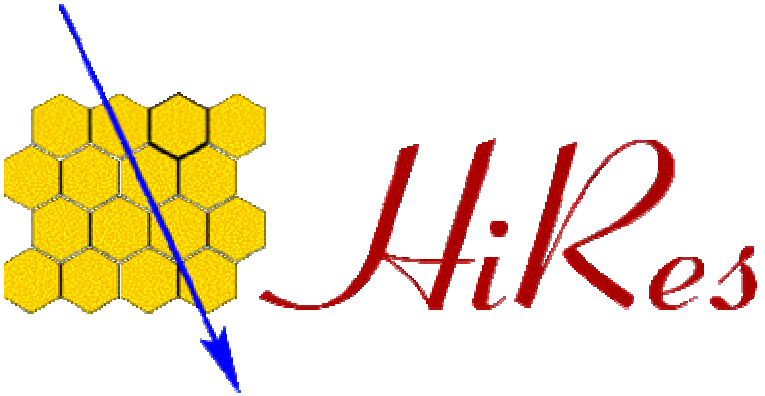
The Search for Point Sources and Other Anisotropy at the High Resolution Fly's Eye



J.N. Matthews
University of Utah

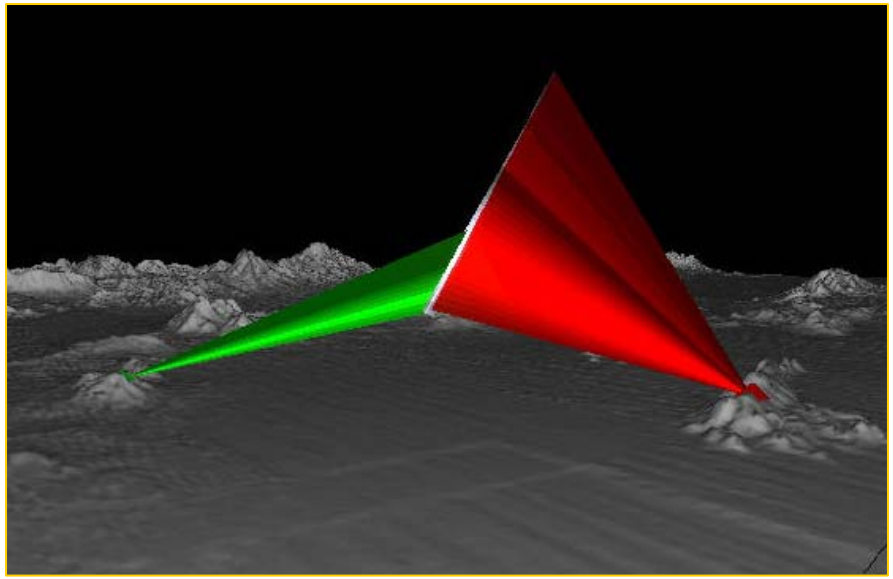
Outline

- Search for Small-Scale Anisotropy/Autocorrelation in HiRes Stereo/AGASA data set.
- Search for Point Sources in the Combined HiRes Stereo/AGASA Data Set.
- Search for Correlations with BL Lacertae Objects
- Large Scale Anisotropy Comparison with AGASA

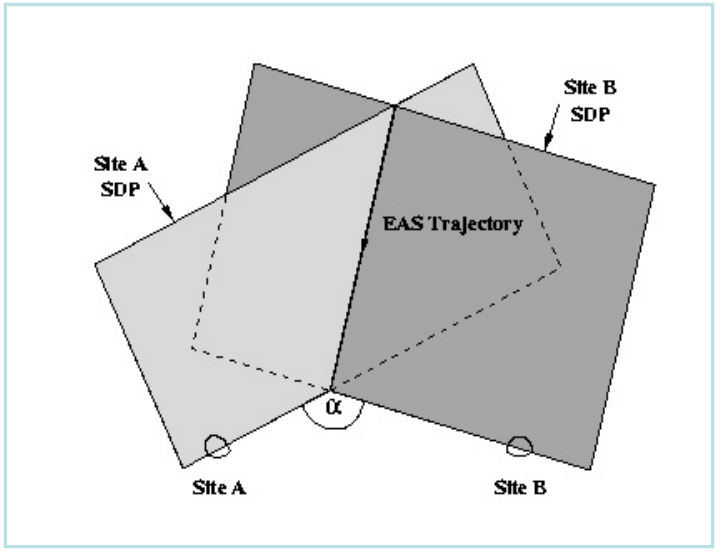
Study Characteristics

- Stereo anisotropy studies: offer excellent pointing resolution (0.6^{o}).
  - Search for point sources.
  - Search for BL Lac correlations.
- Monocular anisotropy studies: better statistics, wider energy range.
  - Search for large-scale structure.

The HiRes Air-Fluorescence Detector



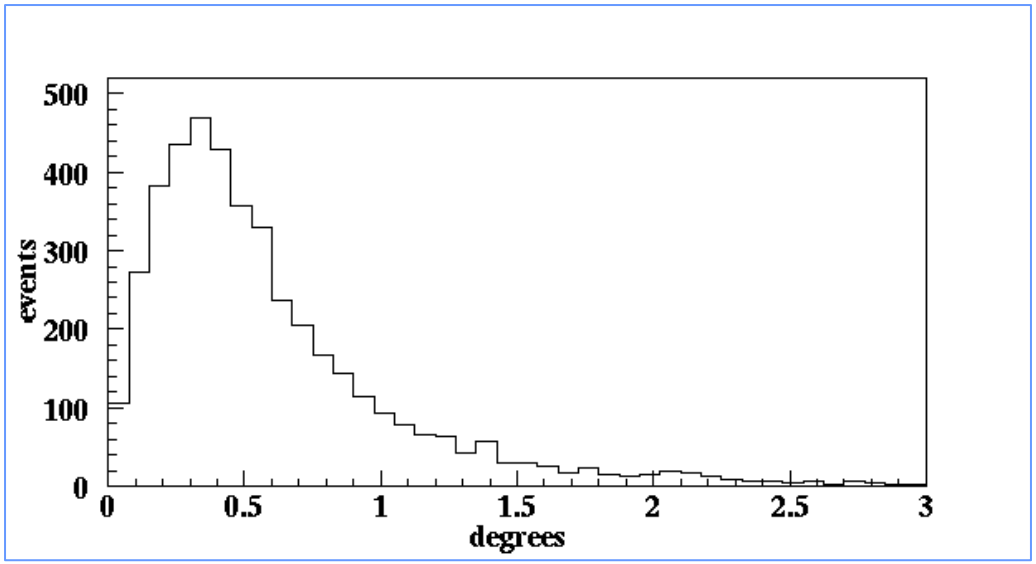
HiRes-I and **HiRes-II** observation of an air shower



- The cosmic ray induced air shower is viewed simultaneously by telescopes at the 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 provide the *sharpest image* of the Northern sky at ultra high energies.
- In Monte Carlo simulations, 68% of events above 10^{19} eV are reconstructed within 0.6º of their true arrival direction.
- From star survey and reconstruction of 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:

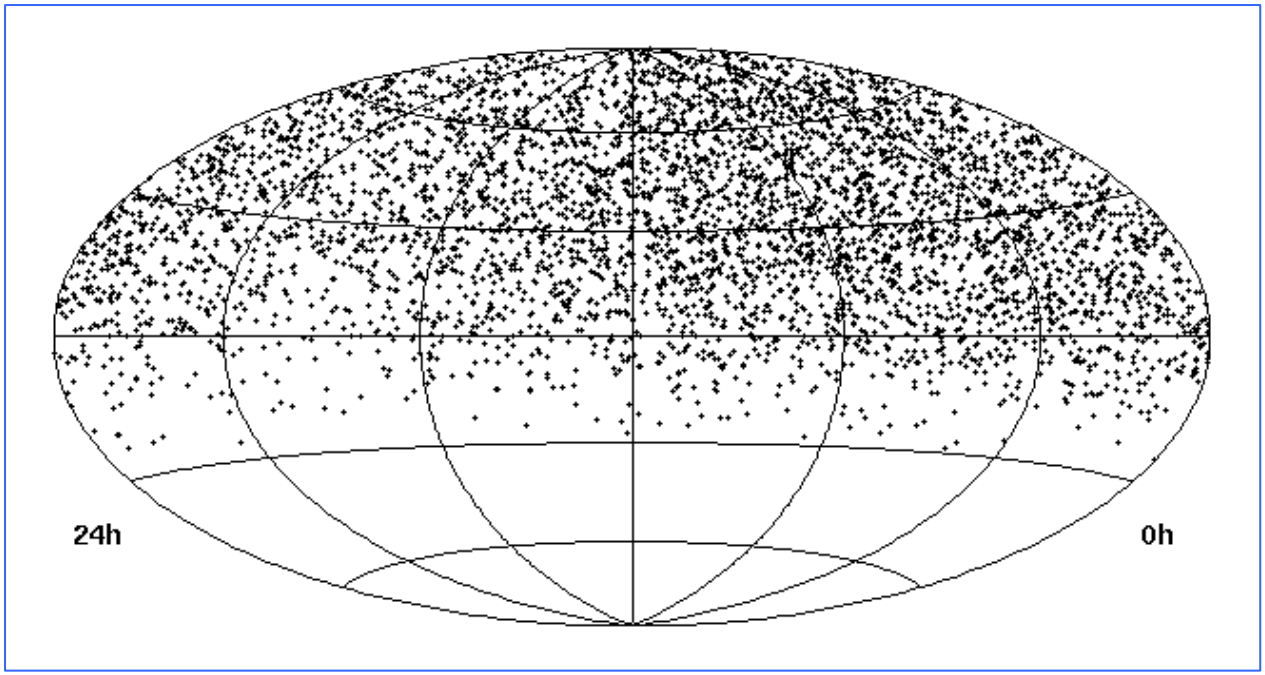
- As long as weather conditions are known, their impact on the reconstructed event geometry and energy is small for a wide range of aerosol contents.
- Analysis uses hourly atmospheric database built from the reconstruction of YAG laser shots.
- **No explicit weather cuts have been applied.**

HiRes Stereo Data Set

HiRes Stereo
Events for
all Energies

Dec. 1999
through
Jan. 2004

4495 Events



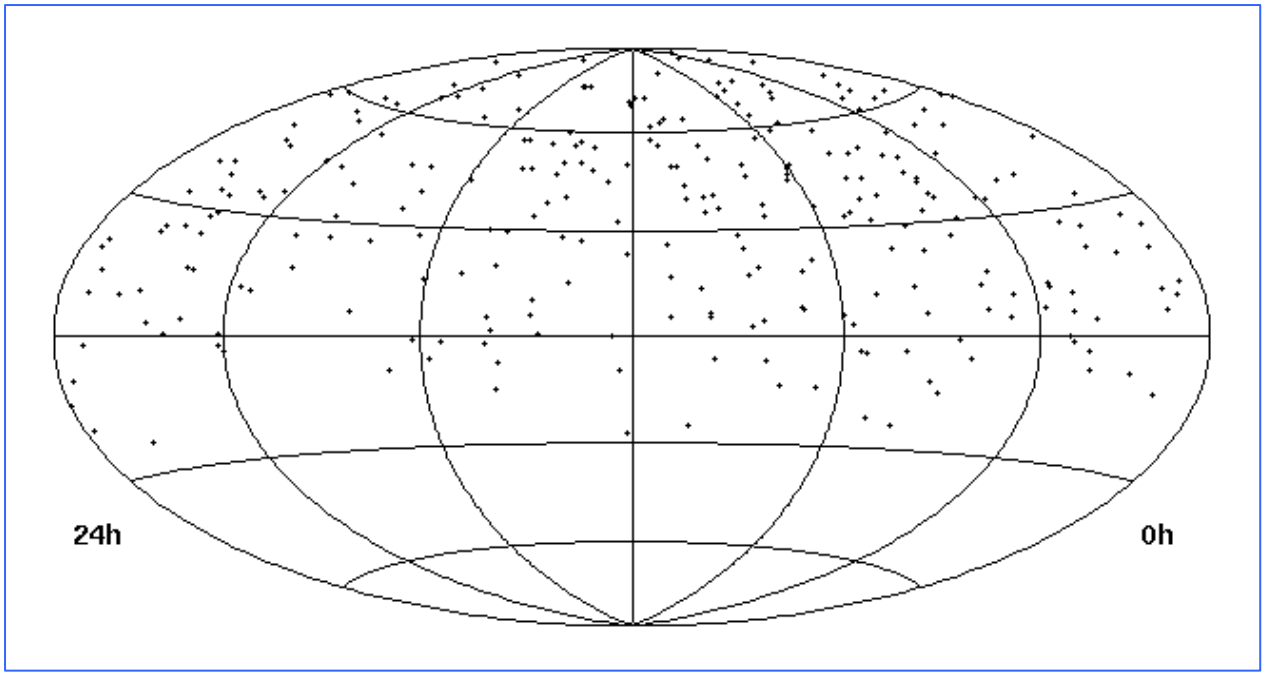
Equatorial Coordinates

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

Dec. 1999 -Jan. 2004

- 271 events above 10^{19} eV
- 47 events above 2.8×10^{19} eV.
- 27 events above 4×10^{19} eV.

- Angular resolution ~ 0.6º.



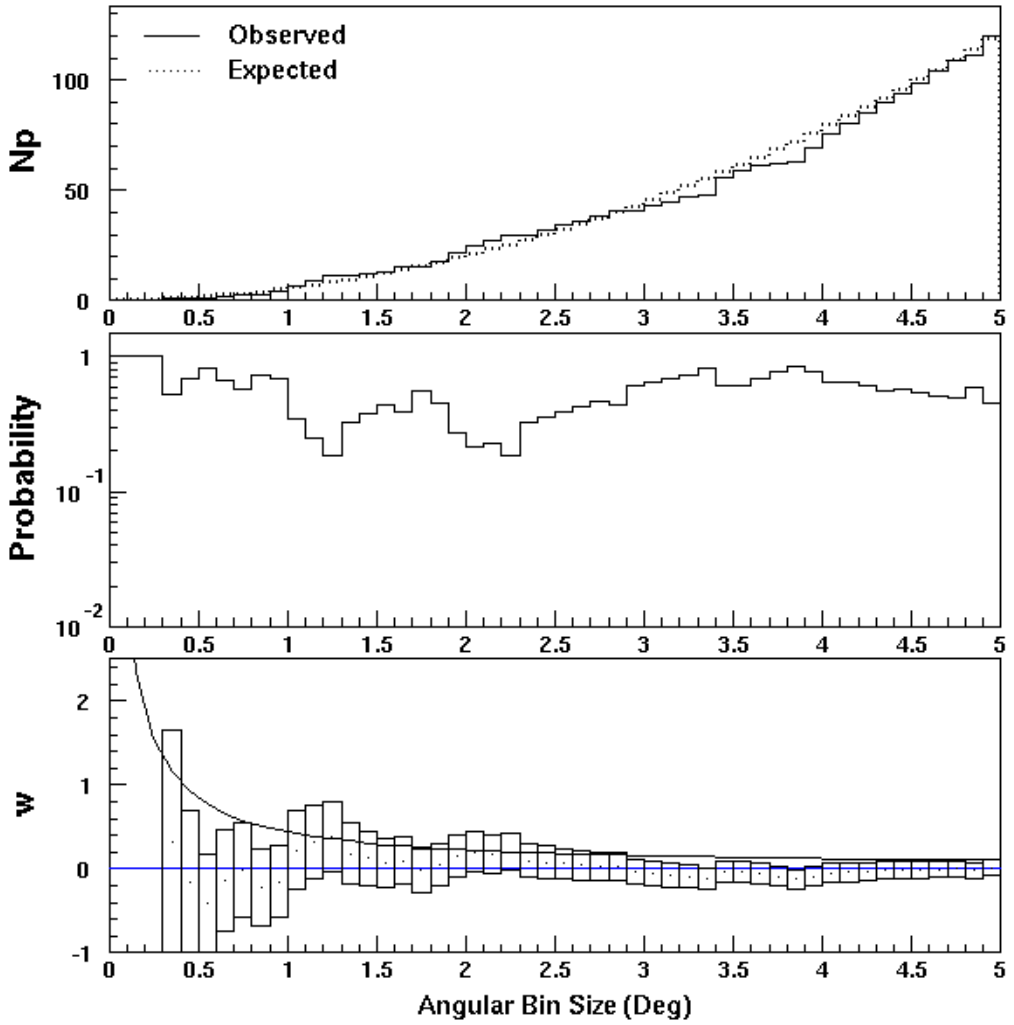
Equatorial Coordinates

HiRes Autocorrelation Function

Angular Correlation:

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

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



271 HiRes events above 10^{19} eV

Abbasi et al., ApJ 610 (2004) L73

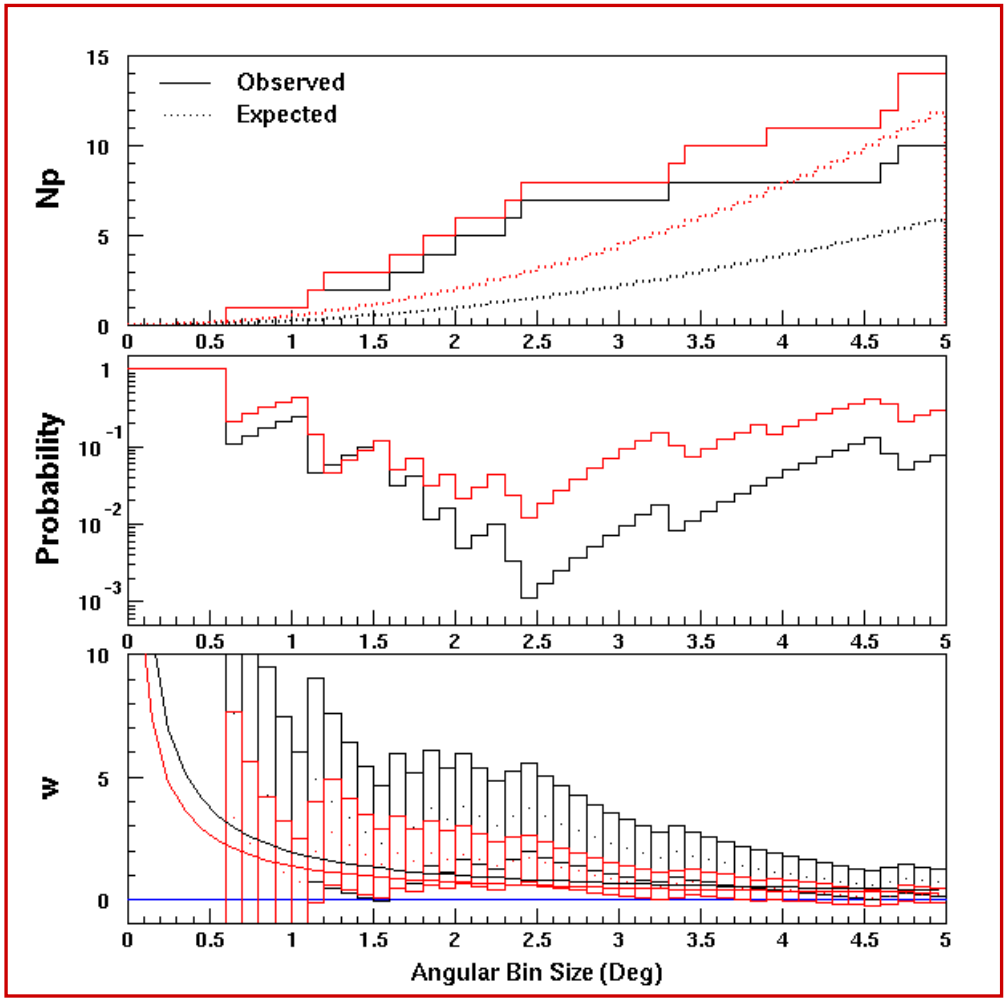
Combined Autocorrelation

AGASA:

- 57 events, E>4x19 eV
- N_p = 7 , for θ < 2.5º
- Prob ~ 0.1%

AGASA + HiRes:

- 57 + 27 evts, E> 4x19 eV
- N_p = *8* , for θ < 2.5º
- Prob ~ 1%



Perhaps AGASA was a little lucky/unlucky
However, again consistent with isotropy at all small angular scales

HiRes

Hot Sources

- However….
- There are six widely discussed “clusters” containing 13 events in the AGASA data
- Assume that these represent the six brightest sources in the sky
- Test this hypothesis

Search for Point Sources

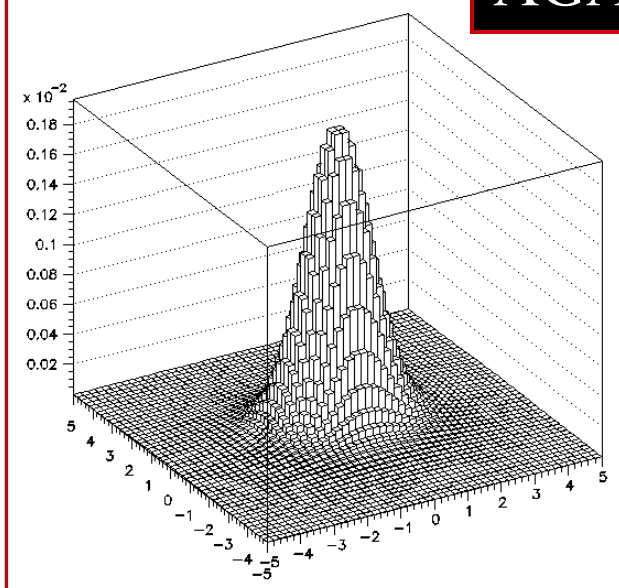
- Search *combined* AGASA/HiRes stereo data above 4×10^{19} eV for cosmic ray point sources.
  - Need to account for different exposure and angular resolution.
  - Method should be “unbinned:” no a priori choice of maximum angular separation that defines a “source event.”

- Maximum likelihood ratio test – compare likelihood for hypothesis that n_s events come from the same location on the sky to null hypothesis $n_s = 0$.

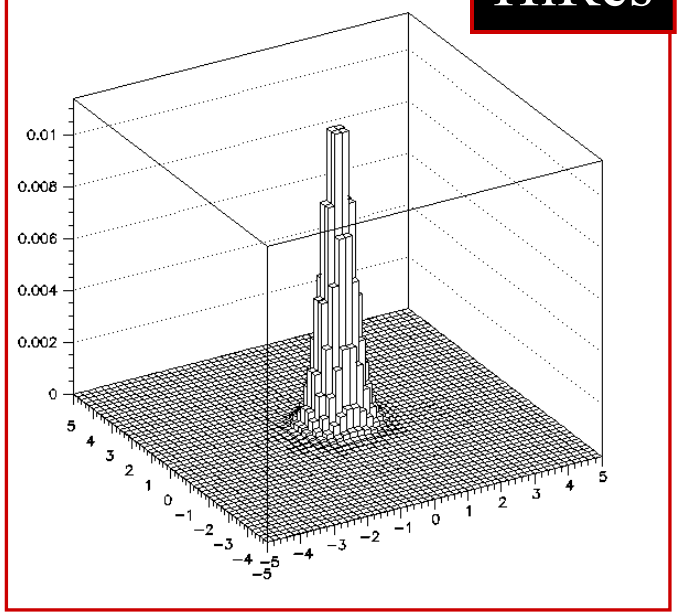
- Treat n_s as a free parameter and apply maximum likelihood method on a dense grid of points in right ascension and declination.

Angular Resolution

AGASA



HiRes



- Use point spread function PSF for each event.
- AGASA: sum of two Gaussians to reproduce 68% and 90% opening angles - from

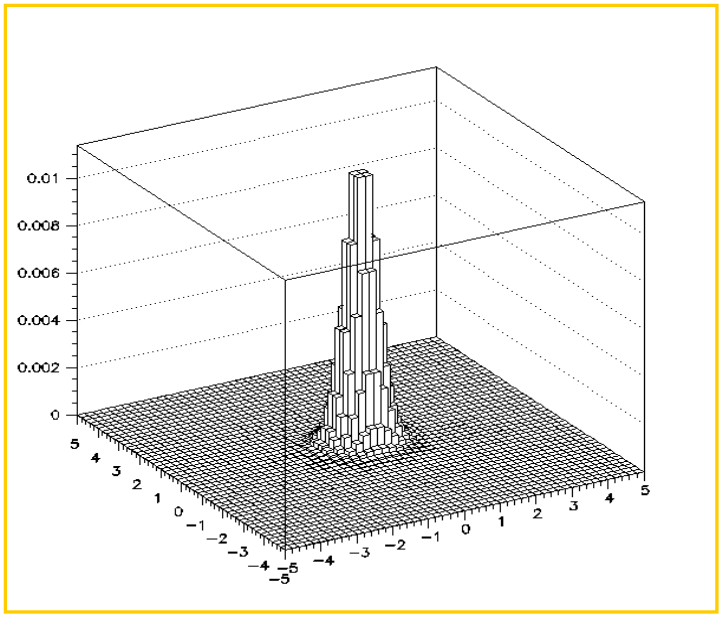
Takeda et al., Astroparticle Phys. 19 (2003) 447

- HiRes: Gaussian with width $\sigma=0.4^{o}$

Maximum Likelihood Point Source Search

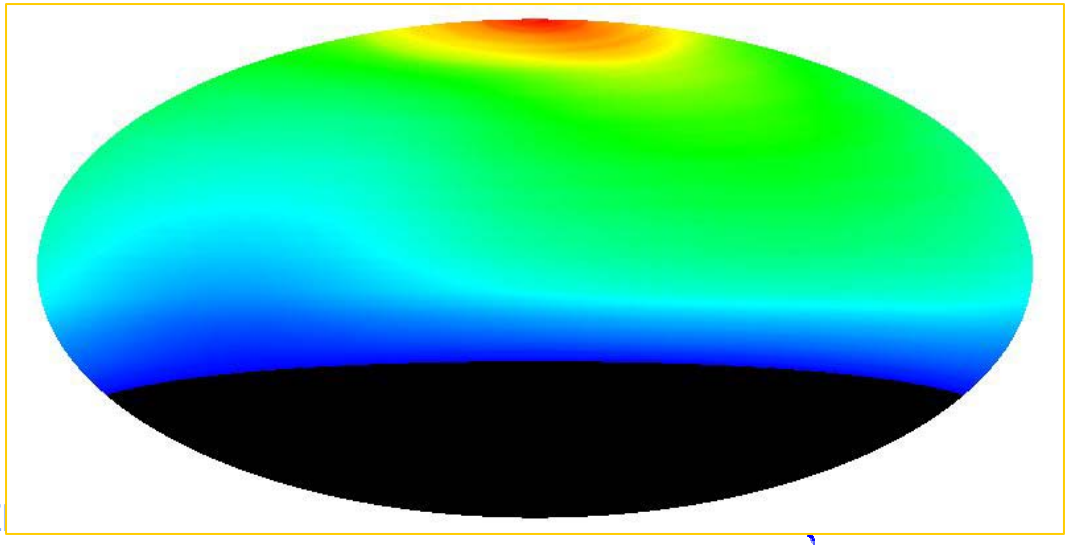
Introduced here as a way to search for a single point source among events with **different errors**. (incorporate the point spread functions of the experiments: HiRes and AGASA)

$Q_i(x_i, x_s)$



$Q_i(x_i,x_s)$ 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.

$R_i(x)$



$R_i(x)$ 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.

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

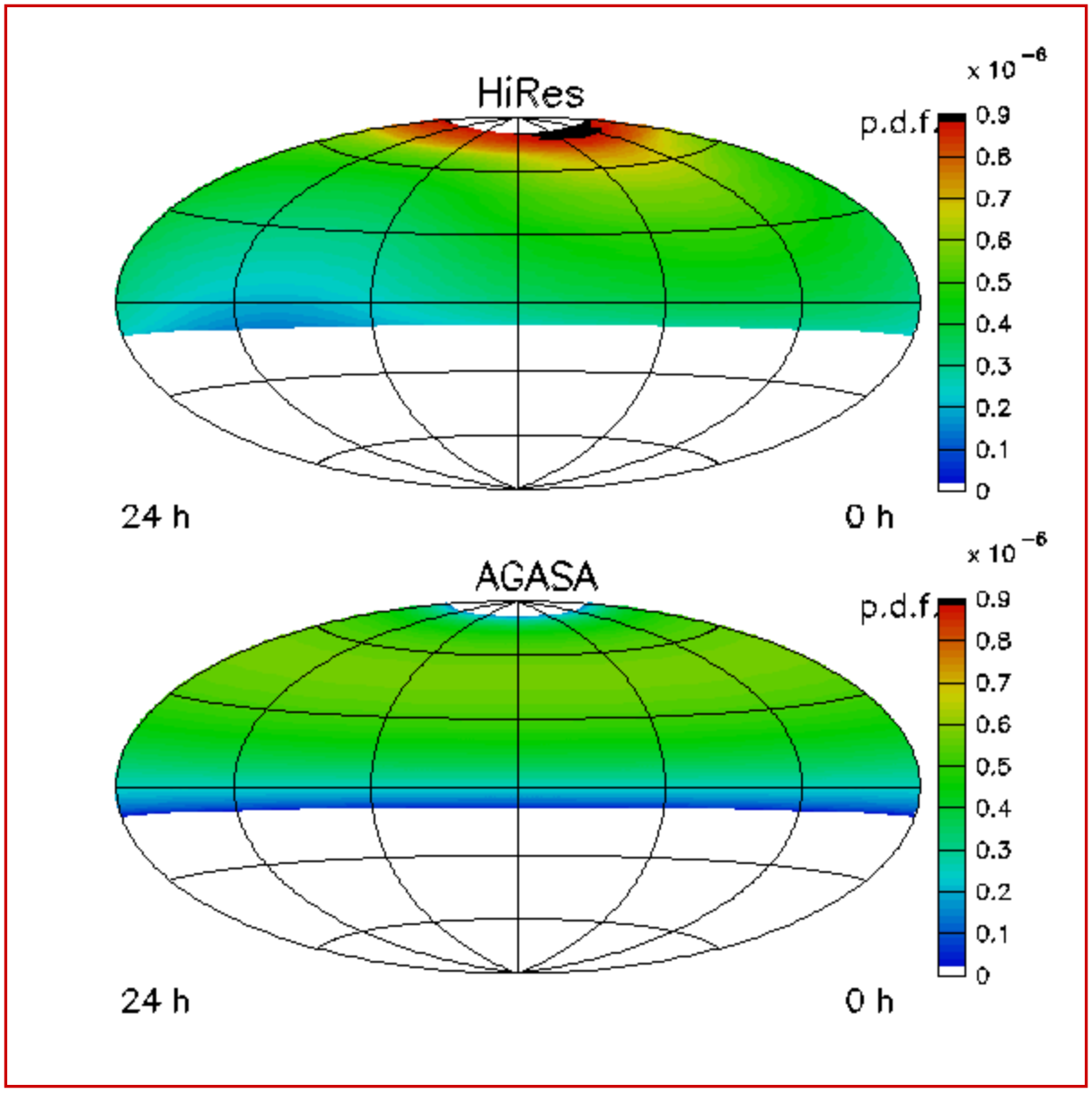
In practice, we maximize ln(R), the log of the ratio of the likelihood of n_s relative to the likelihood of the null hypothesis: $n_s = 0$.

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

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

HiRes

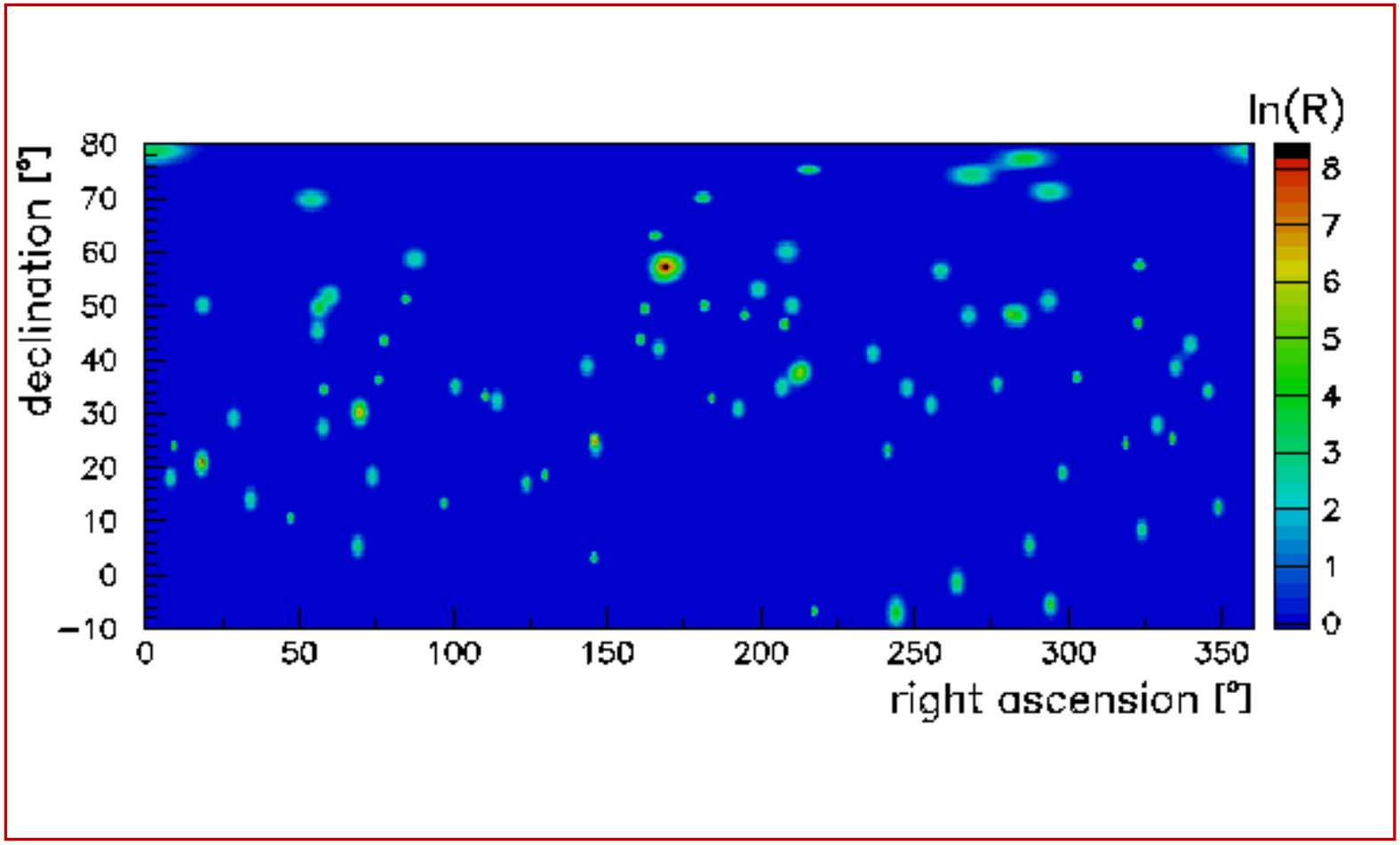
Background



- Normalized probability densities for random background in HiRes stereo and AGASA.
- HiRes exposure shows some dependence on right ascension. (Seasonal viewing)

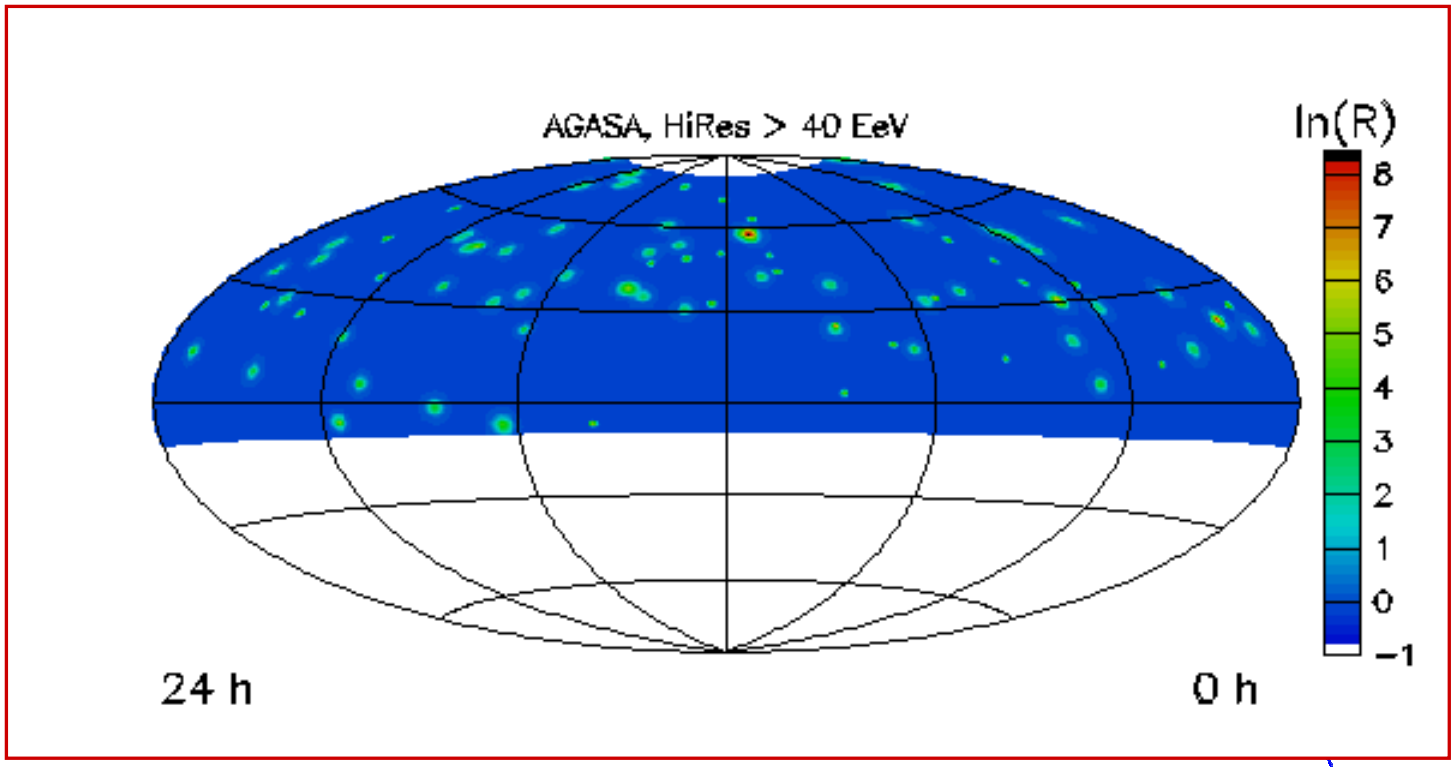
HiRes

AGASA/HiRes > 4.0×10^{19} eV



AGASA/HiRes E > 4.0×10^{19} eV

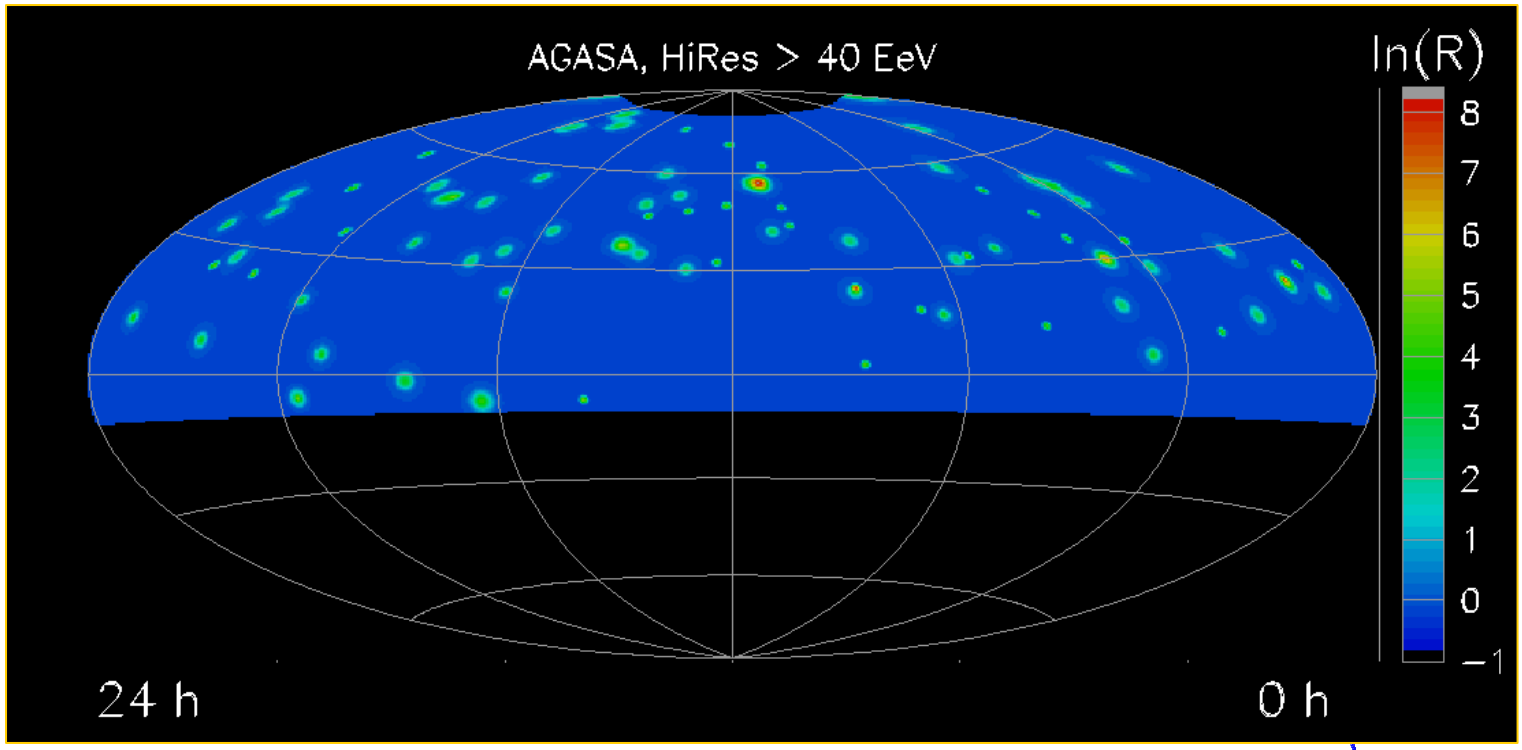
- Maximum *ln(R)*=8.54 (“hottest spot”) is a cluster of 3 nearby AGASA events – the “triplet”
- Position and n_s from likelihood analysis.
- Several other spots with equally large *ln(R).*



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 potential source position, to identify the single spot with highest ln(R). (deviation from null source hypothisis)

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



Maximum Likelihood Point Source Search

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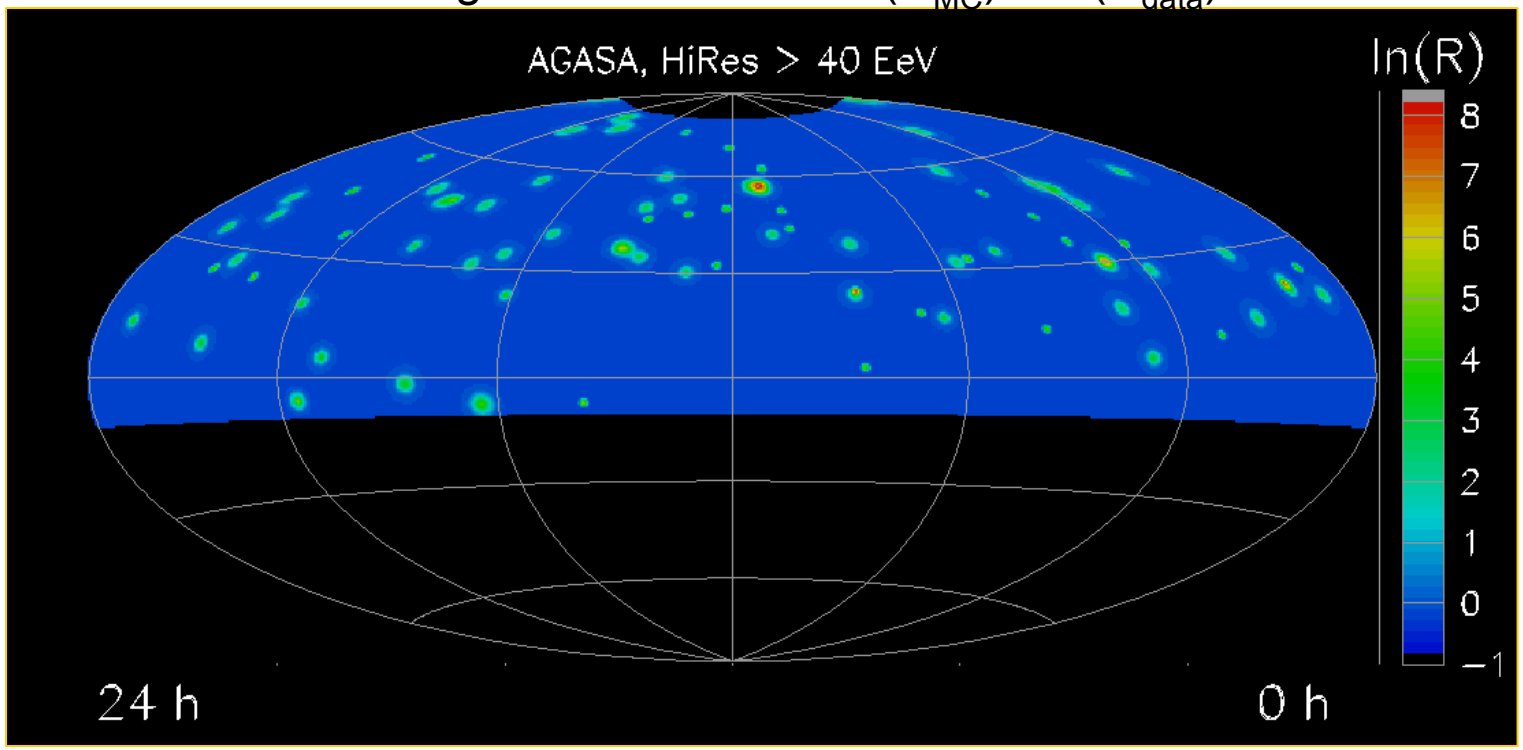
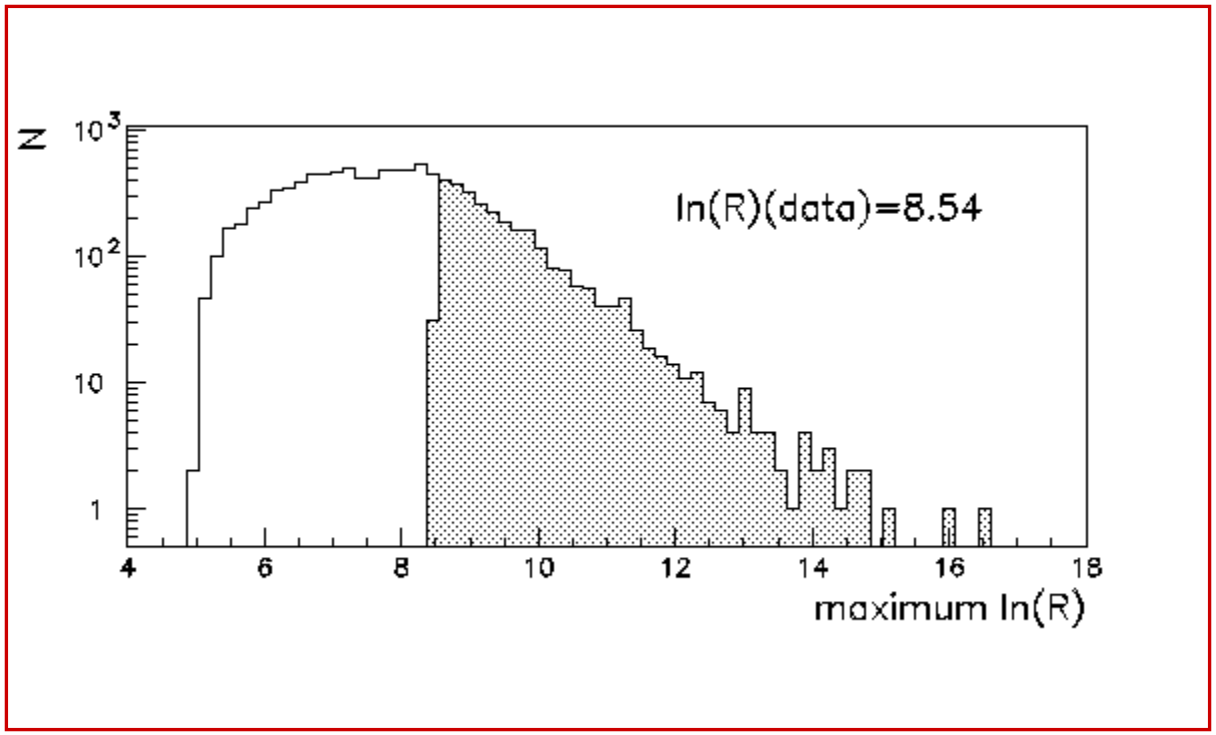


For the AGASA and HiRes combined data set above $4X10^{19}$ eV, the highest value of ln(R) is ln(R) = 8.54 n_s=2.9, at the location of the AGASA triplet. The fraction of Monte Carlo sets with greater ln(R) is 28%.

How Hot ?



For the AGASA and HiRes combined data set above $4X10^{19}$ eV, the highest value of ln(R) is ln(R) = 8.54

n_s=2.9, at the location of the AGASA triplet.

ln(R) for MC data sets, shaded area indicates *ln(R)* >8.54

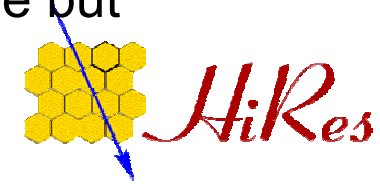
- Evaluate chance probability by applying likelihood analysis to random isotropic MC sets with identical number of events.
- 2793 out of 10^4 random isotropic sets have *ln(R)* > 8.54.
- Chance probability ~ 28%.

No significant point source is found in the combined set of HiRes and AGASA events above **$4x10^{19}$ eV**.

HiRes

What about news of a Quartet ??

- HiRes event with E= 3.7×10^{19} eV is located near the triplet.
- *Literature:* flux difference between HiRes mono and AGASA can be reconciled to some degree by an *ad hoc* change in relative energy scales. DeMarco, Blasi, Olinto. 2003, Astropart. Phys.,20,53
- If one believes the energy is the cause of the difference, question remains: which experiment should lower/raise energies
- Assume that a 30% downward shift in the HiRes energy cut is what is needed (effectively raise the HiRes spectrum to match AGASA's)
- Redo maximum likelihood analysis with a HiRes threshold of 3.0×10^{19} eV keeping in mind that…
    - … this ad hoc change in energy threshold produces a bias that makes the calculation of a meaningful chance probability all but impossible.
    - … and changing the relative energy scale by 30% may equalize the flux in the energy range $\log(E/[\mathrm{eV}]) < 19.8$, but it does not explain why AGASA has less exposure but more events at the highest energies.



Maximum Likelihood Point Source Search

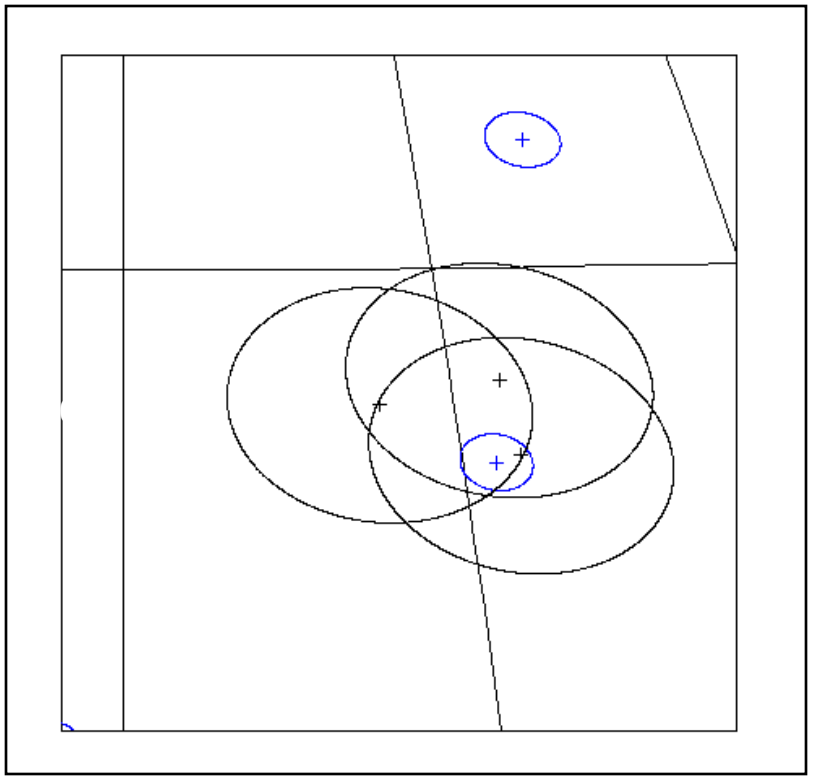
If the HiRes threshold is lowered to 3×10^{19} eV, one more event lands near the triplet. There are now 57 AGASA events and 40 HiRes events.

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.



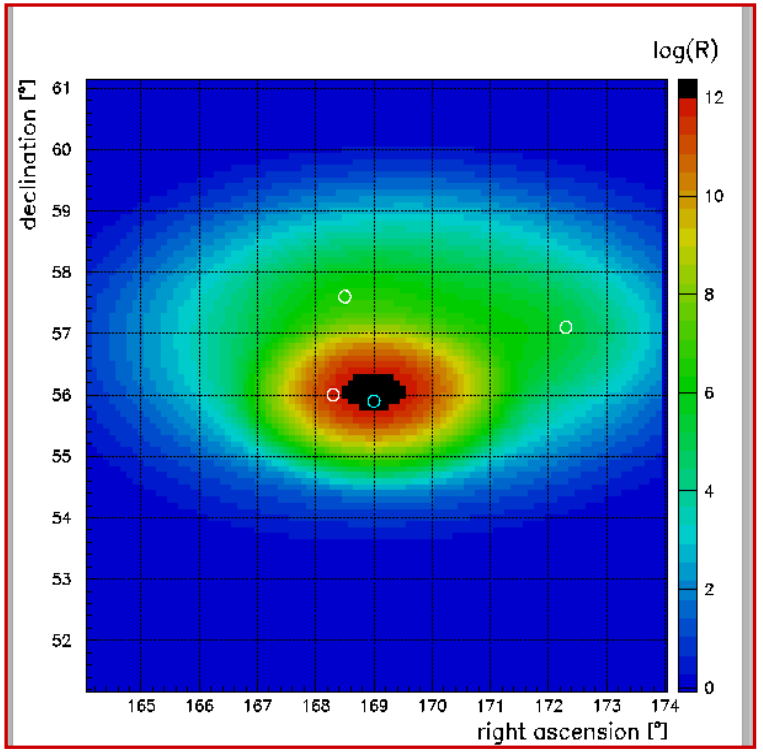
See G. Farrar, astro-ph/0501388 for a different interpretation

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

HiRes

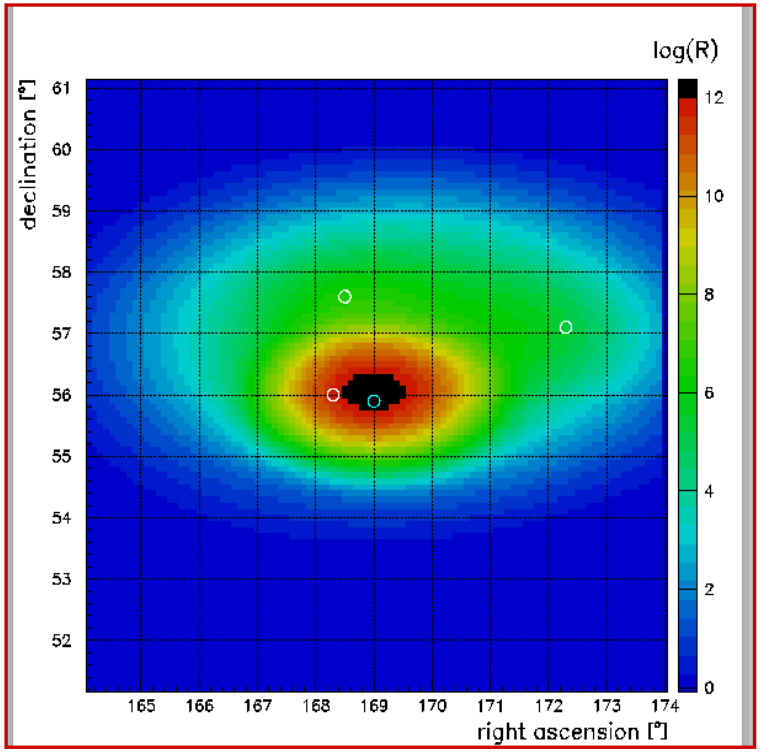
Stereo Anisotropy: Good for Point Sources

- Note the effect of the better angular resolution of the HiRes detector. That one point (blue circle) dominates the uncertainty in the potential source location.
- Angular resolution is VERY important to anisotropy
- This "Quartet" *could be* first point source (Ursa Major).
- **<u>Needs confirmation!!</u>**

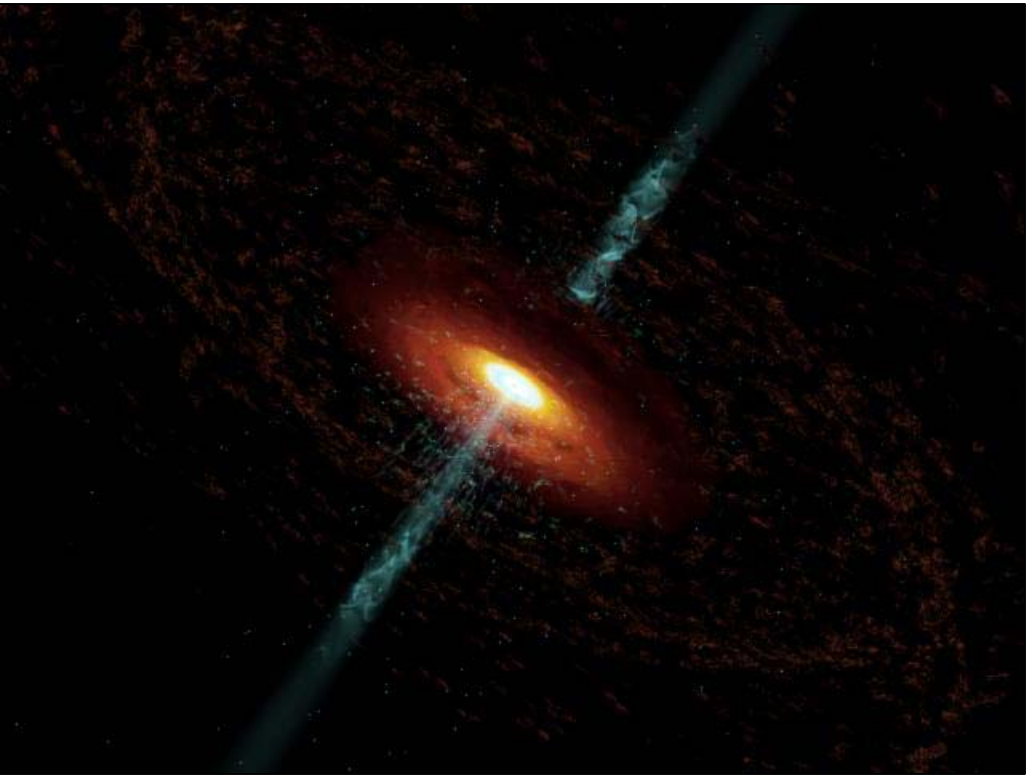


Stereo Anisotropy: Good for Point Sources

- Max likelihood search in AGASA + HiRes data sets (include details of pointing accuracy) yields one possible joint source: the AGASA triplet + one HiRes event.
- The “Quartet” may be first point source (Ursa Major). Chance probability = 0.006. **Needs confirmation.**



BL Lac Correlation



- BL Lac - special type of blazar, active galaxy with jet axis aligned with 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

The history of correlations with AGASA and Yakutsk events involved tuning of cuts to search for correlations. We tested 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 confirmed.

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				

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

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

In addition this recent claim is based upon published HiRes data for which limited information was publicly available. It uses a new 10^{19} eV threshold and thus it represents a new claim which must itself be tested.

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:

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

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^{19} eV are expected to be deflected many degrees by the galactic magnetic field. (Another student is looking for arcs of events correlated with the BL Lacs)

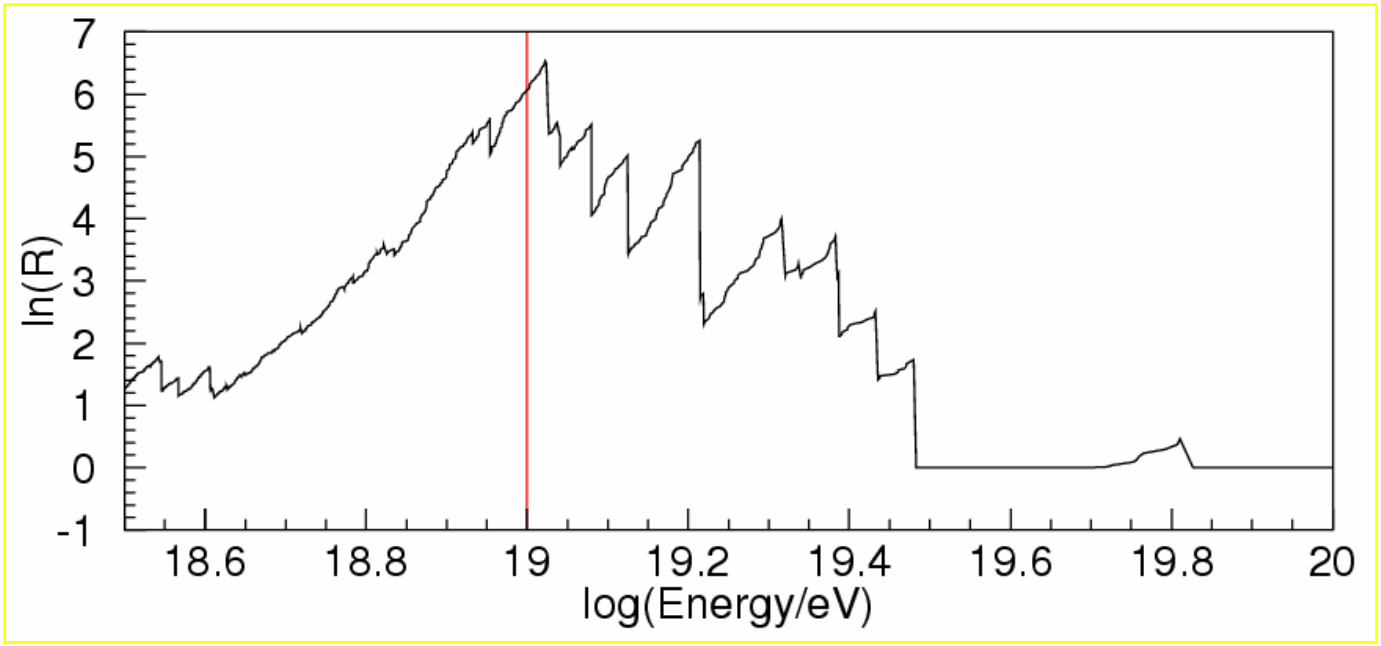
Correlations on the scale of the HiRes angular resolution imply that primary must be neutral (at least over most of its path). Neutrons and photons have a very short mean path (~ few Mpc) at this energy...

Use current sample to decide *a priori* what will be tested with "new data" collected after January 2004.

BL Lac Correlation: Energy Dependence

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

Here, we perform the maximum likelihood analysis with varying energy thresholds, from $10^{18.5}$ to 10^{20} eV:



For high energy events, 10^{19} eV appears to be the optimal energy threshold

BL Lac Correlation: Energy Dependence

If we perform the analysis on all the events below 10^{19} eV, there is correlation: $n_s = 22$ with ln R = 3.10.

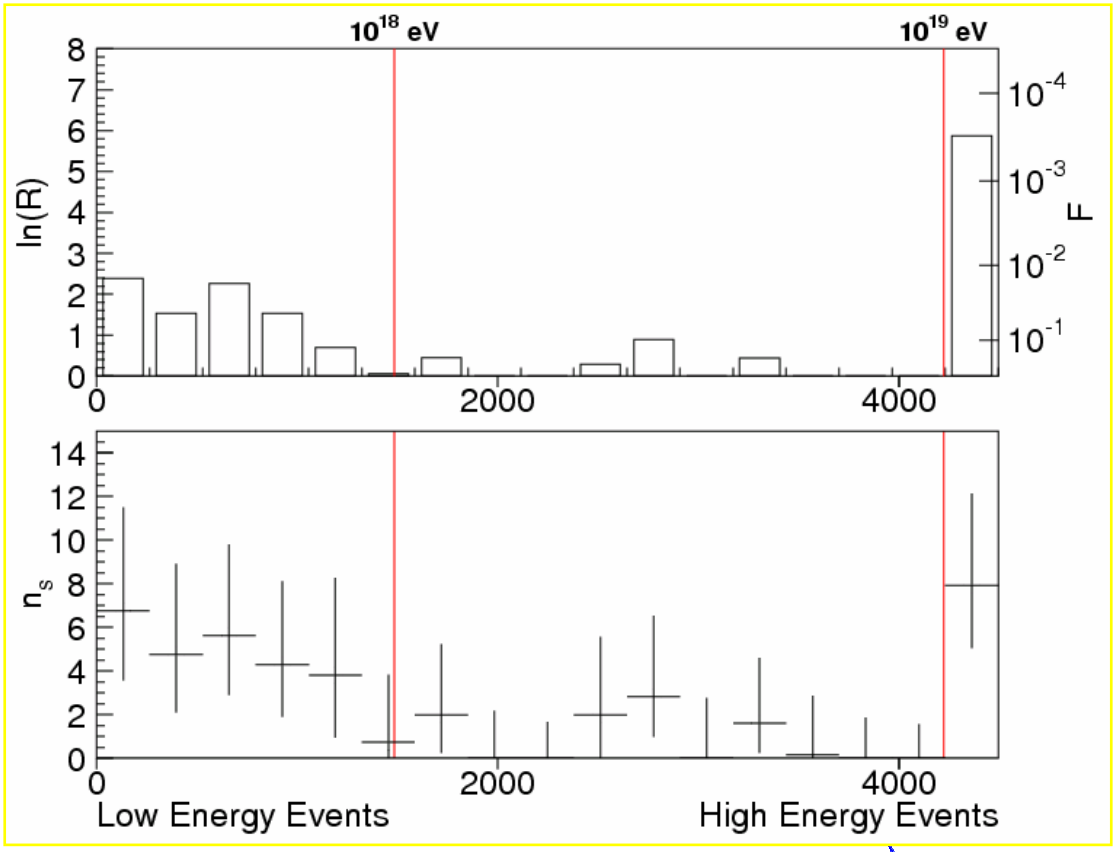
The fraction of isotropic MC sets with stronger signal is $F = 6\times10^{-3}$.

Most of the correlated events are below 10^{18} eV.

For the total HiRes data set:

$n_s = 31$

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



BL Lac Correlation: *The Source Sample*

The confirmed BL Lacs in the Veron Catalog are classified as "BL" or "HP" for High Polarization.

However- 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^{19} 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^{19} 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. ….. So "Almost *Apriori*"

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

TeV BL Lac Correlation

Six BL Lacs are confirmed sources of TeV g-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 max likelihood analysis yields:

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

Above 10^{19} eV: $n_s = 2$ with $F = 2\times10^{-4}$

These are not independent results: the samples overlap.

Analysis has been *a posteriori*, so *F* values are not true chance probabilities.

Correlations can only be confirmed with independent data.

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^{19} eV:

$F = 10^{-5}$

Confirmed TeV blazars, all HiRes events:

$F = 10^{-3}$

These are not independent results: the samples overlap.

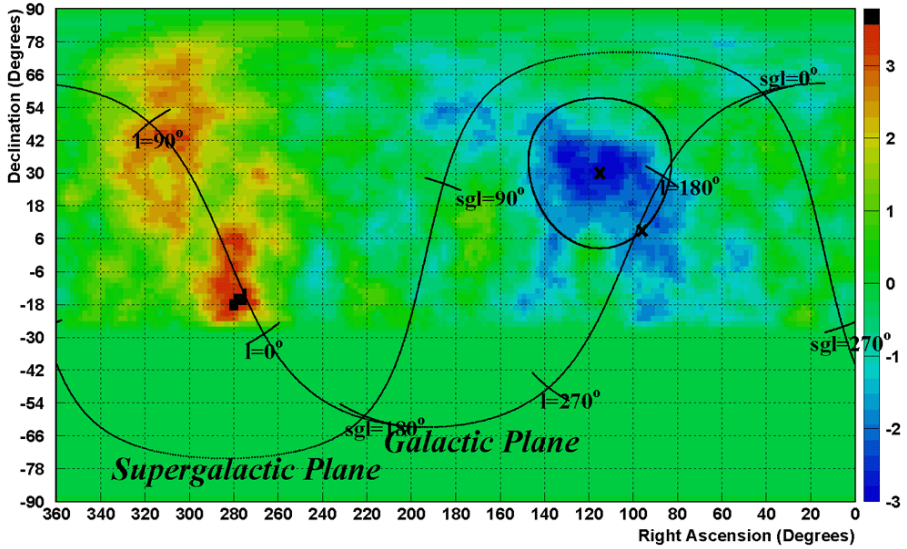
Analysis has been *a posteriori*, so *F* values are not true chance probabilities.

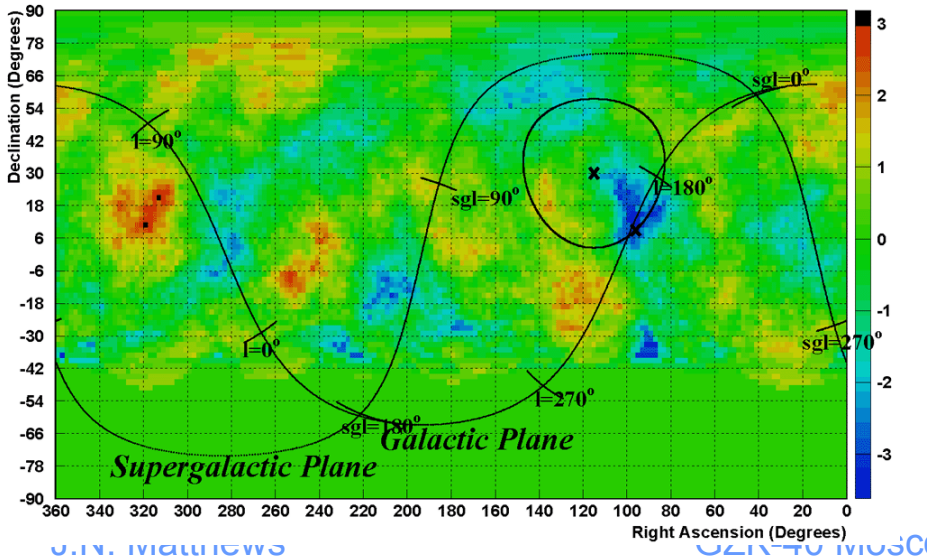
Correlations can only be confirmed with independent data.

Switch to HiRes-II Mono

- HiRes-II mono has large statistics and good geometrical reconstruction
- wider energy range
- Use it to search for large-scale structure

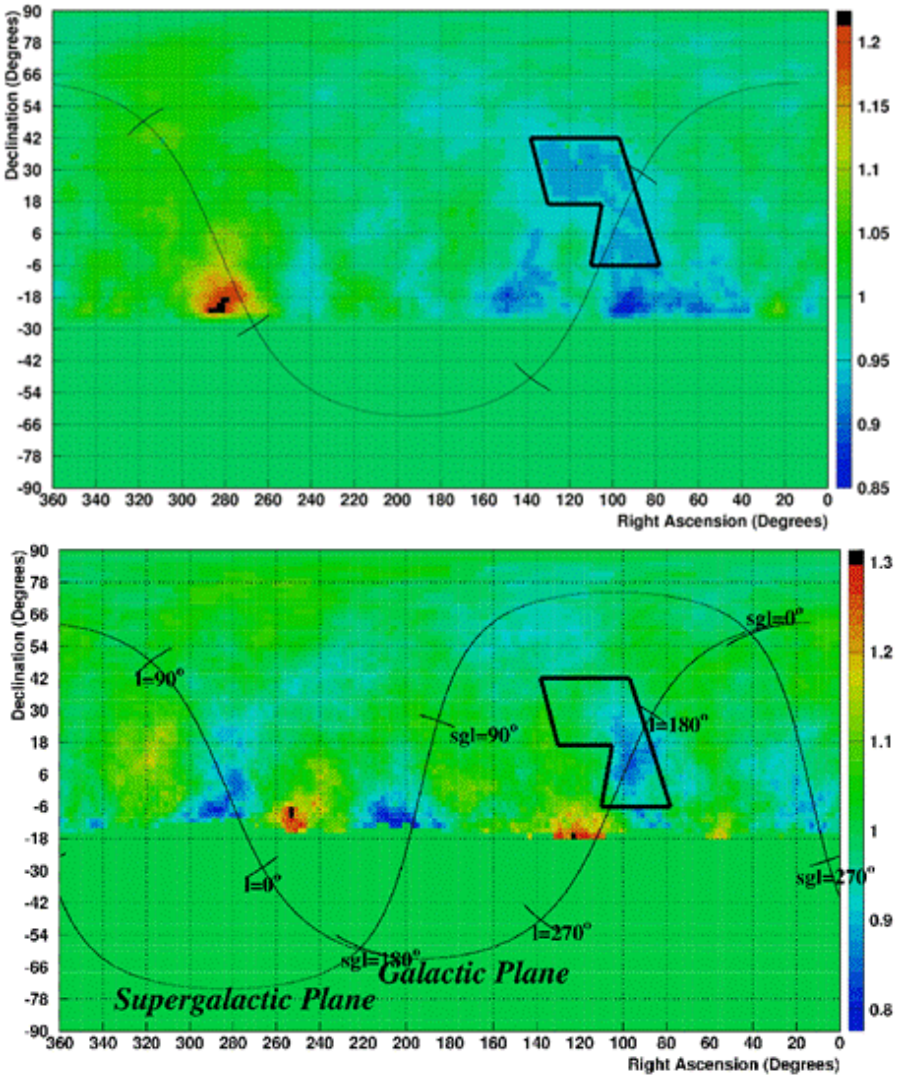
Significance Plots (summed over 20º circles)





- **AGASA** – ABOVE - (data "stolen" from .ps file) observes an excess near galactic center, deficit near anticenter.
- **HiRes** – BELOW - has low exposure near the galactic center: thus better to compare anticenter region
- **Energy Cuts:**
  - HiRes: All Energies
  - AGASA: 1-2 EeV
- Most Significant Deficits near the galactic anticenter:
  - AGASA: S=-3.0σ at (115º,30º)
  - HiRes: S=-3.62σ at (96º,9º)
- "HiRes-AGASA Circle":
  - Centered at (115º,30º)
  - Radius=27.5º, so that the circle passes trough (96º,9º)

Ratio Plots (summed over 20º circles)



AGASA Ratio above ("stolen" from .ps file)

HiRes Ratio below

- "Lucky 7" Region
  - Reflects the "shape" of the AGASA deficit
  - Ends at DEC=-6º because HiRes has low statistics below that value
  - Encloses 362 bins
- Energy Cuts:
  - HiRes: All Energies
  - AGASA: 1-2EeV

HiRes

Generate Isotropic Distribution via the HA - Dec Shuffling Method

- Throw each Hour Angle Declination (HA,DEC) pair for each sidereal time:
  - Each Event Has Sidereal Time (SID) and a (HA,DEC) pair
  - In a double do-loop, go over all recorded sidereal times and over all recorded (HA,DEC) pairs
    - Evaluate RA=SID-HA
    - Then each (RA,DEC) is considered an isotropic event
- Throw these events into bins or circles and when finished, normalize so that the overall number of background events is the same as the overall number of real events (10,326 for all energies)

Prepare plots which reveal larger scale structure (integrate over 20^o circles)

- Divide the sphere into 2x2 degree bins
- Put event directions and locations of each bin center into normalized vectors
  - Let $\mathbf{b}_k$ be the vector which points towards the center of a k-th bin
  - Assign vector $\mathbf{x}_l$ to each event (real or isotropic)
- In a double "do loop", go over each event (first) and then each 2x2 degree bin
  - If $\mathbf{x}_l * \mathbf{b}_k > \cos(20^o)$, increment the k'th bin (i.e. event $\mathbf{x}_l$ is within 20^o of the center of k-th bin)
- Each 2x2 degree bin contains the number of events within 20^o of its center
- Apply statistical analysis to each 2x2 degree bin

Compute Significance and Ratio

- Significance and Ratio are computed for each circle:

$$S=(N_{DATA}-\alpha*N_B)/\mathrm{sqrt}(N_{DATA}+\alpha^2 N_B)$$

$$R=N_{DATA}/(\alpha*N_B)$$

- N_B is the number of background events in the circle
- α is the normalization constant

Simulate the Random Data Set

- Throw the HA-DEC distribution into 2x2 degree bins and normalize it so that 1 is the largest value of any bin
- Call each such bin B_k
- Sample event with a given sidereal time:
  - Take HA (0,360^o) and DEC (-90^o,90^o) from flat distributions
  - Take a real number t (0,1.0) from a flat distribution
  - From sampled HA and DEC, determine the value of k
  - If t<B_k count event, otherwise continue sampling event
    - If event is counted, compute RA=SID-HA and record the event
  - Continue until obtained the desired number of simulated events

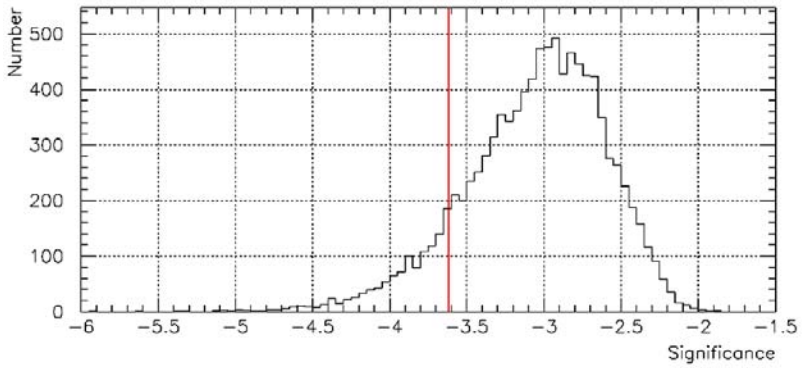
Evaluate the Chance Probability

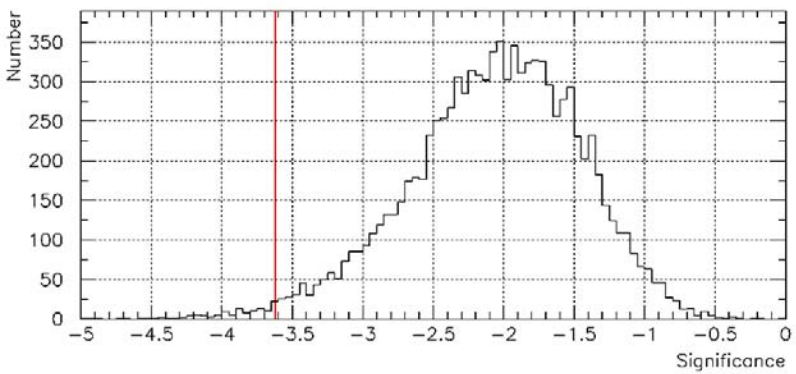
- Chance probability is referring to the probability that HiRes trough near the G.A.C is due to random fluctuations
- Define HiRes-AGASA Circle
  - Centered at the lowest (estimated) AGASA significance (115^o,30^o)
  - Has radius of 27.5^o so that it passes trough (96^o,9^o), the lowest HiRes Significance S_0

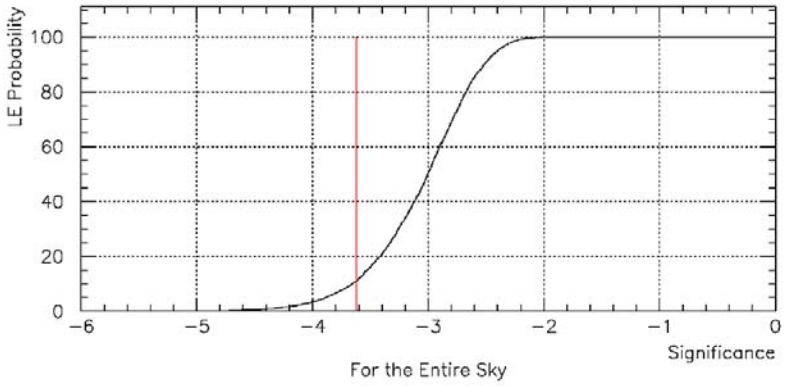
Define the region based on the AGASA ratio shape

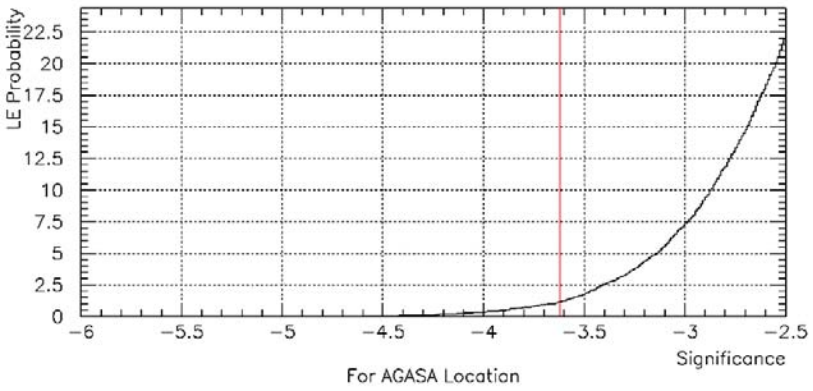
- Determine the χ^2 between the AGASA and HiRes Ratio values for bins in the region, call it χ^2_0
- Make 10,000 simulated sets and for each simulated set:
  - Determine the lowest significance S in the HiRes-AGASA circle
  - Compute χ^2 between the AGASA ratio and the ratio for this set in the region
- Count for how many sets $S<S_0$ AND $\chi^2<\chi^2_0$, then divide this number by 10,000

Distribution of Lowest Significances; All Energies



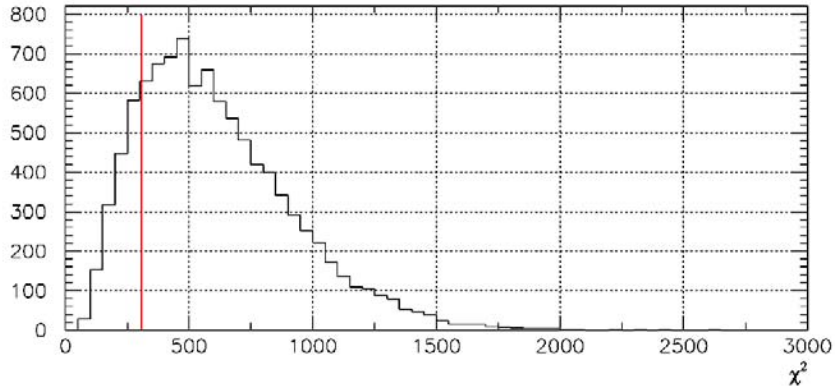


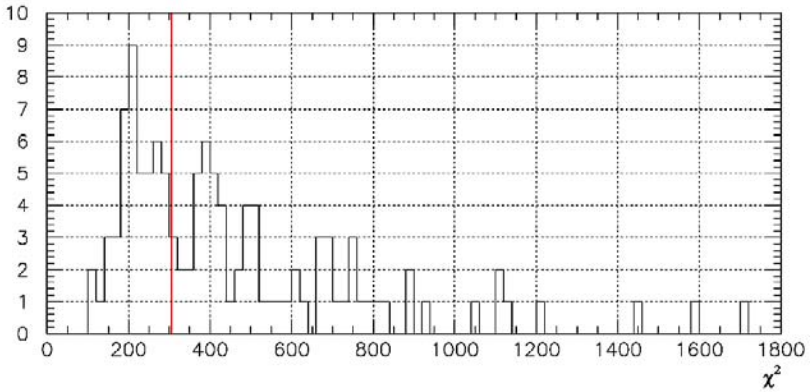


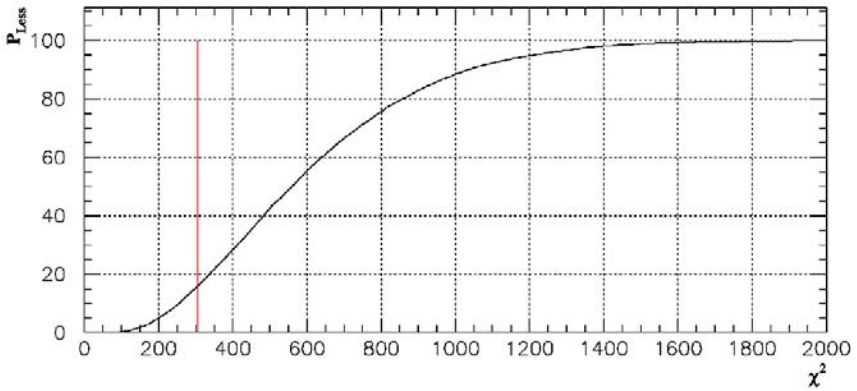


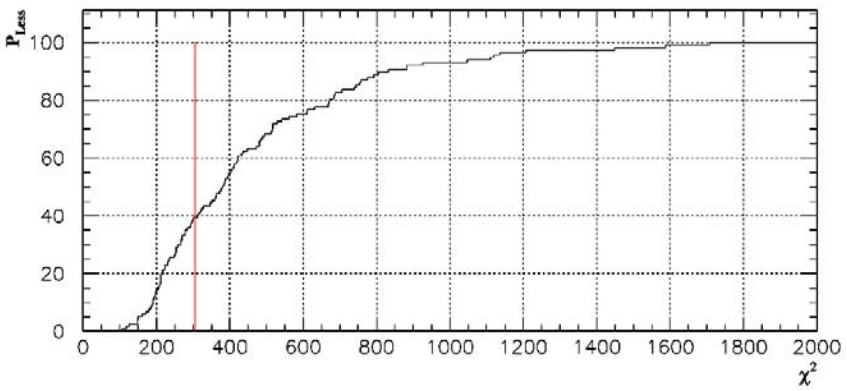
- Left: Entire Sky,
- Right: within 27.5^{o} of AGASA deepest point.
- Red Line Corresponds to S=-3.62σ, actual HiRes Significance.

Distribution of χ^2 values; All Energies





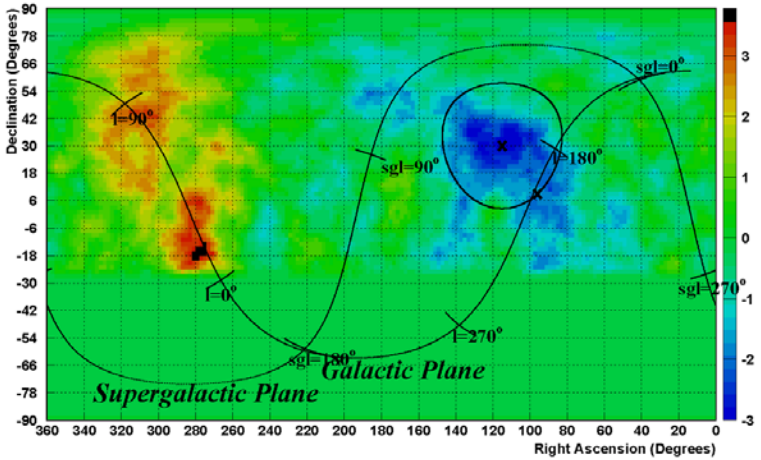




- On the left, we have χ^2 distribution when simulated ratios are compared to AGASA ratio in the region.
- On the right, we have χ^2 values for trials with S<-

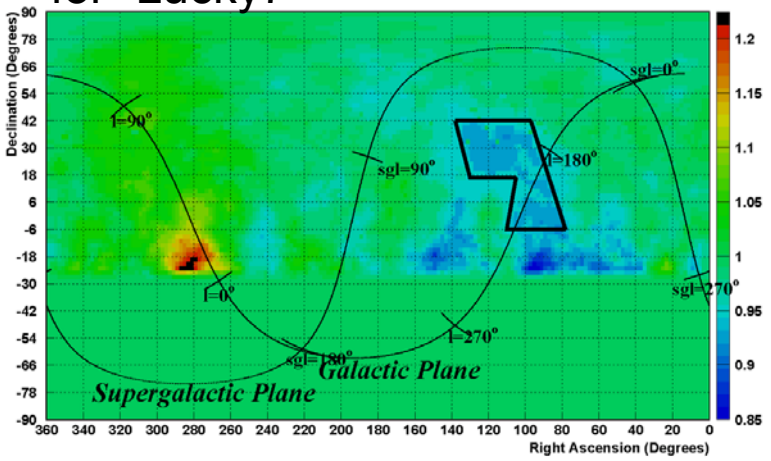
Energies 17.5-18.5

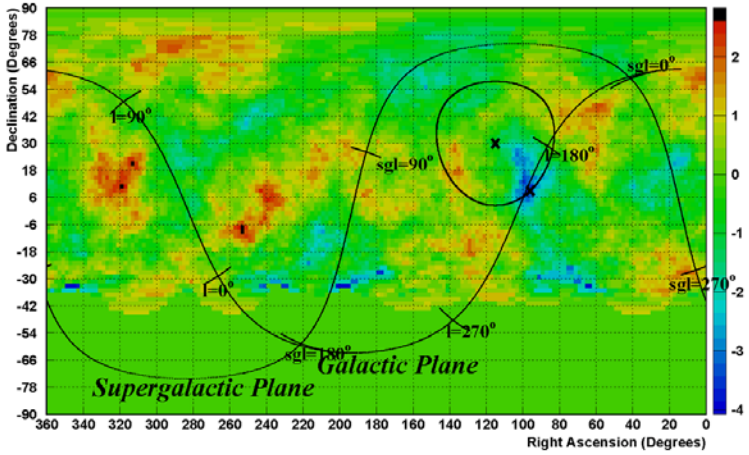
Significance for
Circle Centered at AGASA Min



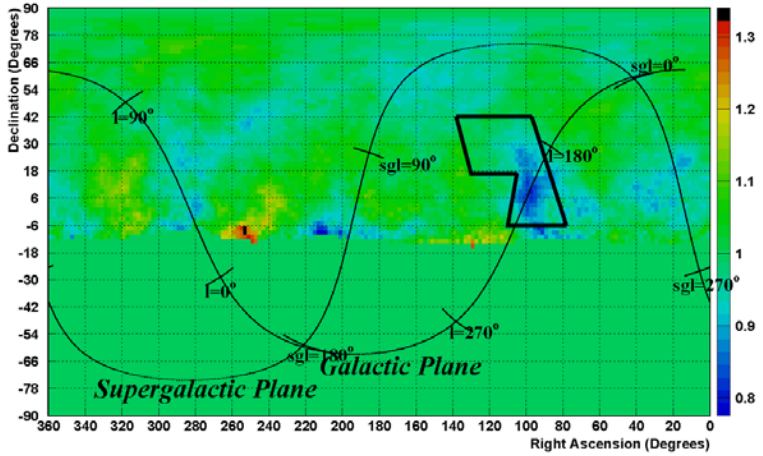
AGASA

Ratio $R=N_{DATA}/(\alpha*N_B)$
for "Lucky7"

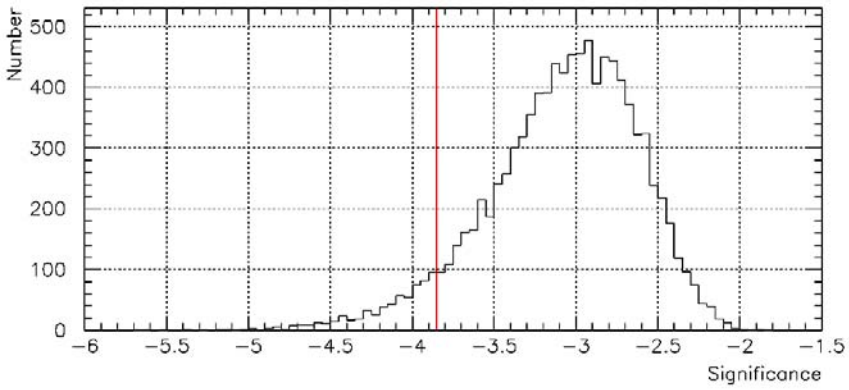


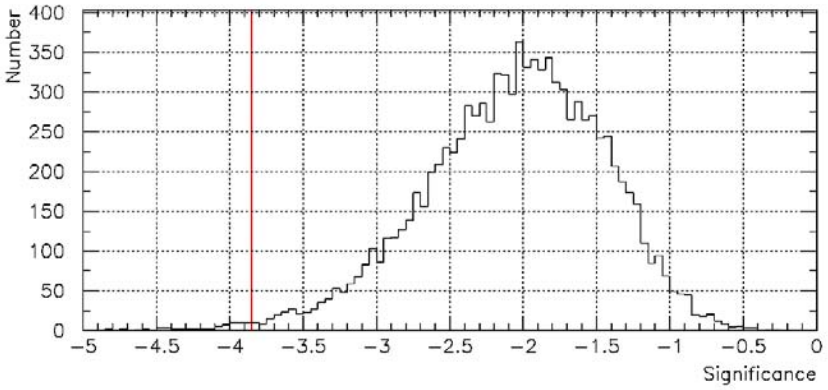


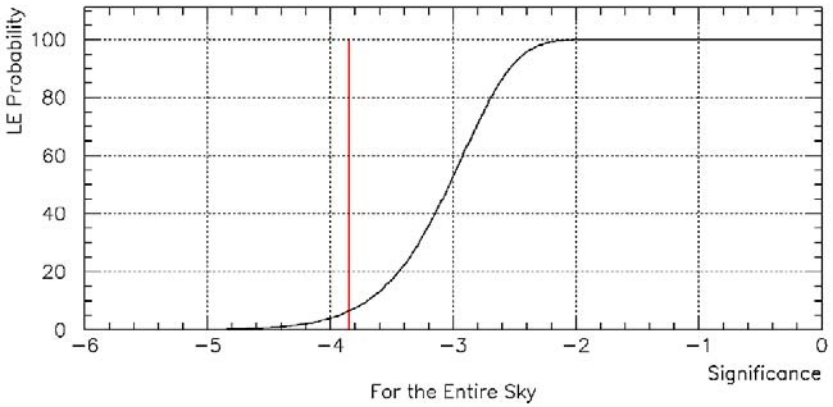
HiRes

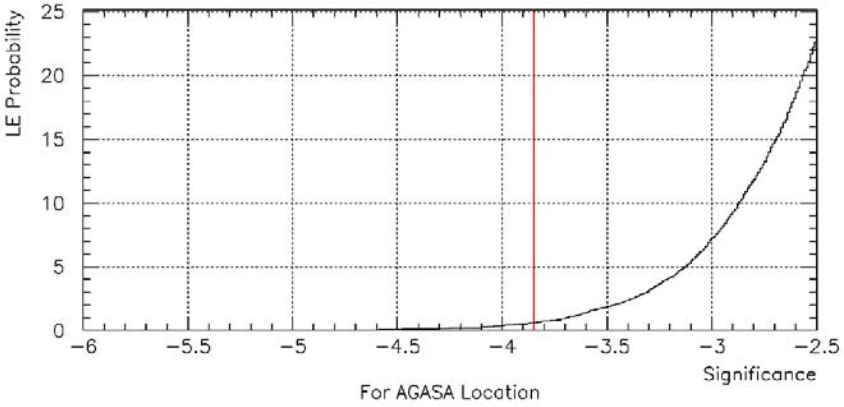


Distribution of Lowest Significances; 17.5-18.5



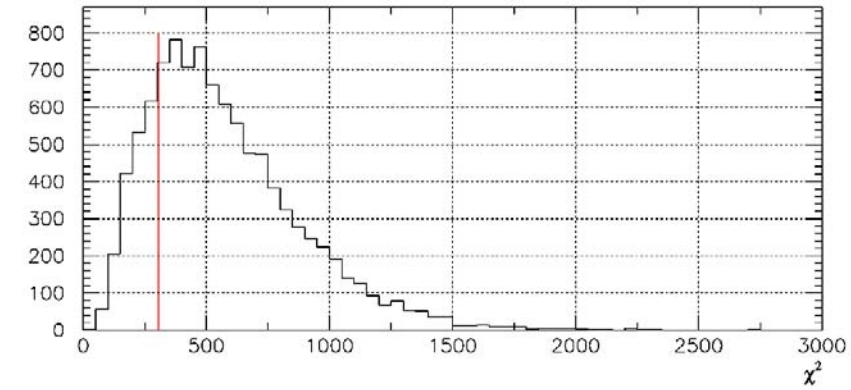


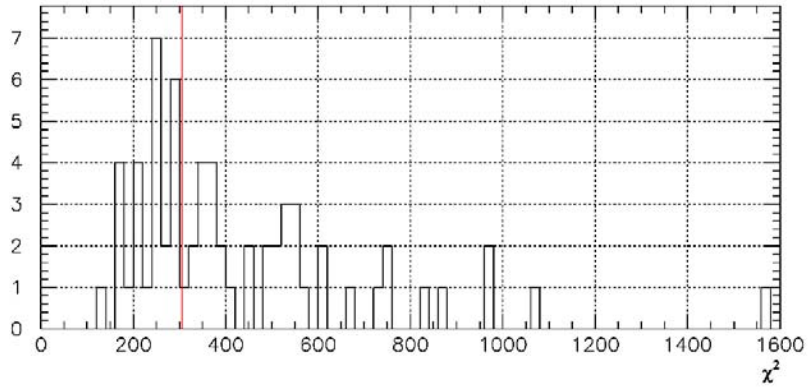


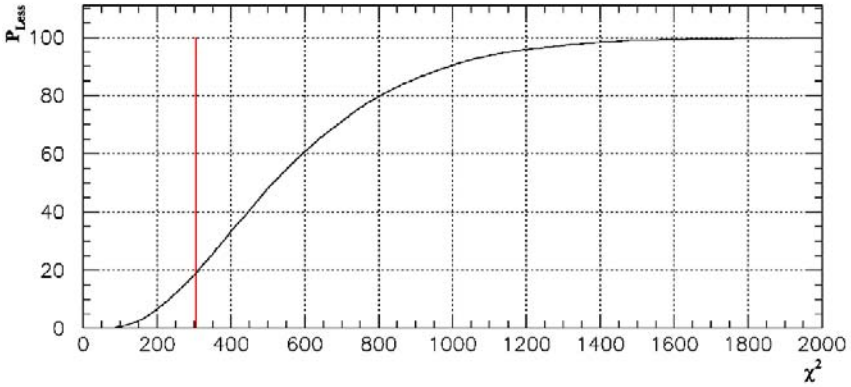


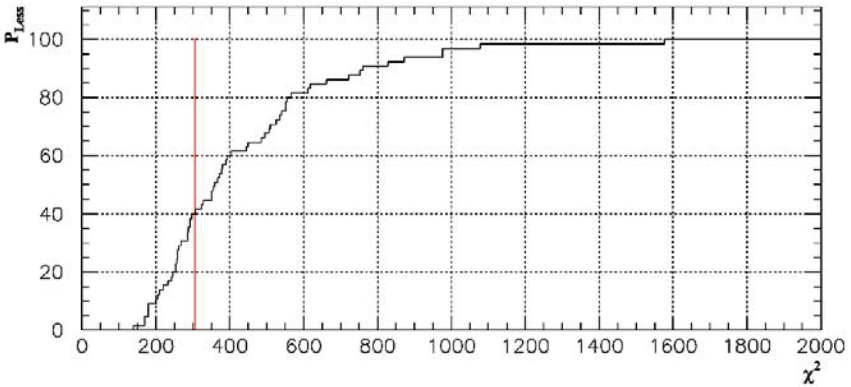
- Entire Sky - anywhere on the sky,
- AGASA location – anywhere within 27.5^{o} of (115,30)^{o}
- Red Line Corresponds to S=-3.85σ, actual HiRes Significance near the G.A.C.

Distribution of χ^2 values; $E = 10^{17.5}$-$10^{18.5}$ eV









- On the left, we have χ^2 distribution when simulated ratios are compared to AGASA ratios in the region.

HiRes

Summary

- AGASA Energy Range is always 1-2 EeV
- For All HiRes Energies:
  - $S = -3.62\sigma$
  - $\chi^2 = 305.7$
  - $P_{Ch}(S < -3.62\sigma) = 0.012$
  - $P_{Ch}(\chi^2 < 305.7) = 0.16$
  - $P_{Ch}(\chi^2 < 305.7, S < -3.62\sigma) = 0.0046$ (2.6 σ)
- For HiRes Energies - $10^{17.5}$-$10^{18.5}$ eV:
  - $S = -3.85\sigma$
  - $\chi^2 = 305.2$
  - $P_{Ch}(S < -3.85\sigma) = 0.0065$
  - $P_{Ch}(\chi^2 < 305.7) = 0.19$
  - $P_{Ch}(\chi^2 < 305.2, S < -3.85\sigma) = 0.0026$ (2.8 σ)

Some Indication of Confirmation Akeno/AGASA Large-Scale Structure

- HiRes-II mono anisotropy data: $10^{17.5} < E < 10^{18.5}$ eV, integrated over 20 deg. circle.
- Deficit of events along an arc in galactic anti-center direction, similar to Akeno/AGASA result.
- Similarity has 10^{-3} chance probability.

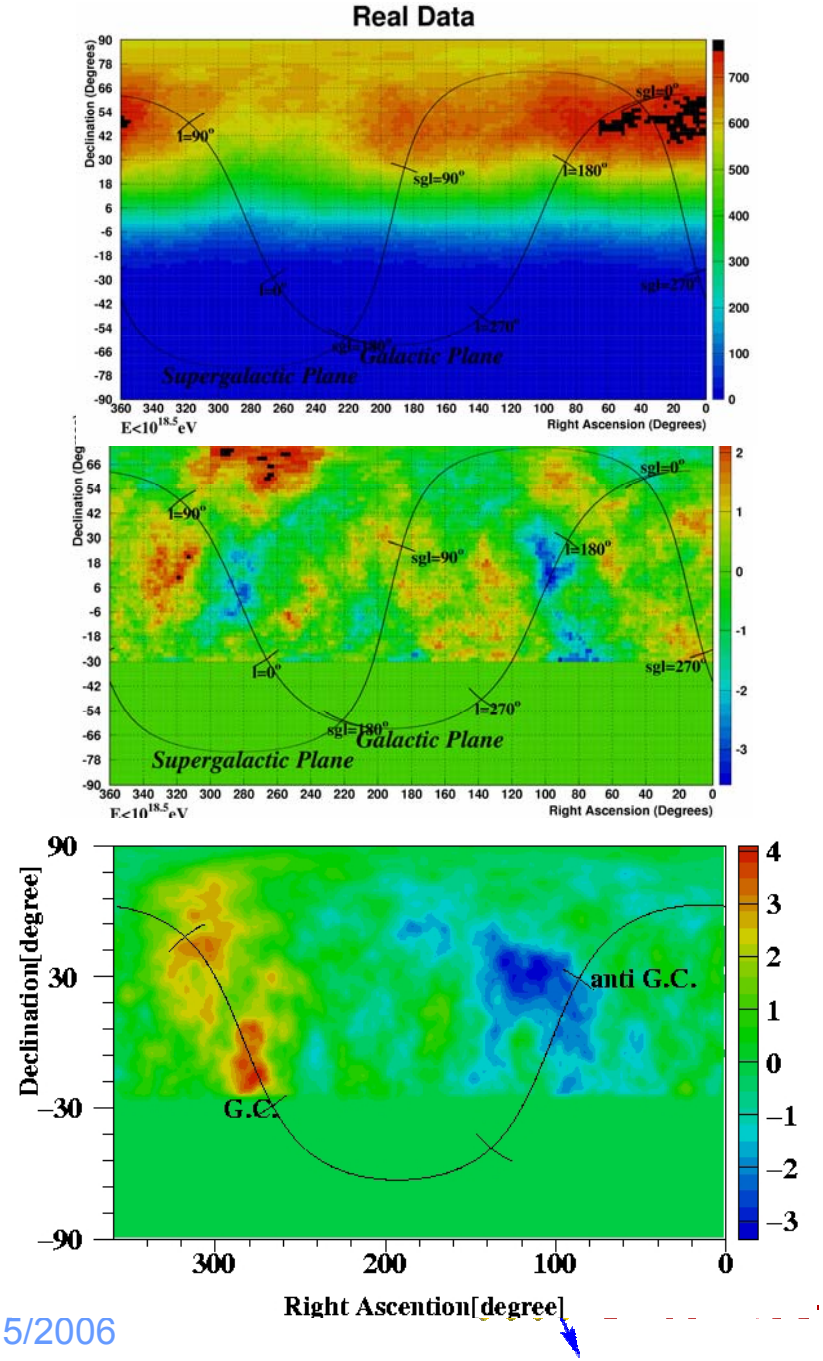
Conclusions

- HiRes events above 10^{19} eV show no small-scale clustering
- 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 previously made claims
  - Newly observed correlations between HiRes and BL Lacs:
    - confirmed BL Lacs brighter than optical magnitude 18
    - TeV γ-ray blazars
  - Must be tested with independent data
- Future
  - Data collected between January 2004 and April 2006 will provide an independent data set (albeit with lower statistics) to provide an independent test of BL Lac correlations
- Some indication that the deficit observed by AGASA at the Anti-Galactic center my be there


HiRes

Some Confirmation of Akeno/AGASA Large-Scale Structure

- HiRes-II mono anisotropy data: $10^{17.5} < E < 10^{18.5}$ eV, integrated over 20 deg. circle.
- No ridge of events in Cygnus arm region.
- Deficit of events along an arc in galactic anti-center direction, similar to Akeno/AGASA result.
- Similarity has 10^{-3} chance probability.




HiRes


HiRes

Stereo Anisotropy: Search for Correlations with BL Lac's

- Choose BL Lac sources from Veron catalog. Use m<18 cut pioneered by Gorbunov *et al.* for searches with AGASA, HiRes data.
  - See correlations with HiRes events.
  - See correlations with TeV gamma ray sources.
  - Chance probability ~ 10^{-5} when using "BL" and "HP" sources in Veron catalog.
- **Needs confirmation**.


HiRes

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:

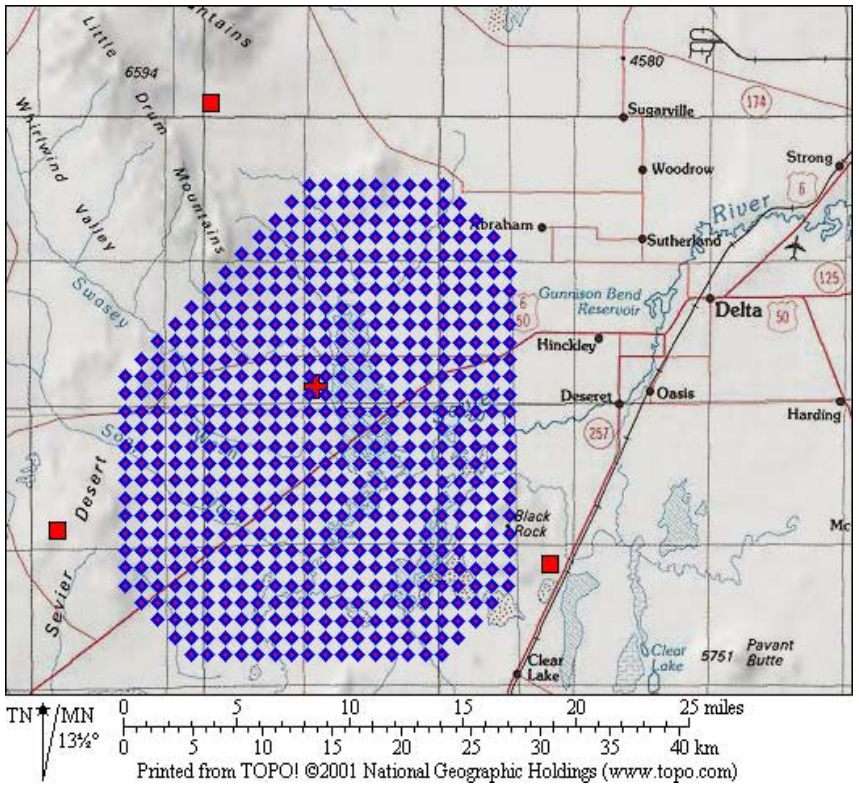
R.U. Abbasi et al., Astrophysical Journal 623 (2005) 164 [astro-ph/0412617]

HiRes / BL Lac Correlations:

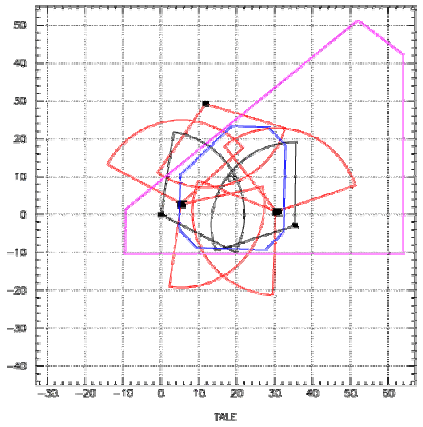
R.U. Abbasi et al., for submitted to Astrophysical Journal,

Future Experiment: The Telescope Array (TA) and TA Low Energy Extension (TALE)

- TA surface detector: 576 scintillation counters, 1.2 km spacing.
- 3 TA fluorescence detectors overlook SD, 108^{o} in azimuth each.
- 2 TALE fluorescence detectors plus infill array:
  - Observe the ankle with flat aperture.
  - Tower detector + infill array cover lower energies.



TA/TALE Anisotropy



- HiRes sees correlations with BL Lac's.
- Point source figures of merit at 10^{19} eV:

(HiRes has 31 events above bkg correlated with BL Lac's)

Experiment	**Aperture** (km^2 ster)	**Resolution**	**Figure of Merit** (A/Resolution^2)
HiRes stereo	300 (avg)	0.5 deg	1200
TA/TALE stereo	340	0.5	1360
TA SD	1500	1.5	667
S. Auger SD	6600	1.5	2933
TA/TALE hybrid stereo	260	0.1	**26000**

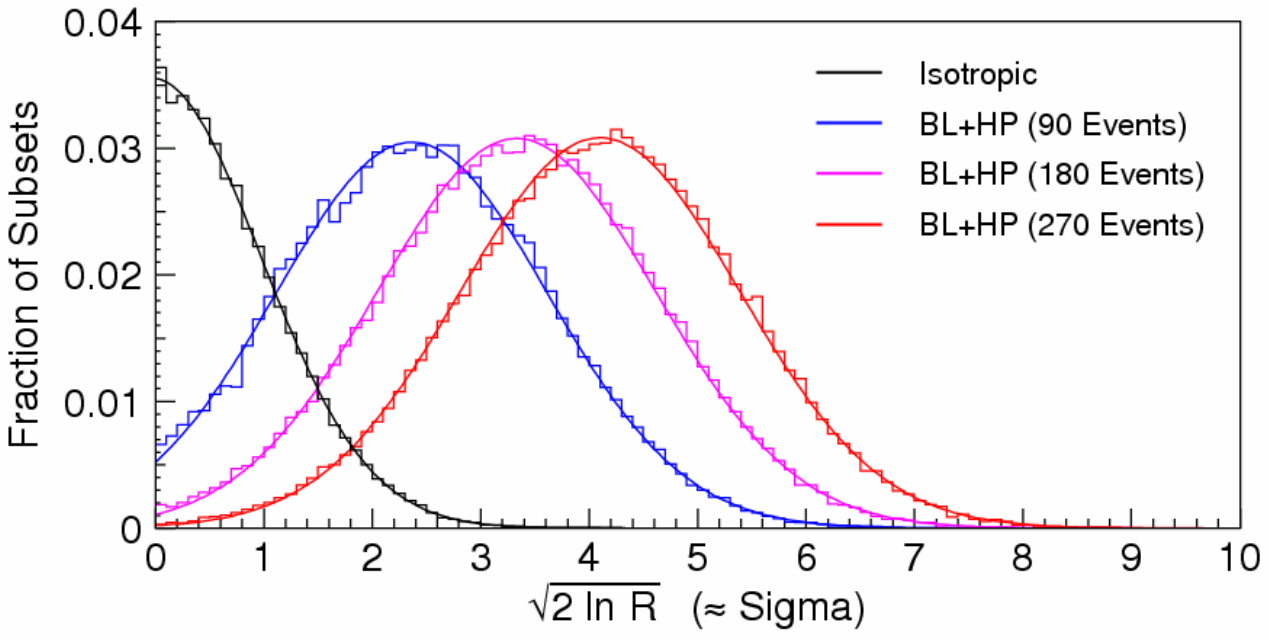
Multi-energy observations are important!

BL Lac Correlation: Sensitivity of Future Data

We estimate the sensitivity which future HiRes data will have by resampling the real HiRes events (Bootstrap resampling)

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

(Arrival directions of past year of data have not been analyzed.)



BL Lac Correlation: New Claim

Most recent claim by Gorbunov *et al.* is based on published HiRes data. It uses a 10^{19} eV threshold, thus it represents 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
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
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.

HiRes

Outline

- Angular Correlation - General Search for Excess Clustering
  - HiRes Stereo Events above 10 EeV
- Point Source Search using Maximum Likelihood Method
  - combined HiRes Stereo and AGASA Data Sets above 40 EeV
- Correlations with BL Lacertae Objects
  - Test previous claims with HiRes data
  - Examine new claim of HiRes / BL Lac correlation
- Conclusion