New Frontiers in Cosmic Rays Physics

Paolo Privitera

THE UNIVERSITY OF CHICAGO
PHYSICAL SCIENCES

Department of Astronomy & Astrophysics
The Enrico Fermi Institute
The Kavli Institute for Cosmological Physics

The Sardinia Expedition

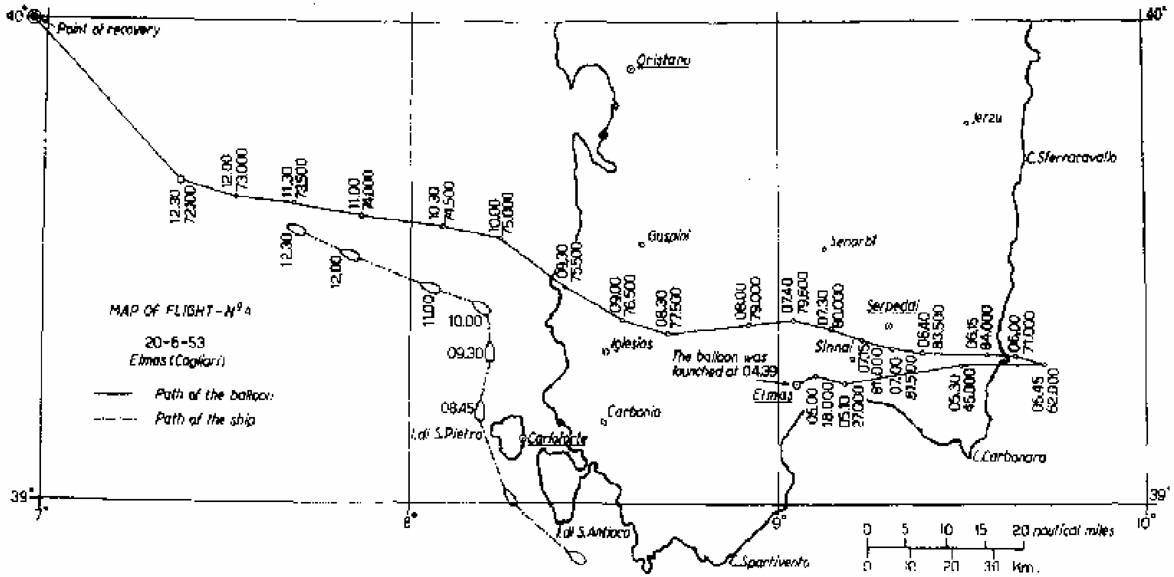


Fig. 4. – Map of a flight.

Report on the Expedition to Sardinia, 1953.

J. Davies

H. H. Wills Physical Laboratory - University of Bristol

C. Franzinetti

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

International Collaboration

University of Bern
University of Bristol
Université Libre of Brussels
University of Caen
University of Catania
University of Copenhagen
University College, Dublin
Institute of Advanced Studies, Dublin
University of Genoa
Max-Planck Institut, Göttingen
Imperial College, London
University of Lund
University of Milan
University of Oslo
University of Padua
École Normale Supérieure, Paris
École Polytechnique, Paris
University of Rome
University of Sydney
University of Trondheim
University of Turin
University of Uppsala
University of Warsaw

IL NUOVO CIMENTO Vol. X, N. 7 1° Luglio 1953

Contributions to the τ-Meson Investigation

E. Amaldi, G. Baroni, C. Castagnoli, G. Cortini and A. Manfredini

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 4 Maggio 1953)

Summary — Two τ-mesons have been observed in photographic emulsions exposed to cosmic rays at an altitude of 26 000 metres. The corresponding data are summarized in par. 2. The process of decay of τ-mesons is considered in par. 3 where, by means of a statistical con-

Contribution to the K-Meson Investigation.

E. Amaldi, G. Cortini and A. Manfredini

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

1. – Introduction.

In this paper we report on a systematic investigation on K-mesons which has been made by scanning the emulsions of a stack exposed for 8 hours at about 25 000 m above sea level, during the Sardinia Expedition 1953.

In the investigation of all events consisting in two tracks showing appreciably different grain densities, we have found 4 K-mesons and 2 hyperons.

IL NUOVO CIMENTO VOL. I, N. 3 1° Marzo 1955

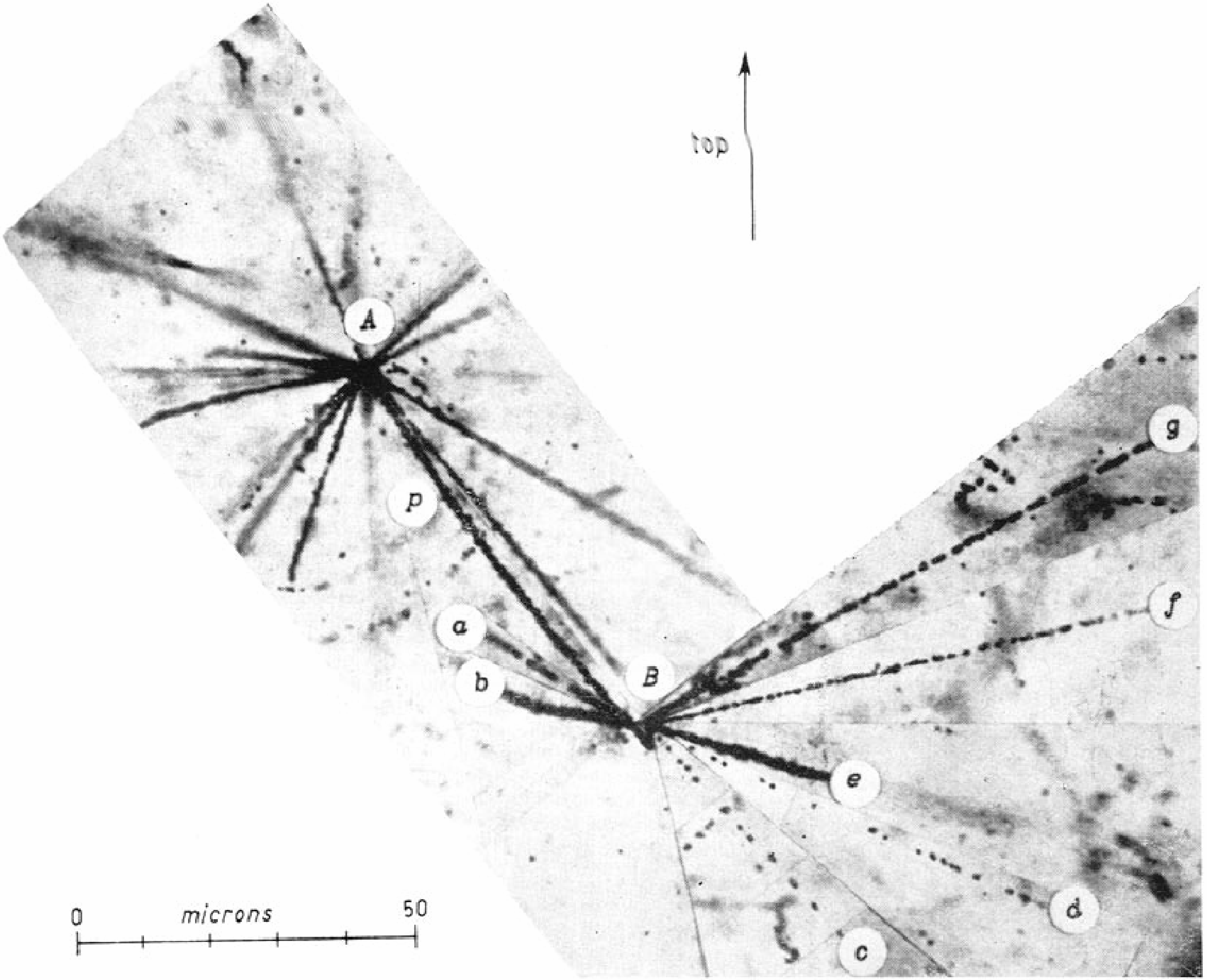
Unusual Event Produced by Cosmic Rays.

E. AMALDI, C. CASTAGNOLI, G. CORTINI, C. FRANZINETTI and A. MANFREDINI

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 18 Febbraio 1955)

Summary. — The authors describe an event consisting of two stars respectively of about 5 and 1-2 GeV energy. The probable value of the number of accidental space coincidences that one expects to observe in the scanned volume, is about $4\cdot10^{-4}$. This value, although it does not allow us to exclude an accidental process, justifies the consideration of interpretations in terms of some physical process. Special attention is devoted to the production, capture and annihilation of a negative proton.



Observed by C. Castagnoli

Fig. 1.

This event is corroborating evidence, but not final proof, for the interpretation given in reference 1 that the new particles observed at the Bevatron are antiprotons. It also gives support to the hypothesis that the star described in reference 5 was indeed due to an antiproton.

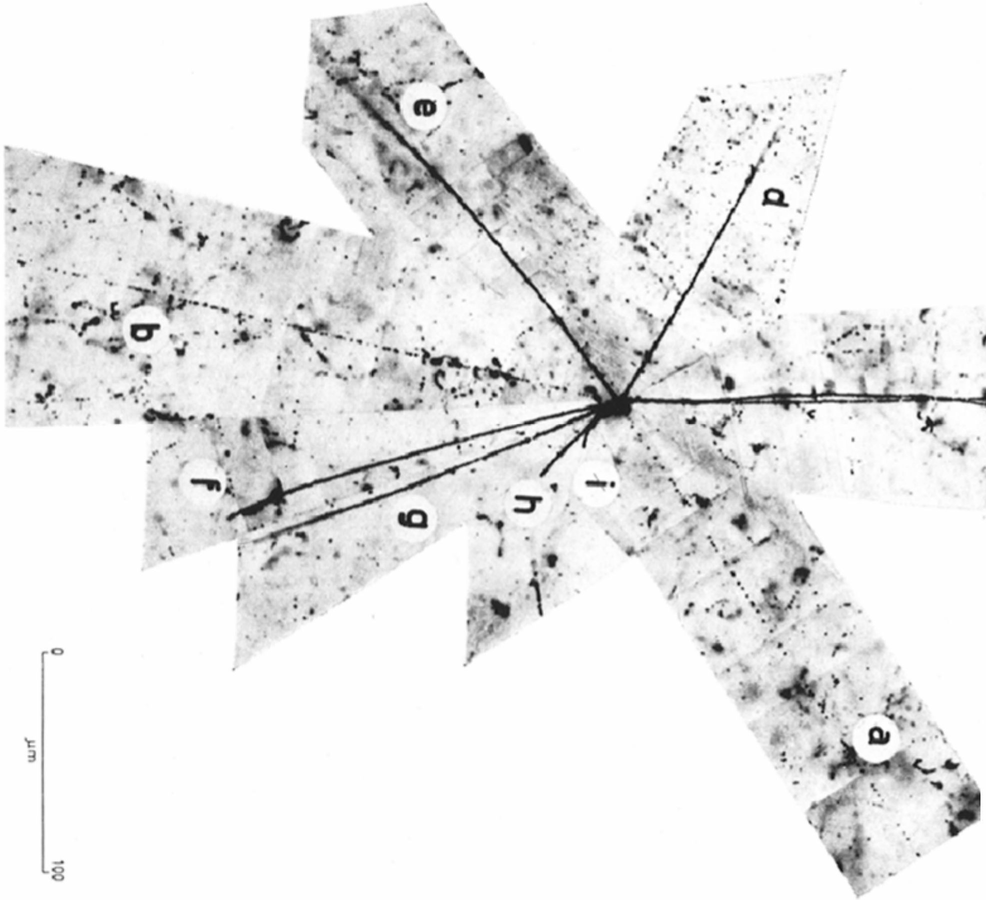


Fig. 6. – The star. *L* indicates the incoming antiproton track. Tracks *a* and *b* are pions, and *c* is a proton. The remaining tracks could be protons or α-particles.

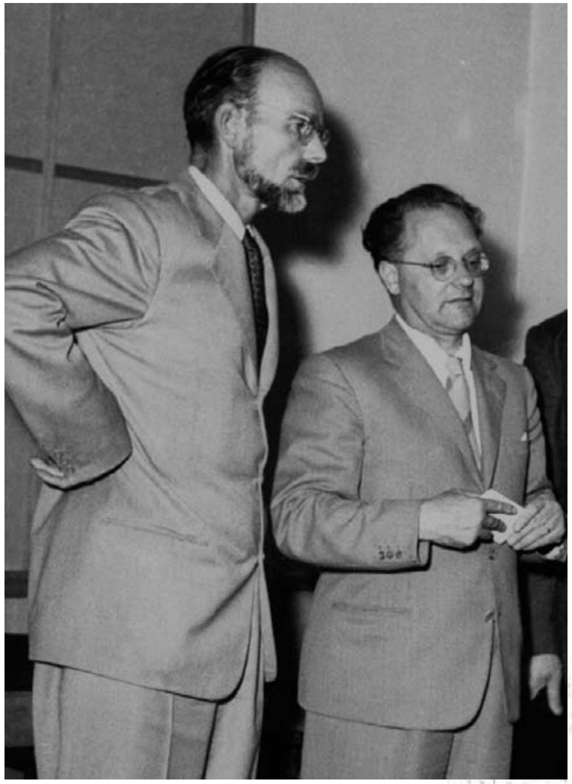
Antiproton Star Observed in Emulsion*

O. CHAMBERLAIN, W. W. CHUPP, G. GOLDHABER, E. SEGRÈ, AND C. WIEGAND, *Radiation Laboratory, Department of Physics, University of California, Berkeley, California*

AND

E. AMALDI, G. BARONI, C. CASTAGNOLI, C. FRANZINETTI, AND A. MANFREDINI, *Istituto di Fisica della Università, Roma Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy*

(Received December 16, 1955)



WHAT ARE COSMIC RAYS?

Revised and Enlarged American Edition

BY PIERRE AUGER

QUESTION NO. 1 REMAINS UNANSWERED

Can we, in the light of this basic knowledge, try to answer Question No. 1, which has baffled physicists from the start? Even when they had known nothing more than the phenomenon of residual ionization, they had asked: "What is the origin of the rays which produce it?" We already know a part of the answer: "Their origin is extraterrestrial"; and this justifies the name "cosmic rays." However, by what processes can we imagine the particles to have attained their high energies?

1944

Cosmic Ray Physicists

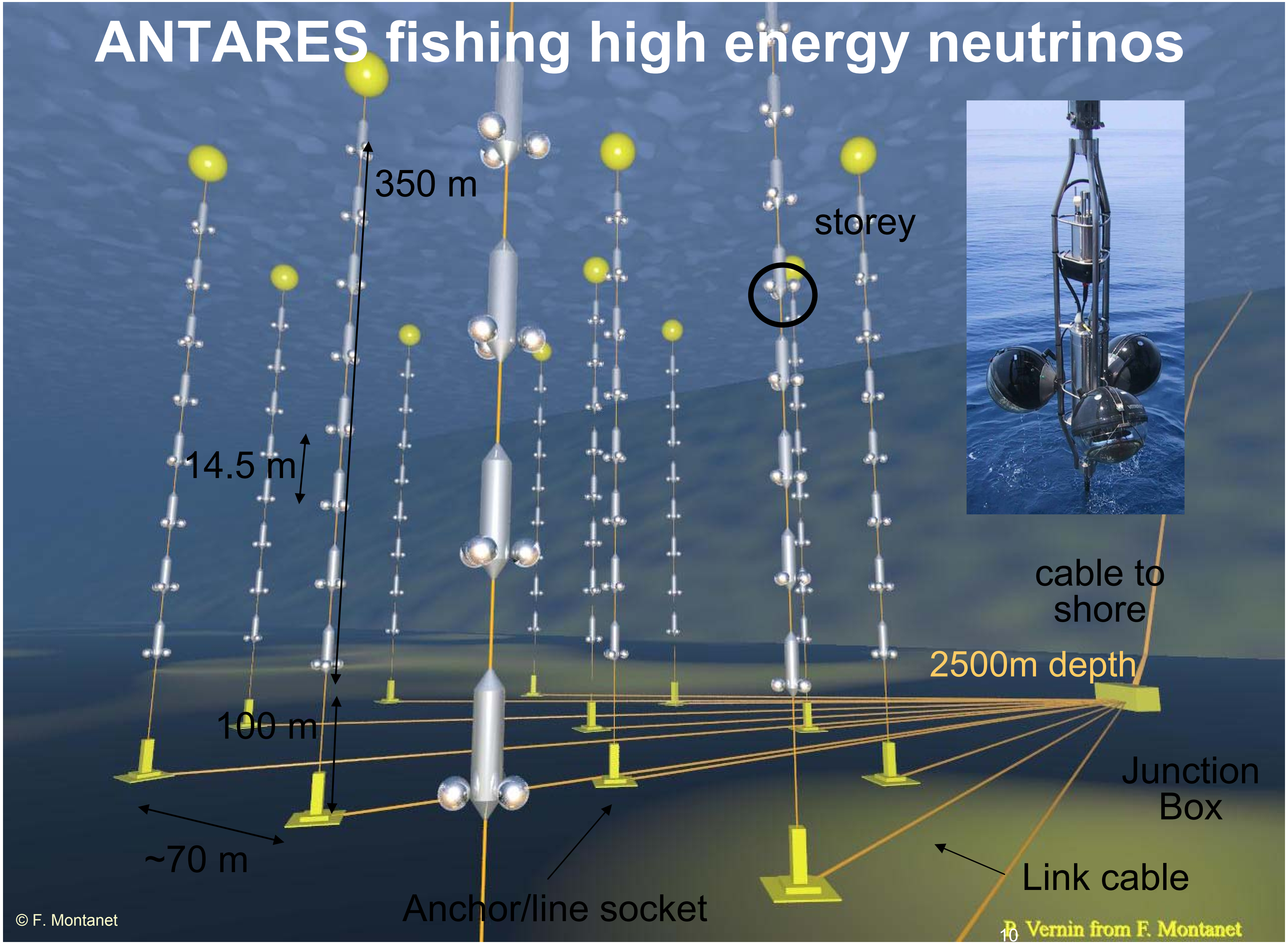
MOUNTAINEERS, MINERS, DIVERS, AND FLIERS

The physicists who carried out these experiments had to be great sportsmen at times. As occasion demanded, they became divers, mountaineers, miners, or airmen. Even their apparatus had to be endowed with adventurous spirit in order to function under the strange conditions in which it was placed.

The “divers”

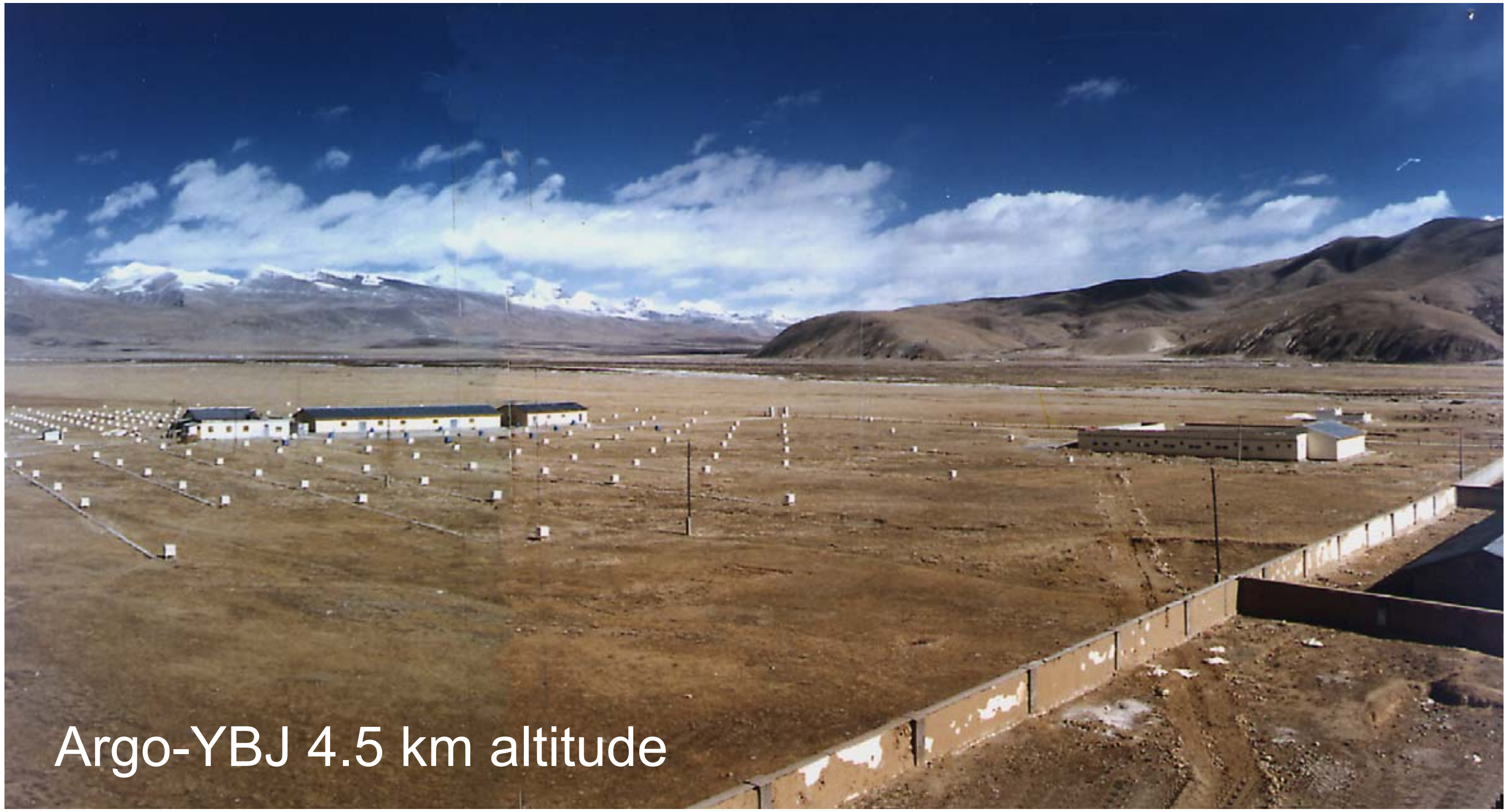
Thus the “divers” put an ionization chamber or counters into a watertight caisson which could be lowered into a lake or ocean to a depth of many hundred yards. In-

ANTARES fishing high energy neutrinos



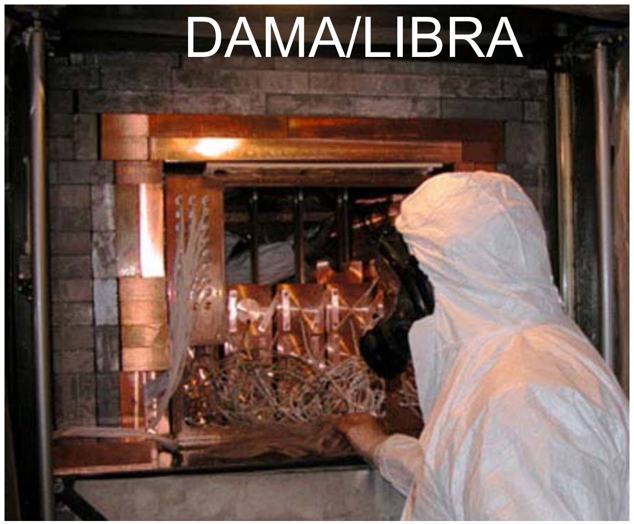
The “mountaineers”

The “mountaineers,” among whose ranks the author of this book is enrolled, have constructed light and portable apparatus which can be readily installed in mountain shelters.

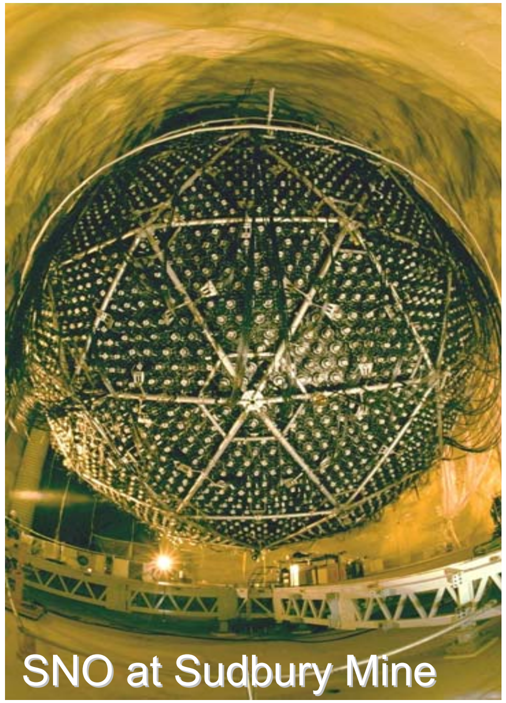


The “miners”

The “miners” had to work in mine galleries with very low ceilings; they used little coal trucks to move their apparatus from place to place. Because the effects observed under great thicknesses of rock are very minute, the counters constructed for this purpose were large and cumbersome (more than a yard long). Moreover, the atmosphere was always so damp in these galleries that the instruments had to be inclosed in air-tight containers.



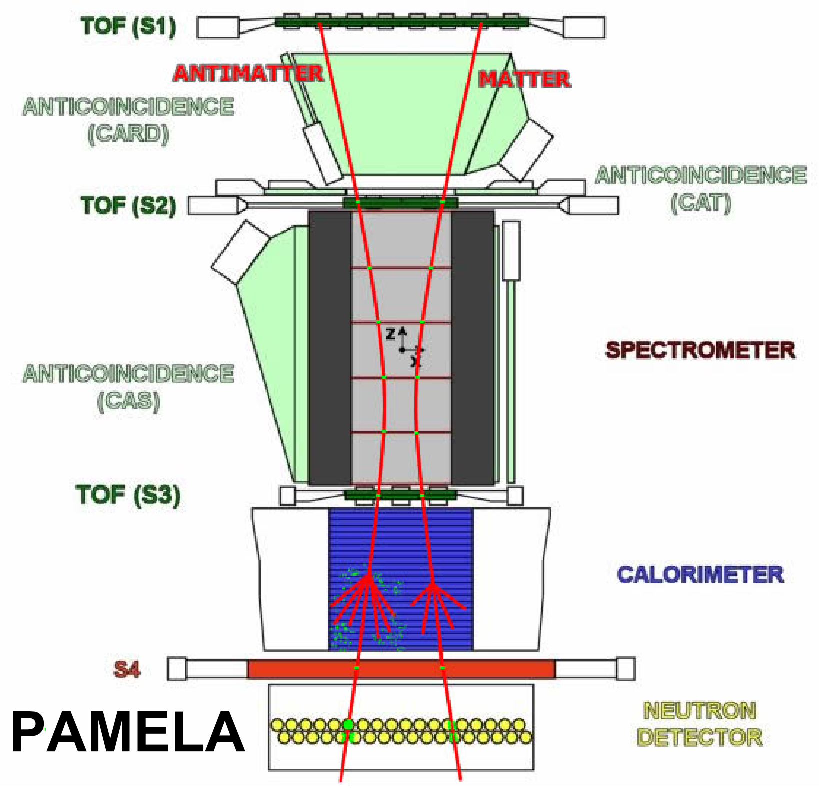
DAMA/LIBRA

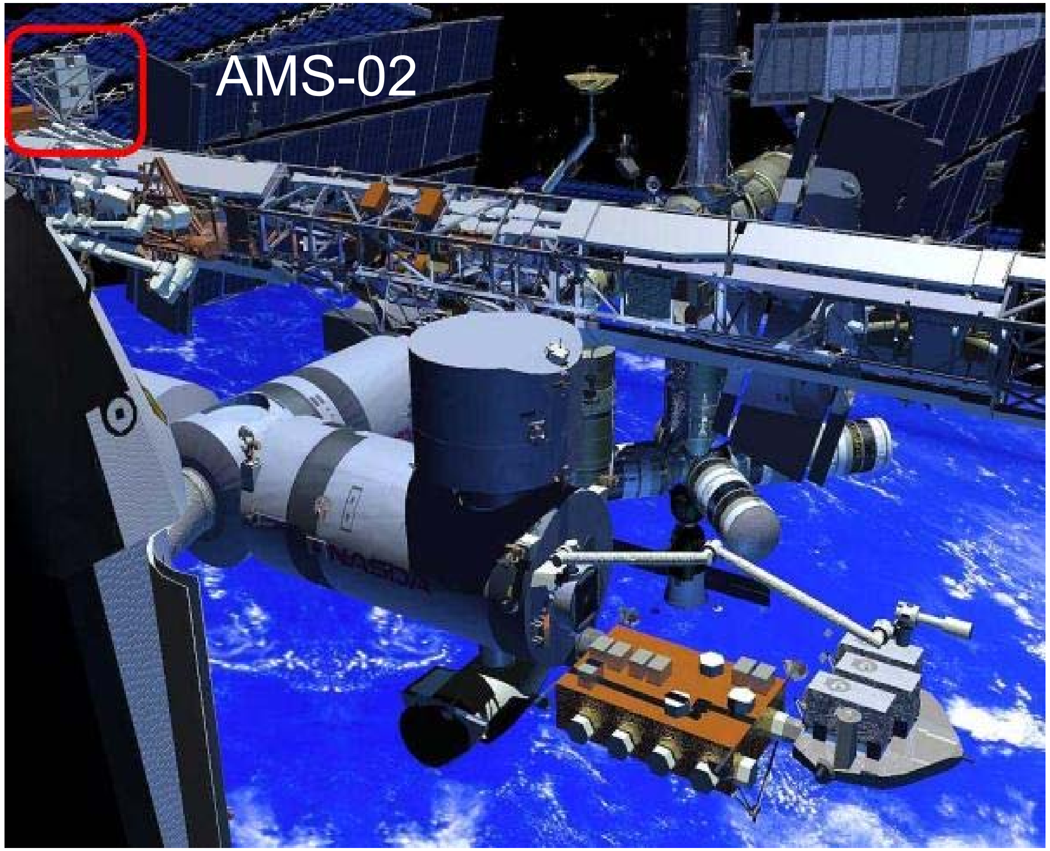


SNO at Sudbury Mine

The "airmen"

Finally, there are the "airmen," who may be grouped into two classes: those who send their cosmic-ray detectors off into the stratosphere unaccompanied, and those—comprising only a handful—who dare to accompany them.





Astro Particle Physics

"Cosmic Rays" have evolved in a vibrant field exploring the frontiers of astrophysics, particle physics and cosmology

- Neutrinos:

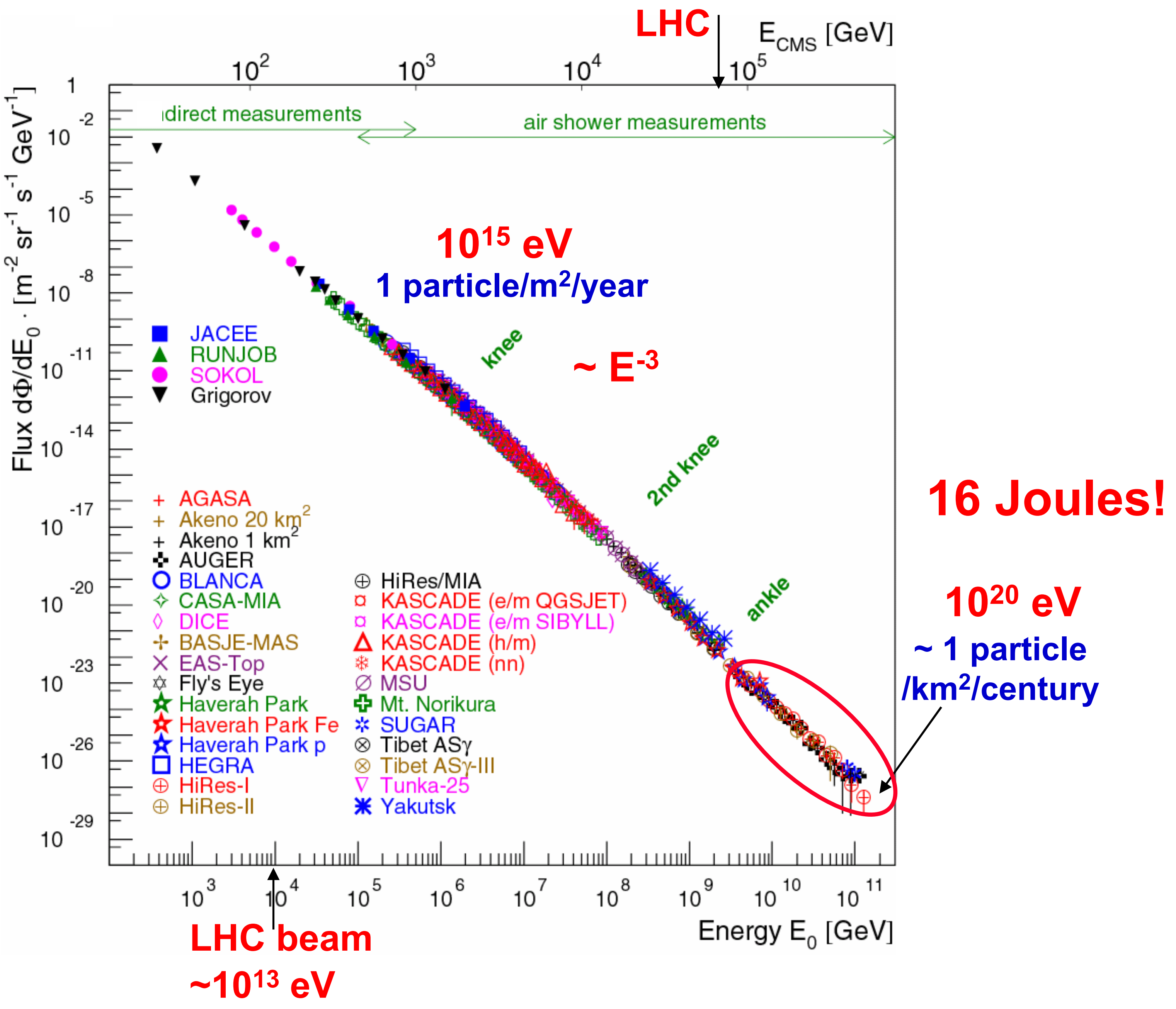
- the birth of neutrino astronomy: SN1987A
- solar and atmospheric neutrinos: neutrino oscillations

- Dark Matter:

direct searches (DAMA), indirect searches, TeV Gamma Rays, Neutrinos, Cosmic Rays in space (PAMELA)

- Extreme events in the Universe: the origin of cosmic rays

The Cosmic Ray spectrum



COSMIC RAY RIVALS TO MEET IN DEBATE

Clash of Millikan and Compton Theories to Form High Point at Scientific Convention.

4,500 TO ATTEND SESSIONS

Atlantic City Meeting This Week to Hear 1,500 Papers—Gerard Swope to Speak on Unemployment.

Special to THE NEW YORK TIMES.

ATLANTIC CITY, Dec. 25.—The nature of cosmic rays, revolving around the specific question whether they enter the earth's atmosphere as electrically charged particles or as photons, will be the subject of debate between two of America's outstanding physicists at the annual meeting of the American Association for the Advancement of Science, which opens here Tuesday.

More than 4,500 scientists, laboratory workers and teachers of science will attend the meeting of the association and its affiliated scientific bodies.

The two physicists who will discuss the nature of cosmic rays, a subject which has agitated the entire scientific world, are Professor Arthur H. Compton of the University of Chicago and Professor Robert A. Millikan, president of the California Institute of Technology. They are the only living American winners of the Nobel Prize for Physics and both are leaders in this field of research.

New York Times, 12/26/1932

The New York Times

VOL. LXXXII....No. 27,390. December 31, 1932

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

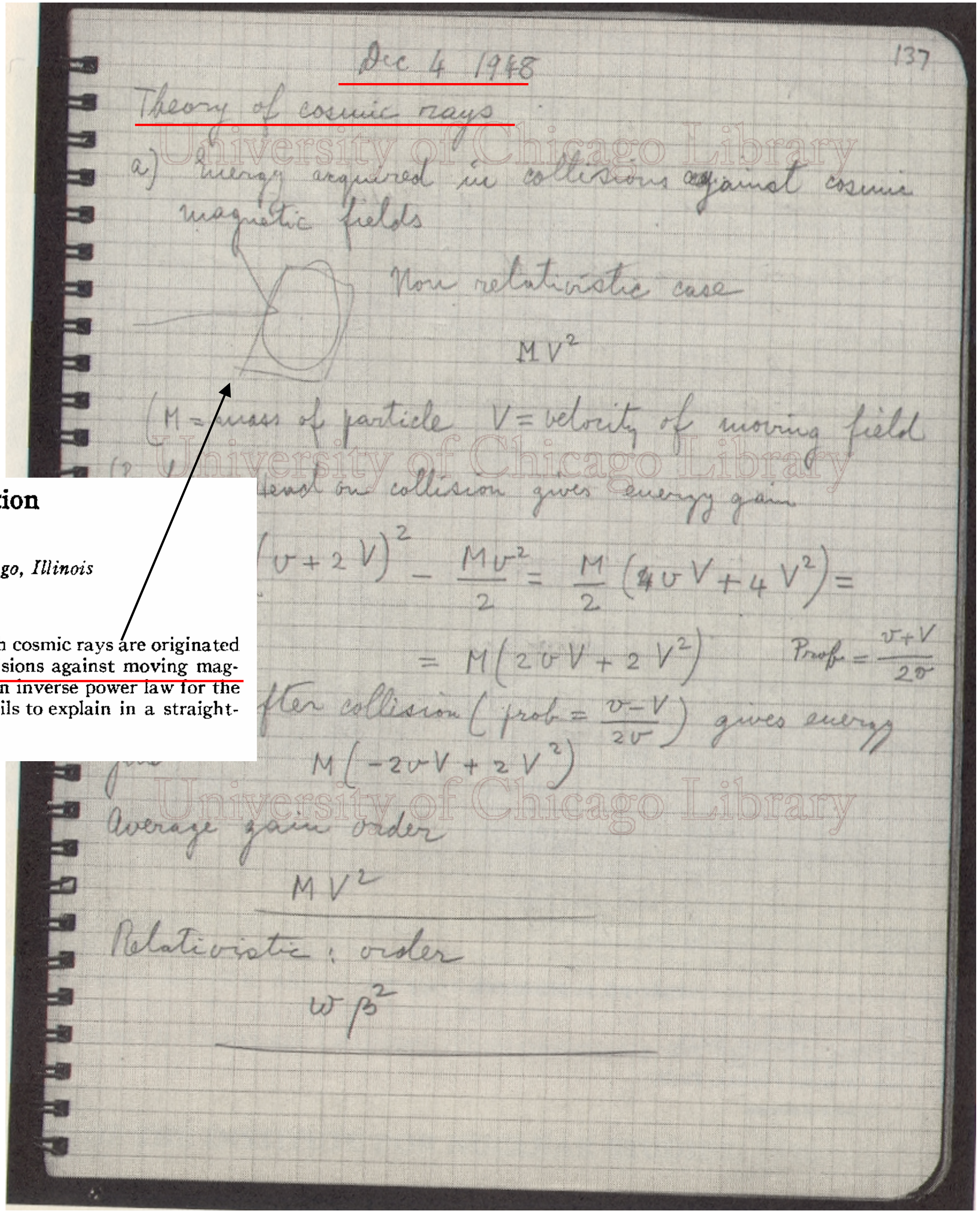
New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

Phys. Rev. 75 (1949) 1169

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.



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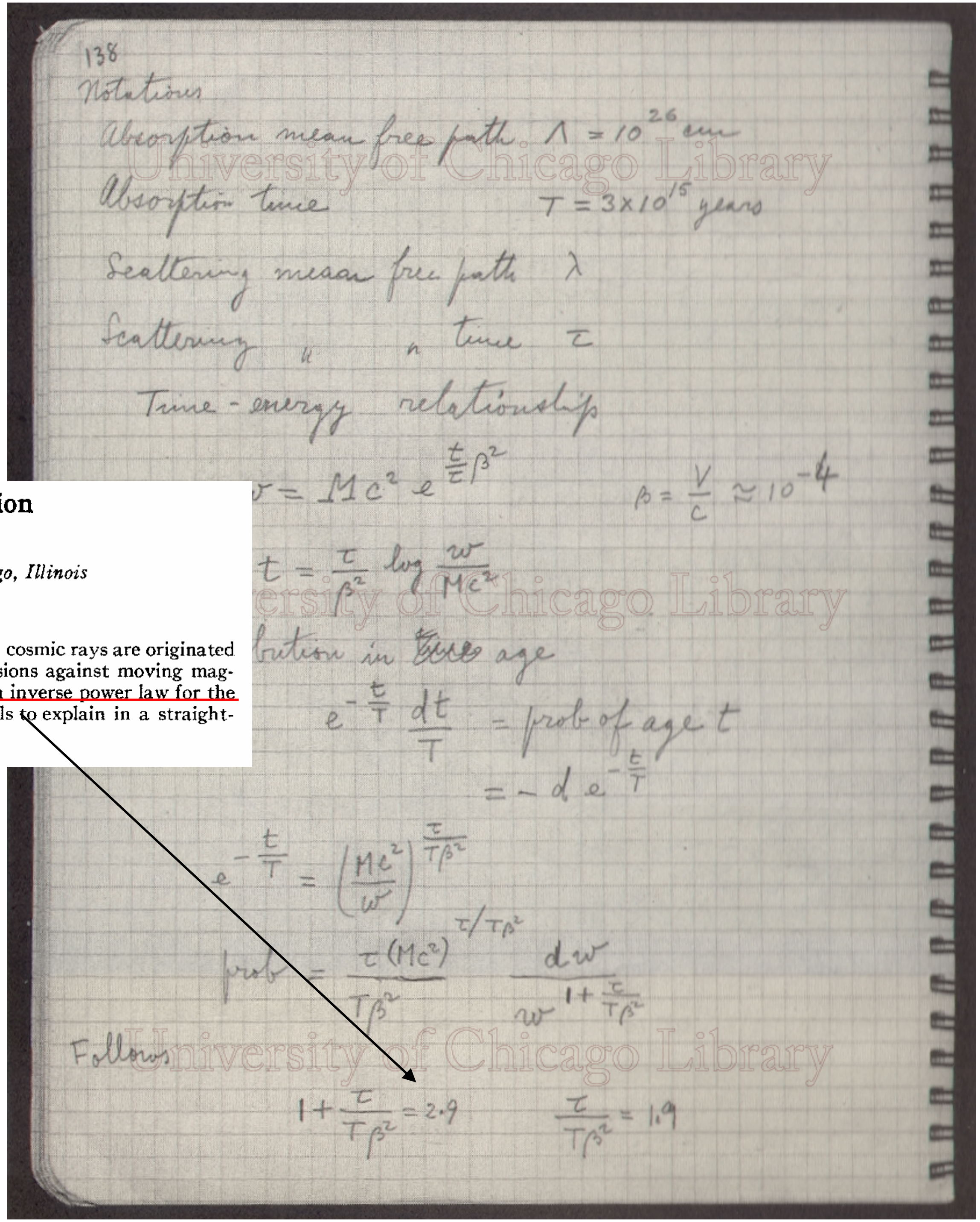
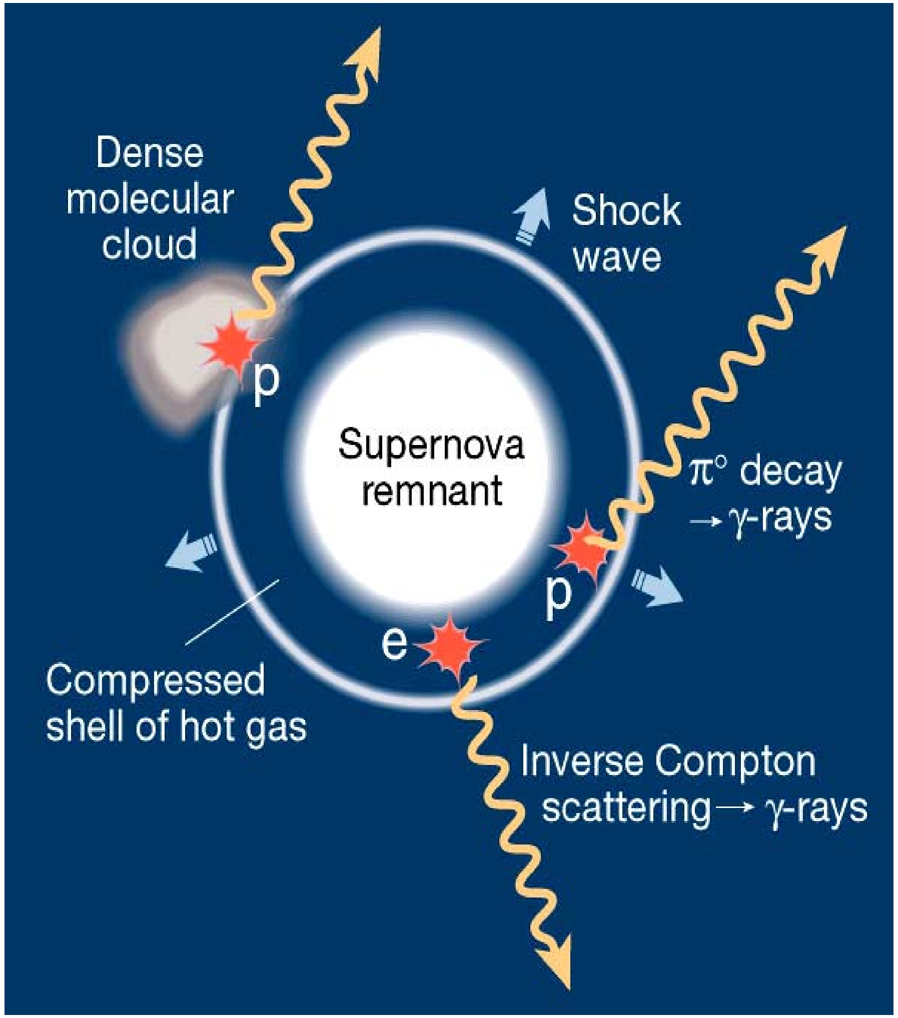
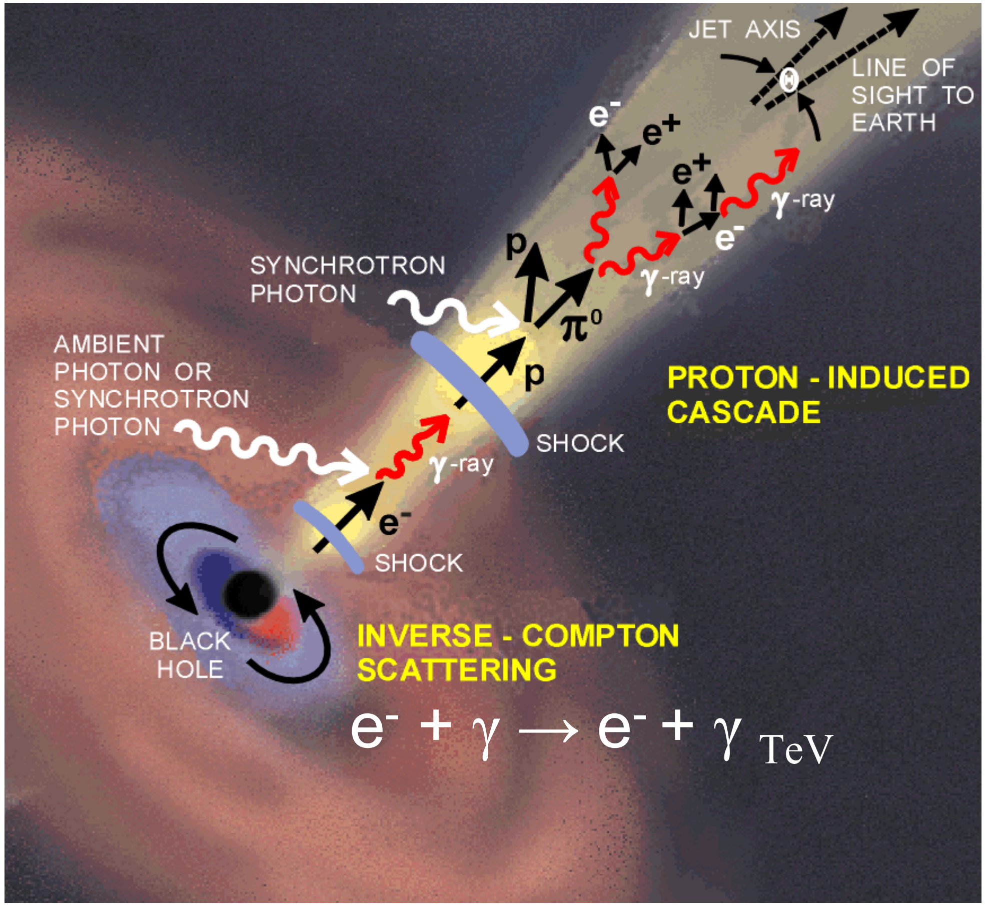
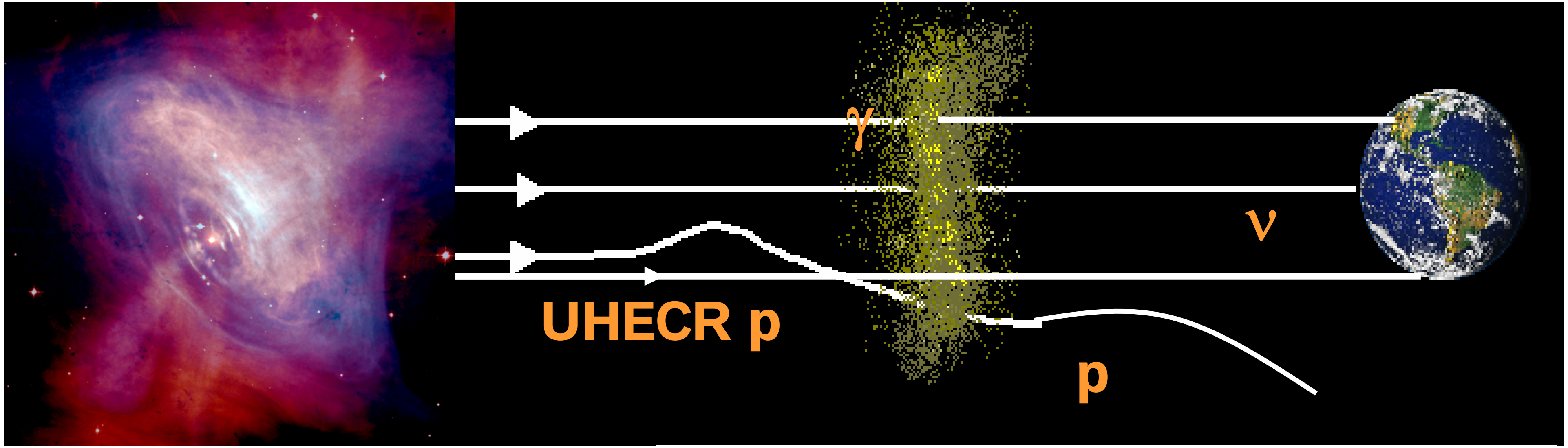


Shock Acceleration of Cosmic Rays



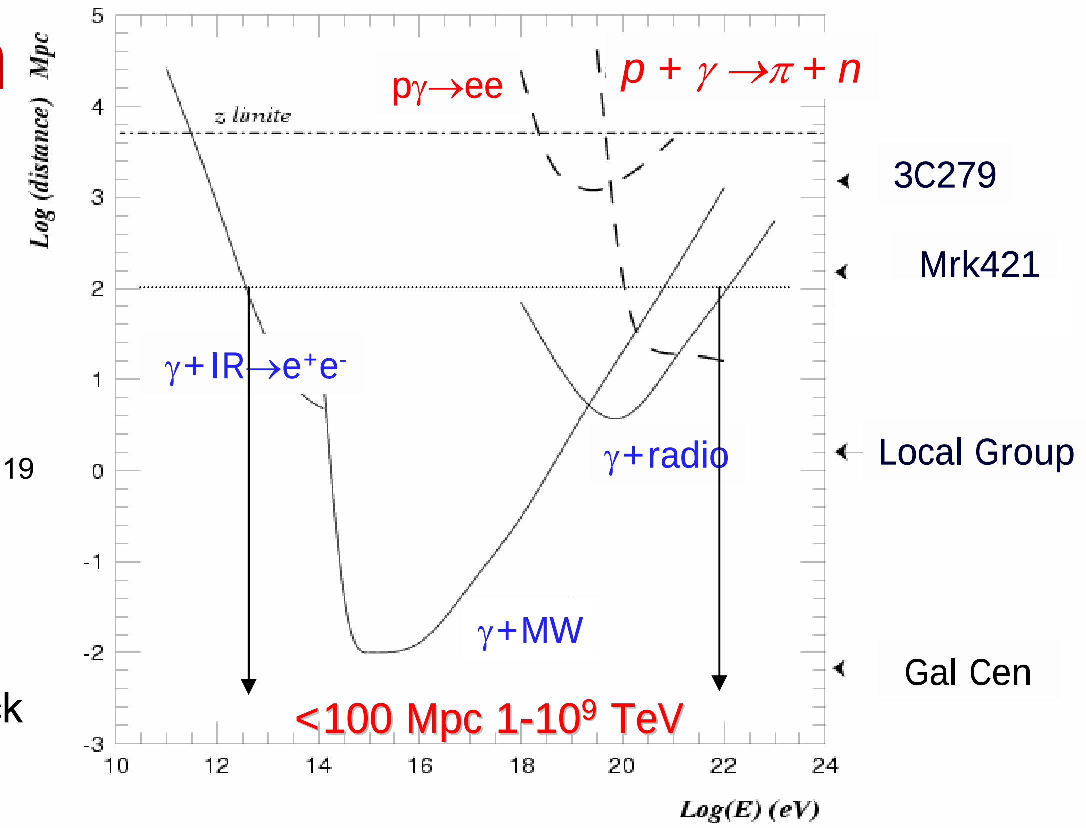


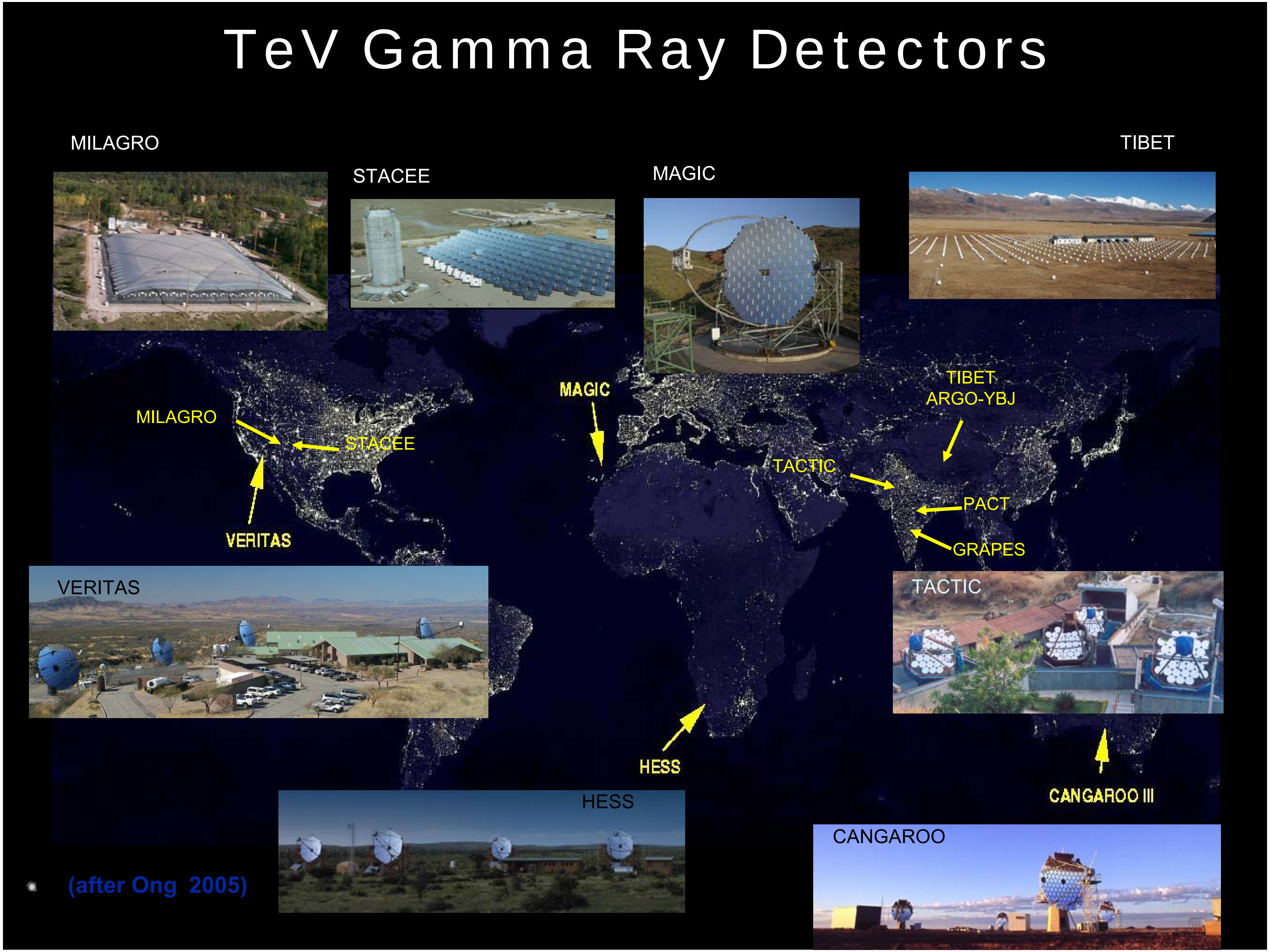
Spectrum at the source $\sim E^{-2}$



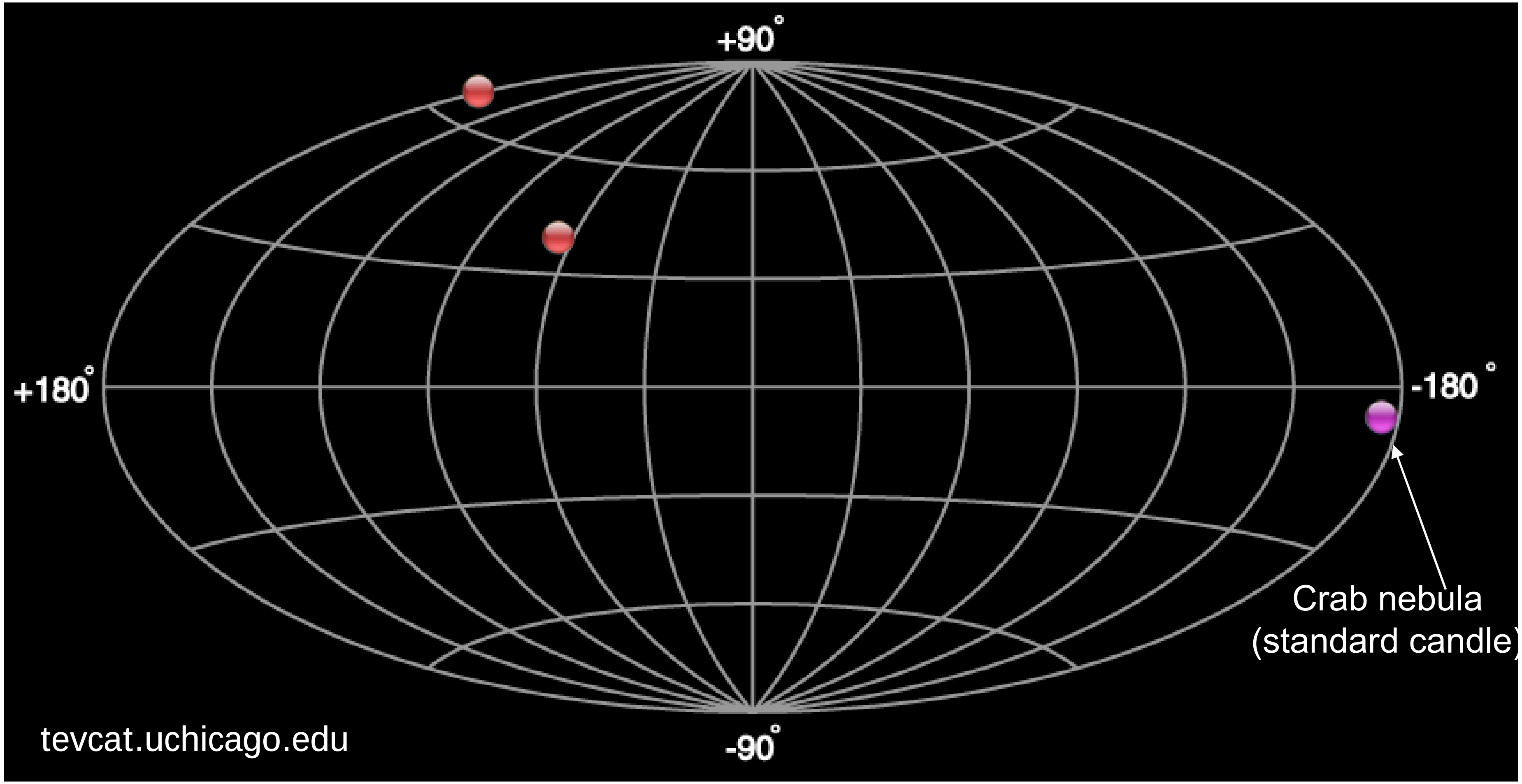
Messengers from the Universe

- TeV Photons: point back to the source, attenuated by interaction with the Extragalactic Background Light
- Ultra-High Energy Cosmic Rays (> $5 \cdot 10^{19}$ eV) : protons minimally deviated by magnetic fields, attenuated by interaction with CMB
- High Energy Neutrinos (PeV): point back to source, no attenuation, small cross section for detection

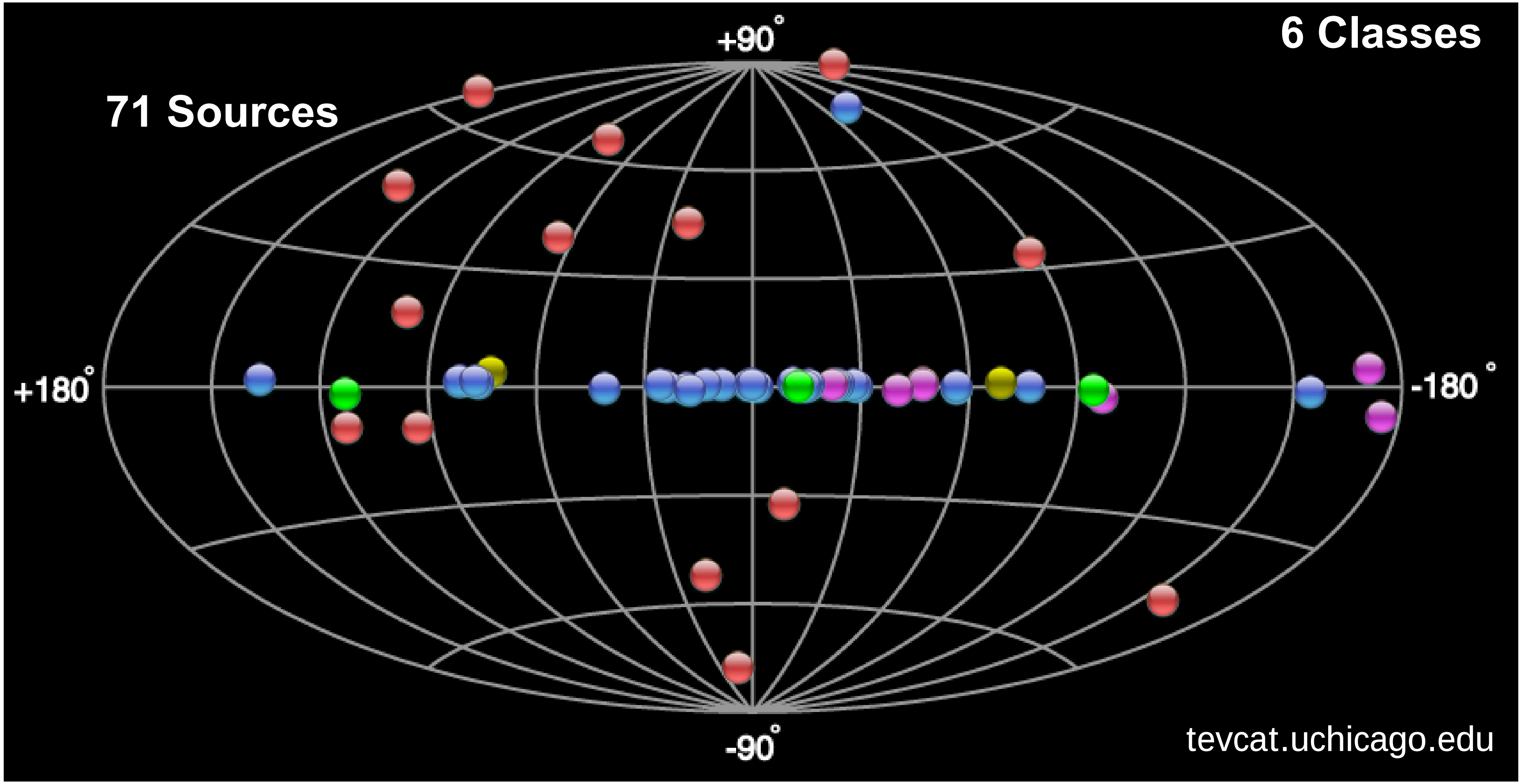



TeV Gamma Ray Detectors
MILAGRO
STACEE
MAGIC
TIBET
MAGIC
TIBET
ARGO-YBJ
MILAGRO
STACEE
TACTIC
PACT
VERITAS
GRAPES
VERITAS
TACTIC
HESS
CANGAROO III
HESS
CANGAROO
(after Ong 2005)

TeV Gamma-Ray Sky - 1997

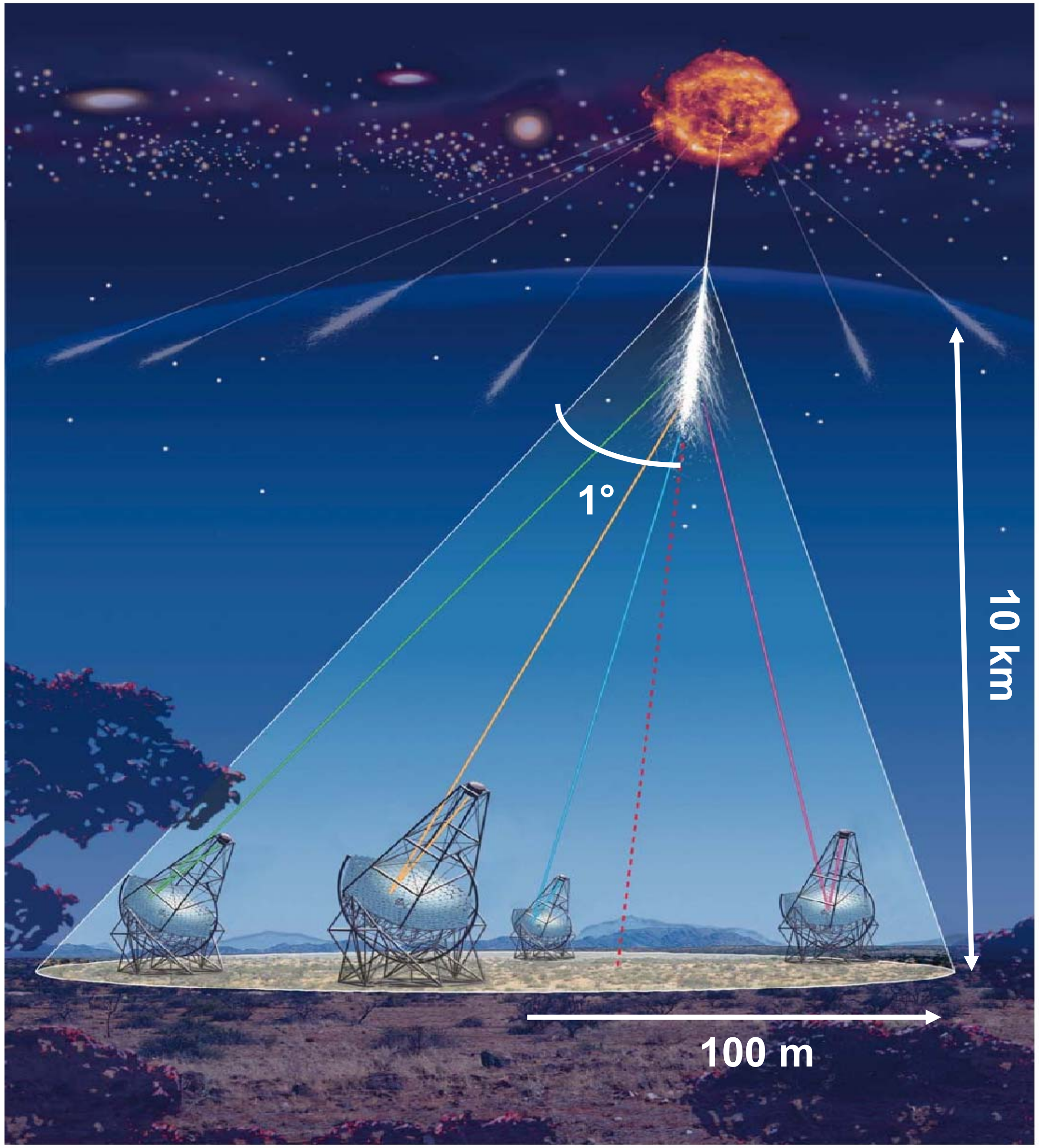


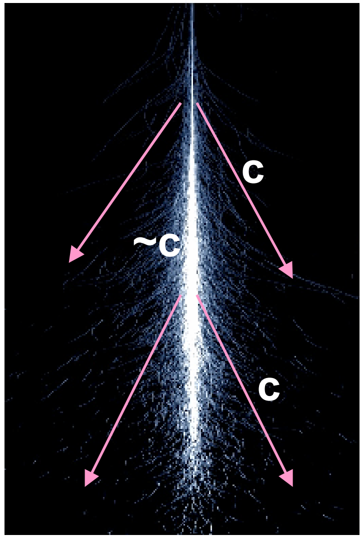
TeV Gamma-Ray Sky - 2007



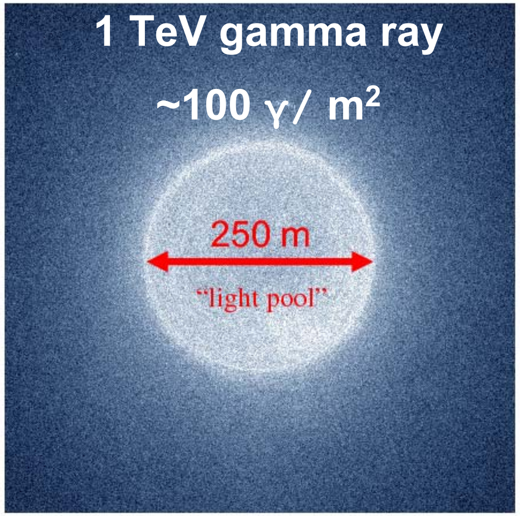
21 Unidentified

Atmospheric Cherenkov Telescopes





Fast ns signal



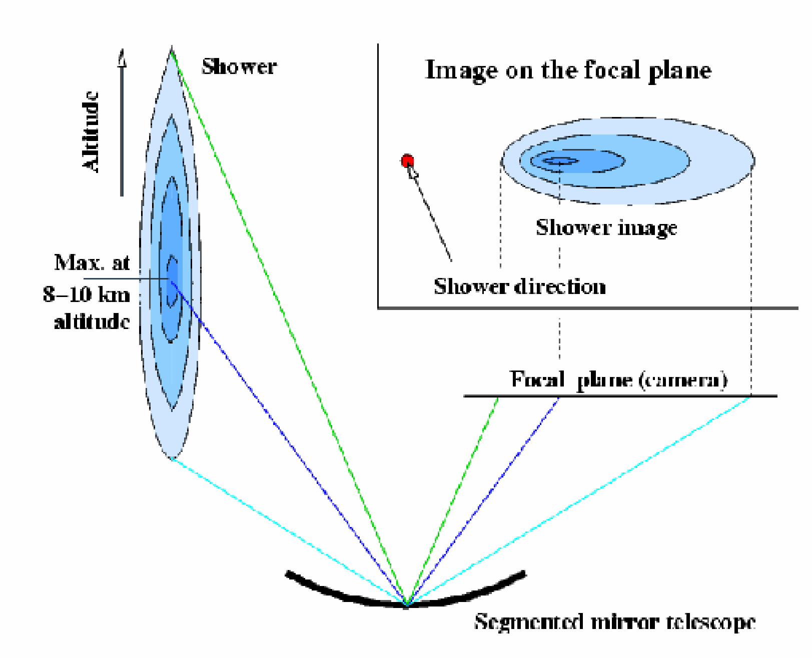
Atmospheric Cherenkov Telescopes

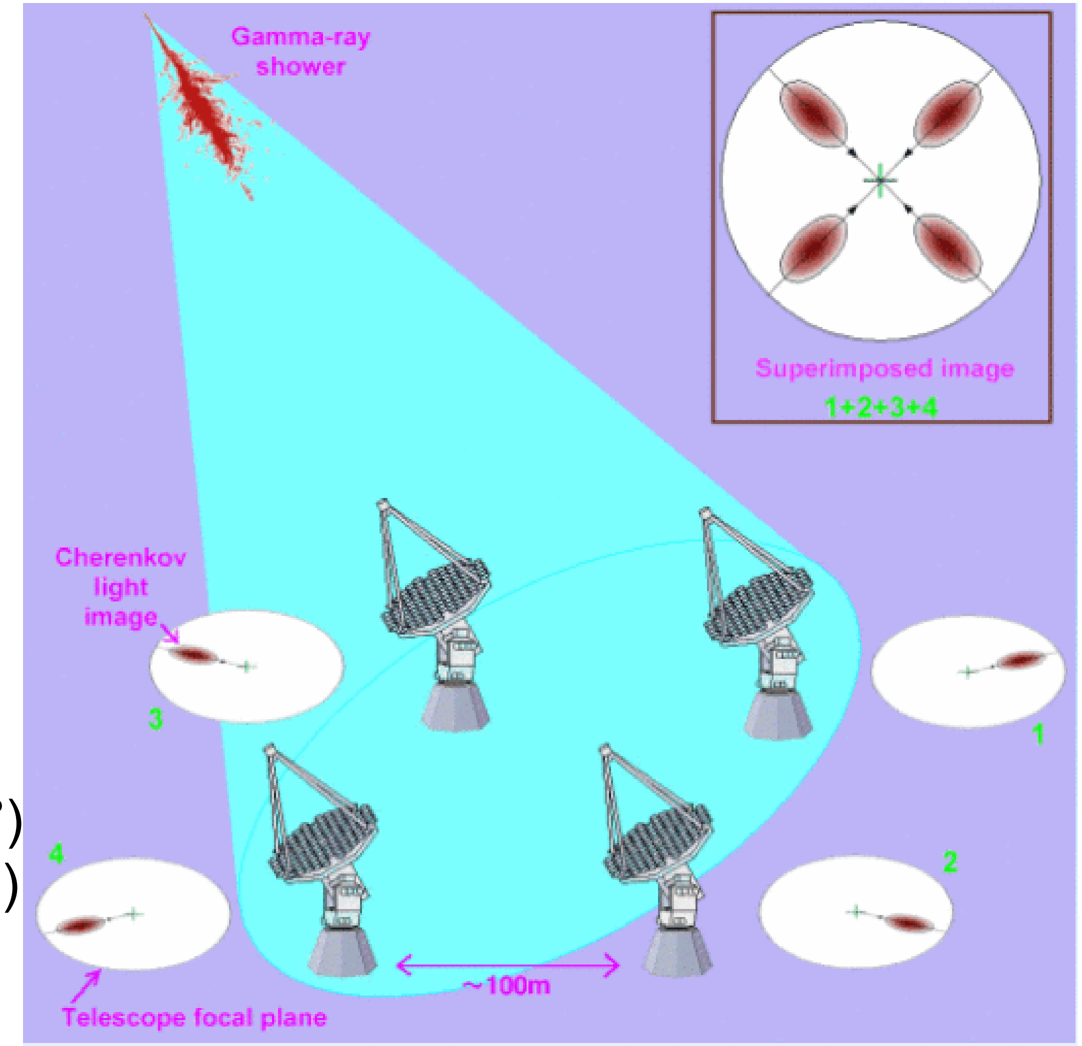
E_{thr} ~ 50 GeV

Atmospheric Cherenkov Telescopes

High Energy Stereoscopic System

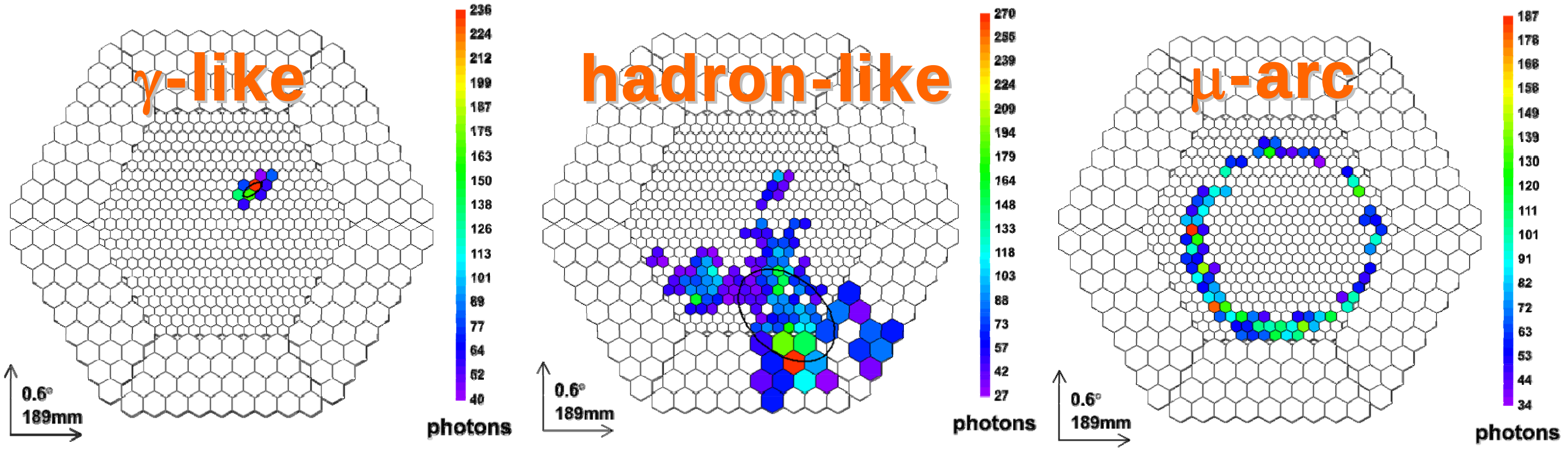
Multiple Telescopes





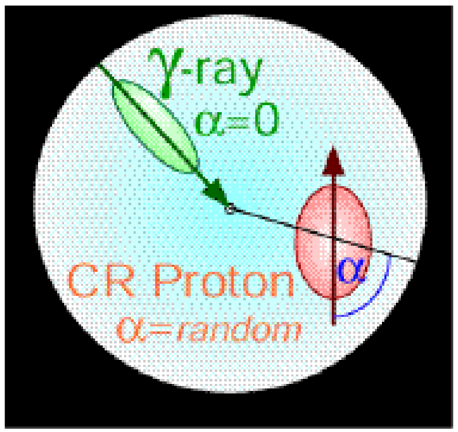
- improve angular resolution (<0.1°)
- improve energy resolution (~20%)
- reduce background
- improve stability

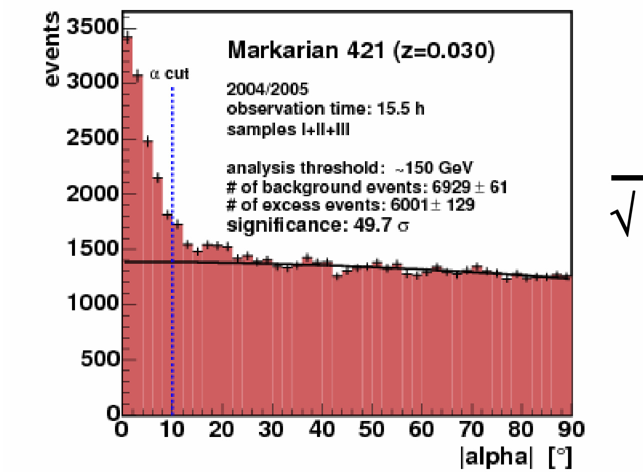
Backgrounds



γ signal ~ 10^{-3}- 10^{-4} hadron bkg

MAGIC





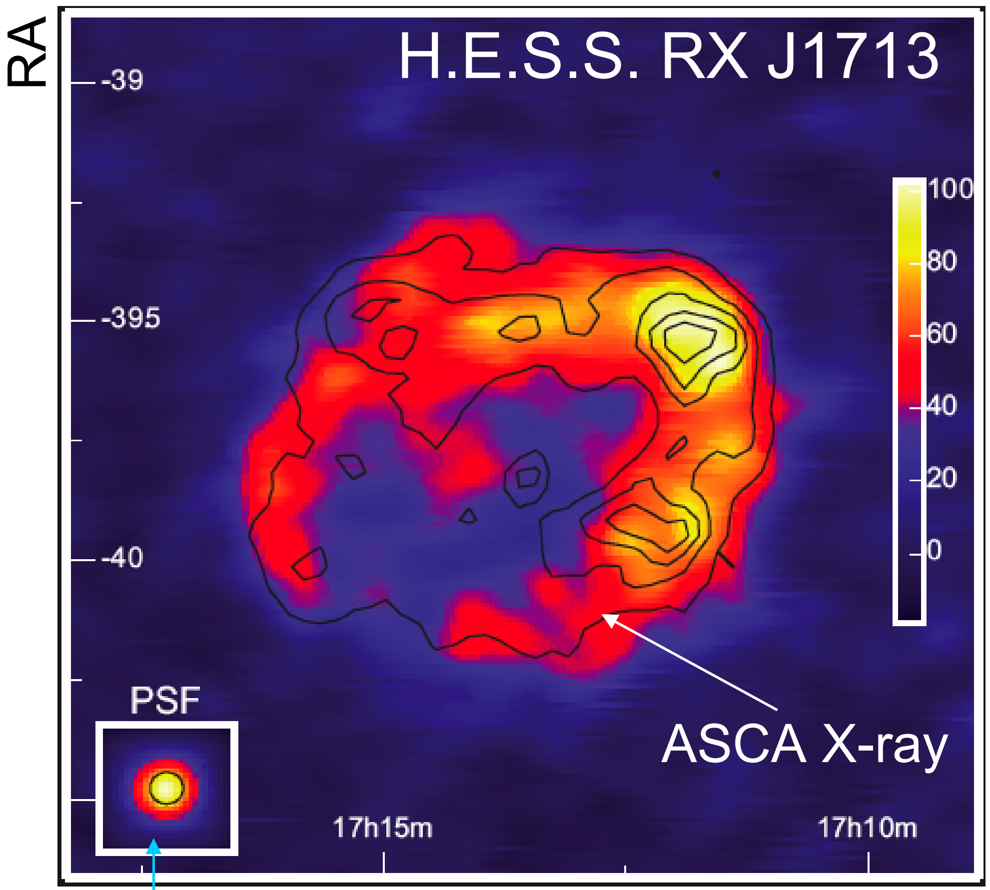
$$\frac{S}{\sqrt{Bkg}} \sim \frac{R_{sign}\, T}{\sqrt{R_{bkg}\, T\, \pi\, \alpha^2}} \sim \frac{\sqrt{T}}{\alpha}$$

High-energy particle acceleration in the shell of a supernova remnant

letters to nature

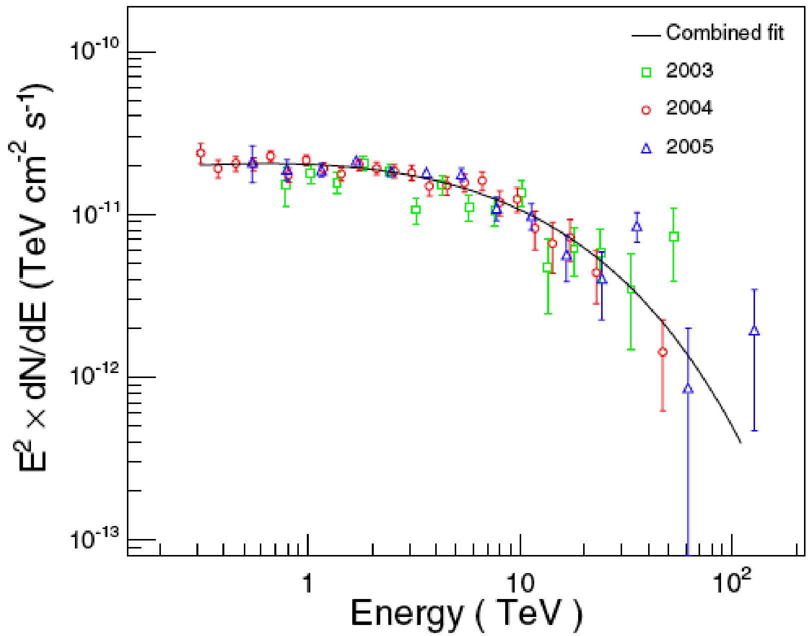
NATURE | VOL 432 | 4 NOVEMBER 2004 |

1 kpc



Dec

~0.04°

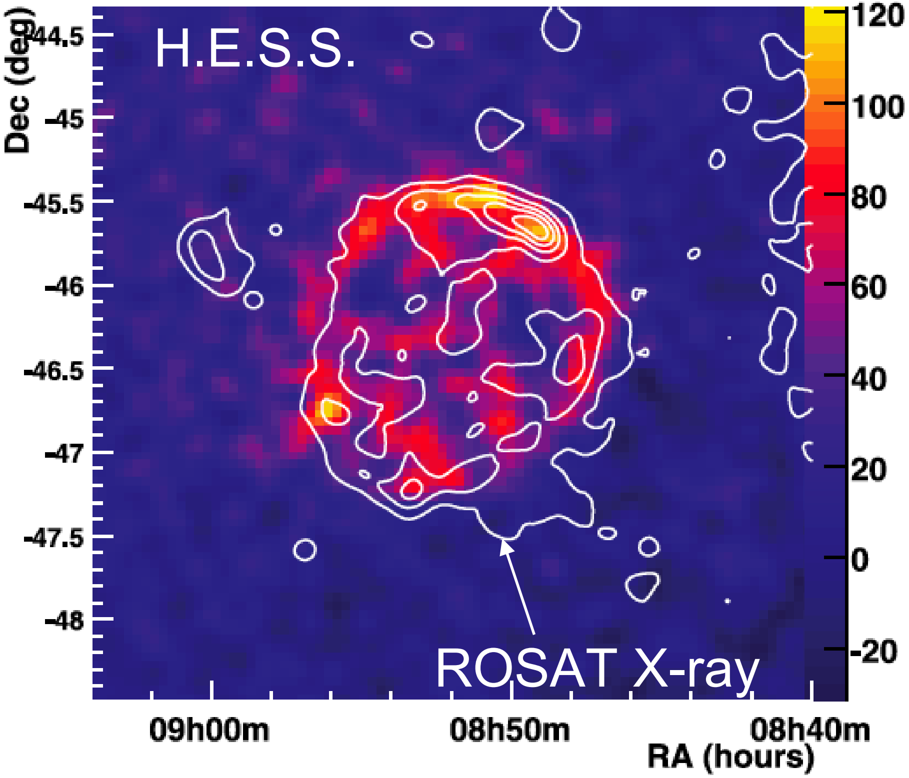


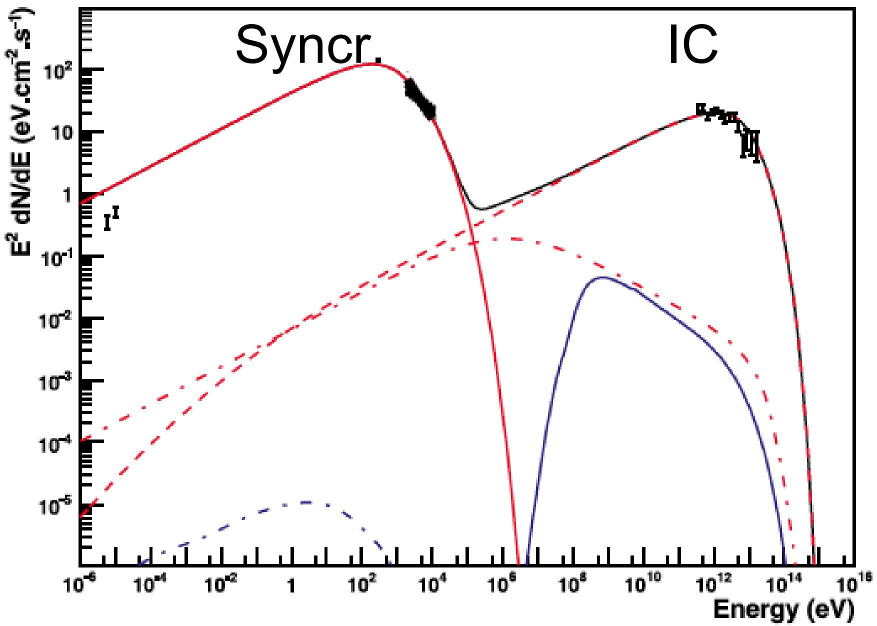
$dN/dE \sim E^{-\Gamma} \exp(-E/E_c)$

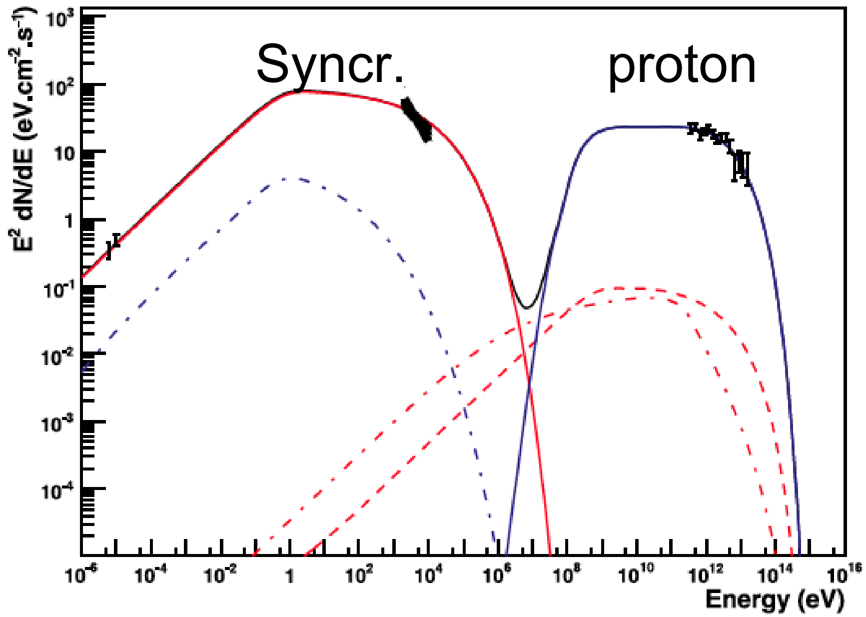
$\Gamma \sim 2$ $E_c \sim 18$ TeV

Electron or proton accelerator?

RX J0852 SNR 0.2 kpc



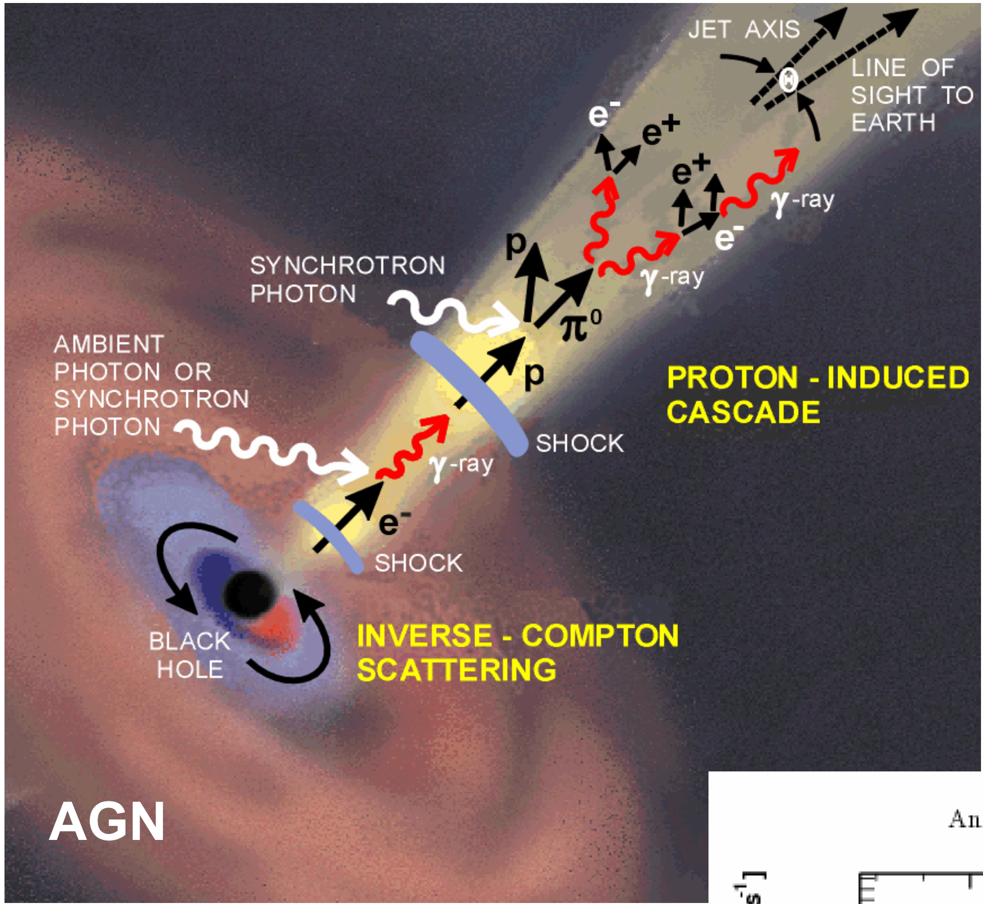




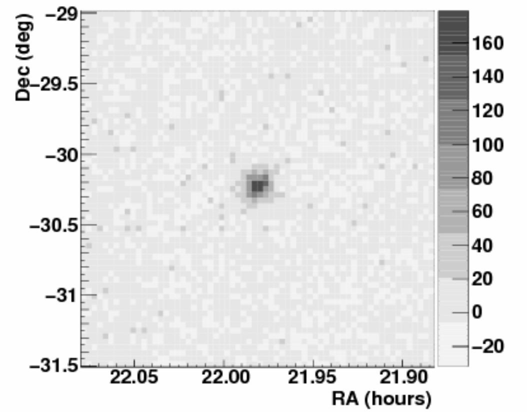
Multiwavelength and variability measurements!
(Fermi Glast)

Extragalactic sources

BLAZARS

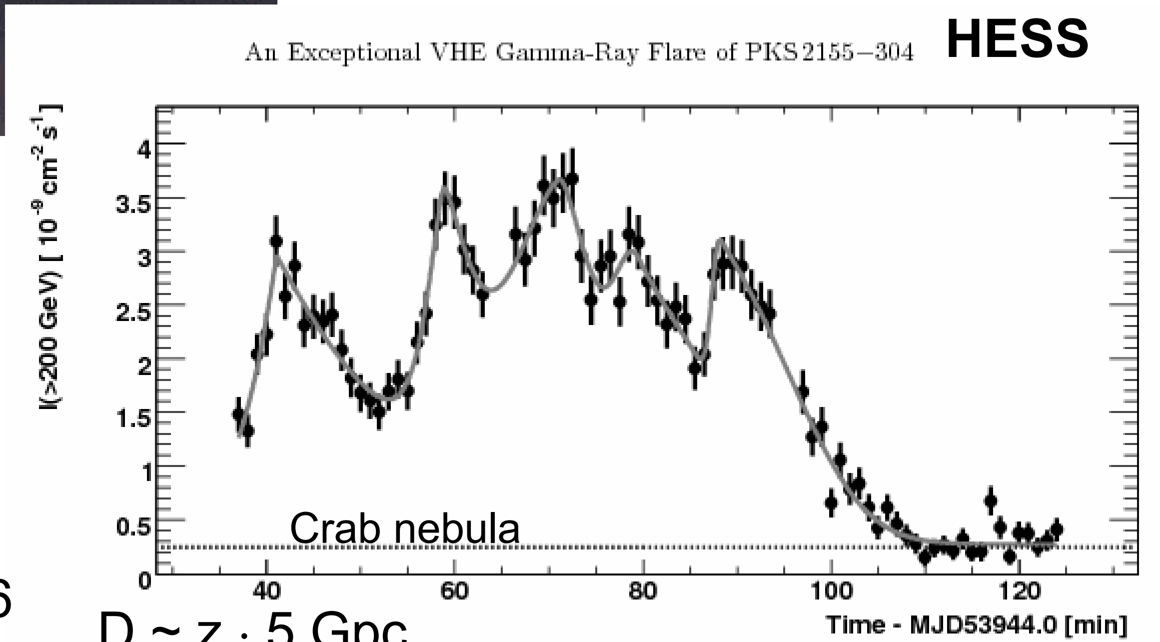


Time variability: size of the emitting region, relativistic jet



PKS2155 redshift = 0.116

HESS



D ~ z · 5 Gpc

Very-High-Energy Gamma Rays from a Distant Quasar: How Transparent Is the Universe?

The MAGIC Collaboration*

Science **320**, 1752 (2008); DOI: 10.1126/science.1157087

3C 279 redshift = 0.536

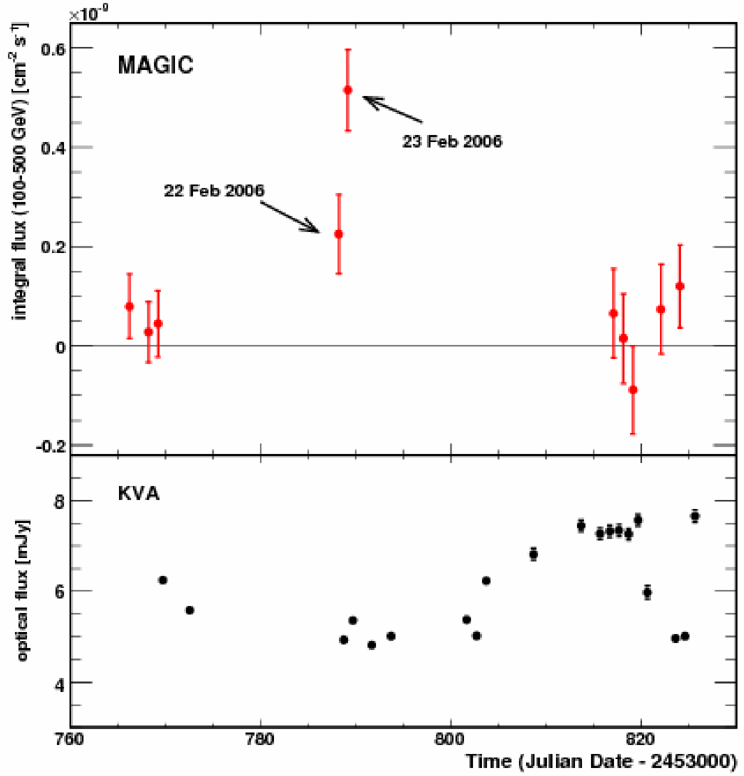
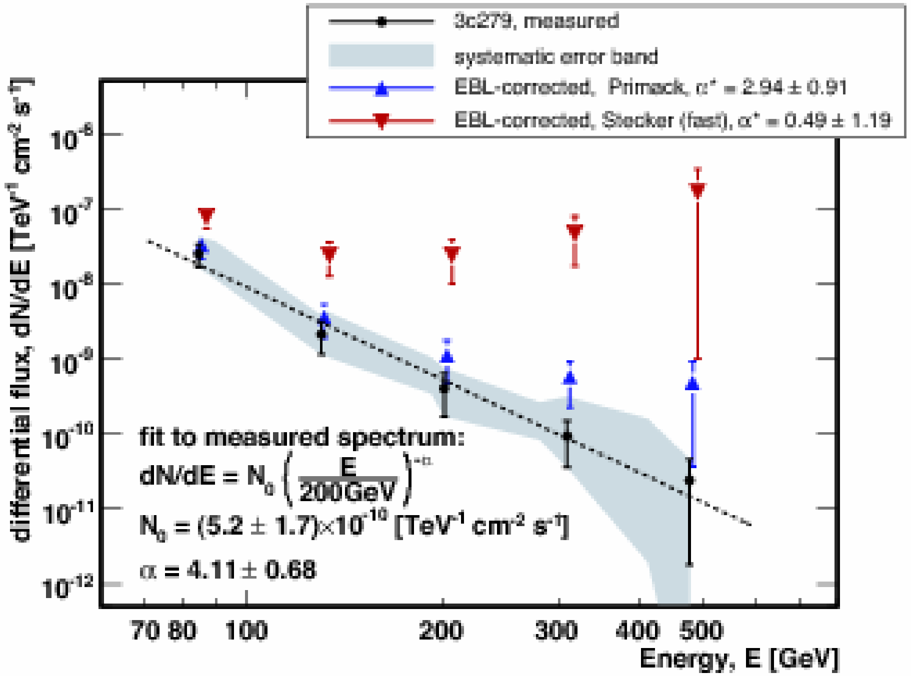


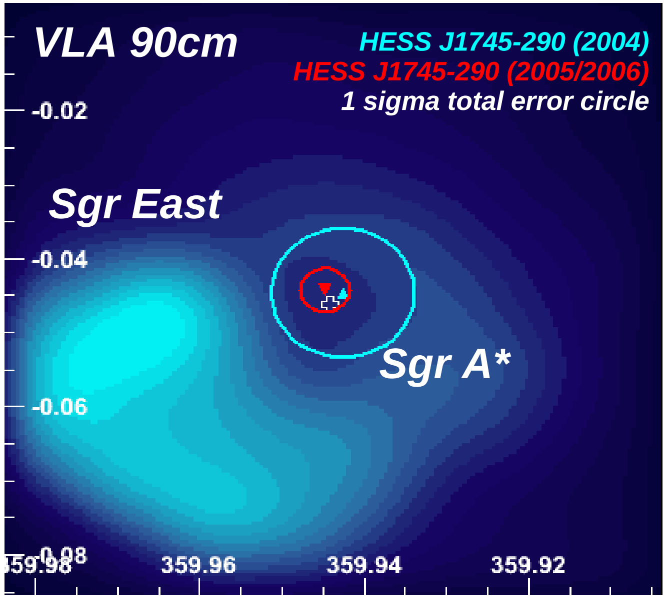
Fig. 1. Light curves. MAGIC (top) and optical R-band data (bott obtained for 3C 279 from February to March 2006. The long-t baseline for the optical flux is at 3 mJy.



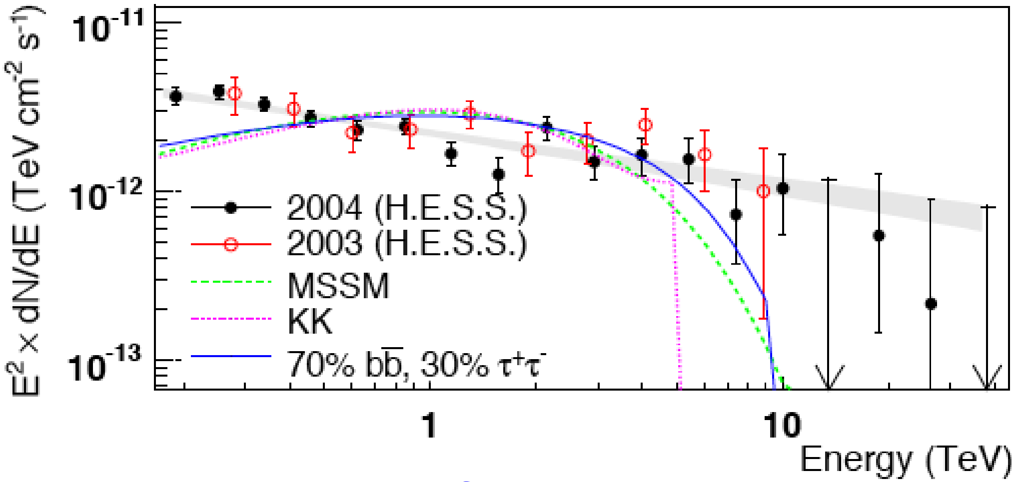
$$\gamma + \gamma_{EBL} \rightarrow e^{+} + e^{-}$$

Extragalactic Background Light: Integrate the history of electromagnetic energy production since the Big Bang

Dark Matter

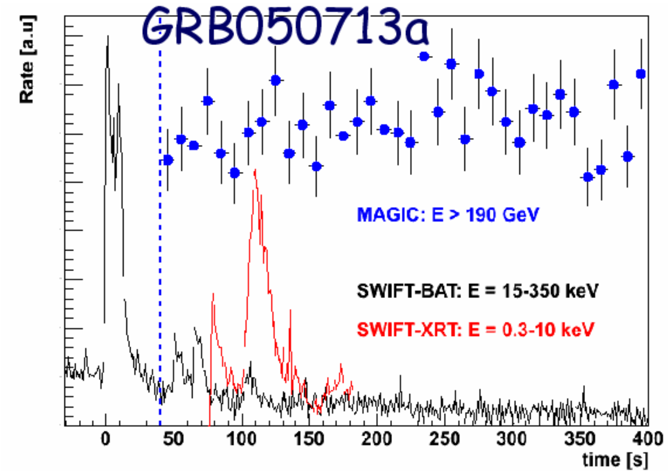


Galactic center



No evidence so far

Gamma Ray Bursts



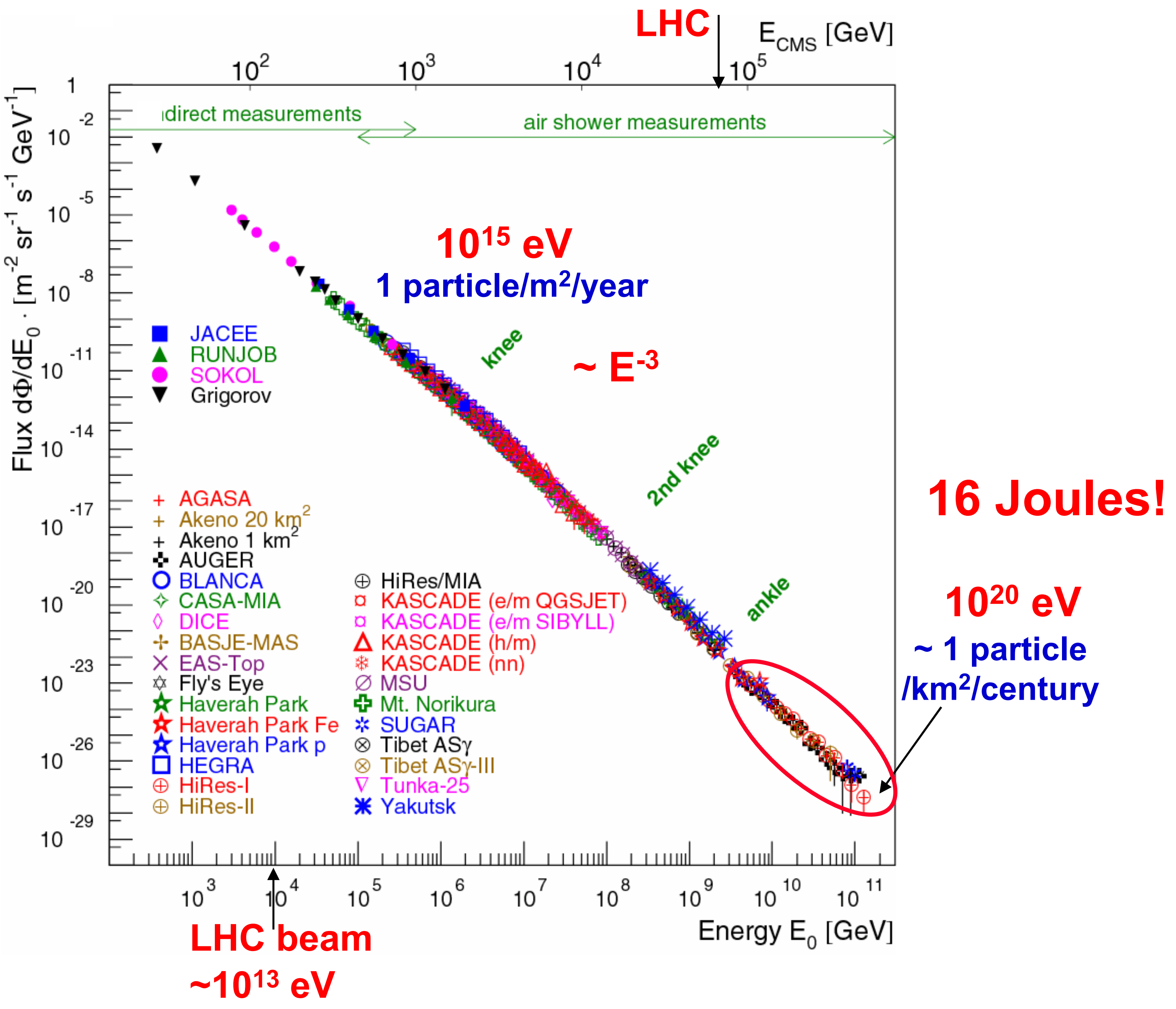
No association found so far

Sources zoology

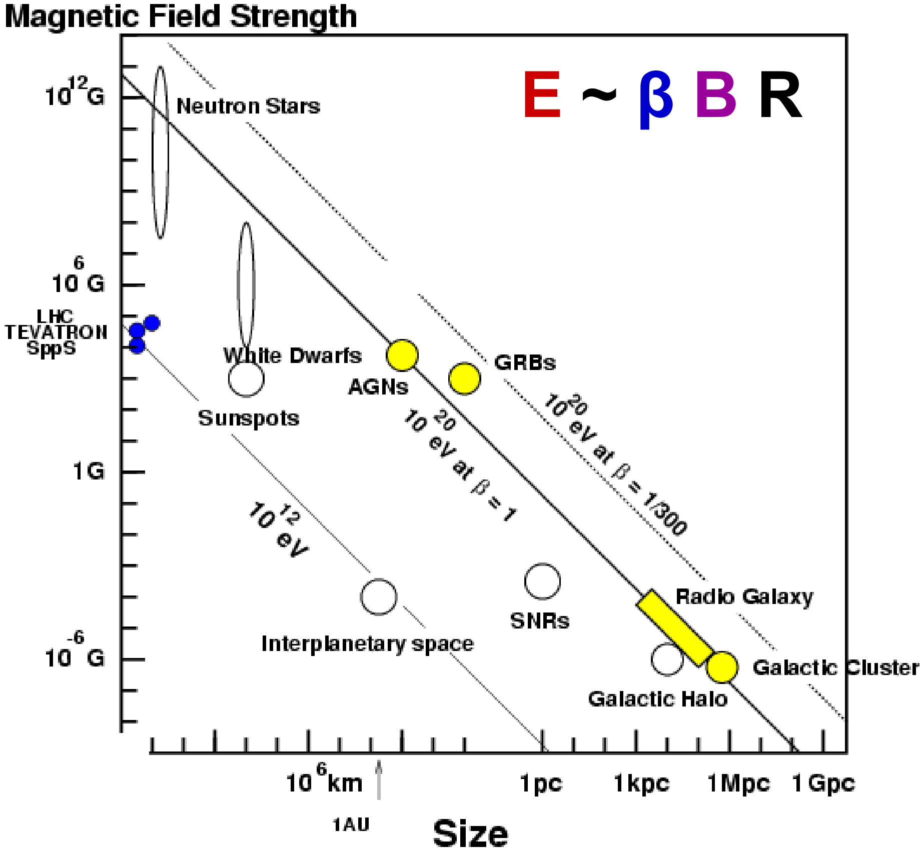
- SNR are not the most common TeV γ emitters in the galaxy
- many Pulsar Wind Nebulae
- many sources without optical counterpart

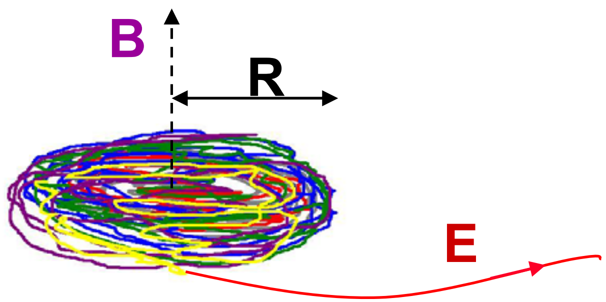
TeV γ rays have opened a new frontier in the Extreme Universe!

Ultra-High Energy Cosmic rays



10^{20} eV accelerator?





Physics (well) beyond the SM?

A few articles titles…..

- Microscopic black hole detection in UHECR
- Lorentz invariance violation …..
- Instant preheating mechanism and UHECR.
- Flipped Cryptons and the UHECRs.
- Super-heavy X particle decay …..
- Strongly interacting neutrinos ……
- Electroweak instantons as a solution …….
- Quantum-gravity phenomenology ……
- Superheavy dark matter……..
- Long-lived neutralino ……
- Cosmic Rays and Large Extra Dimensions
- UHECR from relic topological defects.
- Are UHECR a signal for supersymmetry?.

………

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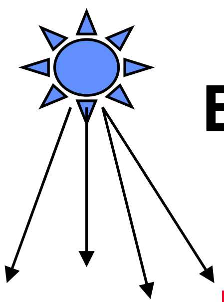


END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

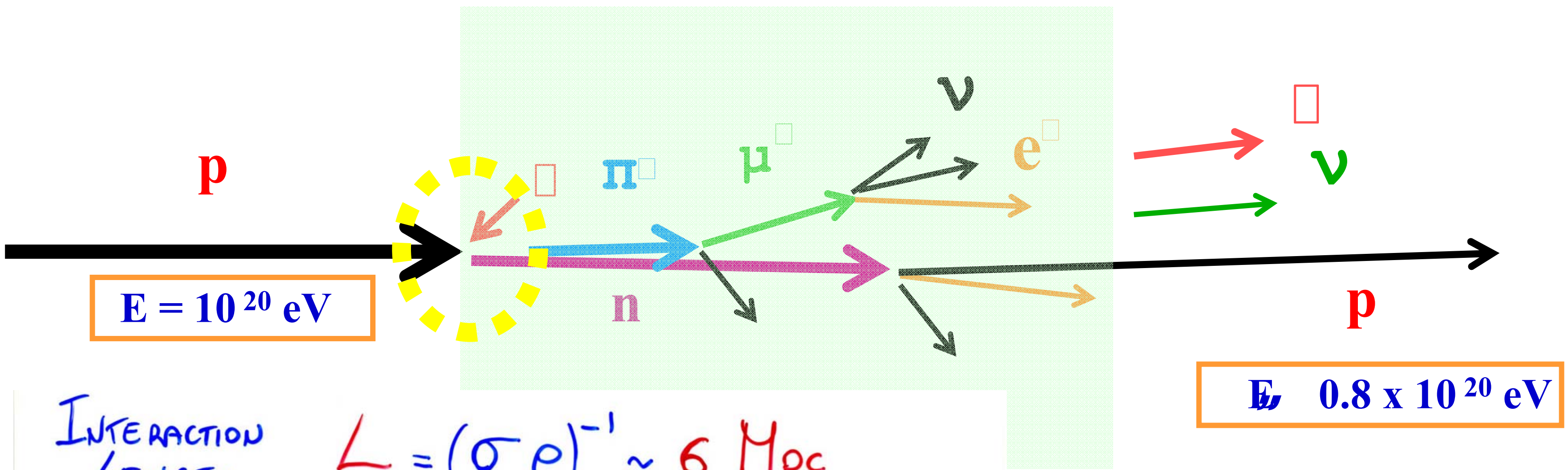
This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

The Greisen-Zatsepin-Kusmin "cutoff"

Pion photoproduction

$$p + \gamma_{2.7\,K} \rightarrow N + \pi$$

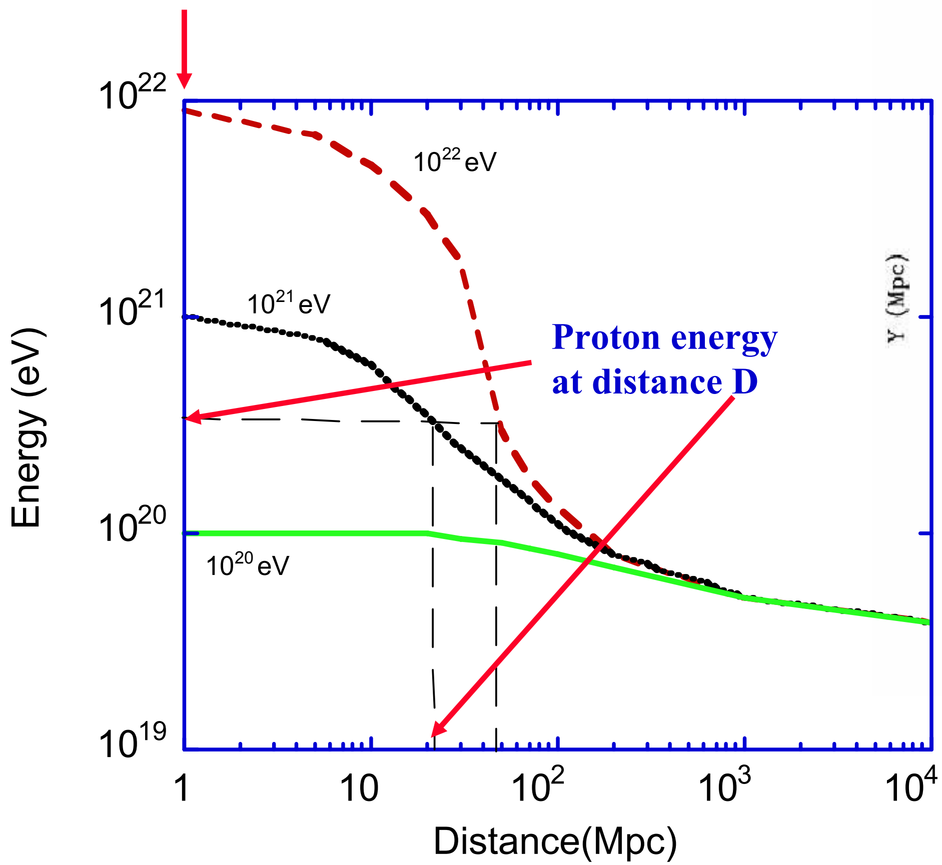
$$\text{for } E_p > 5\ 10^{19}\ \text{eV}$$



INTERACTION LENGTH $L = (\sigma\, \rho_\gamma)^{-1} \simeq 6$ Mpc

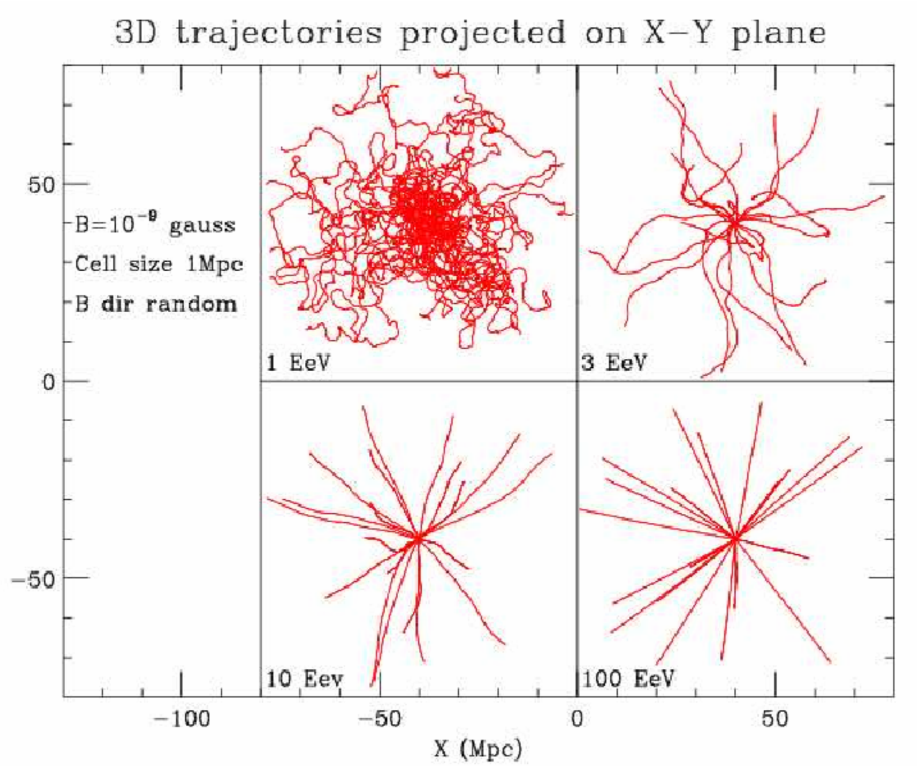
σ: 130 μb; ρ_γ: 400/cm³

The GZK cutoff



UHECR source must be closer than 50-100 Mpc!

Back to the origin

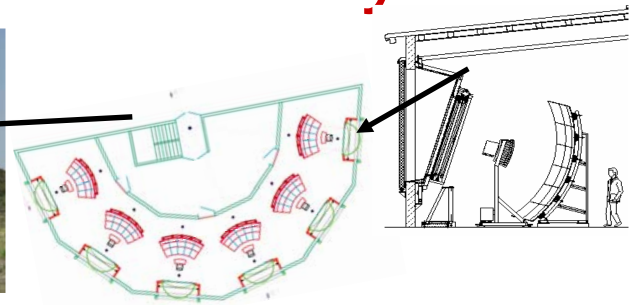


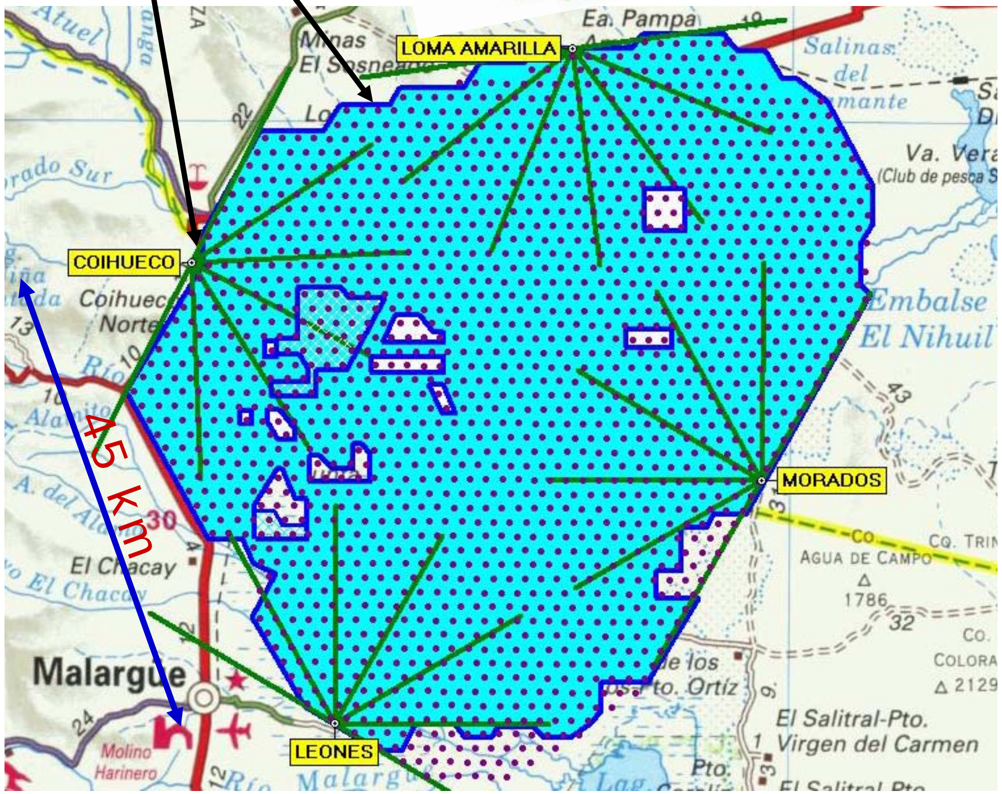
EeV = 10^{18} eV

… and we should be able to see it!

The Pierre Auger Observatory

Argentina, Mendoza, Malargue
1.4 km altitude, 870 g/cm^2





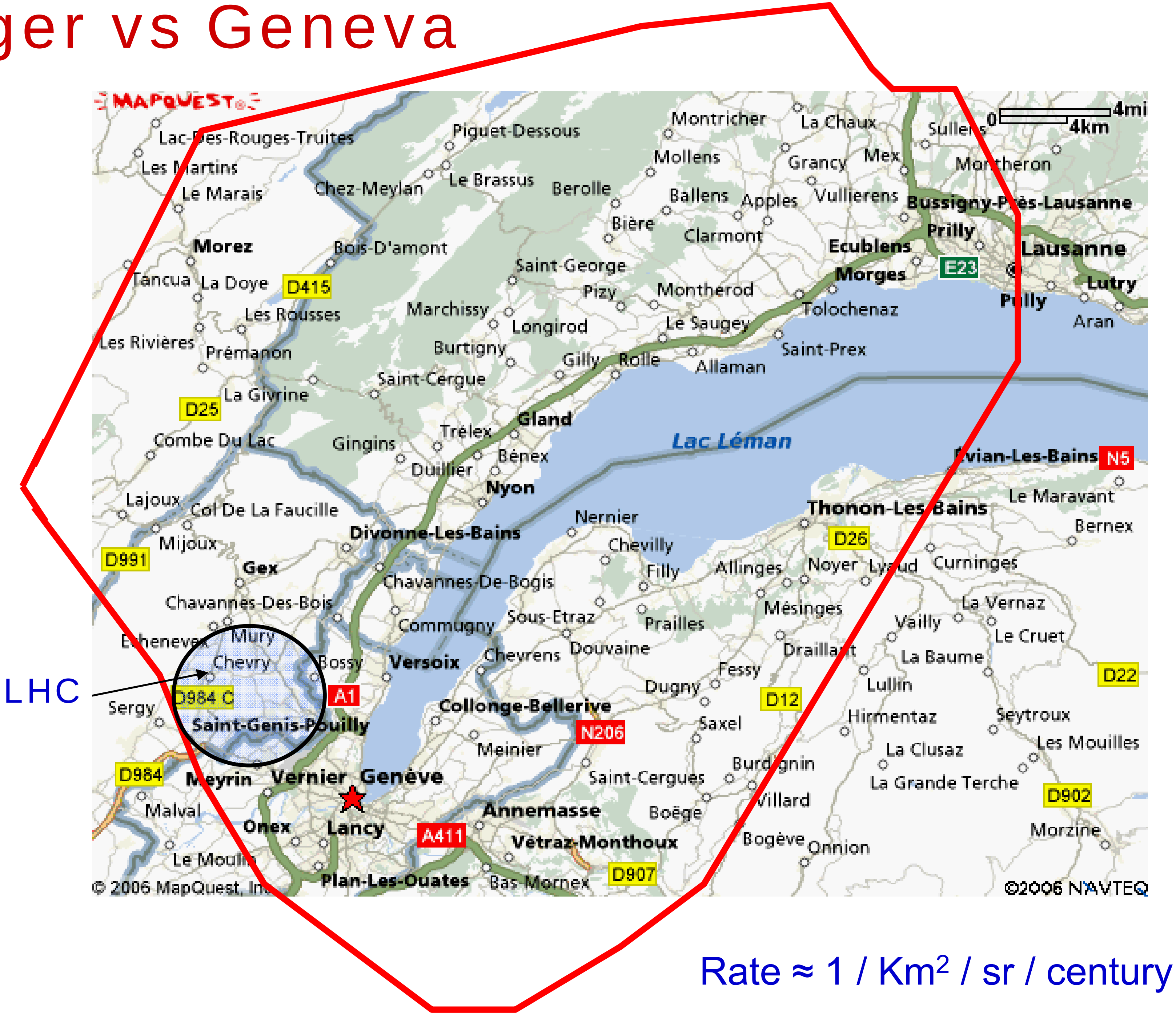
Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy

Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*

PIERRE AUGER OBSERVATORY

1600 water Cherenkov detectors,
1.5 km spacing, 3000 km^2,
4 x 6 fluorescence telescopes

Auger vs Geneva

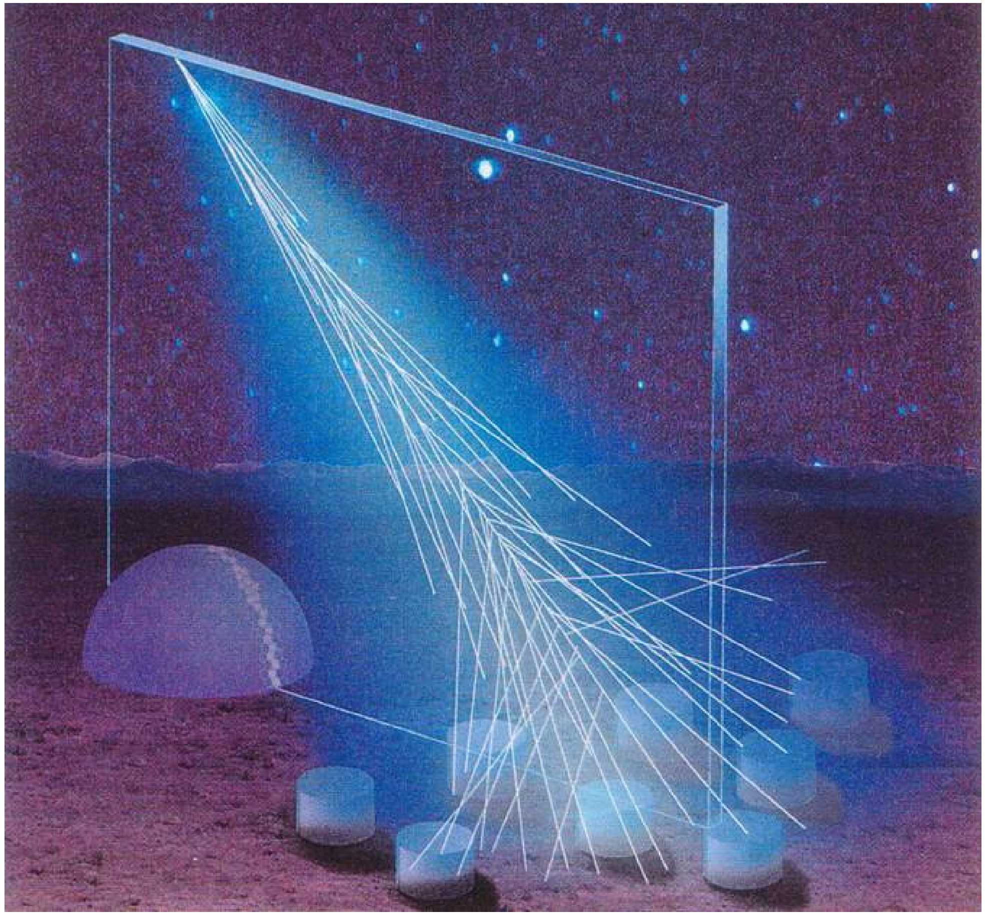


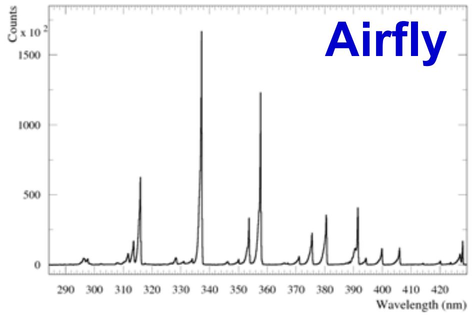
Rate ≈ 1 / Km^2 / sr / century!

The Auger site

SD physicists making friends

The Auger hybrid detector concept





300-400 nm light from de-excitation of atmospheric nitrogen (fluorescence light)
≈ 4 γ's / m /electron

10^{19} eV ⇨ 10^{10} e

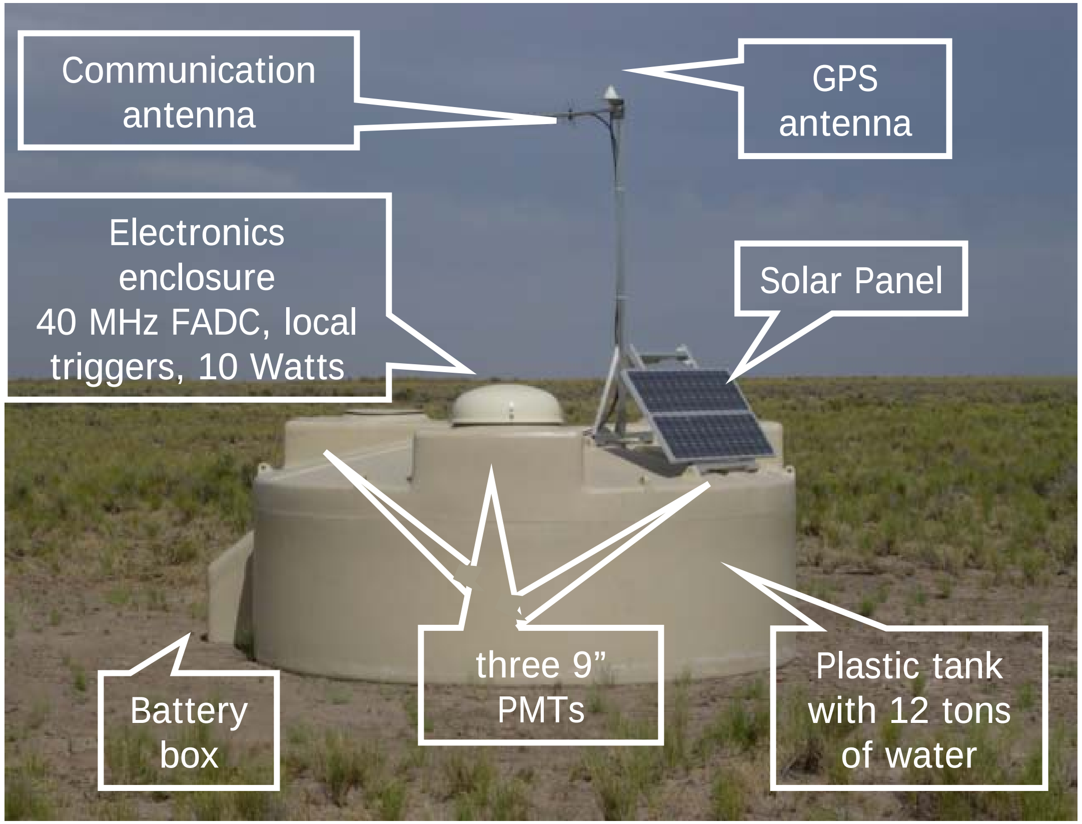
Fluorescence Detector

- E + longitudinal development
- Time ≈ direction
- ≈ 10% duty cycle

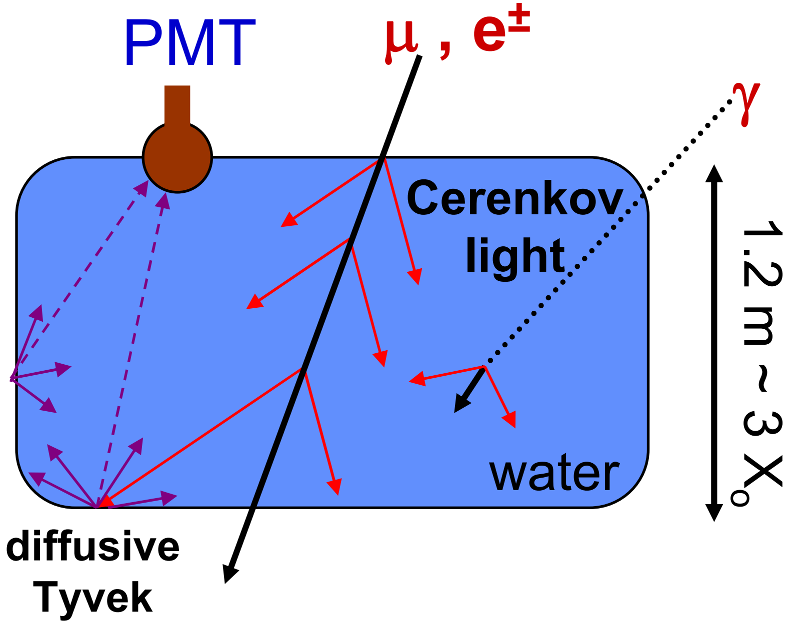
Trigger efficiency
Energy-direction calibration, syst. errors

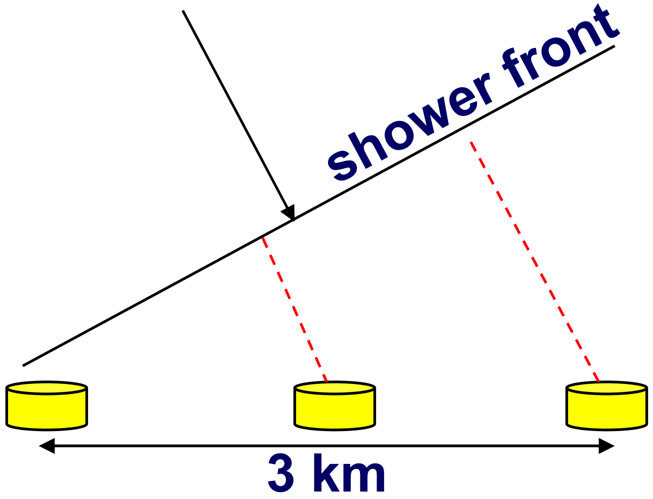
Surface Detector

- Shower size ≈ E
- Time ≈ direction
- 100% duty cycle



Auger Surface Detector





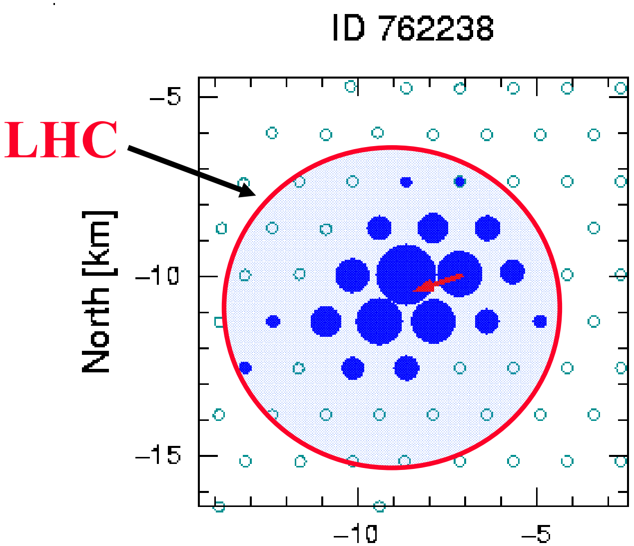
Angular resolution

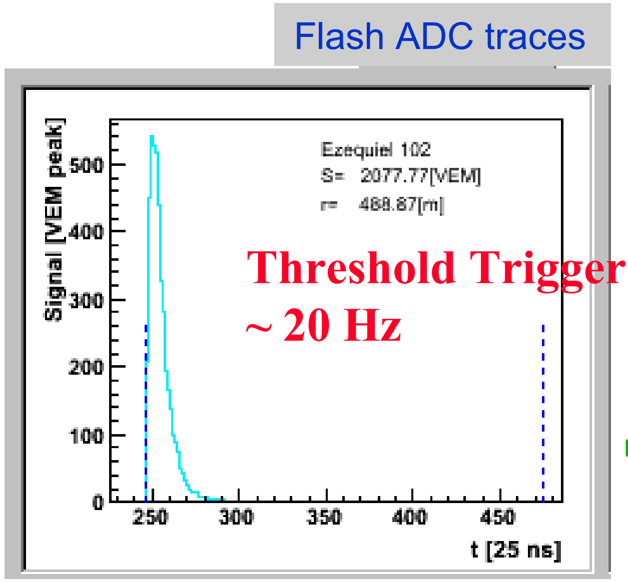
≈100 ns timing accuracy x c

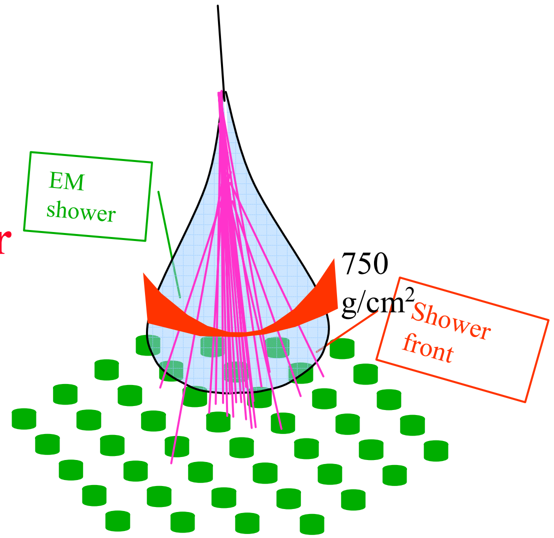
≈30 m

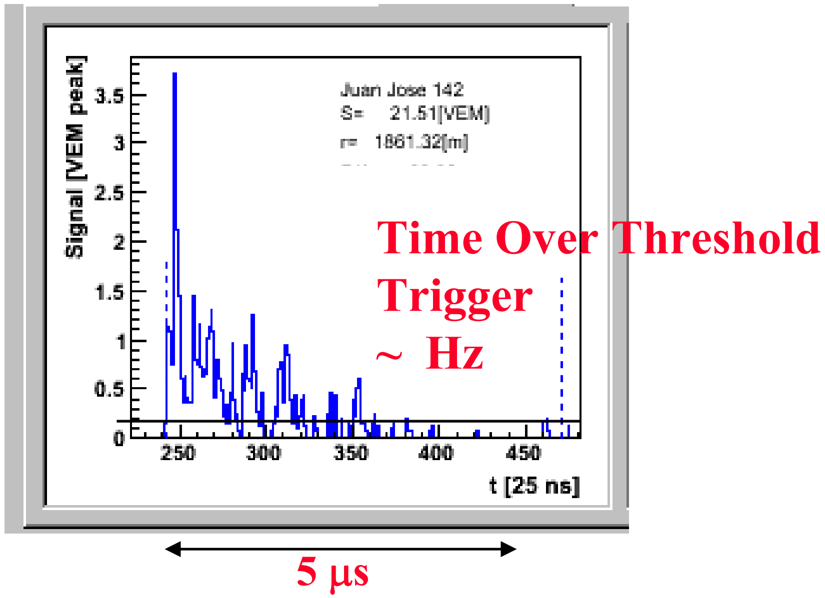
Δθ ≈ 30/3000 = 10 mrad ≈ 0.5°

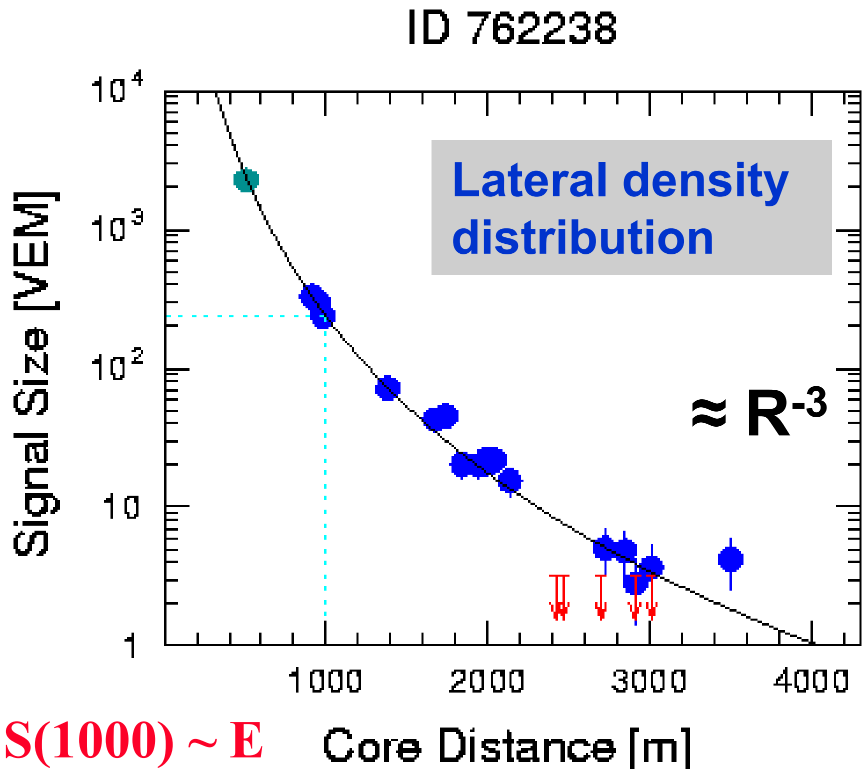
AUGER SD in action ~ 70 EeV





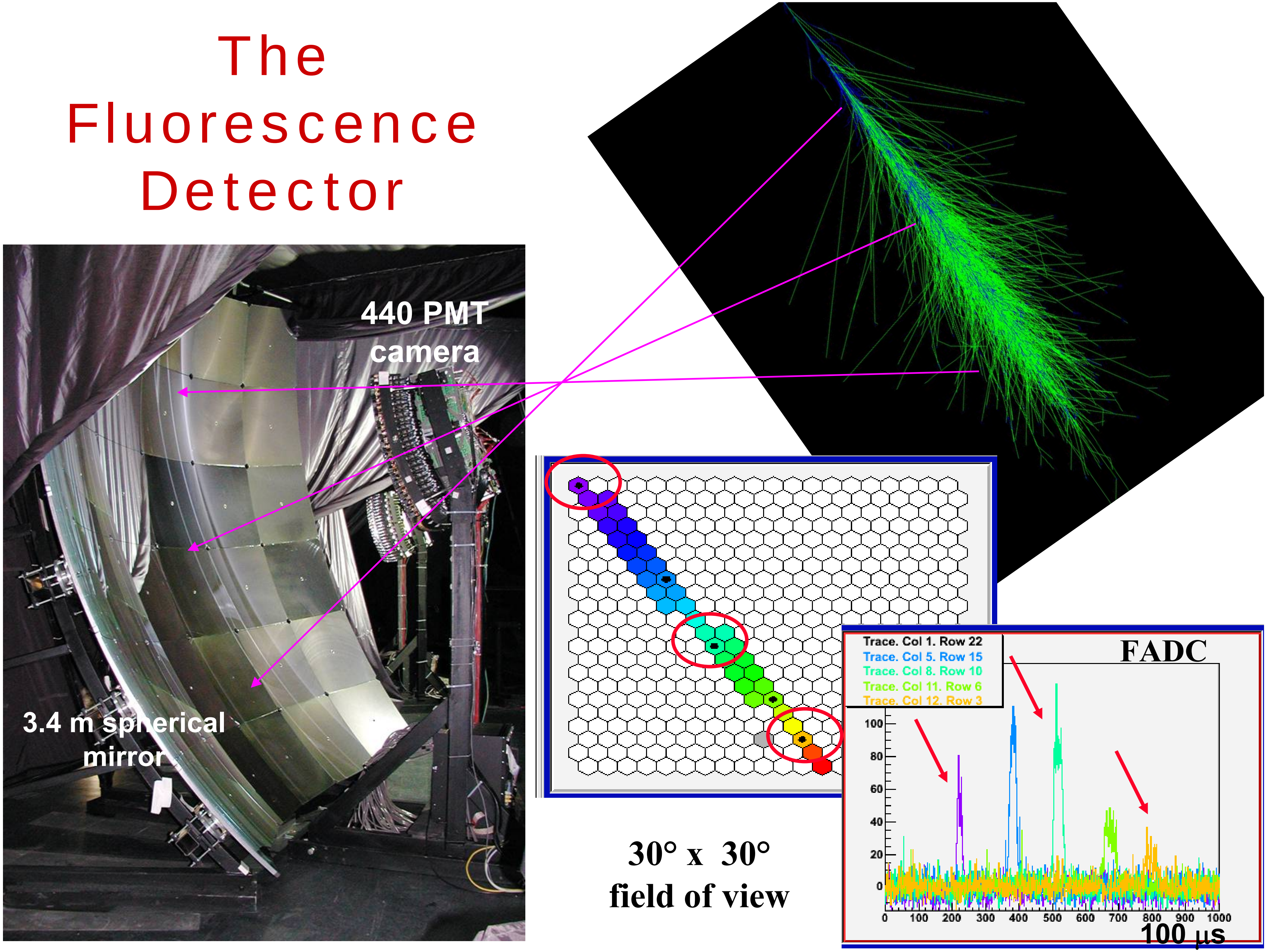






Malargue 2006…

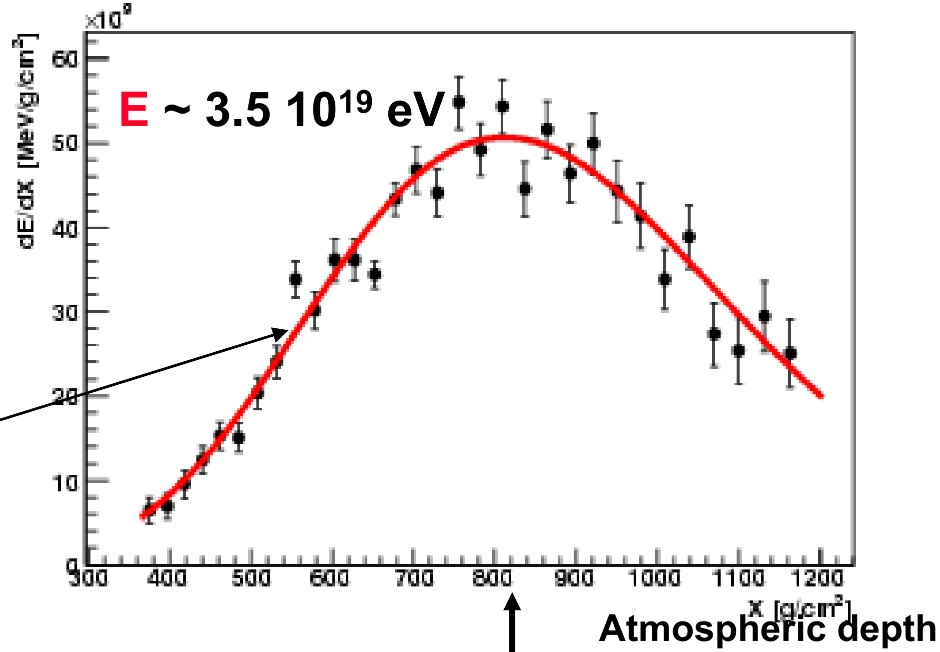
The Fluorescence Detector



UHECR Calorimetry

- Air as an electromagnetic-hadronic calorimeter medium:
  25 radiation lengths, 15 interaction lengths
- UHE cosmic ray, high energy secondary hadrons interaction vs decay, very good hadronic calorimeter   "e/h" → 1 (only 10% of energy not in e.m. cascade)
- Robust energy determination for UHECR

Energy resolution ~ 10%
Systematic unc. ~ 20%

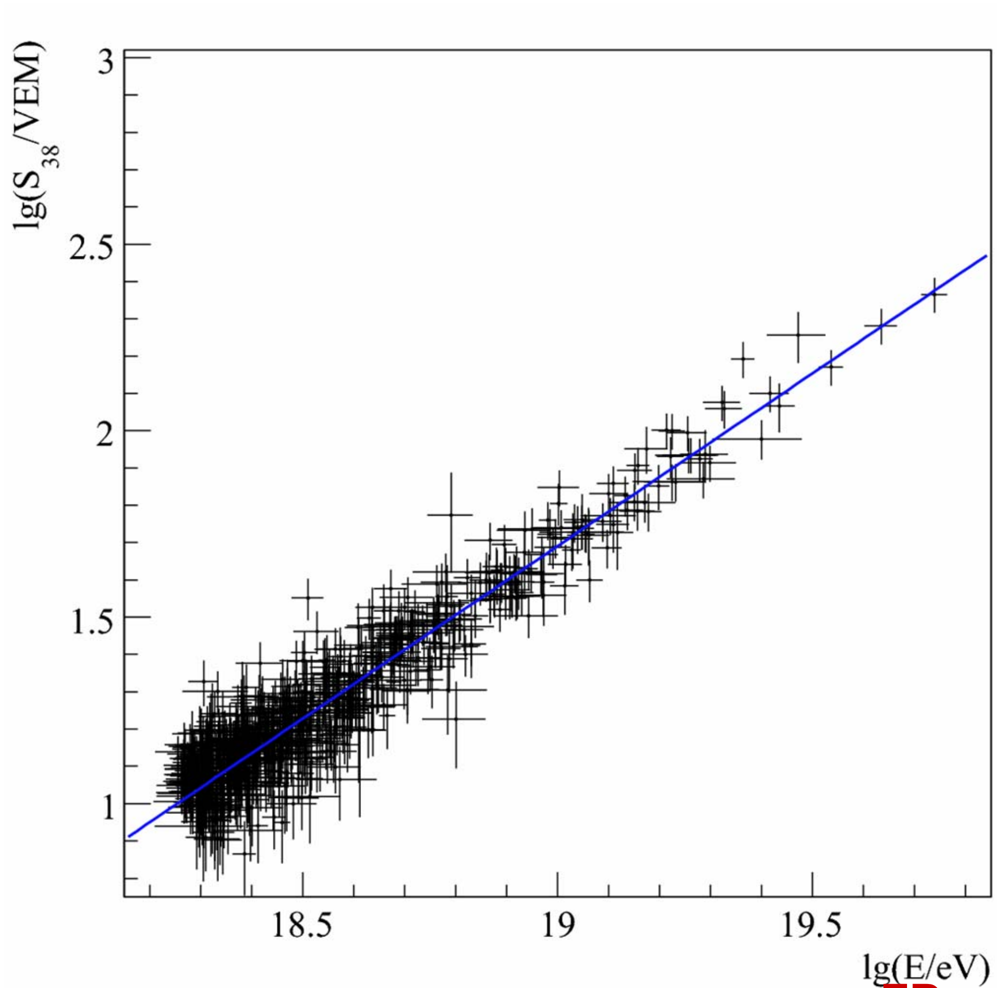


Gaisser-Hillas
(Longo-Sestili)

X_{max} ~ 810 g/cm²

SD Energy Calibration

SD

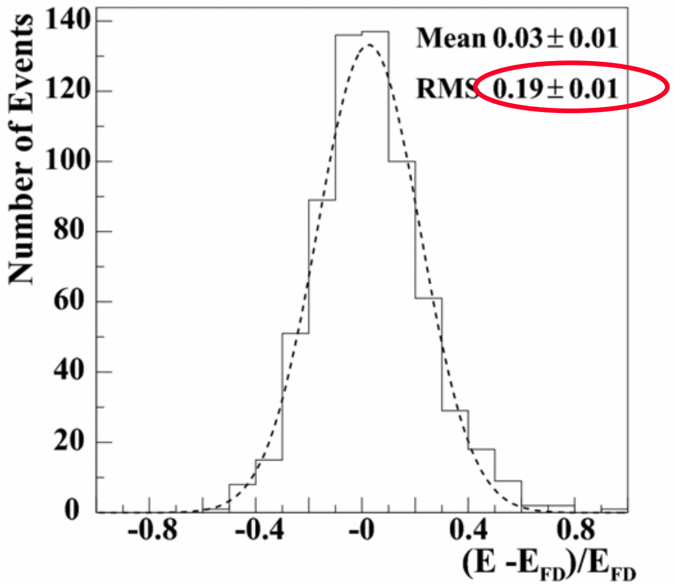


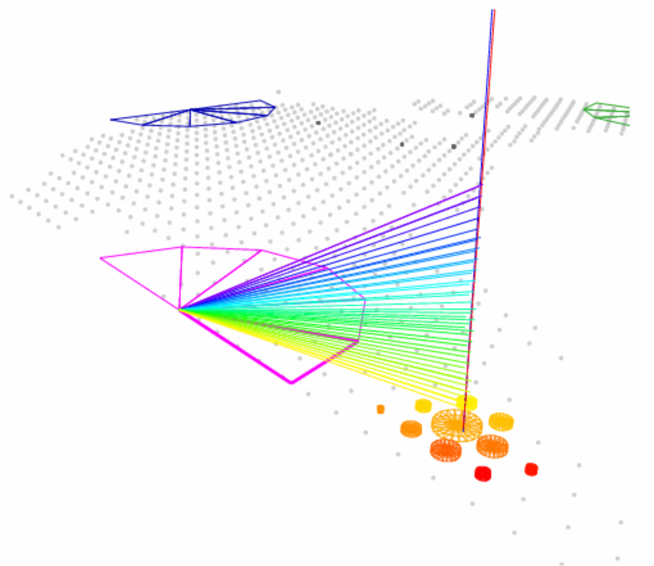
FD

$$E_{SD} = A\ (S_{38})^b$$

b ~ 1

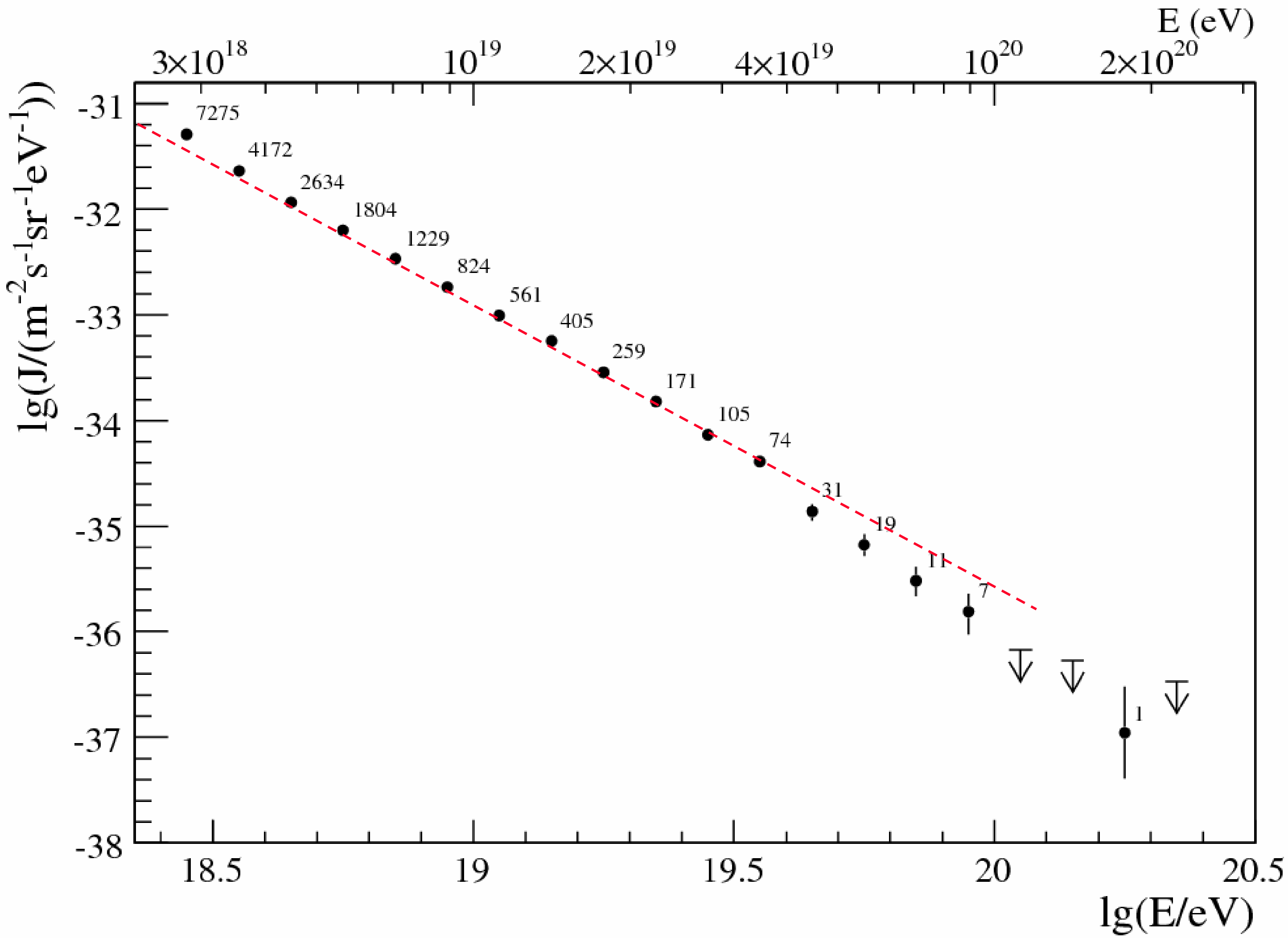
Energy resolution better than 20%





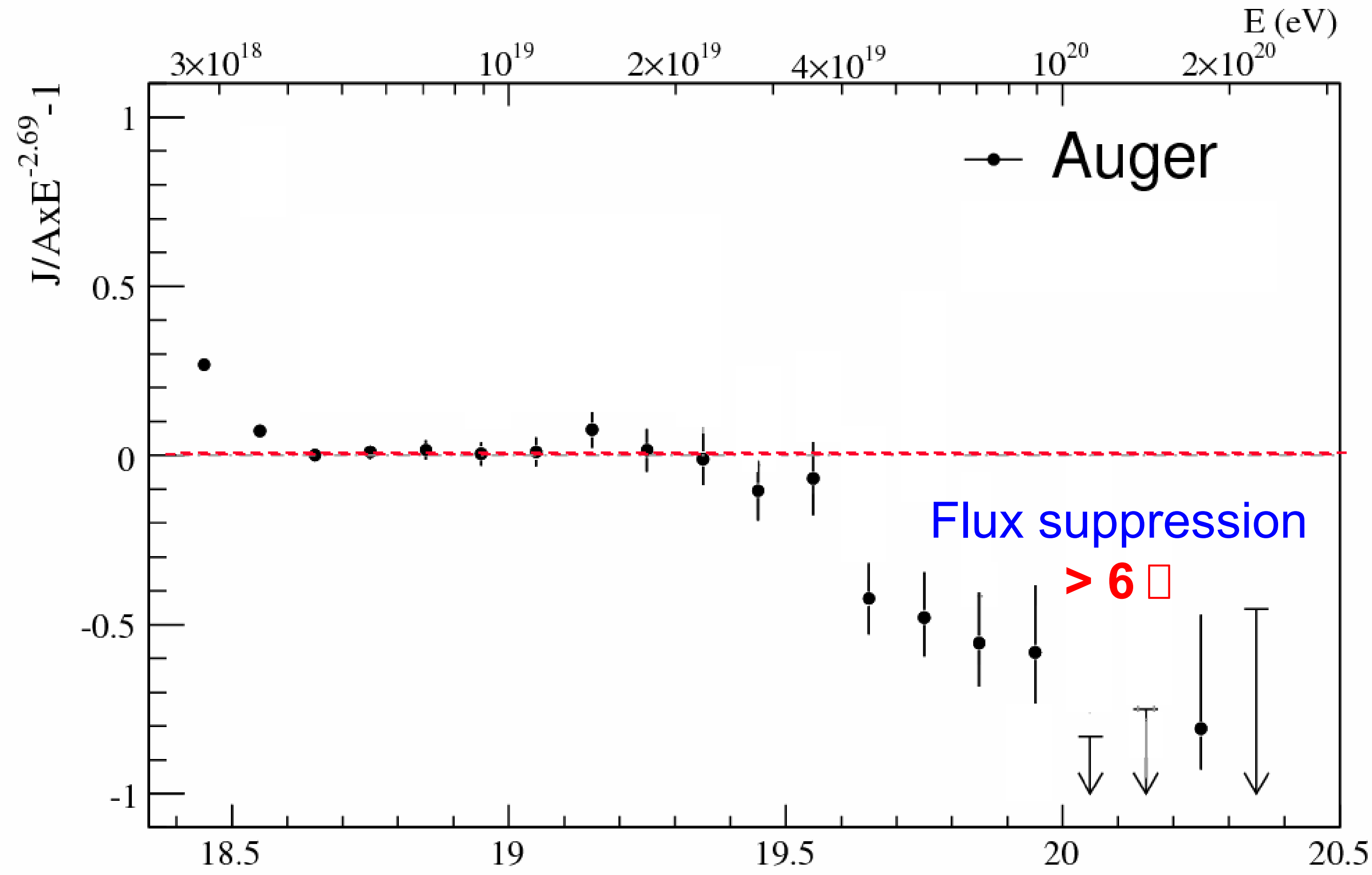
Selected for a Viewpoint in *Physics*
PRL **101,** 061101 (2008) PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2008

Observation of the Suppression of the Flux of Cosmic Rays above 4×10^{19} eV



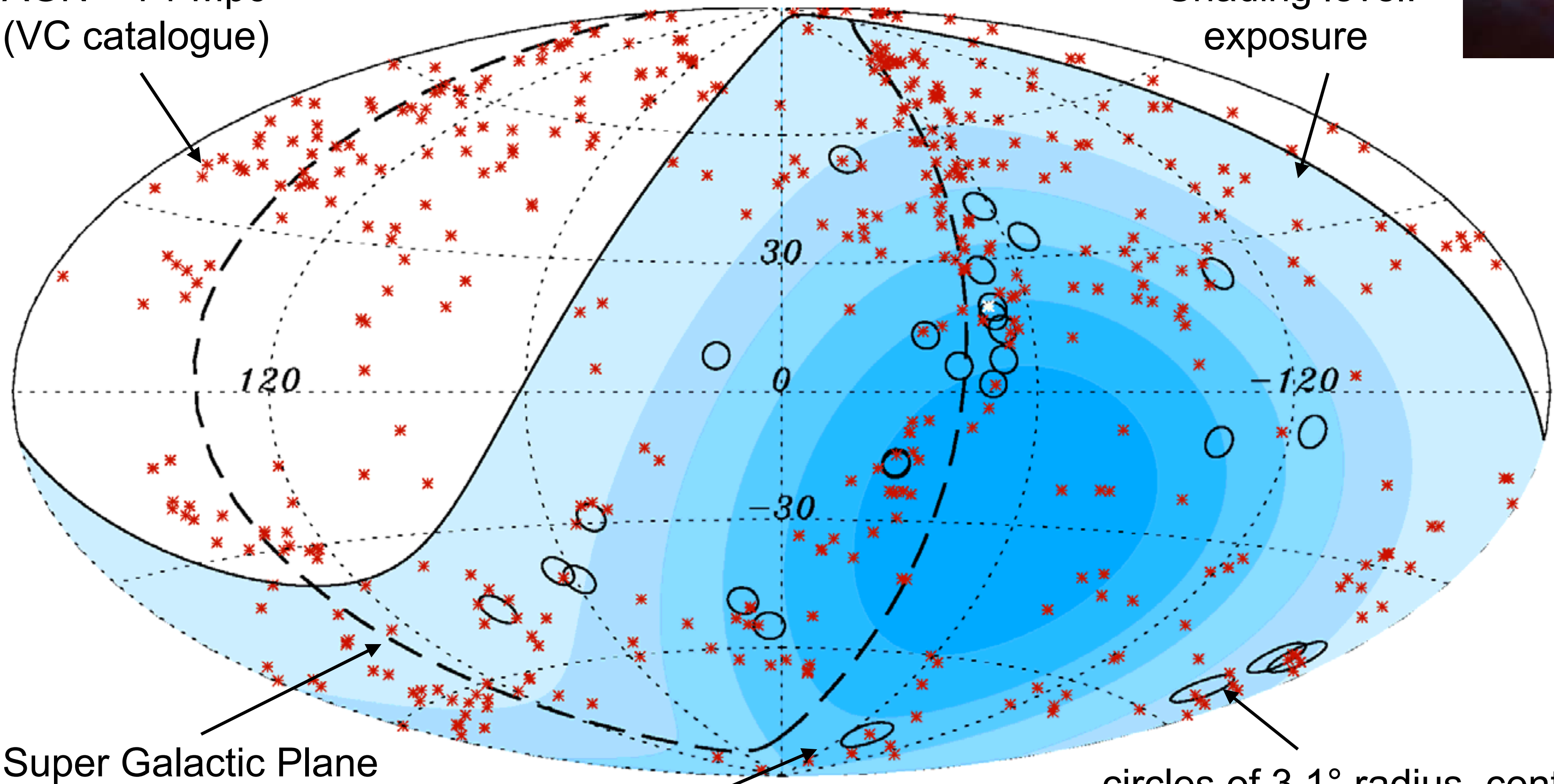
20000 events $> 3 \cdot 10^{18}$ eV

END TO THE COSMIC-RAY SPECTRUM ~~?~~



	expected	observed
$N_{events}(E>4\cdot10^{19}\ eV)$:	**167**	**66**
$N_{events}(E>10^{20}\ eV)$:	**35**	**1**

UHECR Auger sky above $5.7 \cdot 10^{19}$ eV



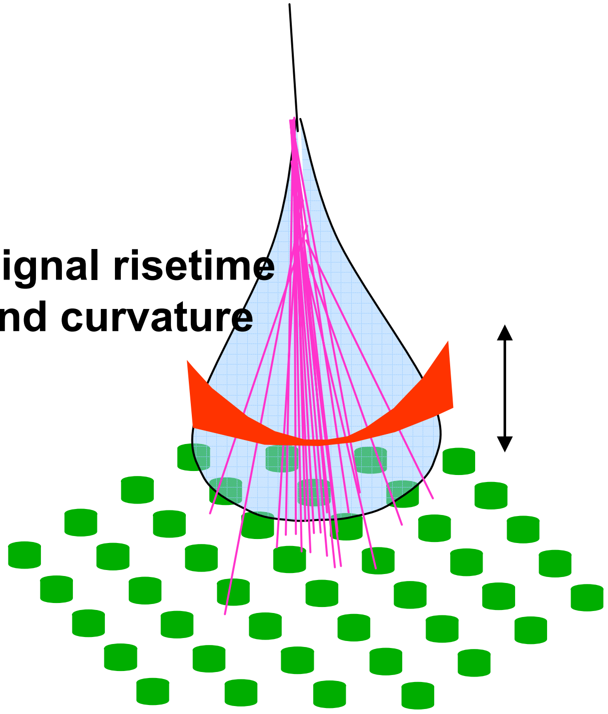
20 / 27 events correlate (5.6 expected for isotropic flux)

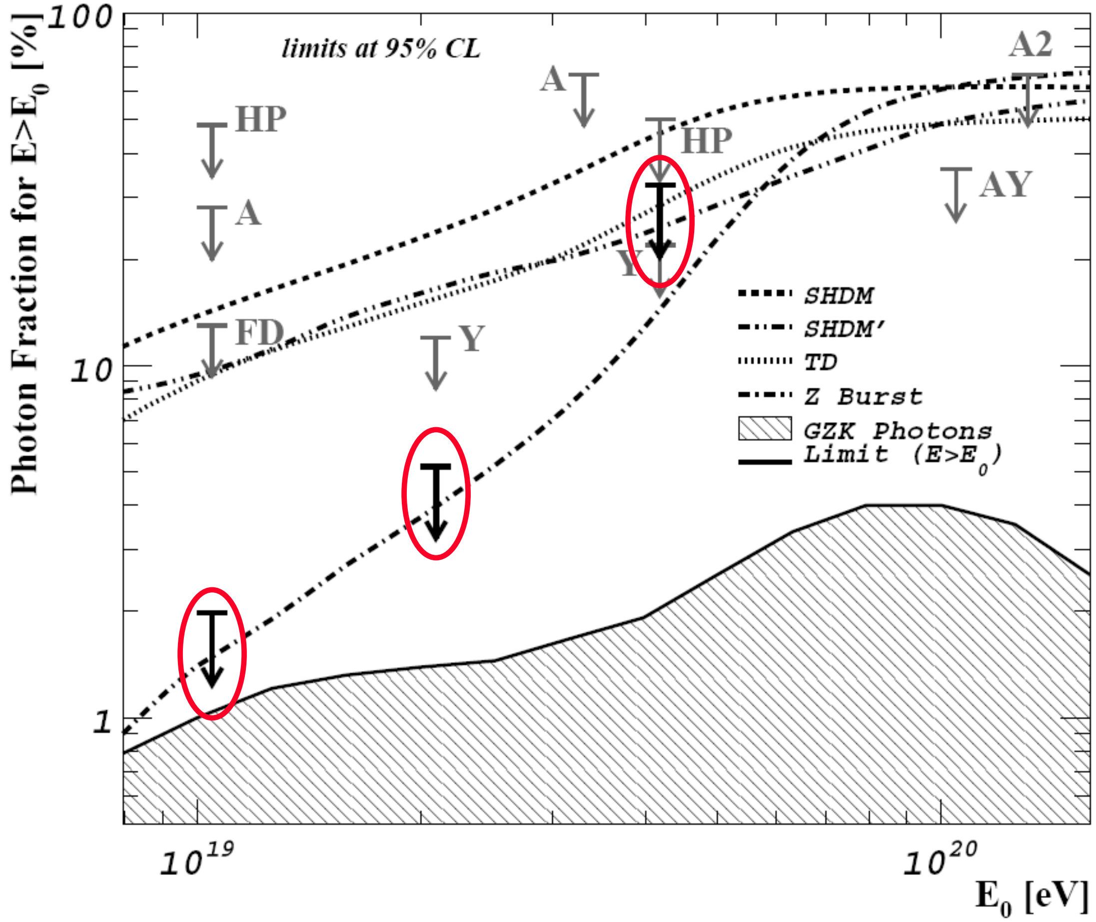
Isotropy of UHECR rejected at 99% CL

Tantalizing possible correlation with nearby extragalactic sources

Exotics Physics limits

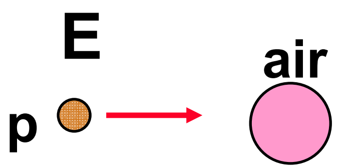
Signal risetime and curvature



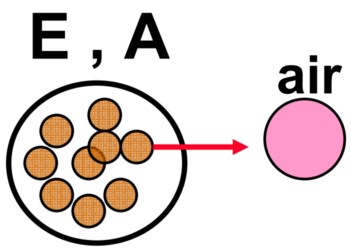


disfavour exotic “particle physics” models

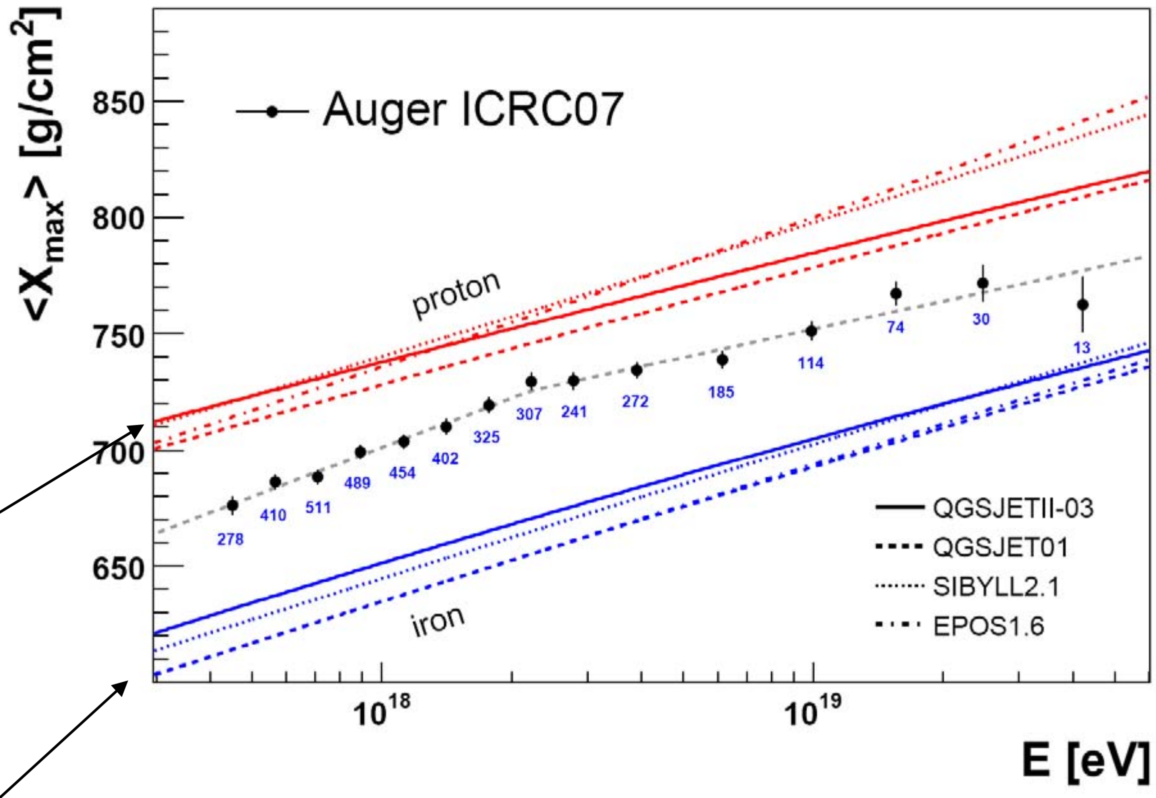
UHECR Composition



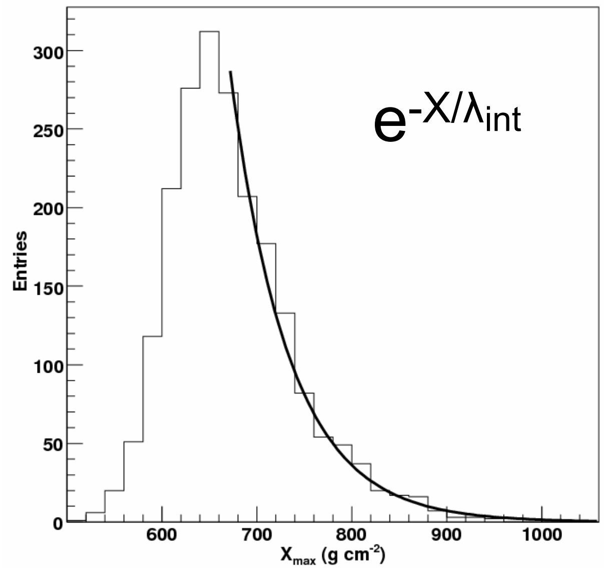
$X_{max} \sim \ln(E)$



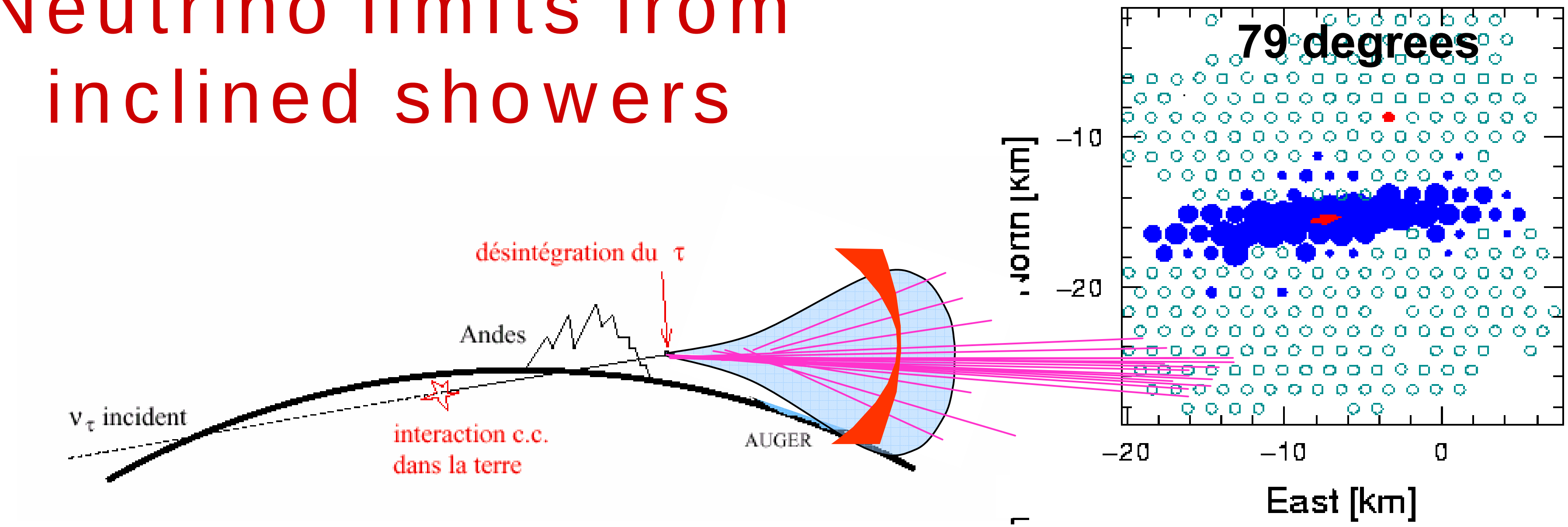
$X_{max} \sim \ln(E/A)$

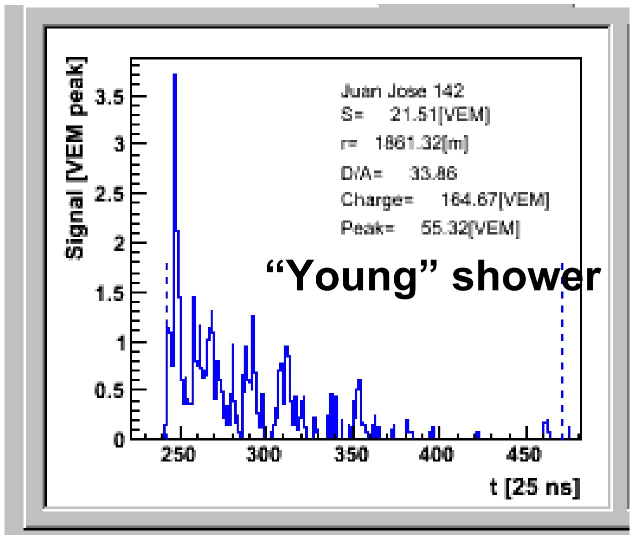


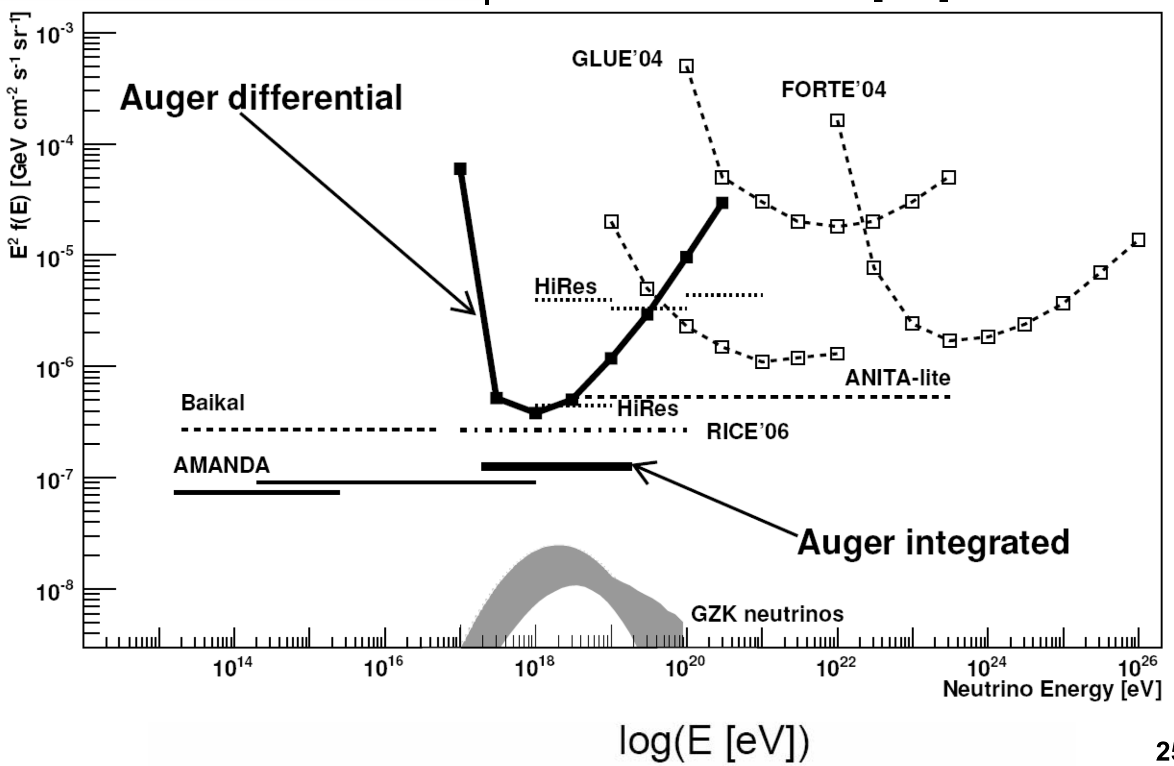
Particle interactions at the highest energy



Neutrino limits from inclined showers

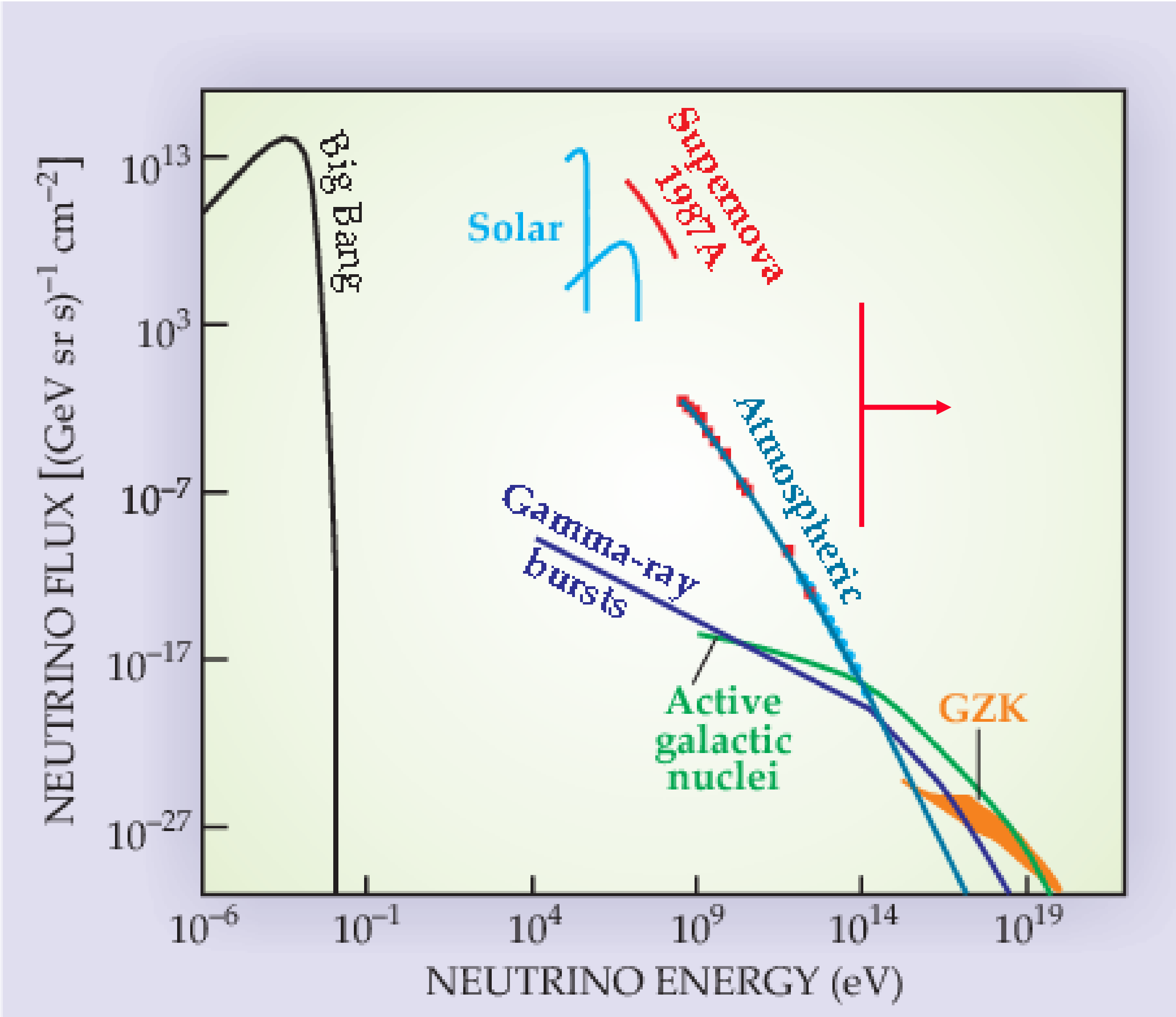


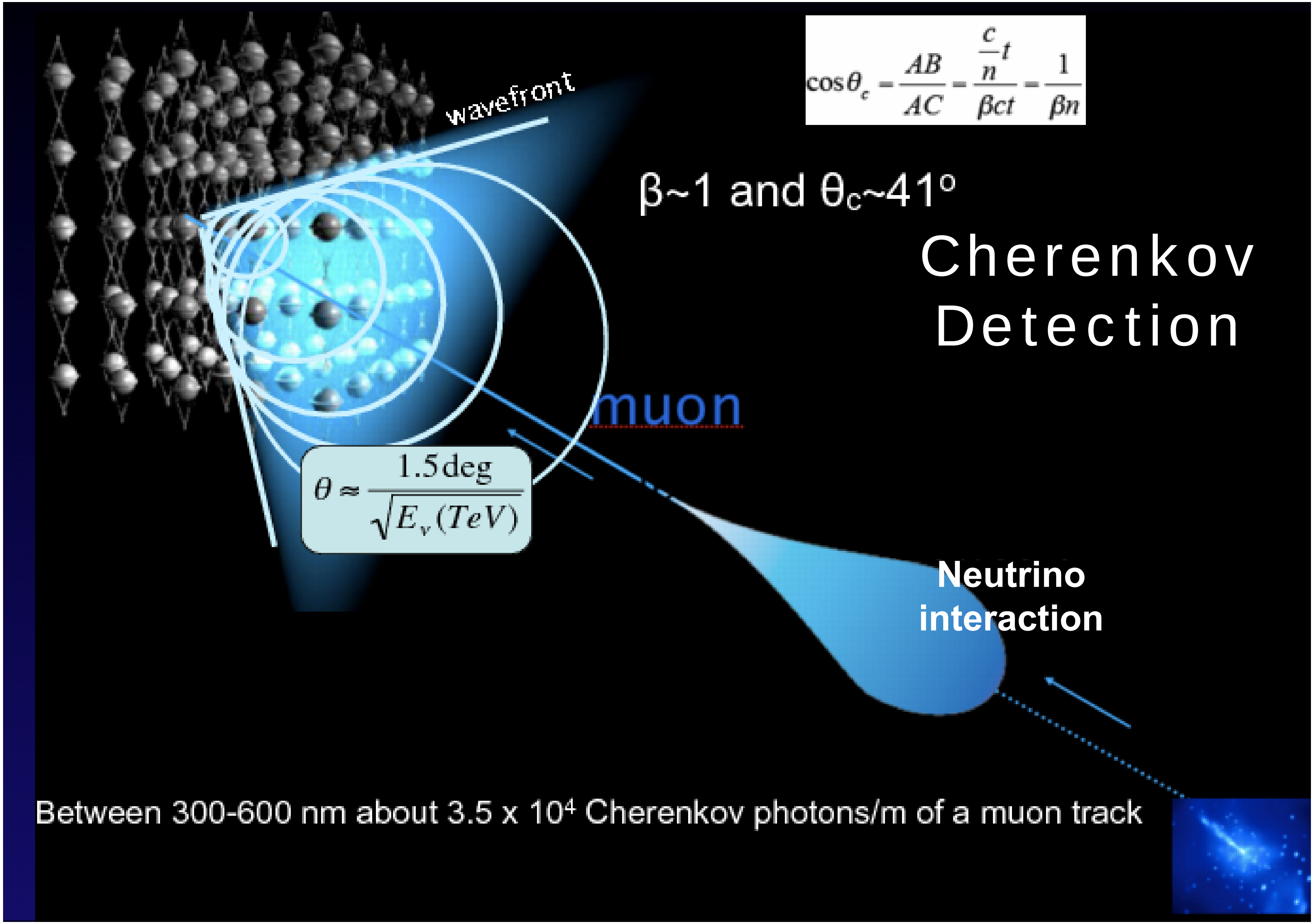




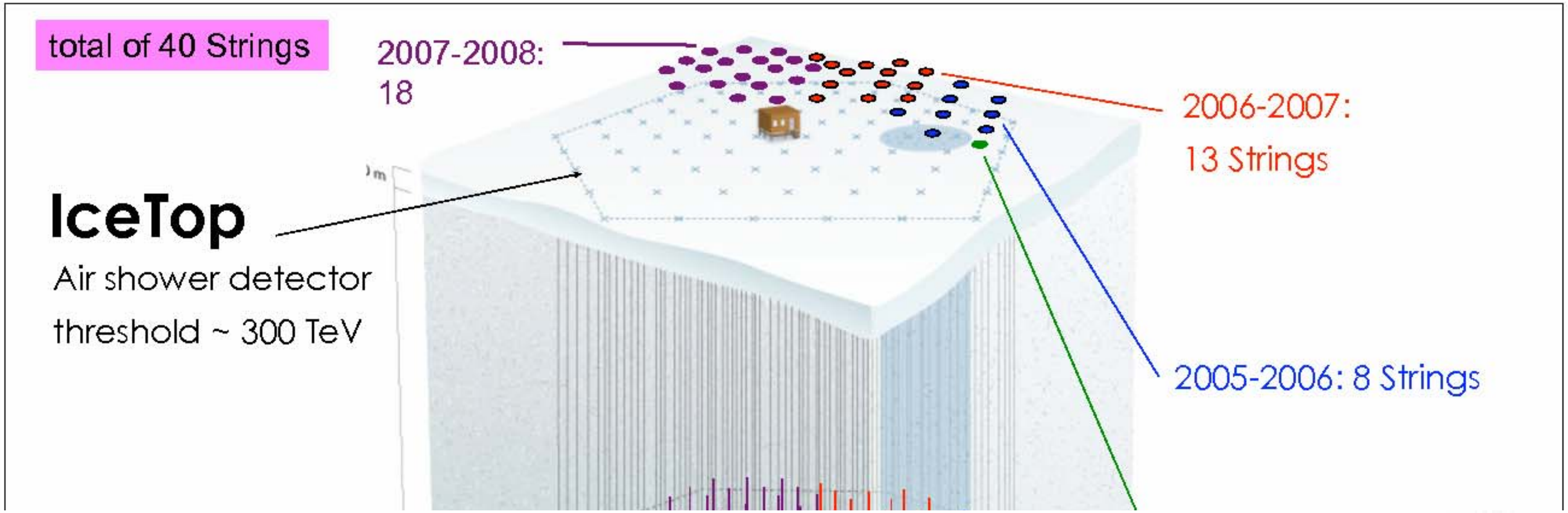
Cherenkov Neutrino Telescopes

High Energy Neutrinos

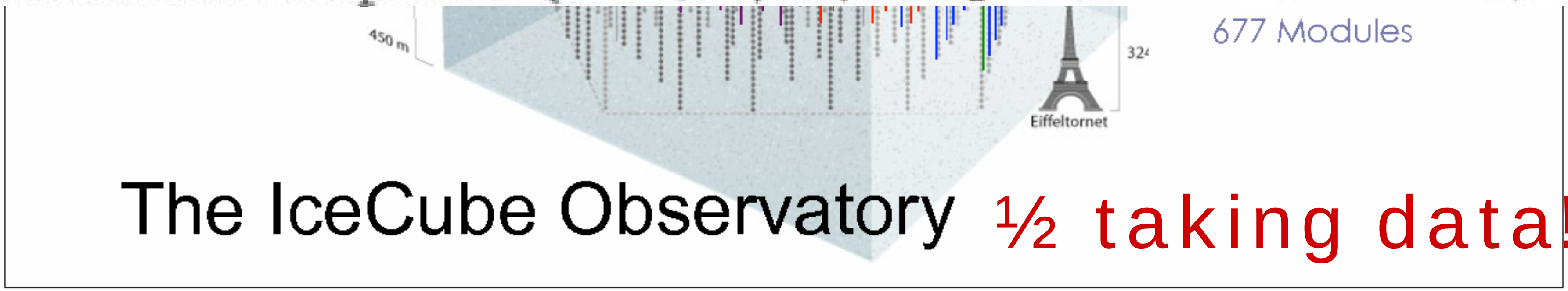




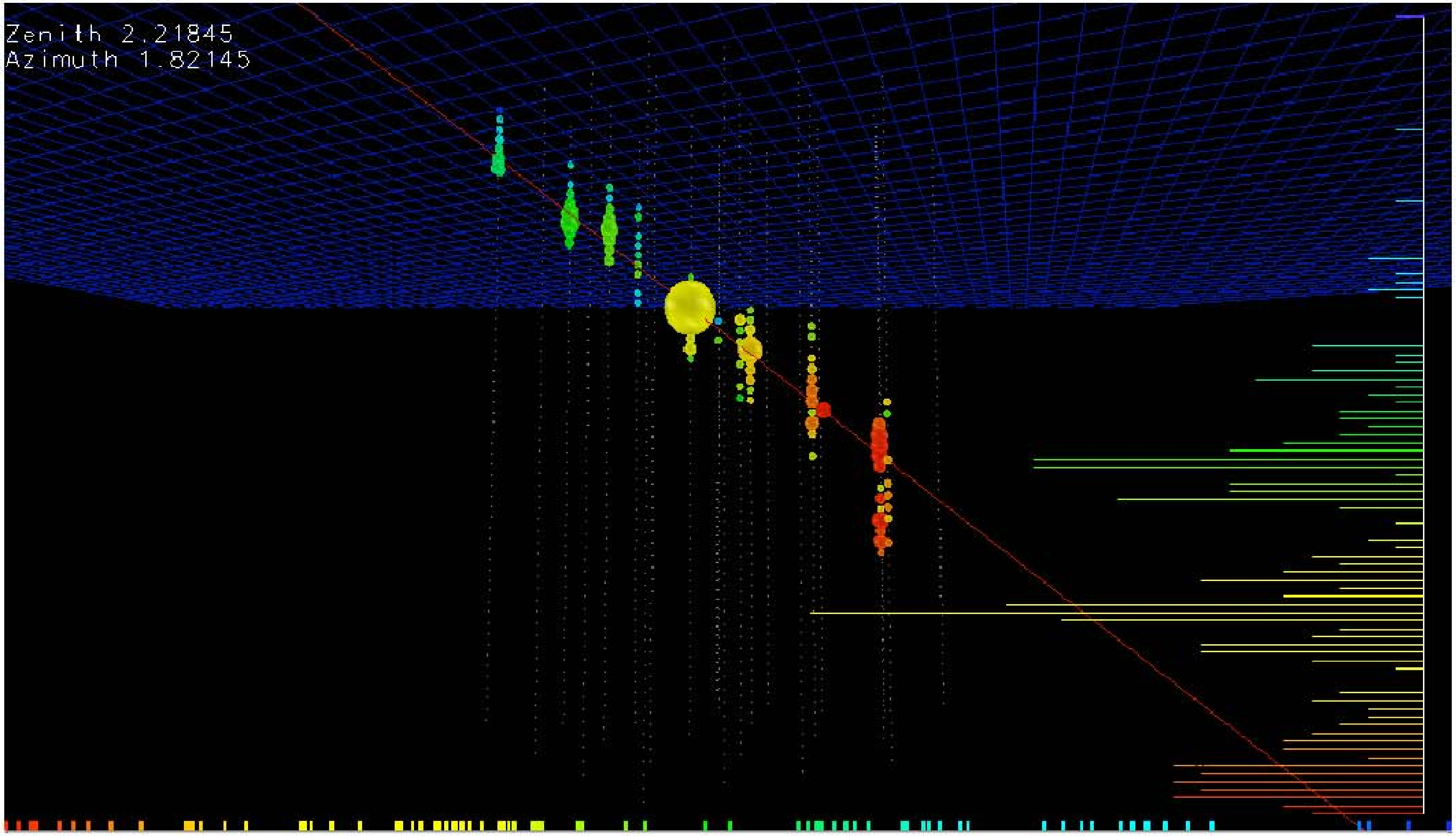
$$\cos\theta_c = \frac{AB}{AC} = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{\beta n}$$
β~1 and θ_C~41°
Cherenkov Detection
wavefront
muon
$$\theta \approx \frac{1.5\deg}{\sqrt{E_\nu(TeV)}}$$
Neutrino interaction
Between 300-600 nm about 3.5 x 10^4 Cherenkov photons/m of a muon track



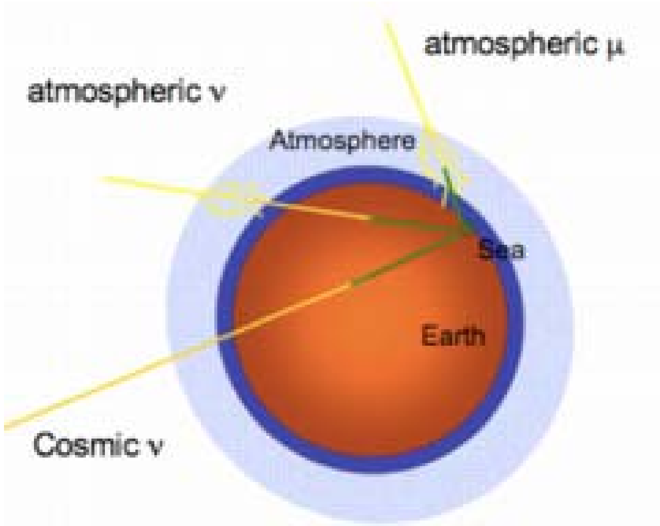
Certain instruments, on the other hand, had to operate in the clefts of glaciers; and, in order to transform such crevasses into temporary laboratories, it was necessary to equip them with electrical power (Pl. I, *A*). (The plates are at the end of

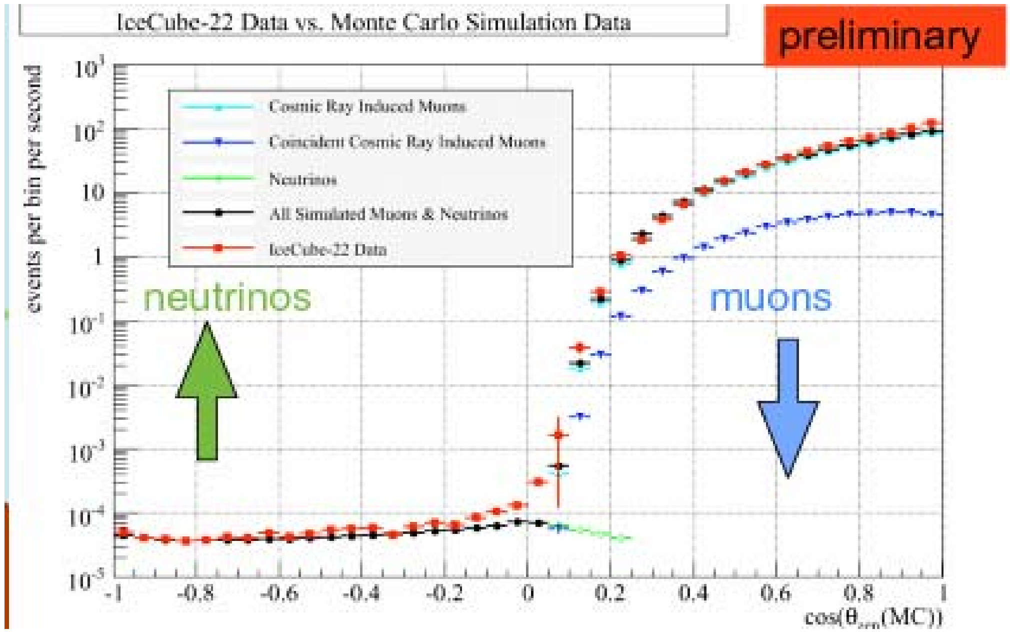


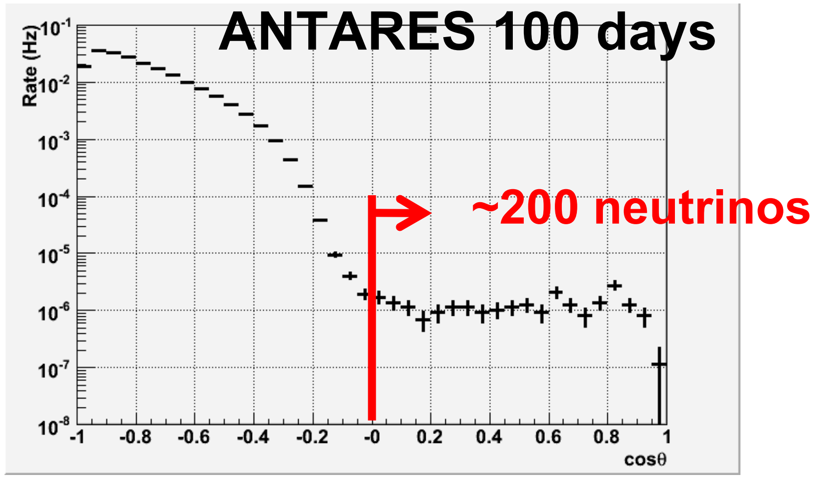
A neutrino event in IC22



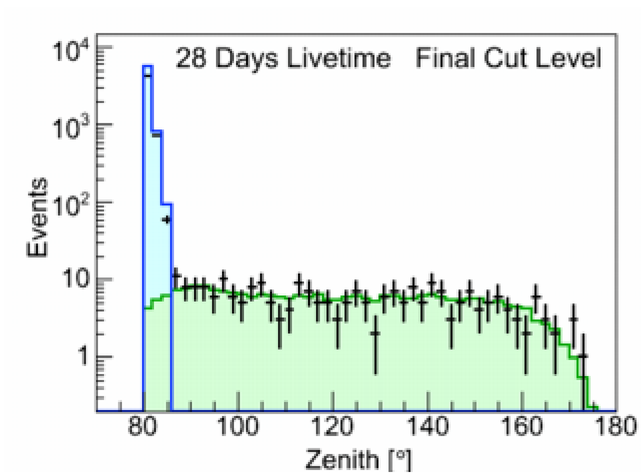
Neutrino detection



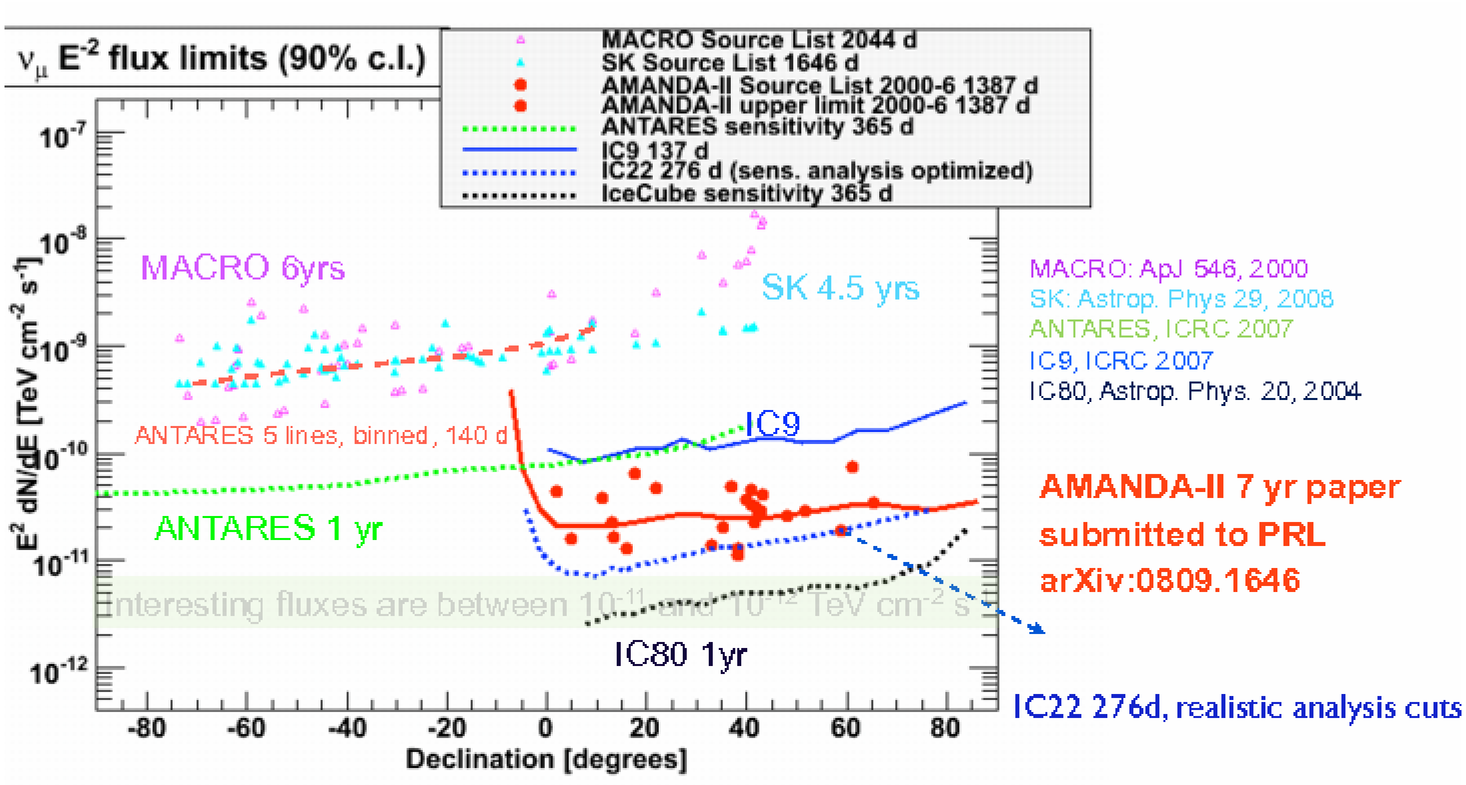


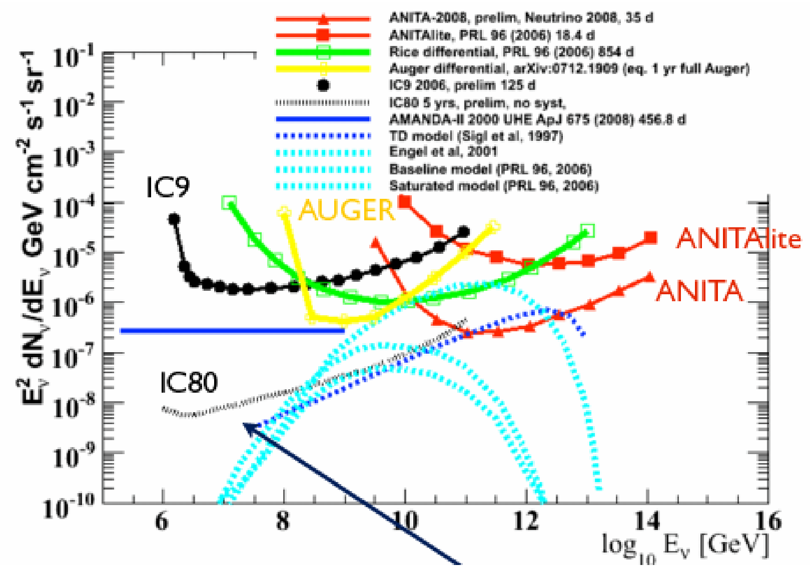


IceCube 22



ANTARES complete and taking data
(important step towards KM3Net)





~1 event/year

No cosmic neutrino yet

Preparing for discovery

Outlook

- TeV gamma rays, Ultra-High Energy Cosmic Rays, High Energy Neutrinos are opening new frontiers in the exploration of the Universe
- Already with the current detectors significant advances of our knowledge in the field are expected

- Coordinated multi-messenger and multi-wavelength measurements are becoming a fundamental part of the field

- Preparation for next generation of detectors has started:

→ TeV Gamma Rays: AGIS and CTA (10 x higher sensitivity)

→ UHECR: AUGER North (21000 km^3) in Colorado, (EUSO from space)

→ High Energy Neutrinos: KM3Net in the Mediterraneum and R&D for neutrino detection (radio and acoustic)

Big Projects…, Big Collaborations…., Adequate Funds……

QUESTION NO. 1 REMAINS UNANSWERED

Can we, in the light of this basic knowledge, try to answer Question No. 1, which has baffled physicists from the start? Even when they had known nothing more than the phenomenon of residual ionization, they had asked: "What is the origin of the rays which produce it?" We already know a part of the answer: "Their origin is extraterrestrial"; and this justifies the name "cosmic rays." However, by what processes can we imagine the particles to have attained their high energies?