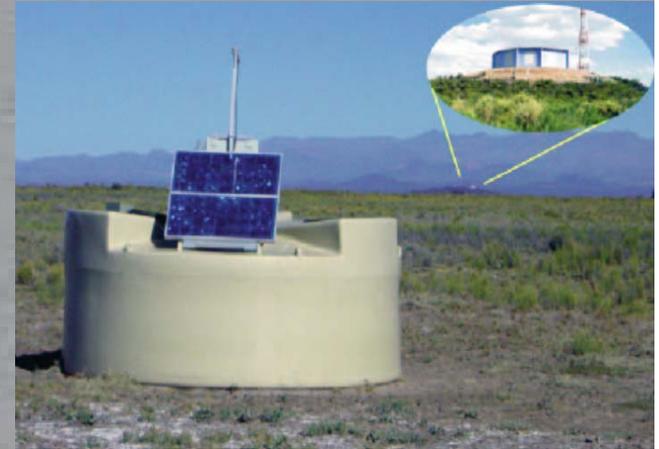


High-Energy Cosmic Ray Physics



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Forschungszentrum Karlsruhe

Institut für Kernphysik

The astrophysical
projects

KASCADE-Grande

and

Pierre Auger Observatory

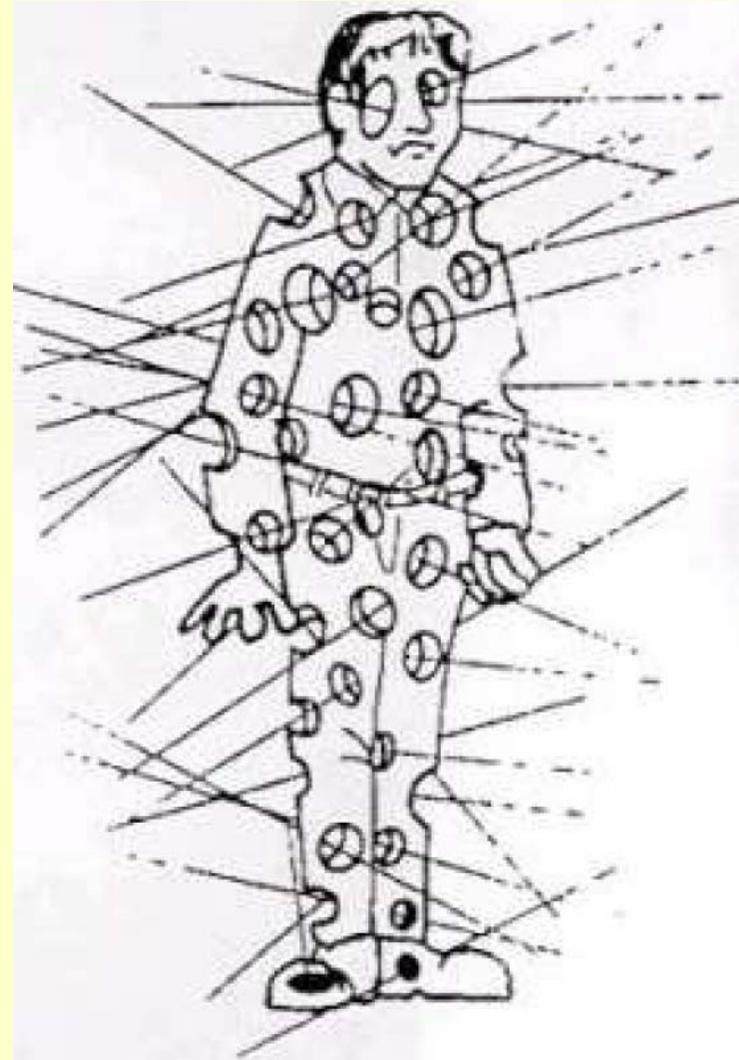
What are Cosmic Rays ?

= high energy, extraterrestrial particles

Warning:



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



What are Cosmic Rays ?

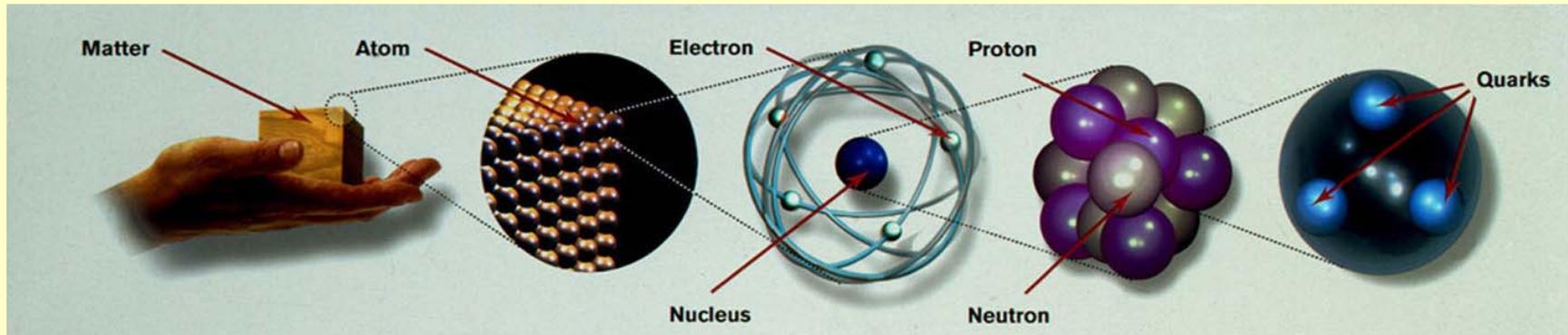
= high energy, extraterrestrial particles

1 La Hydrogen 1 1.00794	2 He Helium 2 4.00260	<table border="1"> <tr> <td>3 Li Lithium 3 6.941</td> <td>4 Be Beryllium 4 9.012</td> <td>5 B Boron 5 10.811</td> <td>6 C Carbon 6 12.011</td> <td>7 N Nitrogen 7 14.007</td> <td>8 O Oxygen 8 15.999</td> <td>9 F Fluorine 9 18.998</td> <td>10 Ne Neon 10 20.180</td> <td>11 Na Sodium 11 22.990</td> <td>12 Mg Magnesium 12 24.305</td> <td>13 Al Aluminum 13 26.982</td> <td>14 Si Silicon 14 28.086</td> <td>15 P Phosphorus 15 30.974</td> <td>16 S Sulfur 16 32.06</td> <td>17 Cl Chlorine 17 35.453</td> <td>18 Ar Argon 18 39.948</td> </tr> </table>										3 Li Lithium 3 6.941	4 Be Beryllium 4 9.012	5 B Boron 5 10.811	6 C Carbon 6 12.011	7 N Nitrogen 7 14.007	8 O Oxygen 8 15.999	9 F Fluorine 9 18.998	10 Ne Neon 10 20.180	11 Na Sodium 11 22.990	12 Mg Magnesium 12 24.305	13 Al Aluminum 13 26.982	14 Si Silicon 14 28.086	15 P Phosphorus 15 30.974	16 S Sulfur 16 32.06	17 Cl Chlorine 17 35.453	18 Ar Argon 18 39.948
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19 K Potassium 19 39.098	20 Ca Calcium 20 40.078	21 Sc Scandium 21 44.956	22 Ti Titanium 22 47.88	23 V Vanadium 23 50.942	24 Cr Chromium 24 51.996	25 Mn Manganese 25 54.938	26 Fe Iron 26 55.845	27 Co Cobalt 27 58.933	28 Ni Nickel 28 58.693	29 Cu Copper 29 63.546	30 Zn Zinc 30 65.38	31 Ga Gallium 31 69.723	32 Ge Germanium 32 72.63	33 As Arsenic 33 74.922	34 Se Selenium 34 78.96	35 Br Bromine 35 79.904	36 Kr Krypton 36 83.80										
37 Rb Rubidium 37 85.468	38 Sr Strontium 38 87.62	39 Y Yttrium 39 88.906	40 Zr Zirconium 40 91.224	41 Nb Niobium 41 92.906	42 Mo Molybdenum 42 95.94	43 Tc Technetium 43 98.906	44 Ru Ruthenium 44 101.07	45 Rh Rhodium 45 102.91	46 Pd Palladium 46 106.42	47 Ag Silver 47 107.87	48 Cd Cadmium 48 112.41	49 In Indium 49 114.82	50 Sn Tin 50 118.71	51 Sb Antimony 51 121.76	52 Te Tellurium 52 127.6	53 I Iodine 53 126.91	54 Xe Xenon 54 131.29										
55 Cs Cesium 55 132.91	56 Ba Barium 56 137.33	57-70 Lanthanides	71 Lu Lutetium 71 174.967	72 Hf Hafnium 72 178.49	73 Ta Tantalum 73 180.948	74 W Tungsten 74 183.85	75 Re Rhenium 75 186.207	76 Os Osmium 76 190.23	77 Ir Iridium 77 192.222	78 Pt Platinum 78 195.084	79 Au Gold 79 196.967	80 Hg Mercury 80 200.59	81 Tl Thallium 81 204.38	82 Pb Lead 82 207.2	83 Bi Bismuth 83 208.98	84 Po Polonium 84 209	85 At Astatine 85 210	86 Rn Radon 86 222									
87 Fr Francium 87 223	88 Ra Radium 88 226	89-102 Actinides	103 Lr Lawrencium 103 260	104 Rf Rutherfordium 104 261	105 Db Dubnium 105 262	106 Sg Seaborgium 106 263	107 Bh Bohrium 107 264	108 Hs Hassium 108 265	109 Mt Meitnerium 109 266	110 Uun Ununennium 110 267	111 Uuu Ununennium 111 268	112 Uub Unbinilium 112 269	113 Uut Untrium 113 270	114 Uuq Unquadrium 114 271	115 Uup Unpentium 115 272	116 Uuq Unhexium 116 273	117 Uuh Unheptium 117 274	118 Uuo Unoctium 118 276									

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

57 La Lanthanum 57 138.905	58 Ce Cerium 58 140.12	59 Pr Praseodymium 59 140.908	60 Nd Neodymium 60 144.24	61 Pm Promethium 61 144.913	62 Sm Samarium 62 150.36	63 Eu Europium 63 151.964	64 Gd Gadolinium 64 157.25	65 Tb Terbium 65 158.925	66 Dy Dysprosium 66 162.50	67 Ho Holmium 67 164.930	68 Er Erbium 68 167.259	69 Tm Thulium 69 168.930	70 Yb Ytterbium 70 173.054
89 Ac Actinium 89 227	90 Th Thorium 90 232.038	91 Pa Protactinium 91 231.036	92 U Uranium 92 238.029	93 Np Neptunium 93 237.048	94 Pu Plutonium 94 244.064	95 Am Americium 95 243.061	96 Cm Curium 96 247.070	97 Bk Berkelium 97 247.070	98 Cf Californium 98 251.080	99 Es Einsteinium 99 252.083	100 Fm Fermium 100 257.103	101 Md Mendelevium 101 258.106	102 No Nobelium 102 259.108



History

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

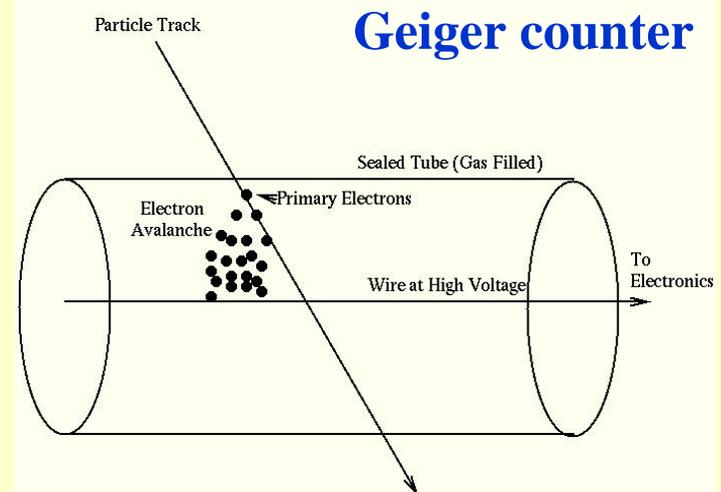


**(Ionizing rays are coming from above !!!
Hess flies up to 5000m)**

Electrometer



Geiger Counter Principles



Water – Cherenkov Detector

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

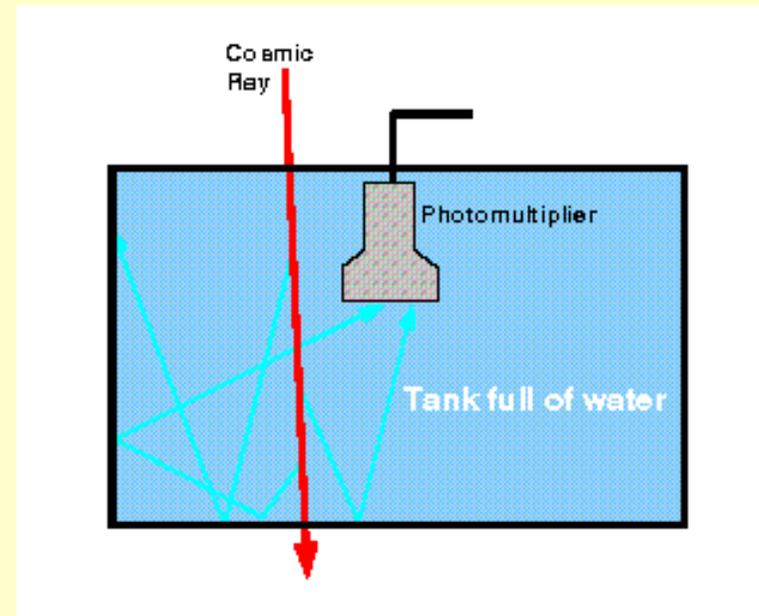
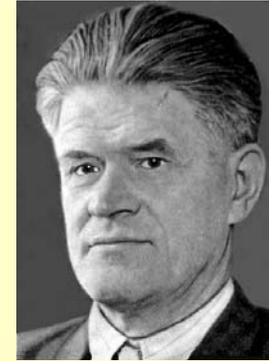
water: $v_{\text{Teilchen}} > 0.75c ! \rightarrow$ Muons $E_{\text{kin}} > 60\text{MeV}$,
Electrons $E_{\text{kin}} > 0.3\text{MeV}$

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

Angle of Emission:

$$\cos \theta = 1/n\beta \left[\frac{h}{2p\lambda} (1-1/n^2) \right]$$

Pavel Alekseyevich
Cherenkov
(1904-1990)



Photons per tracklength:

$$dN/dx = 2\pi\alpha Z^2 \int_{\lambda_1}^{\lambda_2} \lambda^2 (1-1/n^2\beta^2) d\lambda/\lambda^2$$

A water–Cherenkov detector for school experiments

Master thesis Michael Hammer

DETECTORS

(Demonstration
Experiment with
Thermal Cans
To measure
cosmic Ray air
Showers)



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

A water-Cherenkov detector for school experiments

Master thesis Michael Hammer

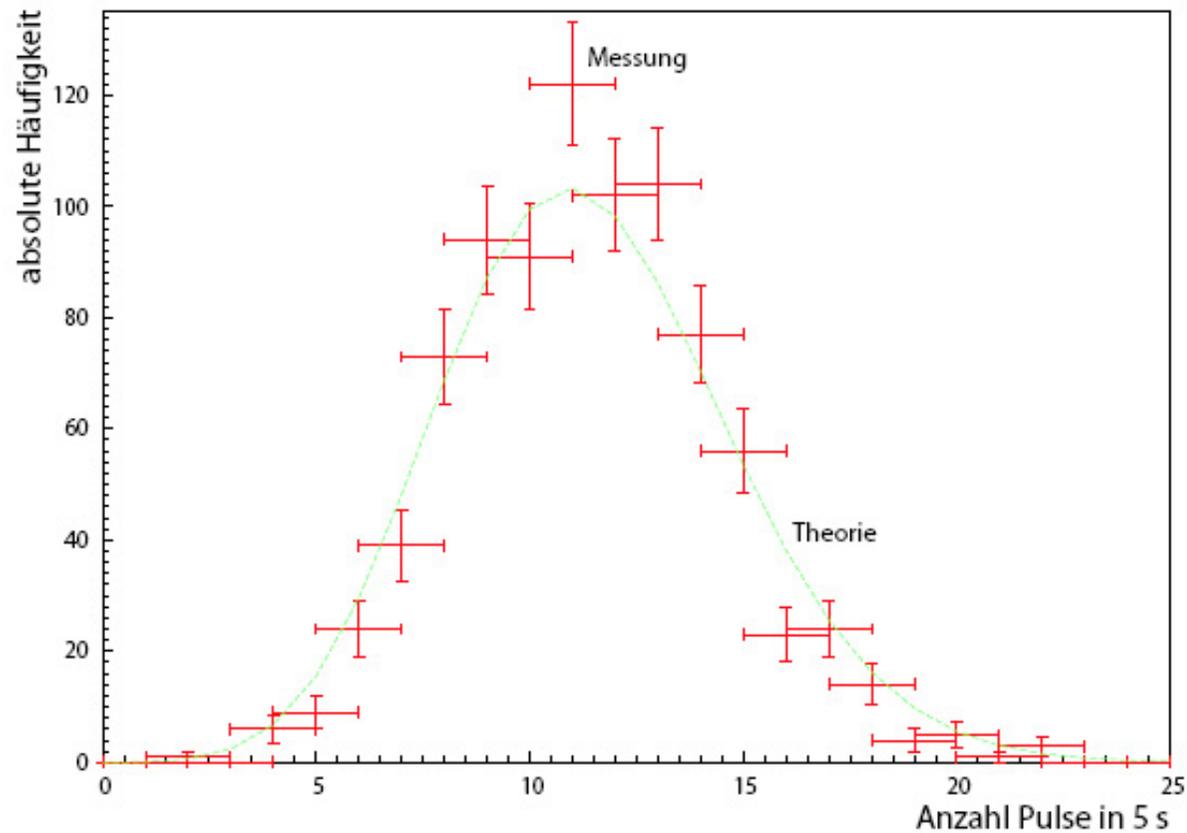


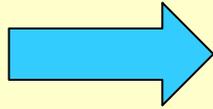
Abbildung 5.5: Messung der Pulsrate, Poissonverteilung

Example: pulse rate measurement: poisson distribution

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

Cosmic Rays

Source



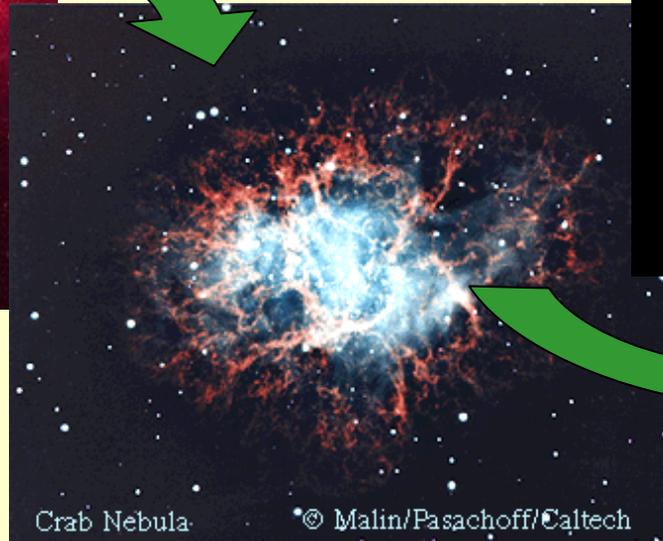
Acceleration



Transport



Injection



Crab Nebula © Malin/Pasachoff/Caltech



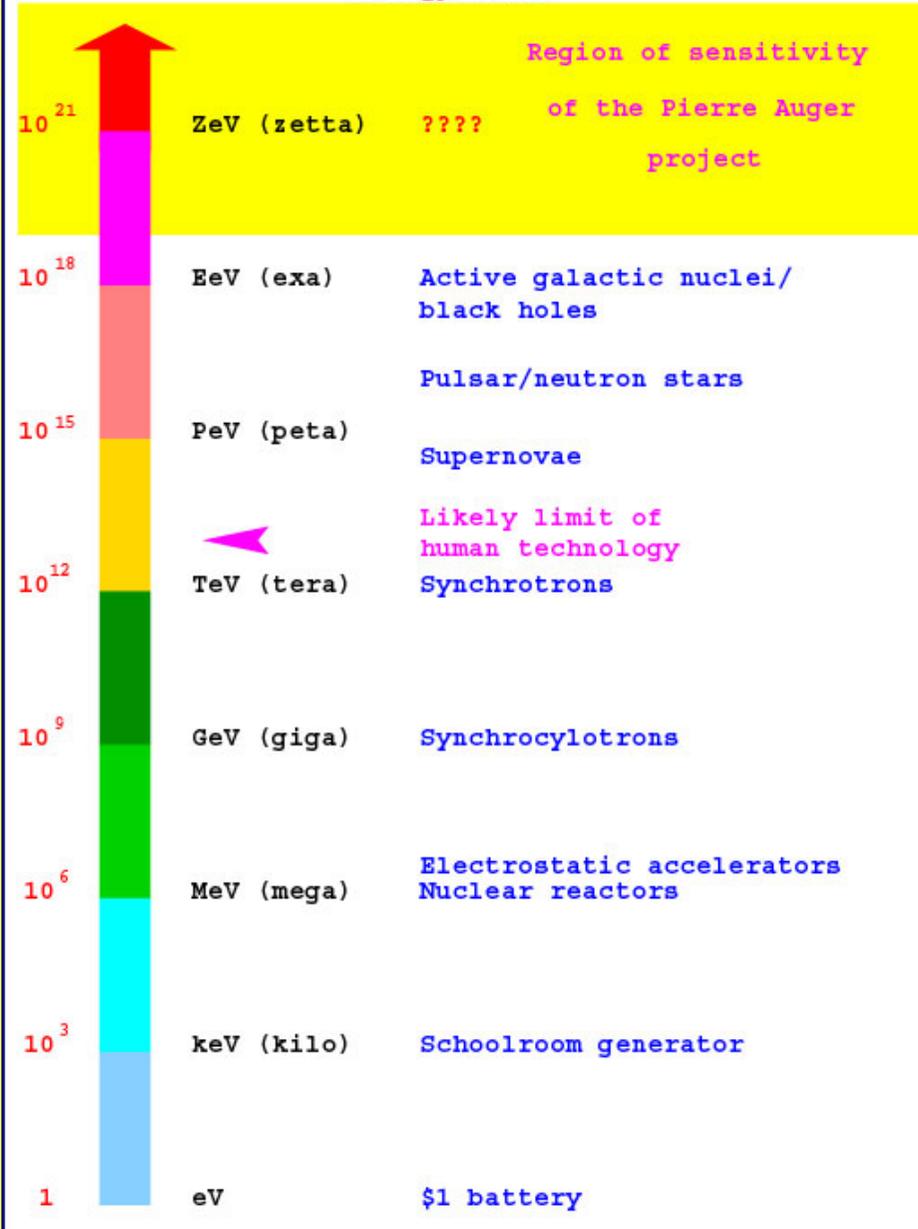
- Supernovae (galactic)
- AGN (extragalactic)

shock acceleration (Fermi)

Spallation

nuclear interactions in interstellar / intergalactic medium

Energy scales



Fluxes of Cosmic Rays

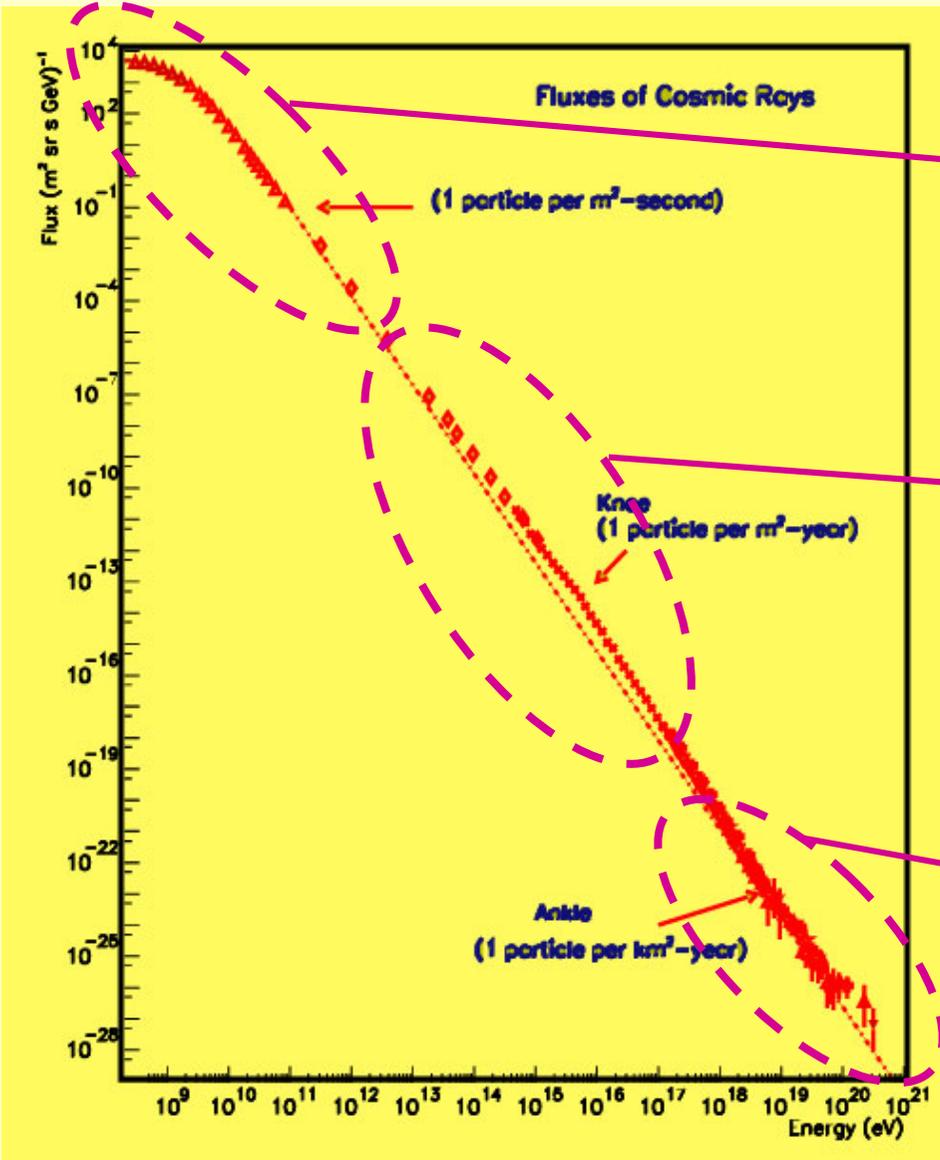
(particle per m^2 -second)

Knee
(1 particle per m^2 -year)

Ankle
(particle per km^2 -year)



Cosmic rays – the energy spectrum



low energies
→ direct measurements

the knee
→ air shower measurements

ultra high energies
→ they should not exist

Cosmic rays – direct measurements



Balloons

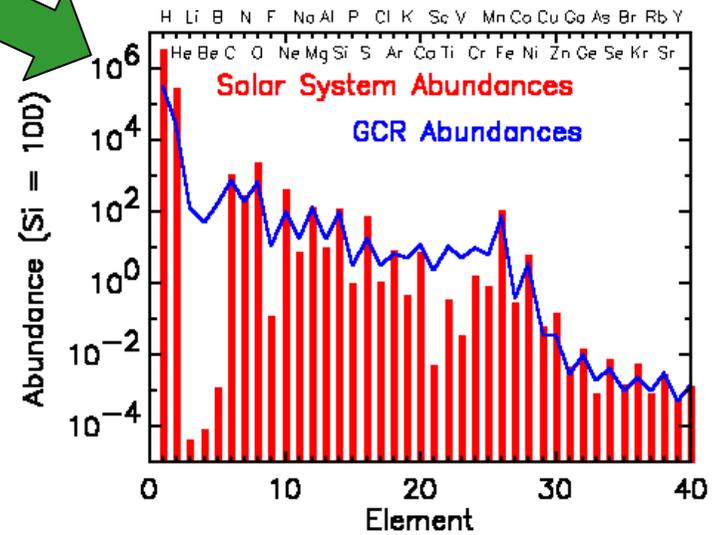


Satellites

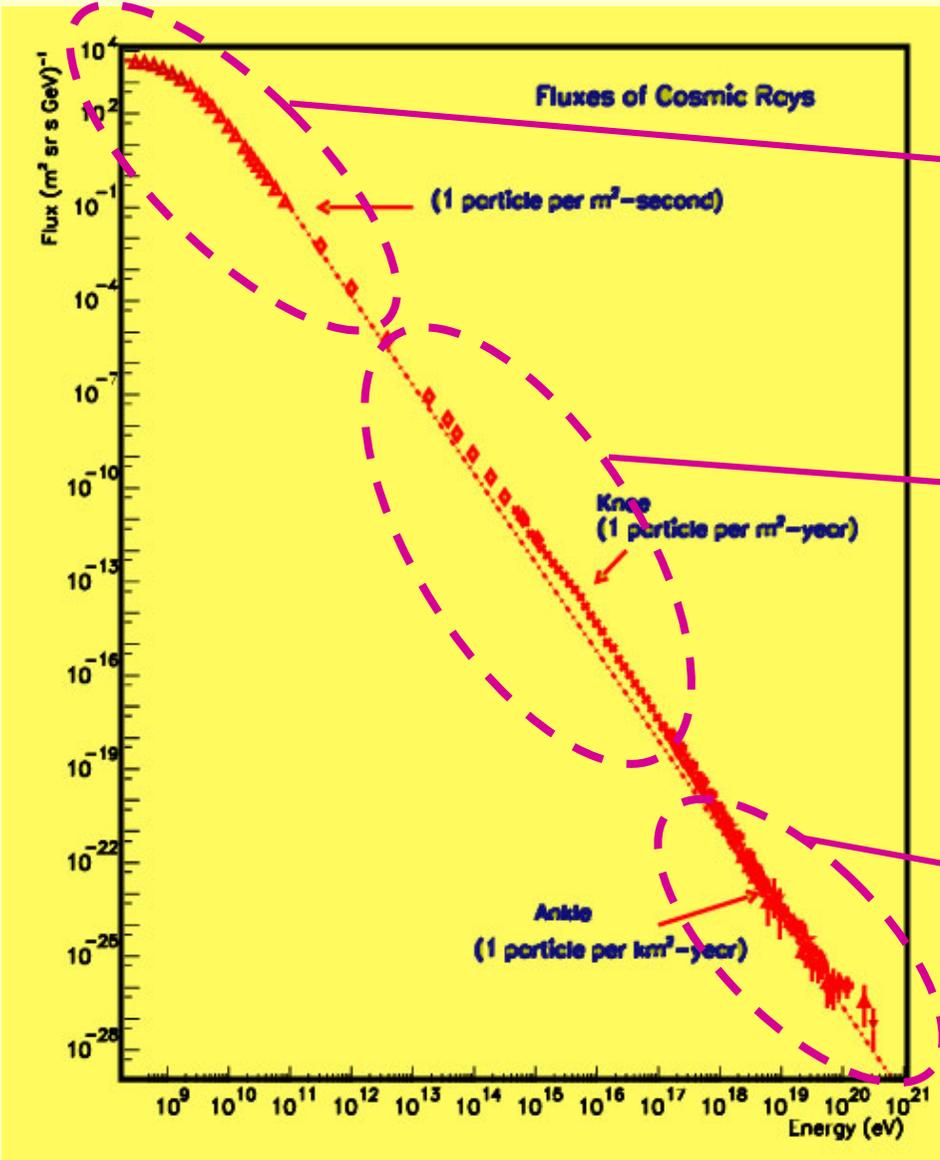


**multi-detector-setups
for simultaneous measurements
of energy, mass, and charge**

**relative abundances
of the chemical
elements**



Cosmic rays – the energy spectrum



low energies



direct measurements

the knee



air shower measurements

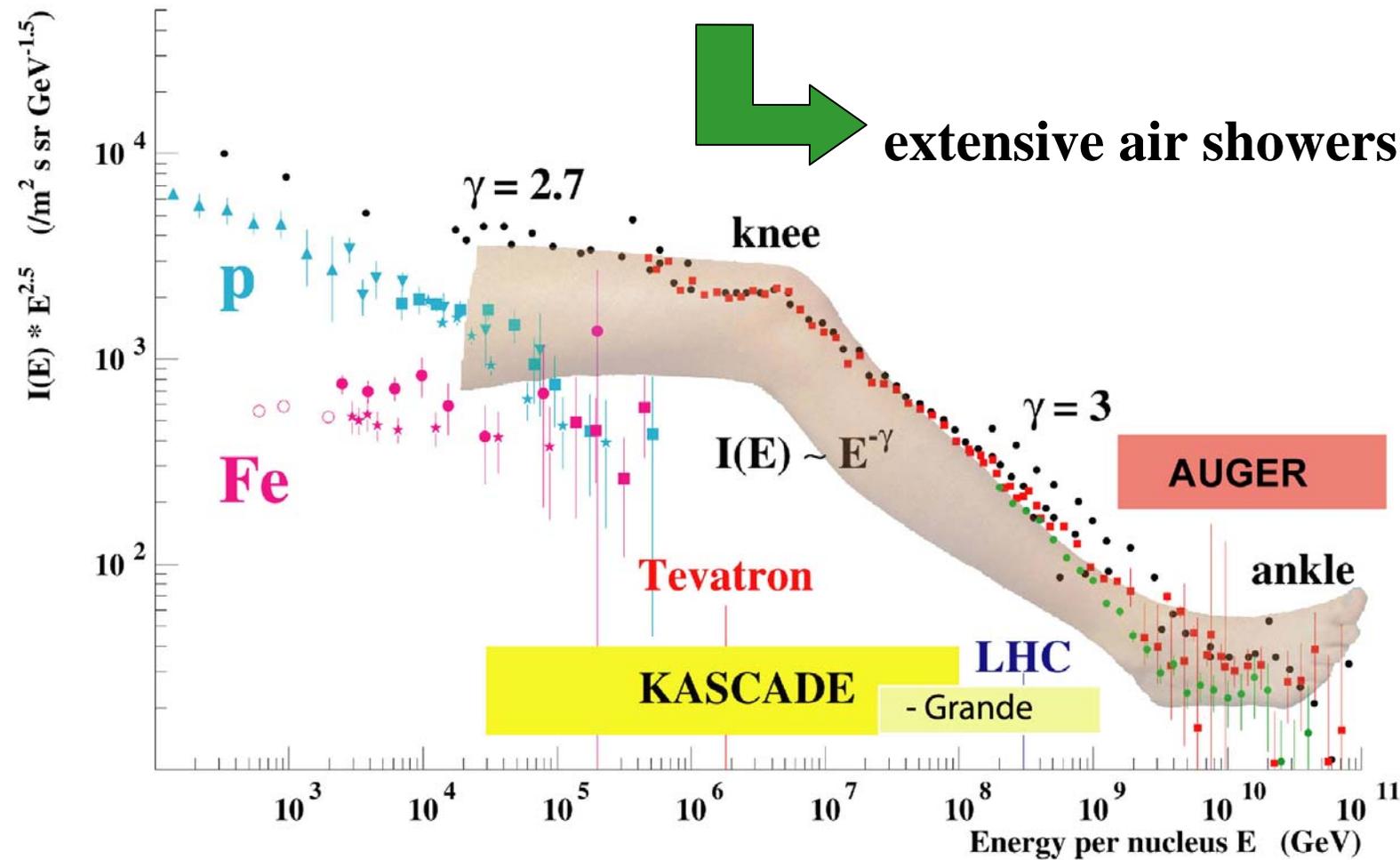
ultra high energies



they should not exist

The knee

Source of knee and ankle?
only indirect measurements !

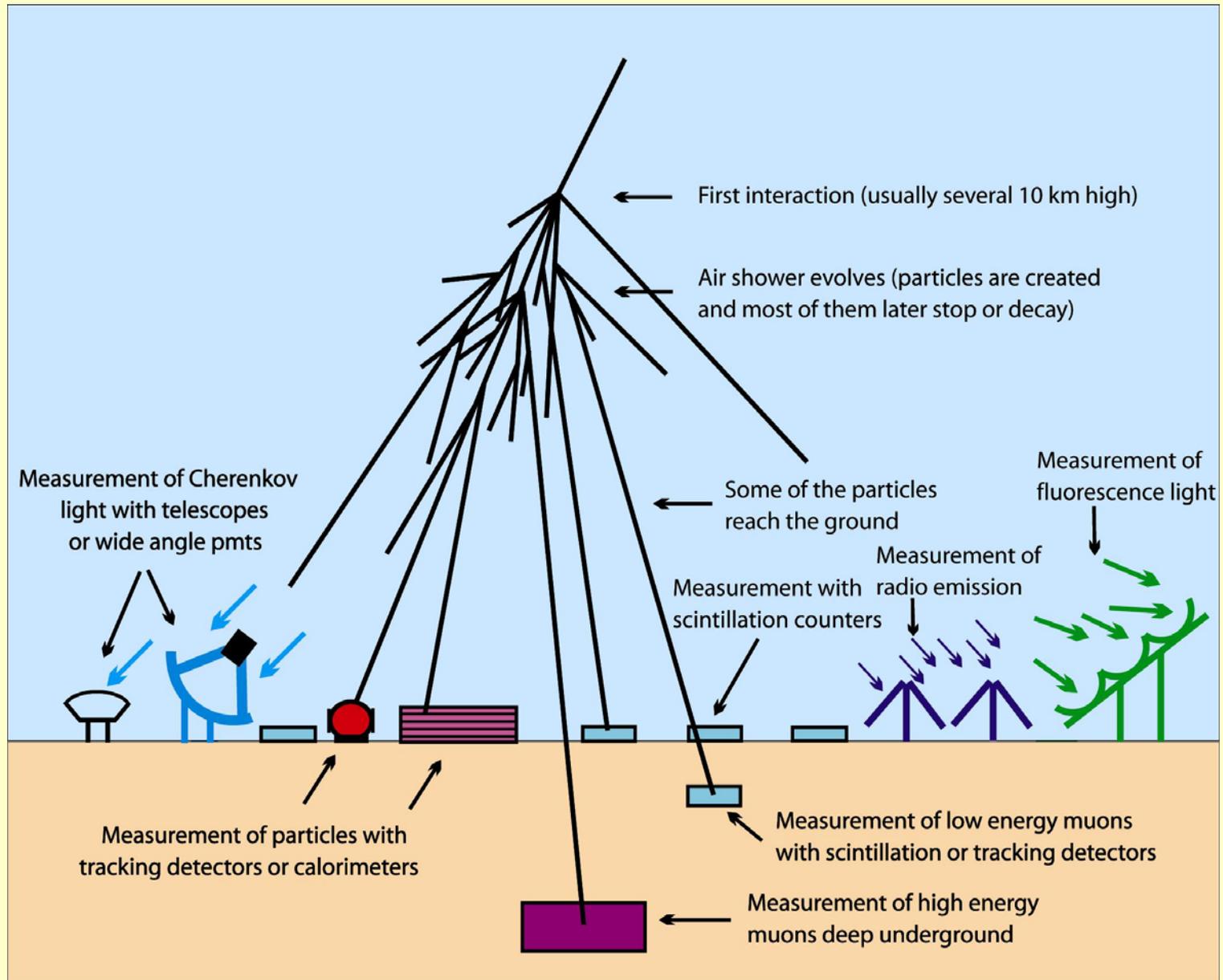


extensive air shower



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

Extensive Air Showers – Detection Techniques



A water–Cherenkov detector for school experiments

Master thesis Michael Hammer

DETECTORS

(Demonstration
Experiment with
Thermal Cans
To measure
cosmic Ray air
Showers)



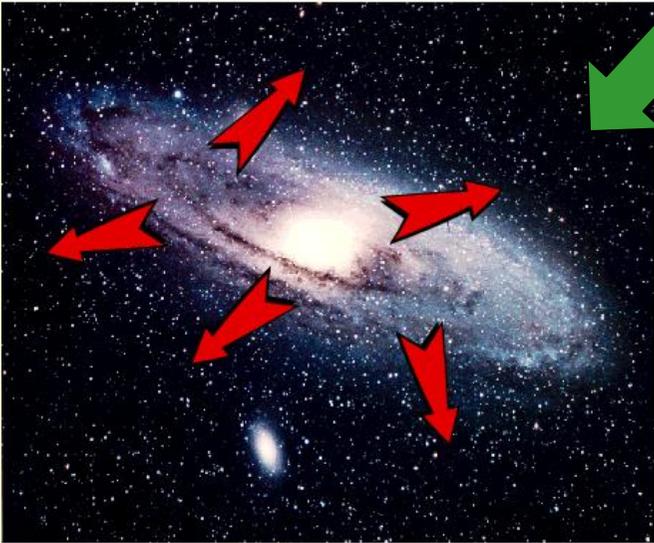
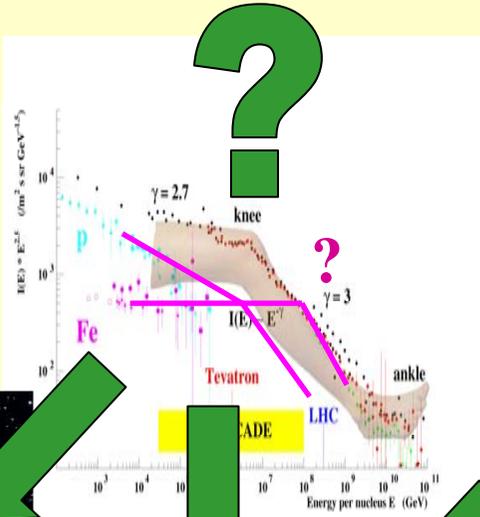
<http://www-ik.fzk.de/~hammer/detectors.html>

The knee - Theories

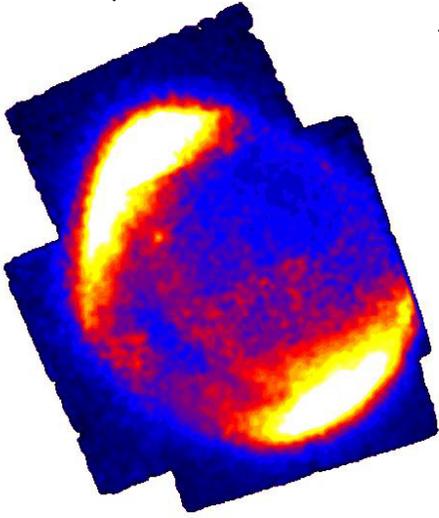
Source of the knee ?

↳ different theories

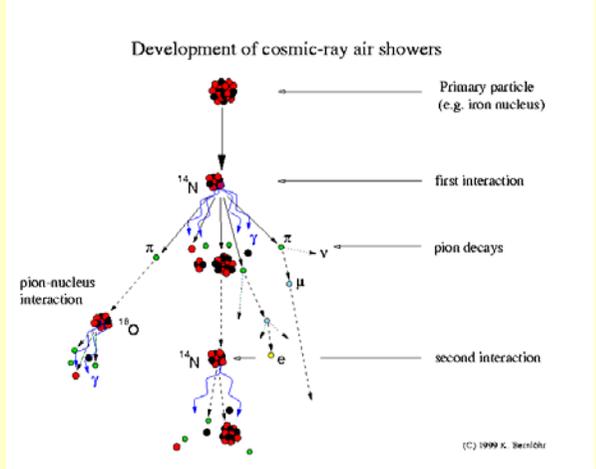
↳ Measurements of energy and mass!



Diffusion →
Escape from our Galaxy
 knee position $\propto Z$ of element



maximum acceleration
 knee position $\propto Z$



unknown effect in first interaction
 knee position $\propto A$

Measurement of EAS

Registration with large area particle detectors

↳ **KASCADE = KARlsruhe Shower Core and Array Detector**

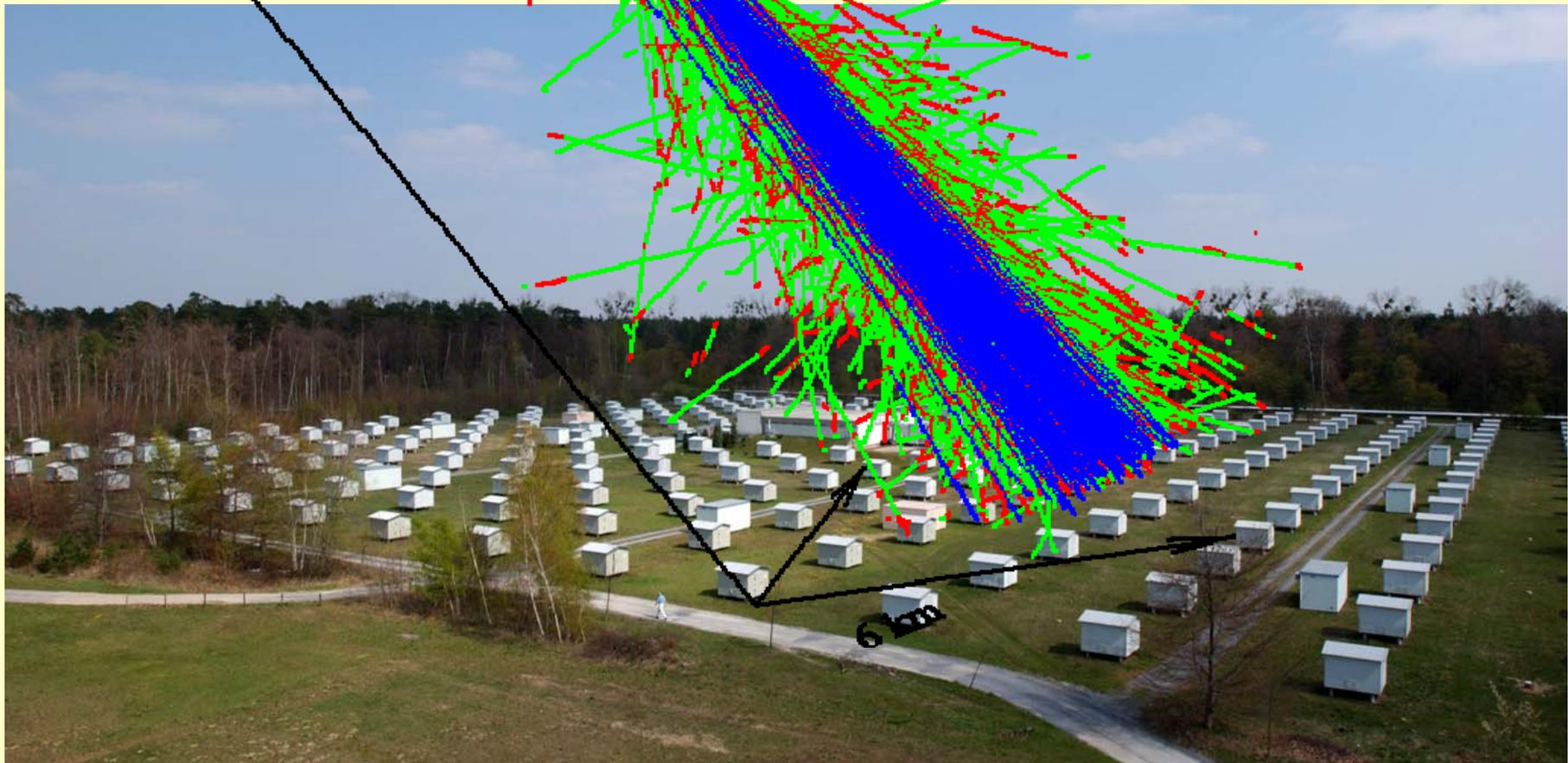


Measurement of EAS

Registration with large area particle detectors

KASCADE = KA Shower Core and Array Detector

12 km
↓

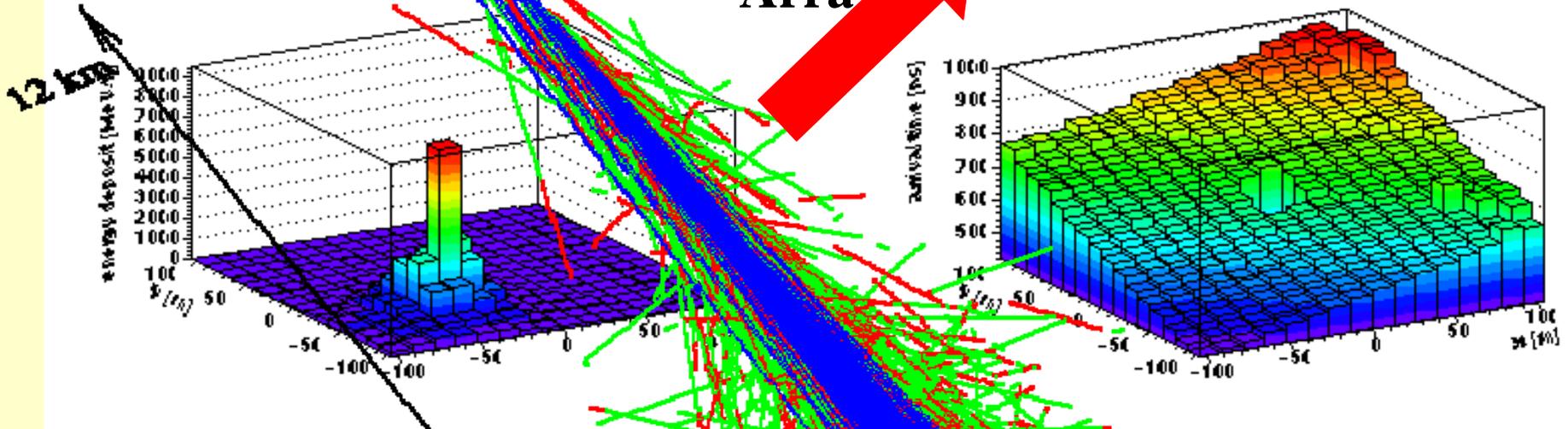


KASCADE

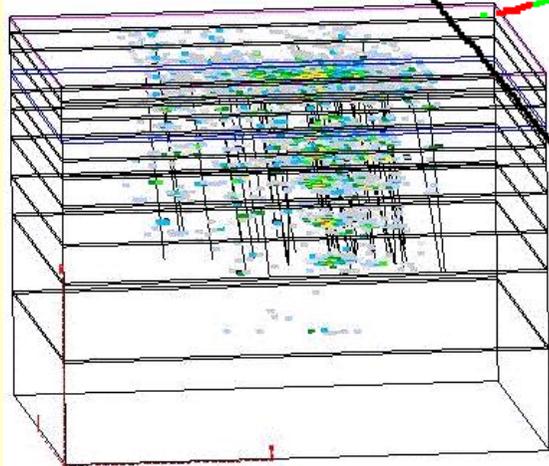
multiparameter
measurements of
single air showers

Energy
Mass
Direction
of the incoming cosmic particle

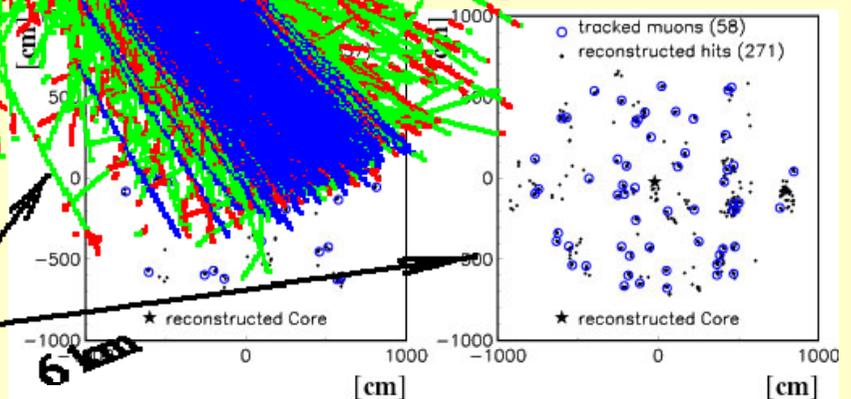
Array



Calorimeter



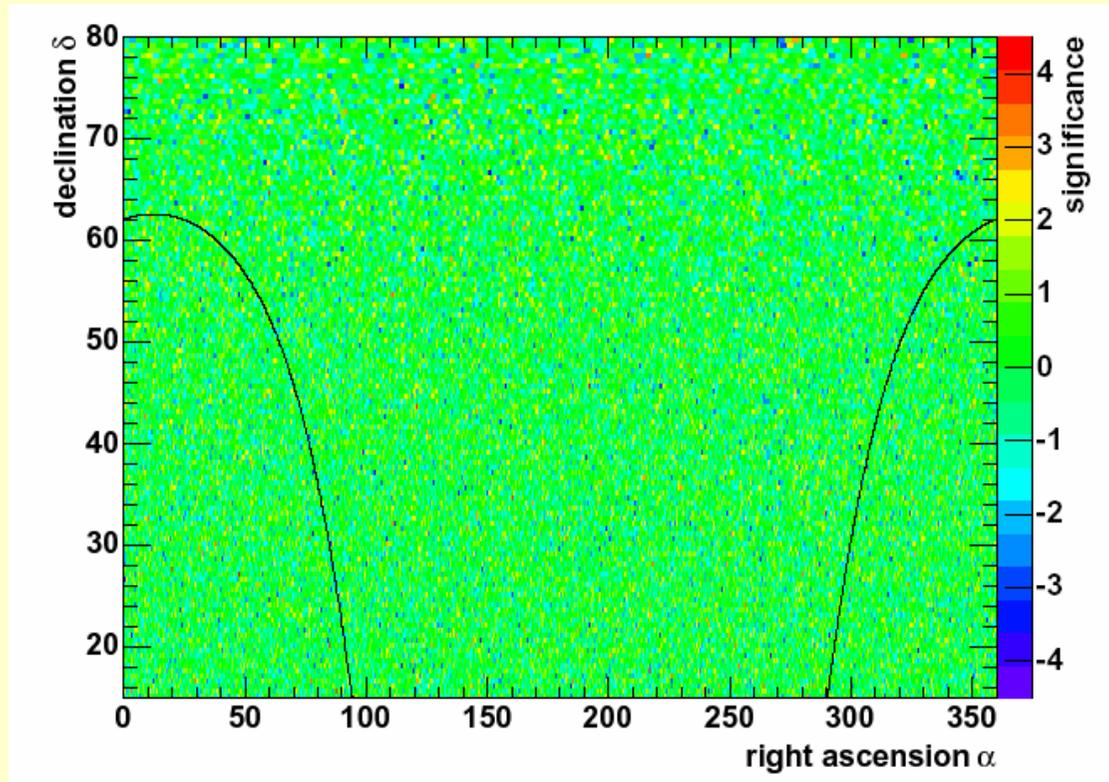
muon chambers



Results KASCADE:

→ sky plot of cosmic rays

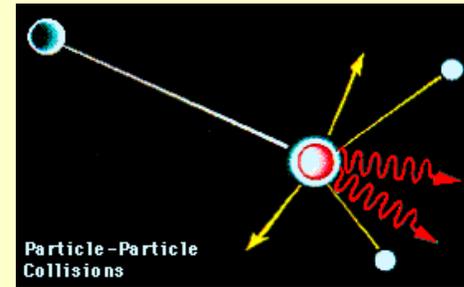
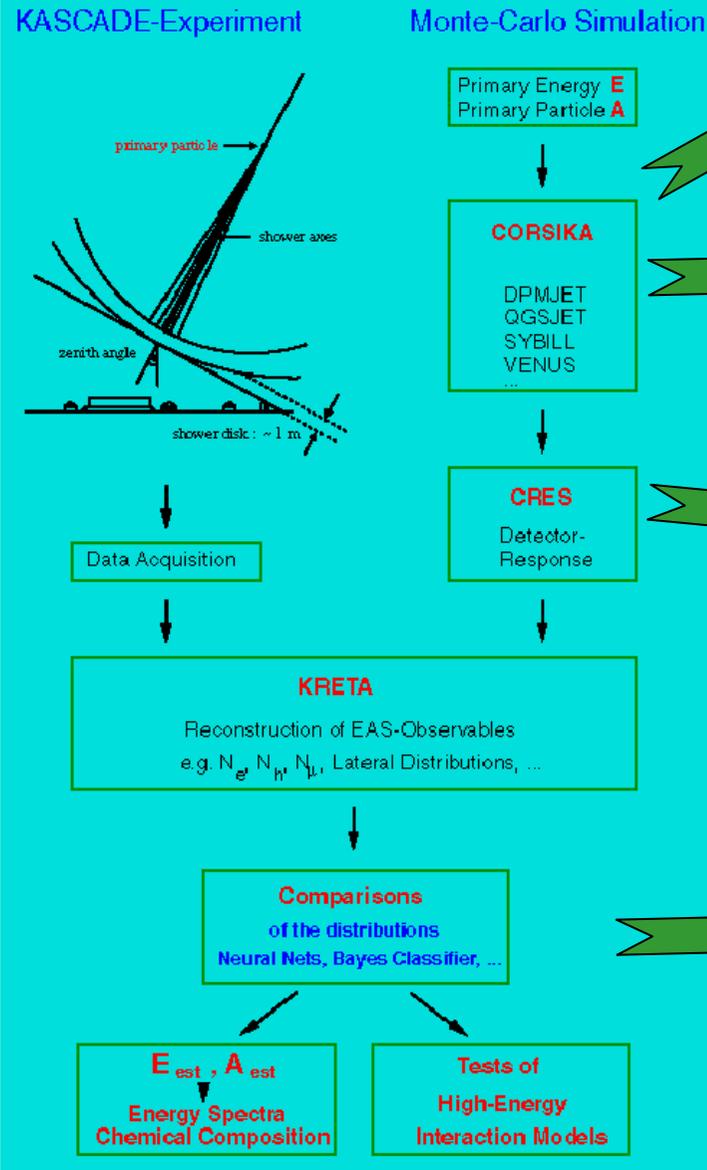
Analysis of arrival directions
and arrival times
(galactic coordinates):



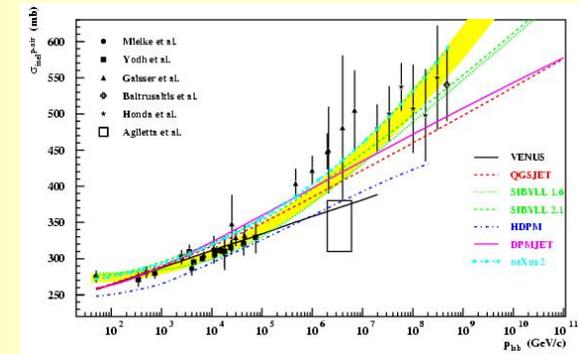
Results:

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

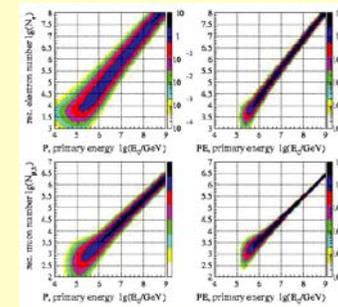
KASCADE - Methodics



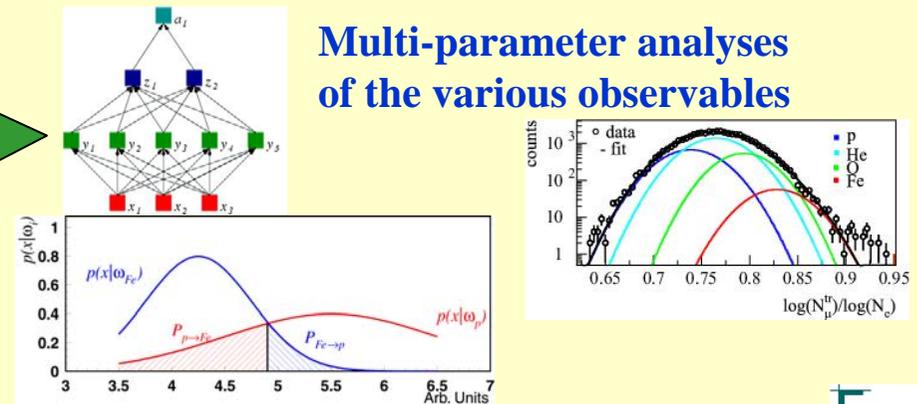
Air shower simulations



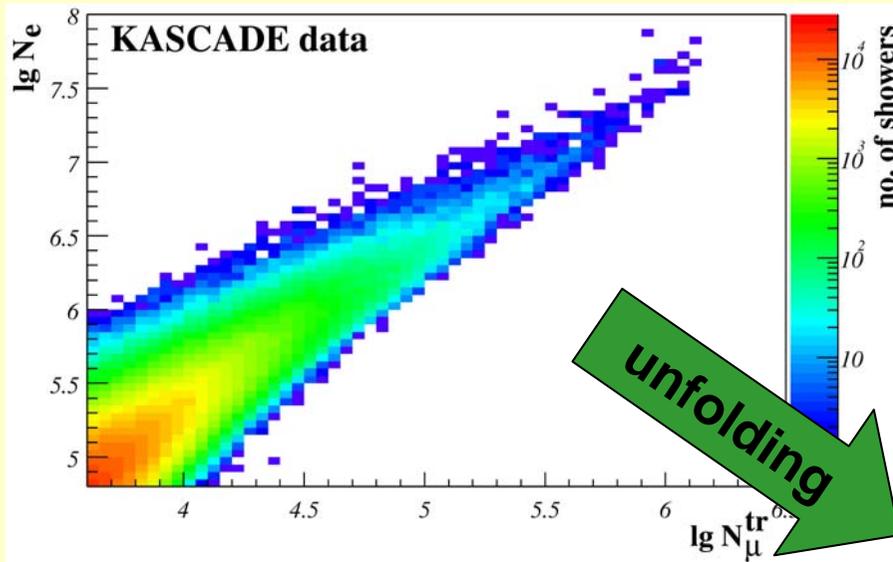
Detector simulations



Multi-parameter analyses of the various observables



Results KASCADE:

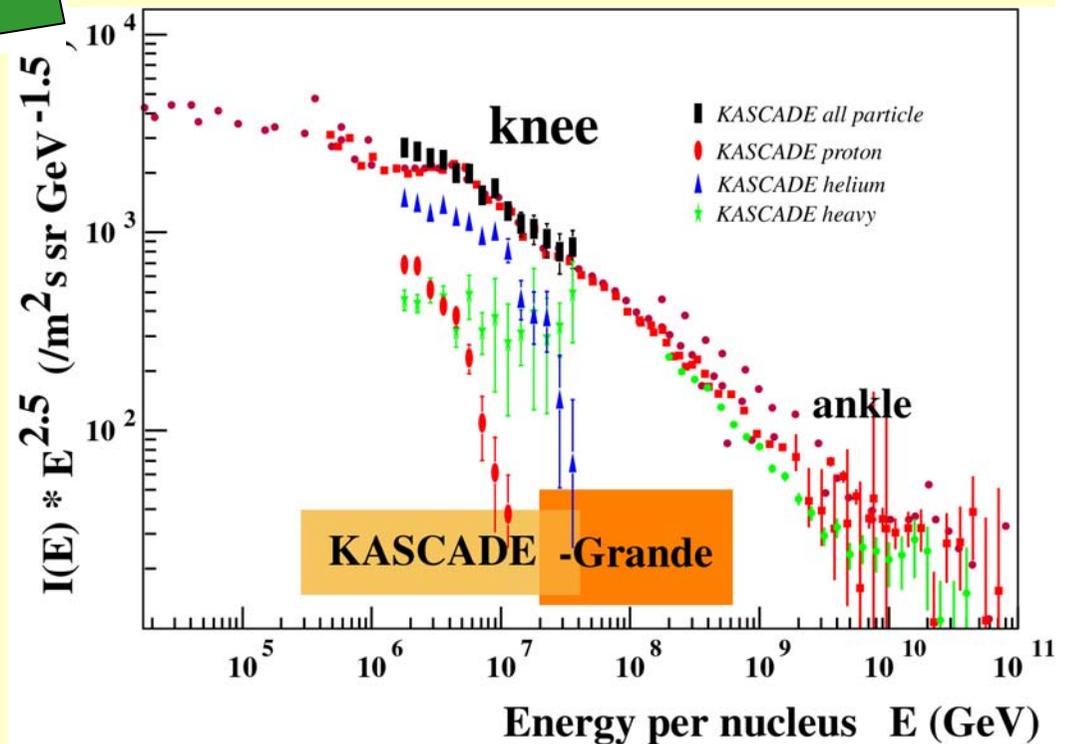


Analysis of 2-dimensional shower size spectrum:

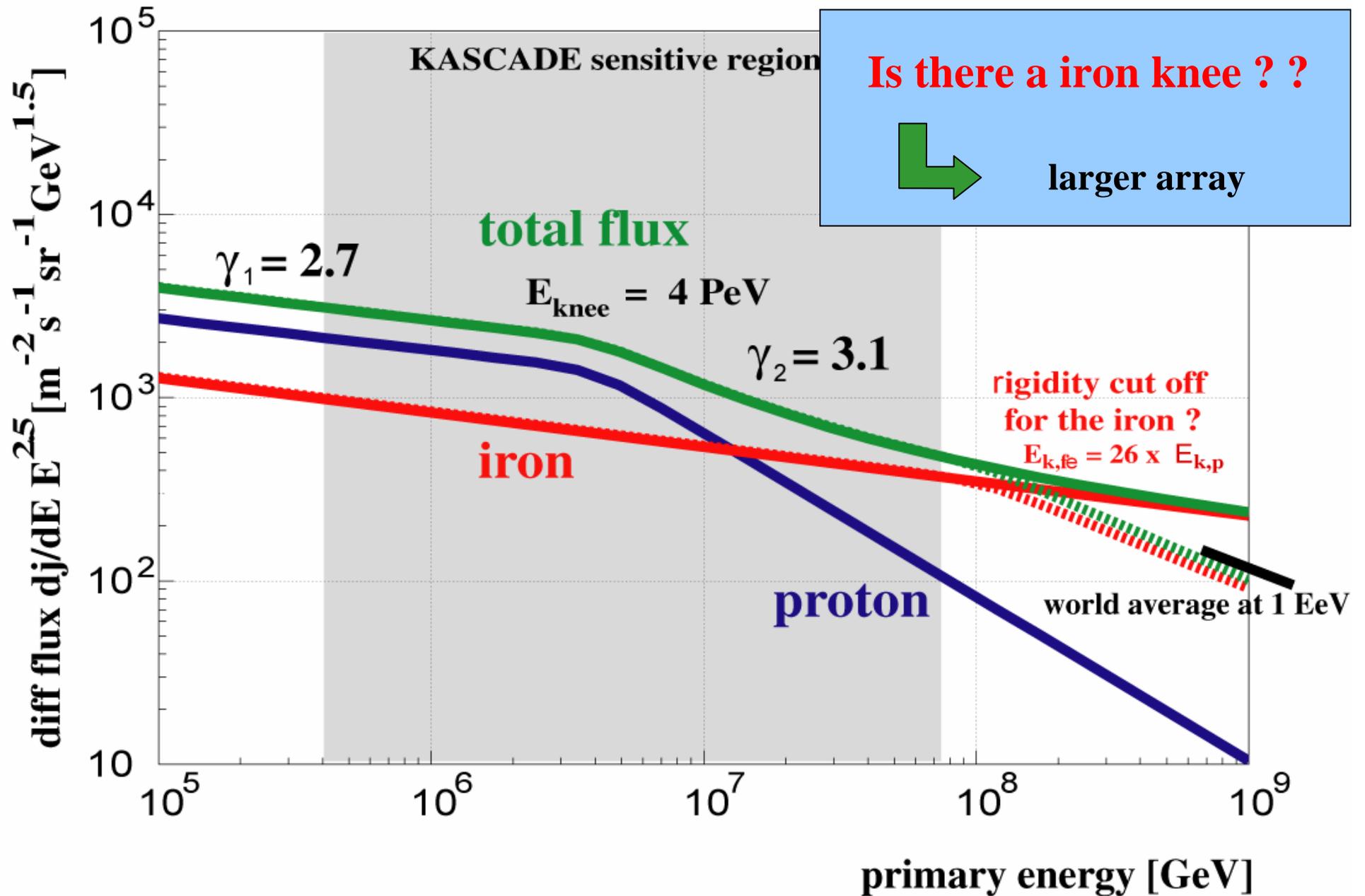
→ energy spectra of single mass groups

Results:

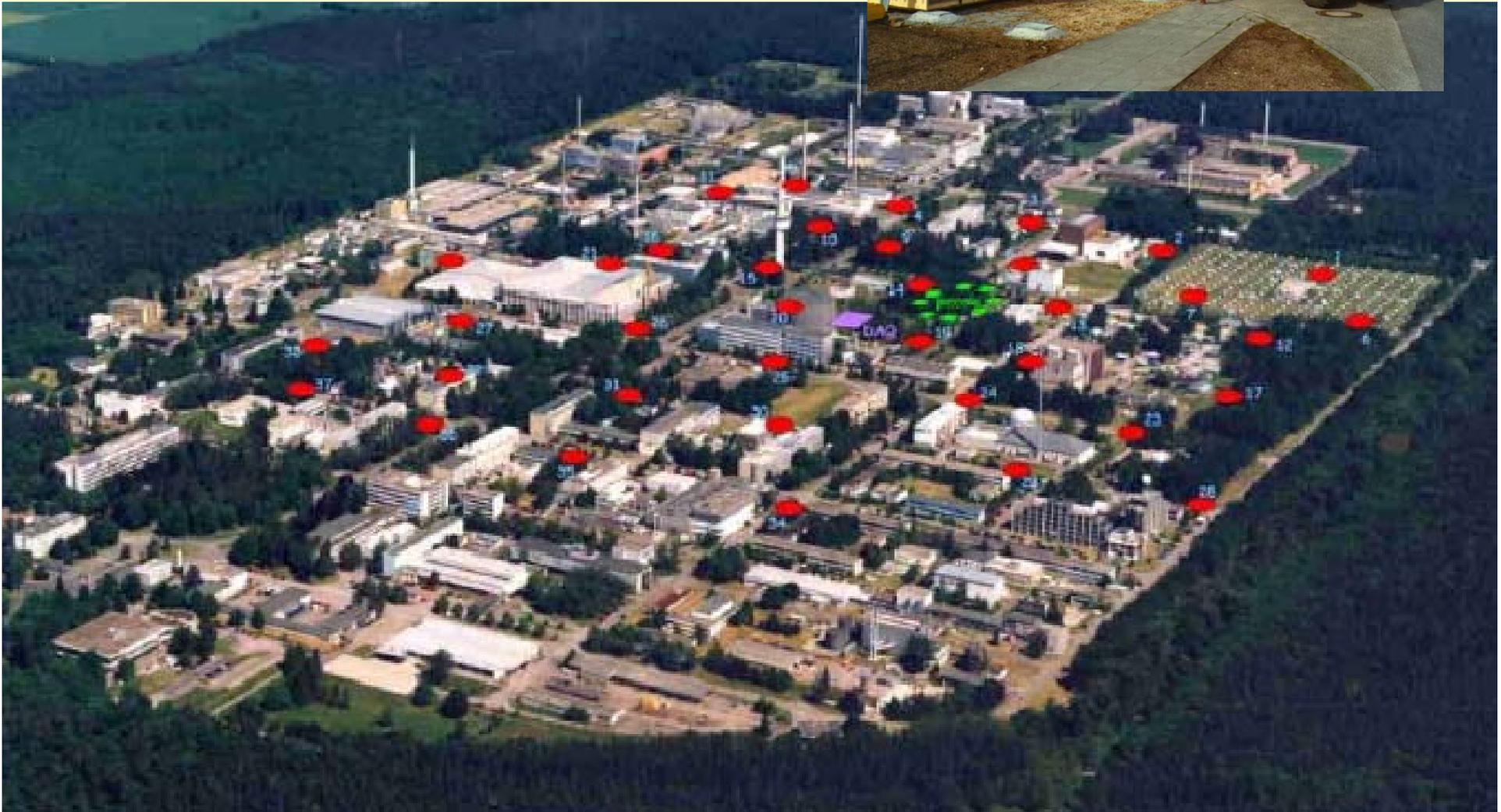
- knee is caused by light elements
- knee positions vary with mass group
- no hadronic interaction model describe data consistently



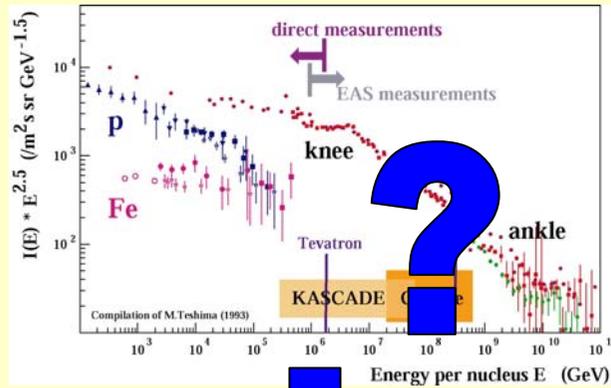
Results KASCADE:



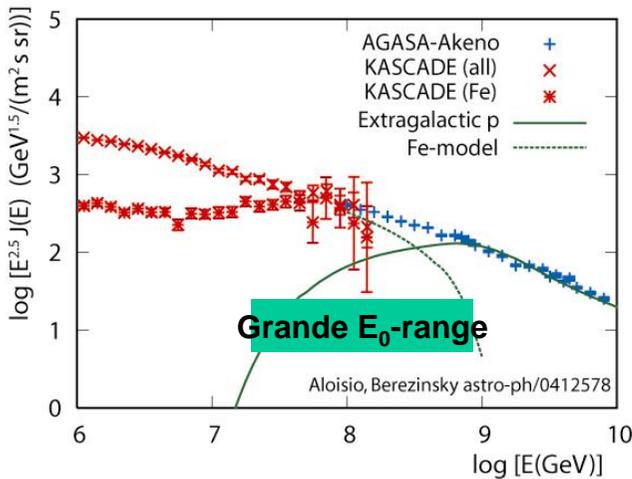
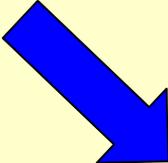
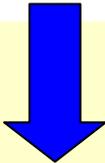
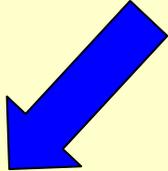
KASCADE – Grande 2003



The Grande energy region - Theories

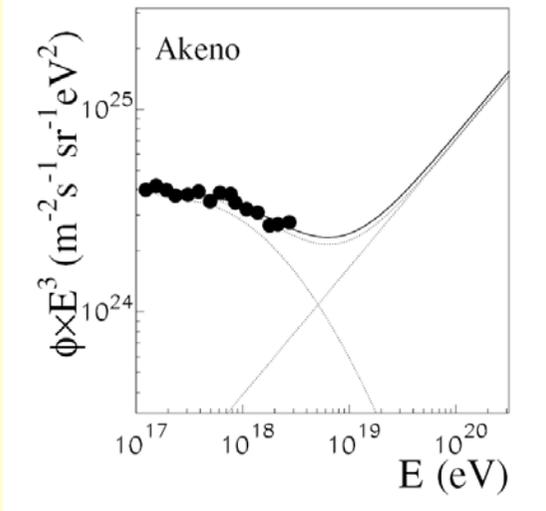


various theories on energy range 10^{17} - 10^{19} eV:



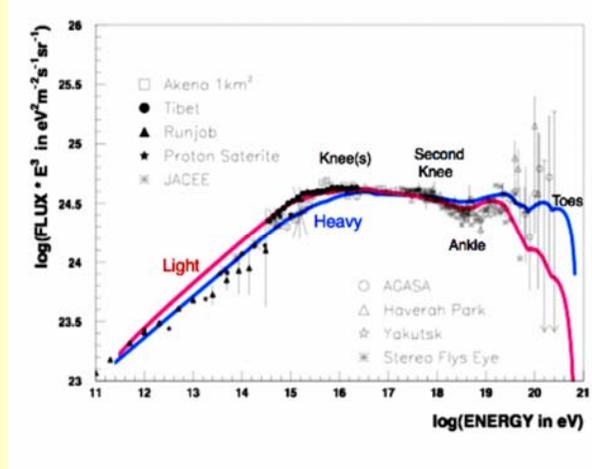
Fe-knee $\sim 10^{17}$ eV
gal-eg transition $\sim 10^{17.7}$ eV
Ankle = eg characteristics

e.g. Berezhinsky



Fe-knee $\sim 10^{18}$ eV
gal-eg transition $\sim 10^{19}$ eV
= ankle

e.g. Wibig et al

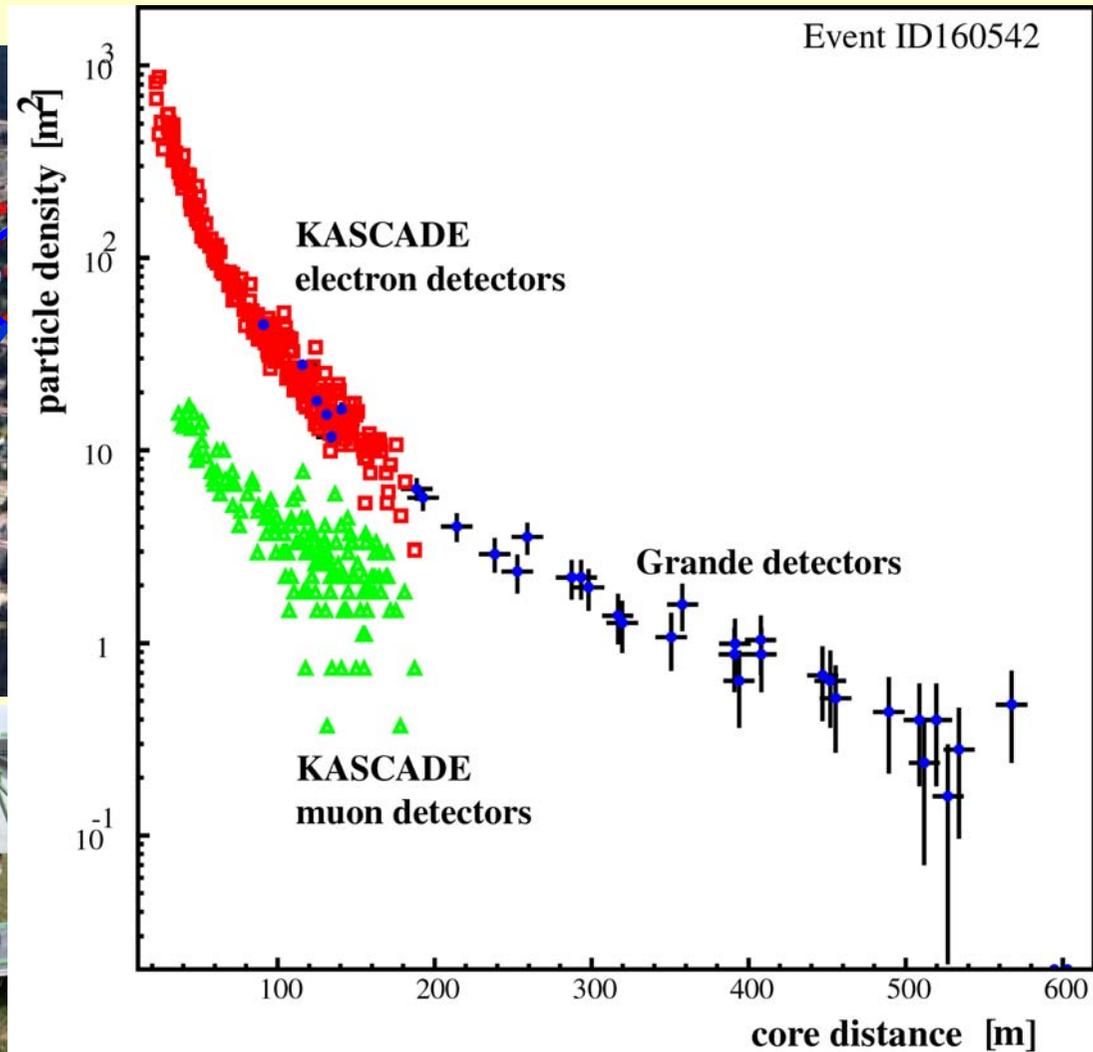
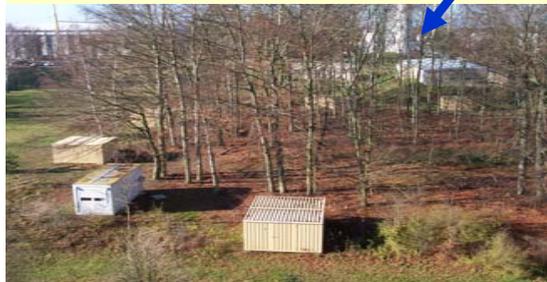
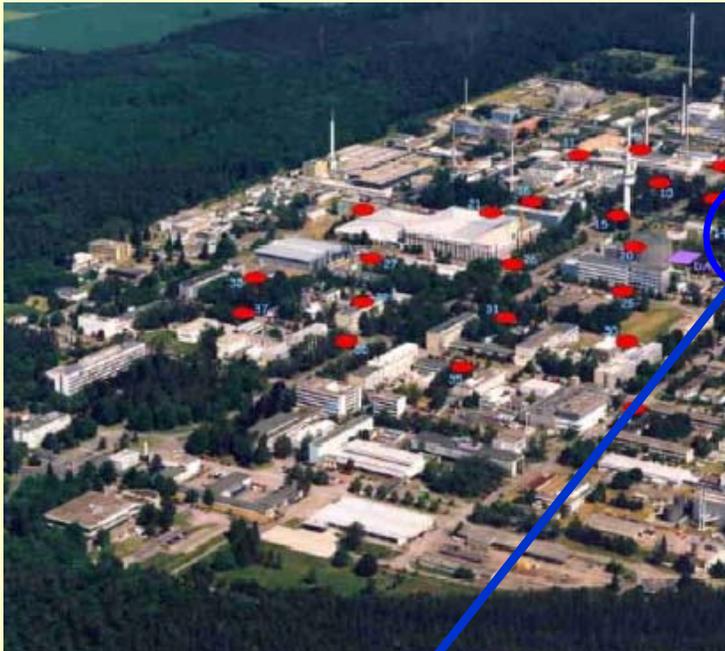


Cannonball modell:
All is galactic
(knee= elastic scattering)

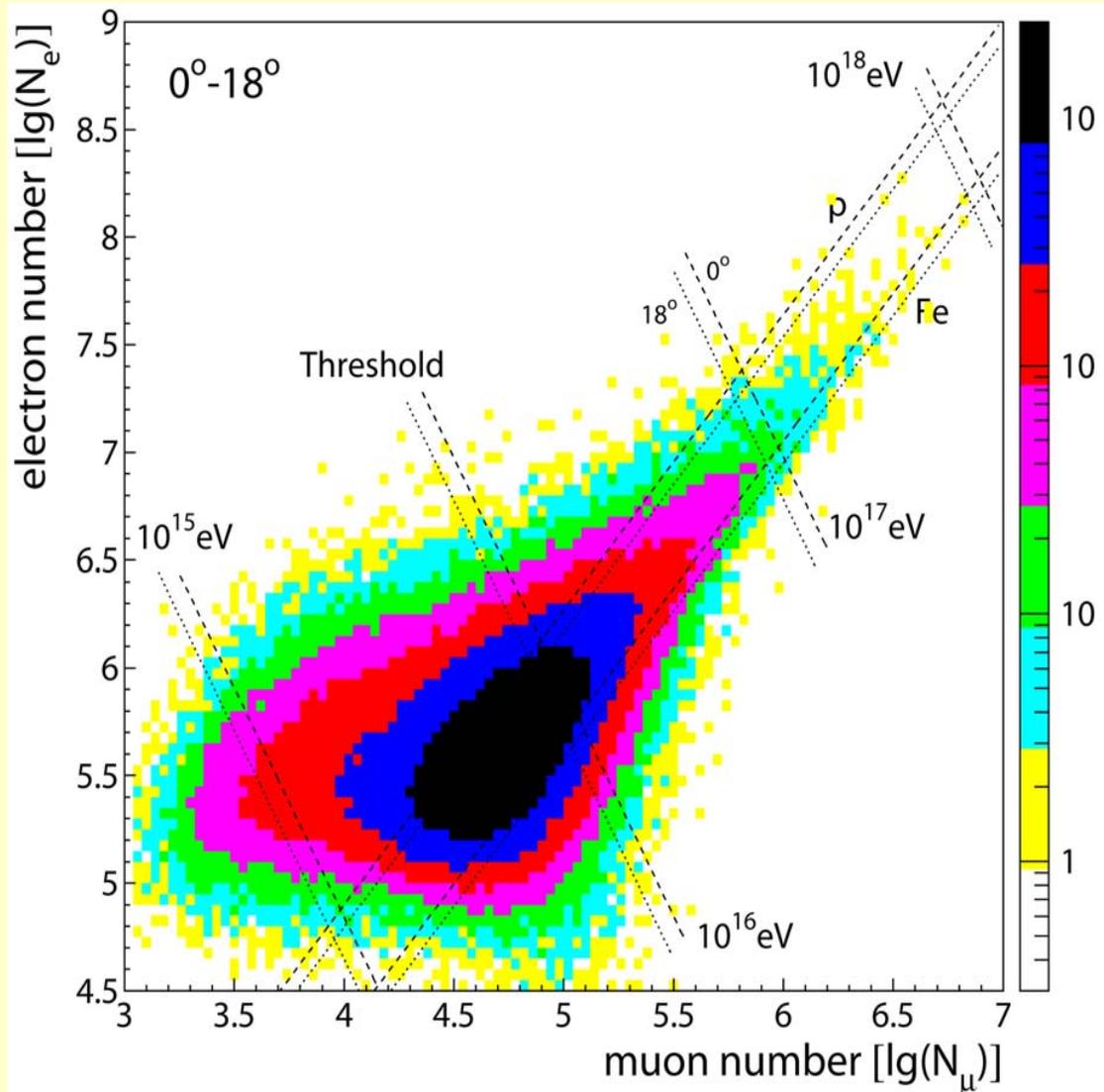
e.g. de Rujula

KASCADE - Grande

Measurements of air showers in the energy range $E_0 = 100 \text{ TeV} - 1 \text{ EeV}$



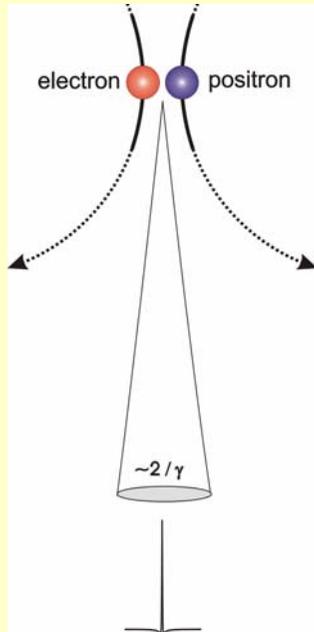
KASCADE – Grande: Status



- 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.

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



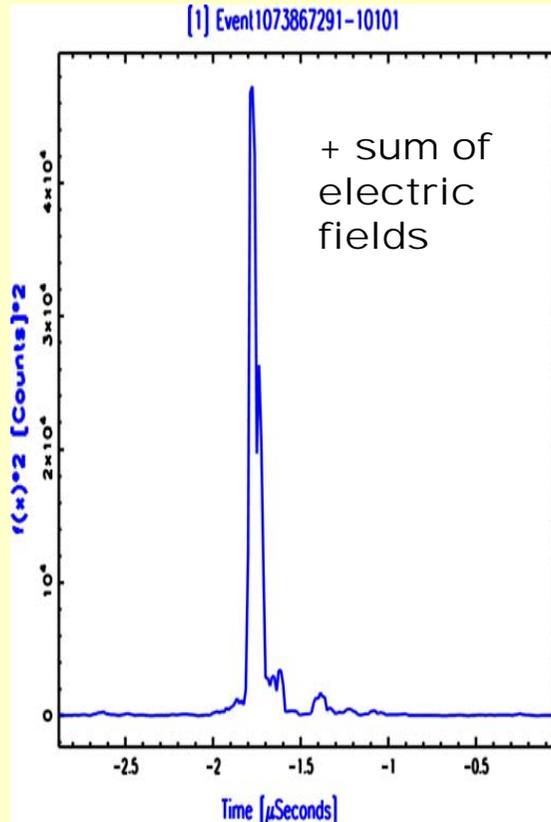
Main goals:

Proof of principle

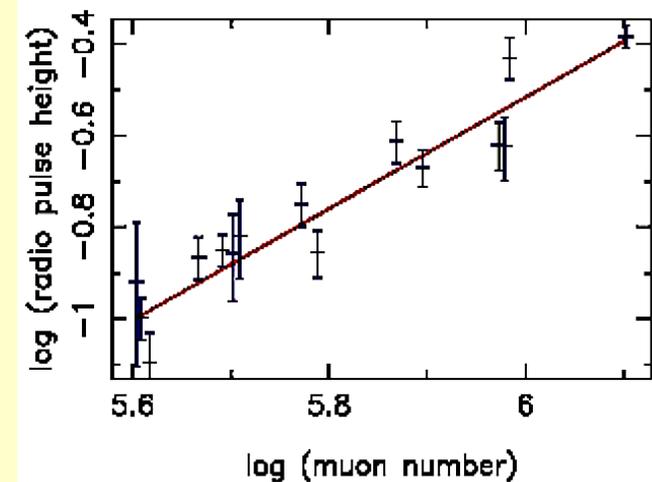
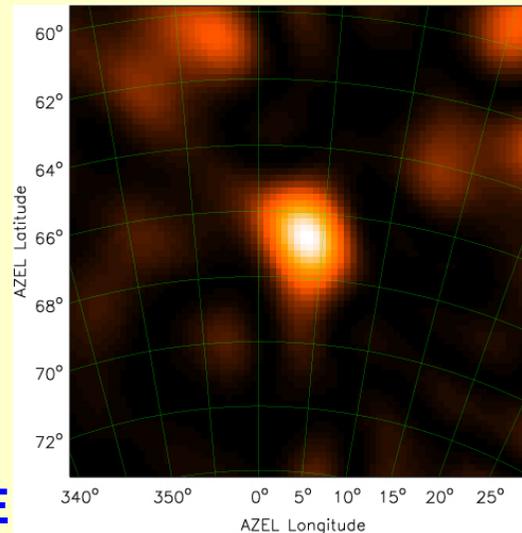
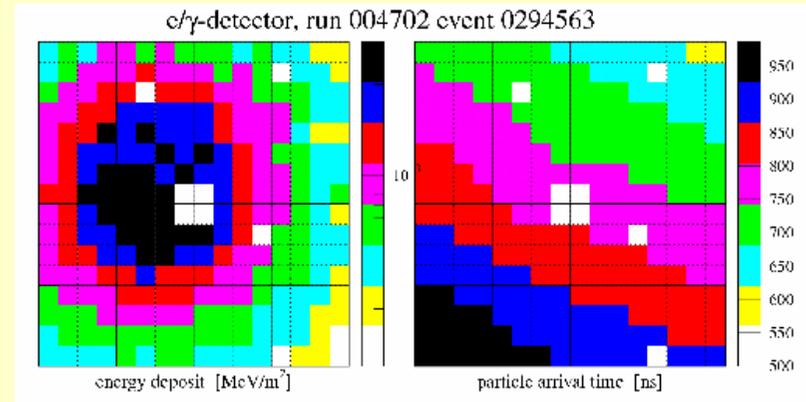
Establish radio measurements as new detection technique

Calibration of radio emission

LOPES radio measurements:



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

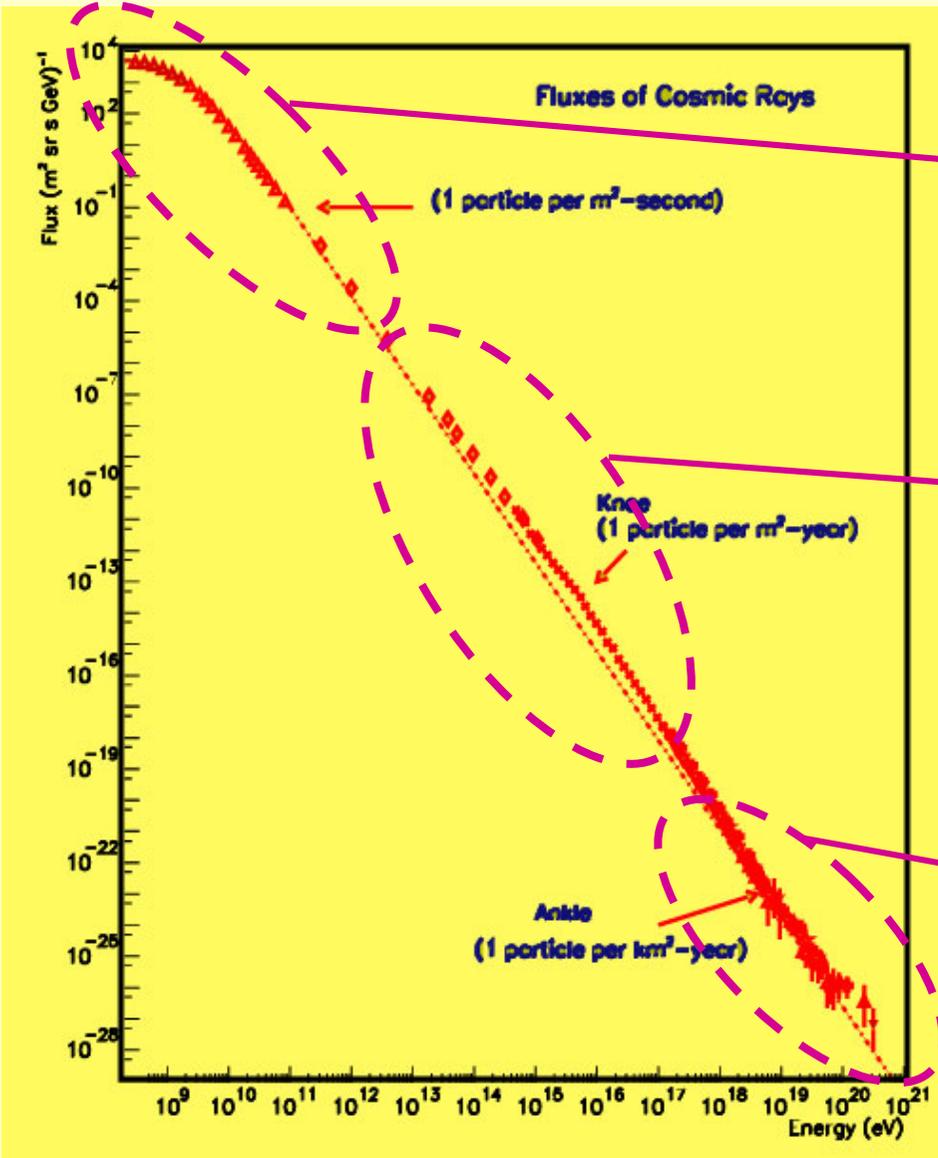


data analyses:

- EAS analyses KASCADE
- radio signal analyses
- sky mapping

LOPES collaboration,
Nature 425 (2005) 313

Cosmic rays – the energy spectrum



low energies

→ direct measurements

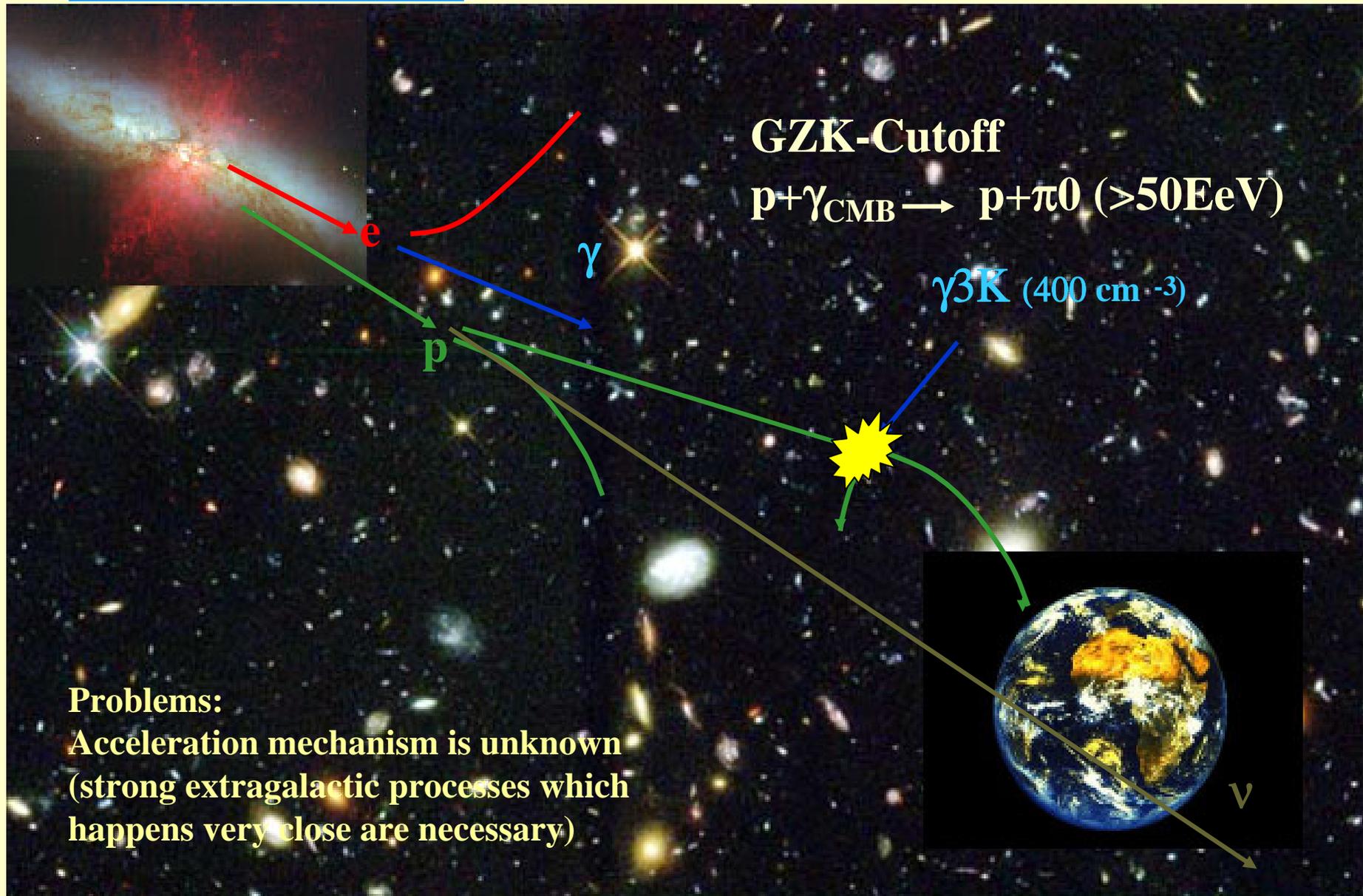
the knee

→ air shower measurements

ultra high energies

→ they should not exist

The GZK Cutoff



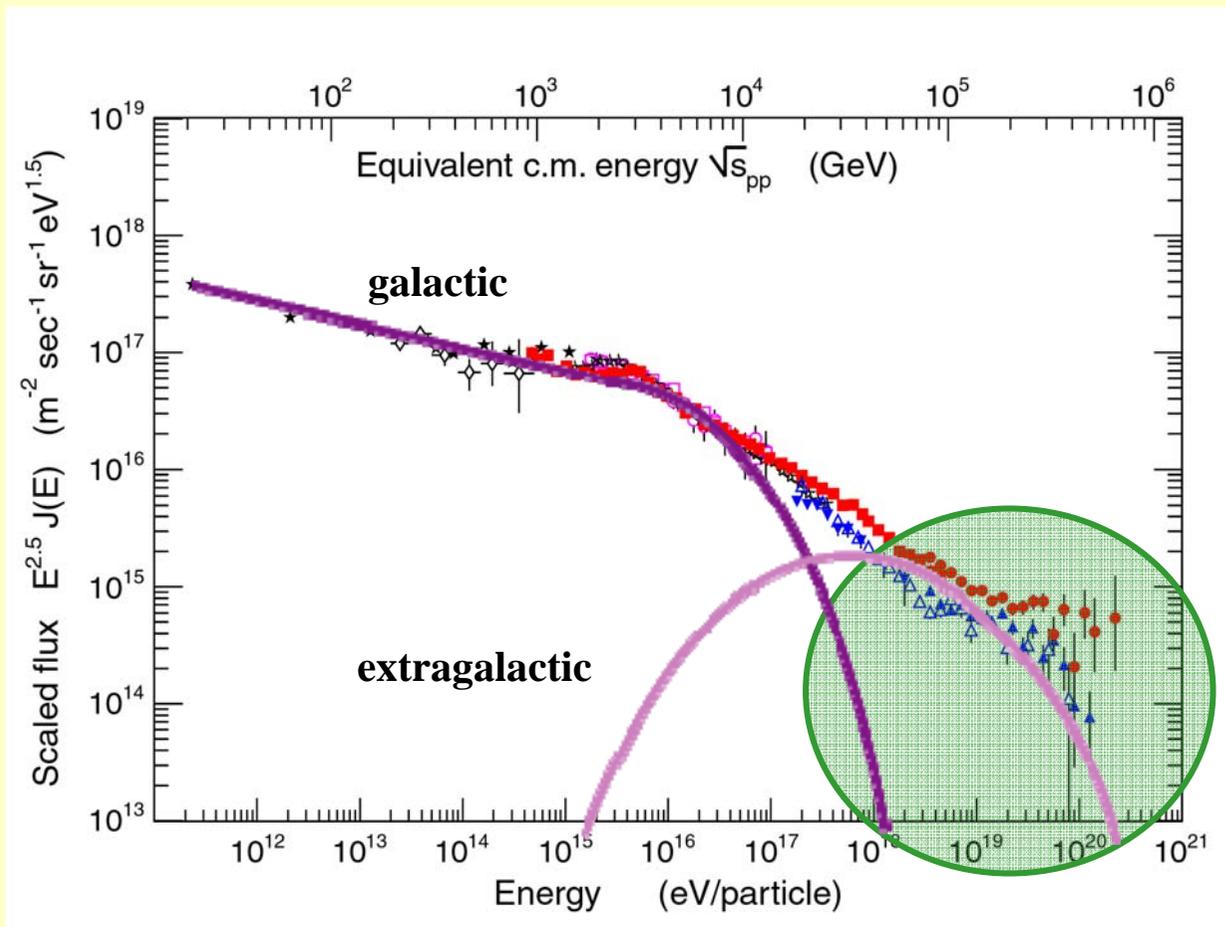
Highest Energies

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

Measurements by
or

large particle detector arrays (AGASA → no cutoff)

fluorescence telescopes (HiRes → cutoff)



The Pierre Auger Project

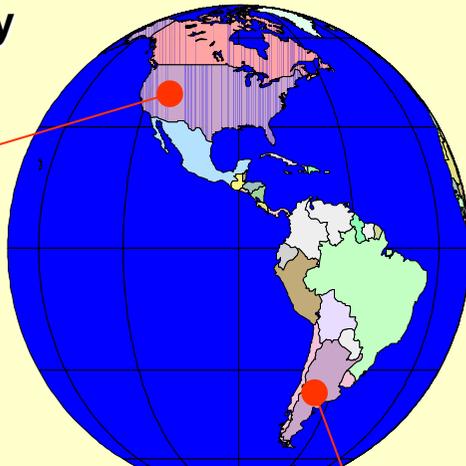
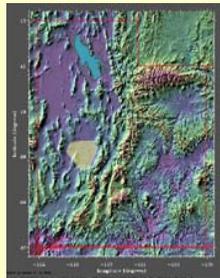
Southern hemisphere:

**Data taking since 2002
final setup 2006 ?**

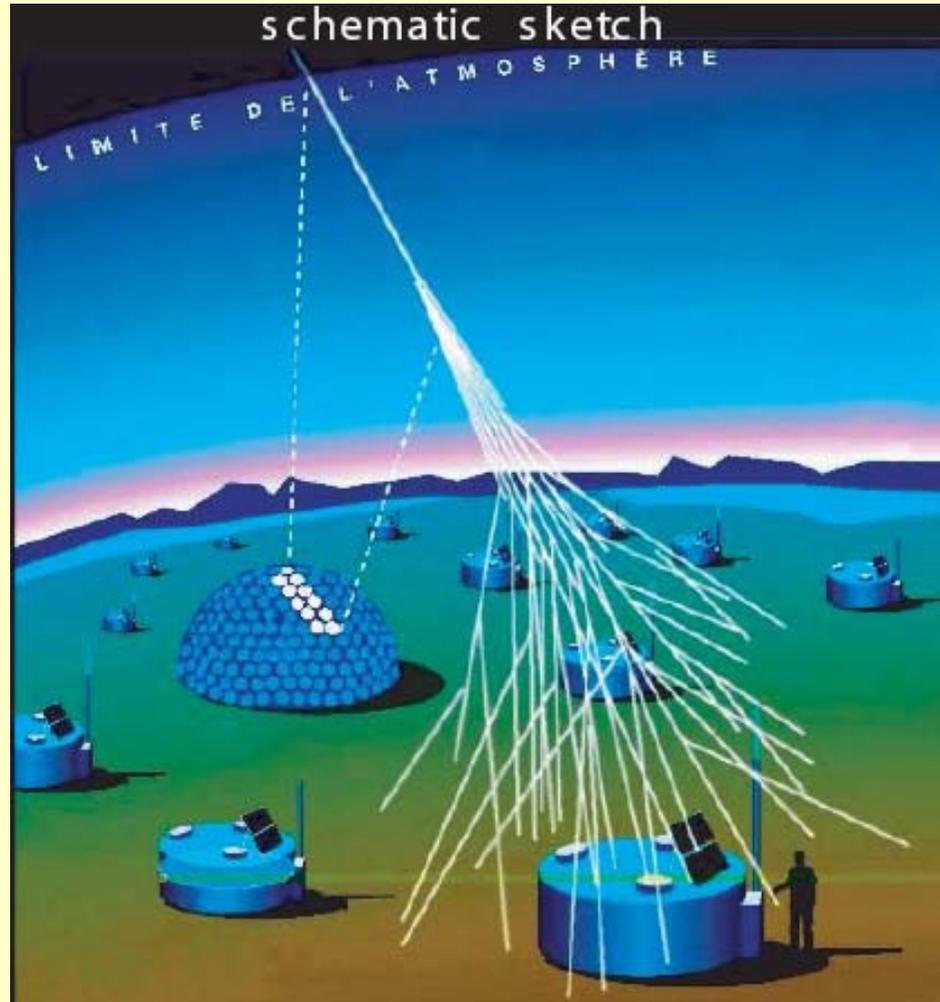
Northern hemisphere:

start of deployment 2008 ?

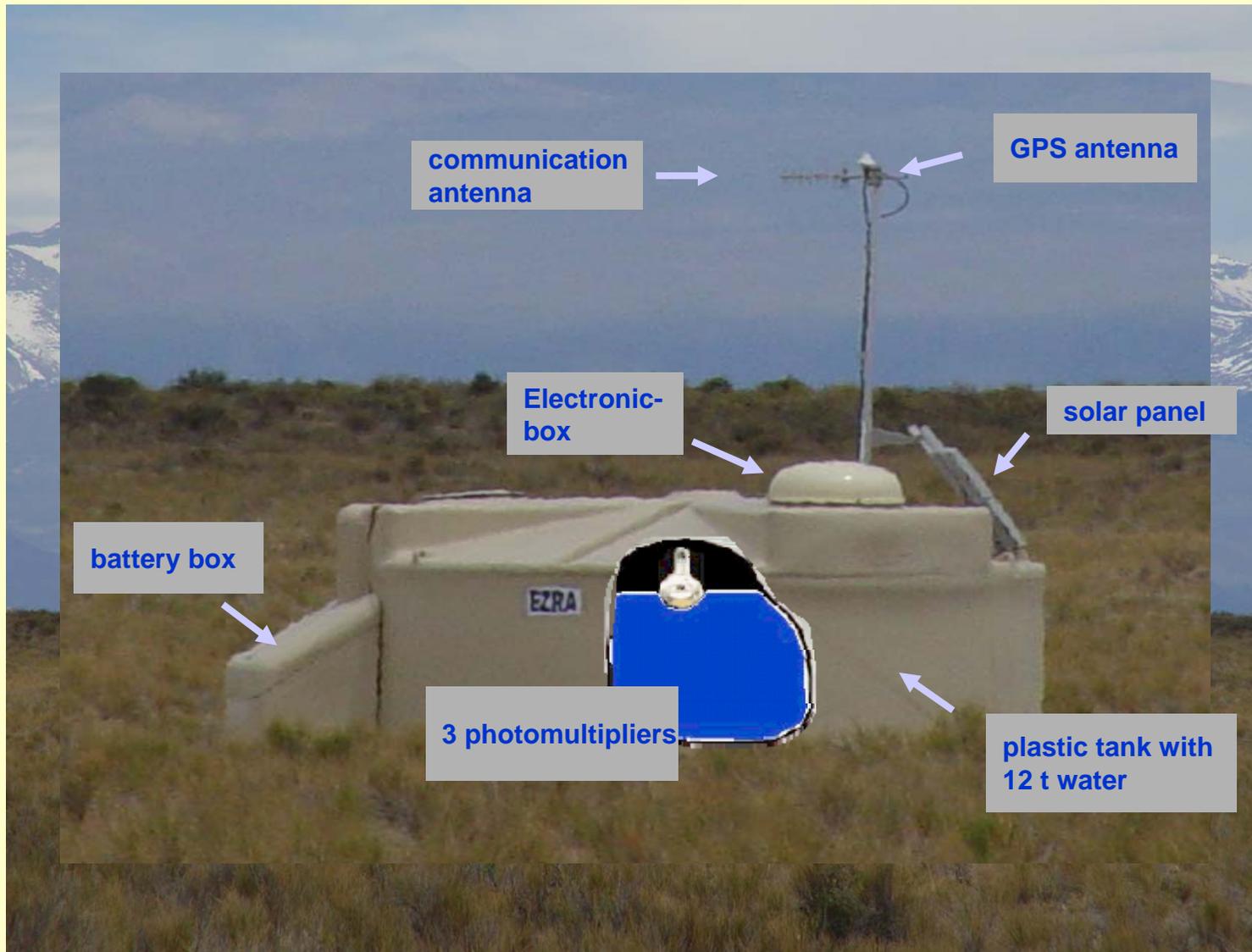
**Northern site
Millard County
Utah, USA**



**Southern site
Malargue
Argentina**



Water – Cherenkov Detector



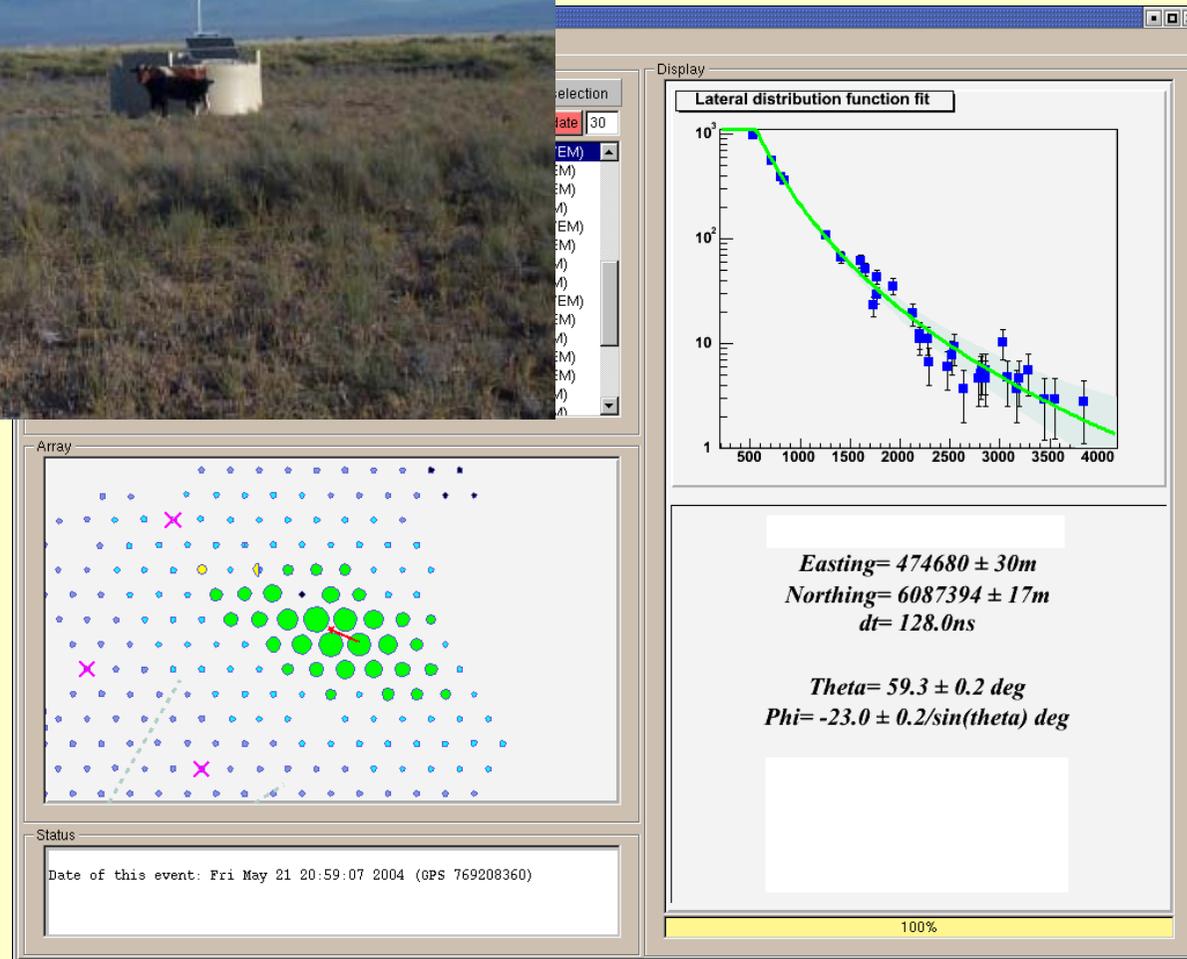
The Pierre Auger Project



Surface Array

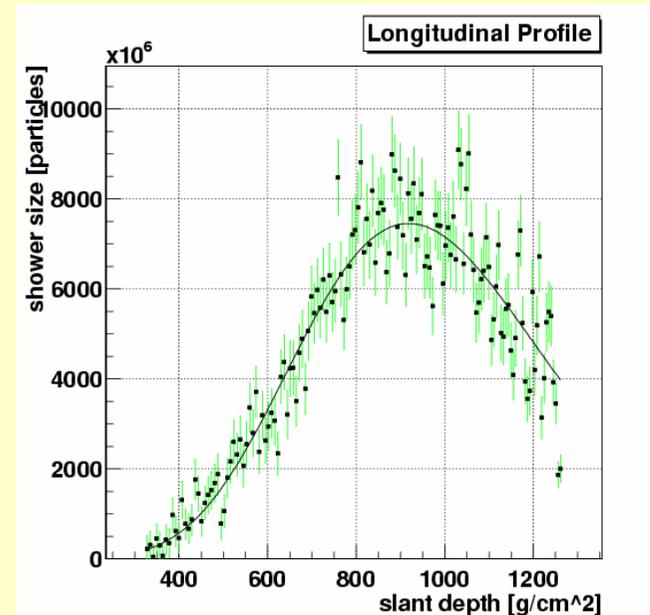
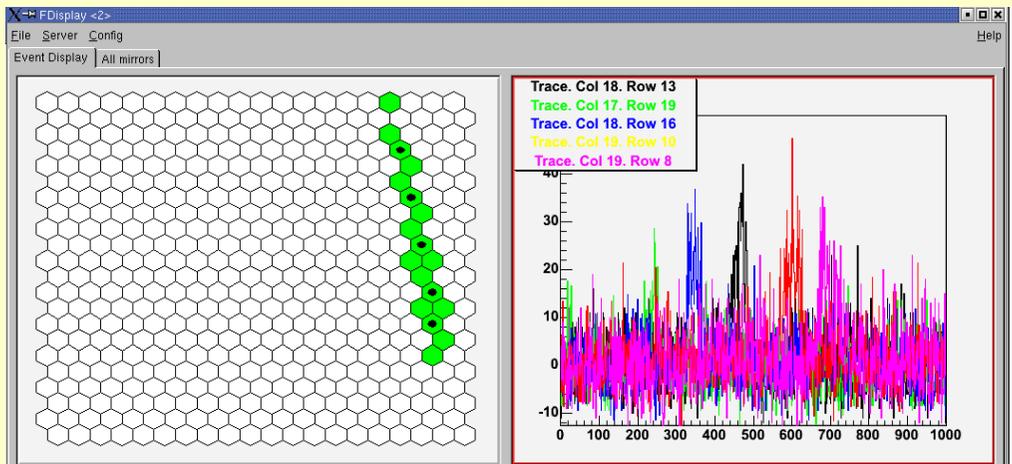
Measurements and further set up
in operation

First events close
and above 10^{20} eV



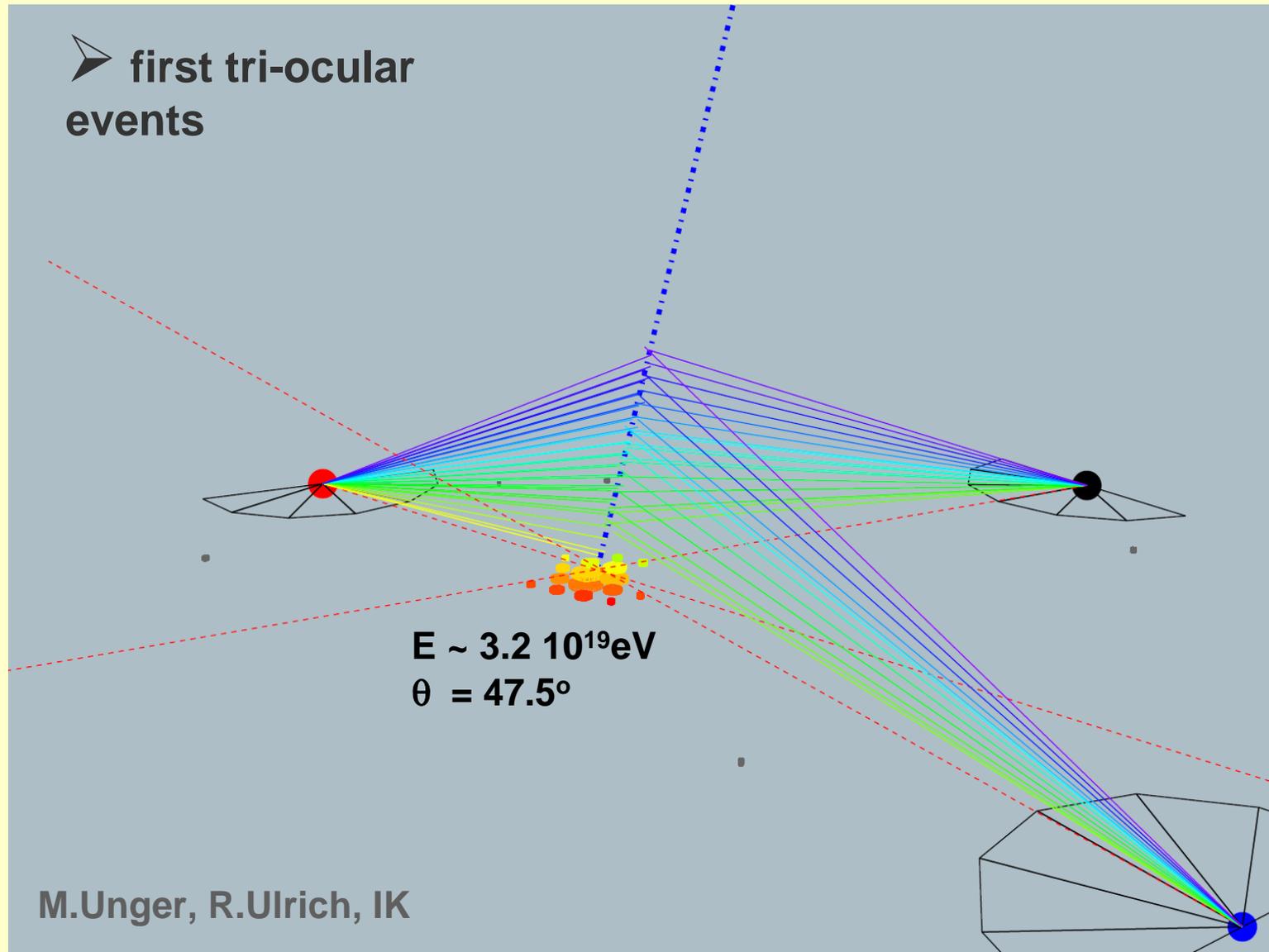
The Pierre Auger Project

Fluorescence Detectors

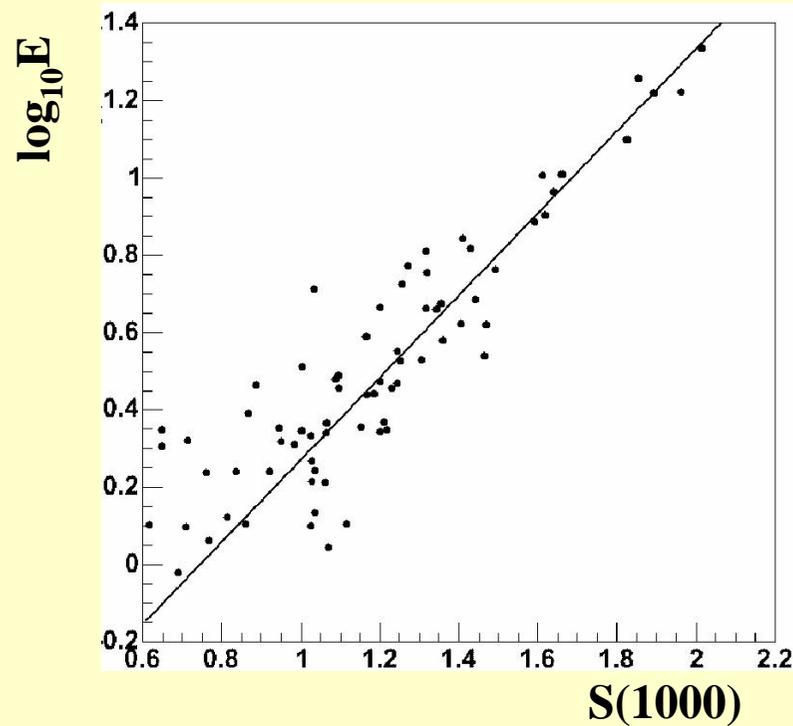


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First results



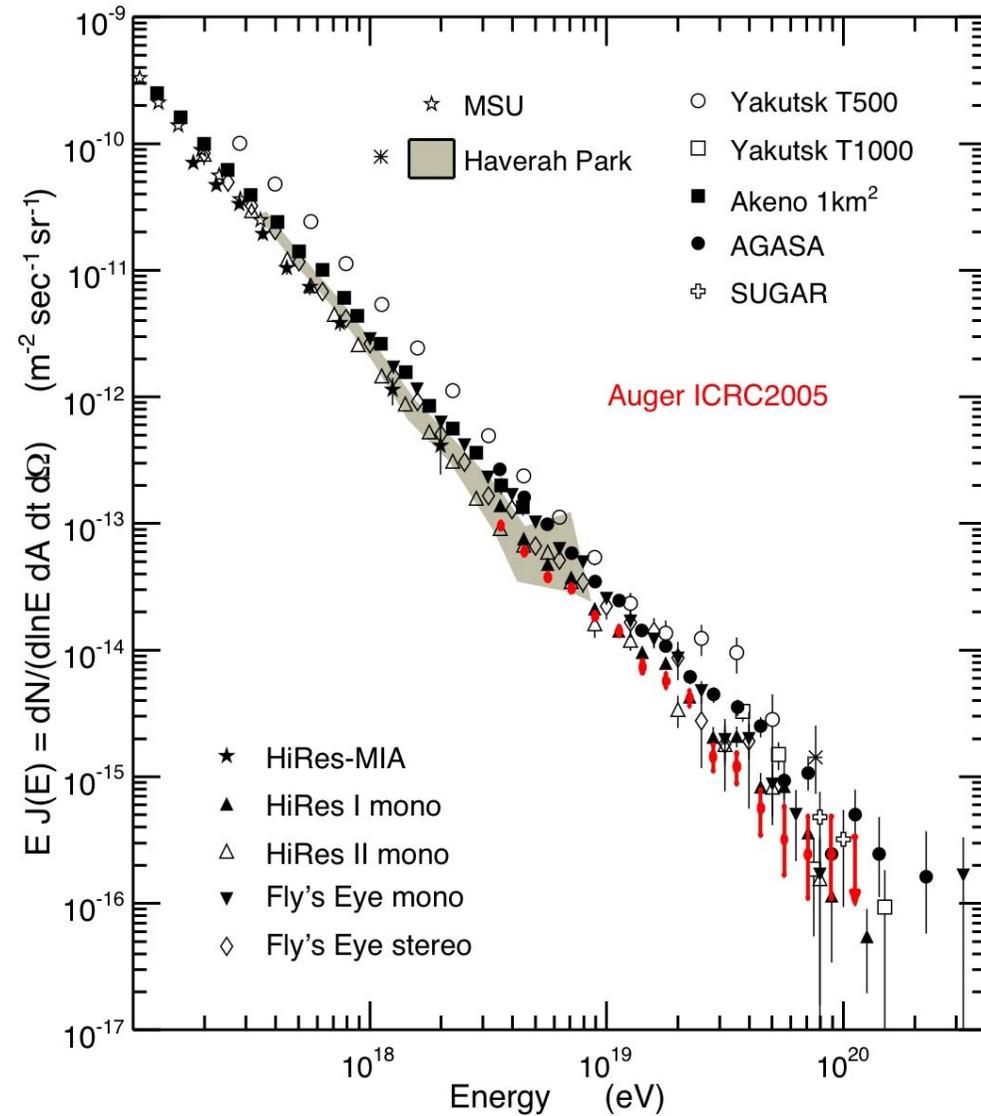
The Pierre Auger Project



Hybrid events: Energy estimation by fluorescence light measurements

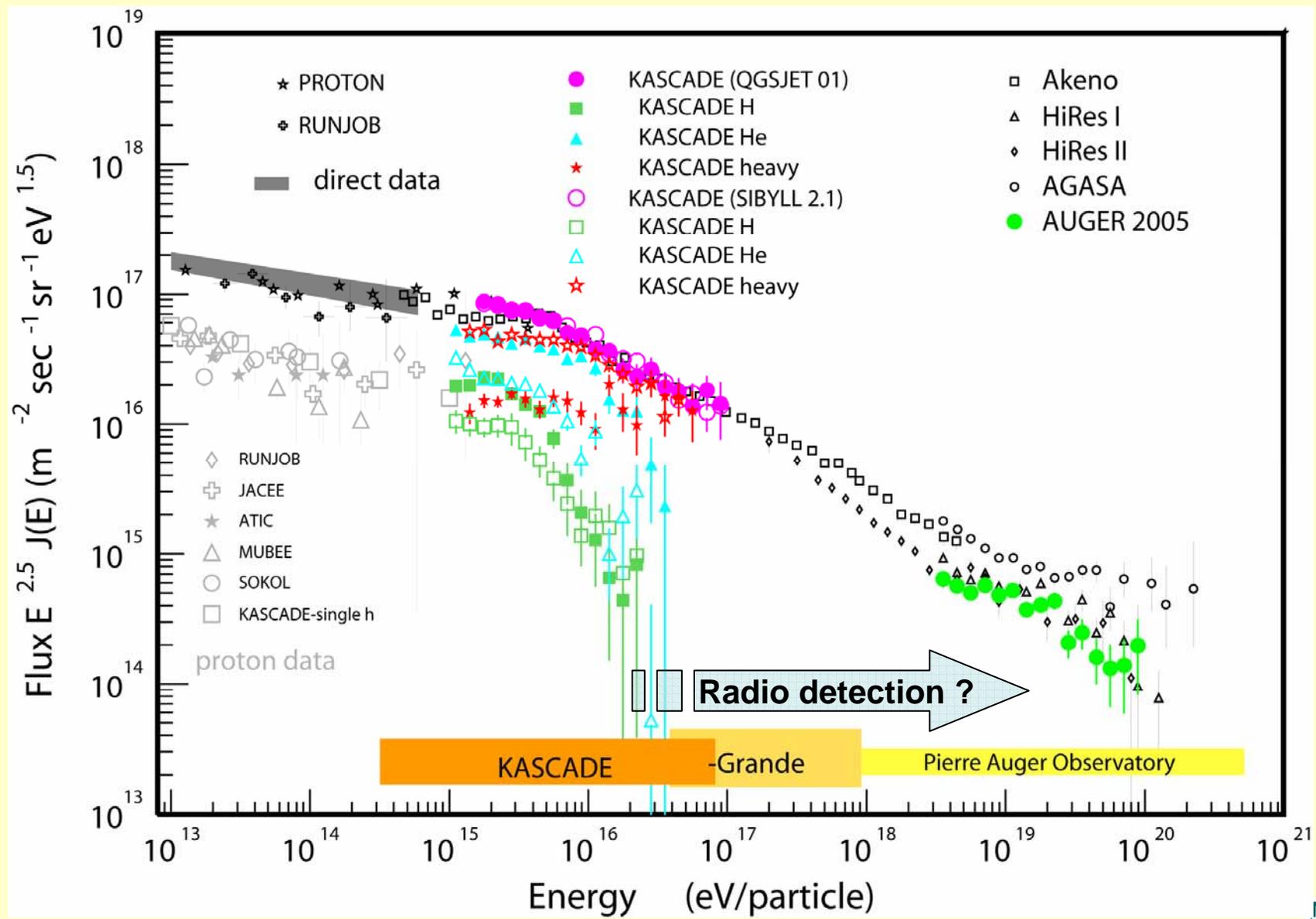
Result will improve by higher statistics and new (better) analysis procedures

First results: Energy Spectrum



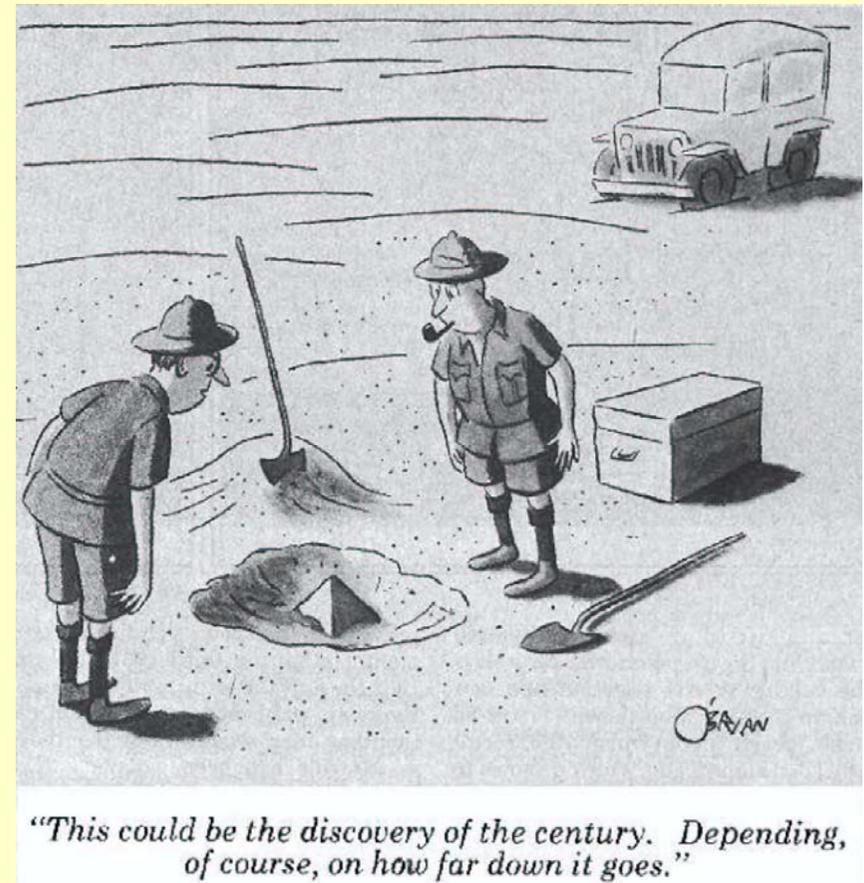


Conclusions



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 composition?
- 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 ?



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



**become
researcher !!**

