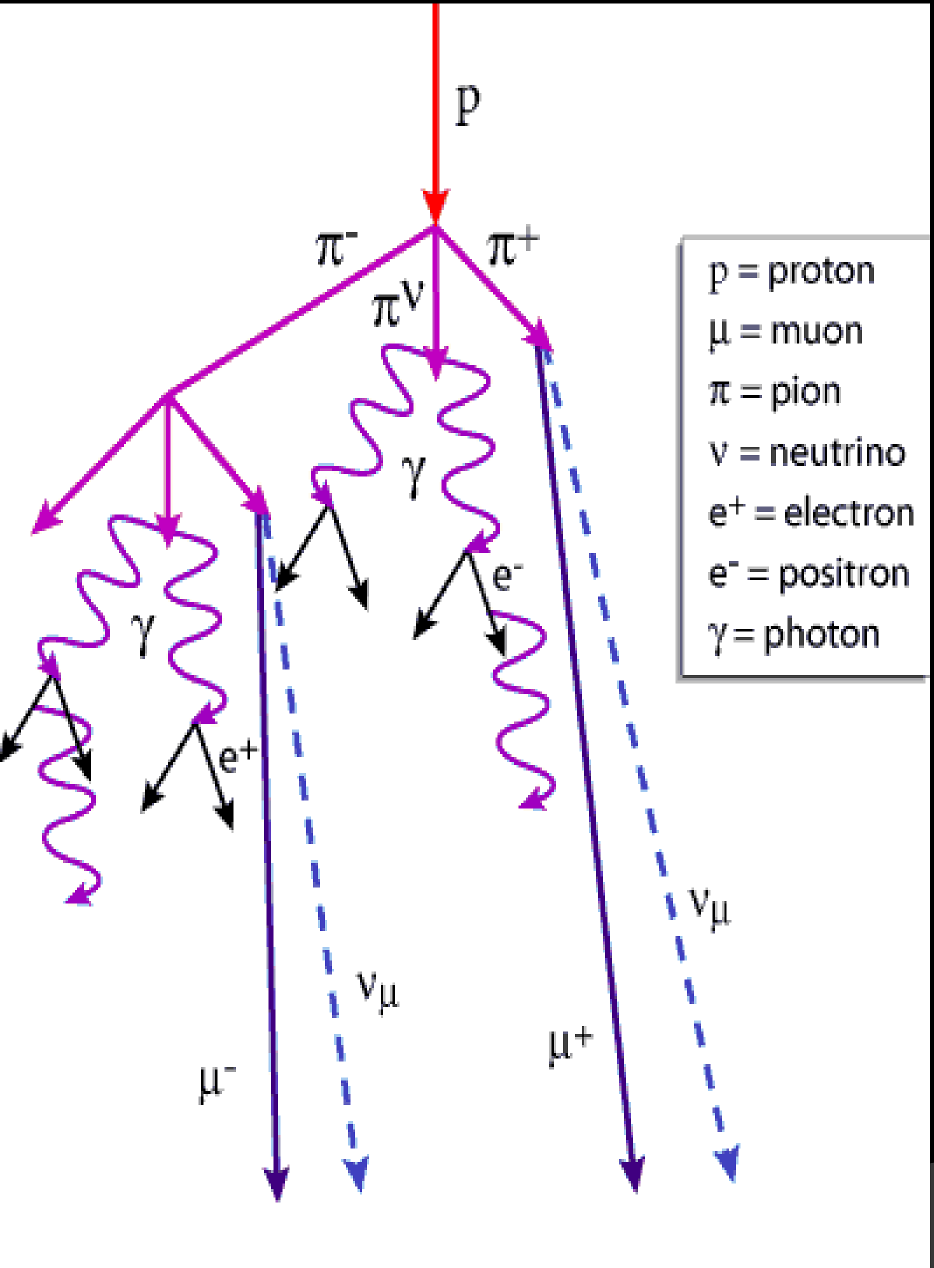
Simulations of Cherenkov Events by Cosmic Ray Muons

John Campbell-UCD School of Physics

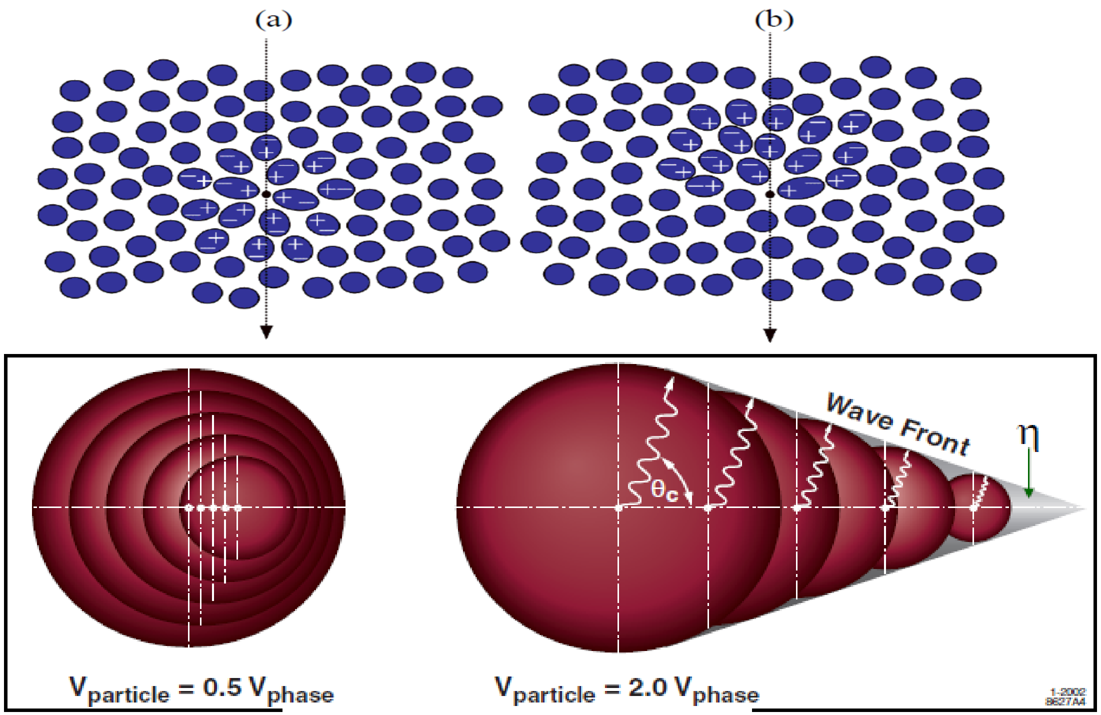
- An explanation of Cherenkov Radiation and Muon Interactions.
- Theoretical models and Physics involved
- Simulations carried out and technology its based on.
- Experimental data from ground based Cherenkov Telescopes, accelerator laboratories on Earth and High Energy detectors in Space.
- Questions.

What are Cosmic Rays?



- Cosmic rays are high energy particles with energies on the order of 10^{18} eV and above, which easily exceeds that of particles generated in even the most powerful man-made particle accelerators.
- The resulting cascade of ultra-relativistic particles are capable of travelling through the atmosphere, generating an air shower which can contain many different components such as a hadron component, an electromagnetic component, a neutrino component, a meson component and a resultant muon component.
- In the diagram, a Cosmic ray particle (usually a proton) collides with a component of the atmosphere and generates a jet of pions. Pions are unstable, with a very short half-life so they decay rapidly into a subsequent shower of muons, gamma rays and neutrinos. The muons, moving at ultra-relativistic velocities are able to survive the trip to the Earth's surface by extension of the muon's half-life due to the time-dilation effects of special relativity.
- It is because the muons move at ultra relativistic speeds that they survive the trip through the atmosphere and are able to interact with the atoms and create Cherenkov radiation.

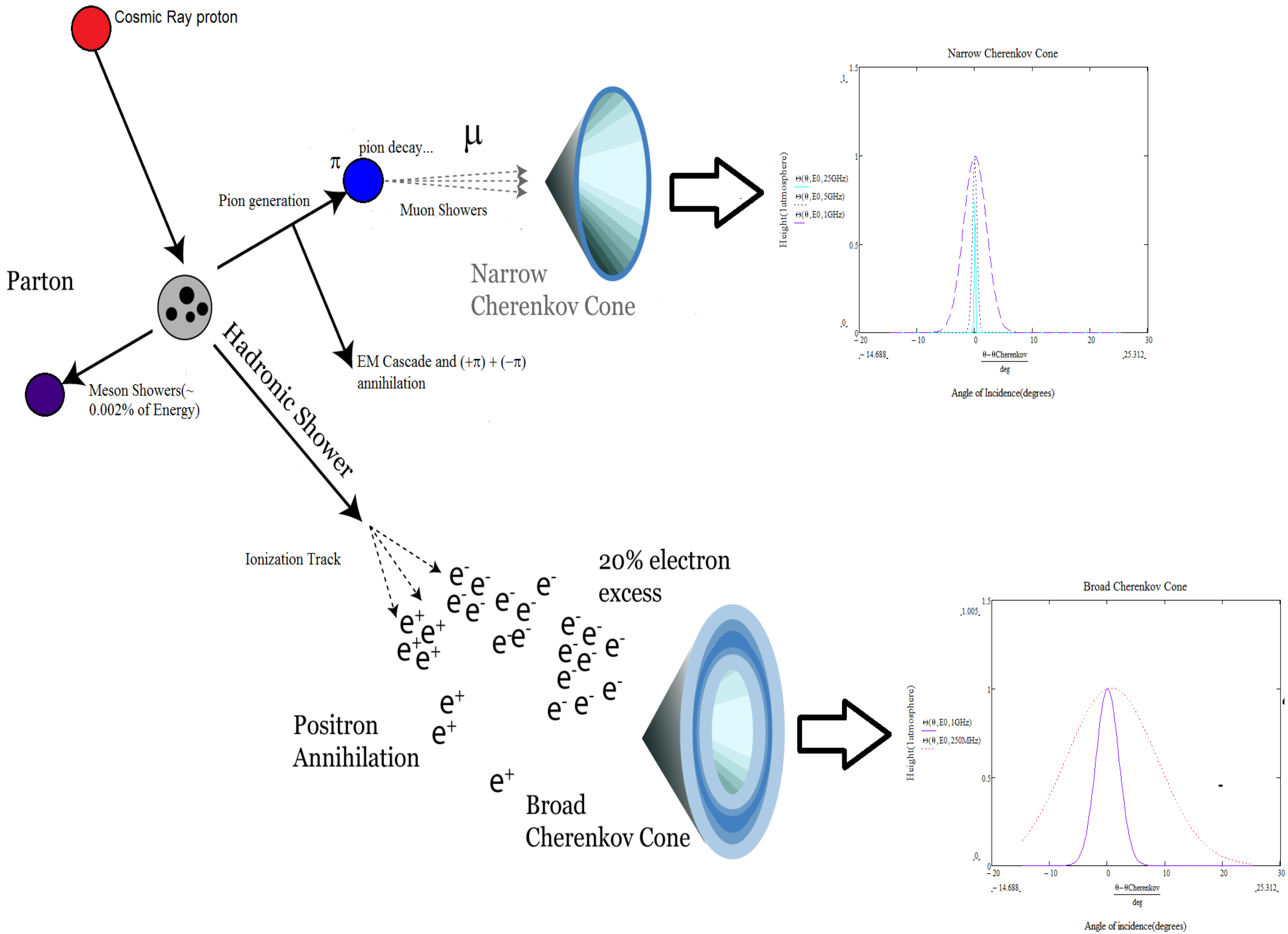
The Cherenkov Effect



$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

$$\frac{dN}{dz} = 2\pi\alpha\left(1 - \frac{1}{(\beta \cdot n(z))^2}\right) \cdot \int_{\lambda_{low}}^{\lambda_{high}} \frac{1}{\lambda^2} d\lambda$$

- In a dielectric medium, the charge of a stationary particle will be cancelled out by effective shielding by isotropic polarization.
- In a non-stationary charged particle, the shielding will react to the region of space where the charge has been, a finite moment ago, creating an anisotropic polarization.
- If the charged particle is travelling at a phase velocity faster than the electric field lines they produce in the air can catch up with them, hence the field lines appear “frozen” in space with respect to the muon. These apparently “frozen” field lines will destructively interfere with the field lines emitted behind the muon trajectory while the field lines constructively interfere with the field lines emitted in front of the muon trajectory.
- The constructive interference creates a burst of electromagnetic radiation.
- The photons emitted along the muon’s path in this way are emitted at an angle, known as the Cherenkov angle, which determines the angular dependence of Cherenkov photons as seen from the observer.
- The criterion for the Cherenkov Effect to occur must be that the value of the refractive index, n, times β,(v^2/c^2), must be greater than 1.
- The Frank-Tamm Equation, numerically calculates the number of Cherenkov Photons produced per meter at a given refractive index over a given interval of observed wavelengths once the Cherenkov Criterion are met.

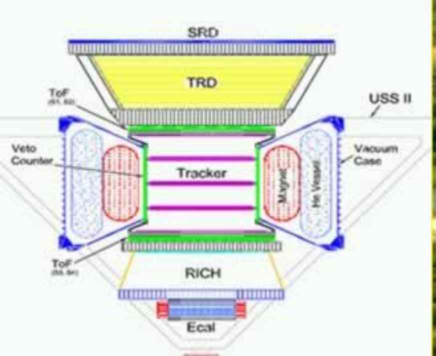


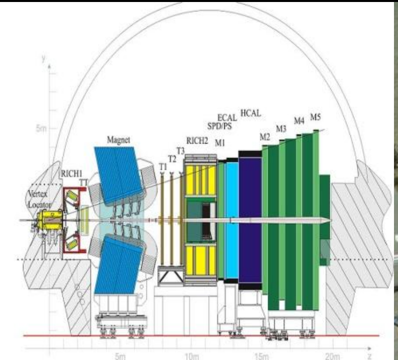
Cosmic Ray proton
Parton
Pion generation
π
pion decay...
μ
Muon Showers
Narrow Cherenkov Cone
EM Cascade and (+π) + (−π) annihilation
Meson Showers(~ 0.002% of Energy)
Hadronic Shower
Ionization Track
20% electron excess
Positron Annihilation
Broad Cherenkov Cone
Narrow Cherenkov Cone
Height(1atmosphere)
Θ(θ,E0,25GHz)
Θ(θ,E0,5GHz)
Θ(θ,E0,1GHz)
θ−θCherenkov
deg
Angle of Incidence(degrees)
Broad Cherenkov Cone
Height(1atmosphere)
Θ(θ,E0,1GHz)
Θ(θ,E0,250MHz)
θ−θCherenkov
deg
Angle of incidence(degrees)

Detecting Cherenkov Photons.

- Detecting the spatial distribution of Cherenkov photons allows us to reconstruct the Cherenkov cone radius and identify the core of the shower.
- Detecting the angular distribution of Cherenkov Photons allows us to reconstruct the Cherenkov angle for a given event which, if the refractive index is known ,can allow us to find the incident angle of the particle(and vice versa to find the refractive index or Cherenkov angle and so on.)
- In either case, detecting Cherenkov photons over a given wavelength range infers that a particle is moving at a particular velocity in a particular medium, thus it is a good way to measure the energy of a particle and identify different events/particles.

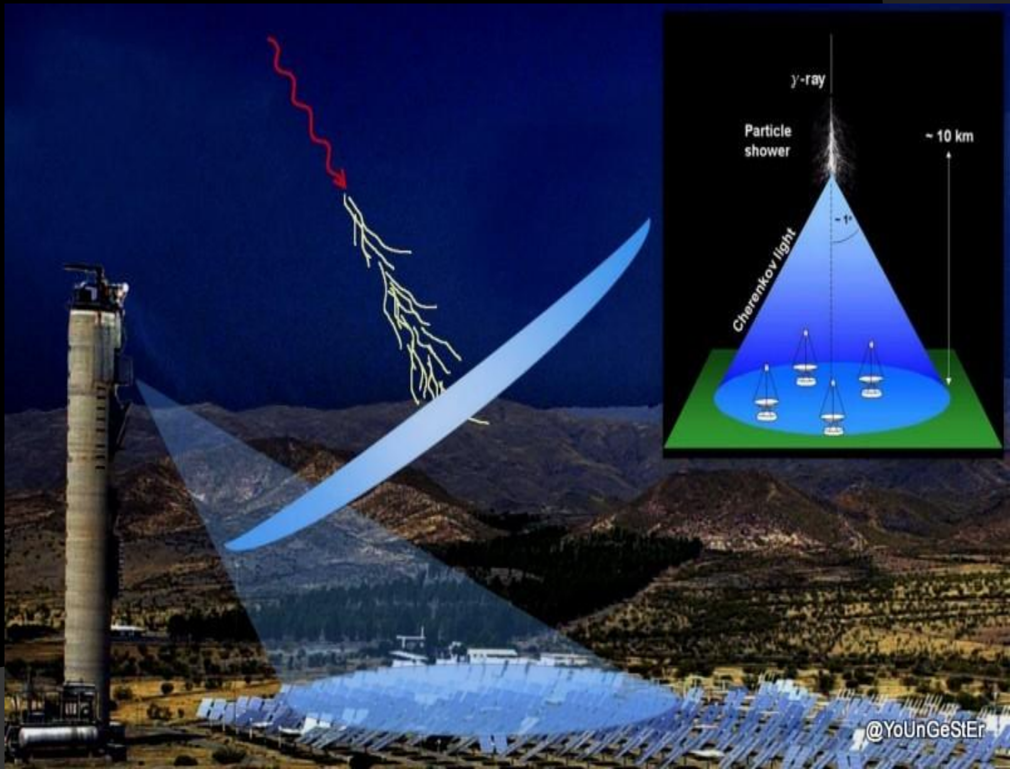
- Solid state detectors used in particle accelerators and reflecting aperture detectors used in Cherenkov Telescopes must be of the type to either preserve spatial or angular distribution for detection and use this information to generate an image of the event.
- Ring Imaging Cherenkov (RICH) detectors and Imaging Atmospheric Cherenkov Telescopes(IACT) record spatial distributions of Cherenkov Photons on the ground and can reconstruct angular distribution.
- Detection of Internally Reflected Cherenkov light(DIRC) detectors and Solar Tower Atmospheric Cherenkov(STAC) detectors preserve the angular information and can reconstruct the spatial distribution.



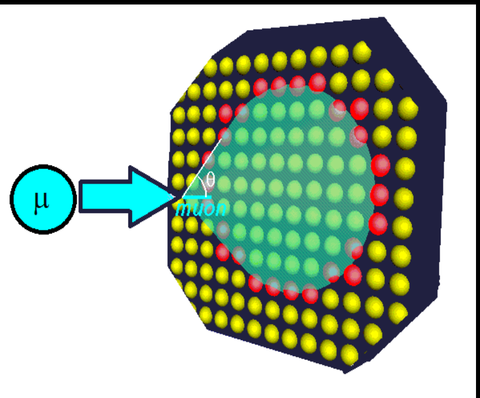


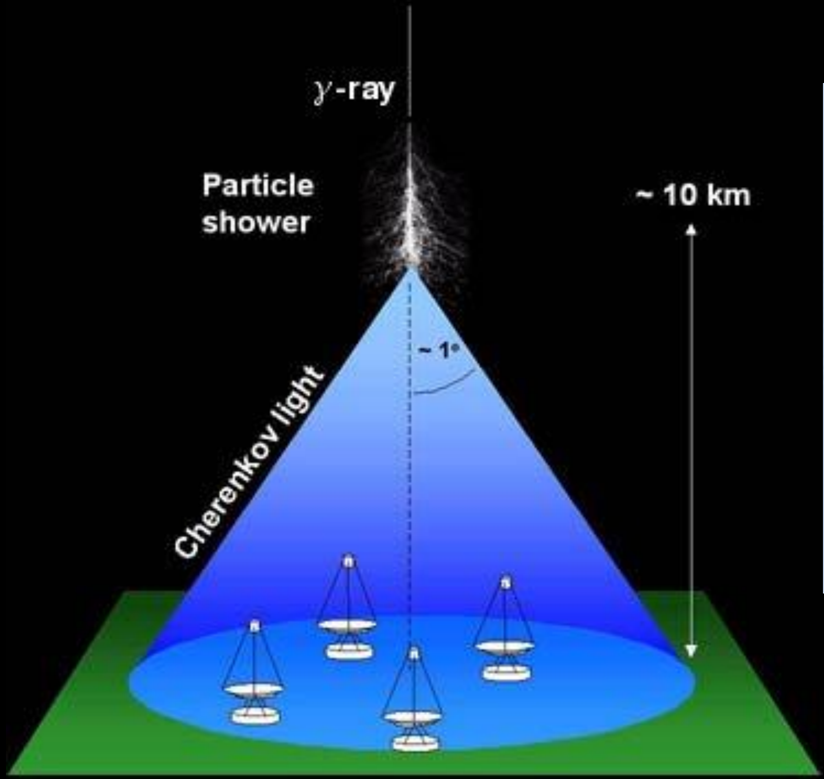
Detecting Cherenkov Air Showers:

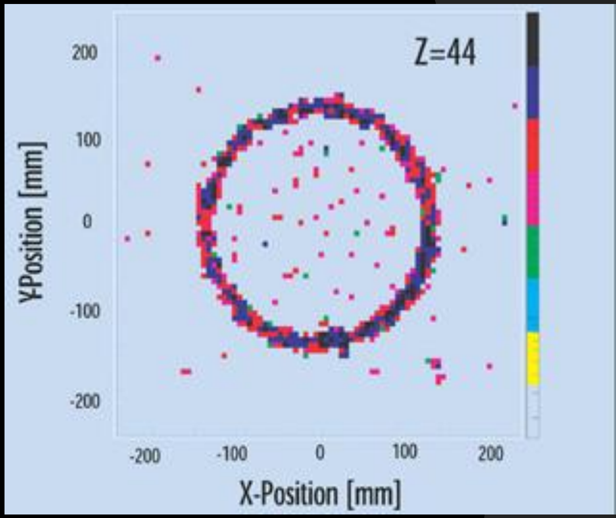
- There are 2 main methods for resolving Cherenkov Air showers:
- (1) use single detectors in an array to detect events in coincidence and reconstruct the air shower manually
- (2) create a large array of reflector apertures and direct the Cherenkov Light, preserving the angle of incidence, to a single detector or perhaps many detectors-> this method preserves the angular information for a single event without manual reconstruction(if the array is large enough)



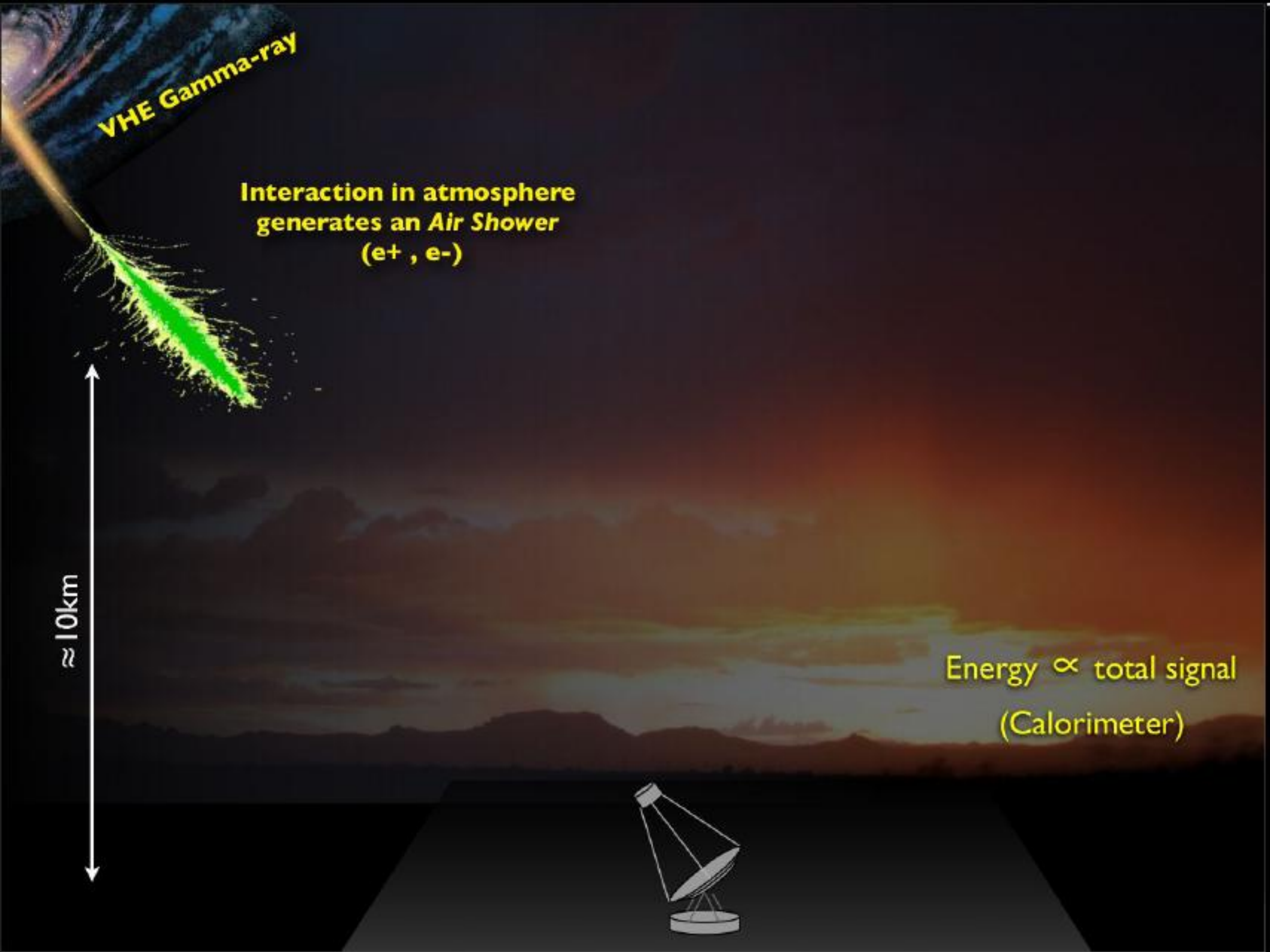
- Full Cherenkov events can be resolved by a single detector, as a ring, if the particle or gamma ray falls into the detector aperture...



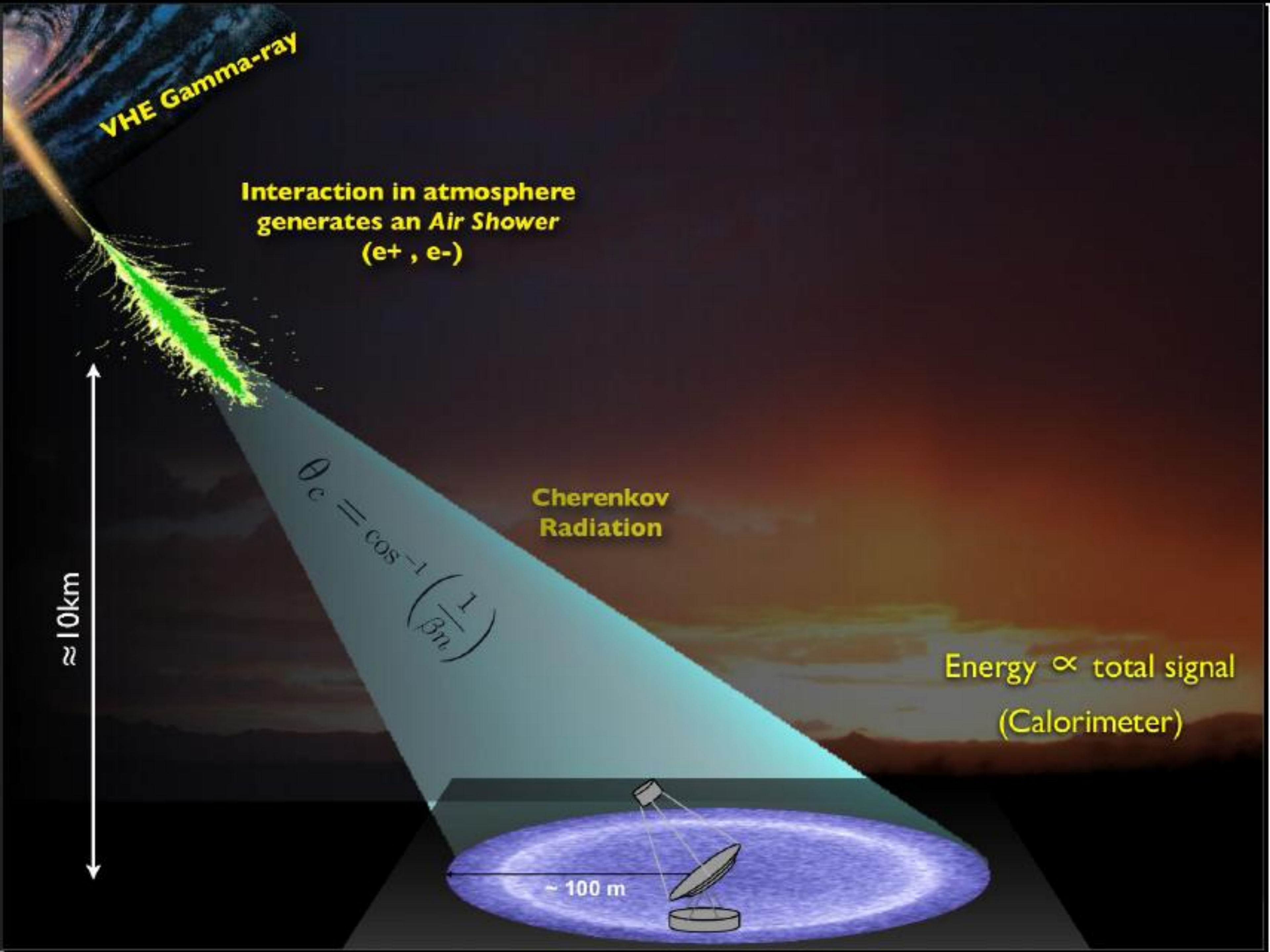




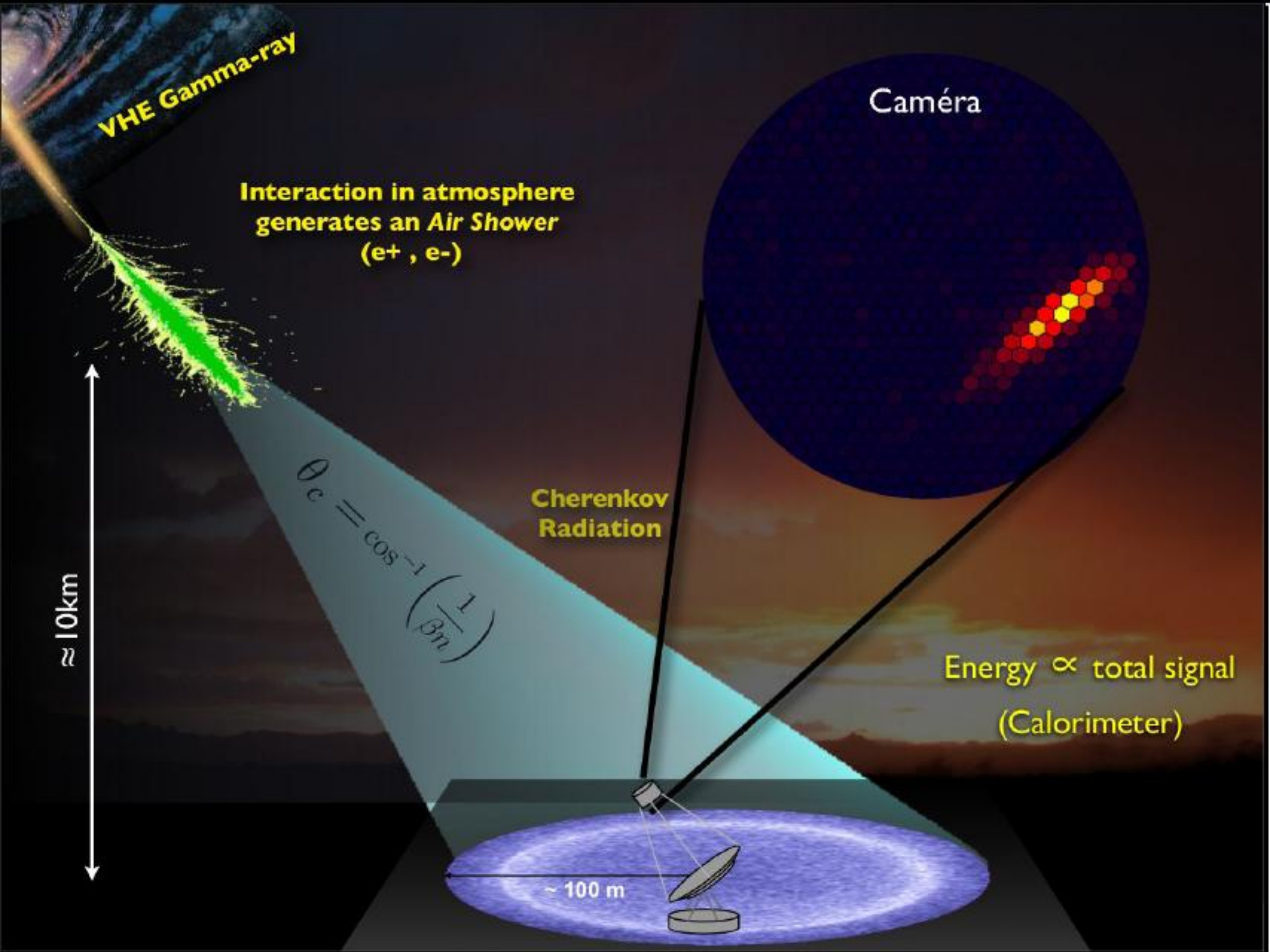
An elliptical distribution of Cherenkov photons is seen if the particle or gamma ray is outside the detector aperture or at an angle grazing pass the detector. Having telescopes in array allows to reconstruct the full cone...



VHE Gamma-ray
Interaction in atmosphere
generates an *Air Shower*
(e+ , e-)
≈ 10km
Energy ∝ total signal
(Calorimeter)



VHE Gamma-ray
Interaction in atmosphere generates an *Air Shower* (e+ , e-)
Cherenkov Radiation
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
≈ 10km
Energy ∝ total signal
(Calorimeter)
~ 100 m



VHE Gamma-ray
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Caméra
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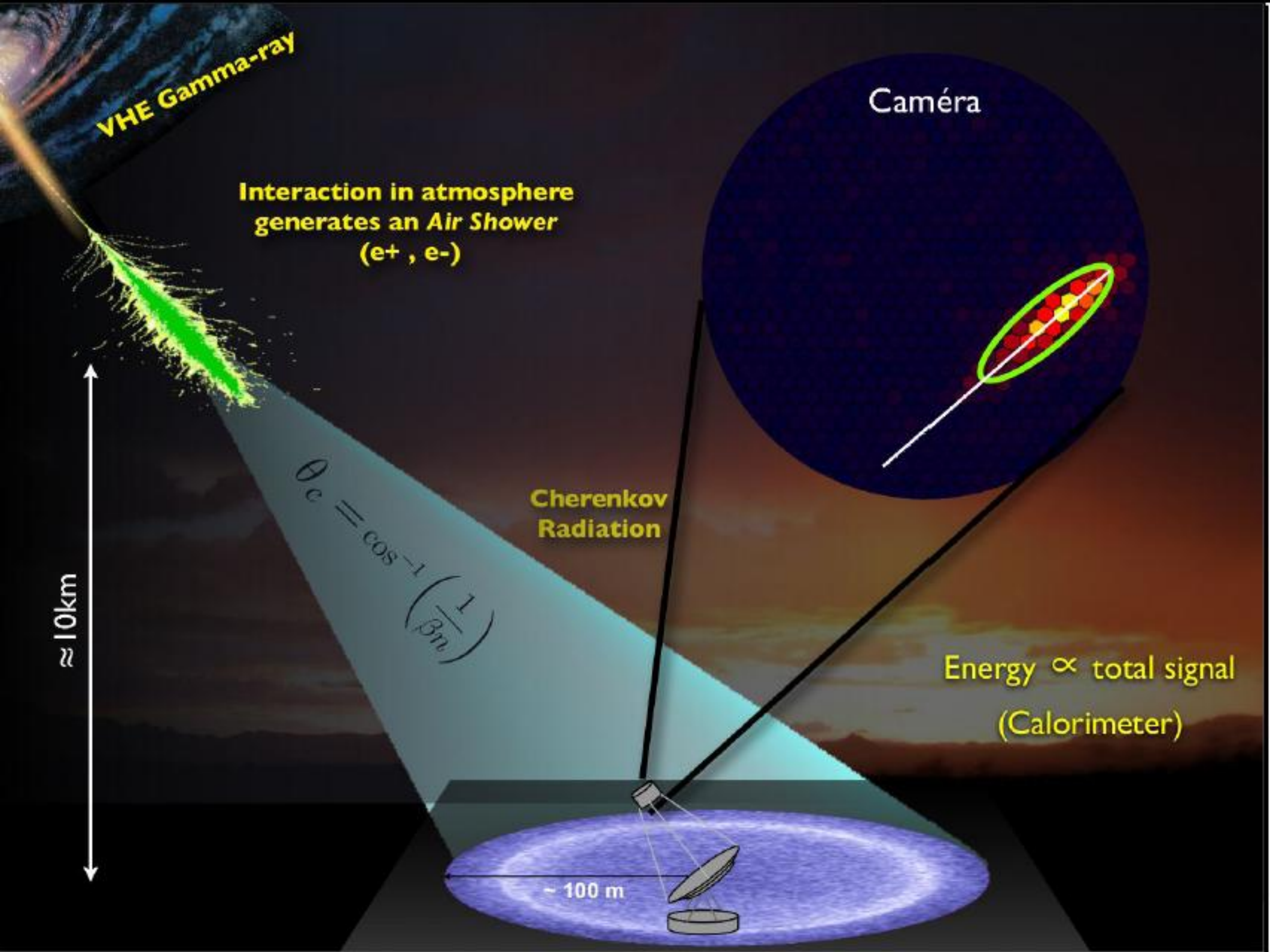
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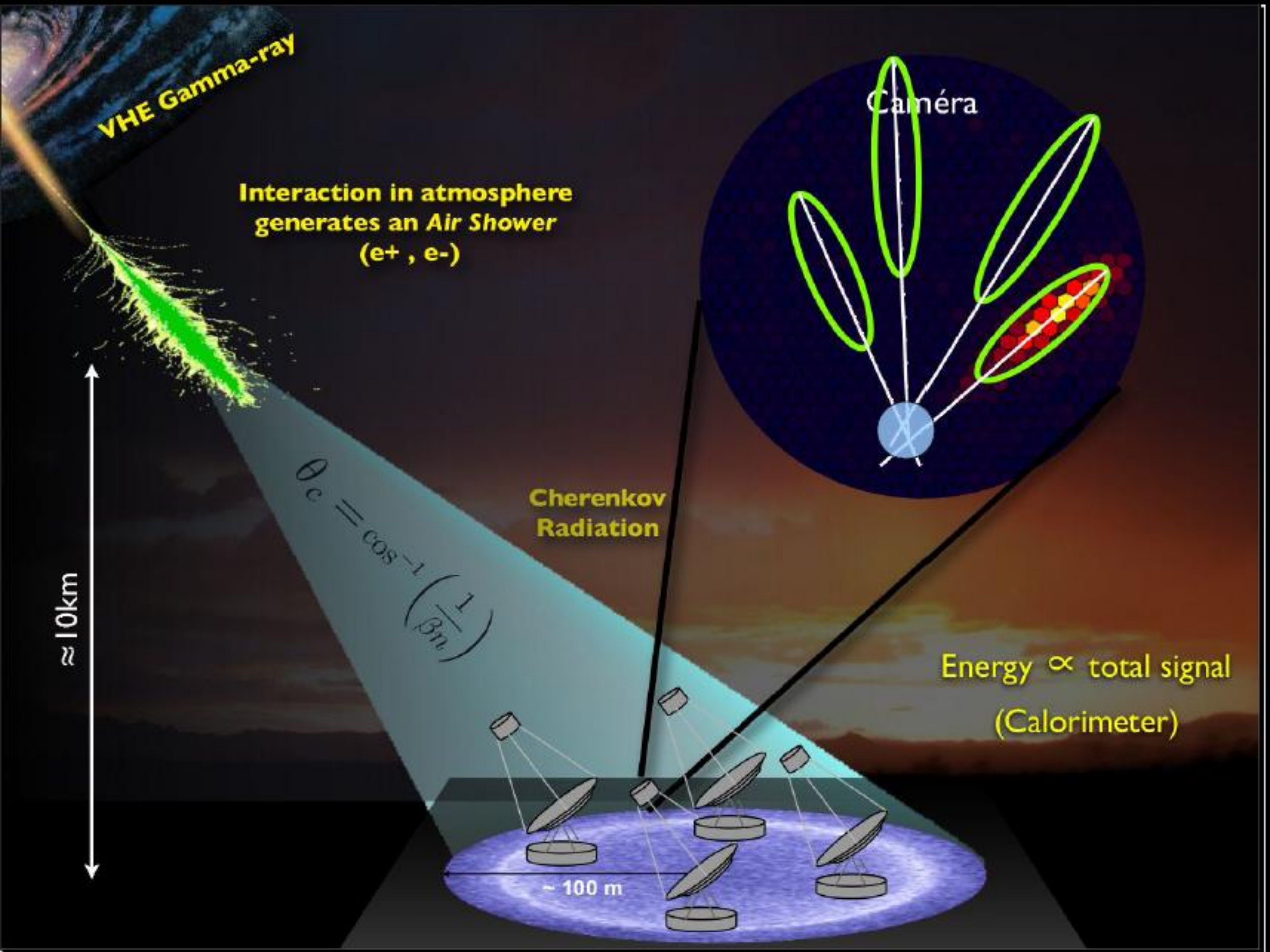

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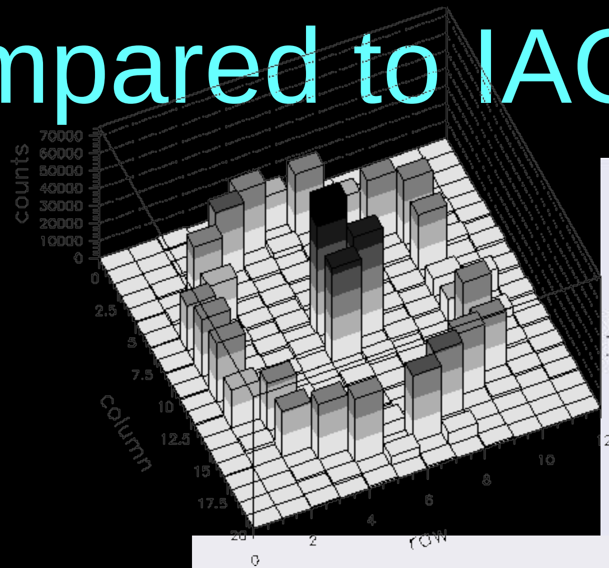
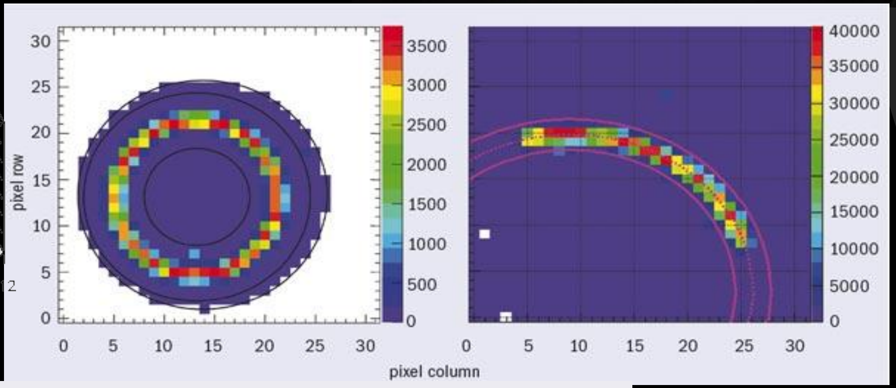
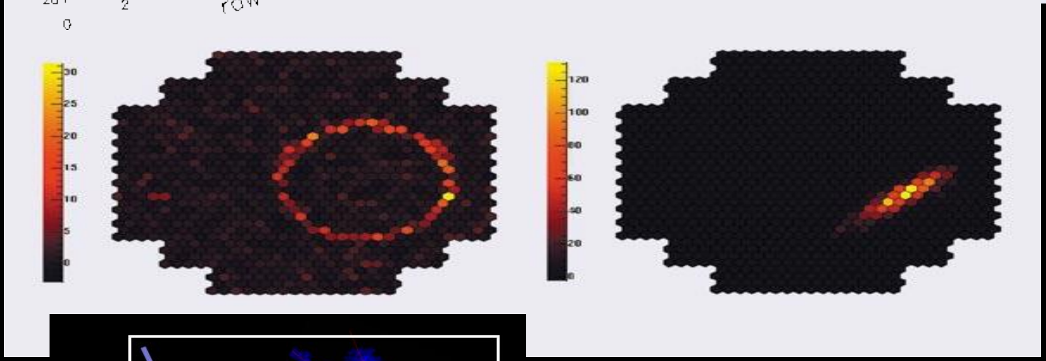
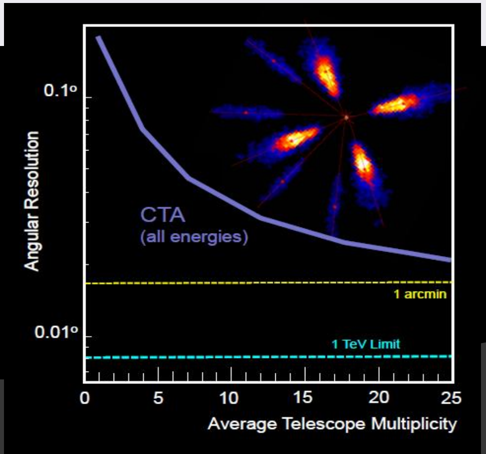
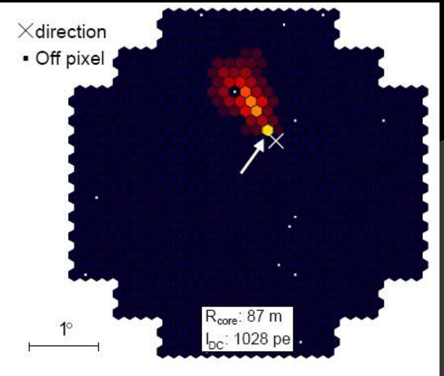
Spatial Detection(RICH compared to IACT)



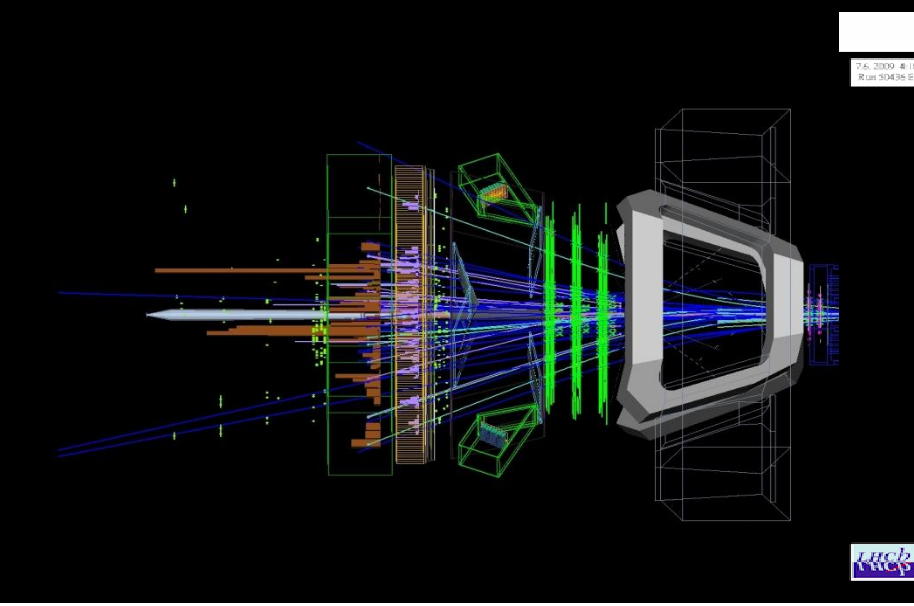


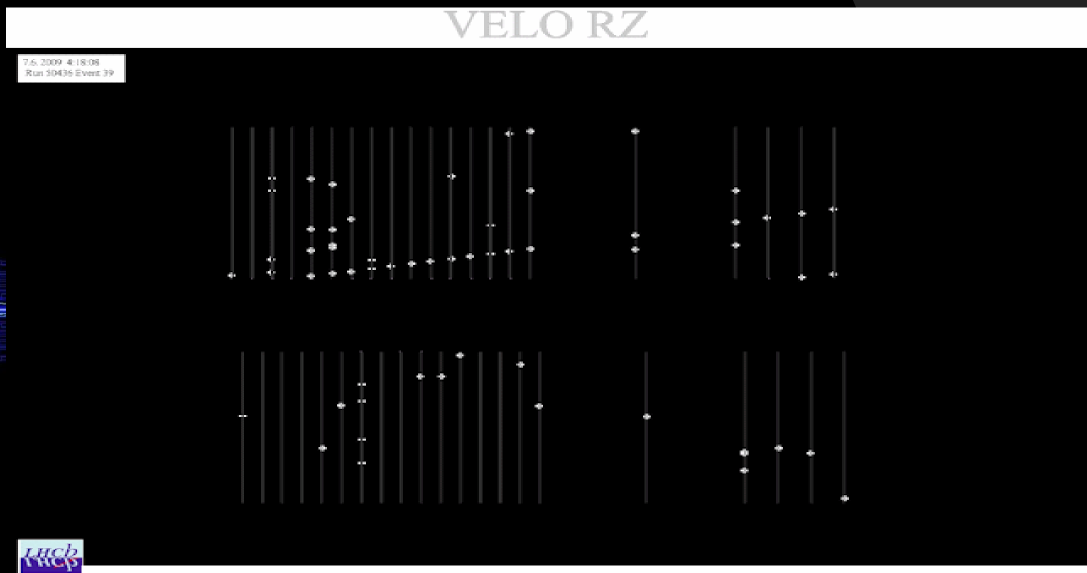


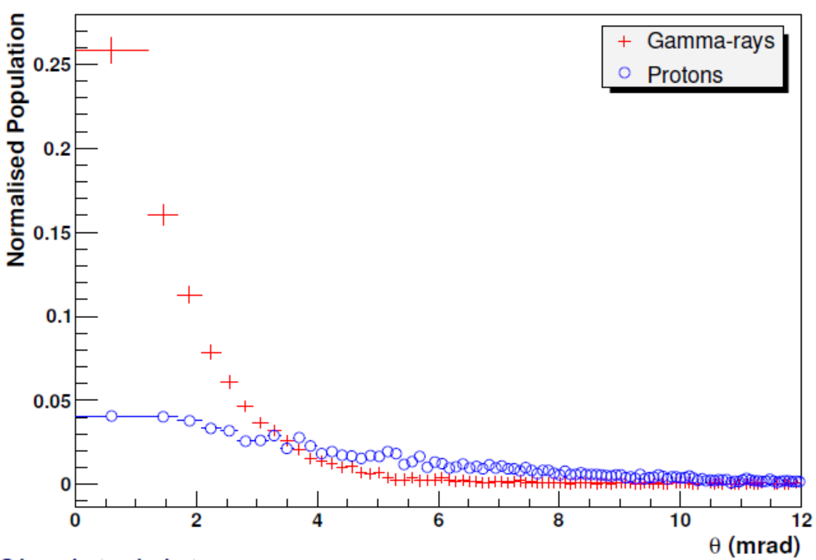


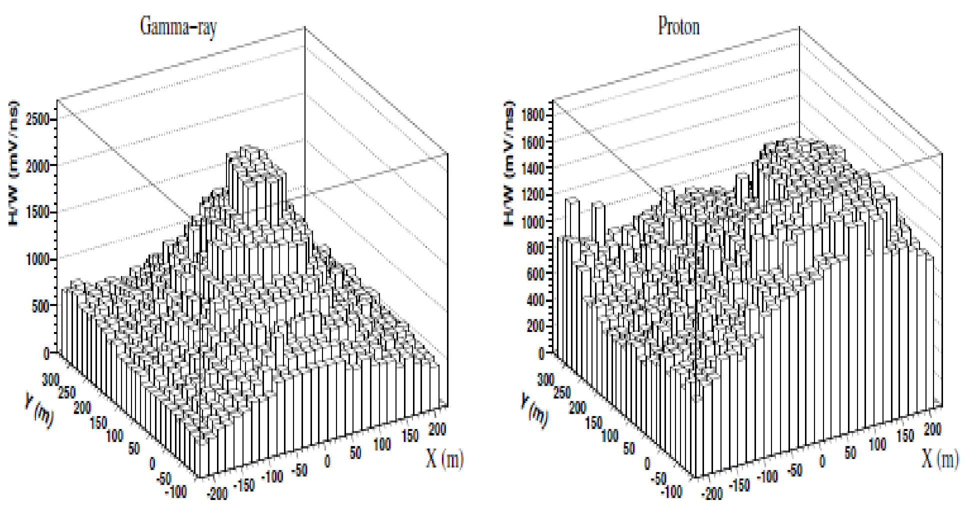


Angular detection(DIRC(LHCb)compared to STACEE)

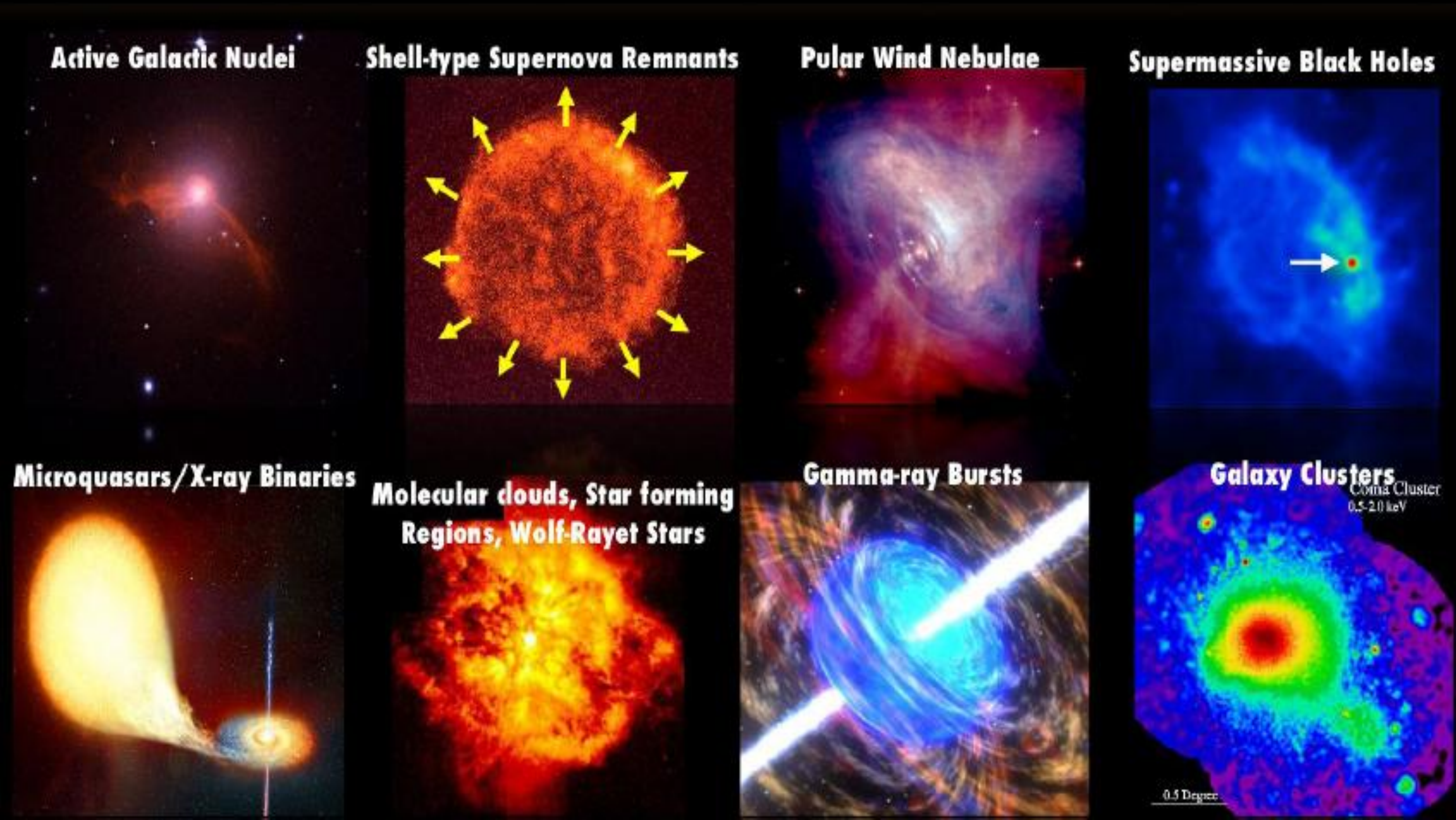






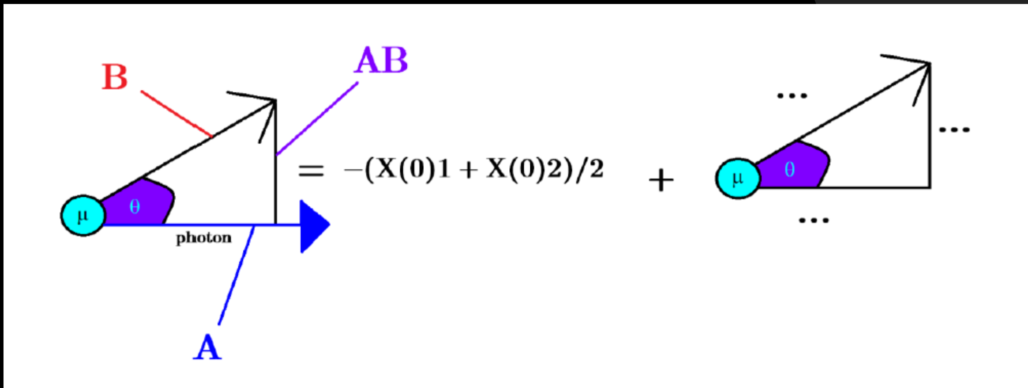


Sources of High Energy Cosmic Rays and Gamma Rays.



Particle-matter interactions

- Aside from random events(such as heavy nuclei present in Cosmic Rays) there are interactions with the atoms in the atmosphere which must be taken into account.
- Due to the high energy of the particles and low atomic number of atoms in the atmosphere, interactions with the nuclei are more important than the interactions with the electrons.
- Bremsstrahlung and Coulomb scattering are therefore the main factors in influencing the Cherenkov photon distribution.
- Excess electrons can be produced through ionisation but on a factor of Z (the typical charge of atomic nuclei) less than the coulomb and bremsstrahlung events.



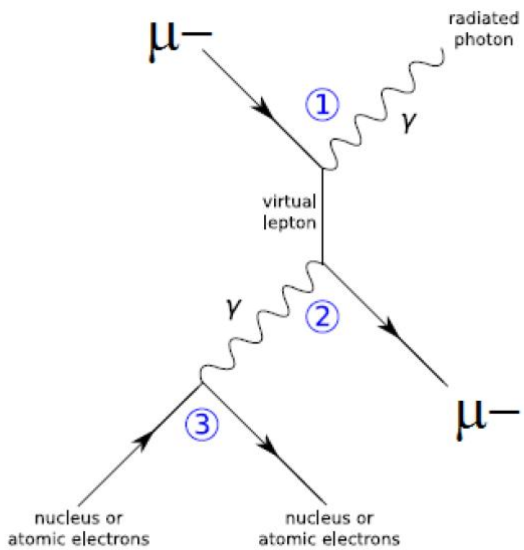
$$n = \eta + e^{-x/x(0)}$$

$$tmax = \frac{X(r)}{100\%} = \mathrm{Log}\left(\frac{\overline{AB}}{X(0)1} + \frac{\overline{BC}}{X(0)2} + \ldots N\right)/\mathrm{Log}(2)$$

$$E(n) = E(0)^{-tmax} \approx tmax(E(0) = Є) \Rightarrow tmax \sim E(n\_max) * tmax =$$

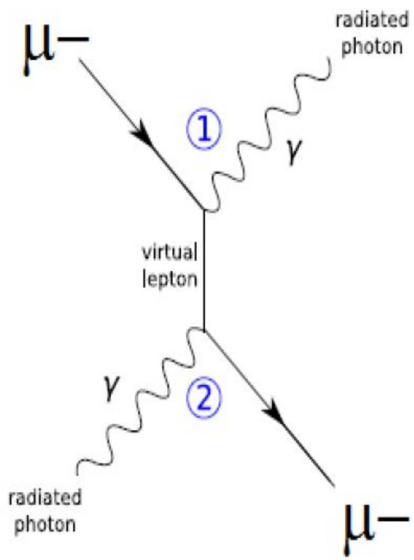
$$[\ \ln (E(0) / Є) / \ln 2\ ] \times (X0)$$

$$\frac{4}{3}\left(\frac{1+x}{1-x}\right)+\frac{1}{2}\left(x^2+(1-z)^2\right)$$



$$\sigma_{\text{nuclei}} \propto \frac{Z^2\alpha^3}{m^2}$$

$$\sigma_{\text{electrons}} \propto \frac{Z\alpha^3}{m^2}$$



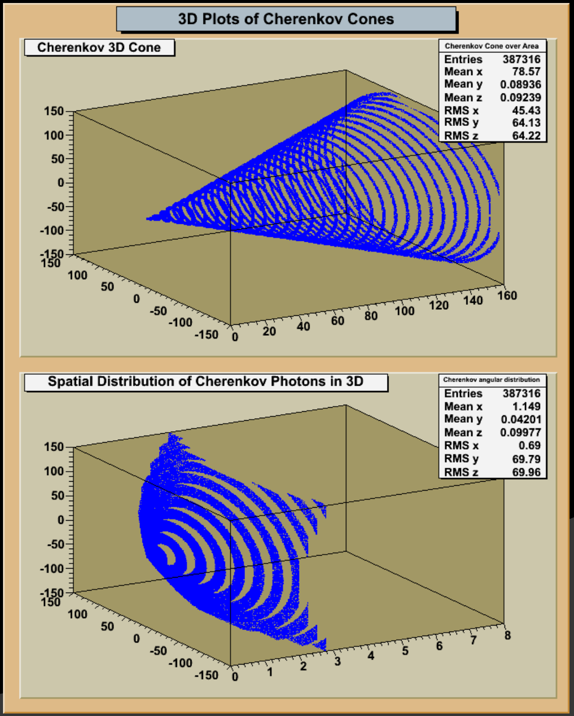
$$\frac{8}{3}\left(\frac{1+x}{1-x}\right)$$

$$\sigma_C = \frac{8\pi}{3}\frac{\alpha^2}{m^2}$$

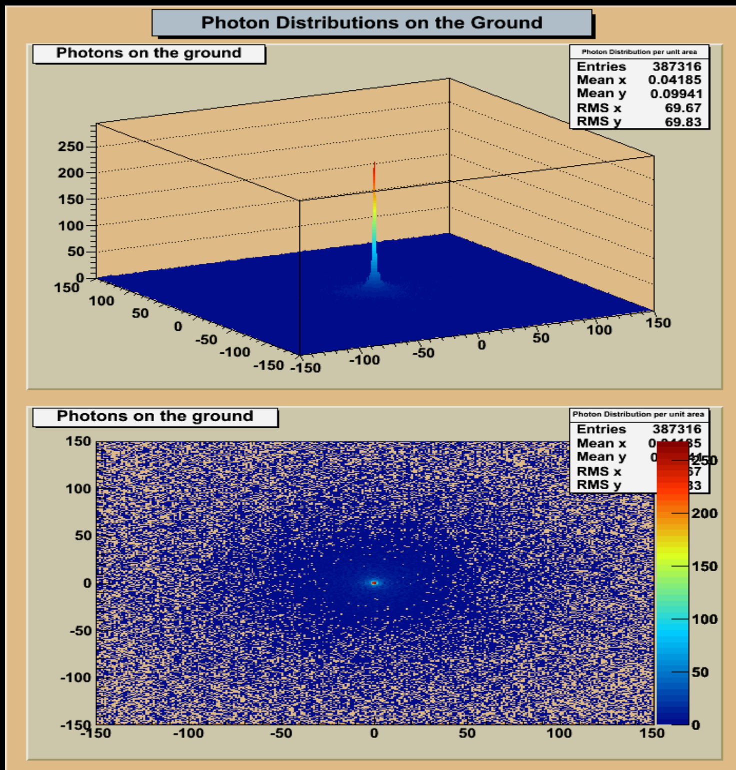
- The diagrams describe Bremsstrahlung and High energy Coulomb Scattering, i.e. electromagnetic interactions of the muon with the field of nuclei as it passes through the atmosphere.
- The first diagram is the standard description of bremsstrahlung of a muon, which the muon exchanges 2 photons and is described by a 2-loop vertex function, which generates the cross section(or probability amplitude squared) of the photons emitted.
- By removing the influence of the atoms and allowing the muon to freely emit the photons in any direction, a high energy approximation to coulomb scattering can be made, which was implemented as a function of impact parameter.
- By simulating the Bremsstrahlung photons and Coulomb interactions as an energy splitting of the muon’s initial energy, the simulation can simulate effects beside Cherenkov Radiation, creating a more complete picture.

Simulating the muon component of an air shower.

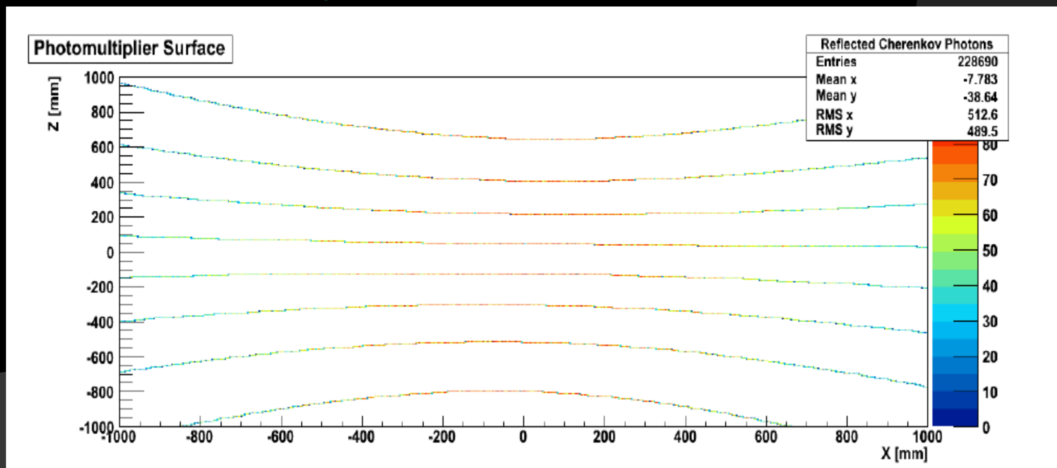
- Using Poisson Statistics working on a mean number of Cherenkov photons, produced by solving the Frank-Tamm equation for a wavelength range(the sensitivity range of a PMT) and a given refractive index which changes as we simulate the muon falling through the atmosphere
- Cherenkov Photons can be given off in rings by calling the formula and generating the distribution over a number of steps along a certain height of the shower(typically 10-8 km)
- Using Monte Carlo statistics within the Cherenkov radius, the photons given off can be distributed randomly within a cone, simulating a full Cherenkov event in 3D.



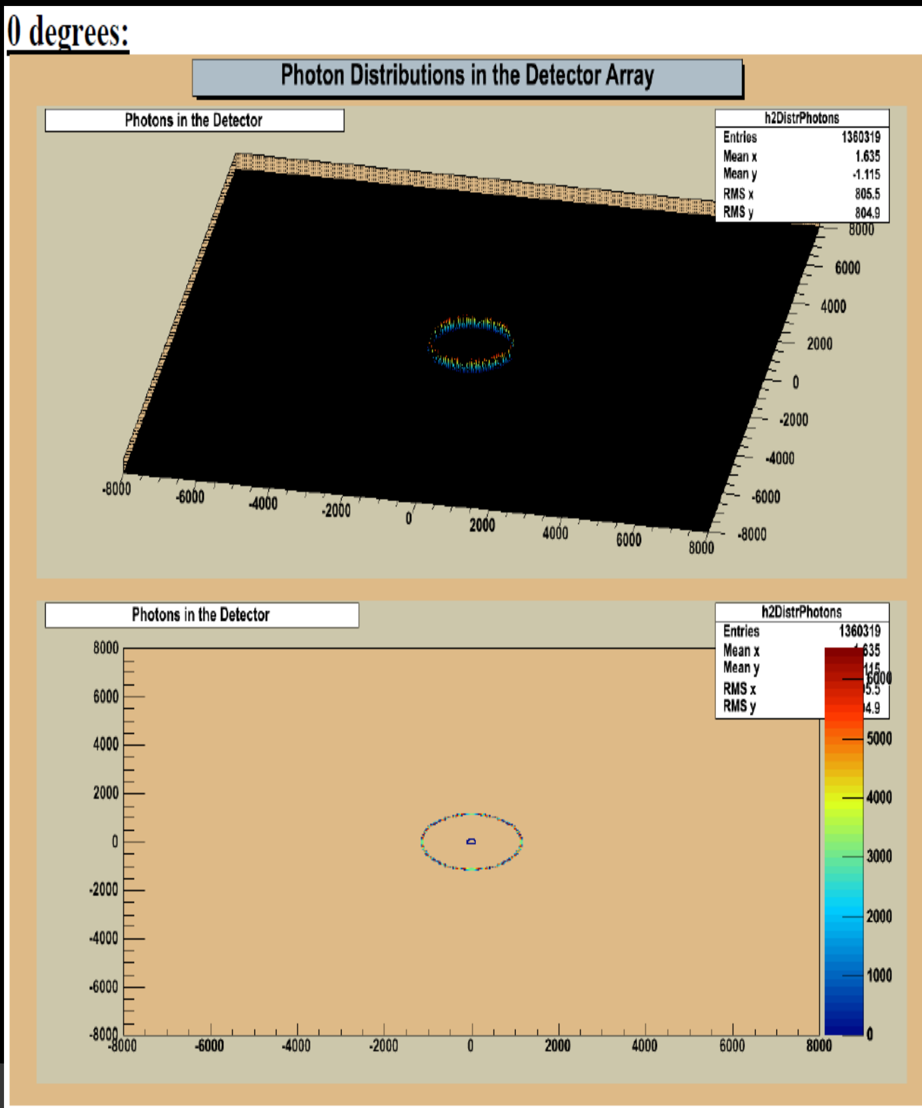
- The Cherenkov and Monte Carlo photons can be distributed as viewed from the ground, which is a random distribution of photons with a well defined shower core.

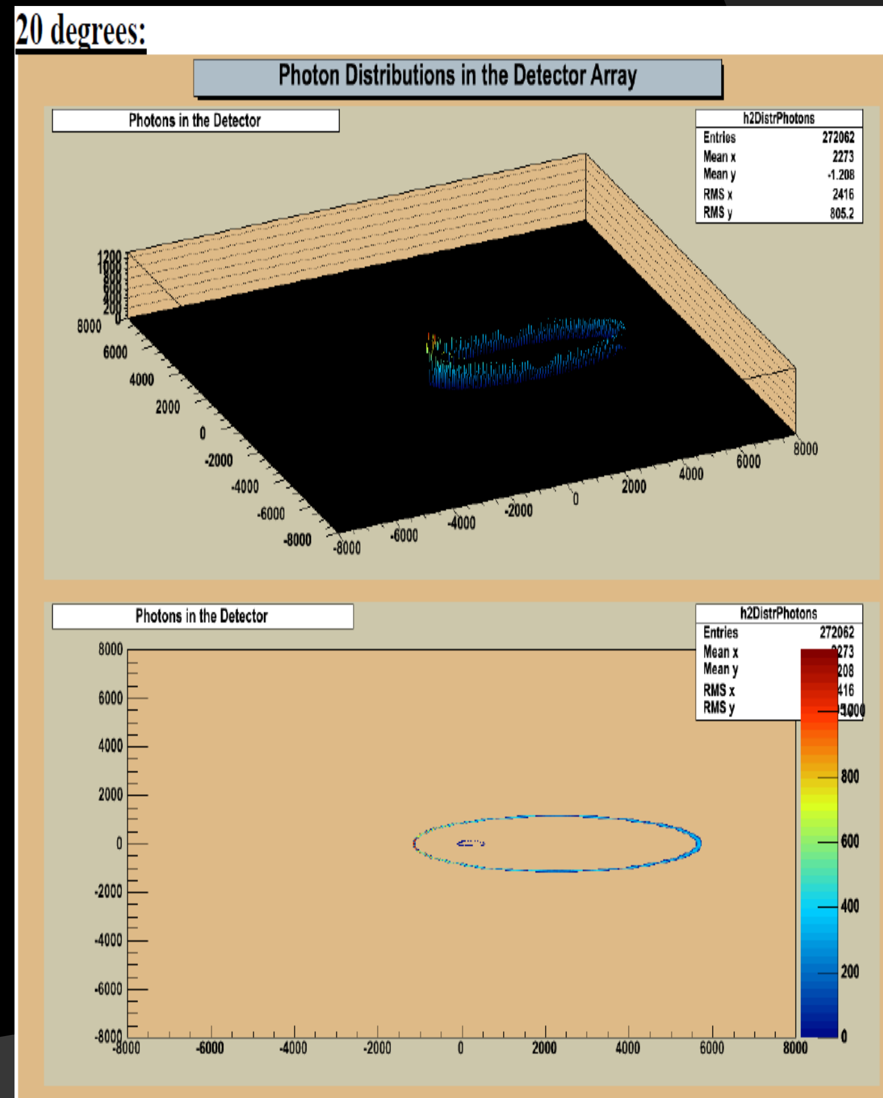


- By simulating an aperture the photons can be reflected and inverted in their directions and can be detected by either hitting or missing a detector placed at a given position relative to the incident photon (Hit versus Position method)
- This can be simulated for a single PMT with a given quantum efficiency and we can see a crude type of ray-tracing of the photons.
- Adding more PMTs generates more complexity and harder statistics to work with.
- Using Poisson statistics again over a given mean field of view (3.5 degrees) for a given number of PMT pixels(499) the responses can be simulated as the photons are detected randomly over time.
- The reconstructed Image can then be displayed as seen in the detector camera.
- Adding further effects(bremsstrahlung, coulomb scattering, ect) adds time to process the information but generates reasonable images.
- Adding more complex dynamics, impact parameters and incident angles adds complexity but better simulates reality.

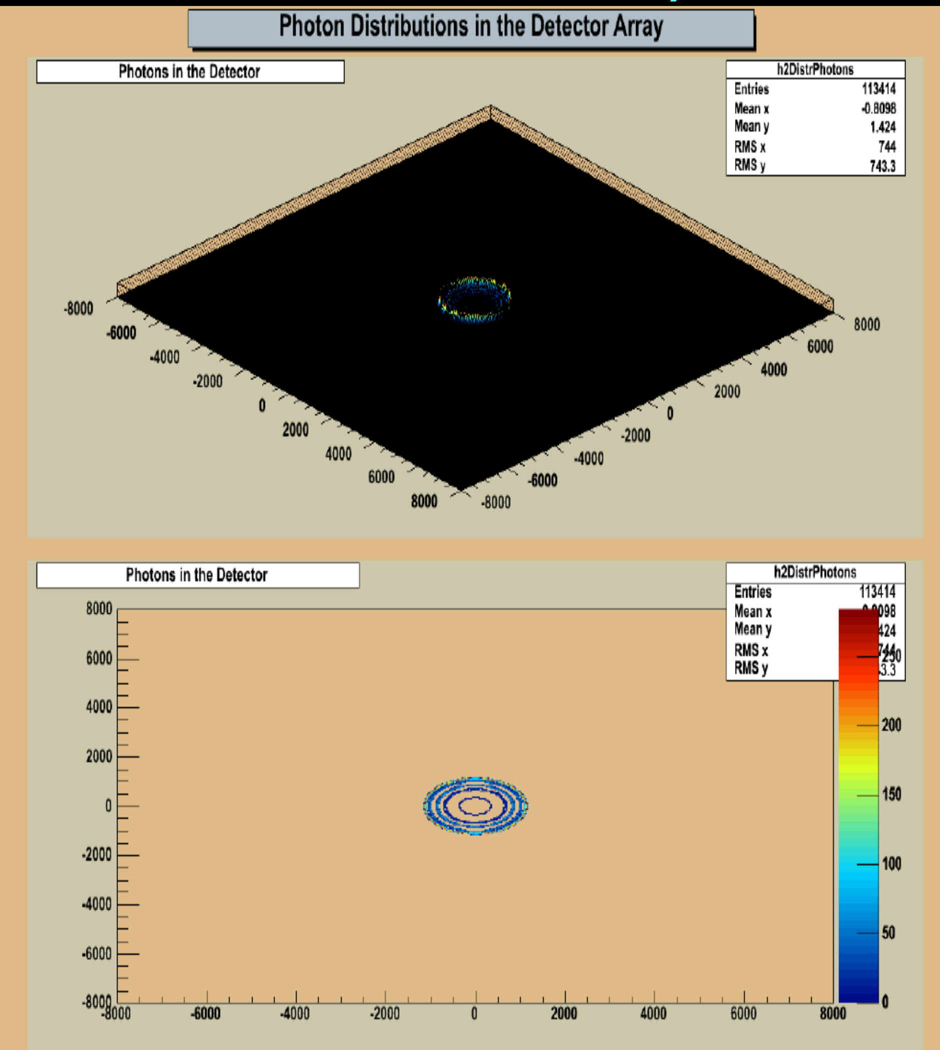


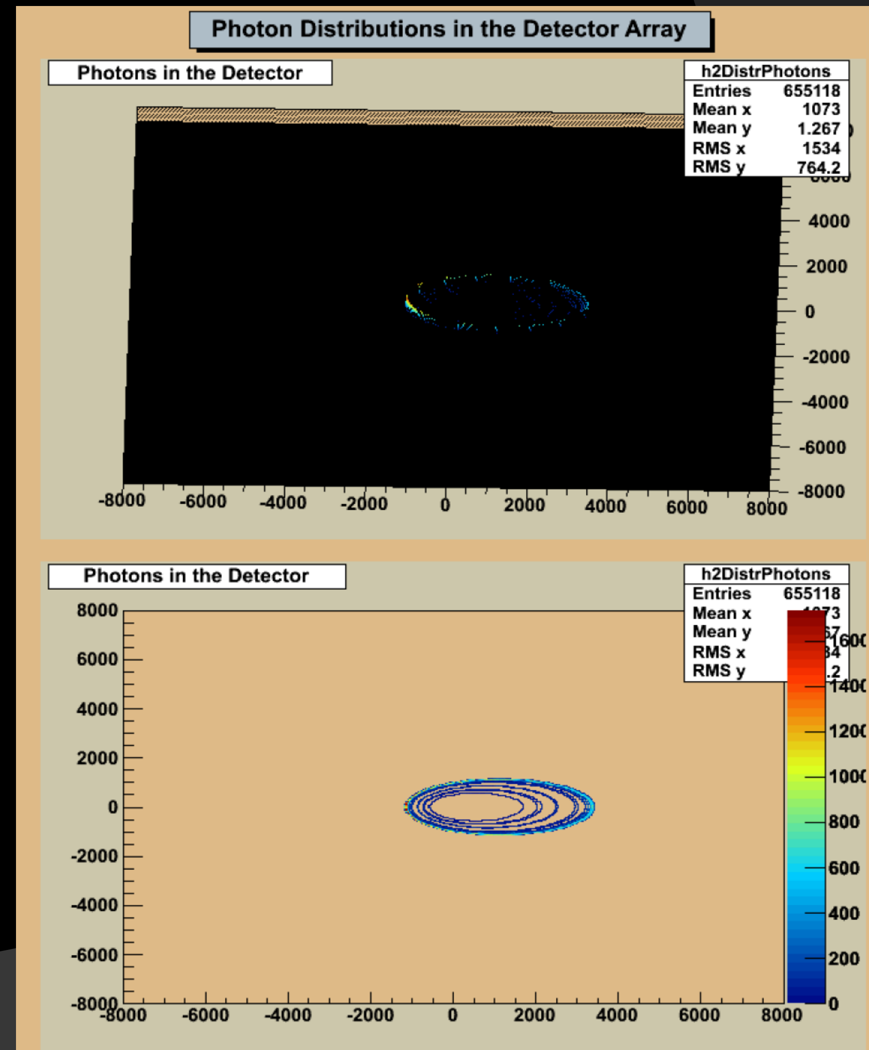
Full images of Cherenkov Rings(different angles of incidence)



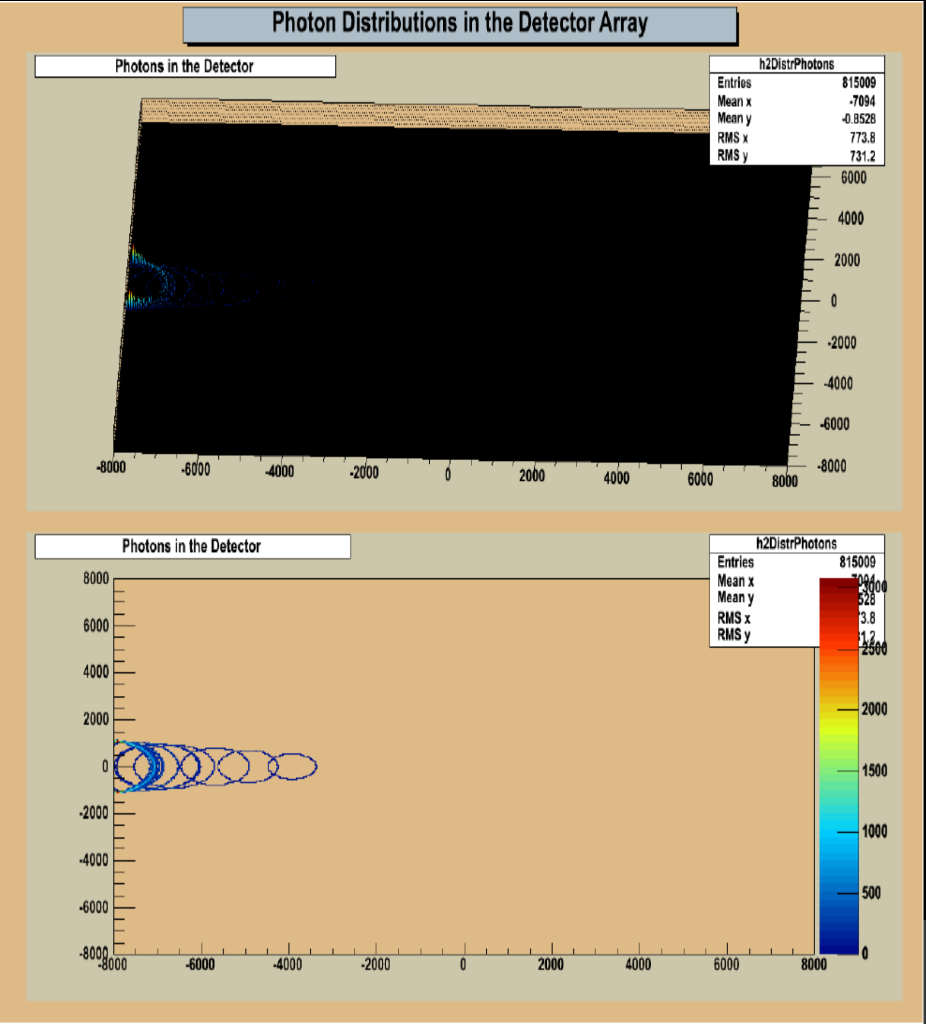


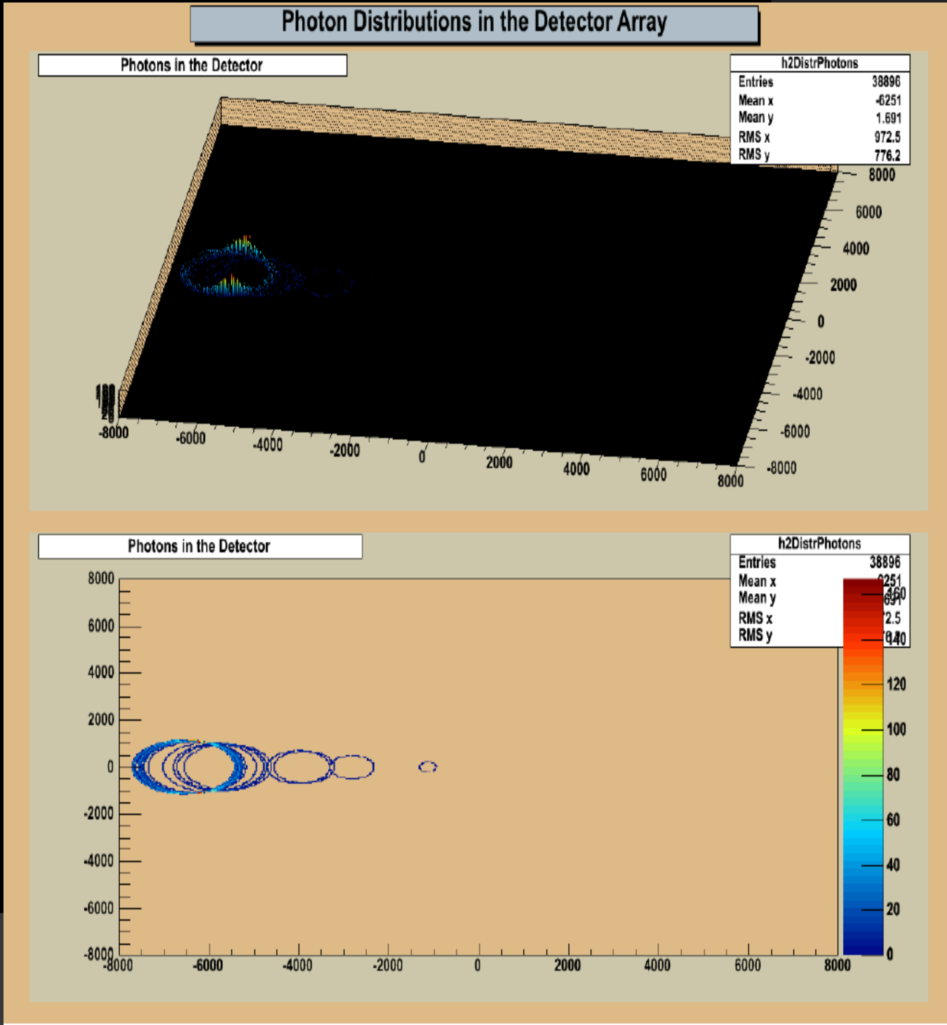
High Energy Bremsstrahlung(different angles of incidence)





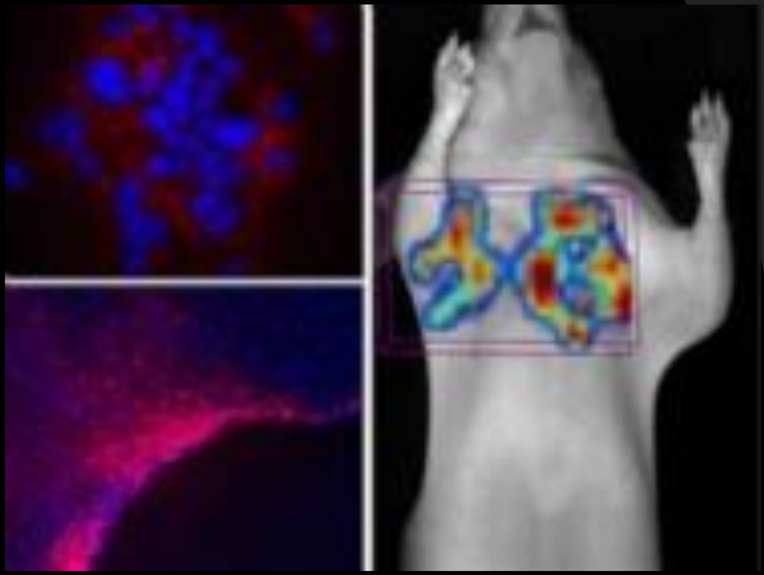
High Energy Coulomb Scattering(different impact parameters)





Applications and further science.

- We can use relativistic particles to perform mapping of organic tissue with high precision.
- Cherenkov Luminescence Tomography can be used to noninvasively image the location of both β+ and β- emitting radionuclides(such as 18F and 11C) used in PET scans.
- Simulations predict the Cerenkov signal increases as the refractive index of the medium is increased allowing for tissue identification.
- Cherenkov photon intensity, emitted is then proportional to the radionuclide activity, which when modelled with the diffusion equation, allows for monitoring metabolic rates, helping to identify cancer in its early stages.

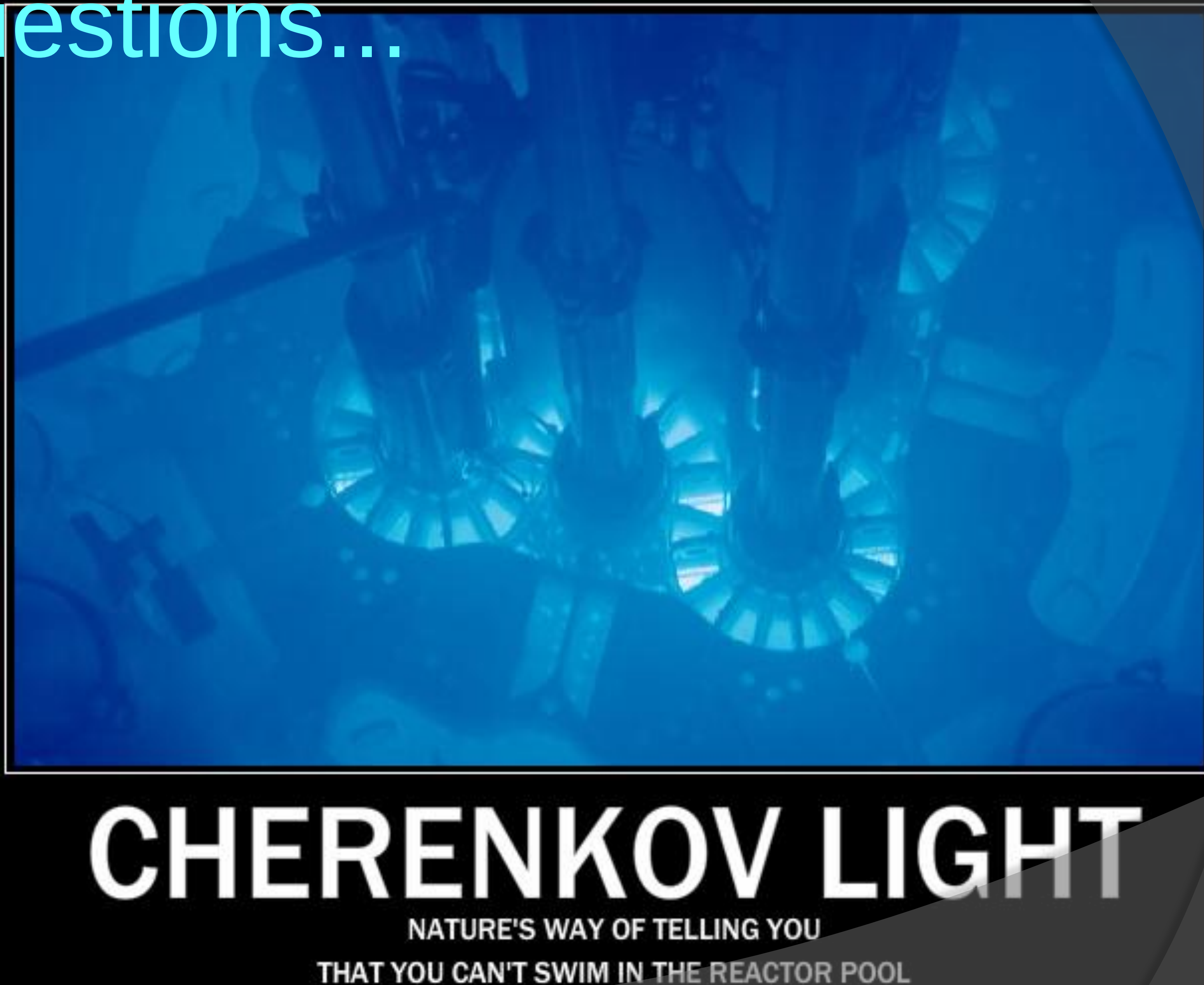


PET scan of a rat using position sensitive avalanche photodiodes which can allow for molecular imaging as well as organ imaging. Non-invasive scanning allows for the direct observation of metabolic changes over time for a defined region.

References:

- **Muon Ring images with an Atmospheric Cherenkov Telescope** G. Vacanti, P. Fleury, Y. Jiang, E. Pare,A.C.Rovero, X.Sarazin, M.Urban, T.C Weekes.
- **Aerogel and Its Applications to RICH Detectors E. Nappi** INFN, Sez. Bari, Istituto Nazionale di Fisica Nucleare, via Amendola 173, I-70126 Bari, Italy
- **Stereoscopic imaging of air showers with the first two HEGRA Cherenkov Telescopes- HEGRA 1995 collaboration.**
- **Ring Imaging Cherenkov Detectors and the Rare Decay Bd -> K^0 +μ^+ +μ^- at LHCb** Thomas Blake, Blackett Laboratory ,Imperial College London
- **High Energy Muon Momentum Estimation from Multiple Coulomb Scattering in Dense Detectors** Tim Bolton ,Kansas State University, Manhattan, KS 66506-2601
- **Measurement of the energy spectrum of the BL Lac object PG1553+113 with the MAGIC Telescope in 2005 and 2006** Humboldt-Universität zu Berlin von Herr Dipl.-Phys. Thomas Hengstebeck
- **Pair production and bremsstrahlung of charged leptons** Yung-Su Tsai *Stanford Linear Accelerator Centers, Stanford University, Stanford California 94305*
- **A C++ Code to Solve the DGLAP Equations Applied to Ultra High Energy Cosmic Rays** Ramon Toldr`a_*Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK*

Questions...


CHERENKOV LIGHT
NATURE'S WAY OF TELLING YOU
THAT YOU CAN'T SWIM IN THE REACTOR POOL