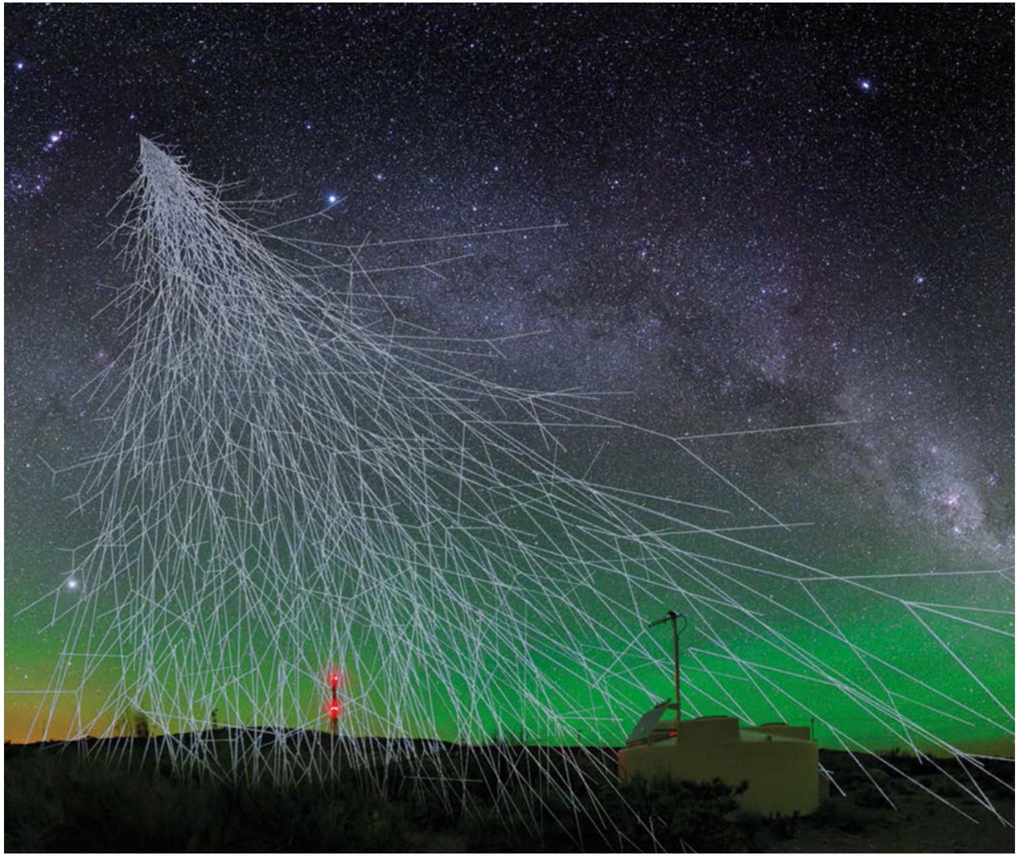
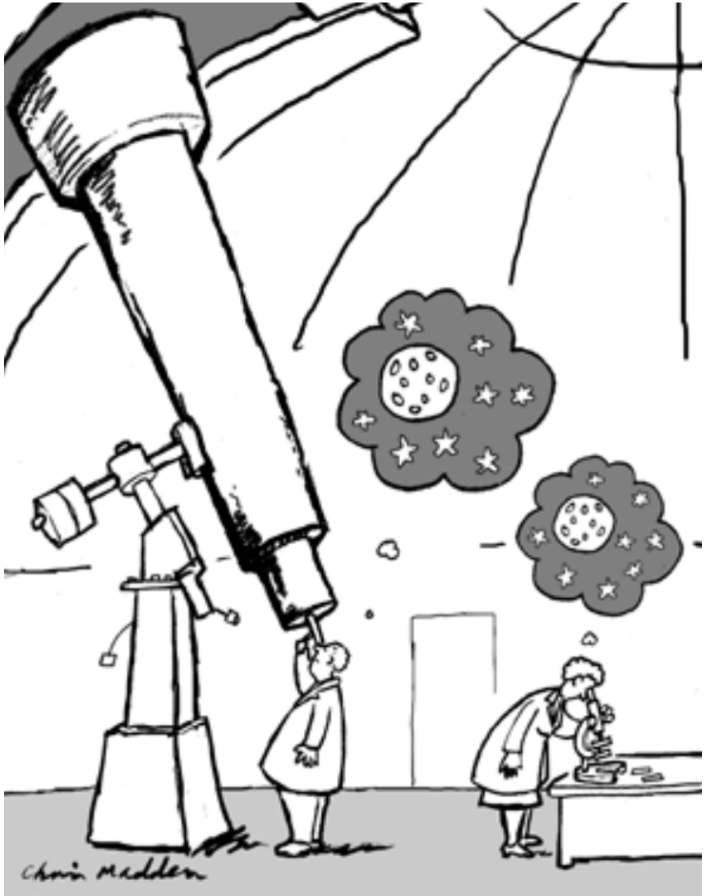
Astroparticle Physics

Rather Brief Introduction and Overview

Ralf Ulrich, KIT



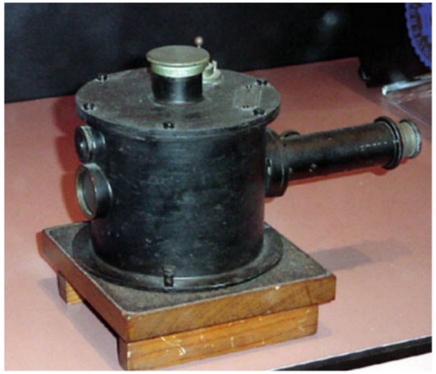

Chris Madden

Astroparticle Physics

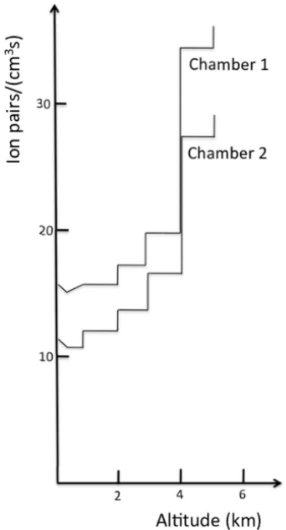
- Part I – Brief overview
  - Origins, History, Introduction
  - The universe at ultra-high energies
  - Experiments: cosmic rays, neutrinos, gamma rays
  - Multi messenger astronomy
- Part II – Cosmic rays and LHC
  - Ultra-high energy interactions
  - Extensive air showers
  - LHC forward physics, QCD

Origins: cosmic rays

1911-1912: Hess performs a series of ballon flights, systematic measurements with improved setup (insulation against pressure and temperature changes**)**



→ **finds that radiation level decreases slowly up to ≈ 700 m in altitude, then increases considerably with height**



“The results of the present observations seem to be most readily explained by the assumption that a radiation of very high penetrating power enters our atmosphere from above.
Since I found a reduction neither by night nor at a solar eclipse, one can hardly consider the Sun as the origin.**”**

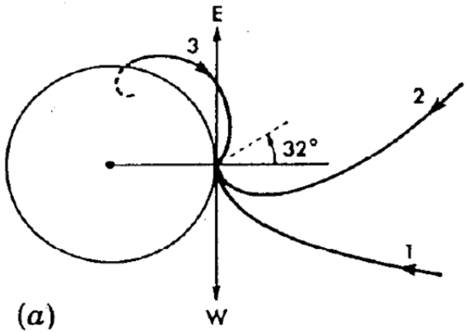
→ **Nobel Prize 1936**

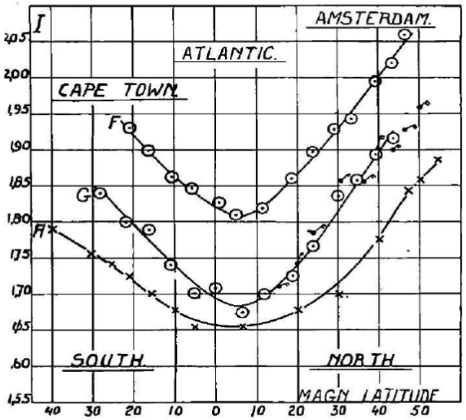
Charged particles from space

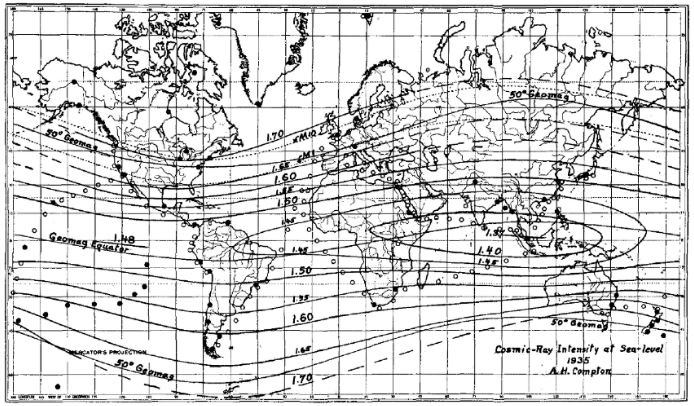
Cosmic rays initially believed to be gamma rays because of their penetrating power

1927: Clay shows dependence on latitude
→ cosmic rays are affected by Earth magnetic field
→ must be charged particles

1931-33: Compton organizes global study
→ confirms Clay's findings





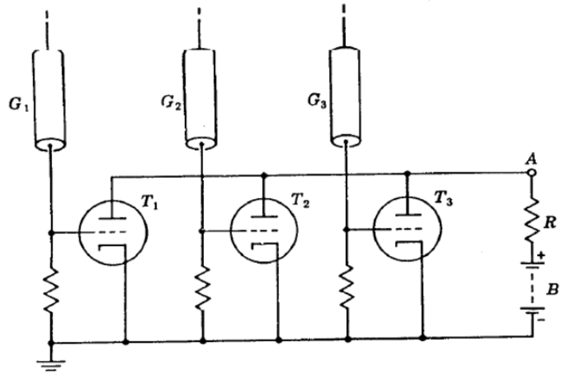


High energy and secondary cascades

1928: Geiger-Müller counter
→ fast response to individual particles
→ possibility to form coincidences !

1932: Rossi shows that (at sea level)
→ 50 % of the radiation penetrates 1 m of lead
→ highest energies must exceed 14 GeV

Rossi also demonstrates production of secondary particles



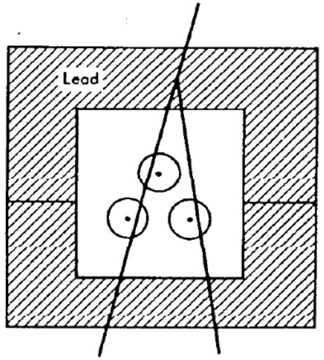


Fig. 4-3 Triangular array of G-M counters used in the first experiment demonstrating the production of secondary particles by cosmic rays. At least two charged particles emerging simultaneously from the lead are needed to produce a coincidence. One of them may be a primary particle, but the other must have been produced in the lead. (If the upper section of the lead shielding is removed, the coincidence rate falls nearly to zero.)

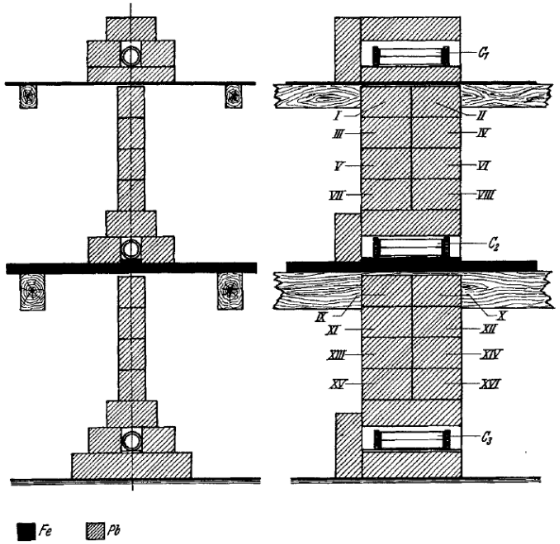
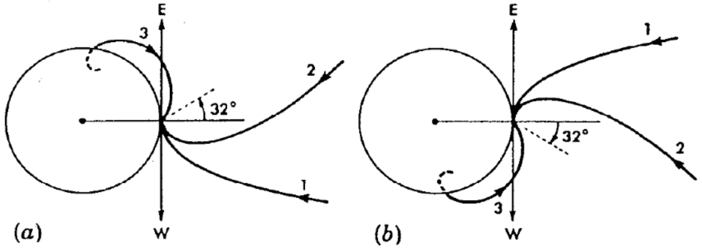


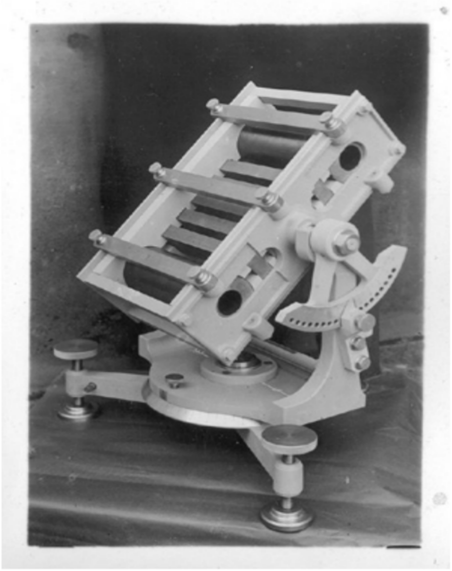
Fig. 2.

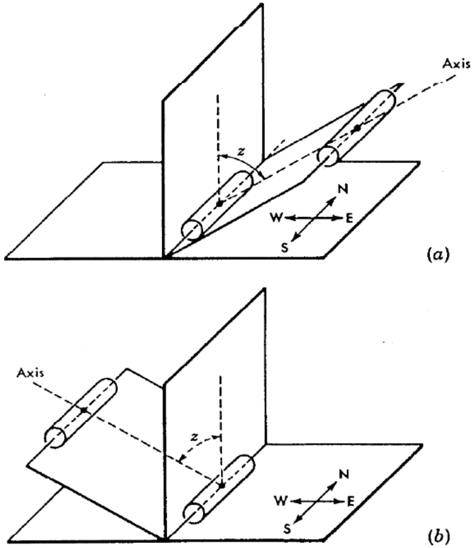
Cosmic rays are positively charged

1932: Johnson and Alvarez & Compton demonstrate east-west asymmetry
(confirmed by Rossi in 1934**)**

→ Cosmic rays are positively charged







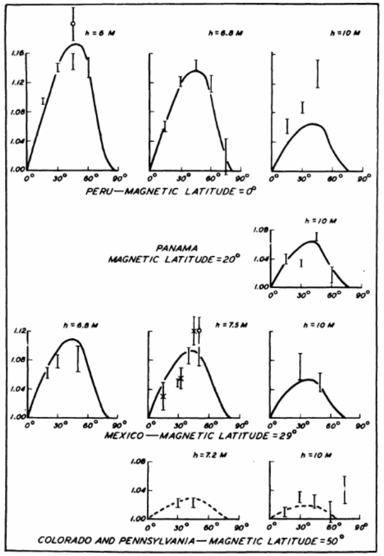
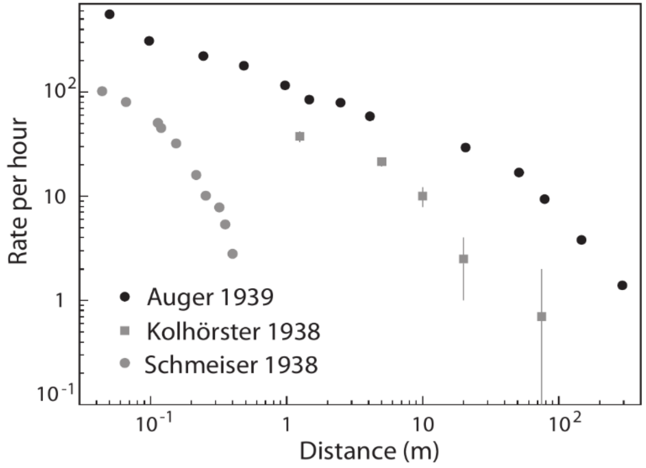


FIG. I—INTENSITY-RATIOS (J_W/J_E) VERSUS ZENITH-ANGLE AT VARIOUS LOCATIONS

Huge energies and extensions

1938/1939: Kohlhörster and Auger observe coincidences between detectors that are up to 300 m apart

→ Cosmic rays cause extented air showers



1941: experiments by Schein and others show that primary cosmic rays are mostly high-energy protons

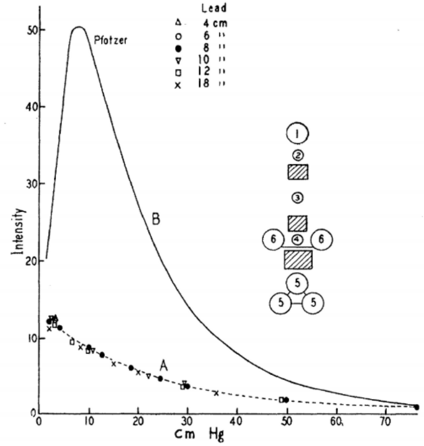
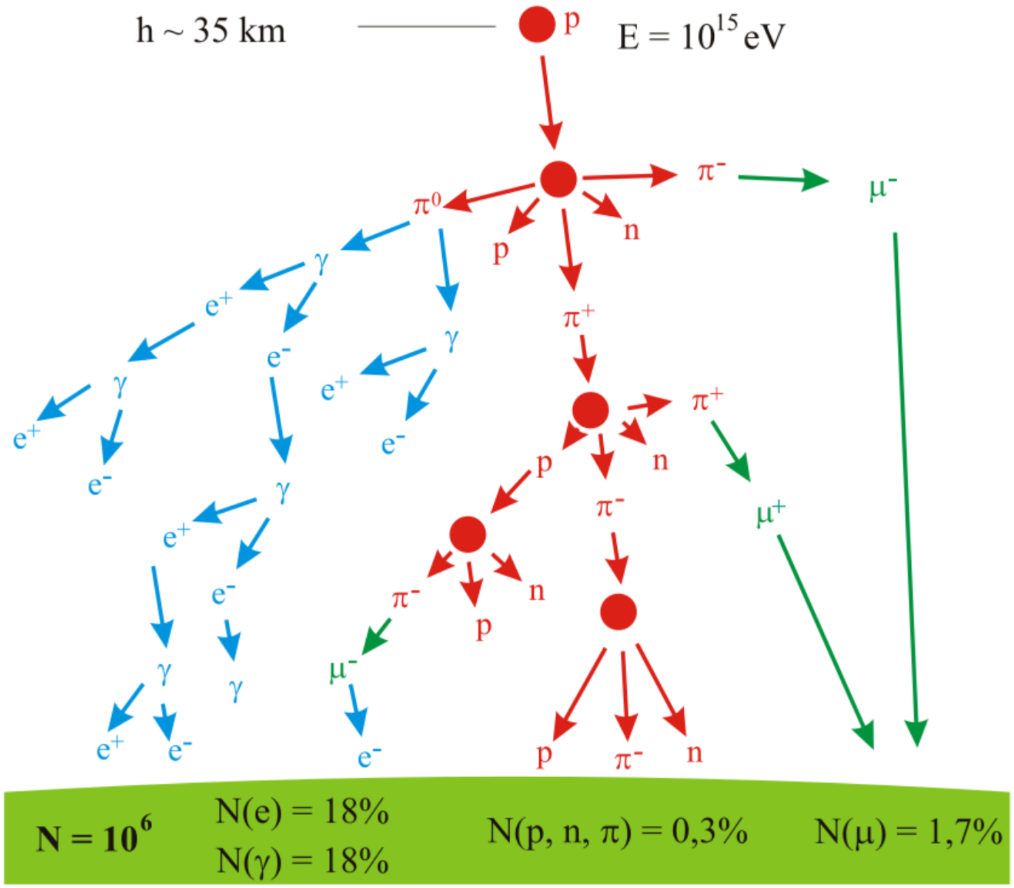
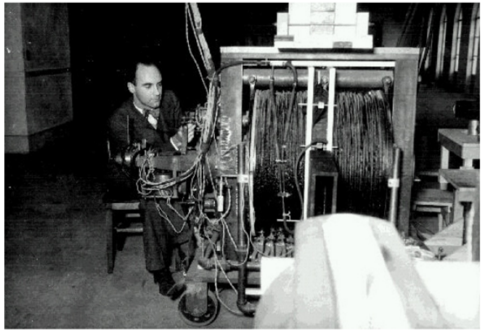


FIG.1. Curve A: Intensity of the hard component for various lead thicknesses as a function of pressure in cm Hg. Curve B: Total vertical intensity of cosmic rays obtained by Pfotzer as a function of pressure.

Secondary particle showers



Cloud chamber, discovery of anti-matter



Invented by Wilson in 1912

→ used in cosmic-ray studies since 1930’s

Vessel filled with supersaturated water vapour

→ created by rapid adiabatic expansion

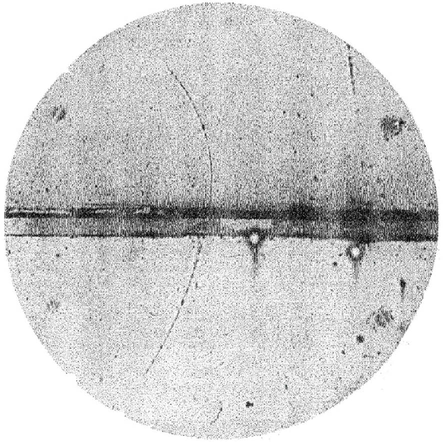
Charged particle creates ionisation clusters along its trajectory

→ act as condensation nuclei
→ trail of water droplets

Particle momentum from curvature of trajectory in magnetic field

Particle energy from density of droplets

→ Momentum + energy → mass = type of particle



discovery of positron
(Anderson, 1932)

Discovery of the 2nd generation

1937: muon discovered by Anderson & Neddermeyer
and Street & Stephenson
using triggered Cloud Chambers

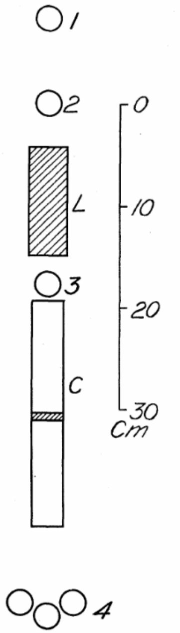


FIG. 1. Geometrical arrangement of apparatus.

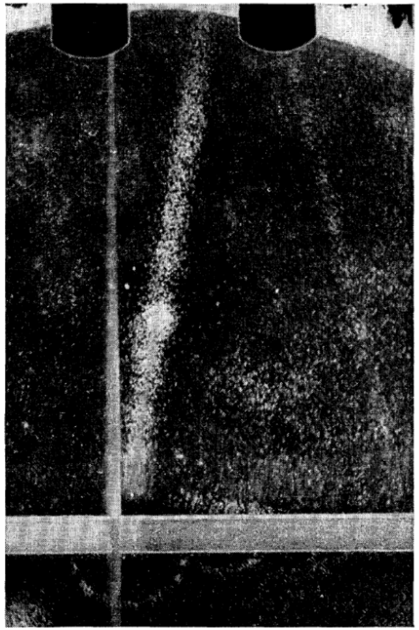


FIG. 2. Track *A*.

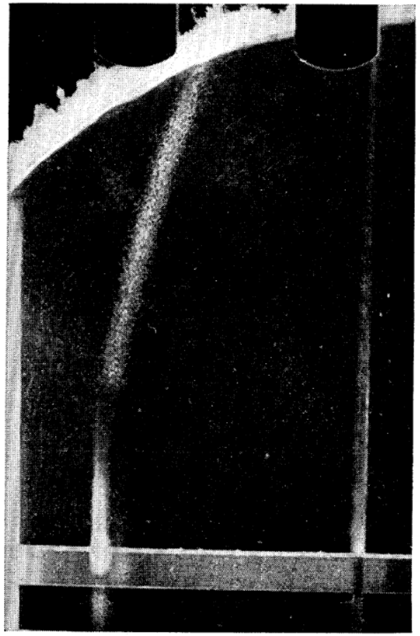


FIG. 3. Track *B*.

Discovery of the pion / mesons

1947: pion discovered by Lattes and by Occhialini & Powell using photographic emulsions

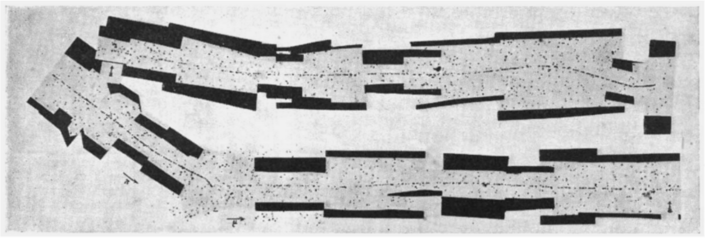


Fig. 1. Observation by Mrs. I. Powell. Cooke × 95 achromatic objective; *C*2 Ilford Nuclear Research emulsion loaded with boron. The track of the μ-meson is given in two parts, the point of junction being indicated by *a* and an arrow

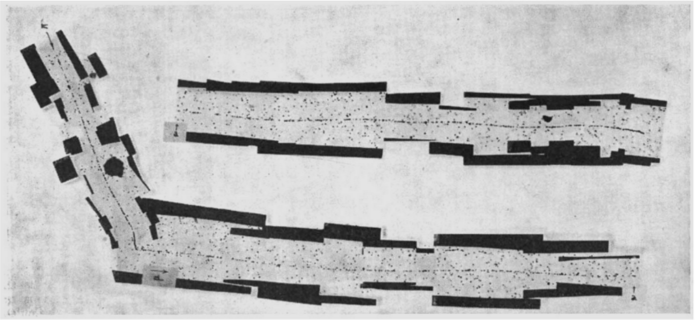


Fig. 2. Cooke × 95 achromatic objective. *C*2 Ilford Nuclear Research emulsion loaded with boron

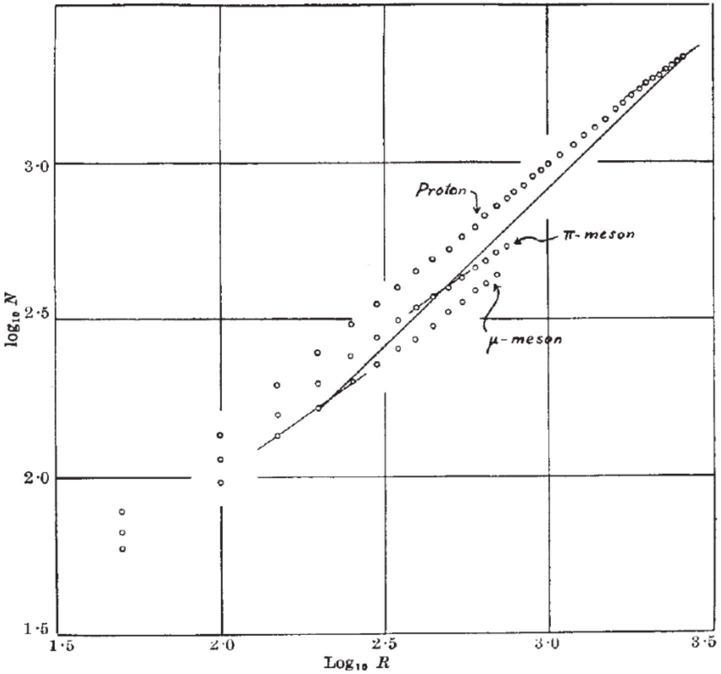


Fig. 5. *N* is total number of grains in track of residual range *R* (scale-divisions). 1 scale-division = 0·85 microns
The 45°-line cuts the curves of the mesons and proton in the region of the same grain density

Discovery of the kaon

1947: kaon discovered by Rochester & Butler using cloud chamber

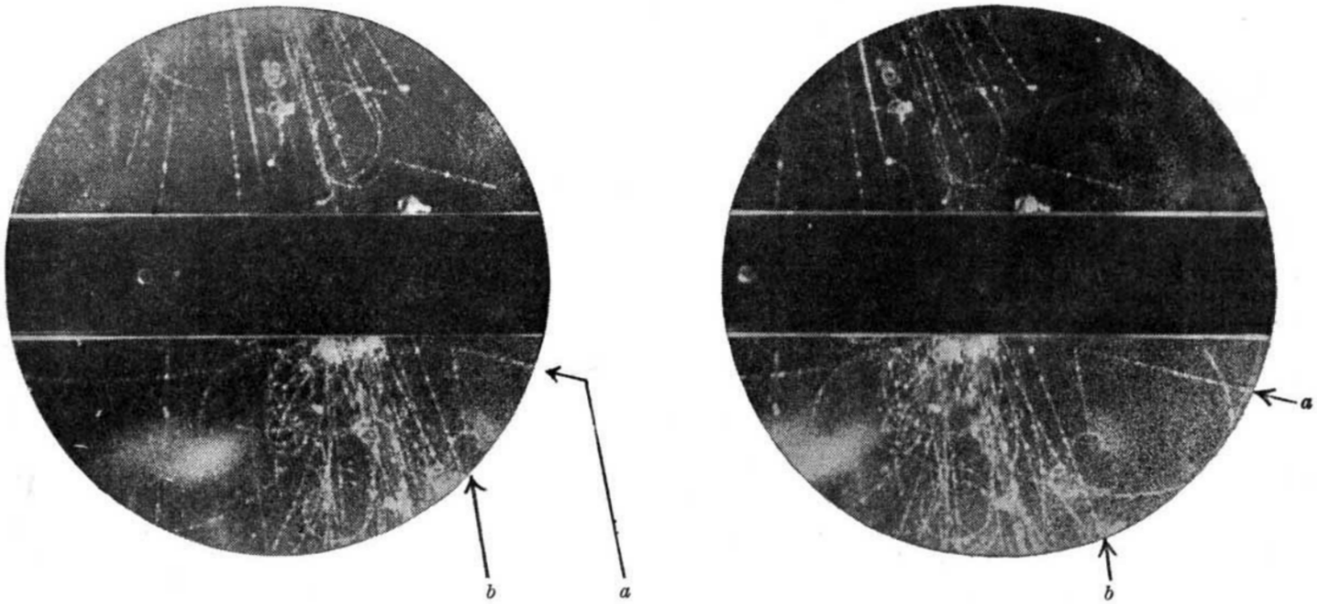


Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

Cosmic rays vs. colliders

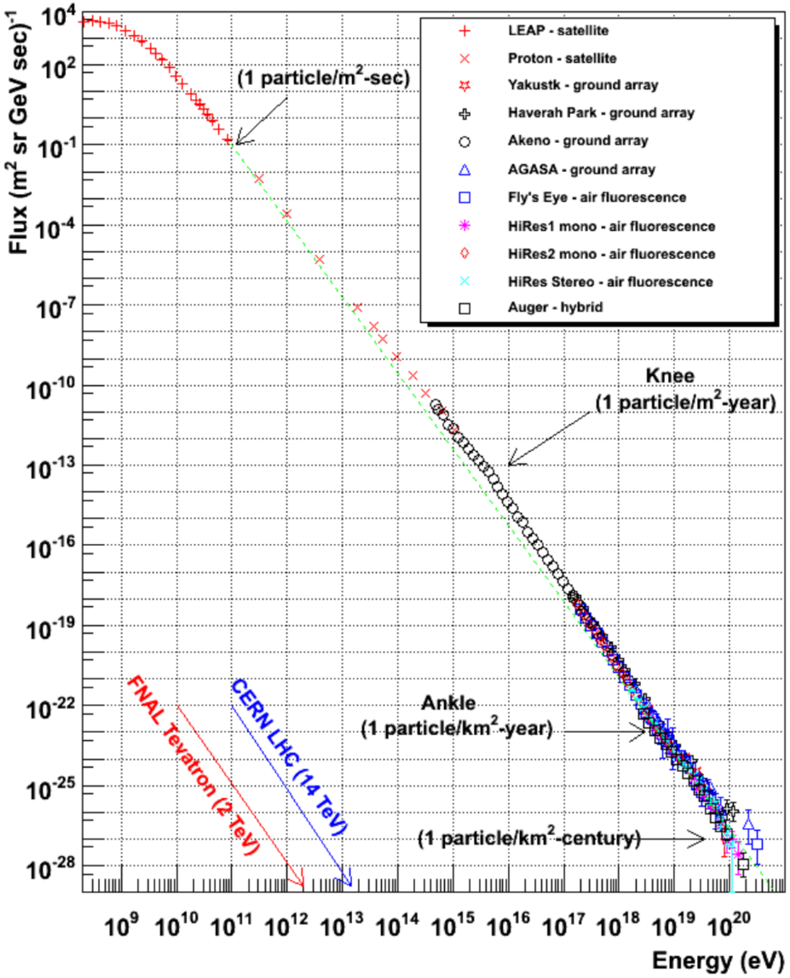
Accelerators provide controlled environment
→ know exactly when
and where collisions happen

Accelerators provide much higher rates, e.g.

10^9 *pp* collisions / sec
at LHC run II (13 TeV)

≈ 10 cosmic rays / m² / day
at ≈ 10 TeV

Rate extremely important to
→ study rare processes
→ measure differential distributions



Introduction and current status

What is astroparticle physics today?

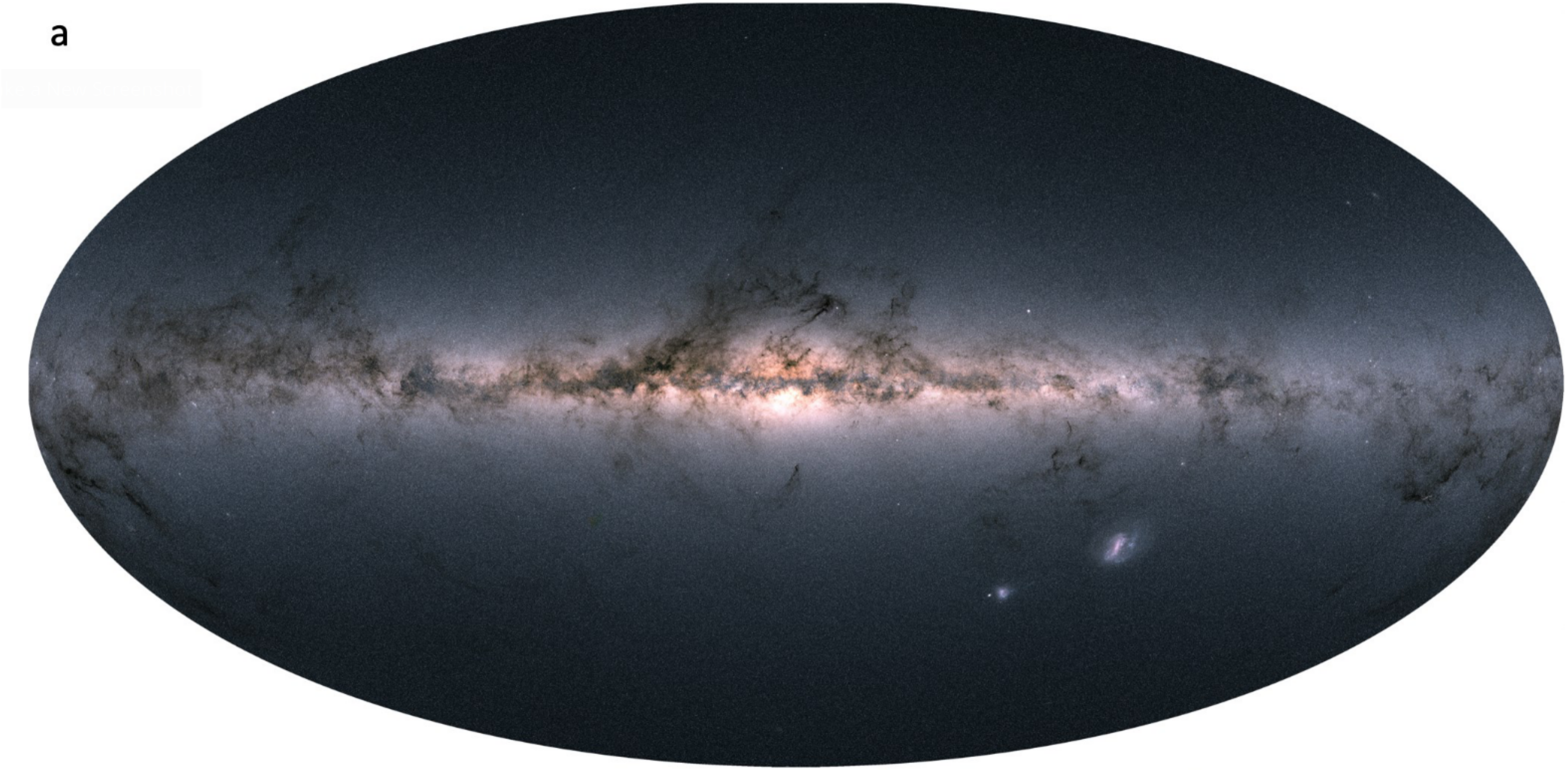
Three Aspects:

- **Learning high-energy physics from astrophysics:**
  - Neutrino properties, cross sections at ultra high energies, new forms of matter (dark matter and dark energy), time variation of fundamental constants, space-time structure
- **Applying high-energy physics techniques to astrophysics:**
  - calorimetry and tracking detectors onboard satellites and balloons, ground based scintillators and Cherenkov detectors, handling of large volume data sets, astronomy with neutrinos
- **Cosmology with input from high-energy physics:**
  - Big Bang theory, nucleon synthesis, candidates for dark matter

Tools and Sites

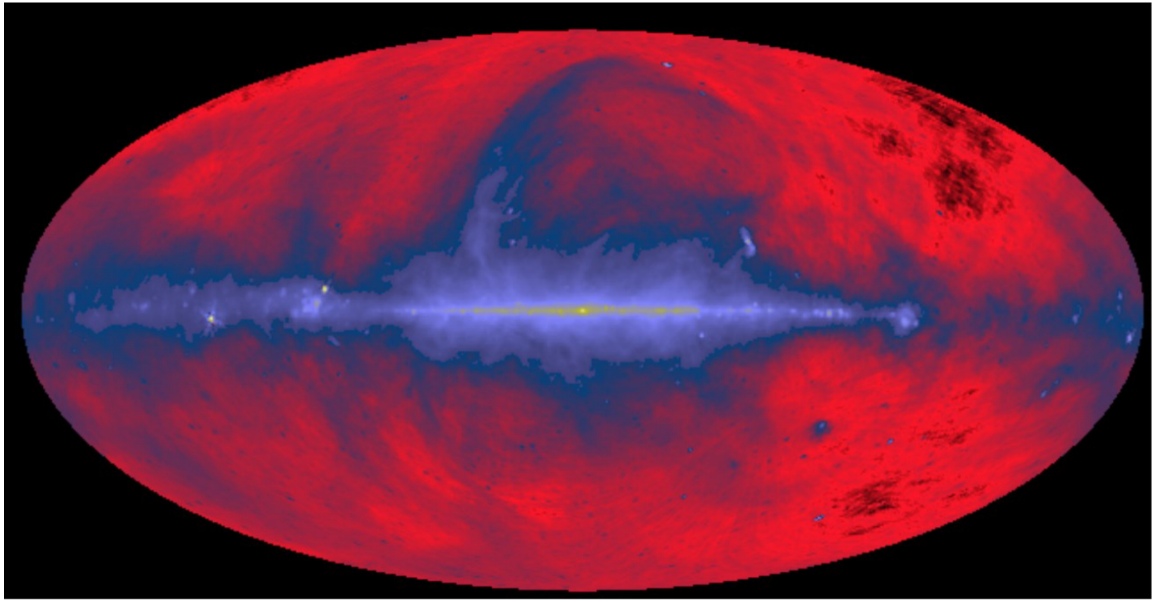
Also an adventure!

GAIA all-sky visible universe



Basically: thermal black-body radiation and some absorption

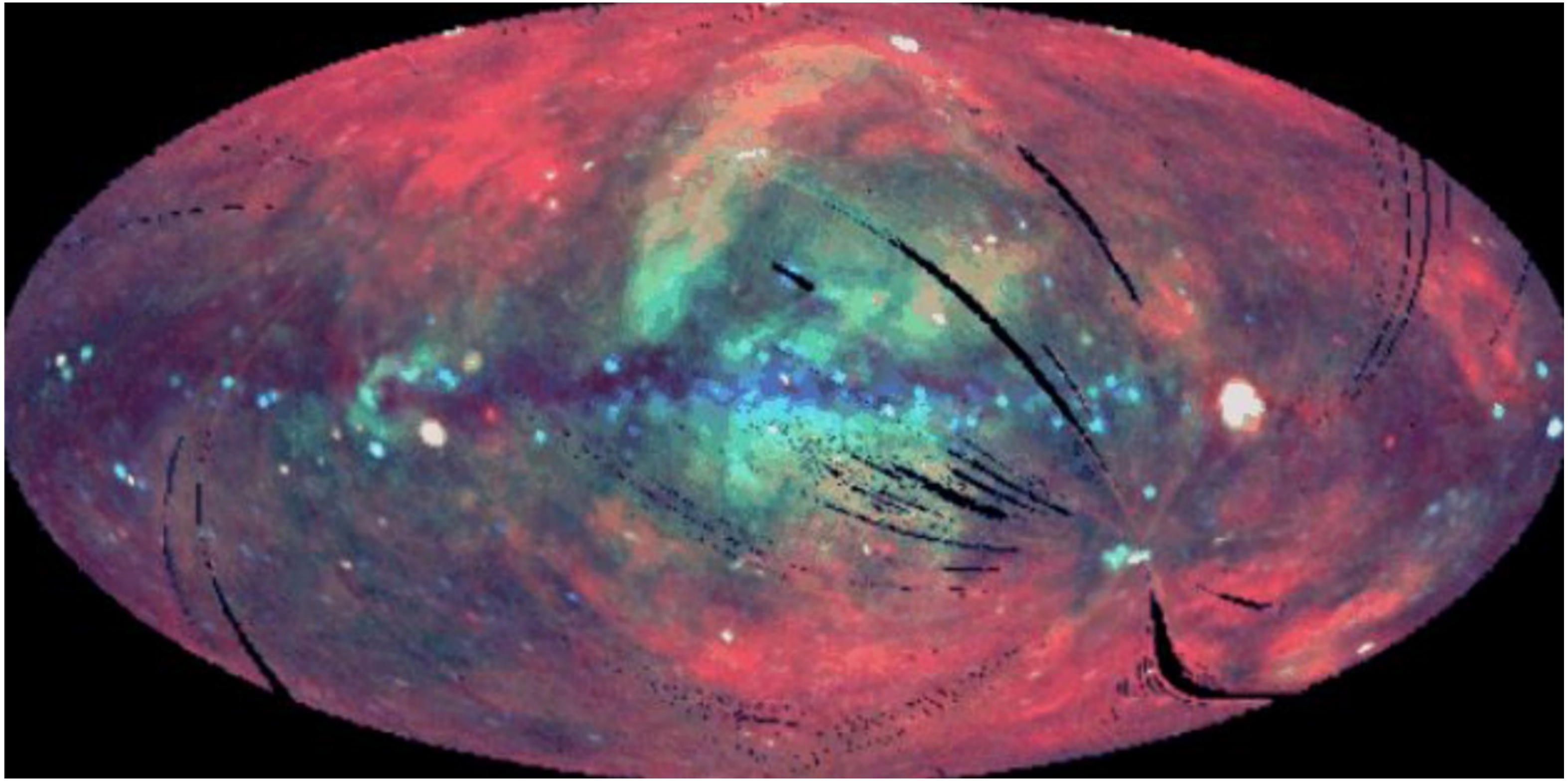
Radio astronomy, all-sky at 408MHz



Non-thermal low-energy emission.

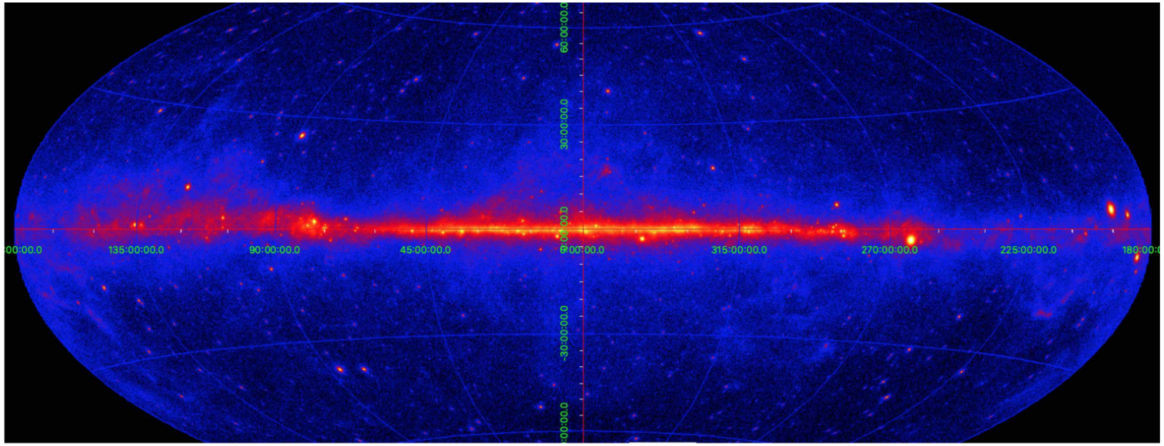
Accelerated charges.

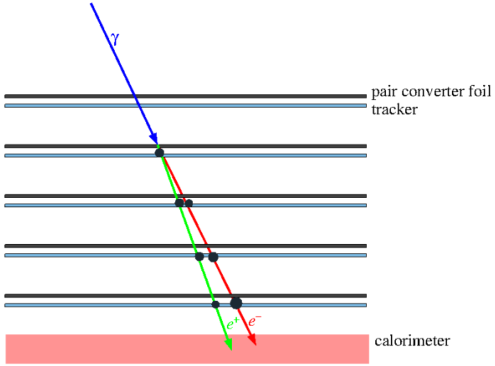
All-sky x-ray keV (ROSAT)

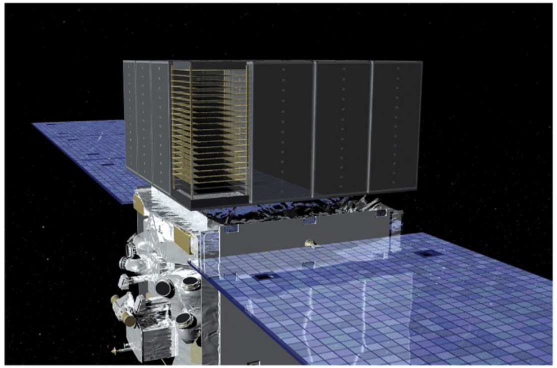


Elements of both, thermal (extremely hot) and non-thermal emission.

All-sky gamma ray >1GeV (Fermi)

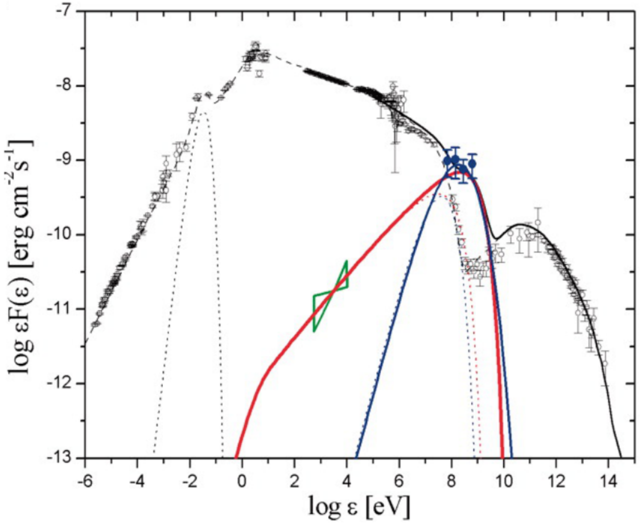


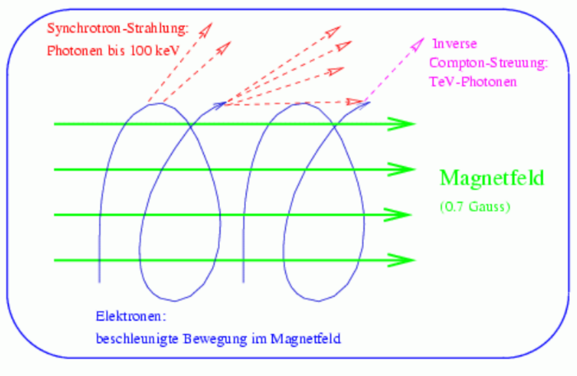


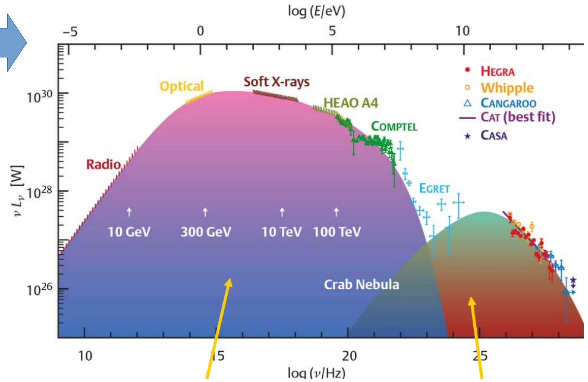


Non-thermal, typical decays, particle physics, inverse compton.

Supernova remnants: Crab nebula



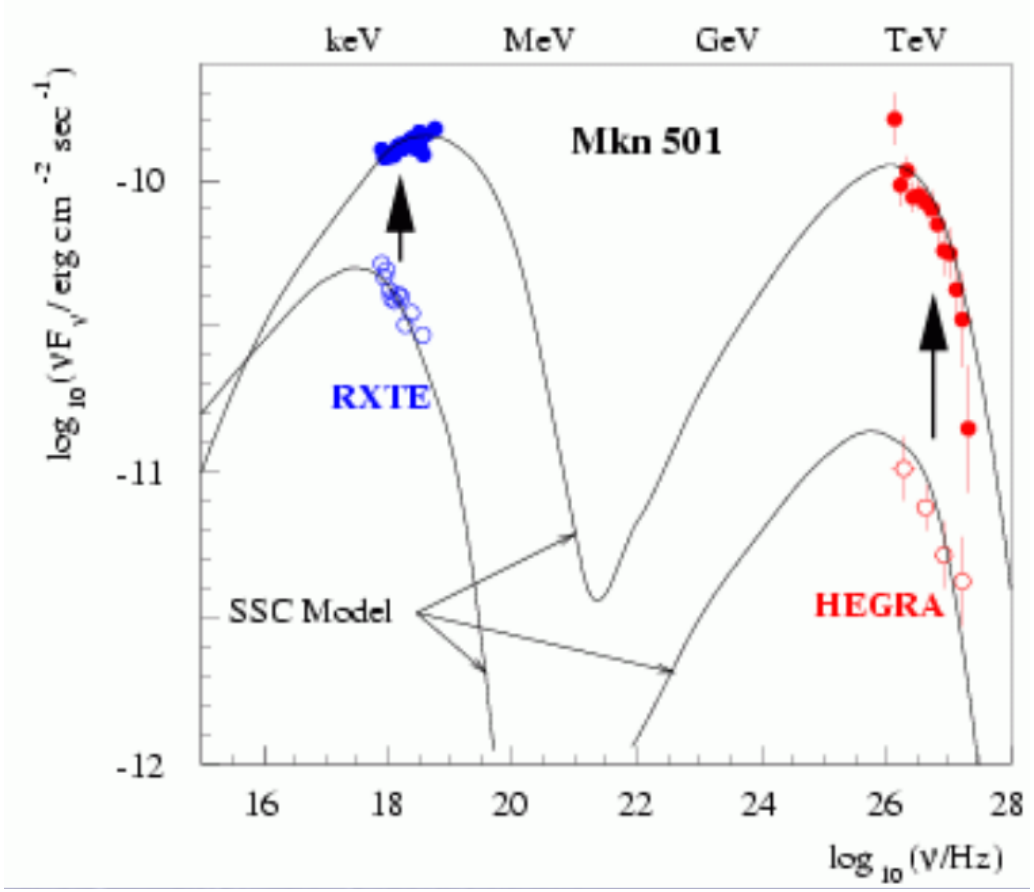




- https://arxiv.org/pdf/1101.2311.pdf

Extragalactic gamma rays

- Supermassive black holes
- Active galactic nuclei



The universe at the highest energies

Ultra-high energy cosmic rays

Air shower observatories

Example: event observed with Pierre Auger Observatory

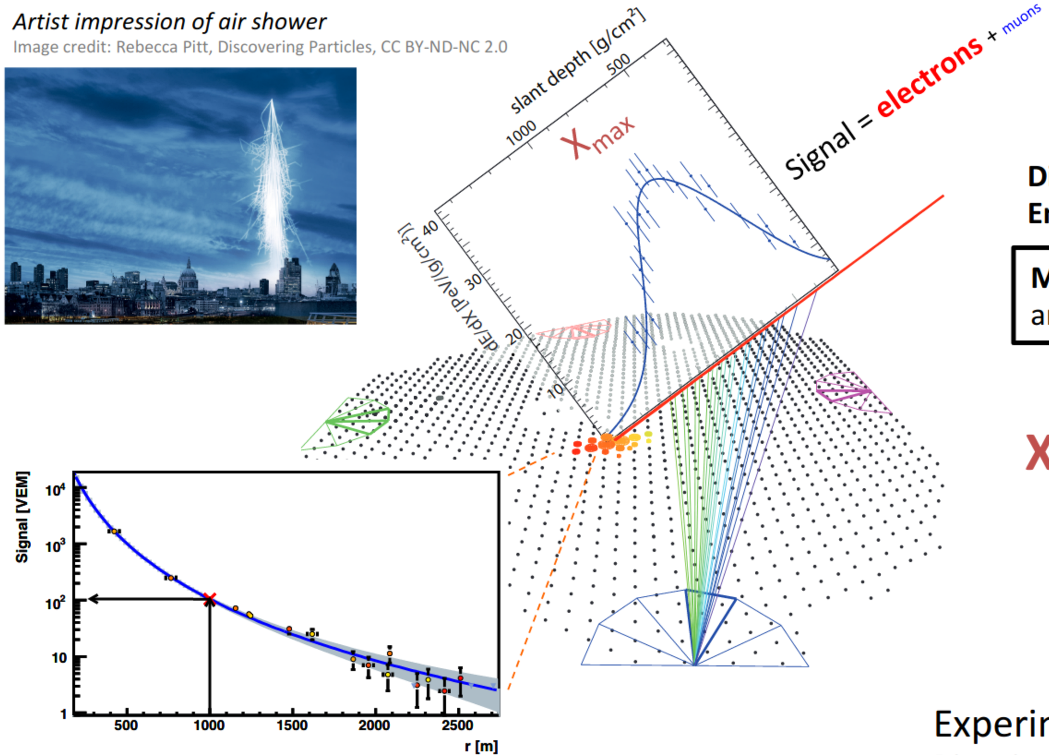

Artist impression of air shower

Image credit: Rebecca Pitt, Discovering Particles, CC BY-ND-NC 2.0

$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\mathrm{ionization}} dX$$

Direction from particle arrival times ✔
Energy from size of **eγ component** ✔

Mass from **depth of shower maximum**
and size of **muonic component**

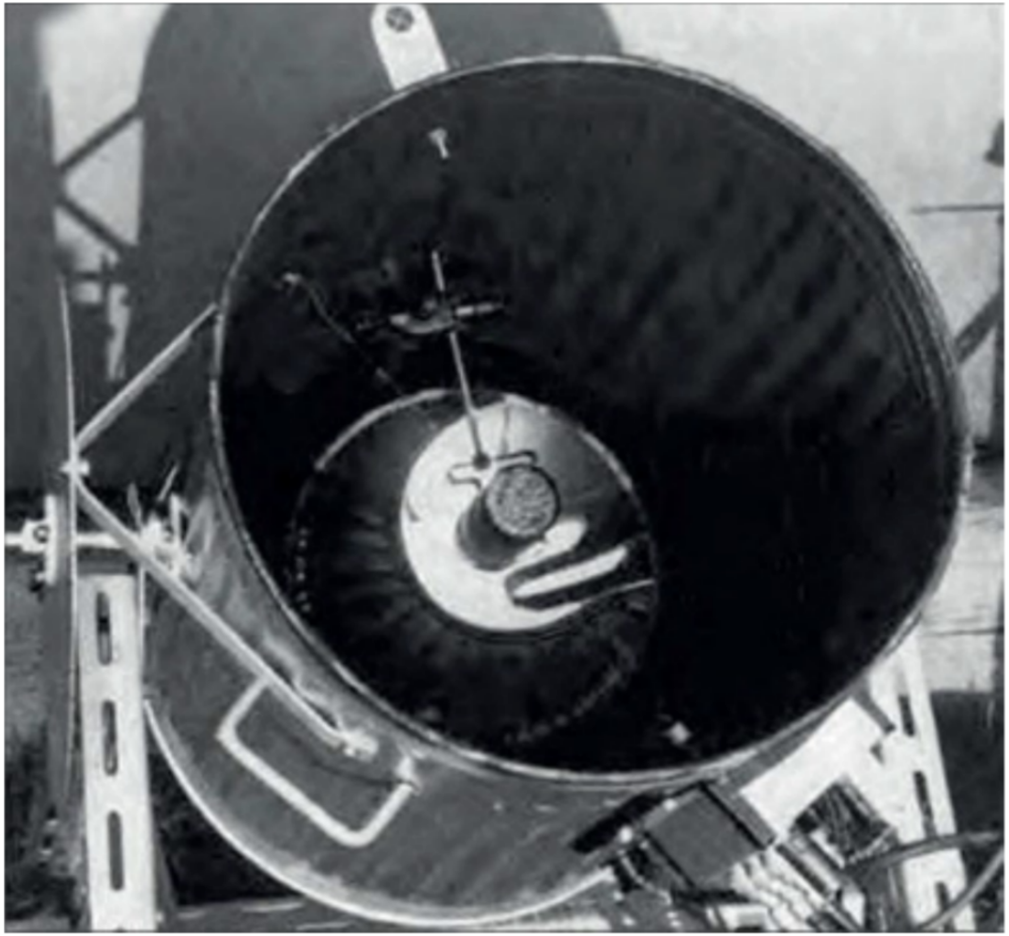
X_{max} Shower depth and Mass
Iron depth = proton depth - **100 g cm-2**
at same CR energy

N_μ Number of muons and Mass
Iron yield = **+40 %** of proton yield
at same CR energy

Vertical showers Signal = **electrons** + **photons** + muons
Inclined showers Signal = electrons + photons + **muons**

Experimental accuracies

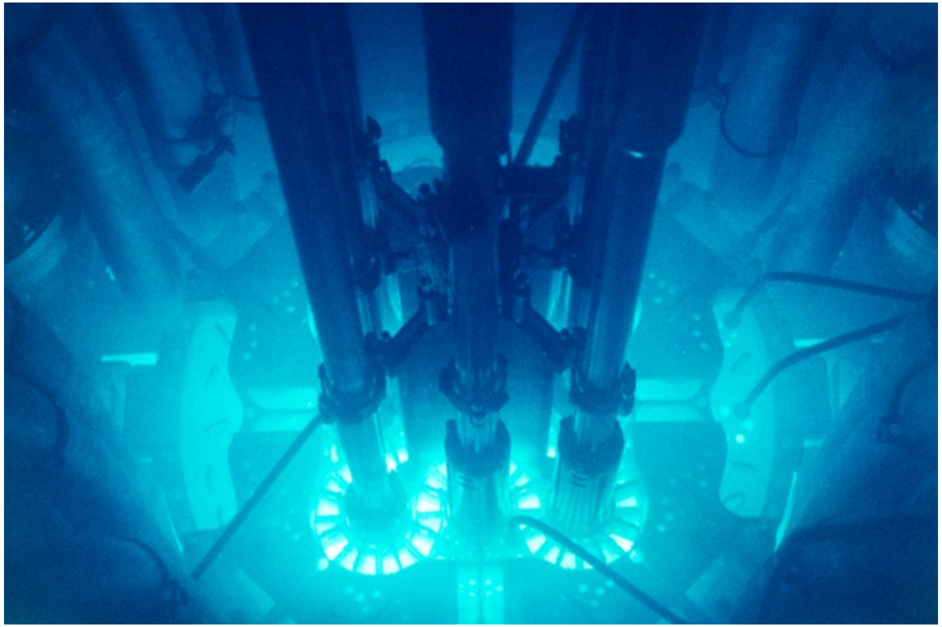
Direction	$0.5 - 1.5^\circ_{\mathrm{stat}}$	
Energy	10-20 $\%_{\mathrm{stat}}$	14 $\%_{\mathrm{sys}}$
X_{max}	$15 - 25\ \mathrm{gcm}^{-2}_{\mathrm{stat}}$	$10\ \mathrm{g\ cm}^{-2}_{\mathrm{sys}}$
N_μ	20 $\%_{\mathrm{stat}}$	11 $\%_{\mathrm{sys}}$

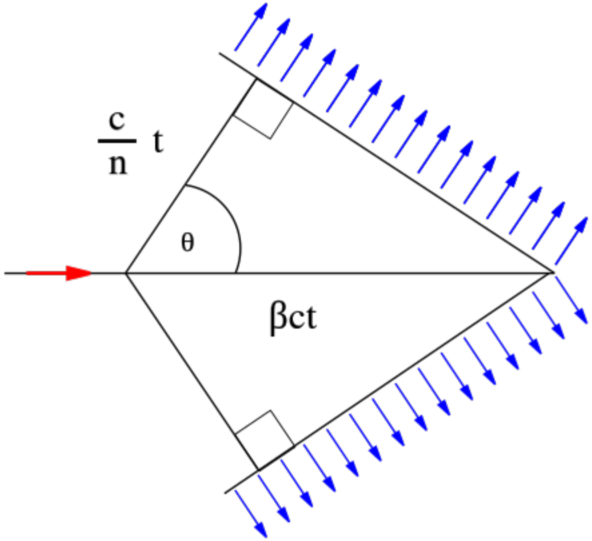


around 1958

Figure 4. The detector used by Galbraith and Jelley for the first observations of atmospheric-Cherenkov radiation: a dustbin with a small parabolic mirror and phototube [3].

Cherenkov radiation





$$\cos\theta = \frac{1}{n\beta}$$

$$\frac{d^2E}{dx\,d\omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$

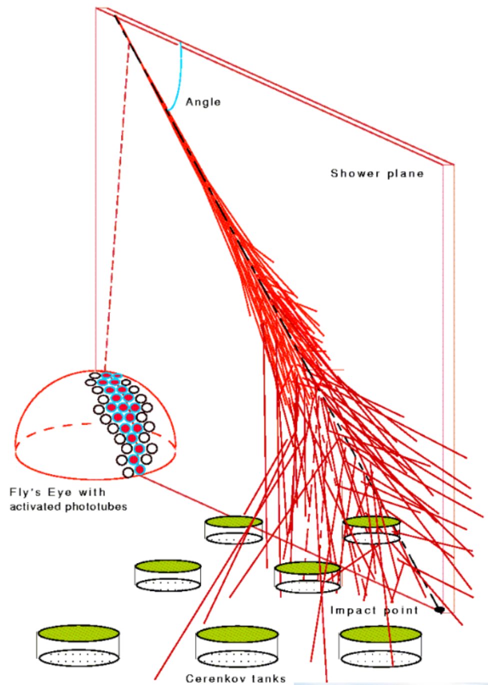
There is a threshold:

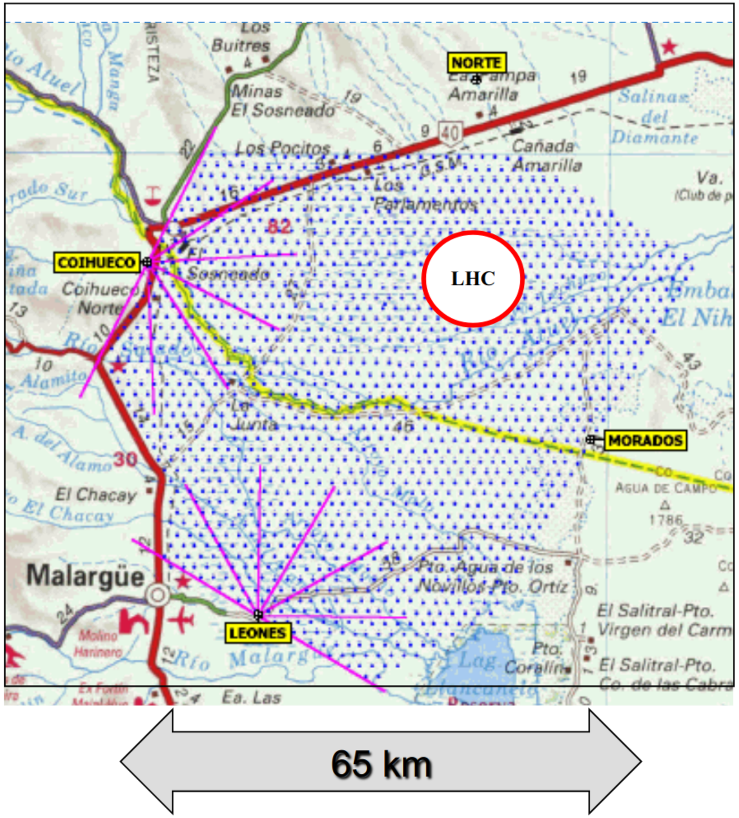
$$\beta_{\text{th}} = \frac{1}{n}$$

$$E_{\text{th}} = \frac{mc^2}{\sqrt{1 - \frac{1}{n^2}}}$$

proton in air, Eth~38GeV
proton in water, Eth~1.4GeV

Pierre Auger Observatory

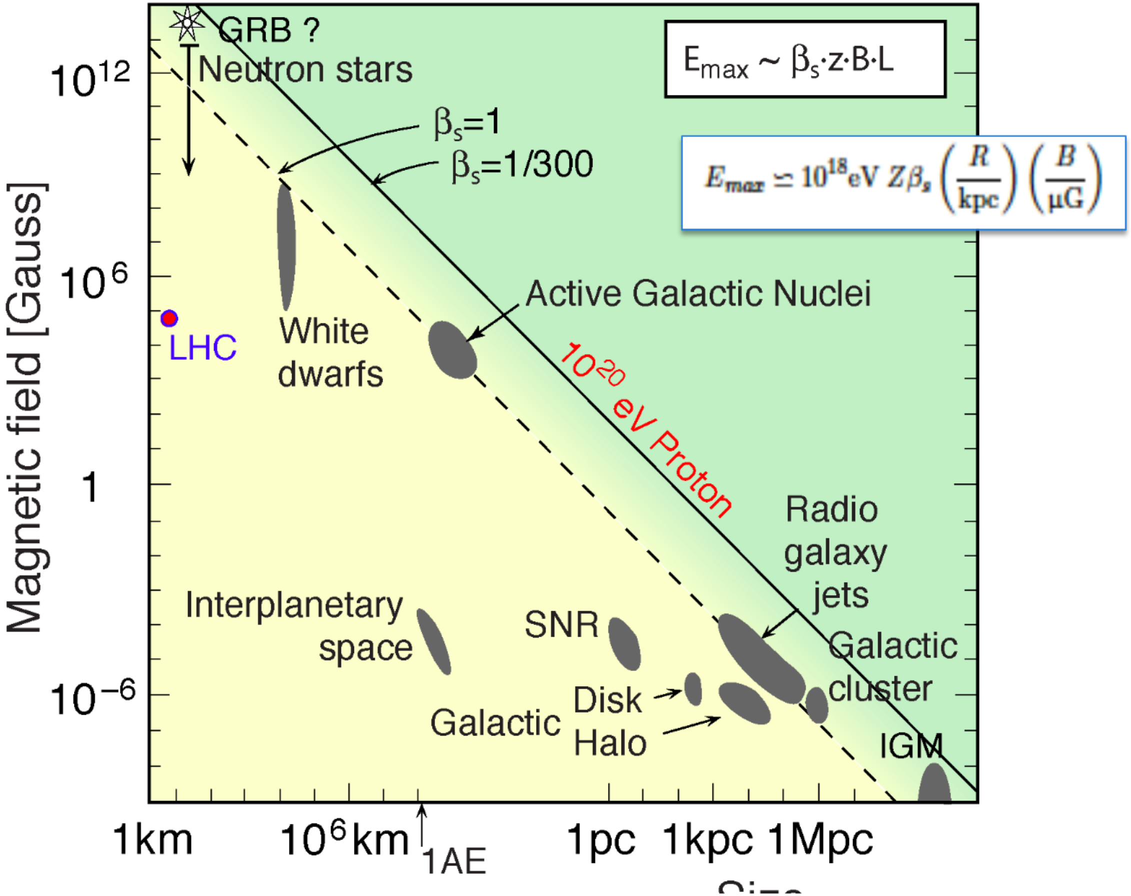




Sources of cosmic rays

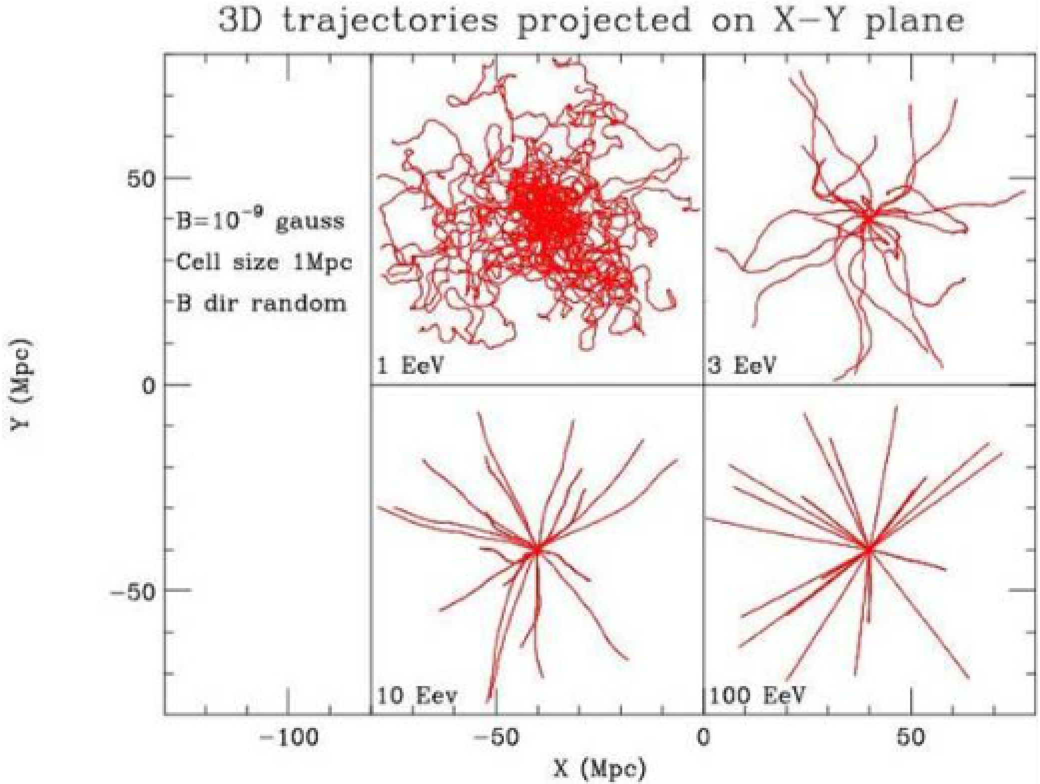
Hillas plot

Main idea: accelerators must confine particles

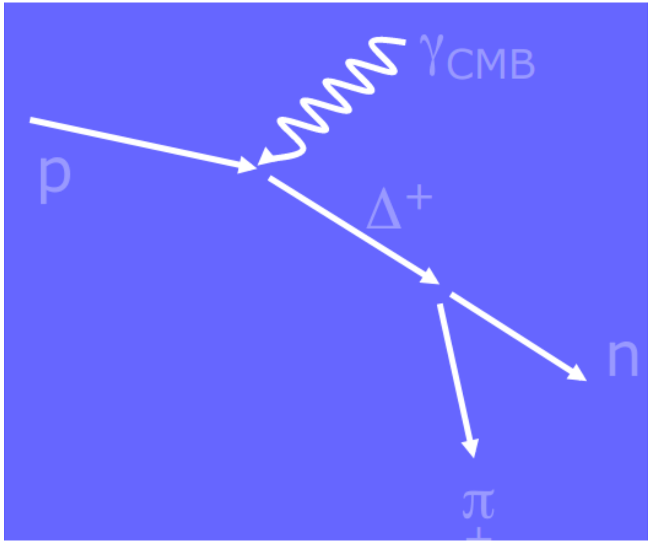


$$E_{max} \simeq 10^{18}\text{eV}\ Z\beta_s \left(\frac{R}{\text{kpc}}\right)\left(\frac{B}{\mu\text{G}}\right)$$

Cosmic rays are charged

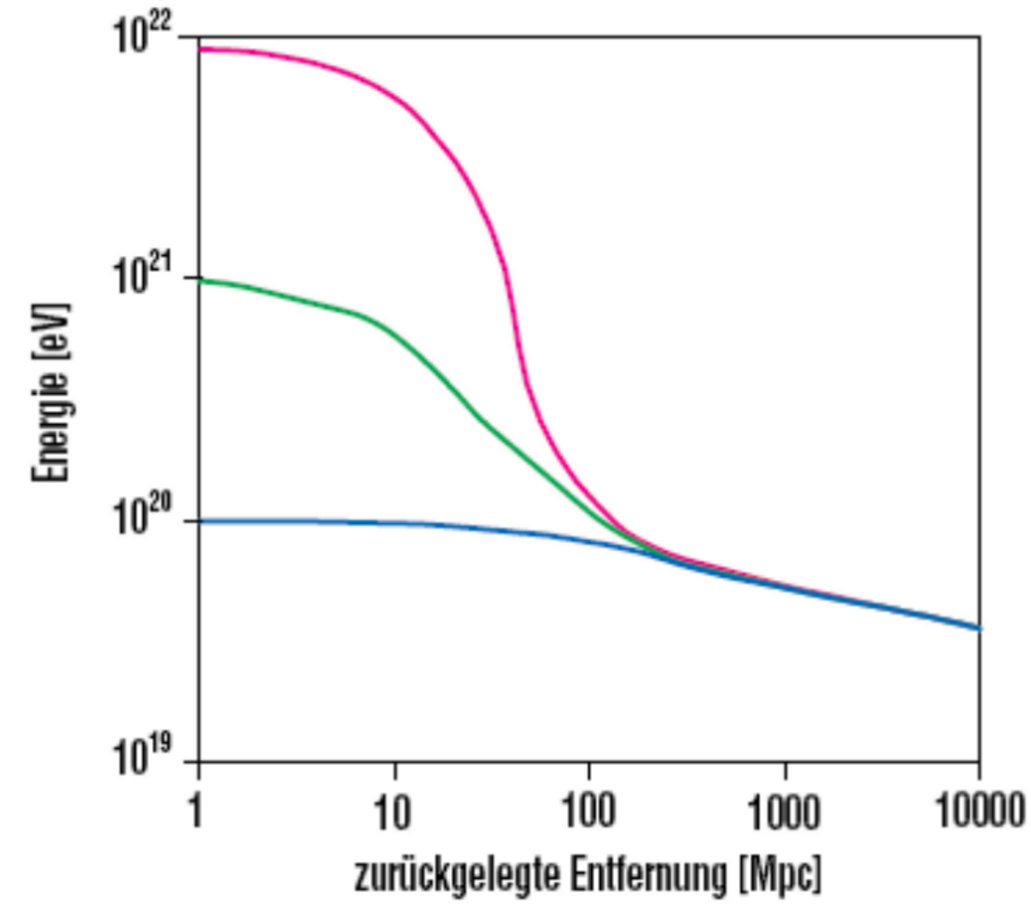


Cosmic rays interact with CMB

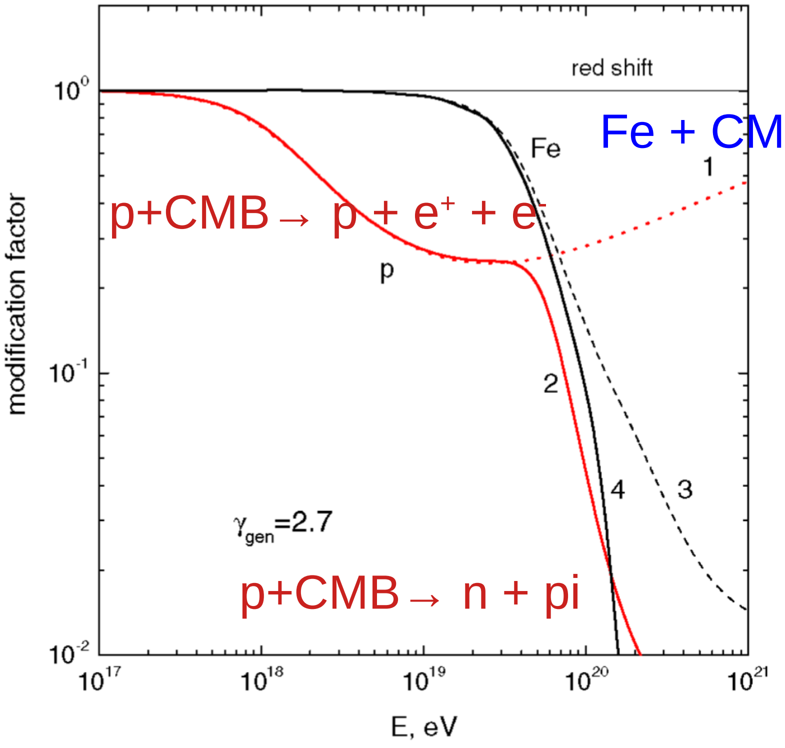


- Greisen-Zatsepin-Kuzmin effect
- There is a threshold energy for the p to produce a delta resonance
- Eth~O(10^{19} eV)
- Kinematics simple, but don't forget the CMB spectrum and various delta resonances

GZK effect on cosmic rays energies



Spectral shape analysis

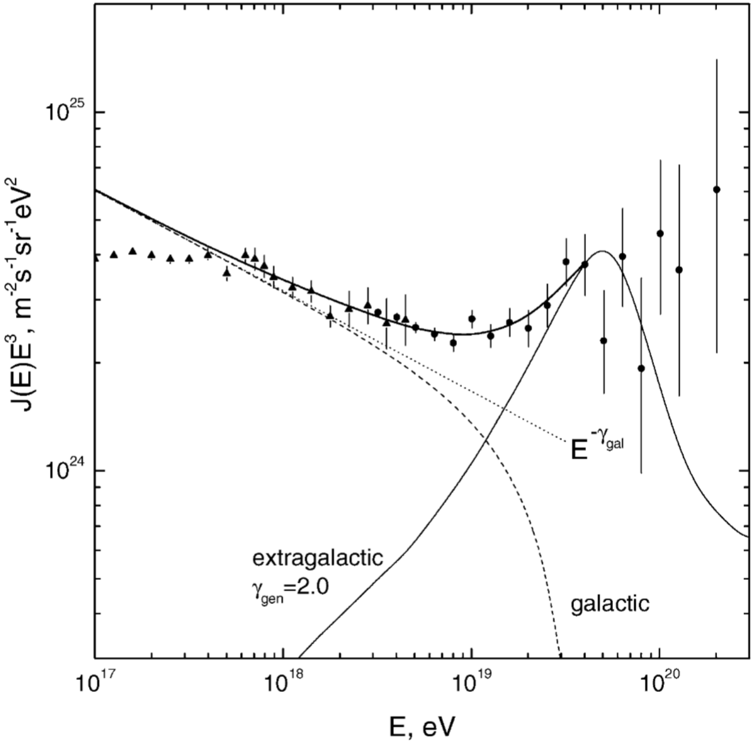


Fe + CMB → GDR

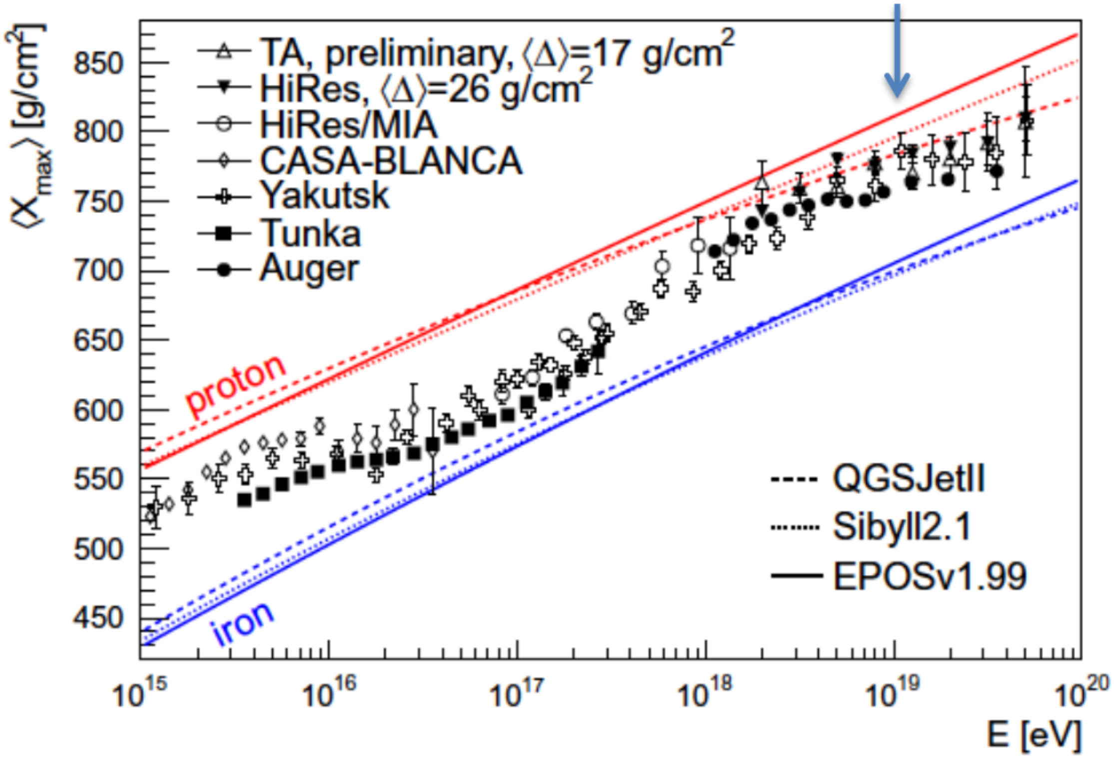
p+CMB → p + e^+ + e^-

p+CMB → n + pi

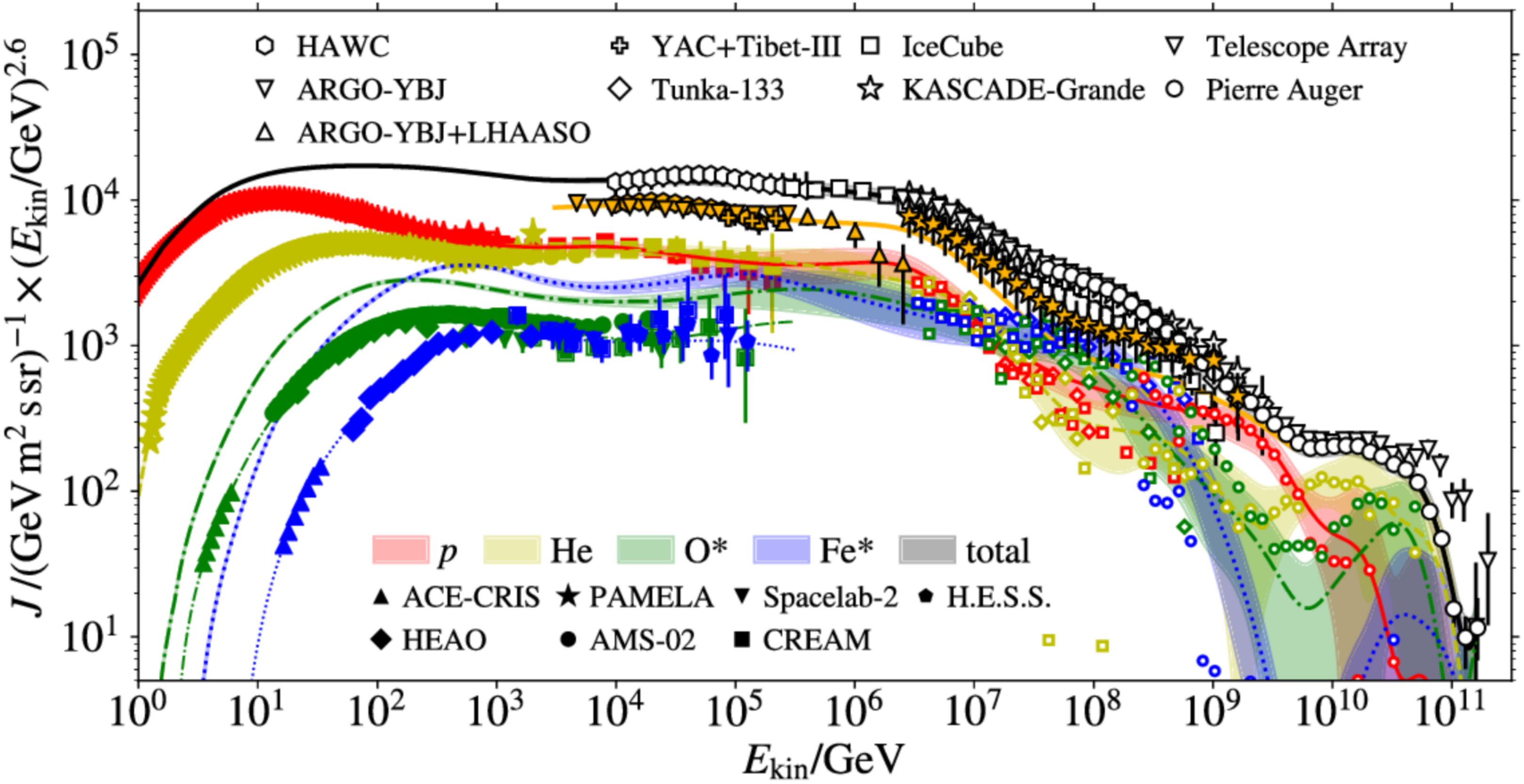
Proton-dominated model:



Not consistent with mass composition measurements



Other models



Status quo

- UHECR modelling complicated
- Sources at least as important than propagation
- “mixed composition” basically everywhere
- No conclusive situation
- Maybe: proton component at highest energies → astronomy

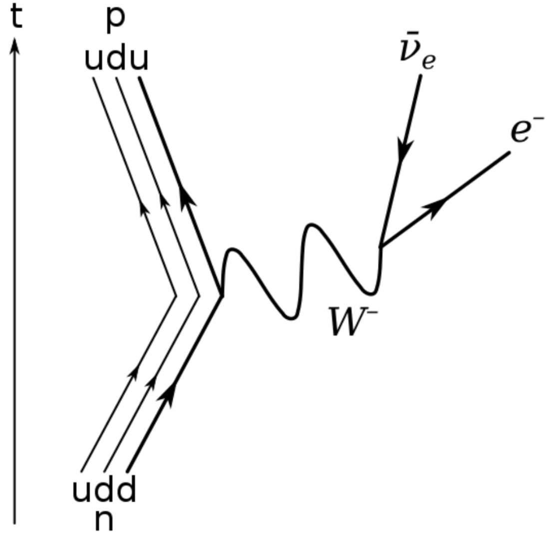
The universe at the highest energies

Ultra-high energy neutrinos

Ultra-high energy detection

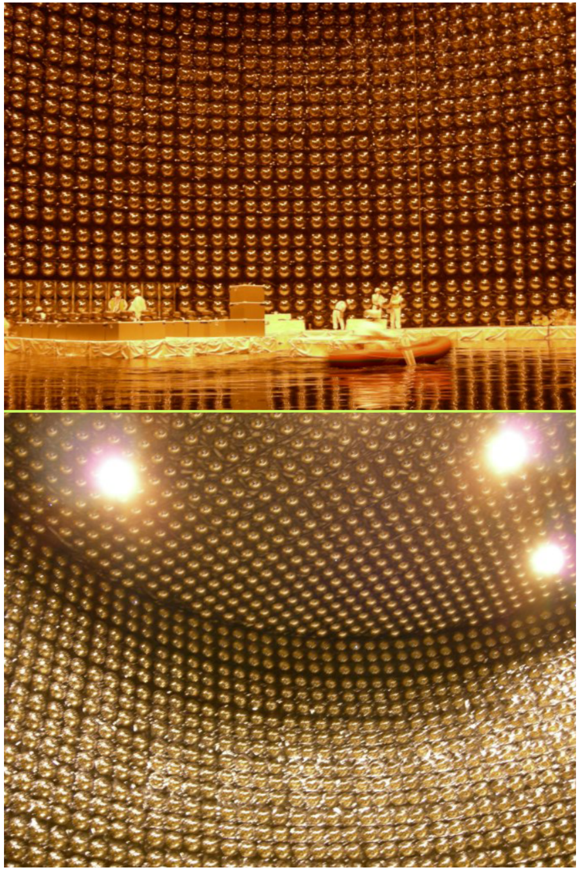
- Charged current:
  - electron, muon, tau

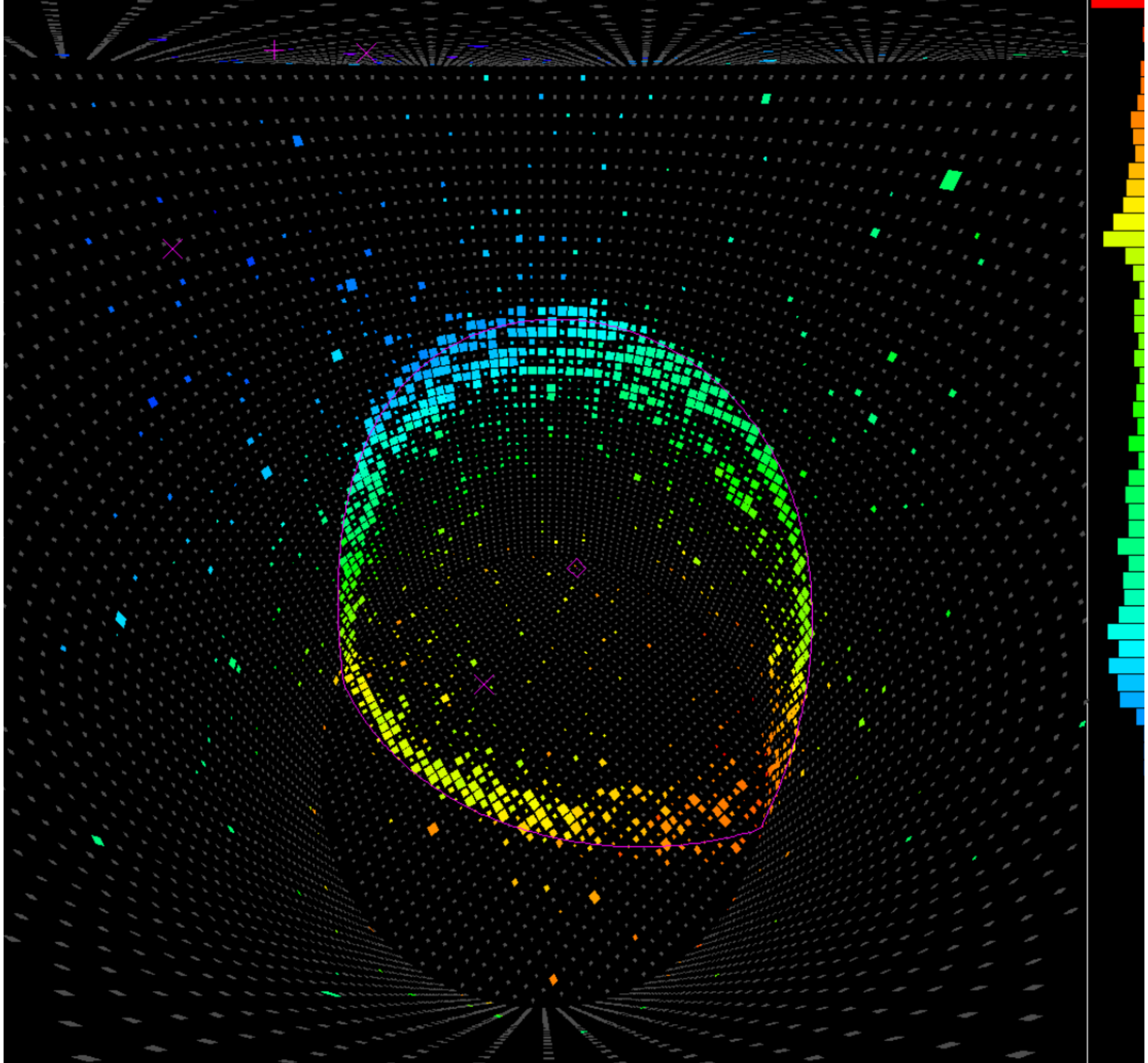
- Leptons can emit Cherenkov radiation in dense media

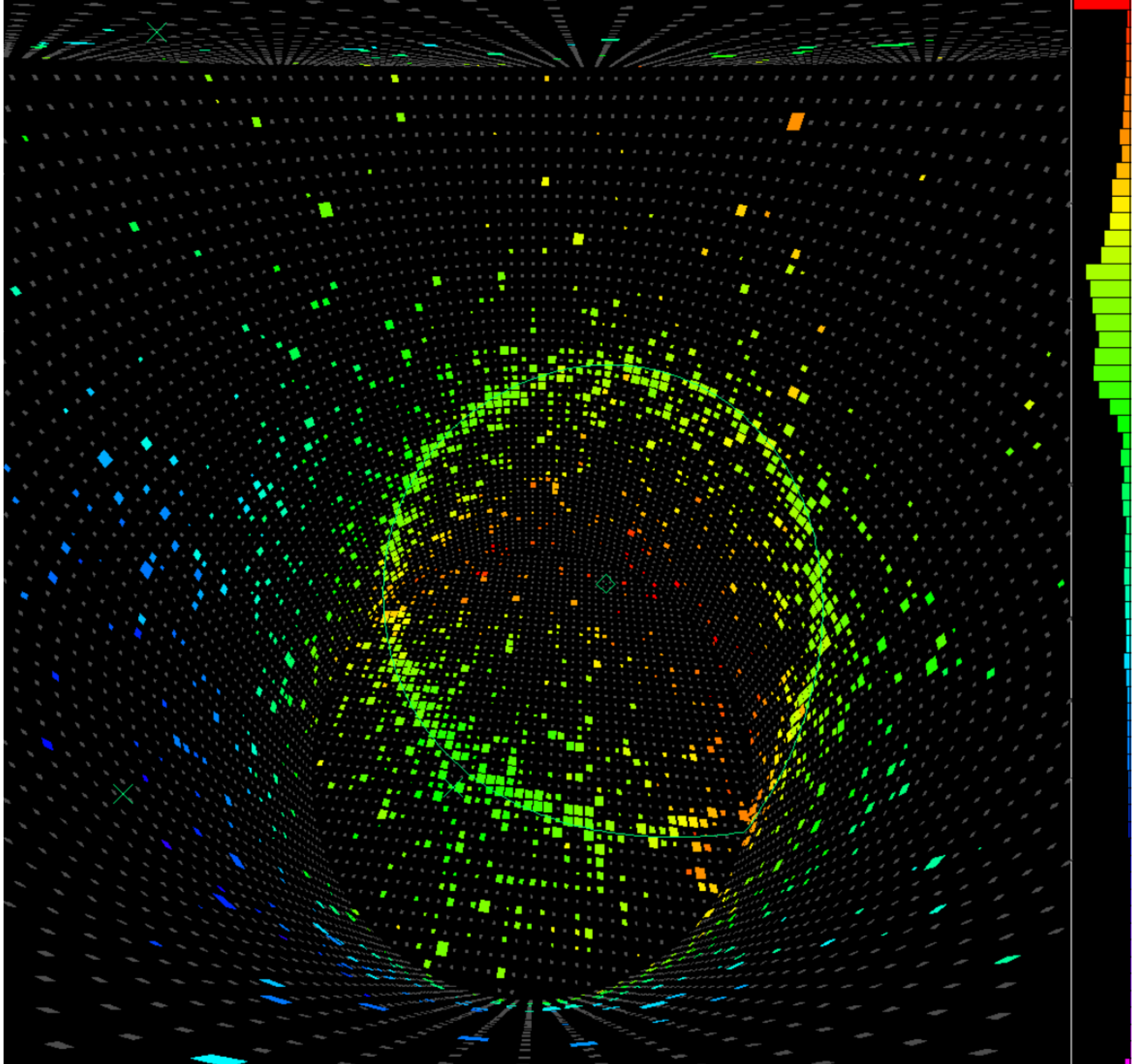


Super Kamiokande

- Super-K started data taking in the mid 1990s
- 40m tall x 40m diameter water tank under a Japanese mountain
- 50,000 tons of water
- 11,200 20” Hamamatsu phototubes
- Built as a neutrino observatory (atmospheric, solar)
- Muon/electron discrimination via ring “fuzziness”

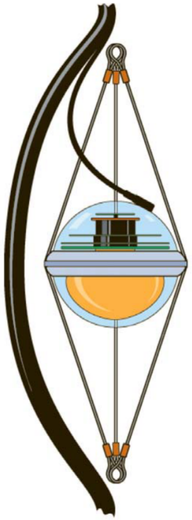


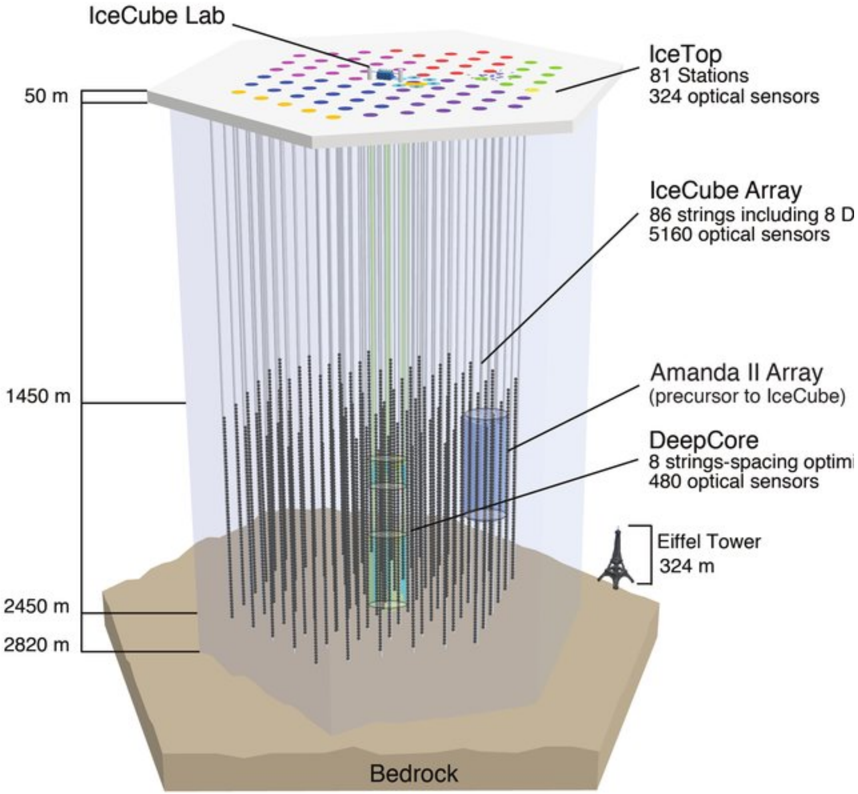




IceCube

Construction

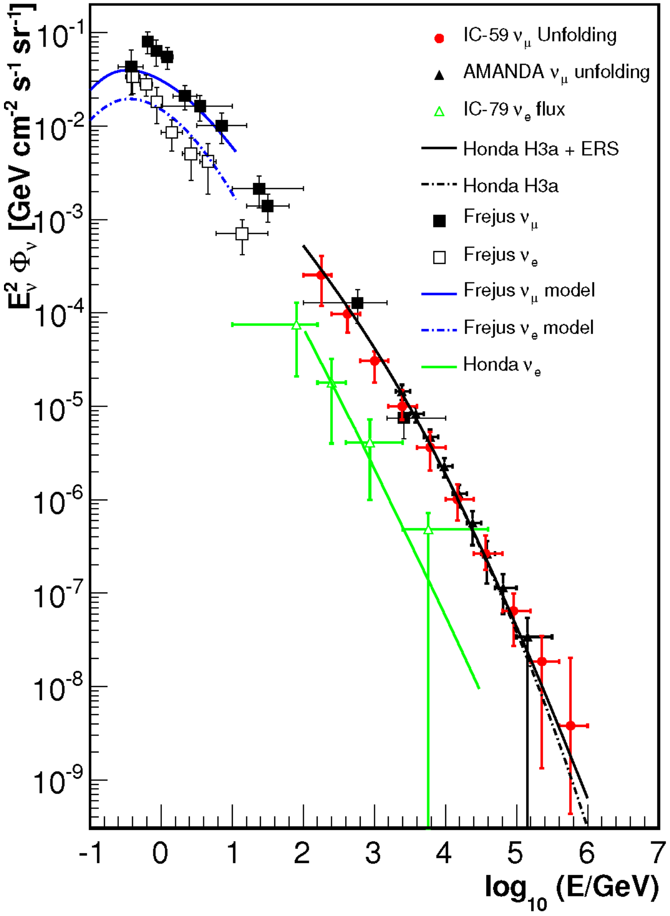


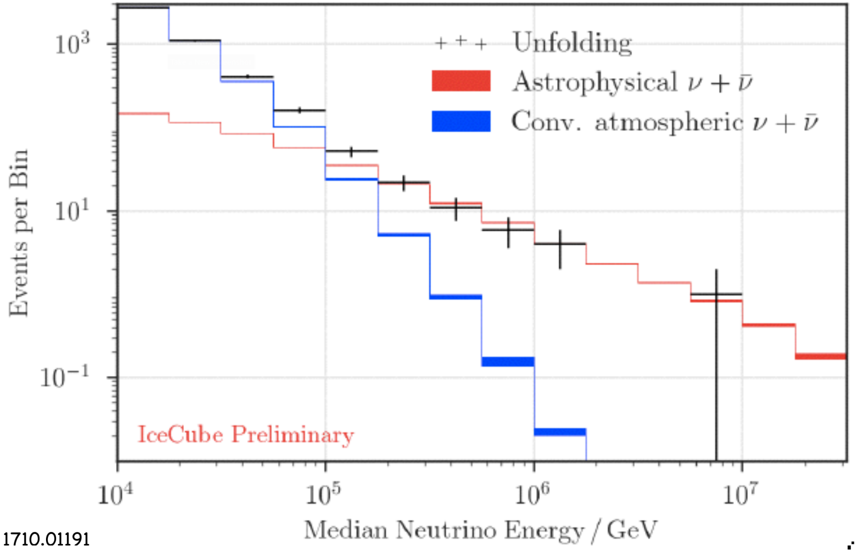


Why neutrino astronomy is attractive?

- No charge → no deflection
- No charge → no absorption, thus, no horizon
- No mass (basically) → speed of light
- Neutrino production is sign of non-thermal processes

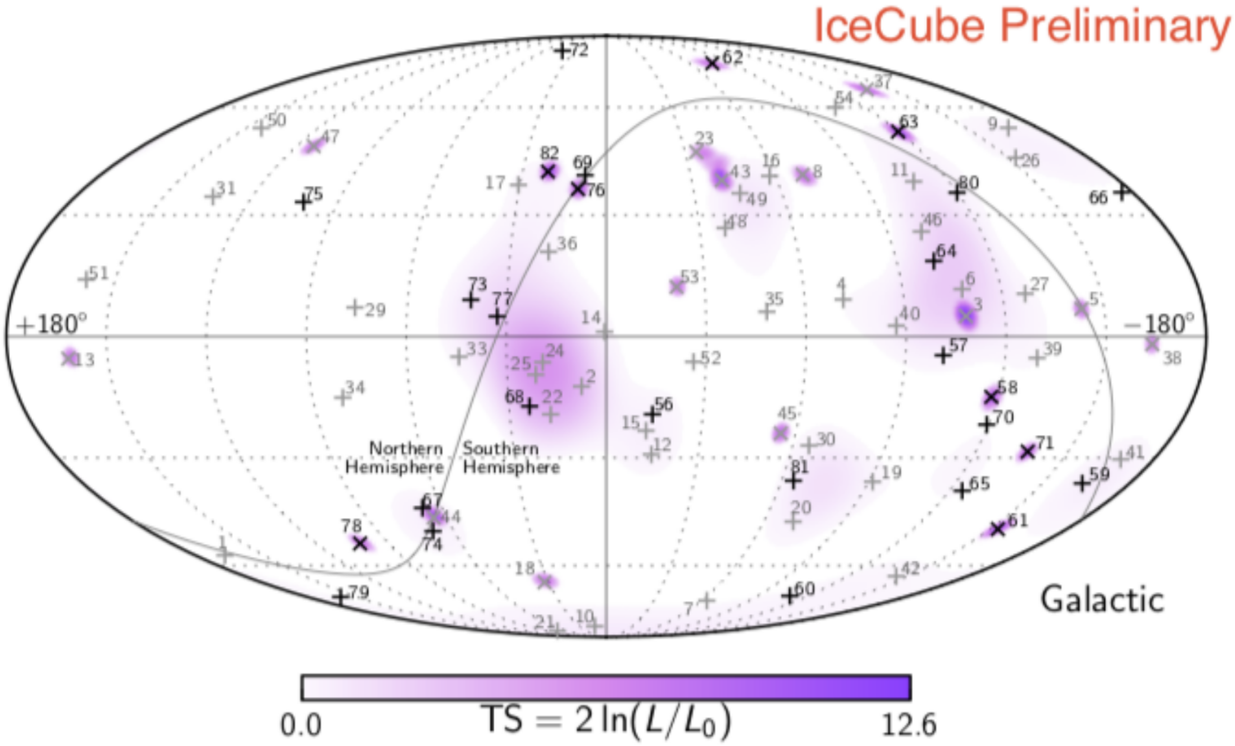
Neutrino spectrum





1710.01191

IceCube sky-map
HESE (high-energy starting events)



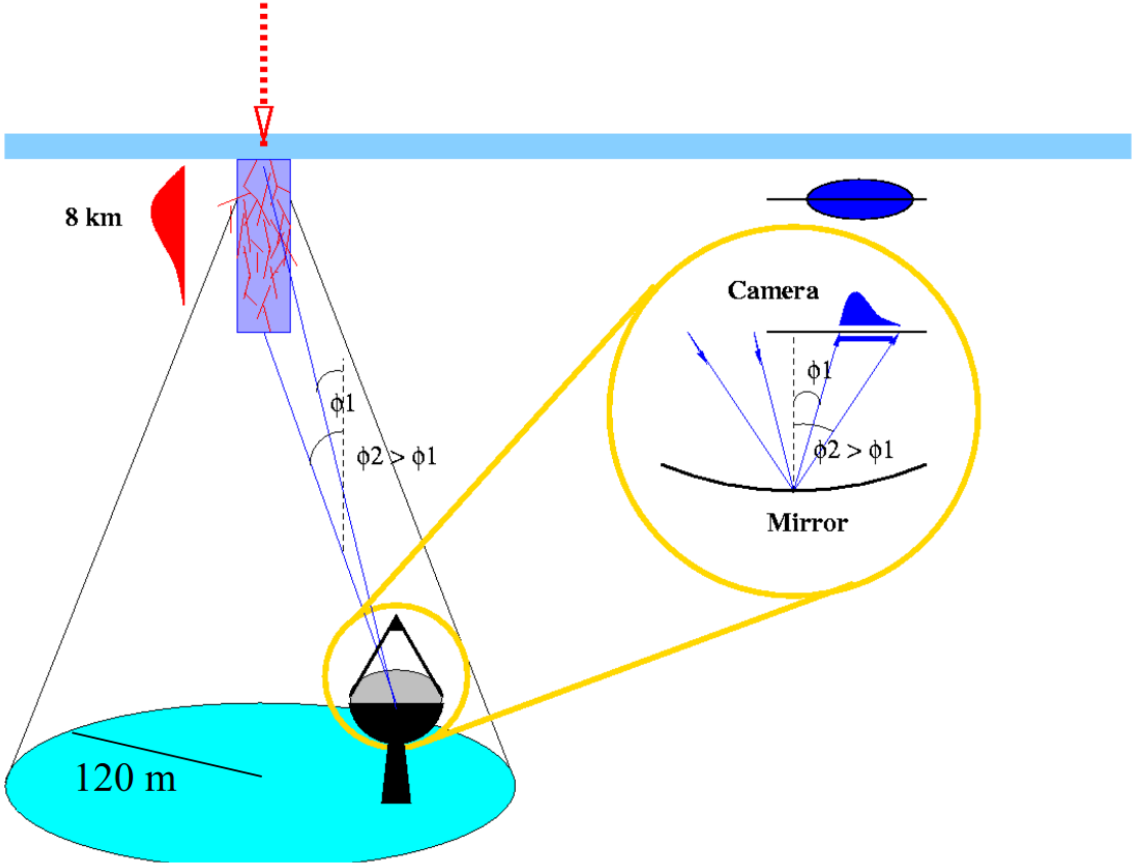
Status

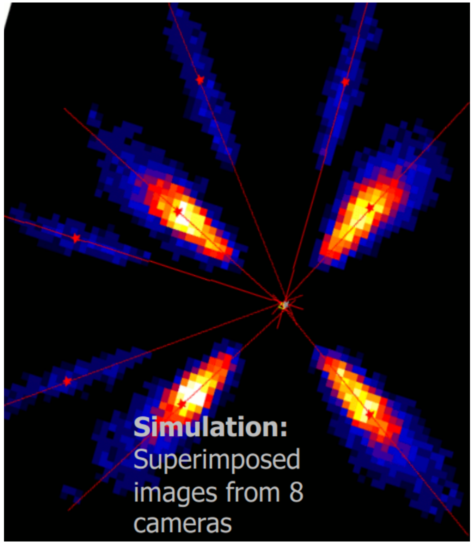
- Very exciting times
- Potential astrophysical neutrinos found
- More statistics and better understanding needed
- Neutrinos are best candidates for multi-messenger measurements

The universe at the highest energies

High-energy gamma rays

Detection principle



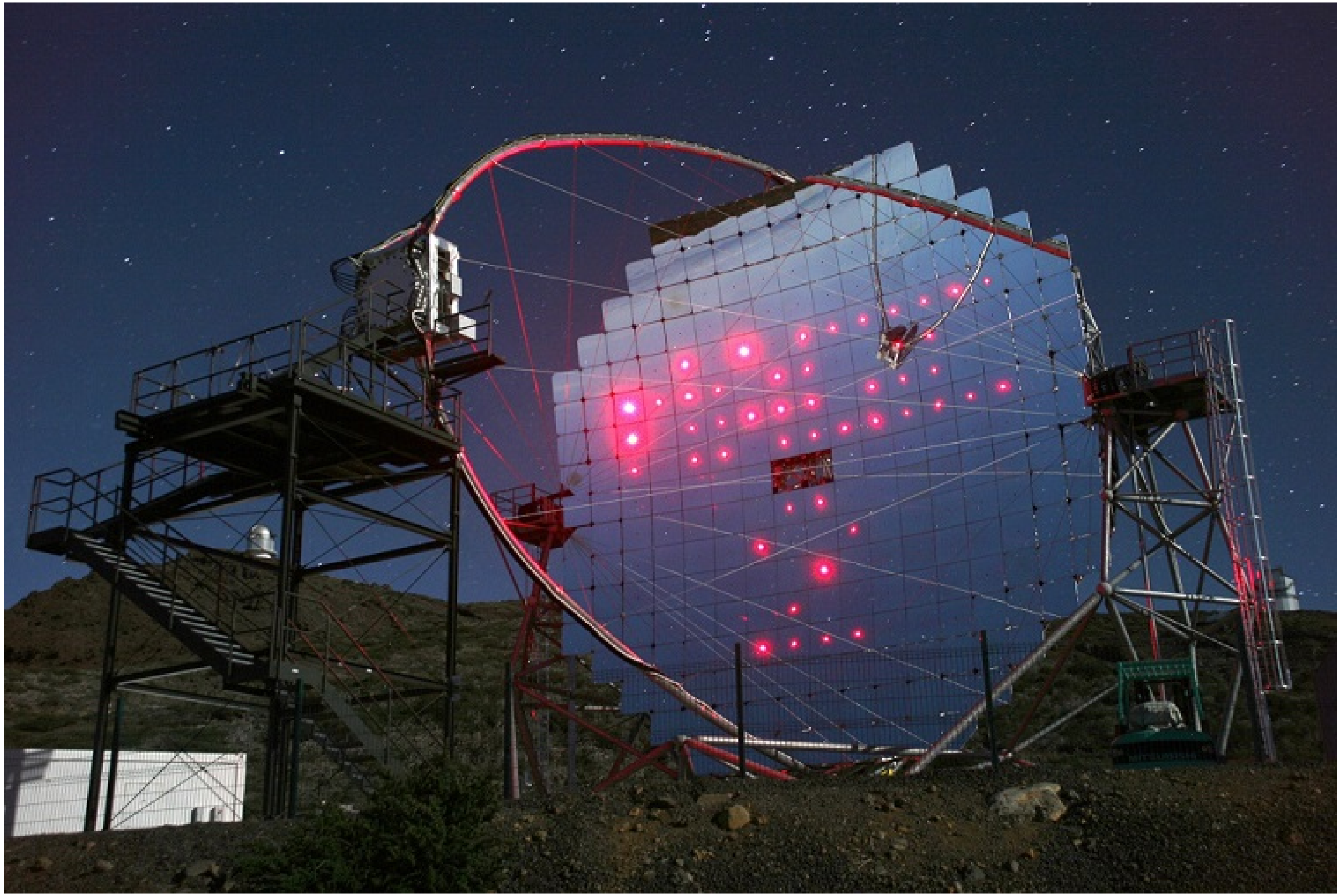


Simulation: Superimposed images from 8 cameras

Imaging Atmospheric Cherenkov Telescopes – IACTs

- High angular resolution
- High energy resolution
- Very small field-of-view
- Very limited observation time, exposure

MAGIC

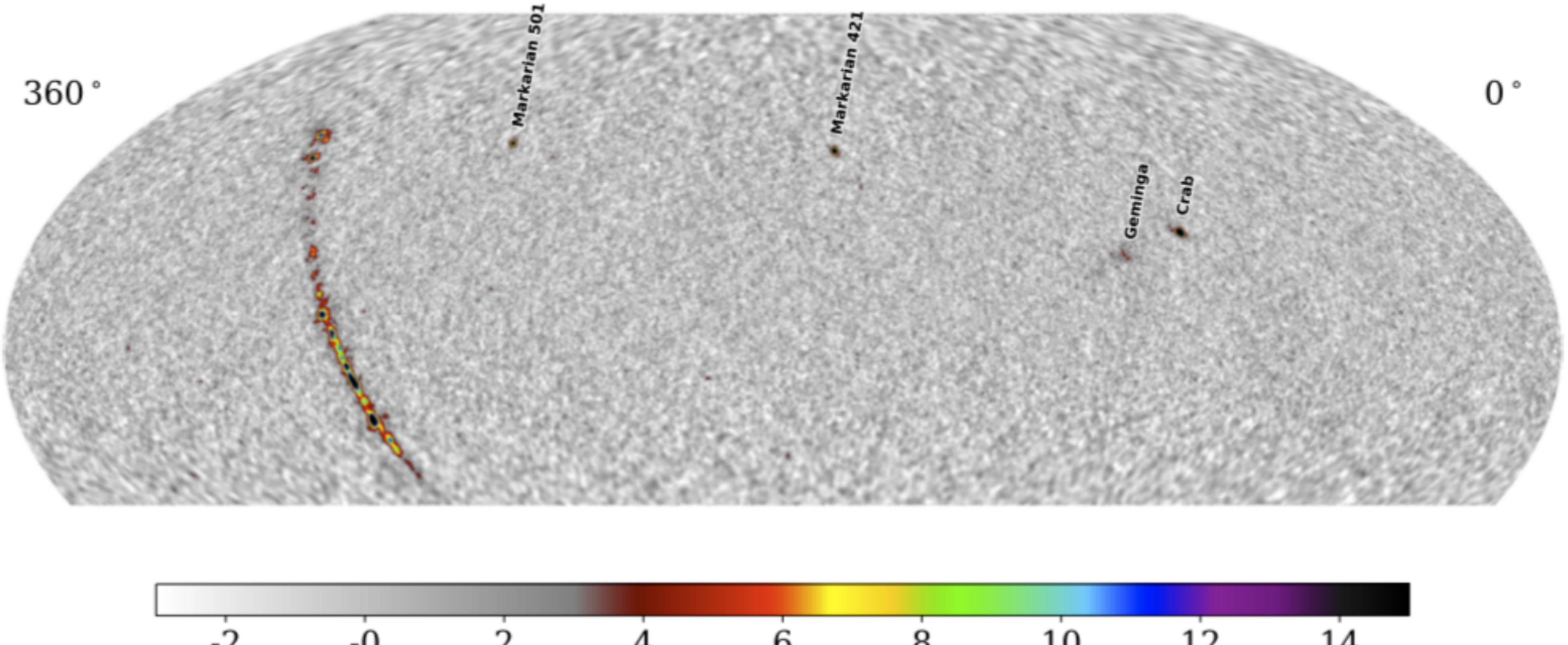


Air shower gamma-ray observatories

- Very dense and low threshold air shower detectors
- High rate
- High exposure, huge field-of-view
- Limited resolution

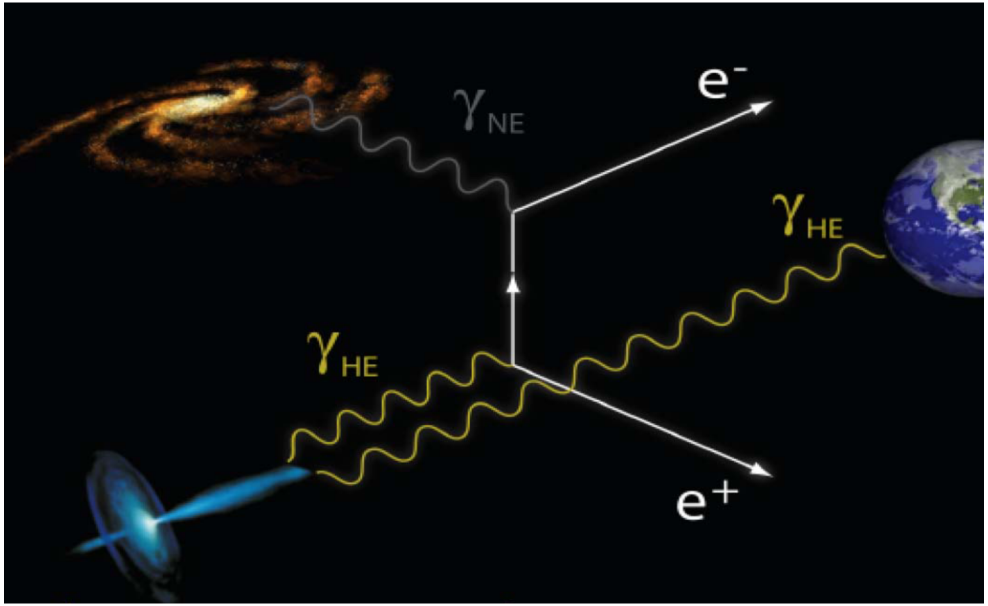
HAWC

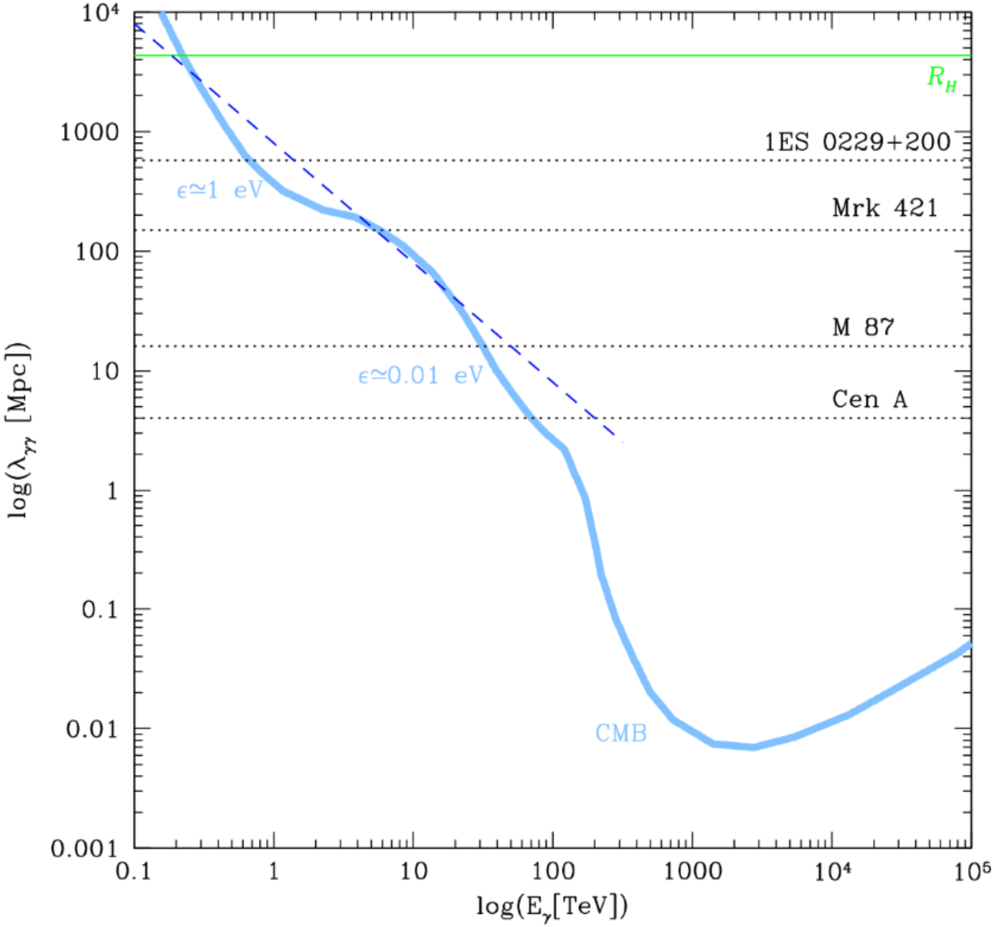
Full-sky map



360°
0°
Markarian 501
Markarian 421
Geminga
Crab
-2
-0
2
4
6
8
10
12
14

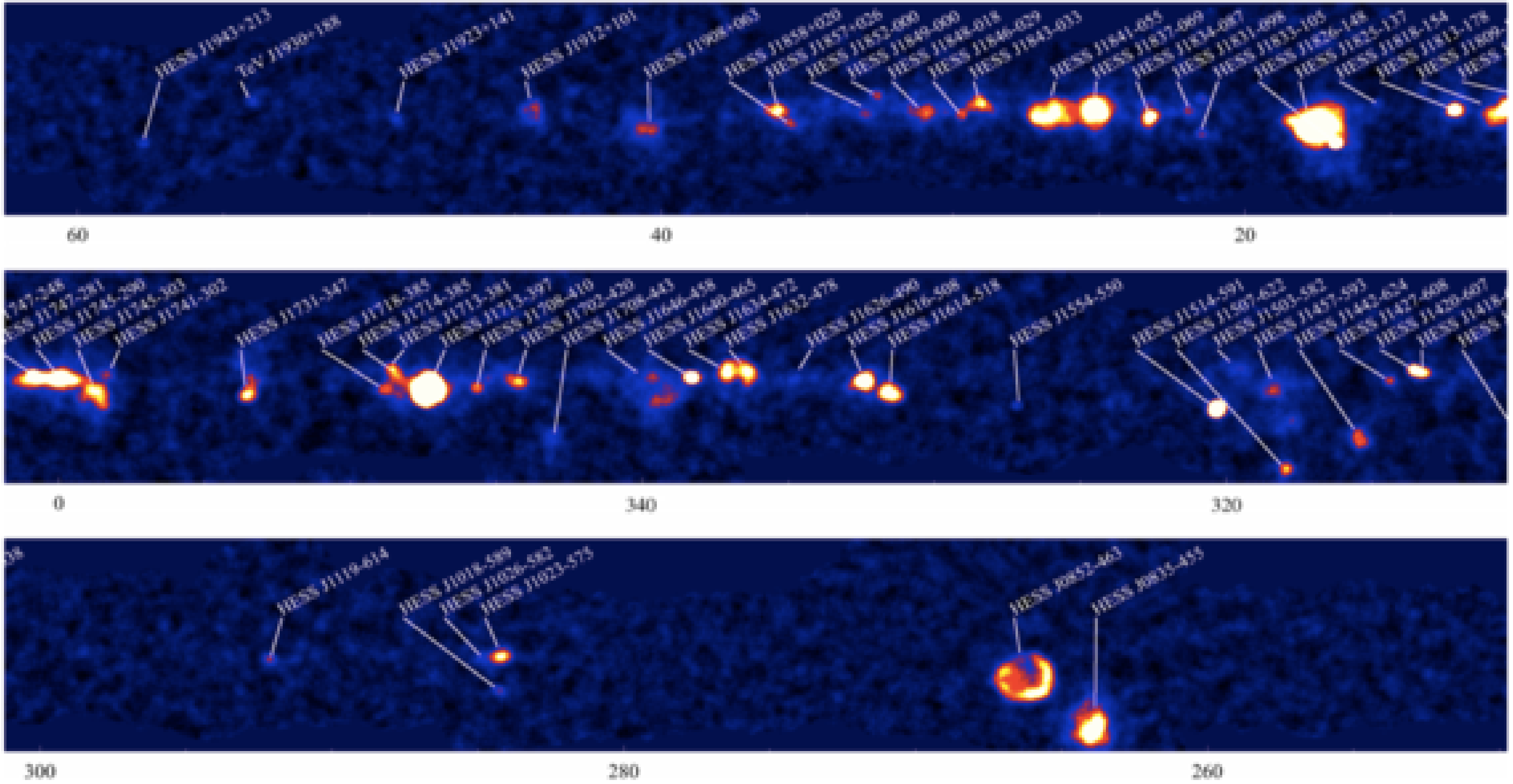
Gamma rays and CMB





$$\lambda_{\gamma\gamma} = \frac{1}{\sigma_{\gamma\gamma} n_{CMB}} \simeq 8\ \mathrm{kpc}$$

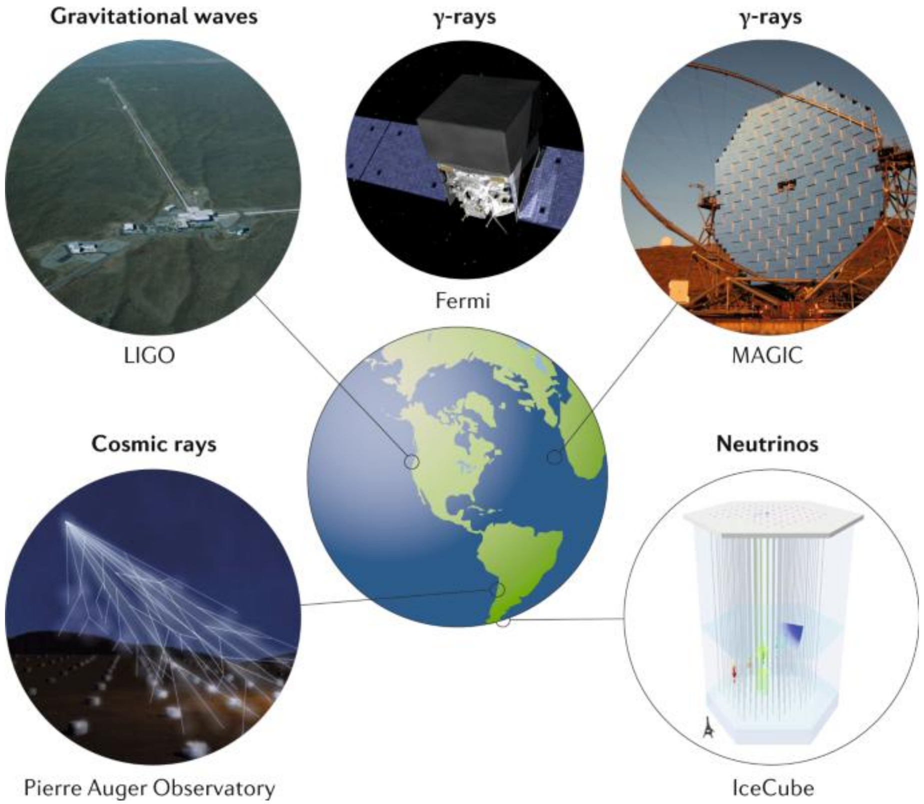
HESS TeV galactic plane survey



Status

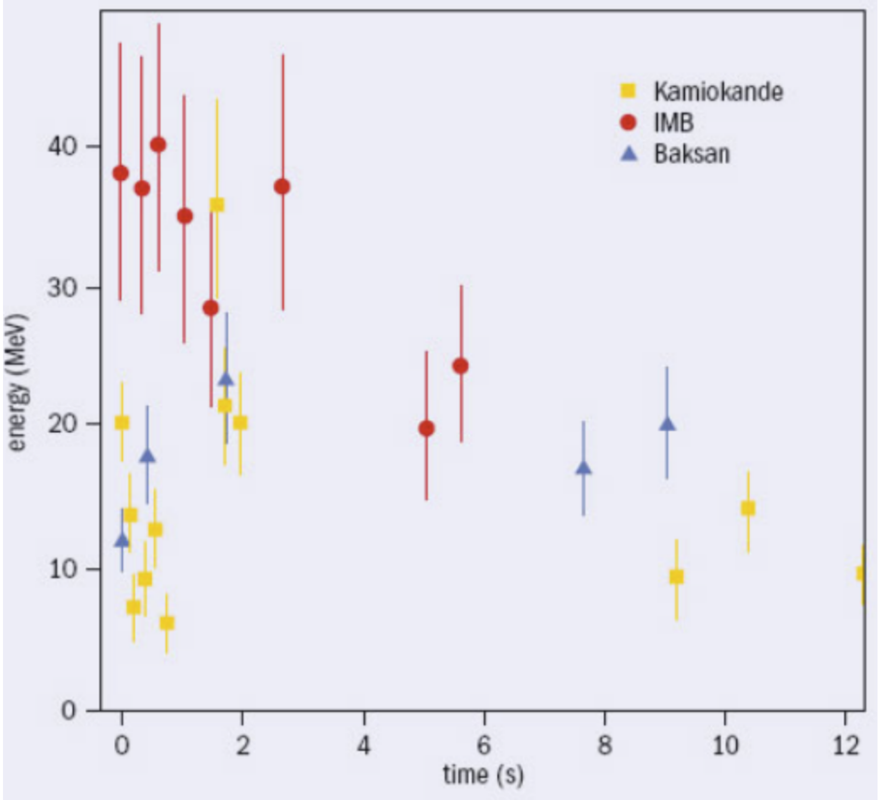
- TeV gamma ray astronomy is a reality
- A wealth of new sources and new morphology
- Concrete data on the high-energy universe

Multi Messenger



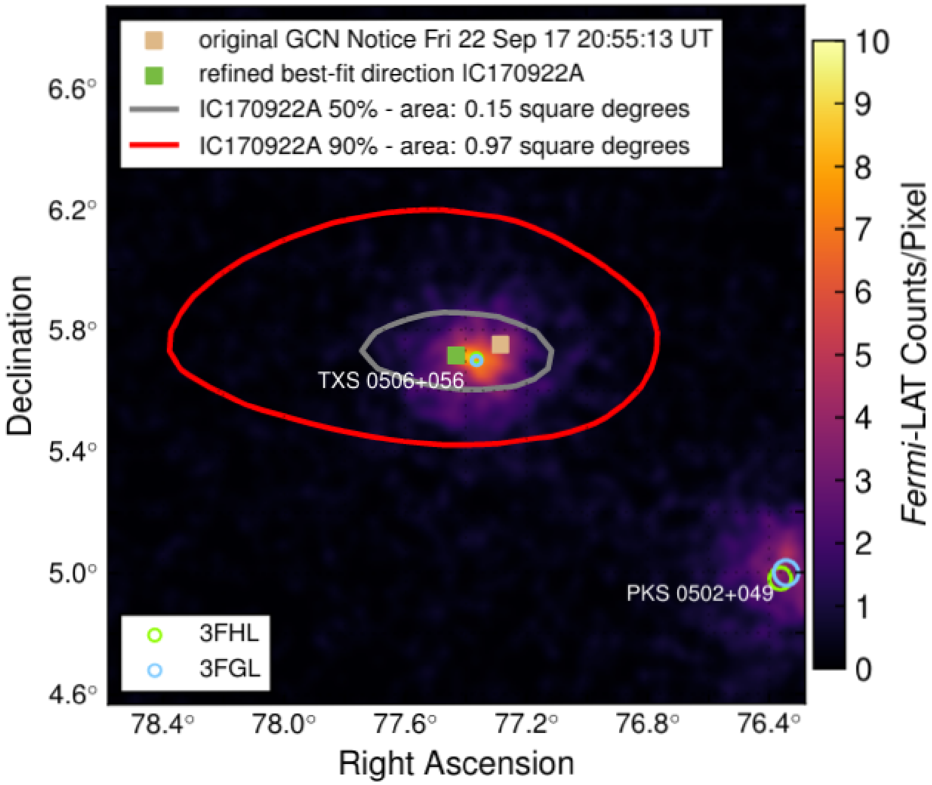
SN1987a in Large Magellan Cloud

- 50kpc



TXS 0506+056

(A)



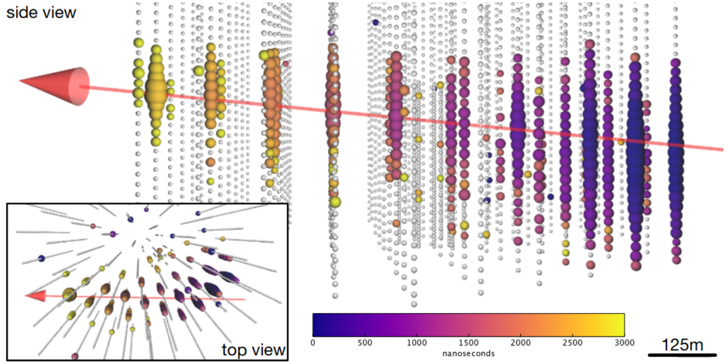


Figure 1: **Event display for neutrino event IceCube-170922A.** The time at which a DOM observed a signal is reflected in the color of the hit, with dark blues for earliest hits and yellow for latest. Time shown are relative to the first DOM hit according to the track reconstruction, and earlier and later times are shown with the same colors as the first and last times, respectively. The total time the event took to cross the detector is $\sim$3000 ns. The size of a colored sphere is proportional to the logarithm of the amount of light observed at the DOM, with larger spheres corresponding to larger signals. The total charge recorded is $\sim$5800 photoelectrons. Inset is an overhead perspective view of the event. The best-fitting track direction is shown as an arrow, consistent with a zenith angle $5.7^{+0.50}_{-0.30}$ degrees below the horizon.

Status

- Extremely exciting
- Huge potential impact on astrophysics, astroparticle physics
- Need far better statistics: larger and more sensitive experiments