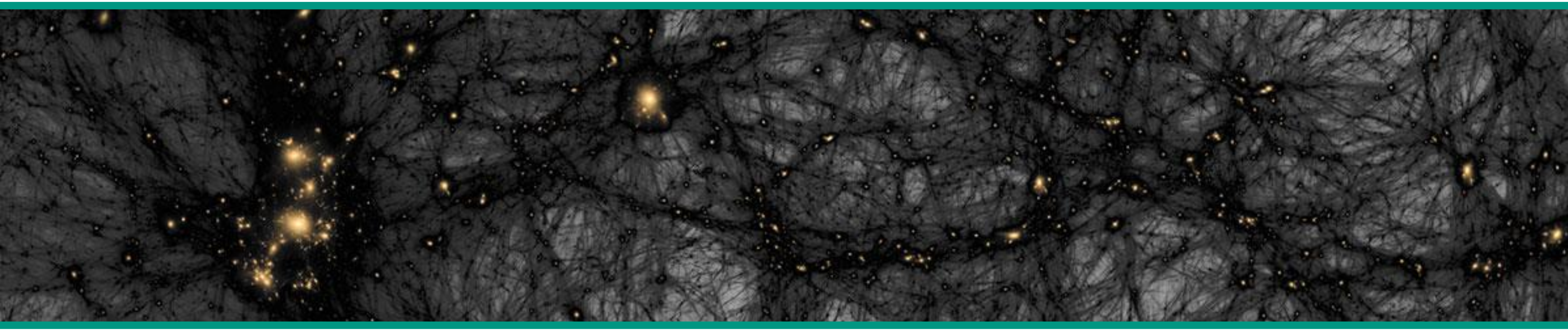
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 4 Nov. 8, 2023



Recap of Lecture 3

- **multi–messenger observations: all–sky maps in $\boldsymbol{CRs}$, gammas, $\boldsymbol{\nu' s}$ & $\boldsymbol{GW}$**

  - Mollweide projection with $\boldsymbol{GC}$ at the centre

  - sources of messengers: $\boldsymbol{SNR}$, $\boldsymbol{GRB}$, $\boldsymbol{AGN}$, pulsars, binary compact objects,…

- **studies of charged cosmic rays ($\boldsymbol{CR}$)**

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

  - energy spectrum of charged $\boldsymbol{CRs}$: characteristic **power law**

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

  - indirect $\boldsymbol{CR}$ detection (above $\sim \mathbf{10^{13}}\boldsymbol{eV}$) via air shower arrays: 3 components

Air showers & jet physics at accelerators

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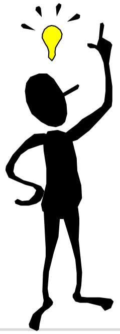
- **synergy**

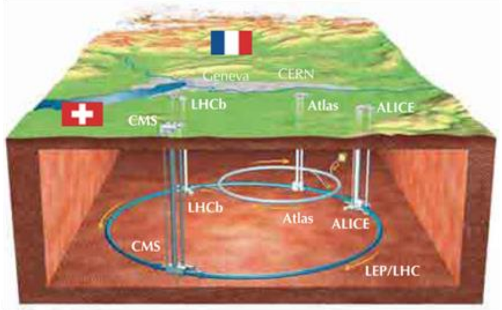
  - in the **calorimetry** of hadrons & electrons

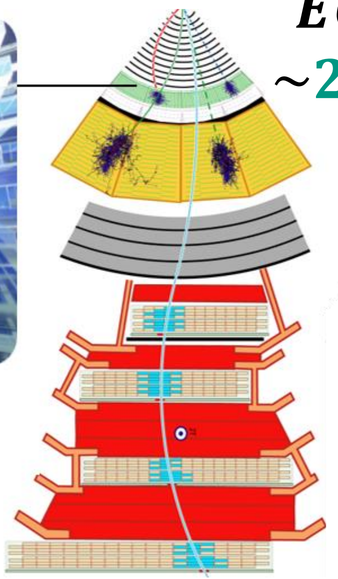
ATP & TP!



shower physics at LHC

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





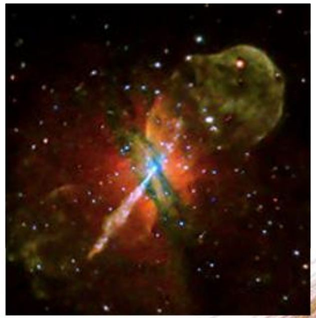
$ECAL$ $\sim 20\ X_0$

$61.200\ PbWO_4$

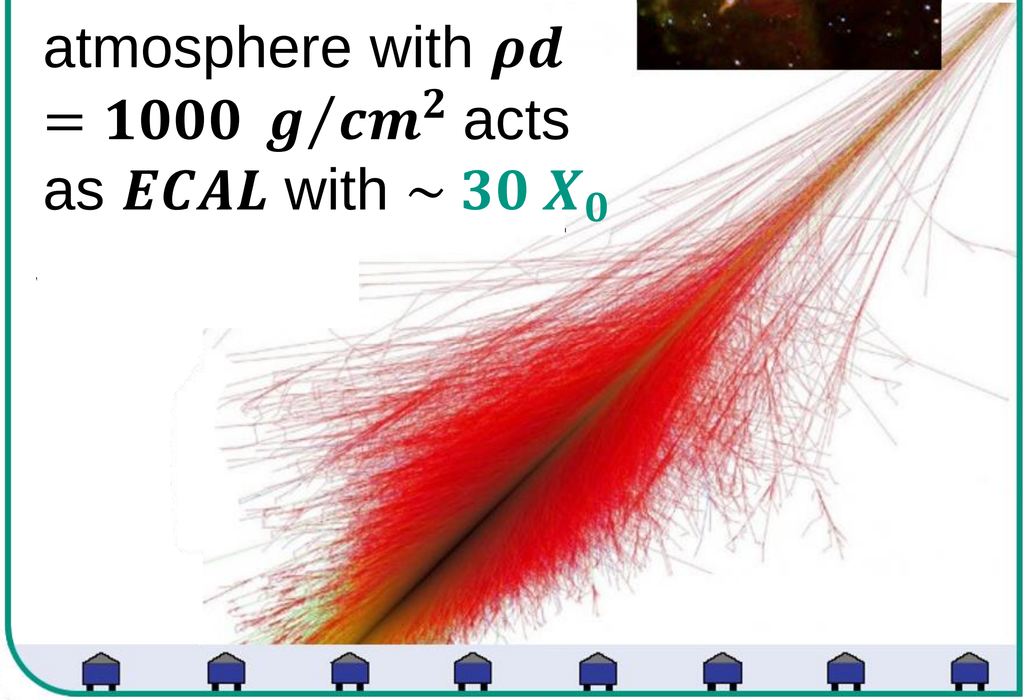
$X_0 = 0.89\ cm$

showers from AGN accelerators

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

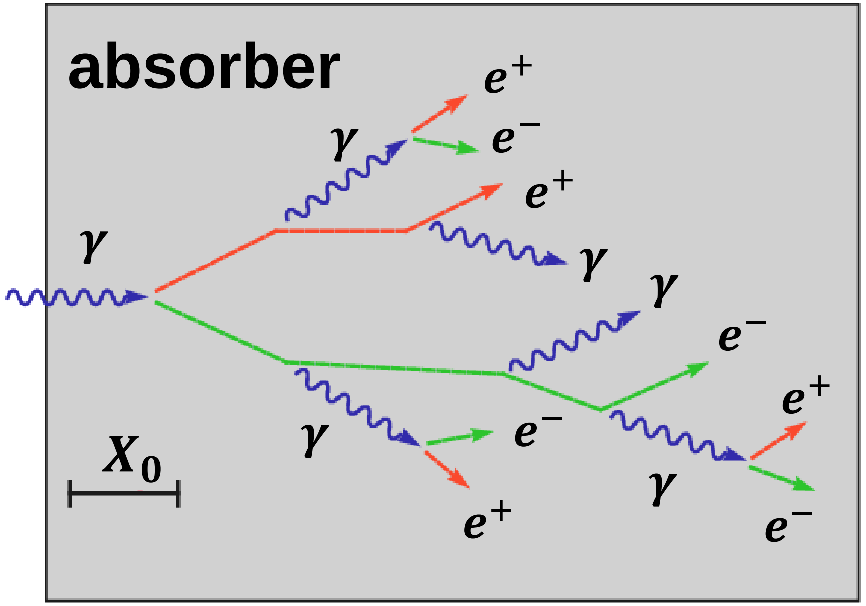


atmosphere with $\rho d = 1000\ g/cm^2$ acts as $ECAL$ with $\sim 30\ X_0$



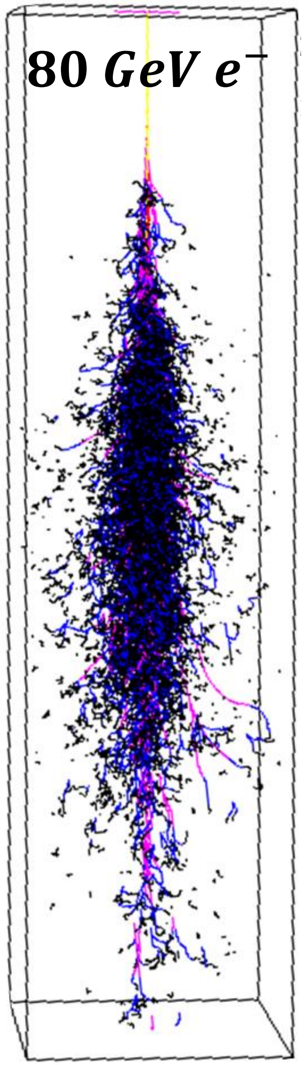
Electromagnetic component of showers

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



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**

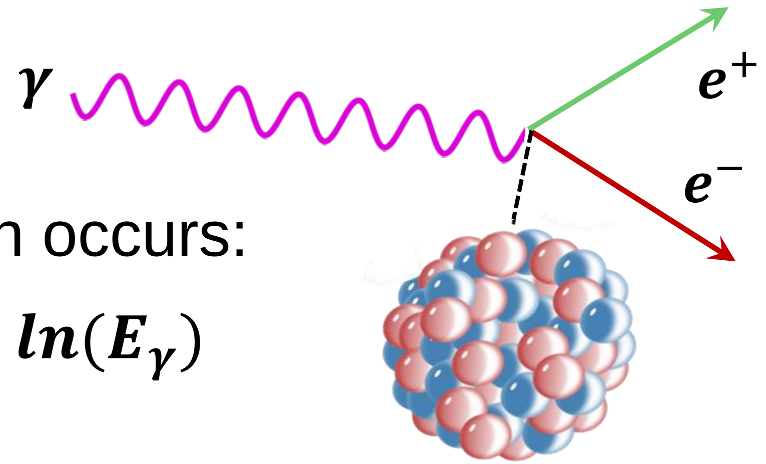


Electromagnetic component of showers

- **majority** $(\sim 98\%)$ **of shower particles: from cascade** $e^- e^+ \gamma$
  - two processes: **pair production** ⬄ **bremsstrahlung**

- **threshold** energy:

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



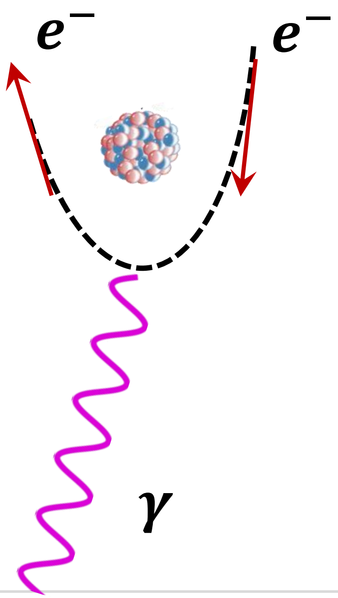
- saturation occurs:

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

kinematics of 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 X_0**

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

  - for highly **relativistic electrons**:

    i.e. after the passing of an atmospheric thickness $X = X_0$,
    the **energy** E of an e^- has dropped from E_0 to a fraction of $1/e$

  - for **high−energy photons**:

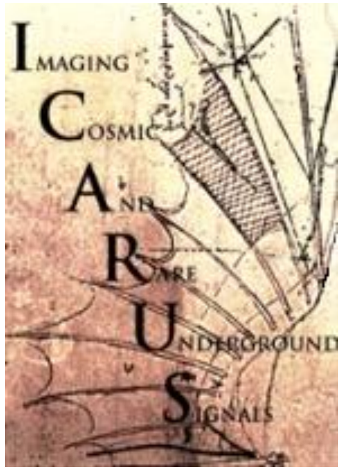
    i.e. the **mean free path λ_{pair}** of high−energy photons
    for **pair production** in the atmosphere is given by

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

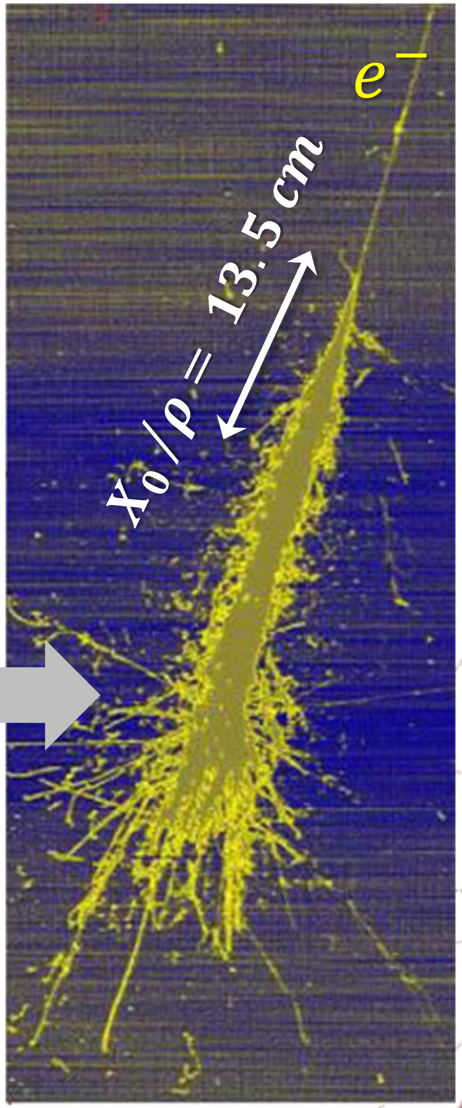
Electromagnetic component of showers

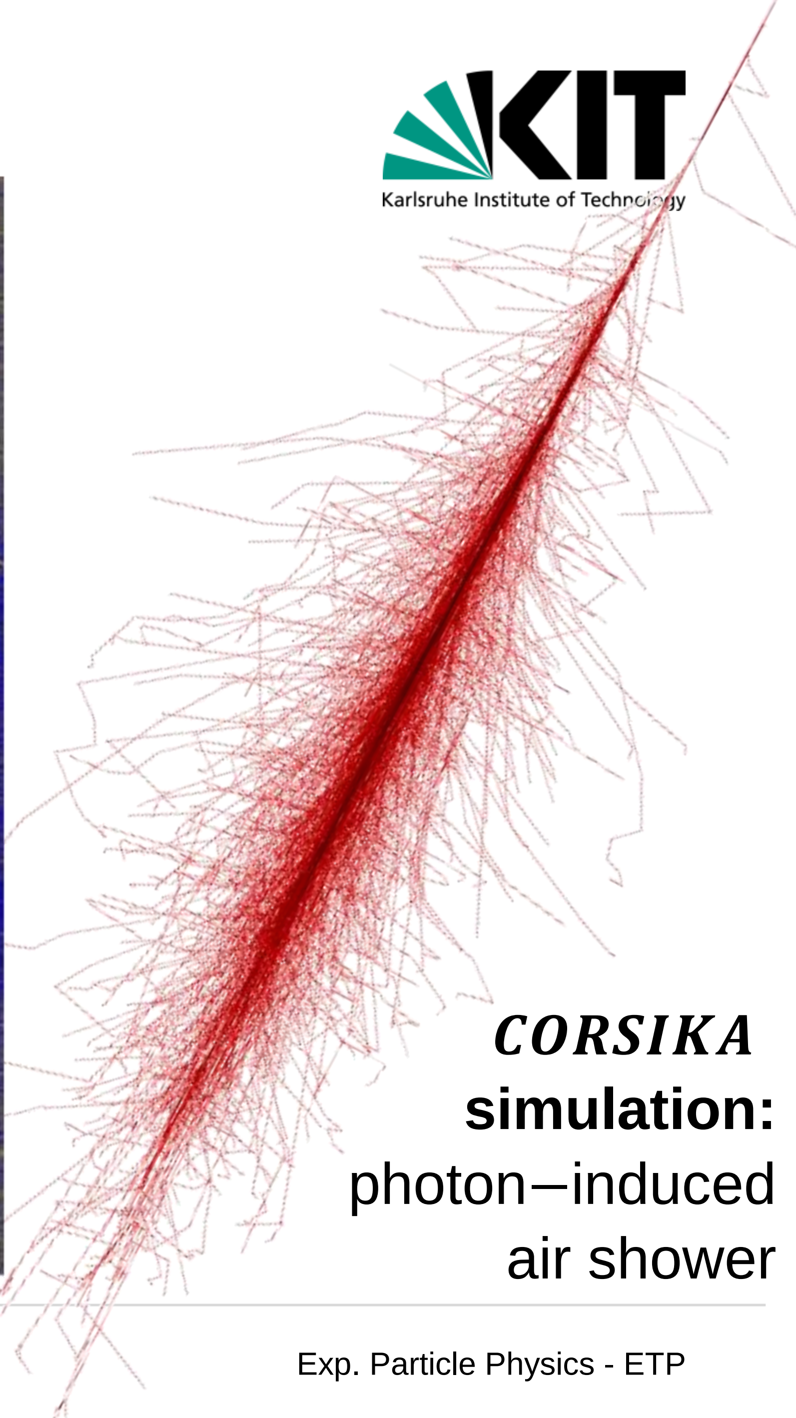
- **electromagnetic showers: experimental signature & modelling**

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





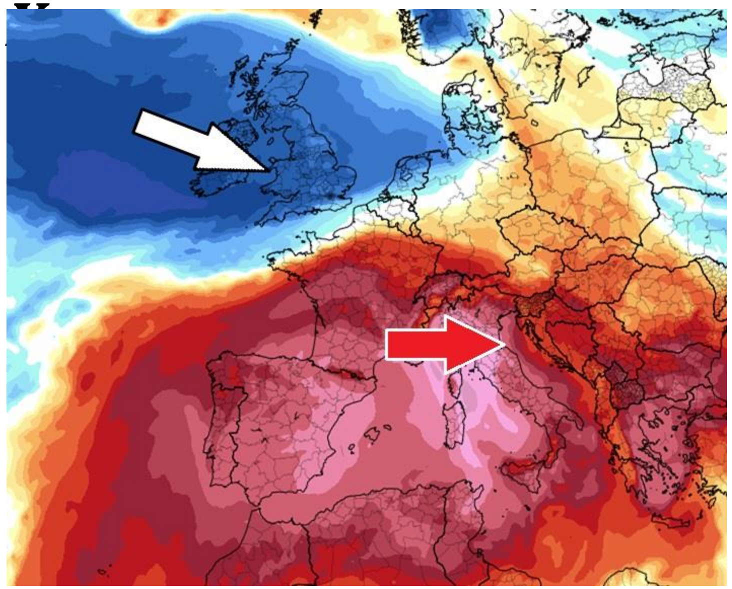
CORSIKA **simulation:**
photon−induced air shower

*see Mod. Ex. Phys. ***III***

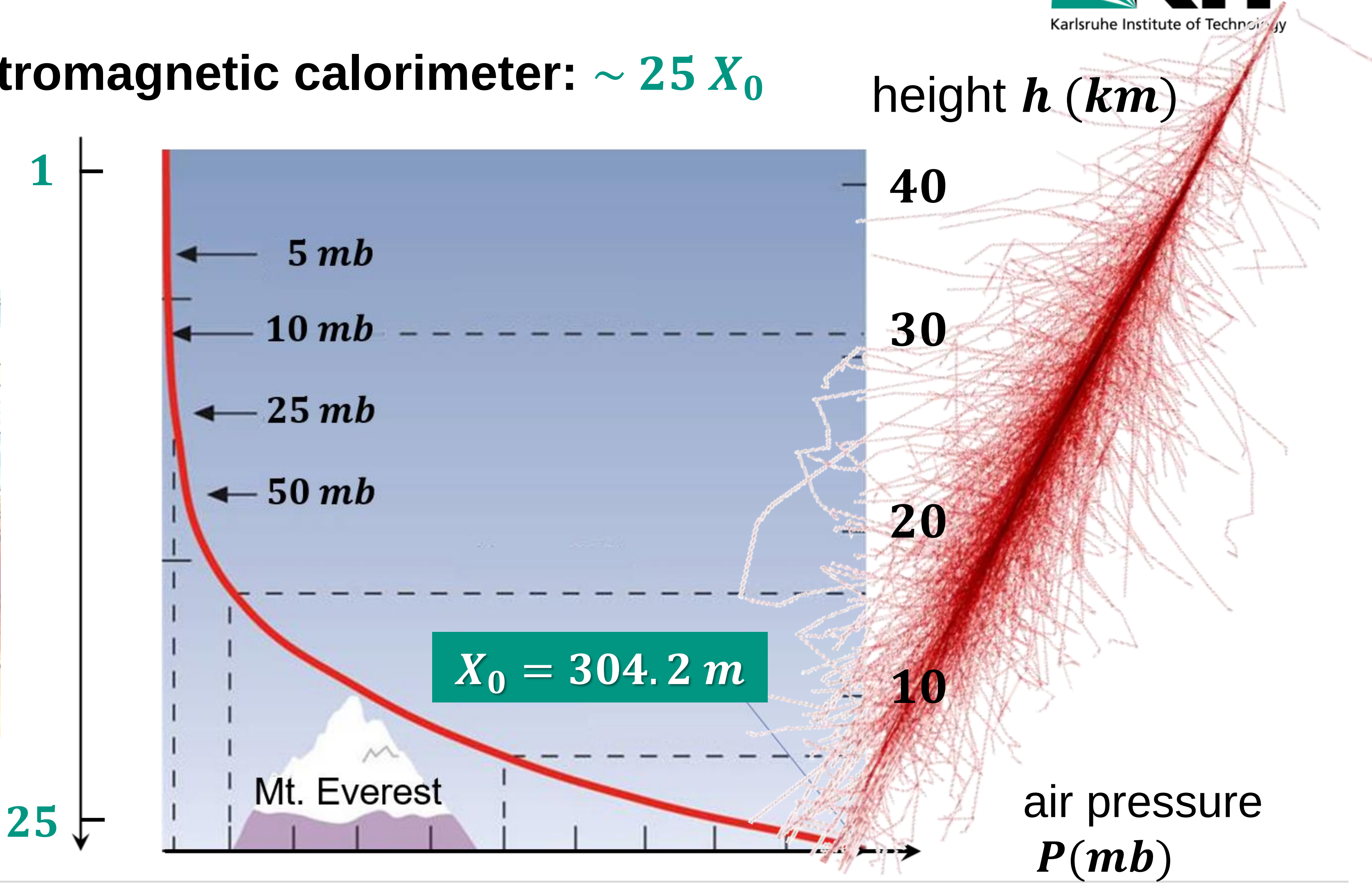
Electromagnetic component of showers

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

- changing atmospheric weather: changes of

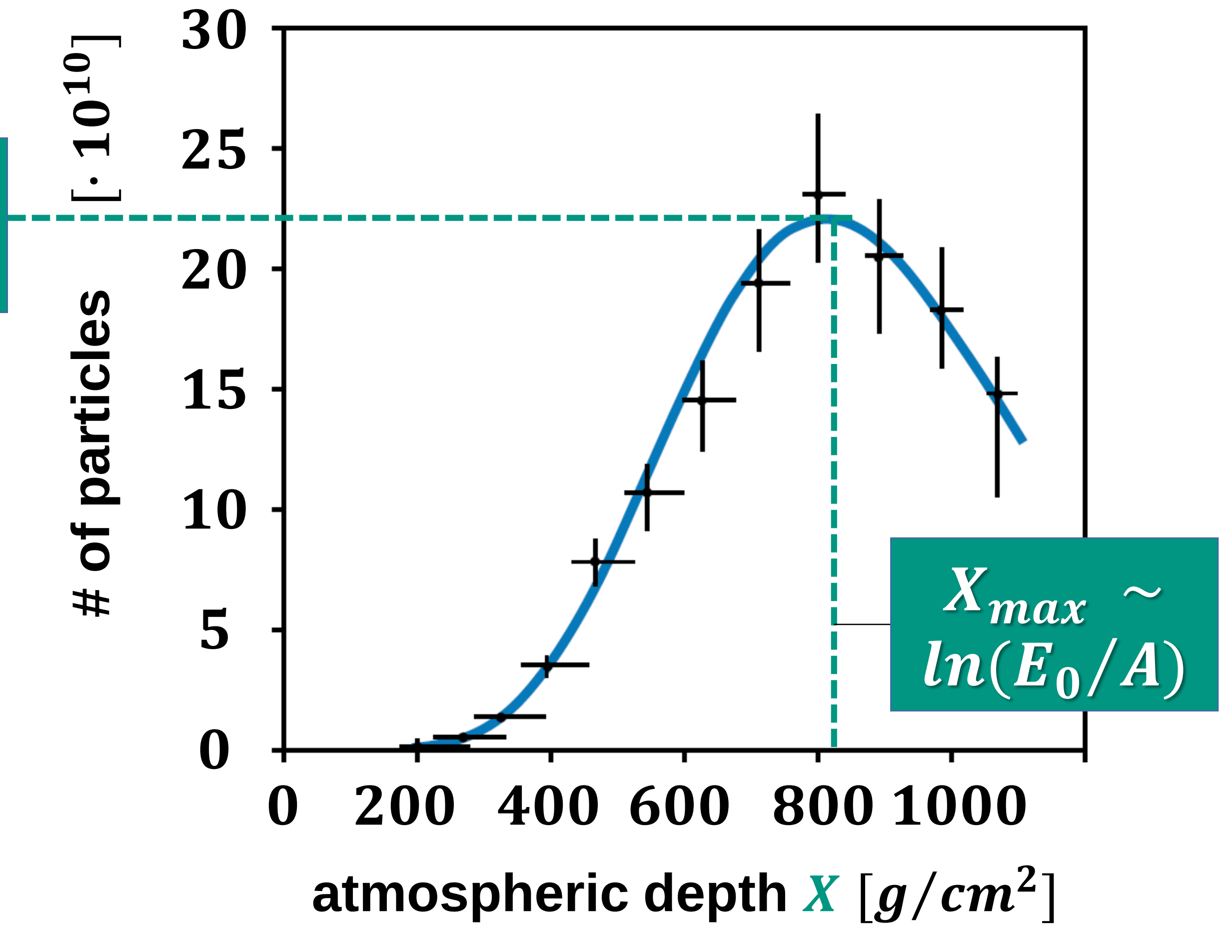


atmosphere (# of X_0)

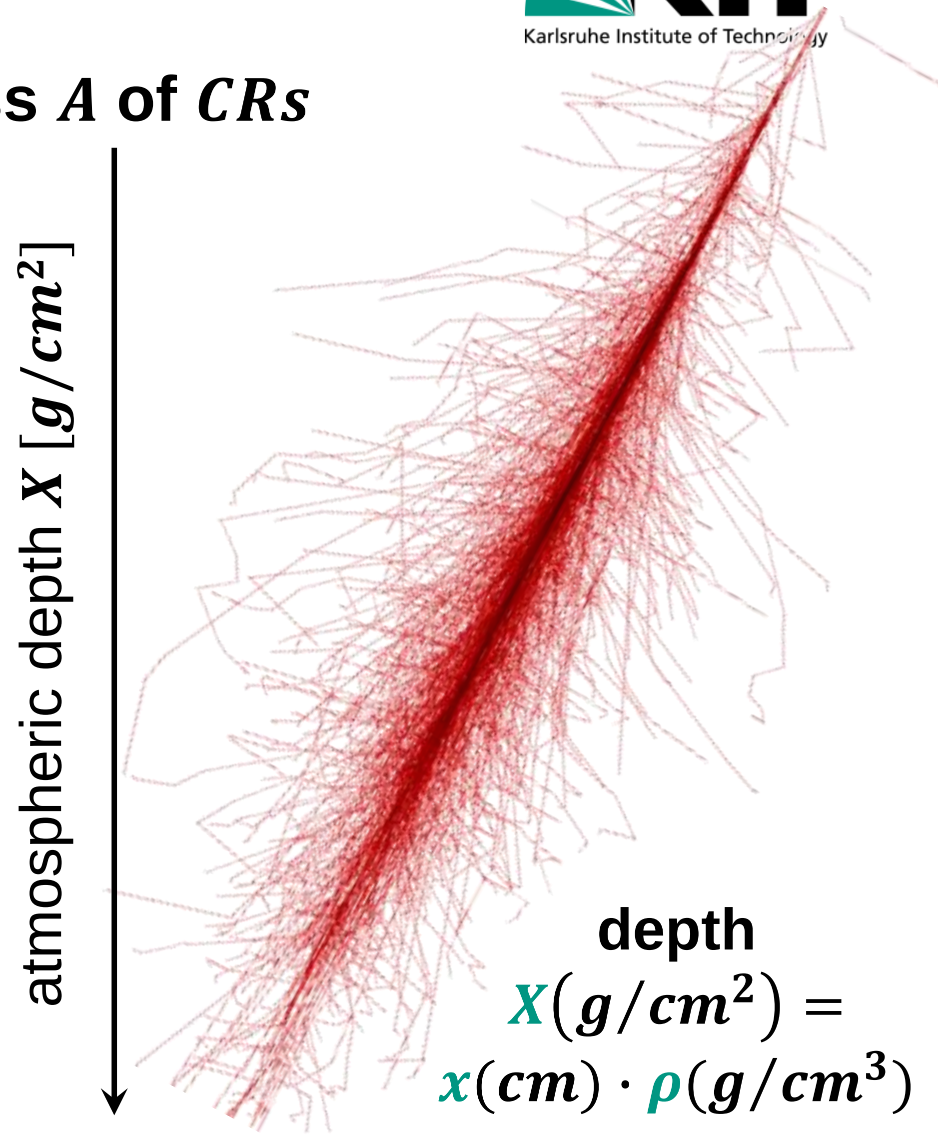


Electromagnetic showers in the atmosphere

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



look up!

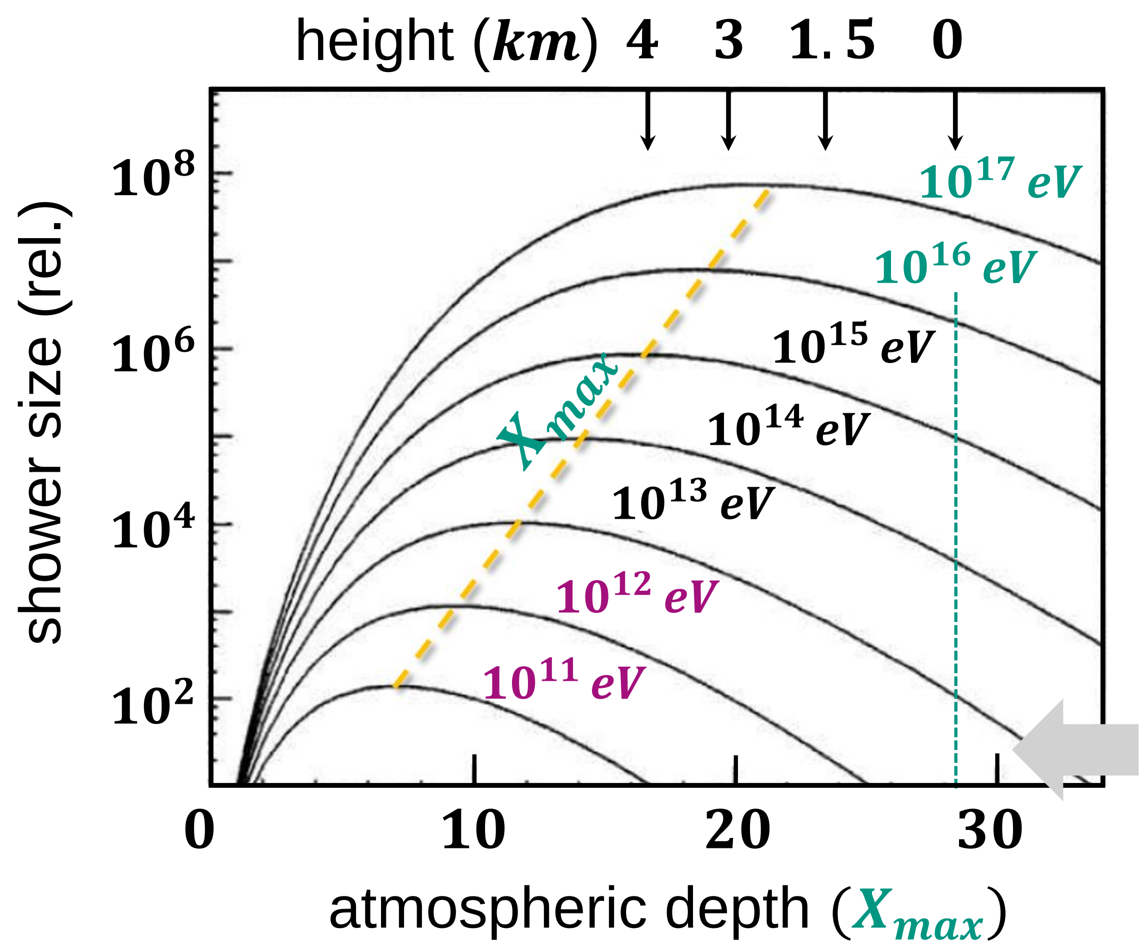


depth

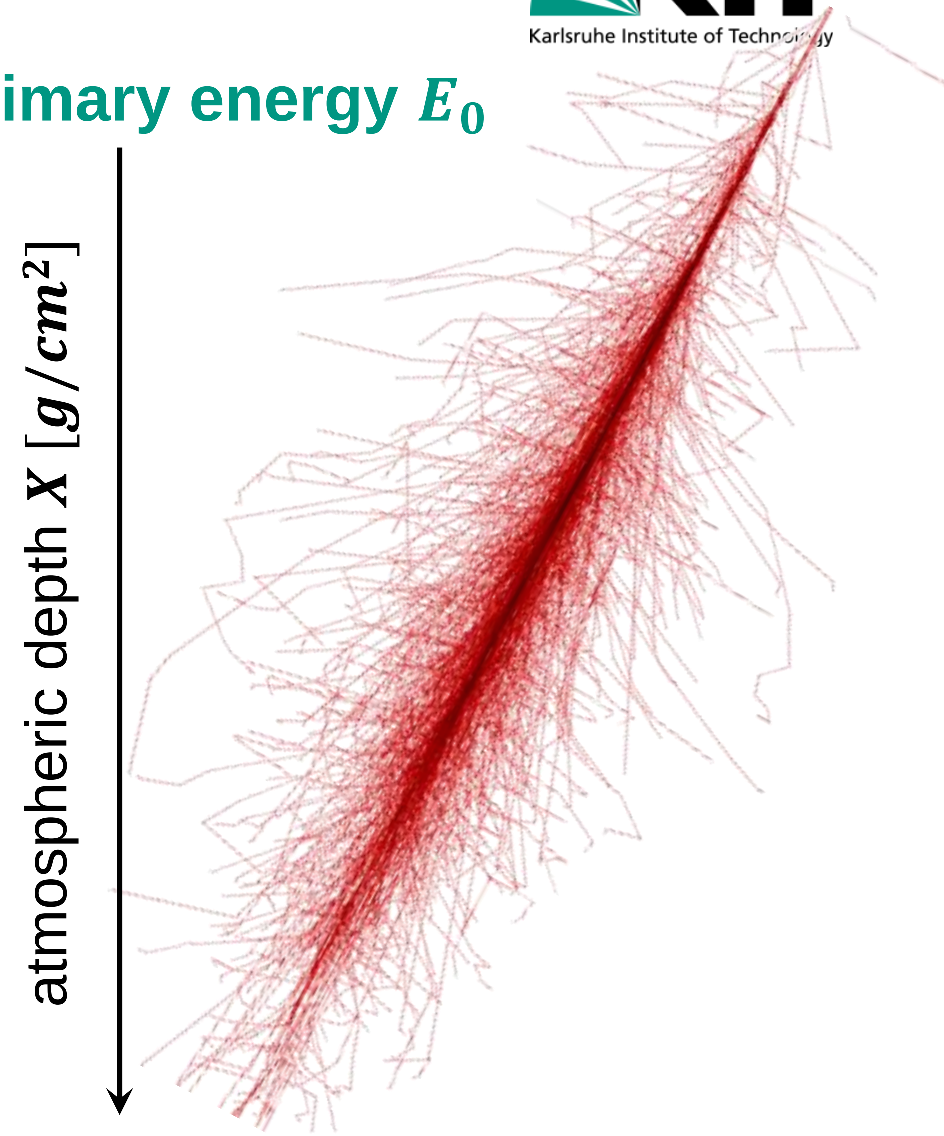
$X(g/cm^2) = x(cm) \cdot \rho(g/cm^3)$

Electromagnetic showers in the atmosphere

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



- primary CR energies $E_0 < 10^{13} eV$ do **not** reach the surface



Muonic component: *mips*

- **muons are *m*inimum *i*onizing *p*article*s* ($m.i.p.s$)**

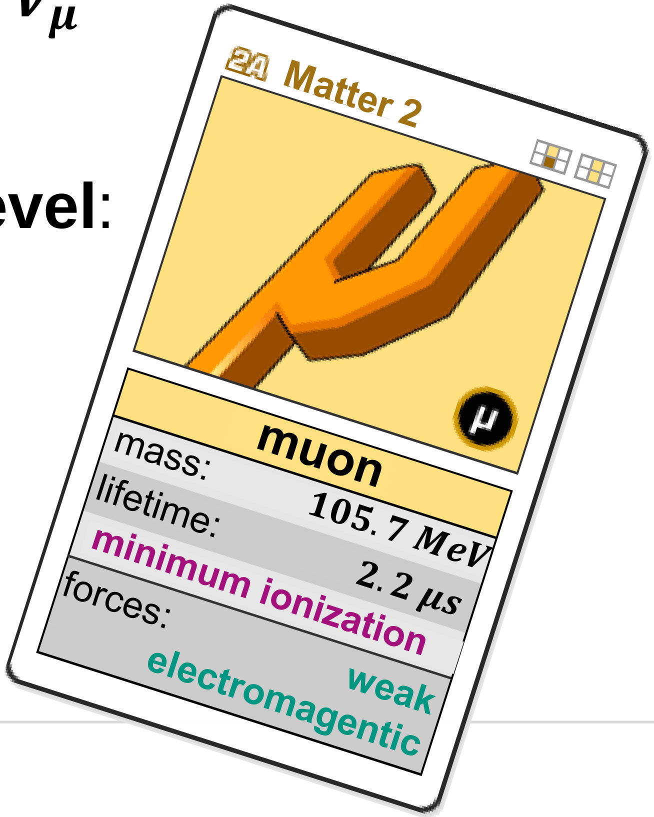
  - ´**cosmic**´ muons (slang: ´**cosmics**´)

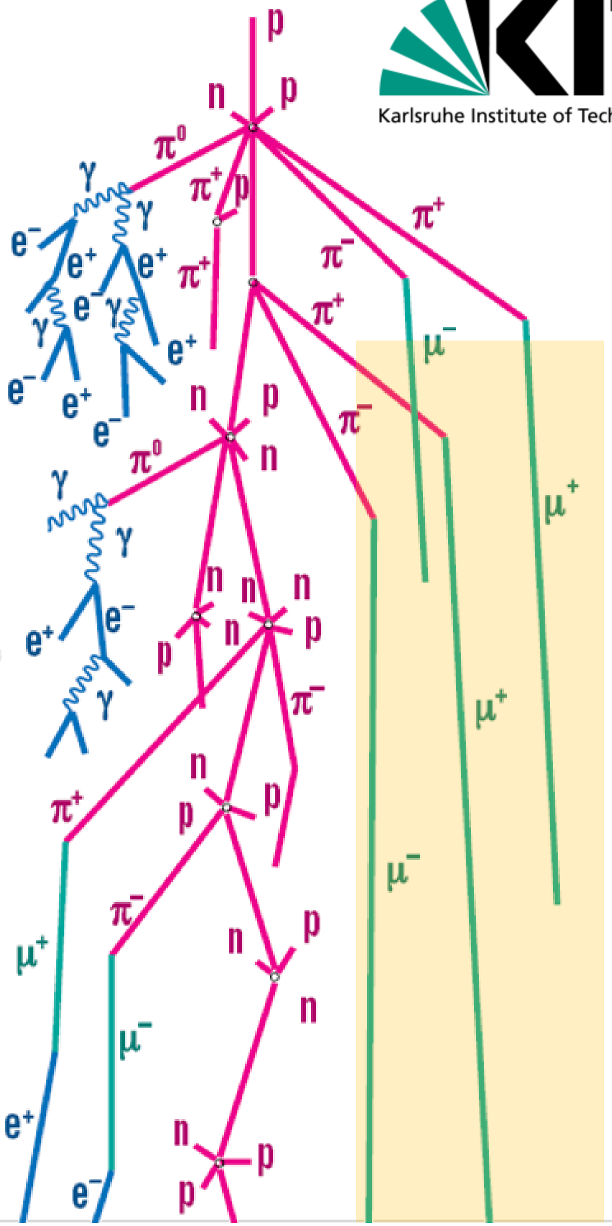
  - from **pion decays** $\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$
    in upper atmosphere

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

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

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





application of air showers: muography

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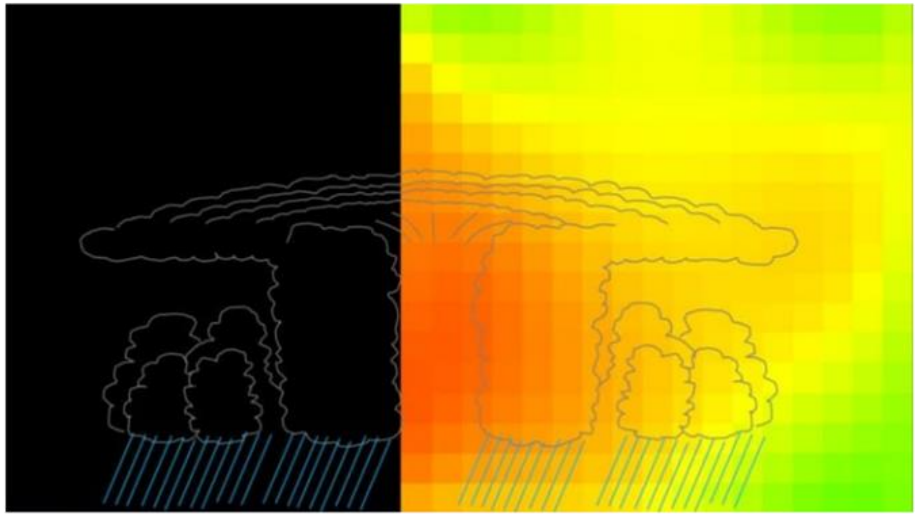
- **muography: muon rate depends on air pressure**

physicsworld

PARTICLE AND NUCLEAR RESEARCH UPDATE

Cosmic muons probe the interiors of tropical cyclones

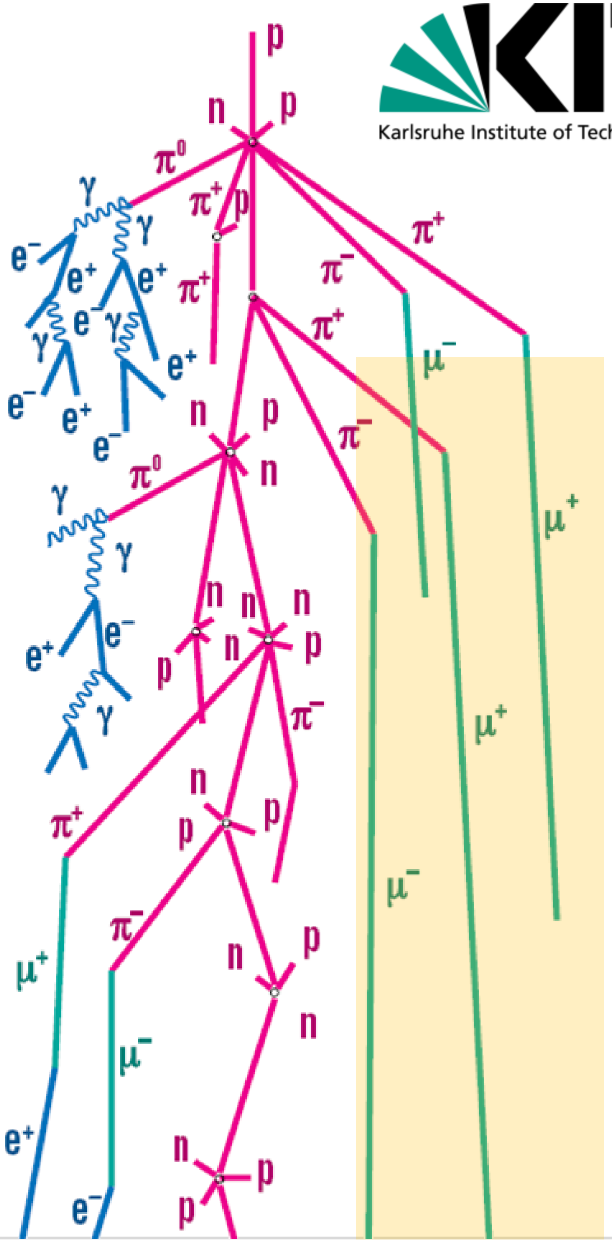
18 Oct 2022



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



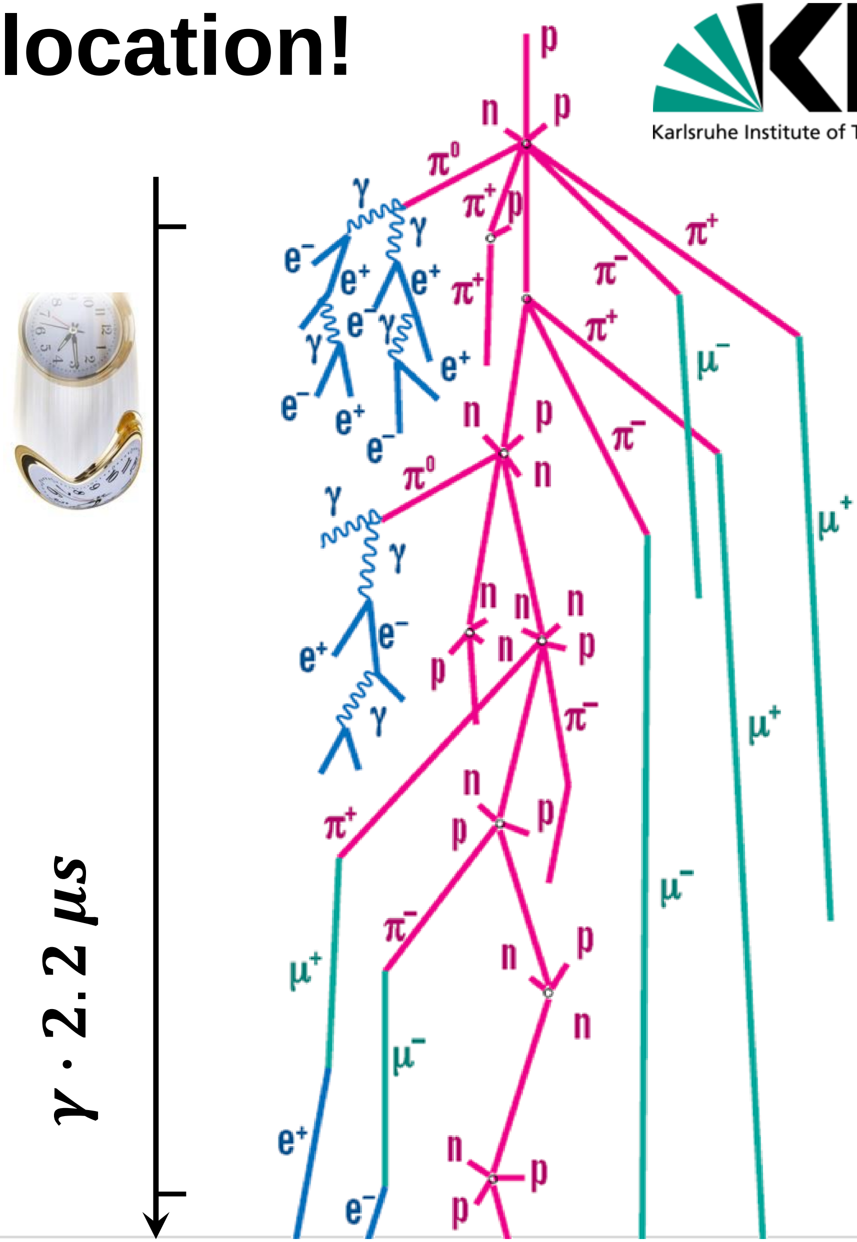
Muonic component: underground location!

- 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

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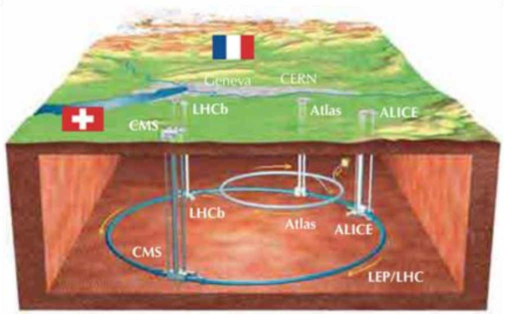
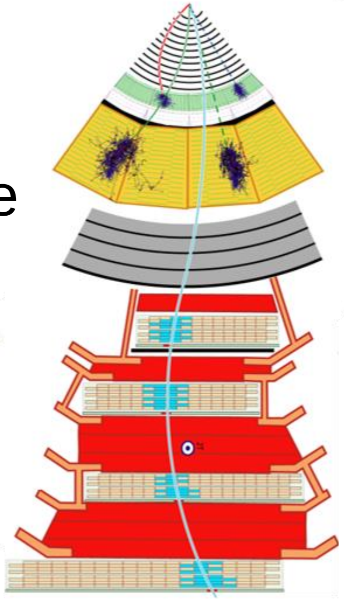
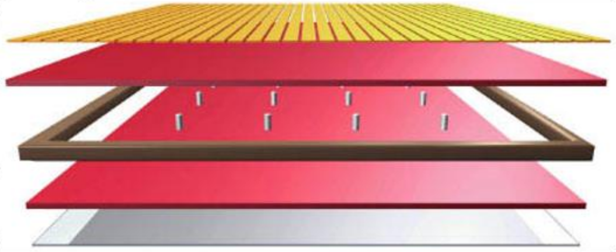
muons from an acclerator (LHC)

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



1400 muon chambers
at magnetic return yoke

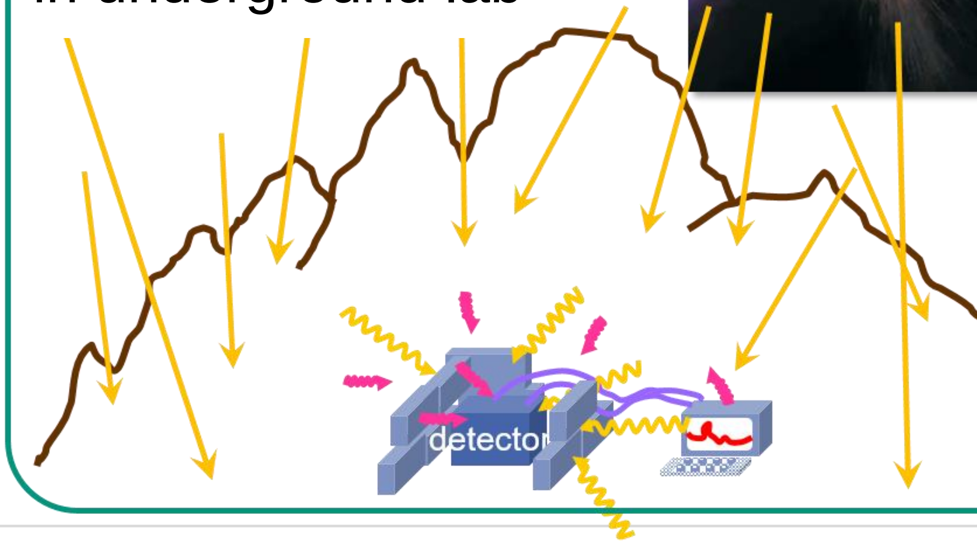




muons from cosmic accelerators

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

shielding against muons
in underground lab



Laboratori Nazionali del Gran Sasso

Hadronic component of air showers

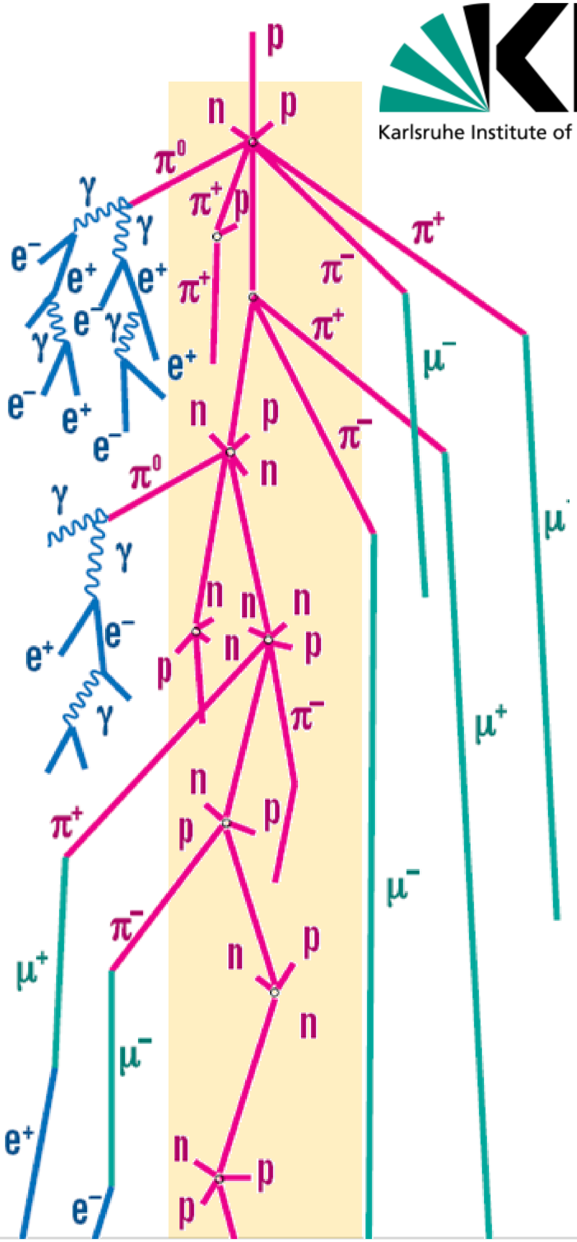
■ Hadronic interactions in the atmosphere

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

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

- hadrons are localized in **shower core** ($\sim\mathbf{0.3}\%$ fraction)

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



Hadronic component of air showers

- **Hadronic interactions in the atmosphere**

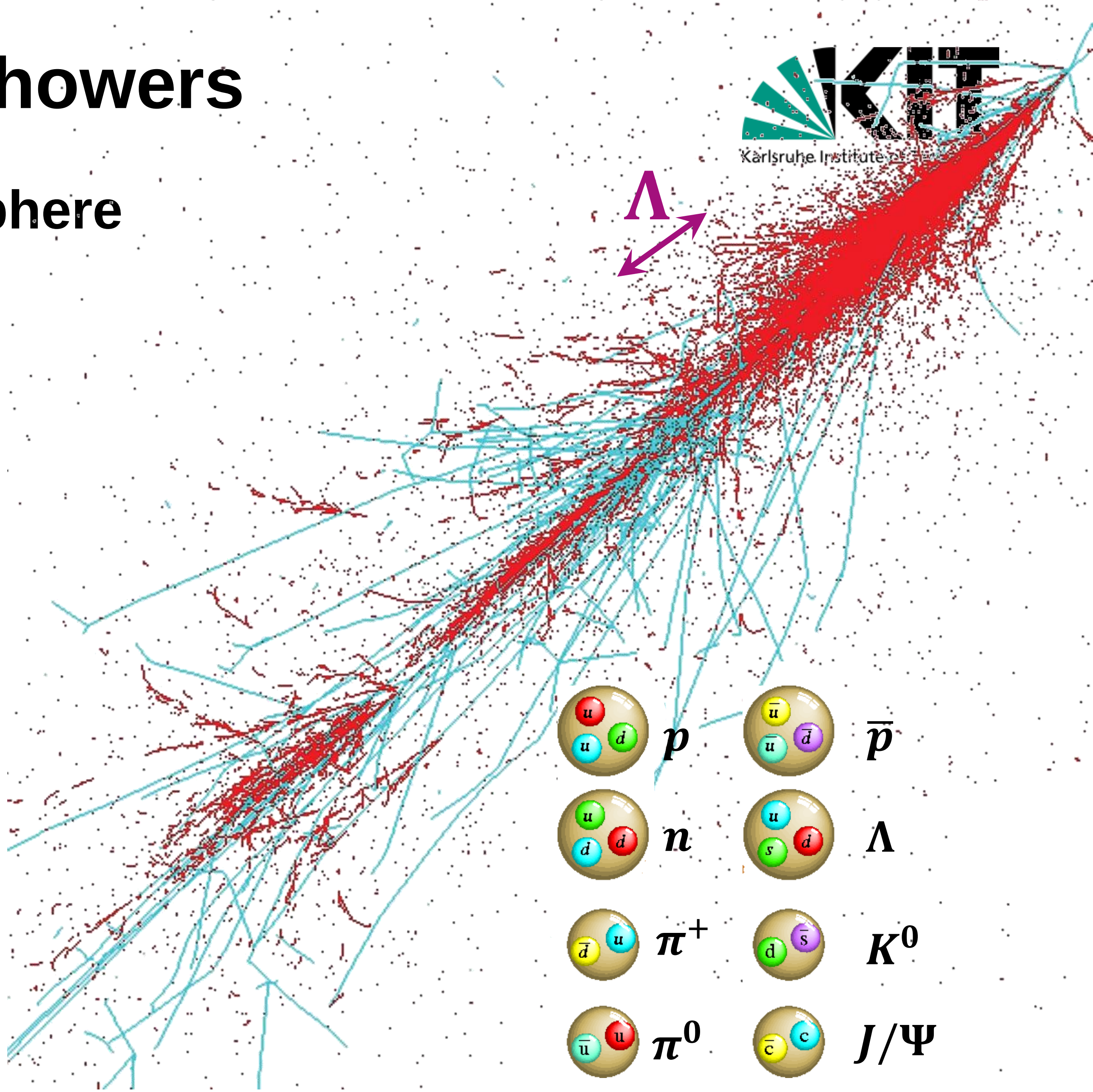
- **hadronic interaction length Λ**
  measured in $[g/cm^2$ or $cm]$

  = 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**

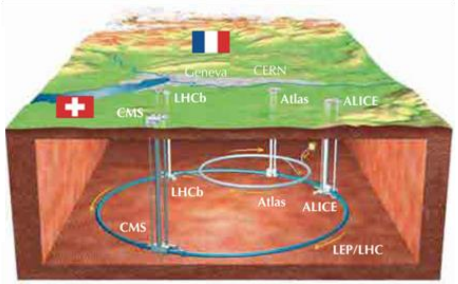


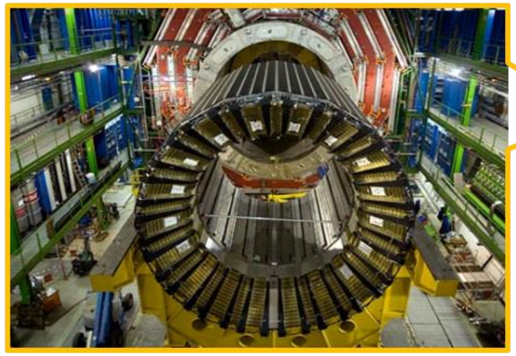
Hadronic component of air showers

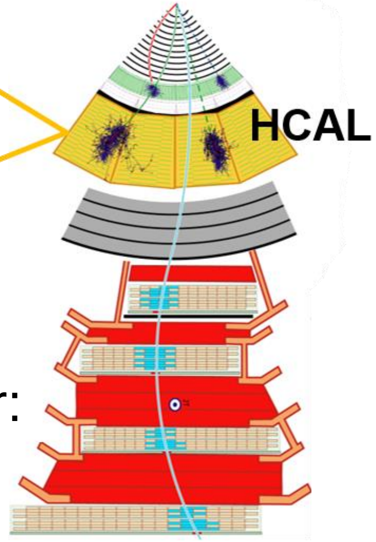
- **Hadronic interactions:** $HCAL$ **characteristics at the** LHC & **in the atmosphere**

$HCAL$ for terrestrial accelerators

accelerators:
protons with up
to $\sqrt{s} = 7\ TeV$







iron (Fe) as absorber:

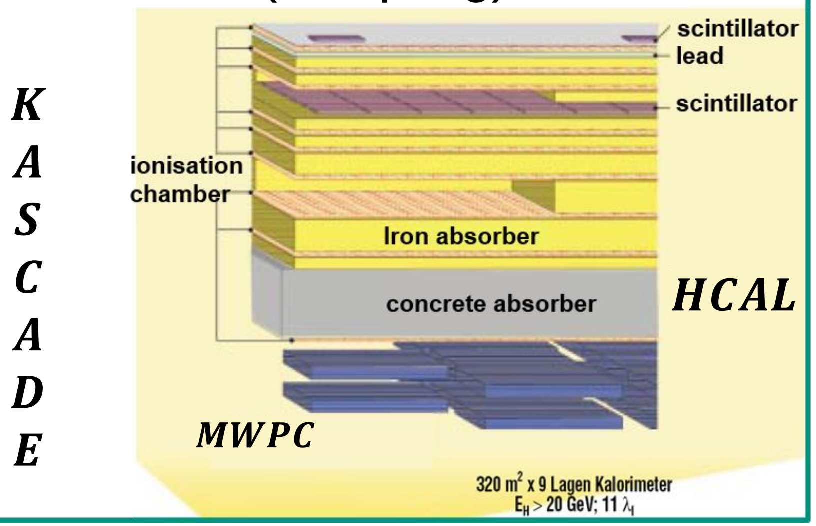
$\Lambda = 16.8\ cm$

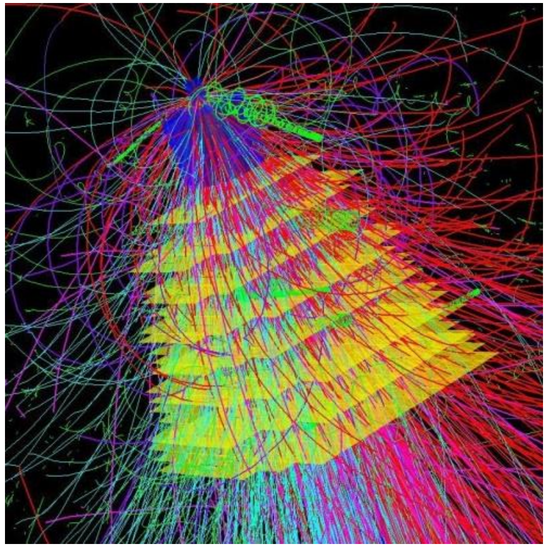
$X_0 = 1.76\ cm$

$HCAL$ for cosmic accelerators

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

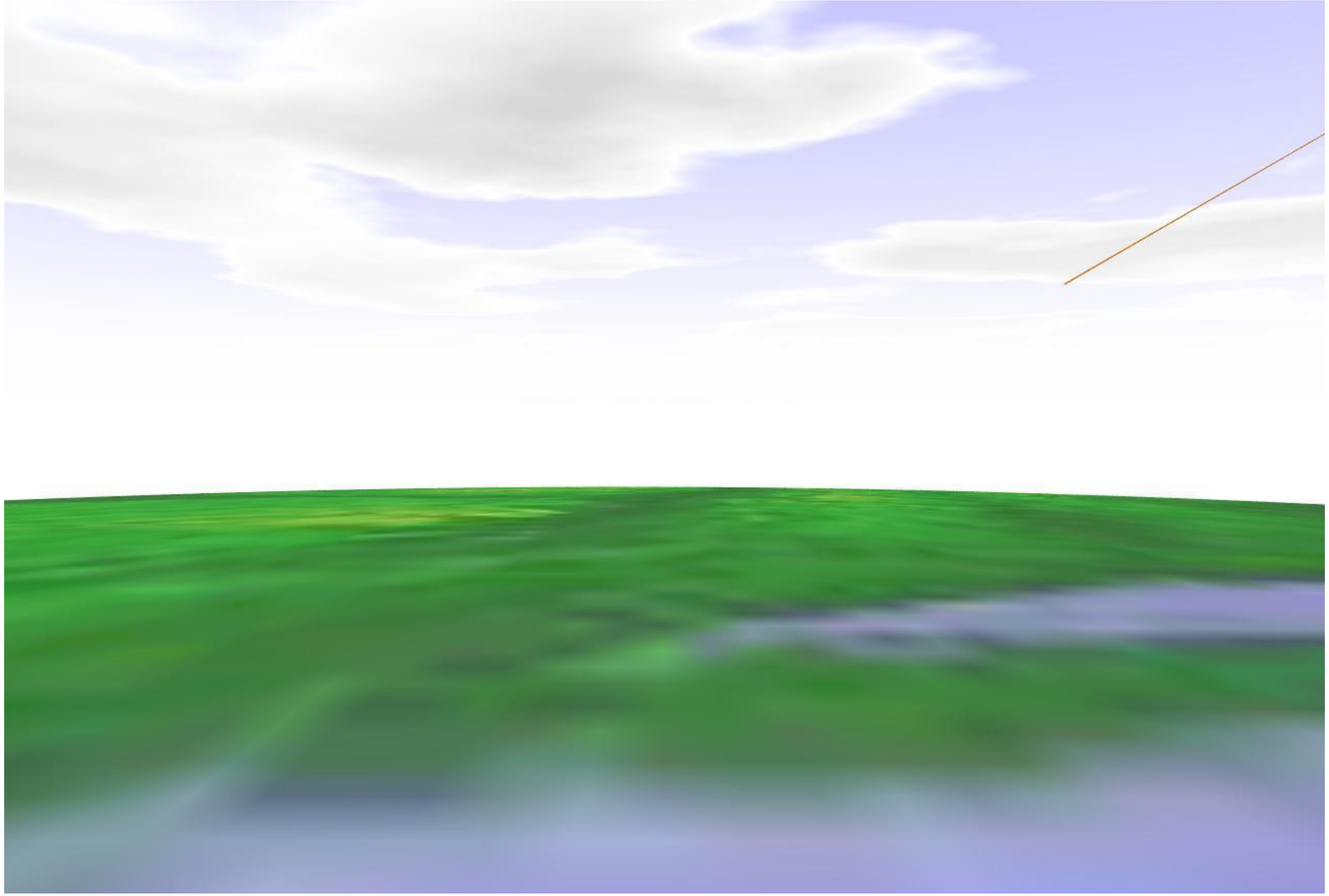
Fe – hadron– (sampling) calorimeter

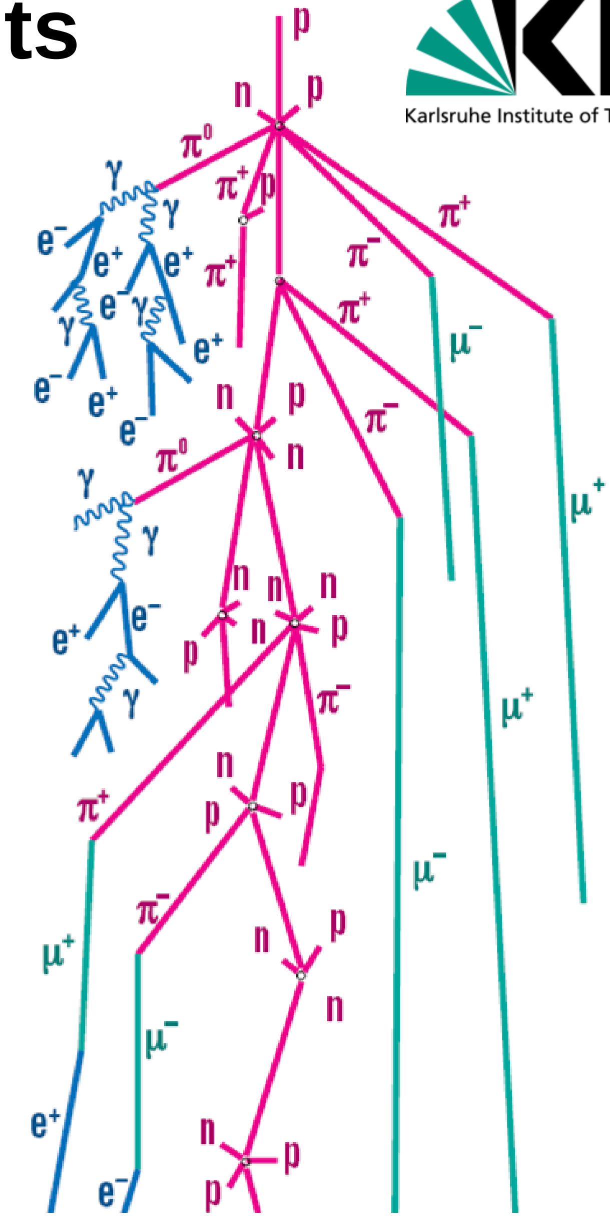




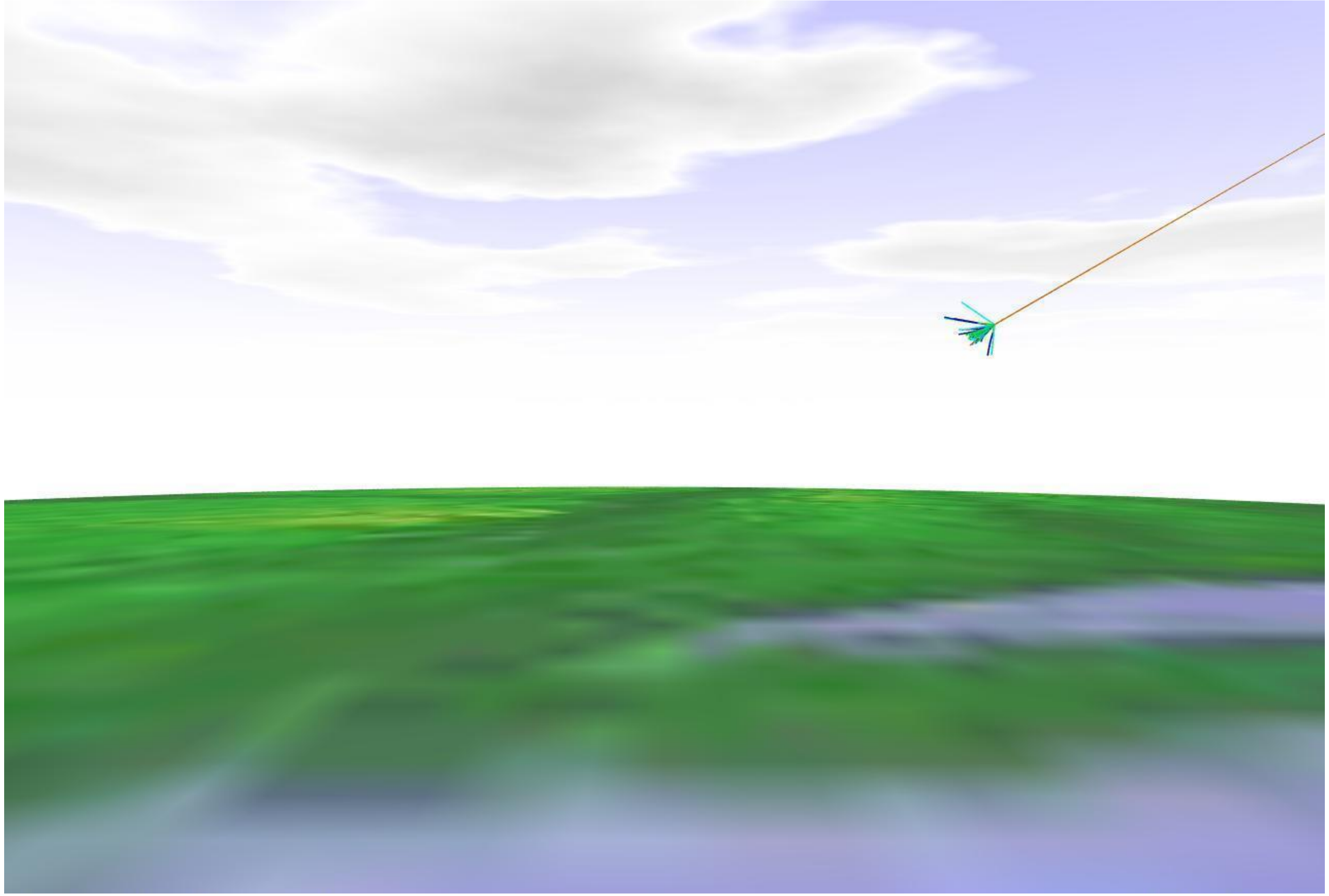
hadronic shower (MC) in an $HCAL$

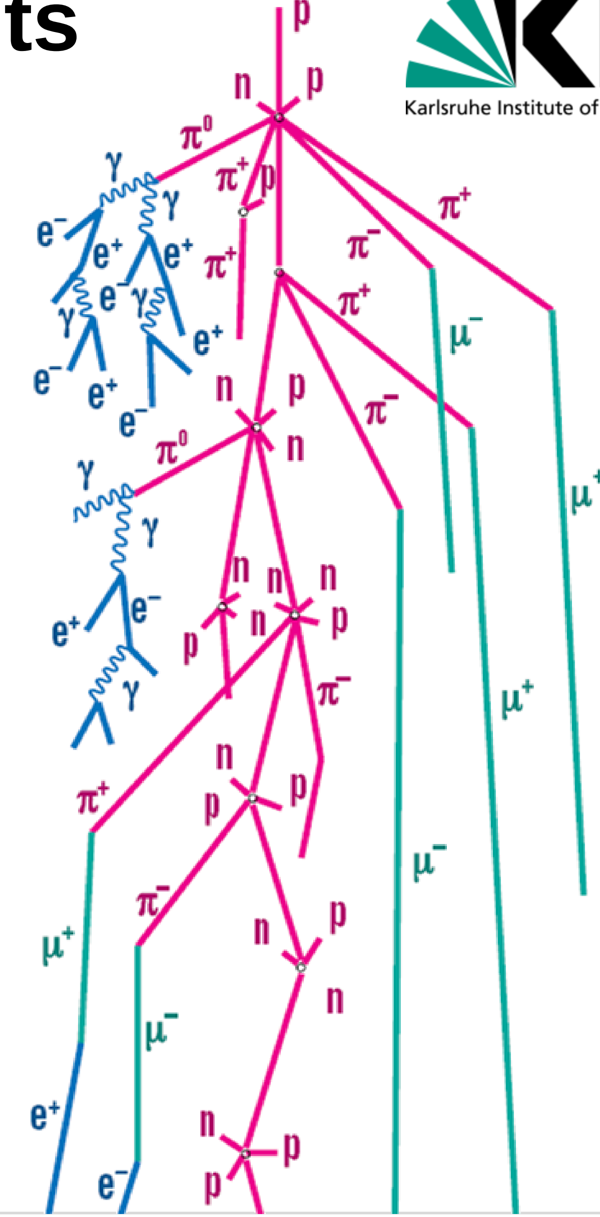
Simulation of air showers: all components



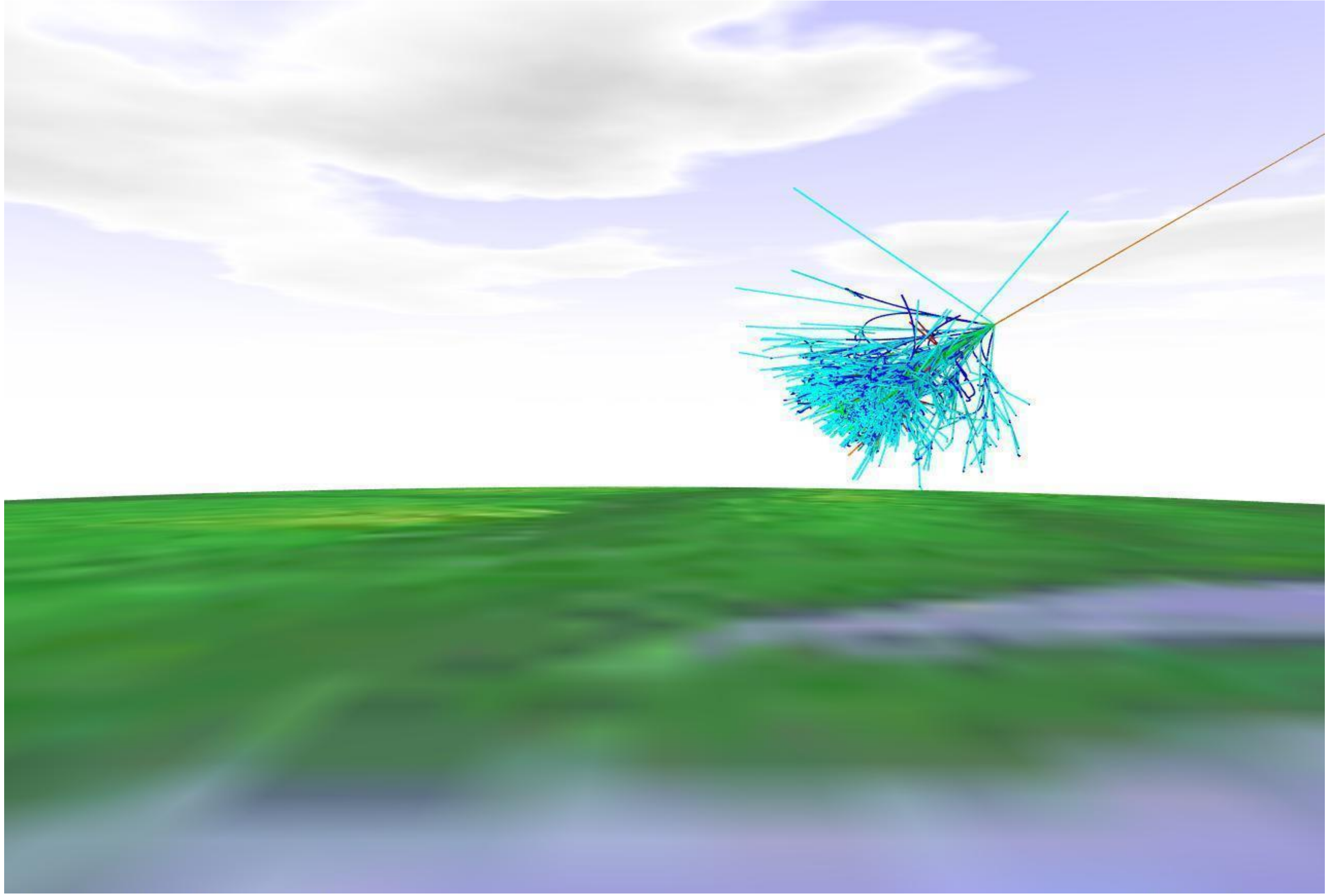


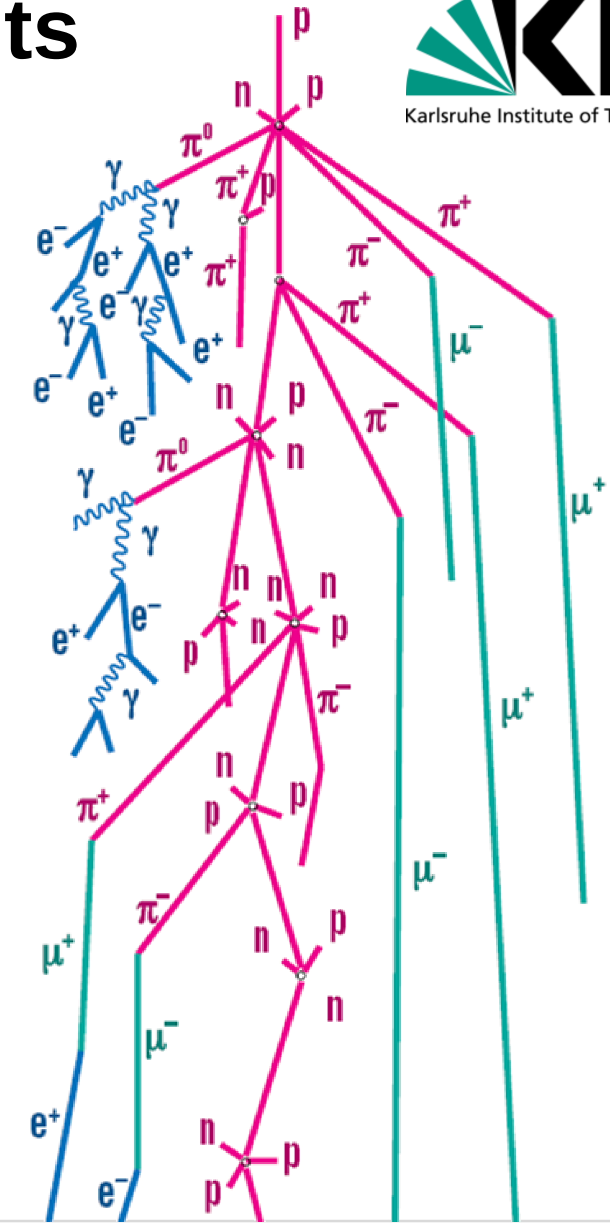
Simulation of air showers: all components



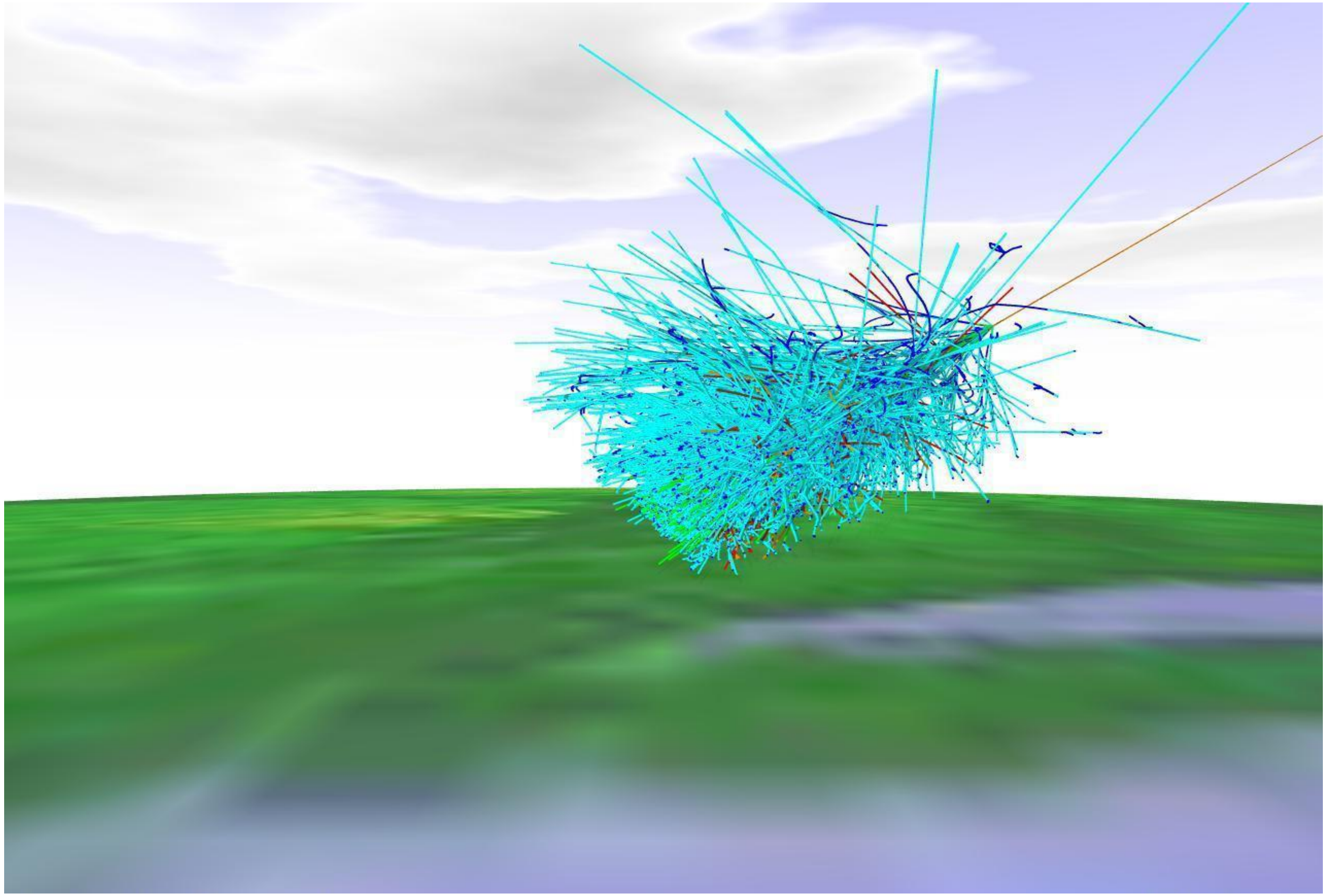


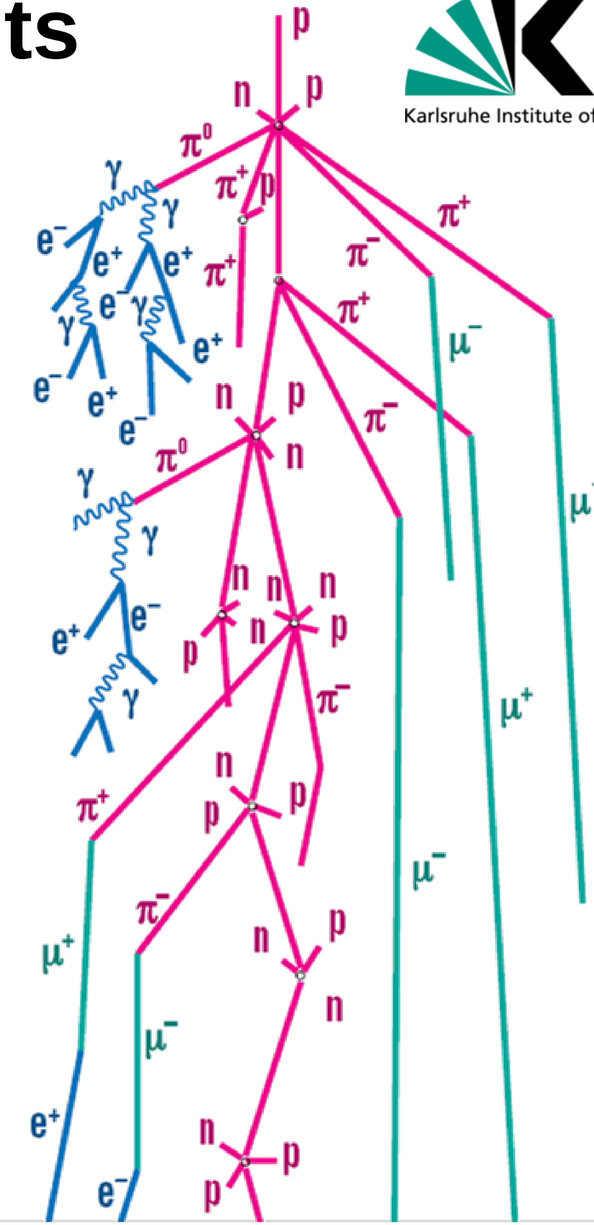
Simulation of air showers: all components



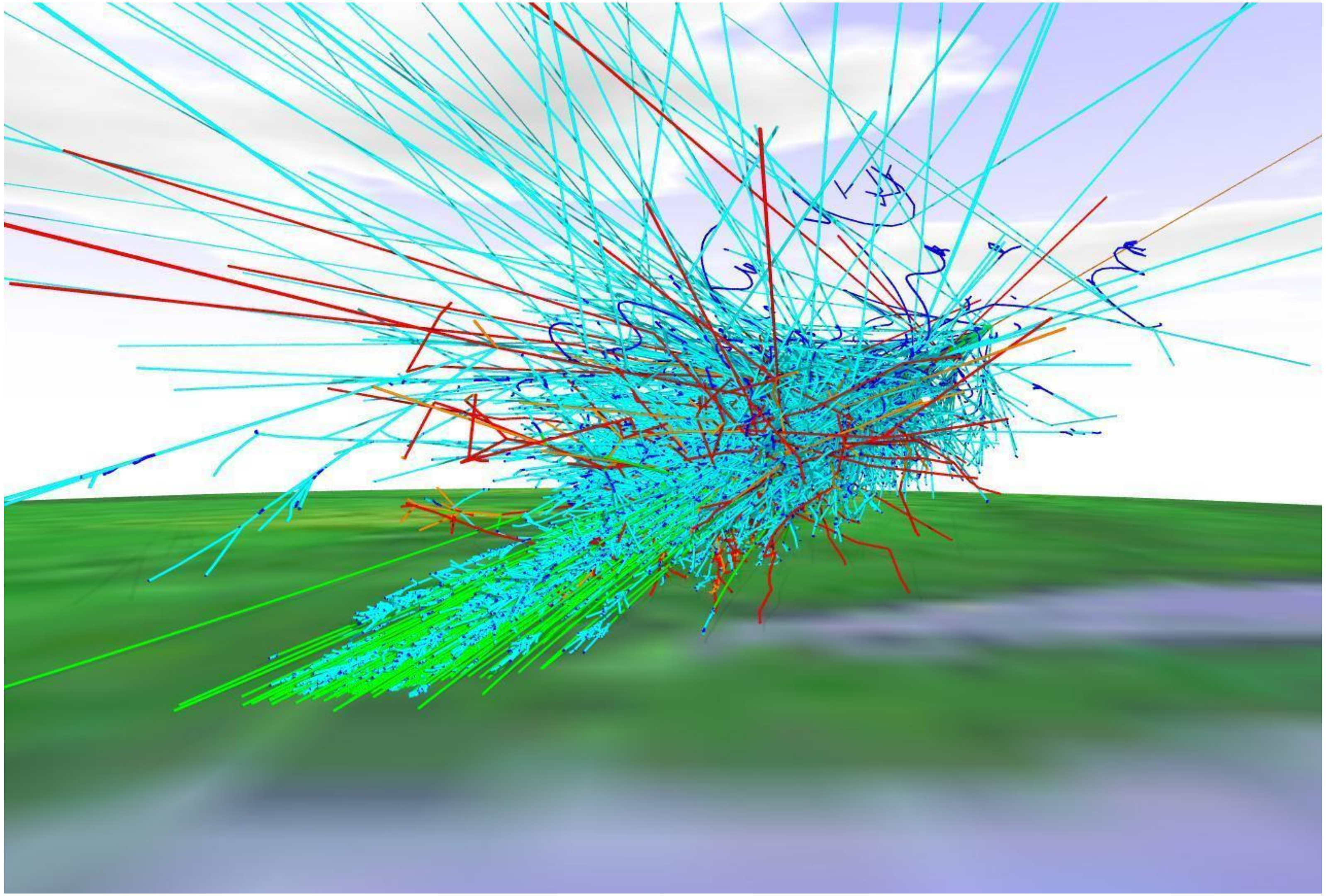


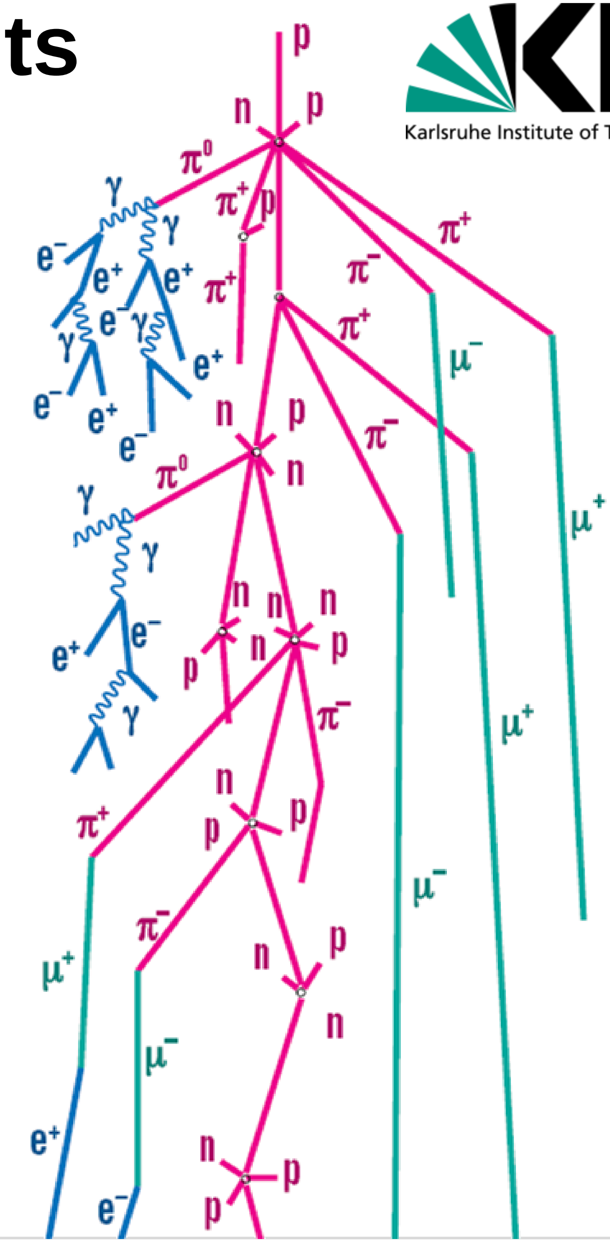
Simulation of air showers: all components



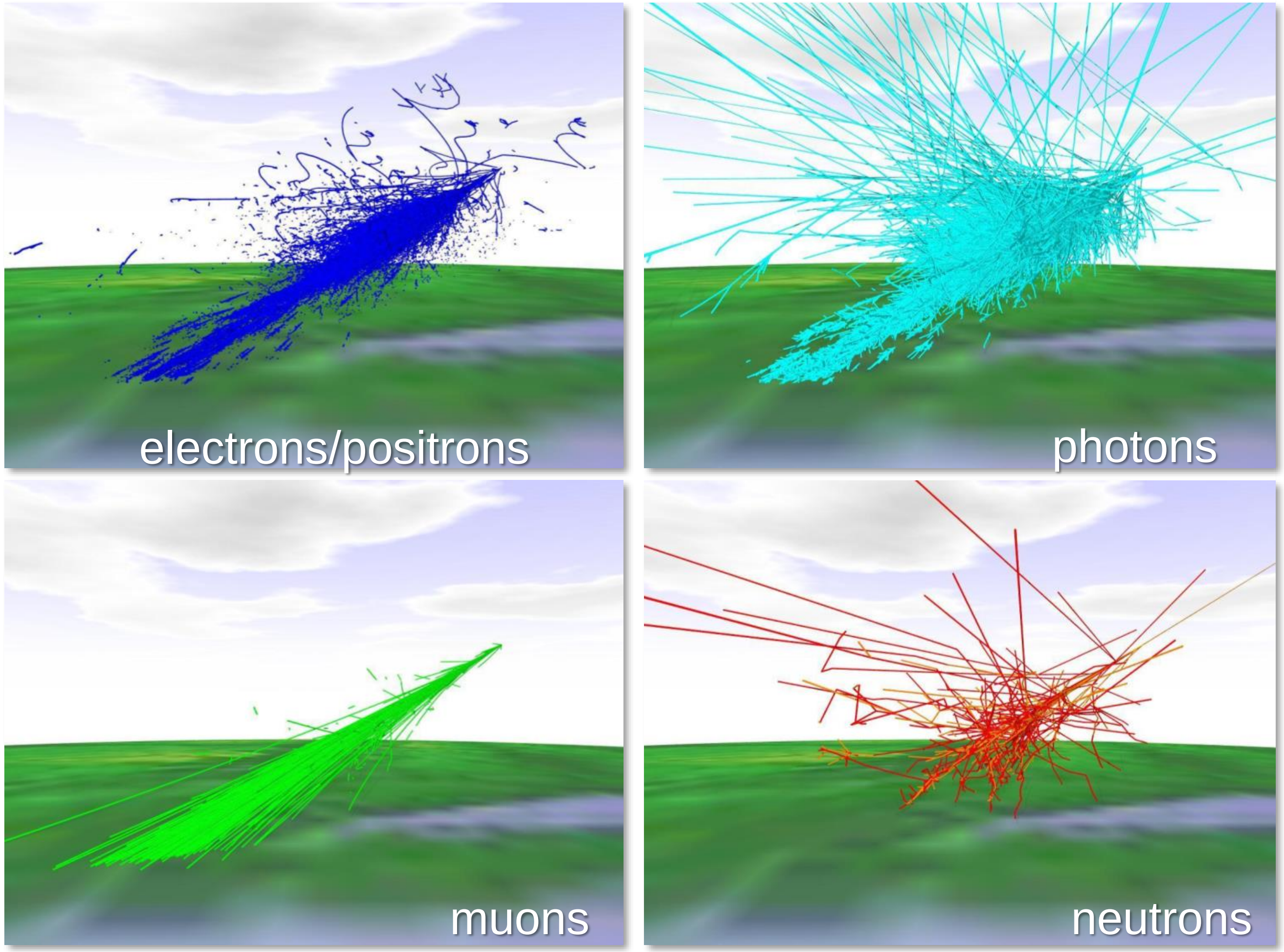


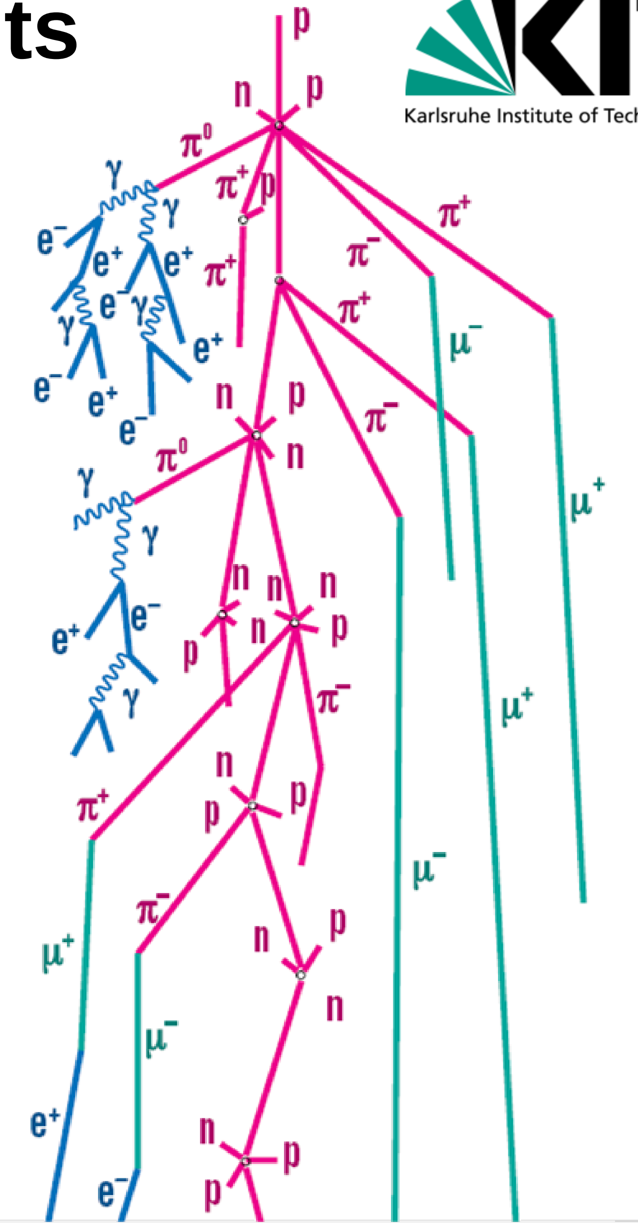
Simulation of air showers: all components





Simulation of air showers: all components





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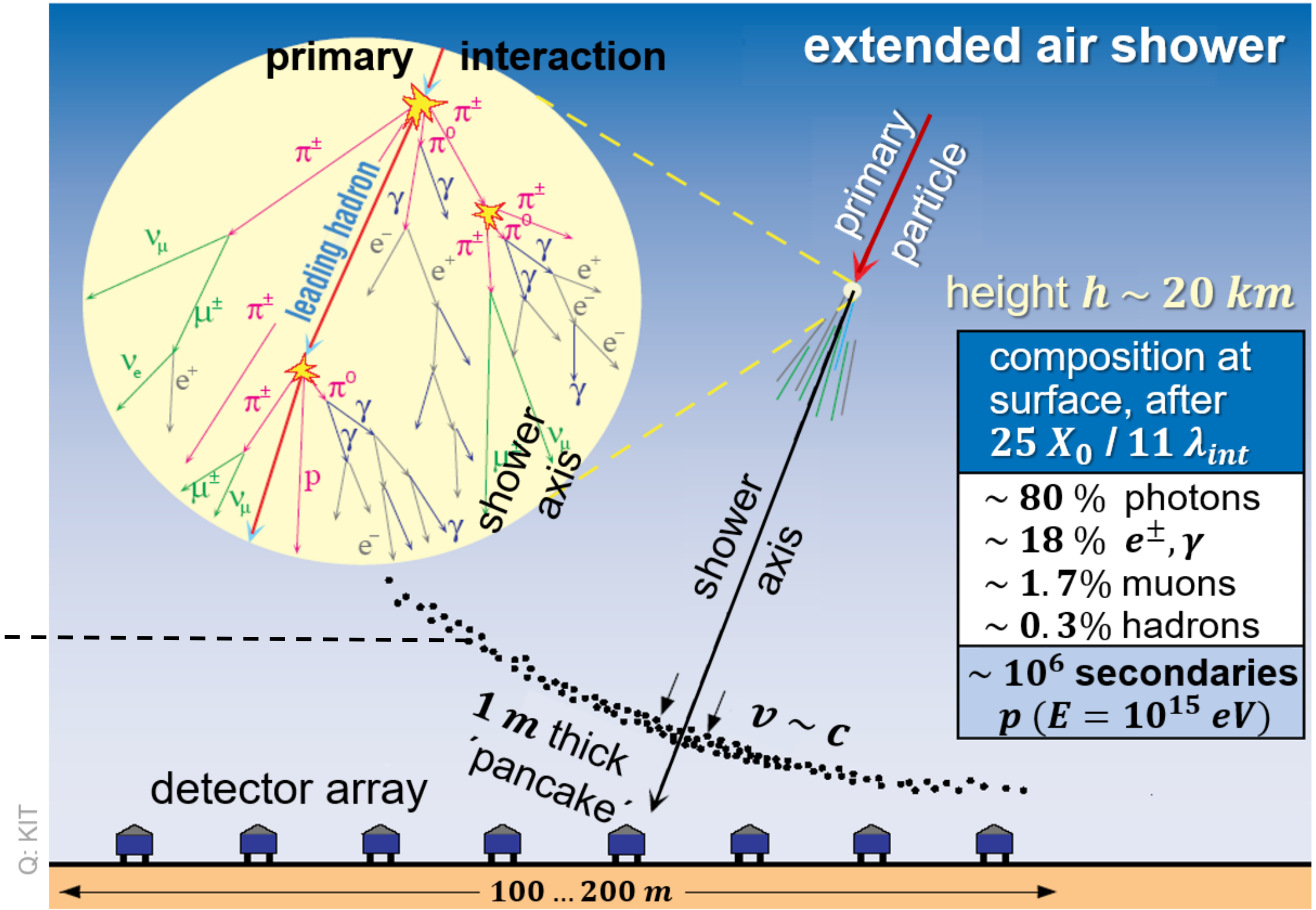
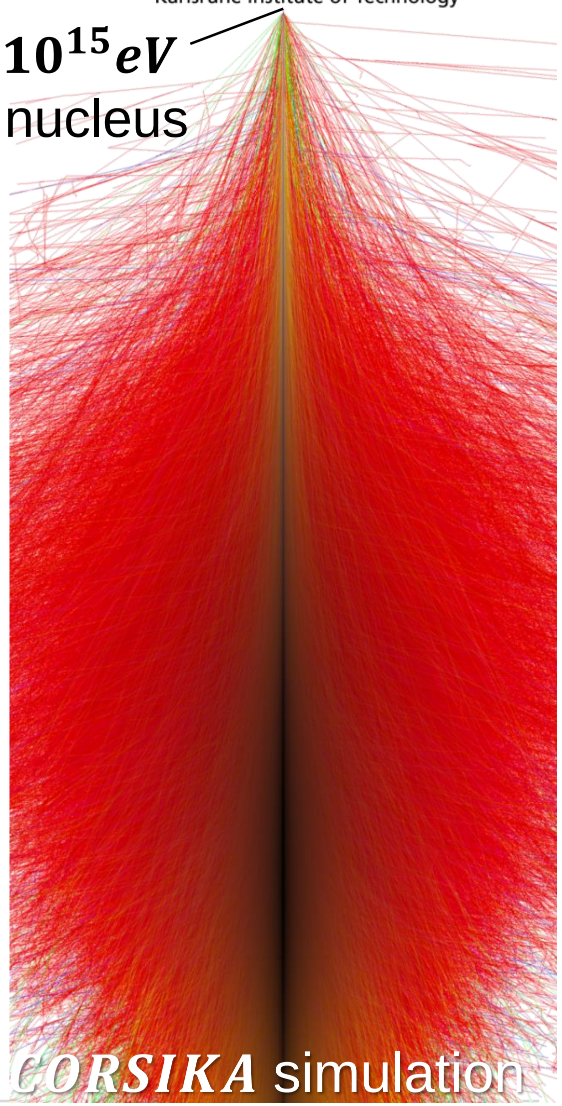
Features of an extended air shower

- **primary CR: Earth´s atmosphere acts as calorimeter**

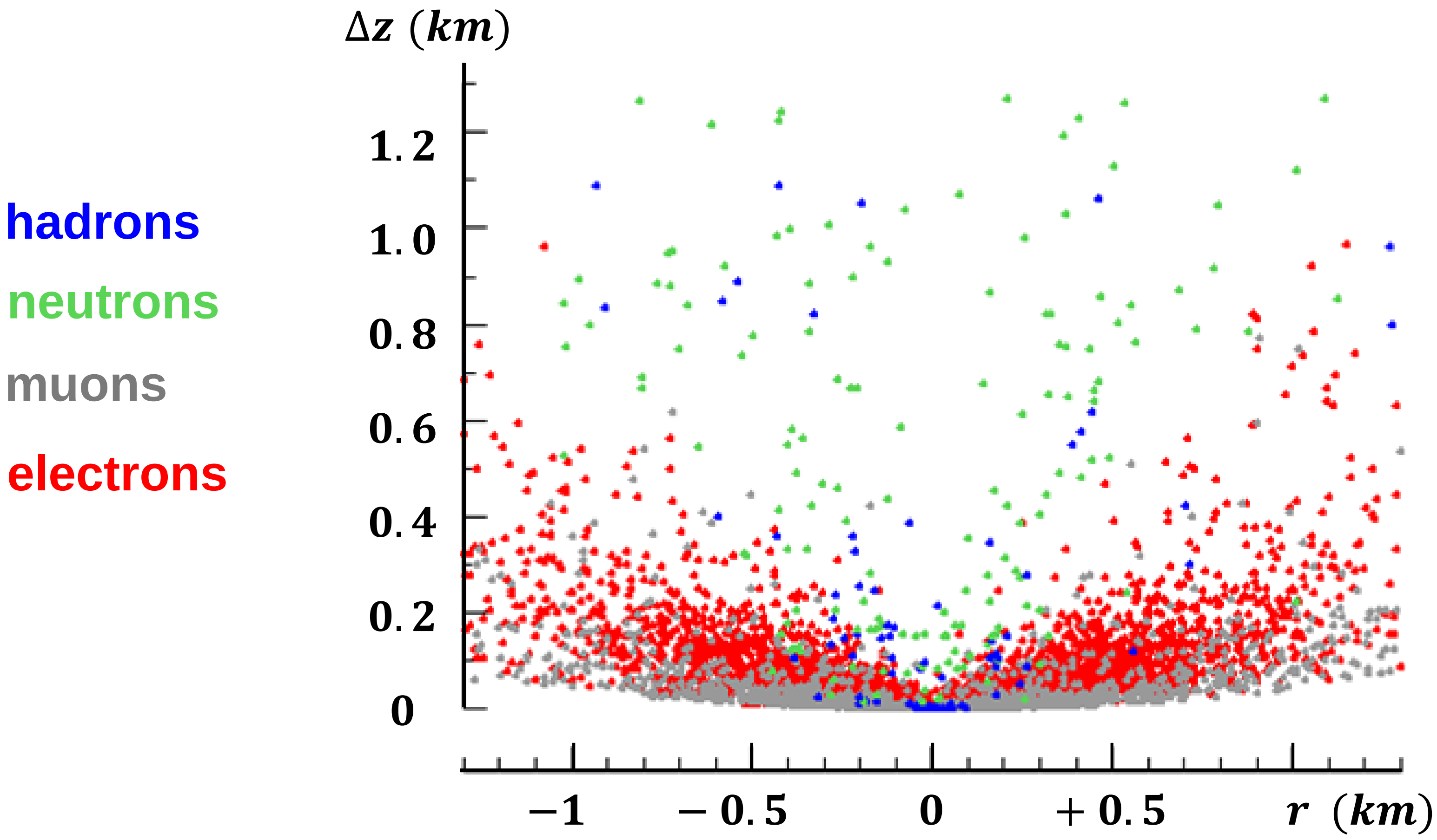
shower front

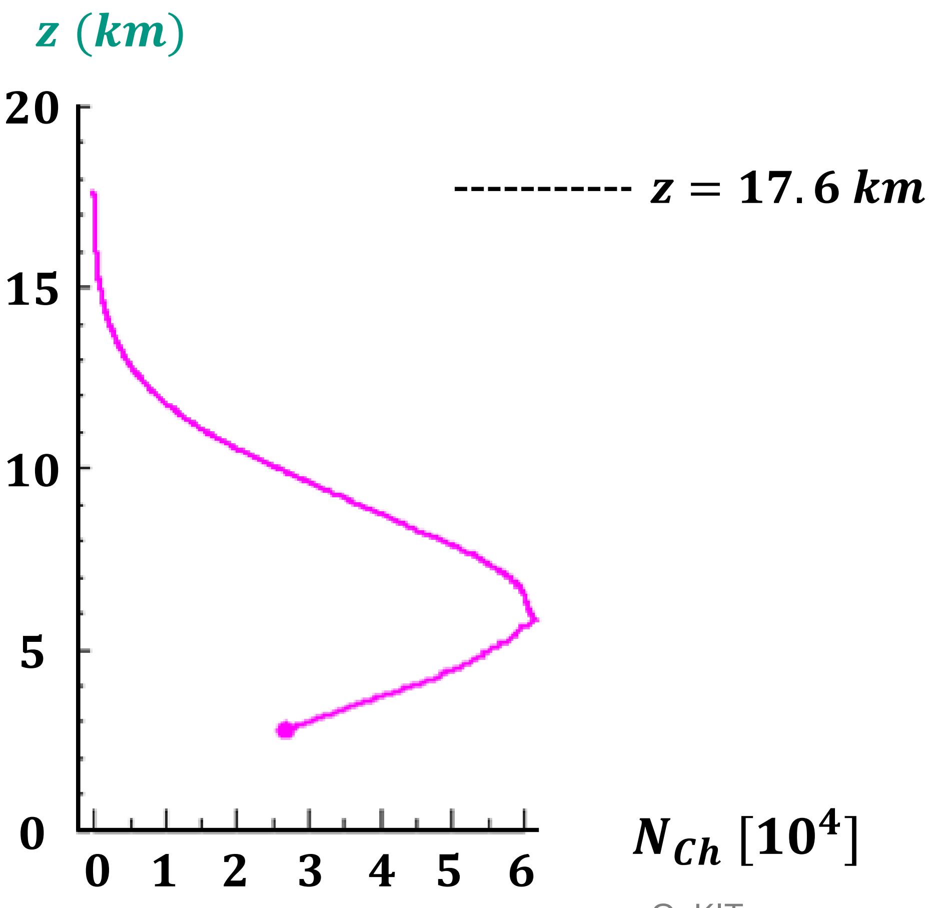




Extended air showers – time development

- 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**

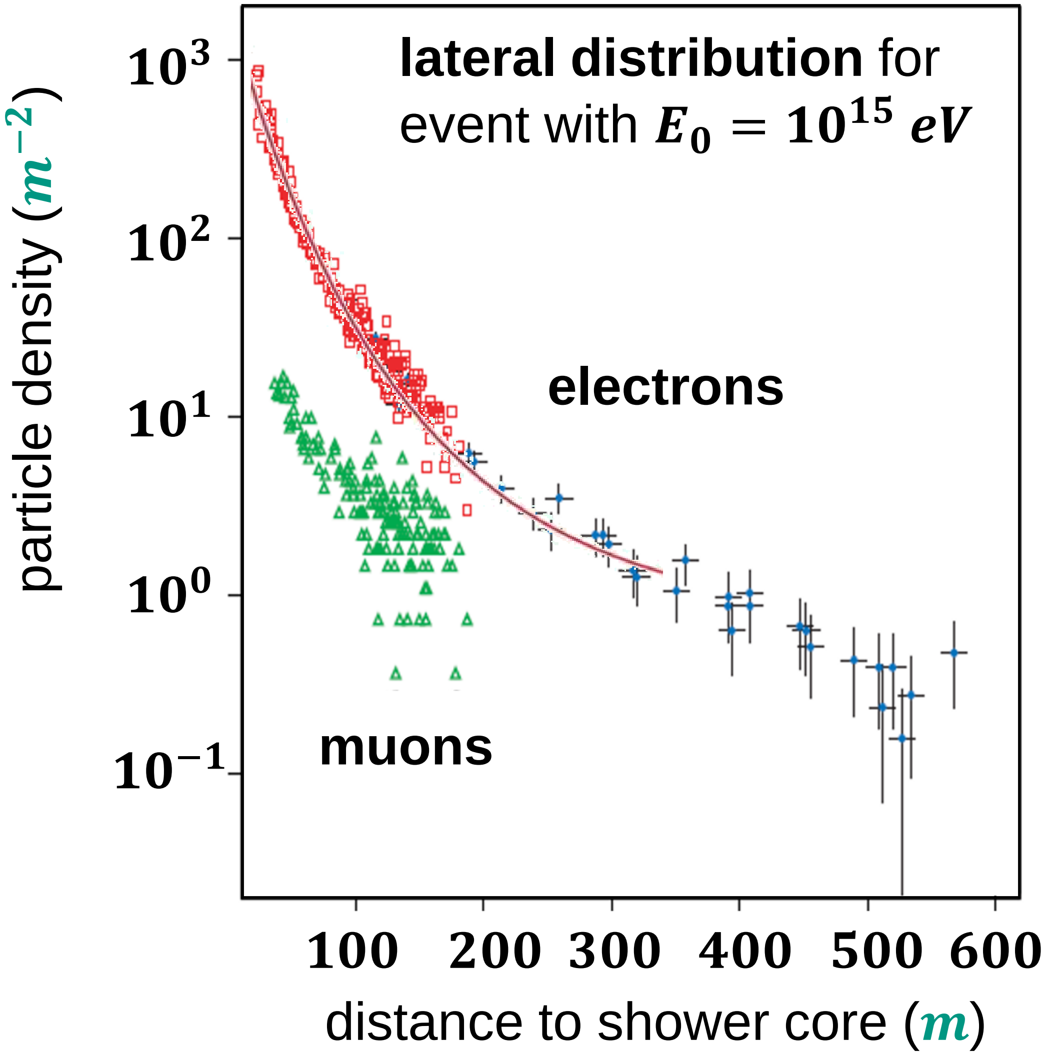
  - extraction of E_0 via

    N_e = number of **electrons** } in a shower
    N_μ = number of **muons**

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

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

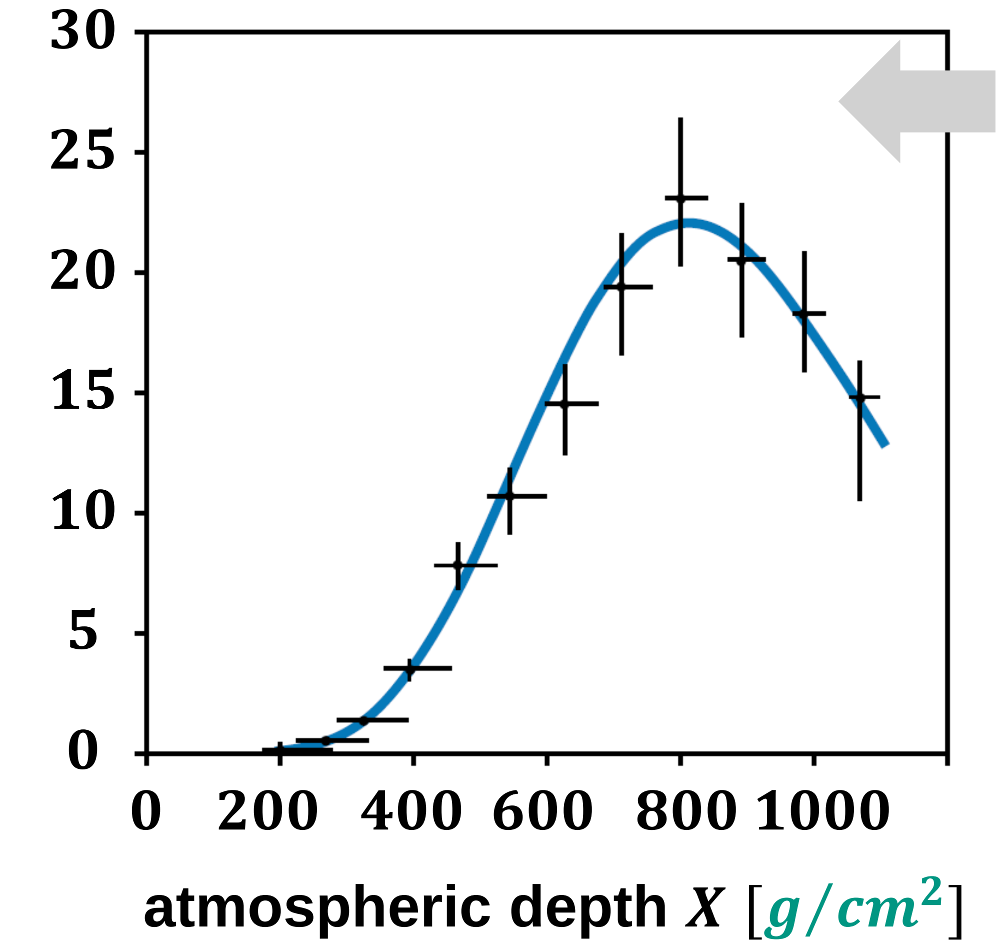
Kenneth Greisen



(*details in $ATP-2$ ´cosmic rays´)

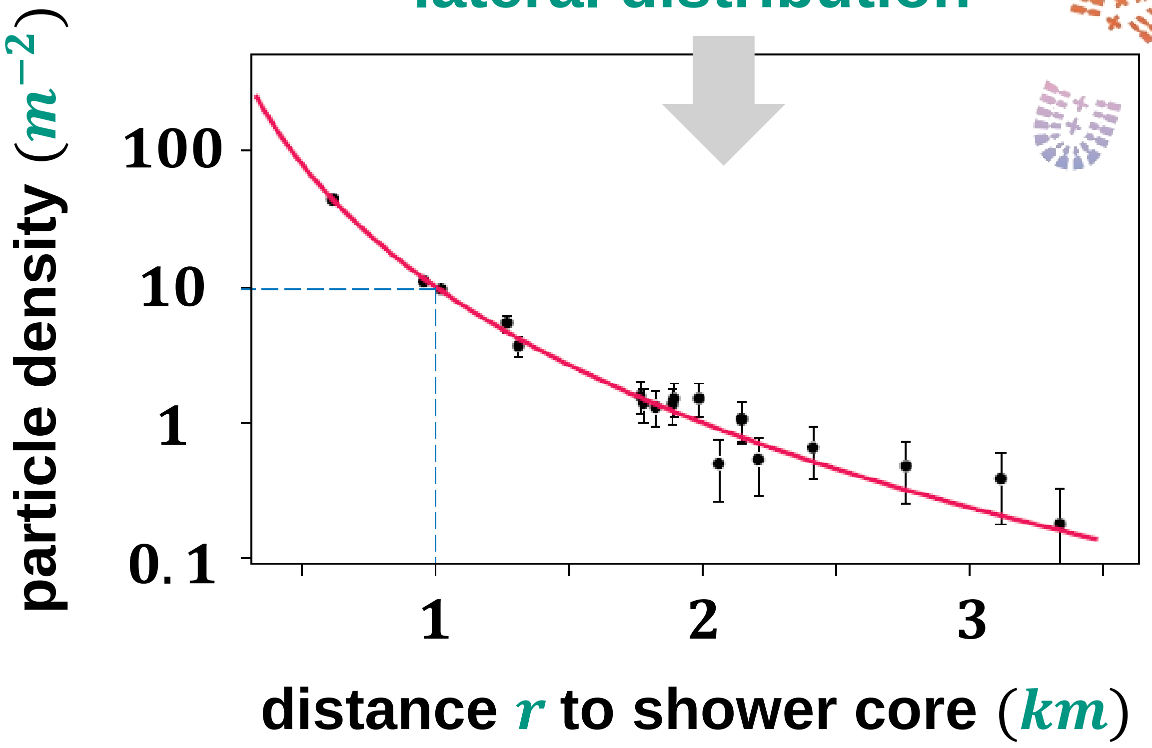
Combining lateral $\rho(r)$ with longitudinal profile

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



longitudinal distribution

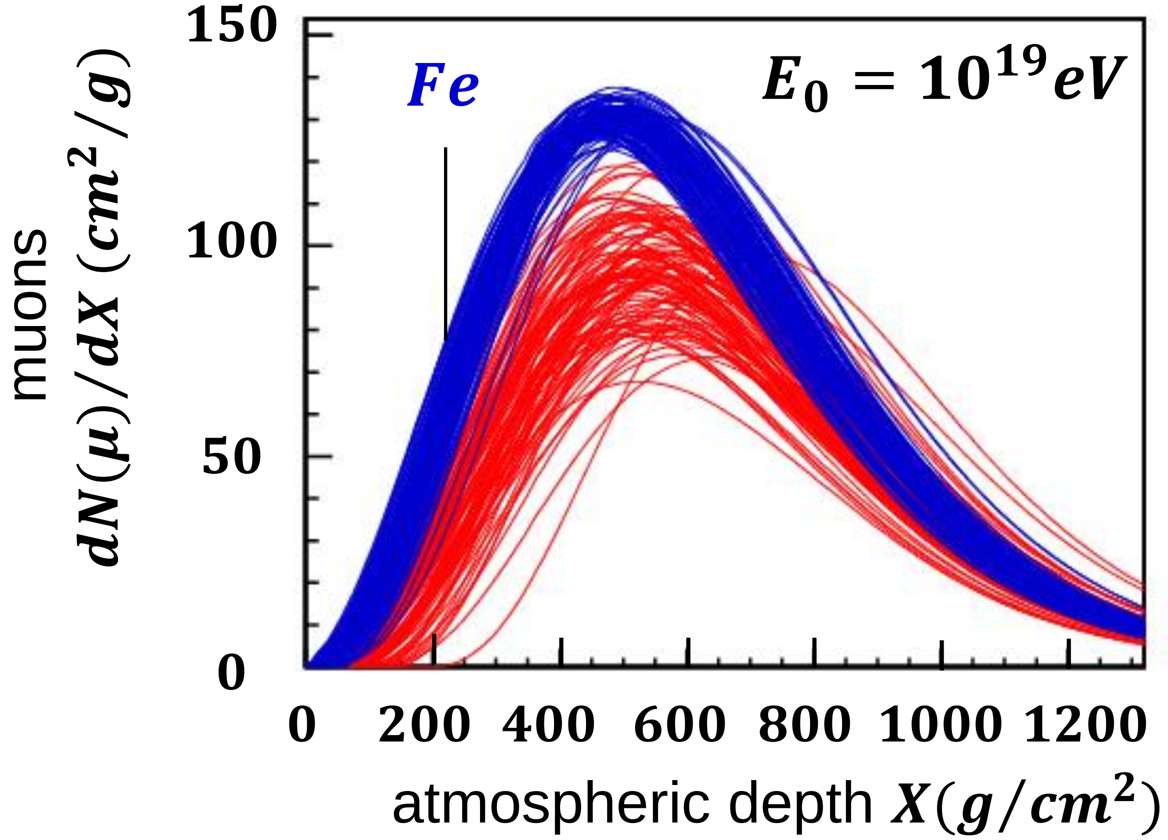
lateral distribution



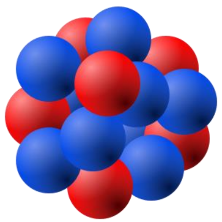
Air showers: determining the primary mass A

- **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 ($Z = 26$)

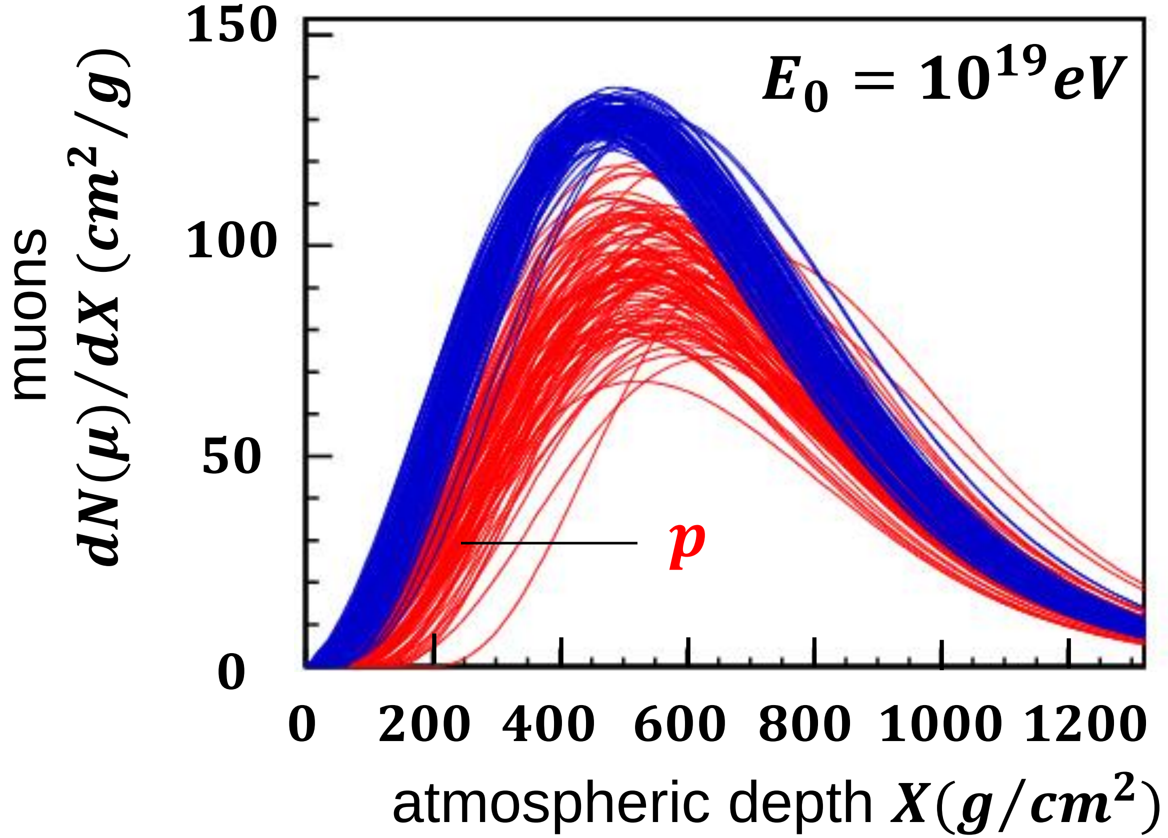
  ⇨ nuclei already interact in **topmost** atmospheric layers

  ⇨ **smaller X_{max}**

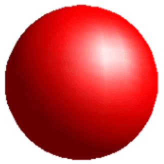
Air showers: determining the primary mass A

- **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 ($Z = 1, \ldots$)

⇨ 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

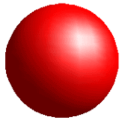
  ⇨ reach surface also from **smaller** X

Air showers: determining the primary mass A

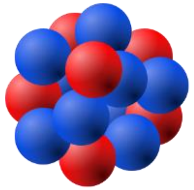
Karlsruhe Institute of Technology

- **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_μ 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

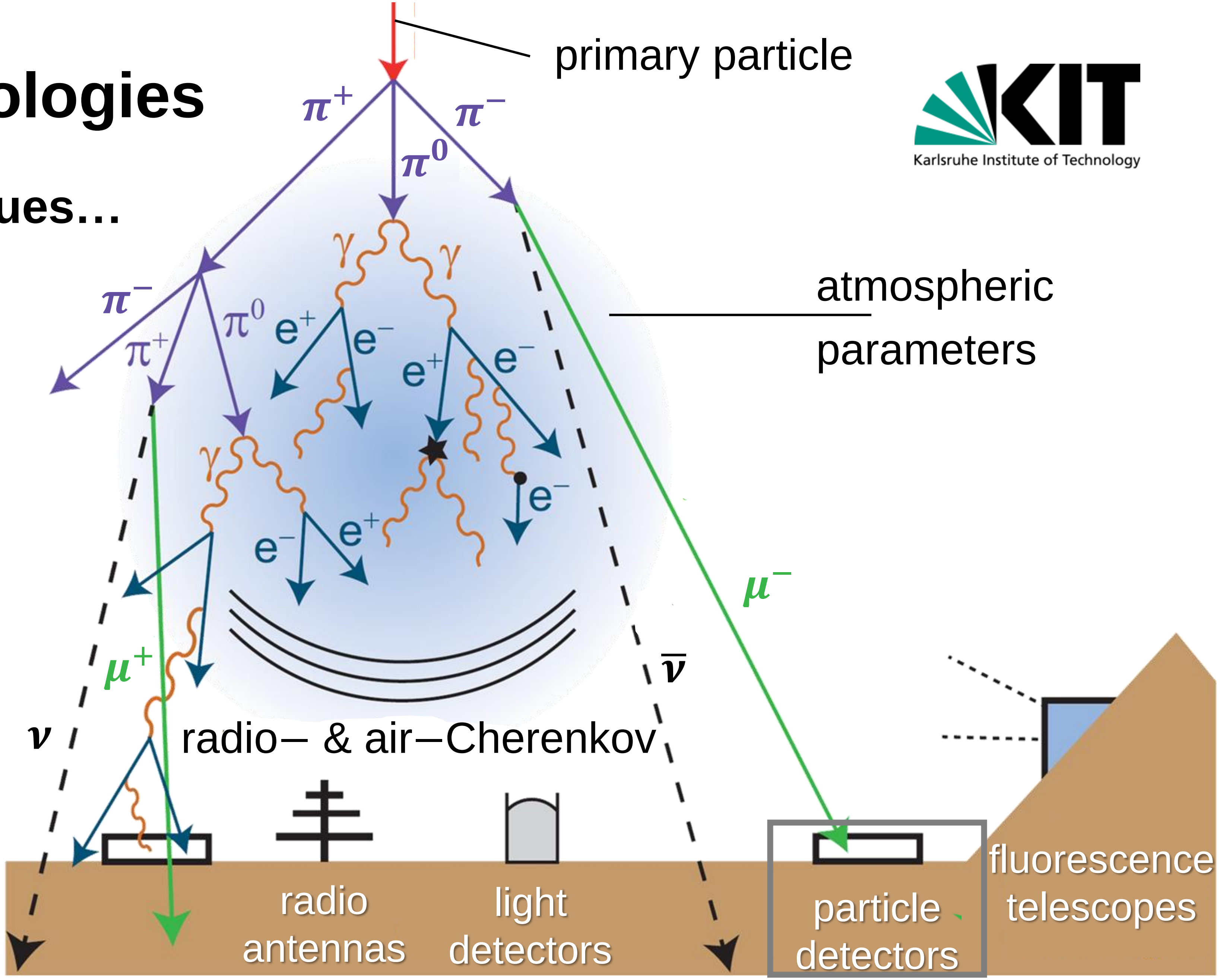
- A wide range of techniques…

longitudinal distributions

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

lateral distributions

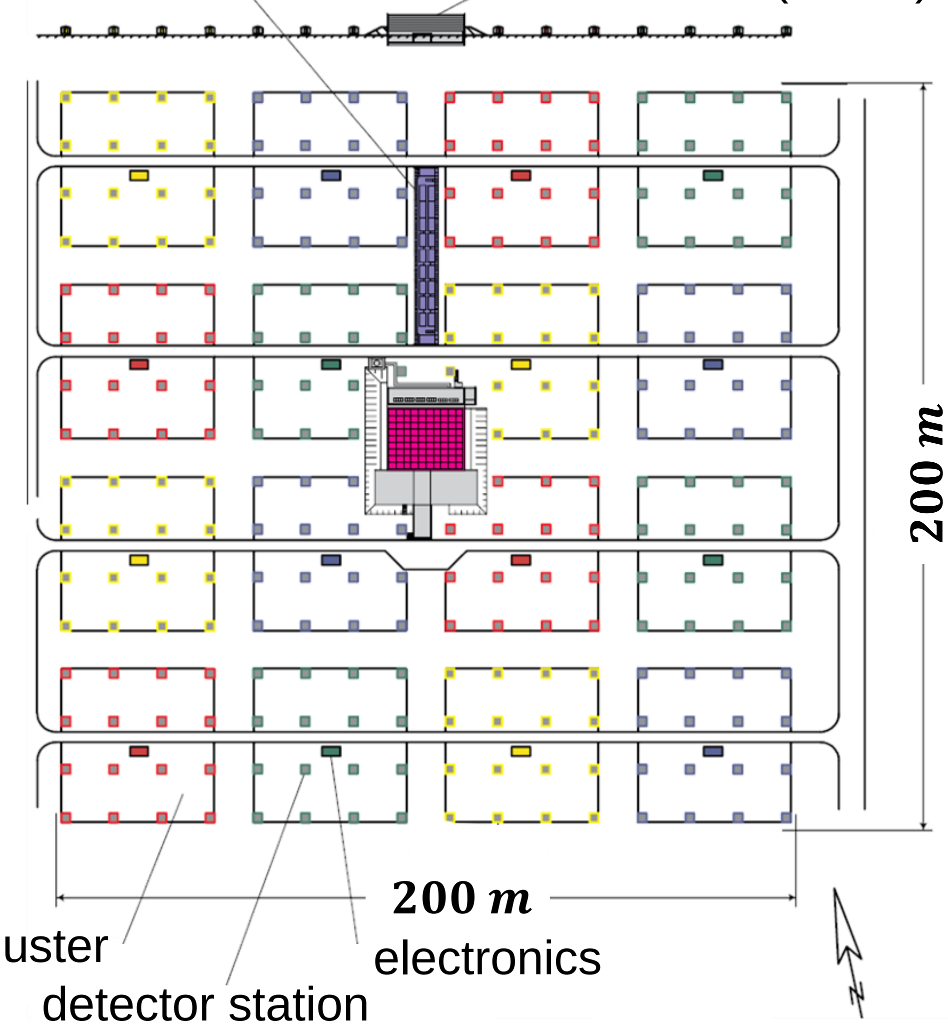
- scintillators
- $MWPC$*
- water Cherenkov



*Multi–Wire Proportional Chamber

$KASCADE$ experiment at KIT

- $KASCADE$ – KArlsruhe Shower Core and Array DEtector ($1996 \ldots 2009$)



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:

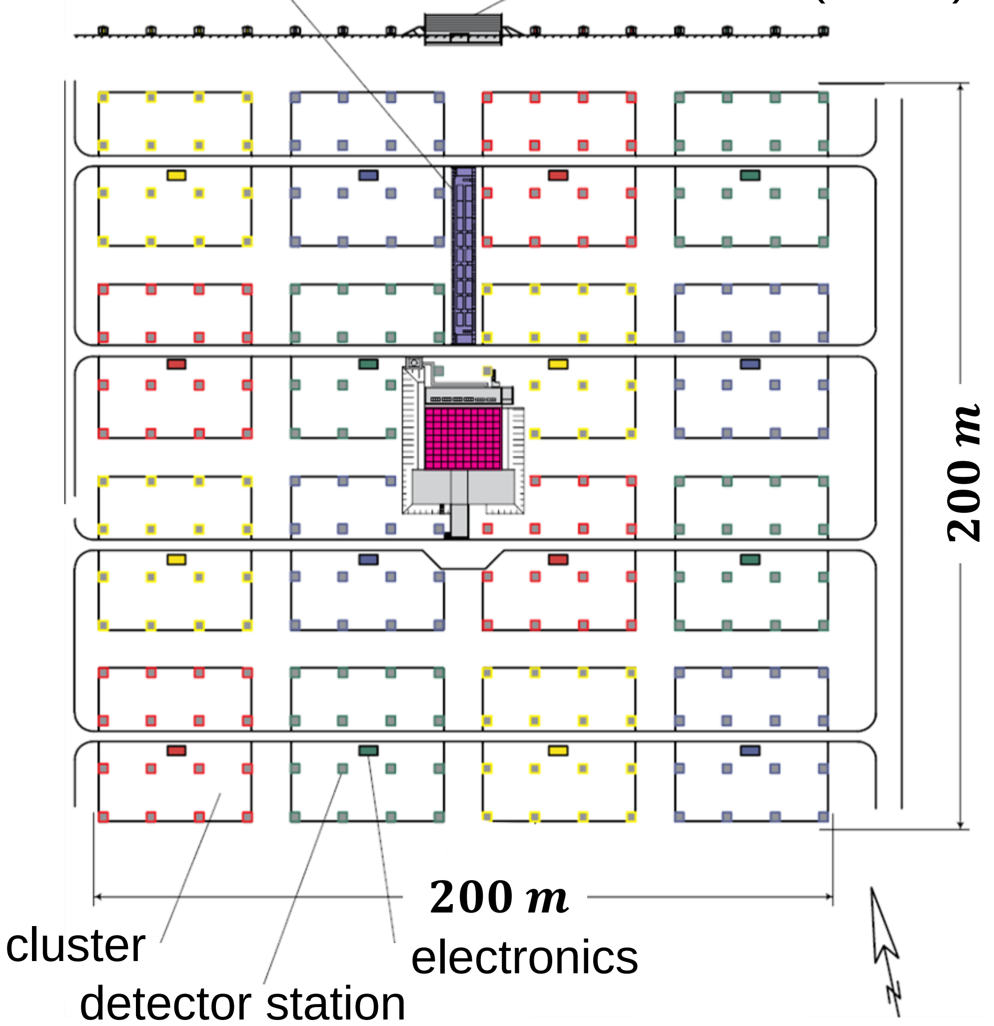
  16×16 detector stations
  detectors for muons / electrons
  trigger electronics for entire shower

  central calorimeter ($HCAL$):

  TMS* ionisation chambers
  ⇨ detection of hadronic shower core

  muon tunnel:

  sampling of muon distribution



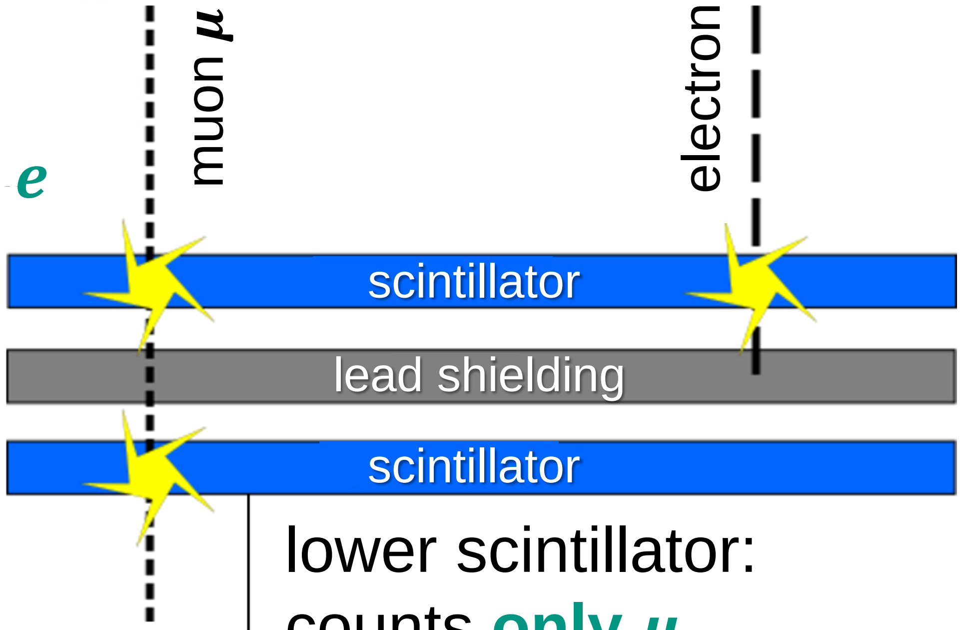
* Tetra–Methyl–Silane

$KASCADE$ experiment

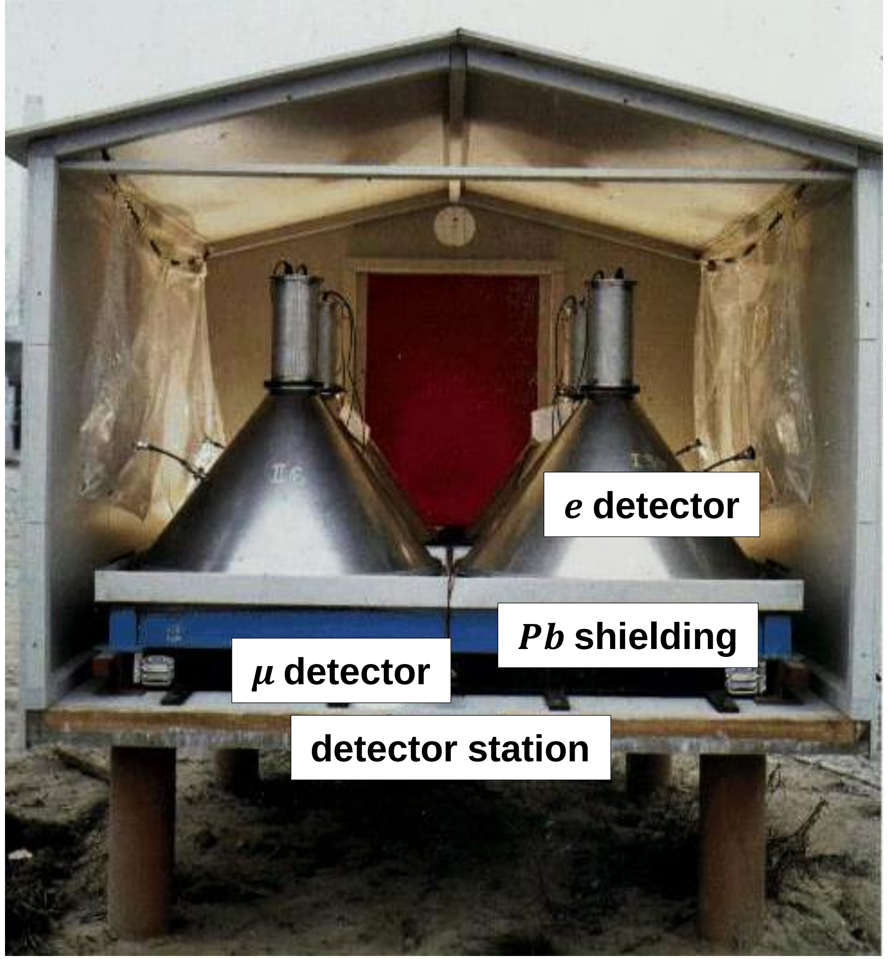
- **The detector array to measure electron & muon distributions separately**

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

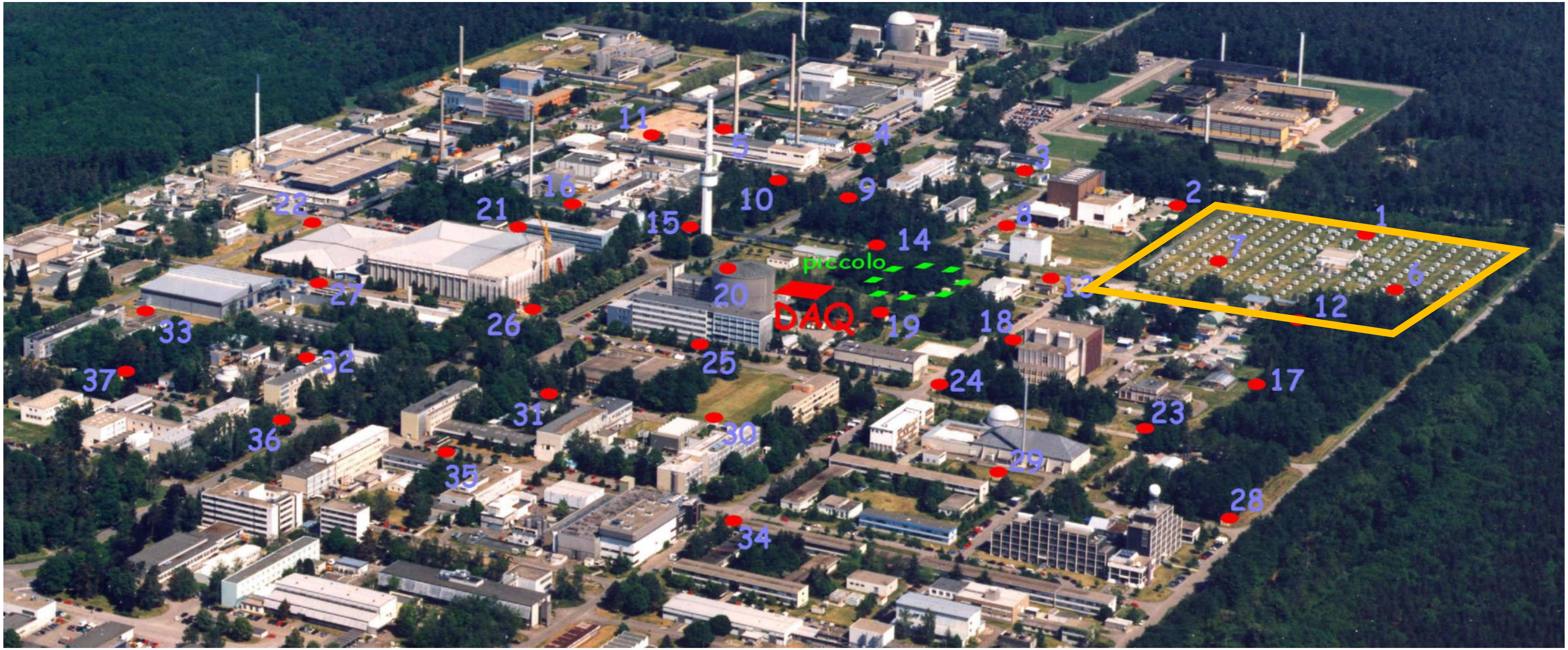


lower scintillator:
counts **only μ**



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

Karlsruhe Institute of Technology

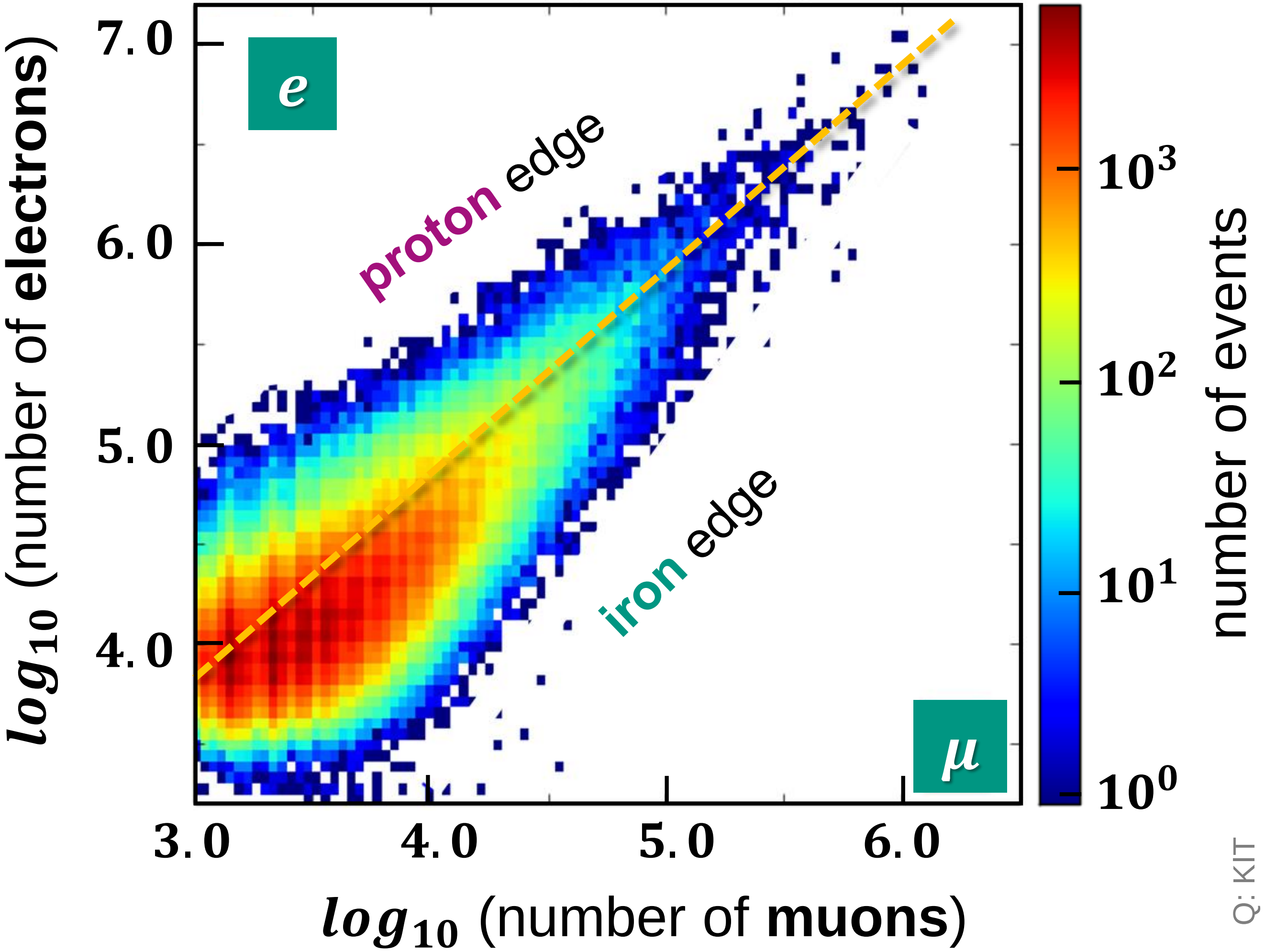
- **measuring N_e and N_μ: using sum $N_e + N_\mu$ & ratio N_e/N_μ**

- 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 at top of atmosphere
  ↳ **ratio N_e/N_μ small: large A**

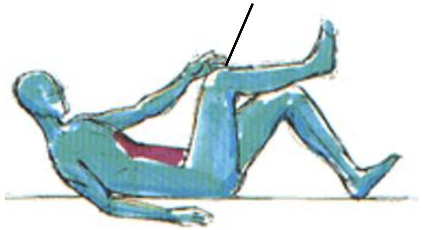
experimental distributions



Q: KIT

$KASCADE$ – experimental observations

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

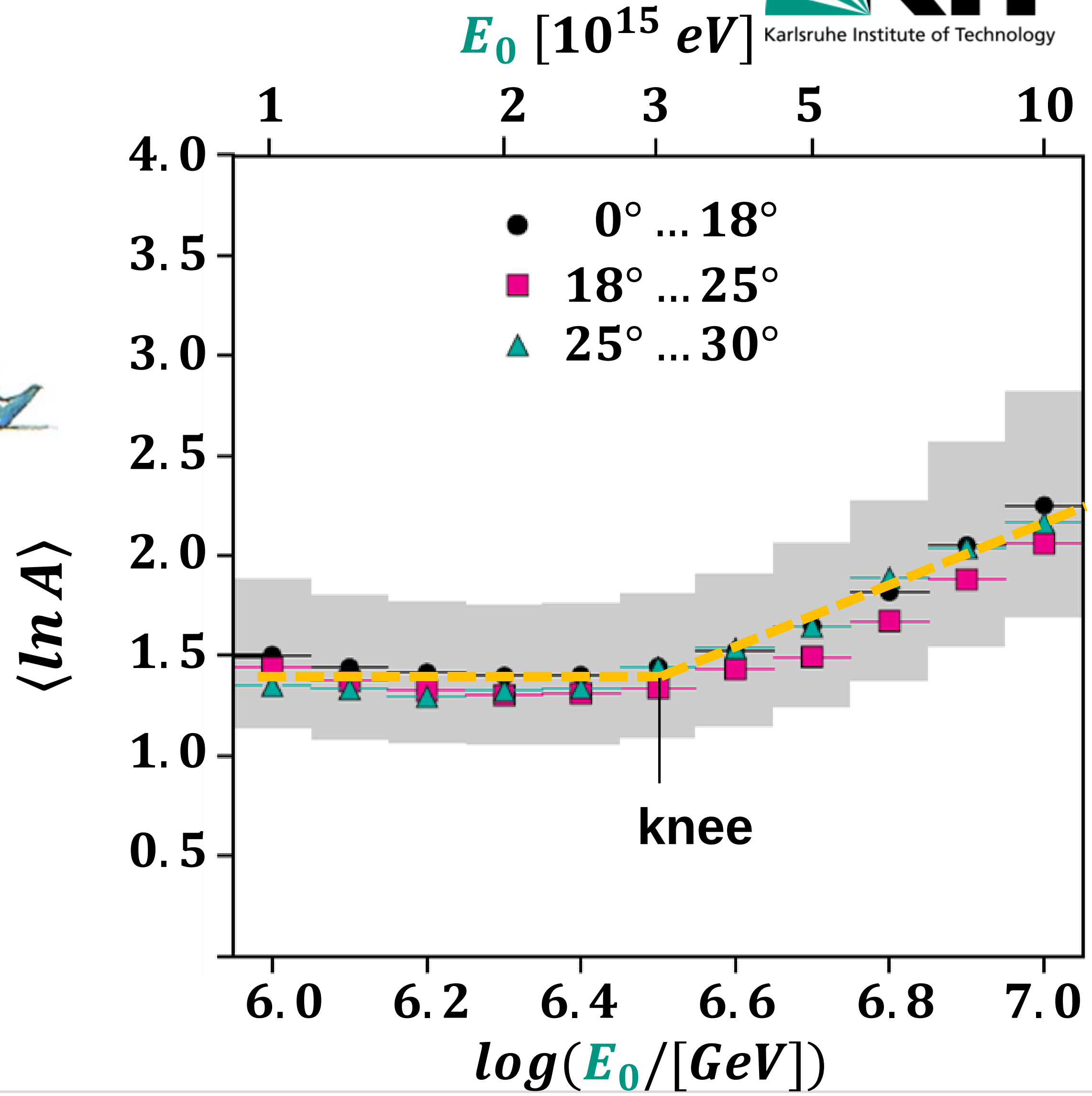


- **knee**: a spectral feature at energies $E_0 \sim 3 - 4 \cdot 10^{15} eV$

- above the **knee**:

  charged CR get ´heavier´

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

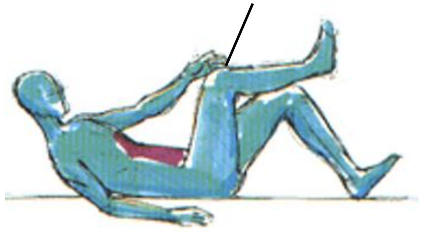


Q: KIT

$KASCADE$ – experimental observations

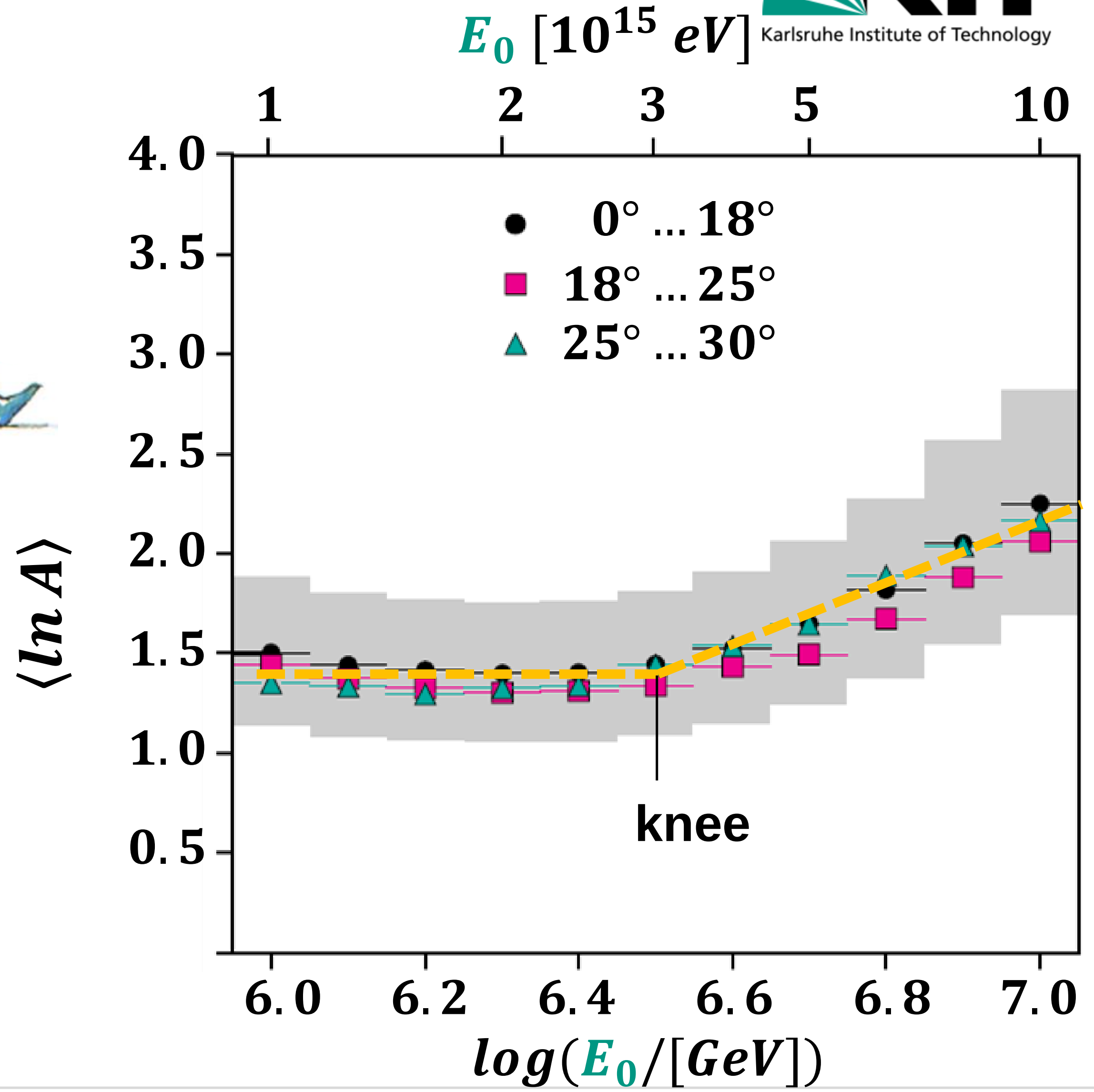
- **Chemical composition of CR changes as function of energy E_0**

- **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 our galaxy) cause a **loss of light nuclei** from source to Earth?



Q: KIT

CR energy spectra – the knee

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

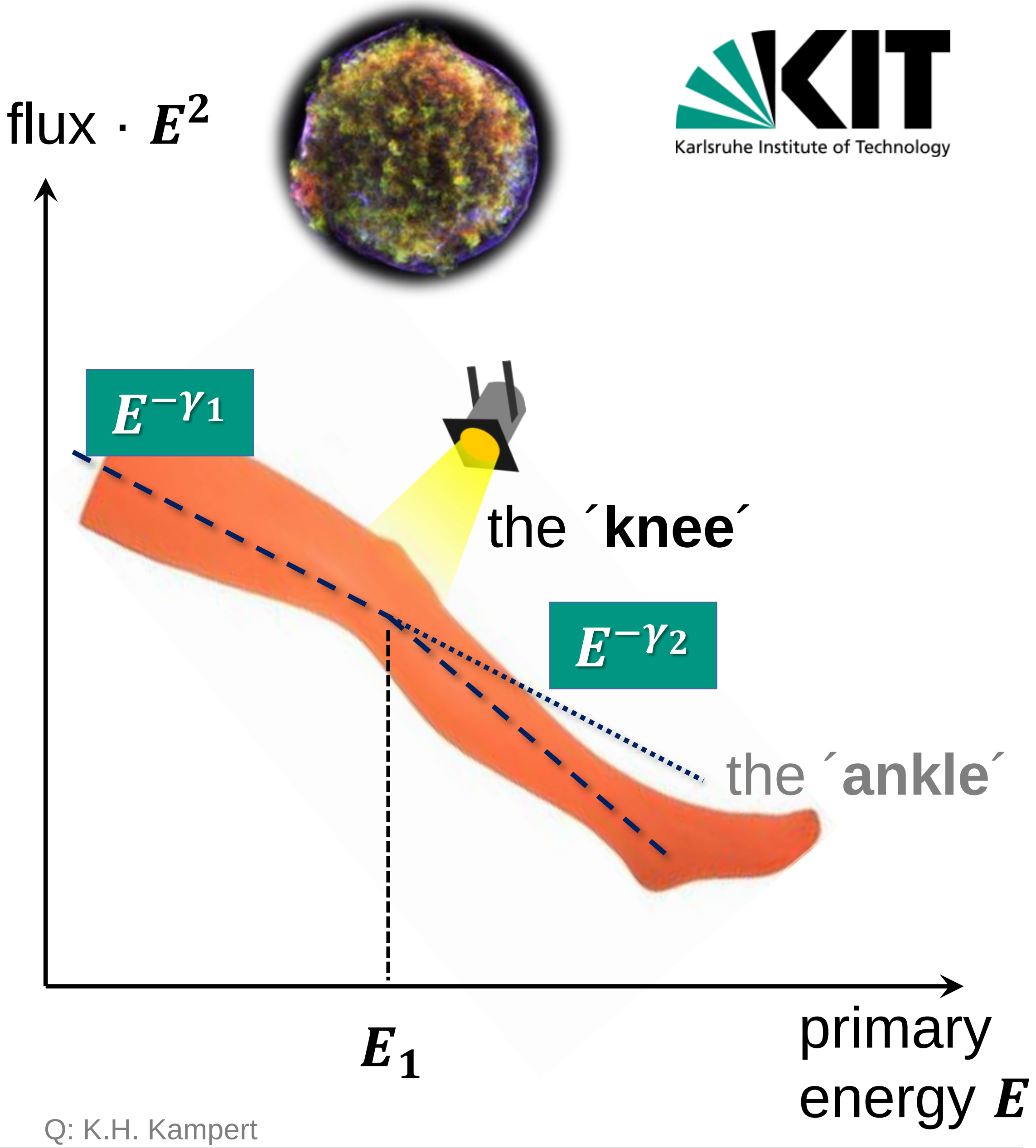
  - at characteristic energy E_1:

    - 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

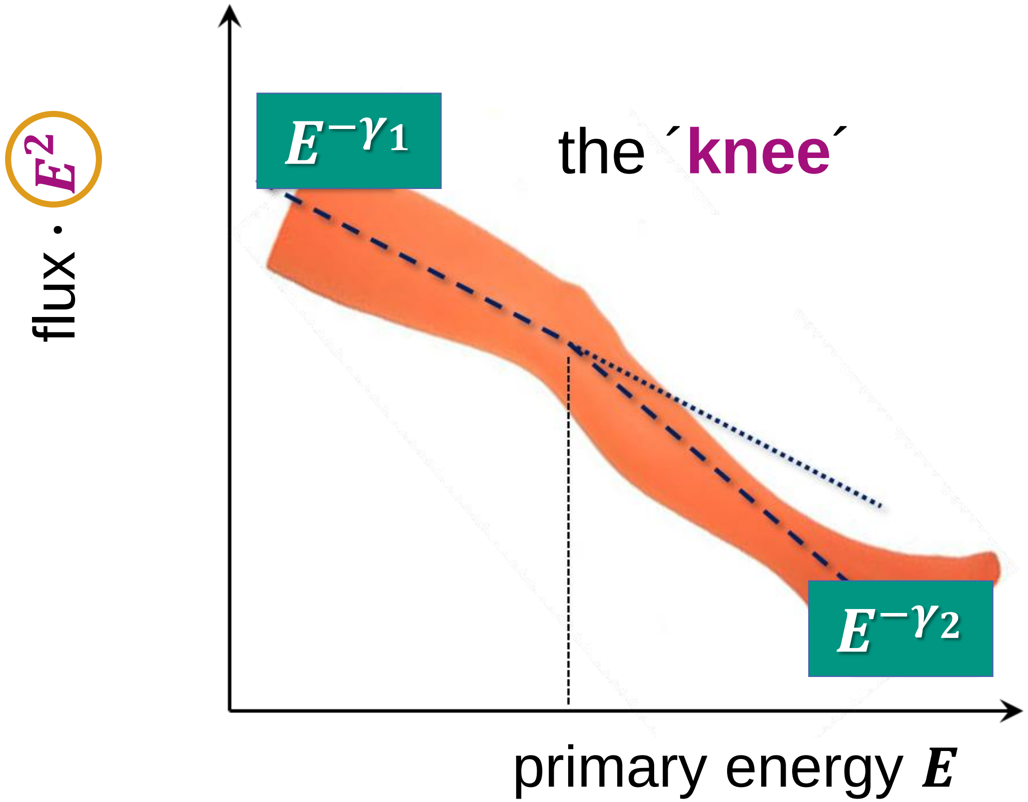
  - the ´**ankle**´: change of accleration sites - **galactic ⇔ extragalactic**

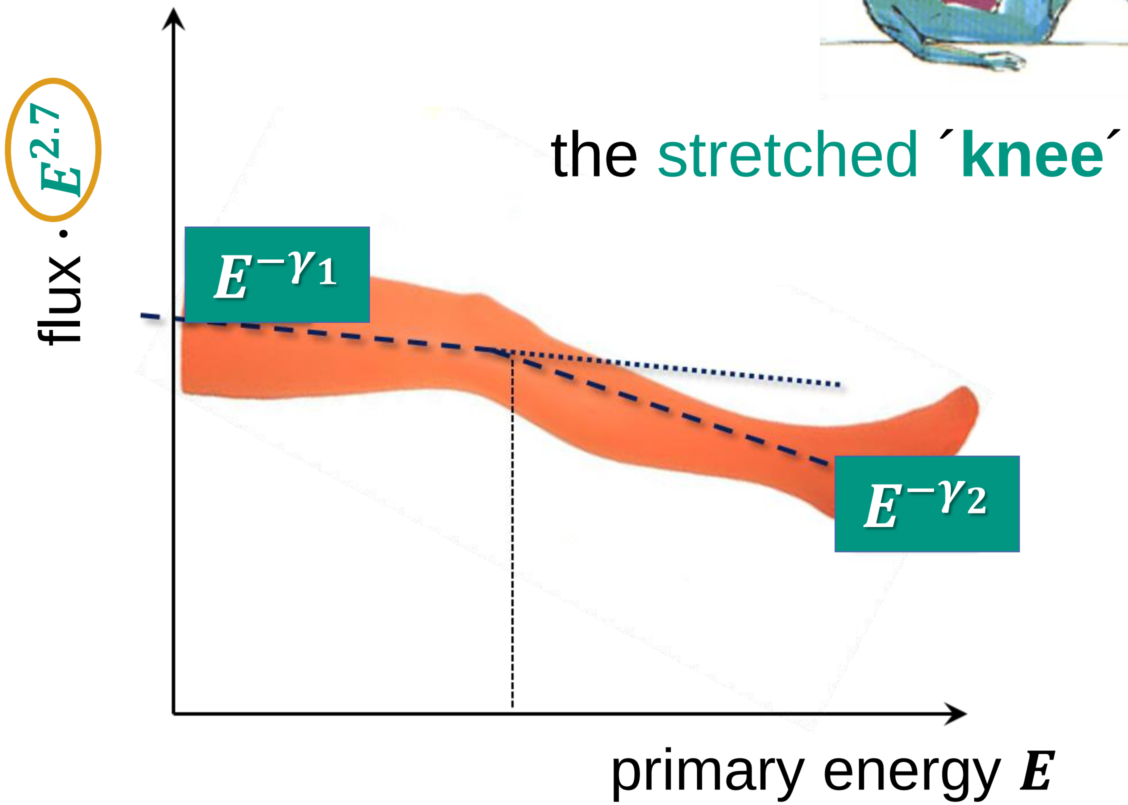


Q: K.H. Kampert

CR – energy spectra multiplied by energy factors

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



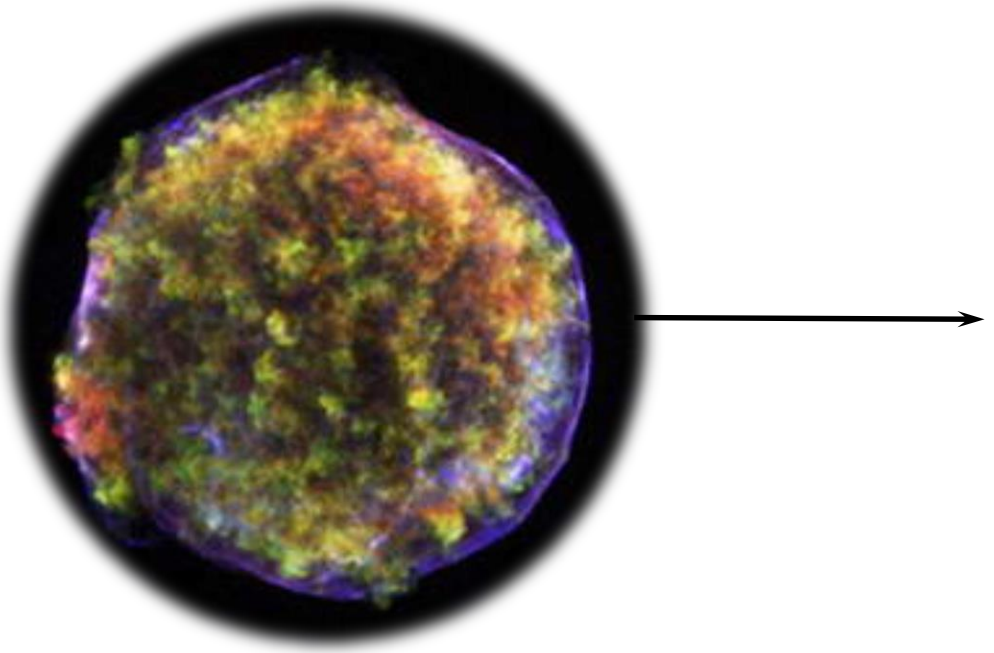


Q: K.H. Kampert

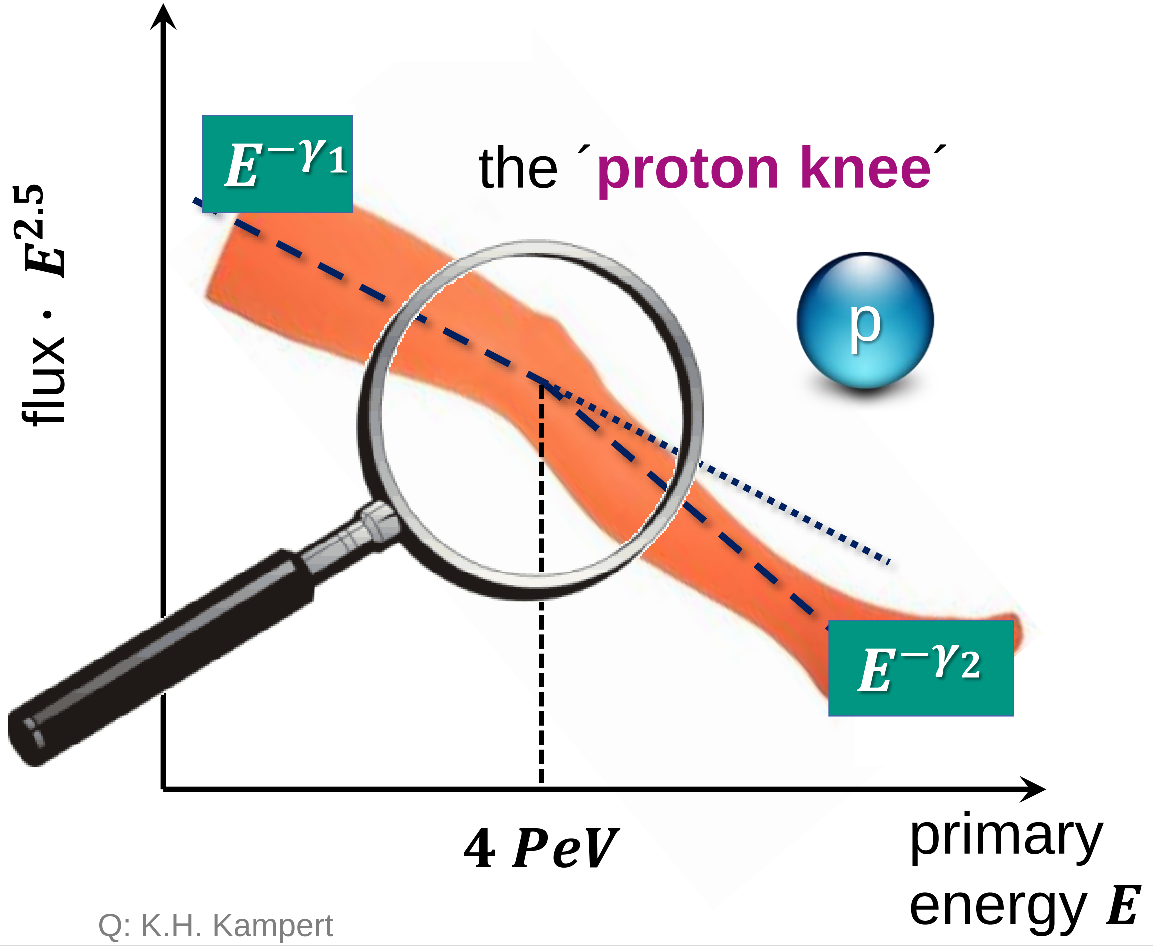
CR energy spectra – the p, Fe knee

- **observation of 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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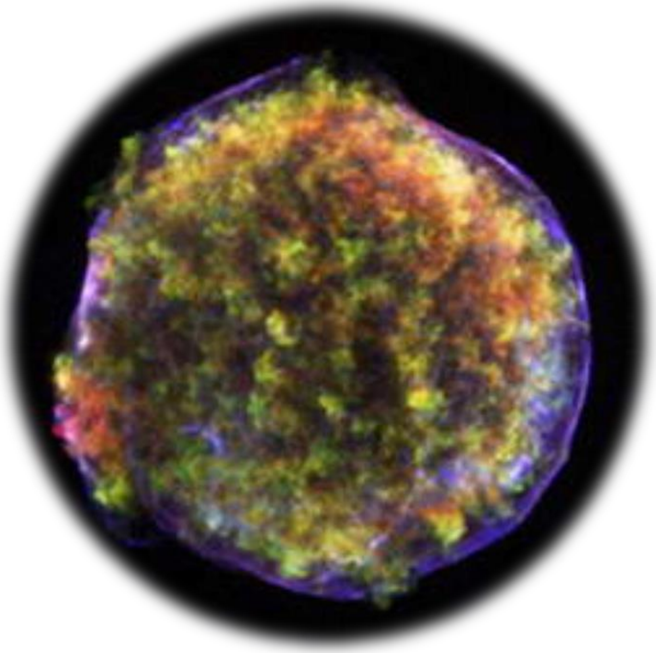
- important: **different** nuclear charges z



acceleration in SN – shock front

Q: KIT