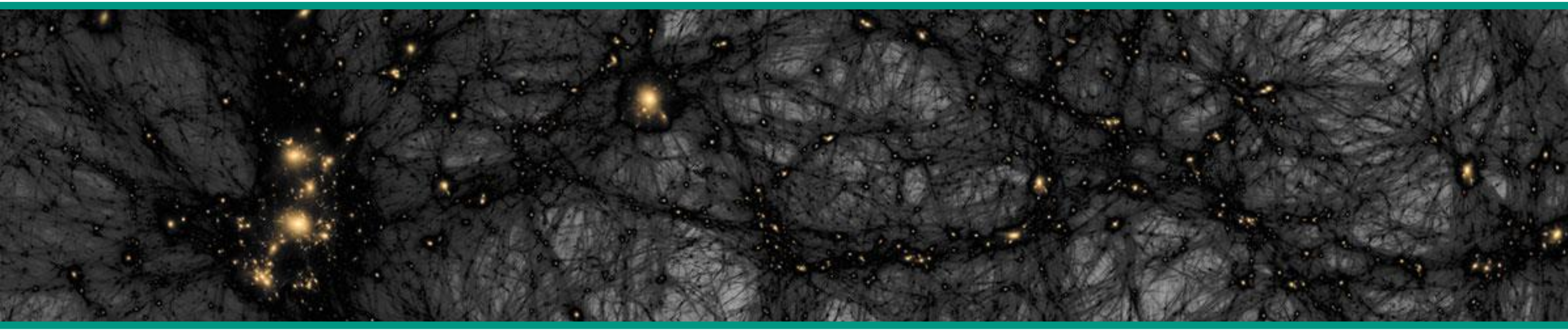
Astroparticle physics I – Dark Matter

WS22/23 Lecture 4 Nov. 9, 2022



Recap of Lecture 3

- **multi-messenger observations: all-sky maps in CRs, gammas, ν´s & GW**

  - Mollweide projection with GC in centre

  - sources: SNR, GRB, AGN, pulsars, binary compact objects,…

- **studies of charged cosmic rays (CR)**

  - V. Hess (***balloon***), P. Auger (***shower***), J. Linsley (***arrays***, up to $10^{20} eV$)

  - energy spectrum of charged CRs: characteristic **power law**

  - direct CR detection via balloons & satellites (up to $\sim 10^{14} eV$): mass composition allows to determine galactic storage time of CRs

  - indirect CR detection (from $\sim 10^{13} eV$) via air showers (**3 components**)

Air showers & jet physics at accelerators

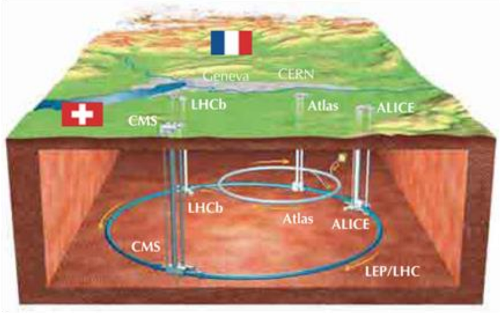
- **links**

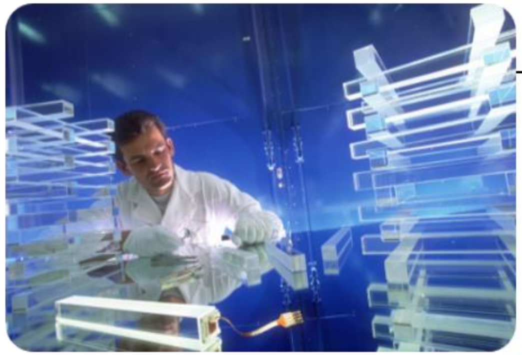
- in the **calorimetry** of hadrons & electrons

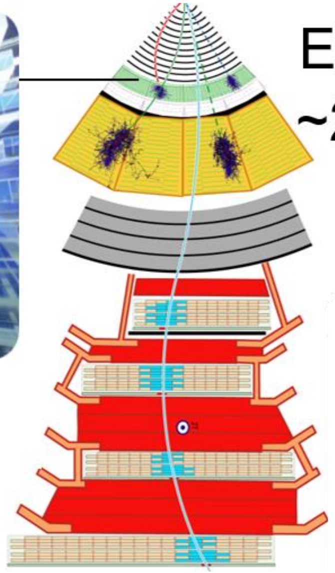
ATP & TP!

shower physics at LHC

accelerators: protons with up to 7 TeV ($\sqrt{s}$ known)







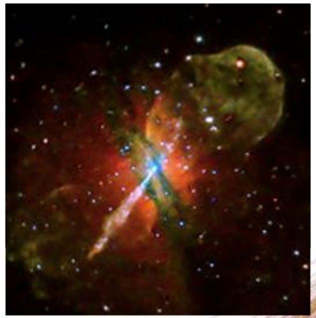
ECAL ~20 X_0

61200 $PbWO_4$

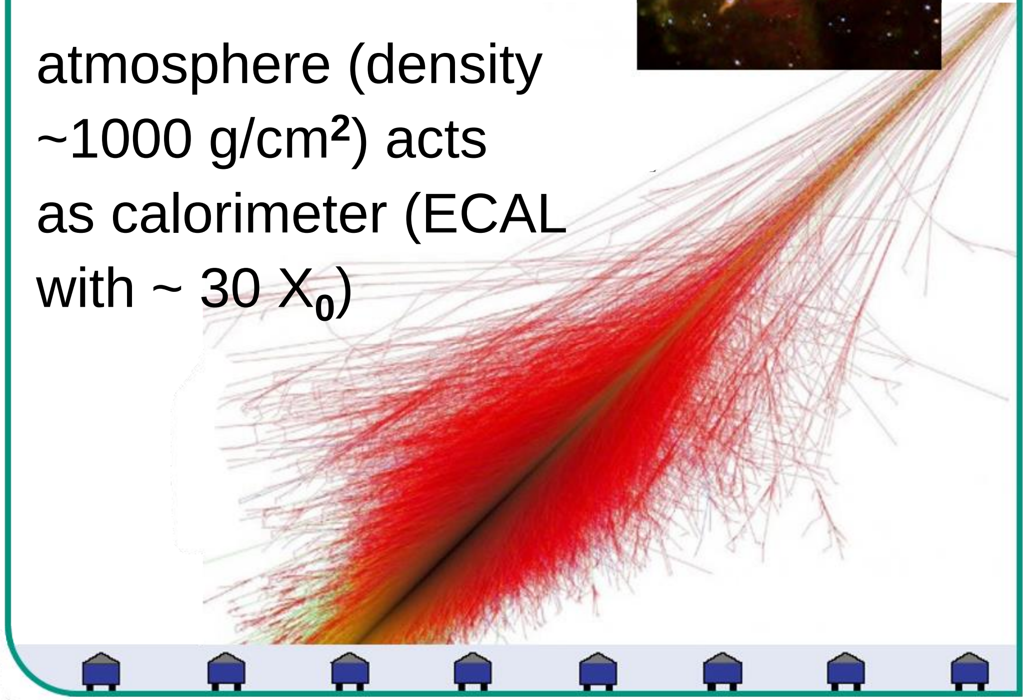
X_0 = 0.89 cm

showers from AGN accelerators

cosmic accelerators: protons (nuclei) with up to 10^{20} eV



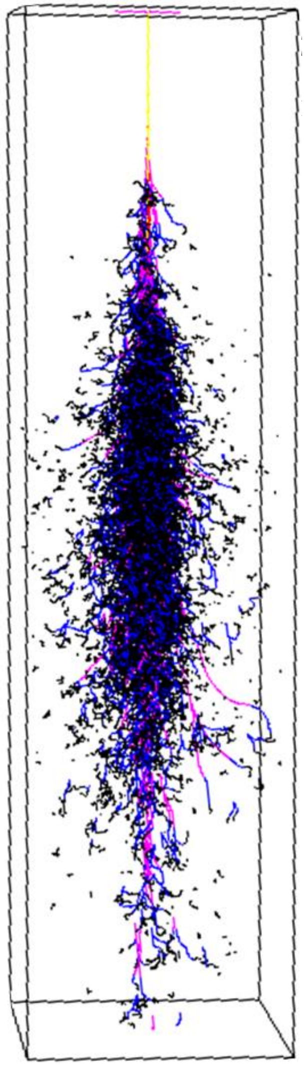
atmosphere (density ~1000 g/cm^2) acts as calorimeter (ECAL with ~ 30 X_0)

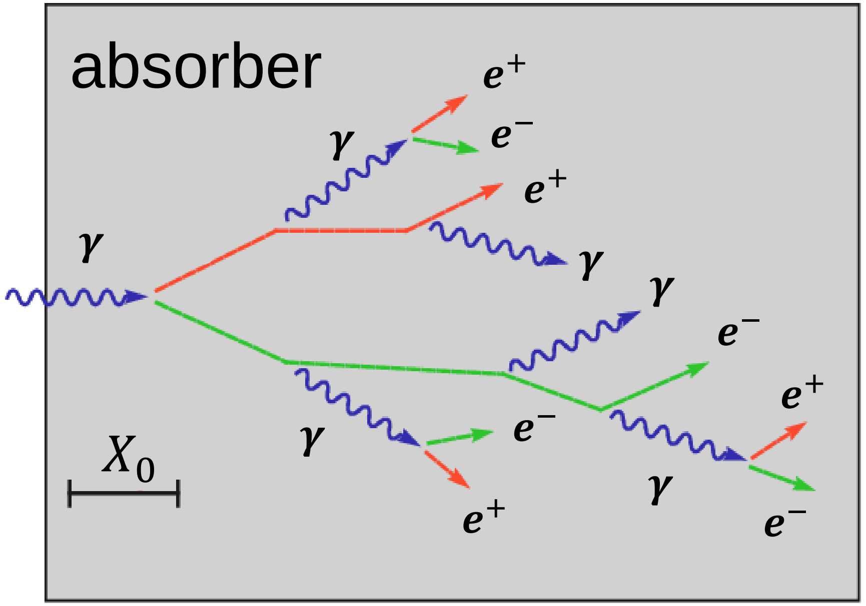


Electromagnetic component of showers

- **majority (~98%) of shower particles as cascade $e^- e^+ \gamma$**
  - cascade processes: **pair production ⬄ bremsstrahlung**
  - **Heitler model for electromagnetic cascades:**

80 GeV e-





Q: aanda.org

- initial increase of # of particles (successive particle ´generations´)
- mean energy per particle decreases
- huge number of secondary, low-energy particles: $e^- e^+ \gamma$
- shower ´dies out´ once $E < E_C$ with: E_C = **critical energy**

Electromagnetic component of showers

- **majority (~98%) of shower particles as cascade $e^- e^+ \gamma$**

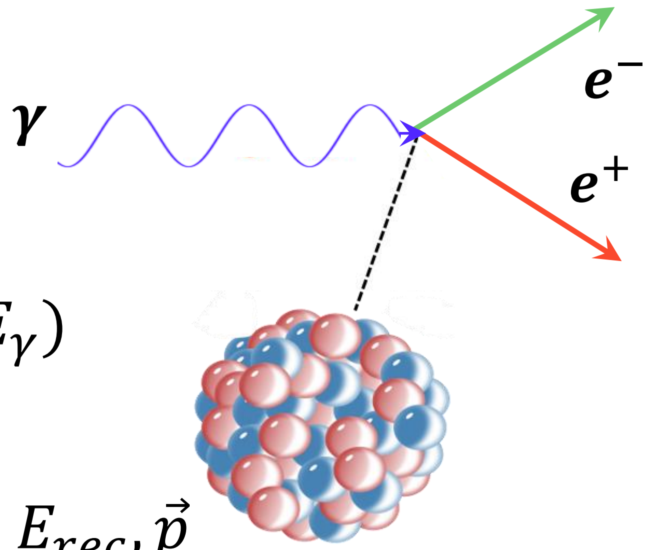
  - two processes: **pair production ⇔ bremsstrahlung**

- threshold energy:

$$E_{\gamma,thres} \cong 2 \cdot m_e = 1.02\ MeV$$

- saturation:

$$\sigma_\gamma(E_\gamma) \sim ln(E_\gamma)$$



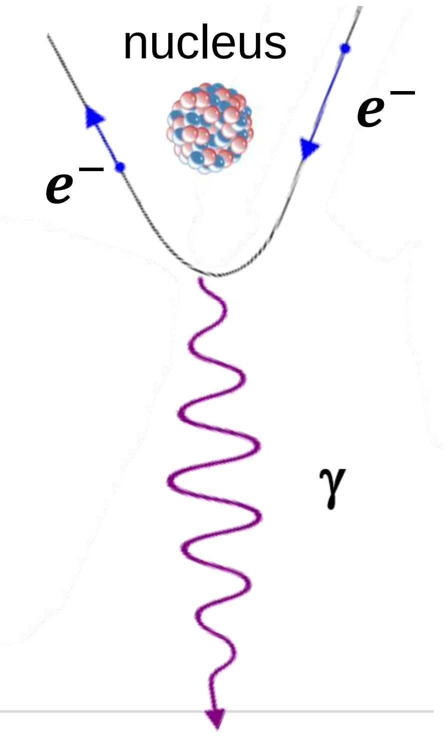
nucleus: $E_{rec}, \vec{p}$

- radiative energy losses at high energies:

$$\left(\frac{dE}{dX}\right)_{brems} = \frac{1}{X_0} \cdot E$$

- important only for very light particles (e^-, e^+):

$$\sigma_{Brems} \sim 1/m^2$$



Electromagnetic component of showers

- **development of electromagnetic showers in the atmosphere**

  - key parameter: **radiation length $\boldsymbol{X_0}$**

  - for highly **relativistic electrons**:

$$E(x) = E_0 \cdot e^{-\frac{X}{X_0}}$$

i.e. after passing an atmosphere thickness $X = X_0$
the **energy** E of the e^- has dropped from E_0 to a fraction of $\boldsymbol{1/e}$

  - for **high-energy photons**:

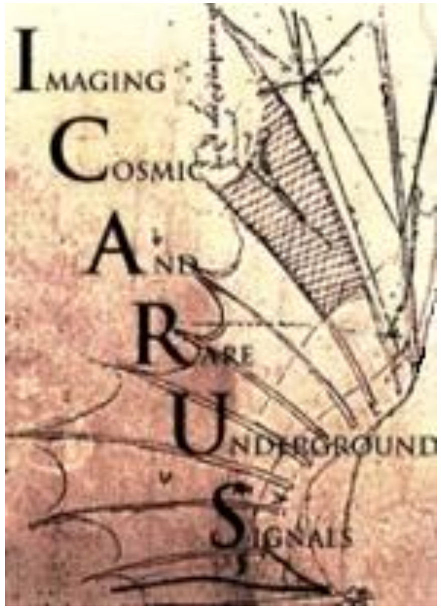
i.e. the **mean free path $\boldsymbol{\lambda}$** of high-energy photons for pair production in the atmosphere is $\lambda = 9/7\ X_0$

$$\lambda_{pair} = \frac{9}{7} \cdot X_0$$

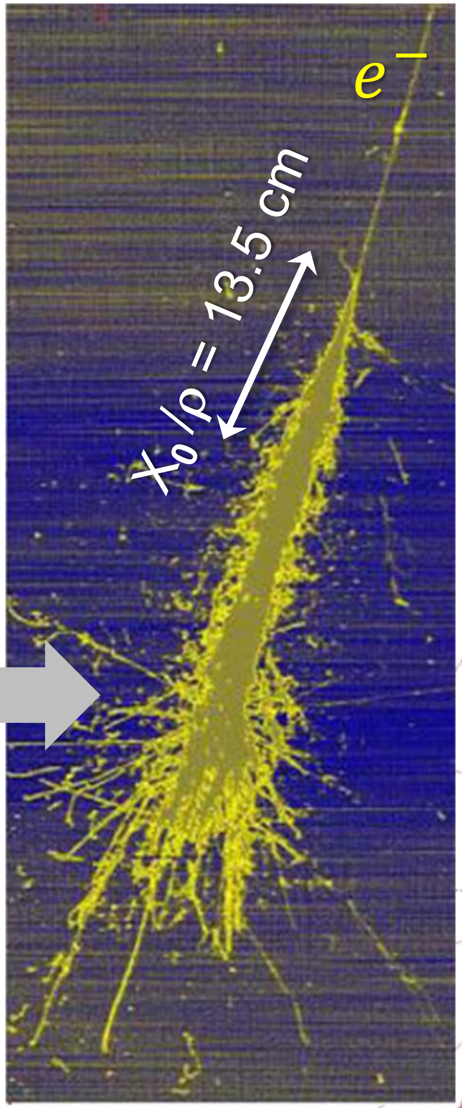
Electromagnetic component of showers

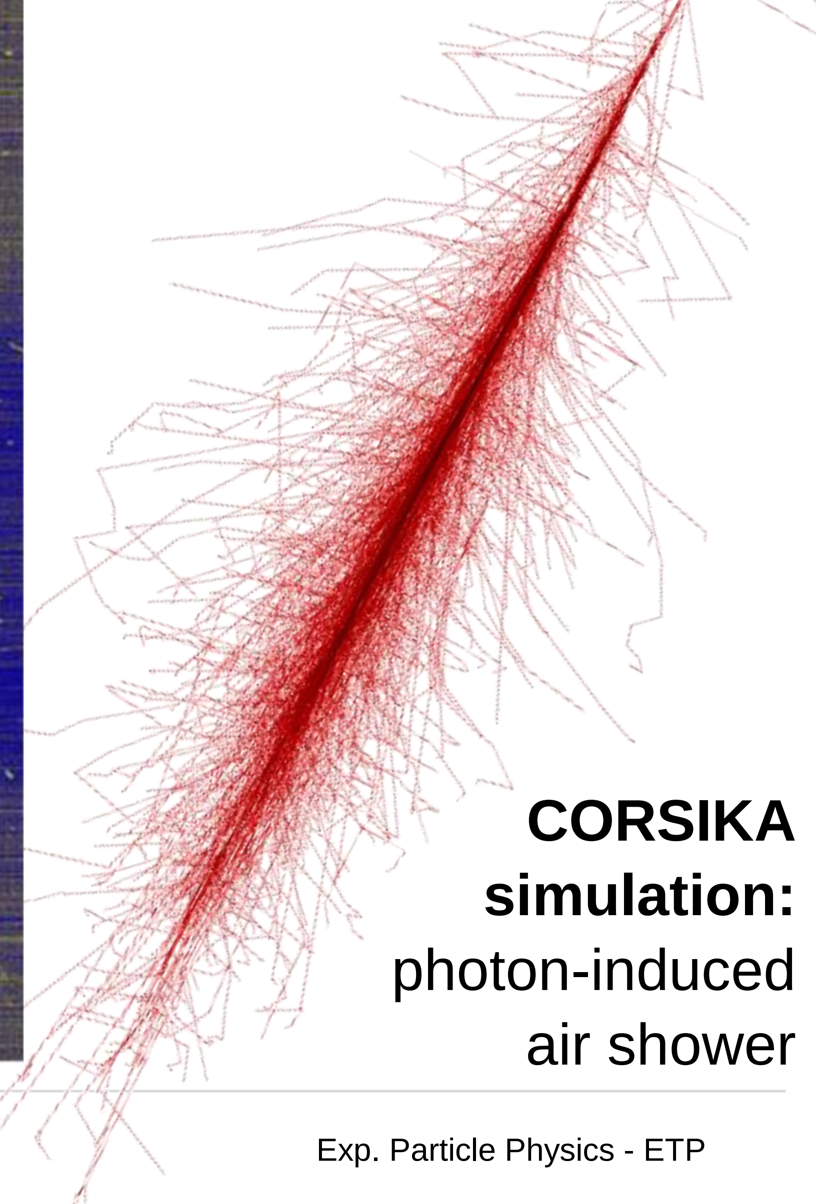
- **electromagnetic showers: experimental signature & modelling**

  experimental shower signatures & Modelling via simulation-codes*



ICARUS experiment:
neutrino-induced particle shower in a liquid argon calorimeter - interactions of a primary high-energy electron





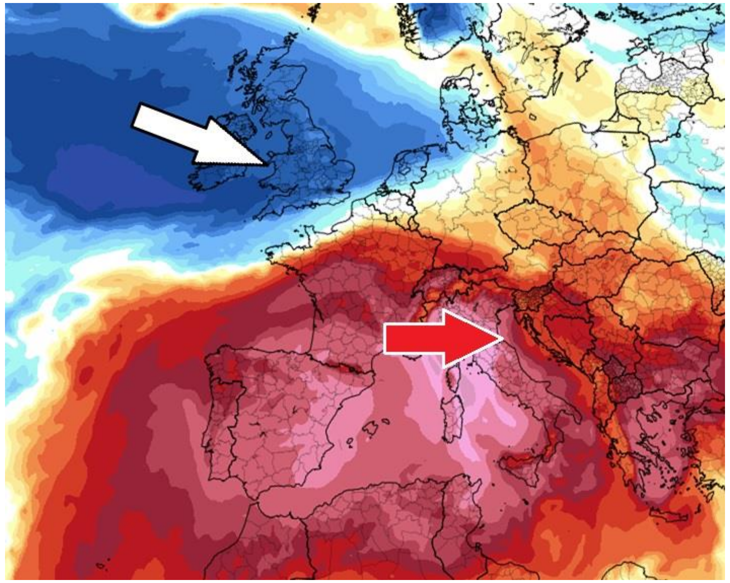
CORSIKA simulation:
photon-induced air shower

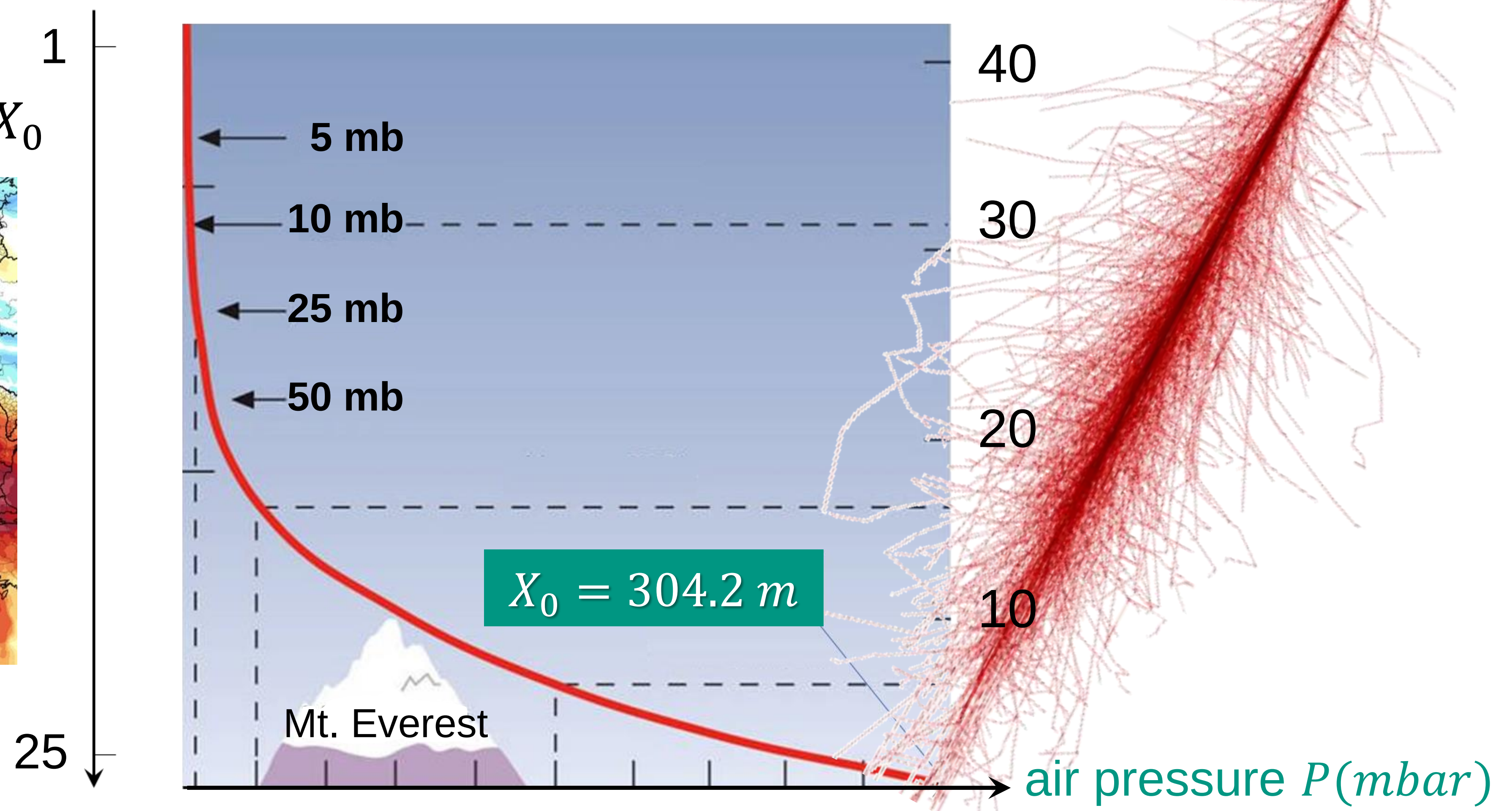
*see Mod. Ex. Phys. III

Electromagnetic component of showers

- **atmosphere as electromagnetic calorimeter: ~$25\ X_0$**

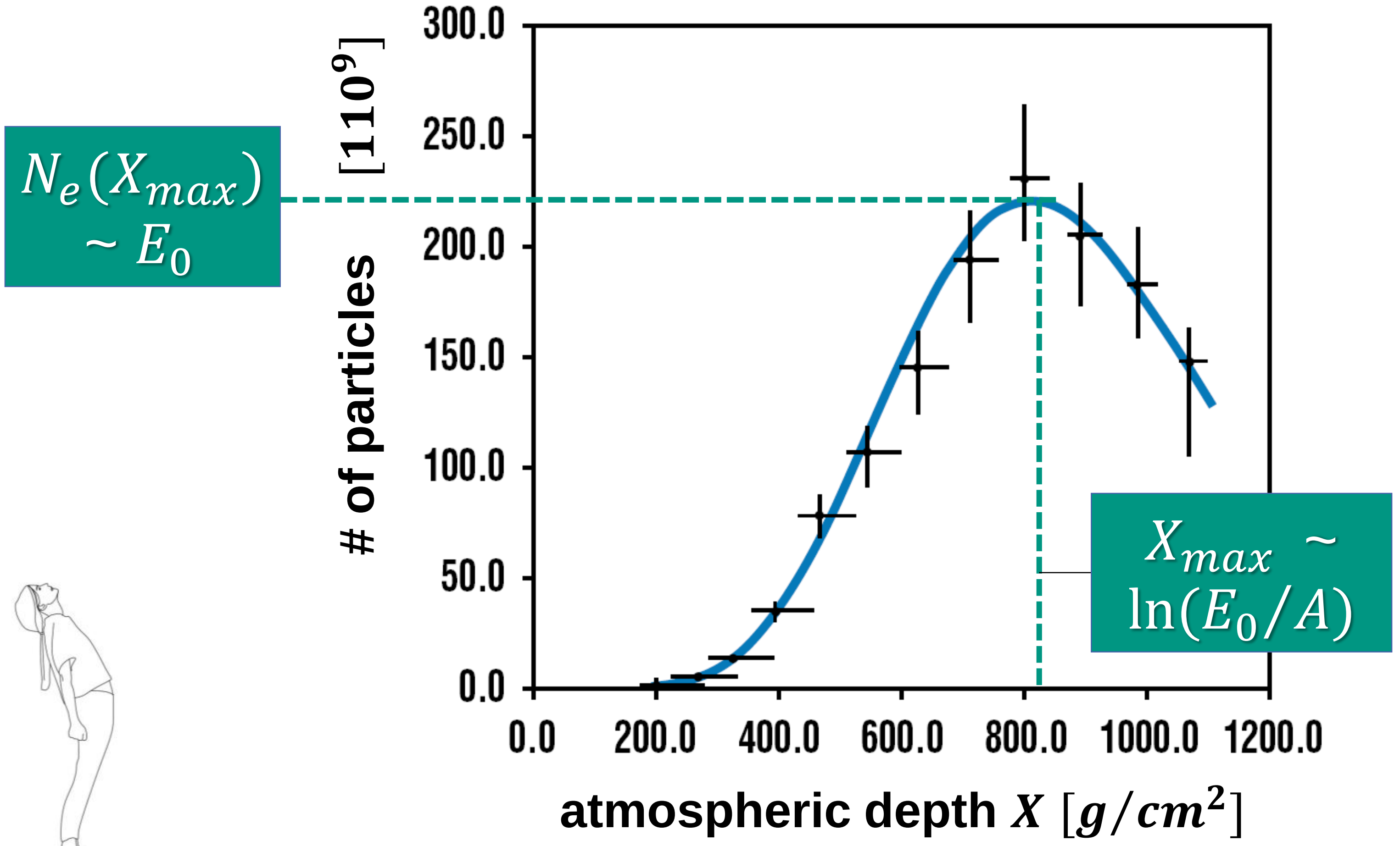
- changing atmospheric weather: changes # of X_0

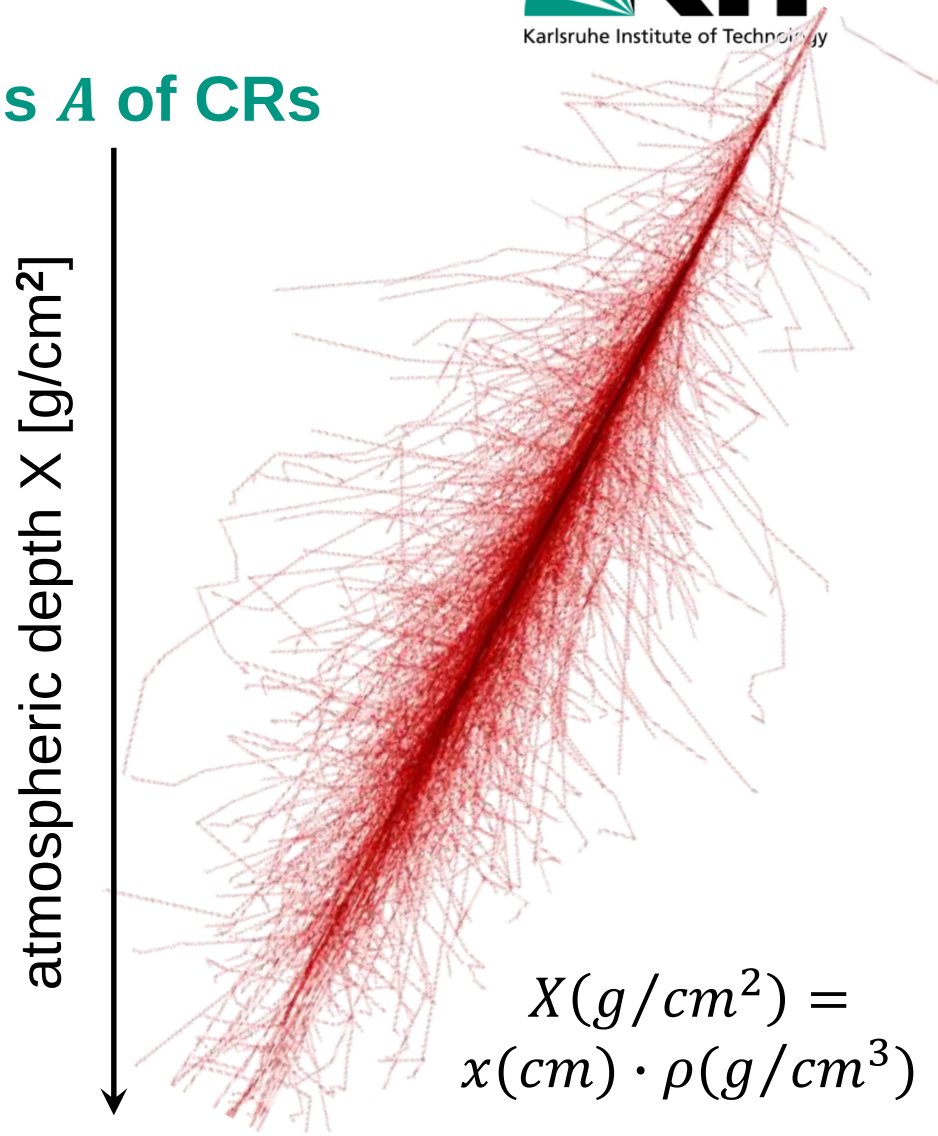




Electromagnetic showers in the atmosphere

- **Key parameter: shower maximum X_{max} for mass A of CRs**

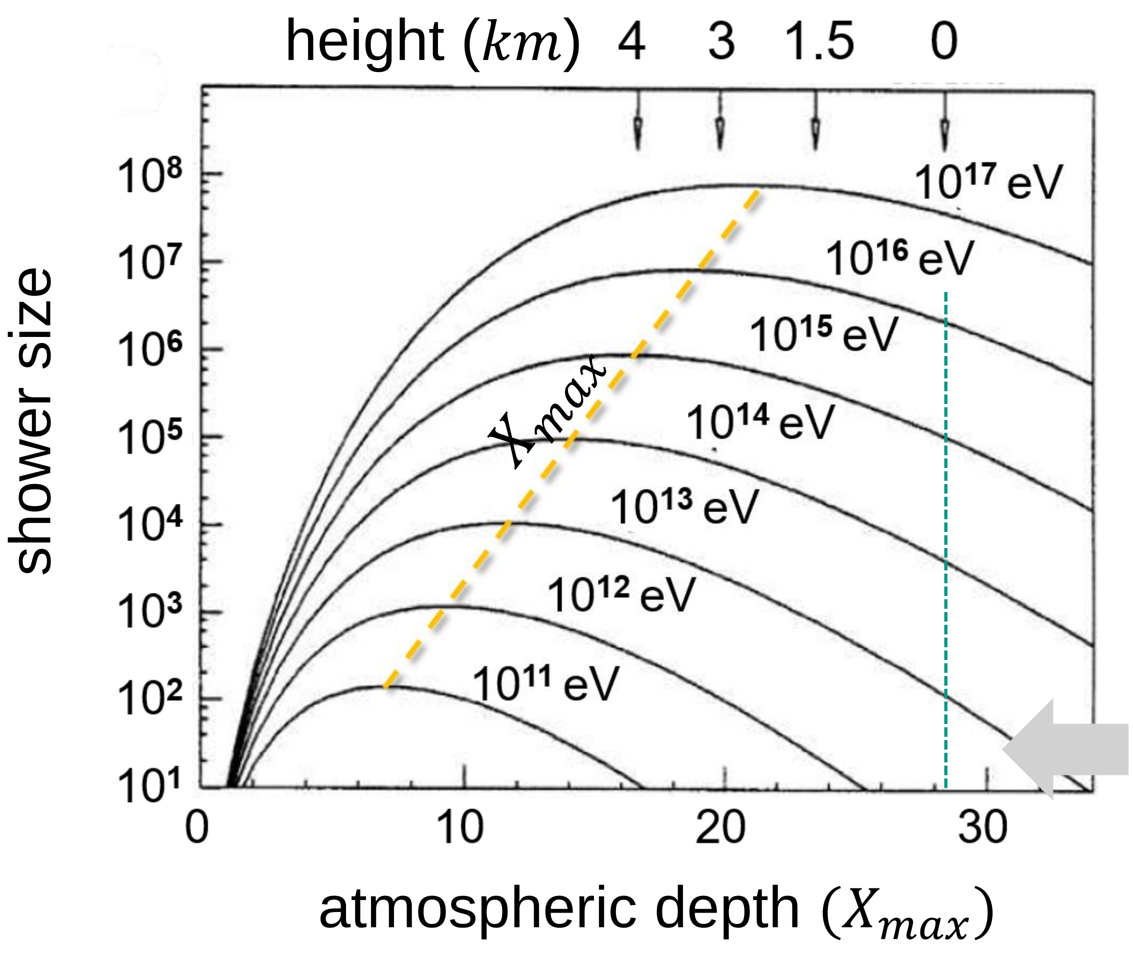




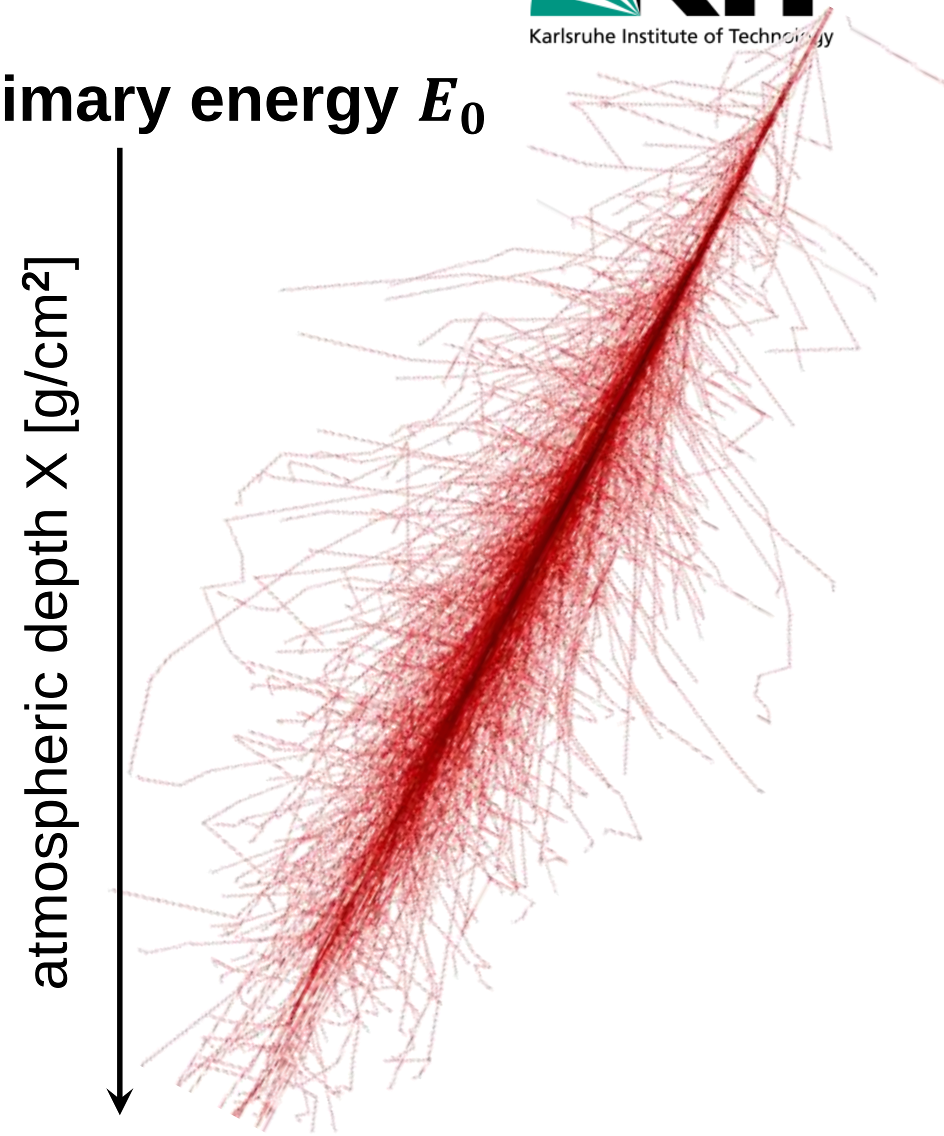
$$X(g/cm^2) = x(cm) \cdot \rho(g/cm^3)$$

Electromagnetic showers in the atmosphere

- shower maximum X_{max} varies as function of primary energy E_0



- primary CR energies $E < 10^{13} eV$ do not reach the surface



Muonic component: mips

- **muons are minimum ionizing particles (m.i.p.s)**

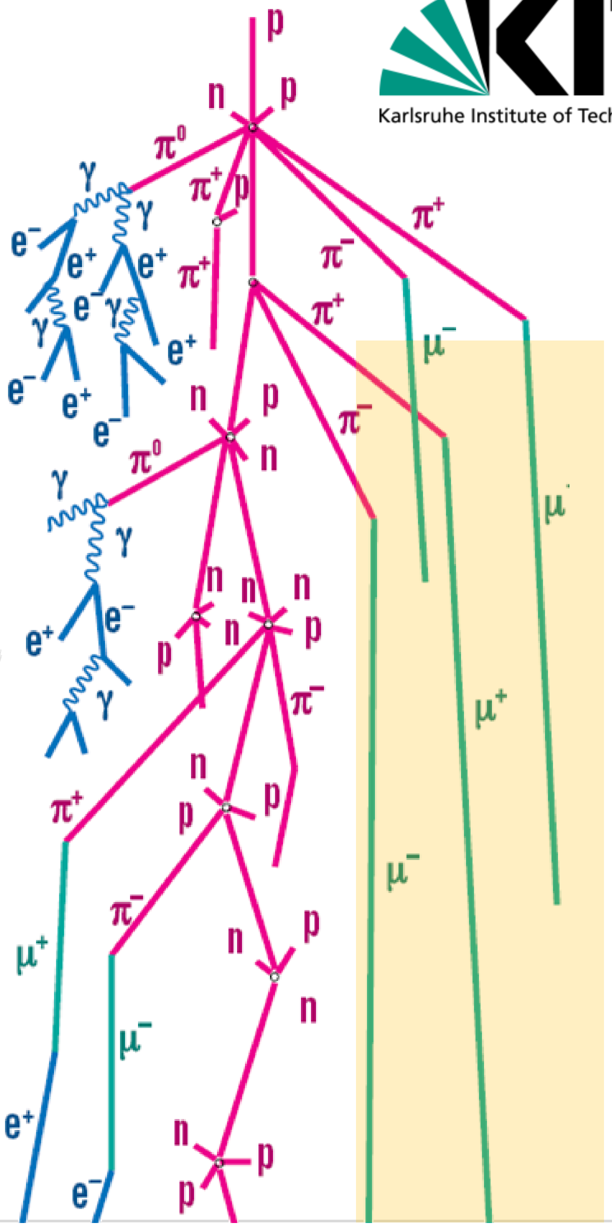
  - „cosmic“ munos (slang: „cosmics“)

  - from pion decays $\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$ in upper atmosphere

  - flux density of muons at sea level: $d\Phi/dA \sim 100\ \mu\text{'s}\ m^{-2} s^{-1}$

  - charge ratio: $\boldsymbol{\mu^{+}/\mu^{-} = 1.2}$

  - overall fraction of secondary particles $\varepsilon_{\mu} \sim 1.7\%$



application of air showers: muography

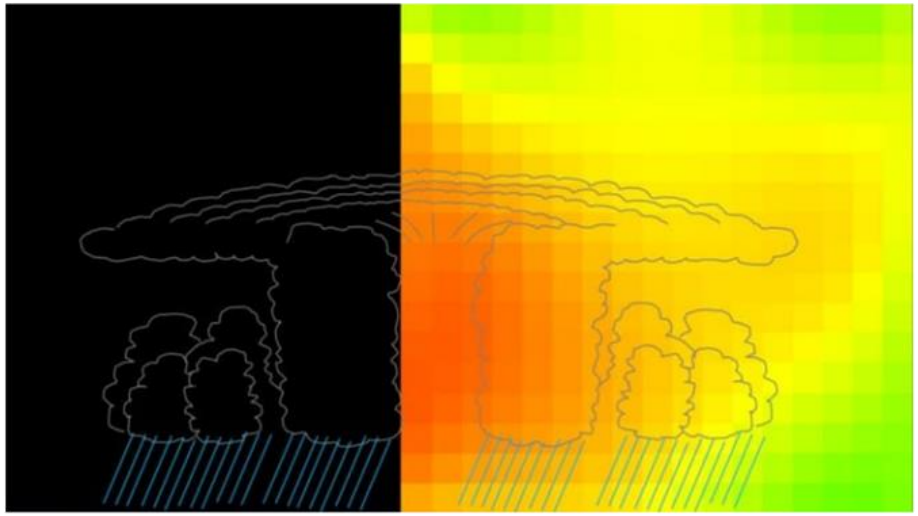
- muography: muon rate depends on air pressure

physicsworld

PARTICLE AND NUCLEAR RESEARCH UPDATE

Cosmic muons probe the interiors of tropical cyclones

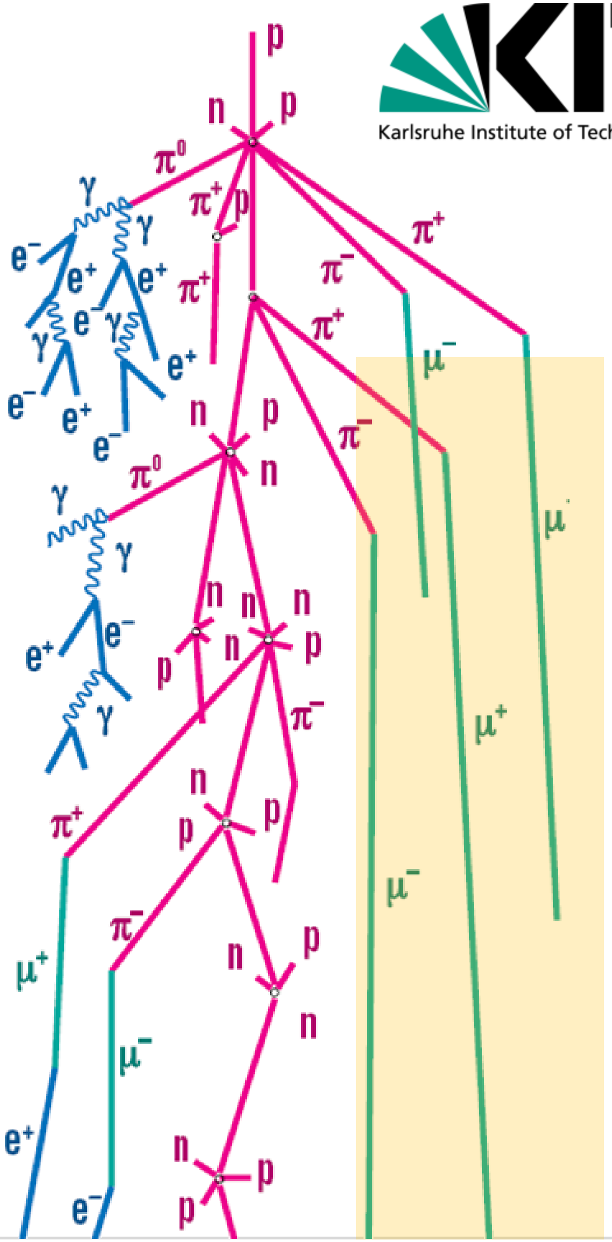
18 Oct 2022



Peering inside: the image on the right shows the interior of a cyclone. The redder areas are regions of lower pressure, and the greener areas are higher pressure. (Courtesy: Hiroyuki KM Tanaka)

Cosmic muons have been used to image structures deep within tropical storms, according to an international team of researchers. Led by Hiroyuki Tanaka at the University of Tokyo, the team used a network of muon detectors to identify differences in air density within several typhoons.

- advantage of using muons from showers: long range of μ in the atmosphere



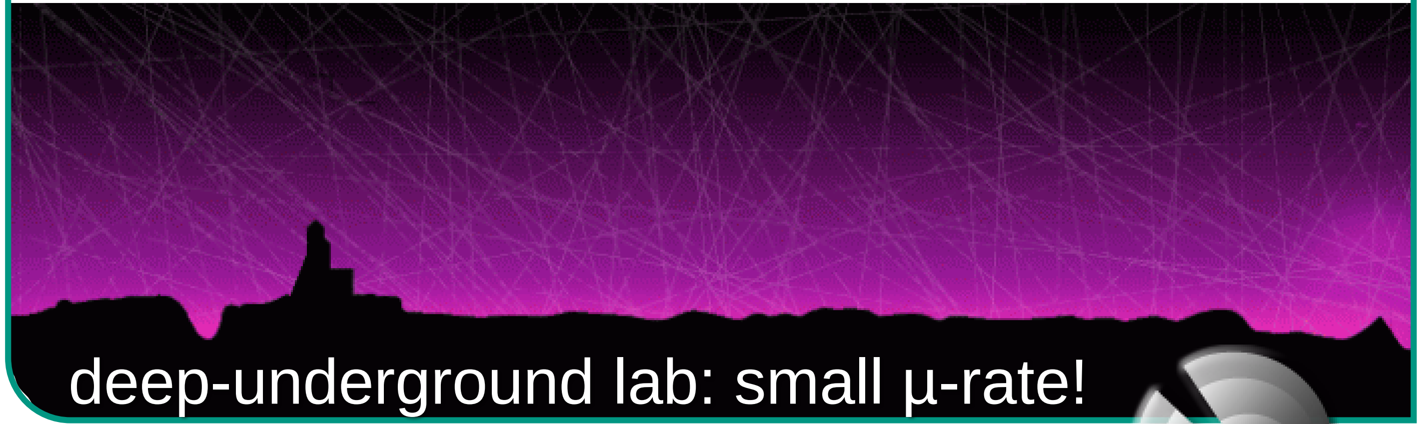
Muonic component: underground location!

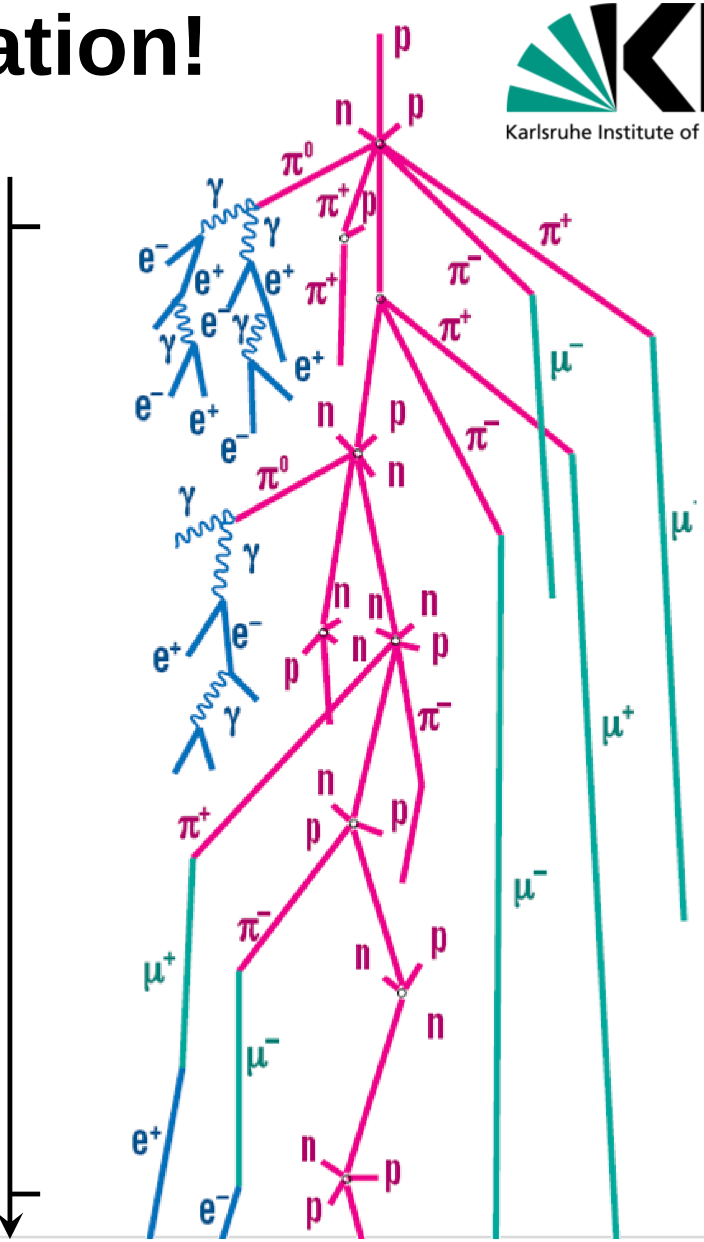
- **muons are penetrating particles**

- relativistic lifetime: $\tau = \gamma \cdot 2.2\ \mu s$

- energy loss: $dE/dx = 2\ MeV/cm$ (H_2O)

- very penetrating shower component, despite massive shielding ➩ underground laboratory



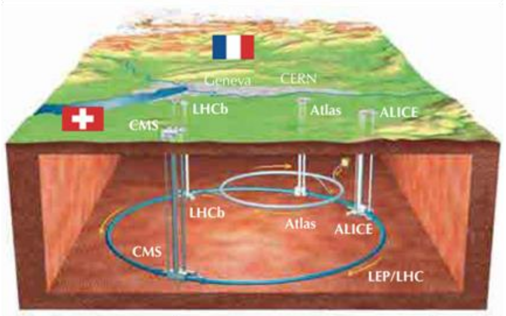


Muons at the LHC and in astroparticle physics

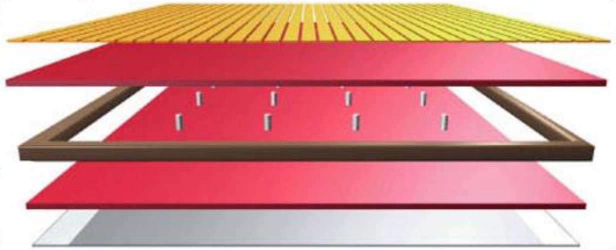
muons from an acclerator (LHC)

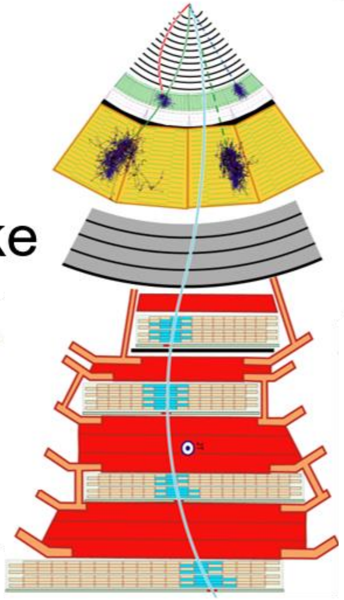
accelerator

protons up to
7 TeV



1400 muon chambers
at magnetic return yoke



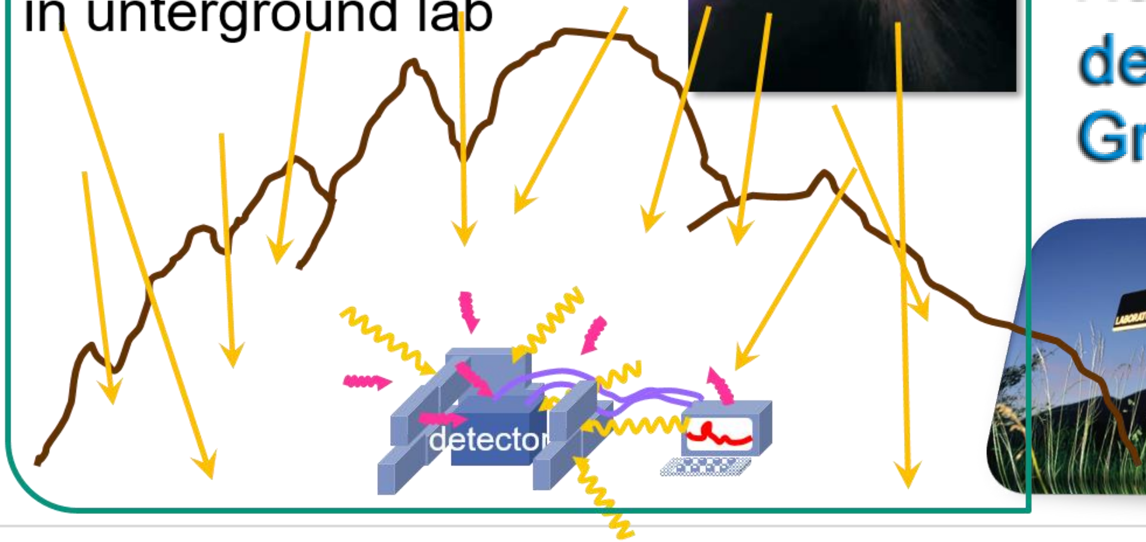


muons from cosmic accelerators

accelerator

protons up to
10^{20} eV

shielding against muons
in unterground lab



Laboratori
Nazionali
del
Gran Sasso

Hadronic component of air showers

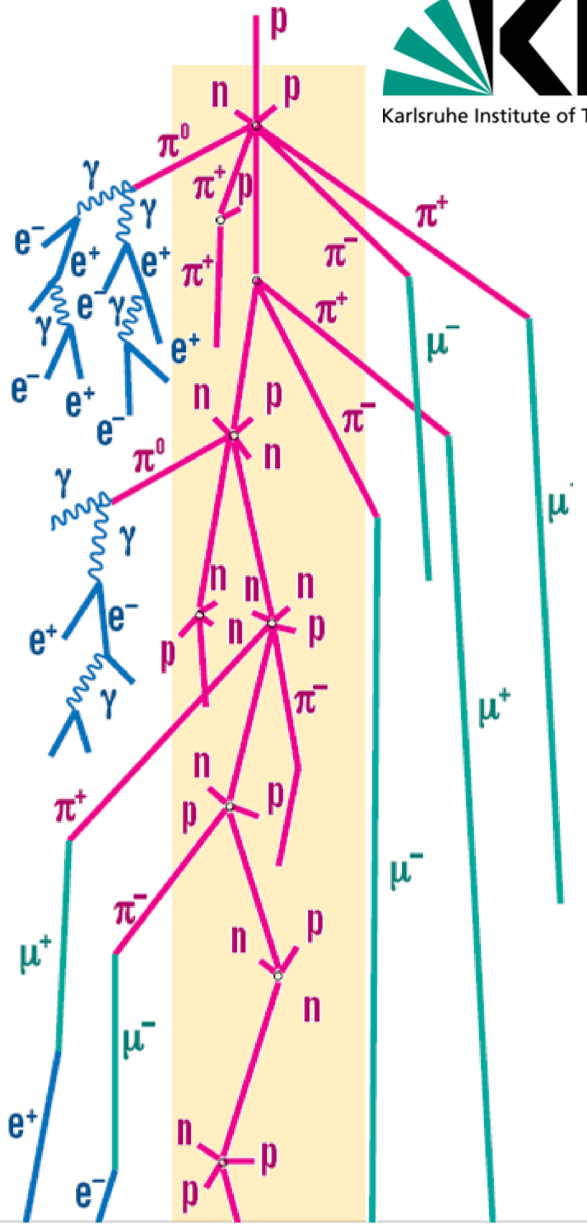
Hadronic interactions in the atmosphere

- **all** hadrons ($p, n, \pi^+, \pi^-, \pi^0, K^+, K^-, K^0, \ldots$):
  processes of the **strong** interaction, decays:
  → **hadronic** (& electromagnetic) **shower**

- charged hadrons ($p, \pi^+, \pi^-, K^+, K^-, \ldots$): also
  → **electromagnetic interaction** (i.e. ionisation)

- hadrons are localized in **shower core** (~0.3% fraction)

- hadrons are characterized by their **large** $\boldsymbol{dE/dx}$



Hadronic component of air showers

- **Hadronic interactions in the atmosphere**

  - **hadronic interaction length Λ**
    measured in [g/cm² or cm]

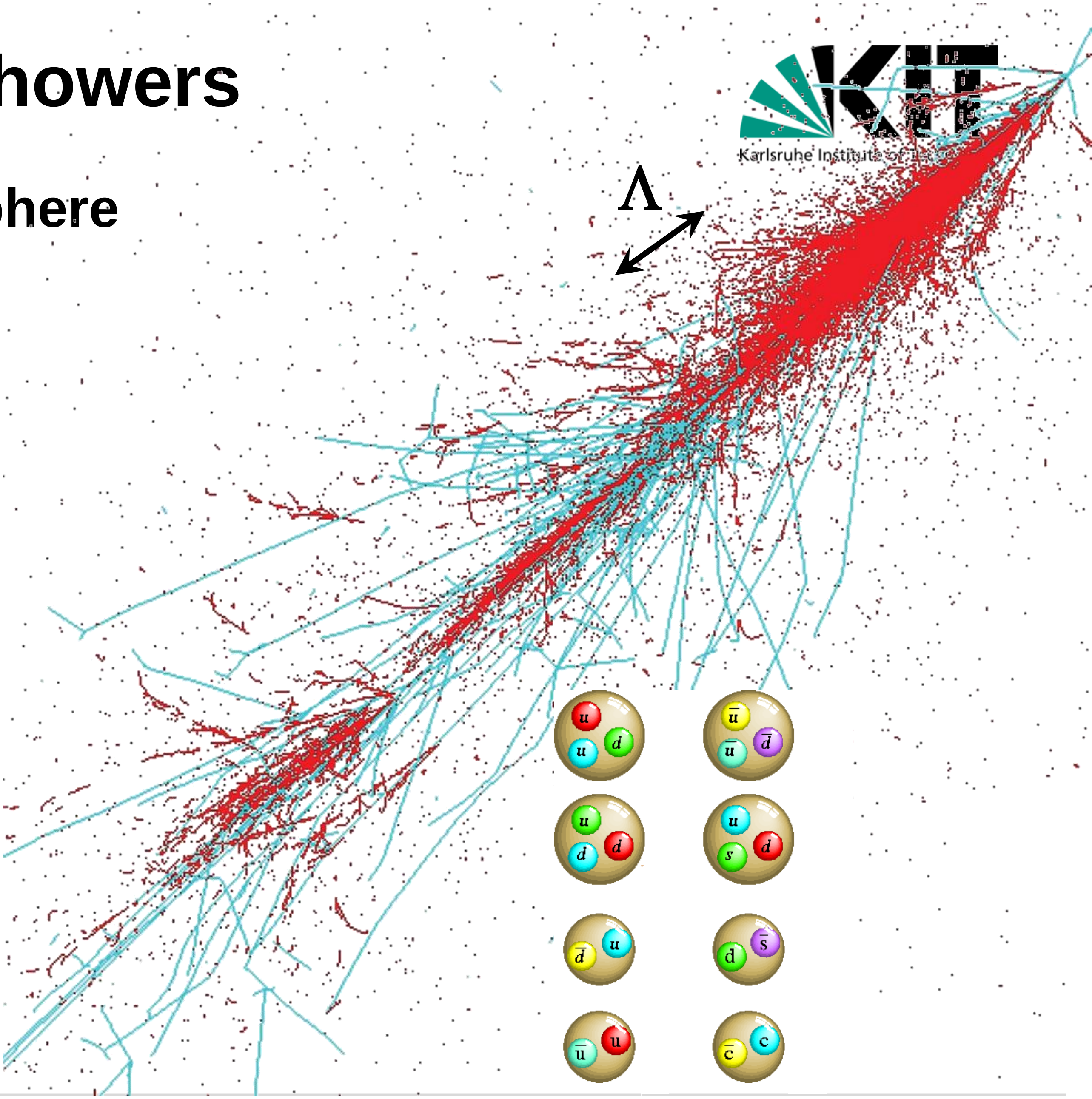
    = mean length for inelastic scattering

$$\Lambda = \frac{1}{\sigma \cdot n}$$

σ: cross section with nucleus

n: number of scatter centres

  - atmospheric thickness corresponds
    ~ 11 hadronic interaction lengths Λ



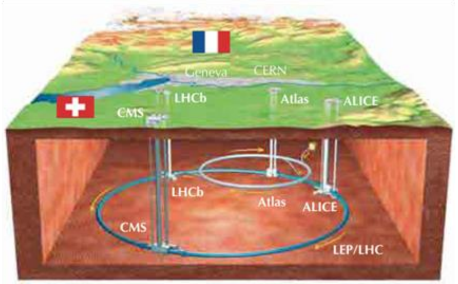
Hadronic component of air showers

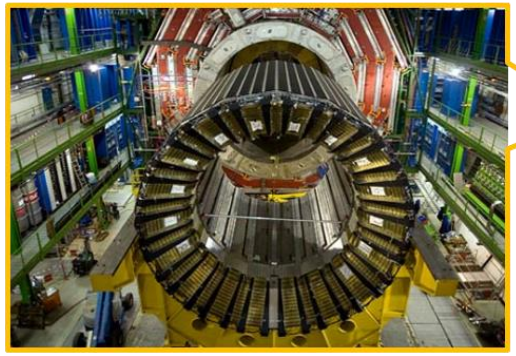
- **Hadronic interactions: HCAL characteristics at LHC and in the atmosphere**

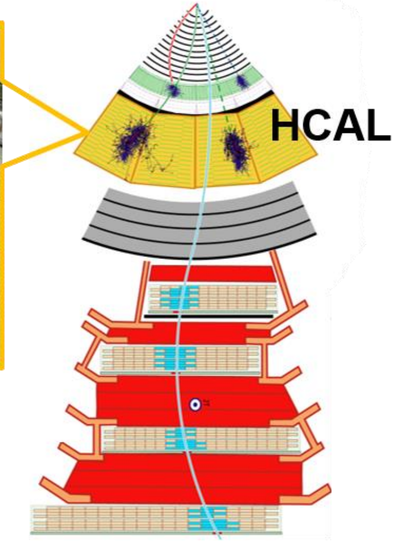
HCAL at the LHC accelerator (CMS)

accelerator

protons up to
7 TeV







- Iron as absorber:
  Λ = 16.8 cm
  X_0 = 1.76 cm

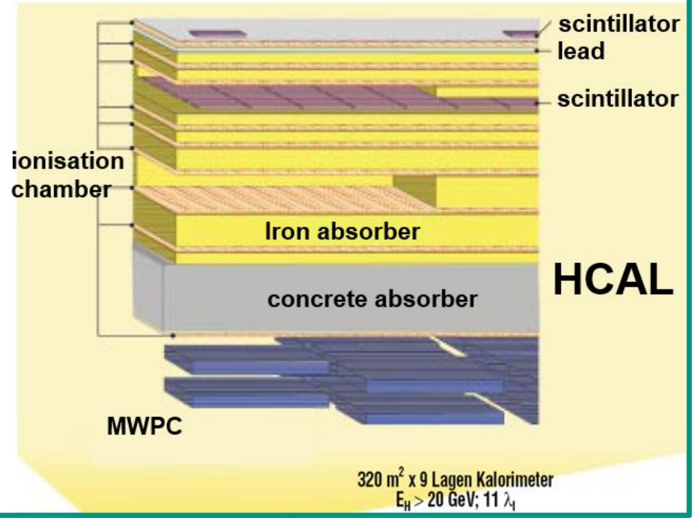
HCAL for cosmic accelerators

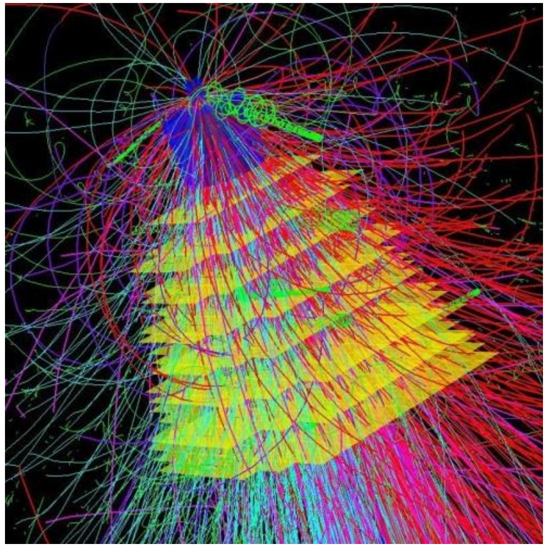
accelerator

protons up to
10^{20} eV

Fe-hadron-(sampling) calorimeter

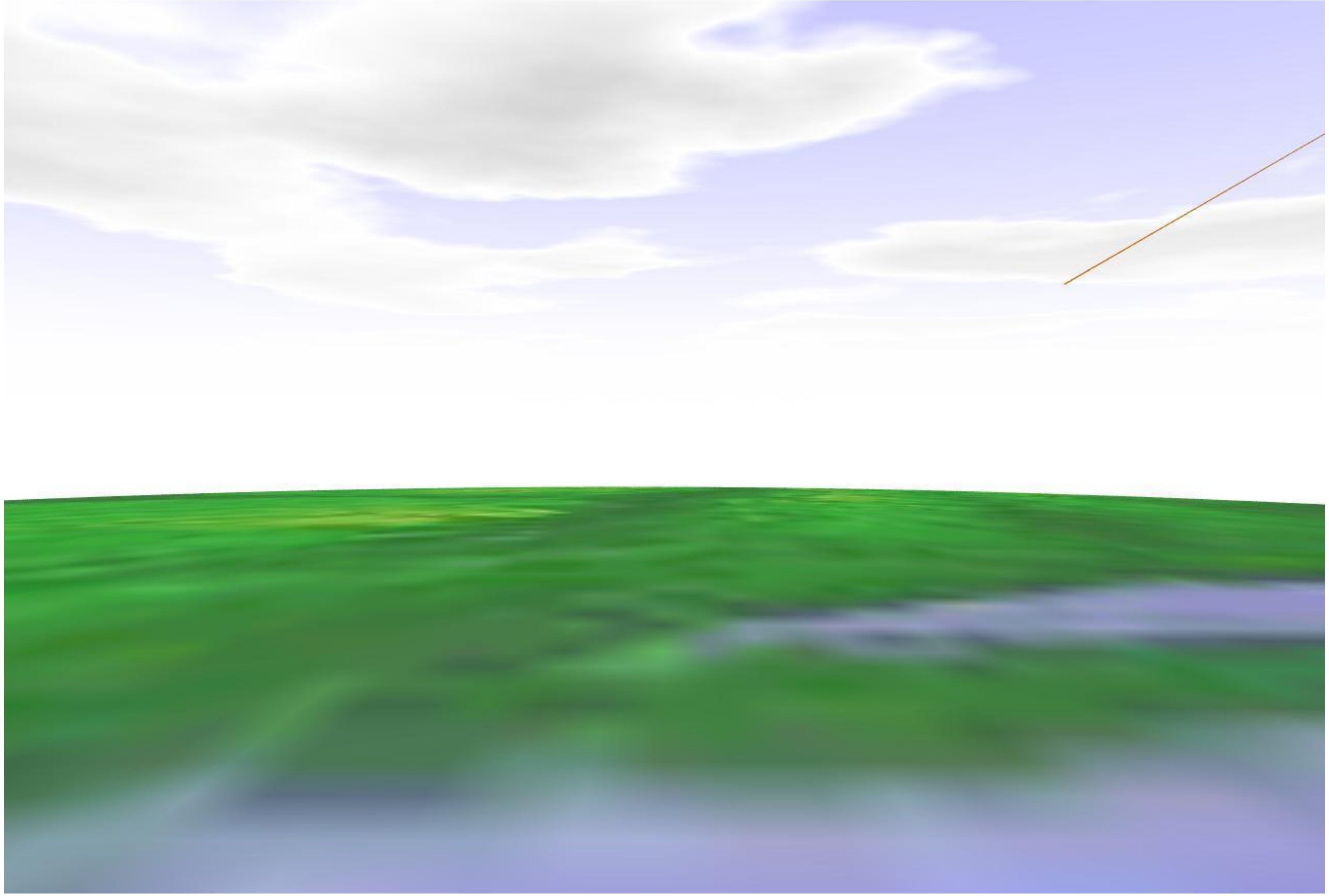
K
A
S
C
A
D
E

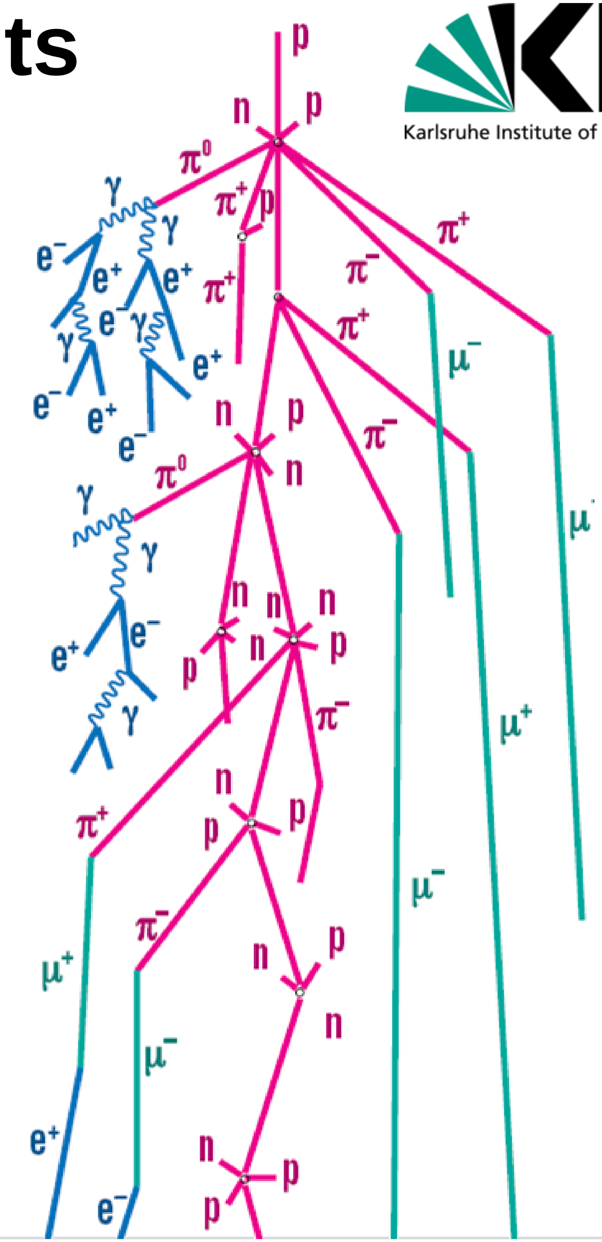




hadronic shower
in an HCAL

Simulation of air showers: all components





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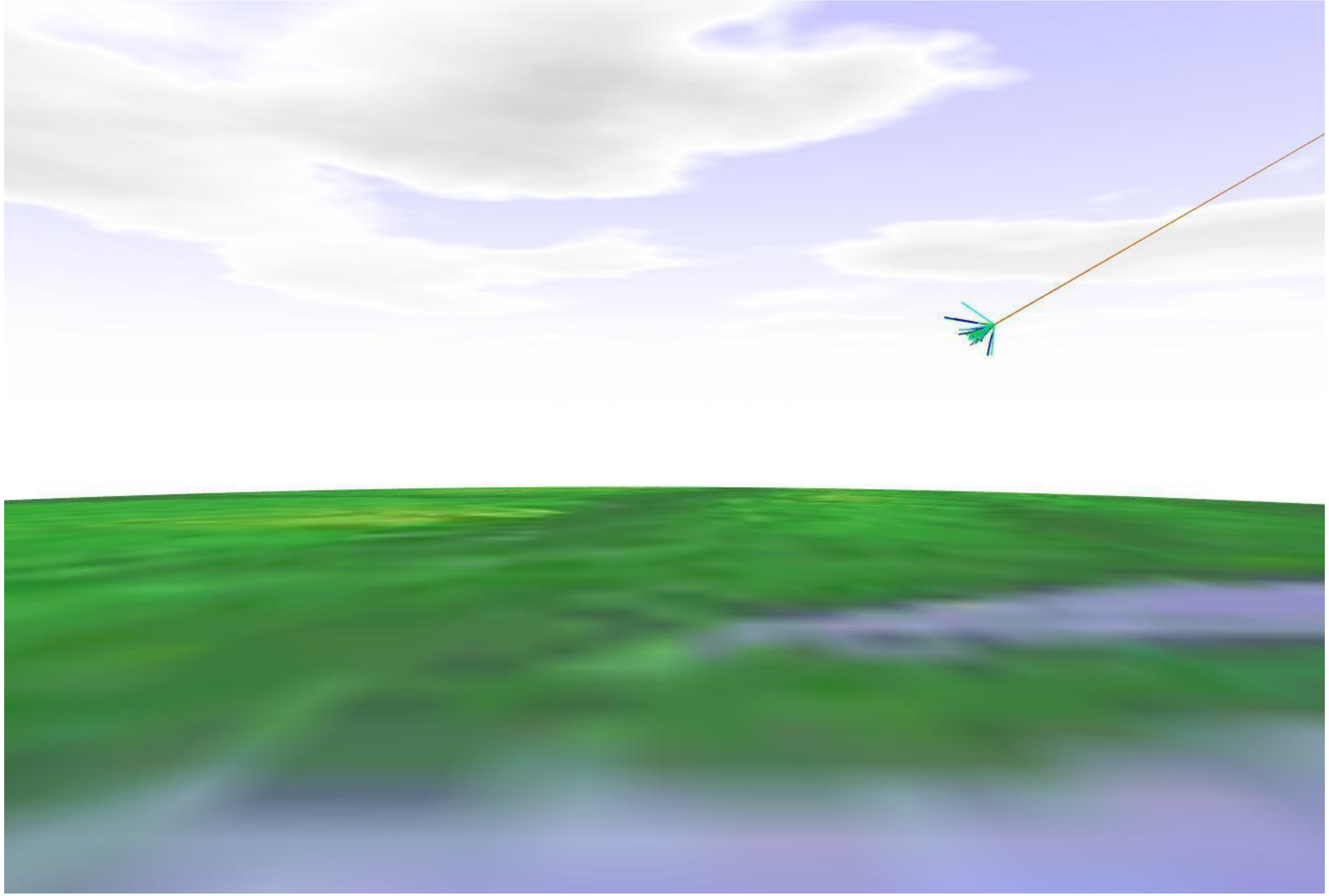

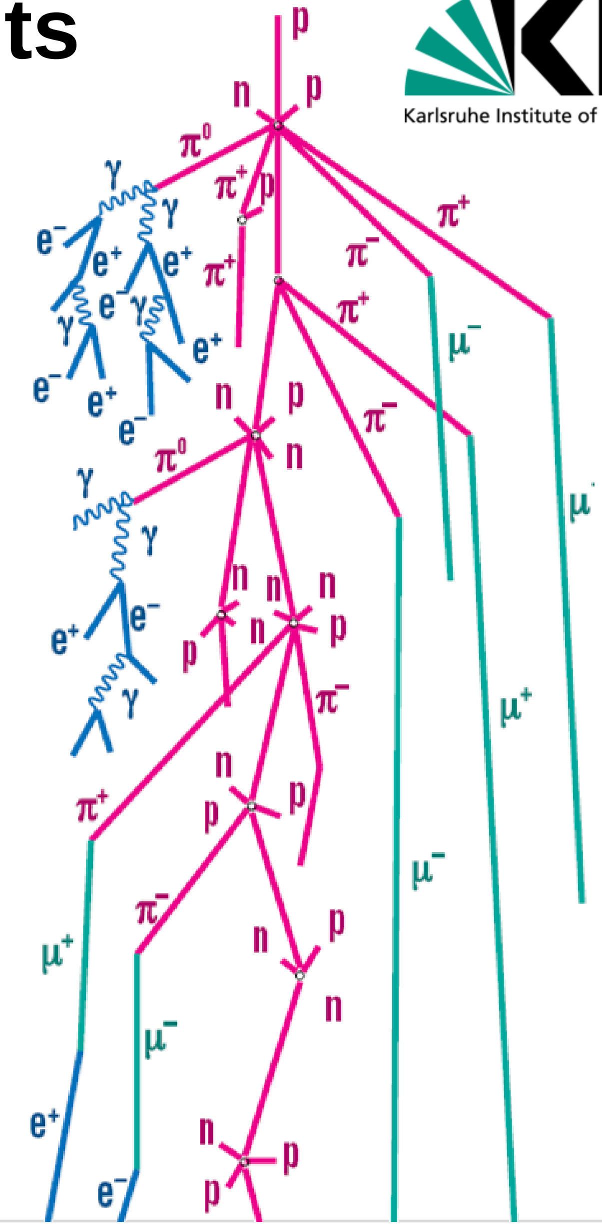

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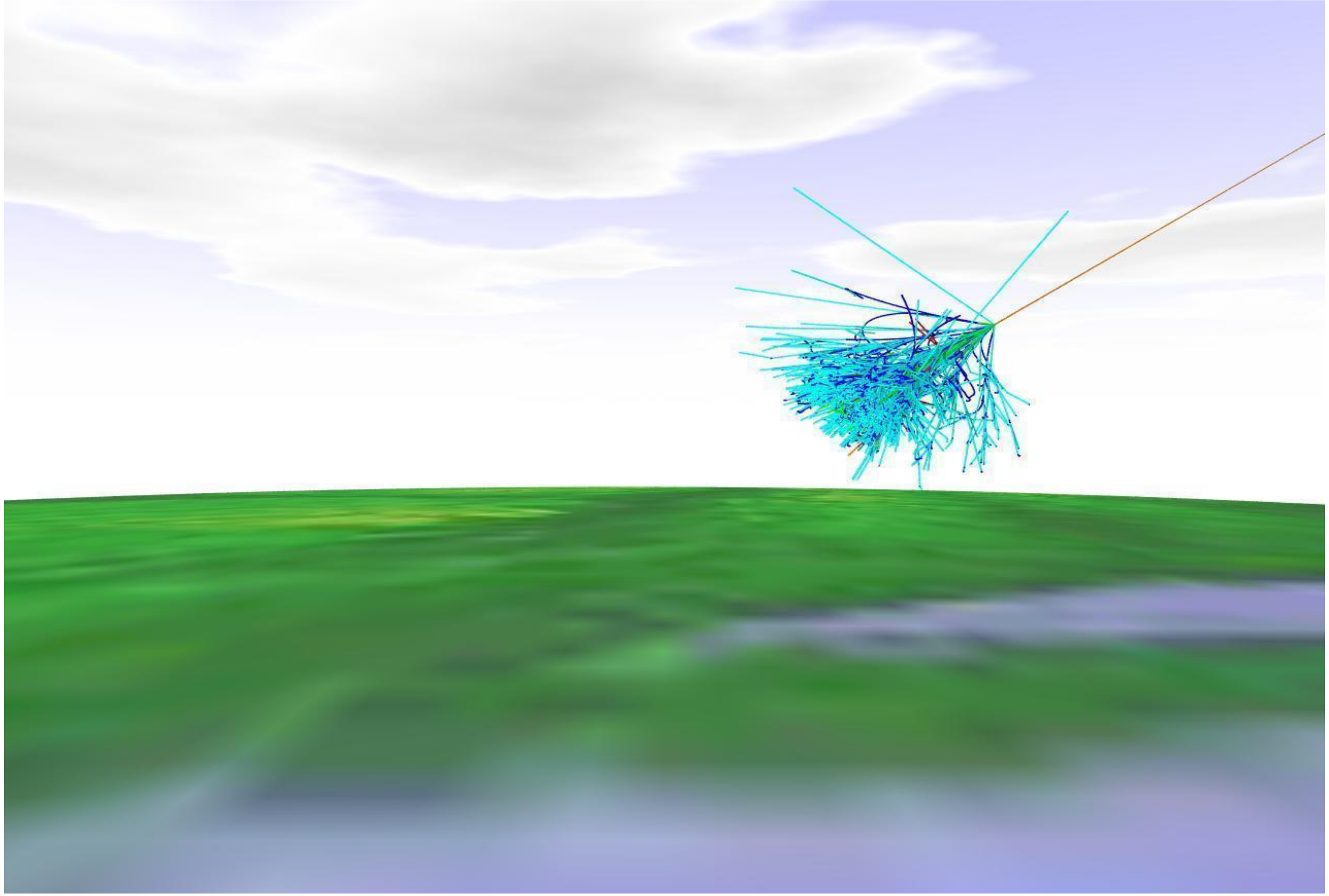

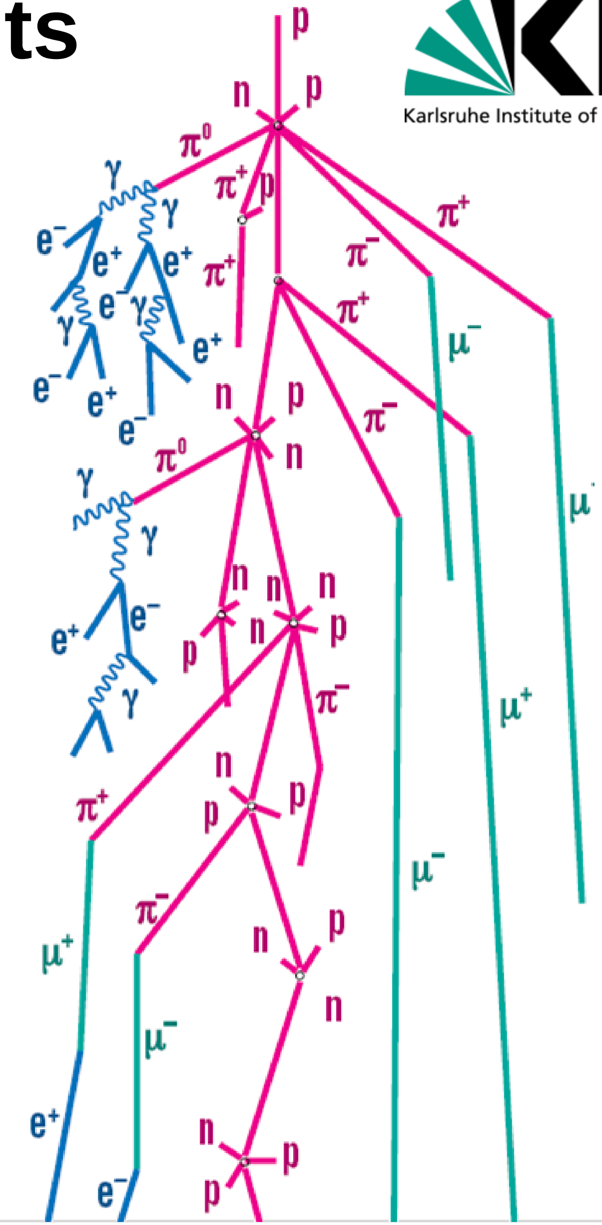

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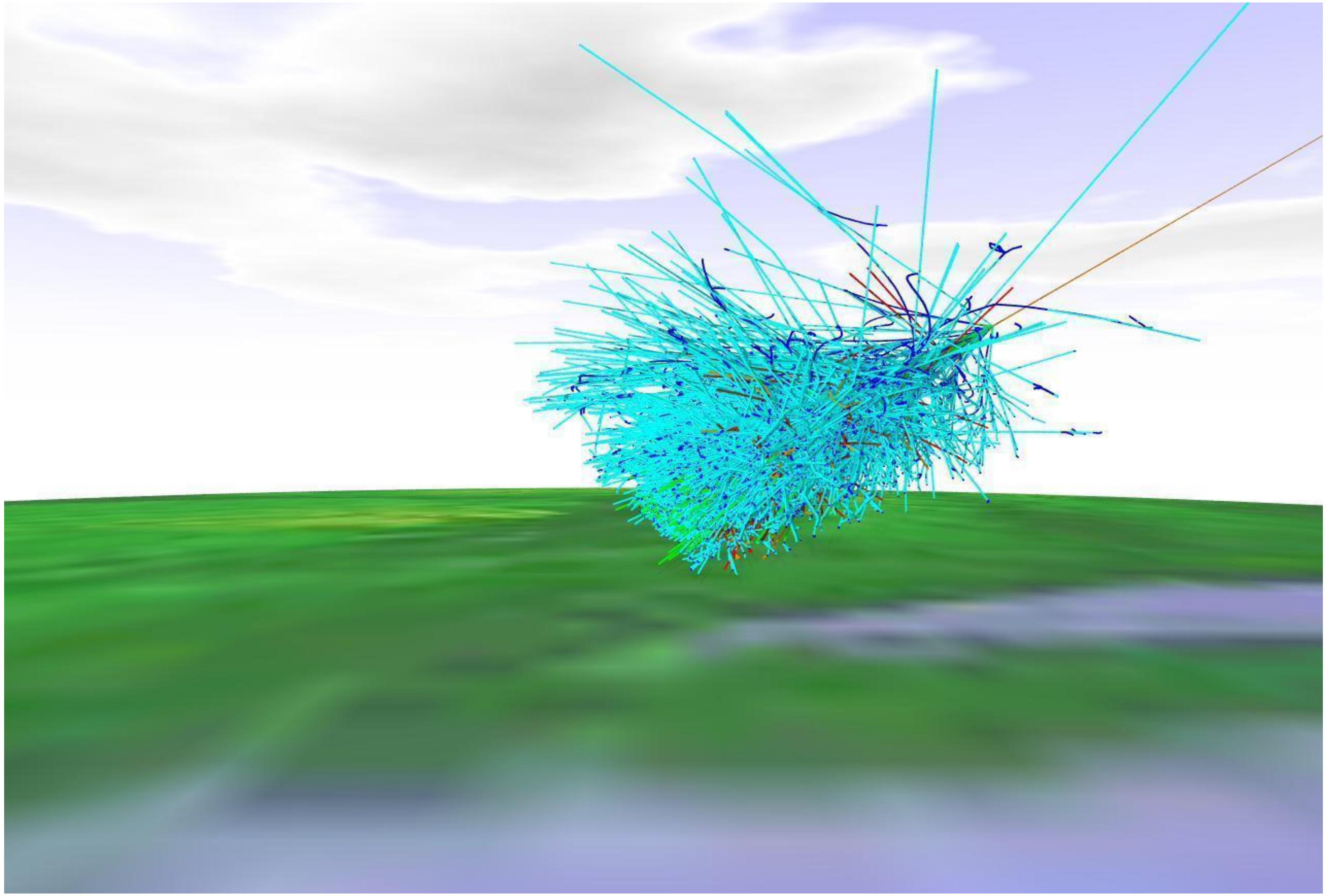
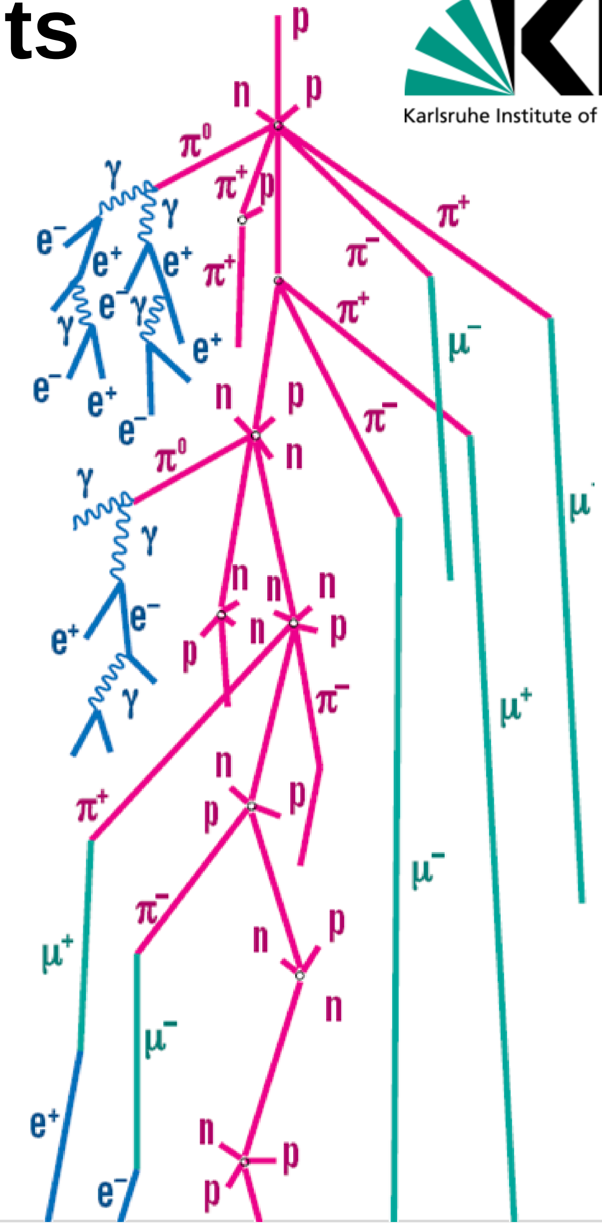
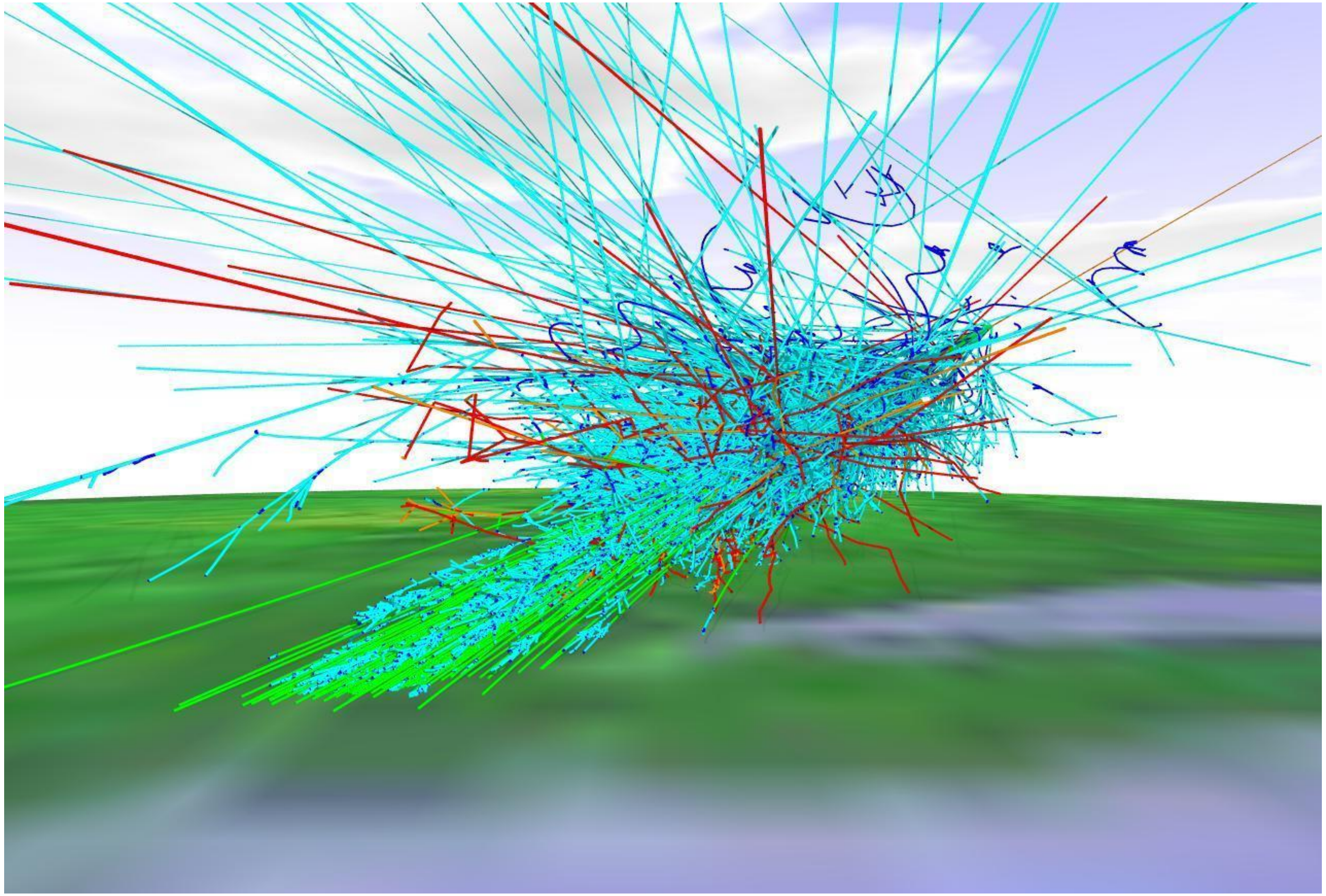
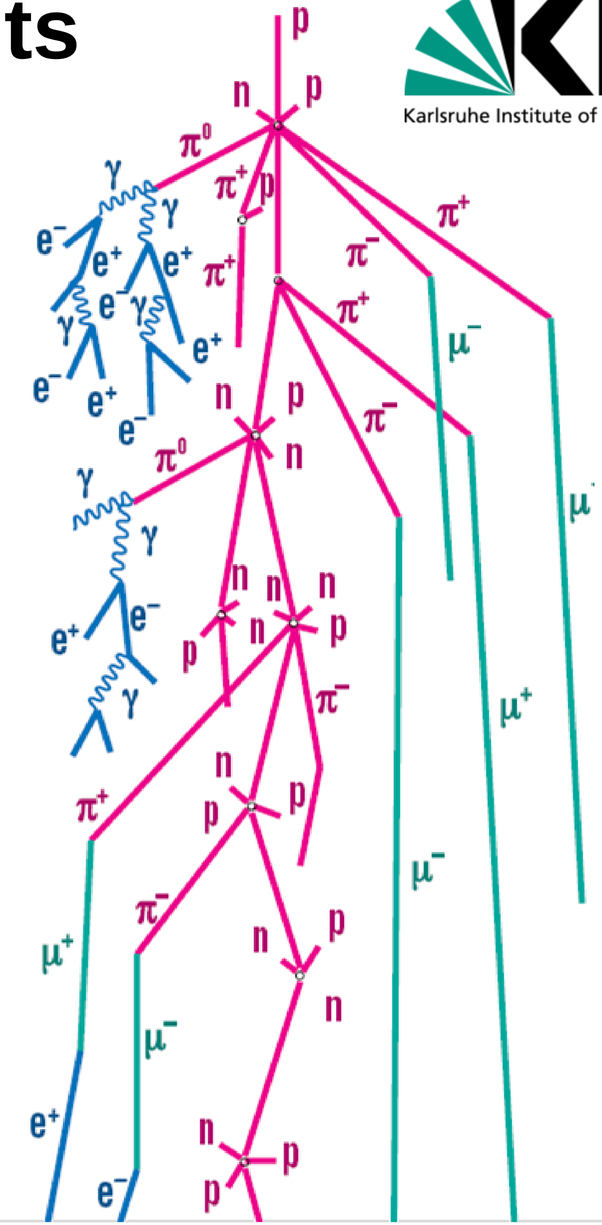




Simulation of air showers: all components





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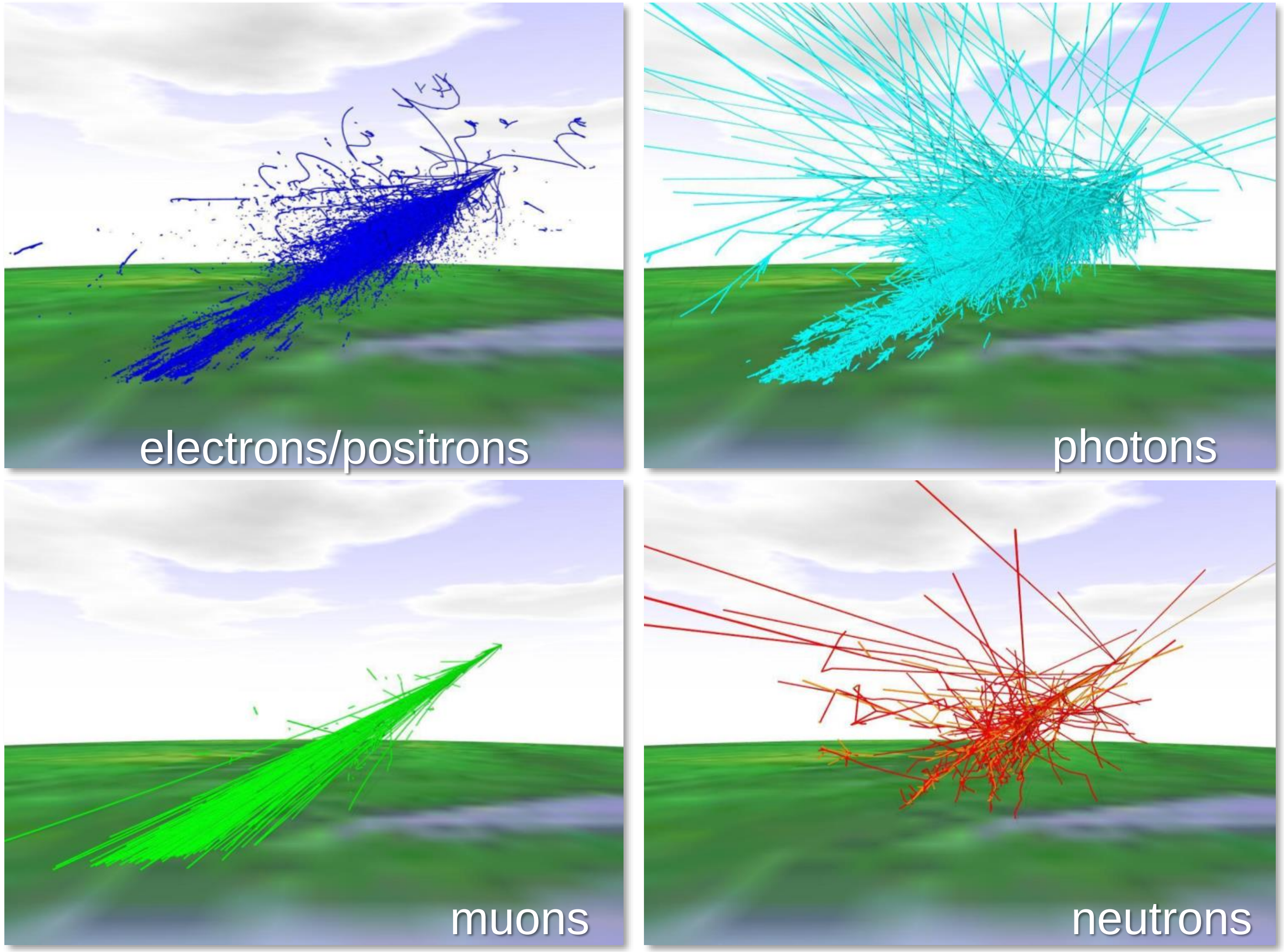
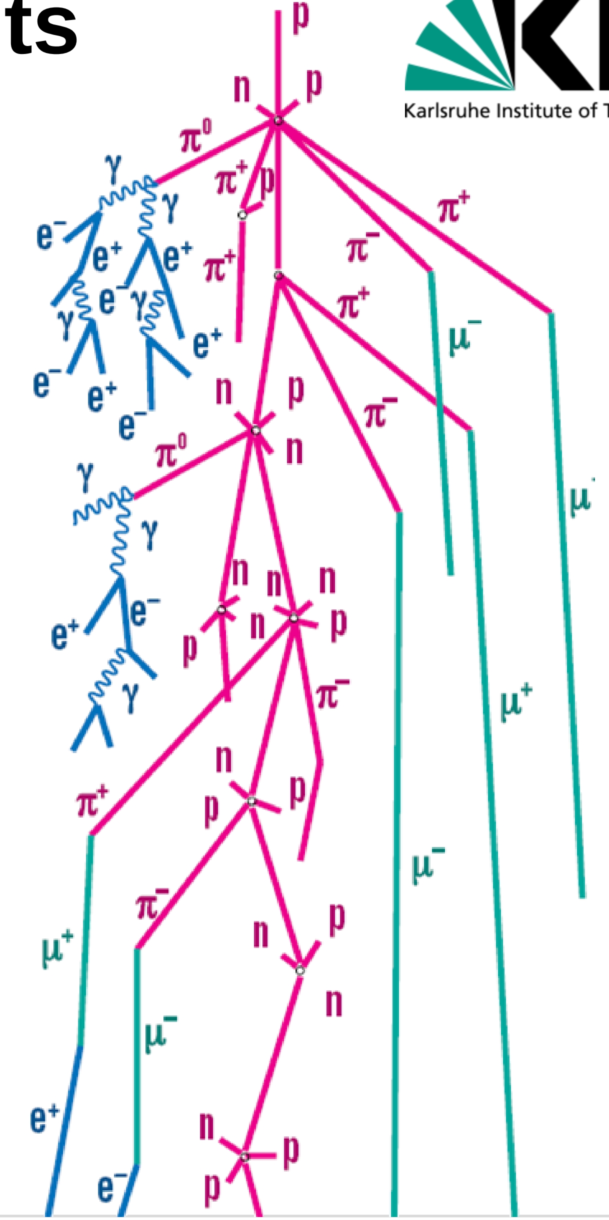
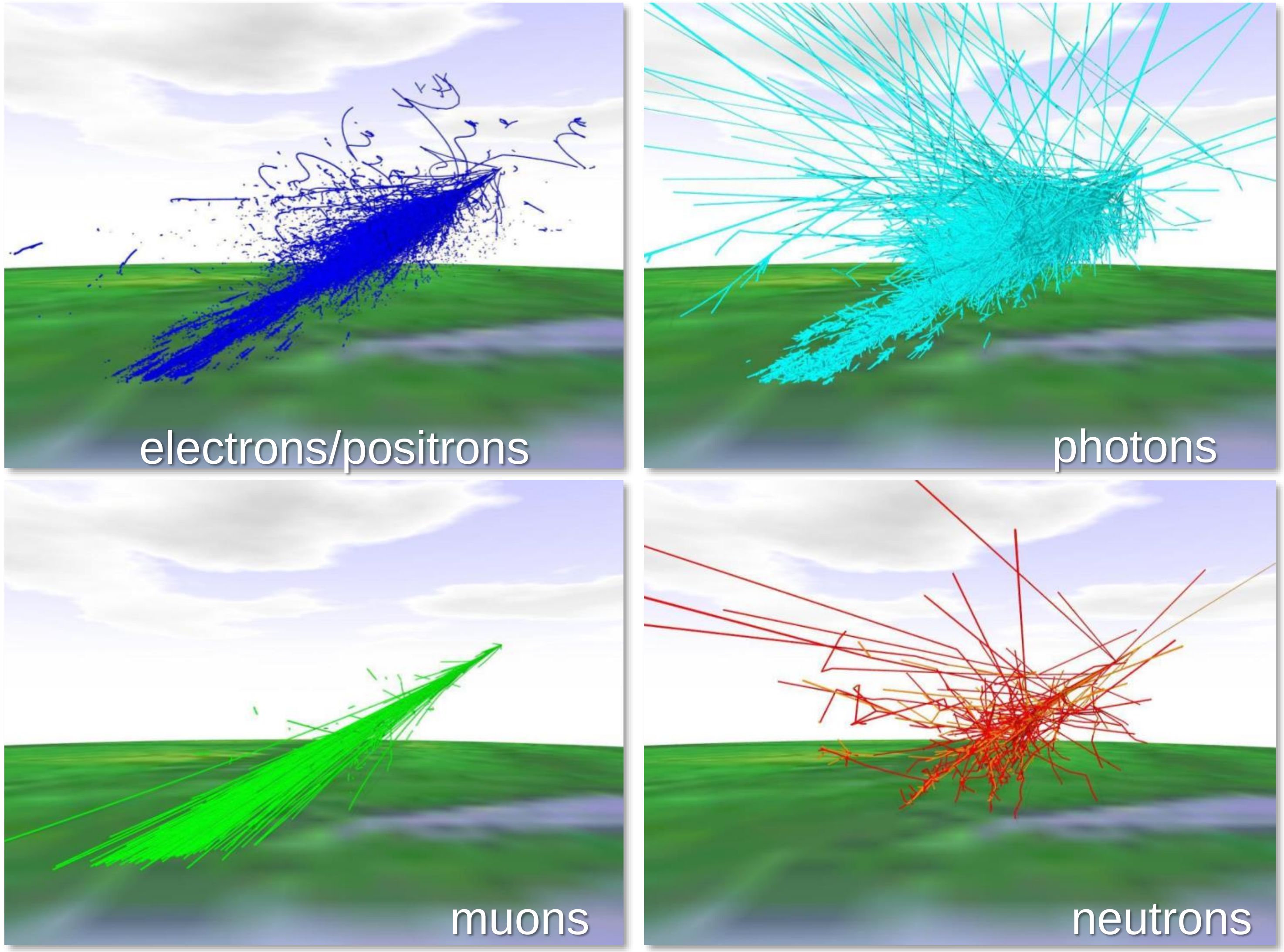
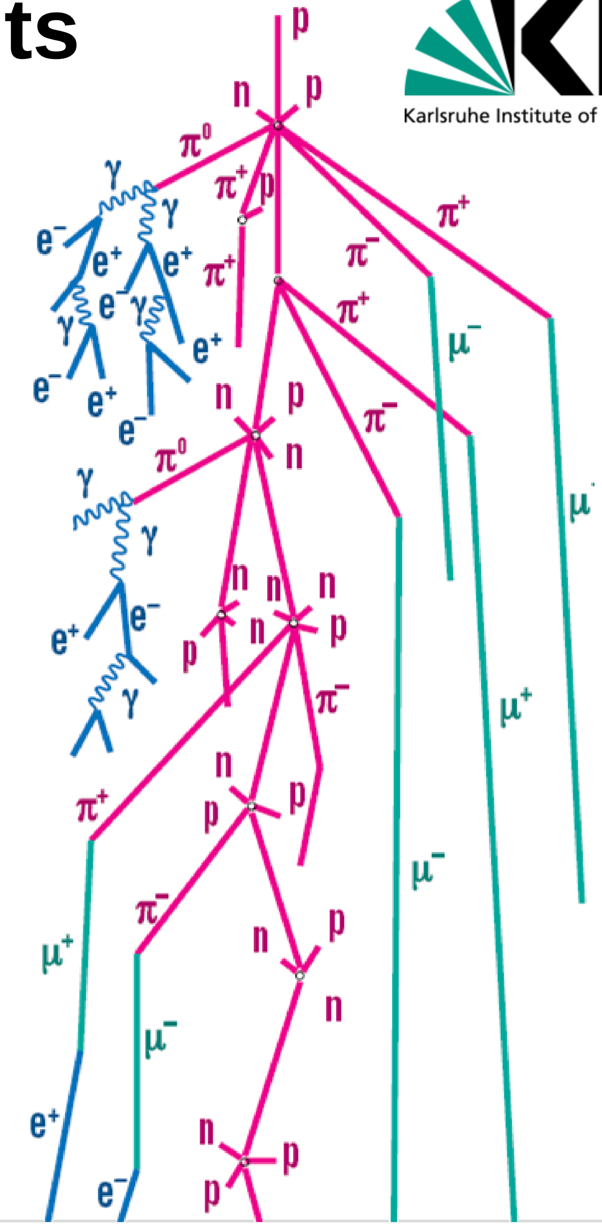




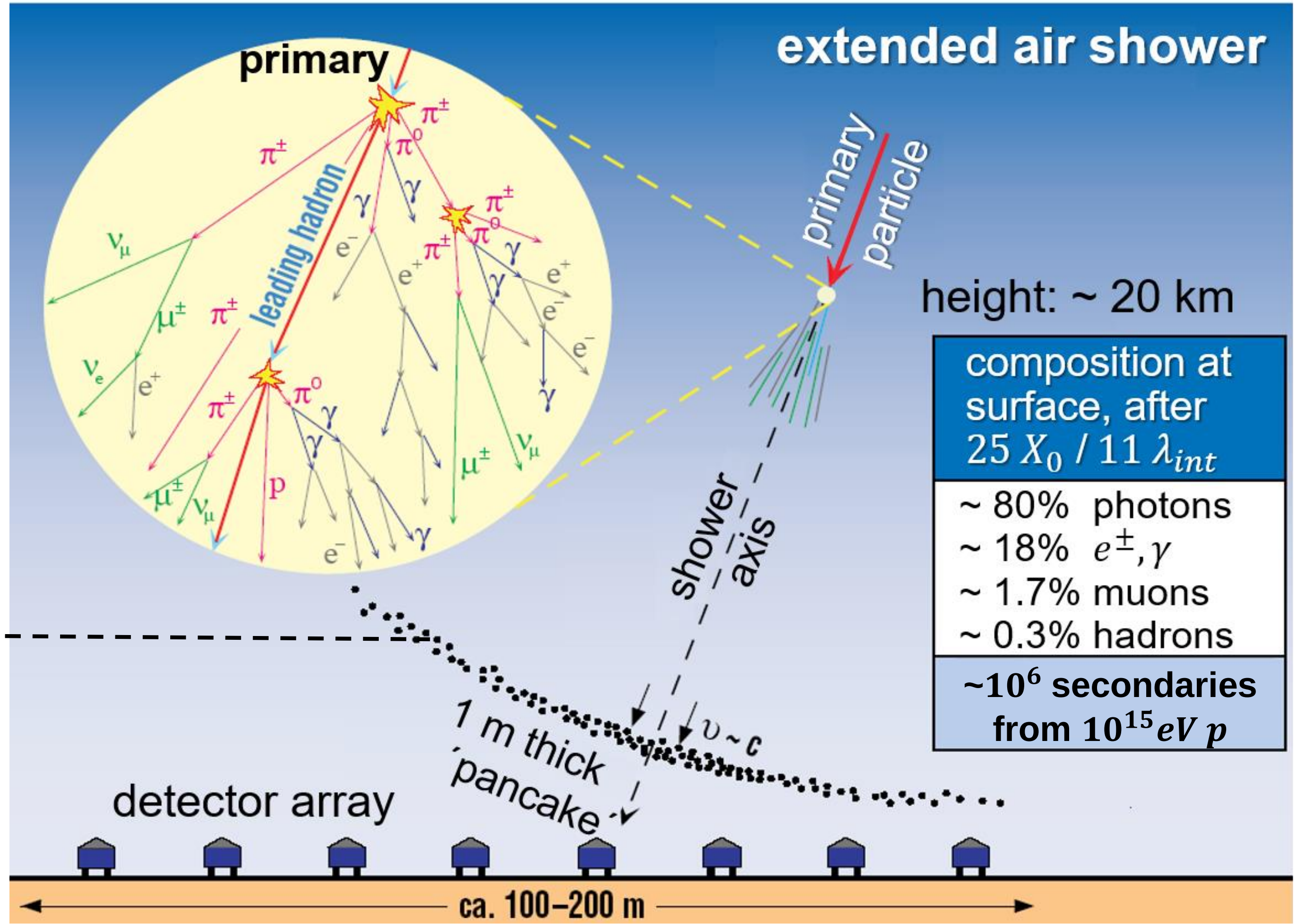
Simulation of air showers: all components





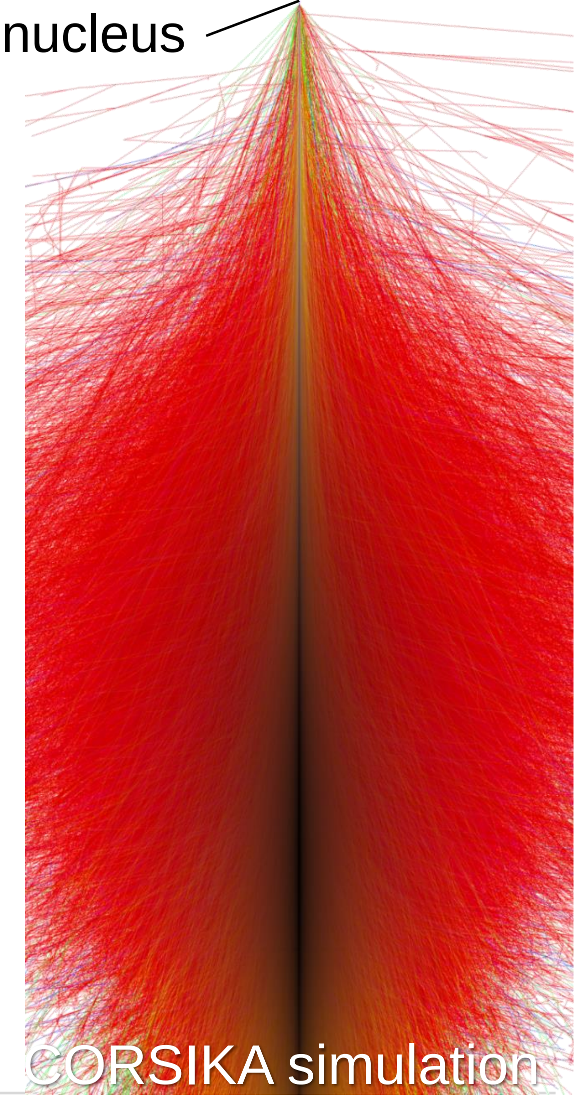
Features of an extended air shower

- **Earth´s atmosphere acts as calorimeter for primary**



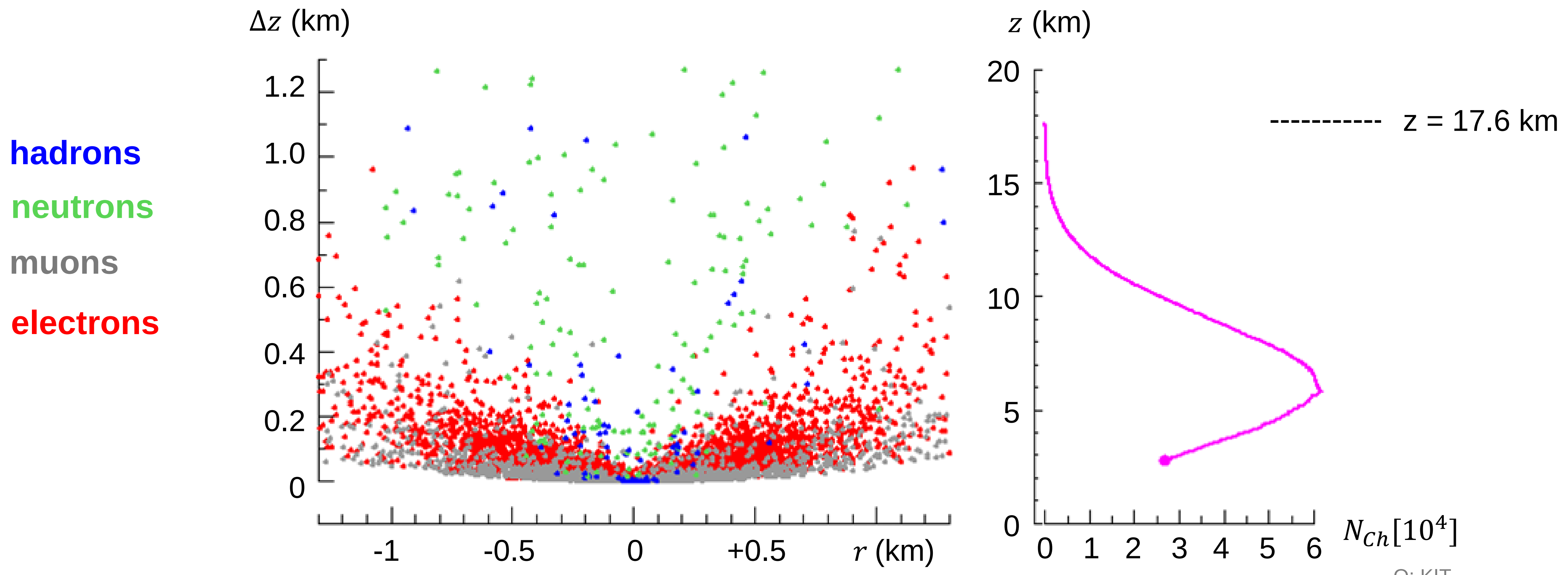
shower front

10^{15} eV
Fe nucleus



Extended air showers – time development

- Longitudinal air shower profile = shower particles as function of height z



Q: KIT

Shower parameters: extracting primary energy E_0

■ **Lateral distribution of air showers = the ´footprint´ at the surface, which allows to determine energy E_0**

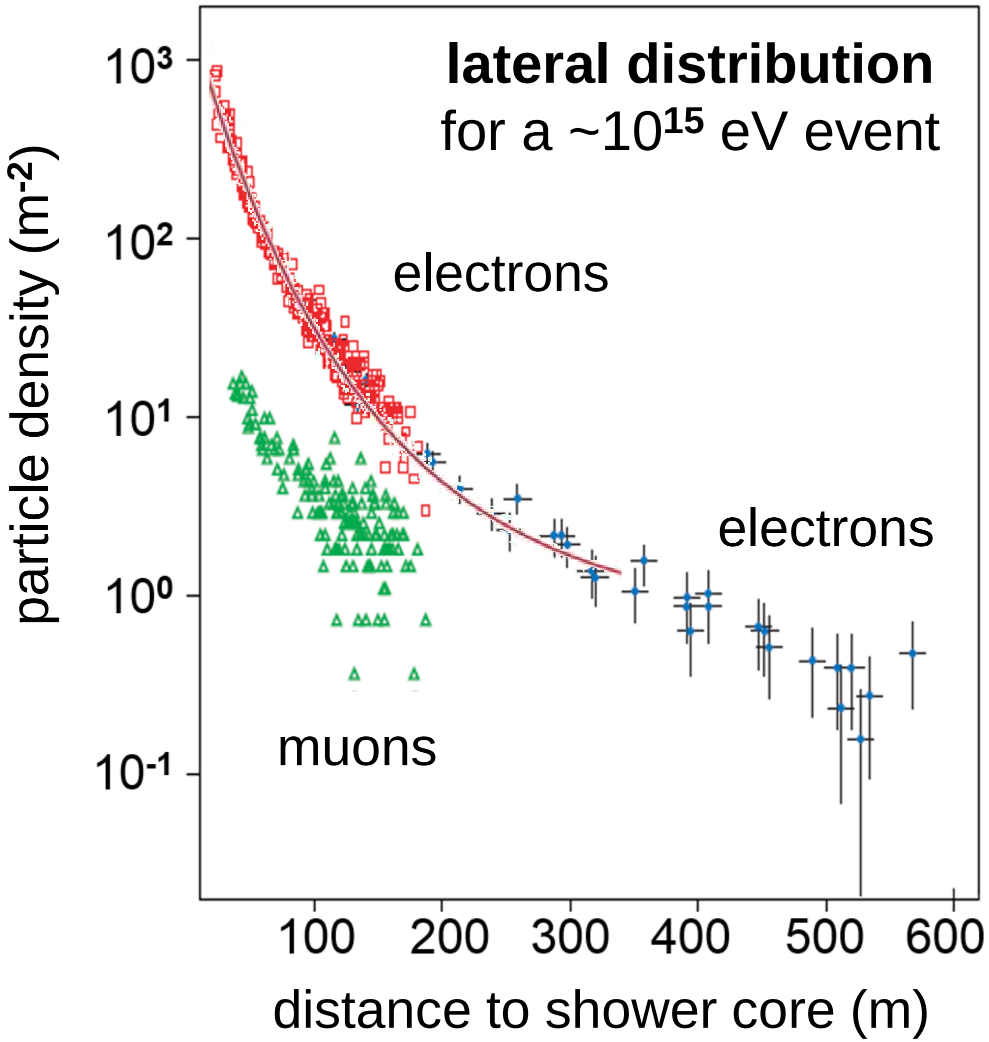
- extraction of E_0 **via**

  N_e = number of electrons ⎫ in the shower
  N_μ = number of muons ⎭

  via integration of lateral distribution $\rho(r)$

- analytical parameterisation of $\rho(r)$ via a so-call **Greisen**-fit*

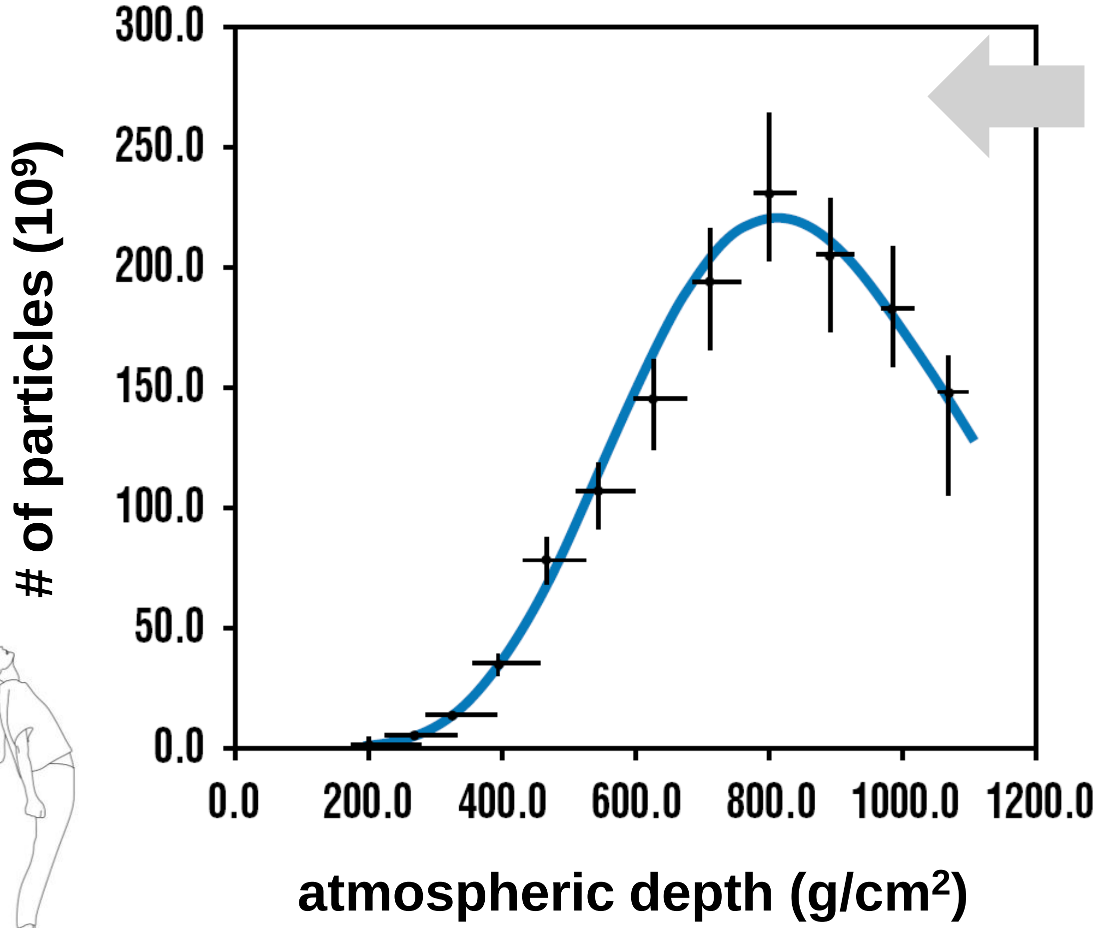

Kenneth Greisen

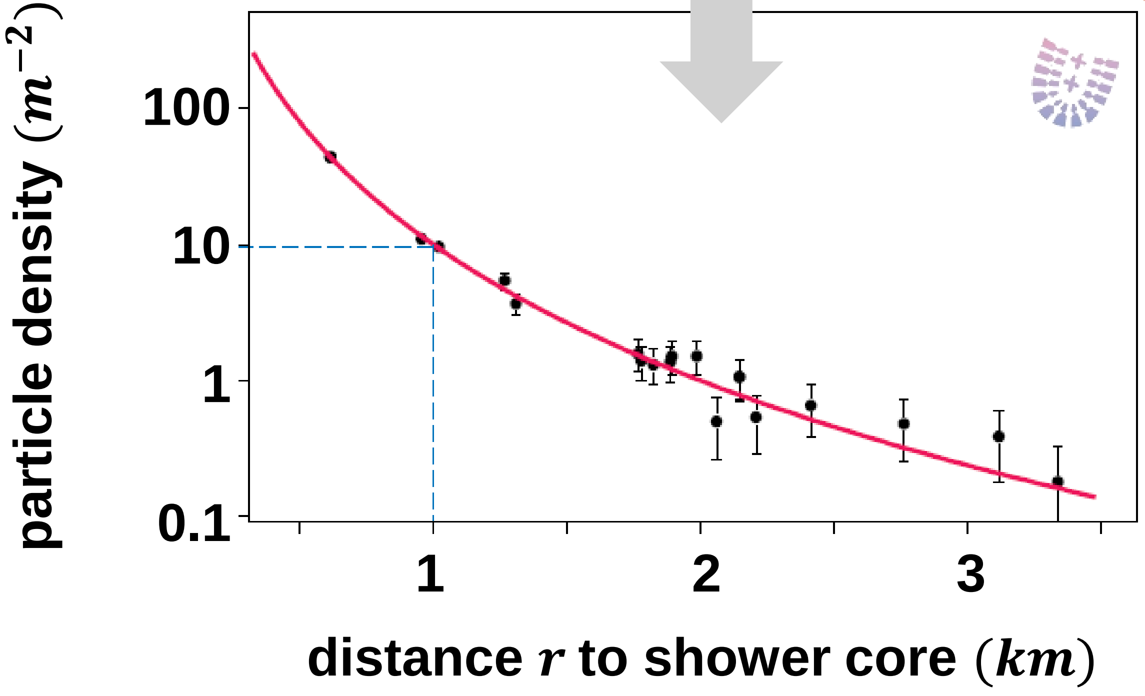


(*details in ATP-2 ´cosmic rays´)

Combining lateral $\rho(r)$ with longitudinal profile

- Reconstructing two key shower parameters: primary energy E_0 & mass A

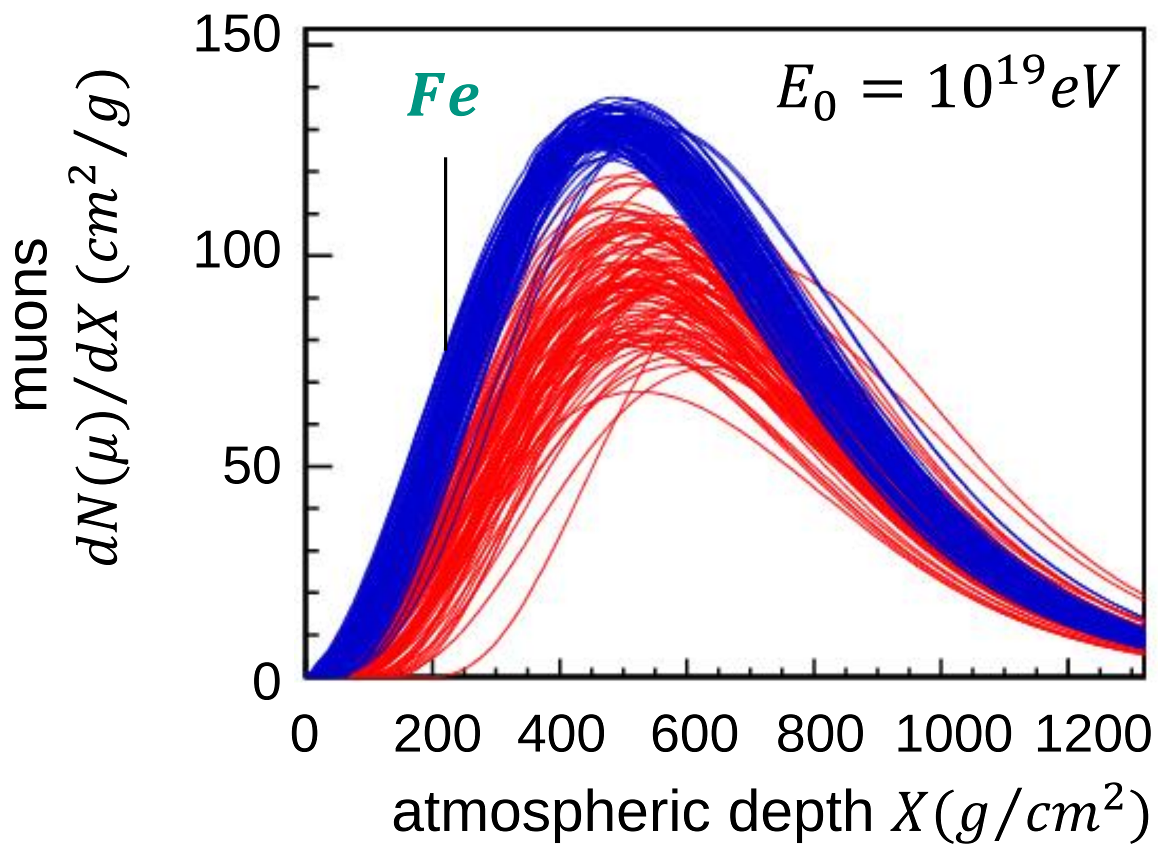




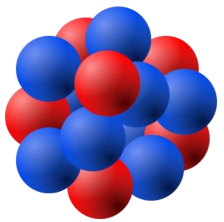
Air showers: determining the primary mass A

- **Method 1: longitudinal distributions – example nucleus Fe vs. proton p**

  - longitudinal profiles allow to discriminate heavy nuclei from light ones & protons



heavy nuclei ($^{56}_{26}Fe$):



- extended size of Coulomb fields ($Z = 26$)

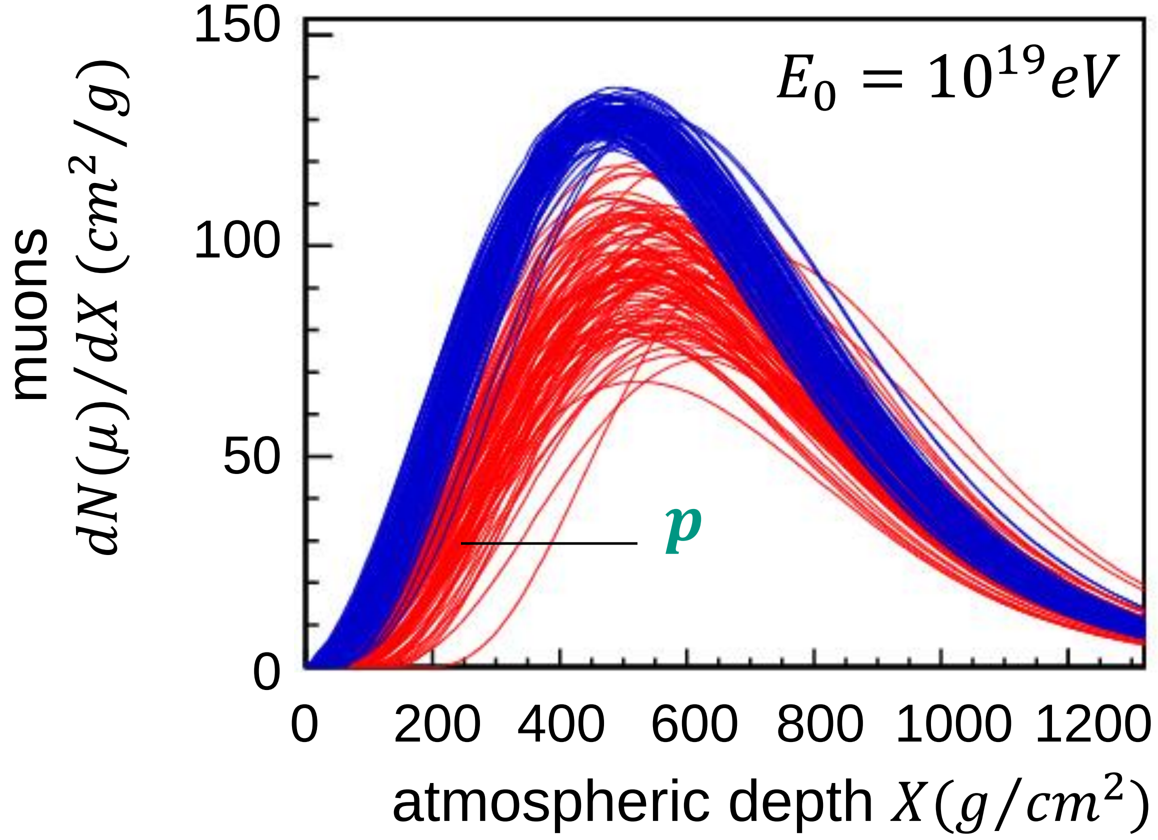
  ⇨ nuclei already interact in topmost atmospheric layers

  ⇨ **smaller X_{max}**

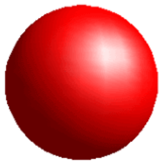
Air showers: determining the primary mass A

- **Method 1: longitudinal distributions – example nucleus Fe vs. proton p**

  - longitudinal profiles allow to discriminate heavy nuclei from light ones & protons



lightest nuclei (incl. p):



- smaller size of Coulomb fields ($Z = 1$, ...)

⇨ light nuclei penetrate to deeper atmospheric layers

⇨ **larger X_{max} & large fluctuations**

Air showers: determining the primary mass A

Karlsruhe Institute of Technology

- **Method 2: lateral distributions – heavy nuclei Fe vs. light ones (proton p)**

- surface measurements allow to determine the **ratio** N_e/N_μ:

electron number N_e – muon number N_μ

electrons (e):

- in general much more e than μ
- e have a short range in atmosphere
  ⇨ reach surface only from **larger X**

muons (μ):

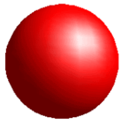
- in general much less μ than e
- μ have a large range in atmosphere
  ⇨ reach surface also from **smaller X**

Air showers: determining the primary mass A

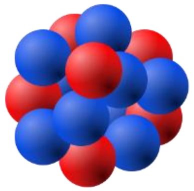
Karlsruhe Institute of Technology

- **Method 2: lateral distributions – heavy nuclei Fe vs. light ones (proton p)**

  - surface measurements allow to determine the **ratio N_e/N_μ**:



X_{max}: $N_e - N_\mu$ ratio



lightest nuclei (p):

- small nuclear charge ($Z = 1, \ldots$)

⇨ **larger X_{max} & large fluctuations**

⇨ **large ratio of N_e/N_μ**

heavy nuclei ($^{56}_{26}Fe$):

- large nuclear charge ($Z = 26$)

⇨ **smaller X_{max}**

⇨ **small ratio of N_e/N_μ**

CR – detector technologies

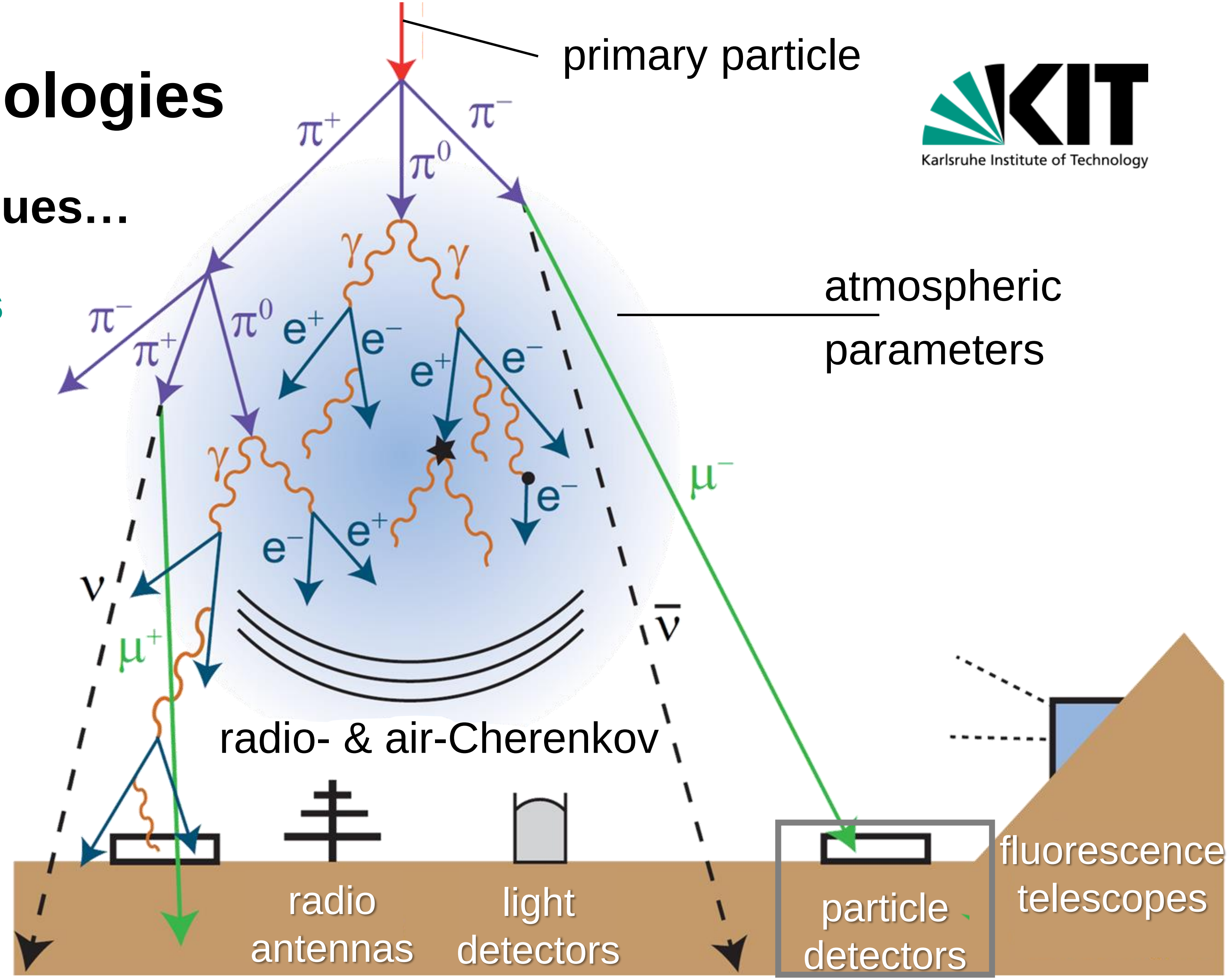
- **A wide range of techniques…**

longitudinal distributions

- telescopes for
  - fluorescence light
  - Cherenkov light
- radio antennas

lateral distributions

- scintillators
- MWPC*
- water Cherenkov



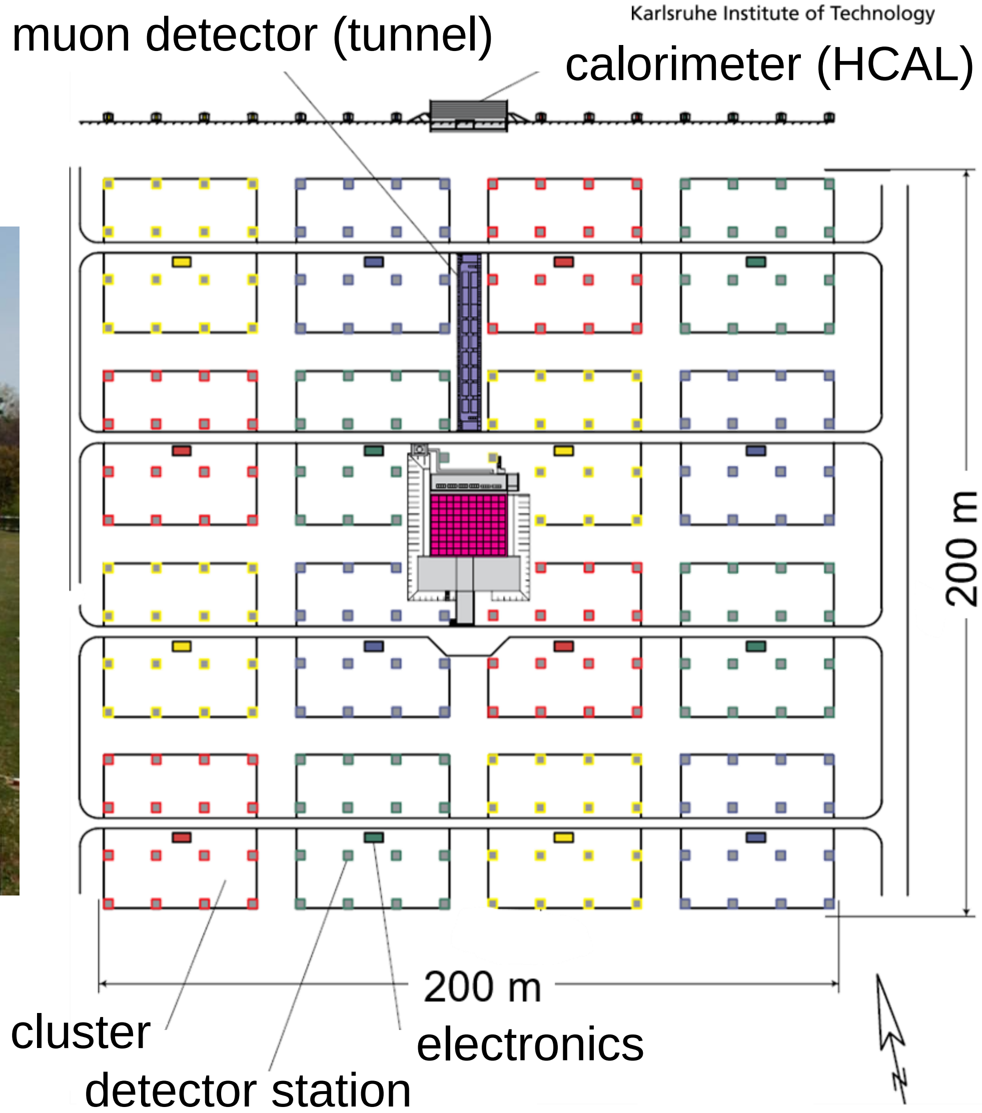
*Multi-Wire Proportional Chamber

KASCADE experiment at KIT

- **KASCADE** - **KA**rlsruhe **S**hower **C**ore and **A**rray **DE**tector (1996-2009)

total area: $A \sim 200 \times 200\ m^2$

coverage: $\varepsilon \sim 2$ % of total area



KASCADE experiment at KIT

- **KASCADE** – three main components

Array:

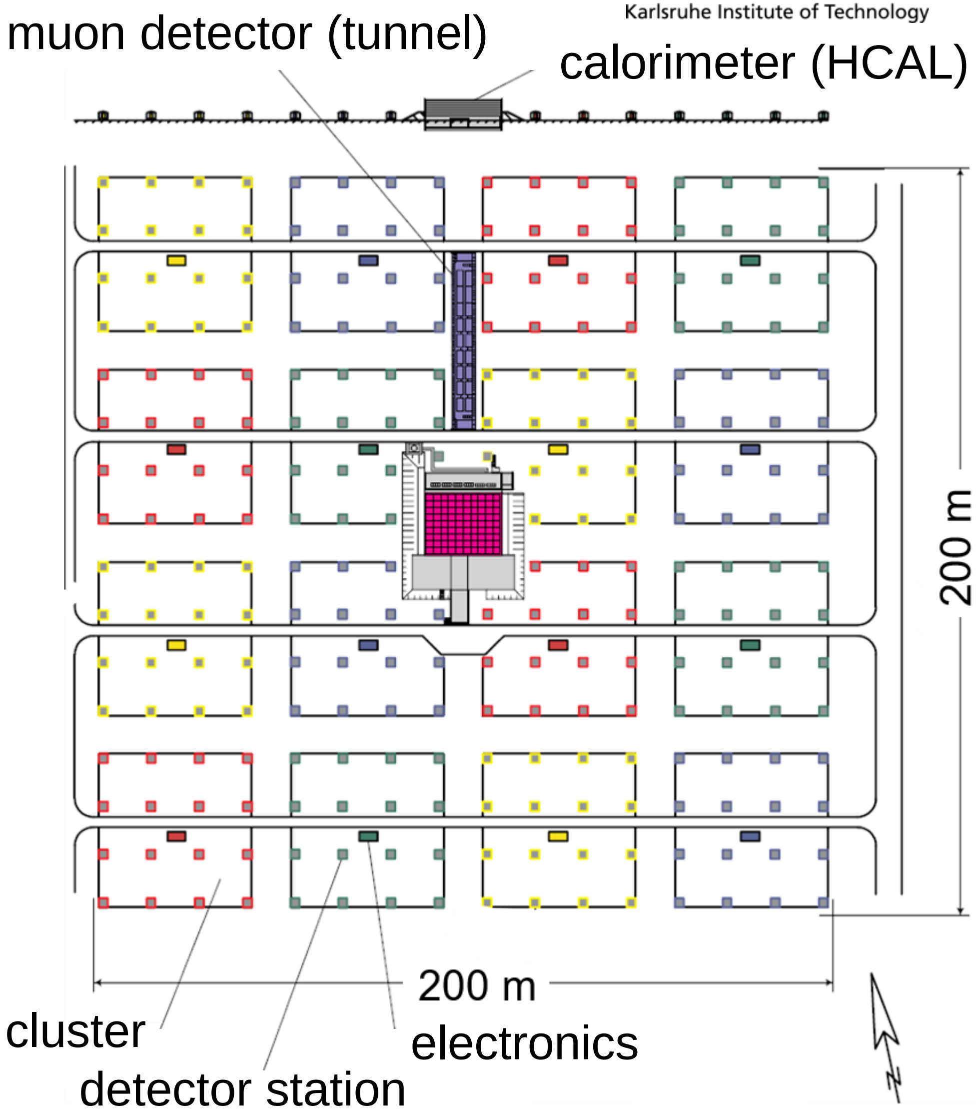
16 × 16 detector stations
detectors for muons / electrons
trigger electronics for entire shower

central calorimeter (HCAL):

TMS* ionisation chambers
⇨ detection of hadronic shower core

muon tunnel:

sampling of muon distribution



* **T**etra-**M**ethyl-**S**ilane

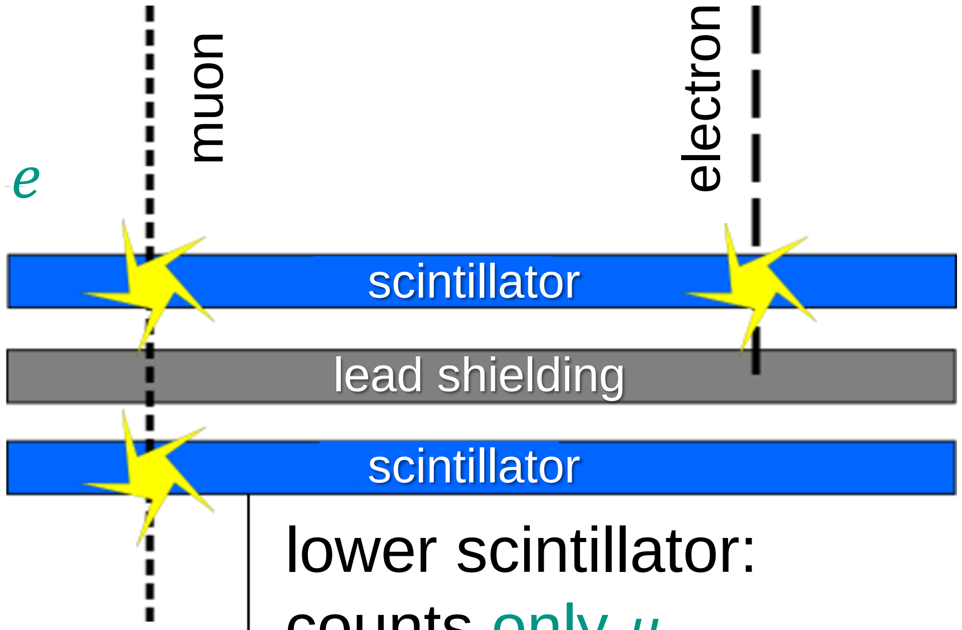
KASCADE experiment at KIT

- **The detector array to measure electron & muon distributions separately**

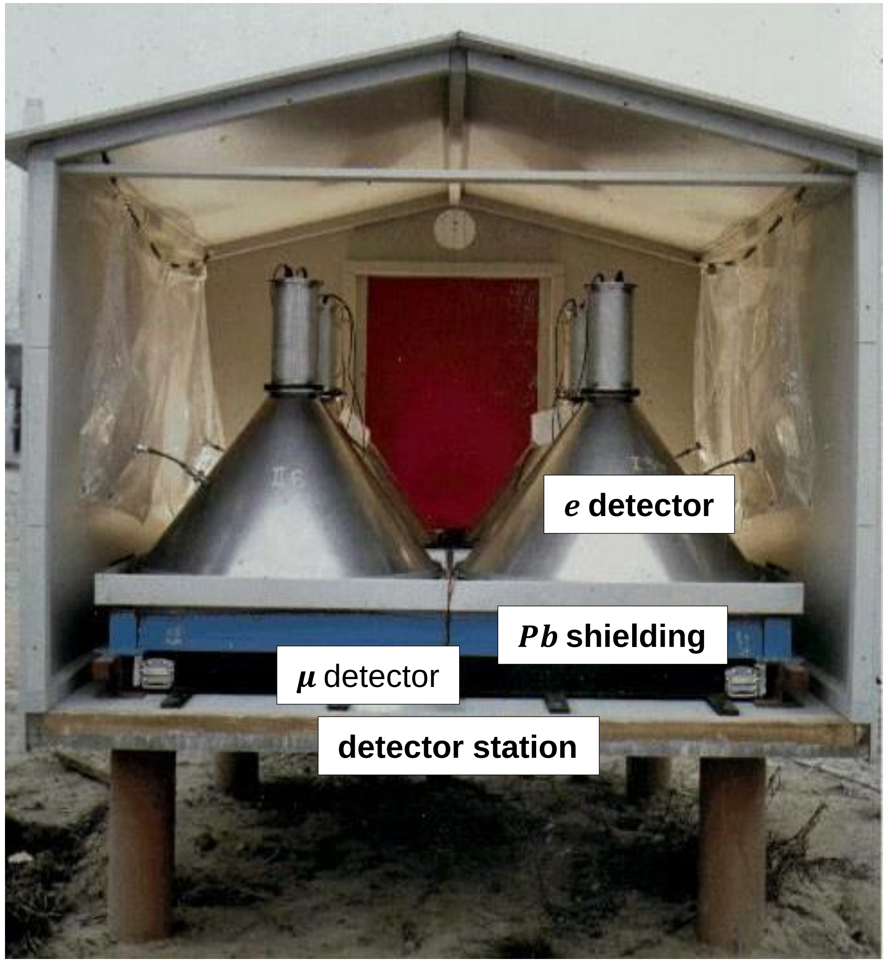
Muon number N_μ and **electron number N_e**:

- separate measurement via 2 scintillator layers with massive Pb – shielding in between

upper scintillator:
counts both μ and e

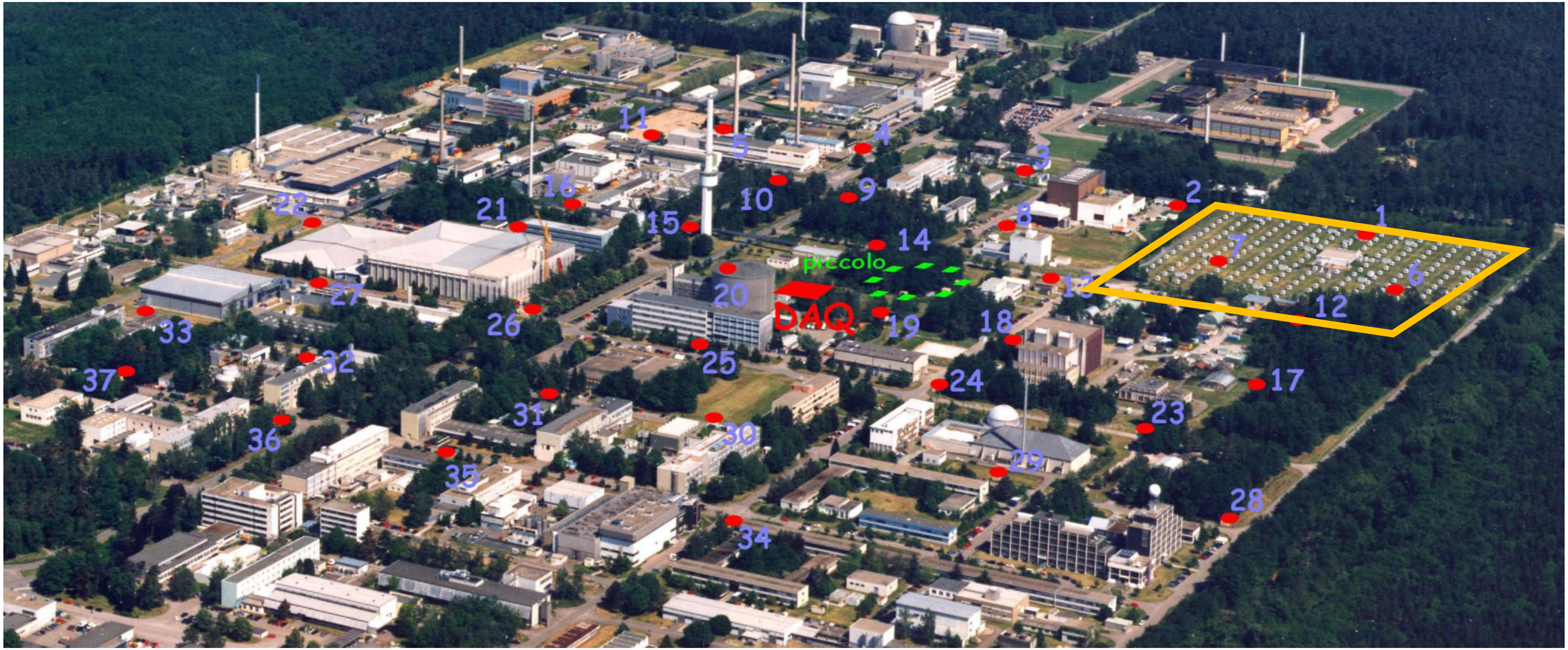


lower scintillator:
counts only μ



KASCADE – Grande experiment at KIT

- Extending the detector array to measure up to higher CR energies



Q: KIT

KASCADE – measuring mass A of primary nuclei

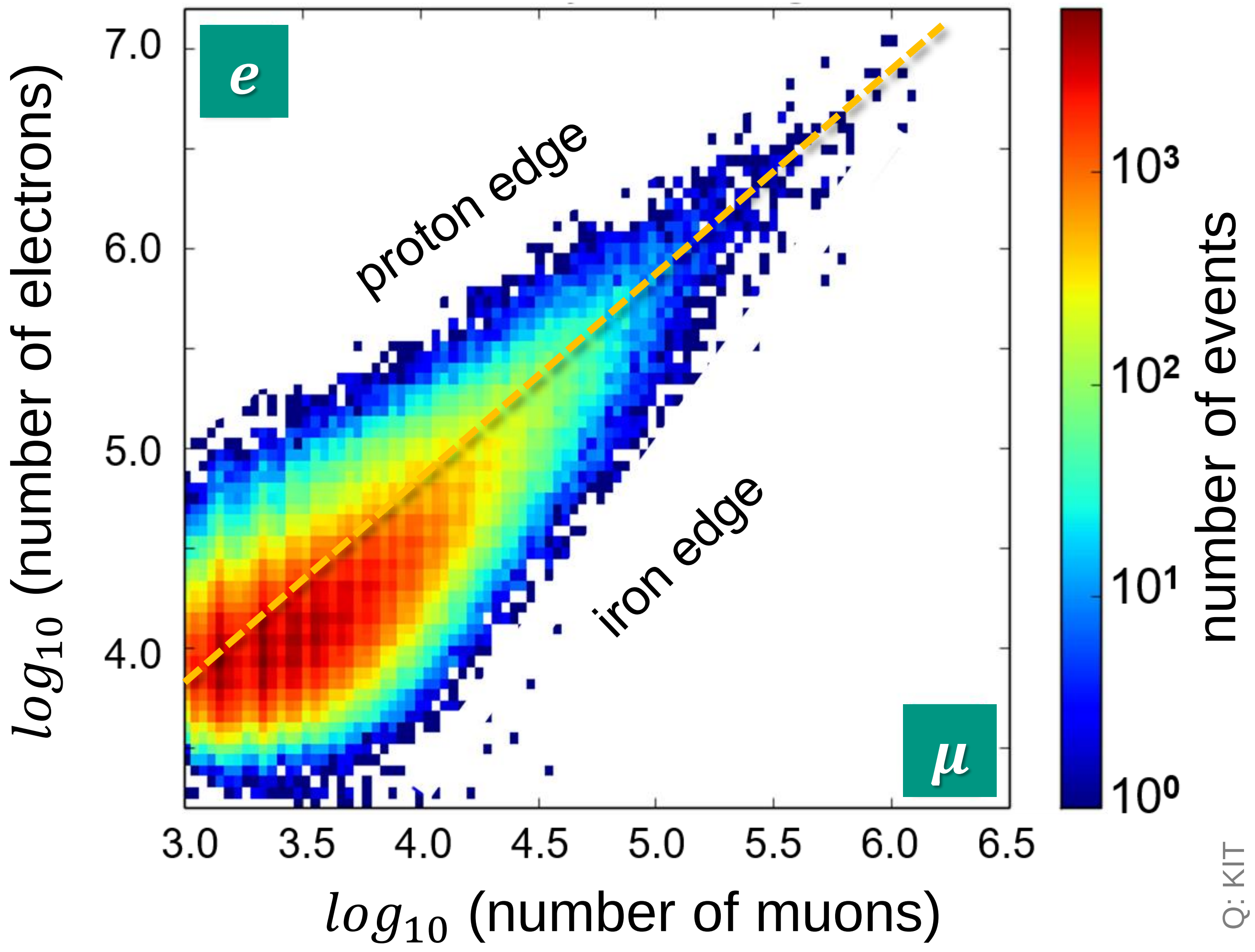
- **measuring N_e and N_μ: using sum $N_e + N_\mu$ & ratio N_e/N_μ**

- good correlation of N_e and N_μ
  ↳ **sum $N_e + N_\mu$ as indicator for primary energy E_0**

- light nuclei ($p, \alpha, {}^{12}C$):
  reactions start deep in atmosphere
  ↳ **ratio N_e/N_μ large: small A**

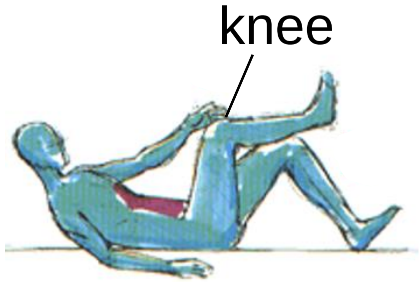
- heavy nuclei (${}^{56}Fe$):
  reactions start deep in atmosphere
  ↳ **ratio N_e/N_μ small: large A**

experimental distributions



KASCADE – experimental observations

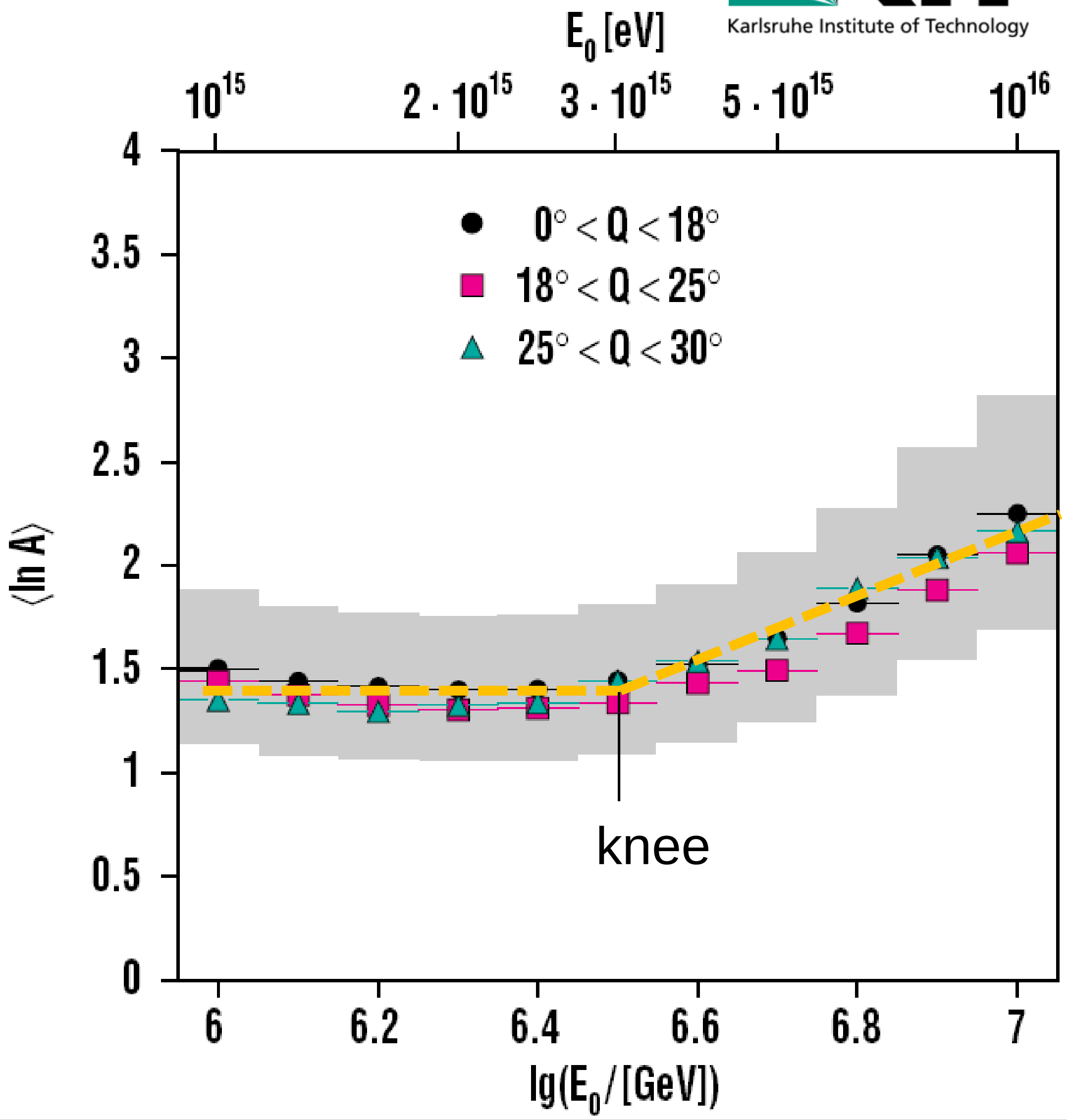
- **Chemical composition of CR changes as function of energy E_0**



- **knee**: a spectral feature at energies $E_0 \sim 3 - 4 \cdot 10^{15} eV$
- above the knee:

charged CRs get „heavier“

mean mass number $\langle A \rangle$ of primary increases with increasing energy E_0

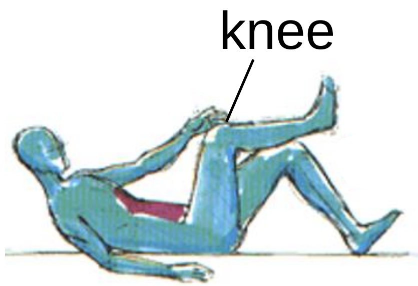


Q: KIT

KASCADE – experimtenal observations

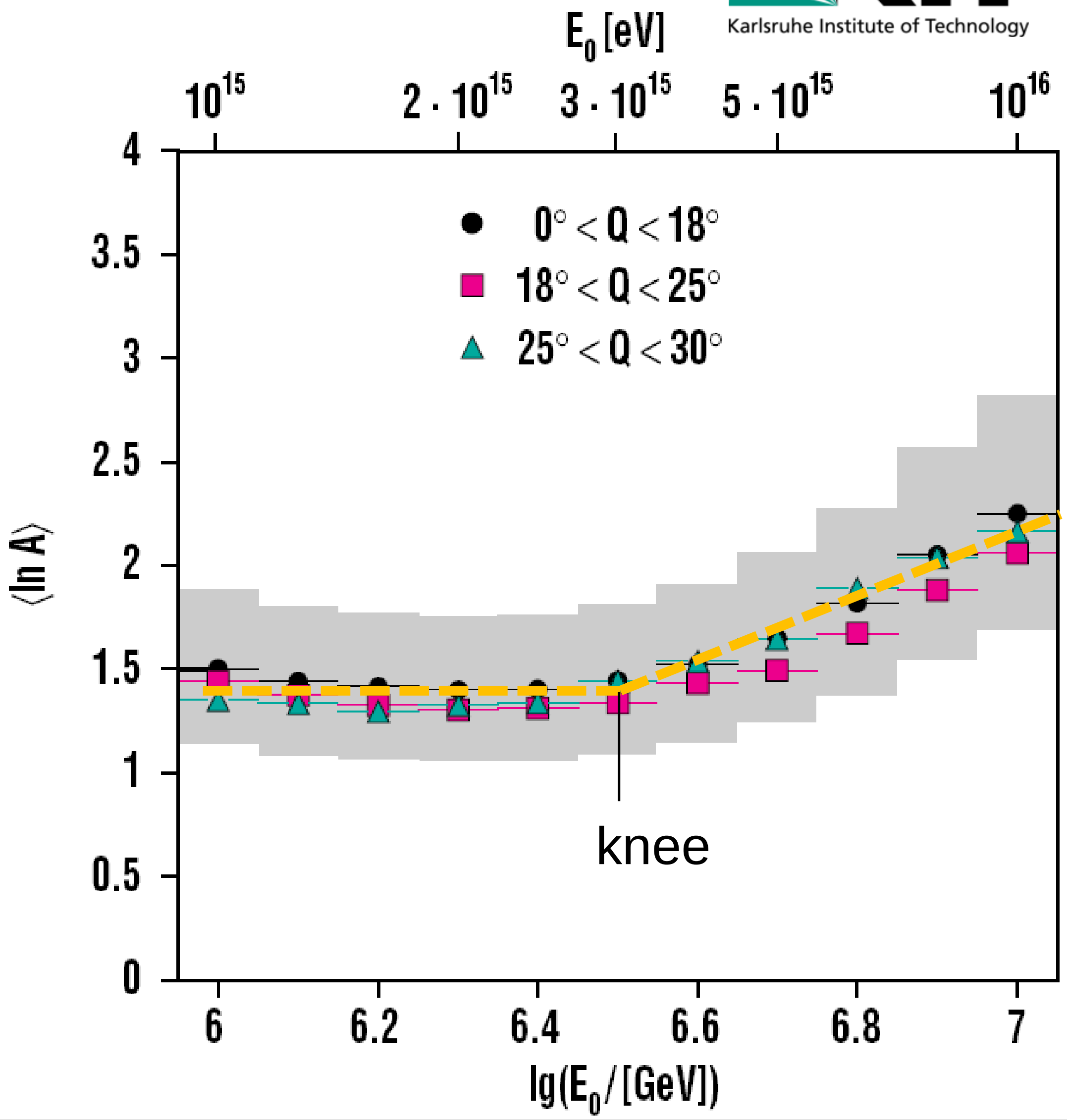
- **Chemical composition of CR changes as function of energy E_0**

  - 2 resulting questions as to the root cause of the knee:



  a) cosmic acclerators:
  do they reach the end of their ´accleration power´ for light nuclei?

  b) propagation effects:
  does the CR propagation in magnetic fields (of the galaxis) cause a loss of light nuclei from source to Earth?



Q: KIT

CR energy spectra – the knee

- **A distinct feature: change of spectral index & mass composition of CRs**

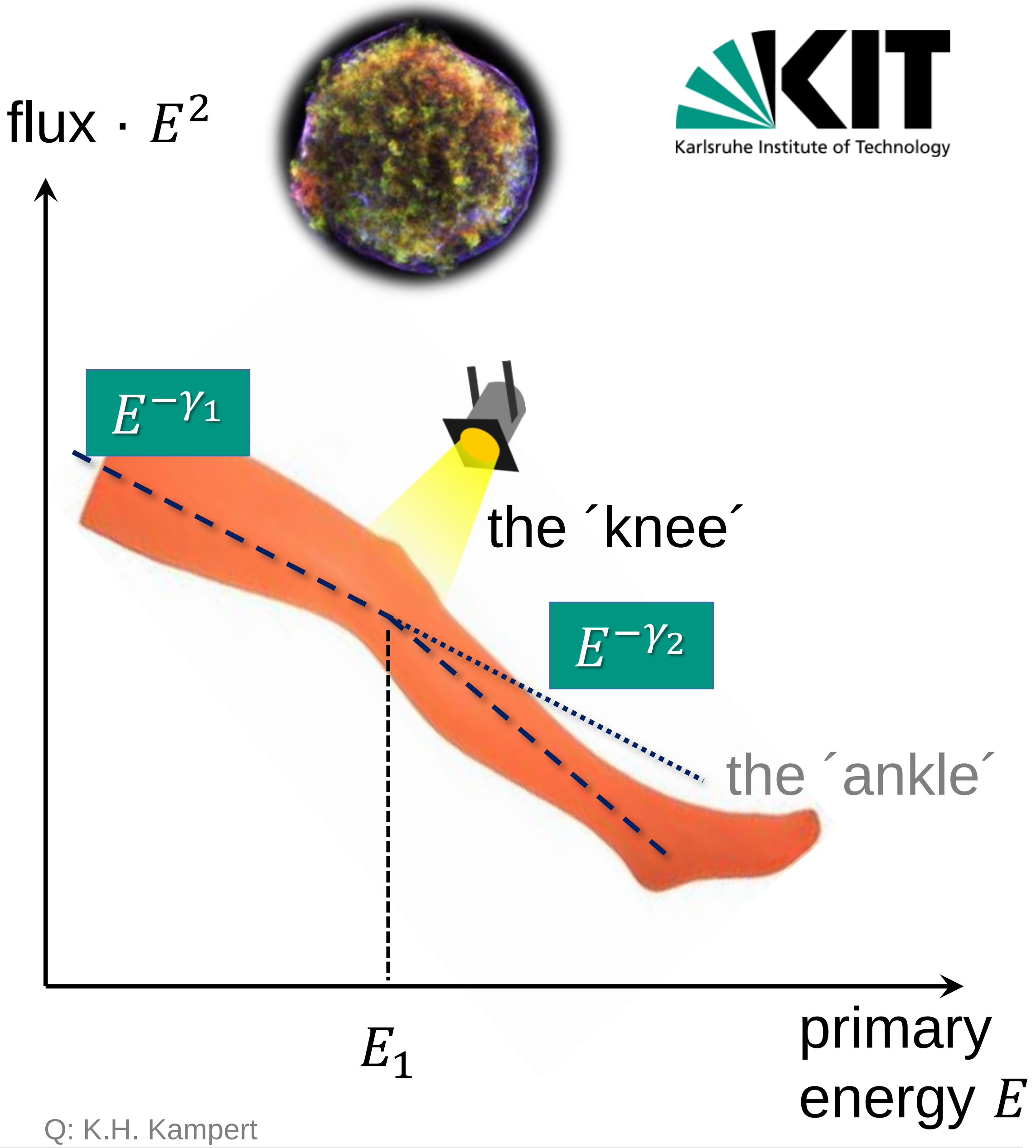
  - at characteristic energy E_1:

    - change of energy spectral index γ

    - change of mass composition:
      light (p) → heavy nuclei (^{56}Fe)

  - galactic CR acclerators = SN shocks
    → SNR reach their maximum energy E_0

  - the ´ankle´: change of accleration sites -
    galactic ⇔ extragalactic

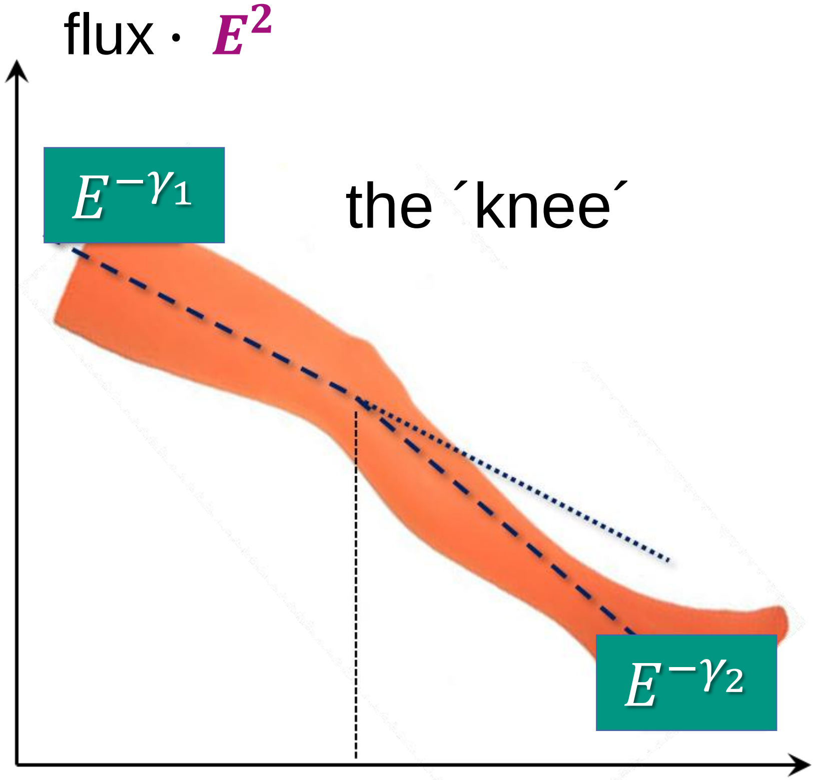


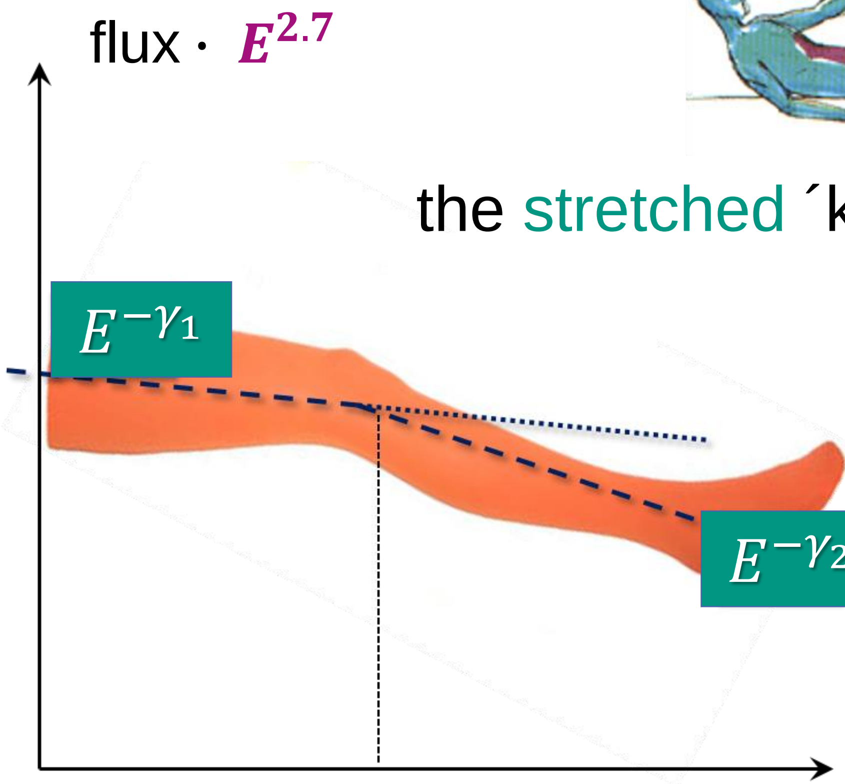
Q: K.H. Kampert

CR-energy spectra multiplied by energy factors

- **CR community routinely multiplies spectra with an energy factor $(E^2 \dots E^3)$**

energy factor $\sim E^{2\dots3}$



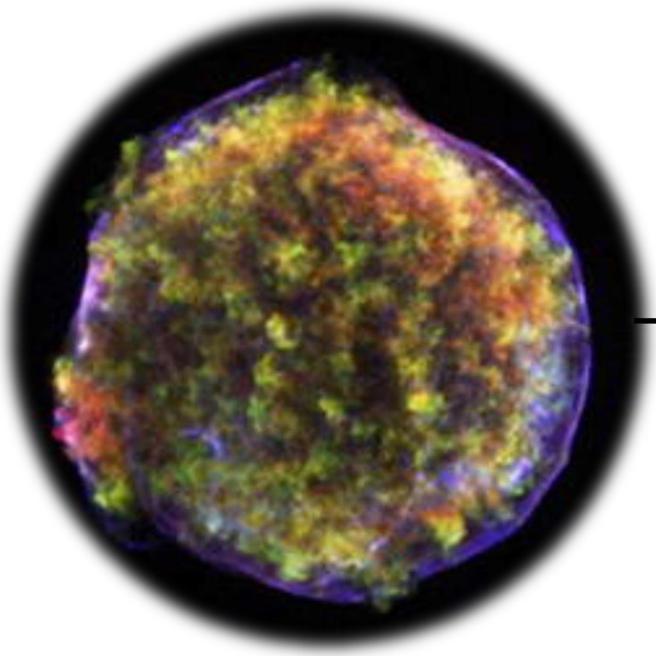


Q: K.H. Kampert

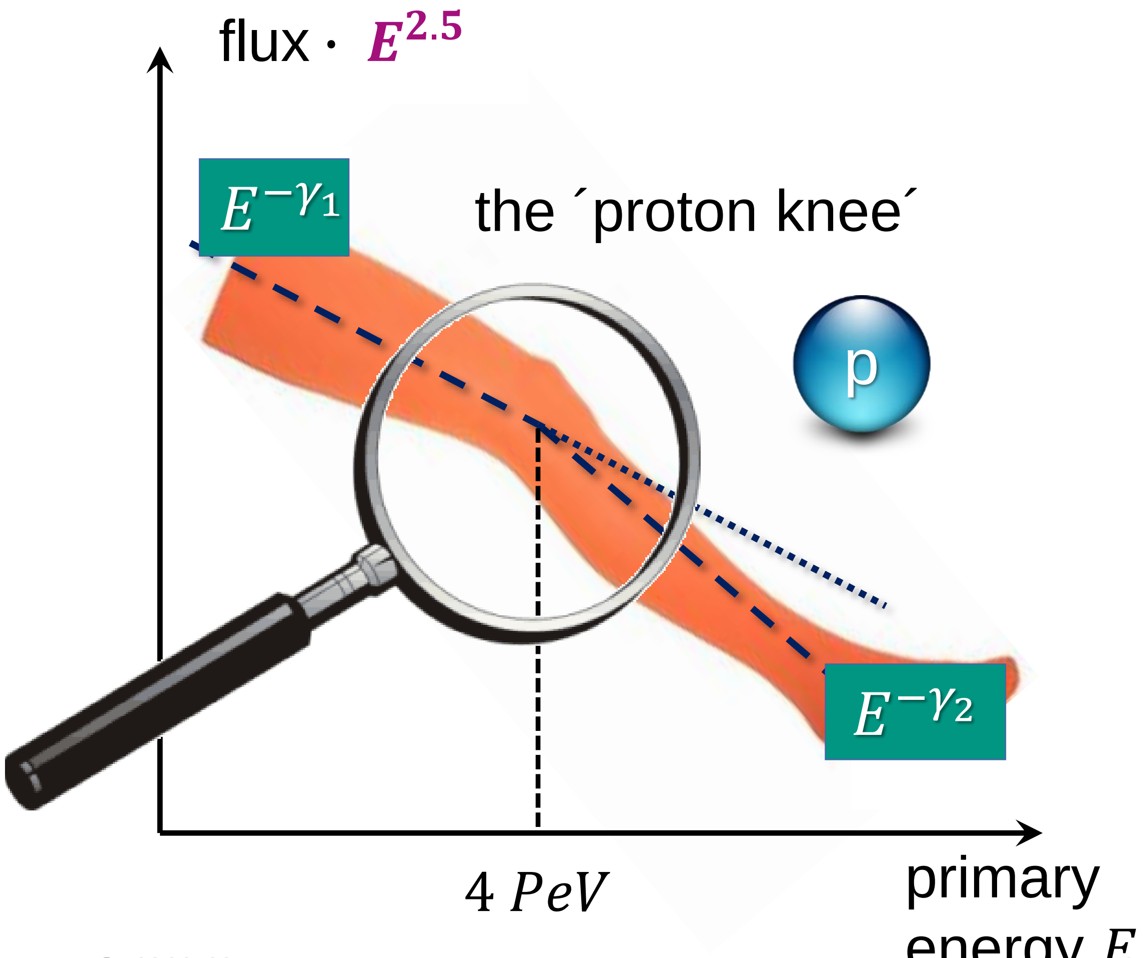
CR energy spectra – the p, Fe knee

- **One observes several ´knees´: from the p –knee up to the Fe –knee**

  - important: different nuclear charges



proton acceleration in SN-shock front



Q: K.H. Kampert

CR energy spectra – the p, Fe knee

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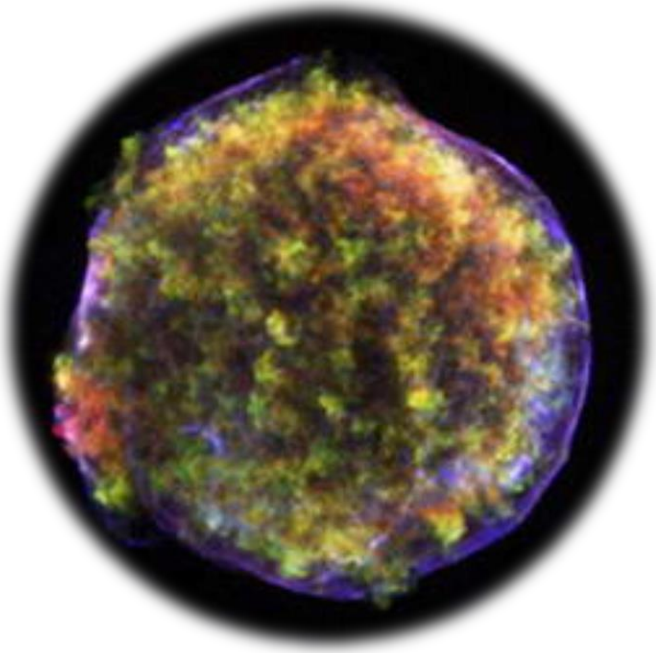
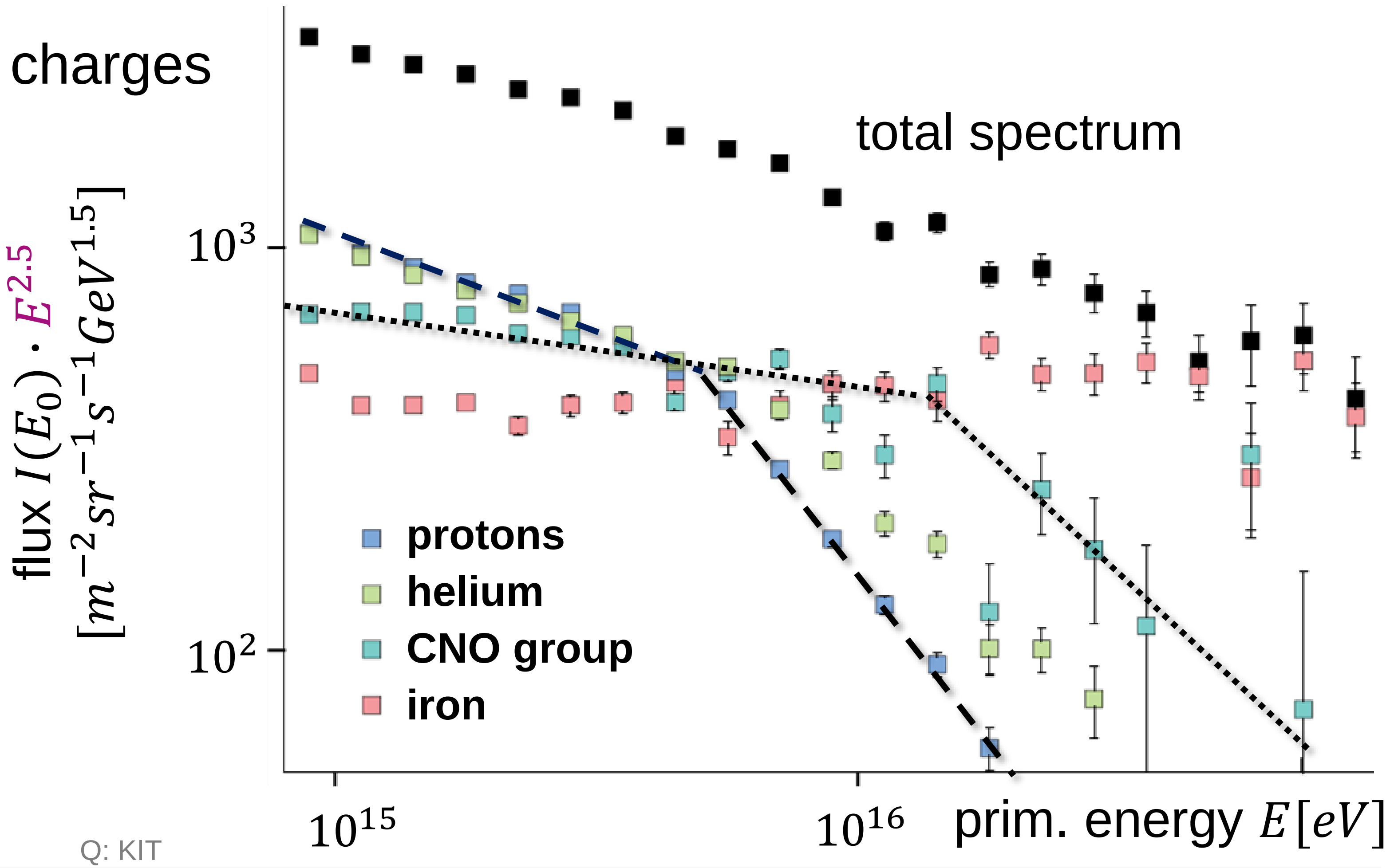


acceleration in SN-shock front



Q: KIT