Machine Learning in Gamma Astronomy*

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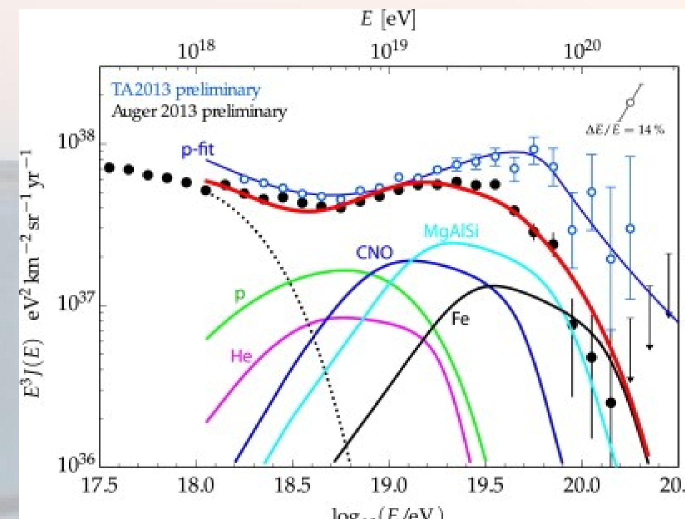
**The presentation is of a review nature and contains borrowed materials from Internet.*

Outline

- Problems of astrophysics
- Experimental methods in astrophysics
- Gamma astronomy
  - Ground based gamma-astronomy (Cherenkov array, IACT)
  - Advantages and disadvantages of gamma astronomy
  - Traditional methods in gamma astronomy (Hillas parameters)
- Machine learning in gamma astronomy
  - Neural networks and rare events
  - Generative models vs. Monte-Carlo
- Conclusion

Stellar astronomy and astrophysics

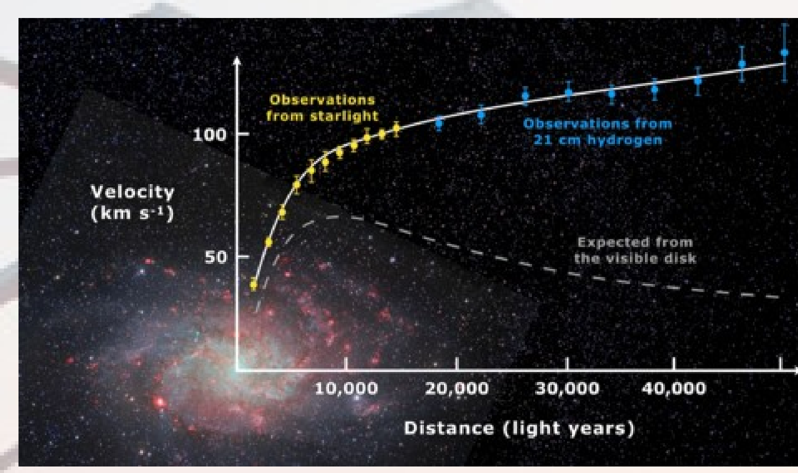
- What is the mechanism by which an implosion of a dying star becomes an explosion?
- What astrophysical process is responsible for the nucleogenesis of these rare isotopes?
- What physical processes create cosmic rays whose energy exceeds the GZK cutoff (Greisen–Zatsepin–Kuzmin limit)?
  Hadron: $5 * 10^{19}$eV,
  Weakly interacting:



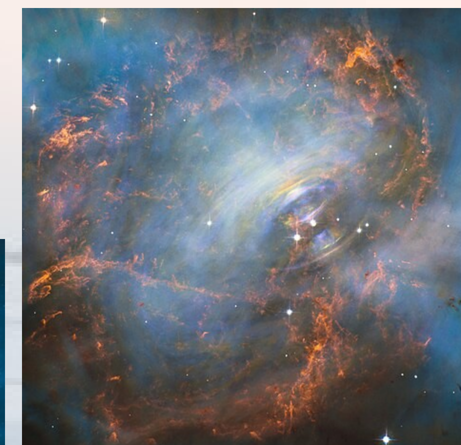
$$p + \gamma_{\rm CMB} \to \Delta^+ \to p + \pi^0 \,,$$
$$p + \gamma_{\rm CMB} \to \Delta^+ \to n + \pi^+ \,.$$

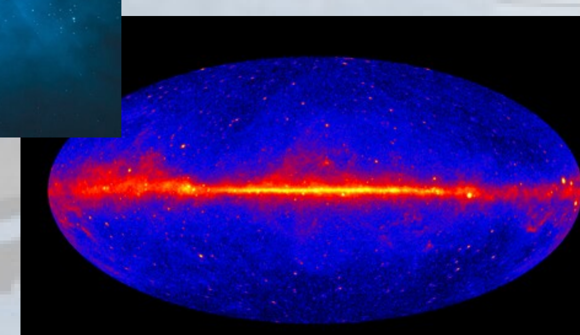
$$E = \frac{m_Z^2}{2m_\nu} = 4.2 \times 10^{21} \left(\frac{\rm eV}{m_\nu}\right) \rm eV,$$

Galactic astronomy and astrophysics



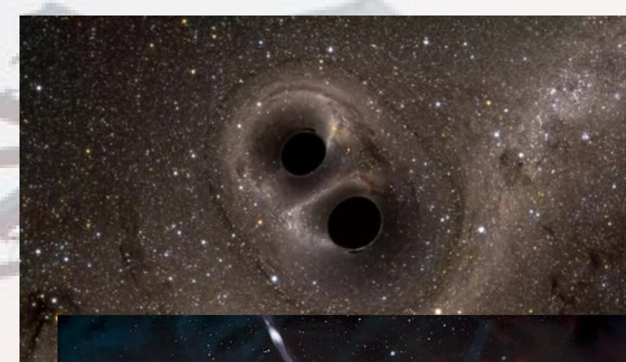
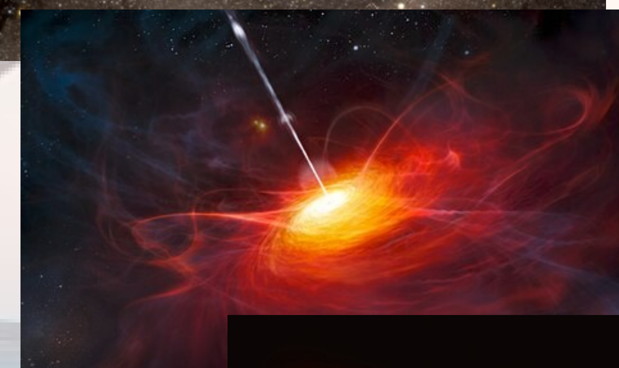
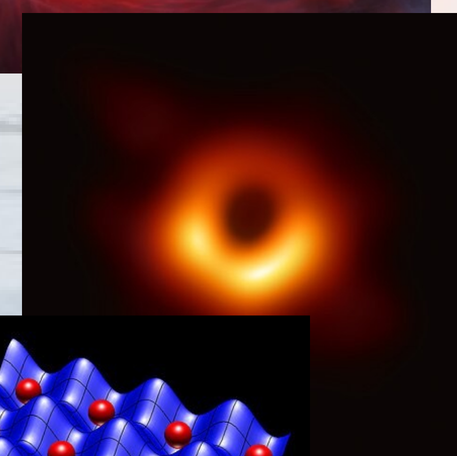
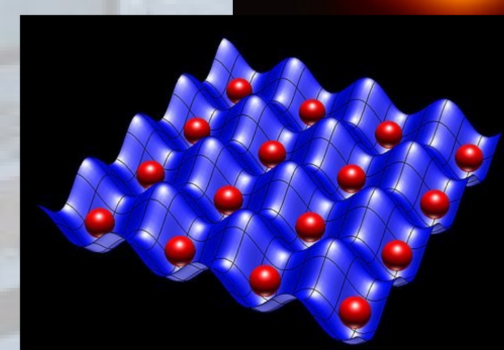
- Is dark matter (solely) responsible for differences in observed and theoretical speed of stars revolving around the center of galaxies?
- Ultraluminous X-ray sources (ULXs): What powers X-ray sources that are not associated with active galactic nuclei but exceed the Eddington limit of a neutron star or stellar black hole?
- What is the origin of the Galactic Center GeV excess?[15] Is it due to the annihilation of dark matter particles or a new population of millisecond pulsars?





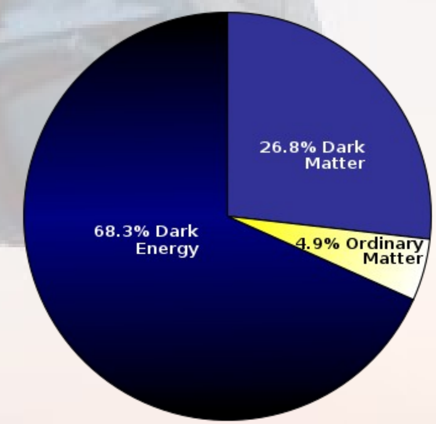
Black hole

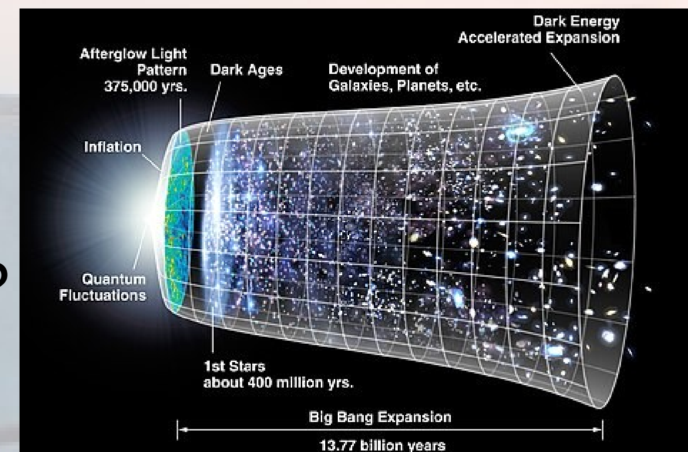
- Does general relativity break down in the interior of a black hole due to quantum effects, torsion, or other phenomena?
- What powers X-ray sources that are not associated with active galactic nuclei but exceed the Eddington limit of a neutron star or stellar black hole?
- How do the most distant quasars grow their supermassive black holes up to 10^{10} solar masses so early in the history of the universe (with redshift greater than 6 to 7)?
- Black hole information paradox and black hole radiation

Cosmology

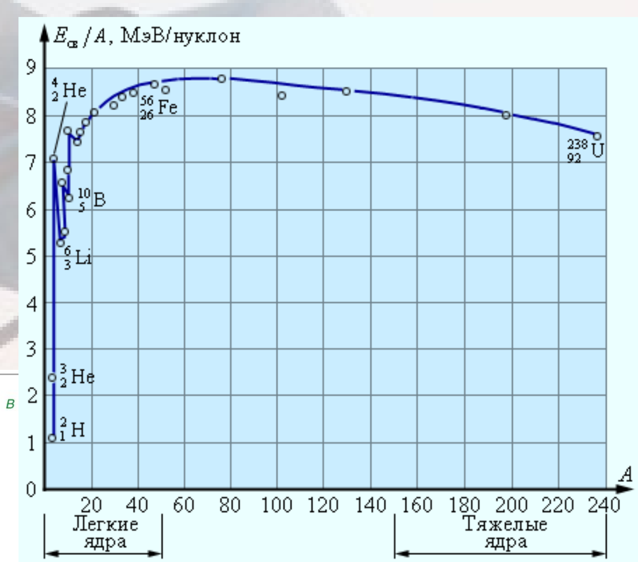
- Dark matter and dark energy
- Why is there far more matter than antimatter in the observable universe?
- Why does the zero-point energy of the vacuum not cause a large cosmological constant?
- The diameter of the observable universe is approximately 93 billion light-years; what is the size of the whole universe? Is it infinite?
- What is the 3-manifold of comoving space, i.e. of a comoving spatial section of the universe, informally called the "shape" of the universe?

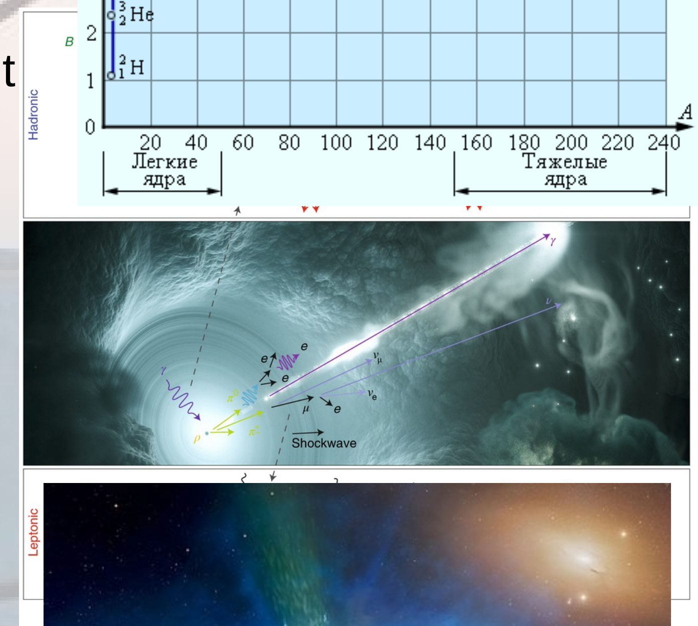


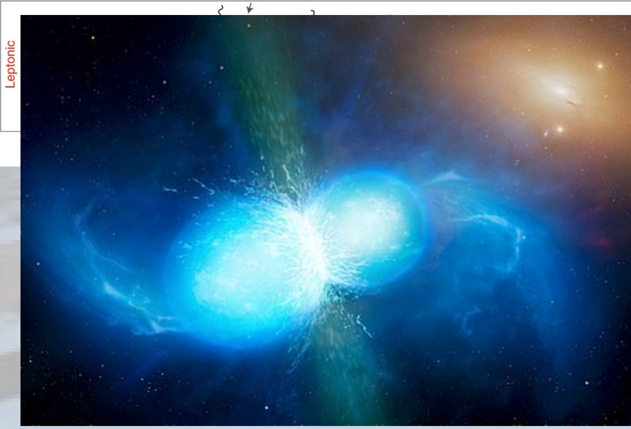


Nucleosynthesis

- The first nuclei were formed a few minutes after the Big Bang, through nuclear reactions in a process called Big Bang nucleosynthesis. After about 20 minutes, the universe had expanded and cooled to a point at which these high-energy collisions among nucleons ended.
- Stellar nucleosynthesis is the nuclear process by which new nuclei are produced. It occurs in stars during stellar evolution. It is responsible for the galactic abundances of elements from carbon to iron.
- Supernova nucleosynthesis occurs in the energetic environment in supernovae, in which the elements between silicon and nickel are synthesized in quasiequilibrium established during fast fusion that attaches by reciprocating balanced nuclear reactions to 28Si.
- The merger of binary neutron stars is now believed to be the main source of r-process elements. Being neutron-rich by definition, mergers of this type had been suspected of being a source of such elements, but definitive evidence was difficult to obtain.
- Nucleosynthesis may happen in accretion disks of black holes.

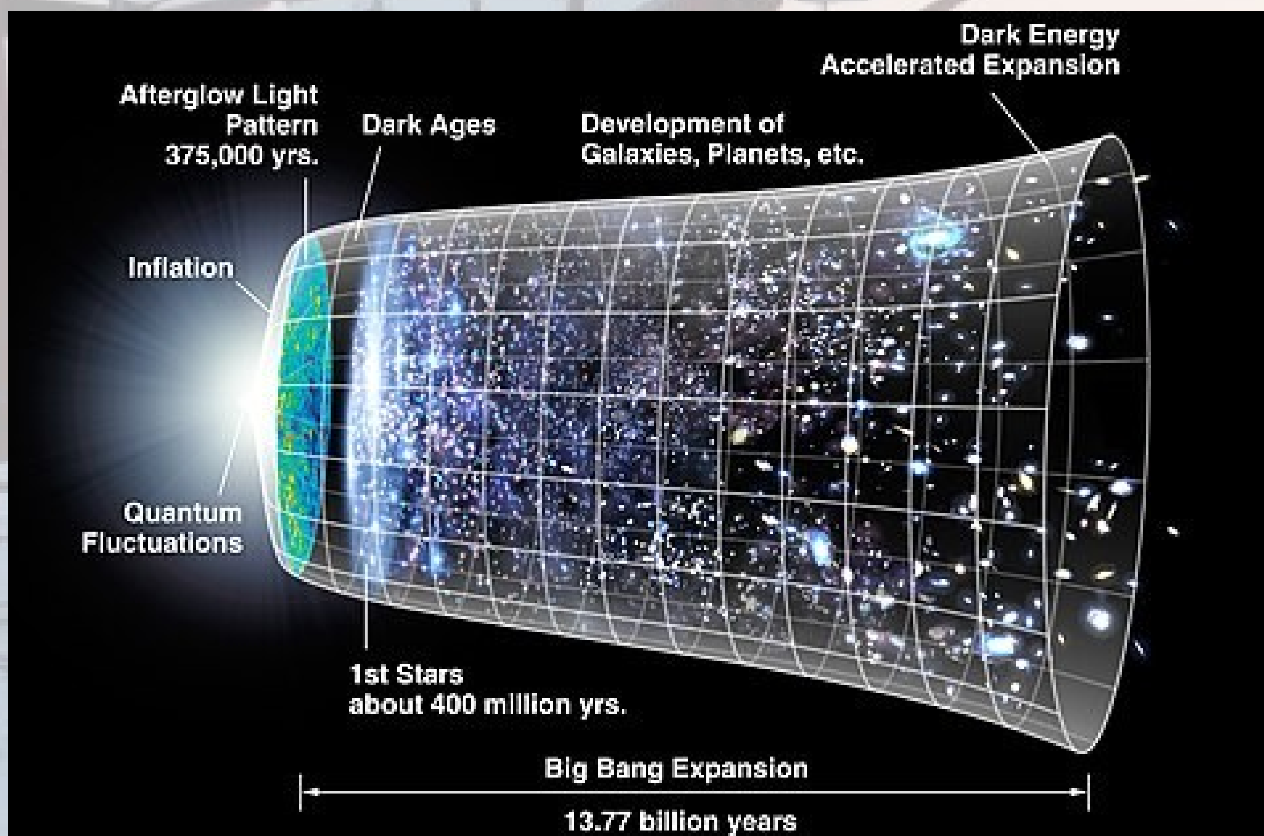




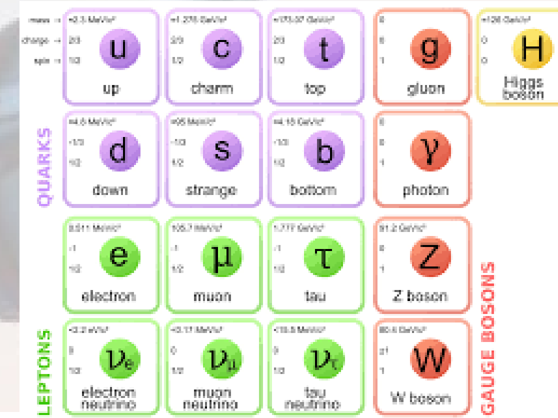


Problems of astrophysics

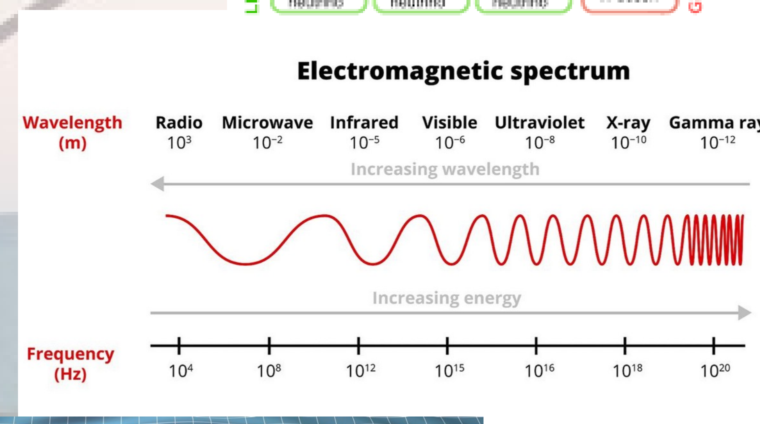
… so on, and so on ...



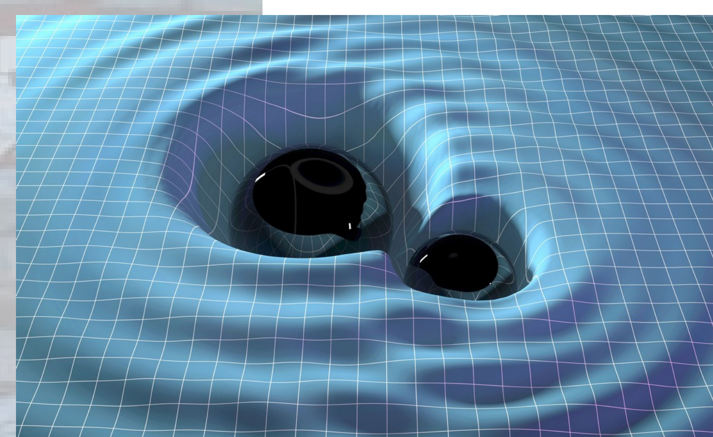
Signals in Universe



- Barions (mostly proton)
  - Nucleagenesys
- EM radiation (from radio to gamma rays)
  - Cosmic accelerators, star physics, early Universe and more

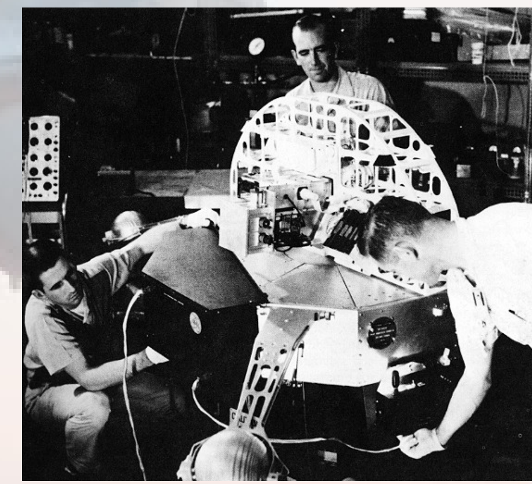


- Neutrinos
  - Star physics, early Universe.
- Gravity waves

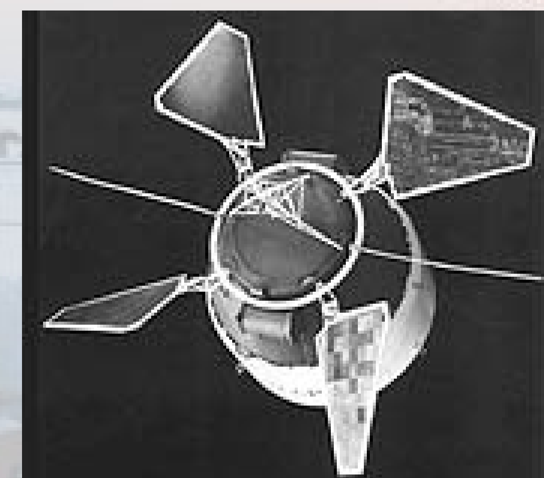


Space facilities in astrophysics

- Orbiting Solar Observatory -3, may be more accurately described as having proof of the discovery of cosmic gamma radiation, since it found a galactic plane anisotropy of high-energy gammas
- Protons 1–3 were largely identical craft massing 12,200 kg, with scientific packages developed under the supervision of Academician S.N.Vernov of SINP MSU. Experiments included a gamma-ray telescope, a scintillator telescope, and proportional counters.
- The Fermi Gamma-ray Space Telescope (FGST,[3] also FGRST) is a space observatory being used to perform gamma-ray astronomy observations from low Earth orbit.
- Spektr-Rentgen-Gamma (Spektr-RG, SRG) — space astrophysical observatory to study the Universe in the X-ray range of electromagnetic radiation.



The OSO-1 sattelite, 1962.



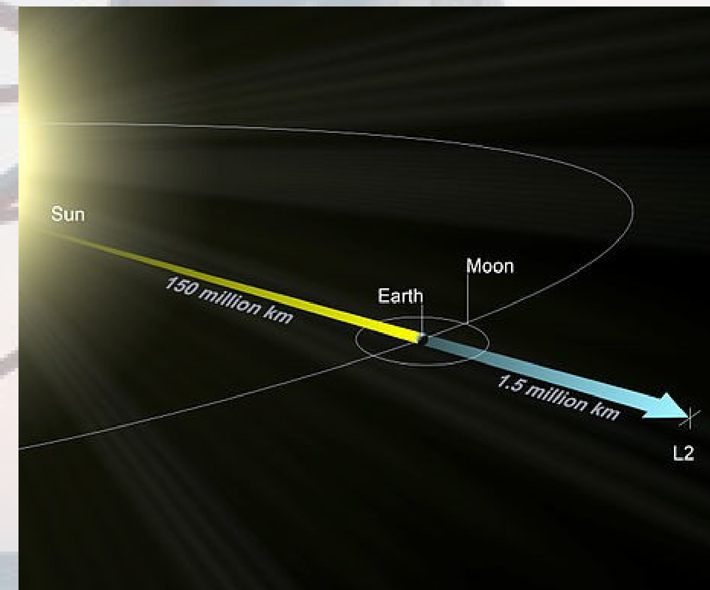
The Proton-1-4 sattelite, 1965-1968.

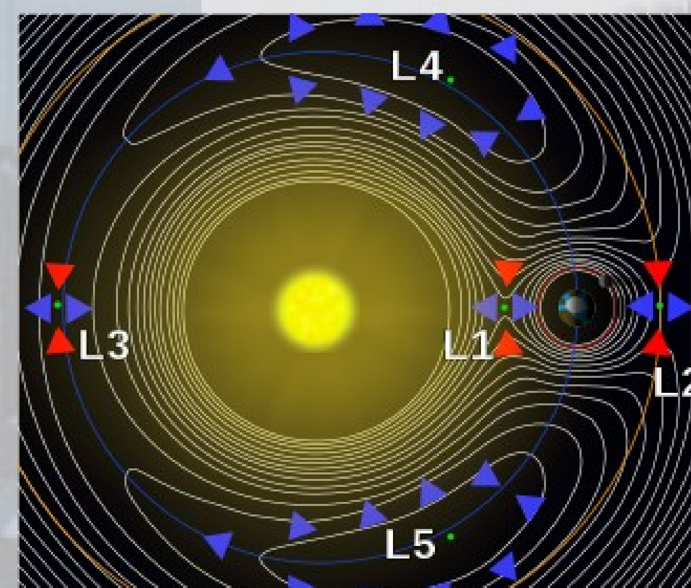
Bonus. The James Webb

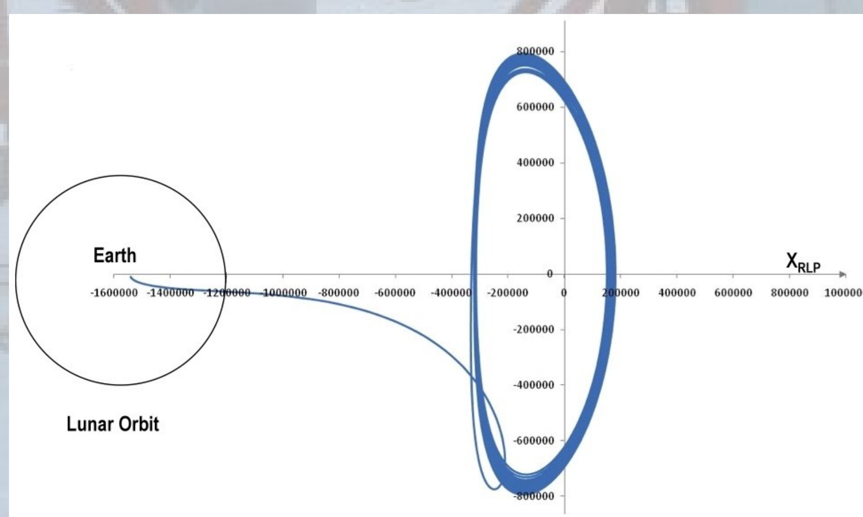
- The James Webb Space Telescope (JWST) is a space telescope designed to conduct infrared astronomy.
- In January 2022 it arrived at its destination, a solar orbit near the Sun–Earth L2 Lagrange point, about 1.5 million kilometers (930,000 mi) from Earth.

Bonus. Lagrange points

- In celestial mechanics, the Lagrange points (also libration points) are points of equilibrium for small-mass objects under the gravitational influence of two massive orbiting bodies.

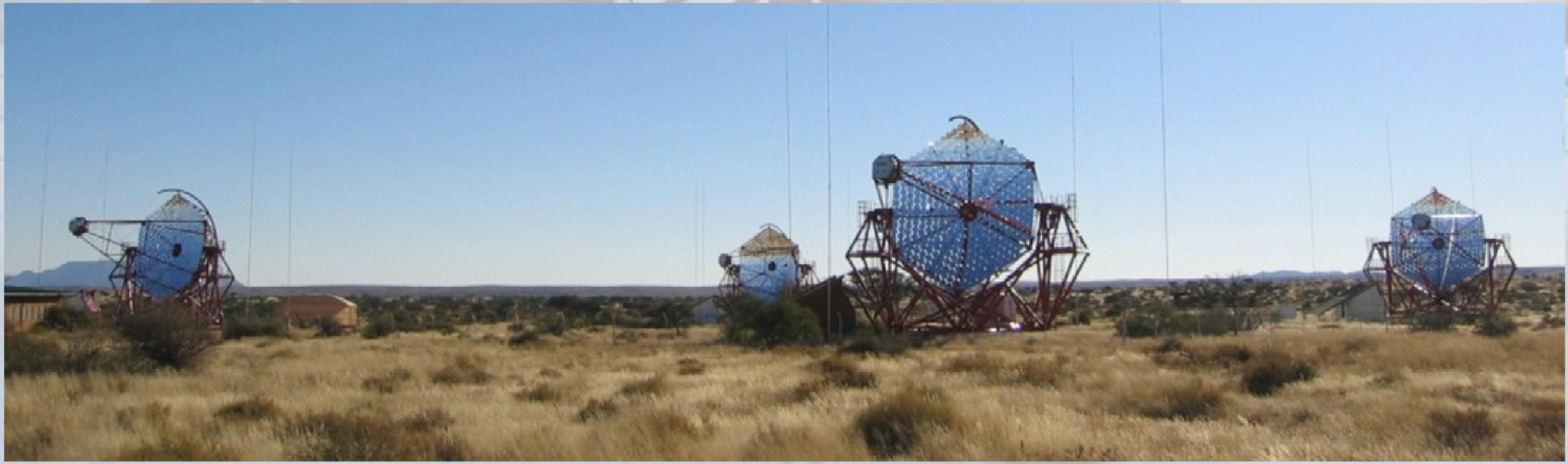






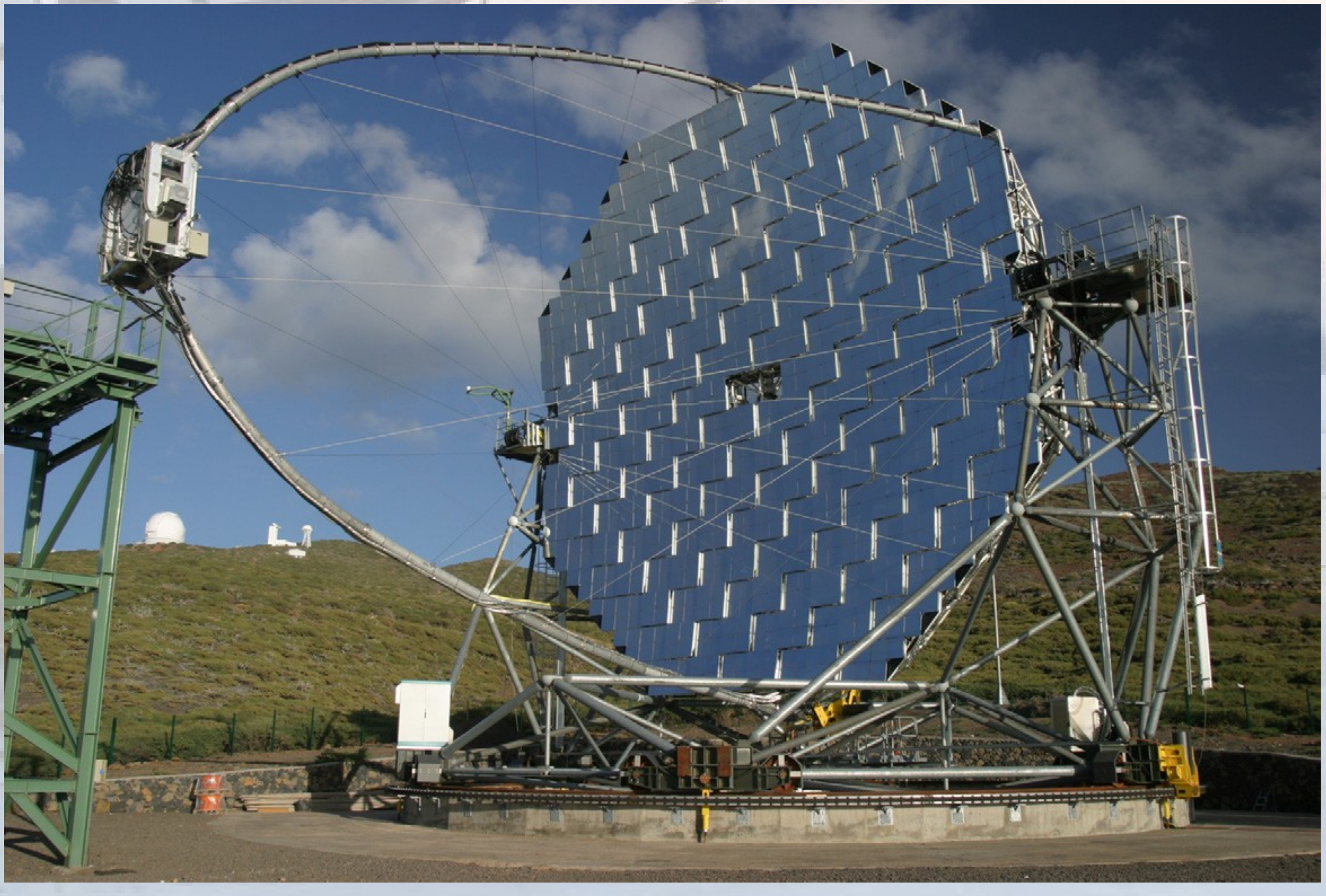
Ground based facilities for gamma astronomy. HESS.

- High Energy Stereoscopic System (HESS) Observatory—an array of four 13 m diameter IACTs equipped with ≈5◦ field of view imagers. The HESS observatory, located in Namibia in the Southern Hemisphere, was completed in 2004.



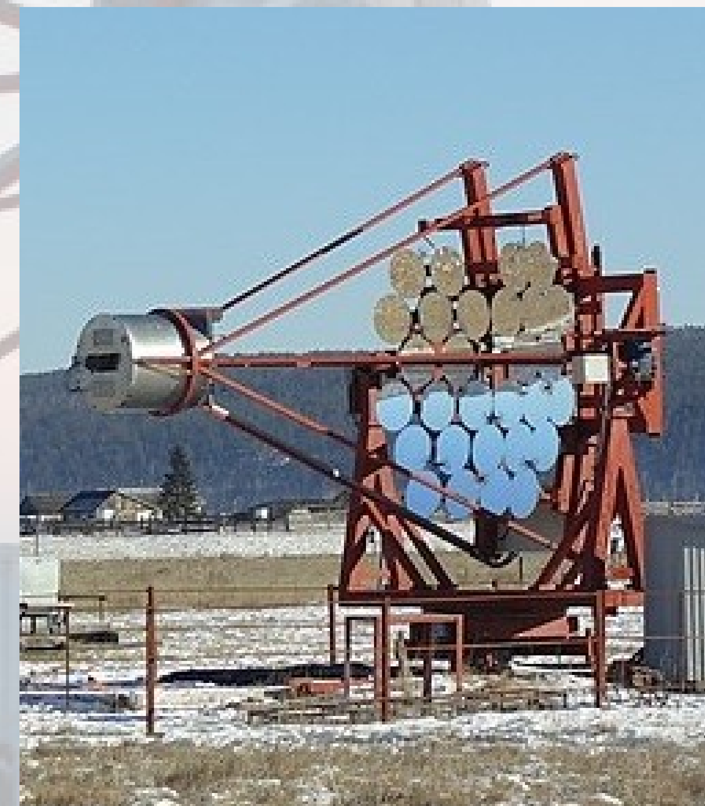
Ground based facilities for gamma astronomy. MAGIC.

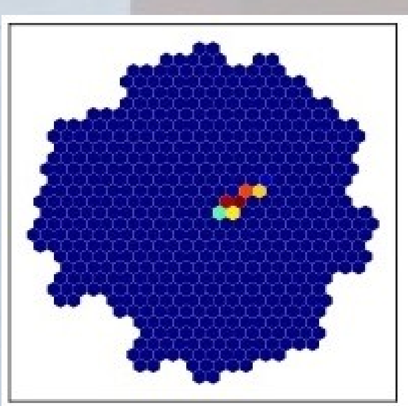
- The 17 m diameter single dish MAGIC telescope located on the Canary Island of La Palma.



TAIGA complex (nearby Baikal lake)

Charged cosmic rays and high energy gamma rays interact with the nuclei of the atmosphere. The result is extensive air showers (EAS) of secondary particles emitting Cherenkov light. Imagine Atmospheric Cherenkov Telescopes (IACT) register the light.

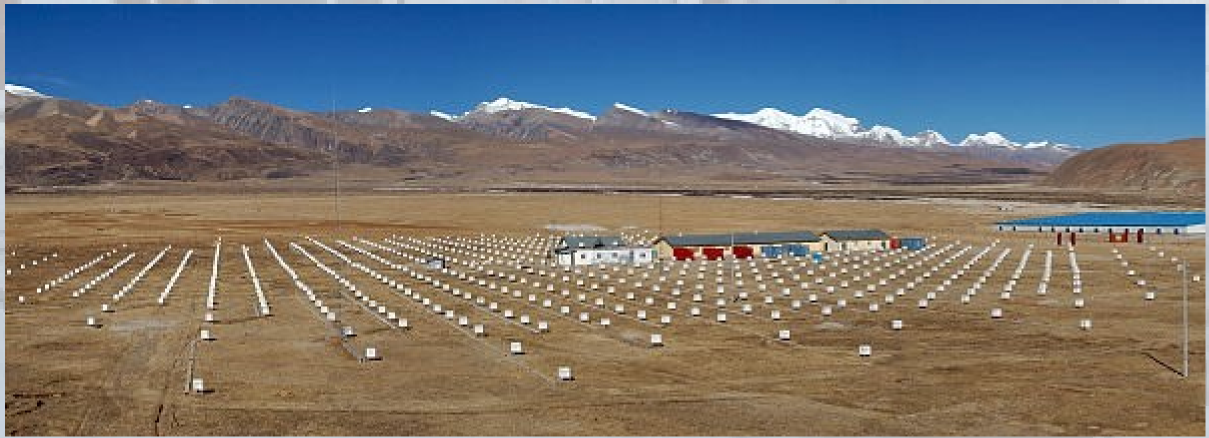




Detected data form "images" of the air shower

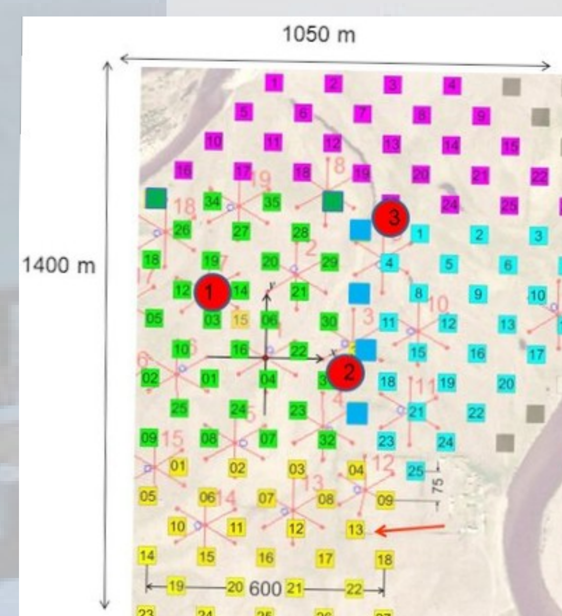
Tibet AS-gamma Experiment

- The air shower array consists of 697 scintillation counters which are placed at a lattice with 7.5 m spacing and 36 scintillation counters which are placed at a lattice with 15 m spacing. Each counter has a plate of plastic scintillator, 0.5 m2 in area and 3 cm in thickness, equipped with a 2-inch-in-diameter photomultiplier tube (PMT). The time and charge information of each PMT hit by an air shower event is recorded to determine its direction and energy. The detection threshold energy is approximately 3 TeV, which is the lowest one achieved by an air shower array in the world.



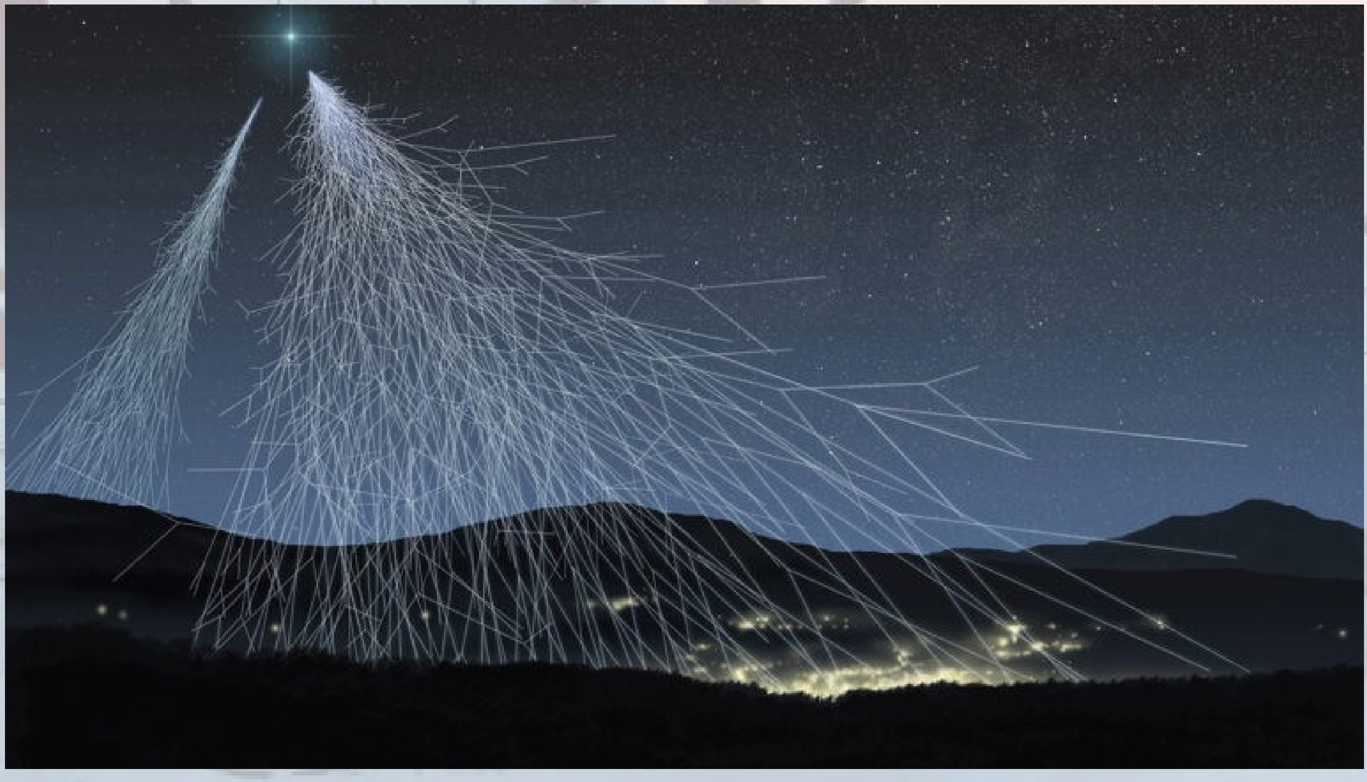
HiSCORE

- TAIGA-HiSCORE is an array of integrating Cherenkov detector stations with a wide Field of View (FoV ~0.6 sr). Each detector station consists of 4 large area PMTs (20 cm and 25 cm in diameter), located next to each other and equipped with a Winston cone to increase the effective light collection area by 4 times.
- The detector stations are placed at distances of 150-200m from each other. The ~100 stations of the array cover an area of ~1 km² (which, at a later phase of the experiment, can be extended to ~10 km²).



EAS: Extensive Air Shower

- The initial particle creates a large number of less energetic particles, which then create even more less energetic particles and so on in a cascade leading to up to 10 billion (10,000,000,000) particles. This pool of secondary particles covers an area of tens of square kilometers (thousands of football fields!) and could be detected and used to reconstruct the information about the primary particle, such as its energy, direction, and mass.



A few mathematics

$$Laboratory\ frame: p_1=(m,\vec{0}), p_2=(E_2,\vec{p}_2)$$

$$p_1^2=p_2^2=m^2=E_2^2-(\vec{p}_2)^2 \rightarrow E_2 \approx |\vec{p}_2|$$

$$C.M.S.: q_1=(E,\vec{p}), q_2=(E,-\vec{p})$$

$$q_1^2=q_2^2=m^2=E^2-(\vec{p})^2 \rightarrow E \approx |\vec{p}|$$

$$R=(p_1+p_2)^2=(m+E_2,\vec{p}_2)^2=m^2+2mE_2+E_2^2-(\vec{p}_2)^2 \approx 2mE_2$$

$$R=(2E,0)^2=4E^2$$

$$\rightarrow 4E^2=2mE_2 \rightarrow E=\sqrt{(mE_2/2)}$$

$$m \approx 0.001\,TeV \rightarrow if\ E_2=1000\,Tev=1\,Pev\ then\ E \approx 1\,TeV$$

So, proton with 1000TeV=1PeV energy is about to 1TeV proton collision in C.M.S. For example, the LHC collide 7+7=14TeV protons.

A few mathematics

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Accelerators use to investigate of particle interaction but Cosmic Rays use for investigation of Universe!

Main tasks

- Identification of primary particle
  - Gammas, hadrons, EM, neutrinos
- Identification of the source in the Universe
  - X-Ray and gamma, neutrino, and possible gravity waves.
  - Not nuclei
- Mass spectra
  - Nuclei
- Energy spectra
  - Gammas, hadrons, EM, neutrinos

Identification of the source and mass spectra

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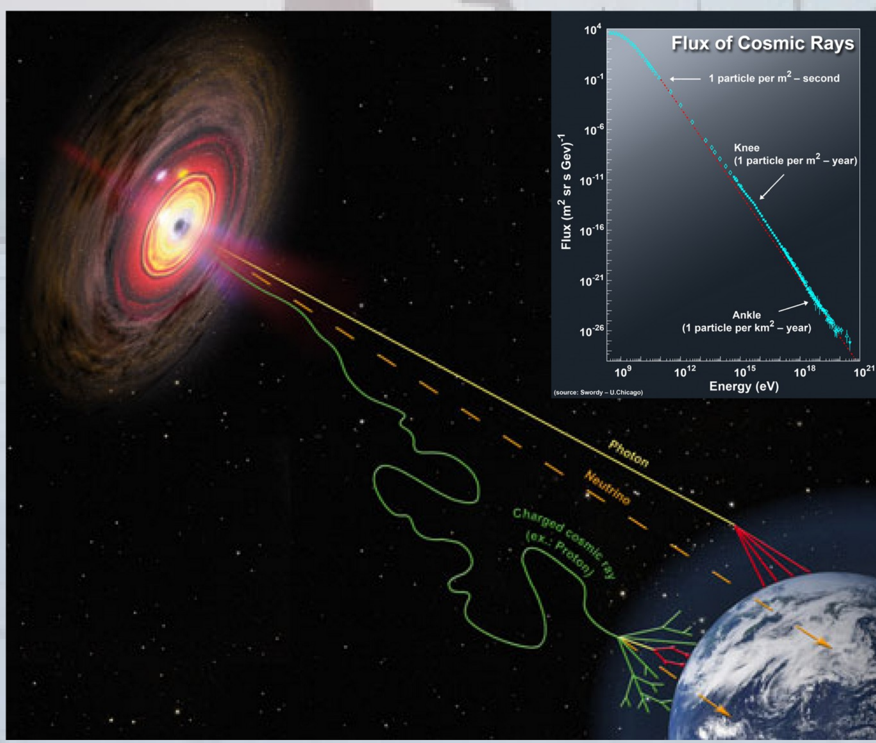
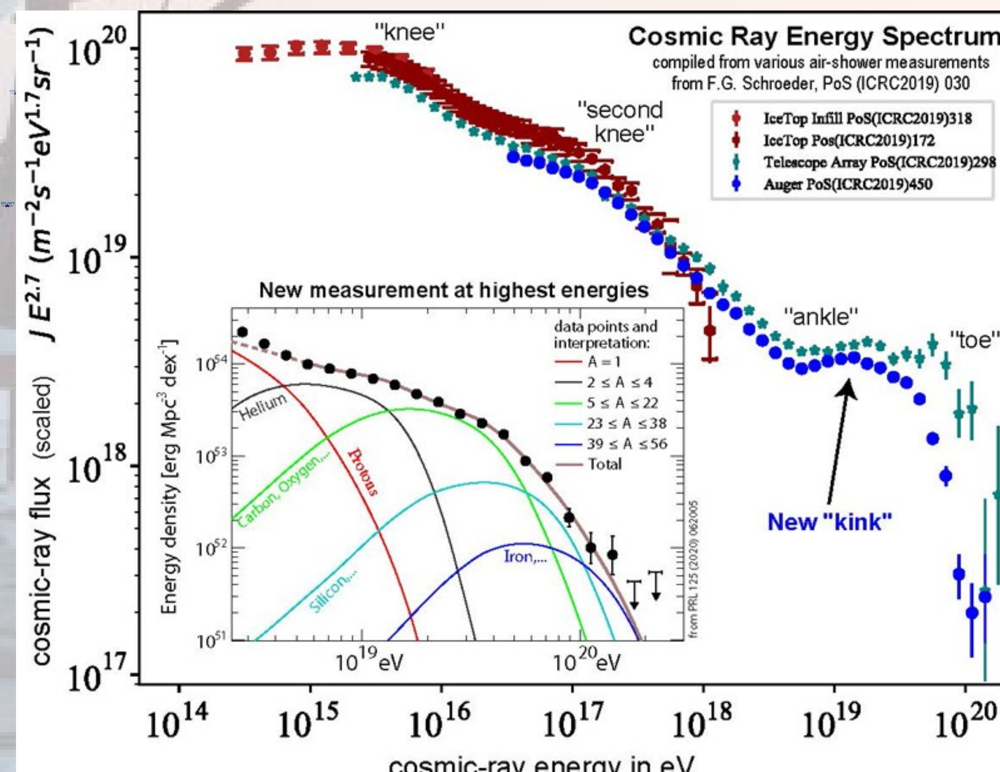
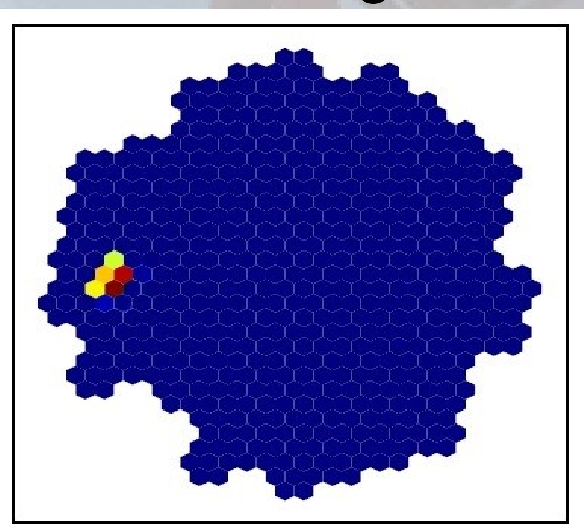




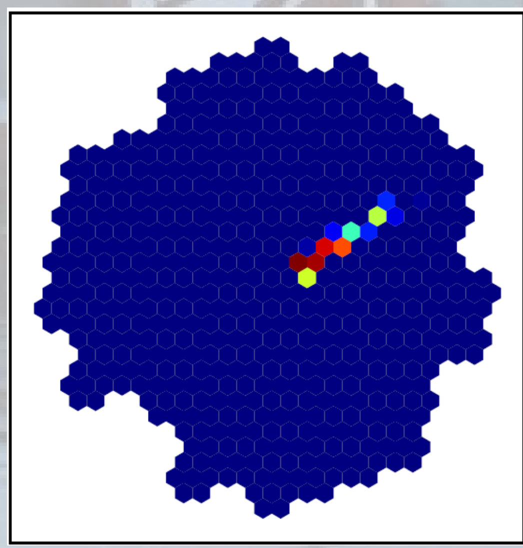
IACT: Gamma vs. hadron images

- High energy gamma rays
  - the particles of interest (0.01% of all particles)
- Hadrons background (mostly protons)

Proton image

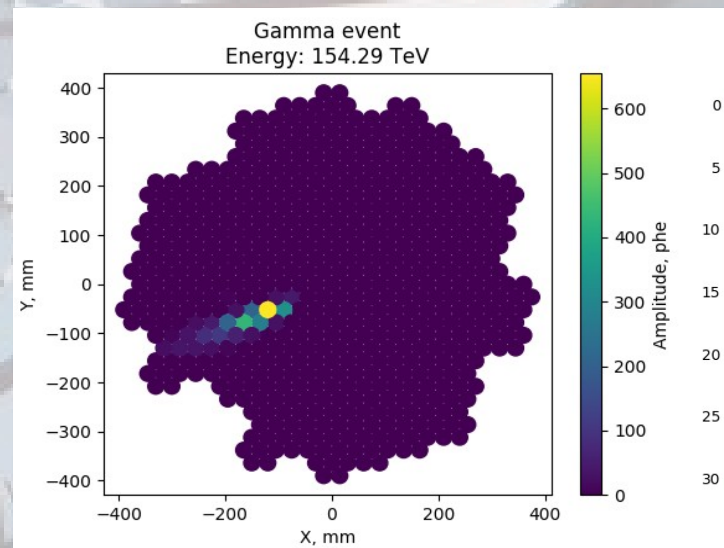


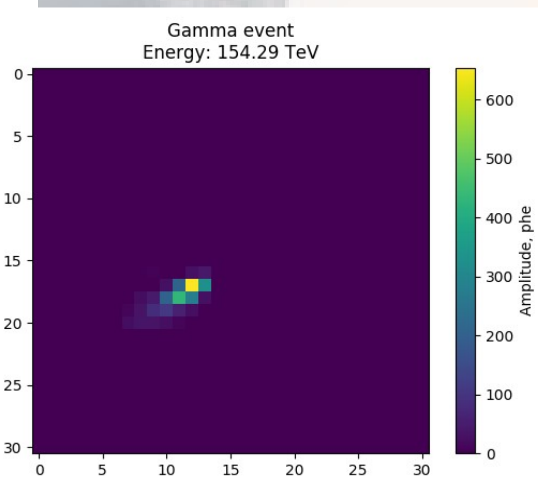
Gamma image

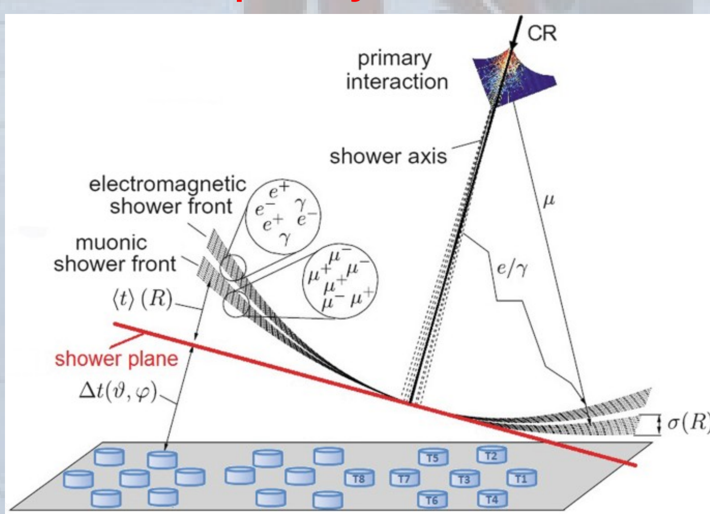


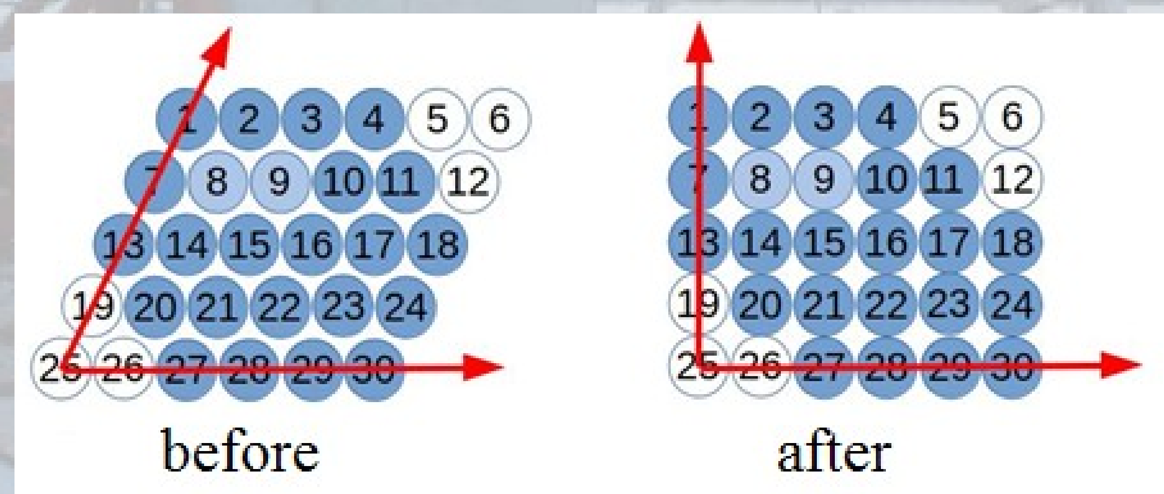
Python frameworks: TensorFlow and PyTourch

- TensorFlow and PyTorch work with squared matrix
- There are technics of transformation:
  - approximation
  - re-bining
  - oblique system of axes



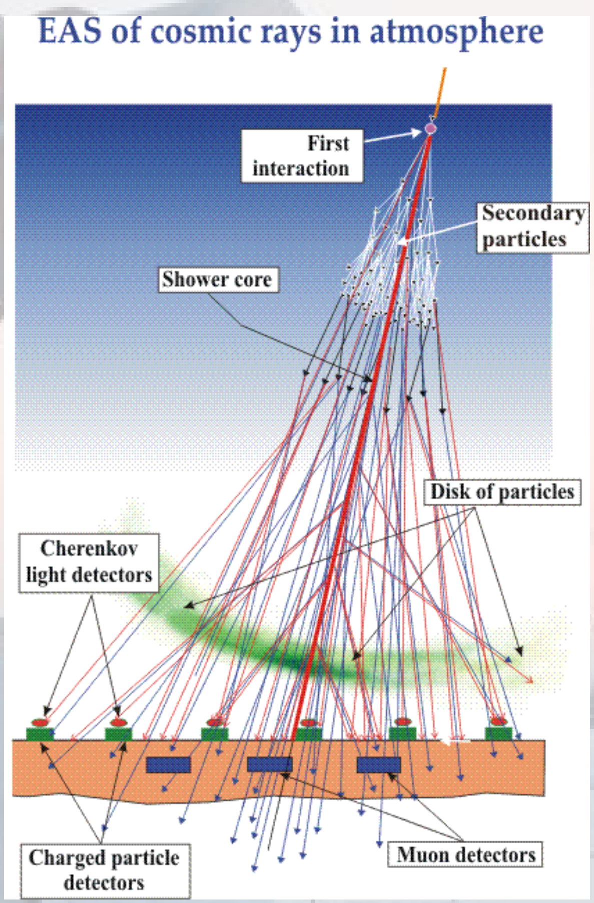


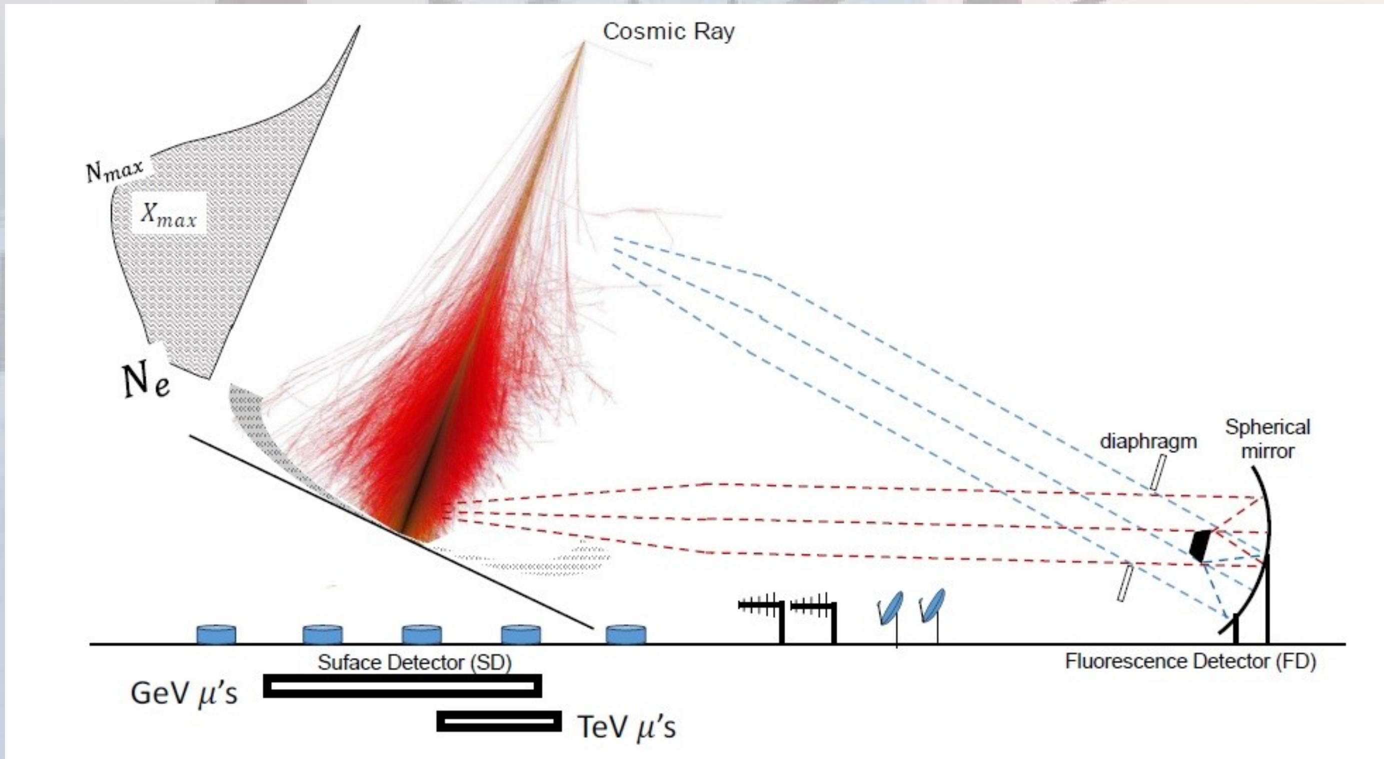




Identifacation of primary particles

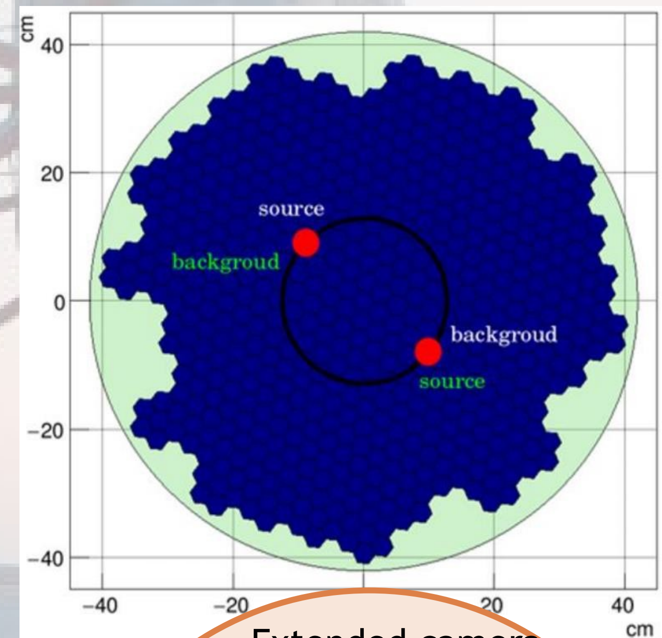
- Gamma/proton separation.
  - Ration 1:10000 for Crab nebula
  - Nuclei have isotropic distribution
  - EAS from nuclei have much more secondary particles

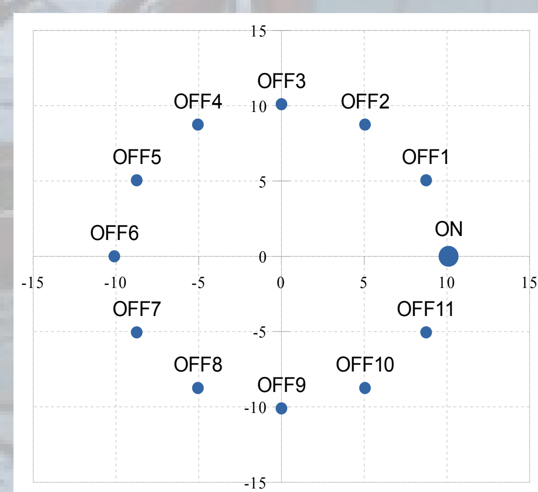


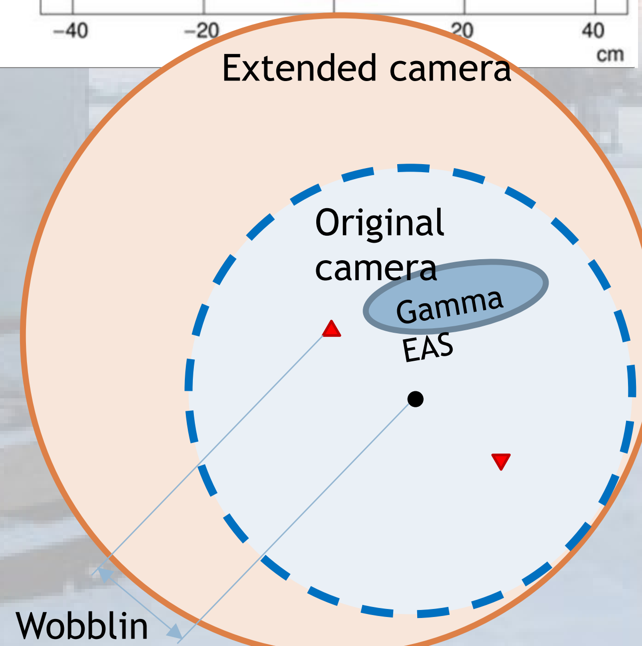


Wobbling

- It’s the telescope operating mode, in which the gamma radiation source is located not in the center of the camera, but at a fixed distance from it. In this mode the source periodically shifts from its position to another (opposite) offset position.

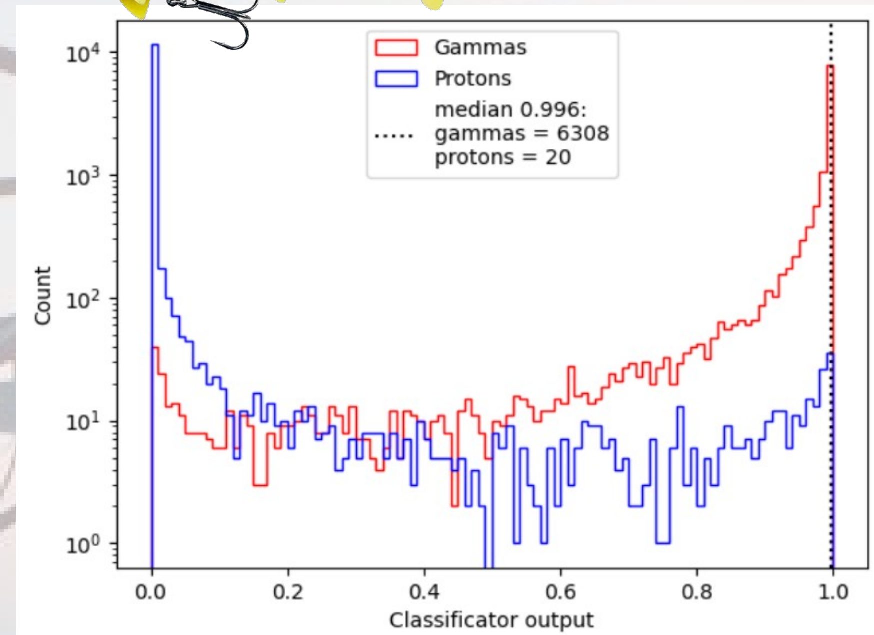


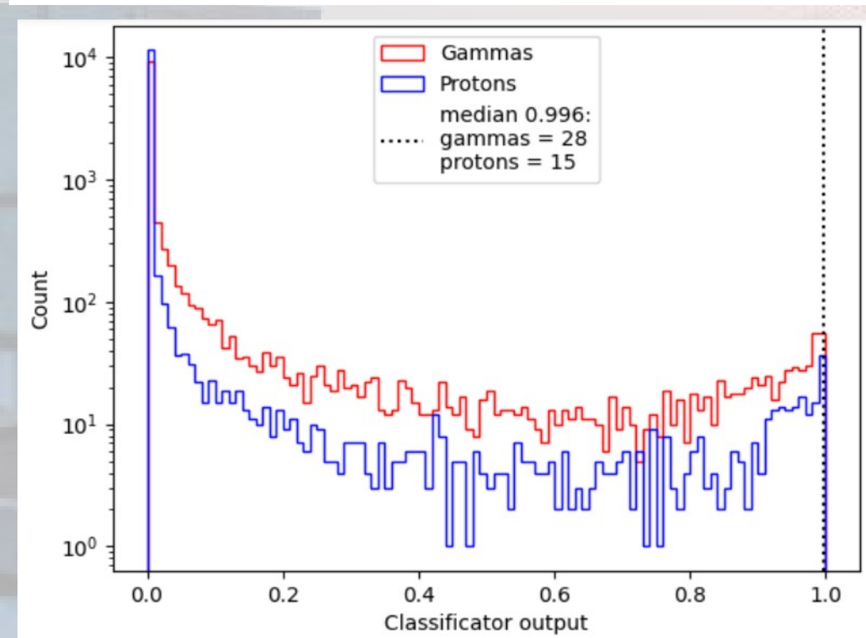




Wobbling

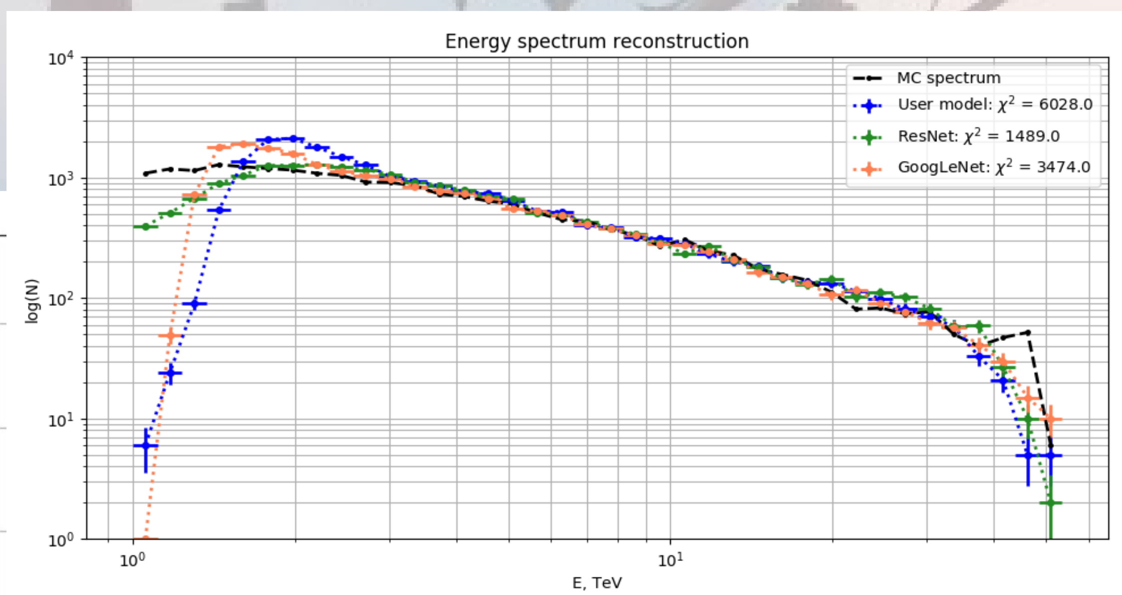
Point	True gamma	Fake gamma (Hadrons)	Total events
OFF1	2	182	184
OFF2	0	151	151
OFF3	0	166	166
OFF4	0	176	176
OFF5	0	166	166
OFF6	0	164	164
OFF7	0	180	180
OFF8	0	171	171
OFF9	1	169	170
OFF10	0	183	183
OFF11	2	164	166
ON	4	163	167

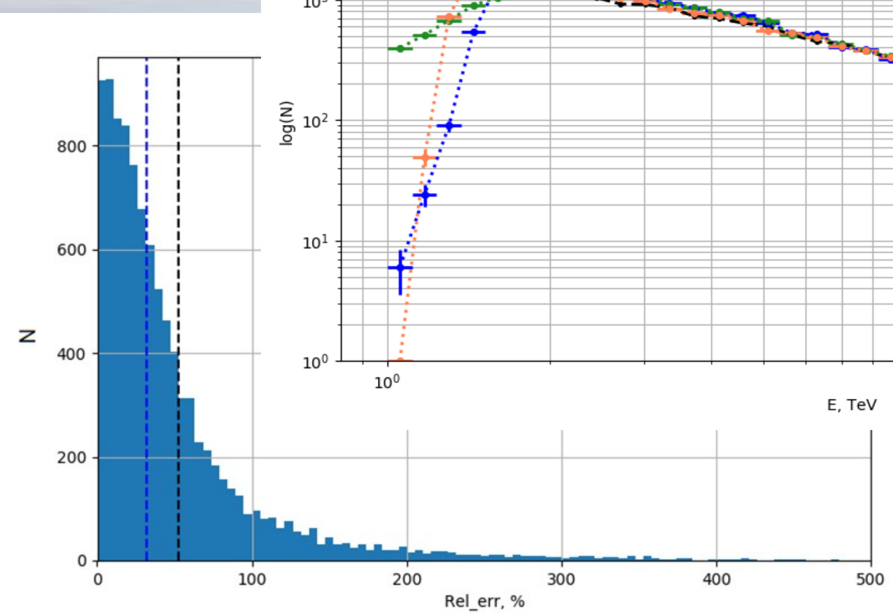


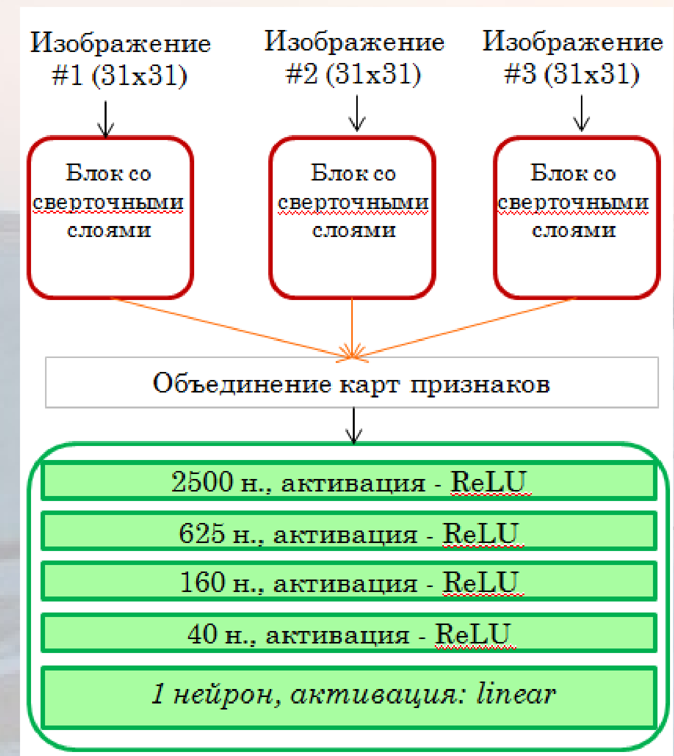


Energy spectra

- Восстановление энергии событий и энергетического спектра проводилось трехканальной CNN.
- Значения χ^2 в моно-режиме 1 546, в случае «стерео-2» – 495, у «стерео-3» – 156. Погрешность уменьшилась с 26% до 15%.







Role of Monte-Carlo

- Monte-Carlo modeling is an obligatory element of modern experiment. It is necessary for the following purposes:
  - software development;
  - checking the operation of the data acquisition system;

Role of Monte-Carlo

- Monte-Carlo modeling is an obligatory element of modern experiment. It is necessary for the following purposes:
  - software development;
  - checking the operation of the data collection system;
  - comparison of experimental results with theoretical models.

$$\tilde{R}(y,Q)=\int K(x,y)*R(x,Q)\,dx$$

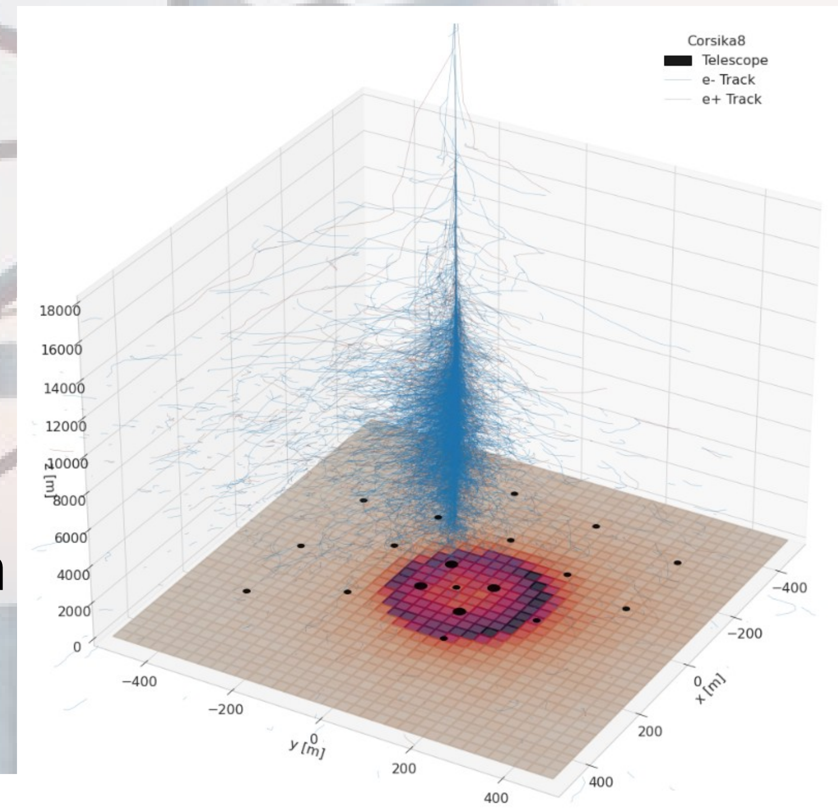
$$Q - \text{физические } параметры\text{, }которые\ мы\ исследуем$$
$$R(x,Q) - сигналы\text{, }которые\ мы\ можем\ наблюдать$$
$$K(x,y) - аппаратная\ функция - все\ что\ стоит\ между$$
$$наблюдаемыми\ величинами\ и\ полученными\ данными$$
$$\tilde{R}(y,Q) - полученные\ данные\ .$$

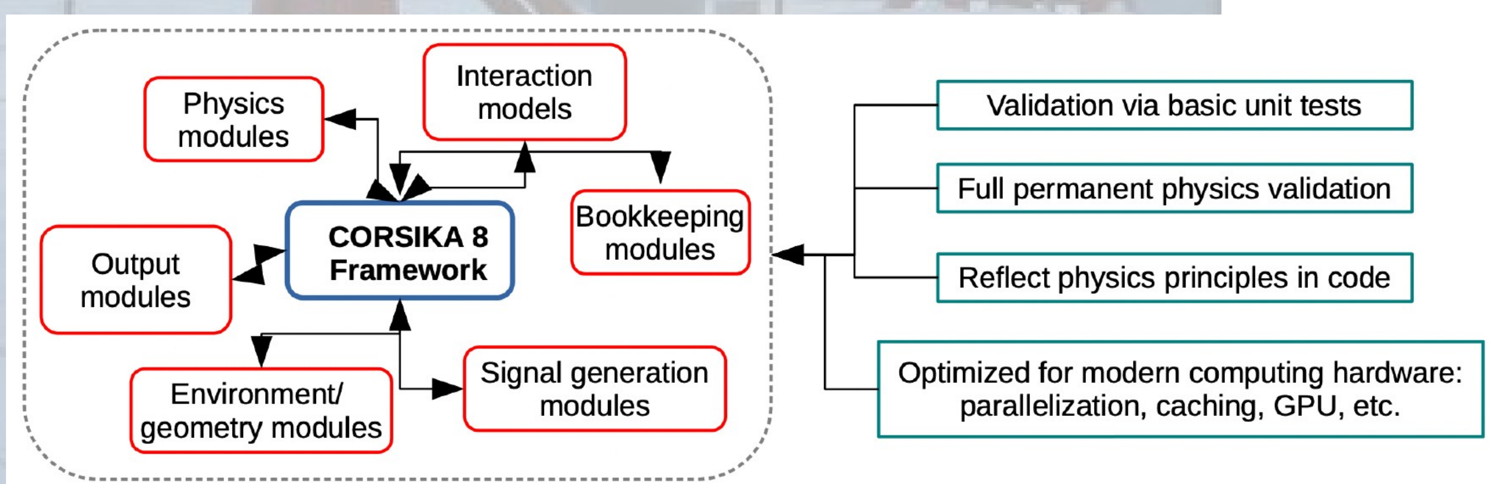
$$Задача: по\ \tilde{R}(y,Q)\ восстановить\ Q$$

- Вместо решения сложной обратной задачи, мы решаем прямую задачу методом МК - ищем такие Q, которые воспроизводят $\tilde{R}(y,Q)$

CORSIKA

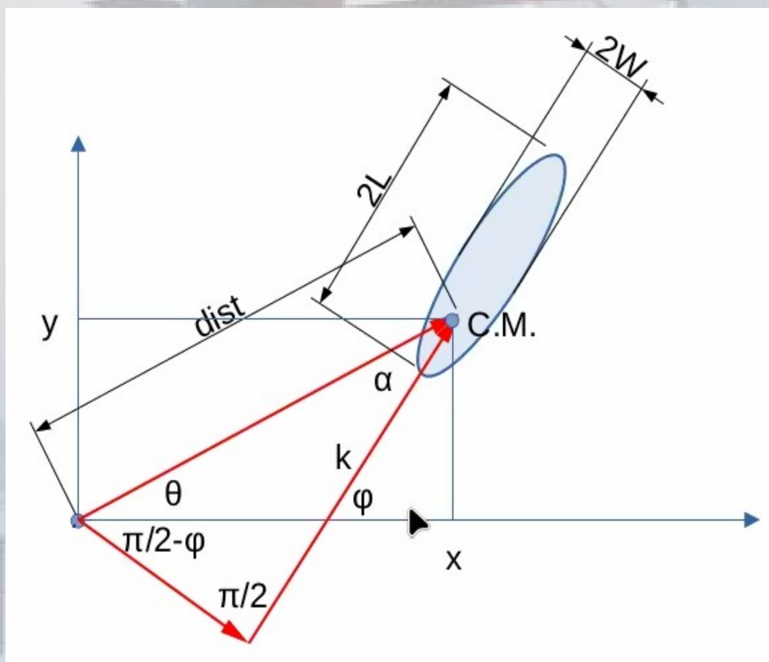
- CORSIKA is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries. The particles are tracked through the atmosphere until they undergo reactions with the air nuclei or - in the case of instable secondaries — decay.
-





IACT image and Hillas parameters

For each event image we can calculate the so-called Hillas parameters, which form a set of geometric features of the image



These parameters are widely used in gamma-ray astronomy for gamma/hadron separation

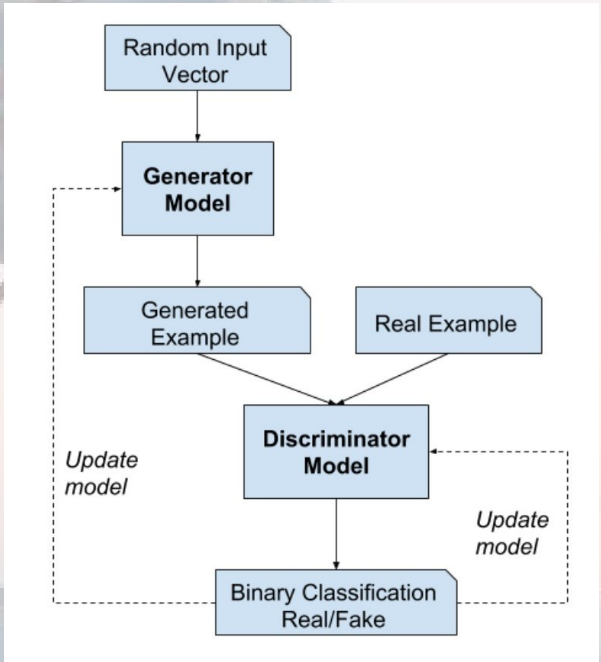
The most important Hillas parameters are:

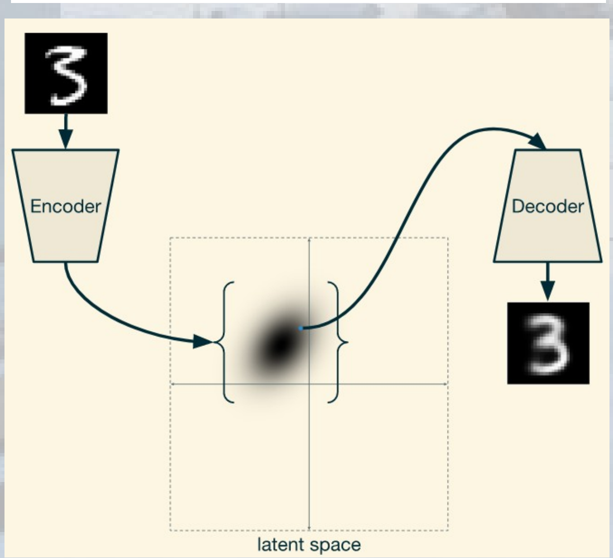
- Image brightness (called <u>image size</u>)
- Width and length of the ellipse
- Number of triggered pixels
- Distance
- Angles: alpha, phi, theta

The <u>key parameter</u> is the <u>energy</u> of the <u>primary particle</u> (can not be directly calculated but mainly correlates with the image size and distance)

Generative models as a replacement of MC

- Traditionally, event images are modeled using a special programs (usual CORSIKA) that perform detailed direct simulation of extensive air showers
  - thereby producing reasonably accurate but
  - resource-intensive and time-consuming results
- Generative Neural networks
  - GAN
  - VAE
  - Normaliztion flow



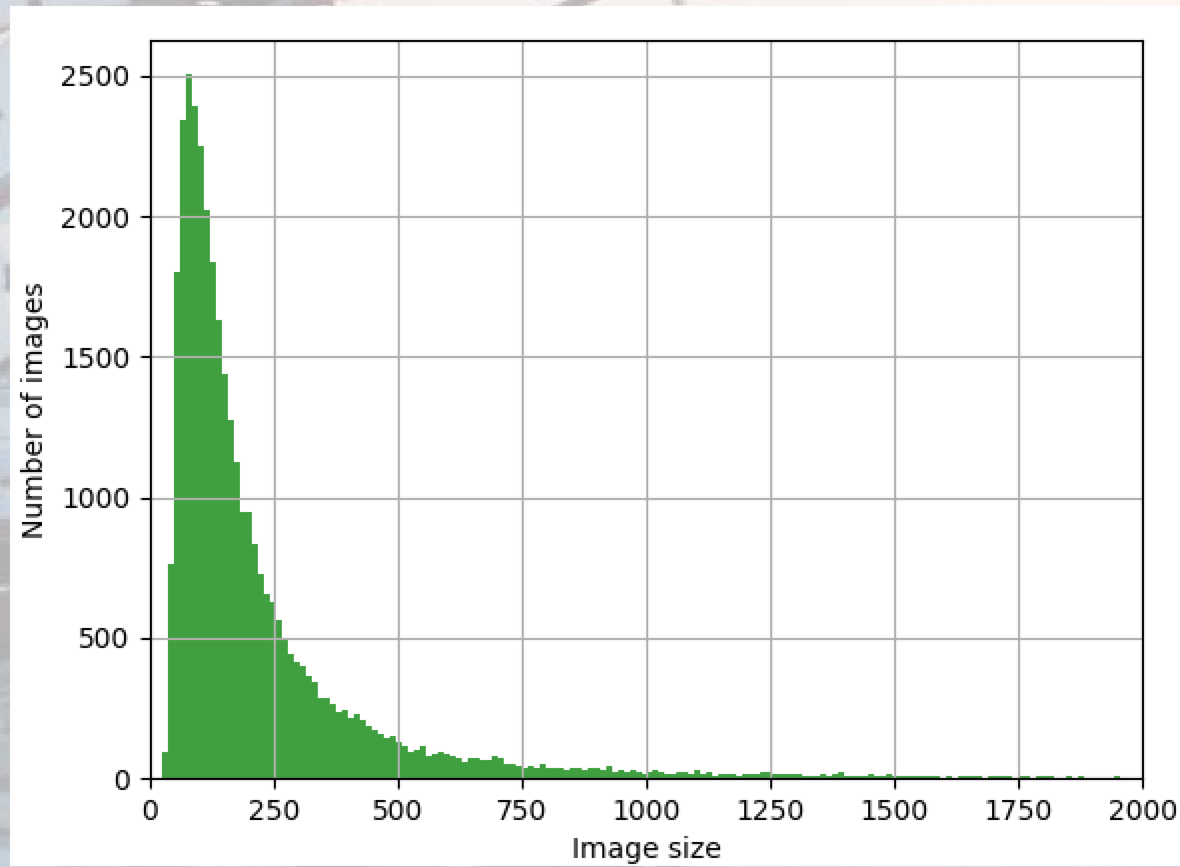


Size distribution of reference images

As reference, we use a sample of gamma images obtained using TAIGA Monte Carlo simulation software

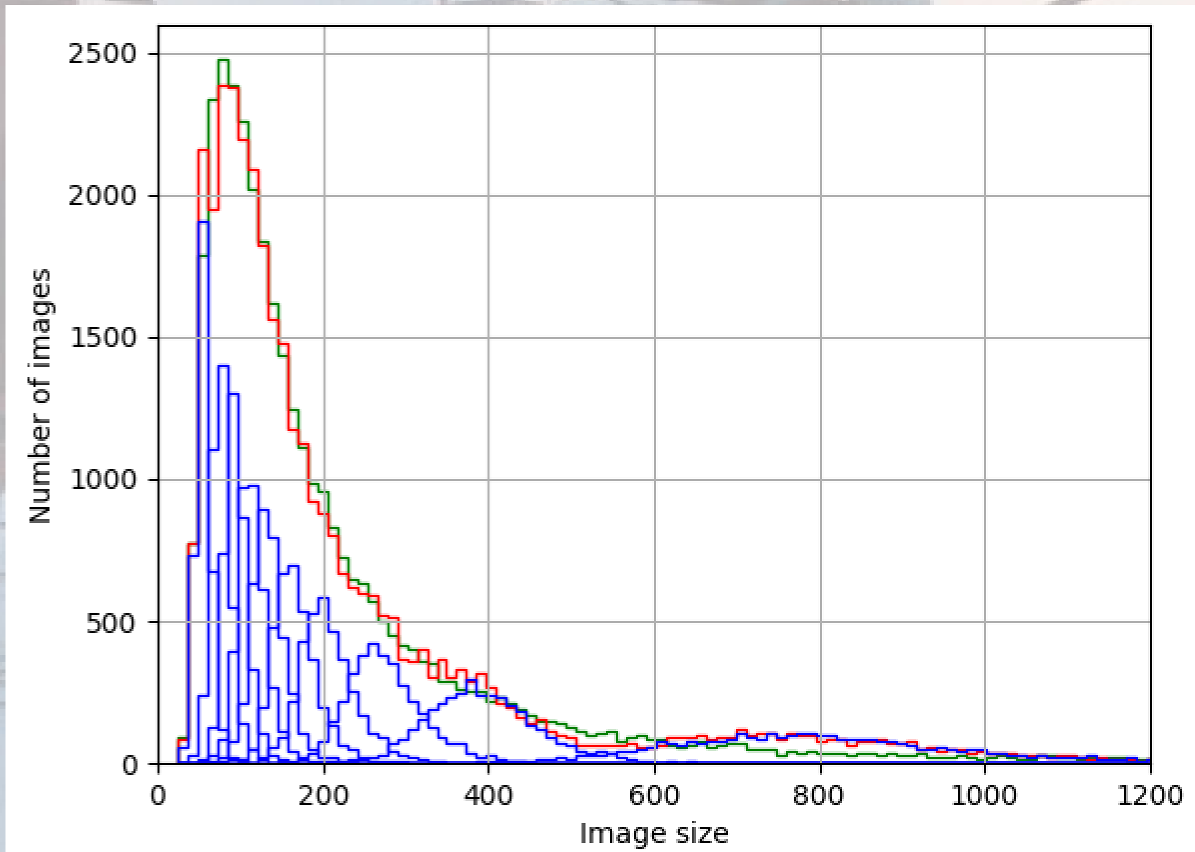
This distribution is very uneven and asymmetrical

This is the distribution that we are trying to reproduce when generating new images



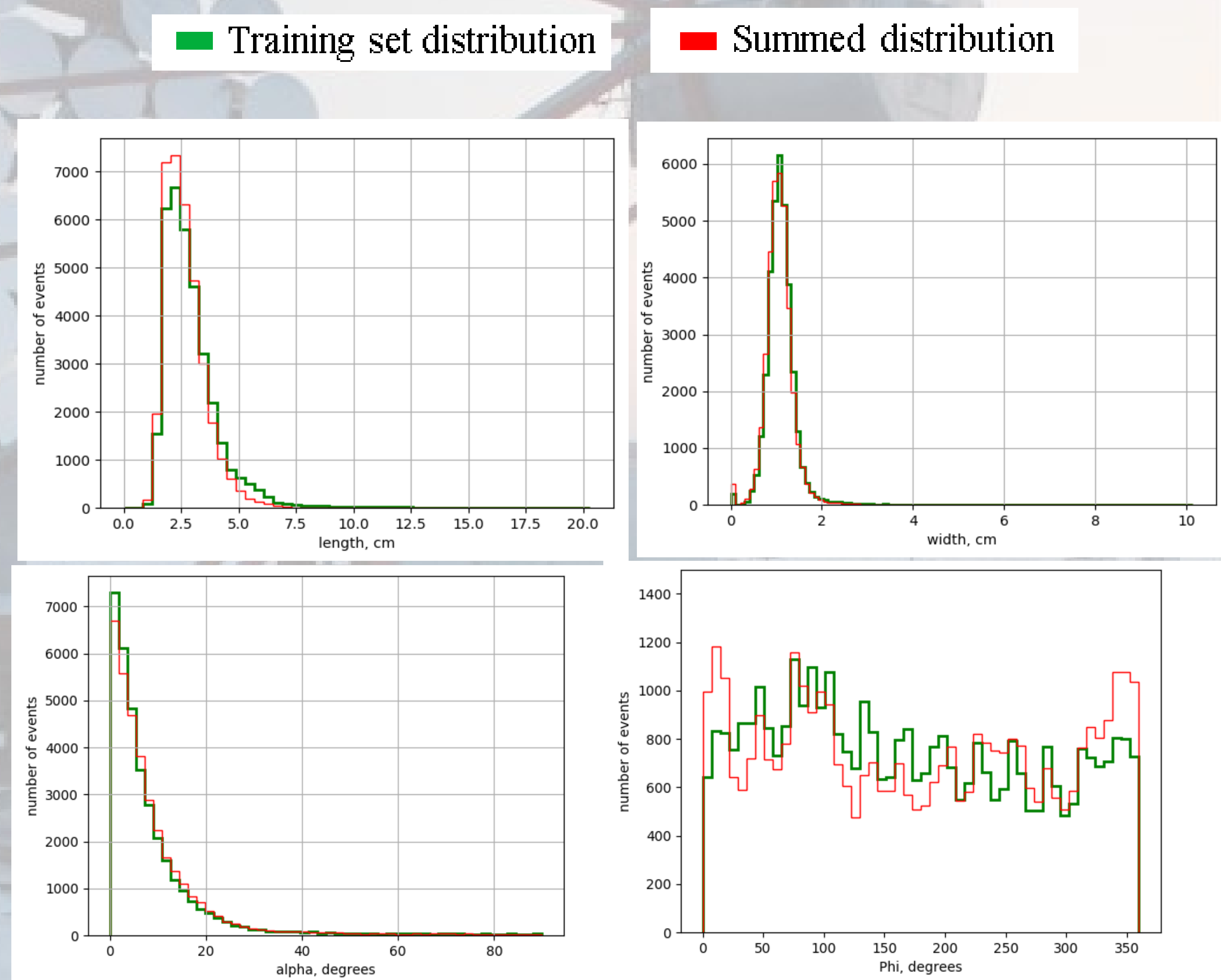
Conditional GAN with 100 classes

- The size distribution summed over all classes is close to the original distribution in the training set



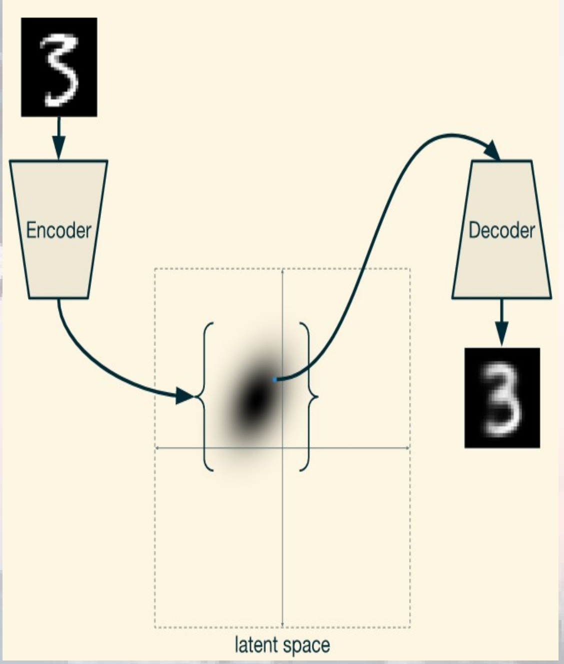
cGAN with 100 classes. Hillas parameters

- Number of triggered pixels and distance
- Hillas parameters. Angles: alpha, phi

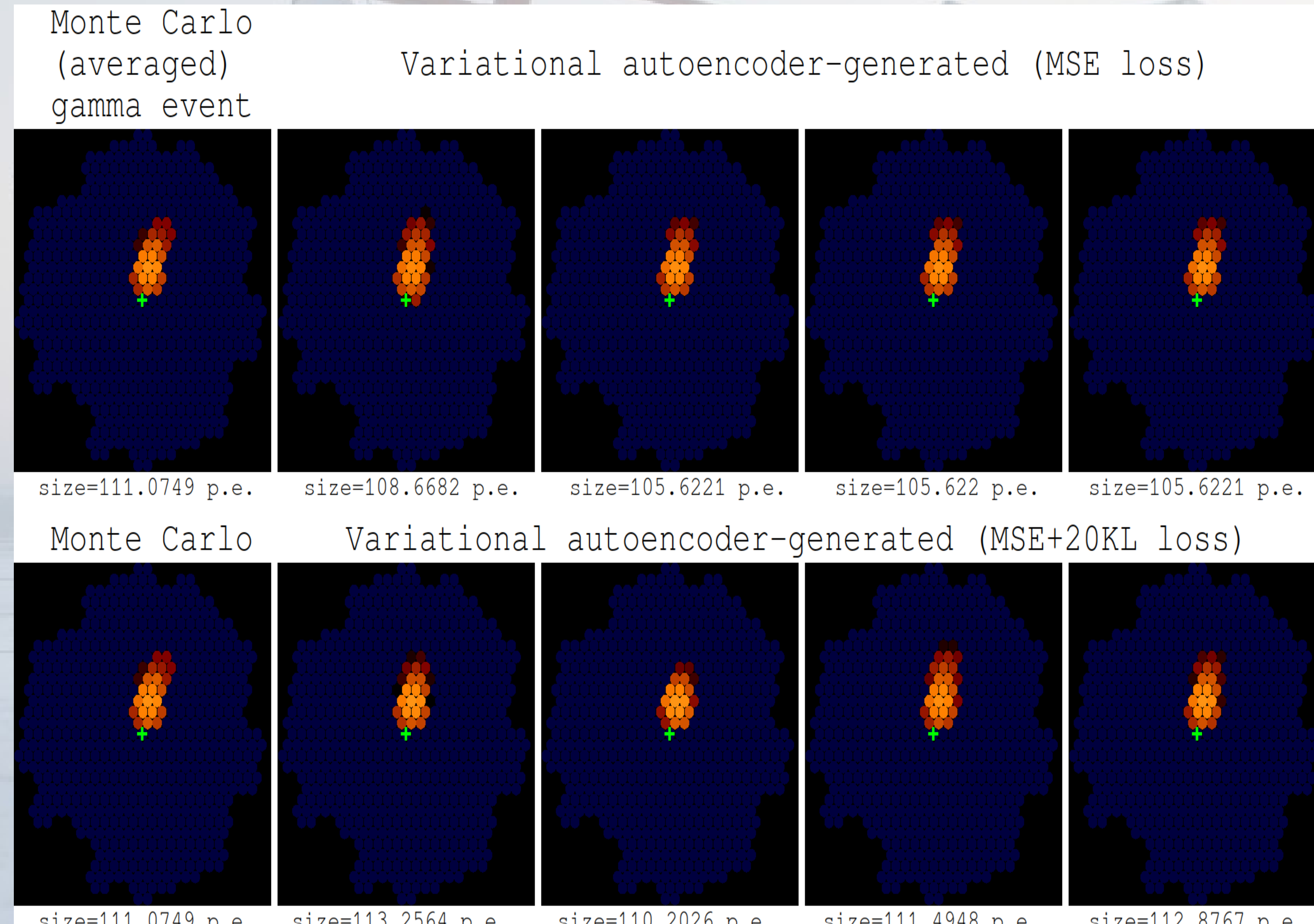


Conditional VAE

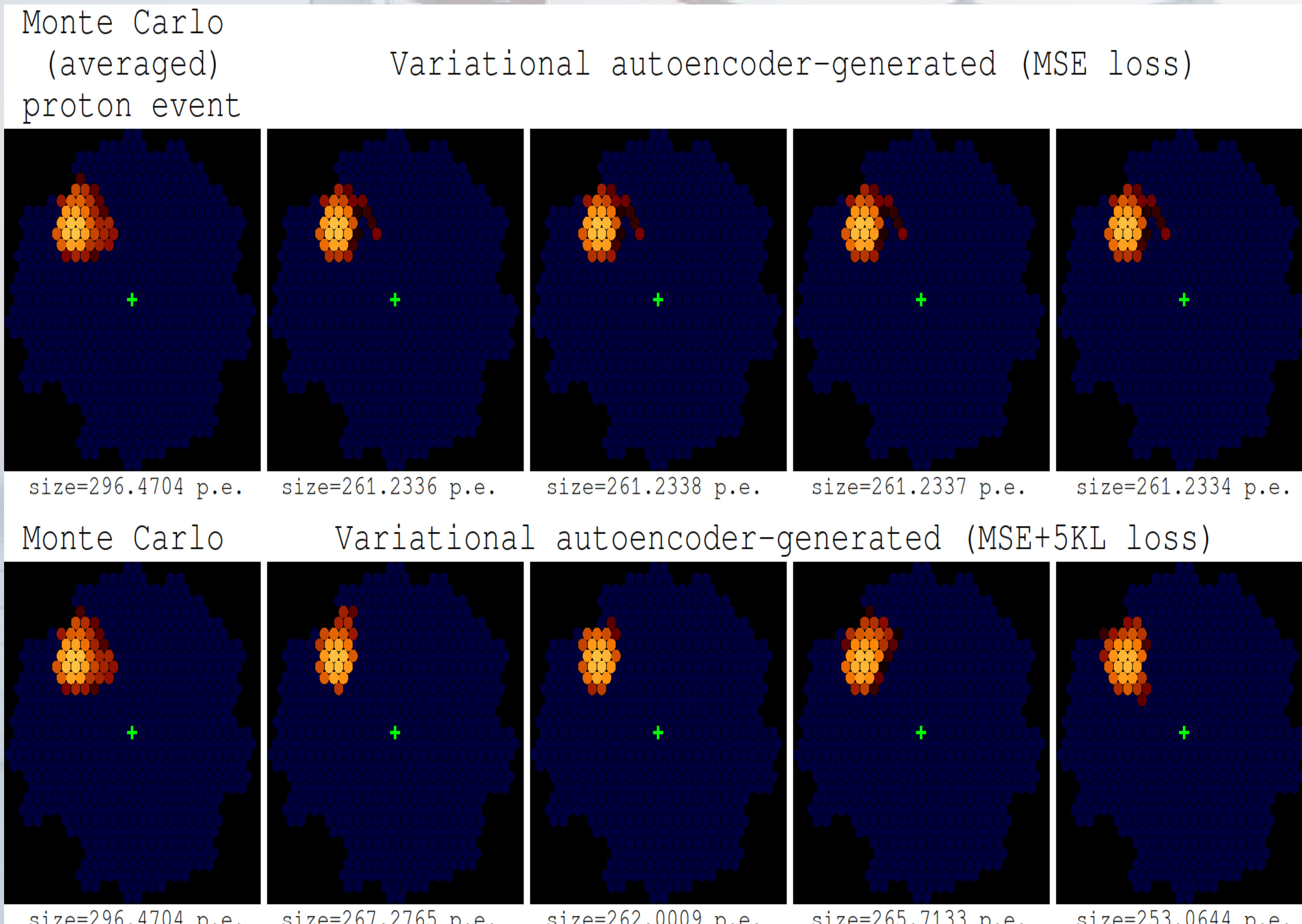
- Variational autoencoder is a probabilistic generative model. A variational autoencoder the encoder maps the input into a distribution in latent variable space, and the decoder reconstructs some image from a vector sampled from this distribution.
- In addition to the latent variables learned by the variational autoencoder, some parameters of the input data can be specified explicitly during training. These parameters are passed both to the encoder and the decoder and can be continuous as well as discrete (e.g. the energy and the type of a primary particle, respectively). When the trained CVAE is used to generate images, the desired values of the parameters can be specified.



Gamma events

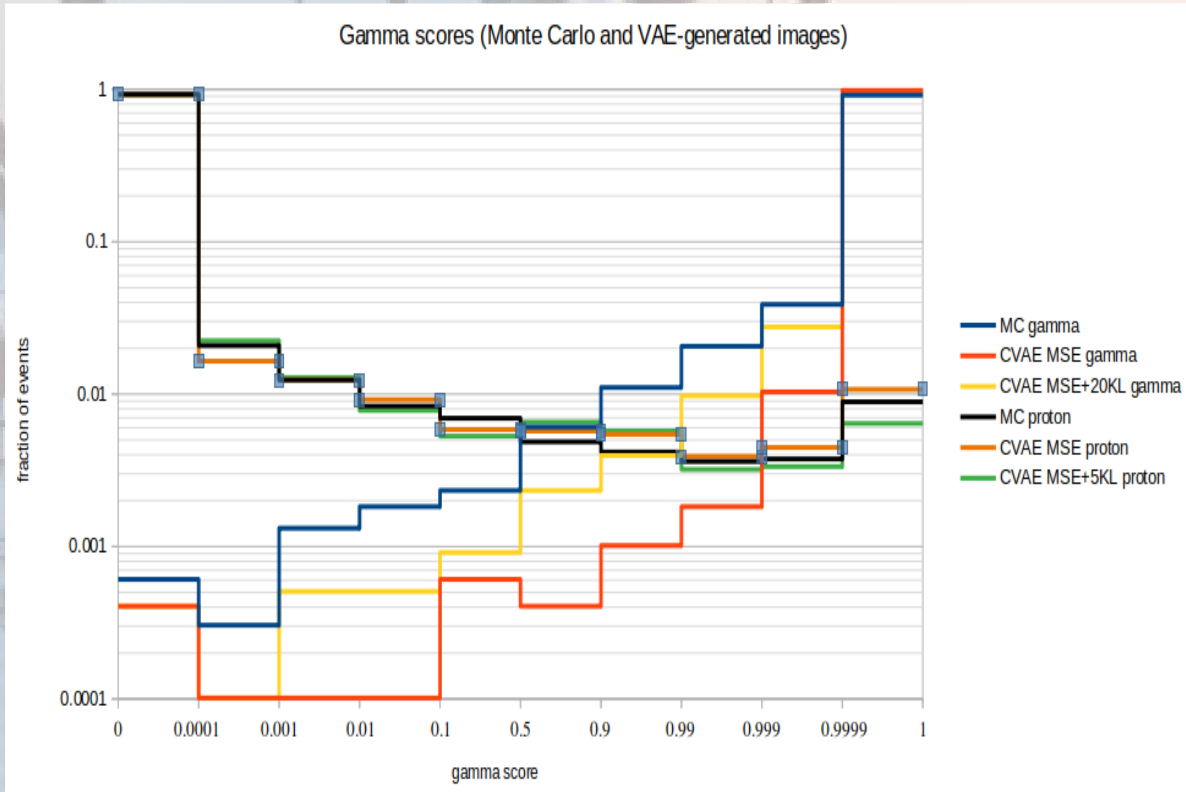


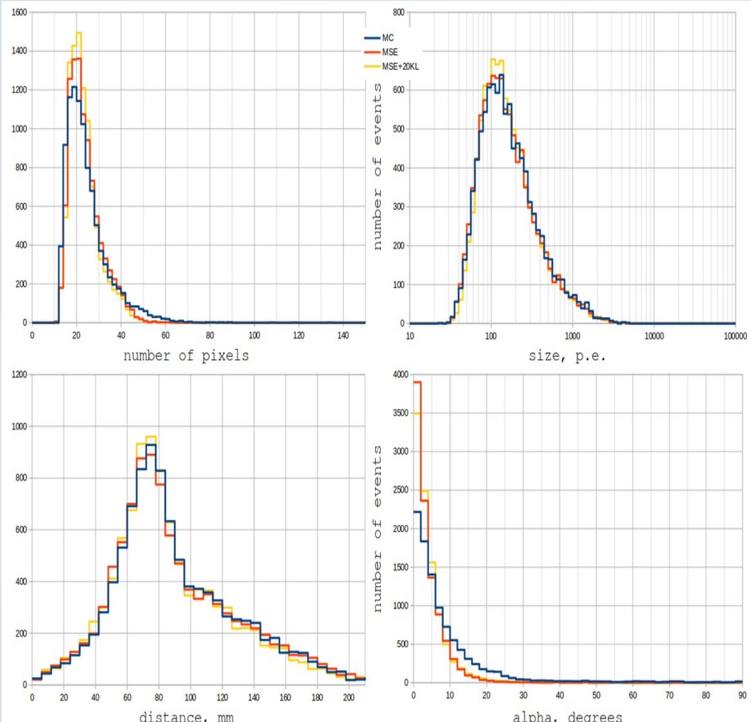
Proton events

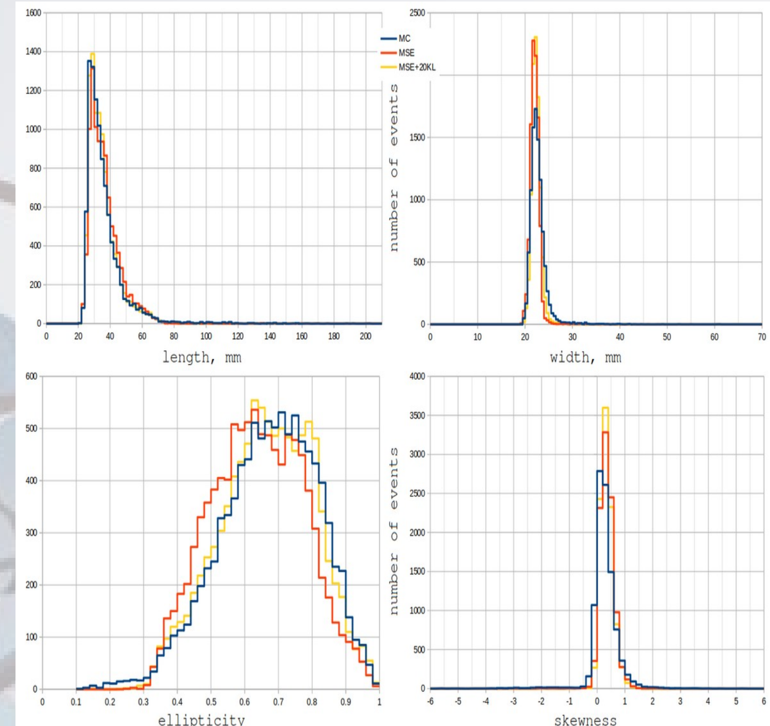


Gamma score

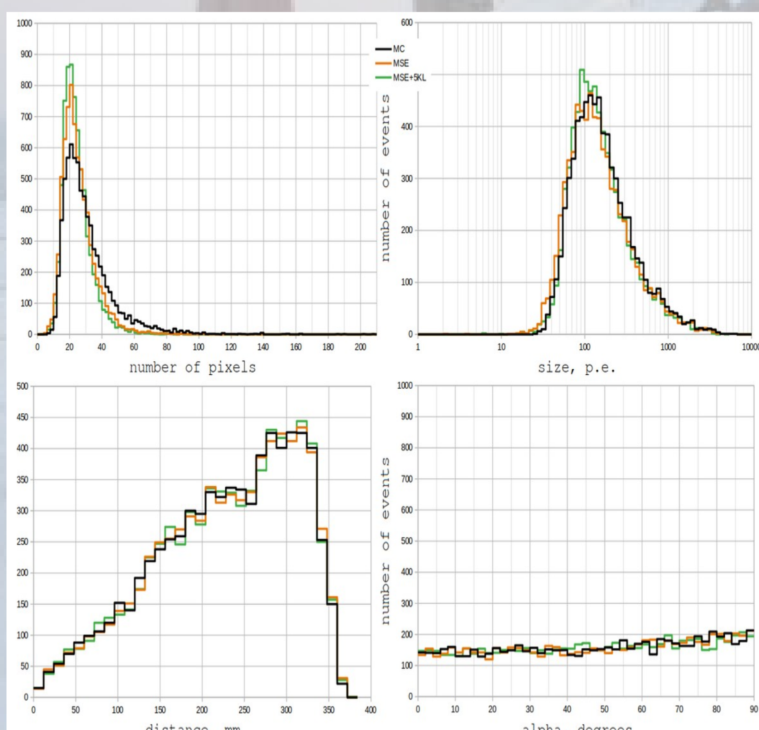
- A classifier neural network was trained on the same set of images as the variational autoencoders.
- The classifier gives the CVAE-generated gamma images the average gamma score 0.99863 for the CVAE with MSE loss and 0.99704 for the CVAE with MSE+20KL loss, respectively.
- For the CVAE-generated proton images the average gamma score is 0.03032 for the MSE autoencoder and 0.02485 for the MSE+5KL autoencoder, respectively.
- For comparison, Monte Carlo-simulated gamma events not used in the training set of the classifier get the average gamma score 0.99227; Monte Carlo-simulated proton events get the average gamma score 0.02612.

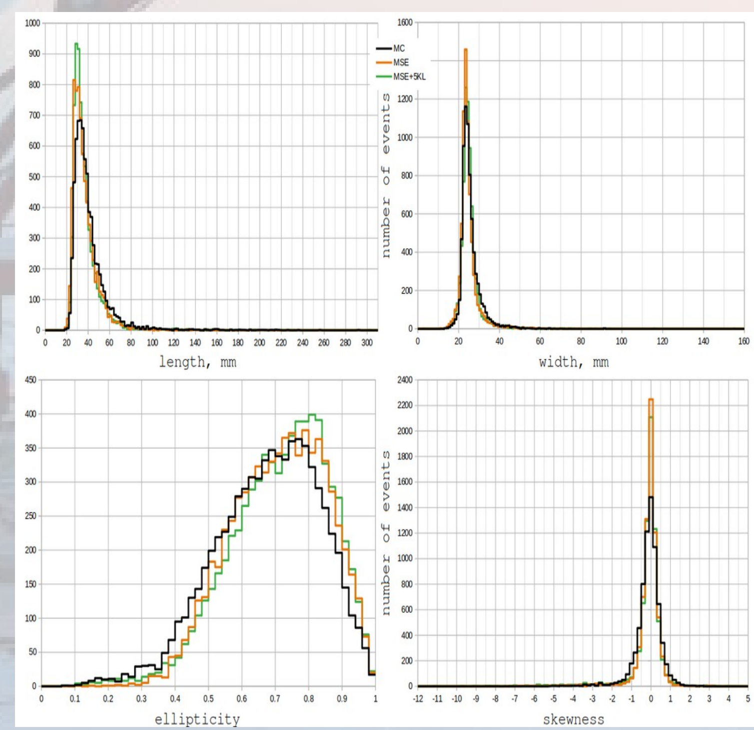






Gammas





Protons

Conclusion

- Machine learning is a powerful tools to investigate the fundamental astrophysics problems like physics of supernova, black holes, pevatrons, and so on.
- Especially in gamma astronomy the following problems can solve successfully:
  - Identification of primary particles
  - Reconstruction of energy spectra
  - Simulation of experimental data
- The full connected and convolution neural networks give the results competitive to traditional approaches based on Hillas parameters.
- Very perspective is using of generative neural models like GAN and VAE.
  - The images generated by the generative models are very similar enough to the Monte Carlo images
  - Important that genarated sample reproduce the statistic properties of the MC and experimental samples.
  - The speed of sample generations is 3-4 order more then CORSIKA program

Thus, machine learning open the new horizon on analyses and simulation of experimental data in gamma astronomy

Thank you!

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