

Recent Results from HiRes

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Columbia University

HiRes Collaboration

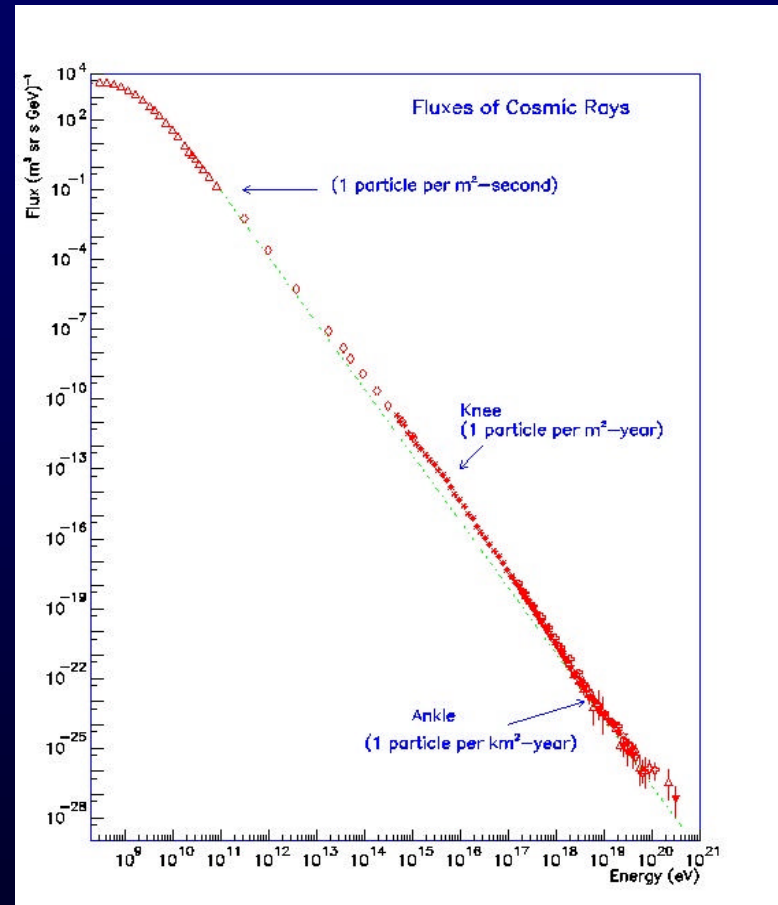


2nd European Union Research Training Network
Meeting on GRBs: An Enigma and a Tool

26 August 2003 Santorini, Greece

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)

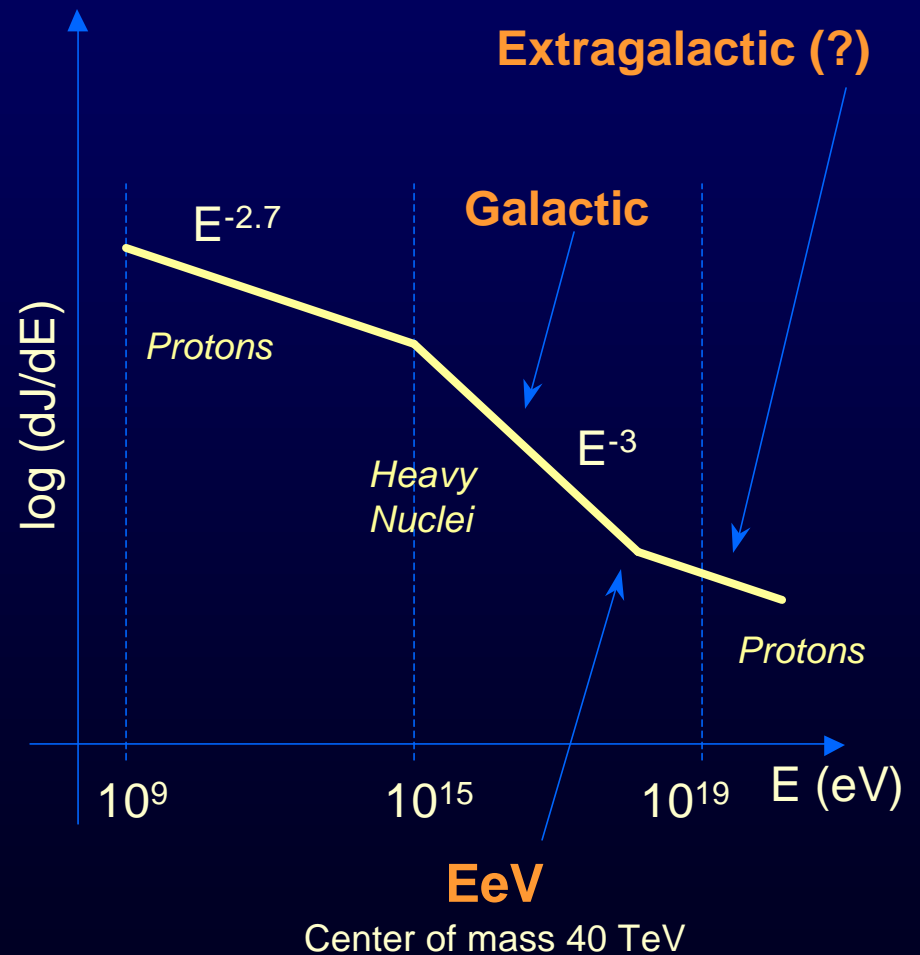
Energy Spectrum

At the ankle ($10^{17} - 10^{18}$ eV):

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

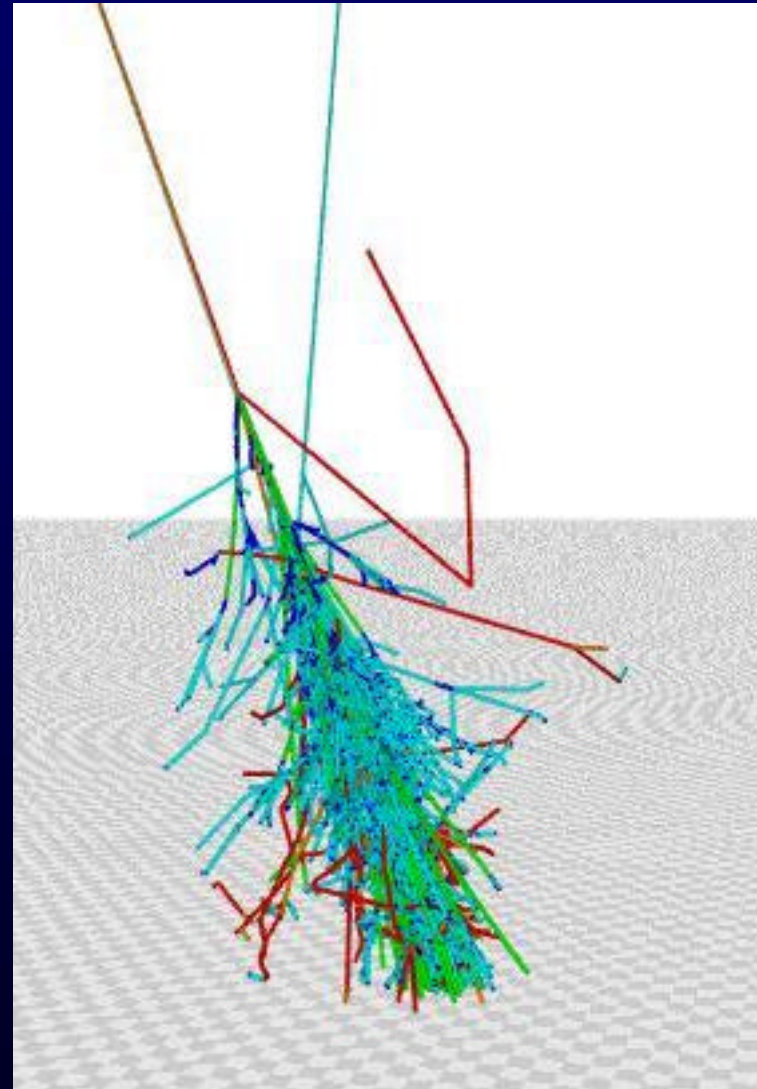
Above 6×10^{19} eV:

- Cutoff due to interaction with 3K background (GZK cutoff) ?
 - Should be relevant for sources beyond 20 Mpc

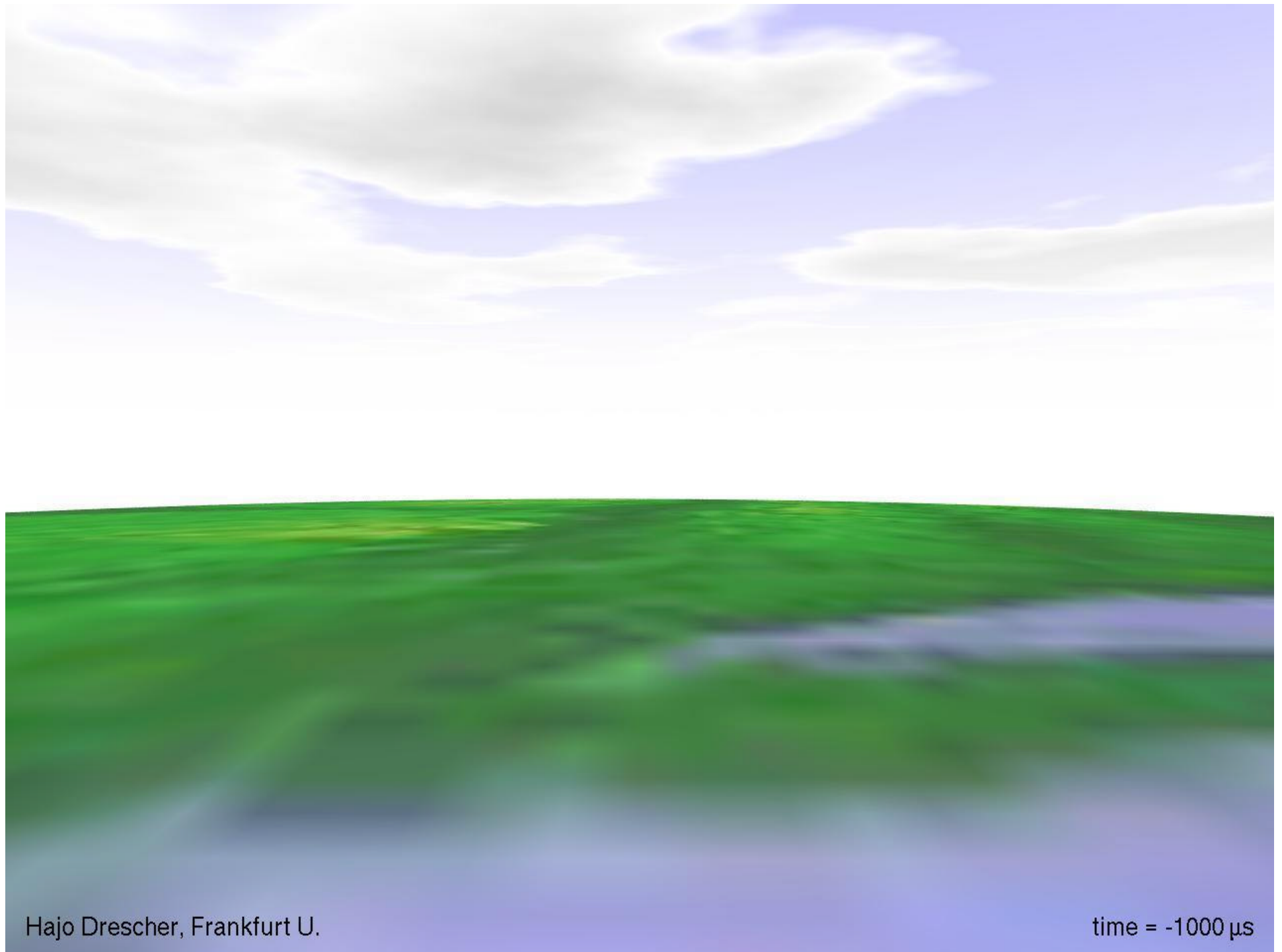


Experimental Techniques

- Ultrahigh energy cosmic rays are detected indirectly
- Incident primary cosmic ray produces air shower in the Earth's atmosphere
- Shower particles excite air molecules, which fluoresce in the UV

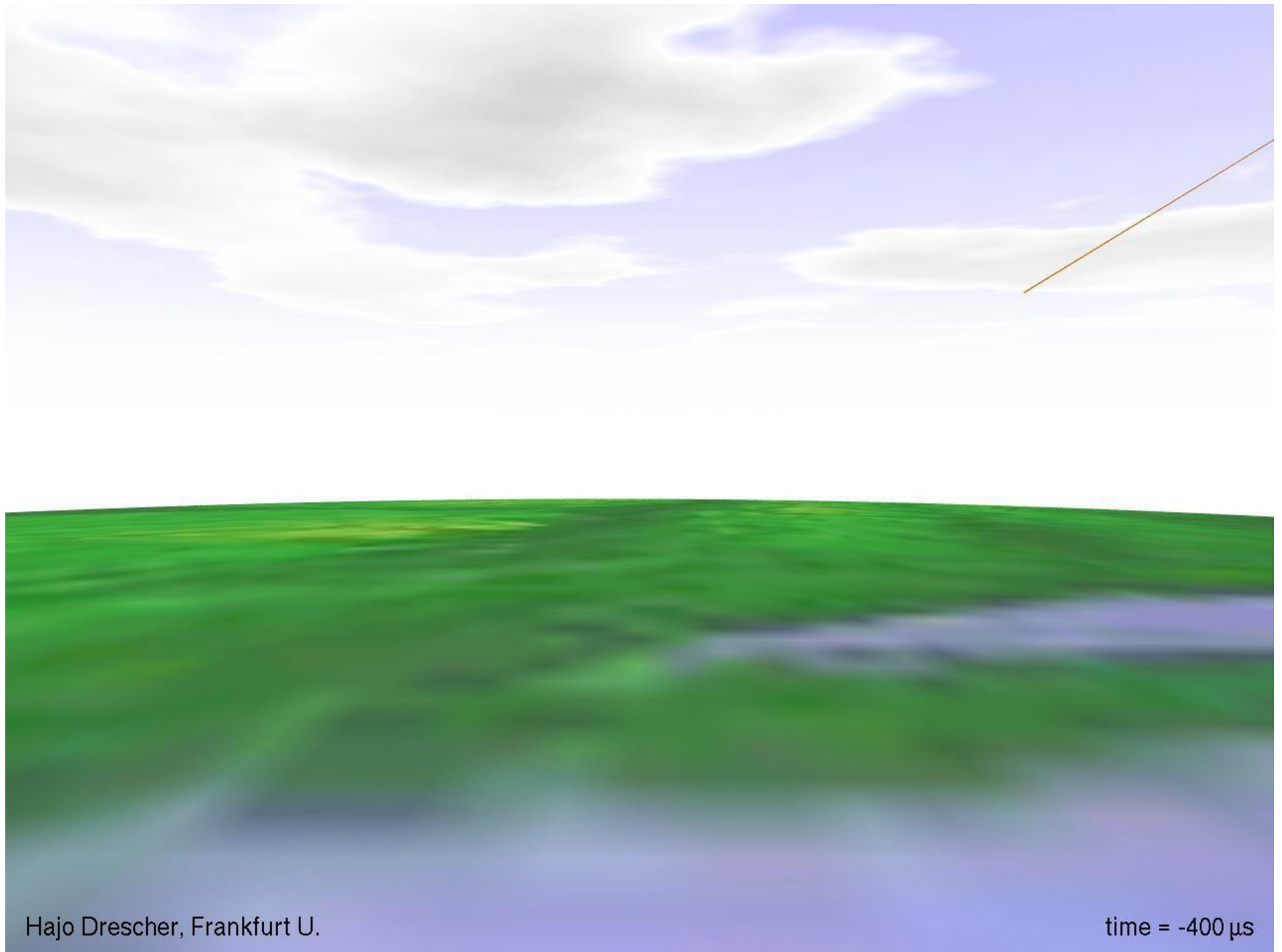


Computer Simulation by H.J. Drescher



Hajo Drescher, Frankfurt U.

time = -1000 μ s



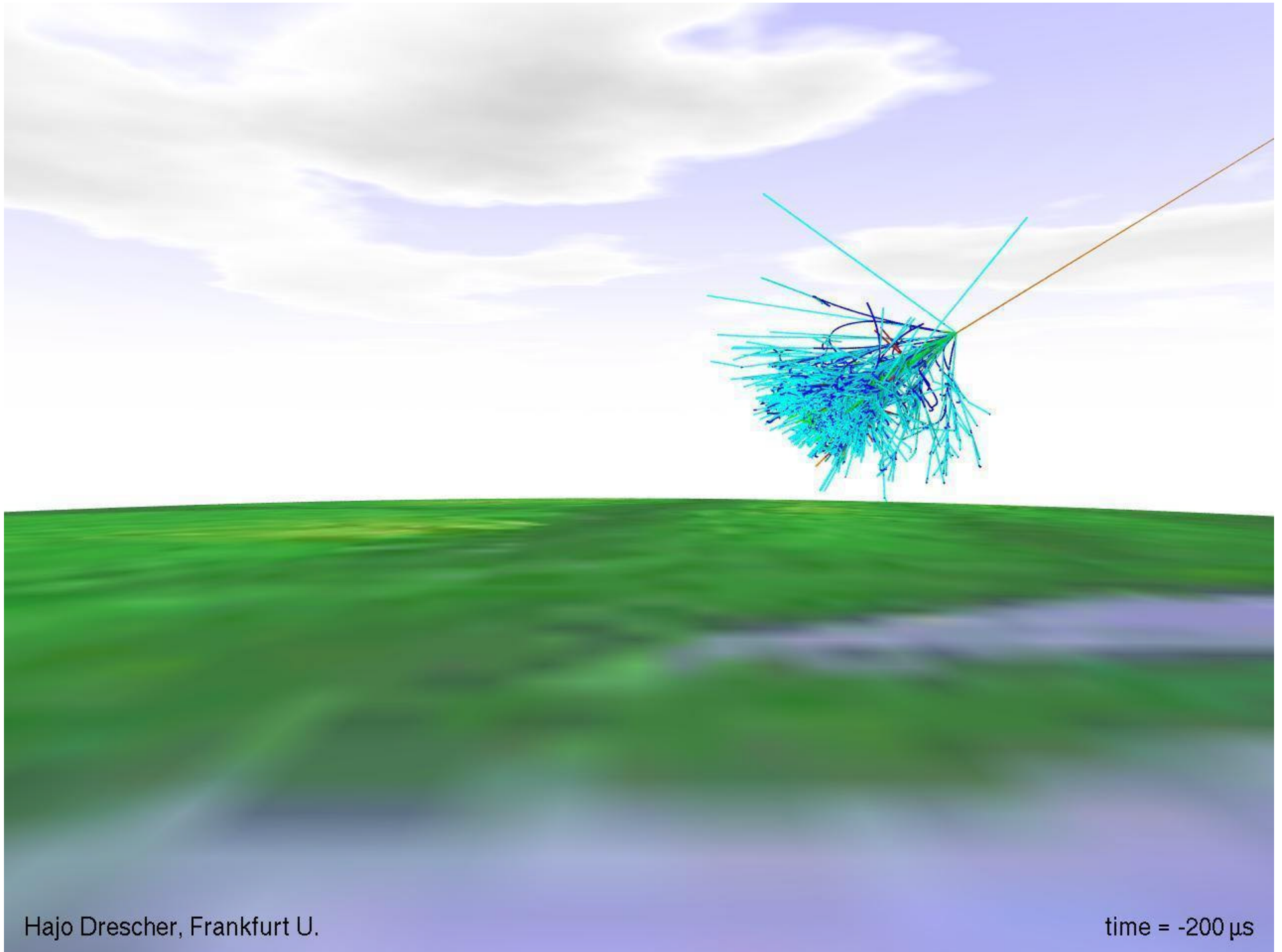
Hajo Drescher, Frankfurt U.

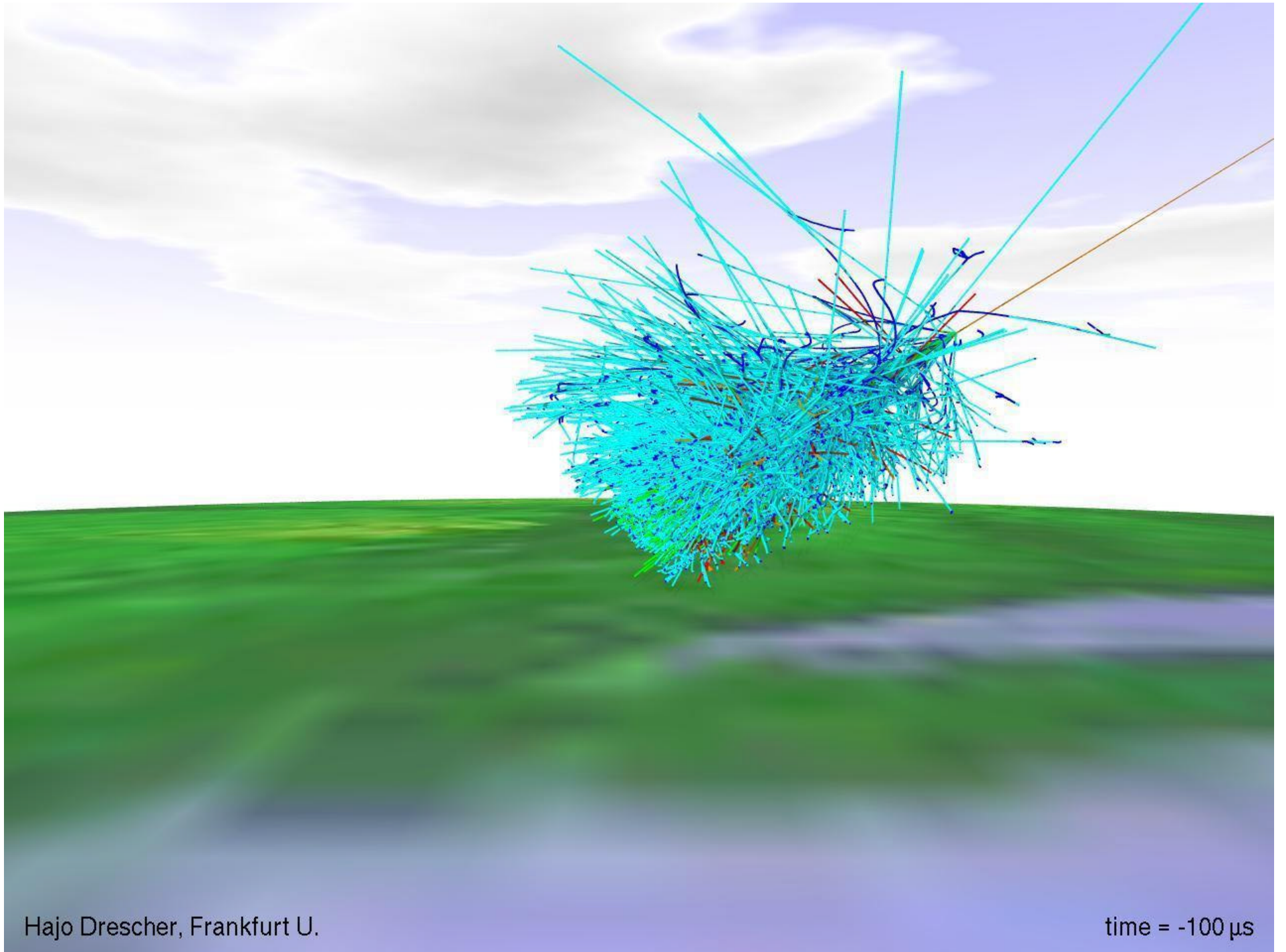
time = -400 μ s



Hajo Drescher, Frankfurt U.

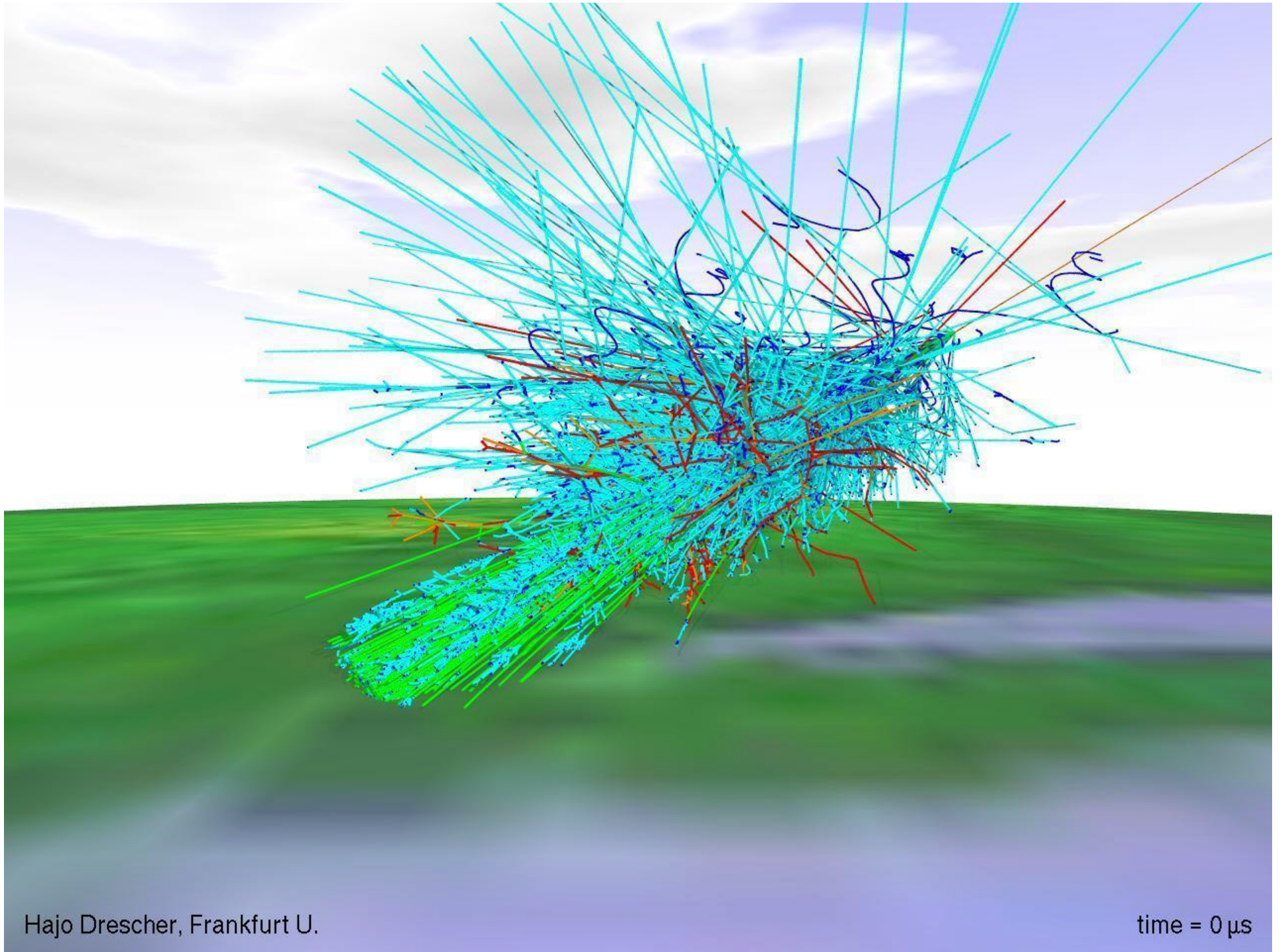
time = -300 μ s





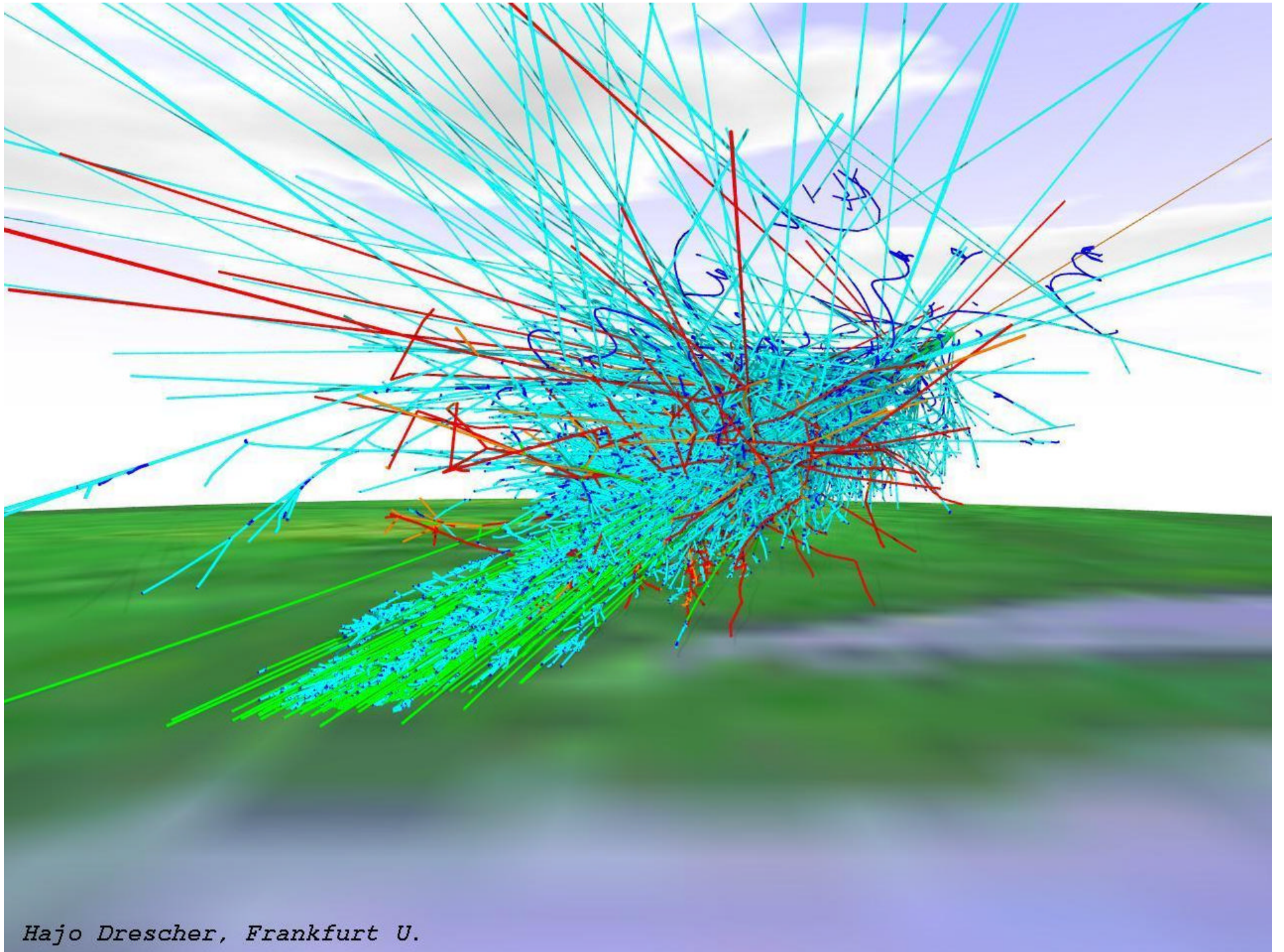
Hajo Drescher, Frankfurt U.

time = -100 μ s



Hajo Drescher, Frankfurt U.

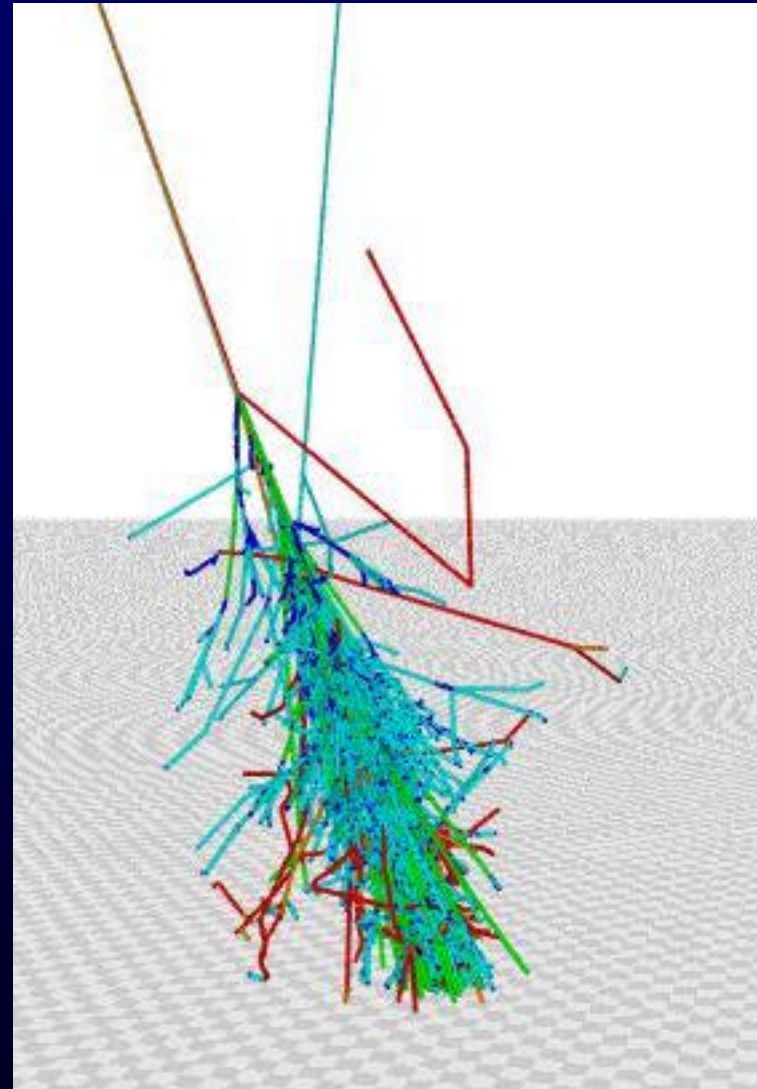
time = 0 μ s



Hajo Drescher, Frankfurt U.

Experimental Techniques

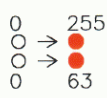
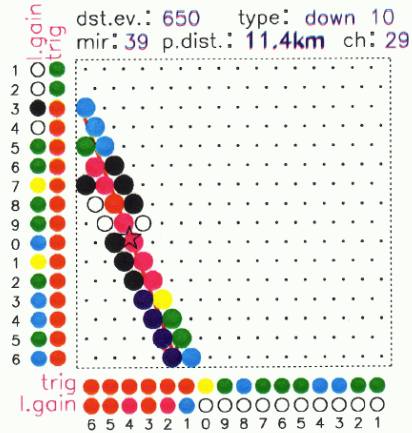
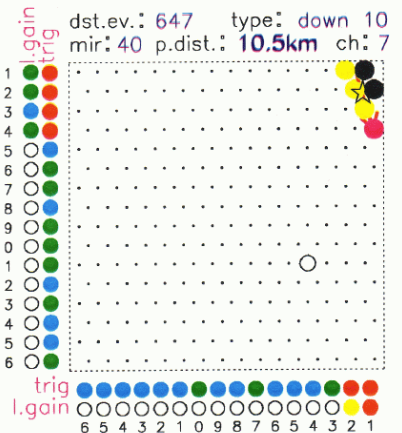
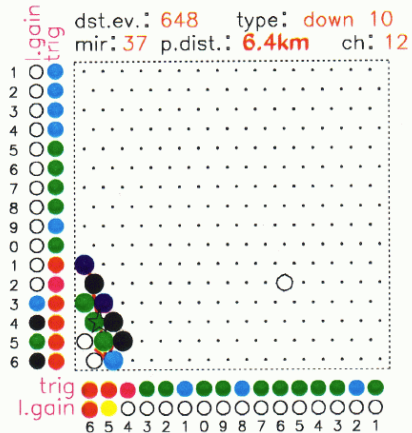
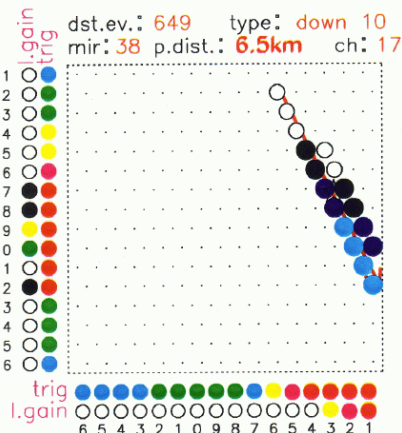
- Ultrahigh energy cosmic rays are detected indirectly
- Incident primary cosmic ray produces air shower in the Earth's atmosphere
- Shower particles excite air molecules, which fluoresce in the UV



Computer Simulation by H.J. Drescher

Air Fluorescence Technique

FILE: chain DATE: 7/11/1999 TIME: 6:54:41.6717452
 PART: 6 NTUPLE.Ev.: 1 No. of mirrors: 4 Tot.No.PE: 14417



Fluorescence light from distant air showers is collected by the mirror, focused onto a PMT camera, and digitized

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
- University of Tokyo



HiRes 2 on Camels' Back
Dugway Proving Grounds, Utah

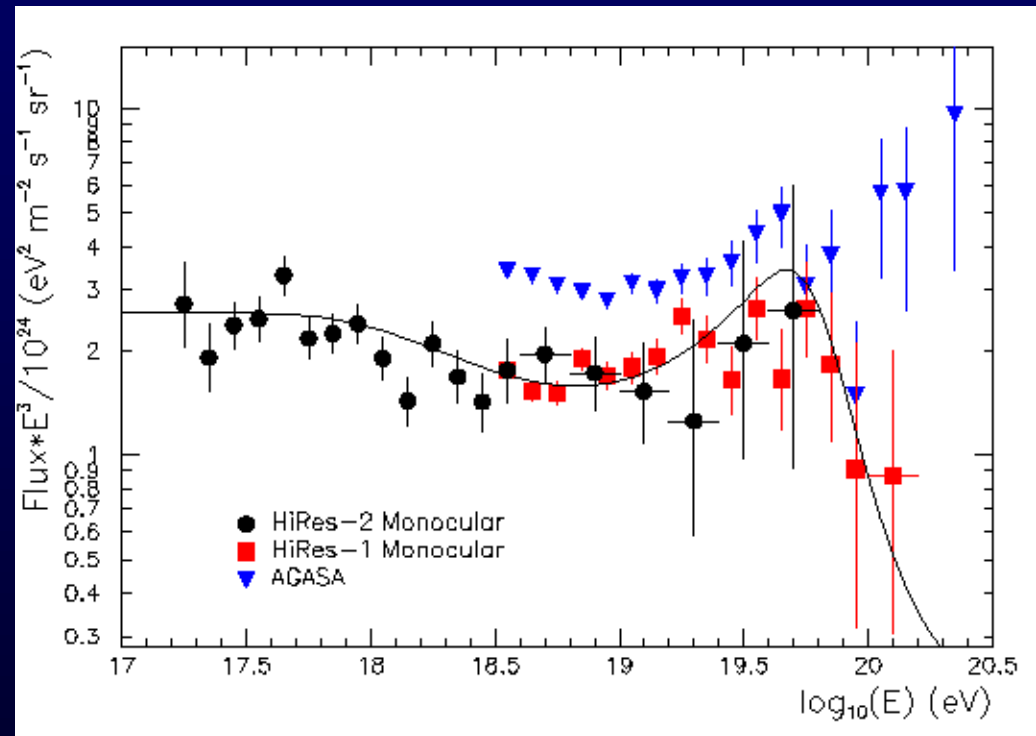
High Resolution Fly's Eye

- 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-Angle Clustering**



Monocular Energy Spectra

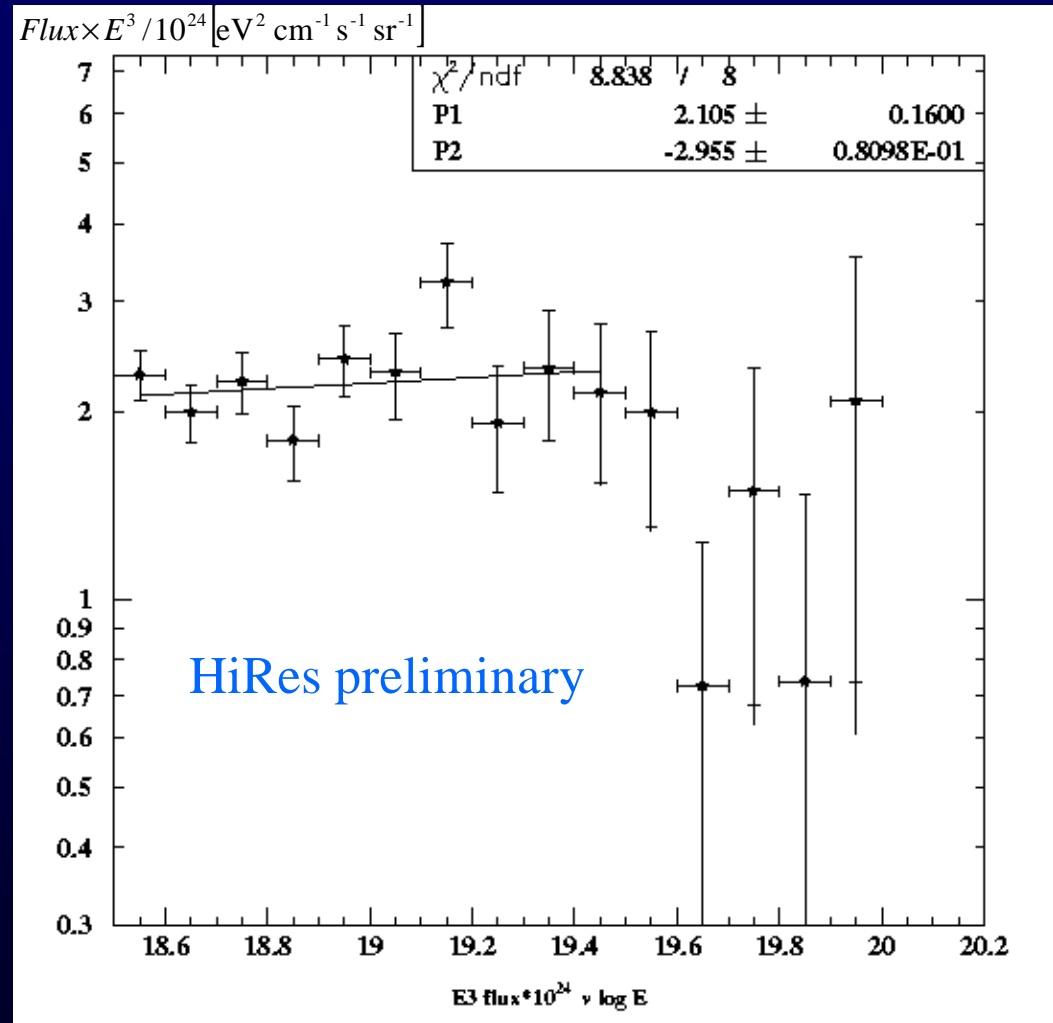
- HiRes spectrum falls steeply above 6×10^{19} eV, as expected if GZK cutoff is observed
- $E > 10^{19.8}$ eV
 - 5 events observed
 - 21.7 expected
 - $P = 1.8 \times 10^{-5}$



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

Prelim. Stereo Energy Spectrum

- HiRes stereo spectrum above $10^{18.5}$ eV

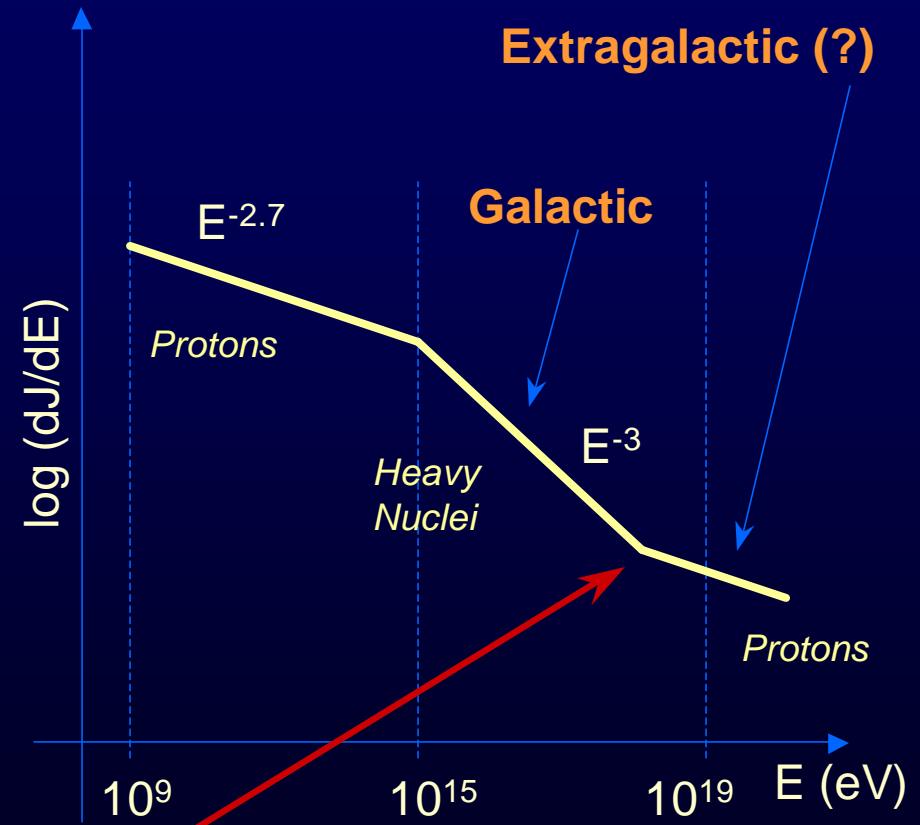
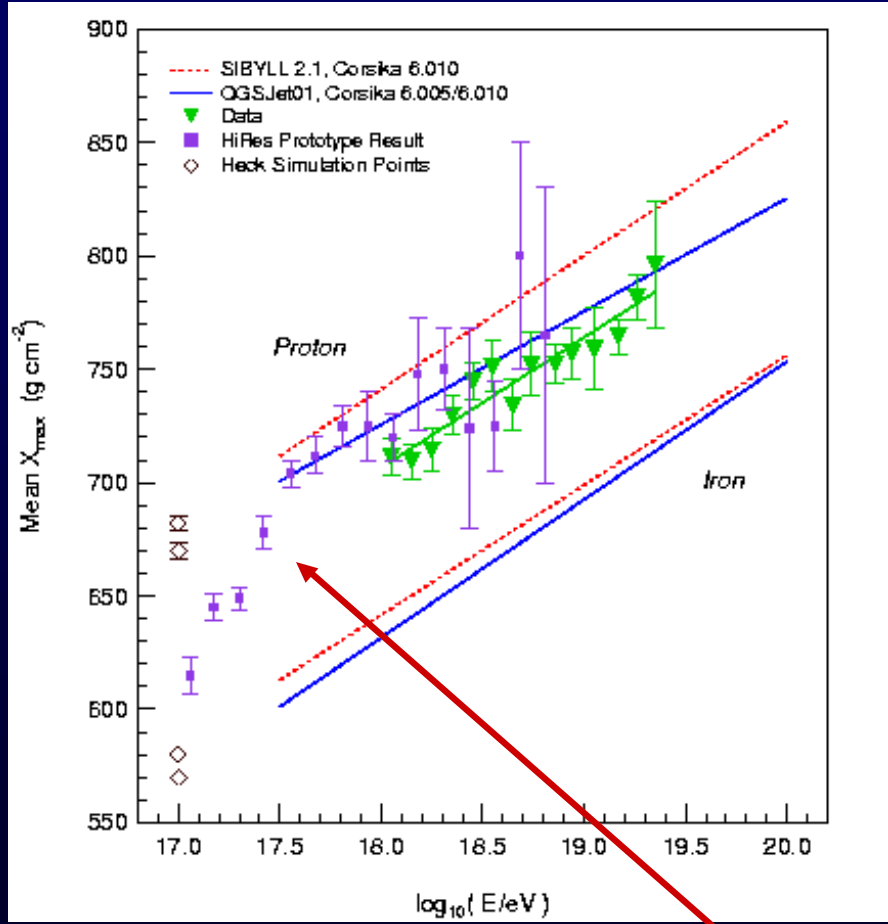


Flux vs. energy for HiRes 1&2 stereo data,
R.W.Springer

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)

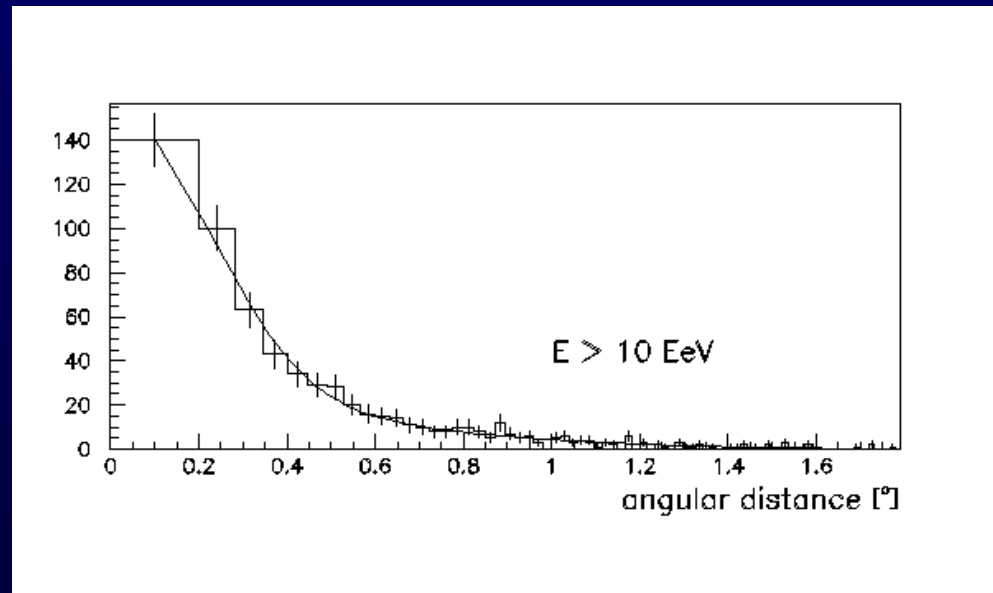
Chemical Composition



ankle

Angular Resolution

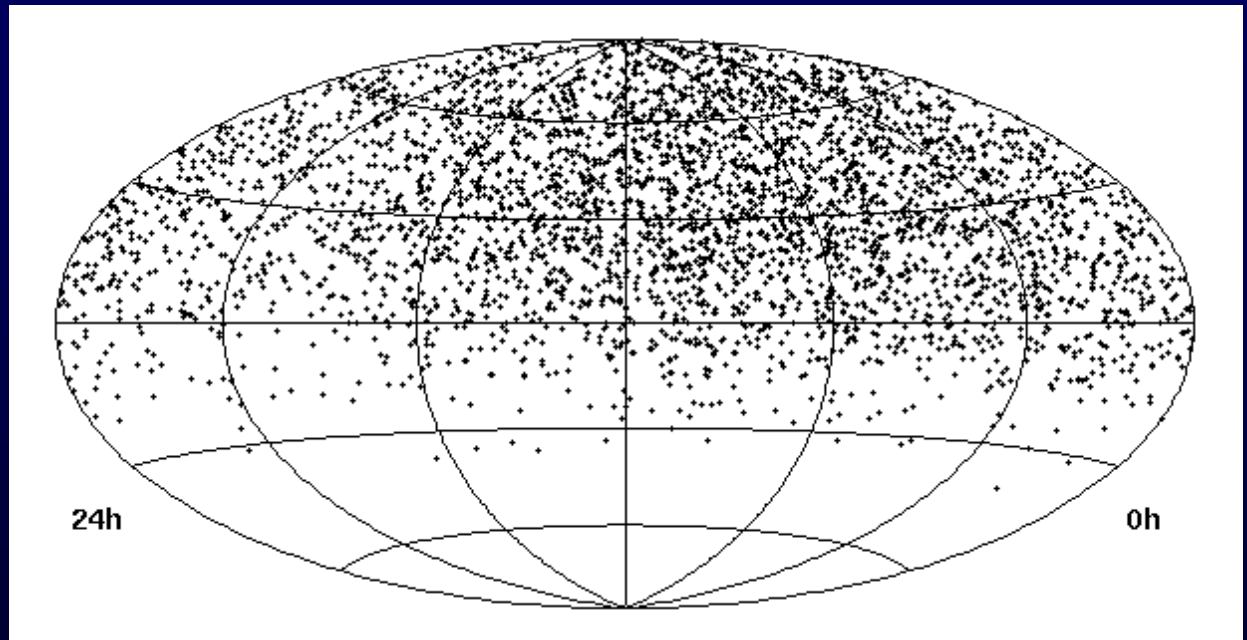
- HiRes stereo observation has sharp angular resolution
- In Monte Carlo simulations, 68% of events are reconstructed within 0.7° of their true arrival direction
- Stereo data set is ideal for small-scale anisotropy study



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

HiRes Stereo Data Set

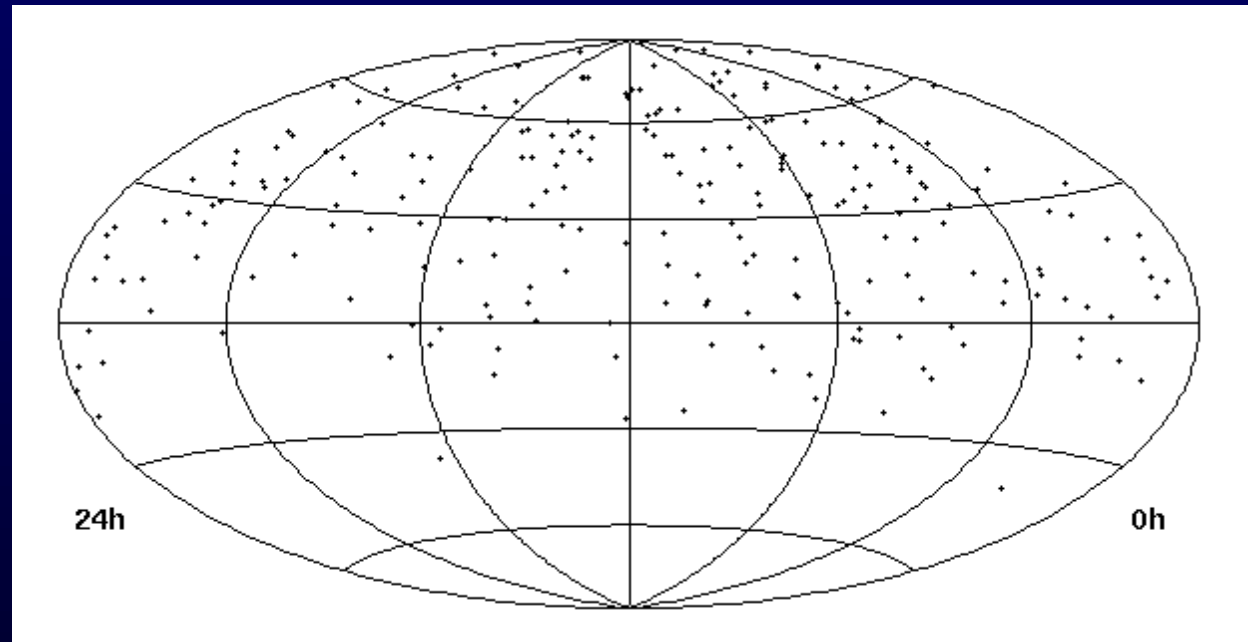
- HiRes stereo skymap with all events taken between November 1999 and June 2003



Equatorial Coordinates

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

- 228 well-reconstructed events above 10^{19} eV
- RMS energy resolution for these events better than 20%
- Angular resolution better than 0.7°



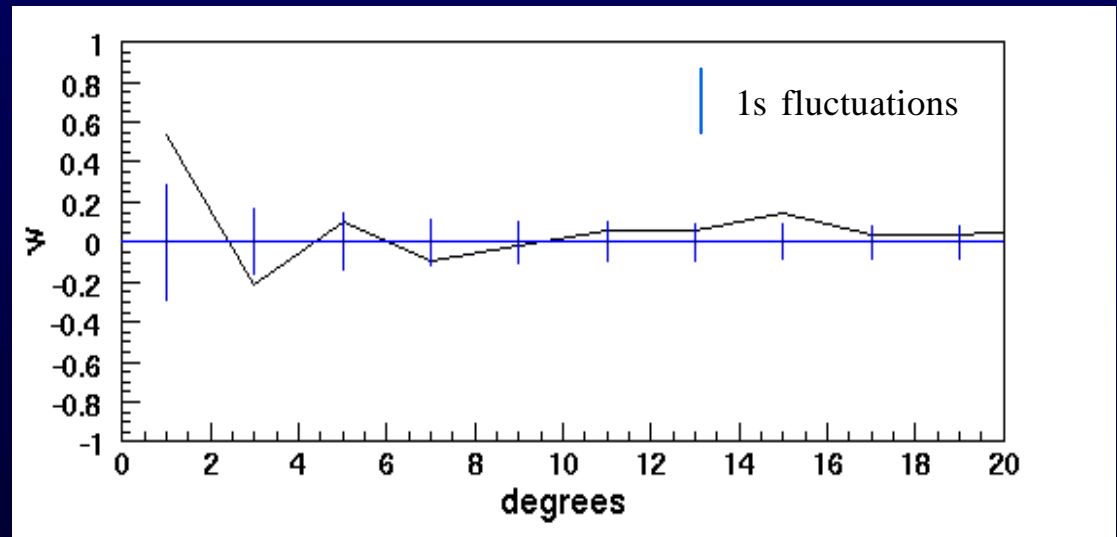
Equatorial Coordinates

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

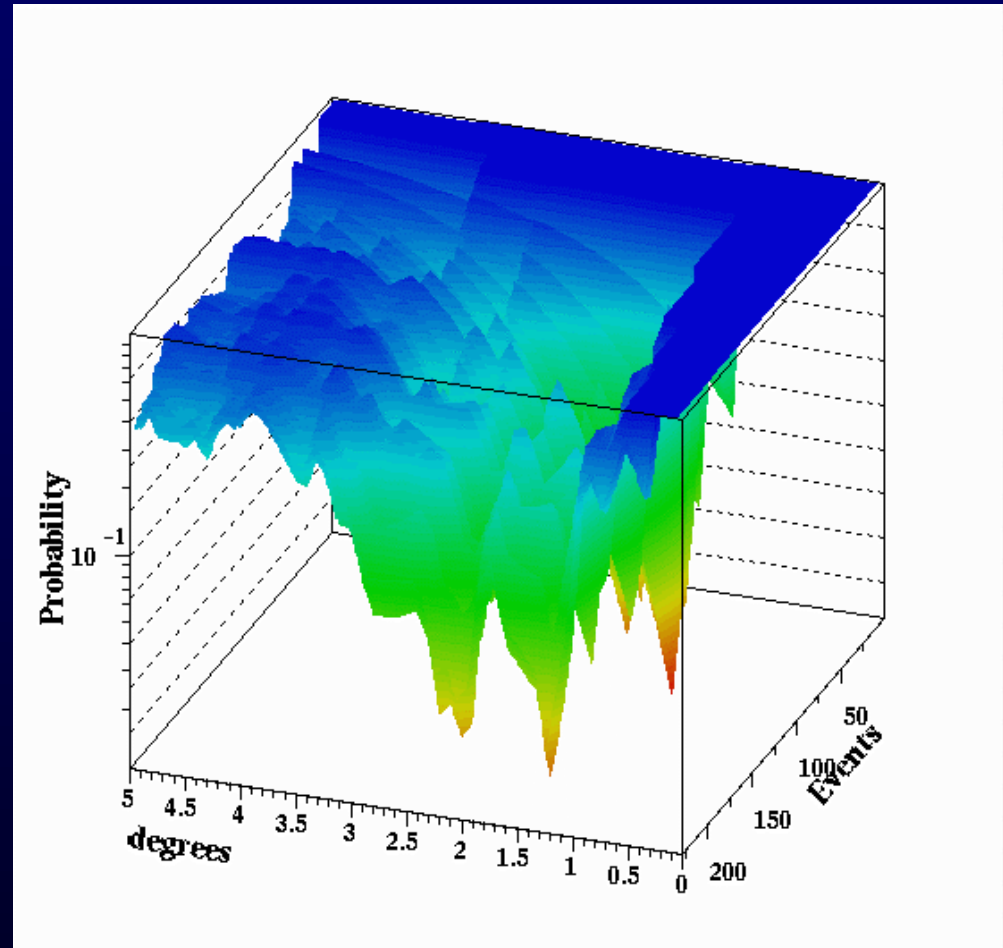
Evaluating Significance:

- 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

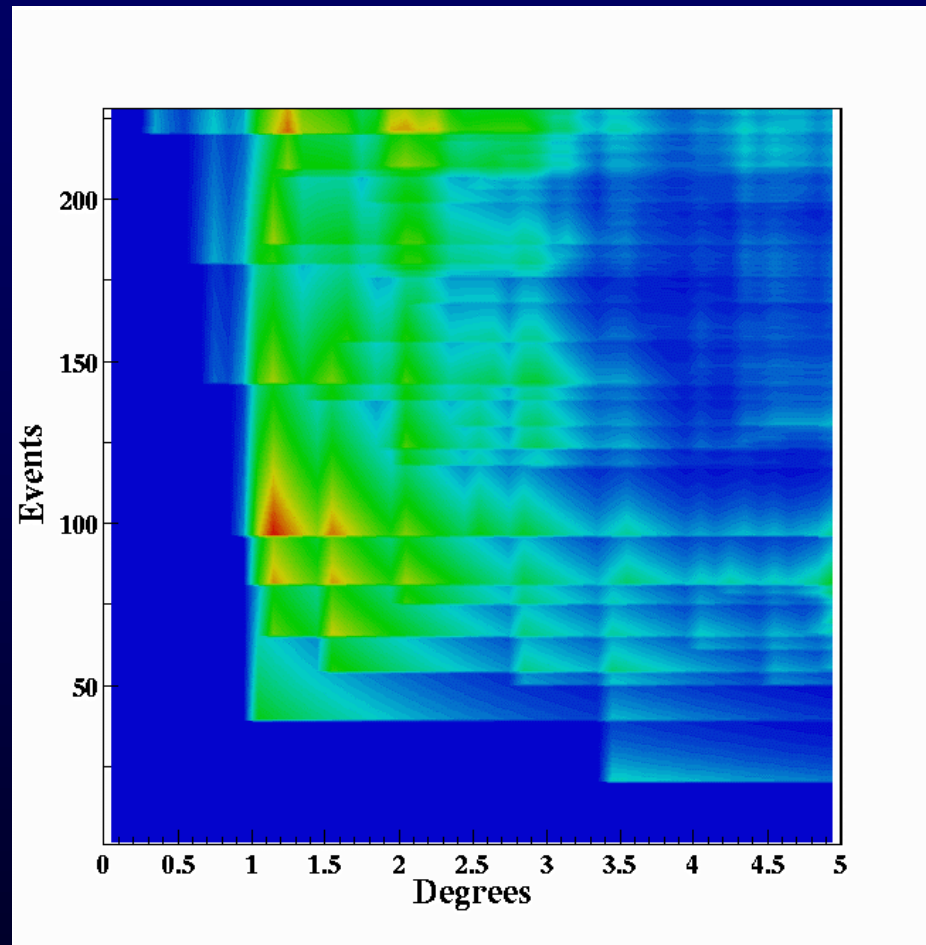


Scan of HiRes Stereo Events $> 10^{19}$ eV

Autocorrelation Scan

HiRes Results:

- Strongest clustering signal:
 - $\theta = 1.2^\circ$
 - $E = 1.7 \times 10^{19}$ eV
 - $P_{min} = 1.1\%$
- Chance probability for scan of Monte Carlo data to have lower minimum:
 - $P_{chance} = 39\%$
- No evidence for clustering

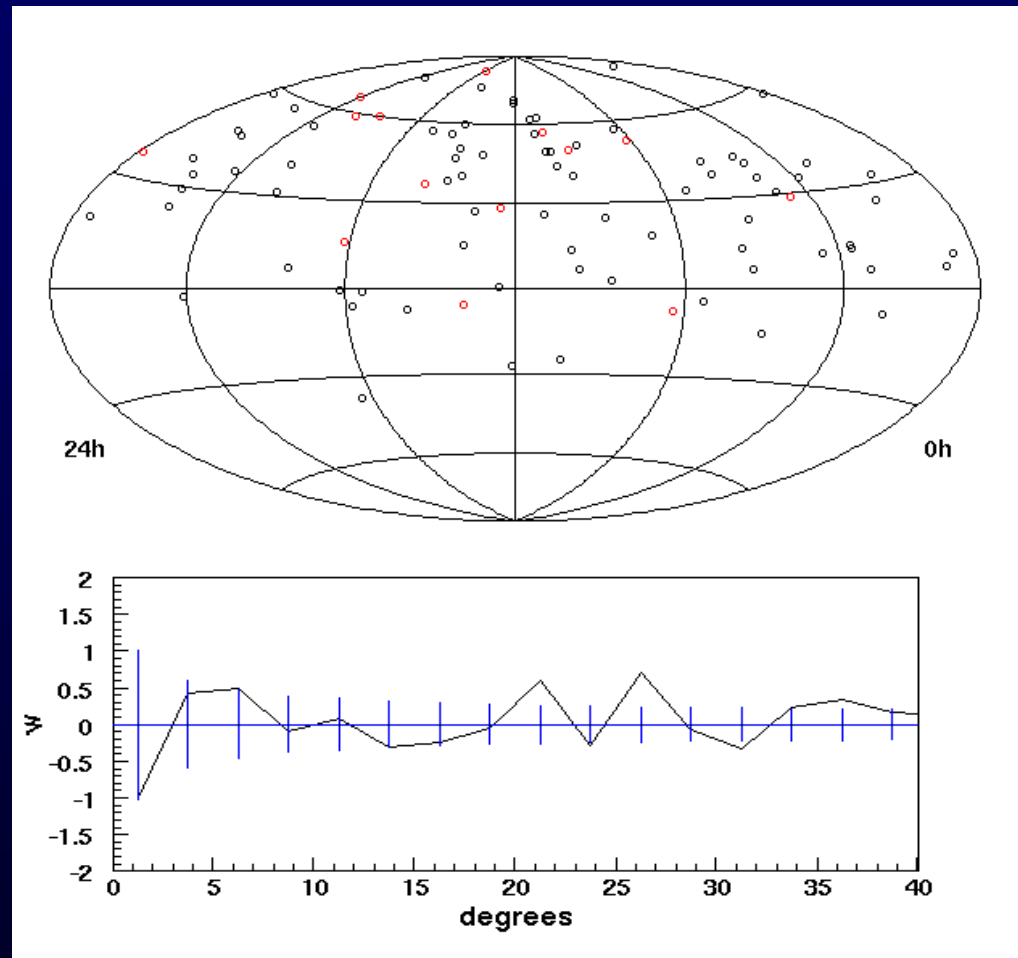


Scan of HiRes Stereo Events $> 10^{19}$ eV

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 ($>2 \times 10^{19}$ eV) is consistent with no correlation.



Above: HiRes (black) , BL Lacs (red)

Below: Two-point cross correlation function

Summary

- Energy spectrum:
 - HiRes 1&2 monocular data currently does not contradict the expected GZK cutoff
- 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