Erice Summer School 2022

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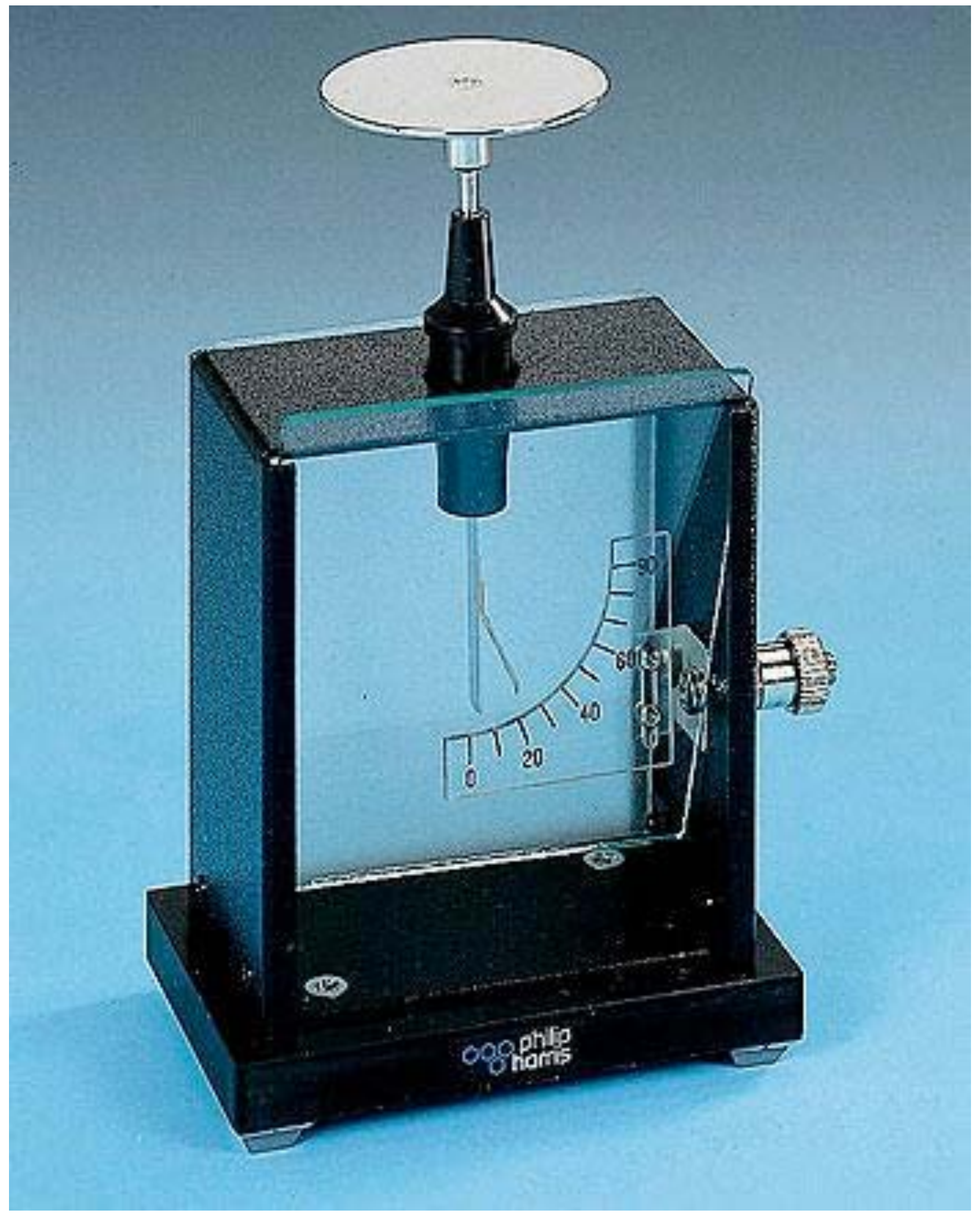
GAMMA RAY DETECTION WITH AIR SHOWERS

Cosmic Ray Discovery

- Physikalische Zeitschrift: “The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above.”

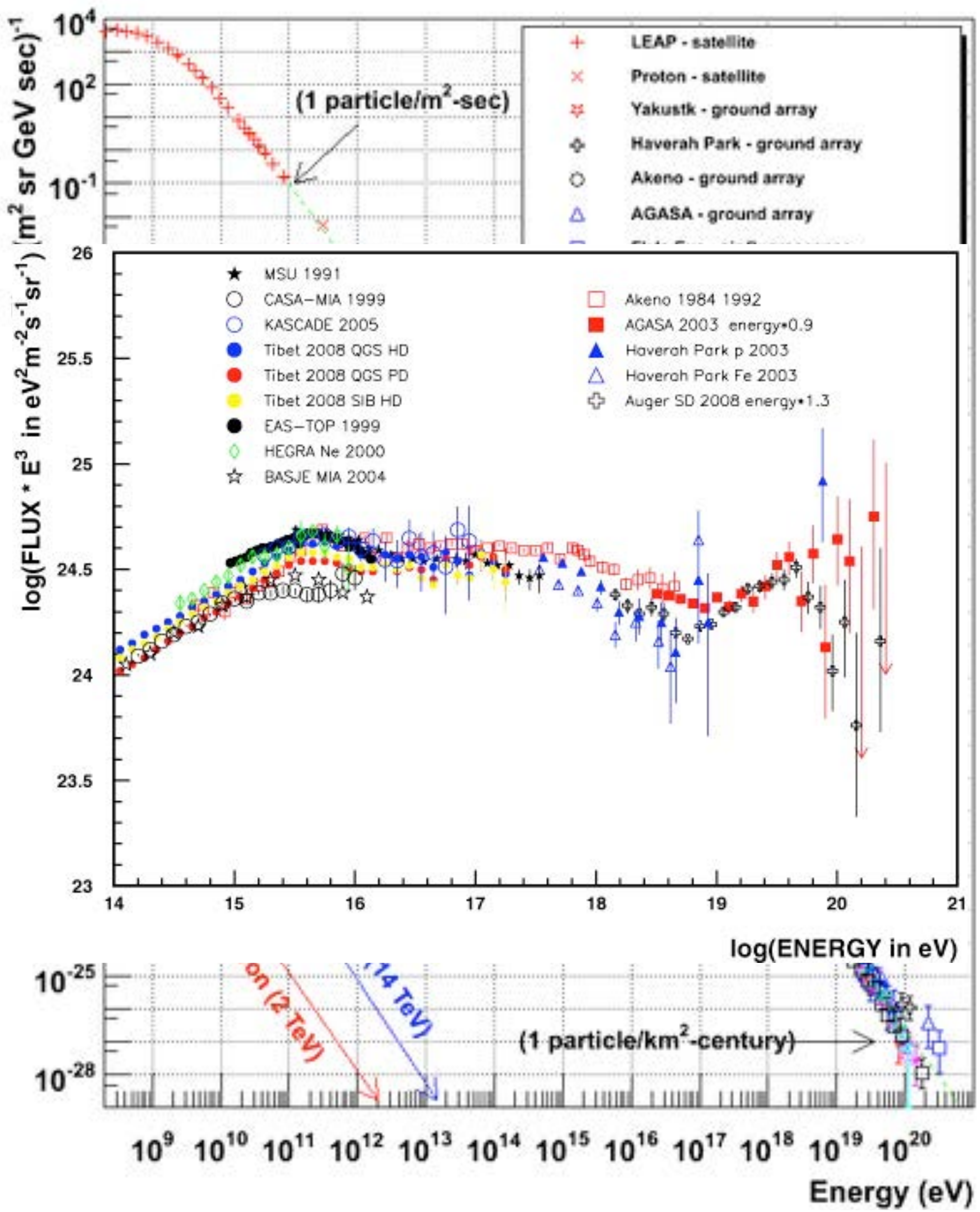
Elevation	Rate
Ground	12
1km	10
2 km	12
3.5 km	15
5 km	27

Victor Franz Hess



V. F. Hess. Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten. Physikalische Zeitschrift, 13:1084-1091, November 1912.

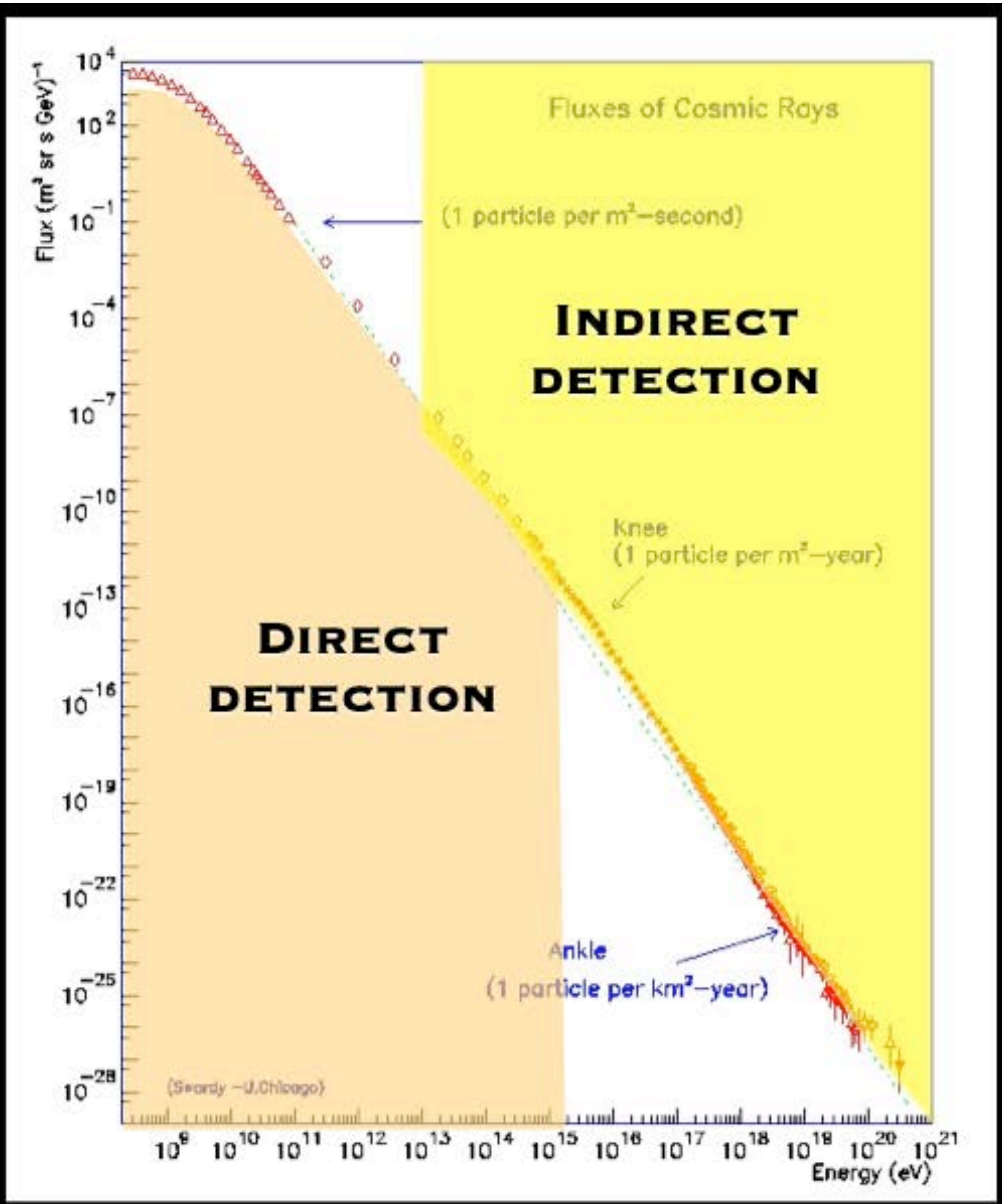

AERO
CLUB
WIEN



Cosmic Rays

- The flux charged cosmic rays follows nearly a single power law over:
  - 10 decades in energy
  - 30 decades in flux
- Single particles have been observed with energies above 10^{20}eV!
- There are several "kinks" in the spectrum where the exponent changes, steepening at the "knee" and flattening at the "ankle".
- The source of the high-energy cosmic rays remains elusive.
- 10^{20}ev$\sqrt{s}$ equivalent is 430 TeV
-

Detectors in Particle Astrophysics



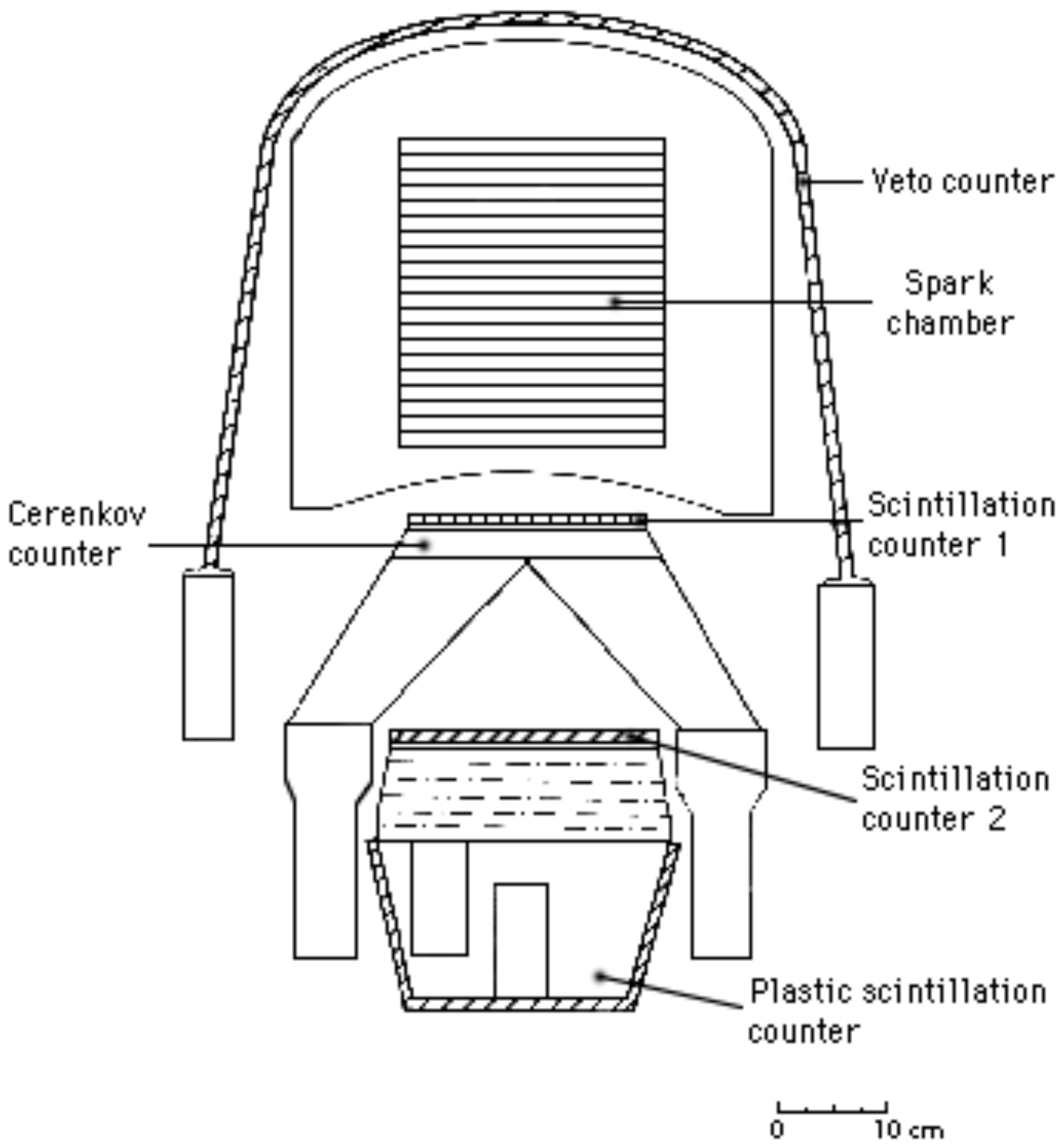
Low-energy CRs: rather high flux ($1/m^2$ s) but absorbed in the upper atmosphere.
Direct detection (top of the atmosphere or in space)

Balloons
Rockets
Satellites

High energy cosmic rays: very rare ($1/km^2$ y), but "penetrating" up to ground (atmospheric air-showers).
Indirect detection: long-lived large arrays (ground level)

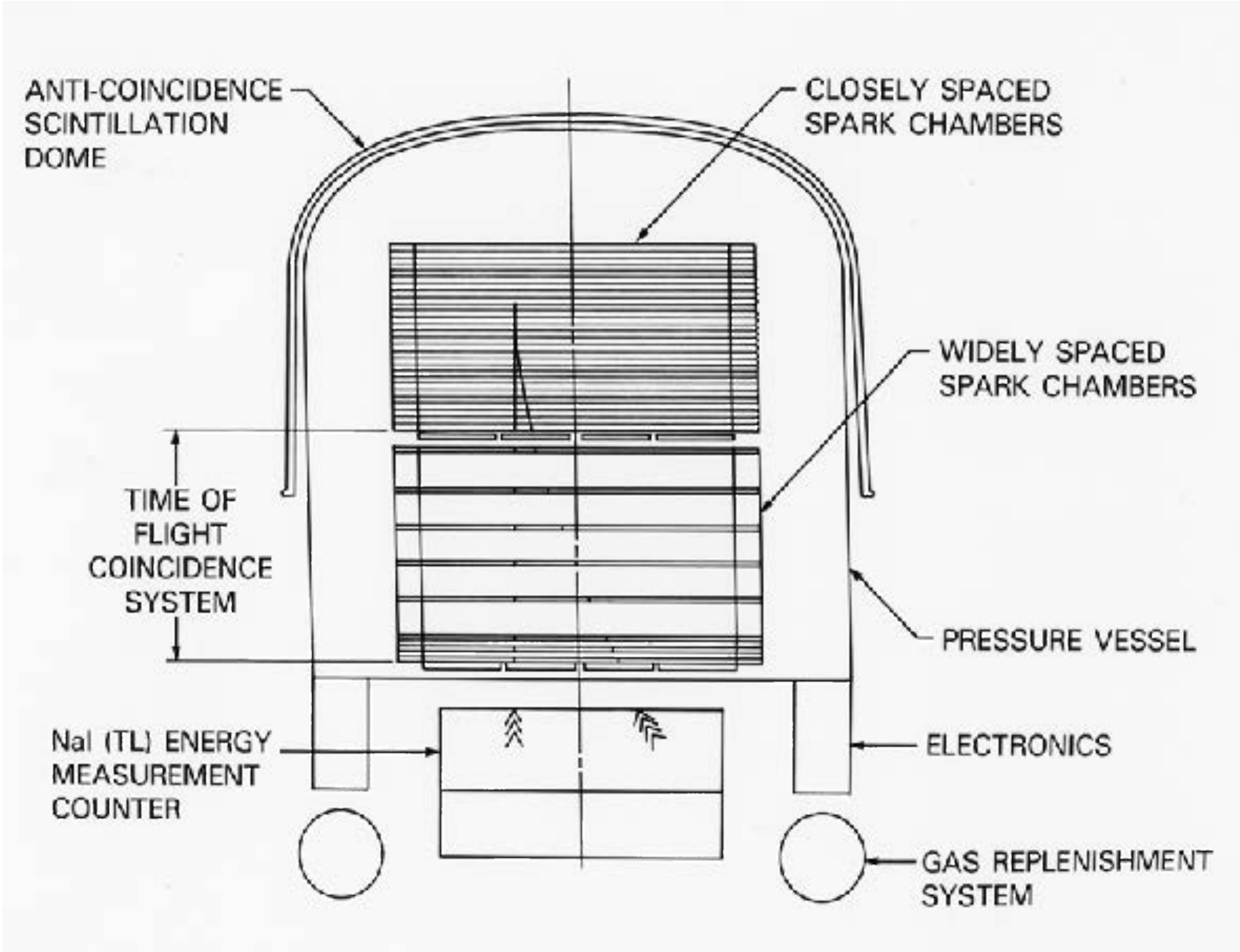
Large telescopes
Extensive Air showers arrays

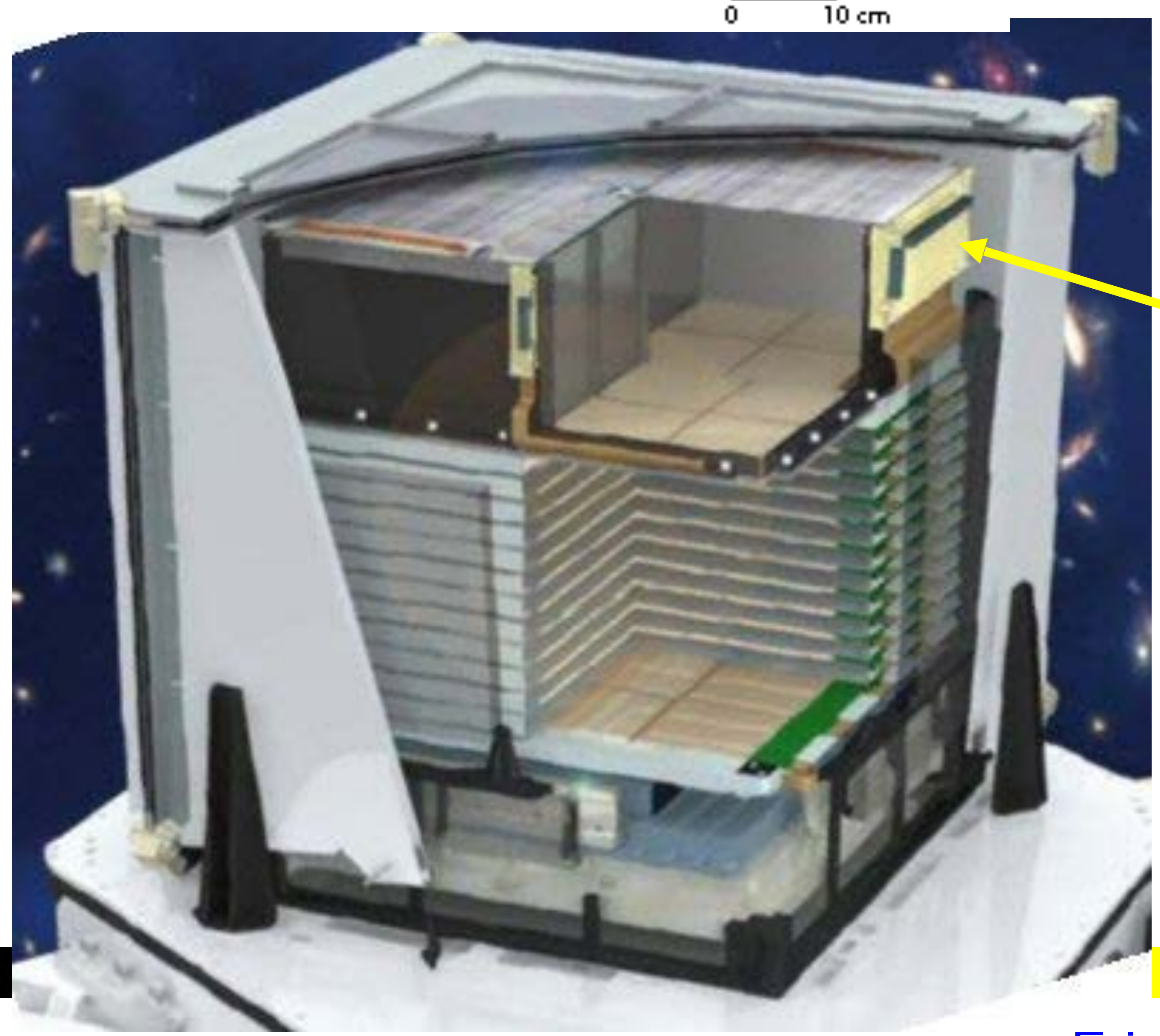
Space-based Gamma Ray Detectors



COS-B
(1975-1982)

EGRET
(1991-2000)

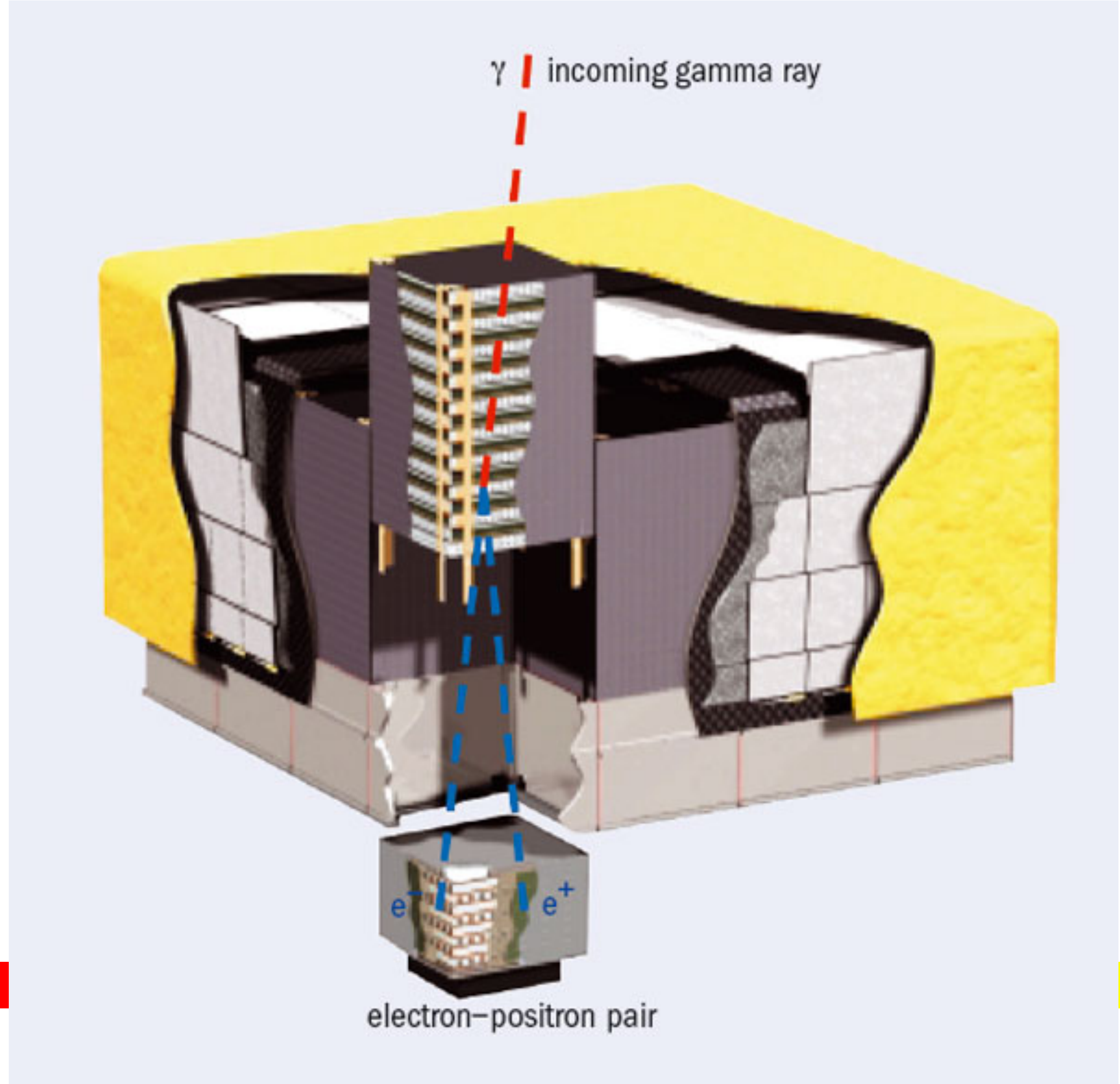




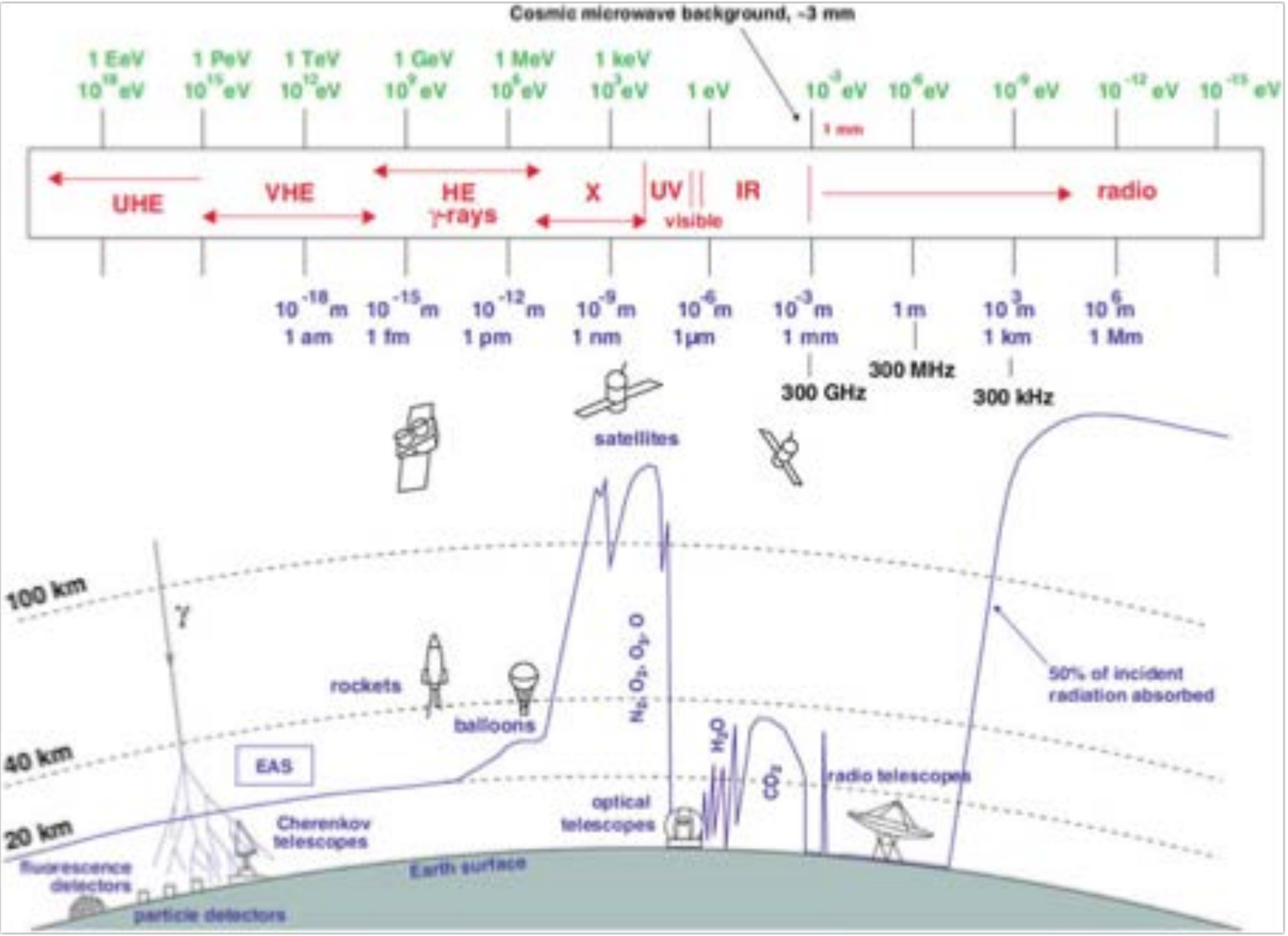
AGILE
(2007-)

HXD

Fermi-LAT
(2008-)

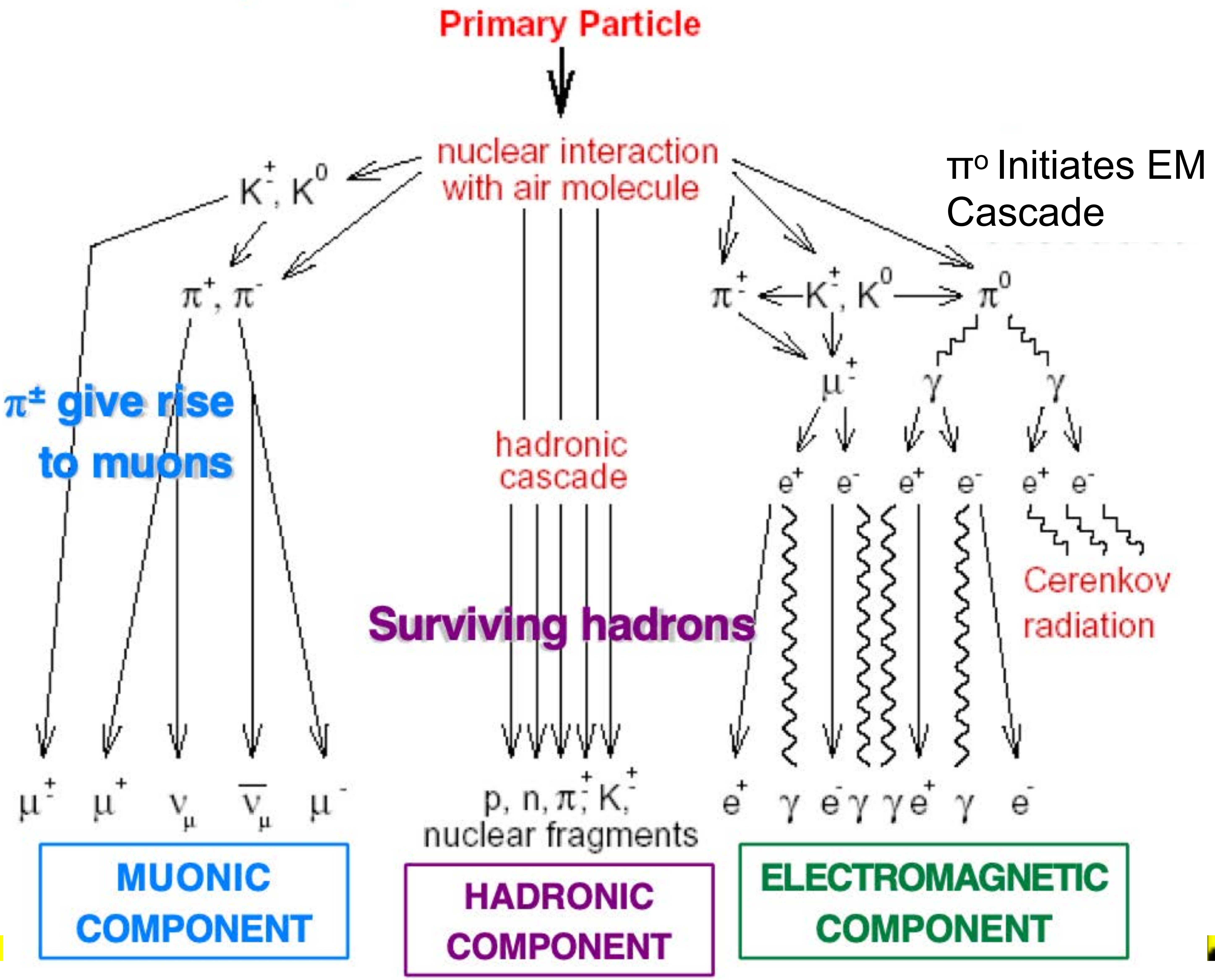


- Techniques (Space, Air, Ground)

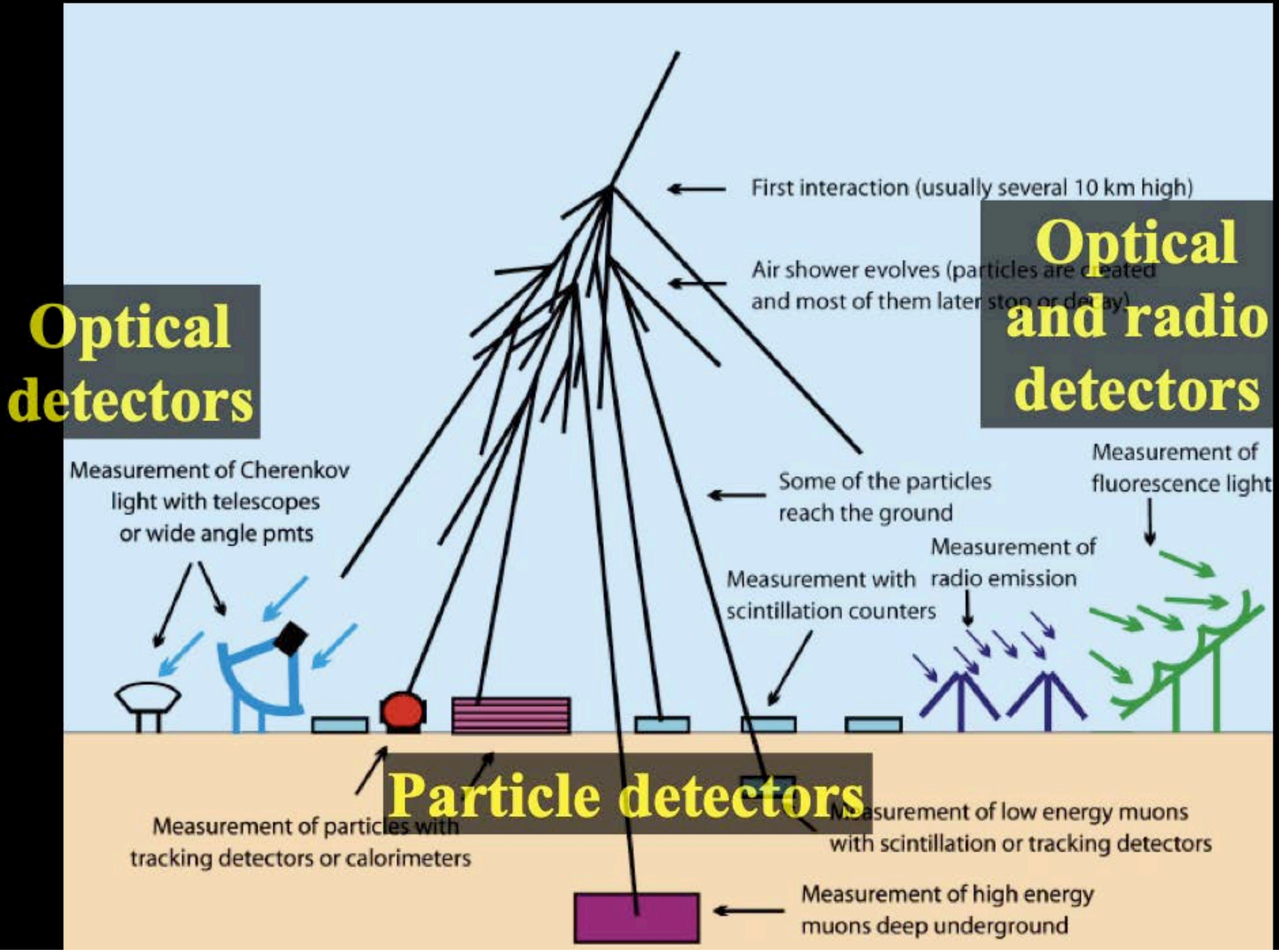


EXTENSIVE AIR SHOWERS

A high energy primary particle, upon entering the atmosphere, initiates a chain of nuclear interactions



DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES

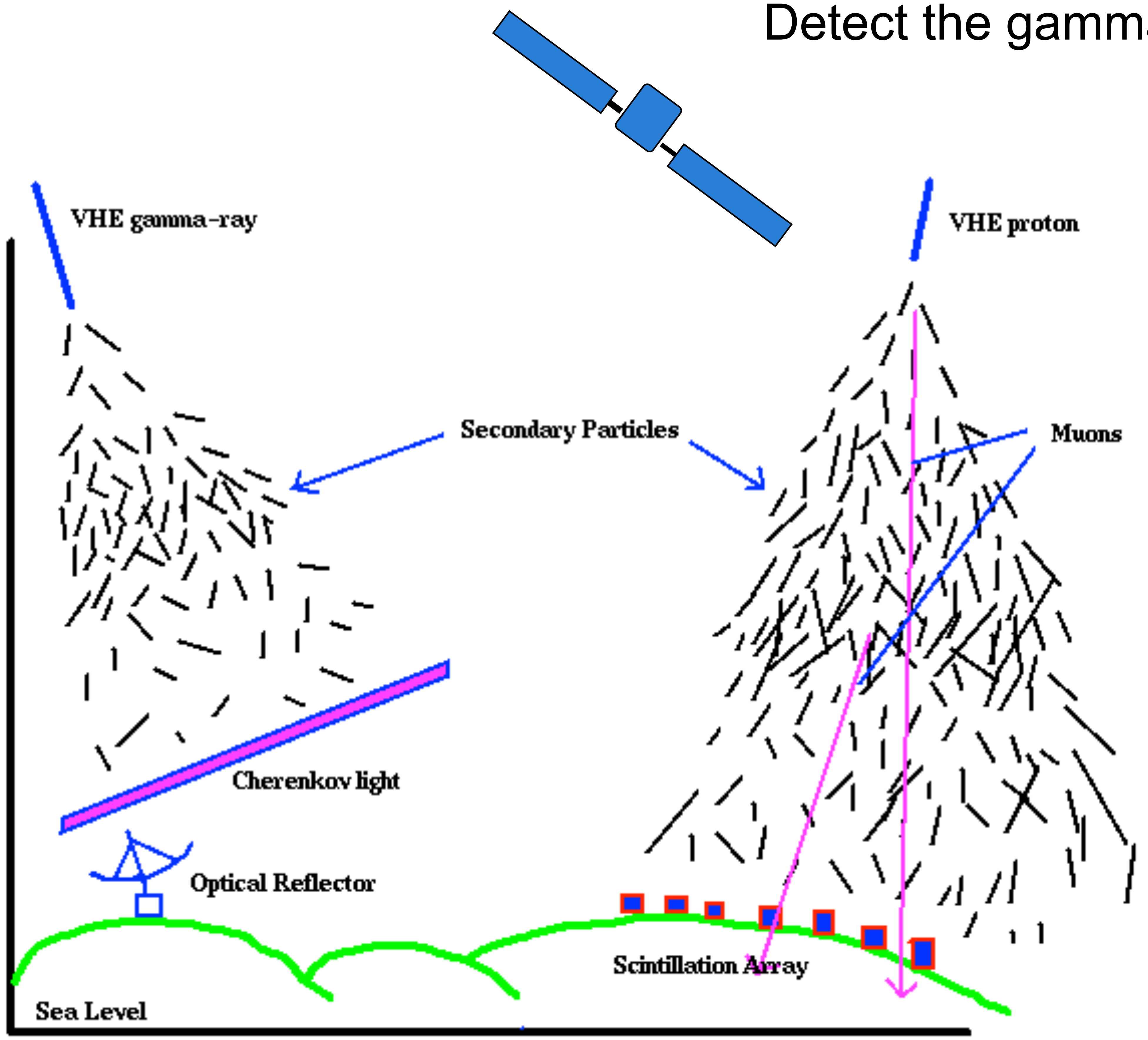


Gamma-Ray/Cosmic-Ray Astronomy

Energy Range	Nomenclature	Method	Technique	Examples
10 MeV – 30 GeV	High Energy (HE)	Satellite Based Direct Detection	Direct Particle Detection	FERMI SWIFT AMS
30 GeV – 100 TeV	Very High Energy (VHE)	Ground Based Indirect Air Shower Detection	Atm. Cherenkov From shower Surface Shower-front detection (Water Cherenkov or Scintillator)	HESS MAGIC HAWC VERITAS LHAASO
>100 TeV	(UHE) (EHE)	Ground based Indirect Air Shower Detection	Surface Shower-front detection (Water Cherenkov or Scintillator) Atm. Fluorescence from shower	AUGER IceTop HiRes TA
10 GeV – 10 PeV	Neutrino	Ground based “Direct” Detection	Water Cherenkov of interaction secondaries	IceCube ANITA

Ground-based Techniques for Gamma-ray Detection

Satellite (Fermi, AGILE, EGRET…) Detect the gamma-rays directly.

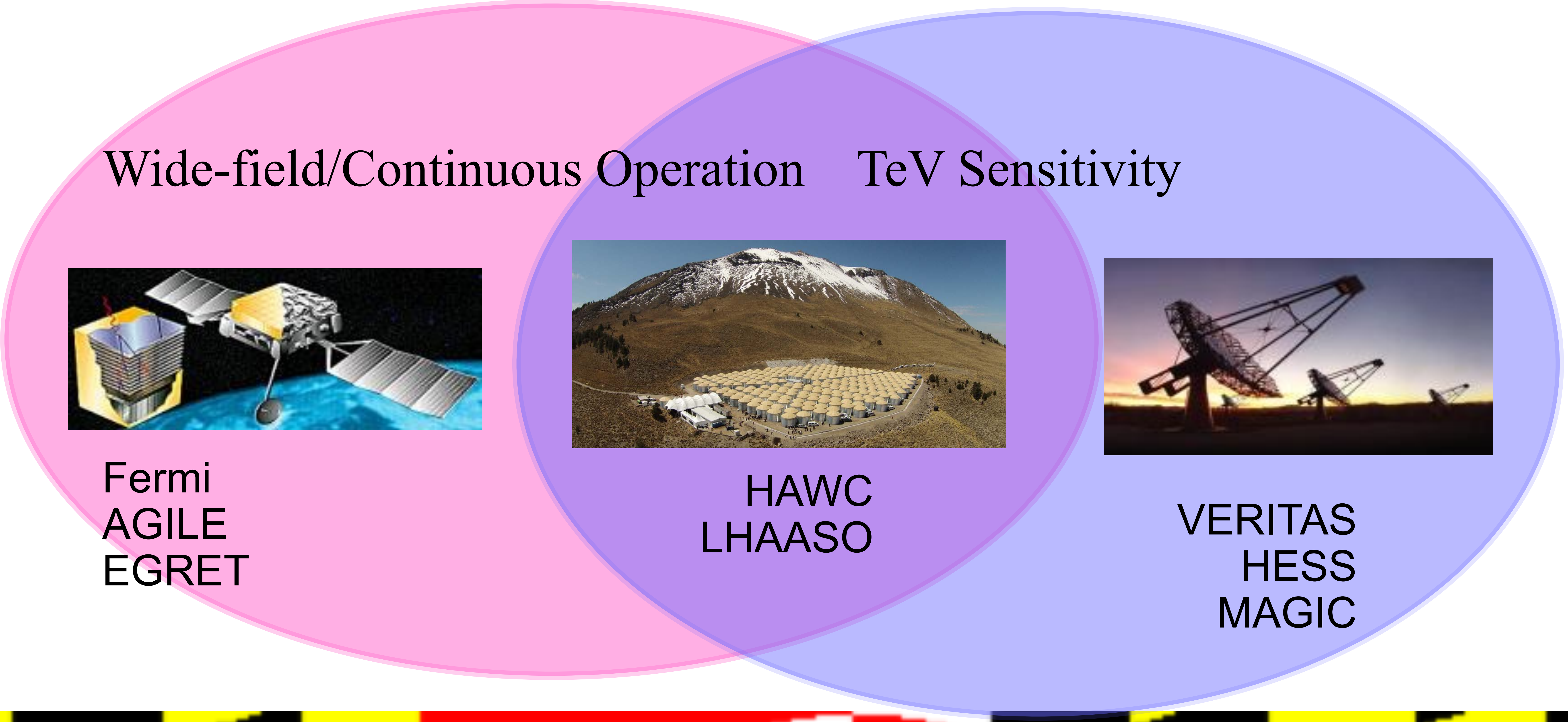


Atmospheric Cherenkov Telescope Array (HESS, MAGIC, VERITAS, CTA..) Detect Cherenkov light from air-shower particles as the traverse the atmosphere.

Ground Array (Milagro, Tibet, ARGO, LHAASO, HAWC…) Detect particles reaching ground level.

Gamma-Ray Detectors

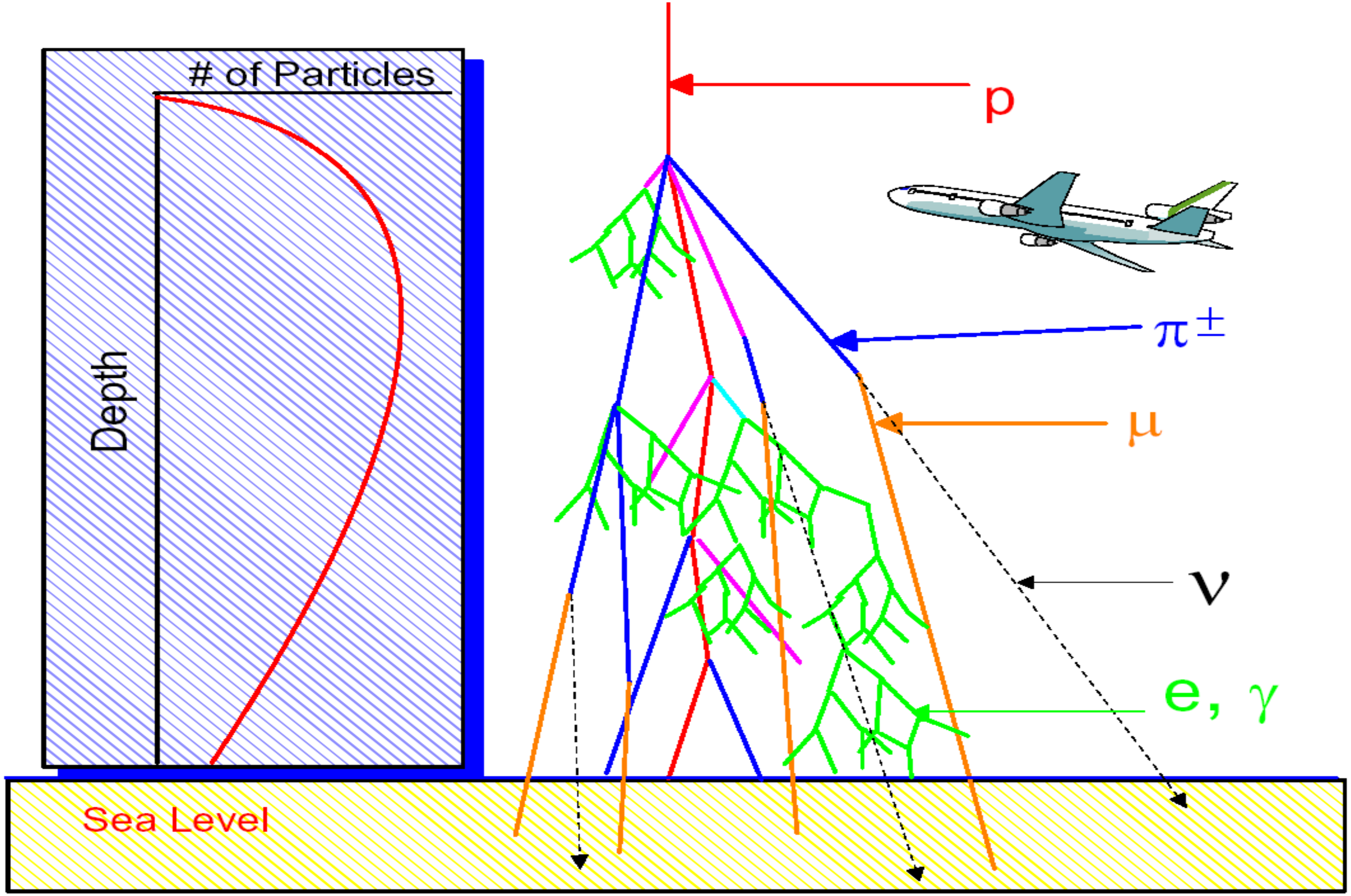
- Space-based detectors - continuous full-sky coverage in GeV
- Ground-based detectors have TeV sensitivity
  - IACTs (pointed) excellent energy and angle resolution
  - HAWC has 24-hour >1/2 sky coverage



What can you do with a wide-field high-duty-cycle detector?

- Deep surveys discovering new objects and object classes
- Extended objects
- Diffuse emission
- High energies
- Transients
- Dark matter
- LIV
- Cosmic rays

Extensive Air Shower Development



Gamma-ray Energy Loss Mechanisms

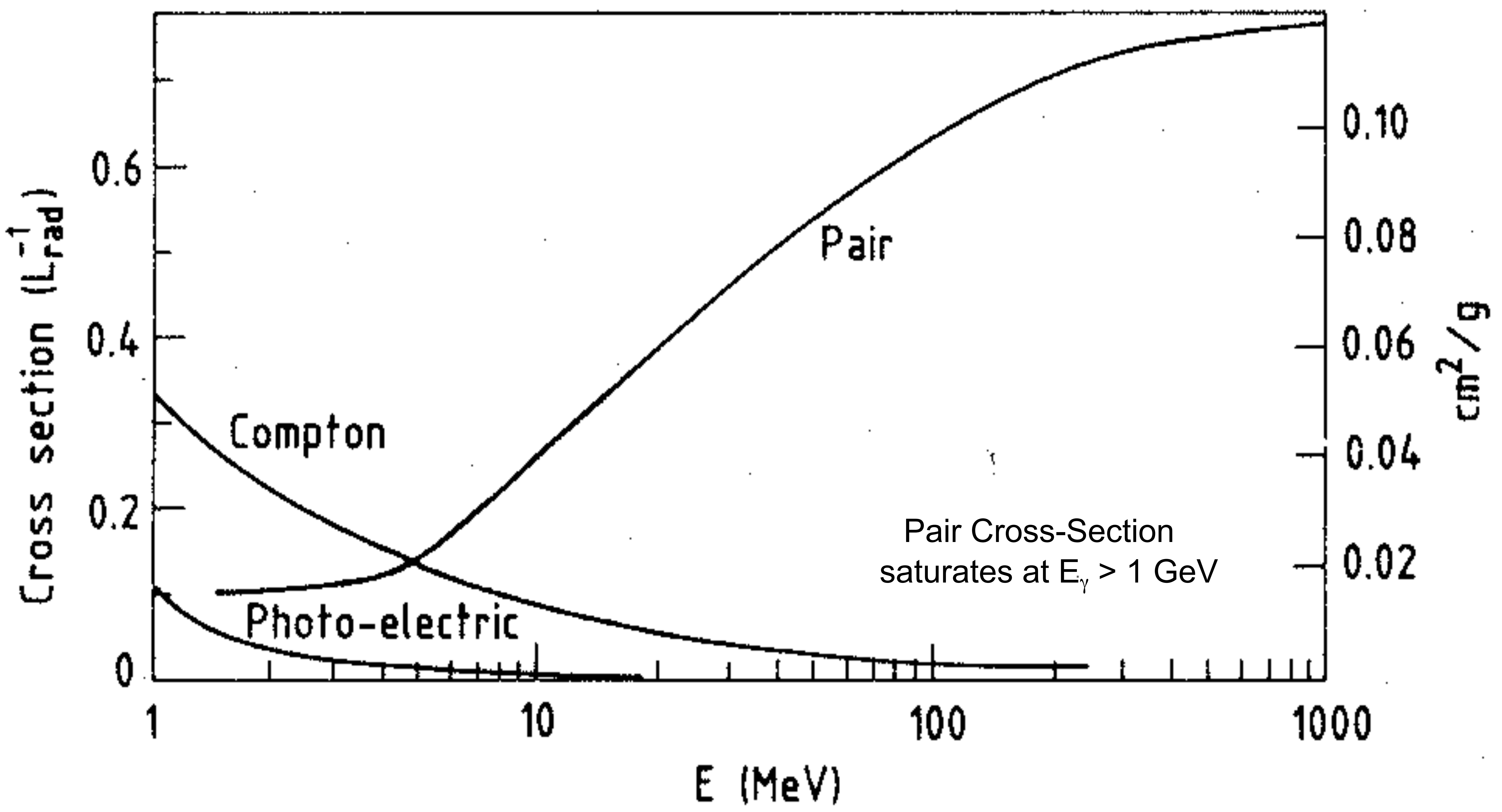
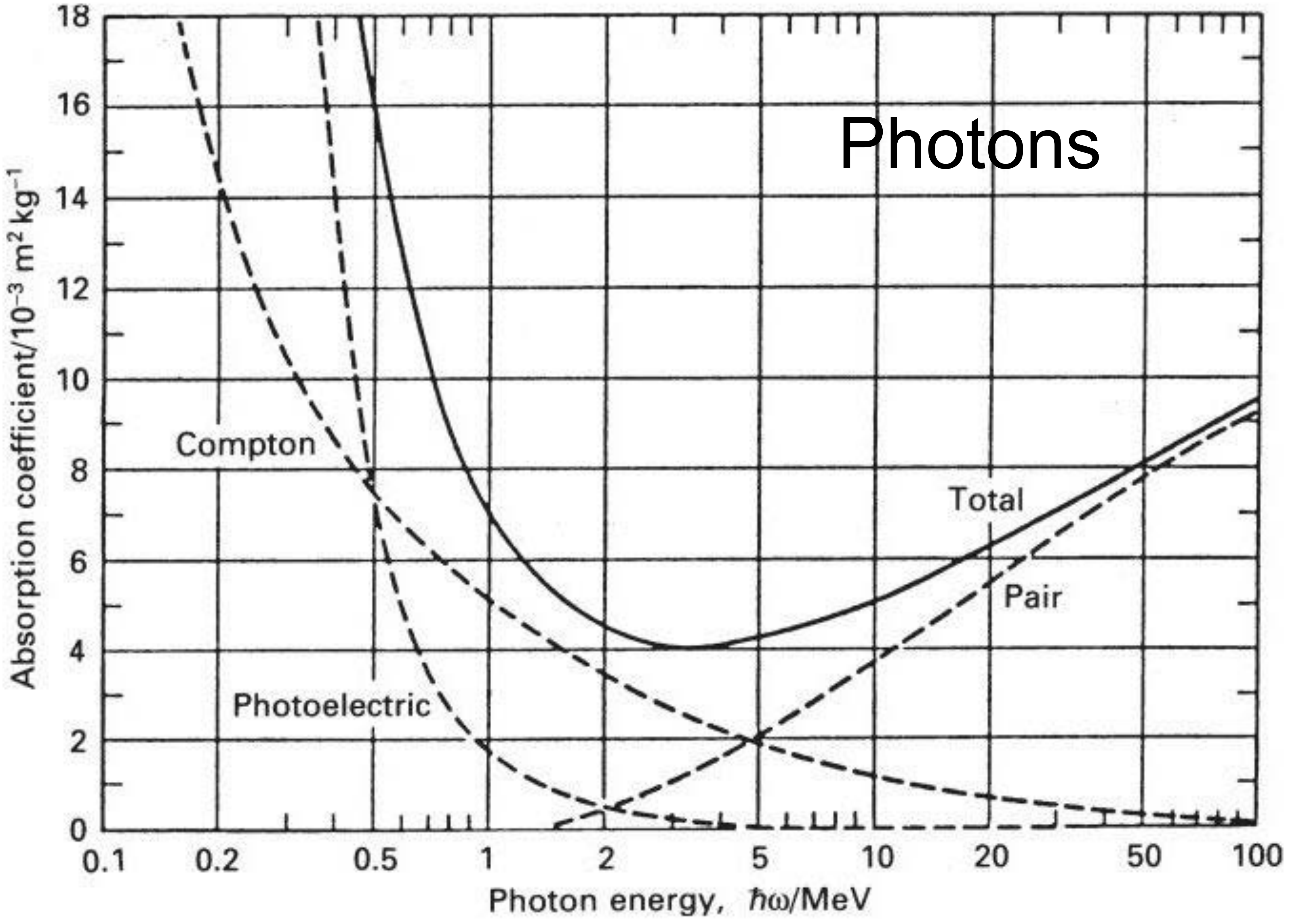
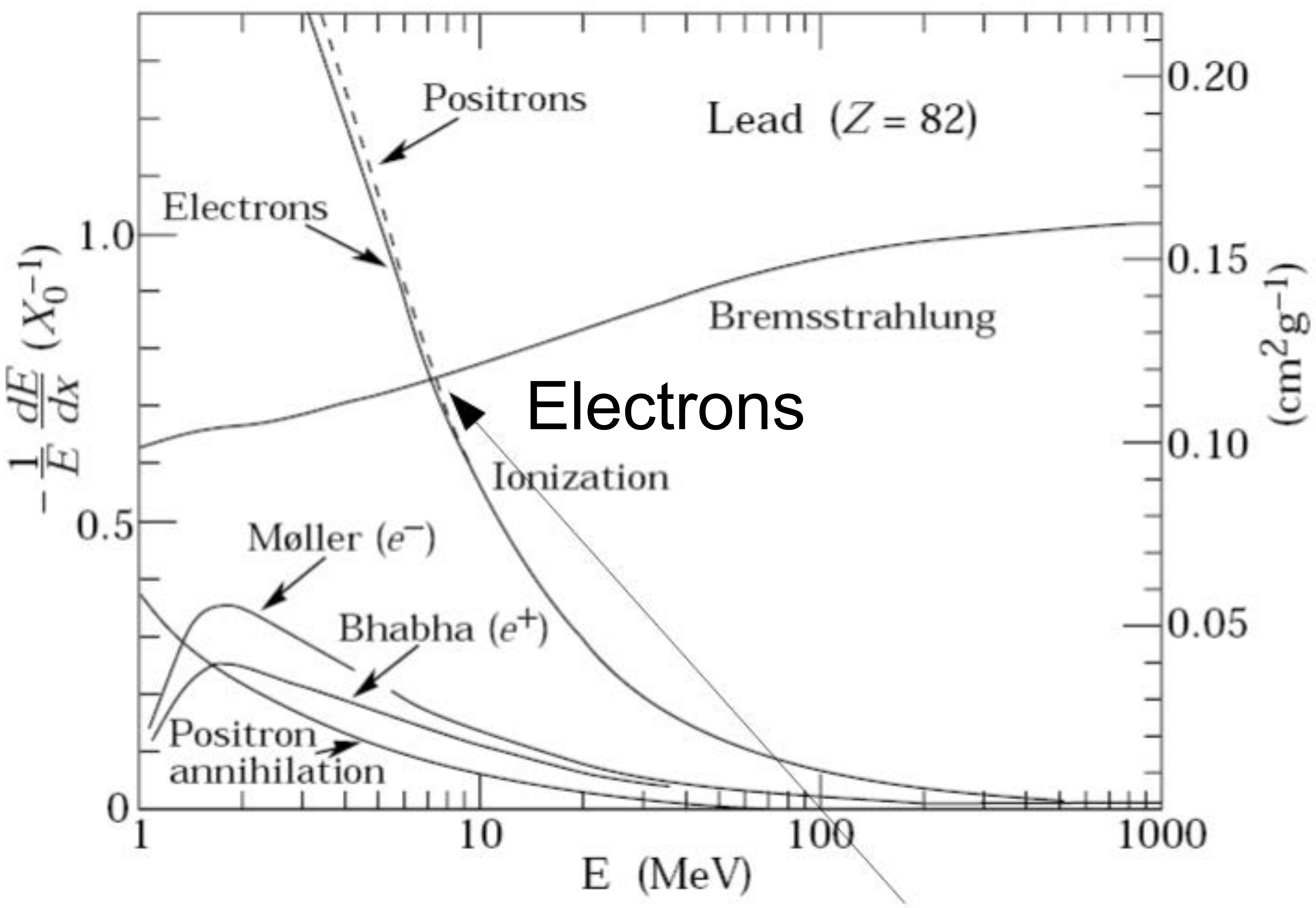


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

At High Energies Pair Production and Bremsstrahlung Dominates EM Interactions

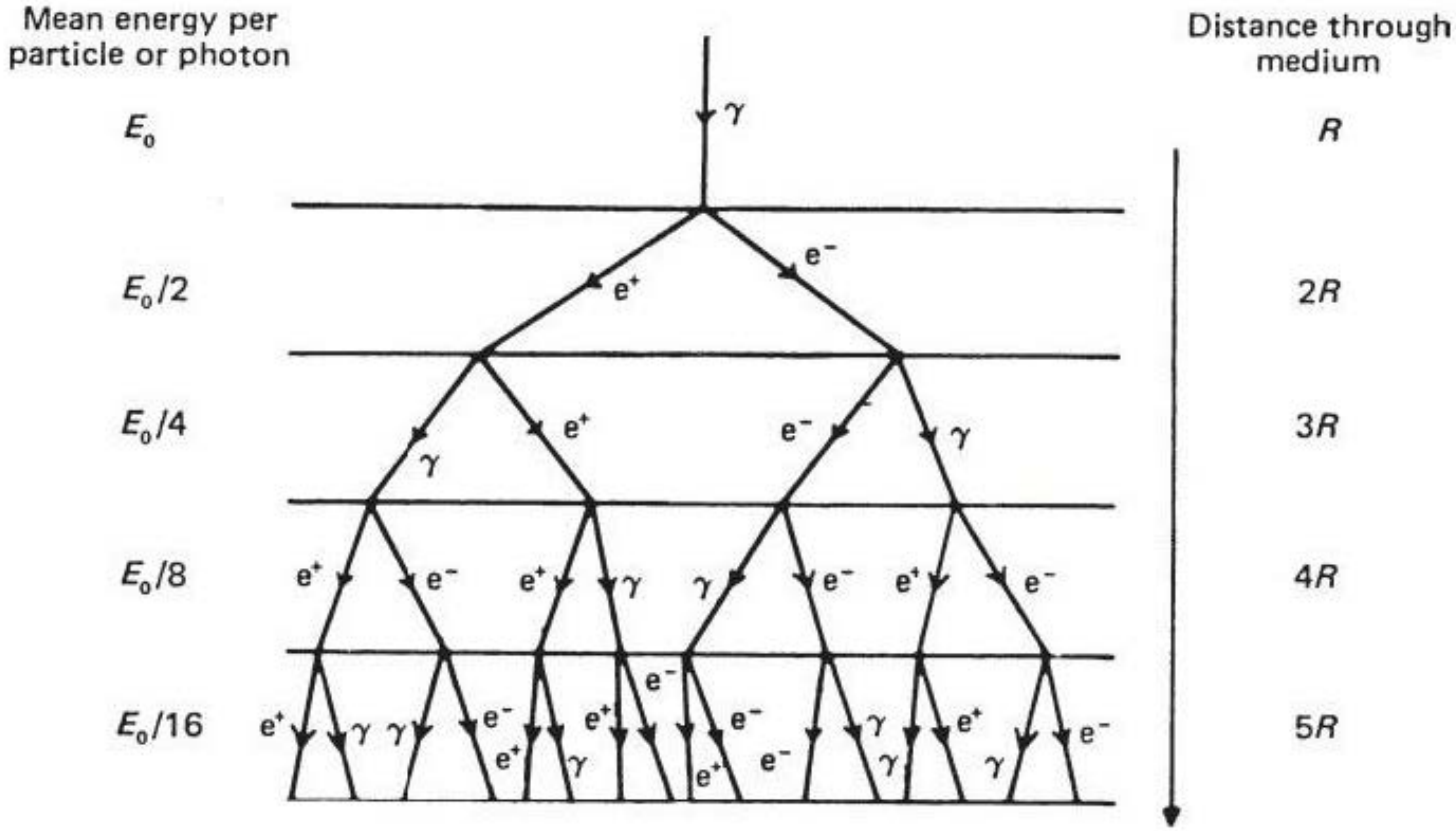




Ec in air is 84 MeV. At this point electrons lose Energy very quickly and showers become photon rich.

Critical energy: $dE/dx_{Ion} = dE/dx_{Brems}$

Electromagnetic Air Shower



Electromagnetic Showers in the Atmosphere

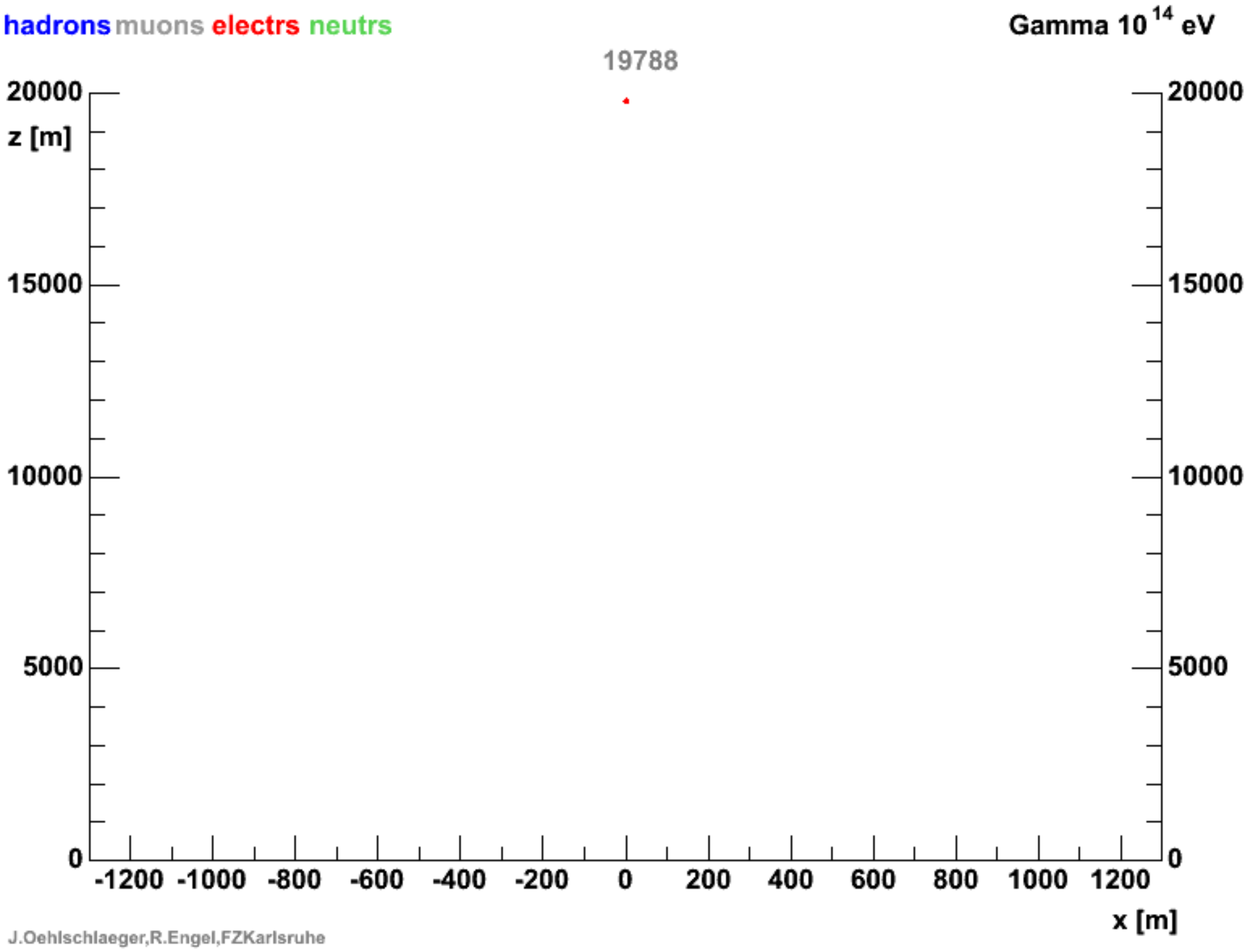
- If EM particle such as photon or electron initiates shower in atmosphere
  - After distance n R.L.(X_0), the number of (photons + electrons + positrons) is 2^n and their average energy is $E_0/2^n$ (pair production length is 9/7 X_0)
  - On average, the shower consists of 2/3 positrons and electrons 1/3 photons
  - Longitudinal development reaches maximum at depth
  - Where E_c ~ 80 MeV in air

$$X_{max} = \frac{\ln(E/E_c)}{\ln 2}$$

in radiation lengths

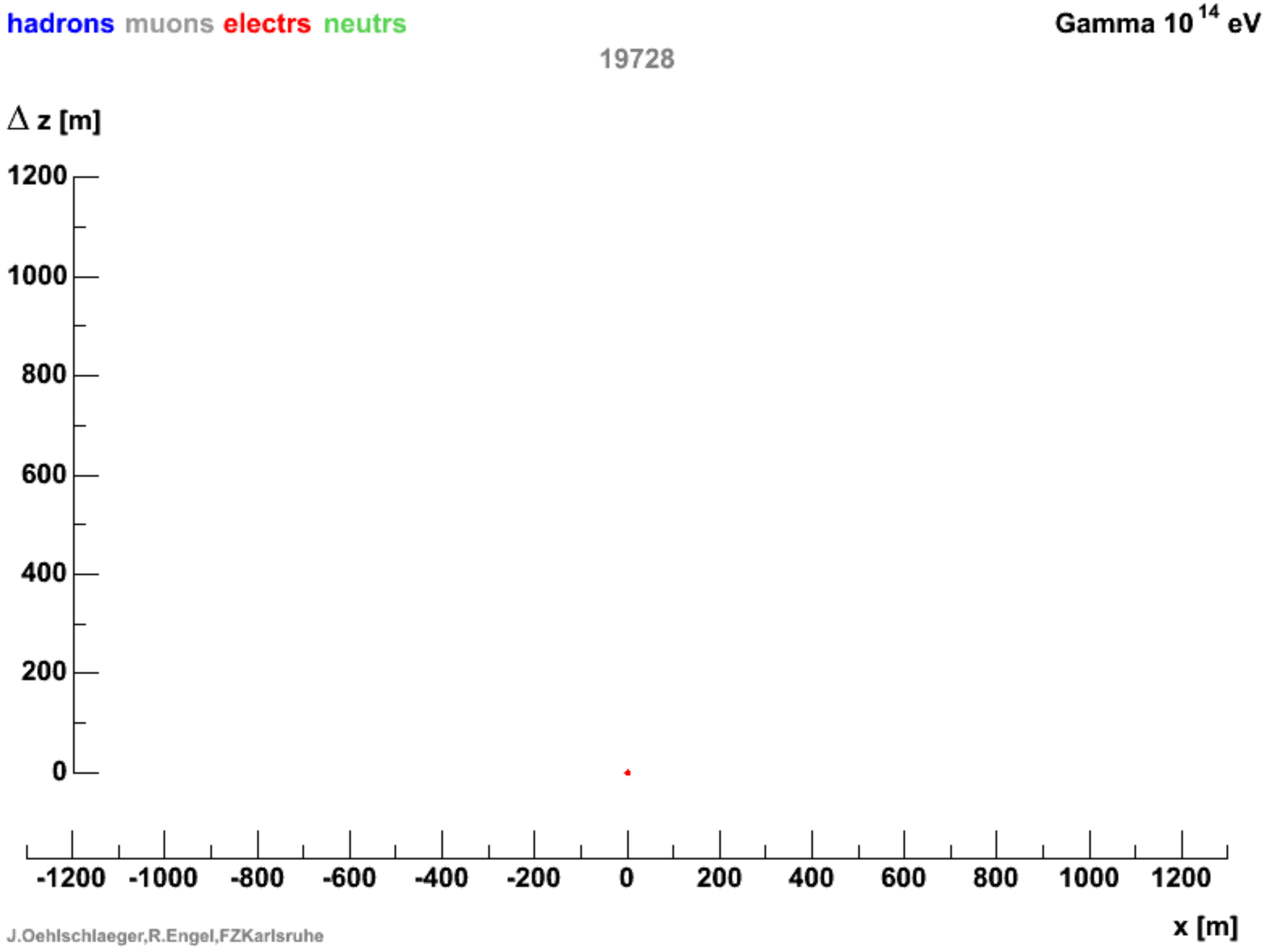
  - Below E_c ionization dominates and electrons stop producing photons via Bremsstrahlung

Gamma Ray 100 TeV

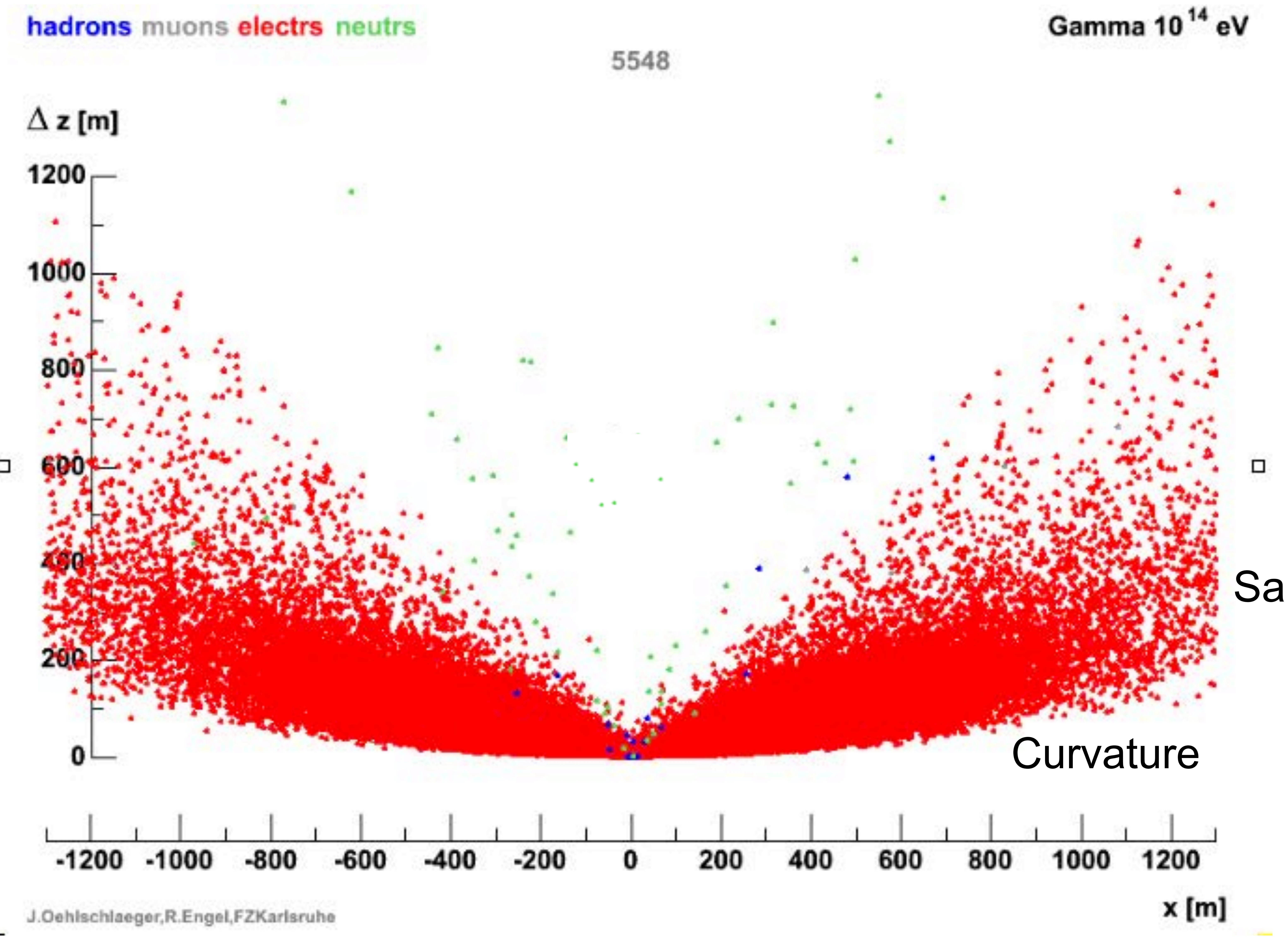


Corsica Movies -
J. Oehlschläger and R. Engel, Institut für Kernphysik, Forschungszentrum Karlsruhe.

Gamma Ray 100 TeV



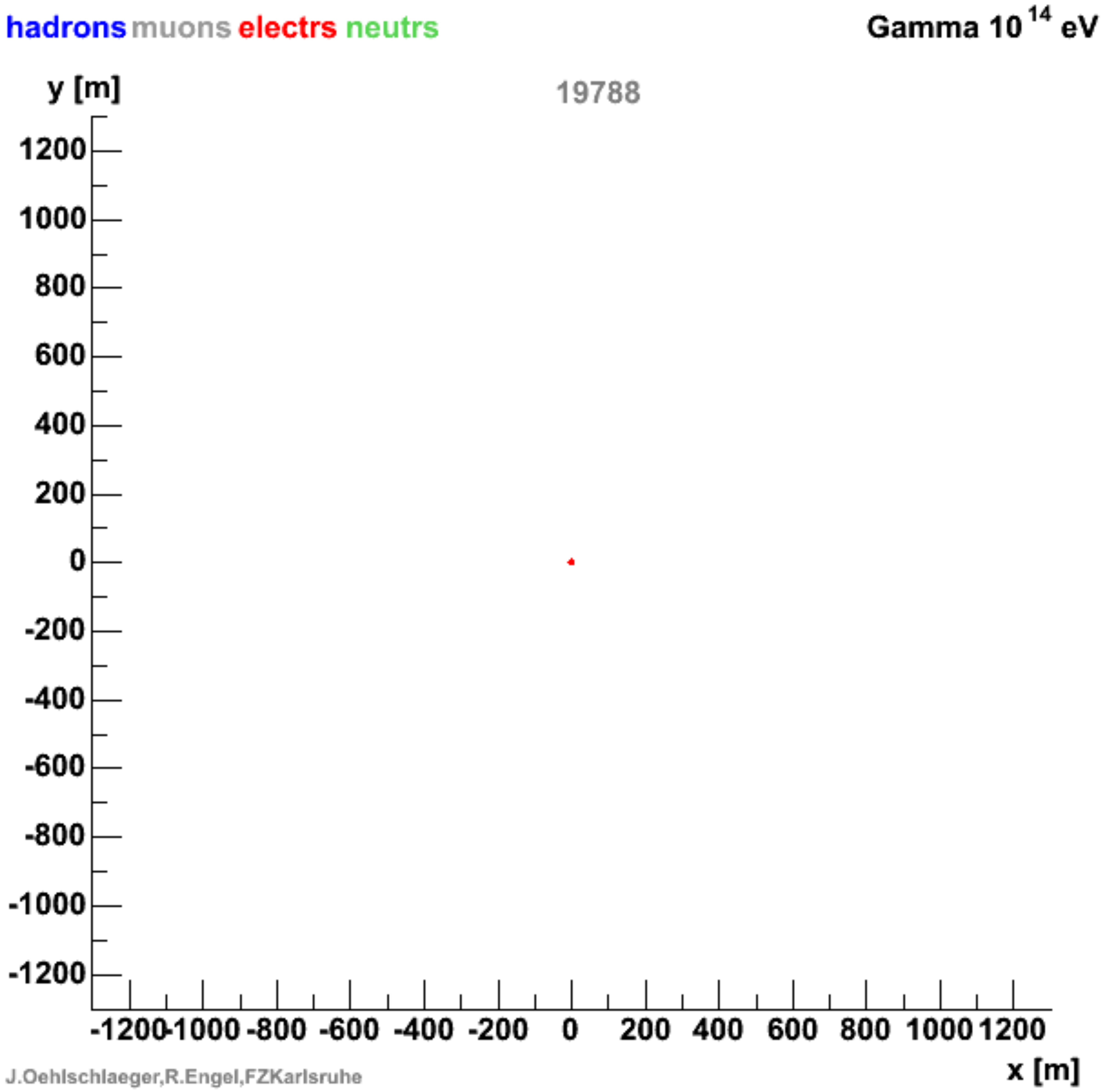
Gamma Ray 100 TeV



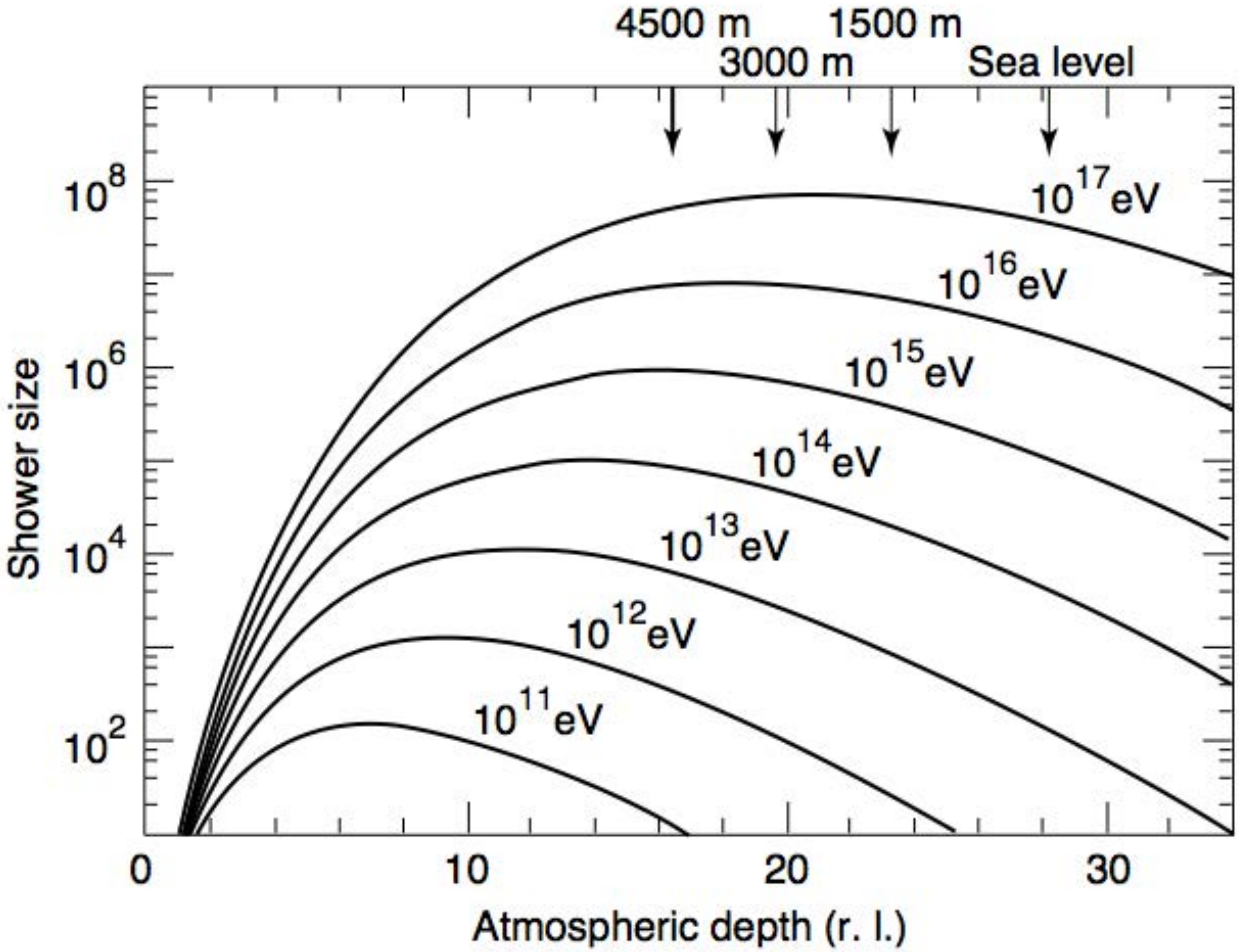
Sampling

Curvature

Gamma Ray 100 TeV



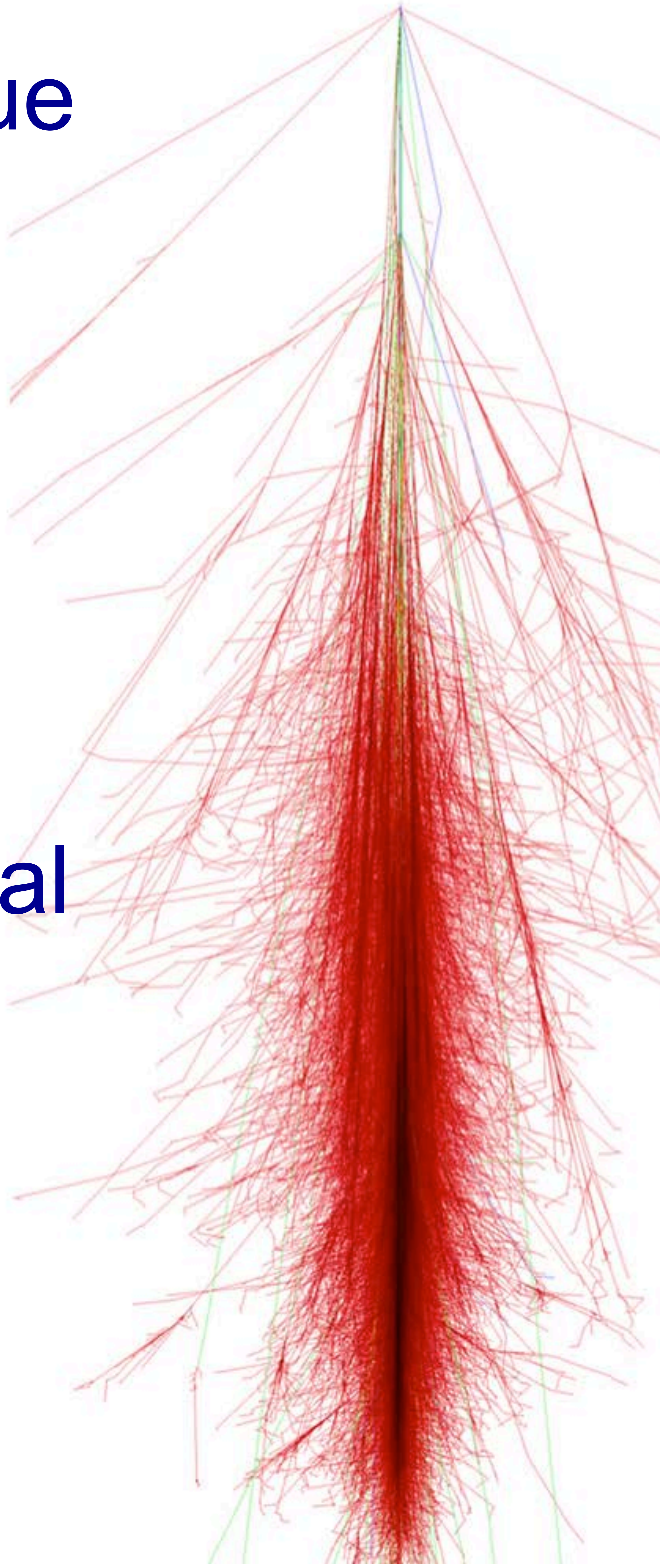
EM Shower



4500 m
1500 m
3000 m
Sea level
10^8
10^6
10^4
10^2
Shower size
10^17 eV
10^16 eV
10^15 eV
10^14 eV
10^13 eV
10^12 eV
10^11 eV
0
10
20
30
Atmospheric depth (r. l.)

Hadronic Showers

- In general showers max out deeper in the atmosphere due to longer hadronic interaction length $X_{had} \sim 90\ g/cm^2$
- Typically modeled numerically
  - Corsika
- Hadronic showers are typically muon-rich with both penetrating muon component and soft EM component reaching ground level
- Lateral development is characterized by Molière unit equal to approximately $0.2X_0$, about 100 m at sea level.
- Hadronic showers are broader than γ



Lateral shower profile:

- The lateral shower profile is dominated by two processes:
  - multiple Coulomb scattering
  - relatively long free path length of low energy photons

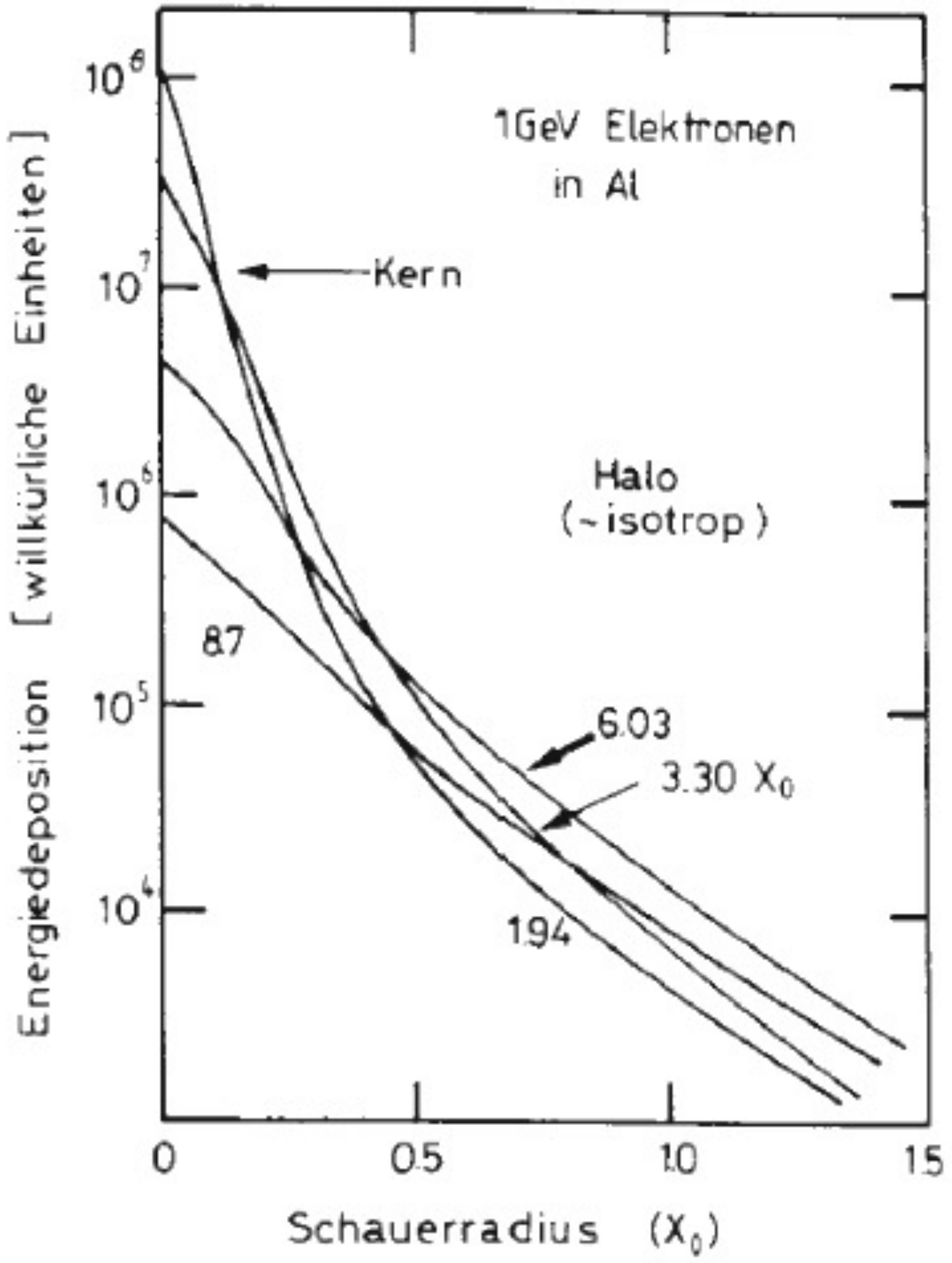
- It is characterized by the so-called Molière radius ρ_M

$$\rho_M = \frac{21\text{MeV}}{E_C} X_0 \approx 7 \frac{A}{Z} \left[\frac{g}{cm^2}\right]$$

- About 95% of the shower energy are contained within a cylinder with radius $r = 2\,\rho_M$

in general well collimated !

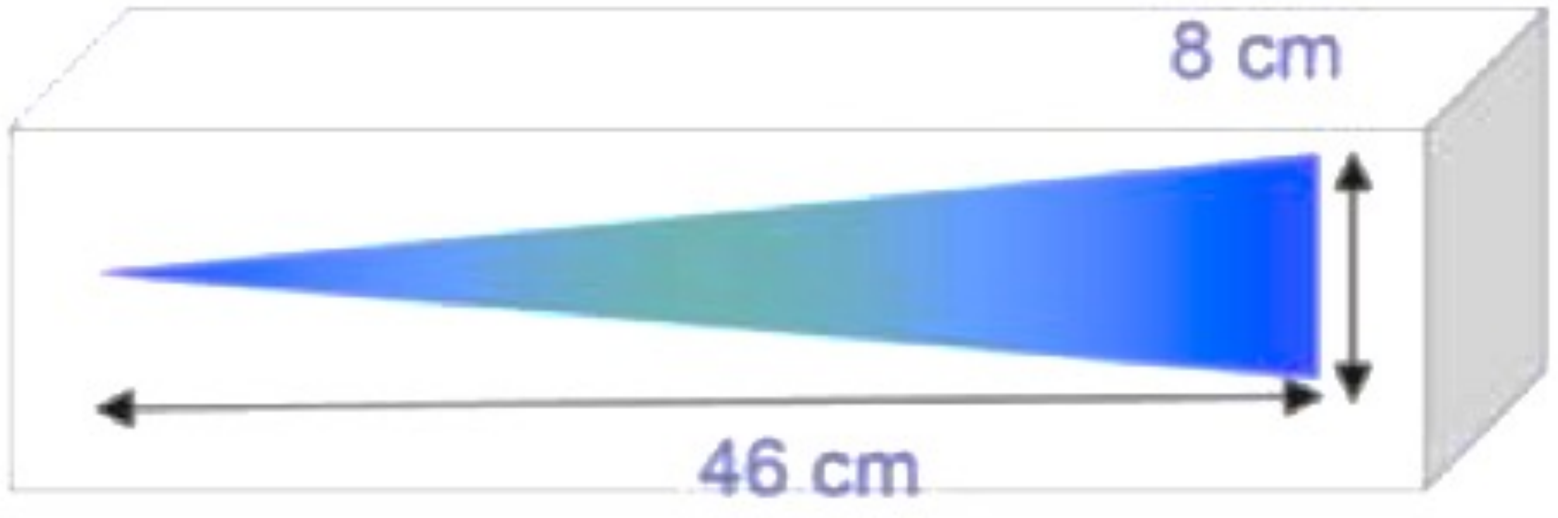
$\rho_M \approx 100$m at sea level



Example: E_0 = 100 GeV in lead glass

E_c=11.8 MeV → $t_{max} \approx 13$, $t_{95\%} \approx 23$

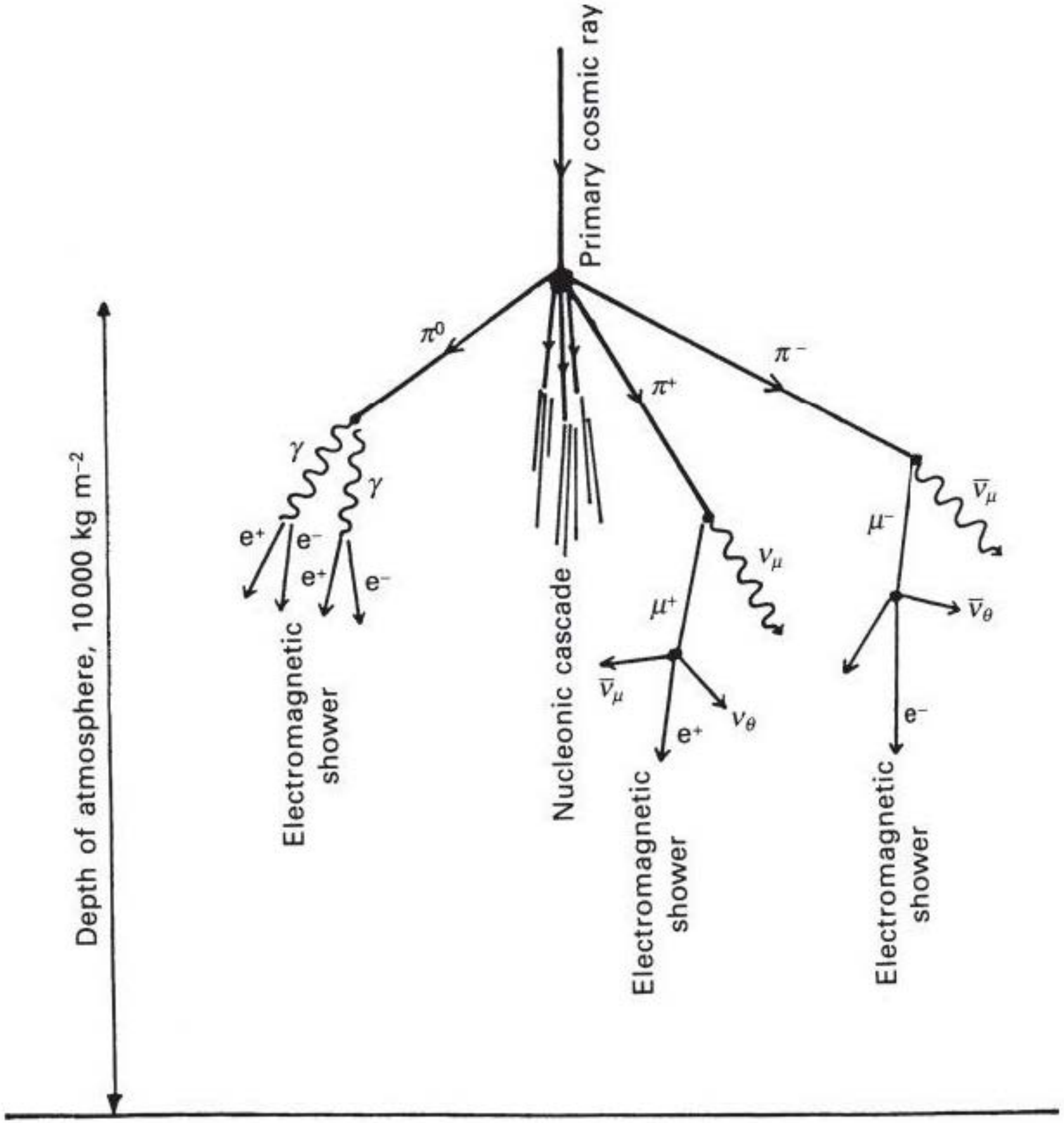
$X_0 \approx 2$ cm, $R_M = 1.8 \cdot X_0 \approx 3.6$ cm



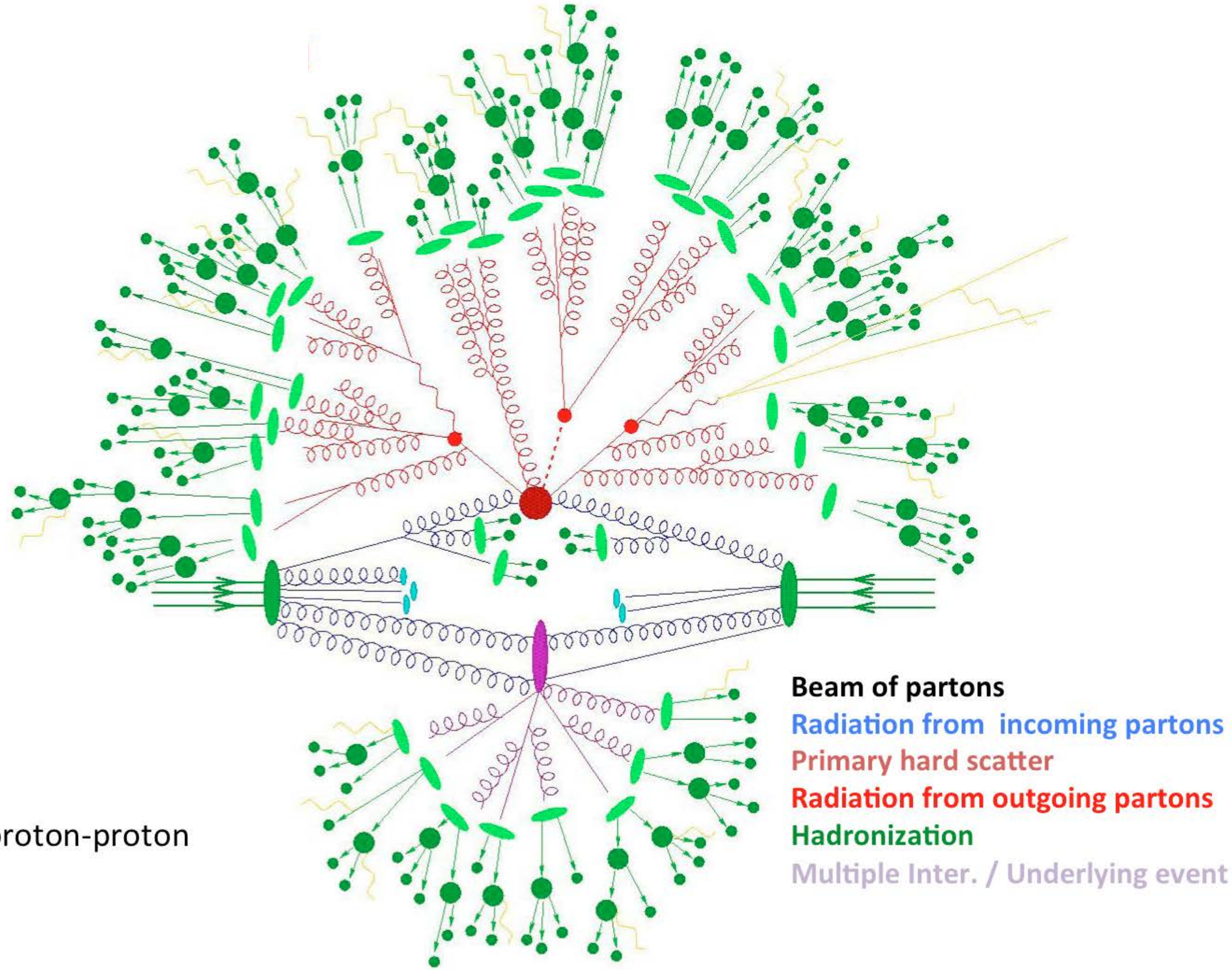
Hadron Induced Air Showers

- When a cosmic ray enters the atmosphere it likely interacts with one of the protons or neutrons in either a Nitrogen or Oxygen atom
  - If it's a proton primary it typically has one strong interaction with one nucleon
  - If it's a nucleus incoming it typically has has one strong interaction with one nucleon and breaks up the primary into N particles
- The atmosphere is ~an exponential with scale height 7-8km
  - Total mass at sea level 1030 gm/cm^2
  - Proton interaction length 80 gm/cm^2
  - Pion interaction length 120 gm/cm^2
  - Pions have more chance to decay higher up due to thinner atmosphere
  - Pi zero's decay immediately into two photons

Nuclear - Electromagnetic (Hadronic) Air Showers



Proton - Proton Collision



Typical proton-proton collision

This is a proton- proton collision
seen in the center of mass

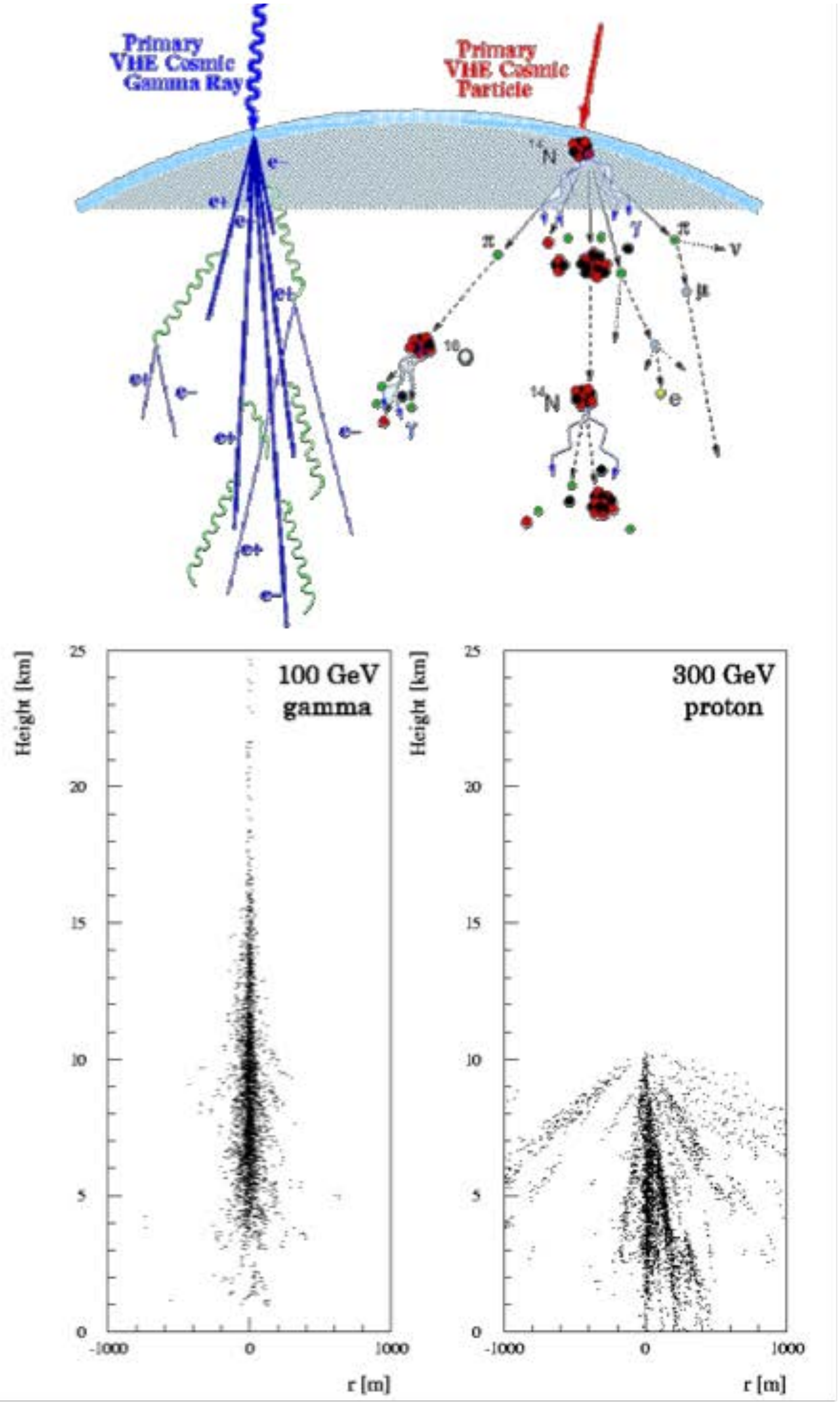
For air showers we are in the lab
frame and everything goes forward

8/30/11 PIC 2011, R. Teuscher IPP/Toronto 2

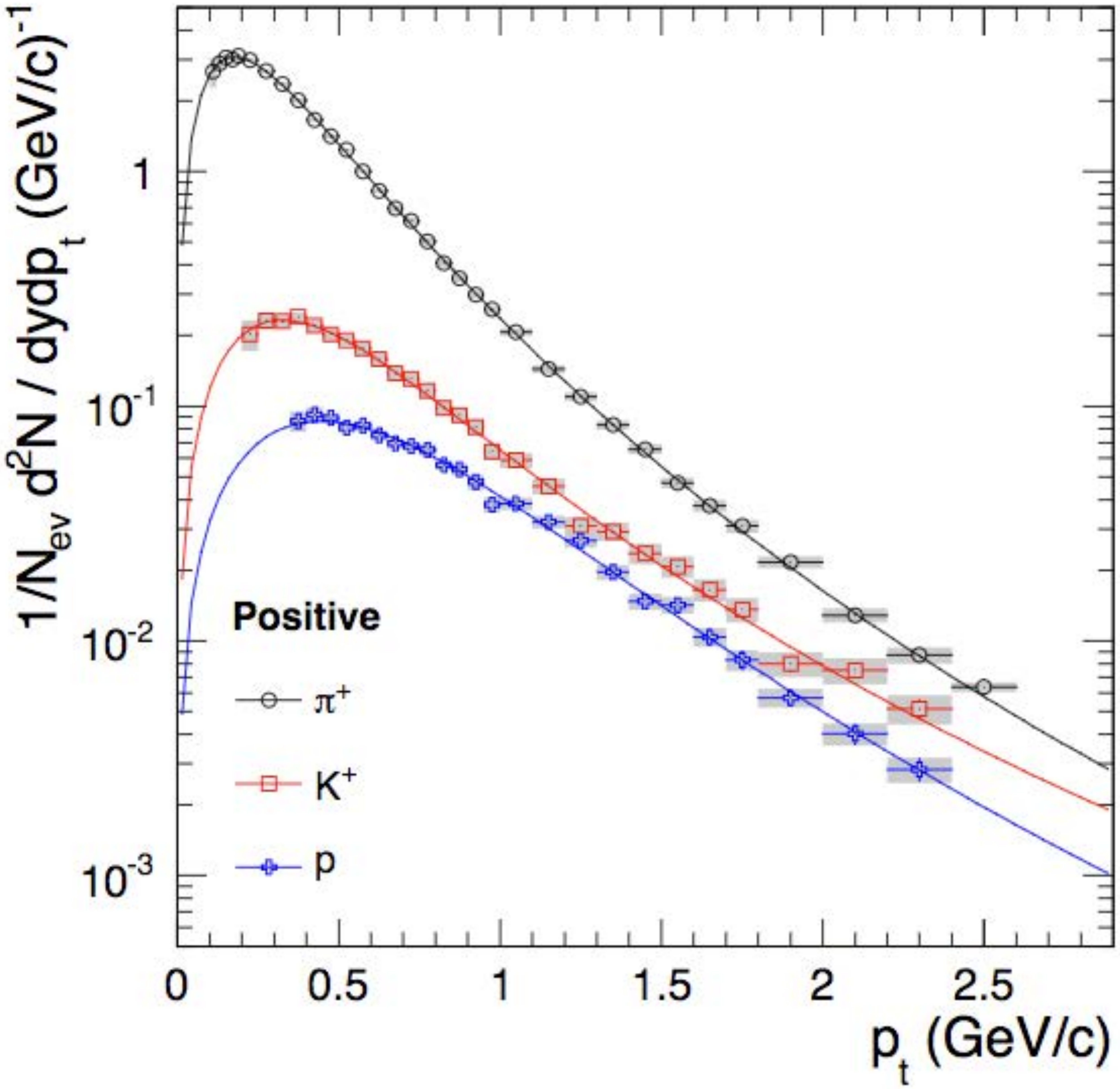
Gamma vs Hadronic Air Showers

Hadronic and e.m. showers

- Electromagnetic showers develop more regularly, with less fluctuations.
- In the 300 GeV shower one can see jets of secondaries.
- At higher energies they are more strongly forward boosted.
- The difference in structure can be used for particle identification.

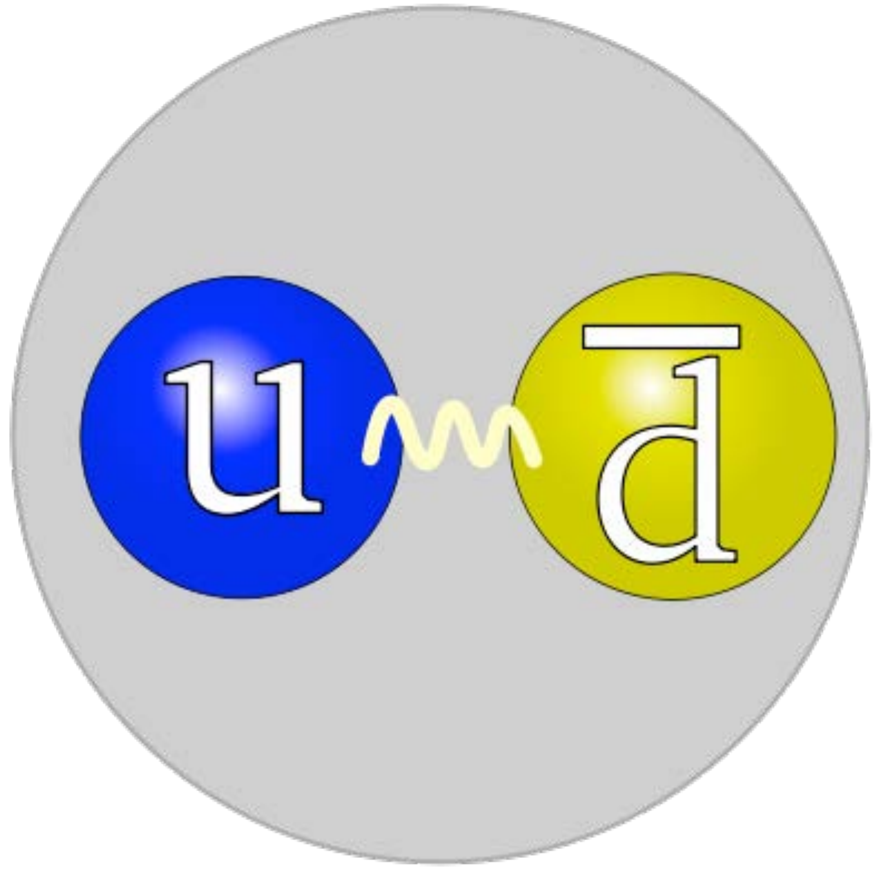


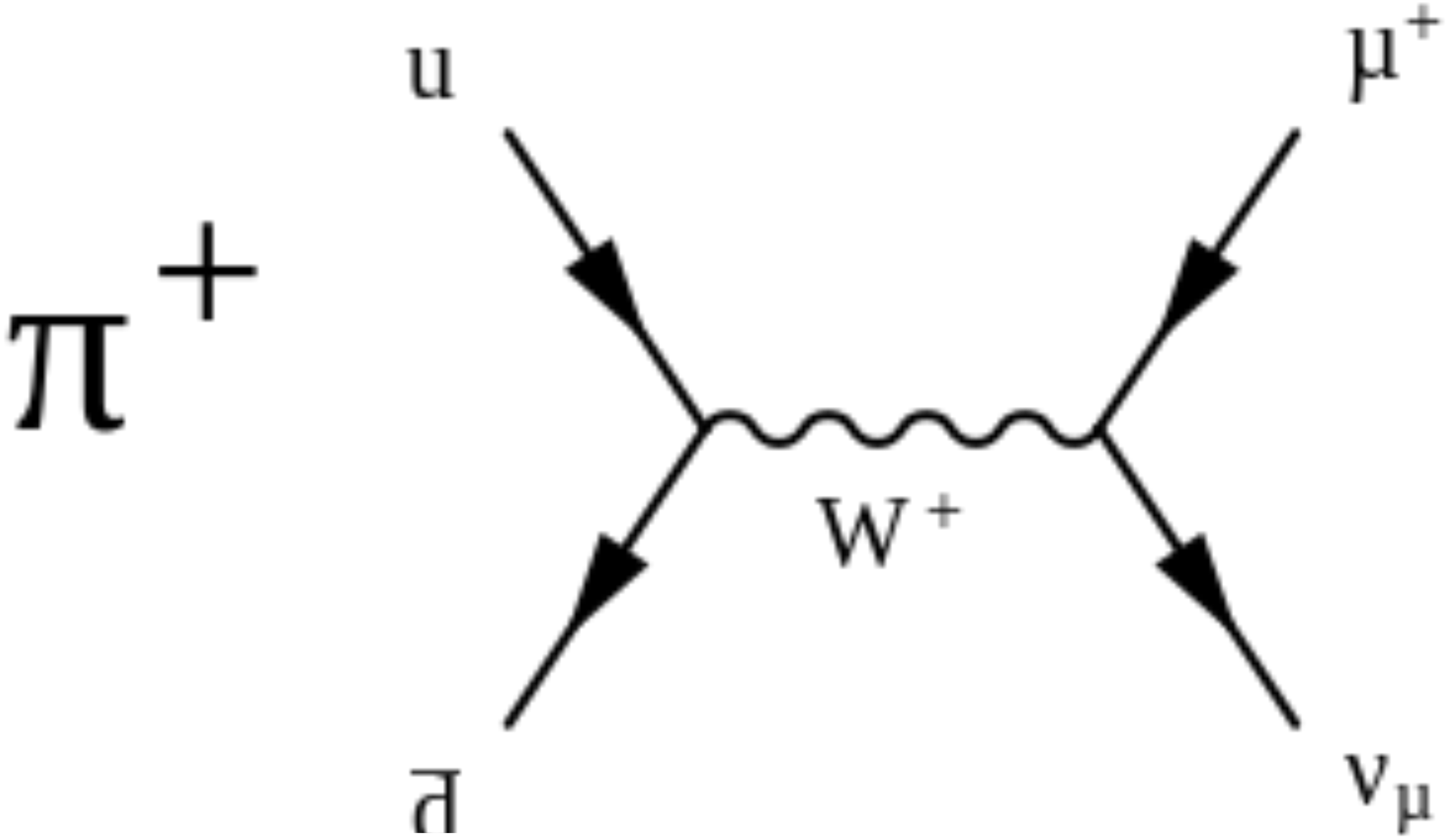
Mostly Pions Produced



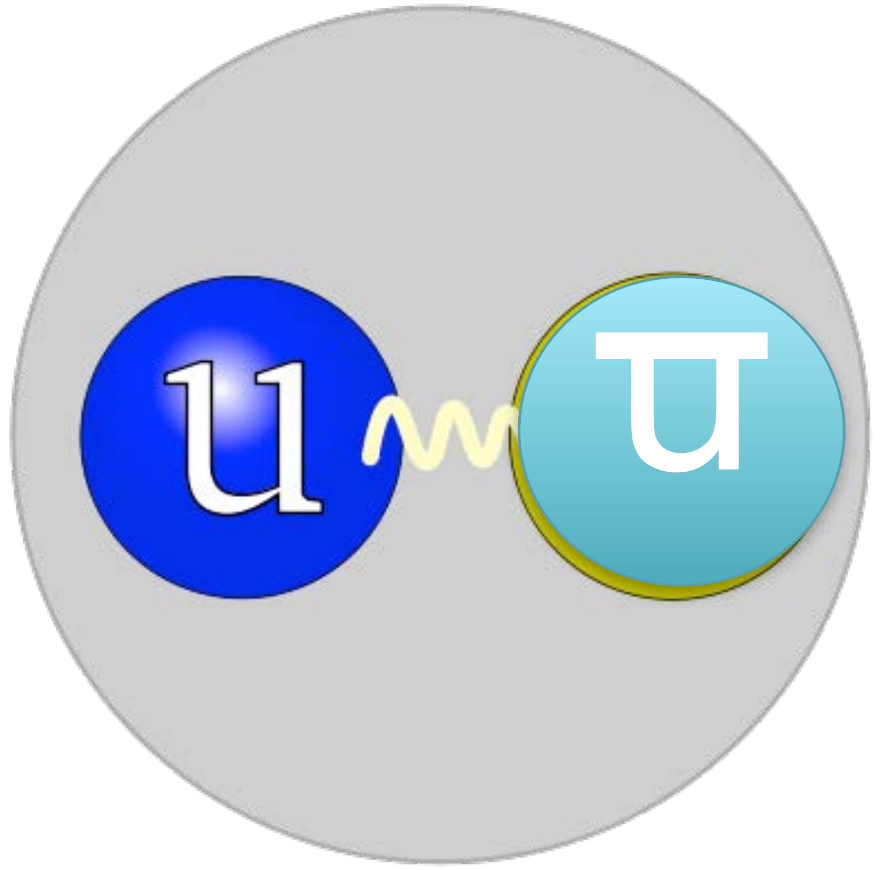
About 90% pions
Equal numbers of
π^+ π^- π^0

Charged Pions can either decay or interact

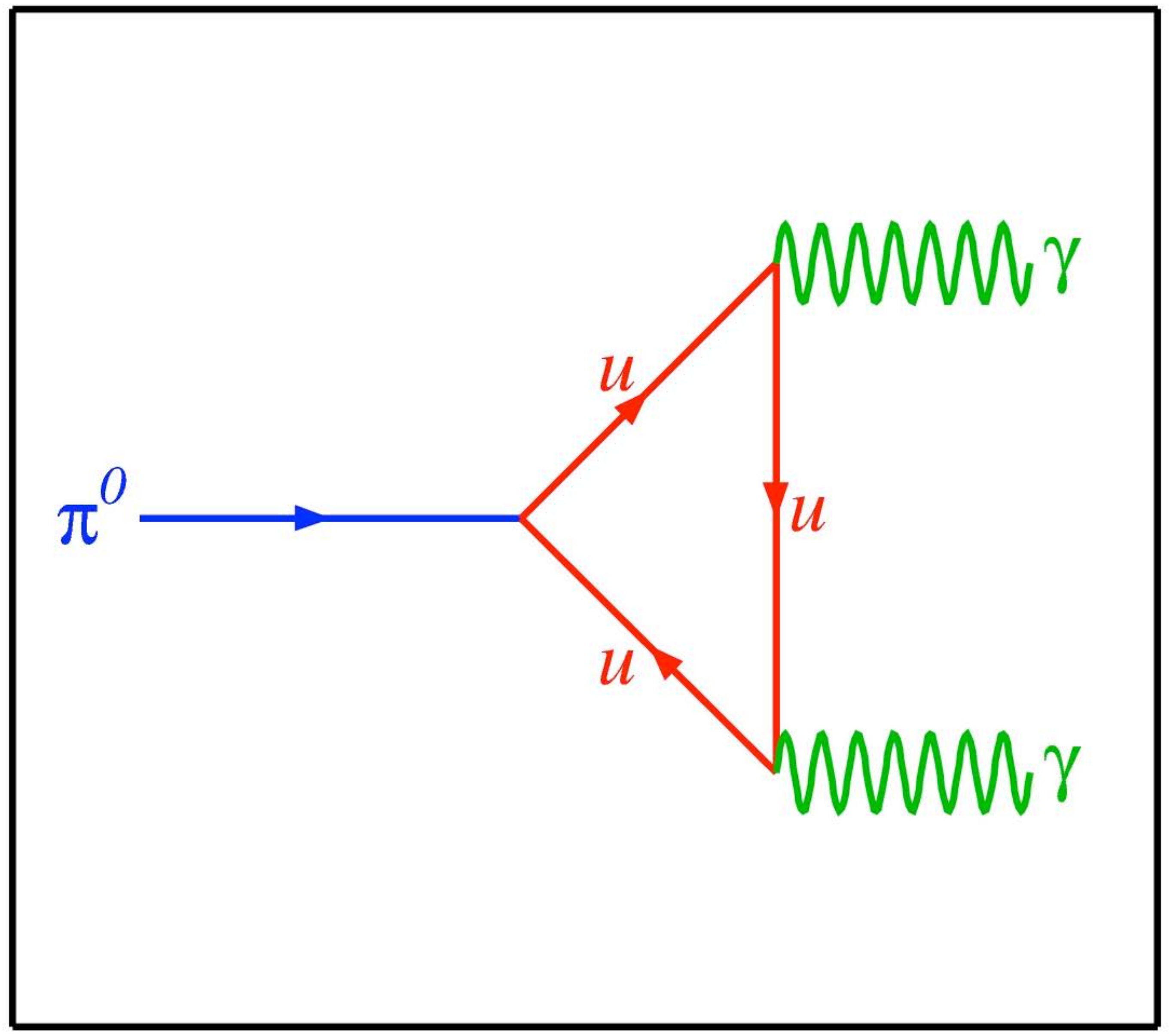




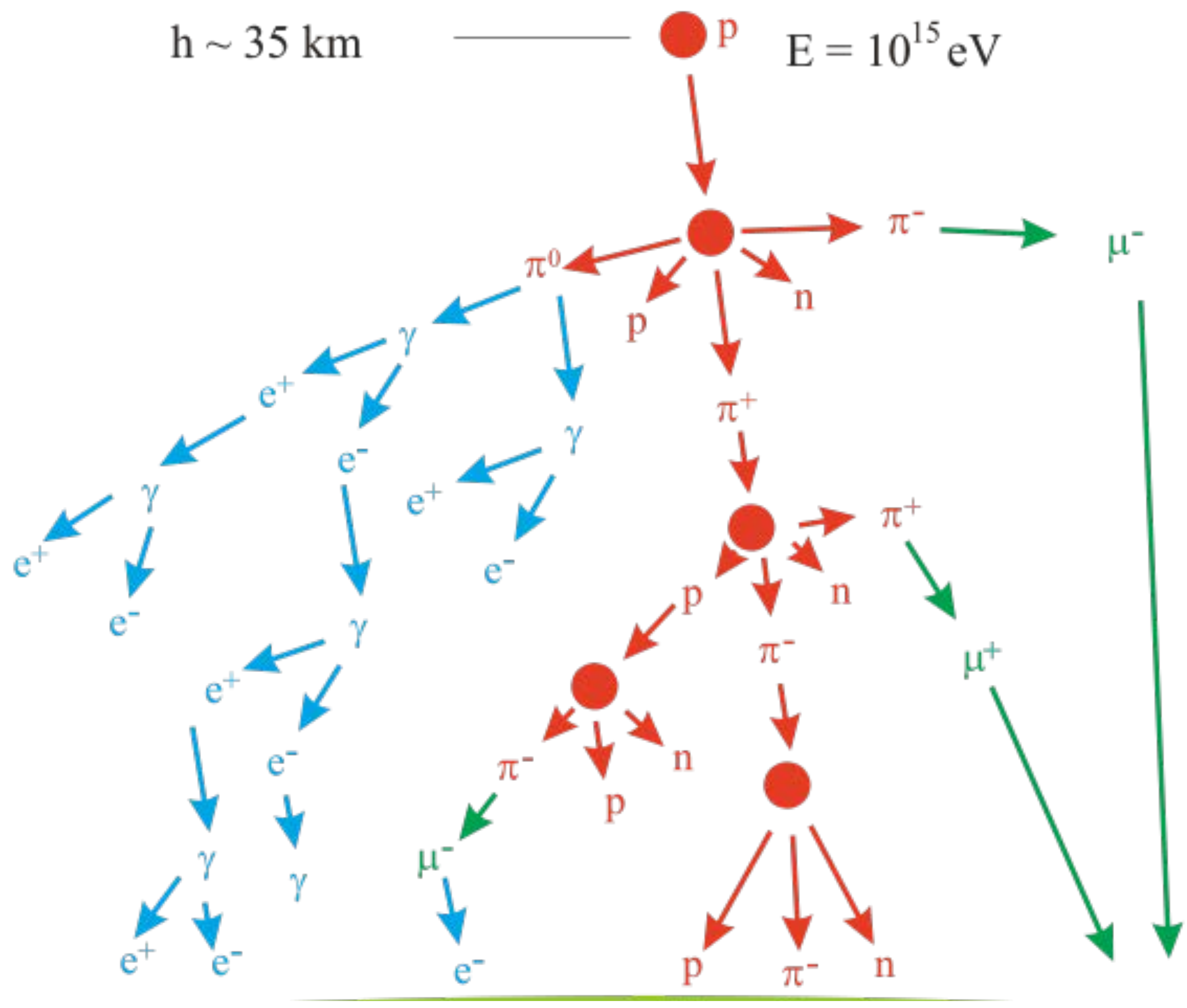
Mass 140 MeV
τ = 2.6x10^{-8}sec
at 14 GeV cτ=800m



π^0 Decay



Mass 135 MeV
τ = 8x10^{-17}sec
at 14 GeV cτ=2μm


h ~ 35 km
p
E = 10^15 eV
π^-
μ^-
π^0
p
n
γ
π^+
e^+
e^-
γ
e^+
e^-
γ
e^+
e^-
π^+
p
n
μ^+
e^-
γ
π^-
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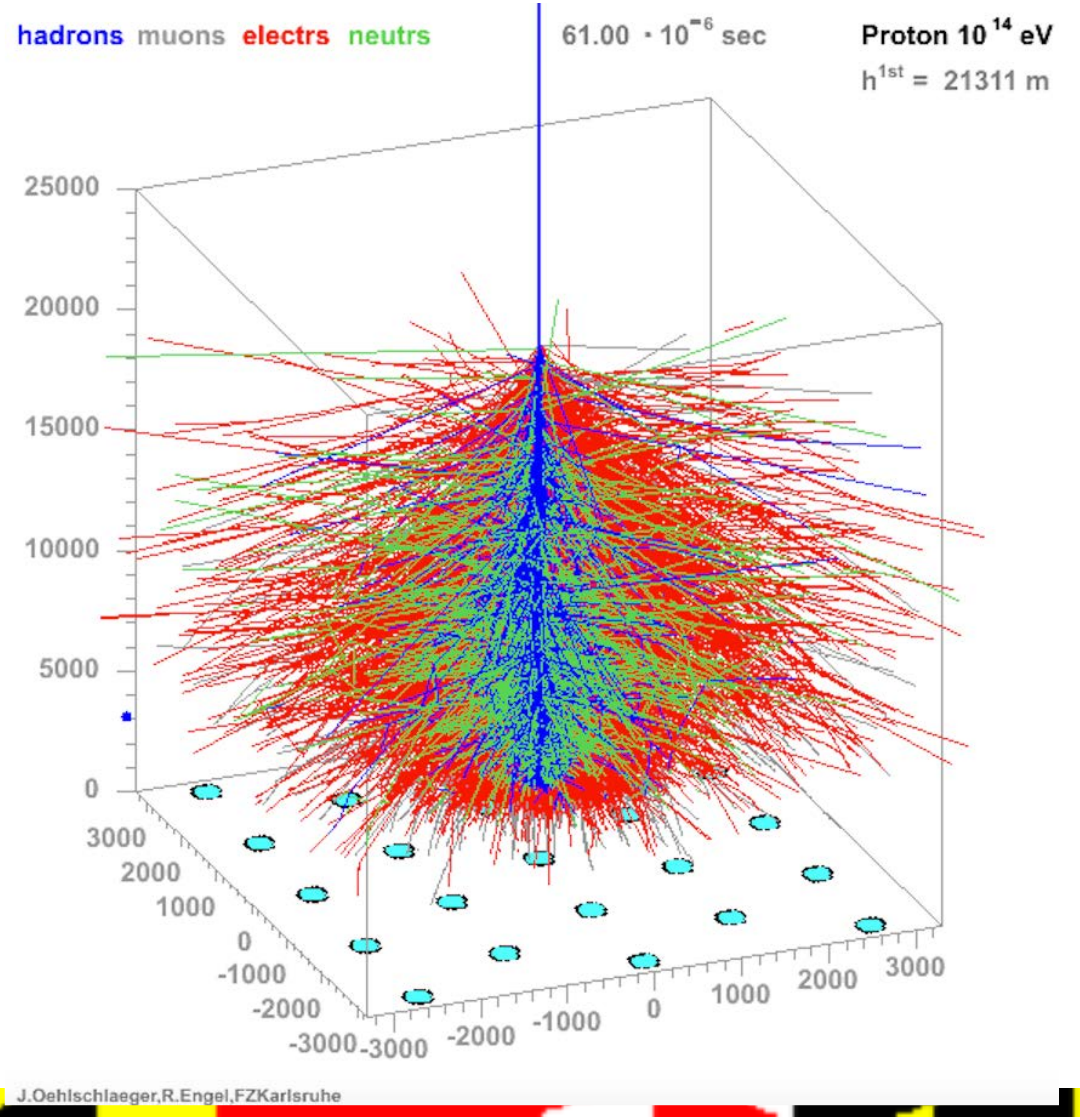
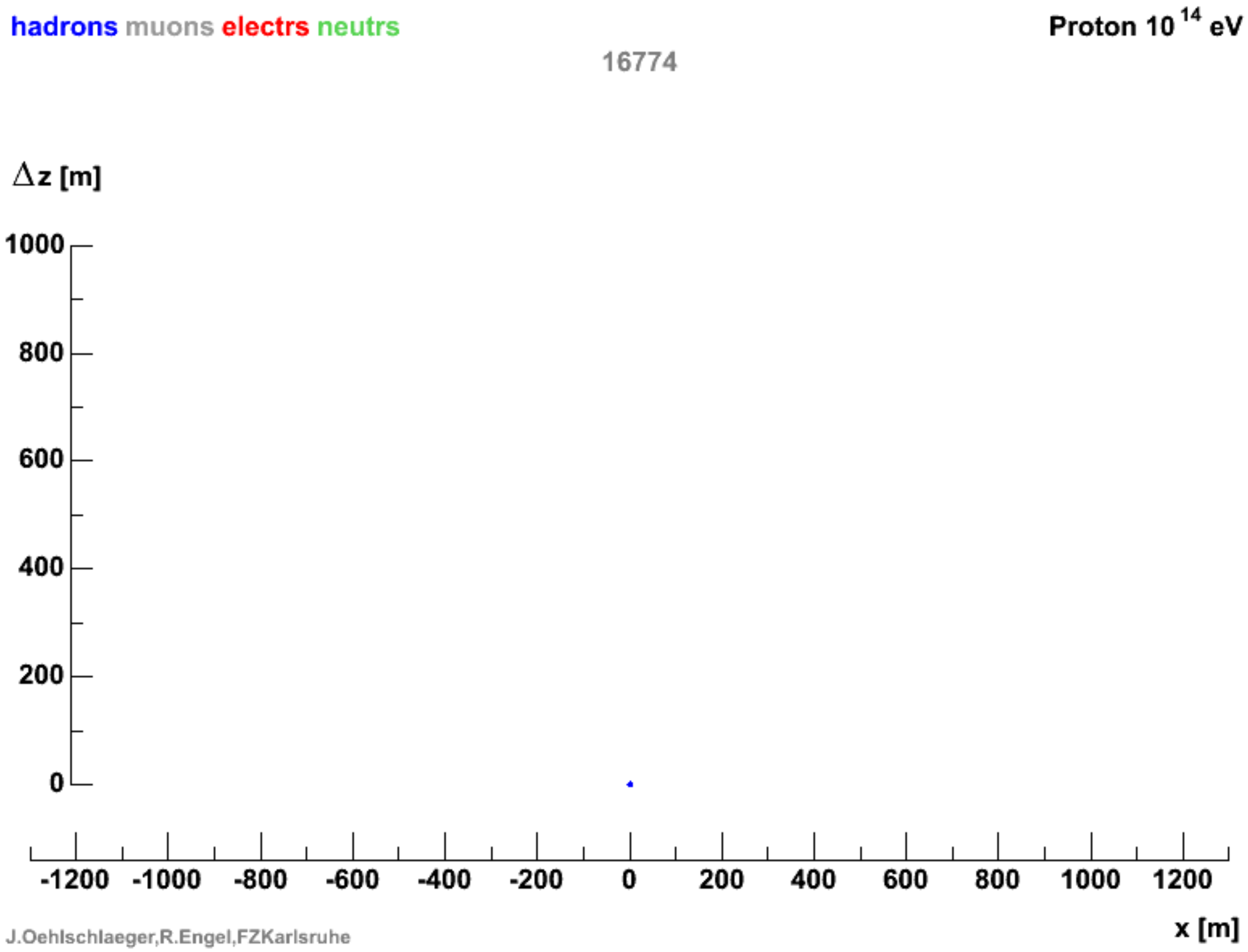
γ
e^+
e^-
e^-
p
π^-
n

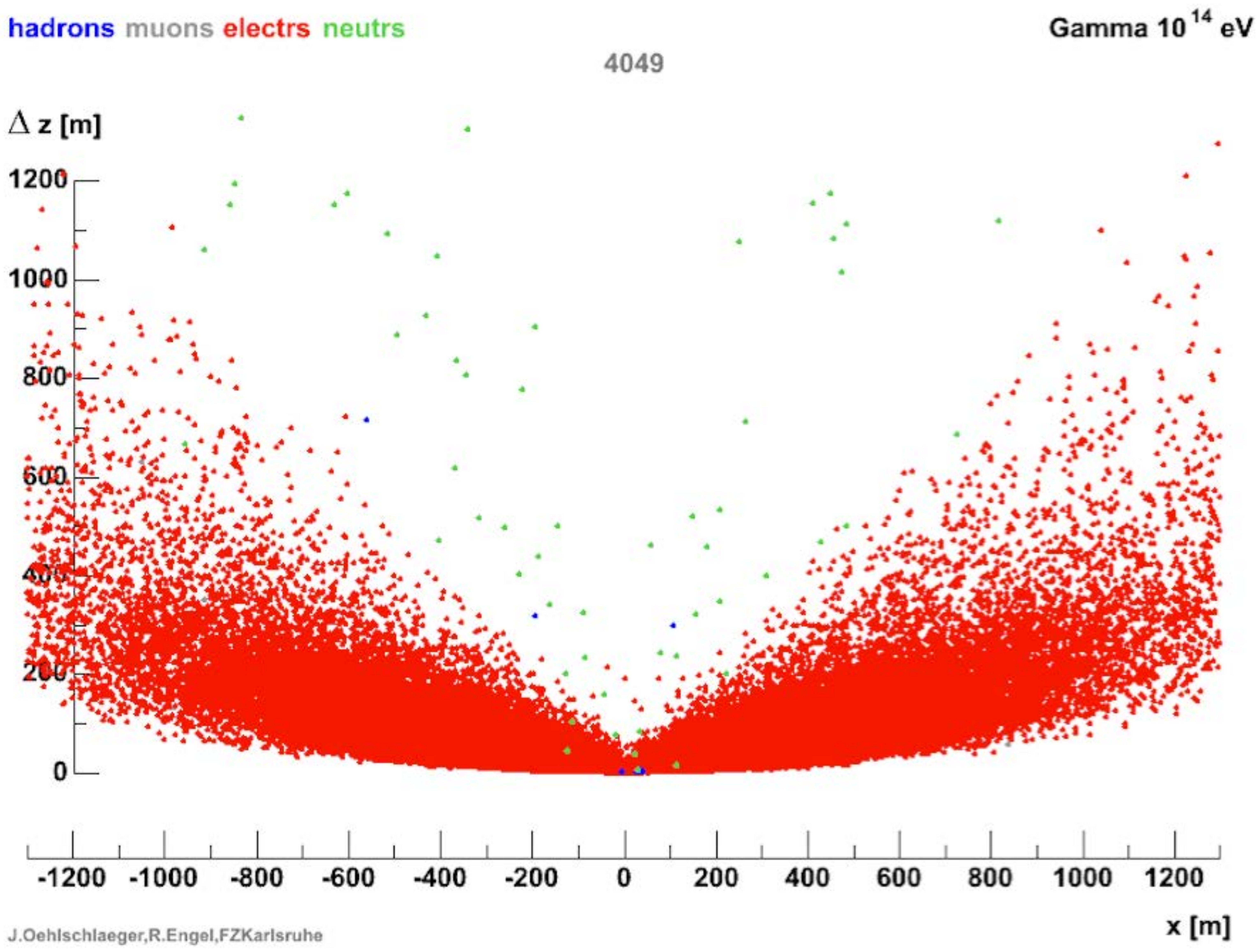
Proton - 100 TeV



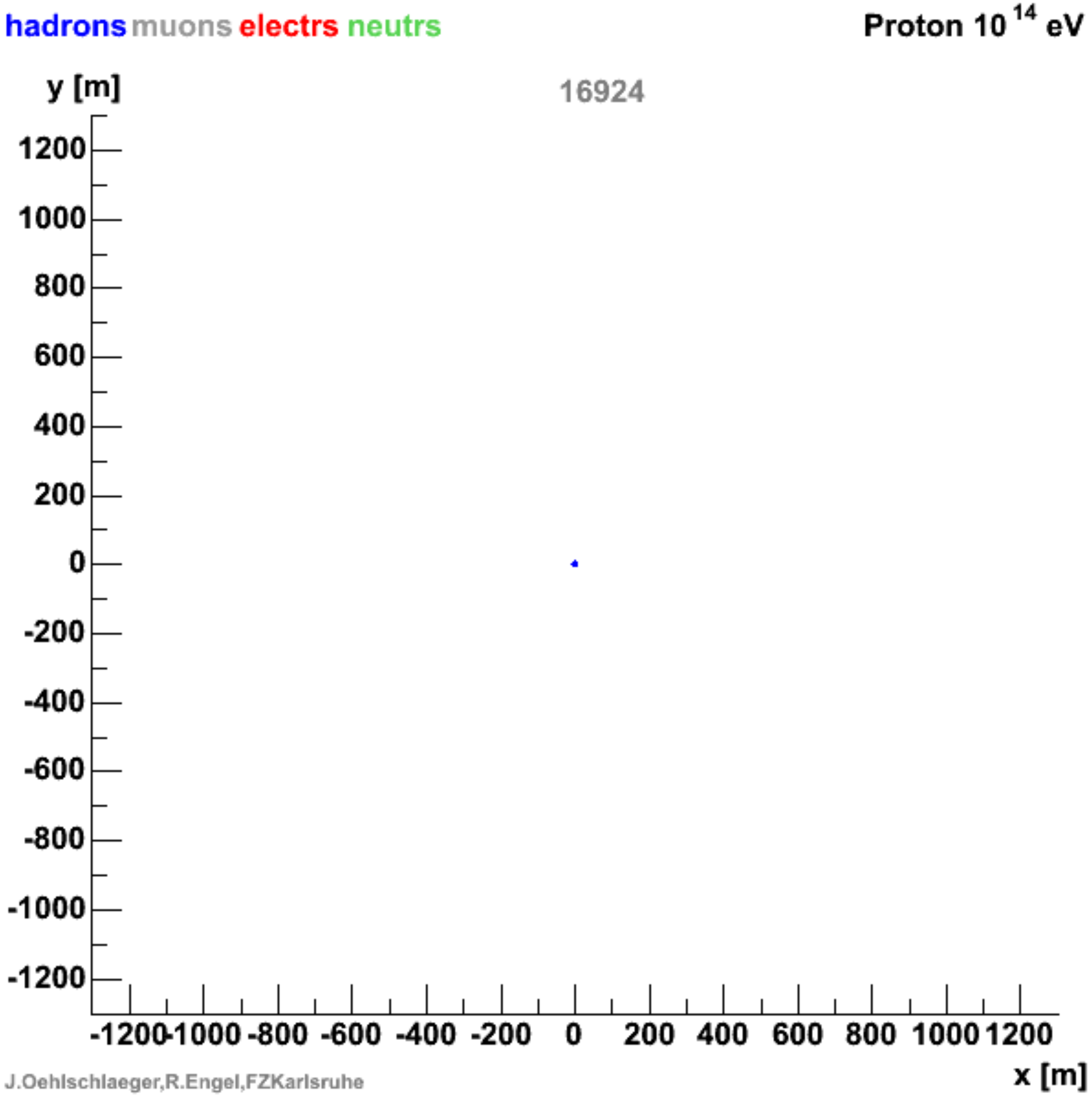
Proton - 100 TeV



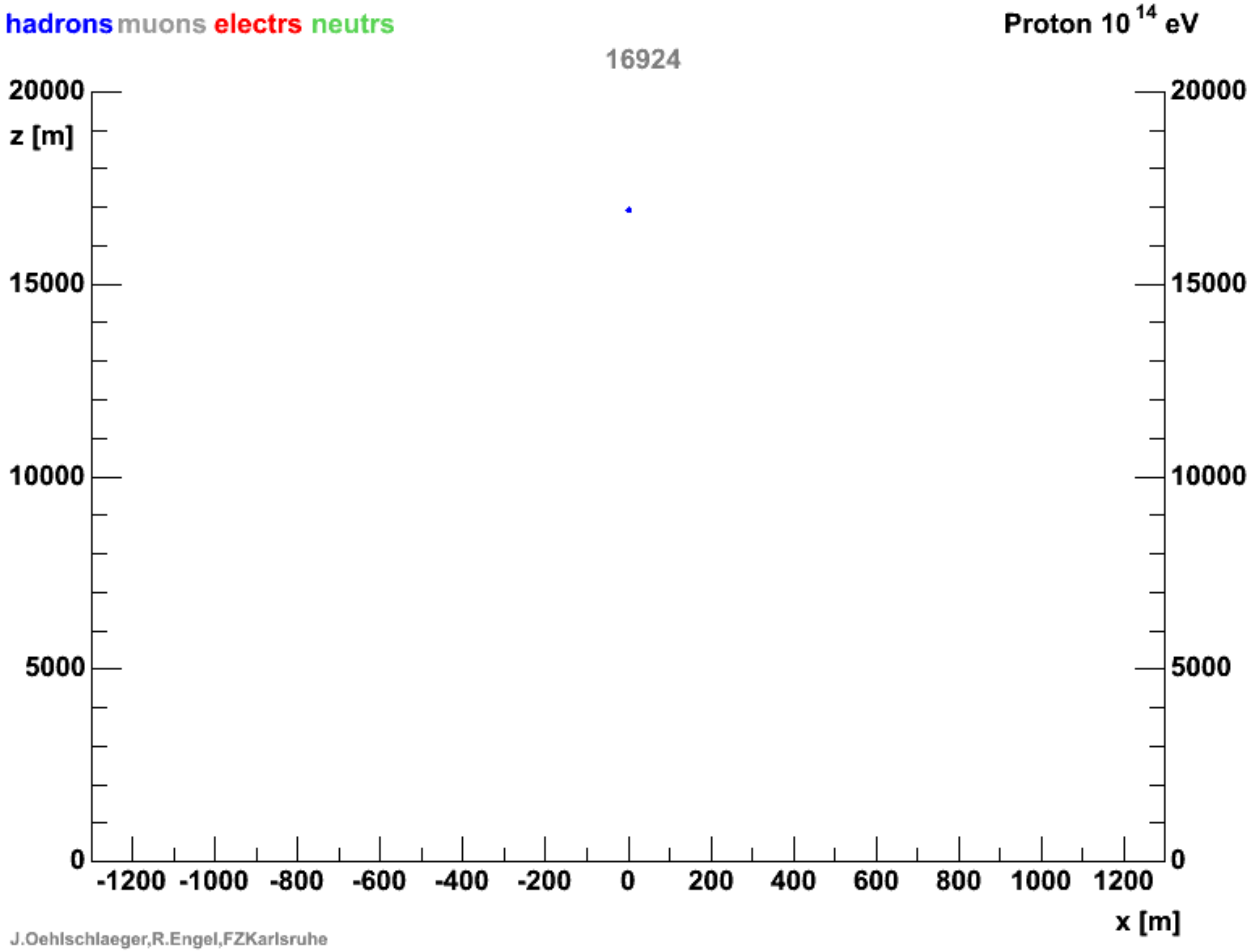
Proton - 100 TeV



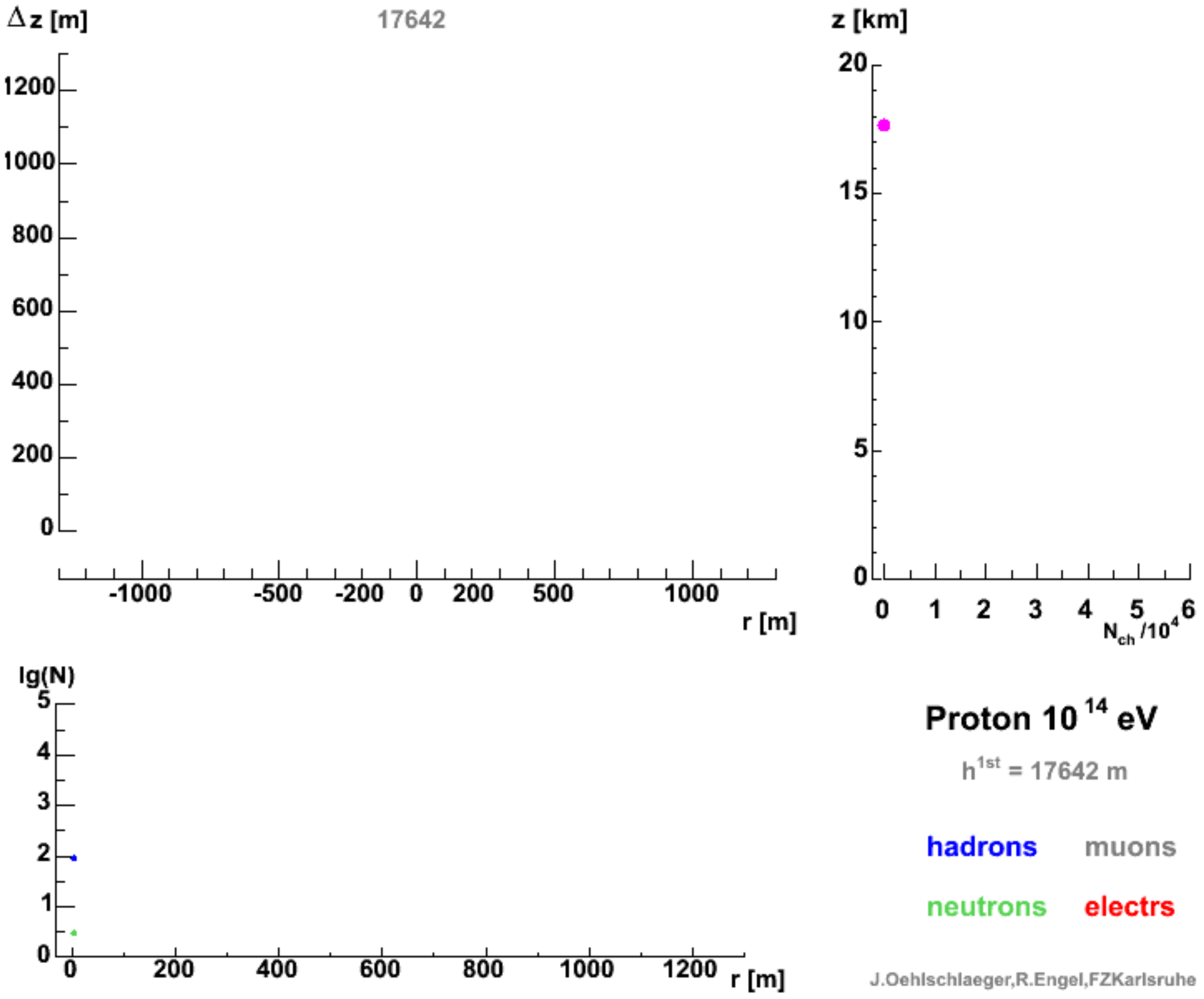
Proton - 100 TeV



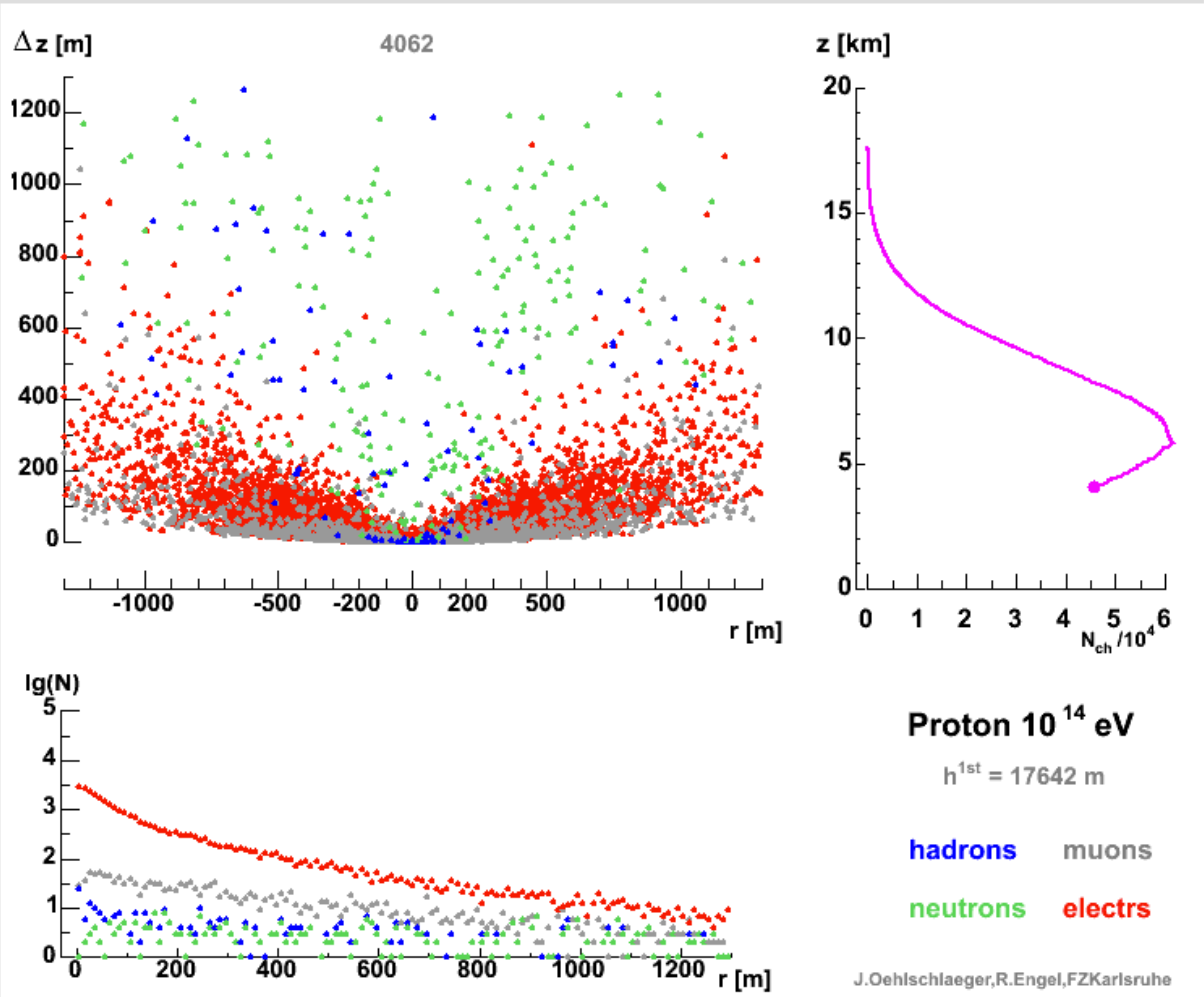
Proton - 100 TeV



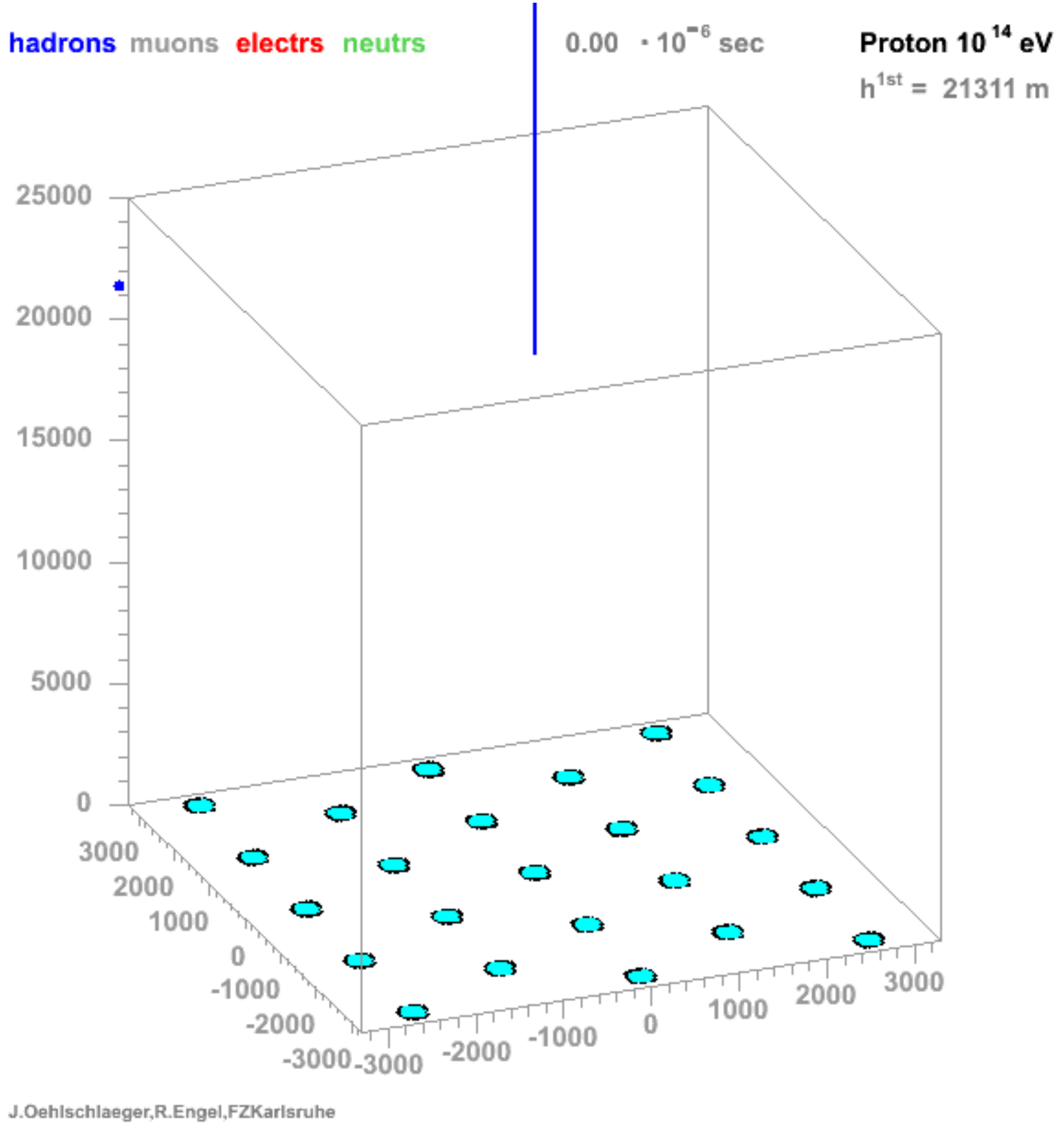
Proton - 100 TeV



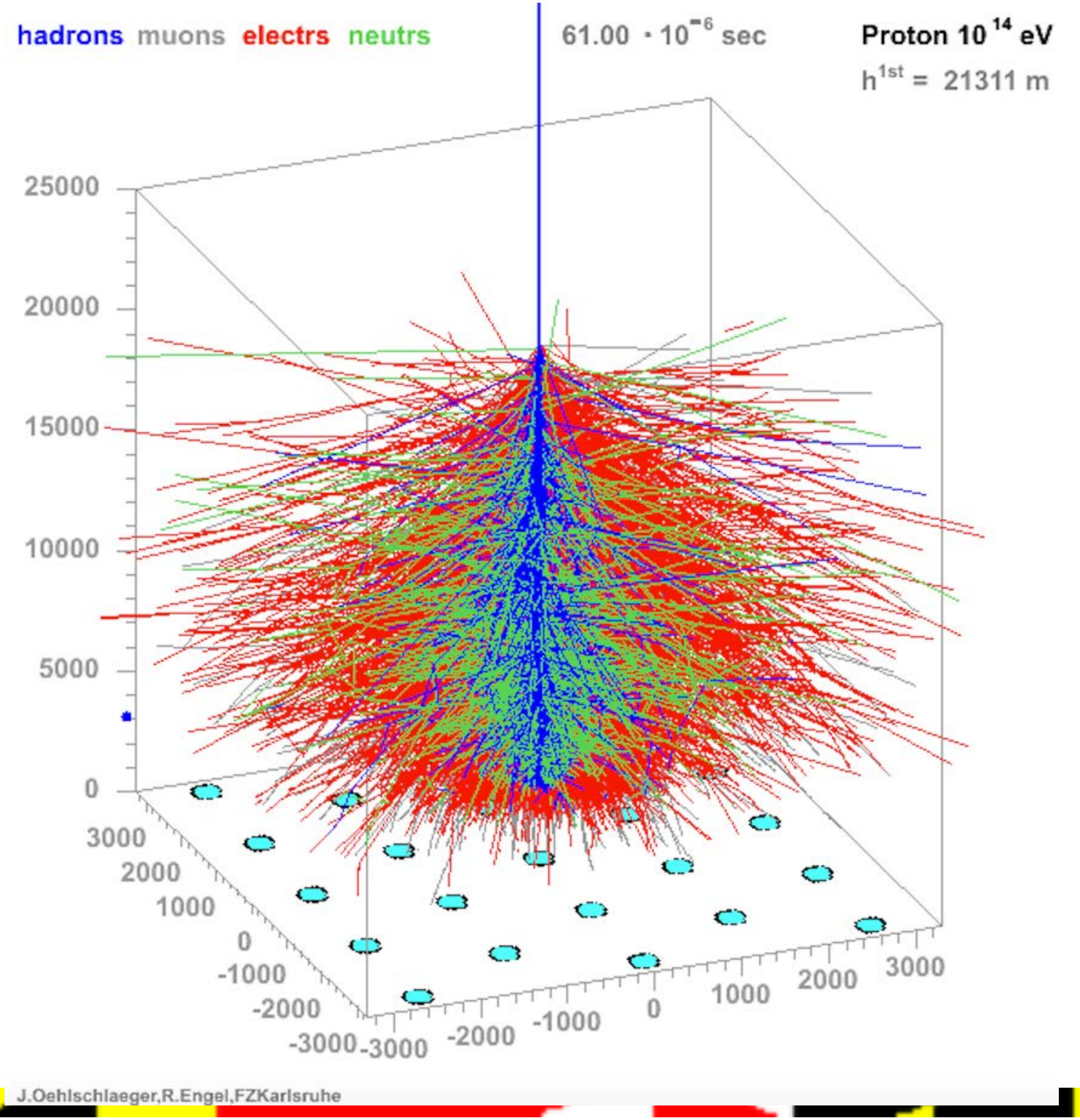
Proton - 100 TeV



Proton - 100 TeV

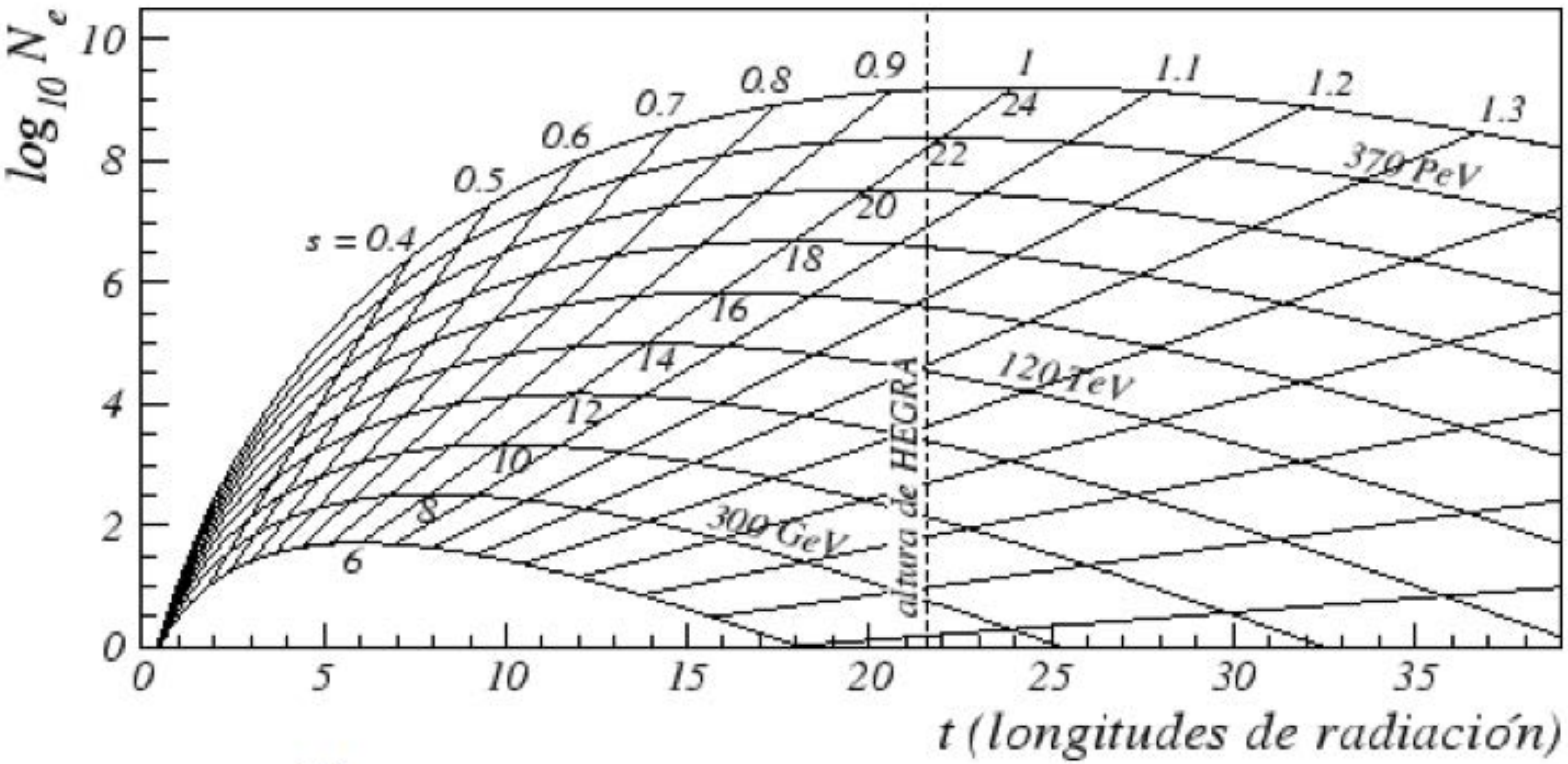


Proton - 100 TeV



Examples

- For 2 TeV gamma ray in the atmosphere
  - Ln ($2x10^6$ MeV/80 MeV)/Ln(2) = 14.6 r.l.
  - r.l. in air is 37gm/cm^2
  - Cascade max is at 540gm/cm^2



The Atmosphere

- The atmosphere is about 80% N_2 and 20% O_2
- Gas law gives us

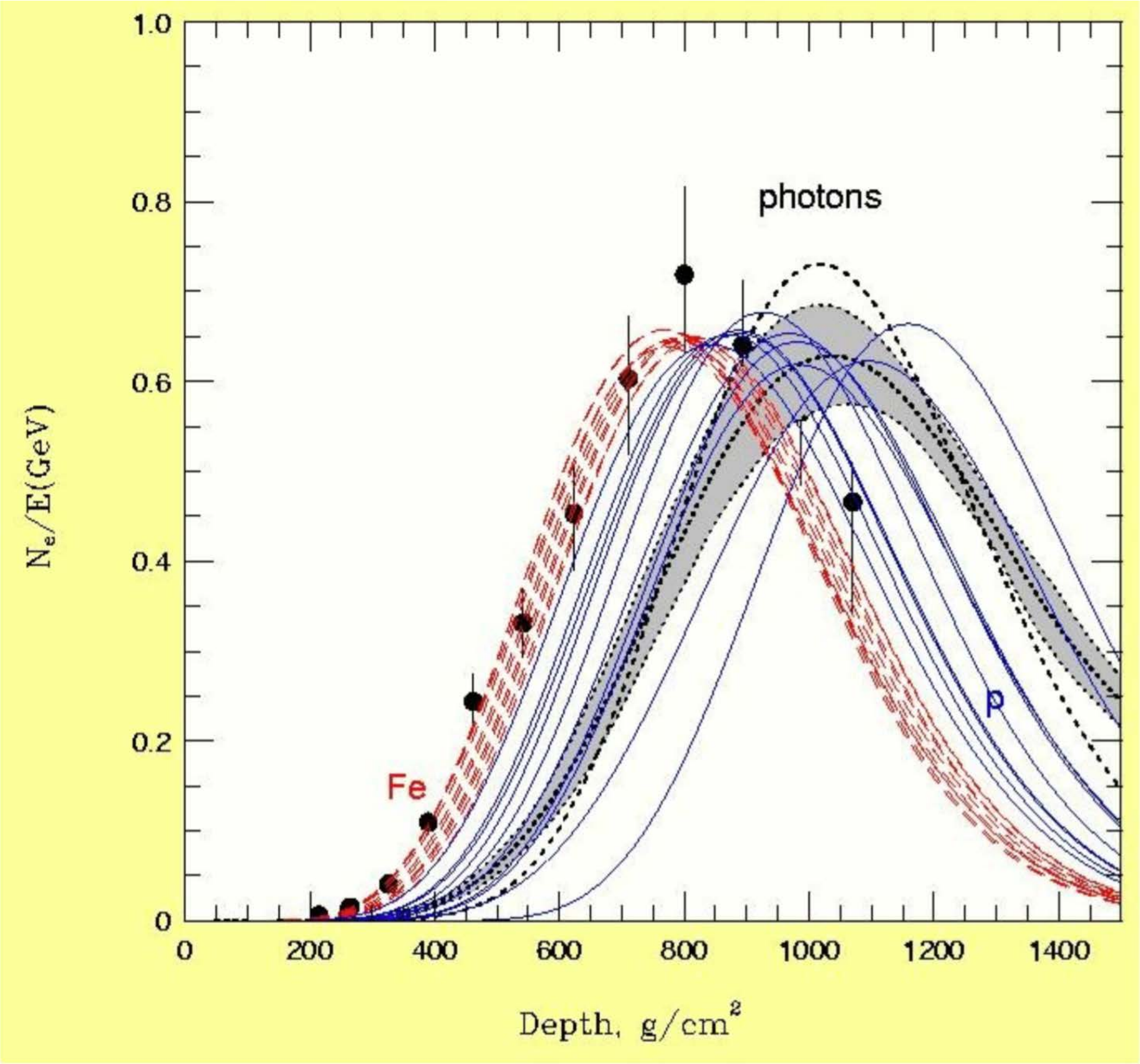
$$P = \frac{\rho R T}{M_0}$$

- Isothermal atmosphere

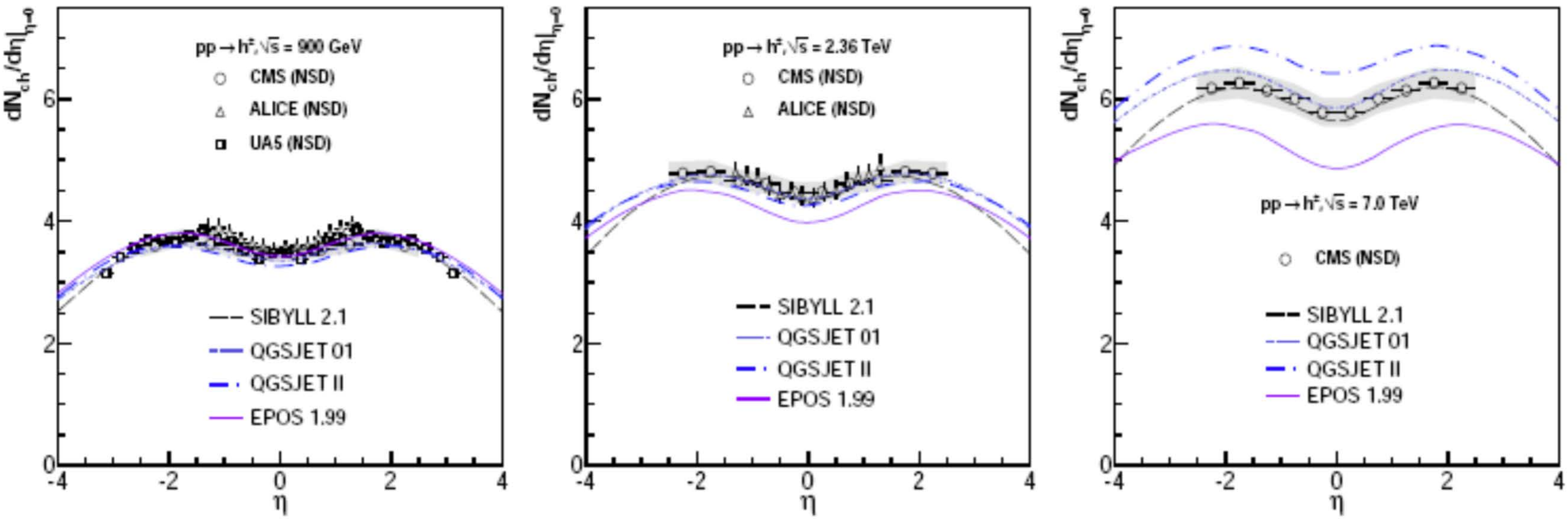
$$P = P_0 e^{-h/h_0} \quad X = X_0 e^{-h/h_0}$$

- Where h_0 = 7km, P_0 = 101kPa, and X_0 =1000g/cm^2.
- So X=540 -> ln (P_0/P) = -h/h_0
- h_{max} ~ 4.7km a.s.l. (a little above HAWC)
  – HAWC measures more than e^+e^-
  – Because r.l. in water is 37gm/cm^2 photons convert ~1'

Depth of Shower Maximum



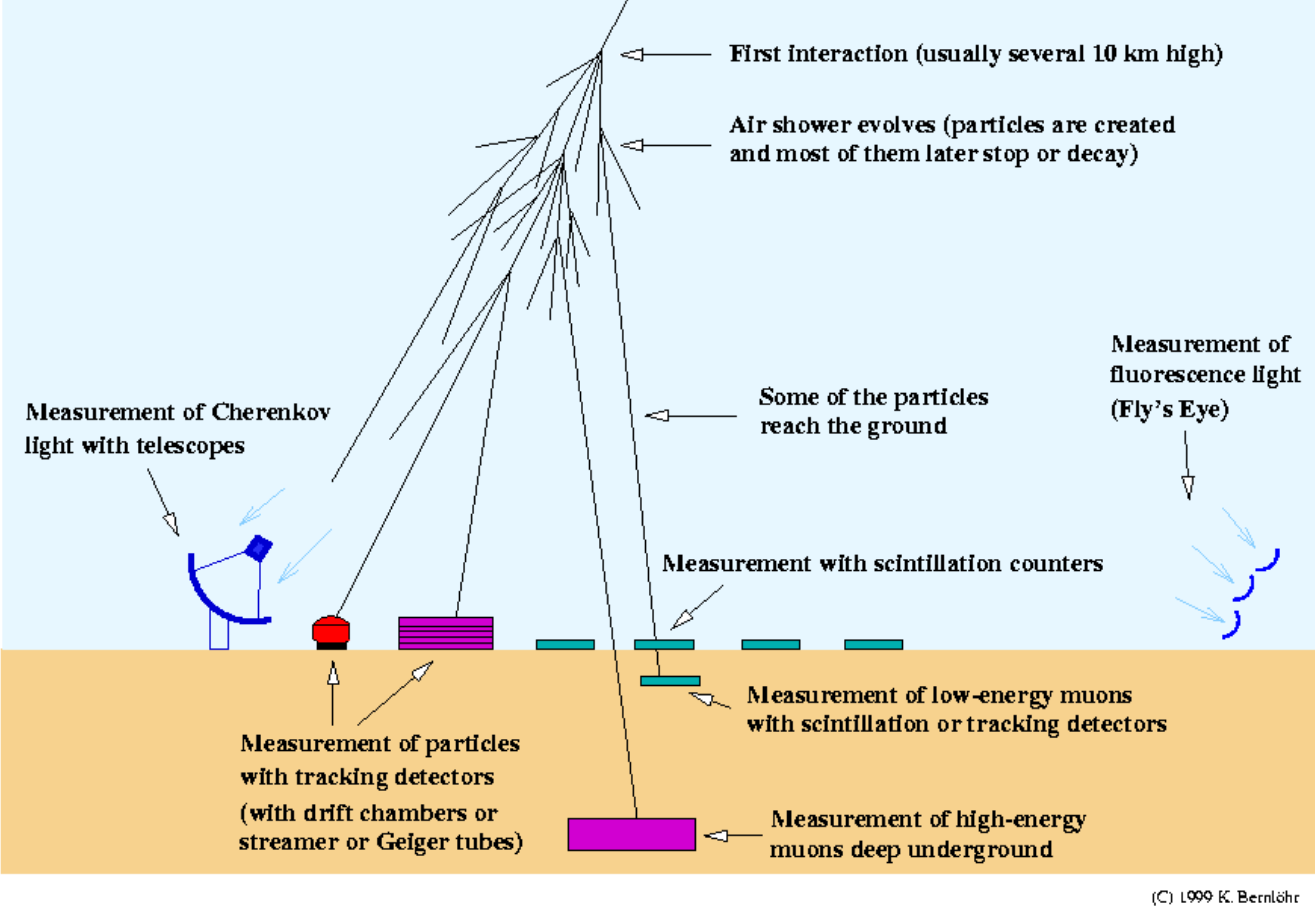
Physics models and LHC data



Air shower development depends mostly on the forward region that is not well measured in collider experiments.

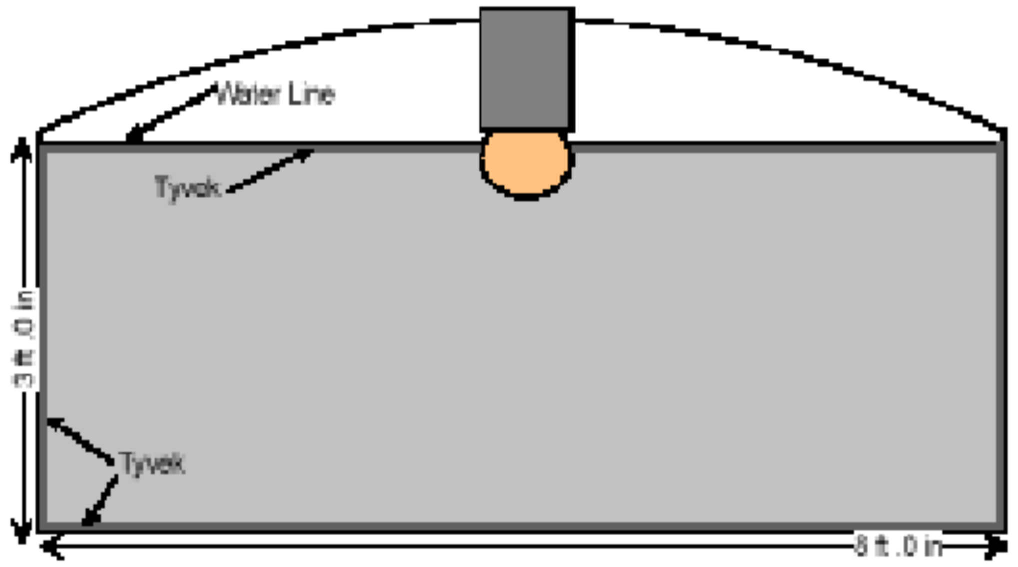
Air Shower Detectors

- Basically five types of detectors - some are used in combination
  - Scintillator Arrays
  - Fluorescence Detectors (FDs)
  - Resistive Plate Carpets
  - Water Cherenkov Detectors
  - Imaging Atmosphere Cherenkov Detectors (IACTs)
- Night Sky Detectors - IACTs, FDs
  - 10-15% duty factor
  - IACTs Integrate shower - good for energy
  - FDs - see shower profile - good for energy and composition
- Surface detectors sample showers at one depth but operate 24/7

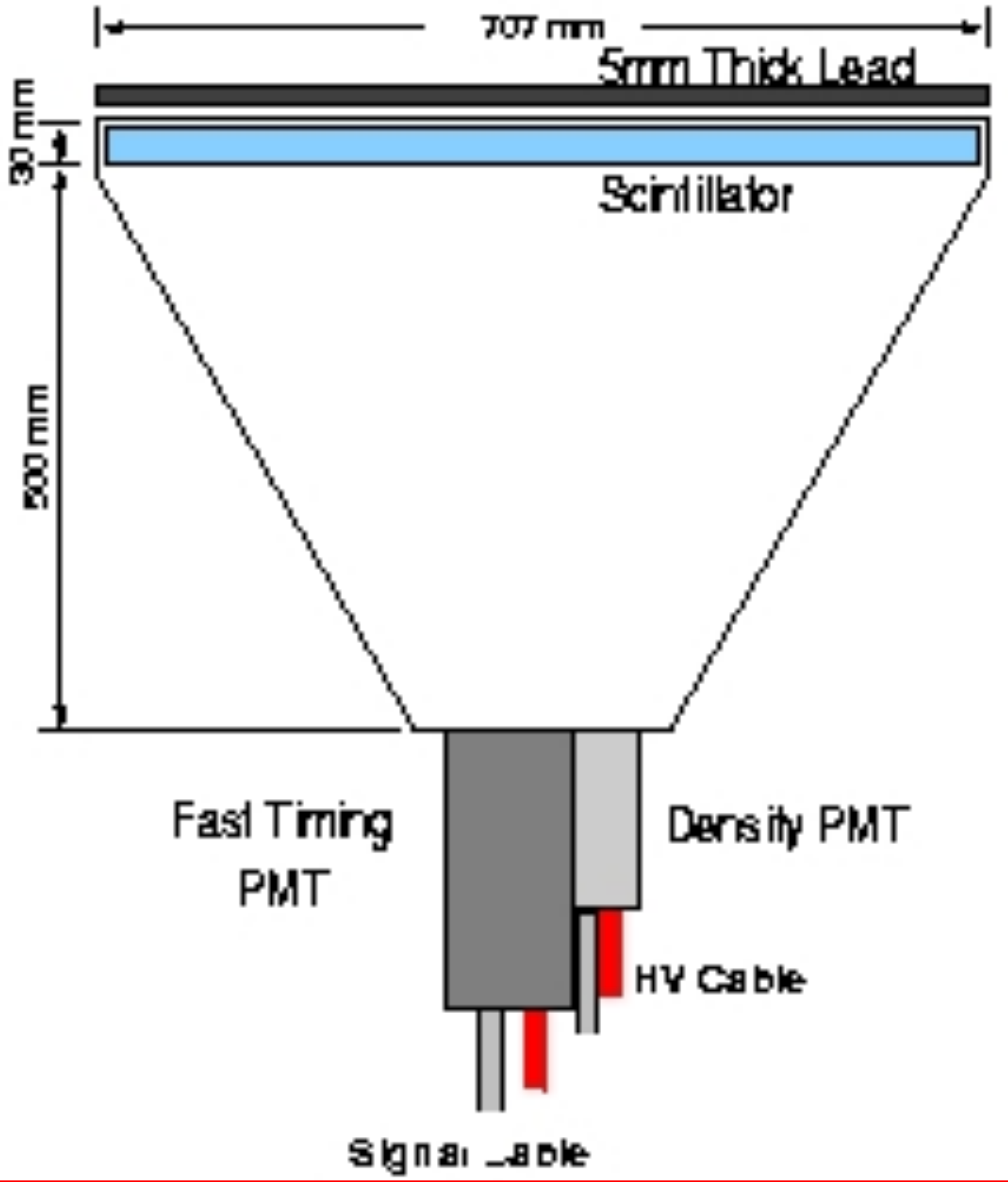

First interaction (usually several 10 km high)
Air shower evolves (particles are created and most of them later stop or decay)
Measurement of fluorescence light (Fly's Eye)
Measurement of Cherenkov light with telescopes
Some of the particles reach the ground
Measurement with scintillation counters
Measurement of low-energy muons with scintillation or tracking detectors
Measurement of particles with tracking detectors (with drift chambers or streamer or Geiger tubes)
Measurement of high-energy muons deep underground
(C) 1999 K. Bernlöhr

Sampling the Shower

- Water Tanks



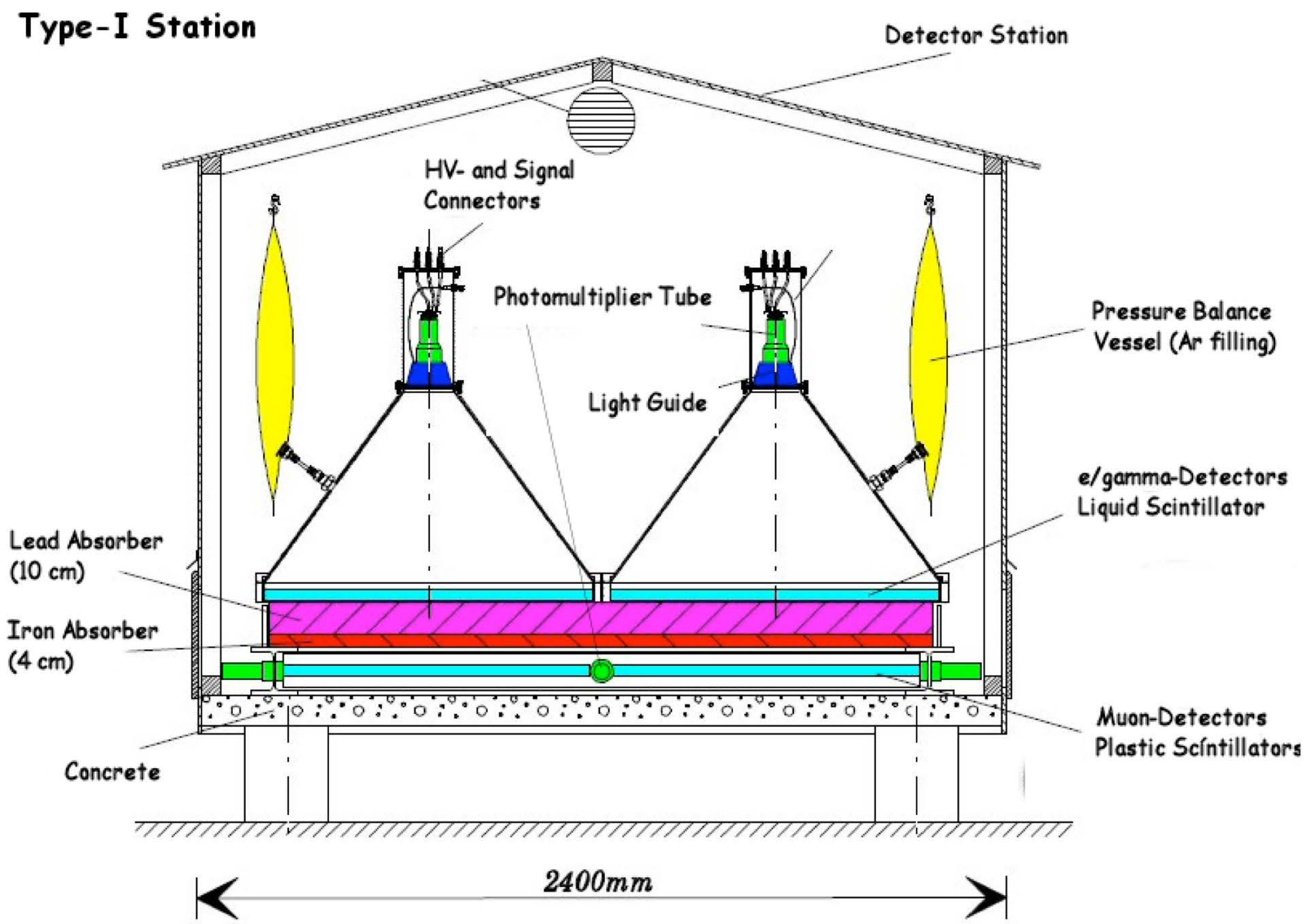
- Scintillators



EAS Detectors - Scintillators

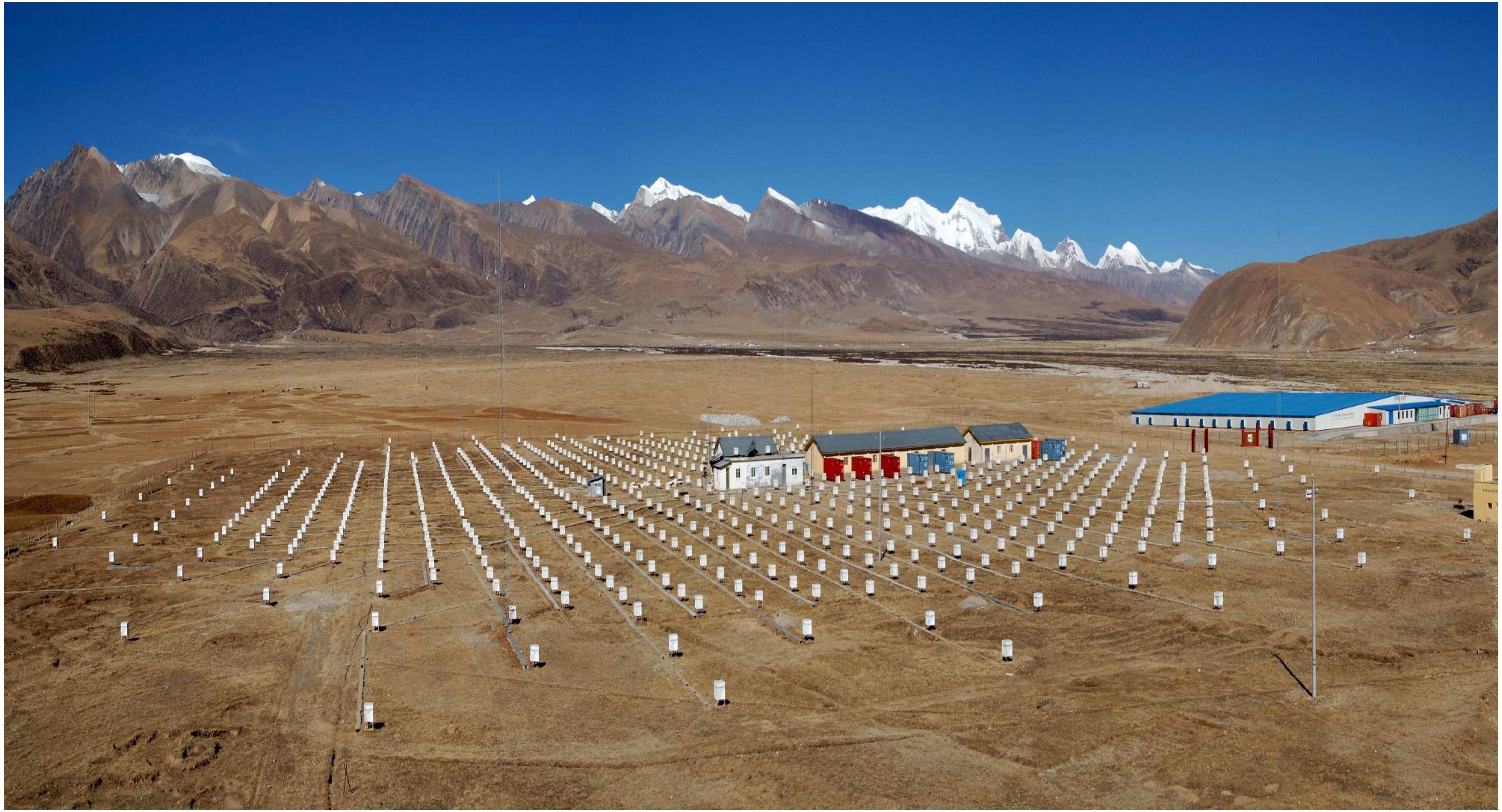
Energy Range 3TeV - 10 PeV

EAS Detectors - Scintillators
KASCADE Grande (Karlsruhe / Germany)



Energy Range 100 TeV - 200 PeV

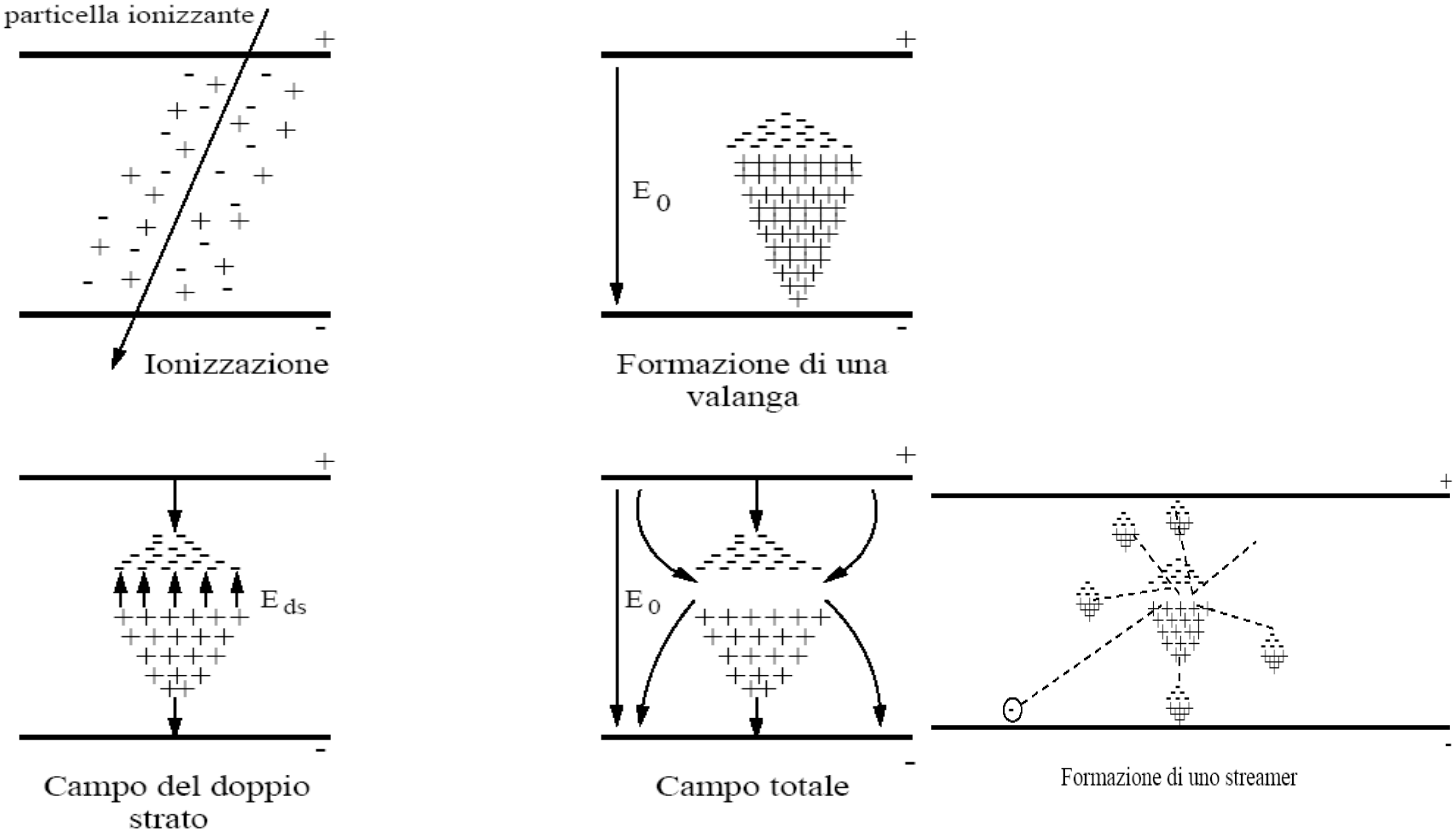
EAS γ - Tibet



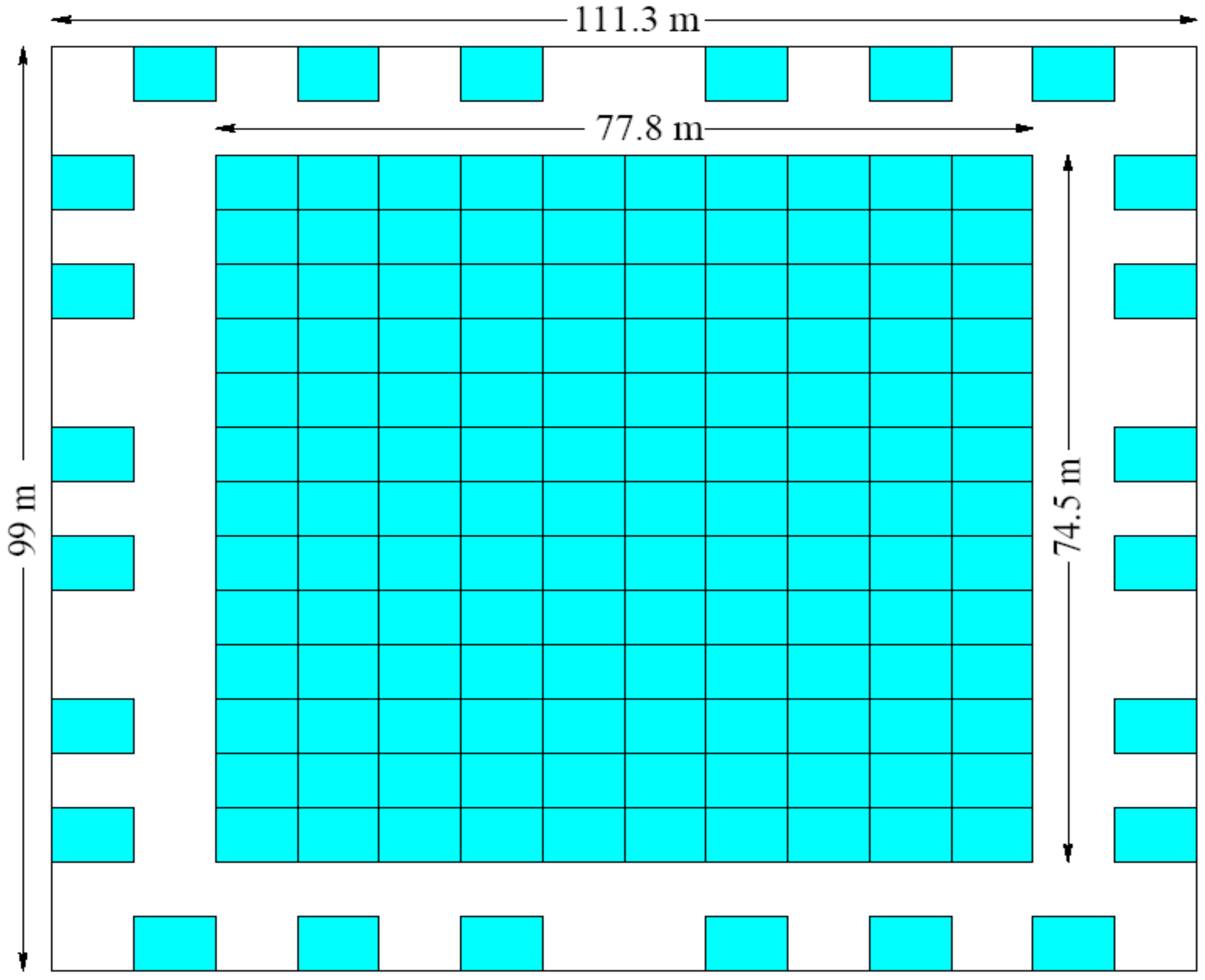
IceTop

ARGO

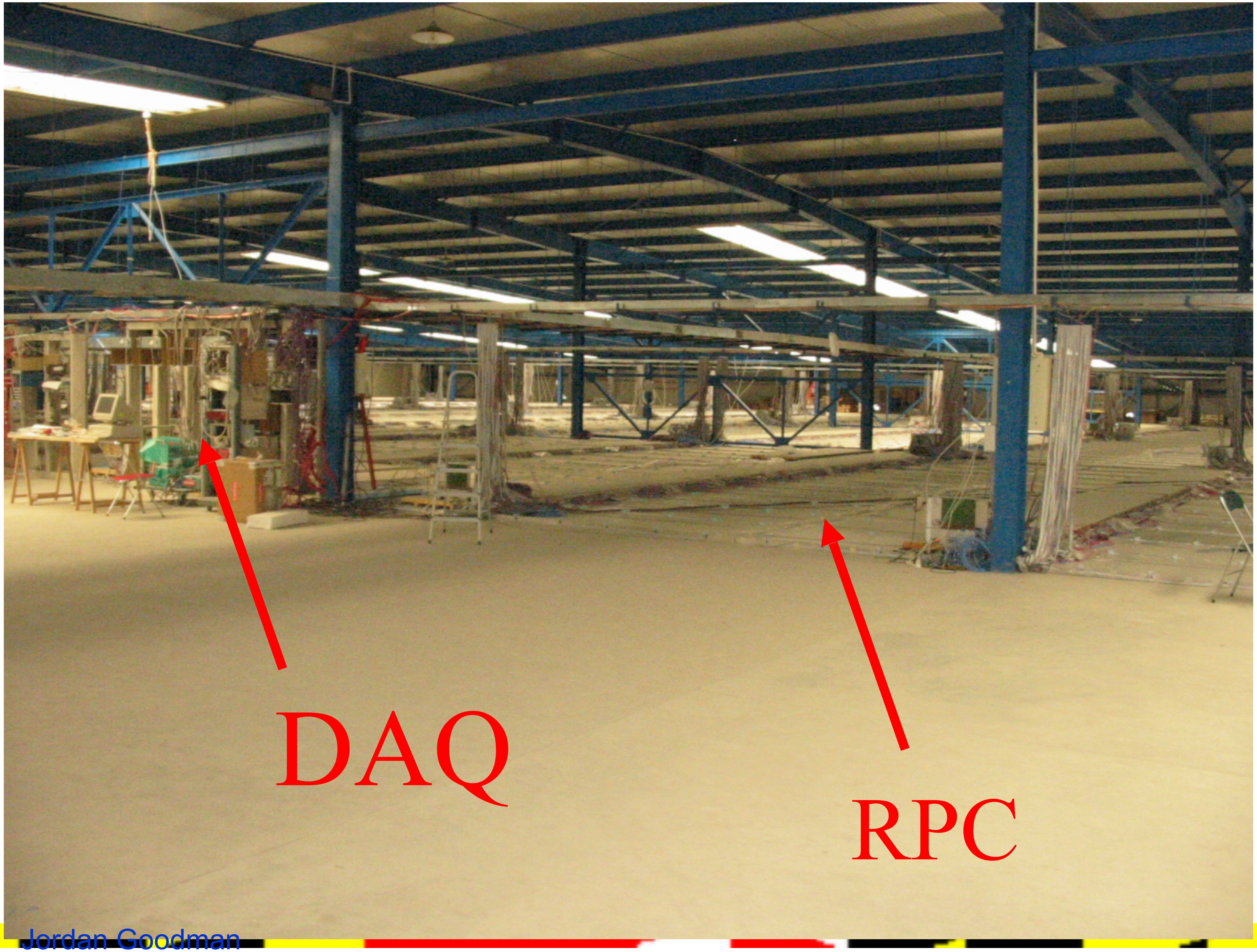
Limited Streamer Tubes



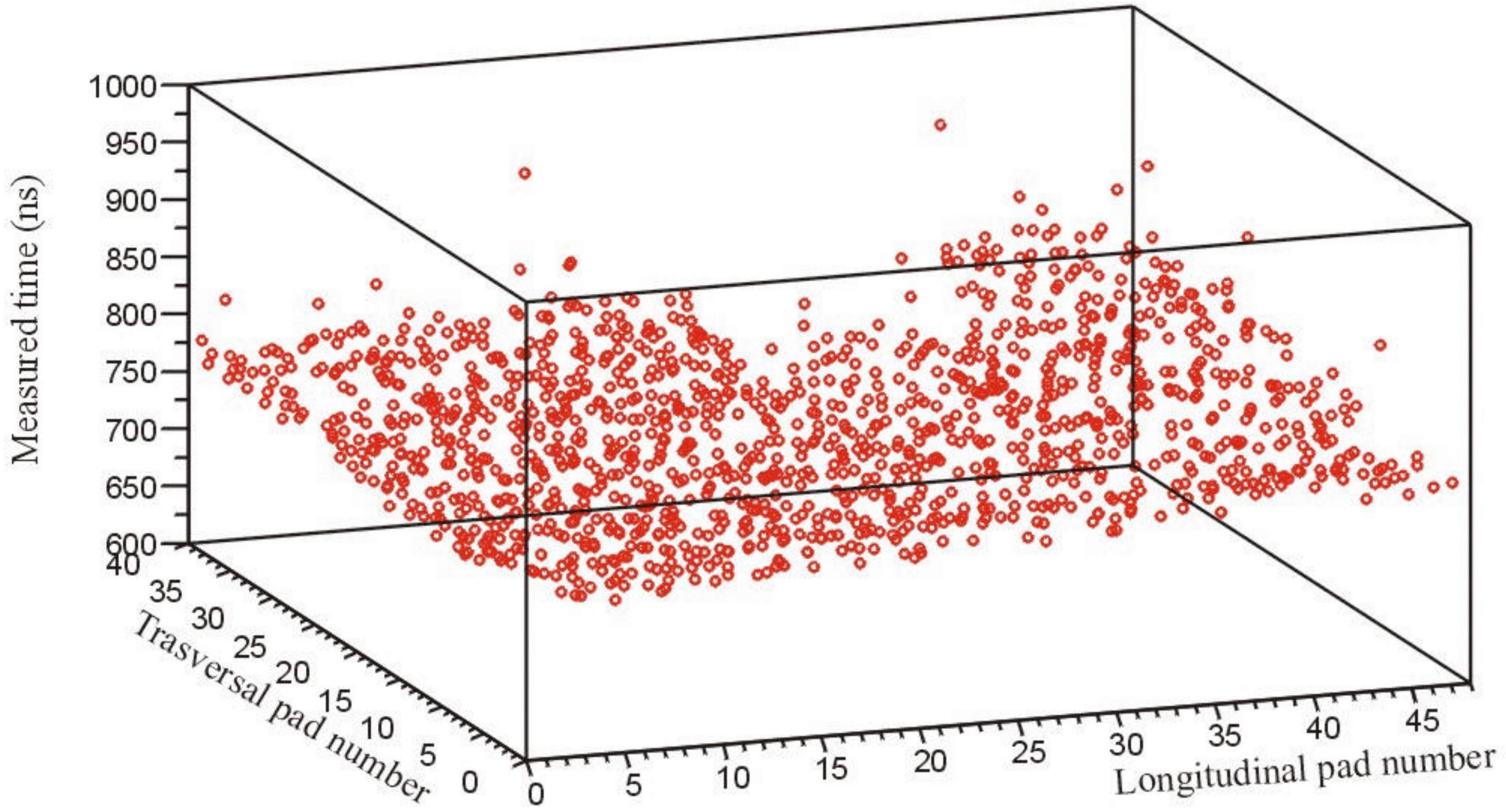
ARGO Design



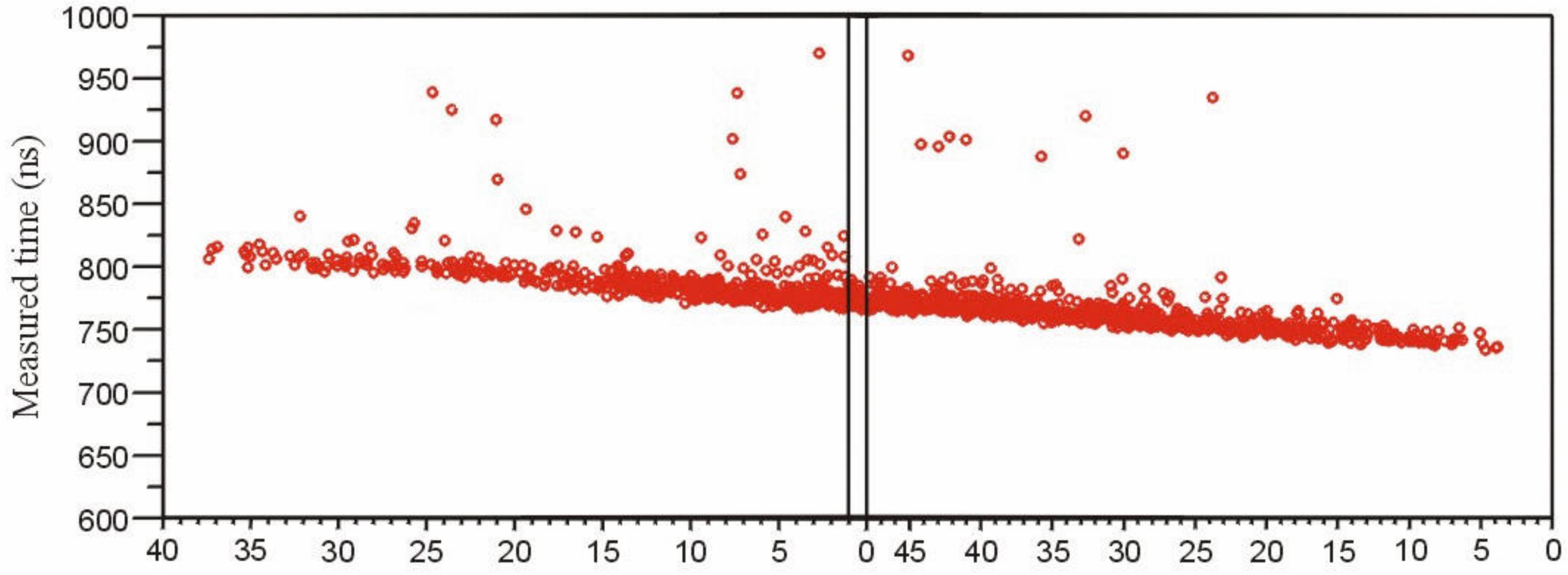
Detector carpet: 10 x 13 Clusters, 1560 RPC
Sampling ring: 6 x 4 Clusters, 288 RPC
Total: 154 Clusters, 1848 RPC
For a complete coverage another 84 Clusters (1008 RPC) are needed


DAQ
RPC

ARGO Events



Picture of an event on 16 clusters

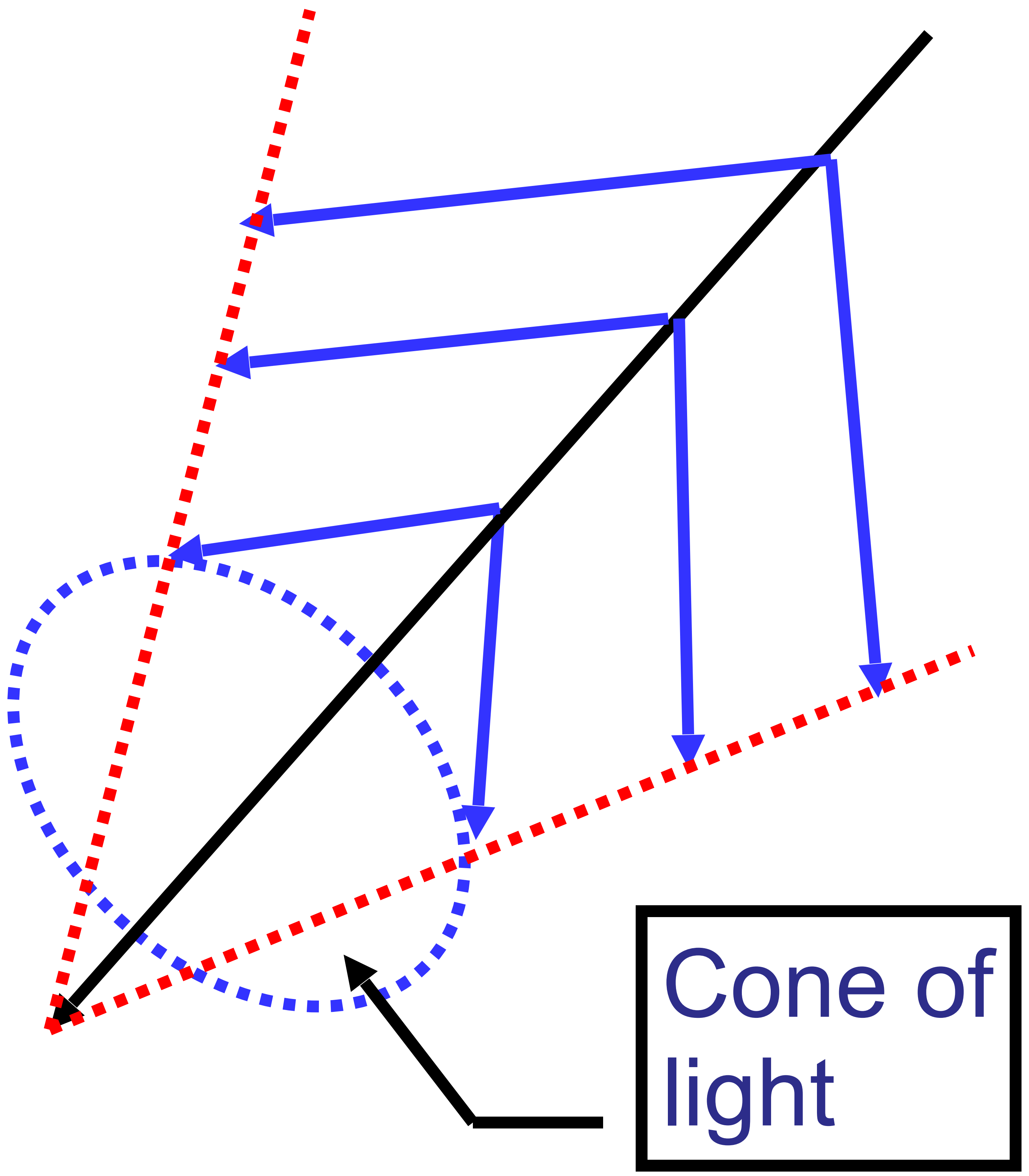


ARGO will be a very capable detector when completed in several years!

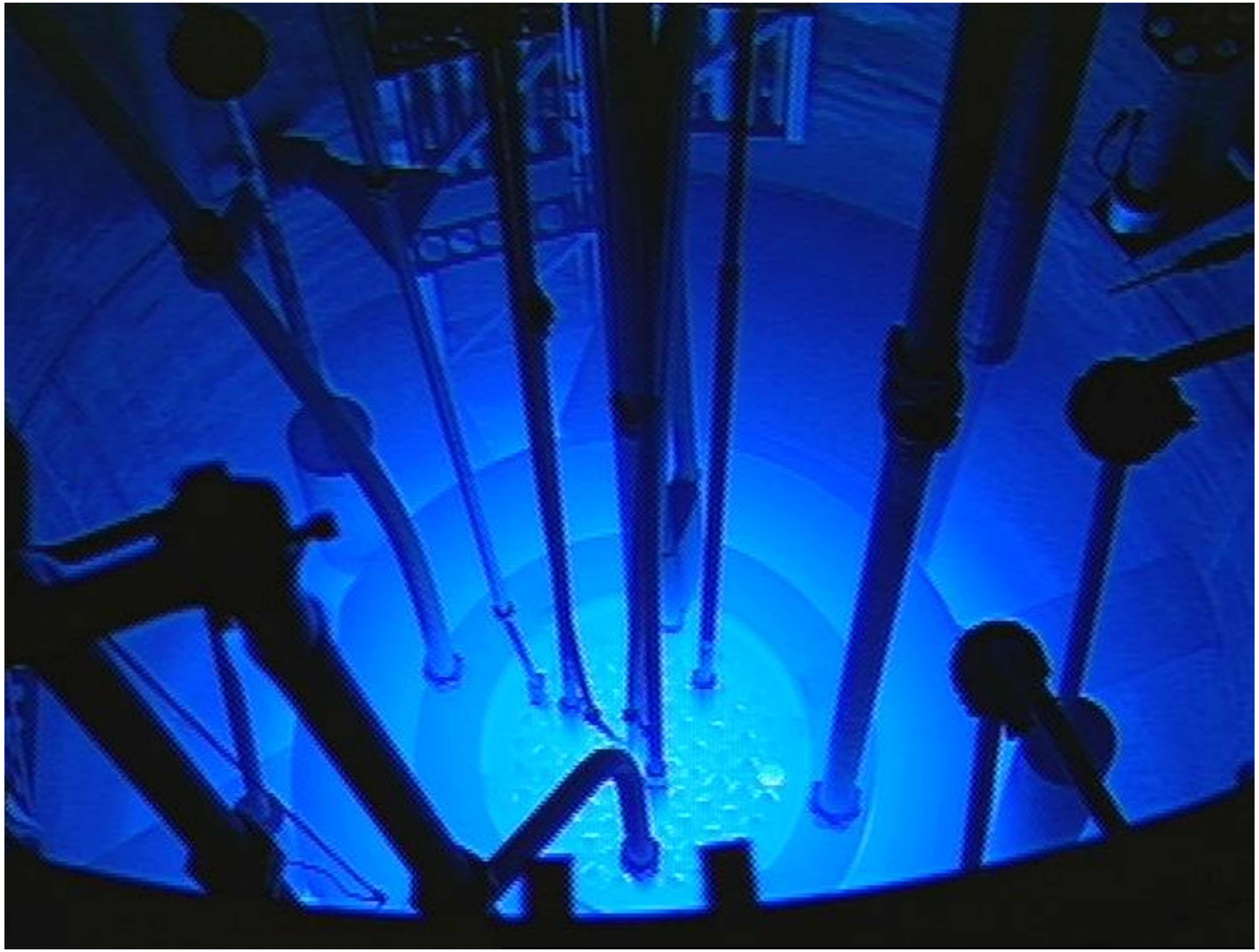
Cherenkov Radiation

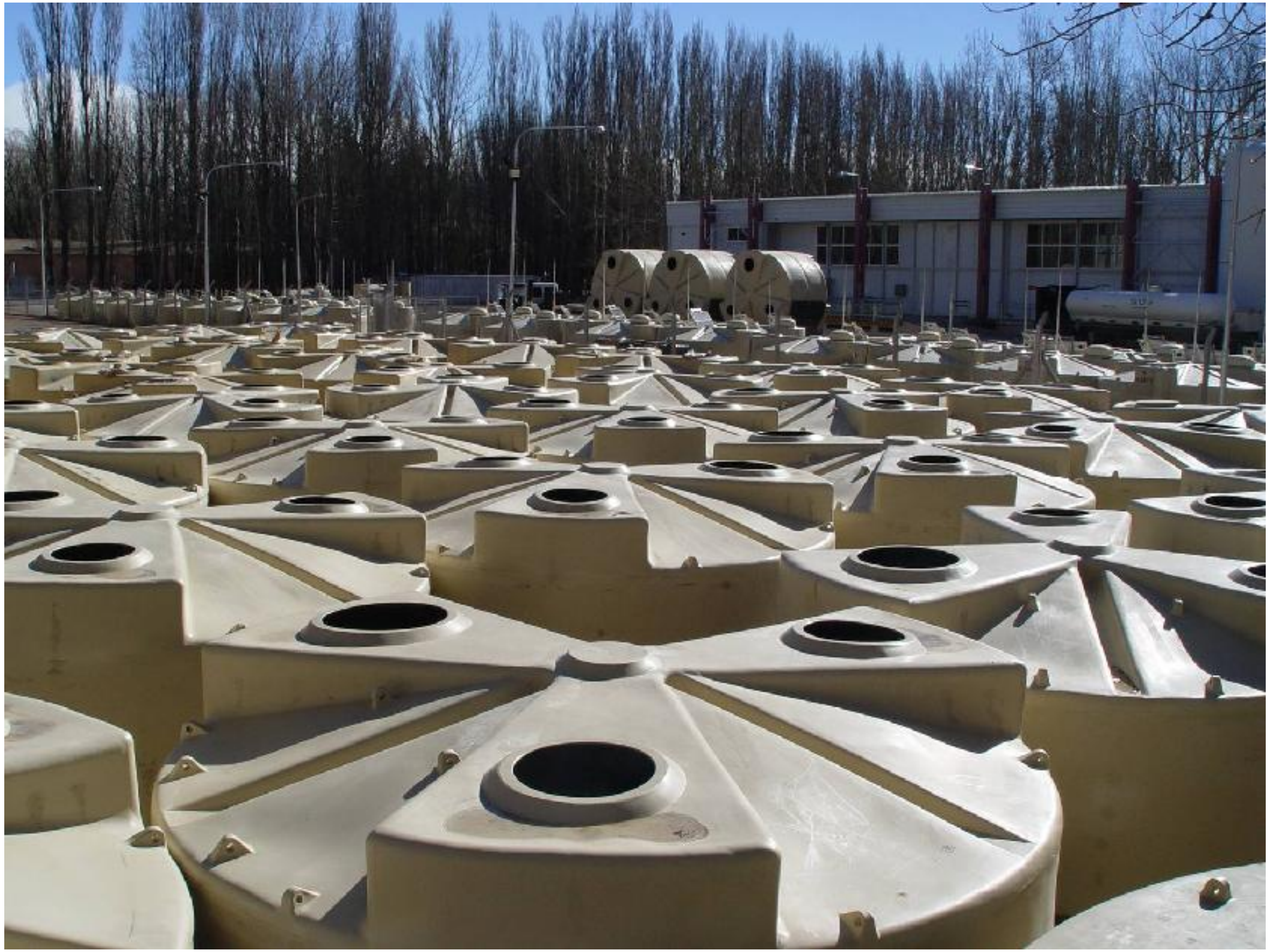
When a charged particle moves through transparent media faster than speed of light in that media.

⇨ Cherenkov radiation

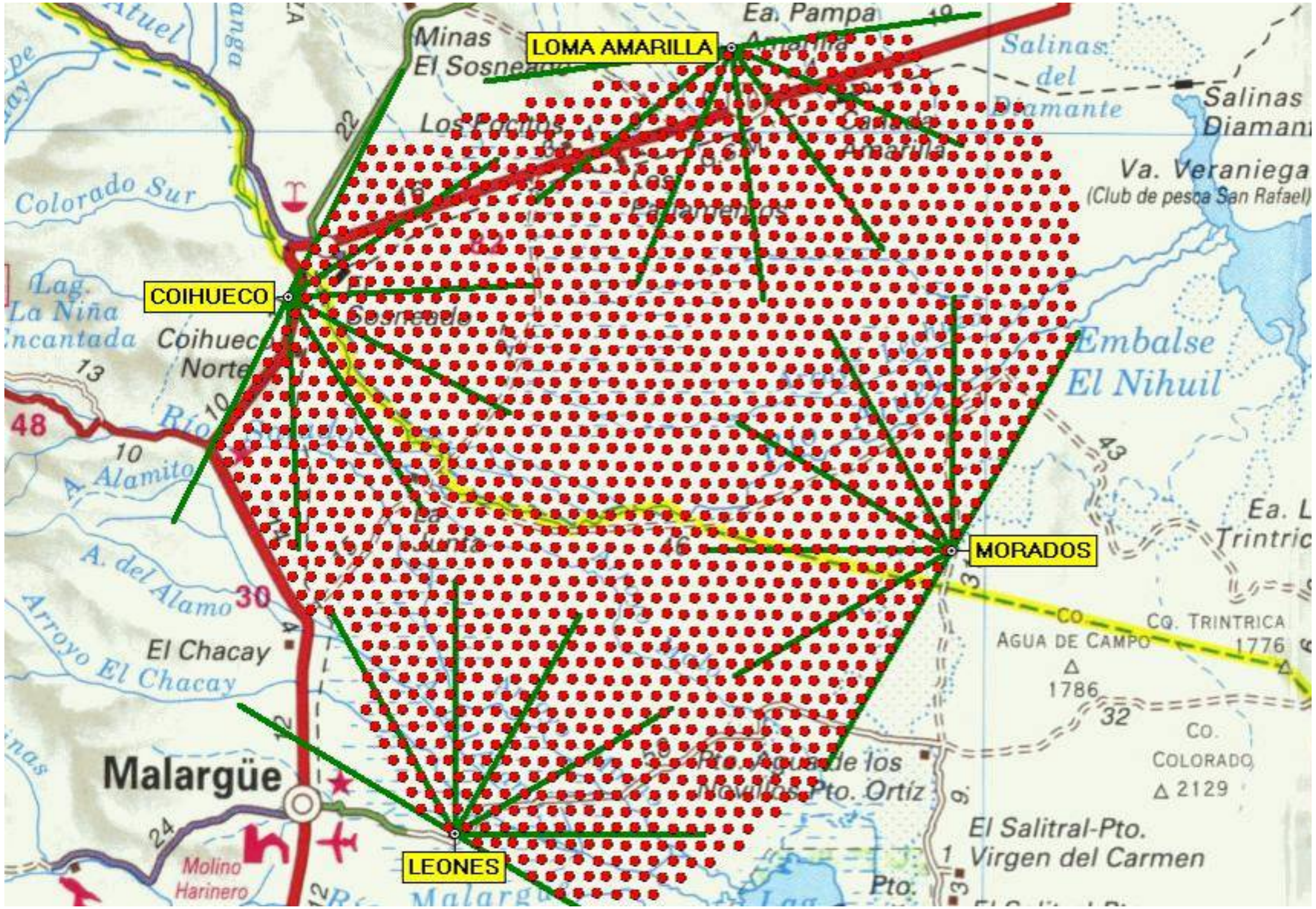


Cherenkov Radiation

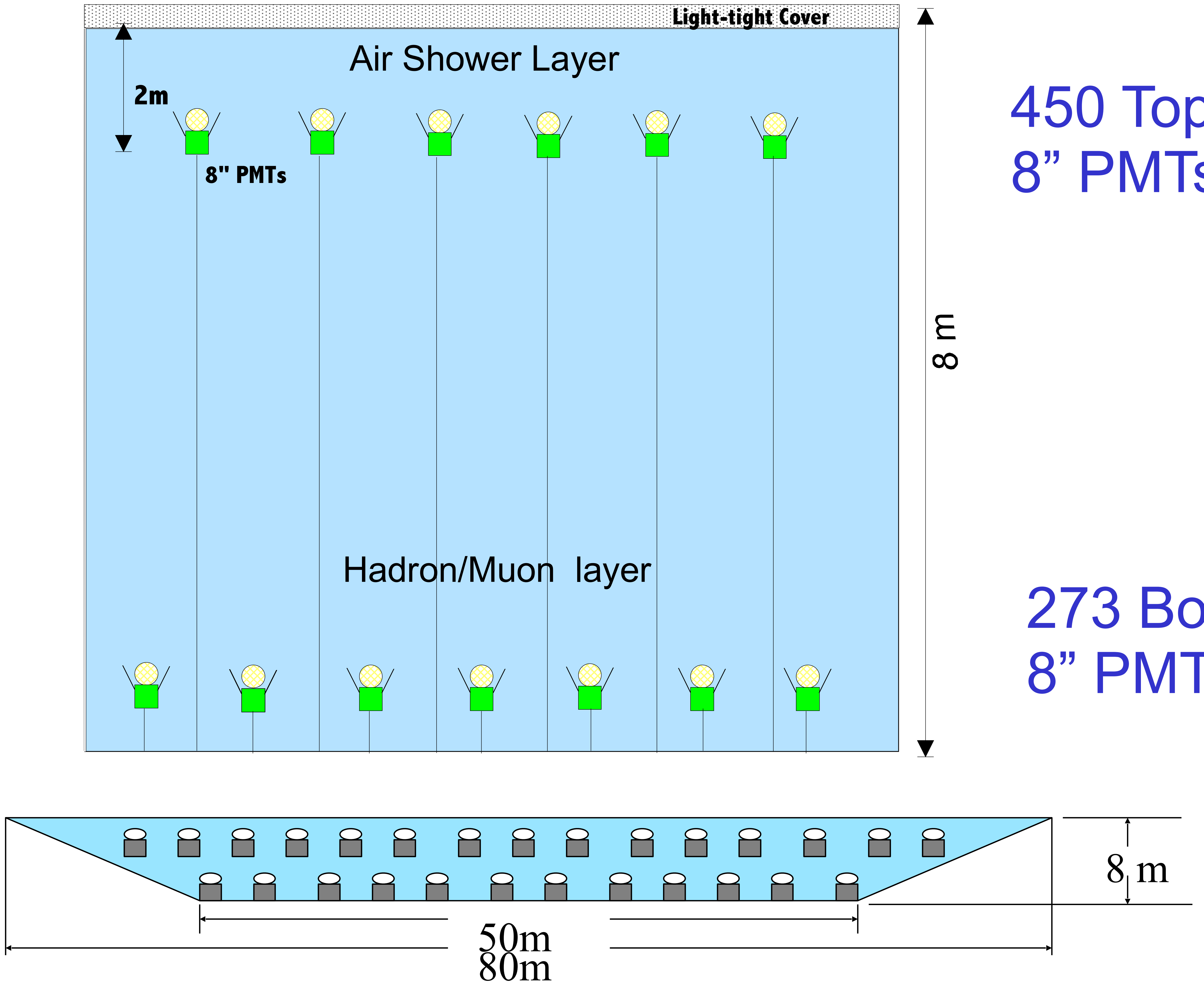




Auger



LOMA AMARILLA
COIHUECO
MORADOS
LEONES
Malargüe
Embalse El Nihuil
Salinas del Diamante
Va. Veraniega
(Club de pesca San Rafael)
Ea. Pampa
Minas El Sosneado
El Chacay
Colorado Sur
El Salitral-Pto. Virgen del Carmen
Molino Harinero



450 Top Layer
8" PMTs

273 Bottom Layer
8" PMTs

Milagro Gamma Ray Observatory
2350m altitude near Los Alamos, NM

A. Abdo, B. Allen, D. Berley, T. DeYoung,B.L. Dingus, R.W. Ellsworth, M.M. Gonzalez, J.A. Goodman, C.M. Hoffman,P. Huentemeyer, B. Kolterman, J.T. Linnemann, J.E. McEnery, A.I. Mincer, P. Nemethy, J. Pretz, J.M. Ryan, P.M. Saz Parkinson, A. Shoup, G. Sinnis, A.J. Smith, D.A. Williams, V. Vasileiou, G.B. Yodh

Los Alamos National Laboratory
UC Santa Cruz
University of Maryland
Michigan State University
UCIrvine University of California, Irvine
New York University
New Hampshire

Milagro

- In the mountains above Los Alamos at 2650m
- In an existing pond
  - 60m x 80m x 8m
  - 175 outriggers
  - 20,000 m^2
- Operated from 2000- 2008
- 1st wide-field TeV Observatory

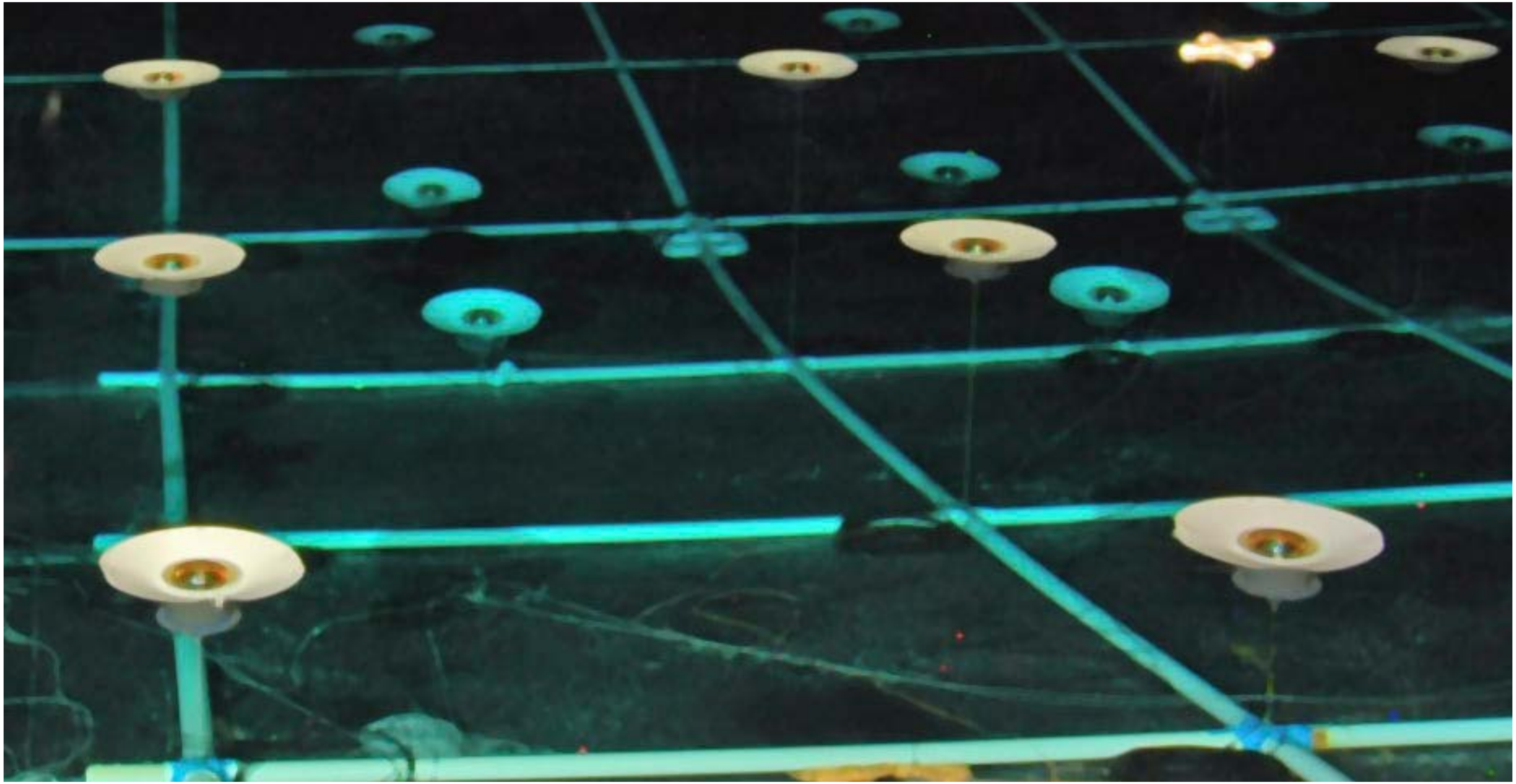
Energy Range (3 Tev - 40 TeV)

Good Hadron Rejection

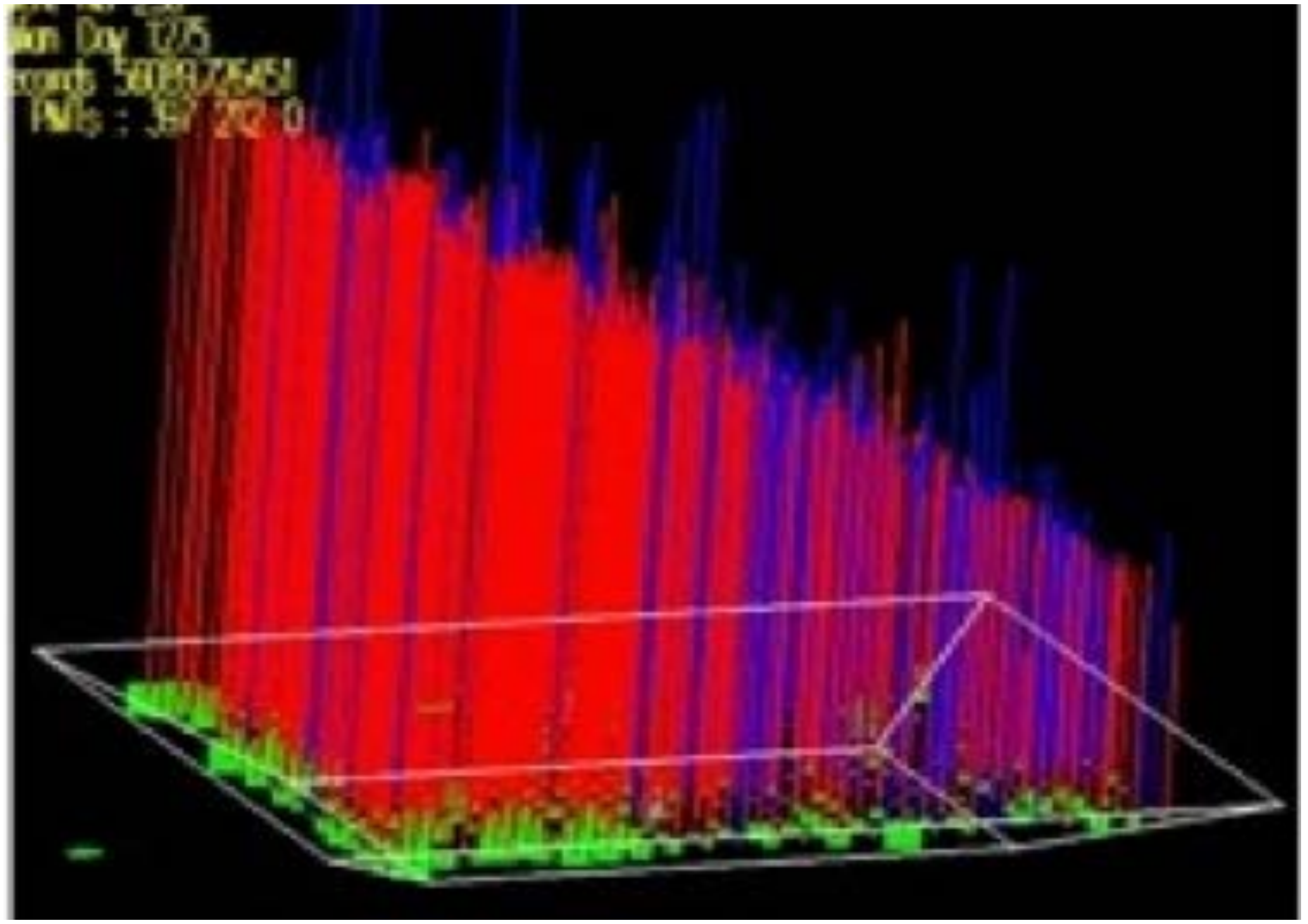
Milagro

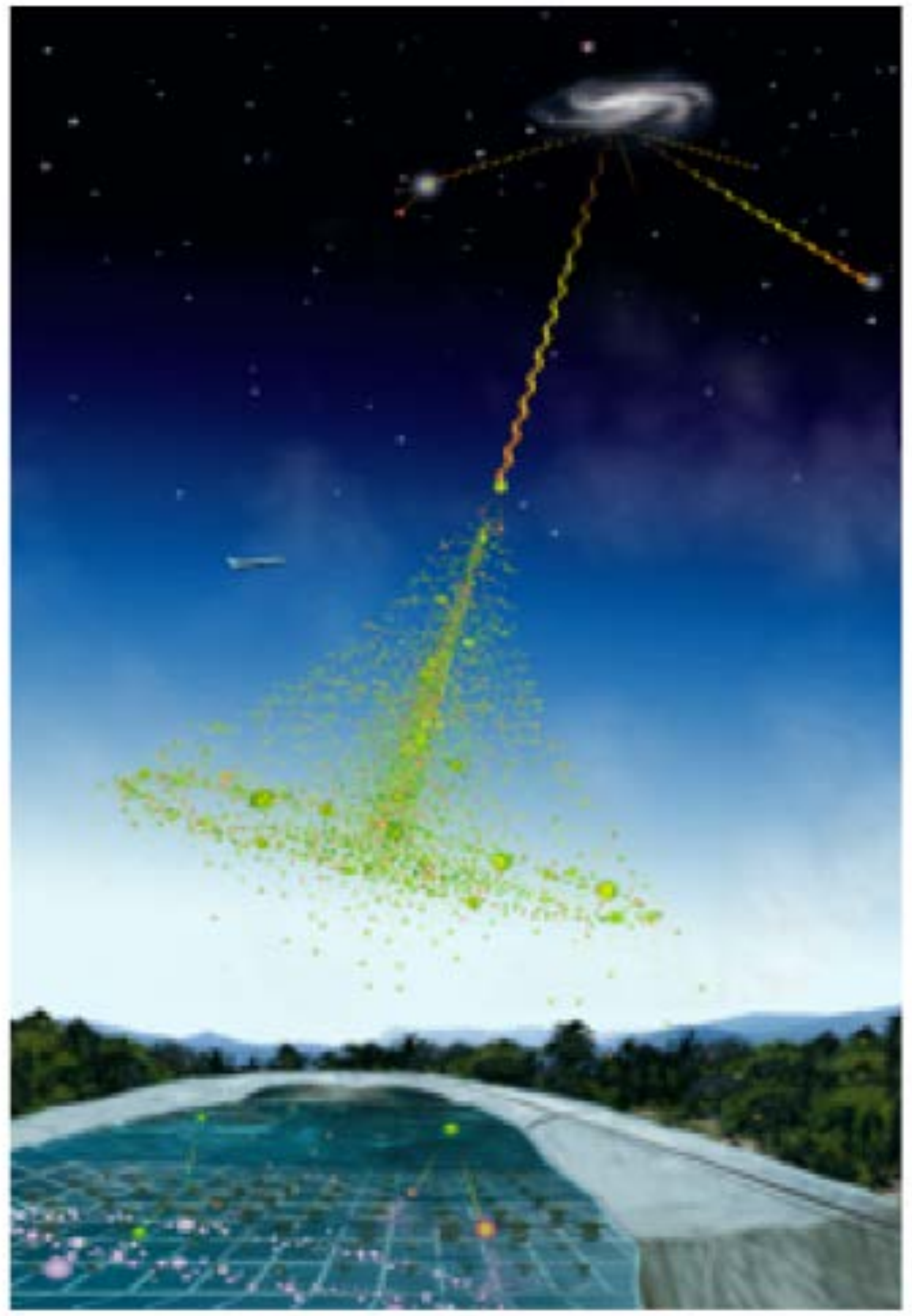
Milagro

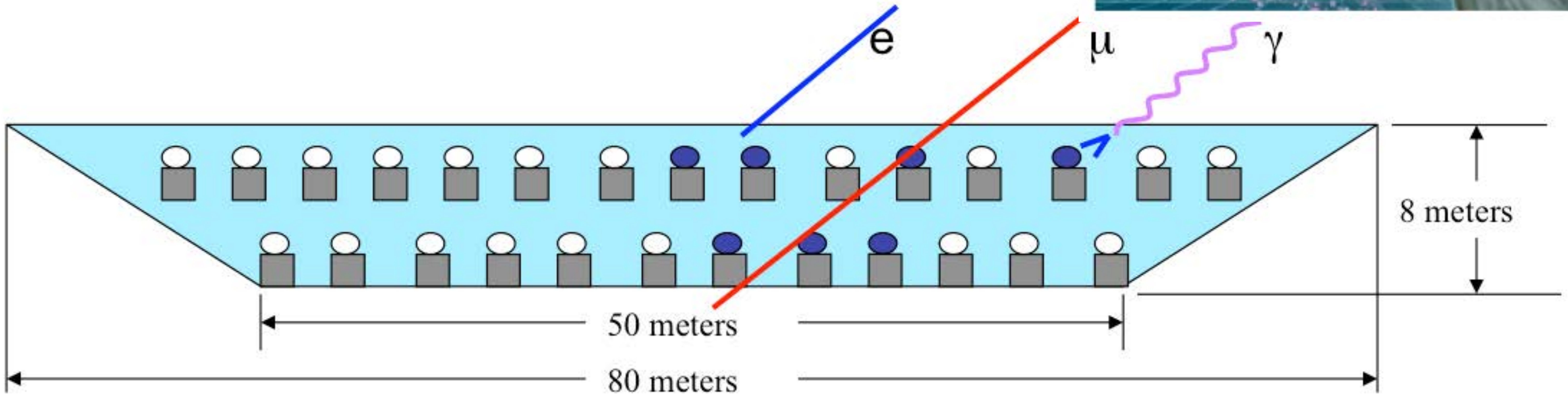
Milagro



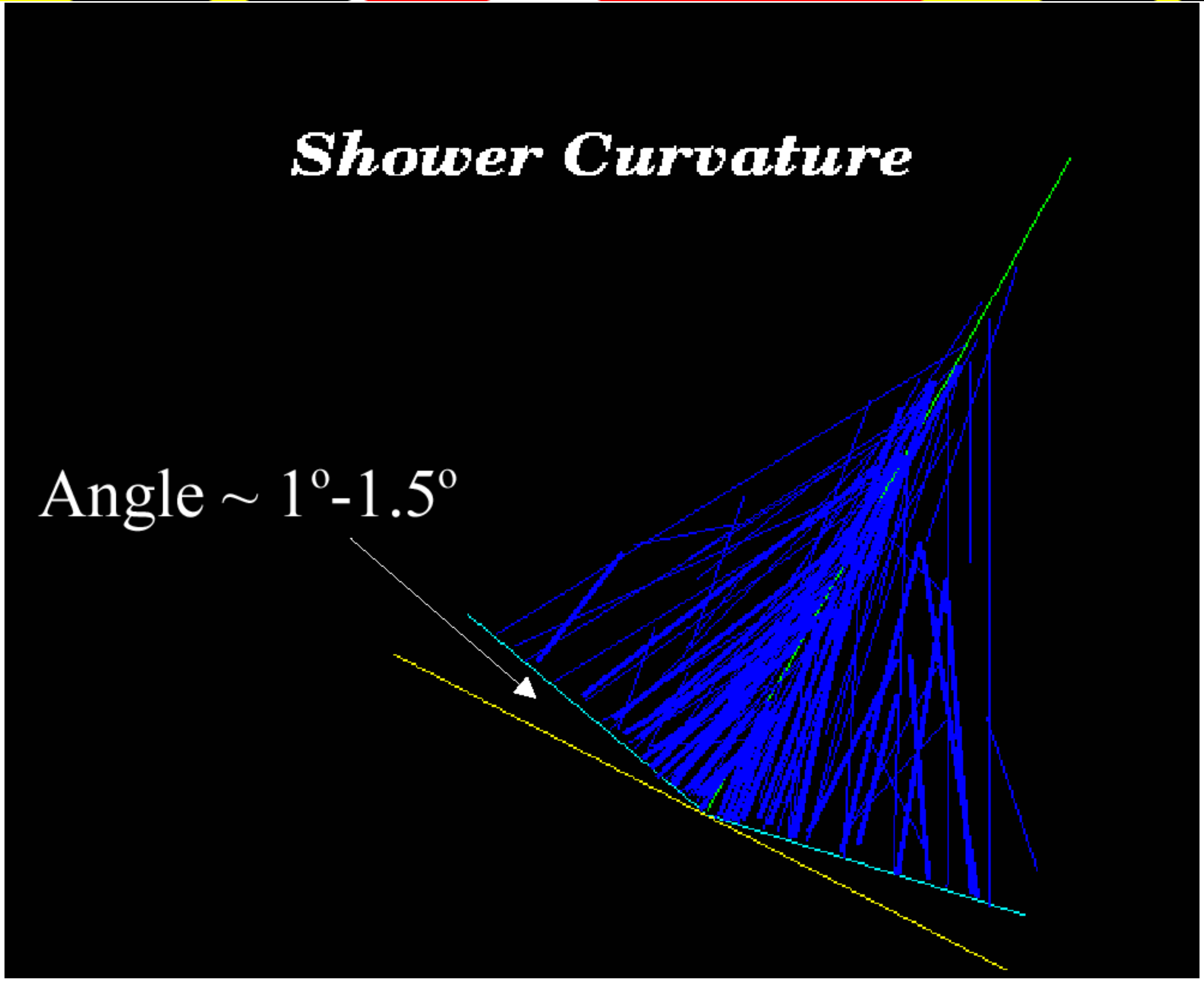
Milagro



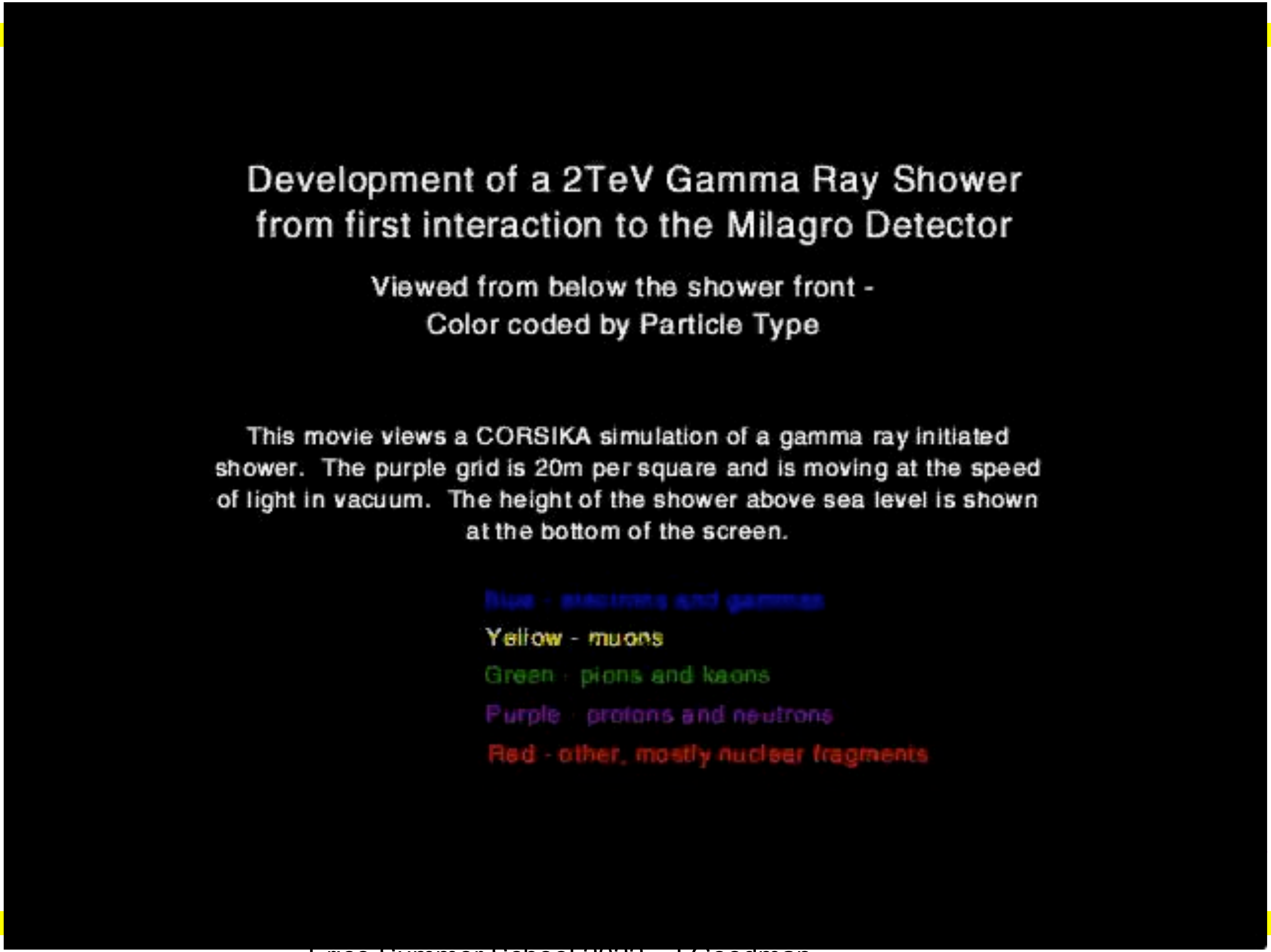




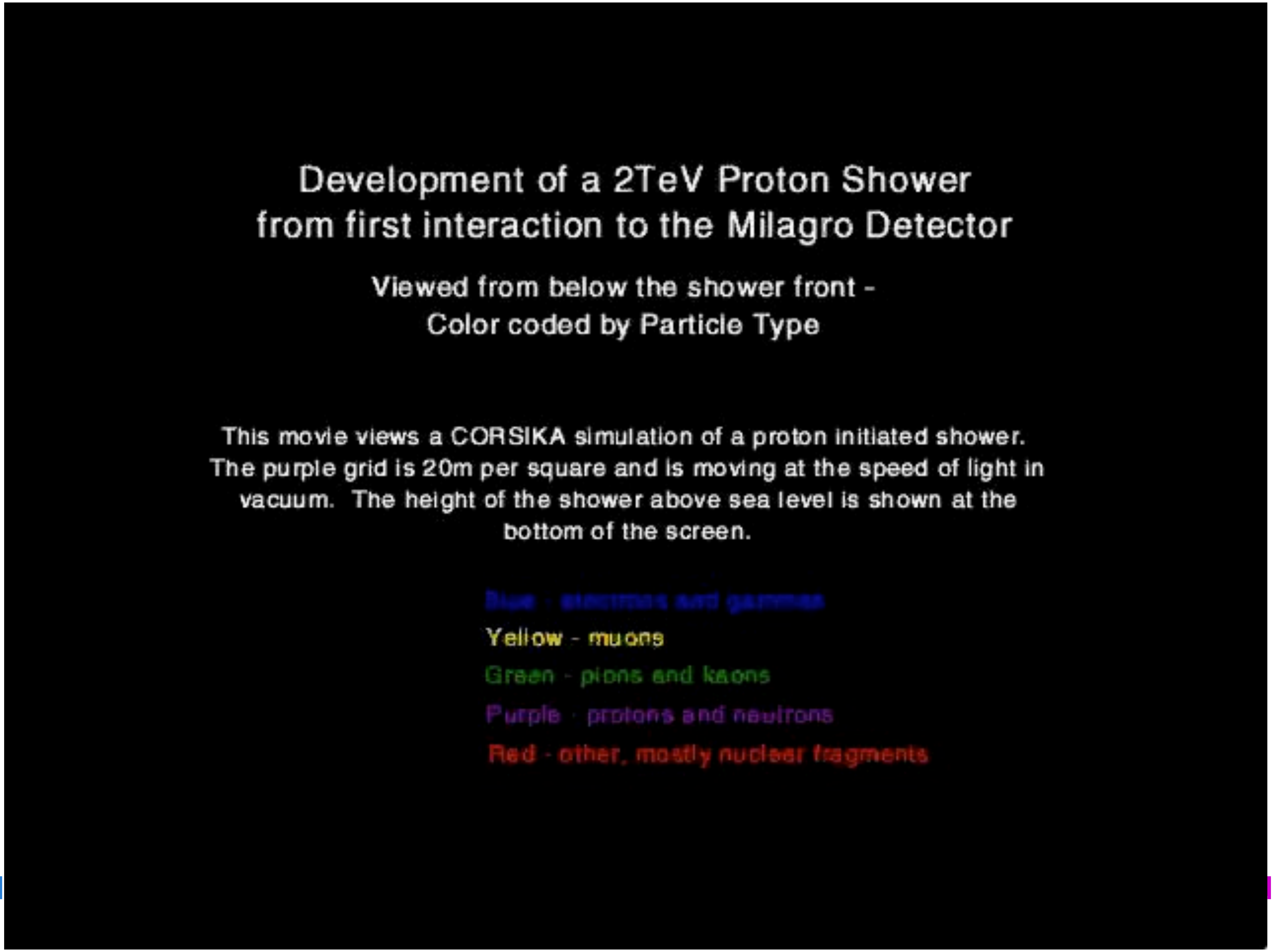
Shower Curvature



Gamma Shower 2 TeV (movies by Miguel Morales)



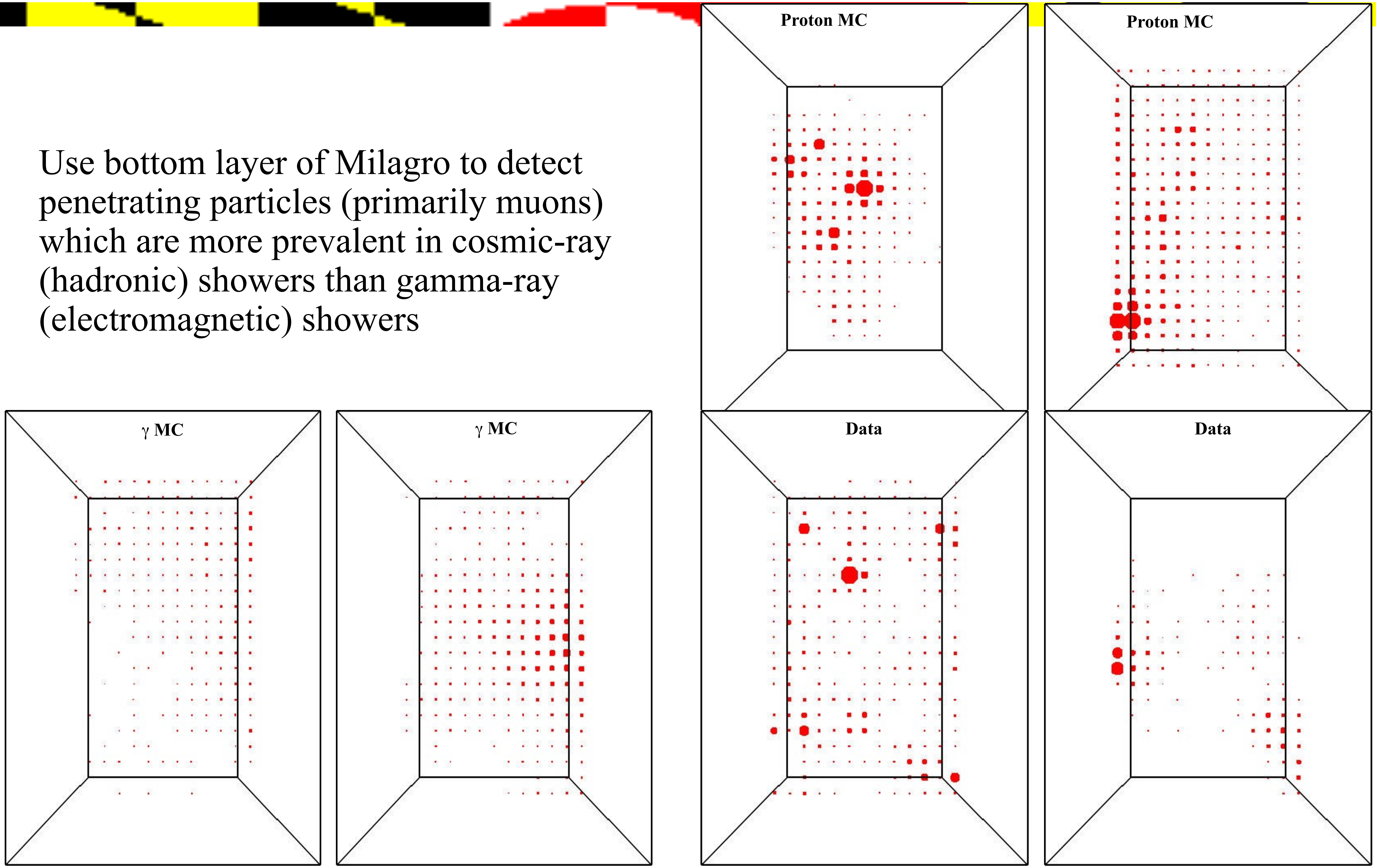
Proton Shower 2 TeV (movies by Miguel Morales)



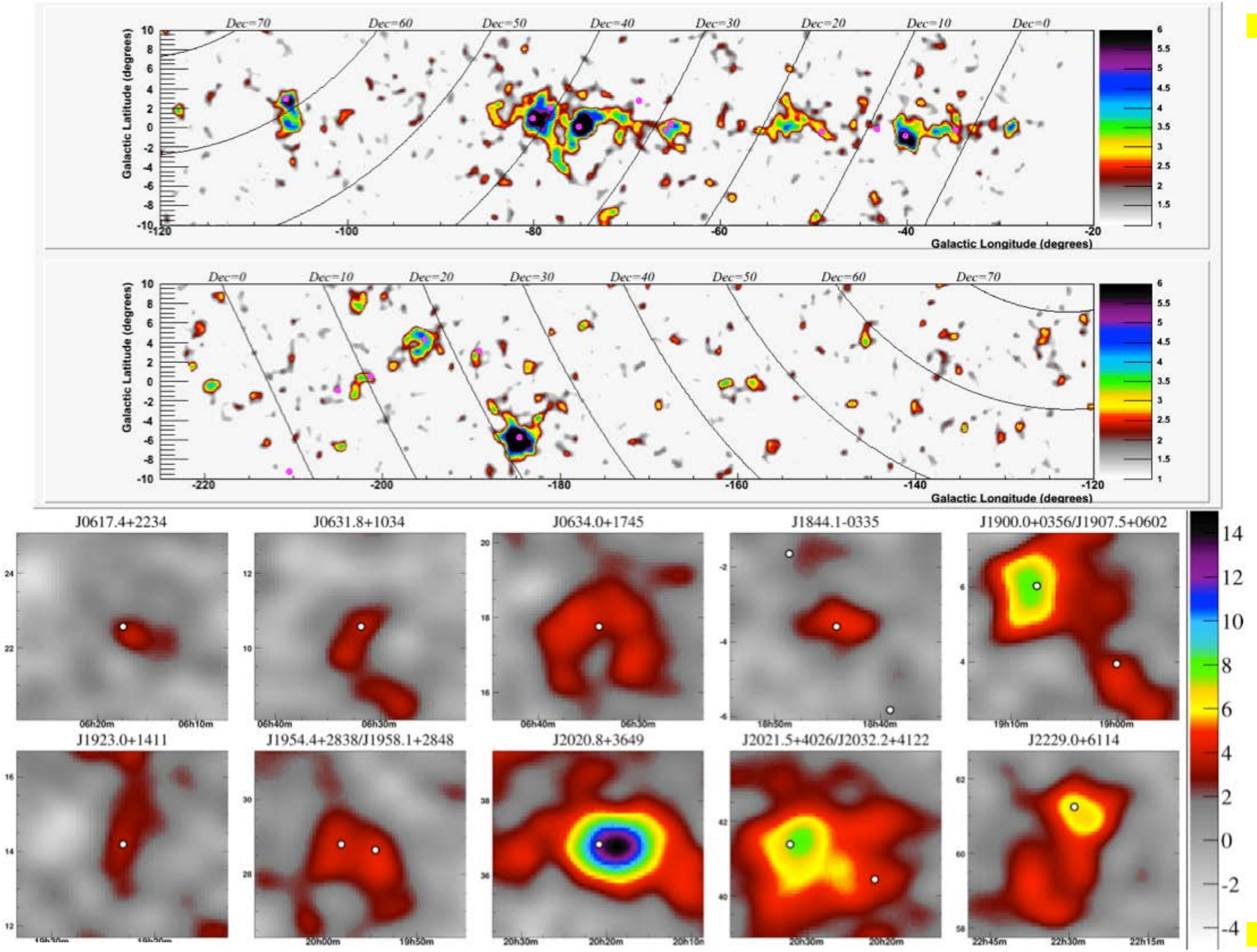
Blu ... rple

Background Rejection in Milagro

Use bottom layer of Milagro to detect penetrating particles (primarily muons) which are more prevalent in cosmic-ray (hadronic) showers than gamma-ray (electromagnetic) showers



Milagro TeV Sources



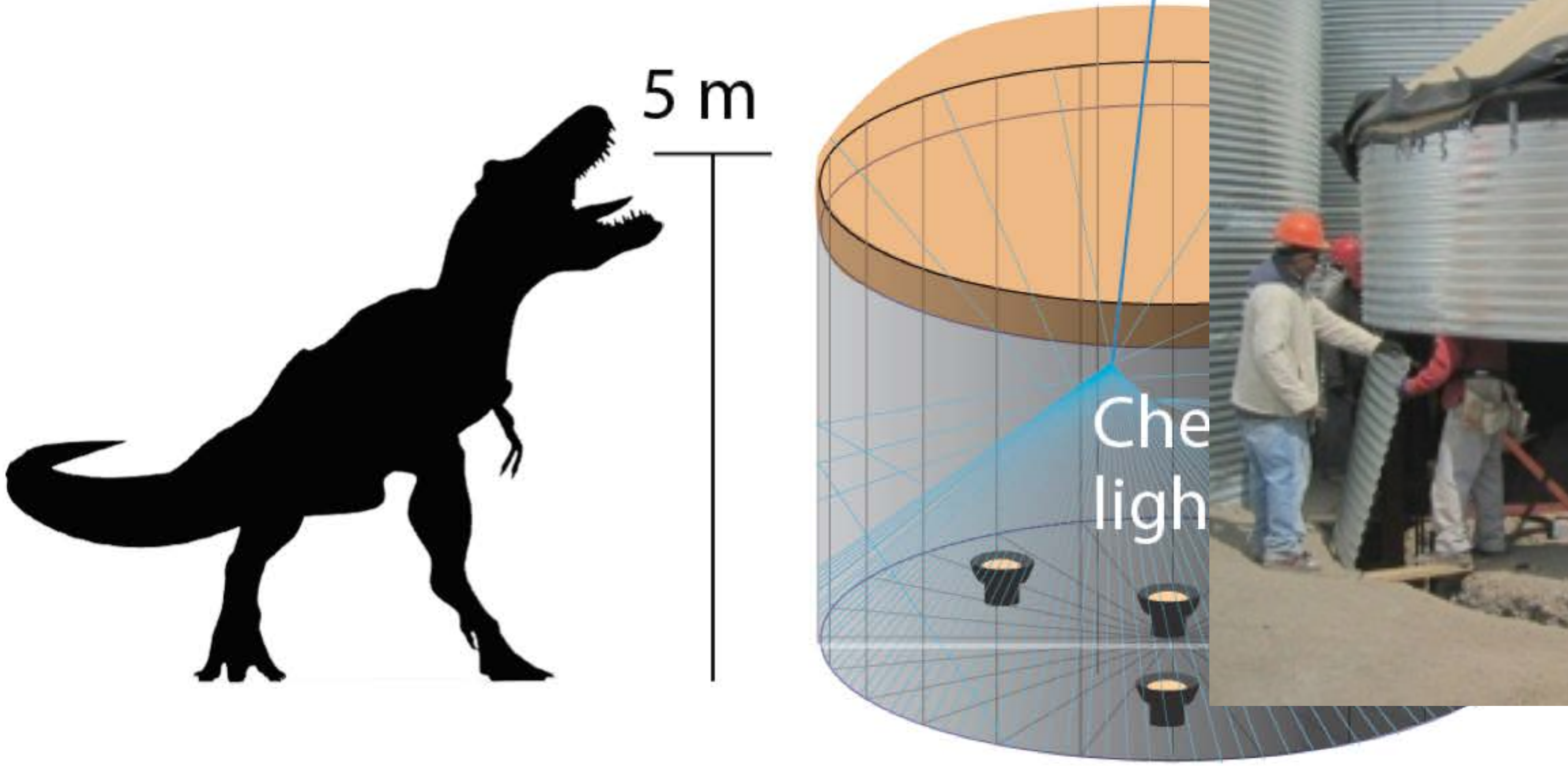
Milagro to HAWC

The HAWC Site

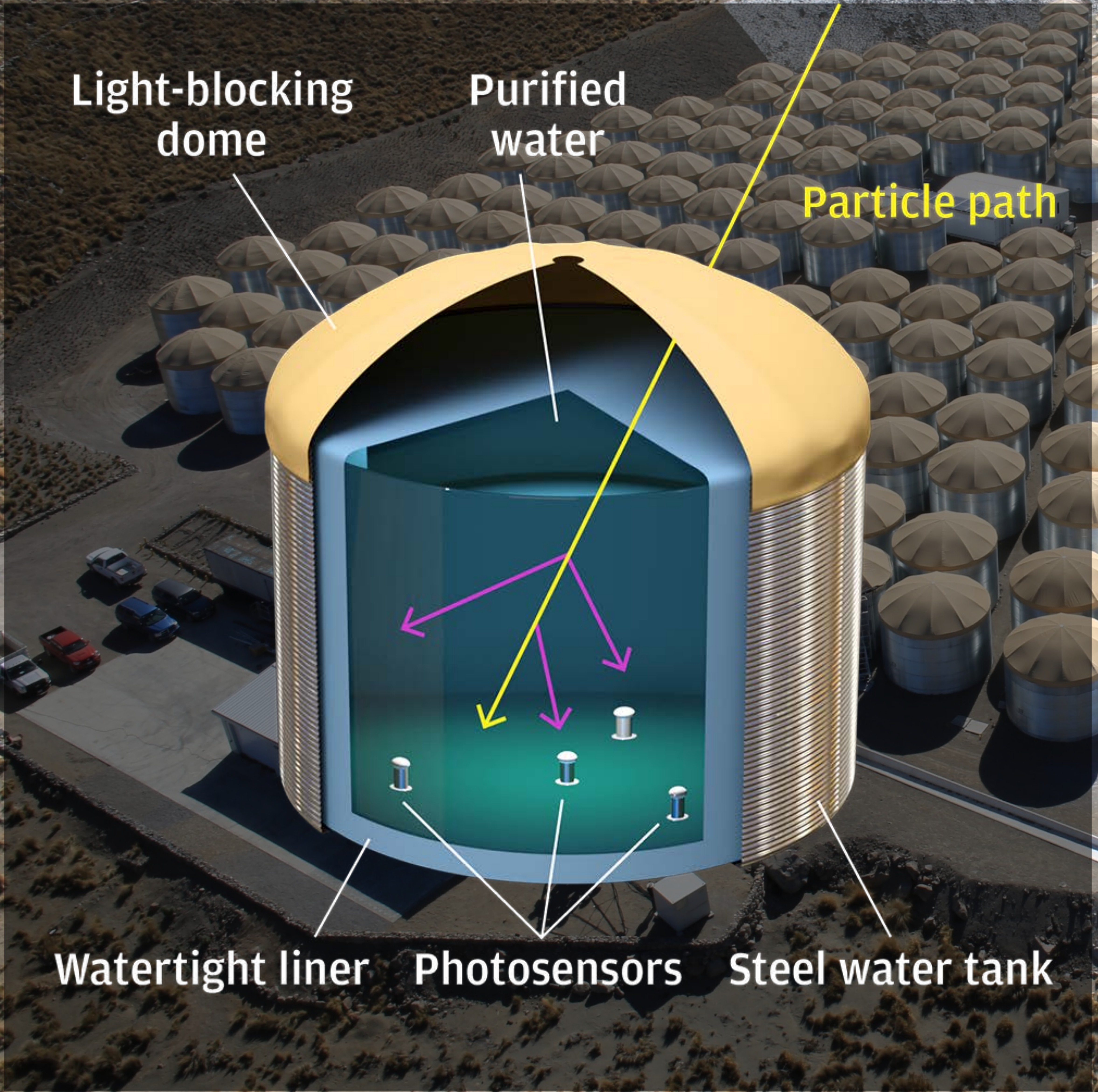
Latitude: 18°59.7’N
Longitude: 97°18.6’W

HAWC
Pico de Orizaba
“Citlaltepetl”
5610m (18,400 ft)
Sierra Negra
“Tliltepetl”
4582m (15,000 ft)

HAWC Tanks



Water Cherenkov Detectors




Mon Apr 22 00:02:58 GMT 2013

HAWC

HAWC


300th WCD tank constructe
~3,900 tanker truck trips


HAWC
HAWC-30: Engineering Test of full detector
HAWC-111: Operations Begins: August 2013 (283 days)
HAWC-250: November, 2014 (~150Days)
HAWC-300: March 2015 – Present : >95% uptime
HAWC Inauguration, HAWC-300: March, 2015
HAWC-300
HAWC-250
HAWC-30
HAWC-111

Outriggers in operation since August 2018

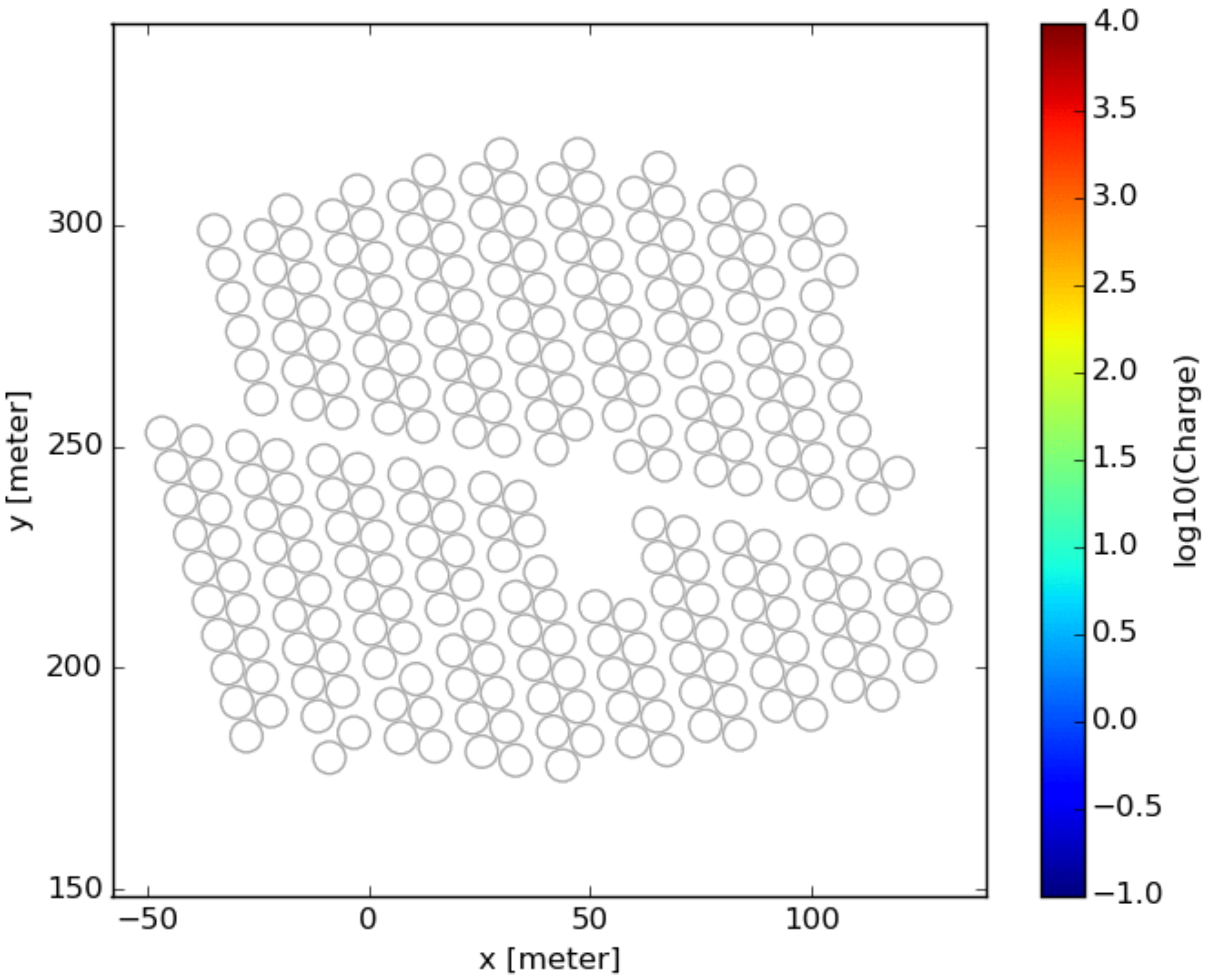

300th WCD tank constructe
~3,900 tanker truck trips

HAWC Electronics

HAWC Data

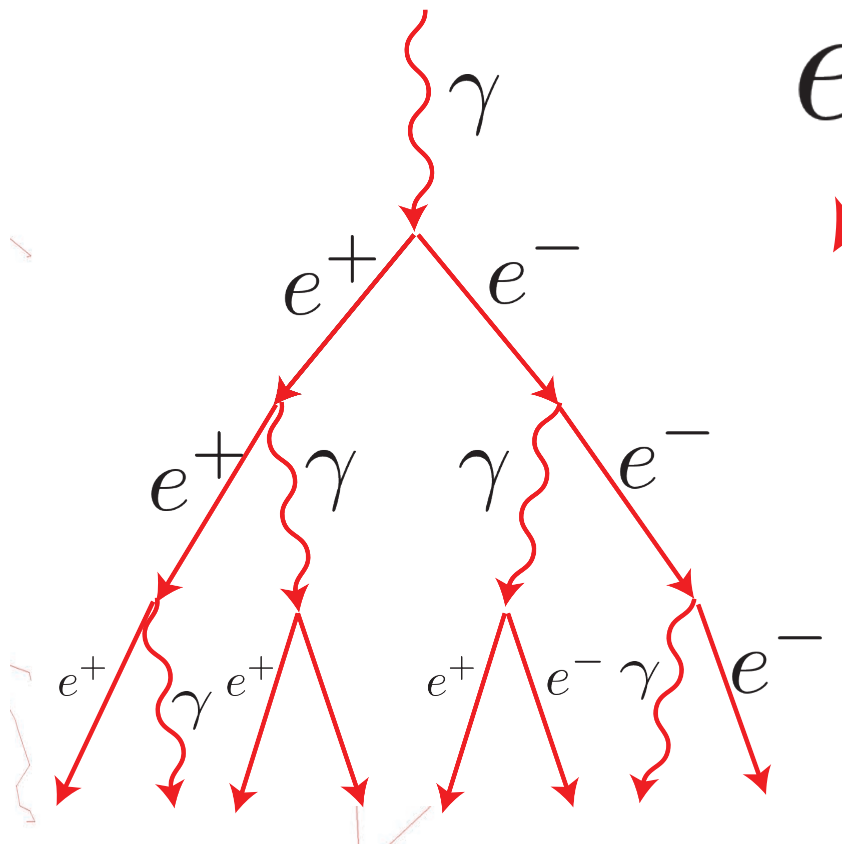
- We read in every PMT hit all the time
  - Raw data rate - 500MB/s -10 VME Backplanes
- Trigger in Software
  - Trigger rate requiring ~30 hits in 300ns is ~25kHz
- Process in near real time
- Rate to disk ~24MB/s -> ~2TB/day (everyday)
- Data is moved by portable disk arrays to UNAM
  - About once a week it's driven to Mexico City (during Covid - used Uber)
  - Moved over Internet II to UMD
- Raw Data plus processed data is stored in Mexico and Maryland
  - About a petabyte a year
  - Currently we have about 7.5 PB of storage at UMD

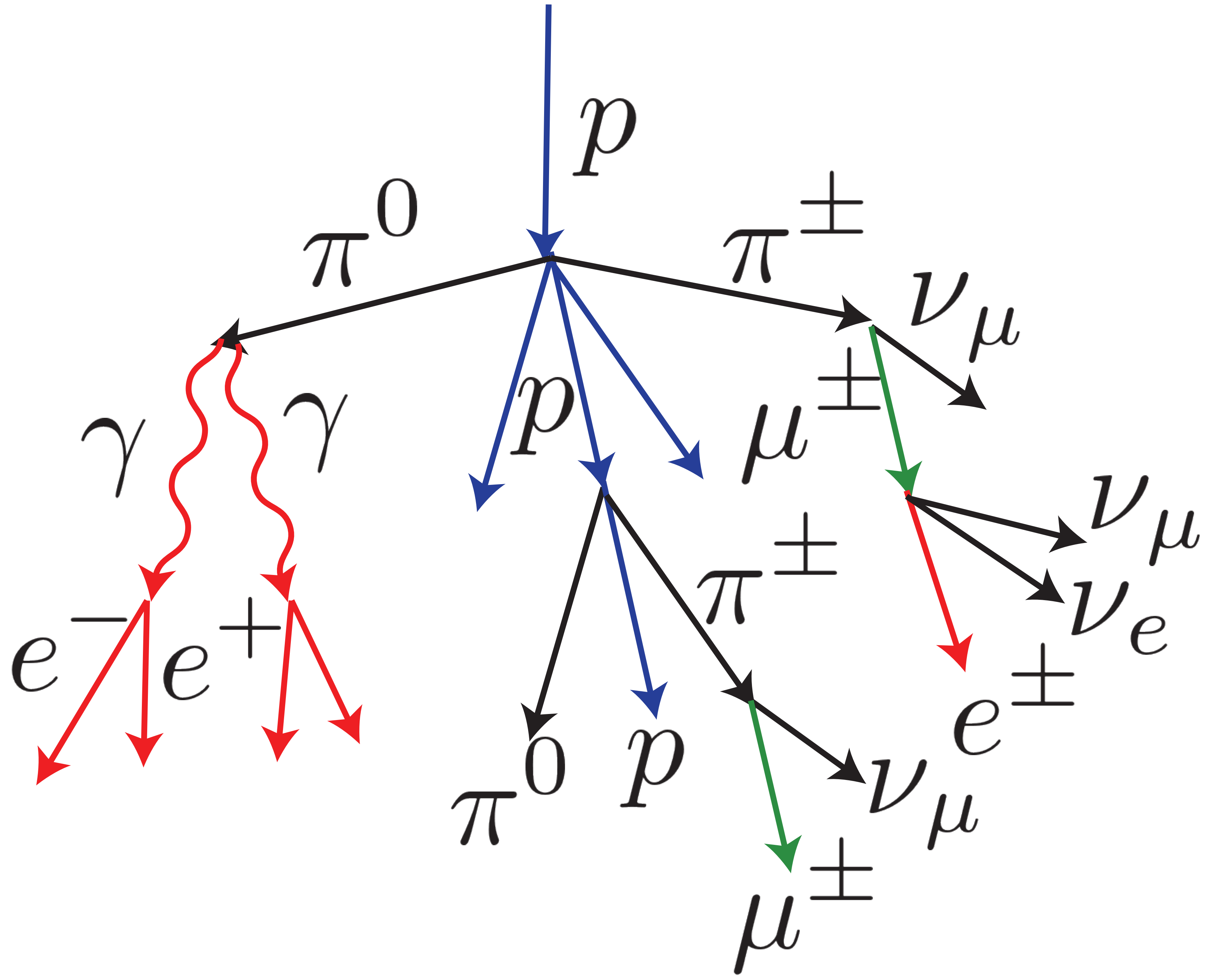
Angle Reconstruction

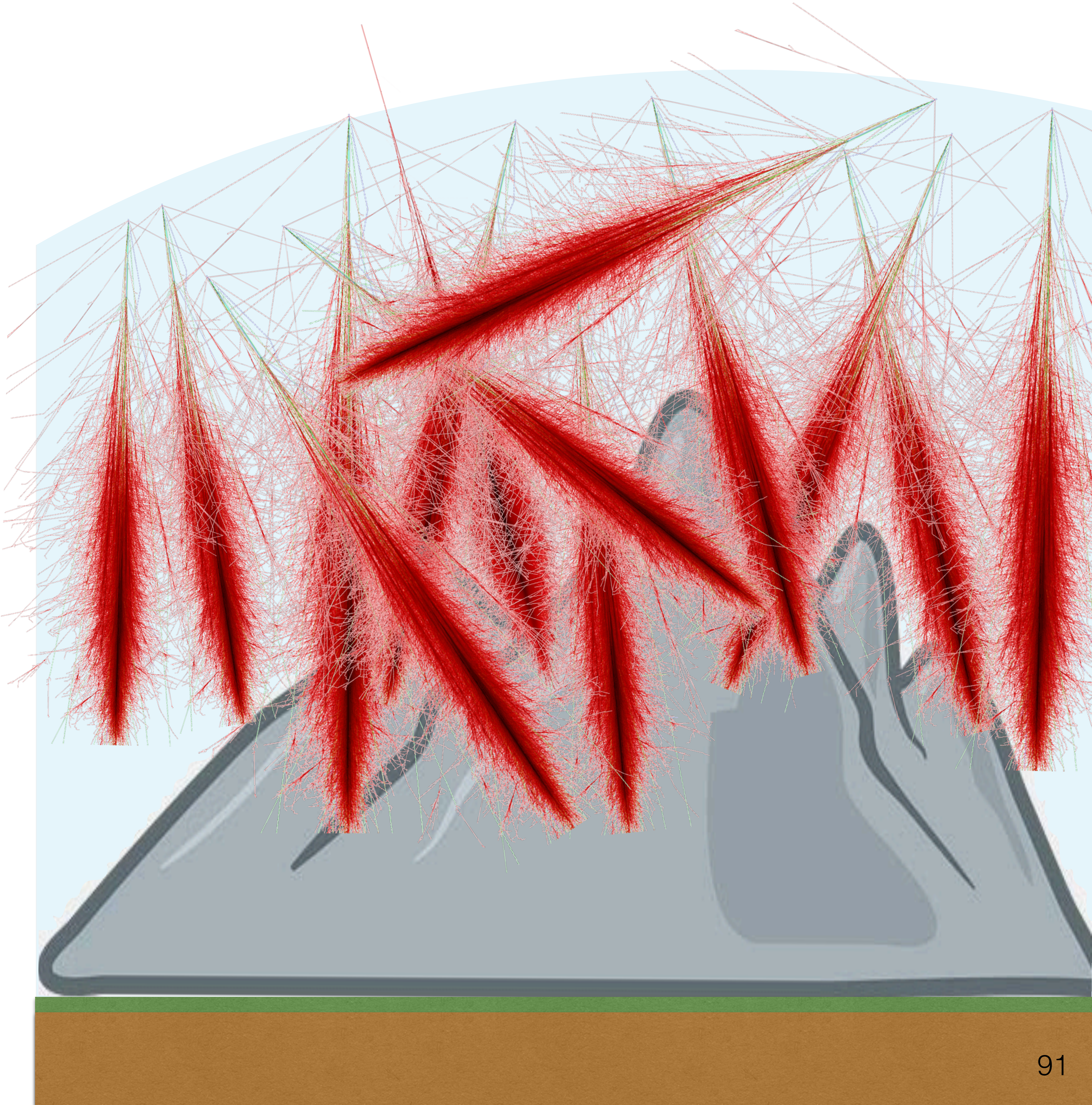


The cosmic ray background

- Charged particles more abundant than γ-rays
- They produce similar showers



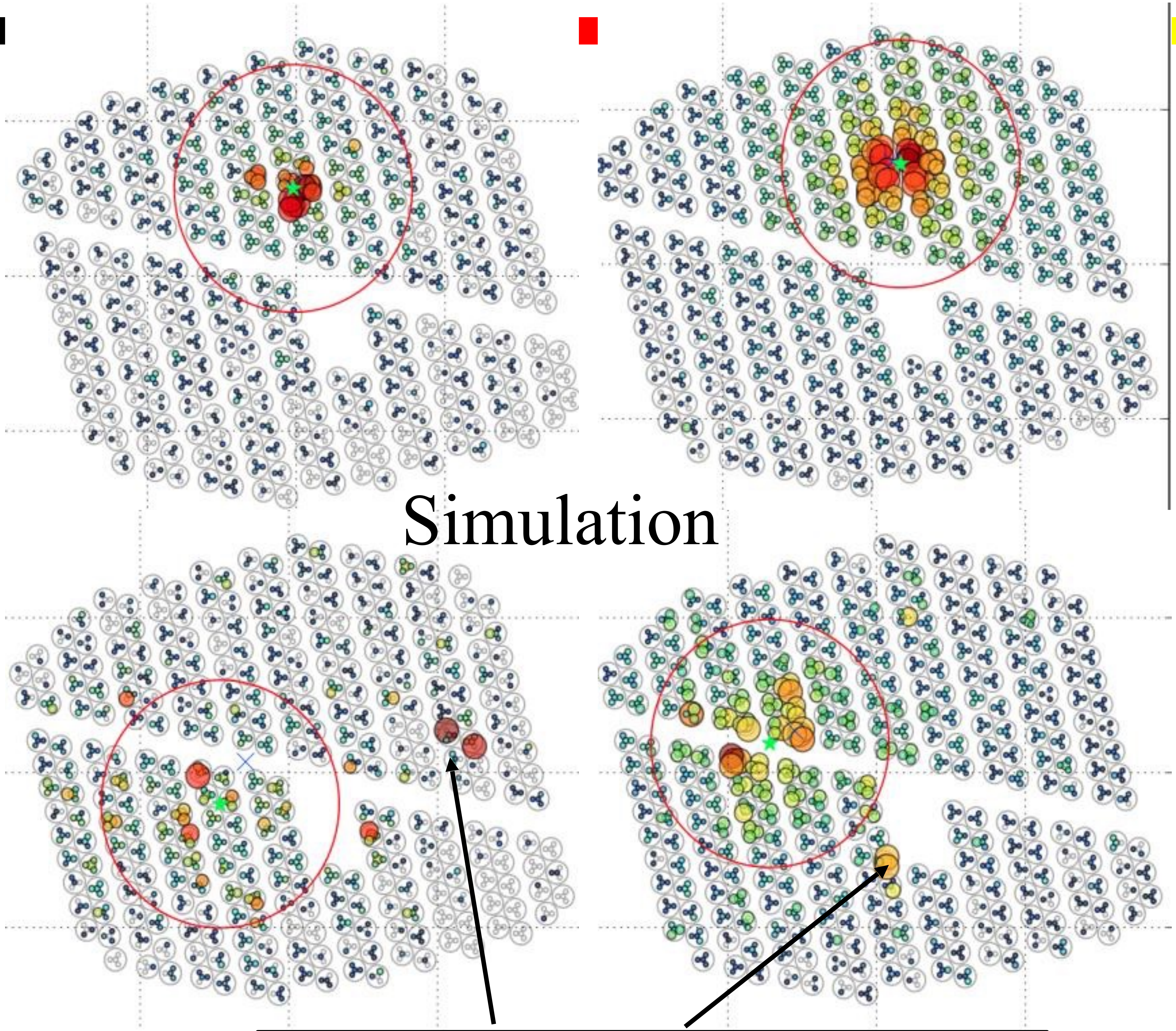




Gamma Hadron Separation (MC)

Gammas

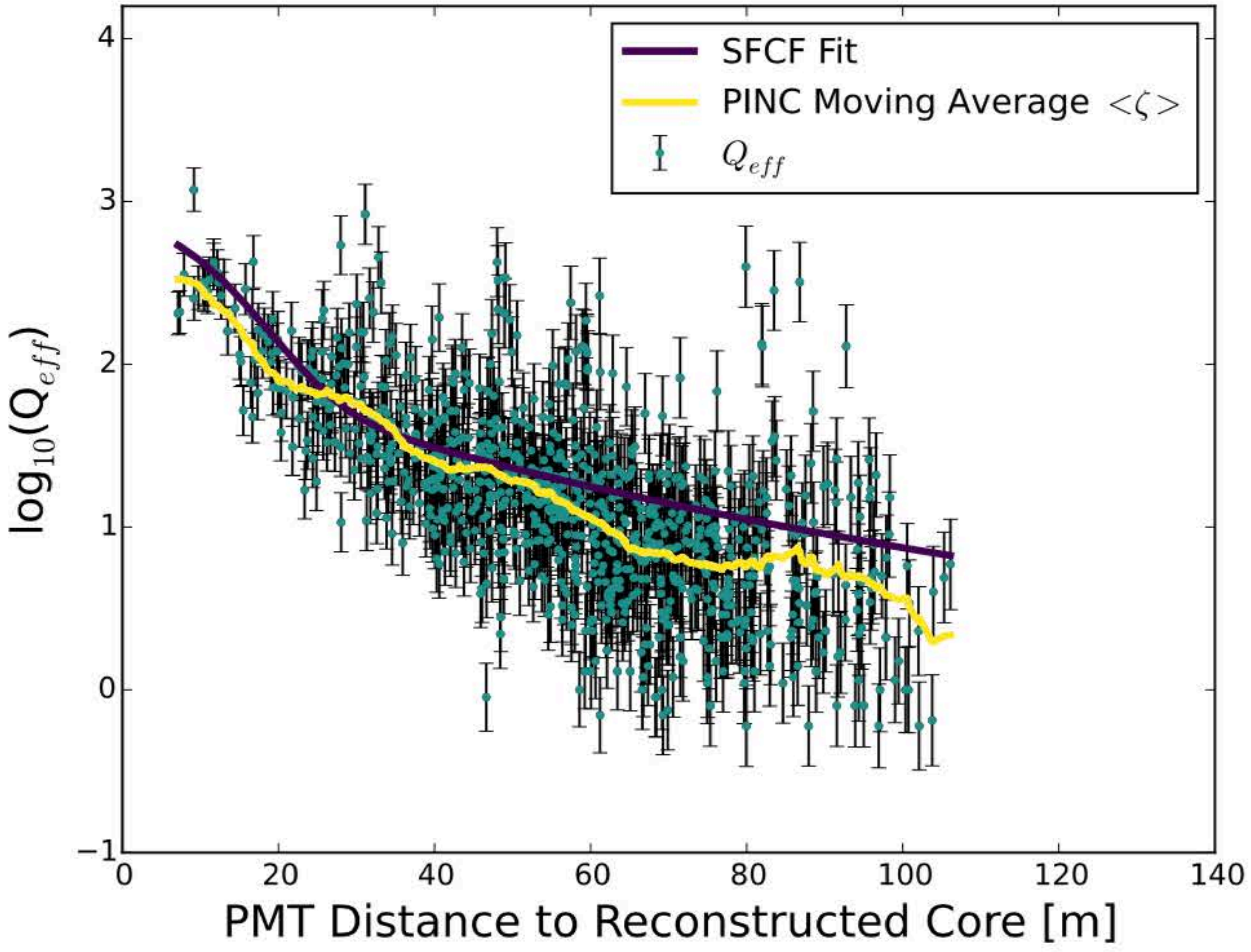
Protons



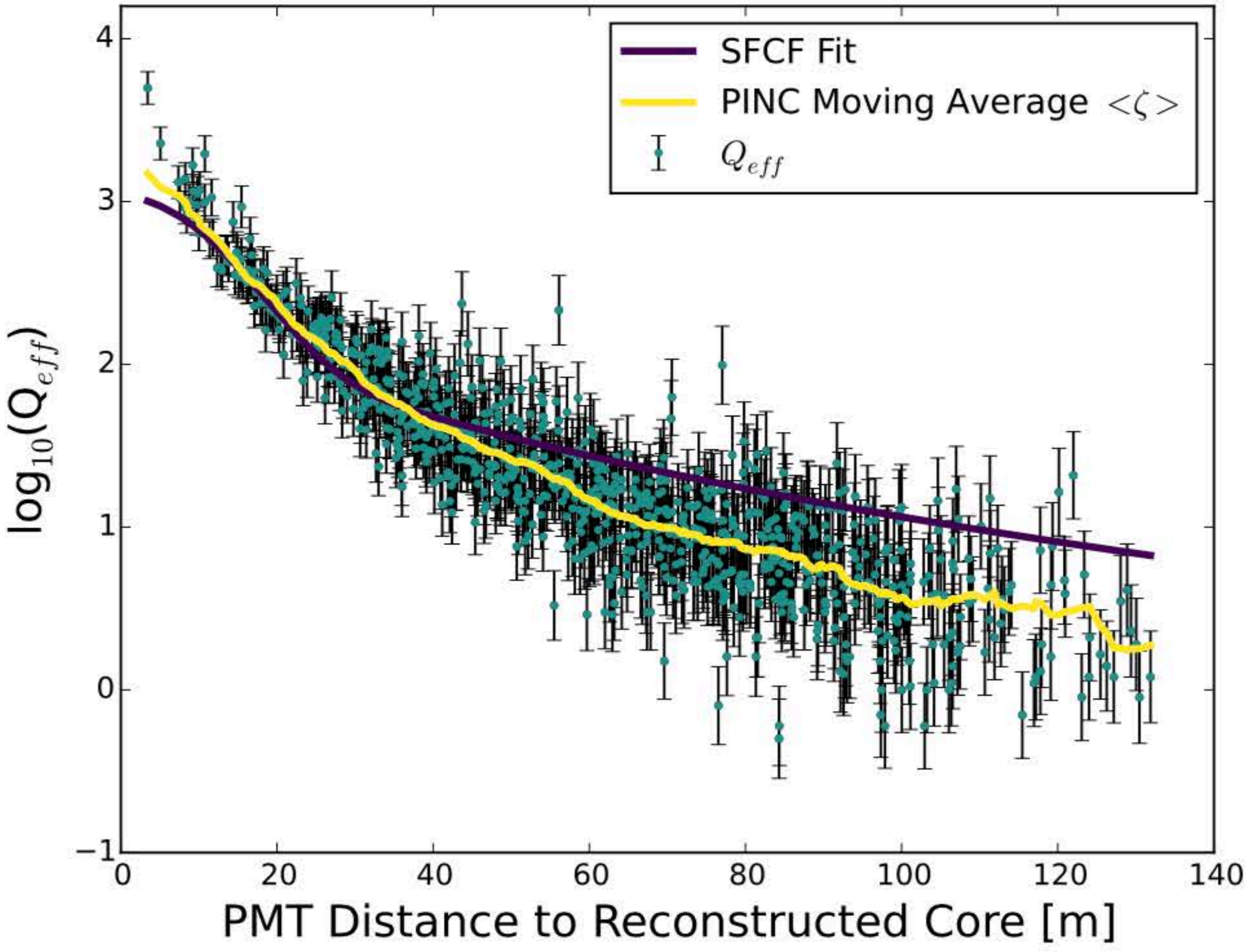
Shower reconstruction

- Measure: time and light level in each PMT.
- Reconstruct: direction, location, energy, and background rejection.
- Reference: Crab paper, ApJ 843 (2017), 39.

Clumpy: hadron-like



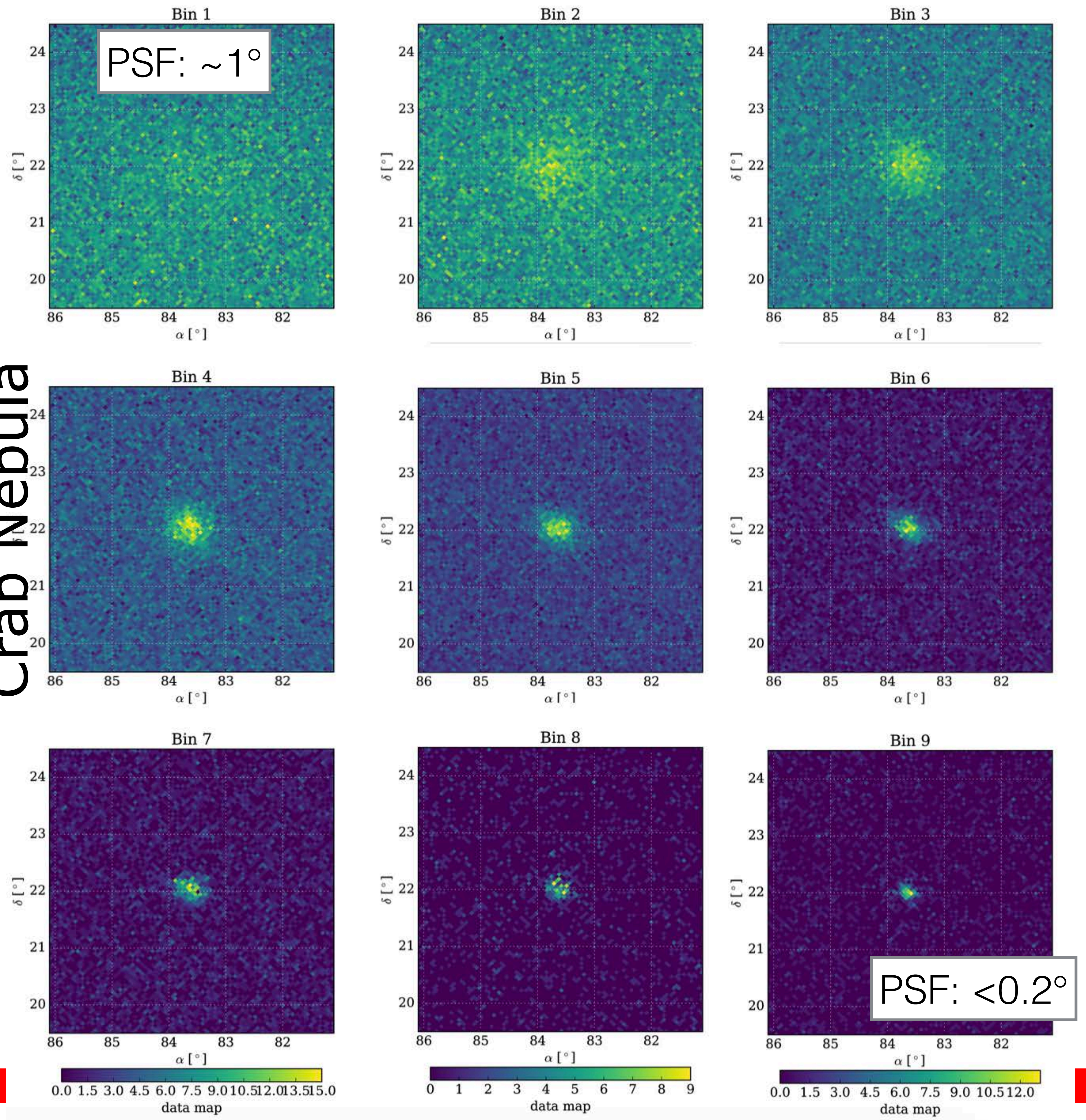
Smooth: gamma-like



Source search and characterization

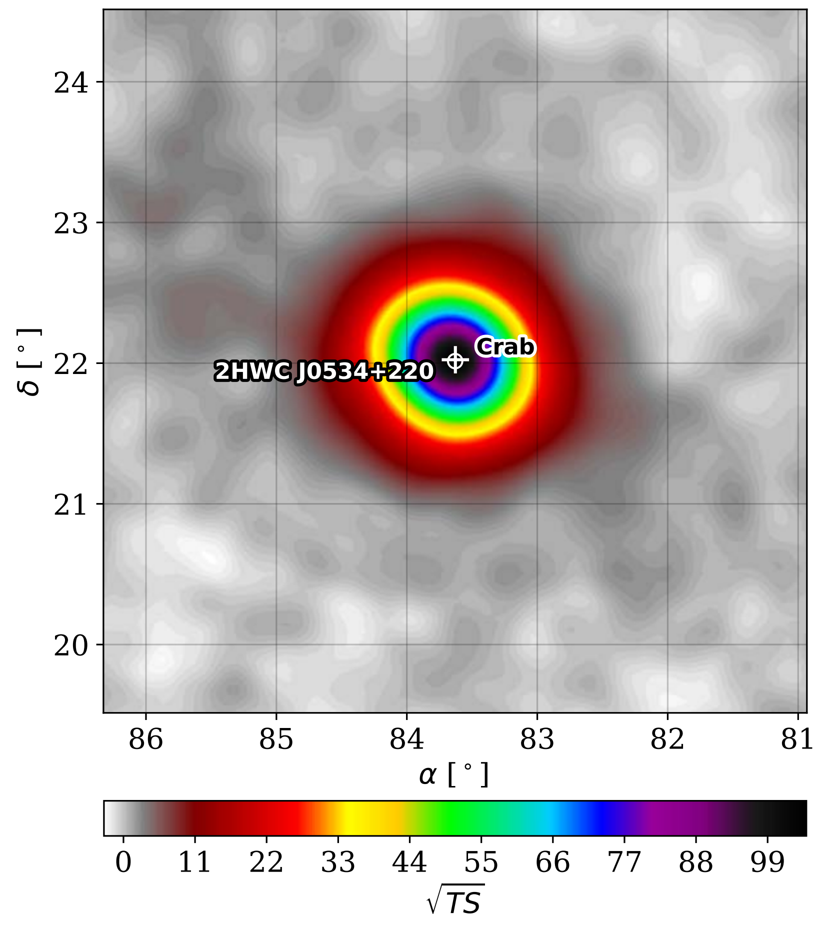
- Events sorted by "size" in *n* bins (with characteristic Point Spread Function, S/N ratio, energy), make *n* maps.
- Likelihood framework use *n* maps to test the presence of sources then characterize them.
- Reference: Crab paper, ApJ 843 (2017), 39.

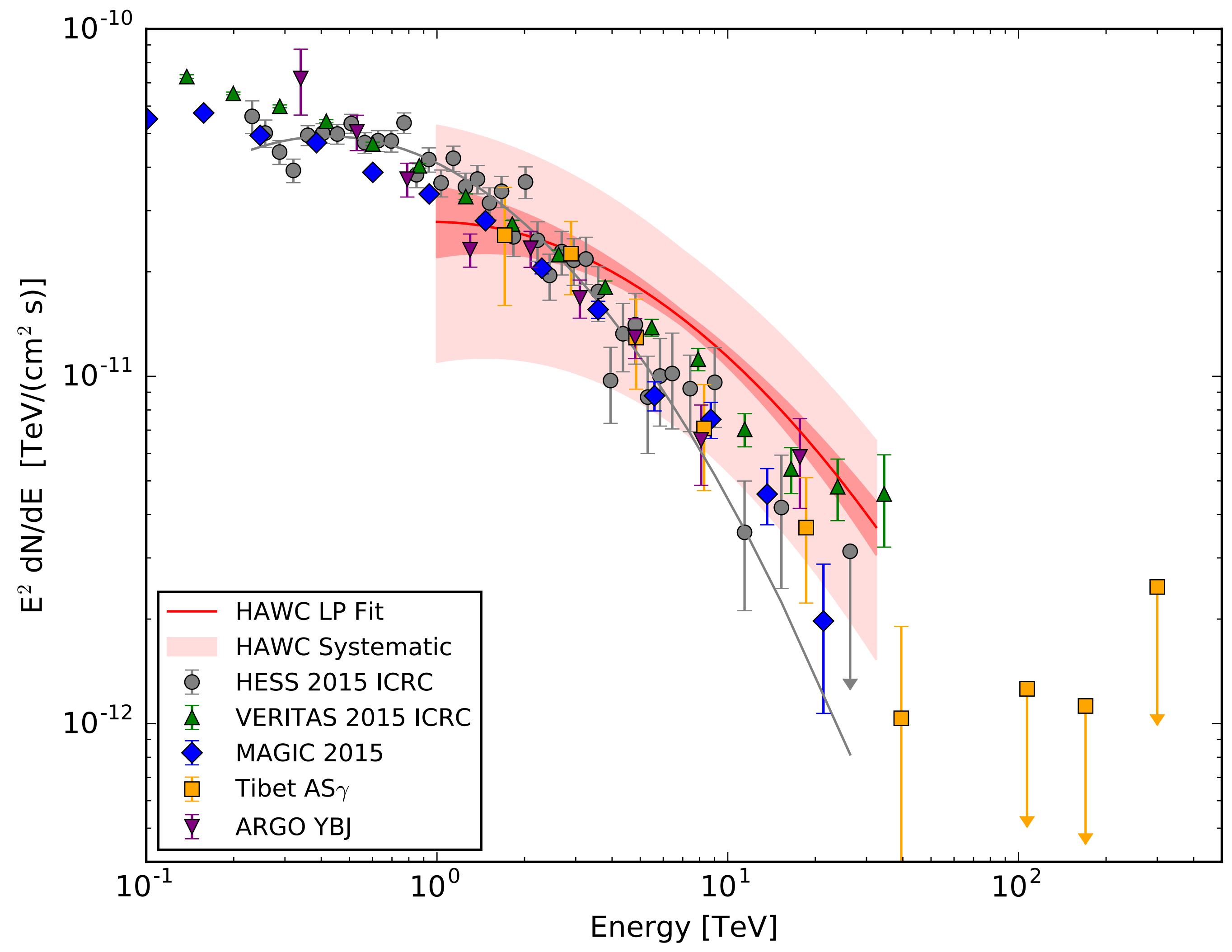
Crab Nebula



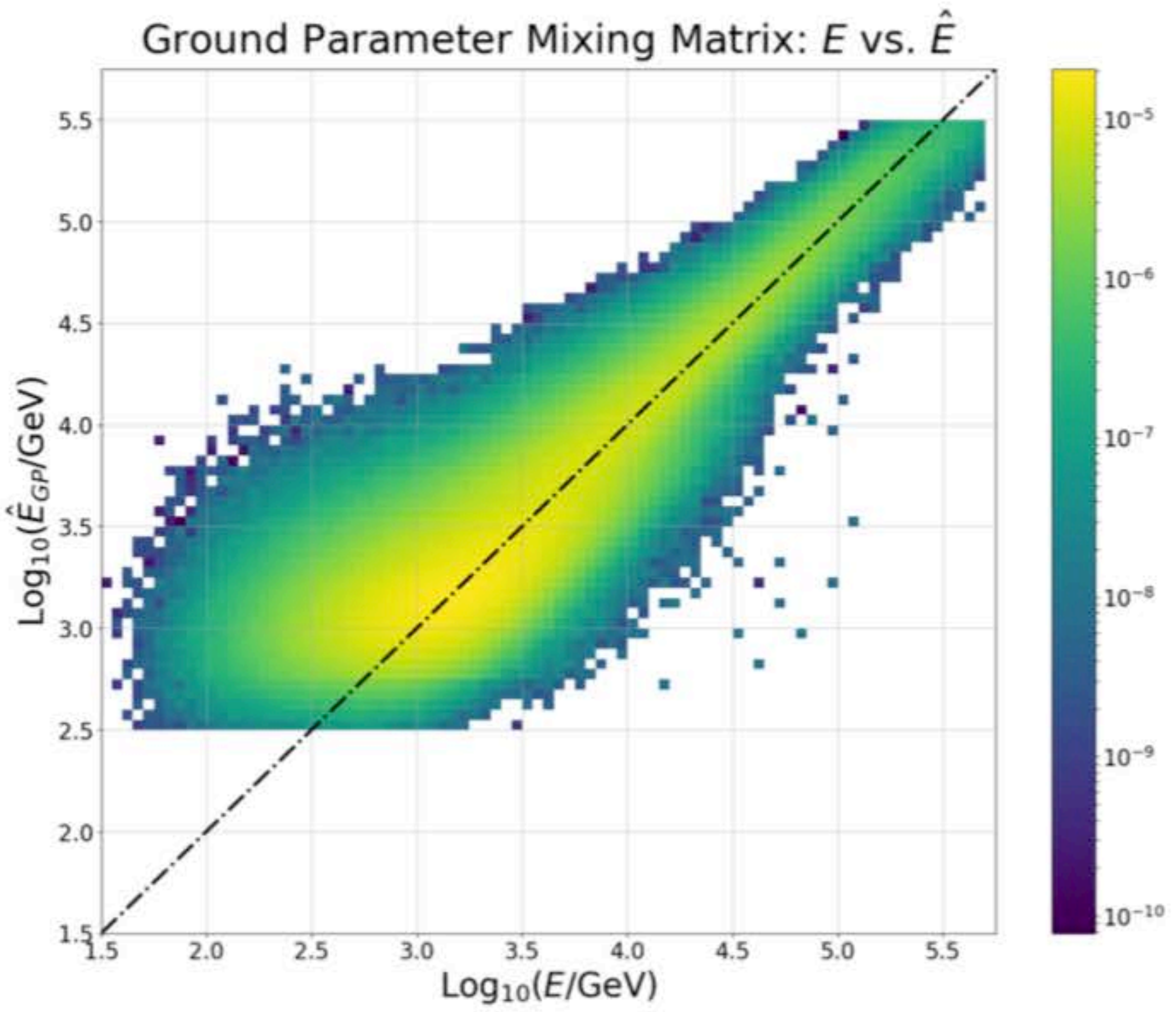
Detector response
Source model

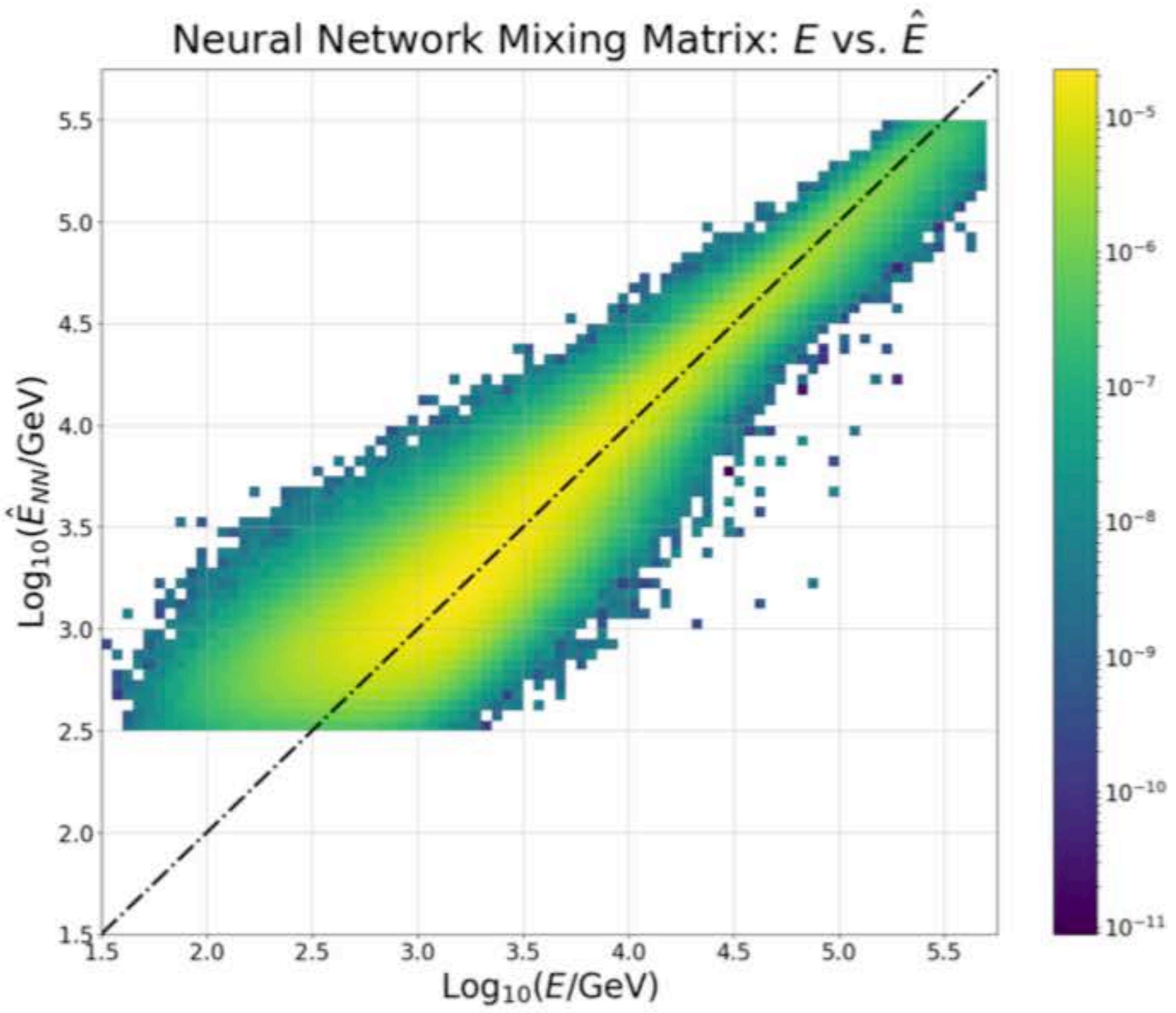
Likelihood framework





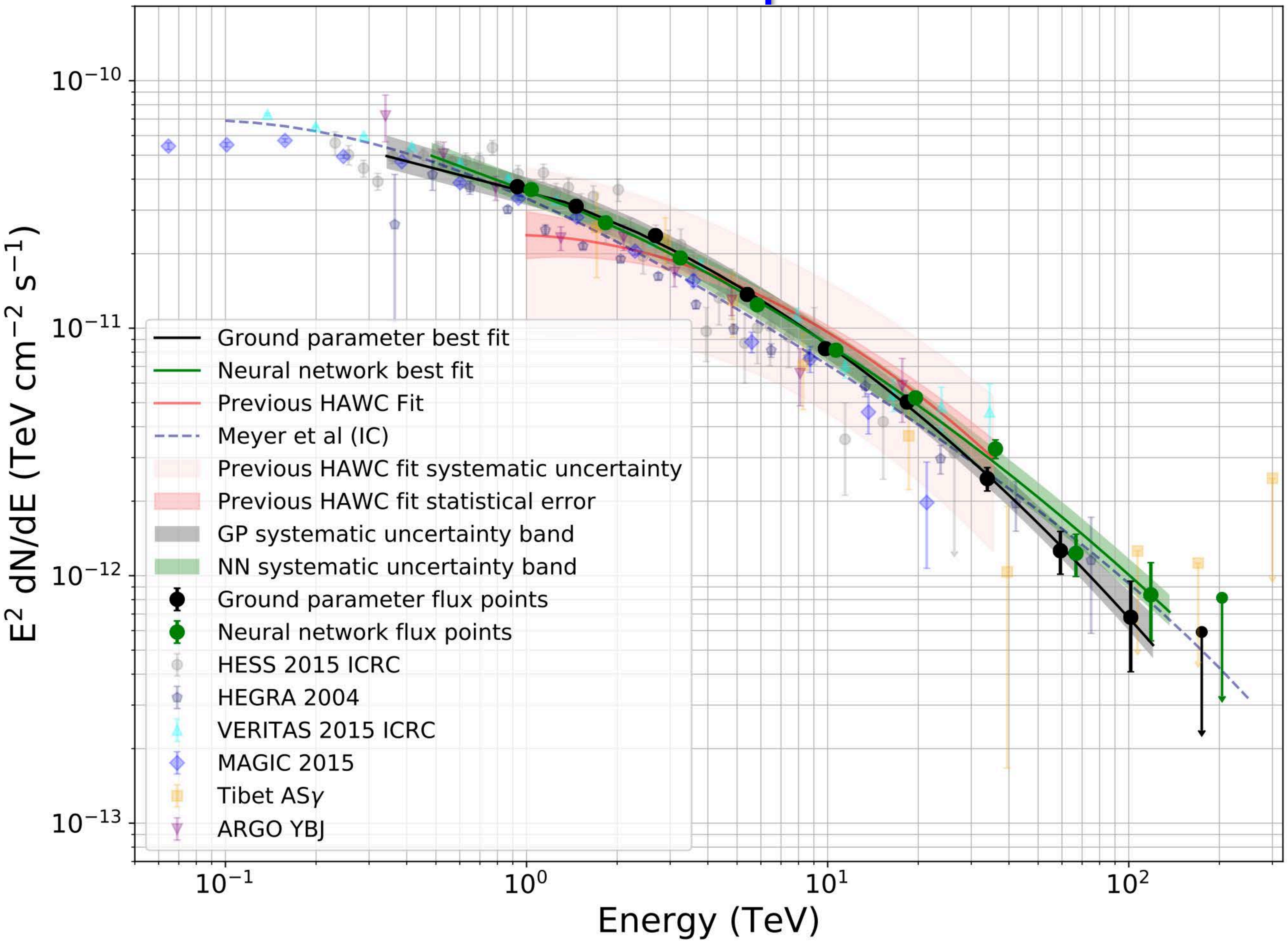
Two Energy Analysis





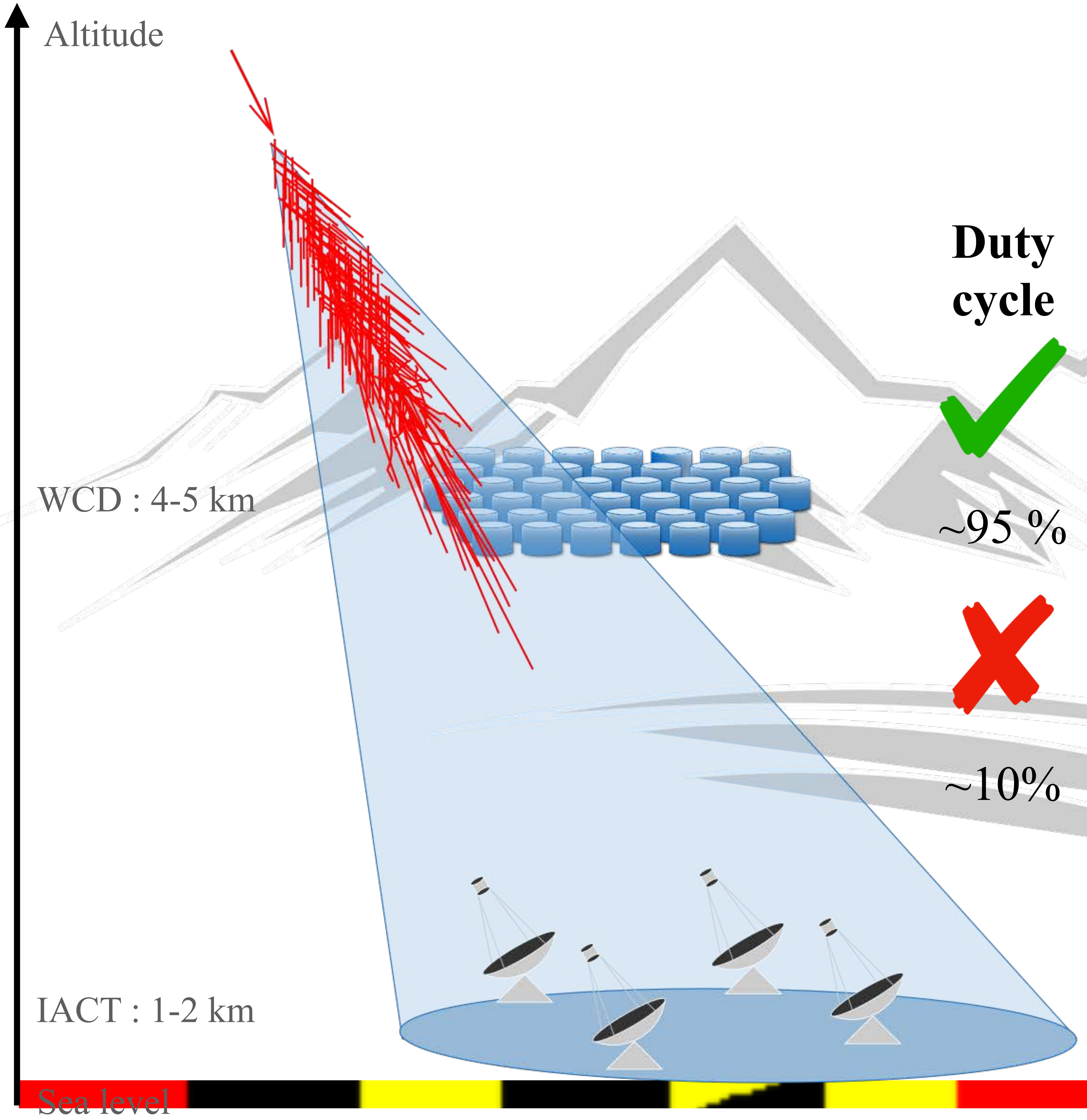
Kelly Malone (PSU/LANL)
Sam Marinelli (MSU)

The Crab Spectrum



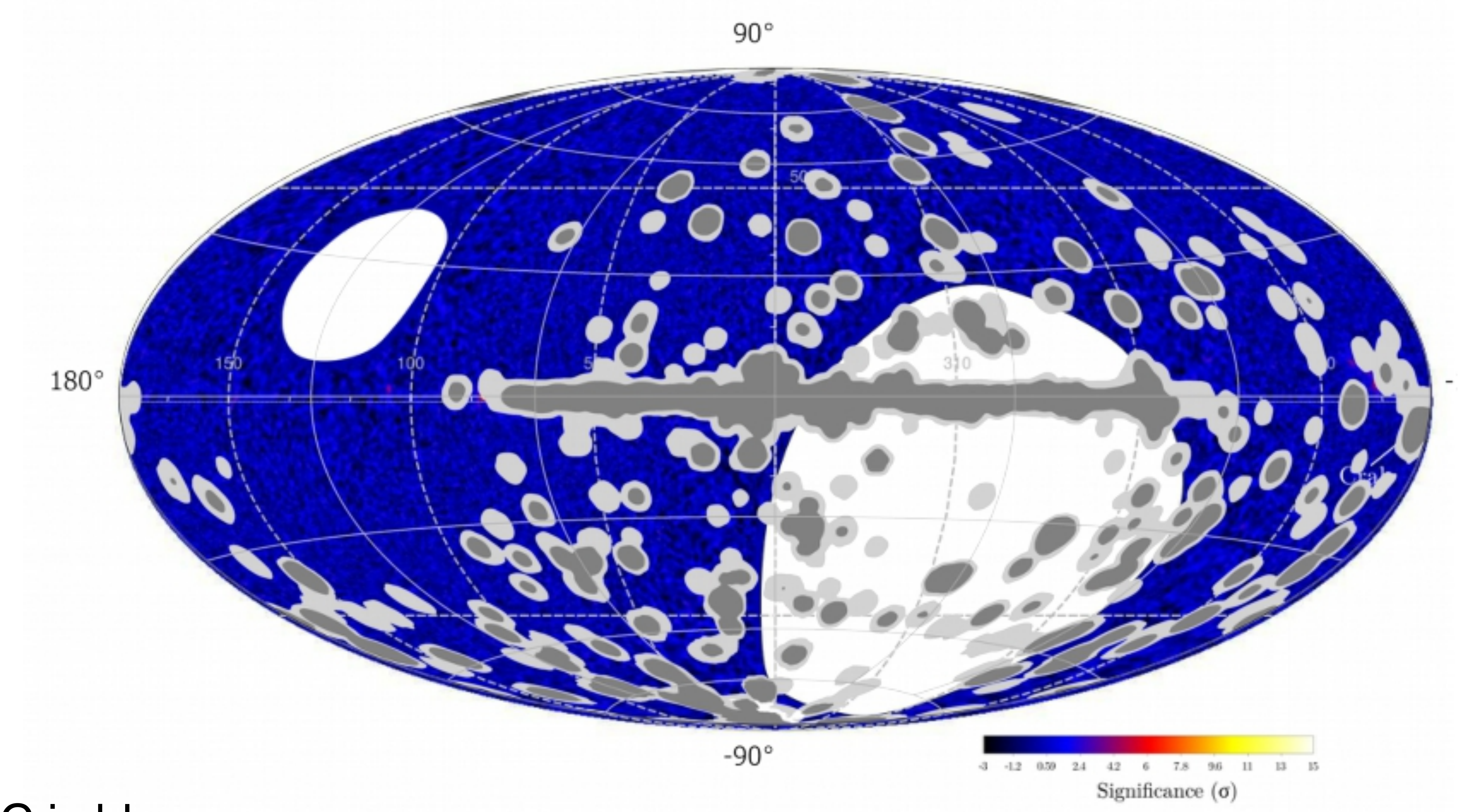
Highest Energies ~100 TeV

WCD and IACT



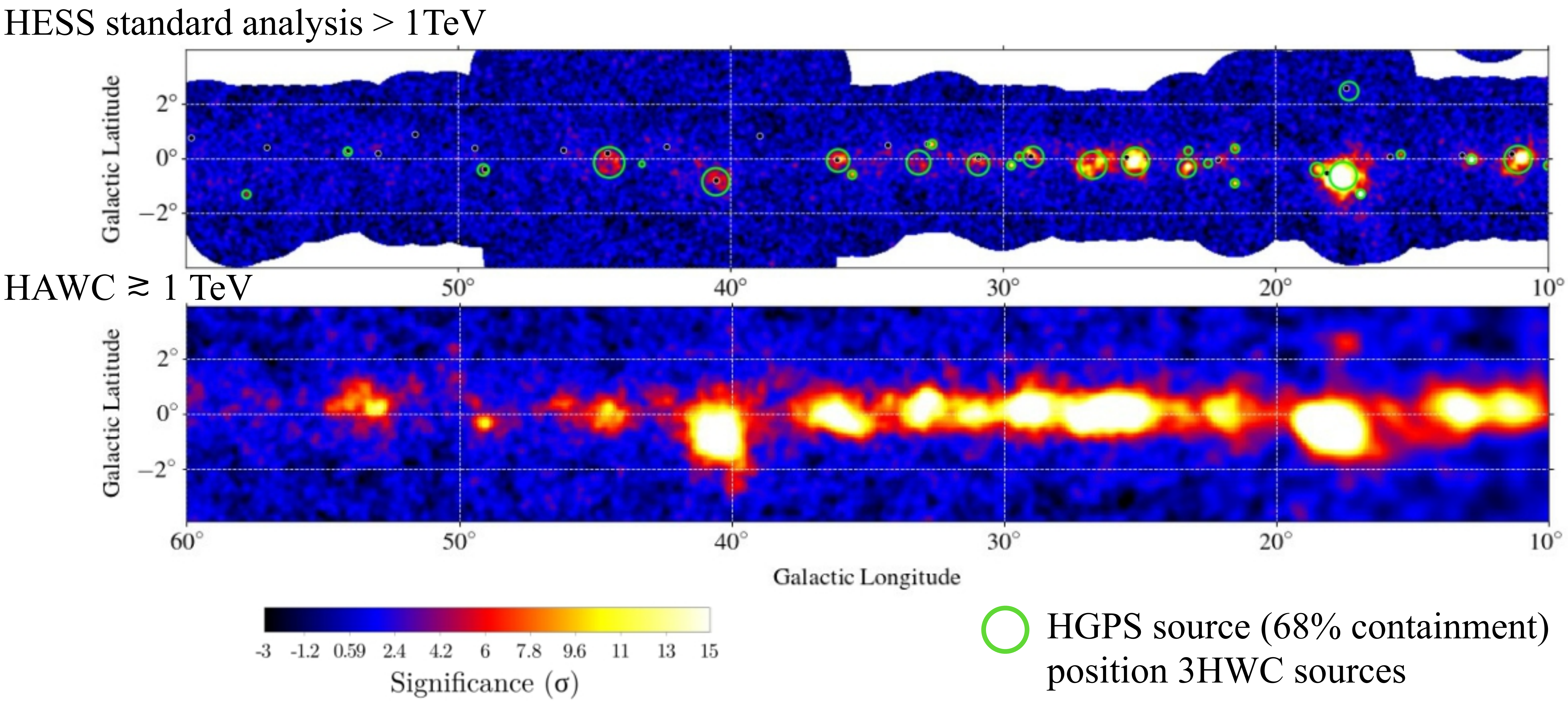
Duty cycle	Field of view	Energy range	Energy resolution	Angular resolution
✓	✓	✓	✗	✗
~95 %	90°	TeV	50% at 1 TeV	1-0.2°
✗	✗	✓	✓	✓
~10%	5°	TeV	10% at 1 TeV	0.1-0.06°

HAWC and H.E.S.S. Observable sky



HAWC is blue
HESS is gray

HAWC and H.E.S.S. Galactic plane

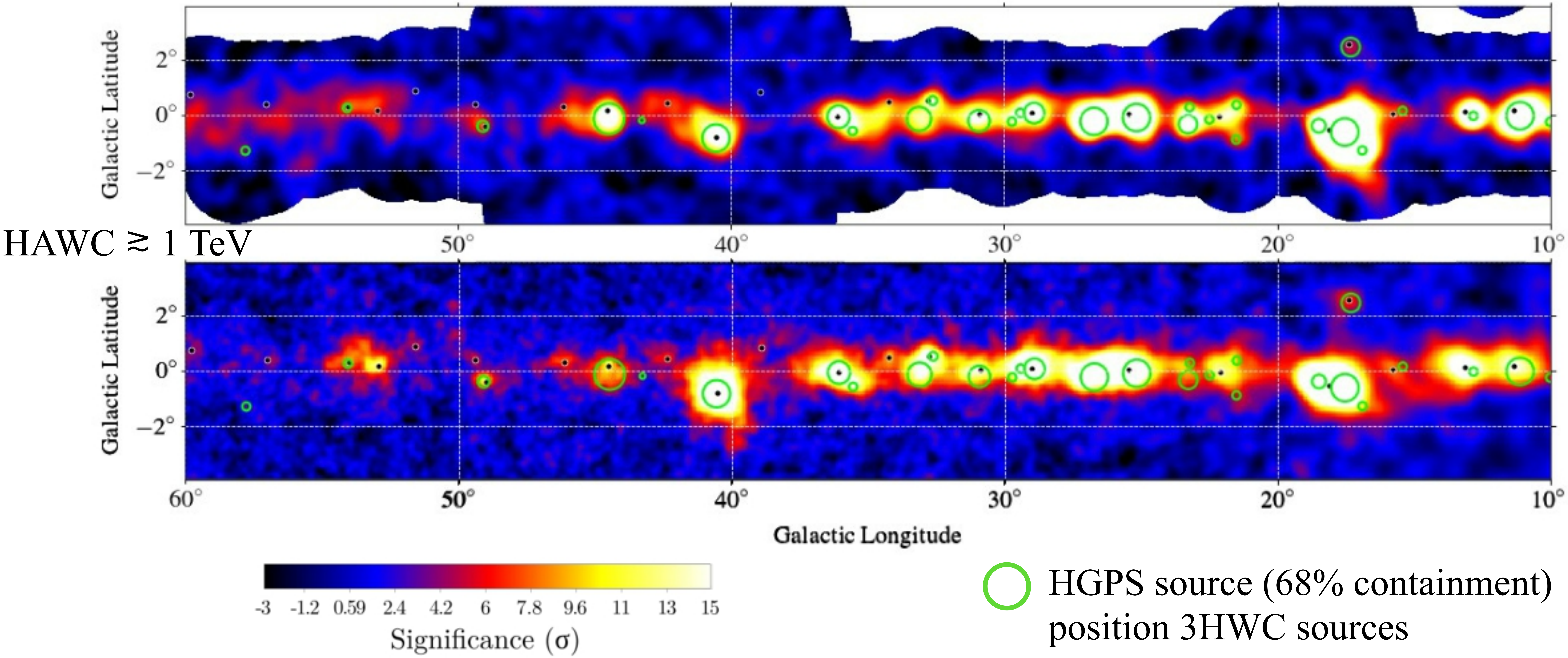


HGPS source (68% containment)
position 3HWC sources

HAWC and H.E.S.S. Galactic plane

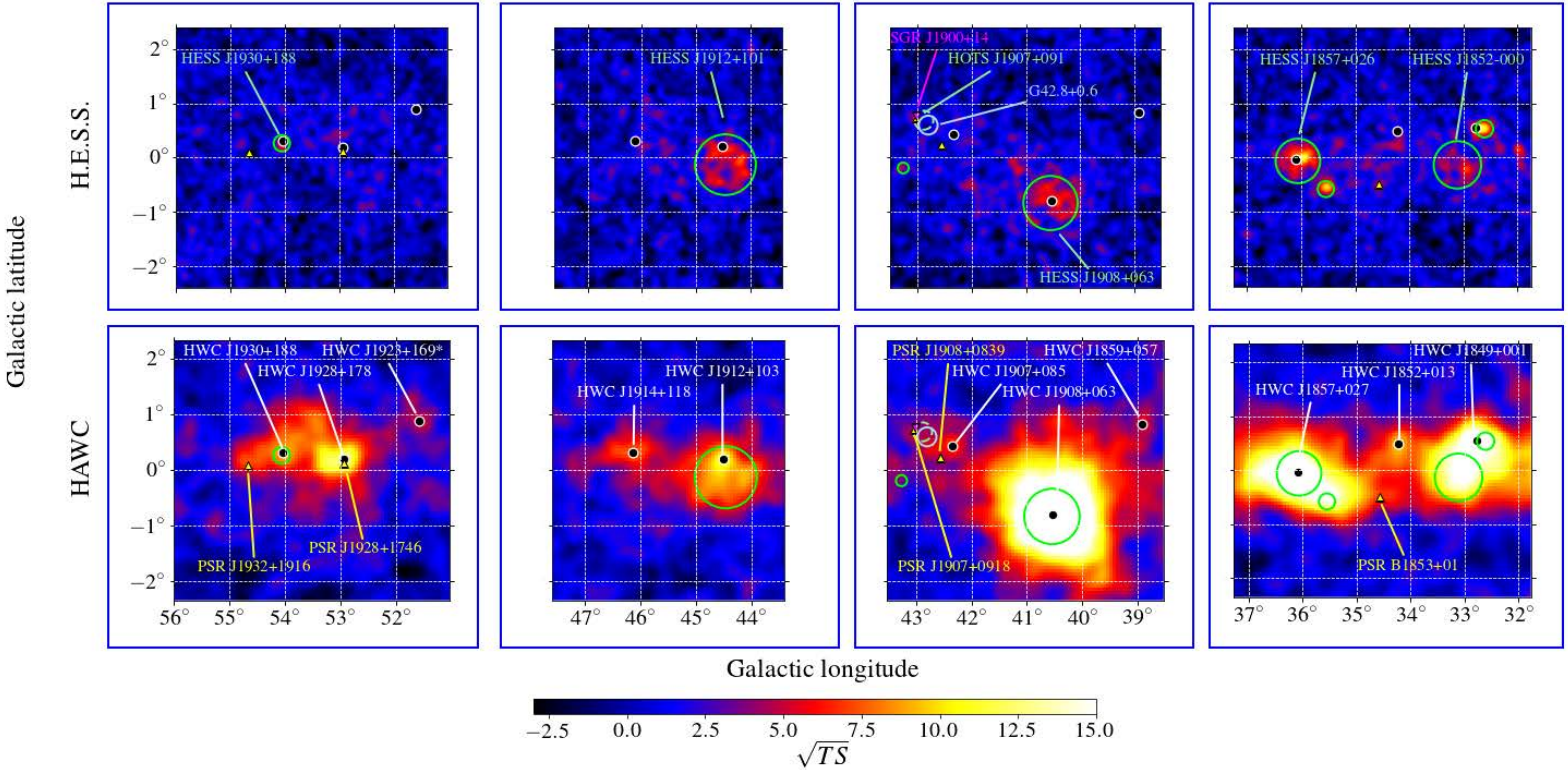
HESS new analysis > 1TeV

- Similar angular resolution 0.4°
- Similar background method
- Similar map making process



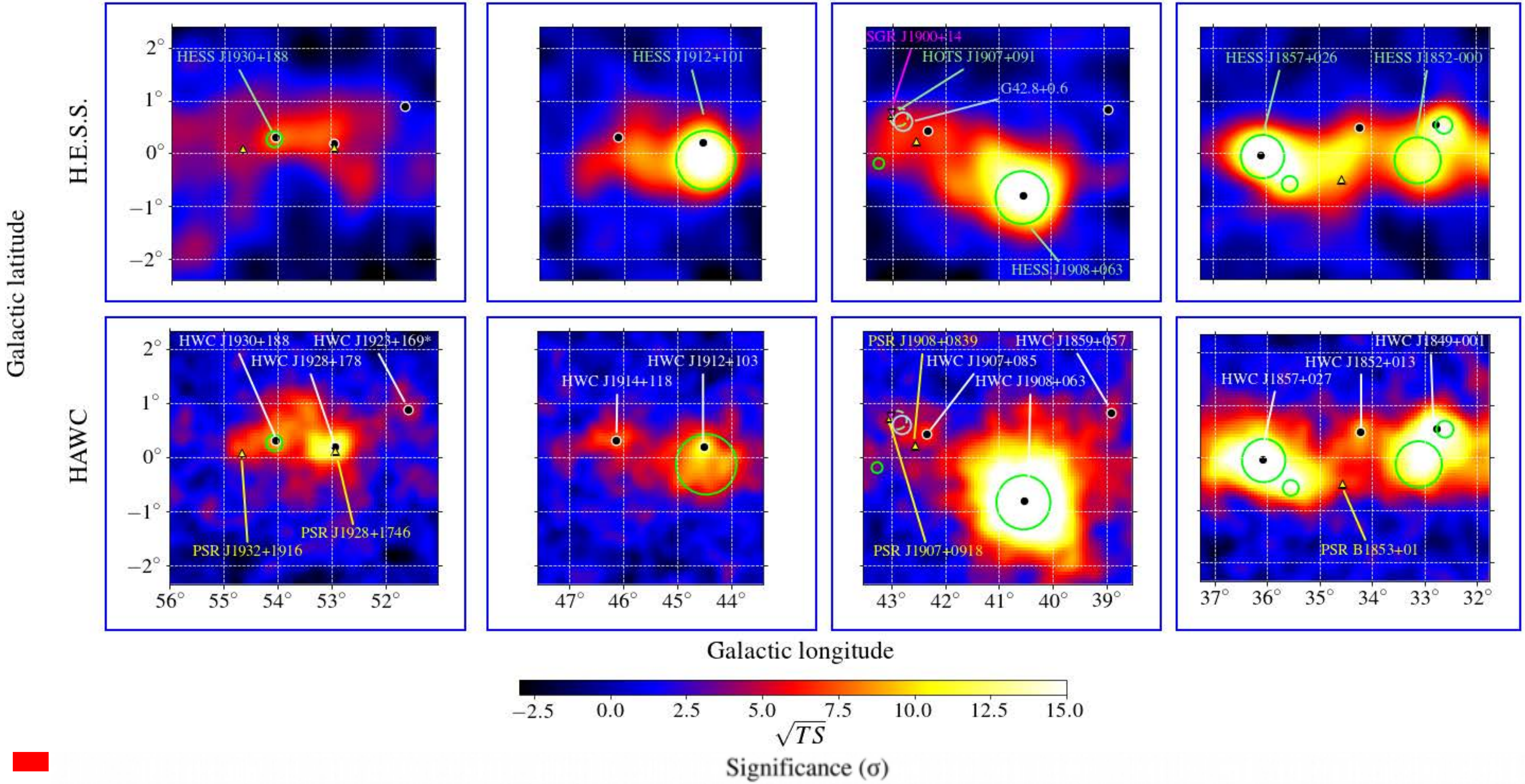
H.E.S.S. detection of HAWC sources

Original Comparison



H.E.S.S. detection of HAWC sources

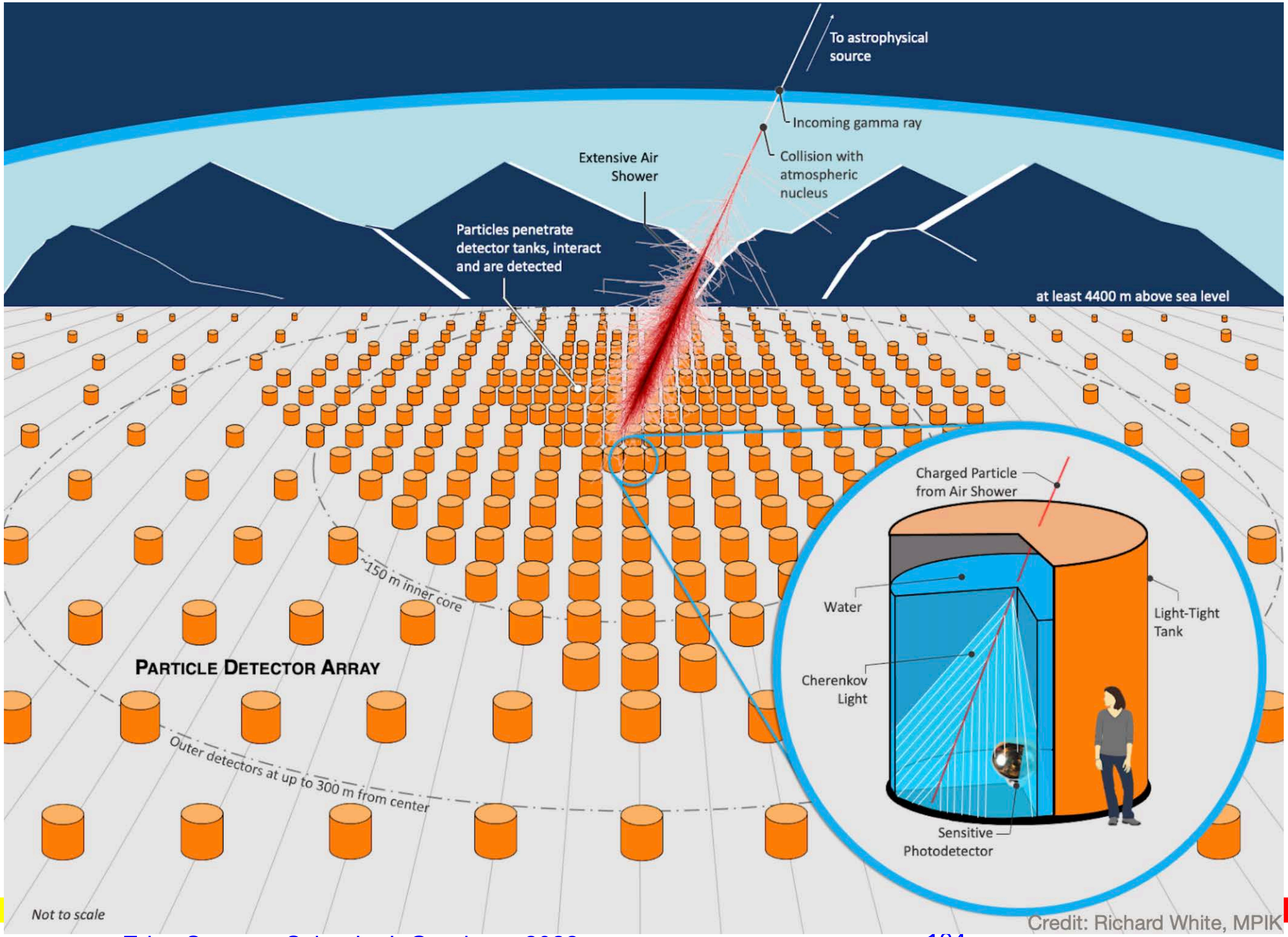
New Comparison



Large High Altitude Air Shower Observatory (LHAASO)

The Future

The Southern Wide-field Gamma-ray Observatory



Credit: Richard White, MPIK