Very High Energy Astrophysics

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Columbia University

Division of Particles and Fields Meeting

University of California, Riverside

30 August 2004

Cosmic Rays and Particle Physics

- Victor Hess's balloon flight in 1912: the birth of "particle astrophysics"

- Hess discovers that radiation enters the Earth's atmosphere from outer space ("cosmic rays")
- Cosmic "rays" are mainly protons and heavier nuclei
- Main laboratory for early particle physics
  - e.g. discovery of the positron by Anderson, 1931

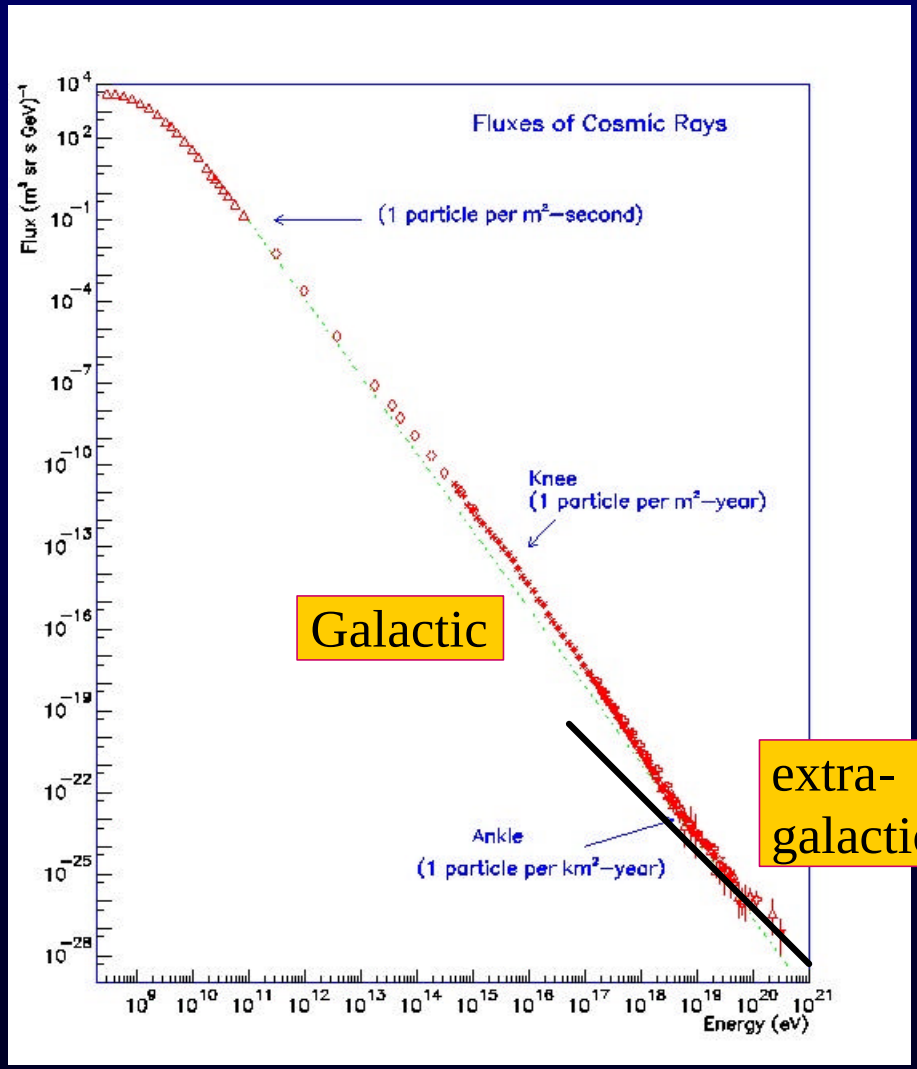
Discovery of Cosmic Rays

- Nobel Price 1936 for
  - Anderson "for the discovery of the positron"
  - Hess "for his discovery of cosmic radiation"

- In the age of accelerators – concentrate on the origin of cosmic rays themselves…
- *Problem:* after 90 years, we still have not identified the sources of high energy cosmic rays – a major problem for astrophysics !

Energy Spectrum

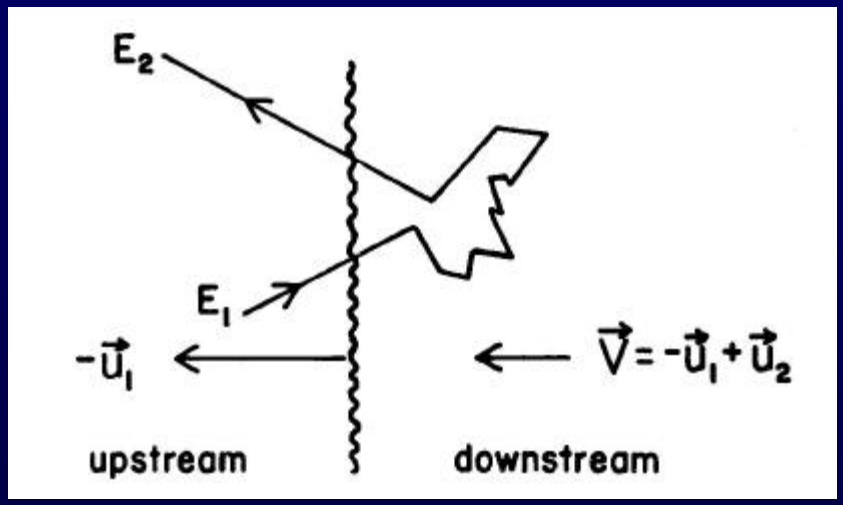
- Accelerator(s) with amazing features…
- …measured spectrum extends to 10^{20} eV, 11 orders of magnitude greater than the equivalent rest mass of the proton
- Cosmic ray spectrum roughly represents a single power law $E^{-2.8}$ *– is this an indication ?*
- Some structure: "knee" and "ankle"



S. Swordy

The "Nonthermal" Universe

- Cosmic ray energy spectrum is nonthermal
- "Nonthermal"
  - energy distribution has no characteristic temperature
  - Energies of the nonthermal Universe (up to 10^{20} eV) are well beyond the capabilities of thermal emission processes
  - Source energy is given to a relatively small number of particles
- Traditional astrophysical sources or extreme solutions (topological defects, …) ?



E. Fermi, On the Origin of Cosmic Radiation, Phys. Rev. 75 (1949) 1169

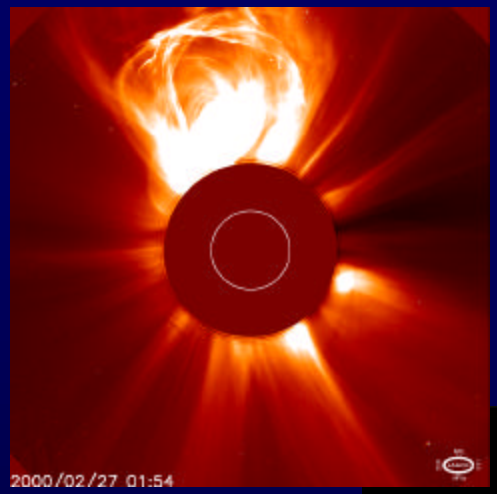
- Fermi acceleration at shock fronts (Supernova remnants, AGN jets,…) ?

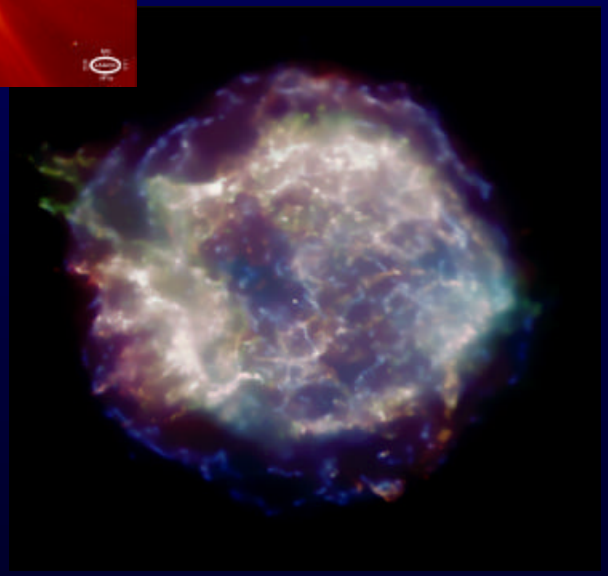
Cosmic Particle Acceleration

- The general concept:
  shock acceleration
- *Scenario 1:*

  Sudden release of energy

  - ➢ Mass ejection
  - ➢ Shock formation
  - ➢ Particle Acceleration
- e.g. Coronal Mass Ejections, Supernova Remnants (SNRs), Gamma Ray Bursts (GRBs)





CME, courtesy SOHO (NASA, ESA)
Cas A, courtesy Chandra (NASA)

Cosmic Particle Acceleration

Crab, FORS team, 8.2 VLT, ESO

- The general concept: shock acceleration
- *Scenario 2:*

  Supersonic flow

  - ➢ flow hits obstacle
  - ➢ shock formation
  - ➢ particle acceleration
- Pulsar winds, Jets of Active Galactic Nuclei (AGN)

Cosmic Accelerators

- Search for the sources and acceleration mechanism(s)
- Cosmic accelerators:
  - Charged particles (e, p, nuclei) are the primary product, but they are deflected in magnetic fields (… of unknown strength and orientation…)

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

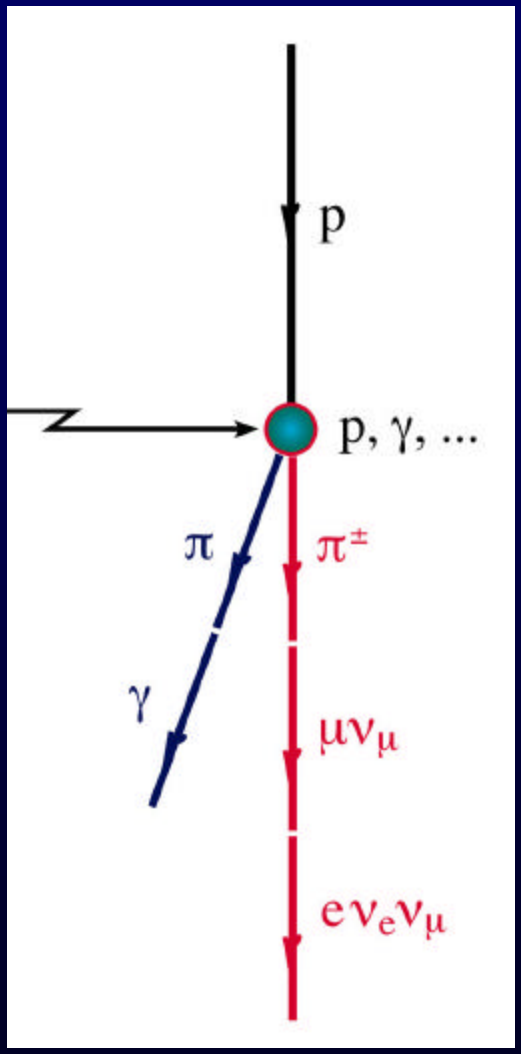
  - Cosmic ray astronomy might be possible at the highest energies (above 4×10^{19} eV, maybe higher…)

Cosmic Messengers

- High energy γ–rays and neutrinos are secondary products of cosmic ray acceleration …
  - High energy protons hit ambient gas and radiation
    - π^0 decay, γ–radiation (observed ?)
    - π^+, π^- decay, neutrinos
  - Electrons: bremsstrahlung, synchrotron losses, inverse Compton scattering
- … and point back to their sources !

- Three messengers:

Ultrahigh Energy Cosmic Rays
High Energy γ–rays
Neutrinos



Vital Field – See Parallel Sessions

- Monday 8:00 – 9:45
  - Test of Lorentz Invariance Violation — *Floyd Stecker*
  - HiRes Results: Spectrum and Small-Scale Anisotropy — *Chad Finley*
  - Ultrahigh Energy Cosmic Rays in CHICOS — *Elina Brobeck*
  - Status of the Pierre Auger Observatory — *David Barnhill*
  - Gamma-Ray Bursts: Jet Content and Geometric Configuration — *Bing Zhang*
  - Results from the VERITAS Prototype — *Brian Humensky*
- Monday 10:15 – 12:00
  - Spectral Evolution in Mrk 421 — *Jeffrey Grube*
  - TeV Gamma-Ray Astrophysics with Milagro and HAWC — *Anthony Shoup*
  - Observations of Supernova Remnants with H.E.S.S. — *Conor Masterson*
  - Gamma-Ray Astronomy with the MAGIC Observatory — *Daniel Ferenc*
  - Recent Observations and Results from STACEE — *Jeffrey Zweerink*

Tomorrow's Parallel Sessions

- Tuesday 8:00 – 9:45
  - Progress with the ANITA Ultrahigh Energy Neutrino Detector *Steven Barwick*
  - Search for Neutrinos from Gamma-Ray Bursts with AMANDA *Kyler Kuehn*
  - Status of the IceCube Neutrino Telescope *Tyce DeYoung*
  - GeV to PeV Energy Photon Interactions in Gamma-Ray Burst Fireballs and Surroundings *Soebur Razzaque*
  - The Gamma-Ray Large Area Space Telescope GLAST *Richard Dubois*
  - Gamma-Ray Observations of the Nearby Starburst Galaxy IC342 *Tomoyuki Nagai*

Searching for Cosmic Accelerators

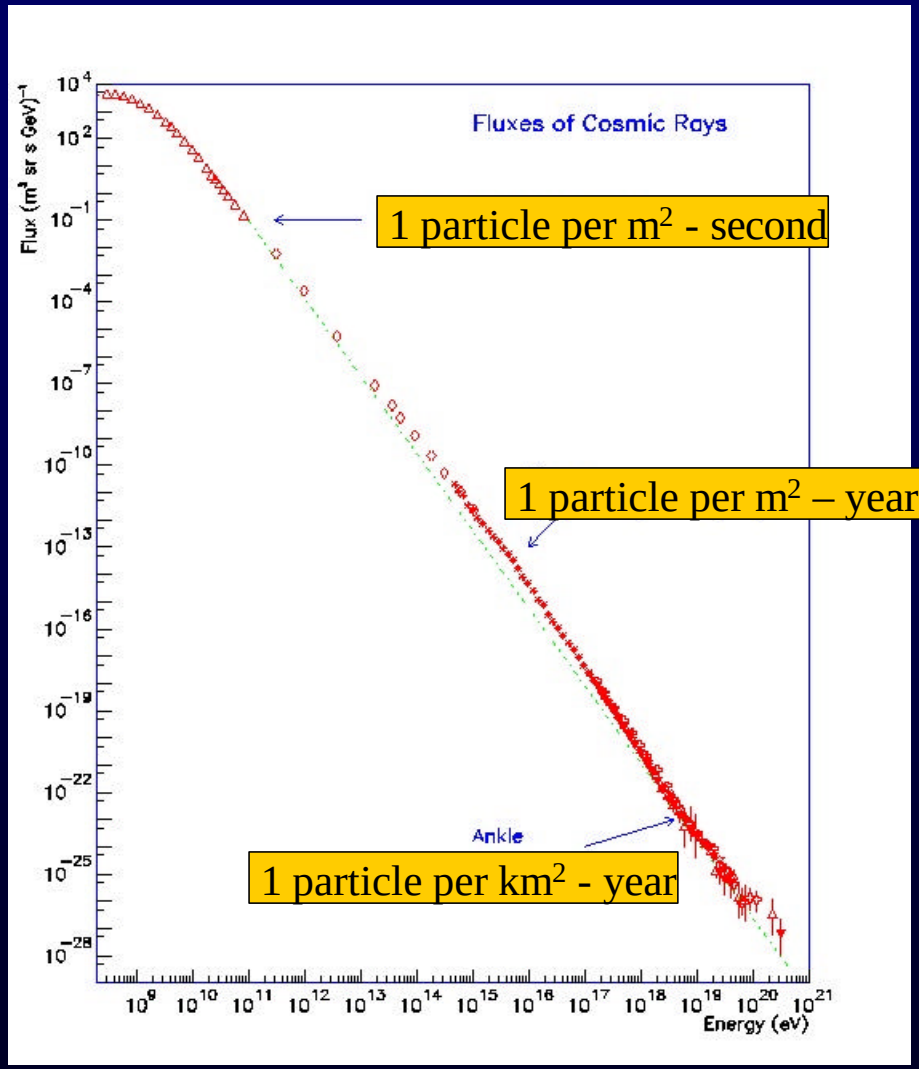
Ultrahigh Energy Cosmic Rays

High Energy g-Rays

Neutrinos

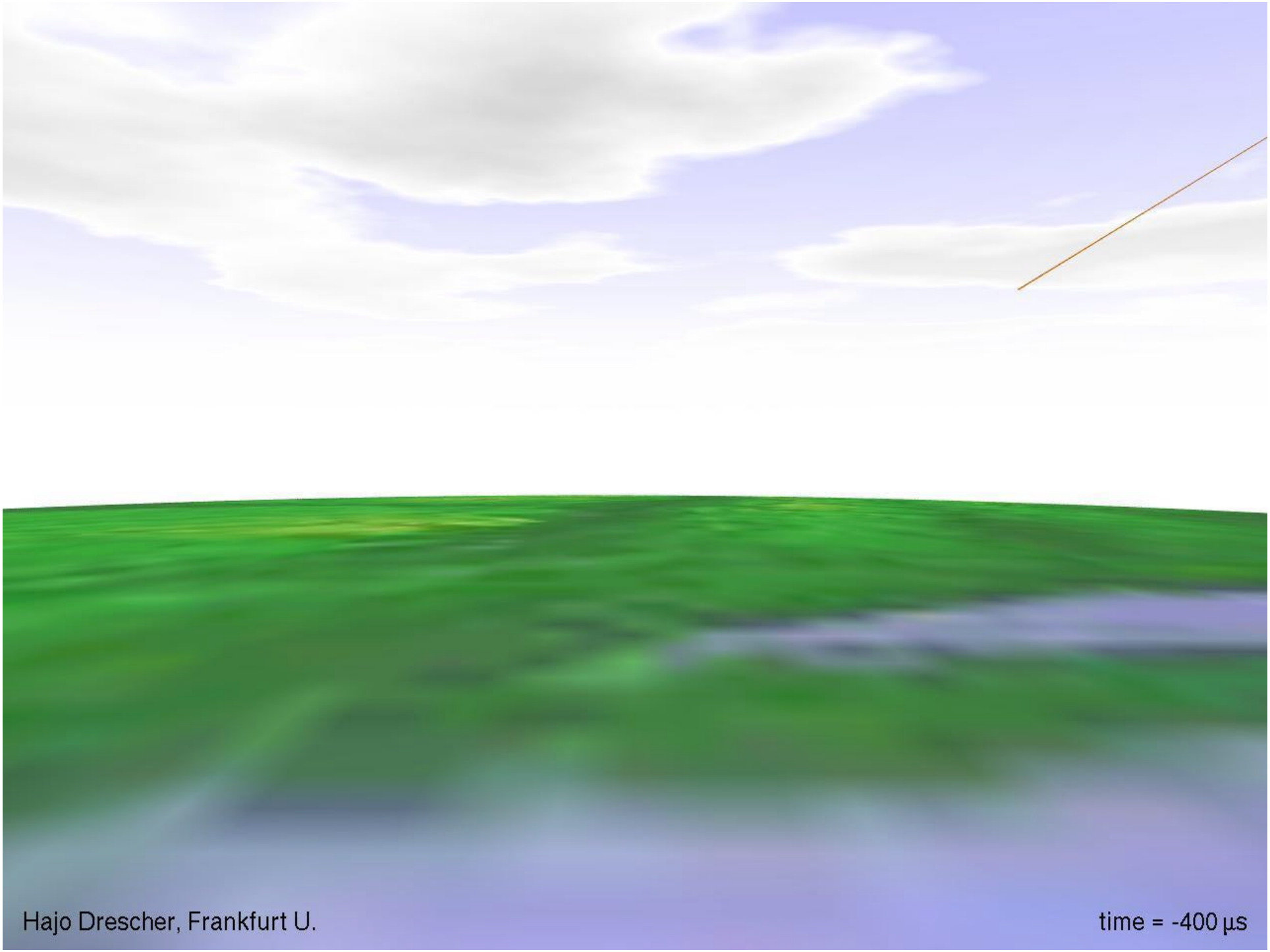
Cosmic Ray Astronomy

- Detecting ultra-high energy cosmic rays is an experimental challenge
- Flux is only of order 1 particle per km^2 per year at energies above the ankle
- No direct detection of the primary cosmic ray possible
- Use Earth's atmosphere as calorimeter: "air shower"
  - air shower arrays (AGASA)
  - air fluorescence detectors (HiRes)



S. Swordy

Computer Simulation by H.J. Drescher
Hajo Drescher, Frankfurt U.
time = -1000 µs


Hajo Drescher, Frankfurt U.
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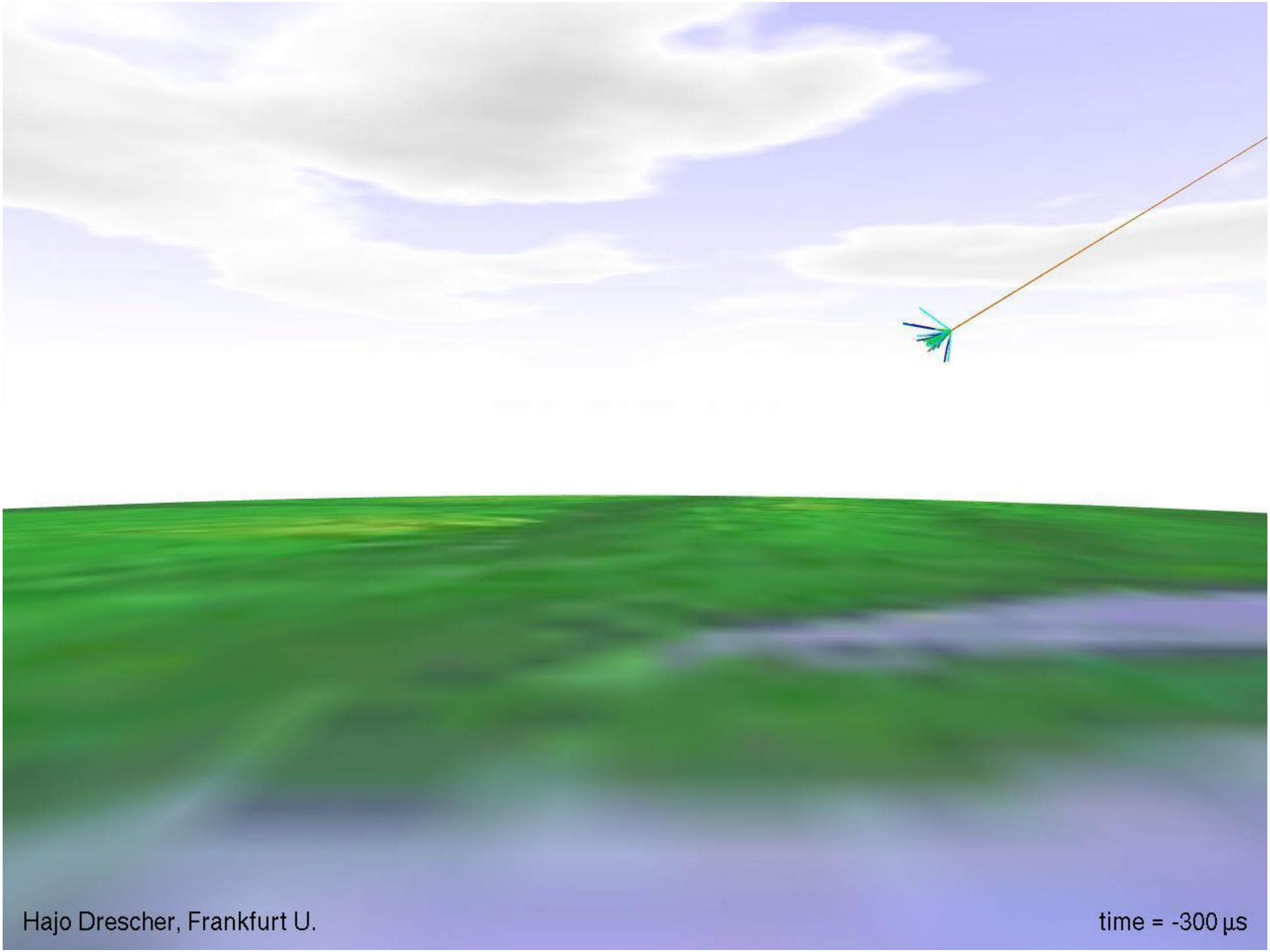
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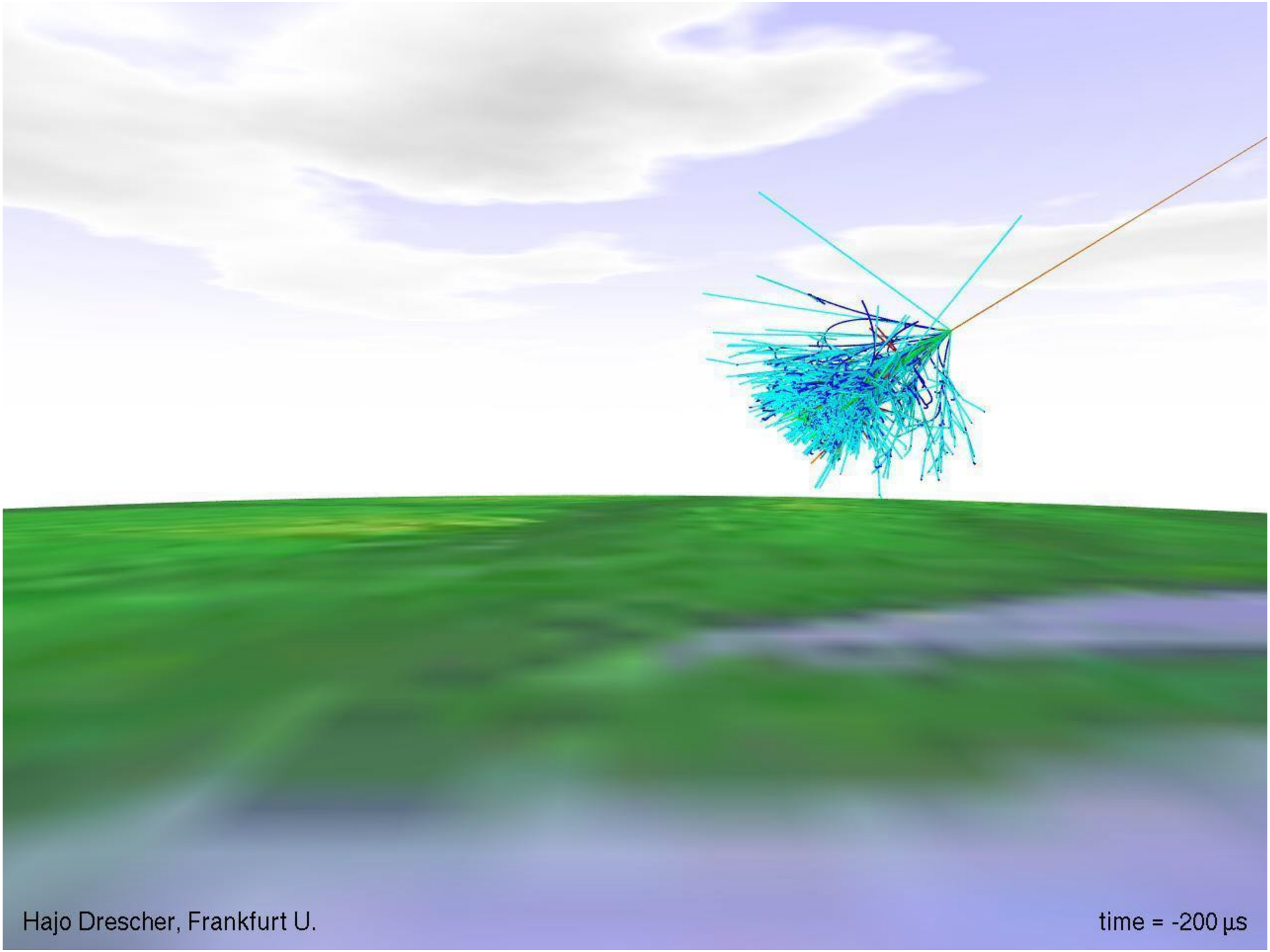
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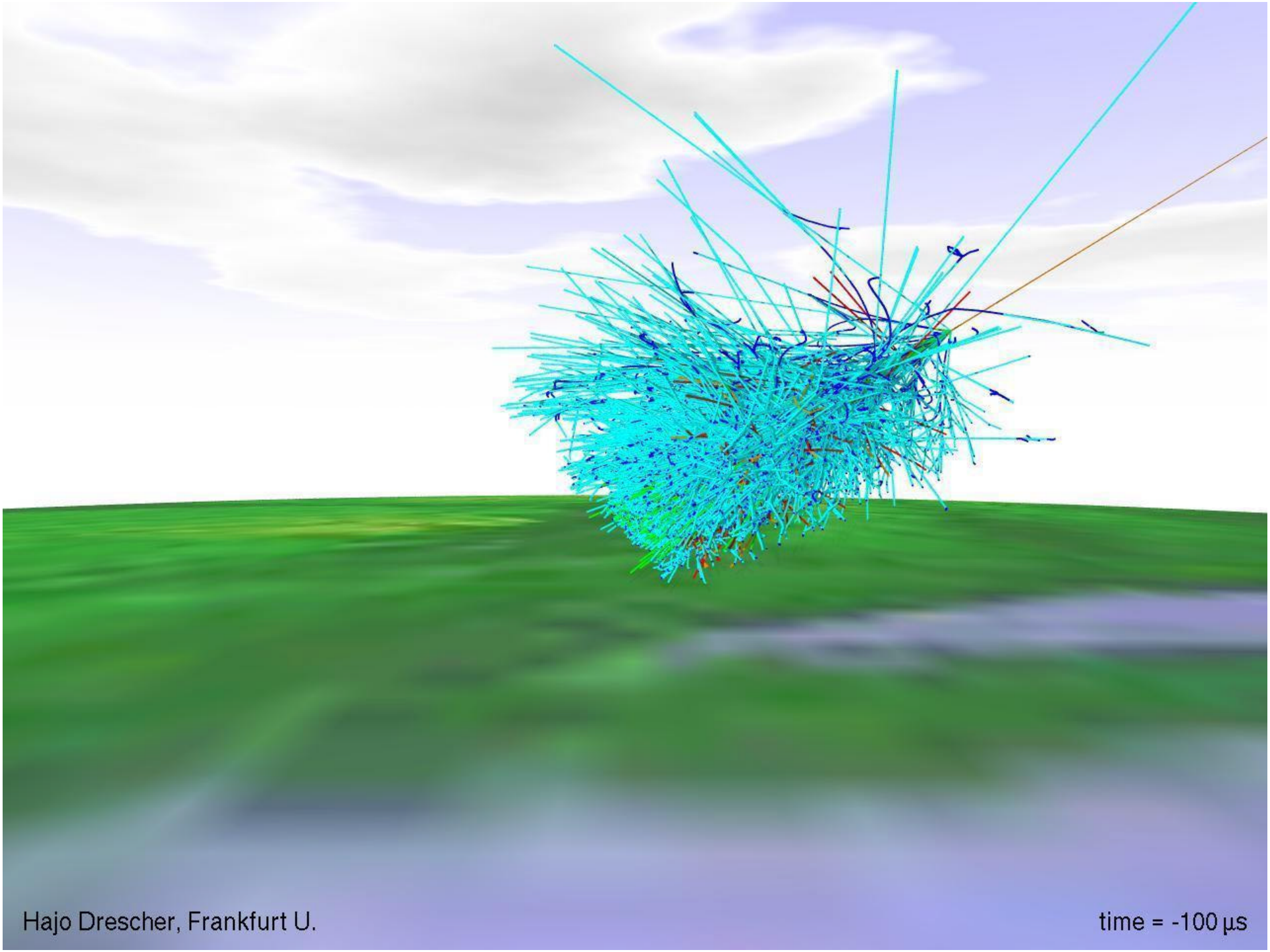
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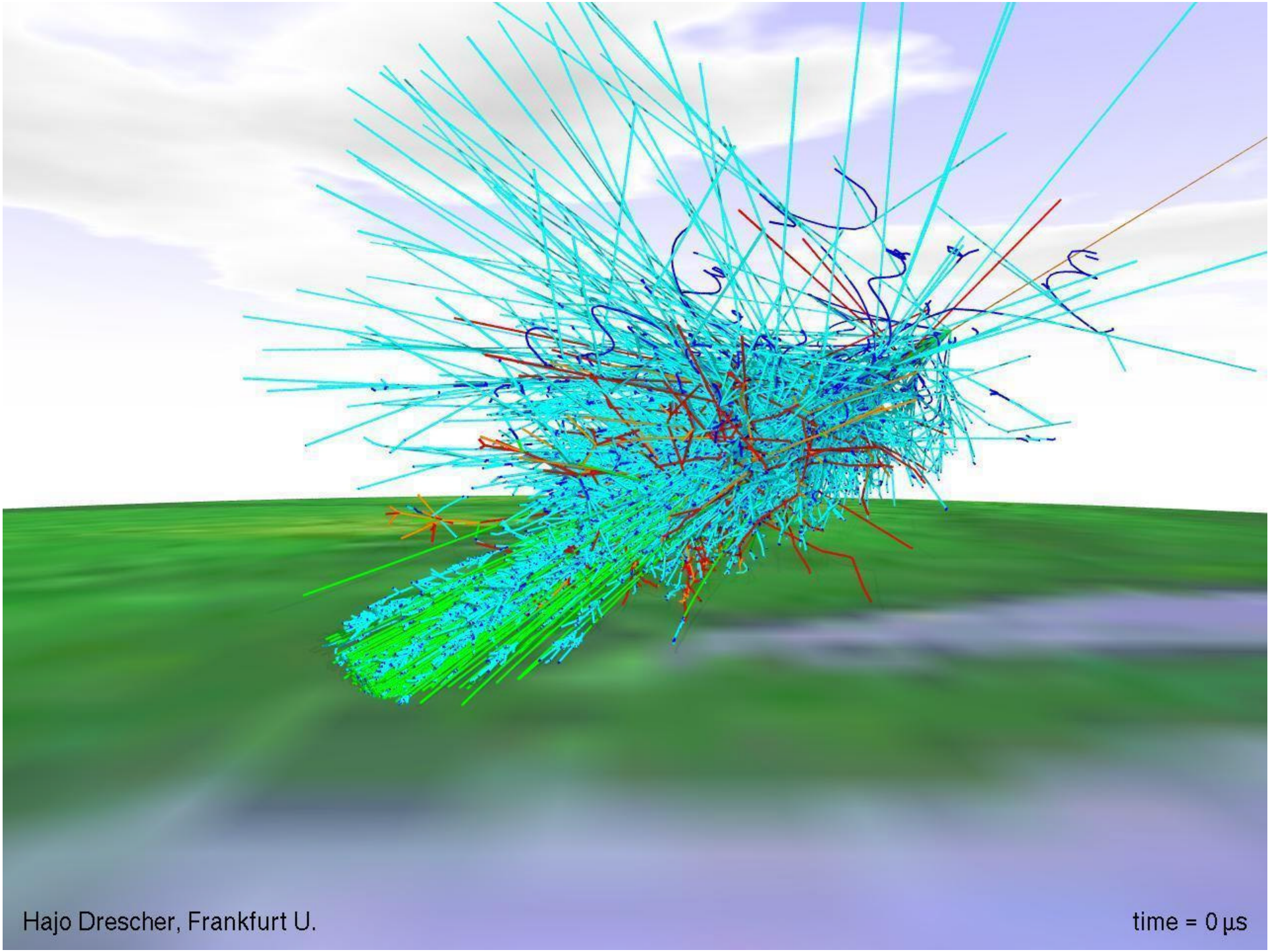
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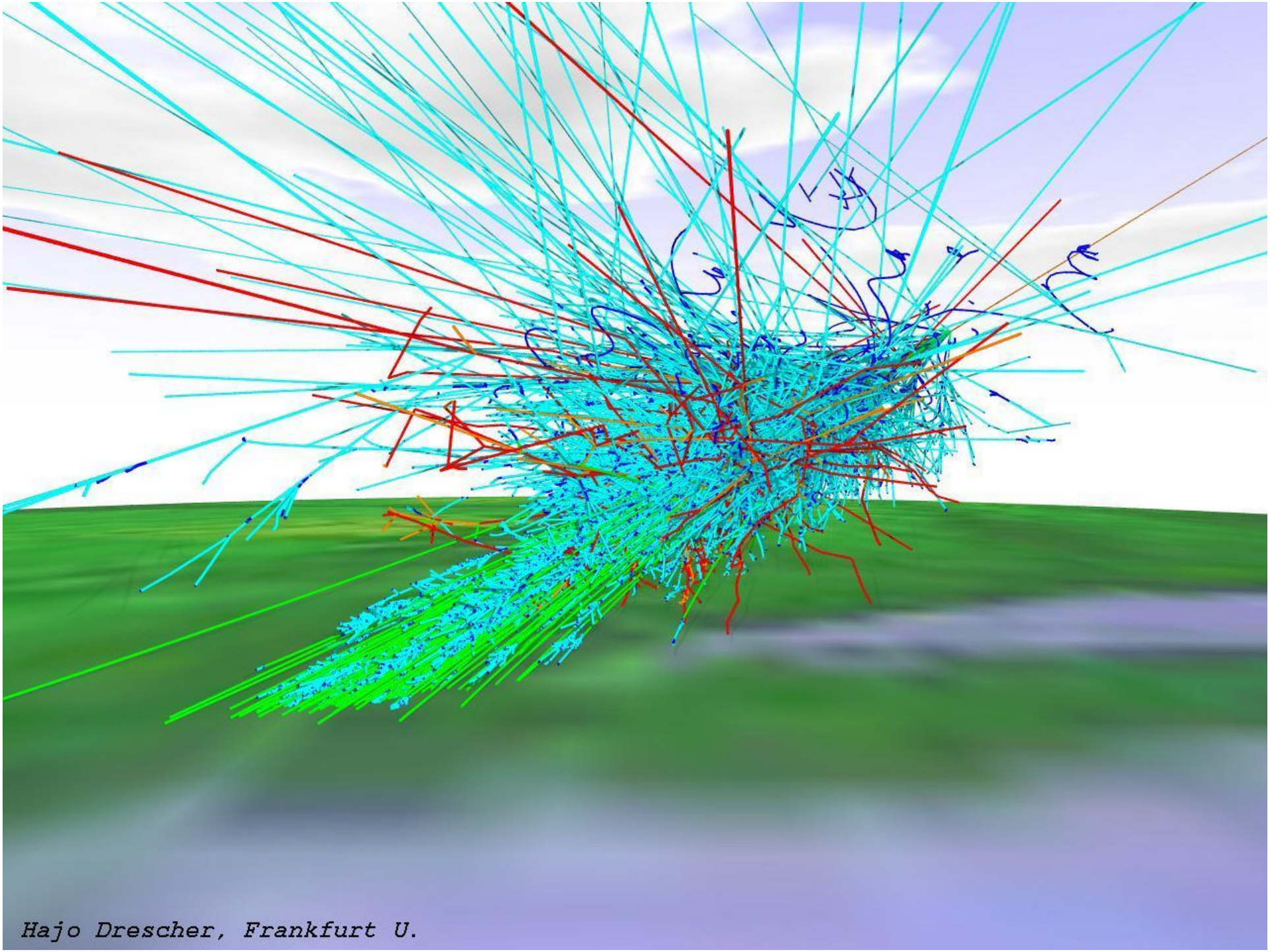
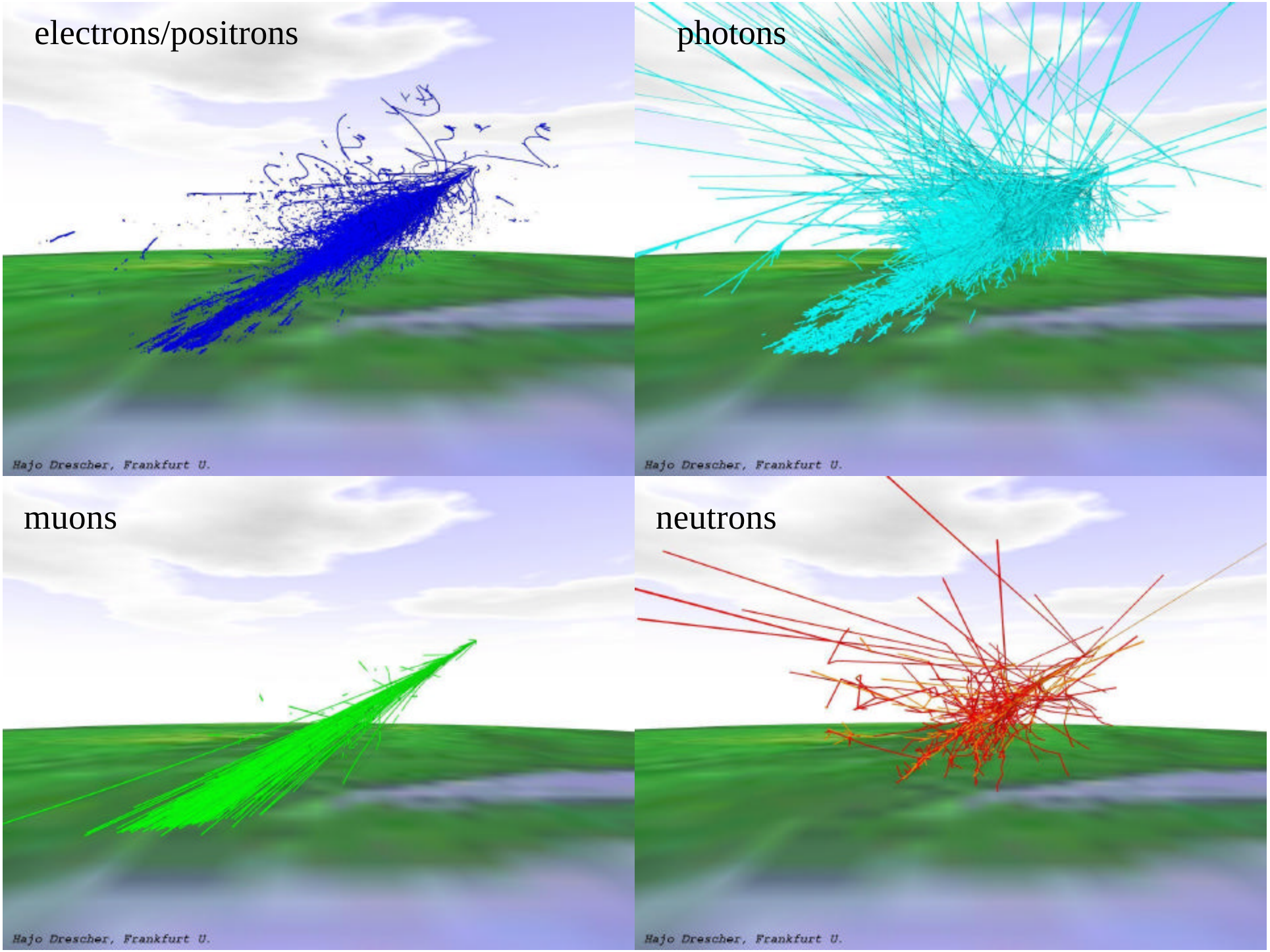

Hajo Drescher, Frankfurt U.


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

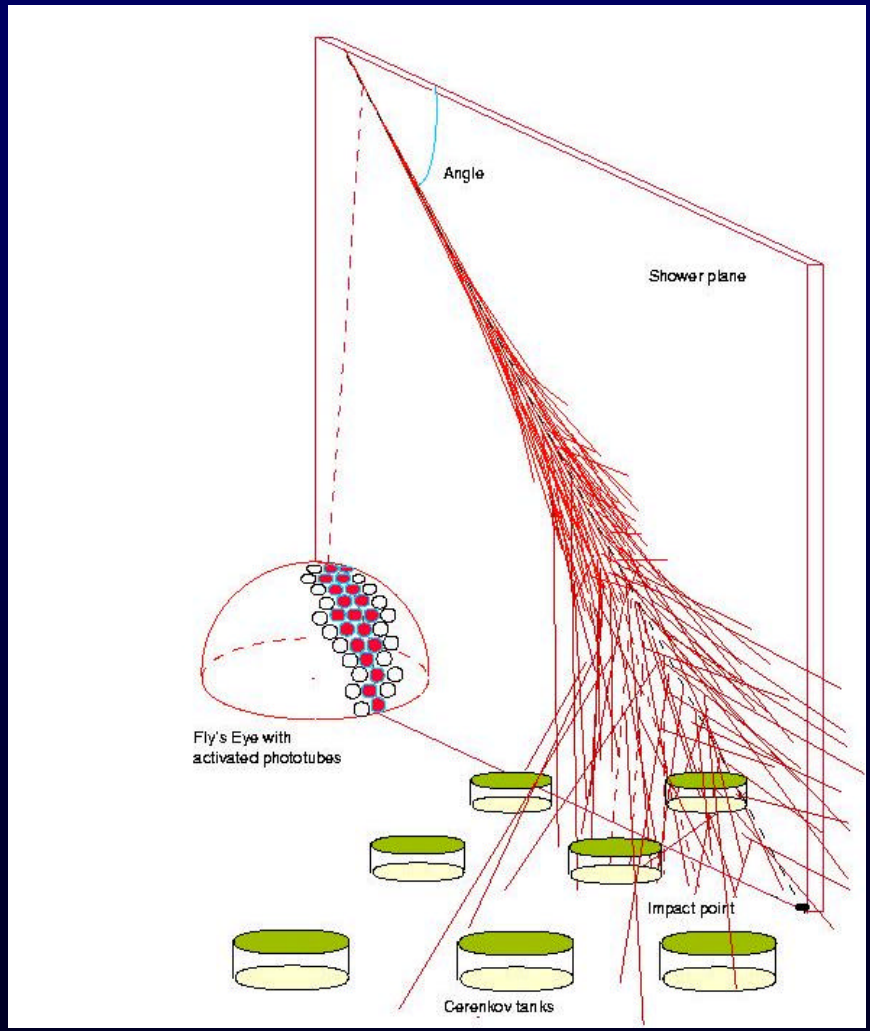
AGASA Array

- 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 2003 (A20 with 12 km^2 for first 5 years)

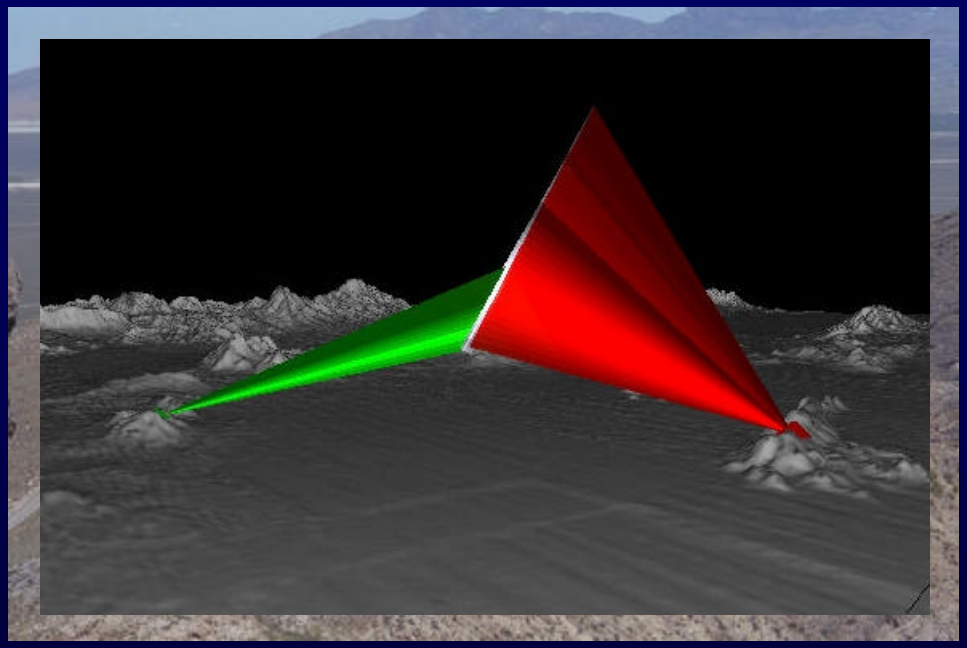
AGASA Collaboration

Air Fluorescence Technique

- 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
- Light can be collected with mirrors and PMT cameras during dark, moonless nights
- Large instantaneous aperture, but only 10 % duty cycle



High Resolution Fly's Eye



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

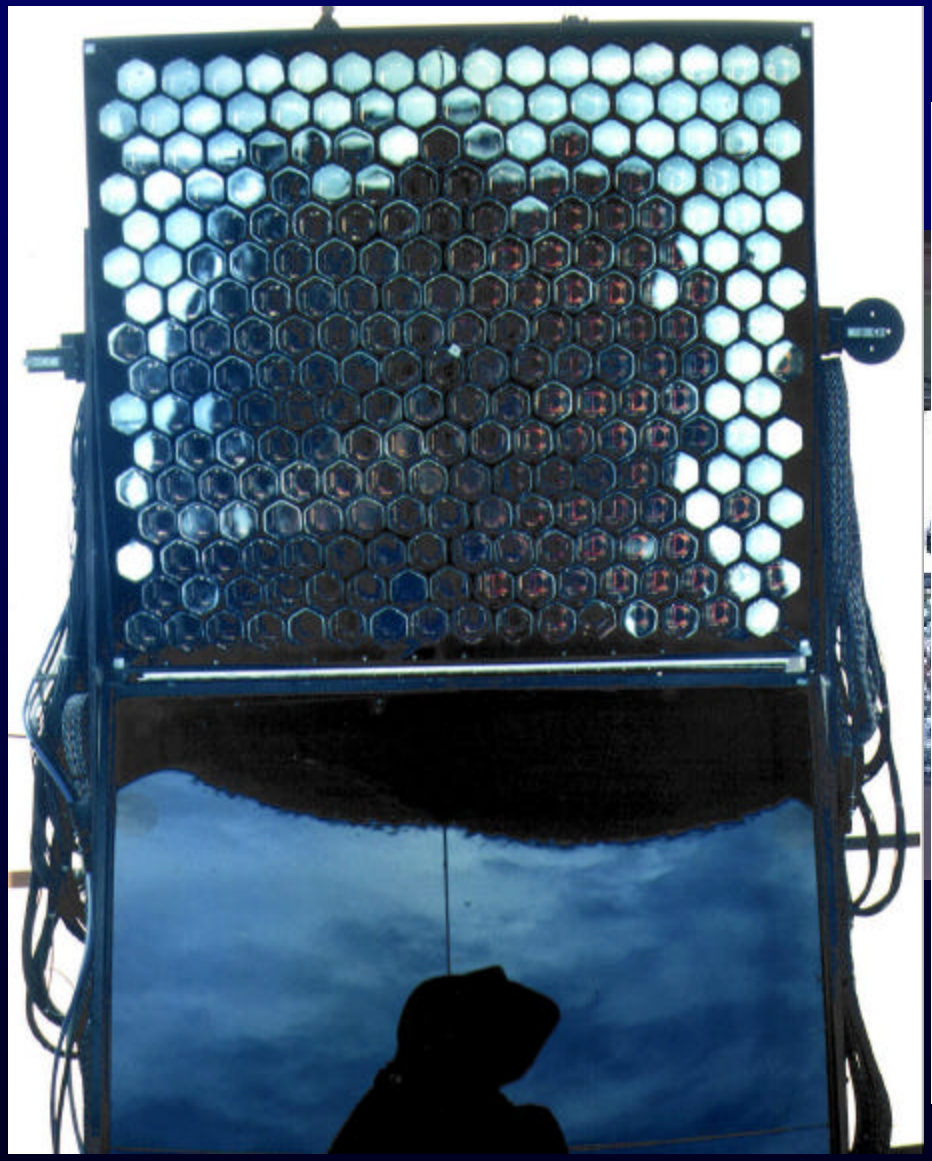
HiRes 1 at Five Mile Hill

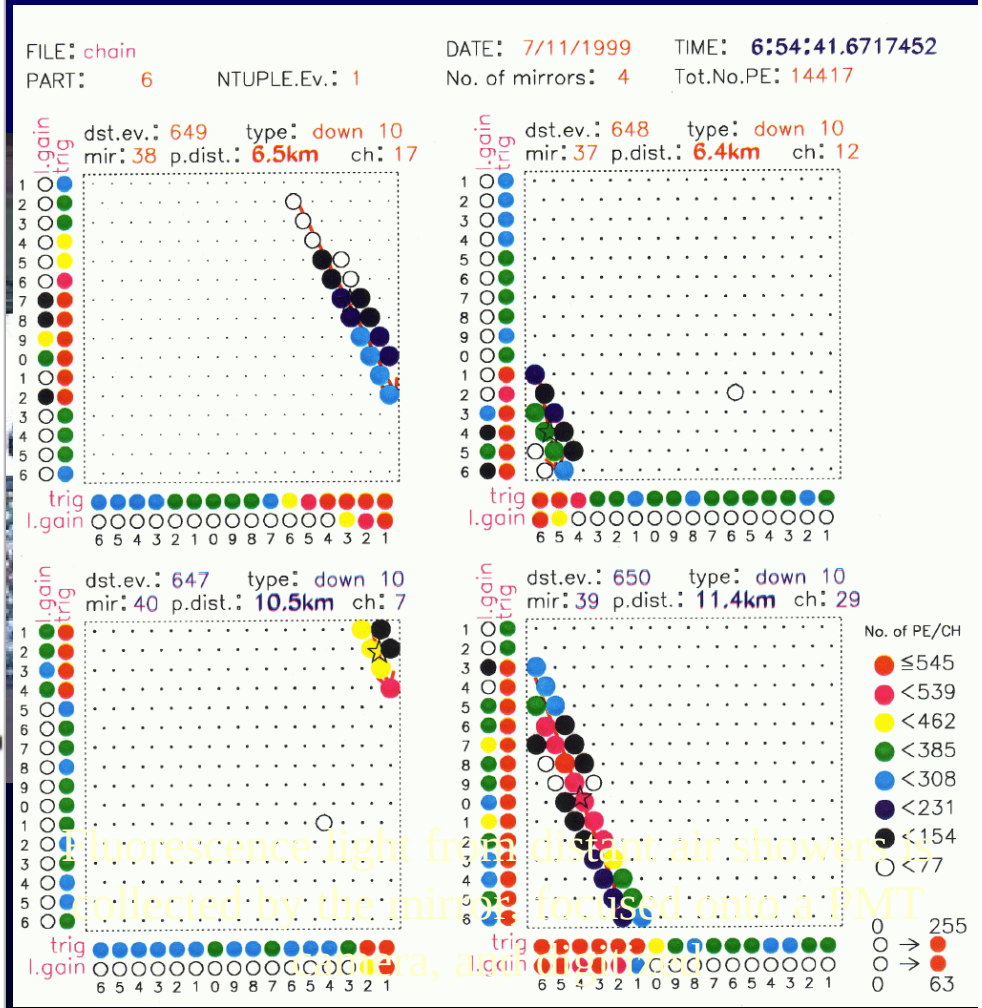
- 22 telescopes with 256 photomultiplier tubes each
- 3° – 16.5^{o} elevation
- 360° azimuth

HiRes 2 at Camels' Back

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

Air Fluorescence Technique





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

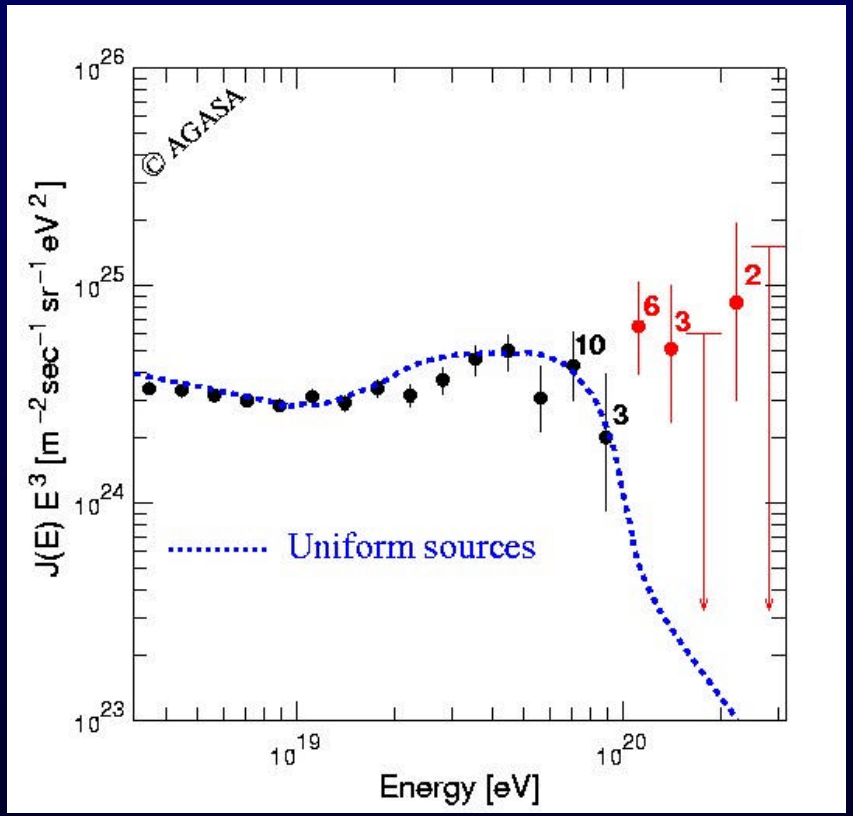
A Small Complication…

- 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 Suppression (1966)

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

Cosmic Ray Energy Spectrum

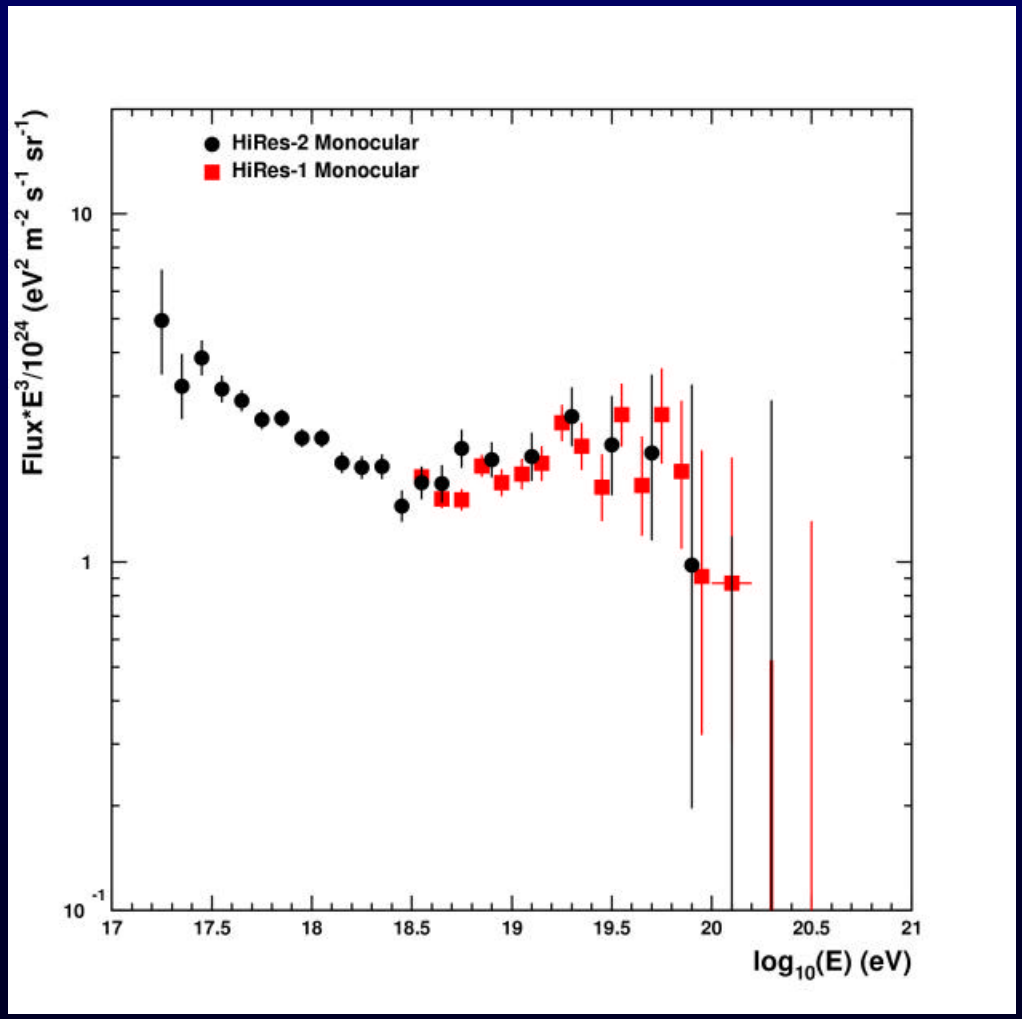
- AGASA claims a continuation of the spectrum incompatible with the GZK suppression
- Nearby sources (<50 Mpc) ?
  - M87 in the Virgo cluster (20 Mpc)
  - NGC315 (80 Mpc)
  - Topological defects
  - Violation of Lorentz invariance ?
  - …



AGASA collaboration

The HiRes Mono Spectra

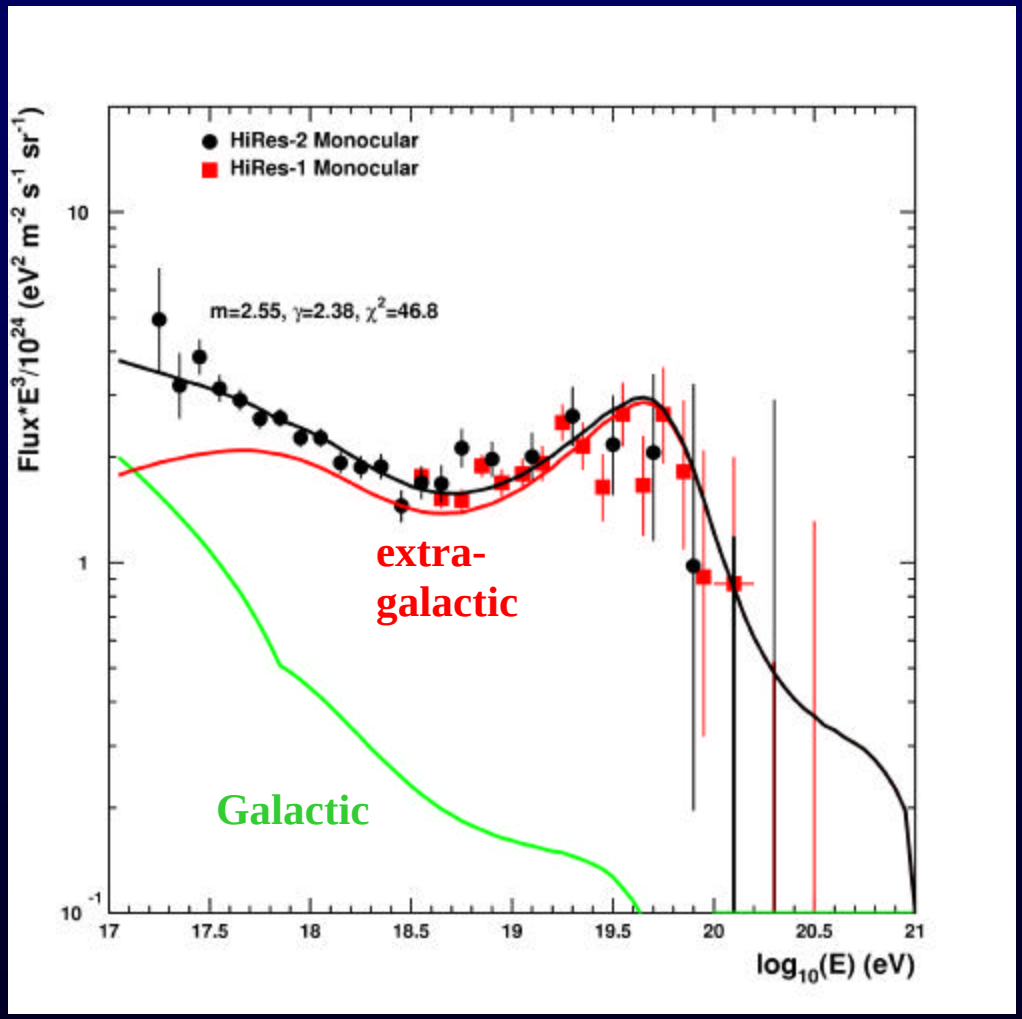
- *Monocular* data: wider energy range $E>10^{17.4}$ eV, better statistics
- HiRes spectrum falls steeply above $5x10^{19}$ eV, as expected from GZK suppression
- $E > 10^{19.8}$ eV
  - 5 events observed
  - 21.7 expected



D. Bergman (HiRes), parallel session

Fit to Models

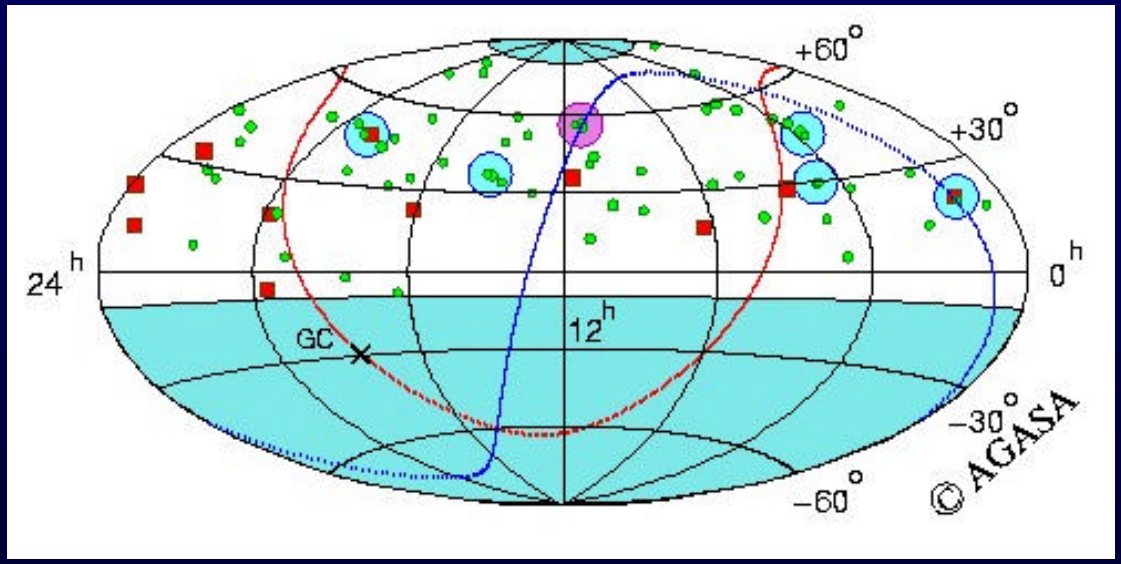
- Data is fitted by Galactic and extragalactic component including GZK suppression
- Assuming uniform source distribution for extragalactic component



D. Bergman, parallel session

Indication for Point Sources ?

- AGASA claims significant small-scale clustering of cosmic ray arrival directions above 4×10^{19} eV



AGASA

E > 4×10^{19} eV

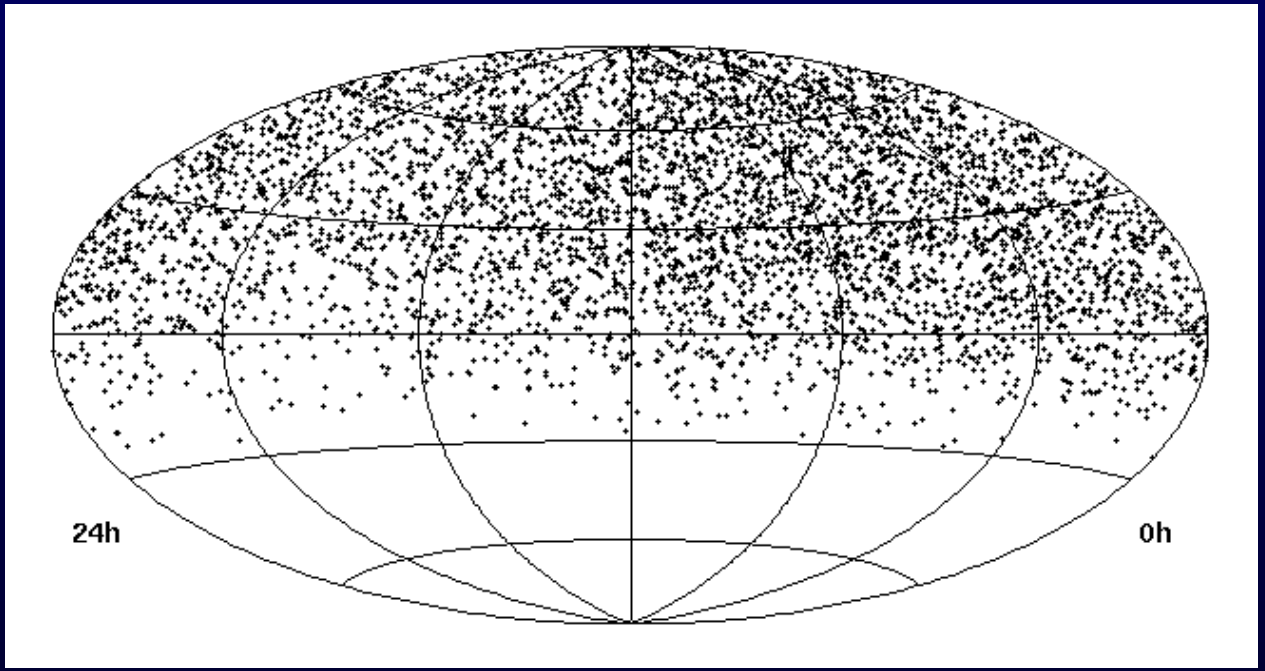
E > 10^{20} eV

AGASA Collab.

- Literature gives chance probabilities of 10^{-1} to 10^{-6} , depending on whether cuts on angular separation and minimum energy can be considered *a priori*
- *need statistically independent data to test claims*

HiRes Stereo Data Set

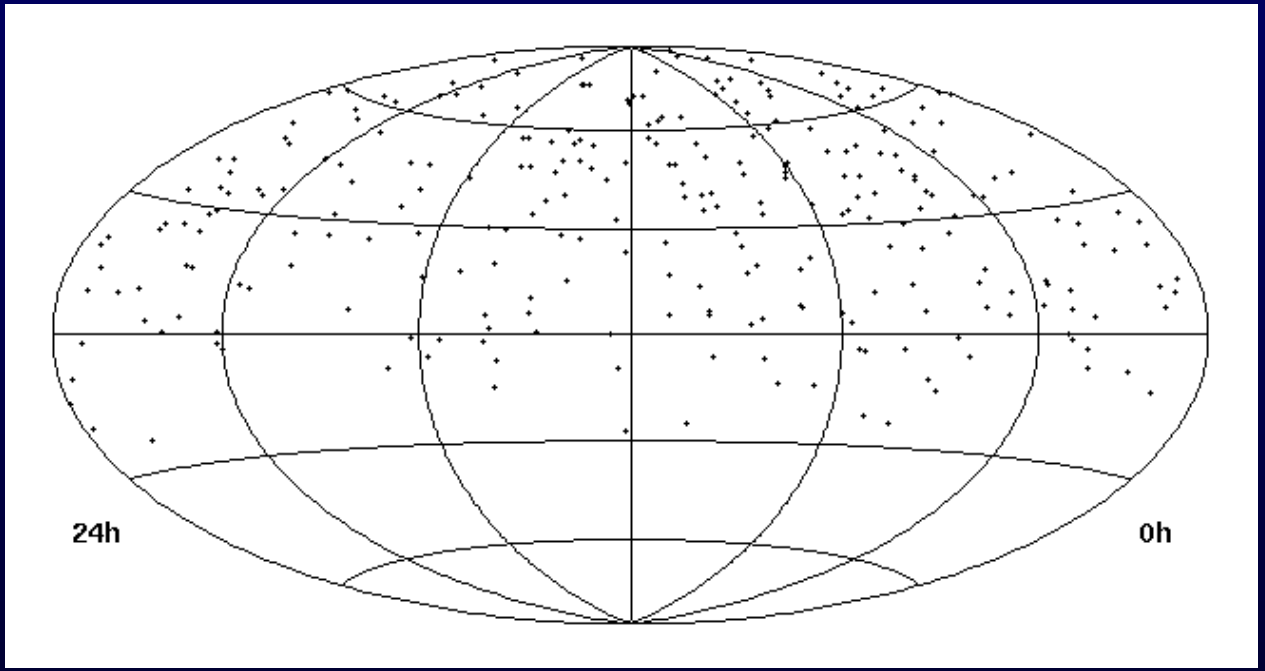
- *Stereo* data: best reconstruction
- Angular resolution ~ 0.6^{o}
- Stereo data from December 1999 to January 2004
- Statistically independent data set to test claims based on AGASA data



Equatorial Coordinates

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

- 271 events above 10^{19} eV after all cuts
- 47 events above 2.8×10^{19} eV
- 27 events above 4×10^{19} eV

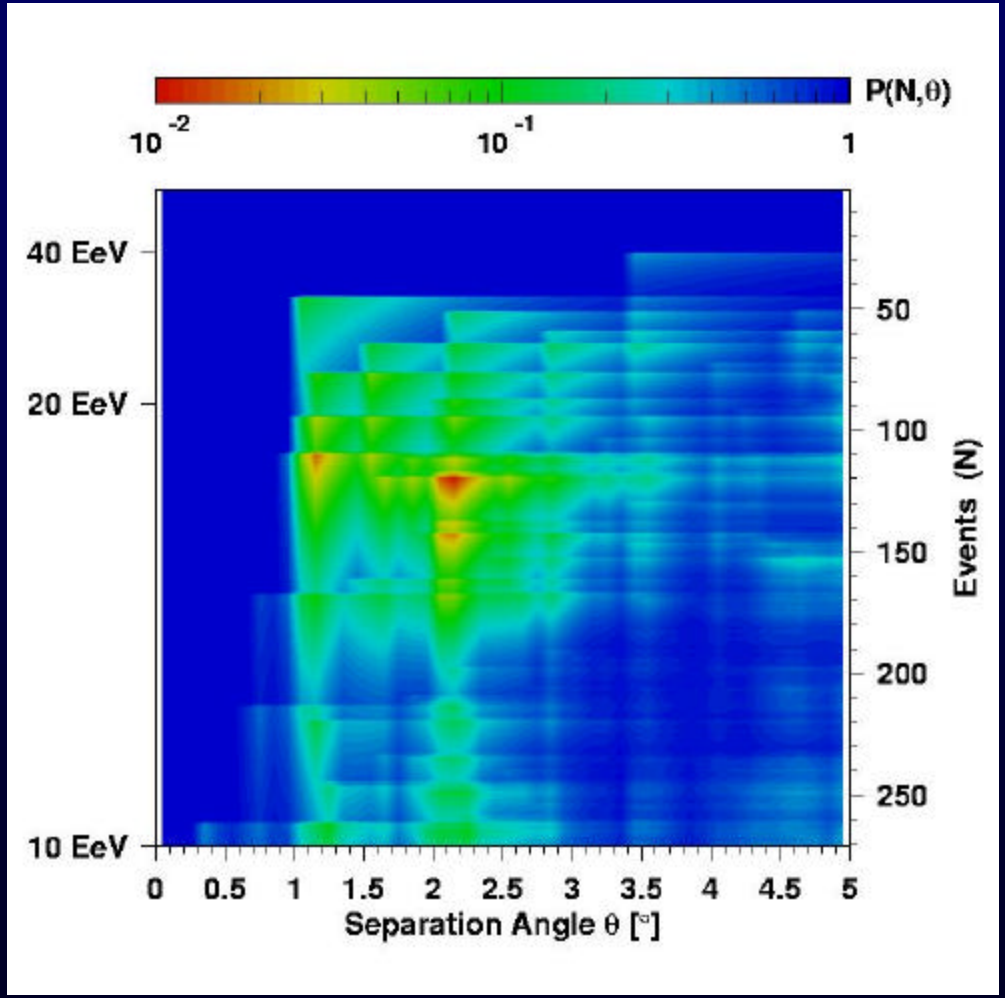


Equatorial Coordinates

HiRes Small-Scale Clustering

- Systematic search for small-scale clustering above $E=10^{19}$ eV at all angular separations from 0° to 5°
- Most significant "signal" has chance probability of 52 % after accounting for the scan
- No significant clustering

C. Finley, parallel session
ApJ 610 (2004) L73



Auto-correlation scan

Status

	AGASA	HiRes
Violation of GZK suppression	yes	no
Small-scale clustering	yes	no
Correlation with astrophysical source classes	Claimed by some authors	No indication
Do cosmic rays exist ?	yes	yes
Are there cosmic rays with energy above 10^{20} eV ?	yes	yes

Status

	AGASA	HiRes
Violation of GZK suppression	yes	no
Small-scale clustering	no[1]	no
Correlation with astrophysical source classes	no[2]	no

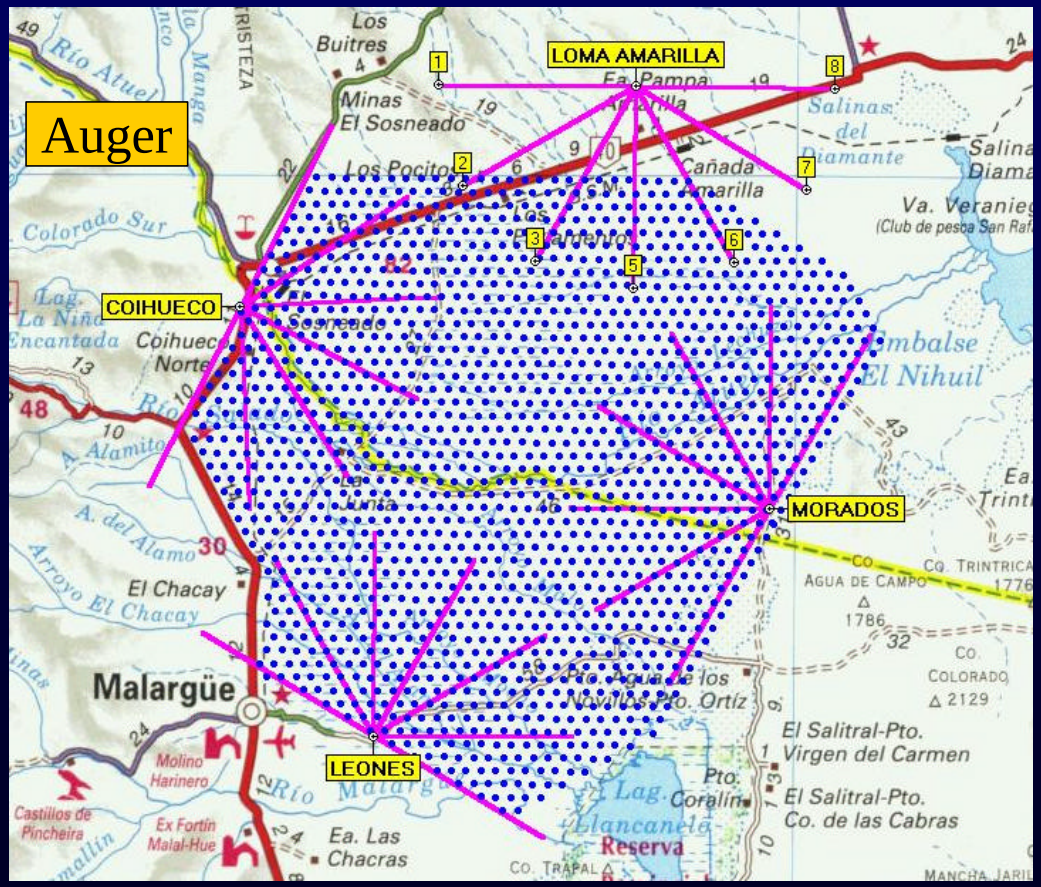
- Statistical significance has been challenged:
  - [2] Evans, Ferrer, Sarkar – Phys. Rev. D 67 (2003) 103005
  - [1] Finley, SW – Astroparticle Phys. 21 (2004) 359

Summary

- The following picture seems to emerge…
  - Cosmic rays with energies above 10^{20} eV exist, but HiRes data does not contradict the GZK suppression
  - With current statistics, arrival directions are isotropically distributed up to the highest energies
  - Composition above 10^{19} eV is dominated by light elements (HiRes, submitted to Astrophys. Journal, astro-ph/0407622)
- Many sources ? Cosmological ?
- Dearth of data is a real handicap…

Pierre Auger Observatory

Malargue, Argentina, 1400 m a.s.l.



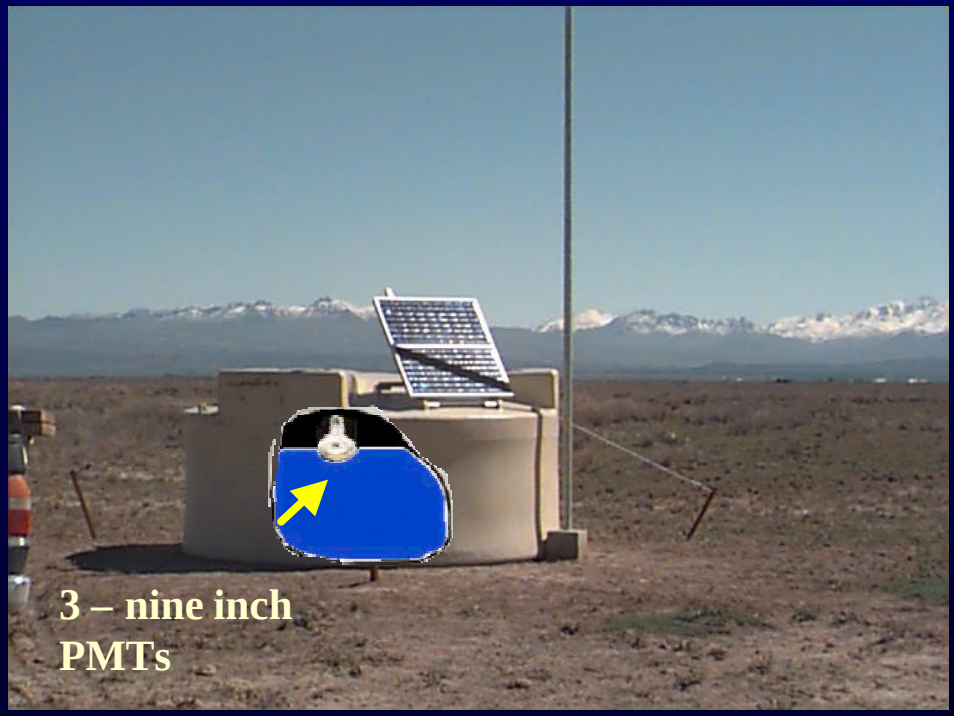
www.auger.org

Hybrid detector:

- Surface Detectors
  - 1600 detector stations
  - 1.5 km spacing
  - 3000 km^2
- Fluorescence Detectors
  - 4 telescope sites
  - 6 telescopes per site
- Planning underway for northern site

Auger Surface Detectors

- Each detector station is a 11,000 liter tank filled with pure water
- 3 PMTs (9 inch) per tank measure Cherenkov light from shower particles
- Self-contained stations working on solar power



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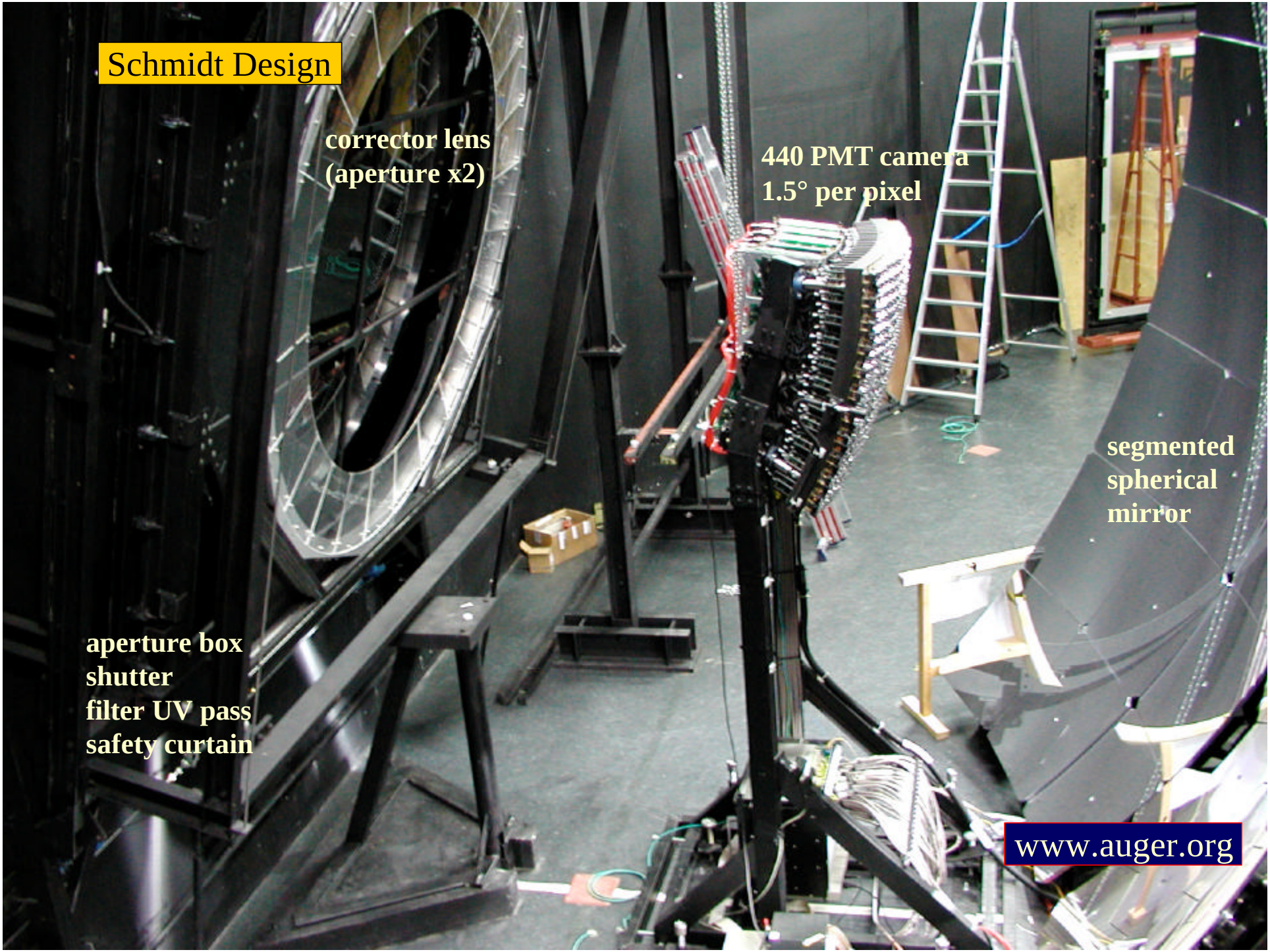
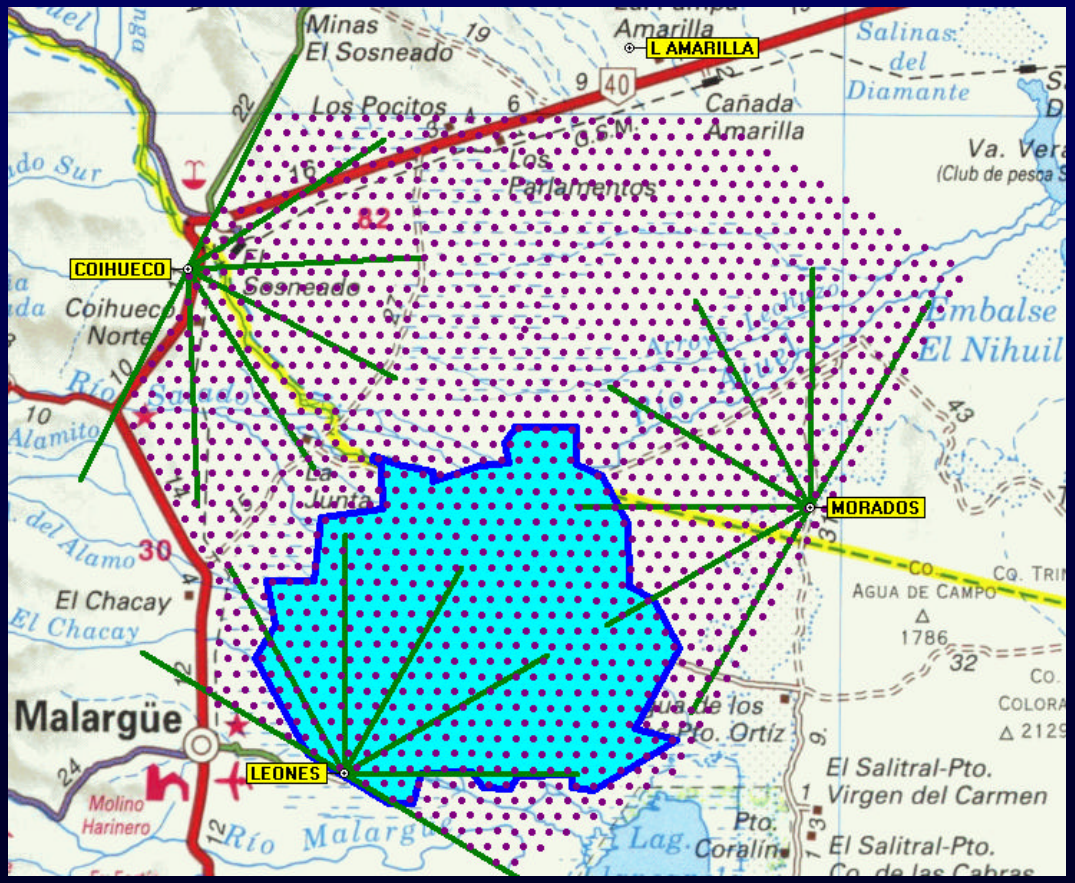

Schmidt Design
corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segmented
spherical
mirror
aperture box
shutter
filter UV pass
safety curtain
www.auger.org

Status of Auger South



www.auger.org

- 400+ surface detectors deployed (corresponds to AGASA times 6)
- Los Leones & Coihueco telescope sites complete
- First physics results in 2005

Searching for Cosmic Accelerators

Ultrahigh Energy Cosmic Rays

High Energy g-Rays

Neutrinos

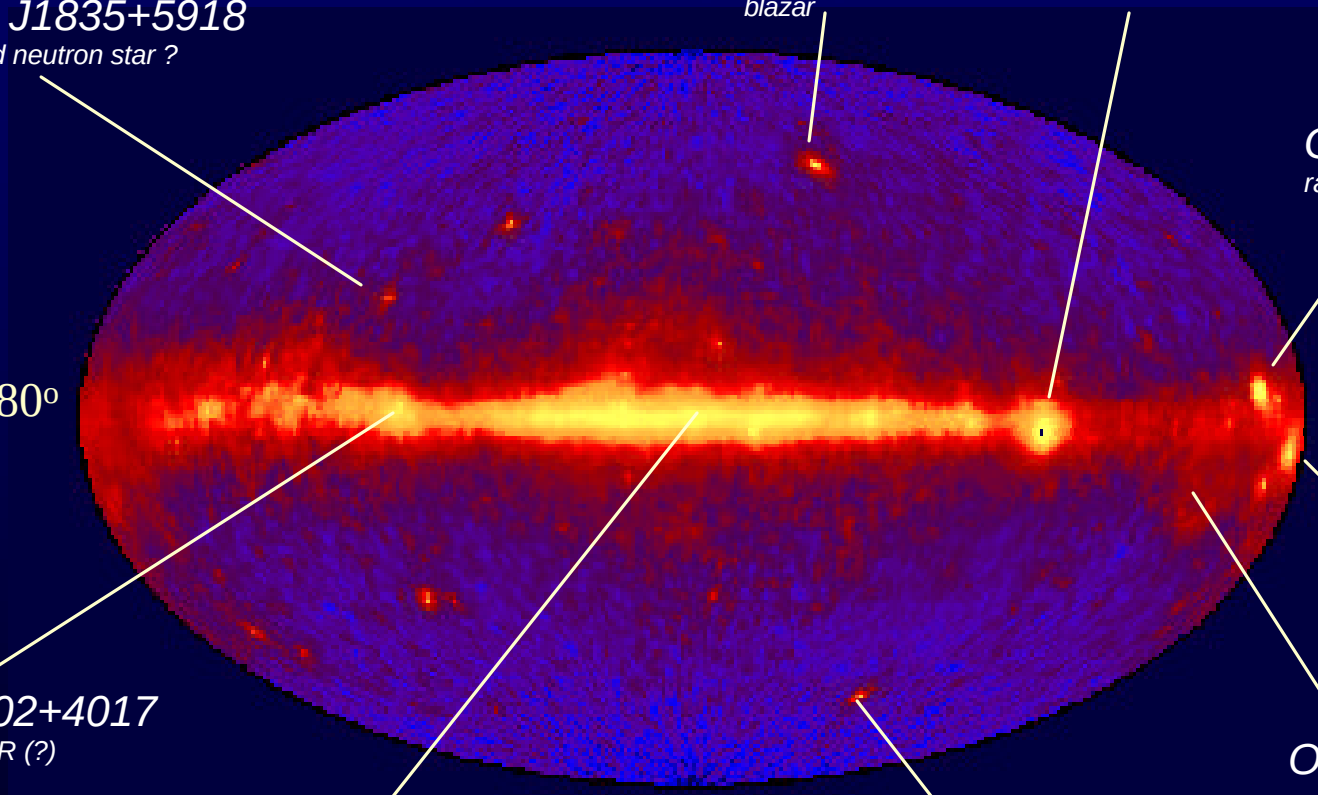
Gamma Rays/ Cosmic Rays ?

- Very high energy γ–rays are tracers of cosmic ray acceleration and propagation
- VHE γ–rays are produced by interactions of cosmic rays with nucleons, radiation fields, magnetic fields
- Unlike charged cosmic rays, γ–rays are not deflected in magnetic fields and point back to their source…
- … but they interact with radiation fields…
  - Infrared background radiation and cosmic microwave background
  - Dense photon fields at the source

- Sources of high energy γ–rays have been detected
  - … – MeV: satellite missions (EGRET, GLAST)
  - GeV – TeV: air Cherenkov telescopes

The EGRET Legacy

- Map of the MeV Sky



3EG J1835+5918
Isolated neutron star ?

3C279
blazar

Vela radio pulsar

Geminga
radio-quiet pulsar

+180°

-180°

Crab
radio pulsar

3EG J202+4017
γ Cygni SNR (?)

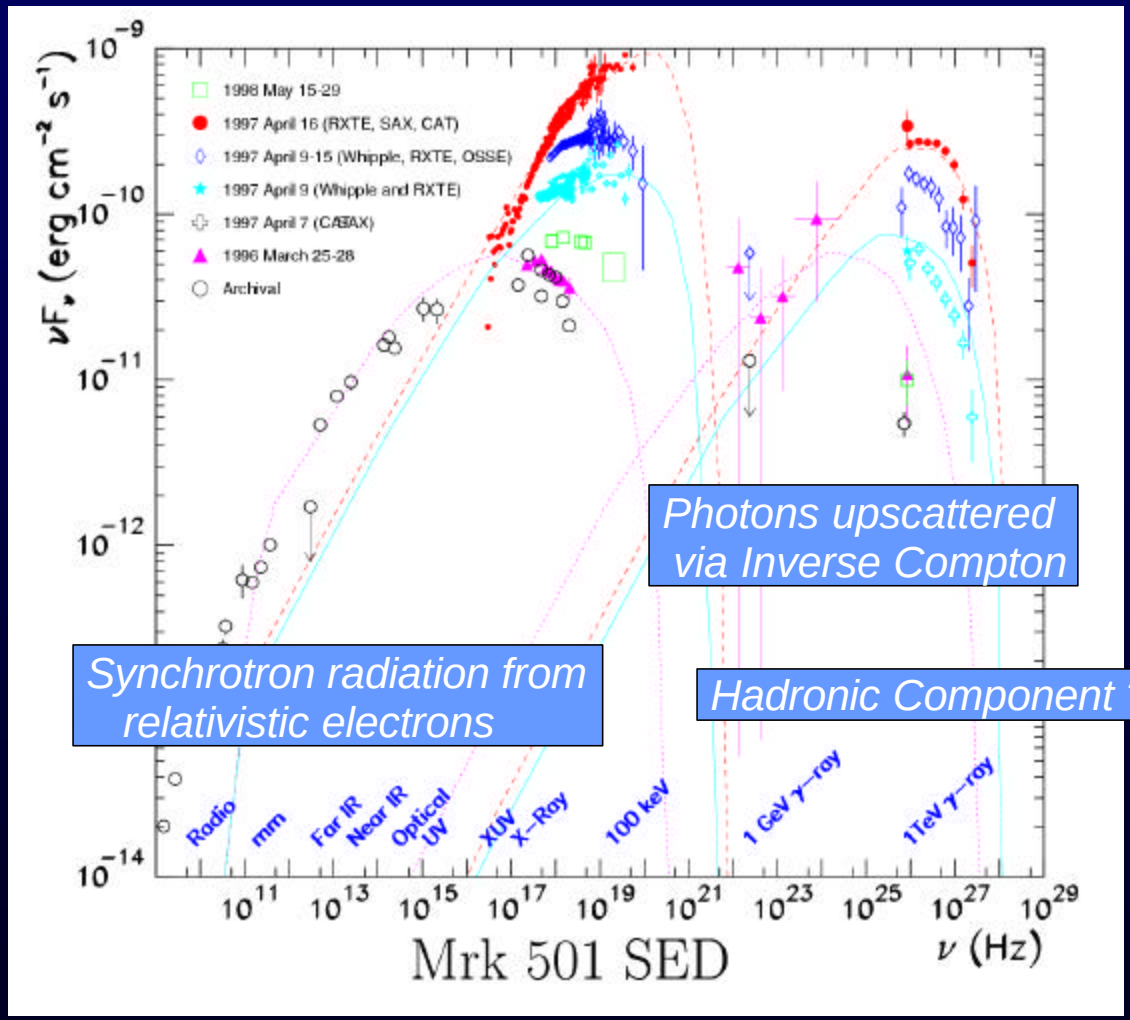
Orion Cosmic ray interactions with ISM

PKS 0208-512
blazar

3EG J1746-2851
Galactic center ?

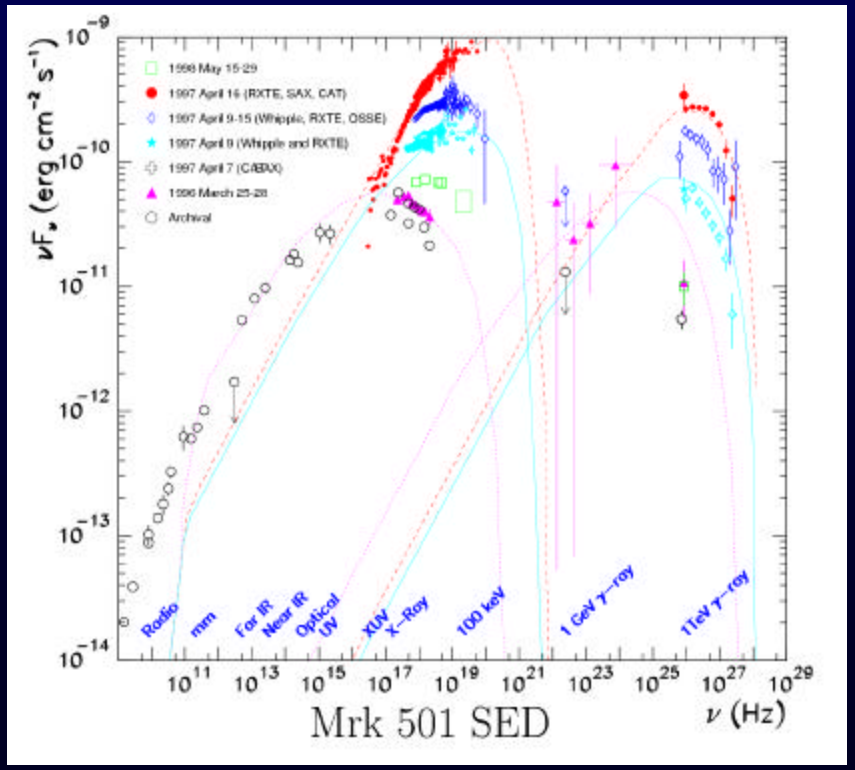
Example of a High Energy Source: Blazar Mrk 501

- Emission is observed over all wavelengths, from radio to TeV
- In νF_ν plot, equal areas under the graph correspond to equal energies
- Energy output is highest at highest energies
- Highly variable flux with flares on time scales minutes to years



Experimental Challenge

…steeply falling flux dictates detector types



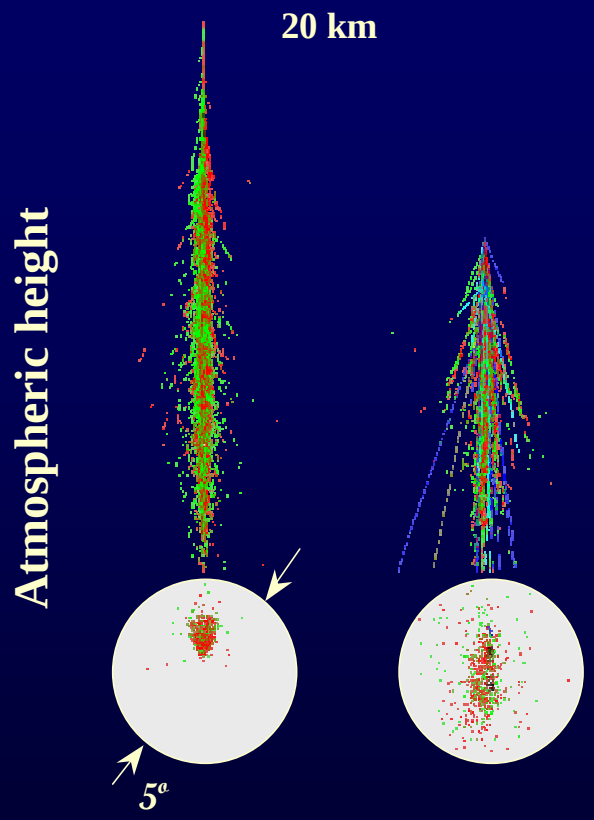
Cherenkov Telescopes

- Detect Cherenkov light from relativistic particles in the air shower
- *Pioneer:* Whipple 10 m Cherenkov telescope in Arizona
- Large camera (array of photomultiplier tubes) in the focal plane of a large optical reflector
- Cherenkov telescopes are pointed instruments – need "some idea" of where to look…

Whipple Collab.

First *galactic* source: Crab SNR (1989)
First *extragalactic* source: Mrk 421 (1992)

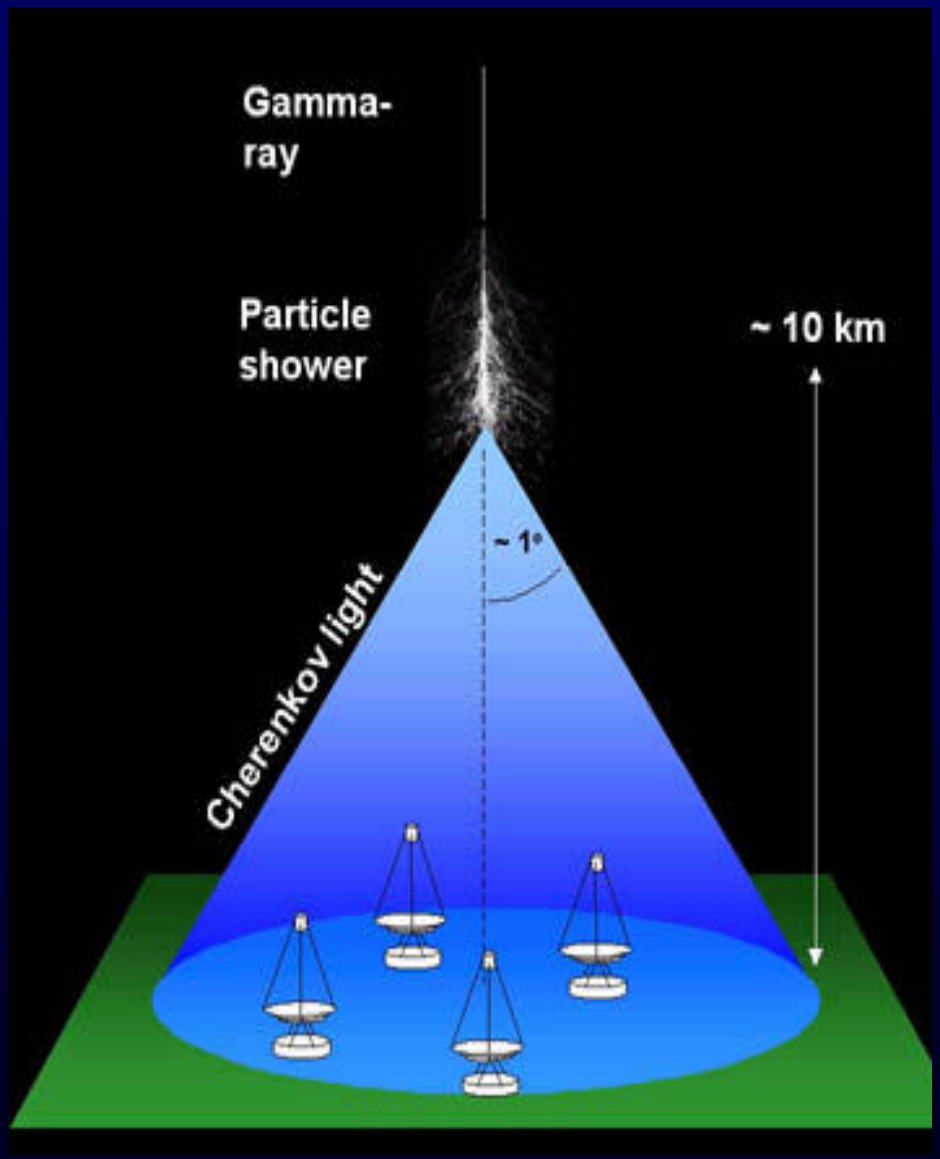
"Imaging" Technique



T. Weekes, Whipple/Veritas

- Main problem is large cosmic ray background
- "Imaging technique" (Hillas, Weekes) helps to discriminate against hadronic background
  - Images of γ–showers are compact
  - Images of hadronic showers are irregular
- High sensitivity, excellent angular resolution …
- … but low duty cycle and small field of view

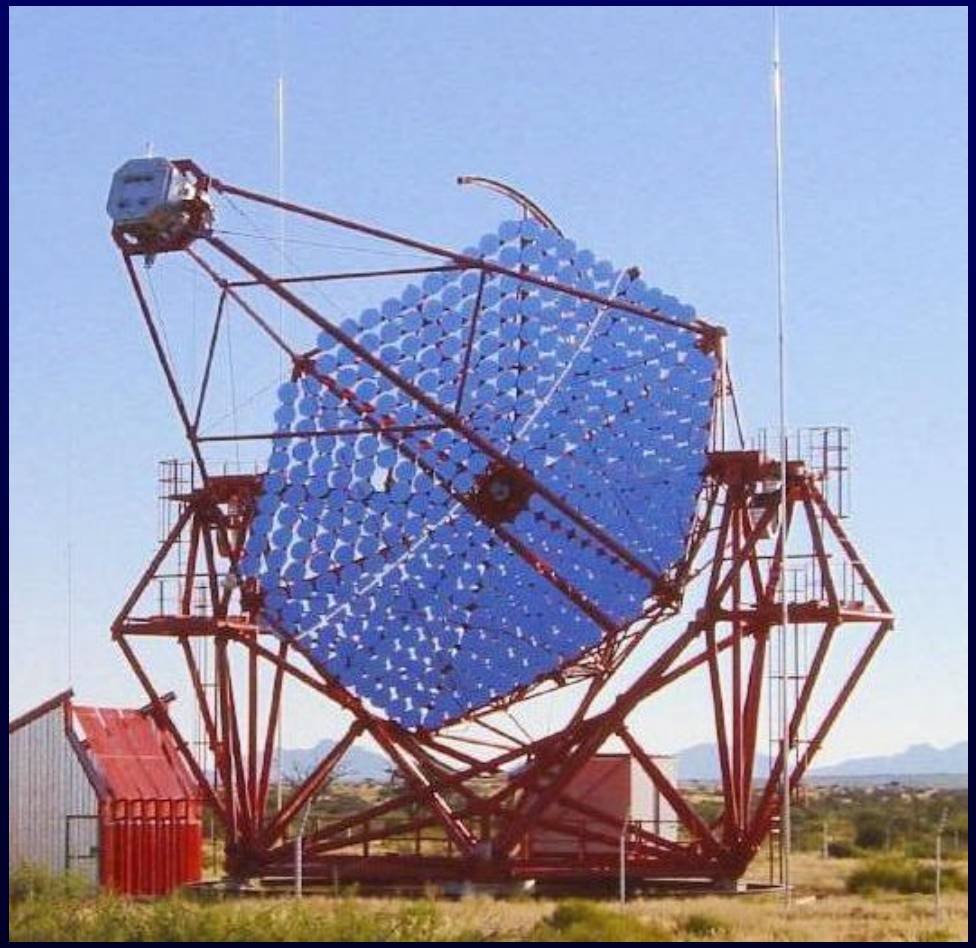
Stereoscopic Imaging



- Large light collection area
- Multiple views of the same shower for improved geometrical resolution and energy resolution
- Improved background rejection

H.E.S.S. Collaboration

High Energy Stereoscopic System H.E.S.S.



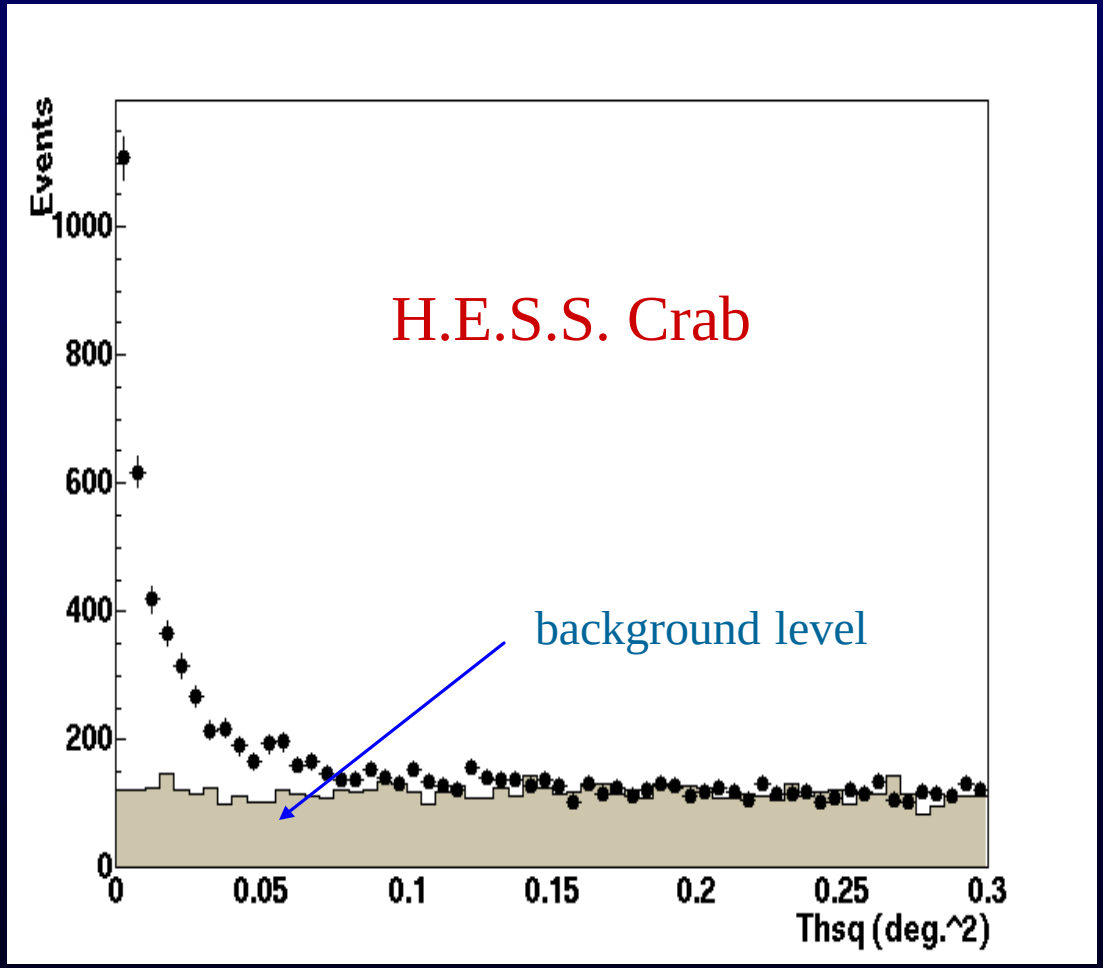
H.E.S.S. Collaboration

- Southern hemisphere (Namibia) 23º16’ S
- 4 telescopes, 120 m spacing
- Reflectors:
  - 13 m diameter
  - 107 m^2 reflectors
- Camera:
  - 960 PMTs
  - each 0.16º, for a total of 5º

- 100 GeV – 10 TeV
- 15–20 % energy resolution
- 0.05º– 0.1º ang. resolution

Standard Candle: Crab SNR

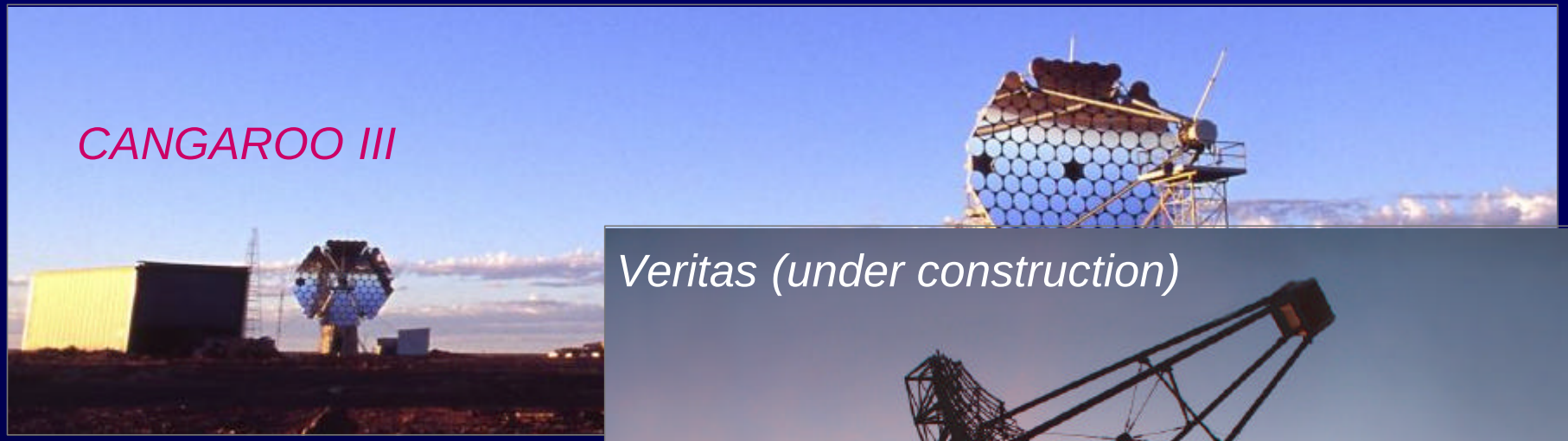
- Crab SNR is the *standard candle* of TeV γ-astronomy (no time variation in high energy flux)
- Flux sensitivity:
  1 Crab in …
  - 50 h (Whipple 1989)
  - 15 min (HEGRA 1997)
  - 30 s (H.E.S.S. 2004)



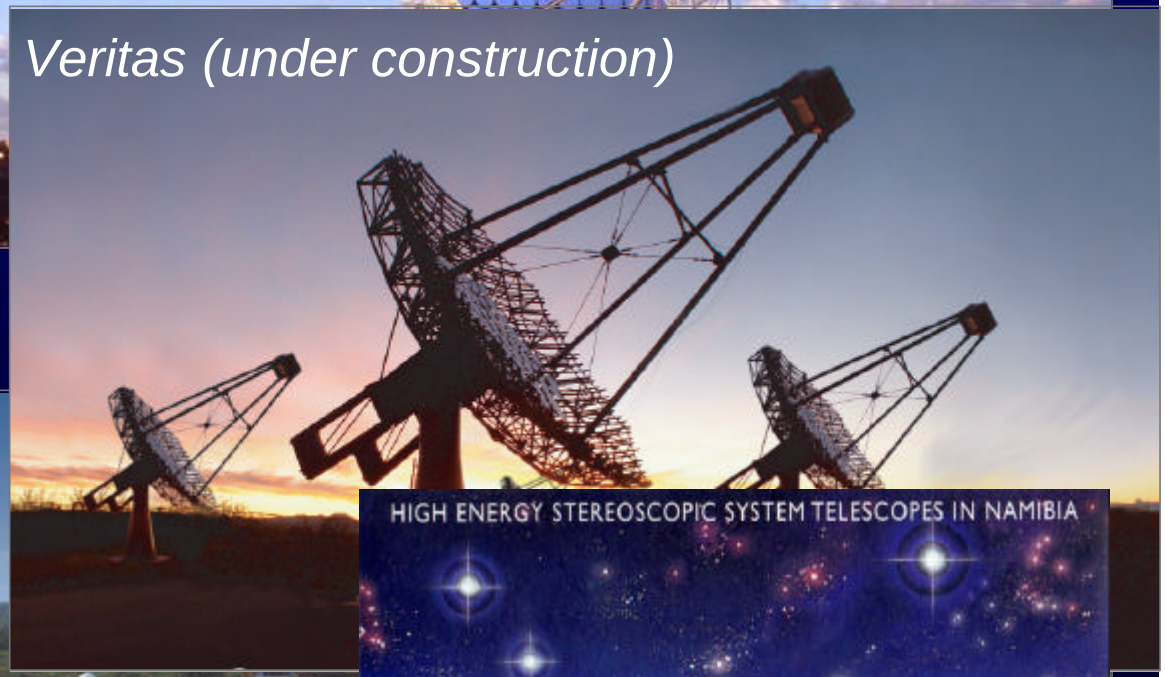
H.E.S.S. Collaboration

Stereoscopic Detectors

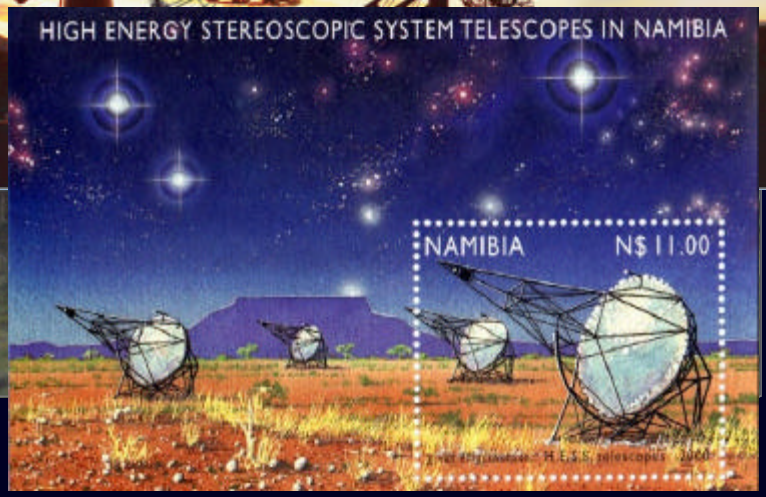
CANGAROO III



Veritas (under construction)

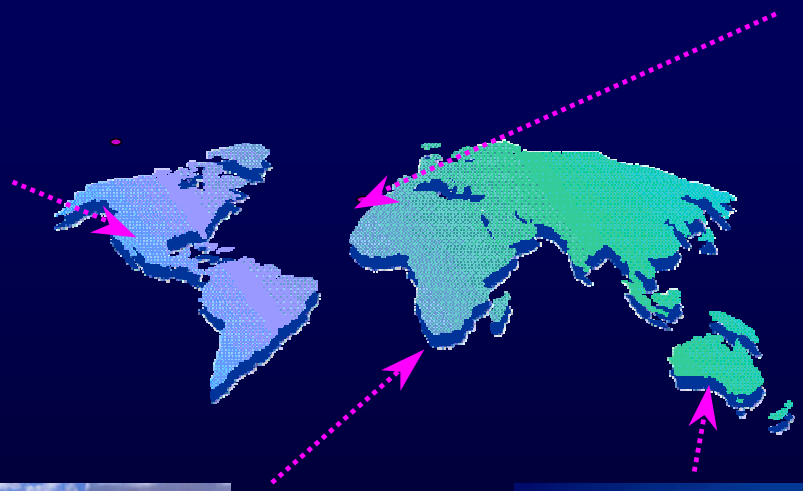


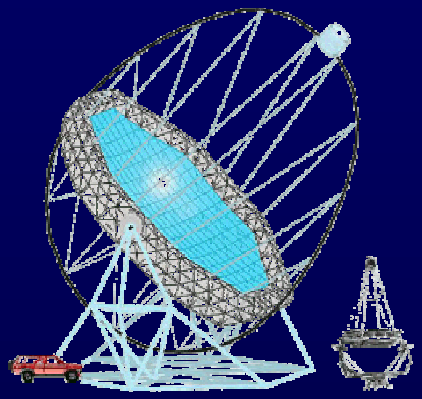
H.E.S.S.



Cherenkov Telescopes

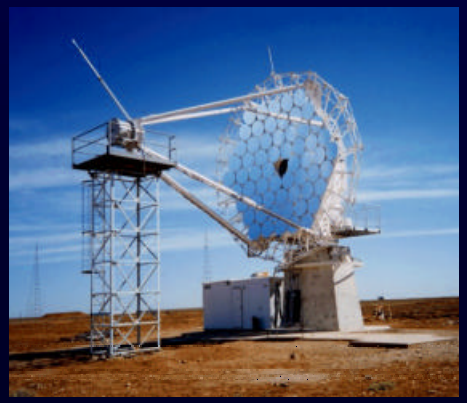
VERITAS,
2004 1 tel.
2006 4 tel.





MAGIC, 1 tel., 2004
2 tel., 2006

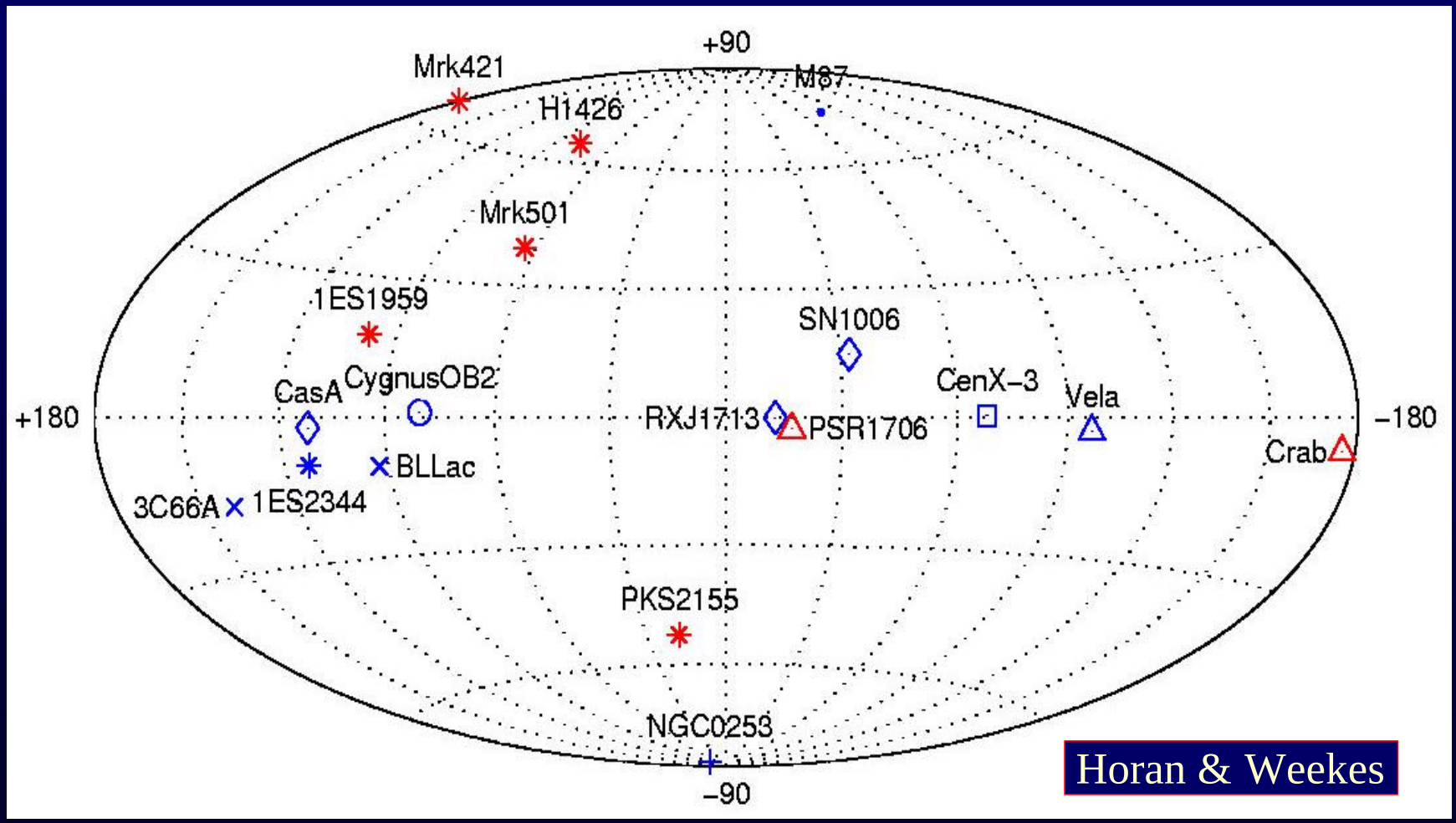
HESS, 4 tel., 2004



CANGAROO III, 4 tel., 2004

T. Weekes

The TeV Skymap



- 10 extragalactic sources, 8 galactic sources

New in 2004

- H.E.S.S. detection of PSR 1259-63 (IAU March 2004)
  - Millisecond pulsar, one of the few known pulsars forming a binary system, mass of central star 10 M_{solar}
  - 4.6 hours, 26 Feb – 5 Mar 2004, 4 telescopes
  - Flux ~ 0.1 Crab
- Galactic Center region (CANGAROO, Whipple, H.E.S.S.)
- Supernova Remnant RX J1713 (CANGAROO, H.E.S.S.)

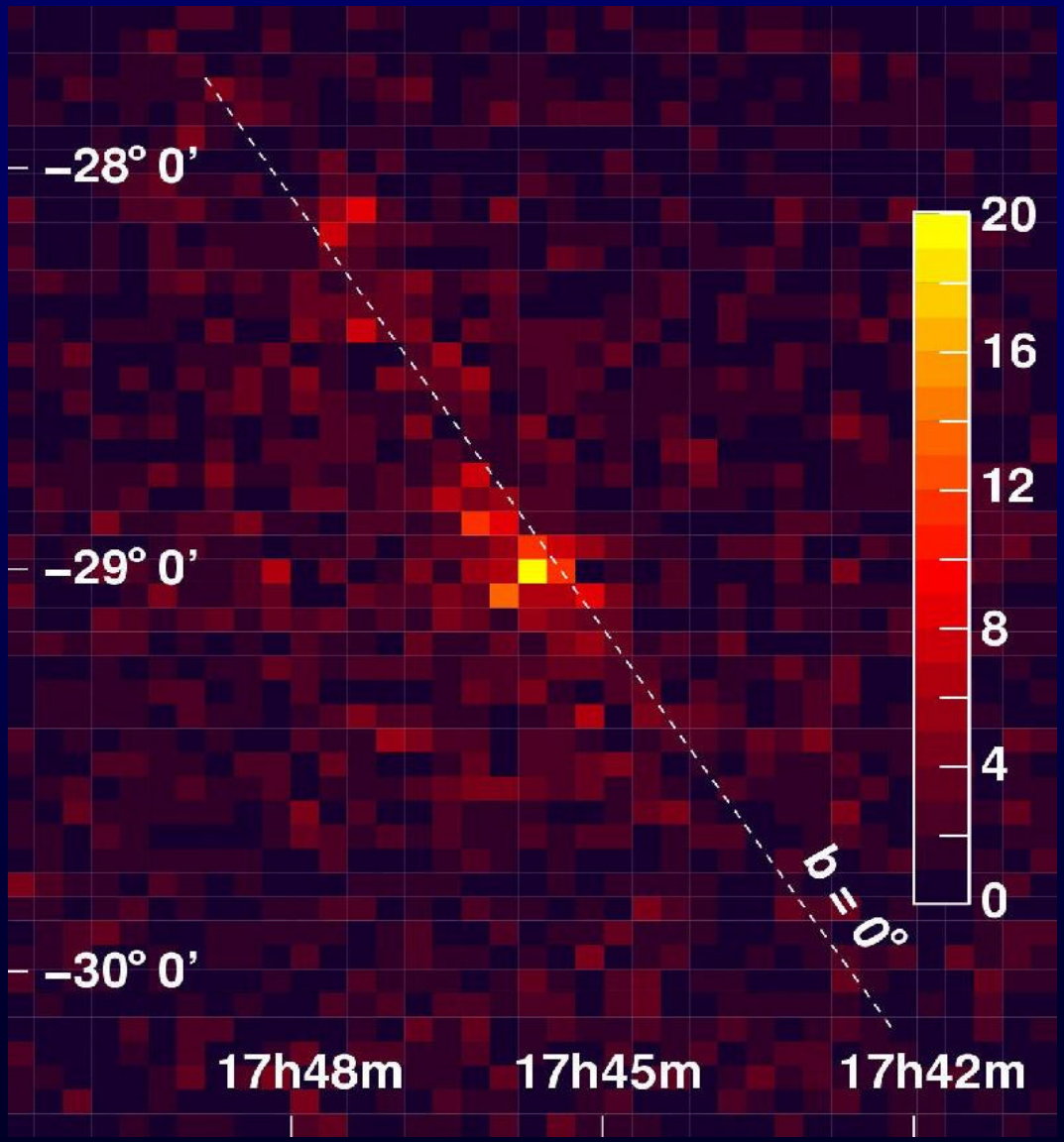
- H.E.S.S. has *not* confirmed some southern sources claimed by CANGAROO (SNR 1006, …)

Galactic Center

- Crowded region of the sky…
- Hour-scale X-ray and rapid IR flaring indicate active nucleus with low bolometric luminosity (compared to more powerful AGN)
- Contains supermassive black hole $2.6 \times 10^6\ M_{solar}$ coincident with radio source Sagittarius A*
- Center also harbors:
  - dense clusters of stars
  - stellar remnants
  - SNR (?) Sgr A East

- Source of TeV γ–rays first claimed by CANGAROO
- Confirmed by Whipple and H.E.S.S.

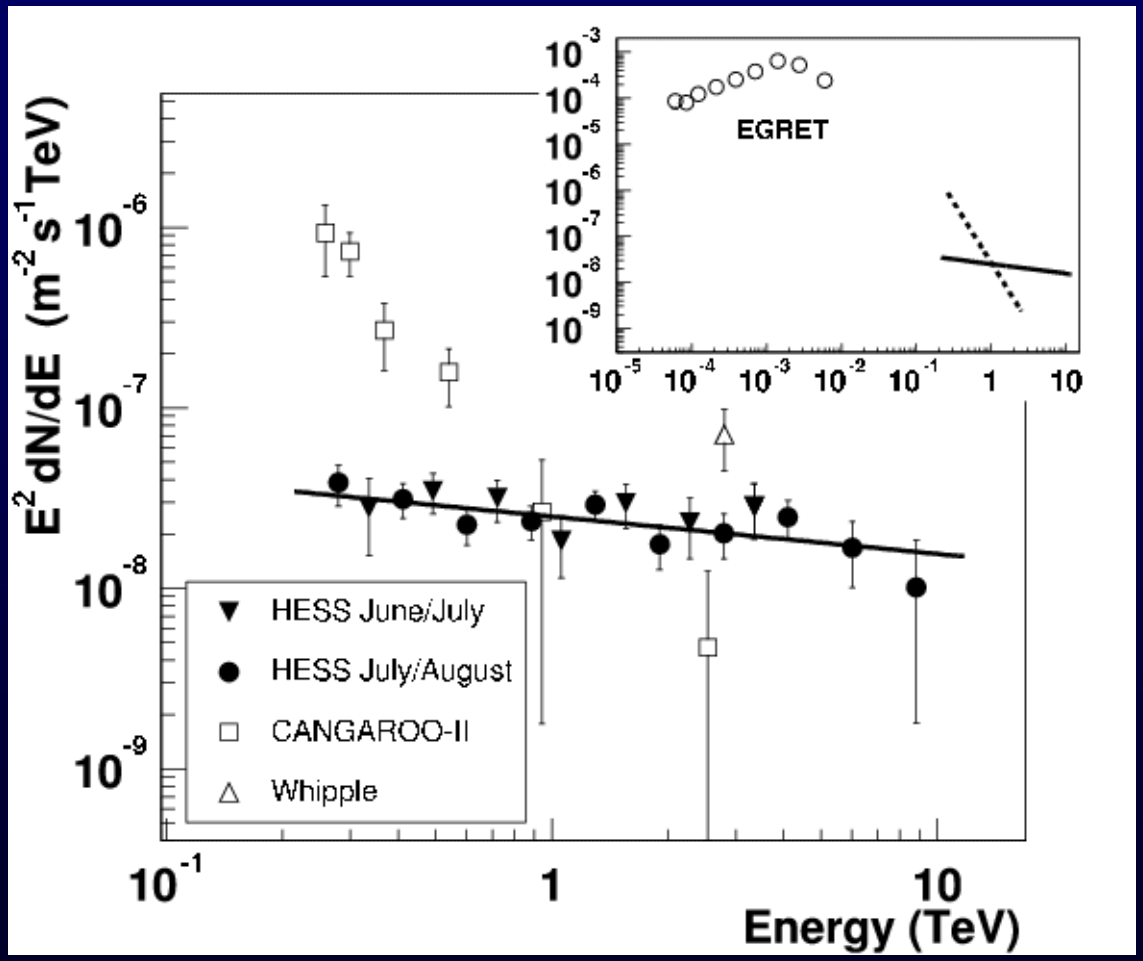
H.E.S.S.



- 2003 data with 2 telescopes (2 data sets)
- Energy threshold 165/255 GeV
- 16 hours, 11σ significance
- 3° field of view centered on Sgr A* for both data sets
- Signal is coincident within 1’ of Sgr A*
- Width and shape are consistent with a point source

H.E.S.S., astro-ph/0408145

Energy Spectrum



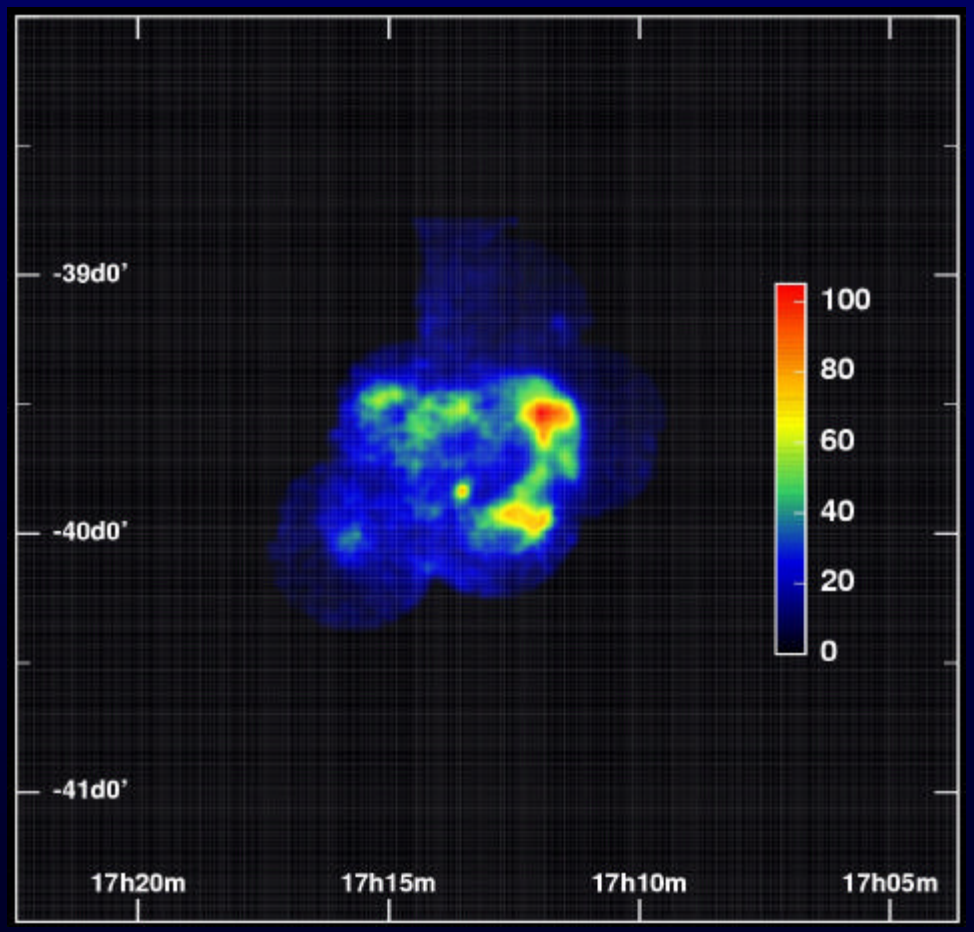
H.E.S.S., astro-ph/0408145

- H.E.S.S. June/July and July/August 2003 data set
- CANGAROO-II spectrum summer 2001/2
- Whipple flux 1995-2003

astro-ph/0403422

- Variability ? Several sources ?

SNR RX 1713.7

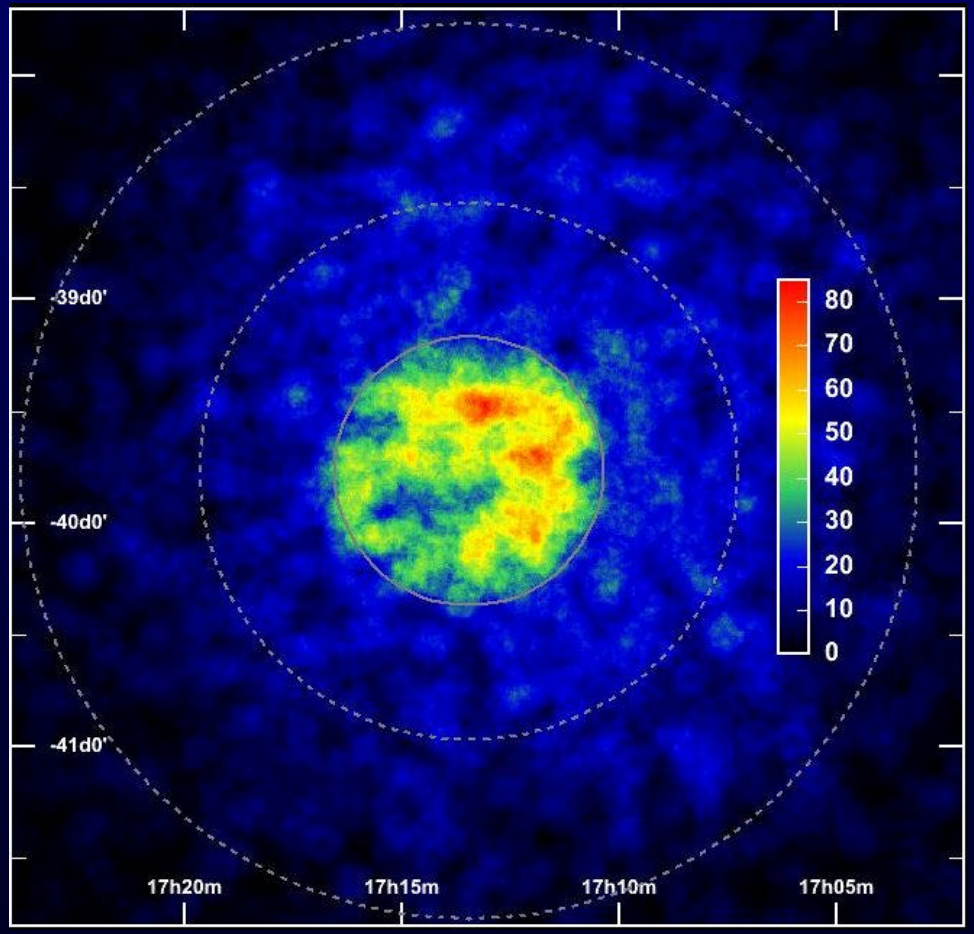


ASCA 1-3 keV (Yasunobu Uchiyama)

- Shell-type SNR from ROSAT all-sky survey
- CANGAROO: extended source, but spectrum inconsistent with inverse Compton spectrum

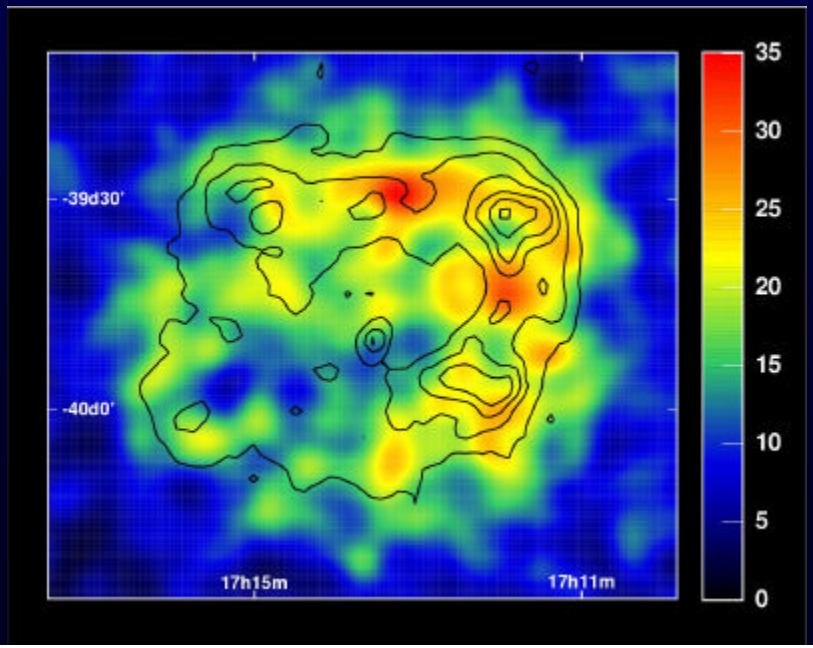
  Nature 416 (2002) 823
- Consistent with π^0 decay: accelerated protons colliding with ambient material ? Site of cosmic ray acceleration ?

TeV g-Ray Image of SNR RX 1713.7



H.E.S.S. Collaboration

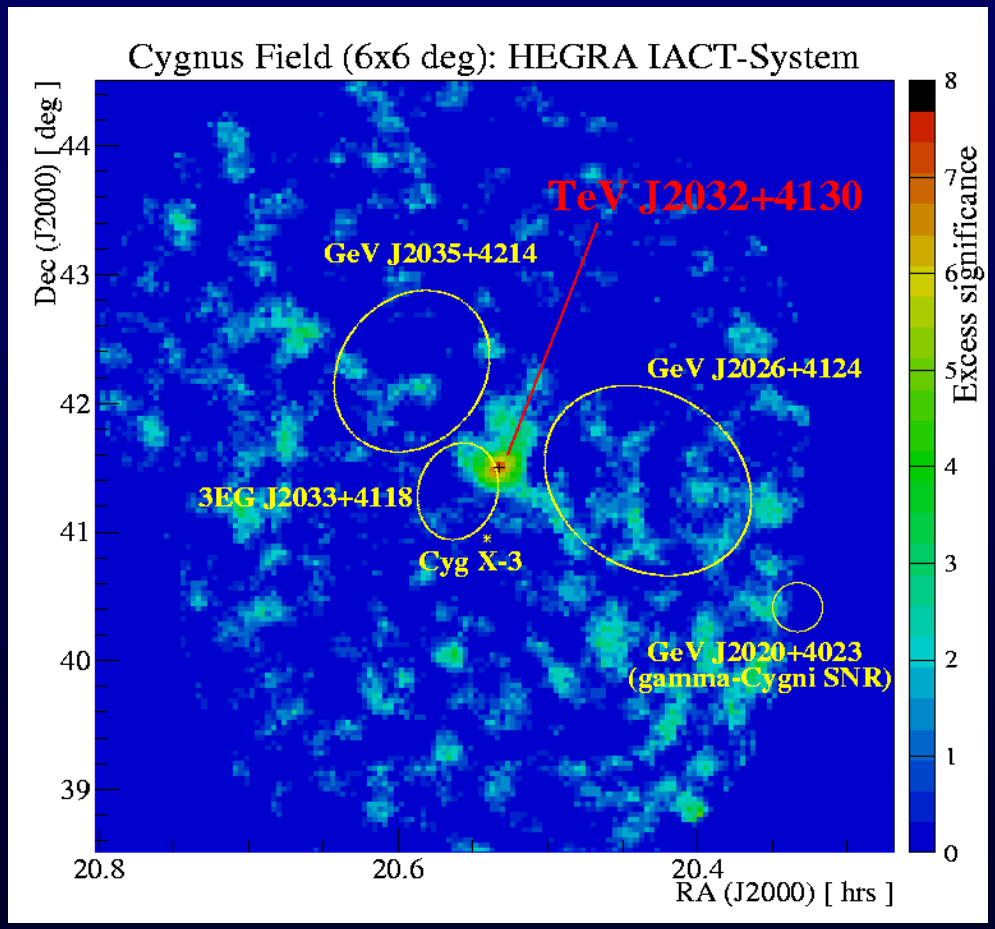
- H.E.S.S. (2 telescopes)
- 20 hours in 2003, 20 σ
- Flux ~ 0.7 Crab
- Uncorrected map



Is there a New Source Class ?

- Unlike space telescopes, Cherenkov telescopes are pointed instruments and at this point not suitable for sky surveys
- Cherenkov telescopes have large field of view (typically of order 5° diameter), so while pointed at a source candidate, *serendipitous detections* in the vicinity are possible
- TeV J2032+4130
  - Reported by Crimean Astrophysical Observatory and HEGRA (Astron. Astrophys. 393 (2002) L37)
  - Recently confirmed in Whipple archival data (astro-ph/0405513)
  - Offset by about 0.7^o from position of Cygnus X3 in the crowded Cygnus region of the Galactic plane

TeV J2032+4130



Astron. Astrophys. 393 (2002) L37

- HEGRA
  - 279 hours with 7 σ
  - Extended source ?
- Whipple archival data
  - 3.3 σ

  astro-ph/0405513
- Candidate associations:
  - Cygnus OB2
  - Unidentified EGRET source
  - Jet from Cygnus X3

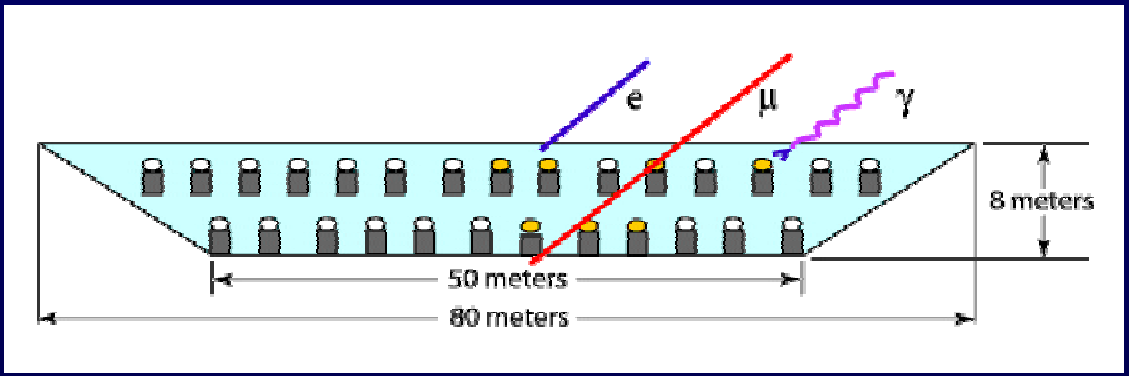
Monitoring the TeV Sky

Fenton Hill near Los Alamos, NM
2630 m a.s.l., operating since 2000

- Milagro Water Cherenkov Detector
  - 723 PMTs in 2 layers in a 60x80x8 m^3 water tank with light-tight cover
  - 175 outriggers
  - 2 sr field-of-view
  - Water as medium allows detection all shower particles
- Other TeV Monitors: Tibet ASγ Experiment and ARGO YBJ

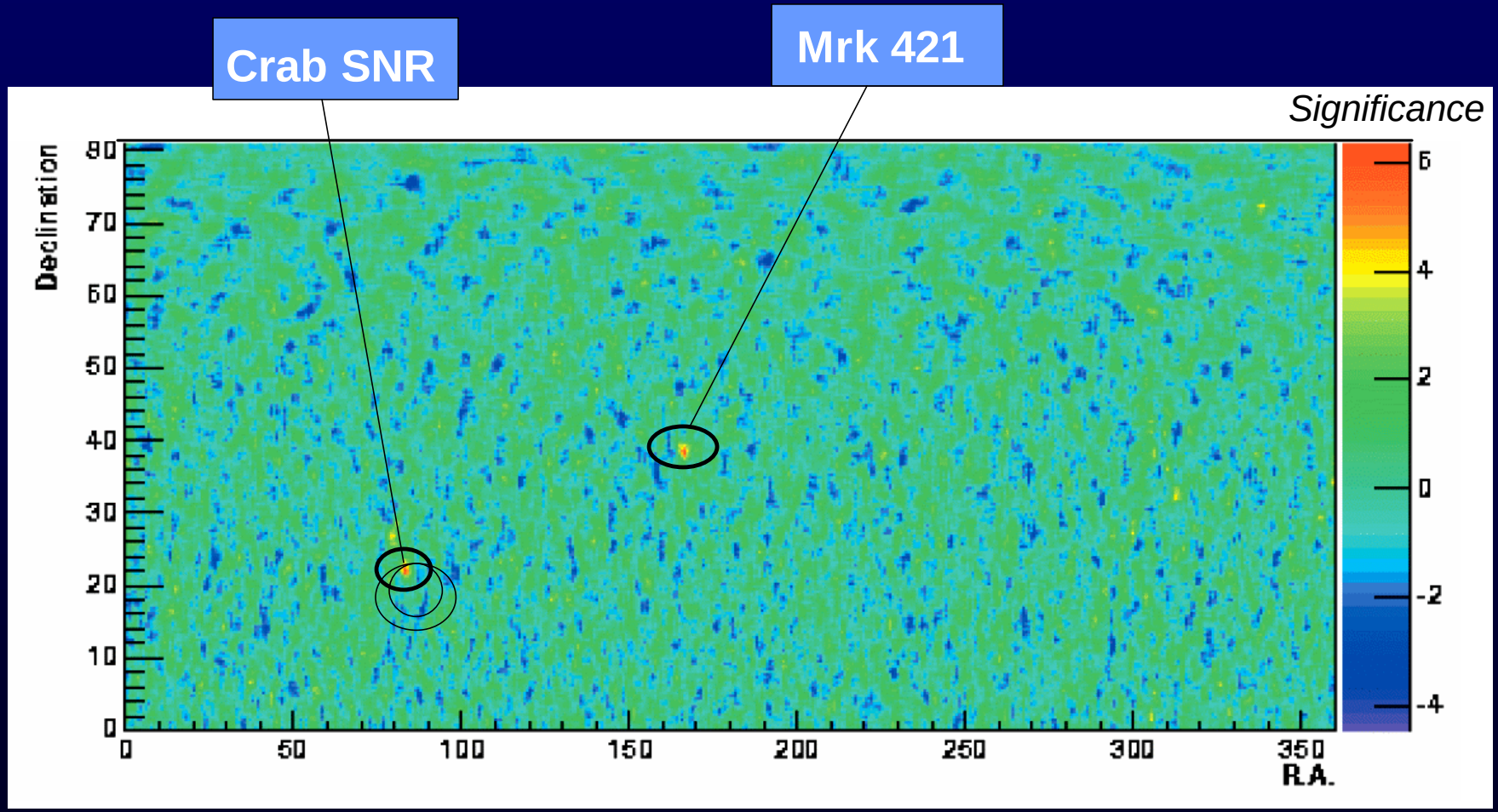
www.lanl.gov/milagro

Milagro Gamma-Ray Observatory



- Air shower layer for arrival direction reconstruction
  - 450 tubes on a 2.8 m x 2.8 m grid under 1.4 m of water
- Hadron layer for (modest) background rejection
  - 273 tubes under 6 m of water
- 2 sr field of view and ~ 100% duty cycle…
- … but poor angular resolution (optimal bin size for point source searches 2.1^{o})
- Flare and Gamma Ray Burst Monitor

Milagro TeV All-Sky Map

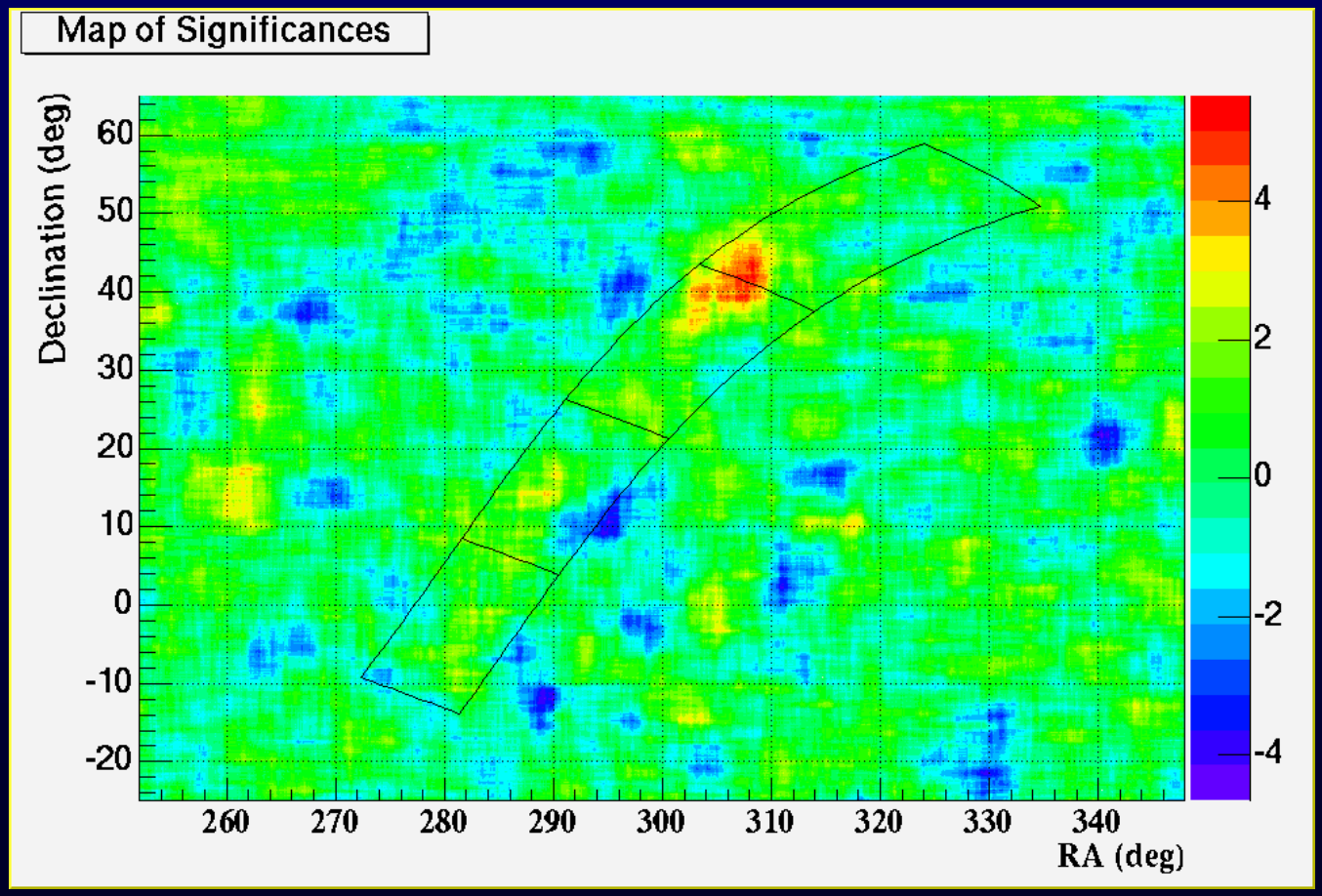


astro-ph/0403097

Milagro Sensitivity

- Milagro has a limited sensitivity to point sources because of its poor angular resolution Milagro is more competitive in searches for extended or diffuse sources: 2d sky search for bin sizes from 2.1^{o} to 6.1^{o}
- 2 additional sources with high significance
  - Unidentified EGRET source 3EG J0520+2556 (5.9 σ with a flux of ~ 0.85 Crab)
  - Excess in the Cygnus region, spatially coincident with Cygnus arm (5.5 σ with a flux of ~ 2 Crab)

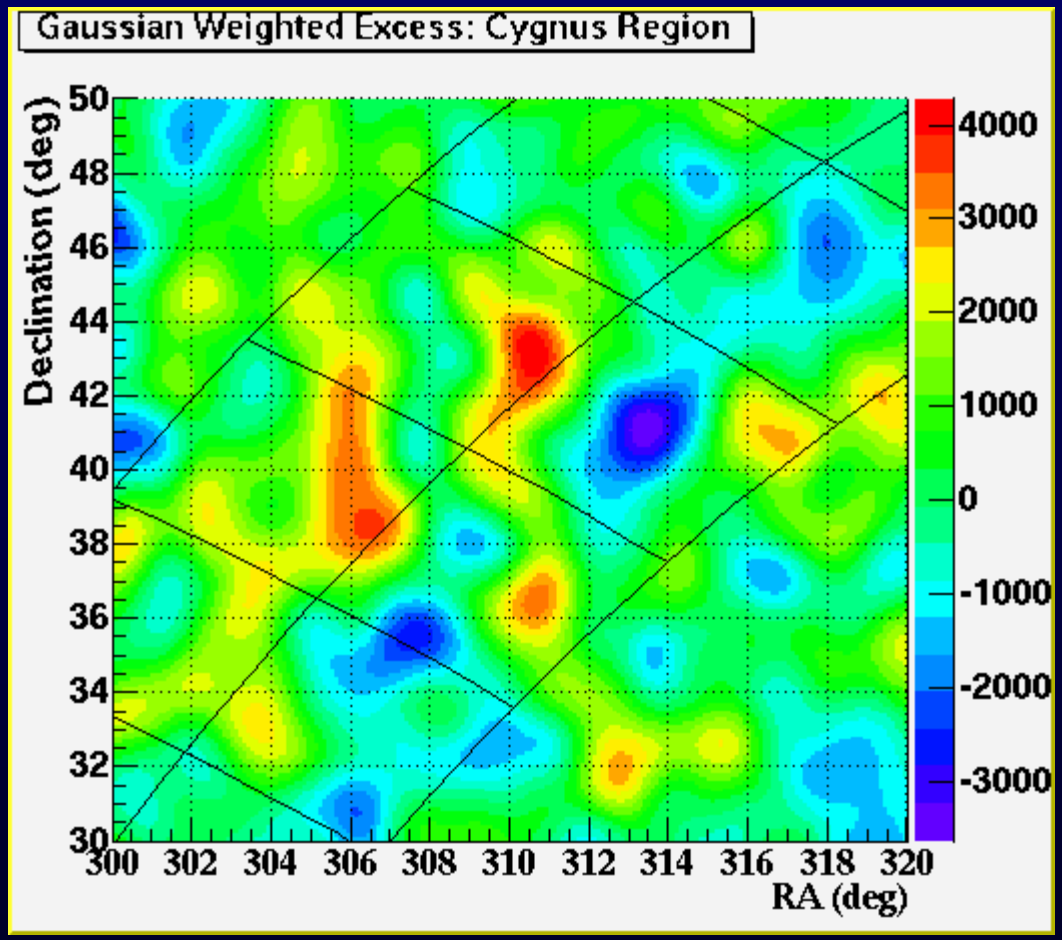
Unidentified Source in Cygnus



Milagro Collaboration

- Significances in the region of the Cygnus arm
- Unknown source in region of high matter density in our Galaxy
- 5.5 σ with flux ~ 2 Crab
- cosmic ray connection ?

Unidentified Source in Cygnus



Milagro Collaboration

- Excess map smoothed with Gaussian of σ=0.75^{o} according to Milagro's point spread function shows two separate regions giving rise to the observed excess
- Unknown source in region of high matter density in our Galaxy
- γ-ray/cosmic ray connection ?

Summary and Status

- TeV sky is now more diverse than (known) MeV-GeV sky
  - SNRs are firmly established as sources of Galactic γ–rays
  - nearby blazars
  - Radio galaxy M87
  - Starburst galaxy NGC 253
  - Galactic center region

Summary in
Horan & Weekes (2004)

- Clearly a new window in astronomy; many of the new sources are *not* in the 3rd EGRET catalog
- First indication for hadron acceleration in SNR RX 1713.7 ?
- Experimental techniques are mature and the new generation of detectors will effectively be limited by the cosmic electron background

Searching for Cosmic Accelerators

Ultrahigh Energy Cosmic Rays

High Energy g-Rays

Neutrinos

Neutrinos

- Some advantages over γ–rays and protons:
  - γ-rays: straight-line propagation, but absorbed in extragalactic backgrounds for E > TeV
  - Neutrinos:
    - straight-line propagation
    - not absorbed: can reveal sources “hidden” because of photon absorption
    - However…
- Major Challenge:
  - neutrinos do not easily interact with detectors either, so neutrino astronomy requires *km-scale detectors*

Neutrino Astronomy

- Potential
  - Detection of neutrinos is the “smoking gun” for hadron acceleration – neutrinos help to distinguish between electromagnetic and hadronic processes
  - Gamma-Ray Bursts: no time delay; time correlation with γ–ray emission
  - “cosmogenic” neutrino flux from cosmic ray interactions with the microwave background (0.1 to a few in IceCube)

$$p\ \gamma_{3K} \rightarrow\ p^{+}\ n$$

Neutrino Experiments

- Large detectors require cheap and readily available detector material
- Detect Cherenkov light from muons in water or ice
- Current and future efforts:
  - Water: Lake Baikal, ANTARES, NESTOR, NEMO
  - Ice: AMANDA-II, IceCube
  - ANITA (Antarctic Impulse Transient Antenna): balloon-borne detector to identify neutrinos from cosmic ray interaction with γ_{CMB}

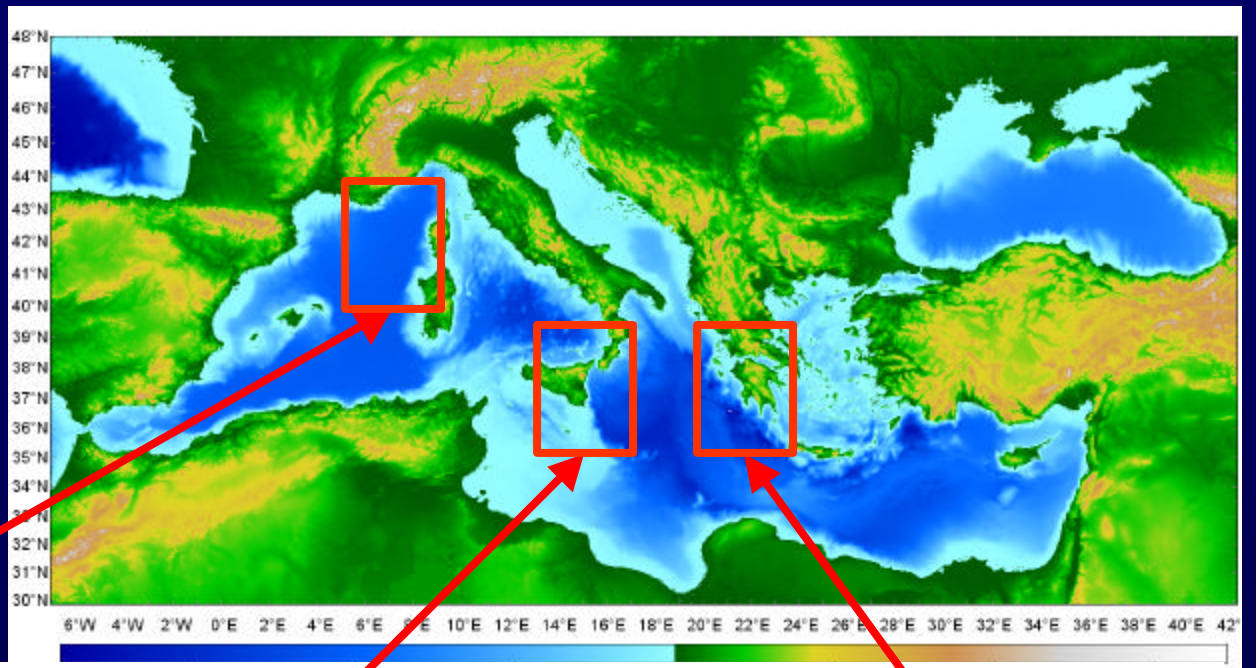
Parallel sessions: S. Barwick, ANITA

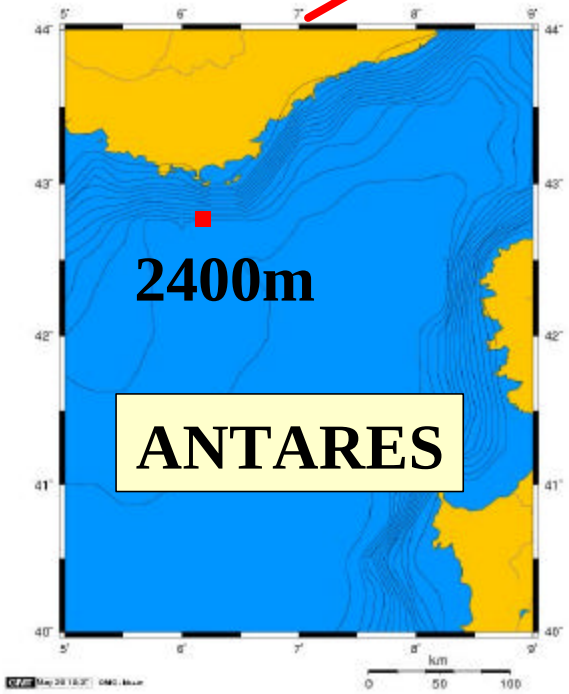
K. Kuehn, AMANDA

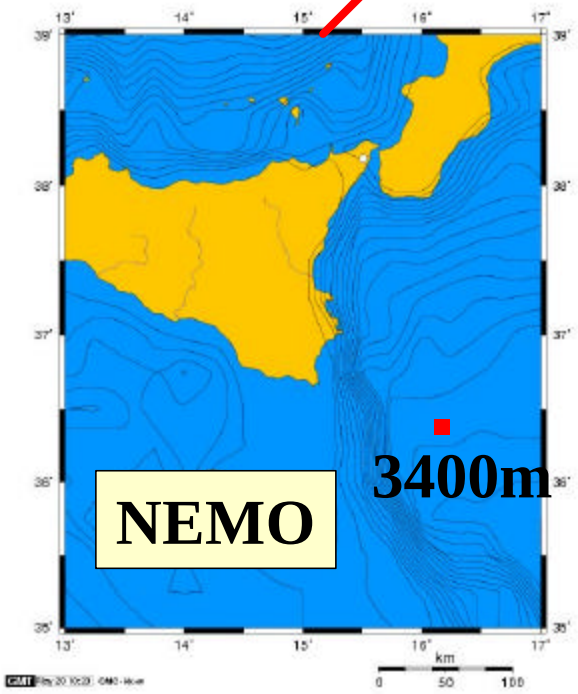
T. DeYoung, IceCube

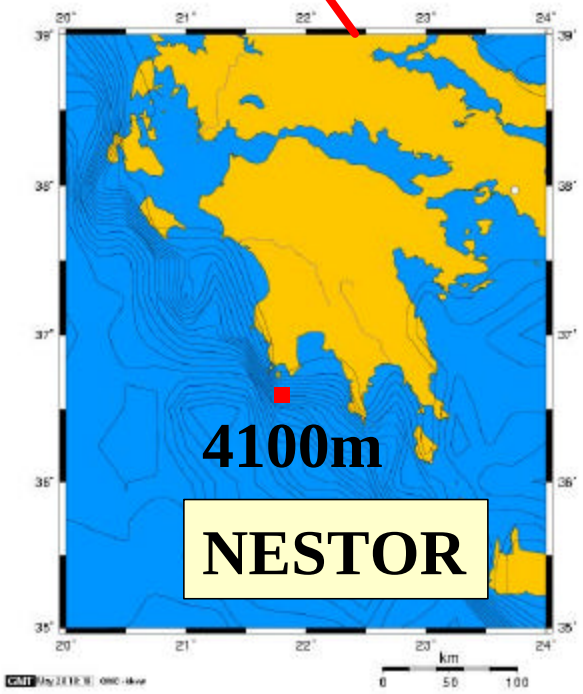
Il Trittico

- First modules installed
- Test of water quality



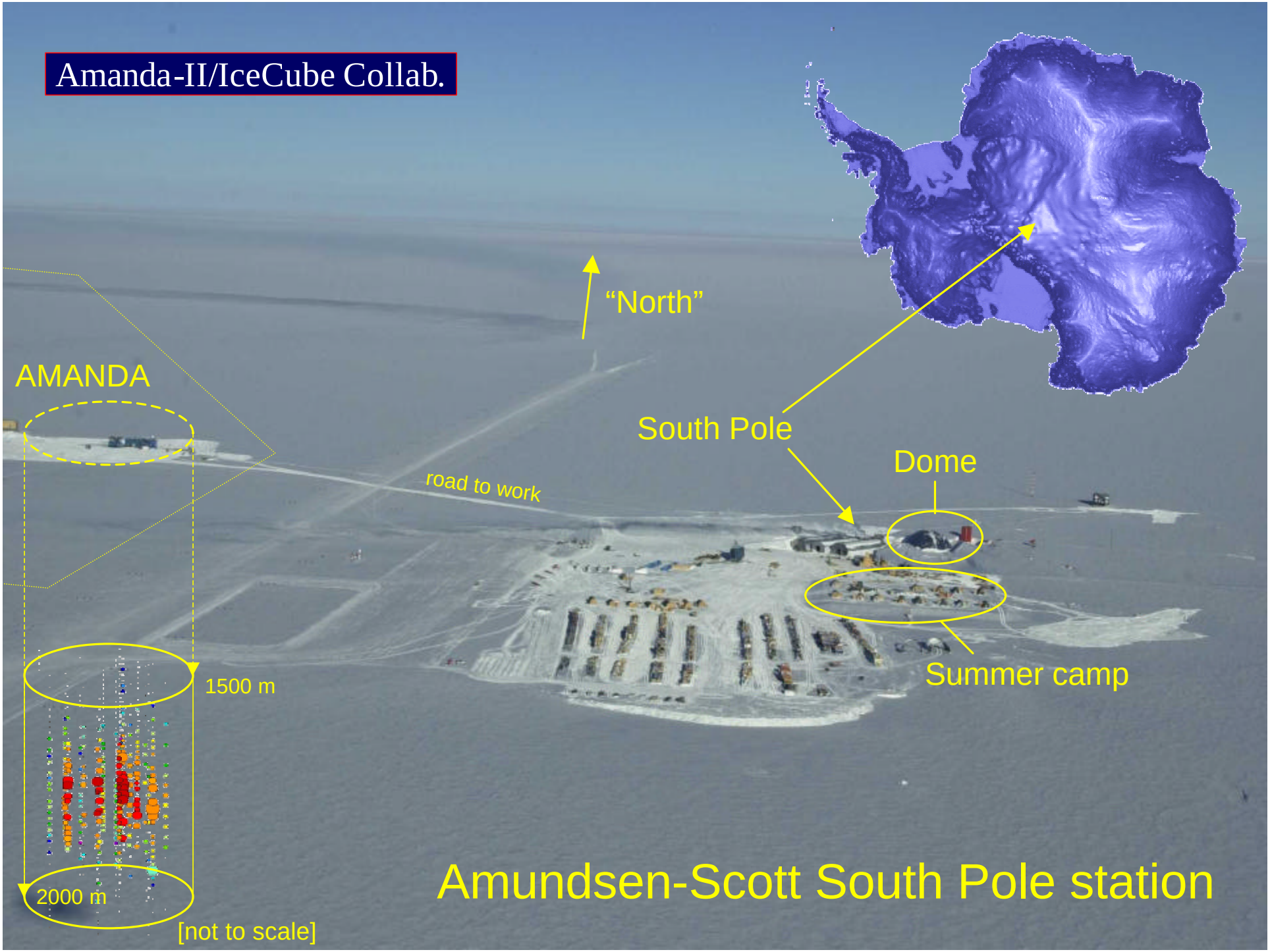




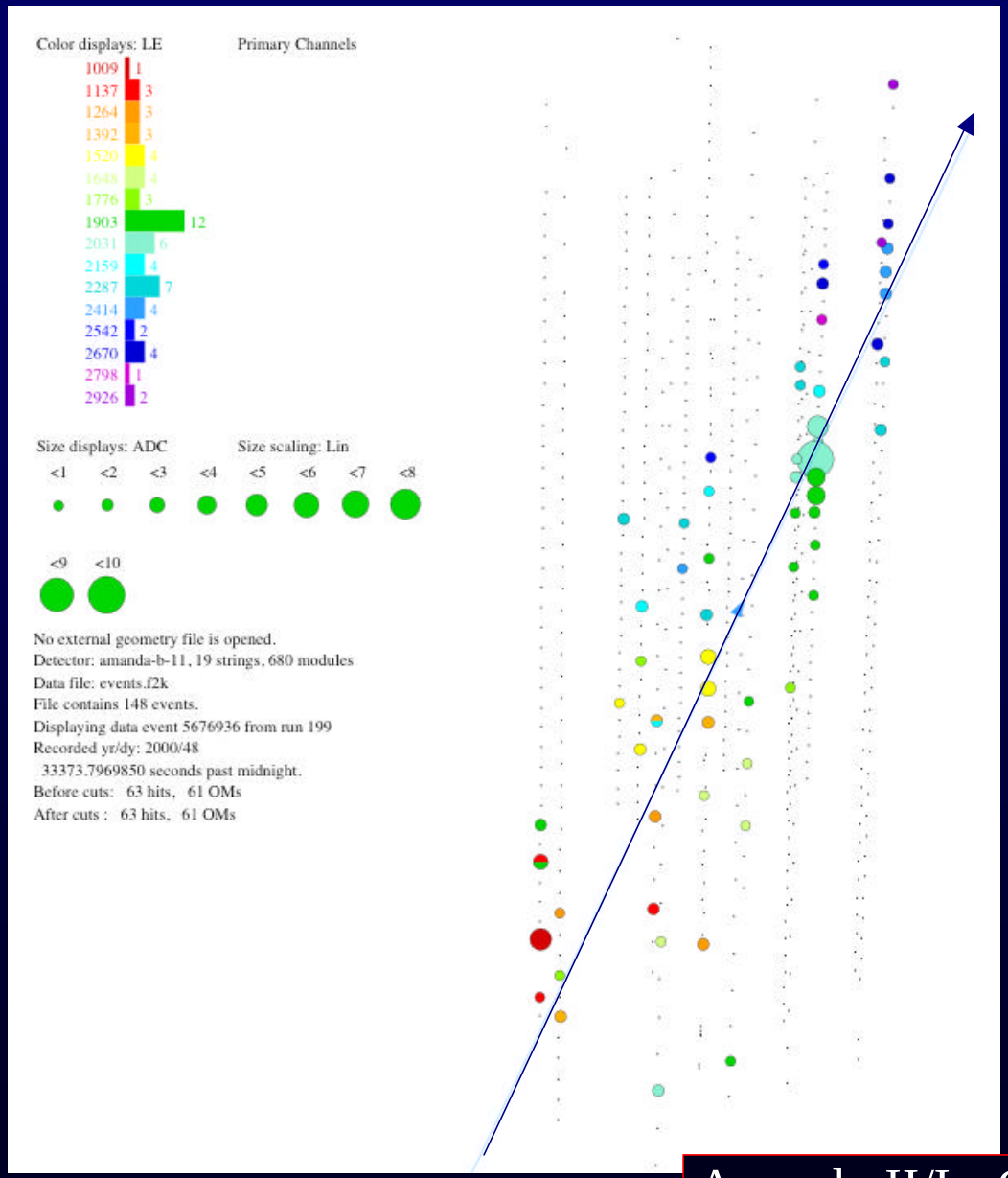


AMANDA-II

- Antarctic Muon and Neutrino Detector Array: Cherenkov detector frozen into Antarctic polar ice cap
- High energy ν_μ interacting with ice or bedrock near the detector produces high energy muons propagating tens of km
- Muon is detected via its Cherenkov light cone
- Advantage of ice
  - very transparent, absorption length 100 m at 400 nm, no bioluminescence or pollution
- Dominant background: atmospheric muons from cosmic rays
  - Use Earth as a filter against atmospheric muons
  - AMANDA monitors the *northern* sky


Amanda-II/IceCube Collab.
"North"
AMANDA
South Pole
Dome
road to work
Summer camp
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station

AMANDA-II

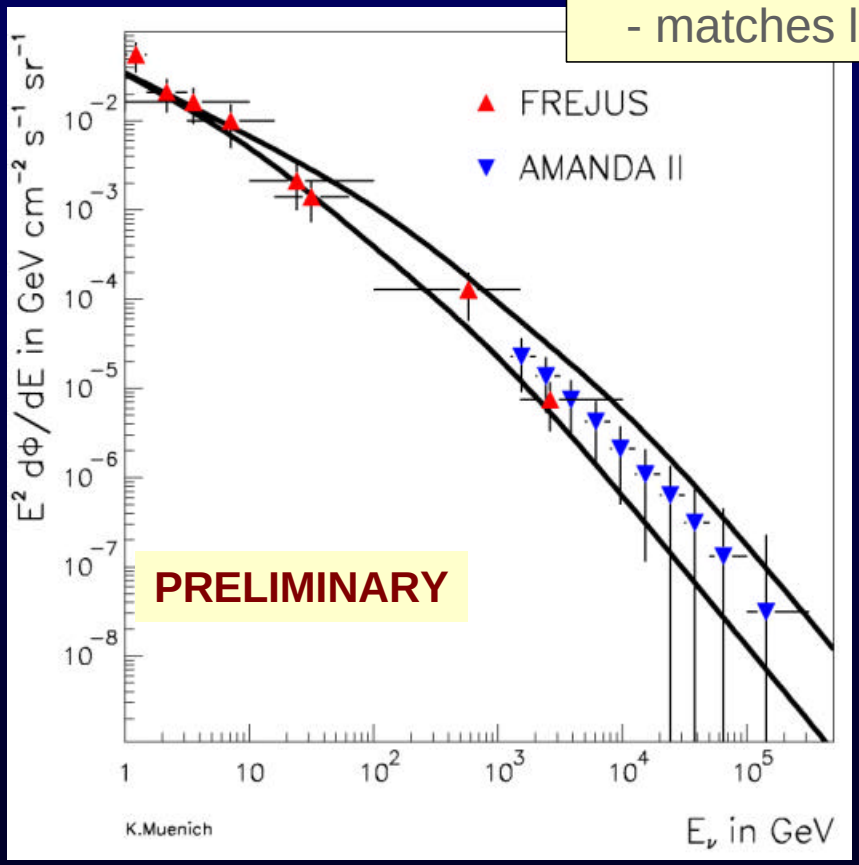


- Muon produces Cherenkov light which is detected by 19 strings of 677 PMTs (8 in.)
- Track direction reconstruction accuracy 2°… 2.5^{o} (median)
- Upward going muon, 61 modules hit

Amanda-II/IceCube Collab.

Atmospheric Neutrinos

First spectrum > 1 TeV (up to 300 TeV)
- matches lower-energy Frejus data



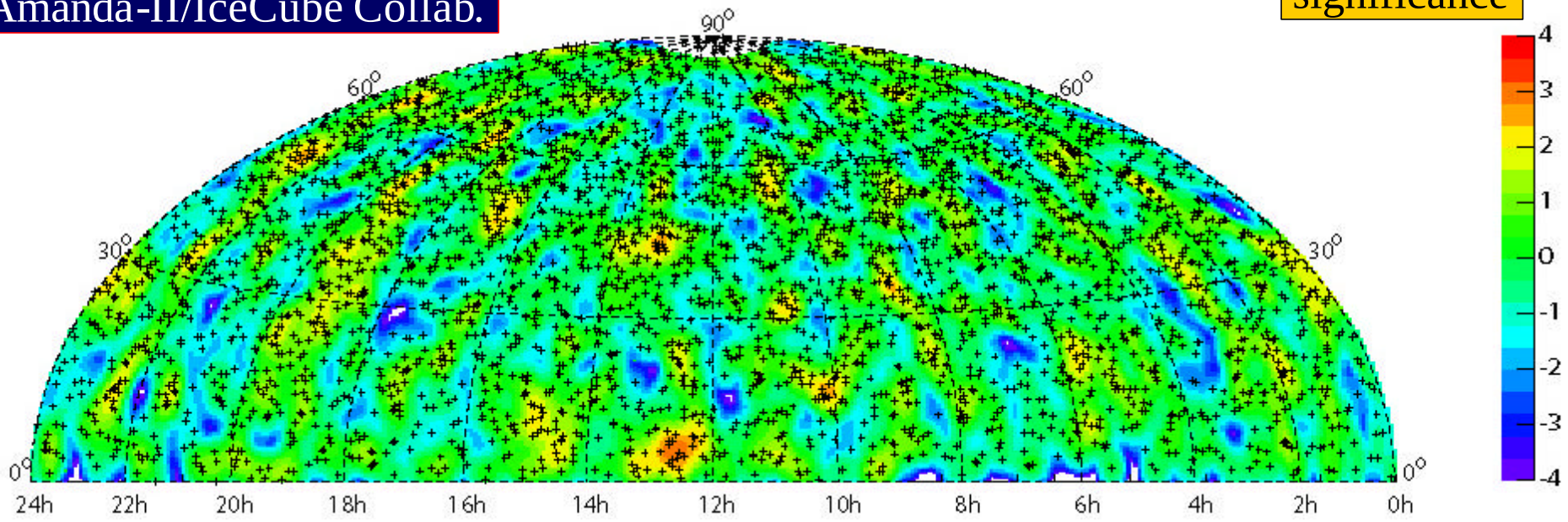
- Background: neutrinos from cosmic ray interactions in the atmosphere
- Can be used as a "test beam"
- spectral index $\alpha = -3.7$, softer than expected for sources ($\alpha = -2.0$)

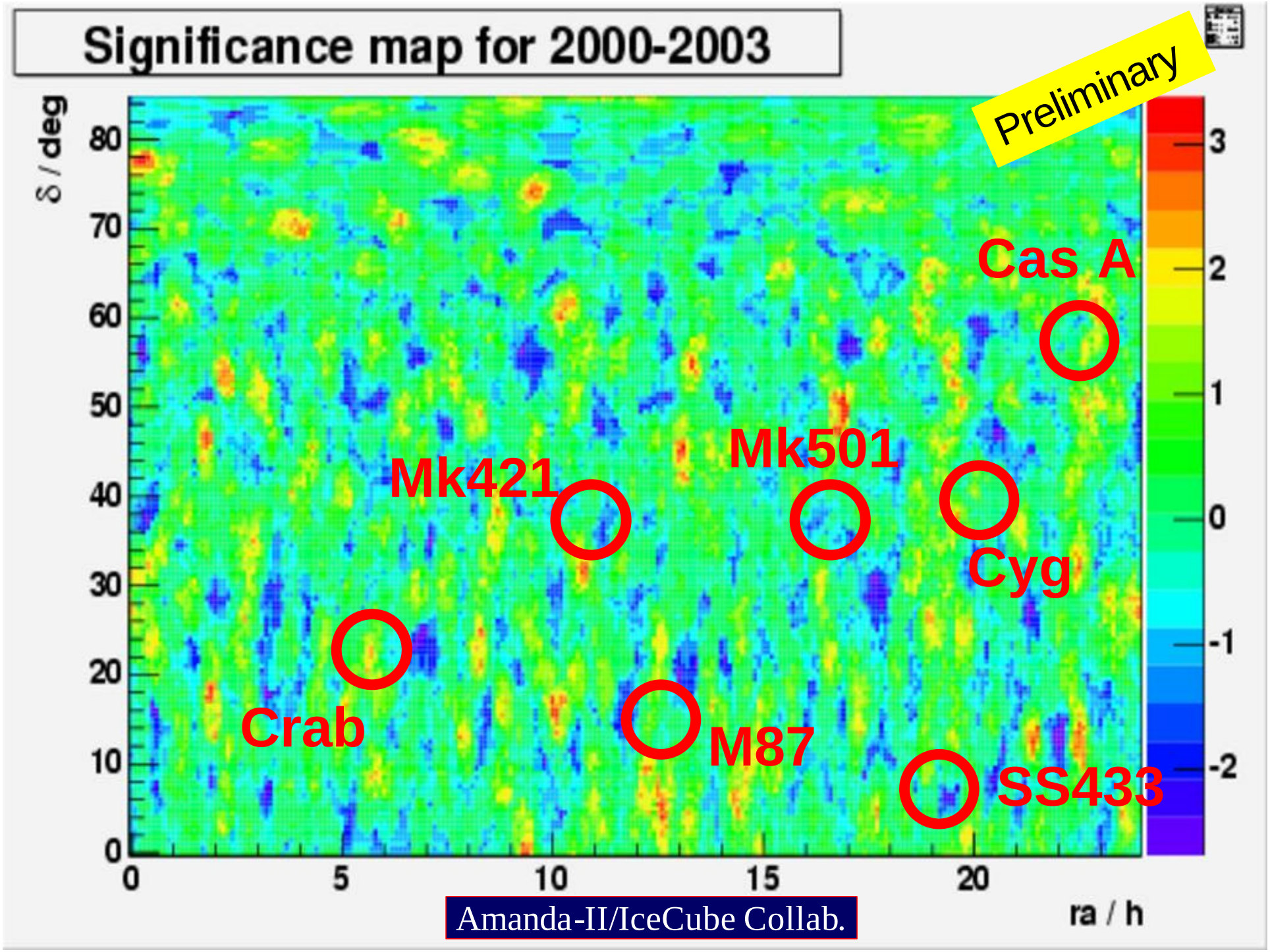
Amanda-II/IceCube Collab.

AMANDA-II 2000-2003

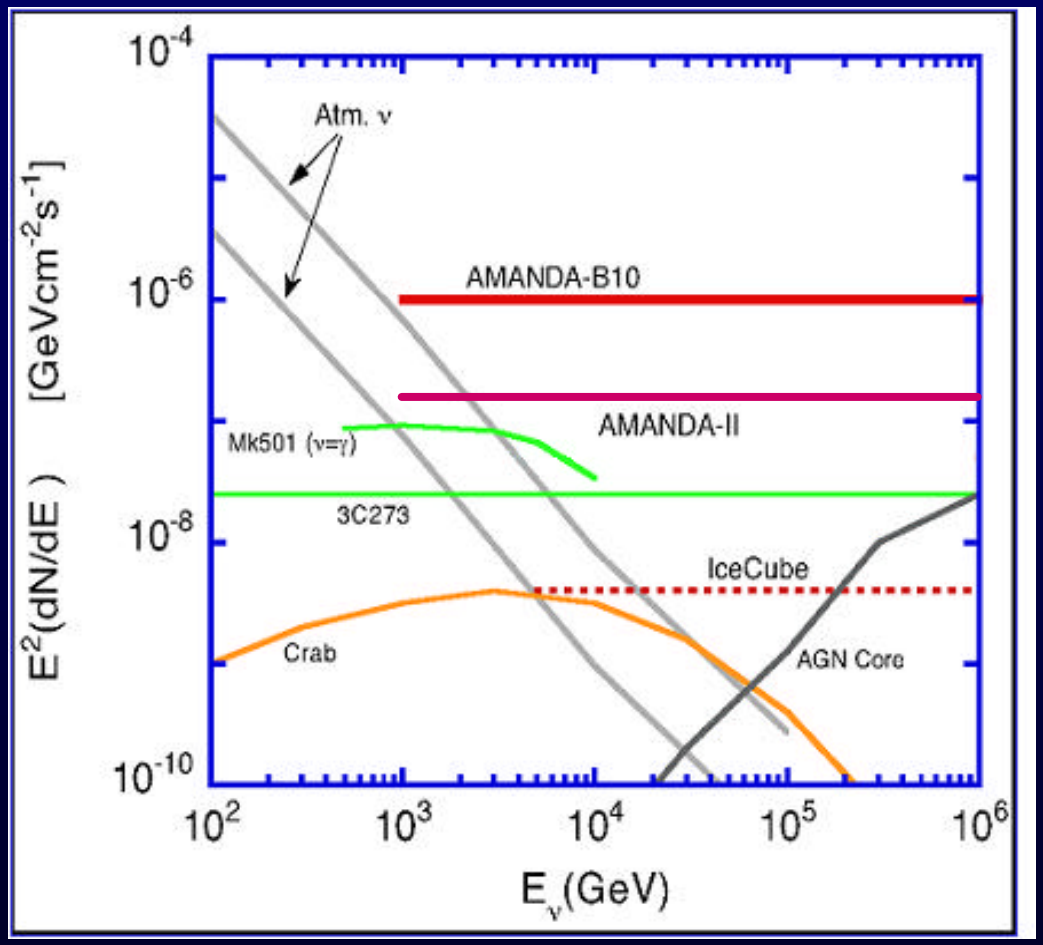
- Recently “unblinded” skymap with 3369 events from 807 days lifetime
- 3438 events expected from atmospheric muon simulation
- No clustering and no evidence for point sources
- Limits for some source candidates are close to neutrino flux predictions

Amanda-II/IceCube Collab.




Significance map for 2000-2003
Preliminary
δ / deg
80
70
60
50
40
30
20
10
0
0
5
10
15
20
ra / h
3
2
1
0
-1
-2
Cas A
Mk501
Mk421
Cyg
Crab
M87
SS433
Amanda-II/IceCube Collab.

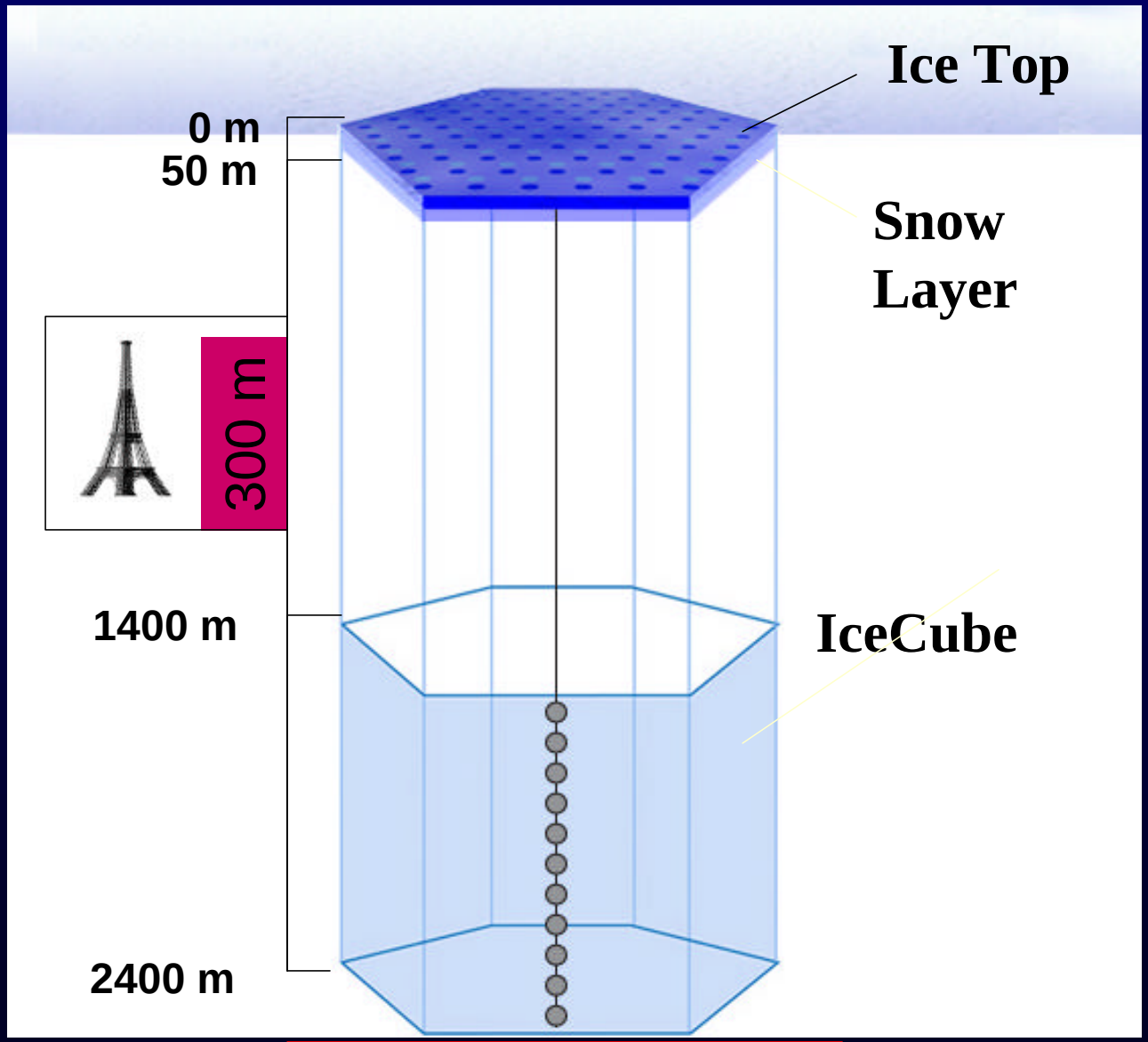
Sensitivity



- Average flux of blazar Mrk 501 during flaring state in 1997: Neutrino sensitivity has reached $\nu \sim \gamma$
- Steep spectrum for atmospheric ν

Amanda-II/IceCube Collab.

IceCube

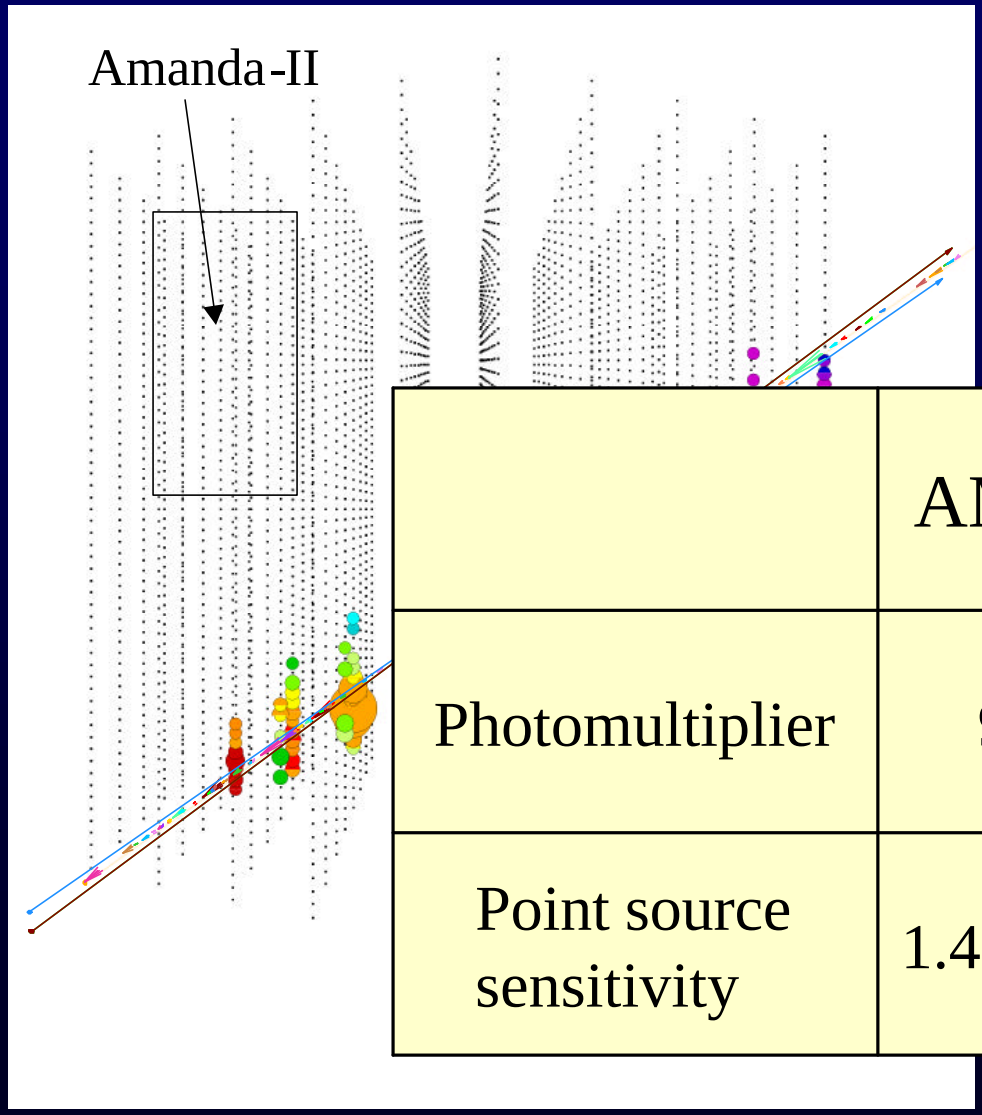


Amanda-II/IceCube Collab.

- 80 strings
- 4800 PMTs (10 in.)
- 1 km^3 instrumented volume
- Detects ν from 10^7 eV (SN) to 10^{20} eV
- Installation 2005-2010

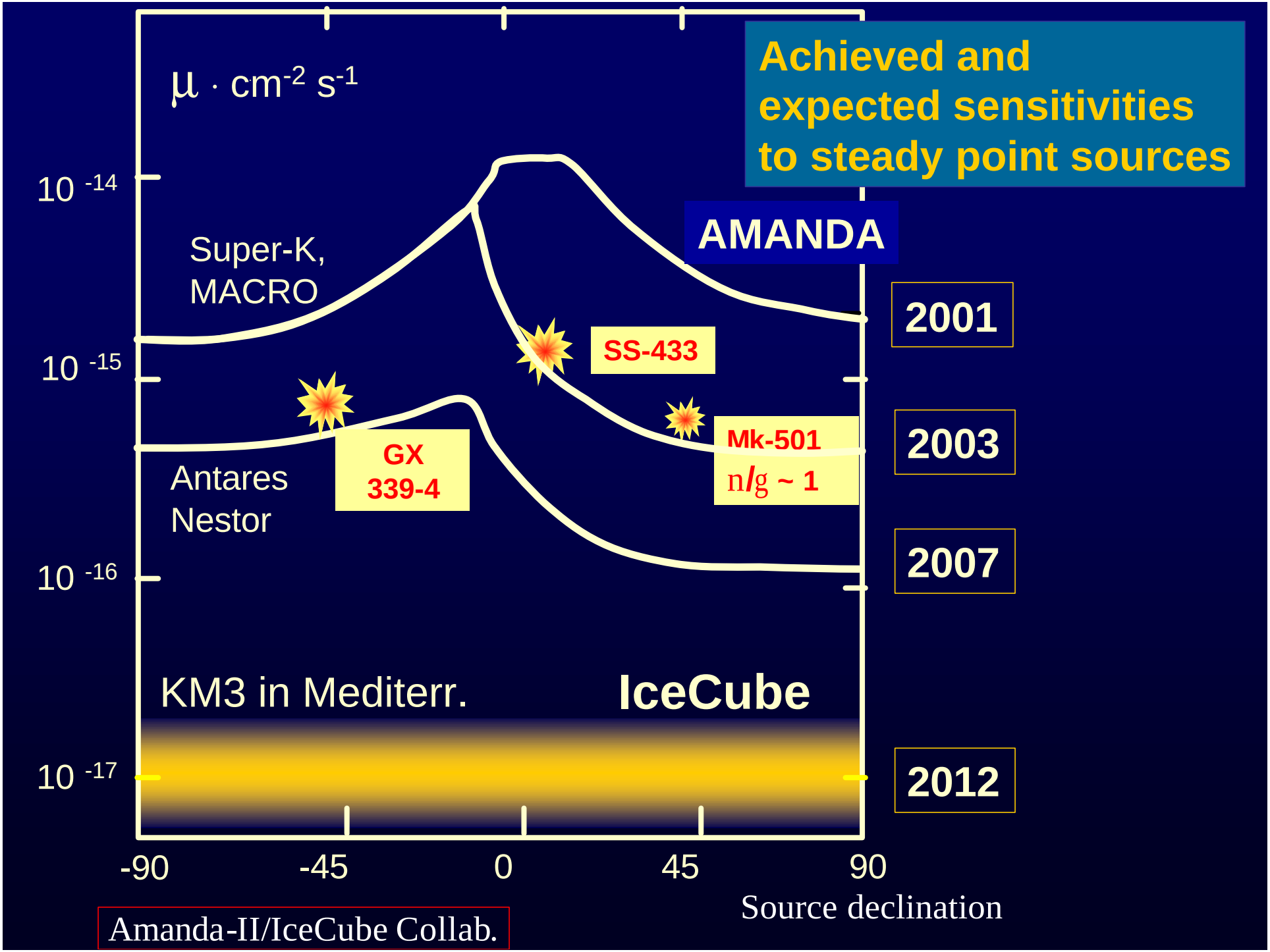
IceCube Event

Amanda-II/IceCube Collab.



- Simulation of a muon event in IceCube

	AMANDA-II	IceCube
Photomultiplier	900 8 inch	4800 10 inch
Point source sensitivity	1.4×10^{-15} cm^{-2} s^{-1}	5×10^{-17} cm^{-2} s^{-1}


Achieved and expected sensitivities to steady point sources
μ · cm-2 s-1
10 -14
10 -15
10 -16
10 -17
Super-K, MACRO
AMANDA
2001
SS-433
2003
Mk-501
n/g ~ 1
GX 339-4
Antares Nestor
2007
KM3 in Mediterr.
IceCube
2012
-90
-45
0
45
90
Source declination
Amanda-II/IceCube Collab.

Summary

- Potential of neutrino astronomy is enormous
- Detection requires large detector volumes
- AMANDA has collected > 5000 neutrino events
- Neutrino sensitivity has reached $\nu \sim \gamma$ (for the average 1997 flux from Mrk501)
- IceCube expects > 300,000 events per year, sensitivity down to < 0.01 Crab from ~1 Crab

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.*

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