# Selected Physics Results from the Pierre Auger Southern Observatory

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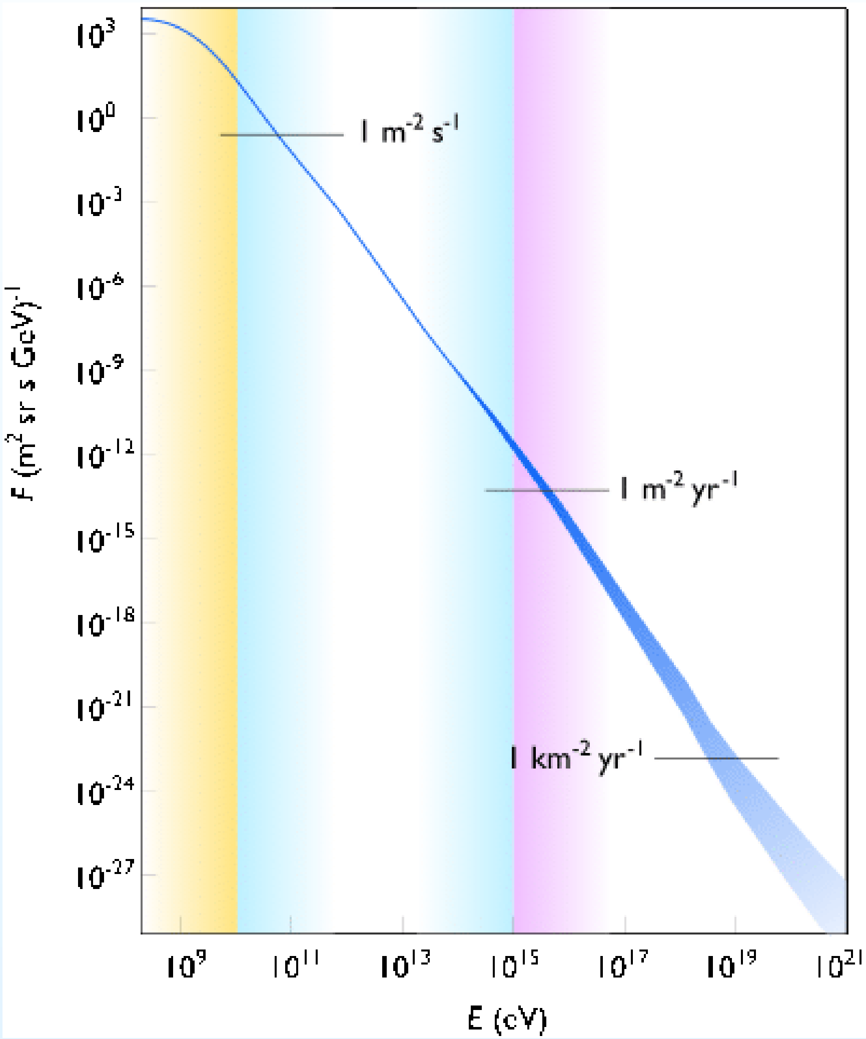
**for the Pierre Auger Collaboration**

# Unraveling the physics of the UHECR sources



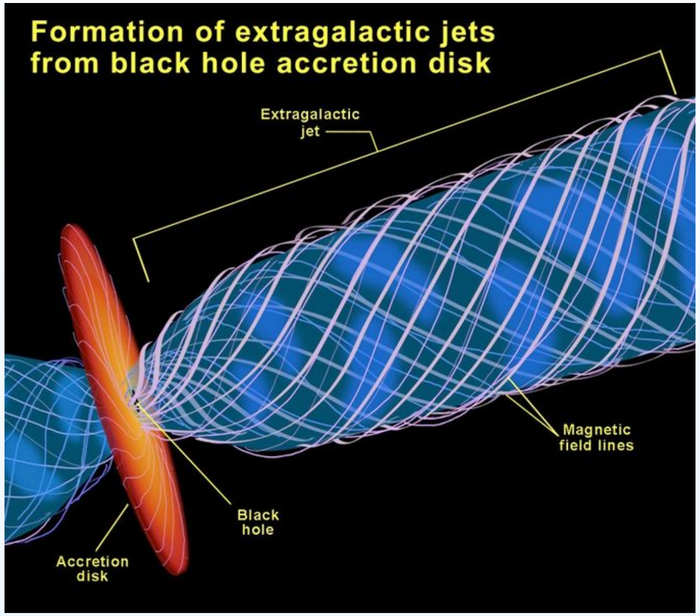

Cosmic rays to energies $\sim 10^{20}$eV exist. Why they exist is not so clear. Are they protons or a cocktail of different nuclei? Do (at least some) point back to their sources?

And how do we learn what physics produces these very energetic particles? Probably we need many different observations *e.g. radio, visible, X-ray, $\gamma$-ray, ...*

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

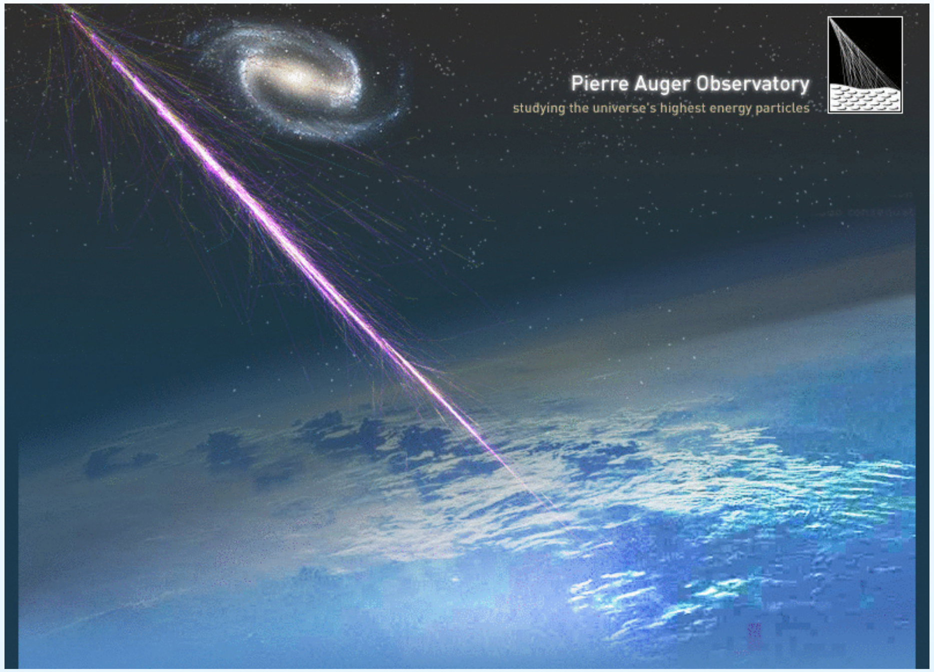
- “protons” (special case of *light* nuclei)
- “iron” (special case of *heavy* nuclei)
- **gamma-rays**
- **neutrinos**

# 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

# Unraveling the physics of the UHECR sources



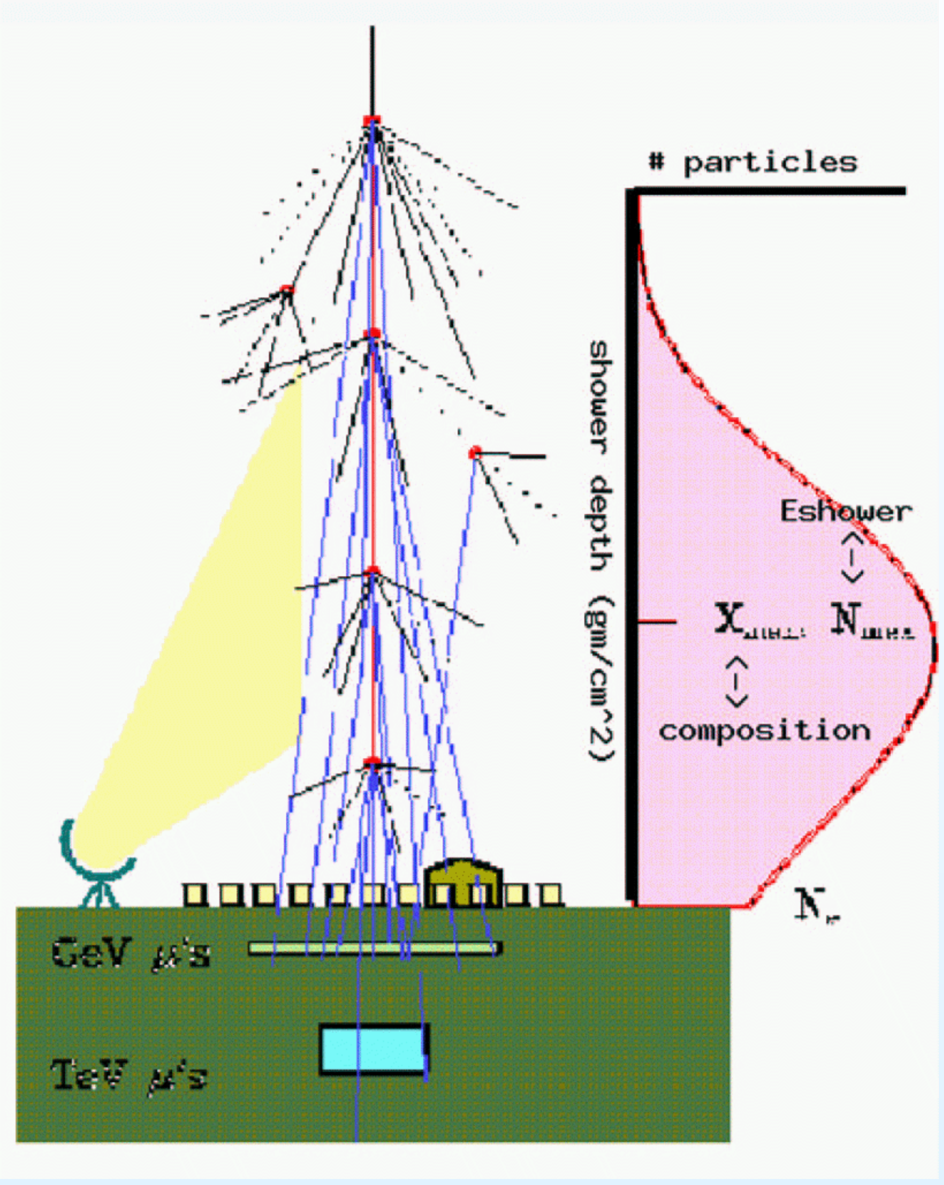

When the UHECRs strike the atmosphere they produce an extensive air shower.

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.

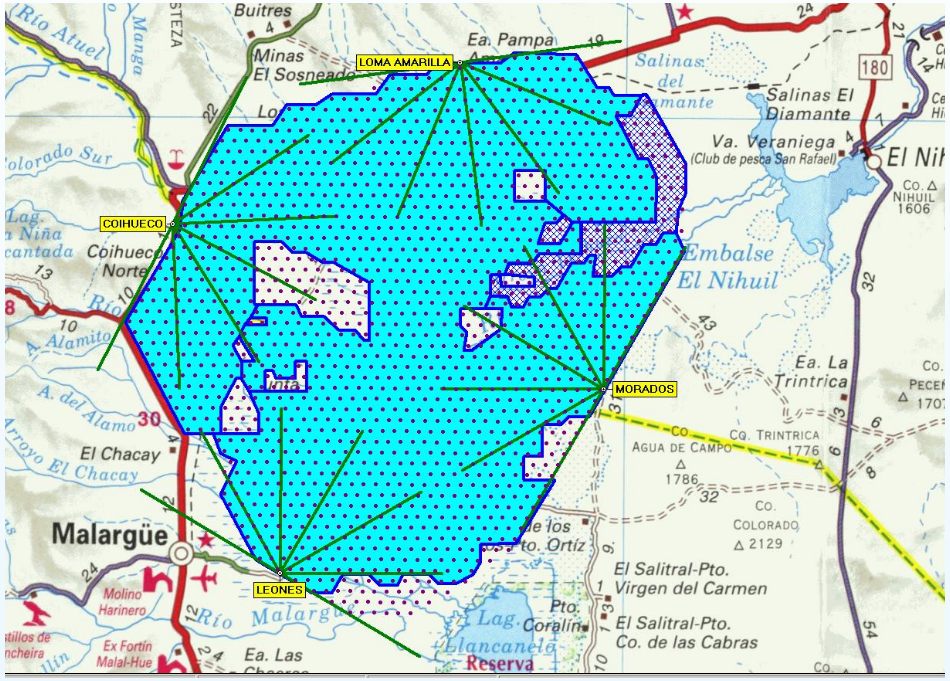
Auger **hybrid** measurements allow the properties of the initial cosmic ray to be reconstructed based on simultaneous measurement of a shower by both **FD** and **SD** components.

# In Auger the atmosphere *IS* the detector!



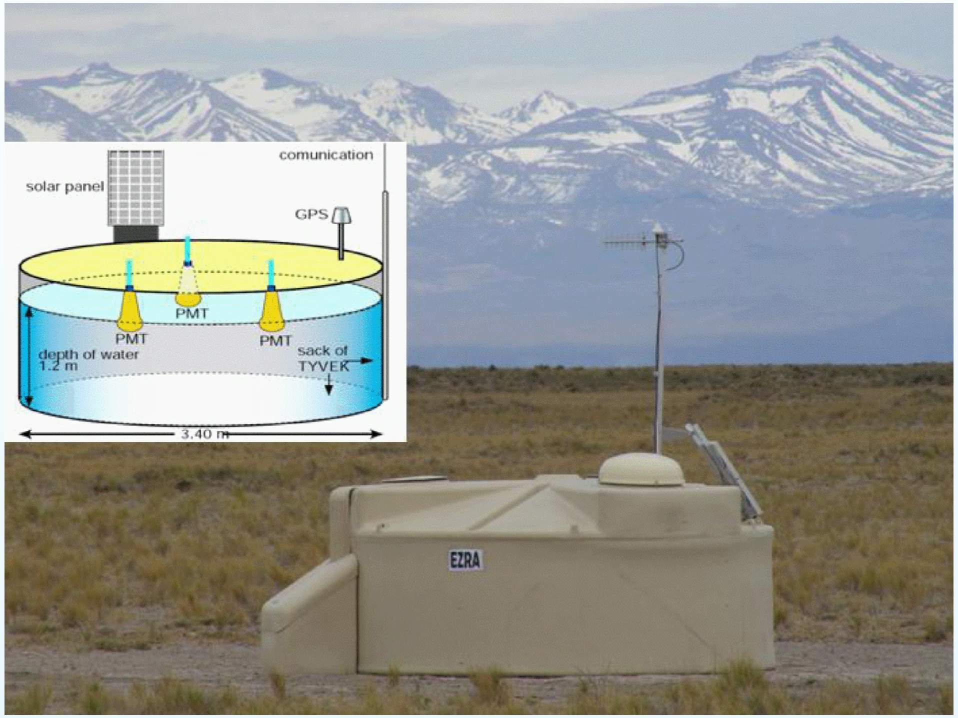

- Energy of *primary* cosmic rays from shower "brightness" as observed in FD and/or SD
- Composition of *primary* cosmic rays from depth of shower maximum, $X_{max}$, and/or from $\mu/e$ ratio.

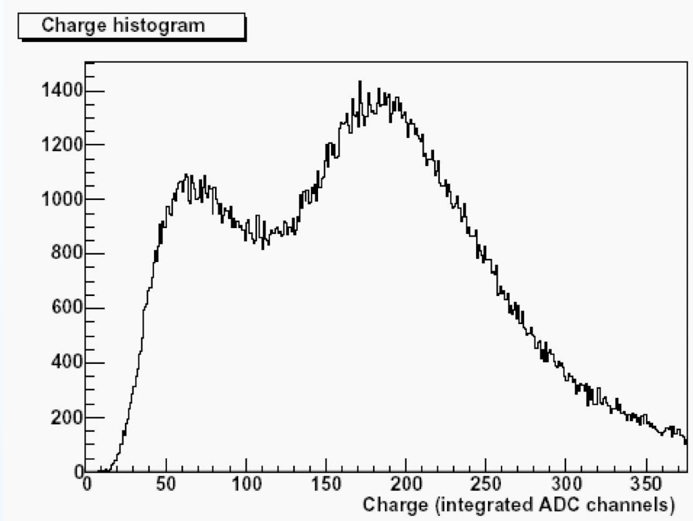
# **Auger Southern Observatory** *January 31, 2008*




- Auger is a collaboration of over 300 PhD scientists from Argentina, Australia, Bolivia, Brazil, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, United Kingdom, United States, and Vietnam.
- The dotted-area shows the final extent of the $\sim$55km $\times$ 55km SD array.
- The **FDs** are at 4-locations: (*Los Leones, Morados, Loma Amarilla, Coihueco*) and over-look the SD ground array.

# Auger Surface Detectors (*aka SD*)



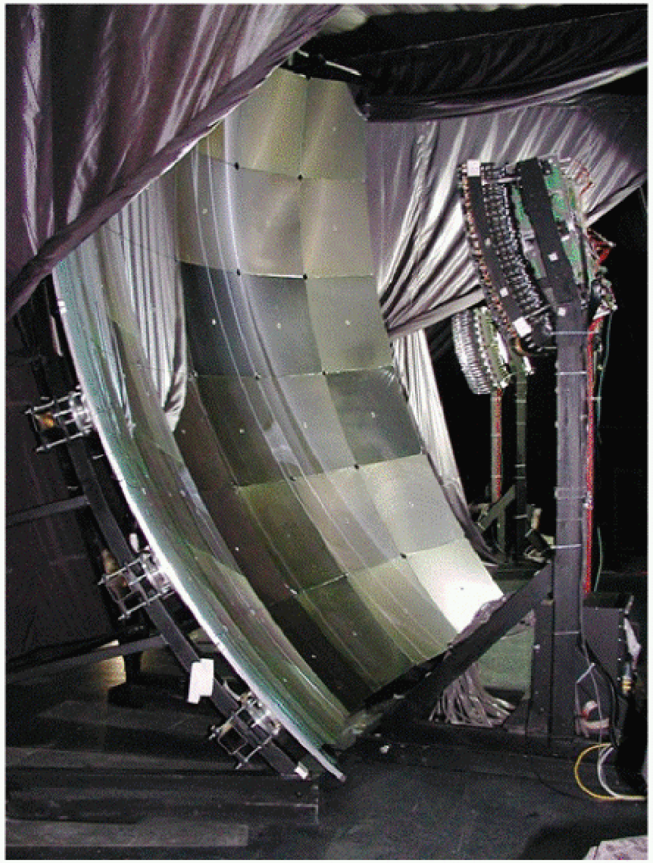

- **Left:** Photo of 1 of 1600 Auger ($10m^2$) surface detectors.
- **Right:** Through-going muons provide a *natural* calibration: Vertical Equivalent Muon (VEM).
- The Auger SD cosmic ray energy scale is obtained either: from the FD using hybrid events **OR** by Monte Carlo simulations (which may not model the physics at our shower energies!) For now we use the FD normalization.

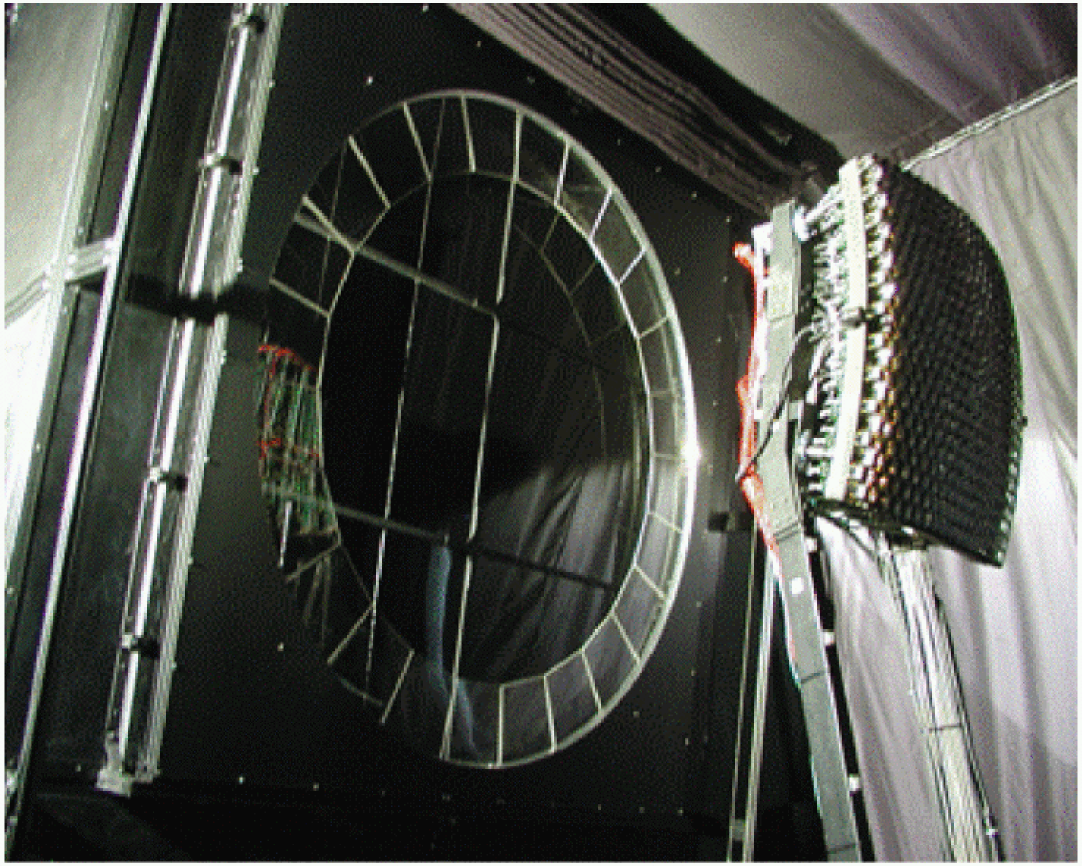
# Auger Fluorescence Detectors (*aka FD*)

One of four Fluorescence Detectors. Each FD includes 6 telescopes.

# Auger Fluorescence Detectors (*aka FD*)

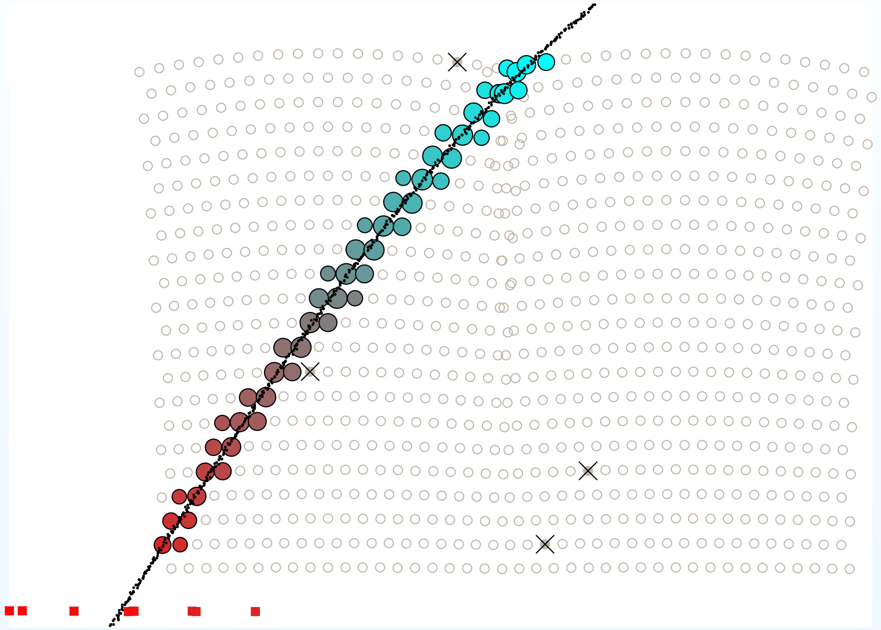
The University of New Mexico

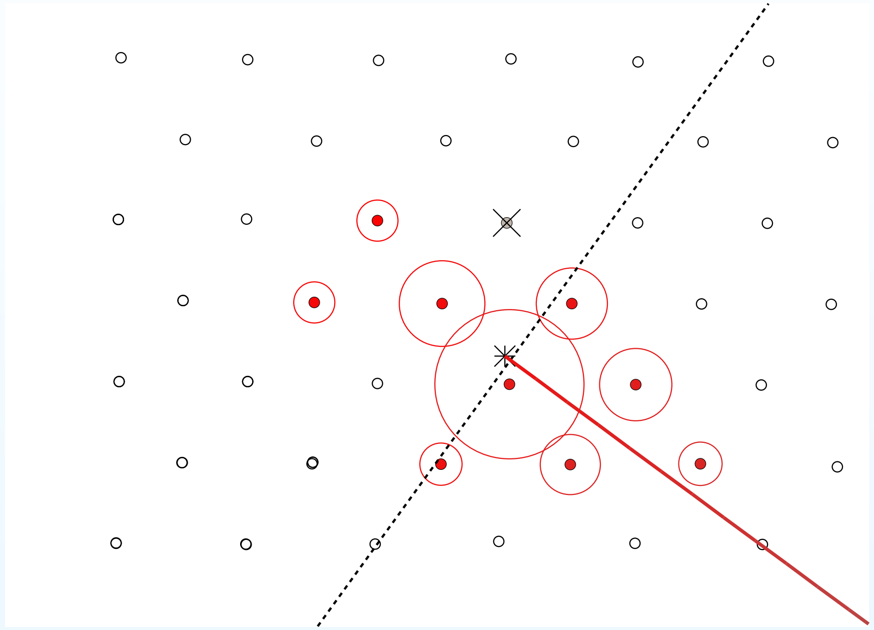




- Telescopes: 2.2m diameter, Schmidt optics that view $180^\circ$ in azimuth and from $\sim 1^\circ$ to $\sim 31^\circ$ from the horizontal
- Cameras: 440 PMTs (*i.e.* $\sim 1.5^\circ$ pixels) with 10 Mhz sampling

# 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 $\sim 1^\circ$ (**SD** only) and $\sim 0.5^\circ$ (**Hybrid** events).

# Why Hybrid?

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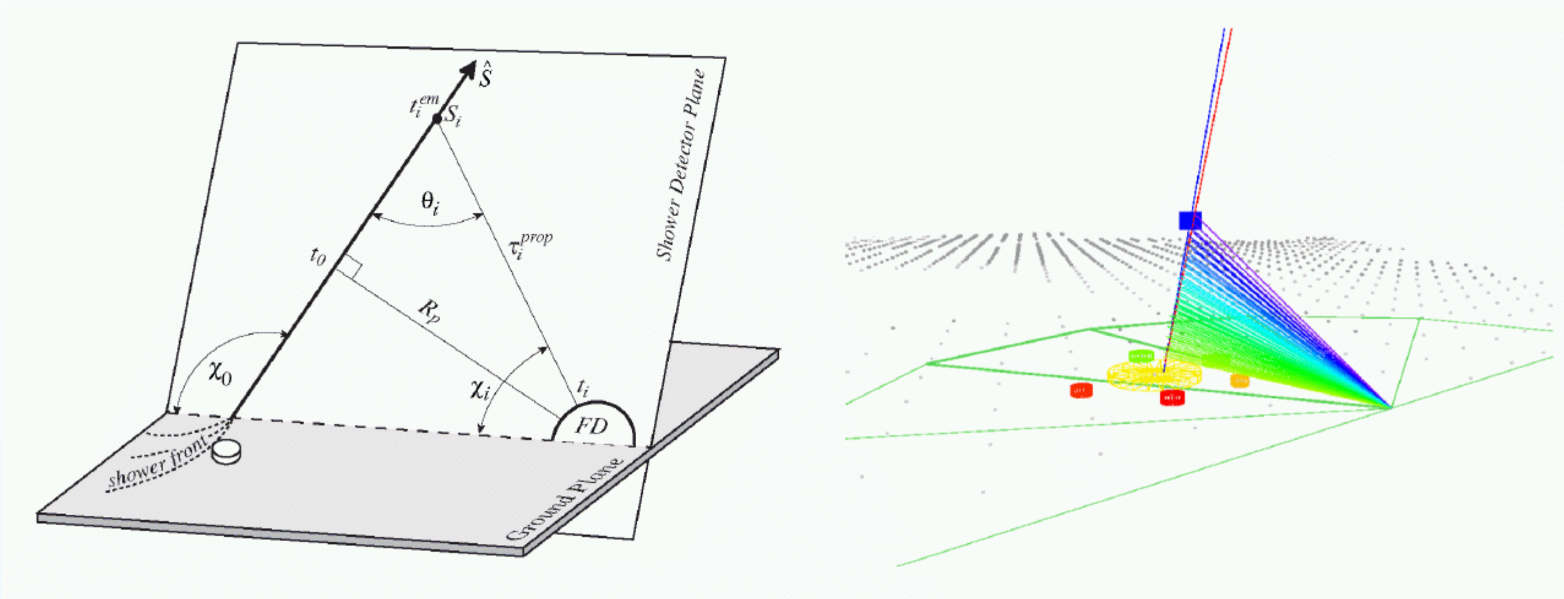
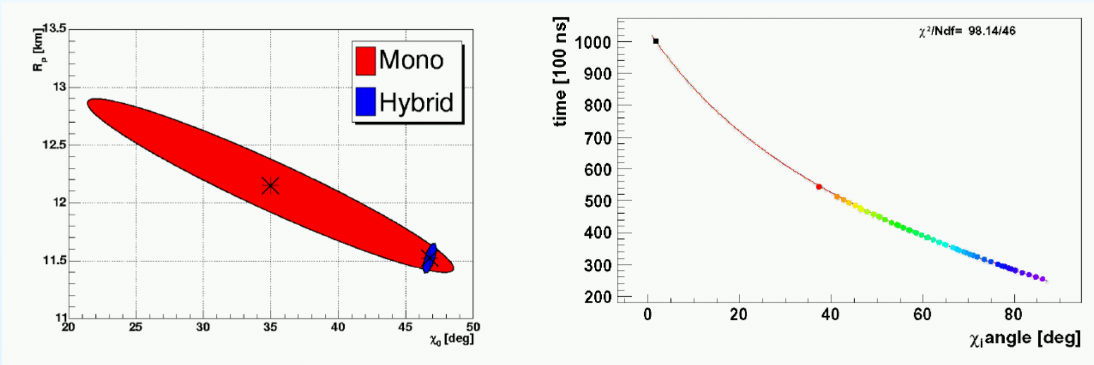
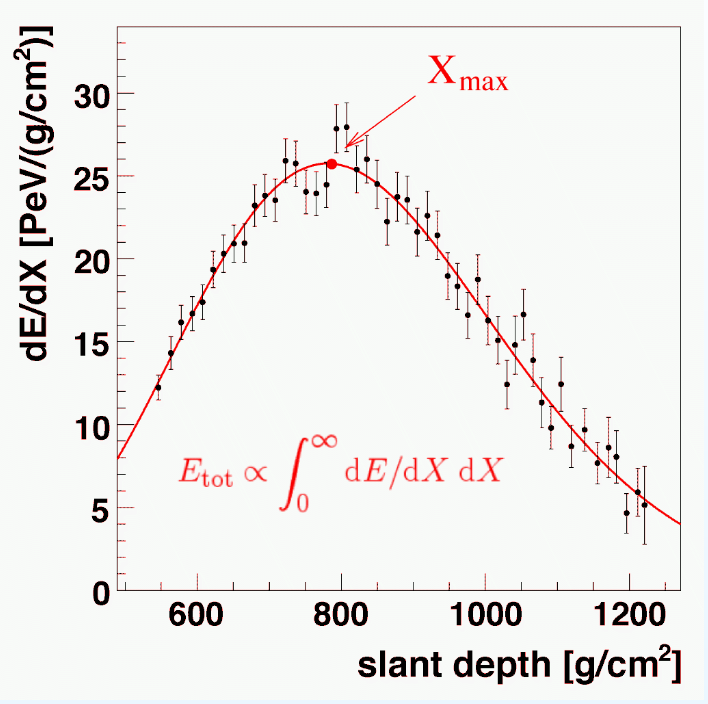



Adding SD timing to the FD reconstruction converts angular error *bananas* into *circles*

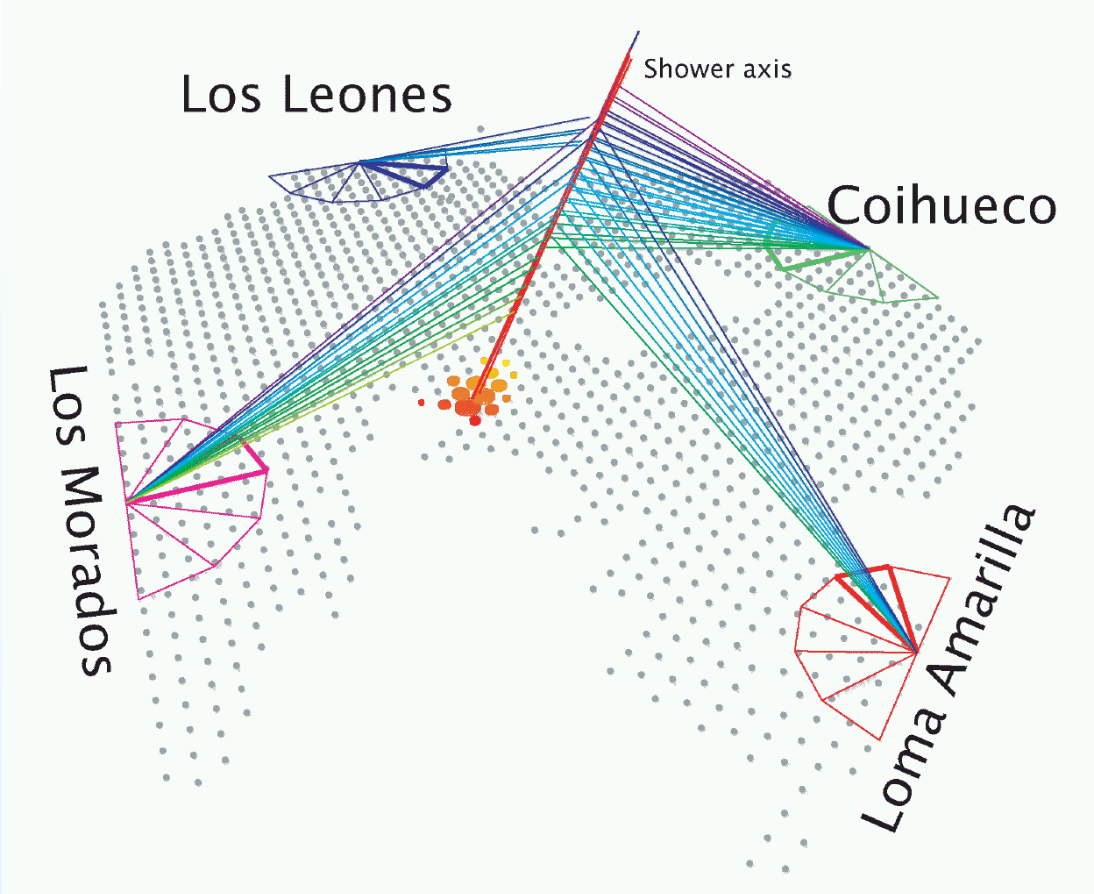
Hybrid events provide a high-precision data sample that **significantly extend the energy reach of Auger**

# FD (hybrid) events



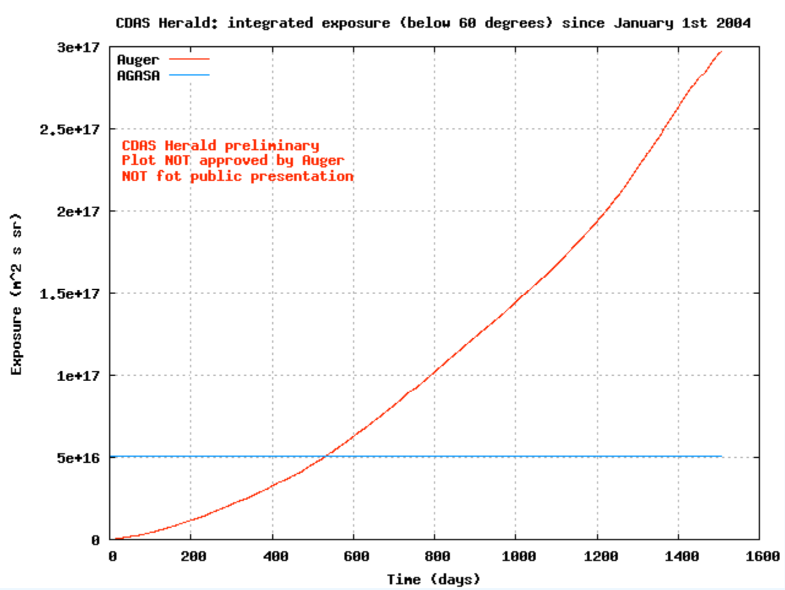

- FD events provide a calorimetric measurement of the shower energy and of the position of shower maximum, $X_{max}$
- However the FD has no *natural* calibration source ...
- Furthermore FD data depend on time varying atmospheric parameters
- **Thus in practice there are many details:** *e.g. fluorescence yield, absolute calibration and atmospheric monitoring*!

# FD stereo-hybrid events



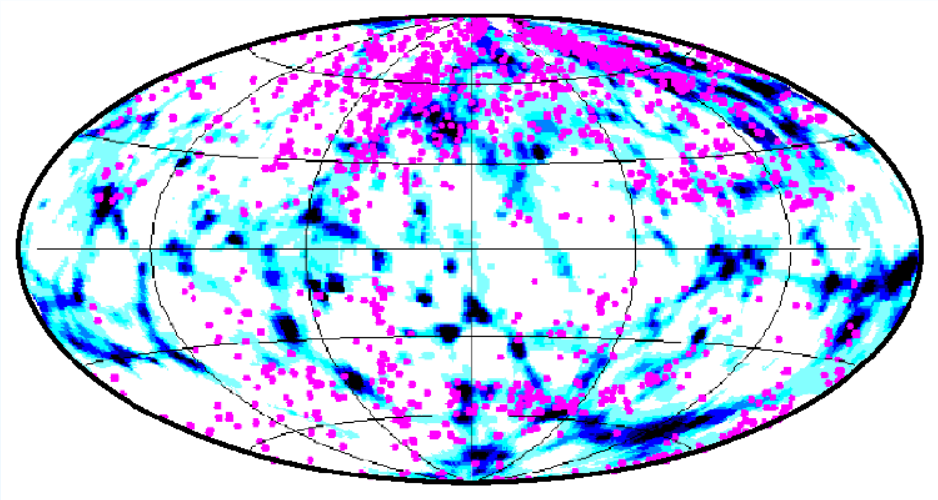

- **Event reconstruction (above):** First 4-fold stereo-hybrid event
- Hybrid, and stereo, events provide <u>essential cross-checks</u> with multiple measurements/event

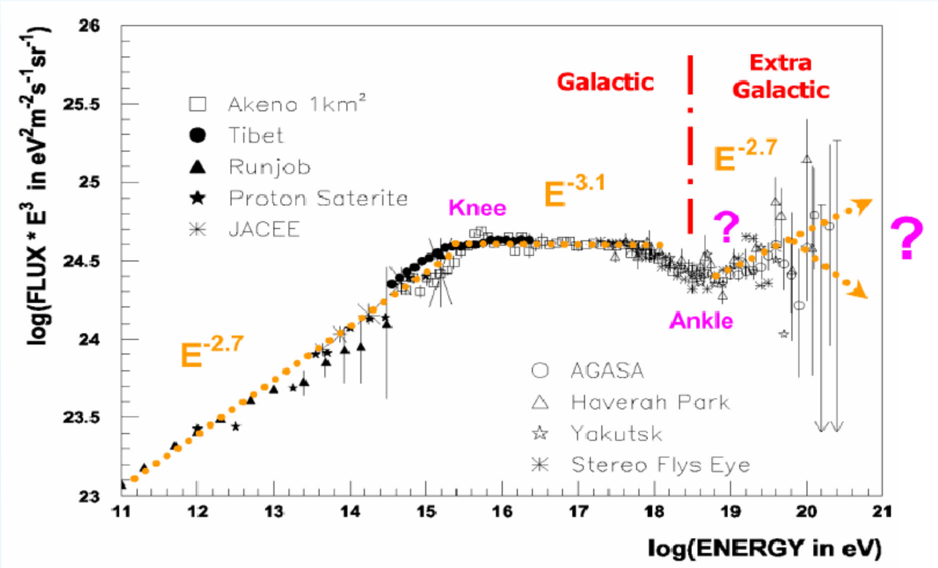
# Auger data taking (January 31, 2008)




- One advantage of a modular experiment is that you can start running well before the detector is totally complete ...
- **Plot** shows the **preliminary** SD *exposure* ($m^2$ s sr) since January 1, 2004
- This exposure is already $\sim 6\times$ **AGASA and probably greater than HiRes-stereo**
- Combine FD and SD measurements will result in **reduced systematic errors** *VS* previous experiments
- Note: Auger is still a *young* experiment with **evolving** monitoring, data reduction software, and data analyses ...

# First question: **Do UHECRs correlate with ... ?**






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

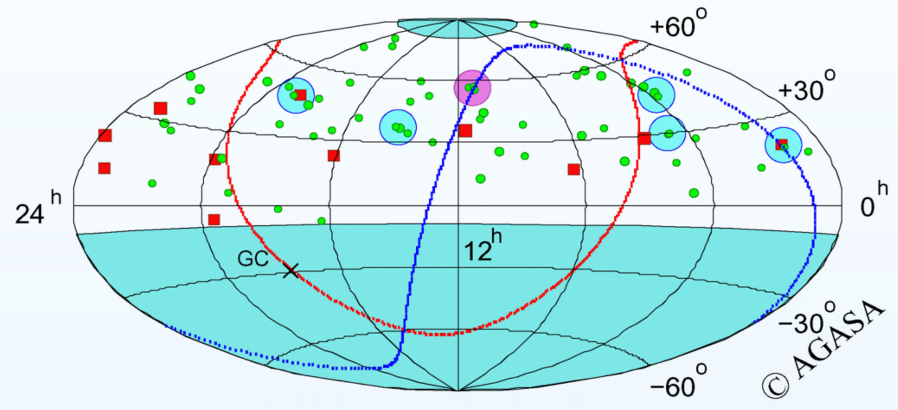
Nearby ($9 < R < 93$ Mpc) universe non-isotropic ... thus highest energy particles should not be isotropic (*93 Mpc* $\approx 0.022$ *in redshift*) if there is a GZK cutoff

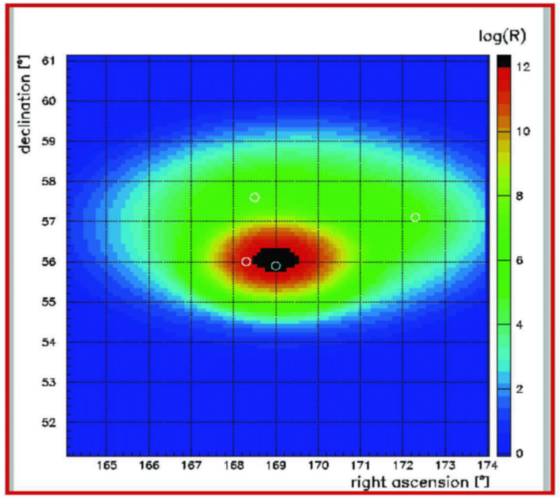
Baring magnetic field surprises, arrival directions should show structure ... **but on what angular scale(s)?**

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

red print = more later

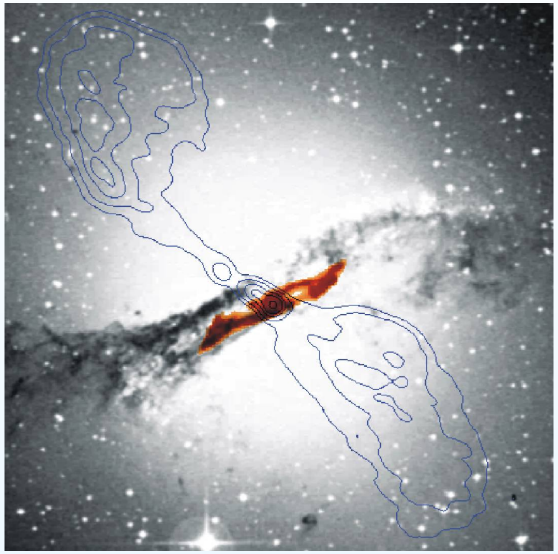
# Previous experiments' evidence for *point sources*



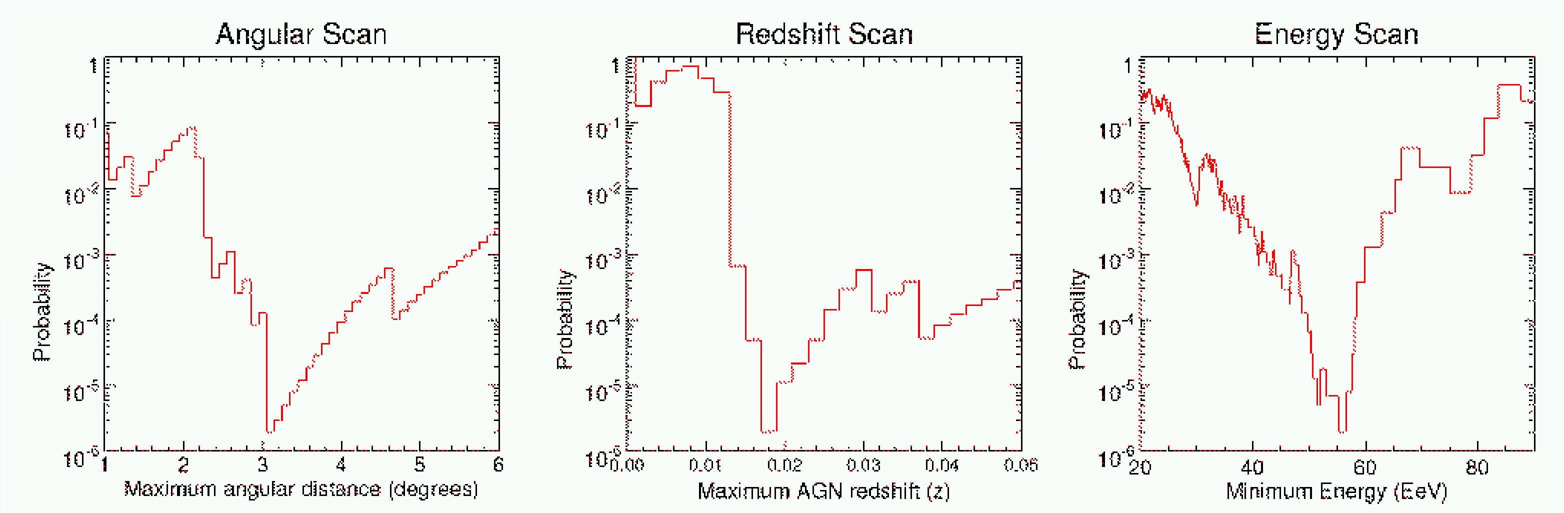

- **IF** sources are *bright* we expect to see multiple cosmic rays/source
- AGASA reported 5 doublets and 1 triplet few-degree sized event-*clusters*
- HiRes, with $> 3$-times the stereo exposure, has **not** verified the AGASA result.
- At somewhat larger angles ($3 \sim 4°$), the AGASA *triplet* plus 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 ...

# Which are *best* candidate sources?



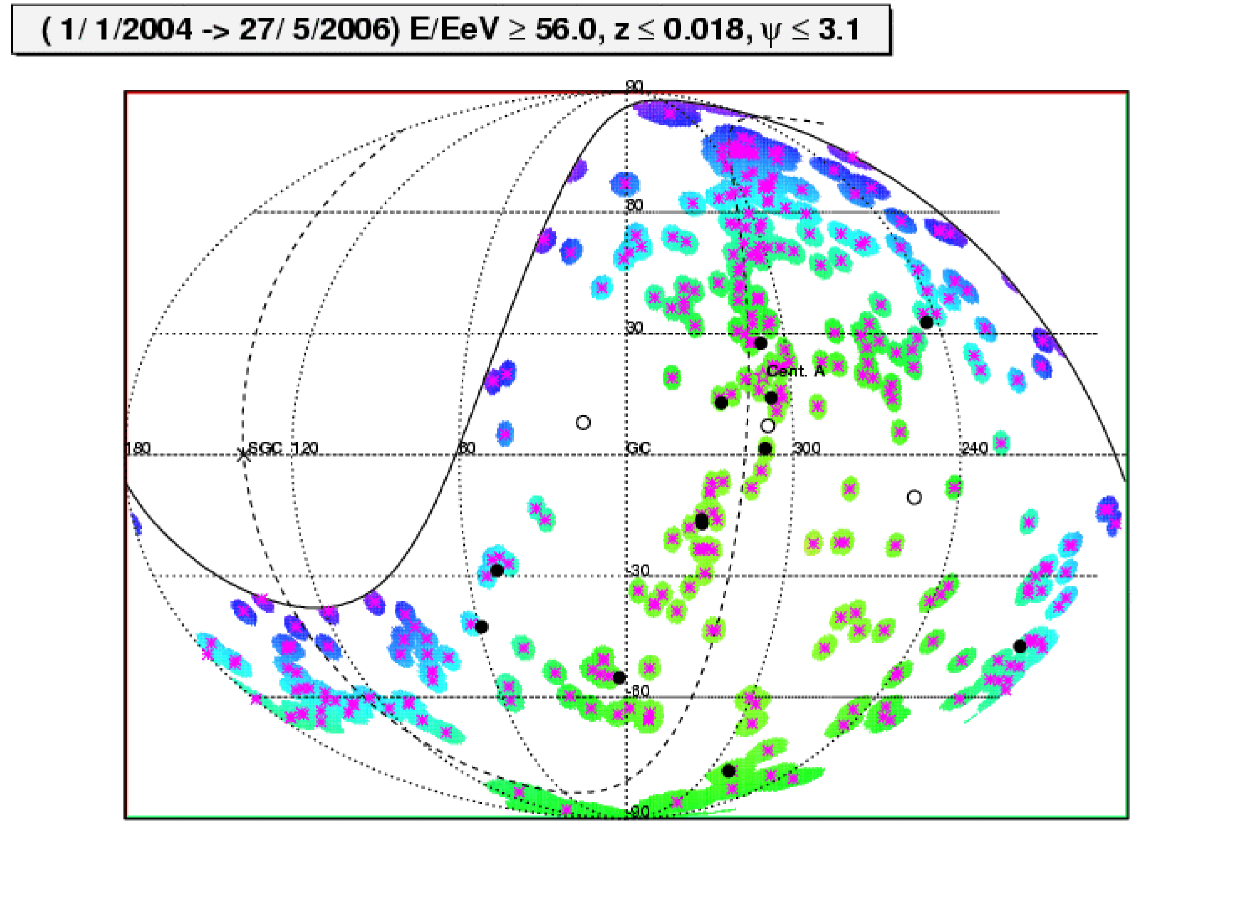
- Popular astrophysical sources for UHECRs include active galactic nuclei (AGNs) and gamma ray bursts (GRBs) ... **but no one knows: that is the Auger goal!**
- AGNs are super-massive black holes emitting jets of relativistic particles along the accretion disk rotation axis.
- Catalogs of AGNs provide a starting point ...
- So far the most significant correlations are with the $12^{th}$ Véron Cetty catalog
- **Centarus-A ($z = 0.0018$), shown above, is one of the nearby AGNs**

# *One* Auger CR:AGN correlation search




- **IF** the sources are faint ($\leq 1$ CR/source) ... then best to look for *correlations* with *candidate* sources; see Astropart.Phys. 27 (2007) 134 [astro-ph/0609655]
- **One** such search looked for correlations between Auger events (from Jan. 1, 2004 to May 27, 2004) and AGNs in the 12$^{th}$ edition of the Véron catalog.
- The search scanned over: AGN maximum redshift ($z \leq 0.05$), event energies ($E \geq 20$EeV) and AGN:CR correlation angles ($1.1^\circ \leq$ 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 = $3.1^\circ$, 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 $3.1^\circ$ 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 $|b| \lesssim 15^\circ$

# 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) | $S_{38} \geq 244.5$ VEM ($E \geq 56$ EeV) |
| | Angular Distance Selection | $d \leq 3.1$ degrees |
| | AGN Redshift Selection | $z \leq 0.018$ ($D \leq 75$ 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.

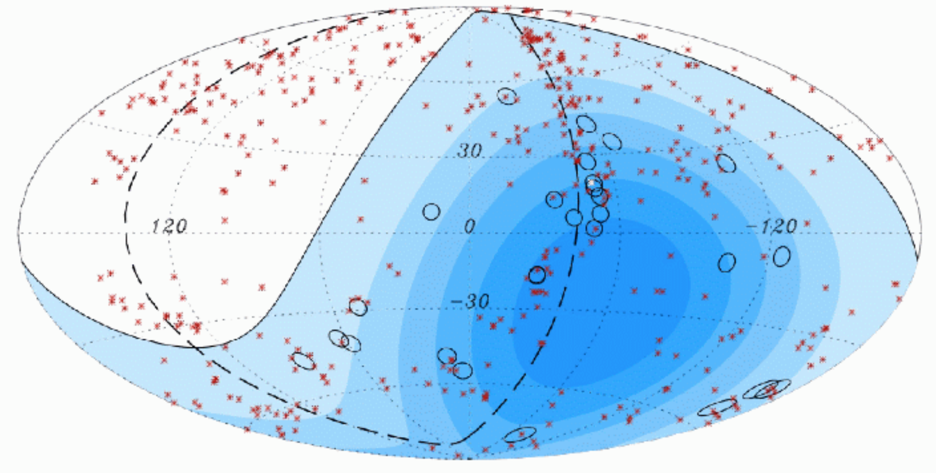
- Our scan to find the minimum probability for chance AGN:CR correlation is likely to emphasize fluctuations ... so do not take $P \approx 10^{-6}$ seriously!
- Instead, accumulate more (independent data) and measure the AGN:CR correlation *signal* **now** with: **clearly defined selections on event 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 (percent) | Power(%) ($P = 57\%$) | Power(%) ($P = 80\%$) |
|---|---|---|---|---|
| 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* $\sim 3.15$ 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: $\leq 1\%$ 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.

# 20+ months into the *Running* Prescription




- Depending on how you define *pass*, the *Running* Prescription passed in May (6/8) or in July (8/11) of 2007; the plot in *Science* includes events through Aug 31, 2007.
- *At a minimum, the Véron catalog: AGN maximum redshift and correlation angle, defines a limited area (effectively 21%) of the sky.* **Thus the Véron catalog AGN:CR correlation signal is evidence for a non-isotropic flux of CRs that is enhanced near known extra-galactic objects.**
- At $\sim 1$ event/month $> 56$ EeV, there are now more data. What do the new data tell us? Unofficially: the combined data may favor a CR:AGN correlation at a larger angle (than 3.1$^\circ$) and with more nearby AGNs (than 75Mpc). And the Virgo cluster, near the edge of our acceptance, still lacks events $> 56$ EeV.

# Alternate *Running* Prescription with Limited Error

- Brian Connolly (Segev BenZvi and Stefan Westerhoff) provided an alternative procedure ... that is of general interest! A generic version is now available as arXiv:0711.3937

- Philosophy: *All relevant information needed to infer parameters from an experiment is contained in the* **observed** *data.* **This is not true of the Auger Running prescription (or of many** *one shot* **trials).**

- Motivation: Recall that the motivation for a running (*vs* fixed length) prescription is to be able to be as responsive as possible to data as they are collected!

- History: The technique comes from an “assembly line” defect analysis studied by Alexander Wald (1947). The relevant issue was how long to run a factory to ensure say $< 40\%$ of the cars were defective ... before shutting it down to re-tool the assembly lines. This technique was important enough to be classified by the U.S. government during W.W.II!

# Connolly/Wald *Running* Prescription (I)

The University of New Mexico

Definitions, and values, for the case of our AGN:CR correlations:

- Background (random AGN:CR coincidence) probability: $p_0 = 0.21$
- Null hypothesis, $H_0$: corresponds to no signal, correlation probability $p_0$
- Model *Signal* probability: $p_1$ (to be tested against $p_0$); this may be one value or a range of values: *e.g.* $p_1 > p_0$. For the (previous) *Running* prescription values: $p_1 = 0.57$ and $p_1 = 0.80$ were chosen.
- Model hypothesis, $H_1$: corresponds to a (model) signal, correlation probability $p_1$
- *Signal* (correlation probability in data): $p$
- Errors:
  - $H_0$ is true, but rejected by the test (*Type-I error*)
  - $H_0$ is false, but accepted by the test (*Type-II error*)
  - Limit probability of *Type-I* error: $\alpha = 0.01$
  - Limit probability of *Type-II* error: $\beta = 0.05$

# Connolly/Wald *Running* Prescription (II)

Sequential test of hypothesis $H_0$ *vs* $H_1$:

- Determine two positive constants: $A$ and $B$ (based on $\alpha$ and $\beta$ ... see below)
- After each new event calculate the probability ratio:

$$R = \frac{P(Data|H_1)}{P(Data|H_0)}$$

- If $R > A$ the running prescription is terminated with the rejection of $H_0$.
- If $R < B$ the running prescription is terminated with the acceptance of $H_0$.
- If $B < R < A$ the running prescription continues ... *i.e.* the result is inconclusive.
- Wald (1943) showed that: $A \geq \frac{1-\beta}{\alpha}$ and $B \leq \frac{\beta}{(1-\alpha)}$
- Furthermore Wald also showed that using "$=$" in the definitions for $A$ and $B$ provides protection against wrong decisions ... *i.e.* $\alpha$ and/or $\beta$ are not increased over the assigned values as long as they are $\lesssim 0.05$ ... **consistent with our choices**

# Connolly/Wald *Running* Prescription (III)

## Sequential test of Auger AGN:CR correlations:

- After each new event calculate the probability ratio:

$$R = \frac{p_1^k \cdot (1-p_1)^{n-k}}{p_0^k \cdot (1-p_0)^{n-k}}$$

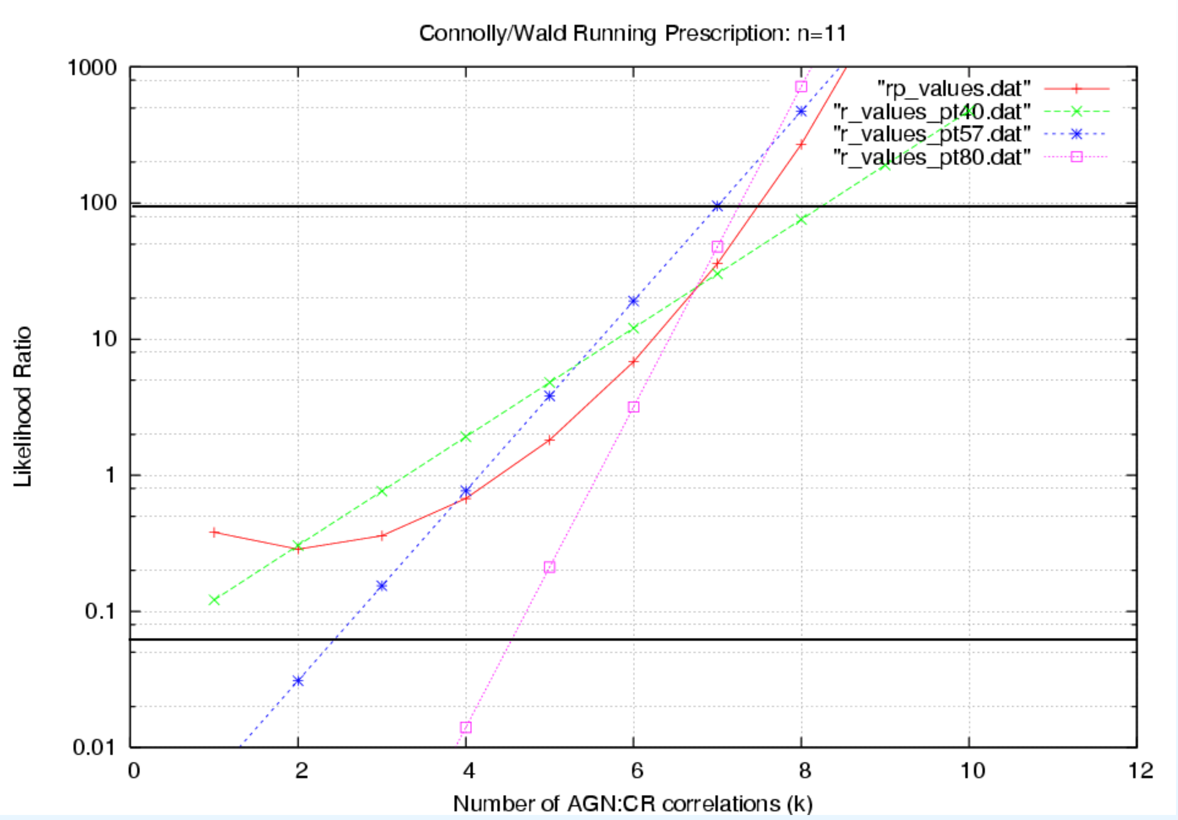
where $k$ events correlate out of $n$ total events and $p_0 = 0.21$. **But what value should we use for $p_1$?**

- One approach is to choose a model $p_1$ with $p_1 > p_0$ but less than, but possibly near, the correlation signal in the data, $p$; see arXiv:0711.3937.
- The new approach, proposed by Connolly, is to integrate over all possible values of $p_1$; then the ratio test becomes (for example):

$$R' = \frac{\int_0^1 p^k \cdot (1-p)^{n-k} dp}{p_0^k \cdot (1-p_0)^{n-k}} = \frac{B(k+1, n-k+1)}{p_0^k \cdot (1-p_0)^{n-k}}$$

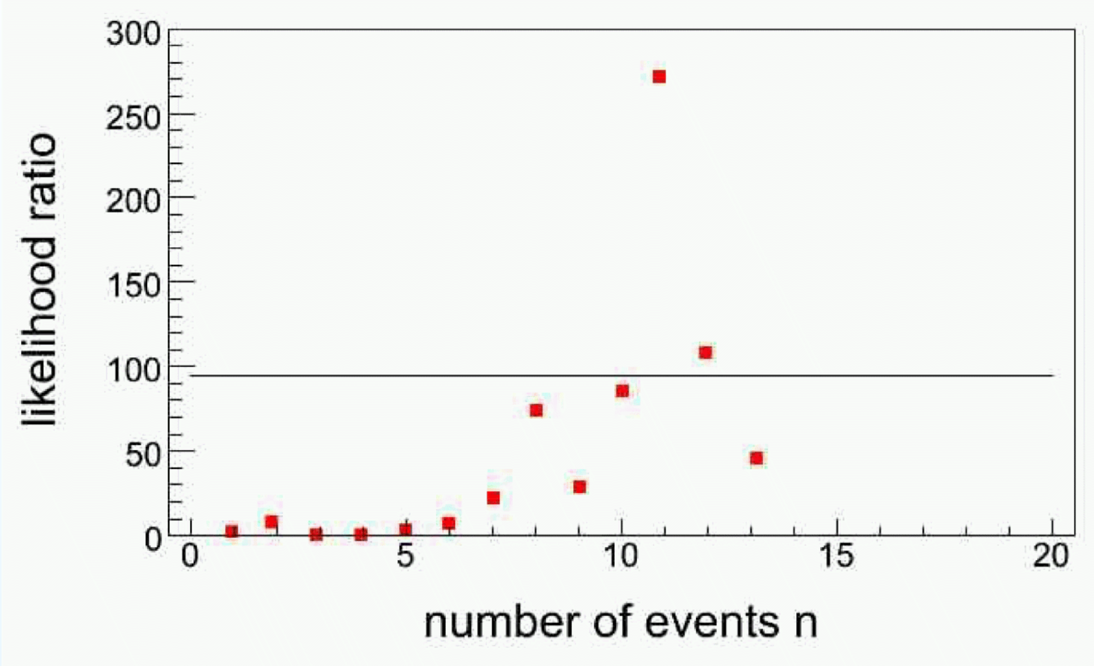
where B( ) is the beta function. This has now been validated in arXiv:0711.3937.

# Connolly/Wald *Running* Prescription (IV)




- With our choice of $\alpha = 0.01$ and $\beta = 0.05$ then $A = 95$ and $B = 0.0505$
- For a data sample ($n$) of 11 events, how sensitive are $R'$, and/or $R$, to the observed number of correlations ($k$)?
- *Plot*: shows $R'$ and $R$ (for three values of $p_1$: 0.4, 0.57, 0.8) *vs* $k$

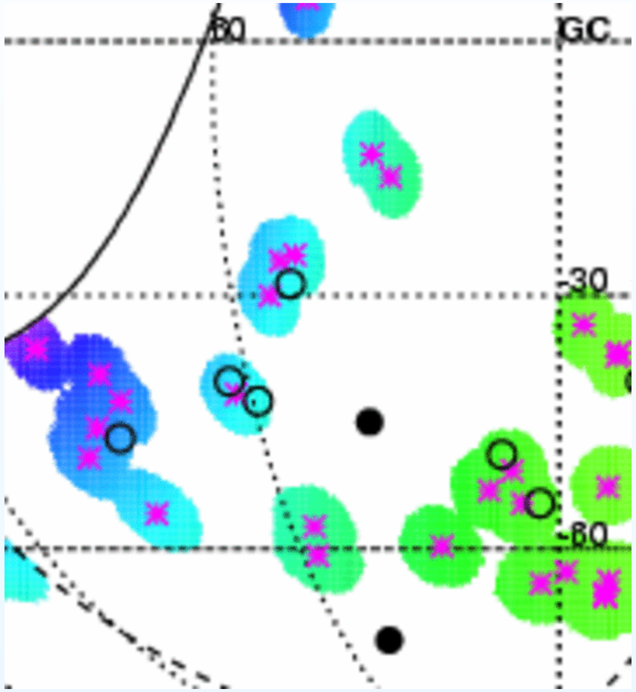
# Connolly/Wald *Running* Prescription (V)

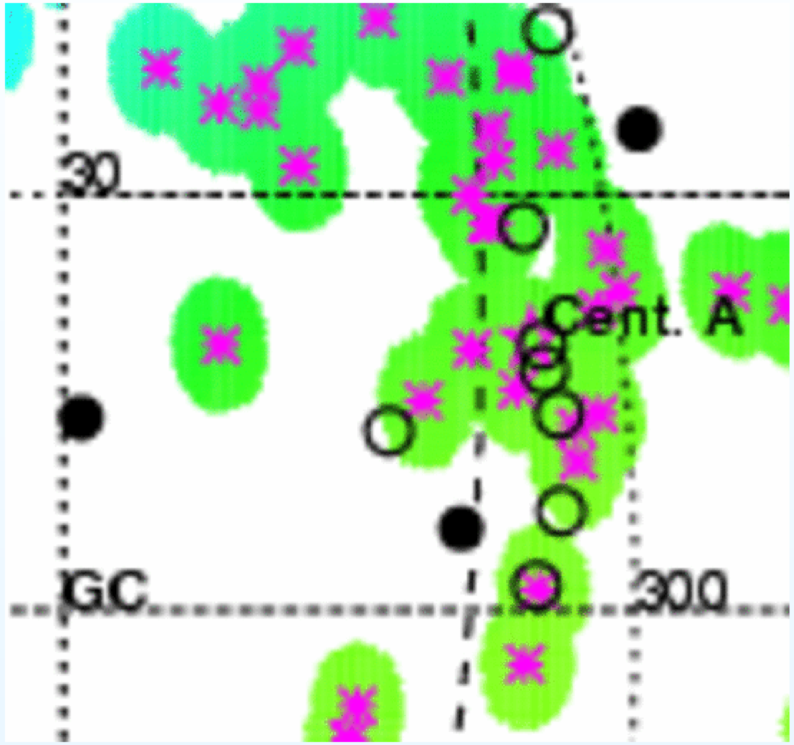



- With our choice of $\alpha = 0.01$ and $\beta = 0.05$ then $A = 95$ and $B = 0.0505$
- If $R' < 0.0505$ the null hypothesis is accepted ... *i.e. this is* **evidence against a signal**
- If $0.0505 < R' < 95$ ... keep going *i.e. we simply do not know*!
- If $R' > 95$ the null hypothesis is rejected ... *i.e. this is* **evidence for a signal** ...

  This occurred when $k = 8$ correlations were observed in $n = 11$ total events

# **Next steps to** *unraveling the source physics*

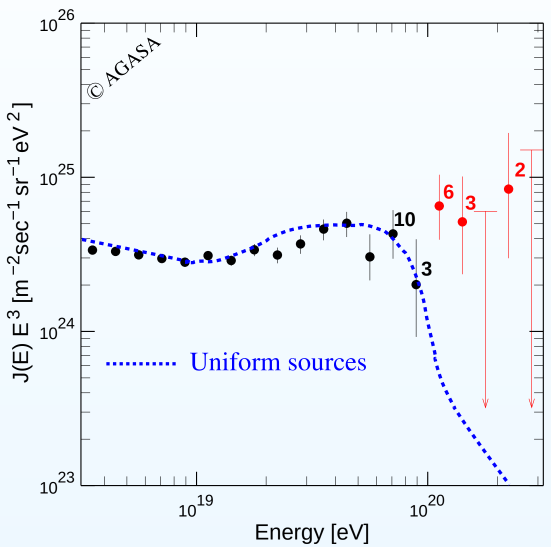


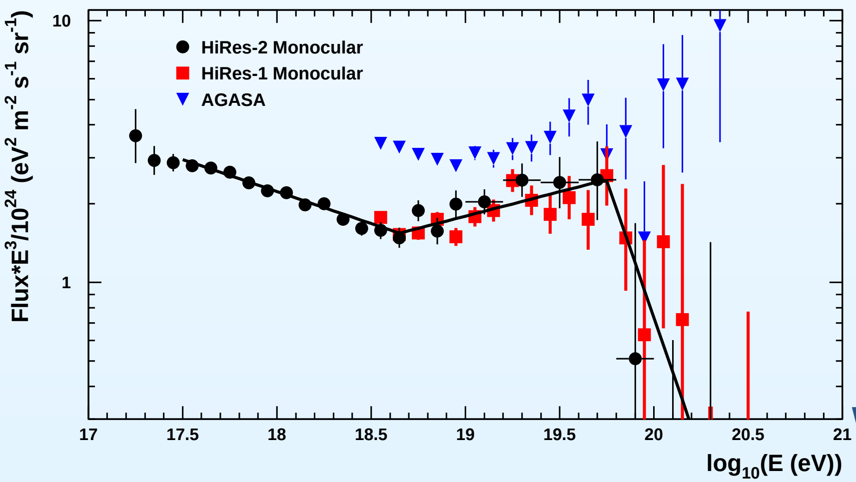




Possible next steps to understanding the physics of the sources of the UHECRs:

- We need to move from *evidence for* to *observation of* AGN:CR correlations
- We need to see *many more than one* CR from a given source ... and we need this for several sources. [**Note: Based on our first 32 events (above 56 EeV), we observe (arguably)** *one* **example with** $> 1$ **CR near an isolated AGN (***Left plot***)**]
- **Centaurus A** (*Right plot*) has several correlating CRs ... but many possible sources.

# Second question: **What evidence for a GZK-cutoff?**




**If the highest energy cosmic rays are non-isotropic, this is strong circumstantial evidence for a GZK cutoff!**

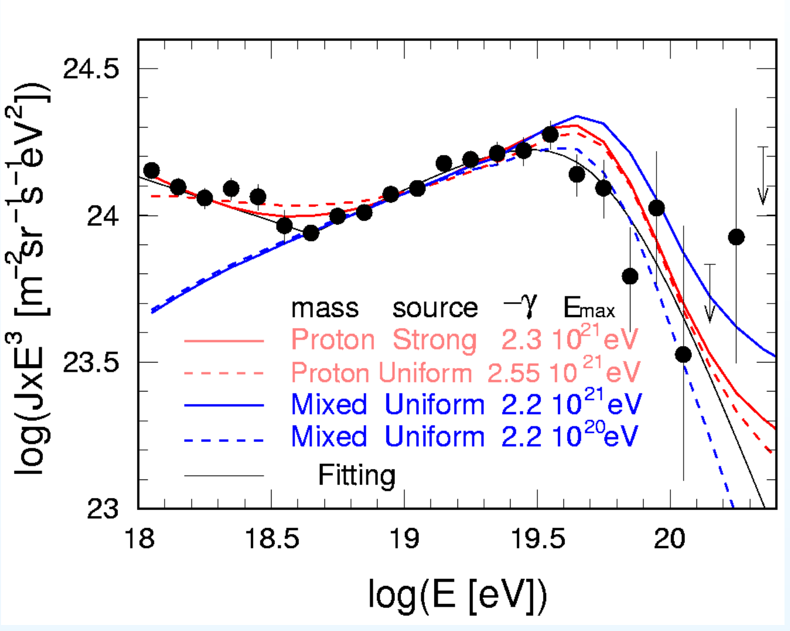
(top) AGASA spectrum

(bottom) HiRes spectrum Phys. Lett. **B619** 271 (2005) and [astro-ph/0703099]:

- The ankle shows up clearly at $4.5 \times 10^{18}$ eV ($\log_{10} E = 18.65$).
- The spectrum steepens again at $5.6 \times 10^{19}$ eV ($\log_{10} E = 19.75$).
- The fall-off of the HiRes spectrum above $10^{19.8}$ eV is evidence for the GZK cutoff.

**What does Auger observe? And does Auger see a** ***cutoff in the UHECR spectrum?***

# Our Approach: **Measuring Flux Suppression**




**(Left plot) The Auger Flux** $\times E^3$ (ICRC'07). The suppression is "obvious" but quantification should be done carefully.

Our *eyes* like the binned-$E^3$ flux plot but their *statistical estimators* have some draw backs.

J. (Doug) Hague has provided two *statistical estimators* that are of general interest!

See: arXiv:0710.3600 and astro-ph/0610865

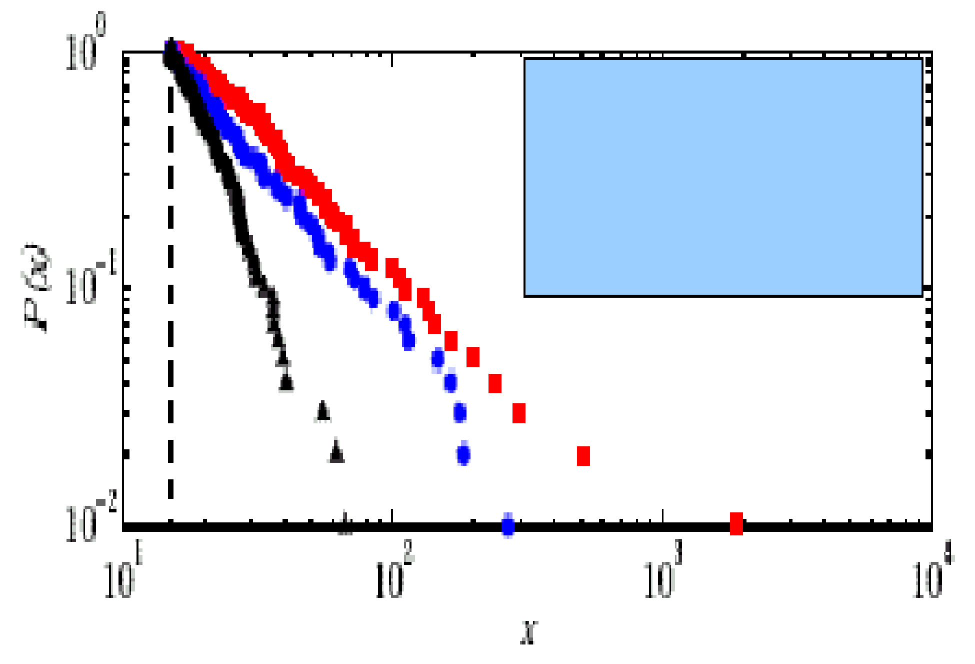
## Our analysis uses the following because:

- Un-binned estimators are less correlated, more precise and more accurate.
- The Tail-Power (TP) statistic (which is identically zero for a pure power-law) can reject **non-**pure power-laws. It is (nearly) independent of the measured spectral index $\gamma$ and can discriminate tail suppression from tail enhancement.
- A Likelihood Ratio Test can measure the characteristic cutoff energy with weak dependence on $\gamma$.

# Hague *Flux Suppression:* A simple example

**(Right plot)** Monte-Carlo events drawn from three toy distributions *adapted from Clauset et al. (arXiv:0706.1062v1)*

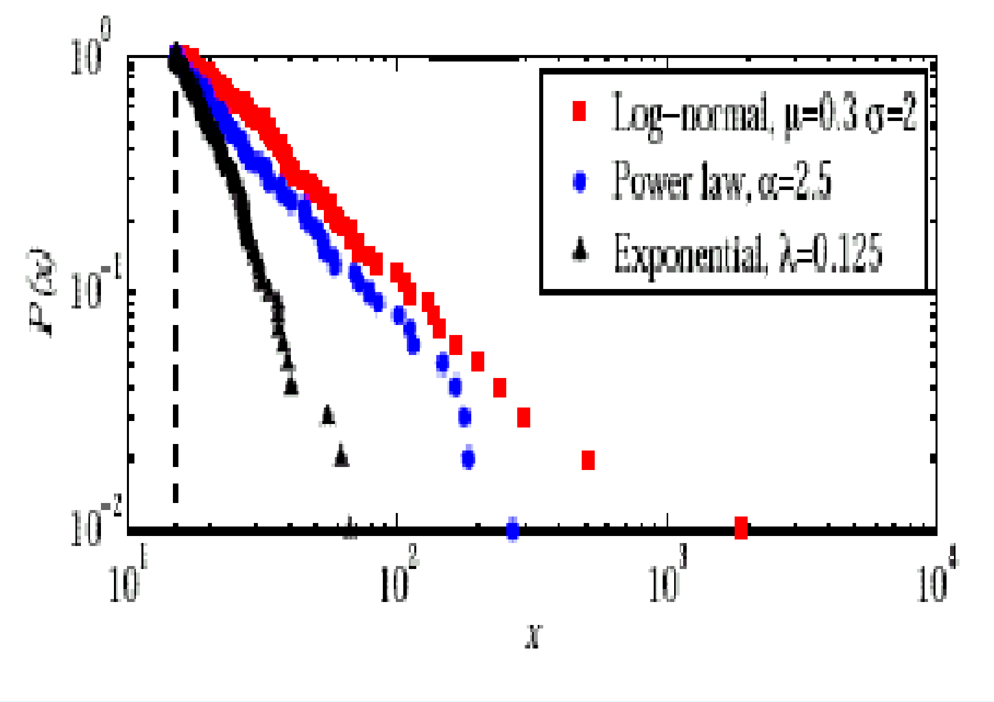
A power-law is a line on a log-log plot.




Which is the power-law?

# Hague *Flux Suppression:* A simple example

**(Right plot)** Monte-Carlo events drawn from three toy distributions *adapted from Clauset et al. (arXiv:0706.1062v1)*




A power-law is a line on a log-log plot.

Which is the power-law?
A line is an okay fi t to all of these distributions!

Today's issue: to quantify the goodness of a power-law fi t

# Hague *Flux Suppression:* Un-Binned Estimators

- Binned methods can be used but a heavy-tail (*e.g.* power-law) distribution with binning is not favored by statistics community:
  - The binning produces known biases and large errors.
- Un-binned is easy, accurate and precise.
- We study three models "$f$" with parameters "$\theta = \{\theta_0, \theta_1, \ldots\}$":
  - The *pure* power-law: $\theta = \{E_{min}, \gamma\}$
  - and two models with tail *suppression*:
    1. the double power-law: $\theta = \{E_{min}, \gamma, E_b, \delta\}$
    2. a Fermi-like power-law: $\theta = \{E_{min}, \gamma, E_{1/2}, w_c\}$
- Parameters are determined by maximizing the log-likelihood:

$$\mathcal{L}(\theta) = \sum_{i=1}^{N} \ln f(E_i|\theta)$$

- Systematic (CR event) energy uncertainties are incorporated by shifting all event energies and then re-maximize the likelihood.
- Statistical (CR event) energy errors and acceptance information can be taken into account by the appropriate convolution.

# Hague *Flux Suppression:* Fitted Models

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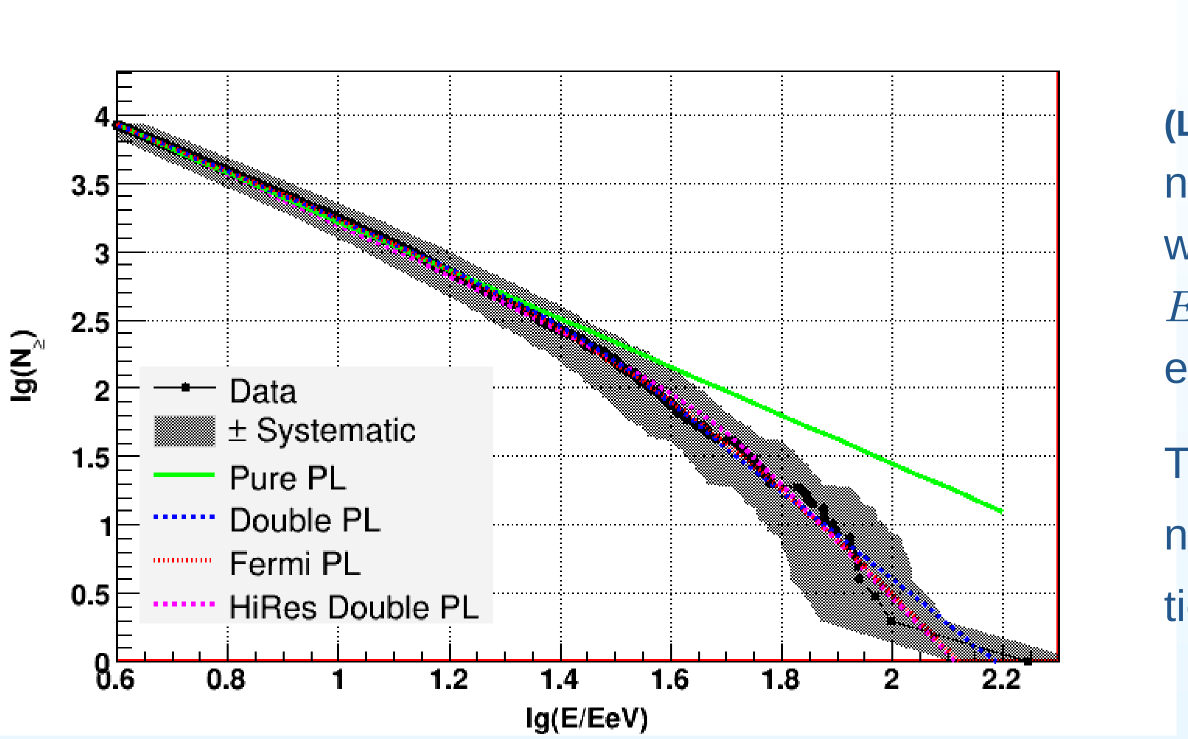



**(Left plot)** A log-log plot of the number of (Auger) events with energy greater than $E_{min}$ *vs* event minimum energy ($E_{min}$).

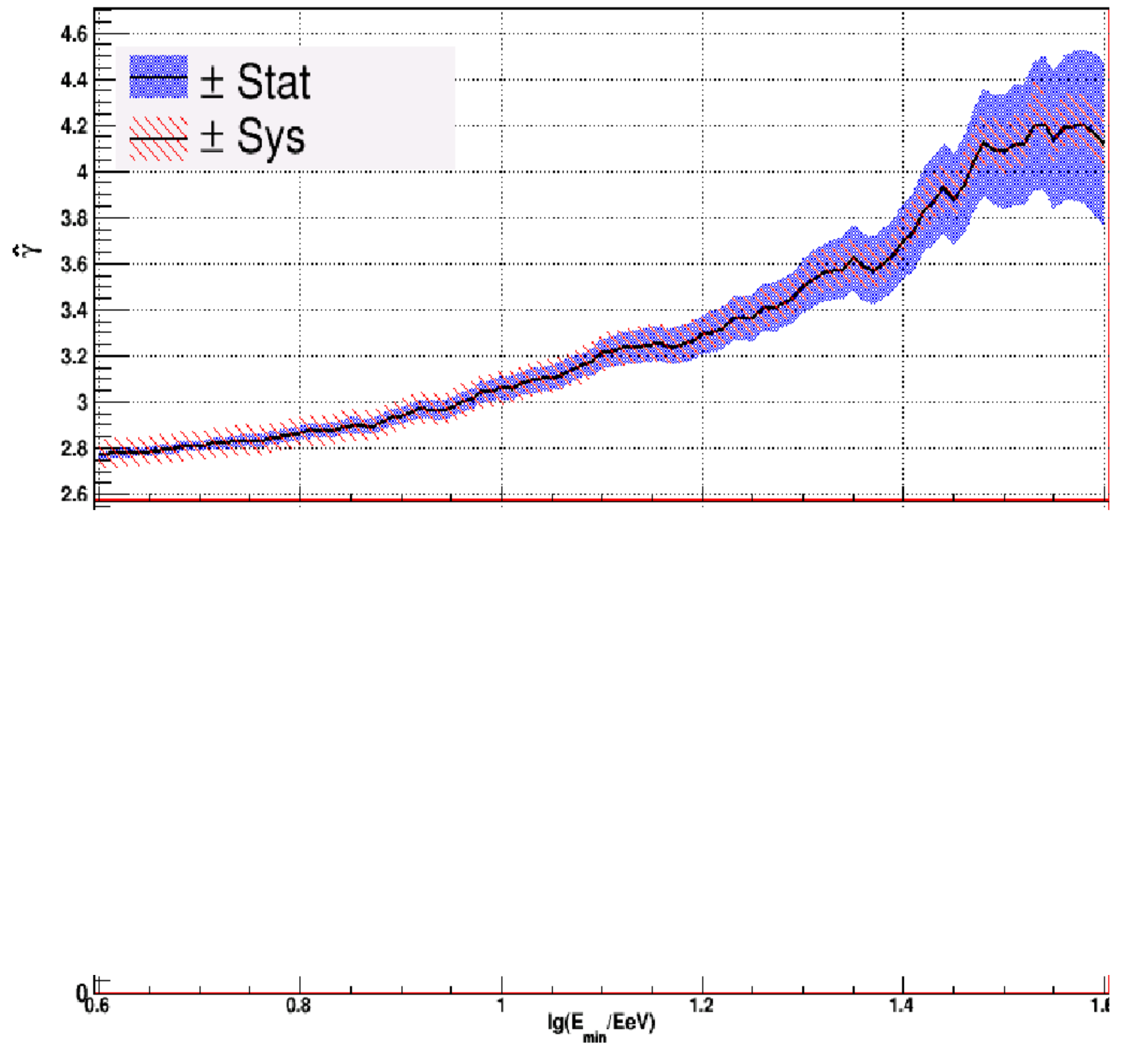
The vertical axis is "one minus the (cumulative distribution function) CDF."

We plot:

- each event energy (with its systematic errors shown in gray)
- the three models; pure power-law, double power-law and Fermi-like power-law
- the reported HiRes double power-law (normalized to the Auger flux).

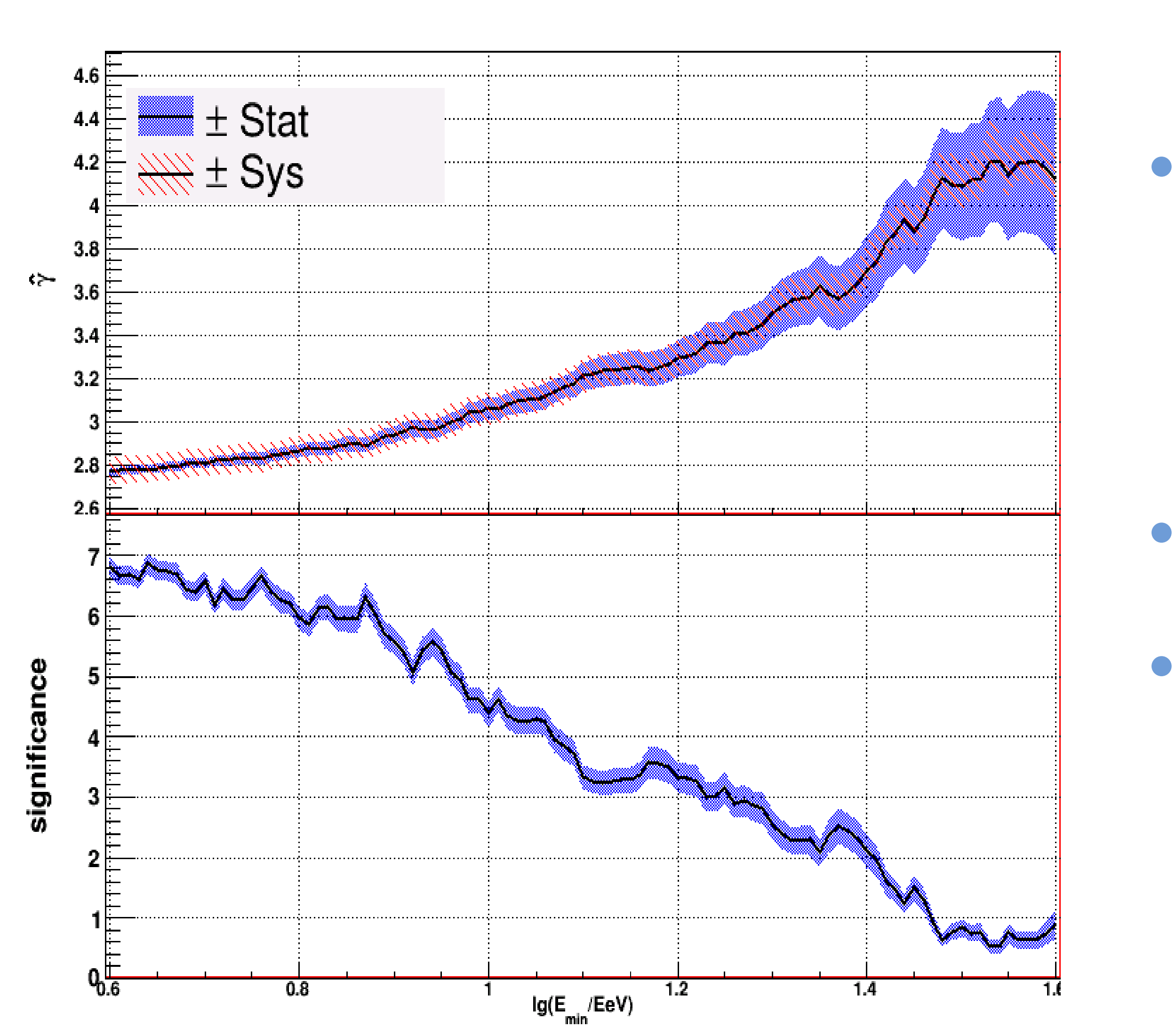
**Next:** we must now quantify the flux suppression.

# Hague *Flux Suppression:* The Hill plot




- For each $E_{min}$, we determine the un-binned estimate of the pure power-law *spectral index* $\gamma$ (by maximizing the likelihood: **Top plot**).
- The systematic (energy) errors dominate for low $E_{min}$ but statistical errors dominate at large $E_{min}$.
- The index **increases** as the energy **increases.**
- There is suppression (*i.e.* the slope increases)! But how do we determine the significance?

# **Hague** *Flux Suppression:* **The TP-statistic**




- The TP-statistic can discriminate between flux suppression (increasing slope with energy) and enhancement (decreasing slope with energy).
- It is (nearly) *independent* of $\gamma$.
- We can directly measure the *significance* in standard deviations of the flux suppression (**Bottom plot**)

## **Hague** *Flux Suppression:* **Likelihood Ratio**

- We can use the likelihoods to discriminate models. The Likelihood Ratio is:

$$\mathcal{R} = \frac{\mathcal{L}(\text{data} \mid \text{suppressed model hyp.})}{\mathcal{L}(\text{data} \mid \text{pure power law hyp.})}$$

- This test directly compares the best-fi t suppressed model to the best fi t pure power-law.
- Since $\mathcal{R}^2 \sim \chi_1^2$ we can estimate the (asymptotic) *Probability of False Acceptance*:

  $P_{\text{FA}} \equiv$ probability of accepting the *suppressed* model given that the data are drawn from a *pure* power-law.

  **If** the data are drawn from a power-law **then** the chance that we would falsely accept either suppressed model is $P_{FA}$.

# Hague *Flux Suppression:* Summary

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| Model | Name | Value | Stat | $^{+Sys}_{-Sys}$ | $p$-value | Conclusion |
|---|---|---|---|---|---|---|
| Power-Law | $\gamma$ | 2.78 | 0.02 | $^{-0.06}_{0.08}$ | $\geq 6\sigma$ | Rejected |
| Double PL | $\gamma$ | 2.68 | 0.02 | $^{-0.05}_{0.08}$ | $\lg P_{FA} = -4.12$ | Favored |
| | $E_b$ | 35 | 2 | $^{7}_{7}$ | | |
| | $\delta$ | 4.22 | 0.22 | $^{-0.10}_{0.17}$ | | |
| Fermi PL | $\gamma$ | 2.63 | 0.02 | $^{-0.05}_{0.08}$ | $\lg P_{FA} = -4.29$ | Favored |
| | $E_{1/2}$ | 56 | $^{5}_{4}$ | $^{13}_{13}$ | | |
| | $w_c$ | 0.16 | $^{-0.03}_{0.02}$ | $^{-0.005}_{0.008}$ | | |

- The *preliminary result* is that we **can**:
  1. Reject the pure power-law model at a confidence level greater than six sigma.
  2. Favor either suppressed model with confidence better than $1/10,000$.
  3. Verify that the data are consistent with $E_{GZK} = 56 \pm 5$(stat)$\pm 15$(sys) EeV ... agrees with HiRes and with Berezinsky protons!
- This analysis alone **cannot** verify the GZK-cutoff, for that we need additional information on: CR composition (*e.g. all protons?*) and CR astrophysics (*e.g. sources uniformly distributed? constant source injection spectrum?*).

# Third question: **What about the CR *composition*?**

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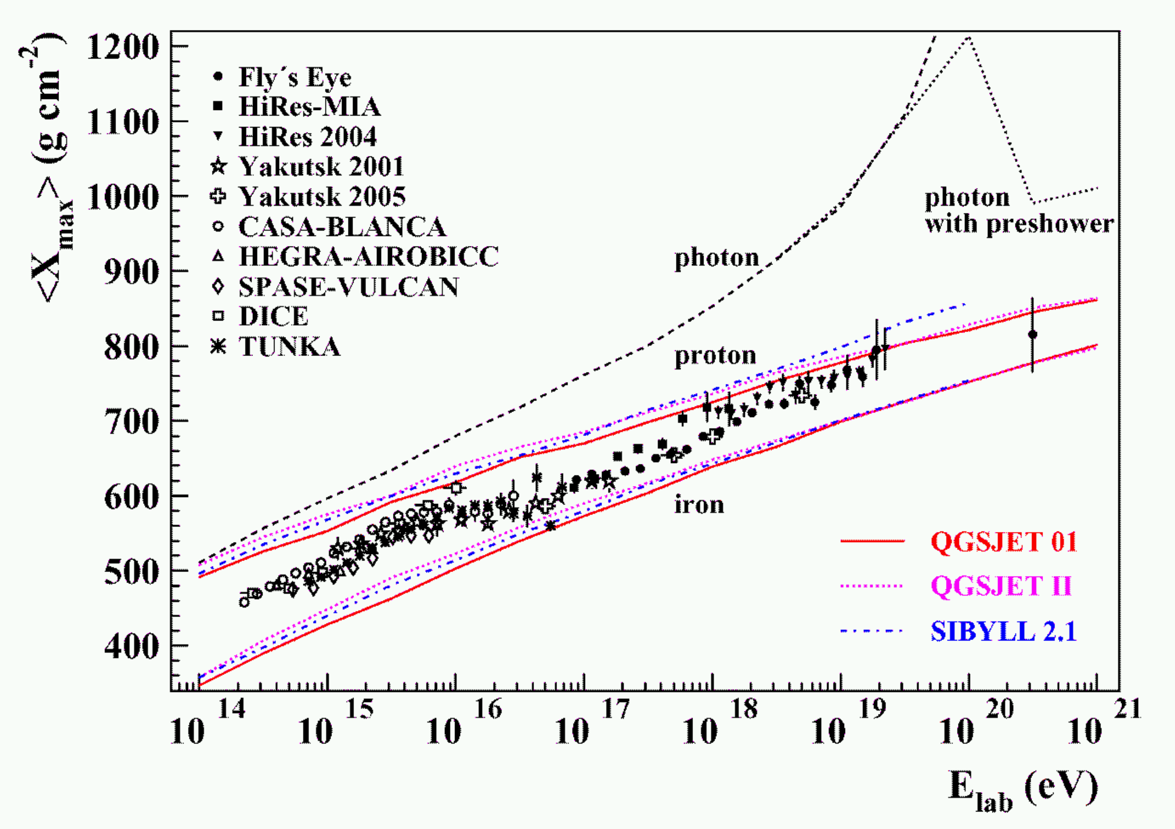



- Plot of the average depth of shower maximum $< X_{max} >$ *vs* shower energy $E$.
- Model predictions are given for CR primary: photons, protons and iron nuclei.
- While photons are **most** distinctive, very high energy photons interact with the Earth's magnetic field (denoted by *pre-shower*) making them more *proton-like*.

# Auger's most direct *composition* measurements

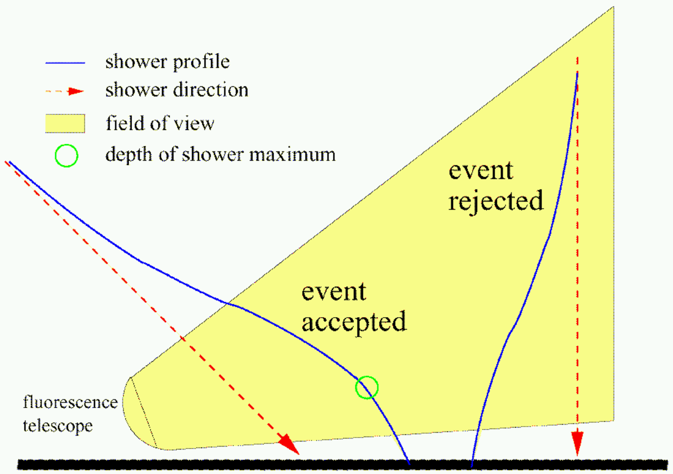
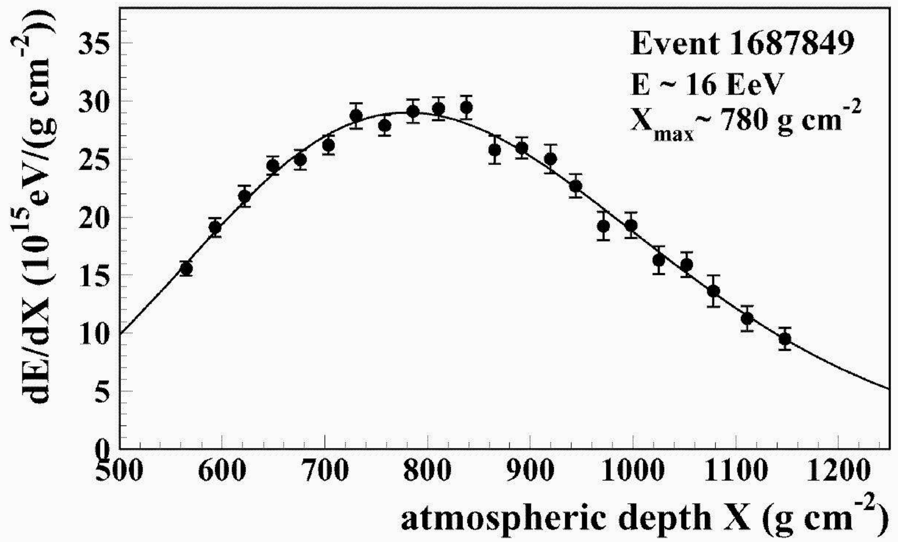
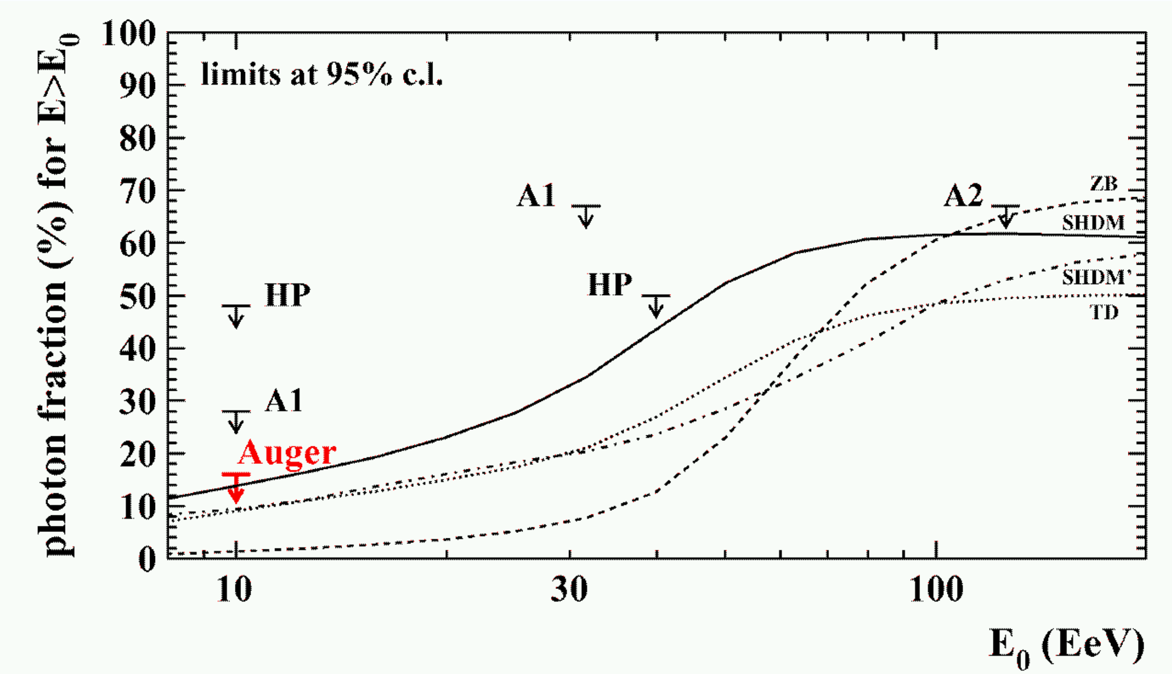



Fig. 4. Photon showers and the selection requirement of observing $X_{\max}$. For near-vertical photon showers, $X_{\max}$ is below the field of view of the telescopes; possibly the showers even reach ground before being fully developed as in the example shown. Such photon showers were rejected by the quality cuts. The situation changes when regarding more inclined photon events. The slant atmospheric depth that corresponds to the lower edge of the field of view increases with zenith. $X_{\max}$ can then be reached within the field of view, and the photon showers pass the $X_{\max}$ quality cut. Requiring a minimum zenith angle in the analysis, the reconstruction bias for photons is strongly reduced.



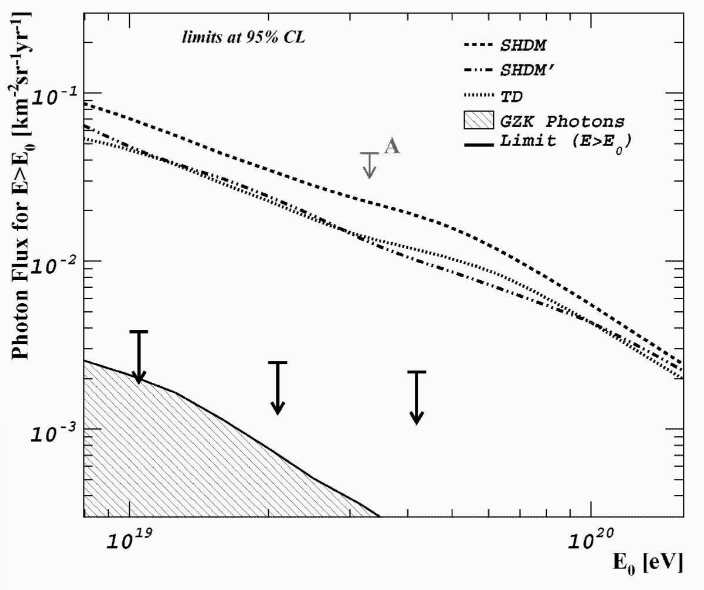

- The fluorescence detectors image the shower development and thus directly measure $X_{max}$, with typical reconstruction uncertainties $\sim 20$ g cm$^{-2}$.
- However, Auger hybrid events have potential biases:
  - At the lowest energies, shower $X_{max}$ may not enter the telescope field of view
  - At the highest energies, shower $X_{max}$ may extend past the telescope field of view; atmospheric depth for vertical showers is $\sim 860$ g cm$^{-2}$.

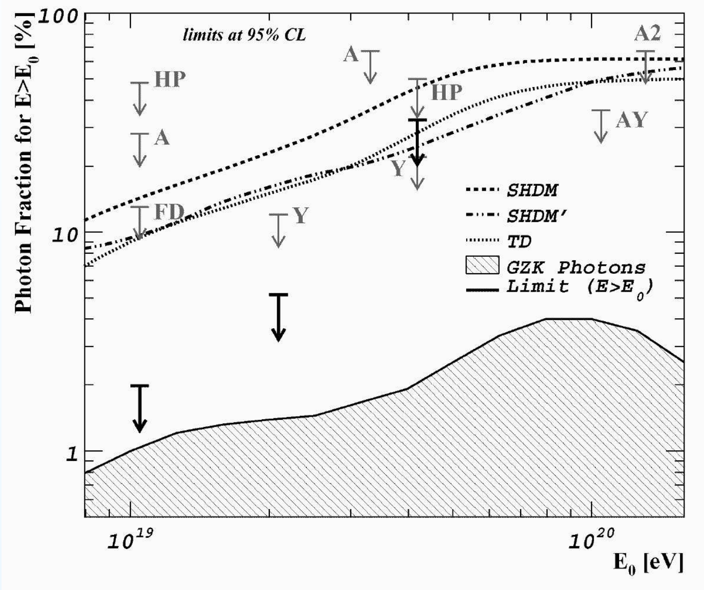
# Upper-limit on CR $\gamma$-Fraction (FD)




- Plot of 95% c.l. upper limits on the (integrated) CR $\gamma$-fraction above the energy plotted
- Plot also shows previous upper limits from: Haverah Park (HP), and AGASA (A)
- Representative theory predictions include: Z-burst (ZB), Top-down (TD) and Super Heavy Dark Matter particles (SHDM)
- **Auger** FD-hybrid result, Astropart. Phys. **27** 155 (2007), close to restricting models ...

# Upper-limit on CR $\gamma$-Fraction (SD)




- 95% c.l. upper limits on the (integrated) CR $\gamma$-flux (**Left**) and $\gamma$-fraction (**Right**) above the energy plotted
- Plot(s) include upper limits from AGASA (A), Haverah Park (HP) and Yakutsk (Y)
- Representative theory predictions include: Top-down (TD), Super Heavy Dark Matter particles (SHDM), and GZK-photons
- **Auger** SD result, arXiv:0712.1147, are now restricting models ... and approaching observing GZK-photons!
- One caveat is that the SD results rely on Monte Carlo shower simulations ...

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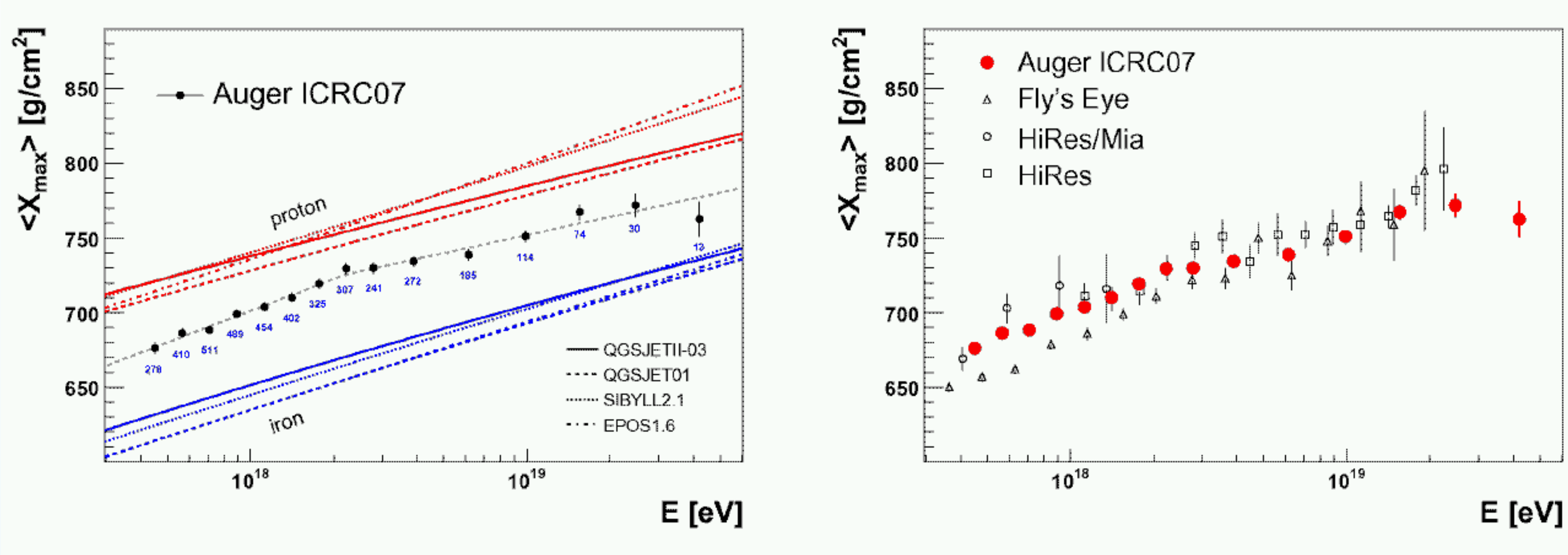
# What about the CR *composition*?




- CR composition is measured using the correlation between depth of shower maximum ($X_{max}$) and primary particle type (proton, iron)
- $X_{max}$ is directly measured by the Auger fluorescence detectors ... but as noted earlier: there are potential biases at lowest and highest energies
- Many in Auger argue that the AGN:CR correlations can only be consistent with proton primaries ... **but Auger composition measurements are inconsistent!**
- And why should we believe the shower simulations ... which are extrapolated far above collider data! **This is *either* an opportunity or big problem!**

# Summary

- Auger is an interesting experience ...
- And doing science with a detector that is the size of Rhode Island **IS** a challenge ...
- The spectrum *cutoff* at $\sim 10^{20}$eV is now clear, with the observation of GZK-photons the *next* goal
- The reported AGN:CR correlation is interesting but this needs to be turned into science ...
- I have particularly enjoyed the new statistical ideas from very junior colleagues: Brian Connolly and Doug Hague!

# Additional/backup slides

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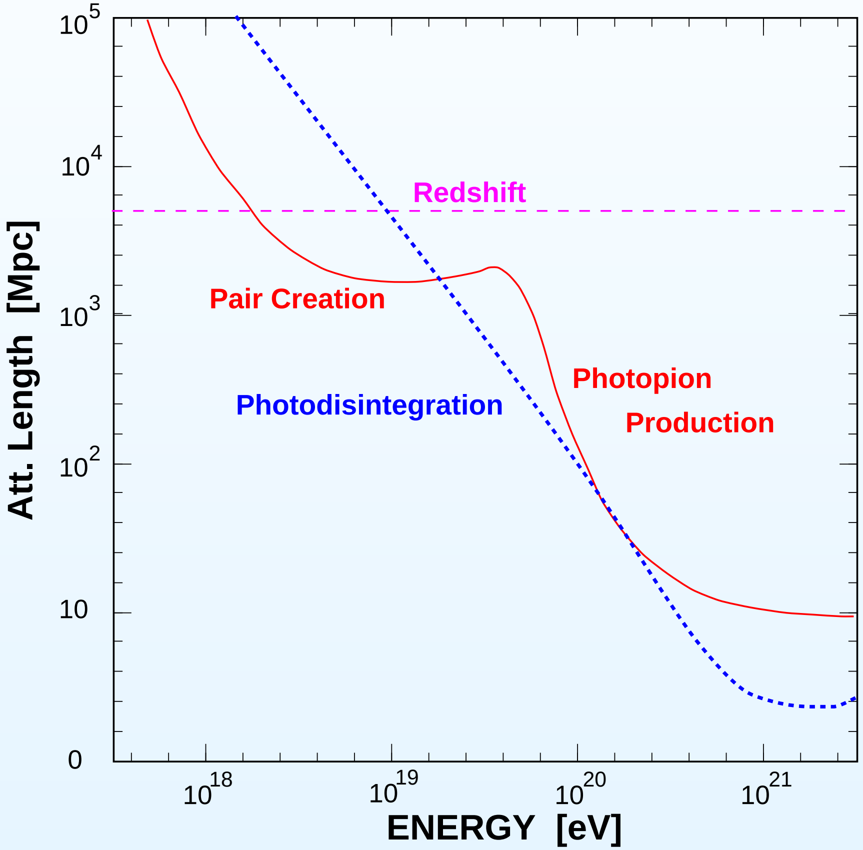
Additional slides

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

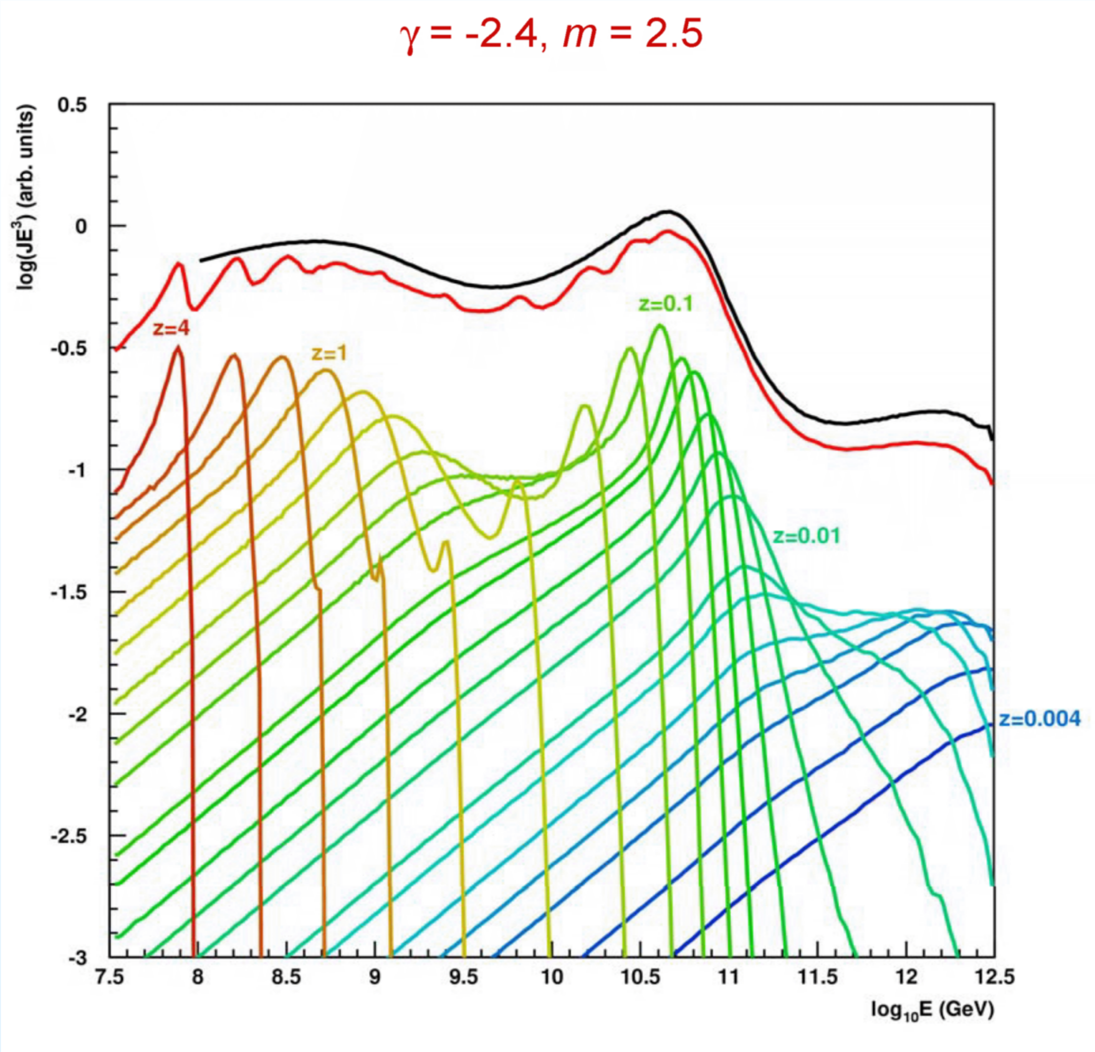



- Cosmic rays interact with the cosmic micro-wave background (CMB) radiation; after a distance, $d$:

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

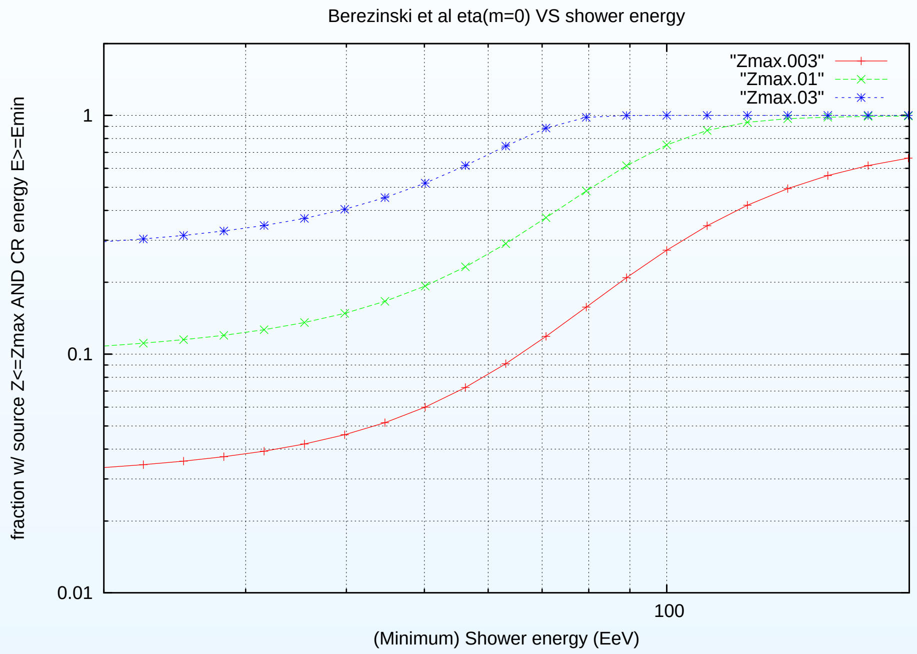
- Steep drop of $\Lambda_{atten}$ near $10^{20}$eV from the onset of $\pi$ photo-production: $\gamma_{CMB}\, p \rightarrow \pi\, X$.

# The *GZK-feature* is complex ...



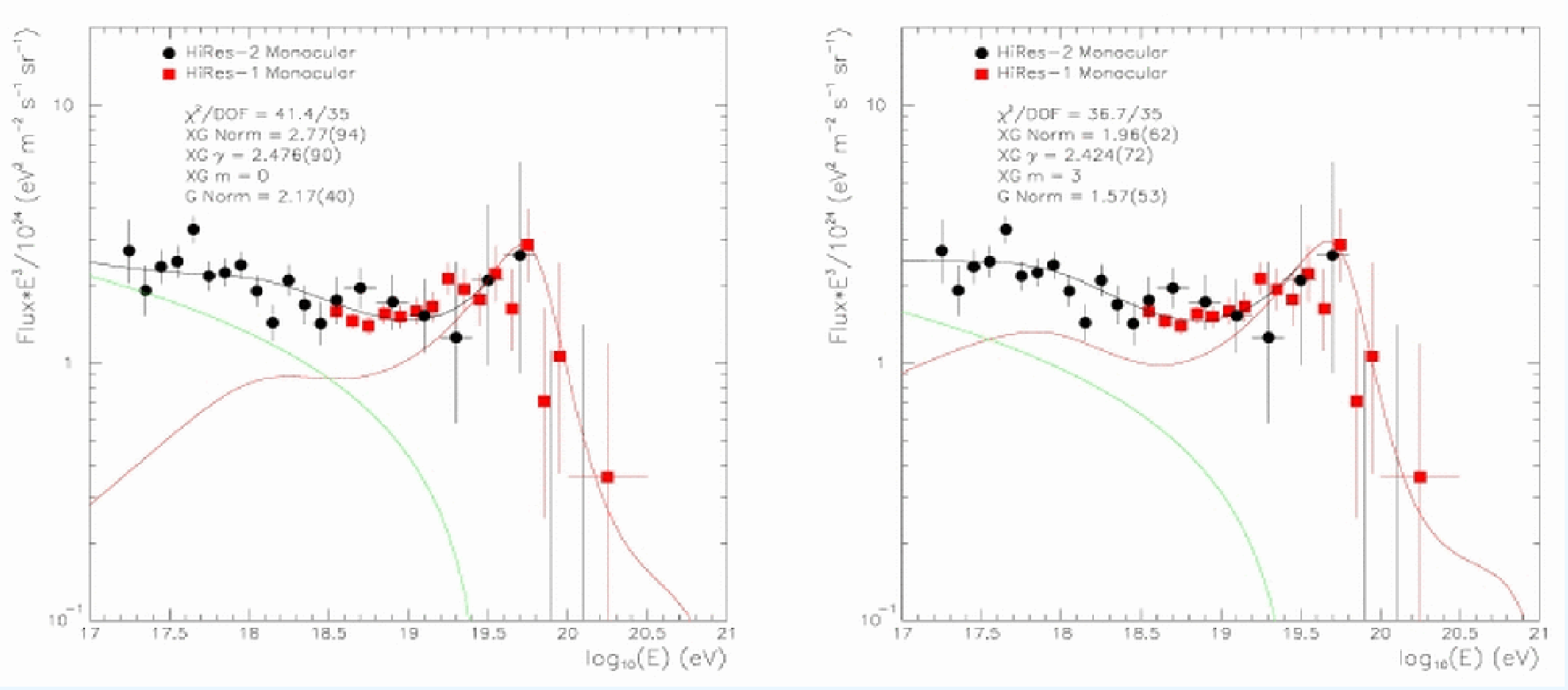

- Schematic showing how *cosmologically*-distant sources may build up the cosmic ray spectrum we measure today!
- Very distant sources, $z \gtrsim 0.5$ dominate at CR energies $< 10^{19}$eV.

# The GZK cutoff *limits* the possible source distance




- Figure shows predicted **fraction of cosmic ray events** *VS* **energy** (in overlapping redshift regions) **assuming proton primaries and GZK cutoff**
- *Note* **the higher** $E_{min}$**: the greater the fraction of nearby (***e.g.* $z_{max} \leq 0.01$**) sources** and these may appear bright as source **apparent brightness** $\propto z^{-2}$
- *However we need events to study*, **thus the steep,** $E^{-3}$**, spectrum argues for as low a value of** $E_{min}$ **as possible**

# Cosmic ray composition ... details (I)



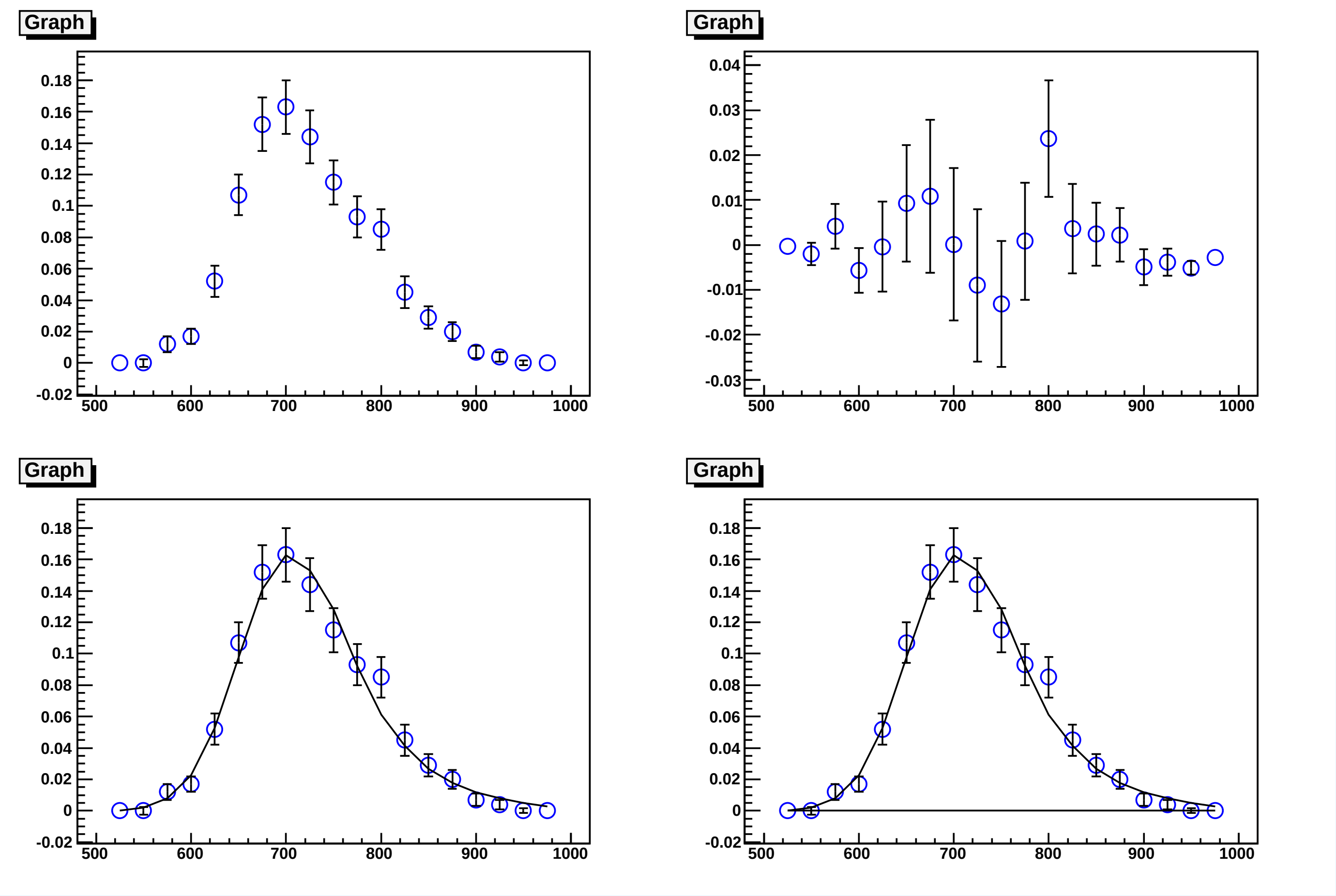

- GZK physics is not only at $10^{20}$eV!
- **The extra-galactic spectrum** *also* **extends to energies below the GZK cutoff**
- The division between *galactic* and *extra-galactic* contributions allows significant *wiggle room* for models!
- *Composition* **information would help ...**

# Cosmic ray composition ... details (II/a)

**Test analysis:** HiRes stereo $> 10^{18}$eV. Two *minima* ... one with **100%p : 0%Fe**!

Offset QGSjet p,Fe $X_{max}$ distributions **less deep** into the atmosphere

*i.e.* move QGSjet-p $< X_{max} >$ **toward** the data

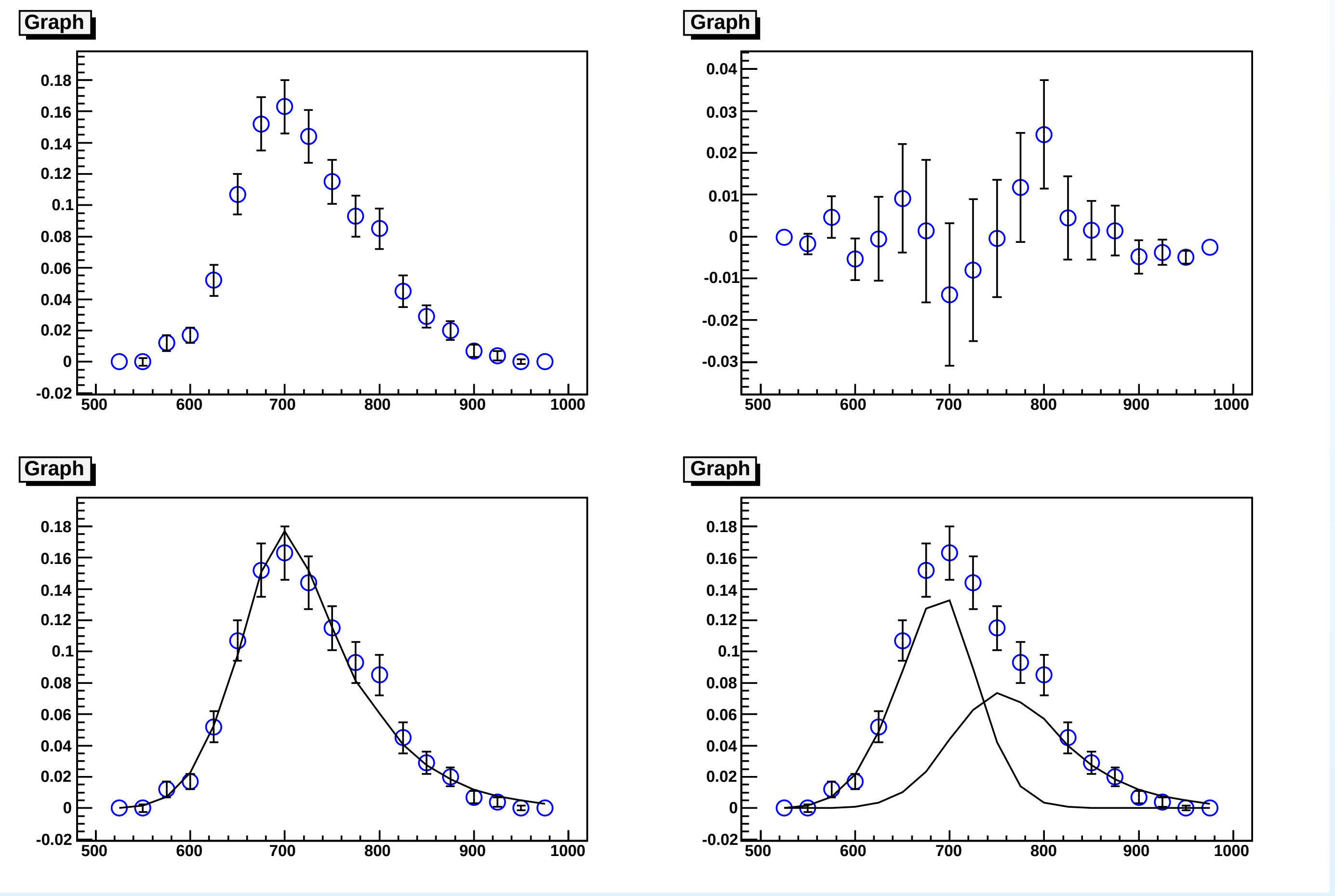


# Cosmic ray composition ... details (II/b)

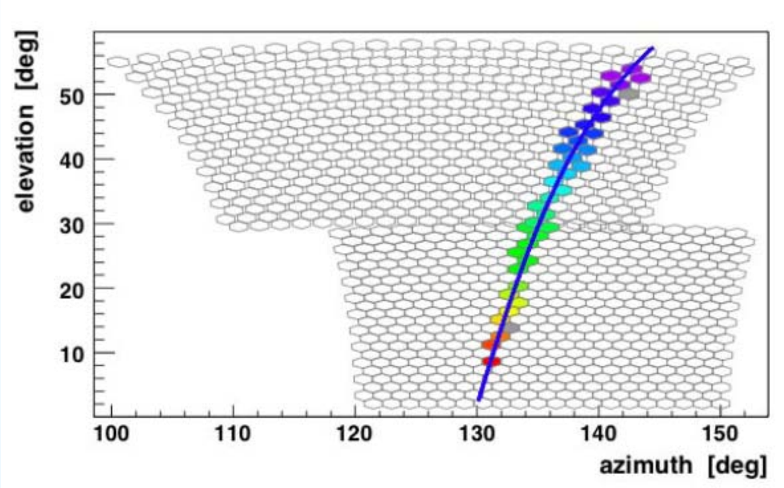
**Test analysis:** HiRes stereo $> 10^{18}$eV. Two *minima* ... one with **44%p : 56%Fe**!

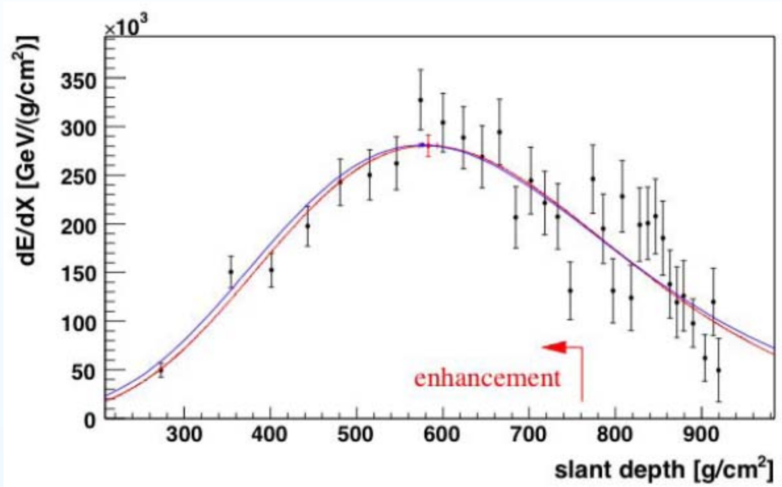
Offset QGSjet p,Fe $X_{max}$ distributions **deeper** into the atmosphere

*i.e.* move QGSjet-p $< X_{max} >$ **away from** the data



# Auger *HEAT* Enhancement




To extend Auger's high quality *hybrid*-events to lower energies <u>three</u> additional: **High Elevation Auger Telescope(s)** (HEAT) are currently under construction at the Coihueco FD site.

These telescopes **raise the FD viewing angle** because lower energy showers:

- can only be observed when they are close to the FDs ... **which then appear more overhead**
- reach shower maximum higher in the atmosphere ... **which is more overhead**