Study of the Cosmic Ray Sky with HiRes Stereo

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HiRes Collaboration

Kavli Institute for Theoretical Physics

3 May 2005

High Resolution Fly's Eye

- University of Utah
- Columbia University
- Rutgers University
- University of New Mexico
- University of Montana
- University of Adelaide
- Los Alamos National Laboratory
- University of Tokyo

HiRes 2 on Camels' Back
Dugway Proving Grounds, Utah

http://hires.phys.columbia.edu
http://www.cosmic-ray.org

Outline

- The HiRes experiment
- The HiRes stereo data set
- Search for anisotropies
  - Two-point correlation and scan
  - Skymap above 40 EeV and 10 EeV
- Correlation with BL Lac objects
- Chemical composition
- Mono spectrum

Recent Journal Publications (Stereo)

- Search for Point Sources of Ultra-High-Energy Cosmic Rays above 4×10^{19} eV Using a Maximum Likelihood Ratio Test
  Astrophys. J. 623 (2005) 164 (arXiv:astro-ph/0412617)

- A Study of the Composition of Ultra-High-Energy Cosmic Rays Using the High Resolution Fly's Eye
  Astrophys. J. 622 (2005) 910 (arXiv:astro-ph/0407622)

- Study of Small-Scale Anisotropy of Ultra-High-Energy Cosmic Rays Observed in Stereo by HiRes
  Astrophys. J. 610 (2004) L73 (arXiv:astro-ph/0404137)

In preparation:

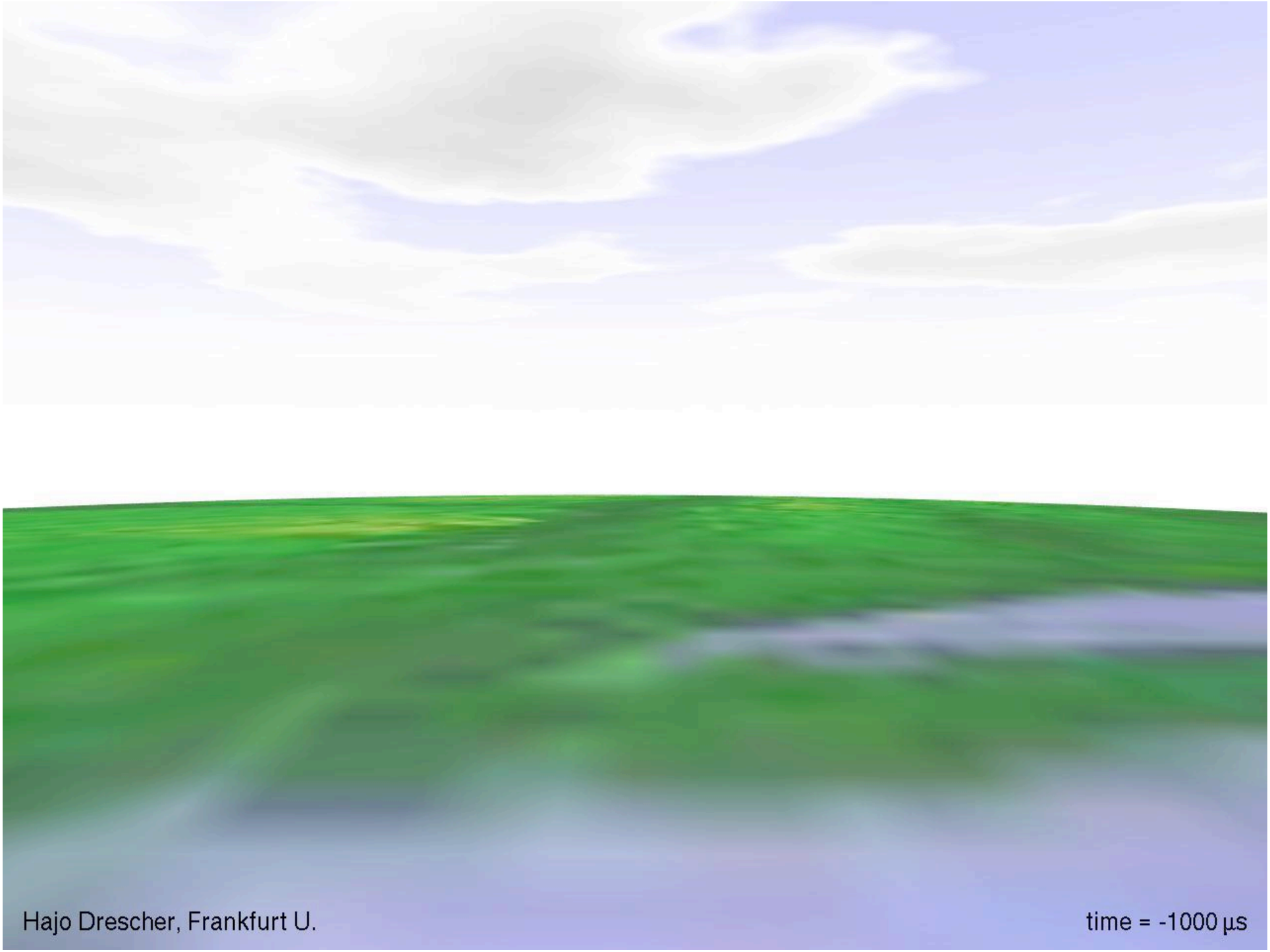
- Search for Cross-Correlations of Ultra-High-Energy Cosmic Rays with BL Lacertae Objects
  Astrophys. J.

Recent Journal Publications (Mono)

- Observation of the Ankle and Evidence for a High-Energy Break in the Cosmic Ray Spectrum
  submitted to Phys. Letters B (arXiv:astro-ph/0412617)

- A Search for Arrival Direction Clustering in the HiRes 1 Monocular Data Above $10^{19.5}$ eV
  Astroparticle Phys. 22 (2004) 139 (arXiv:astro-ph/0404366)

- Search for Global Dipole Enhancements in the HiRes 1 Monocular Data above $10^{18.5}$ eV
  Astroparticle Phys. 21 (2004) 111 (arXiv:astro-ph/0309457)


Hajo Drescher, Frankfurt U.
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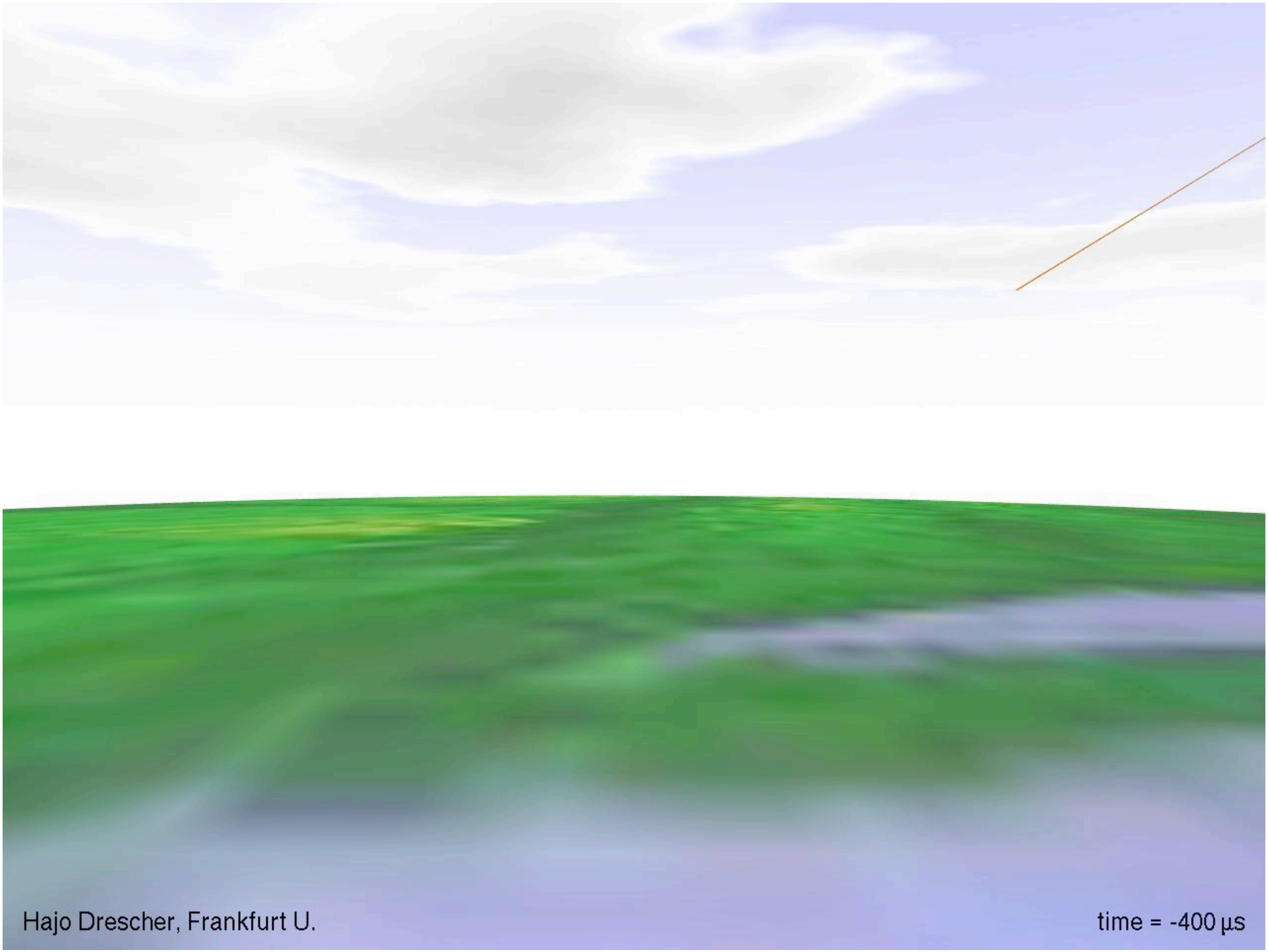
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Hajo Drescher, Frankfurt U.
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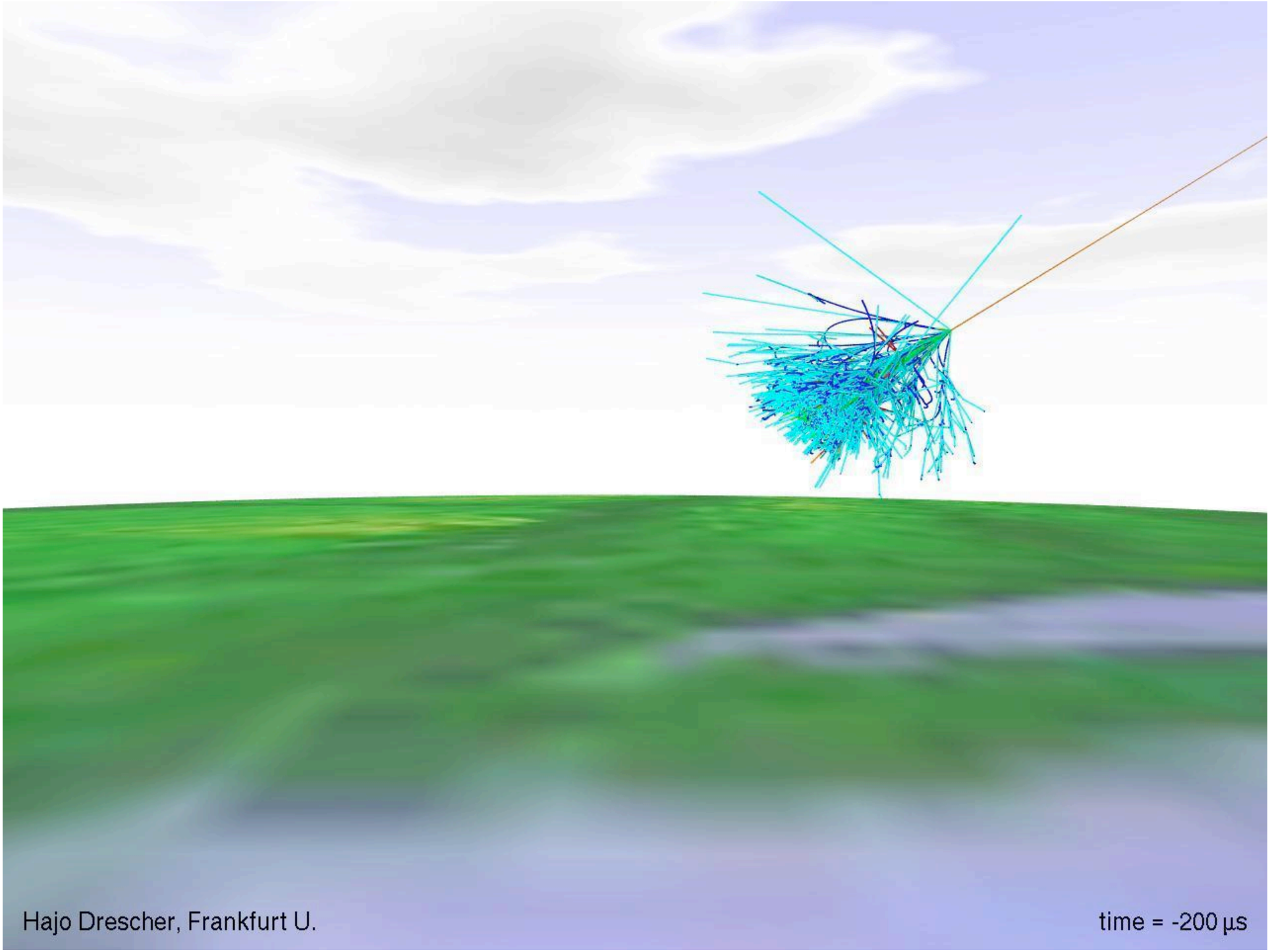
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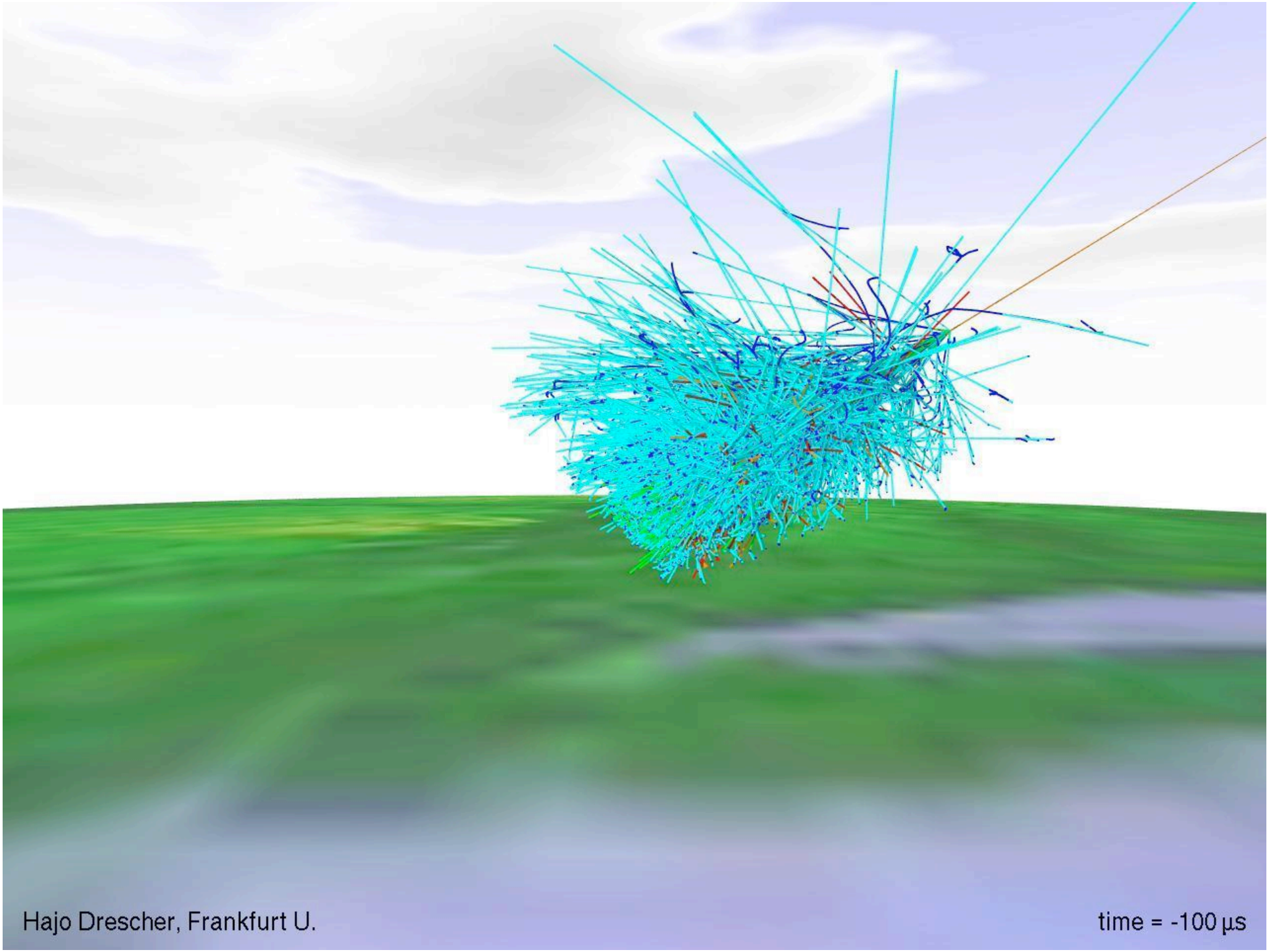
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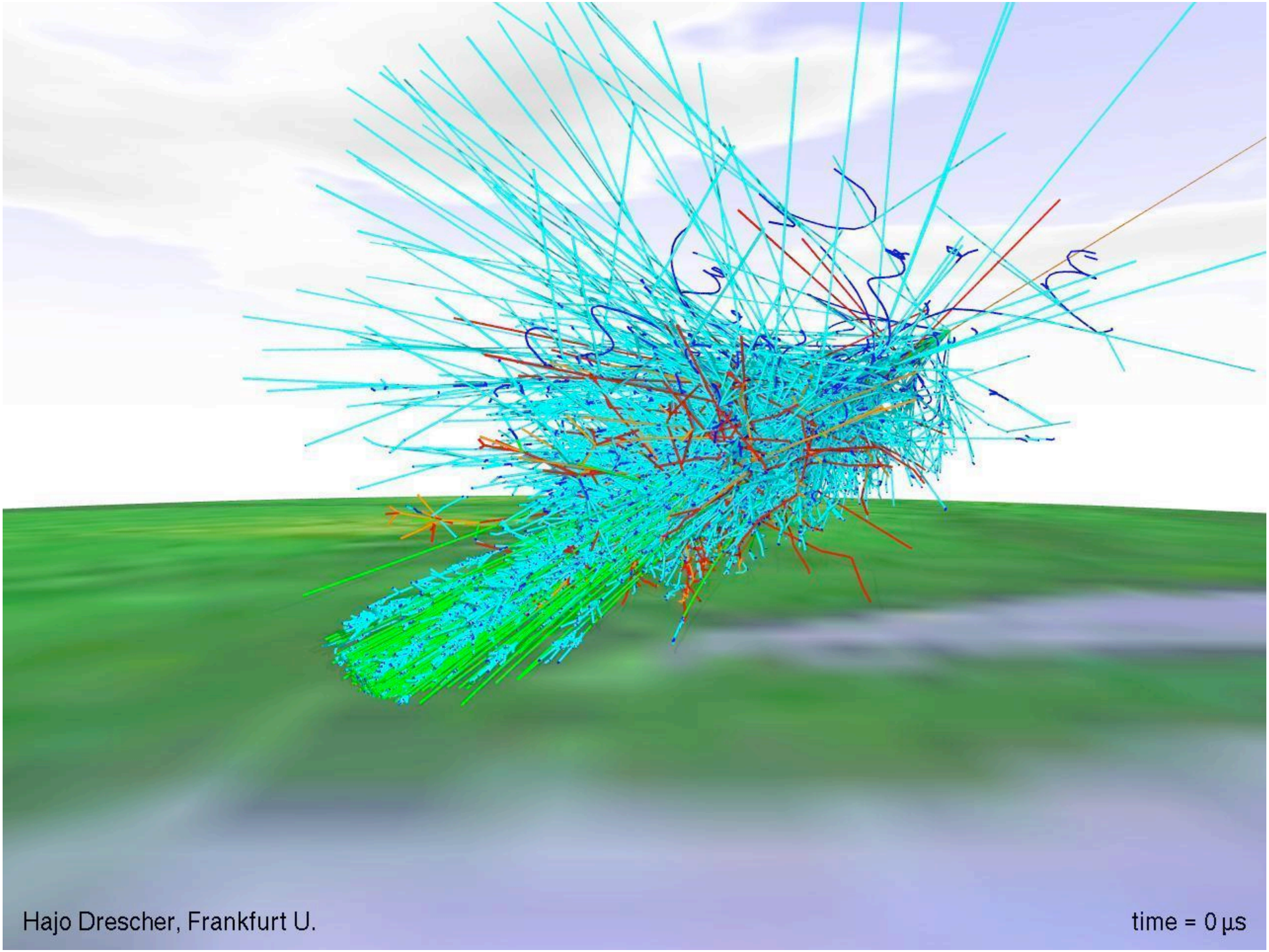
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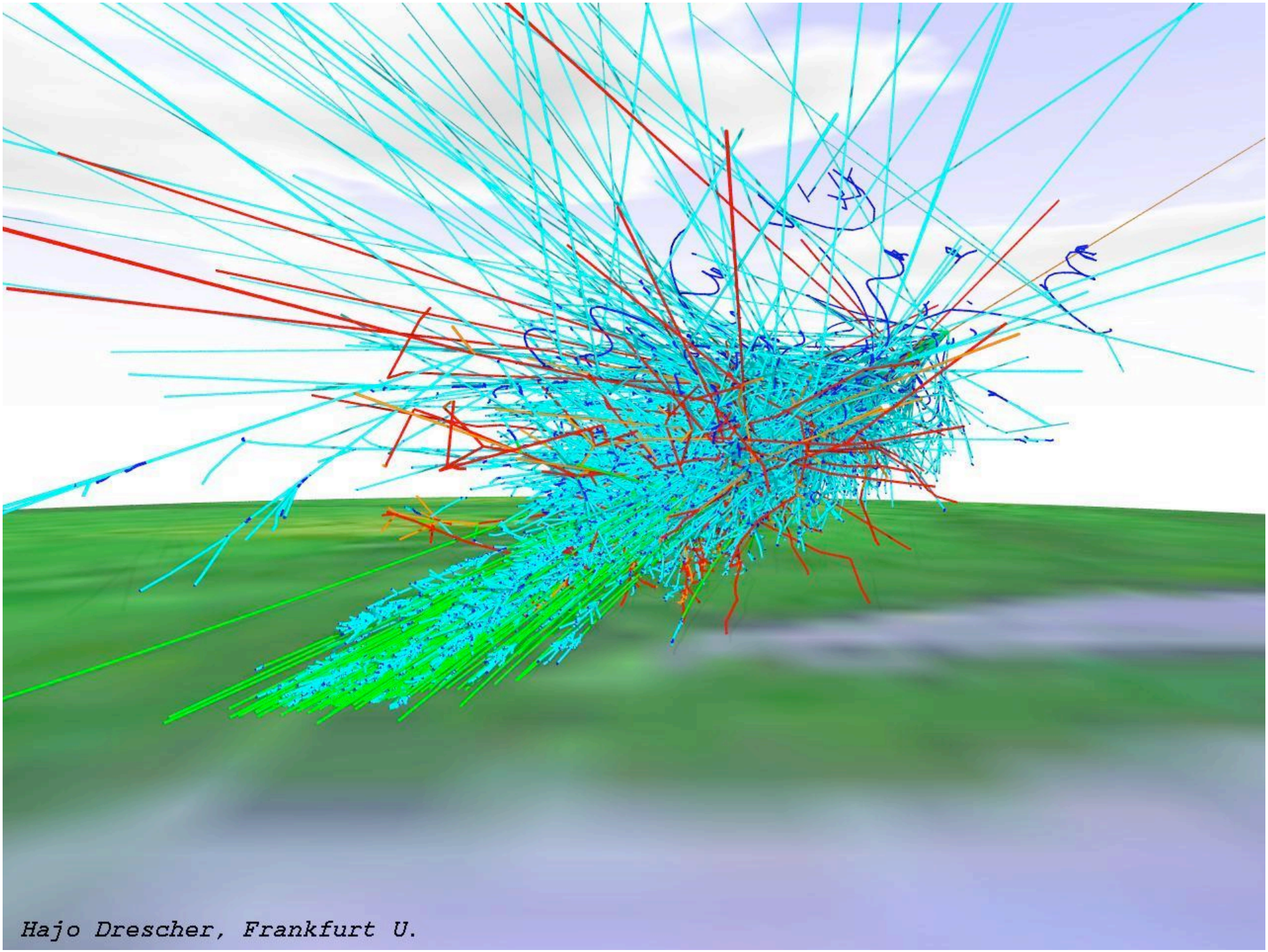
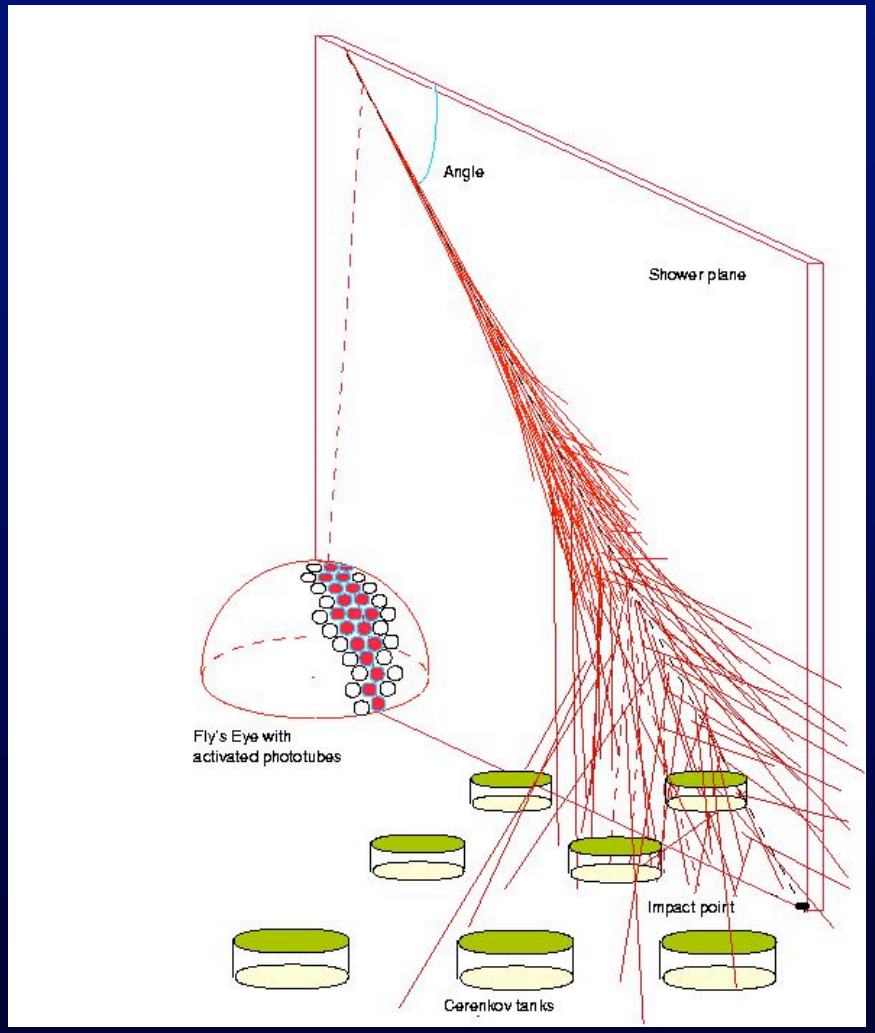
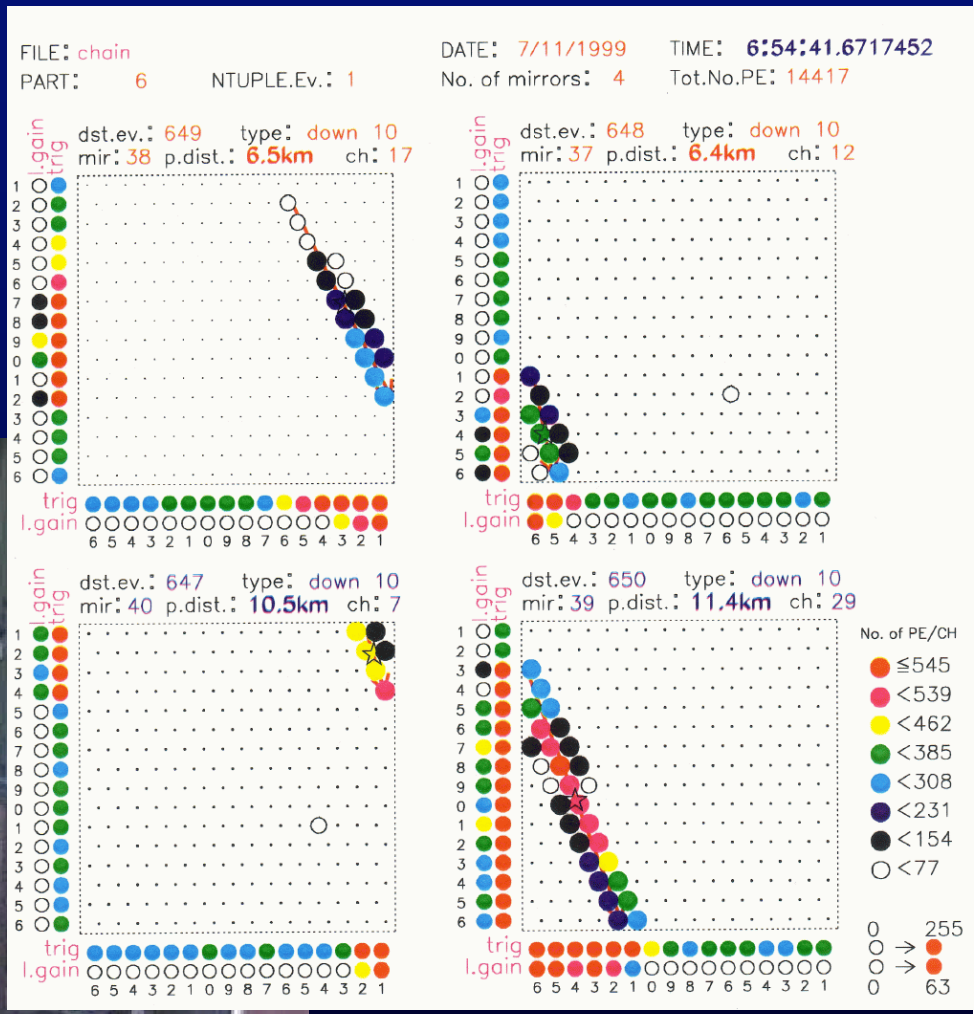

Hajo Drescher, Frankfurt U.

Detection Techniques

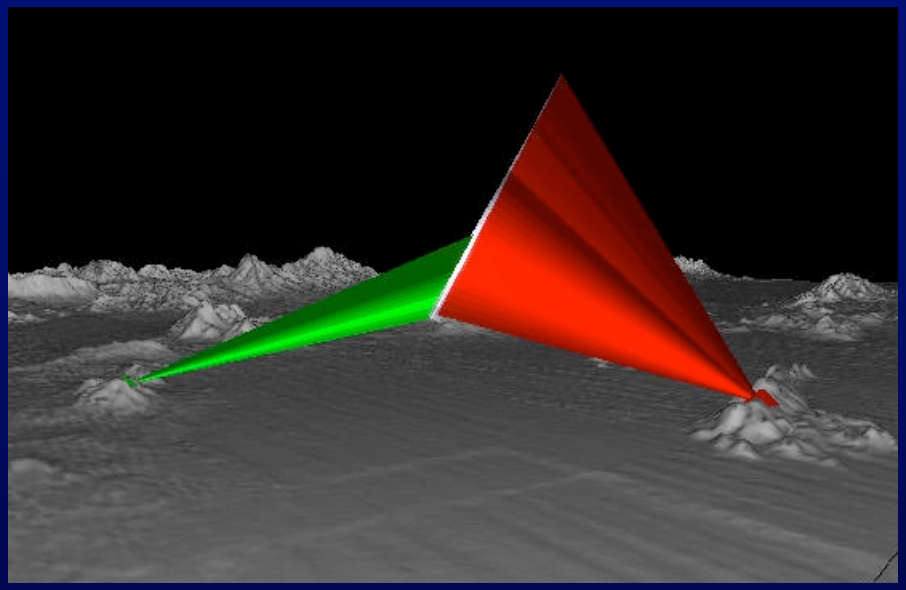
- Ground arrays sample the shower front arriving at ground level, air fluorescence detectors observe shower development in the atmosphere
- Air fluorescence detectors operate on clear, moonless nights with good atmospheric conditions, when the fluorescence light can be observed with photomultiplier tubes
- Air fluorescence detectors have a duty cycle of only about 8 to 10 % of a surface detector, but have a large “detector volume”



Air Fluorescence Technique



HiRes Stereo Detector



- HiRes is a stereo air fluorescence detector with two sites located at Dugway Proving Grounds, Utah.
- 112^{o} W longitude, 40^{o} N latitude, vertical atmospheric depth 860 g/cm^{2}

HiRes 1 at Five Mile Hill

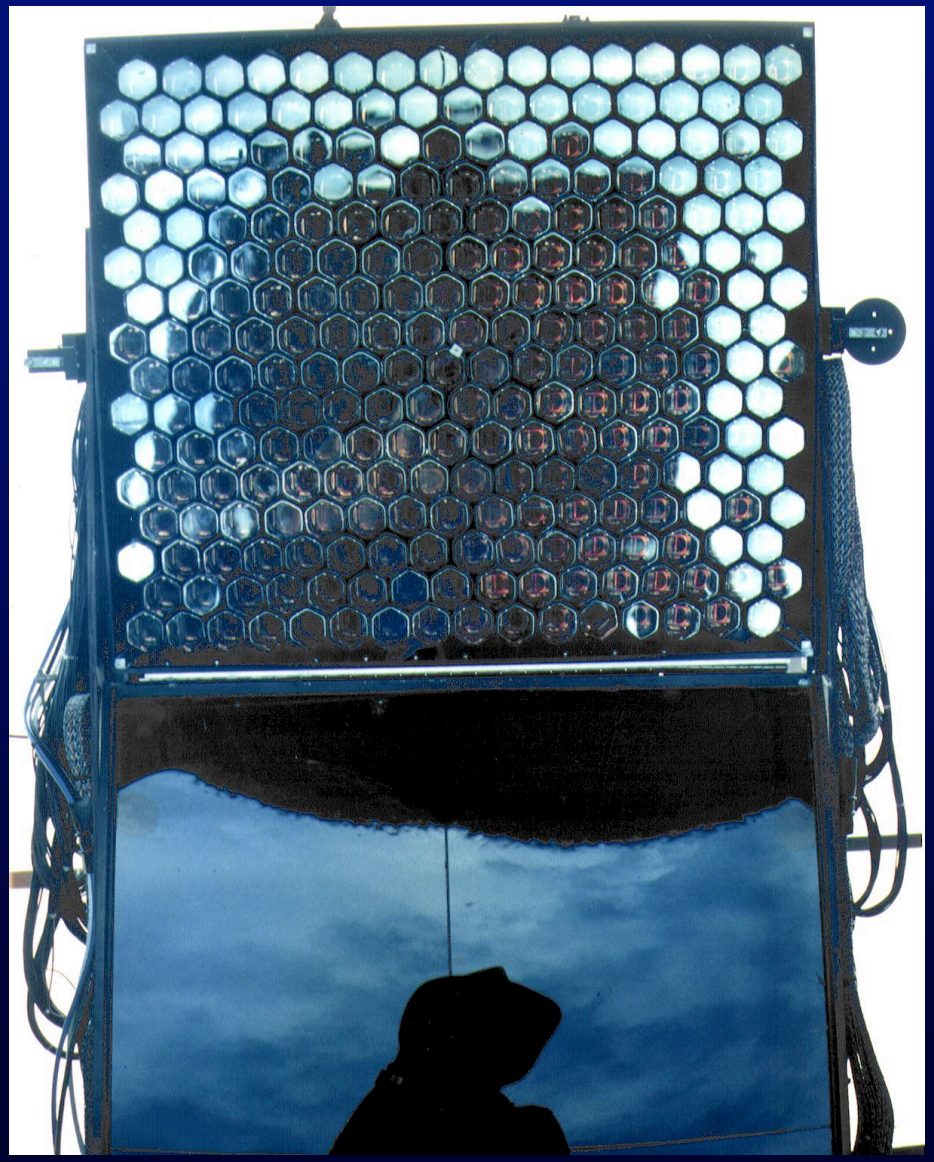
- 22 telescopes with 256 photomultiplier tubes each
- 3^{o} – 16.5^{o} elevation
- 360^{o} azimuth

HiRes 2 at Camels' Back

- 12.6 km to the SW of HiRes 1
- 42 telescopes with 256 photomultiplier tubes each
- 3^{o} – 30^{o} elevation above horizon
- 330^{o} azimuth
- FADC system

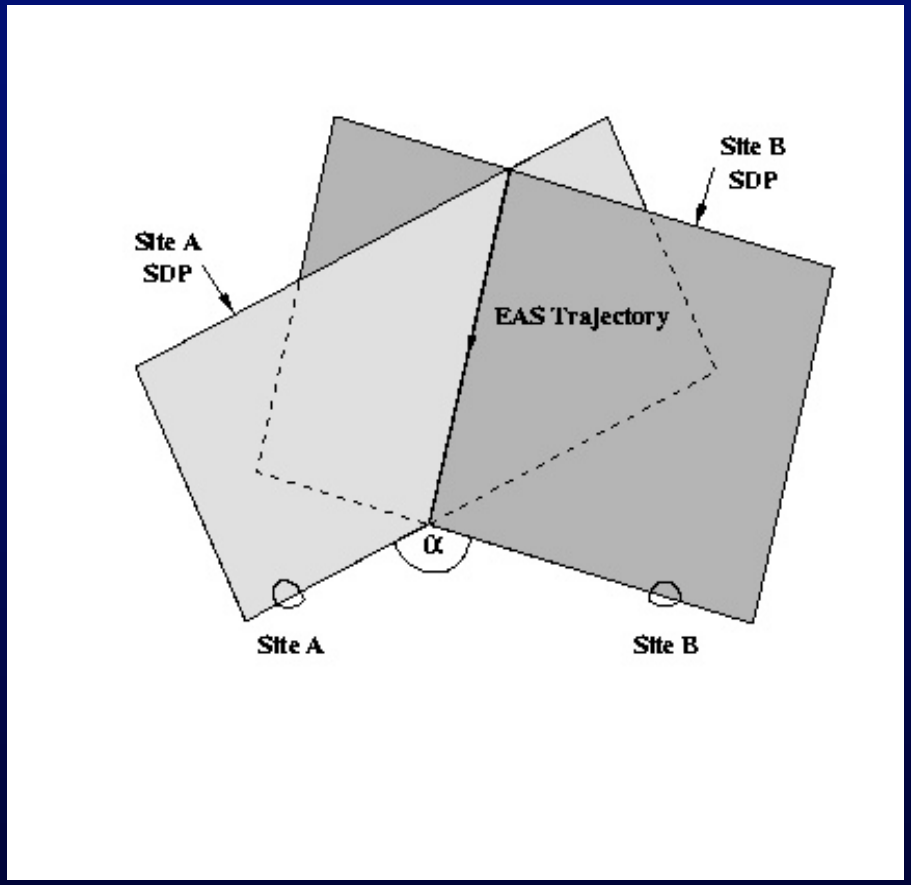
Status of HiRes

- HiRes 1 monocular data
  - June 1997 – present
- HiRes stereo data
  - November 1999 – present
  - About 3080 hours of stereo exposure through April 2005
  - HiRes is scheduled to take data through March 2006



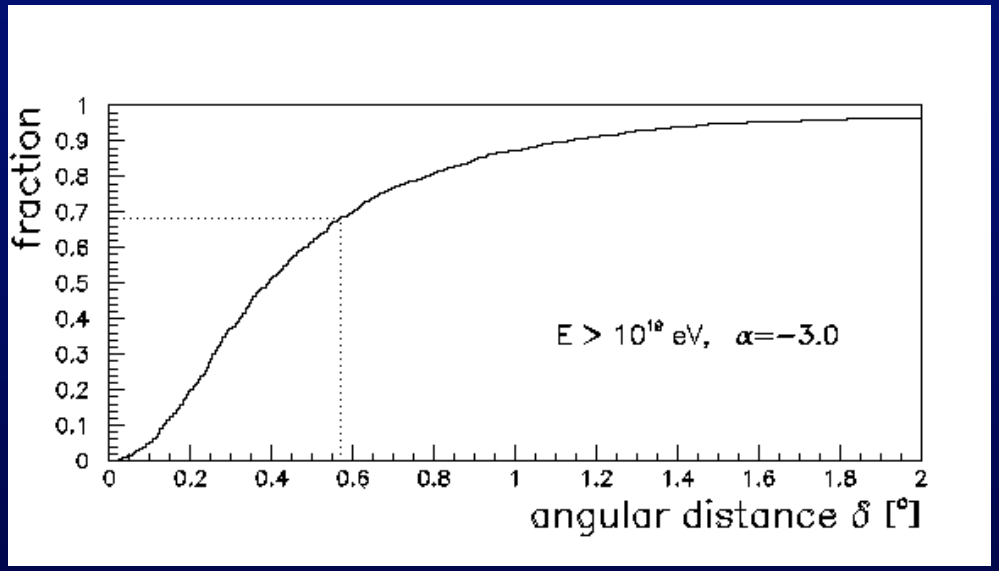
Stereo Reconstruction

- 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 observation has very good angular resolution.
- In Monte Carlo simulations, 68% of events are reconstructed within 0.58º 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.

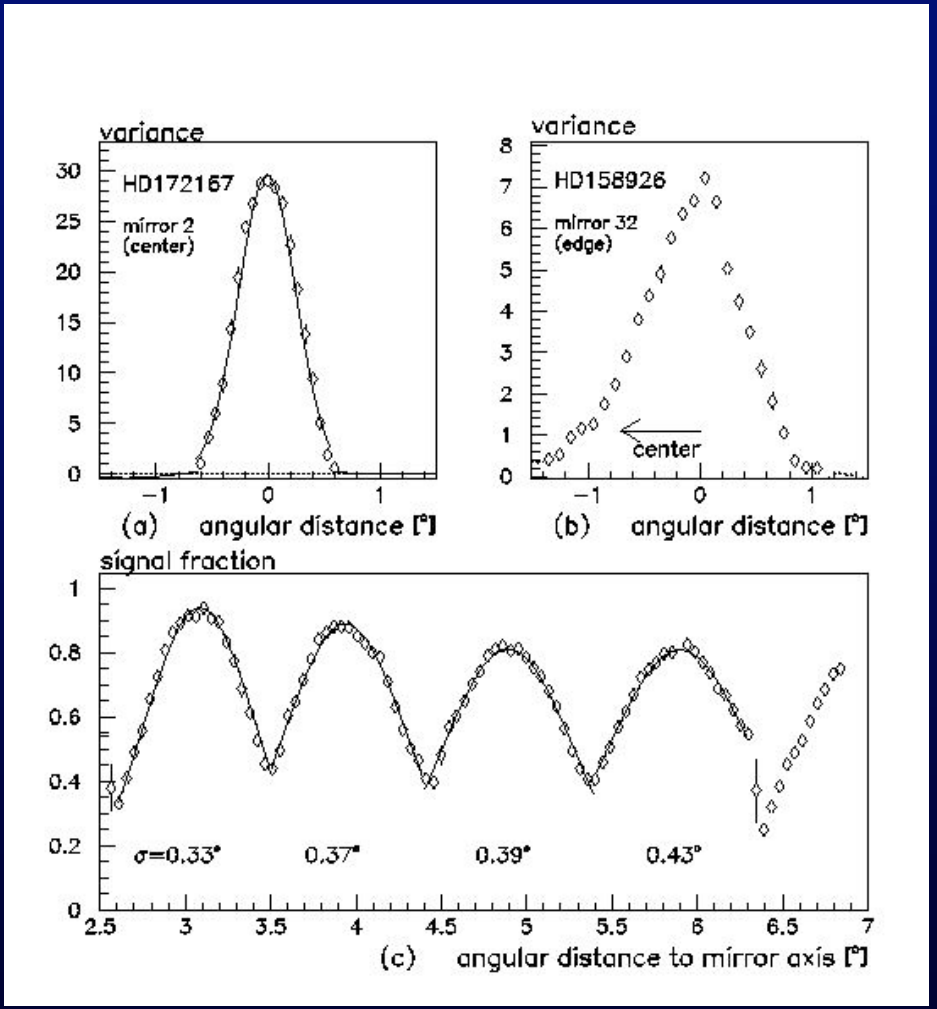


Fraction of events with reconstructed direction within angular distance δ to true direction, for HiRes Monte Carlo stereo events.

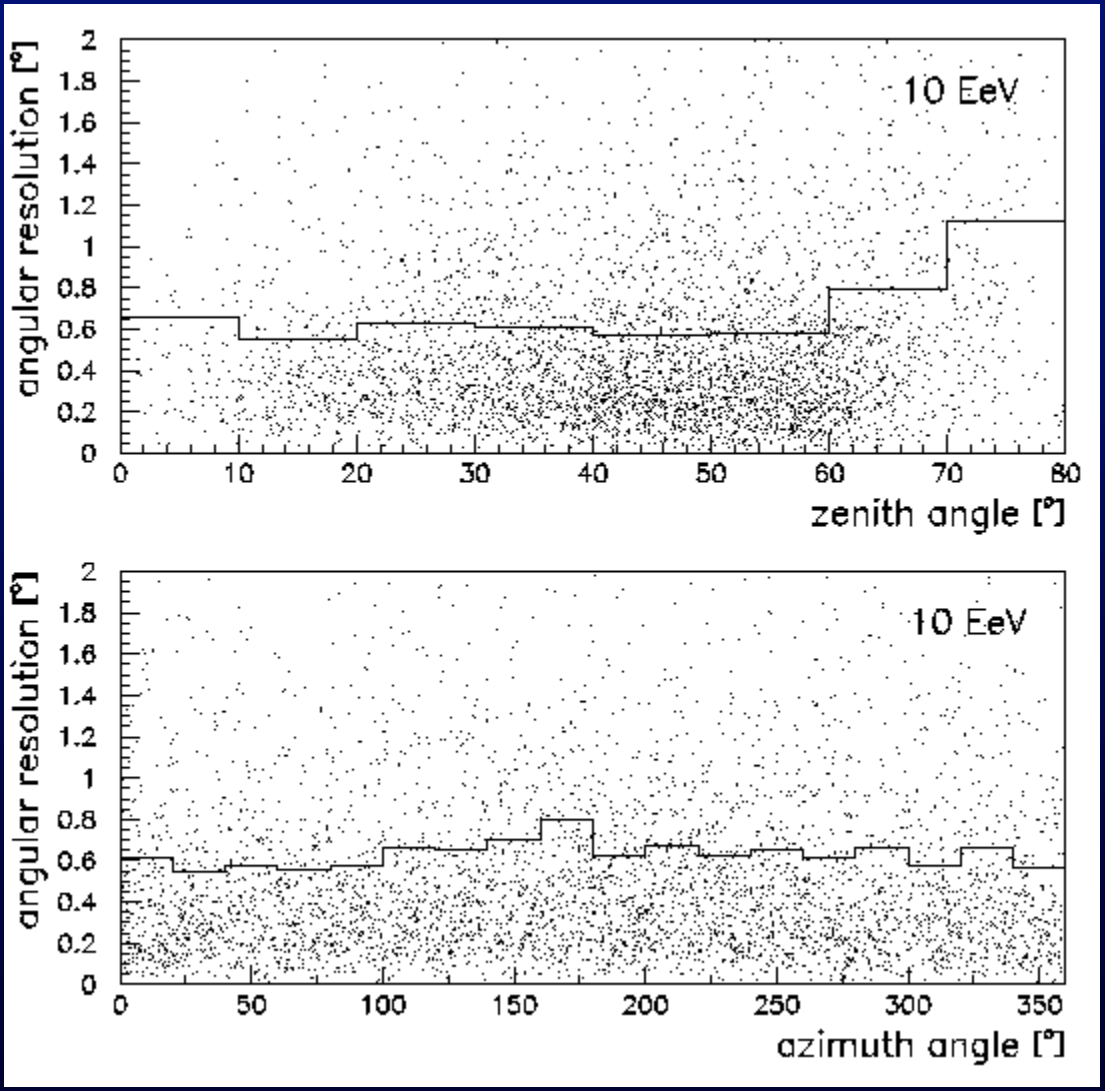
Star Tracks

- Stars allow analysis of optical parameters of the mirrors.
- Near the center of the mirror, intensity distribution is roughly Gaussian.
- Closer to the edge, spherical aberrations become an issue (shape becomes asymmetric and width increases).
- Use results from star analysis in simulation and ray tracing code (energy determination !).

Astroparticle Phys. 18 (2002) 237



Angular Resolution



- No dependence on zenith angle θ for $\theta < 70^{o}$
- Weak dependence on azimuth angle ϕ
- Small dependence on energy: at higher energies, showers are on average further away

HiRes Stereo Data Set

Quality Cuts:

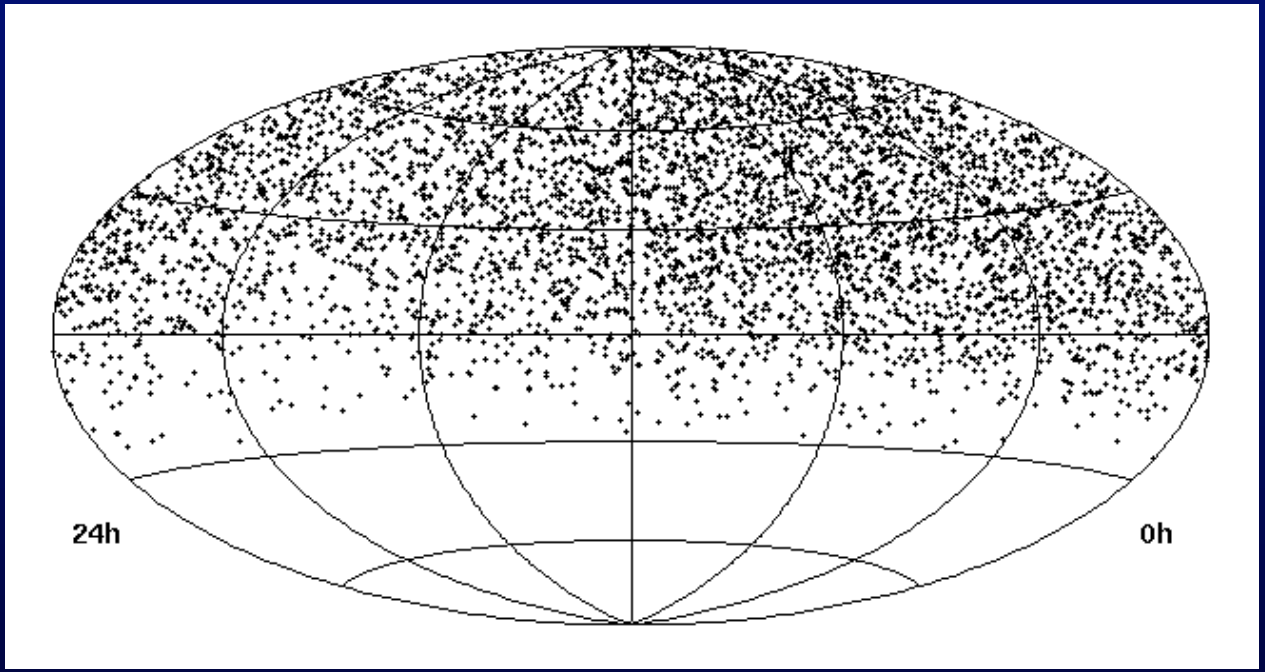
- Quality cuts for event reconstruction are based on detailed MC studies aiming at minimal tails and maximal acceptance.
  - Track length > 3° , χ^2 /dof < 5 for geometry and energy fit
  - Energy uncertainty < 20%, angular uncertainty < 2° in zenith and azimuth
  - Zenith angle < 70°

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

- Stereo data starting December 1999
- Several years of running result in a relatively smooth skymap



Equatorial Coordinates

Small-Scale Anisotropy

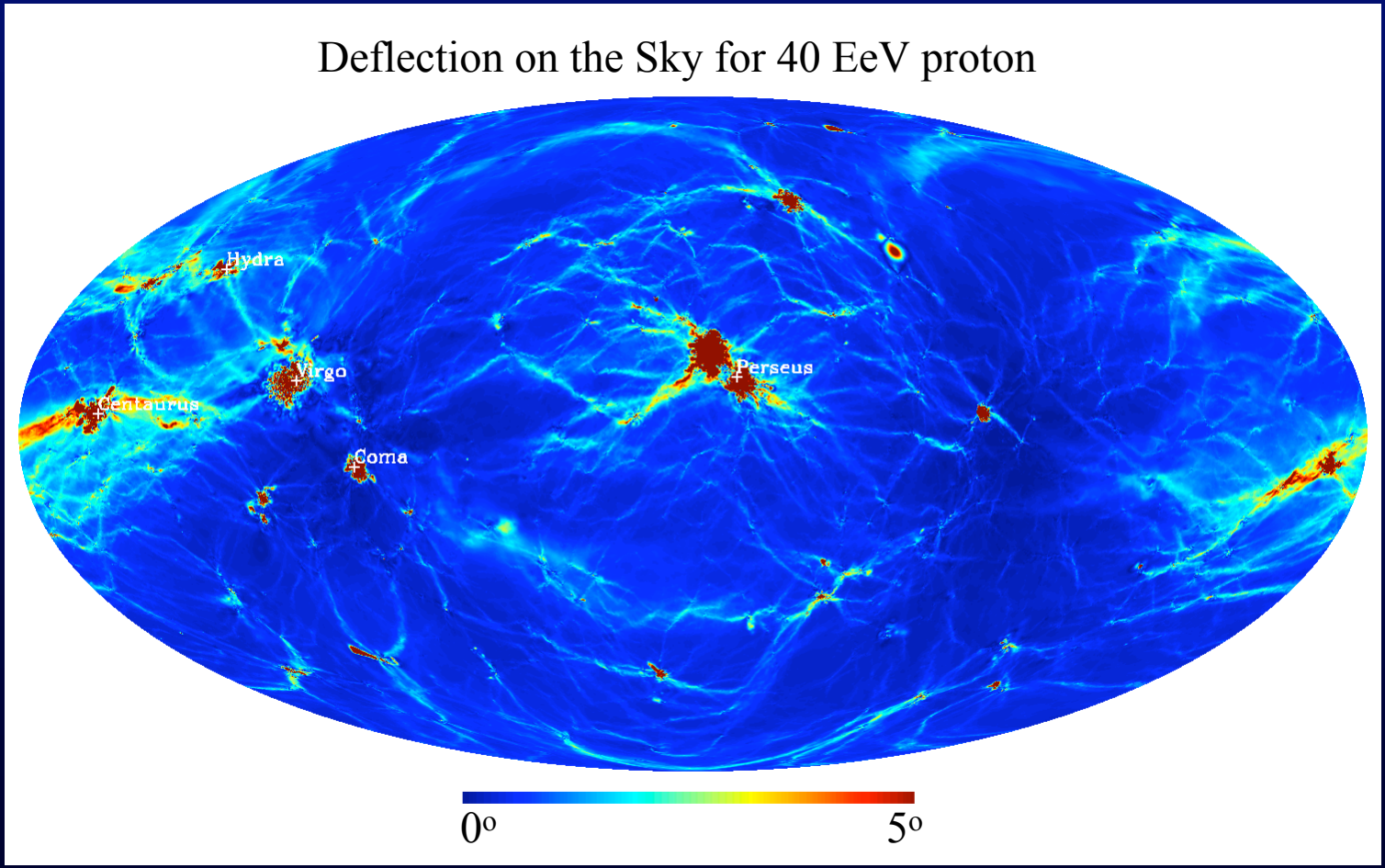
Motivation:

- Arrival directions of cosmic rays above ~ 4×10^{19} eV observed by previous experiments have shown hints of small-scale clustering (~ a few degrees).
- Clustering could be the result of cosmic rays arriving from nearby extragalactic sources, and could offer clues to the origins of these particles.

- Clustering is expected to be strongest at the highest energies, where deflections in magnetic fields are smallest.
- World data set is small and has been thoroughly studied. Need to test clustering claims with independent data.
- HiRes stereo detector has taken data since December 1999.

Cosmic Ray Astronomy ?

- Dolag, Grasso, Springel and Tkachev, astro-ph/0310902

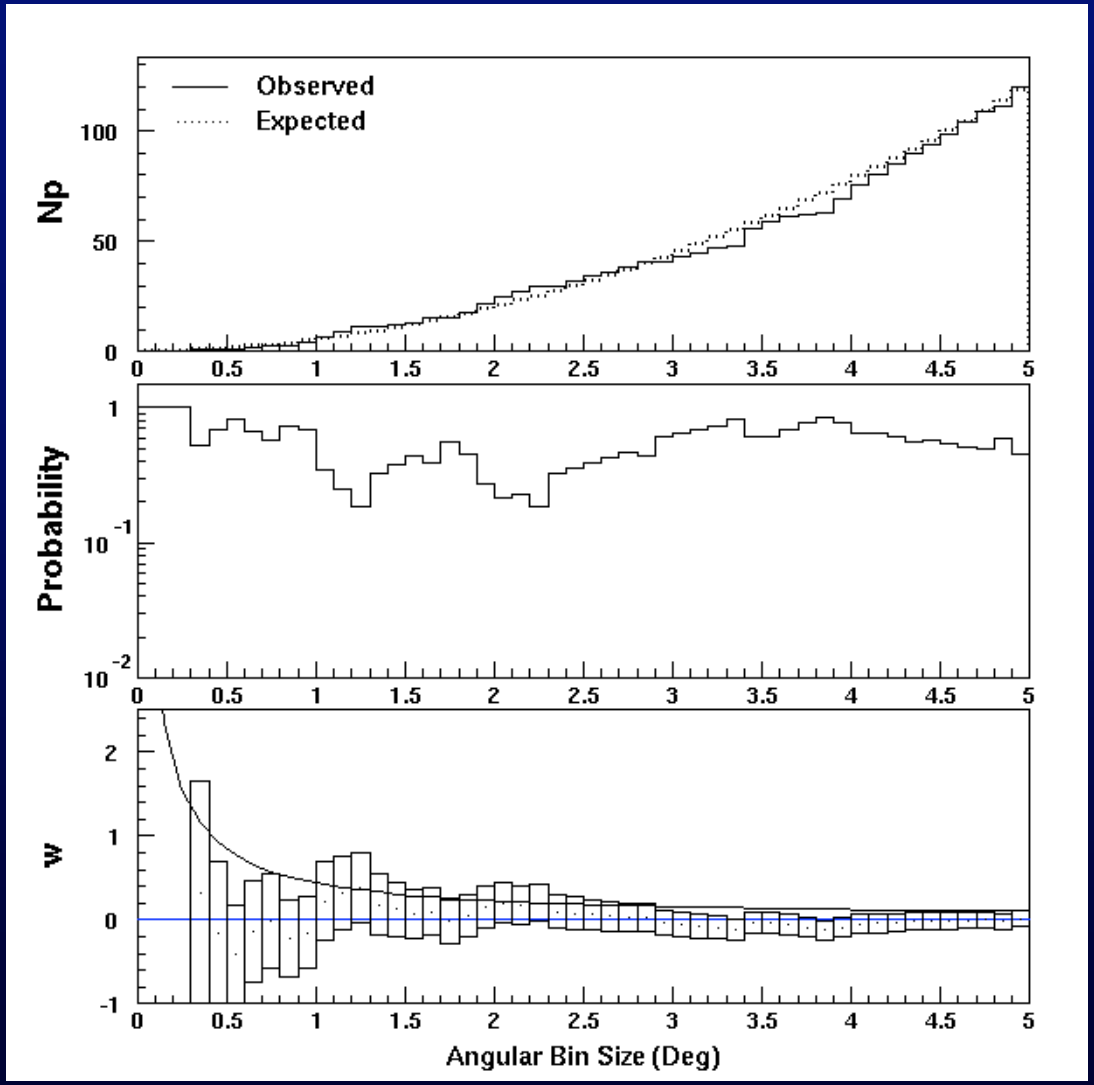


Autocorrelation Function

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 EeV) is consistent with isotropy at all small angular scales.



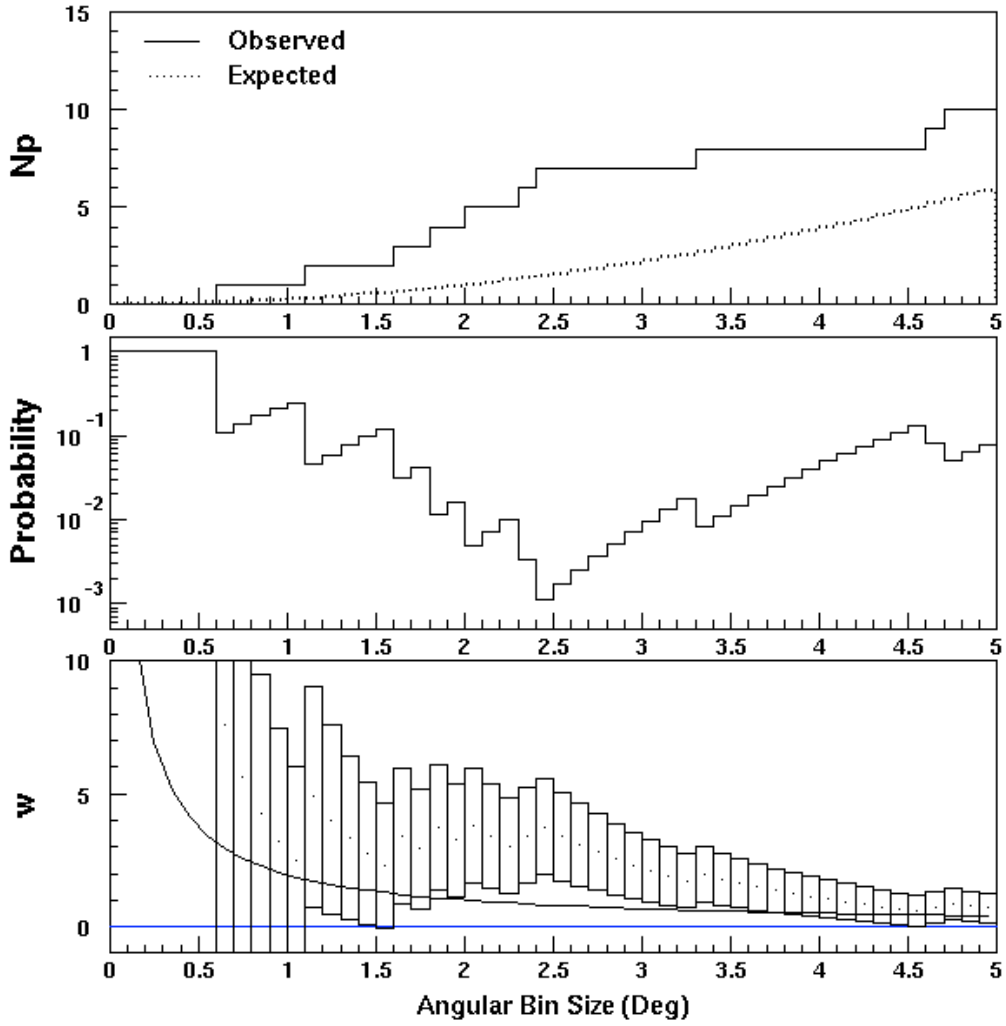
Abbasi et al., ApJ 610 (2004) L73

271 HiRes events above 10^{19} eV

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

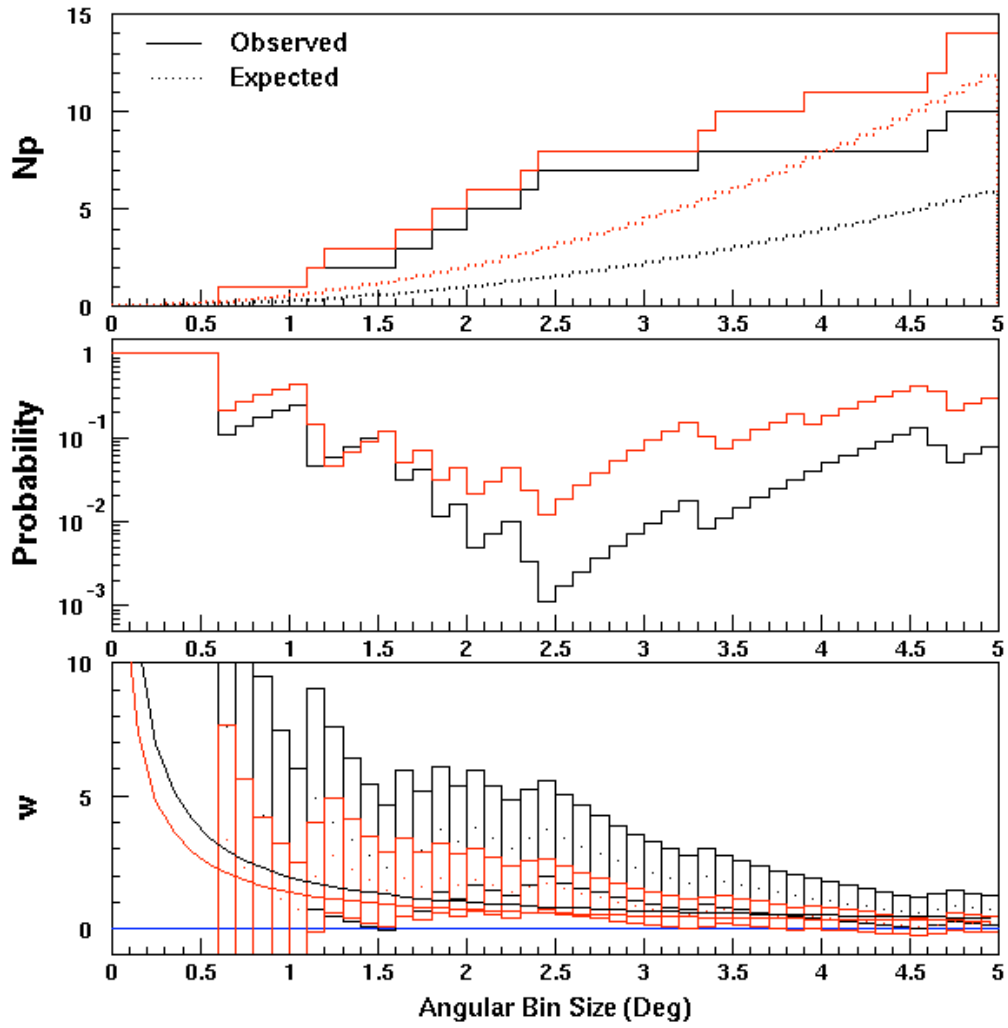
AGASA:

- 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%

Finley et al., astro-ph/0411130



57 AGASA events above 4×10^{19} eV

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

Correlation Scan

Evaluating Significance:

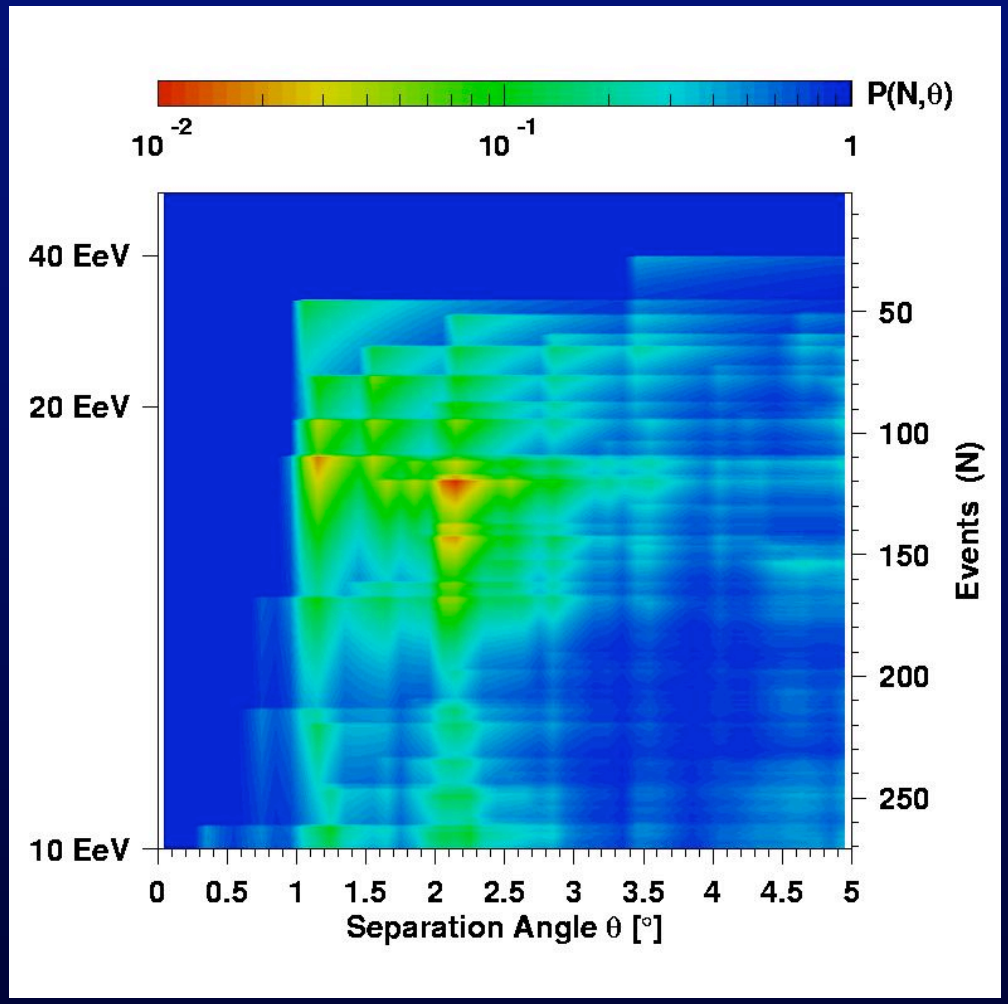
- A limitation of the correlation function is the necessity of choosing a minimum energy for the data set:
  - A higher energy threshold may reduce deflections of charged cosmic ray primaries by magnetic fields...
  - ... but it also weakens the statistical power of the data set.
- No *a priori* optimal choice for energy threshold or angular separation exists for clustering searches.

Autocorrelation Scan

Solution:

- Scan over angular separations and energy thresholds simultaneously.
- Identify the angular separation and energy threshold which maximize the clustering signal.
- Evaluate the significance by performing identical scans over Monte Carlo data sets.
- Some details in

C. Finley, SW, Astroparticle Physics 21 (2004) 359

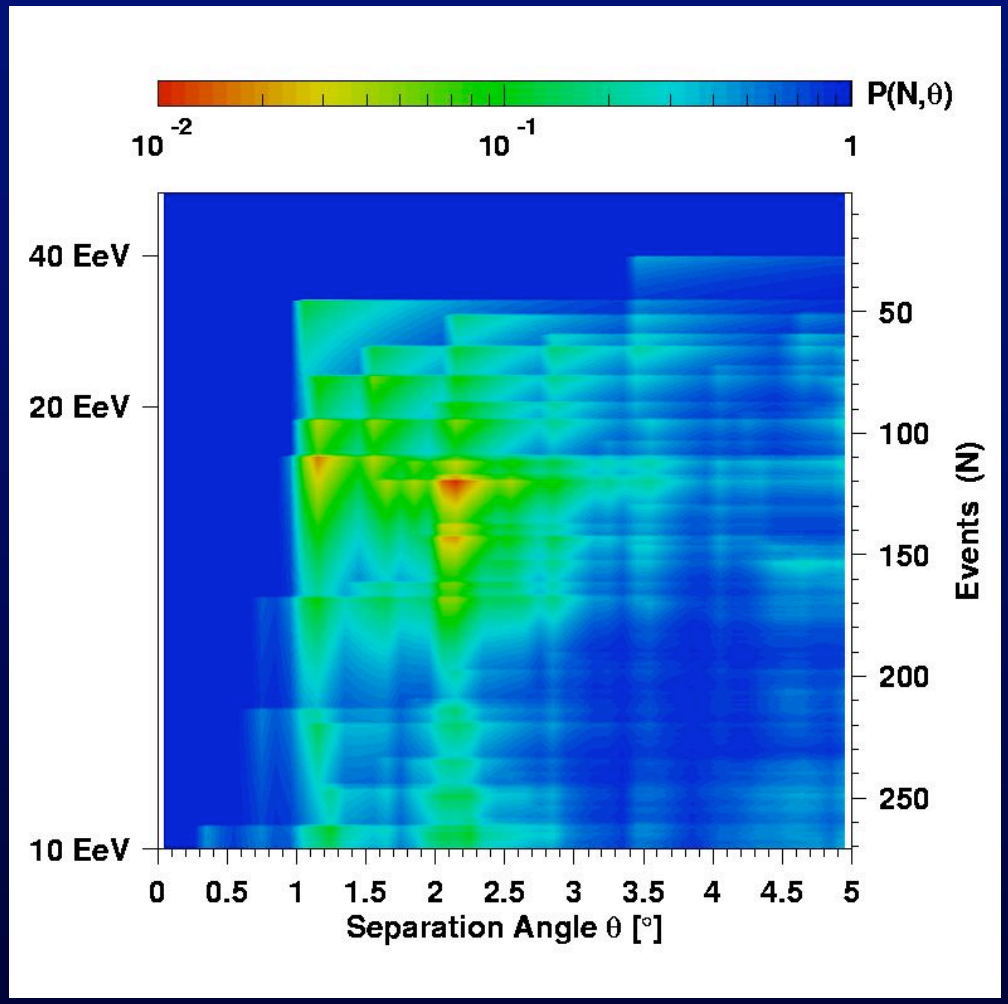


Scan of HiRes Stereo Events > 10^{19} eV

Autocorrelation Scan

HiRes Results:

- Strongest clustering signal:
  - $E = 1.7\times10^{19}$ eV, $\theta = 2.2°$
  - $n_{pairs} = 10 \quad (N = 120)$
  - $P_{min} = 1.9\%$
- However, there is a statistical penalty for scanning.
- True significance is chance probability for scan of Monte Carlo data to have lower minimum:
  - $P_{chance} = 52\%$
- No significant clustering signal observed.

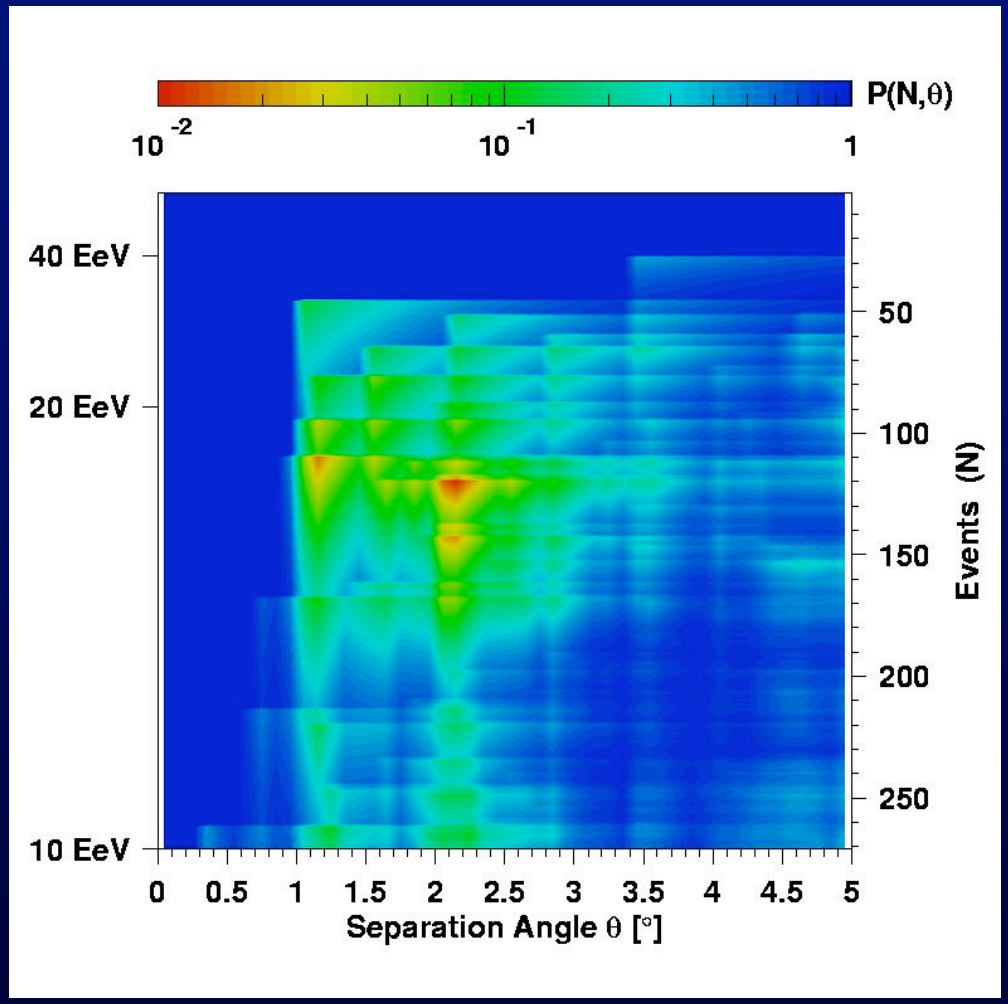


Scan of HiRes Stereo Events > 10^{19} eV

Autocorrelation Scan

Sensitivity to Clustering:

- This scanning method is sensitive to clustering which occurs at higher energies.
- For example, two pairs of events (with angular separations ~ HiRes resolution) among the 27 events above 4×10^{19} eV has strong significance. P_{chance} for the whole scan ~ 1%.
- Conversely, the observed value P_{chance} = 52% excludes the possibility that sources actually contributed two pairs (which were missed because of angular errors) at more than 99% confidence level.



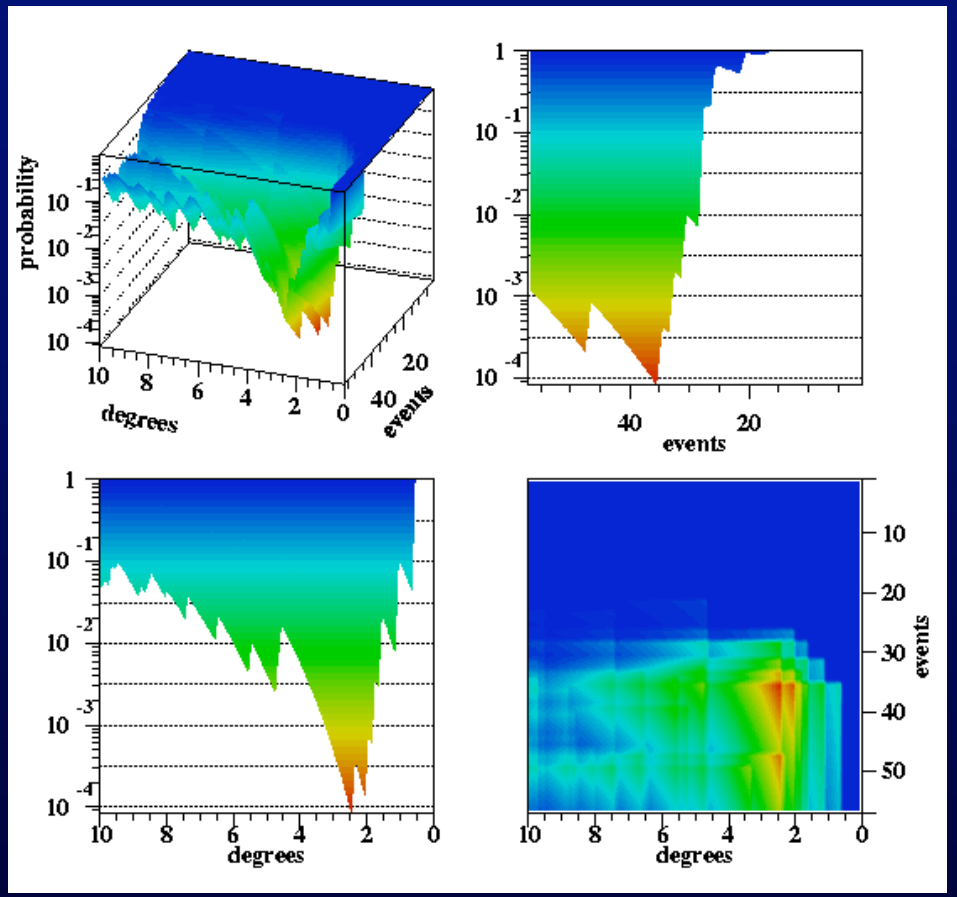
Scan of HiRes Stereo Events > 10^{19} eV

Abbasi et al., ApJ 610 (2004) L73

AGASA Autocorrelation Scan

AGASA Data:

- Strongest clustering signal:
  - $\theta = 2.5^{\circ}$
  - $E = 4.9\times10^{19}$ eV
  - $P_{min} = 8.4\times10^{-5}$
- Chance probability for scan of Monte Carlo data to have lower minimum:
  - $P_{chance} = 0.3\%$
- About 2.8 σ evidence for clustering



Scan of AGASA Events > 4×10^{19} eV

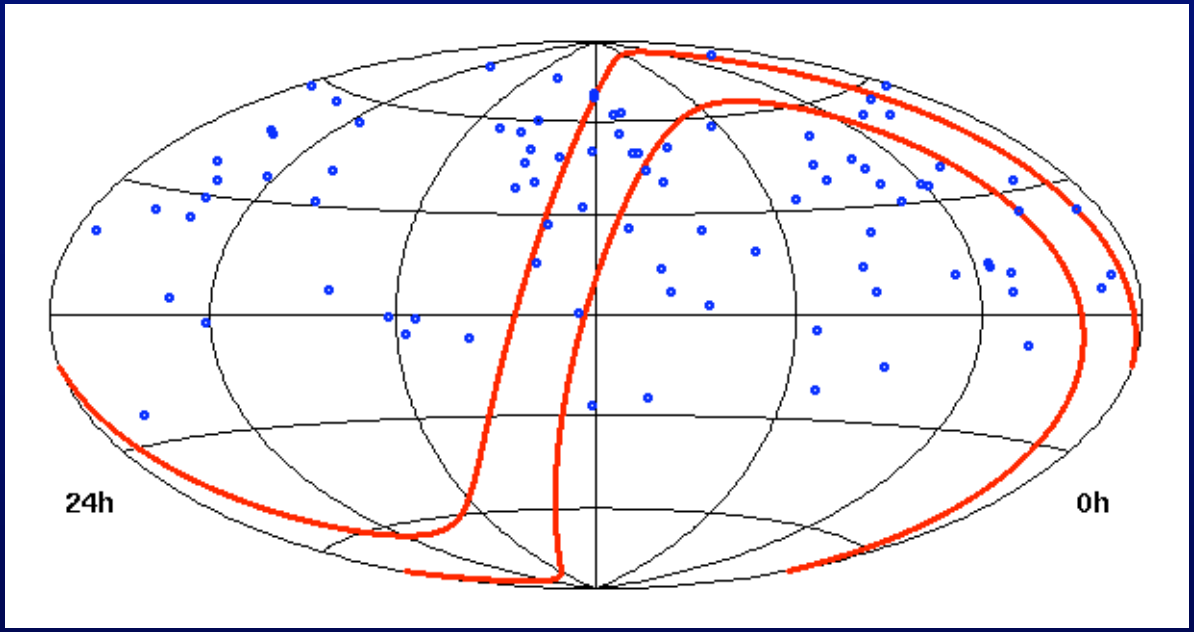
C. Finley, SW, Astroparticle Phys. 21 (2004) 359

AGASA Clustering

- Hint for small-scale anisotropy or chance fluctuation in an isotropic distribution ?
- Test the original claim by excluding the contribution of the original data to the clustering signal.
  - Cuts identified in first paper (1996, data before 10/1995) are now considered *a priori* for the data set after 10/1995.
    - P_{chance}= 19 %
  - Allow for cross-correlations with the original data set
    - P_{chance}= 12 %
- AGASA clustering signal is weaker than claimed.

Supergalactic Plane Correlation

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



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

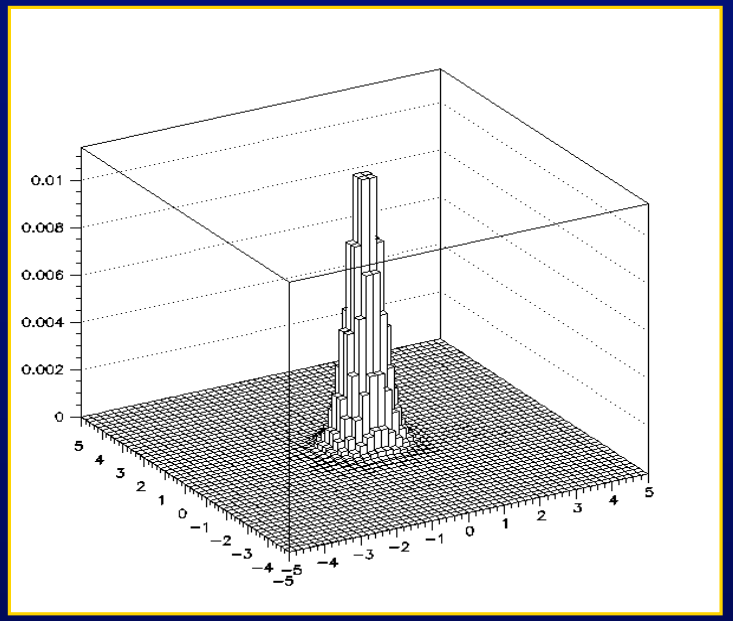
- We count the number of events within 10º of the plane, and compare with Monte Carlo.

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

Maximum Likelihood Point Source Search

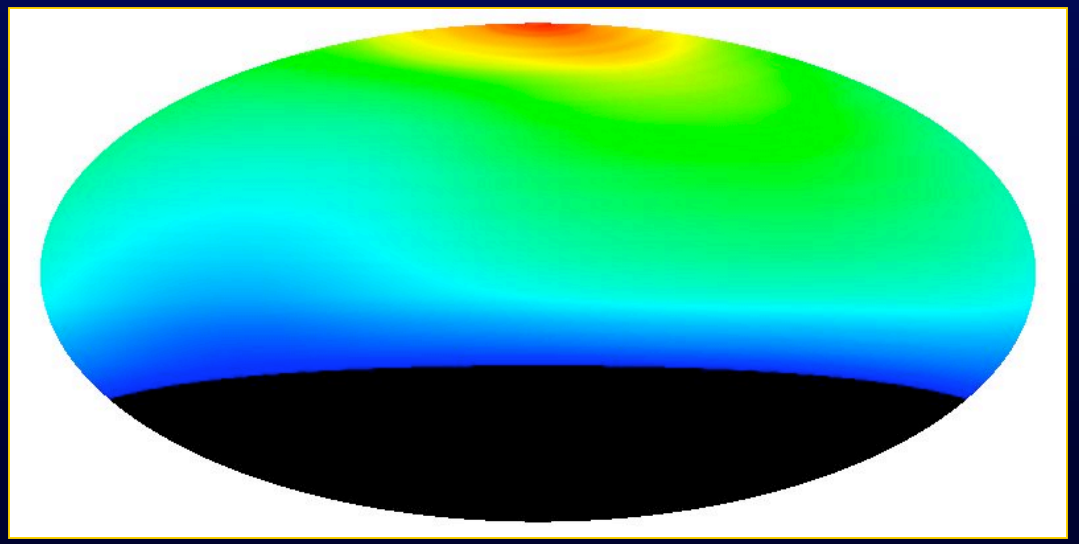
Introduced here as a way to search for a single point source among events with different errors.

$Q_i(x_i, x_s)$



$Q_i(x_i,x_s)$ 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: $n_s = 0$.

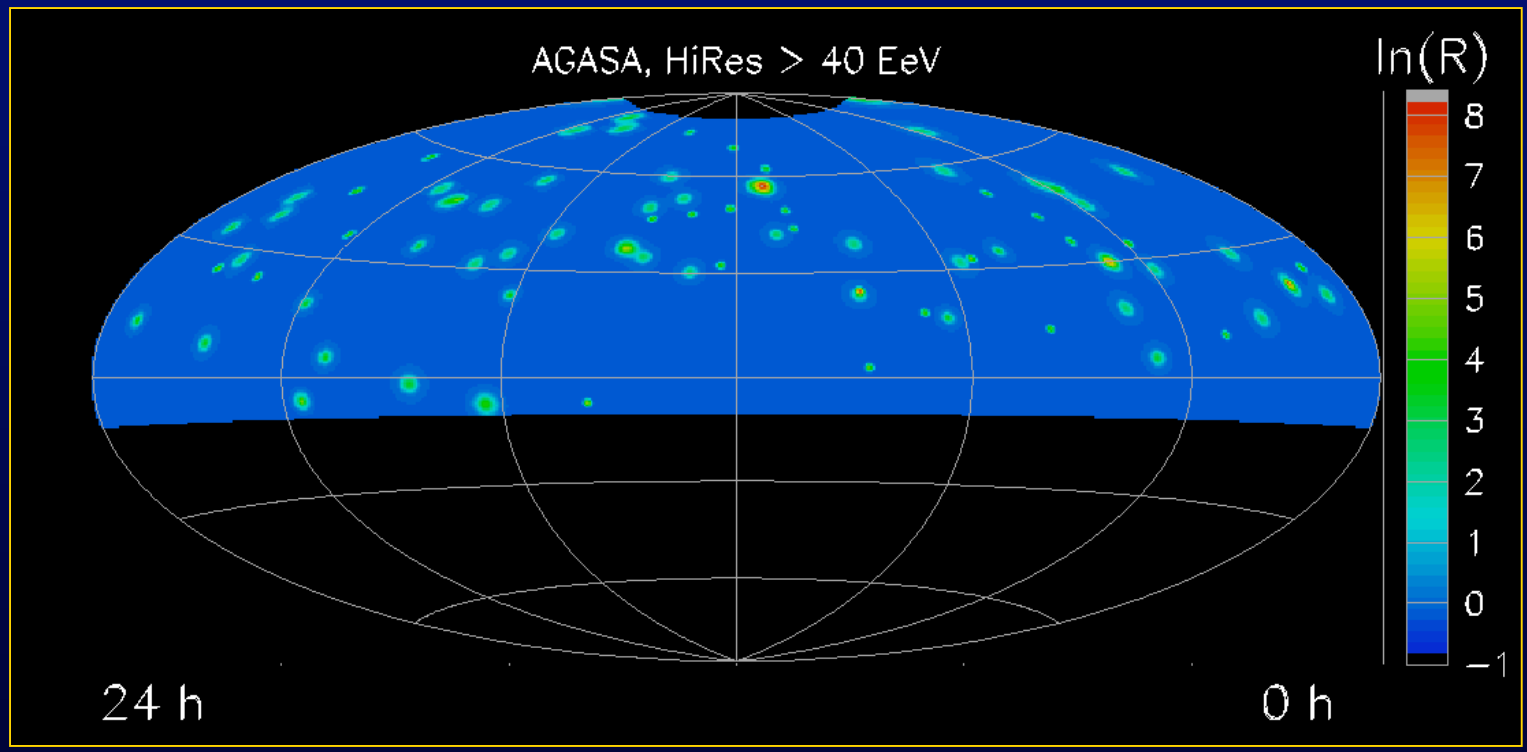
$$\ln(\mathrm{R}) = \ln \frac{L(n_s, x_s)}{L(0, x_s)}$$

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

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 Monte Carlo data sets and counting the fraction with $\ln(R_{MC}) > \ln(R_{data})$.



For the AGASA and HiRes combined data set above 40 EeV, 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%.

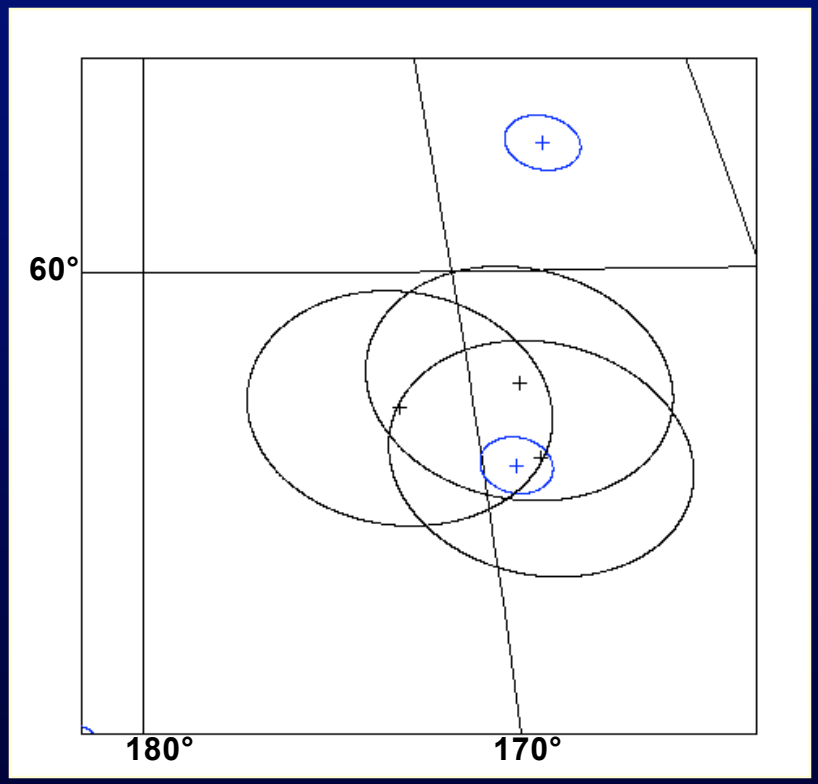
Maximum Likelihood Point Source Search

No significant point source is found in the combined set of HiRes and AGASA events above **40 EeV**.

If the HiRes threshold is lowered to 30 EeV, 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%.

Important: *we can not transform this number into a chance probability !*



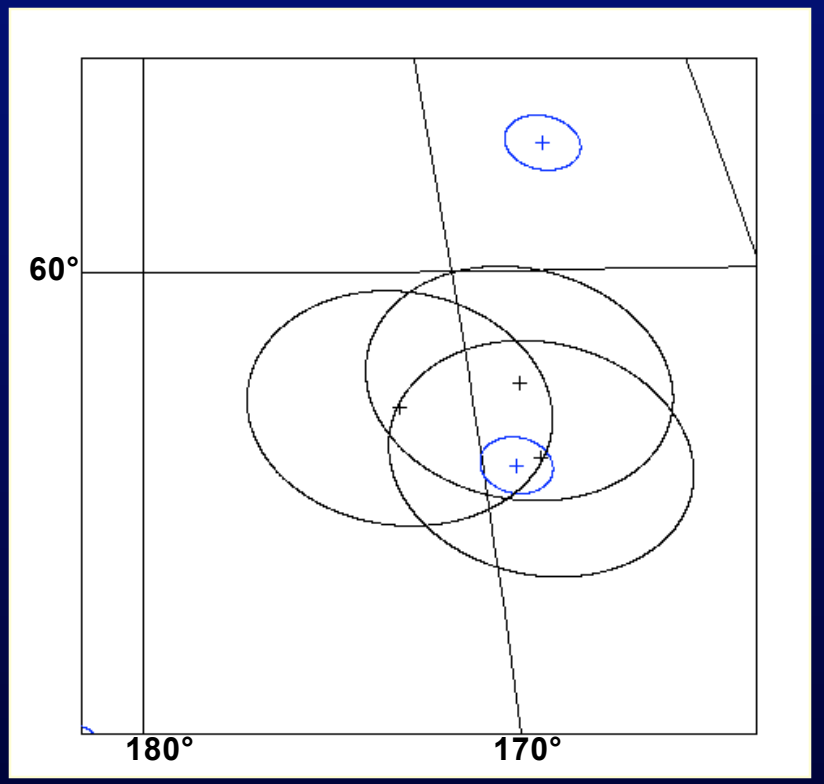
Maximum Likelihood Point Source Search

No significant point source is found in the combined set of HiRes and AGASA events above **40 EeV**.

This result contains some biases:

- the clustered AGASA events which were originally used to *establish* the 40 EeV threshold are still included in the sample
- the HiRes energy threshold has to be *changed* to include an event that contributes to the cluster

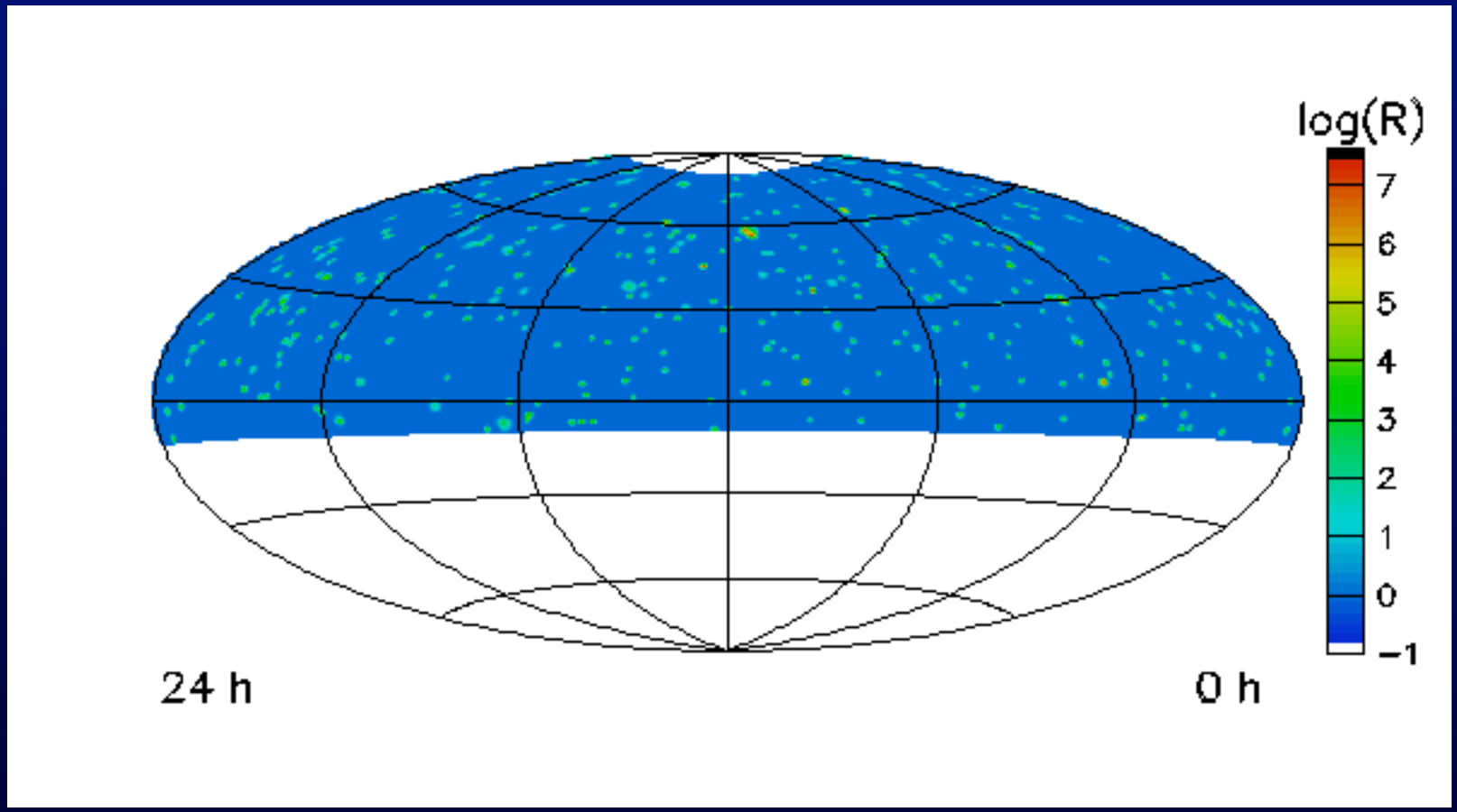
These biases imply that 0.5% is a *lower bound* on the chance probability.



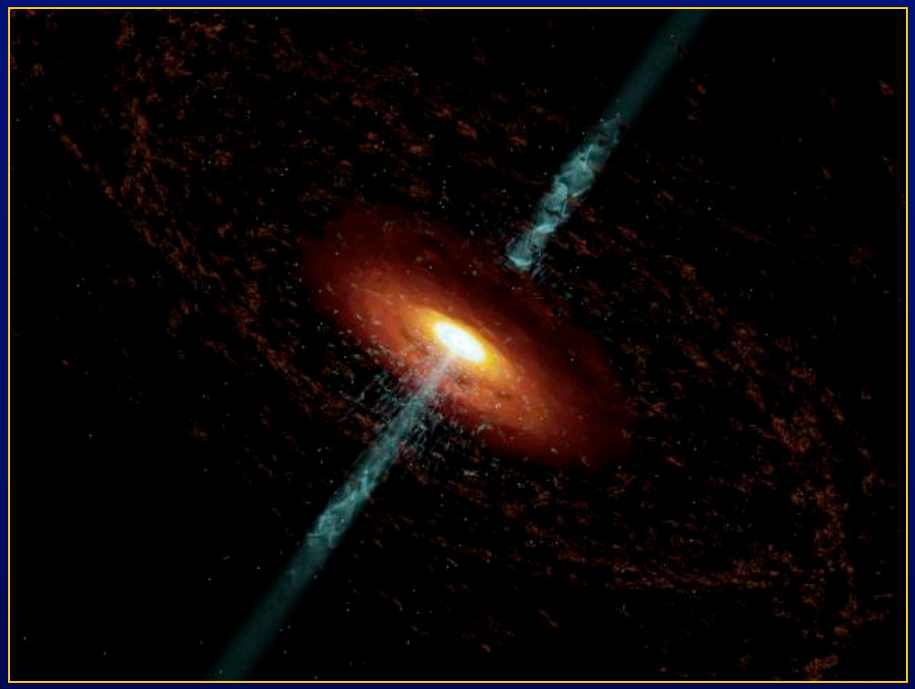
Abbasi et al., ApJ 623 (2005) 164

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

Skymap above 10 EeV



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 Correlation

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						

Tinyakov & Tkachev, JETP 74 (2001) 445.
Gorbunov et al., ApJ 577 (2002) L93.
Tinyakov and Tkachev, Astropart. Phys. 18 (2002) 165.
Gorbunov et al., JETP Lett. 80 (2004) 145.

BL Lac Correlation

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				

Is this the confirmation of an *a priori* claim ?

- Original correlation between Sample 3 and AGASA events was weak (2%, without estimate of statistical penalty)
- The HiRes data shows no excess correlation with this sample when the same energy threshold 4×10^{19} eV is used
- When the HiRes threshold is lowered to 1×10^{19} eV, the correlation is apparent only when taking advantage of the sharper angular resolution of HiRes

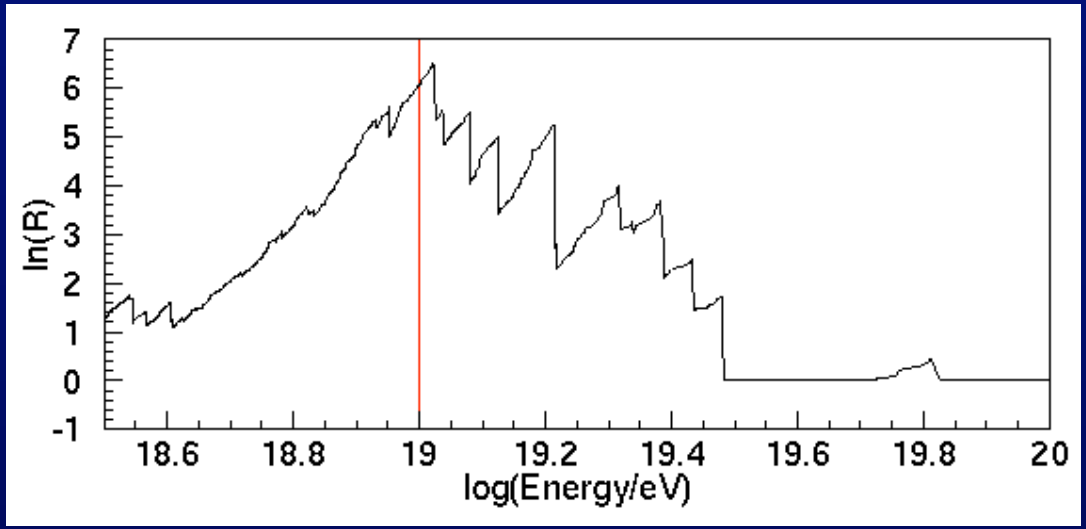
This represents a new claim which needs to be tested with independent data !

BL Lac Correlation

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				

- Use maximum likelihood technique to eliminate dependence on bin size
- Account for different exposure at different locations by weighting the contributions of individual sources by the exposure at the position of the source: *Q_i is now a weighted sum over source locations*
- Maximum log likelihood ration is ln(R) =6.08 for n_s=8.0
- Fraction of isotropic simulated data sets with higher ln(R) is F= 2×10^{-4}

Energy Dependence



ln(R) as a function of energy

- 1×10^{19} eV stands out as the threshold that maximizes the significance of the correlation
- How did Gorbunov et al. pick this threshold ?
  - Analysis is based on a list of published HiRes arrival directions above 10^{19} eV that does not give individual energies (ApJ 610 (2004) L73)
  - In this HiRes paper, the threshold of 10^{19} eV was picked for the two-point correlation scan "to safely encompass the energy region of interest," which was expected to be around 4×10^{19} eV, so this energy threshold was purely accidental

Strategy

- Correlation is interesting and warrants further studies
- Investigate how the correlation depends on the energy threshold and source sample
- Identify hypotheses which should be tested *with independent data*
- Investigate:
  - Energy dependence of correlations
    - Most of the correlations comes from events with energies between 10^{19} and $10^{19.5}$ eV
    - Magnetic fields would deflect a proton primary in this energy range by many degrees, yet correlations are consistent with the 0.5º angular resolution of the detector
    - Perform correlation analysis for the *entire data set* without energy cut
  - Source catalog
    - “BL” vs “HP” in Veron Catalog
    - Veron Catalog vs. 6 confirmed TeV blazars

Energy Dependence

- Correlation analysis for the HiRes data set with E < 10 EeV
  - ln(R) = 3.10 for n_s=22, F= 6×10^{-3}
  - However…
    - Region between $10^{18.5}$ eV and 10^{19} eV has a *deficit* of correlating events
    - "Signal" comes from data *below 10^{18} eV*

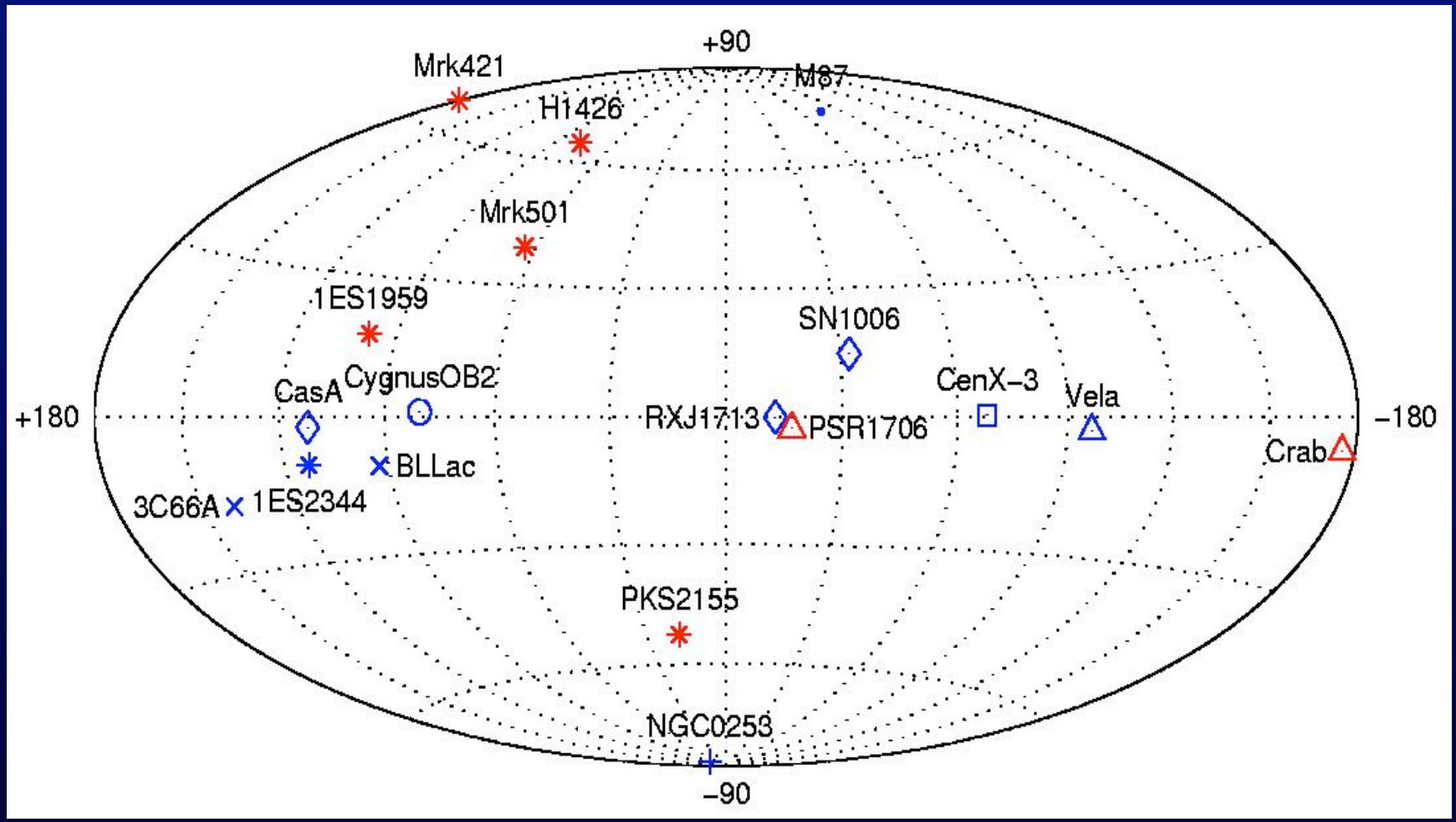
Catalog Considerations

- Veron Catalog is not an unbiased catalog of BL Lacs - it mainly represents a complete survey of the literature
- Confirmed BL Lacs are labeled “BL” or “HP” if they show a high degree of optical polarization
- Previous correlation analyses have not included sources marked as “HP” - but roughly half of the confirmed TeV gamma-ray sources are “HP” objects, among them Mrk 501
- Fraction *F* of simulated data sets with larger likelihood ratio ln(R)

HiRes events	“BL”	“BL”+”HP”
E>10 EeV	2×10^{-4}	1×10^{-5}
all	6×10^{-3}	5×10^{-4}

- m<18 cut which was identified as optimal for AGASA improves the correlations with HiRes as well

TeV Blazars



Horan & Weekes, New Astron. Rev. 48 (2004) 527

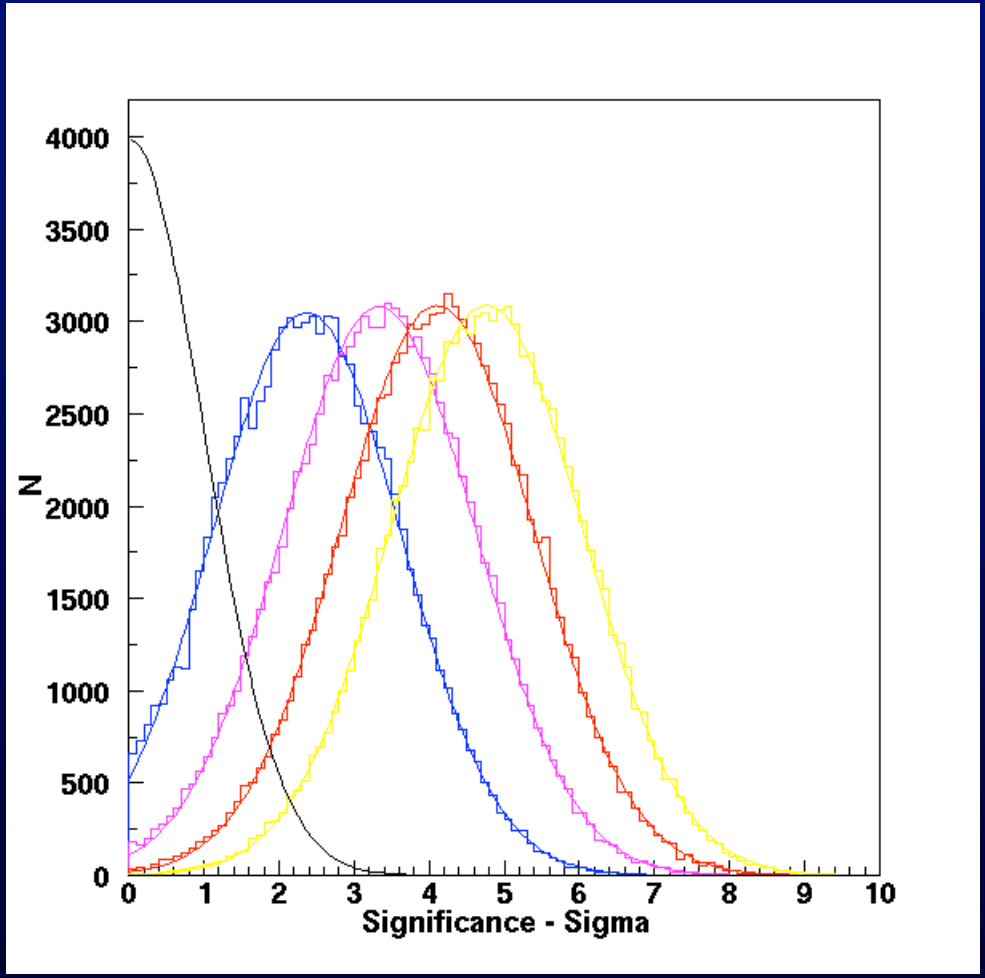
TeV Blazars

- Six confirmed TeV gamma-ray sources (Horan & Weekes 2004) are among the closest and brightest BL Lacs
- Five objects are in the field of view of HiRes (applying a 70º zenith angle cut)
  - Mrk 421
  - H1426+428
  - Mrk 501
  - 1ES1959+650
  - PKS2155-304 (outside the field of view)
  - 1ES2344+514

- Result of maximum likelihood analysis

HiRes events	"BL"	"BL"+"HP"	TeV blazars
E>10 EeV	2×10^{-4}	1×10^{-5}	2×10^{-4}
all	6×10^{-3}	5×10^{-4}	1×10^{-3}

Test with Future Data



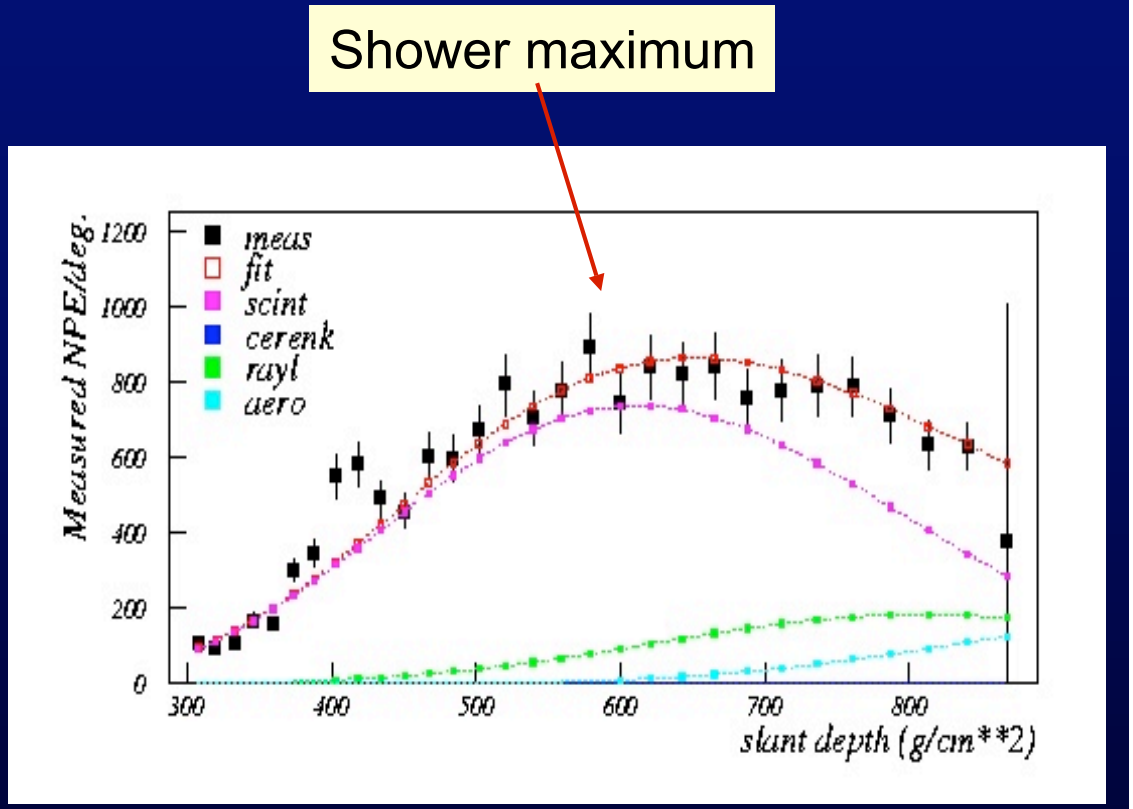
- Expected significance distributions after 1,2,3, and 4 more years of data taking for the hypothesis
  - "BL" + "HP" with m<18
  - E>10 EeV
- Good chance of verifying/falsifying the claim with two more years of data

Chemical Composition

- Speed of air shower development depends on the mass of the primary.
  - Heavier nucleus induces earlier shower development.
- Shower maximum for heavier nuclei is higher in the atmosphere than for proton primary.
- Intrinsic fluctuations in the depth of shower maximum.
  - No resolution of primary on event-by-event basis.
  - Mean shower maximum vs. energy indicates the dominant chemical component (light or heavy).

HiRes Energy and X_{max} Estimation

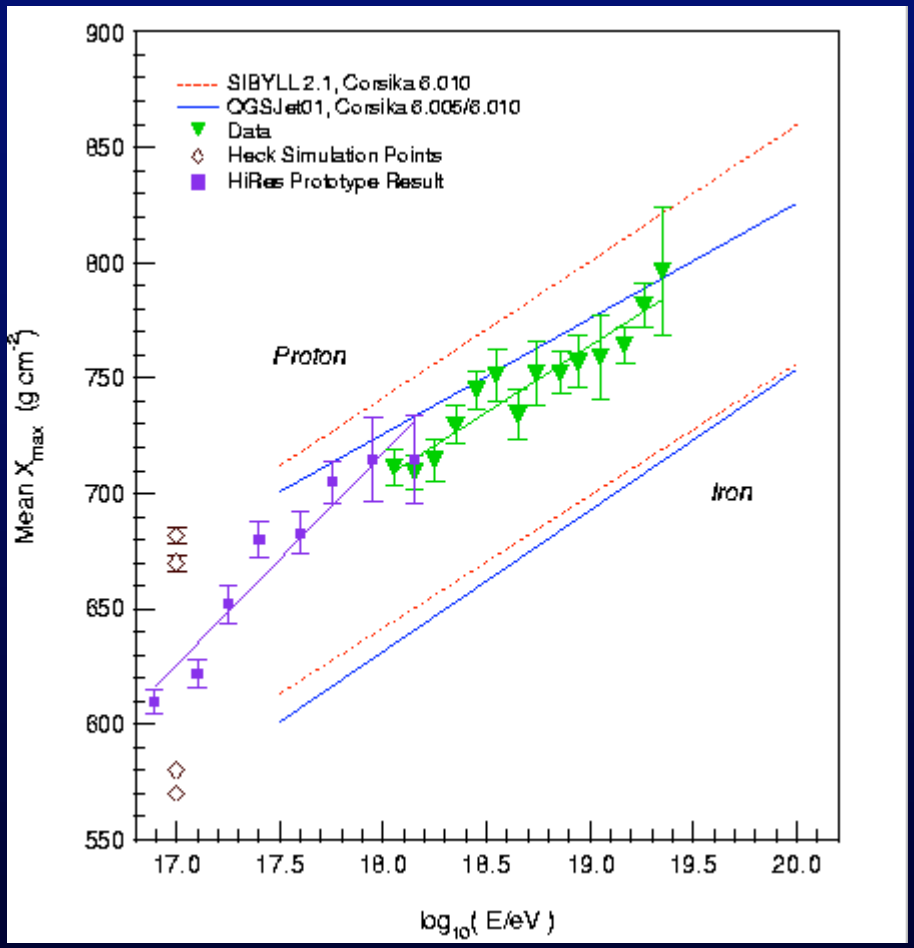
- Total shower energy is determined from the integral over the light intensity along the track.
- Measured light must be corrected for contamination from scattered or direct Cherenkov light.



Composition

- Stereo measurement of elongation rate $\langle X_{max} \rangle$ vs. energy
- Stereo measurement of elongation rate ~50 g/cm^2/decade favors *light* composition above $10^{18.0}$ eV.

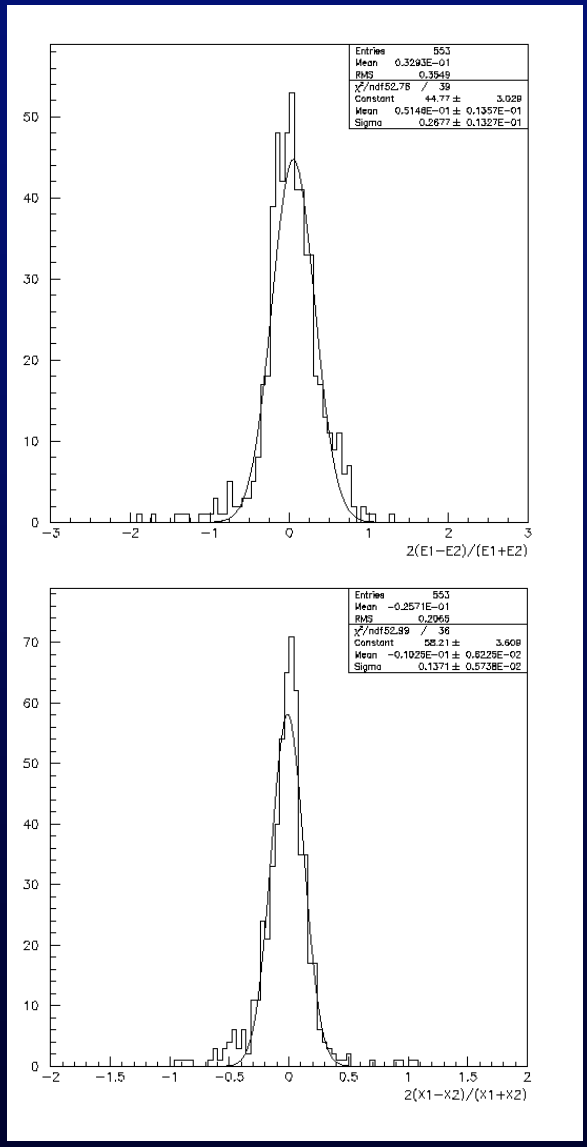
Abbasi et al., ApJ 622 (2005) 910



Resolution in HiRes Stereo Composition

- Pulls in energy and X_{max} are centered.
- Resolution:
  - 20% in energy
  - 15 g/cm^2 in X_{max}
- Systematic uncertainty in X_{max} ~ 15 g/cm^2 .

Abbasi et al., ApJ 622 (2005) 910



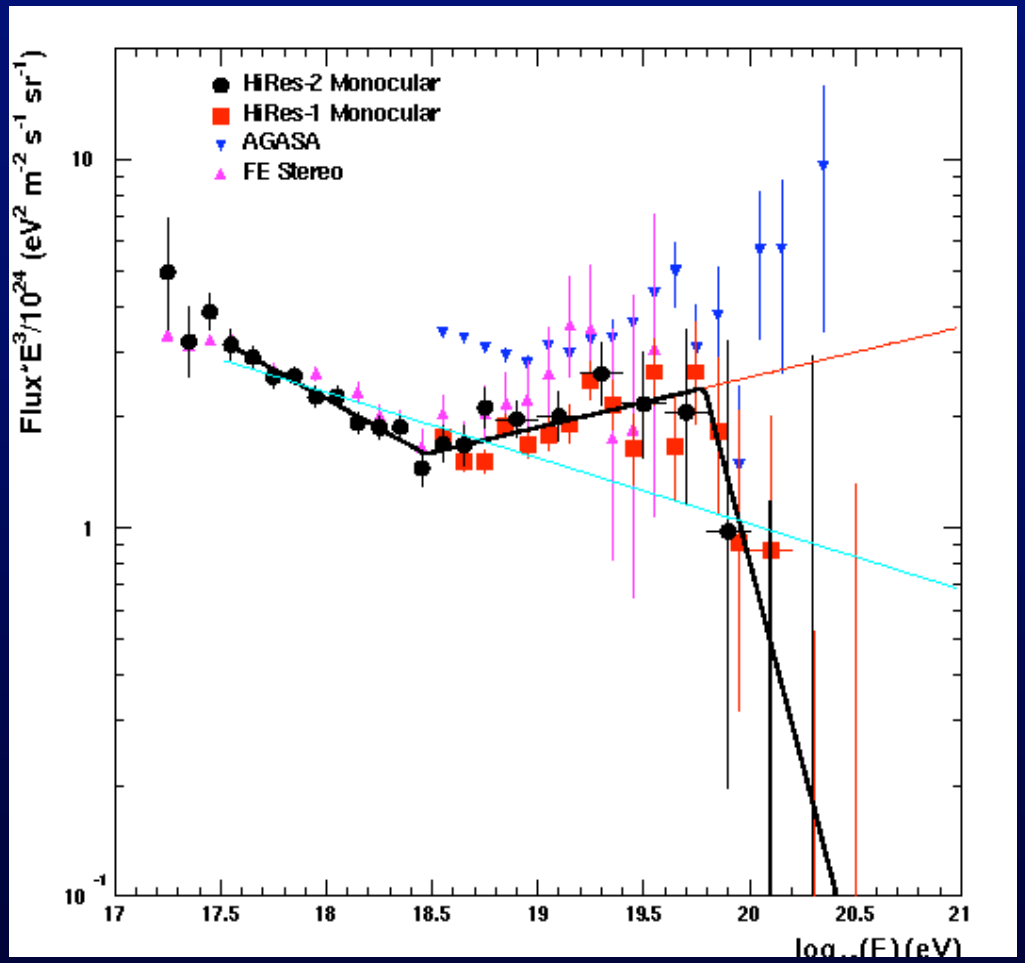
Energy

X_{max}

HiRes 1 Monocular Spectrum

- HiRes 2 monocular spectrum continues to be in agreement with HiRes 1 spectrum in the region of overlap
- Fit of spectrum to a straight line gives a χ^2 of 114 for 37 d.o.f

Abbasi et al., submitted to Phys. Letters B (astro-ph/0501317)



Conclusions

- Cosmic rays with energies above 10^{20} eV exist, but HiRes data does not currently contradict the GZK suppression.
- Composition above 10^{19} eV is dominated by light elements.
- Angular Correlation for HiRes Stereo data above 10^{19} eV:
  - HiRes events above 10 EeV show no small-scale clustering
  - Combined HiRes and AGASA above 40 EeV show reduced correlation
- Maximum Likelihood Point Source Search
  - Combine events with different errors
  - No significant point source above 10 EeV /40 EeV observed
- BL Lac Correlations
  - No correlation between HiRes events and BL Lacs in tests of previously made claims
  - Current claim of correlation between HiRes and BL Lacs is a new claim, and must be tested with new data

Conclusions

- Future
  - HiRes is scheduled to run through March 2006
  - Decisive, independent test of BL Lac correlations should be possible
  - HiRes is producing the sharpest picture of the Northern sky in ultrahigh energy cosmic rays