KIT – University of the State of Baden-Württemberg and National Research Center of the Helmholtz Association

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Experimental High-Energy Astroparticle Physics

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Astroparticle Physics

Content:

1. Introduction in HEAP
   - source-acceleration-transport
   - short history of cosmic ray research
   - extensive air showers
2. High-Energy Cosmic Rays
   - KASCADE, KASCADE-Grande and LOPES
3. Extreme Energy Cosmic Rays
   - Pierre Auger Observatory, JEM-EUSO
4. TeV-Gamma-rays & High-energy Neutrinos
   - TeV gamma rays

     H.E.S.S., MAGIC, CTA
   - high-energy neutrinos

     IceCube and KM3Net

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   - **TeV gamma rays**

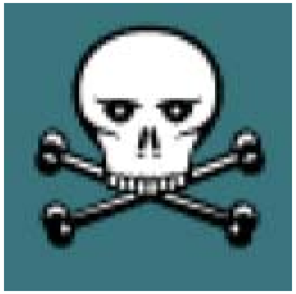
     H.E.S.S., MAGIC, CTA
   - **high-energy neutrinos**

     IceCube and KM3Net

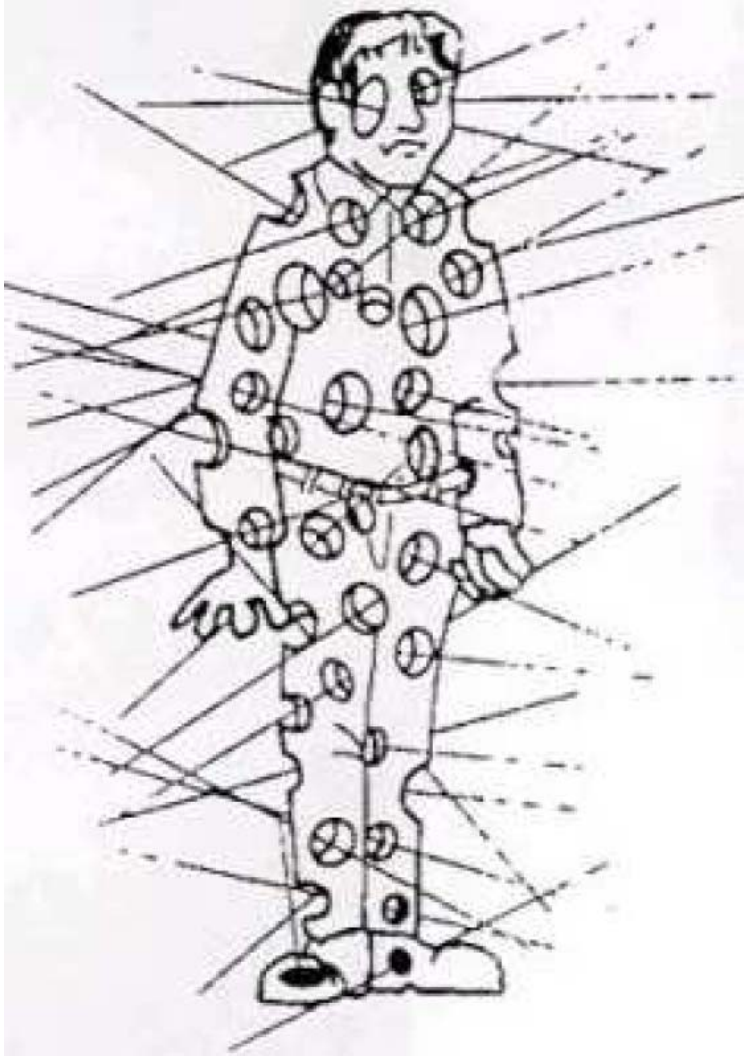
What are cosmic rays ?

= high-energy, extraterrestric particles

Warning:



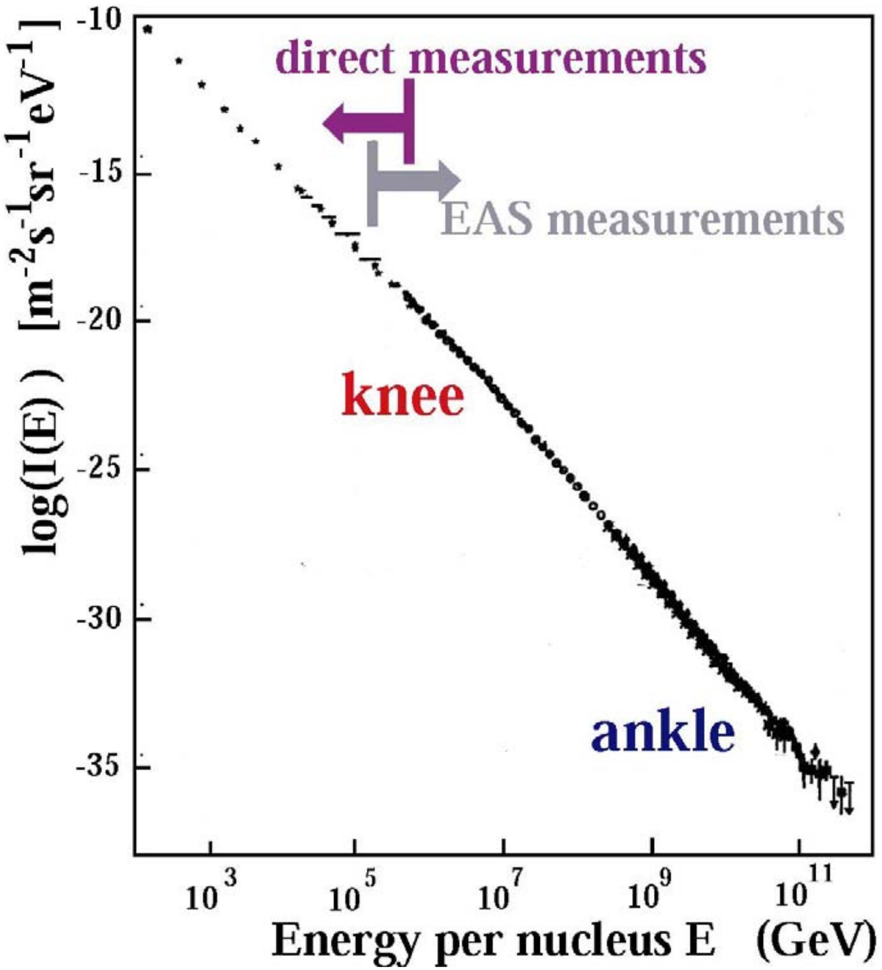
c. 100.000 particles will pass your body in each 1 hour !!



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

Charged Cosmic Rays: the energy spectrum



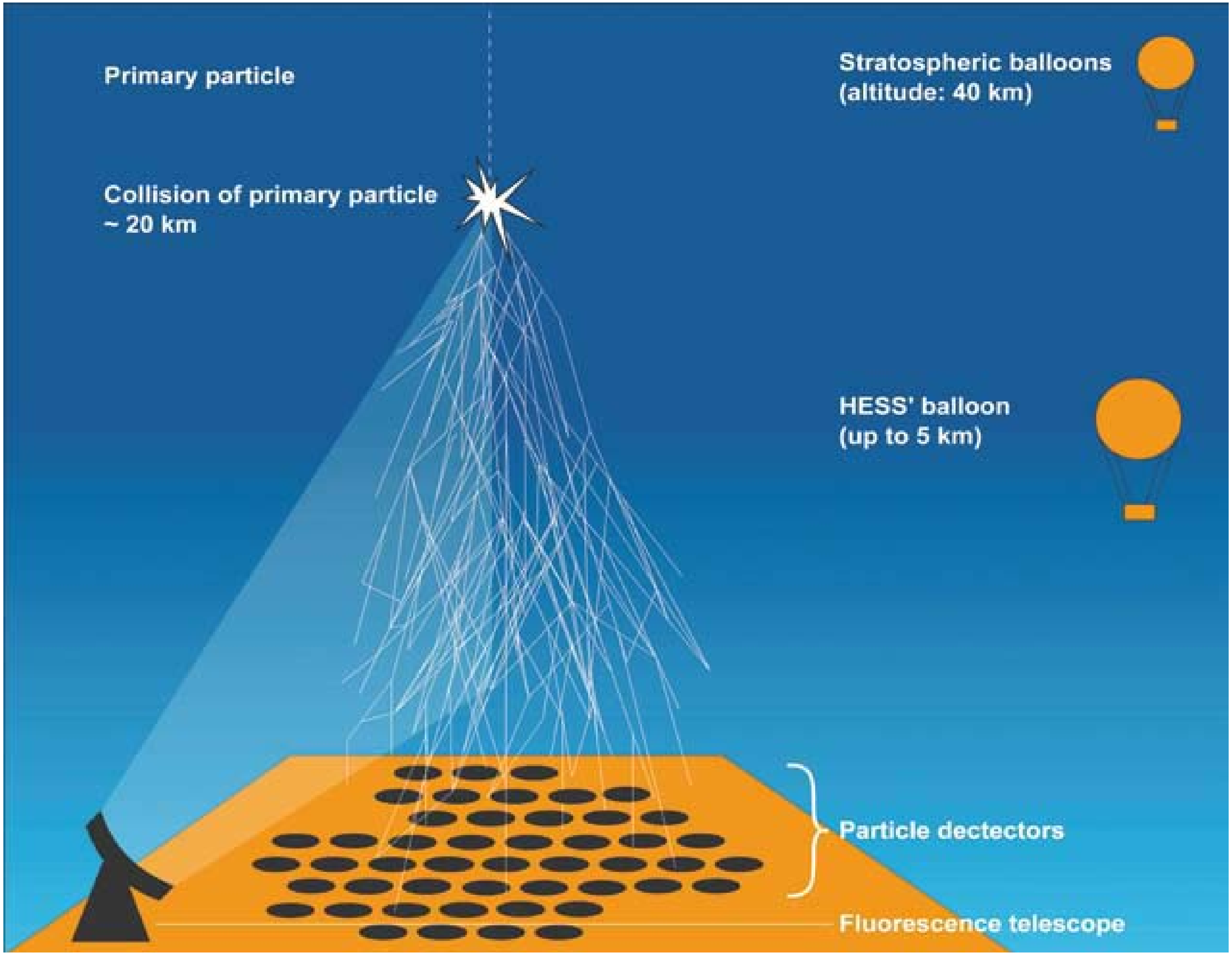
← 1 particle per m^2 s

← 1 particle per m^2 year

← 1 particle per km^2 year

above 10^{14} eV : Only indirect measurements possible !

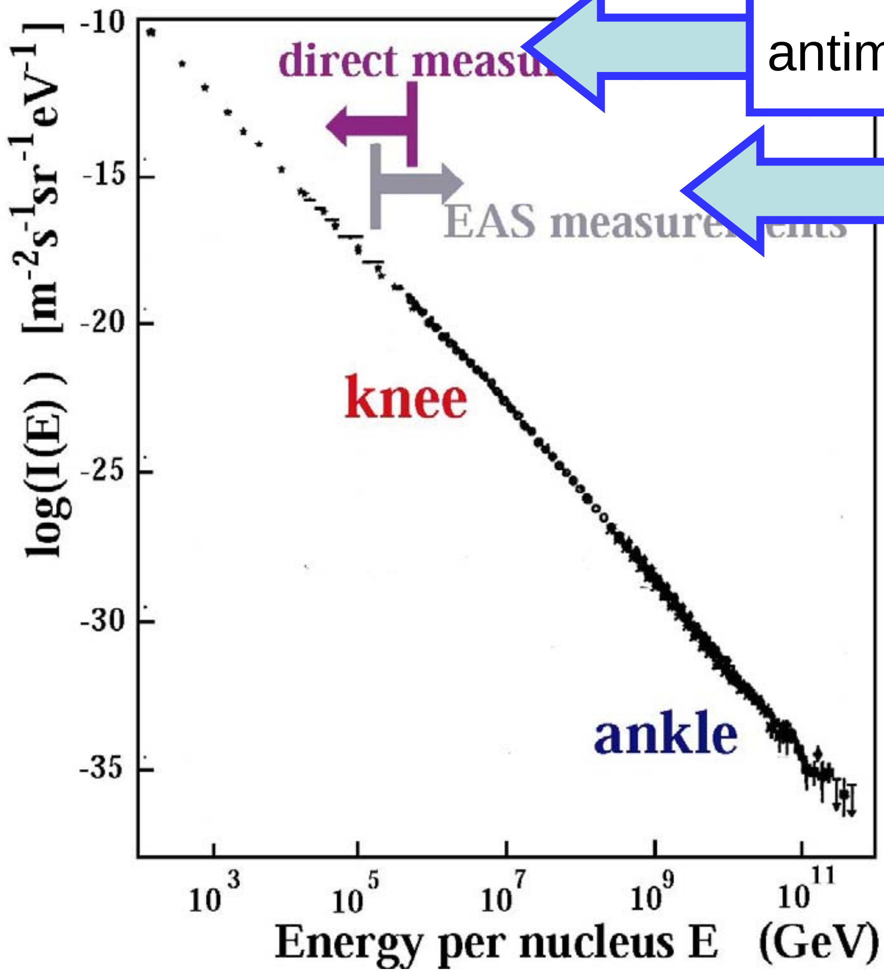
Cosmic rays – air shower measurements



above 10^{14} eV : Only indirect measurements possible !

→ **EAS**

Charged Cosmic Rays: the energy spectrum



antimatter, dark matter, mass composition

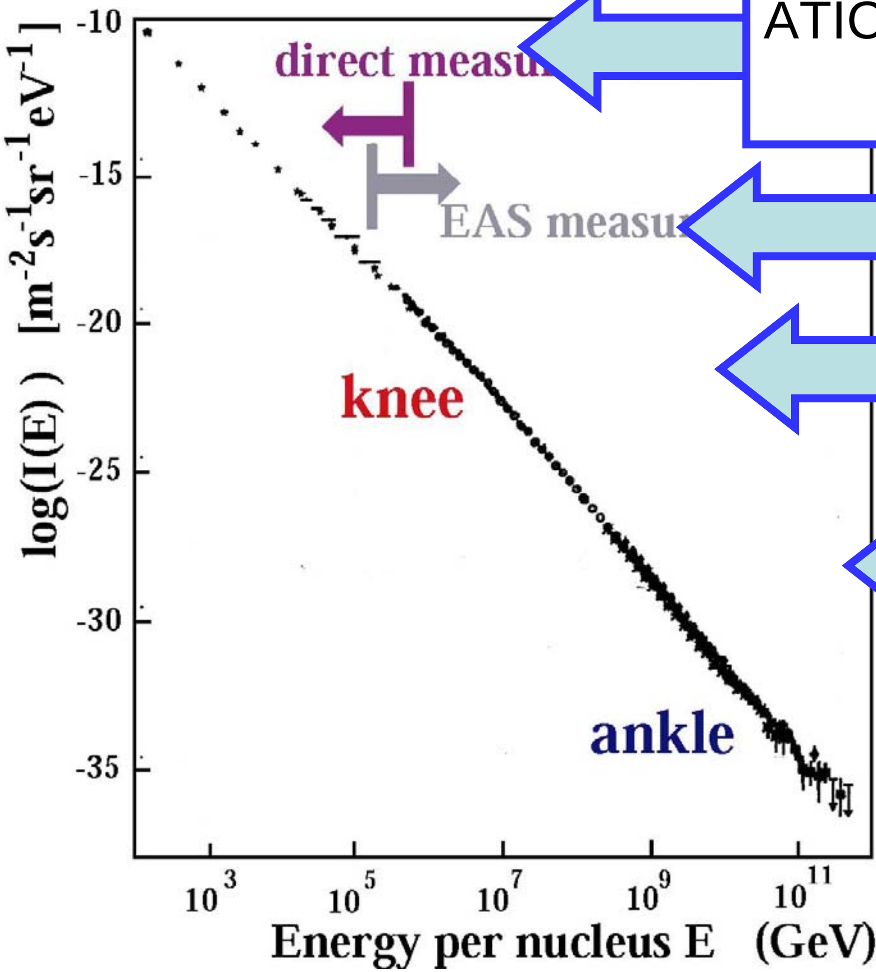
primary mass composition

galactic sources
mass composition

galactic → extragalactic

CR astronomy,
GZK physics,
HE neutrinos,
γ astronomy, …

Charged Cosmic Rays: the energy spectrum



- ATIC, CREAM, … — balloon
- Pamela, AMS — space
- NUCLEON — space
- KASCADE + many others — surface
- KASCADE-Grande, IceTop/IceCube, Tunka-133 — surface
- Auger — surface
- TUS, JEM-EUSO — space

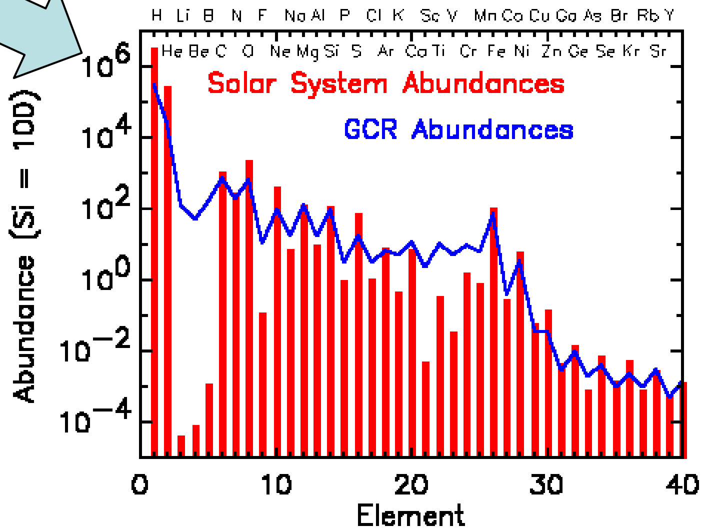
Cosmic rays – direct measurements

Balloons

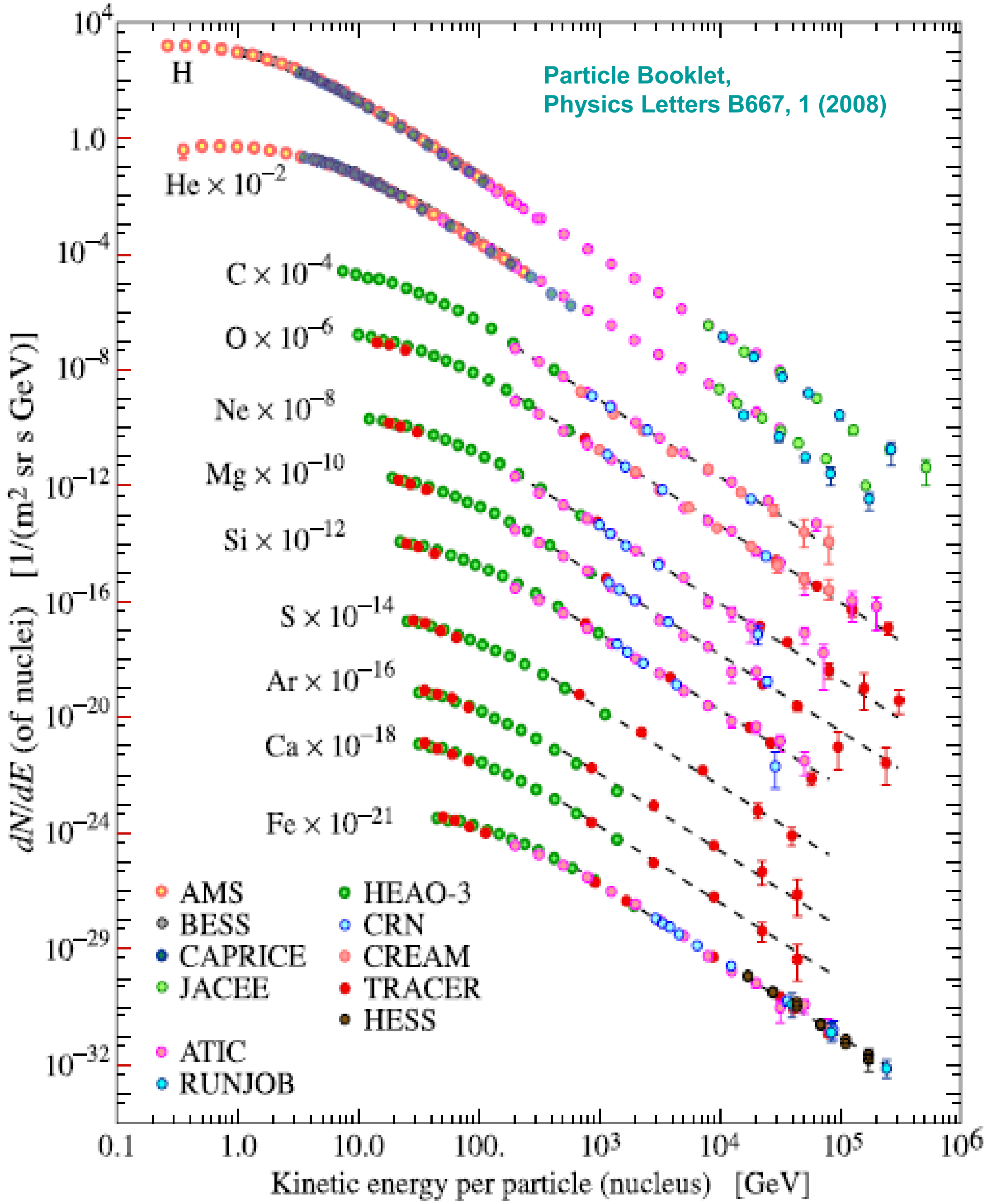
Satellites

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

relative abundancies of the chemical elements

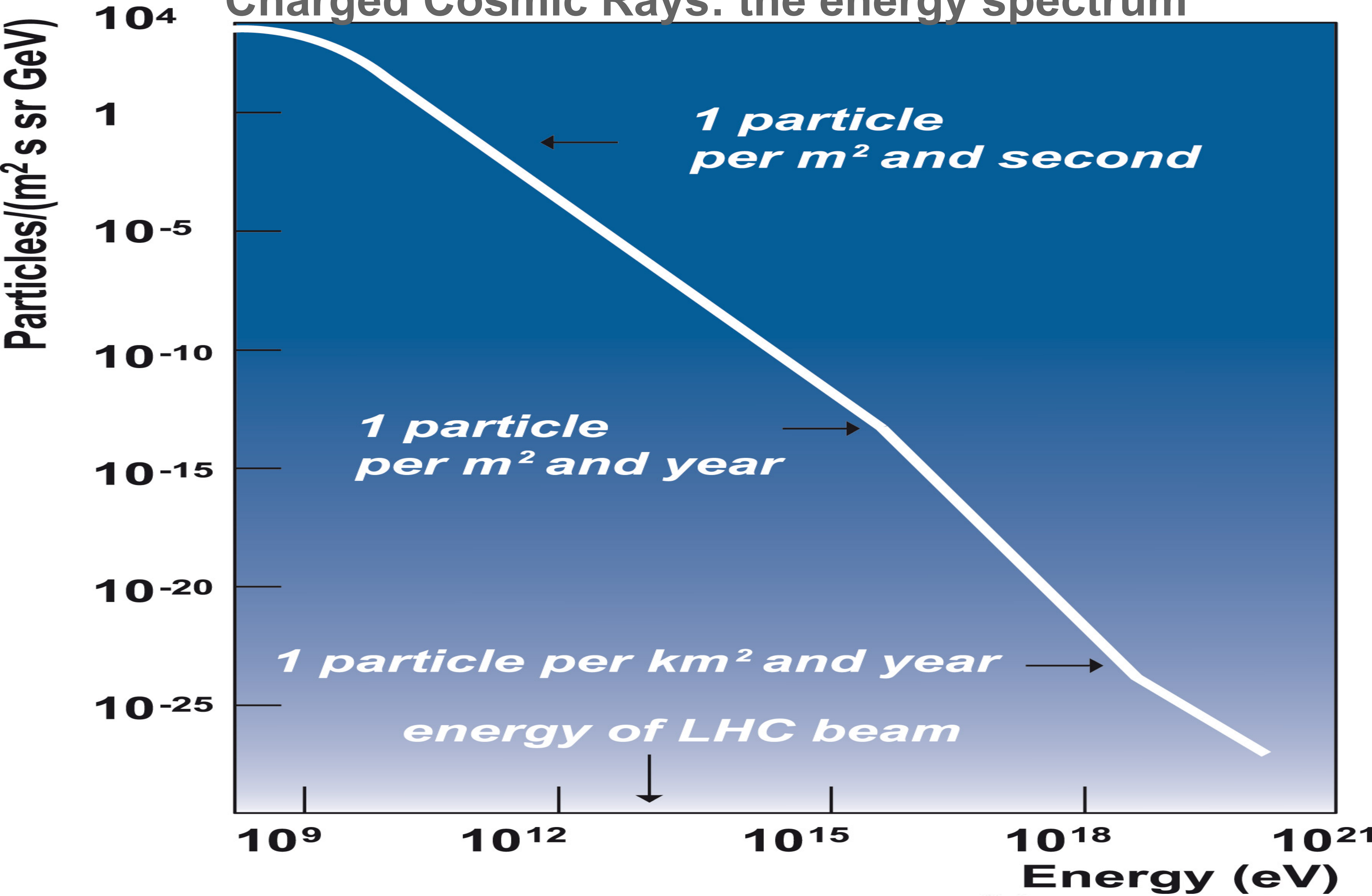


Direct measurements



- **dN / dE ~ $E^{-\gamma}$ with γ ~ 2.7**
- **Acceleration by Supernova Remnants, only?**

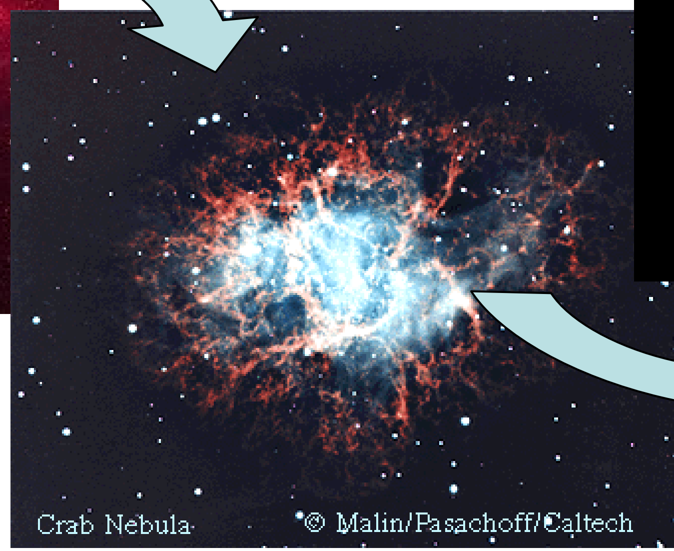
Charged Cosmic Rays: the energy spectrum



Cosmic Rays

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

Injection



Spallation

-Supernovae (galactic)
-AGN (extragalactic)

shock acceleration (Fermi)

nuclear interactions in interstellar / intergalactic medium

Cosmic Rays: Power of the sources?

Estimate of the energy density of cosmic rays:

$$\rho = 1\ \text{eV/cm}^3$$

Which power is needed to keep this energy density ?

$$L = V\,\rho\,/\,\tau \approx 5\ 10^{40}\ \text{erg/s}$$

With V as volume of our Galaxy (300pc thick, radius 15kpc) and
τ = time of the particles in the volume: $6\ 10^{6}$ years

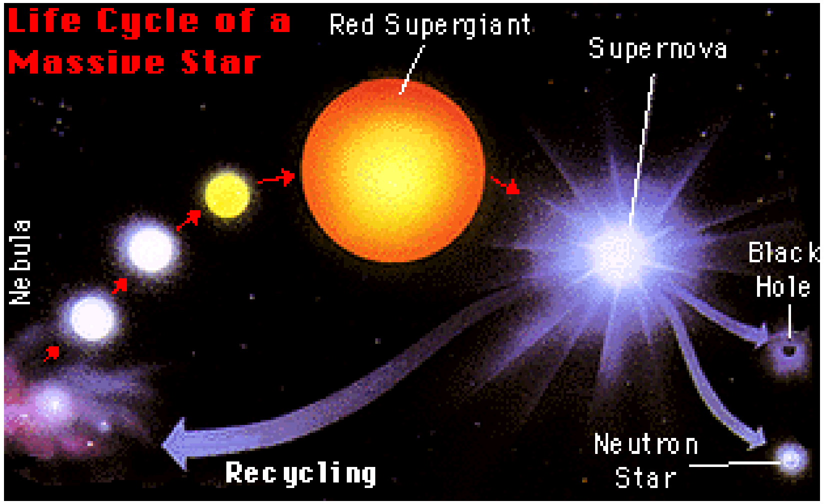
e.g.:
Supernovae: 10^{51} erg/s energy release, 1 SN per 30 years and 10% efficiency in cosmic rays

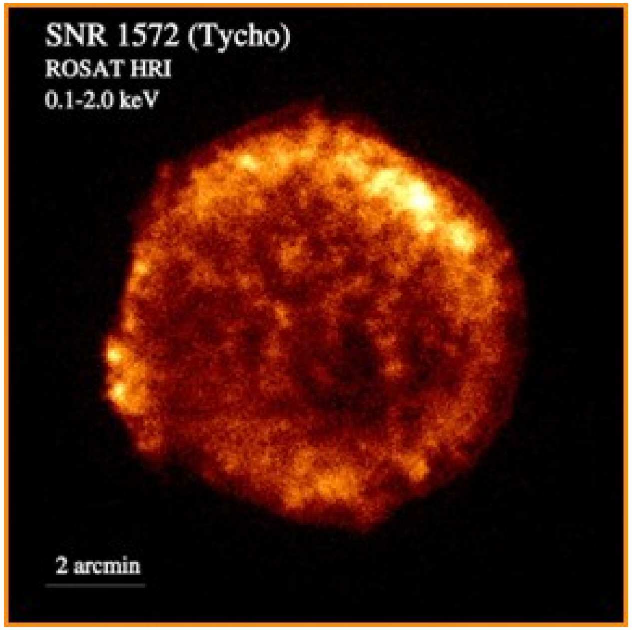
CR likely galactic origin!

similar power values:
star winds of red super giants
= 10^{50} erg/s (problem: efficiency)
or pulsars or binary systems

1 erg = 10^{-7} J = 100 nJ
1 erg = 624.15 GeV = 6.2415×10^{11} eV
1 erg = 1 g·cm²/s²

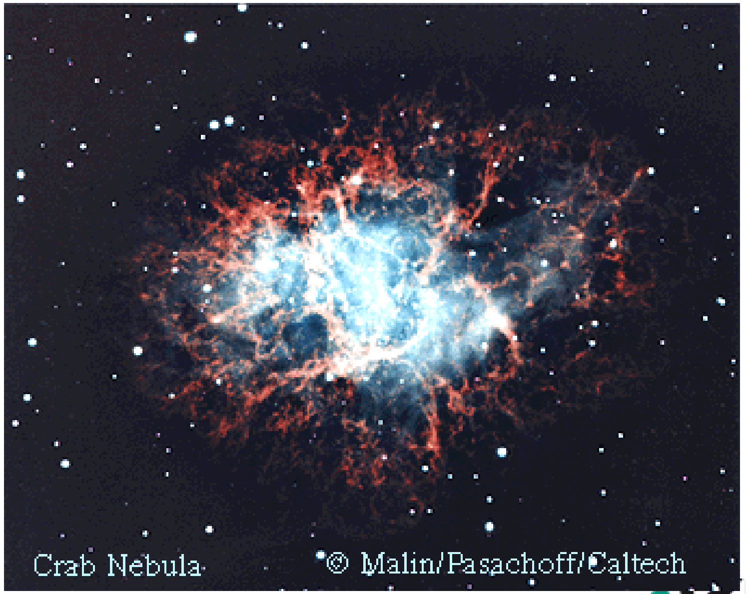
Cosmic Rays: Sources?





Galactic Sources:

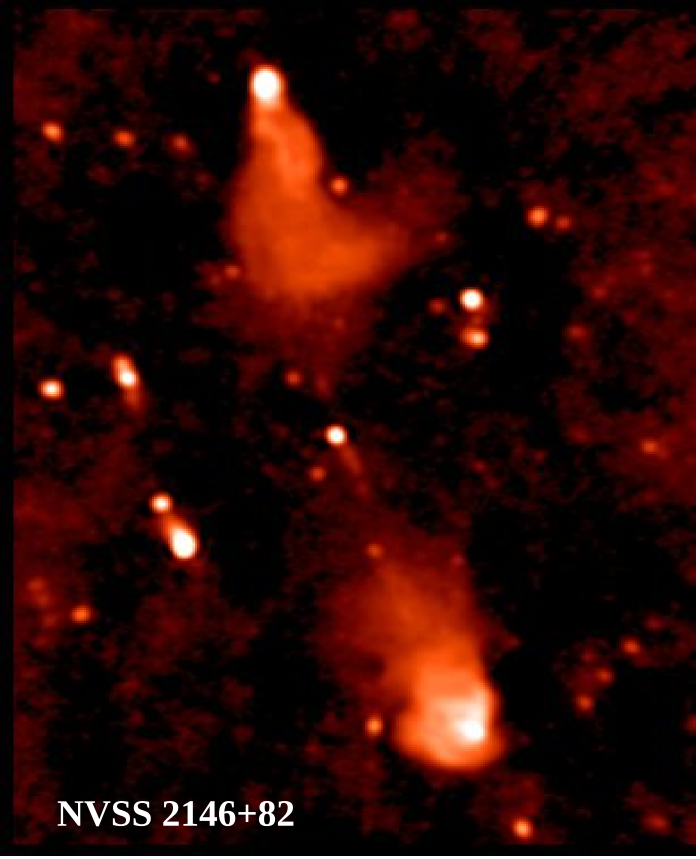
- Supernovae
- Supernova remnants
  - Star formation regions ?
  - Microquasars ?
  - Pulsars ?
  - The Sun

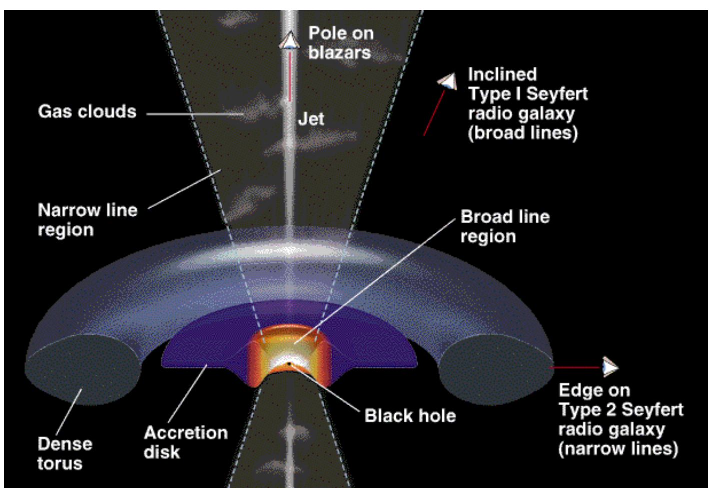


Cosmic Rays: Sources?

Extragalactic Sources ?

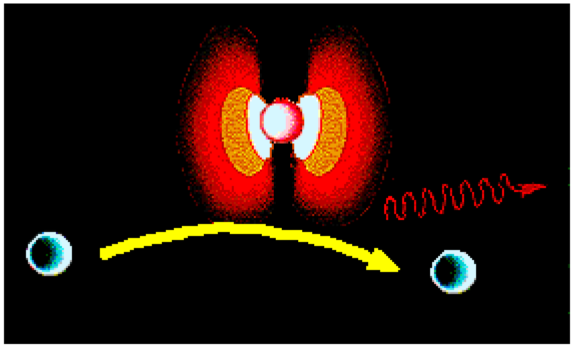
- Aktive Galactic Nuclei (AGN) ?
  quasars, radio galaxis, galaxy clusters
- Merging Galaxies
- relic particles ?
  superheavy GUT-particles, topological defects



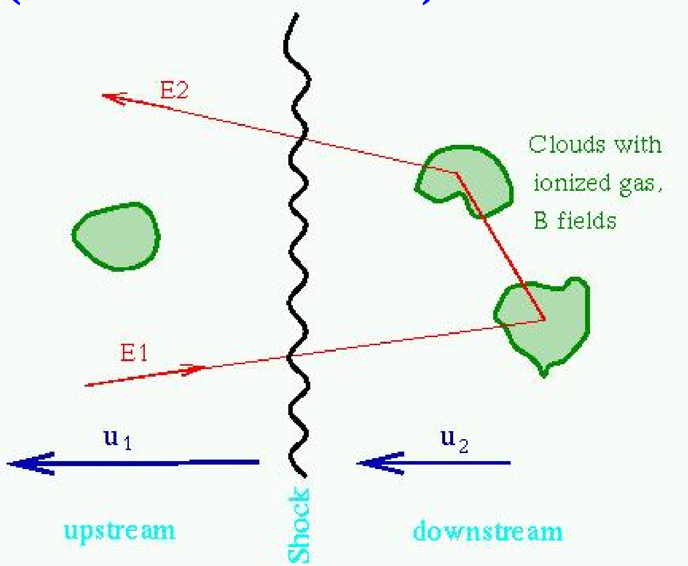


Cosmic Rays: Acceleration? : general remarks

Acceleration in magnetic fields



Acceleration at shock fronts (Fermi-Acceleration)



The acceleration mechanisms requires following conditions:

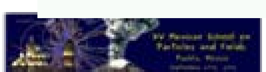
1.) power law dependence of all particle types

$dN(E) \propto E^{-x}\, dE$ with $x=2.2\text{-}3$

2.) energies up to 10^{20} eV

3.) elemental composition similar to solar abundances

problem: storage period of particles in the acceleration zone have to be long (e.g. synchrotron) and the zone have to be stable.



Cosmic Rays: Fermi Acceleration

Fermi-mechanism 1st order at strong shock waves

simple calculation in lab system:
shock front with velocity V and
gas behind with velocity U ➔

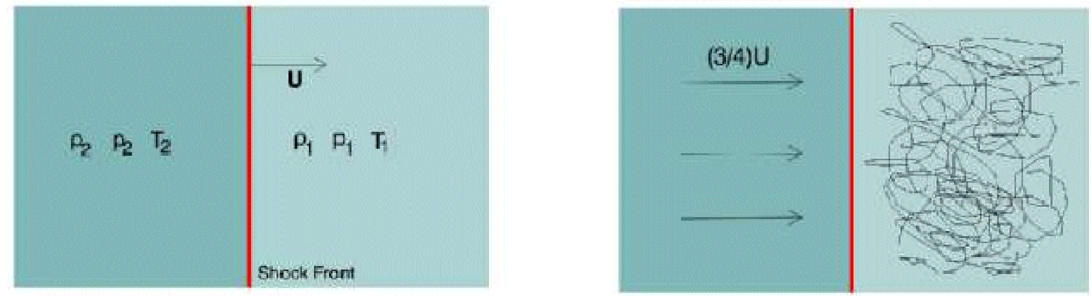
$$\Delta E_1 = \tfrac{1}{2}\, m\, (v + (V - U))^2 - \tfrac{1}{2}\, m\, v^2$$
$$= \tfrac{1}{2}\, m\, (2v(V-U) + (V-U)^2)$$

with v >> V,U and V>U

➔always head-on collisions!

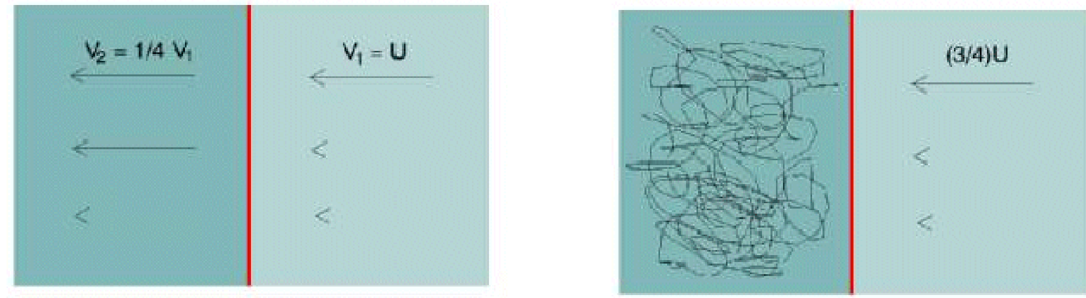
➔energy gain

$$\Delta E/E = 2\,(V-U)\,/\,v$$



(a) Shock front traveling at speed U

(c) rest frame of downstream medium



(b) seen in rest frame of shock front

(d) rest frame of upstream medium

relativistic calculations and taking
Into account the scatter angles:

$$\Rightarrow \Delta E/E = 4/3\;(V-U)\,/\,c$$

➔ classical kinematic describes how often particles pass the shock

➔ escape probability is similar to the energy gain: $P \approx \varepsilon$.

$$\Rightarrow N(E)\, dE \;\propto E^{-2}\, dE \quad !!!$$

(strong shocks are observed at supernova remnants)

Cosmic Rays: Acceleration > 100 TeV ?

idea: acceleration in Pulsars

Pulsar:

- remnant of a supernova explosion
- radius 10 km, density $6 \cdot 10^{13}$ g/cm^2 (density of nuclei) (neutron stars, decay of n are stopped)
- creation by gravity collaps but with conservation of the angular momentum:

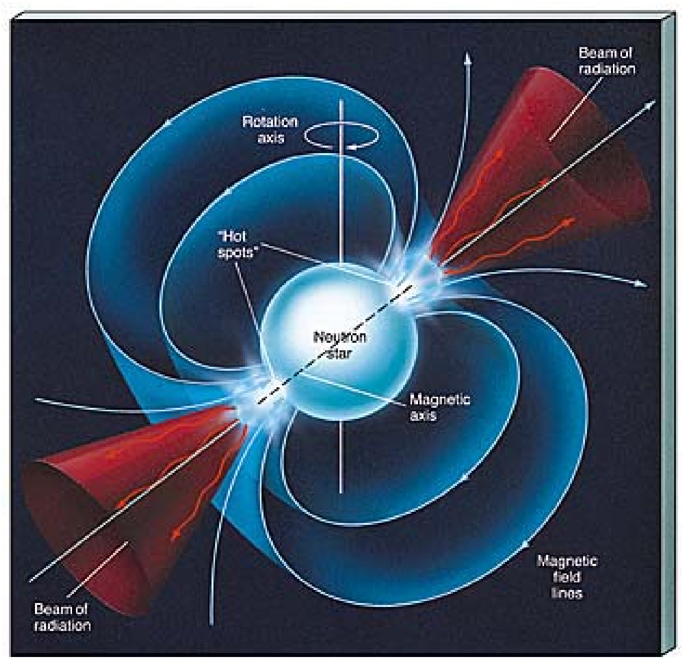
➔ $T_{Pulsar} = 1 – 30$ ms

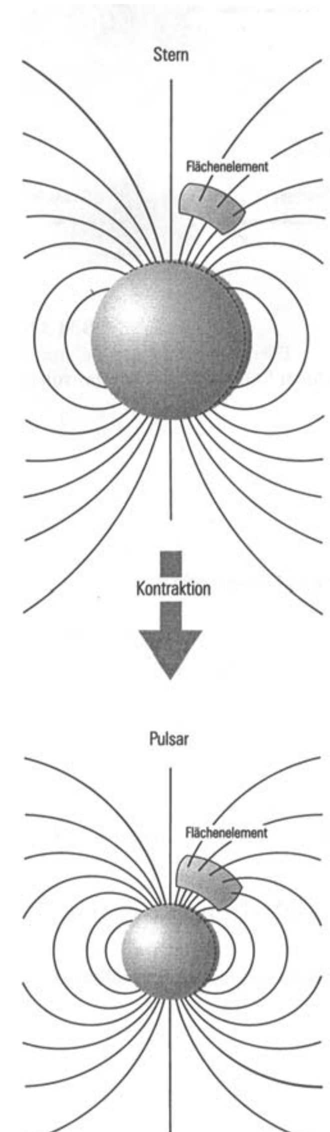
➔ very high magnetic fields:

$B_{Star} = 0.1$ Tesla ➔

$B_{Pulsar} = 2.5 \cdot 10^8$ Tesla

➔ **very strong electrical fields by induction**

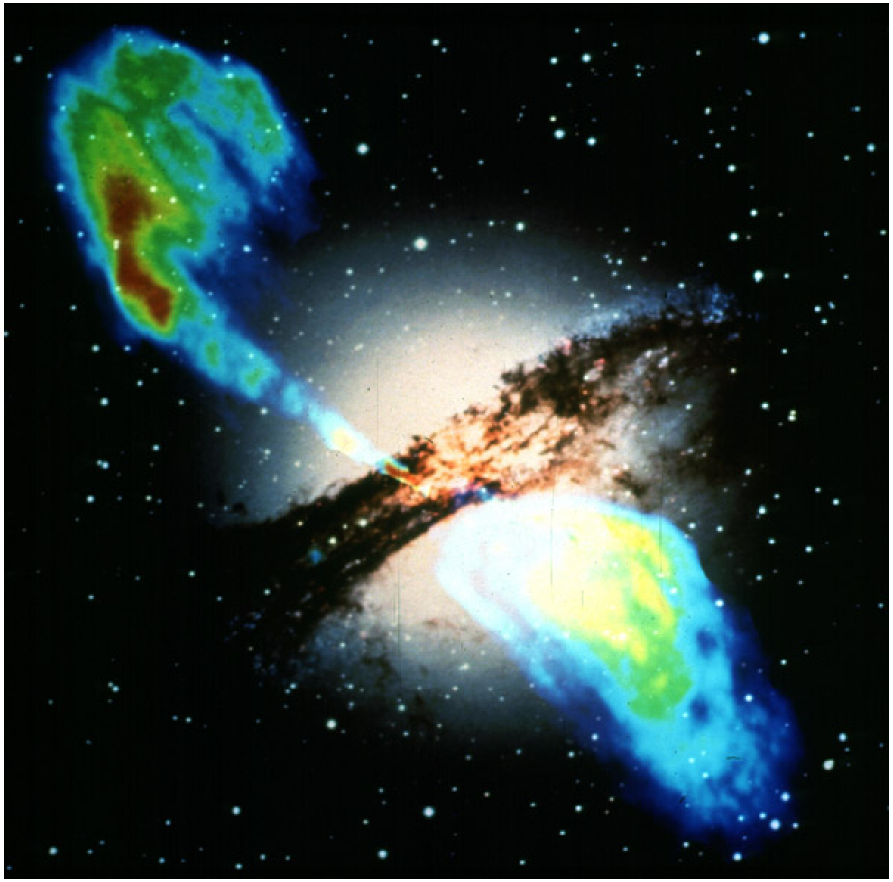




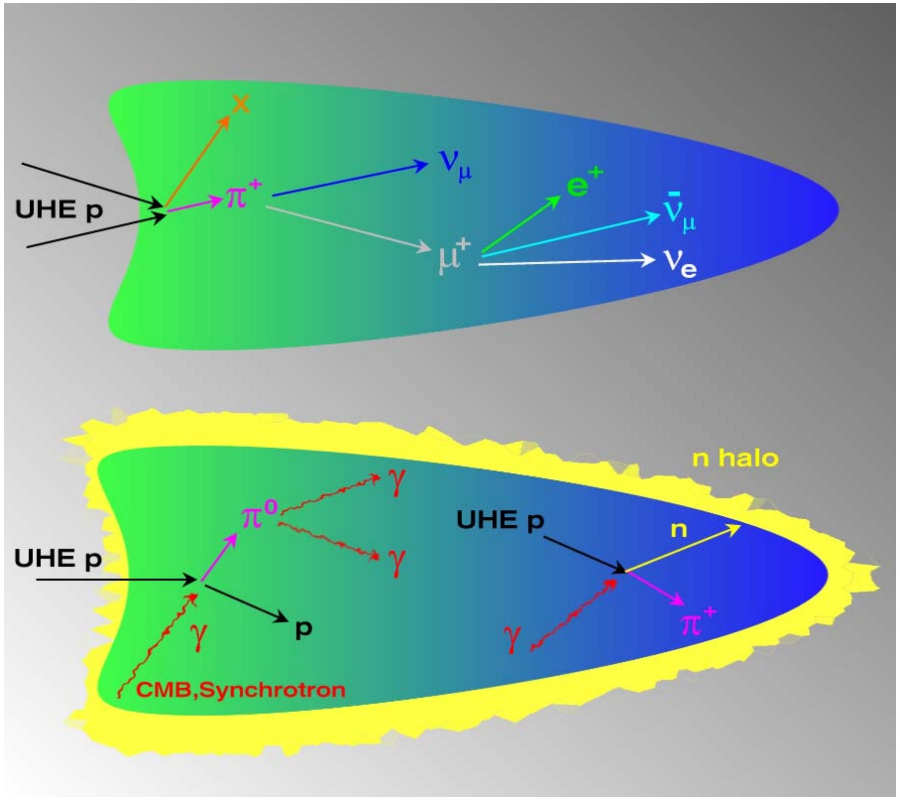
Cosmic Rays: Acceleration > 100 TeV ?

idea: acceleration in AGN:

problem: interaction of the accelerated particles inside the jet

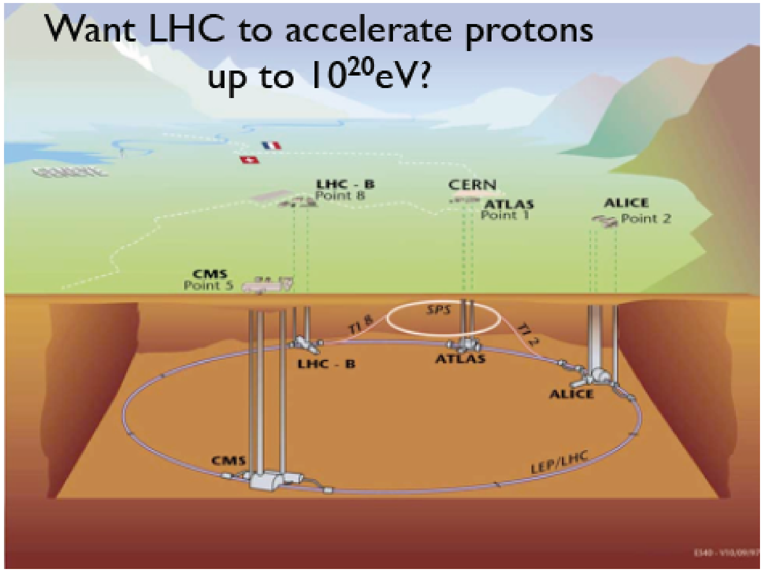


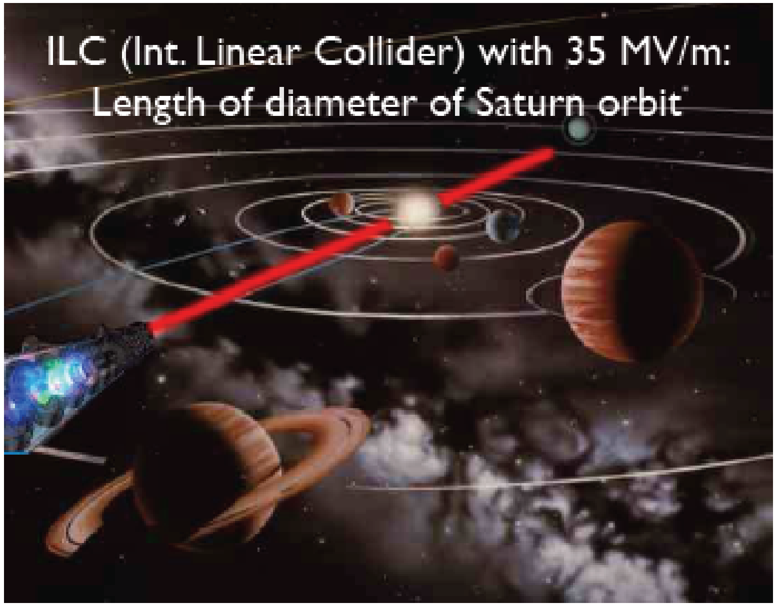
Centaurus A, HST optical and radio

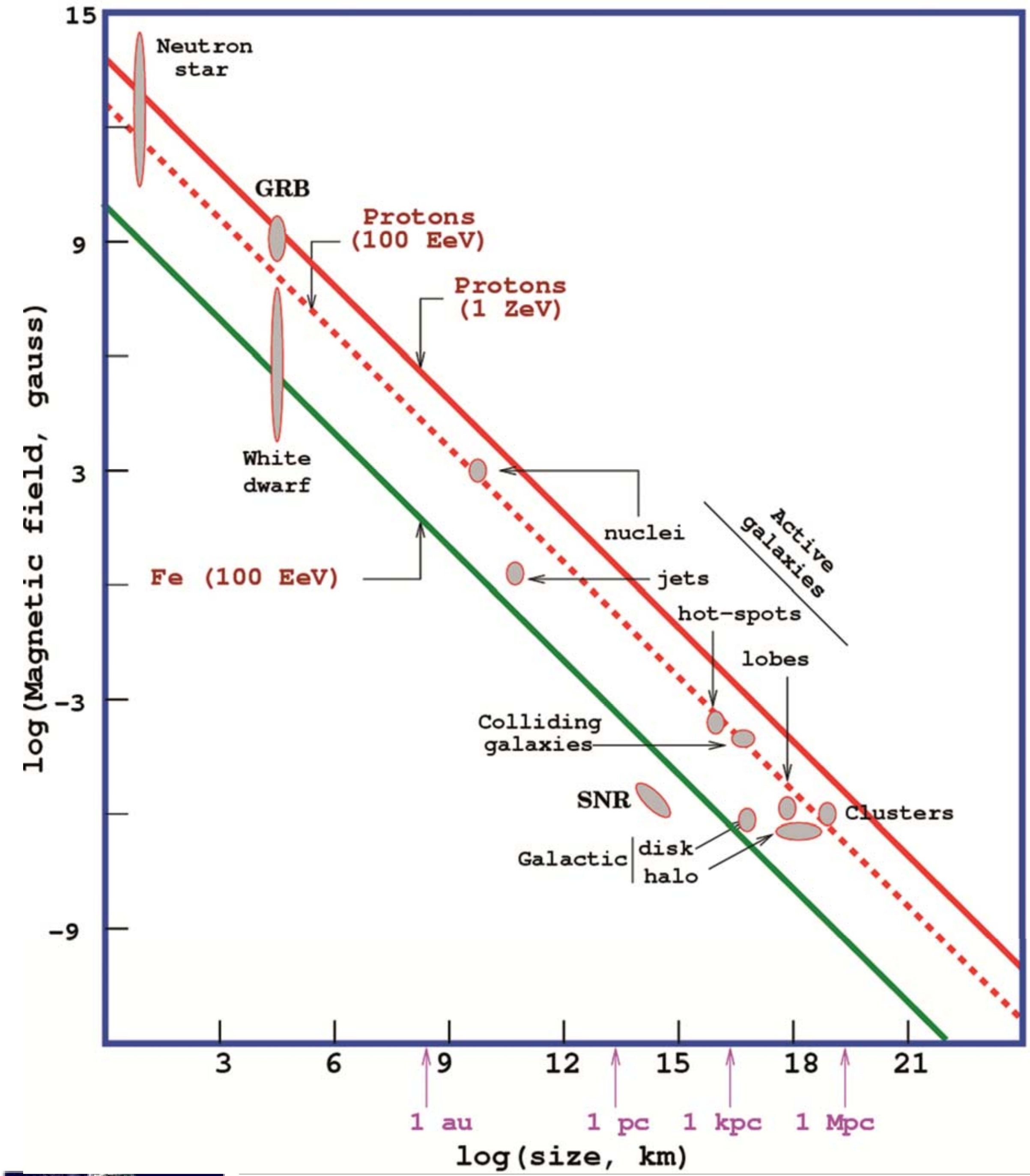


TeV- gamma radiation from AGN's are observed (timely and spectral very variable)

Cosmic Rays: Acceleration summary







Cosmic Rays: Acceleration summary

Hillas-Diagramm:

$$E_{max} \sim zBL$$

Cosmic Rays: Acceleration summary

acceleration in the sun: $E_{max} = 10^{10}$ eV/n

acceleration in Supernova shocks: $E_{max} \approx 10^{14}$ eV/n

acceleration at Supernova in a wind: $E_{max} \approx 10^{16}$ eV/n

reacceleration of 10^{14} eV/n in Pulsars: $E_{max} \approx 10^{17}$ eV/n

Supernova in a wind + binary system: $E_{max} \approx 10^{19}$ eV/n

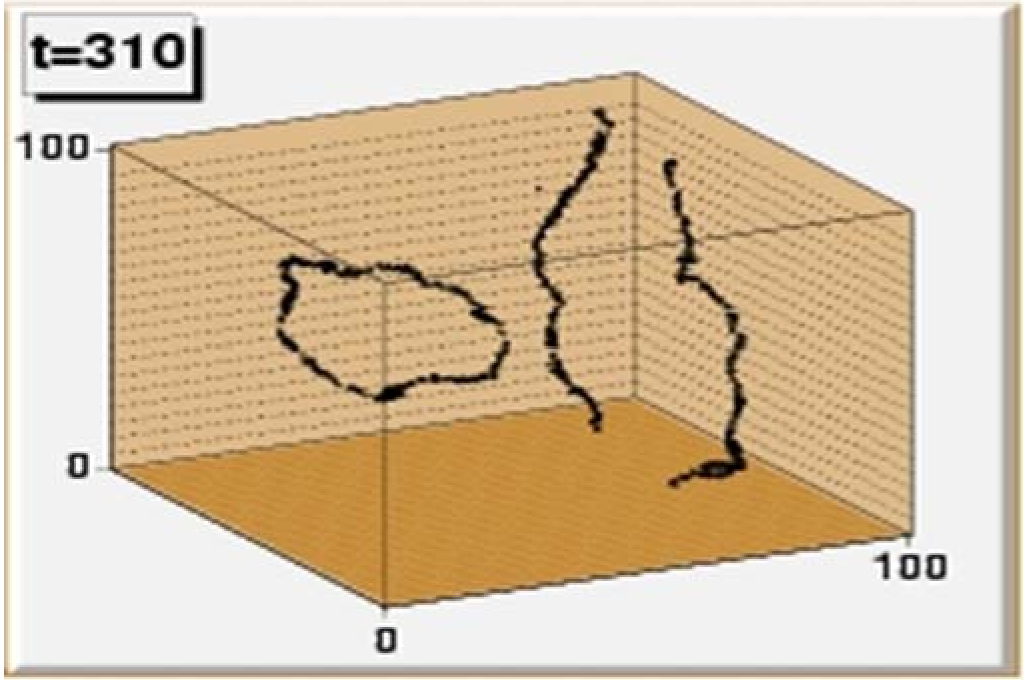
extreme Pulsars (short rotation time): $E_{max} \approx 10^{19}$ eV/n

acceleration in AGNs, Radio-Jets: $E_{max} \approx 10^{20}$ eV/n

Exotic decays

Exotic UHECR Sources

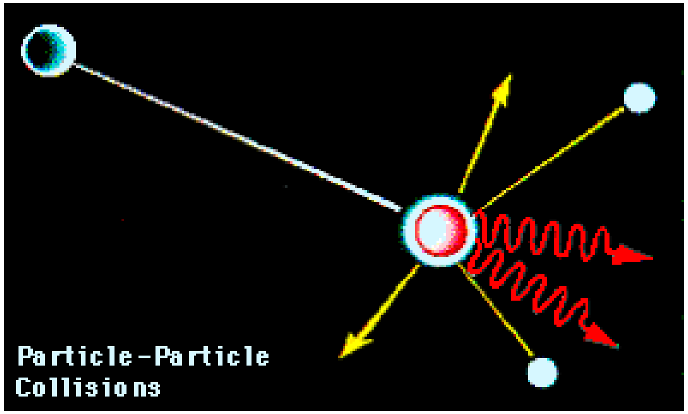
- "Top Down"solutions
- (topological defects),
- SUSY,
- VHE Neutrinos,
- Monopoles,
- etc.



Cosmic Strings

Cosmic Rays: Transport

Transport through interstellar/intergalactic medium



Density at the interstellar medium:
1 particle per cm^3
Density at the intergalactic medium:
6 particles per m^3

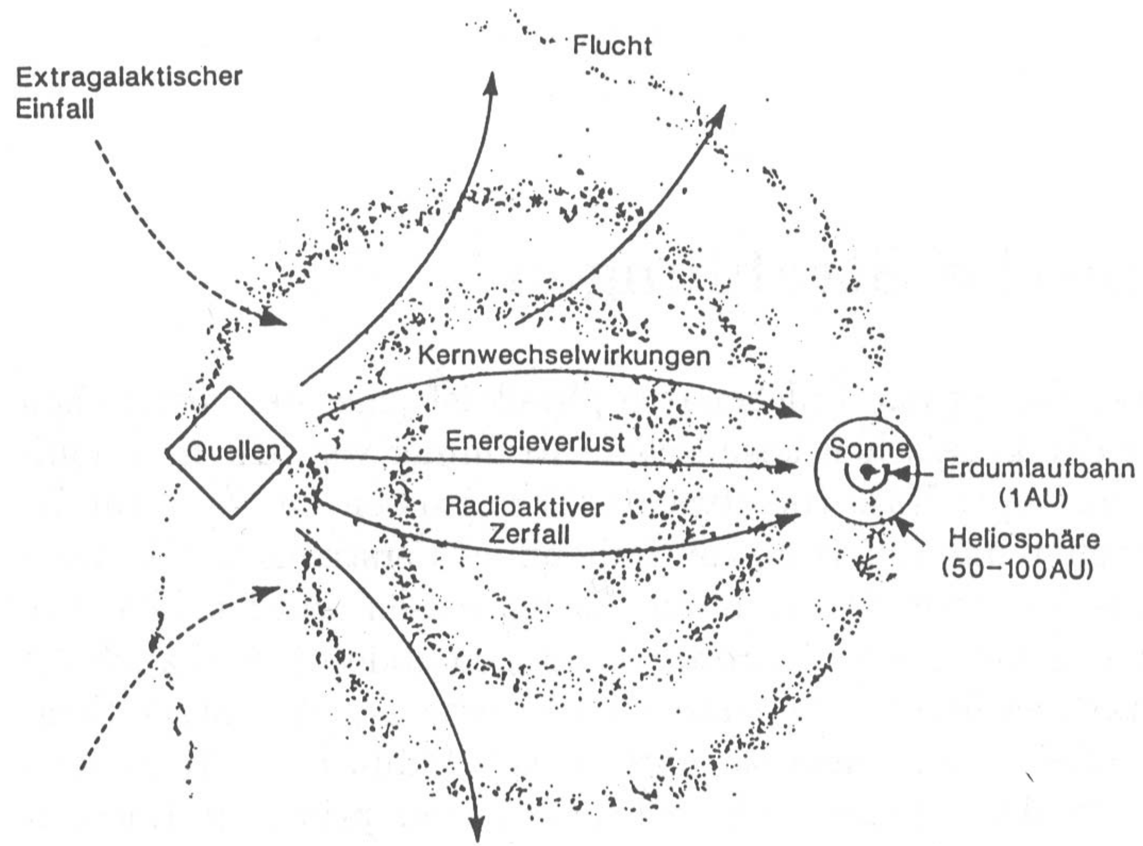
Cosmic Rays: Transport

content of the ISM:

-) clouds
-neutral or ionised H(He..)-gas
-density $\rho=10^{-24}$ g/cm^3
-interactions by particle collisions

-) magnetic fields
B= 1 – 3 μG
diffusion

-) microwave background
2.7K = 2.3 10^{-4} eV
= 5.6 10^{10} Hz = 5 10^{-3} m
Interactions by photo-pion production (= GZK)



Cosmic Rays: Transport Equation

Diffusion equation for relativistic particles:

$$\frac{dN_i}{dt} = \frac{d}{dE}[b_i(E)N_i(E)] + Q_i + \nabla(D_i \nabla N_i)$$

$N_i = N_i(E,x,t)\, dE$ = number (density) of a specific particle i at the position x and time t in the energy range E+dE

Q_i = injection rate of these particles into a volume dV

The particle gains (-) or looses (+) energy as $-(dE/dt)=b(E)$

➔ $dN(E)/dt = d/dE[b(E)N(E)]$ is the timely development of the particle spectrum

➔ in the volume by energy gains and looses

additionally injection and escape to the volume by diffusion (dependent on particle density N_i)

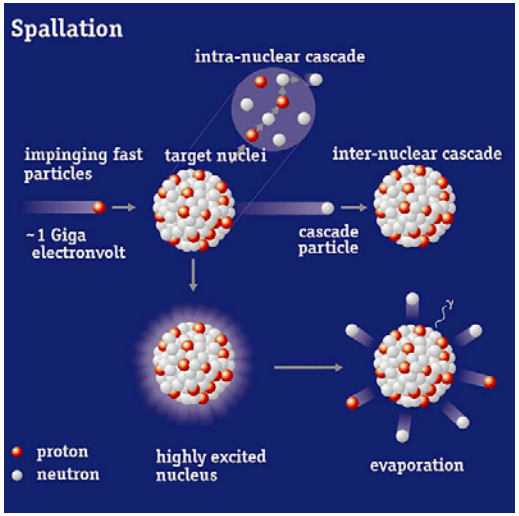
$D = 1/3\, \lambda\, v$

λ = free pathlength = $10 g/cm^2$ for protons in ISM = $3 g/cm^2$ for iron in ISM

Cosmic Rays: Transport Equation

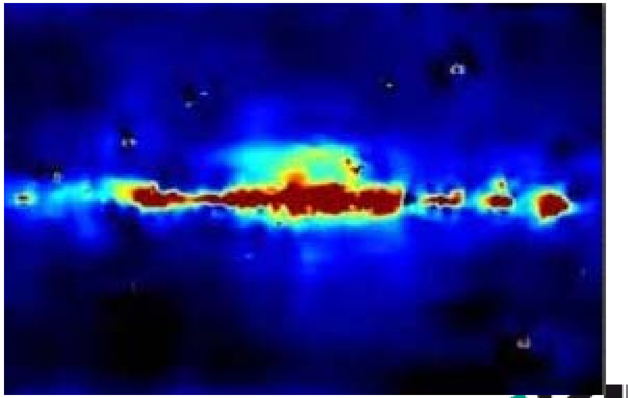
$$dN_i/dt = d/dE[b_i(E)N_i(E)] + Q_i + \nabla(D_i \nabla N_i) - N_i/\tau_i + \sum_{j>i} P_{ji}/\tau_j N_j$$

effects of spallation: change (+ or -) of N_i



τ_i = lifetime of species i
(attention: Lorentz-Dillation: increases lifetime)

P_{ji} = probability that a collision creates a species j out of species i

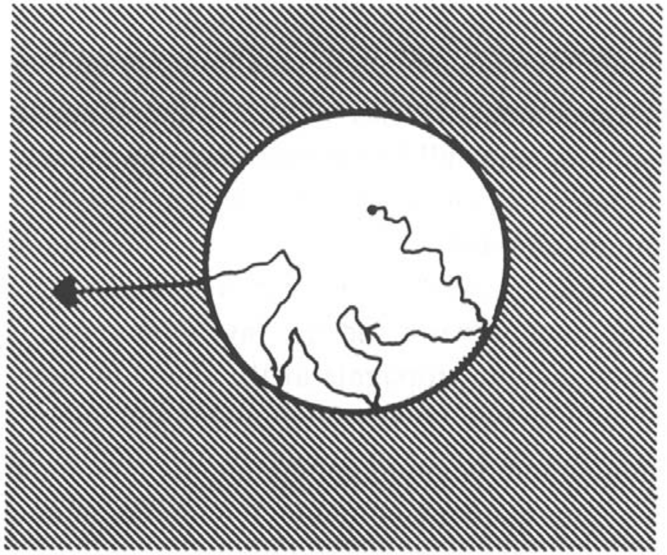


➔ explain the change of the slope from the source (γ=-2.0) to observation (γ=-2.7)

All calculations are in good agreement with the assumption of a halo built with high-energetic particles !!

Cosmic Rays: Transport: Leaky Box Model

‚Confinement' in our Galaxy:



-) high energy particles pass ca. $5 g/cm^2$ matter (from comparisons of spallation calculations with Measurements at low energies, e.g. Cr/Fe-ratio)
-) average density in our Galaxy: $N = 10^{-6} m^{-3}$

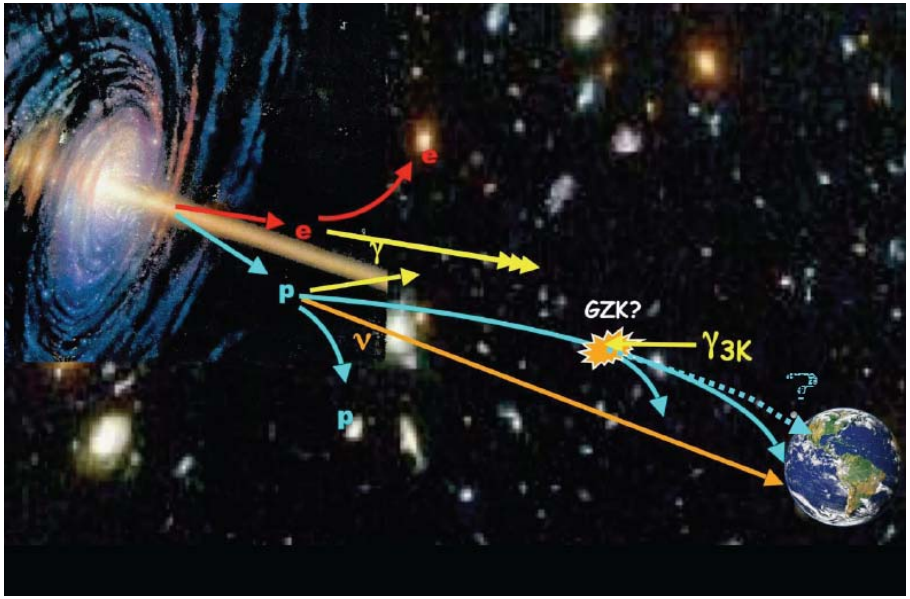
with $\lambda = \rho \cdot c \cdot t$ ➔
$t_{esc} \approx 3 \cdot 10^6$ years
escape time from Milky Way
(or larger, if longer confinements in less dense regions)

🡨proof that particles have scrumpled pathes, as straight path would need only 10^4 years

Best description by the ‚Leaky Box Model'
= free diffusion inside the box, reflections at the edge of the box
probability of transmission out of the box

$$dN / dt + N / t_{esc} = 0 \quad ➔ \quad N \propto \exp(-t / t_{esc})$$

Cosmic Rays transport at highest energies: GZK Greisen-Zatsepin-Kuzmin Effect



Pion photo production

($E_p > 5 \times 10^{19}$ eV due to CMB) :

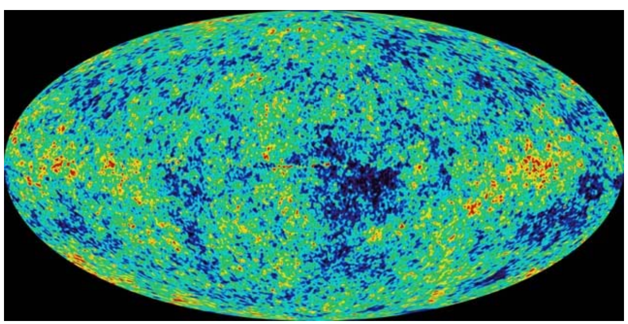
$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$

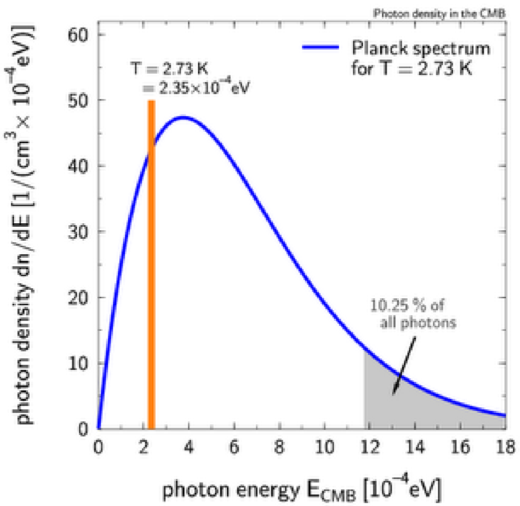
$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$

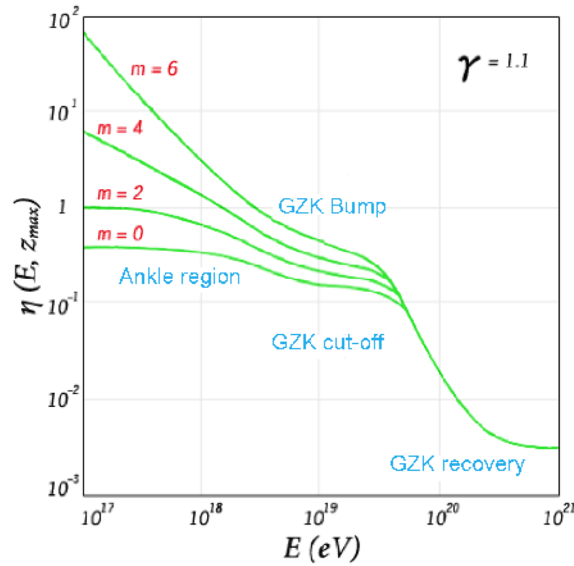
Interaction length ~ 6 Mpc

Energy loss ~ 20% / interaction

➜ Nearby sources (<50 Mpc)







1 lyr = 9.46 × 1015 m

1 pc = 3.26 lyr ~ π lyr

Cosmic Rays: History - 1910

~1900: Electroscopes discharge, even if they are shielded from radioactive sources
➔Rutherford: radioactivity at the walls, etc...

(γ-radiation and its absorption coefficient was known ➔ after 80m in air only 50% ➔ Eiffeltower at 330m: no radiation)

~1910: Theodor Wulf
➔at 330m: Ionisation decrease to 60%

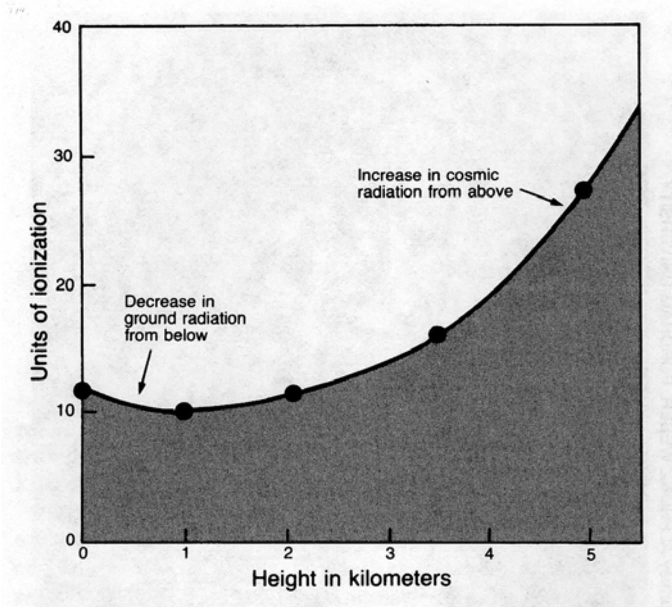
The Jesuit padre Theodor Wulf clambers in the year 1910 the Paris Eiffel-Tower to find the source of the ionizing radiation in the Earth‘s Atmosphere.

Electrometer

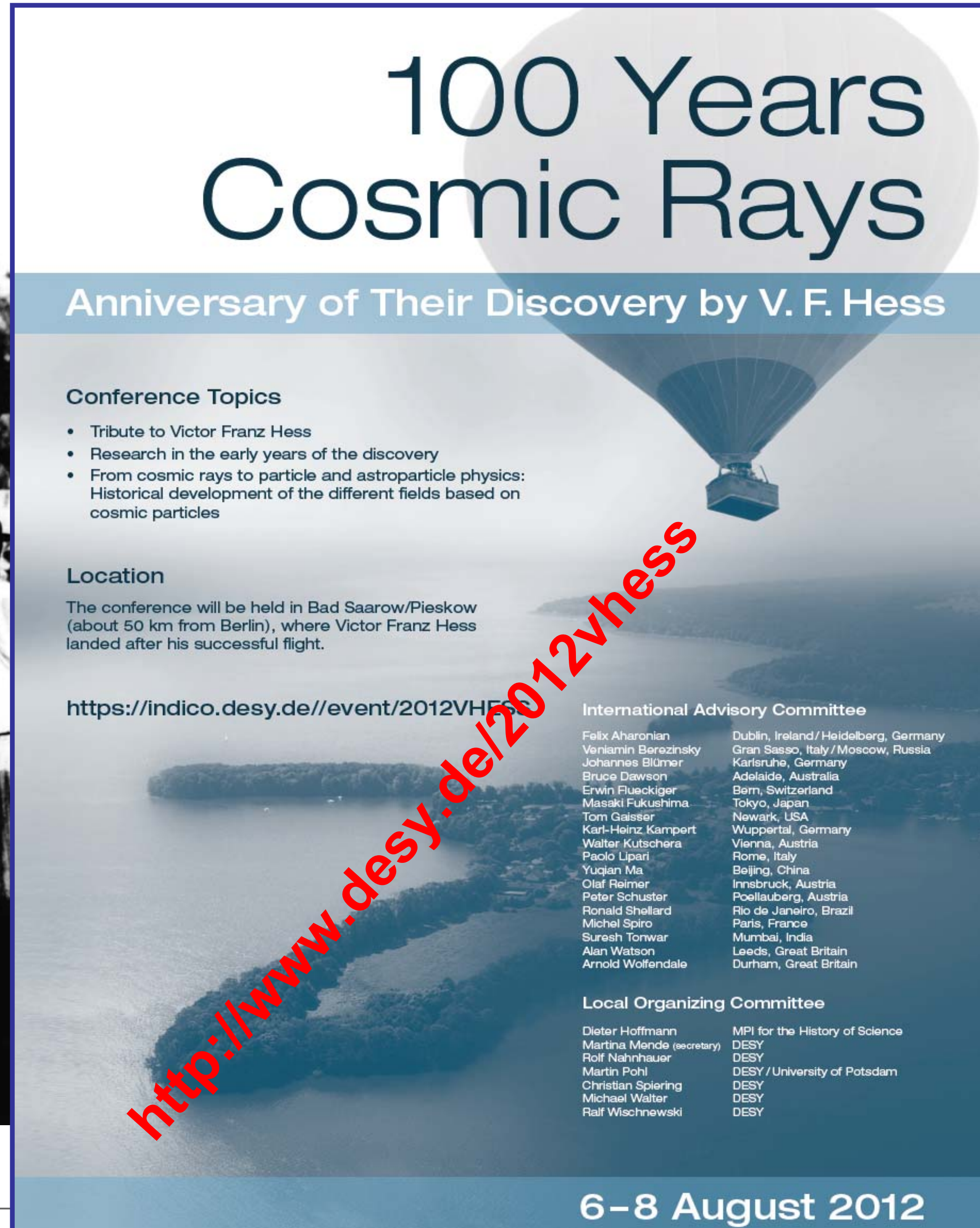
Cosmic Rays: History - 1912

Victor Hess 1912:
There are particles coming from ‚outside‘ (Cosmos)

Finding:
Ionisation increase with height !
(Hess reached 5000m)



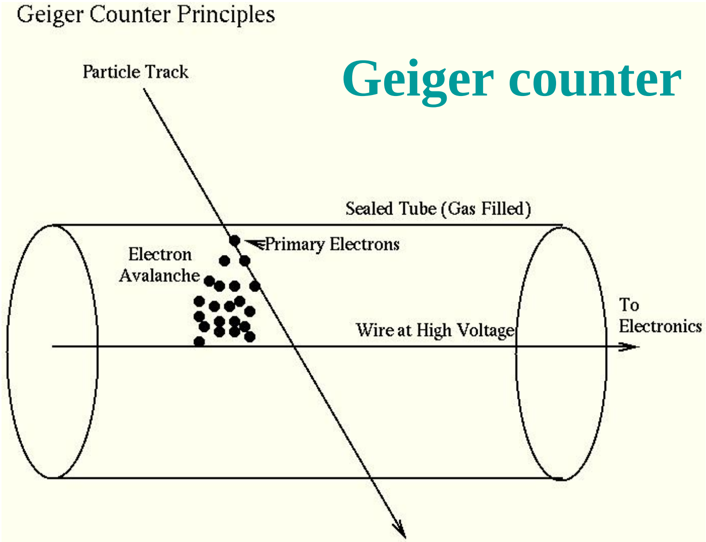
Cosmic Rays History



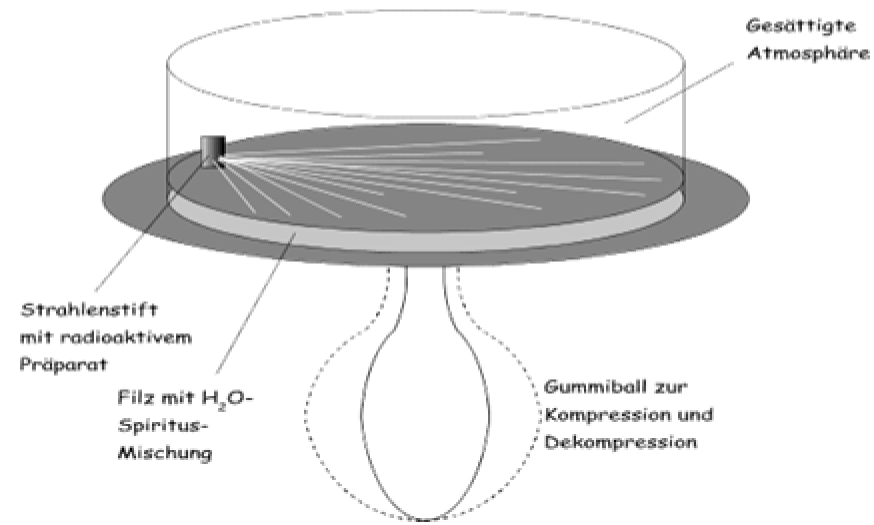
Cosmic Rays: History – 1912-25

Start of the development of:
Particle detectors – particle physics

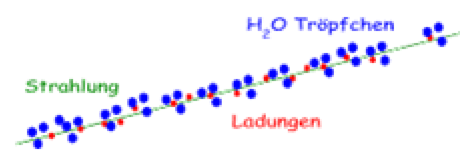
Geiger counter



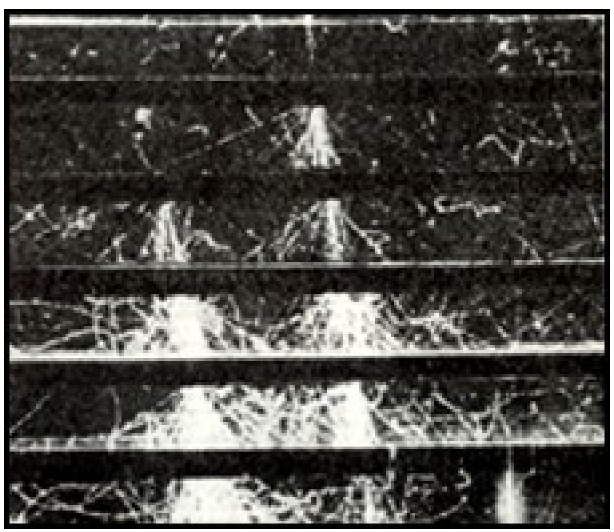
Cloud chamber



- Gesättigte Atmosphäre: Luftmoleküle haben max. Menge d. Gasgemischs angelagert.
- Schnelle Expansion => Abkühlung => Übersättigung => Kondensation an Ladungen

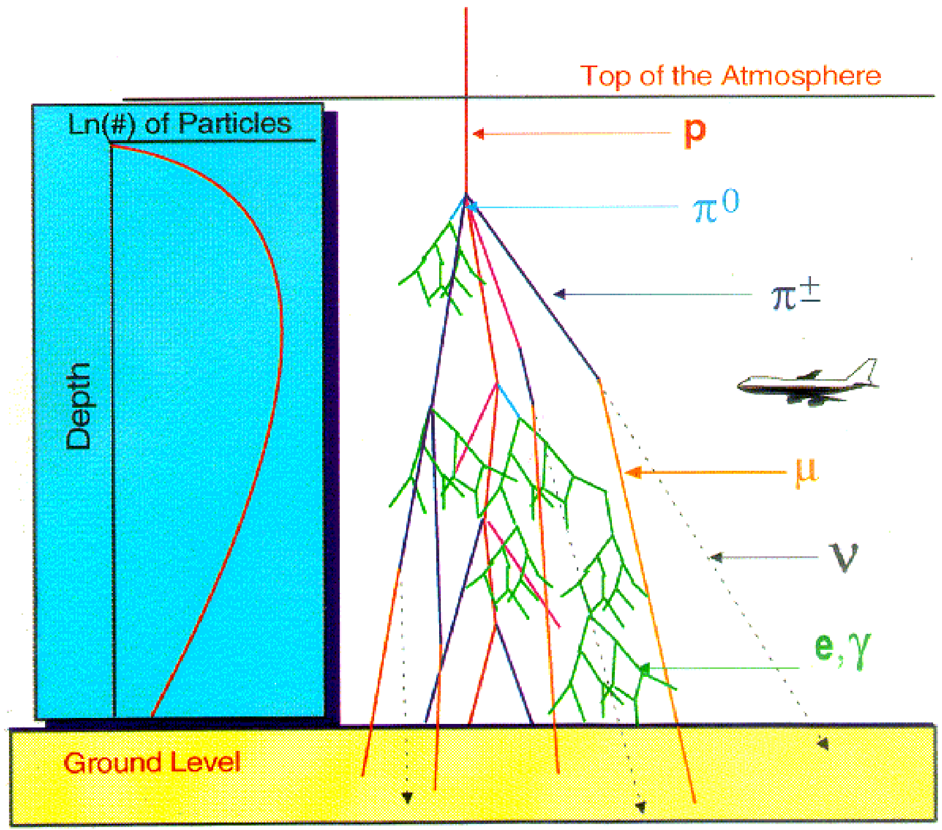


Spark chamber



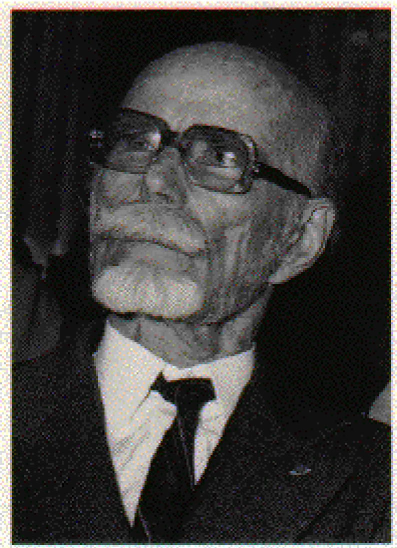
Cosmic Rays: History – 1930-40

==> First Detection of extended air-showers!



Extensive Air Showers

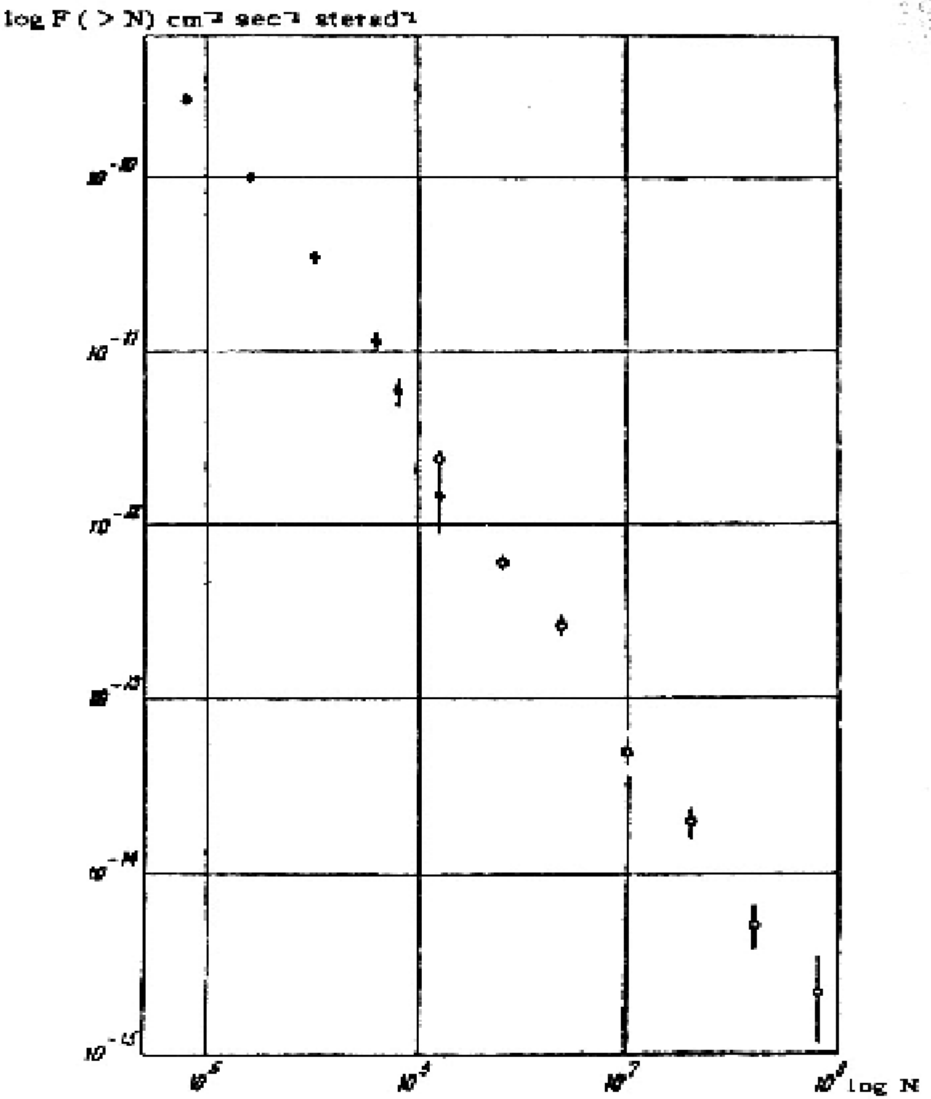
1936: coincidence measurements at the Jungfraujoch



Pierre Auger

Following years: separation of cosmic ray and particle (accelerator) physics

Cosmic Rays: History - 1958



The “first knee”

G.V.Kulikov & G.B.Khristiansen

Soviet Physics JETP Volume 35(8), No 3, March 1959

measured N_{ch} spectra

hodoscope counters in a 20x20 m^2 array

„the observed spectrum is a superposition of the spectra of particles of galactic and metagalactic origin“

Cosmic Rays: History - 1962

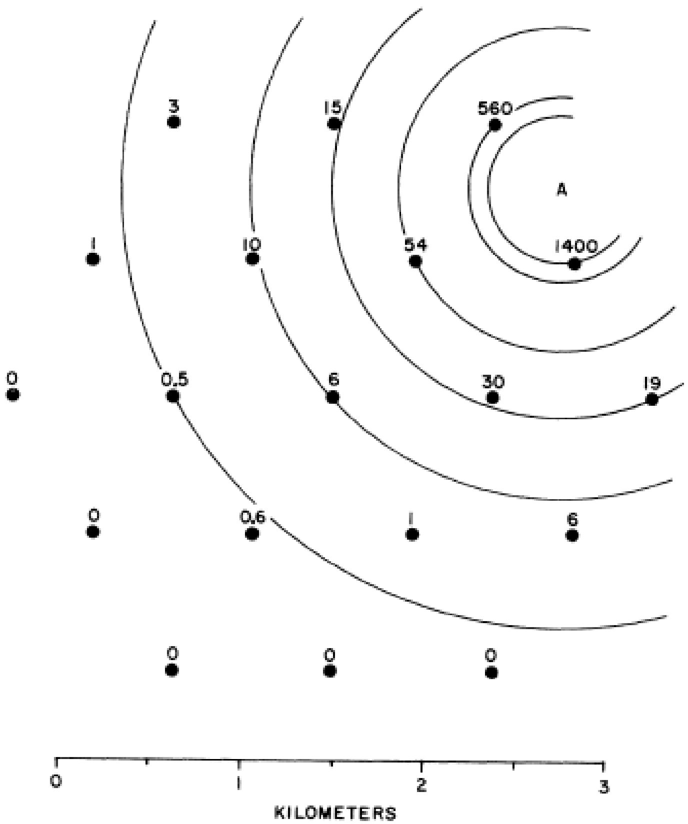


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m² scintillation detectors. The numbers near the circles are the shower densities (particles/m²) registered in this event, No. 2-4834. Point "A" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

The first event above 10^{20}eV

Volcano Ranch array,

New Mexico US

20 scintillators spaced in 147m

J. Linsley

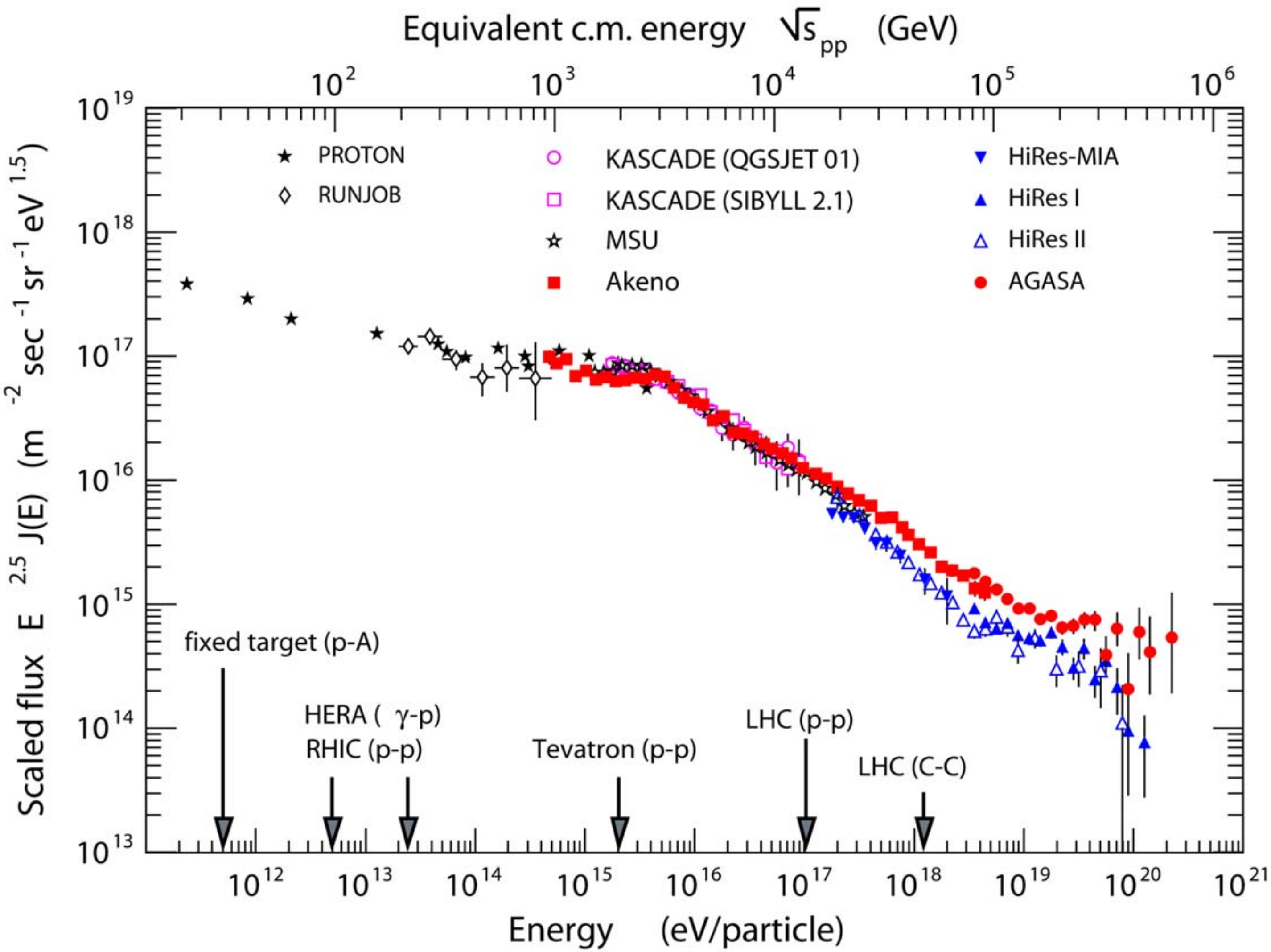
Phys.Rev.Lett. 10 146-148,1963

Extensive air showers

above 10^{14} eV :

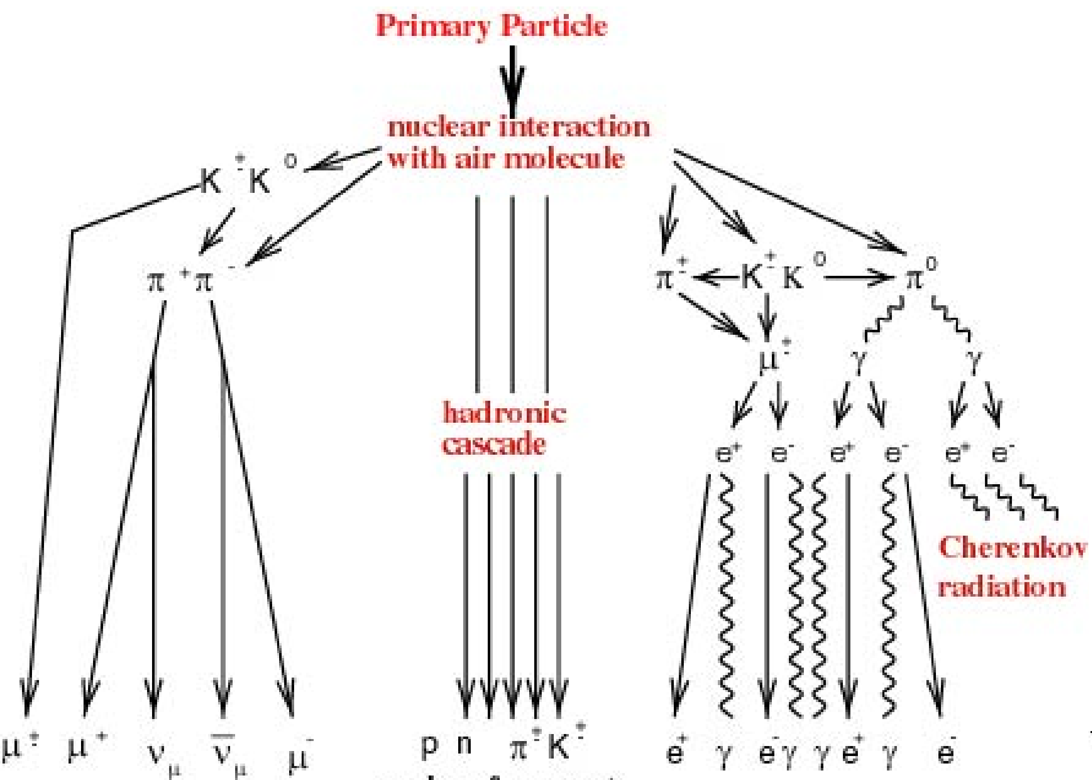
Only indirect measurements possible !

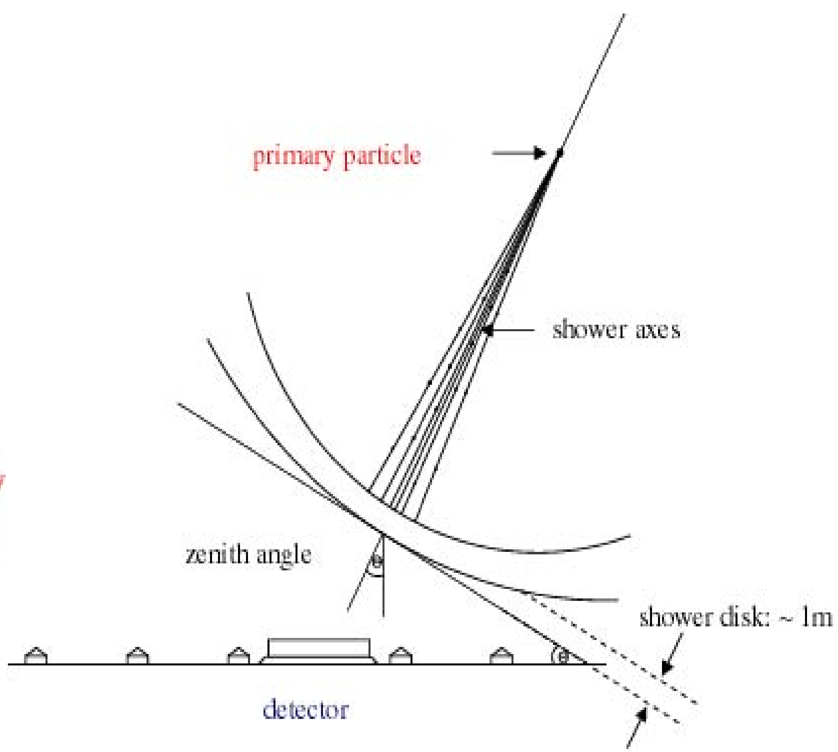
→ **EAS**



Air shower interactions: Above all man-made energies for single particles and in extreme forward direction!

Extensive Air Showers - schematic



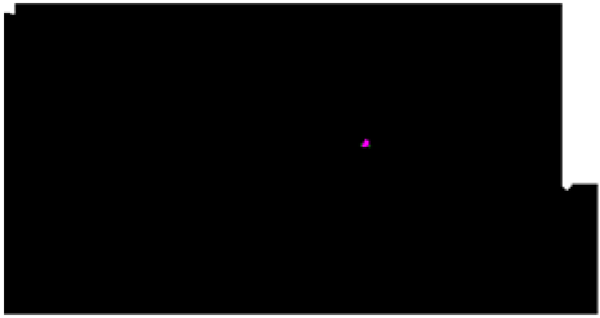


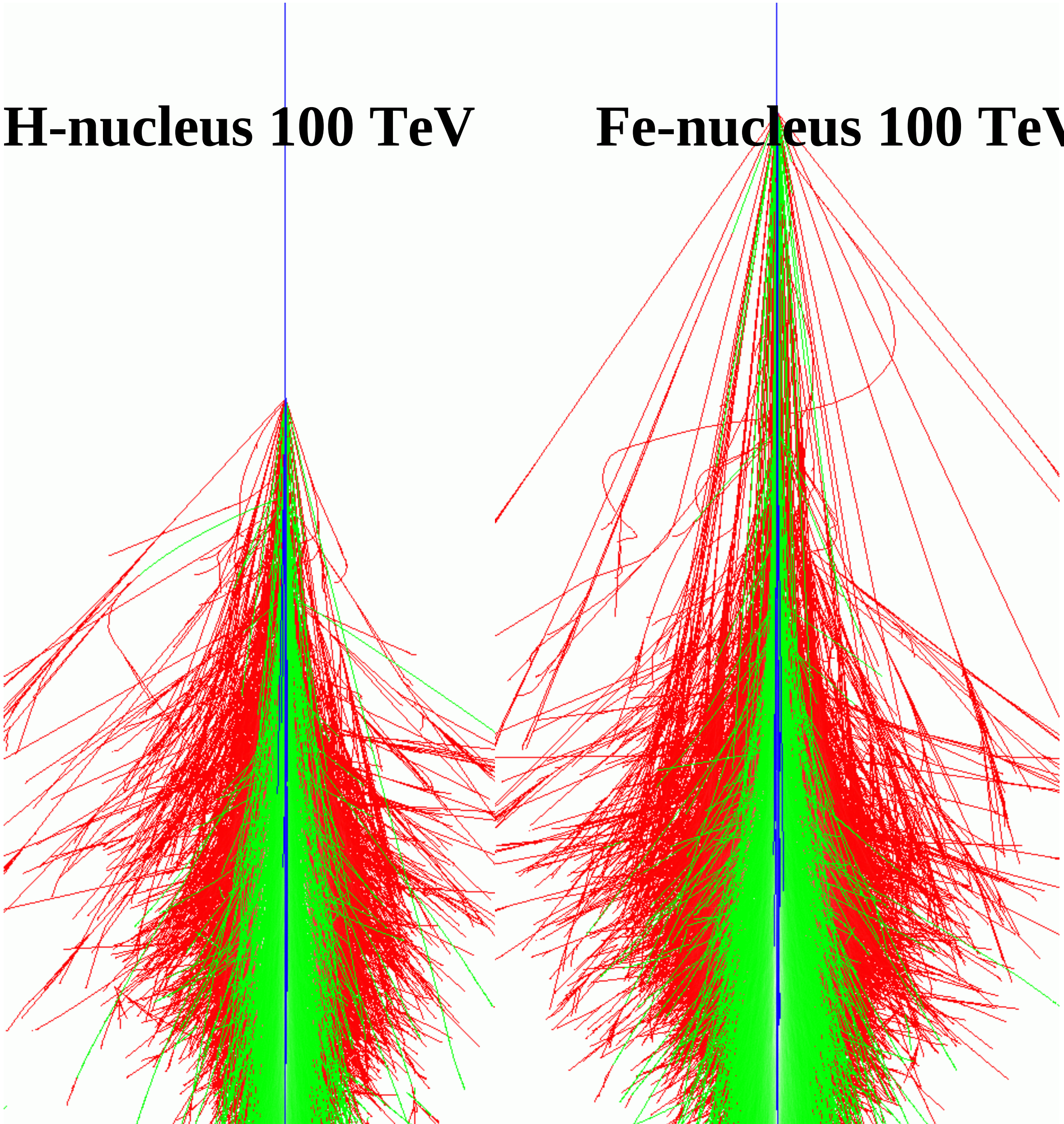
muonic component, neutrinos — **~10%**

hadronic component — **~ 1%**

electromagnetic component — **~90%**

Extensive Air Showers



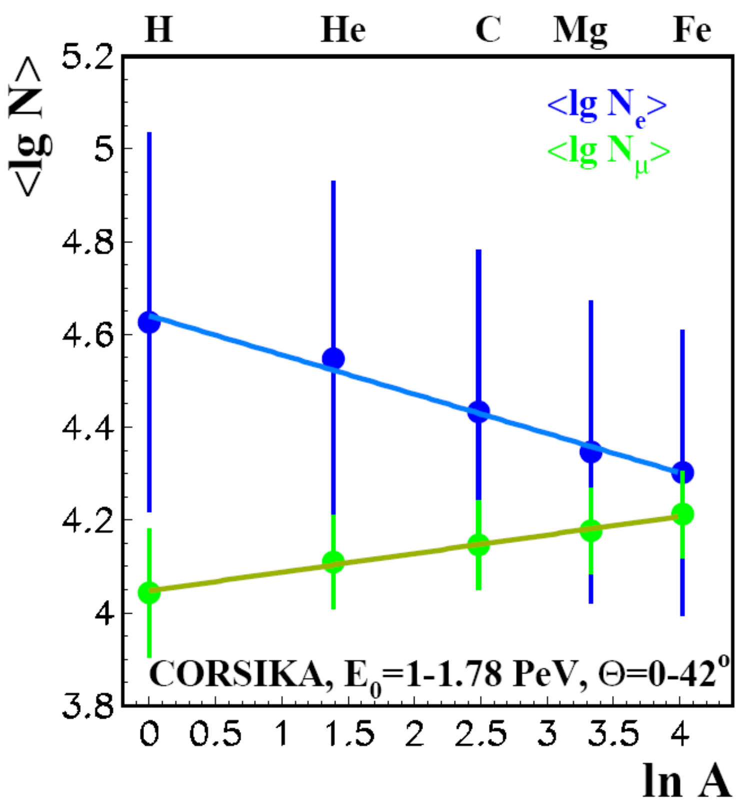


Differences at the shower development in the Atmosphere hint to energy und mass of the incident primary particle.

EAS – hadronic interactions: nucleus-nucleus

Superposition model: Fe-nuclei (E) = 56 x proton (E/56) valid, since binding energy << energy of nucleons (< 8MeV << >100TeV)

➔ additive observables Q: $\langle Q^A(E) \rangle = A \cdot \langle Q^P(E/A) \rangle$

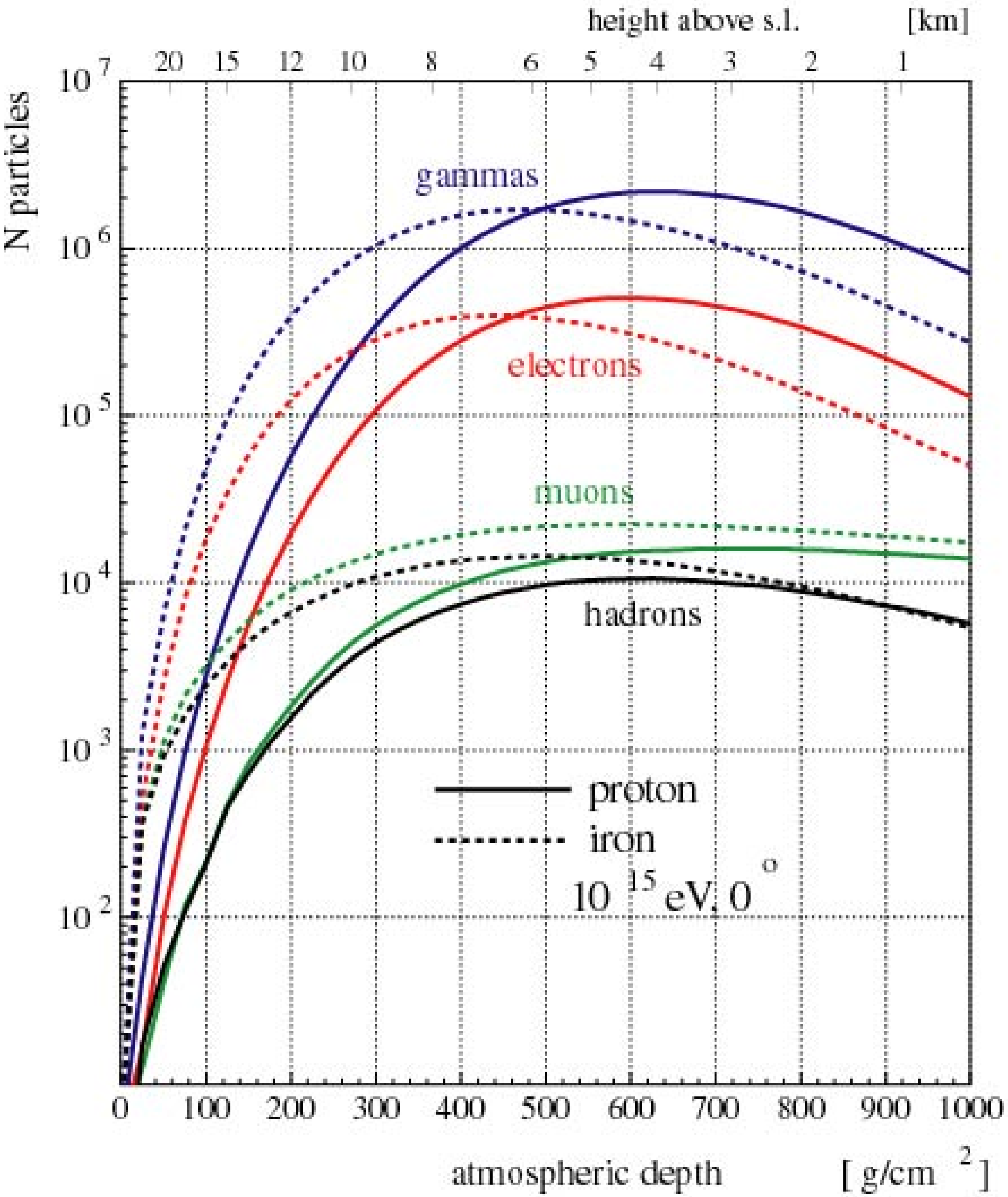


Fluctuations: $\sigma_{Q^A}(E) = \sigma_{Q^P}(E/A)/\sqrt{(A)}$

increasing A ➔

- more secondary particles with less energy ➔ less electrons (after maximum), more muons
- surviving hadrons have less energy
- larger deflection angles ➔ flatter lateral distributions of the secondary particles

Extensive Air Showers



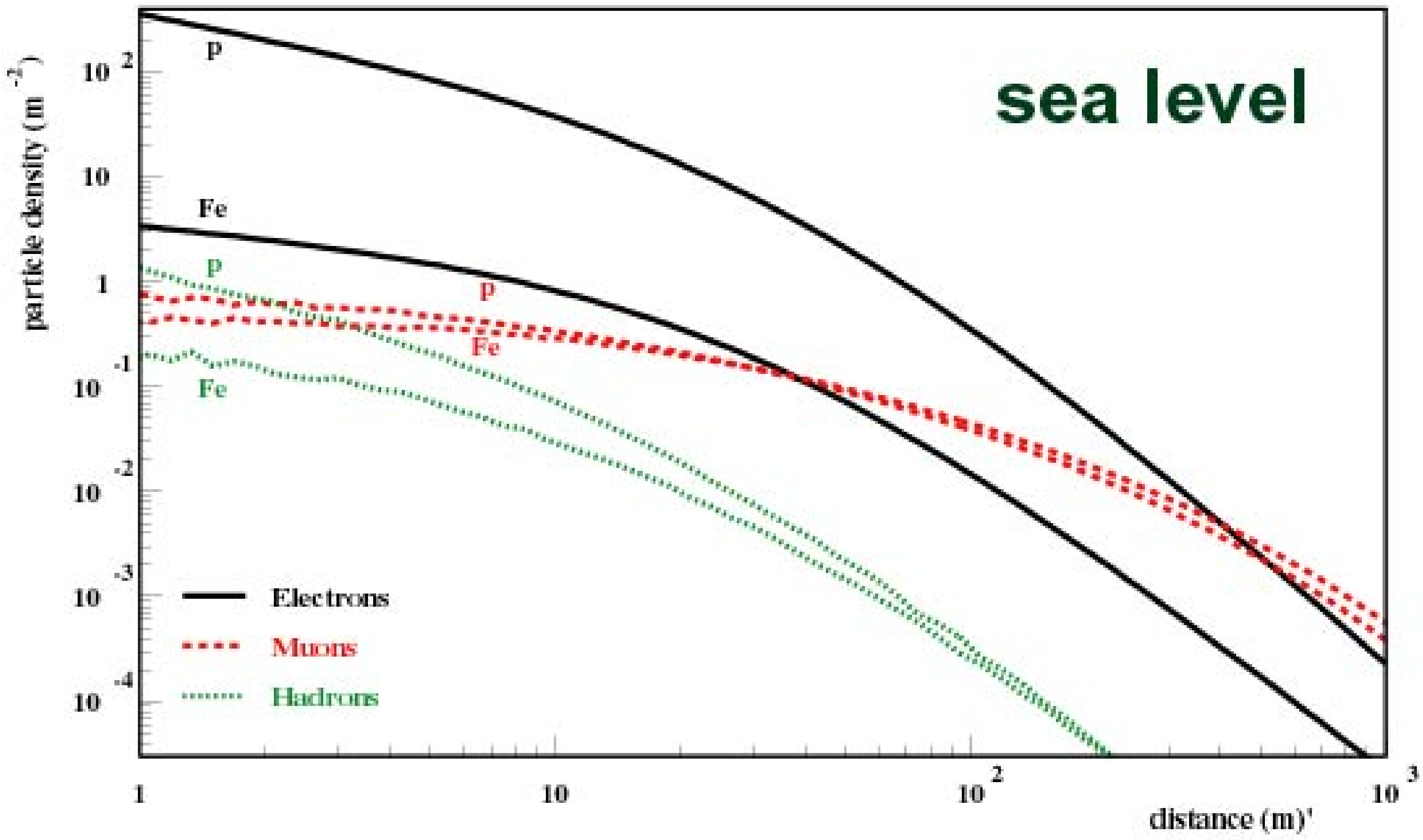
Sensitivity to energy and mass:

Particle number and particle distributions: Longitudinal distributions.

Extensive Air Showers

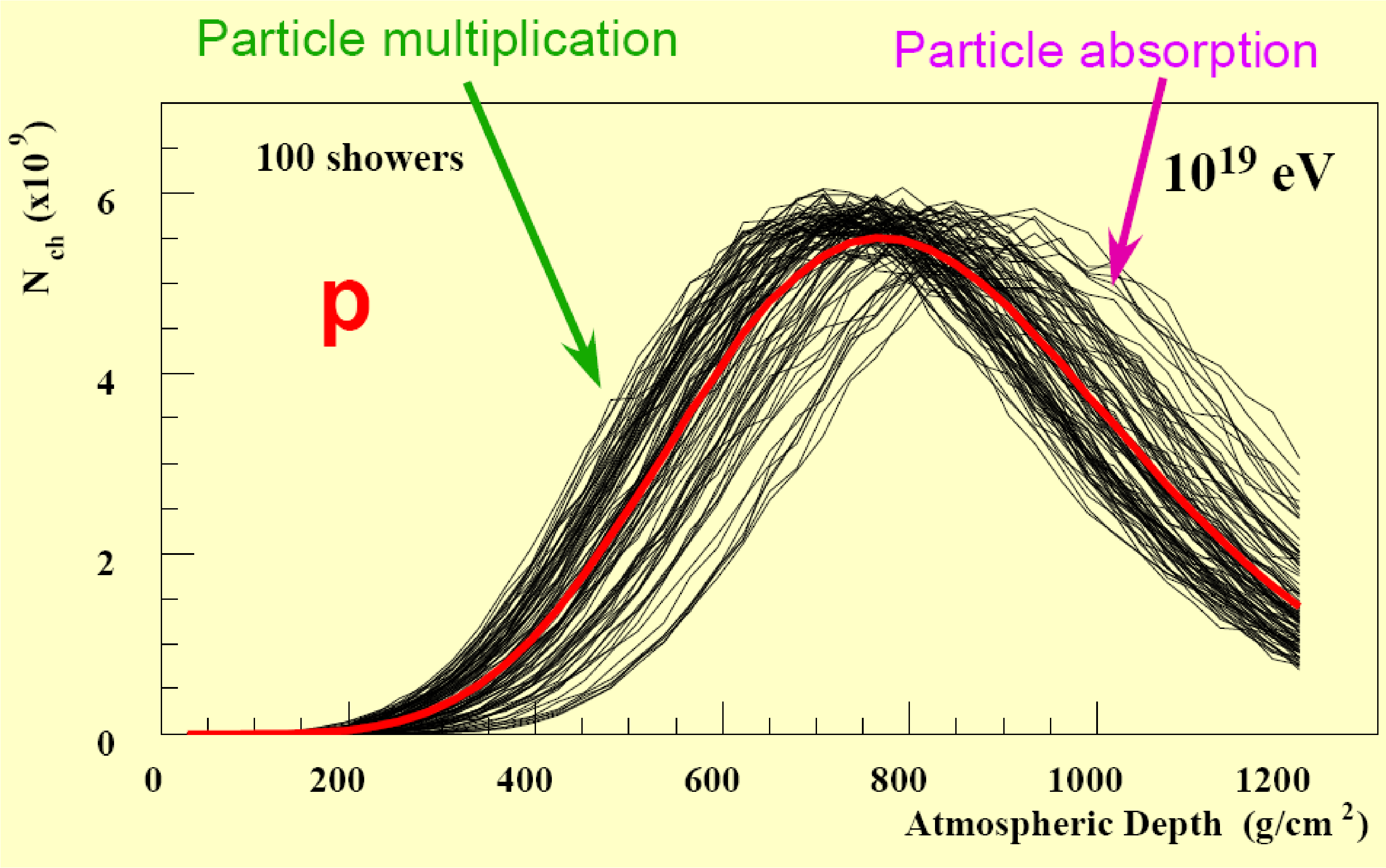
Sensitivity to energy und mass:

Particle number and particle distributions: Lateral distributions

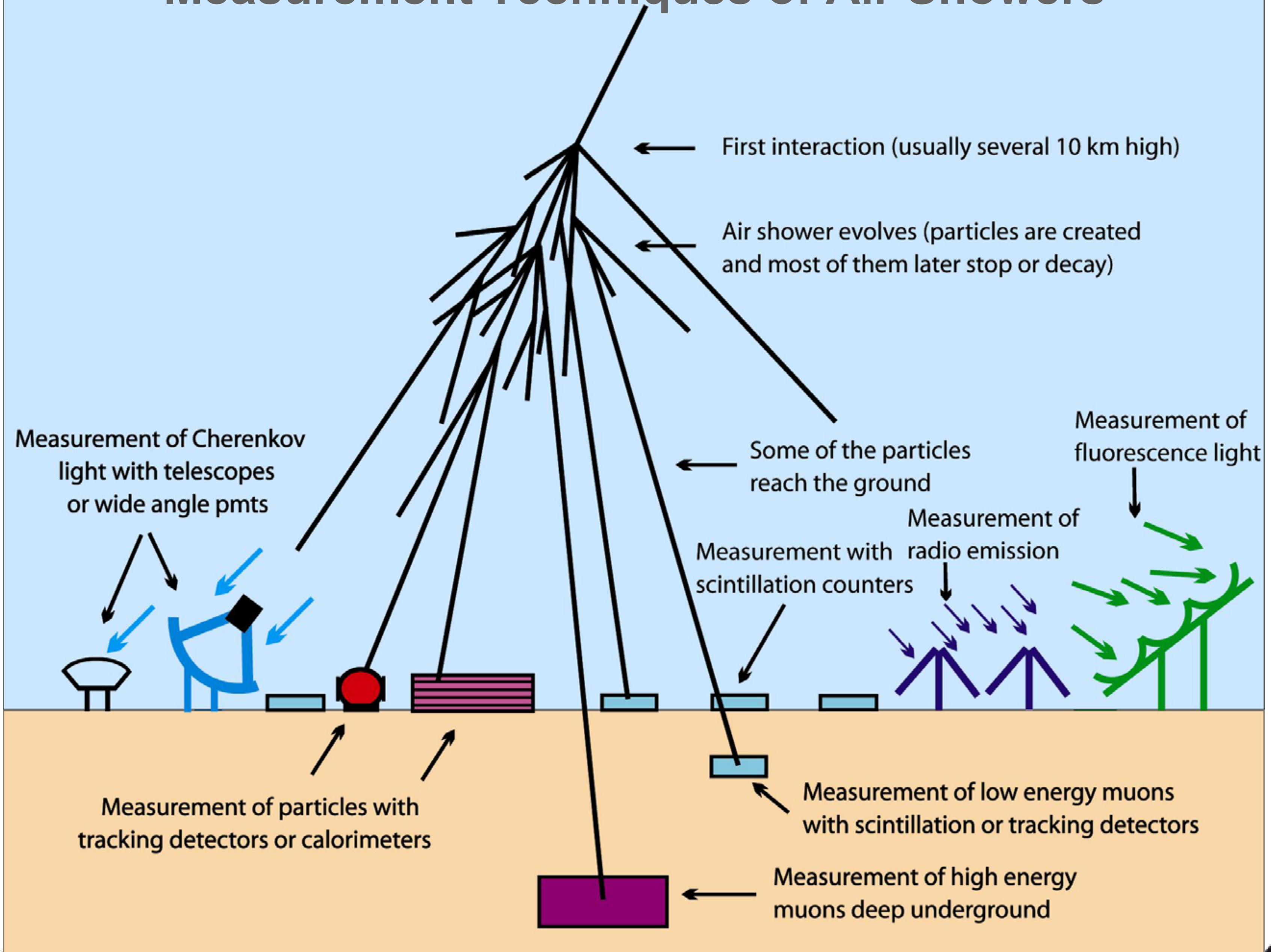


Extensive Air Showers

Problem: Shower-to-shower Fluctuations



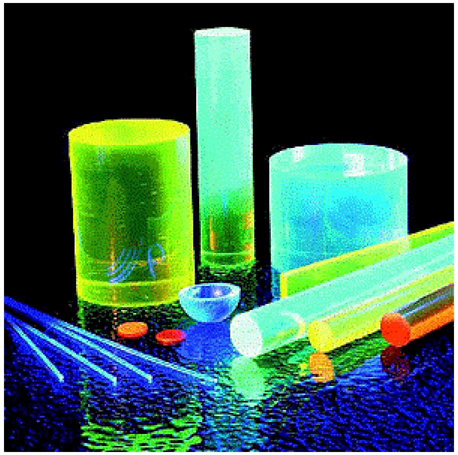
Measurement Techniques of Air Showers

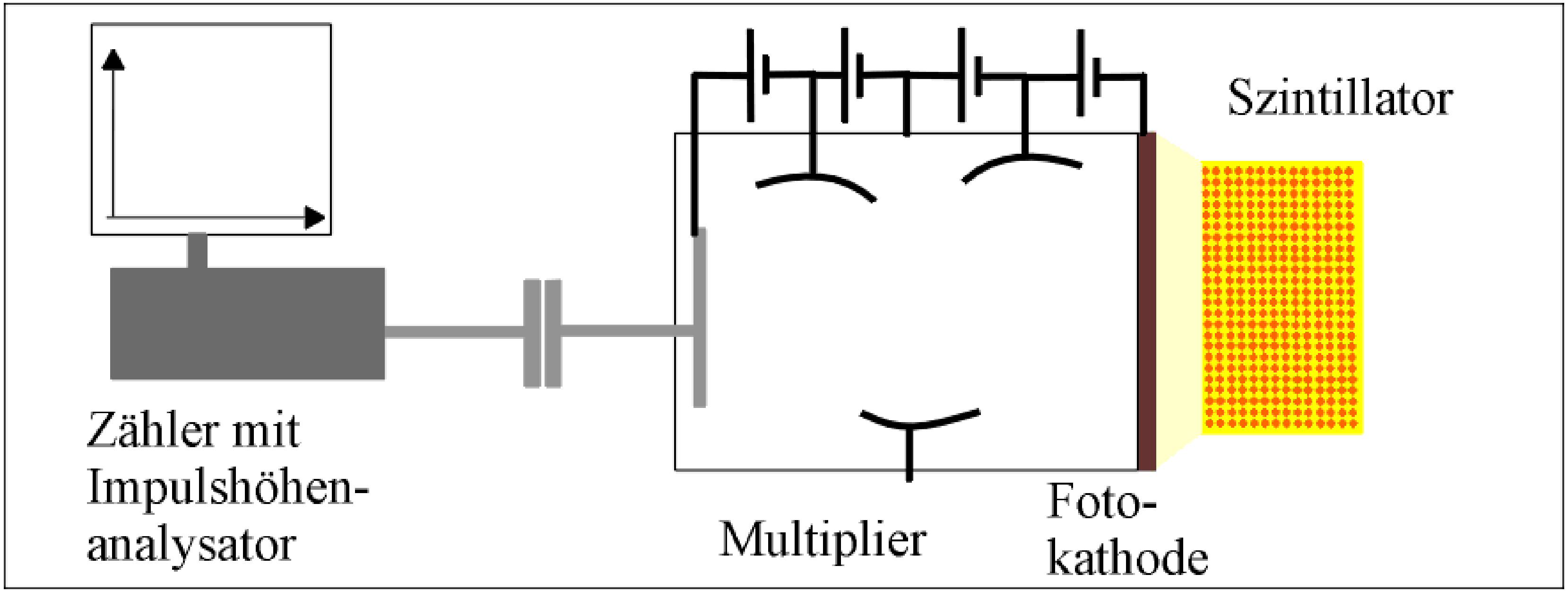


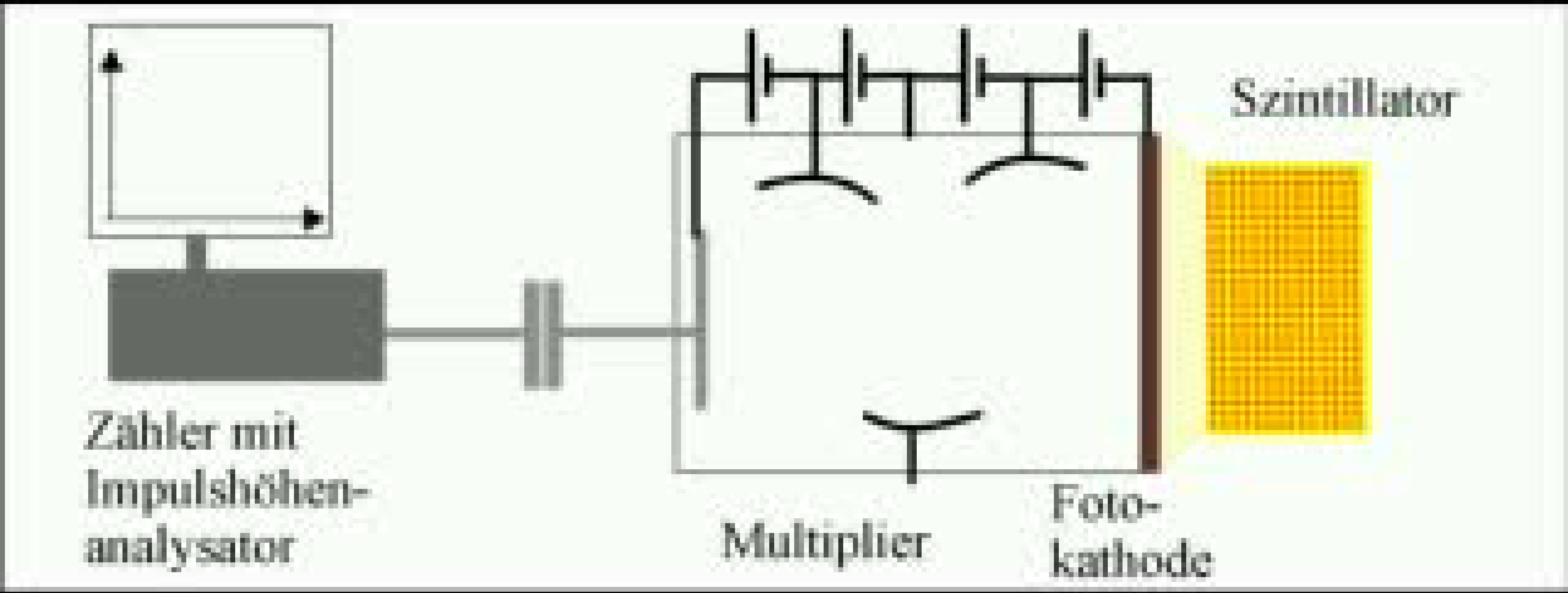
Particle Detection: Scintillators

Scintillation counter:

- Ionizing radiation generates light in the scintillators
- Light generates Electrons (photo effect)
- Electrons are multiplied (PMT)
- Number of electrons (charge) is counted






Szintillator
Zähler mit
Impulshöhen-
analysator
Multiplier
Foto-
kathode

Water Cherenkov Detector

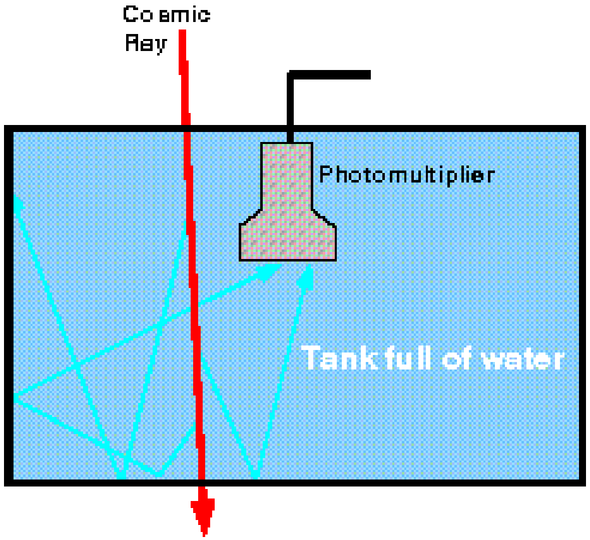
Pavel Alekseyevich Cherenkov (1904-1990)

Cherenkov-Counter:

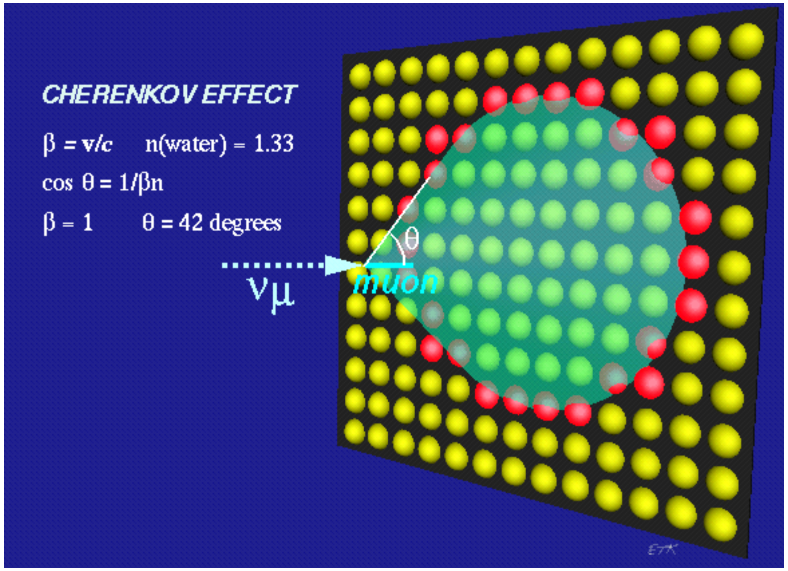
•Particle detector for charged particles named after physicist Pavel Cherenkov

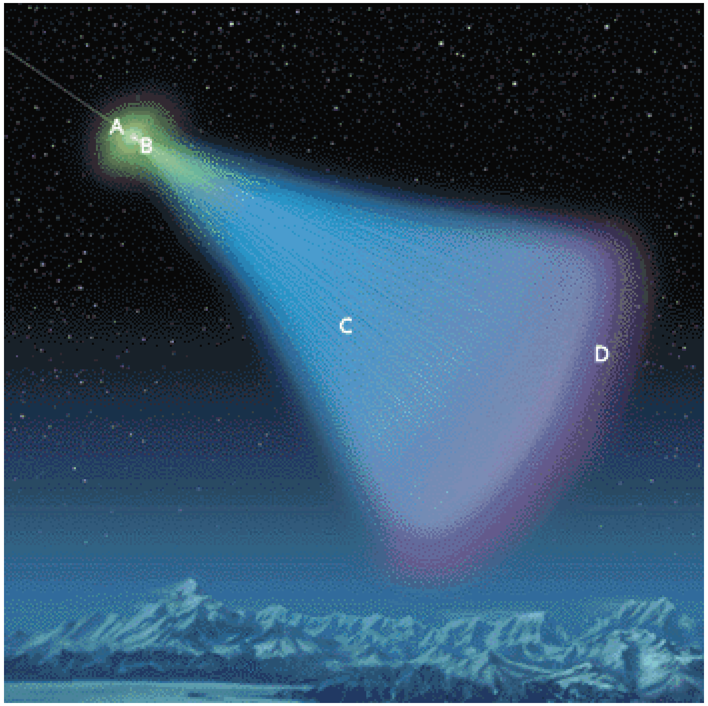
•Principle: If the speed of charged particles in a medium exceeds the speed of light in this medium (e.g. water) they emit radiation (in optical light)

•The principle of a Cherenkov counter is based on the detection of this Cherenkov-radiation



Water Cherenkov Detector





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

i.e. Cherenkov-radiation, if $v_{particle} > c_{medium}$

In water: n= $v_{particle} > 0.75c$,

i.e. muons $E_{kin} > 60MeV$, electrons $E_{kin} > 0.3MeV$

Fulfilled in air shower particles

Angle of emission:

$\cos\theta = 1/n\beta$ [h/2pλ (1-1/n²)]

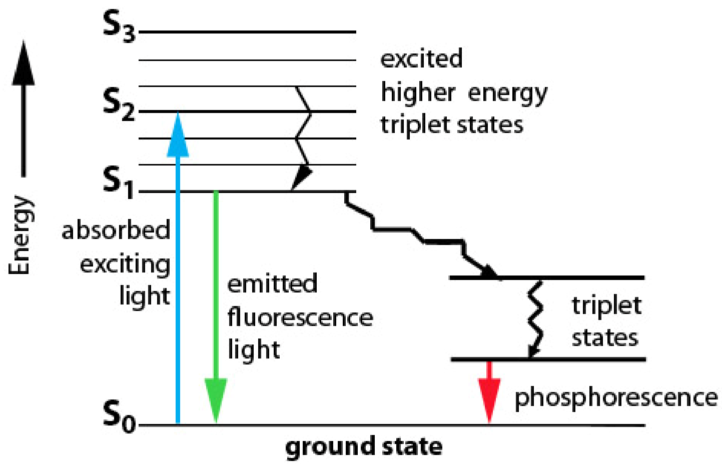
photons per track length :

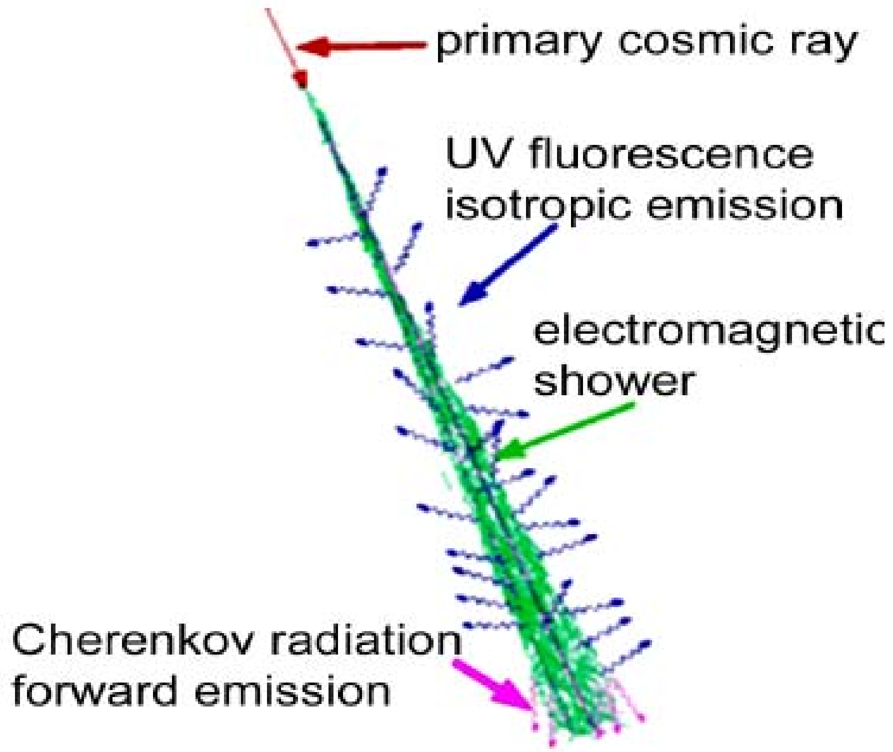
$dN/dx = 2\pi\alpha Z^2 \int_{\lambda 1}^{\lambda 2} (1-1/n^2\beta^2)\, d\lambda/\lambda^2$

Fluorescence Light Detection

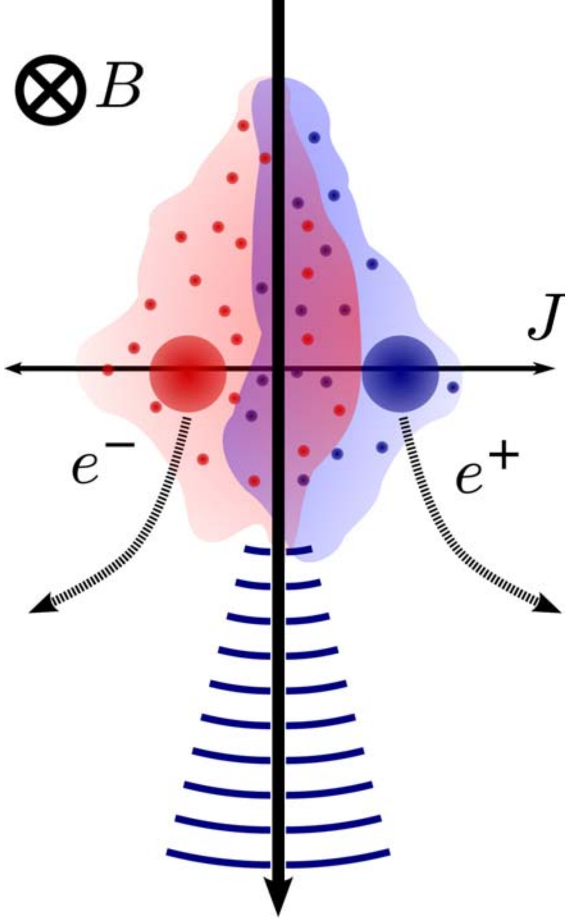
Charged particles excites Nitrogen in atmosphere.

De-excitation: Fluorescence light (isotropic)

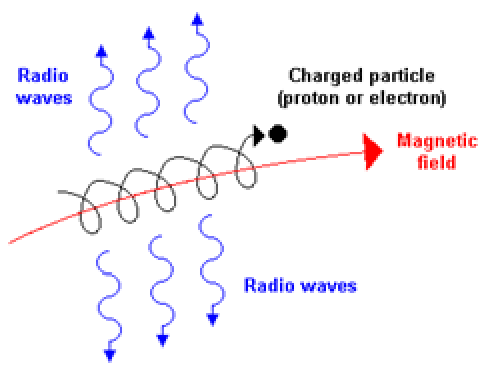




Radio Detection of EAS



- Characteristic energy for electrons is 30-100 MeV
- Charge separation in Earth's magnetic field
  ➔ electric dipole
- Gyration of electrons along a small arc
  ➔ emission of synchrotron radiation
- time varying charge excess in EAS
  ➔ electric dipole
- atmosphere's refraction index ≠ 1
  ➔ Cherenkov like radio emission
- Electrons are in a shower disk of small thickness (2 m < one wavelength at 100 MHz)
  ➔ coherent emission
  ➔ beamed into propagation direction



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   - **short history of cosmic ray research**
   - **extensive air showers**
2. **High-Energy Cosmic Rays**
   - **KASCADE, KASCADE-Grande and LOPES**
3. **Extreme Energy Cosmic Rays**
   - **Pierre Auger Observatory, JEM-EUSO**
4. **TeV-Gamma-rays & High-energy Neutrinos**
   - **TeV gamma rays**

     H.E.S.S., MAGIC, CTA
   - **high-energy neutrinos**

     IceCube and KM3Net

Discussion / Question / Exercise

- **ideal air-shower detector?**
- **what are the rôle of EAS-neutrinos?**
- **why sources of cosmic rays are not known?**

Discussion / Question / Exercise

- **ideal air-shower detector?**
  - **longitudinal sensitivity 100%**
  - **electron-muon separation**
  - **independent stations**
- **what are the rôle of EAS-neutrinos?**
  - **missing mass (reconstruction)**
  - **particle physics (oscillations)**
  - **background in neutrino detectors**
- **why sources of cosmic rays are not known?**
  - **magnetic fields**
  - **leptonic/hadronic acceleration models**
  - **various source populations**