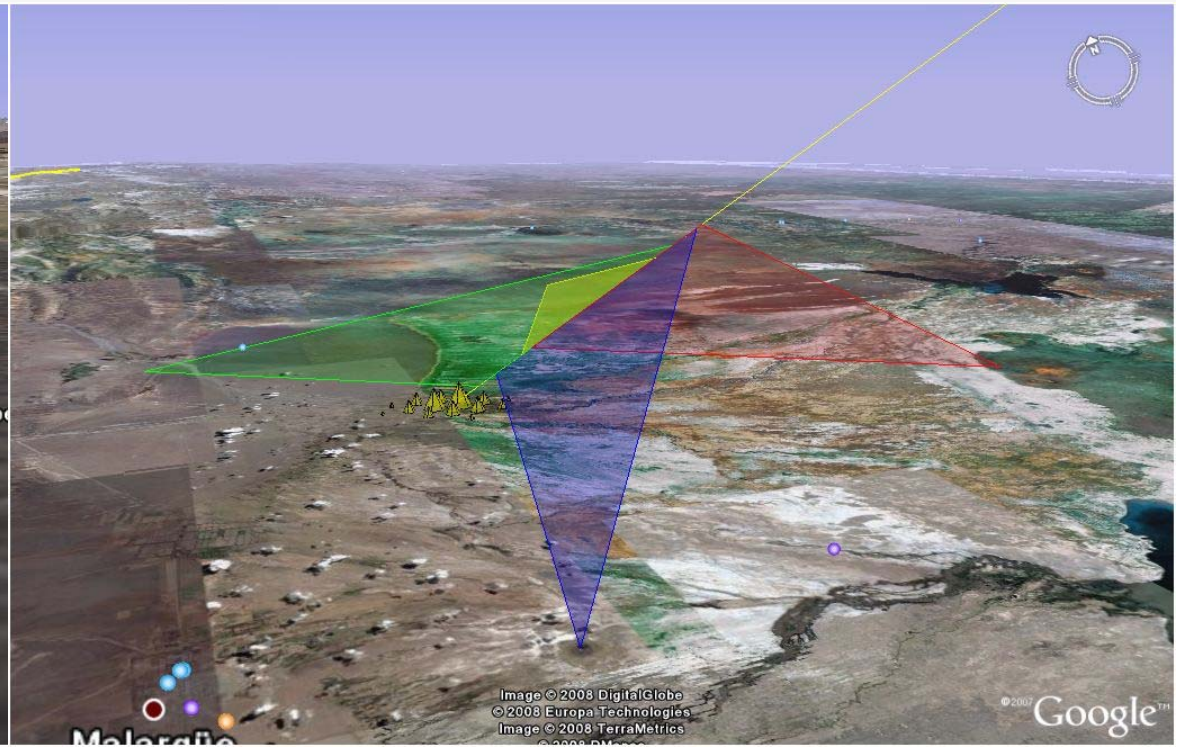
The southern site has an array of 1600 water Cherenkov stations covering 3000 km^2 (the area of Rhode Island). It also has four "eyes" that watch air showers develop in the atmosphere above the surface array at night. They see nitrogen fluorescence produced by the passage of secondary shower particles. Air fluorescence is proportional to electromagnetic energy loss, so it provides a calorimetric measurement of the primary particle's energy.



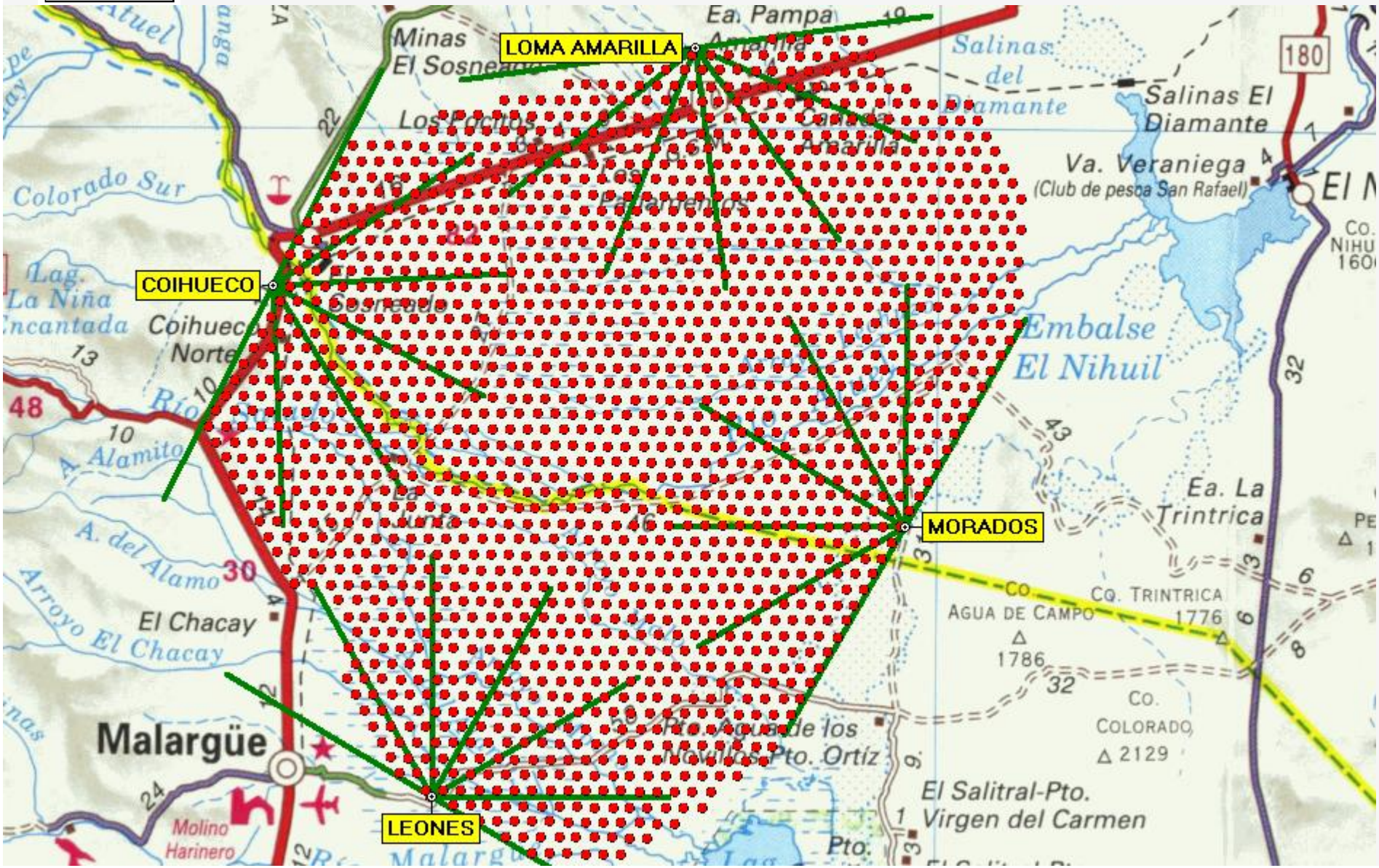
Exploring the Auger Observatory

With Google Earth

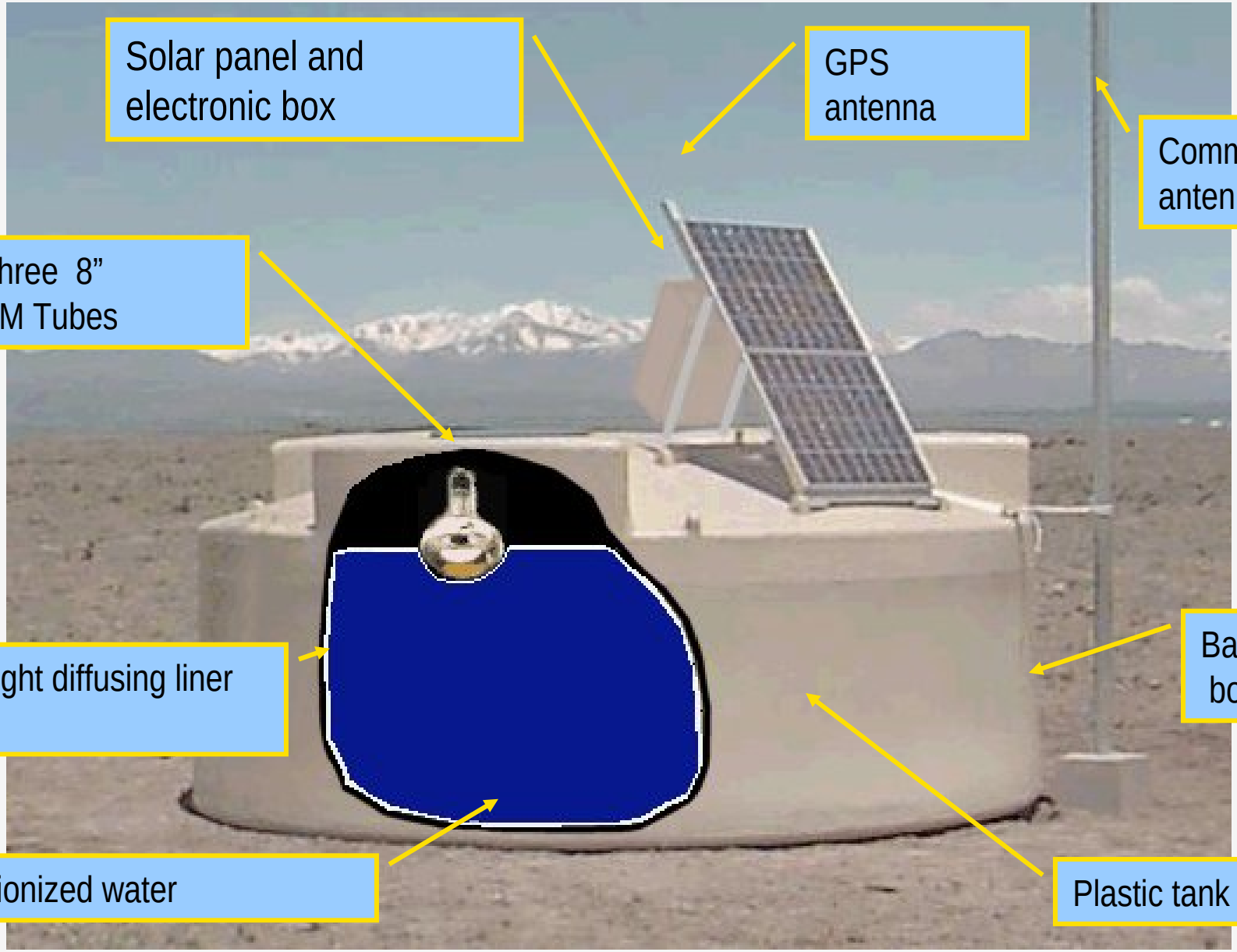


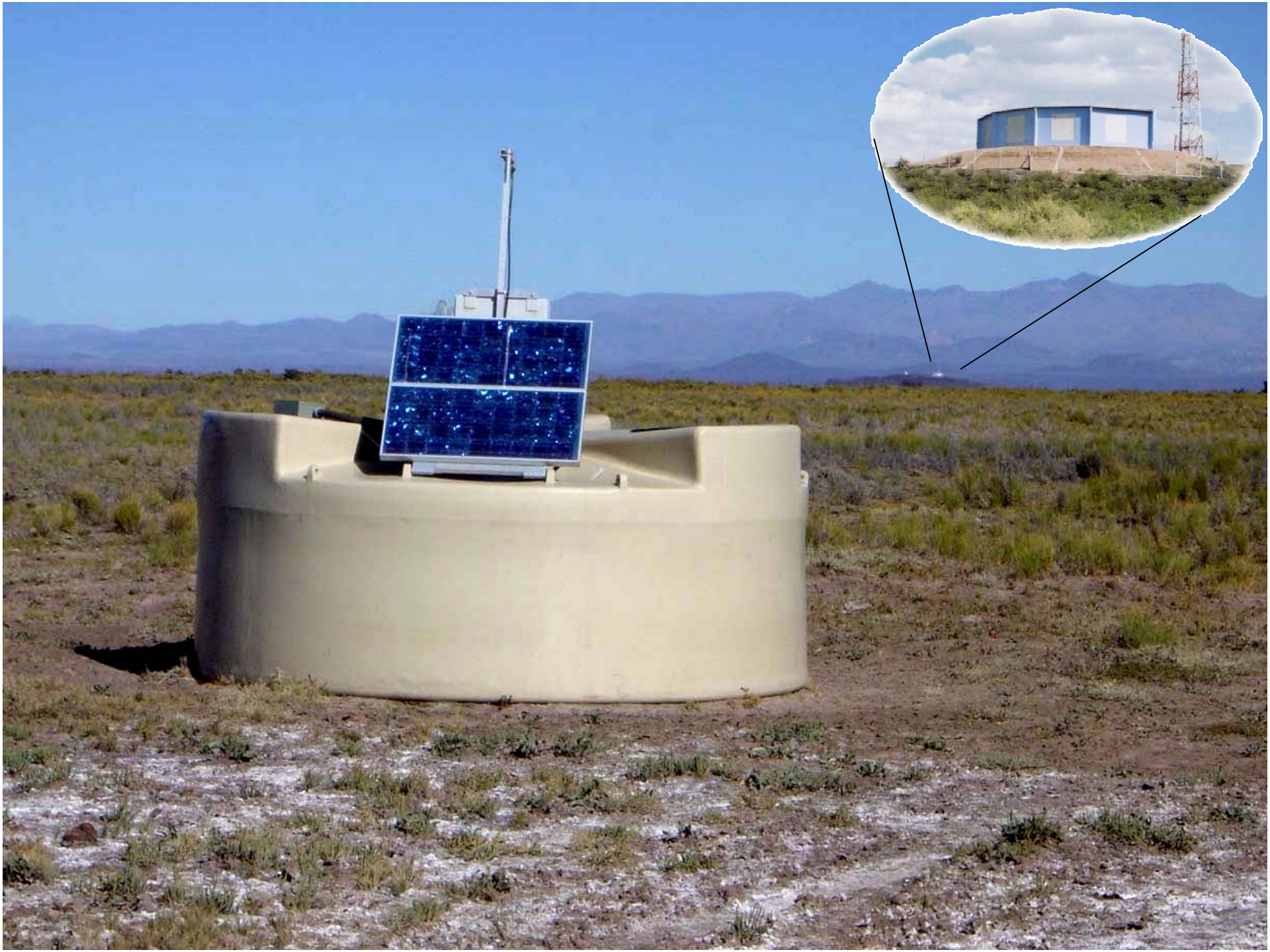


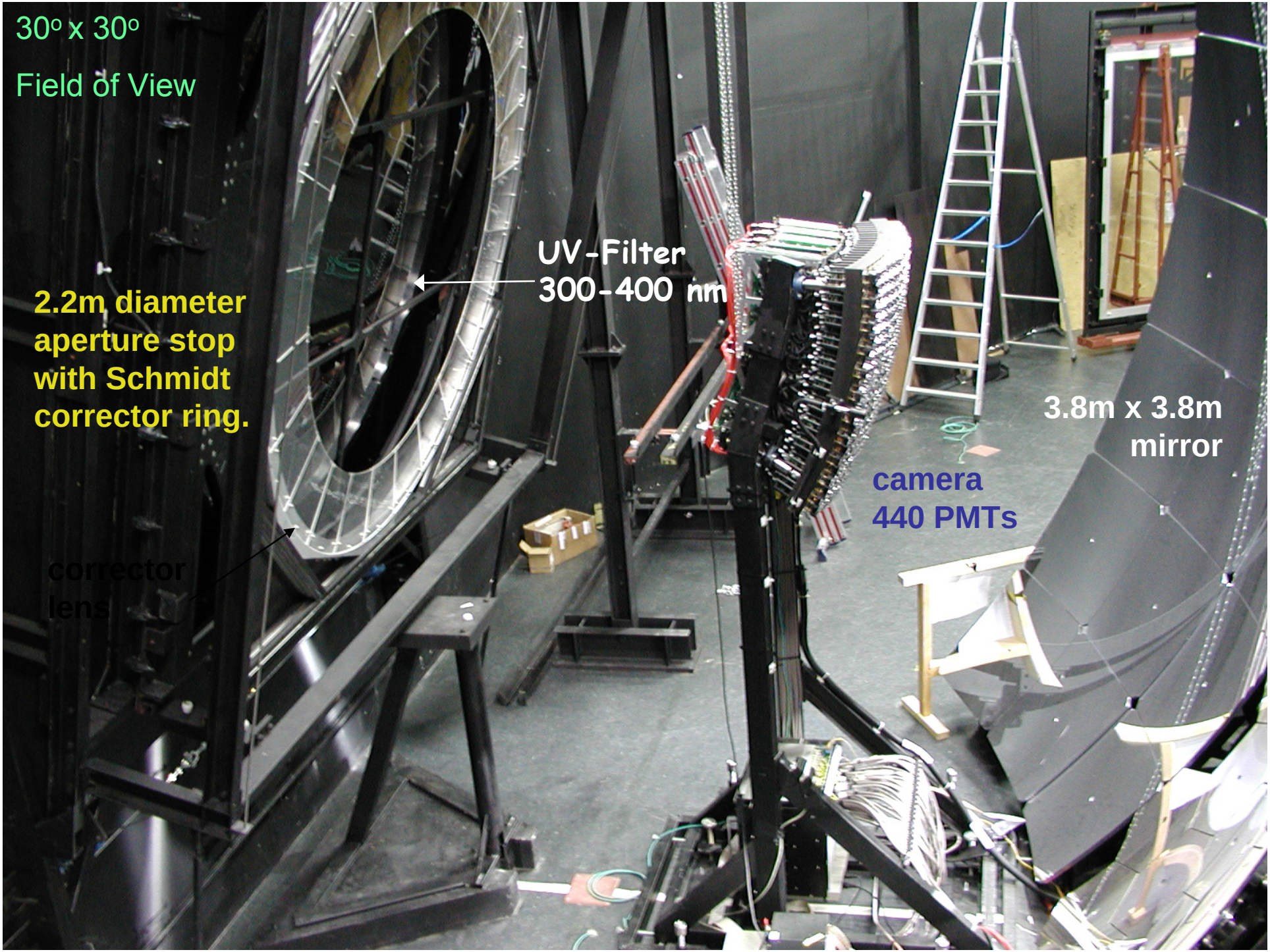
Layout of Auger South



Auger Water Cherenkov Detector






30° x 30°
Field of View
UV-Filter
300-400 nm
2.2m diameter
aperture stop
with Schmidt
corrector ring.
3.8m x 3.8m
mirror
camera
440 PMTs
corrector
lens

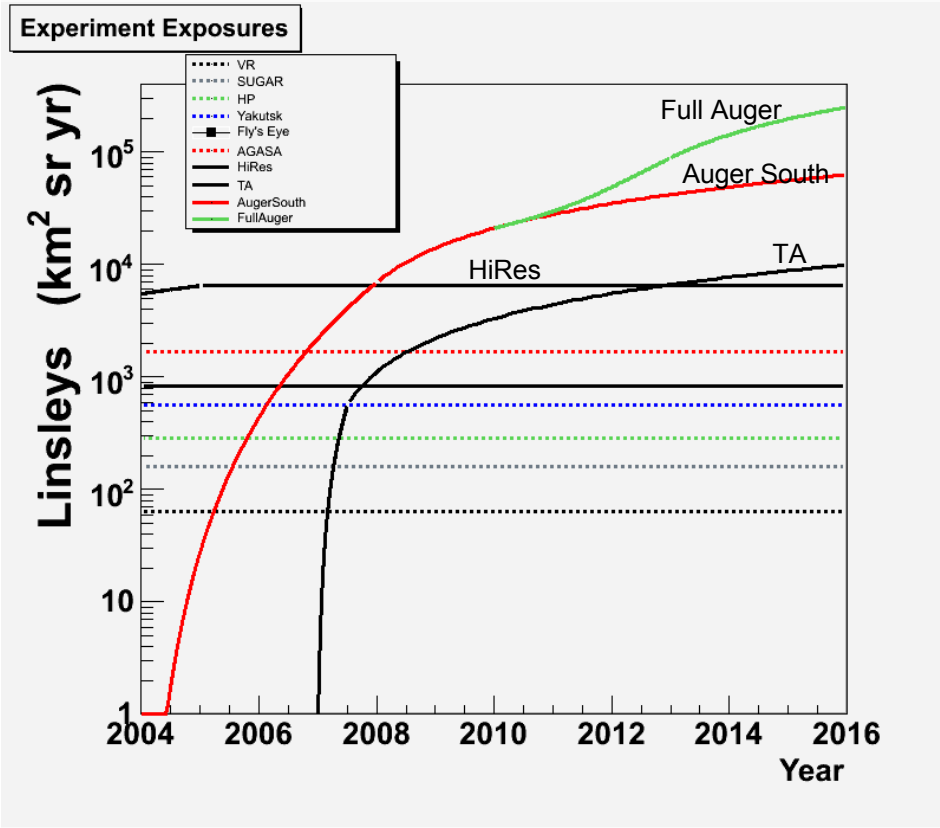
The Future

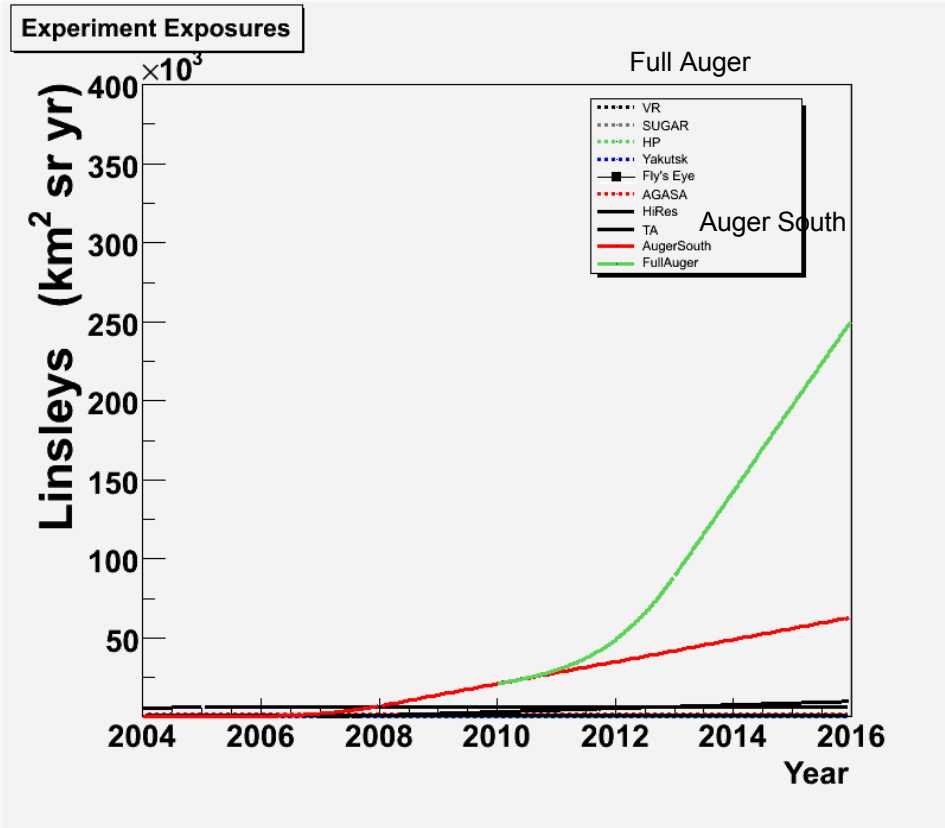
Identify the UHE sources throughout the GZK sphere.

Measure individual energy spectra of the brighter sources.

Exploit the "proton beam" to study hadronic interactions in an energy range complementary to LHC.

Auger North: Much larger aperture with exposure to the northern sky.





The Quest for Exposure

Auger North

Because 30 events/year is not enough!

We need thousands for cosmic ray astronomy

(individual source spectra)

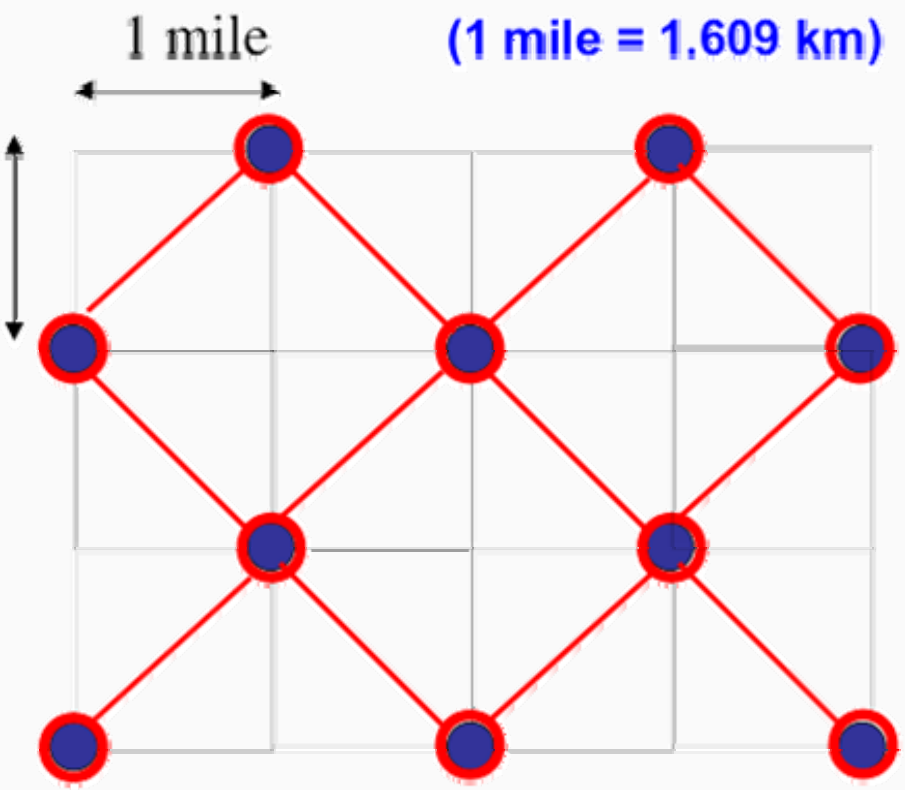
Because we want to see nearby sources also in the northern sky.

Because we should map the full sky above and below the GZK threshold.

SQUARE GRID - 1.414 mile separation

8,000 square miles ***(20,000 km²)***

(1 mile = 1.609 km)



The particle physics is most interesting at the highest energies where the flux is minuscule.

7 times the collecting area of Auger South.

Area equal to Massachusetts.

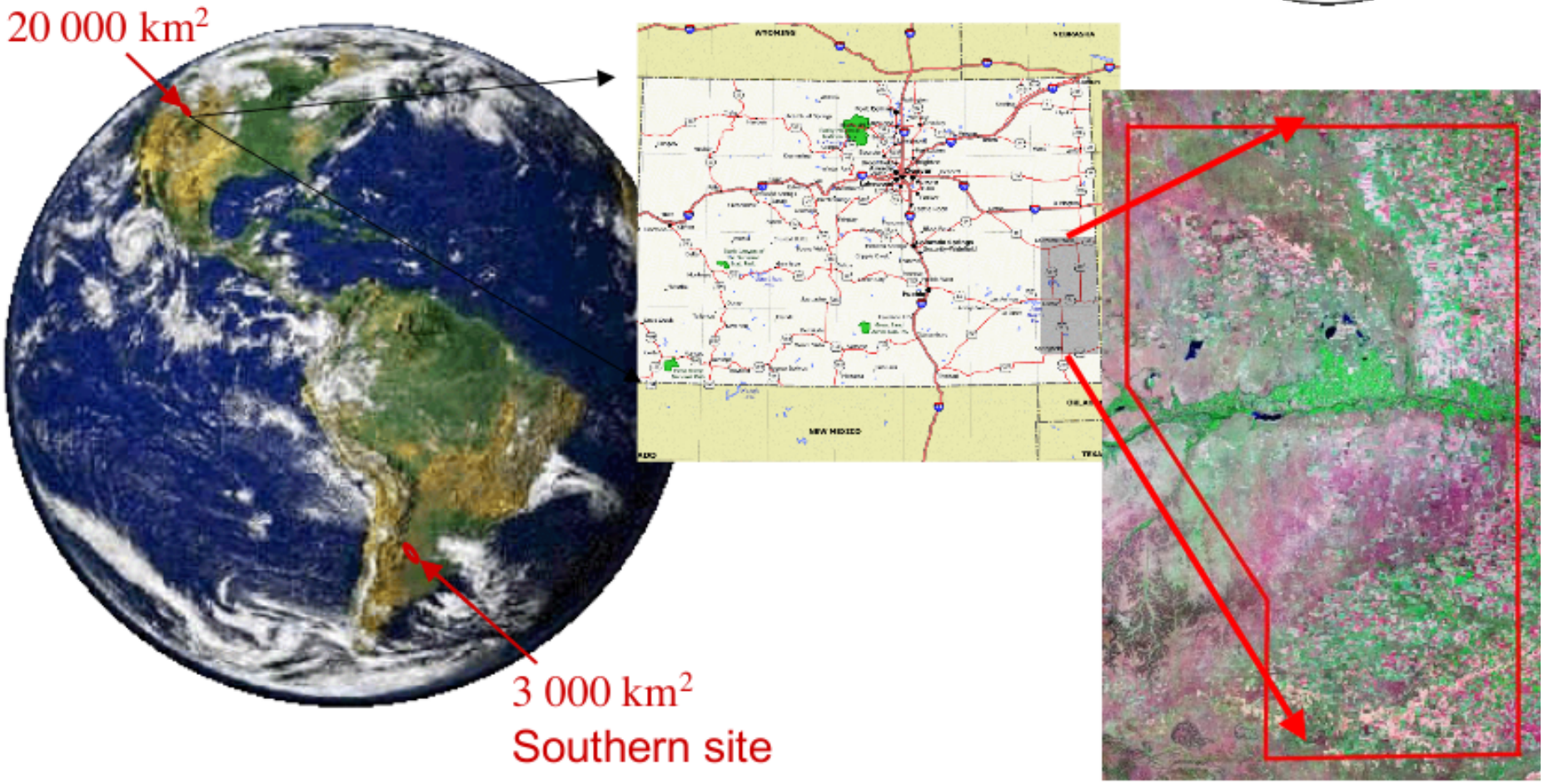
Full coverage by fluorescence detectors.

An extensive grid of roads covers much of southeast Colorado running North-South and East-West with 1-mile separations.

The Pierre Auger Observatory

Planned for North & South - full sky coverage

Auger North in Southeast Colorado designed to reach very high statistics above GZK energies



Anisotropy studies have the potential to cut the Gordian knot.

From the correlation of arrival directions and sources, it may become evident that the cosmic ray flux is surely a pure proton beam.

Auger air shower measurements could then be used to infer properties of hadronic interactions at C.M. energies of 150-450 TeV.

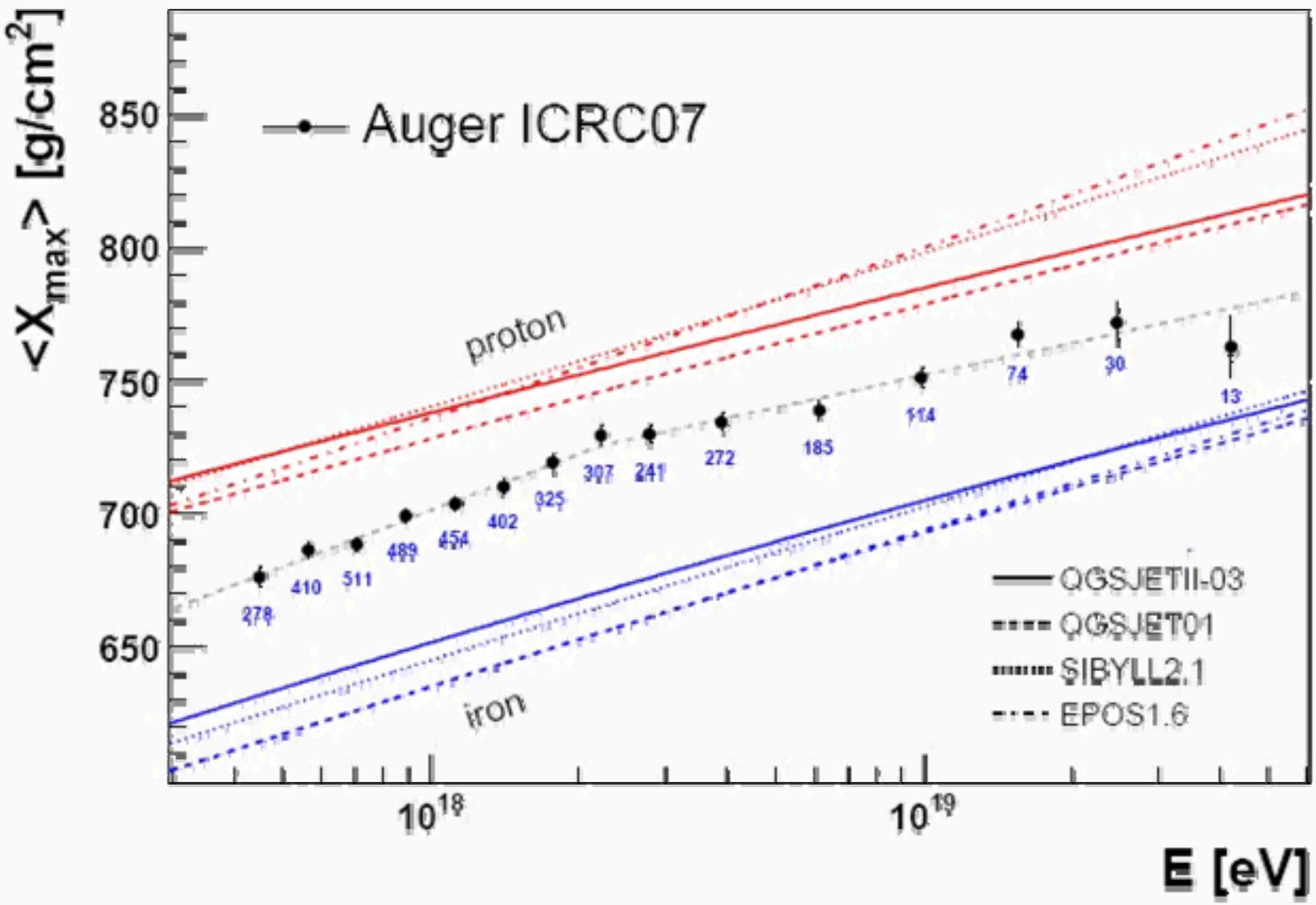
The unknown composition presently confuses the interpretation of air shower measurements, which reveal the speed of air shower development and the muon richness.

For a *fixed* interaction model, iron showers reach maximum size earlier, because they behave like a superposition of 56 nucleon showers each with $1/56^{th}$ of the total energy. (Nucleon-induced showers of lower energy reach maximum size in less grammage.)

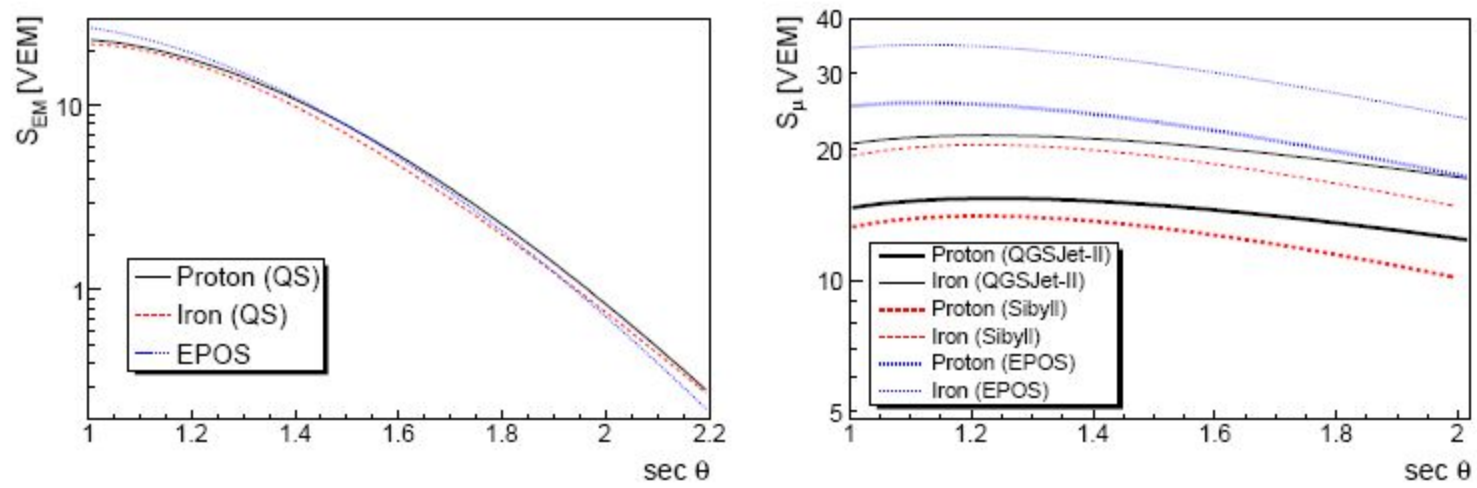
For a *fixed* interaction model, iron showers produce more muons because fewer generations are needed for pions to get down to decay energies, and that means more energy is left in the hadronic cascade. (Roughly 1/3 of the energy is transferred to the electromagnetic cascade by π° decay in each generation.

Depth of Shower Maximum

As a Function of Energy



Universality



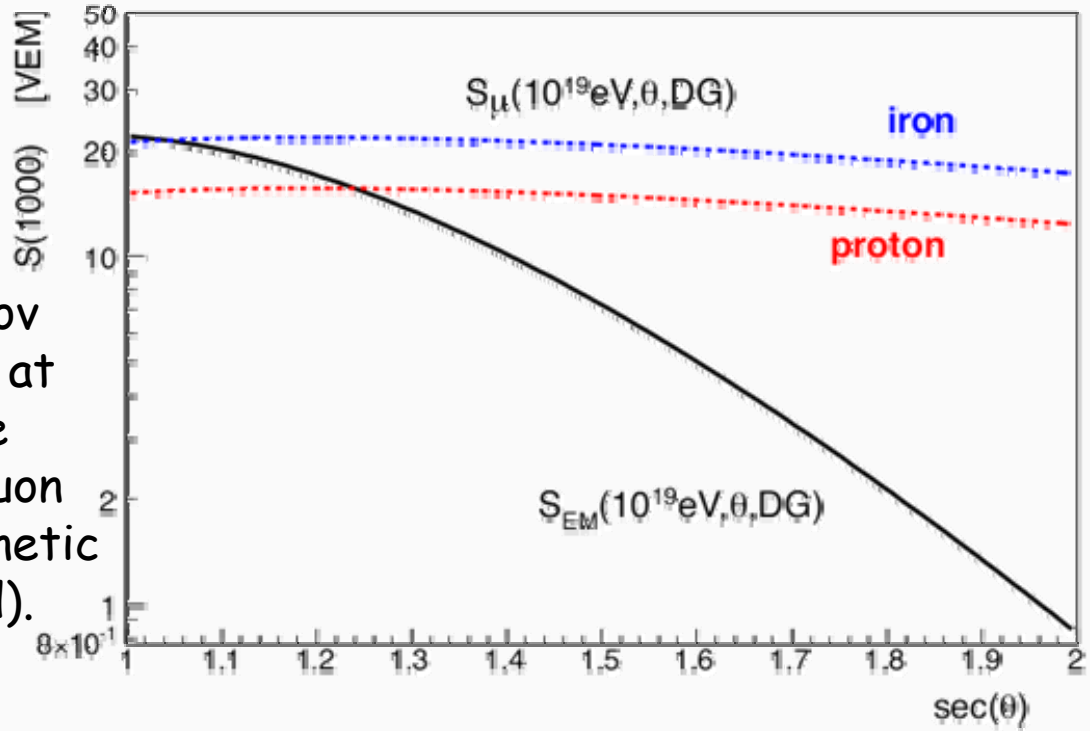
The electromagnetic and muon densities have very different attenuation curves.

There is little model-dependence in the *shapes* of those curves.

[Engel, Unger]

Universality

Water Cherenkov signal expected at 1000m from the shower core (muon and electromagnetic parts separated).



The signal attenuation (with grammage) can be measured accurately by the signal at different zenith angles for showers of the same rate (per km^2 sr), hence same energy.

A 2-parameter fit gives the electromagnetic part (determining the energy) and also the muon richness (of the average shower for that energy).

Tentative indications from preliminary studies:

Higher shower energies than obtained by air fluorescence measurements.

Richer muon content than expected even for iron (using usual models).

Auger Observational Results

Energy Spectrum

Surface detector (full-time duty factor), calibrated by air fluorescence.

Hybrid events, lower energy threshold, smaller duty factor (in progress).

Large zenith angle showers - additional aperture (in progress).

Anisotropy

AGN correlation above 60 EeV. Only upper limits below 60 EeV.

Non-confirmation of flux from galactic center.

No confirmed excess of small-angle clustering.

No detected point sources.

Null result on BL Lacs.

Null result on large scale patterns.

Particle types

16% upper limit on photons at 10 EeV using depths of maximum.

2% upper limit using surface detector observables. (This eliminates most top-down origin scenarios.)

Upper limit on tau neutrino flux (Earth-skimming → upward-going air showers).

Upper limit on *all*-flavor neutrino flux (near-horizontal electromagnetic showers).

www.auger.org

Pierre Auger Observatory

studying the universe's highest energy particles

Thank you!

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for other information:

- Scientific and technical papers
- Event displays (1% of the data)
- Google Earth and Google Sky stuff