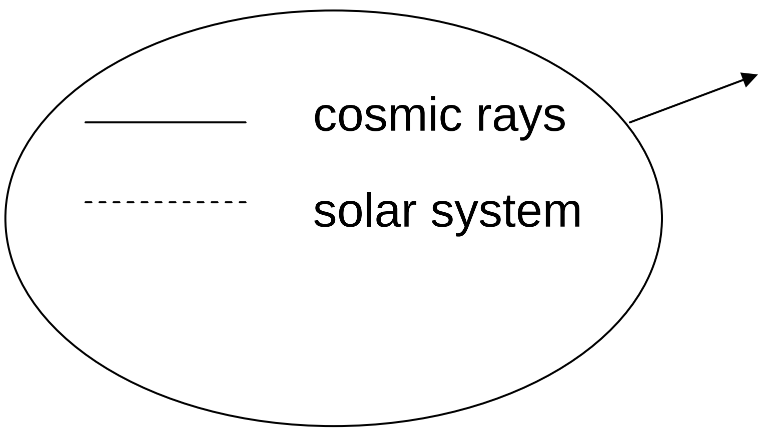
QuarkNet Cosmic Rays

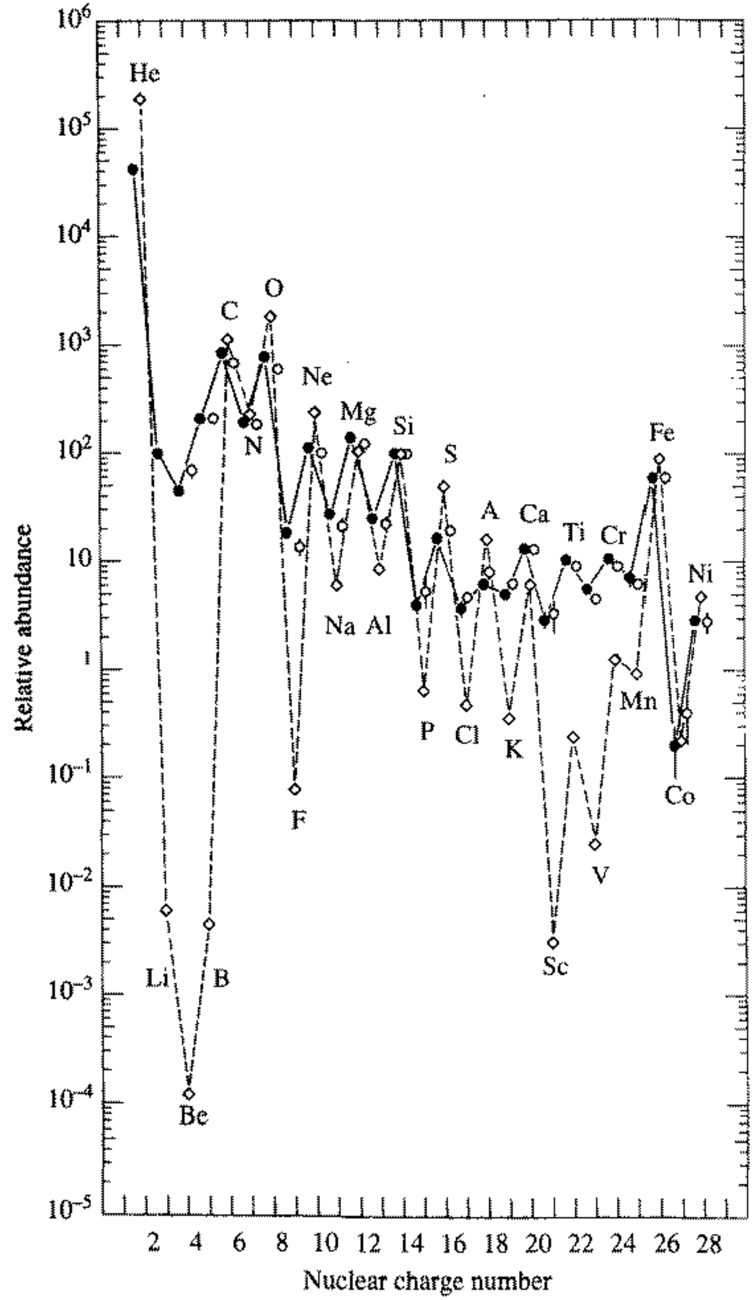
- Outside earth's atmosphere, these are charged particles, 86% protons
- These *primary* cosmic ray particles interact with air high in the atmosphere (~15 km), creating showers of secondary particles
- By time the secondaries reach sea level, the muons dominate the flux
- The detectable (vertical) rate at sea level is $\approx 1/cm^2/min$ (e.g. in CRDs)
- Outside the solar system, CRs have an energy density of ≈ 1 eV/cm^3
  - Starlight: 0.6 eV/cm^3
  - CMB: 0.26 eV/cm^3
- ~30% of natural radiation (sea level)
- Provide charge and seeds for lightning

from QuarkNet CRD manual

composition of primaries

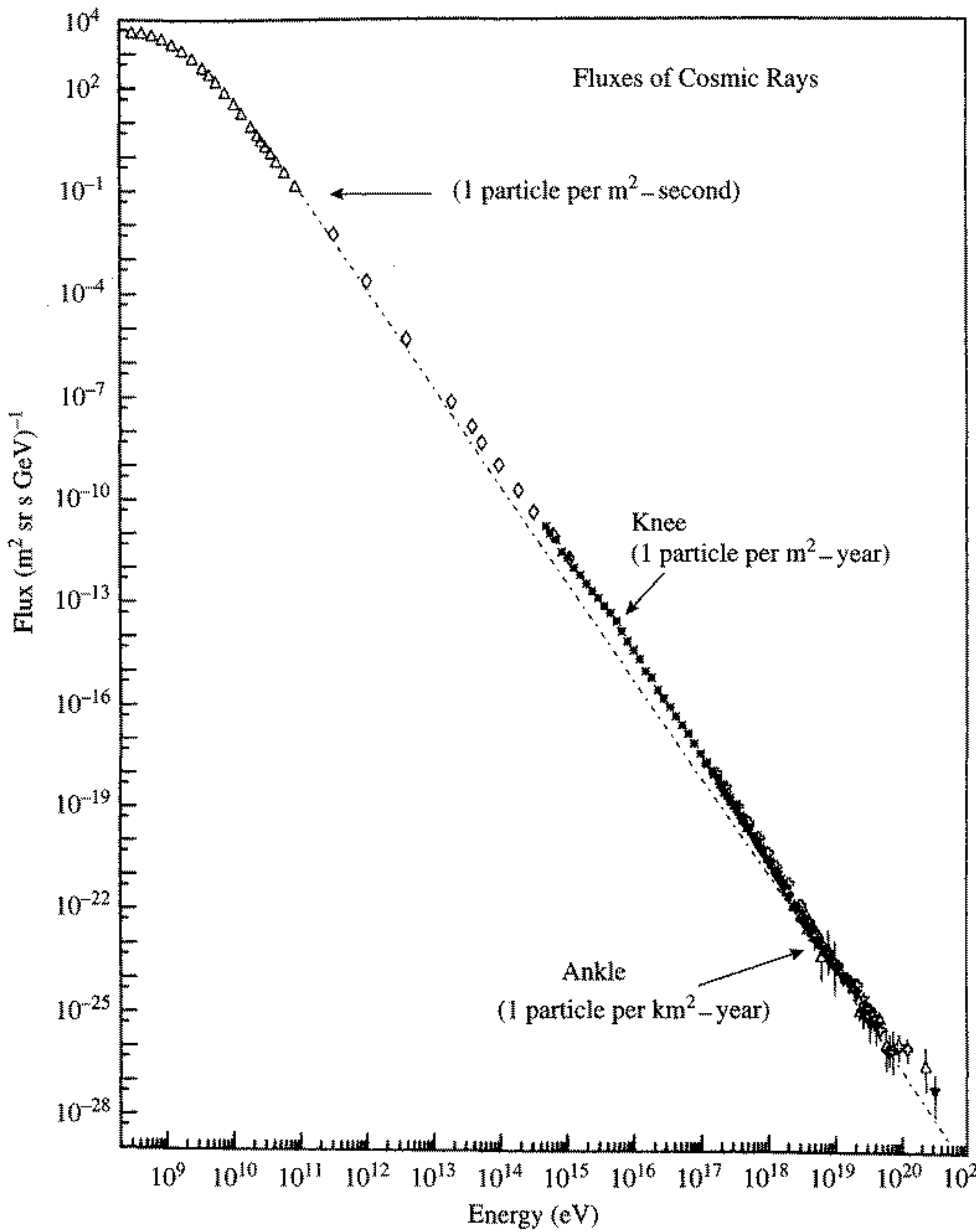
- 90% protons (*not* anti-protons)
- The remainder mostly follow solar system abundances (eg meteorites and solar photosphere)
    - Spallation of O and C nuclei, for example, create more Li, Be, B than is typical of solar system





energy and origin of primaries

- Steeply falling, power law energy spectrum
- For E$\lesssim 10^{14}$ eV, spectrum and flux are consistent with acceleration by shock waves from supernovae ("Fermi acceleration")
- For larger energy, mechanism is unknown (black hole at galactic center??)
- For E>10^{19} eV, protons would not be captured by galactic magnetic field (3×10^{-10} T)
  - p_t [GeV] = (0.3q/e)B[T] R[m]
- So higher energy CRs must be extra-galactic... but GZK cutoff...

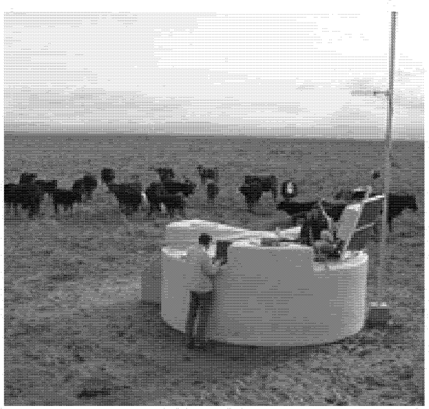


Auger CR observatory
www.auger.org

- Sites in Mexico and Argentina
- Array of detectors: (40x1.5 km)x(40x1.5 km)
- GZK: extragalactic CRs attenuated:

  $p + \gamma\ (\text{CMB}) \rightarrow \Delta^+ \rightarrow p + \pi^\circ,\ \ n + \pi^+$

  - 411 CMB photons/ cm^3 ; $E = k \times 2.7K = 2.4 \times 10^{-4}$ eV
  - No protons $>10^{20}$ eV from further than 5 Mpc
- Summer 2007: No excess above GZK cutoff



No bull.
The Pierre Auger Array, which comprises more than 1200 detectors like this one, sees no excess of ultra-high energy cosmic rays.

A Comedown for Cosmic Rays

By Adrian Cho
*Science*NOW Daily News
3 July 2007

MERIDA, MEXICO--An otherwise inexplicable excess in the highest energy cosmic rays crashing into Earth has been explained in the simplest way: The excess simply doesn't exist. The new result may disappoint physicists who had perceived hints of exciting new phenomena in the overabundance of individual subatomic particles cruising along with as much energy as a large hailstone. It also leaves some mysteries unanswered.

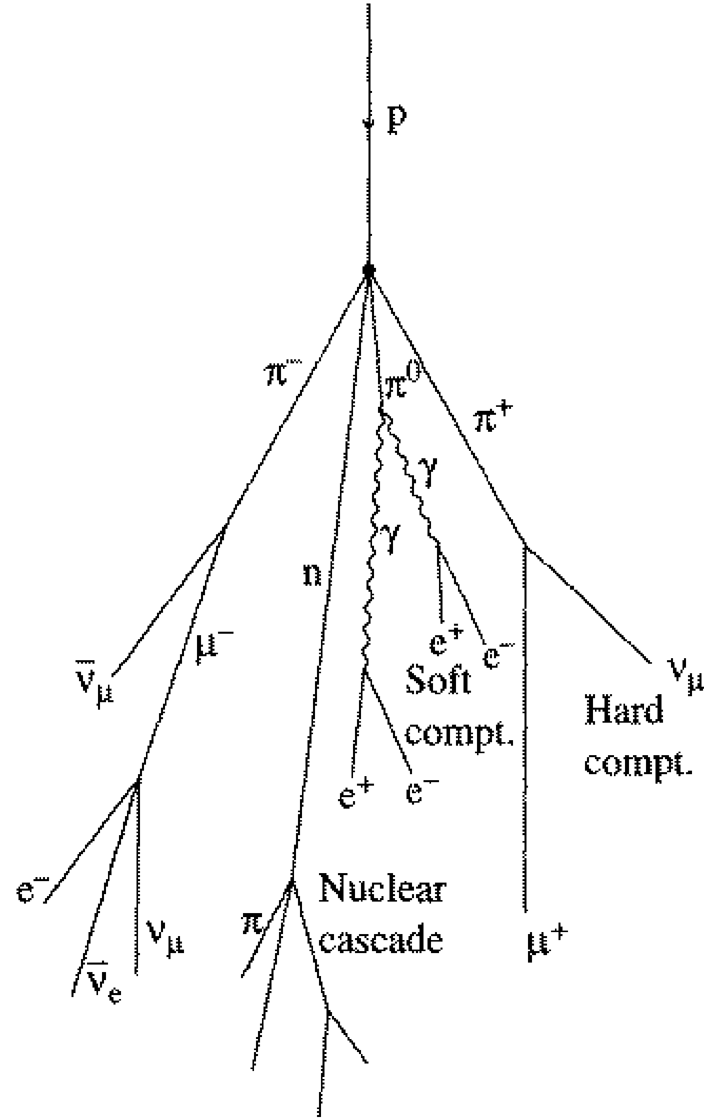
Really energetic particles should hit Earth only very rarely. After all, the number of cosmic rays pelting Earth decreases steadily as the energy of the rays increases. Above a specific energy, the rate ought to drop even faster. For example, if the rays consist mainly of protons, then at such tremendous energies they ought to break into other subatomic particles when they collide with photons in the afterglow of the big bang, the cosmic microwave background.

The cosmic ray showers

- Primaries interact in the atmosphere – the maximum production of pions and muons is at $z \approx 15$ km, making showers of (mostly) short-live particles.(e.g. pion ($\pi^{\pm}$) lifetime is 2.6×10^{-8} s)
- Characteristic shower angle:

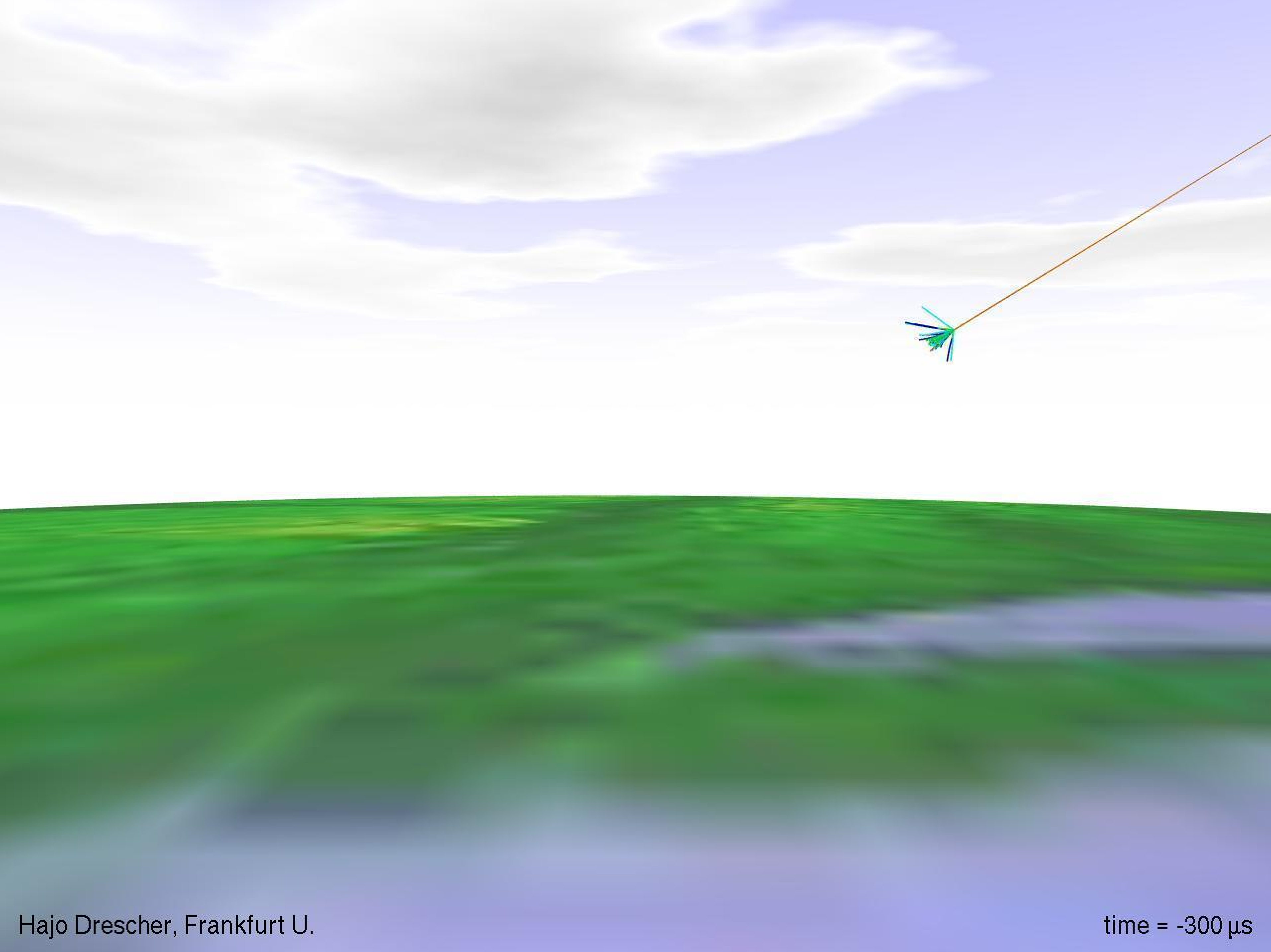
  $\theta \approx p_t / p_L \approx 0.2$ GeV/E
- The long-lived secondaries are:
  - $e^{\pm}$, photons: mostly absorbed
  - neutrinos (ν): practically invisible
  - muons ($\mu^{\pm}$): τ_{μ}=lifetime is 2.2×10^{-6} s
- Without time dilation, muons would travel $d < c\tau = 660$ m, with a survival fraction

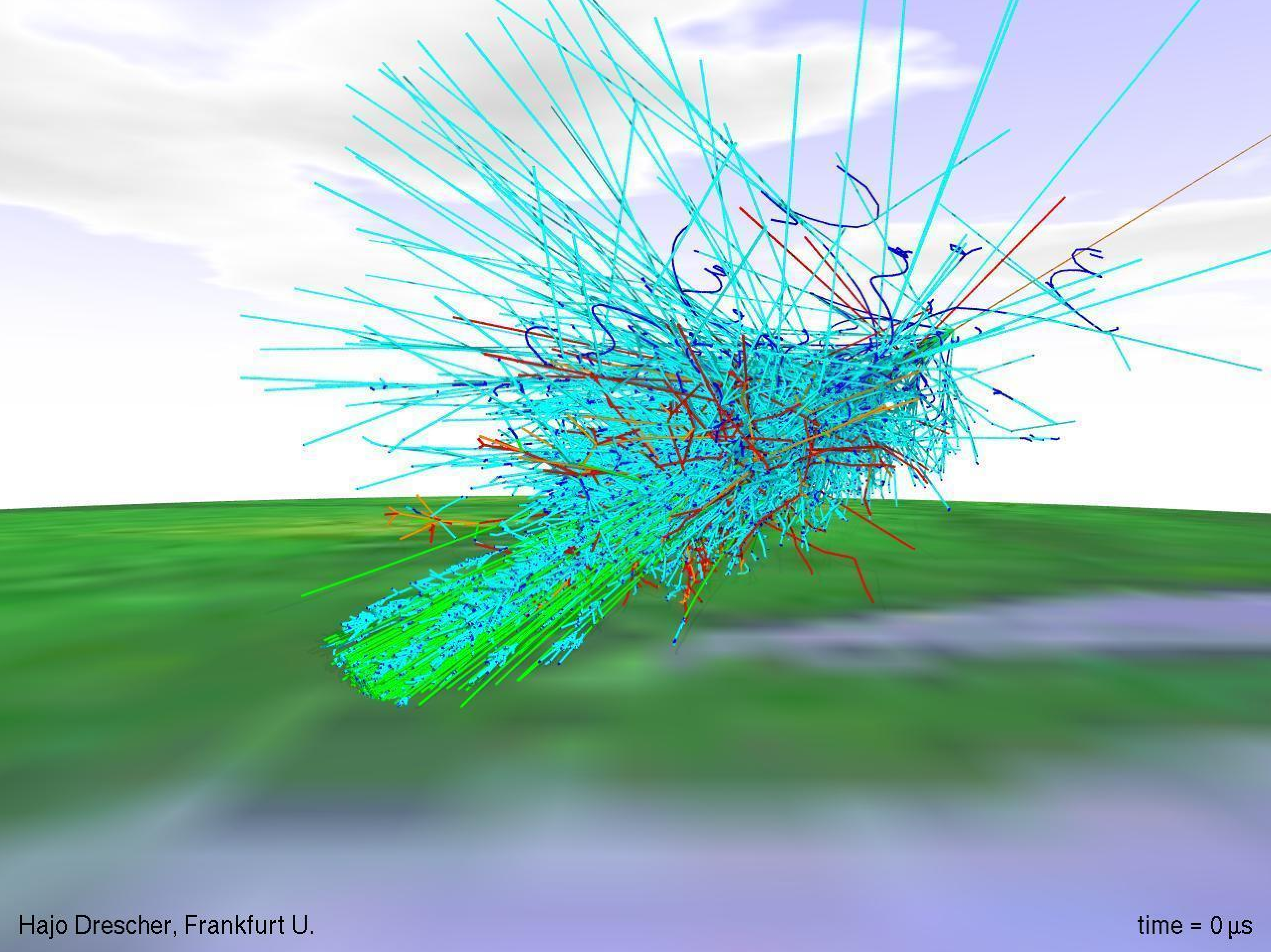
  $$e^{-0.66/15} \approx 10^{-10}$$
- Instead, for a 10 GeV muon, $\gamma \approx 10/0.1 = 100$, then mean distance is 66 km. (OK)
- Simulated event: start...end
- Movie
- Sim_tool



cosmic rays at earth's surface

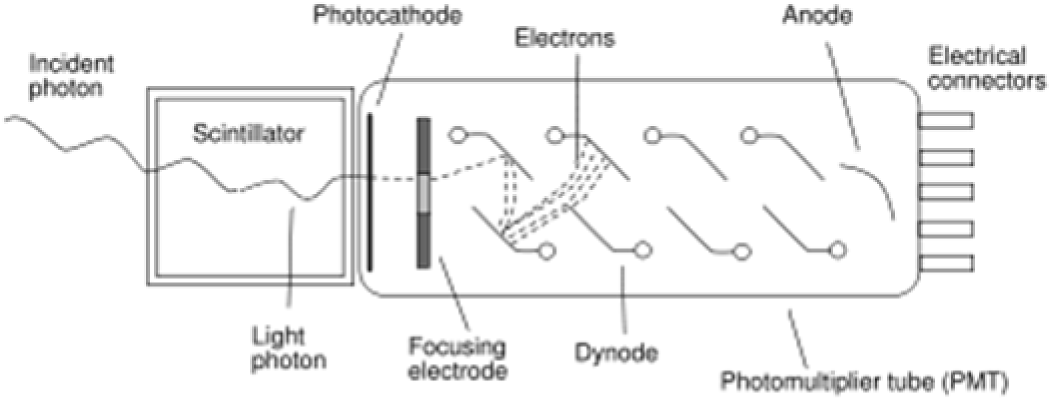
- Predominantly muons
- Detectable (vertical) flux is ≈1/ cm^2/ min
- Mean energy ≈ 4 GeV
- Originate at altitude of 15 km, on average
- The very low energy muons (≈1-3 GeV) mostly decay
  - 15 km decay length corresponds to a 2.4 GeV muon
- The higher energy muons lose about 2 GeV (on average) due to ionization in the atmosphere
  - and about 4 MeV / cm in concrete

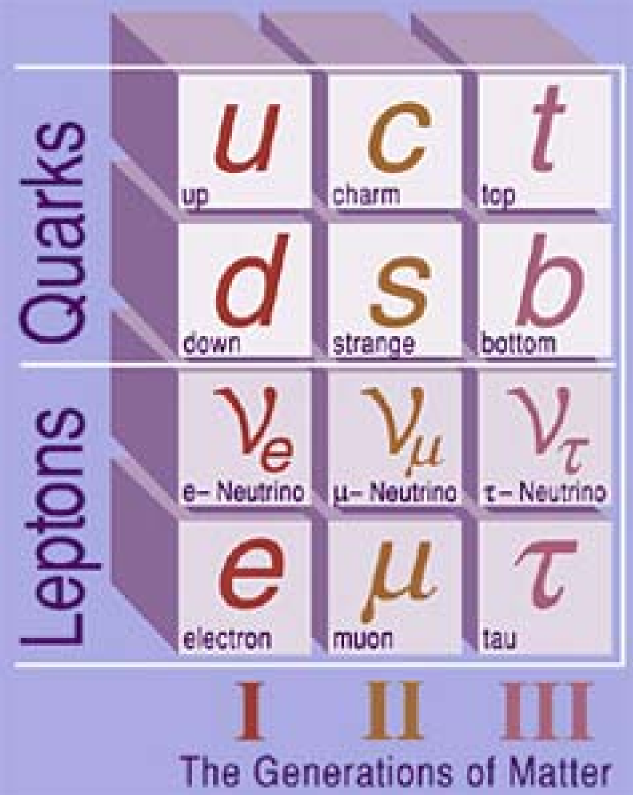

Hajo Drescher, Frankfurt U.
time = -300 μs


Hajo Drescher, Frankfurt U.
time = 0 µs

steps for cosmic ray detection

- A "minimum ionizing particle" (MIP), e.g. a typical cosmic ray muon, passes through a plastic scintillator, depositing (on average) about 2 MeV / cm (ionization of the plastic)
- Typically, the scintillation yield is ~1 photon per 100 eV of ionization $\Rightarrow$ 2×10^4 photons/ cm for each muon
- Some fraction of the photons are collected at the photomultiplier tube (PMT) – depends on geometry and indices of refraction
- The photocathode of the PMT converts a blue photon to an electron with efficiency of ~10%
- The PMT multiplies an electron by a factor $\sim10^6$
  - depends on high voltage setting, number of stages N (N=10 to 12 typically), and geometry
  - Gain $\propto$ (few)^N





FERMIONS

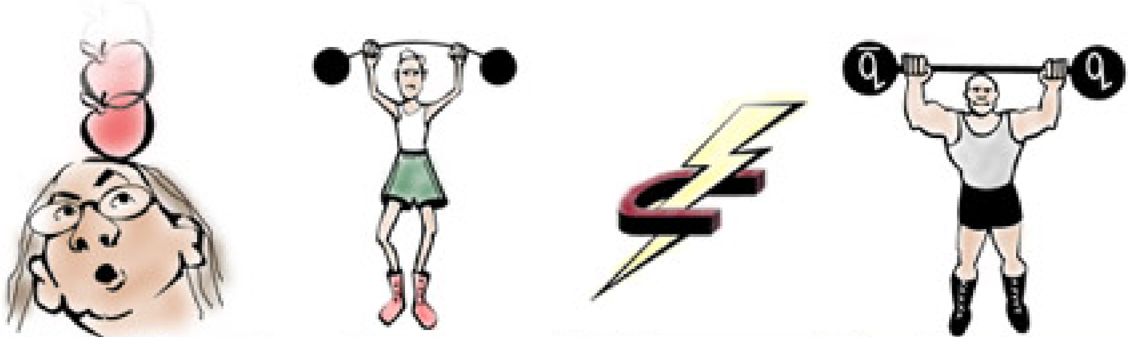
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

lavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3



	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0