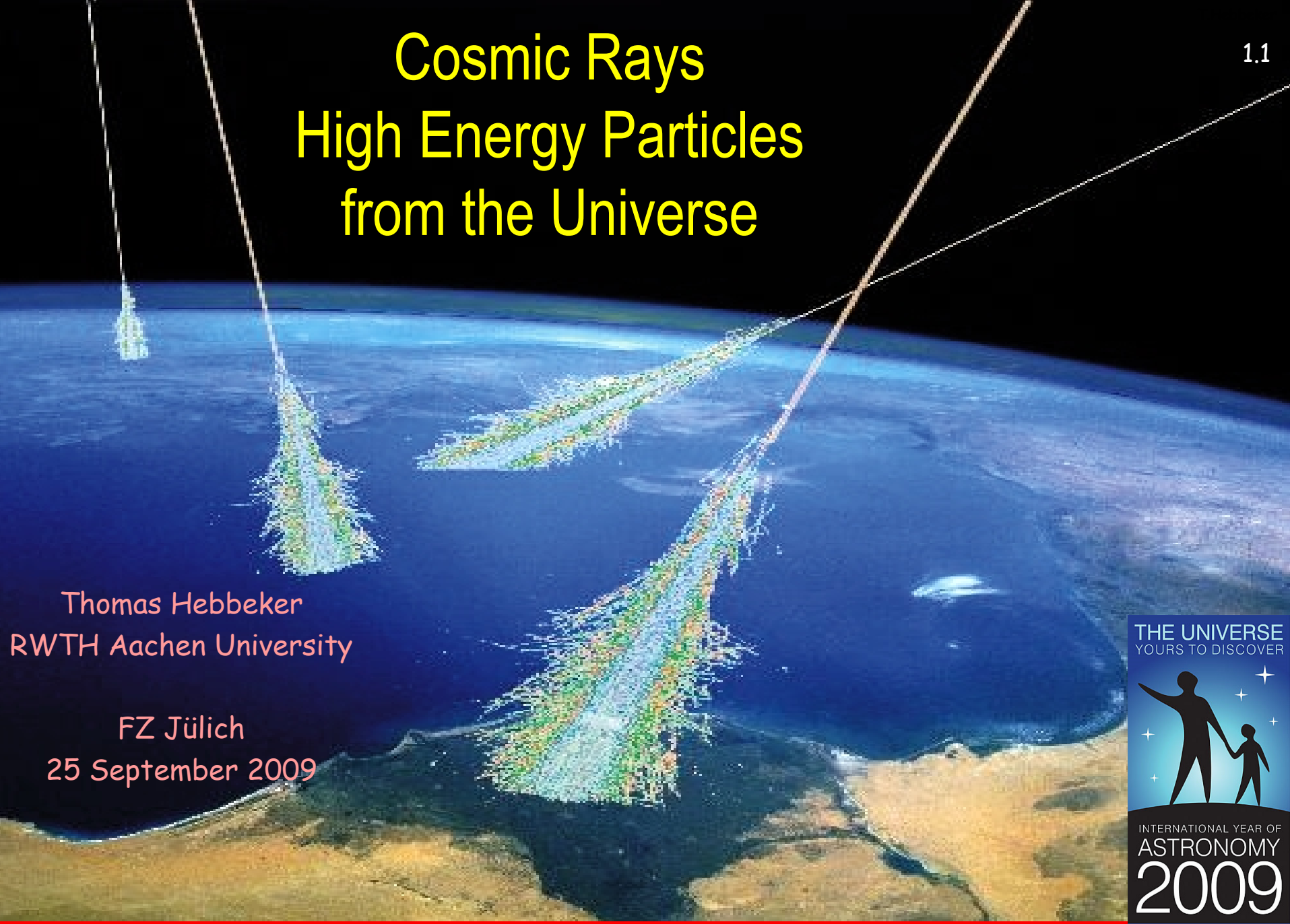
Cosmic Rays
High Energy Particles
from the Universe



Thomas Hebbeker
RWTH Aachen University

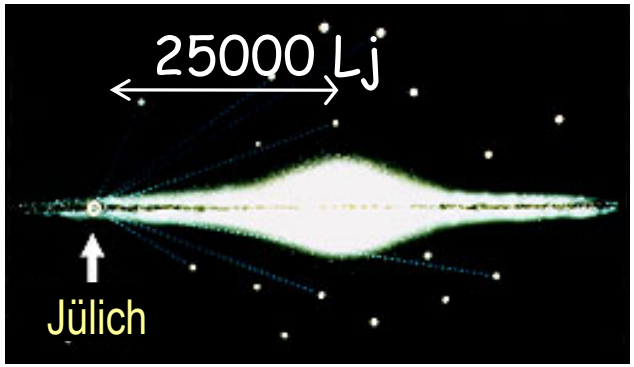
FZ Jülich
25 September 2009

Cosmic Rays

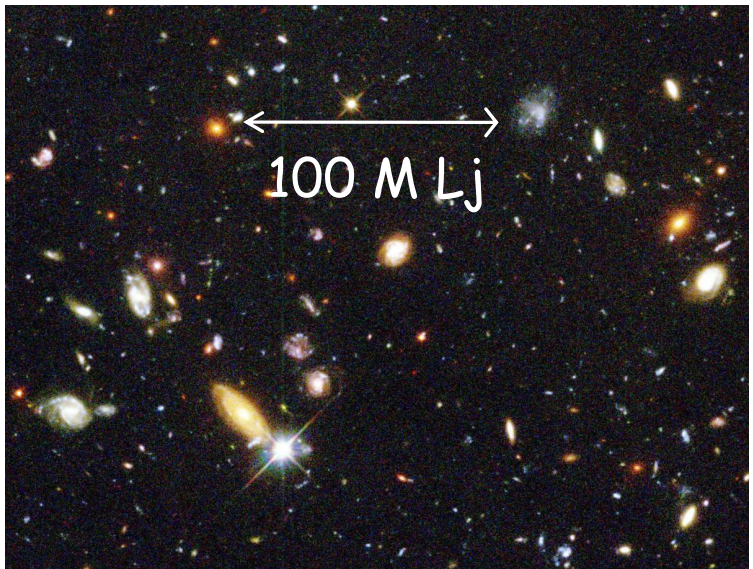
- Discovery / Properties
- Influence on Earth / Life / Science
- High Energy Cosmic Rays
- Cosmic Sources and Propagation
- Auger-Observatory
- First Auger Results

Cosmic Particles ?

from within our galaxy ?



from extragalactic sources ?



sun

on earth:

γ : $5 \cdot 10^{21} / m^2 / s$

ν : $6 \cdot 10^{14} / m^2 / s$

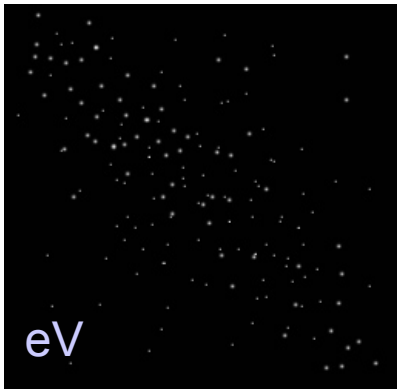
p : $2 \cdot 10^{12} / m^2 / s$

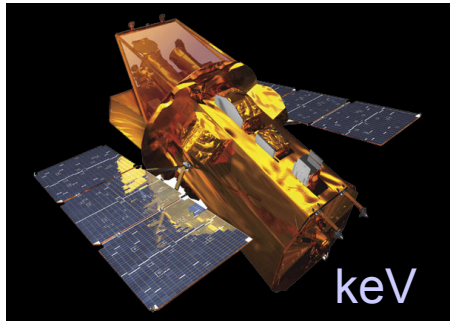
low energy (< GeV)

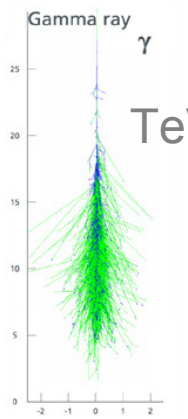
T.Hebbeker

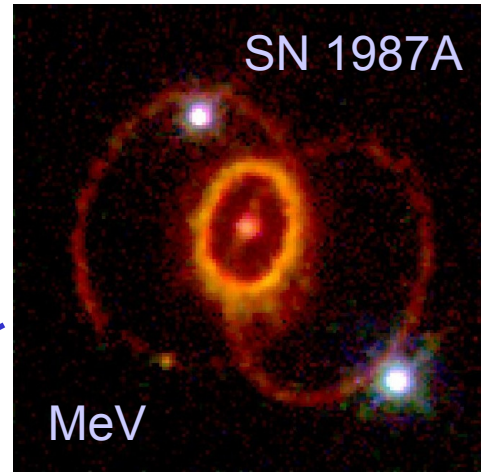
Cosmic **Particles** ?

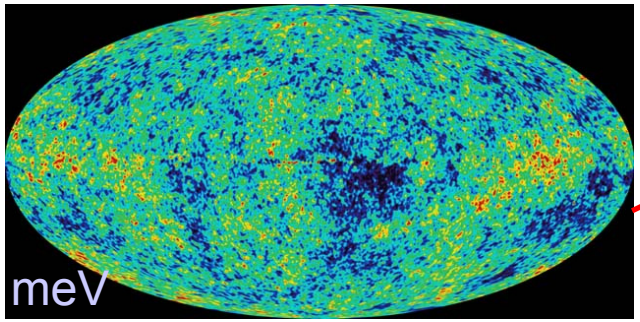
photons γ



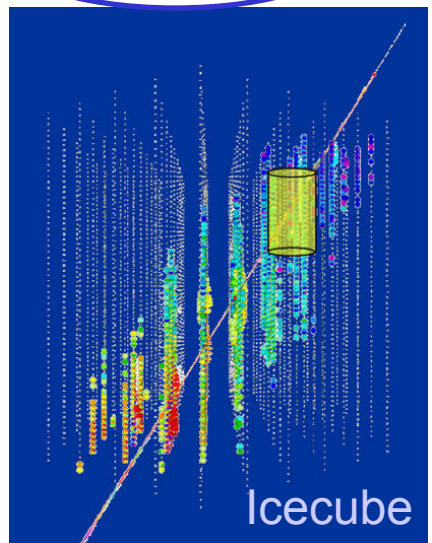








neutrinos ν



charged particles

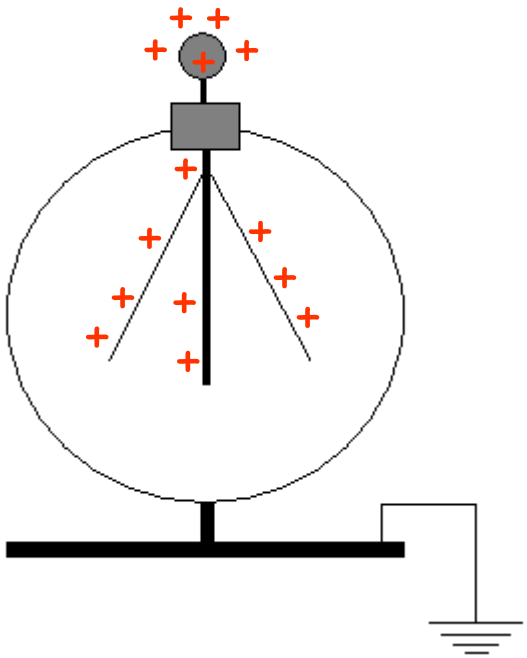
Discovery of Cosmic Radiation

Viktor Hess

Nobel 1936

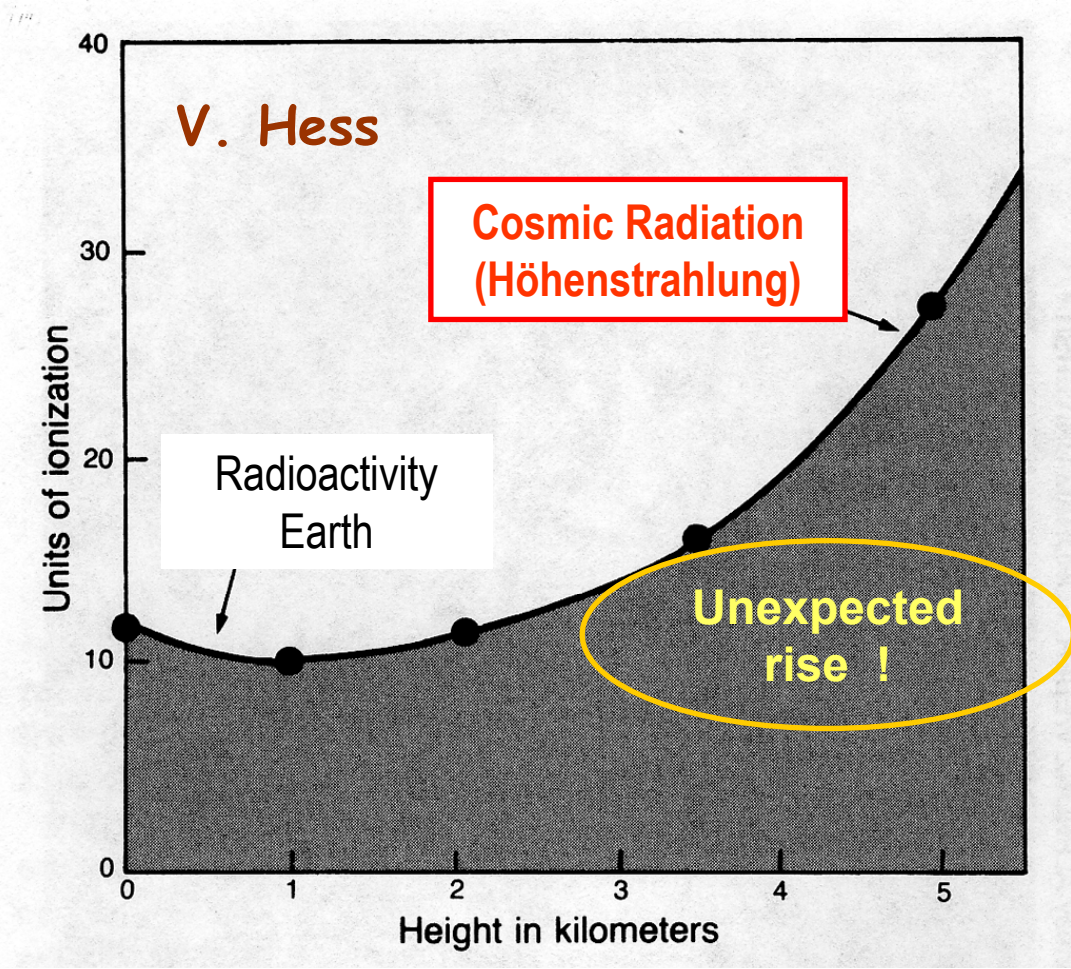
Electrometer Measurements

Ionizing radiation discharges electrometer



Speed of discharging:

⇨ Ionization

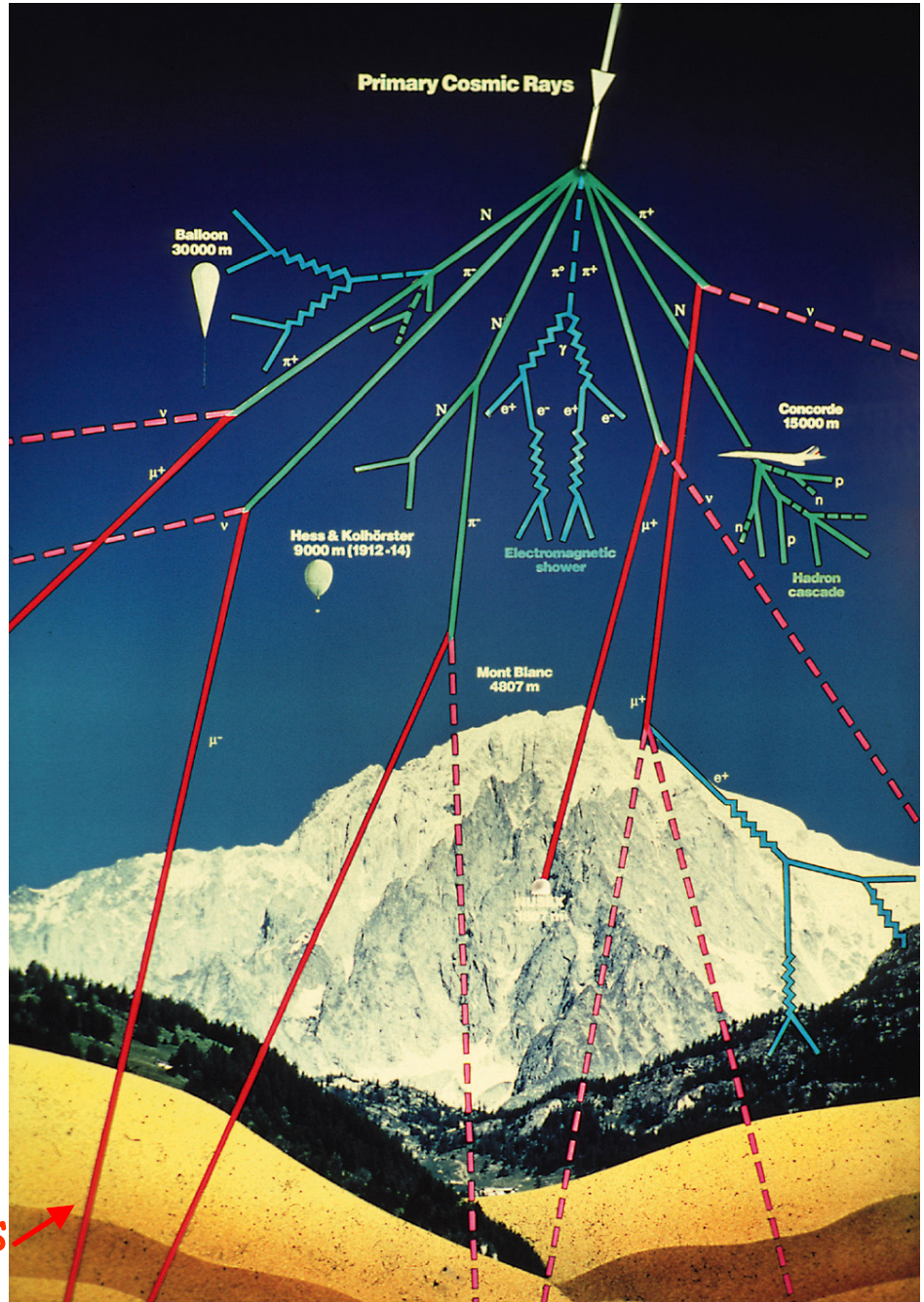


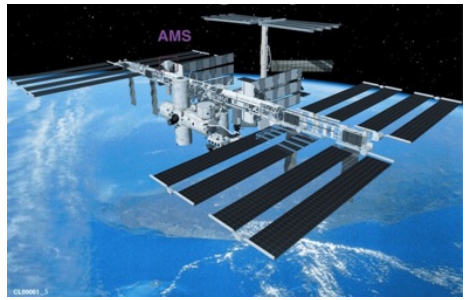
(Charged) Cosmic Radiation

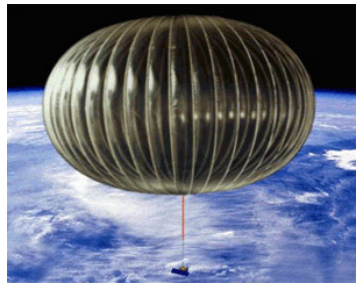
$$\sim \frac{10000}{m^2\, s}$$

from all directons

no time dependence







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

Earth:

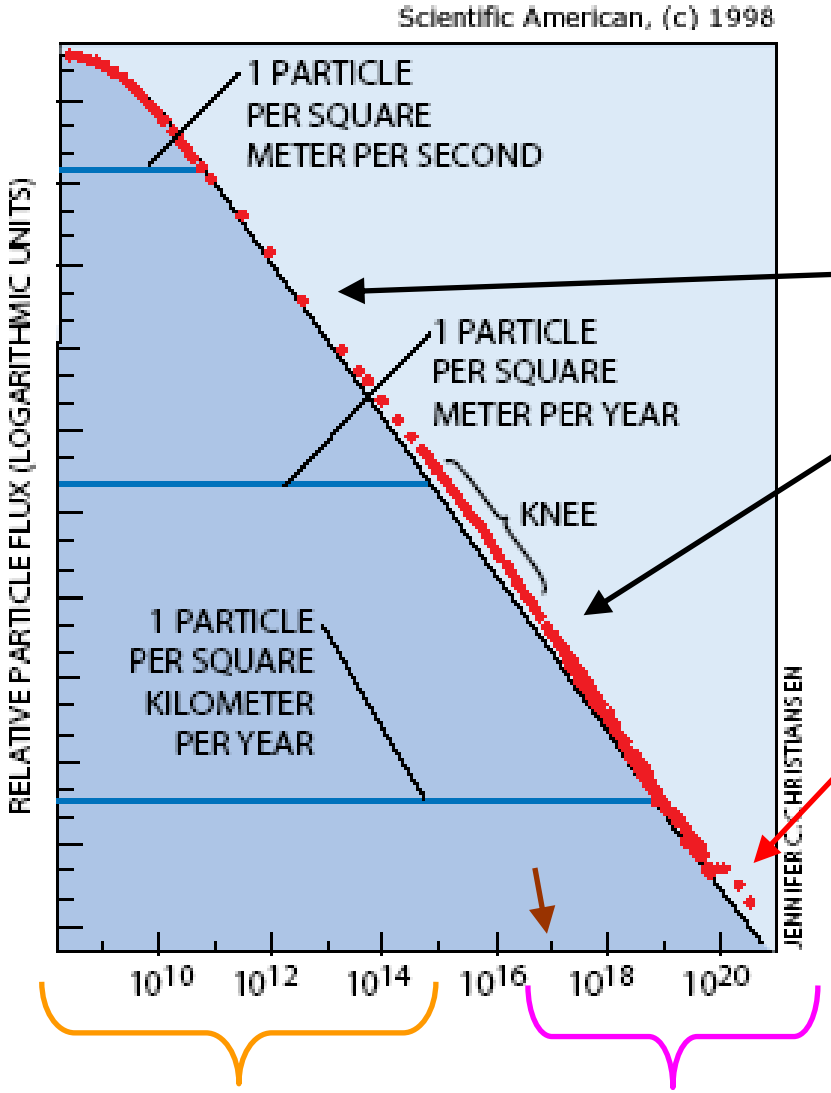
mainly muons

Composition and Energy Spectrum of Cosmic Rays

Composition

at low energies:

87% p, 12% He



power law:

$$\phi \sim E^{-2.7}$$

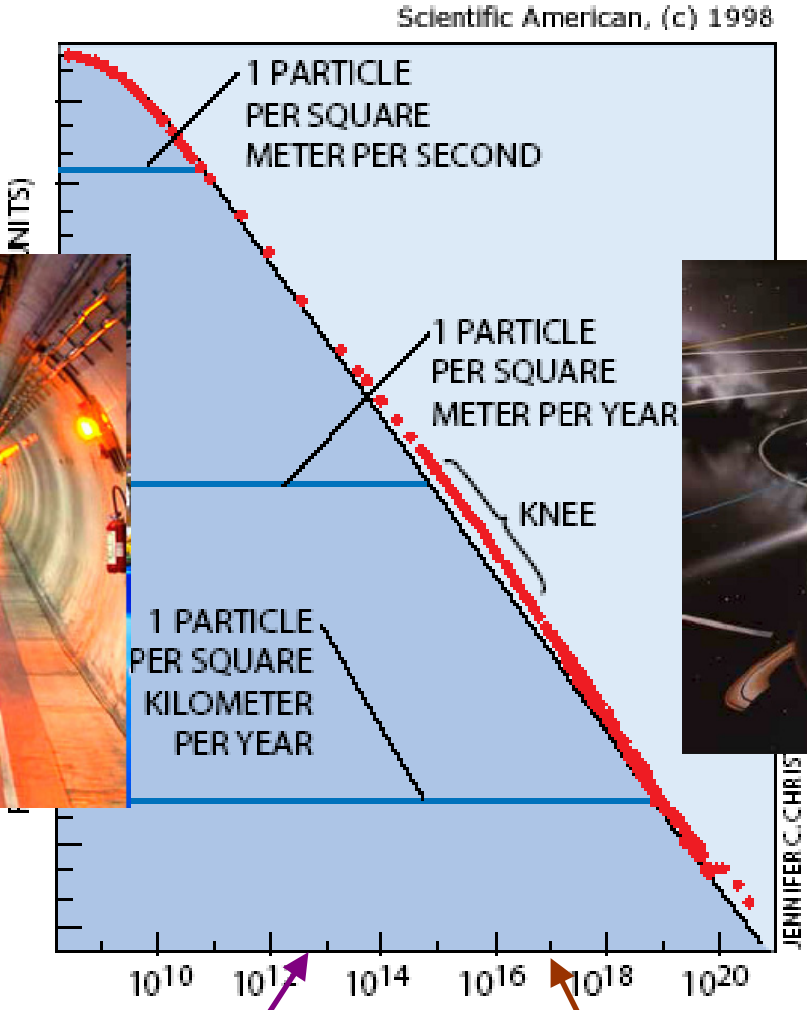
$$\phi \sim E^{-3.1}$$

Origin ?:

Supernovae in Milky Way ?

extragalactic sources ???

Cosmic Rays and LHC



LHC proton beam energy

7 TeV

LHC proton proton center of mass energy

14 TeV

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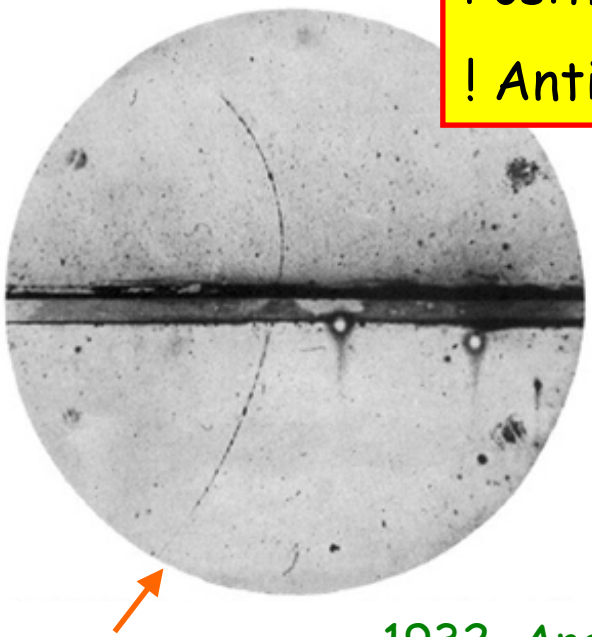
Discoveries in Cosmic Ray Experiments

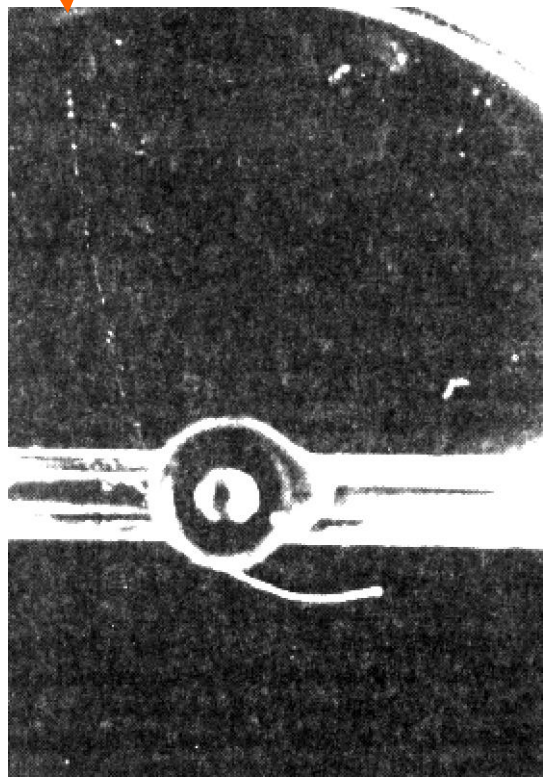
Positron

! Antimatter !



Cloud chambers

1932 Anderson



Muon

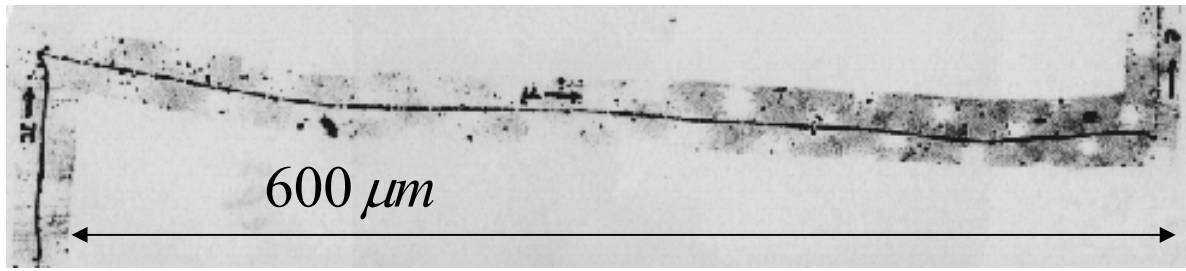
1937 Anderson, Neddermeyer

Pion

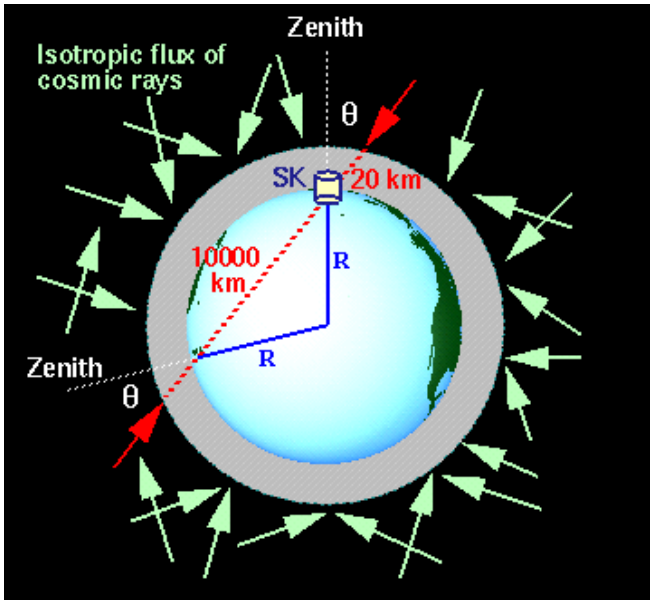
$$\pi \rightarrow \mu \rightarrow e$$

1937 Powell

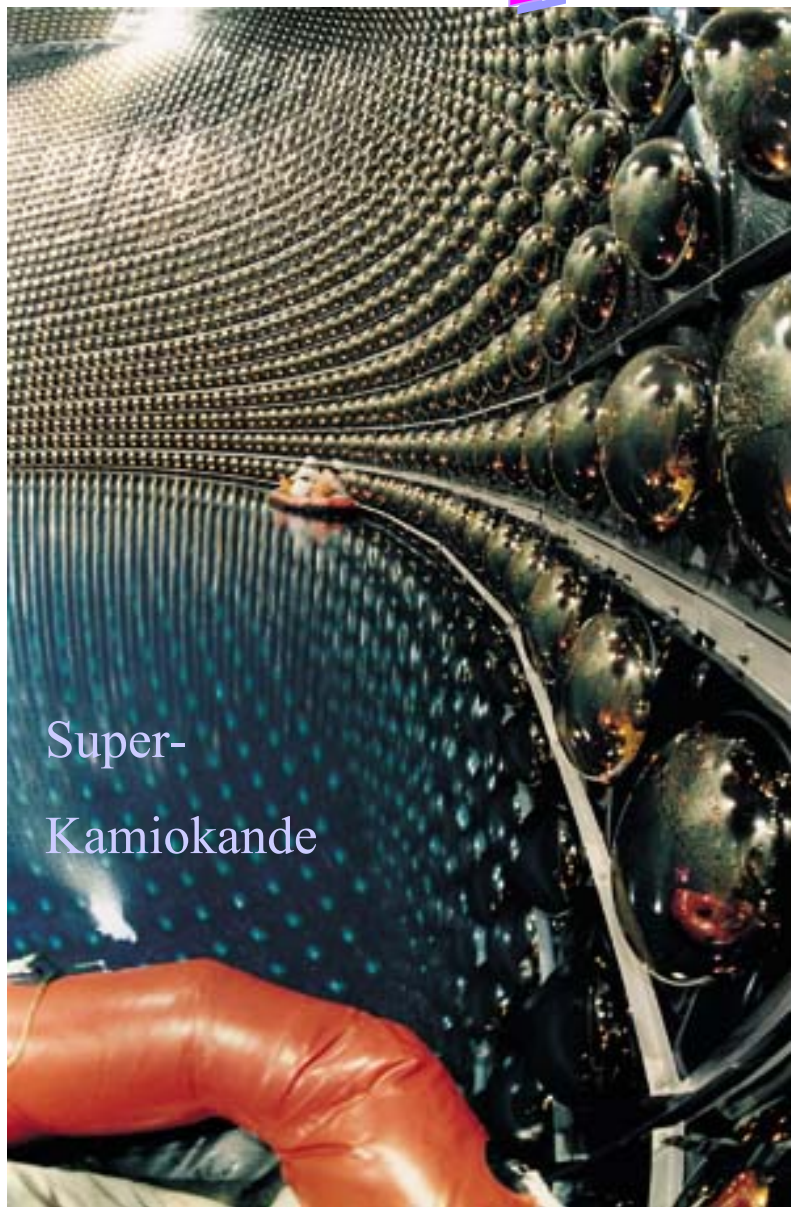
emulsion



Neutrino Oscillations



M. Koshiba et al. Nobel 2002



Atmosphere:

$$p + A \rightarrow \pi \rightarrow \nu_\mu$$

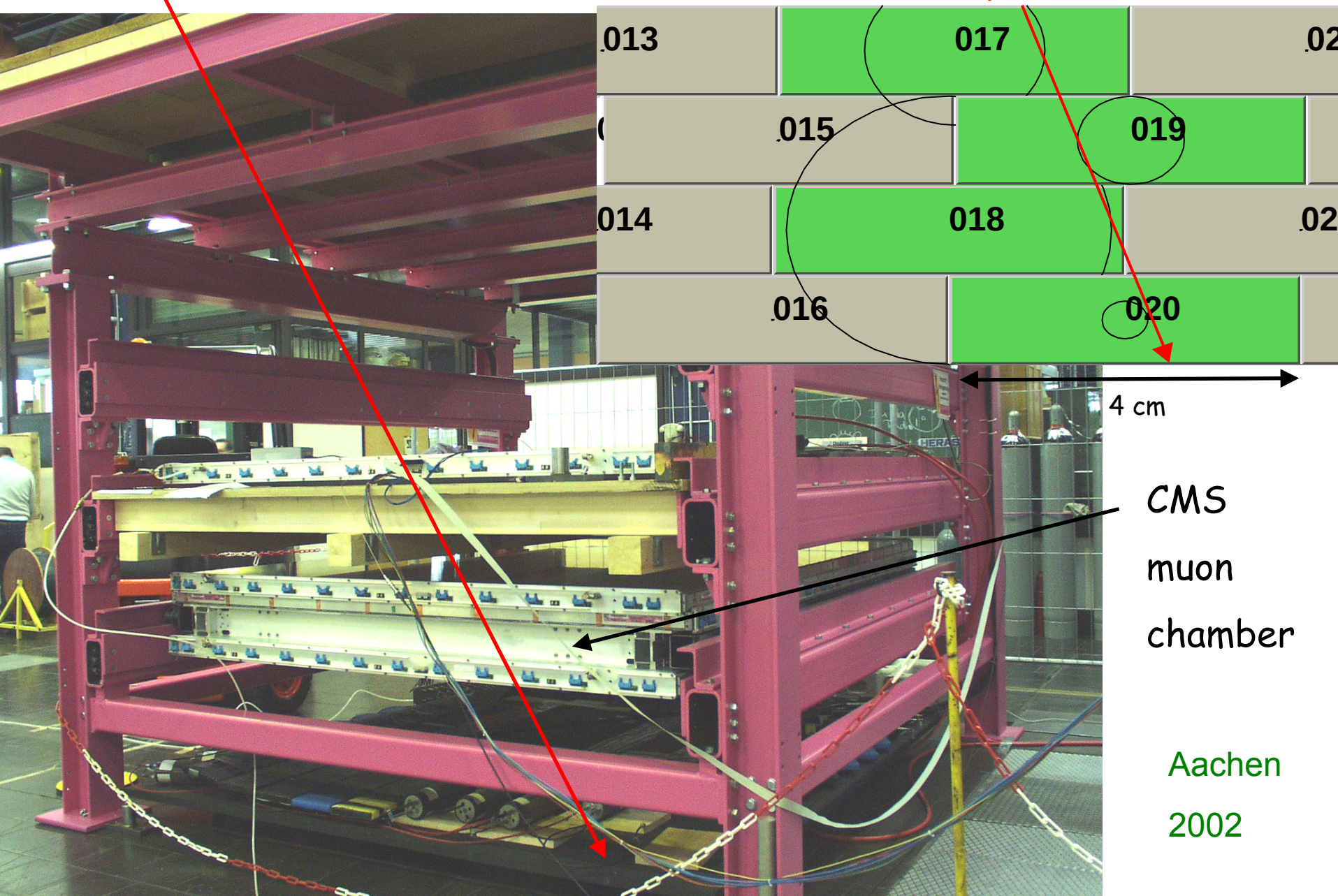
Detection:

$$\nu_\mu + A \rightarrow \mu \rightarrow Cerenkov$$

Result:

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

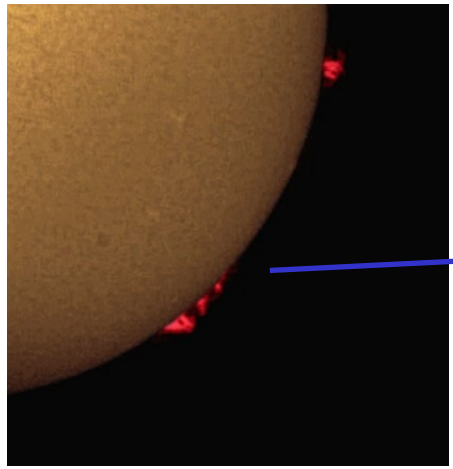
Tests of Particle Detectors

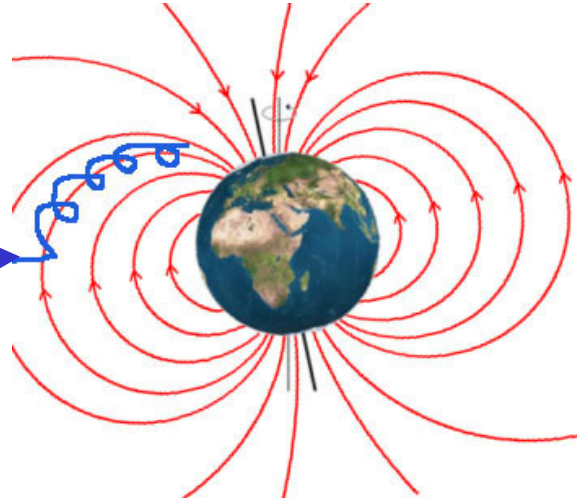


Polar Light (Aurea Borealis)

Trapping of low energy particles from sun („solar wind") by magnetic fields

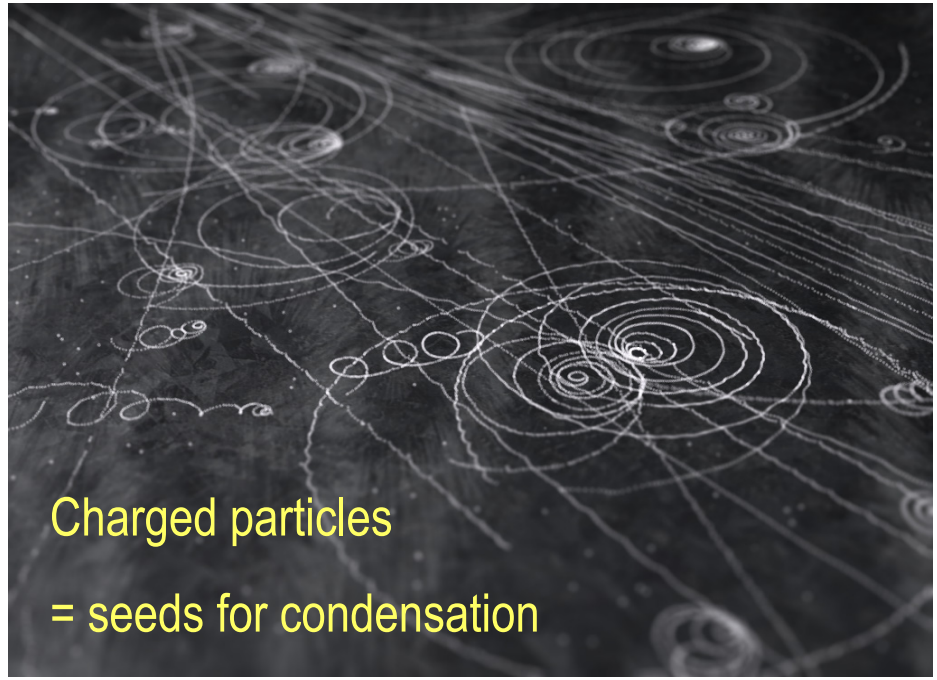
Excitation of air molecules

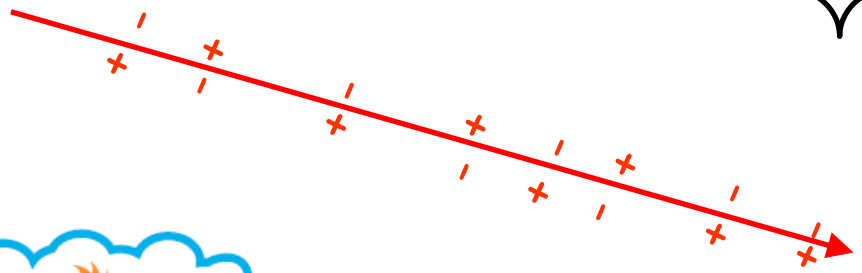




Cloud Formation ?

cloud chamber / bubble chamber





cloud

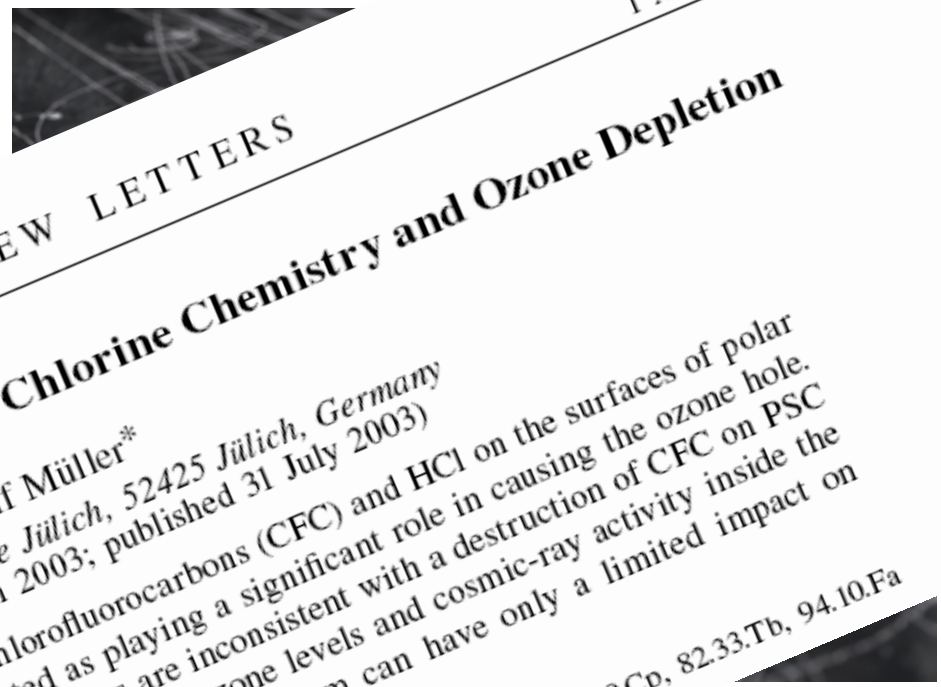
CERN

Cosmics Leaving OUtdoor Droplets

Can cosmic rays initiate cloud formation ?

Influence on climate ?

Cloud Formation ?



PHYSICAL REVIEW LETTERS
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Impact of Cosmic Rays on Stratospheric Chlorine Chemistry and Ozone Depletion

Rolf Müller*
ICG-I, Research Centre Jülich, 52425 Jülich, Germany
(Received 13 March 2003; published 31 July 2003)

Dissociation induced by cosmic rays of chlorofluorocarbons (CFC) and HCl on the surfaces of polar stratospheric clouds (PSC) has been suggested as playing a significant role in causing the ozone hole. However, observed stratospheric CFC distributions are inconsistent with a destruction of CFC on PSC surfaces and no significant correlation exists between ozone levels and cosmic-ray activity inside the polar regions. Model simulations indicate that this mechanism can have only a limited impact on chemical ozone loss and thus on the recovery of stratospheric ozone.

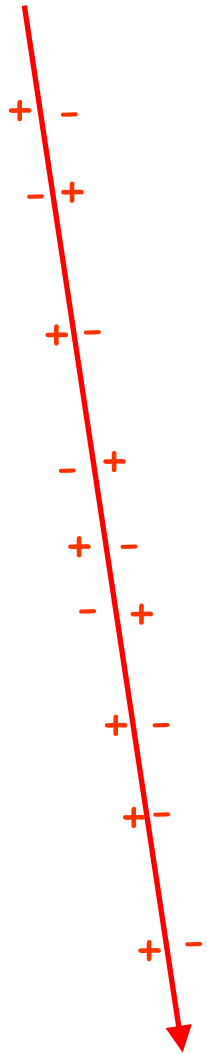
DOI: 10.1103/PhysRevLett.91.058502
PACS numbers: 92.70.Cp, 82.33.Tb, 94.10.Fa

Can cosmic rays initiate cloud formation ?

Influence on climate ?

Cosm Outdoor Droplets

Lightnings ?



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

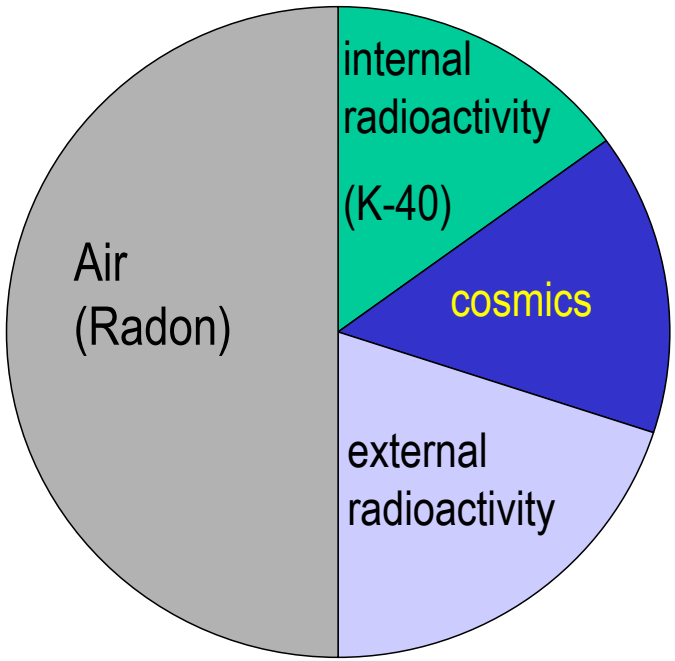
?

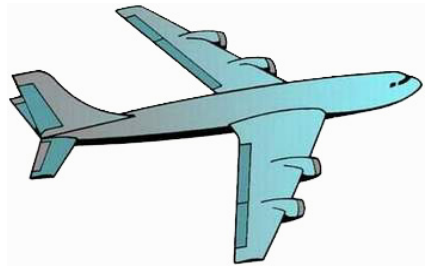
Radiation Exposure of Humans

Natural sources:

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

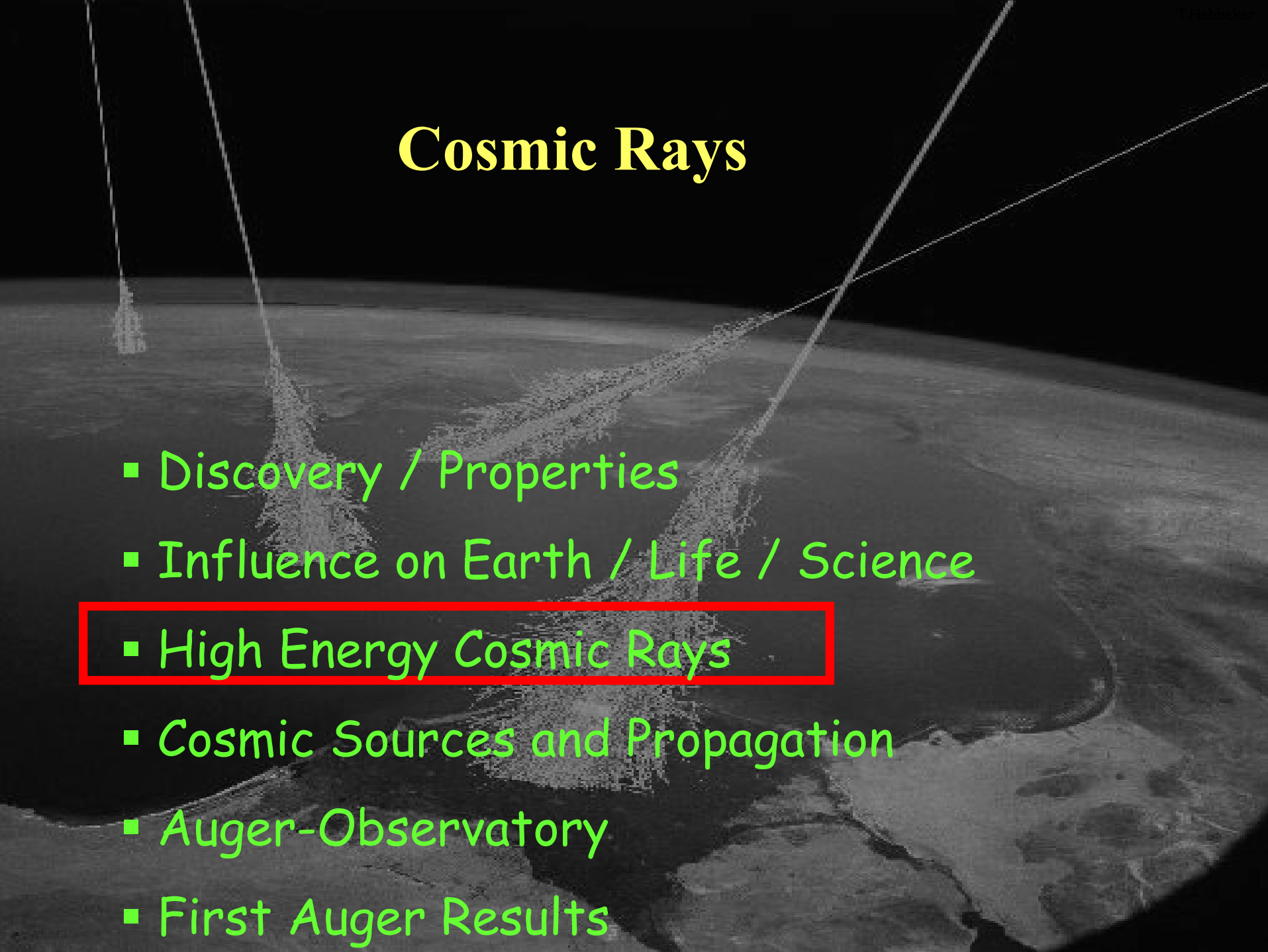
whole body





Increased radiation levels !

(Hess !)



Cosmic Rays

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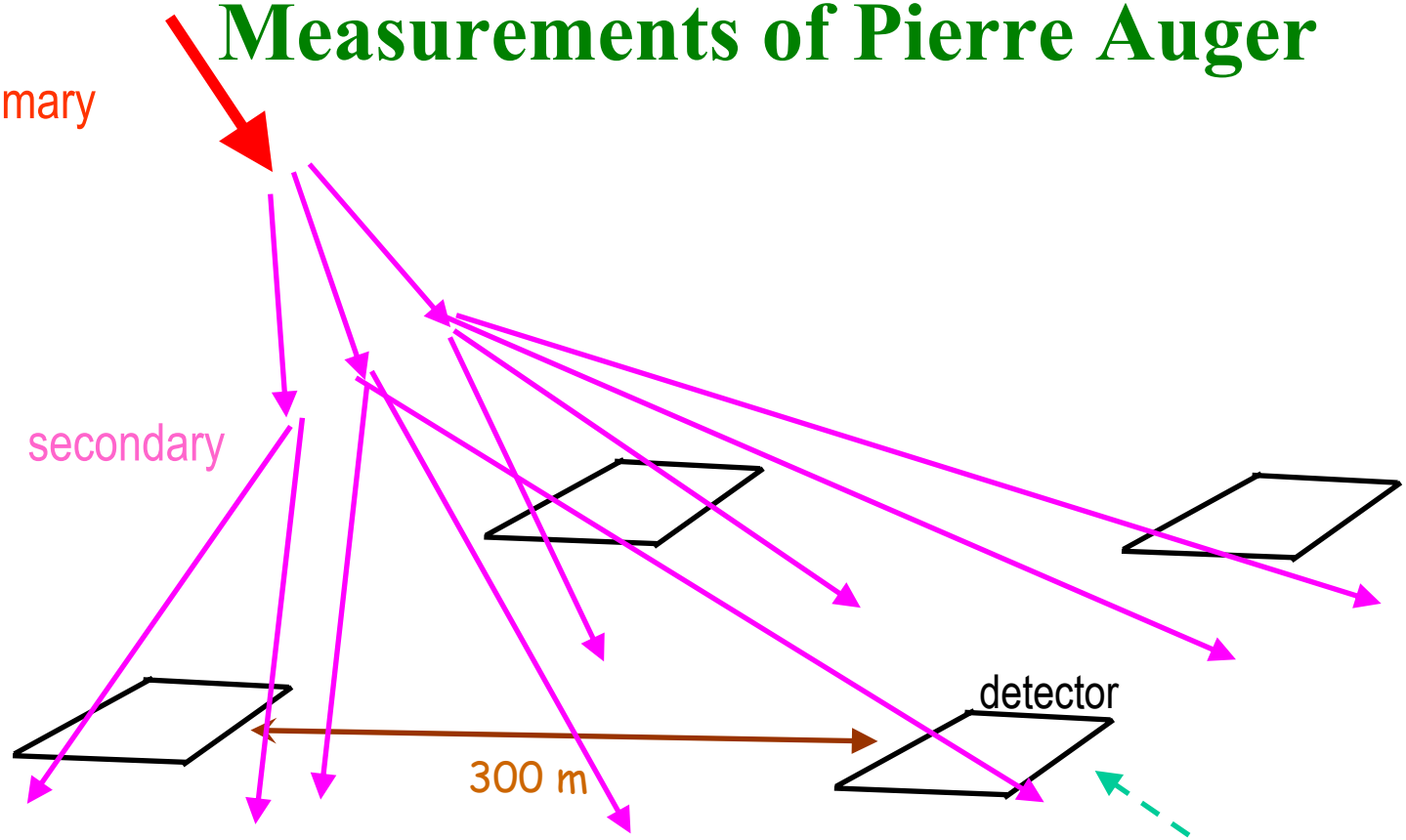
Measurements of Pierre Auger

Also:
'Auger electrons'



1938 Jungfraujoch 3500 m

Geiger-Müller-counters

Results: Coincidences for detectors 300 m apart

Extended Air Shower

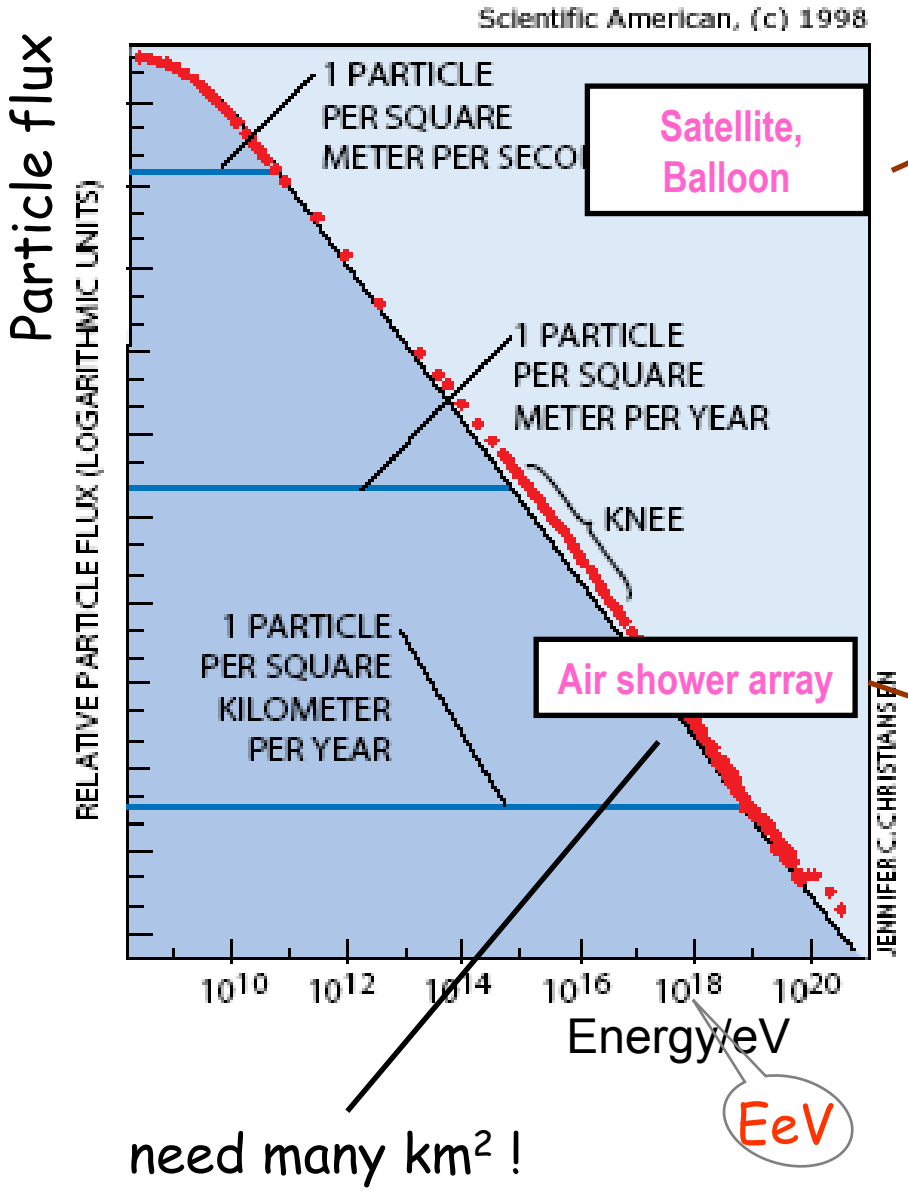
estimate: 1 million secondary particles, **energy 10^{15} eV = 1000 TeV !!!**

Pierre Auger Experiment

MEASURING COSMIC RAYS IN THE SWISS ALPS

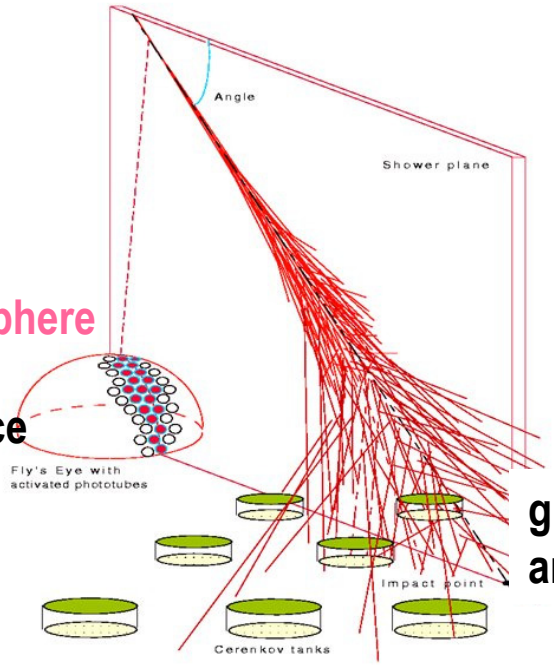
The author (*left*) and his collaborator, P. Ehrenfest, set up their apparatus in the Jungfraujoch.

Cosmic Ray Detection Methods



bottom of atmosphere

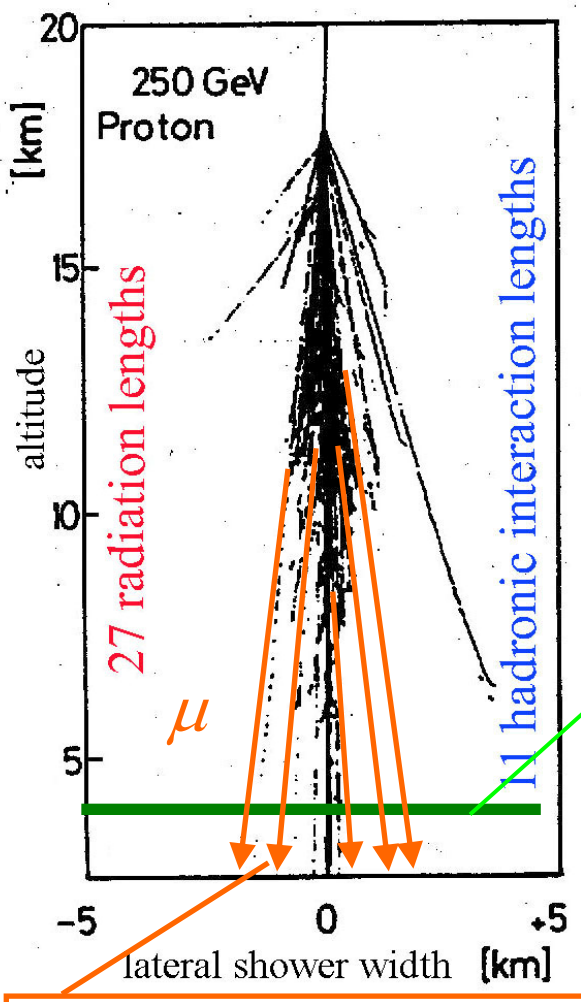
fluorescence telescope

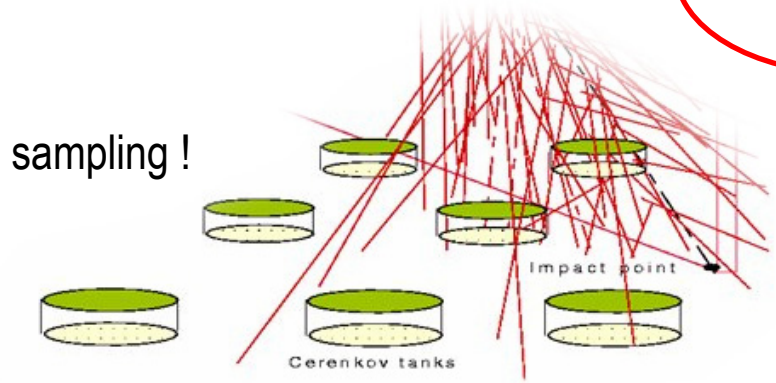


ground array

Ground Arrays

100% duty cycle





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

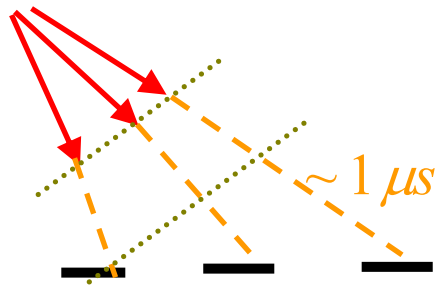
Jungfraujoch !

Muons reach ground

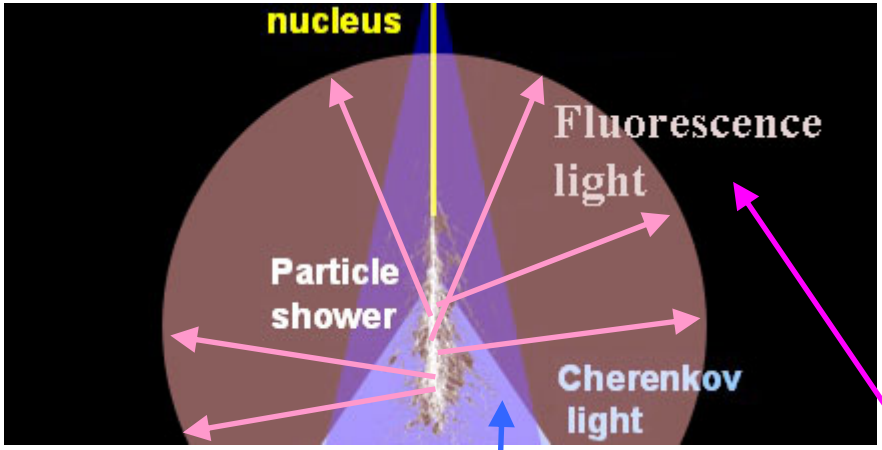
$10^7 @ 1\,EeV$

Ground array measures:

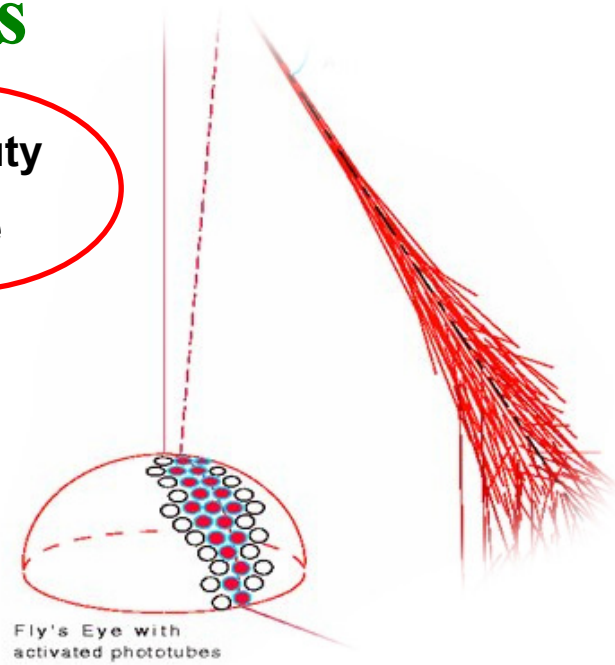
- **lateral** shower profile
- **energy** ~ # particles
- **direction** from timing



Telescope Measurements



10% duty cycle



Cherenkov light:

relativistic electrons, forward

Fluorescence light:

$10^{13}\ \gamma$ / *EeV*

300-400 nm

excited nitrogen molecules

isotropic emission

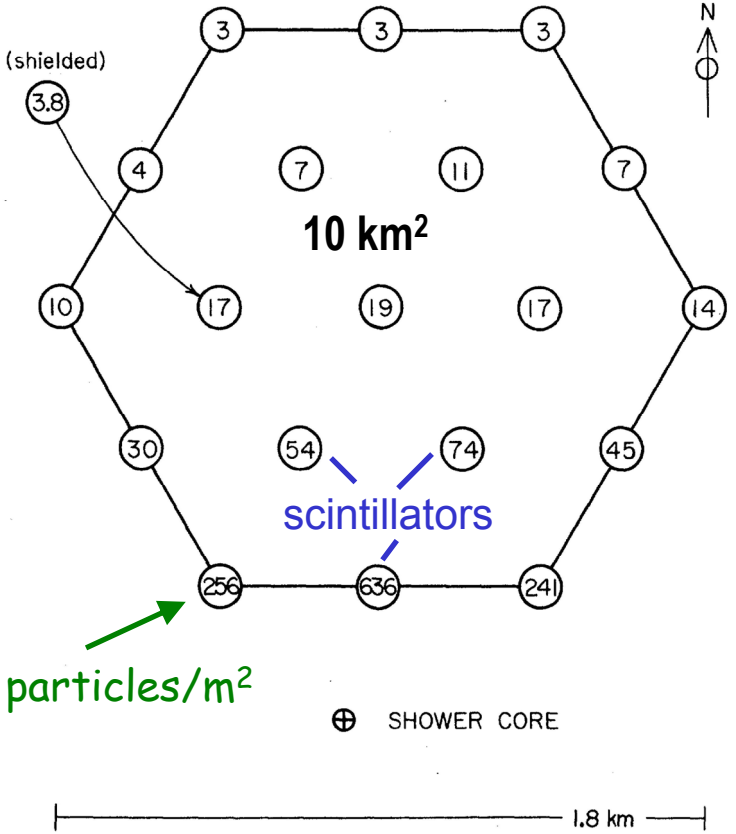
visible over several km (by night)

Fluorescence detector measures:

- **longitudinal** shower profile
- **energy** ~ total light yield
- arrival **direction** (profile+timing)

Volcano Ranch Detector

10^{20} eV



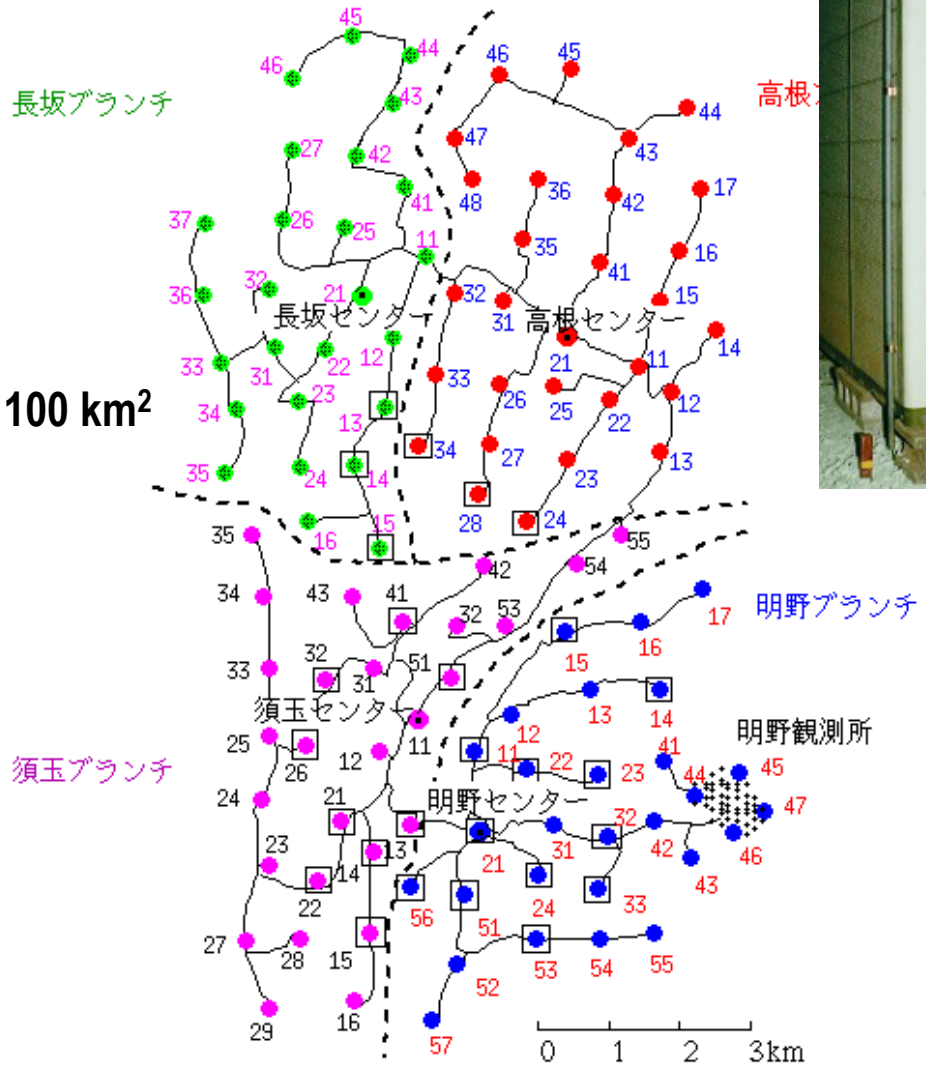
1962: energy $2 \cdot 10^{20}$ eV

Agasa-Detector

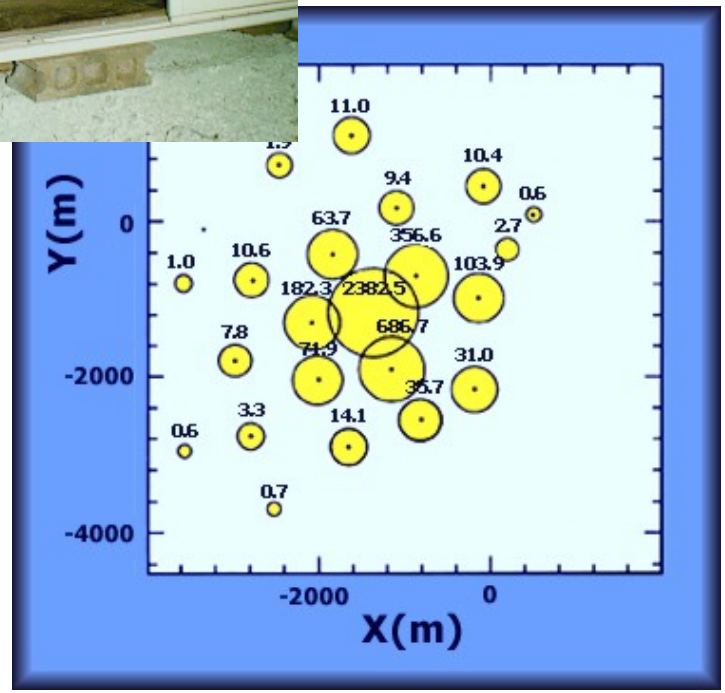
T.Hebbeker

~1995 Japan

111 water tanks
(Cerenkov light
produced in tank)

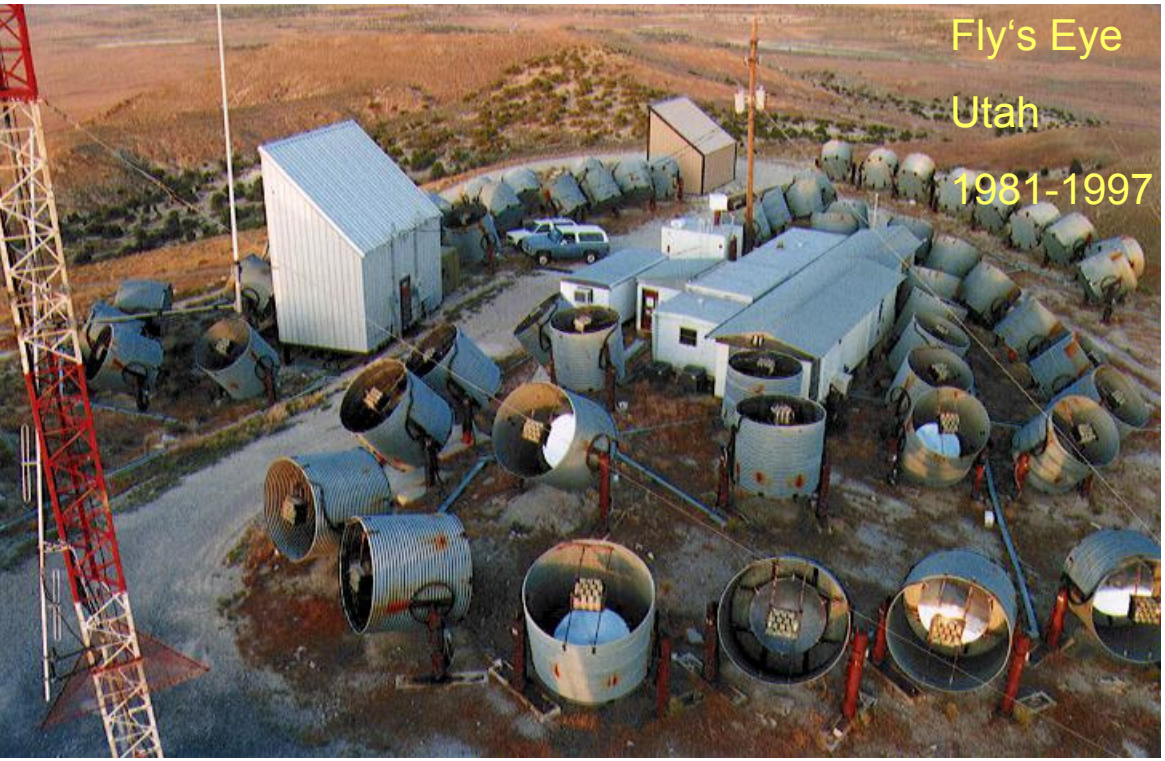


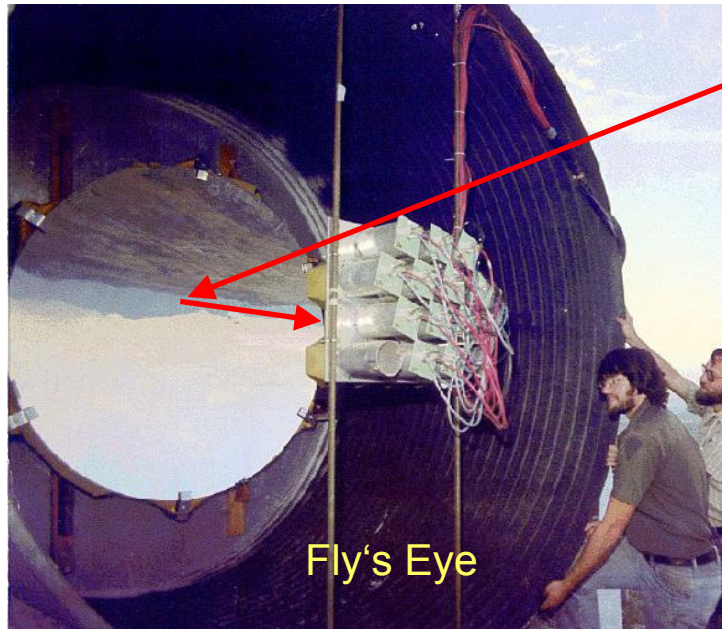
Highest energy show



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

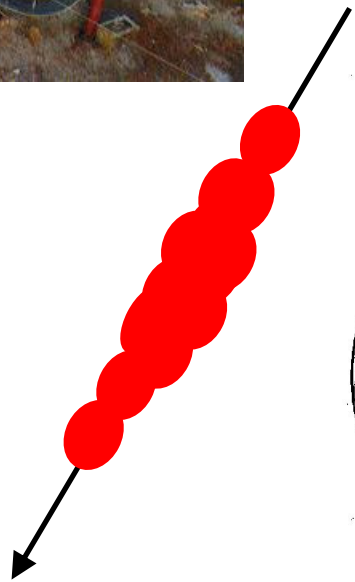
Fly's Eye / HiRes Detectors

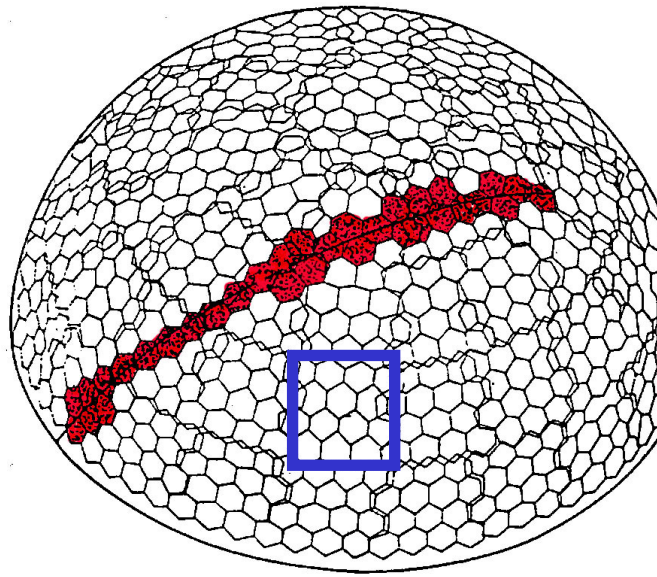




1991: energy $3 \cdot 10^{20}$ eV

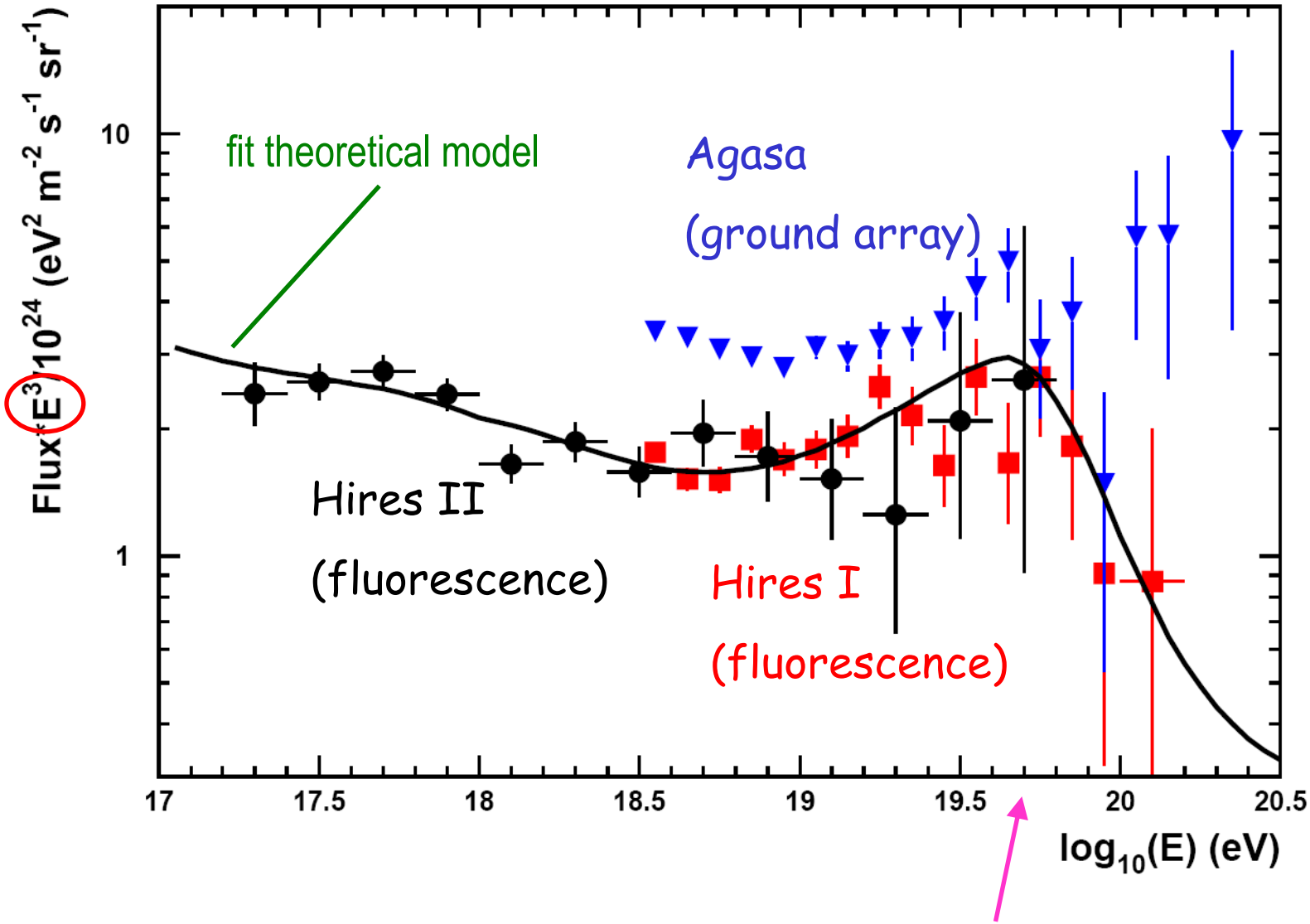
! record !





Discrepancies between Agasa and Hires

2003

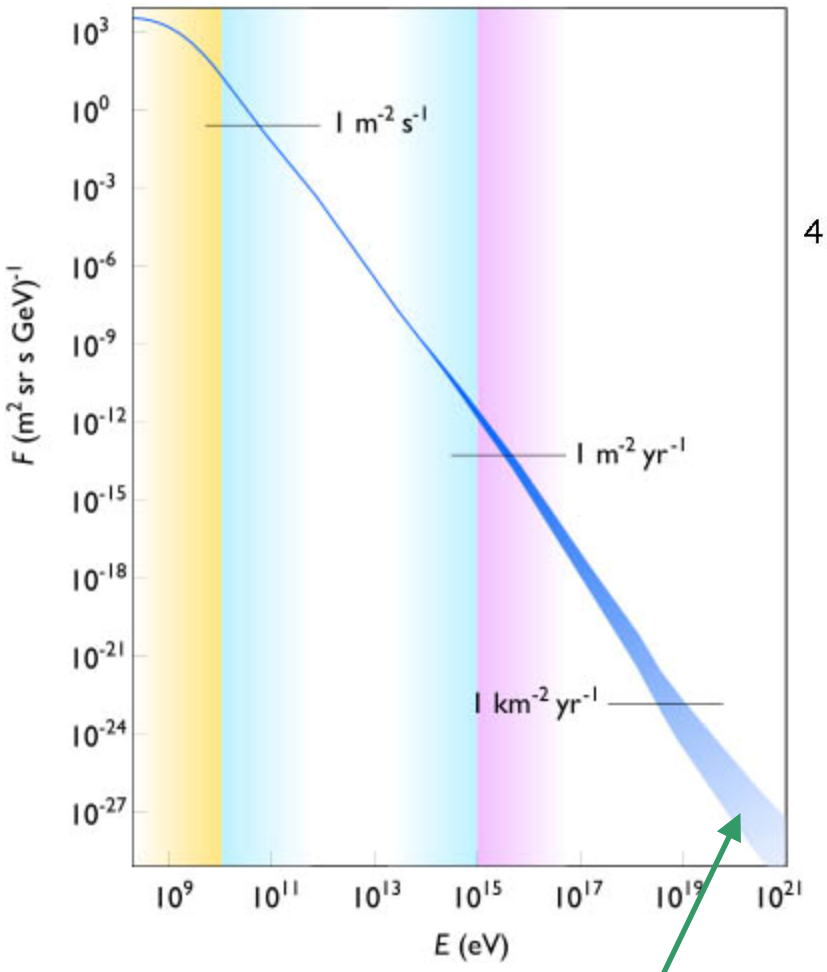


Who is right ? Does spectrum fall off at 50 EeV ?

T.Hebbeker

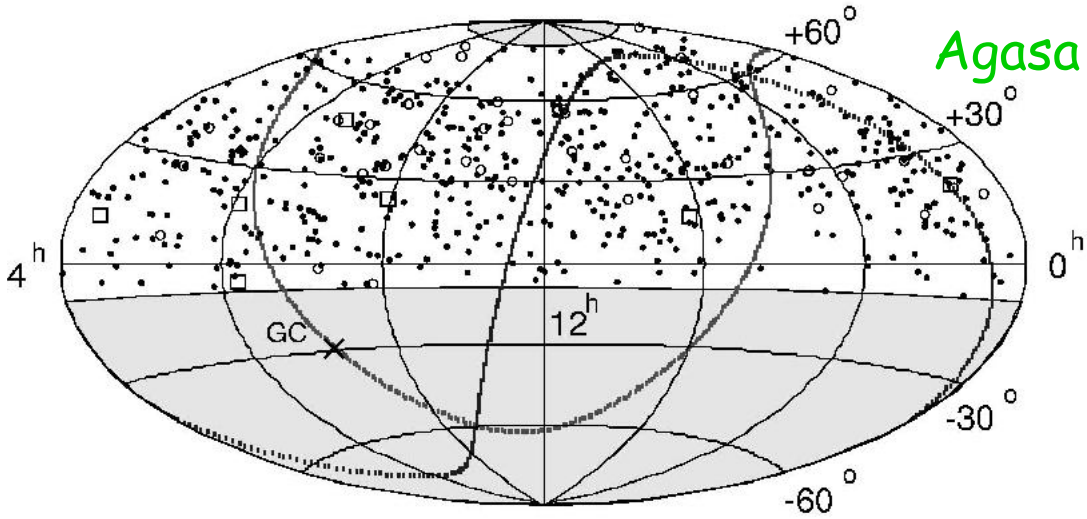
Results of air shower observatories

Energy spectrum of charged cosmic rays



Ultra high energies, but rare

Arrival directions



isotropic distribution

Fundamental Questions:

Where from ?

Acceleration ? Max. energy ?

Composition = particle type ?

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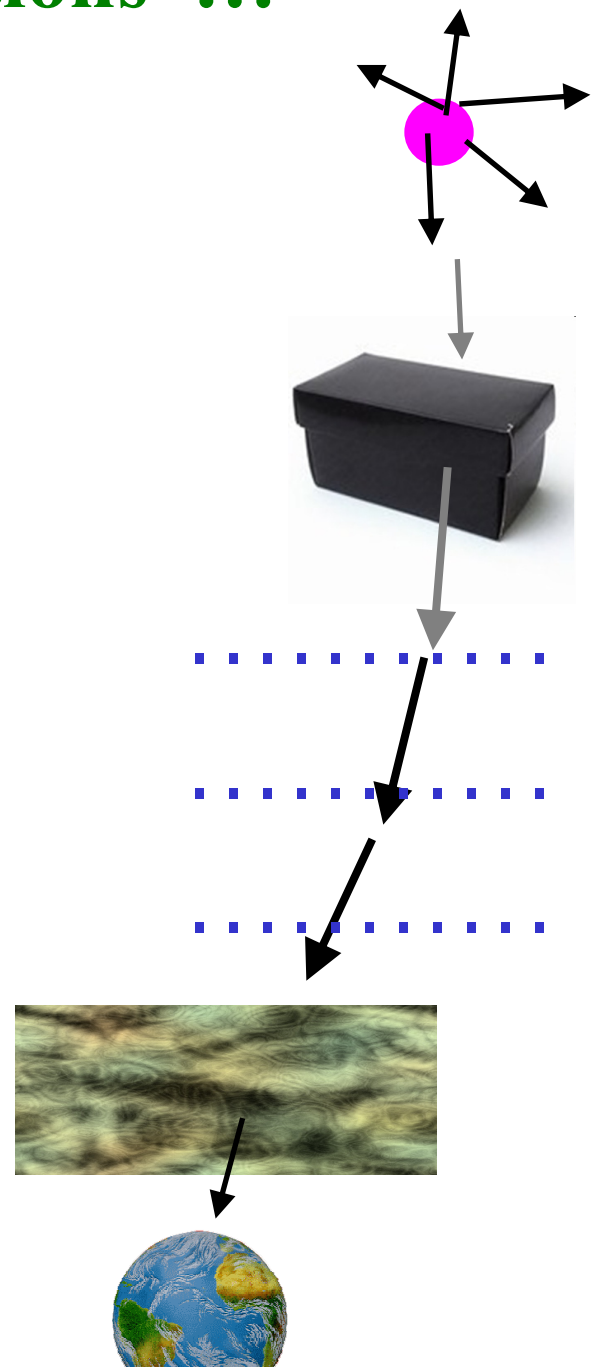
Questions Questions Questions …

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



GZK Cutoff (Greisen-Zatsepin-Kuzmin)

Proton

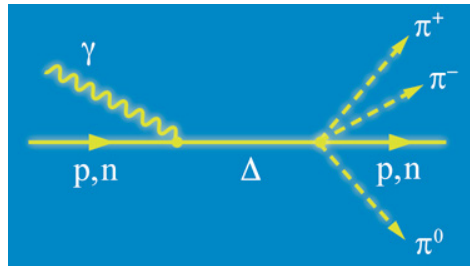
100 EeV

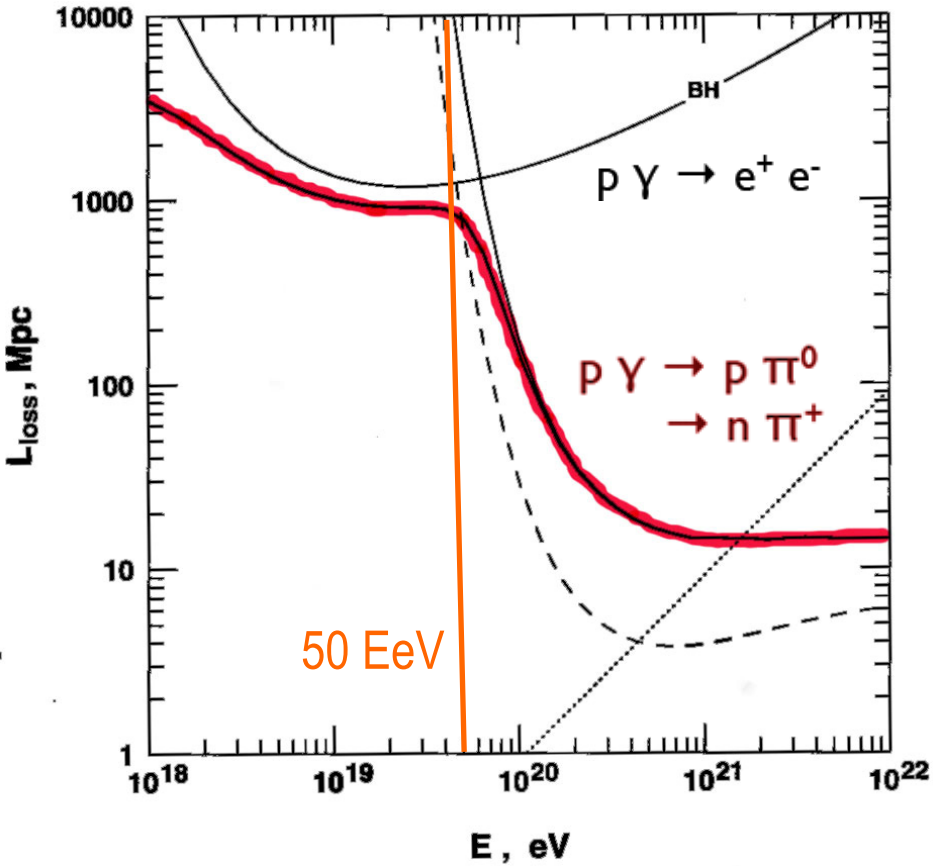
CMB

400 γ / cm^3

2.7 K = 0.63 meV

$E_{CMS} \sim 1.1 GeV$





$$p + \gamma \rightarrow \Delta^+ \rightarrow p/n + \pi$$

cross sections known !

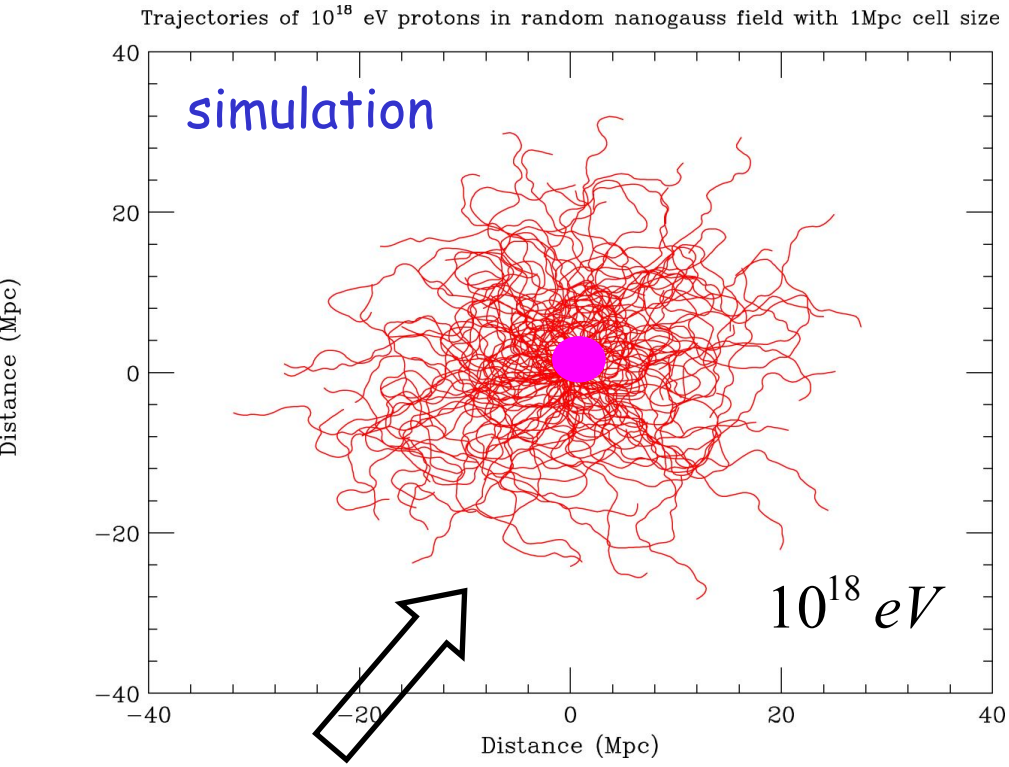
For protons with

E > 50 EeV (GZK cutoff)

range limited to

~ 50 Mpc ~ 150 MLj

Deflection in cosmic magnetic fields

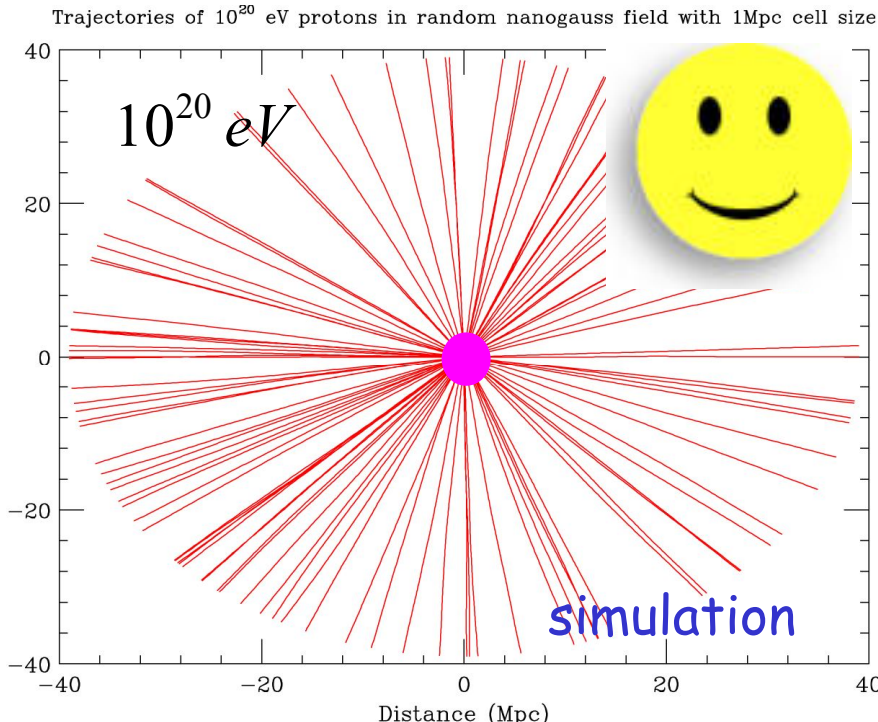


inside galaxy: $B \sim 10\,\mu G$

intergalactic space: $B \sim n\,G$

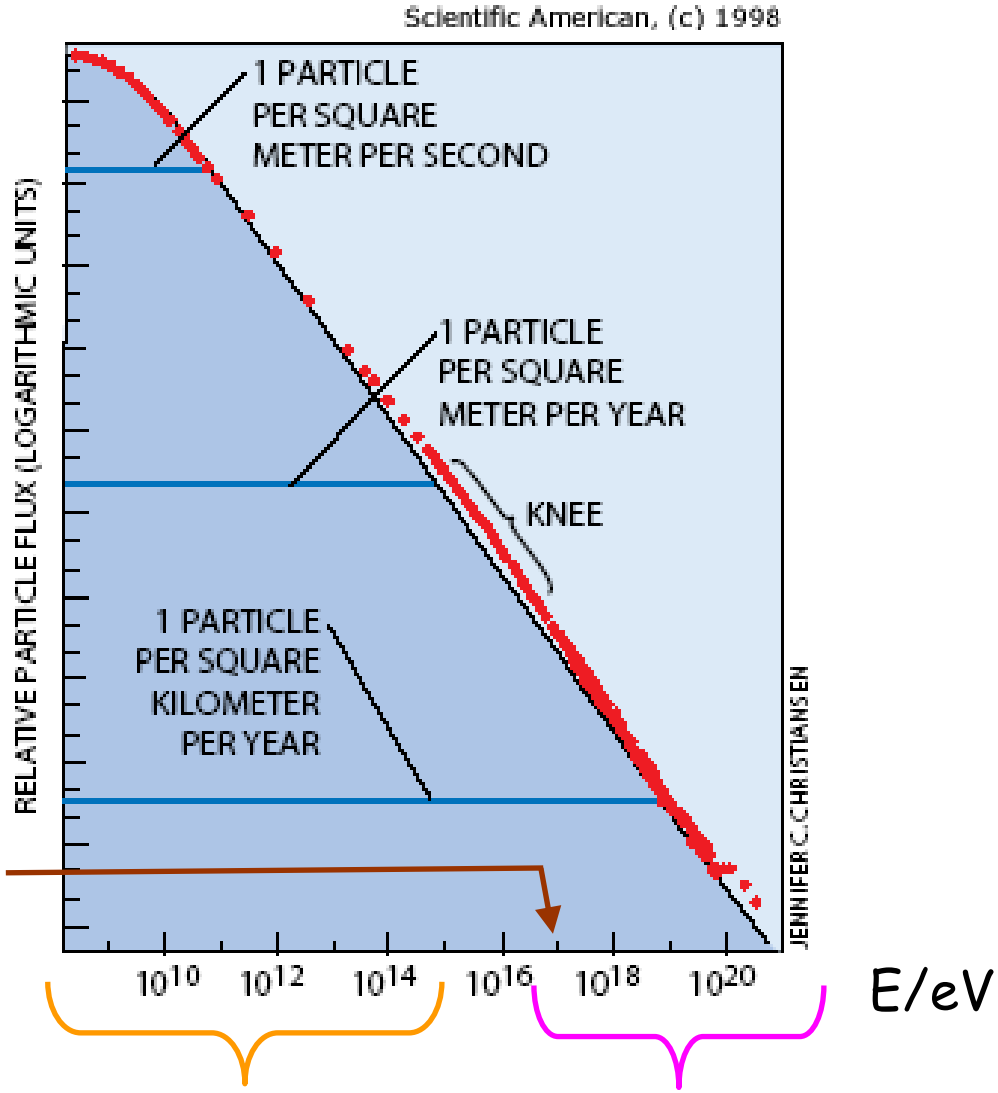
Upon arrival at earth:

Information on source direction is lost



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

Sources/Accelerators of charged cosmic rays



Hypotheses:

Supernovae in Milky Way ?

extragalactic sources AGNs ???

Supernovae – cosmic rays up to the knee ?

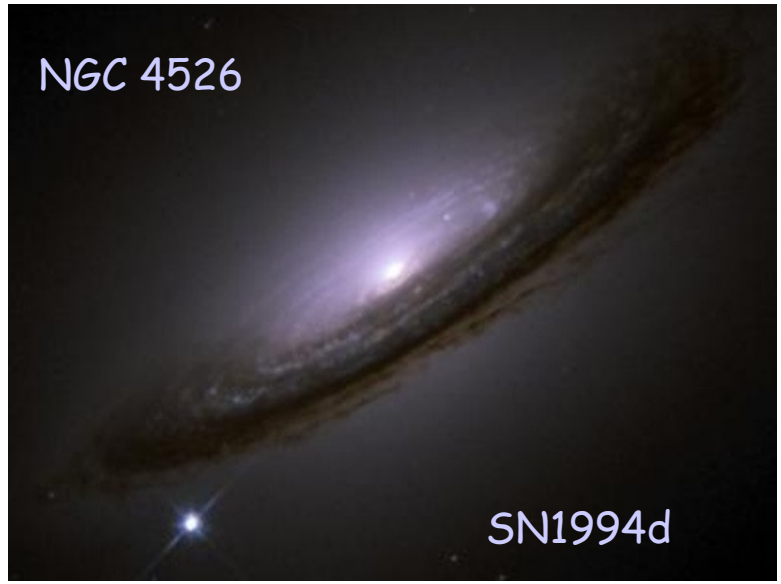
Hypothesis supported by:

- energy balance

  Milky way:

  energy density 0.5 eV/cm^3

  need 3 SN per century



- acceleration mechanism

  shock wave + interstellar medium

  can explain E^{-x}, $E^{p}_{\max} \sim 10^{15}\, eV$

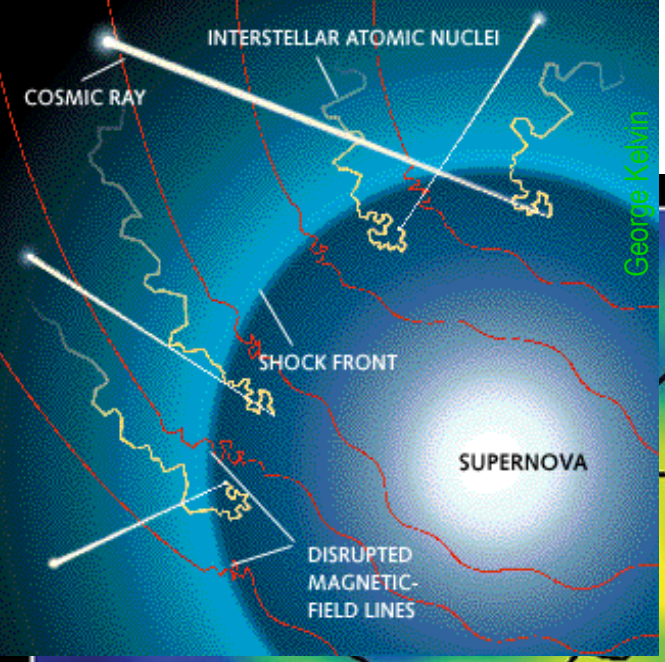
- HESS observations

  of TeV gamma rays

  confirm acceleration model

HESS TeV Gamma Sky

T.Hebbeker



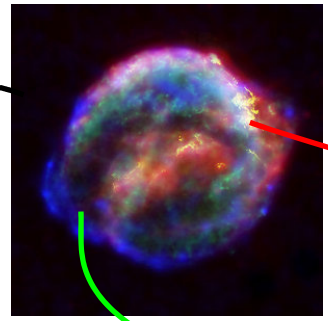
Shock wave accelerates particles from interstellar medium

Supernova remnant RX J1713.7

Supernovae and cosmic rays in milky way

T.Hebbeker

SN (every 30 years)

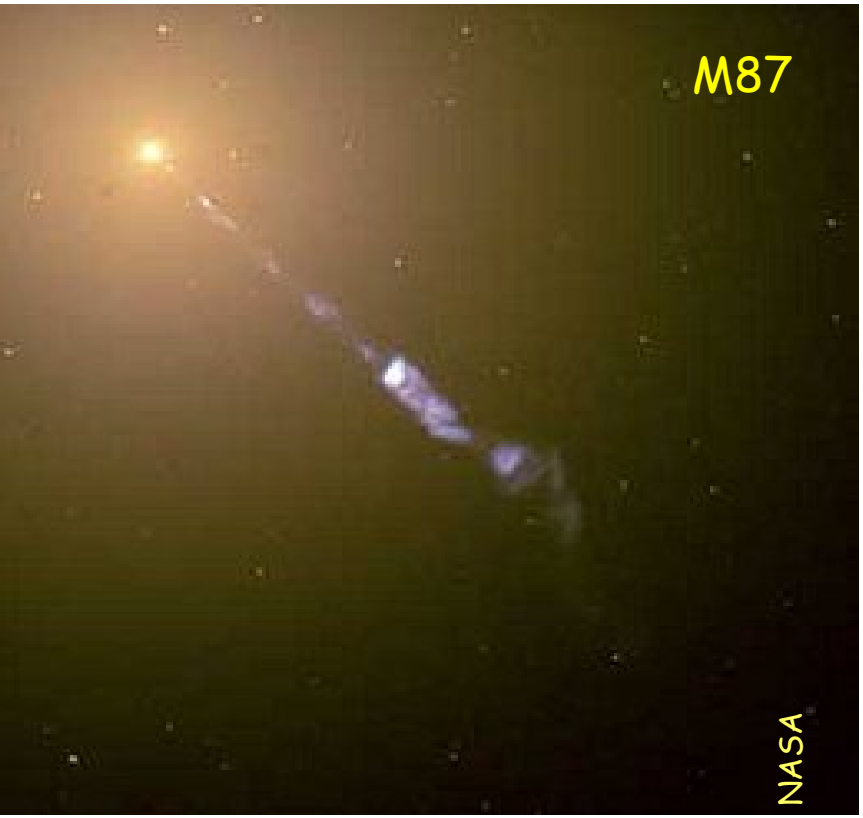


galactic
magnetic fields

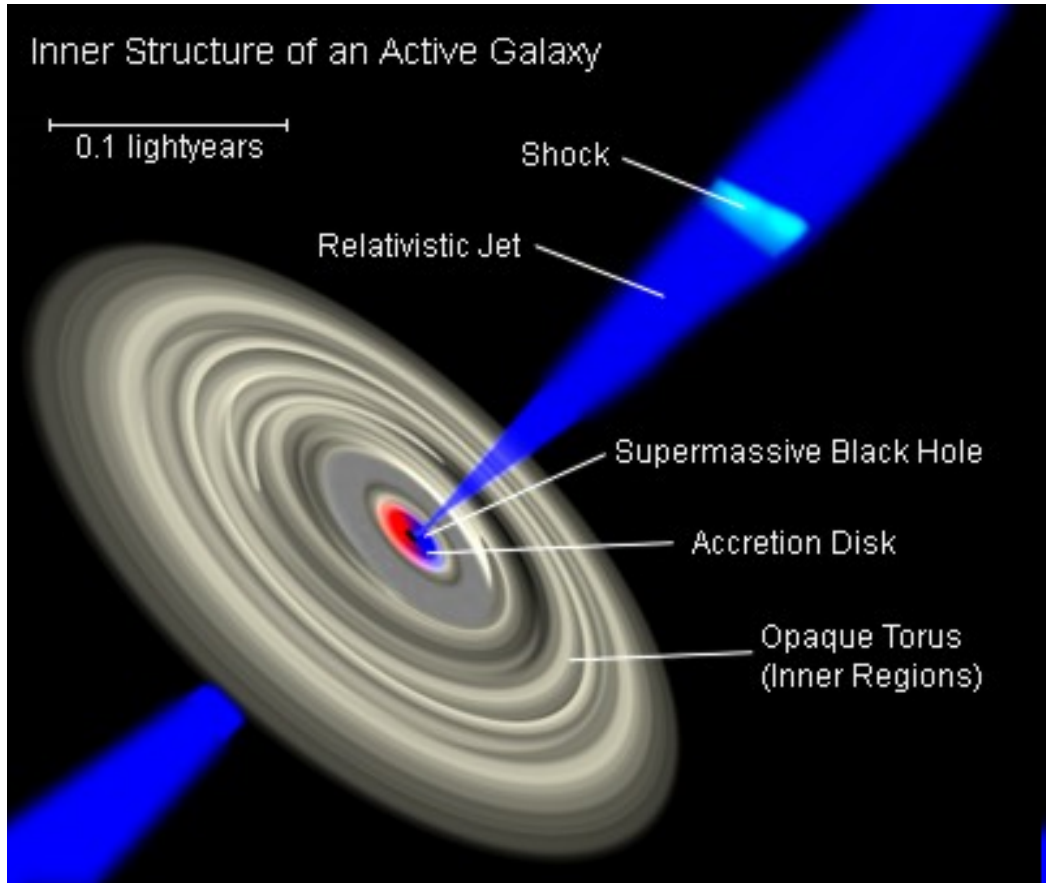
travel 10 million years

Information on production time and source location lost !

Highest Energies – from Active Galactic Nuclei ? (AGN)



center = massive black hole,
feeds ‚jets'



Hypothesis:
AGNs = source of ultra high energy cosmic rays


Centaurus A radio galaxy with Active Galactic Nucleus
ESO

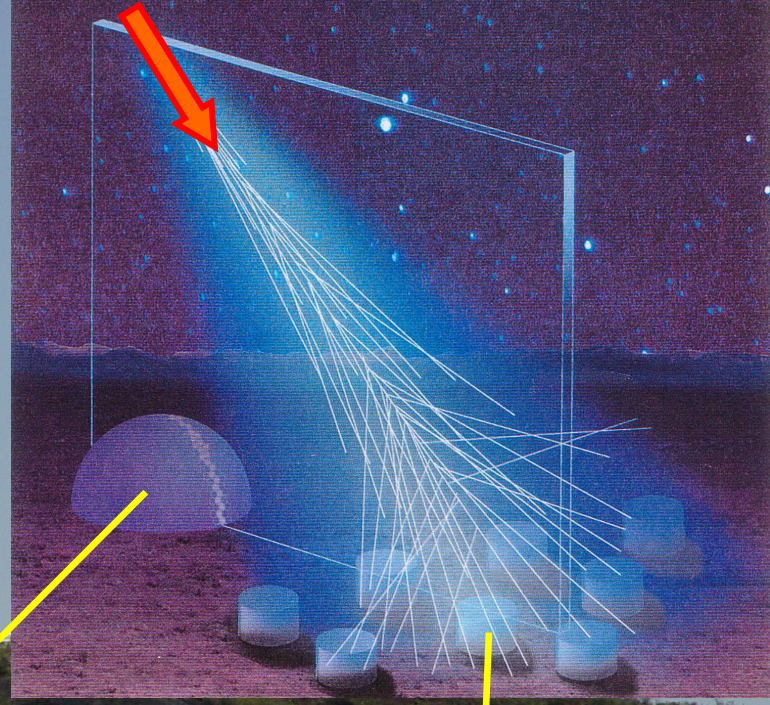
Cosmic Rays

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

Auger Observatory

start data taking 2004

detector completed 2008



24 x

Fluorescence
Detectors
(Telescopes)

FD

$E > 1EeV = 10^{18}\ eV$

1600 x

1500 m distance

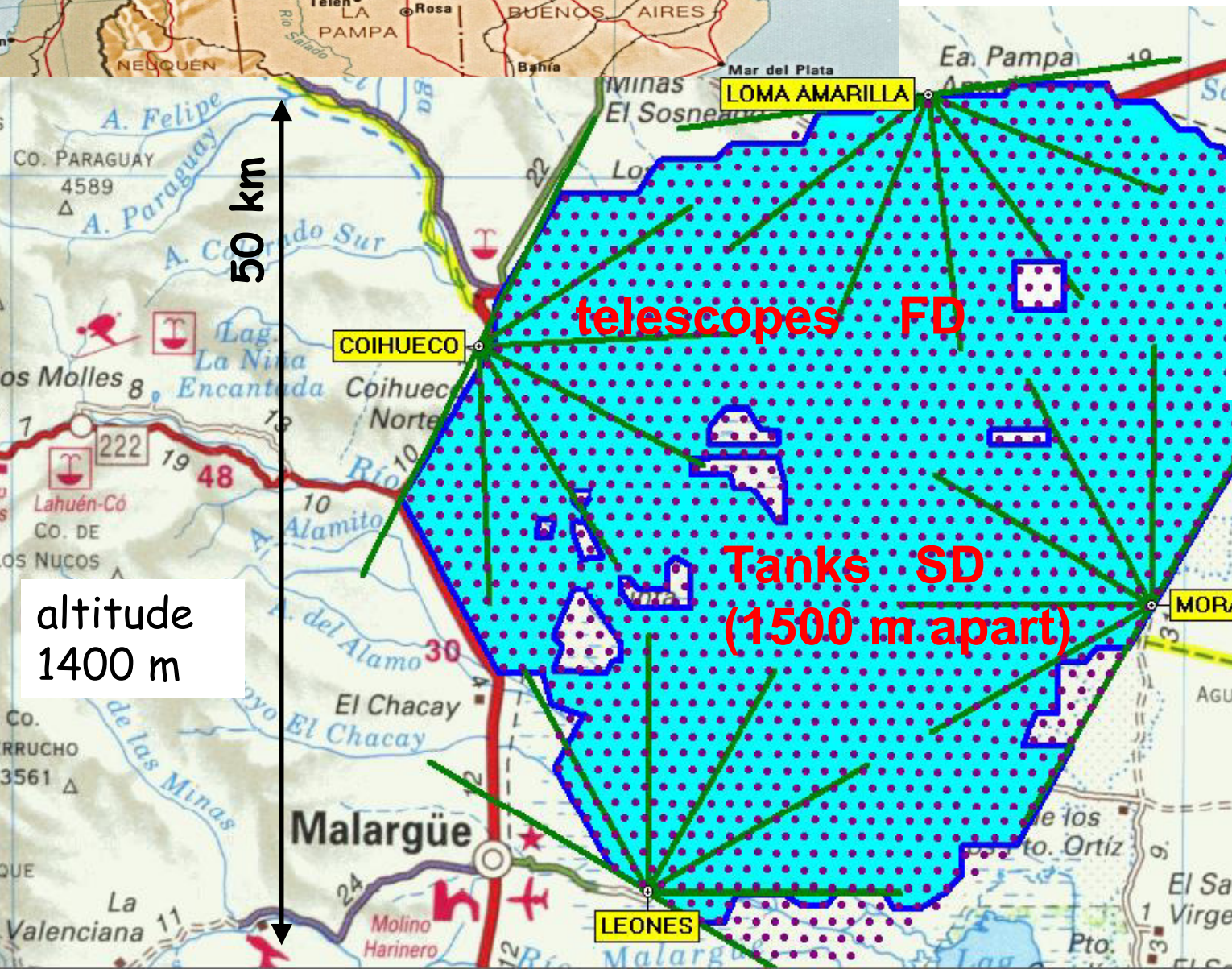
Surface Detectors
(water tanks)

SD

- **3000 km² - biggest**
- **two detection methods** (hybrid)

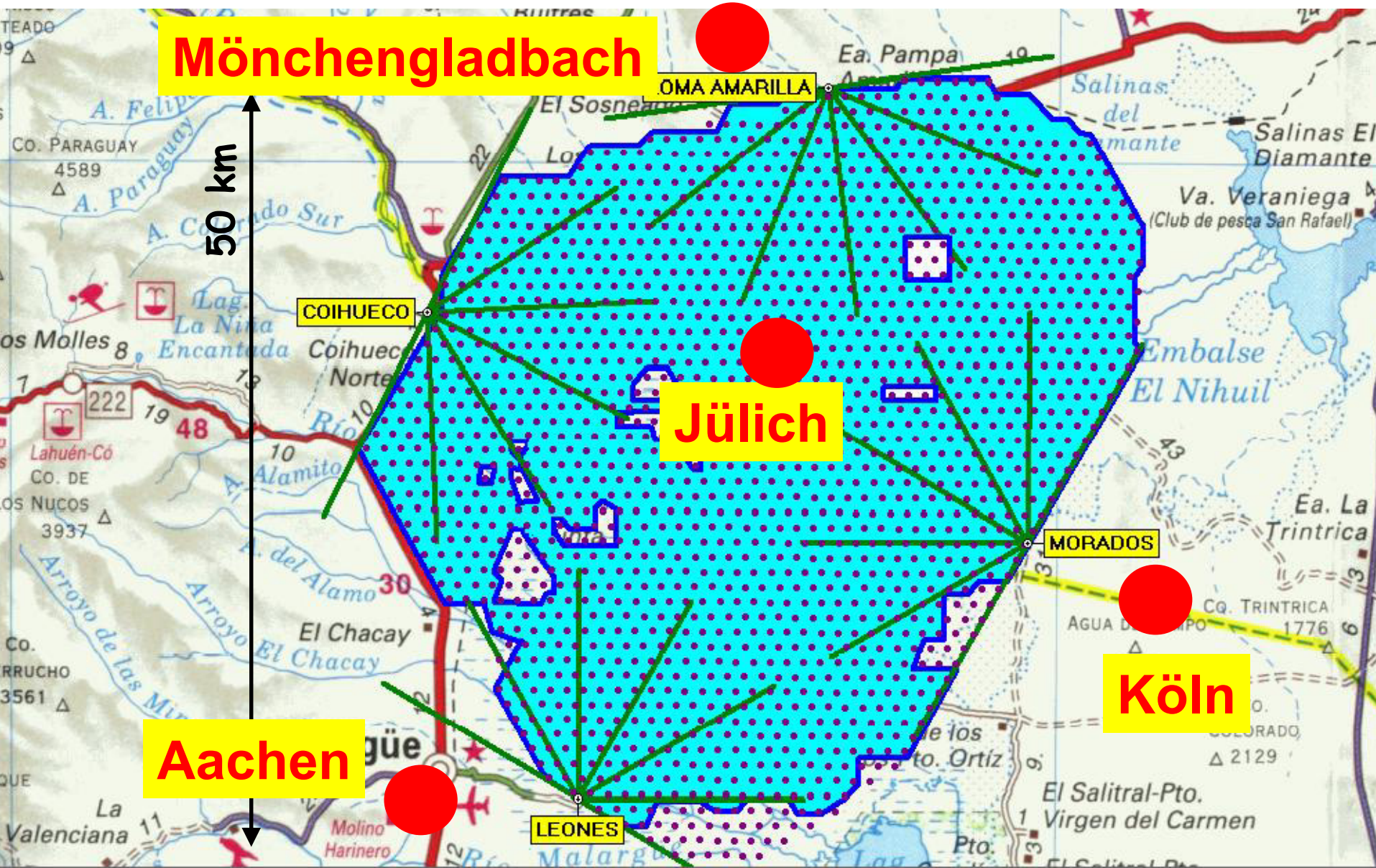
T.Hebbeker

Auger-Observatory Argentina

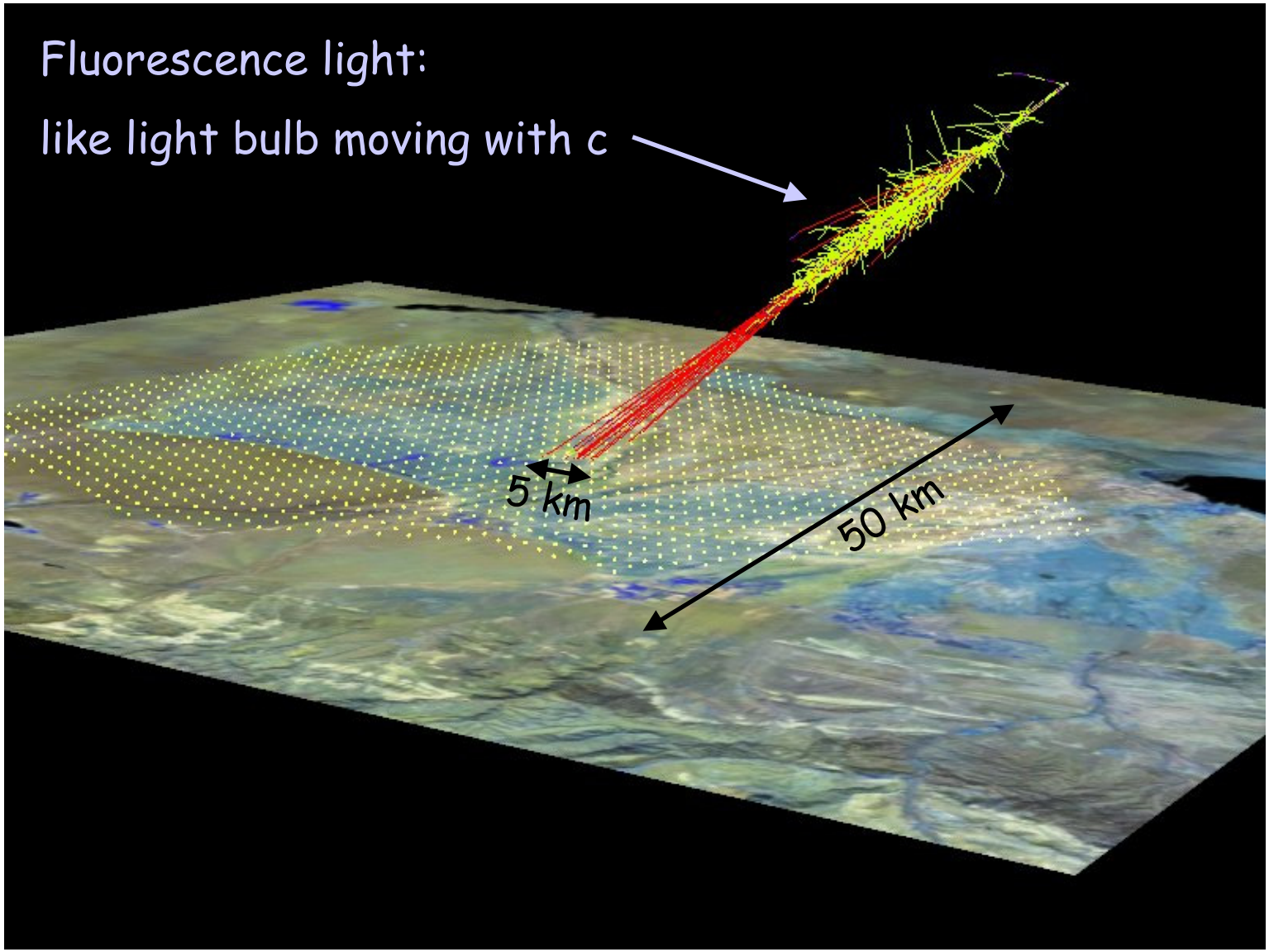


T.Hebbeker

Auger-Observatory Argentina

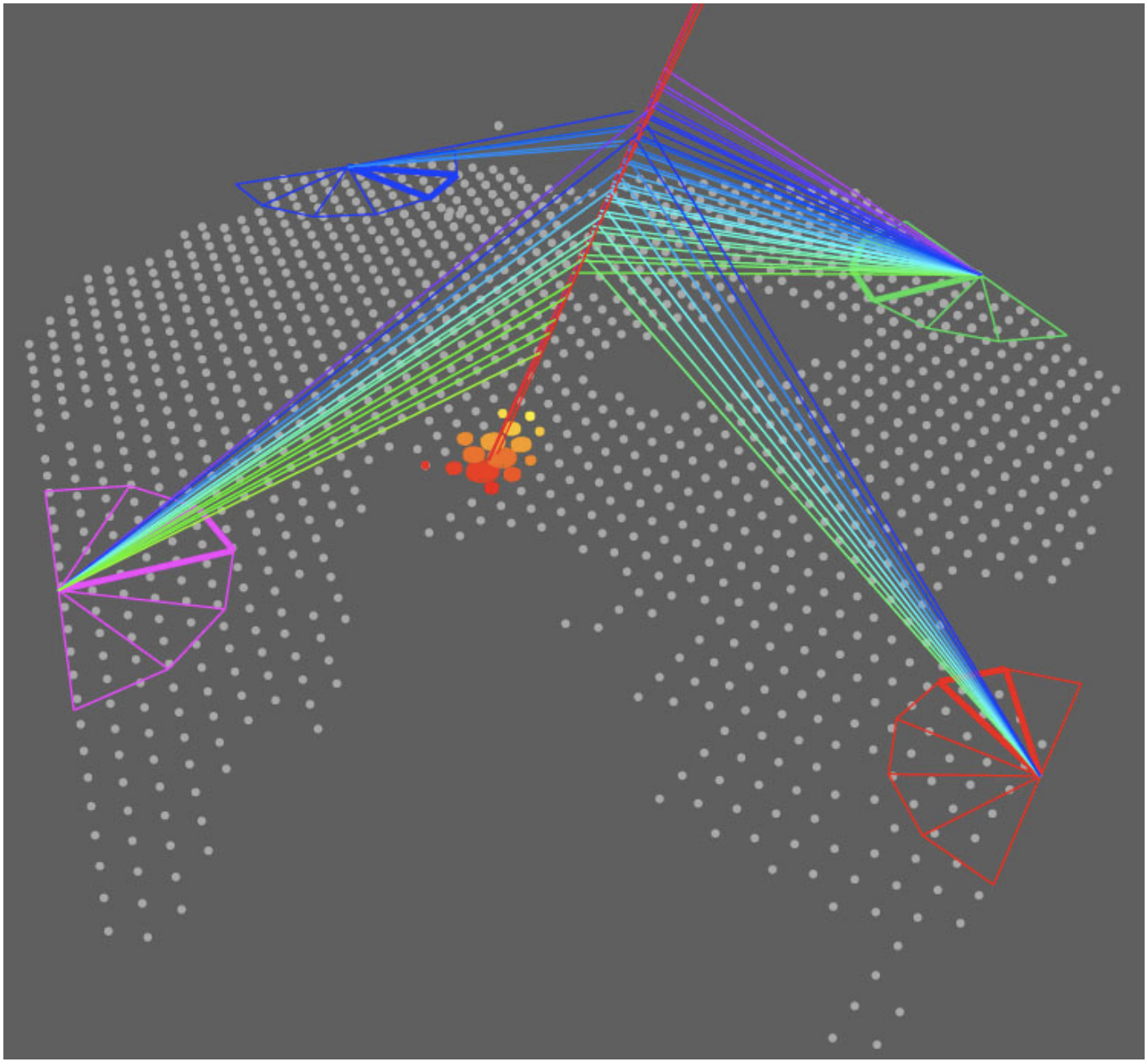


Ultra high energy cosmic shower



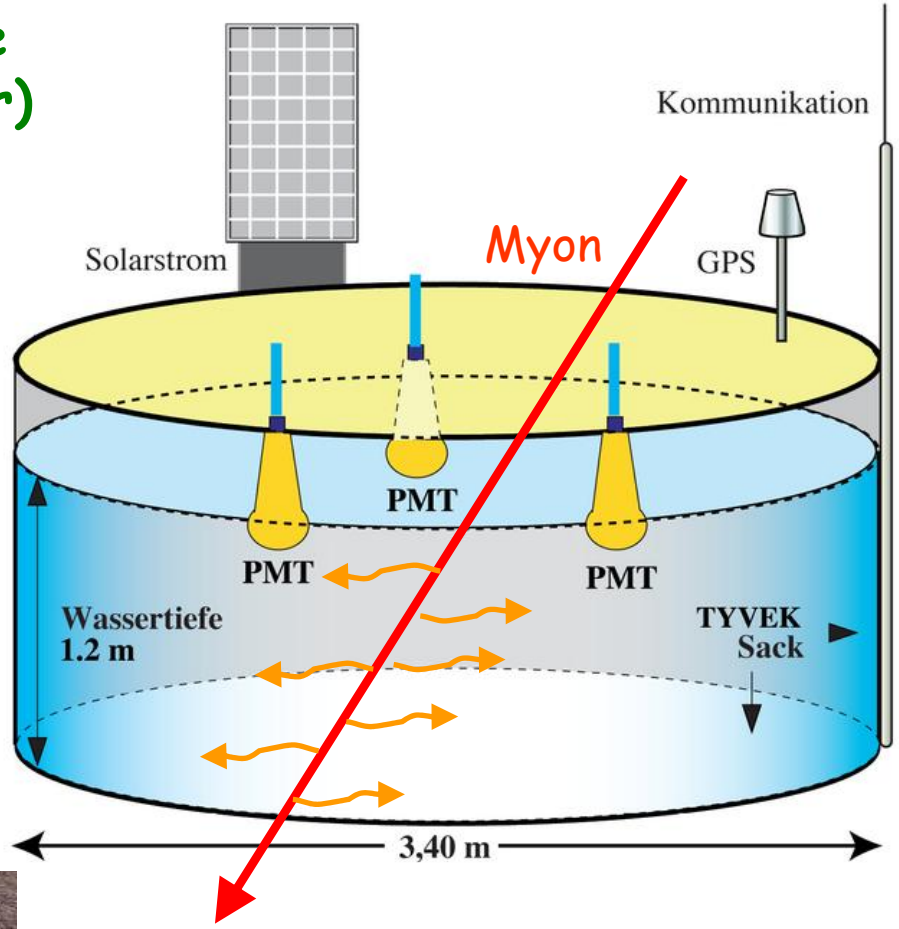
simulation

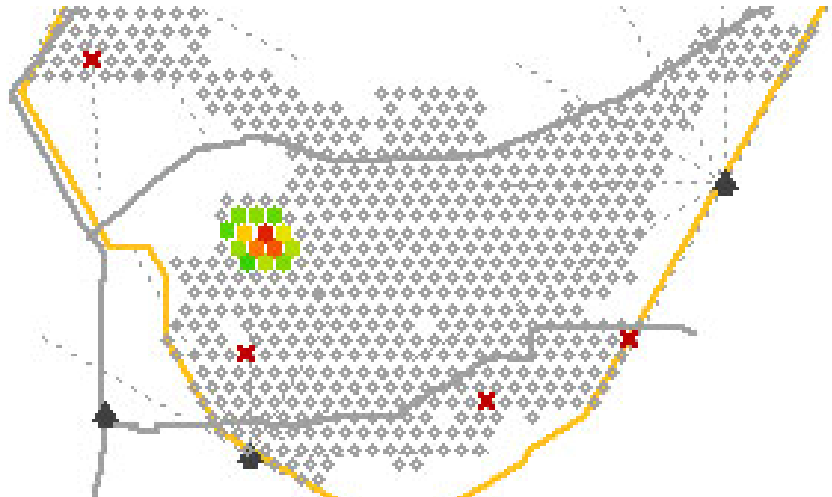
Ultra high energy shower seen by Auger




Auger observatory
Aerial View

AUGER – SD (Surface Detector)





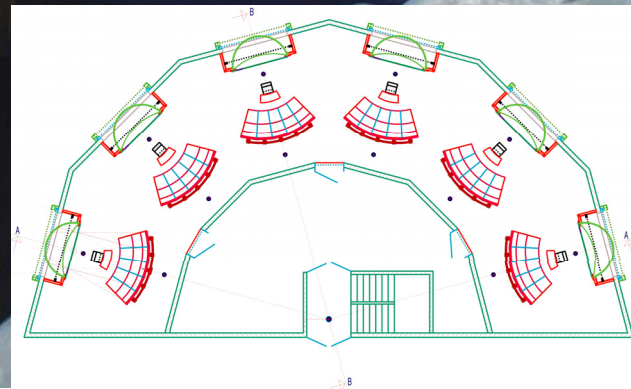
angular resolution ~ 1°

AUGER – FD

(Fluorescence Detector)

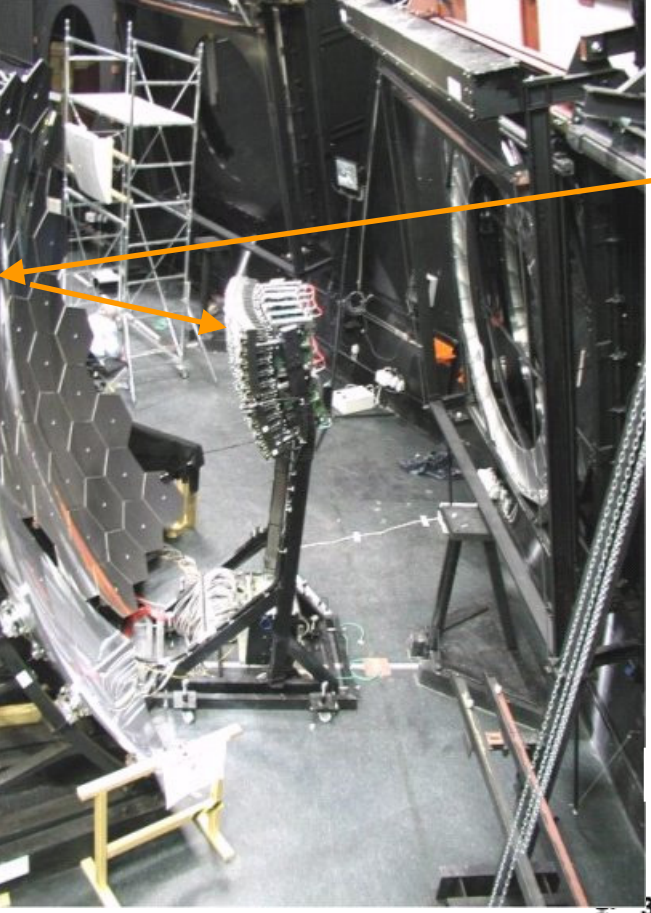
Measurements only in moonless nights !

13% duty cycle



Auger Fluorescence Telescope

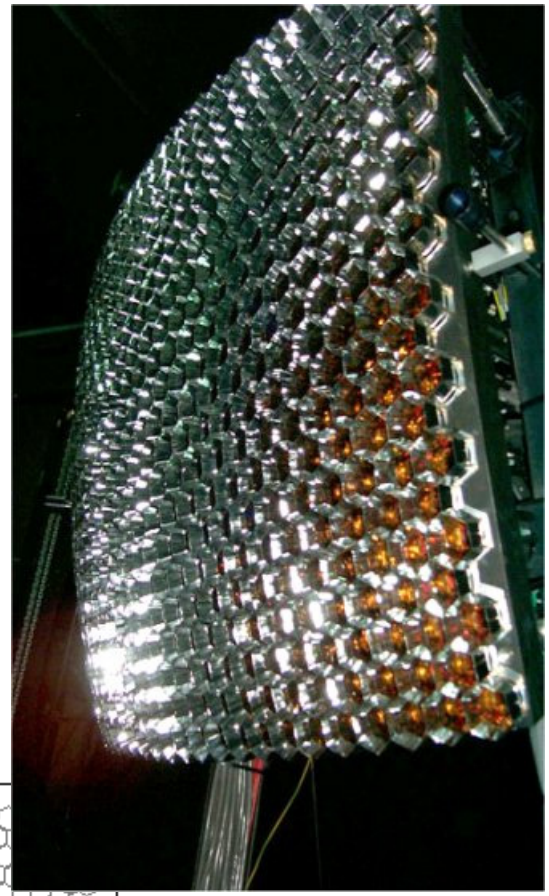
T.Hebbeker



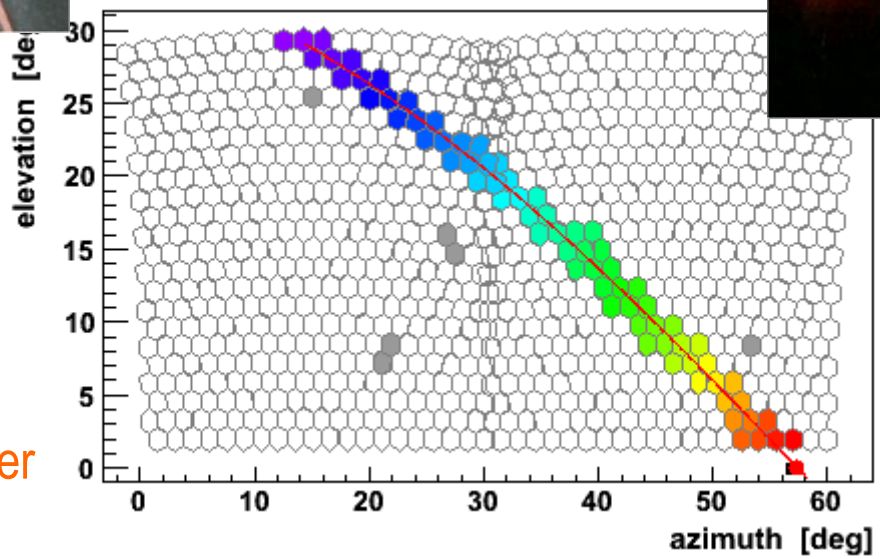
mirror 3.4 m

Camera:

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



energy meas.
~ 20%

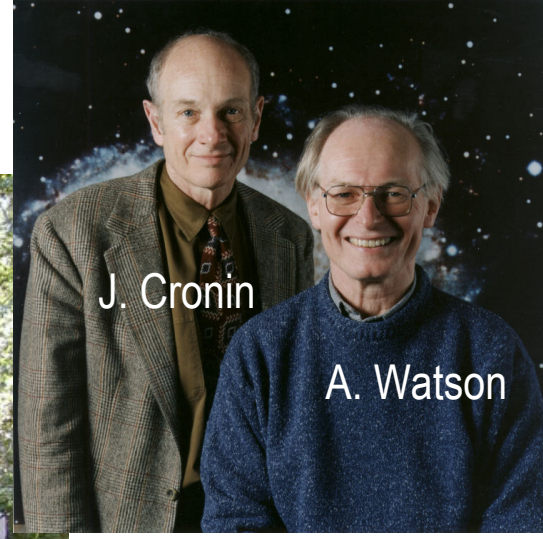


Trace of a shower seen by camera

color code

= arrival time

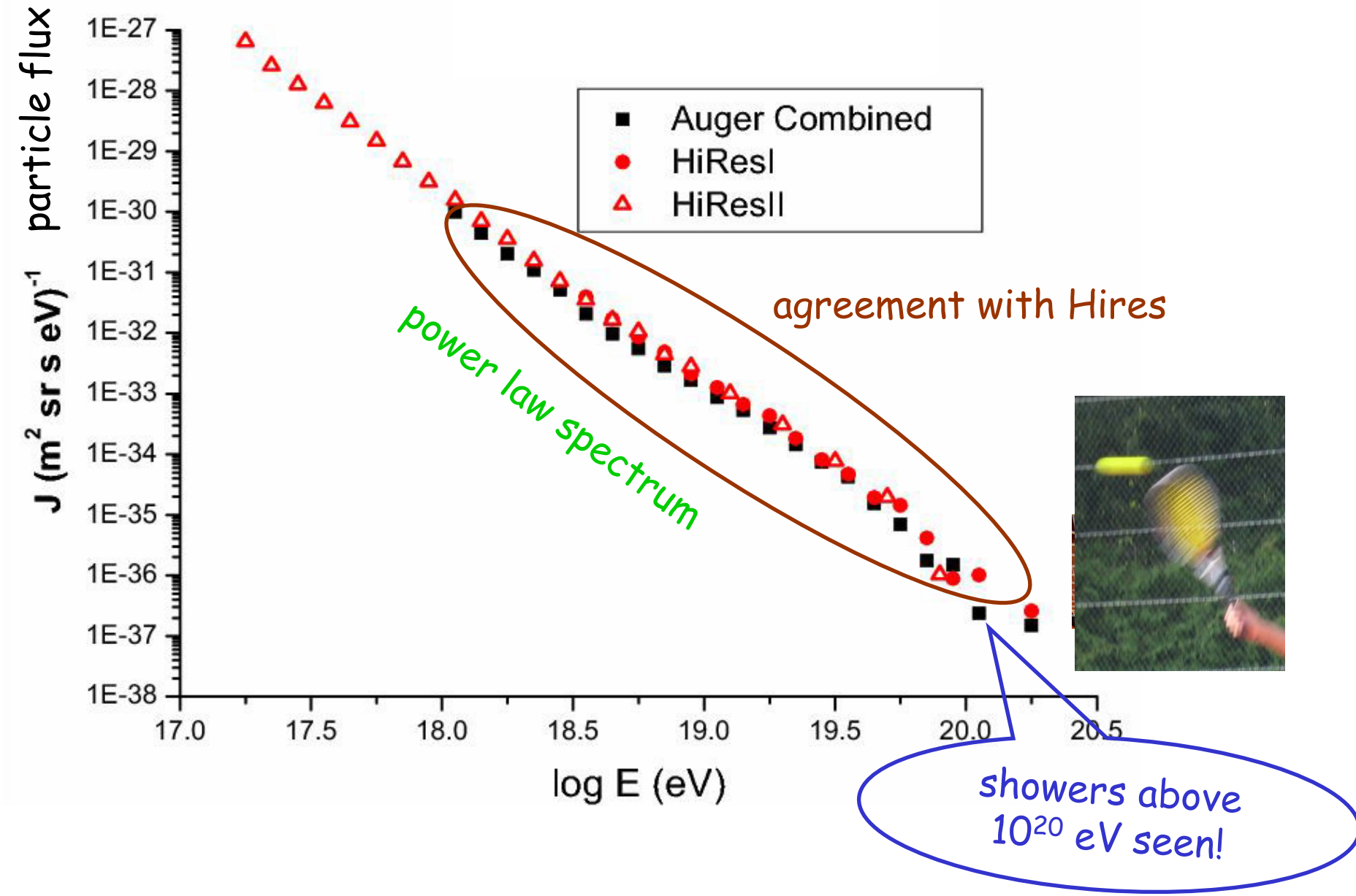
AUGER Collaboration



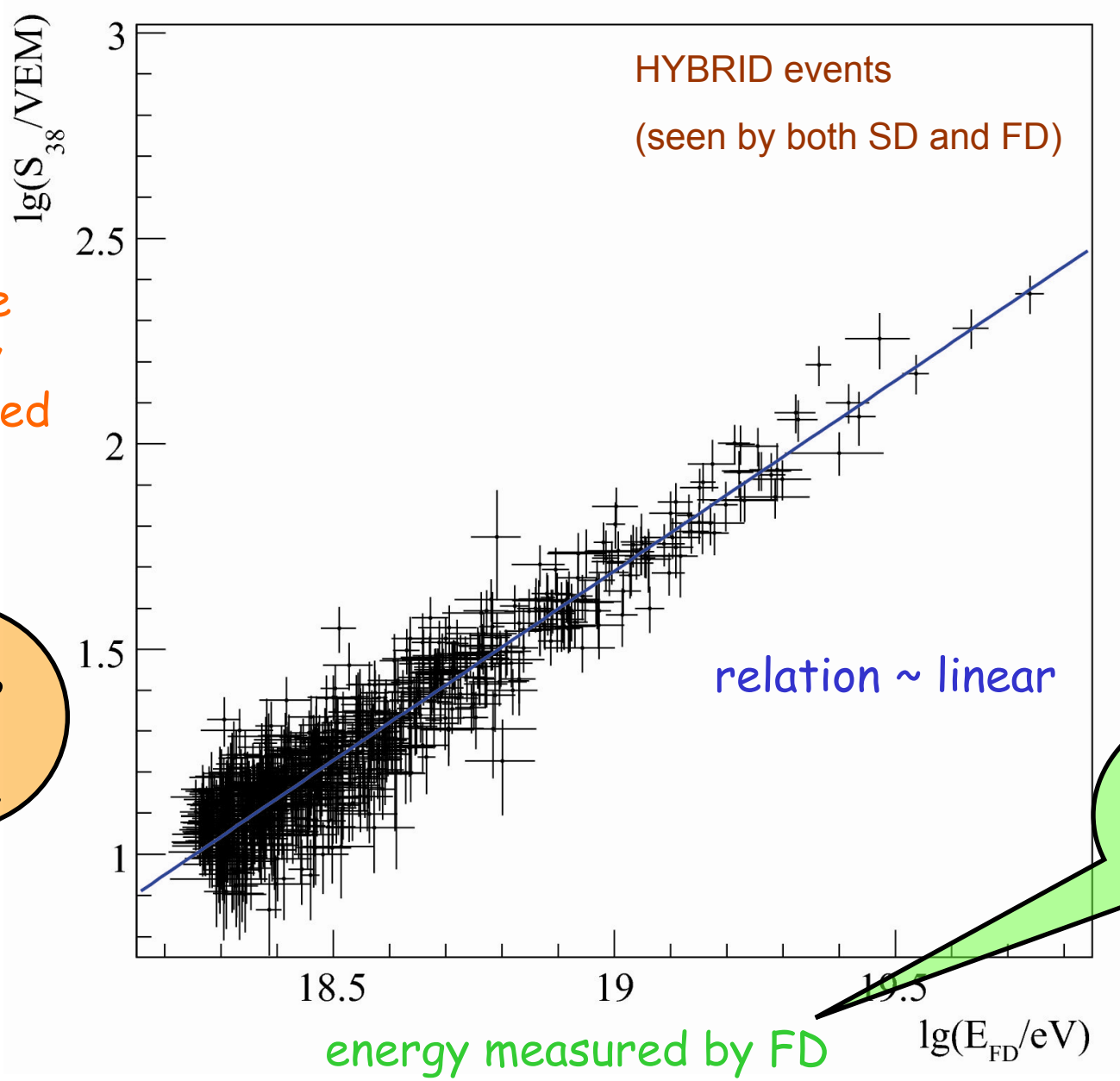
Cosmic Rays

- 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



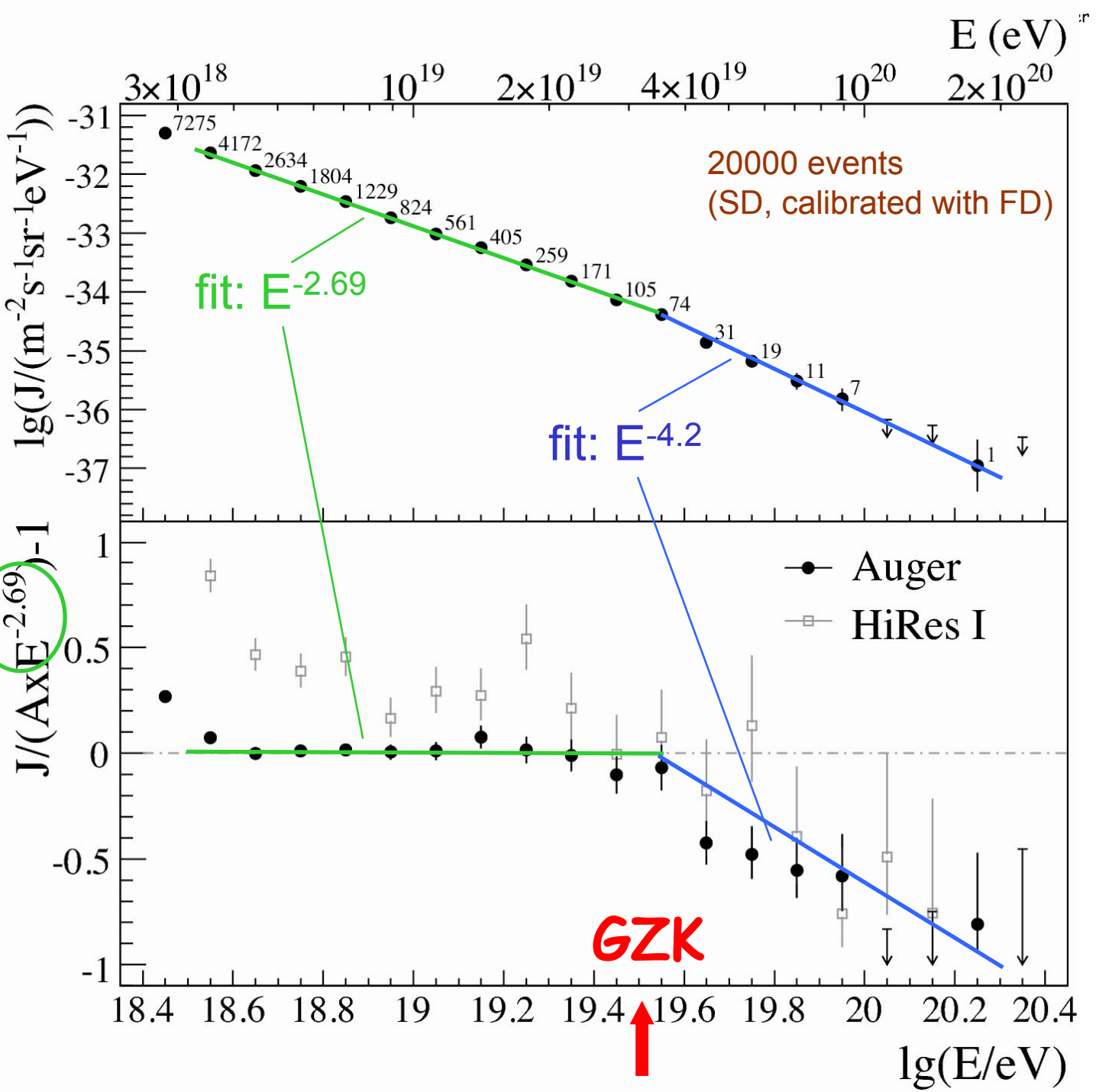
Particle density measured in SD

100% duty cycle

Absolute calibration (22%)

energy measured by FD

Auger GZK cutoff



drop of spectrum near

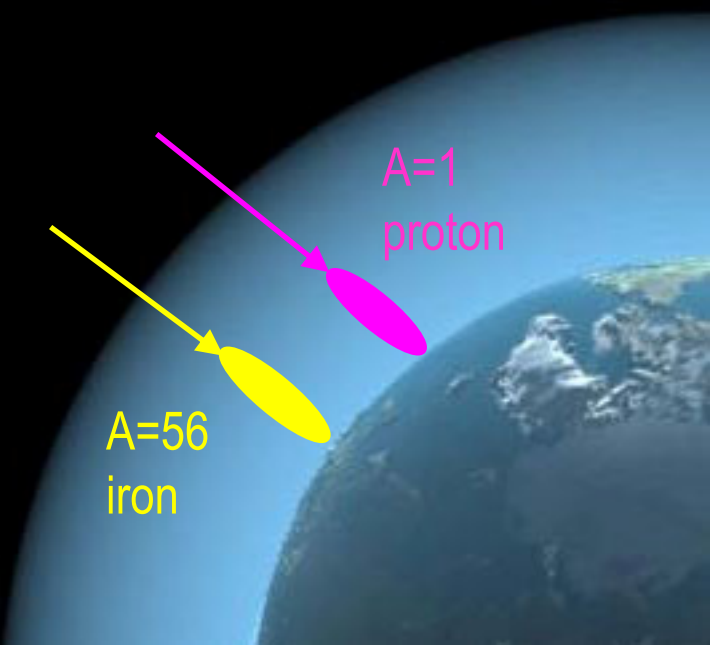
GZK cutoff

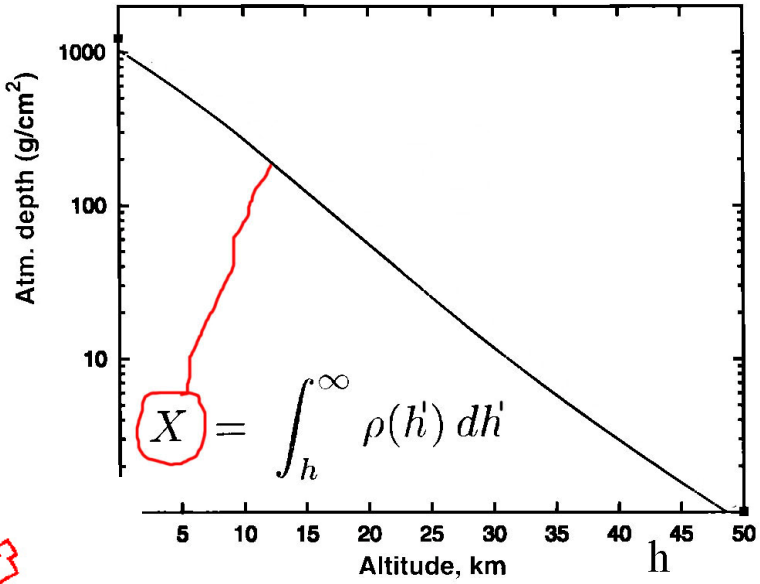
clearly visible

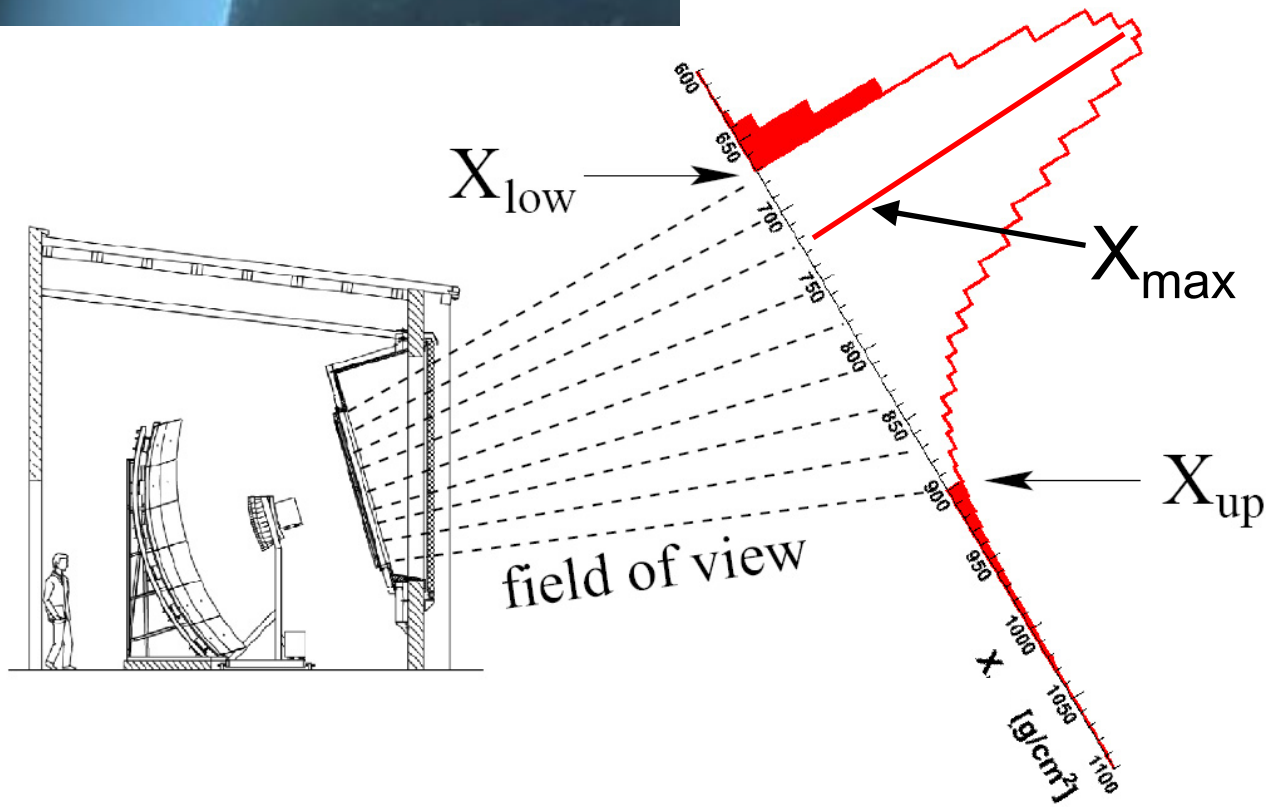
could be due to GZK or E_{max} (accelerator) or both….

Chemical Composition ?

T.Hebbeker

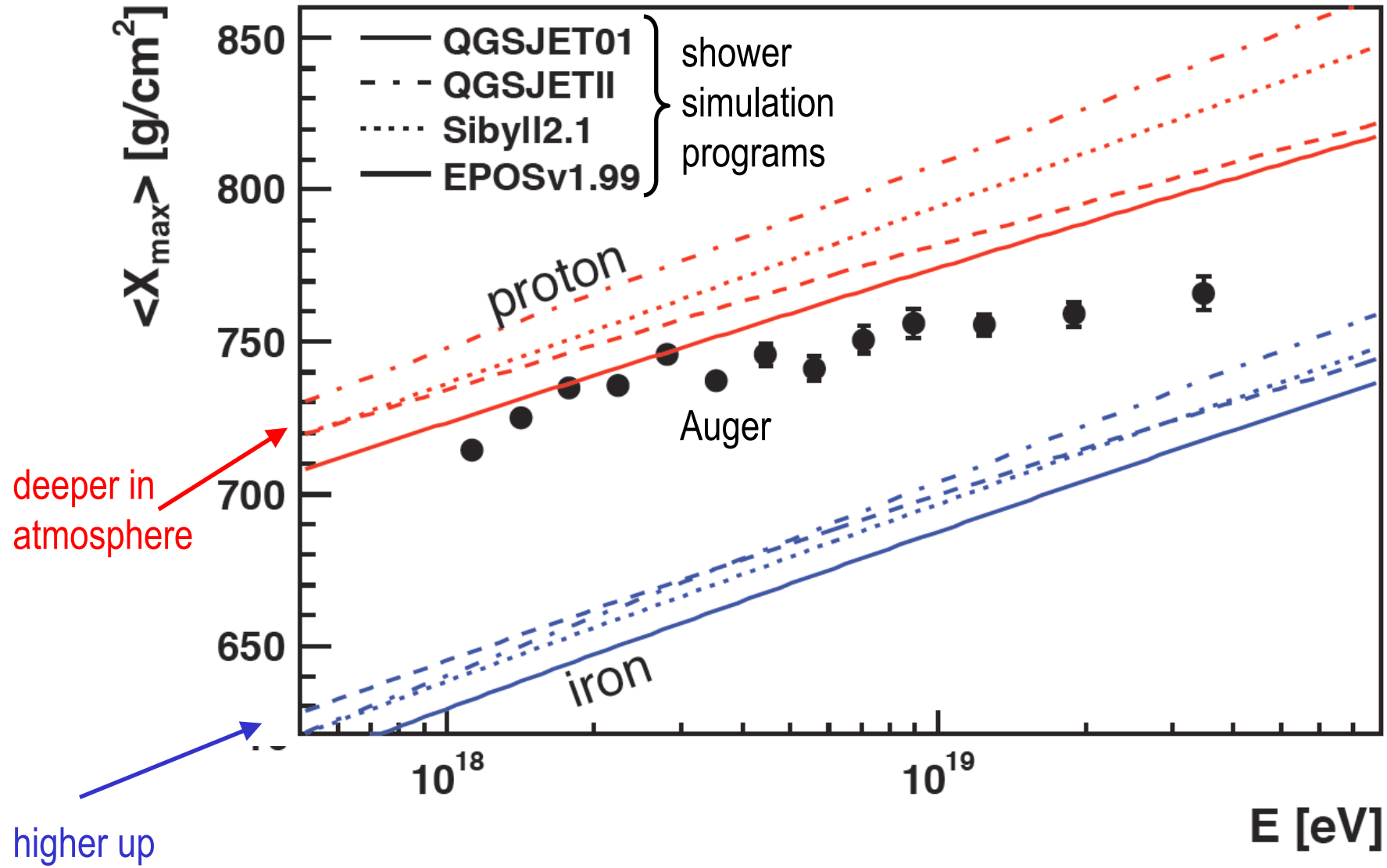






Measure <X_{max}> with FD !

Auger - Chemical Composition

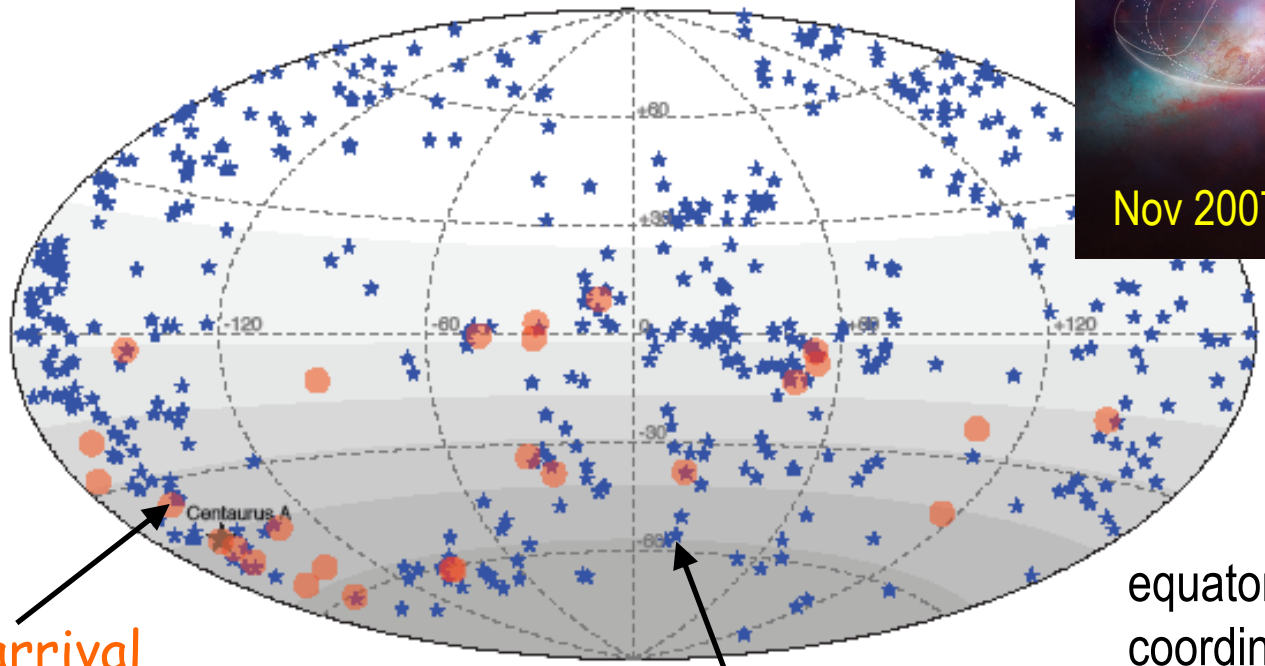


composition changing from proton towards iron

Auger – First Results – Arrival Directions

here only ultra high energy particles

E > 55 EeV



measured arrival directions, 27 events

equatorial coordinates

AGN positions

! Anisotropy

! correlation with AGN's !

! extragalactic !

Auger Anisotropy Analysis - Statistics

Analysis of data collected till May 2006

- find maximum angular correlation events ⟷ AGNs after **tuning**:

„prescription"

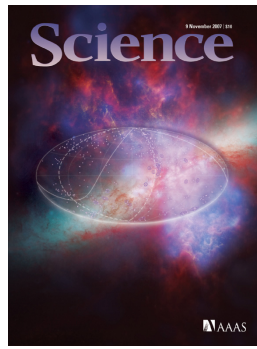
- lower shower energy threshold = 55 EeV — B fields
- maximum AGN distance = 75 Mpc = 250 MLj — GZK !
- maximum angular separation event – AGN = 3.1° — B +resolution

out of 15 events 12 correlate

chance correlation
0.21 per event

Analysis of data collected June 2006 - August 2007

out of 13 **NEW** events 9 correlate



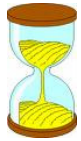
Analysis of data collected September 2007 - March 2009

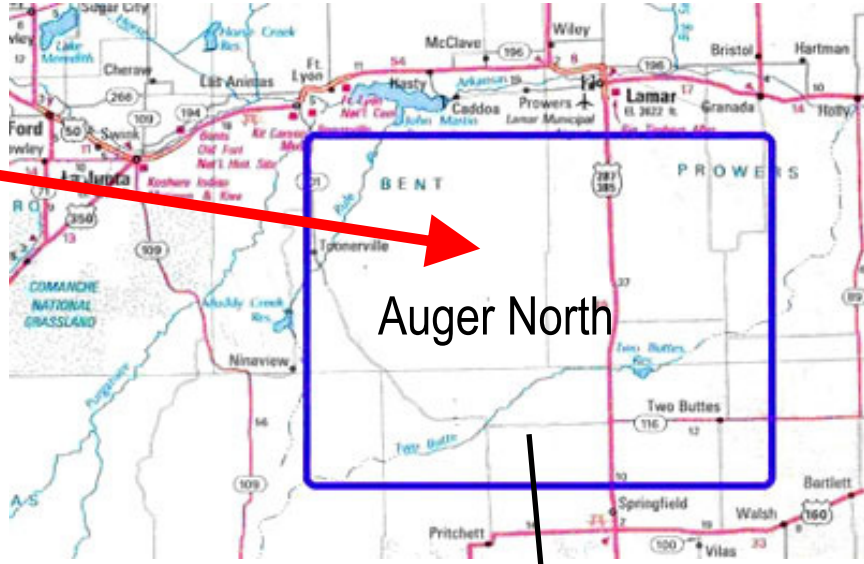
out of 31 **NEW** events 8 correlate

correlation weaker !

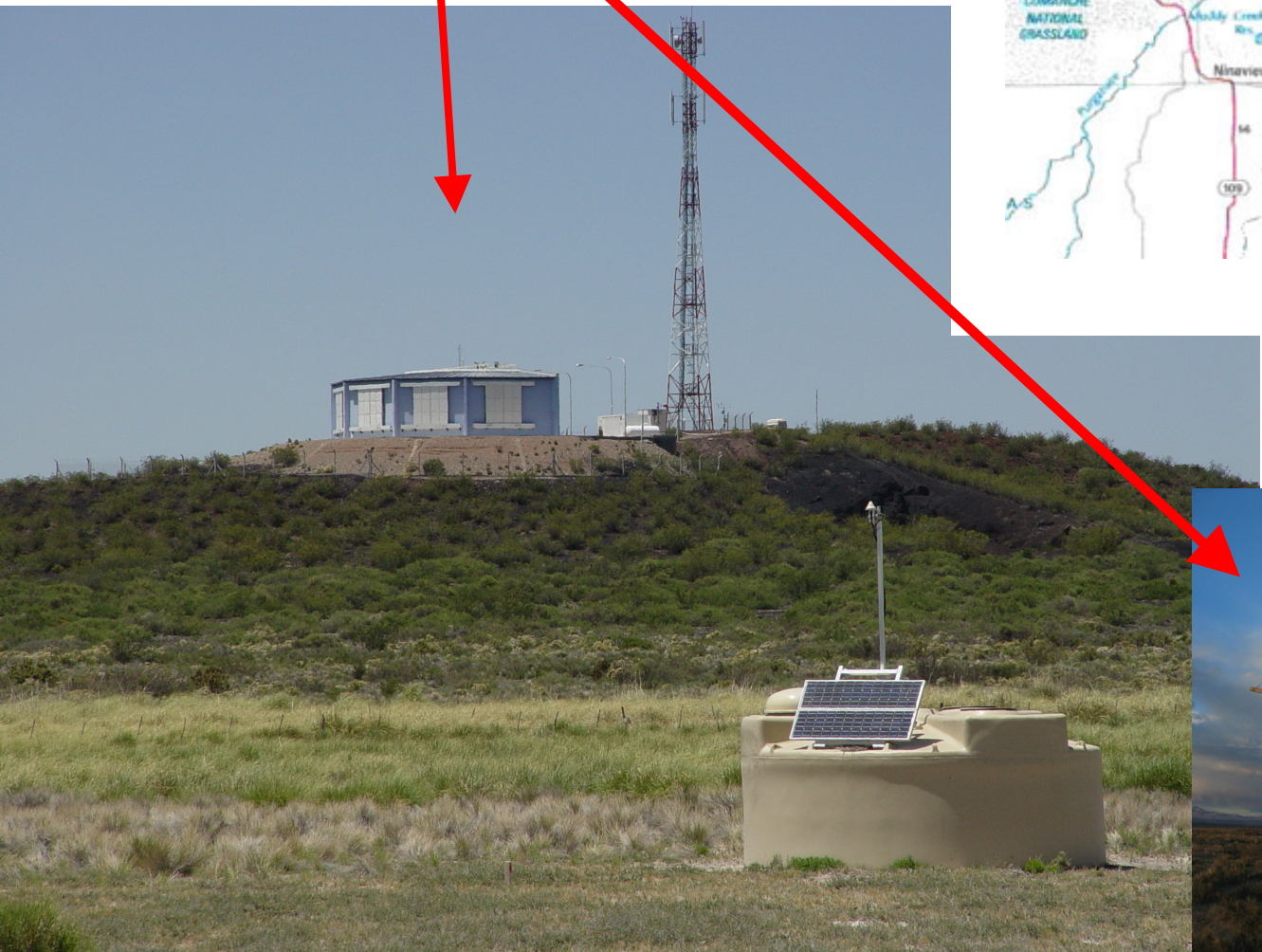
Future of the Auger Observatory

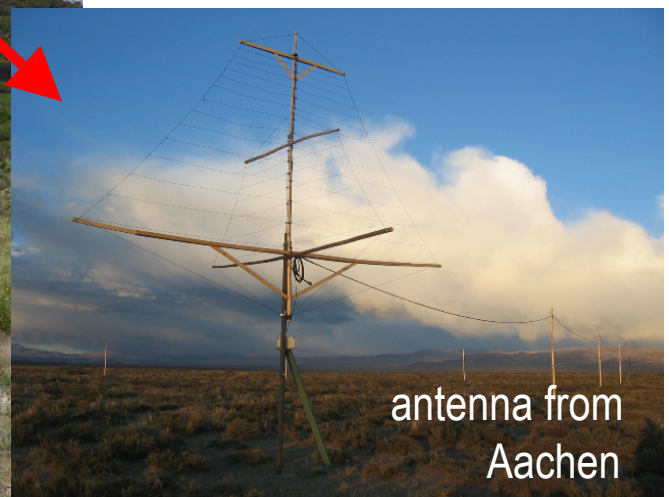
- measurements during several years
- second site Colorado/USA
- new: radio detection





20000 km²
northern hemisphere





Auger Team Aachen

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

and

several

more….

2007

RWTH AACHEN
Phys. Inst. III A

NGC 3190 (ESO)

SUMMARY

Ultra high energy cosmic rays:

- origin still not known

- exciting new results
  from AUGER:
  - anisotropy
  - GZK cutoff
  - composition

A new window to the sky is opening

Cosmic ray astronomy

APPENDIX

Am Freitag, den 25. September 2009, 14.00 Uhr s.t., spricht

Prof. Dr. Thomas Hebbeker

(RWTH Aachen)

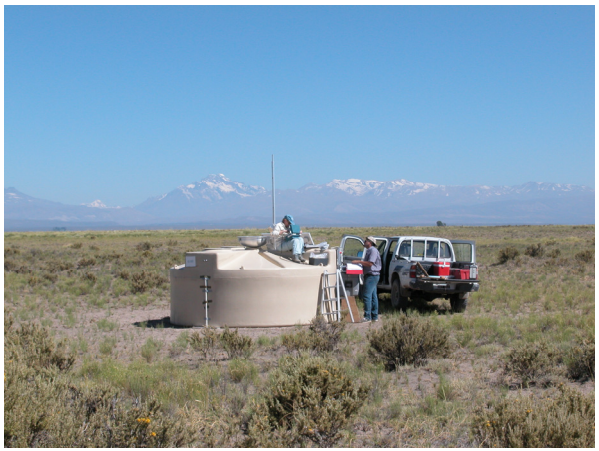
im Hörsaal des Forschungszentrums Jülich über das Thema

Kosmische Strahlung – Hochenergetische Teilchen aus dem Universum

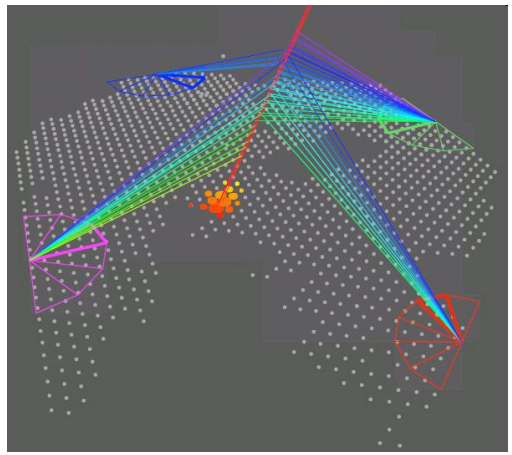
In jeder Sekunde treffen mehrere Tausend geladene Teilchen mit Energien oberhalb von 1 GeV auf die obere Schicht der Erdatmosphäre und erzeugen dort sekundäre Teilchen- und Lichtschauer, die auf der Erdoberfläche nachgewiesen werden können. Einige wenige dieser primären Teilchen haben Energien von über 10^{20} eV, weit mehr als an irgendeinem existierenden oder zukünftigen Beschleuniger machbar ist bzw. sein wird. Seit der Entdeckung dieser natürlichen, sog. *Kosmischen Strahlung* durch Victor Hess (Nobelpreis Physik 1936) versuchen Wissenschaftler, die Entstehung und die Wege dieser Strahlung zu verstehen:

- Was sind die kosmischen Beschleuniger?
- Wie erreichen sie die Erde?
- Was können sie uns über das Universum mitteilen?

Der Vortrag gibt eine allgemeine Einführung in die Geschichte und die Physik der Kosmischen Strahlung. Im weiteren Verlauf werden neueste Erkenntnisse zu ultra-hochenergetischen Teilchen diskutiert, die mit dem *Pierre Auger Observatorium* in Argentinien (3000 Quadratkilometer groß, Betrieb seit 2004) nachgewiesen worden sind.

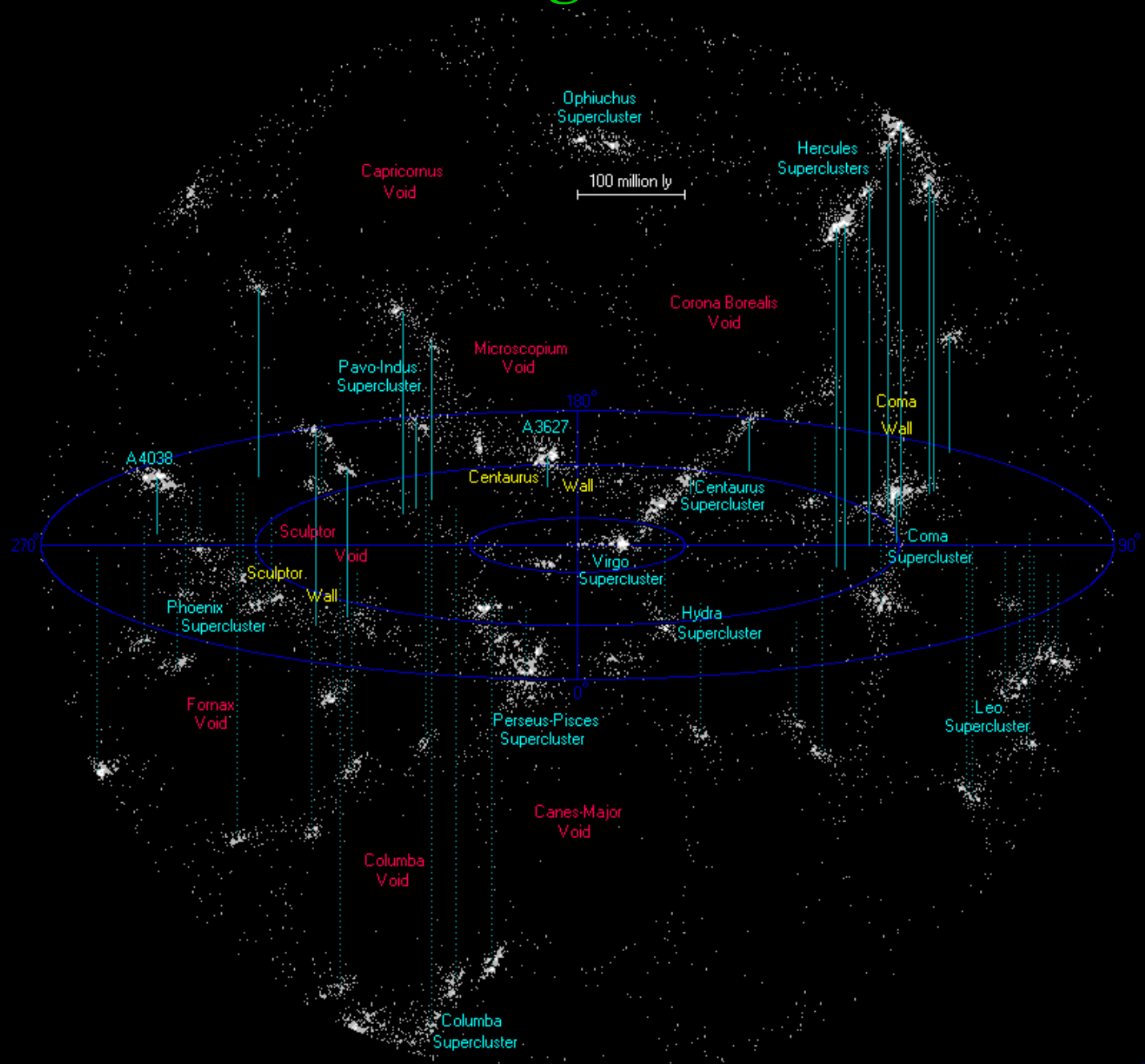


Zwei Wissenschaftler der Auger-Kollaboration bei der Installation von Elektronik eines Detektors in der argentinischen Pampa.



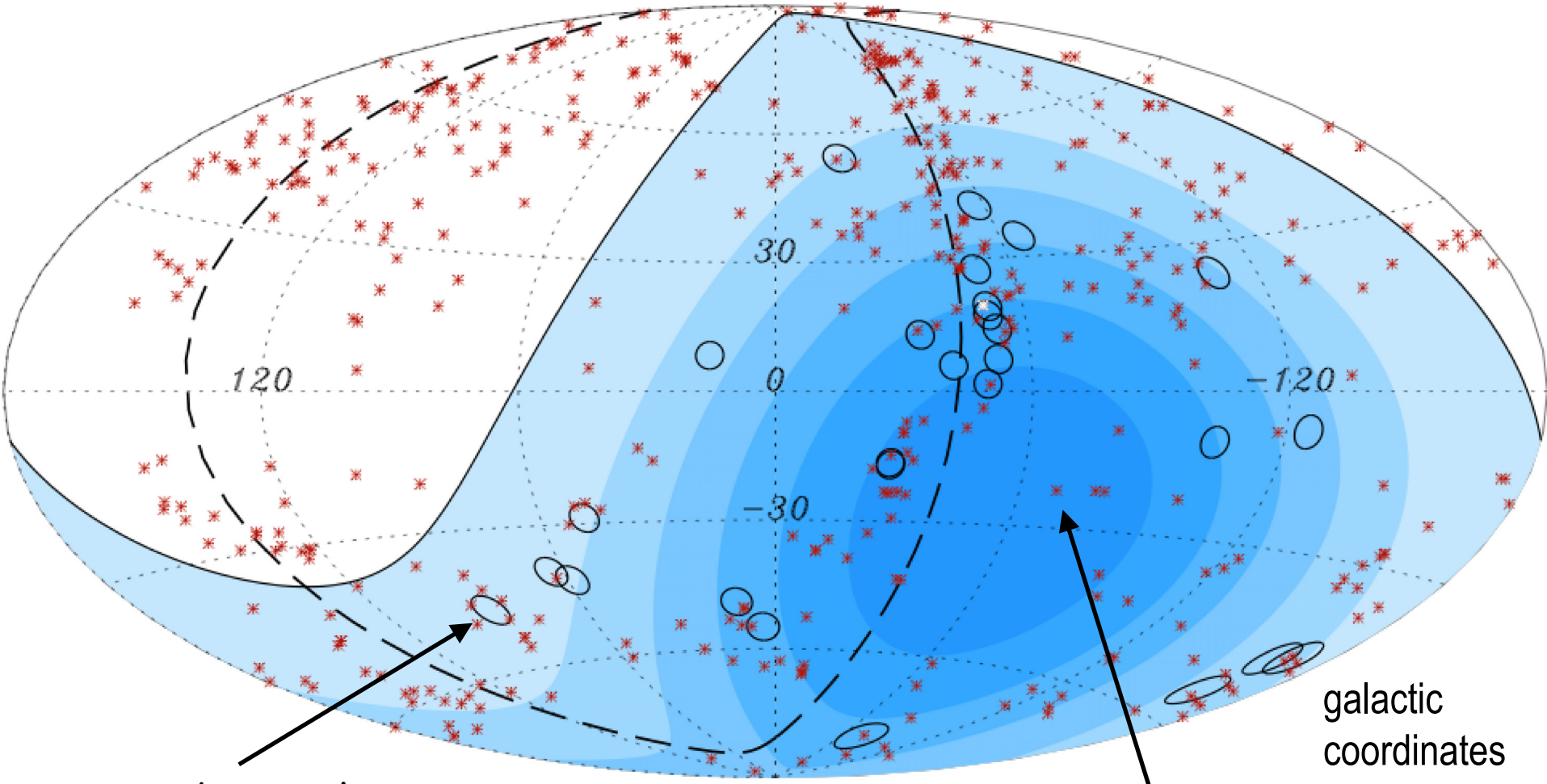
Ein Ereignis der Kosmischen Strahlung wie es mit dem Pierre Auger Observatorium nachgewiesen wird.

Cosmic Neighborhood



Auger – First Results – Arrival Directions

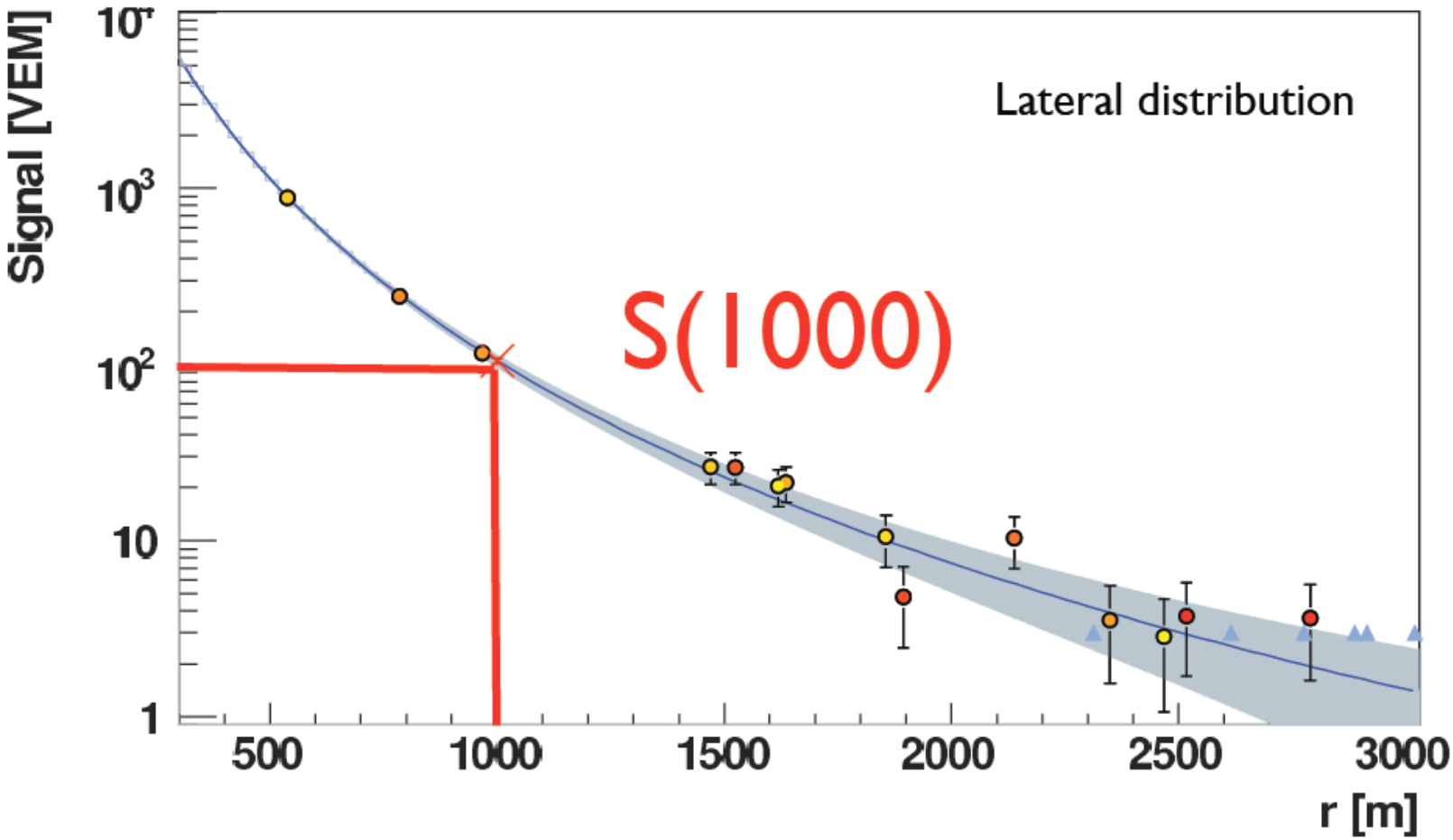
T.Hebbeker



correlation between arrival directions and nearby AGN's

not less and not more

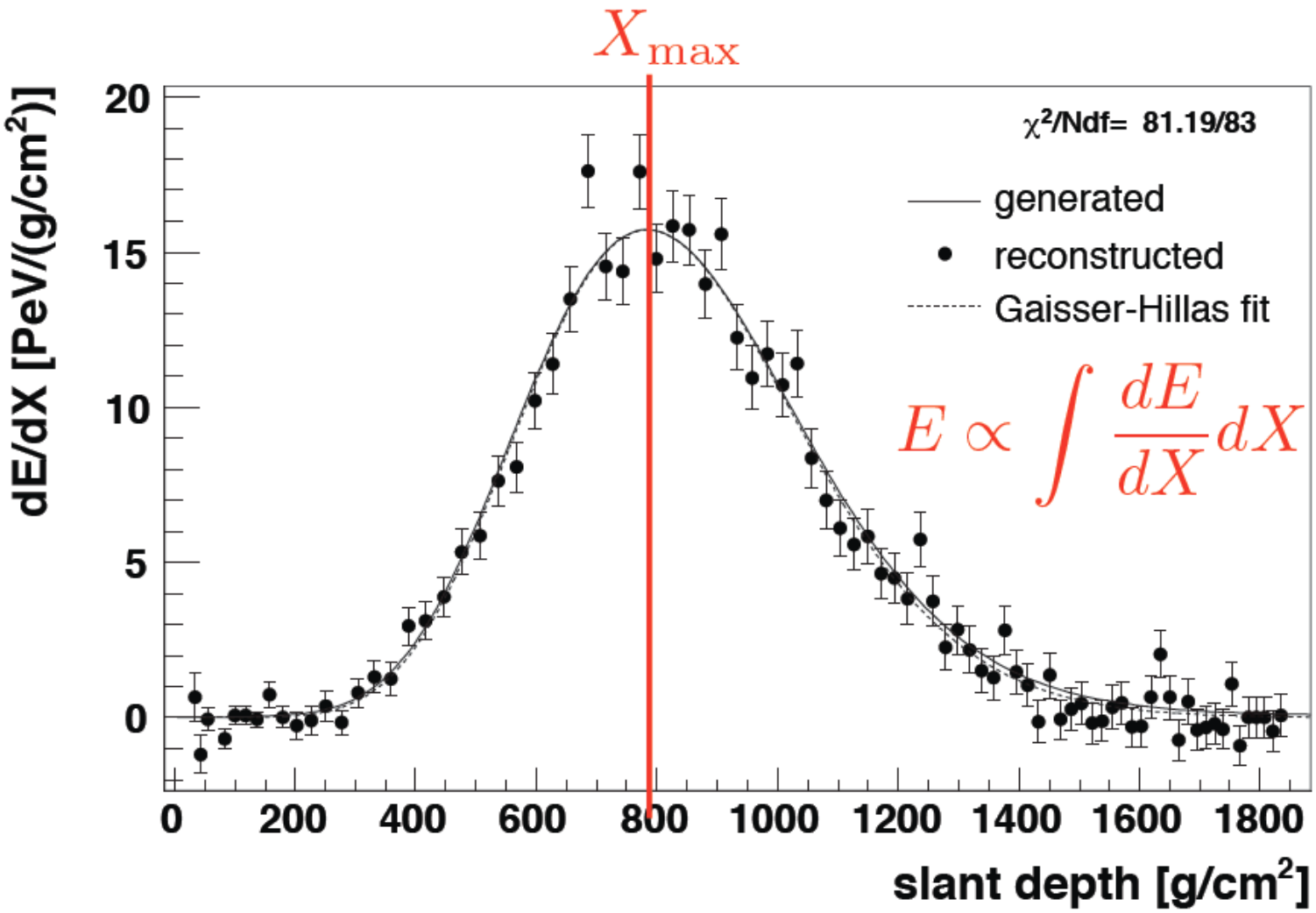
Lateral shower profile



$$S(r) = S_{1000}\left(\frac{r}{r_{1000}}\right)^{\beta}\left(\frac{r + r_{700}}{r_{1000} + r_{700}}\right)^{\beta+\gamma}$$

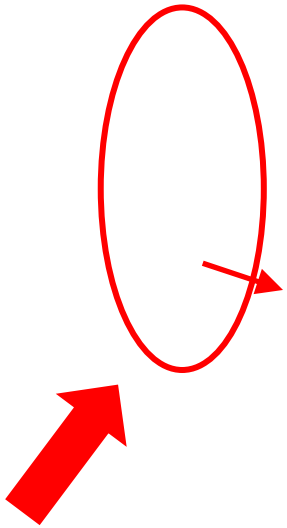
~ E

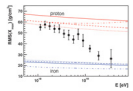
Longitudinal shower profile



$$S(X) \sim \left(\frac{X - X_0}{X_{\max} - X_0} \right)^{(X_{\max} - X_0)/\lambda} \cdot e^{(X_{\max} - X)/\lambda}$$

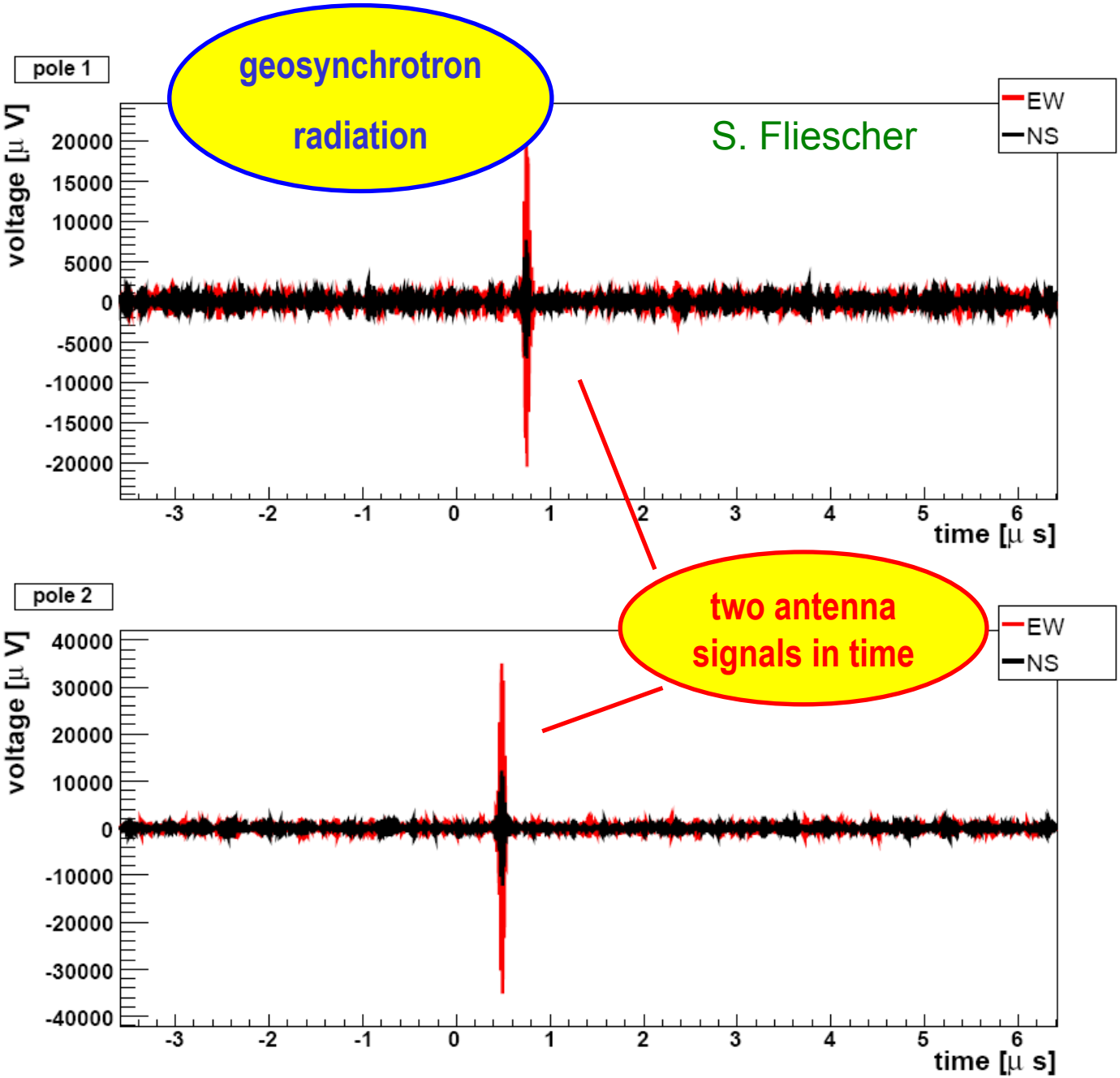
Auger - Chemical Composition

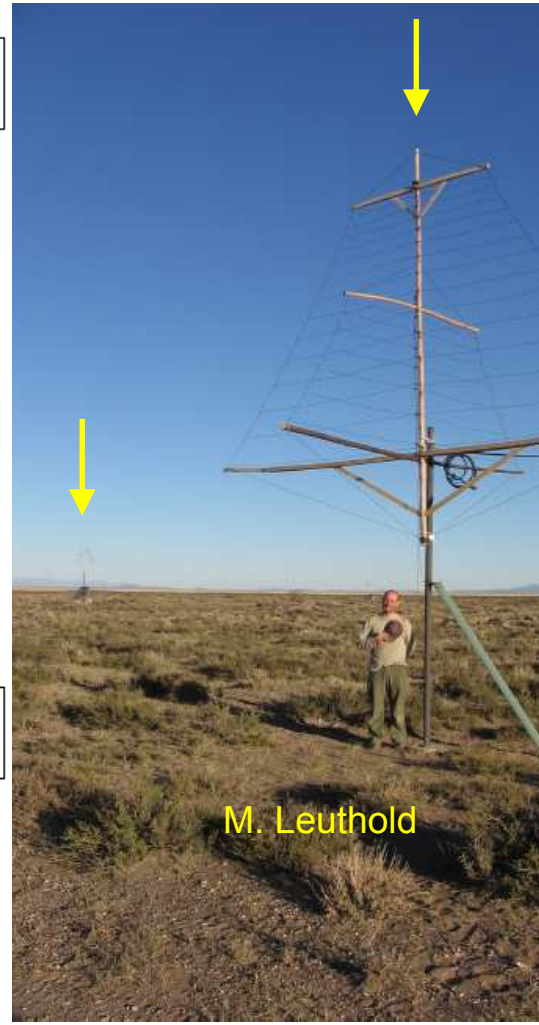




composition changing from proton to iron

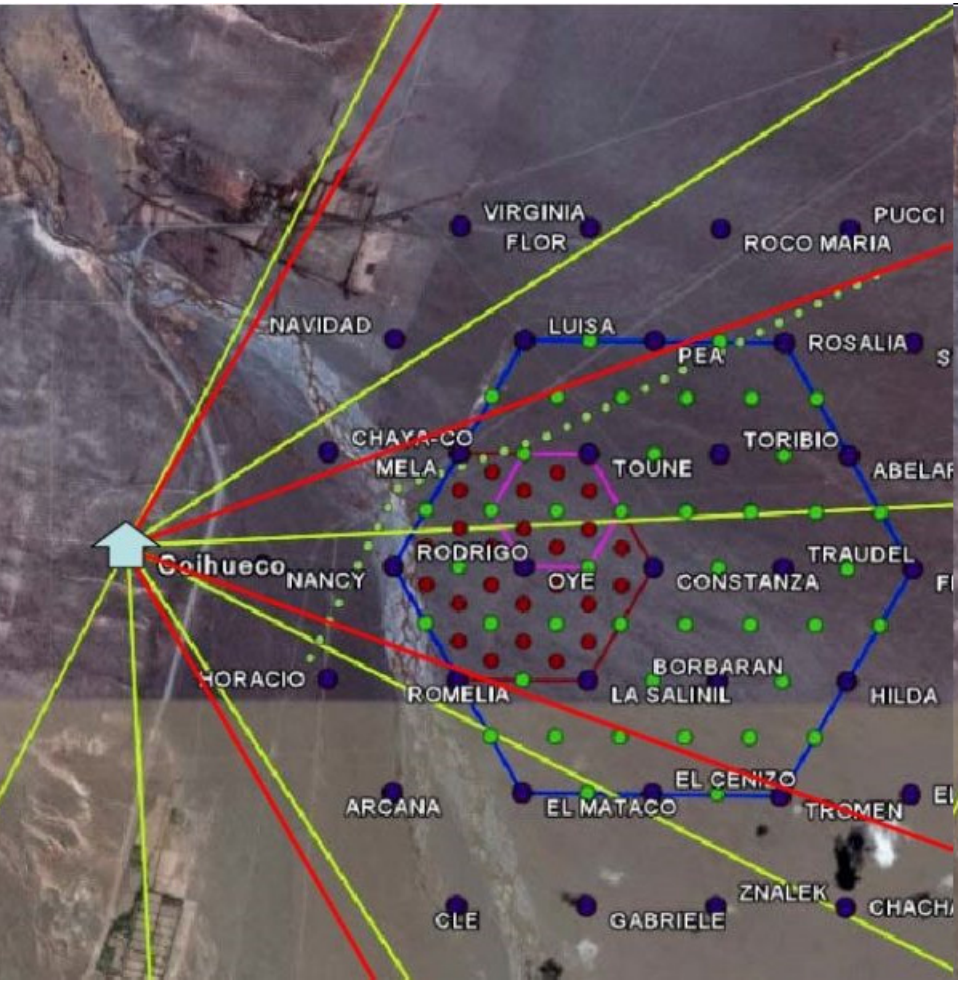
Aachen activities – example 1 – radio detection

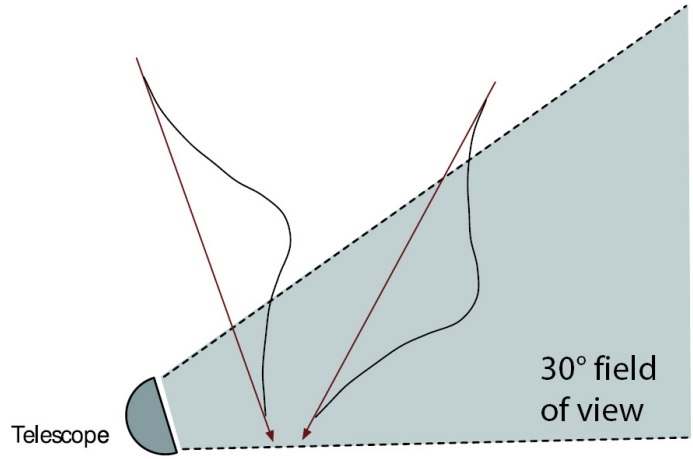




HEAT = High Elevation Auger Telescopes

extend energy range down to 10^{17} eV (from 10^{18} eV)





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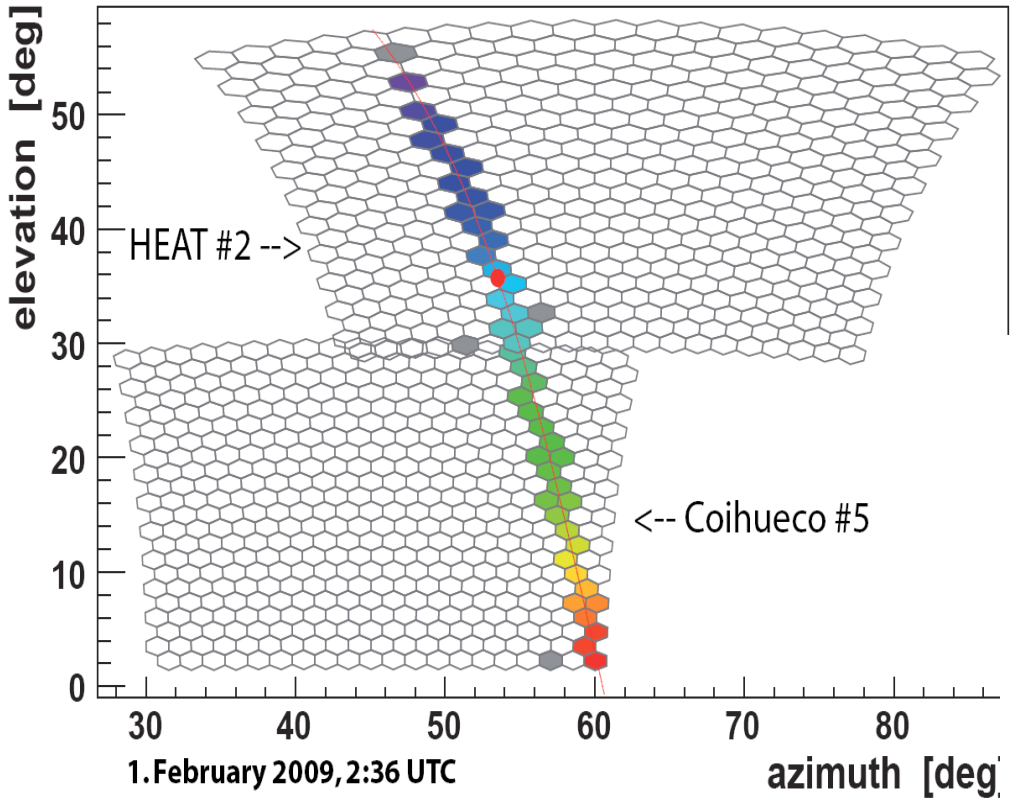
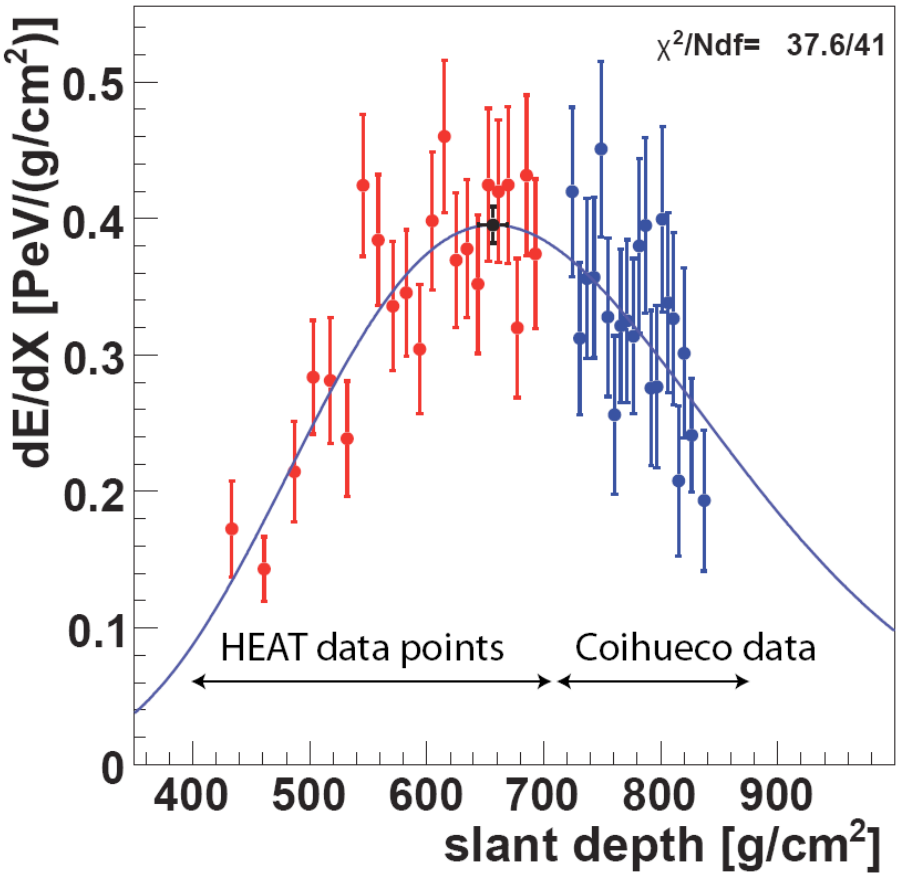
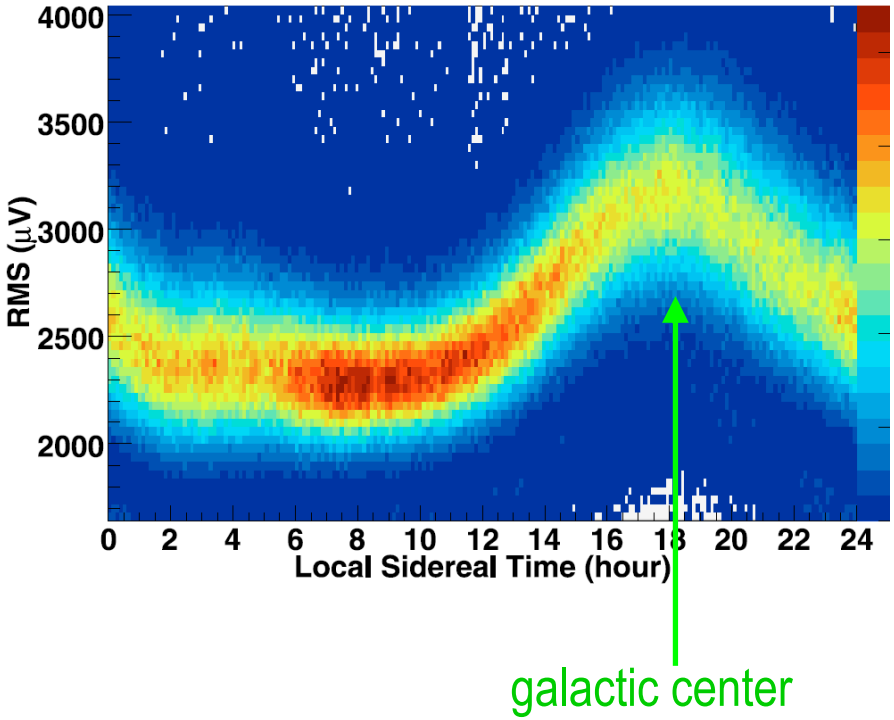
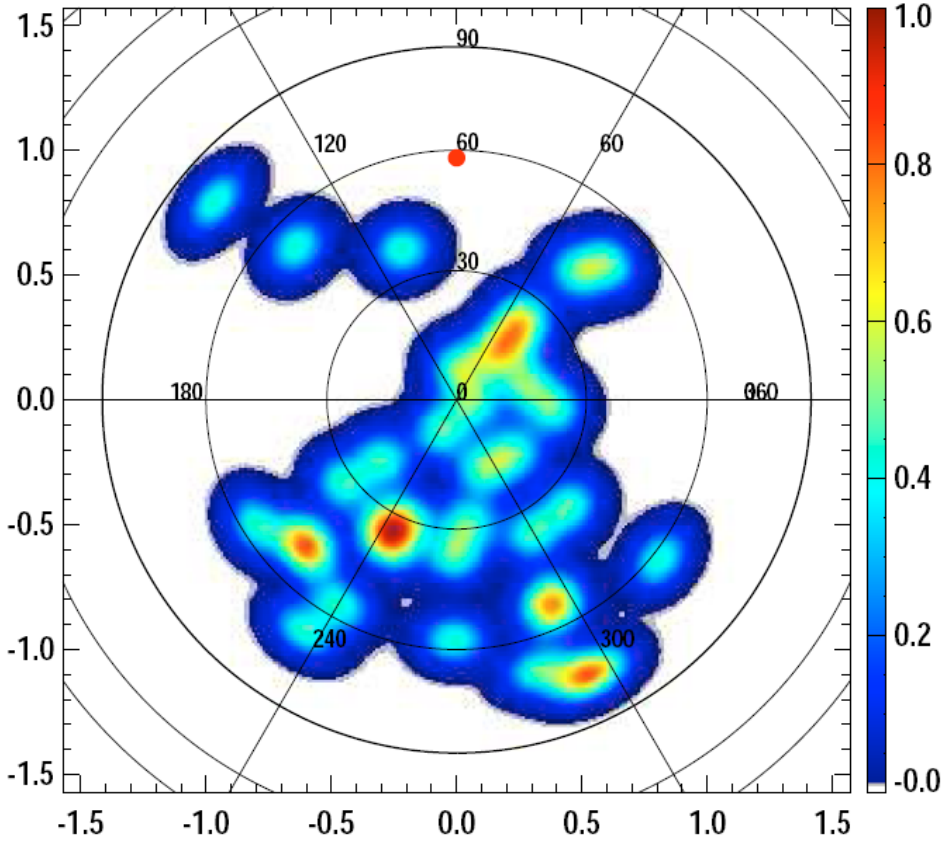




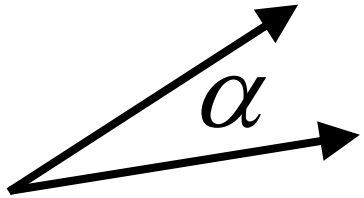
Auger – Radio detection of cosmic rays



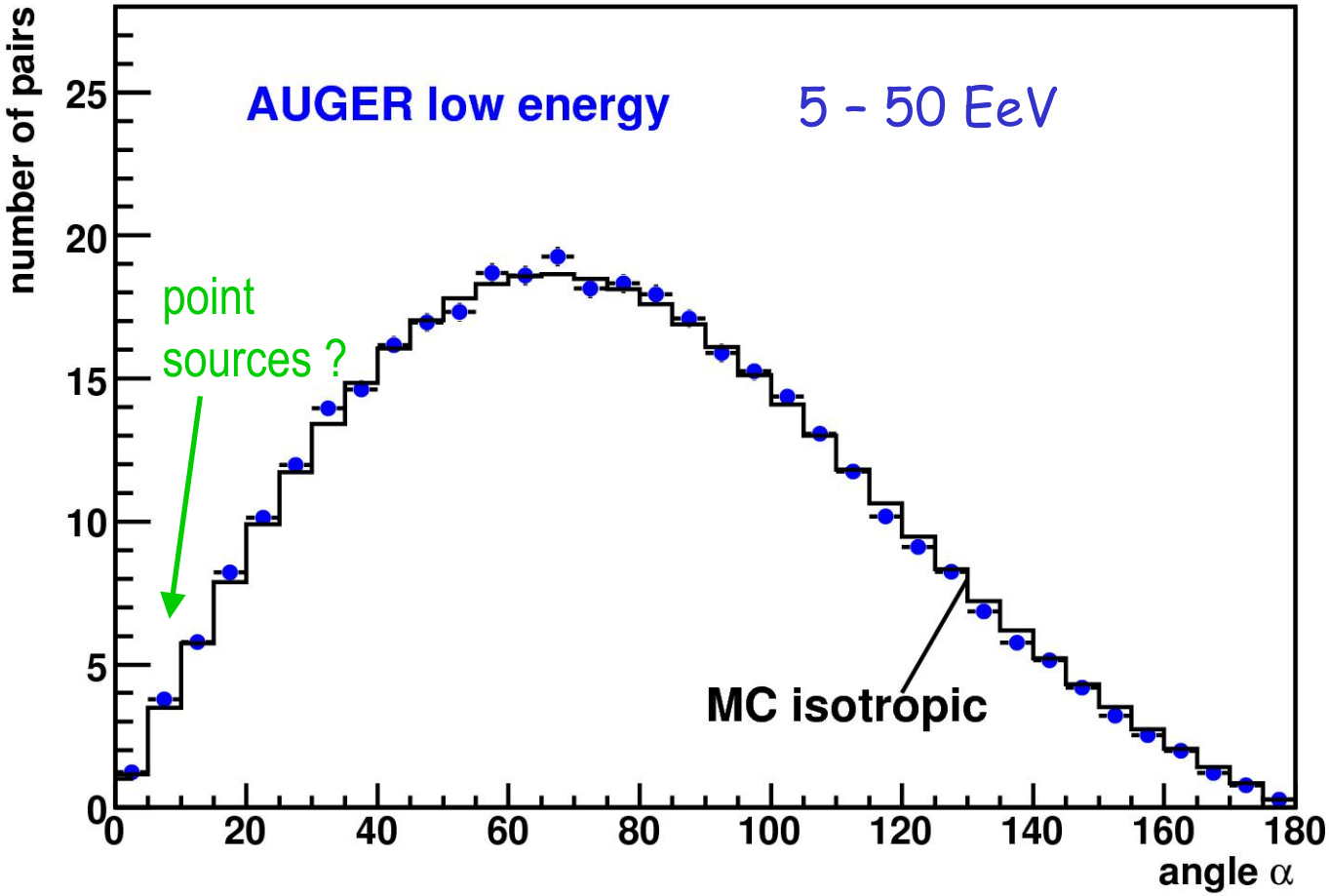


Aachen activities – example 2 – arrival directions

autocorrelation study



plot space angle α between all pairs of shower directions

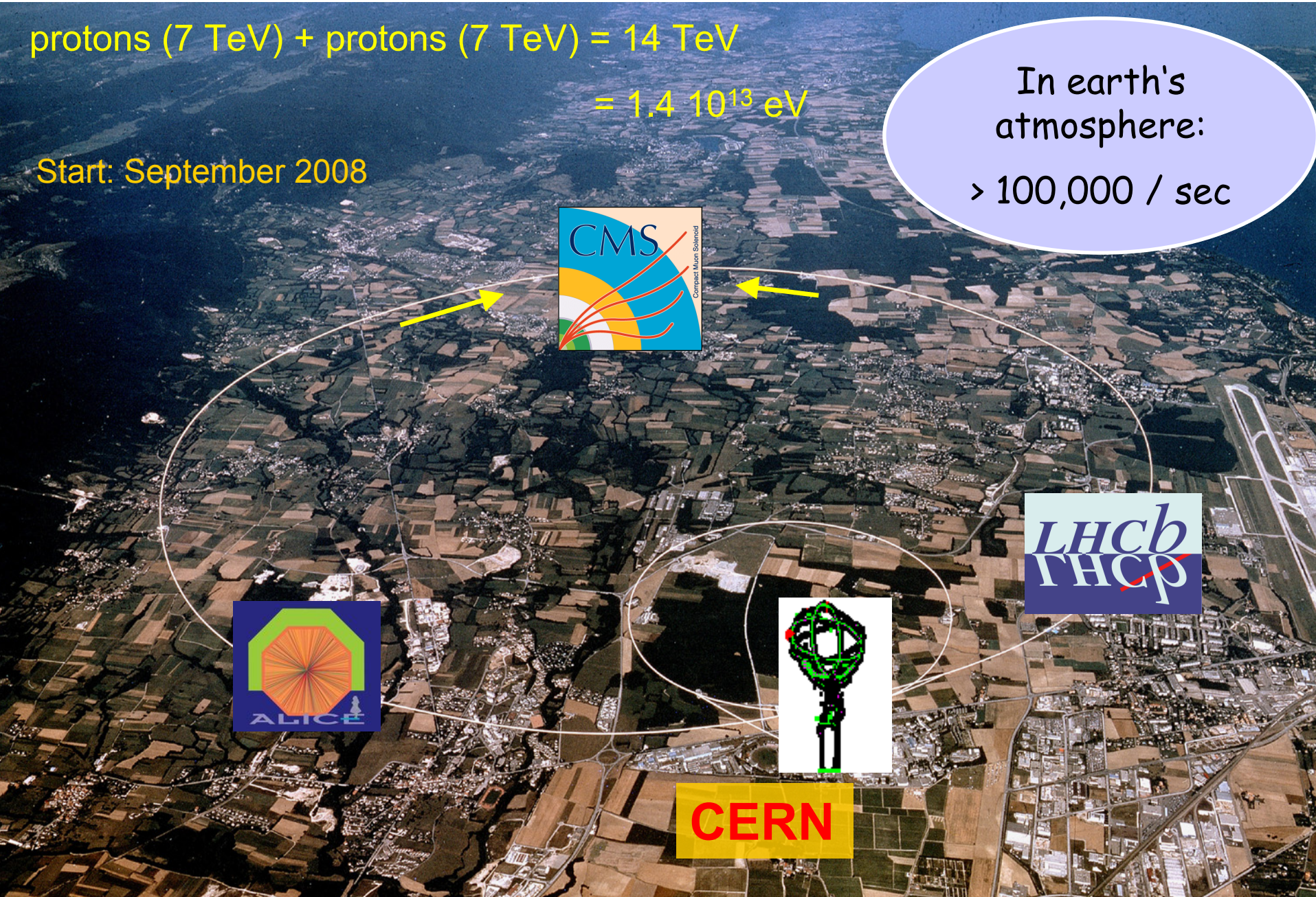


Auger Observatory Aerial View

T.Hebbeker

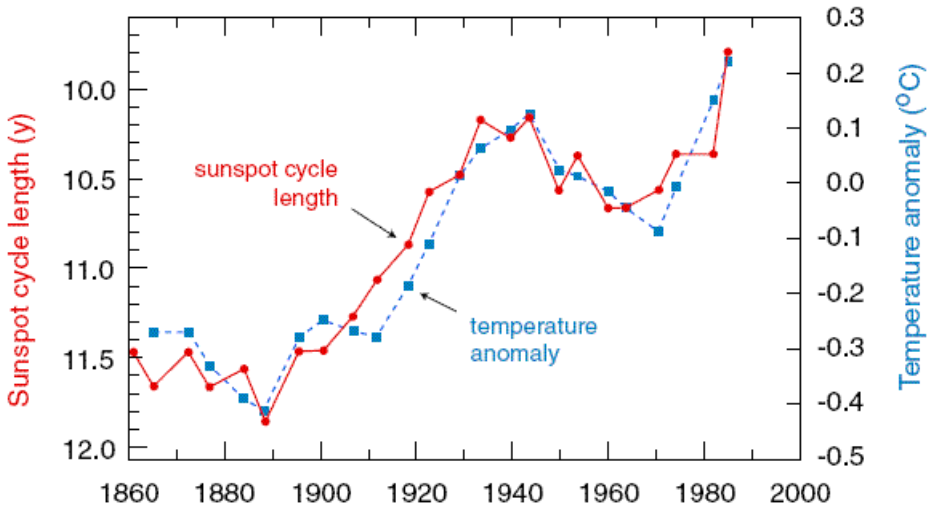
T.Hebbeker

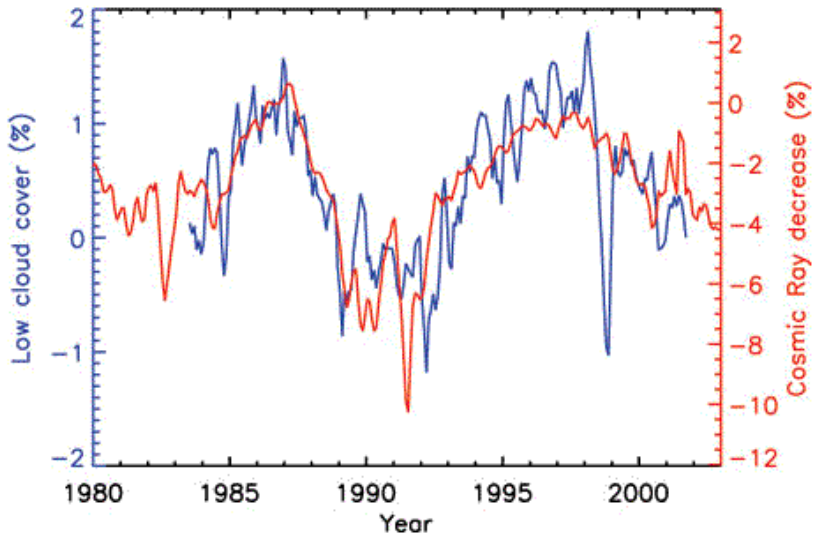
LHC = Large Hadron Collider



Atmosphere Studies and CLOUD Experiment

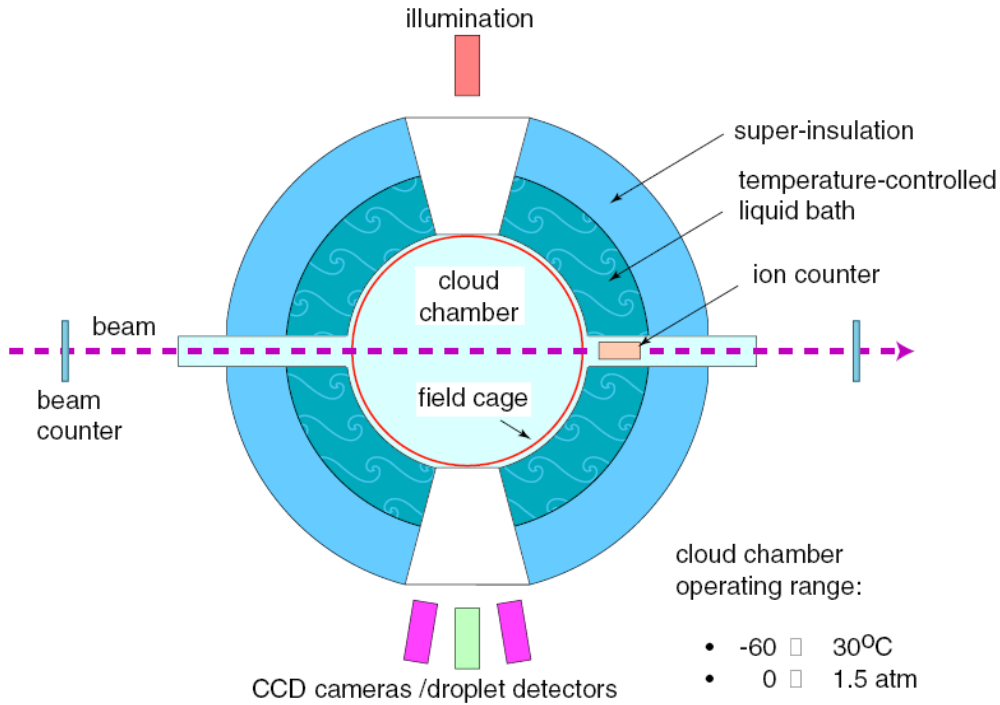
T.Hebbeker



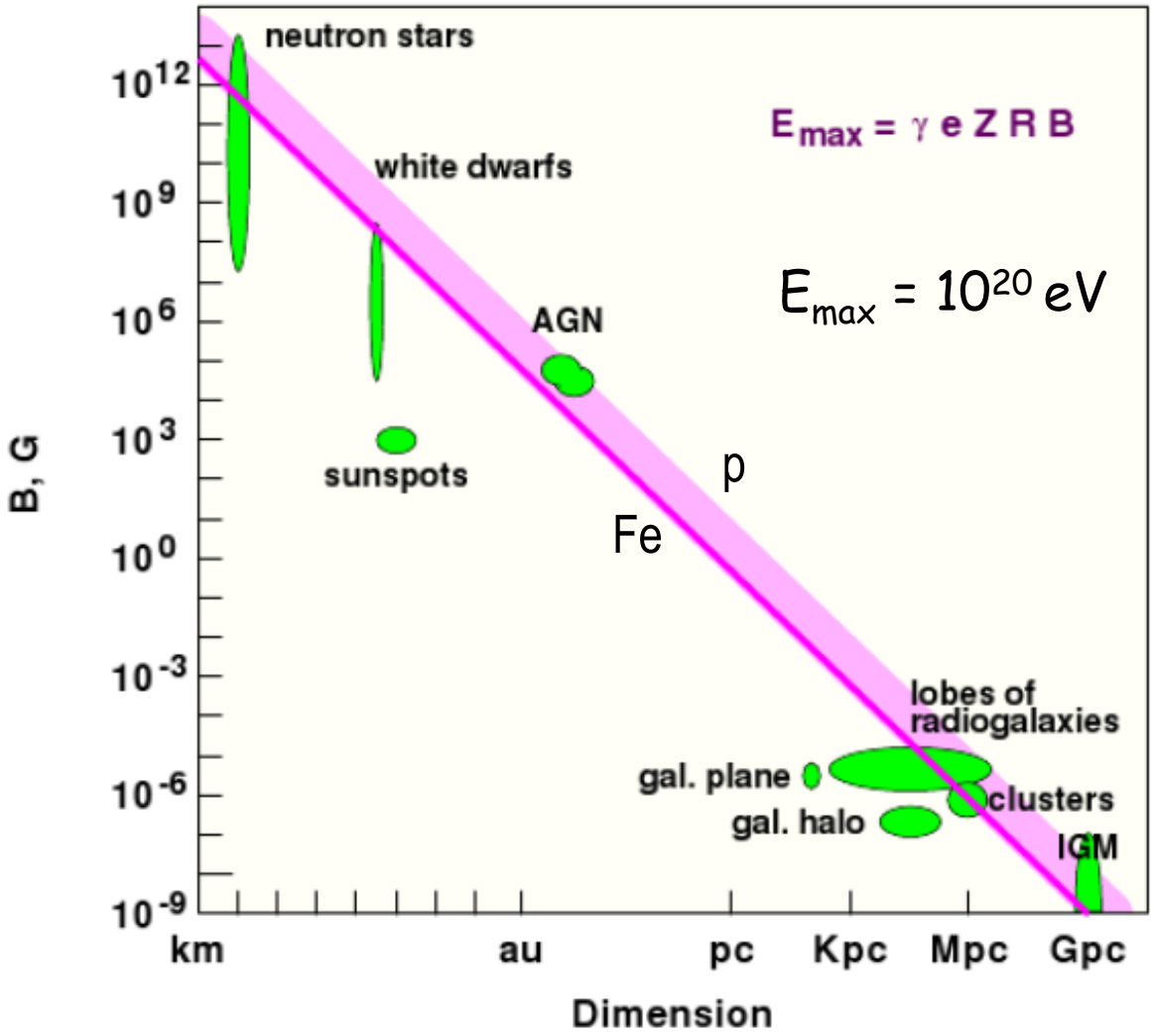


CERN: experiment CLOUD

= Cosmics Leaving OUtdoor Droplets



Hillas Plot


neutron stars
white dwarfs
AGN
sunspots
$E_{max} = \gamma\, e\, Z\, R\, B$
$E_{max} = 10^{20}$ eV
p
Fe
lobes of radiogalaxies
gal. plane
clusters
gal. halo
IGM
B, G
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
km
au
pc
Kpc
Mpc
Gpc
Dimension