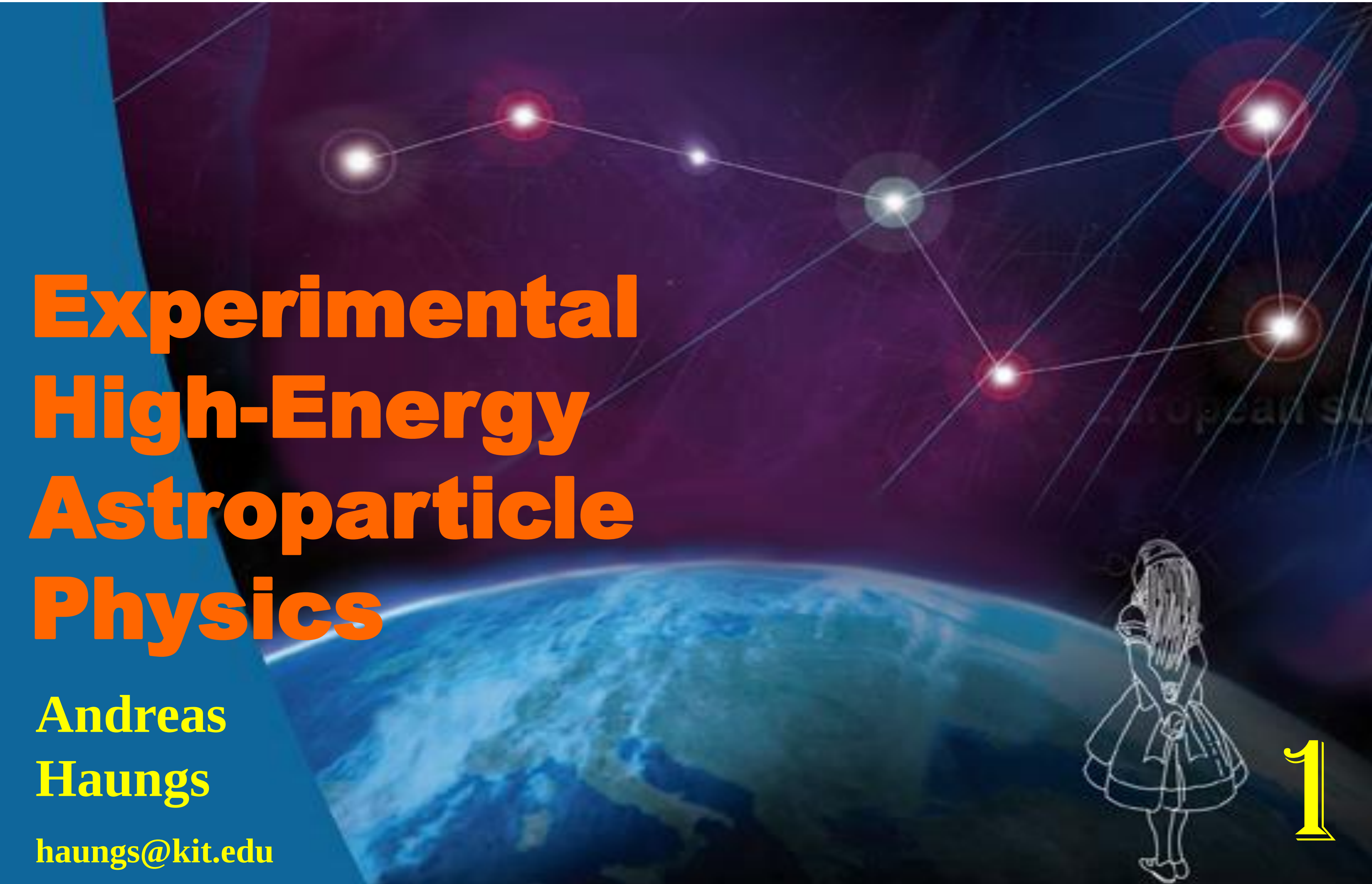
KIT – University of the State of Baden-Württemberg and
National Research Center of the Helmholtz Association



Experimental High-Energy Astroparticle Physics

Andreas Haungs

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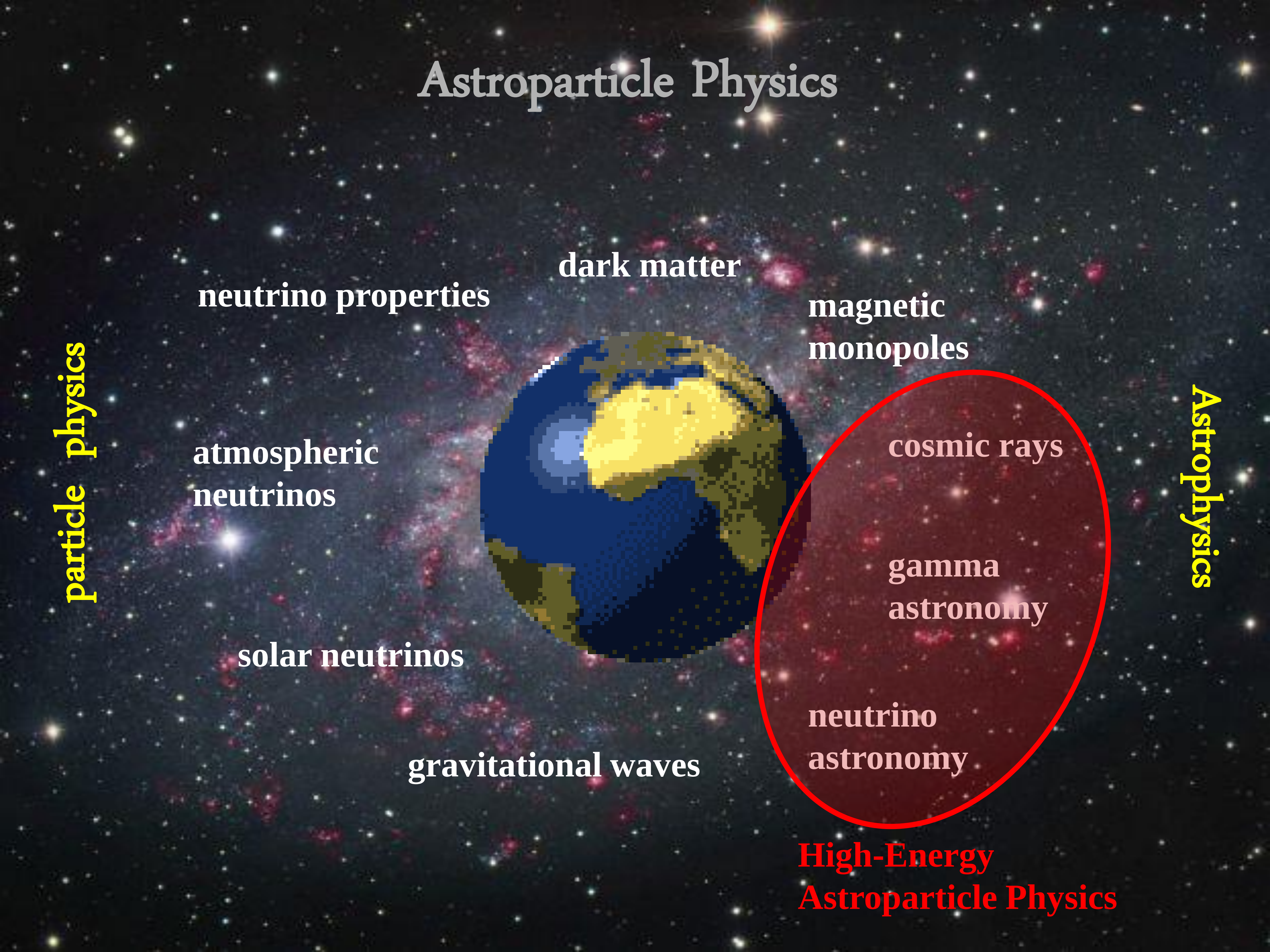
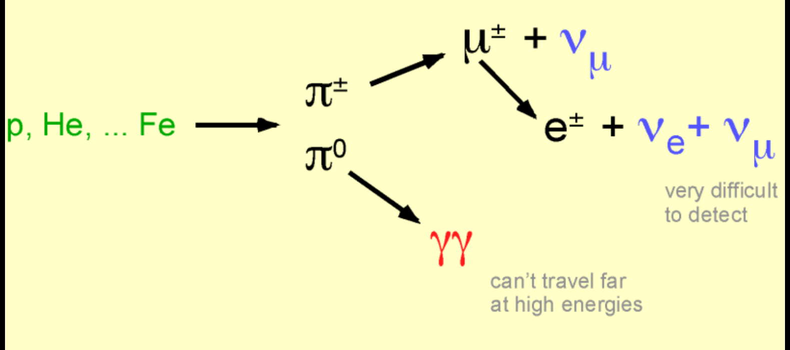
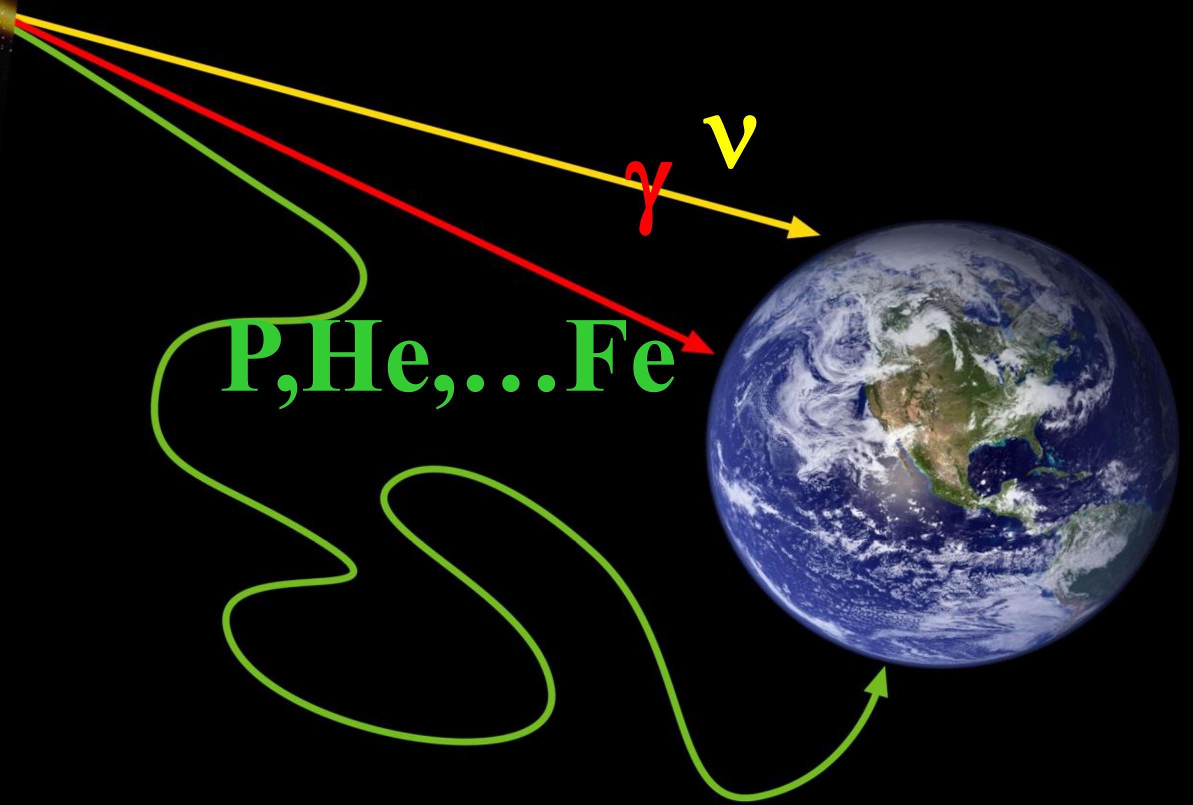

Astroparticle Physics
dark matter
neutrino properties
magnetic monopoles
particle physics
Astrophysics
atmospheric neutrinos
cosmic rays
gamma astronomy
solar neutrinos
neutrino astronomy
gravitational waves
High-Energy Astroparticle Physics

Multi-messenger Approach in Astroparticle Physics



Cosmic rays, gammas and neutrinos are linked.



GZK:

$$p+\gamma_{2.7K} \rightarrow \Delta^{+}(1232)$$
$$\rightarrow p+\pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n+\pi^{+} \rightarrow pe^{+}\nu$$

Content:

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

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

     IceCube and KM3Net

Content:

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     H.E.S.S., MAGIC, CTA
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     IceCube and KM3Net

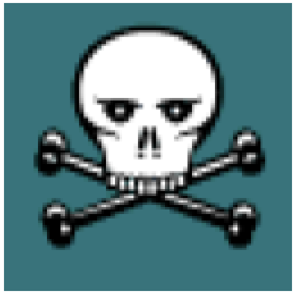
Discussion / Question / Exercise

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

What are cosmic rays ?

= high-energy, extraterrestric particles

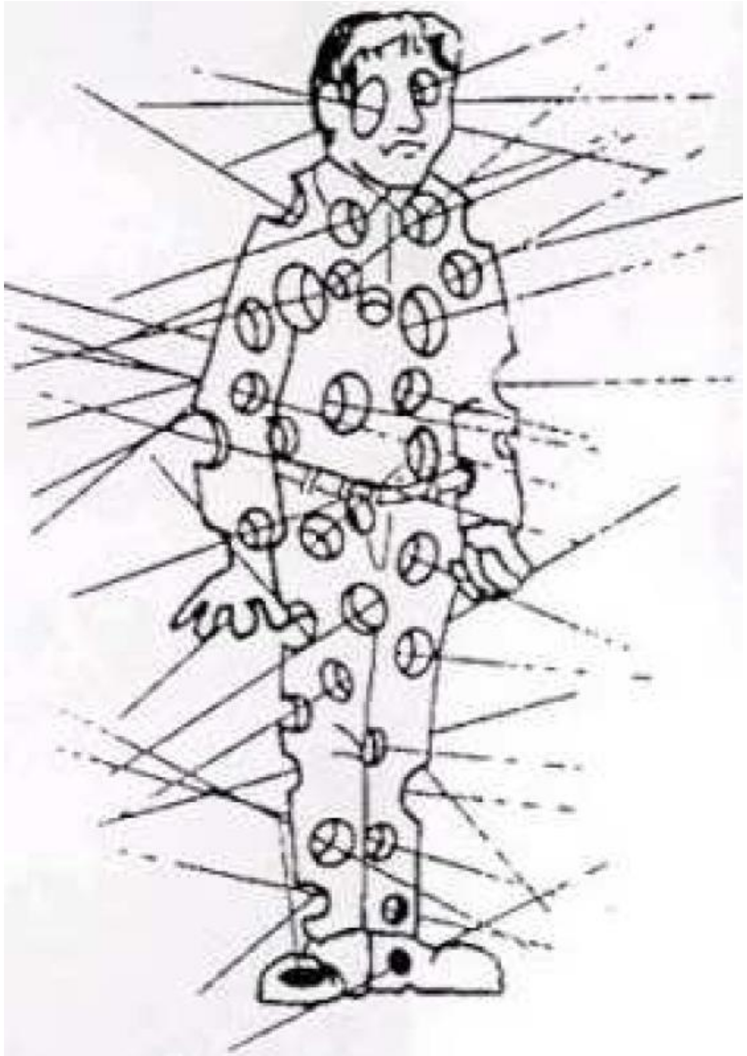
Warning:



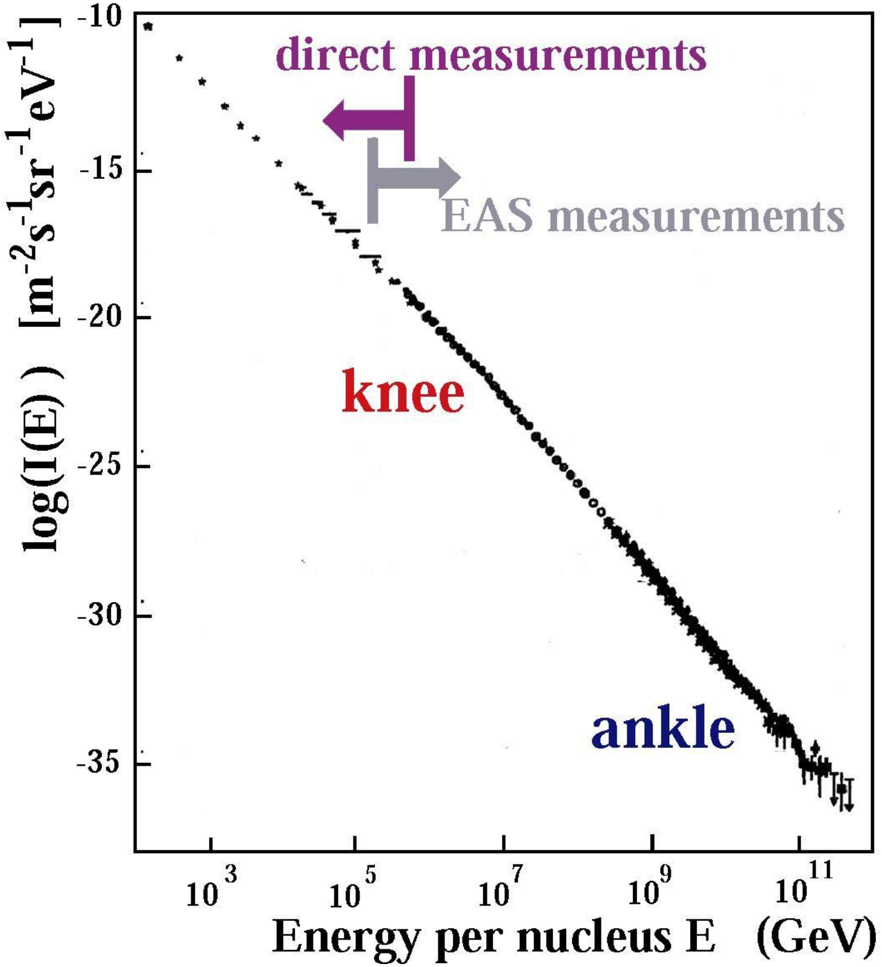
c. 100.000 particles will pass your body in each 1 hour !!

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



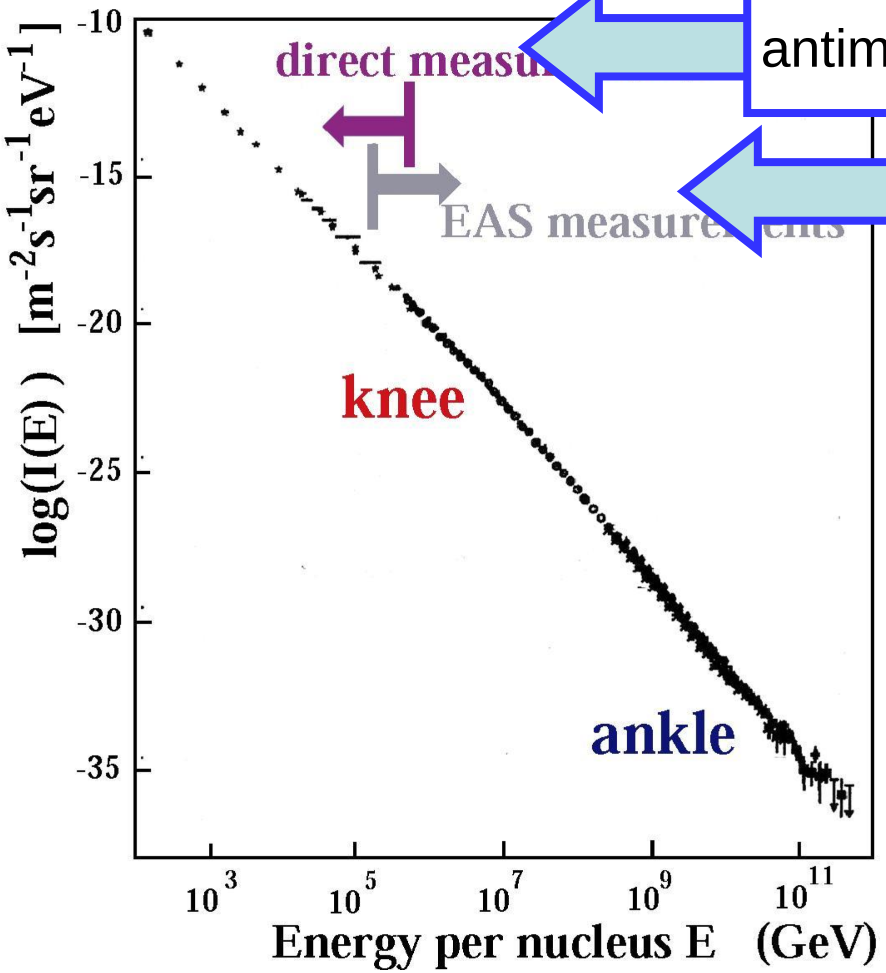
← 1 particle per m^2 s

← 1 particle per m^2 year

← 1 particle per km^2 year

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

Charged Cosmic Rays: the energy spectrum



antimatter, dark matter, mass composition

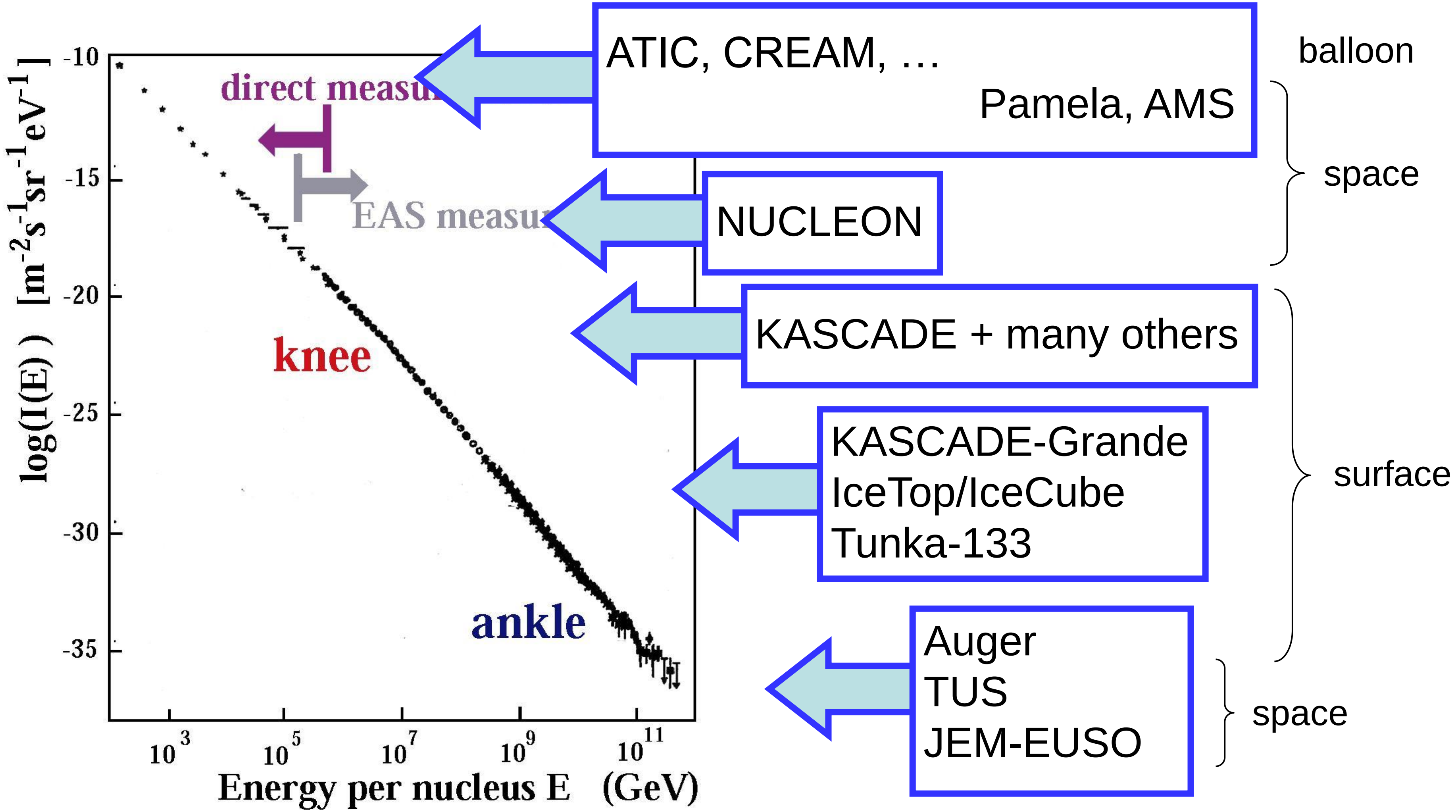
primary mass composition

galactic sources
mass composition

galactic → extragalactic

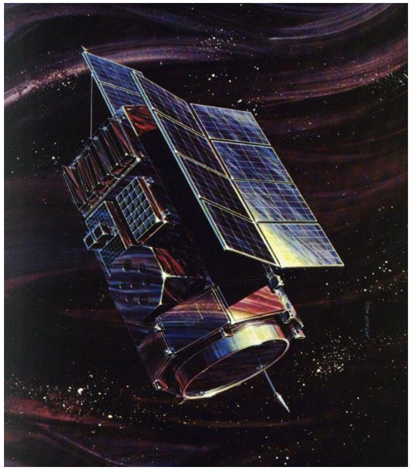
CR astronomy,
GZK physics,
HE neutrinos,
γ astronomy, …

Charged Cosmic Rays: the energy spectrum



Cosmic rays – direct measurements

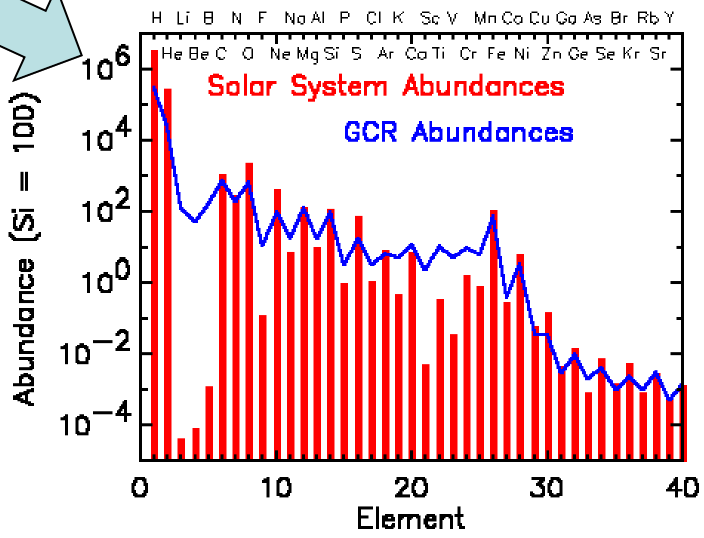
Balloons

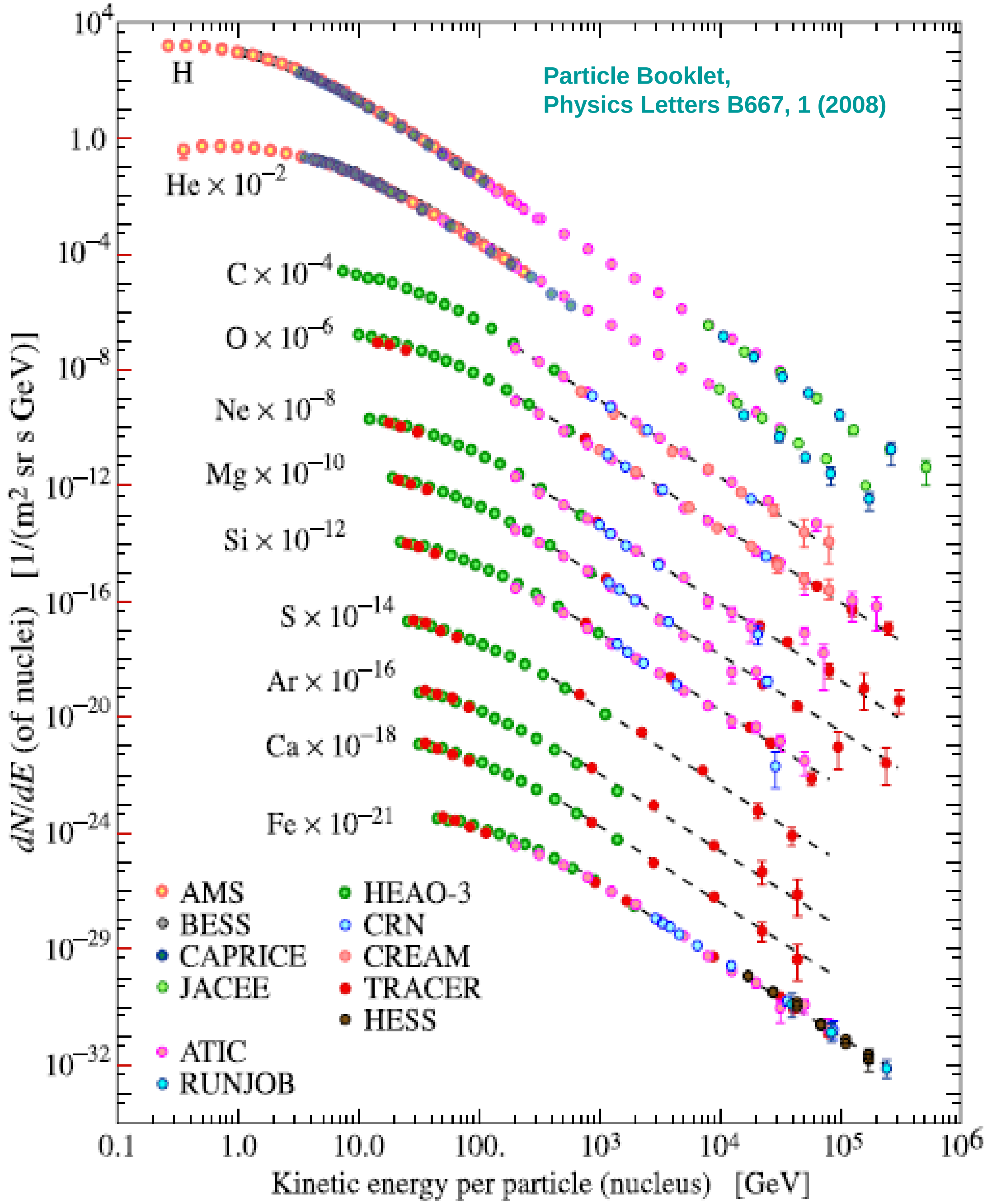


Satellites

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

relative abundancies of the chemical elements

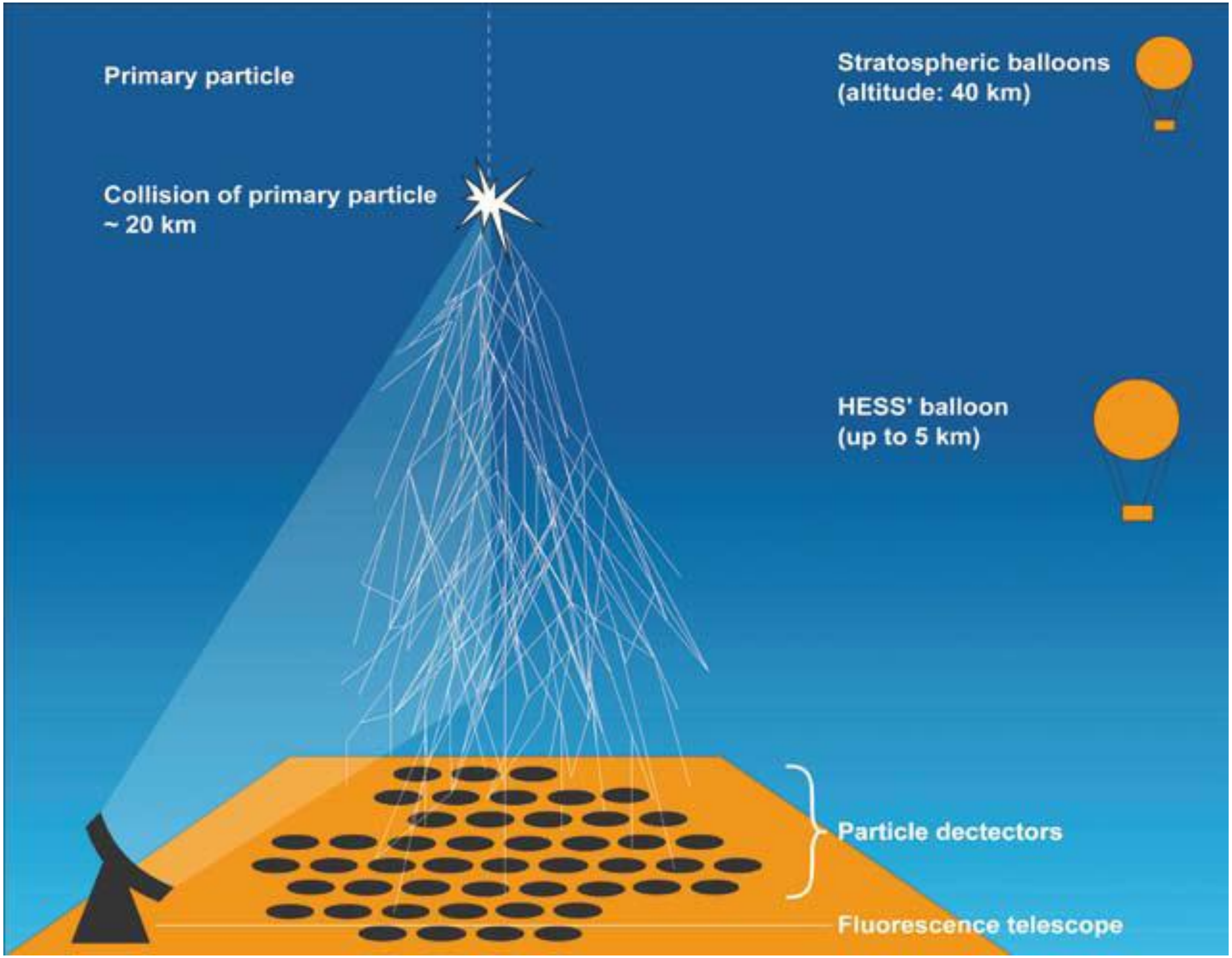




Direct measurements

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

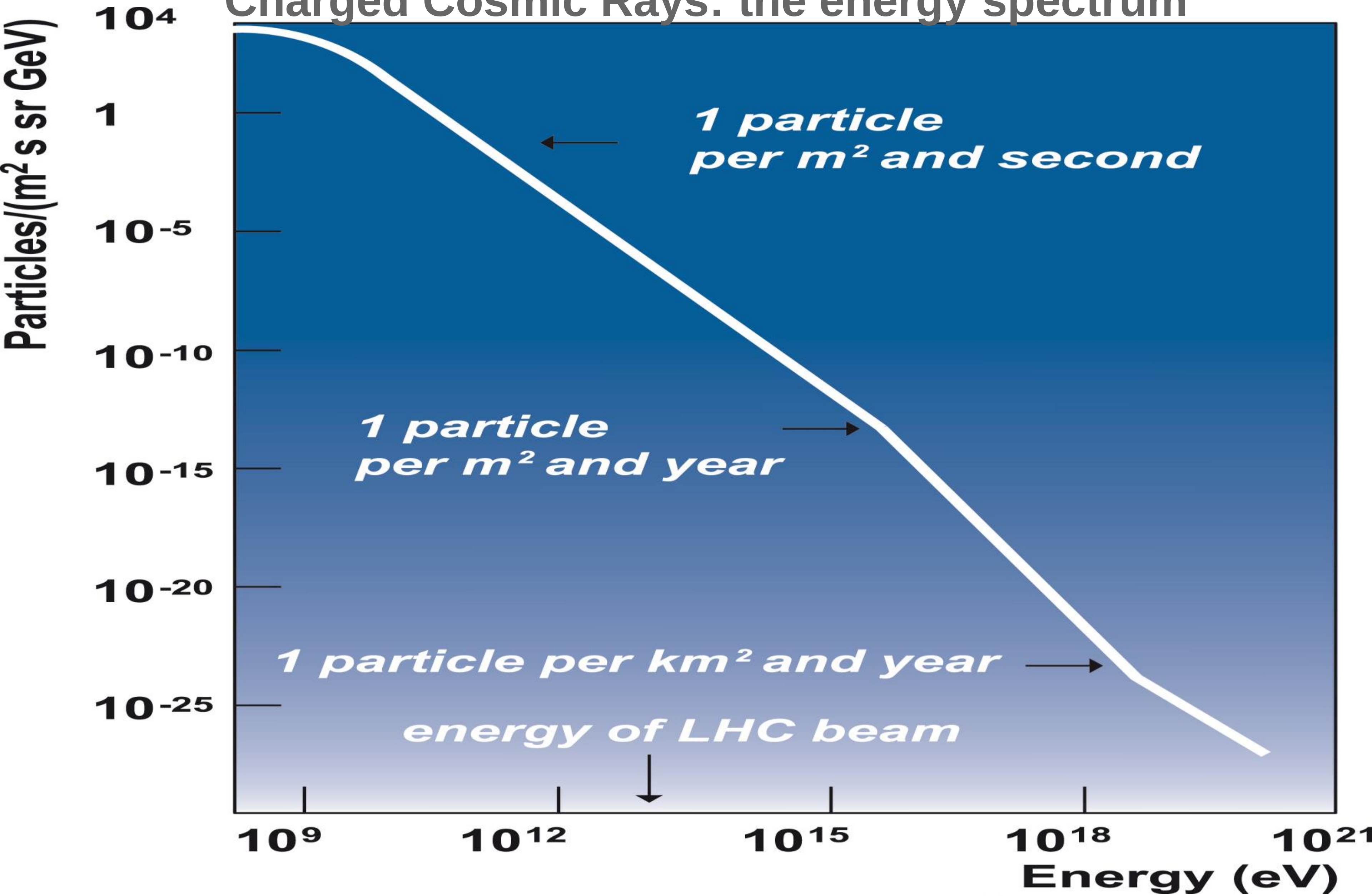
Cosmic rays – air shower measurements



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

→ **EAS**

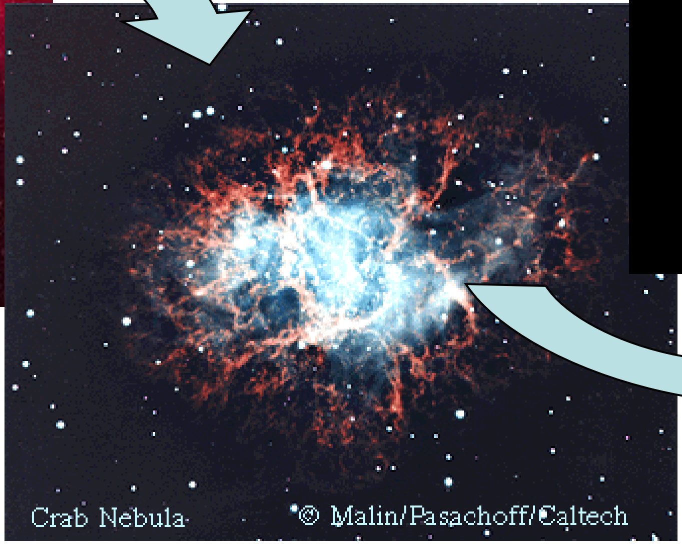
Charged Cosmic Rays: the energy spectrum



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

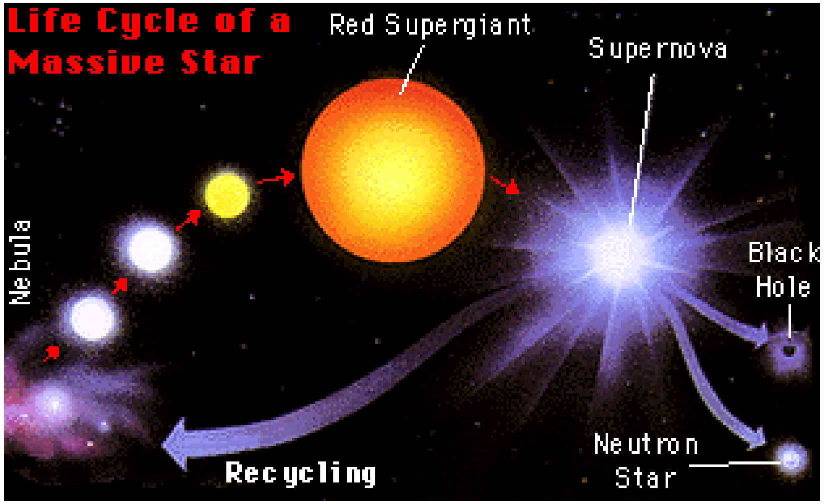
e.g.:
Supernovae: 10^{51} erg/s energy release, 1 SN per 30 years and 10% efficiency in cosmic rays

CR likely galactic origin!

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

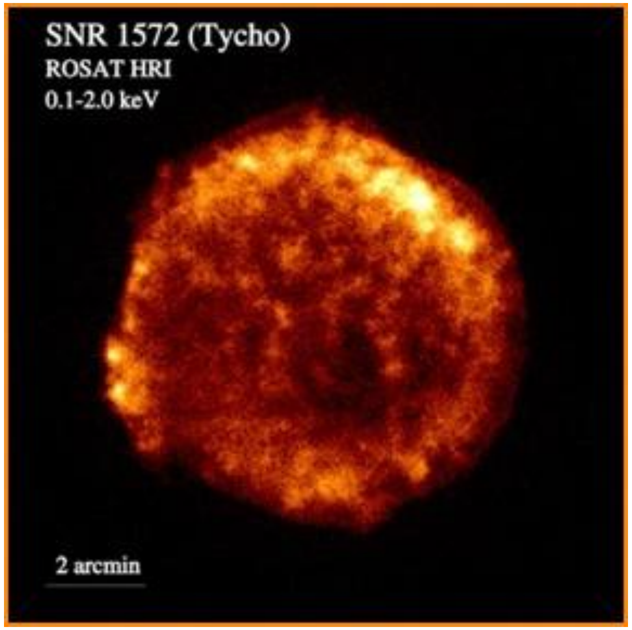
1 erg = 10^{-7} J = 100 nJ
1 erg = 624.15 GeV = 6.2415 $\times 10^{11}$ eV
1 erg = 1 g·cm²/s²

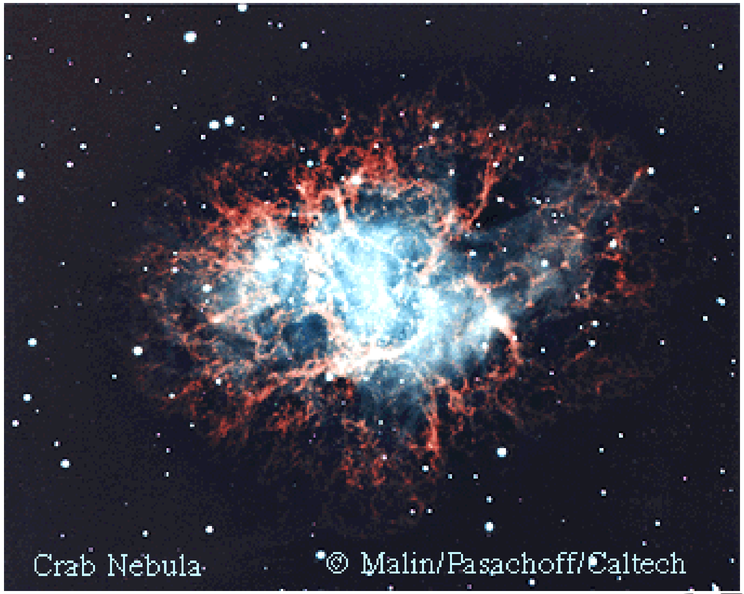
Cosmic Rays: Sources?



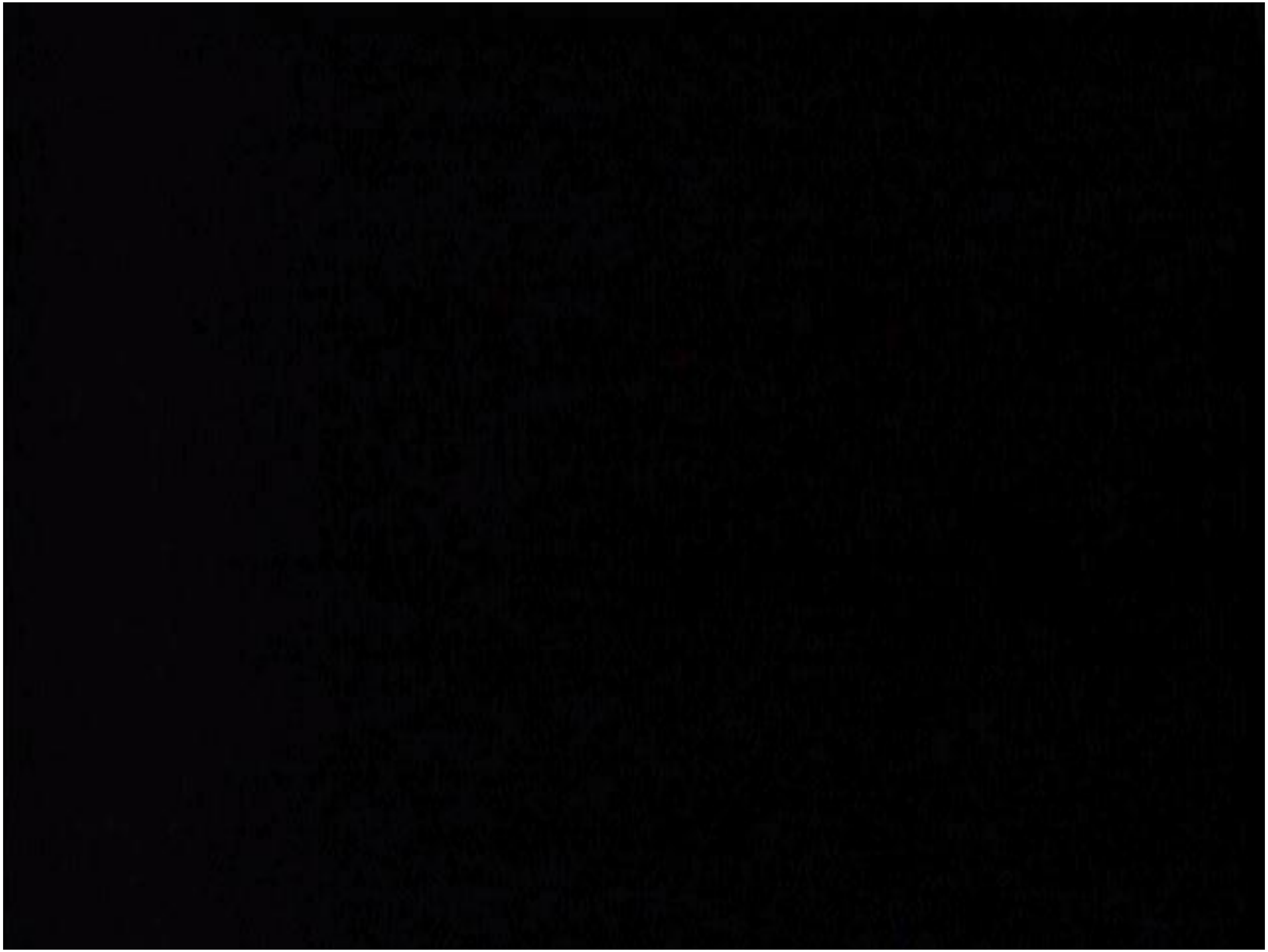
Galactic Sources:

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





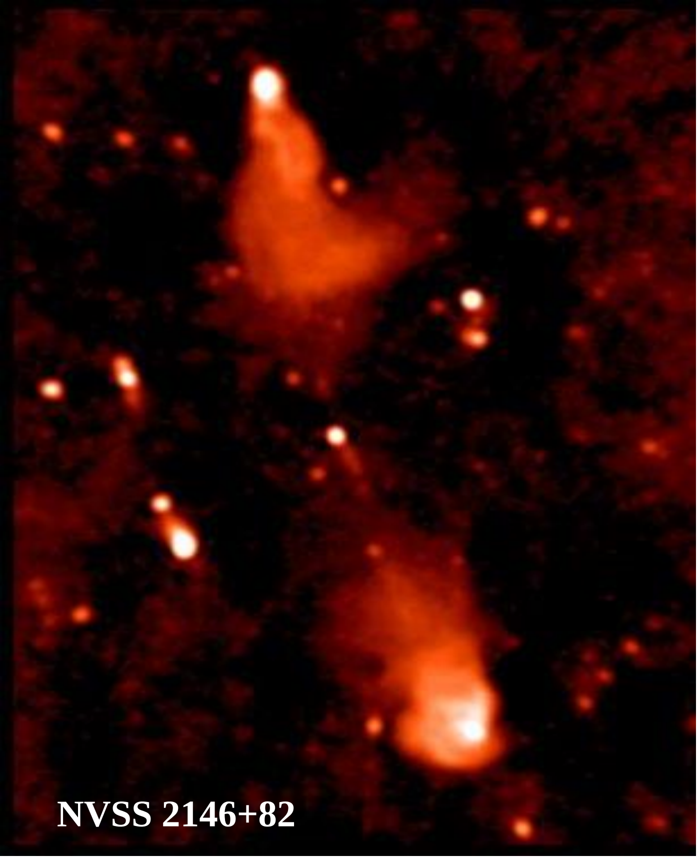
Galactic Sources:

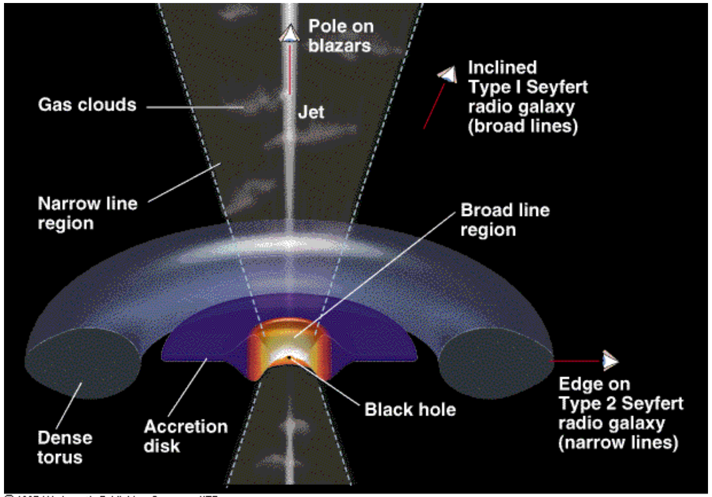


Cosmic Rays: Sources?

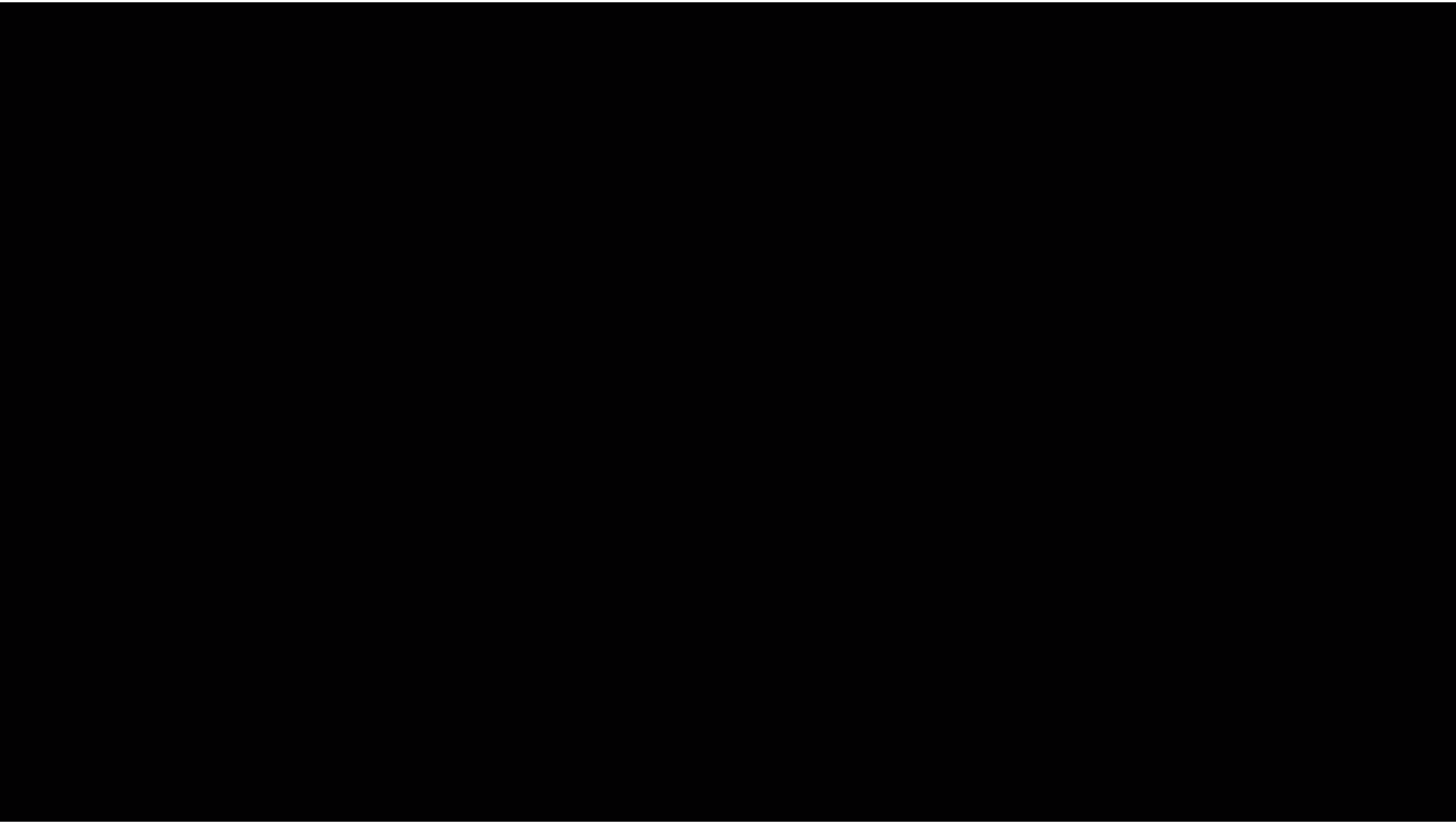
Extragalactic Sources ?

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

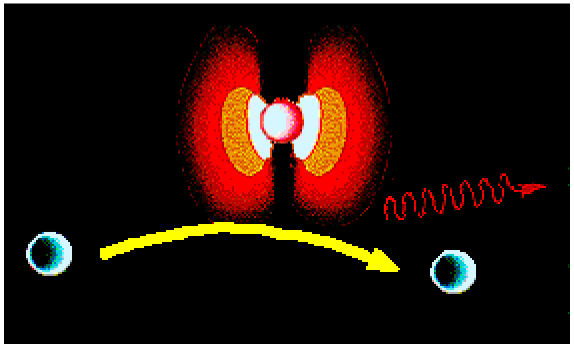




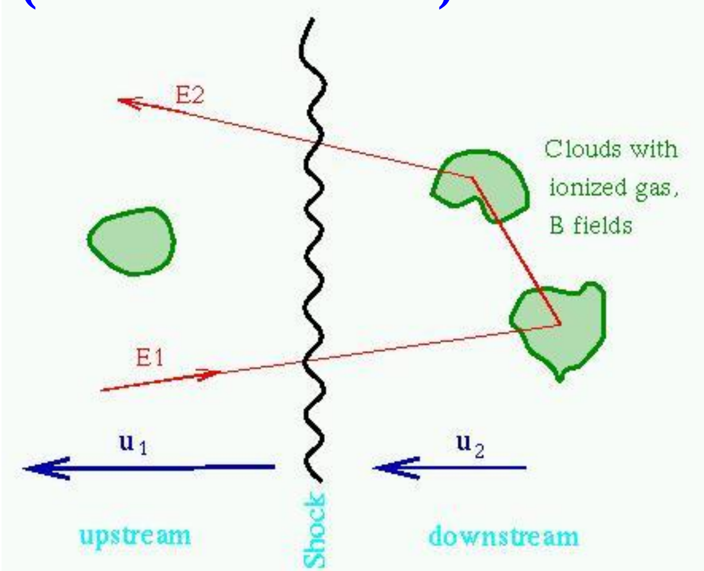
Extragalactic Sources ?



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=2.2-3

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.

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

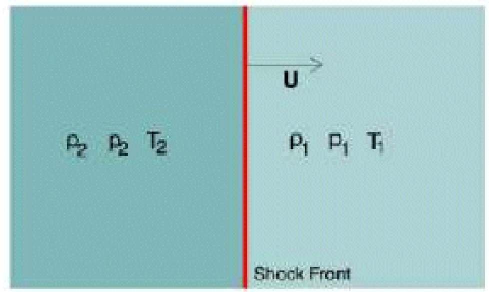
➔always head-on collisions!

➔energy gain

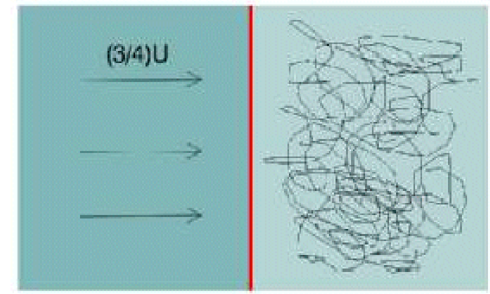
$$\Delta E/E = 2\,(V-U)\,/\,v$$

relativistic calculations and taking Into account the scatter angles:

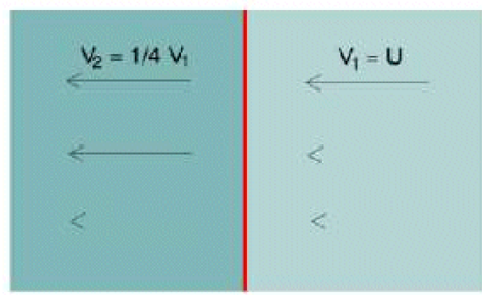
➔ $\Delta E/E = 4/3\ (V-U)\,/\,c$



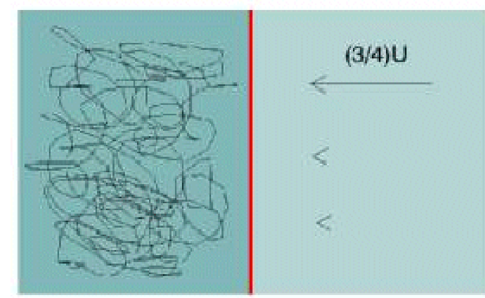
(a) Shock front traveling at speed U



(c) rest frame of downstream medium



(b) seen in rest frame of shock front



(d) rest frame of upstream medium

➔ classical kinematic describes how often particles pass the shock

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

➔ $N(E)\, dE \ \propto E^{-2}\, dE$ **!!!**

(strong shocks are observed at supernova remnants)

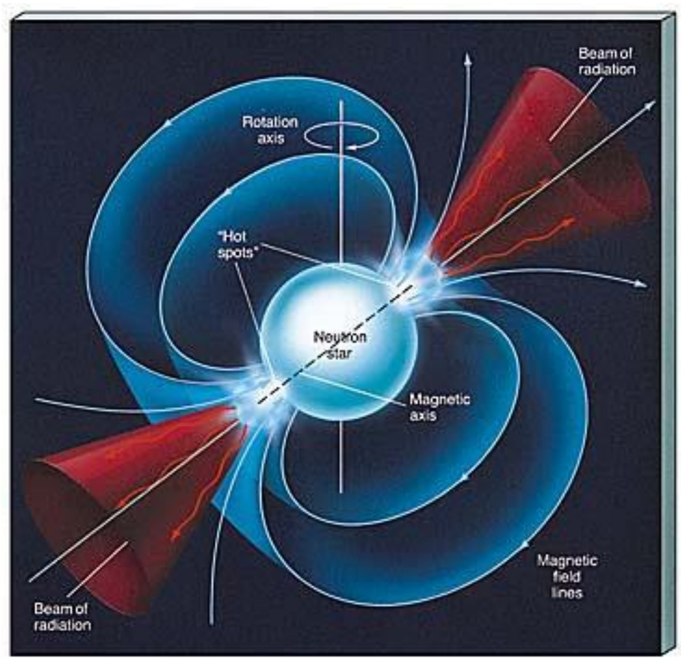
idea: acceleration in Pulsars

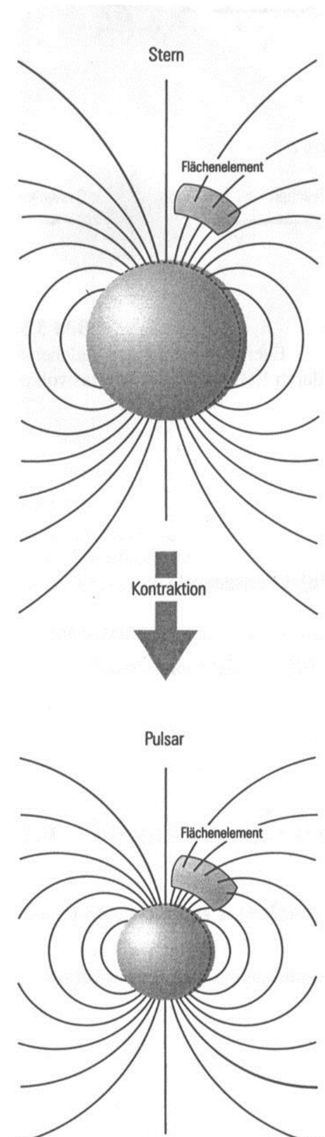
Pulsar:

- 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:

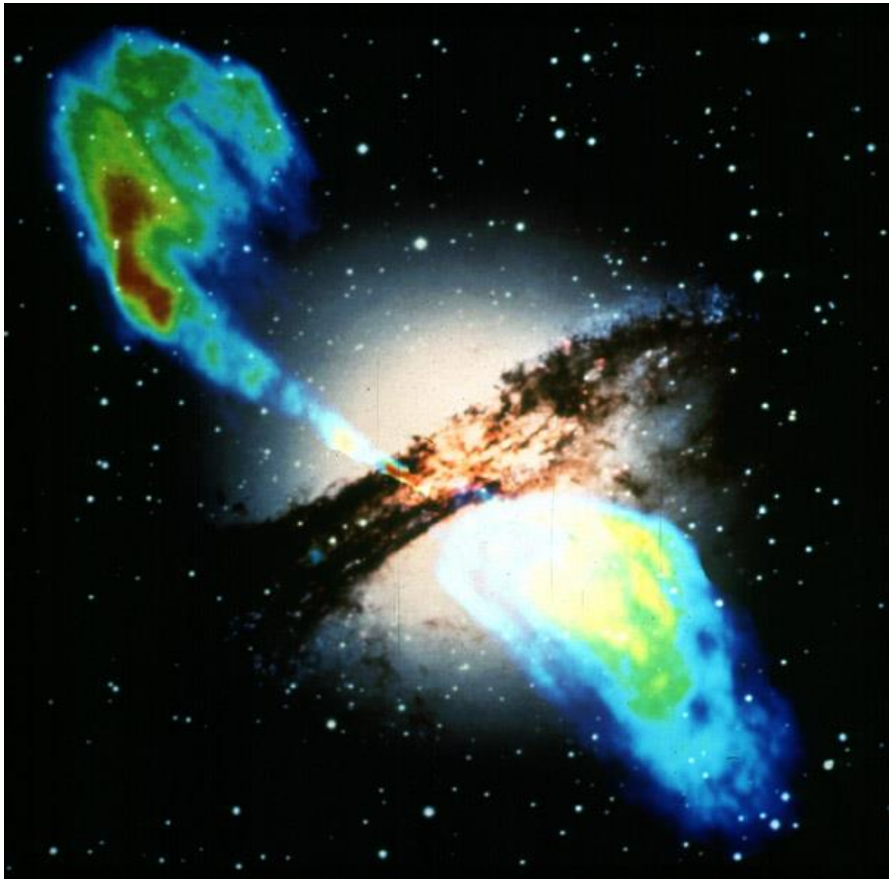
➔ T_{Pulsar} = 1 – 30 ms
➔ very high magnetic fields:
B_{Star} = 0.1 Tesla ➔
$B_{Pulsar} = 2.5 \cdot 10^8$ Tesla

➔ very strong electrical fields by induction



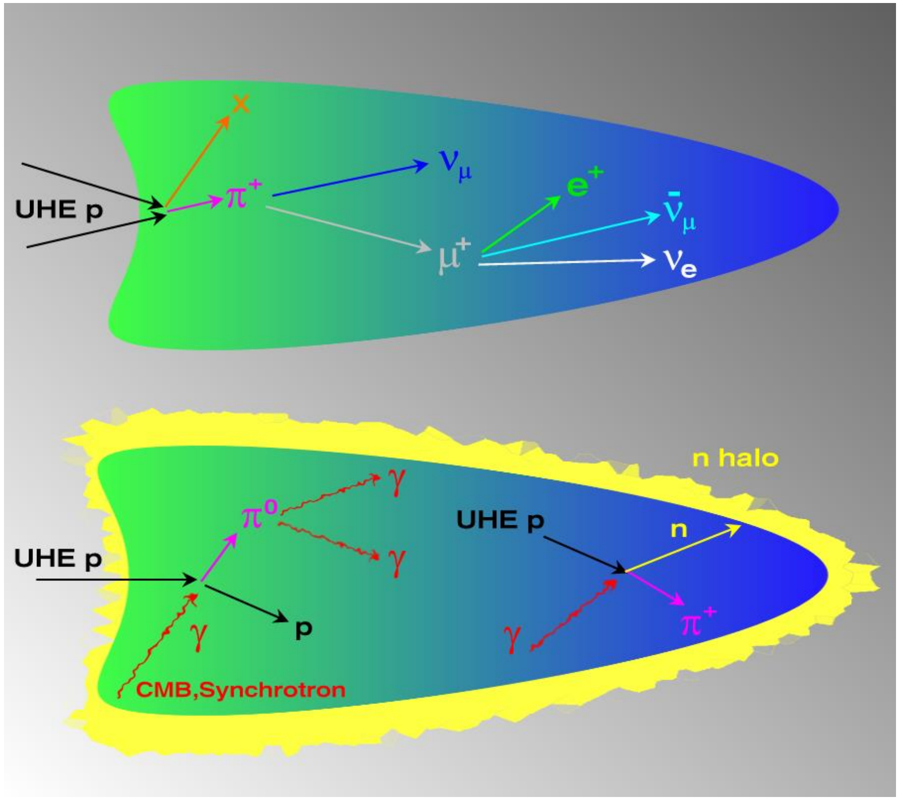


idea: acceleration in AGN:



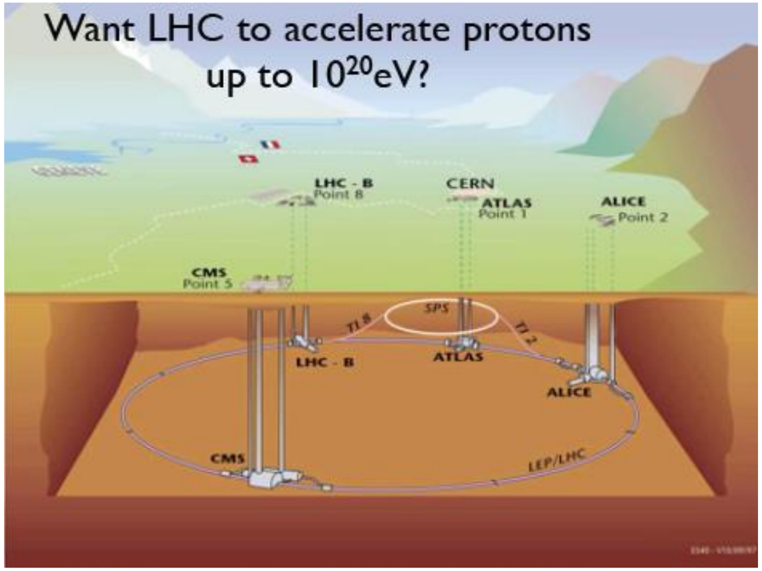
Centaurus A, HST optical and radio

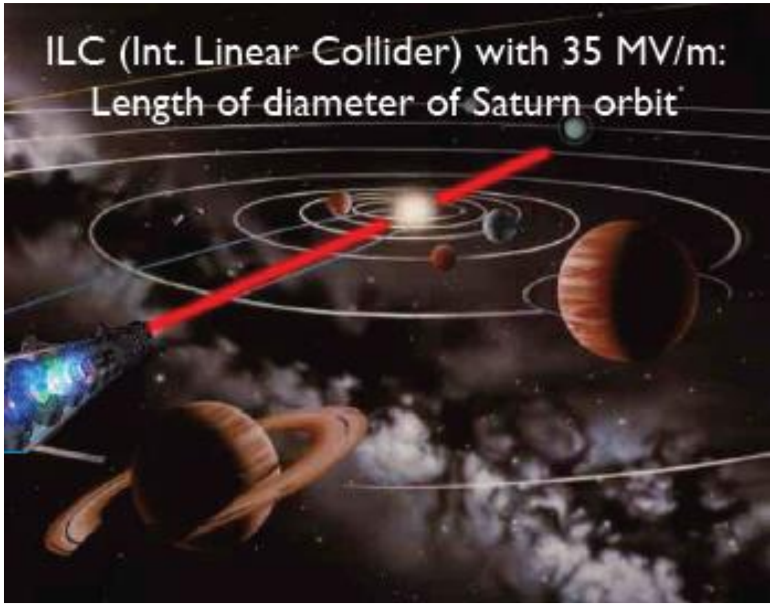
problem: interaction of the accelerated particles inside the jet

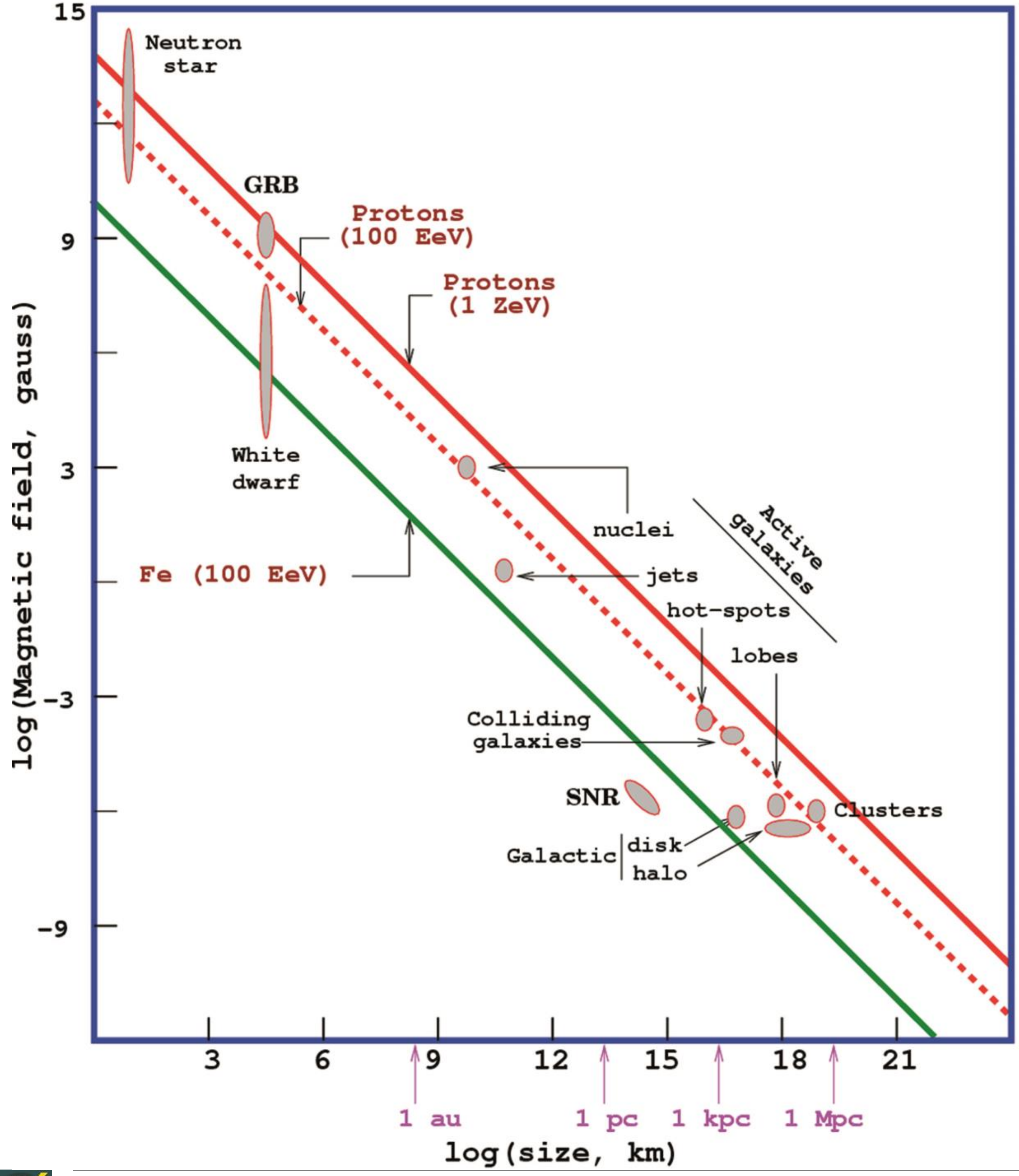


TeV- gamma radiation from AGN's are observed (timely and spectral very variable)

Cosmic Rays: Acceleration summary







Cosmic Rays: Acceleration summary

Hillas-Diagramm:

$$E_{max} \sim zBL$$

Cosmic Rays: Acceleration summary

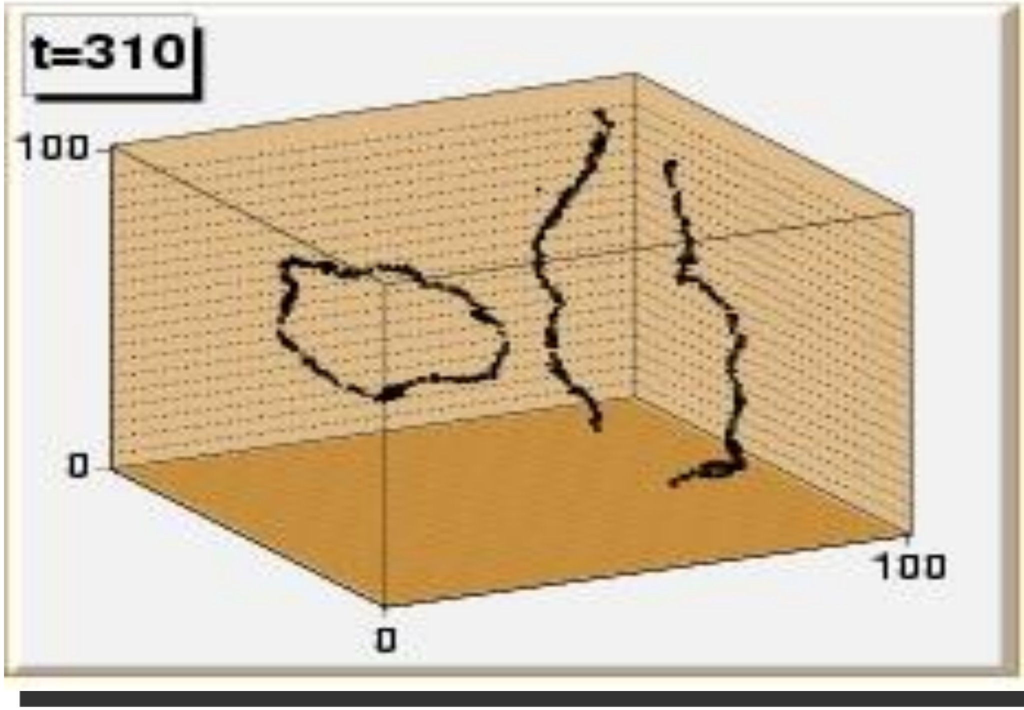
acceleration in the sun:	$E_{max} = 10^{10}$ eV/n
acceleration in Supernova shocks:	$E_{max} \approx 10^{14}$ eV/n
acceleration at Supernova in a wind:	$E_{max} \approx 10^{16}$ eV/n
reacceleration of 10^{14} eV/n in Pulsars:	$E_{max} \approx 10^{17}$ eV/n
Supernova in a wind + binary system:	$E_{max} \approx 10^{18}$ eV/n
extreme Pulsars (short rotation time):	$E_{max} \approx 10^{18}$ eV/n
acceleration in AGNs, Radio-Jets:	$E_{max} \approx 10^{19}$ eV/n

Cosmic Rays: Acceleration summary

Exotic decays

Exotic UHECR Sources

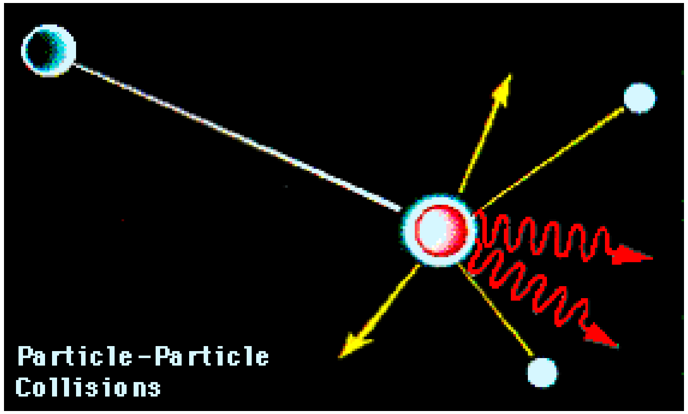
“Top Down”solutions (topological defects), SUSY, VHE Neutrinos, Monopoles, etc.

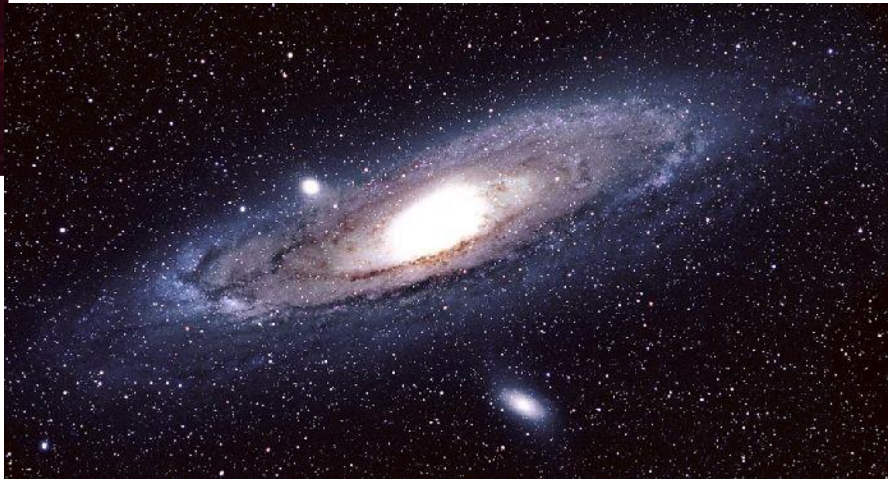


Cosmic Strings

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

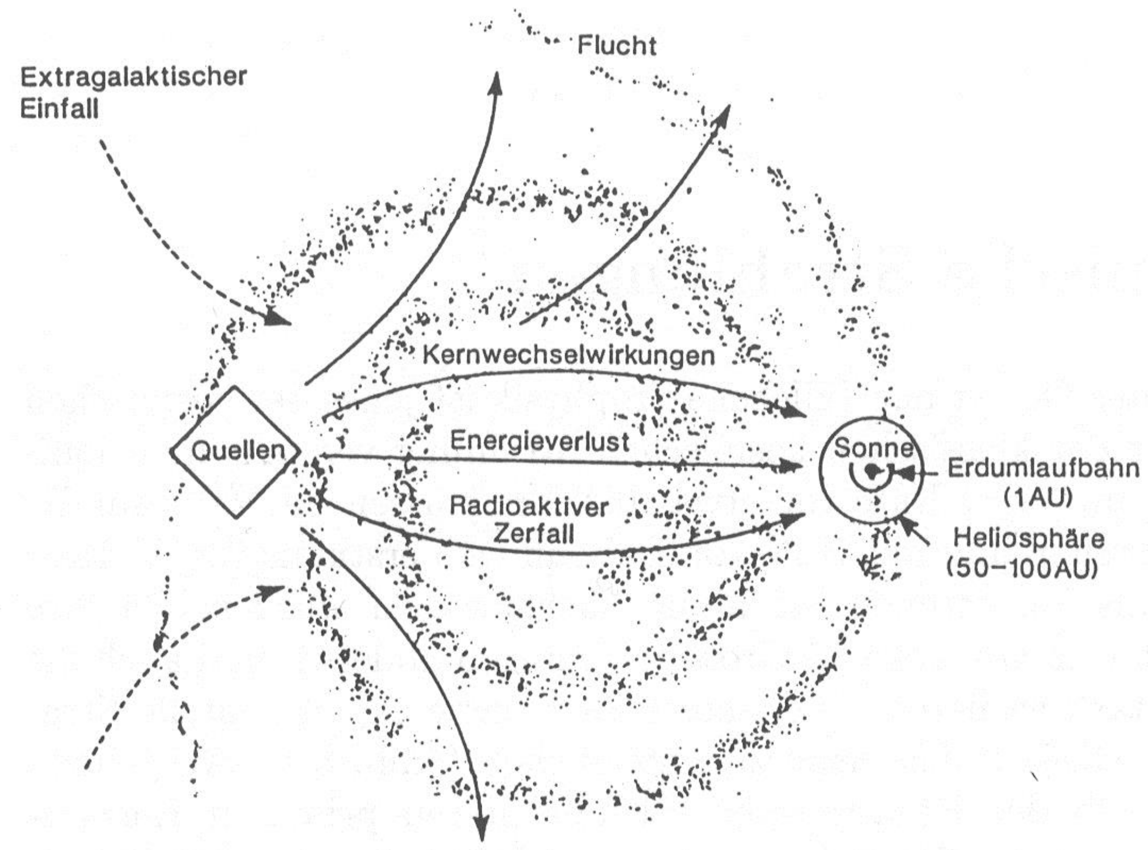
Cosmic Rays: Transport

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:

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

$N_i = N_i(E,x,t)\, dE$ = 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 = 10g/cm^2 for protons in ISM = 3 g/cm^2 for iron in ISM

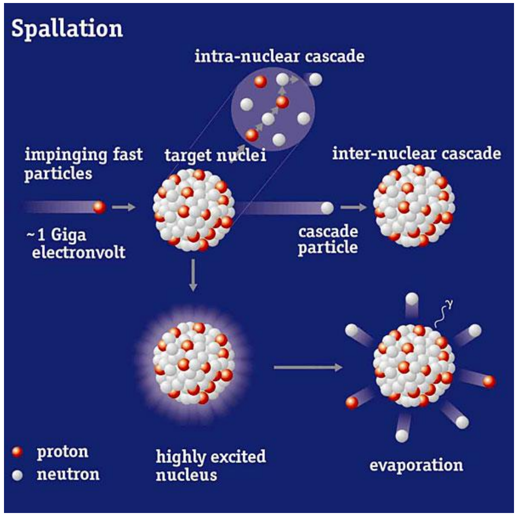
Cosmic Rays: Transport Equation

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

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

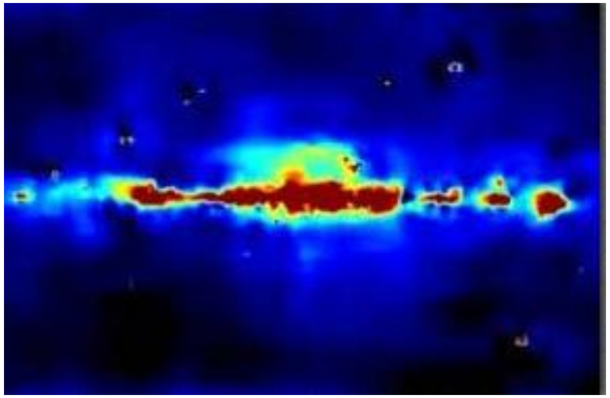
τ_i = lifetime of species i
(attention: Lorentz-Dillation: increases lifetime)

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)

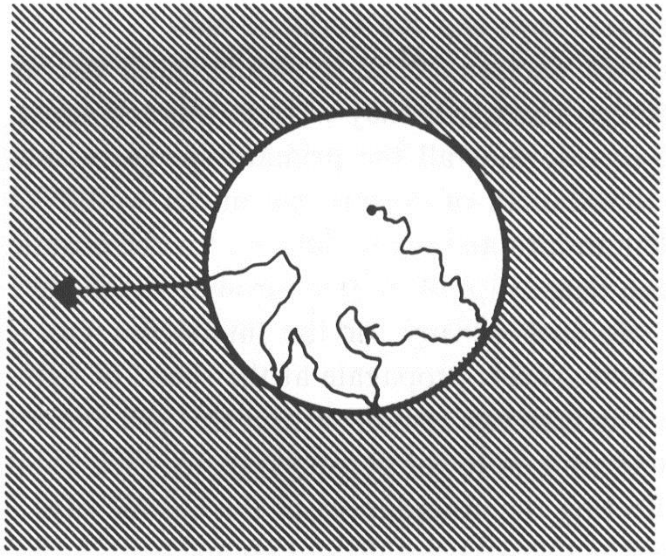
All calculations are in good agreement with the assumption of a halo built with high-energetic particles !!



Cosmic Rays: Transport: Leaky Box Model

‚Confinement' in our Galaxy:

-) high energy particles pass ca. 5g/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}



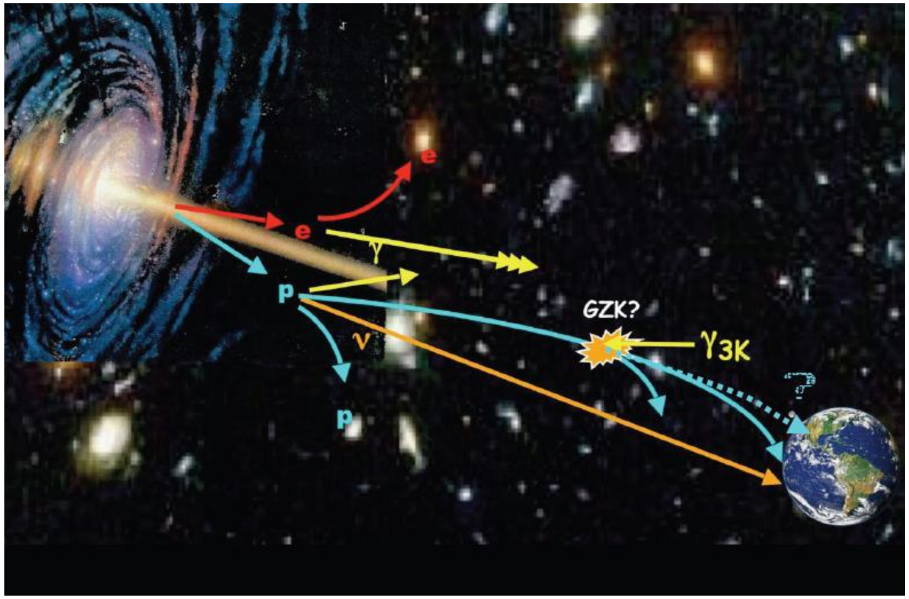
with $\lambda = \rho \cdot c \cdot t$ ➔
$t_{esc} \approx 3 \cdot 10^6$ years
escape time from Milky Way
(or larger, if longer confinements in less dense regions)

🡐 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

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

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

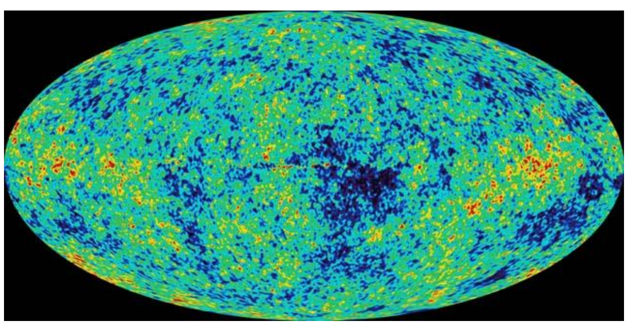


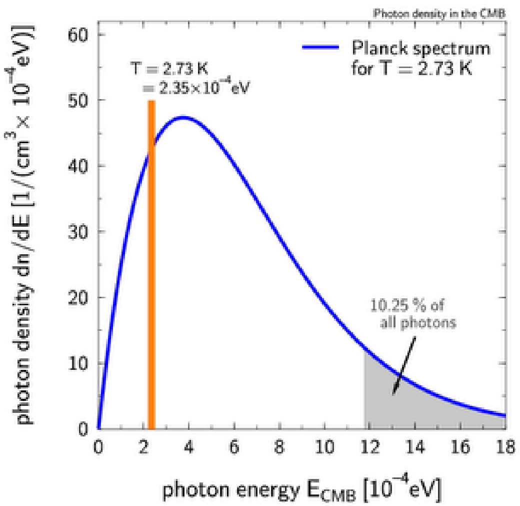
Pion photo production
($E_p > 5 \times 10^{19}$ eV due to CMB) :

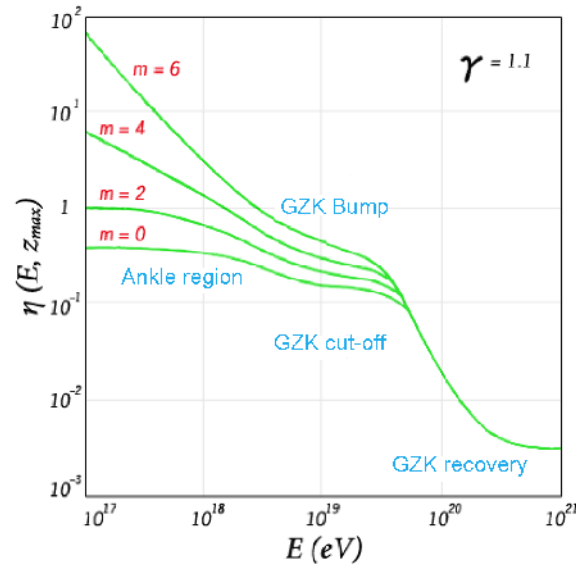
$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$
$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$

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%

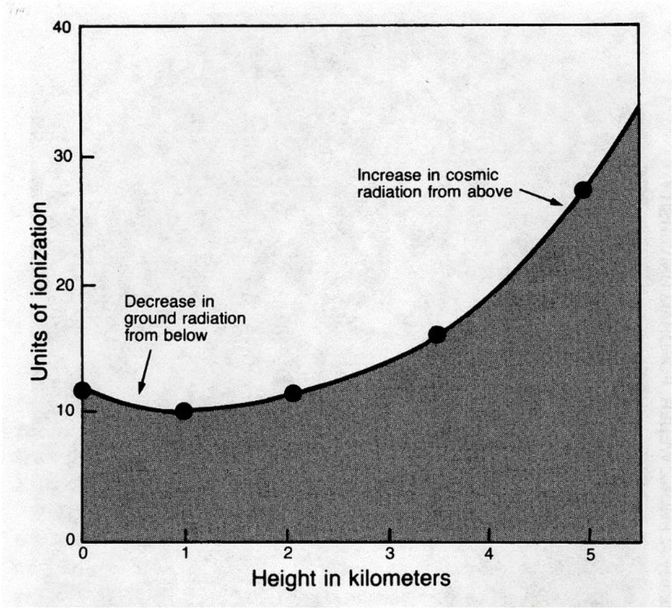
The Jesuit padre Theodor Wulf clambers in the year 1910 the Paris Eiffel-Tower to find the source of the ionizing radiation in the Earth‘s Atmosphere.

Electrometer

Cosmic Rays: History - 1912

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

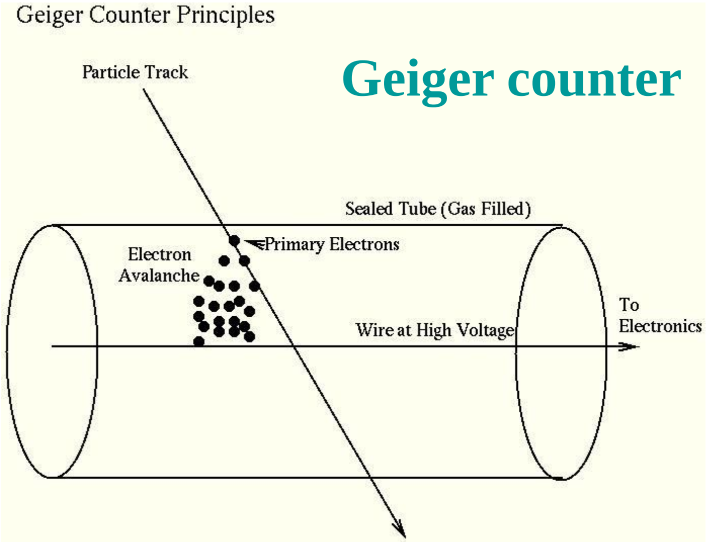
Finding:
Ionisation increase with height !
(Hess reached 5000m)



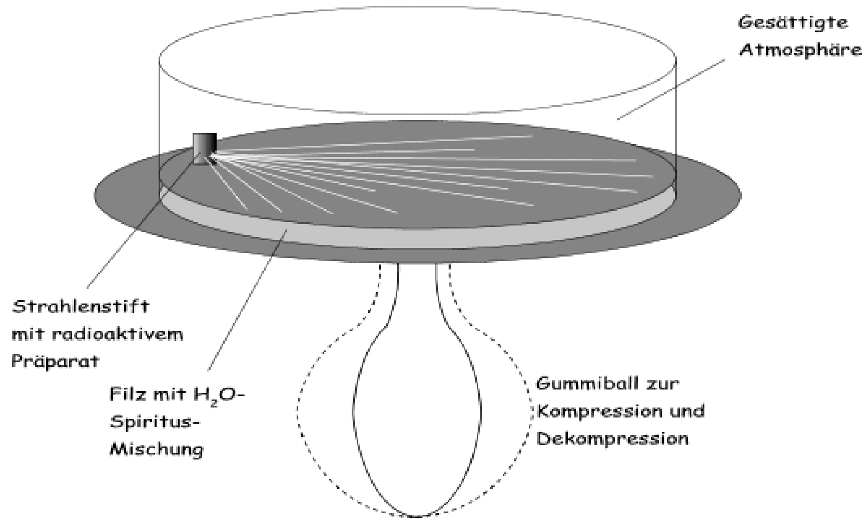
Cosmic Rays: History – 1912-25

Start of the development of:
Particle detectors – particle physics

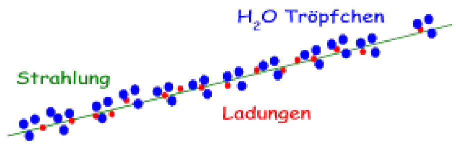
Geiger counter



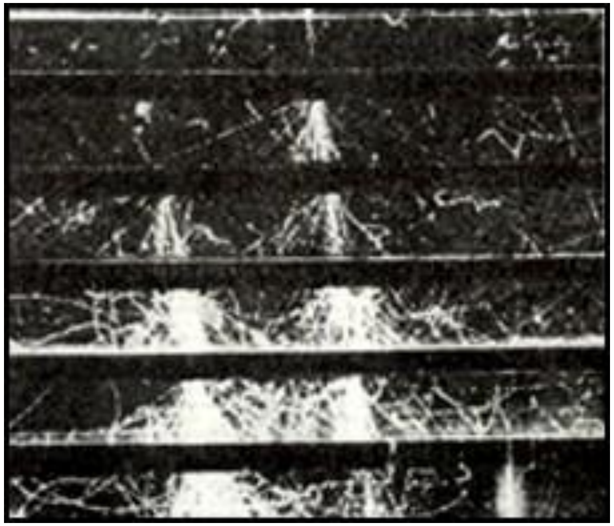
Cloud chamber



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

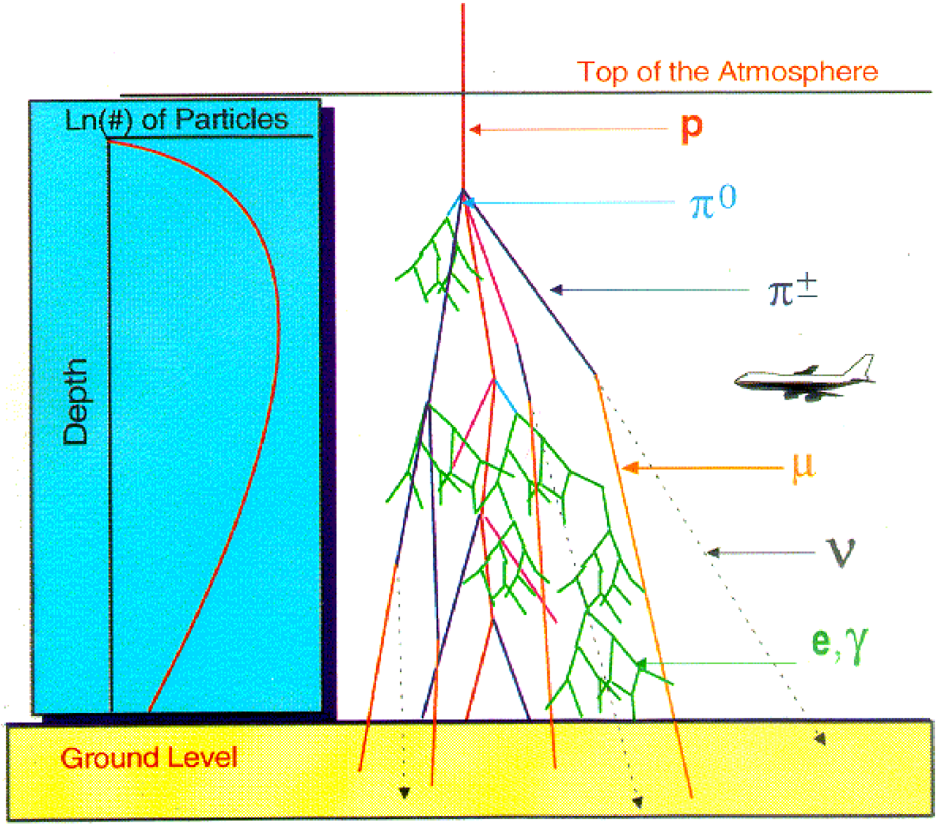


Spark chamber



Cosmic Rays: History – 1930-40

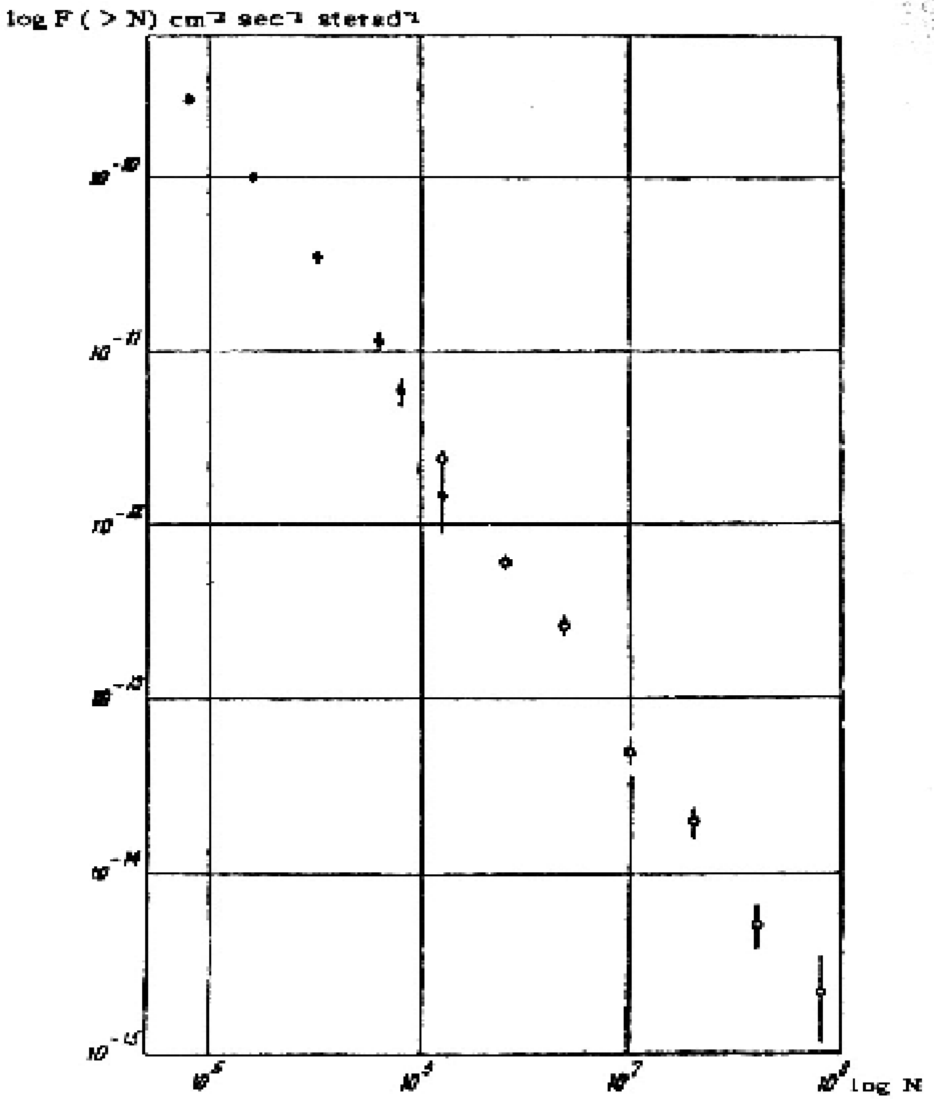
==> First Detection of extended air-showers!



1936: coincidence measurements at the Jungfraujoch

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

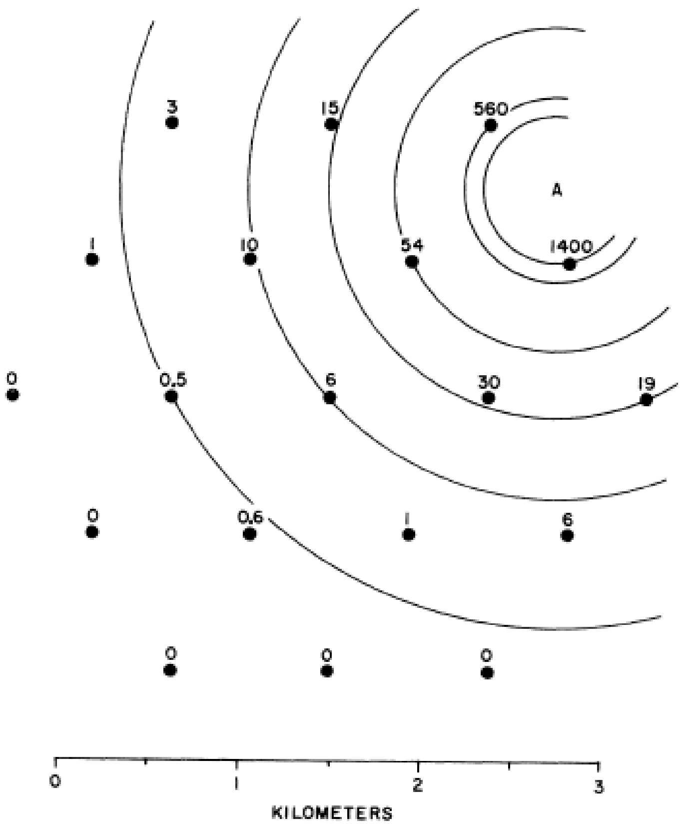


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "*A*" is the estimated location of the shower core. The circular contours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

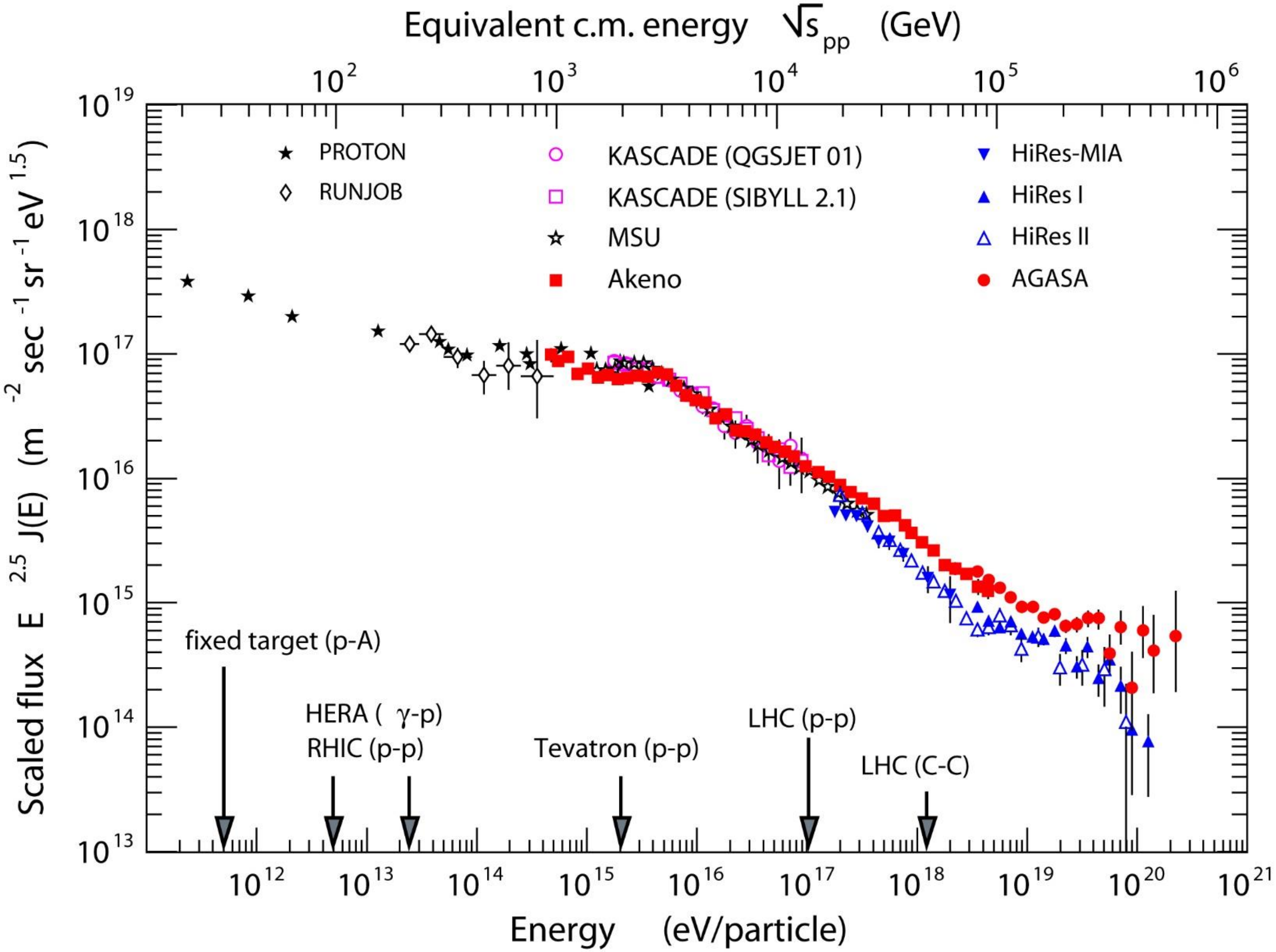
J. Linsley

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

Extensive air showers

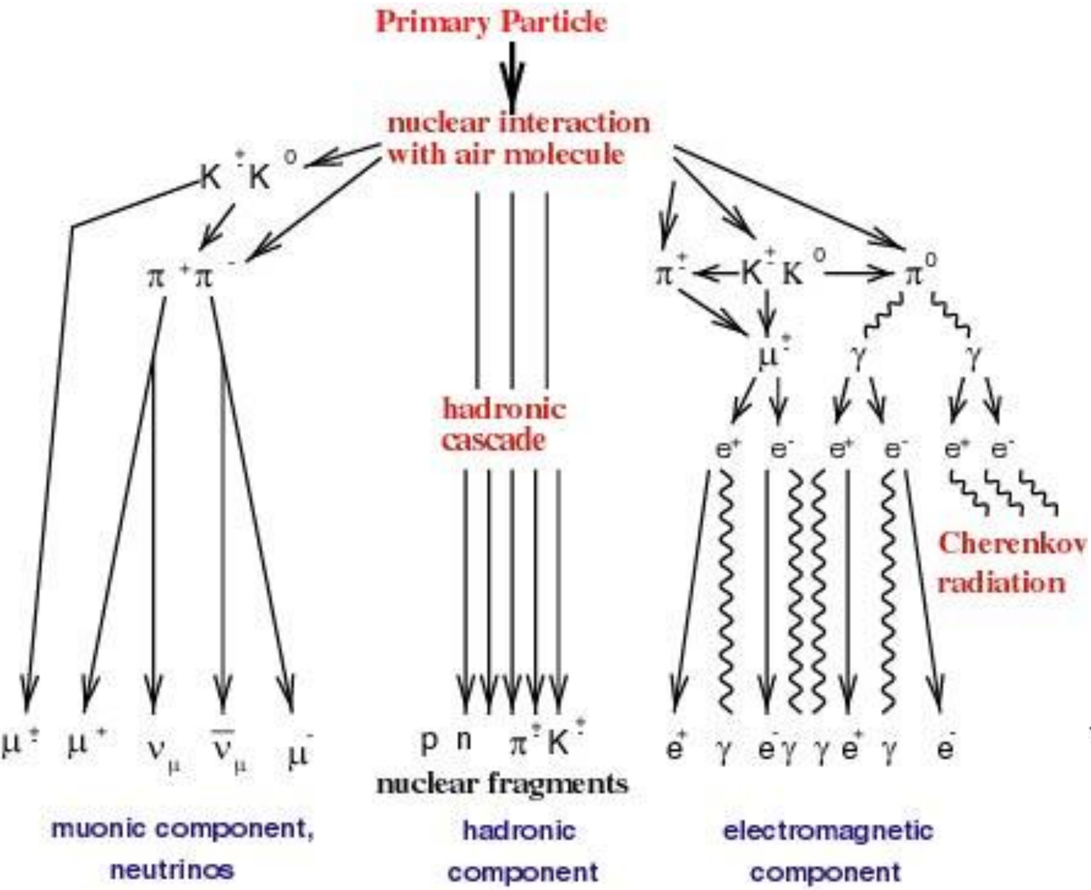
above 10^{14} eV :
Only indirect measurements possible !

EAS



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

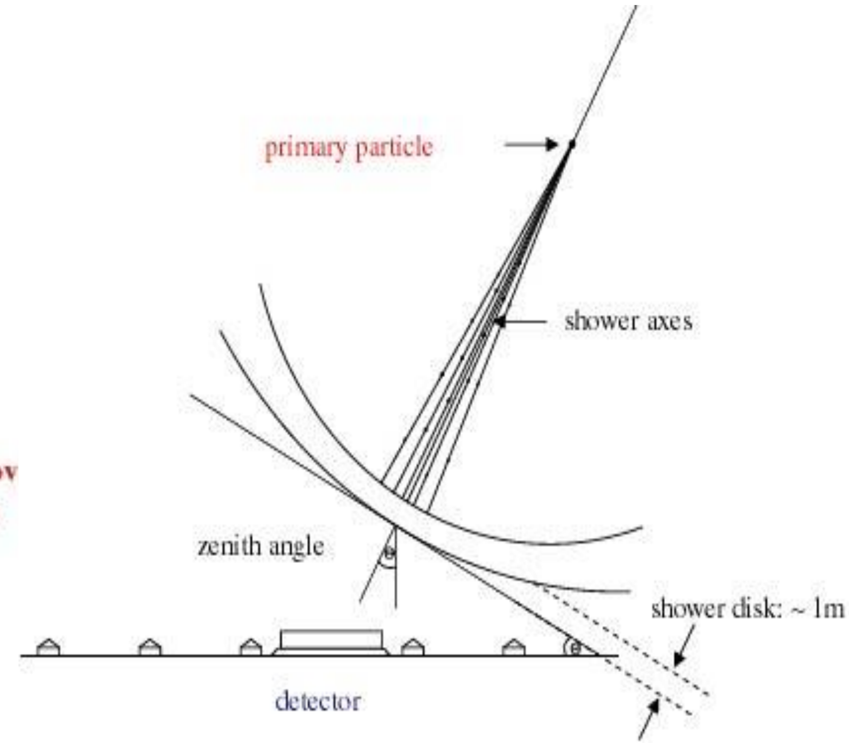
Extensive Air Showers - schematic



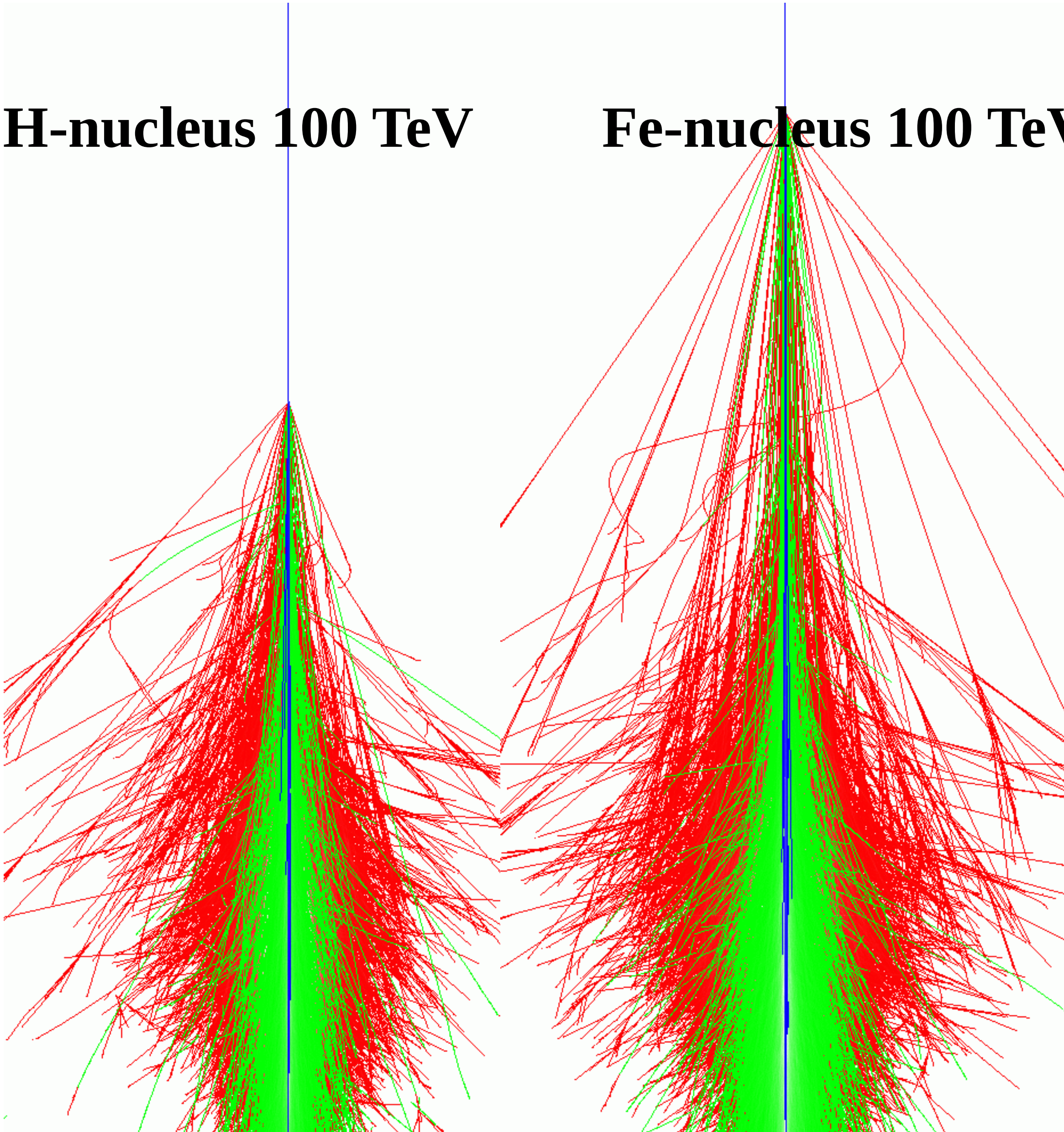
~10%

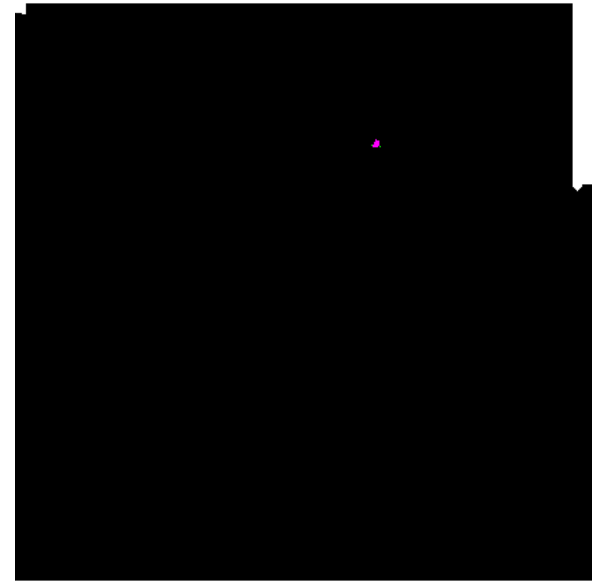
~ 1%

~90%



Extensive Air Showers



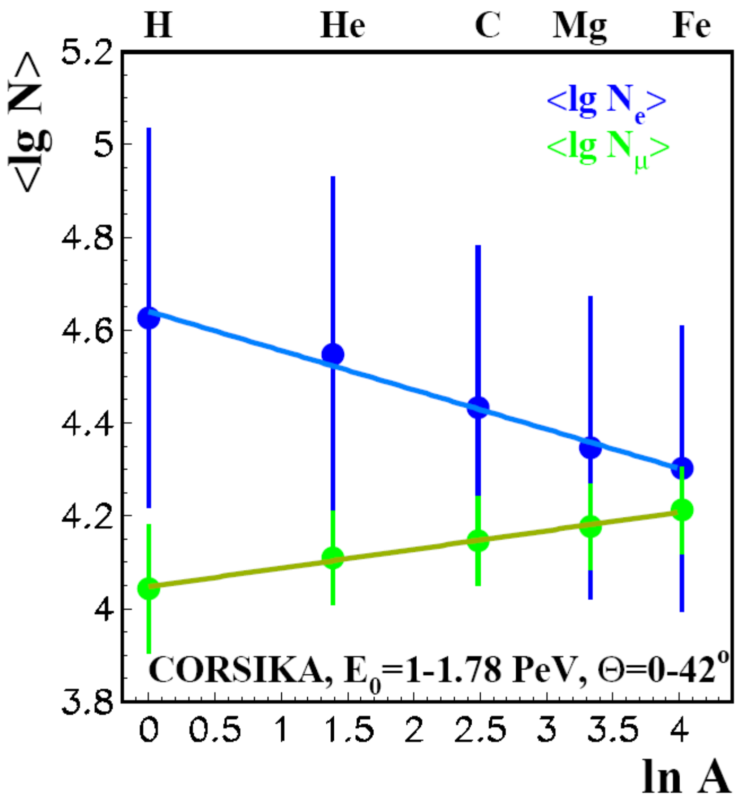


Differences at the shower development in the Atmosphere hint to energy und mass of the incident primary particle.

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

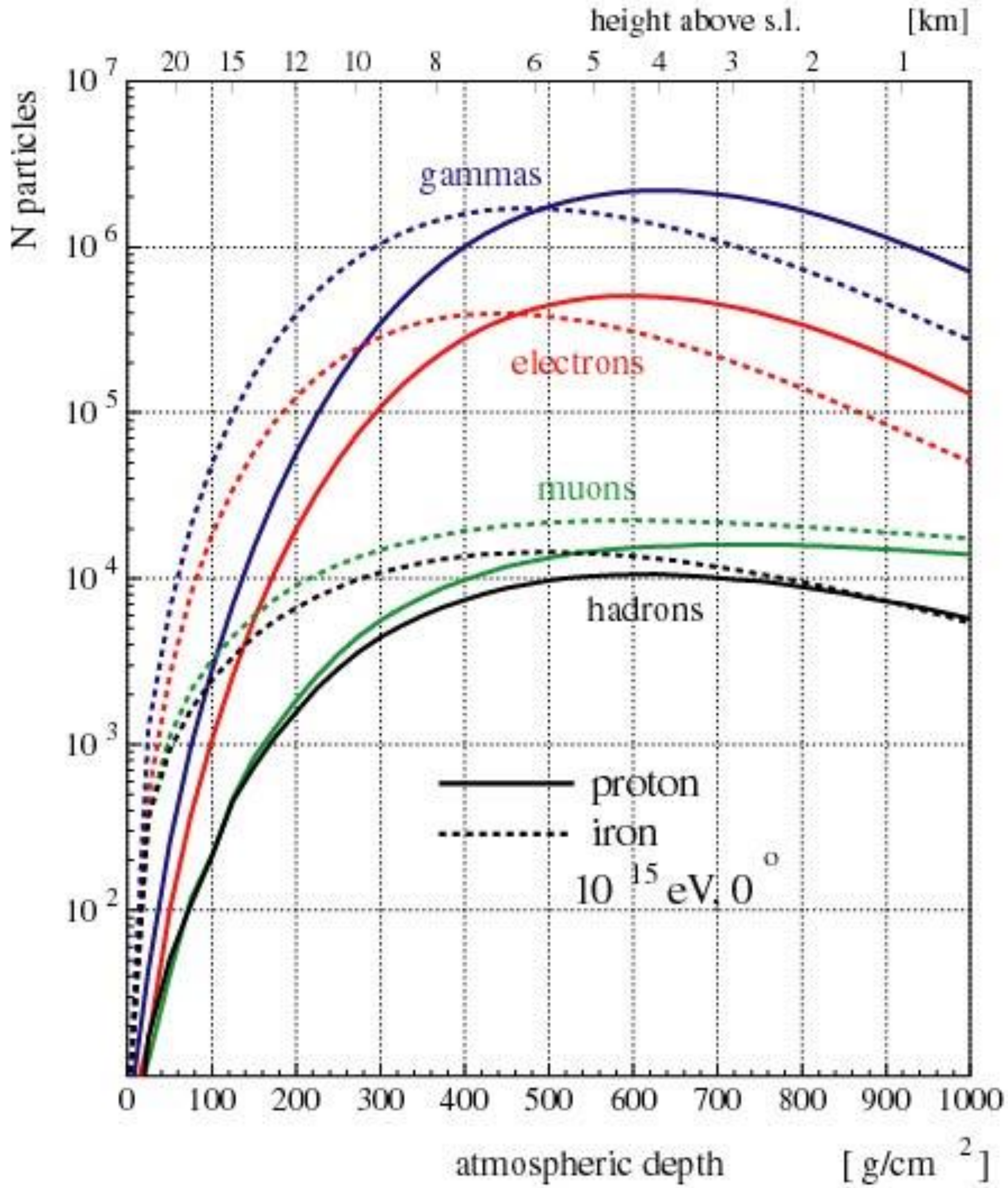


Fluctuations: $\sigma_{Q^A}(E) = \sigma_{Q^P}(E/A)/\sqrt{(A)}$

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



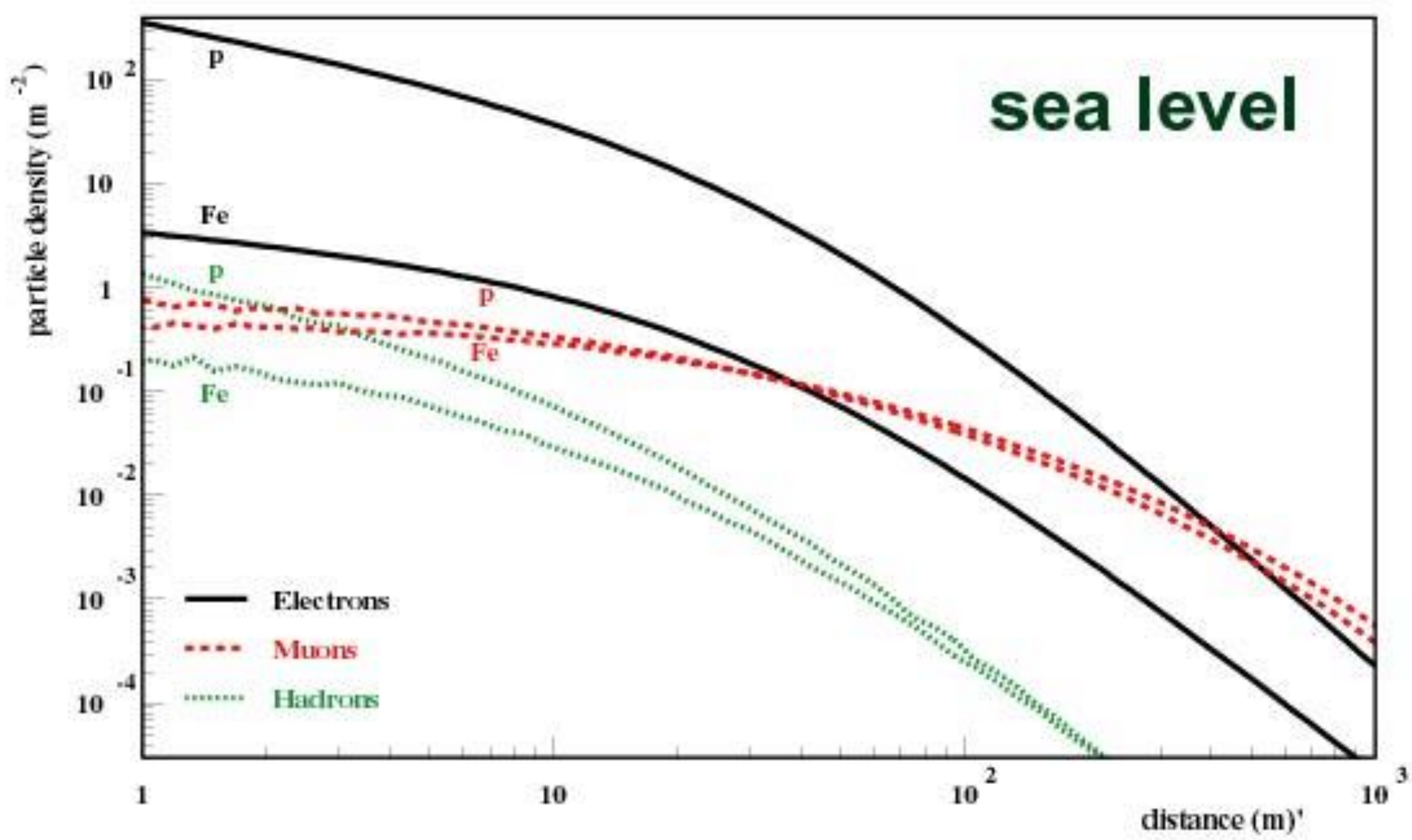
Sensitivity to energy and mass:

Particle number and particle distributions: Longitudinal distributions.

Extensive Air Showers

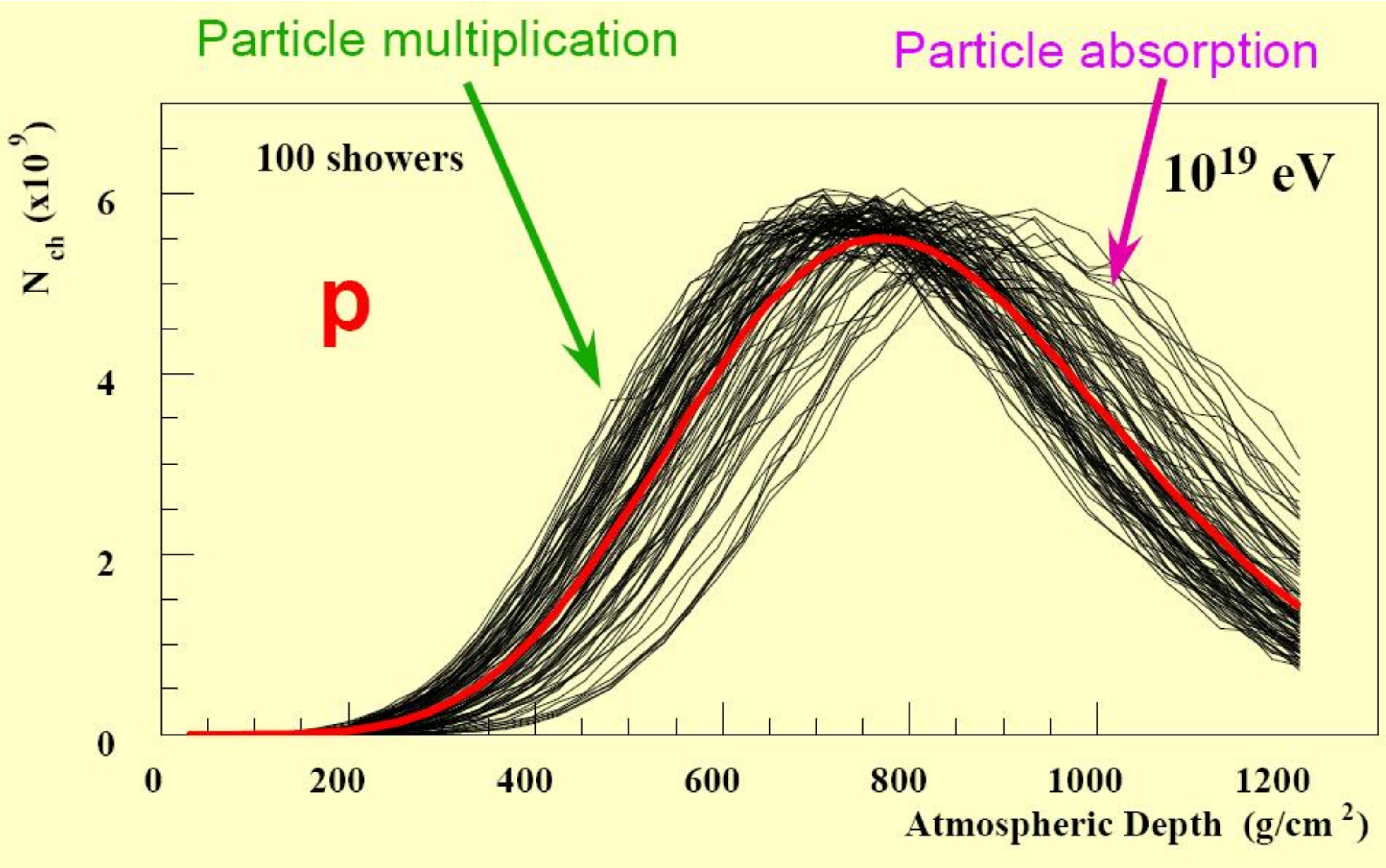
Sensitivity to energy und mass:

Particle number and particle distributions: Lateral distributions

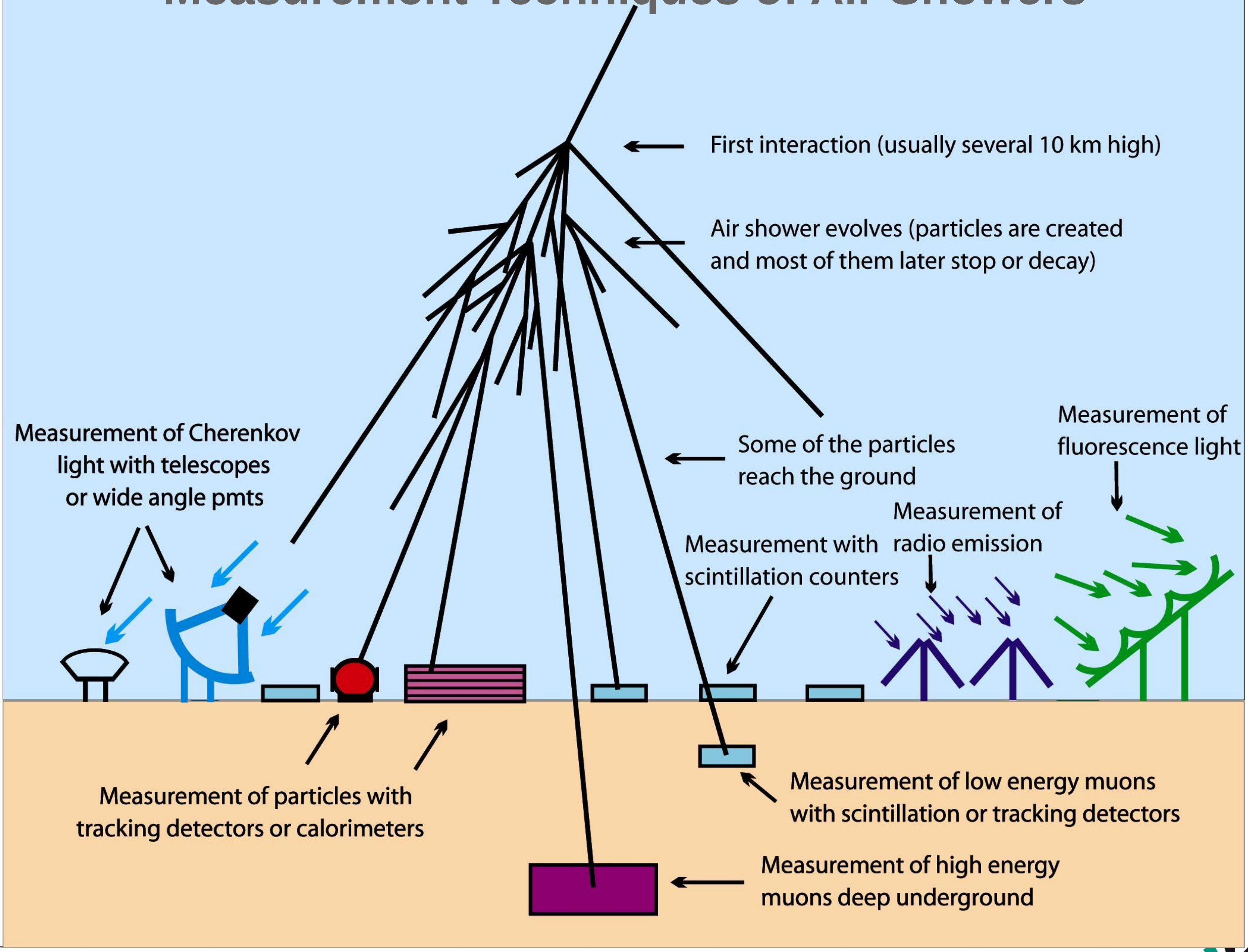


Extensive Air Showers

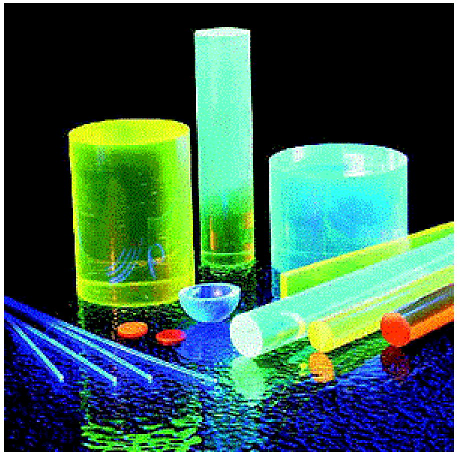
Problem: Shower-to-shower Fluctuations



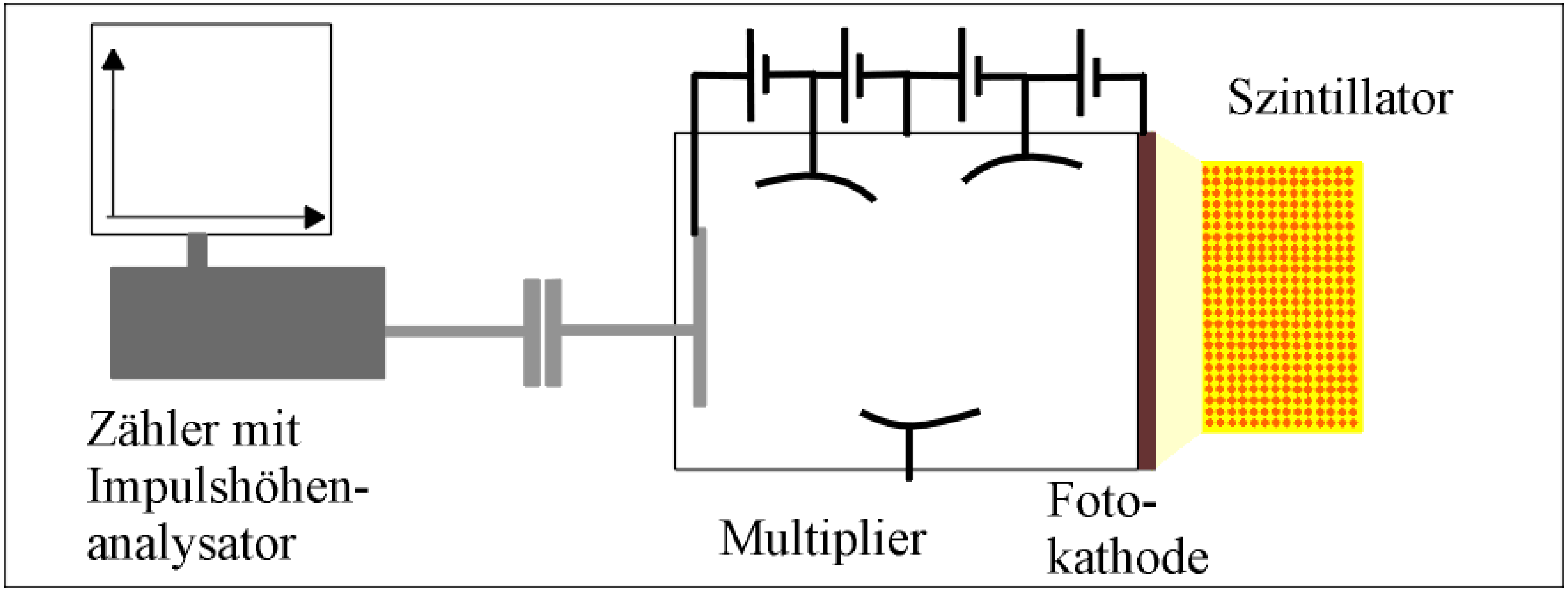
Measurement Techniques of Air Showers

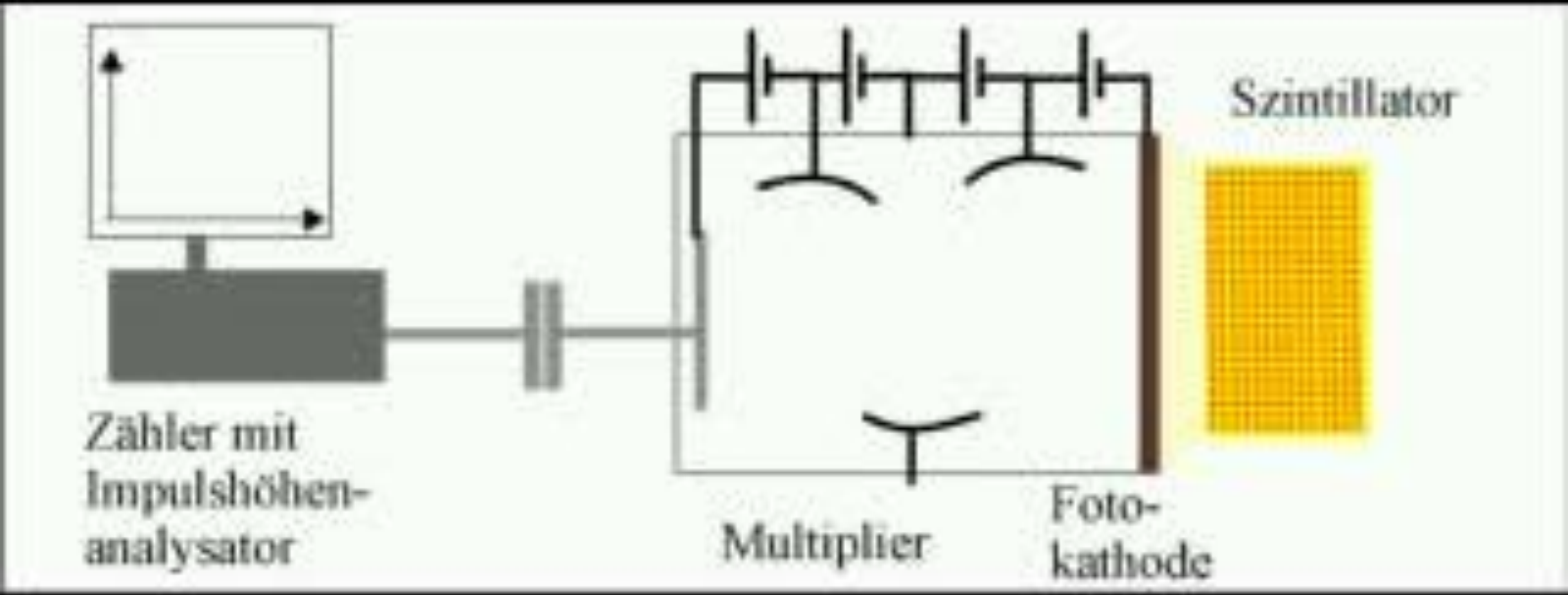


Particle Detection: Scintillators

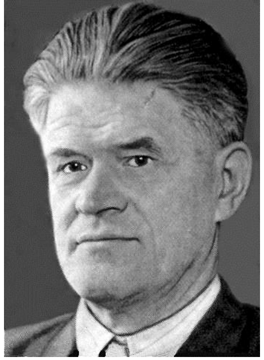


Scintillation counter:
- Ionizing radiation generates light in the scintillators
- Light generates Electrons (photo effect)
- Electrons are multiplied (PMT)
- Number of electrons (charge) is counted




Szintillator
Zähler mit Impulshöhen-analysator
Multiplier
Foto-kathode

Water Cherenkov Detector



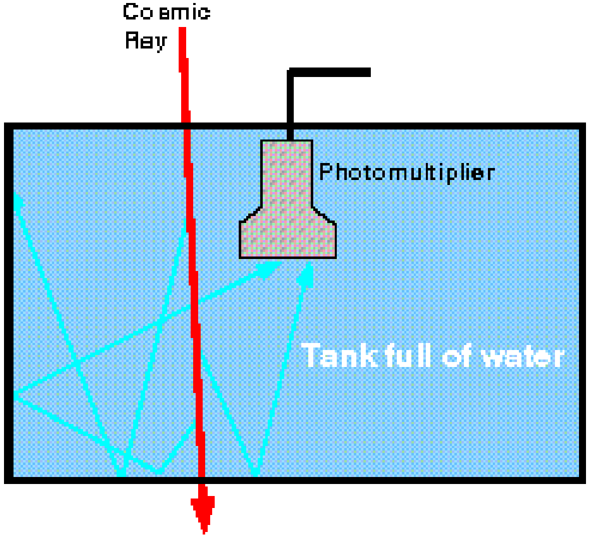
Cherenkov-Counter:

Pavel Alekseyevich
Cherenkov
(1904-1990)

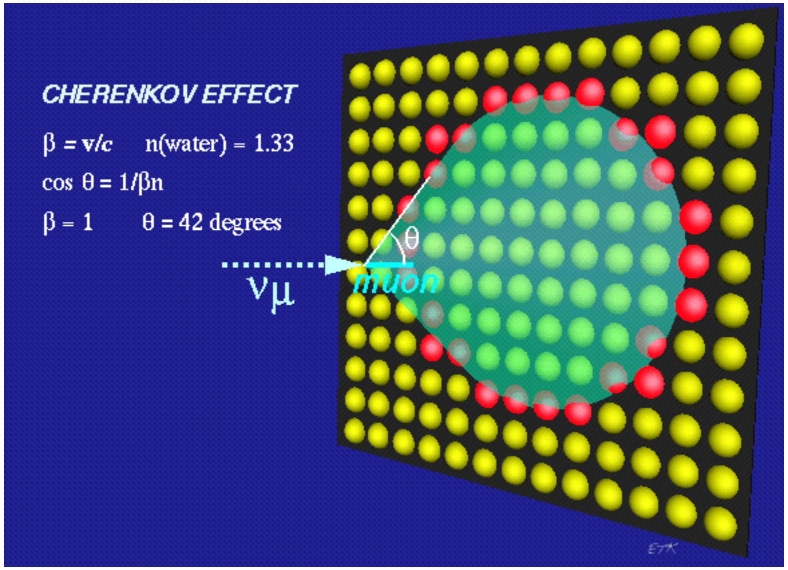
•Particle detector for charged particles named after physicist Pavel Cherenkov

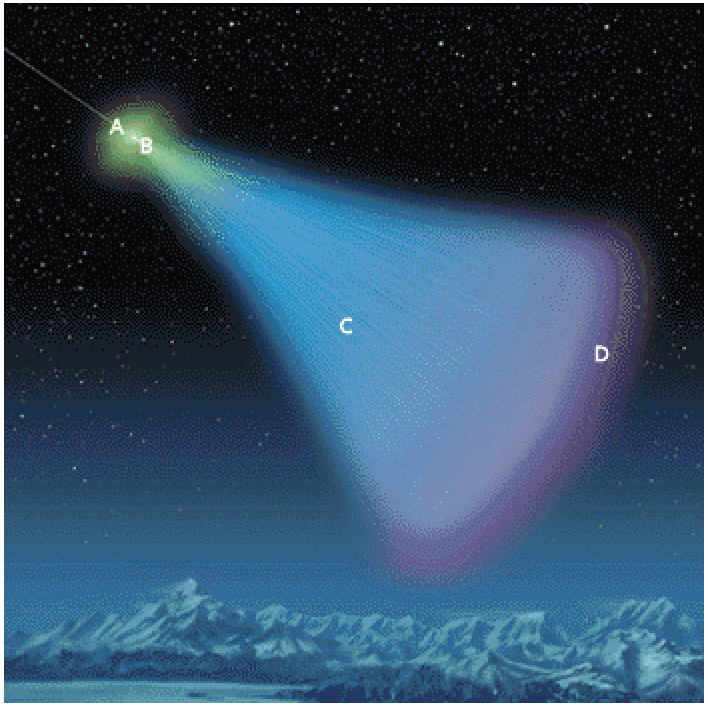
•Principle: If the speed of charged particles in a medium exceeds the speed of light in this medium (e.g. water) they emit radiation (in optical light)

•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)]

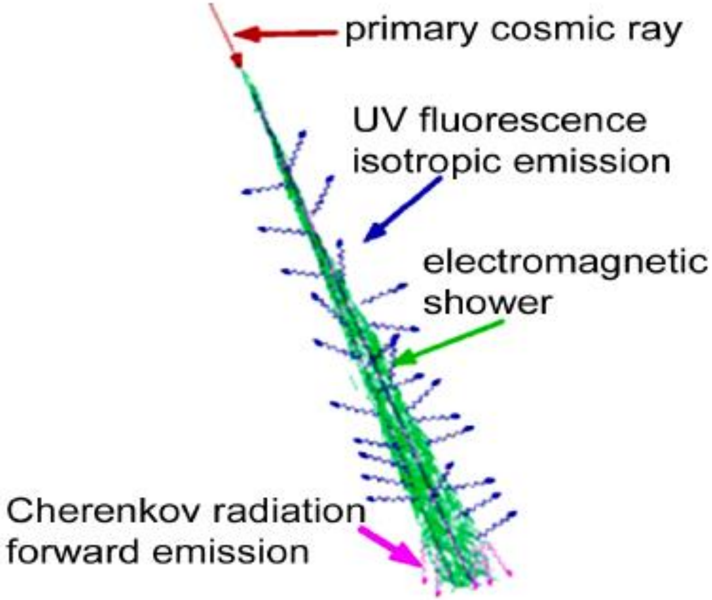
photons per track length :

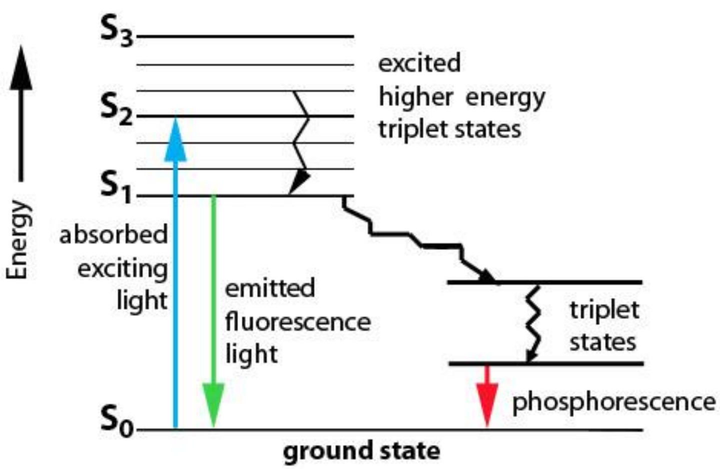
$dN/dx = 2\pi\alpha Z^2 \int_{\lambda 1}^{\lambda 2} (1-1/n^2\beta^2)\, d\lambda/\lambda^2$

Fluorescence Light Detection

Charged particles excites Nitrogen in atmosphere.

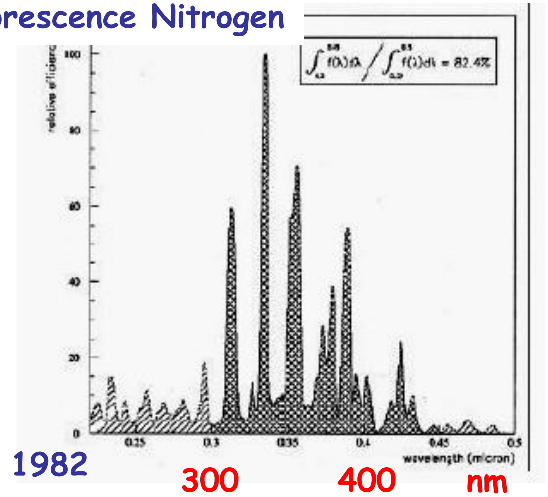
De-excitation: Fluorescence light (isotropic)





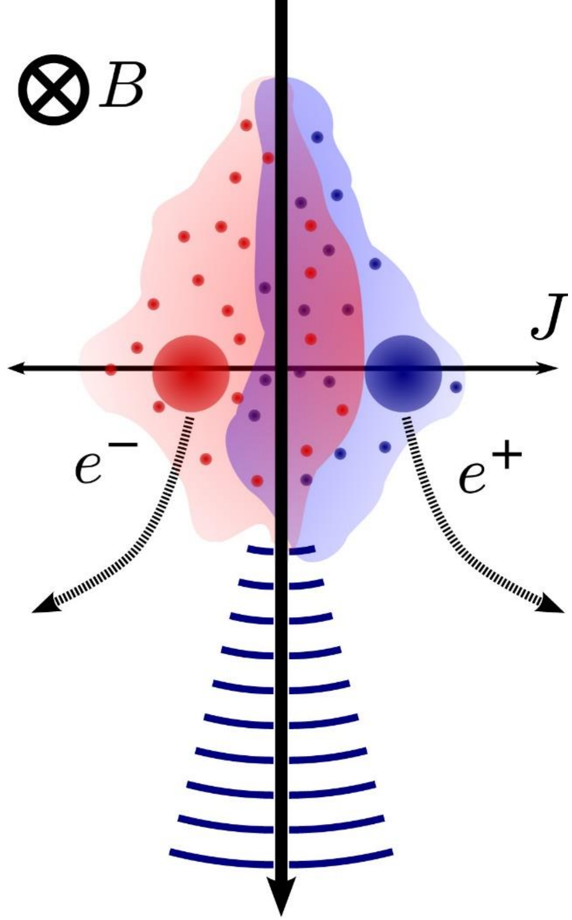
Emission of fluorescence Nitrogen

λ_{abs}~15Km
4÷5 y/m.
Ne>10^8 e
E~ 10^{18} eV

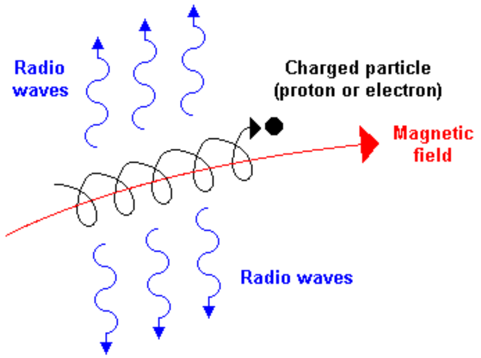


Fly's Eye Utah 1982

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



Content:

1. **Introduction in HEAP**
   - **source-acceleration-transport**
   - **short history of cosmic ray research**
   - **extensive air showers**
2. **Ultra-High Energy Cosmic Rays**
   - **KASCADE, KASCADE-Grande and LOPES**
   - **Pierre Auger Observatory, JEM-EUSO**
3. **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 is the rôle of EAS-neutrinos?**
  -
  -
  -
- **why sources of cosmic rays are not known?**
  -
  -
  -

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  - **longitudinal sensitivity 100%**
  - **electron-muon separation**
  - **independent stations**
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  - **magnetic fields**
  - **leptonic/hadronic acceleration models**
  - **various source populations**

Exercise with KCDC

https://kcdc.ikp.kit.edu

Exercise with KCDC

Determination of the Attenuation Length of the Electron Component in extensive air-showers

Attenuation Length Λ_e : describes the average decrease of the electron number N_e with increasing atmospheric depth X (at fixed primary energy)

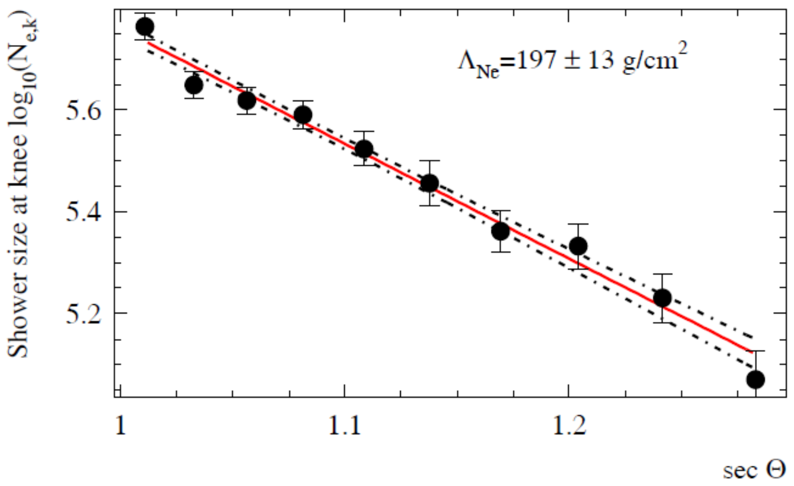
$$\langle N_e(X) \rangle \propto \exp\left(-X/\Lambda_{N_e}\right)$$

Why of interest?

➔*Understanding of shower development*

➔*Test of hadronic interaction models*

➔*Composition measurements*



You need:

➔*KASCADE EAS-data from KCDC*

➔*Read/Analysis/fitting/plotting tools*