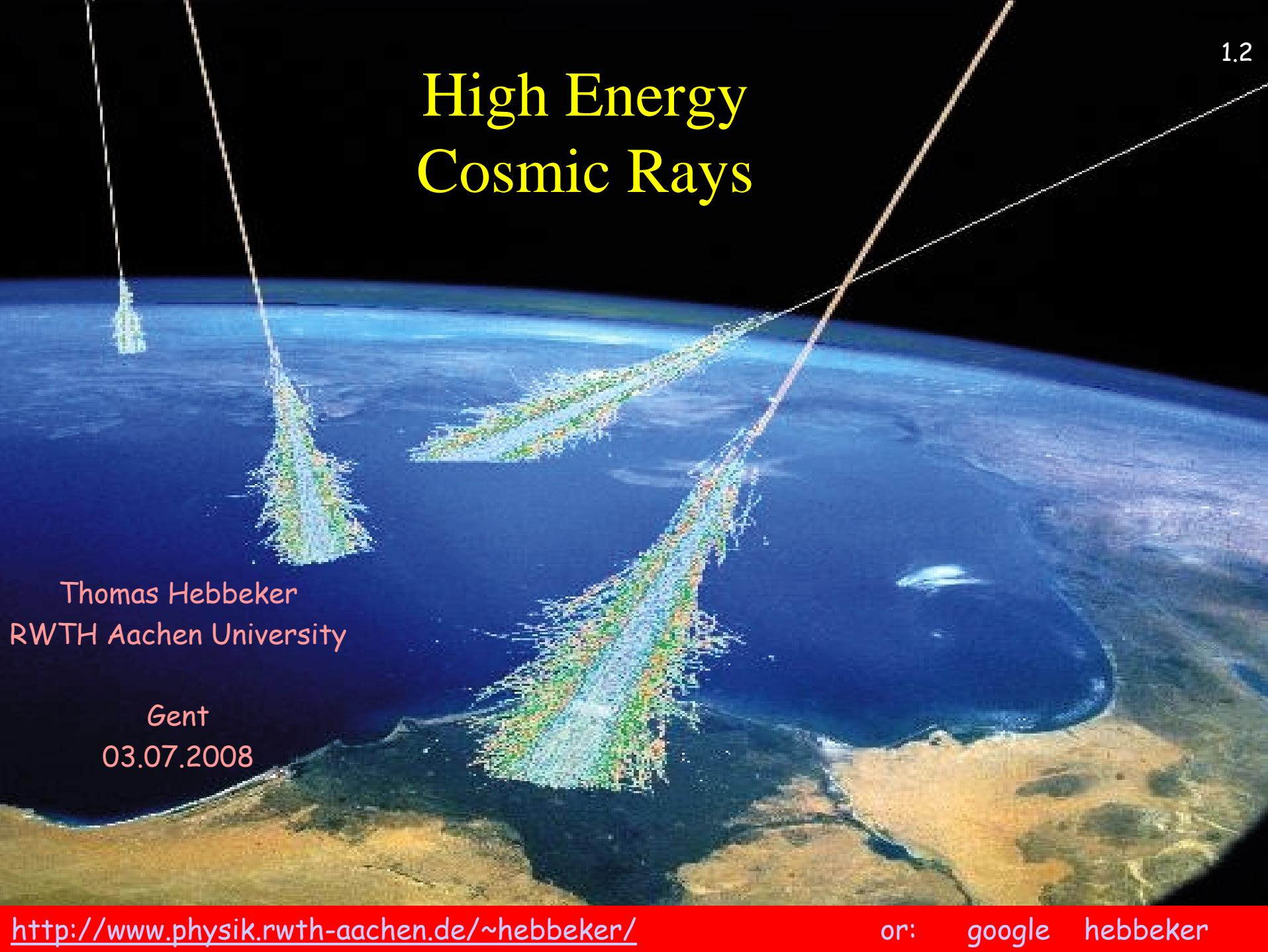


1.2

High Energy Cosmic Rays



Thomas Hebbeker
RWTH Aachen University

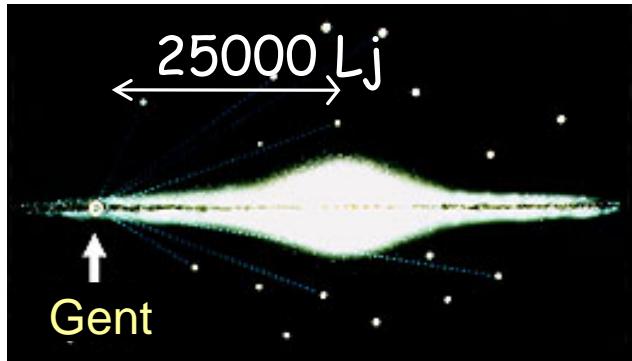
Gent
03.07.2008

Cosmic Rays

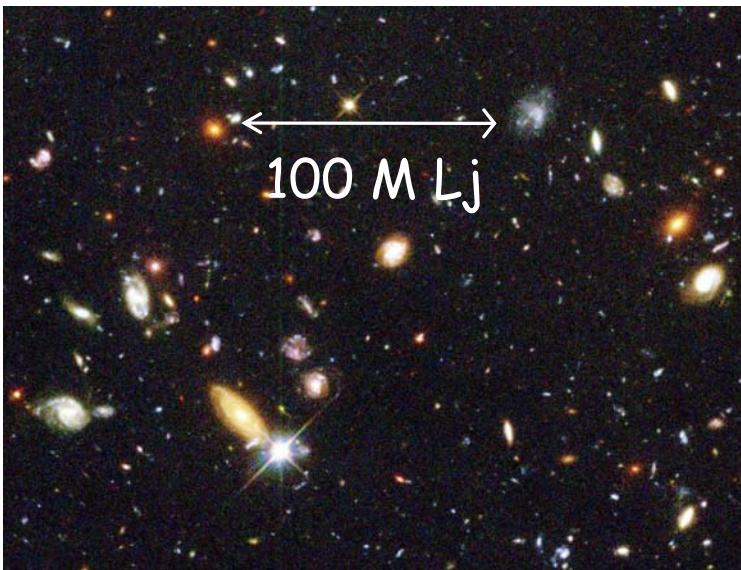
- Discovery / Properties
- Influence on Earth / Life / Science
- High Energy Cosmic Rays
- Cosmic Sources and Propagation
- Auger-Observatory
- First Auger Results

Cosmic Particles ?

from within our galaxy ?



from
extragalactic
sources ?



on earth:

$$\gamma : 5 \cdot 10^{21} / m^2 / s$$

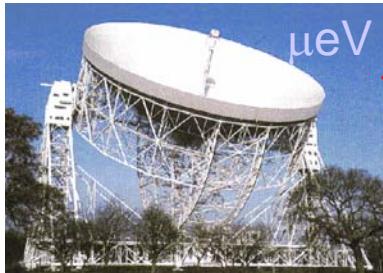
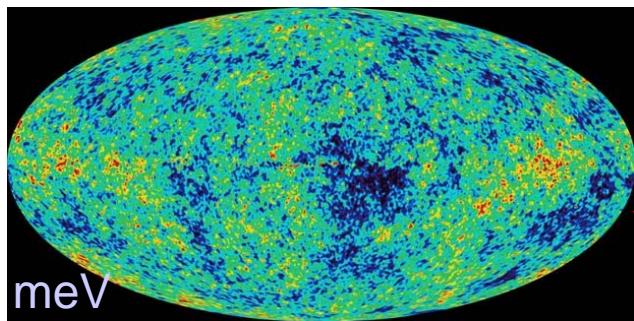
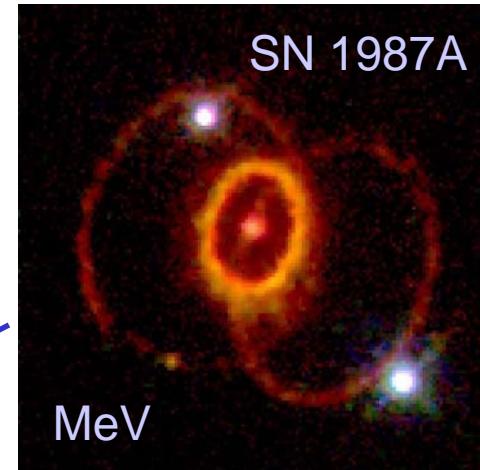
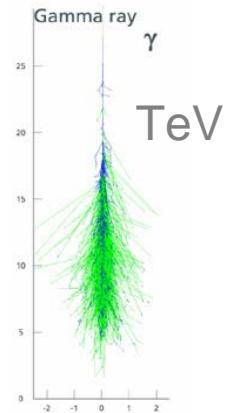
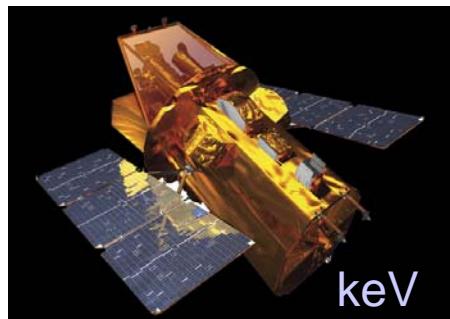
$$\nu : 6 \cdot 10^{14} / m^2 / s$$

$$p : 2 \cdot 10^{12} / m^2 / s$$

low energy (< GeV)

Cosmic Particles ?

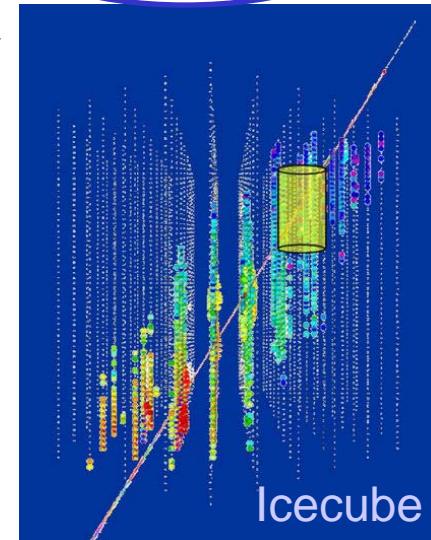
photons γ



μ eV



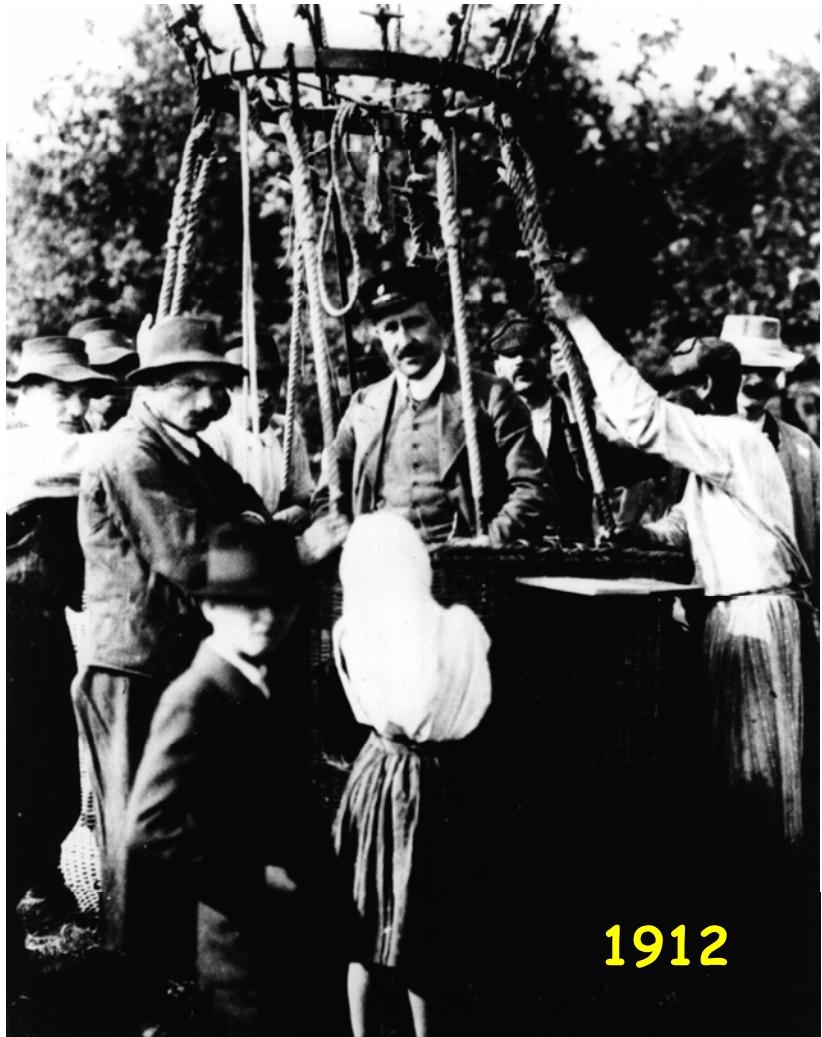
neutrinos ν



Discovery of Cosmic Radiation



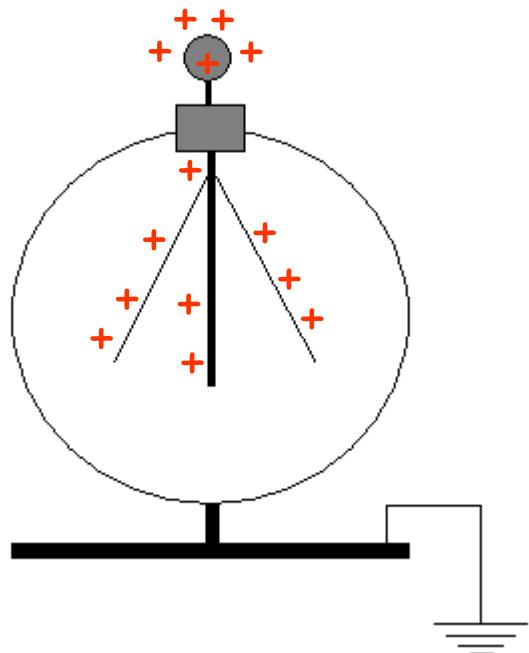
Nobel 1936



Viktor Hess

Electrometer Measurements

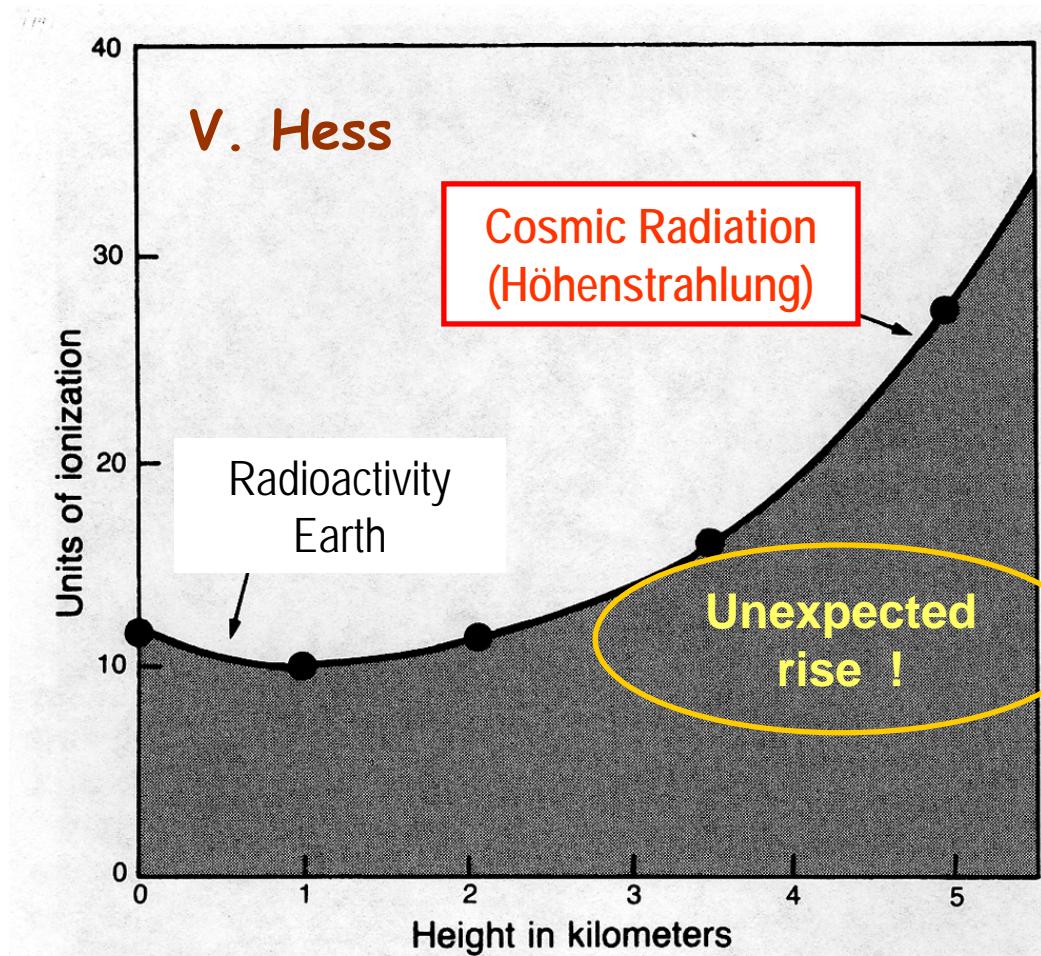
Ionising radiation
discharges electrometer



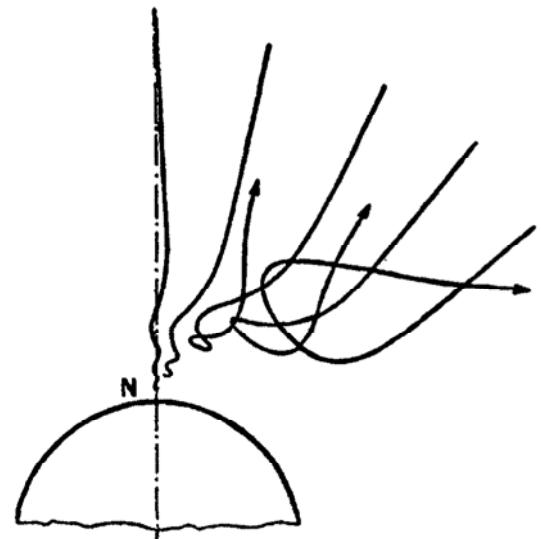
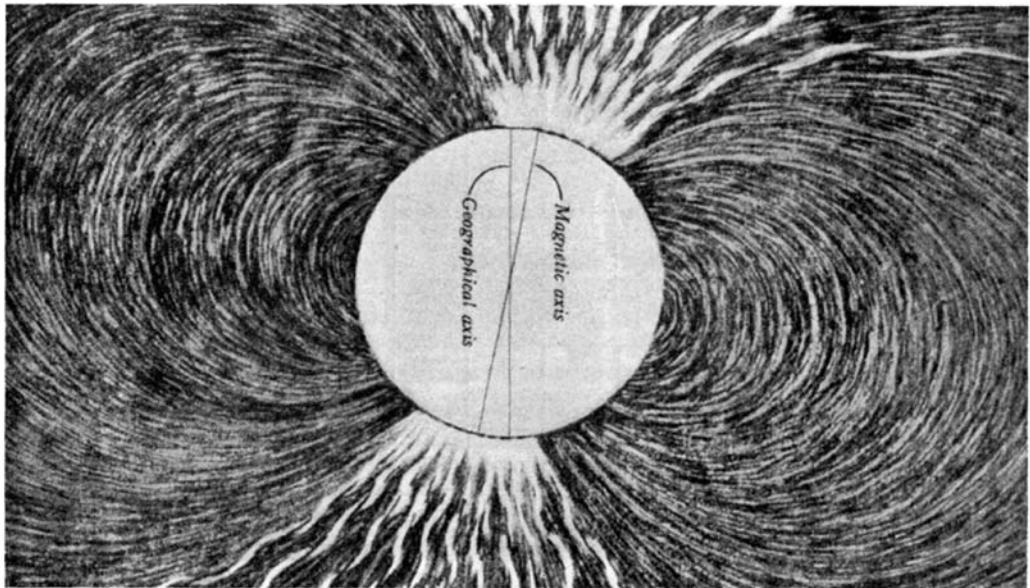
Electrometer:

Speed of discharging:

→ Ionization

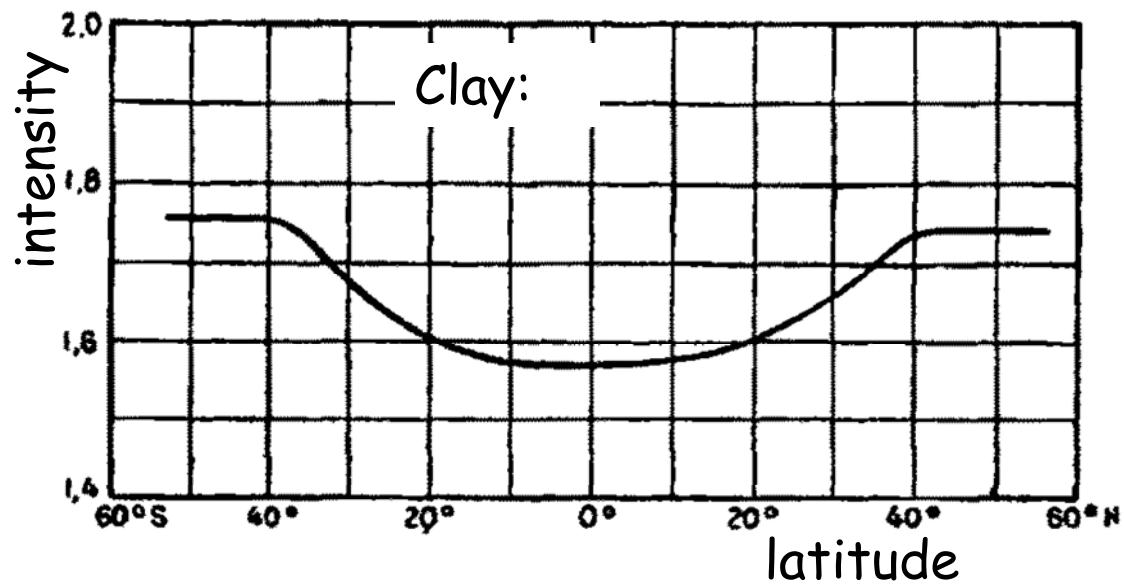


Electric Properties of Cosmic Rays



H.L. Bradt 1948

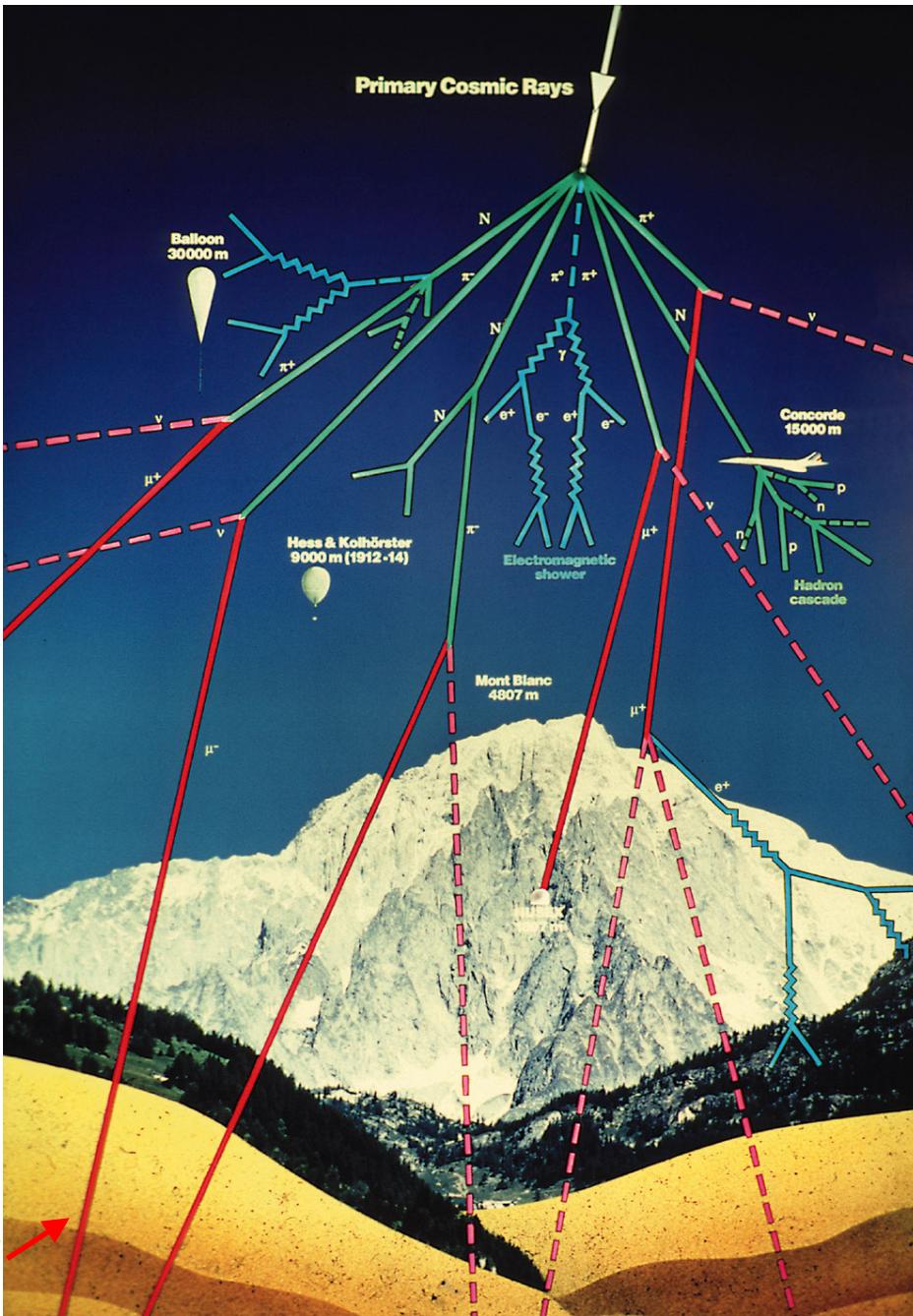
Geomagnetic cutoff =
several GeV



1927 Clay, 1930 Compton:
geomagnetic latitude dependence:
particles **charged** !

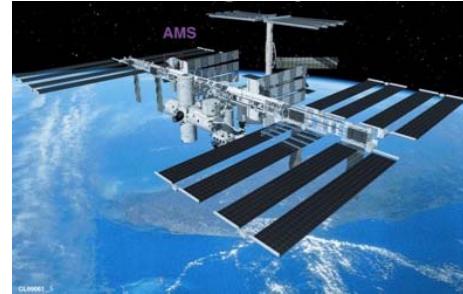
(Charged) Cosmic Radiation

$$\sim \frac{10000}{m^2 s}$$



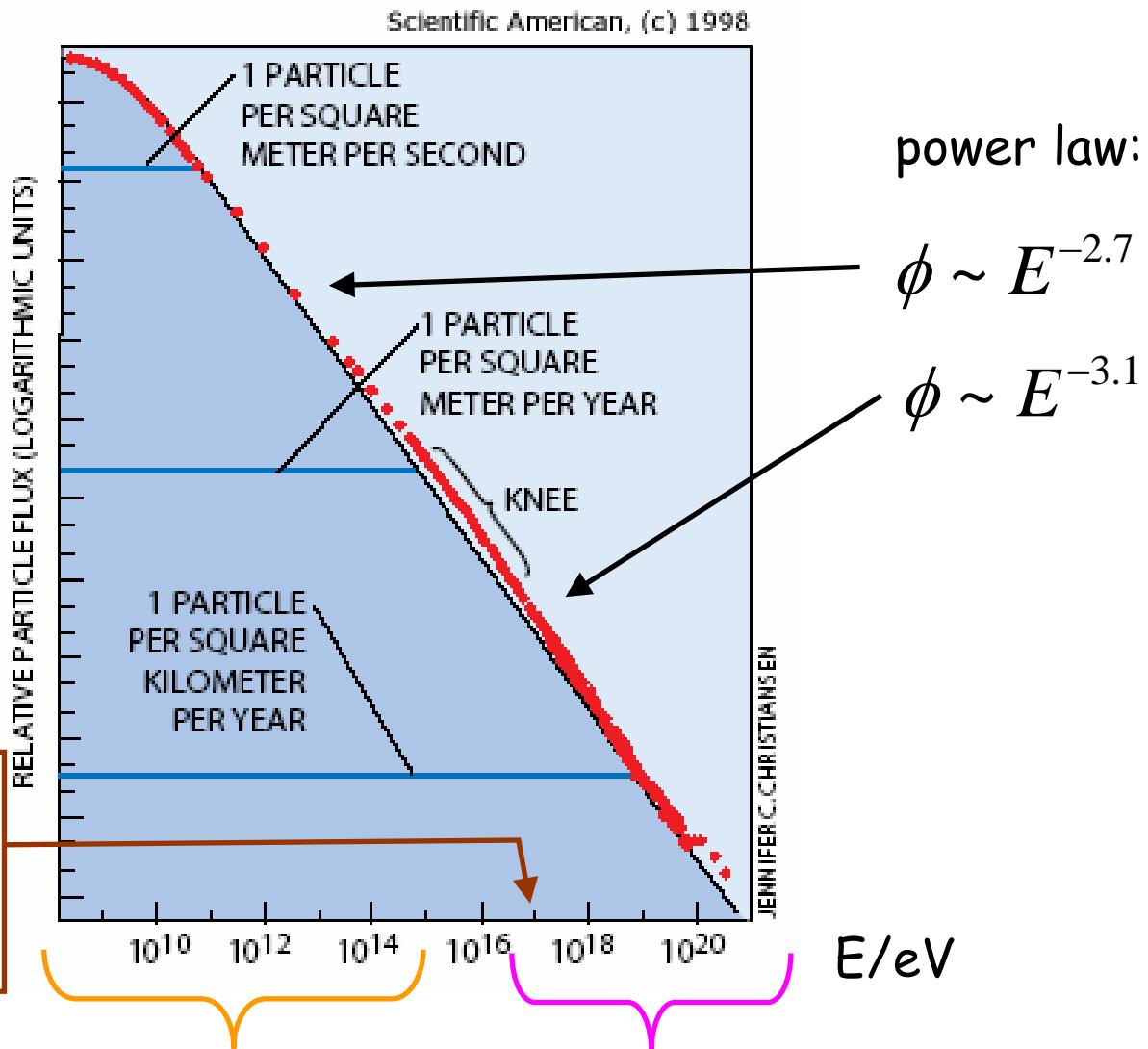
$$\sim \frac{100}{m^2 s}$$

Earth:
mainly muons



Energy Spectrum and Composition of Cosmic Rays

composition
at low energies:
87% p, 12% He



Origin ?:

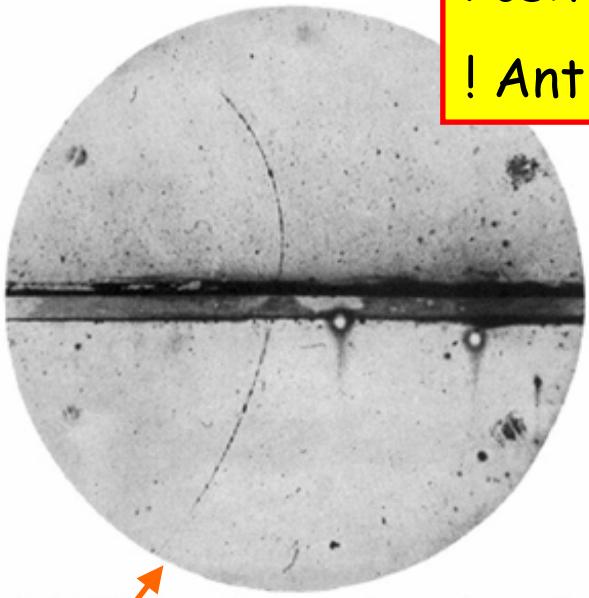
Supernovae in
Milky Way ?

extragalactic sources ???

Cosmic Rays

- Discovery / Properties
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- Cosmic Sources and Propagation
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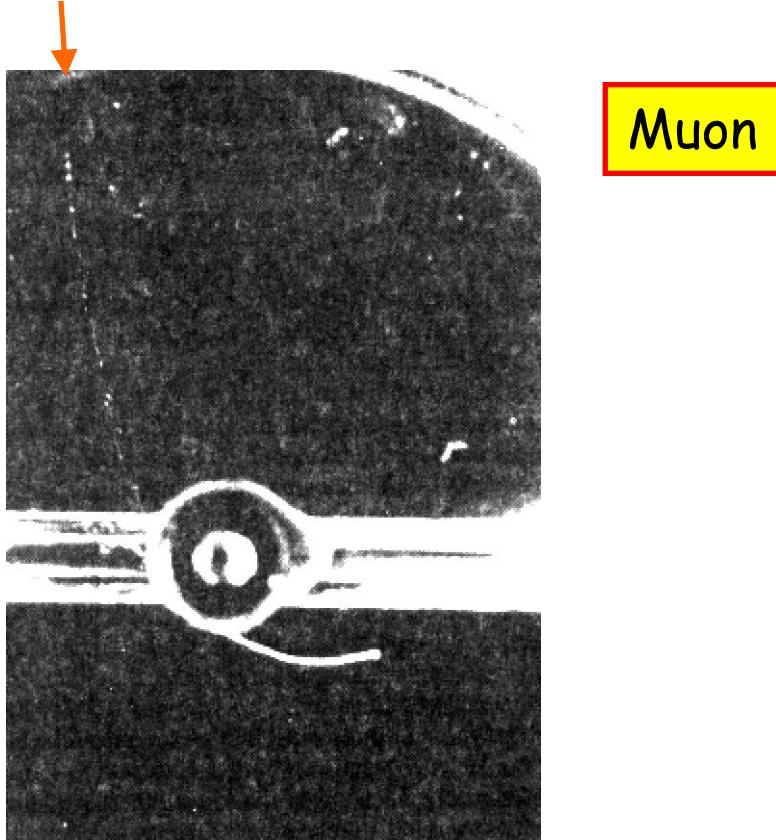
Discoveries in Cosmic Ray Experiments



1932 Anderson

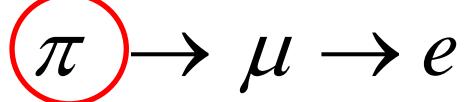
Positron
! Antimatter !

Cloud
chambers



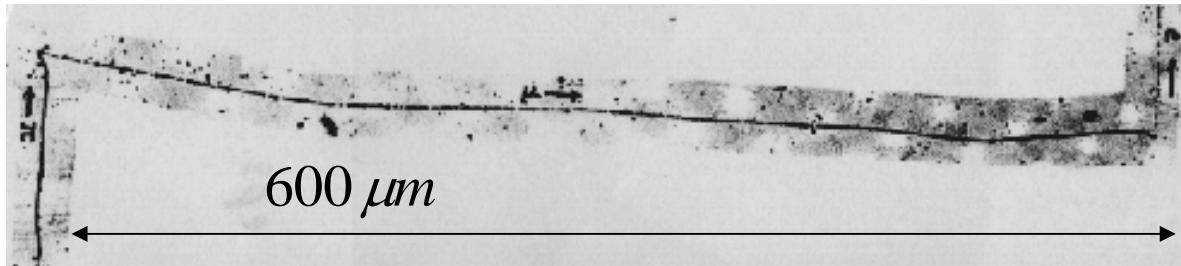
1937 Anderson, Neddermeyer

Pion



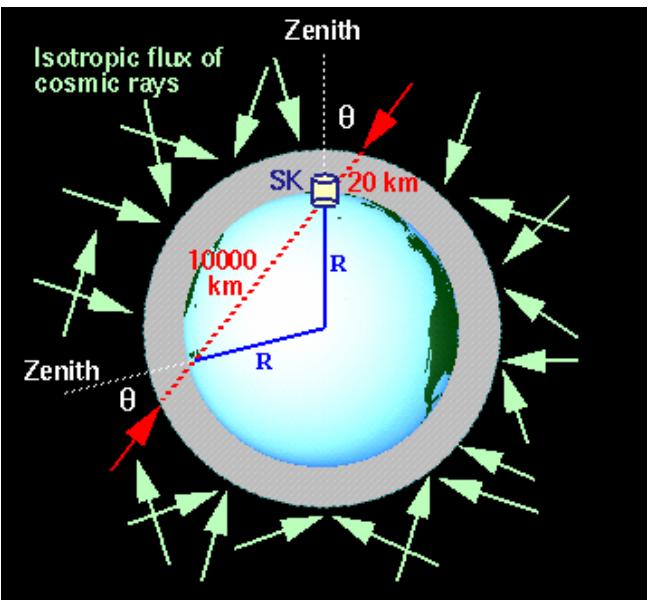
1937 Powell

emulsion



600 μm

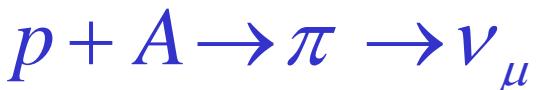
Neutrino Oscillations



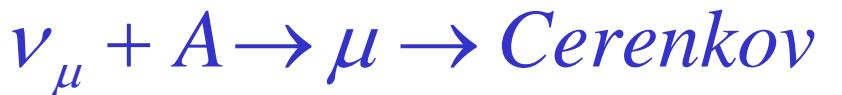
M. Koshiba et al.

Nobel
2002

Atmosphere:



Detection:

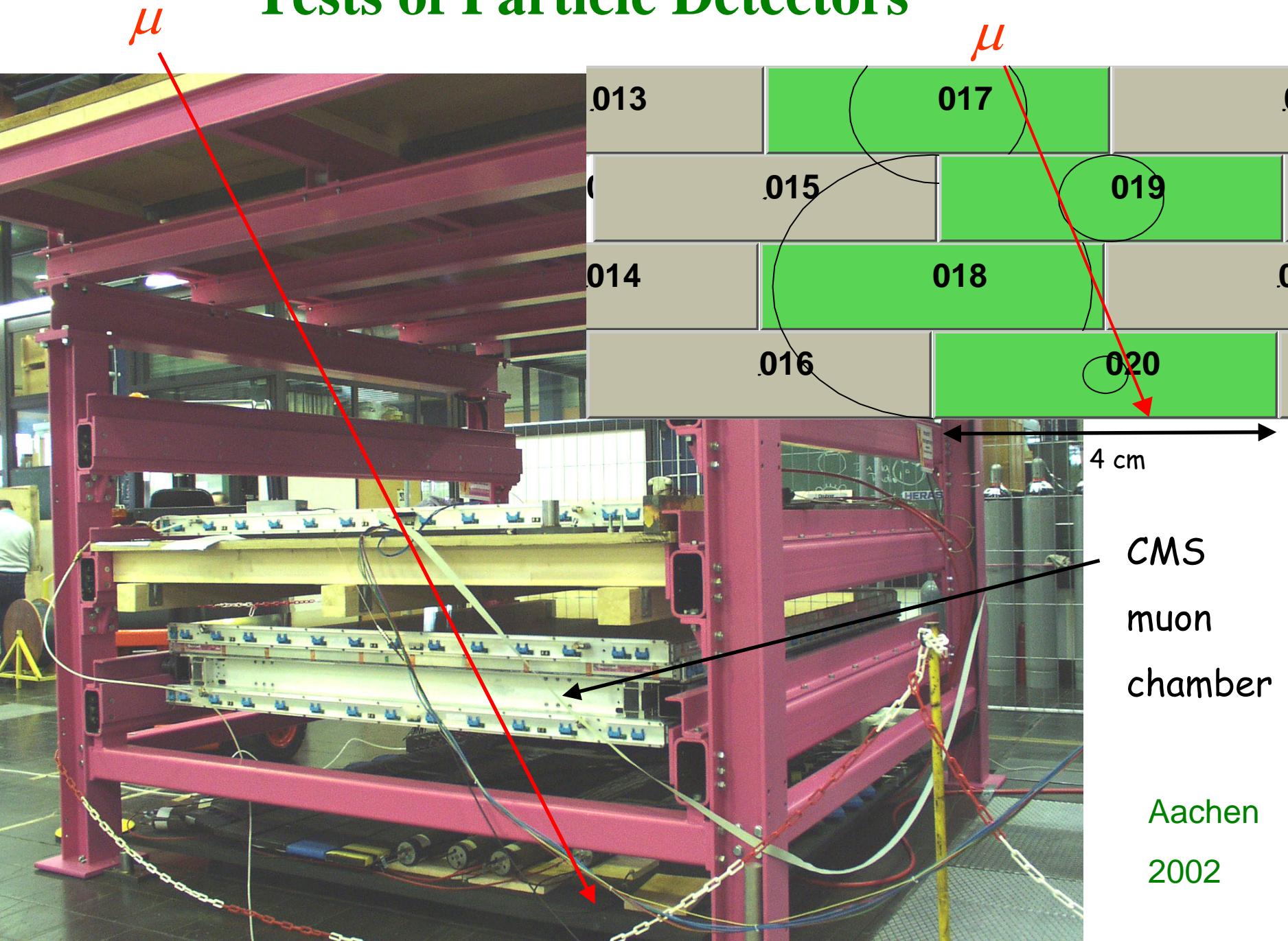


Result:

lack of μ , due to $\nu_\mu \rightarrow \nu_\tau$



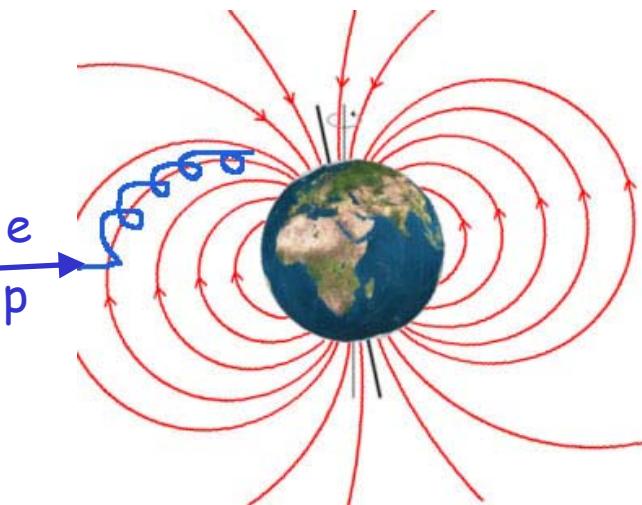
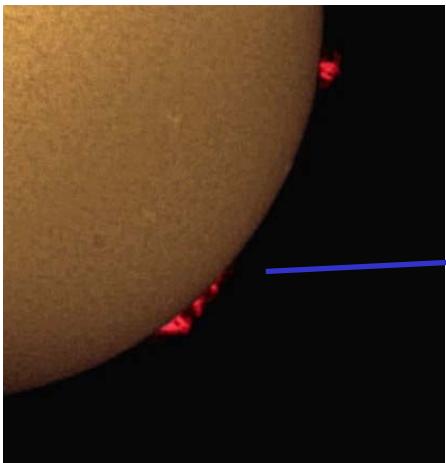
Tests of Particle Detectors



Polar Light (Aurea Borealis)

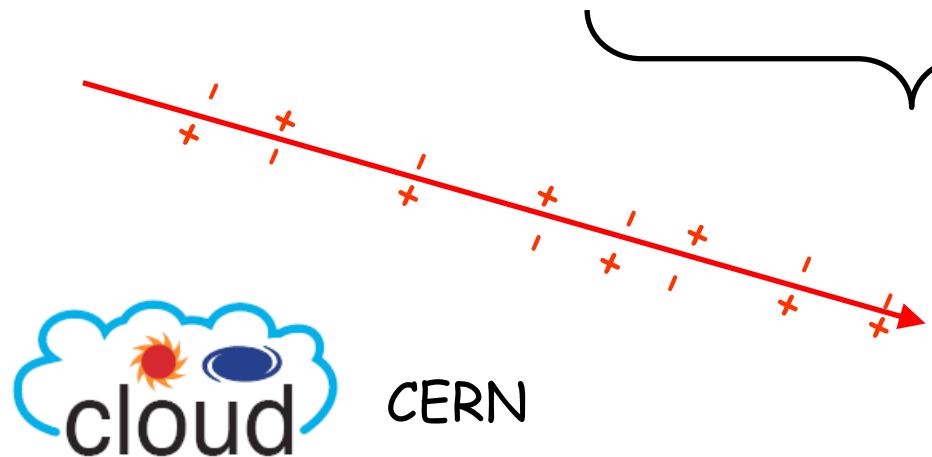
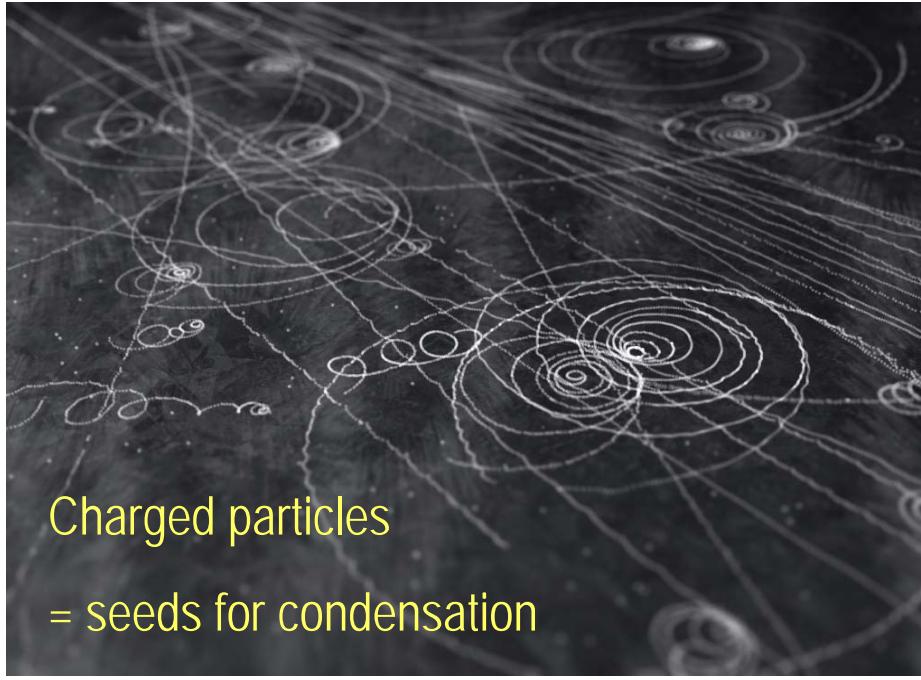


Trapping of low energy
particles from sun („solar
wind“) by magnetic fields
Excitation of air molecules



Cloud Formation ?

cloud chamber

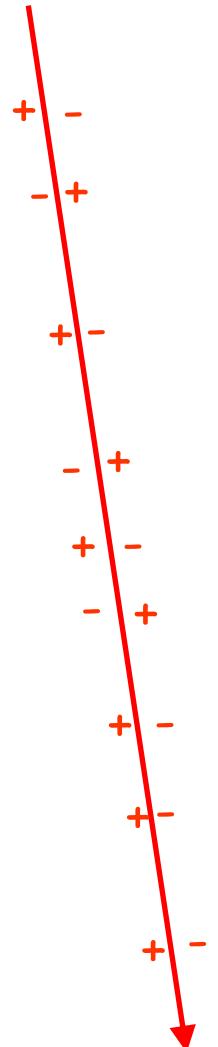


CERN

Cosmics Leaving OUtdoor Droplets

Can cosmic rays initiate
cloud formation ?
Influence on climate ?

Lightnings ?



Cosmic rays produce a line of free charges
which might trigger / guide the lightning

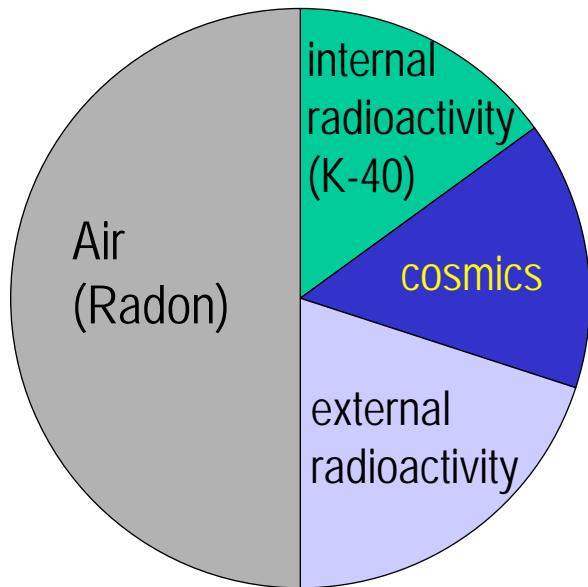
?

Radiation Exposure of Humans

Natural sources:

~ 1 m Sv / year ~ 1 m Gy / year ~ 0,1 J / year

whole body



Increased radiation levels !
(Hess !)

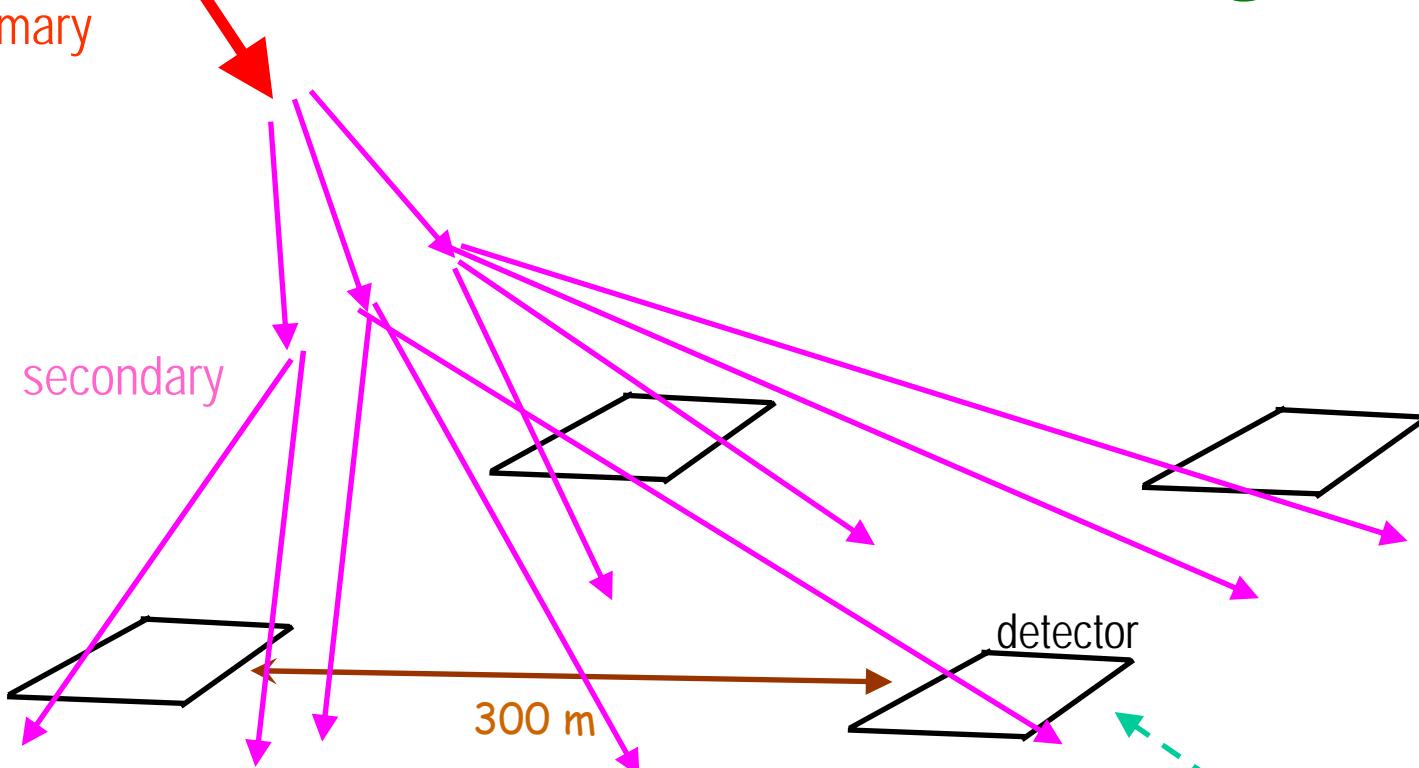
Technical sources:

~ 1 m Sv / Jahr ~ natural exposure

Cosmic Rays

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Measurements of Pierre Auger



1938

Jungfraujoch
3500 m

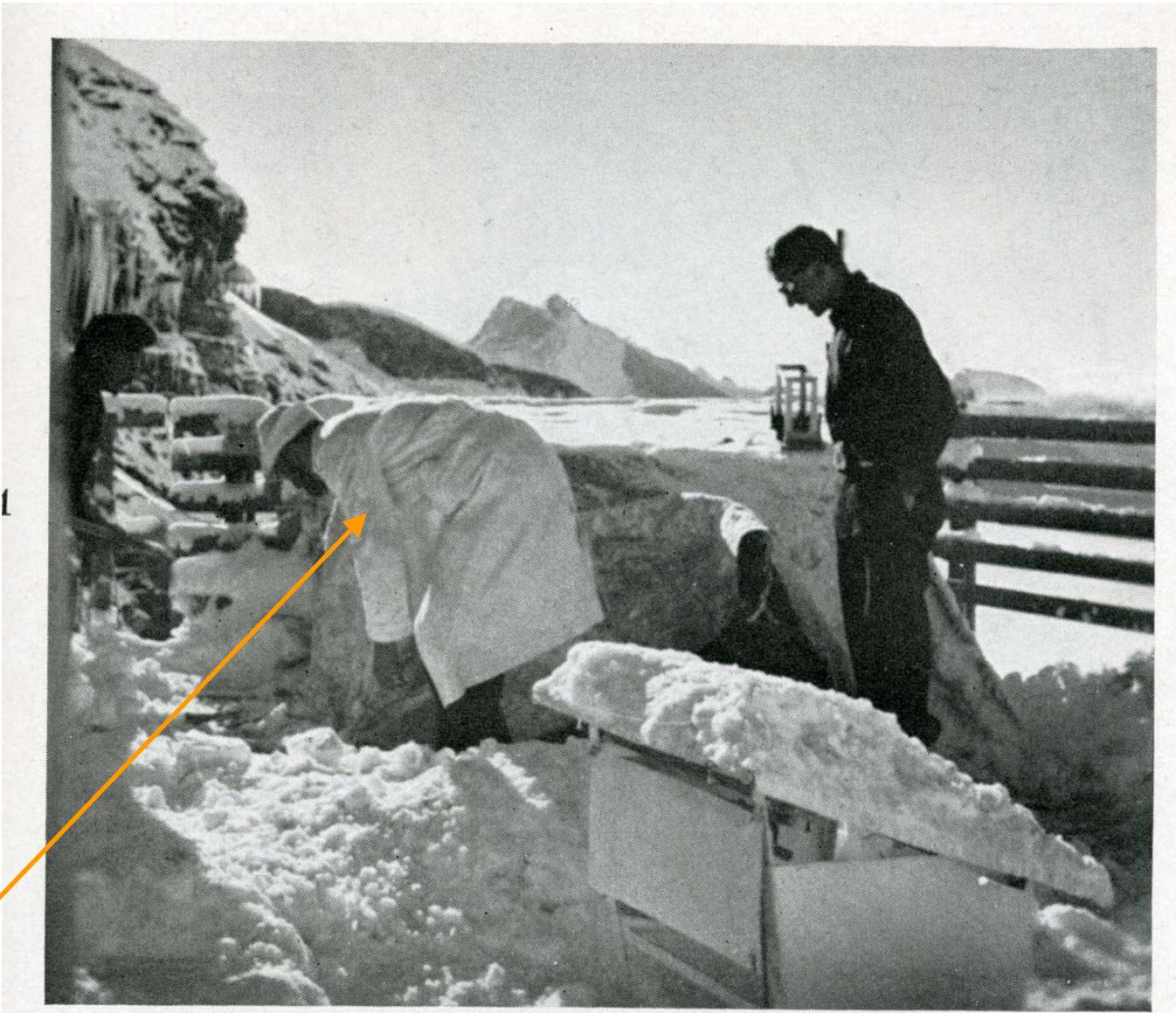
Geiger-Müller-counters

Results: Coincidences for detectors 300 m apart

estimate: 1 million secondary particles, energy 10^{15} eV = 1000 TeV !!!

Extended Air Shower

Pierre Auger Experiment



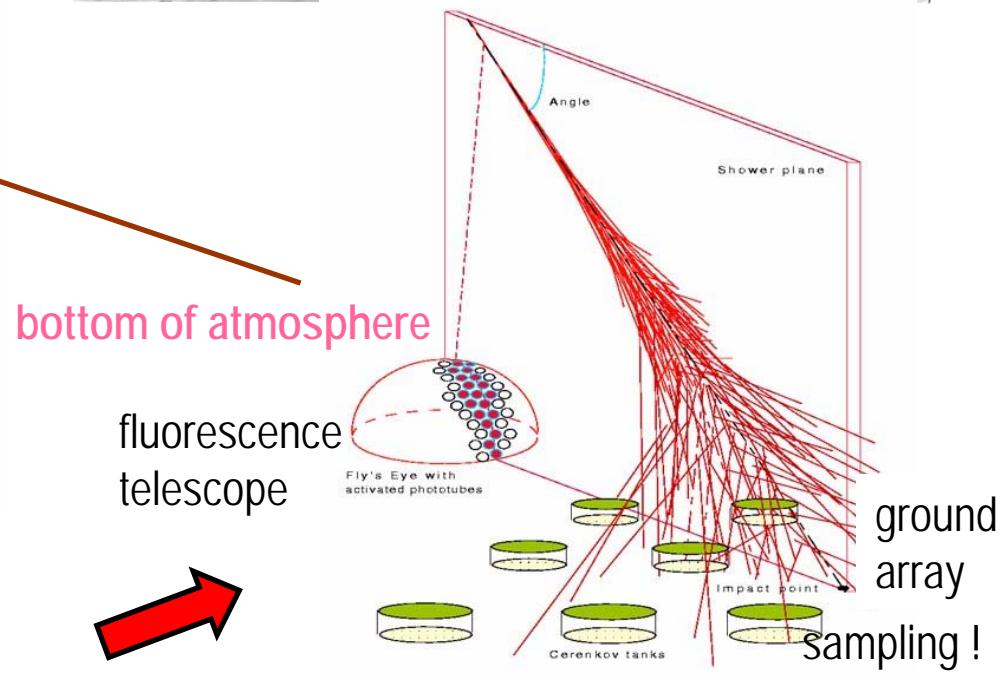
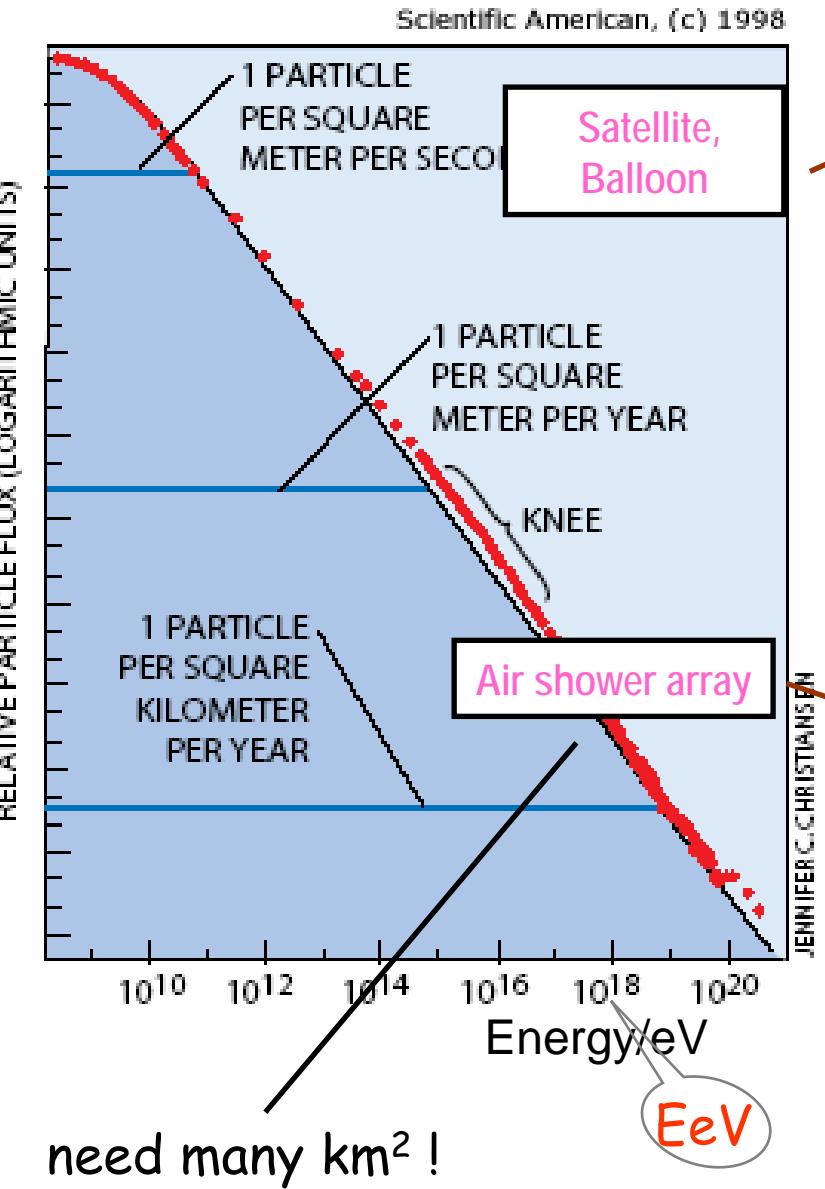
MEASURING COSMIC RAYS IN THE SWISS ALPS

The author (*left*) and his collaborator, P. Ehrenfest, set up their apparatus in the Jungfraujoch.

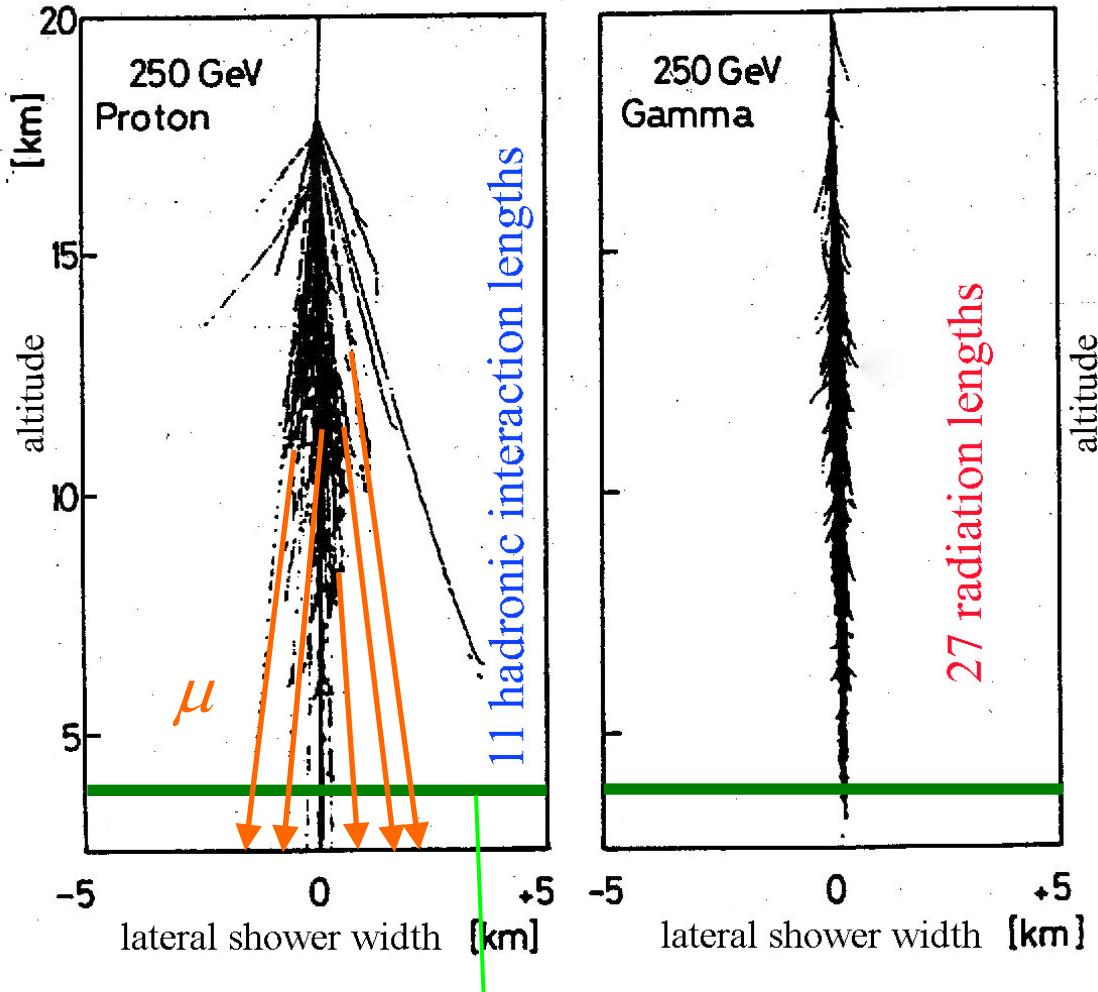
Pierre Auger

Cosmic Ray Detection Methods

Particle flux



Ground based measurements



Atmosphere absorbs
hadronic and
electromagnetic shower
components

Muons reach ground

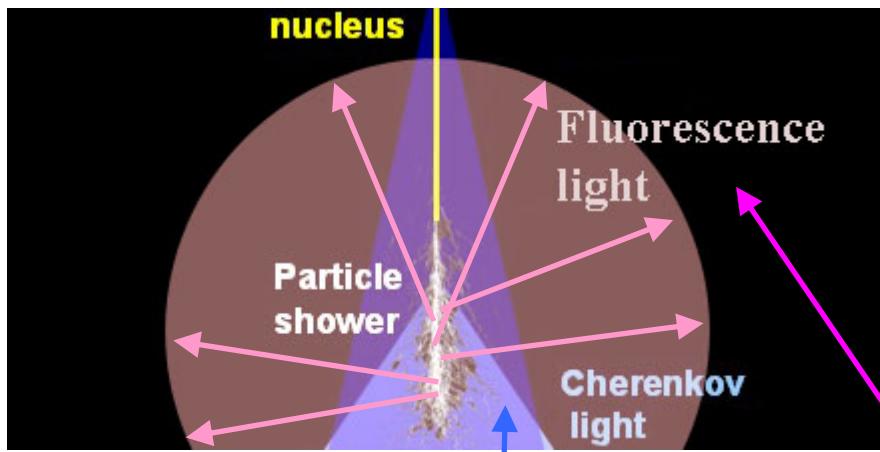
10^7 @ 1 EeV

At higher altitudes and ultra high energies also
hadrons and e^- , e^+ , γ can be measured

Jungfraujoch !

Ground array measures lateral shower profile

Telescope Measurements



Cherenkov light:

relativistic electrons, forward

Fluorescence detector measures
longitudinal shower profile

Atmosphere =
Calorimeter



Fluorescence light:

$10^{13} \gamma$
/ EeV

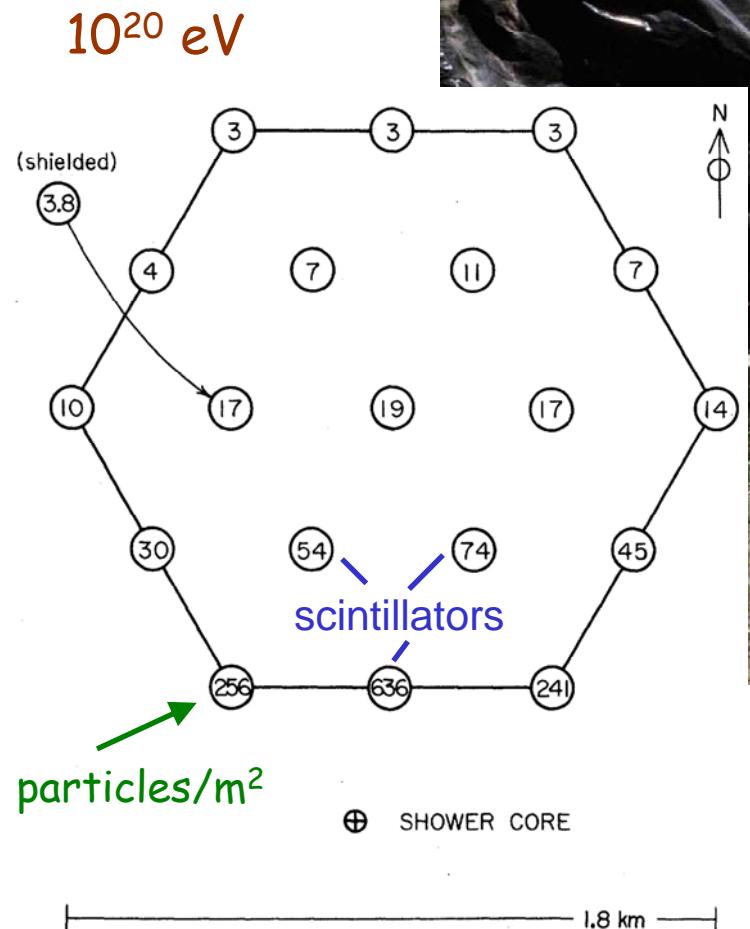
300-400 nm

excited nitrogen molecules

isotropic emission

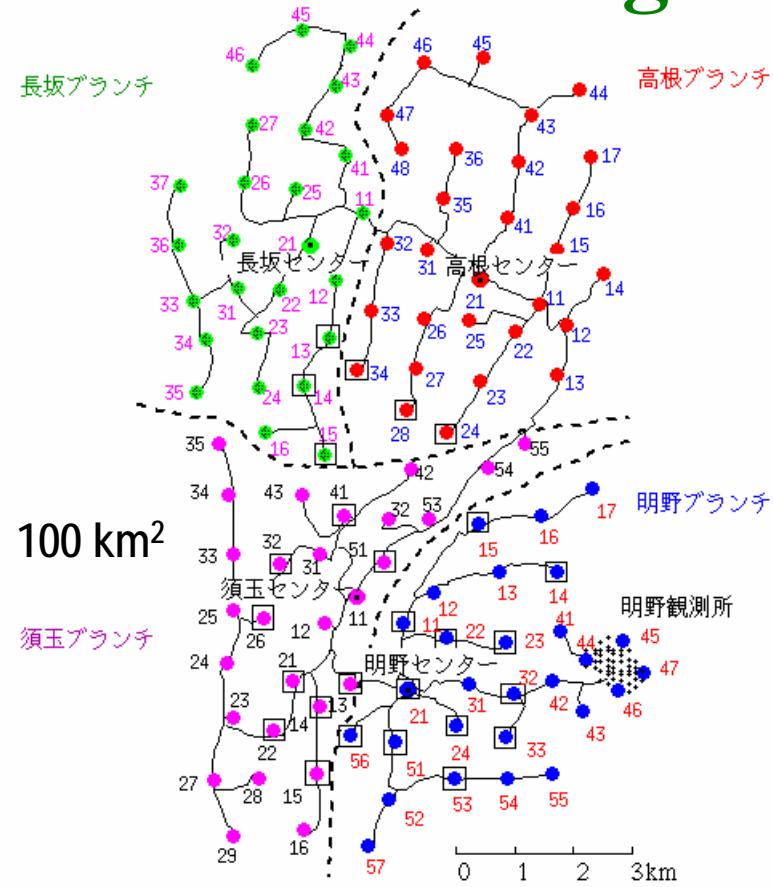
total light yield ~ shower energy
visible over several km (by night)

Volcano Ranch Detector

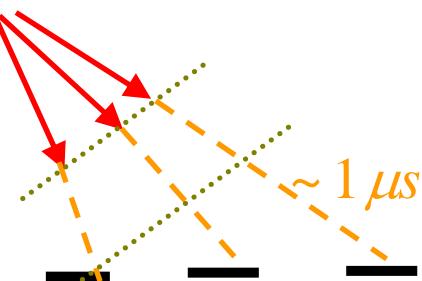
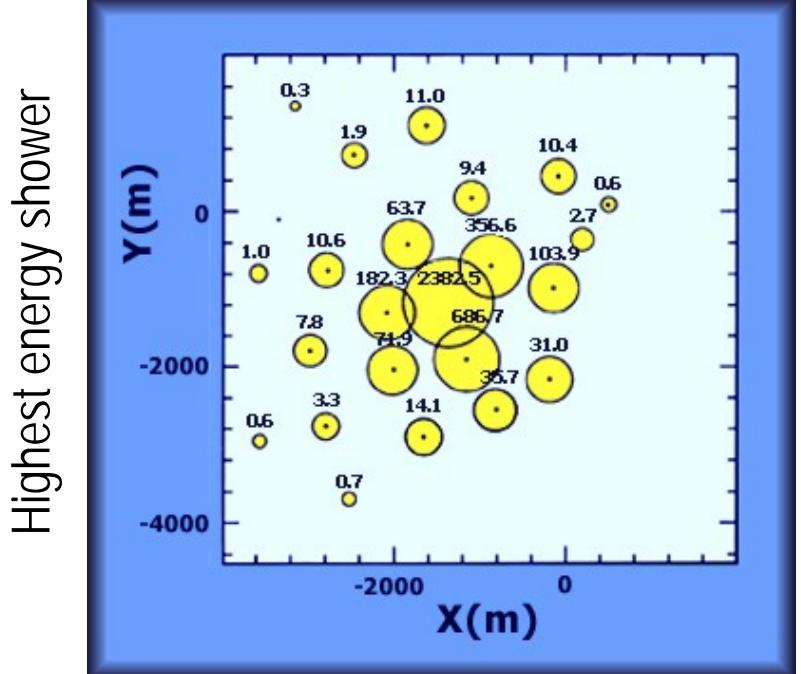


1962: energy $2 \cdot 10^{20}$ eV

Agasa-Detector



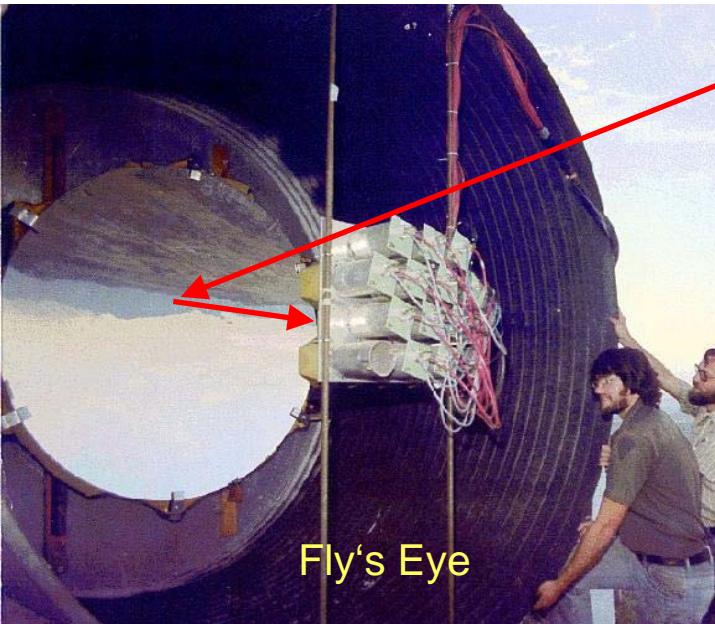
~1995 Japan
111 water tanks
(Cerenkov light produced in tank)



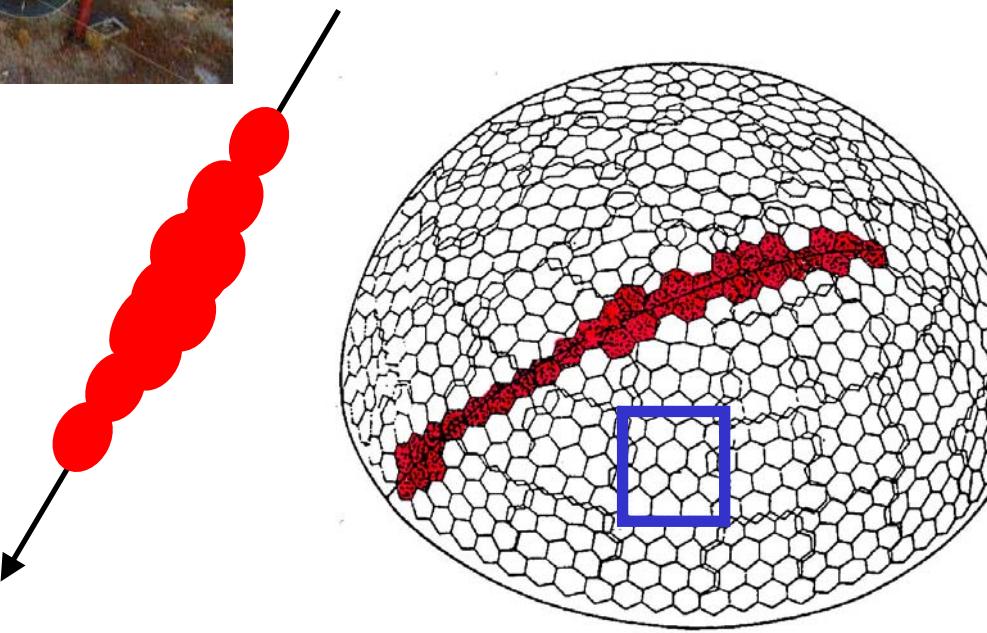
- energy measurement:
light intensity
- direction measurement:
arrival time

1993: energy $2 \cdot 10^{20} \text{ eV}$

Fly's Eye / HiRes Detectors

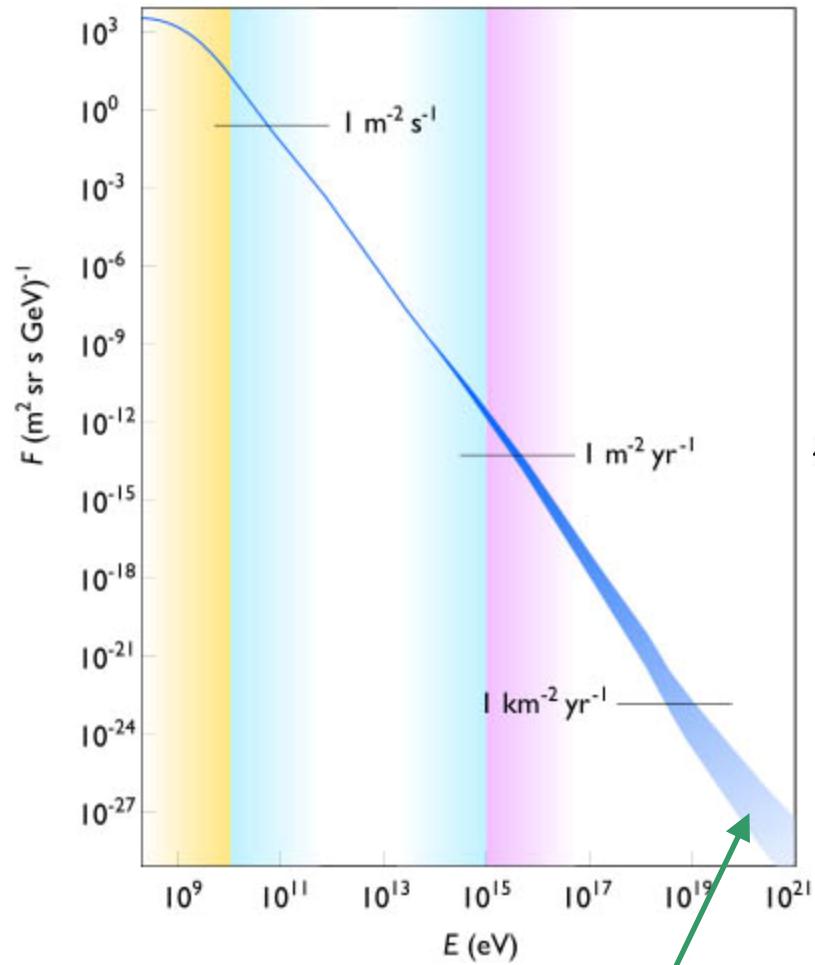


1991: energy $3 \cdot 10^{20}$ eV

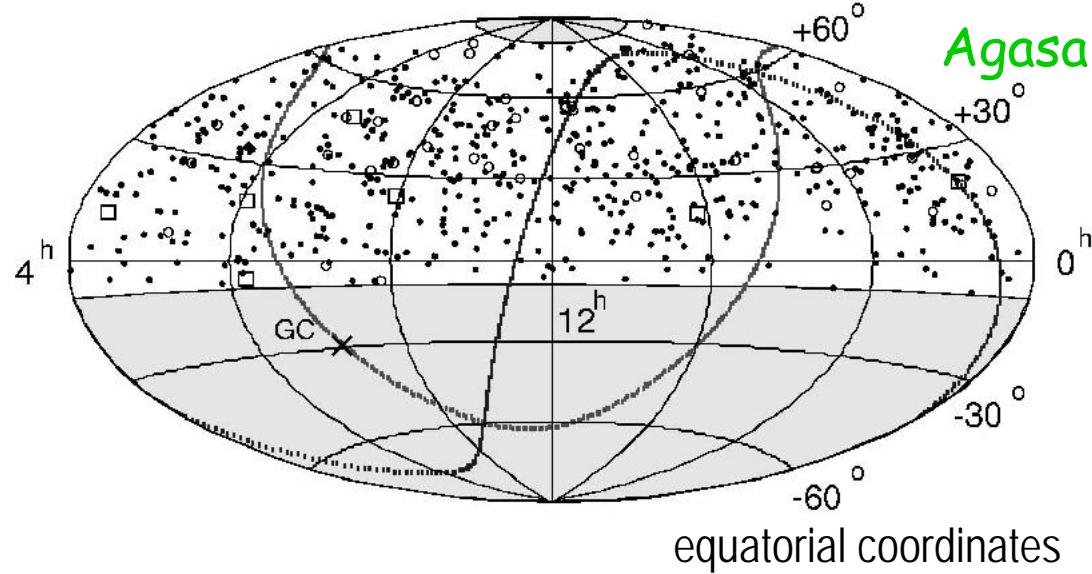


Results of air shower observatories

Energy spectrum of charged cosmic rays



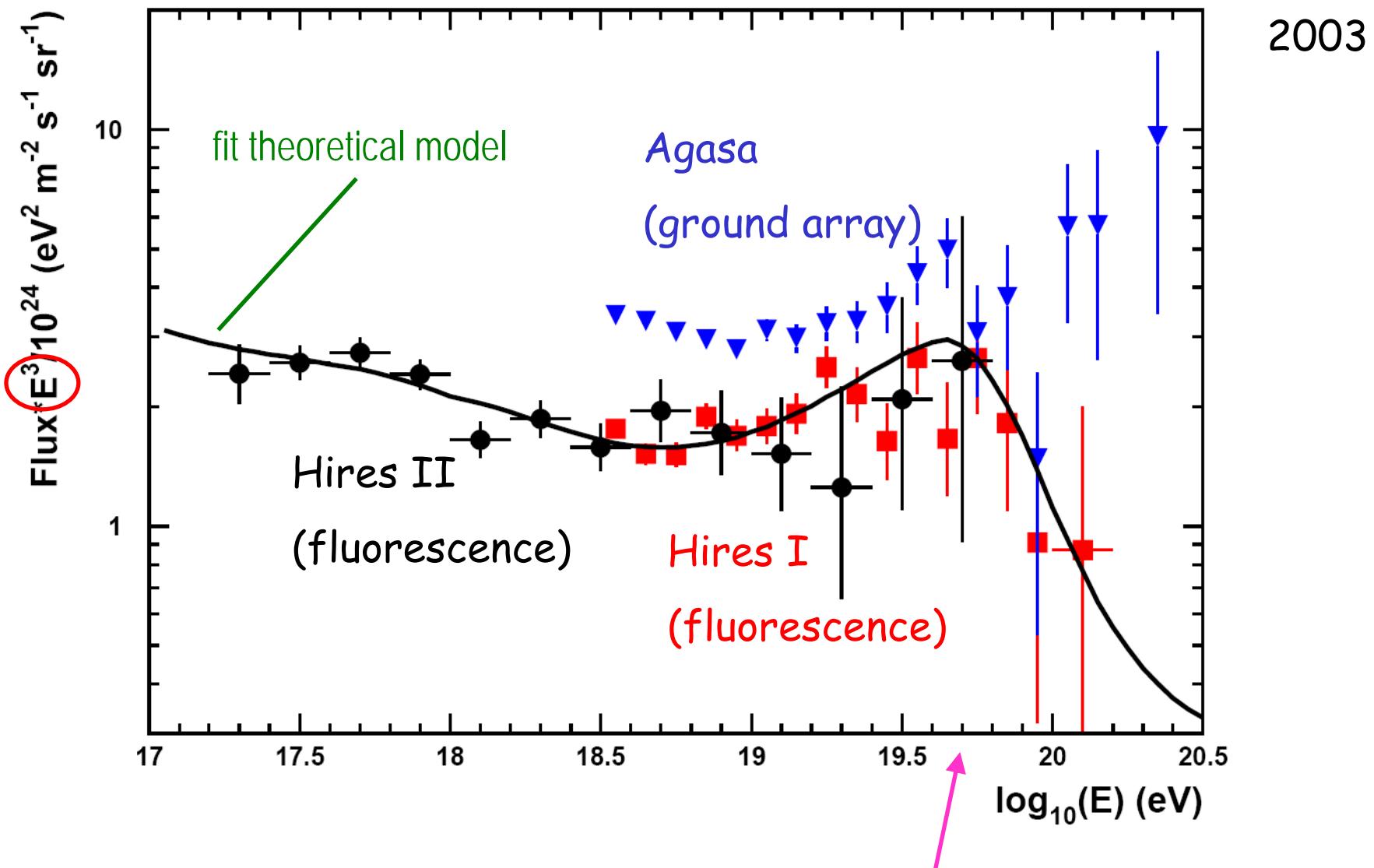
Arrival directions



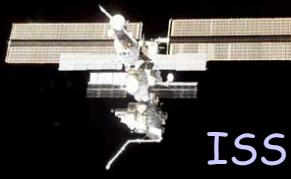
isotropic distribution

Ultra high energies, but rare

Discrepancies between Agasa and Hires



Who is right ? Does spectrum fall off at 50 EeV ?



Cosmic Rays 2004

primary (protons, nuclei)

energy reaches 10^{20} eV

secondary

Fundamental Questions:

Where from ?

Acceleration ? Max. energy ?

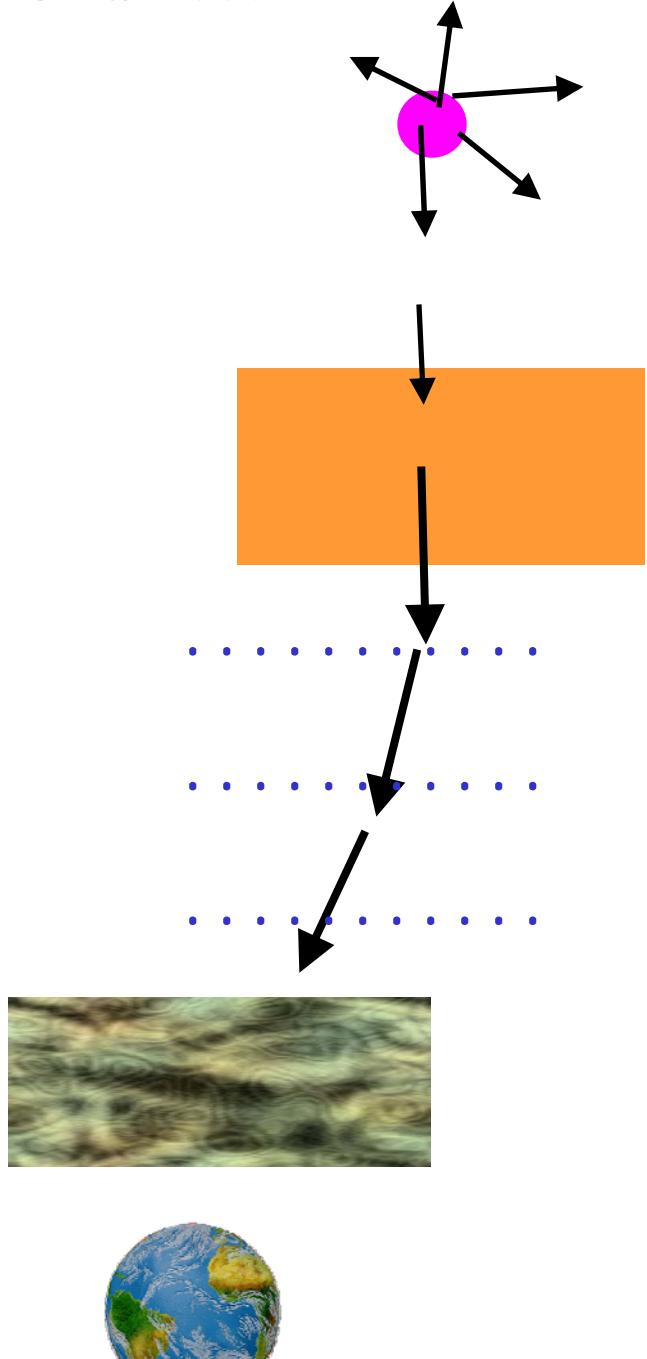
Composition ?

Cosmic Rays

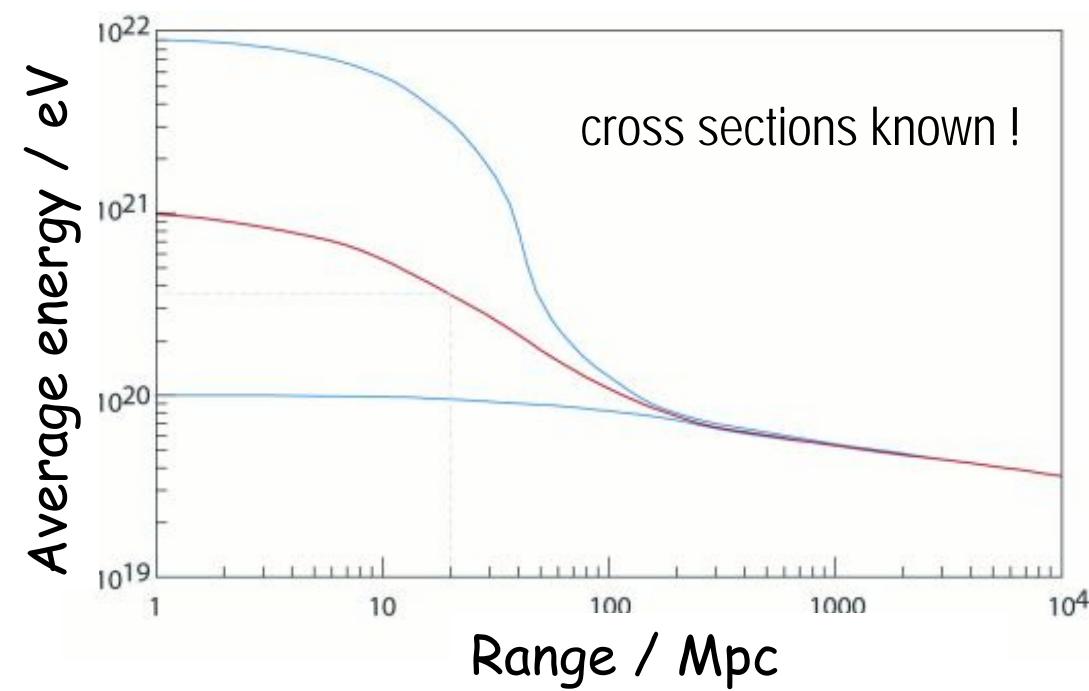
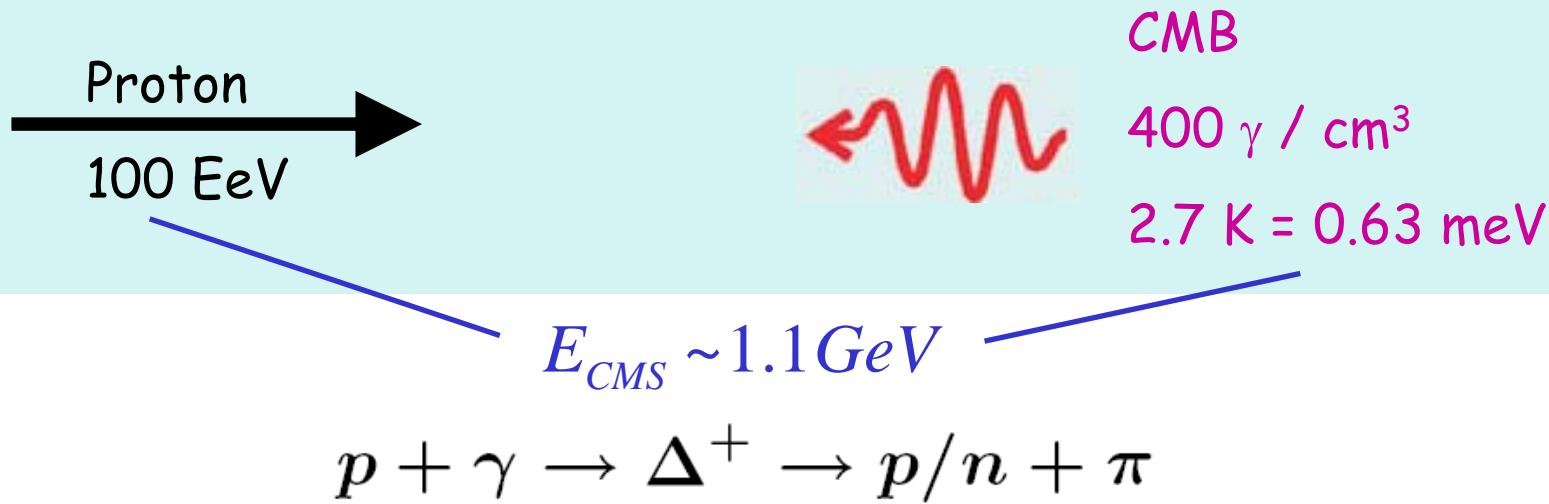
- Discovery / Properties
- Influence on Earth / Life / Science
- High Energy Cosmic Rays
- Cosmic Sources and Propagation
- Auger-Observatory
- First Auger Results

Questions Questions Questions ...

- Sources ?
- Acceleration Mechanism ?
- Deflection by magnetic fields ?
- Absorption ?

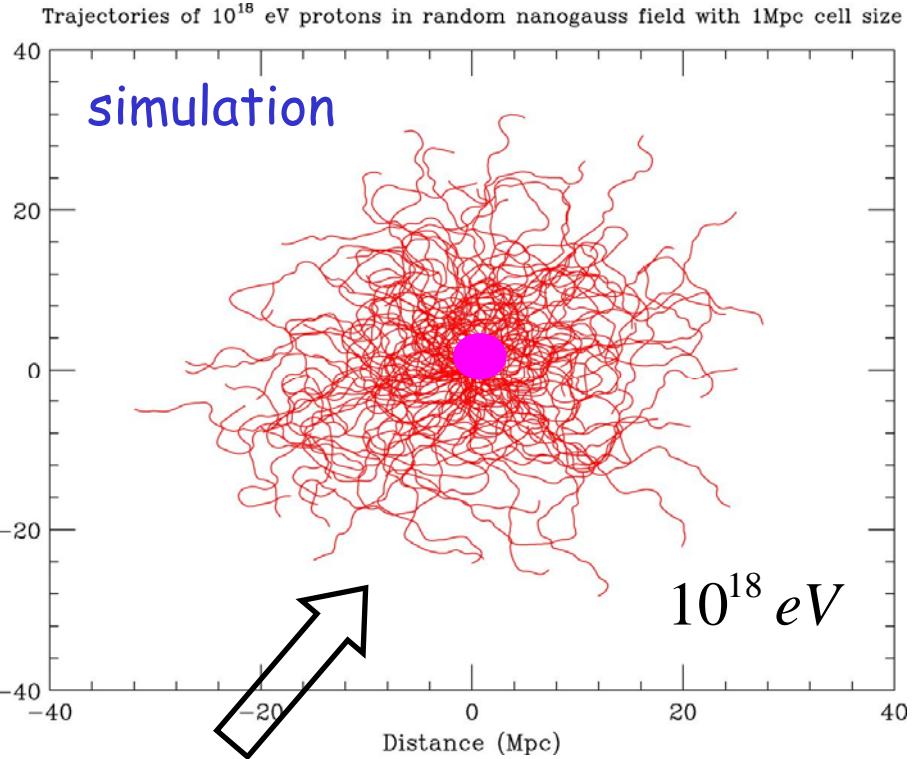


GZK Cutoff (Greisen-Zatsepin-Kuzmin)



For protons with
 $E > 50 \text{ EeV}$ (GZK cutoff)
range limited to
 $\sim 100 \text{ Mpc} \sim 300 \text{ MLJ}$

Deflection in cosmic magnetic fields

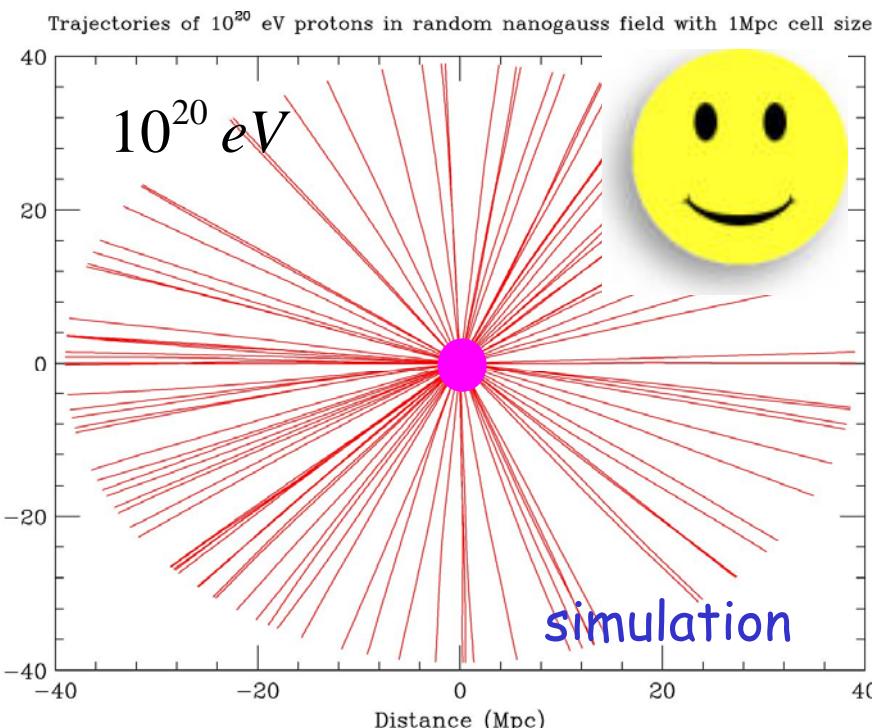


Upon arrival at earth:
Information on source
direction lost

(1 Mpc ~ 3 MLj = distance between neighbor galaxies)

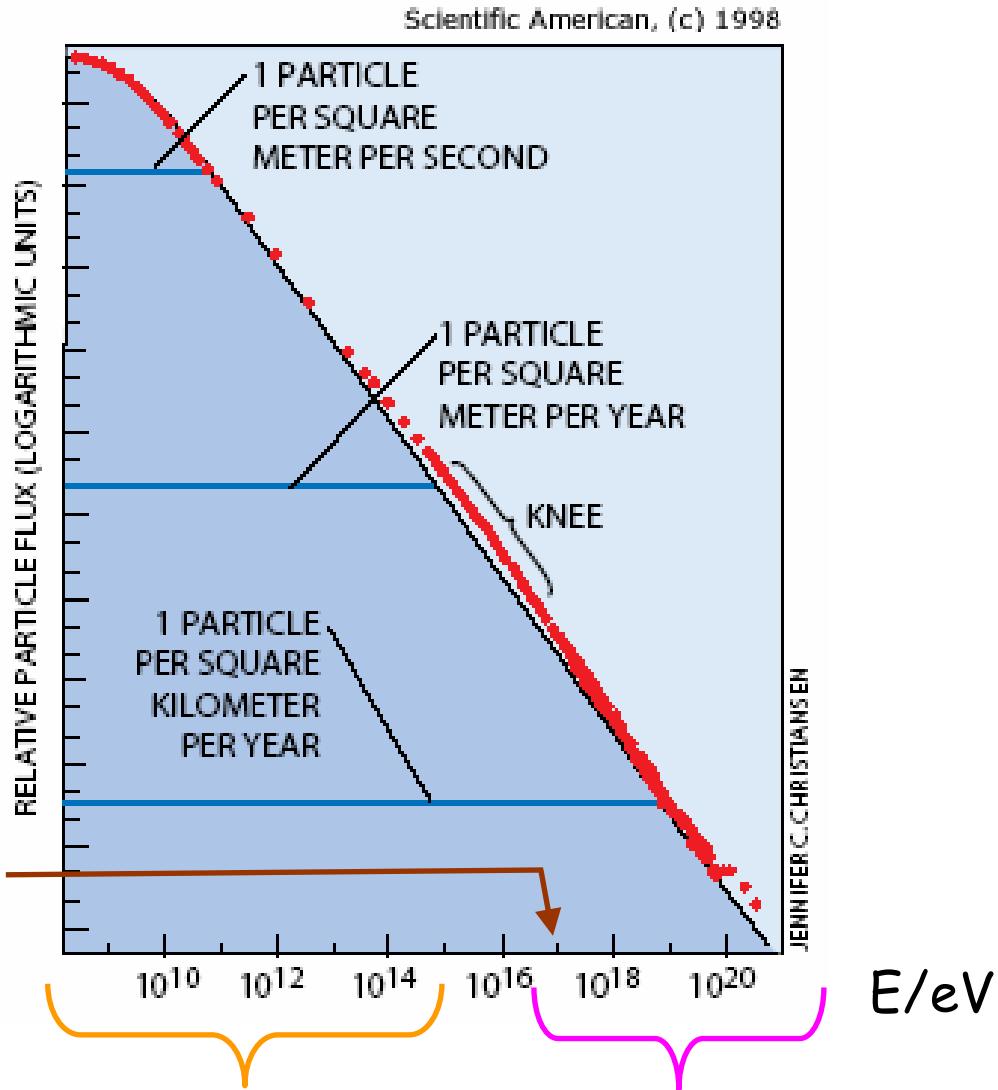
inside galaxy: $B \sim 10 \mu G$

intergalactic
space: $B \sim n G$



Sources/Accelerators of charged cosmic rays

T.Hebbeker



Hypotheses:

Supernovae in
Milky Way ?

extragalactic sources
AGNs ???

Supernovae – cosmic rays up to the knee ?

Hypothesis supported by:

- **energy balance**

Milky way:

energy density 0.5 eV/cm^3

lifetime cosmics 10 million years

need 3 SN per century

- **acceleration mechanism**

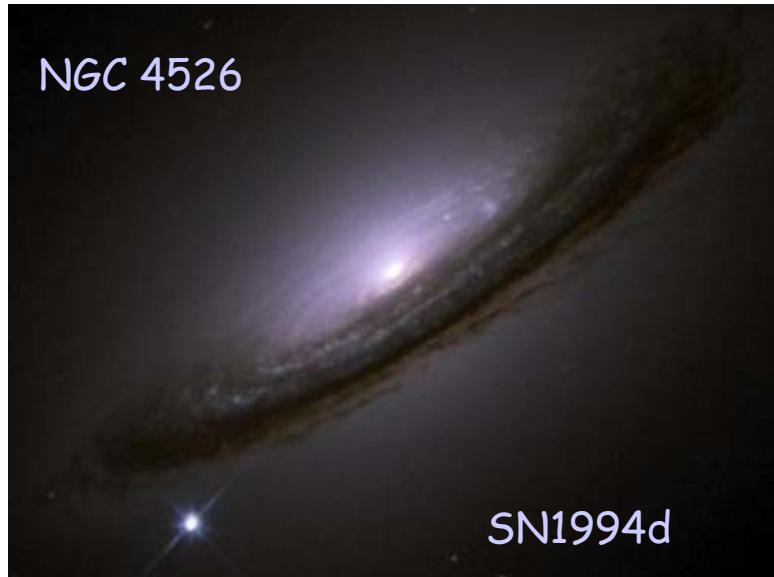
shock wave + interstellar medium

can explain E^{-3} , $E_{\max}^p \sim 10^{15} \text{ eV}$

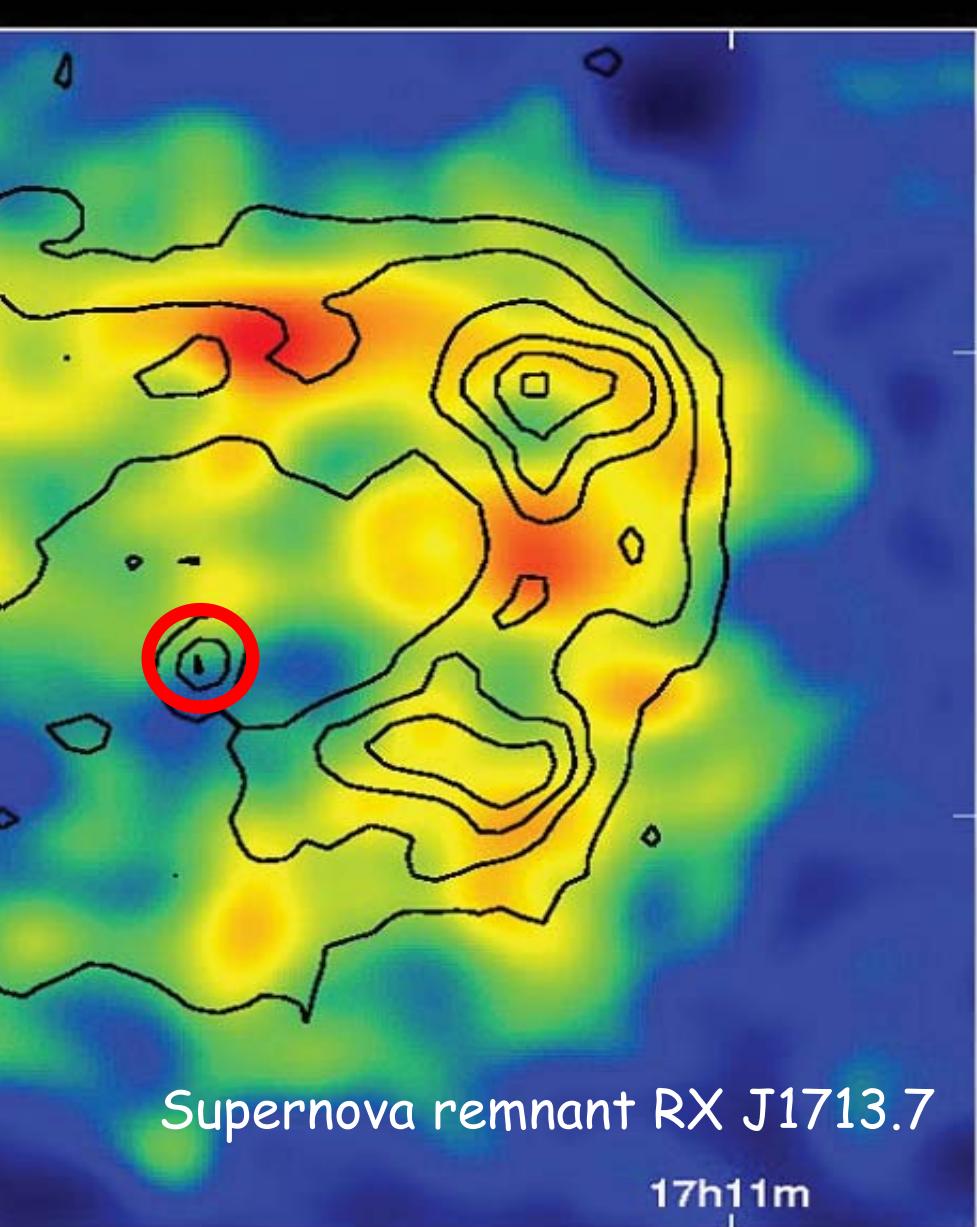
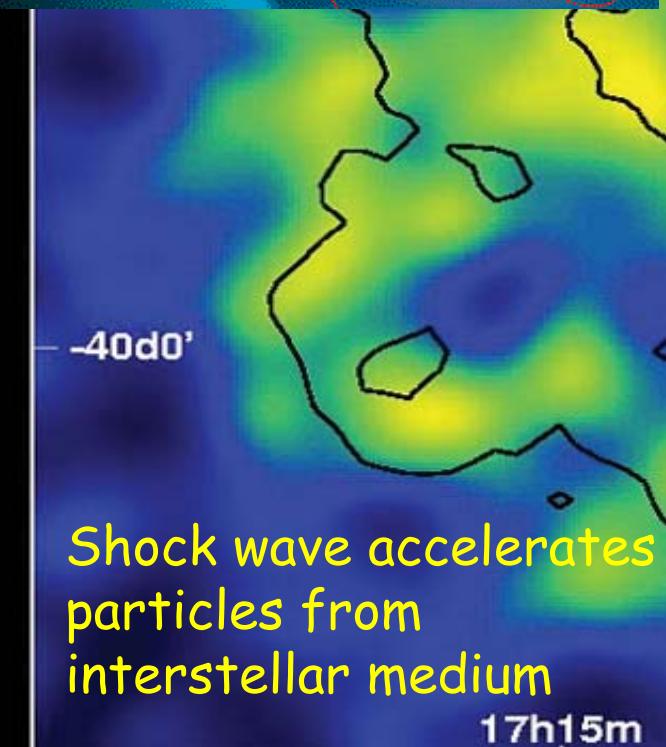
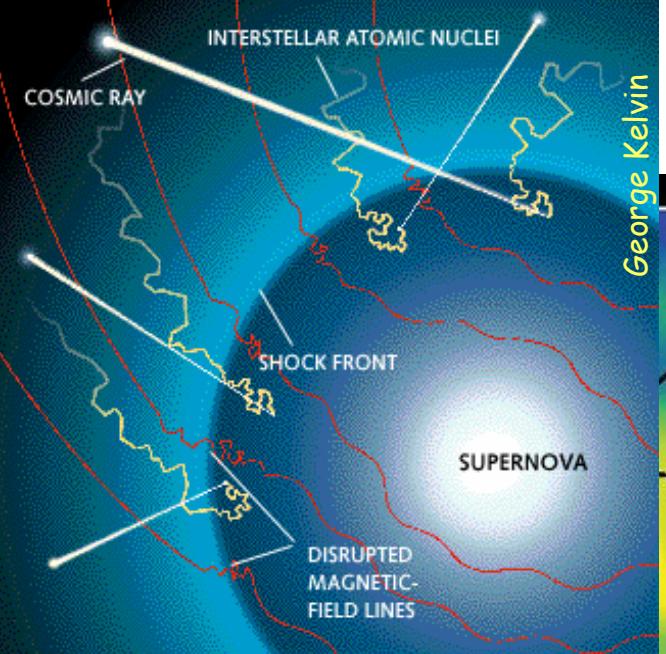
- **HESS observations**

of TeV gamma rays

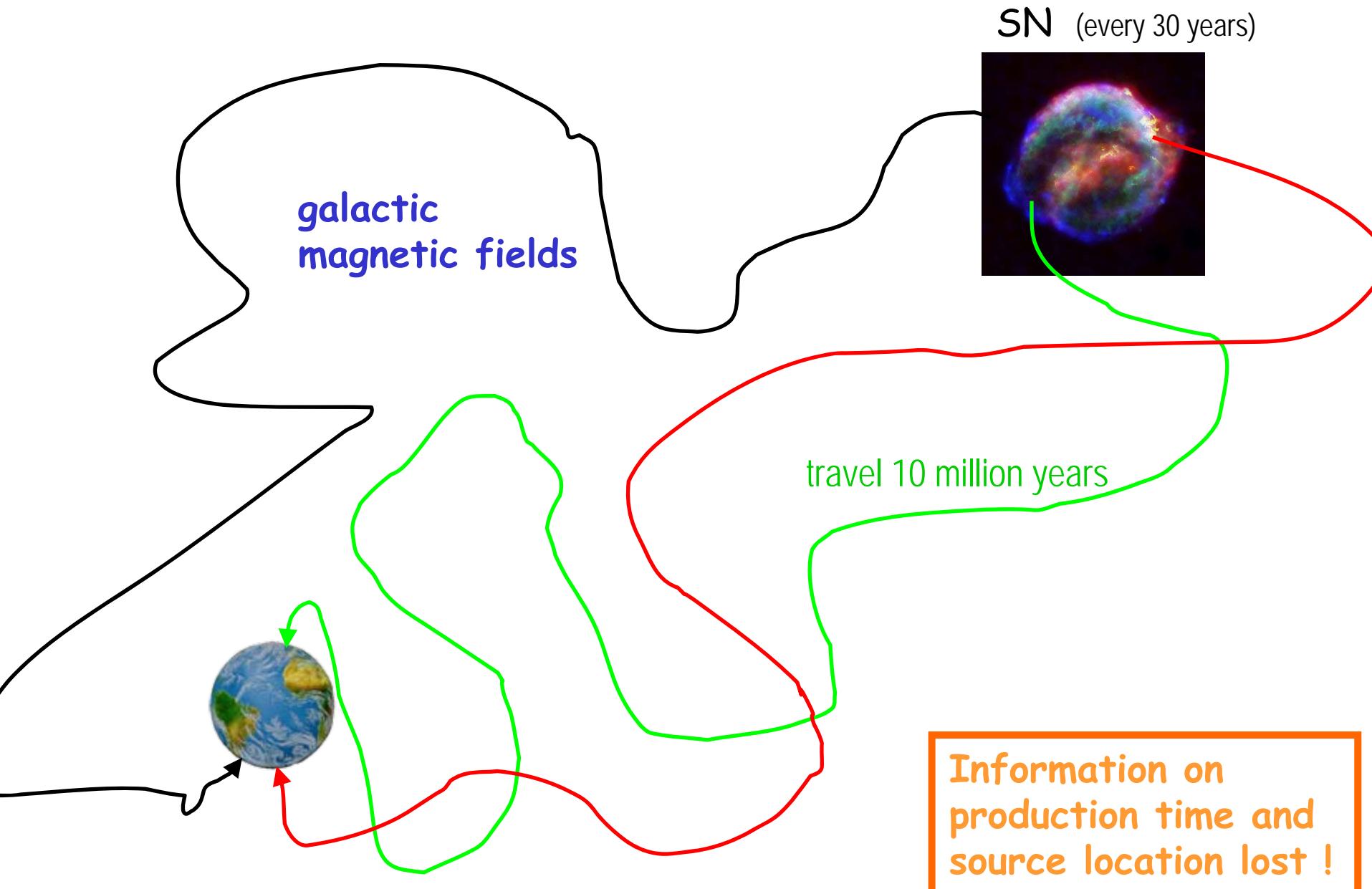
confirm acceleration model



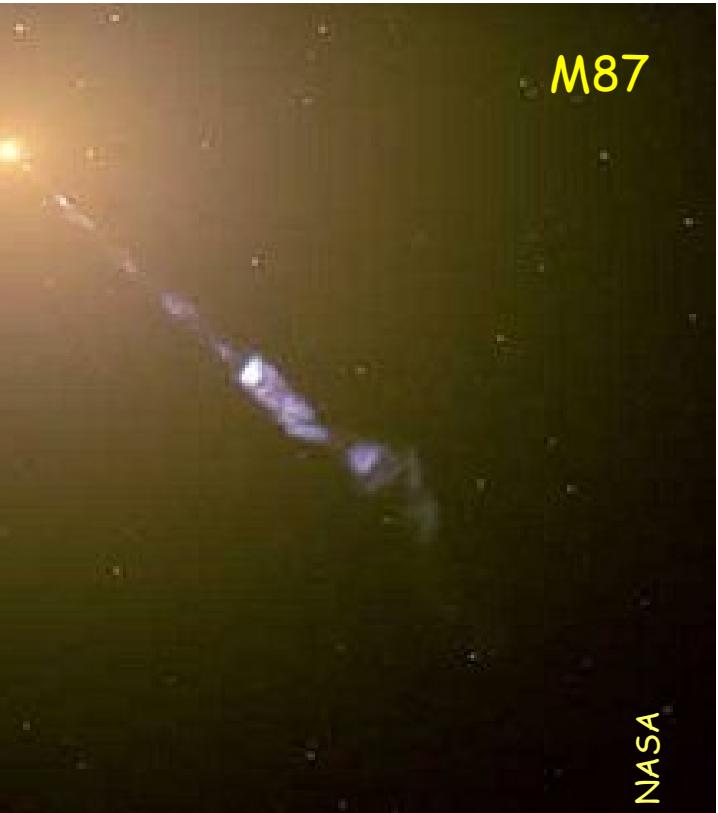
HESS TeV Gamma Sky



Supernovae and cosmic rays in milky way

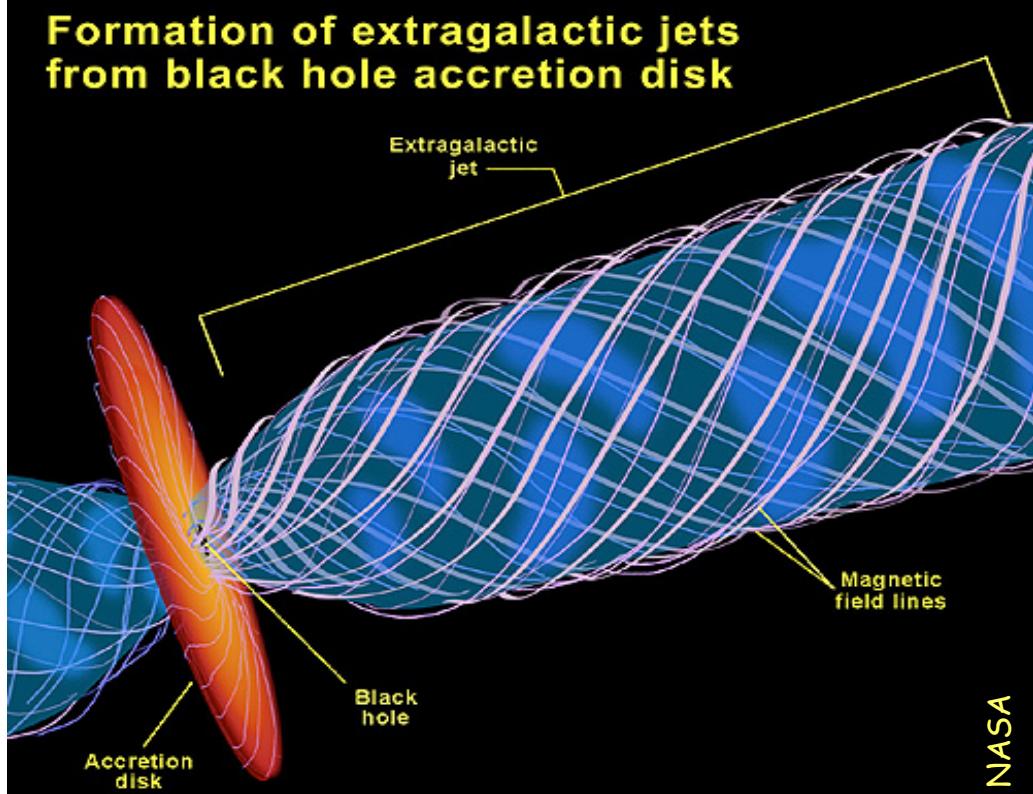


Highest Energies – from Active Galactic Nuclei ? (AGN)



Hypothesis:
AGNs = source of ultra high
energy cosmic rays

center = massive black hole,
feeds ,jets'



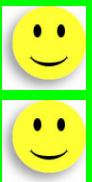
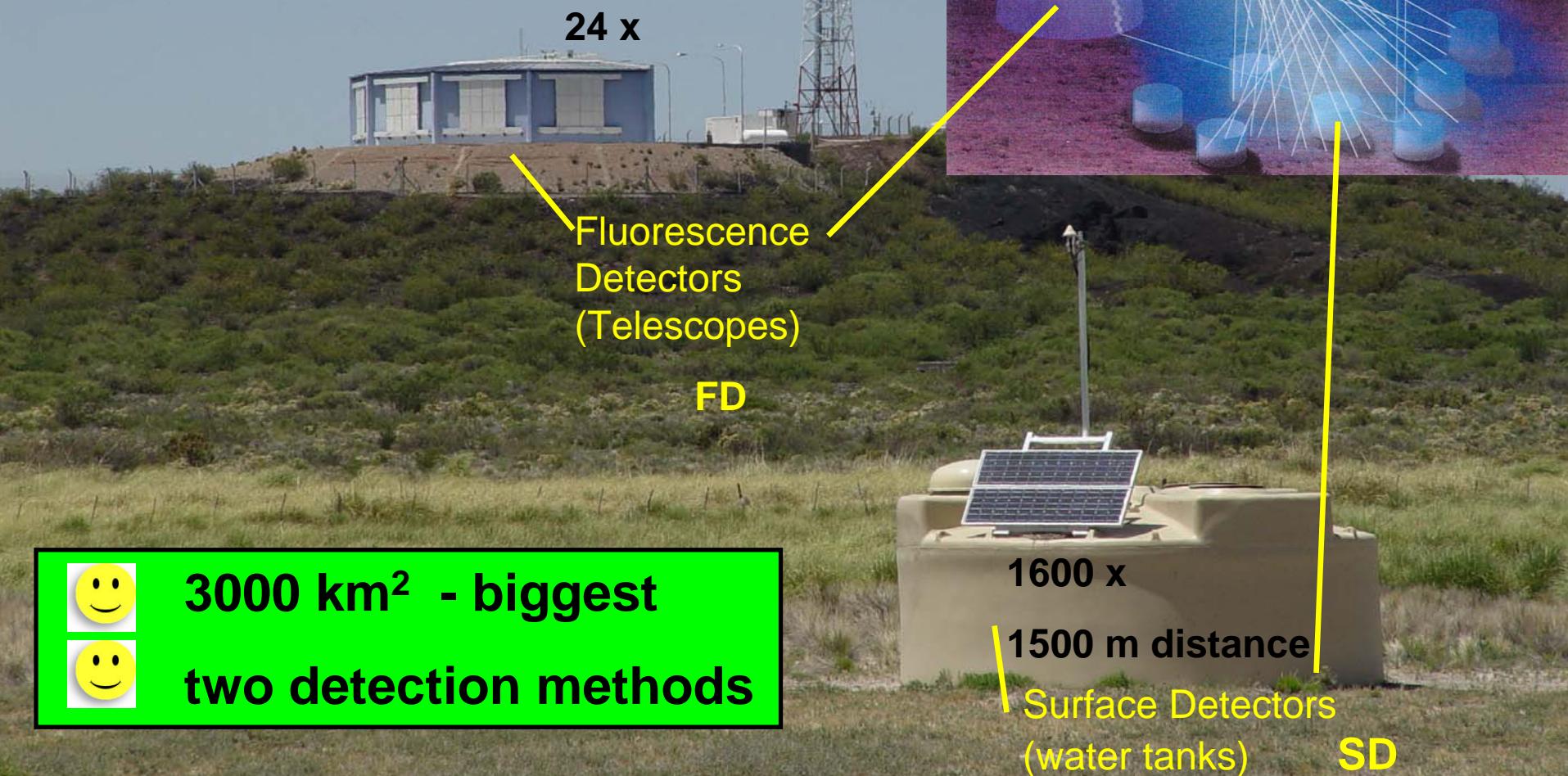
Cosmic Rays

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Auger Observatory

start data taking 2004

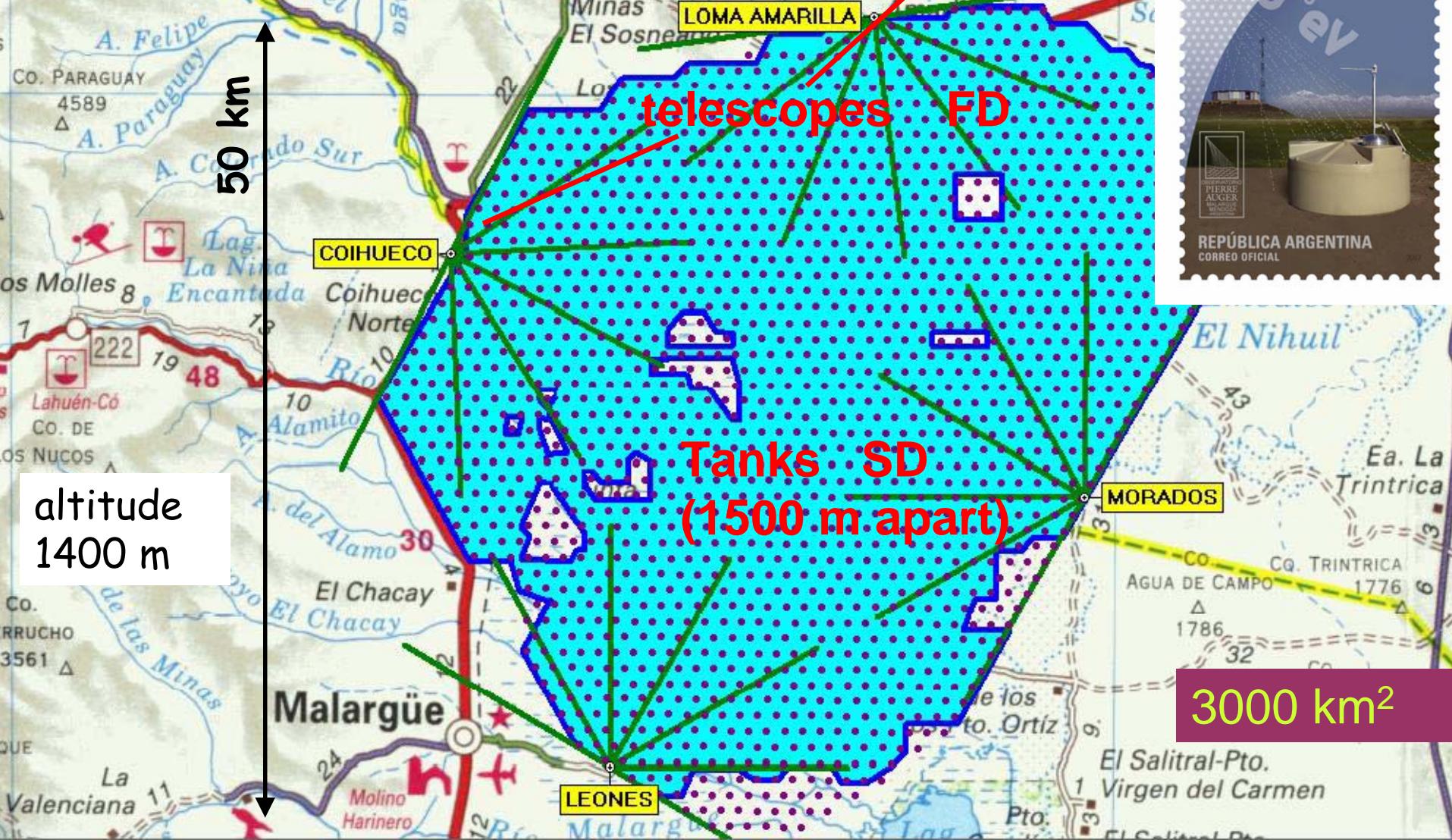
detector completed 2008



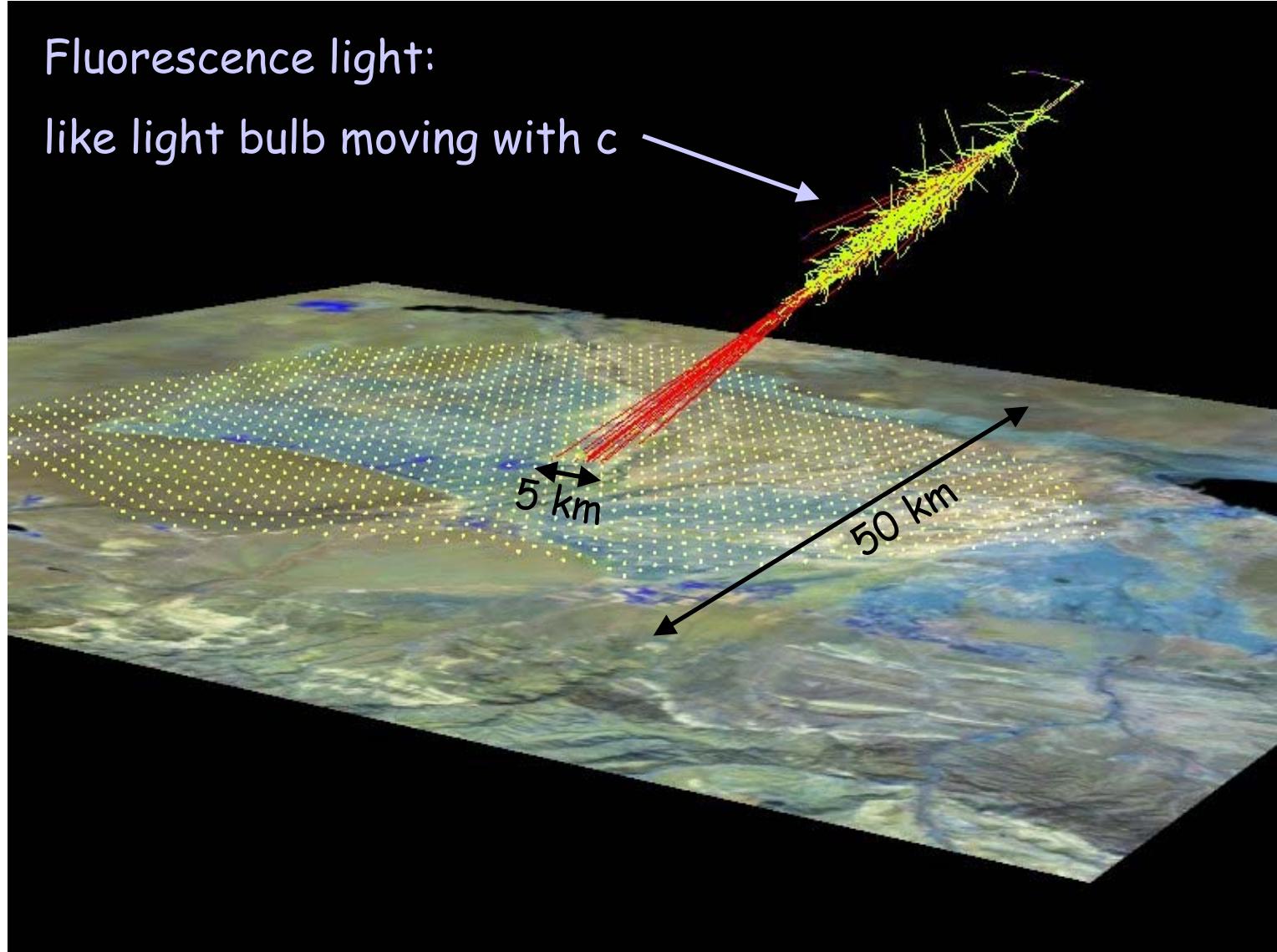
3000 km² - biggest
two detection methods

Auger-Observatory

Argentina

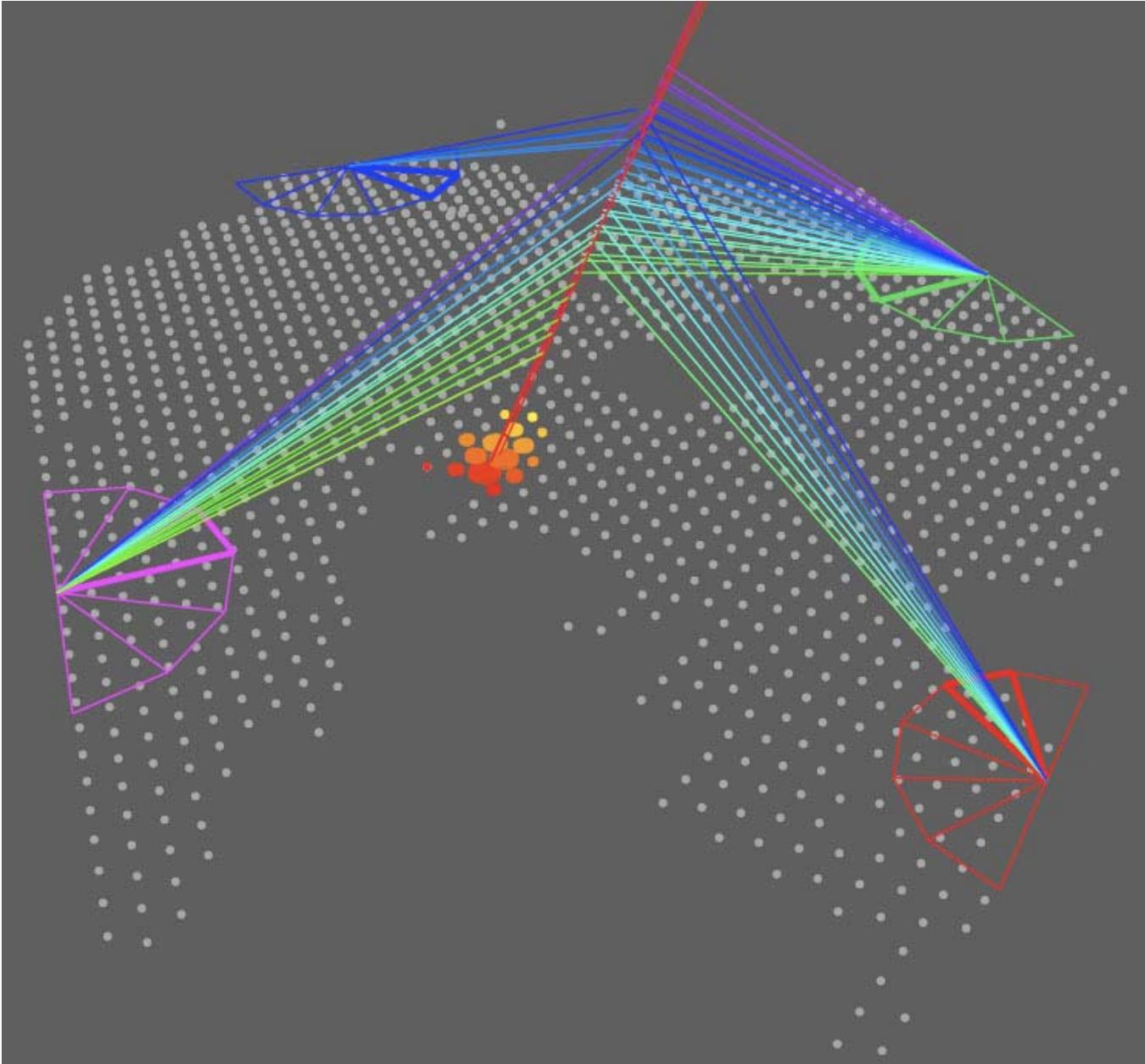


Ultra high energy cosmic shower



simulation

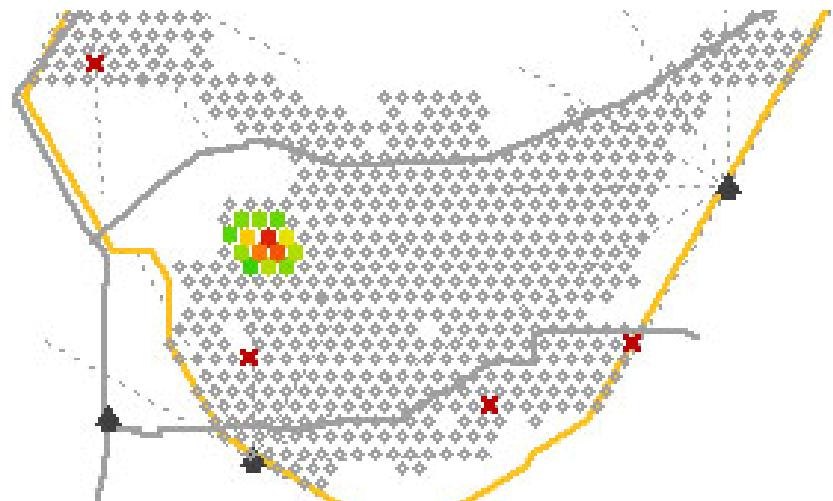
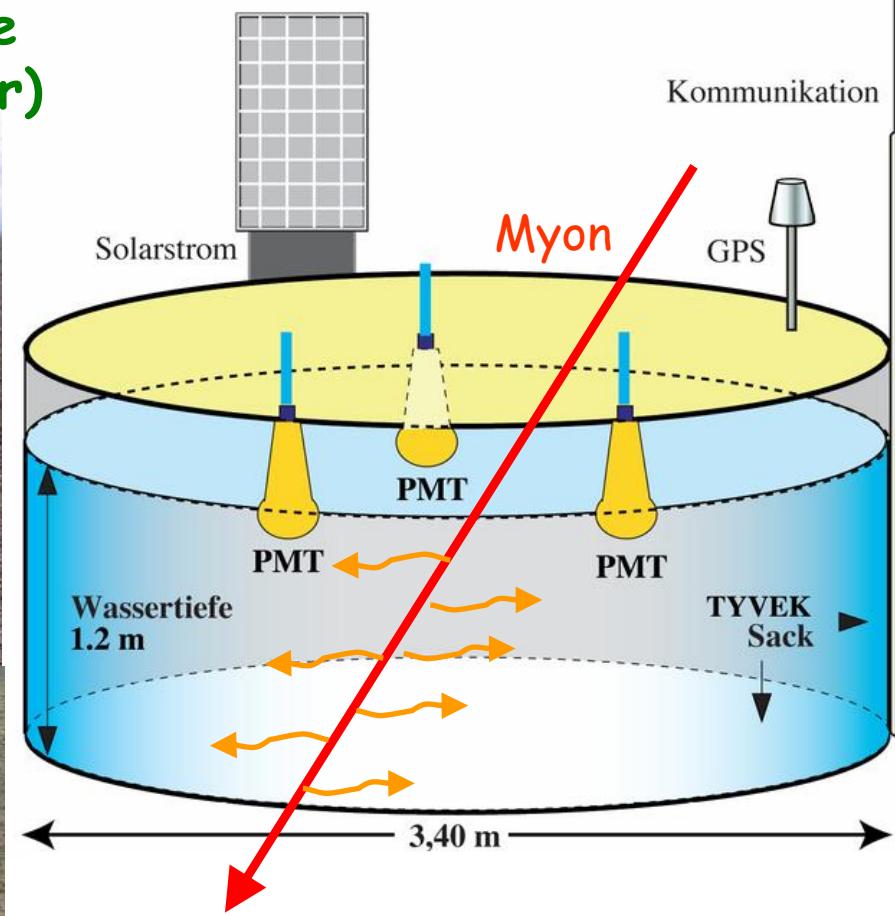
Ultra high energy shower seen by Auger



AUGER – SD

(Surface Detector)

angular
resolution $\sim 1^\circ$

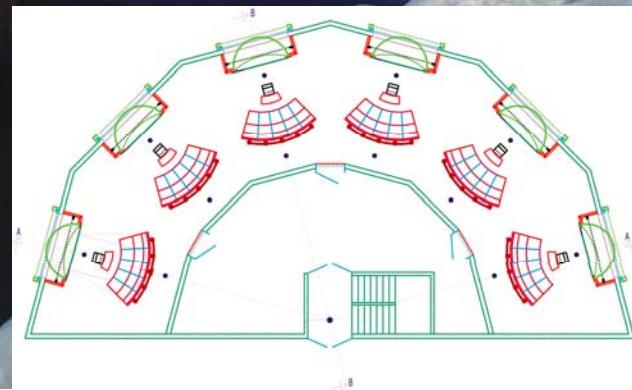
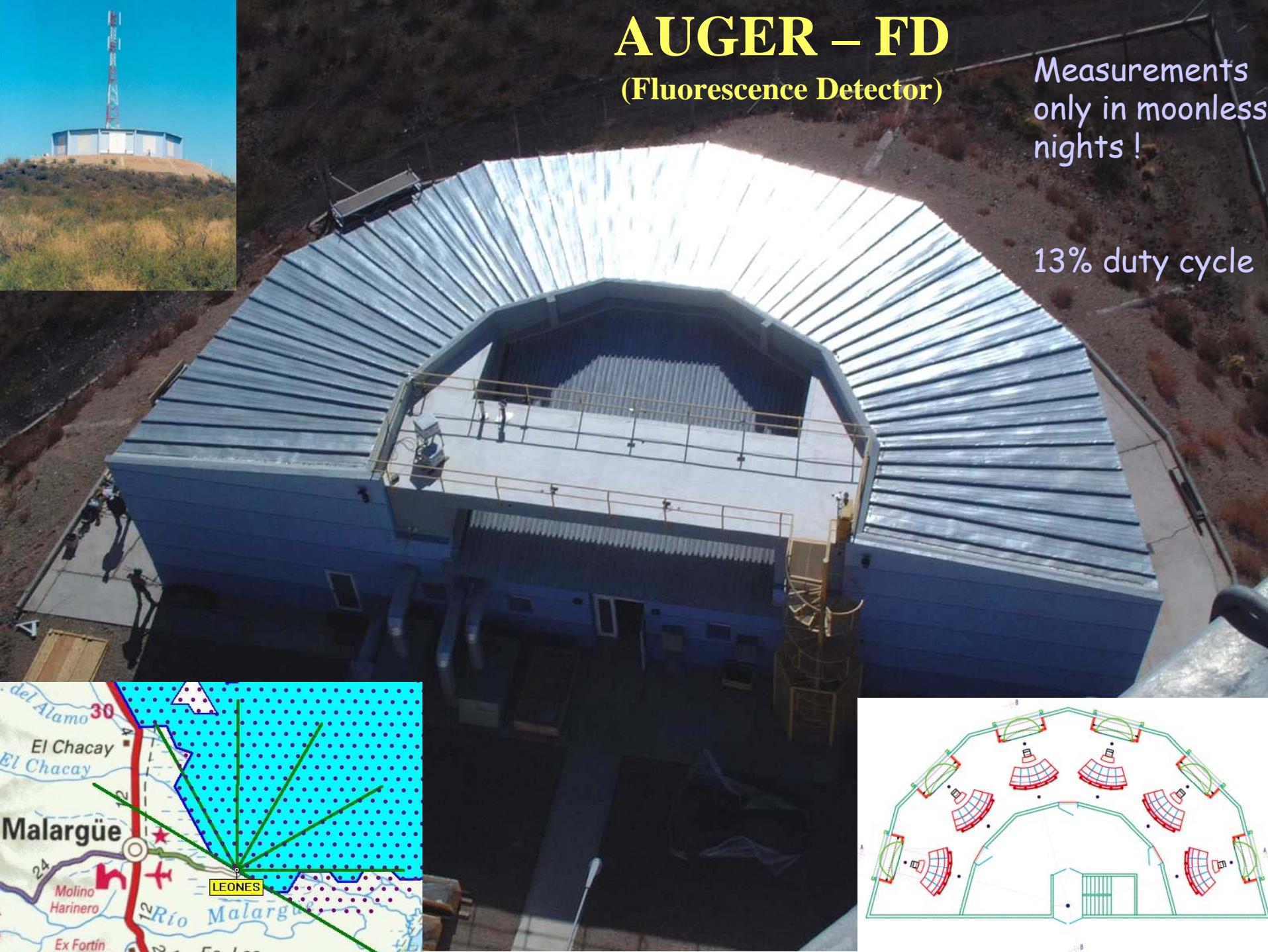


AUGER – FD

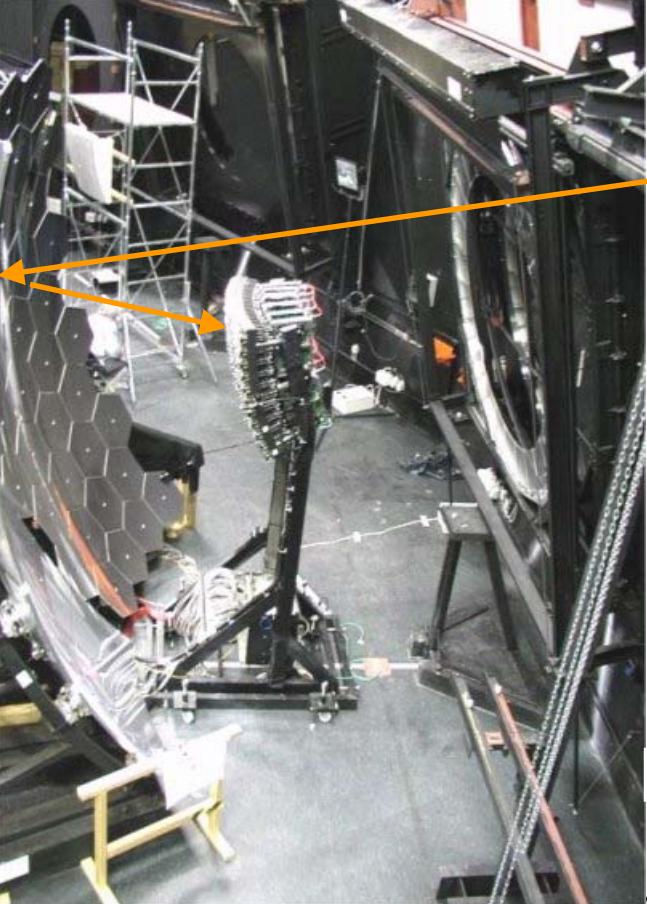
(Fluorescence Detector)

Measurements
only in moonless
nights !

13% duty cycle



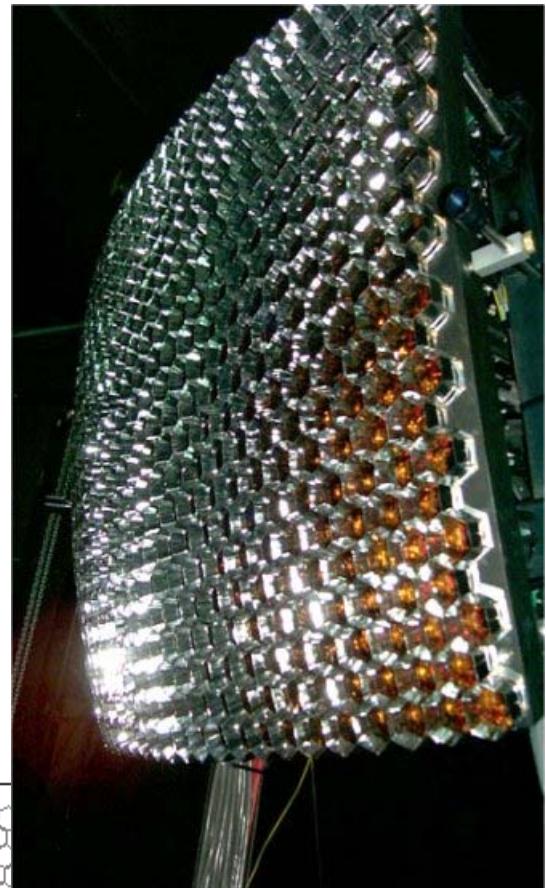
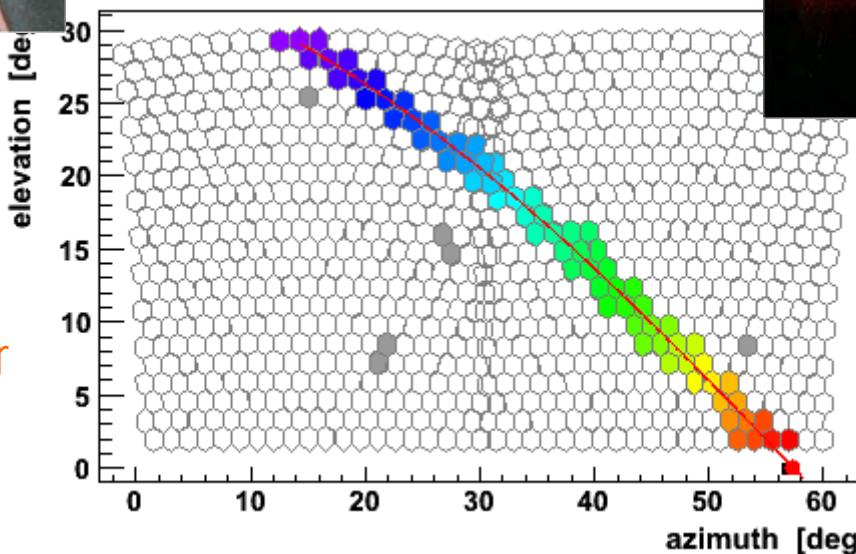
Auger Fluorescence Telescope



Trace of a shower
seen by camera

Camera:

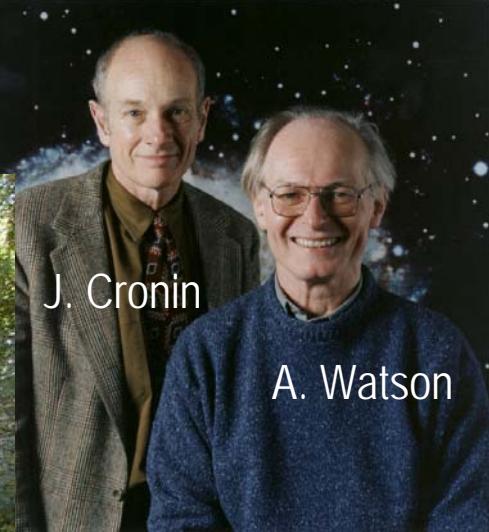
- 440 pixels (PM)
- 100 ns
- 1000000 ASA



color code
= arrival time

AUGER Collaboration

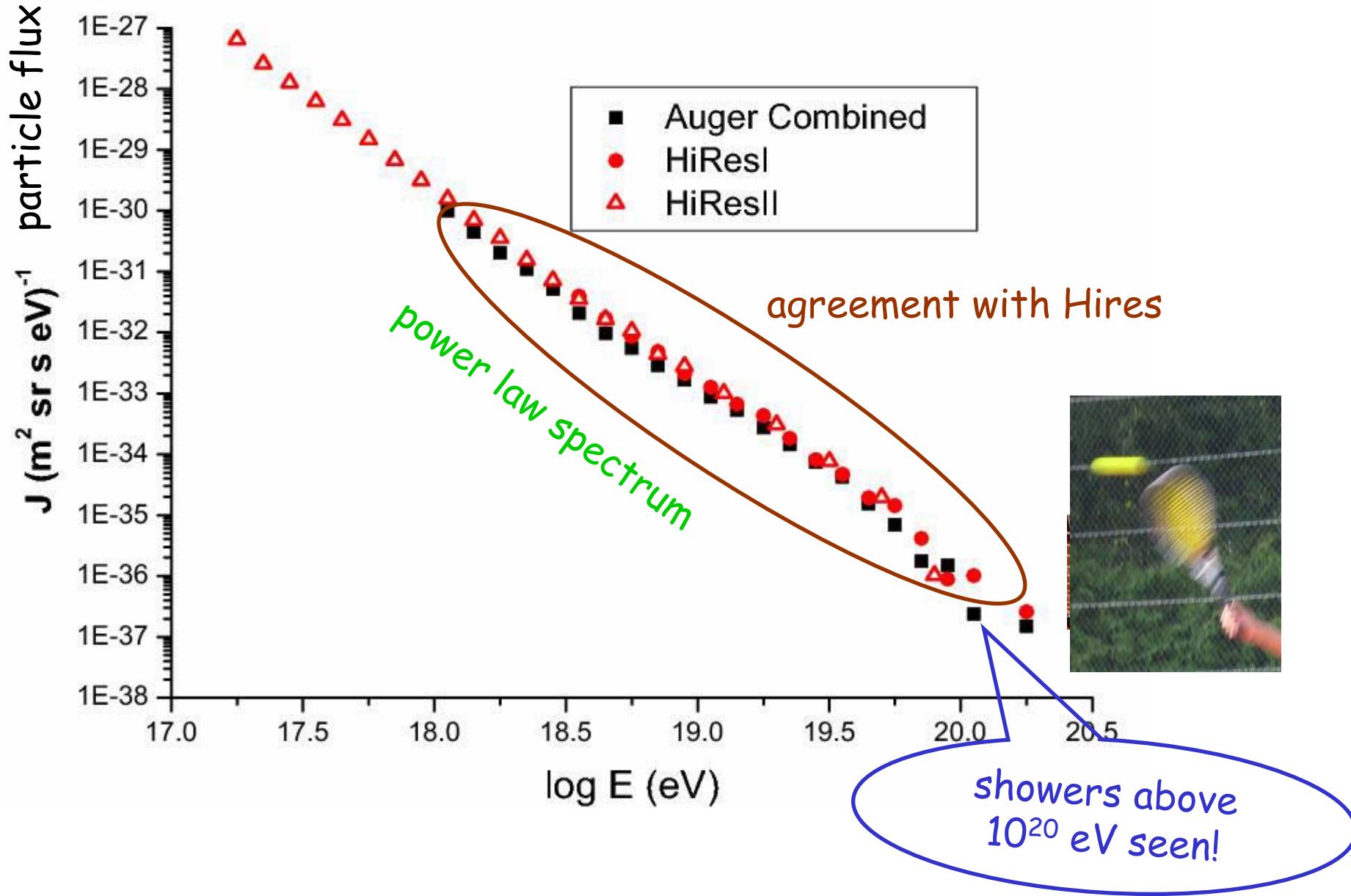
2006



Cosmic Rays

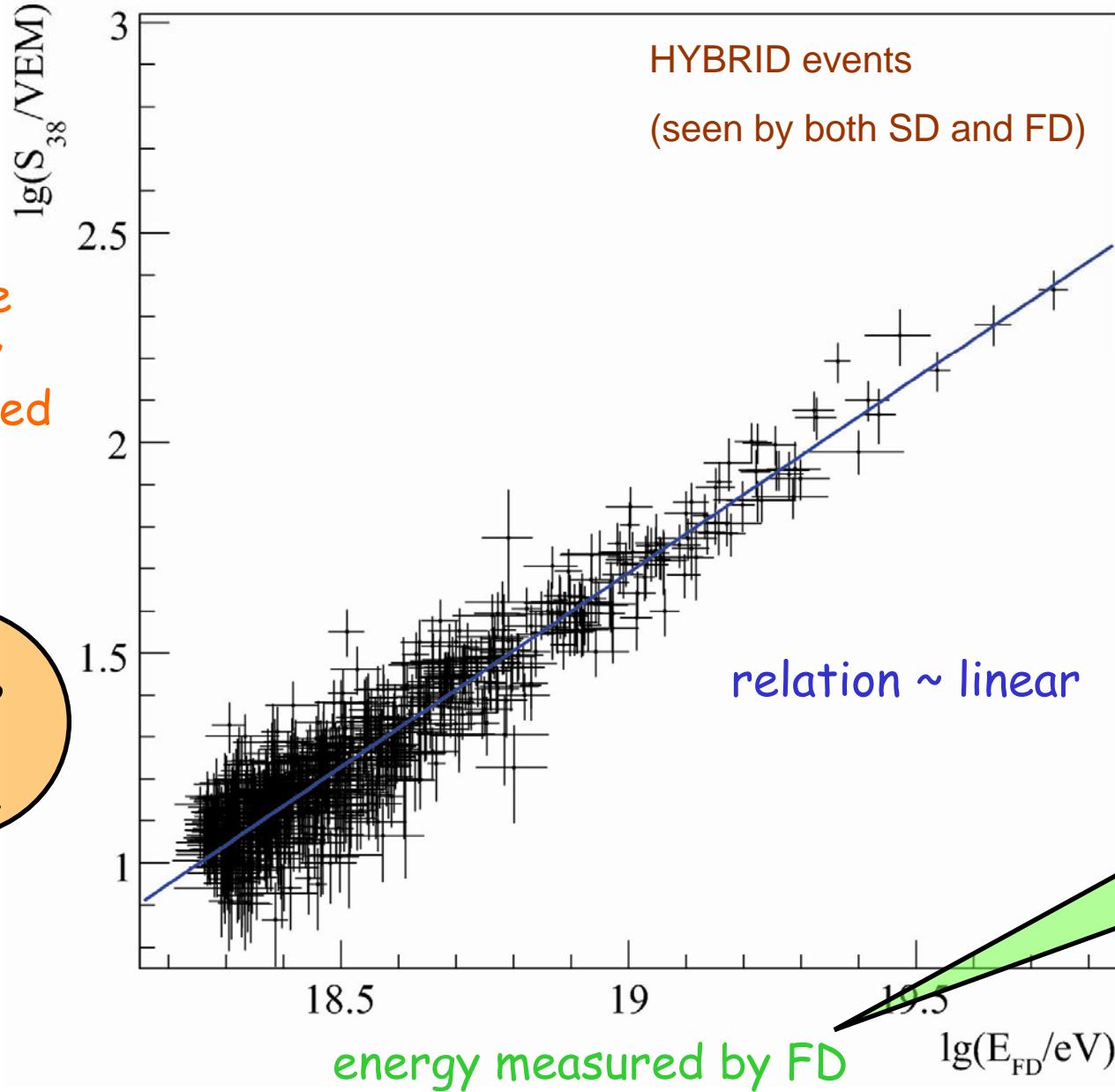
- Discovery / Properties
- Influence on Earth / Life / Science
- High Energy Cosmic Rays
- Cosmic Sources and Propagation
- Auger-Observatory
- First Auger Results

Auger – energy spectrum



Auger – energy calibration

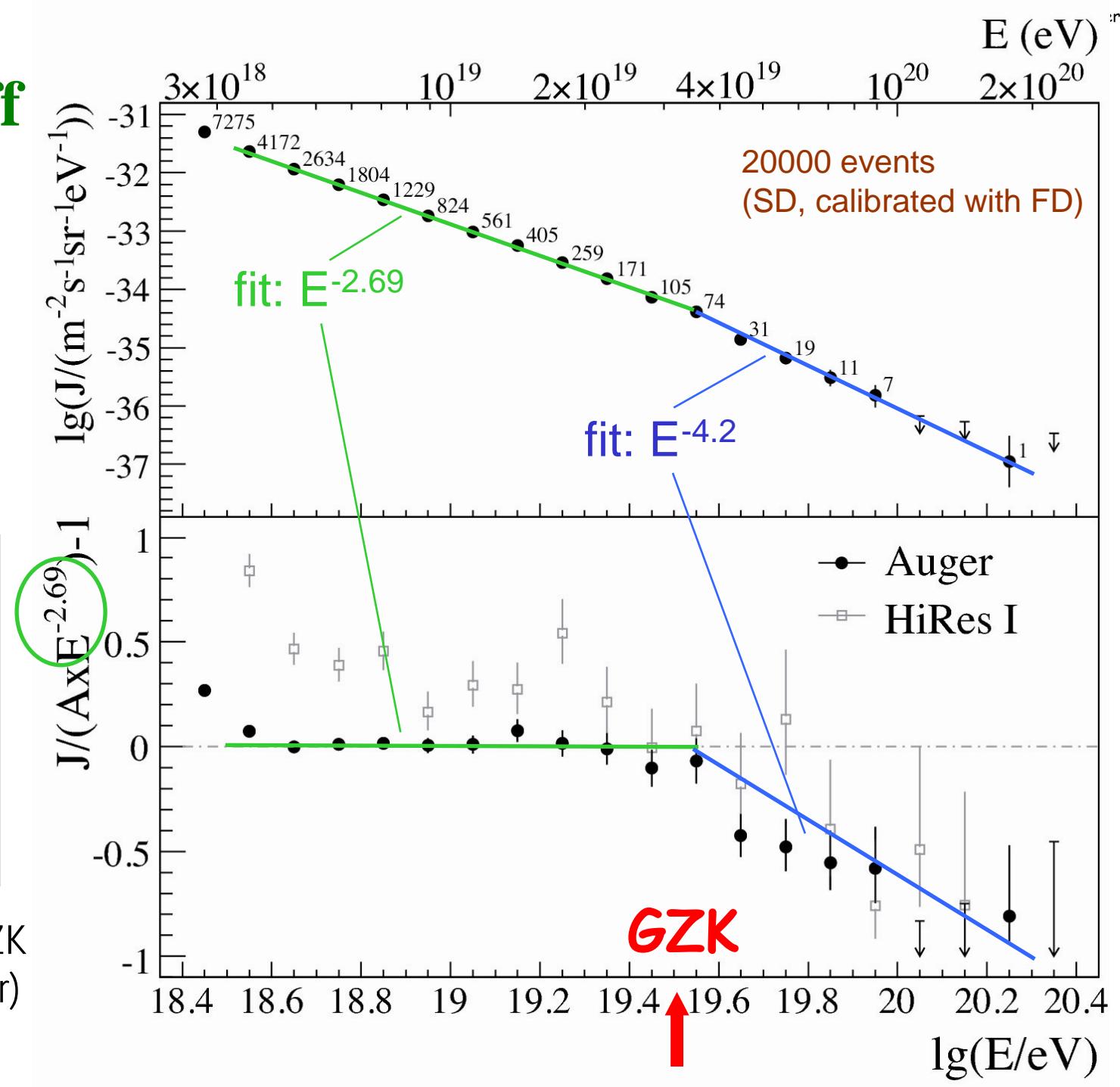
Particle
density
measured
in SD



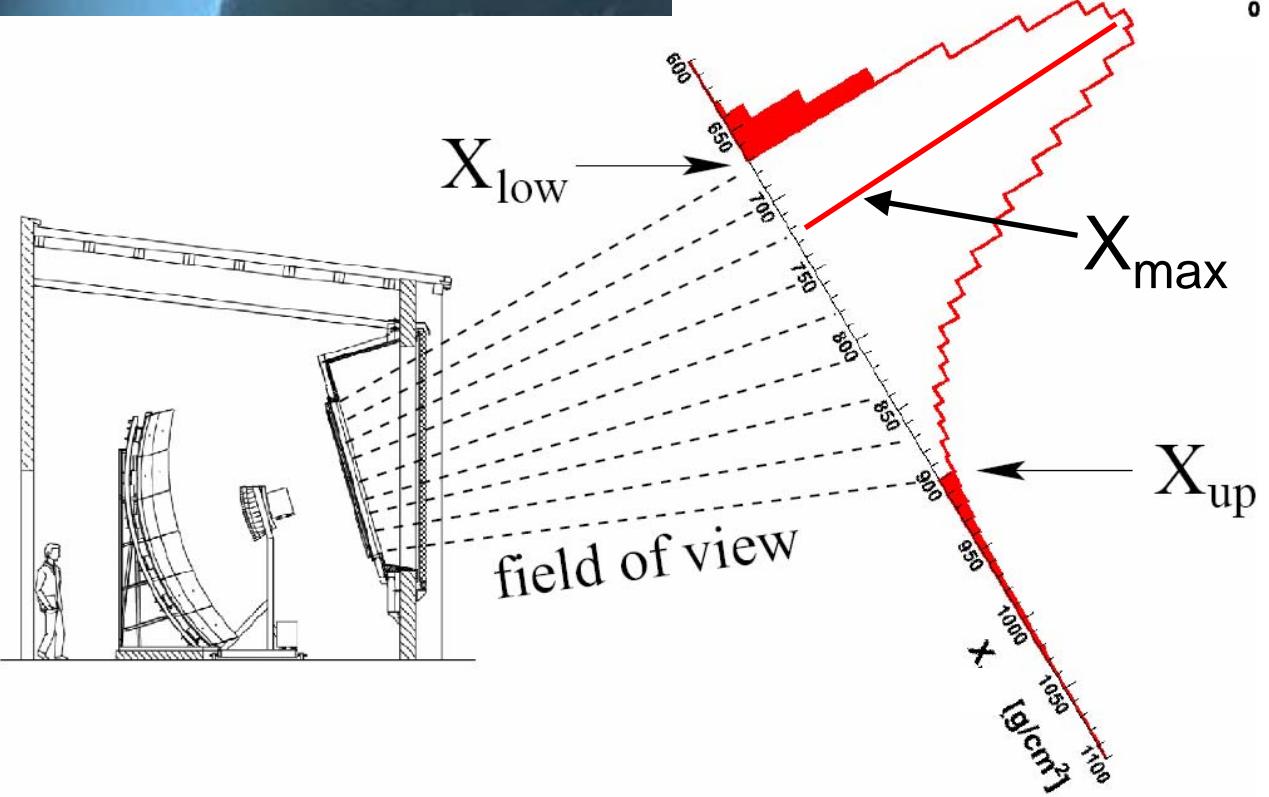
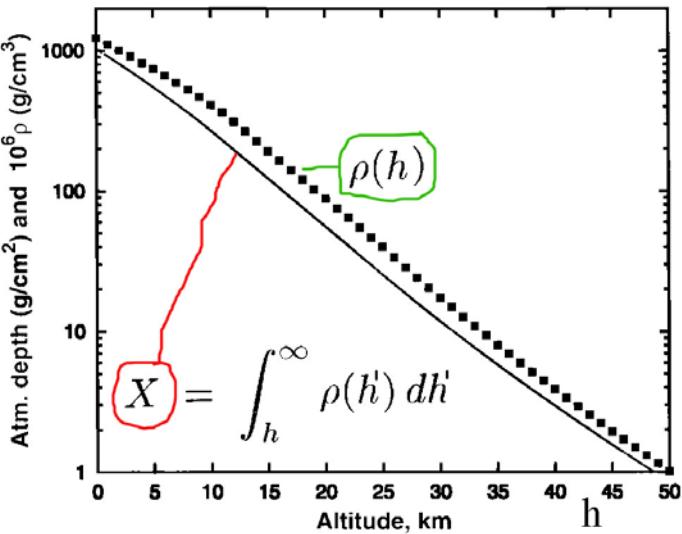
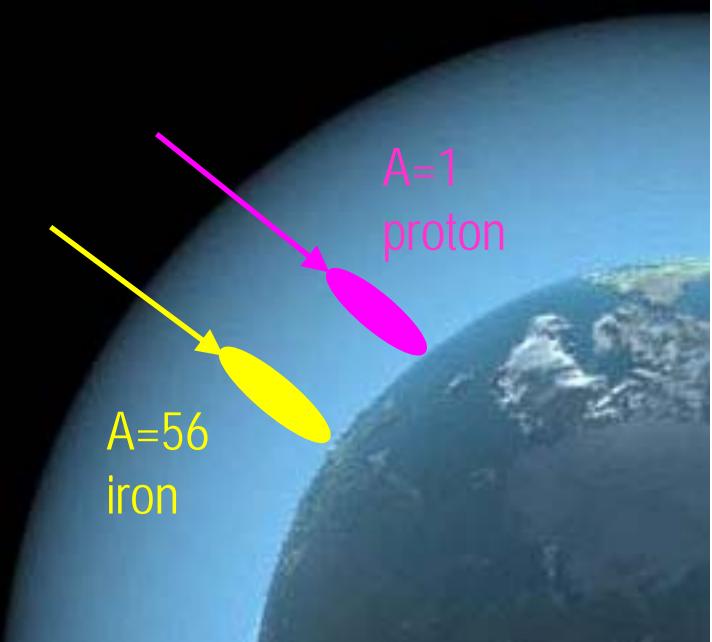
Auger GZK cutoff

drop of
spectrum near
GZK cutoff
clearly visible
(6σ)

could be due to GZK
or E_{\max} (accelerator)
or both....

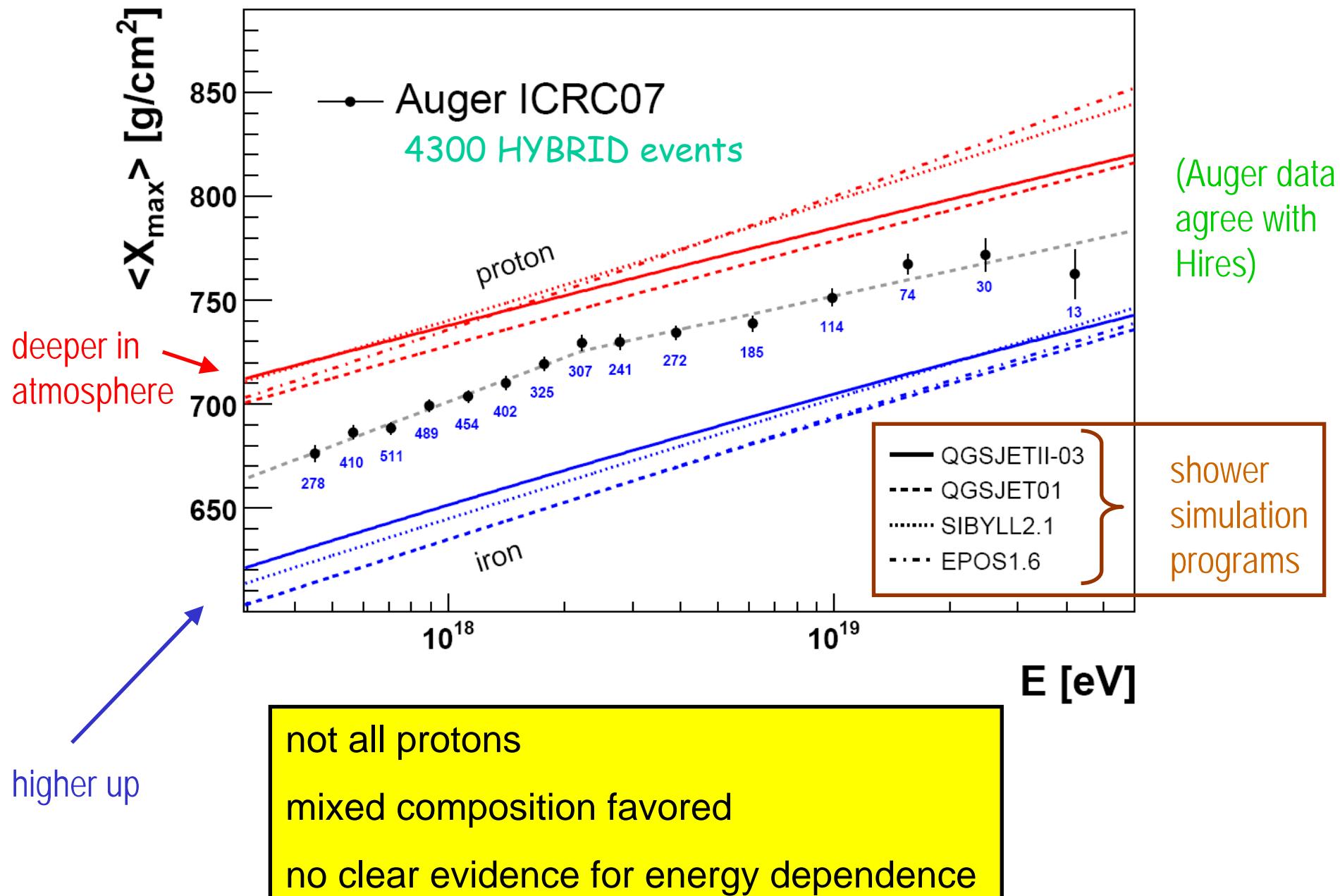


Chemical Composition ?



Measure
 $\langle X_{\text{max}} \rangle$
 with FD !

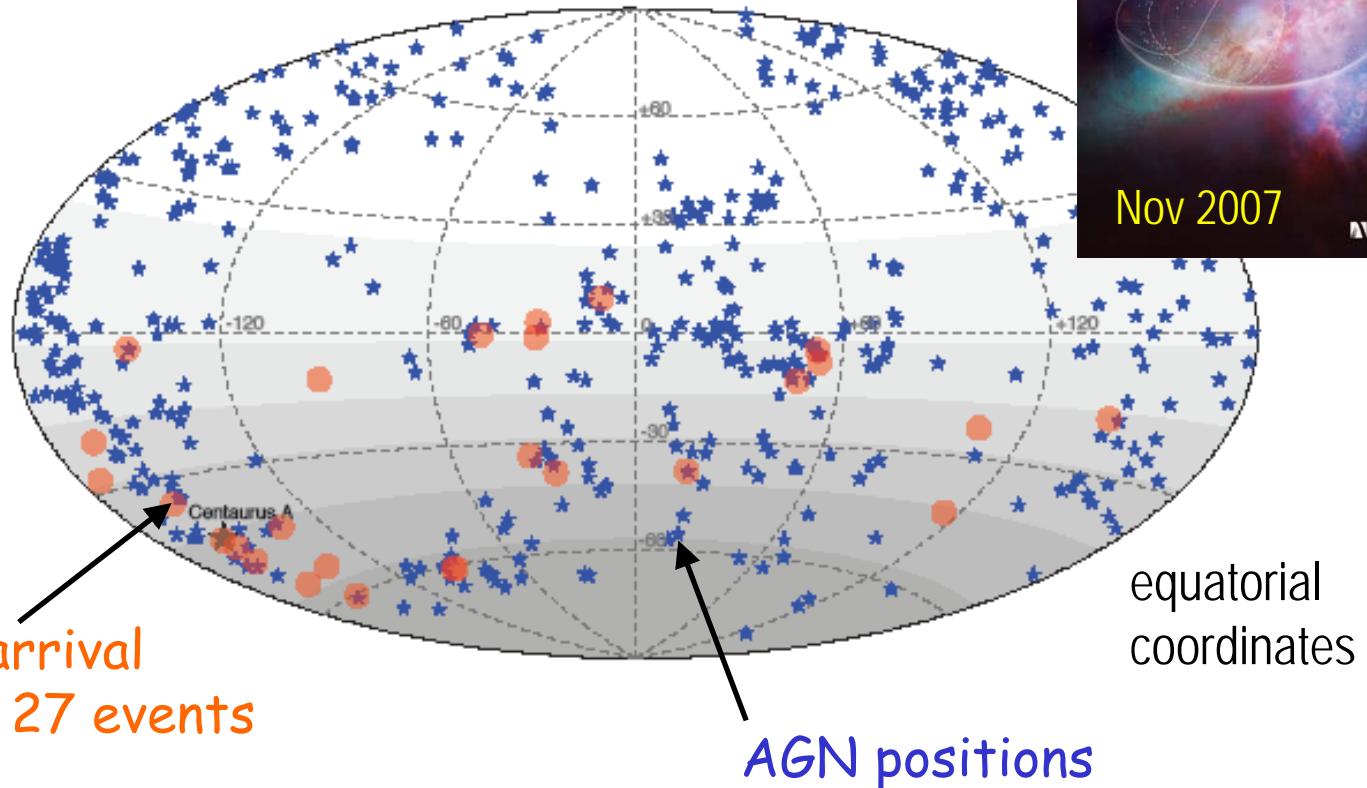
Auger - Chemical Composition



Auger – First Results – Arrival Directions

here only ultra high energy particles

$E > 56 \text{ EeV}$



! Anisotropy !

! correlation with AGN's !

! extragalactic !

Auger Anisotropy Analysis - Statistics

Veron-Cetty catalogue

Analysis of data collected till May 2006

- find maximum angular correlation events \leftrightarrow AGNs after **tuning**:
- lower shower energy threshold = 56 EeV
- maximum AGN distance = 75 Mpc = 250 MLj GZK !
- maximum angular separation event - AGN = 3.1°

„prescription“

out of 15 events 12 correlate

chance correlation
0.21 per event

Analysis of data collected June 2006 - August 2007

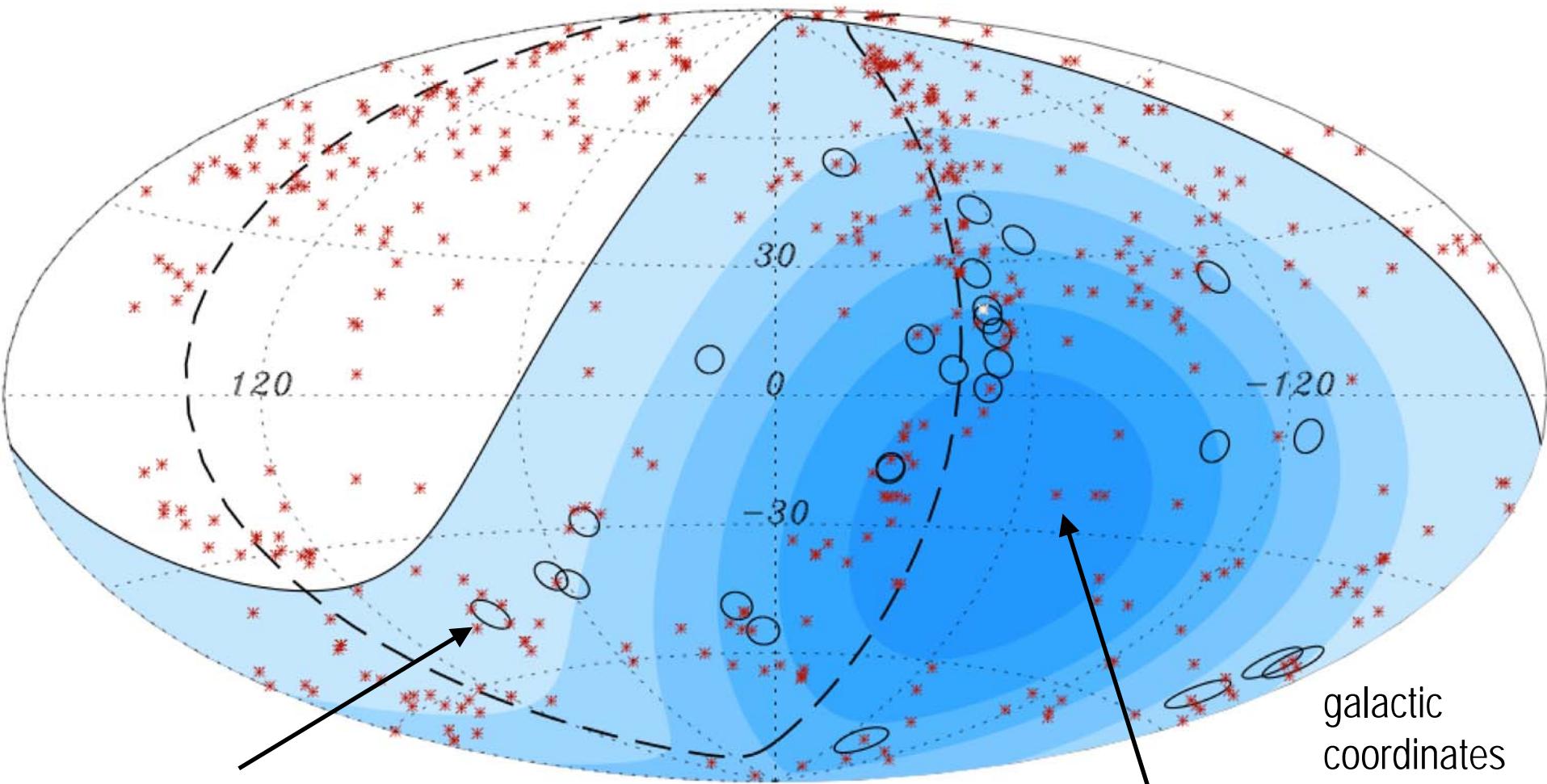
! prescription fixed before taking data !

out of 13 events 8 correlate

chance probability 0.17%



Auger – First Results – Arrival Directions



measured arrival
directions, 27 events

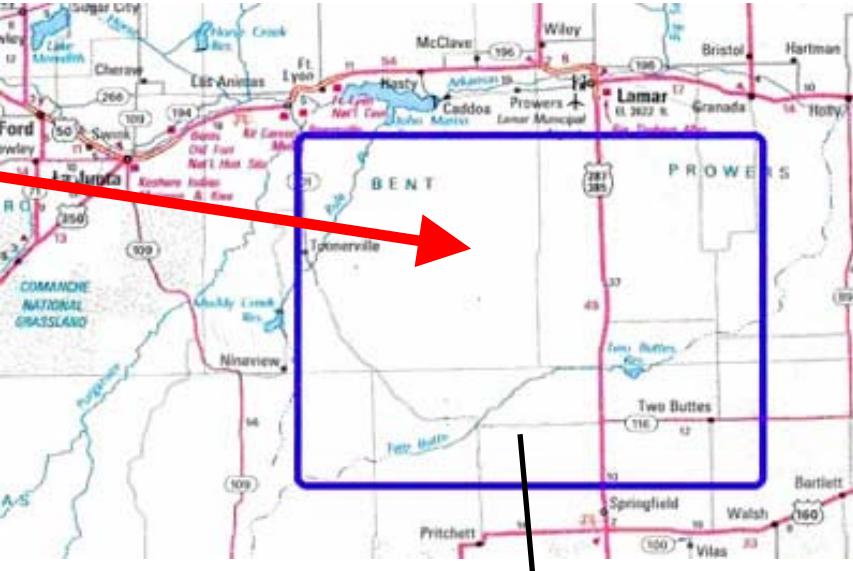
AGN positions

correlation between arrival directions and nearby AGN's

not less and not more

Future of the Auger Observatory

- measurements during several years
- second site Colorado/USA
- new: radio detection



20000 km²
northern hemisphere



antenna from
Aachen

Auger Team Aachen

2007



RWTHAACHEN

Phys. Inst. III A

SUMMARY

Ultra high energy cosmic rays:

- origin and composition still not known
- exciting new results
from AUGER:
anisotropy
GZK cutoff

A new
window to
the sky is
opening

Cosmic ray
astronomy



APPENDIX

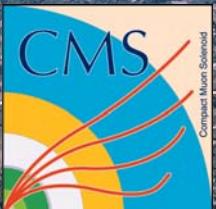
LHC = Large Hadron Collider

protons (7 TeV) + protons (7 TeV) = 14 TeV

$$= 1.4 \cdot 10^{13} \text{ eV}$$

Start: September 2008

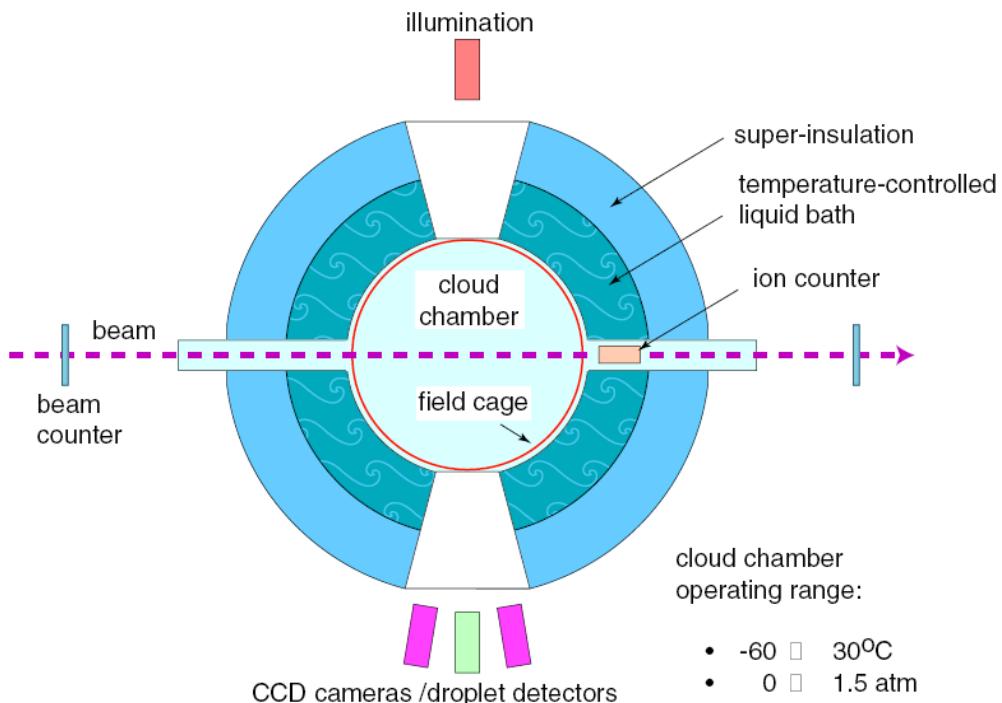
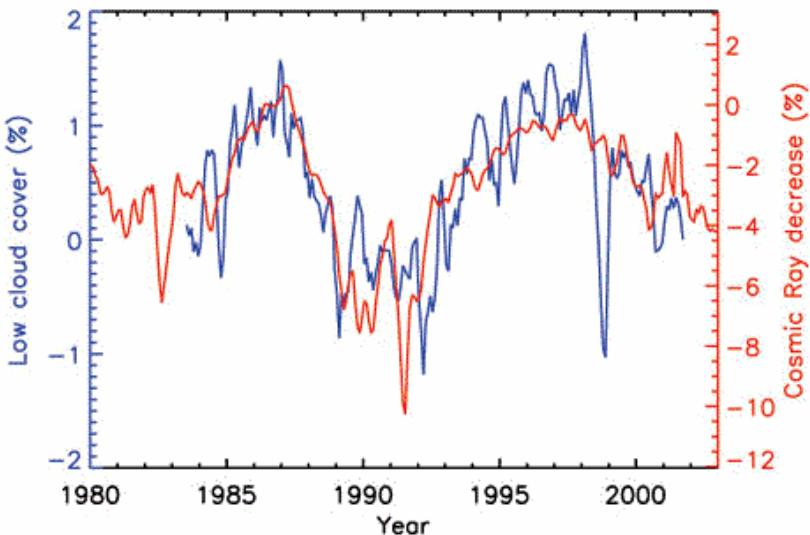
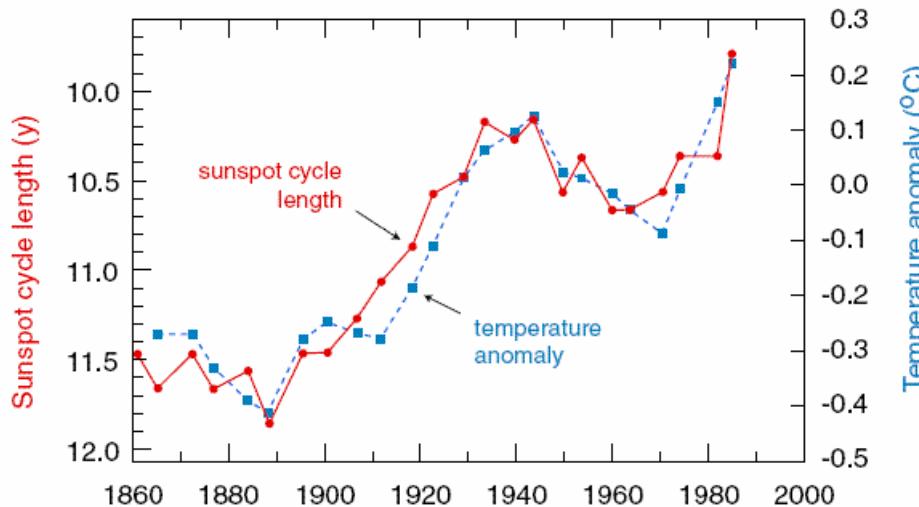
In earth's atmosphere:
 $> 100,000 / \text{sec}$



CERN



Atmosphere Studies and CLOUD Experiment

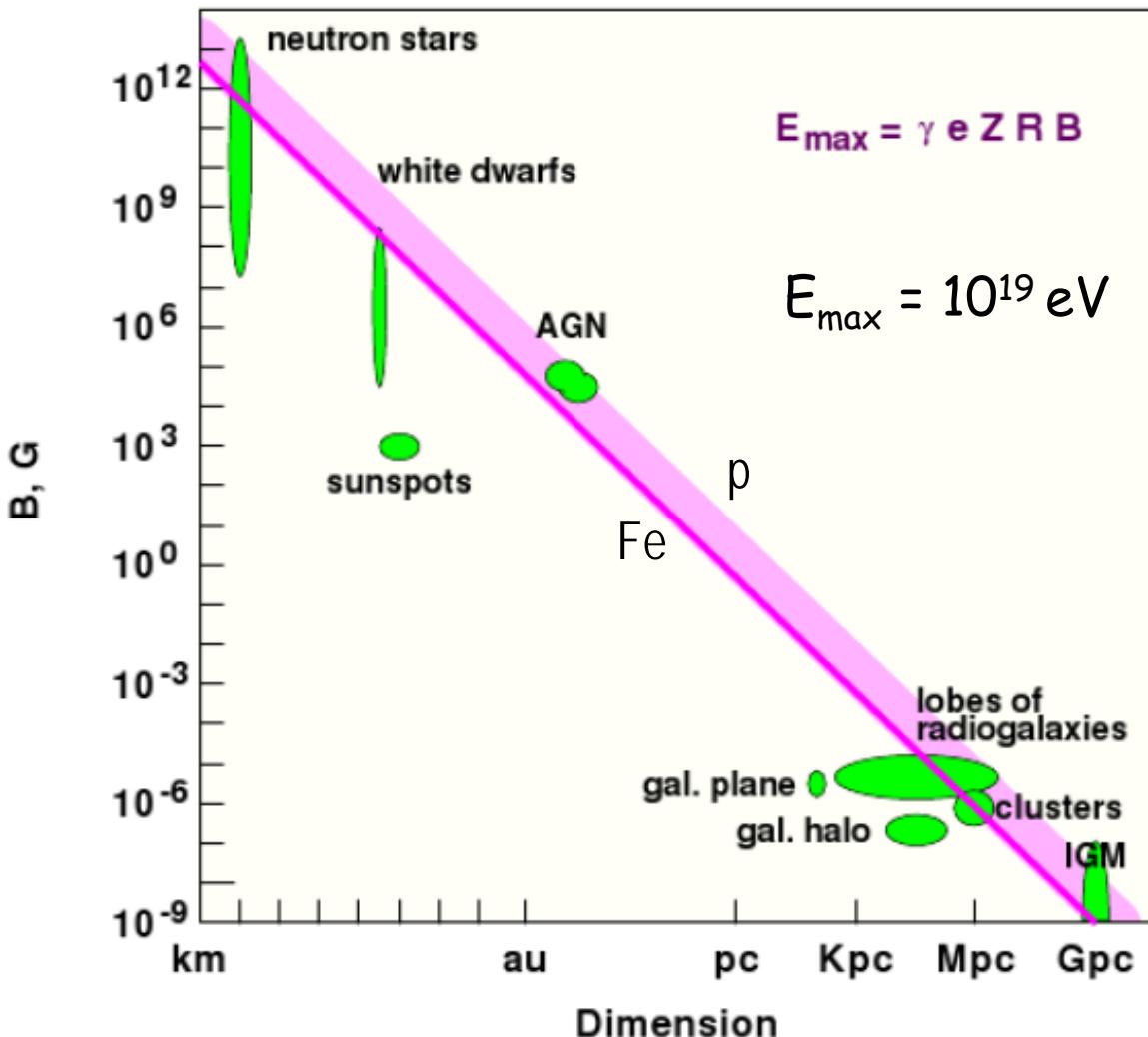


CERN: experiment **CLOUD**



= Cosmics Leaving OUtdoor Droplets

Hillas Plot



The highest energies = kinetic energy tennisball ?

proton



Tennisball (50g)



$$E = 3 \cdot 10^{20} \text{ eV} \quad \rightarrow \quad E = 50 \text{ J}$$

$$v = 160 \text{ km/h}$$



BUT:

relativistic



$$E = p c$$

$$p = 3 \cdot 10^{20} \text{ eV}/c$$



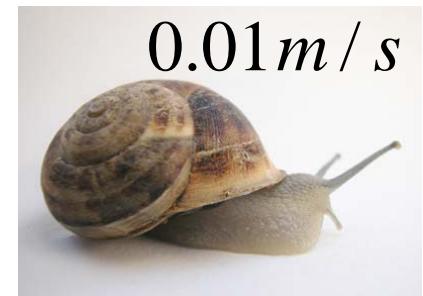
nonrelativistic



$$E = \frac{p^2}{2m}$$

$$p = 1.6 \cdot 10^{-7} \text{ Ns}$$

$$v = 3 \cdot 10^{-6} \text{ m/s}$$



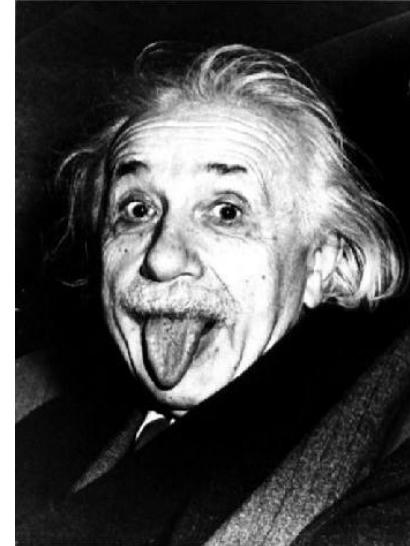
BUT:

relativistic



$$E = p c$$

nonrelativistic



$$E = \frac{p^2}{2m}$$

$$p = 3 \cdot 10^{20} \text{ eV}/c$$



$$p = 1.6 \cdot 10^{-7} \text{ Ns}$$

$$v = 3 \cdot 10^{-6} \text{ m/s}$$

0.01 m/s

