HiRes – Mapping the High Energy Universe

Stefan Westerhoff

Columbia University

HiRes Collaboration

Fermilab Wine & Cheese Seminar

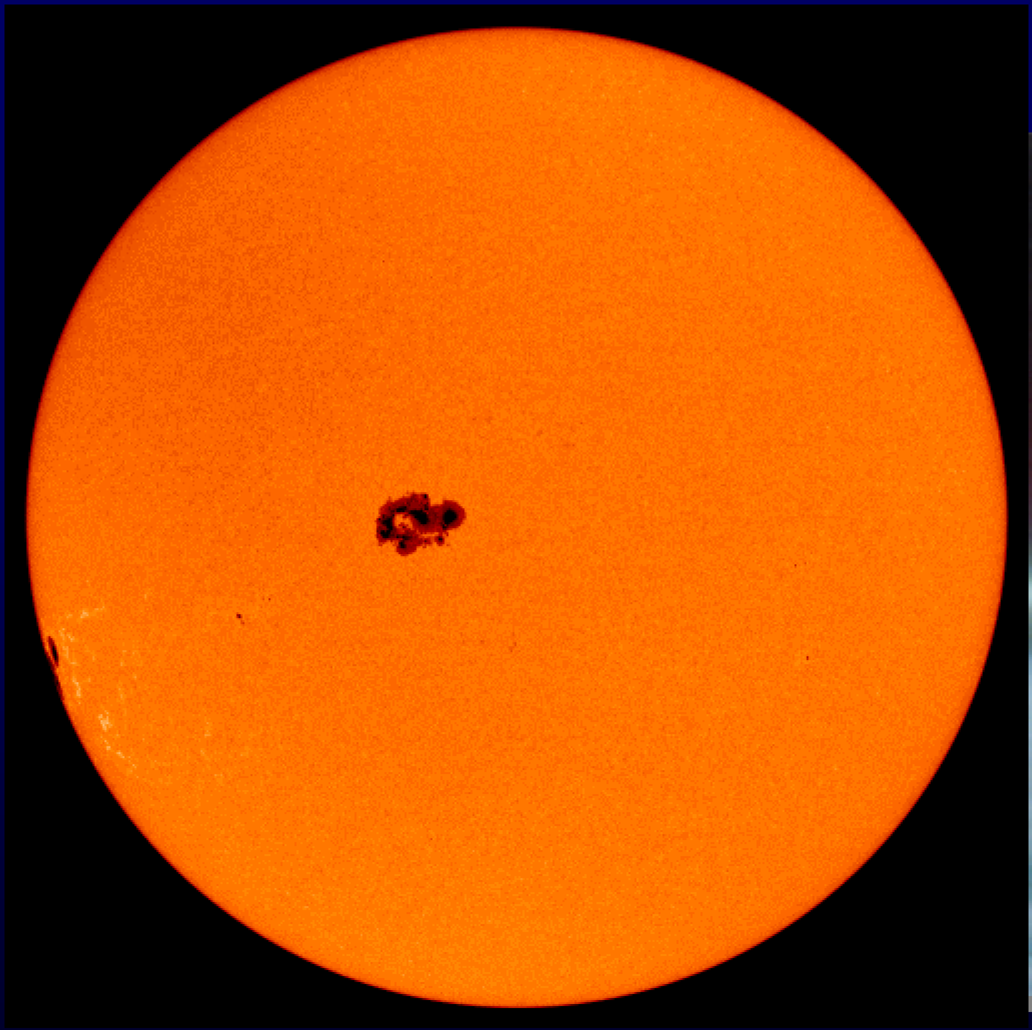
24 October 2003

Particle Astrophysics- A New Window in Astronomy

- Classical Astronomy – electromagnetic spectrum from radio to X-rays
- Gamma-ray Astronomy – photons from MeV to TeV
- Cosmic Rays – protons and heavier nuclei with energies up to 10^{20} eV, the highest particle energies observed in the Universe
  - Protons and nuclei are charged and therefore subject to deflection in magnetic fields – an unknown parameter !
  - Larmor radius

$$R \cong 1 \text{ kpc} \left[\frac{E_{EeV}}{B_{\mu G}} \right] \frac{1}{Z}$$

Cosmic Rays



Aurora light, seen from Space Shuttle Discovery

Discovery of Cosmic Rays

- Electroscopes discharge slowly even in the absence of radioactive material, so there appears to be a background radiation
- To study its origin, Victor Hess made measurements of the radiation level at different altitudes to distance the electroscopes from radiation sources in the Earth (1912)

Discovery of Cosmic Rays

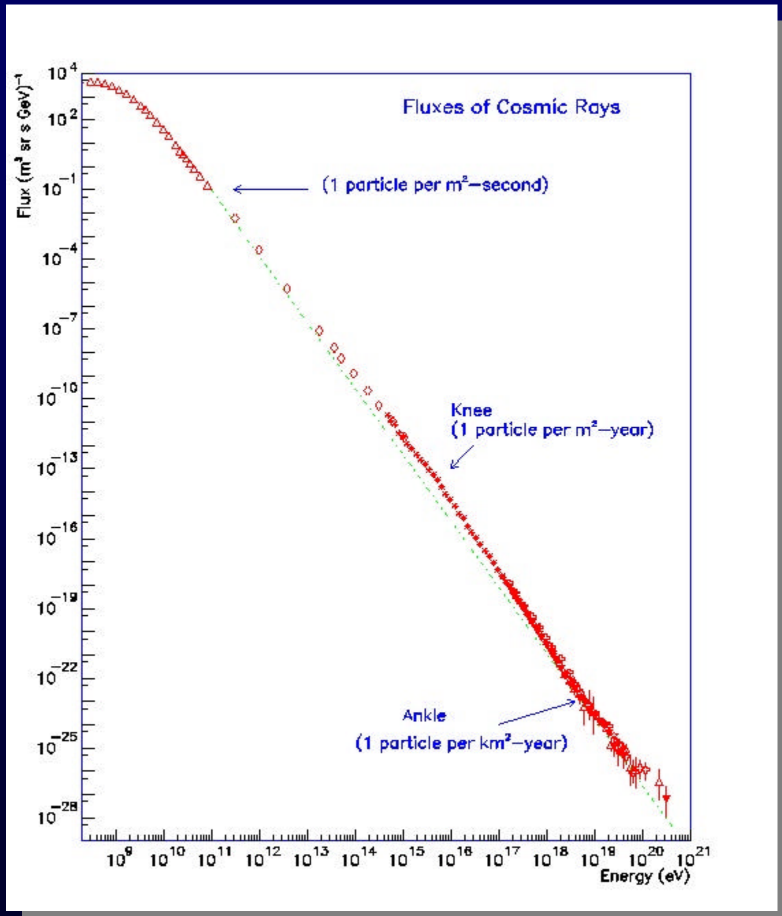
- Going up as high as 17,500 feet, Hess showed that the radiation level increases with altitude, so the radiation enters the Earth's atmosphere from outer space ("cosmic rays")
- Until the advent of accelerators, cosmic rays were the main laboratory for particle physics
  - e.g. discovery of the positron by Anderson, 1931
- Nobel Price 1936 for
  - Anderson "for the discovery of the positron"
  - Hess "for his discovery of cosmic radiation"

Open Questions

- 90 years after their discovery, the research emphasis is now on the cosmic particles themselves
  - What and where are the sources of cosmic rays ? How are they accelerated to these energies ?
  - How do they get here ? How do they propagate astronomical distances without substantial energy loss ?
  - Is their arrival distribution isotropic or do they point back to (few) sources ?
- Accessible to Experiment
  - Energy Spectrum
  - Composition
  - Arrival Direction

Energy Spectrum

- Cosmic ray spectrum roughly represents a single power law $E^{-2.8}$
- There is structure: knee and ankle
- Measured spectrum extends to 10^{20} eV, 11 orders of magnitude greater than the equivalent rest mass of the proton



Cosmic Ray Flux vs. Energy
(S. Swordy, AUGER design report)

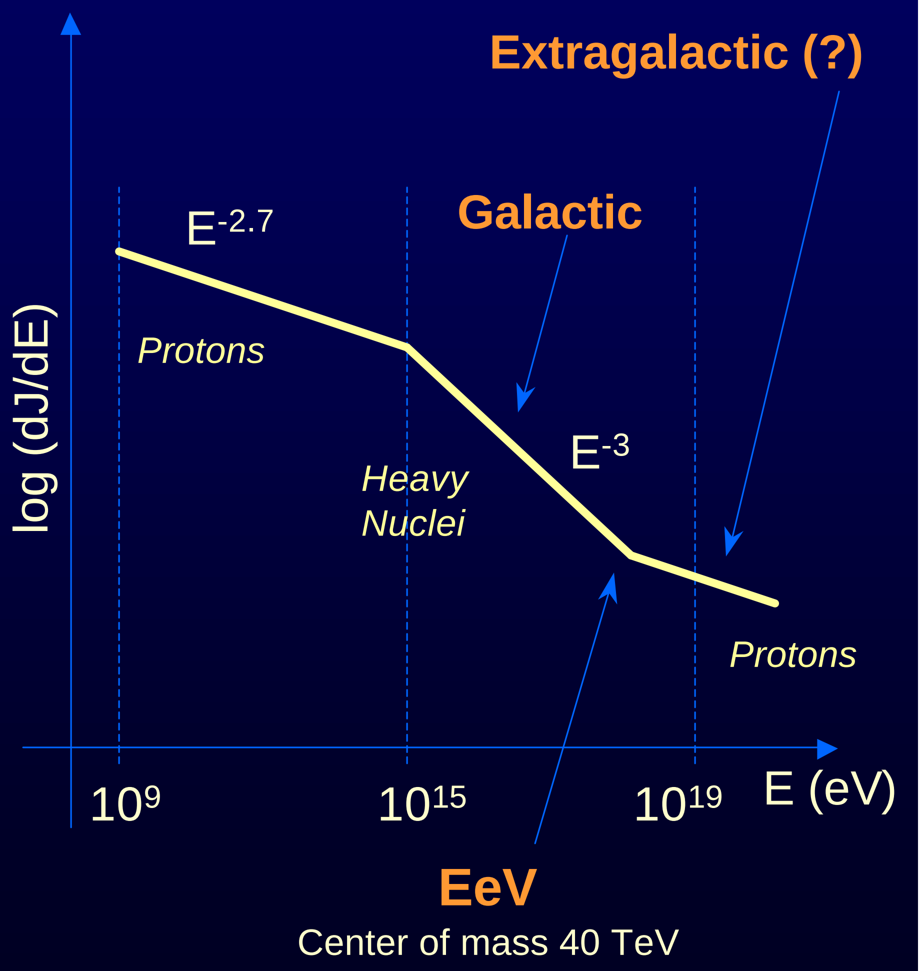
Energy Spectrum

Below the ankle

- Galactic Origin (supernovae)
- Knee is caused by change in composition (confinement problem)

At the ankle (10^{17} –10^{18} eV)

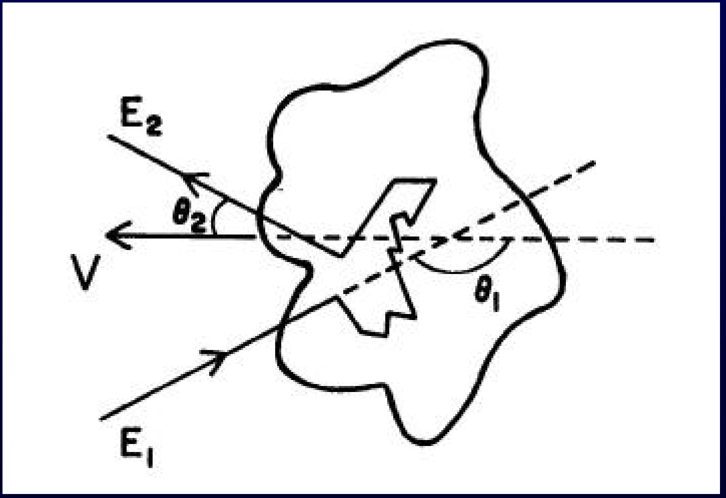
- Composition changes
  - Heavy nuclei to light primaries (protons)
- Change in source ?
  - Galactic to extragalactic



Fermi Acceleration

- E. Fermi, On the Origin of Cosmic Radiation, Phys. Rev. 75 (1949) 1169
- Charged particles are reflected from irregularities in the magnetic field (moving clouds of magnetized plasma) which move randomly with velocity V
- Particles gain energy *statistically* in these reflections

- If particles remain in the acceleration region for a time τ, the energy distribution is a power law



2nd order Fermi acceleration

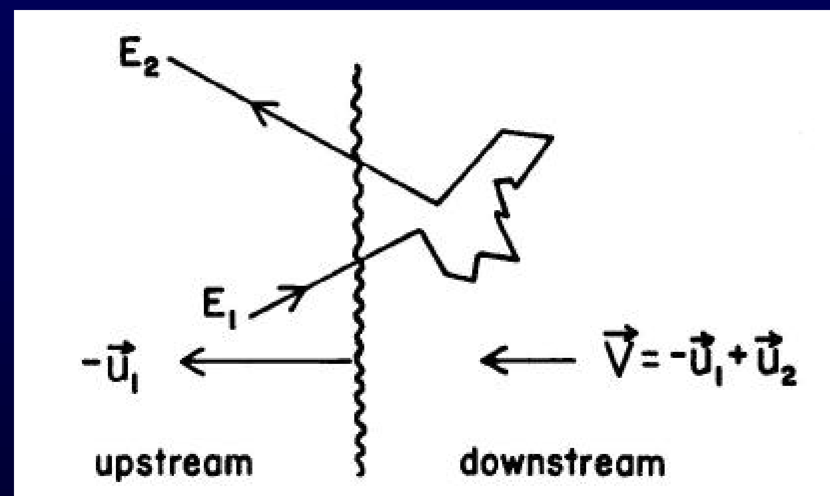
$$\Delta E/E \propto \beta^2$$

$$\beta < 10^{-4}$$

Fermi Acceleration

- Random velocities of interstellar clouds are very small, so 2nd order Fermi acceleration is rather inefficient
- Fermi acceleration is more efficient at strong plane shock fronts (supernovae)
- Particles gain energies in repeated encounters
- Particles scatter many times within a confined region and eventually escape

- At high energies, it becomes difficult to magnetically confine the particles



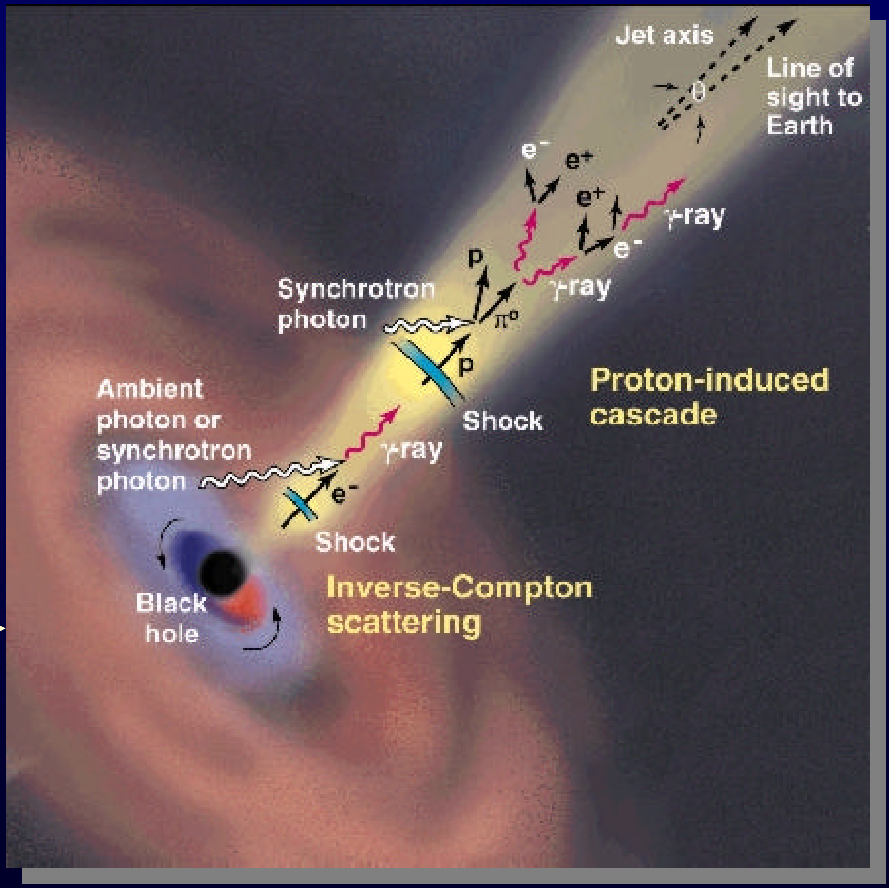
1st order Fermi acceleration

$$\Delta E/E \propto \beta$$

$$\beta < 10^{-1}$$

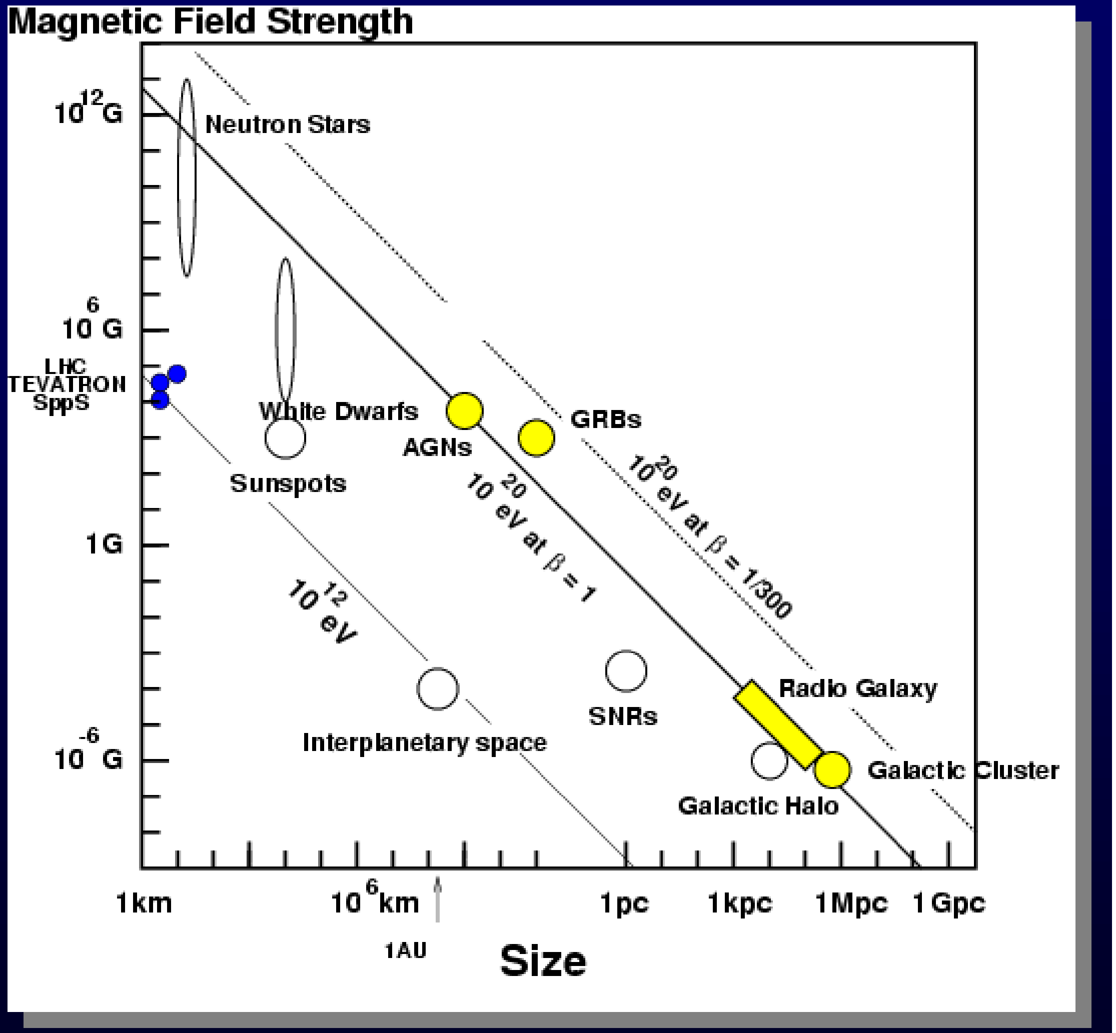
Sites of Shock Acceleration

- Supernova blast waves
  - Fermi mechanism provides a strong case for supernova explosions as the powerhouse for cosmic rays below the ankle
- Active Galactic Nuclei →
- Gamma Ray Bursts



The Challenge

- Size of the acceleration region containing the field must be greater than twice the Larmor radius
- Hillas' plot shows size and magnetic field strength of possible sites – objects below the diagonal line cannot accelerate protons to 10^{20} eV



A.M. Hillas, Ann. Rev. Astron. Astrophys.,1984

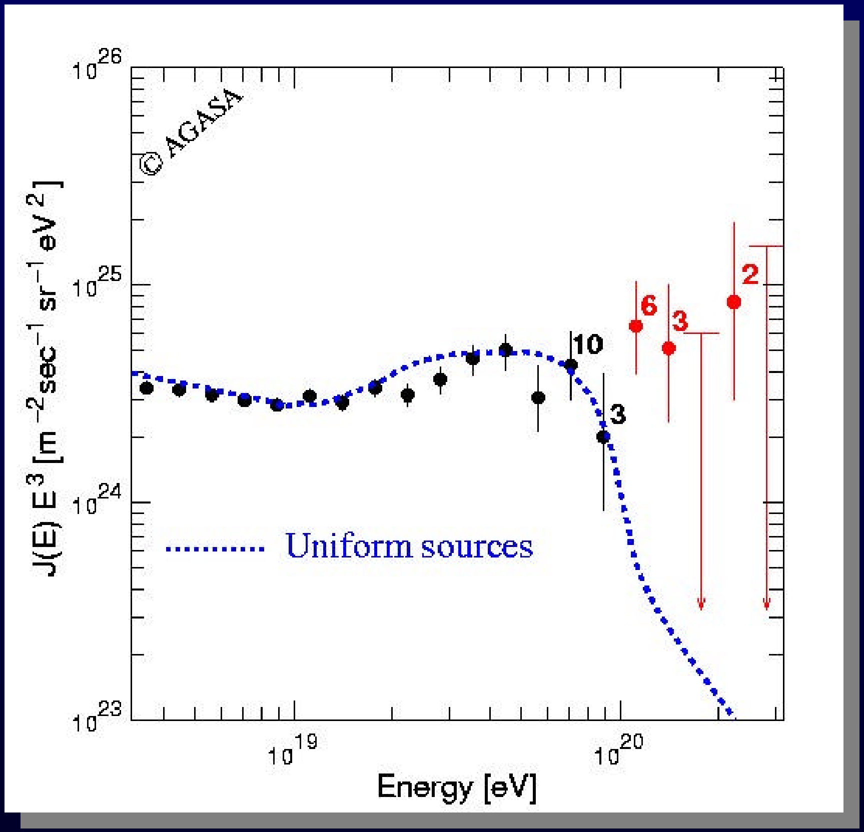
GZK Suppression

- Cosmic rays interact with the 2.7 K microwave background
- Protons above 5×10^{19} eV suffer severe energy loss from photopion production
- Proton (or neutron) emerges with reduced energy, and further interaction occurs until the energy is below the cutoff energy
- Greisen-Zatsepin-Kuz'min Cutoff (1966)

$$
\begin{aligned}
pg_{\text{3K}} &\rightarrow e^{+}e^{-}p \\
&\rightarrow p^{+}n \\
&\rightarrow p^{0}p
\end{aligned}
$$

Cosmic Ray Energy Spectrum

- Cosmic ray particles with energies above the GZK cutoff energy have been observed
- Nearby sources (<50 Mpc) ?
  - M87 in the Virgo cluster (20 Mpc)
  - NGC315 (80 Mpc)
  - Topological defects
  - …



AGASA collaboration

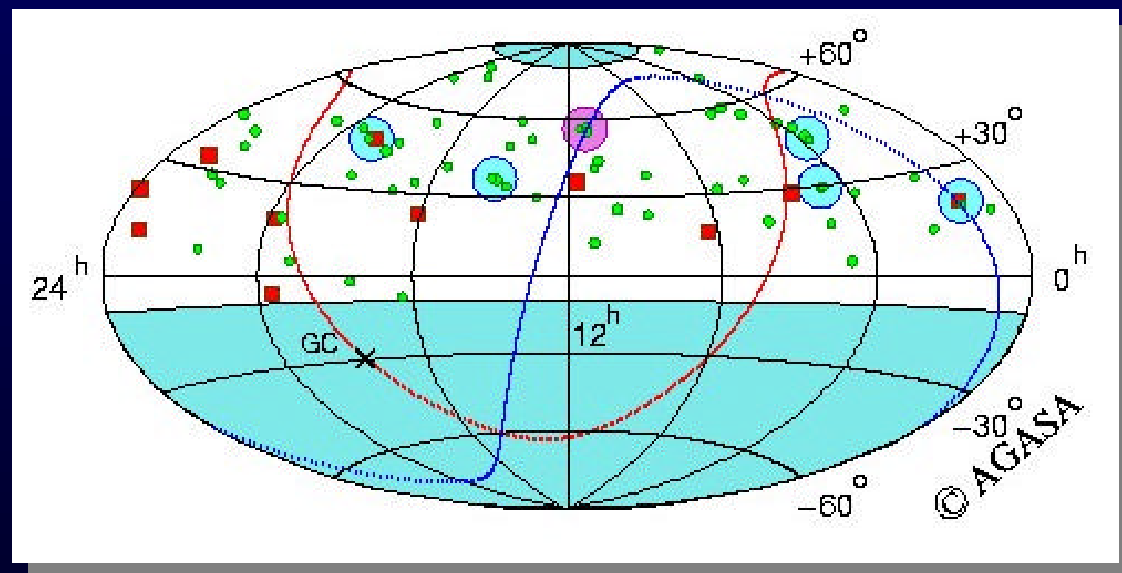
Small-Scale Anisotropy

- Highest energy particles should point back to their sources
- Significant clustering of cosmic ray arrival directions has been claimed in AGASA data above 4×10^{19} eV
- 5 doublets and 1 triplet in 72 events, angular separation <2.5°

AGASA

E > 4×10^{19} eV

E > 10^{20} eV



Distribution of arrival directions of cosmic rays above 4×10^{19} eV (in equatorial coordinates)

Small-Scale Anisotropy

- Clustering of cosmic ray arrival directions would favor compact sources
- Clustering is expected to be strongest at the highest energies, where deflections in magnetic fields are smallest
- Literature gives chance probabilities of 10^{-2} to 10^{-6} for this clustering signal, depending on whether cuts on angular separation and minimum energy can be considered *a priori*
- See C. Finley & SW, astro-ph/0309159 (submitted to Astropart. Phys.), for a critical discussion
- Correlations with known source classes have been claimed (BL Lacs, …), but significance is low

The Case for New Data

- Statistically independent data sets are needed to verify/falsify previous results based on poor statistics
- More and better data at the highest energies is needed to understand the GZK suppression (or the lack thereof) and arrival direction distributions
- The ball is in our court…

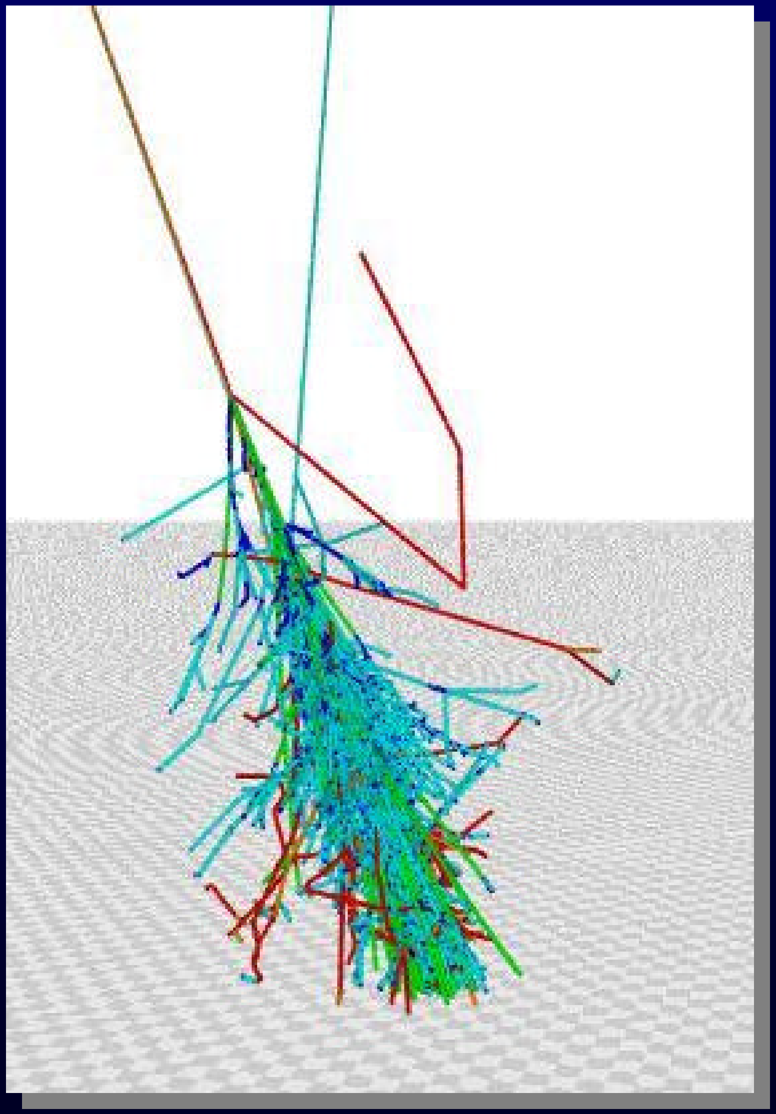
UHECR Industry

- Reassessment of the GZK cutoff in the spectrum of UHE cosmic rays in a universe with low photon-baryon ratio (astro-ph/0309803)
- Do we observe ultra high energy cosmic rays above the Greisen-Zatsepin-Kuzmin cutoff due to violation of Lorentz invariance? (astro-ph/0309421)
- Gamma-Ray Bursts and Magnetars as Possible Sources of Ultra High Energy Cosmic Rays: Correlation of Cosmic Ray Event Positions with IRAS Galaxies (astro-ph/0308257)
- Constrained Simulations of the Magnetic Field in the Local Supercluster and the Propagation of UHECR (astro-ph/0308155)
- Super-heavy X particle decay and Ultra-High Energy Cosmic Rays (hep-ph/0308028)
- Ultra High Energy Cosmic Rays and de Sitter Vacua (astro-ph/0307413)
- The Galactic magnetic field and propagation of ultra-high energy cosmic rays (astro-ph/0307165)
- On the cross correlation between the arrival direction of ultra-high energy cosmic rays, BL Lacertae, and EGRET detections: A new way to identify EGRET sources? (astro-ph/0307079)
- The Small Scale Anisotropies, the Spectrum and the Sources of Ultra High Energy Cosmic Rays (astro-ph/0307067)
- Constraining superheavy dark matter model of UHECR with SUGAR data (astro-ph/0306413)
- Probing TeV gravity with extensive air-showers (astro-ph/0306344)
- On the composition of ultra-high energy cosmic rays in top-down scenarios (astro-ph/0306288)
- Cosmic Ray Acceleration by Stellar Associations? The Case of Cygnus OB2 (astro-ph/0306243)
- 35 more….

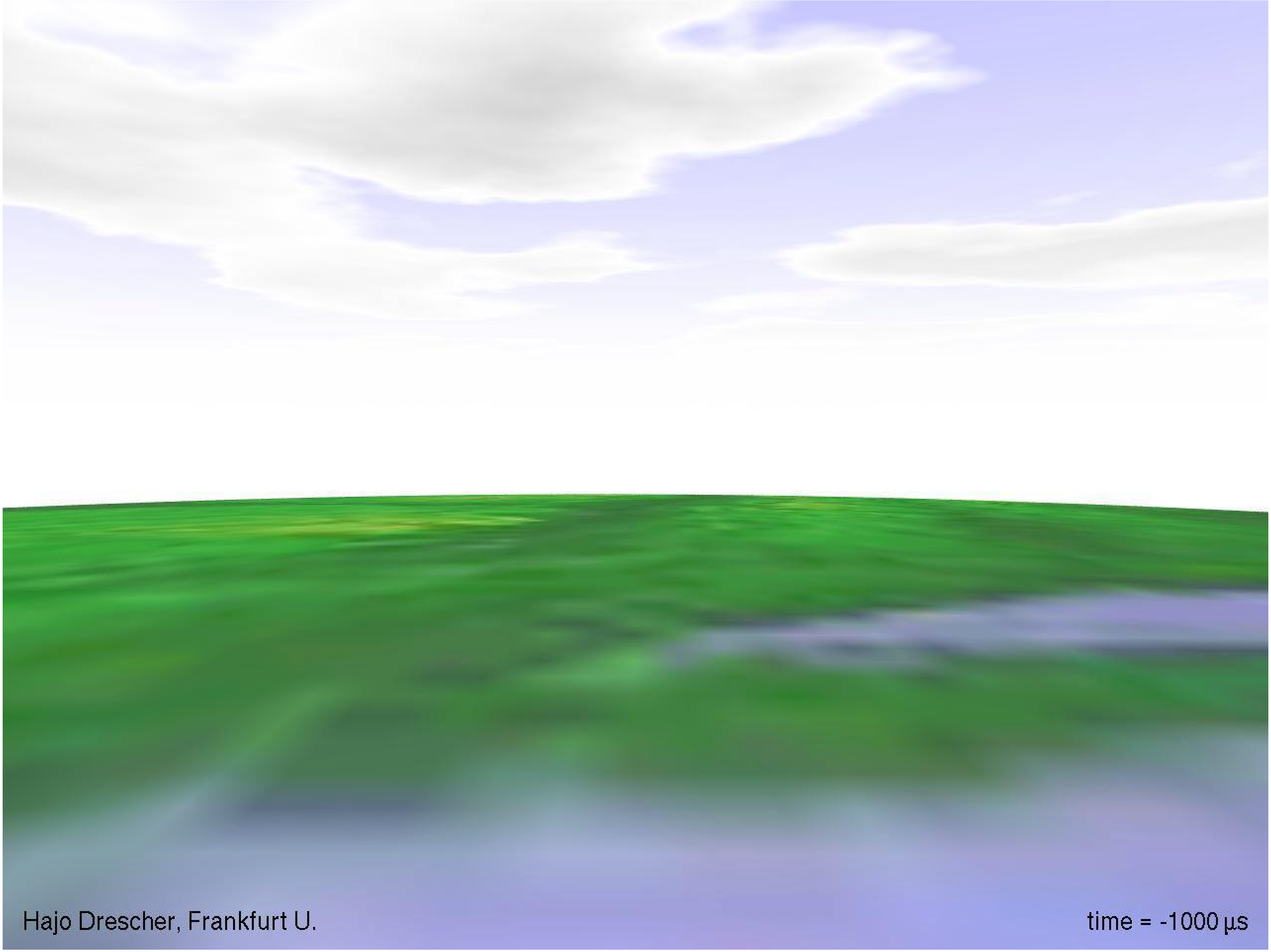
- Experimental Techniques
  - Surface Detectors (AGASA,…)
  - Air Fluorescence Detectors (HiRes,…)

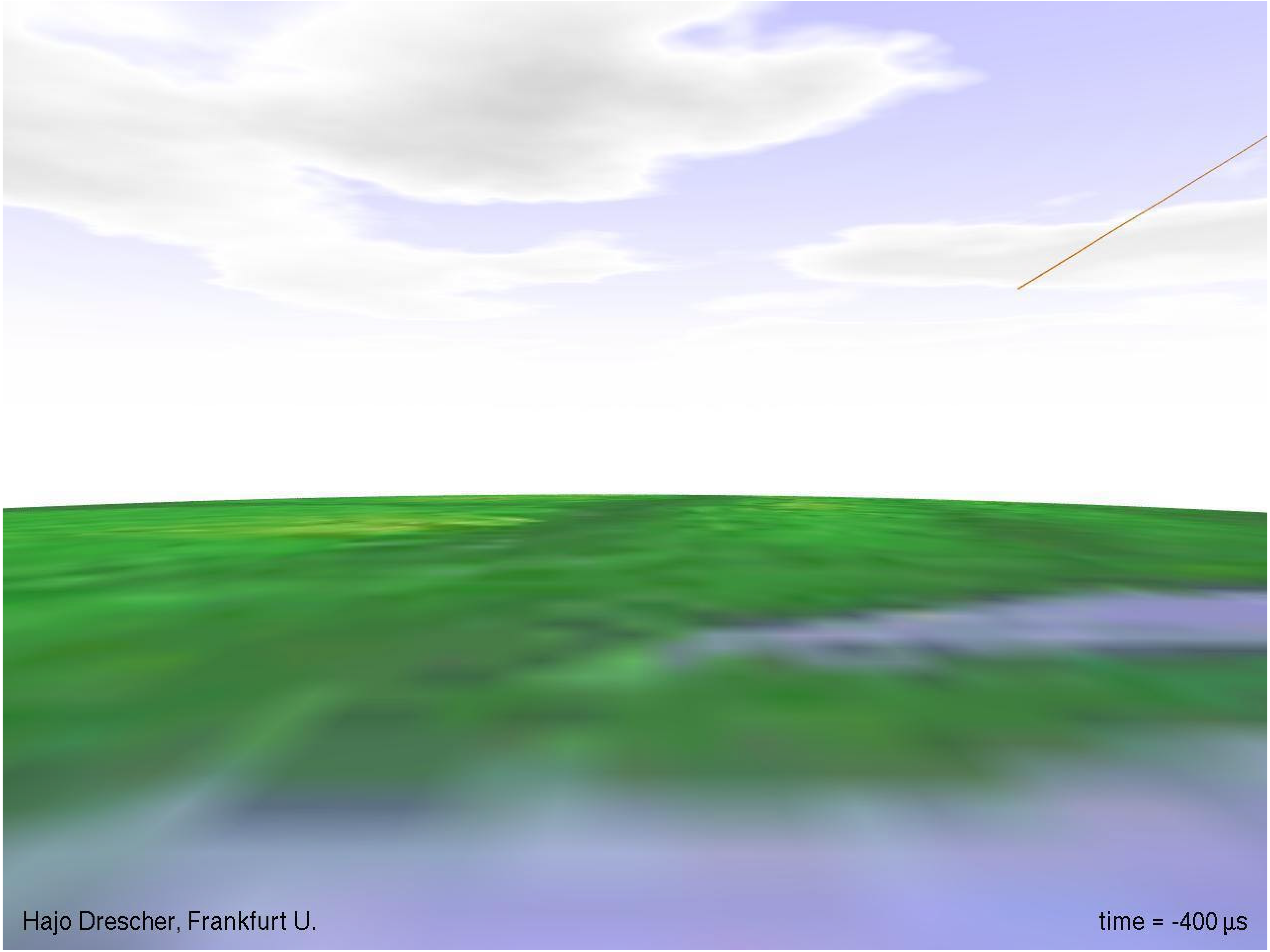
Experimental Techniques

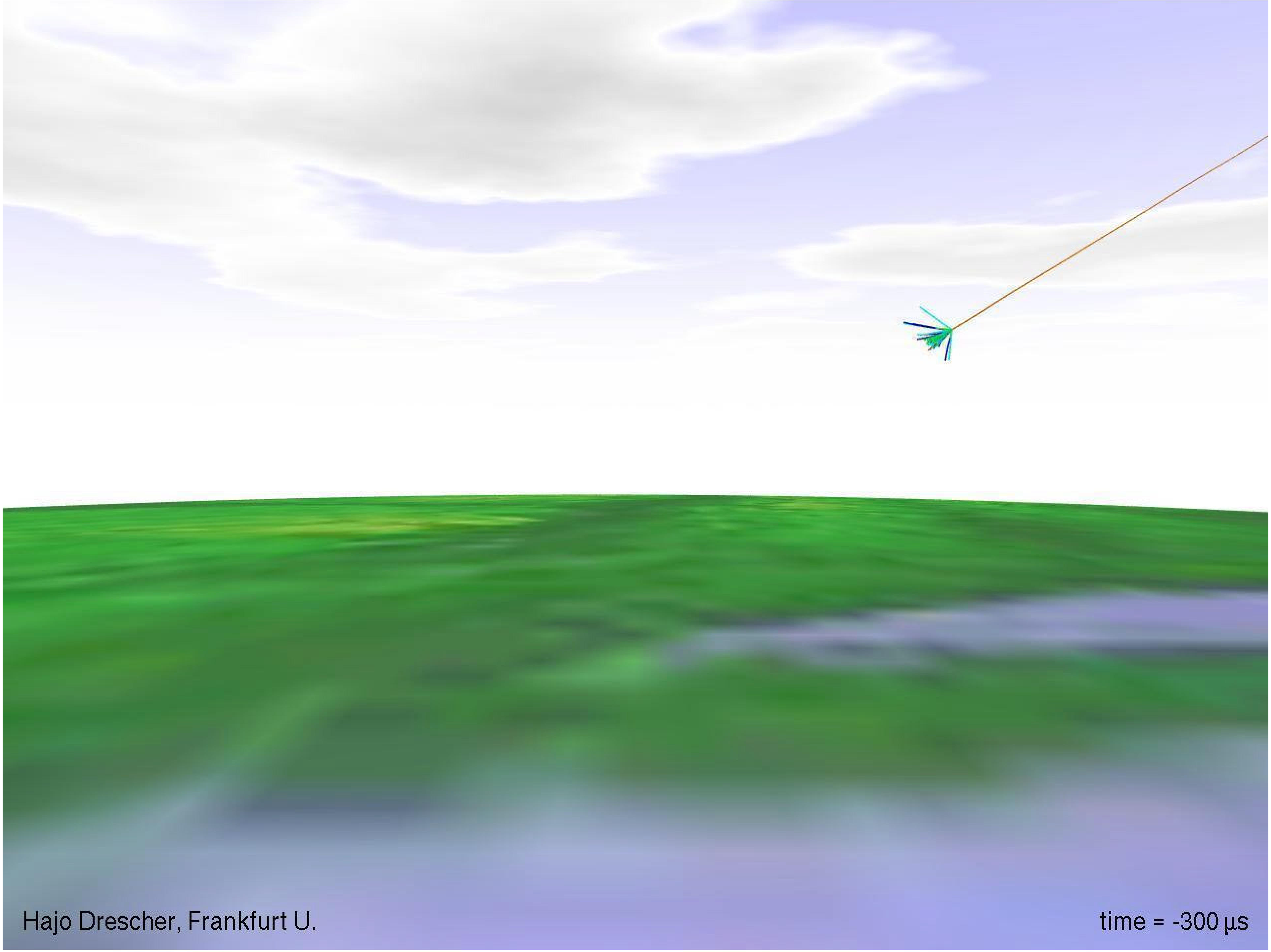
- Large detector volume is needed as flux is low
- Detectors are earth-bound, and the cosmic ray primary is detected indirectly
- Incident primary cosmic ray produces air shower in the Earth's atmosphere
- Earth acts as a (rather complicated) calorimeter

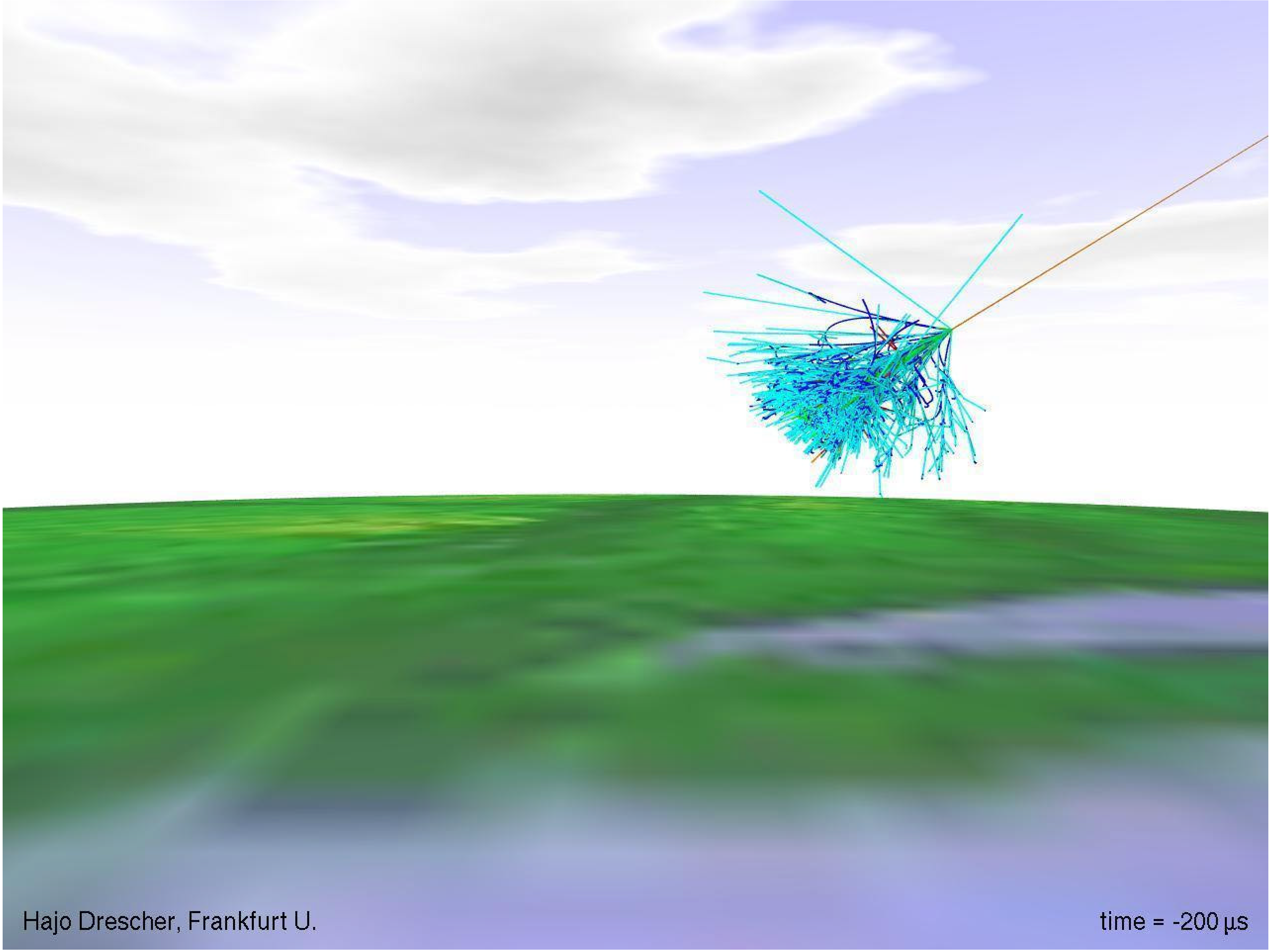


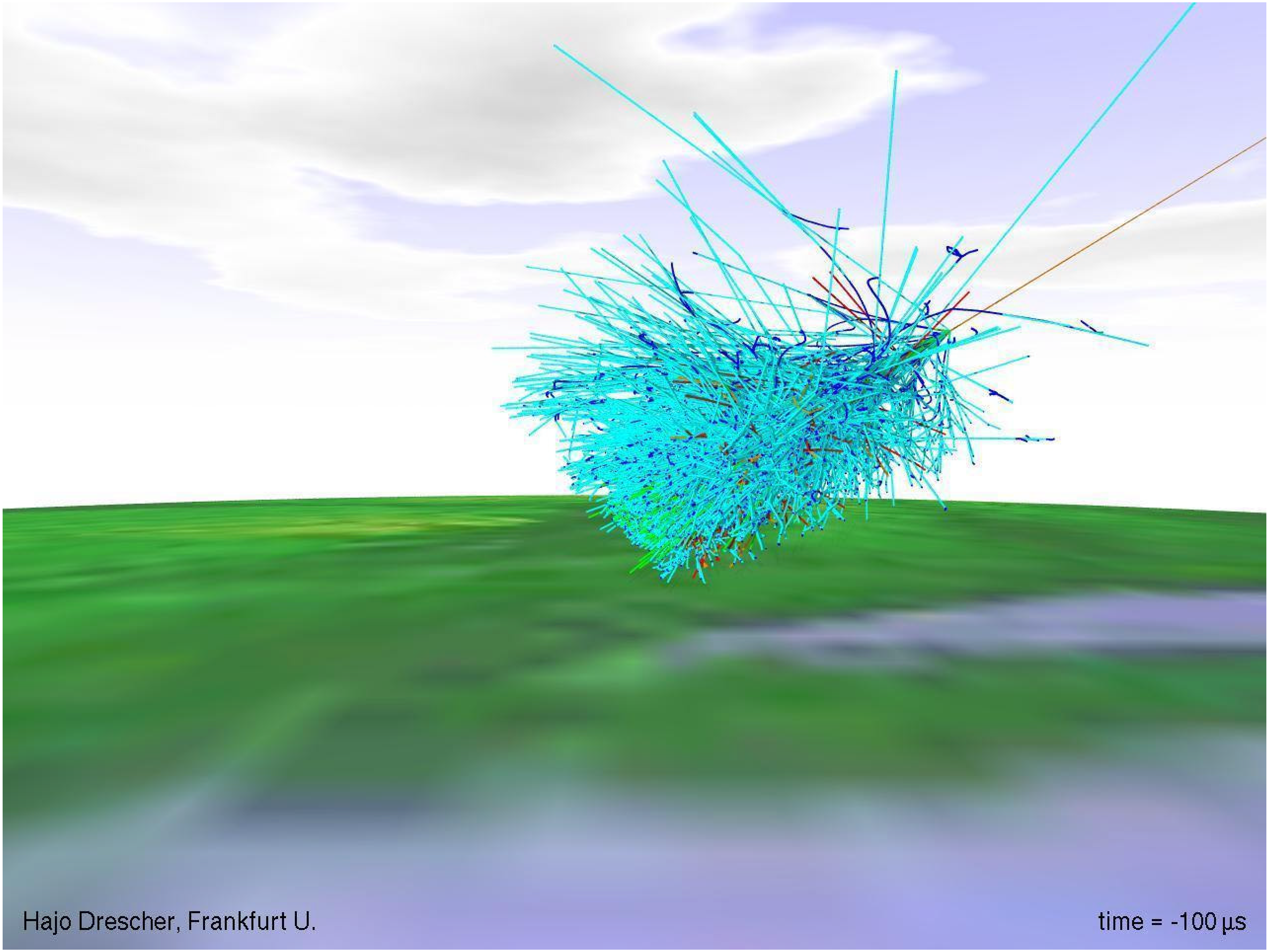
Computer Simulation by H.J. Drescher

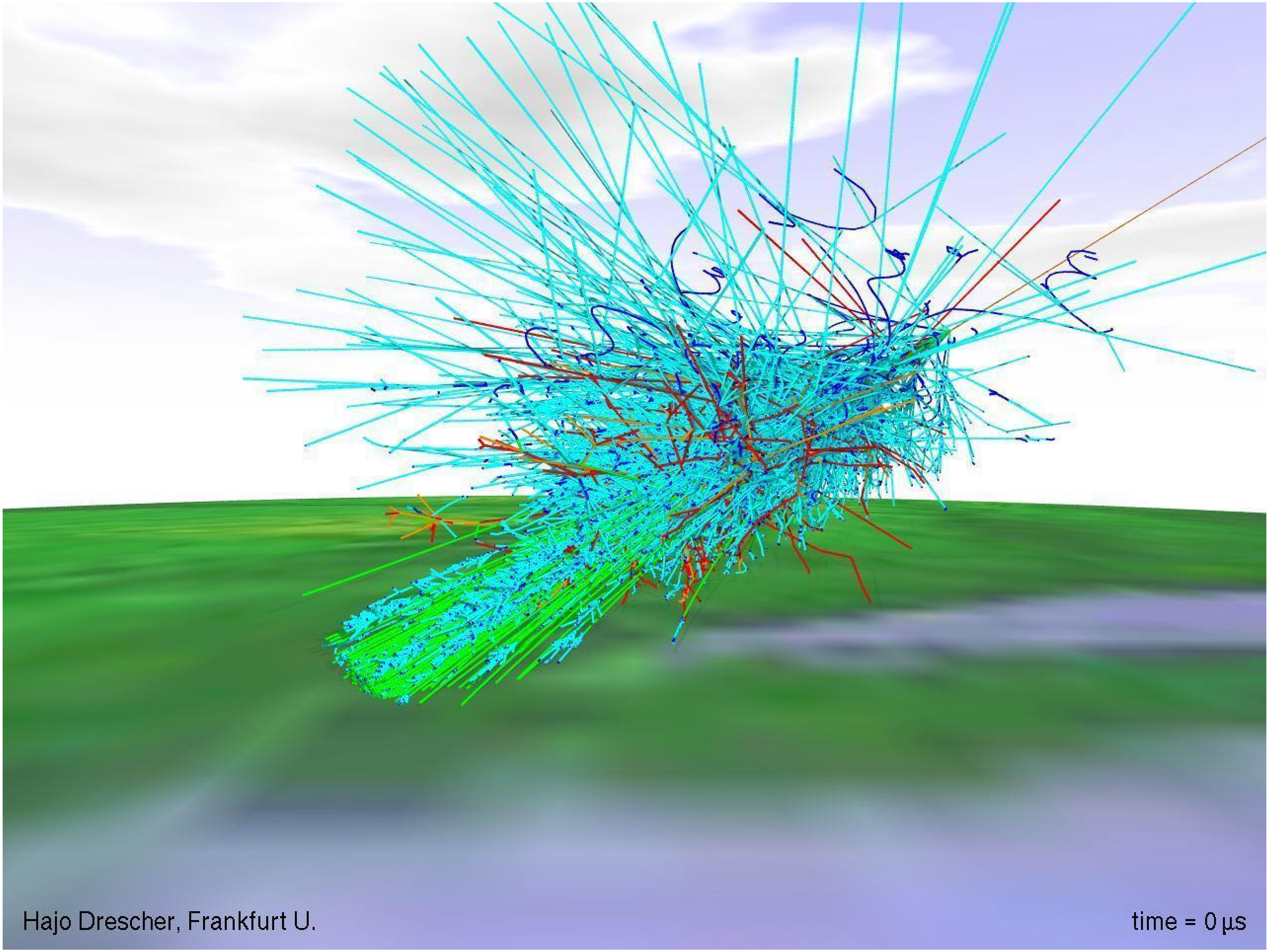

Hajo Drescher, Frankfurt U.
time = -1000 µs

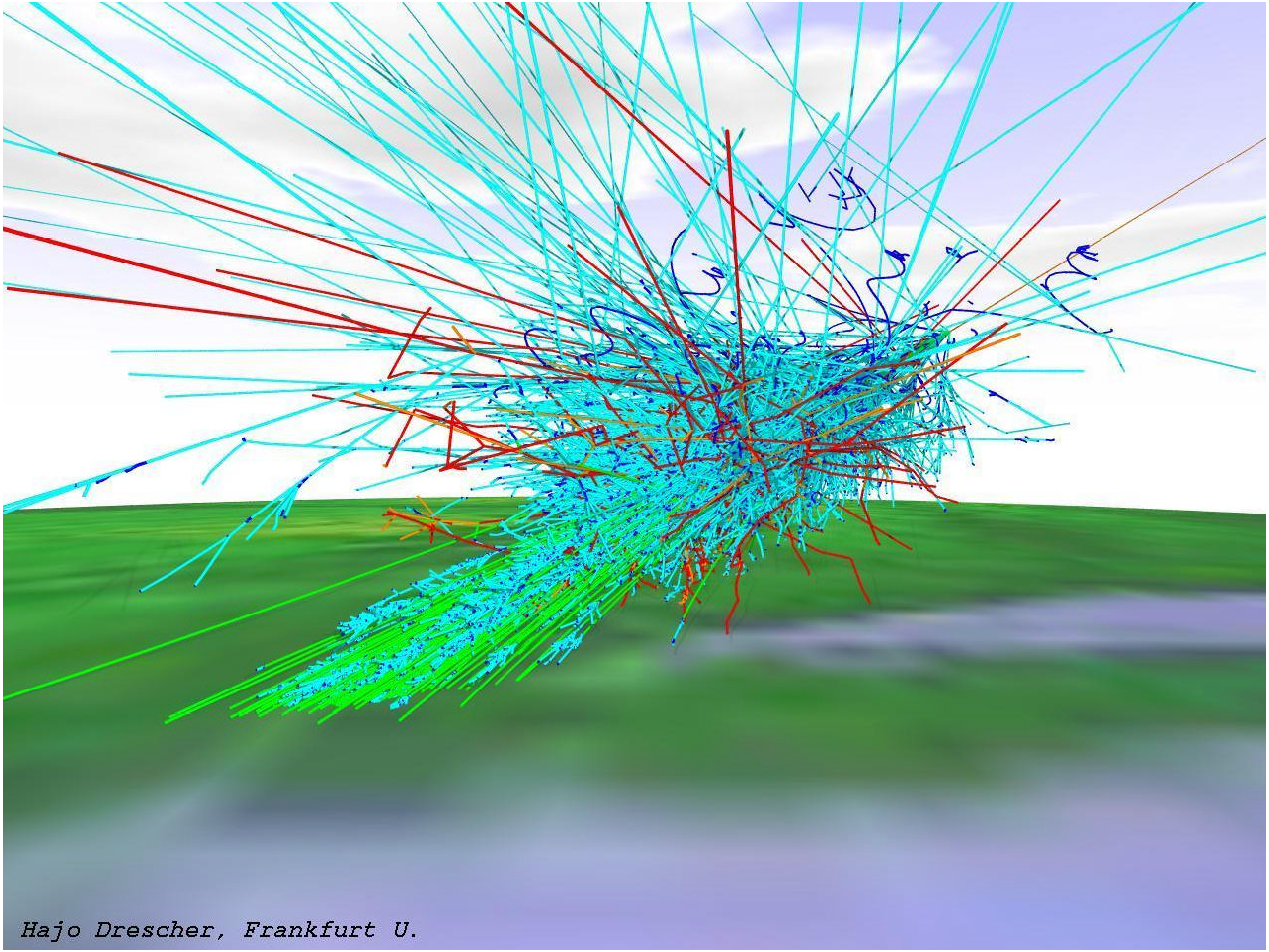

Hajo Drescher, Frankfurt U.
time = -400 μs

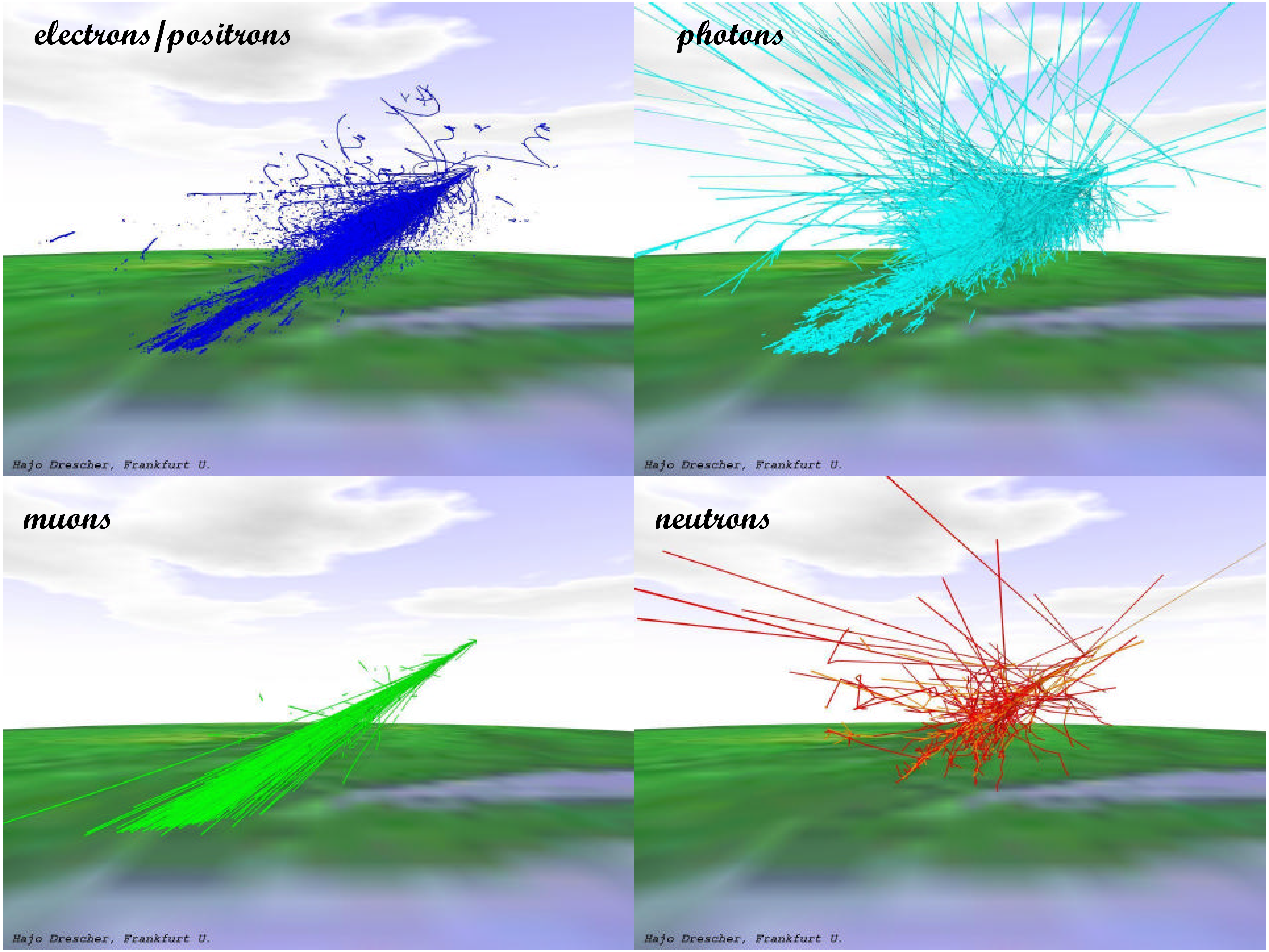

Hajo Drescher, Frankfurt U.
time = -300 µs


Hajo Drescher, Frankfurt U.
time = -200 µs


Hajo Drescher, Frankfurt U.
time = -100 µs


Hajo Drescher, Frankfurt U.
time = 0 μs


Hajo Drescher, Frankfurt U.



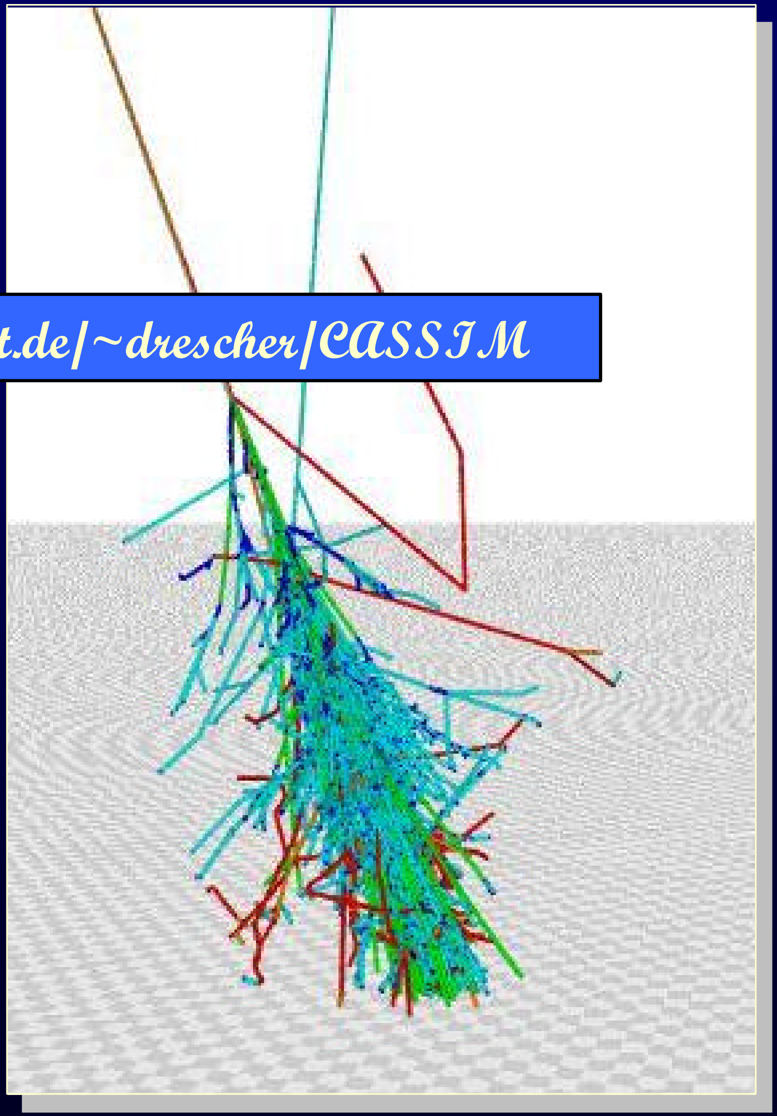
electrons/positrons
Hajo Drescher, Frankfurt U.
photons
Hajo Drescher, Frankfurt U.
muons
Hajo Drescher, Frankfurt U.
neutrons
Hajo Drescher, Frankfurt U.

Experimental Techniques

- See more showers at

  http://www.th.physik.uni-frankfurt.de/~drescher/CASSIM

- Experimental challenge: Properties of the incident primary cosmic ray particle (type, energy, arrival direction) have to be determined by analyzing the cascade



Computer Simulation by H.J. Drescher

Air Shower Cascades

- Air showers at 10^{19} eV may contain 10^{10} charged particles and extend over an area of 10-20 km^2
- Thickness of the shower front is several μs
- Electromagnetic components are some 100 times more numerous than muons (at 1.5 km altitude)
- Mean energy of electromagnetic component is 10 MeV, muonic component 1 GeV
- Muons are typically the leading particles within the shower front

Air Shower Technique

- Detect charged particles reaching the surface of the Earth with array of scintillation counters or water Cherenkov counters
- AGASA, Auger, CASA-MIA,…

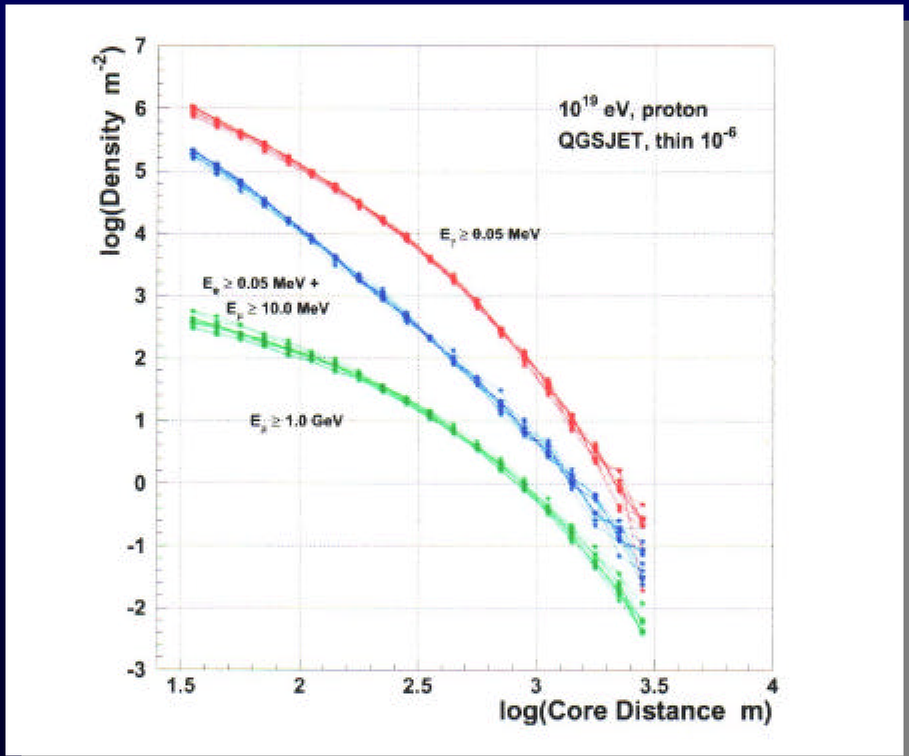
AGASA Array

- Akeno Giant Air Shower Array
  - 111 scintillation counters of 2.2 m^2 area
  - 100 km^2 area, about 1 km spacing
  - 900 m above sea level
  - Coincidence of 5 adjacent detectors forms a trigger
  - Data from 1984 to present (A20 with 12 km^2 for first 5 years)

AGASA Energy Estimation

Astroparticle Physics 19 (2003) 447

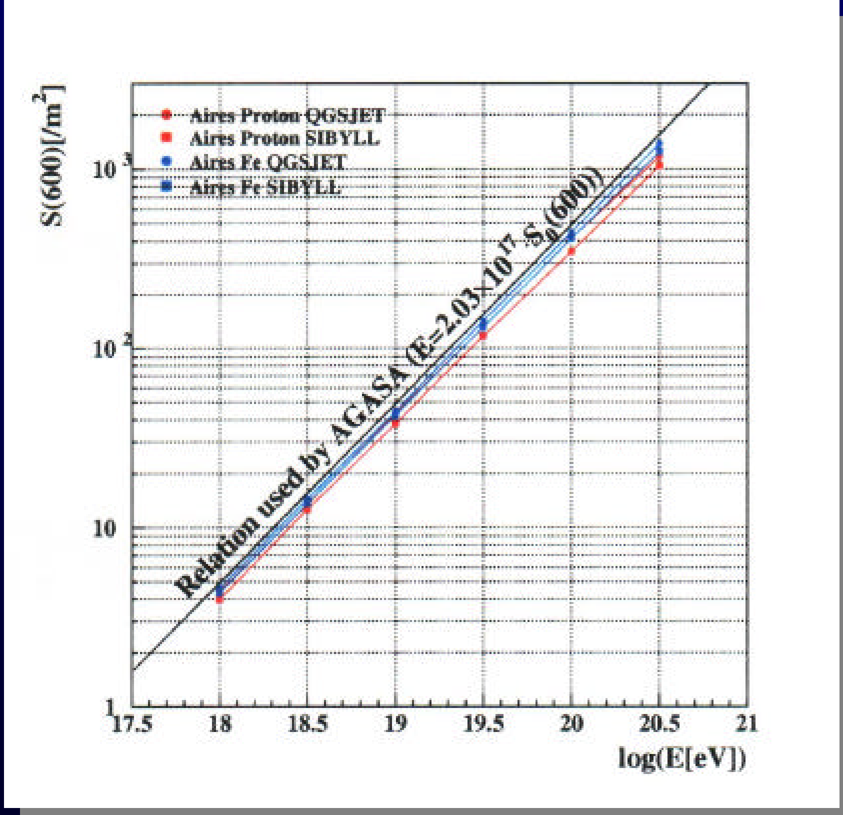
- AGASA measures the local density of charged particles as a function of distance to the shower axis
- Fit lateral distribution function to the data



AGASA Energy Estimation

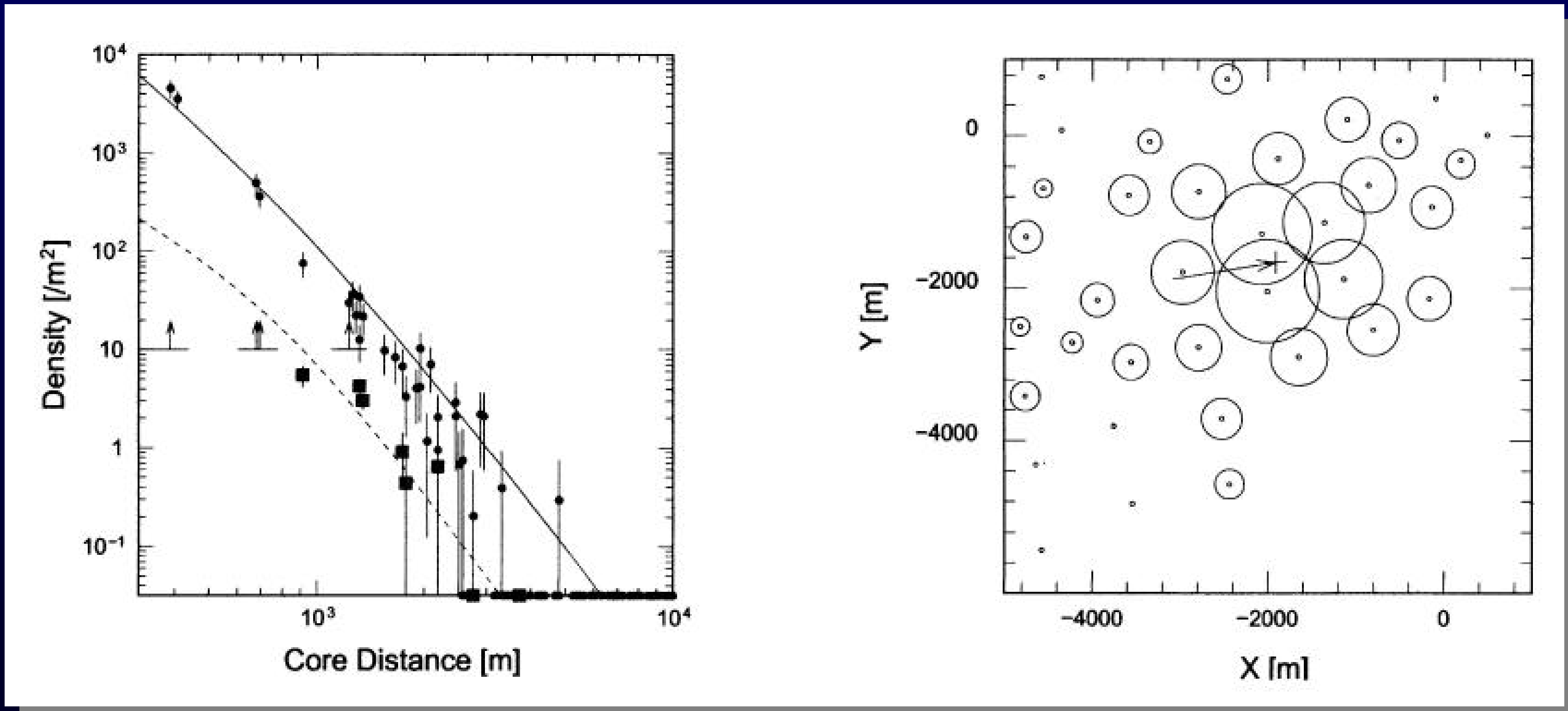
- Density at 600 m from shower core, S(600), is found to correlate with the shower energy
- S(600) depends only weakly on interaction model and shower fluctuations
- Empirical formula

$$E = 2.03 \times 10^{17} S_0(600)\ \text{eV}$$



AGASA Event at 200 EeV

- Candidate for the highest energy event



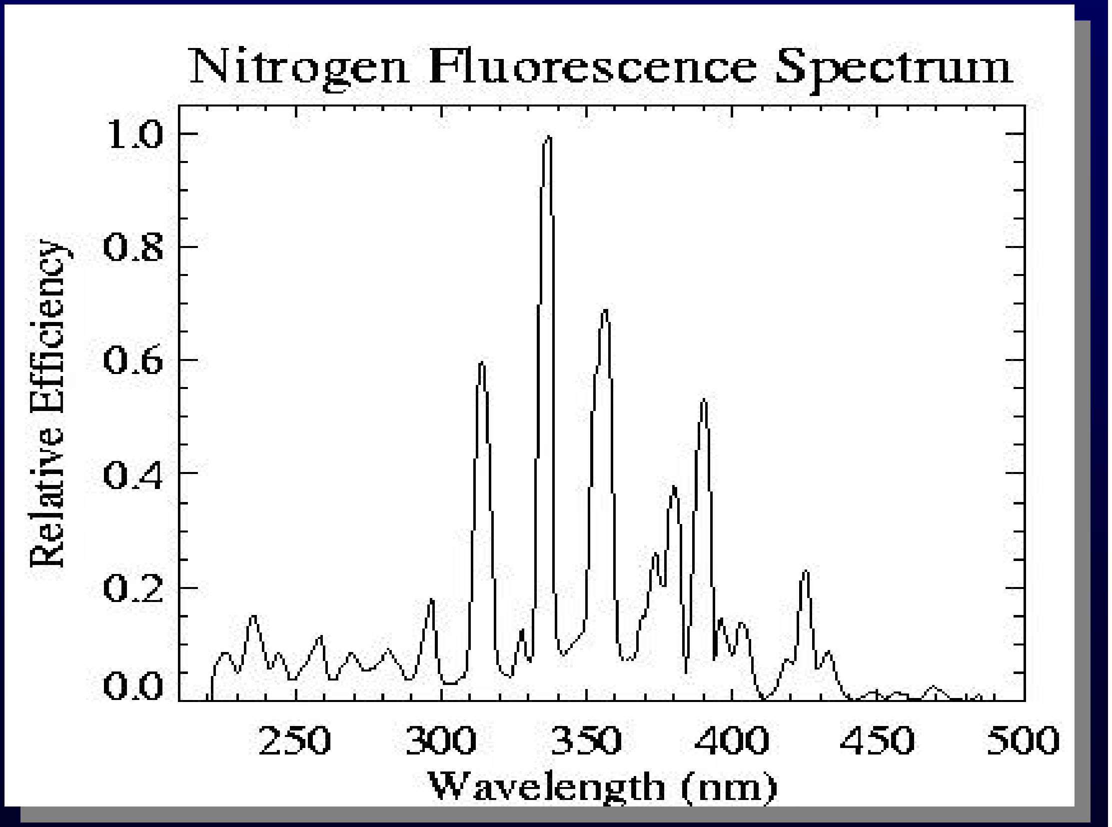
Air Shower Technique

- Shortcomings
  - Shower is sampled long after the shower maximum, even for high detector altitudes
  - Shower is sampled at one altitude only
  - Sampling density is small
  - No measurement of shower maximum
- Advantages
  - 100 % duty cycle
  - No dependence on optical parameters of the atmosphere
  - Stable running
- Goal
  - Detector to see full shower development and measure height of first interaction

Air Fluorescence Technique

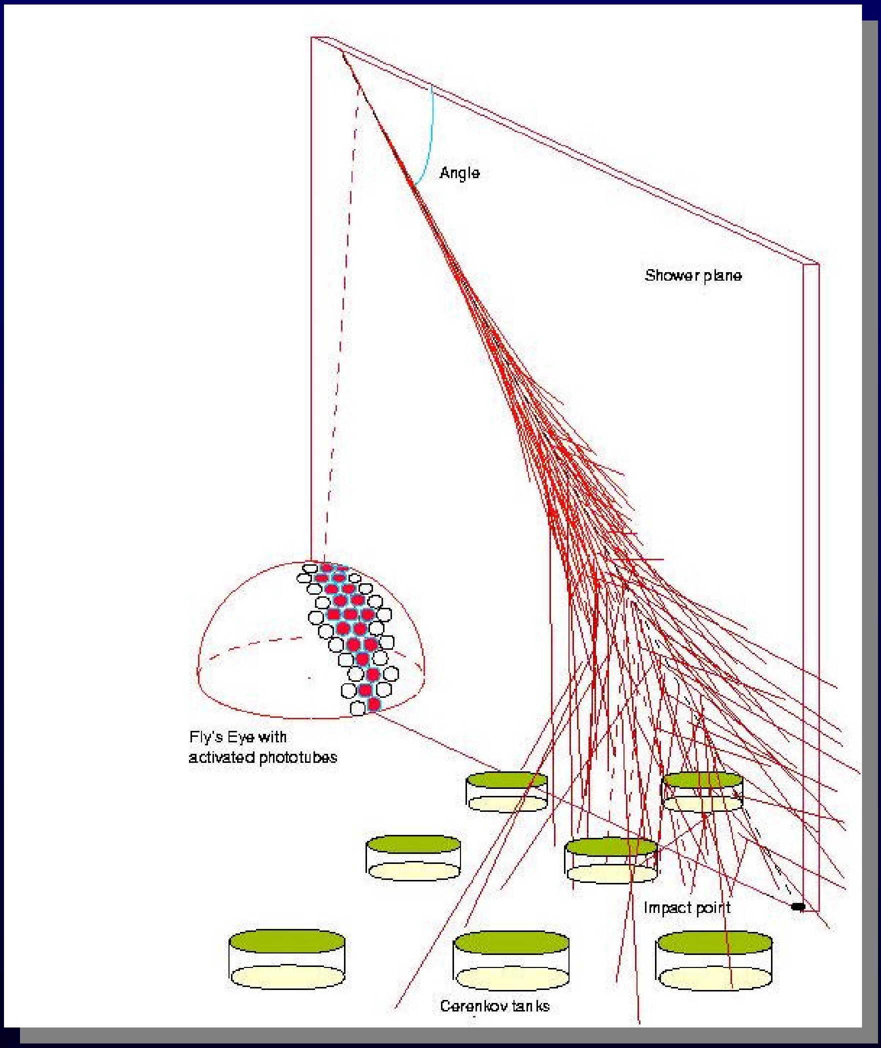
Greisen (1960)

- Particles of the air shower cascade excite air molecules, which fluoresce in the UV
- Nitrogen fluorescence light is emitted isotropically, and the amount of light is proportional to the number of particles in the shower



Detection Techniques

- 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"



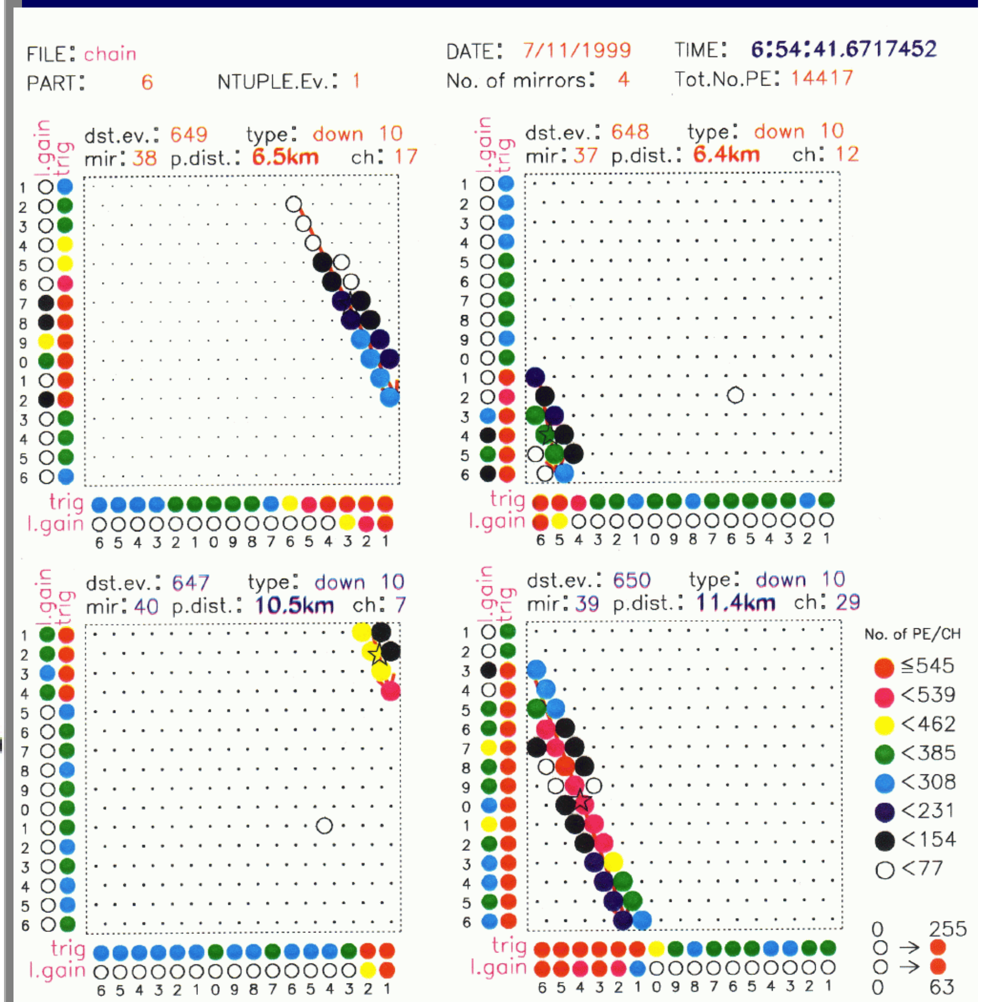
Pioneer of the Air Fluorescence Technique– Fly's Eye

Dugway, Utah 1981-1992

High Resolution Fly's Eye

- Dugway Proving Ground, Utah
- 112^{o} W, 40^{o} N, vertical atmospheric depth 850 g/cm^{2}

Air Fluorescence Technique



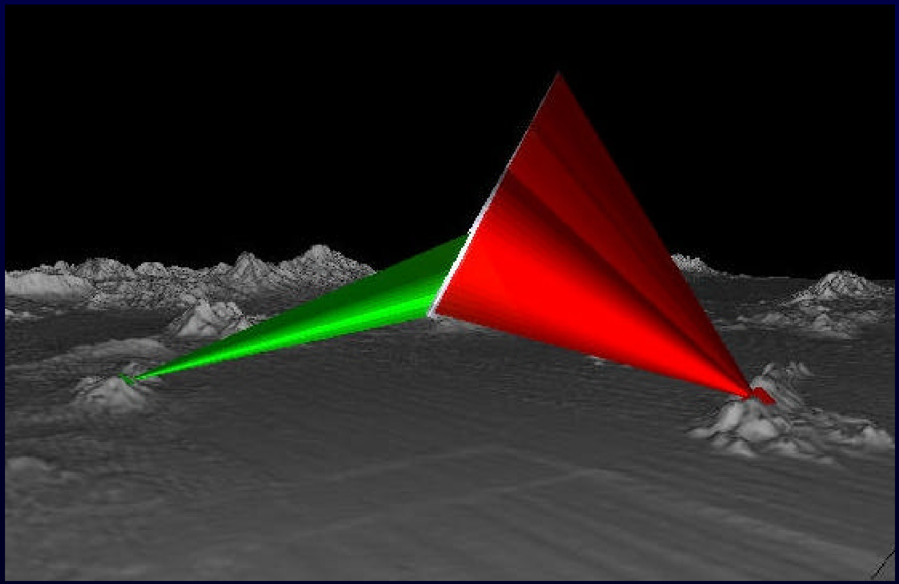
High Resolution Fly's Eye

- University of Utah
- Columbia University
- Rutgers University
- University of New Mexico
- University of Montana
- University of Adelaide
- University of California, Los Angeles
- Los Alamos National Lab

- At Columbia
  - Brian Connolly
  - Segev BenZvi, Chad Finley, Andrew O'Neill
  - Michal Seman, Bruce Knapp, Eric Mannel, John Boyer

Five Mile Hill and Camels' Back

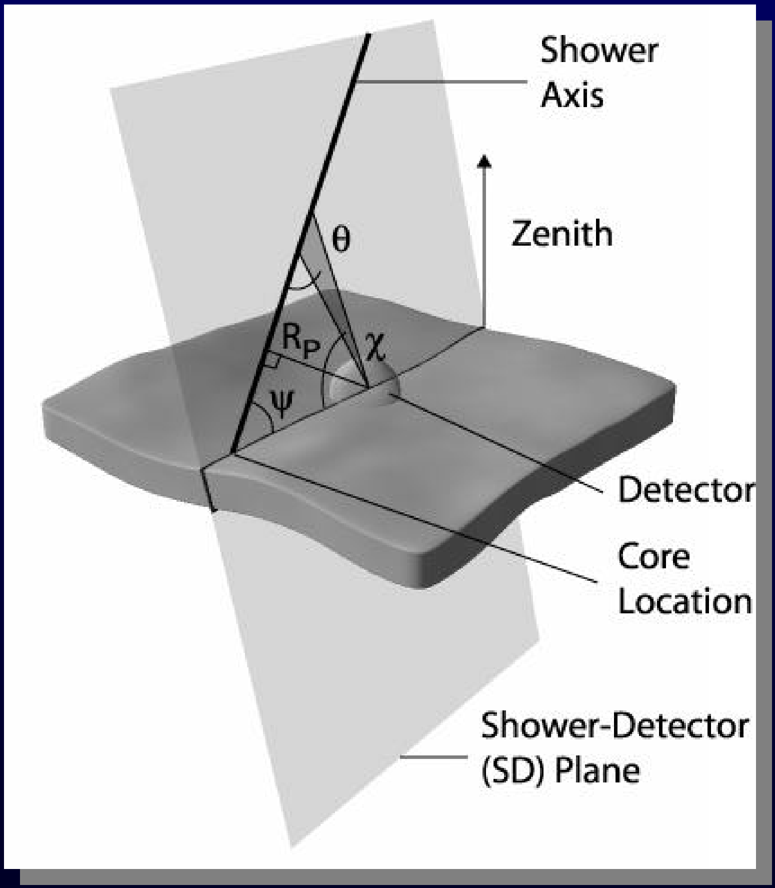
- HiRes 1 at Five Mile Hill
- 22 telescopes with 256 photomultiplier tubes each
- 3^o – 16.5^o elevation
- 360^o azimuth



- 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

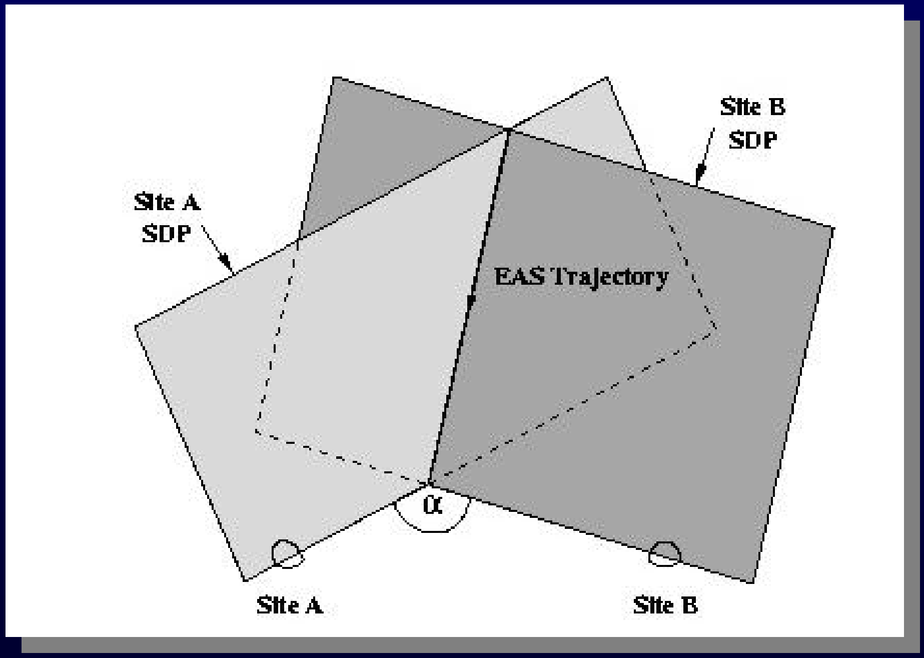
Event Reconstruction

- Fluorescence light generated by passage of an air shower is viewed by a succession of PMTs
- Each PMT has a fixed field of view and detects light from a part of the shower trajectory
- Track gives shower-detector plane
- Position of shower within the plane is determined using the PMT times

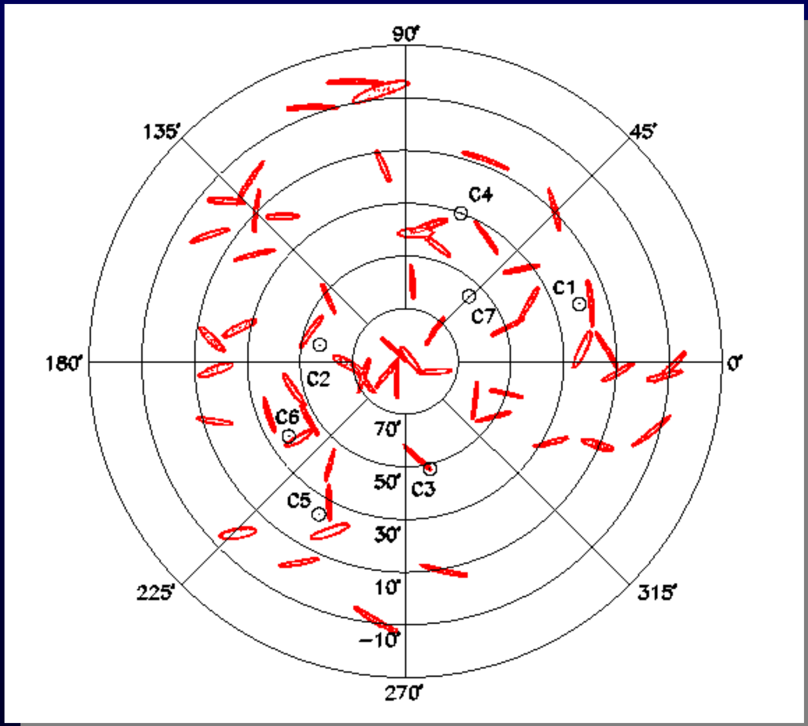


Stereo Reconstruction

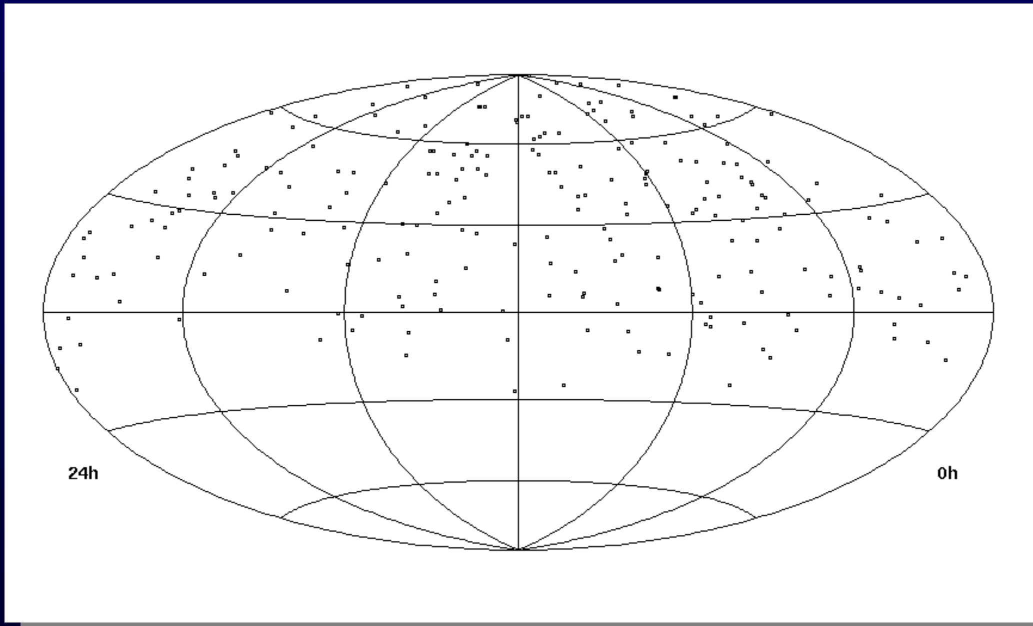
- Shower is viewed simultaneously with two sites
- Each site determines a shower detector plane
- Timing can be used for a global fit
- Dependence on atmospheric parameters reduced



Stereo vs. Mono Reconstruction



Mono data with E > $3 \cdot 10^{19}$ eV



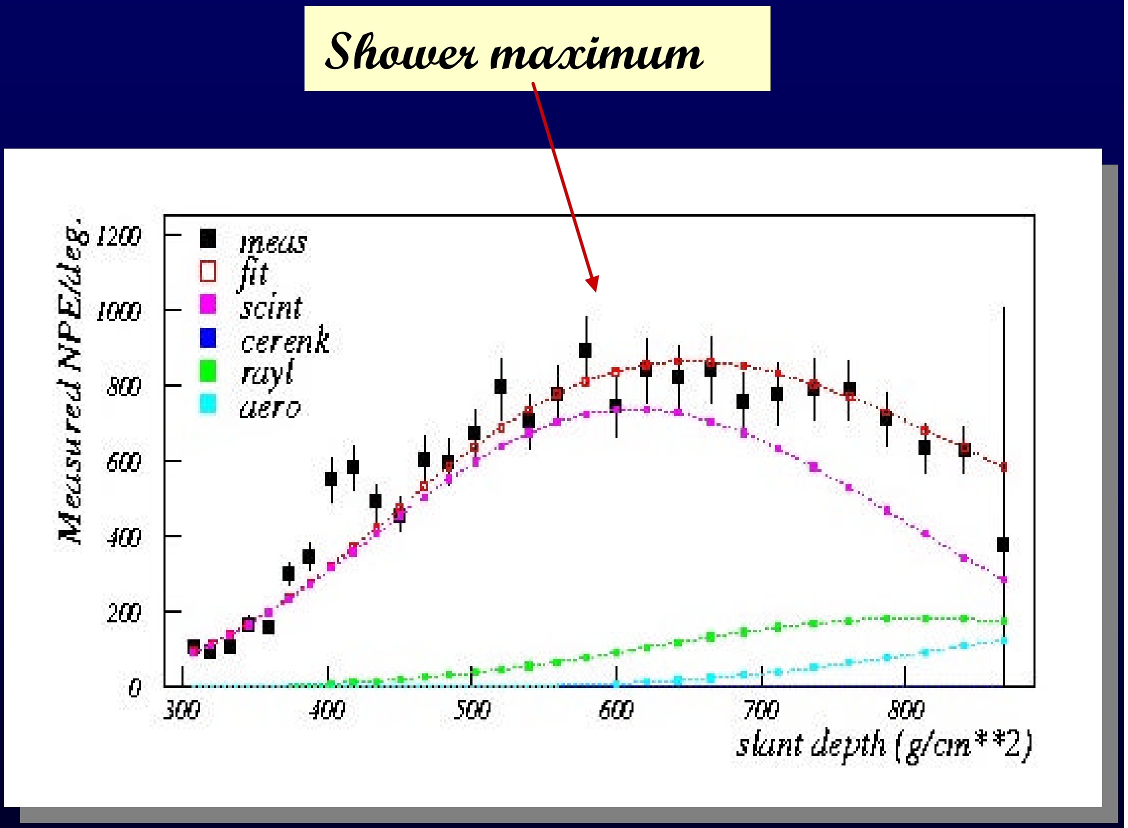
Stereo data with E > 10^{19} eV

HiRes Energy Estimation

- Keyword: Atmosphere
- Rayleigh scattering from atmospheric molecules
  - Well-understood in terms of distribution of scattering centers, angular distribution, and extinction length for UV light
- Mie scattering from aerosols
  - Distribution of aerosols depends on weather conditions
  - Variations in size and shape changes scattering phase function
  - Model-dependent: *standard desert aerosol model*
- HiRes needs to continuously monitor the atmosphere
  - lasers, Xenon flashers, shoot-the-shower,…

HiRes Energy Estimation

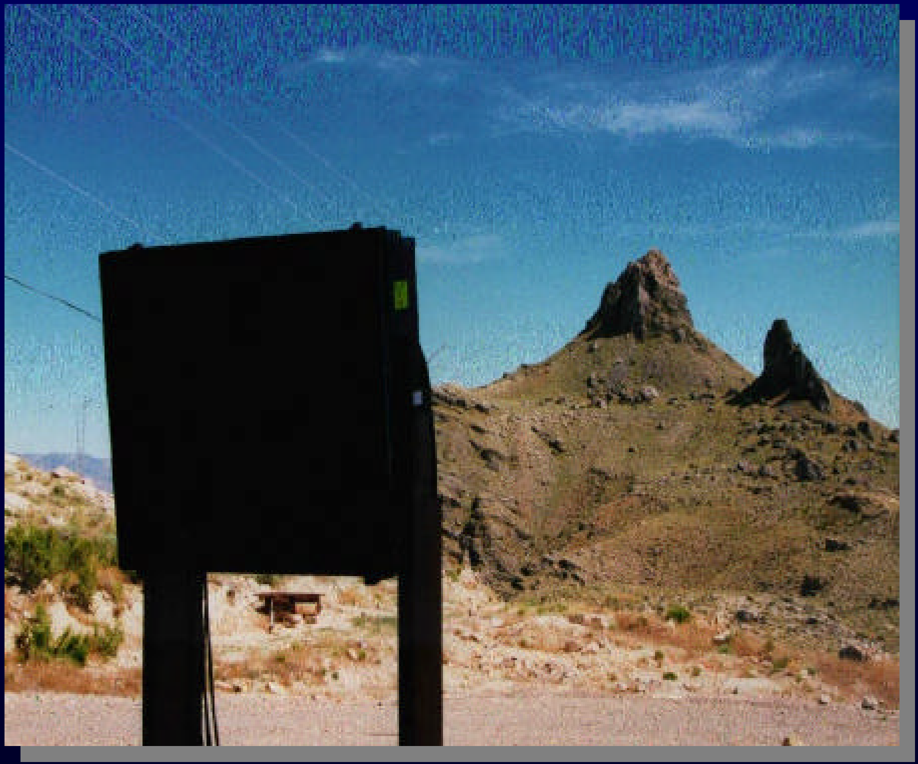
- Total shower energy is determined from the integral over the light intensity along the track
- Measured light must be corrected for contamination from scattered or direct Cherenkov light



- Results
  - –Energy Spectrum
  - –Chemical Composition
  - –Anisotropy of Arrival Directions

HiRes Data Sets

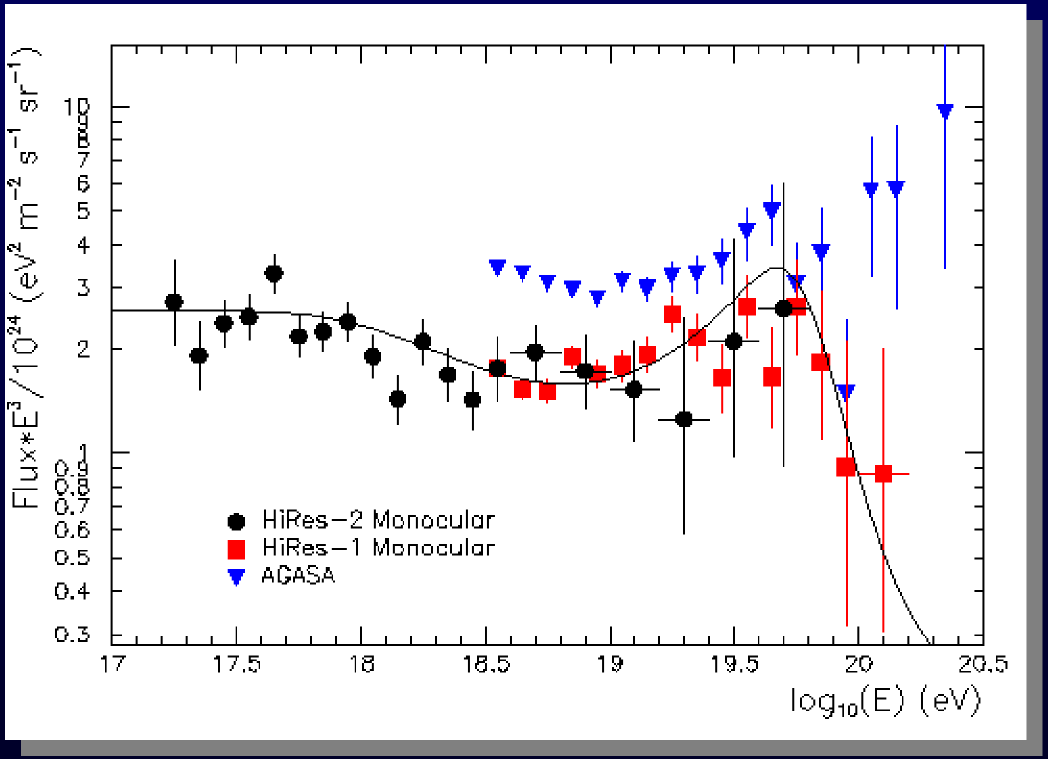
- HiRes 1 monocular data
  - June 1997 – present
- HiRes 1/2 stereo data
  - November 1999 – present
- Results from stereo data set
  - Energy spectrum
  - Chemical composition
  - Small-scale anisotropy



Monocular Energy Spectra

- HiRes spectrum falls steeply above 6×10^{19} eV, as expected if GZK cutoff is observed
- $E > 10^{19.8}$ eV
  - 5 events observed
  - 21.7 expected
  - $P = 1.8\times10^{-5}$

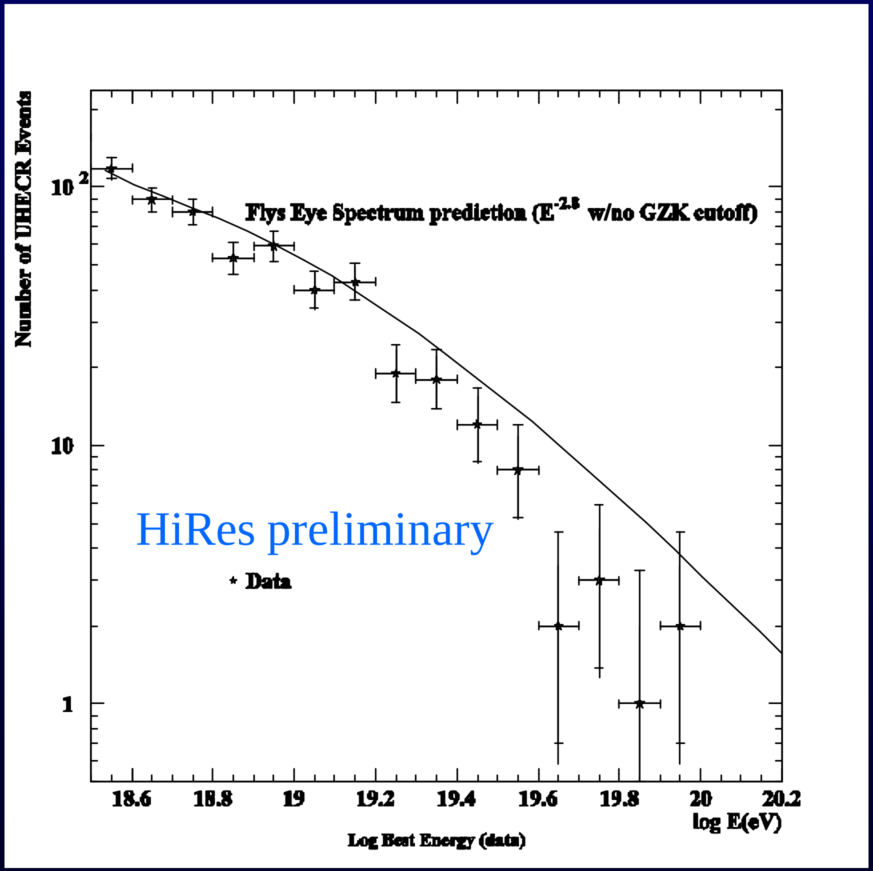
astro-ph/0208243 (subm. to PRL)



Flux vs. energy for HiRes 1&2 monocular data, and AGASA data

Prelim. Stereo Energy Spectrum

- HiRes stereo spectrum above $10^{18.5}$ eV
- Stereo energy resolution 15.5 % (21 % including atmospheric uncertainties)
- Agreement with HiRes 1/2 spectrum, but still large statistical uncertainties

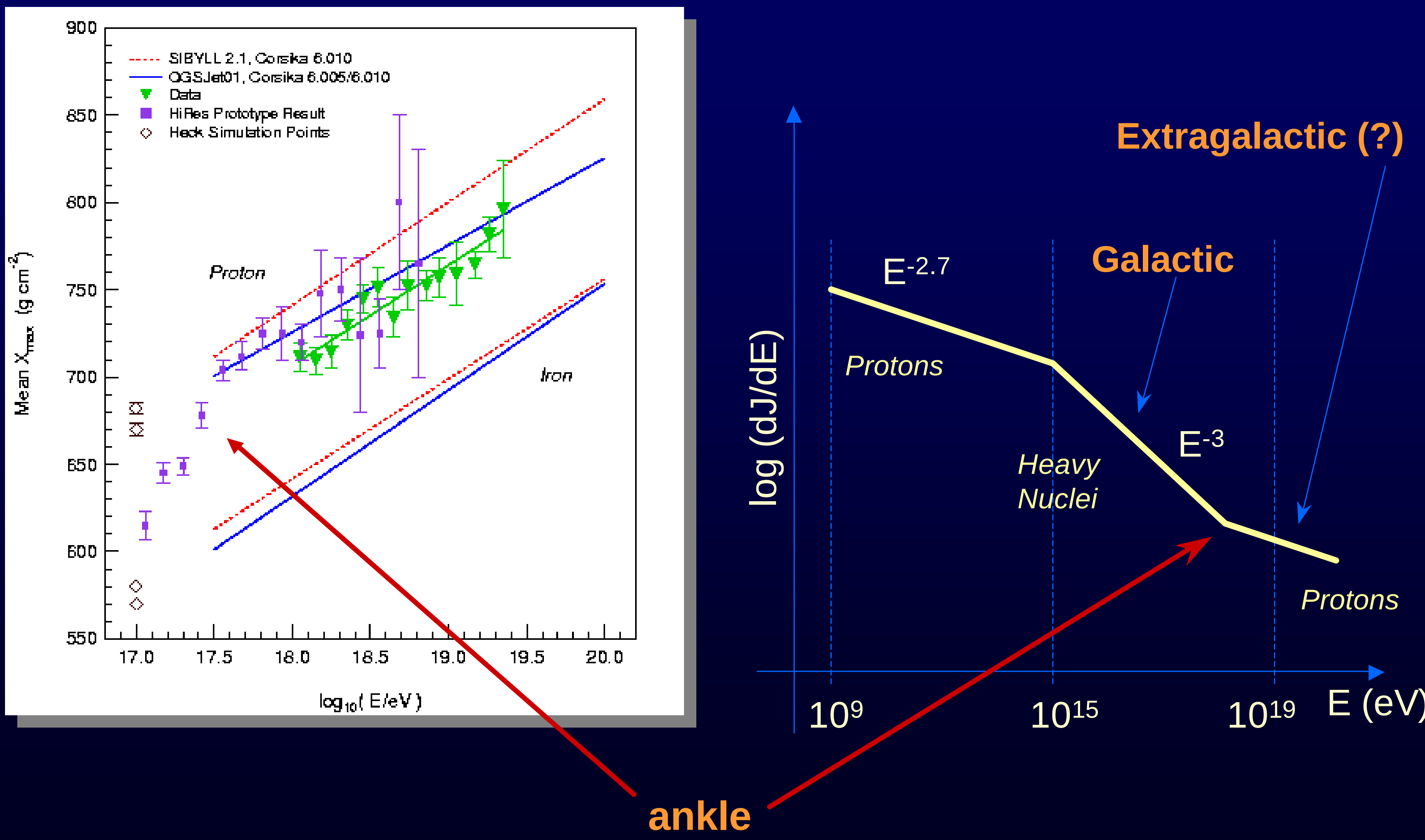


Flux vs. energy for HiRes 1&2 stereo data, R.W.Springer

Chemical Composition

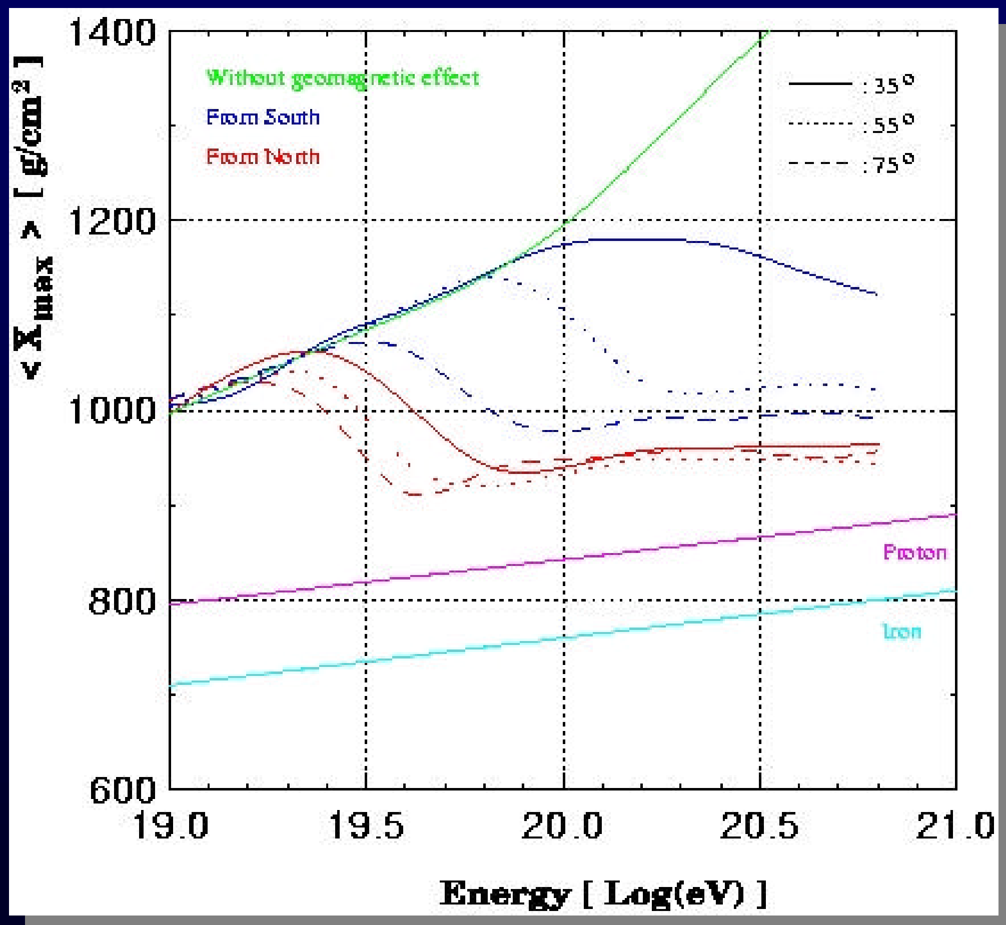
- Speed of air shower development depends on the mass of the primary
  - Heavier nucleus induces earlier shower development
- Shower maximum for heavier nuclei is higher in the atmosphere than for proton primary
- Intrinsic fluctuations in the depth of shower maximum
  - No resolution of primary on event-by-event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

Chemical Composition



g Primaries ?

- Additional effects for γ-rays change mean shower maximum altitude at higher energies above 10 EeV
  - LPM effect
  - Geomagnetic effect (also introduces North/South dependence)



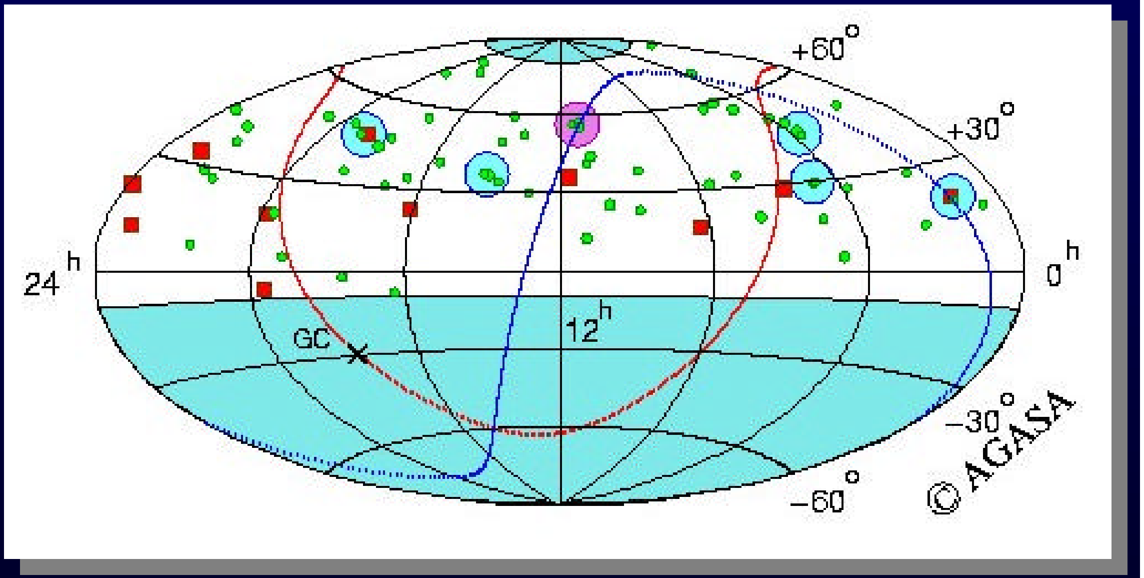
Small-Scale Anisotropy

- Statistically independent HiRes stereo data set can be used to test the claim that cosmic ray arrival directions show significant clustering at the highest energies

AGASA

E > 4×10^19 eV

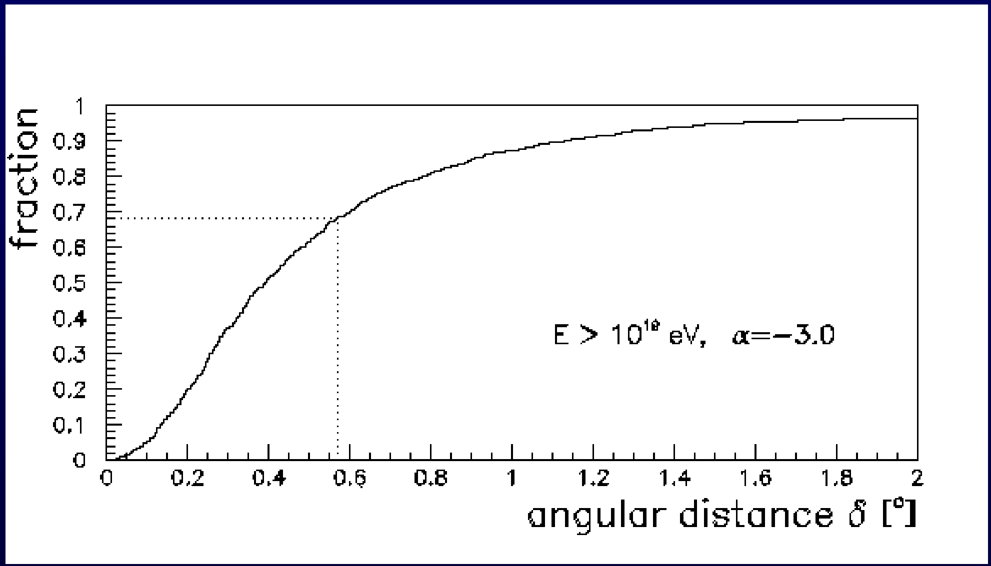
E > 10^20 eV



Distribution of arrival directions of cosmic rays above 4×10^{19} eV (in equatorial coordinates)

Angular Resolution

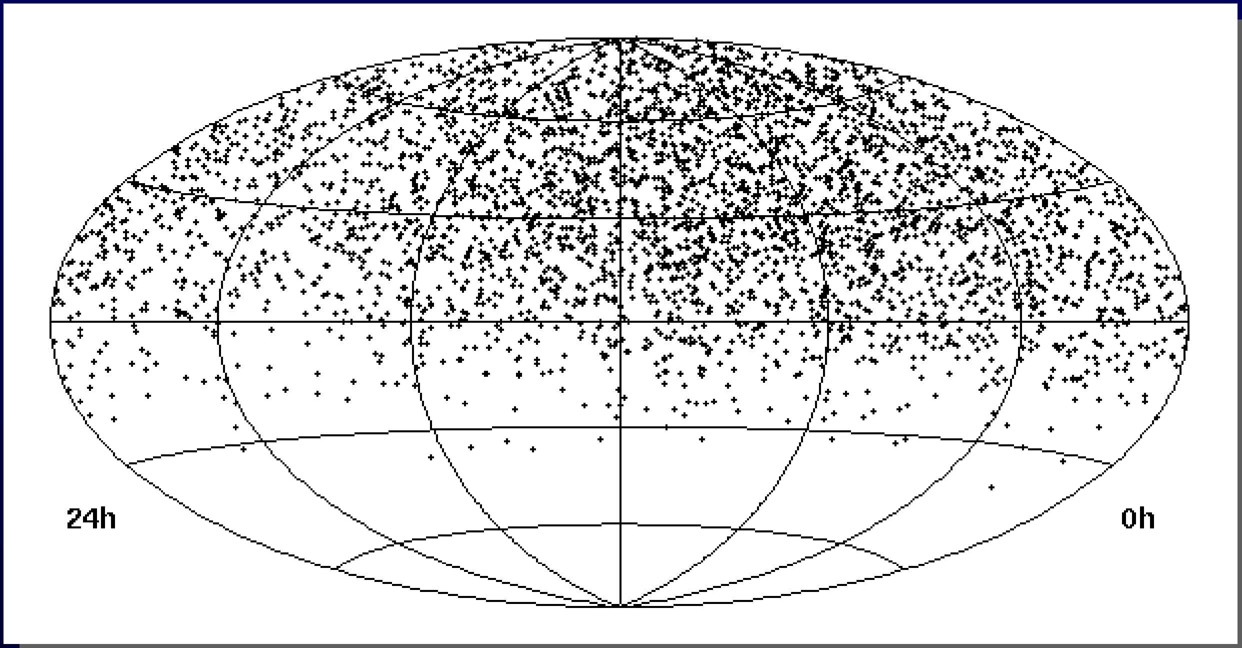
- HiRes stereo observation has very good angular resolution
- In Monte Carlo simulations, 68% of events are reconstructed within 0.58º of their true arrival direction
- Stereo data set is ideal for small-scale anisotropy study



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

HiRes Stereo Data Set

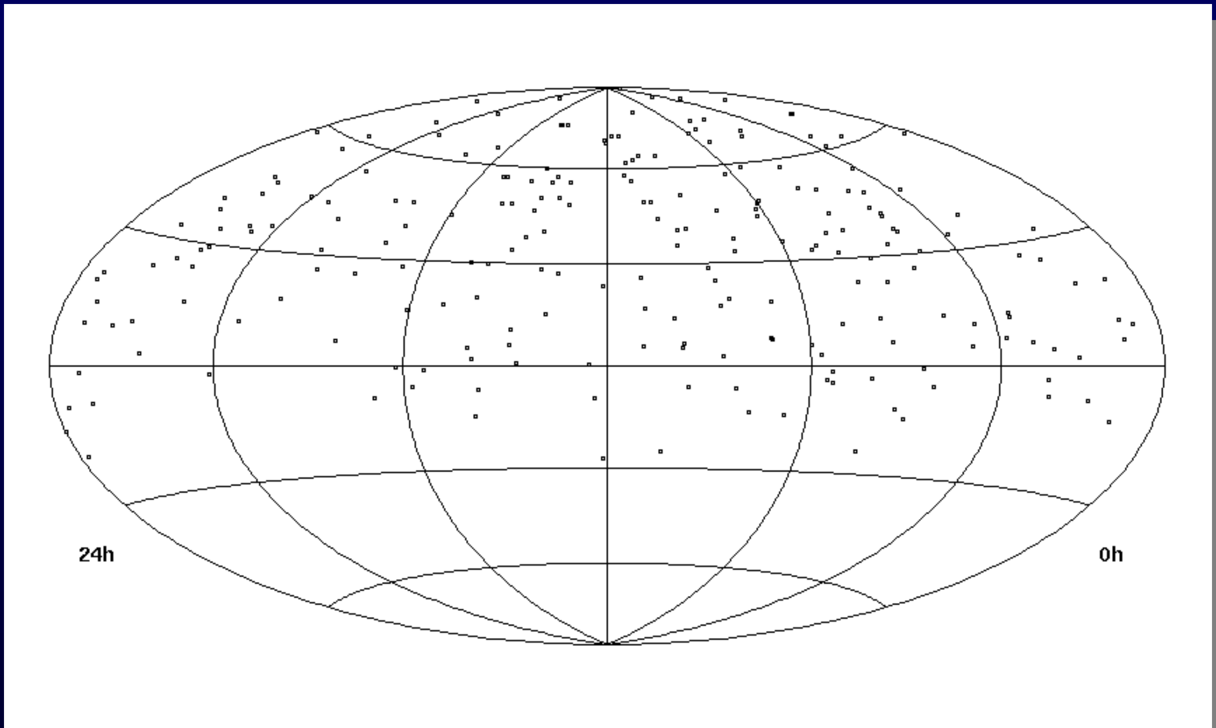
- HiRes stereo skymap with all events taken between November 1999 and June 2003



Equatorial Coordinates

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

- 222 well-reconstructed events above 10^{19} eV
- RMS energy resolution for these events better than 20%
- Angular resolution better than 0.6º
- Zenith angle <70º



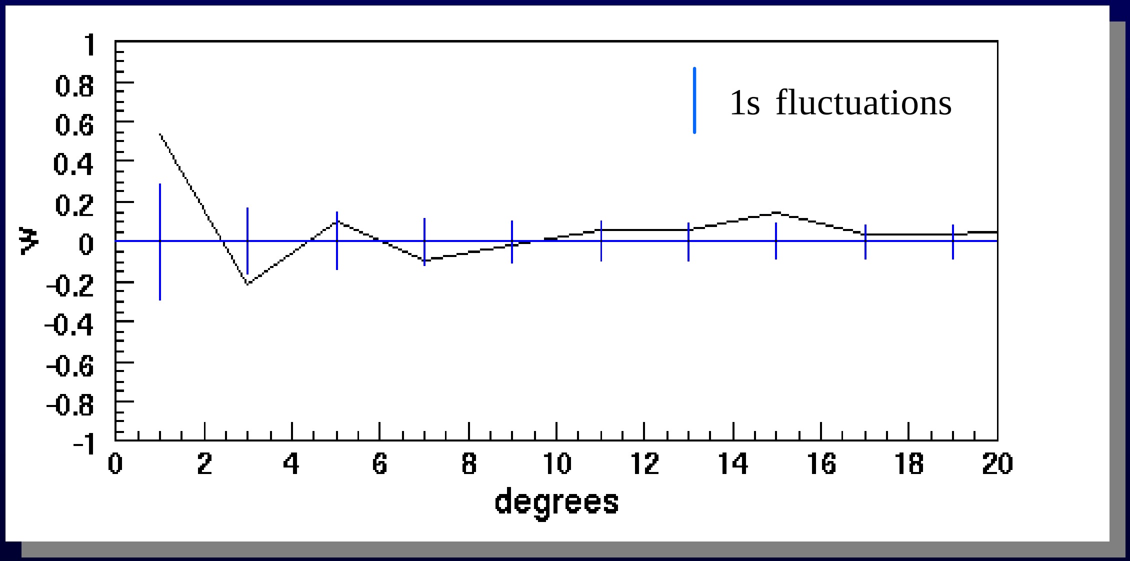
Equatorial Coordinates

Autocorrelation

Two-Point
Correlation Function:

- Count number of events separated by ?
- Perform same count on Monte Carlo data sets with same event number and similar exposure
- Clustering shows up as excess over fluctuations at small angular scales

Two-point correlation for
HiRes Stereo Events > 10^{19} eV



$$w(?) = N(?) / N_{MC}(?) - 1$$

Autocorrelation

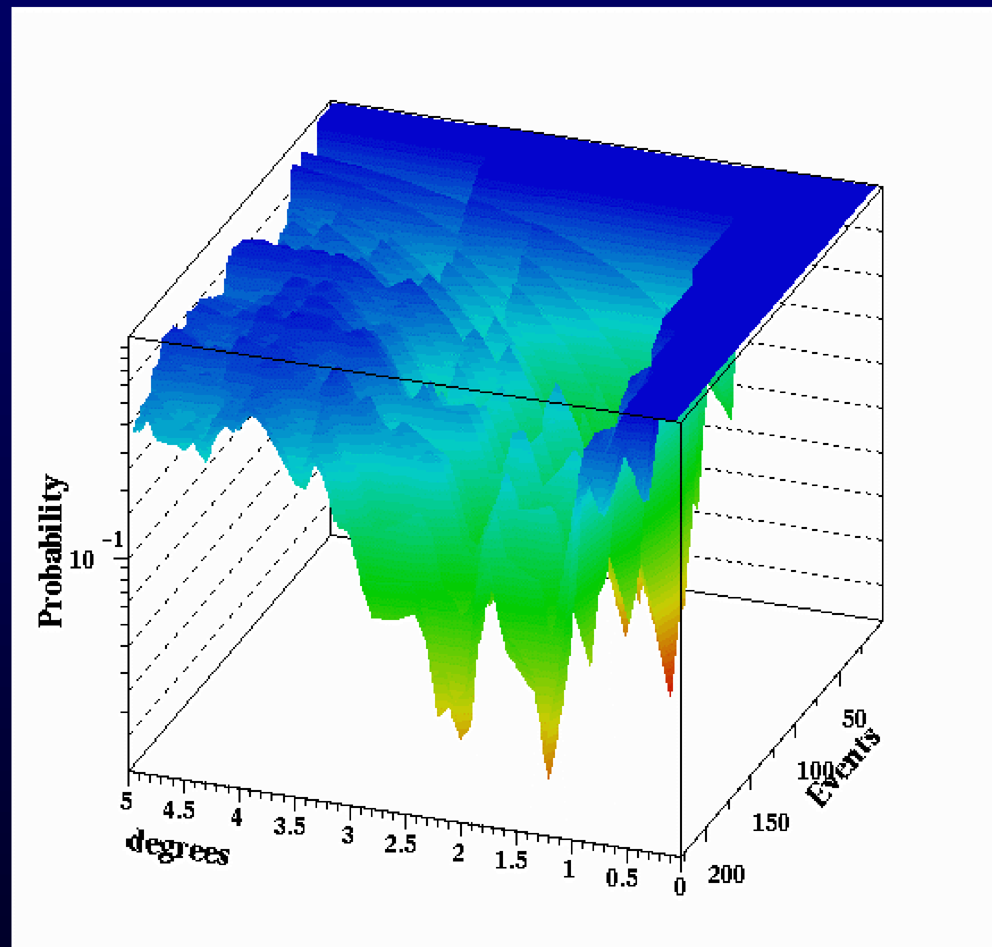
Evaluating Significance:

- 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

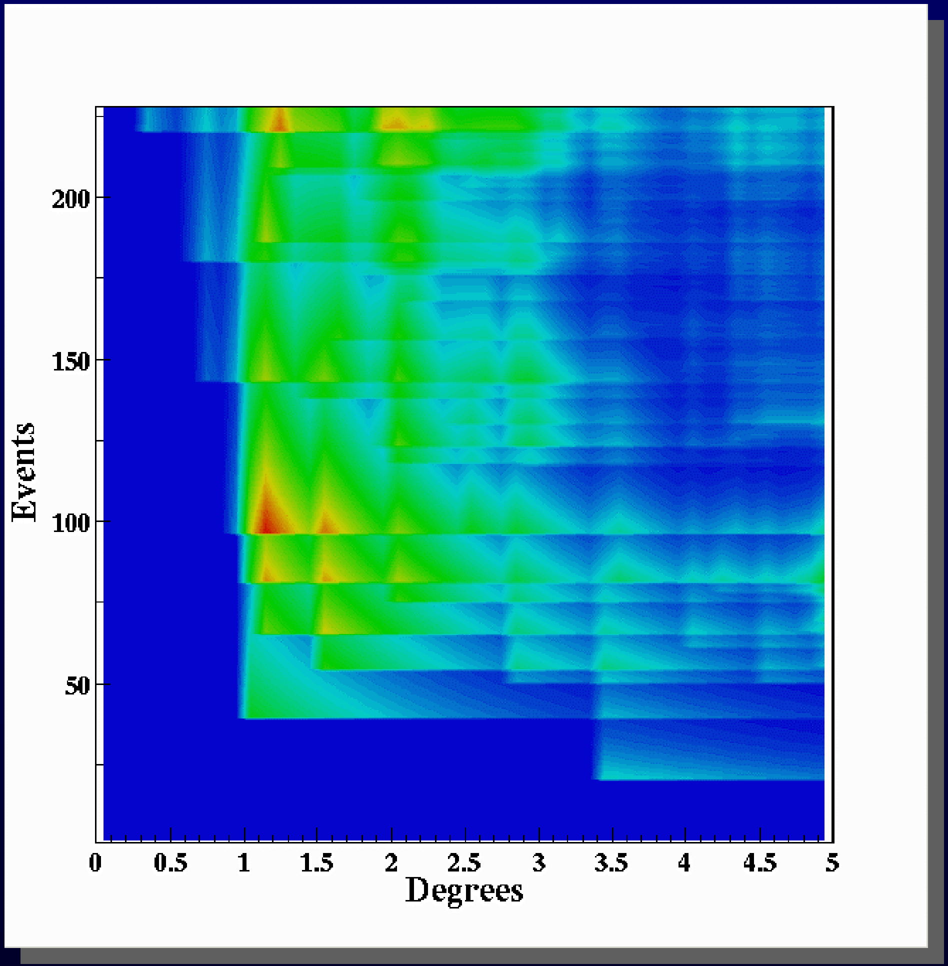


Scan of HiRes Stereo Events $> 10^{19}$ eV

Autocorrelation Scan

HiRes Results:

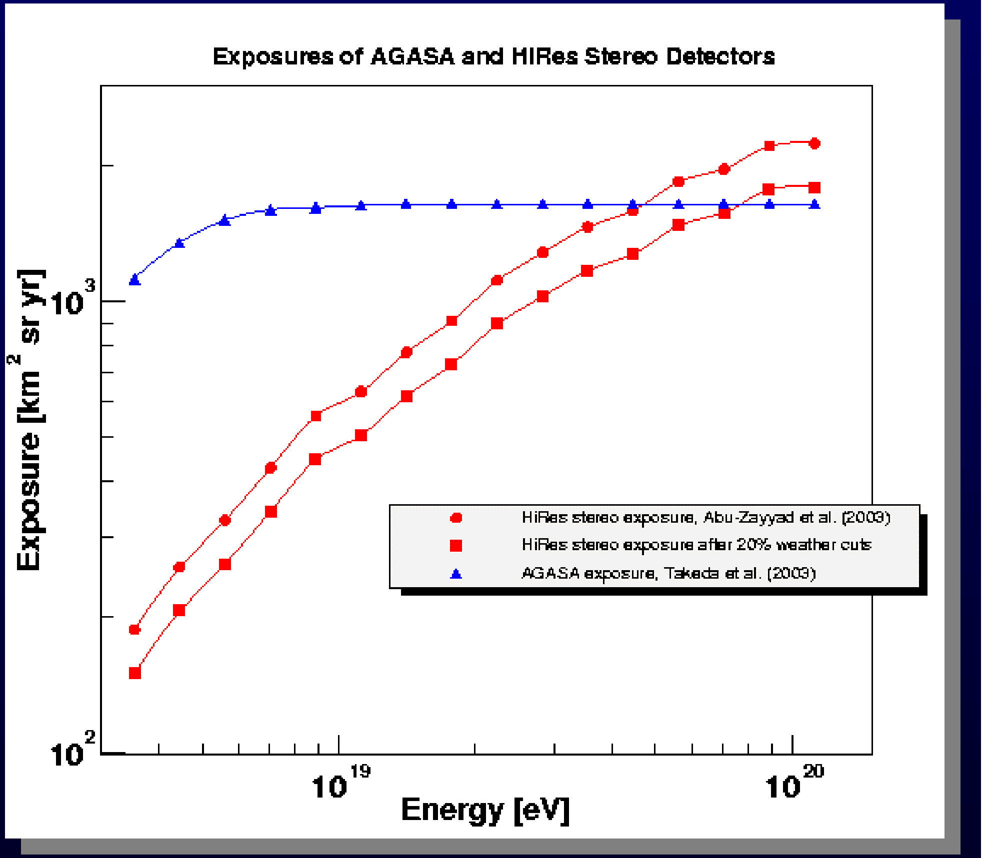
- Strongest clustering signal:
  - *?* = 1.2º
  - $E = 1.7\times10^{19}$ eV
  - $P_{min} = 1.1\%$
- Chance probability for scan of Monte Carlo data to have lower minimum:
  - $P_{chance} = 39\%$
- No evidence for clustering



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

AGASA vs. HiRes Exposure

- Exposure (aperture times observation time) of HiRes reaches AGASA's exposure
- HiRes recorded fewer events above 4×10^{19} eV
- Angular resolution increases sensitivity: 3 doublets in 34 events (original AGASA claim) gives P_{chance}
  - 0.016 AGASA
  - 0.00015 HiRes

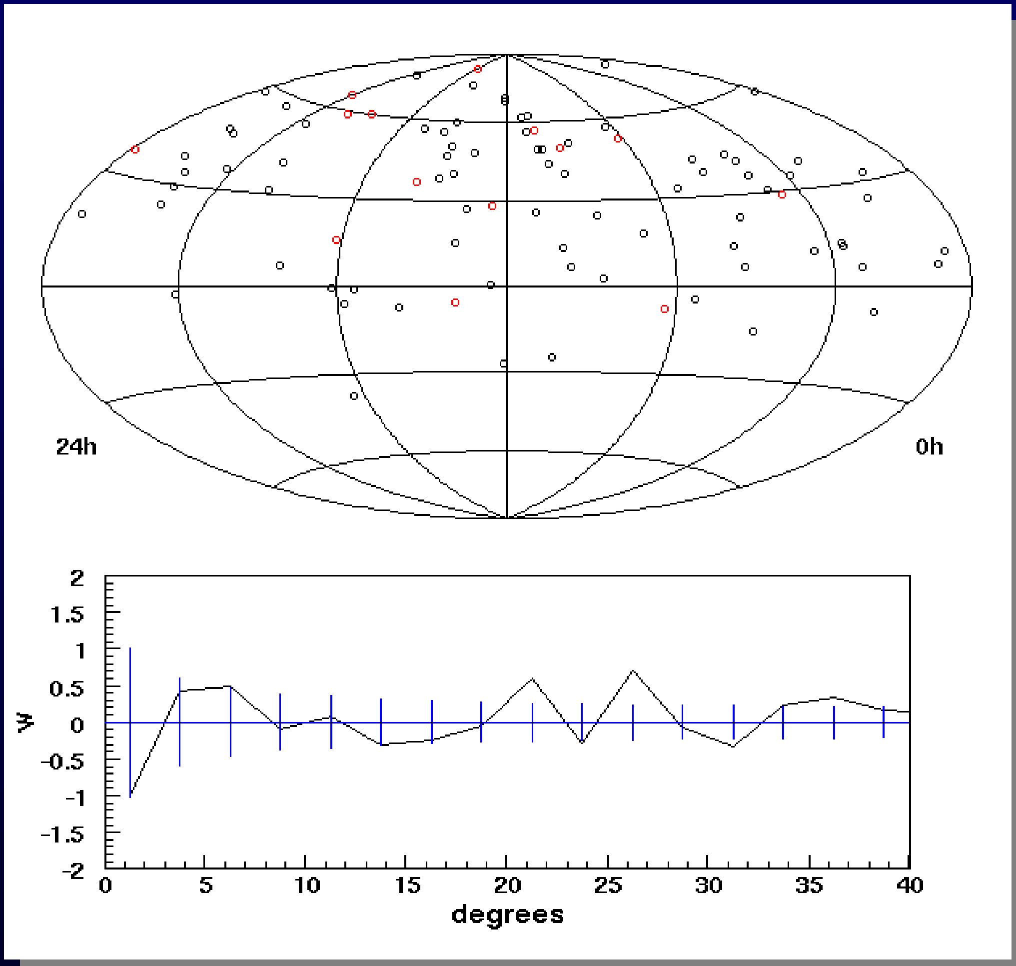


ApJ Letter in prep.

BL Lac Correlation Study

BL Lac Correlation?

- AGASA arrival directions have previously been correlated with positions of 14 gamma-ray loud BL Lac objects (ApJ 577(2002)L93)
- However, the two-point correlation function between these BL Lacs and HiRes events (>2×10[19] eV) is consistent with no correlation.

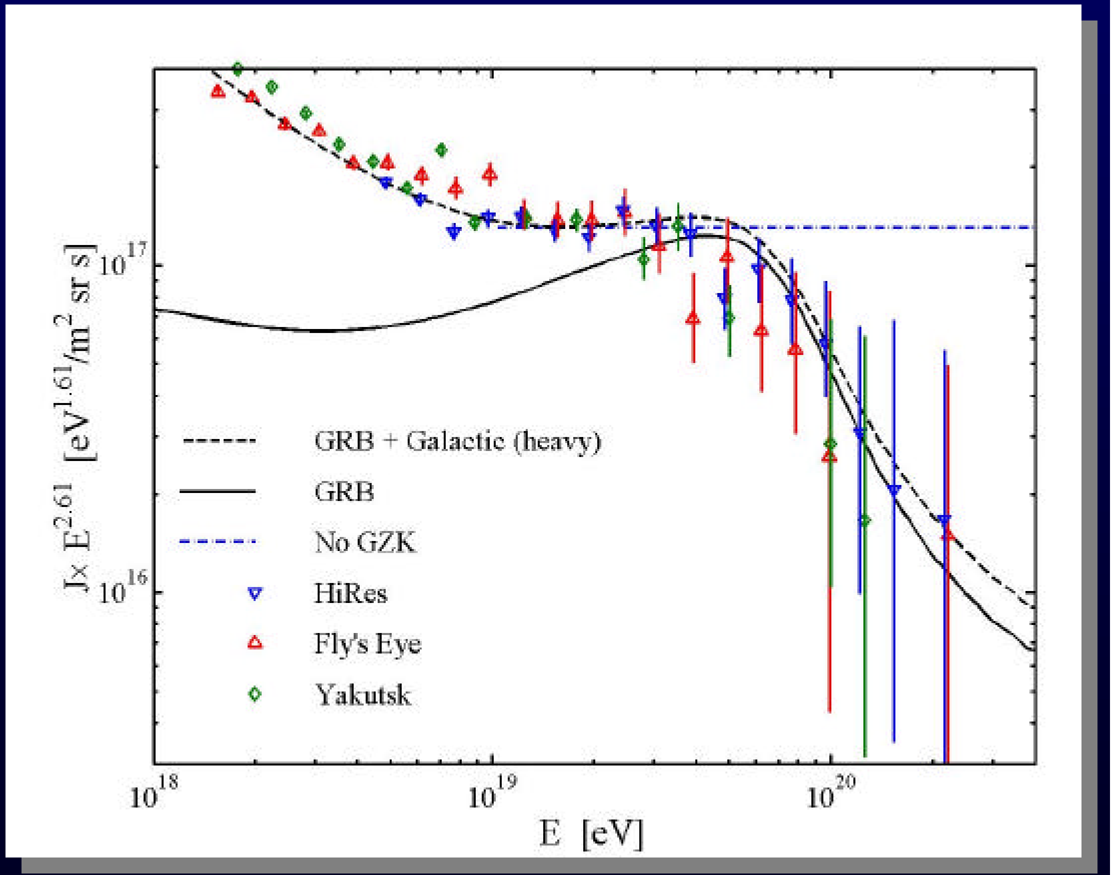


Above: HiRes (black) , BL Lacs (red)
Below: Two-point cross correlation function

Gamma Ray Bursts

- Shock acceleration site, with γ-ray emission established
- Time delay between cosmic ray and γ-ray component $10^5 \ldots 10^7$ years
- Smoking gun: neutrino component (ICECUBE and SWIFT)
- See also Wick, Dermer & Atoyan, astro-ph/0310667

Waxman, Bahcall, hep-ph/0206217

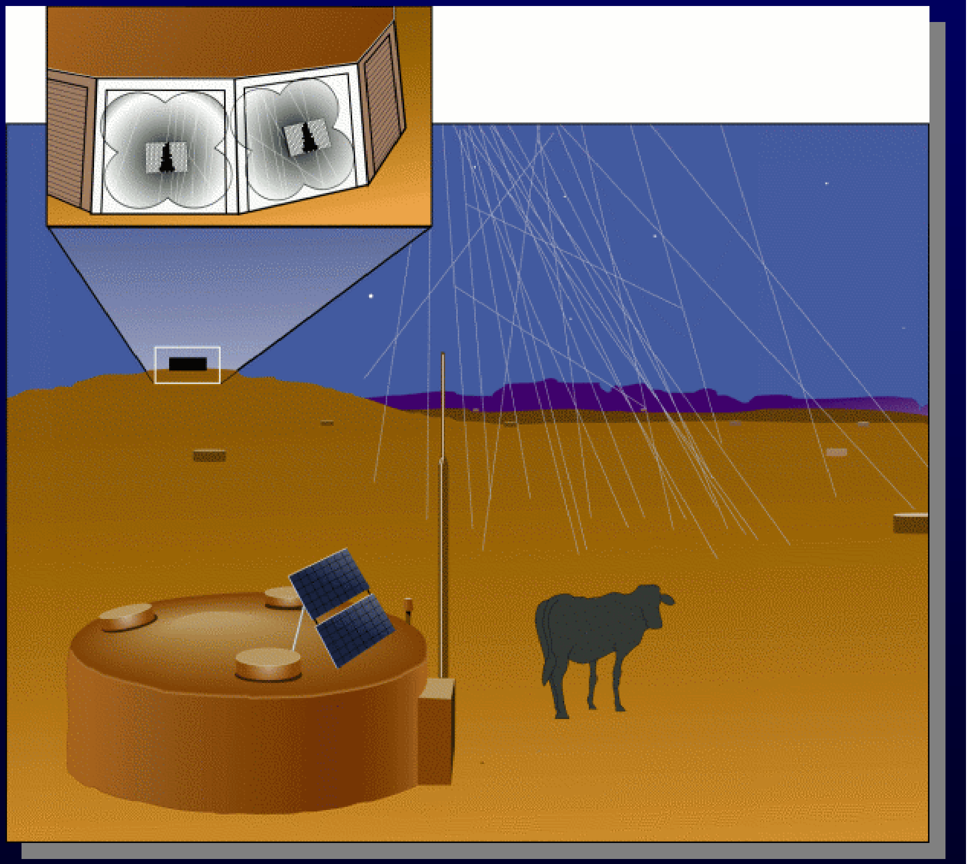


Summary

- Energy spectrum:
  - HiRes 1&2 monocular data currently does not contradict the expected GZK suppression
- Chemical Composition:
  - Around the ankle, the mean composition changes from heavy to light (Galactic to extragalactic origin ?) and is constant above 10^{19} eV
- Arrival Directions
  - No indication of small-angle clustering of arrival directions in HiRes stereo data
  - No correlation with gamma-ray loud BL Lac objects
- HiRes will take data for at least 3-5 more years

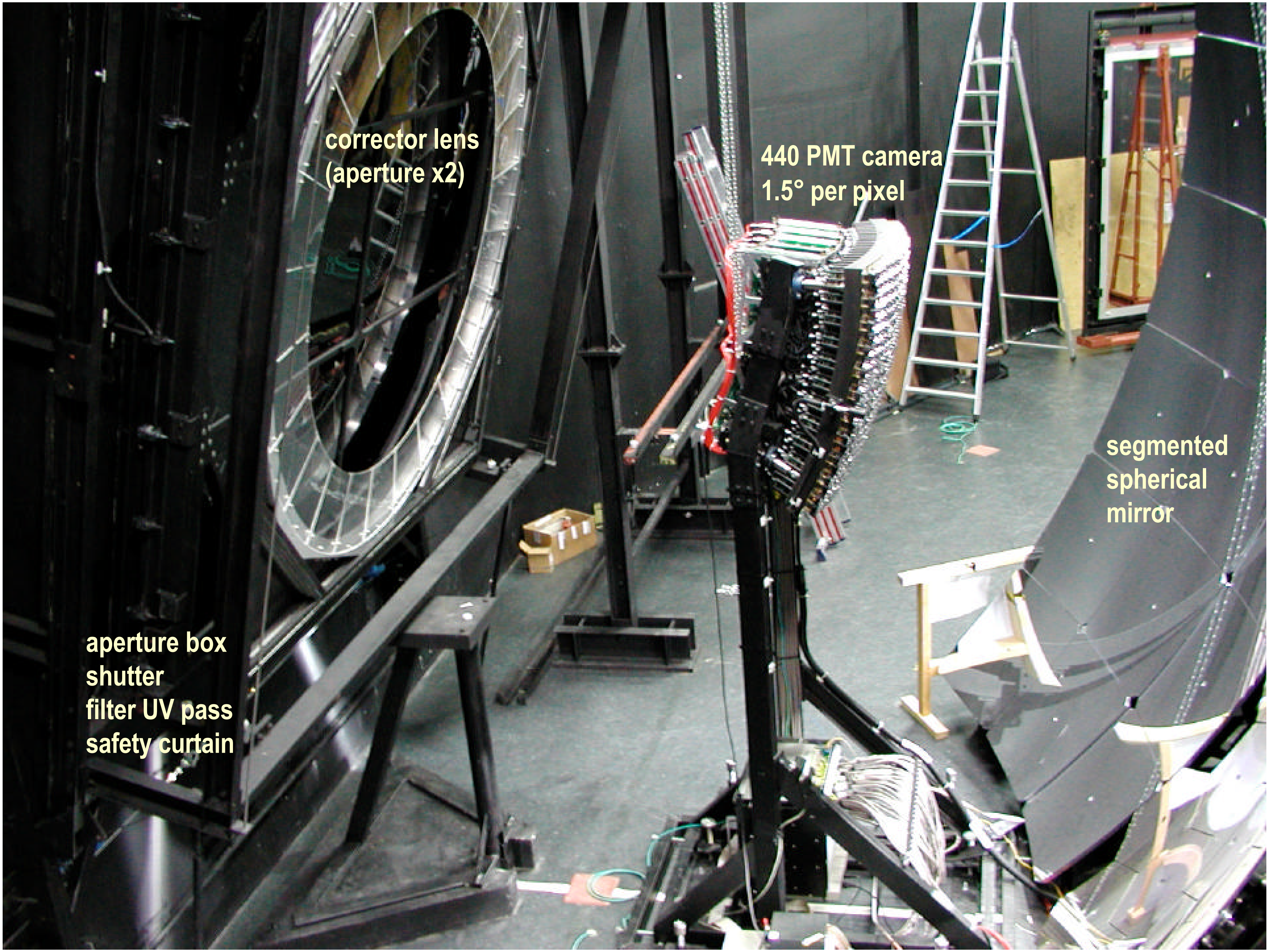
Pierre Auger Observatory

- Southern site in Mendoza (Argentina),1400 m a.s.l.
- Hybrid detector combines the two detection methods by using air fluorescence detectors embedded in a ground array
- Designs calls for a matching site in the Northern hemisphere



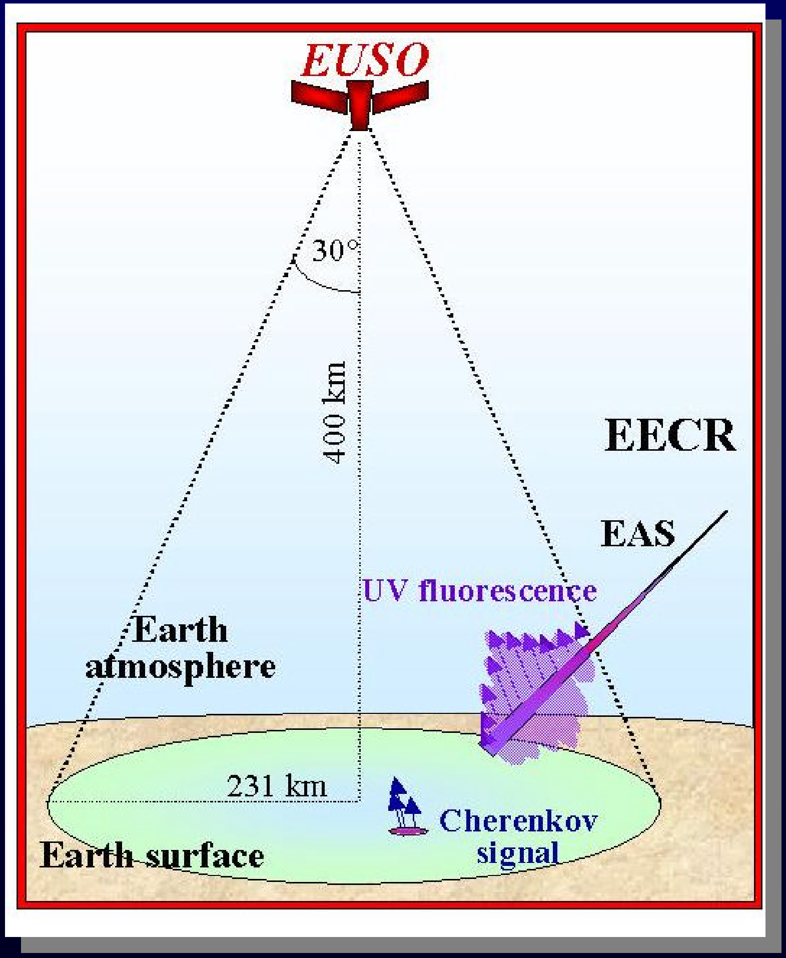
Auger Ground Array

- 1600 particle detectors (water Cherenkov) on a regular grid with 1.5 km grid spacing
- Total area 3,000 square kilometers
- Each detector station is a 11,000 liter tank filled with pure water
- Self-contained stations working on solar power


corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segmented
spherical
mirror
aperture box
shutter
filter UV pass
safety curtain

Air Fluorescence in Space

- Extreme Universe Space Observatory
- View fluorescence lights from air showers from the International Space Station
- Large instantaneous detector aperture
- Neutrino astronomy ?



Victor Hess, Nobel Lecture, 1936

- On what can we now place our hopes of solving the many riddles which still exist as to the origin and composition of cosmic rays?
- It must be emphasized here above all that to attain really decisive progress *greater funds must be made available.*