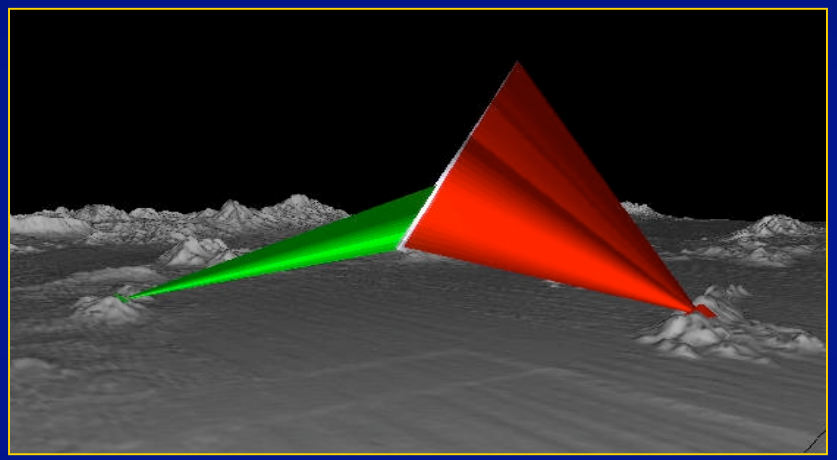
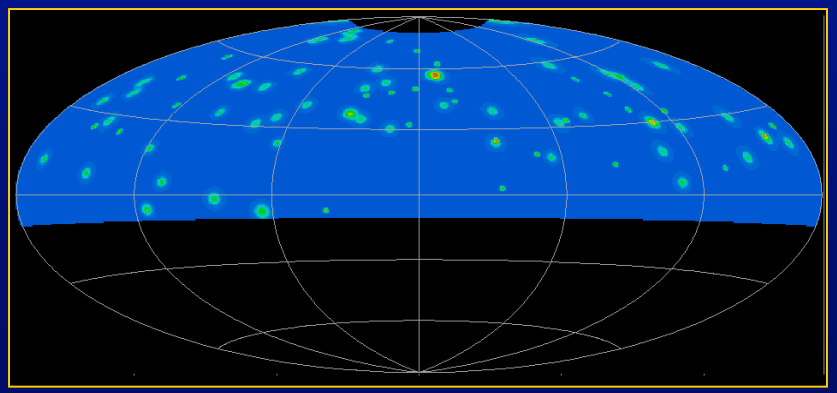
Recent Results for Small-Scale Anisotropy with HiRes Stereo Data





John Matthews

University of Utah

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TeV Particle Astrophysics

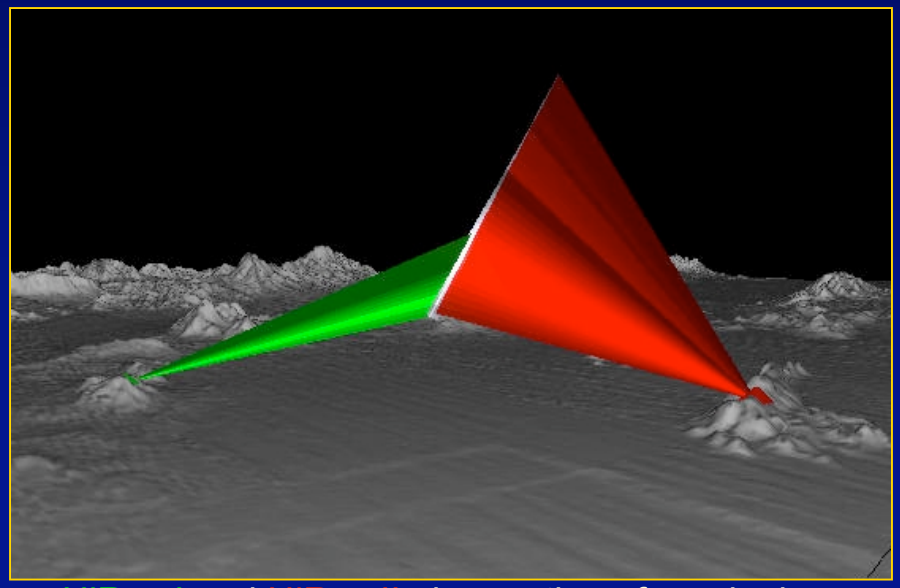
Fermilab: Batavia, IL

15 July 2005

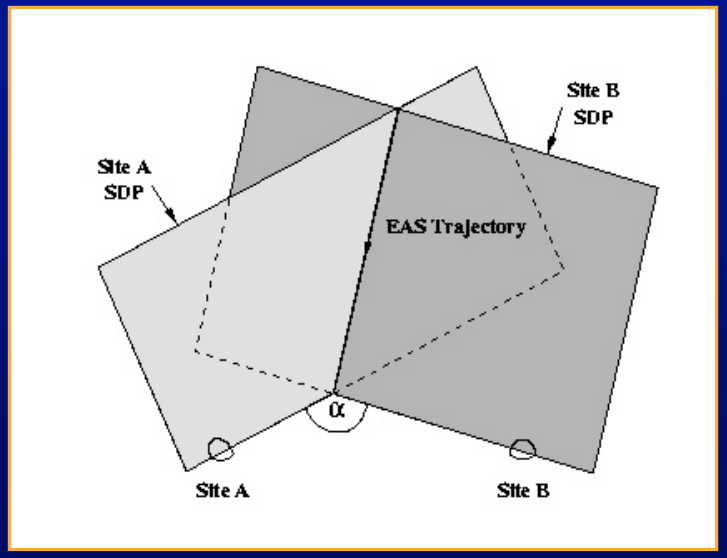
Outline

- Description of Detector and Stereo Data Set
- Angular Correlation - General Search for Excess Clustering
  - HiRes Stereo Events above 10^{18} eV
- Point Source Search using Maximum Likelihood Method
  - combined HiRes Stereo and AGASA Data Sets above 4×10^{19} eV
- Correlations with BL Lacertae Objects
  - Test previous claims (based on AGASA/Yakutsk) with HiRes data
  - Examine new claim of HiRes / BL Lac correlation
- Conclusion

HiRes Air-Fluorescence Detector



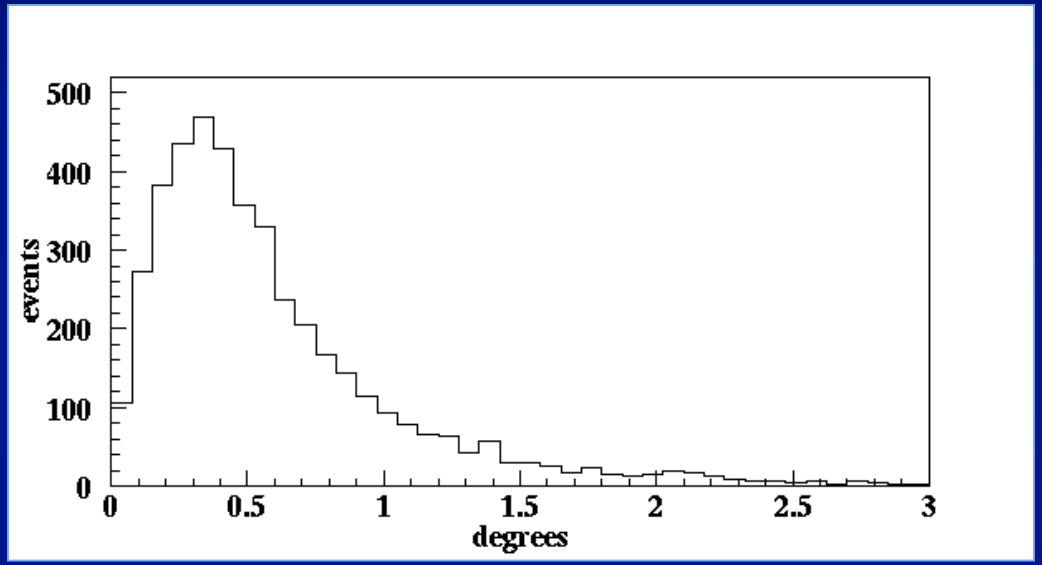
HiRes I and HiRes II observation of an air shower



- Cosmic ray induced air shower is viewed simultaneously with two sites.
- Each site determines a shower detector plane.
- Shower geometry is determined by a global χ^2-minimization using the pointing *and* timing information of all tubes.
- Dependence on atmospheric parameters is reduced.

Angular Resolution

- HiRes stereo observations are providing the *sharpest image* of the Northern sky at ultrahigh energies.
- In Monte Carlo simulations, 68% of events above 10^{18} eV are reconstructed within 0.6º of their true arrival direction.
- From star survey and lasers: systematic error is not larger than 0.2º, mainly caused by uncertainties in mirror pointing.



Distribution of opening angles between true and reconstructed arrival directions for HiRes Monte Carlo events.

HiRes Stereo Data Set

Quality Cuts:

- Quality cuts for event reconstruction are based on detailed MC studies aiming at minimal tails and maximal acceptance:
  - χ^2 /dof < 5 for geometry and energy fit.
  - Energy uncertainty < 20%
  - angular uncertainty < 2° in zenith and azimuth.
  - Zenith angle < 70°.

Weather Cuts:

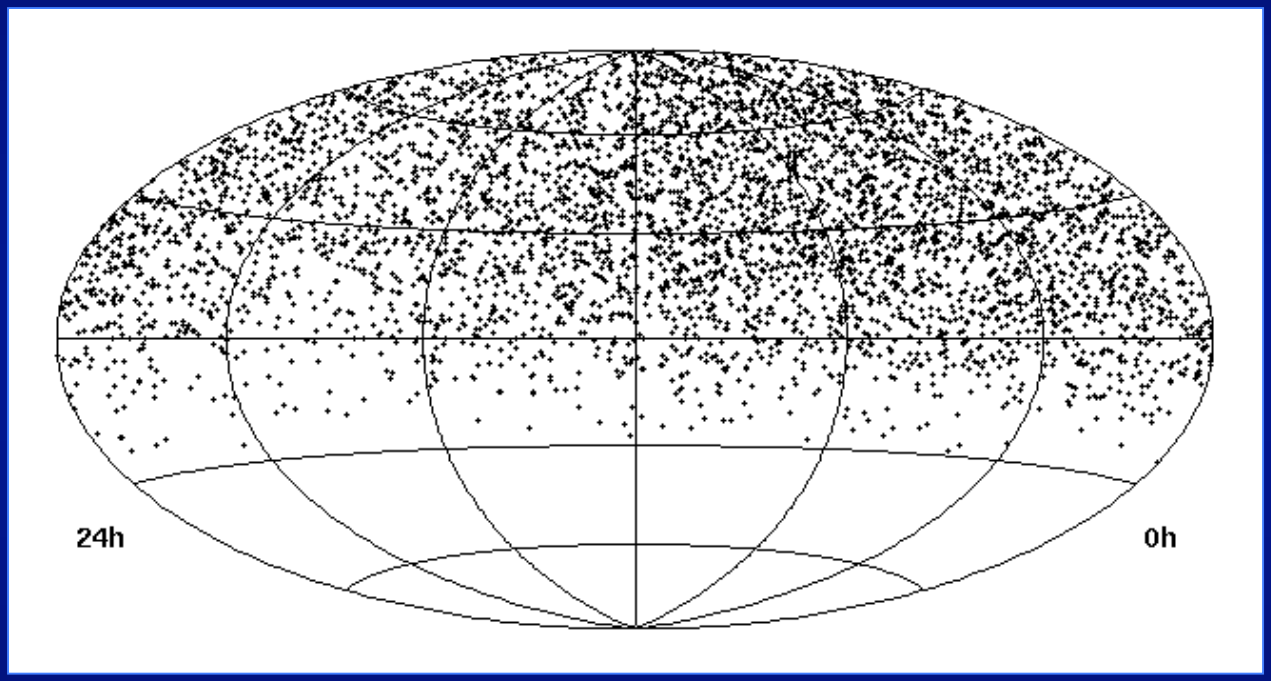
- No explicit weather cuts have been applied.
- As long as weather conditions are known, their impact on the reconstructed event geometry and energy is small for a wide range of aerosol contents.
- Analysis uses hourly atmospheric database built from the reconstruction of YAG laser shots.

HiRes Stereo Data Set

HiRes Stereo
Events
all Energies

Dec. 1999
through
Jan. 2004

4495 Events

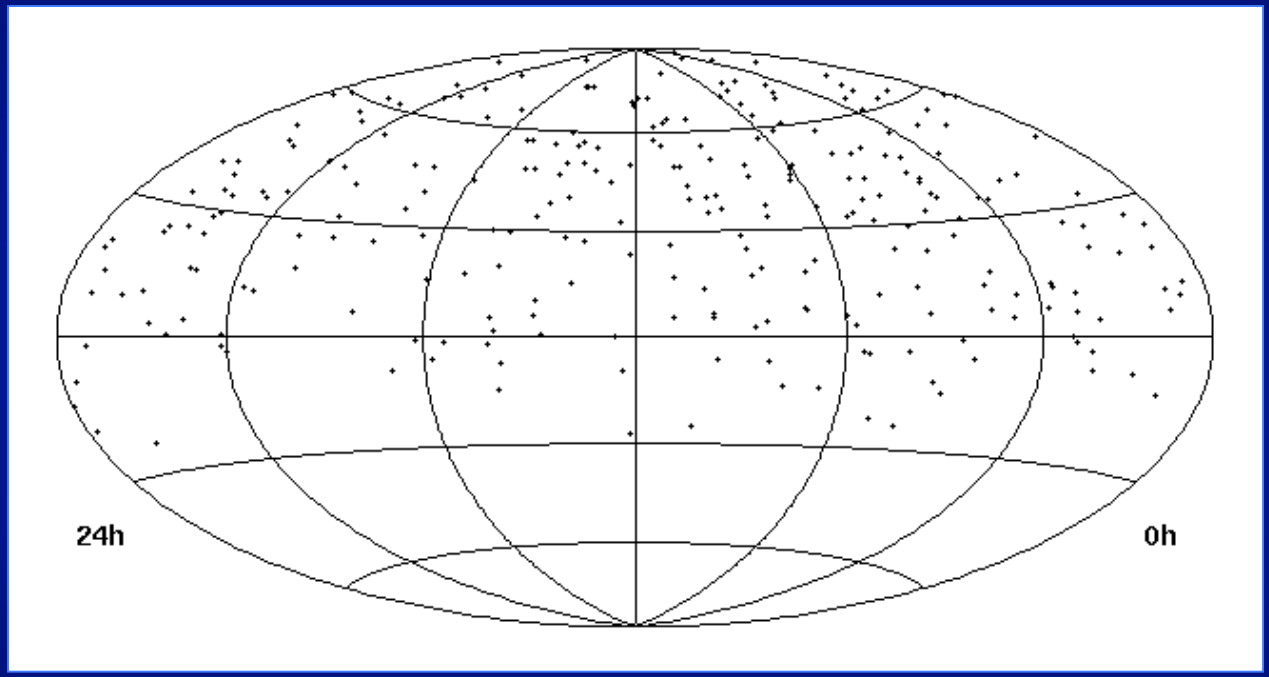


Equatorial Coordinates

HiRes Stereo Data Set ($>10^{19}$eV)

271 Events
above 10^{19} eV

Dec. 1999
through
Jan. 2004



Equatorial Coordinates

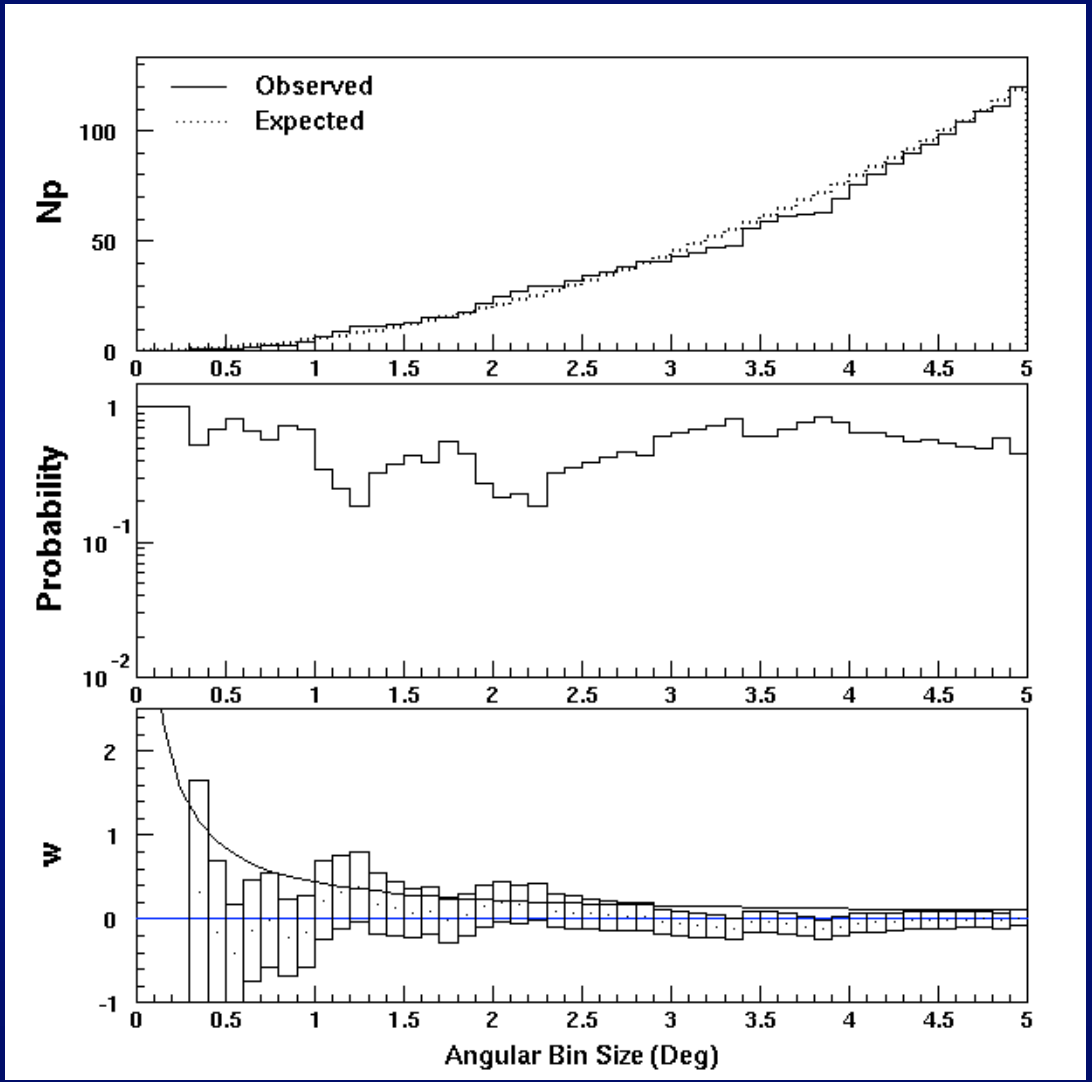
Autocorrelation Function

Angular Correlation:

- Count number of pairs N_p with separation < θ
- Use Monte Carlo with isotropic distribution to determine:
  - expected value for $\langle N_p \rangle$
  - probability of observing N_p
- $w = N_p / \langle N_p \rangle - 1$

HiRes ($E > 10^{19}$ eV) is consistent with isotropy at all small angular scales.

Abbasi et al., ApJ 610 (2004) L73

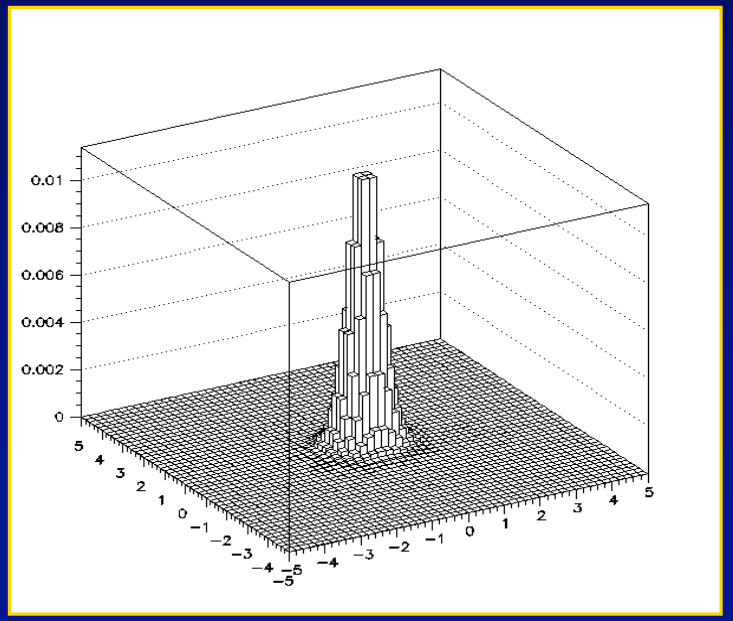


271 HiRes events above 10^{19} eV

Maximum Likelihood Point Source Search

Introduced here as a way to search for a single point source among events with different errors.

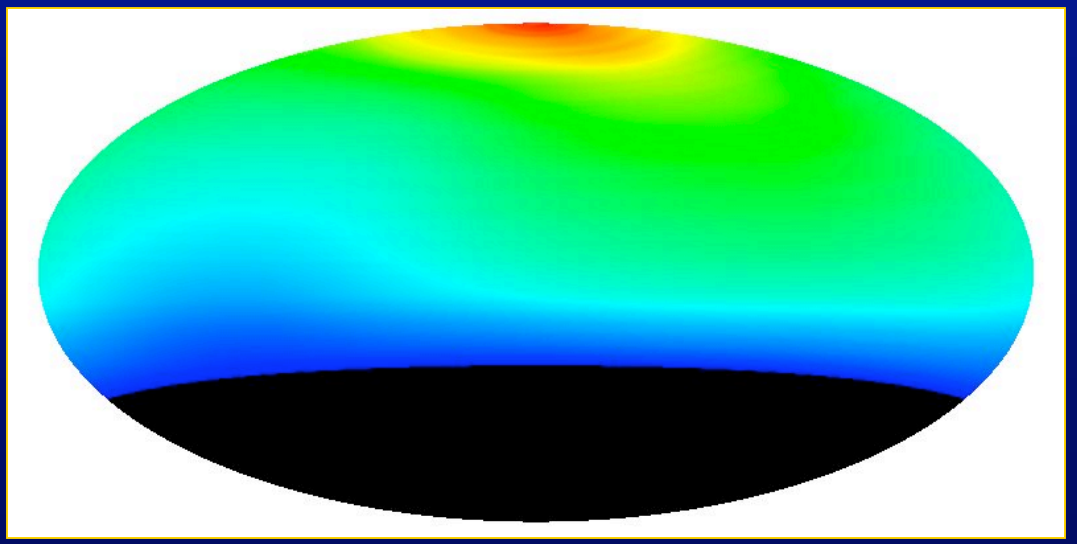
$Q_i(x_i, x_s)$ is the probability for an event observed at x_i to have a true arrival direction at x_s. Q_i depends on the angular resolution of the event.



$$Q_i(x_i, x_s)$$

$$R_i(x)$$

$R_i(x)$ is the probability distribution for the event to be observed anywhere in the sky. R_i depends on the detector acceptance and exposure.



Maximum Likelihood Point Source Search

The test hypothesis is that n_s events arrived from a source located at x_s, and the remaining N-n_s events are background.

Under this hypothesis, the probability associated with a given event is the weighted sum P_i of the source and background probabilities.

$$P_i(x, x_s) = \frac{n_s}{N} Q_i(x, x_s) + \frac{N - n_s}{N} R_i(x)$$

The product of P_i for all events gives the likelihood L for a particular choice of n_s. The best estimate for n_s is the value which maximizes L.

$$L(n_s, x_s) = \prod_{i=1}^{N} P_i(x_i, x_s, n_s)$$

In practice, we maximize ln(R), the log of the ratio of the likelihood of n_s relative to the likelihood of the null hypothesis: $n_s = 0$.

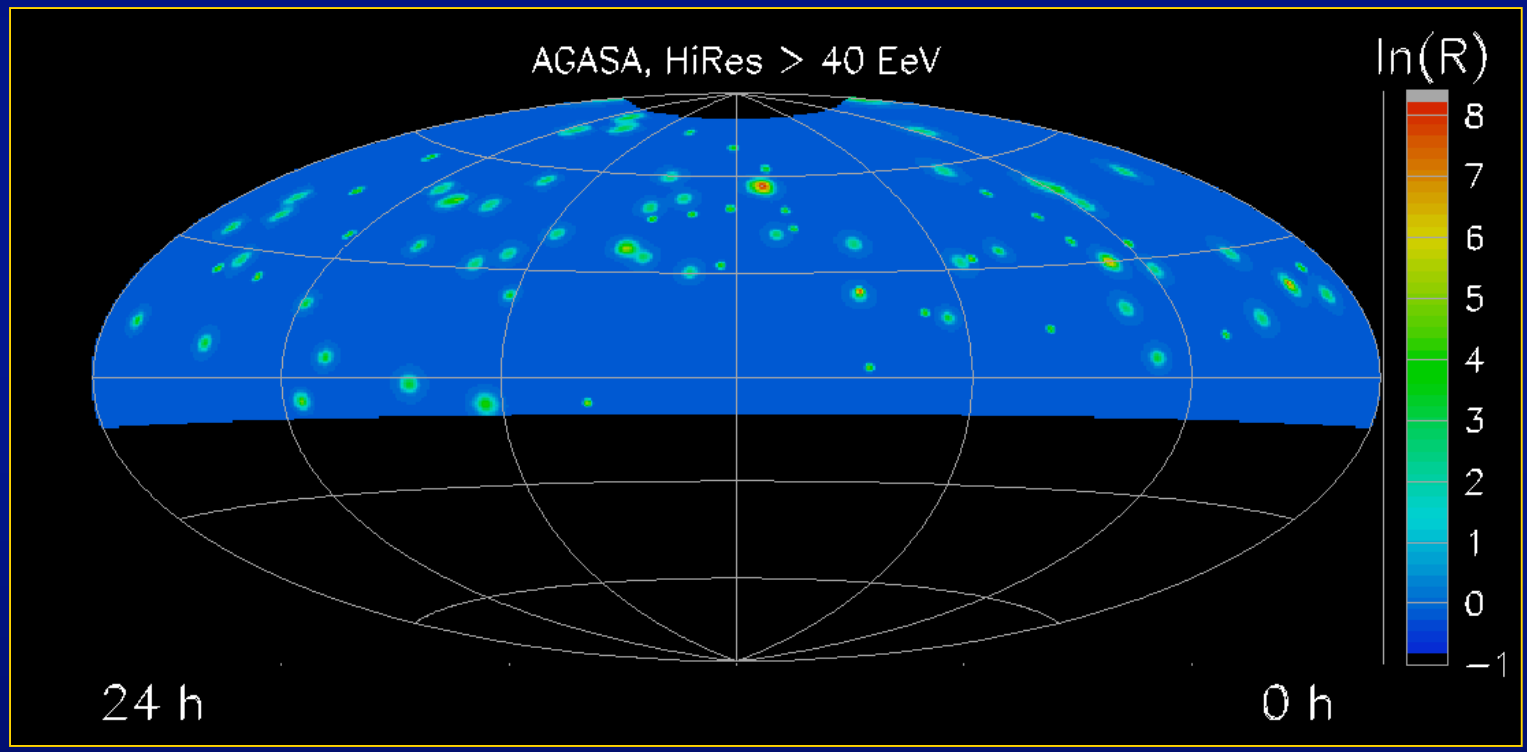
$$\ln(\mathrm{R}) = \ln \frac{L(n_s, x_s)}{L(0, x_s)}$$

ln(R) is the measure of deviation from the null hypothesis of no source events.

Maximum Likelihood Point Source Search

Given a set of data, we scan over a fine grid of locations in the sky, treating each as a source position, to identify the single spot with highest ln(R).

The significance is determined by scanning over many Monte Carlo data sets and counting the fraction with $\ln(R_{MC}) > \ln(R_{data})$.



For the AGASA and HiRes combined data set above 4×10^{19} eV, the highest value of ln(R) is ln(R) = 8.54 for n_s=2.9, at the location of the AGASA triplet.

The fraction of Monte Carlo sets with greater ln(R) is 28%.

Maximum Likelihood Point Source Search

No significant point source is found in the combined set of HiRes and AGASA events above **4×10^{19} eV**.

If the HiRes threshold is lowered to 3×10^{19} eV, one more event lands near the triplet. There are now 57 AGASA events and 40 HiRes events.

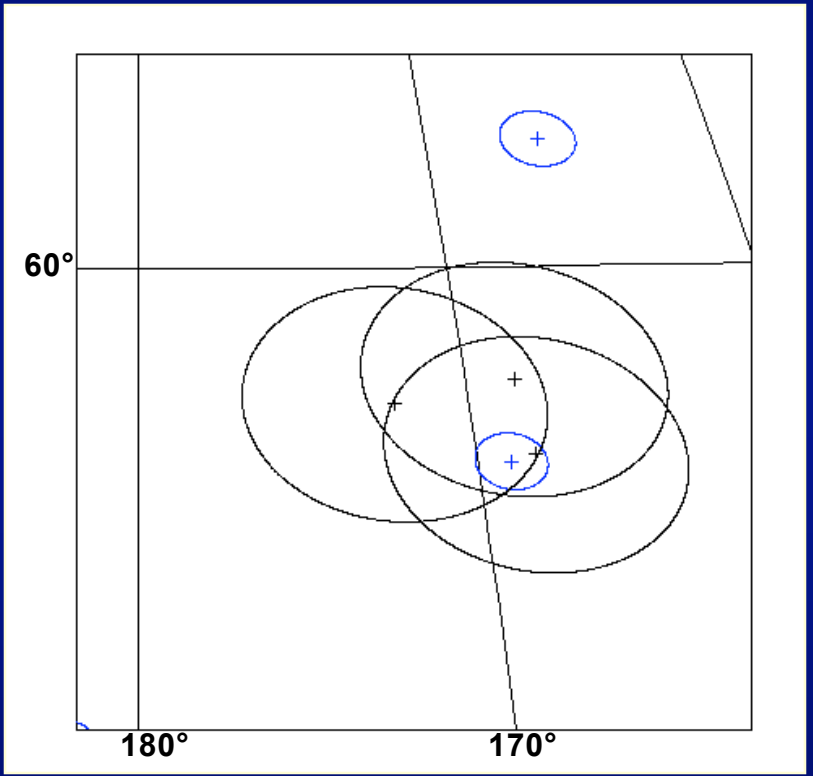
The new highest value of ln(R) = 12.98, and the fraction of MC sets with higher ln(R) is 0.5%

This result contains some biases:

- the clustered AGASA events which were originally used to *establish* the 4×10^{19} eV threshold are still included in the sample
- the HiRes energy threshold has to be *changed* to include an event that contributes to the cluster

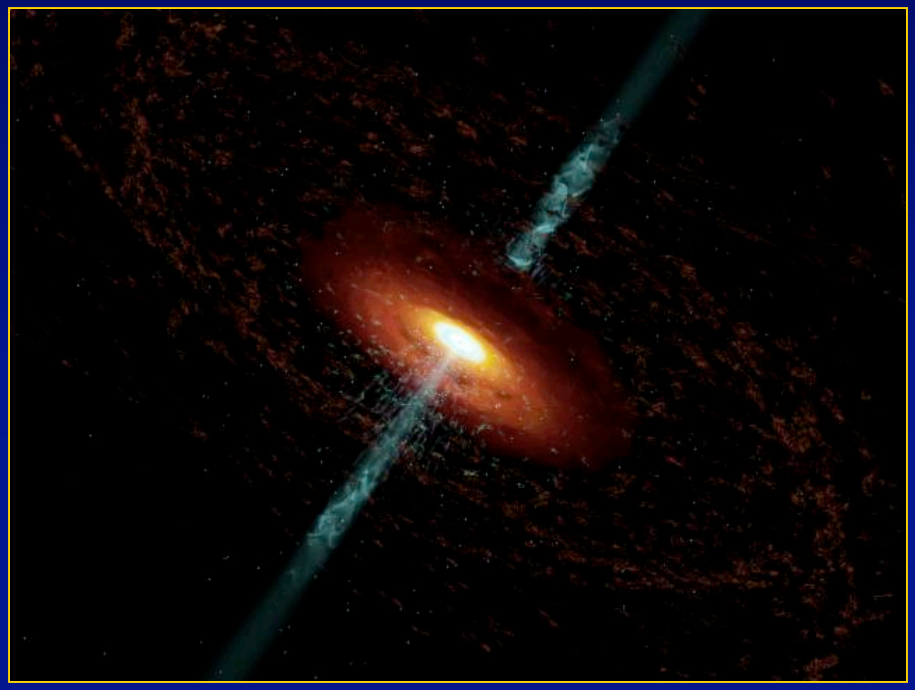
These biases imply that 0.5% is a *lower bound* on the chance probability.

Abbasi et al., Astrophys.J. 623 (2005) 164.



See G. Farrar, astro-ph/0501388 for a different interpretation

BL Lac Correlation



Somewhat controversial recent history regarding correlations of UHECR with BL Lac objects:

Tinyakov and Tkachev, JETP 74 (2001) 445.
Tinyakov and Tkachev, Astropart. Phys. 18 (2002) 165.
Gorbunov et al., ApJ 577 (2002) L93.
Evans et al., Phys.Rev. D67 (2003) 103005.
Torres et al., Astrophys.J. 595 (2003) L13.
Gorbunov et al., JETP Lett. 80 (2004) 145.
Stern and Poutanen, ApJL, in press, astro-ph/0501677.

BL Lac - class of blazar, active galaxy with jet axis aligned along our line of sight.

Blazars are established sources of TeV γ-rays

Good candidates for accelerating cosmic rays to EeV energies

BL Lac Correlation: Previous Claims

Recent history of correlations with AGASA and Yakutsk events involves highly tuned claims. We test each claim with HiRes data:

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (9th Ed.) BL Lacs			22	AGASA >48 EeV Yakutsk >24 EeV	65	2.5°	8	$< 10^{-4}$
m < 18	z > 0.1 or unknown	$S_{6cm} > 0.17$ Jy		HiRes > 24 EeV	66	2.5°	0	1.00
Catalog: Veron (10th Ed.) BL Lacs correlated with EGRET sources			14	AGASA >48 EeV Yakutsk >24 EeV	65	2.9°	8	10^{-4}
no cut	no cut	no cut		HiRes > 24 EeV	66	2.9°	1	.70
Catalog: Veron (10th Ed.) BL Lacs			156	AGASA > 40 EeV	57	2.5°	12	.02
m < 18	no cut	no cut		HiRes > 40 EeV	27	2.5°	2	.78

Tinyakov & Tkachev, JETP 74 (2001) 445.
Tinyakov and Tkachev, Astropart. Phys. 18 (2002) 165.
Gorbunov et al., ApJ 577 (2002) L93.

No previous claims are confirmed.

BL Lac Correlation: New Claim

Most recent claim by Gorbunov is based on published HiRes data.
It uses a 10 EeV threshold, so it is a new claim.

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (9th Ed.) BL Lacs			22	AGASA >48 EeV Yakutsk >24 EeV	65	2.5°	8	$< 10^{-4}$
m < 18	z > 0.1 or unknown	$S_{6cm} > 0.17$ Jy		HiRes > 24 EeV	66	2.5°	0	1.00
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m < 18	no cut	no cut		HiRes > 40 EeV	27	2.5°	2	.78
Catalog: Veron (10th Ed.) BL Lacs			156	HiRes > 10 EeV	271	0.8°	10	10^{-3}
m < 18	no cut	no cut						

Gorbunov et al., JETP Lett. 80 (2004) 145.

BL Lac Correlation: New Claim

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (10th Ed.) BL Lacs			156	HiRes > 10 EeV	271	0.8°	10	10^{-3}
m < 18	no cut	no cut		Need to test with new data				

The 0.8º angular bin size was estimated by Gorbunov et al. to be optimal for the HiRes angular resolution of 0.6º.

We perform an *unbinned* maximum likelihood analysis (modified for a multiple-source hypothesis). Result:

$n_s = 8.0$ with $\ln R = 6.08$.

The fraction of isotropic MC sets with stronger signal:

$F = 2\times10^{-4}$.

The Correlation is real…. The Significance needs to be tested!

BL Lac Correlation: New Claim

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (10th Ed.) BL Lacs			156	HiRes > 10 EeV	271	0.8°	10	10^{-3}
m < 18	no cut	no cut		Need to test with new data				

Charged primaries with energies ~ 10 EeV are expected to be deflected many degrees by the galactic magnetic field.

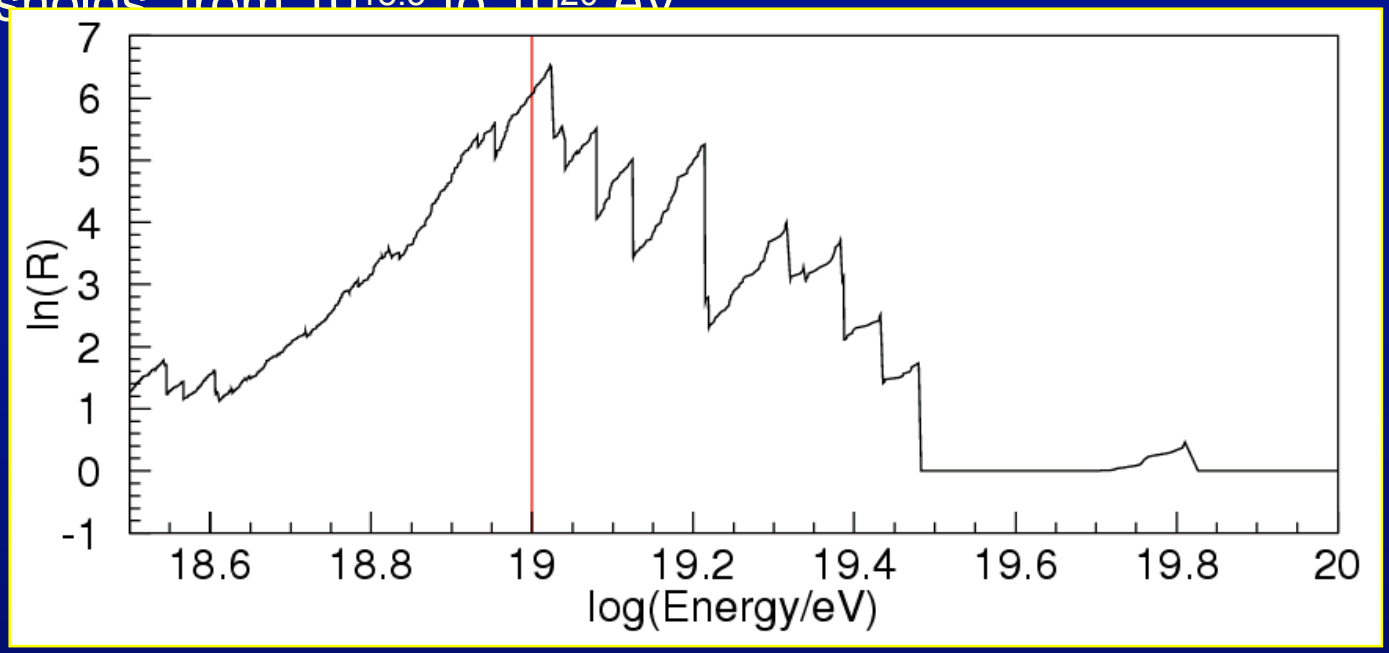
Correlations on the scale of the HiRes angular resolution imply that primary must be neutral (at least over most of its path). Neutrons and photons have a very short mean path (~ few Mpc) at this energy...

Arrival directions have not been examined for anisotropy searches for the data collected since 2004 January. Use current sample to decide *a priori* what will be tested with new data.

BL Lac Correlation: Energy Dependence

Directional data above 10^{19} eV was published without individual energies, thus Gorbunov *et al*. had no choice but to use a 10^{19} eV threshold.

performing the maximum likelihood analysis while varying energy thresholds from $10^{18.5}$ to 10^{20} eV:



For high energy events, 10^{19} eV is optimal energy threshold

BL Lac Correlation: Source Sample

Confirmed BL Lacs in the Veron Catalog are classified as “BL” or “HP” for high polarization.

But, all of the samples by Tinyakov *et al*. and Gorbunov *et al*. include only the BL Lacs classified as “BL”.

It is natural to consider the “HP”. (Indeed, half of the confirmed TeV γ-ray BL Lacs are classified as “HP”.)

We perform the analysis on the 47 “HP” BL Lacs, using the same m<18 cut as before, and HiRes events above 10^{18} eV.

We find: $n_s = 3.0$, with $F = 6\times10^{-3}$.

For the BL+HP set of confirmed BL Lacs and HiRes events above 10^{18} eV we find: $n_s = 10.5$, with $F = 10^{-5}$.

BL Lac Correlation: Source Sample

Summary of statistically independent results:

Confirmed BL Lacs		HiRes Events			
		< 10 EeV		> 10 EeV	
Mag.	**Class**	n_s	***F***	n_s	***F***
m<18	"BL" (157)	22	6×10^{-3}	8	2×10^{-4}
	"HP" (47)	0	0.7	3	6×10^{-3}
m≥18	"BL" (193)	0	0.7	0	0.4
	"HP" (21)	0	0.7	0	0.8

The m<18 cut was optimized by Tinyakov et al. to maximize BL Lac correlations with AGASA.

This cut isolates BL Lacs which correlate with HiRes events as well.

TeV BL Lac Correlation

Six BL Lacs are confirmed sources of TeV γ-rays. Five are in the northern hemisphere and well observed by HiRes.

We perform the maximum likelihood analysis on each source individually using all HiRes events:

Name	z	V Mag	n_s	*F*
Mrk 421	0.03	12.9	0.3	0.2
H1426+428	0.13	16.5	0	0.4
Mrk 501	0.03	13.8	3.3	6×10^{-4}
1ES1959+650	0.05	12.8	2.0	8×10^{-3}
PKS2155-304	0.12	13.1	-	-
1ES2344+514	0.04	15.5	0	0.7

For the TeV blazars taken as a set, the likelihood analysis finds:

All energies: $n_s = 5.6$ with $F = 10^{-3}$

Above 10^{18} eV: $n_s = 2$ with $F = 2\times10^{-4}$

BL Lac Correlation: Summary of New Results

Gorbunov sample and all HiRes events:

$F = 2\times10^{-4}$

Confirmed BL Lacs ("BL+HP") with m<18, HiRes above 10^{18} eV:

$F = 10^{-5}$

Confirmed TeV blazars, all HiRes events:

$F = 10^{-3}$

These are not independent results: the samples overlap.

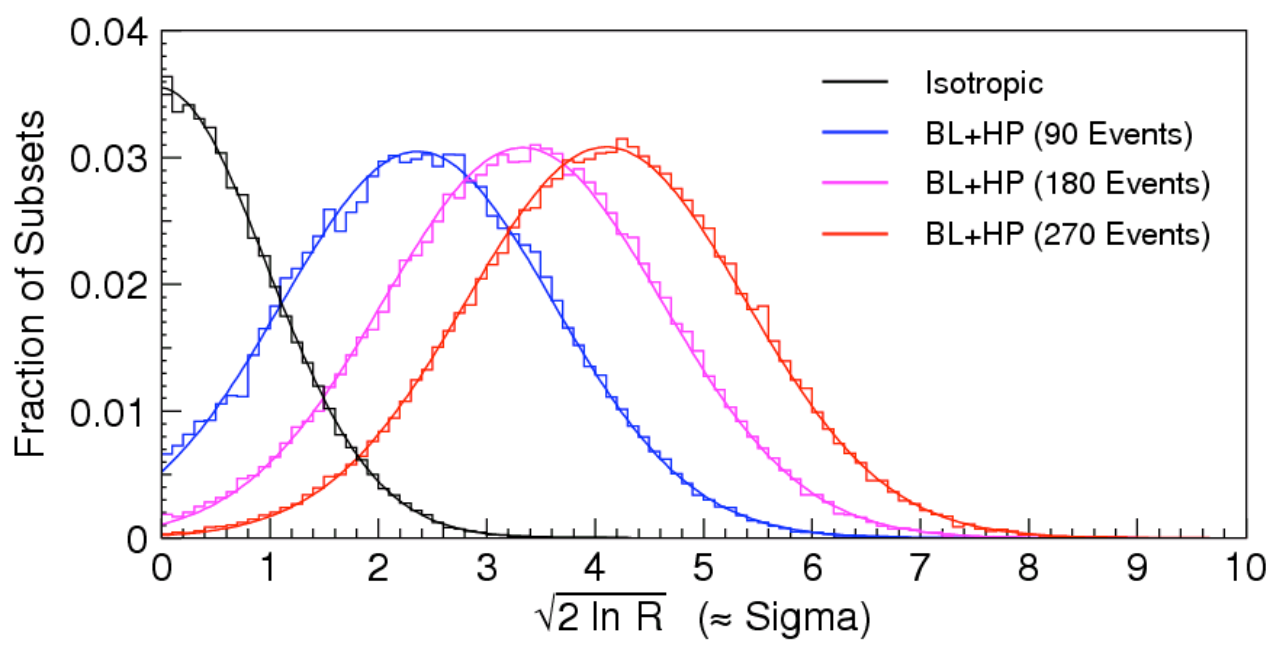
HOWEVER, the analysis has been *a posteriori*, so *F* values are not true chance probabilities. Correlations can only be confirmed with independent data.

BL Lac Correlation: Sensitivity of Future Data

We estimate the sensitivity which future HiRes data will have by re-sampling the present real HiRes events (Bootstrap re-sampling)

We simulate 1, 2, 3 years of new data to estimate the distribution of possible signal strengths if the observed correlations are real.

(Data from Jan 2004 - Present have yet not been analyzed for this)



Conclusions

- HiRes events above 10^{18} eV show no small-scale clustering
- Combined Data Maximum Likelihood Point Source Search
  - No significant point source above 4×10^{19} eV observed
  - "Quadruplet" below 4×10^{19} eV with 0.5% *a posteriori* probability
- BL Lac Correlations
  - No correlation between HiRes events and BL Lacs in tests of previous claims (based on AGASA and Yakutsk data)
  - Confirmed and examined new correlations between HiRes and BL Lacs:
    - BL Lacs brighter than optical magnitude 18
    - TeV γ-ray blazars
  - Must be tested with independent data to see if they are real sources
- Future
  - Data taking through spring 2006 will nearly double the data set
  - Independent test of BL Lac correlations should be possible

Publications

Angular Correlation / Energy Scan for HiRes Stereo Data above 10^{19} eV:

R.U. Abbasi et al., Astrophysical Journal 610 (2004) L73 [astro-ph/0404137]

Combined HiRes / AGASA Maximum Likelihood Point-Source Search:

R.U. Abbasi et al., Astrophysical Journal 623 (2005) 164 [astro-ph/0412617]

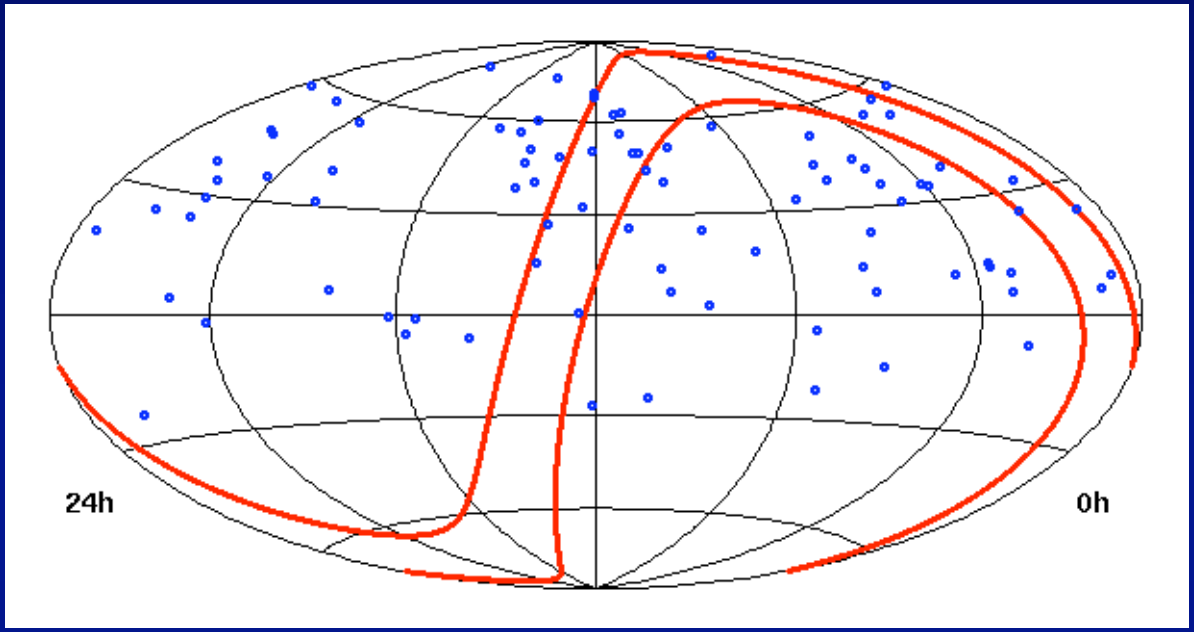
HiRes / BL Lac Correlations:

R.U. Abbasi et al., submitted to Astrophysical Journal (7/2005) [astro-ph/0507120]

Supergalactic Plane Correlation

- Many possible accelerator sites have been identified near the supergalactic plane.
- Possible excess UHECR flux from within 10º of the plane has been previously reported.

  Uchihori et al., Astropart. Phys. 13 (2000) 151.



HiRes events (>2×10^{19} eV) and Supergalactic plane (lat. B = +10º , -10º)

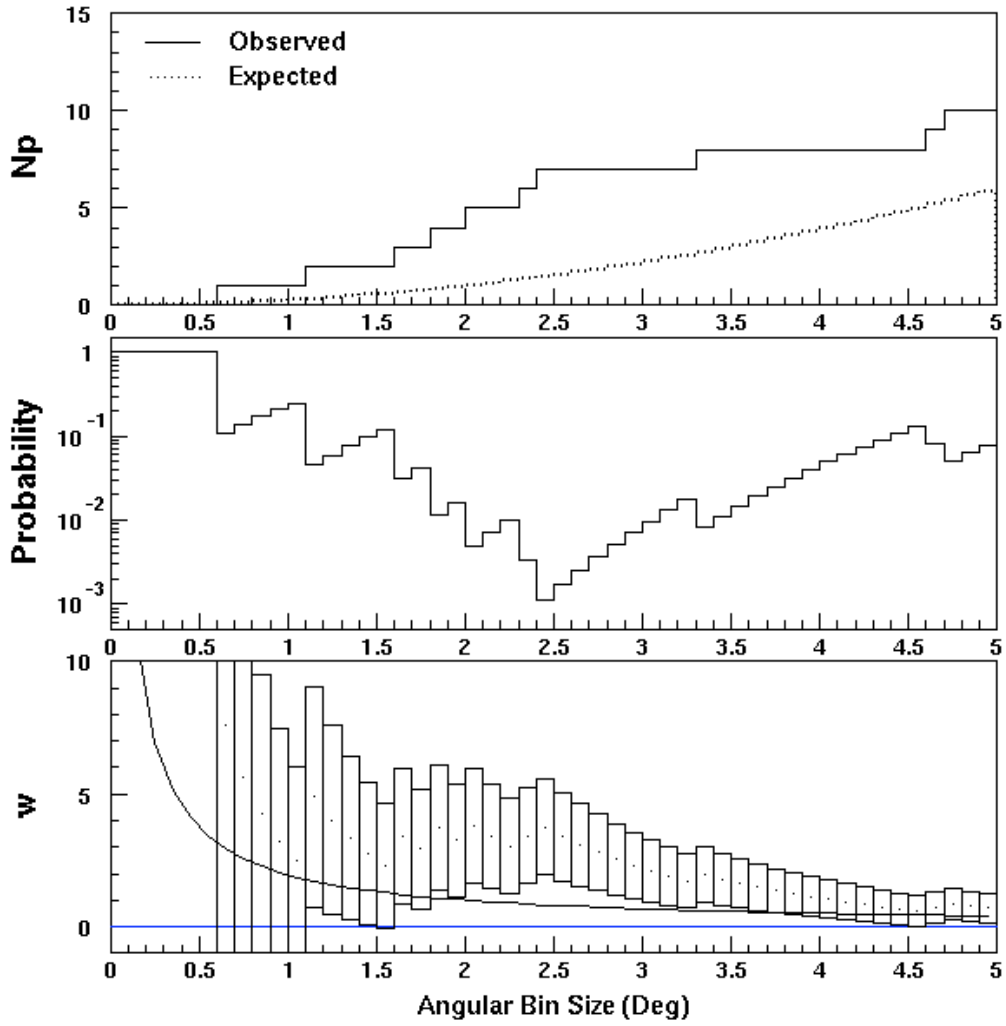
- We count the number of events within 10º of the plane, and compare with Monte Carlo.

Energy Threshold:	2×10^{19} eV	4×10^{19} eV
Mean:	17.1	5.2
Observed:	18	5
Chance Probability:	46%	65%

Combined Autocorrelation

AGASA:

- 57 events above 40 EeV
- $N_p = 7$, for $\theta < 2.5°$
- Prob ~ 0.1%



57 AGASA events above 4×10^{19} eV

Combined Autocorrelation

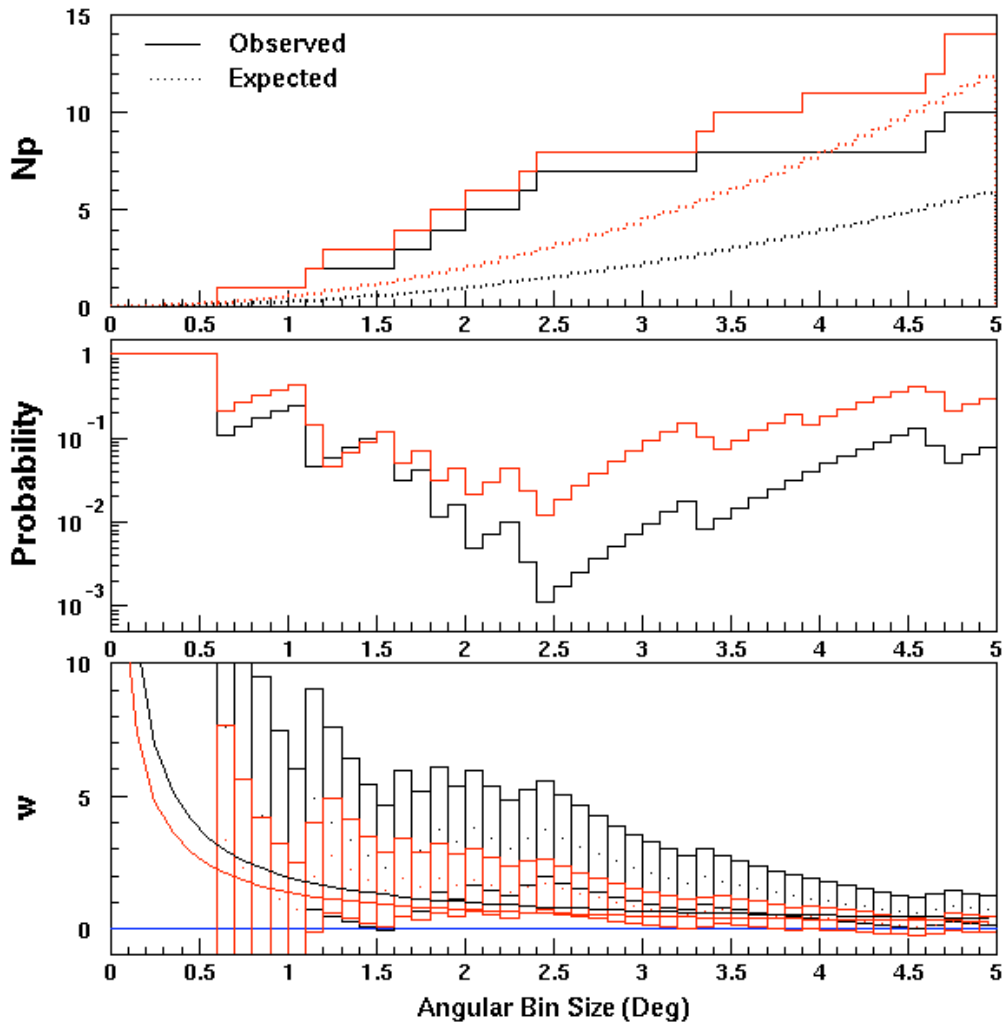
AGASA:

- 57 events above 40 EeV
- $N_p = 7$, for $\theta < 2.5°$
- Prob ~ 0.1%

AGASA + HiRes:

- 57 + 27 events (>40 EeV)
- $N_p = 8$, for $\theta < 2.5°$
- Prob ~ 1%

C. Finley, astro-ph/0411130.



57 AGASA events above 4×10^{19} eV

57 AGASA + 27 HiRes events above 4×10^{19} eV