

Evidence for Correlation of the Highest Energy Cosmic Rays and Extra-galactic Objects (AGNs)?

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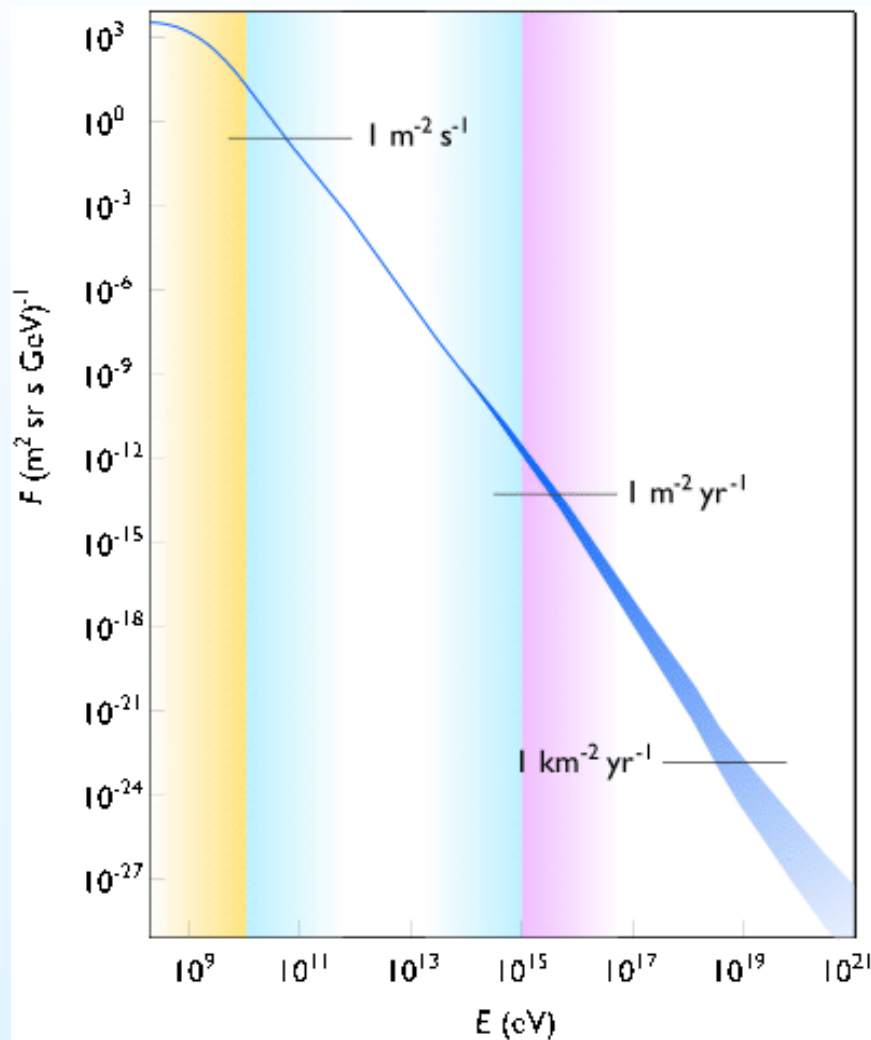
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**Bernie R. Becker, Michael S. Gold, J. Doug Hague, JAJM for the Pierre Auger
Collaboration**

Unraveling the physics of the UHECR sources



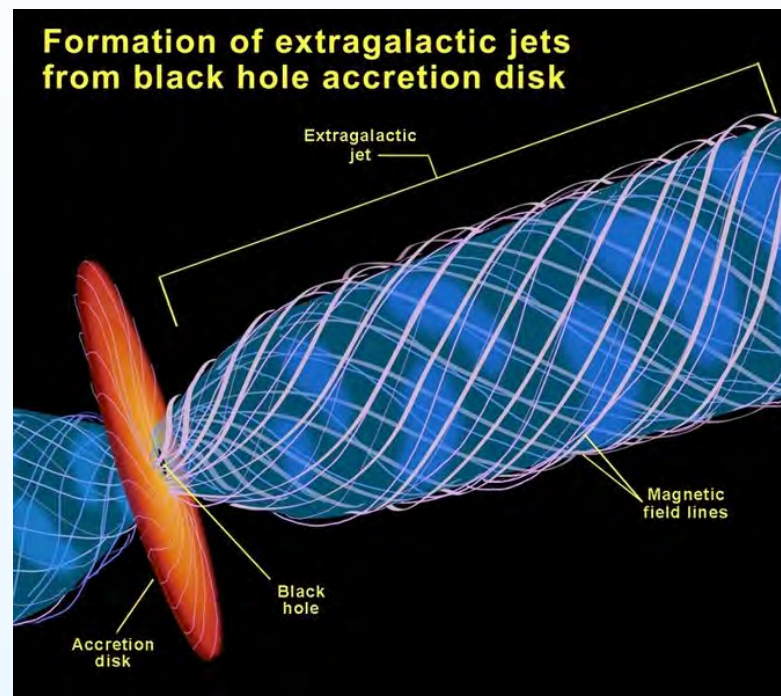
The physics of the sources of the Ultra-High Energy Cosmic Rays (UHECRs) ... right hand side of plot ... is best unraveled using many different observations *e.g. radio, visible, X-ray, γ -ray, ...*

Where we come in ... **Auger extends these measurements to include:**

- “protons” (special case of *light* nuclei)
- “iron” (special case of *heavy* nuclei)
- gamma-rays
- neutrinos

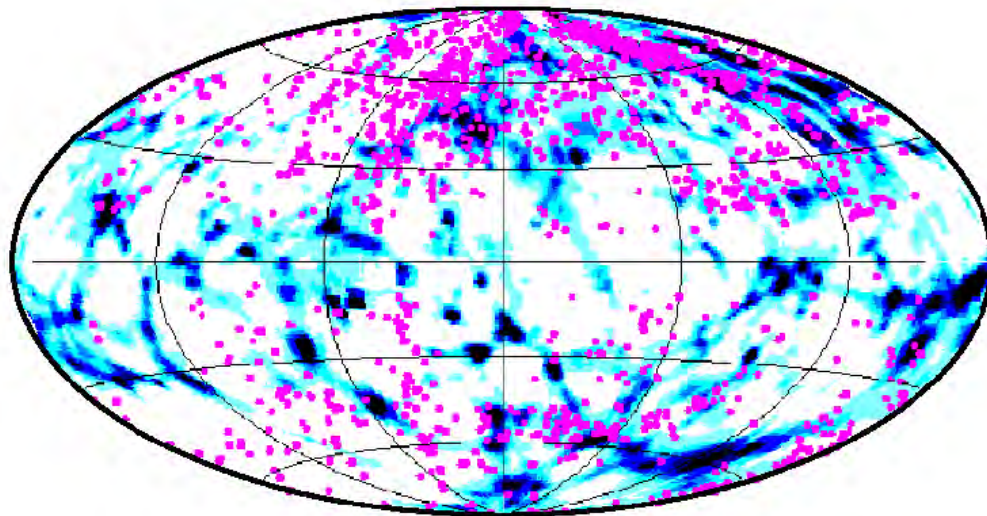
Today we focus on the highest energy CRs, near 10^{20} eV, as these should have: **the least deflection in magnetic fields and the most nearby sources.**

Classes of possible sources for the UHECRs



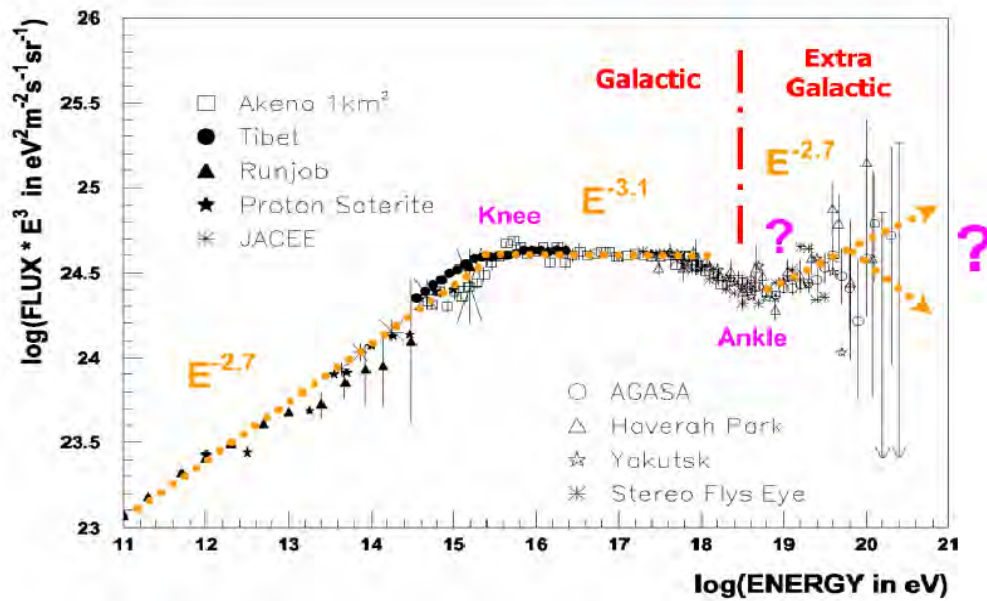
- Extreme astrophysical sources: super-massive black holes/AGNs, GRBs, colliding galaxies, ...
- Particle physics motivated: massive relic particles or relics of early universe

Today's question: Do UHECRs correlate with ... ?



Auger's *photon fraction limit* result suggest **astrophysical sources** for the highest energy cosmic rays

Nearby ($9 < R < 93$ Mpc) universe non-isotropic ... thus highest energy particles should not be isotropic ($93 \text{ Mpc} \approx 0.022$ in redshift)



Baring magnetic field surprises, arrival directions should show structure ... but on what **angular scale(s)**?

And what is the best way to search for signal(s): *clusters, correlations, ...* ?

Unraveling the physics of the UHECR sources



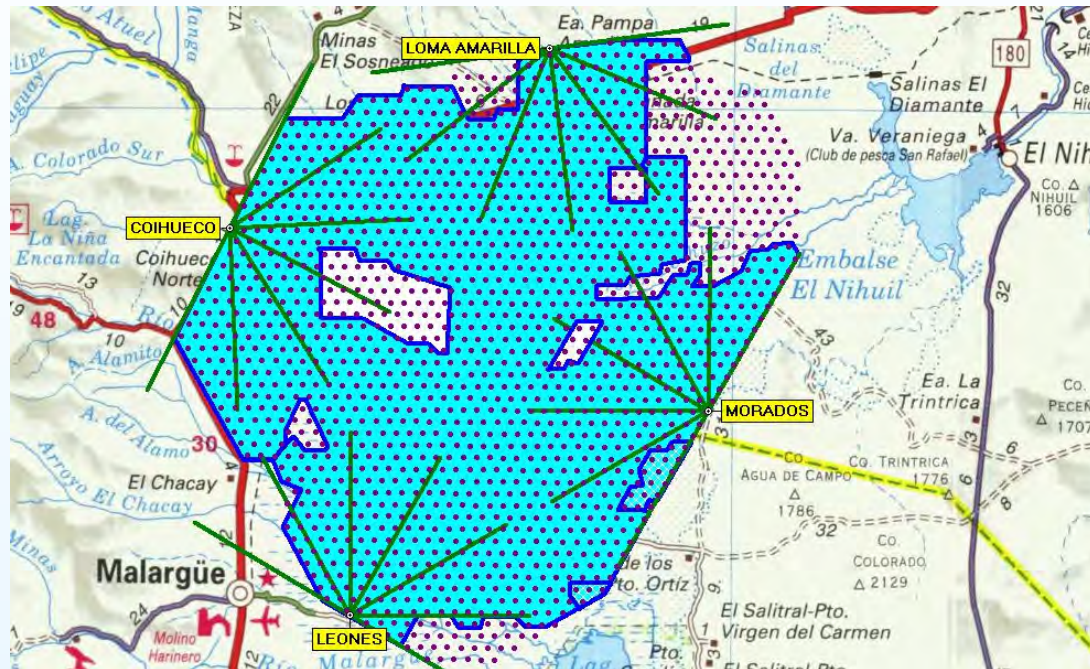
When the UHECRs strike the atmosphere they produce an extensive air shower.

Auger **surface detectors (SD)** allow the properties of the initial cosmic ray to be reconstructed based on measuring the shower particles that reach the ground.

Auger **fluorescence detectors (FD)** allow the properties of the initial cosmic ray to be reconstructed based on measuring the air fluorescence light from the air shower in the atmosphere.

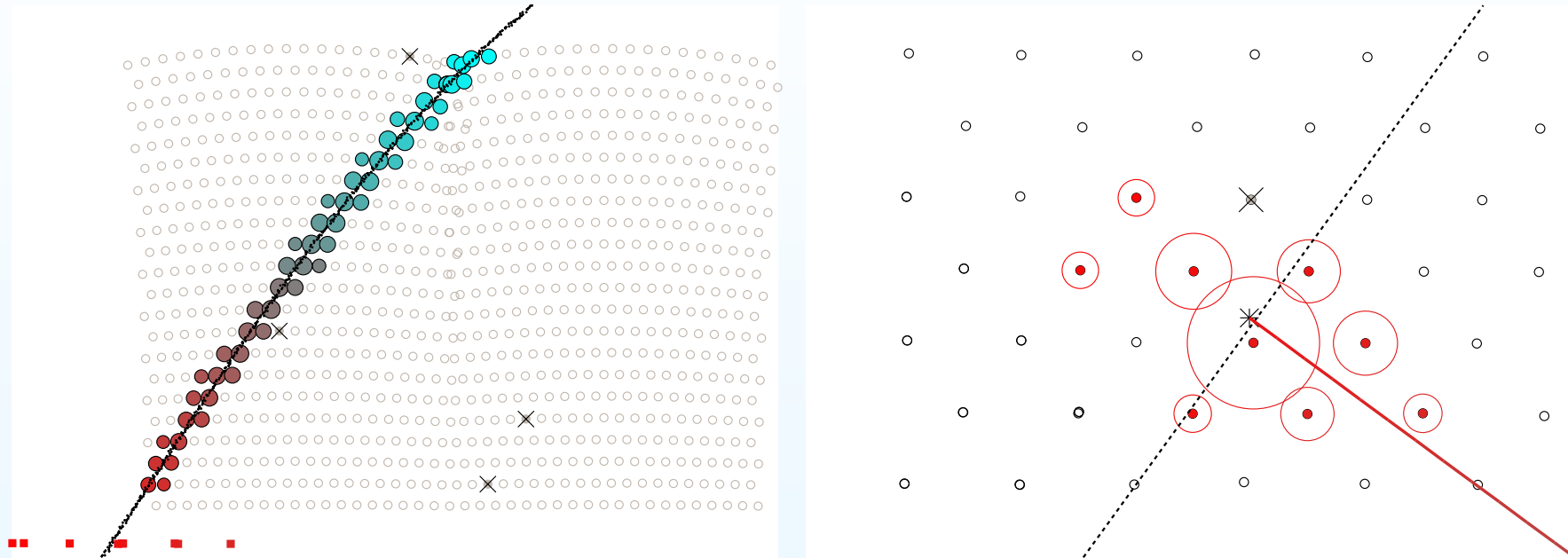
Auger **hybrid** measurements allow the properties of the initial cosmic ray to be reconstructed based on simultaneous measurement of a shower by both **FD** and **SD** components.

Auger Southern Observatory status *summer 2007*



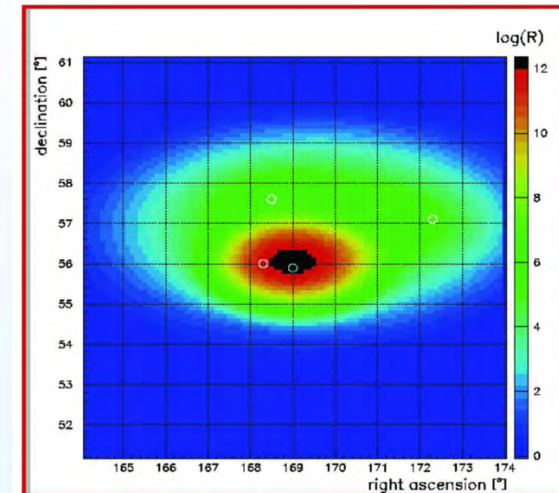
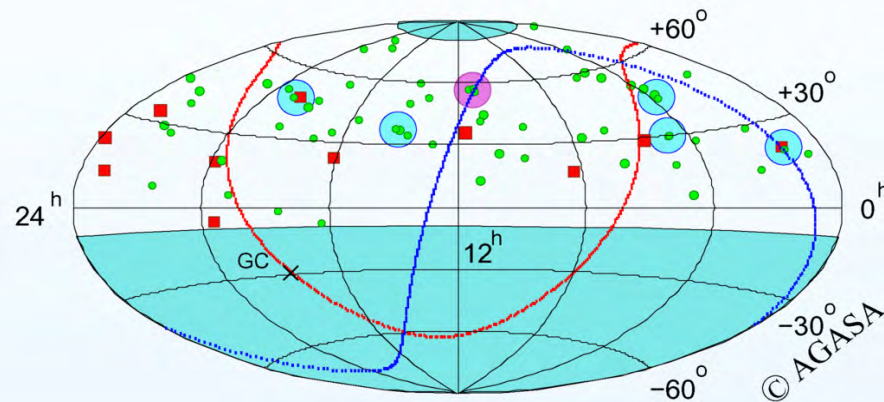
- Auger is a collaboration of over 250 scientists from Argentina, Australia, Bolivia, Brazil, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, United Kingdom, United States, and Vietnam.
- The blue area shows the (summer 2007) extent of the 3000 km² SD array.
- All four FDs (*Los Leones, Morados, Loma Amarilla, Coihueco*) are fully operational.

Air shower: FD, SD, and Hybrid reconstruction



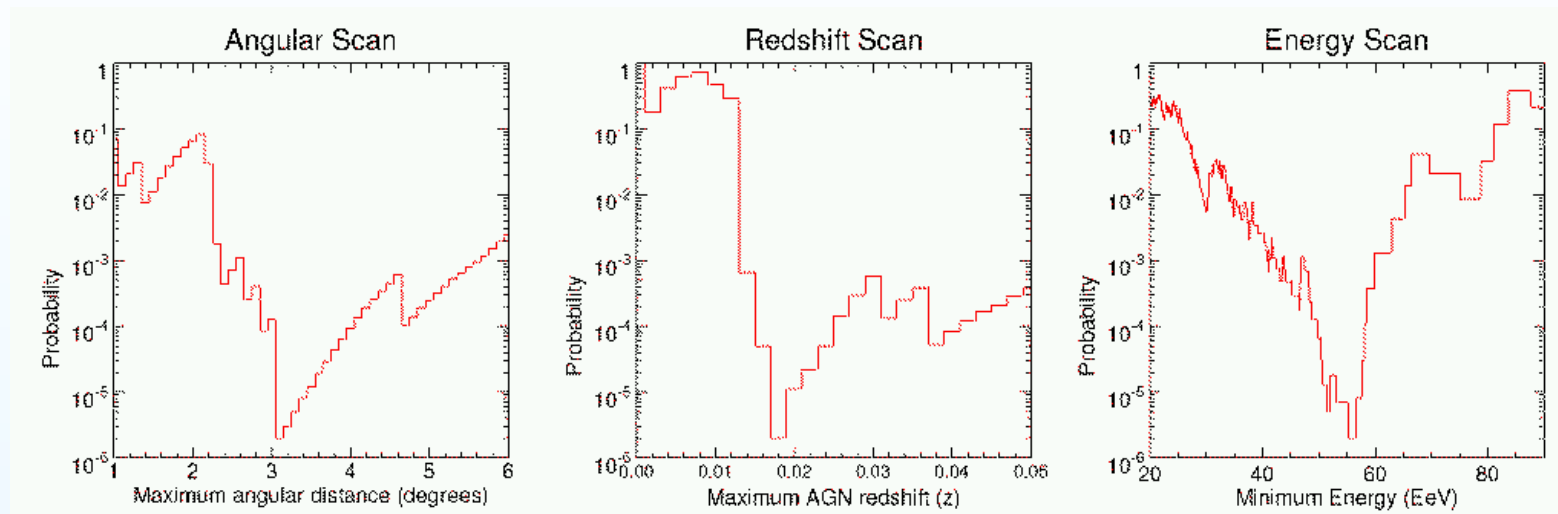
- **Left plot:** FD view of a UHECR air shower. The colored *dots* show the photo-multiplier (telescope camera pixels) that recored this event. *The event travels downward from the top (green dots) to the bottom (red dots).*
- **Right plot:** SD view of (the same) UHECR air shower. The red circles show the detectors that recorded this event. *The shower front proceeds from lower right to upper left.*
- Shower energies are measured with a statistical precision of $\sim 10\%$, and arrival directions with an angular precision of $\lesssim 1^\circ$ (**SD** only) and $\lesssim 0.5^\circ$ (**Hybrid** events).

Previous experiments' evidence for *point sources*



- IF sources are *bright* we expect to see multiple cosmic rays/source
- AGASA reported 5 doublets and 1 triplet few-degree sized event-clusters
- HiRes, with ~ 3 -times the stereo exposure, has **not** verified the AGASA result.
- At somewhat larger angles, the AGASA triplet plus a HiRes event may be the first *quartet event-cluster*!
- Are any point sources? and Do they correlate with anything (e.g. with known AGNs)?
- BUT IF sources are *faint* we may only see correlations with *candidate* sources ...

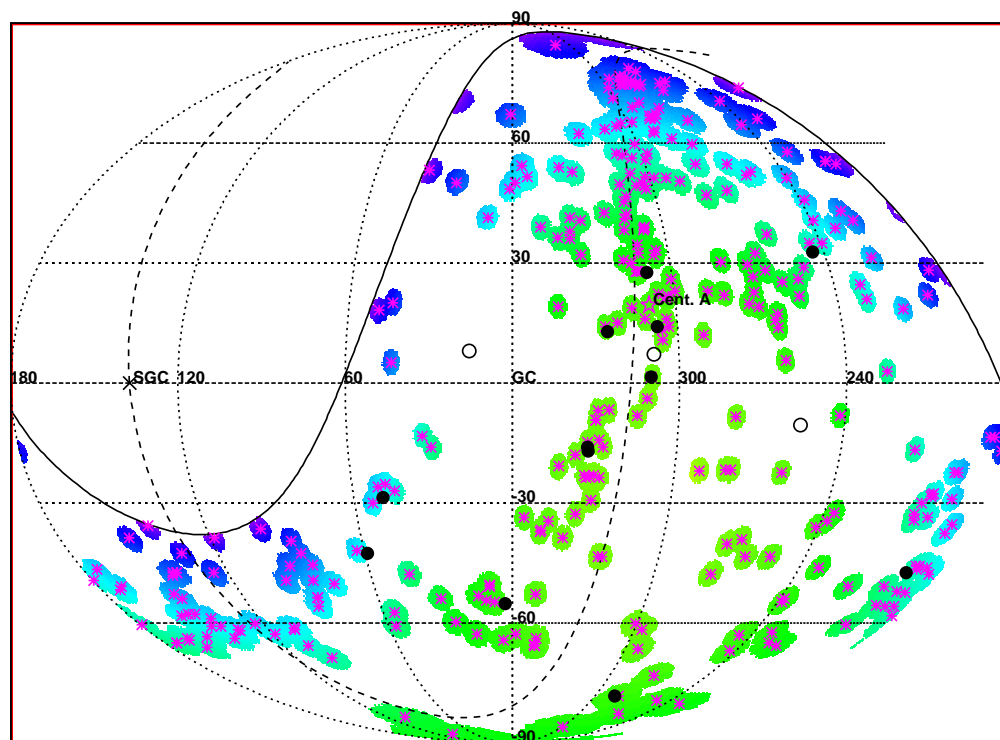
One Auger CR:AGN correlation search



- IF the sources are faint ... then best to look for *correlations* with *candidate* sources; see Astropart.Phys. 27 (2007) 134 [astro-ph/0609655]
- Today we report on **one** such search for correlations between Auger events from Jan. 1, 2004 to May 27, 2004 and AGNs in the 12th edition of the Véron catalog.
- The search scanned over: AGN maximum redshift ($z \leq 0.05$), event energies ($E \geq 20\text{EeV}$) and AGN:CR correlation angles ($1.1^\circ \leq \text{angle} \leq 6.1^\circ$).
- In that parameter space, the minimum value of the probability, P , for chance (*i.e.* accidental) correlation was $P \approx 10^{-6}$ for: angle = 3.1° , maximum redshift $z_{max} = 0.018$ and minimum event energy $E_{min} = 56\text{EeV}$.

Distribution of the 15 events above 56EeV

(1/ 1/2004 -> 27/ 5/2006) $E/E_{\text{TeV}} \geq 56.0$, $z \leq 0.018$, $\psi \leq 3.1$



- Plot of nearby AGNs (*), each within a 3.1° colored disk reflecting Auger acceptance, and CRs that correlate (filled circles) and that do not correlate (open circles).
- The Véron catalog has a significant bias for galactic latitudes $|l| \lesssim 15^\circ$

To test this observation we define a *Prescription*

	Anisotropy Criteria	Definition/Selection
Dataset	Prescription Starts	28 May 2006
	Prescription Expires	34 events above Energy Selection [†]
	Event Quality	Standard Quality Cuts [15]
	AGN Catalog	Veron-Cetty 12th Edition Catalog [10]
	Probability to make a false claim	Less than 1.05%
Parameters	Shower size (Energy)	$S_{38} \geq 244.5 \text{ VEM } (E \geq 56 \text{ EeV})$
	Angular Distance Selection	$d \leq 3.1 \text{ degrees}$
	AGN Redshift Selection	$z \leq 0.018 (D \leq 75 \text{ Mpc})$

[†]Equivalently, the prescription will expire when 20 non-correlated events are observed, since in this case it will become impossible to satisfy the prescription with 34 events.

- Our scan to find the minimum probability for chance AGN:CR correlation is likely to emphasize fluctuations ... so do not take $P \approx 10^{-6}$ seriously!
- Instead, accumulate more (independent data) and measure the AGN:CR correlation *signal now* with: **clearly defined selections on event energy, Véron catalog AGN maximum redshift, and correlation angle.**
- *At a minimum, the Véron catalog: AGN maximum redshift and correlation angle, defines a limited area (effectively 21%) of the sky. A Véron catalog AGN:CR correlation signal would be evidence for a non-isotropic flux of CRs that is enhanced near known extra-galactic objects.*

Choose a *Running* Prescription with Limited Error

N	k_{min}	Threshold	Power(%)	
		(percent)	($P = 57\%$)	($P = 80\%$)
4	4	0.19	11	41
6	5	0.32	19	66
8	6	0.40	26	80
10	7	0.44	31	88
12	8	0.47	36	93
13	8	0.55	49	97
15	9	0.58	52	98
16	9	0.67	63	99
18	10	0.70	64	100
20	11	0.71	66	100
21	11	0.75	74	100
23	12	0.77	75	100
24	12	0.81	82	100
26	13	0.82	82	100
27	13	0.86	87	100
29	14	0.87	87	100
30	14	0.91	91	100
31	14	0.99	93	100
33	15	1.00	93	100
34	15	1.05	95	100

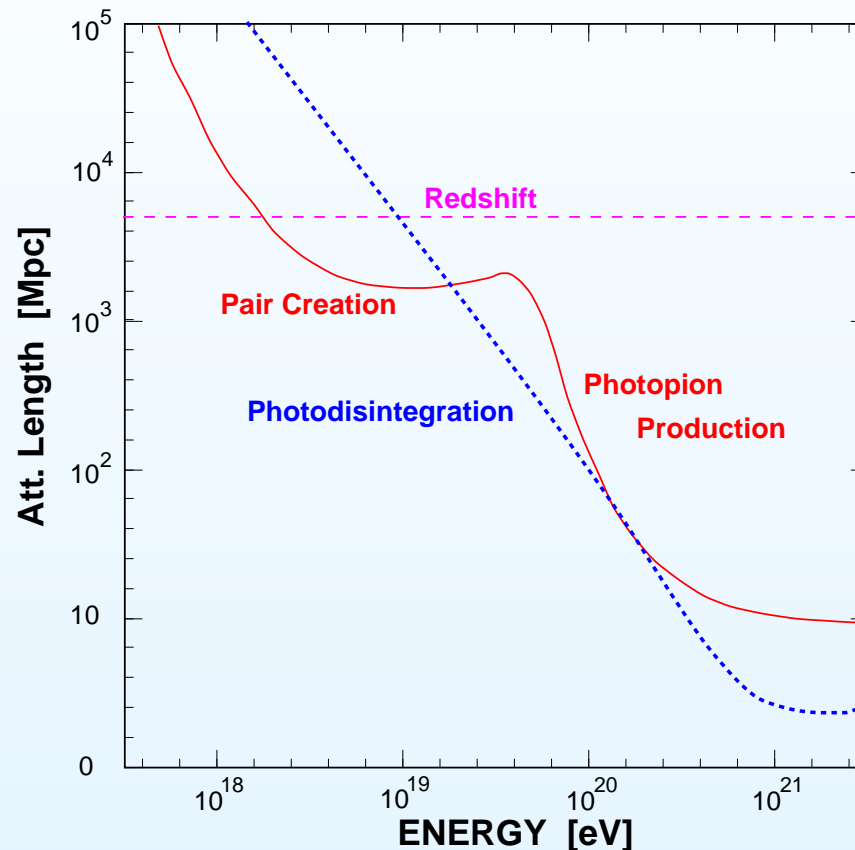
- In the initial parameter scan, the AGN:CR correlation *signal* was 12 of 15 CRs vs ~ 3.15 expected by chance.
- Two candidate *signals* were chosen with probabilities: 0.57 and 0.8 as a counter to the chance (\equiv NULL) hypothesis
- A *prescription* was drafted with probabilities: $\leq 1\%$ for the NULL hypothesis **to pass** and $\leq 5\%$ for the NULL hypothesis **not to be excluded** (if either of the candidate *signals* were correct).
- In the **Table**, N is the number of events and k_{min} the number of AGN:CR correlations since the start of the *Running* Prescription.

15+ months into the *Running Prescription*

- Auger accumulates ~ 1 event/month > 56 EeV ...
- *At a minimum, the Véron catalog: AGN maximum redshift and correlation angle, defines a limited area (effectively 21%) of the sky. A Véron catalog AGN:CR correlation signal would be evidence for a non-isotropic flux of CRs that is enhanced near known extra-galactic objects.*
- *Whatever the outcome of the Running Prescription, it is by definition a $O(1\%)$ test!*
- An article has been submitted to Science ...
- By the rules of Science magazine I can not say more *today!*

Additional slides

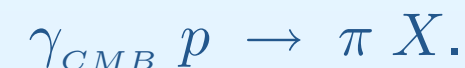
What is the CMB/GZK *wall* at 10^{20} eV?



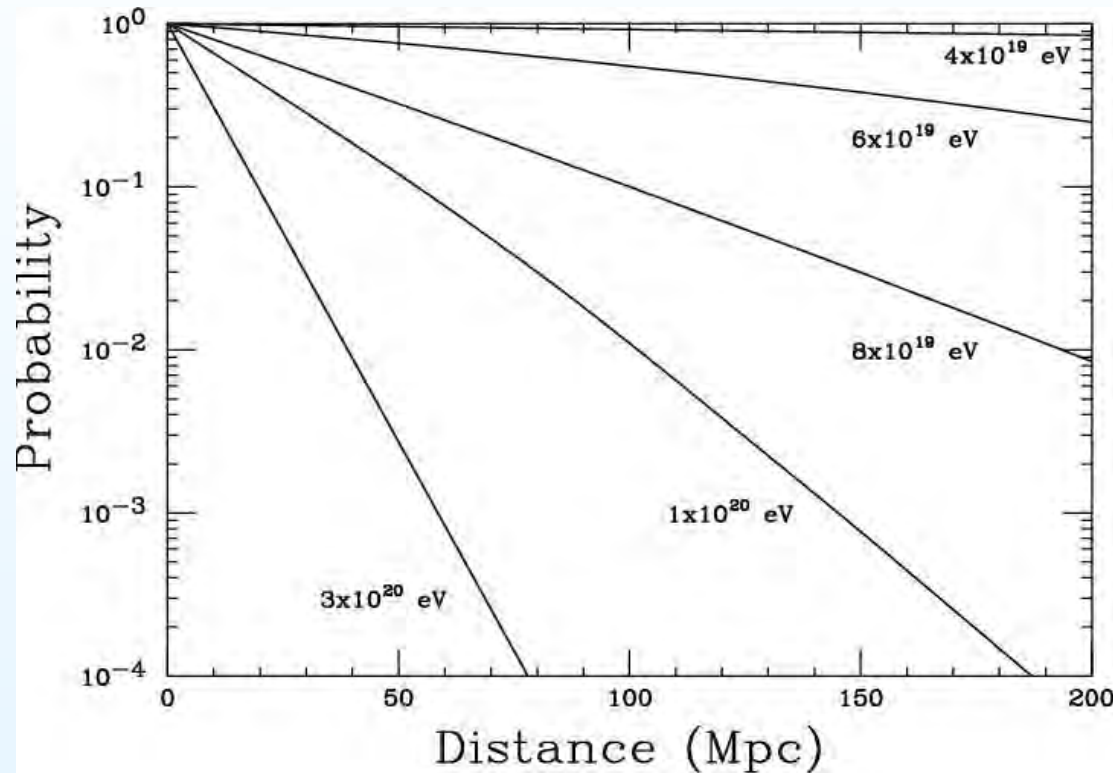
- Cosmic rays interact with the cosmic micro-wave background (CMB) radiation; after a distance, d :

$$E = E_0 \cdot e^{-d/\Lambda_{atten}}$$

- Steep drop of Λ_{atten} near 10^{20} eV from the onset of π photo-production:

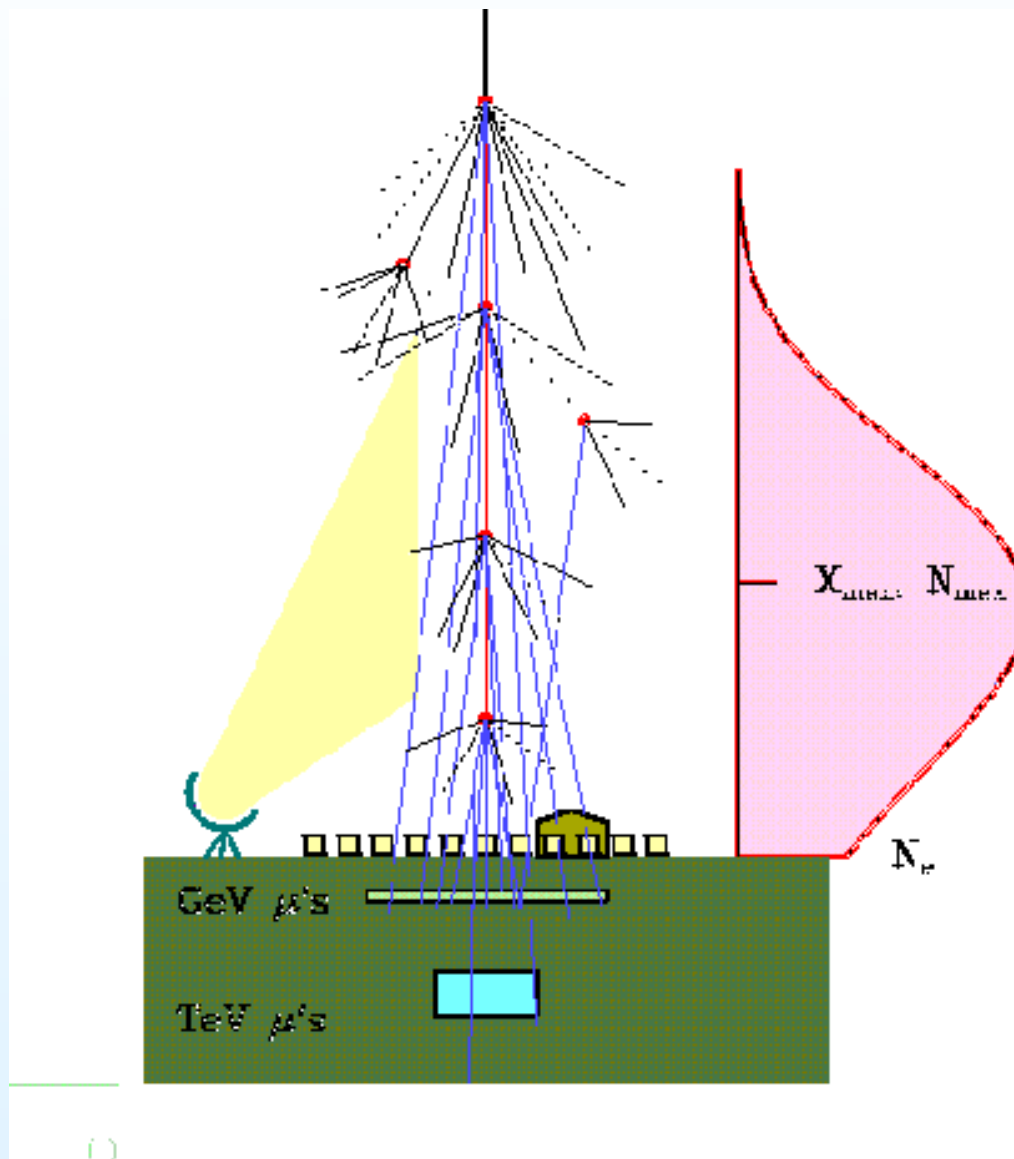


The GZK cutoff *limits* the possible source distance



- Probability that an observed event at a given energy has its source at a distance greater than the indicated distance.
- A source spectrum proportional to $E^{-2.5}$ is assumed.

In Auger the atmosphere IS the detector!



- Energy of *primary* cosmic rays from shower “brightness” as observed in FD and/or SD
- Composition of *primary* cosmic rays from depth of shower maximum, X_{max} , and/or from μ/e ratio.



The Pierre Auger Project

A new cosmic ray observatory designed for a high statistics study of the

The Highest Energy Cosmic Rays

Using

Two Large Air Shower Detectors

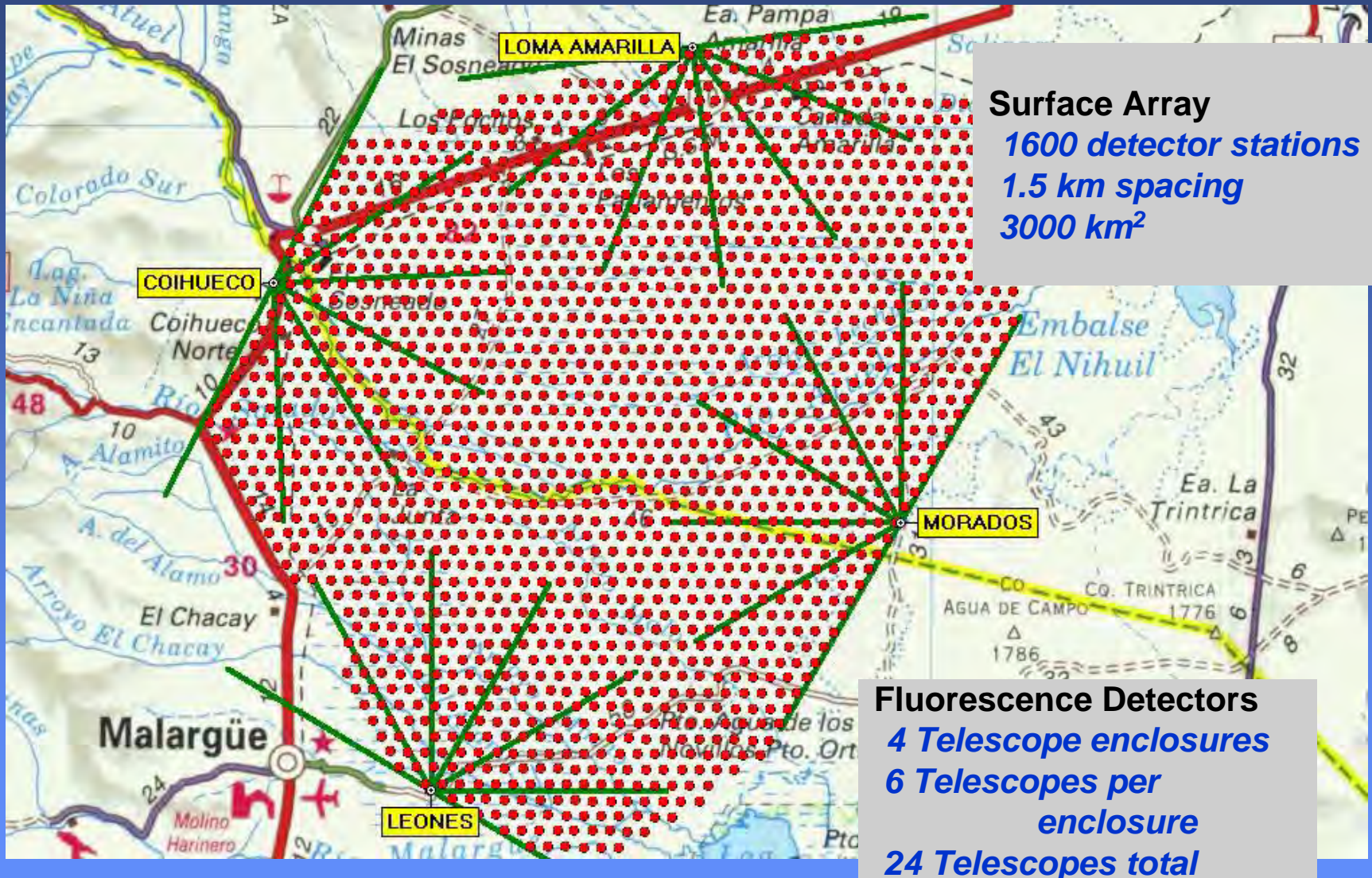
Colorado, USA
(in planning)



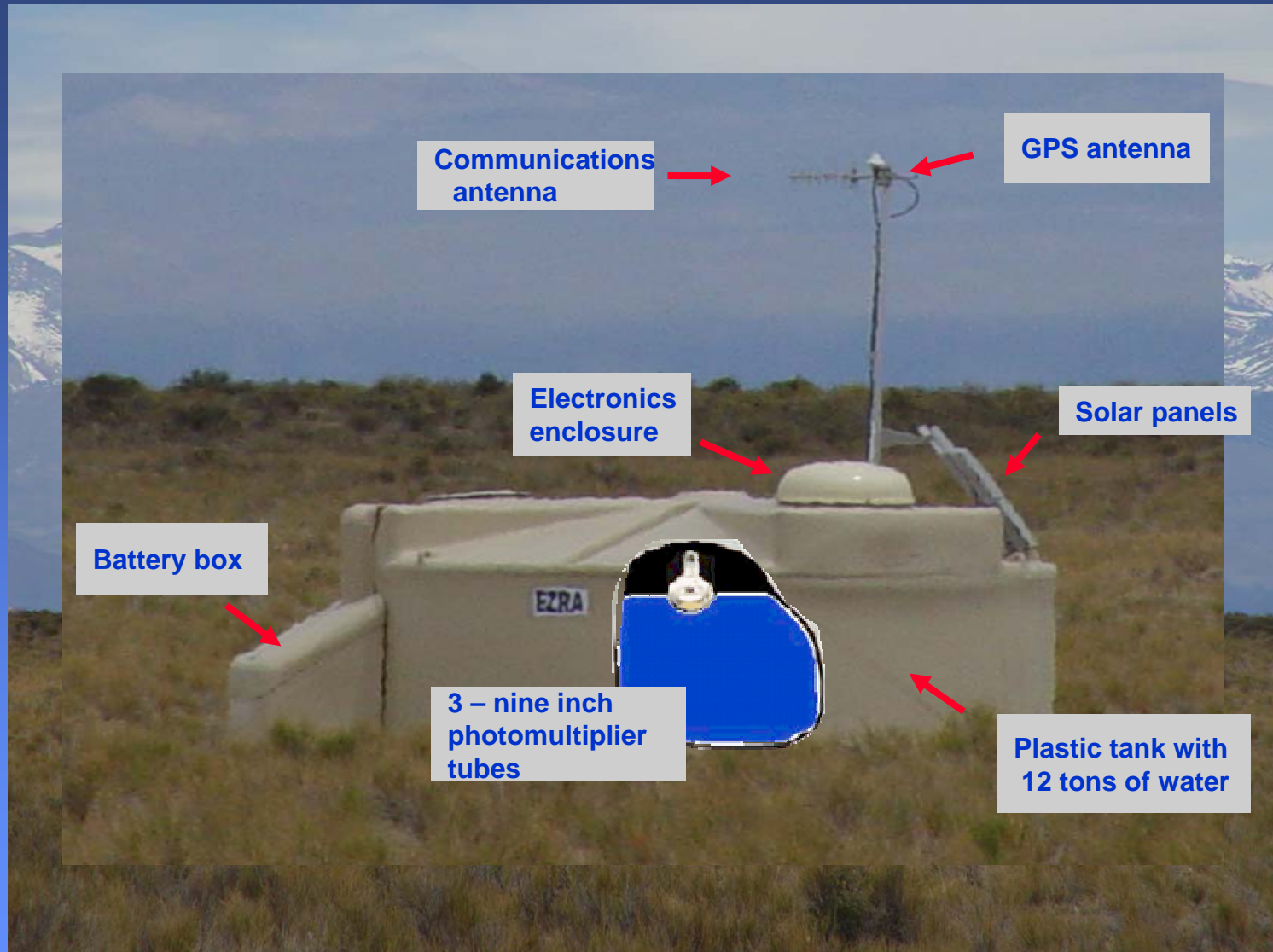
Mendoza, Argentina
(construction underway)



The Observatory Plan



The Surface Array *Detector Station*

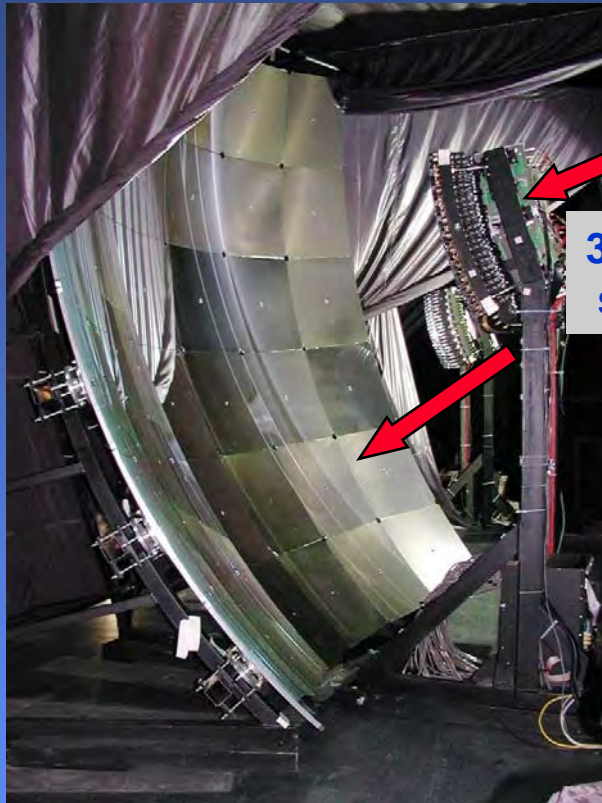


Surface Detector Progress

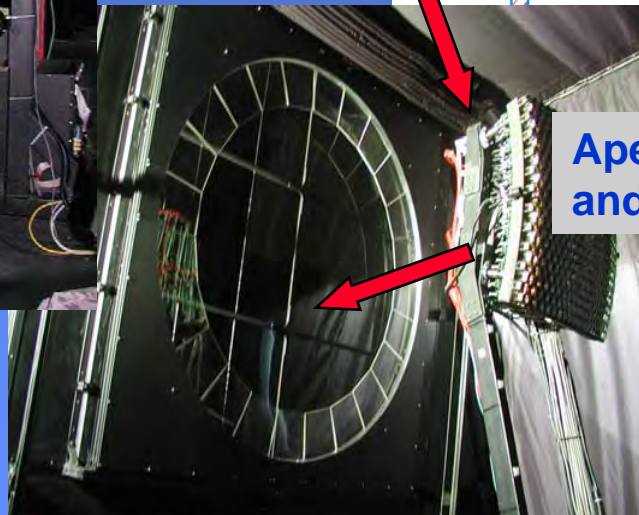
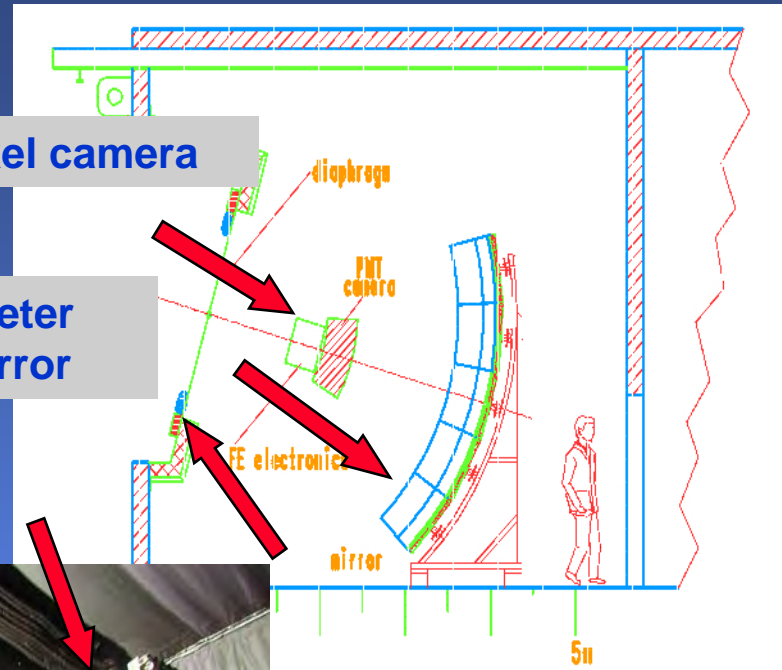
Deployment Status



The Fluorescence Detector



3.4 meter diameter
segmented mirror



Aperture stop
and optical filter

The Fluorescence Detector

Los Leones



ICRC August 2005
Pierre Auger Collaborative

Atmospheric Monitoring and Fluorescence Detector Calibration

Atmospheric Monitoring



Central Laser Facility
(laser optically linked to
adjacent surface detector
tank)

- Atmospheric monitoring
- Calibration checks
- Timing checks

Lidar at each
fluorescence eye for
atmospheric profiling
- “shooting the
shower”

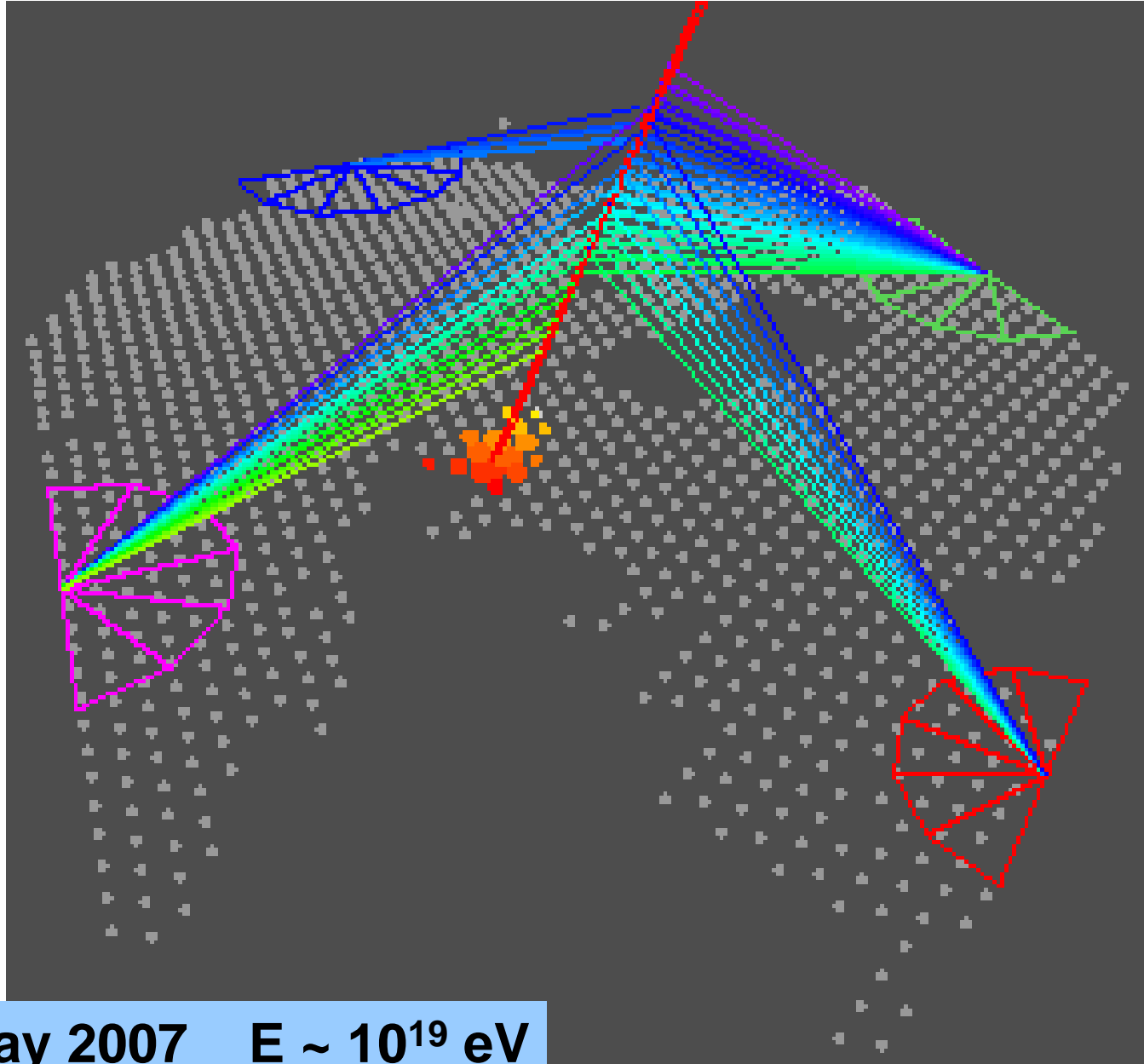


Absolute Calibration



Drum for uniform
illumination of each
fluorescence camera –
part of end to end
calibration .

First 4-fold Event



Aaron S. Chou, SSI 2007

20 May 2007 $E \sim 10^{19}$ eV