Fermi Summer School 2017

Jordan Goodman - University of Maryland

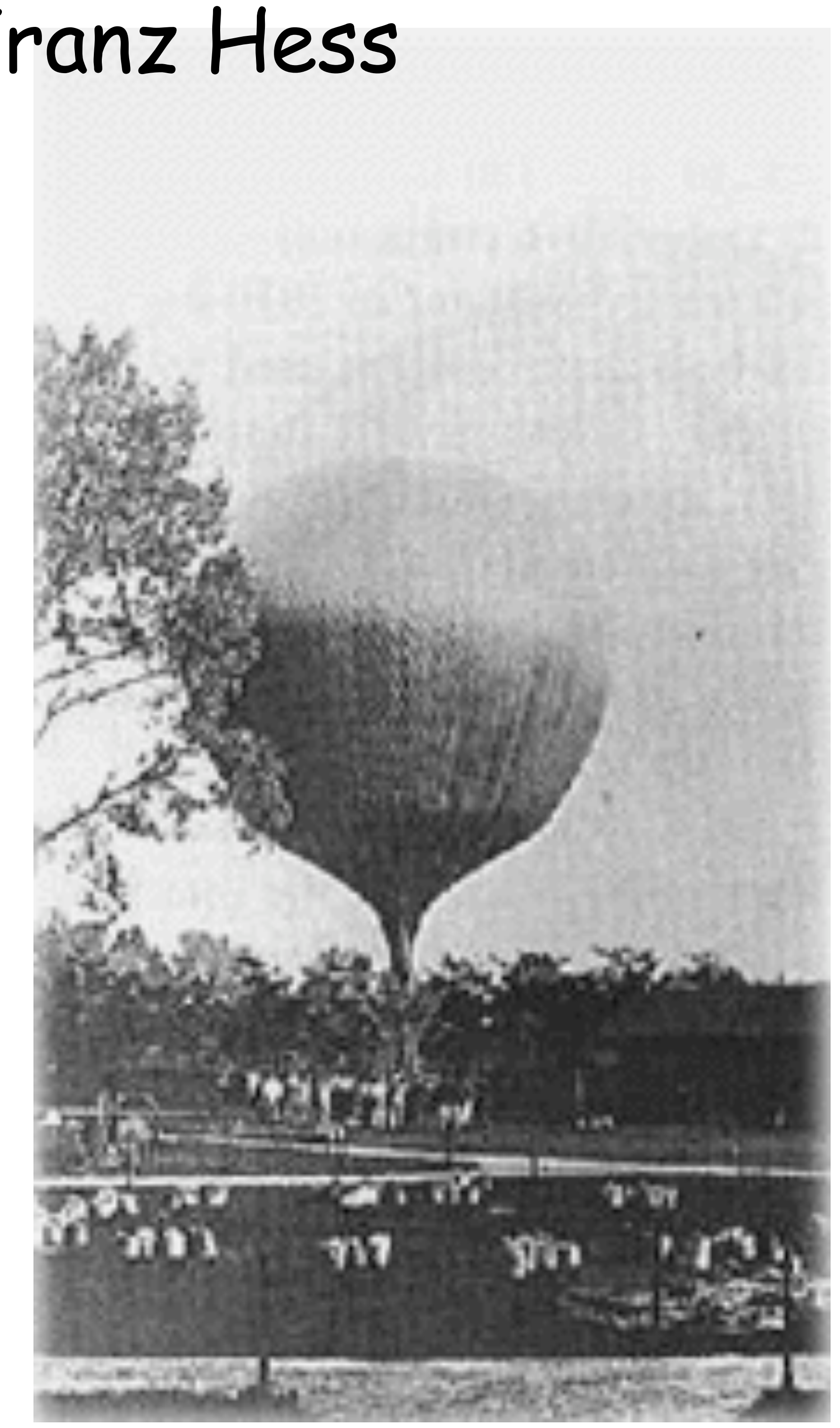
AIR SHOWERS

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.”

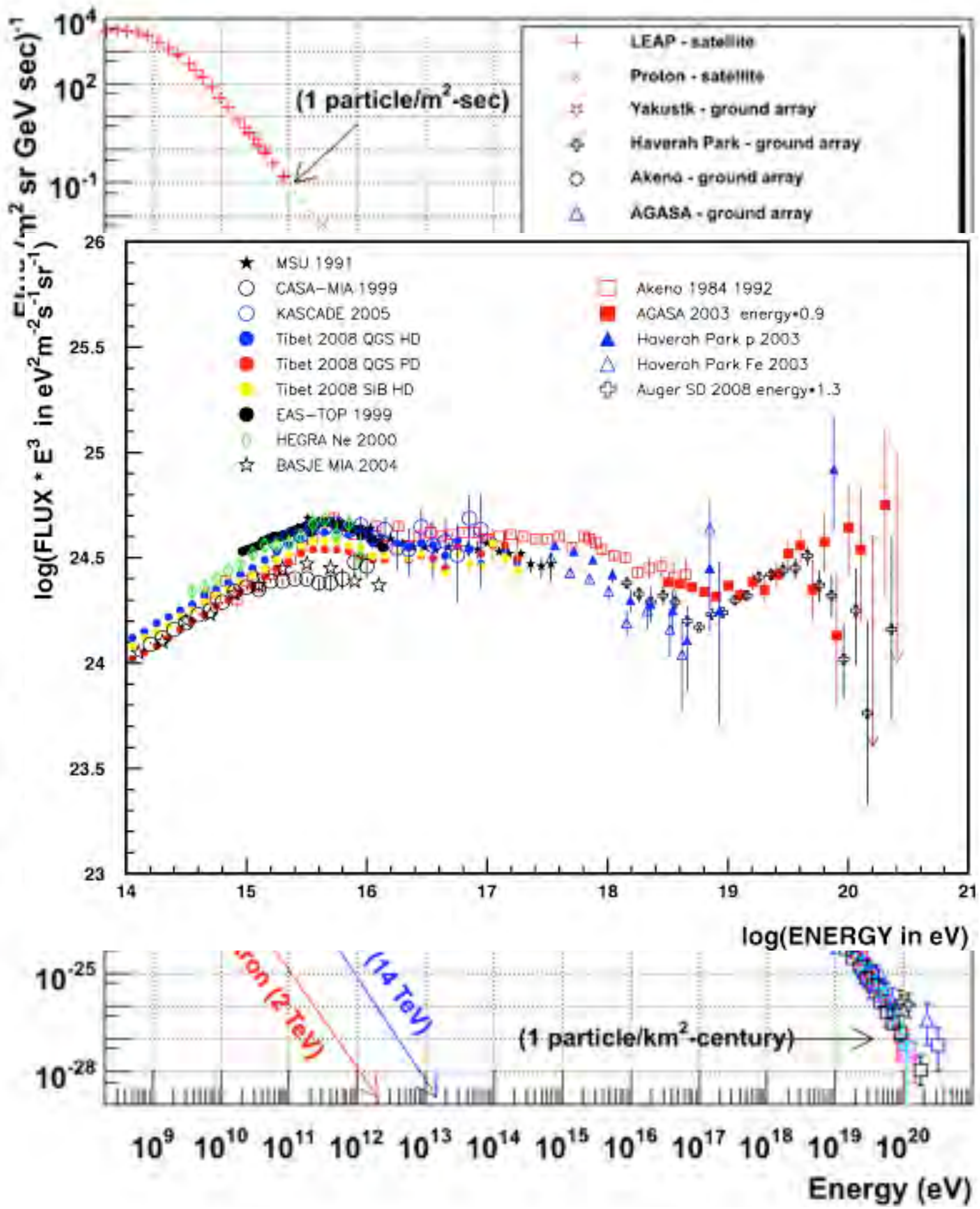
Victor Franz Hess

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



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

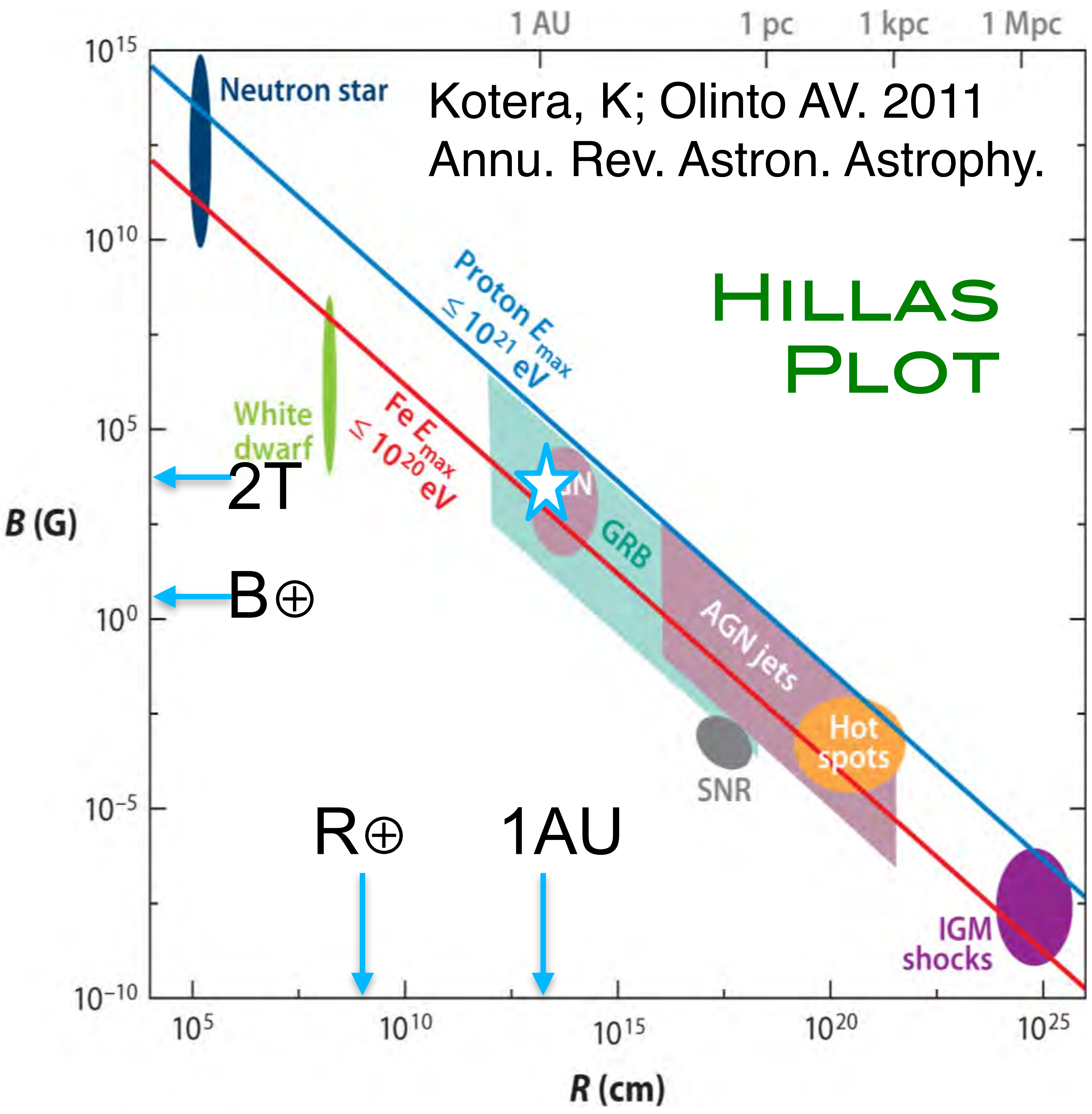
AERO
CLUB
WIEN



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

Candidate accelerators



p=0.3 Br

p in Gev/c

B in Tesla

r in meters

B=2T r=1.5×10^{11}m

p=10^{11} GeV/c

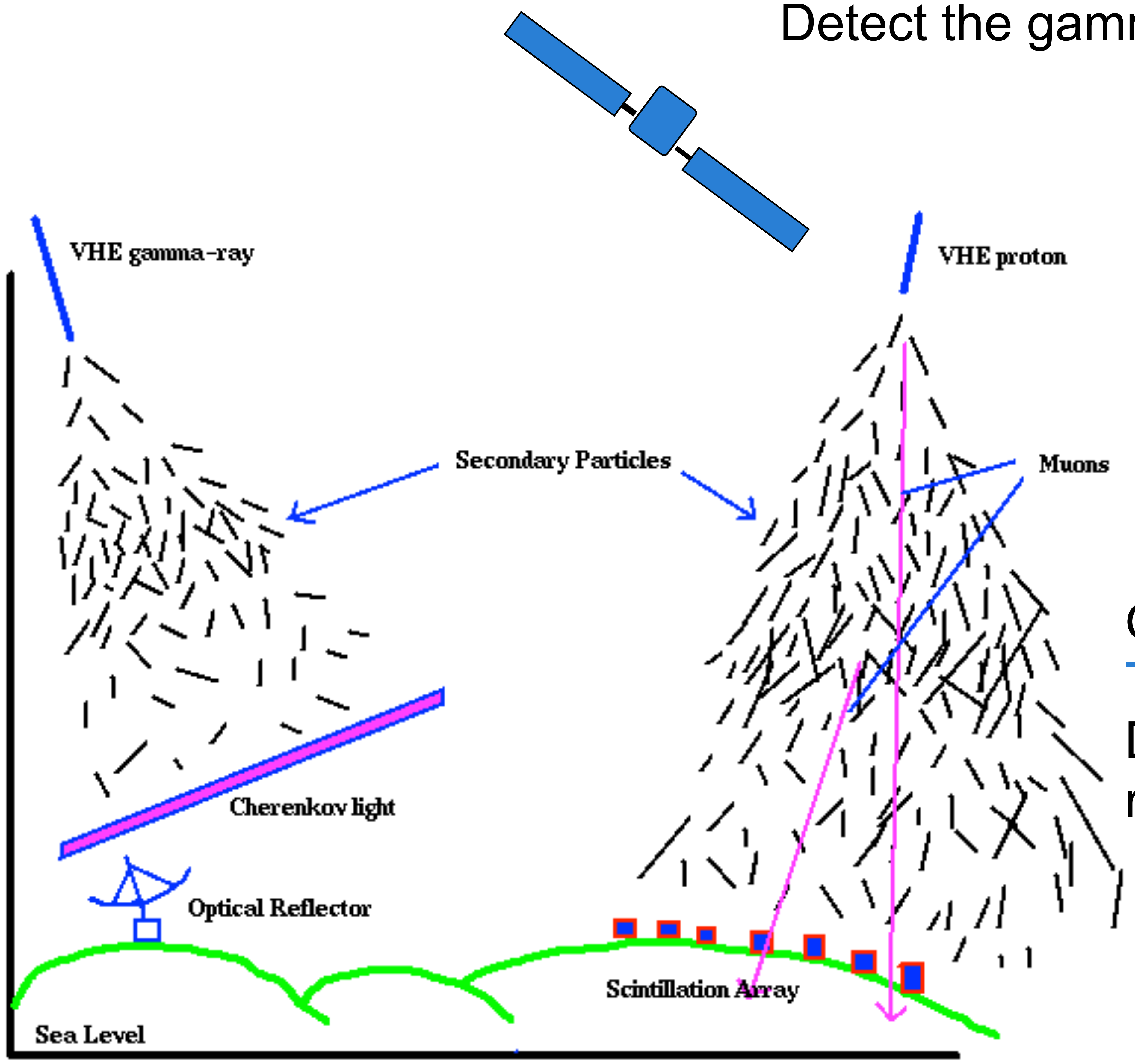
=10^{20} eV/c

Large magnetic field

Techniques for Gamma-ray Detection

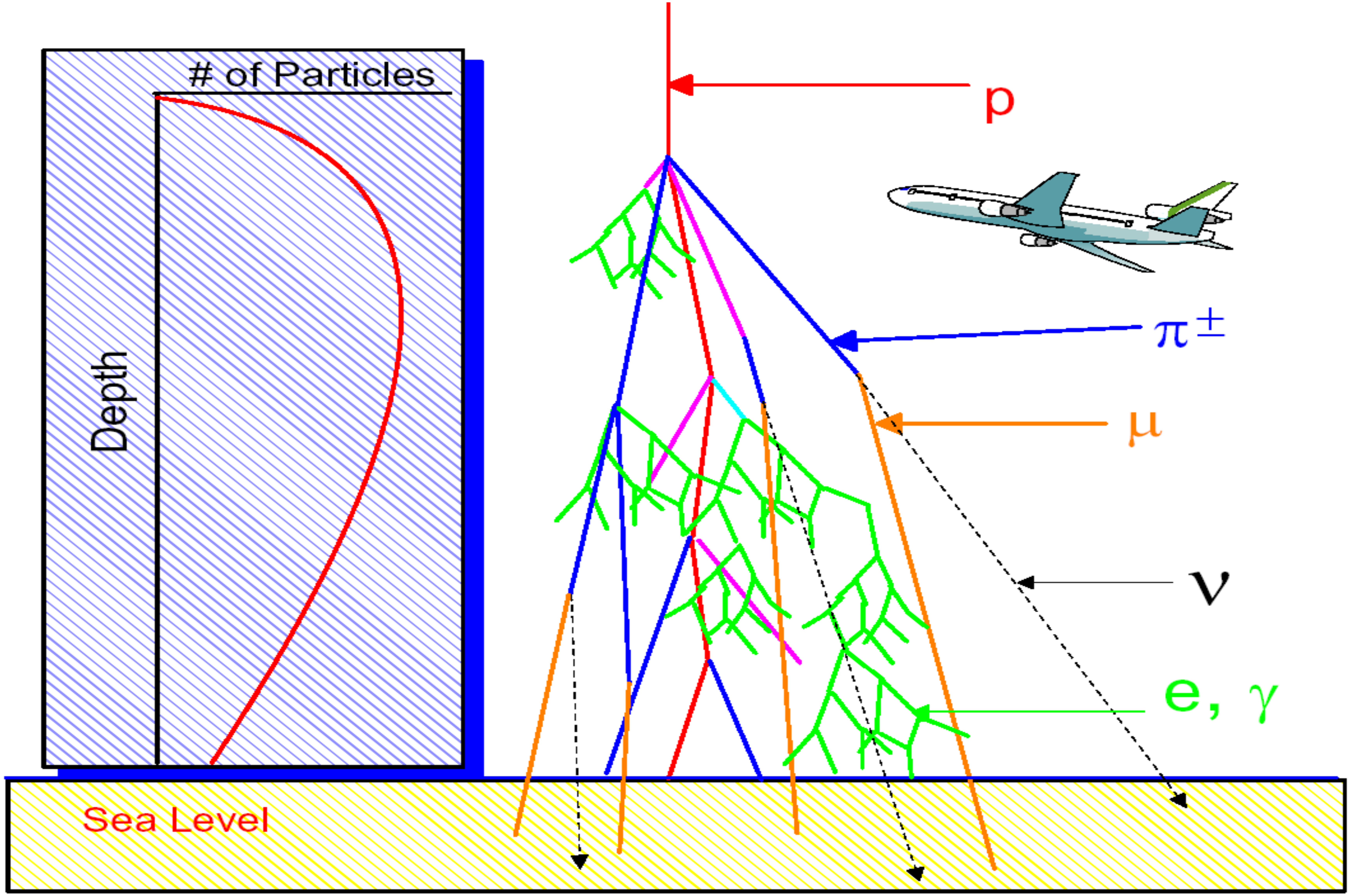
Satellite (Fermi, AGILE, EGRET…)
Detect the gamma-rays directly.

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

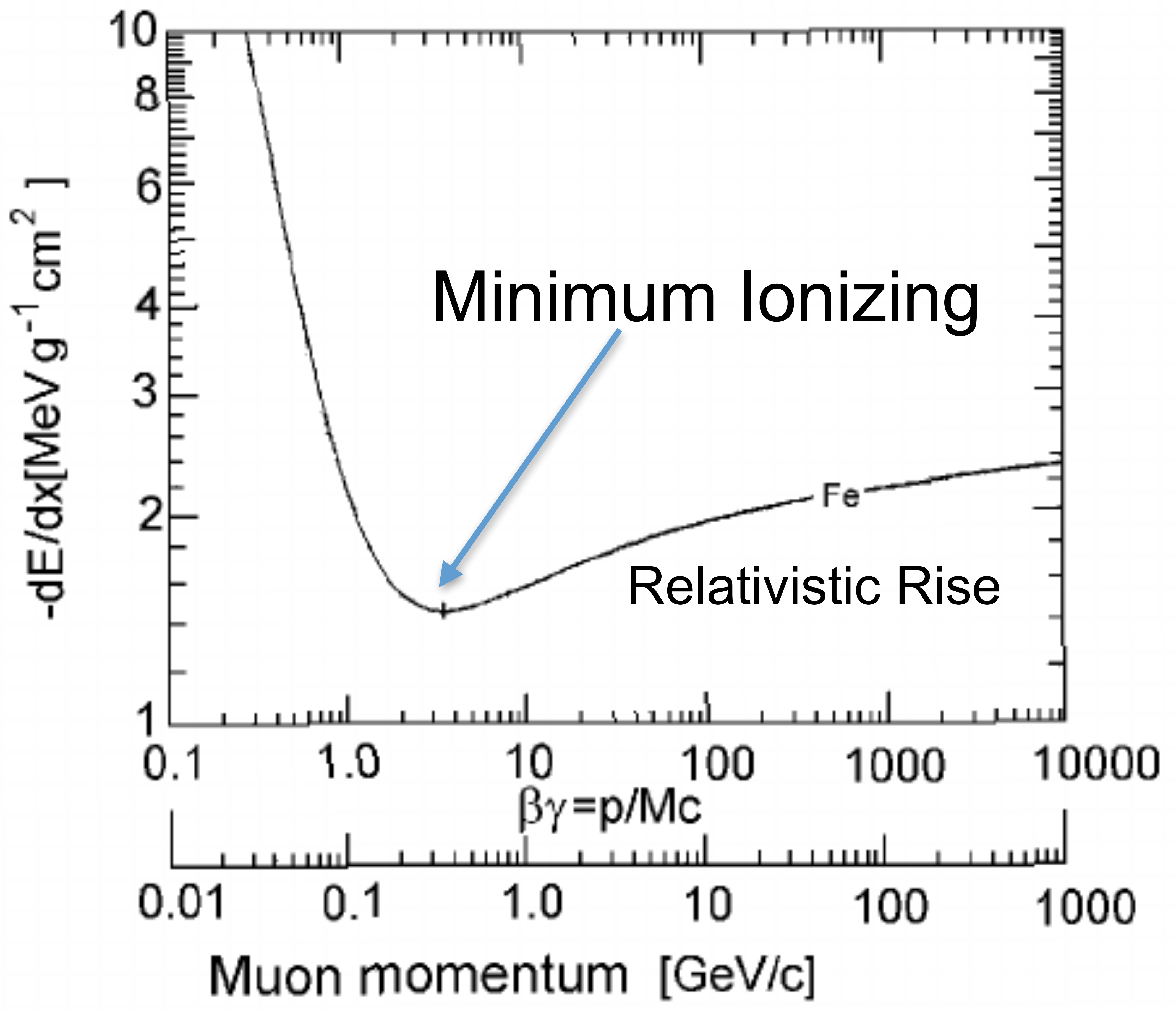


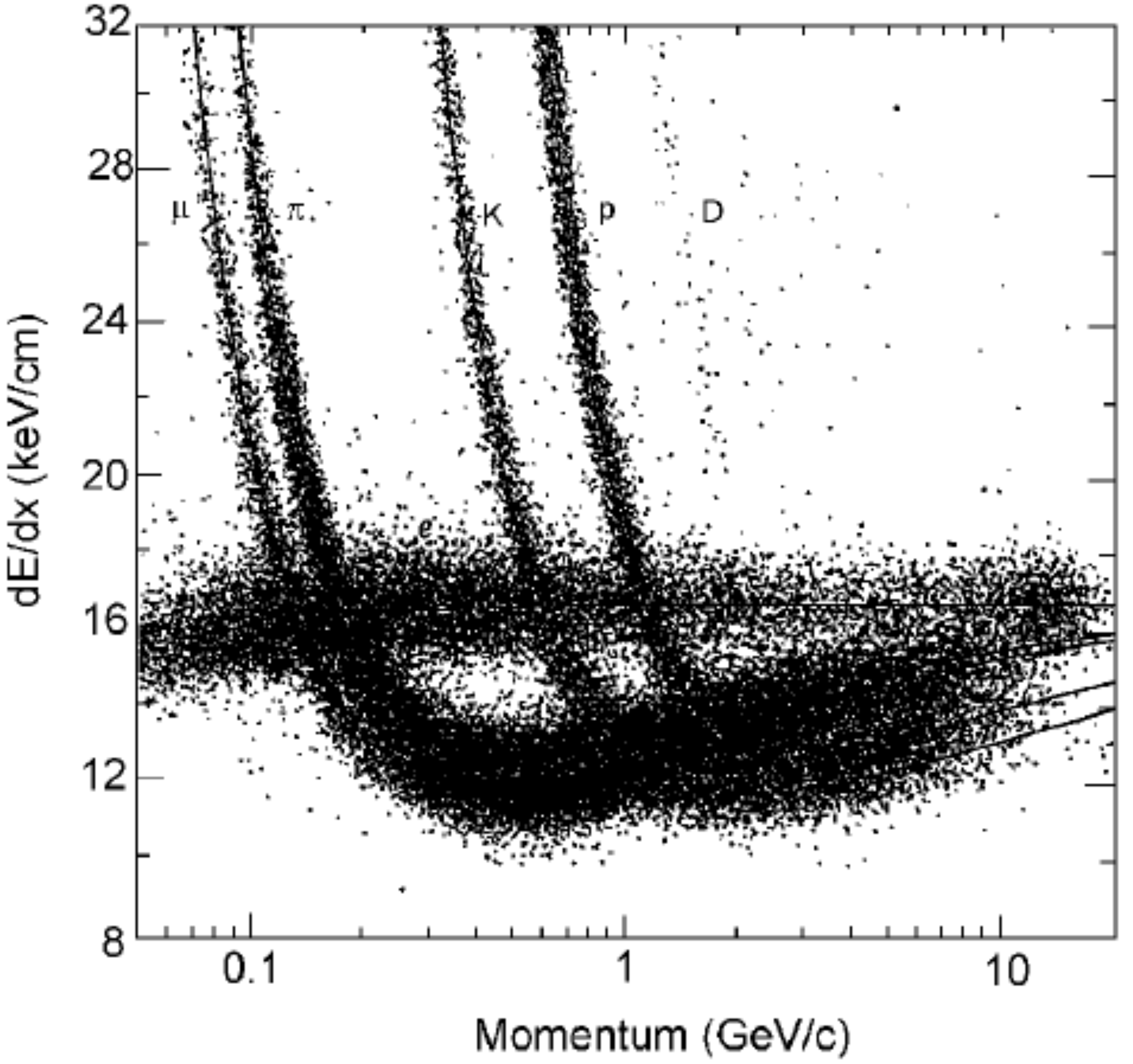
Ground Array (Milagro, Tibet, ARGO, HAWC…)
Detect particles reaching ground level.

Extensive Air Shower Development

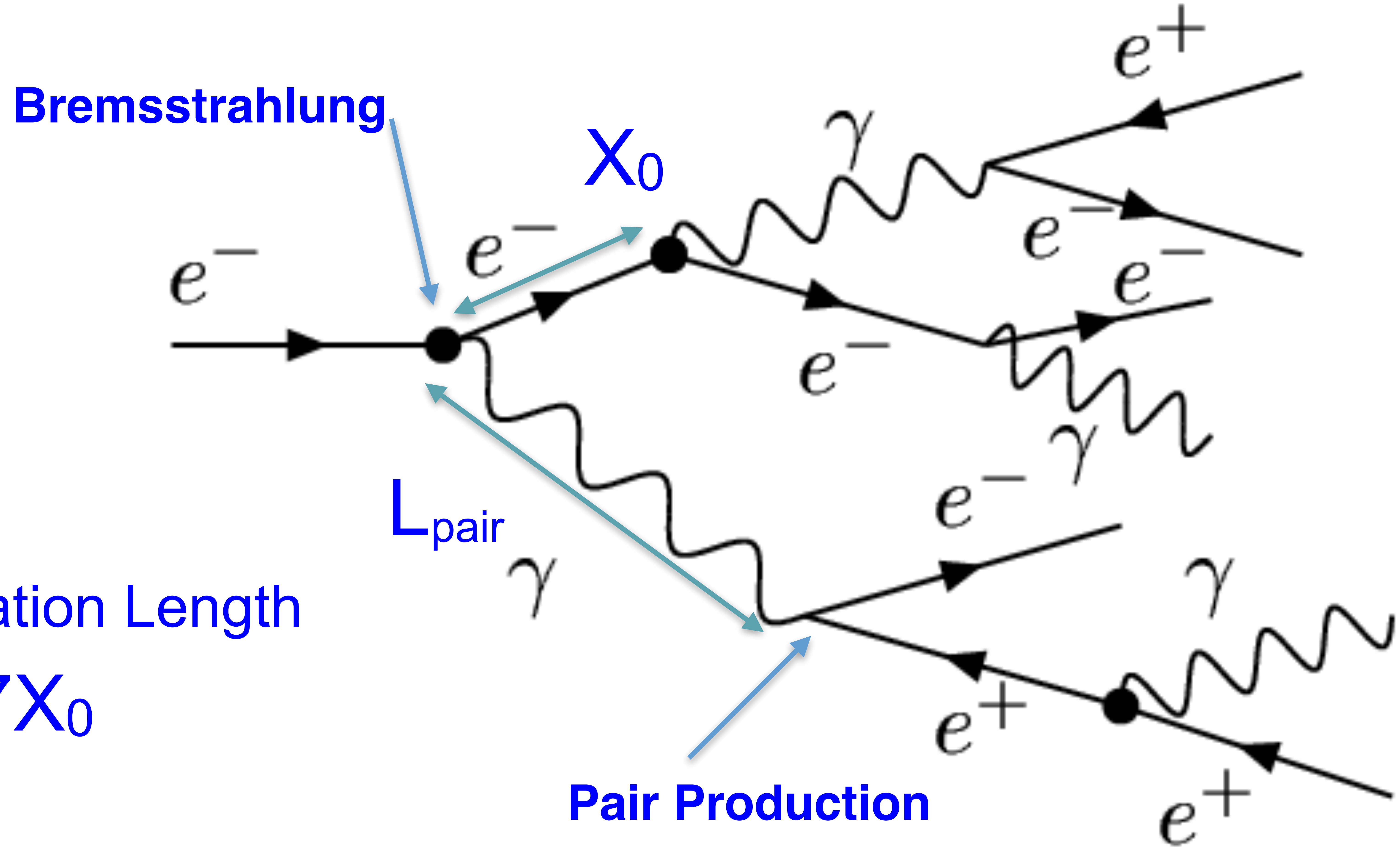


Ionization Energy Loss for Charged Particles





Electromagnetic Shower



X_0= Radiation Length

$L_{pair} \sim 9/7 X_0$

Gamma-ray Energy Loss Mechanisms

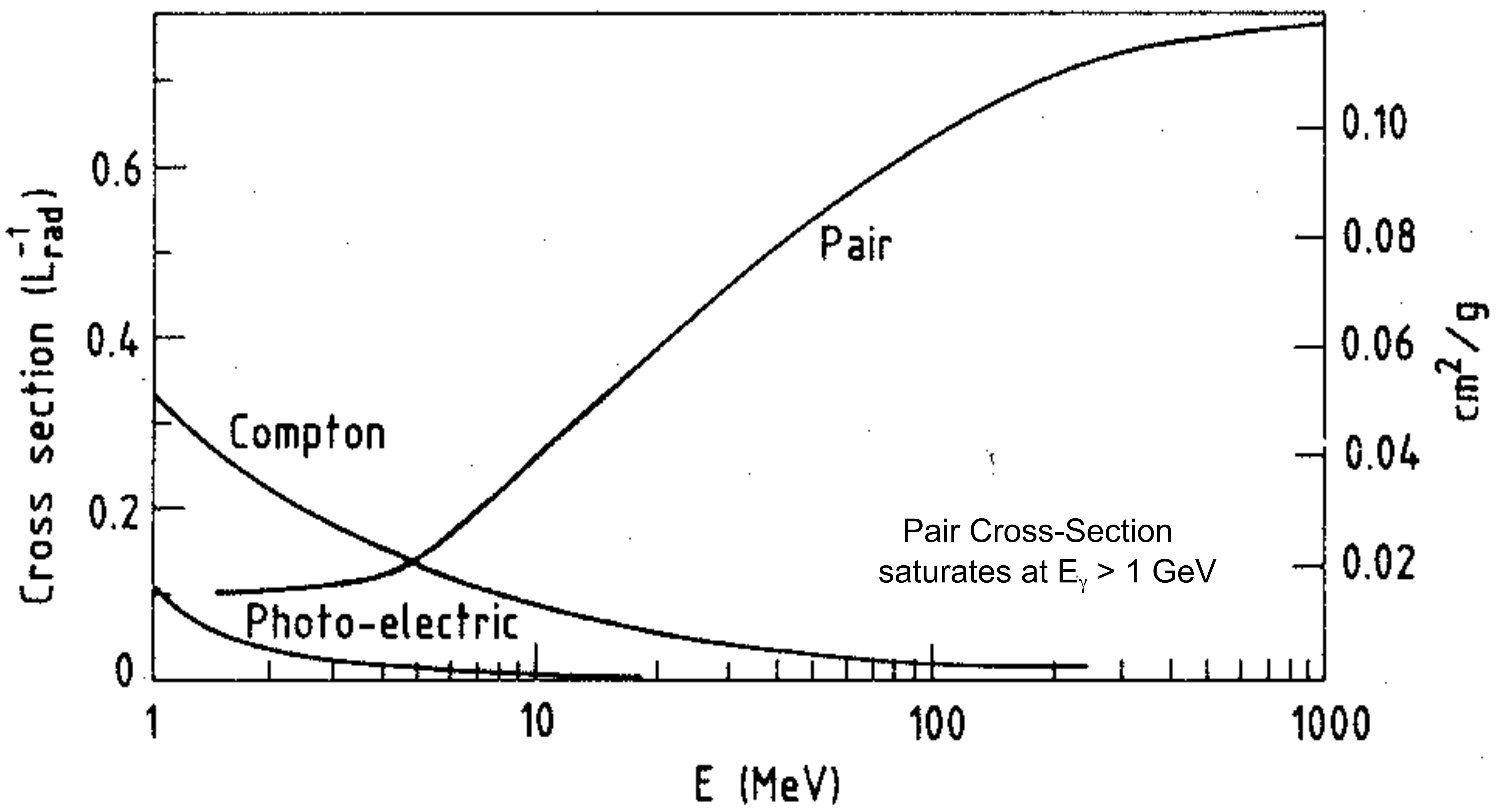
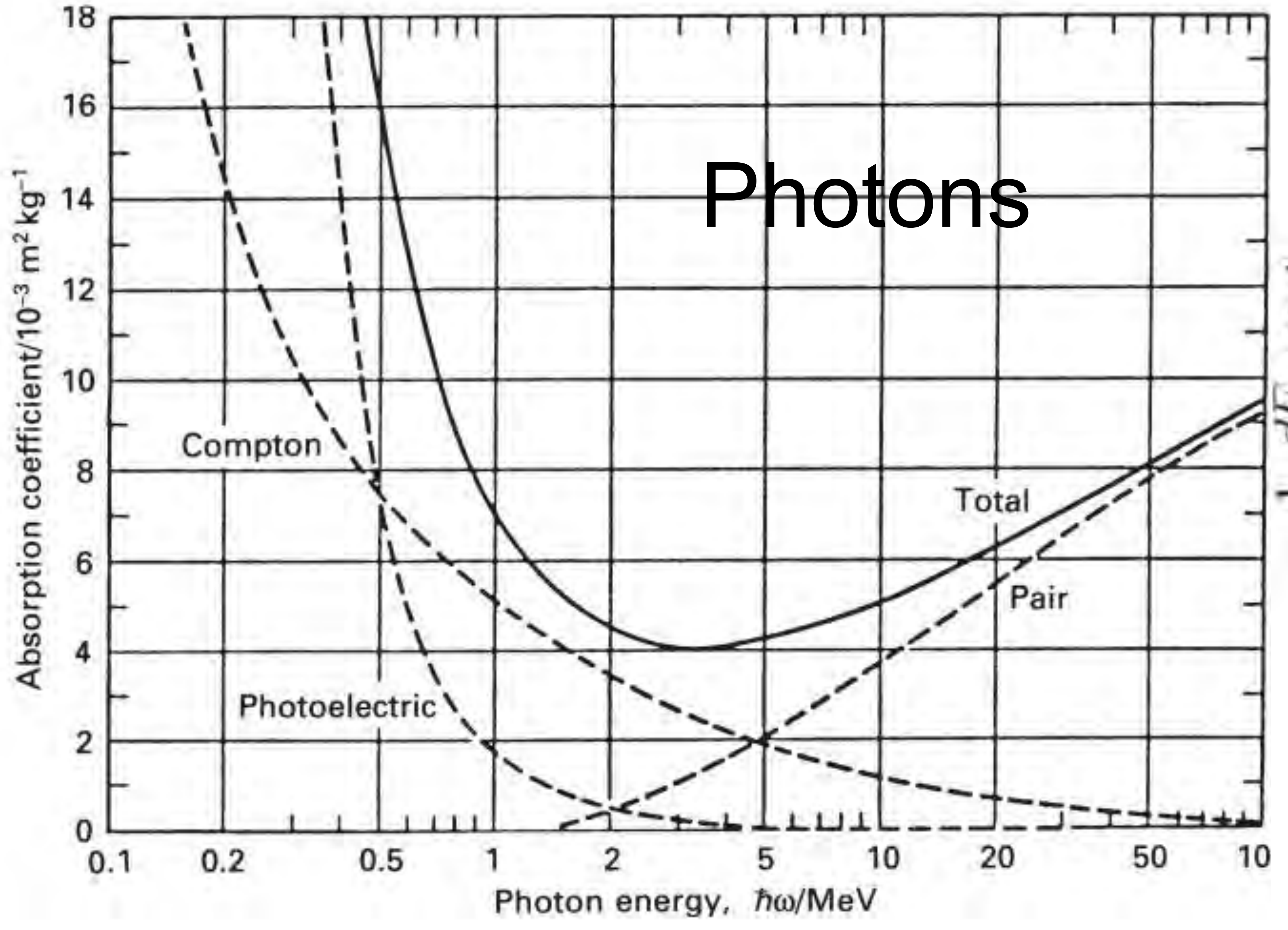
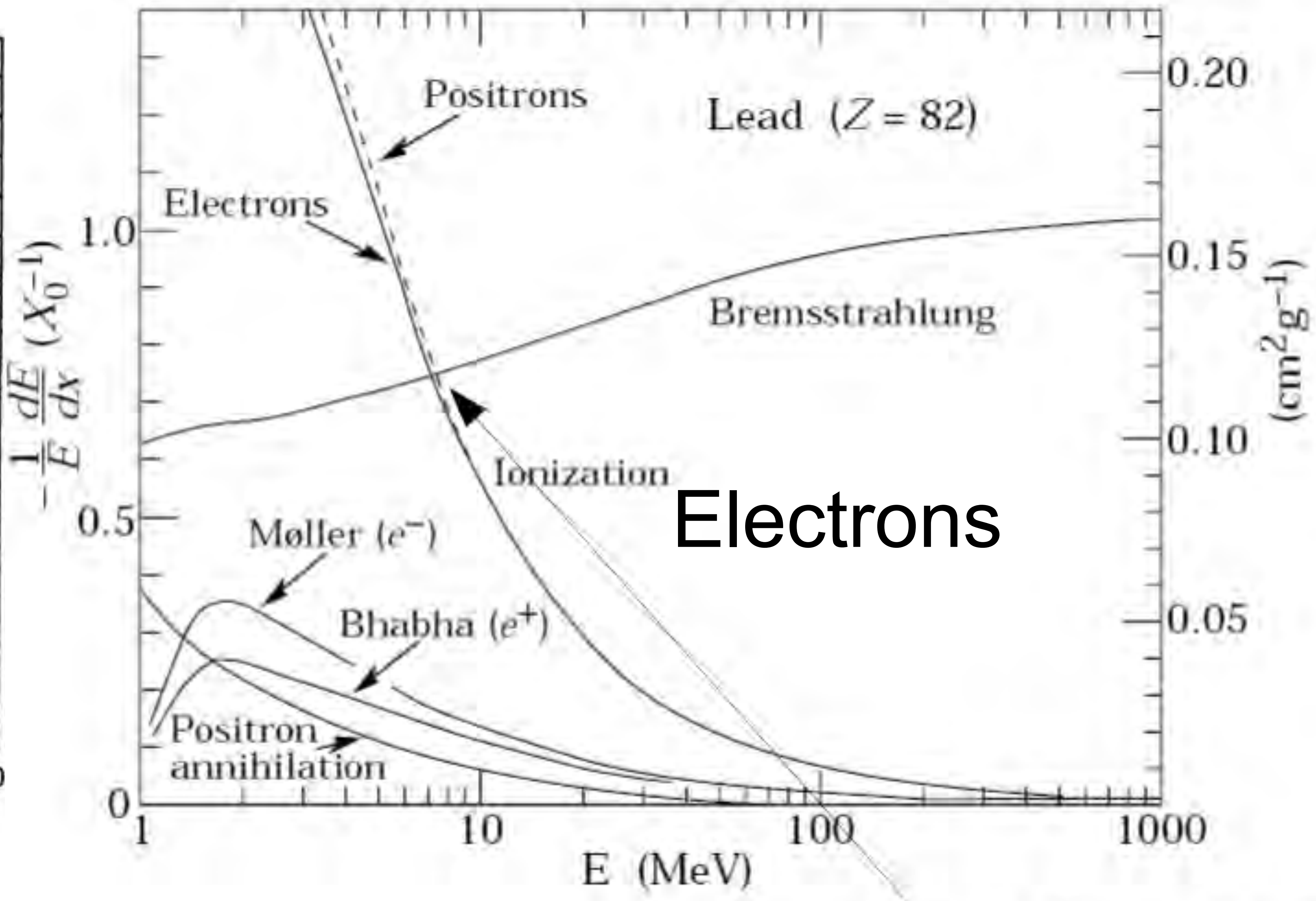


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

At High Energies Pair Production and Bremsstrahlung Dominates EM Interactions





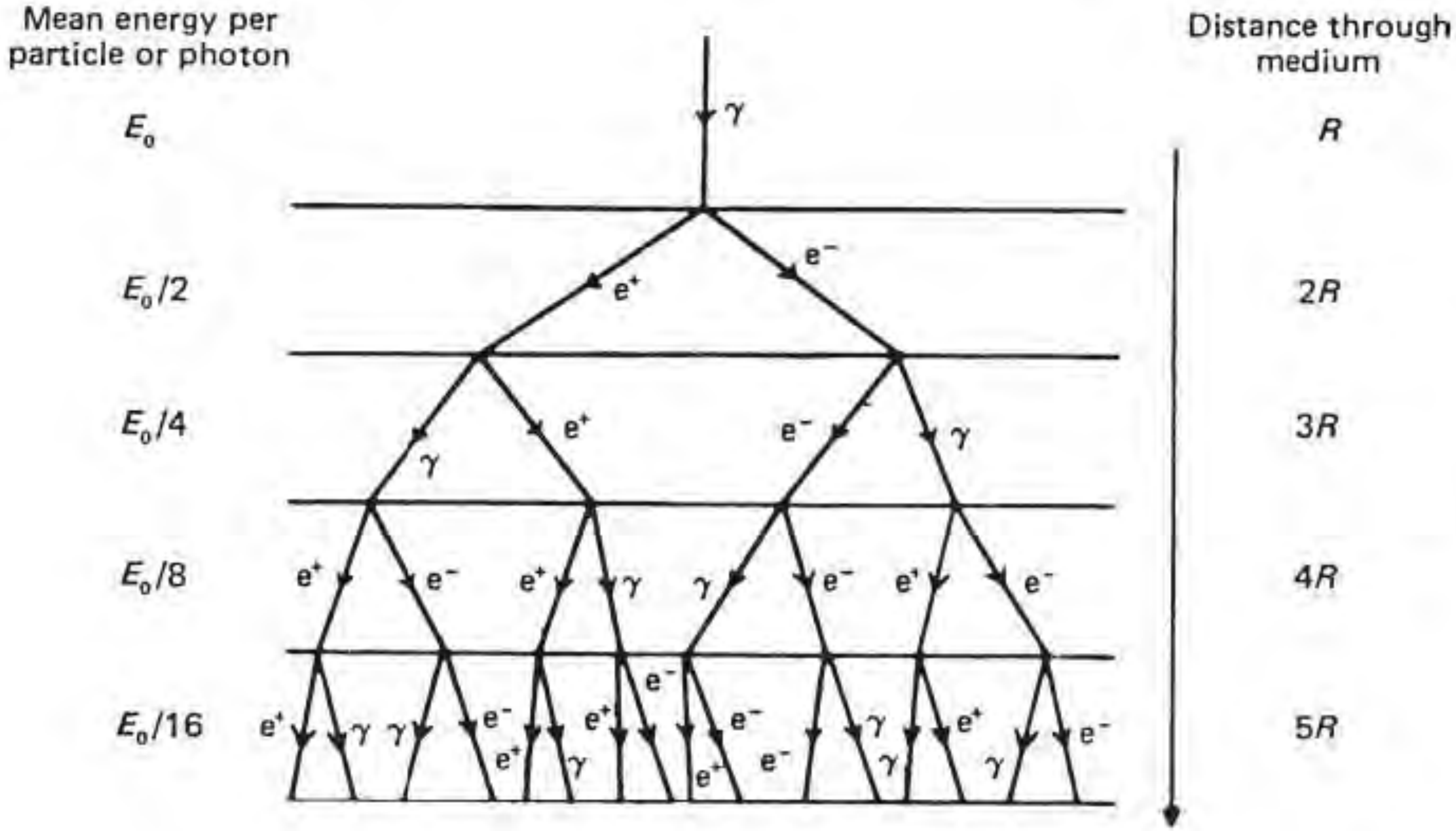
Critical energy: $dE/dx_{Ion} = dE/dx_{Brems}$

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

Bremsstrahlung

- Bremsstrahlung Cross Section goes like $1/m^2$.
- So for electrons it's important at 10's of MeV
- For Muons it's not important until ~20 MeV $(m_{muon}/m_{electron})^2$ which is ~ TeV
  - It's an important energy loss mechanism for IceCube TeV muons

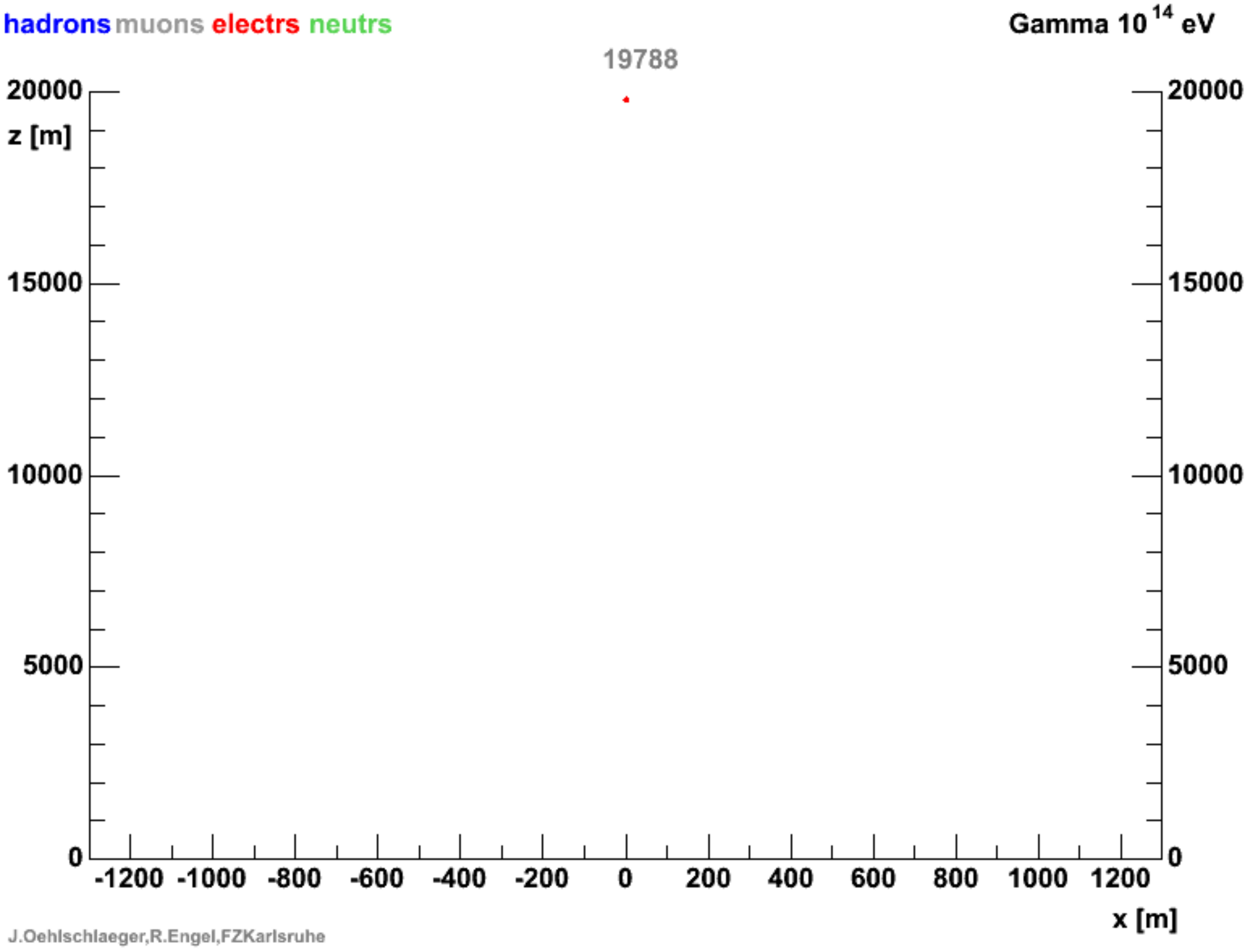
Electromagnetic Air Shower



Electromagnetic Showers in the Atmosphere

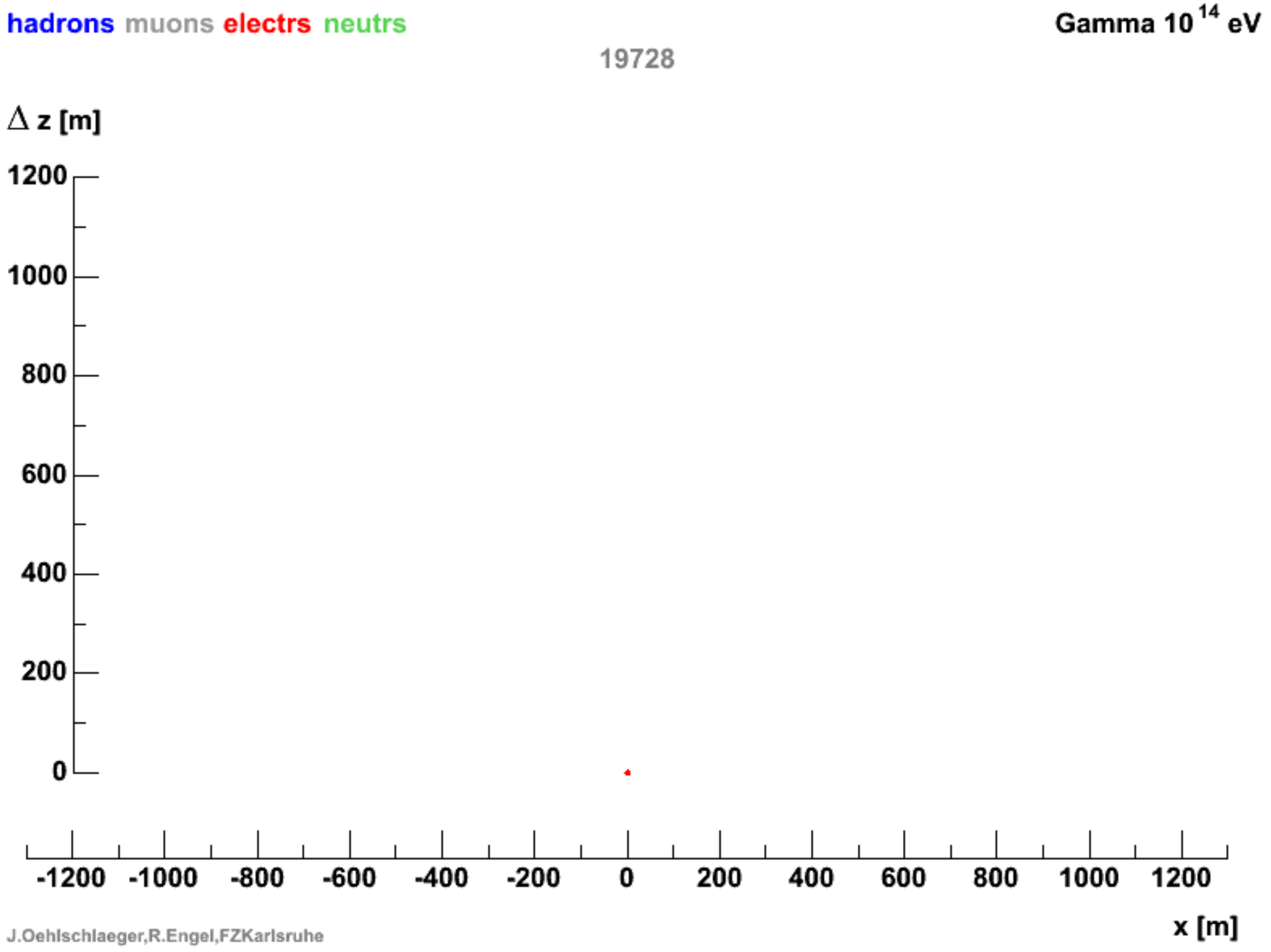
- If EM particle such as photon or electron initiates shower in atmosphere
  - After distance n R, the number of (photons + electrons + positrons) is 2^n and their average energy is $E_0/2^n$
  - On average, the shower consists of 2/3 positrons and electrons 1/3 photons
  - Longitudinal development reaches maximum at depth
  - Where E_c ~ 80 MeV in air $$X_{max} = \frac{\ln(E/E_c)}{\ln 2}$$
  - Below E_c ionization dominates and electrons stop producing photons via Bremsstrahlung

Gamma Ray 100 TeV

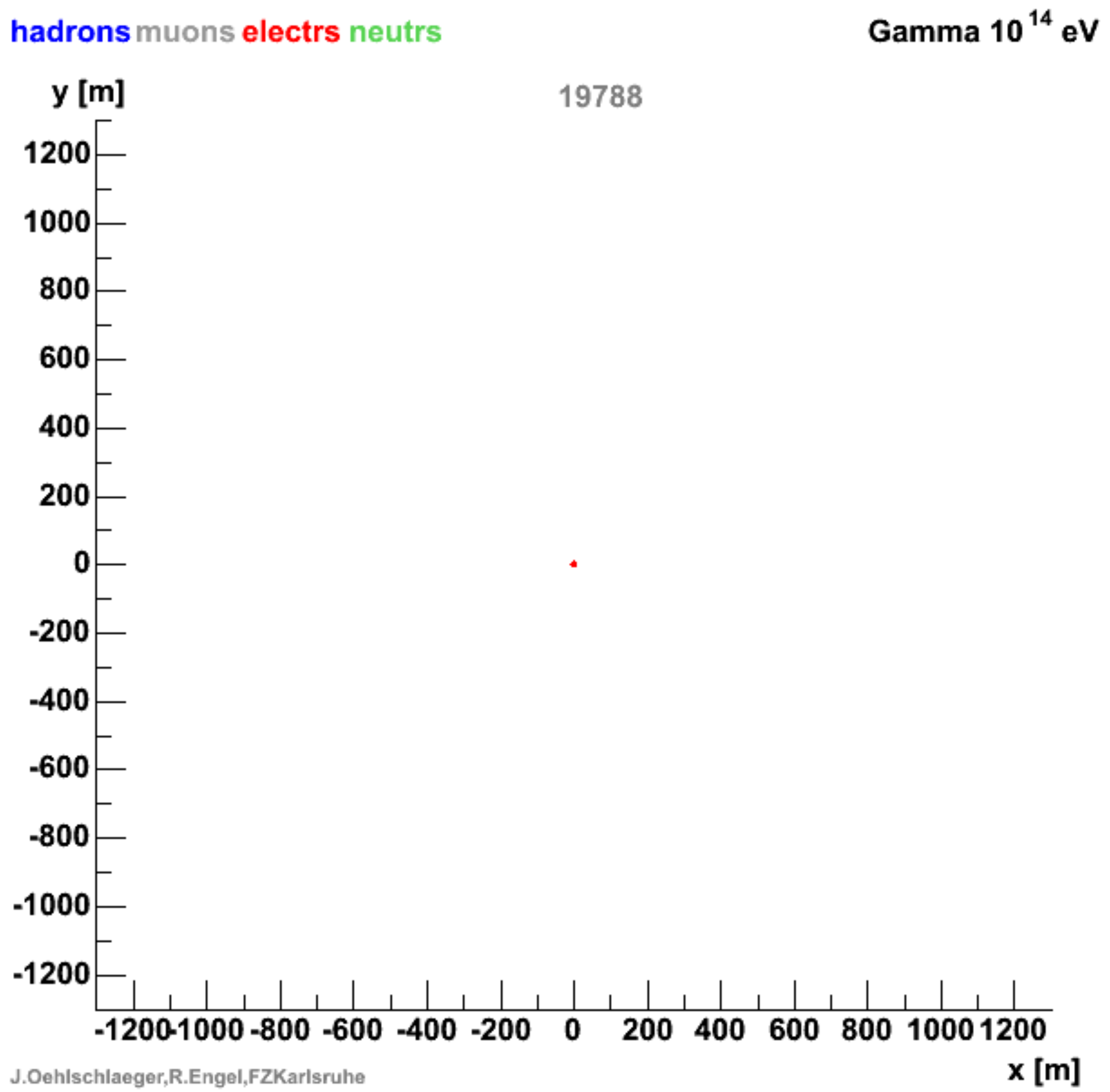


Corsica Movies -
J. Oehlschläger and R. Engel, Institut für Kernphysik, Forschungszentrum Karlsruhe.

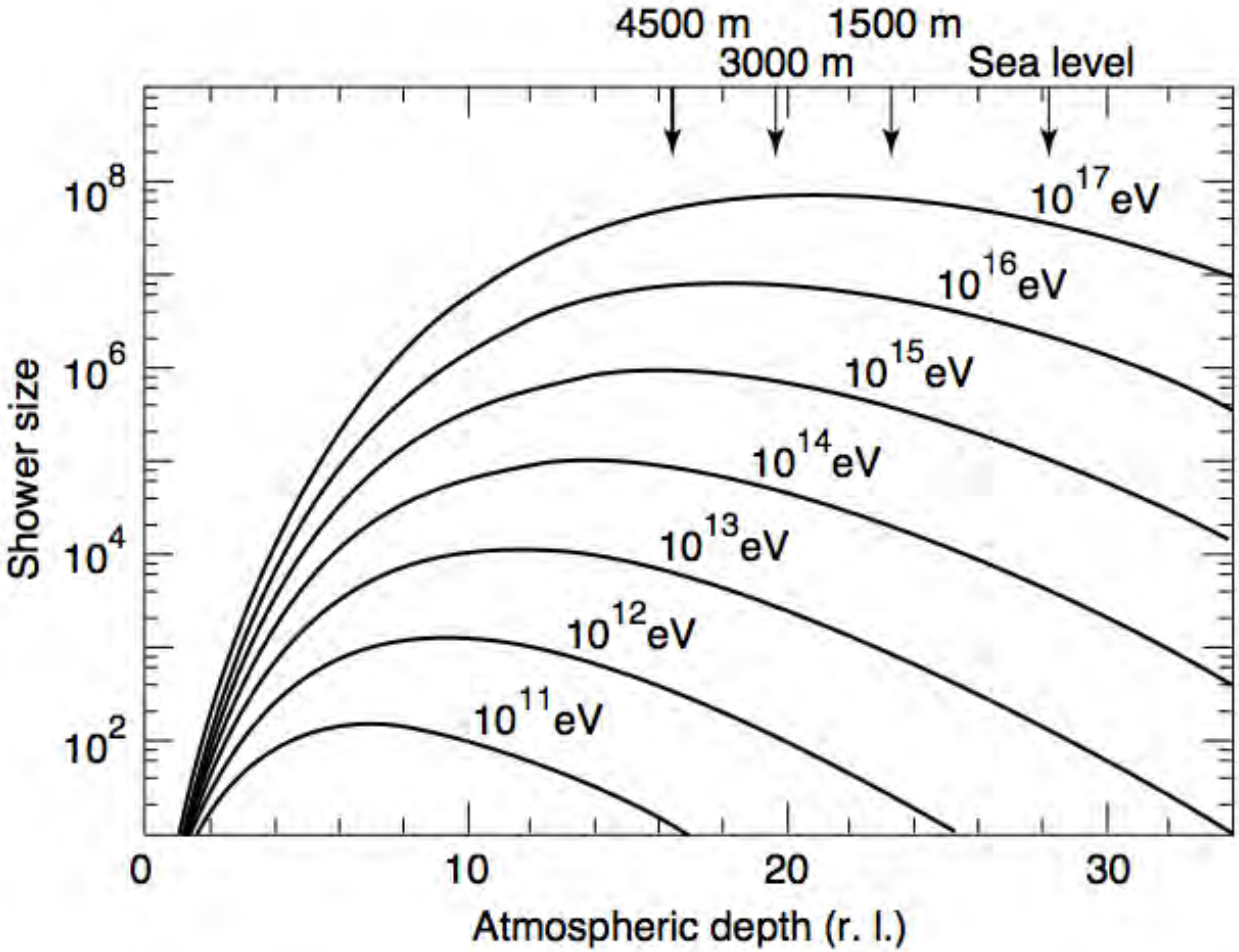
Gamma Ray 100 TeV



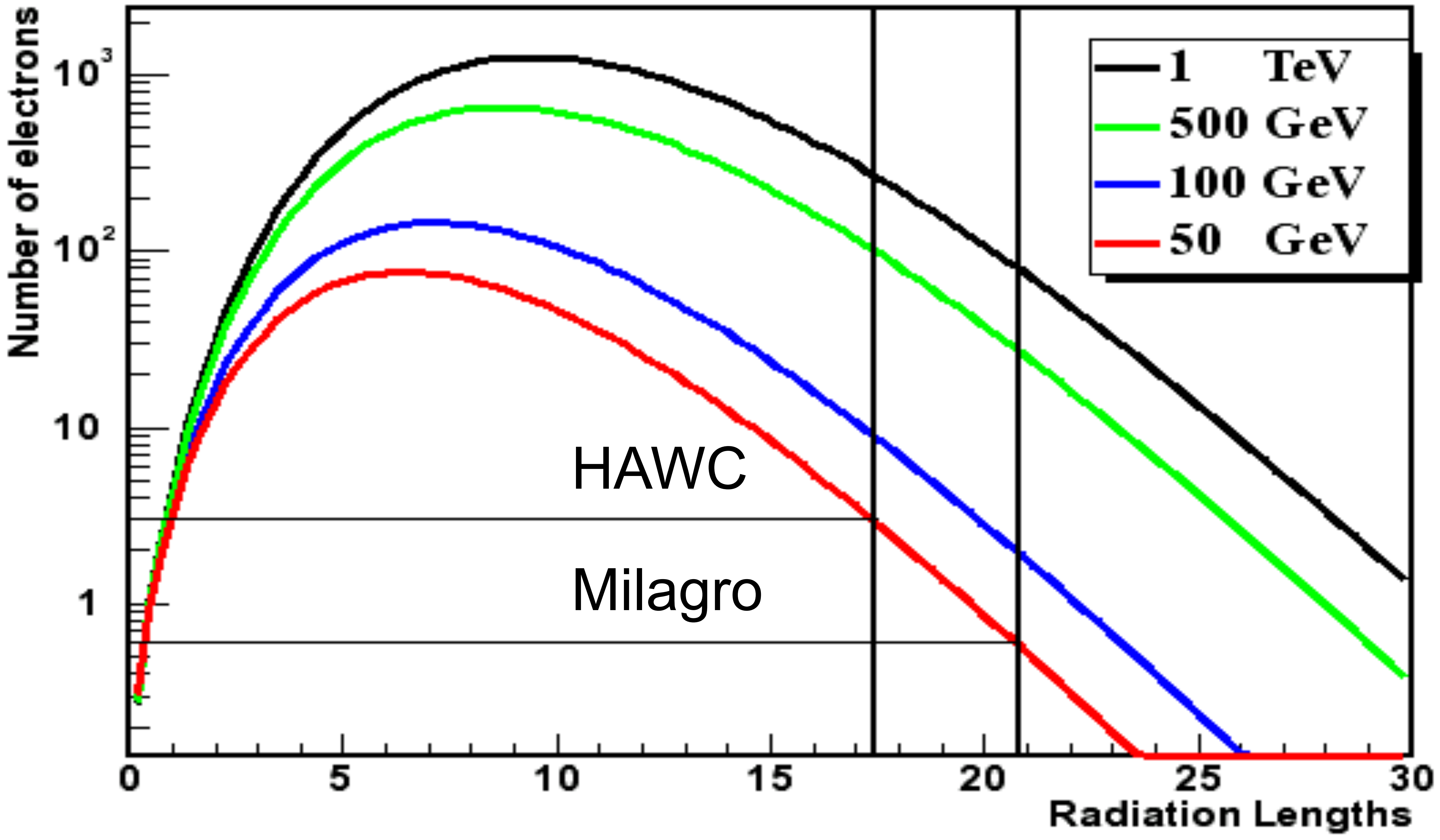
Gamma Ray 100 TeV

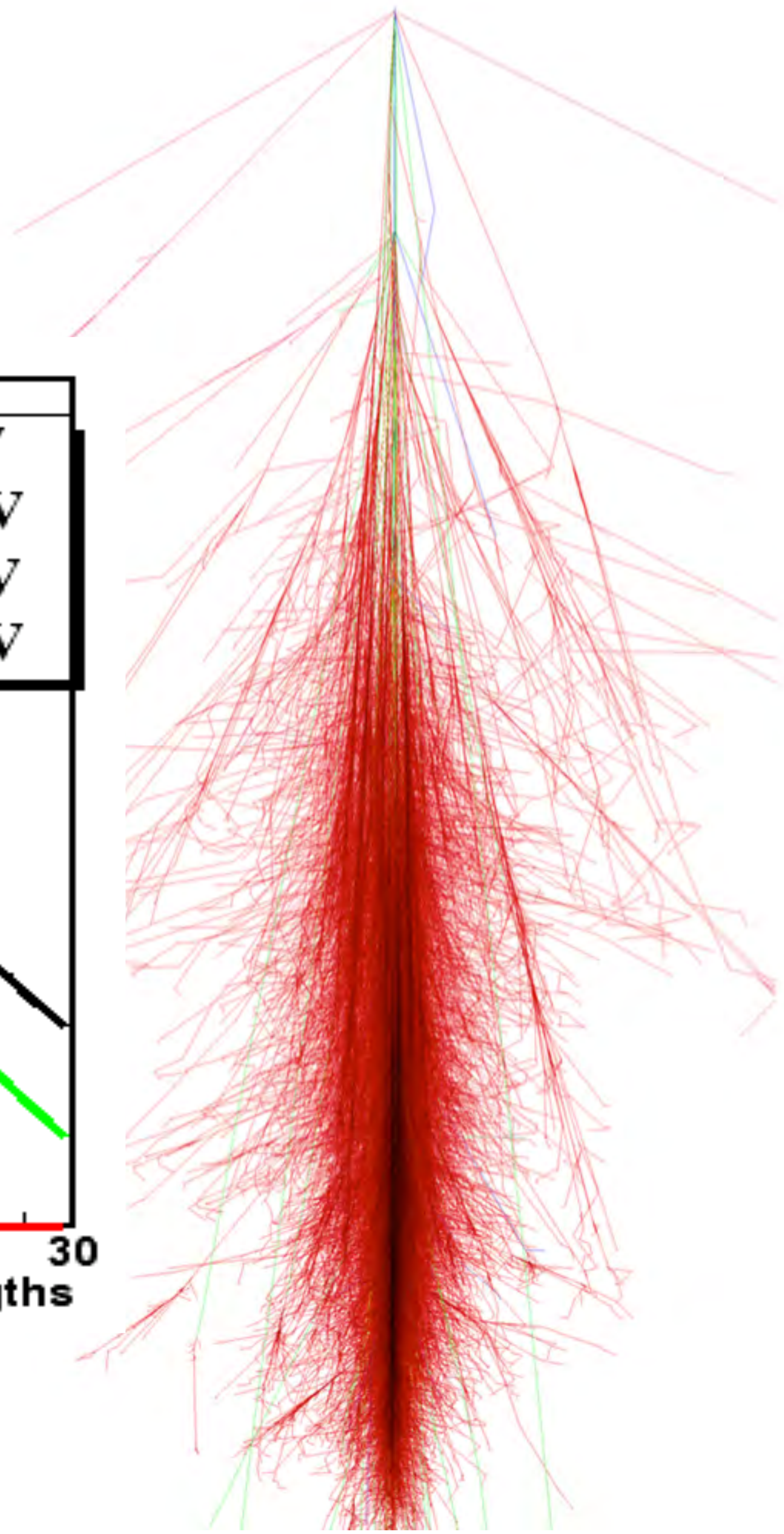


EM Shower


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

EM shower


Number of electrons
10^3
10^2
10
1
0
5
10
15
20
25
30
Radiation Lengths
1 TeV
500 GeV
100 GeV
50 GeV
HAWC
Milagro



Lateral shower profile:

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

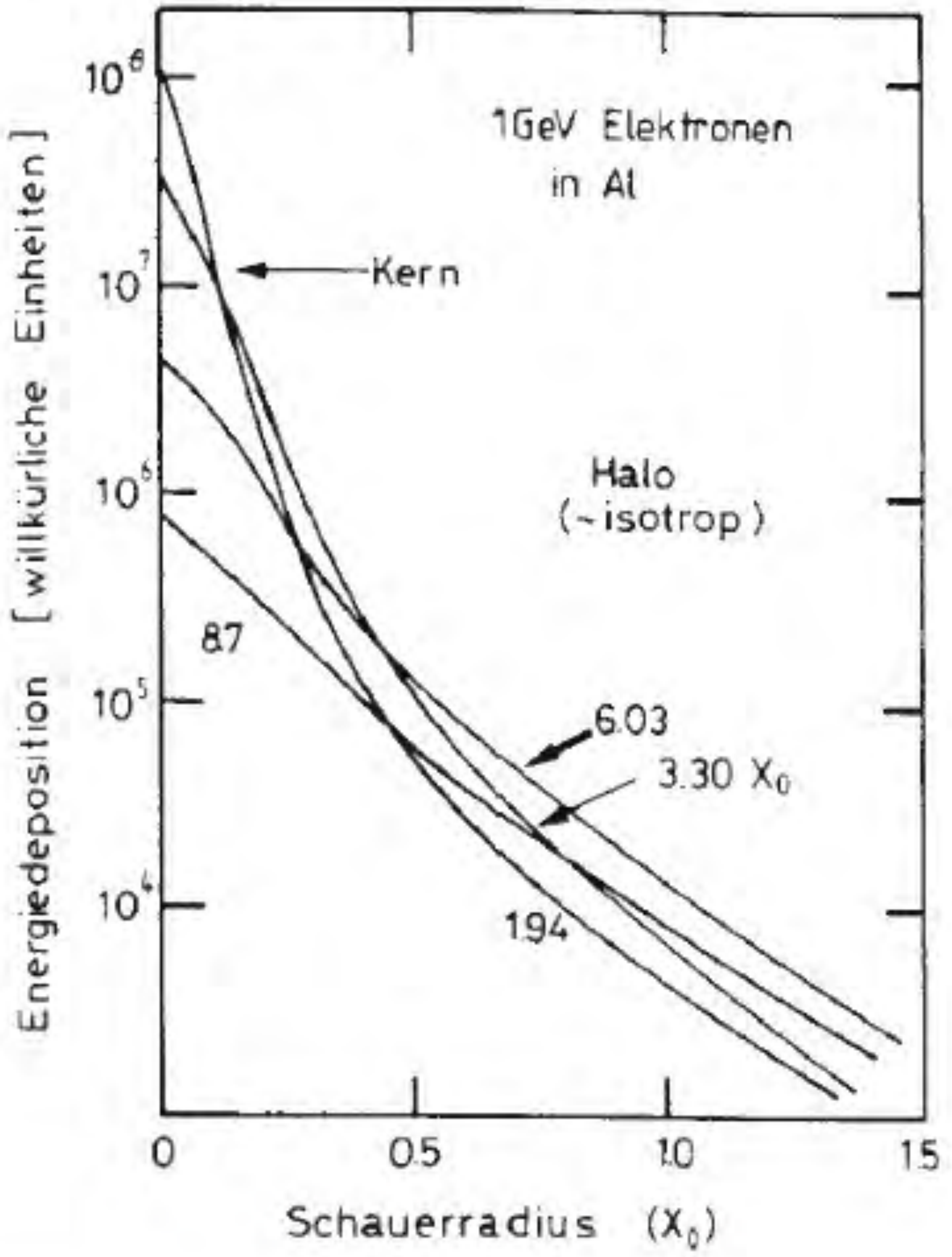
- It is characterized by the so-called Molière radius ρ_M

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

- About 95% of the shower energy are contained within a cylinder with radius r = 2 ρ_M

in general well collimated !

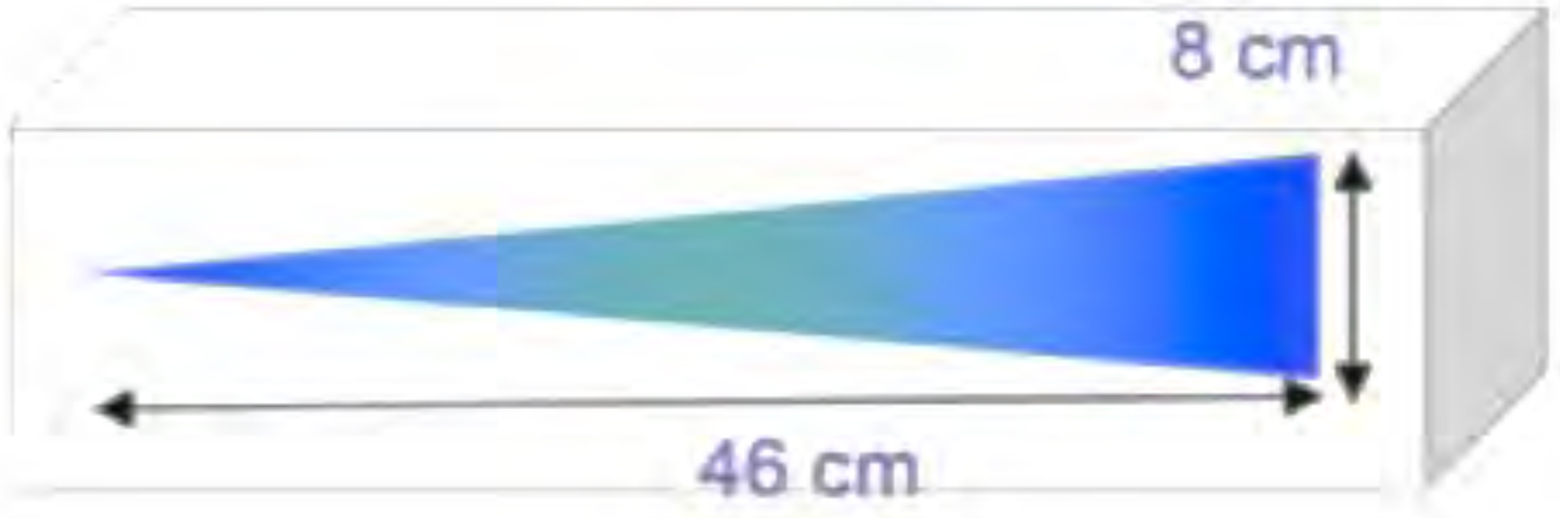
$\rho_M \approx$ 100m at sea level



Example: E_0 = 100 GeV in lead glass

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

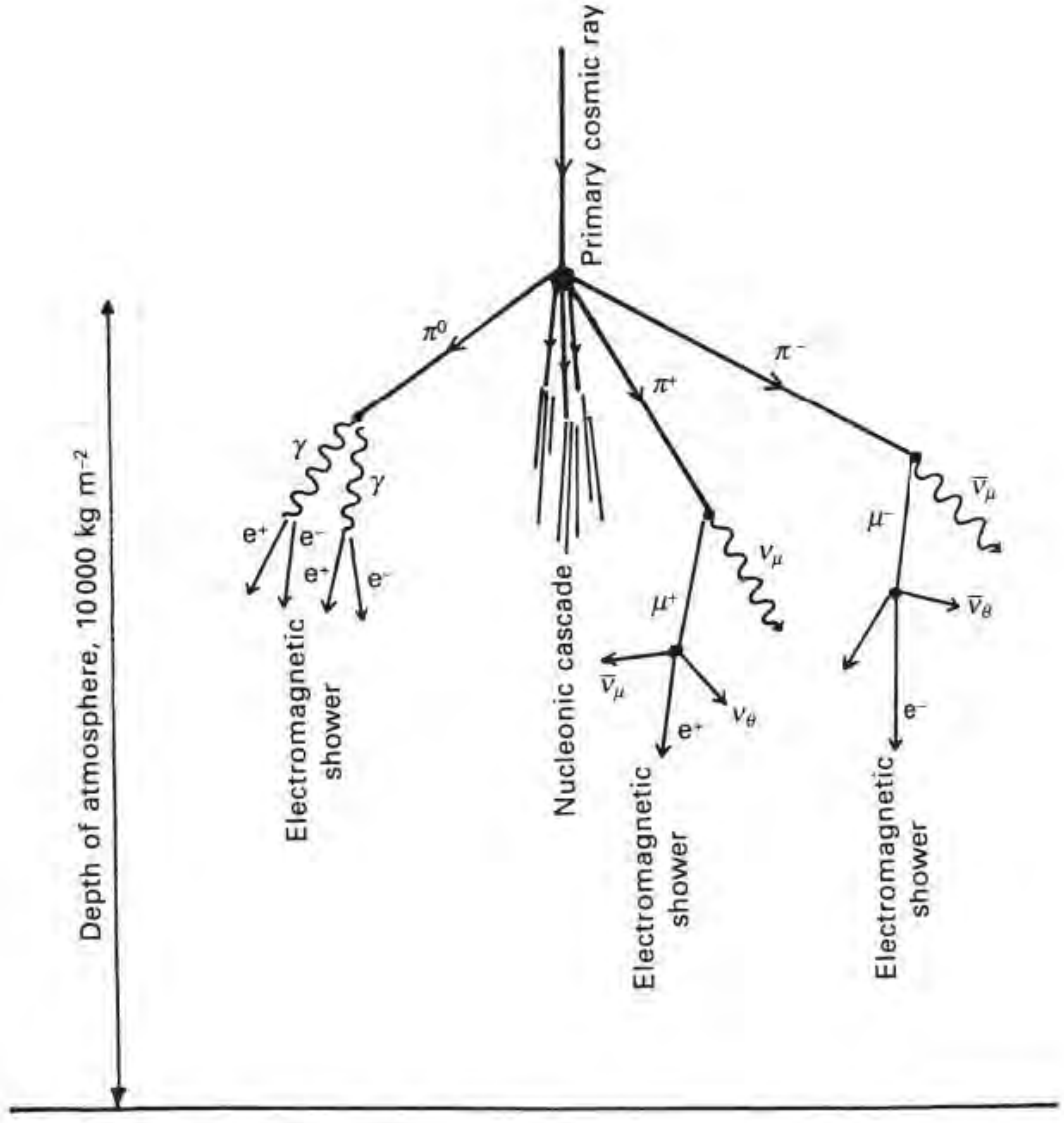
X_0 ≈ 2 cm, R_M= 1.8·X_0 ≈ 3.6 cm



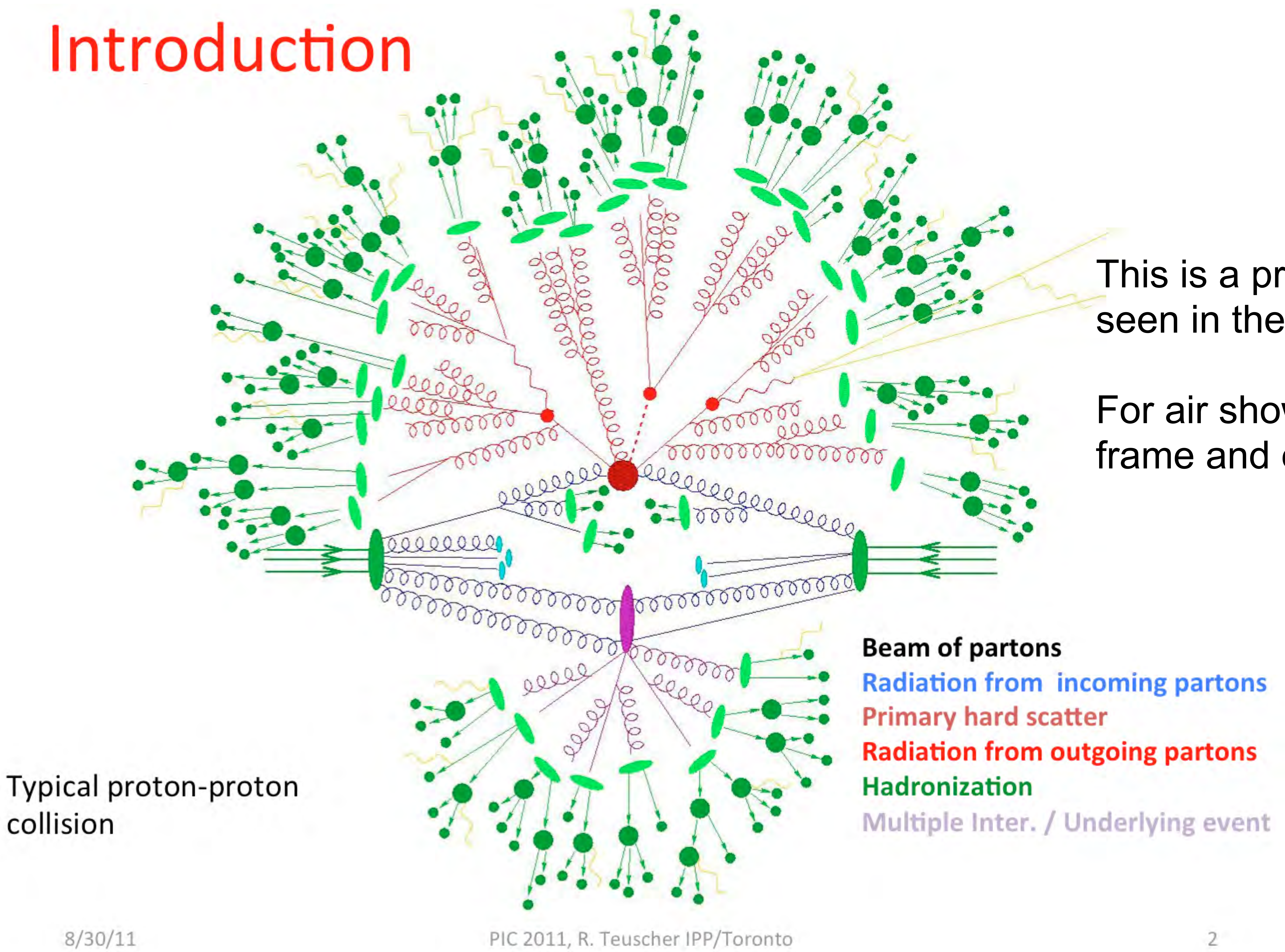
Hadron Induced Air Showers

- 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



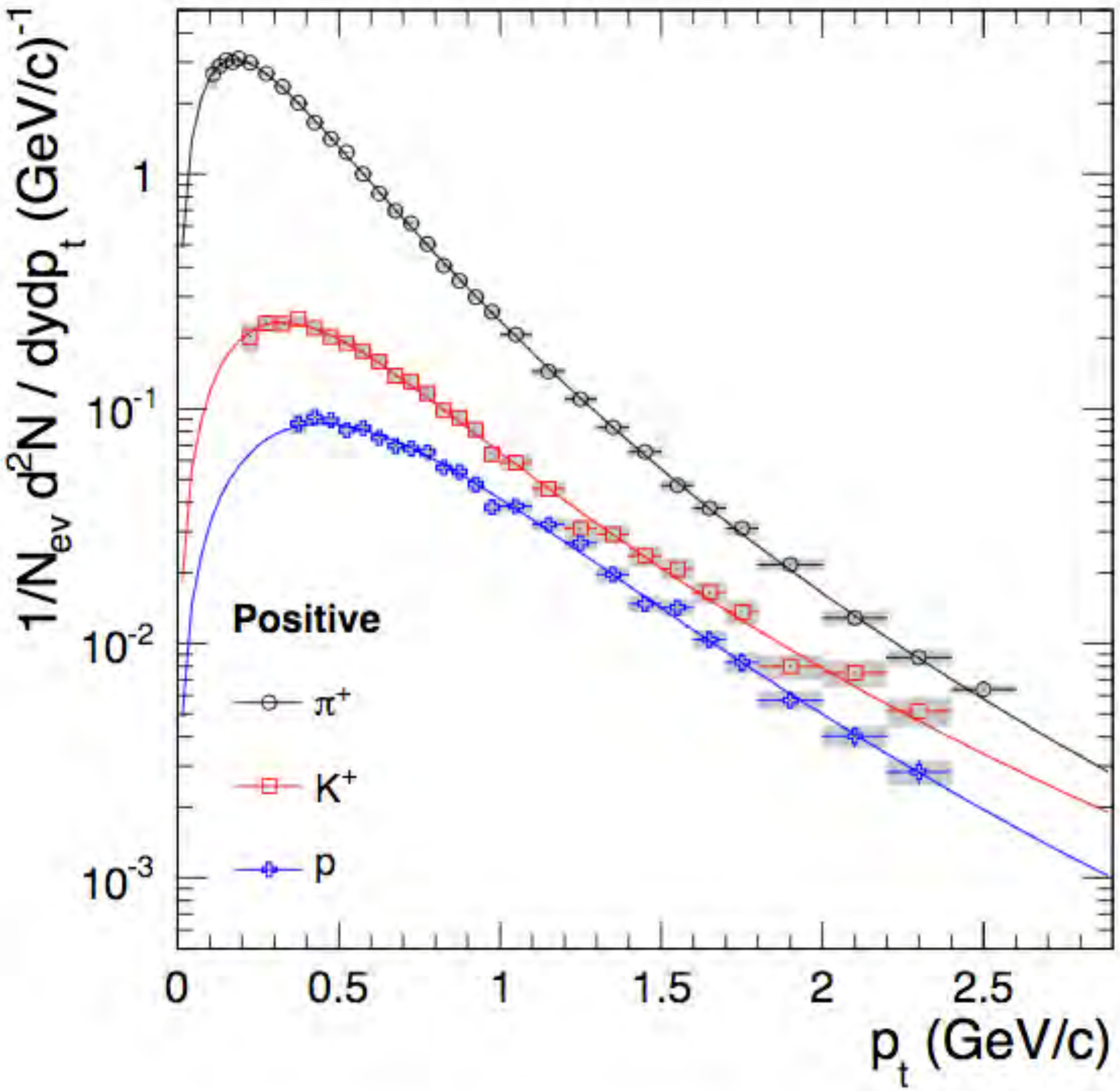
Proton - Proton Collision



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

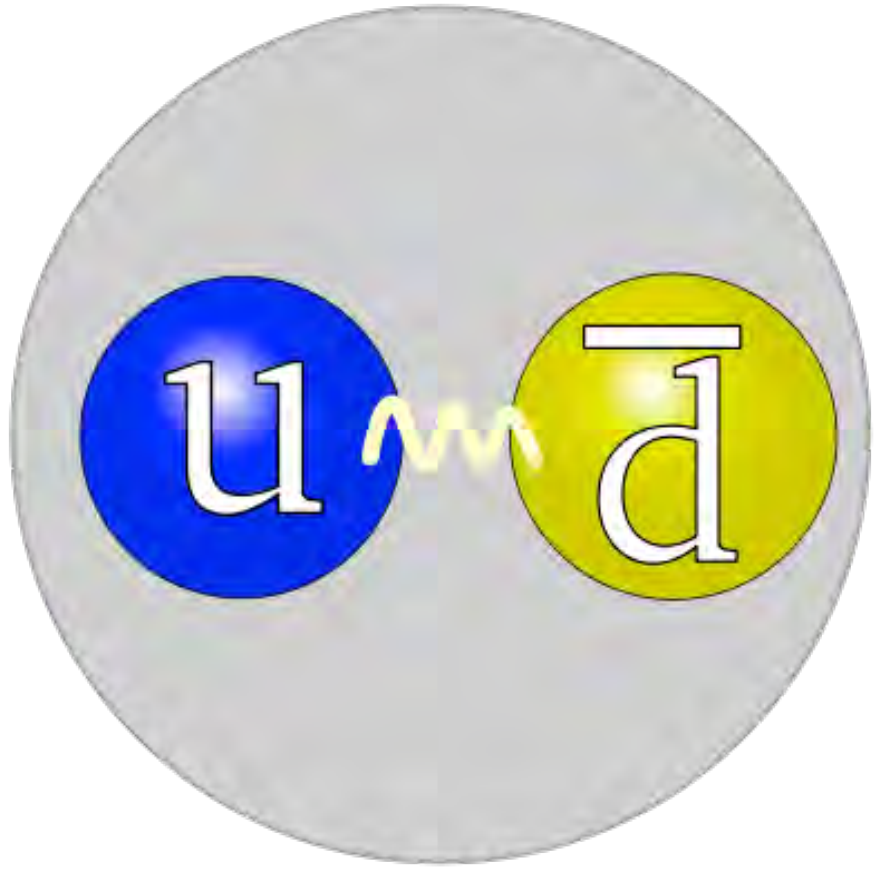
For air showers we are in the lab frame and everything goes forward

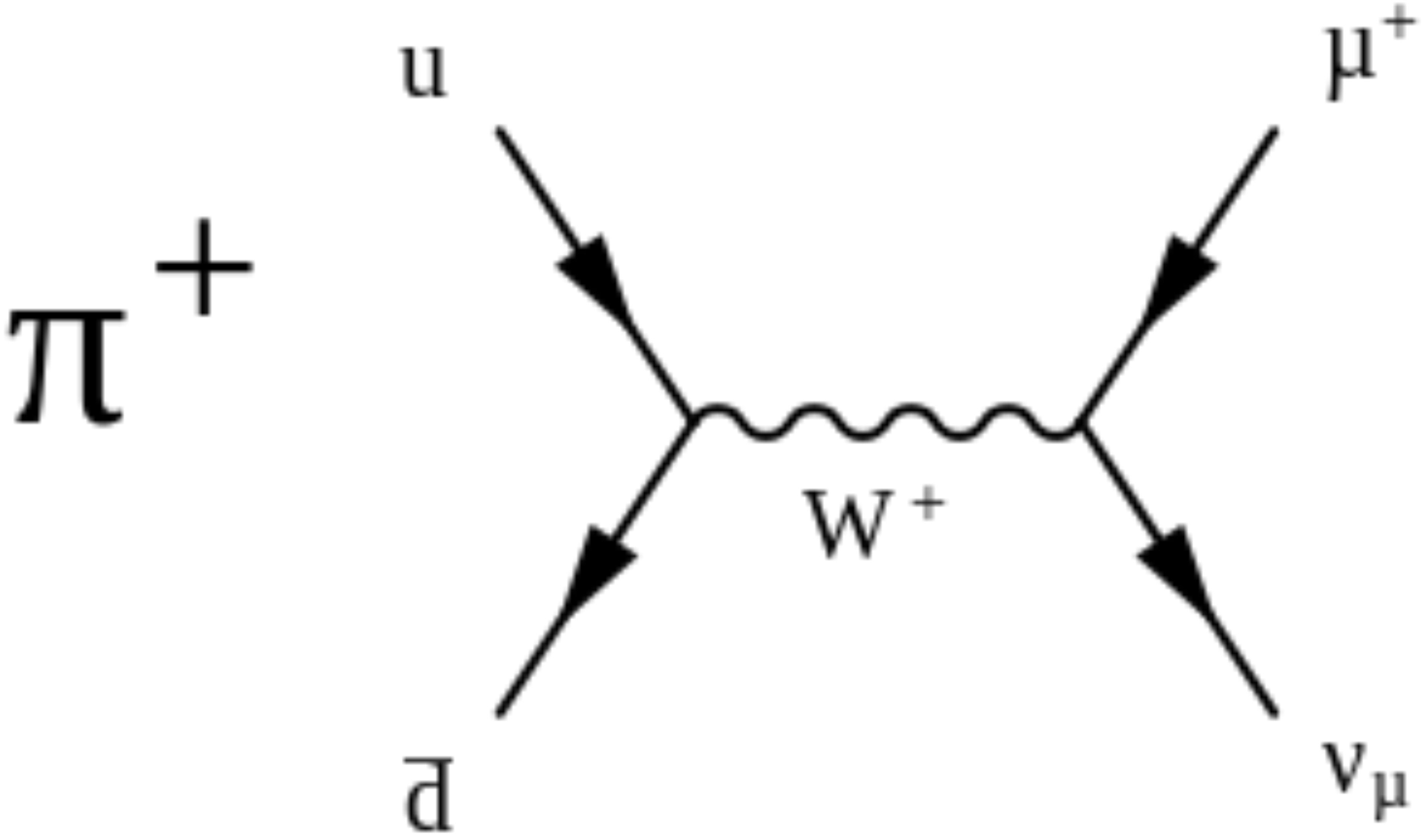
Mostly Pions Produced



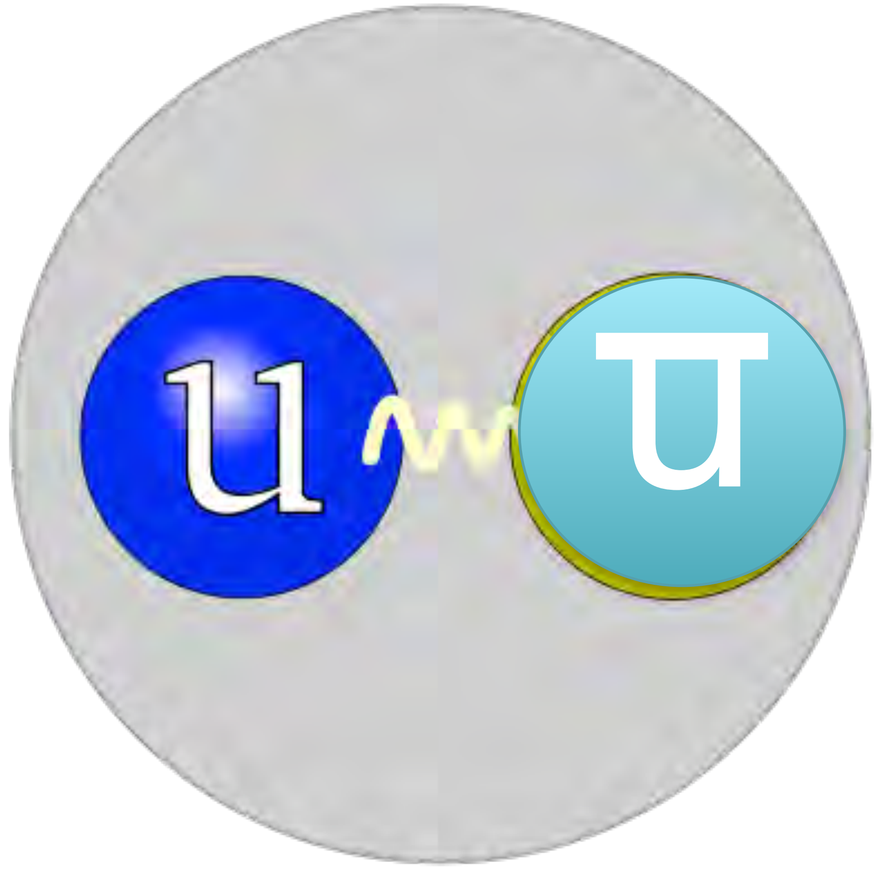
About 90% pions
Equal numbers of
$\pi^+\ \pi^-\ \pi^0$

Charged Pions can either decay or interact

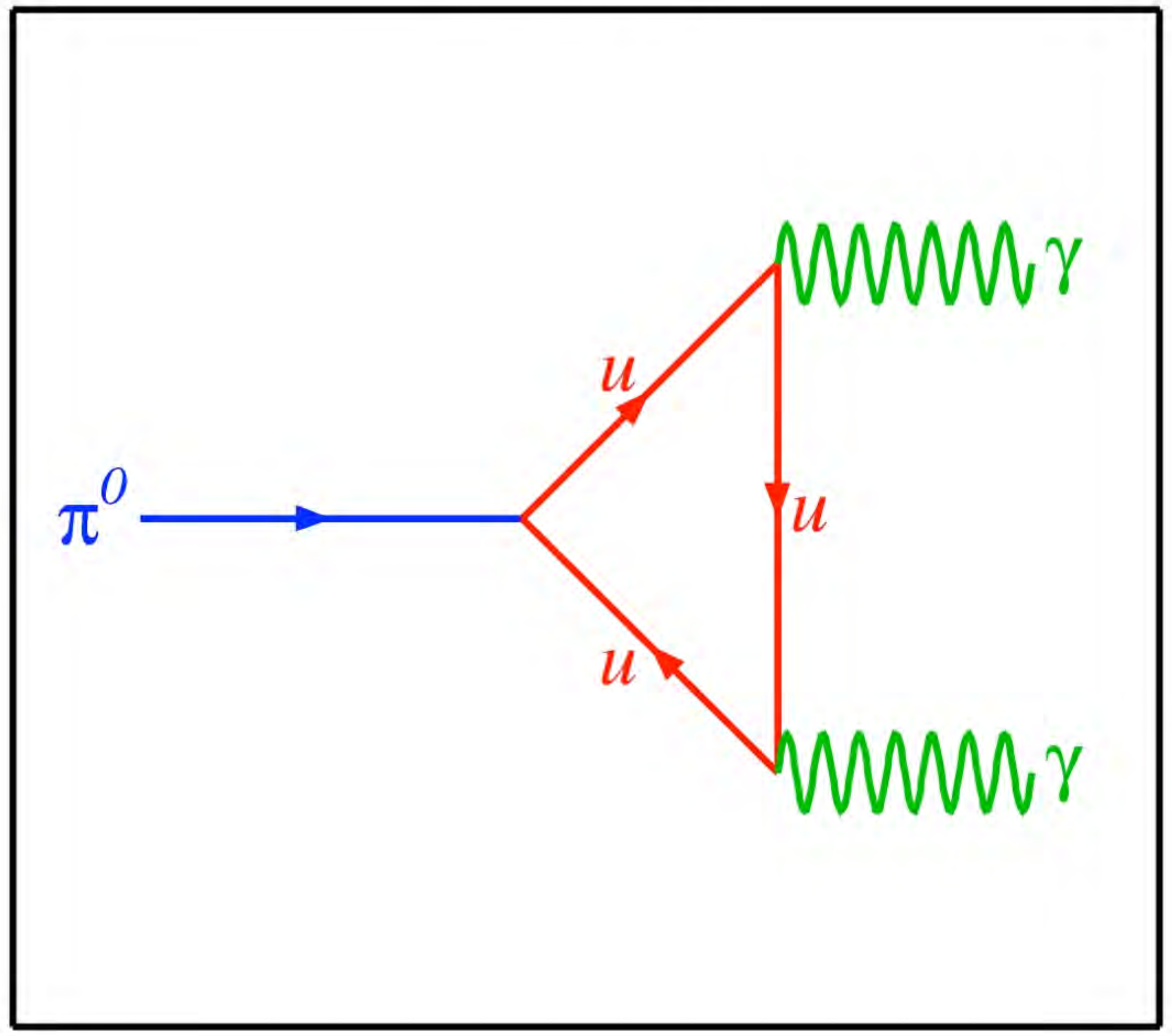




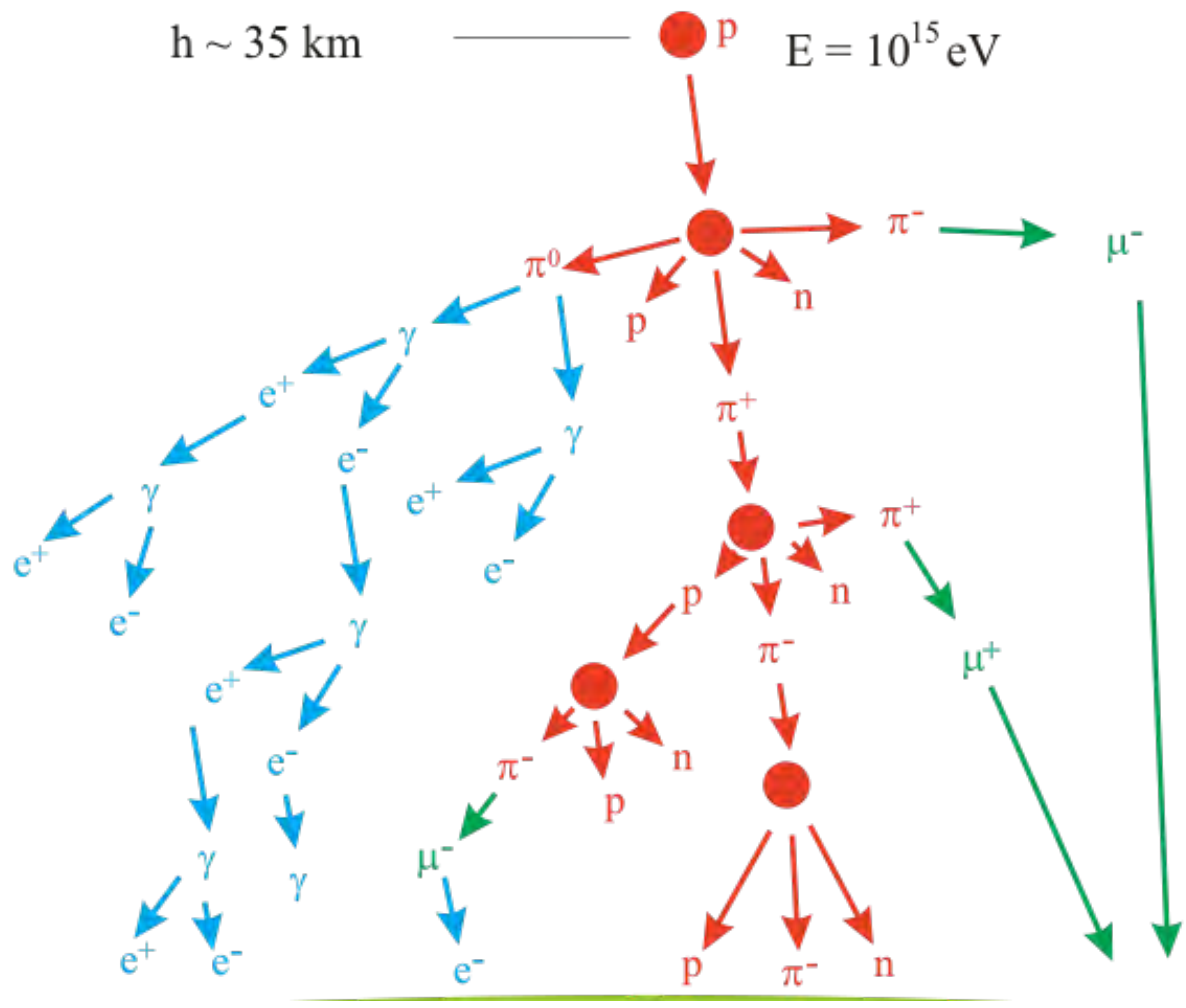
Mass 140 MeV
τ = 2.6x10^{-8}sec
at 14 GeV cτ=800m



π^0 Decay

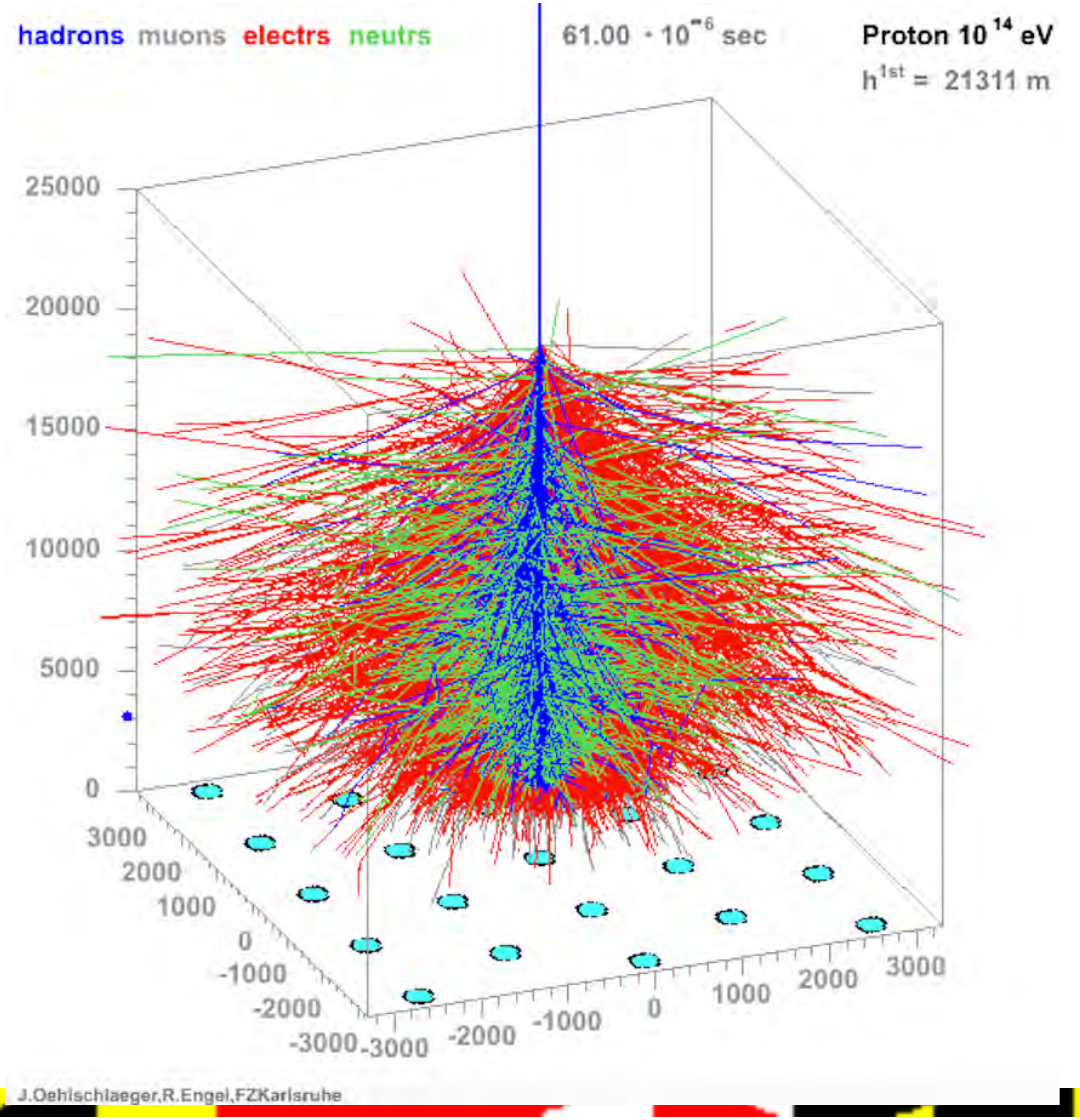


Mass 135 MeV
τ = 8x10^{-17}sec
at 14 GeV cτ=2μm

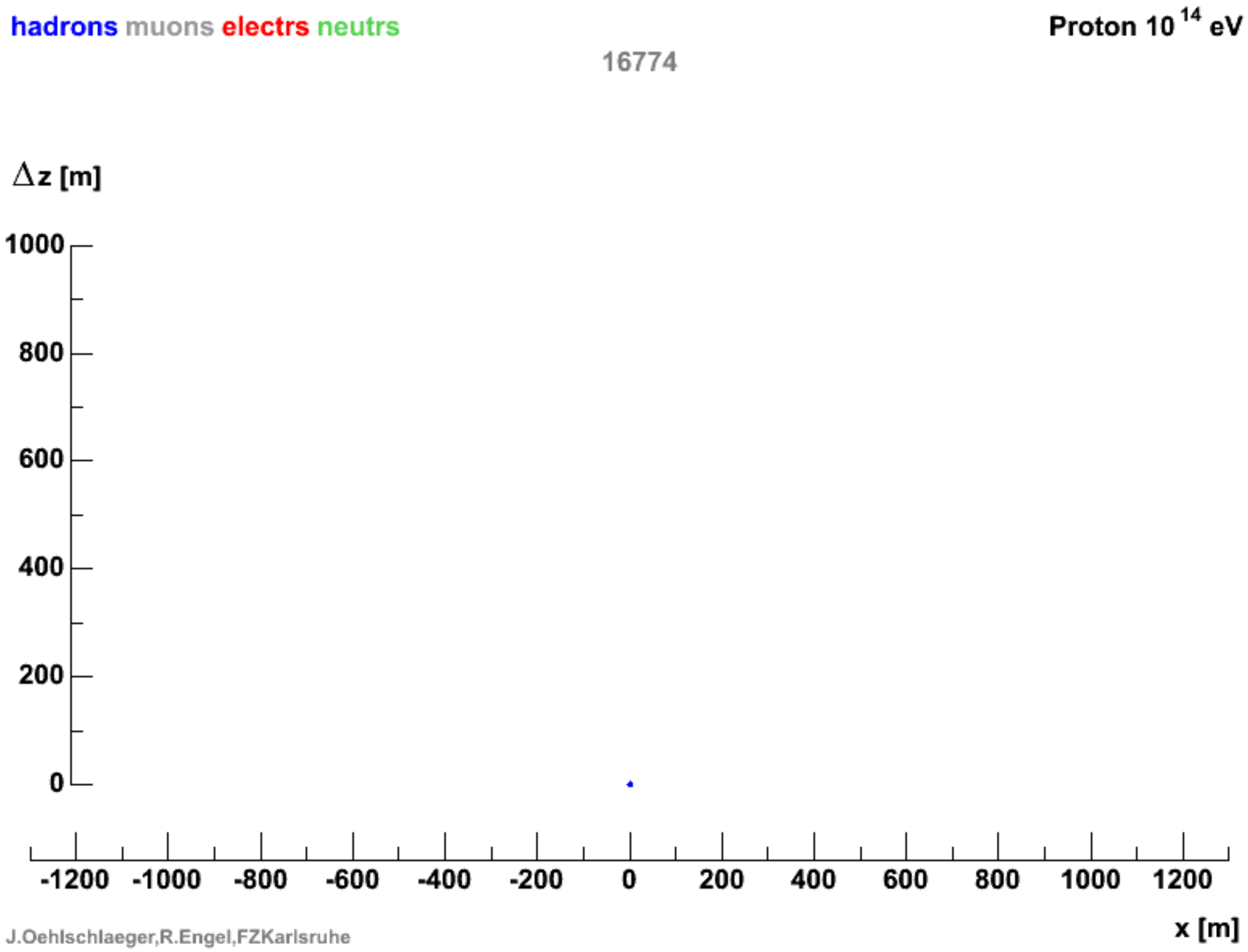


h ~ 35 km
p
E = 10^15 eV
π^-
μ^-
π^0
p
n
γ
π^+
e^+
e^-
γ
e^+
γ
e^+
e^-
π^+
p
n
e^+
e^-
e^-
γ
π^-
μ^+
e^+
e^-
π^-
n
p
μ^-
γ
γ
e^+
e^-
e^-
p
π^-
n

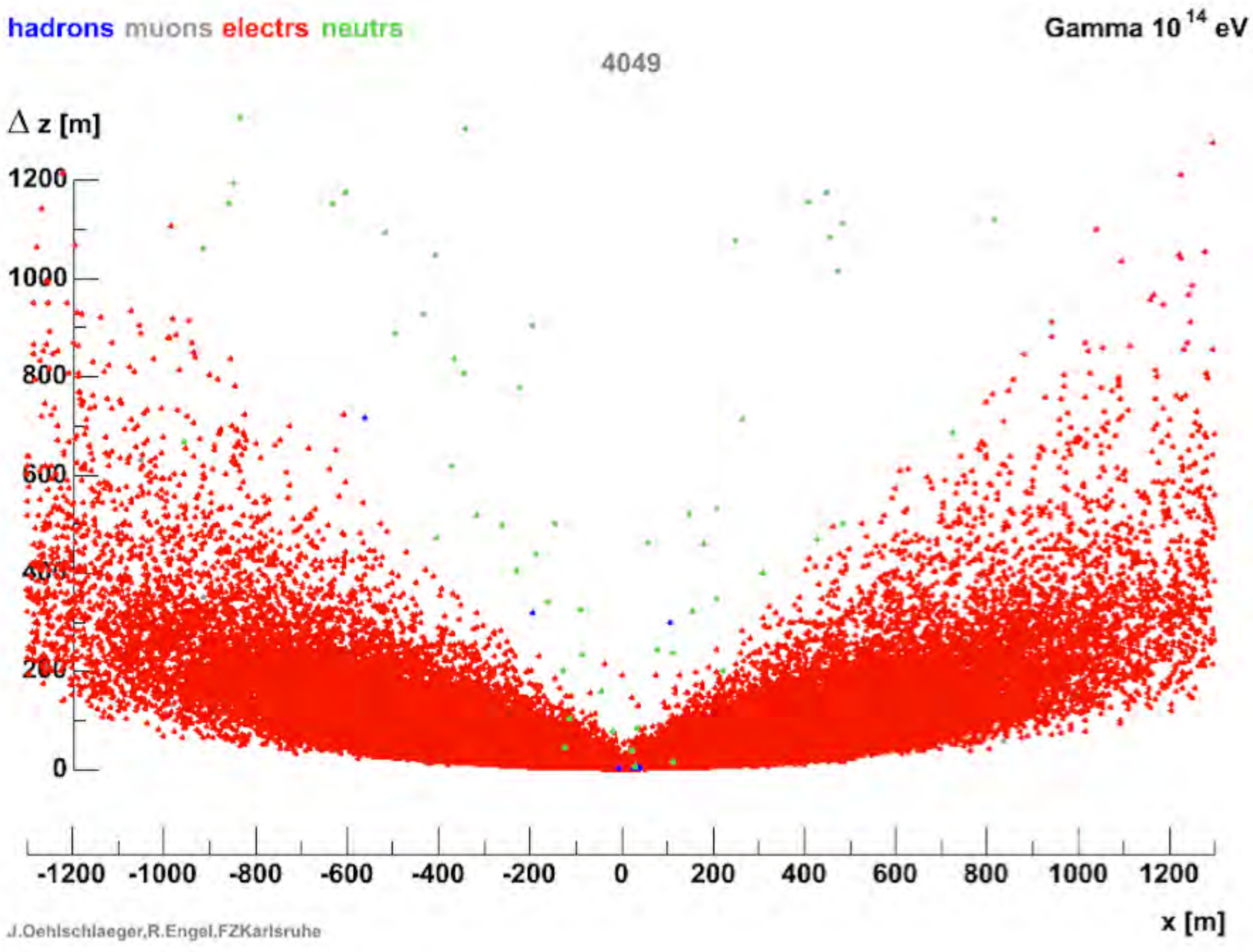
Proton - 100 TeV



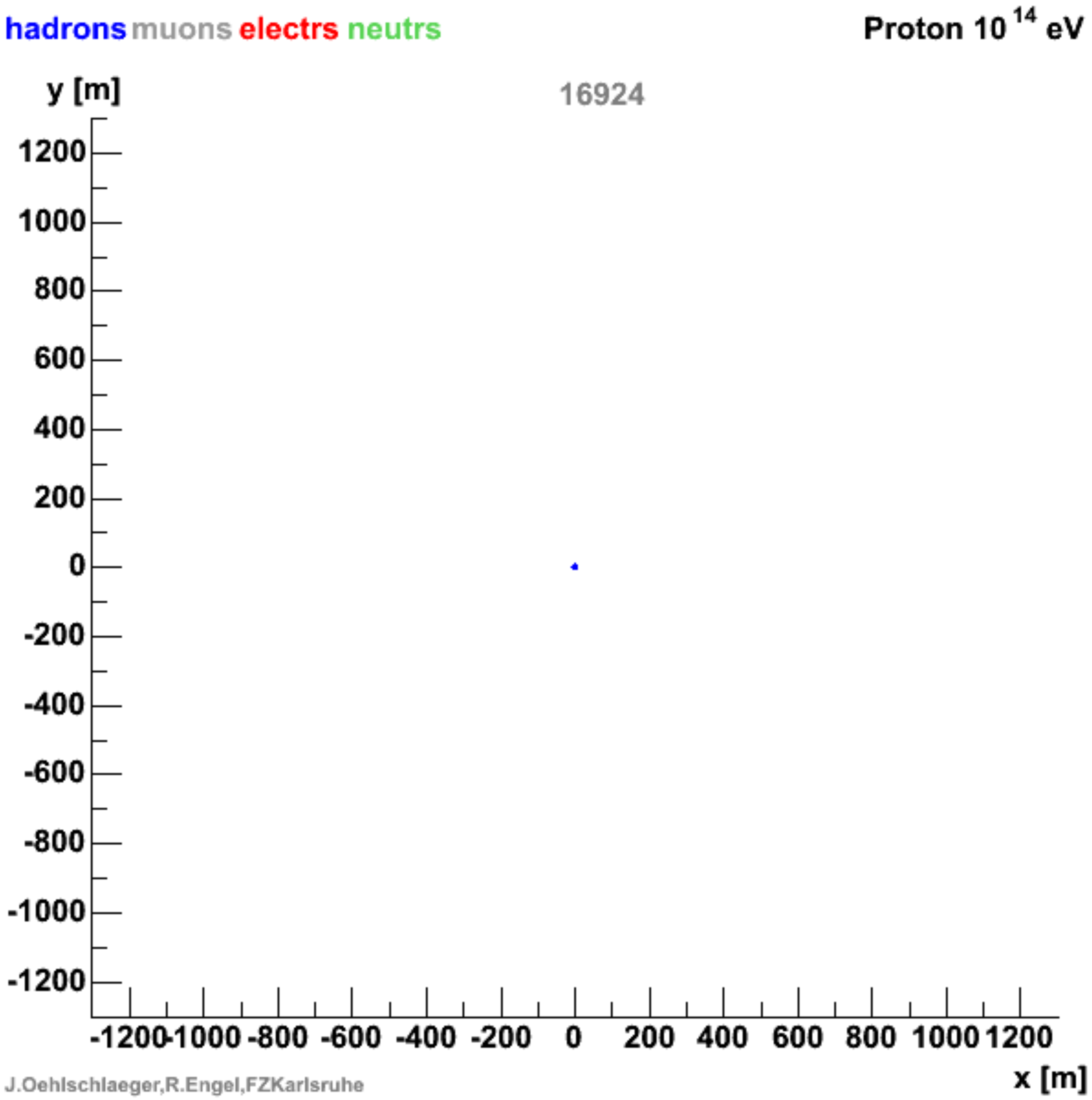
Proton - 100 TeV



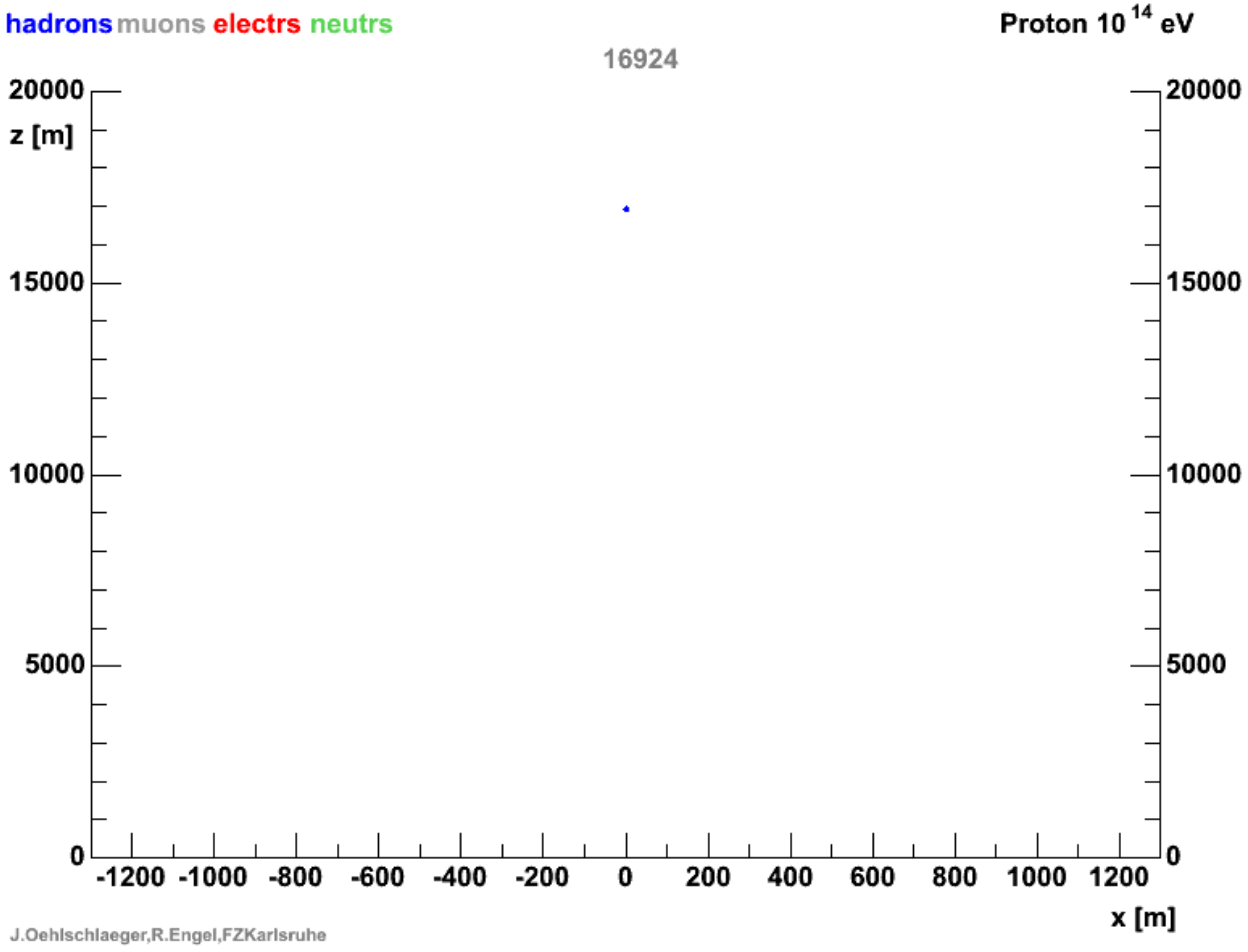
Proton - 100 TeV



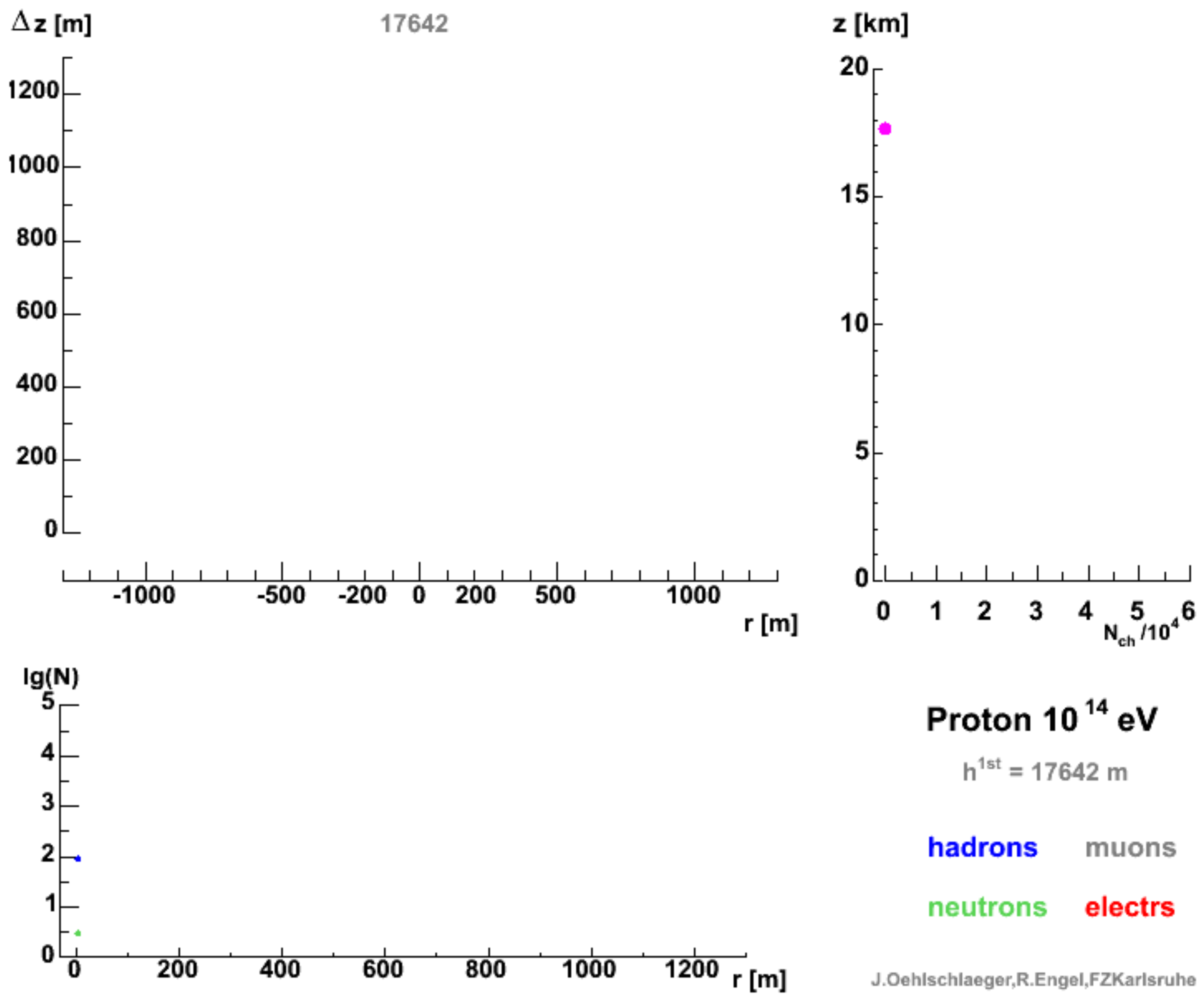
Proton - 100 TeV



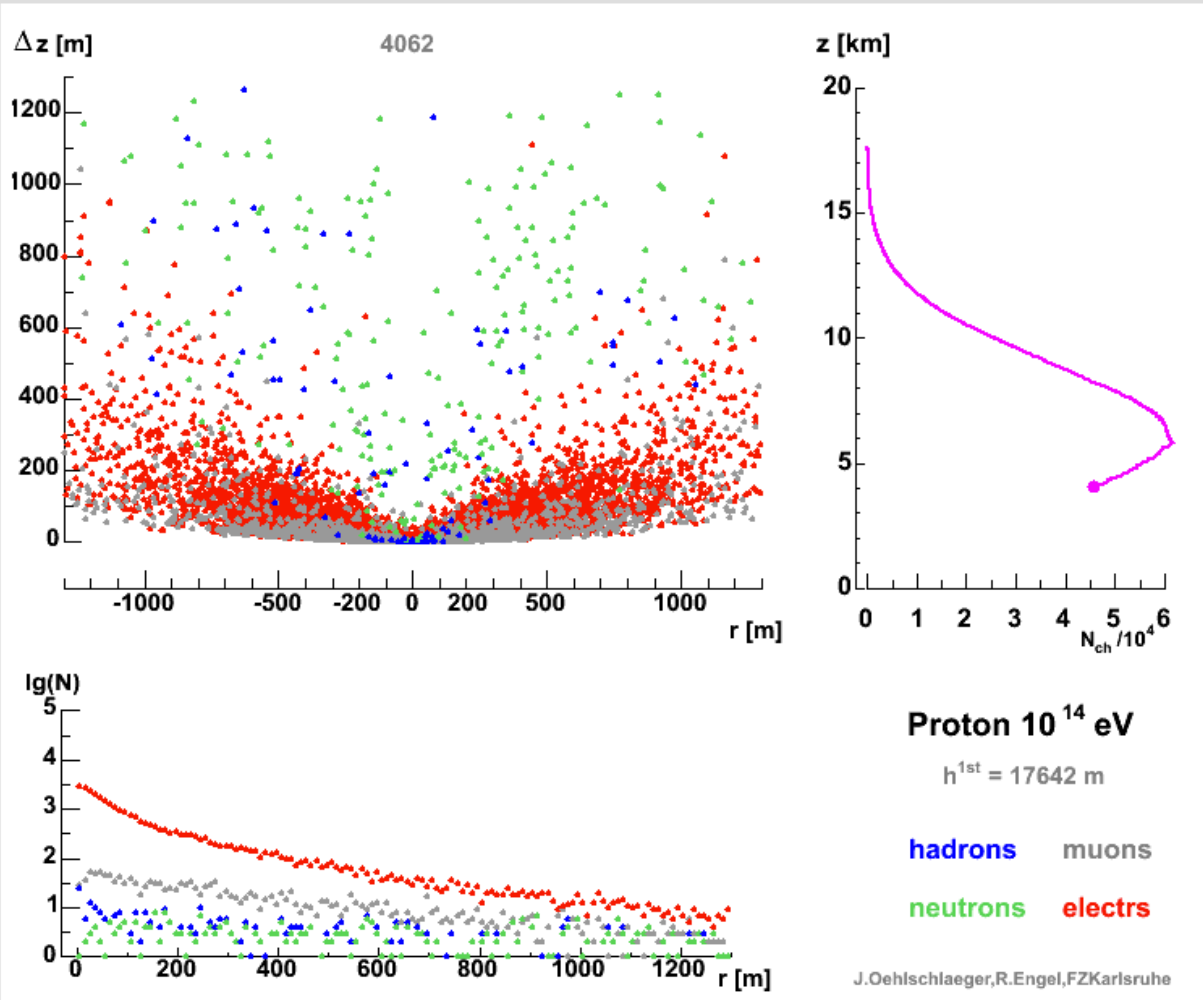
Proton - 100 TeV



Proton - 100 TeV

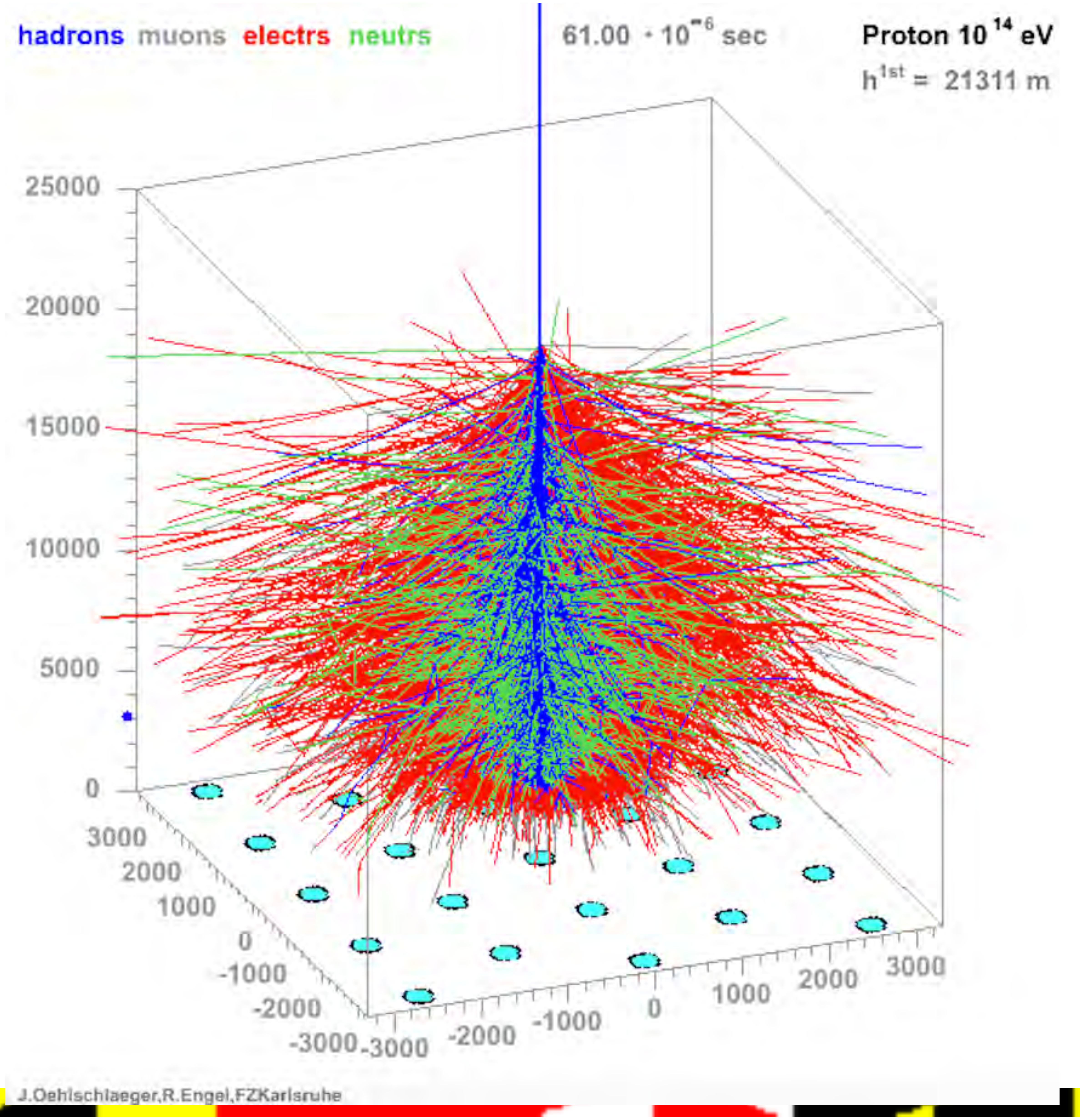


Proton - 100 TeV



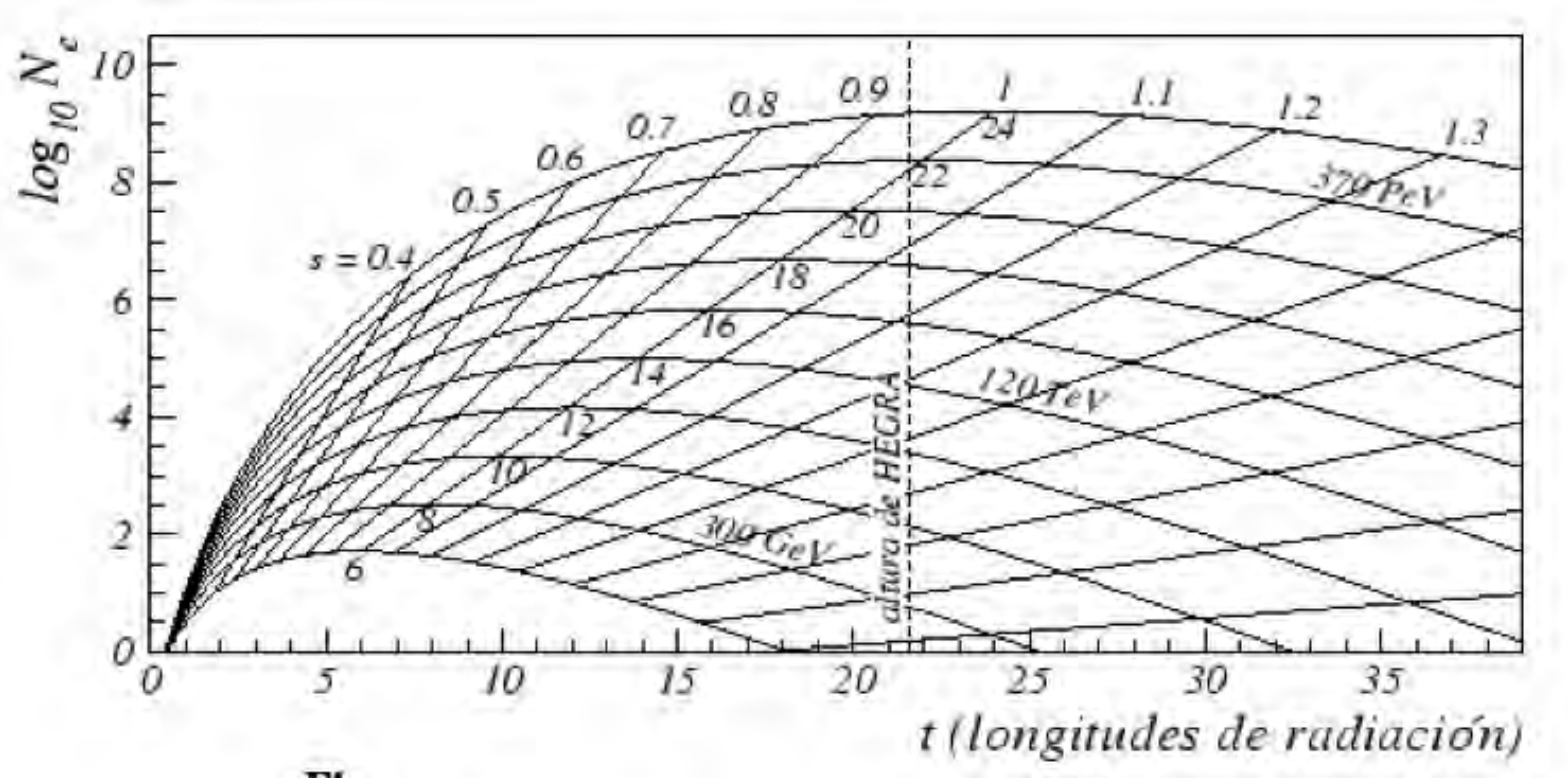
Proton - 100 TeV

Proton - 100 TeV



Electromagnetic Showers

- For 2 TeV gamma ray in the atmosphere
  - Ln (2×10^6 MeV/80 MeV)/Ln(2) = 14.6 r.l.
  - r.l. in air is $37 gm/cm^2$
  - Cascade max is at $540 gm/cm^2$



The Atmosphere

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

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

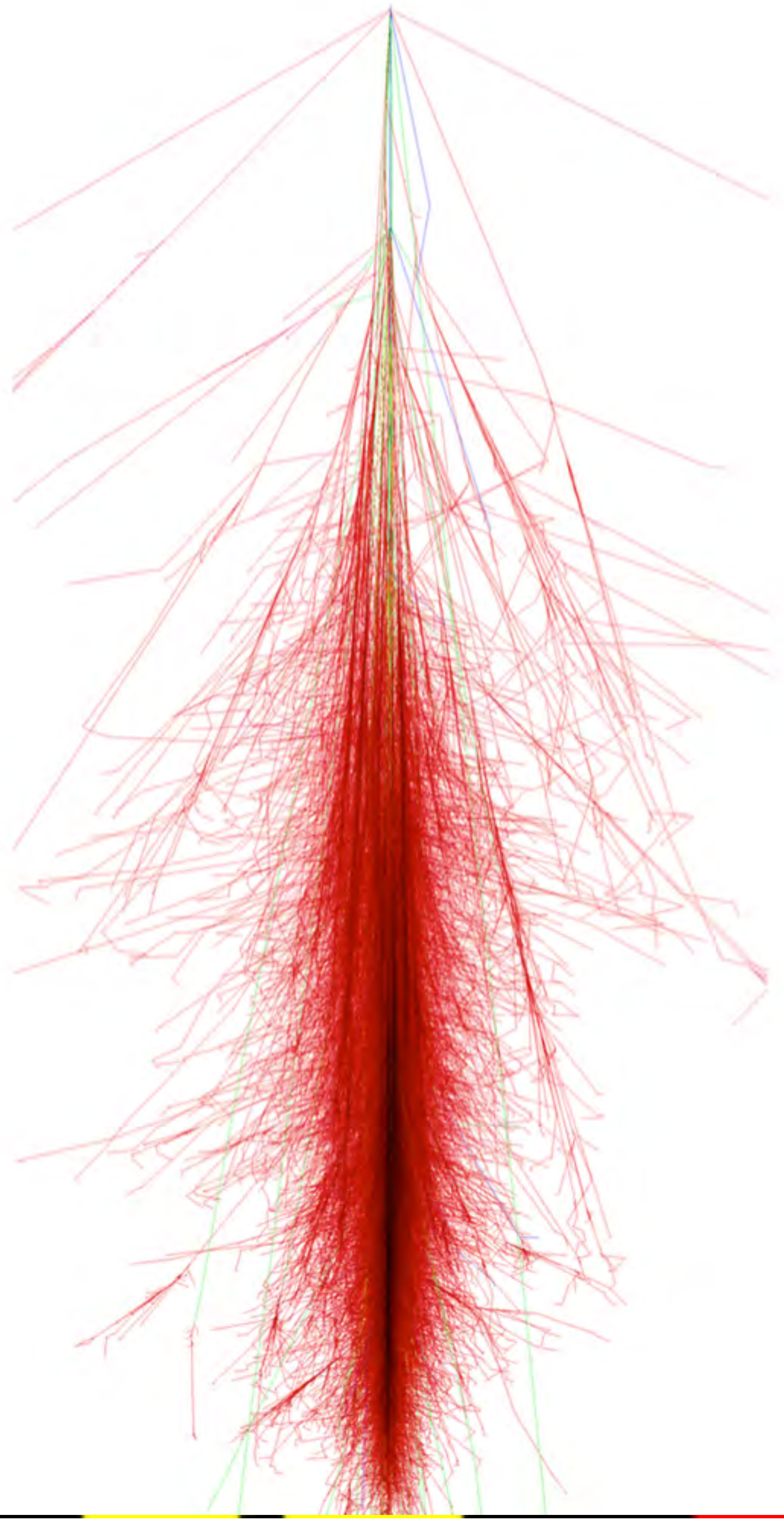
- Isothermal atmosphere

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

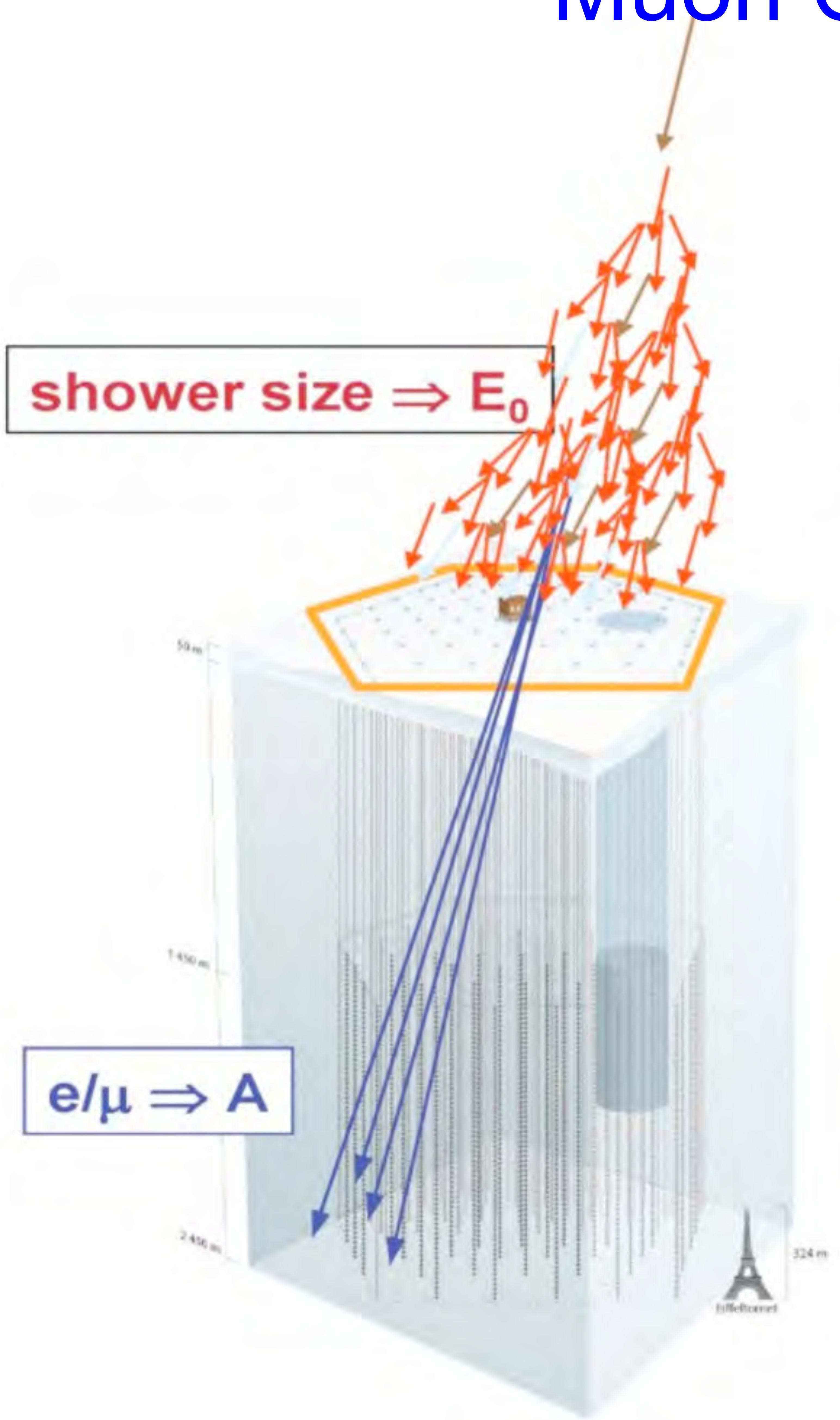
- Where h_0 = 7km, P_0 = 101kPa, and X_0 =1000g/cm^2.
- So X=540 -> ln (P_0/P) = -h/h_0
- h_{max} ~ 4.7km a.s.l. (a little above HAWC)
  - HAWC measures more than e^+e^-
  - Because r.l. in water is 37gm/cm^2 photons convert ~1'

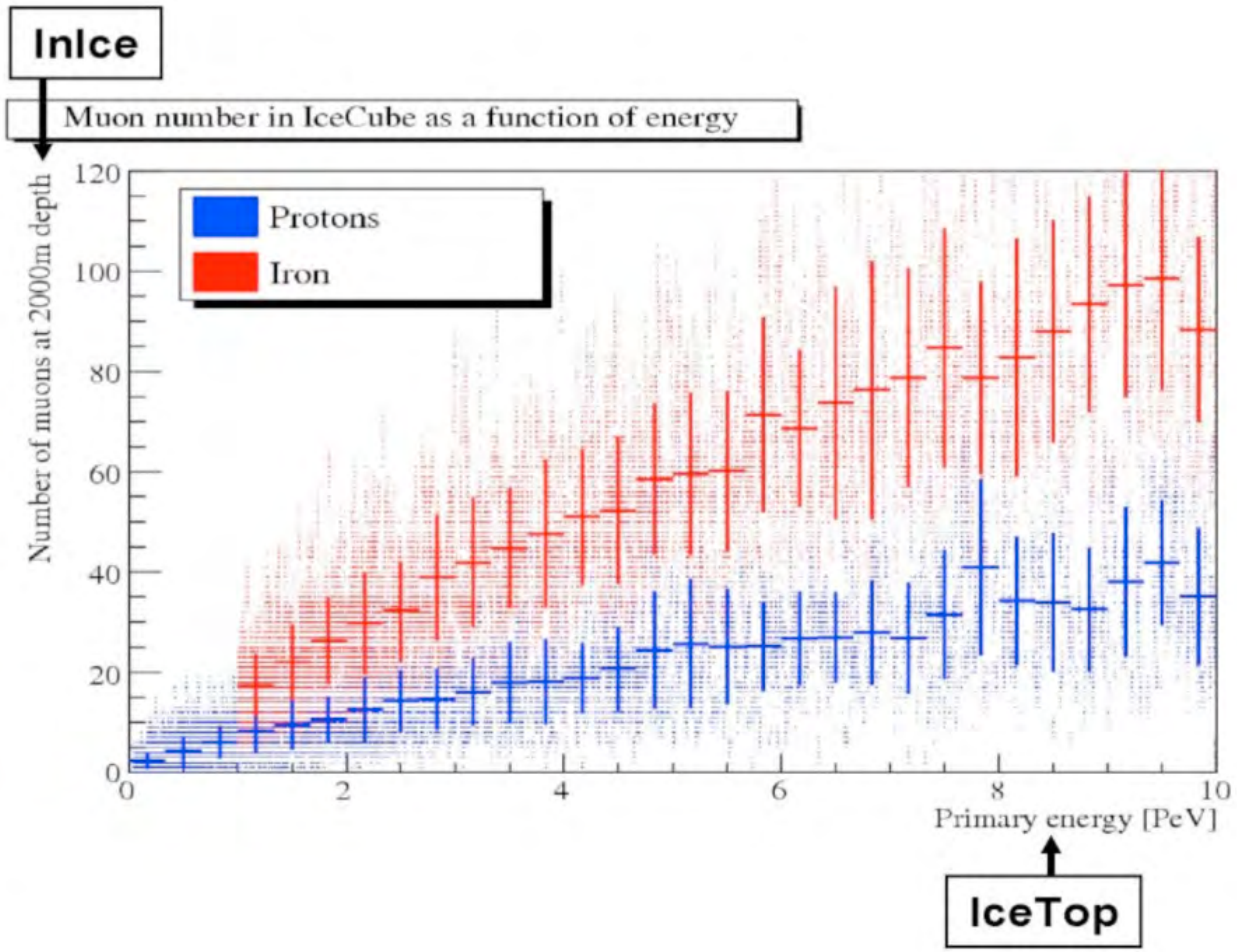
Hadronic Showers

- 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

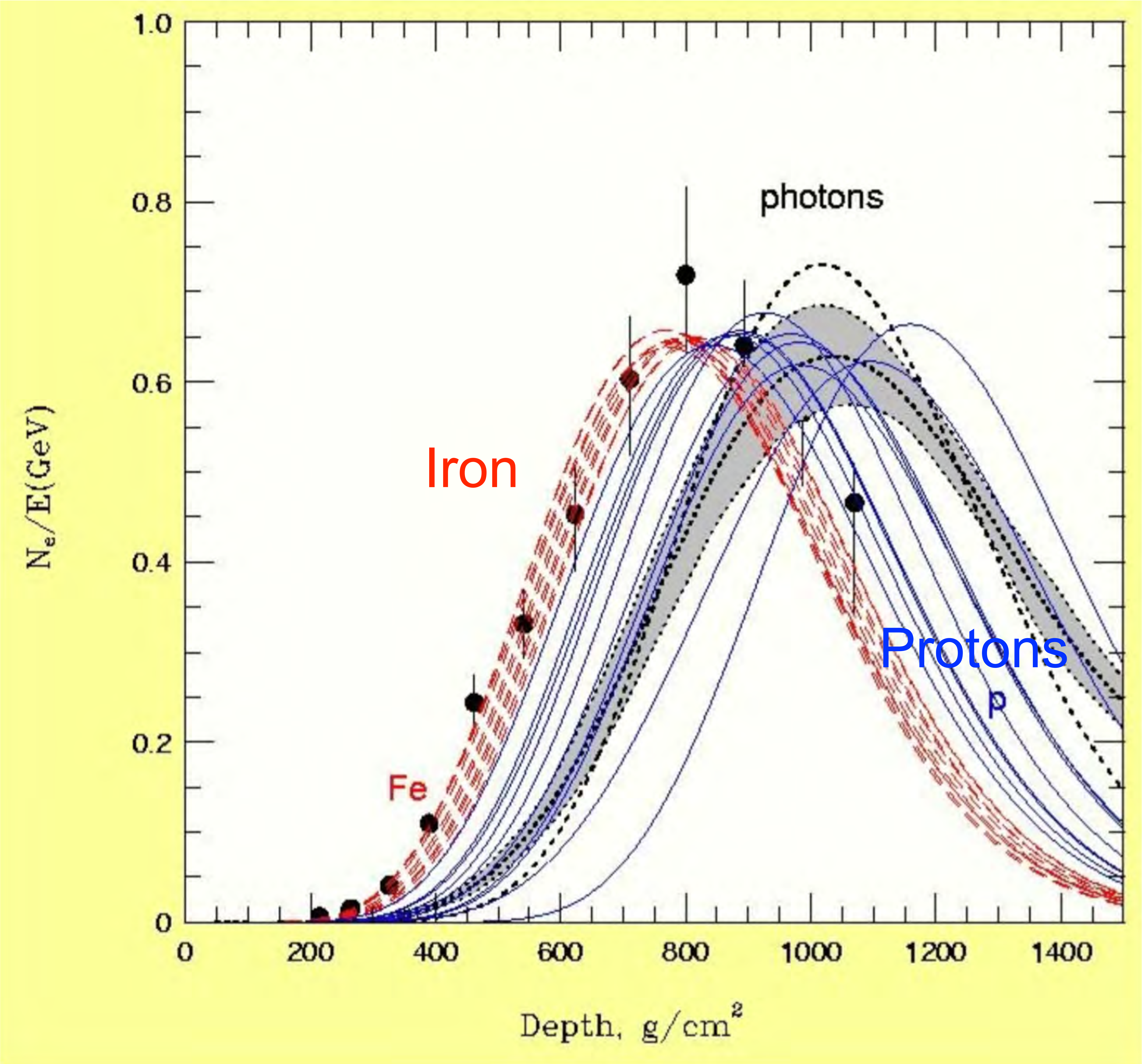


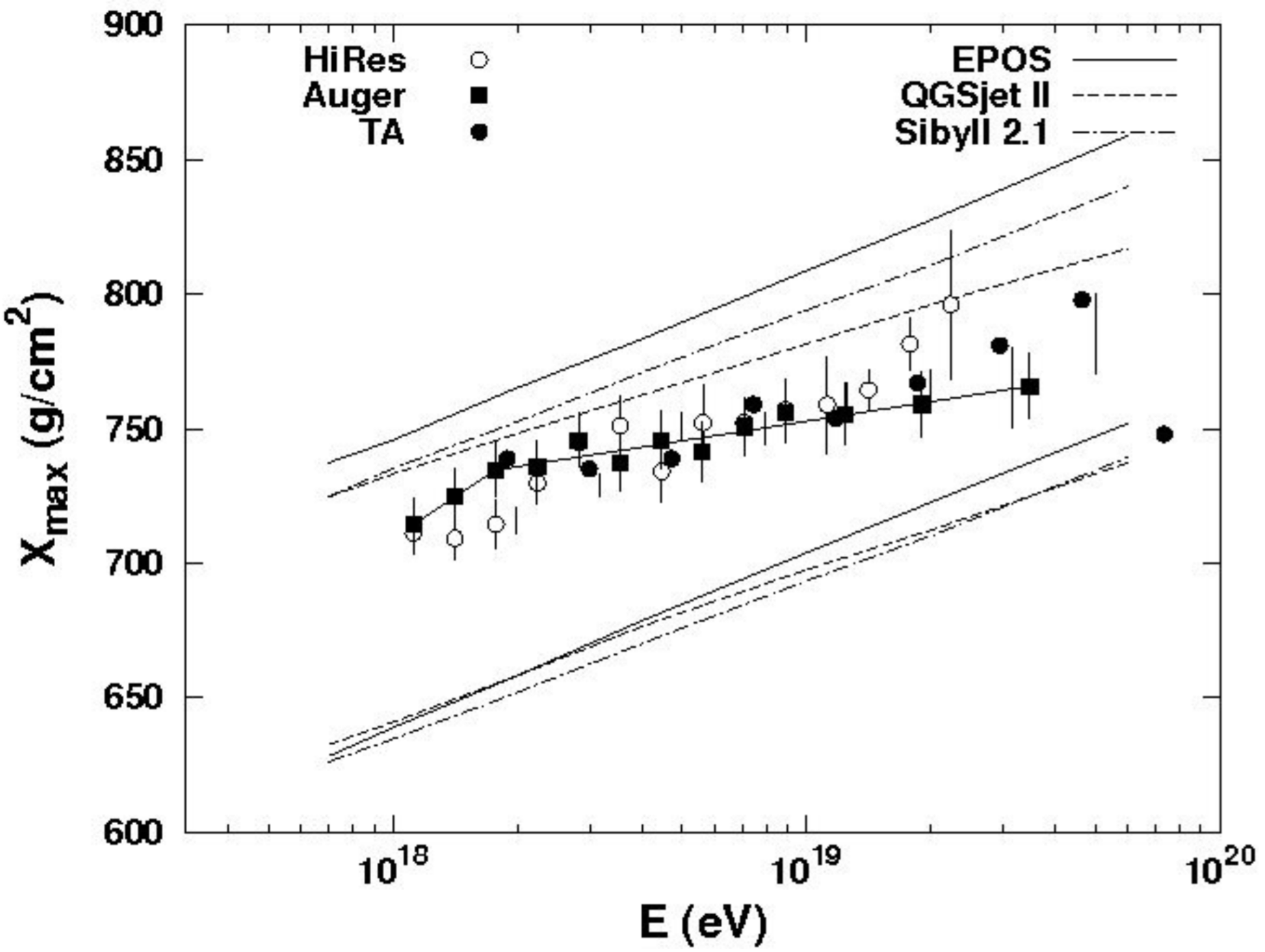
Muon Content vs Primary





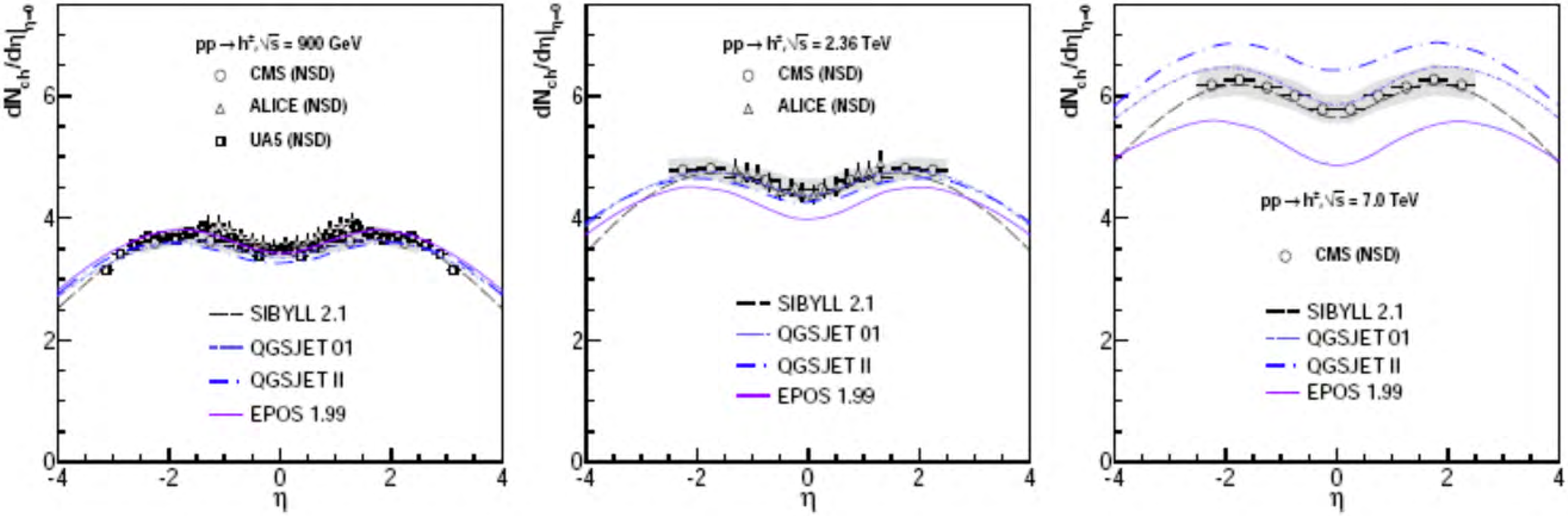
Depth of Shower Maximum





HiRes
Auger
TA
EPOS
QGSjet II
Sibyll 2.1
X_{max} (g/cm^2)
900
850
800
750
700
650
600
10^{18}
10^{19}
10^{20}
E (eV)

Physics models and LHC data

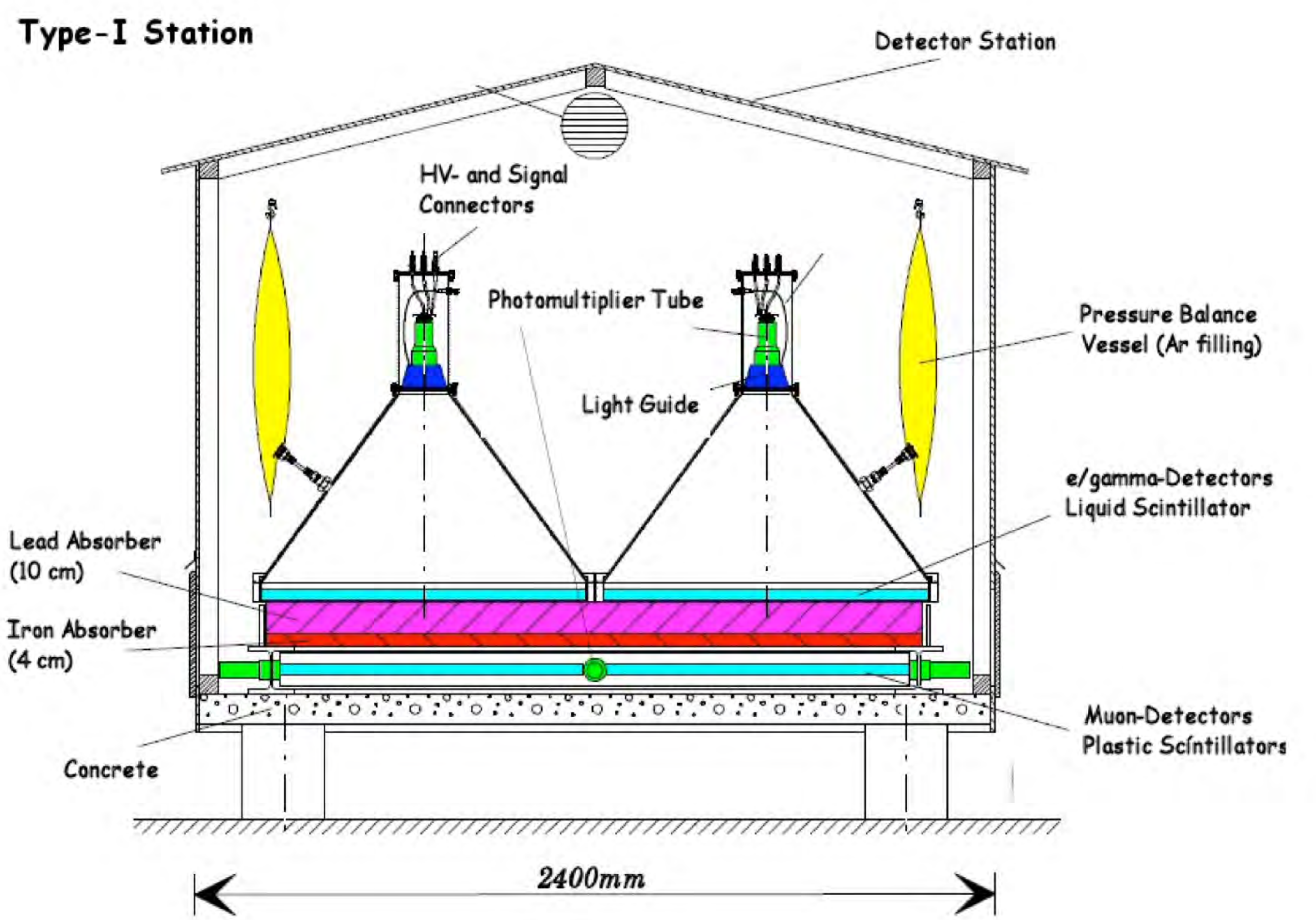


Air shower development depends mostly on the forward region that is not measured in collider experiments.

Air Shower Detectors

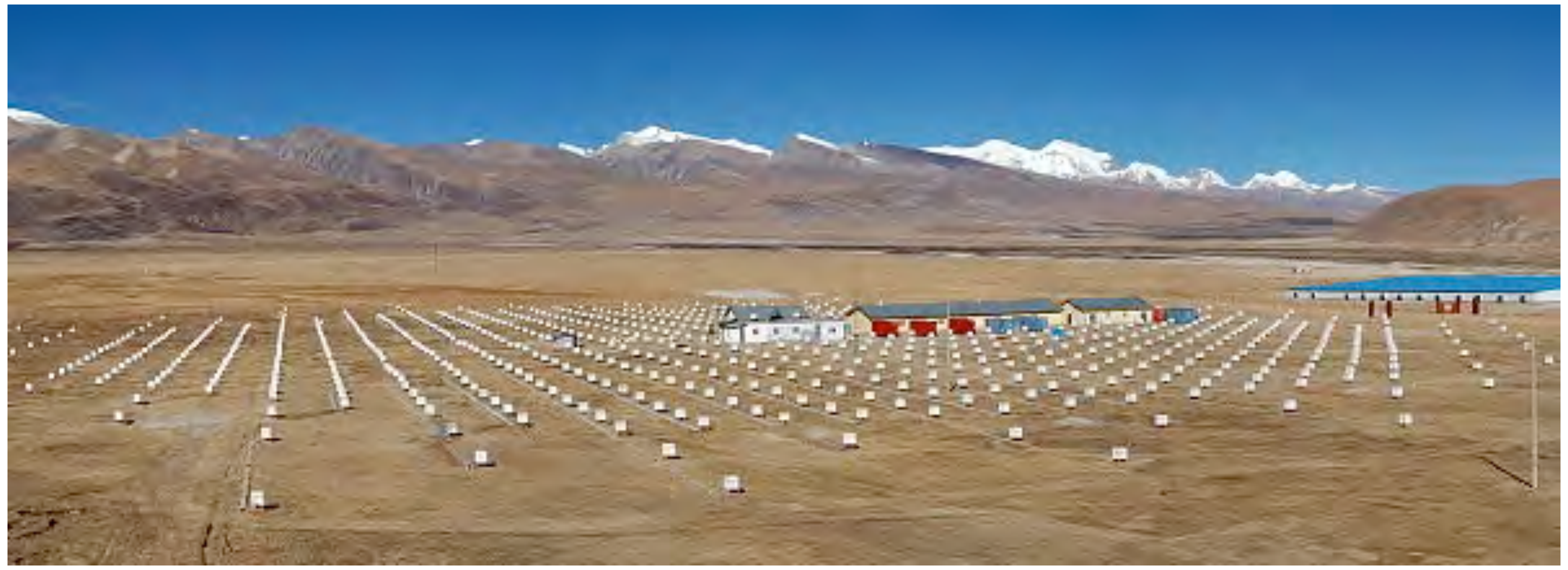
- Basically five types of detectors - some are used in combination
  - Scintillator Arrays
  - Fluorescence Detectors (FDs)
  - Resistive Plate Carpets
  - Water Cherenkov Detectors
  - Imaging Atmosphere Cherenkov Detectors (IACTs)
- Night Sky Detectors - IACTs, FDs
  - 10-15% duty factor
  - IACTs 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

EAS Detectors - Scintillators
KASCADE Grande (Karlsruhe / Germany)



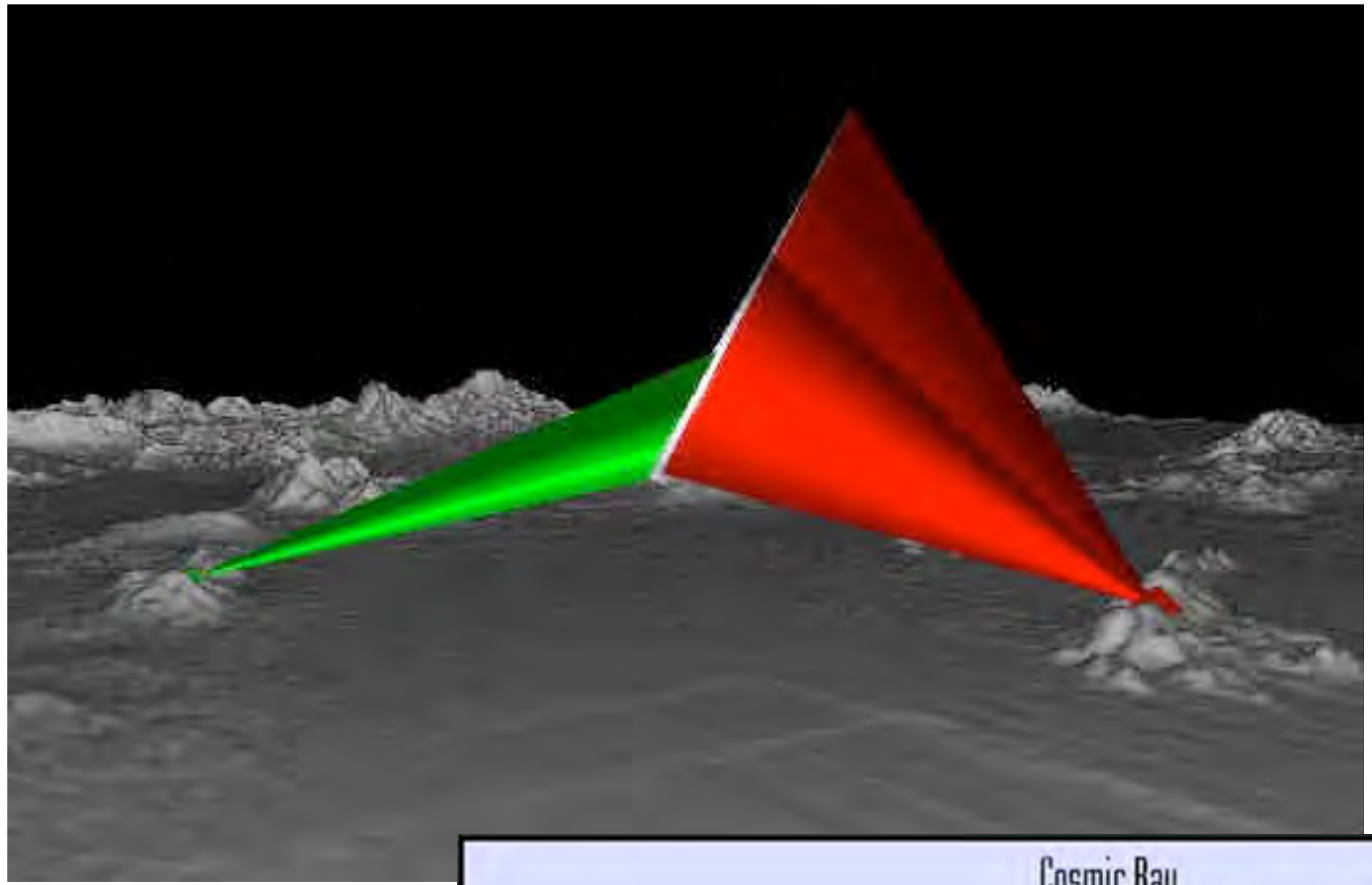
Energy Range 100 TeV - 200 PeV

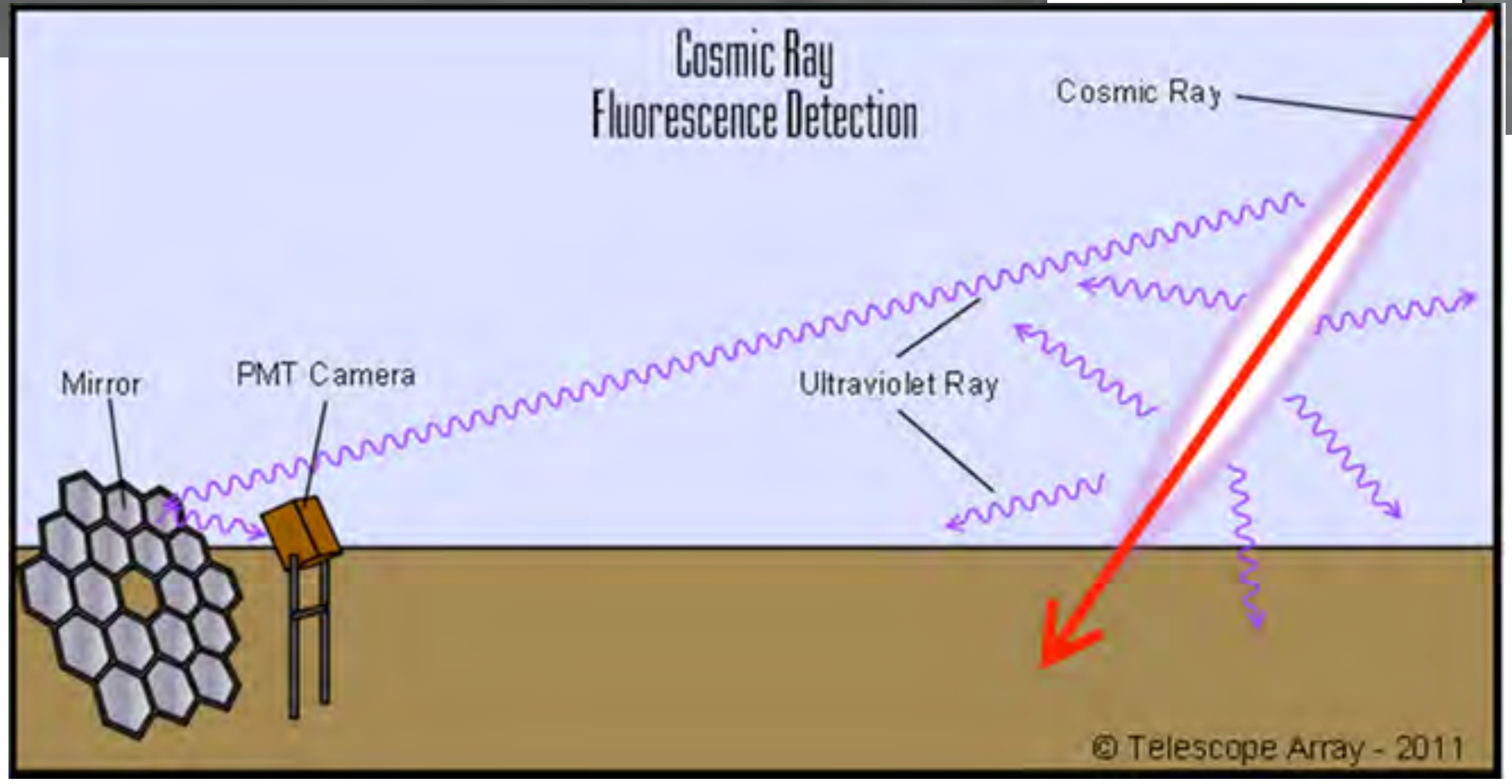
EAS Detectors - Scintillators
EAS -γ Tibet



Energy Range 3TeV - 10 PeV

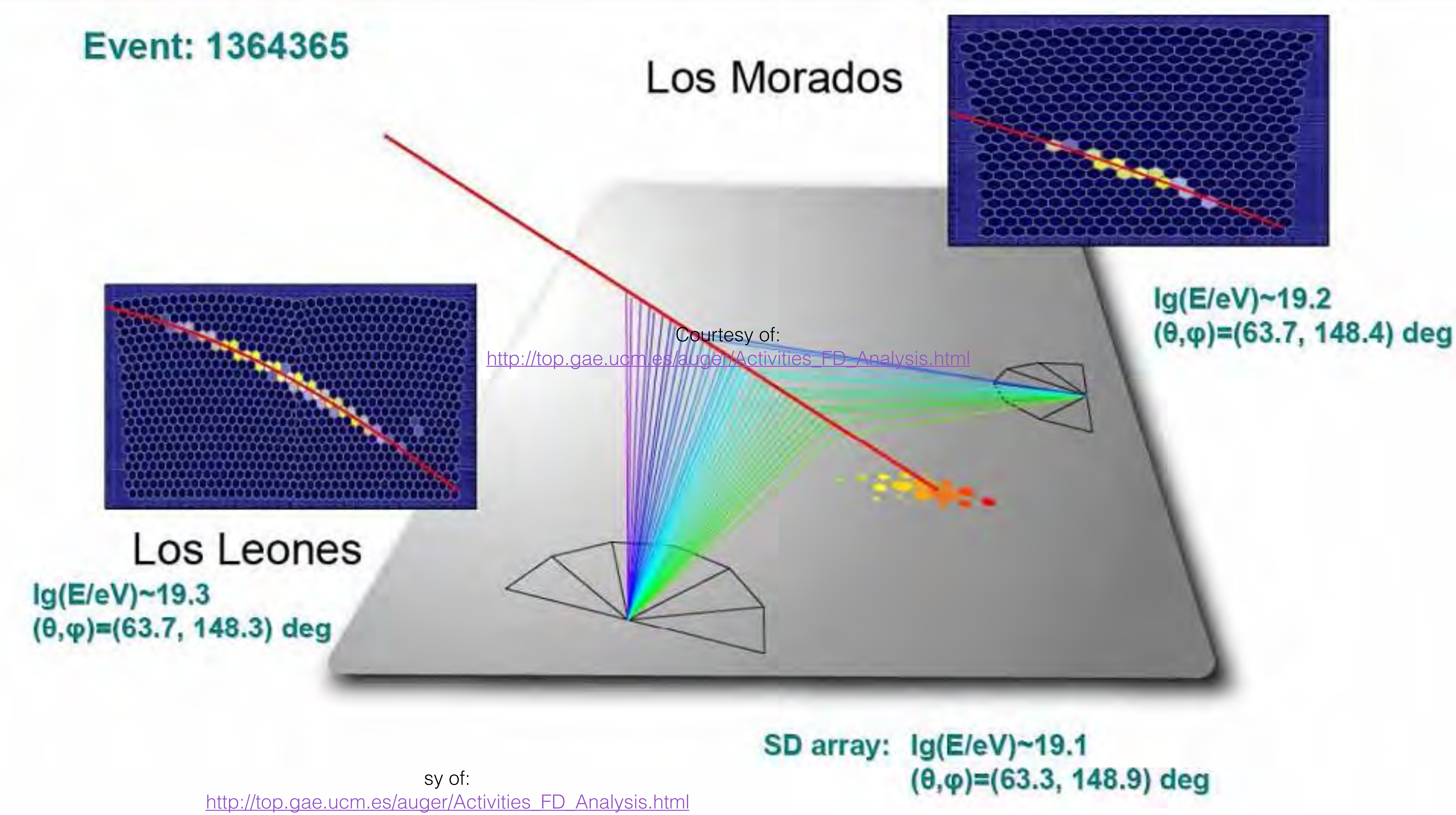
EAS Detectors - Fluorescence
HIRES





Energy Range (10^{17} -10^{20}ev)

Pierre Auger Observatory: Fluorescence Detector



Courtesy of:
http://top.gae.ucm.es/auger/Activities_FD_Analysis.html

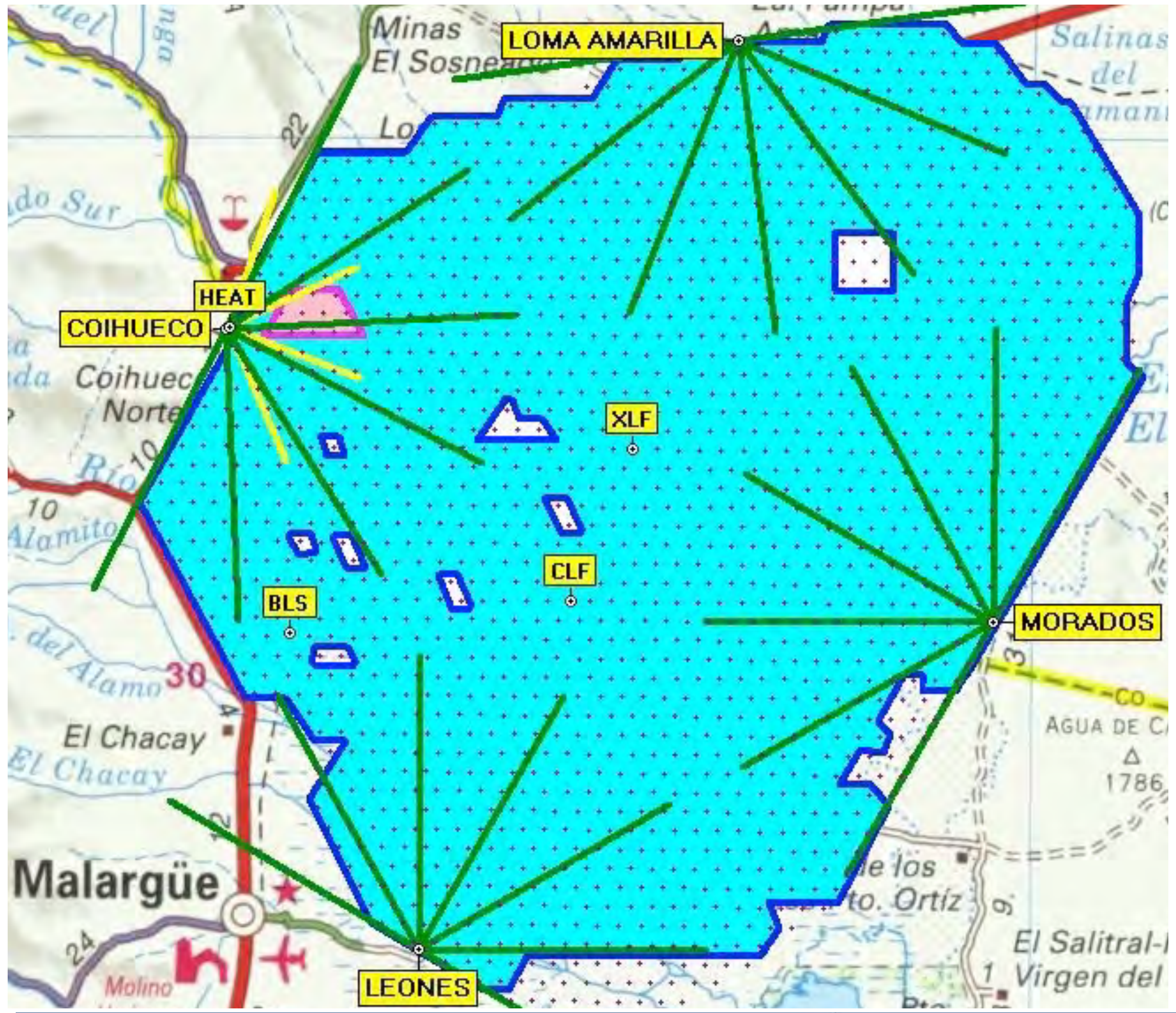
sy of:
http://top.gae.ucm.es/auger/Activities_FD_Analysis.html

Pierre Auger Observatory

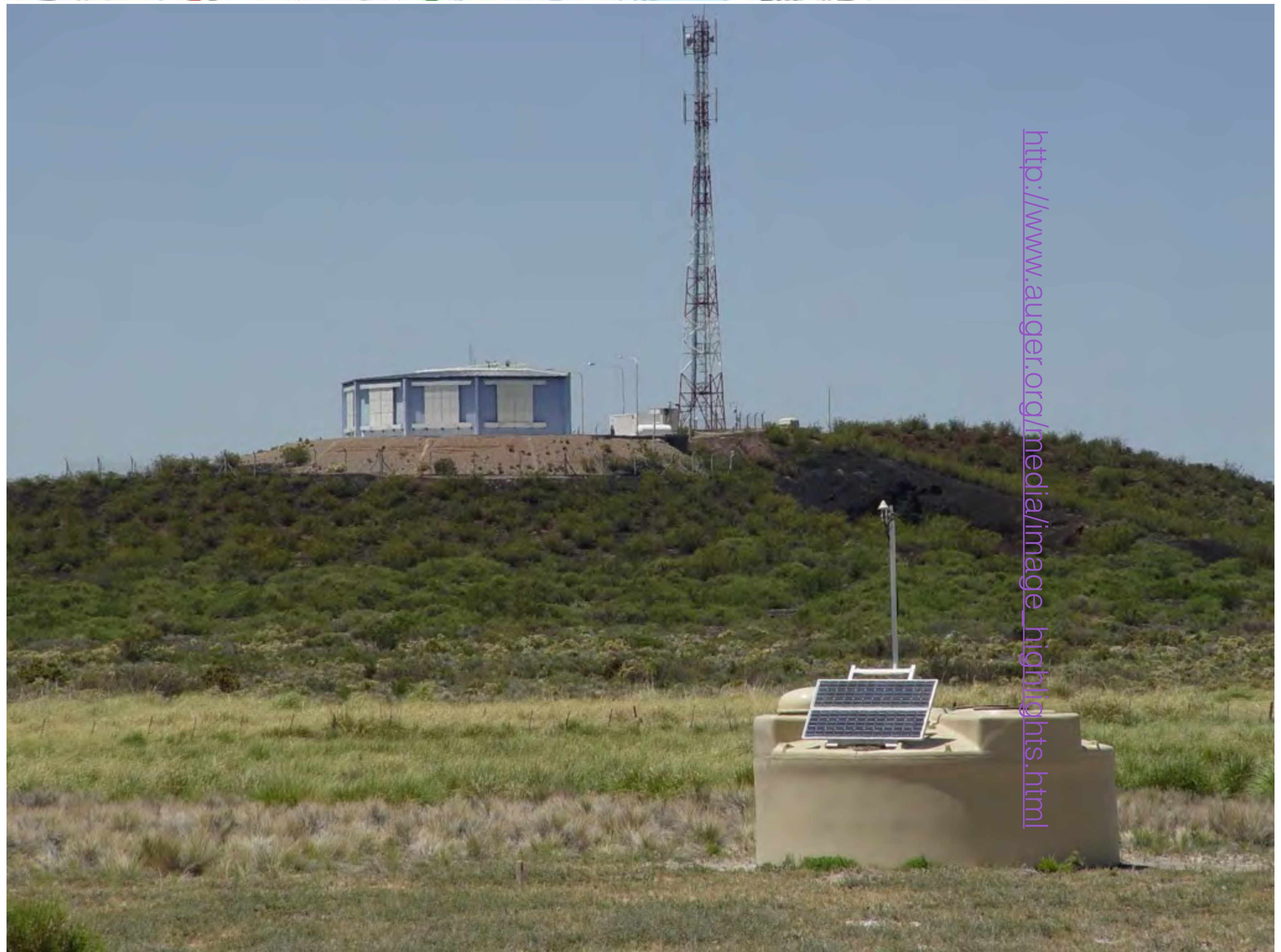
Water Cherenkov and FD - Hybrid

- Two complementary detectors.
- Over 1600 surface detectors covering ~3000 km^2 arranged as an array on a triangular grid with 1500 m spacing.
- 24 air-fluorescence telescopes distributed equally between four sites overlooking a large potion of the surface detector array.

Energy Range (10^{17} -10^{21}ev)

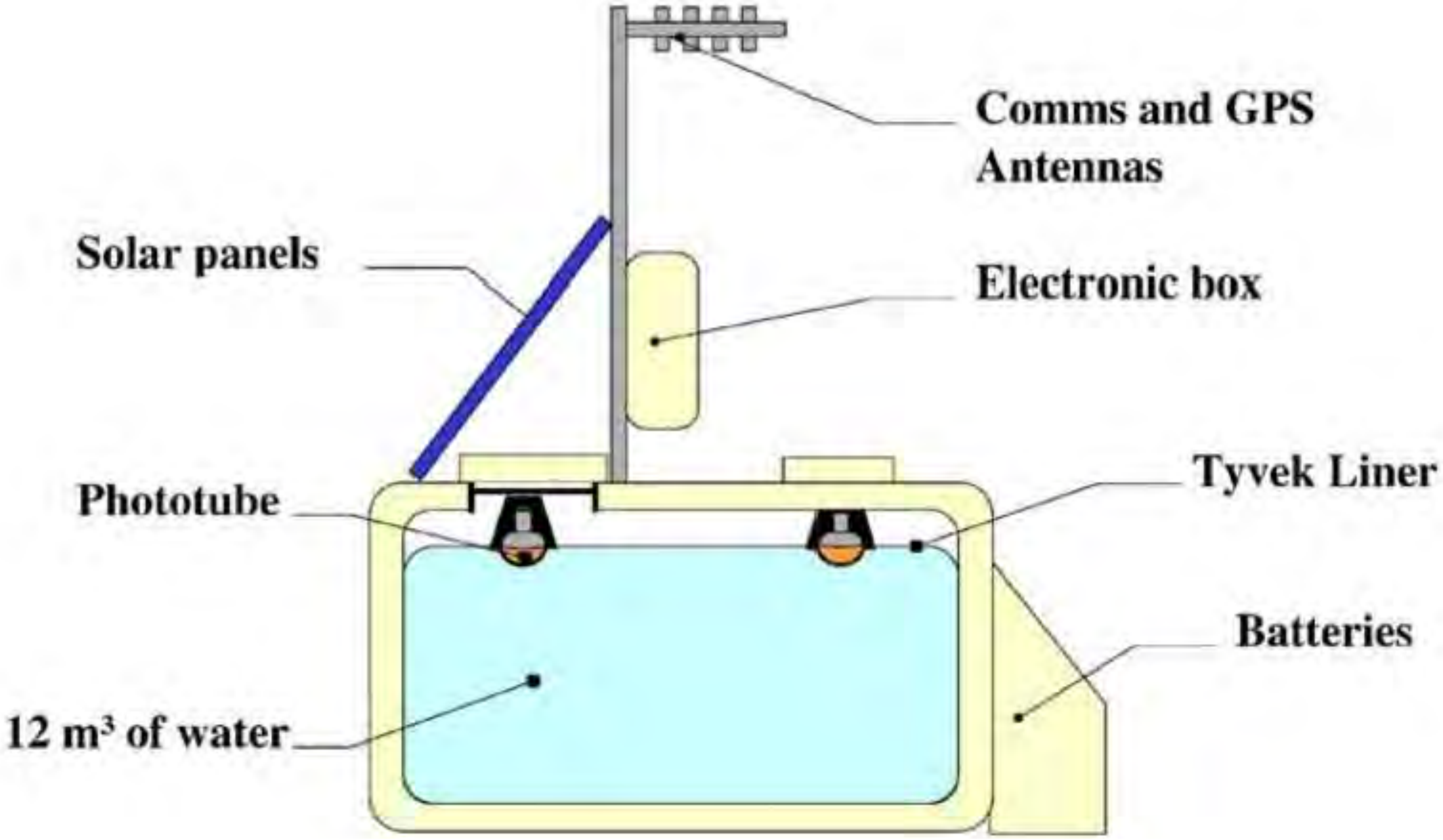


From I. Allekotte



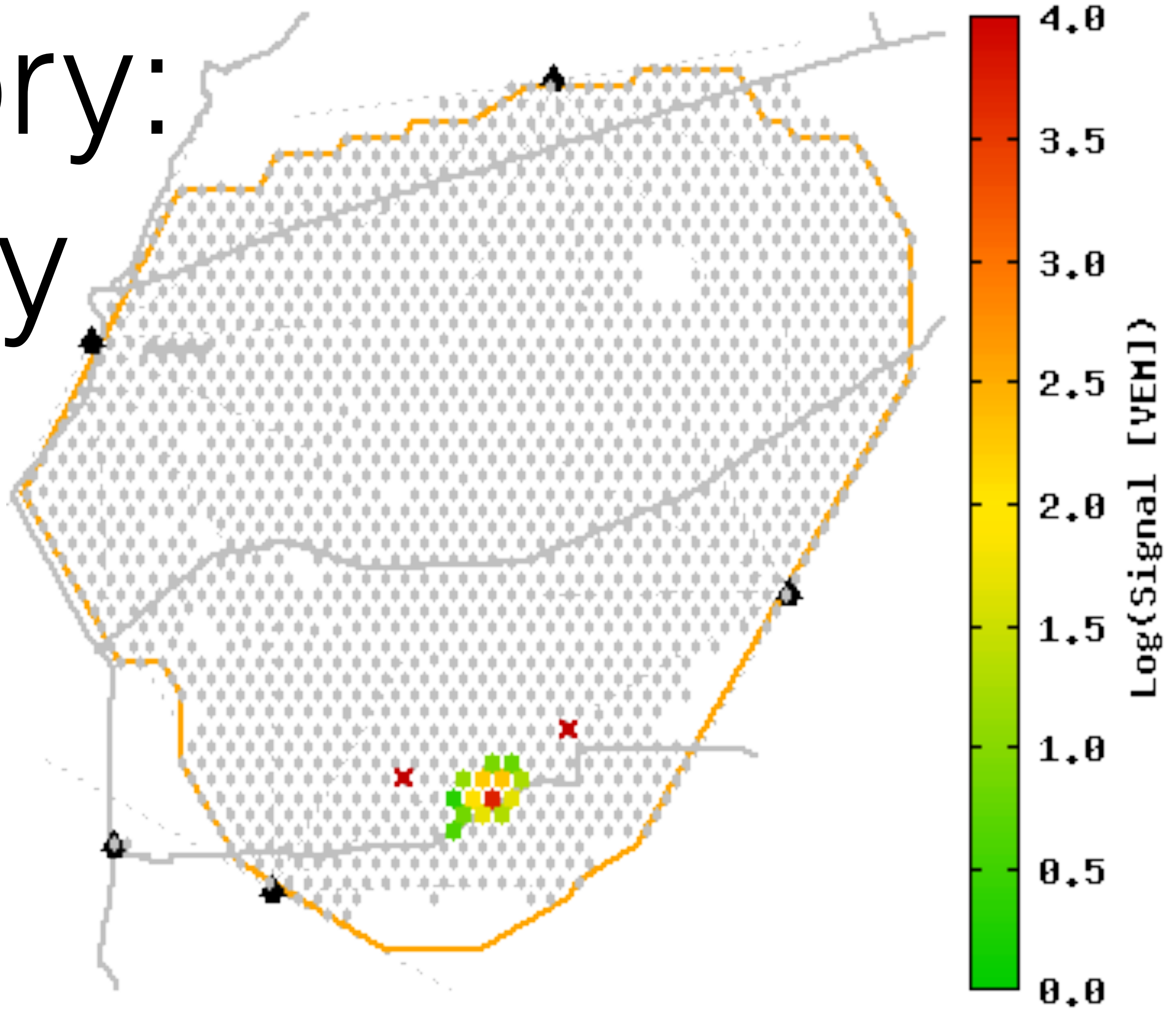
http://www.auger.org/media/image_highlights.html

Pierre Auger Observatory: Surface Detector Array

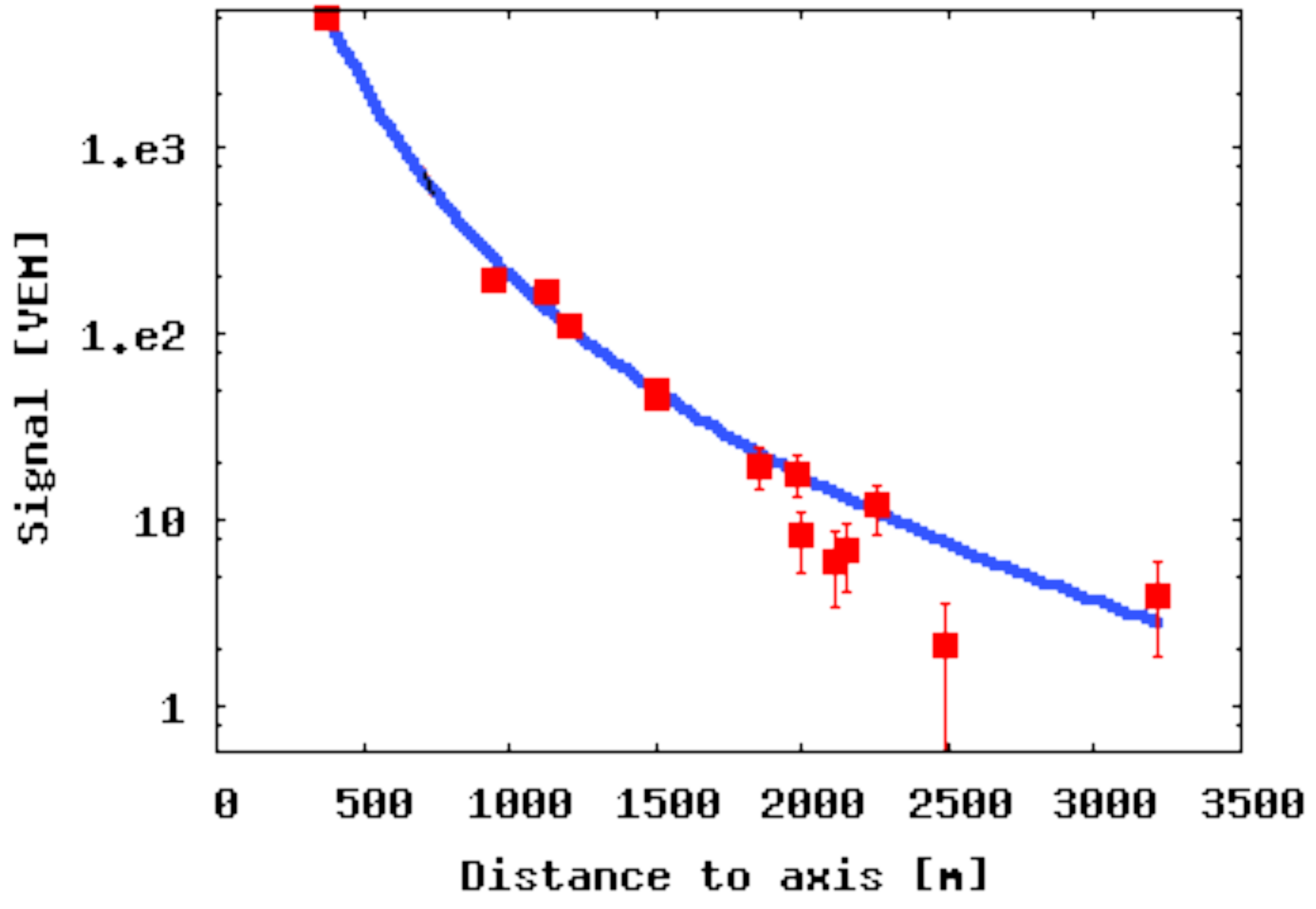


Courtesy of
Ph.D. Thesis, University Paris Diderot,Carl Blaksley
http://arxiv.org/abs/arXiv:1406.5818

Pierre Auger Observatory: Surface Detector Array

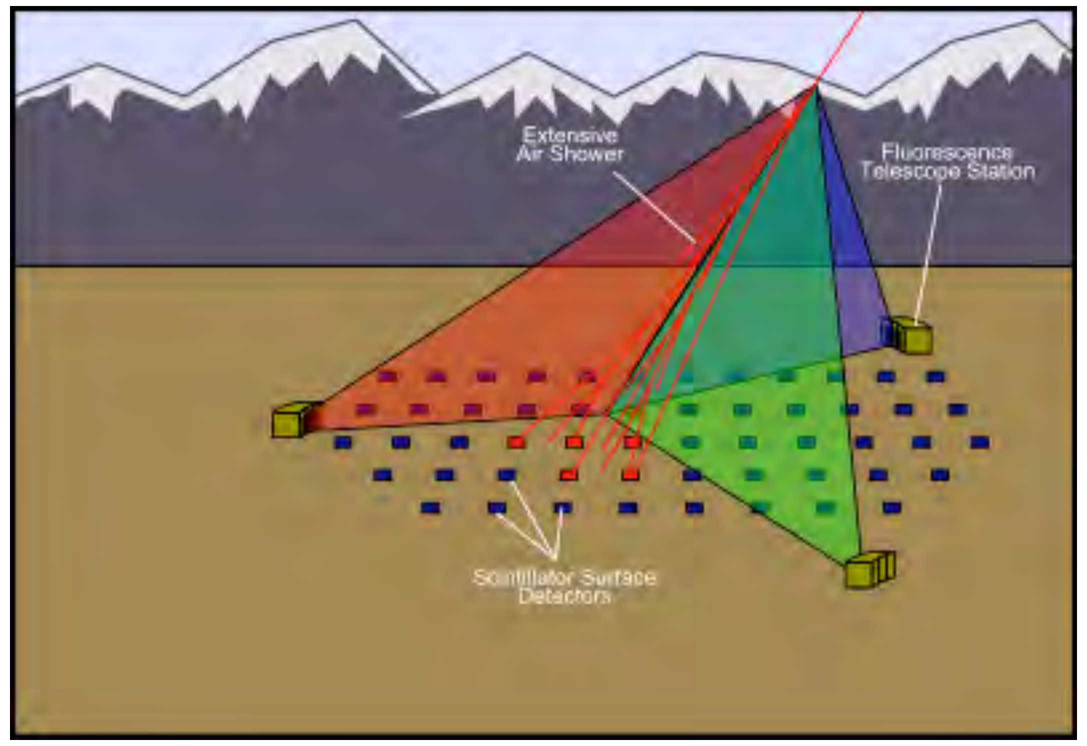


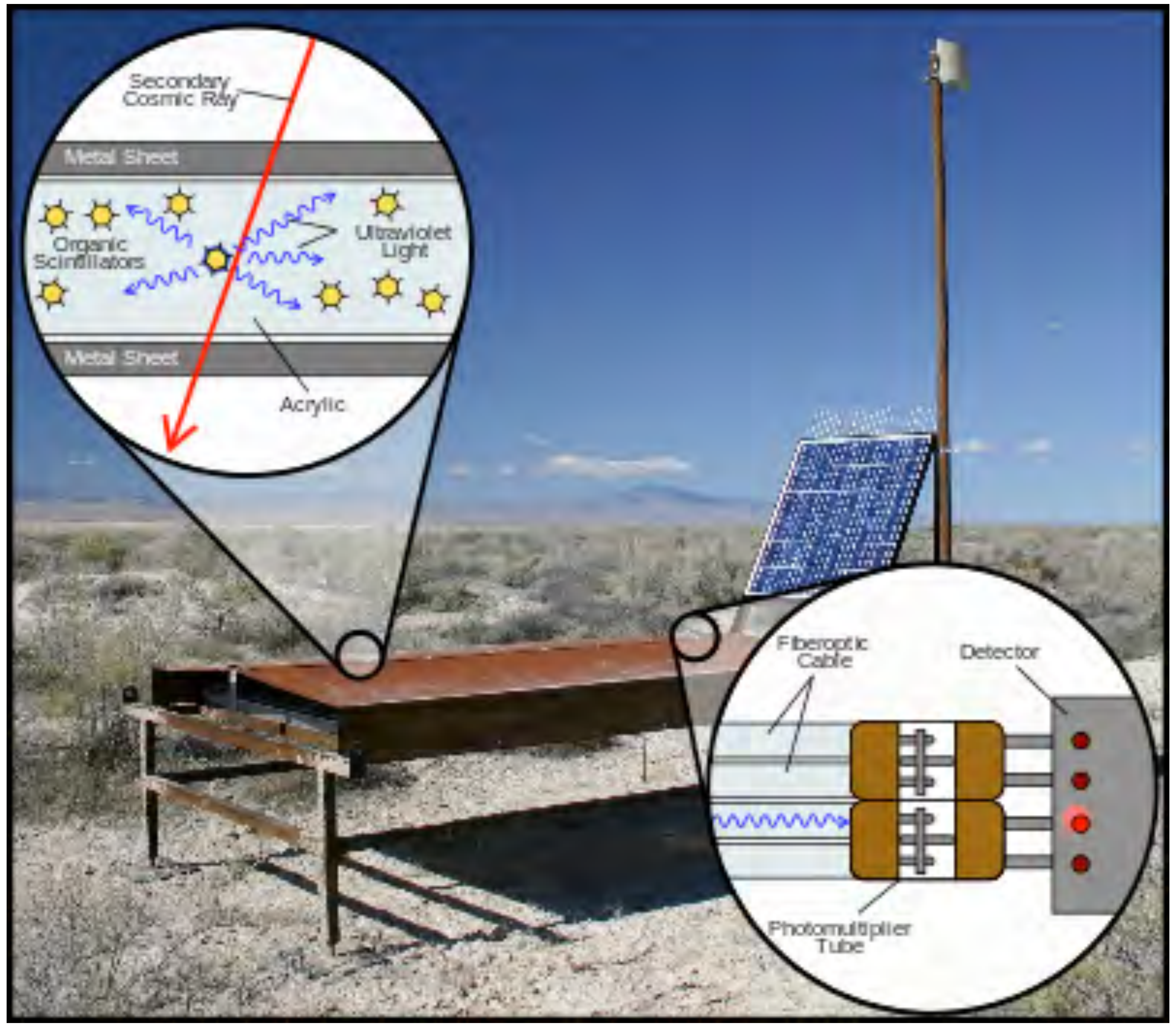
- Surface detector covers an area of 3000 km^2 or roughly the size of the state of Rhode Island (3140 km^2).
- Precise measurement of the arrival times between tanks can be fit to provide accurate directional information.
- With calibration from the Fluorescence detector energy estimations are also possible.
- Near 100% duty cycle



Telescope Array - Utah

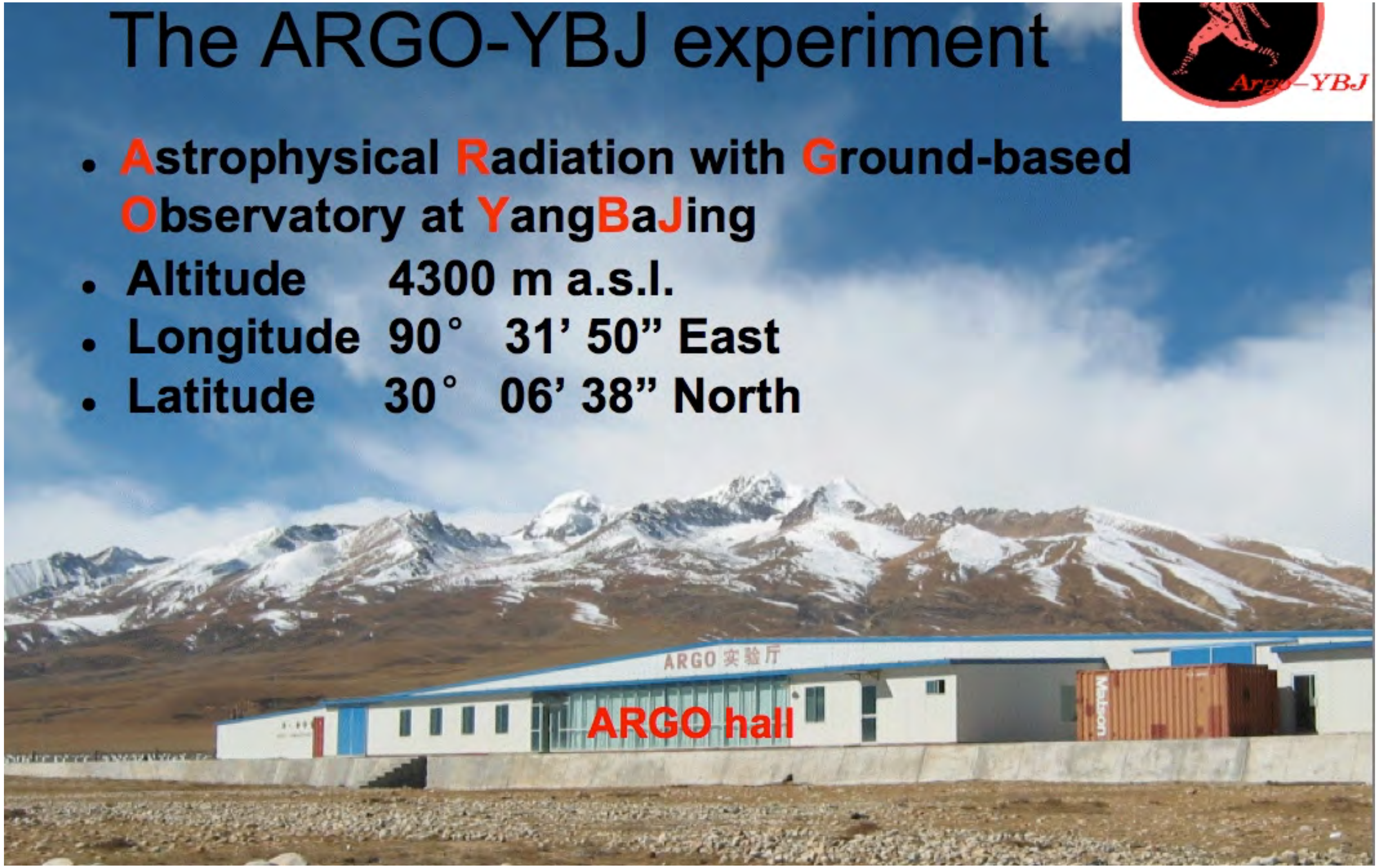
TELESCOPE ARRAY PROJECT





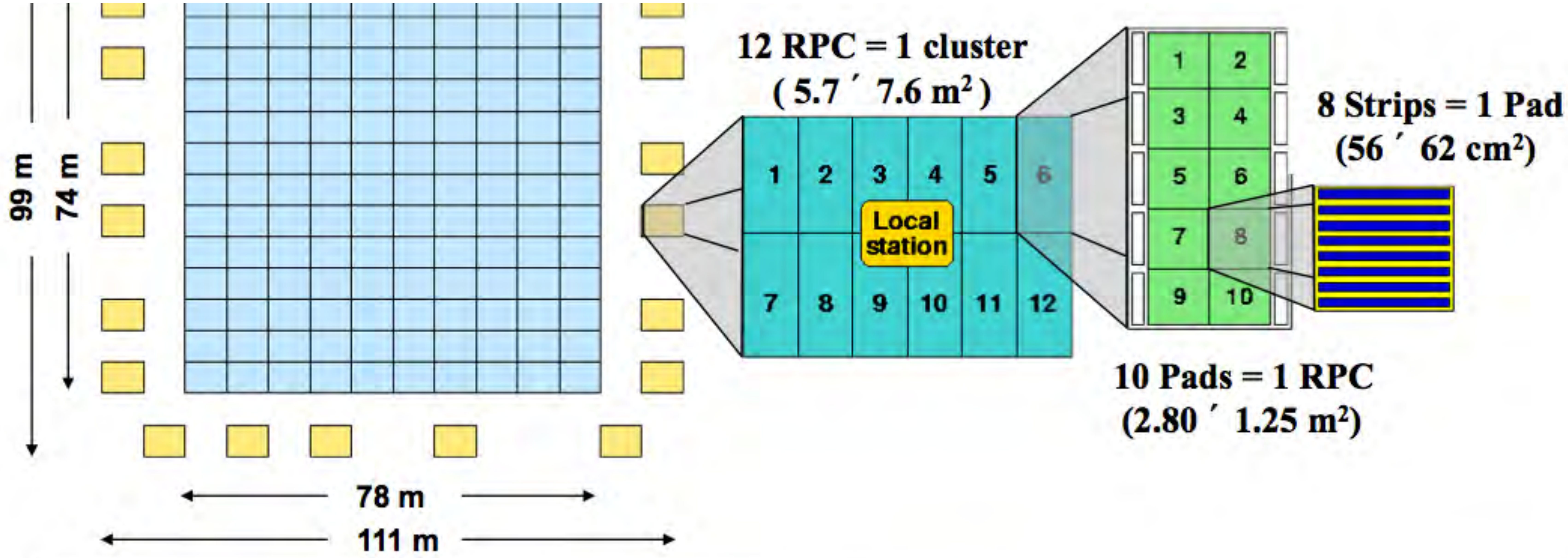
Scintillator
and FD - Hybrid

ARGO



Energy Range (500 Gev - 10 TeV)

ARGO



- ✓ Layer of Resistive Plate Chambers (RPC)
- ✓ Active area : central carpet ~ 5600 m^2
  sampling guard-ring ~ 1000 m^2
- ✓ Data taking : since July 2006 with the central carpet
  since November 2007 with the carpet + guard-ring

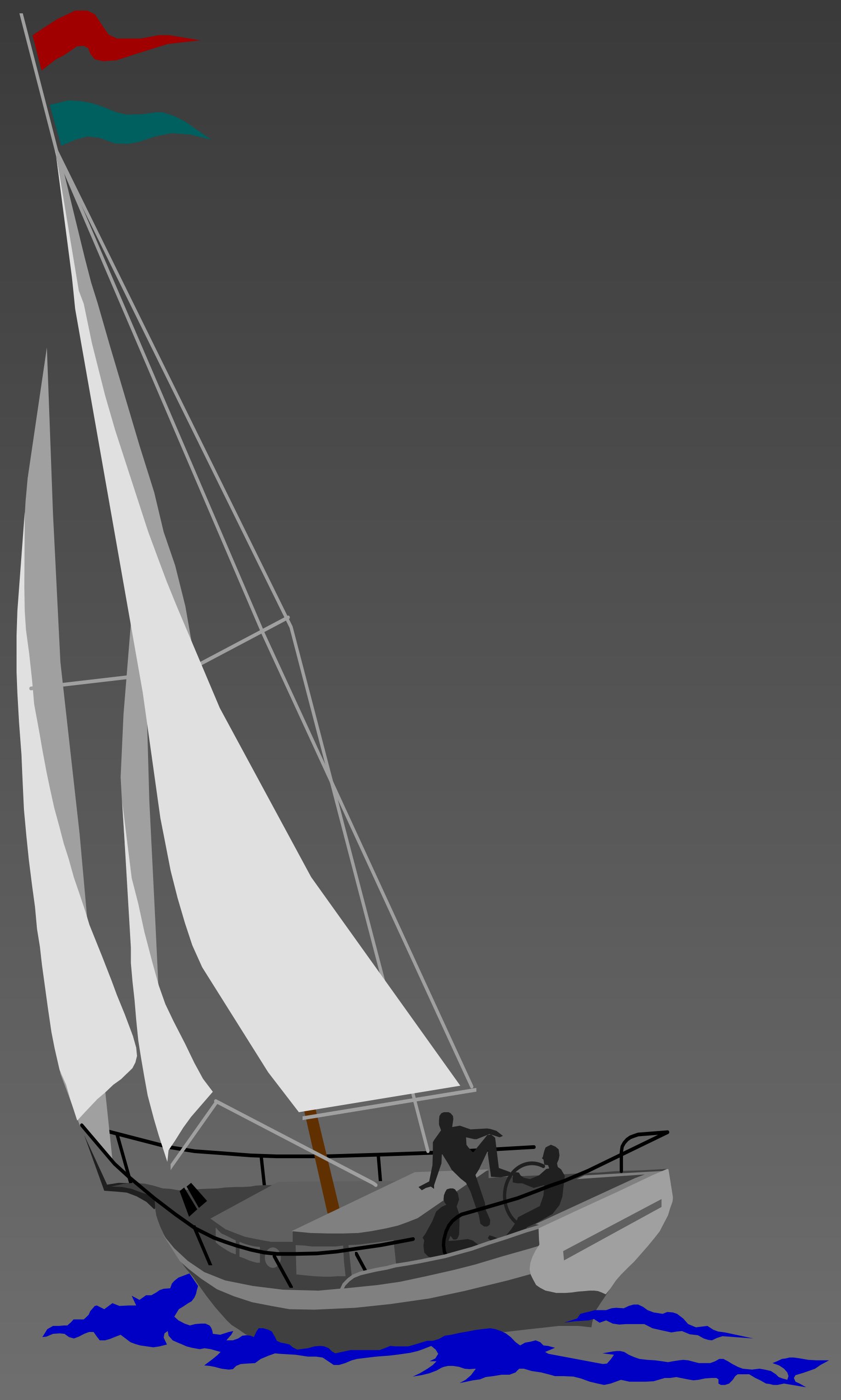
Analog charge read-out is working

No Real Hadron Rejection

Cherenkov Radiation

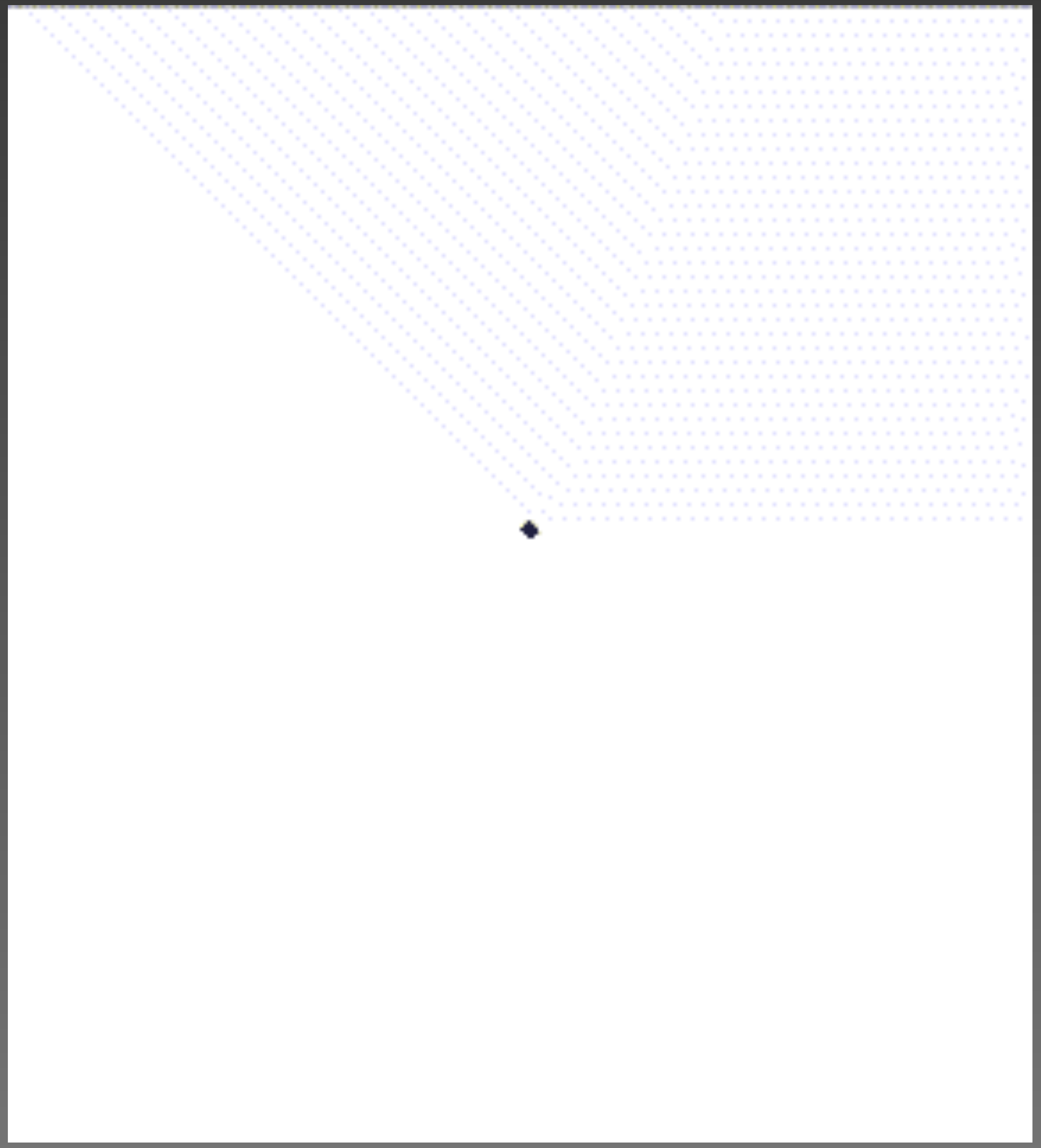
Boat moves through water faster than wave speed.

Bow wave
(wake)

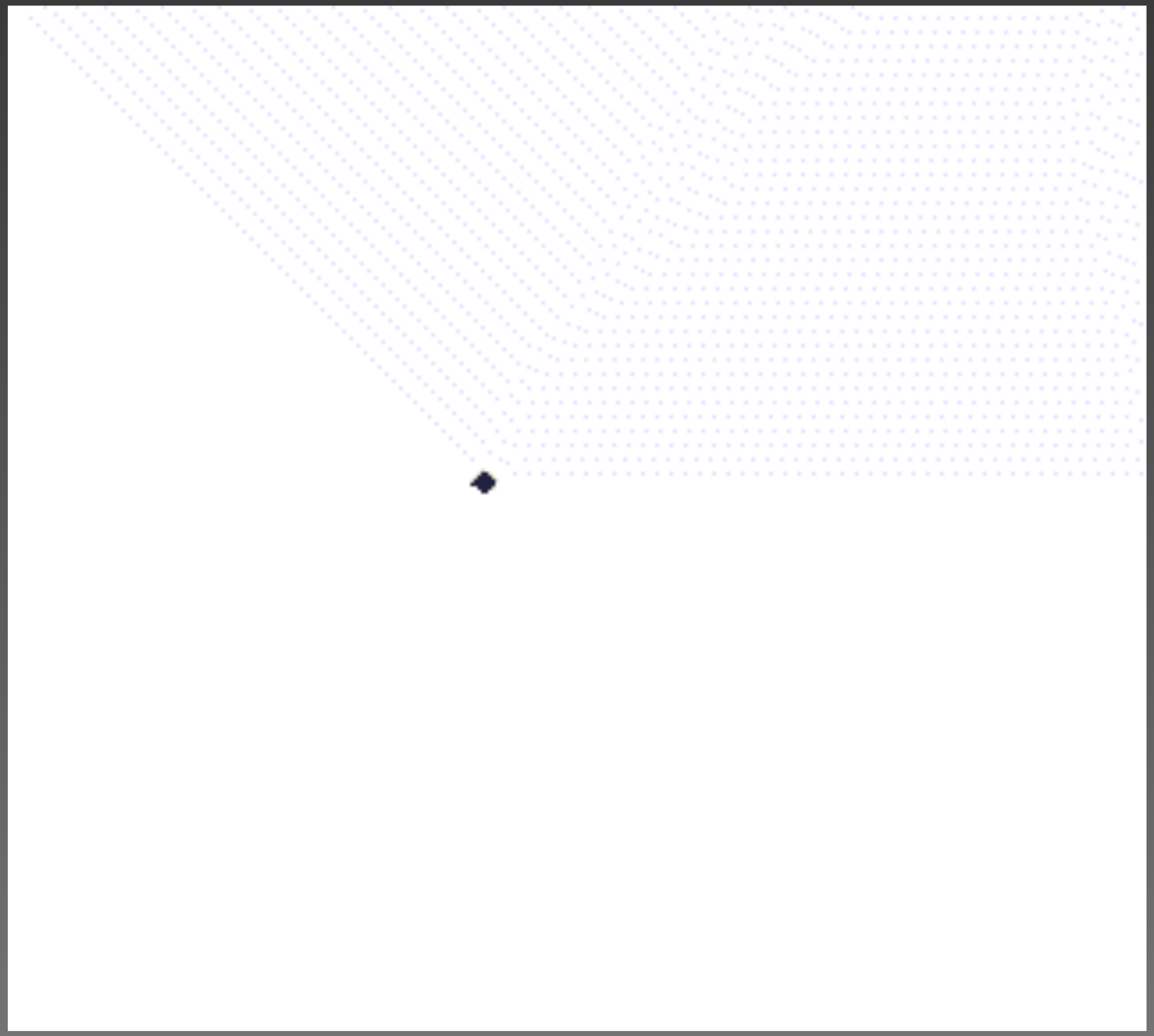


Cherenkov Radiation

Slower than wave speed



Faster than wave speed



Cherenkov Radiation

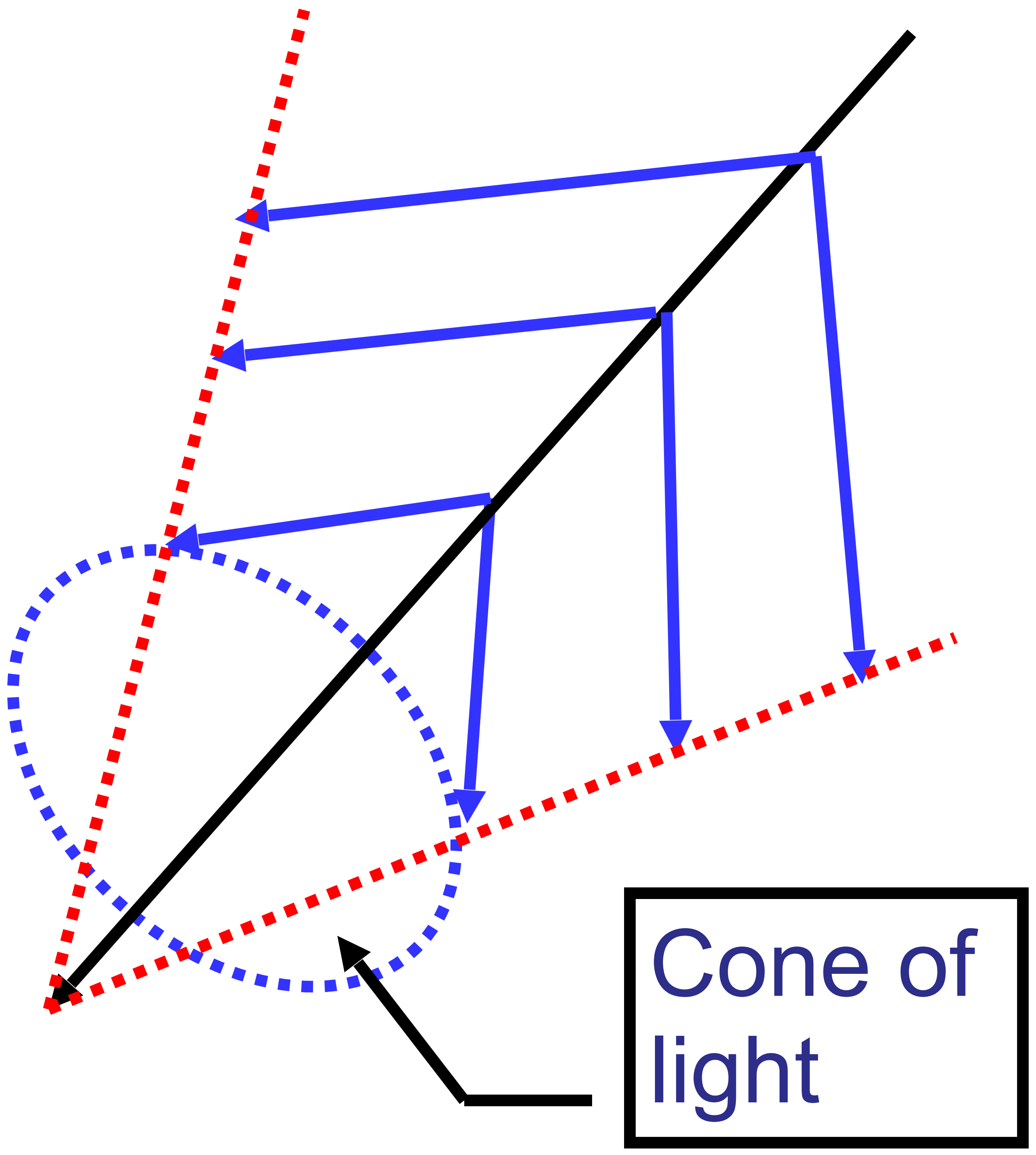
Aircraft moves through air faster than speed of sound.

Sonic Boom

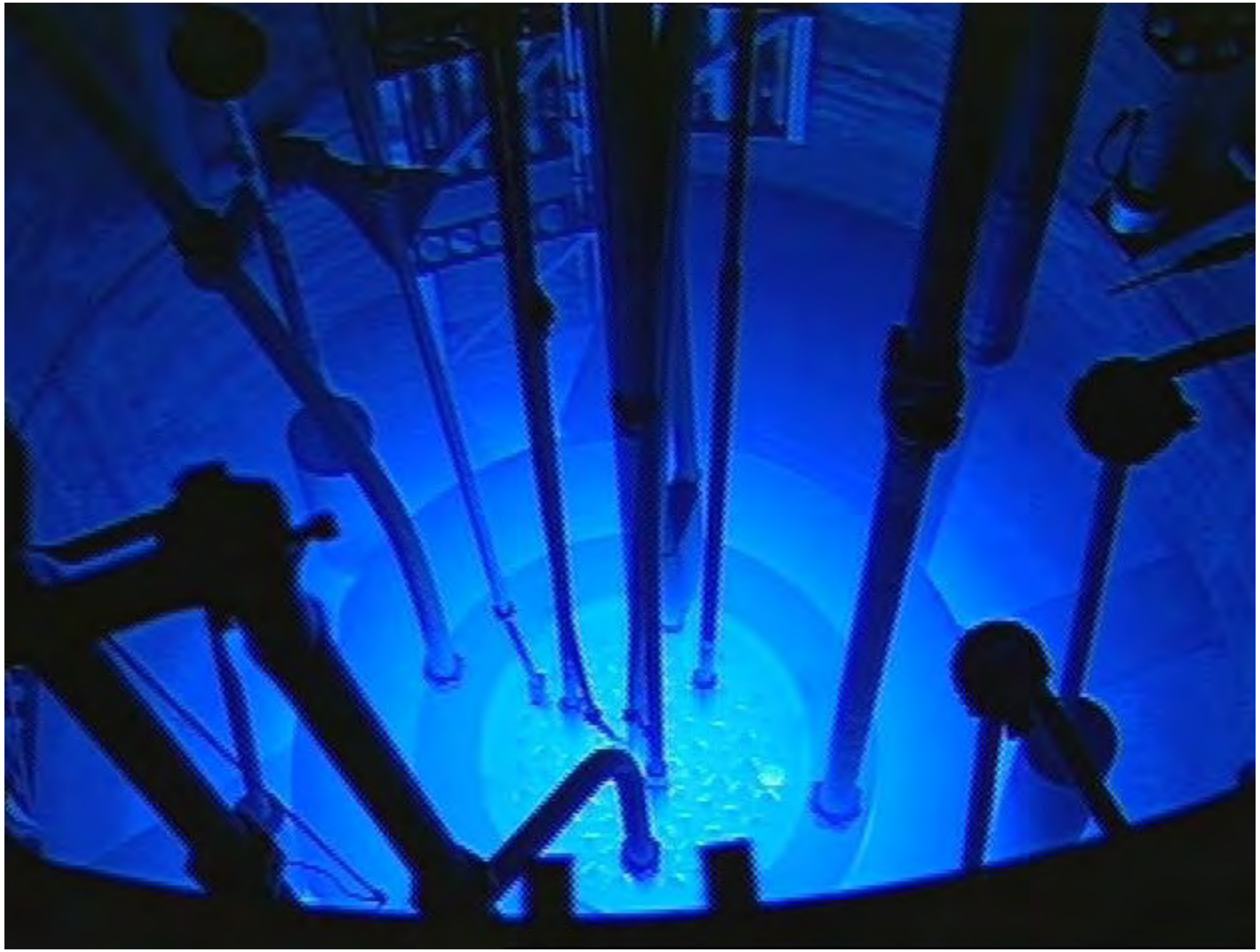
Cherenkov Radiation

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

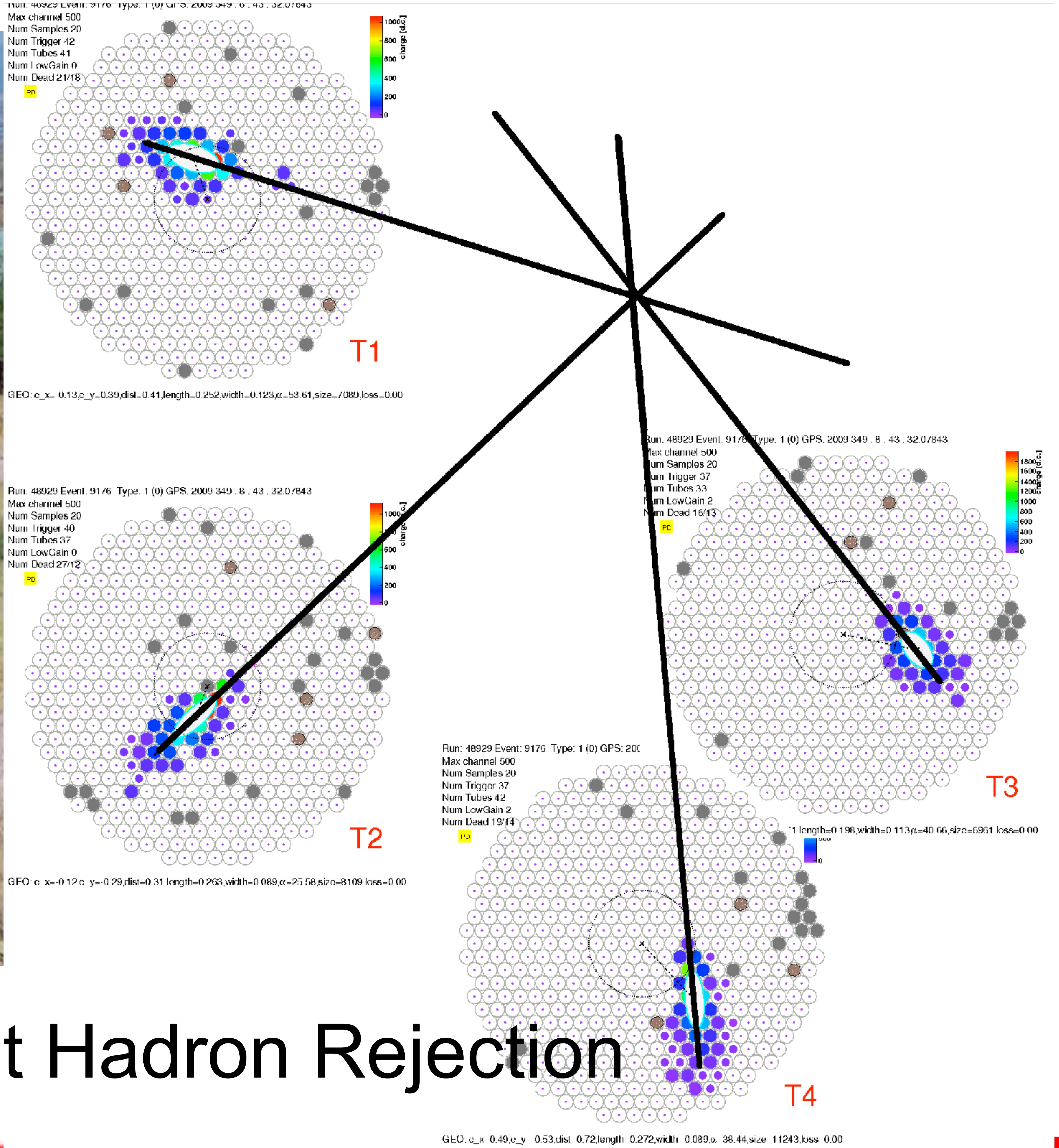
⇨ Cherenkov radiation



Cherenkov Radiation



EAS Detectors - IACT's



Energy Range (100 Gev - 20 TeV) Excellent Hadron Rejection

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
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

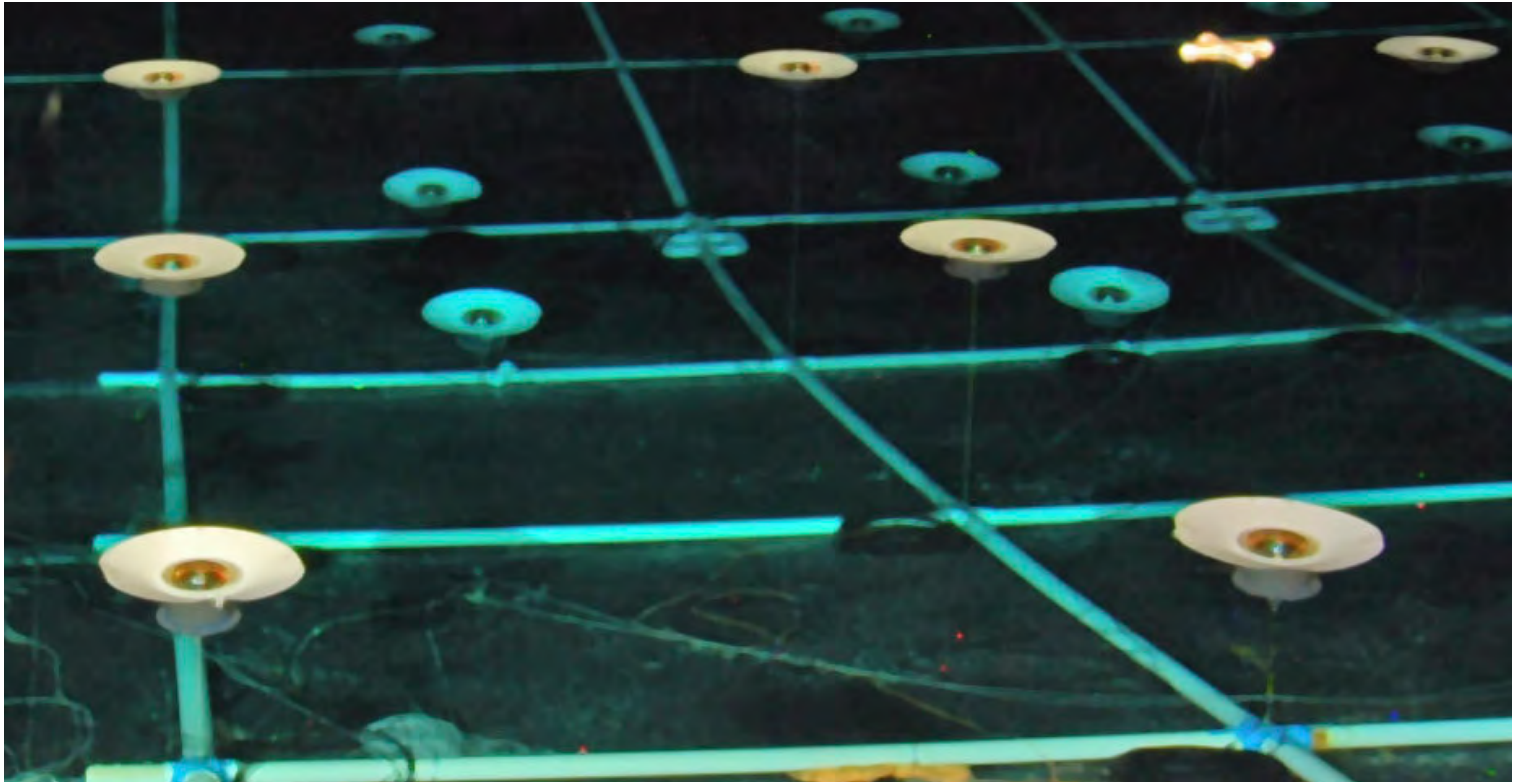
Energy Range (3 Tev - 40 TeV)

Good Hadron Rejection

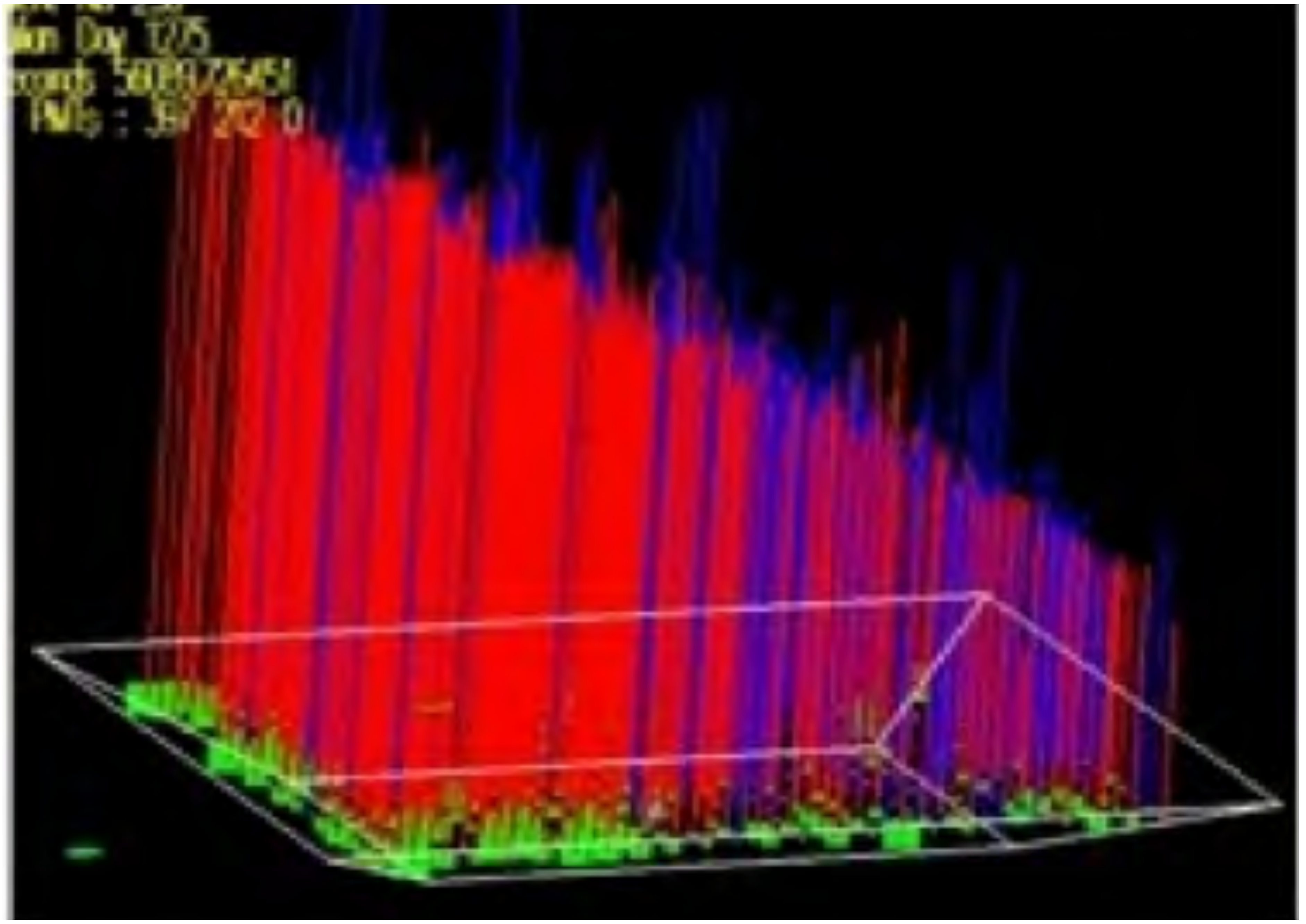
Milagro

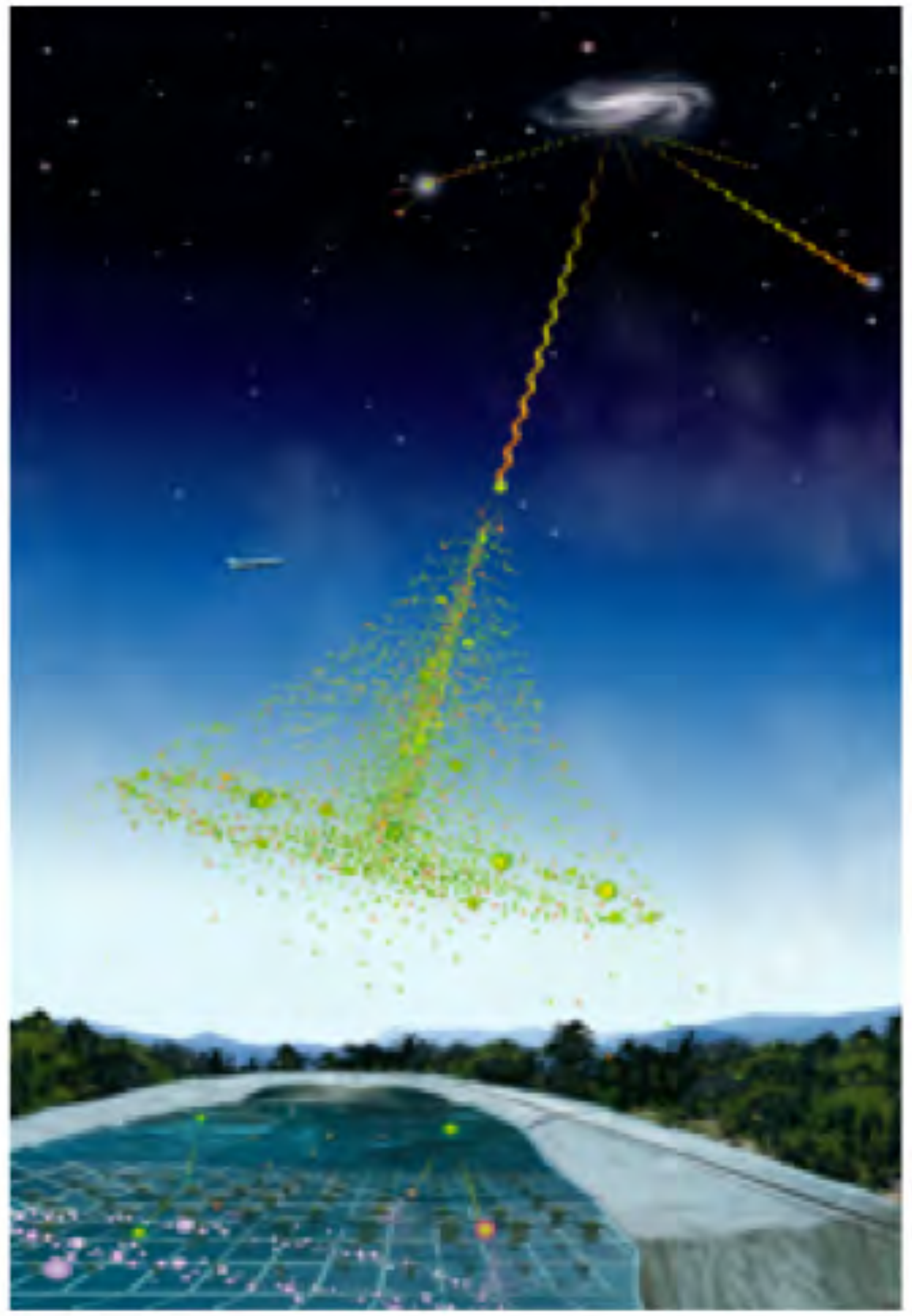
Milagro

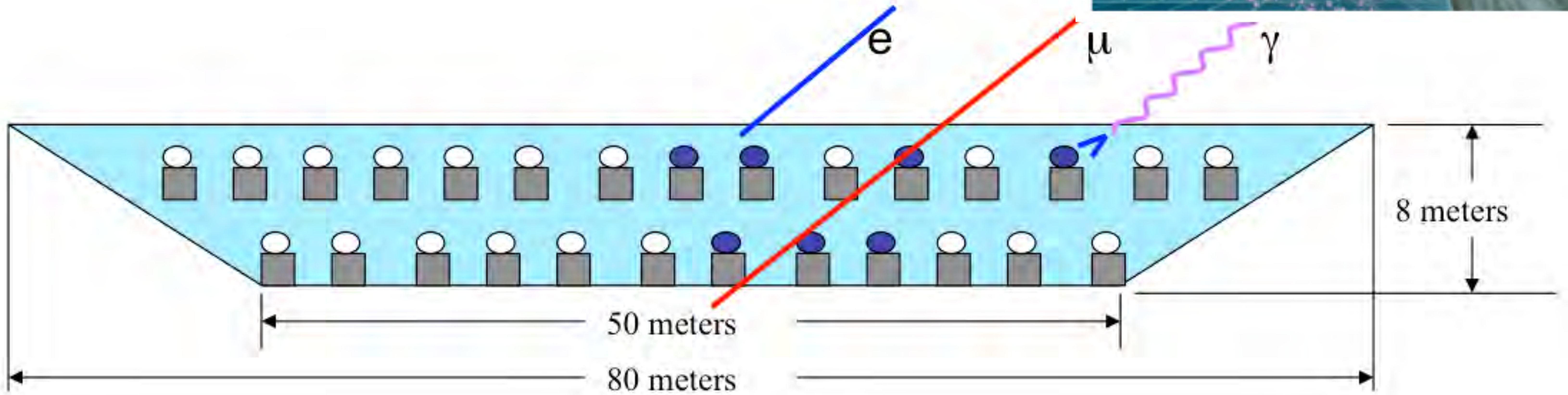
Milagro

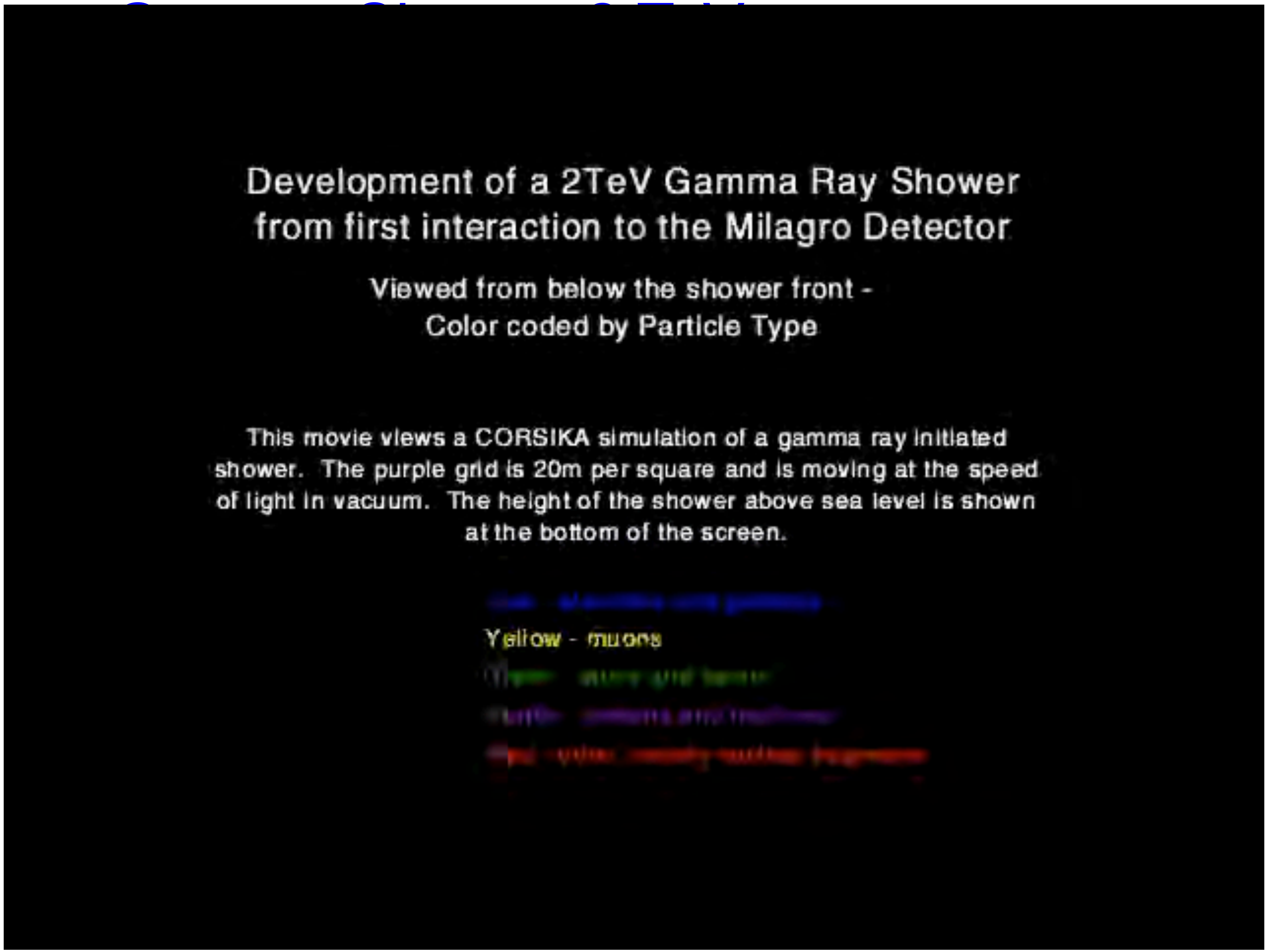


Milagro

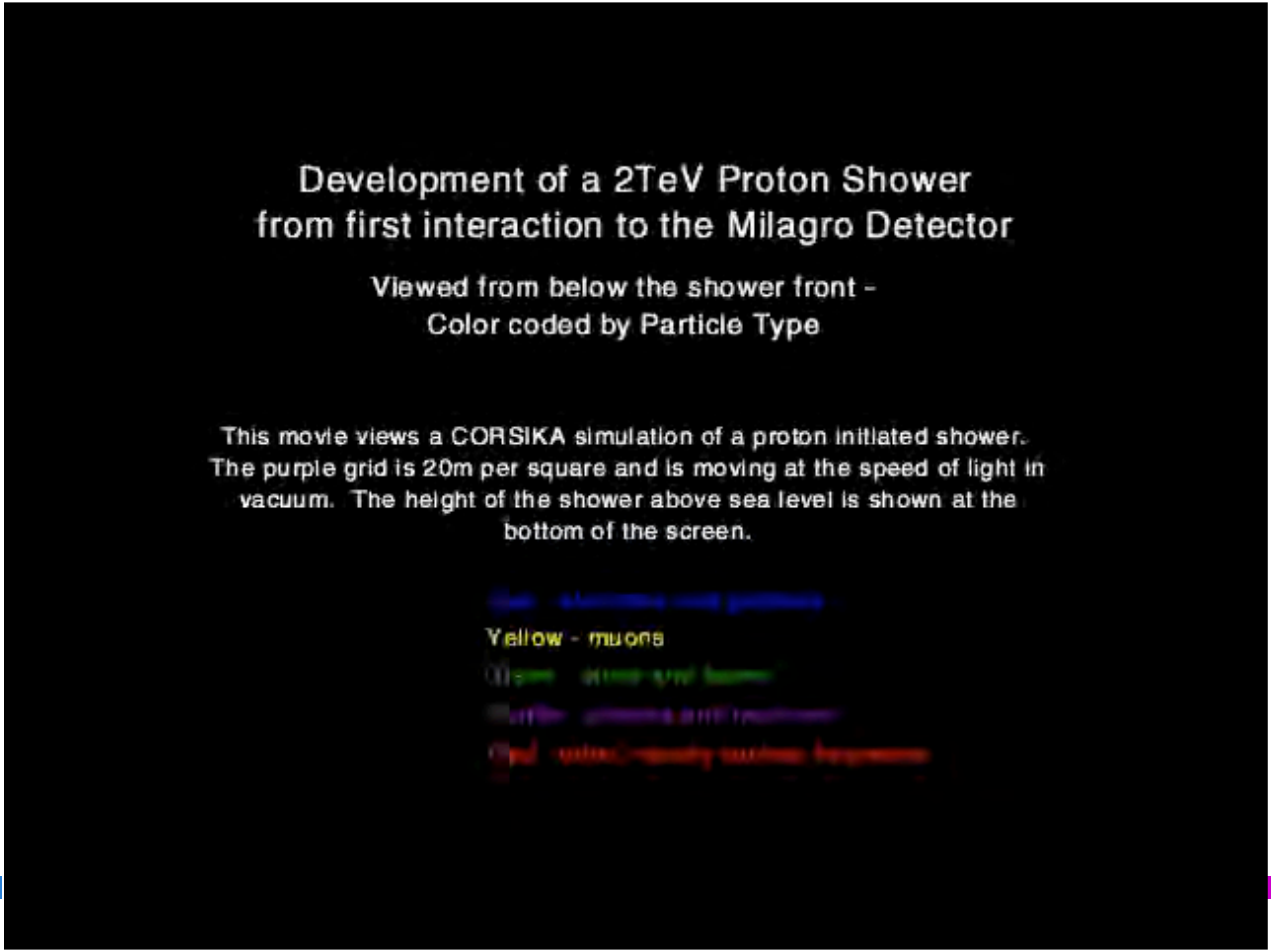







Development of a 2TeV Gamma Ray Shower
from first interaction to the Milagro Detector
Viewed from below the shower front -
Color coded by Particle Type
This movie views a CORSIKA simulation of a gamma ray initiated shower. The purple grid is 20m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.
Yellow - muons

Proton Shower 2 TeV (movies by Miguel Morales)

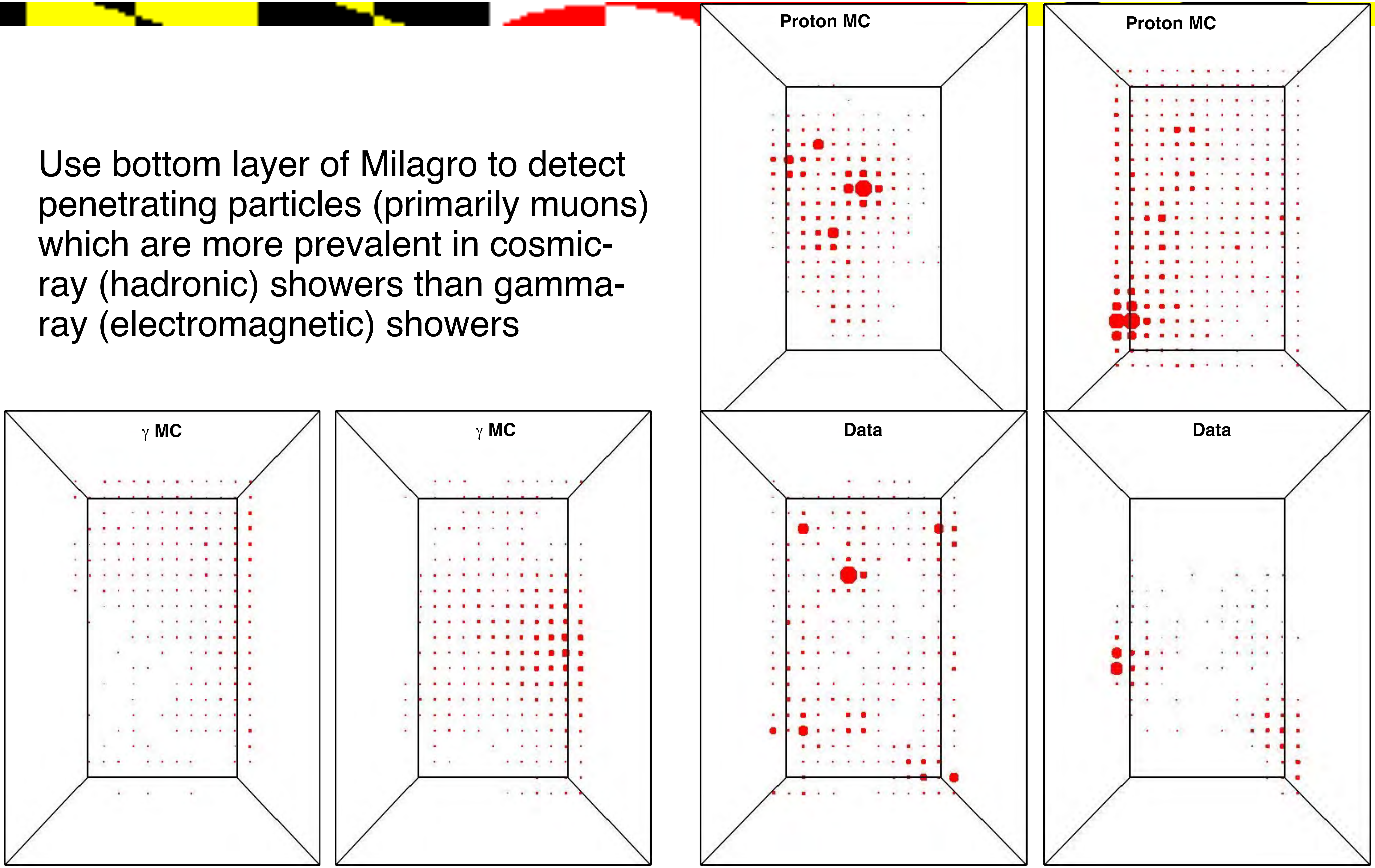


Blu

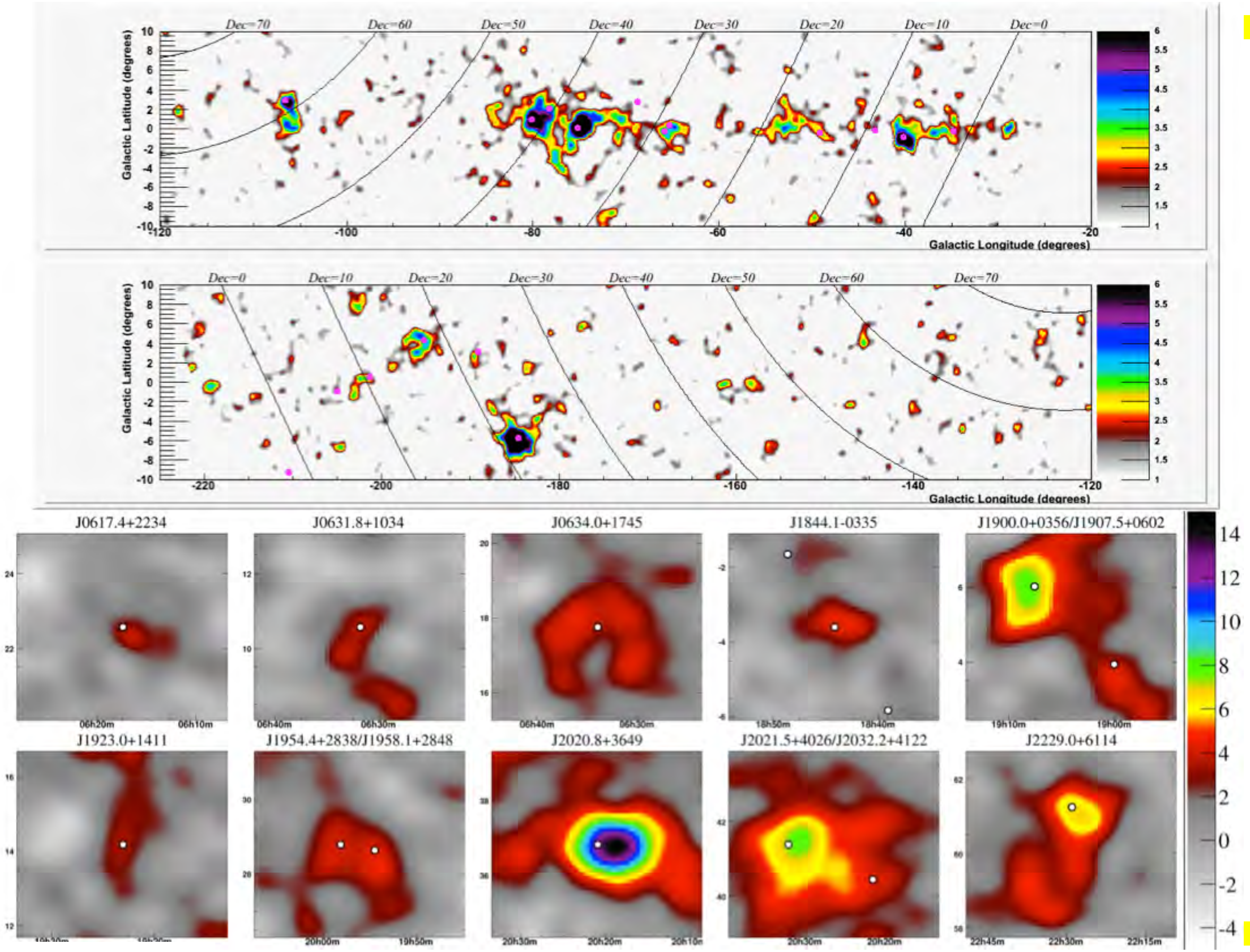
rple

Background Rejection in Milagro

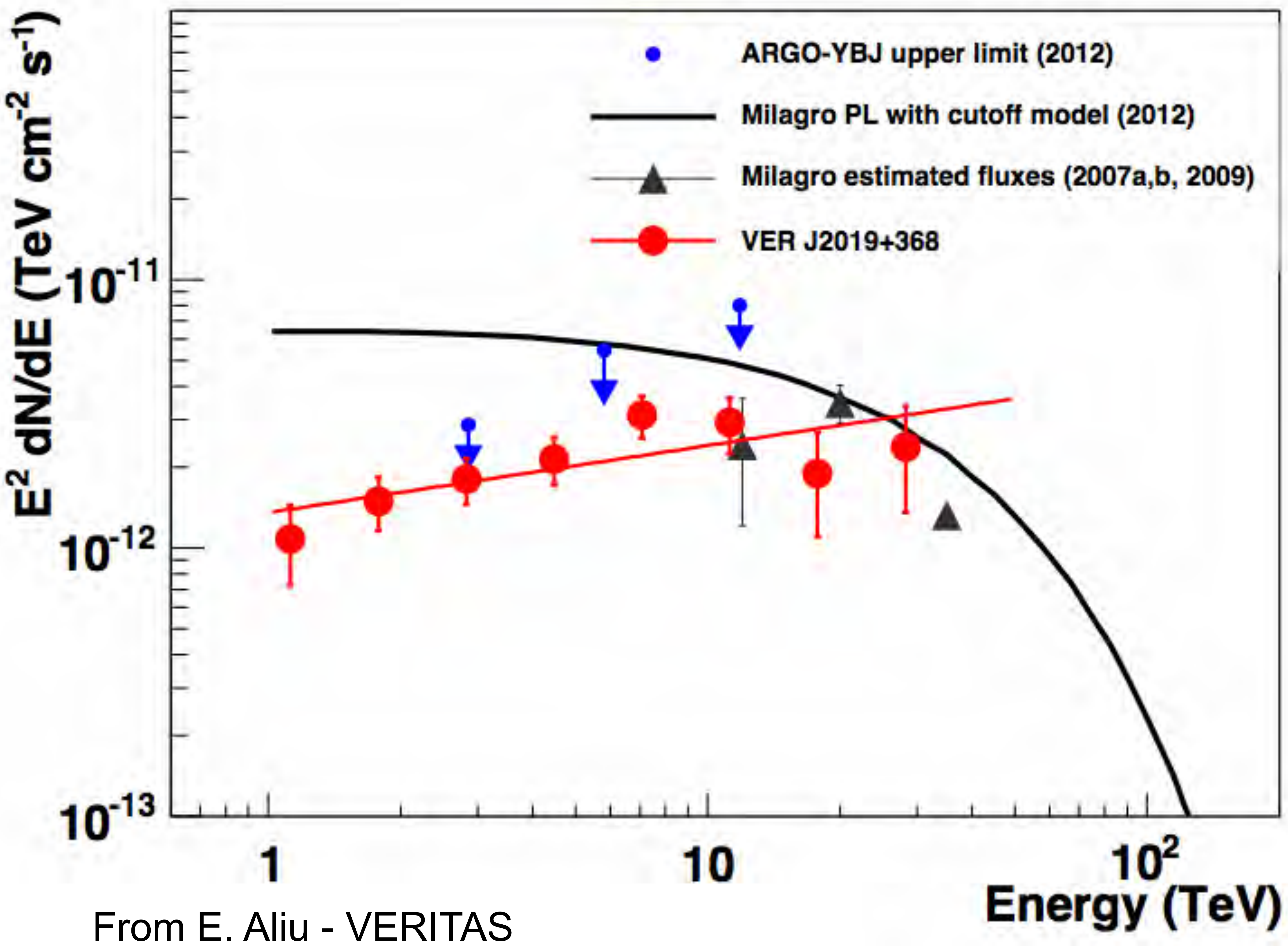
Use bottom layer of Milagro to detect penetrating particles (primarily muons) which are more prevalent in cosmic-ray (hadronic) showers than gamma-ray (electromagnetic) showers



Milagro TeV Sources



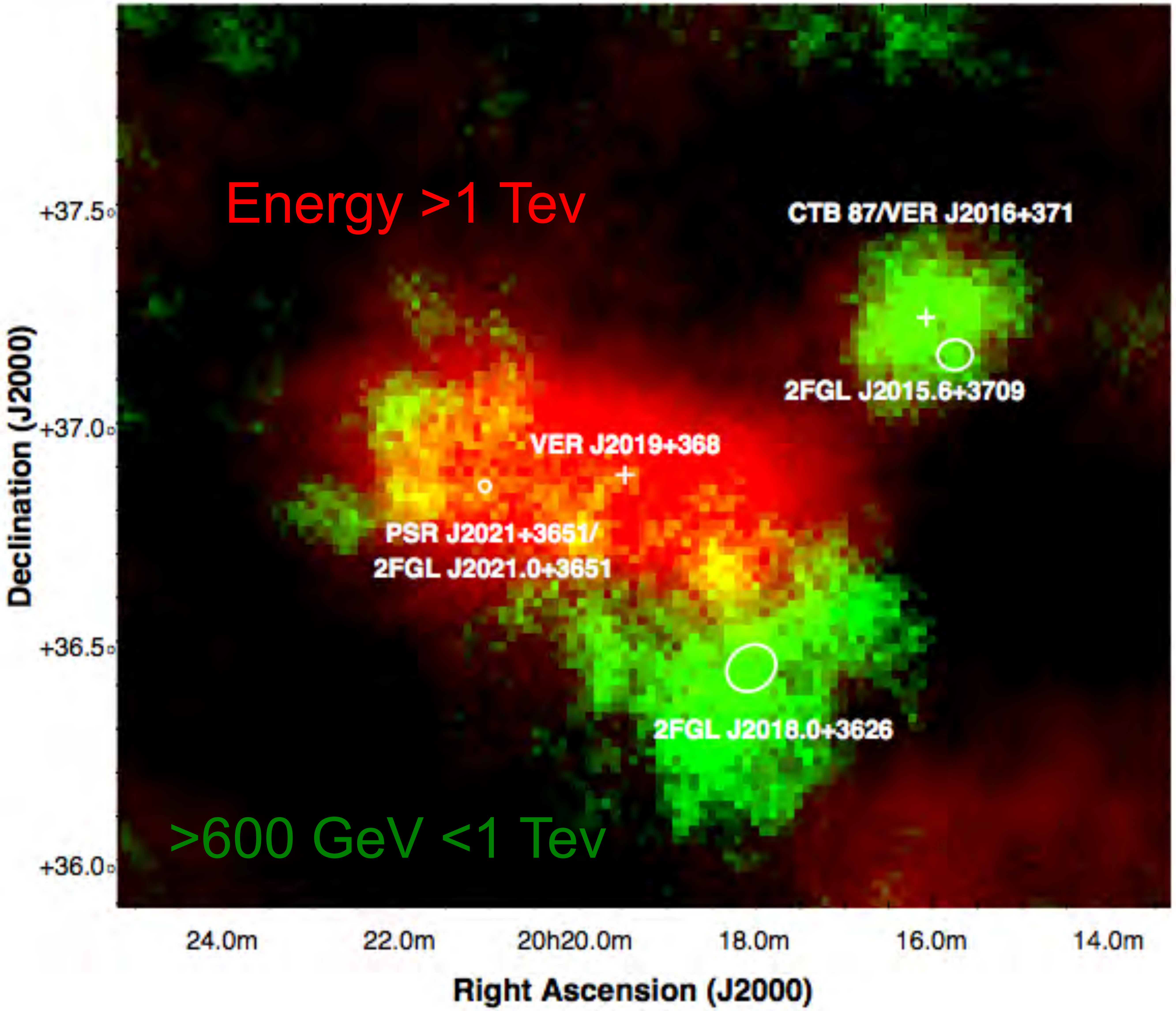
VERITAS Spectrum 2019+37



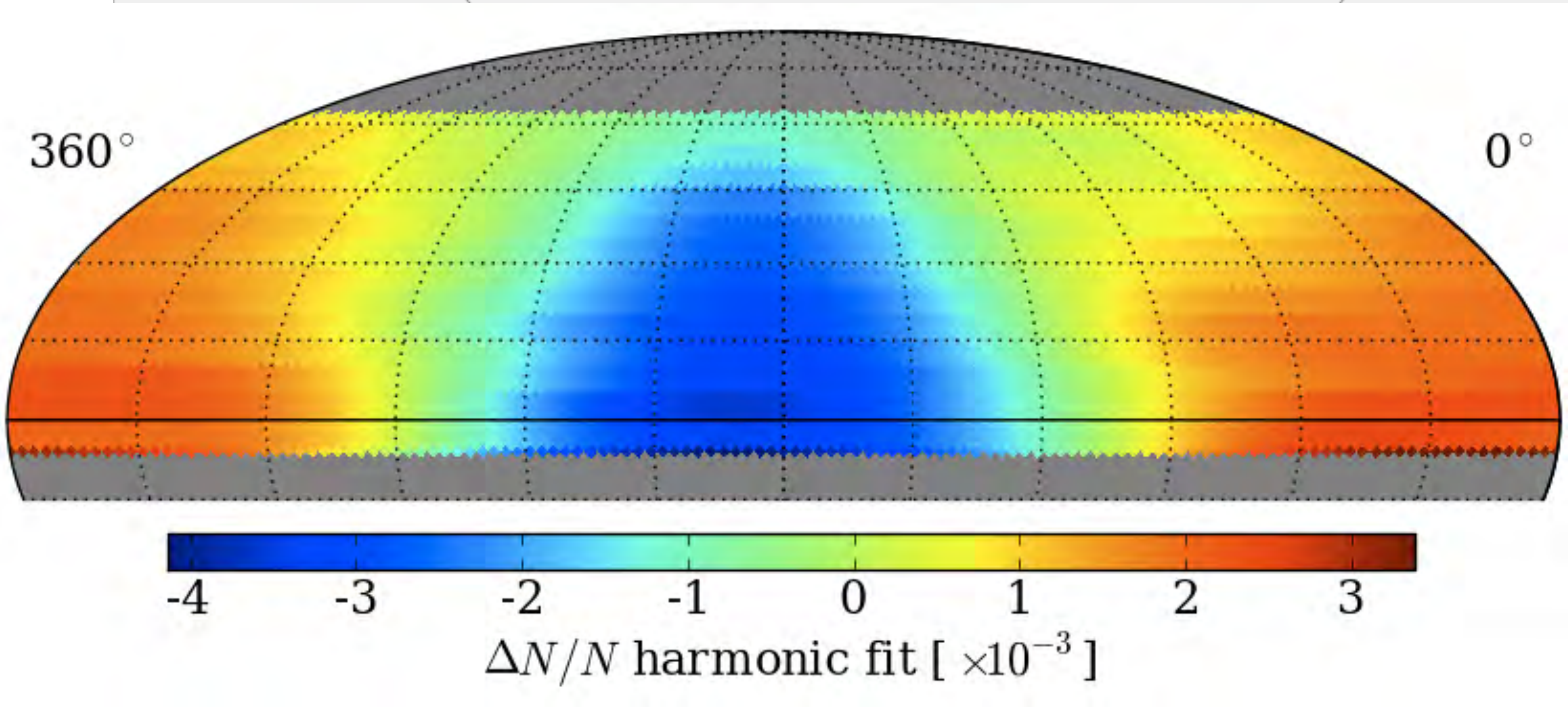
From E. Aliu - VERITAS

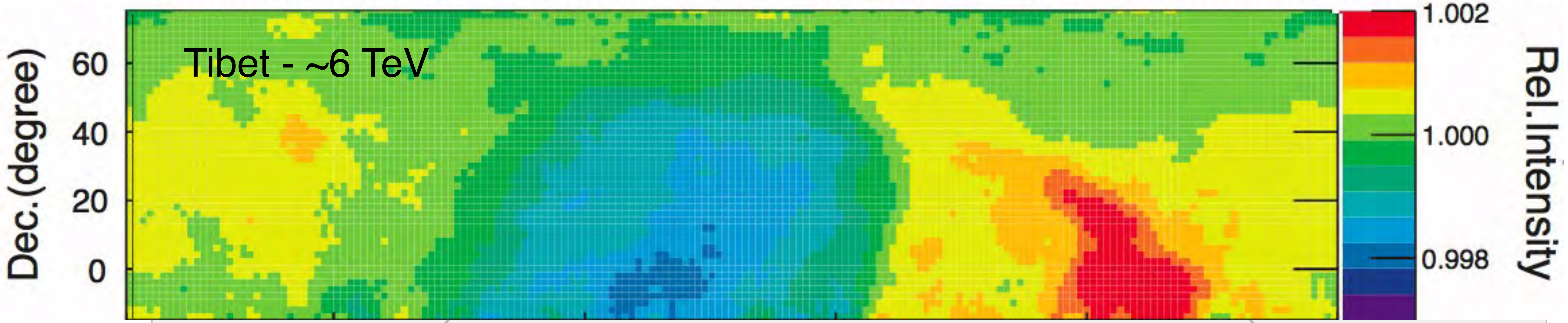
http://arxiv.org/pdf/1404.1841v1.pdf

- Measuring the spectrum from 30-100 TeV will tell if this a hadron accelerator
- High energy emission comes from a different spot than the lower energy

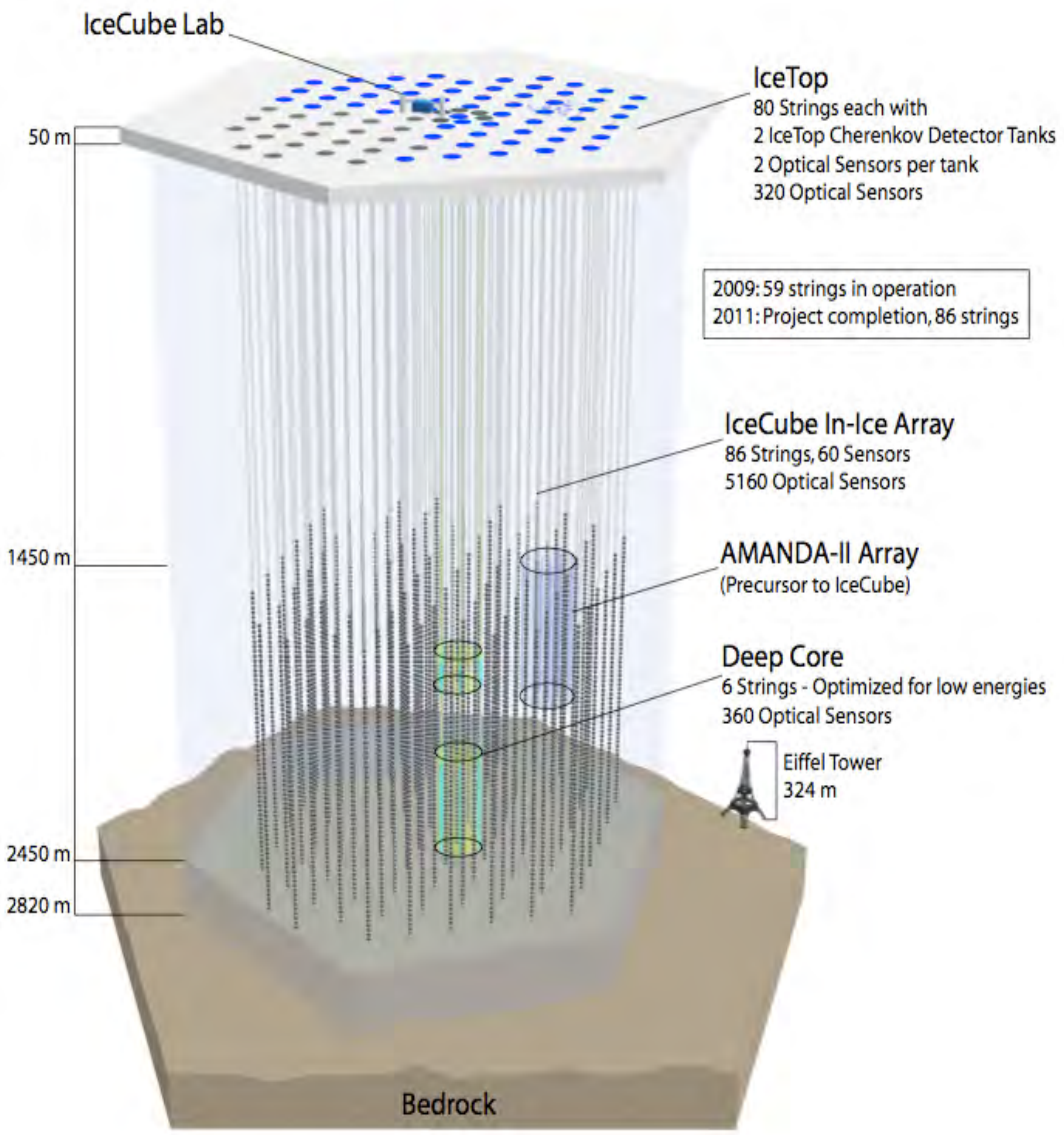

Energy >1 Tev
CTB 87/VER J2016+371
2FGL J2015.6+3709
VER J2019+368
PSR J2021+3651/
2FGL J2021.0+3651
2FGL J2018.0+3626
>600 GeV <1 Tev
+37.5°
+37.0°
+36.5°
+36.0°
Declination (J2000)
24.0m
22.0m
20h20.0m
18.0m
16.0m
14.0m
Right Ascension (J2000)

Milagro - ~6 TeV

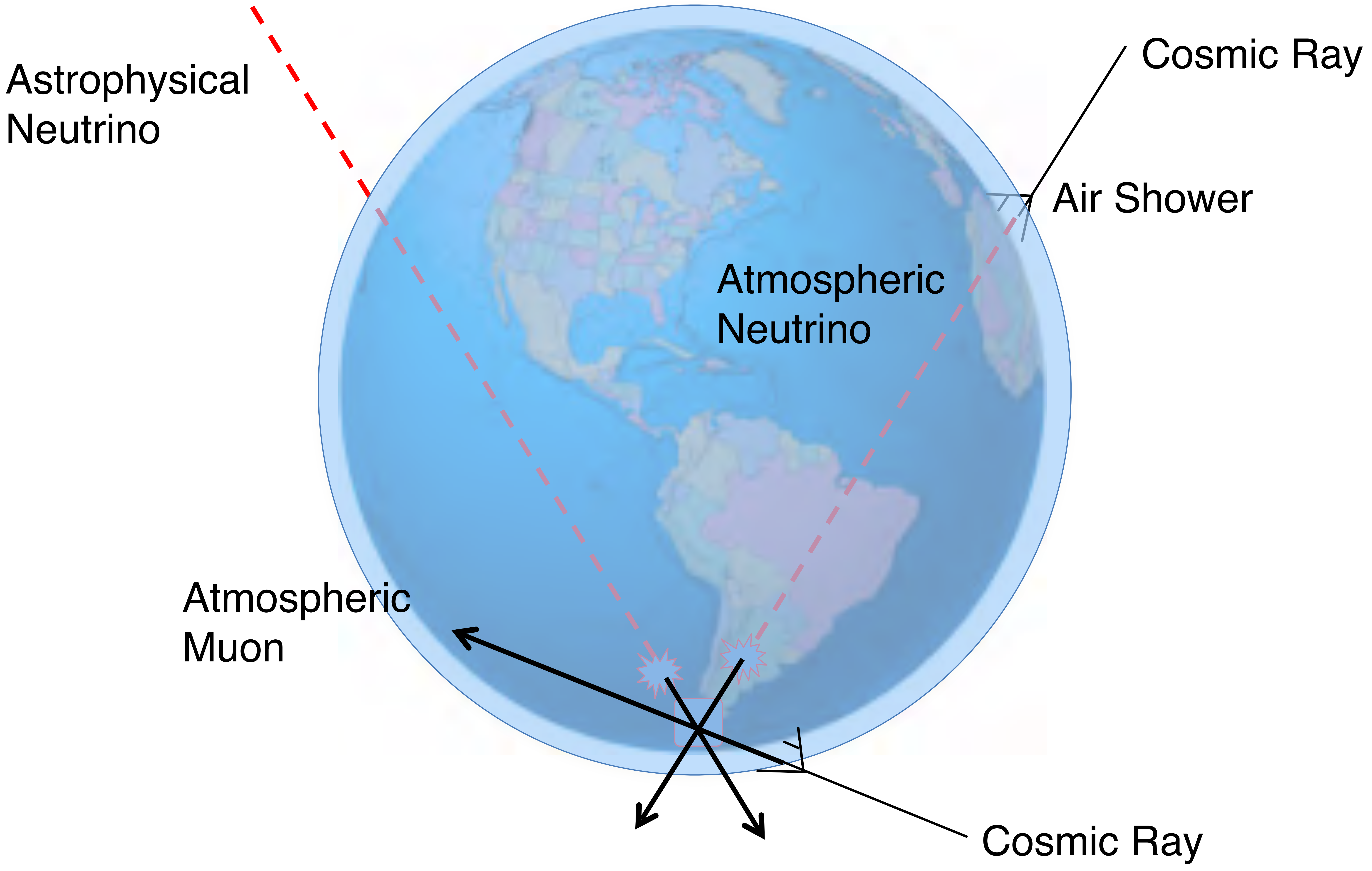




IceCube

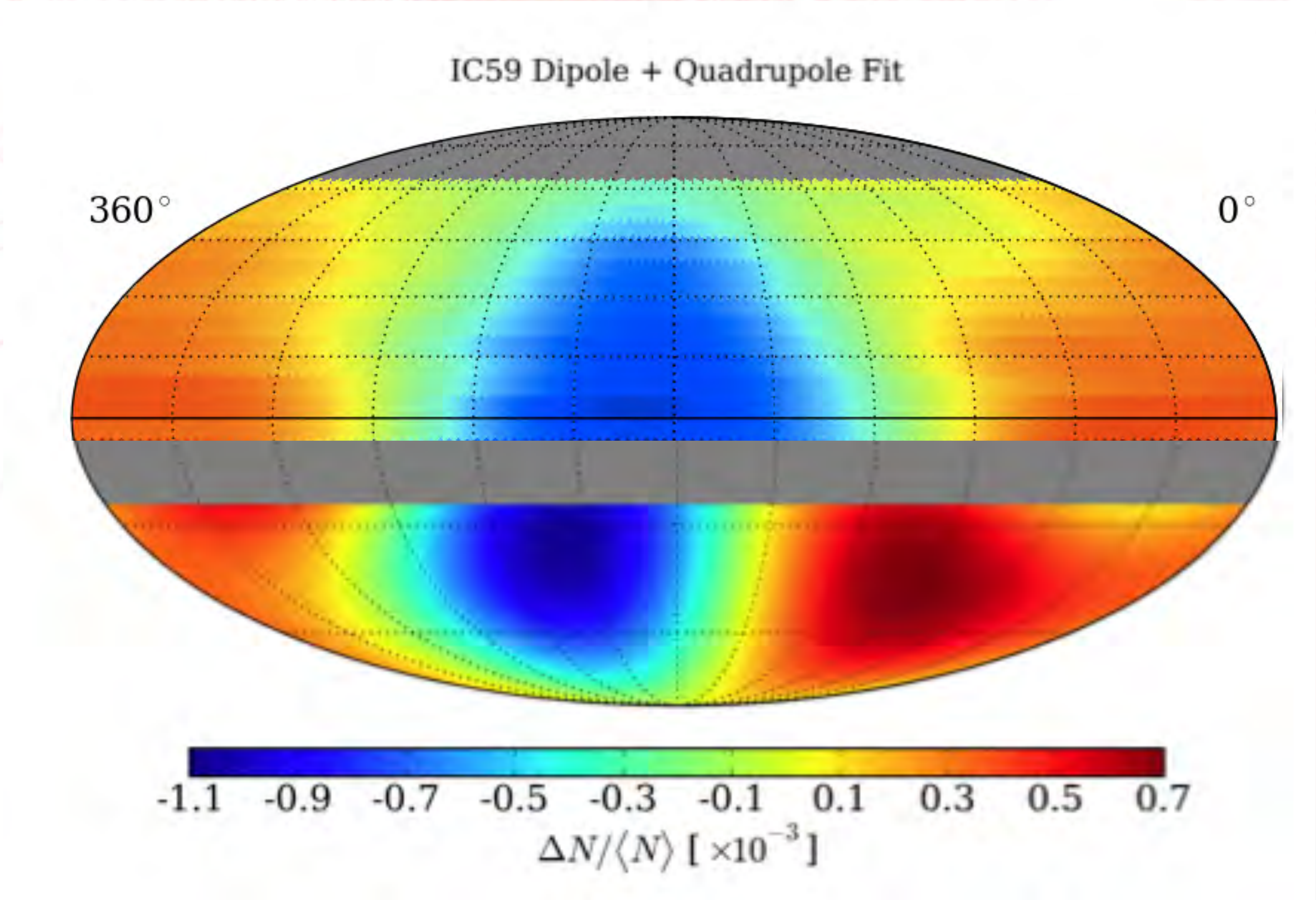

IceCube Lab
IceTop
80 Strings each with
2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors
50 m
2009: 59 strings in operation
2011: Project completion, 86 strings
IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors
1450 m
AMANDA-II Array
(Precursor to IceCube)
Deep Core
6 Strings - Optimized for low energies
360 Optical Sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

IceCube

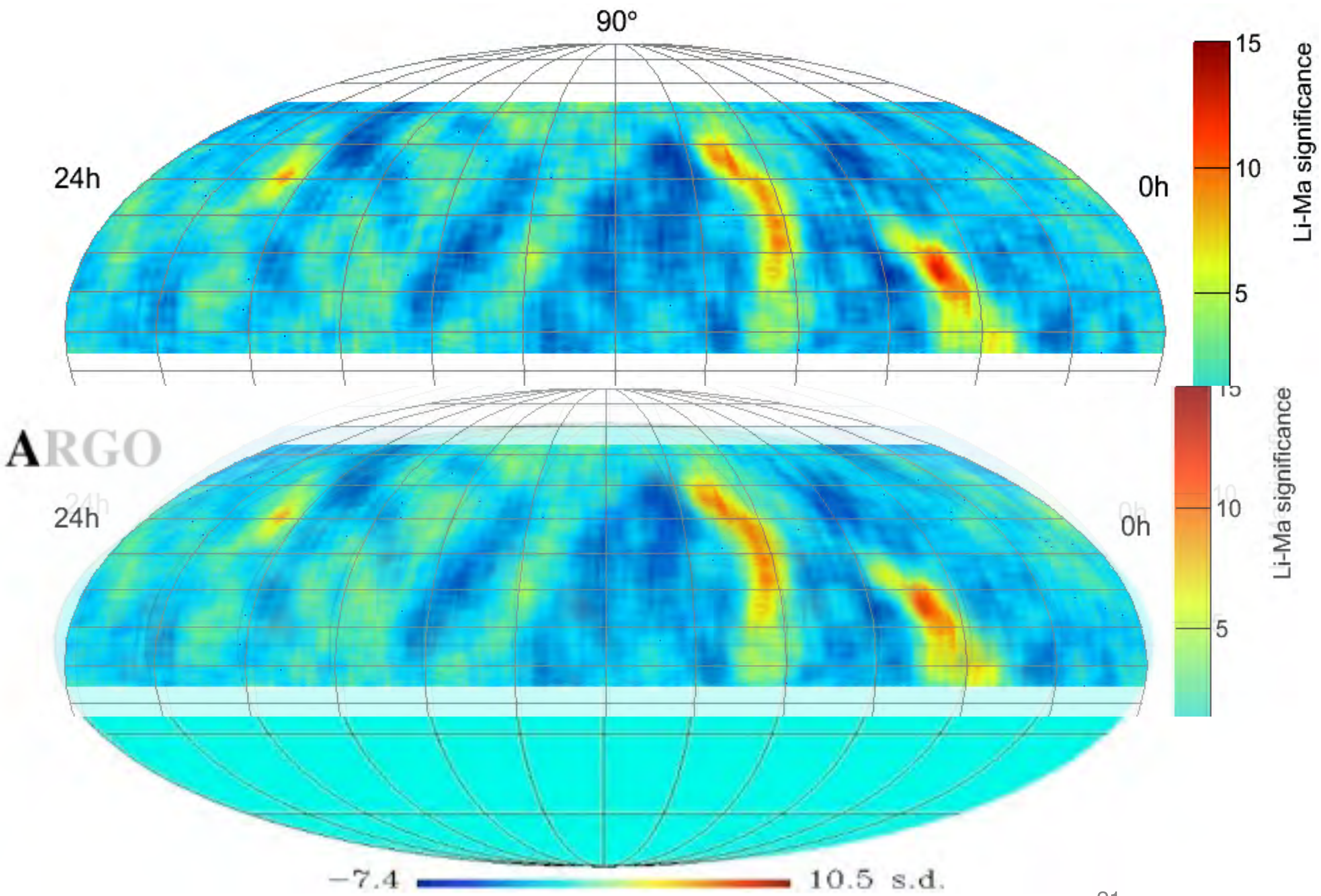


IcCube uses Atmospheric muons from the Southern Hemisphere

Milagro & IceCube



Milagro Results



http://people.roma2.infn.it/~aldo/RICAP09_trasp_Web/Vernetto_ARGO_RICAP09ar.pdf

High Altitude Water Cherenkov