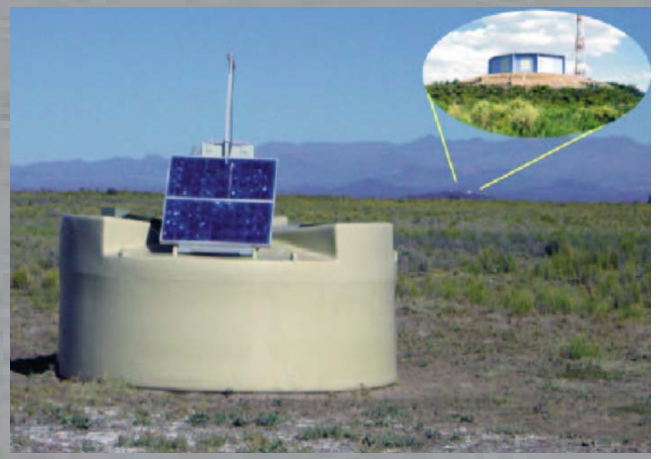
High-Energy Cosmic Ray Physics



The astrophysical projects KASCADE-Grande and Pierre Auger Observatory

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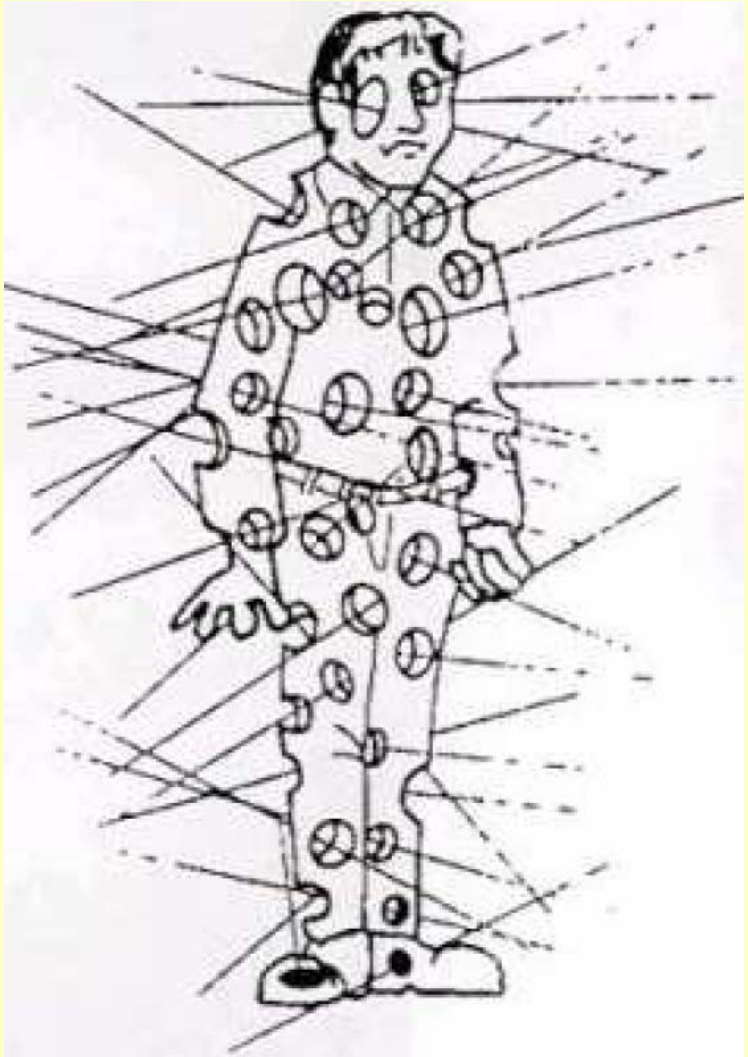
Forschungszentrum Karlsruhe
Institut für Kernphysik

What are Cosmic Rays ?

= high energy, extraterrestric particles

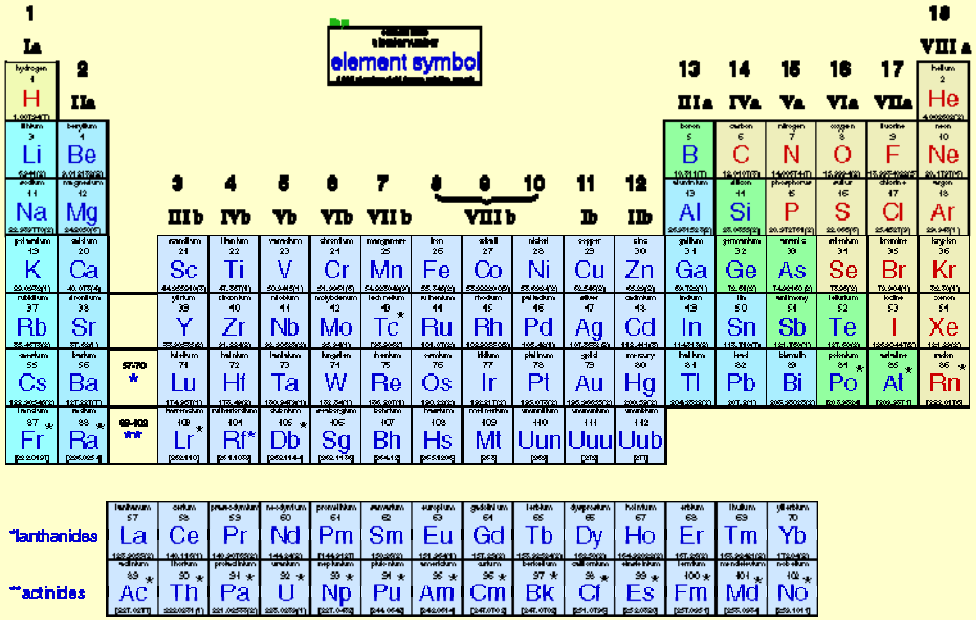
Warning:

c. 150.000 particles will pass your body during this lecture !!



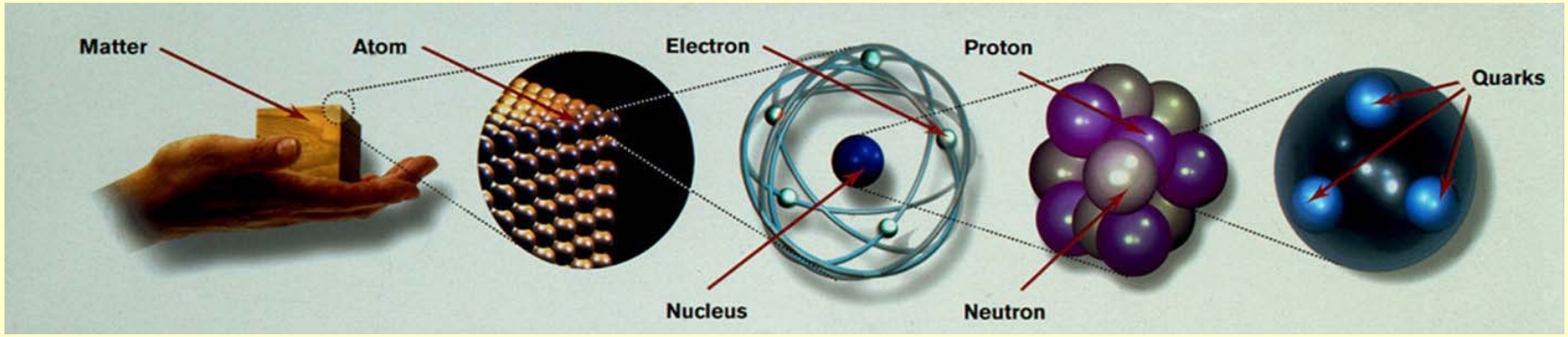
What are Cosmic Rays ?

= high energy, extraterrestric particles



primary cosmic rays:
fully ionised atoms 98%
(mainly Hydrogen and Helium nuclei)
<1% Electrons
<1% Photons

secondary cosmic rays:
high energy particles generated in the atmosphere by primary cosmic rays



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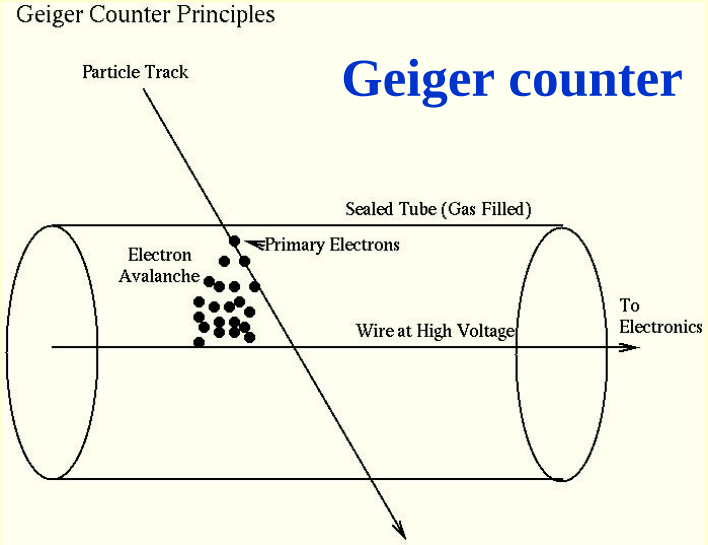
History

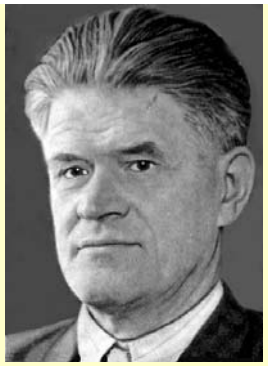
Victor Hess 1912:
The rays are coming from the cosmos !!

Electrometer



Water – Cherenkov Detector

Pavel Alekseyevich Cherenkov (1904-1990)



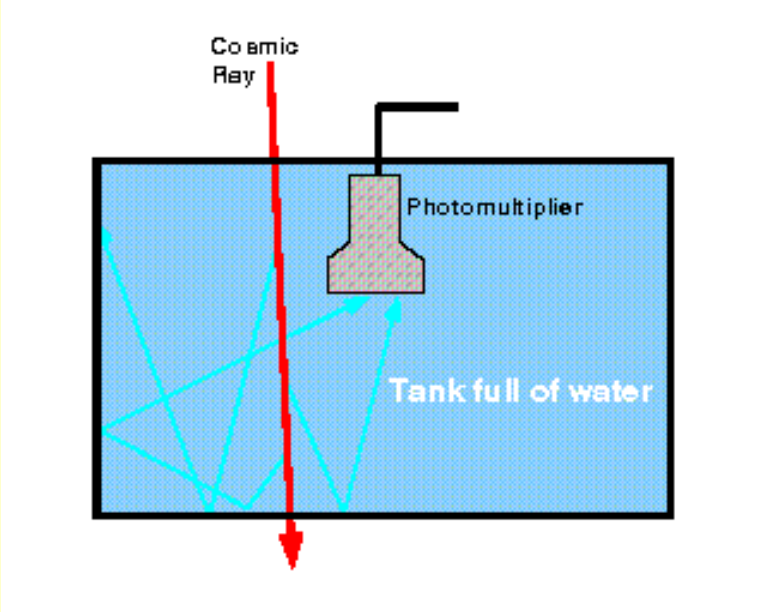
Cherenkov-Counter:

•After Russian Physicist Pavel Cherenkov named detector for measuring charged particles.

•If a charged particle in a specific medium (e.g. water) moves faster than the light in this medium a wavefront of light is emitted.

threshold: $\beta = v/c \geq 1/n$

water: $v_{Teilchen} > 0.75c$! ➔ Muons $E_{kin} > 60MeV$, Electrons $E_{kin} > 0.3MeV$



•The registration of this Cherenkov-emission is the principle of Cherenkov detectors.

Angle of Emission:

$\cos\theta = 1/n\beta\ [\ h/2p\lambda\ (1-1/n^2)]$

Photons per tracklength:

$dN/dx = 2\pi\alpha Z^2 \int_{\lambda 1}^{\lambda 2} (1-1/n^2\beta^2)\ d\lambda/\lambda^2$

A water–Cherenkov detector for school experiments

Master thesis Michael Hammer

DETECTORS

(**D**emonstration **E**xperiment with **T**h**E**rmal **C**ans **T**o measure c**O**smic **R**ay air **S**howers)

http://www-ik.fzk.de/~hammer/detectors.html

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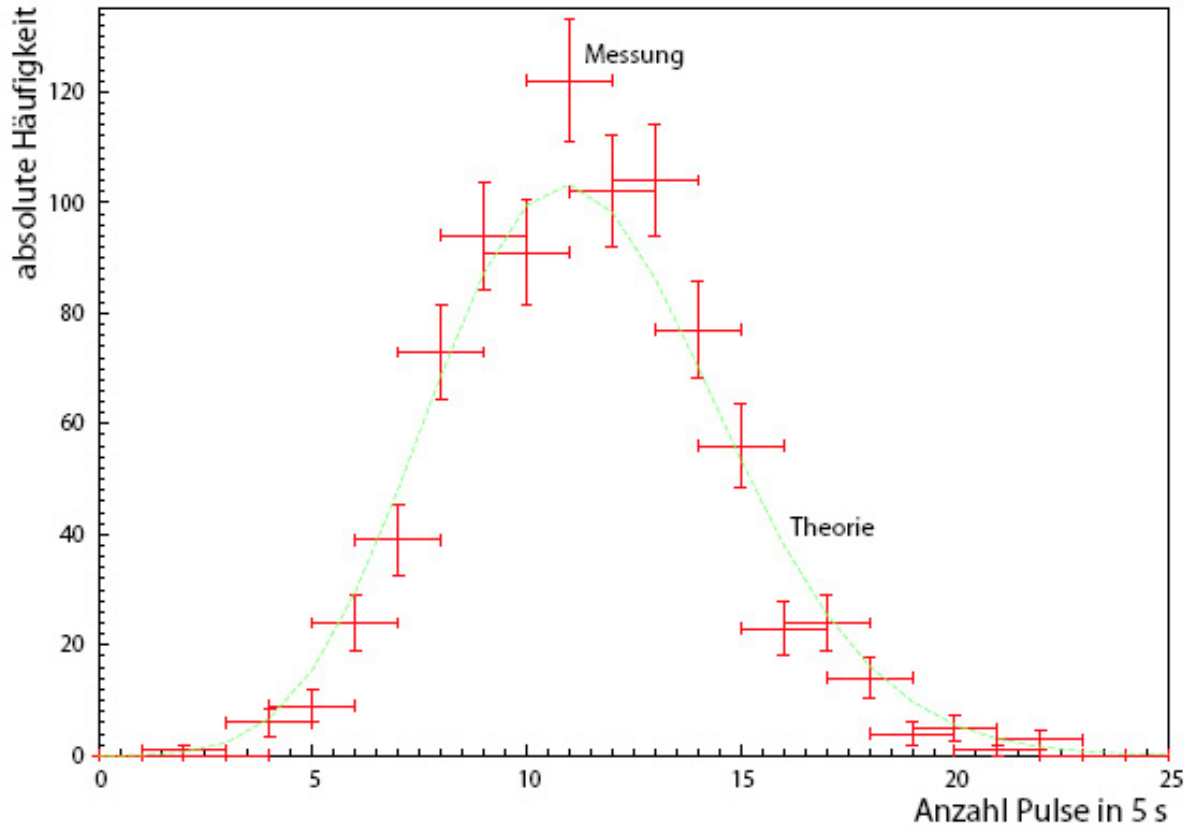

Abbildung 5.5: Messung der Pulsrate, Poissonverteilung

Example: pulse rate measurement: poisson distribution

http://www-ik.fzk.de/~hammer/detectors.html

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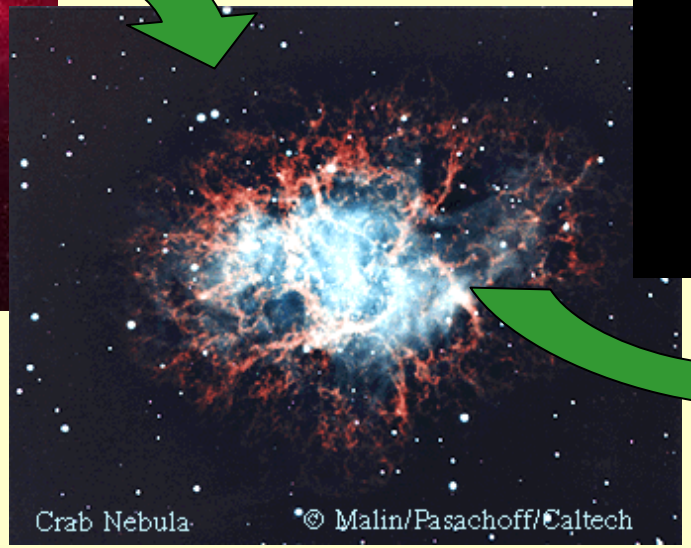
Cosmic Rays

Source → **Acceleration** → **Transport**

Injection



Spallation

-Supernovae
(galactic)
-AGN
(extragalactic)

shock acceleration
(Fermi)

nuclear interactions
in interstellar /
intergalactic medium

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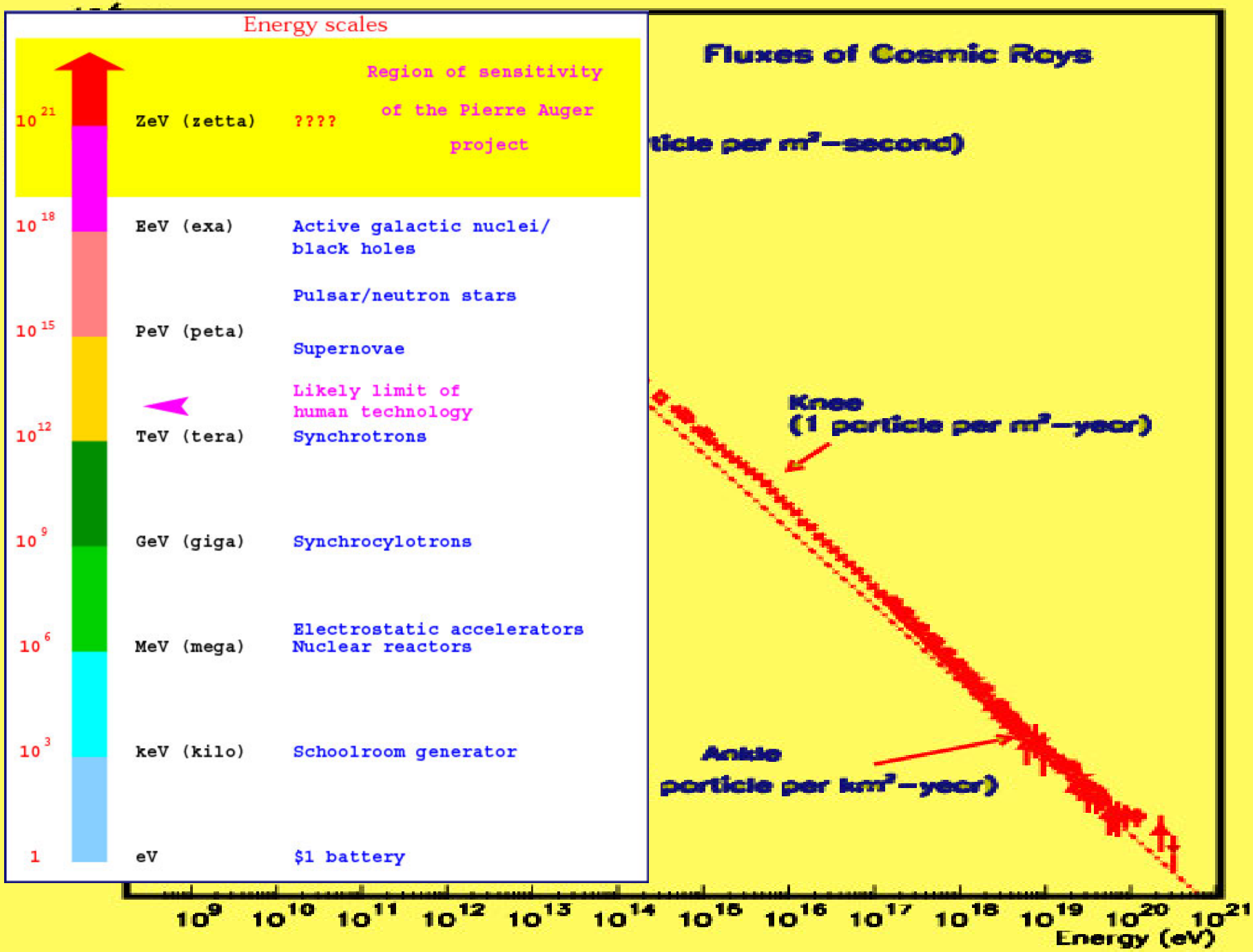
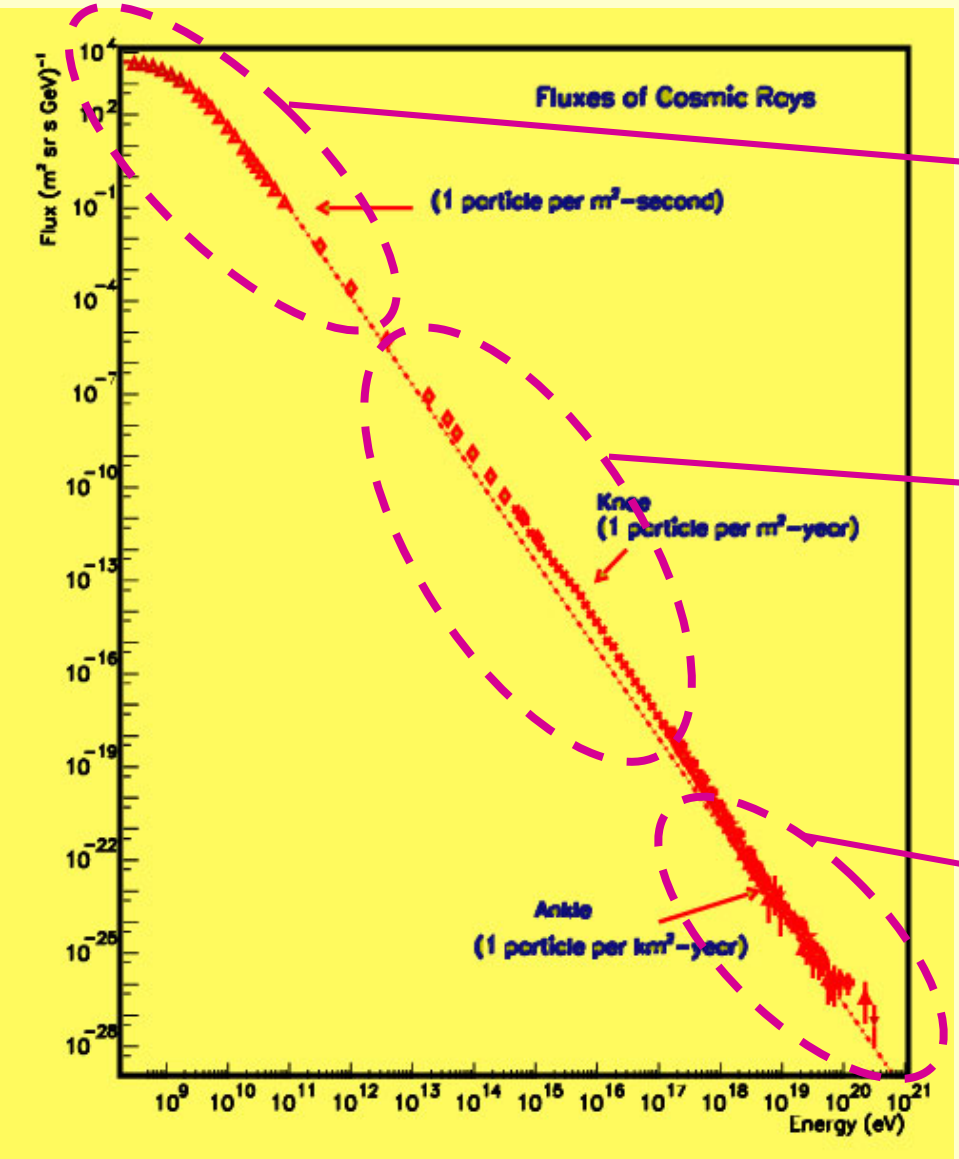

Energy scales
Region of sensitivity of the Pierre Auger project
10^{21} ZeV (zetta) ????
10^{18} EeV (exa) Active galactic nuclei/ black holes
Pulsar/neutron stars
10^{15} PeV (peta) Supernovae
Likely limit of human technology
10^{12} TeV (tera) Synchrotrons
10^{9} GeV (giga) Synchrocylotrons
10^{6} MeV (mega) Electrostatic accelerators Nuclear reactors
10^{3} keV (kilo) Schoolroom generator
1 eV $1 battery
Fluxes of Cosmic Rays
ticle per m²–second)
Knee
(1 particle per m²–year)
Ankle
particle per km²–year)
10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}
Energy (eV)

Cosmic rays – the energy spectrum



low energies

→ **direct measurements**

the knee

→ **air shower measurements**

ultra high energies

→ **they should not exist**

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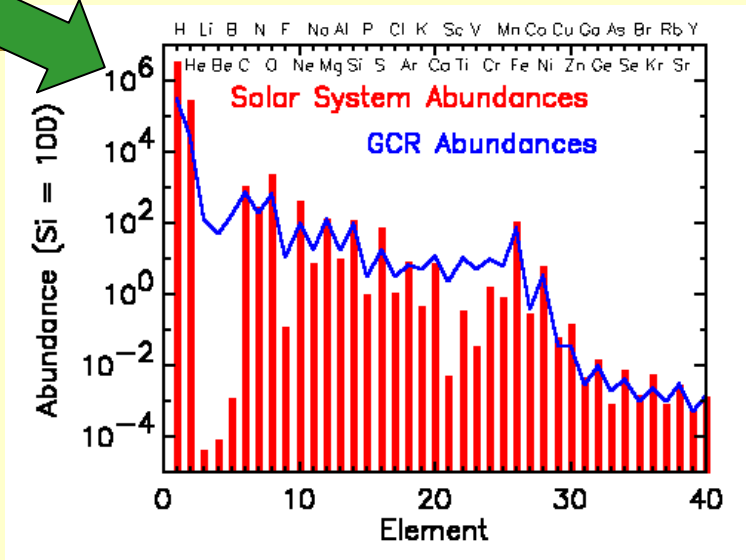
Cosmic rays – direct measurements

Balloons

multi-detector-setups
for simultaneous measurements
of energy, mass, and charge

Satellites

relative abundancies
of the chemical
elements



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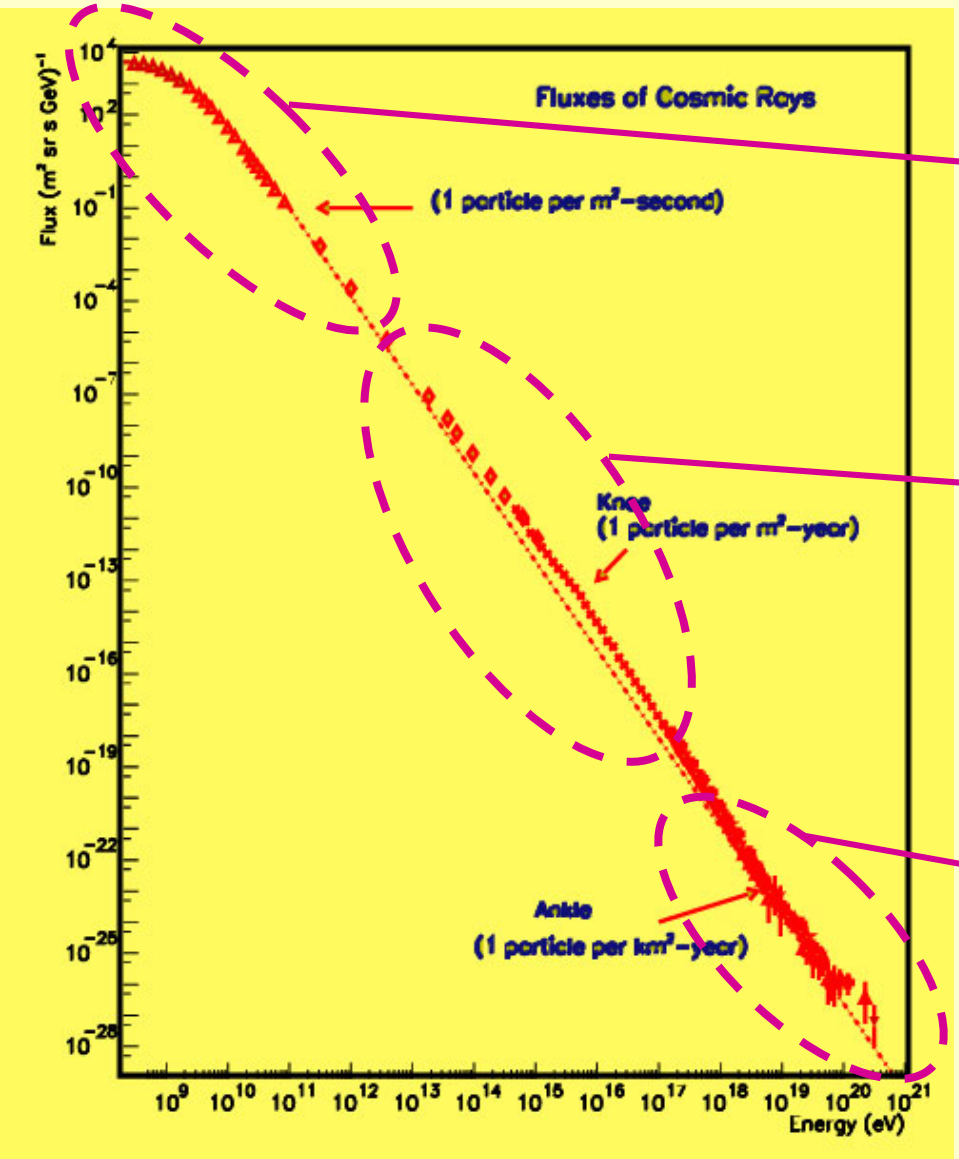
Cosmic rays – the energy spectrum



low energies

→ **direct measurements**

the knee

→ **air shower measurements**

ultra high energies

→ **they should not exist**

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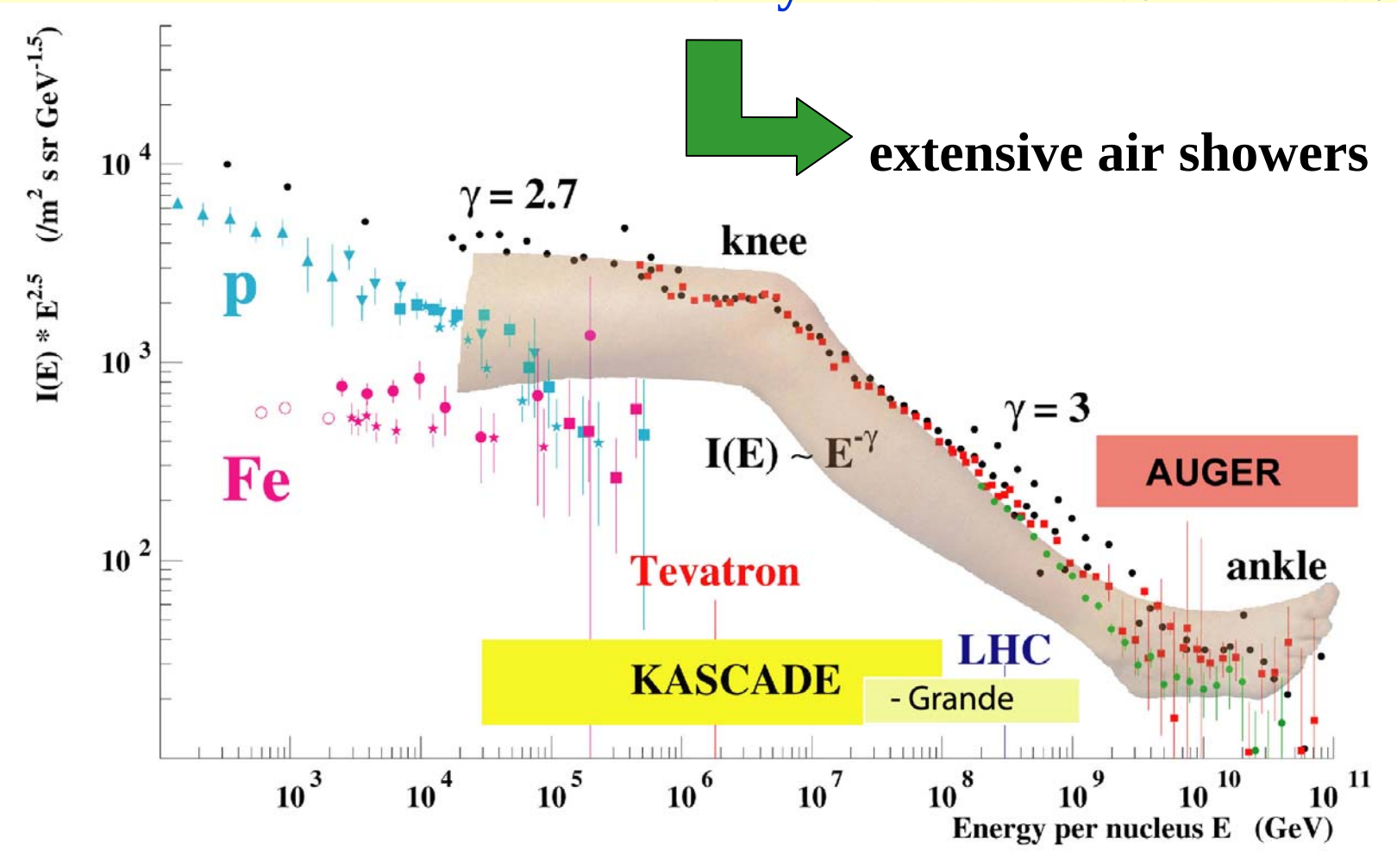
The knee

Source of knee and ankle?

only indirect measurements !



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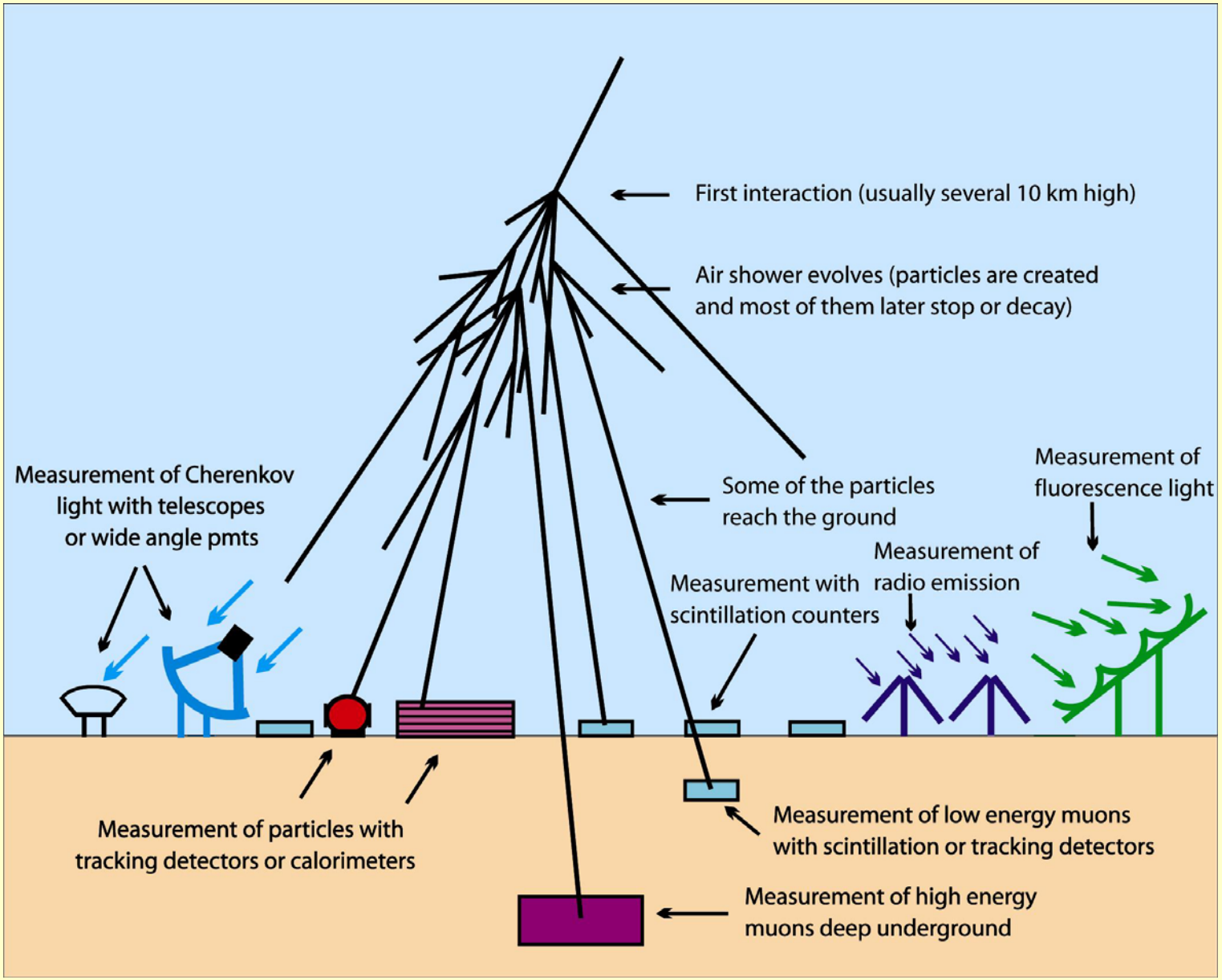
extensive air shower

Differences in the shower developments give hints to the energy and mass of the primary

Extensive Air Showers – Detection Techniques



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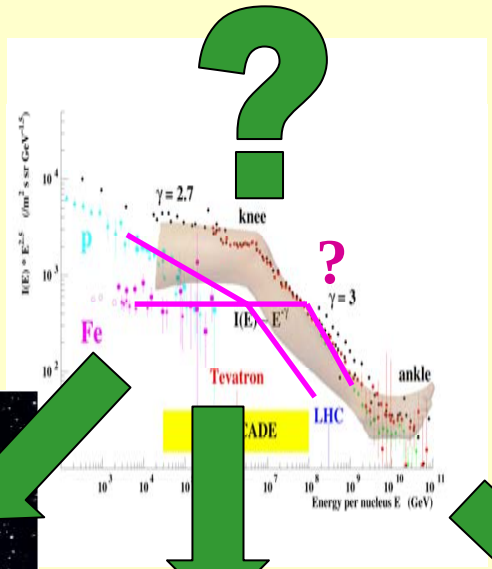
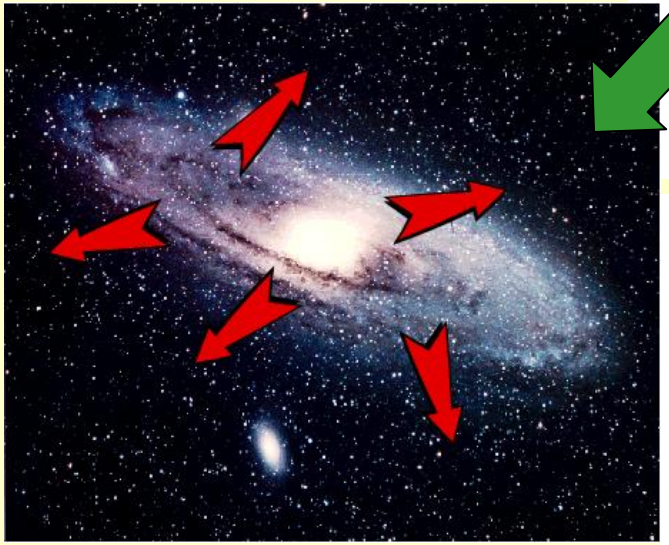
The knee - Theories

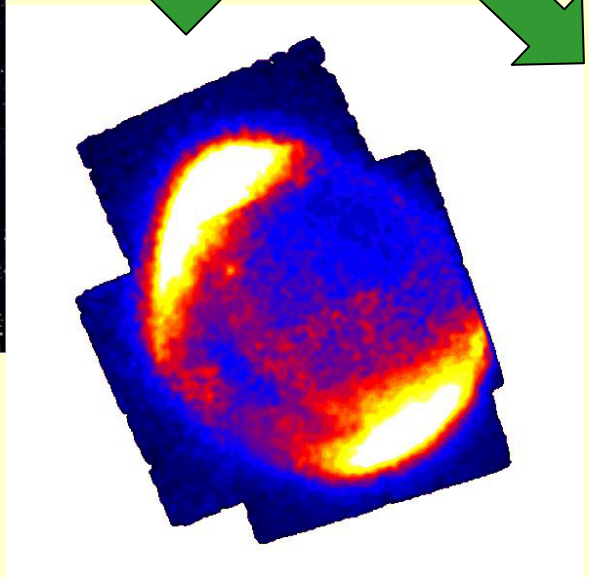


Source of the knee ?

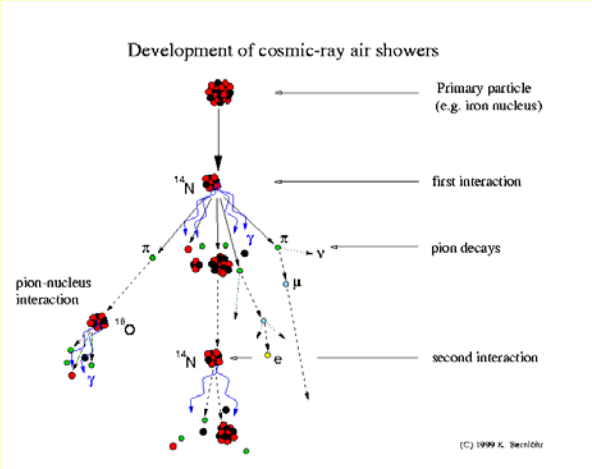
- different theories
- **Measurements of energy and mass!**



Diffusion ➔
Escape from our Galaxy
knee position ∝ Z of element



maximum acceleration
knee position ∝ Z



unknown effect in first interaction
knee position ∝ A

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Measurement of EAS

Registration with large area particle detectors

KASCADE = KArlsruhe Shower Core and Array DEtector

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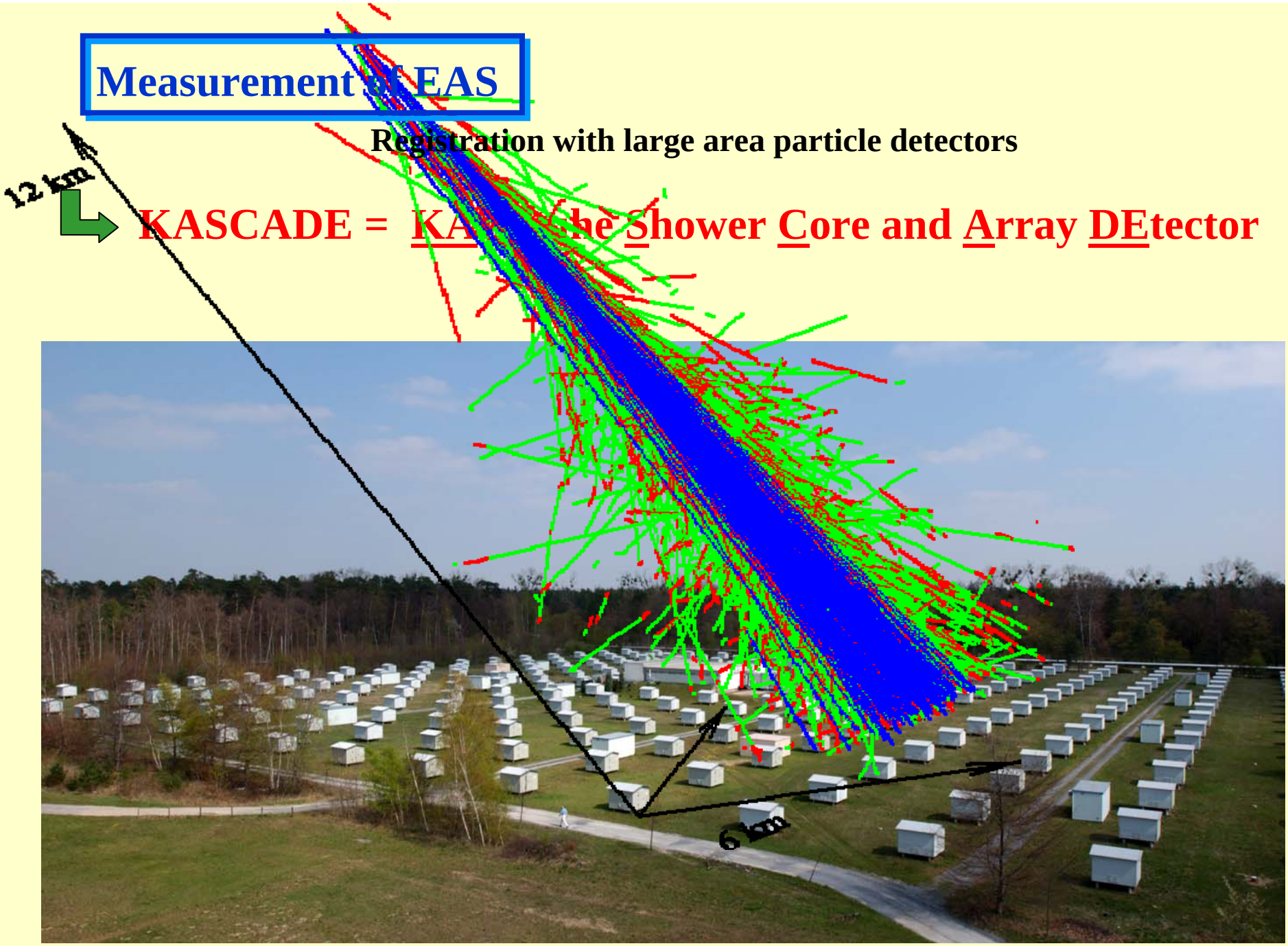
Measurement of EAS

Registration with large area particle detectors

KASCADE = KA(rlsruhe) Shower Core and Array DEtector



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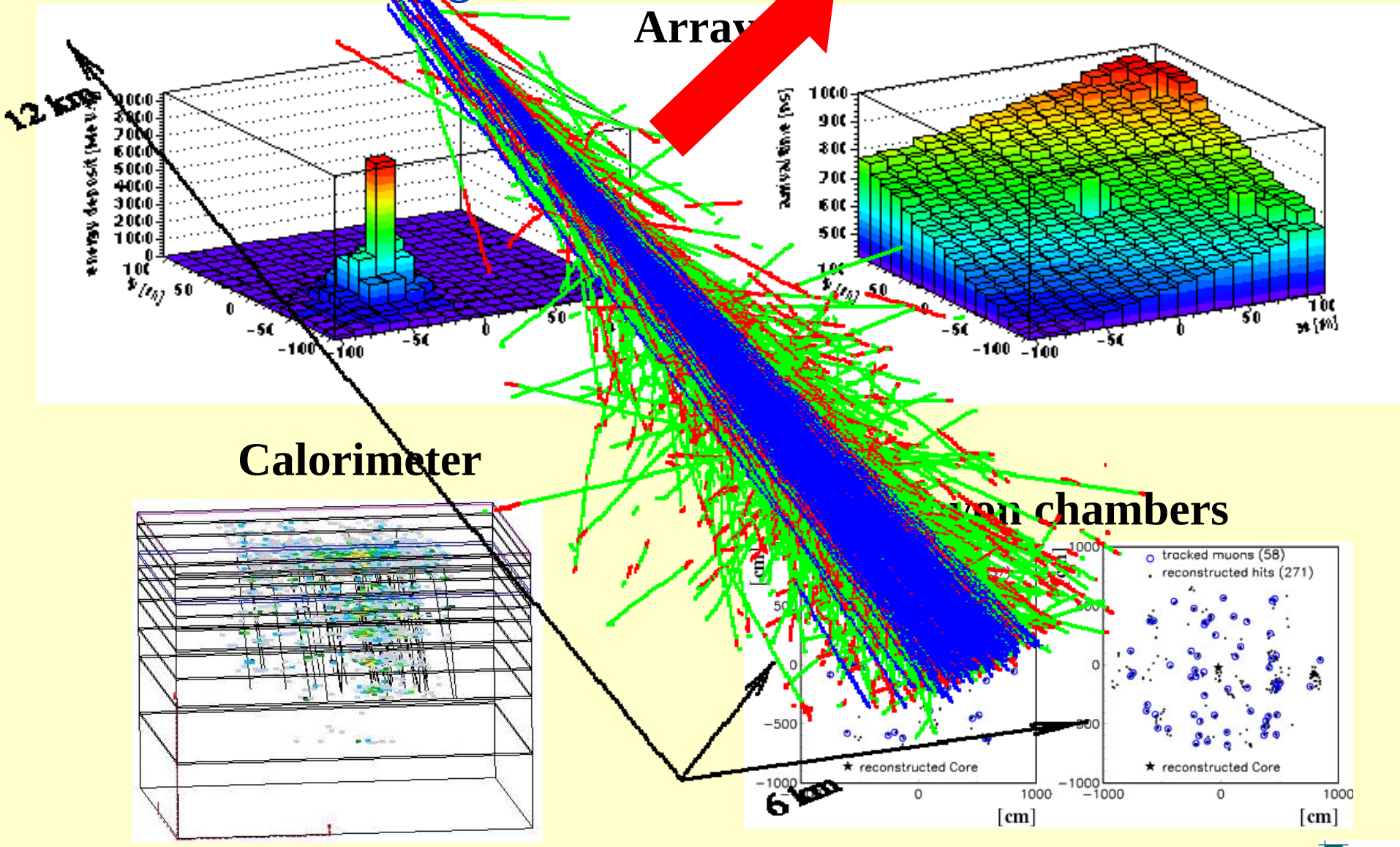
KASCADE

multiparameter measurements of single air showers

Energy
Mass
Direction
of the incoming cosmic particle



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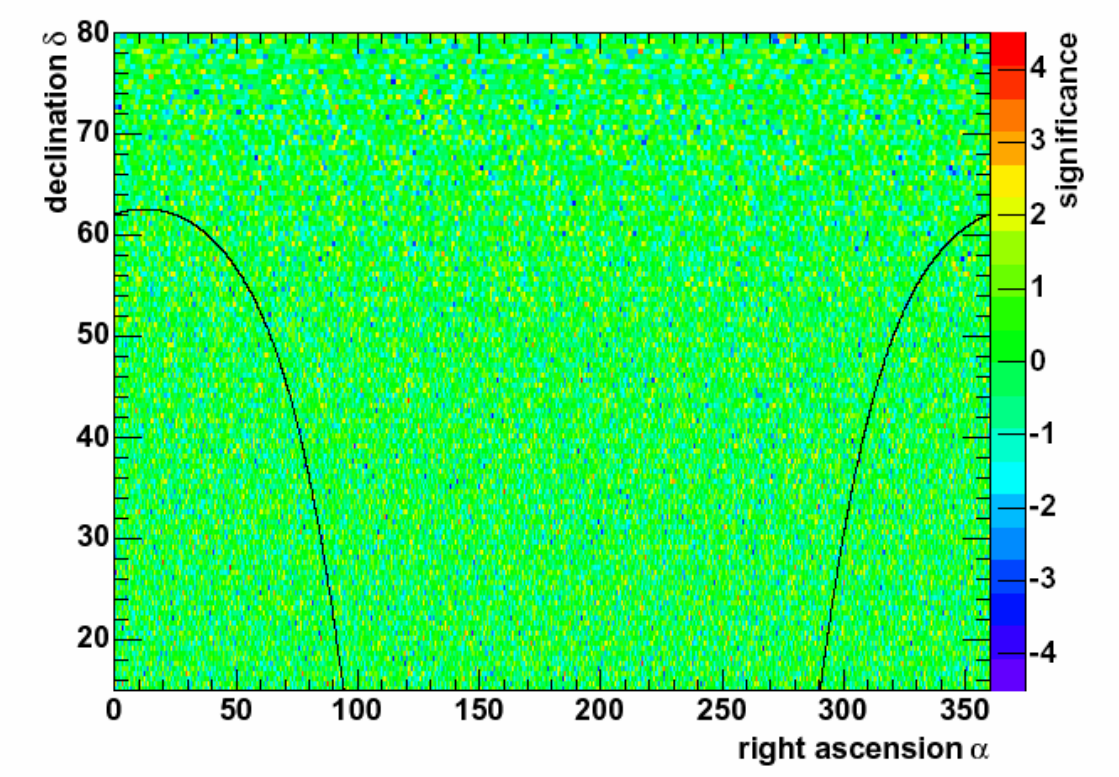
Results KASCADE:

Analysis of arrival directions and arrival times (galactic coordinates):

➔ sky plot of cosmic rays



Results:
- **charge cosmic rays have no point source**
- **no large scale anisotropy**
- **no gamma rays as primaries**

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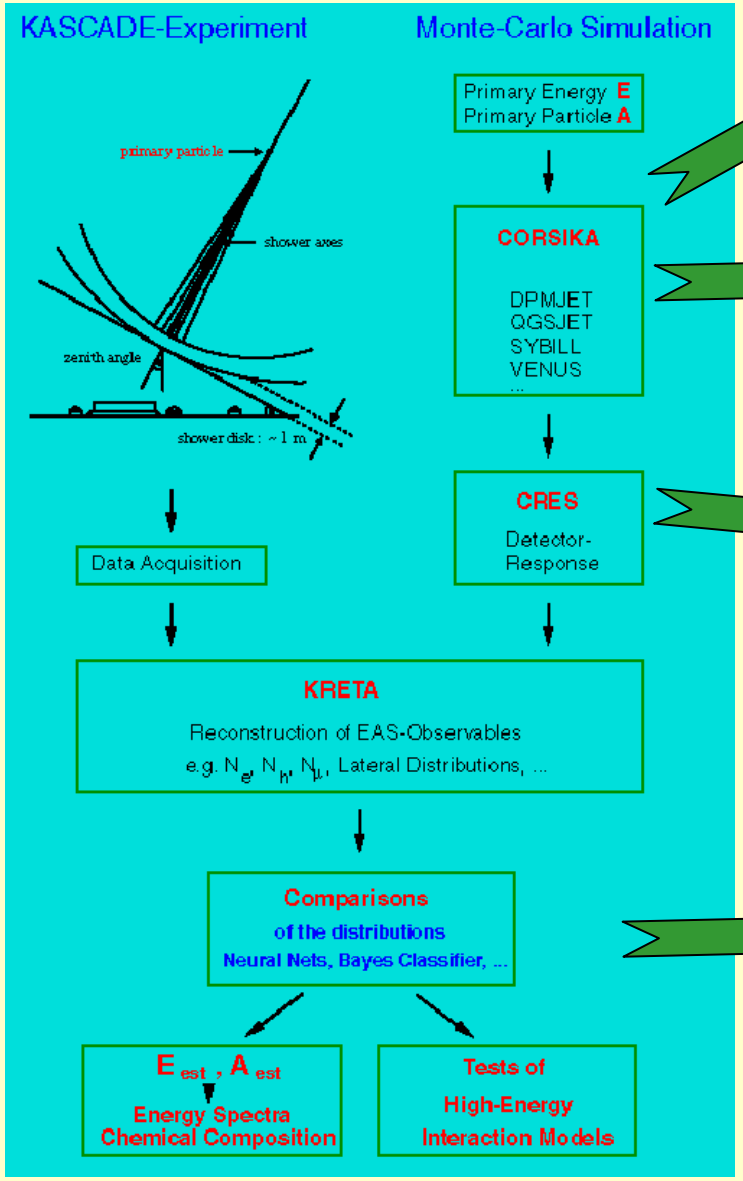
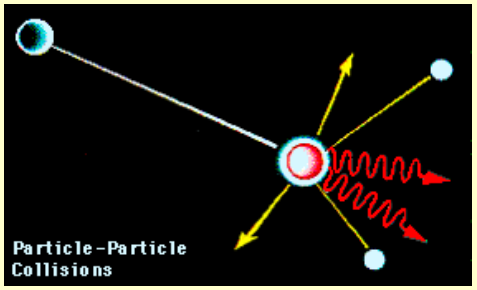
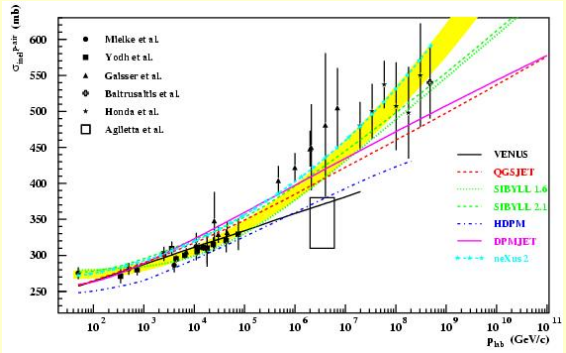
KASCADE - Methodics

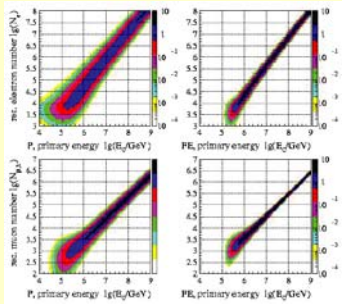




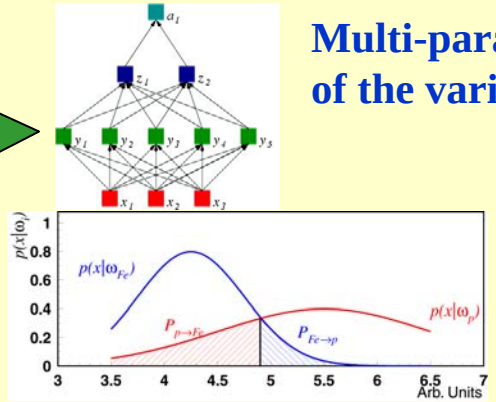
nucleus-nucleus interactions



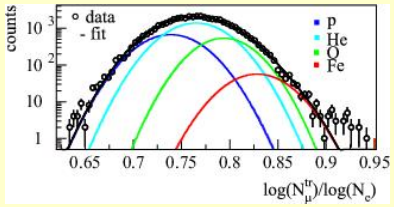
Air shower simulations



Detector simulations



Multi-parameter analyses of the various observables



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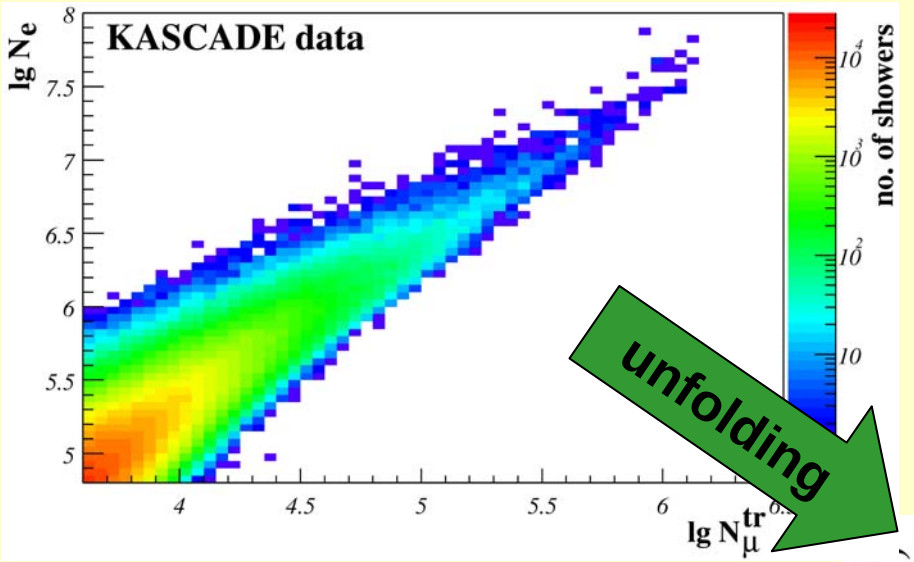
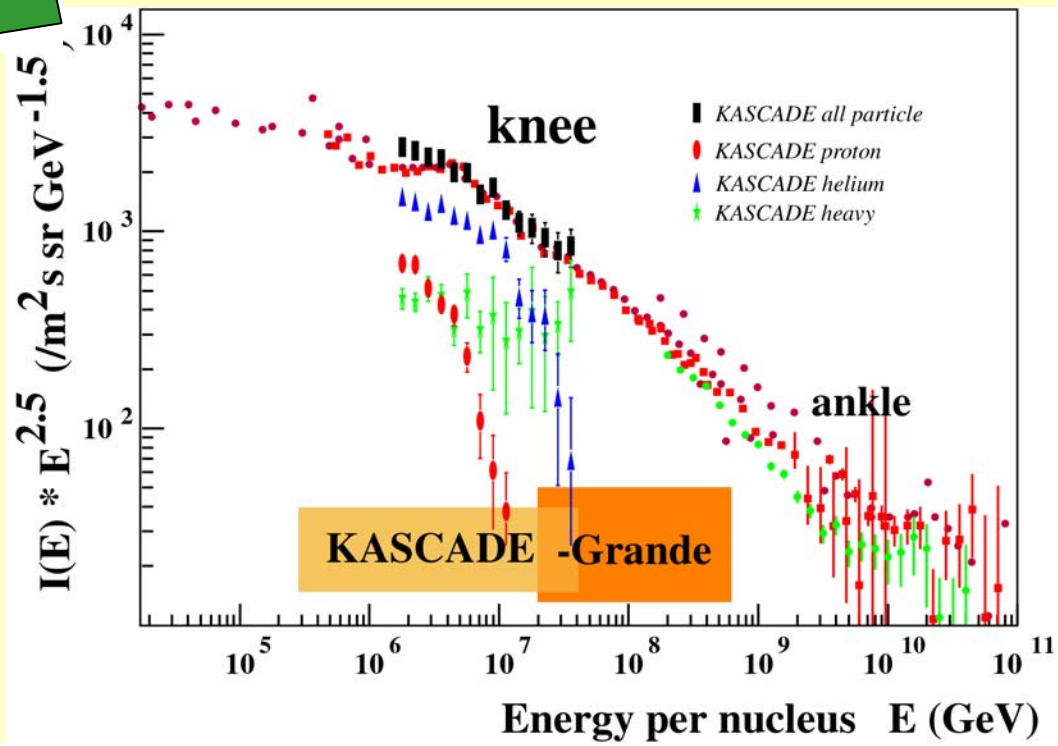
Results KASCADE:

Analysis of 2-dimensional shower size spectrum:

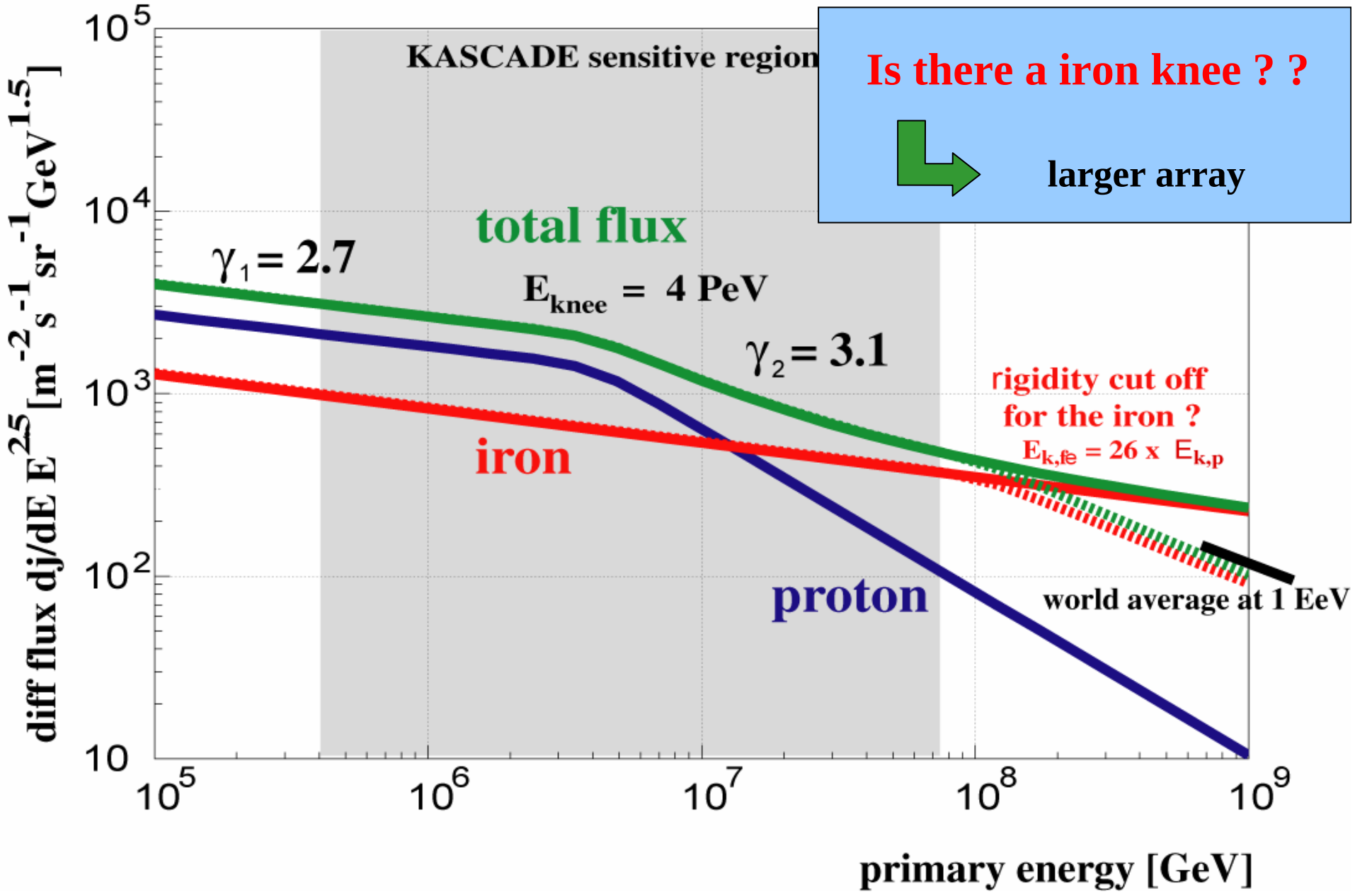


➔energy spectra of single mass groups



Results:
- knee is caused by light elements
- knee positions vary with mass group
- no hadronic interaction model describe data consistently

Results KASCADE:

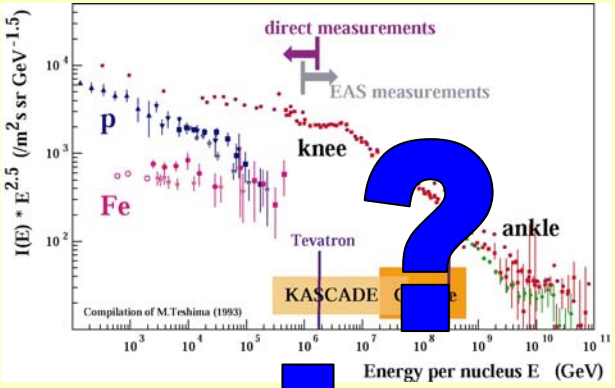


Is there a iron knee ? ?

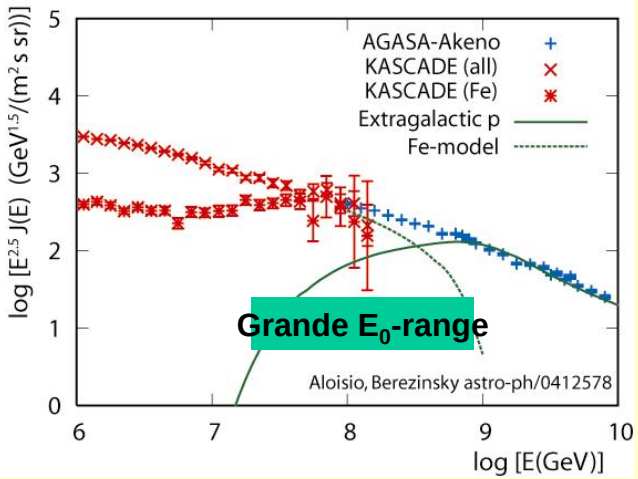
larger array

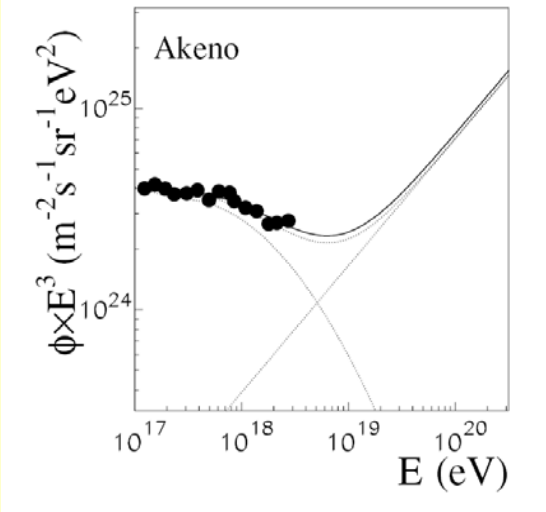
KASCADE – Grande 2003

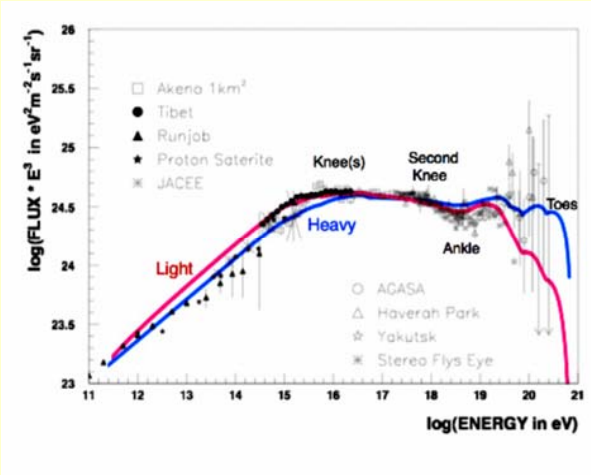
The Grande energy region - Theories



various theories on energy range 10^{17}-10^{19}eV:







Fe-knee ~10^{17} eV
gal-eg transition ~$10^{17.7}$eV
Ankle = eg characteristics

e.g. Berezinsky

Fe-knee ~10^{18} eV
gal-eg transition ~10^{19}eV
= ankle

e.g. Wibig et al

Cannonball modell:
All is galactic
(knee= elastic scattering)

e.g. de Rujula

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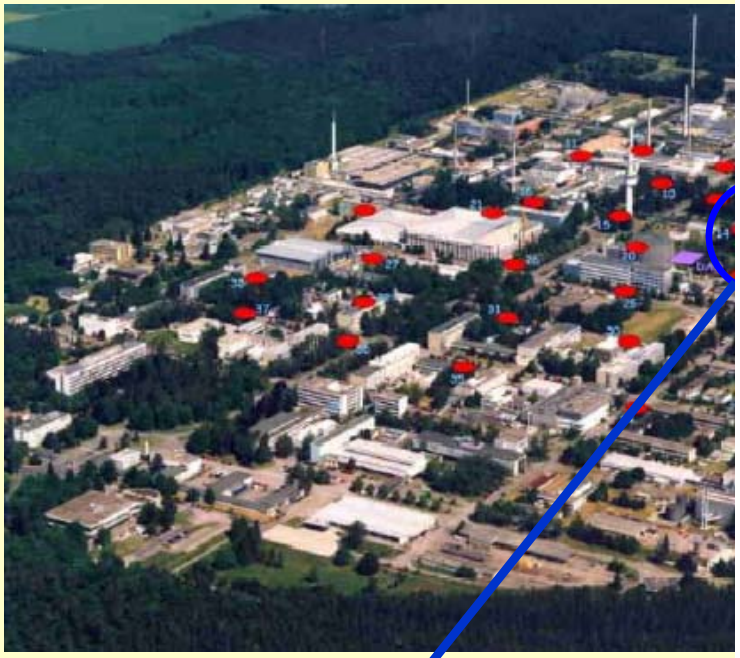
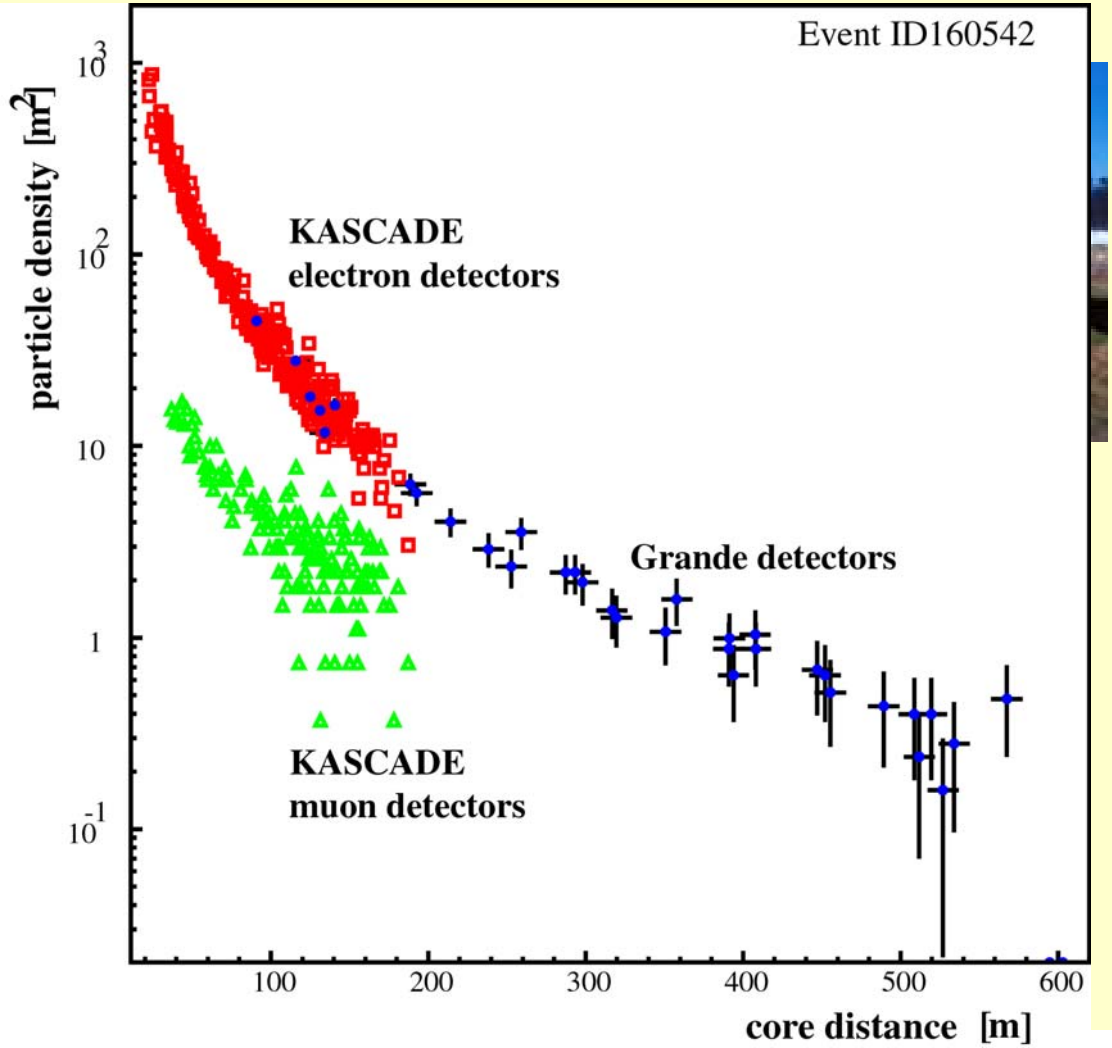
KASCADE - Grande

Measurements of air showers in the energy range E_0 = 100 TeV - 1 EeV





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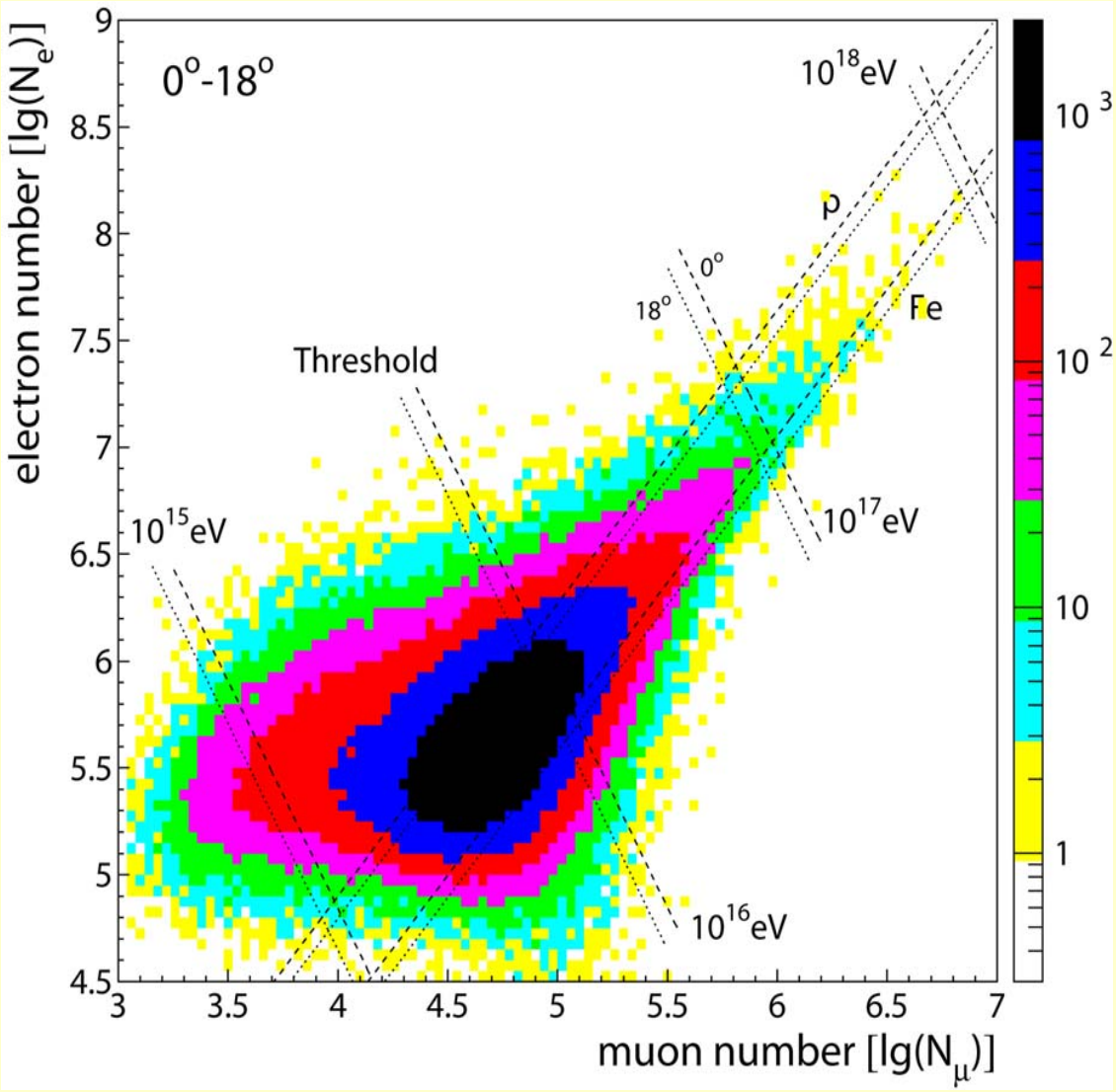
KASCADE – Grande: Status



- continuously data taking
- reconstruction of electron and muon number also at Grande per single shower

➔ **Unfolding also with Grande possible**

- presently: optimization of operation, calibration, reconstruction, etc.

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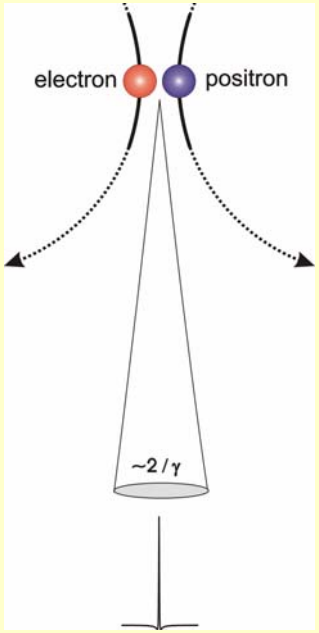
KASCADE-Grande + LOPES

Radio Detection of Air-Showers:

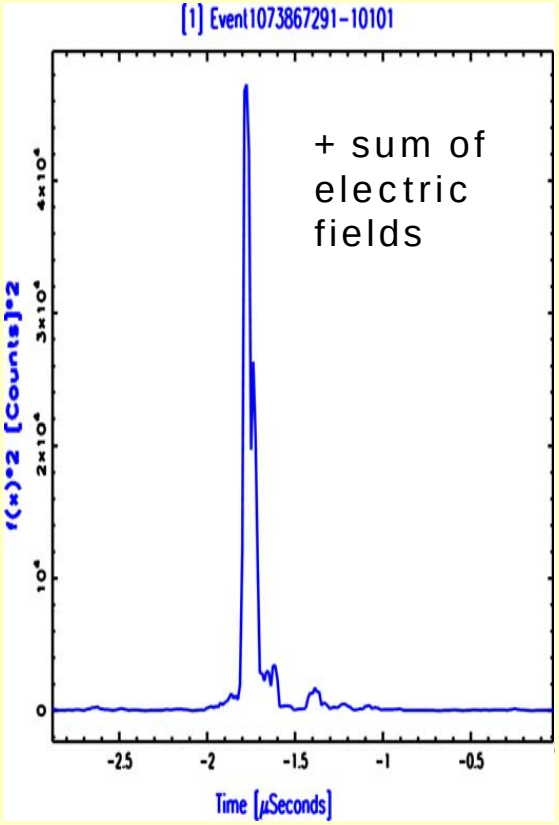


- deflection of electron-positron pairs in the Earth's magnetic field
  ➔ coherent emission at low frequencies

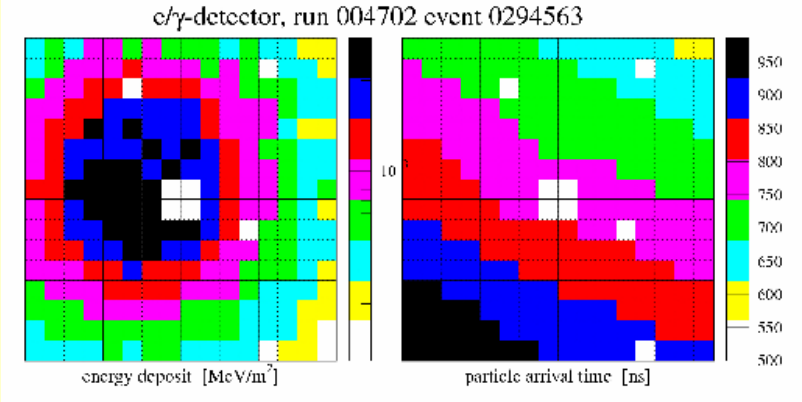
- with radio detection
  ➔ see shower development
  ➔ observe 24 hrs/day

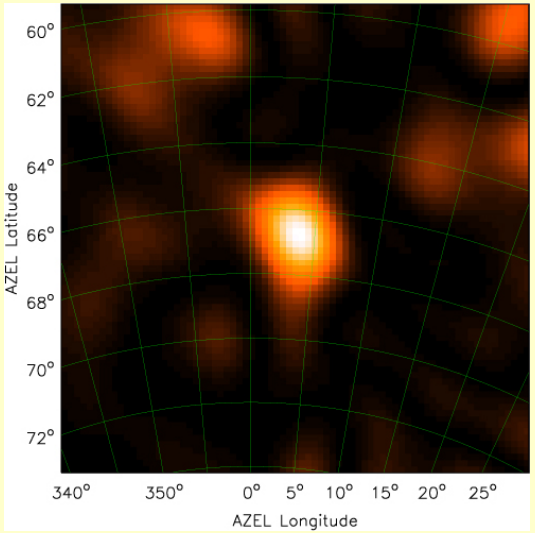
Main goals:
Proof of principle
Establish radio measurements as new detection technique
Calibration of radio emission

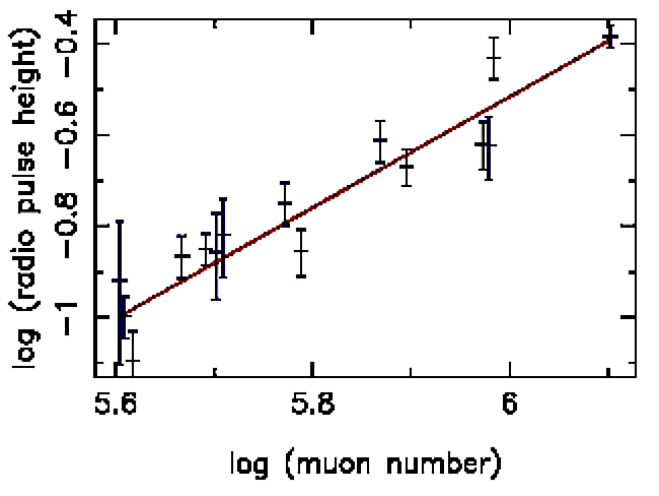
LOPES radio measurements:



- energy ≈ 10^{17} eV
- EAS core inside antennas
- $\Theta = 25.5^o$, $\Phi = 42.5^o$
- signal is coherent







data analyses:

- **EAS analyses KASCADE**
- **radio signal analyses**
- **sky mapping**

LOPES collaboration, Nature 425 (2005) 313

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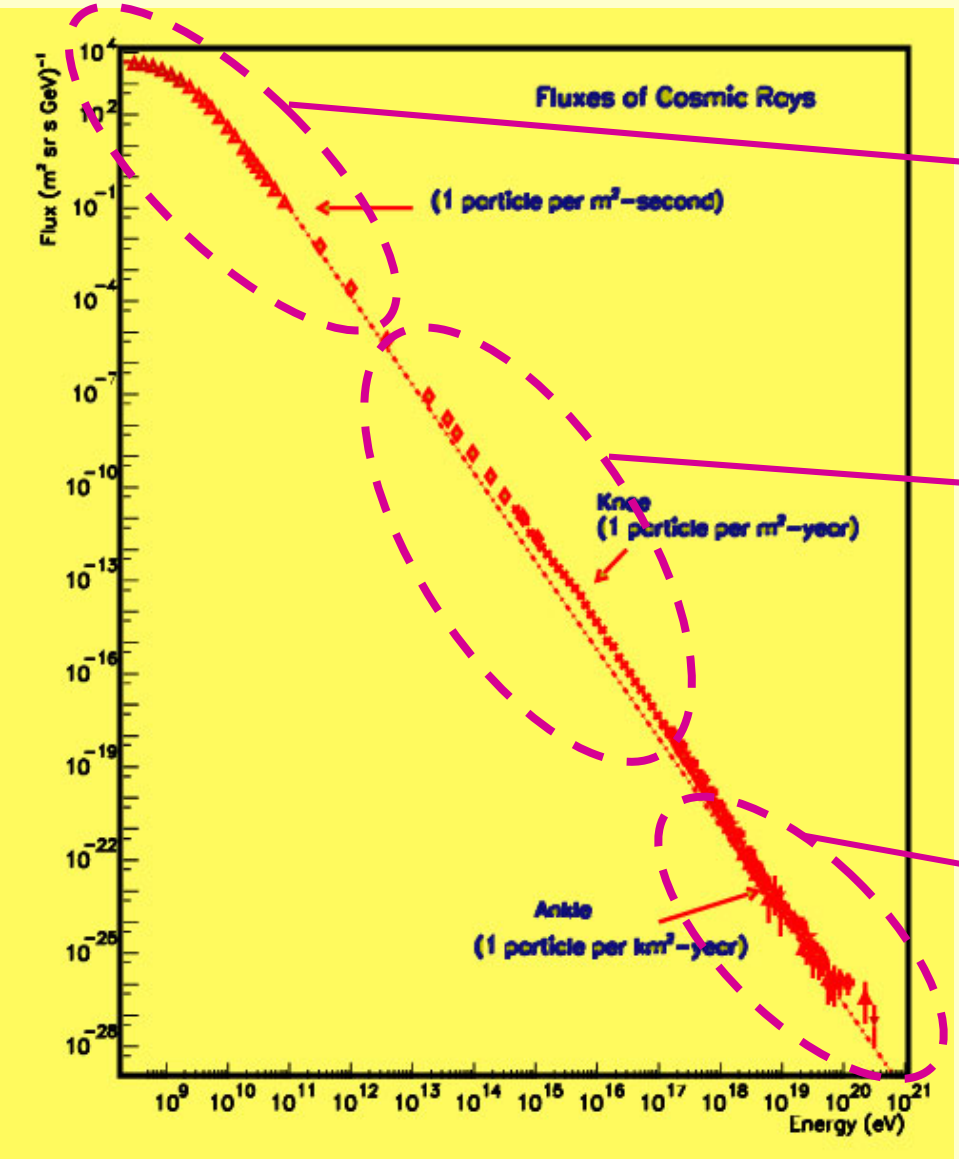
Cosmic rays – the energy spectrum



low energies

→ **direct measurements**

the knee

→ **air shower measurements**

ultra high energies

→ **they should not exist**

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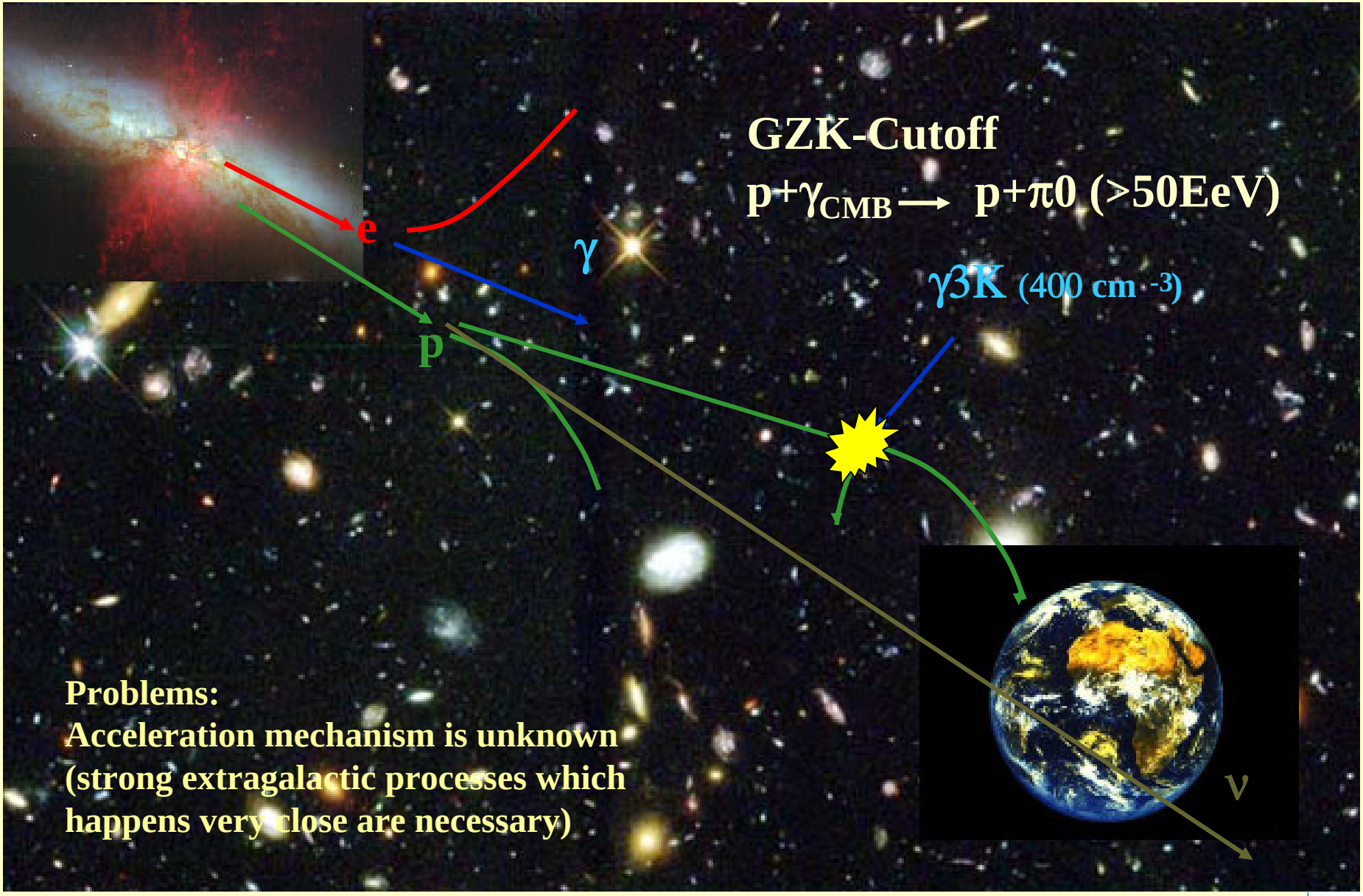
The GZK Cutoff



Problems:
Acceleration mechanism is unknown (strong extragalactic processes which happens very close are necessary)

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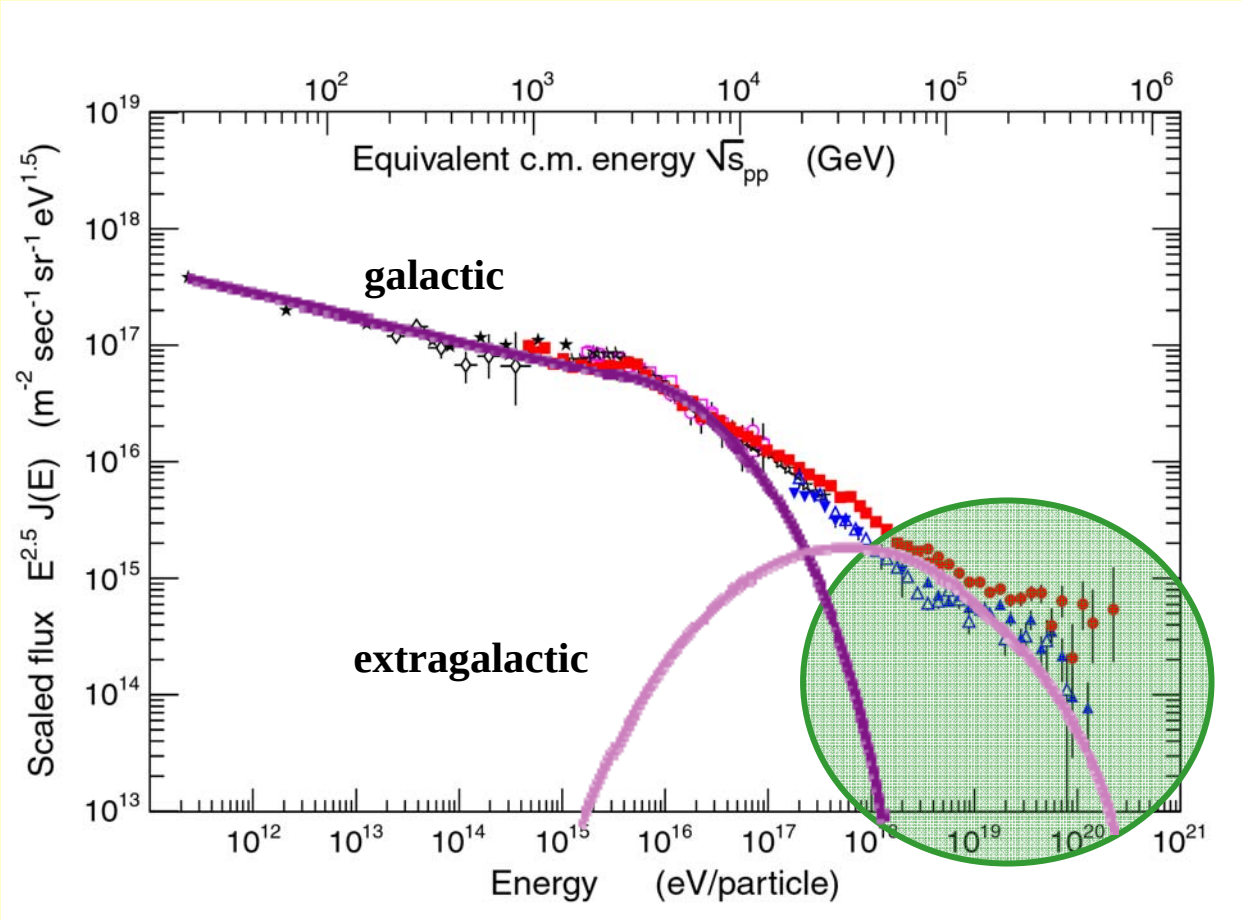
Highest Energies

Source, acceleration, and mass of the particles unknown – but they exist !

Measurements by **large particle detector arrays (AGASA ➔ no cutoff)**

or **fluorescence telescopes (HiRes ➔ cutoff)**



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Southern hemisphere:

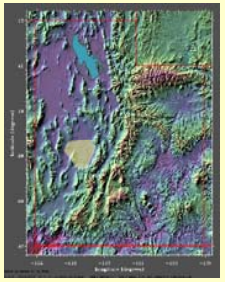
Data taking since 2002

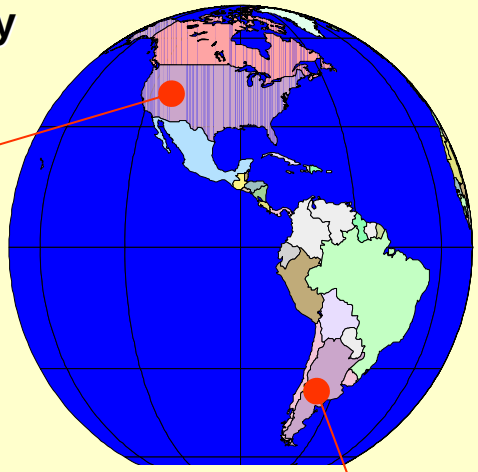
final setup 2006 ?

Northern hemisphere:

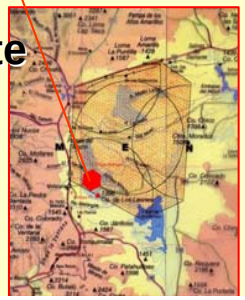
start of deployment 2008 ?

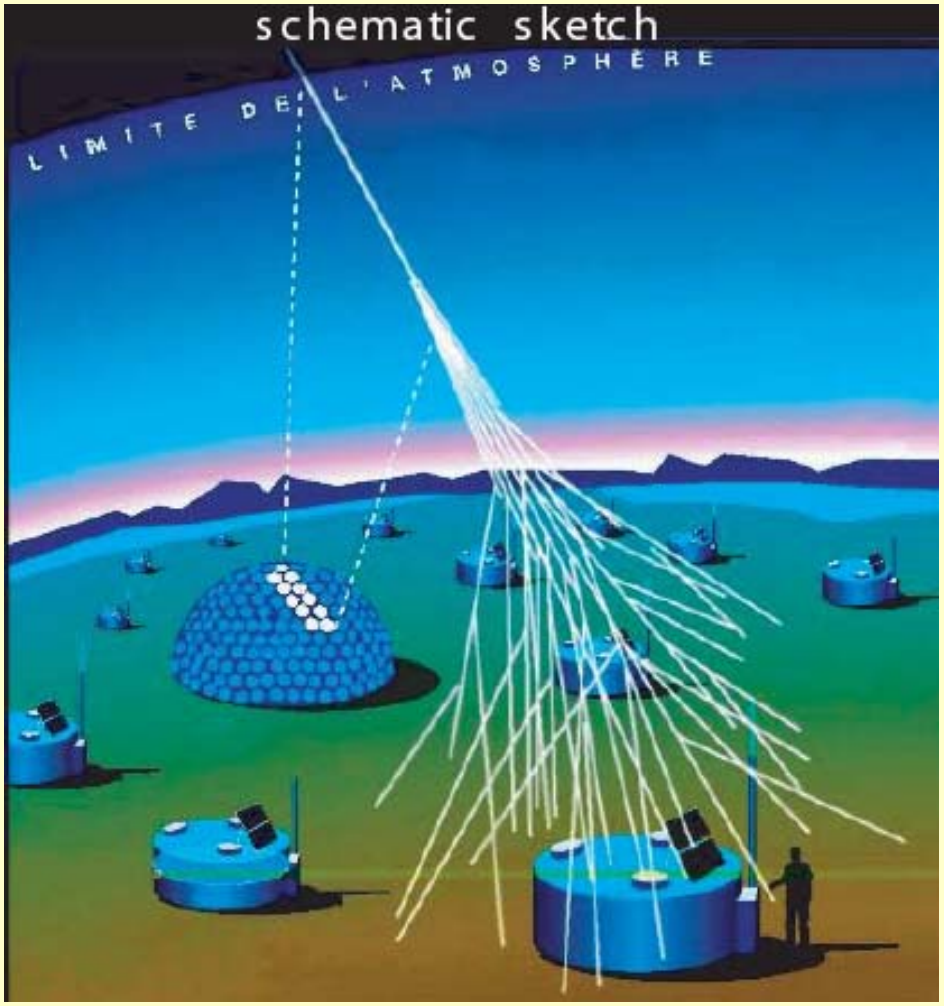
Northern site
Millard County
Utah, USA





Southern site
Malargue
Argentina





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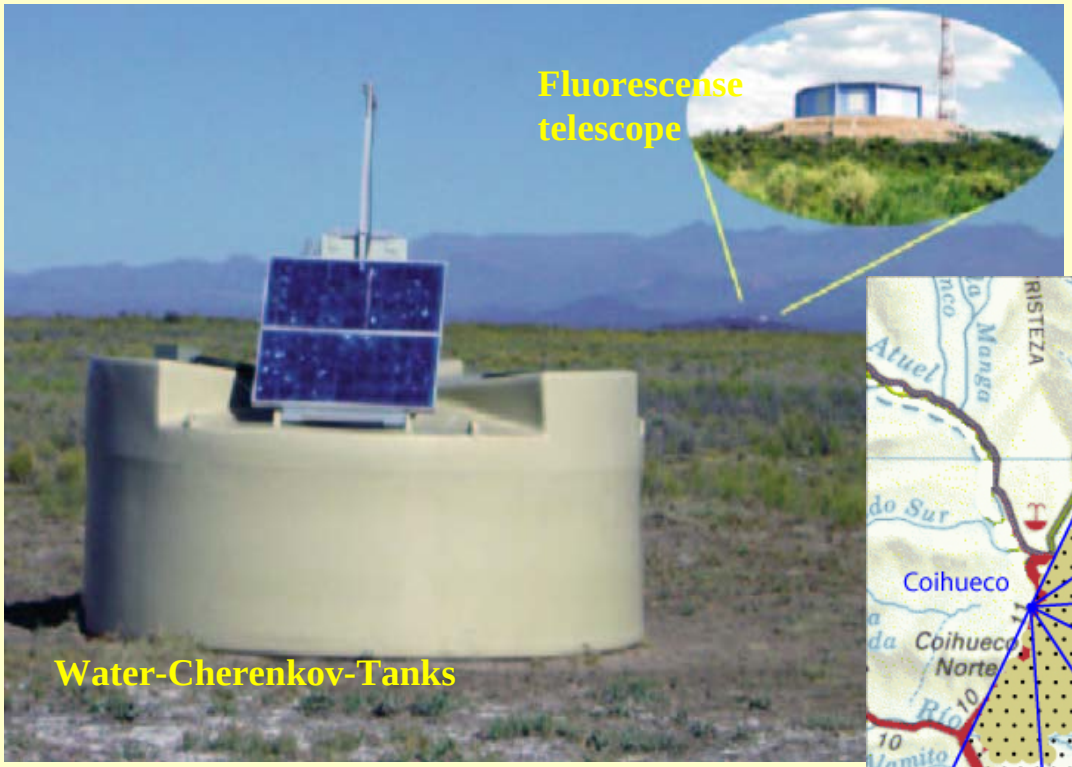

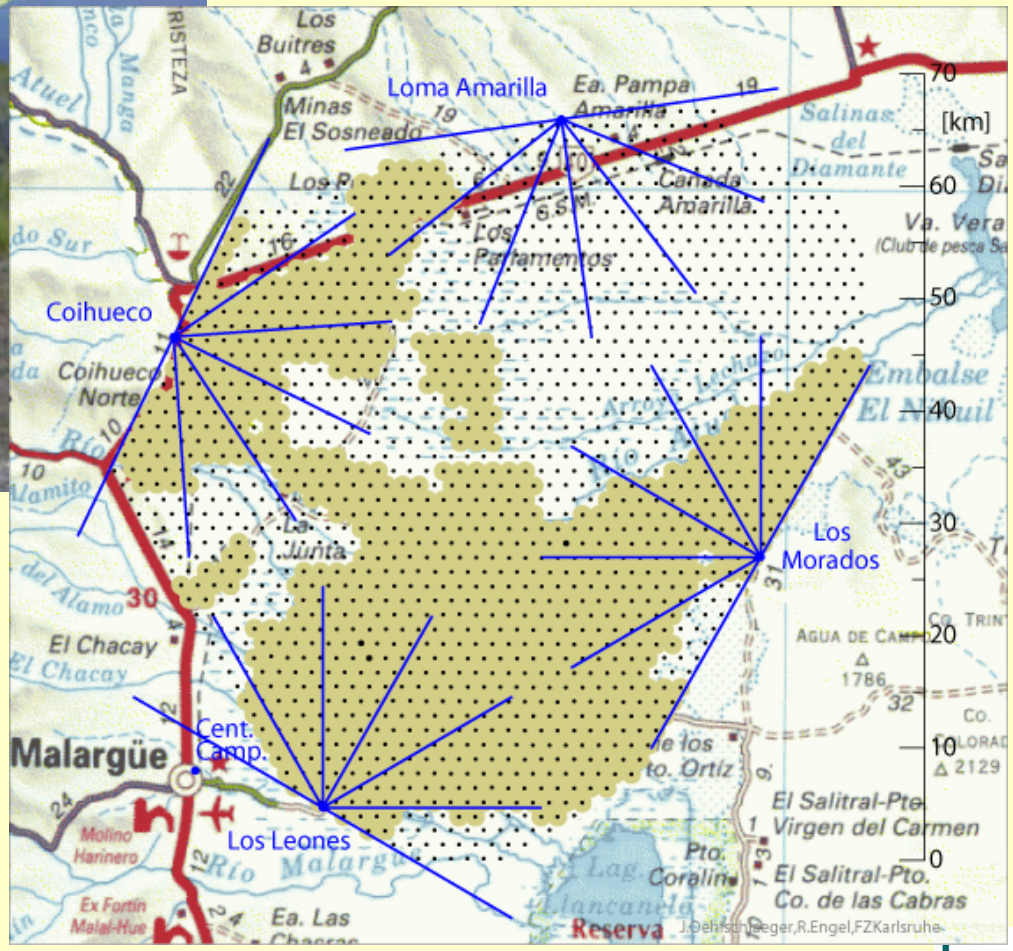

sensitive detector area:
c. 3000 square kilometers

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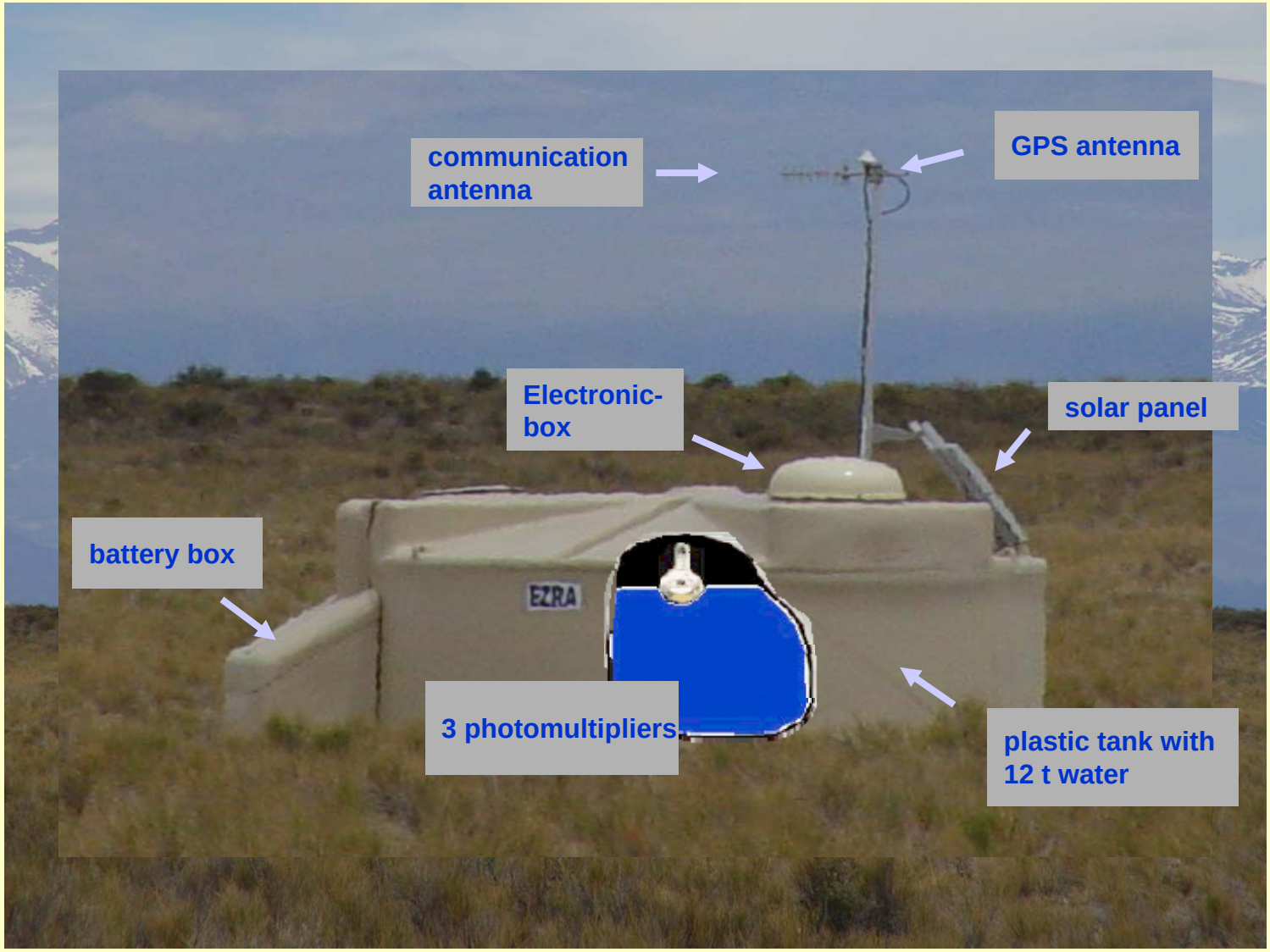
Water – Cherenkov Detector



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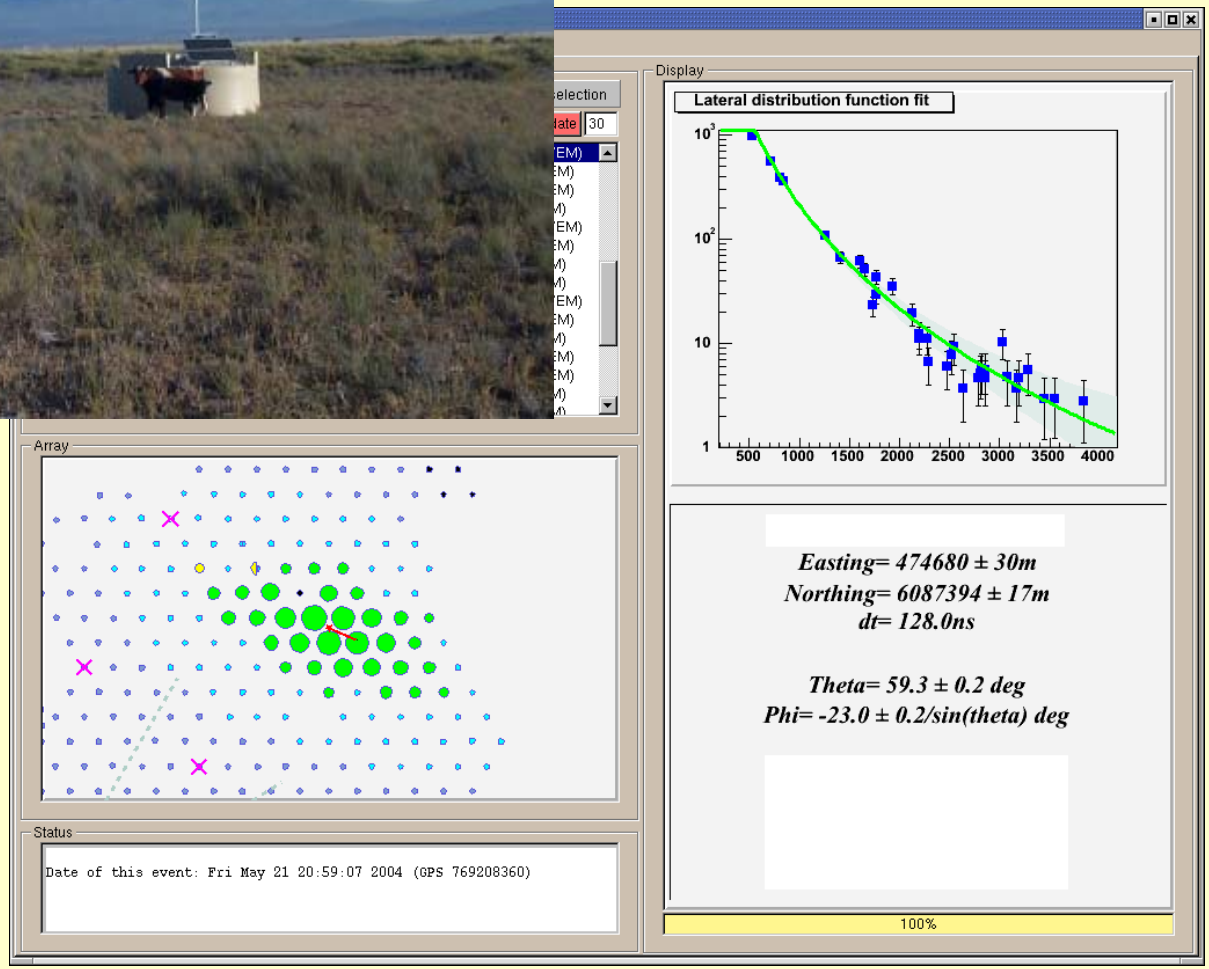
Surface Array

Measurements and further set up in operation



First events close and above 10^{20} eV

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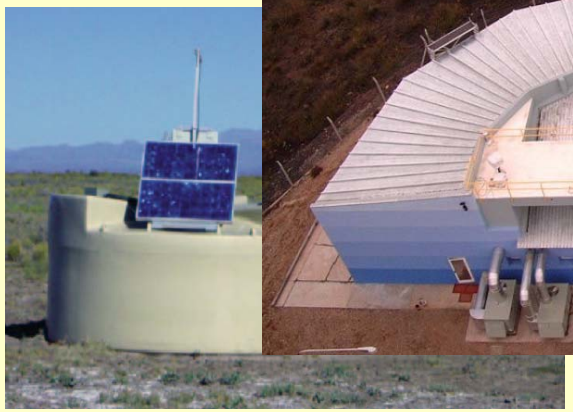
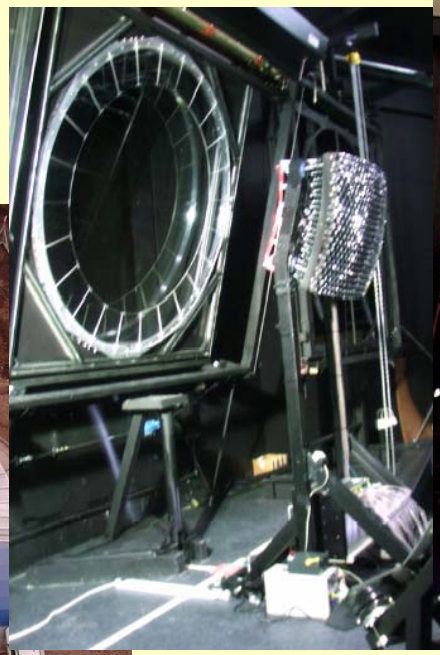
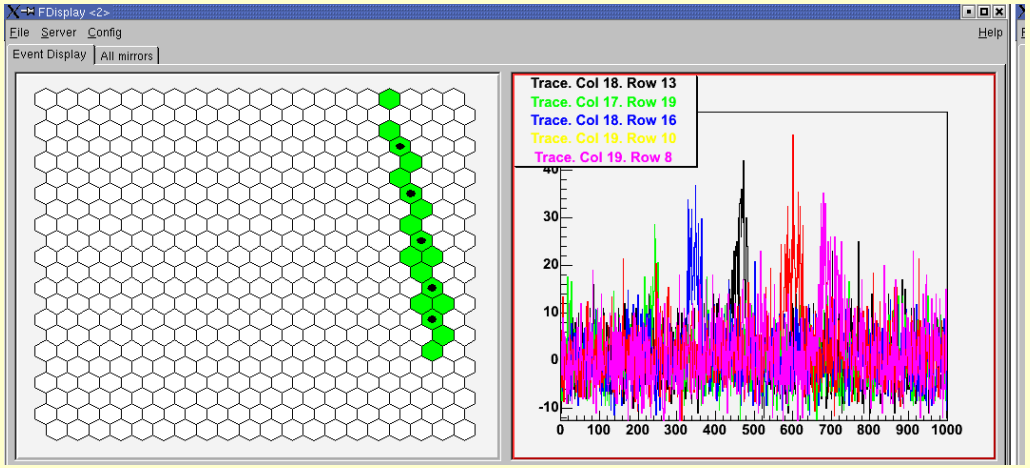
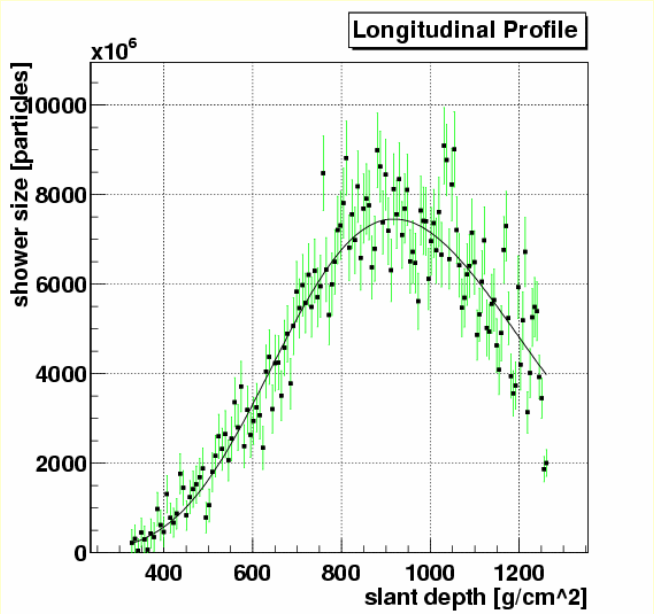
Fluorescense Detectors









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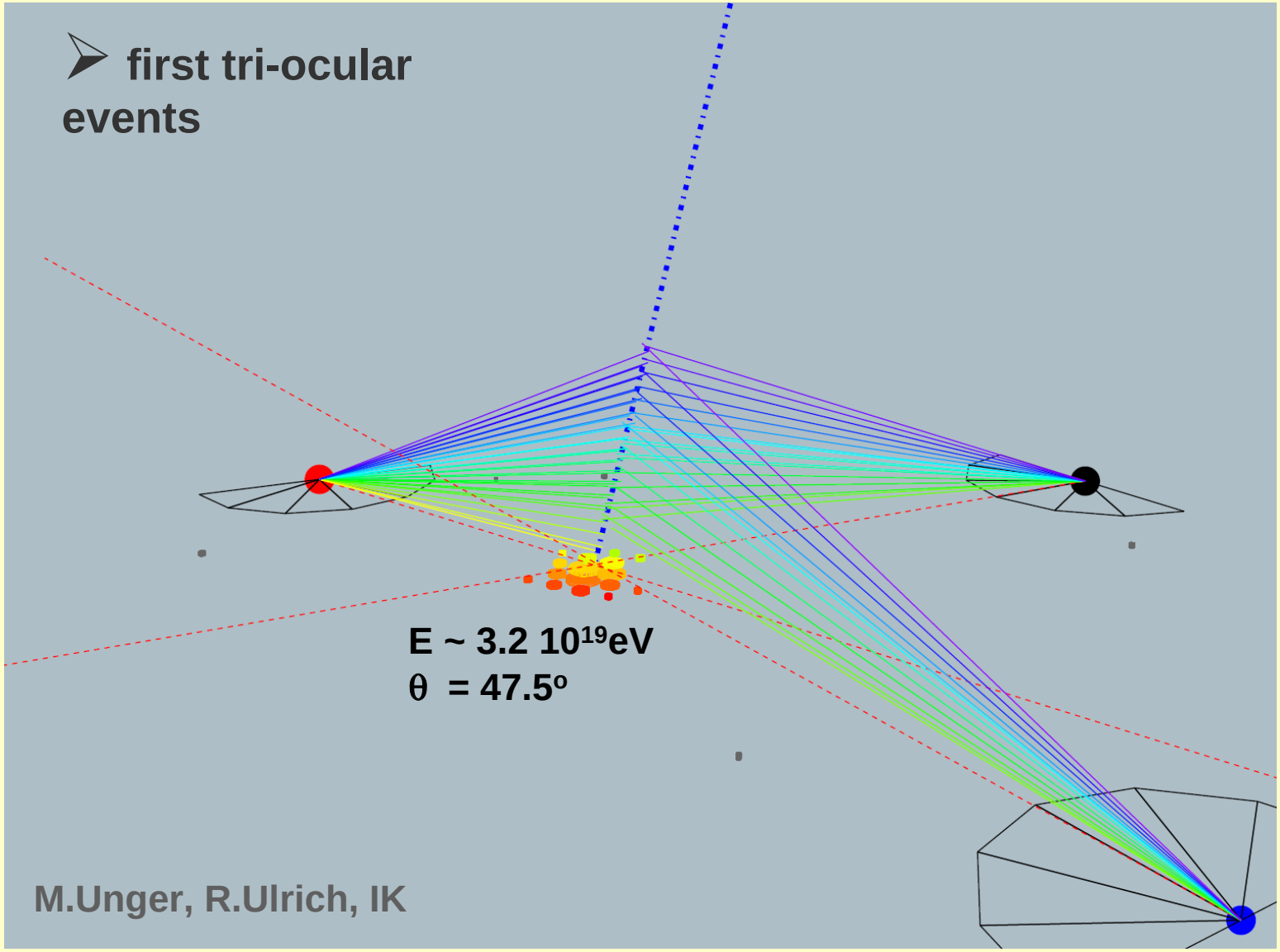
First results



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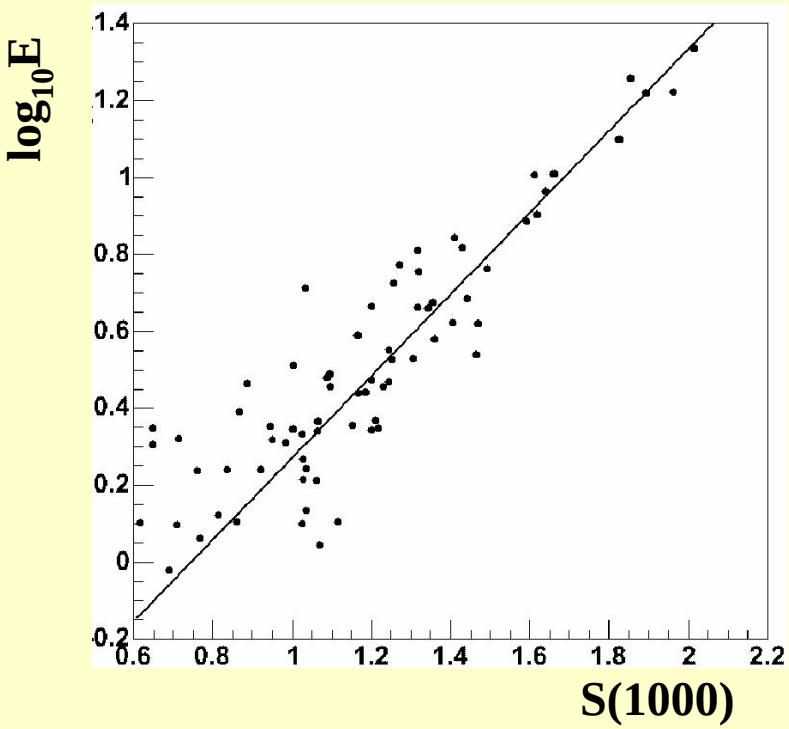
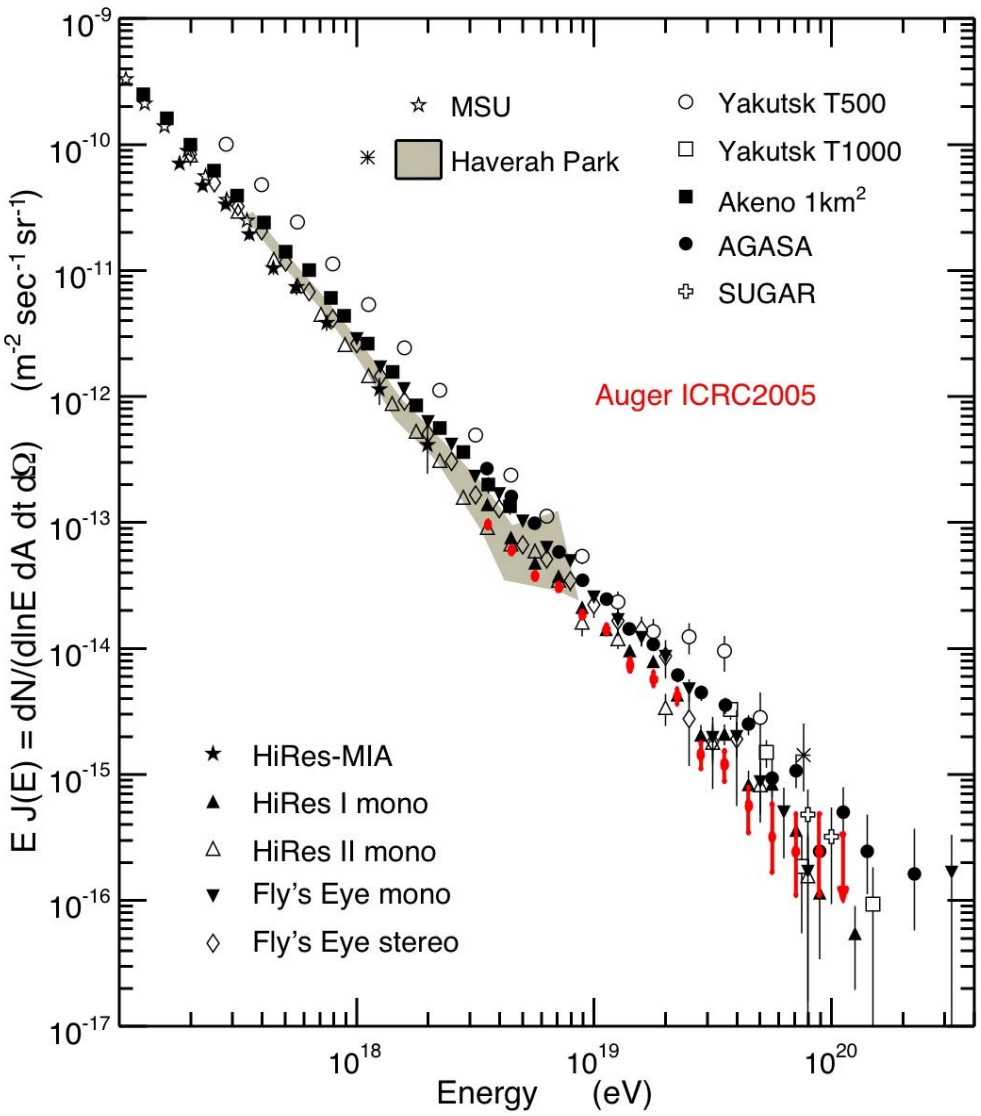
First results: Energy Spectrum





Hybrid events: Energy estimation by fluorescence light measurements

Result will improve by higher statistics and new (better) analysis procedures

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62 tank event

J.Oehlschlaeger,R.Engel,FZKarlsruhe

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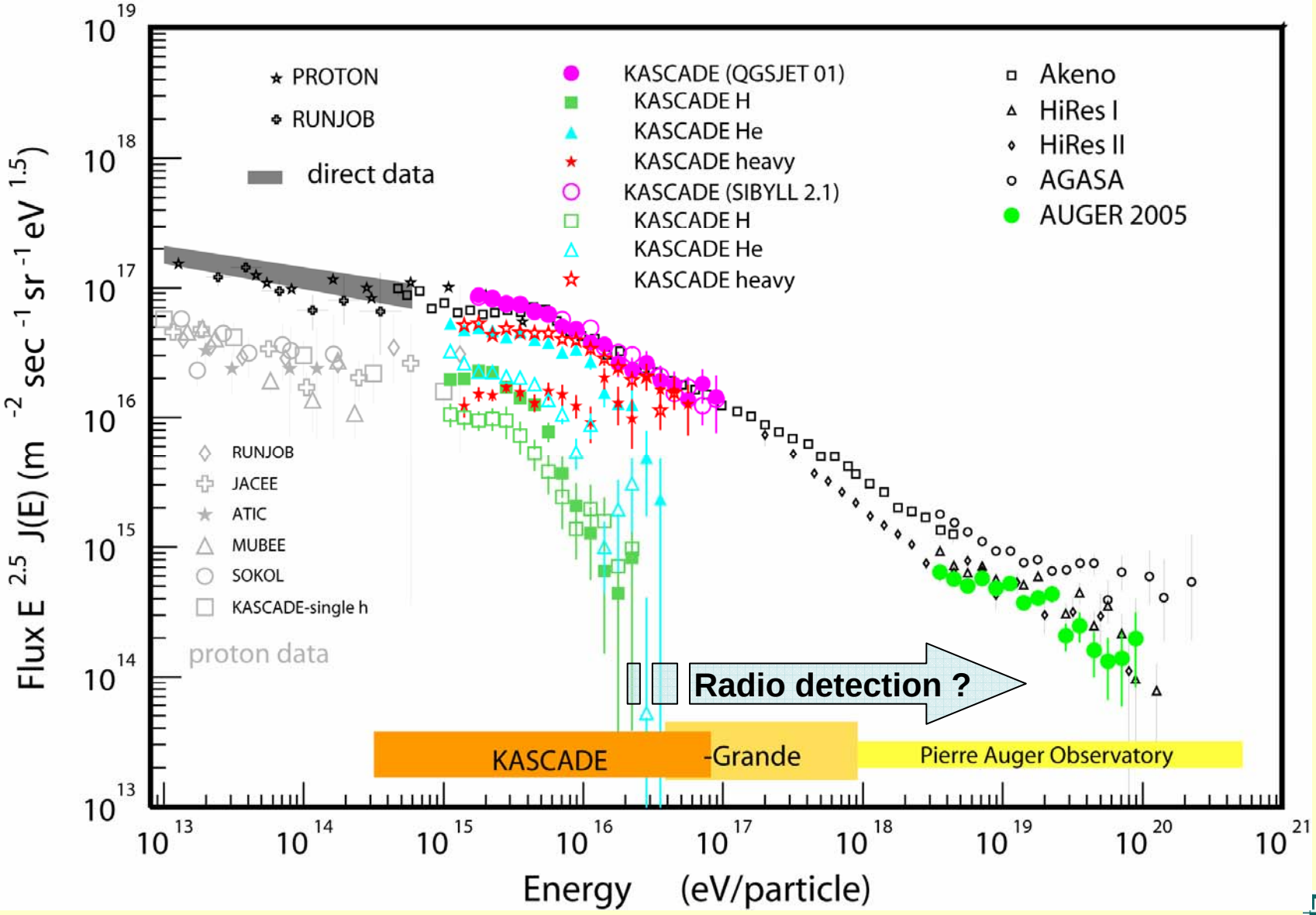
Conclusions



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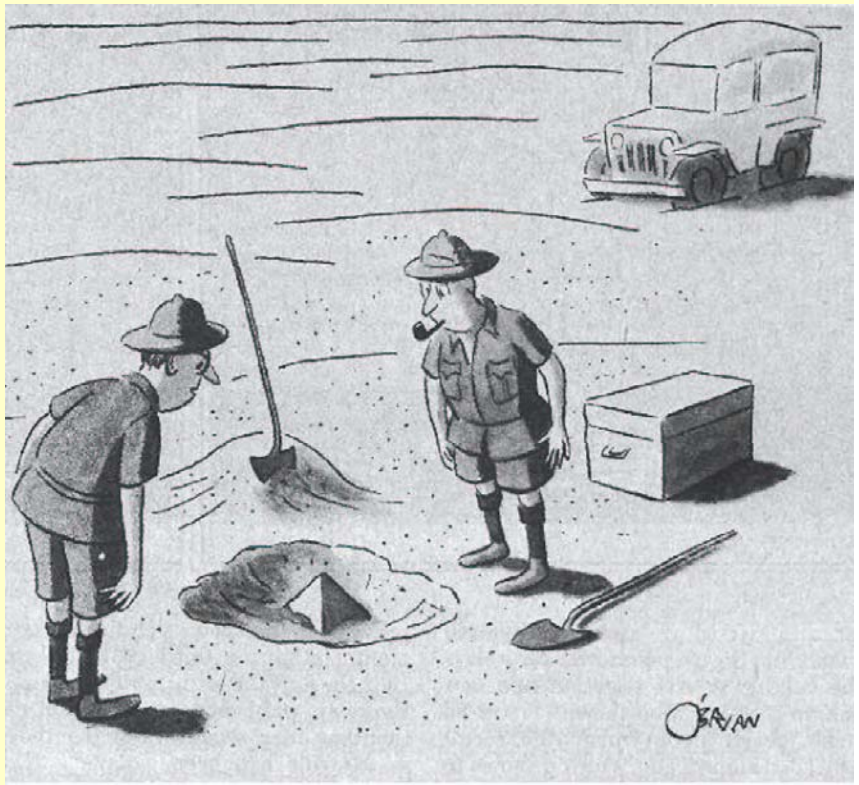
General questions in high-energy cosmic ray physics:

Exist the iron knee ?
Where is the iron (heavy) knee ?
Crossover galactic – extragalactic CR ?
Is there a cut-off ?
What is the compositionß
Why spectrum covers such a large range ?
Sources of the Cosmic Rays ?
From what they have their energy ?
Why is there the knee ?
Why we have so high energy particles ?



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Needs a lot of research.....
Needs a lot of researcher.....

become researcher !!

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