

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

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## **Unraveling the physics of the UHECR sources**





The physics of the <u>sources</u> 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,*  $\gamma$ *-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

<u>Nearby</u> (9 < R < 93 Mpc) universe non-isotropic ... thus highest energy particles should not be isotropic (93 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.

# The University of New Mexico

## 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 km<sup>2</sup> sp 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  $\sim$  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 12<sup>th</sup> edition of the Véron catalog.
- The search scanned over: AGN maximum redshift ( $z \le 0.05$ ), event energies ( $E \ge 20$ EeV) and AGN:CR correlation angles ( $1.1^{\circ} \le$ angle  $\le 6.1^{\circ}$ ).
- In that parameter space, the minimum value of the probability, P, for chance (*i.e.*accidental) correlation was  $P \approx 10^{-6}$  for: angle =  $3.1^{\circ}$ , maximum redshift  $z_{max} = 0.018$  and minimum event energy  $E_{min} = 56$ EeV.

## **Distribution of the 15 events above 56EeV**





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 <sup>†</sup>
	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) Angular Distance Selection	$S_{38} \ge 244.5 \text{ VEM} \ (E \ge 56 \text{ EeV})$ $d \le 3.1 \text{ degrees}$
	AGN Redshift Selection	$z \le 0.018 \ (D \le 75 \ { m Mpc})$

<sup>†</sup>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**



- In the initial parameter scan, the AGN:CR correlation *signal* was 12 of 15 CRs  $VS \sim 3.15$  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: ≤ 1% for the NULL hypothesis to pass and ≤ 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  $\sim 1$  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/backup slides** 



# **Additional slides**

23rd Annual New Mexico Symposium, Socorro, Oct 19, 2007 - p.14/17

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



- The University of New Mexico
- 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  $\Lambda_{atten}$ near  $10^{20}$ eV from the onset of  $\pi$ photo-production:

 $\gamma_{\rm CMB} \ p \ \rightarrow \ \pi \ X.$ 

## 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 /S 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  $\mu/e$  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



Mendoza, Argentina (construction underway)



## **The Observatory Plan**



#### The Surface Array Detector Station



#### Surface Detector Progress Deployment Status



## **The Fluorescence Detector**



#### **The Fluorescence Detector** Los Leones



## **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

#### Absolute Calibration



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

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

ICRC August 2005 Fierre Auger Collaboration





## First 4-fold Event

