The KM3NeT Neutrino Detector: an Overview and the Detection of an Ultra-High-Energy Neutrino

Rastislav Dvornický
on behalf of KM3NeT collaboration

Department of Nuclear Physics and Biophysics, FMFI,
Comenius University in Bratislava,
dvornicky@fmph.uniba.sk

KM3NeT

UNIVERZITA KOMENSKÉHO V BRATISLAVE

Overview:

- Neutrinos
- Cosmic rays
- Principle of neutrino telescopes
- KM3NeT
- Ultra-high energy neutrino with KM3NeT

Neutrinos

Original - Photocopie of PLC 0393

Abschrift/15.12.[illegible] PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des nähreren auseinandersetsen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

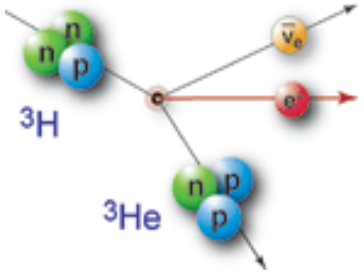
Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publisieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stünde, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

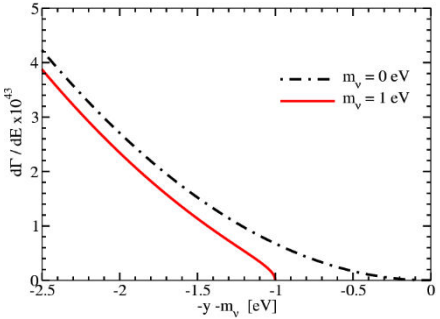
Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

I have done a terrible thing I **invented** a particle that cannot be detected

W. Pauli (1930)





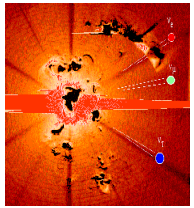




Tübingen

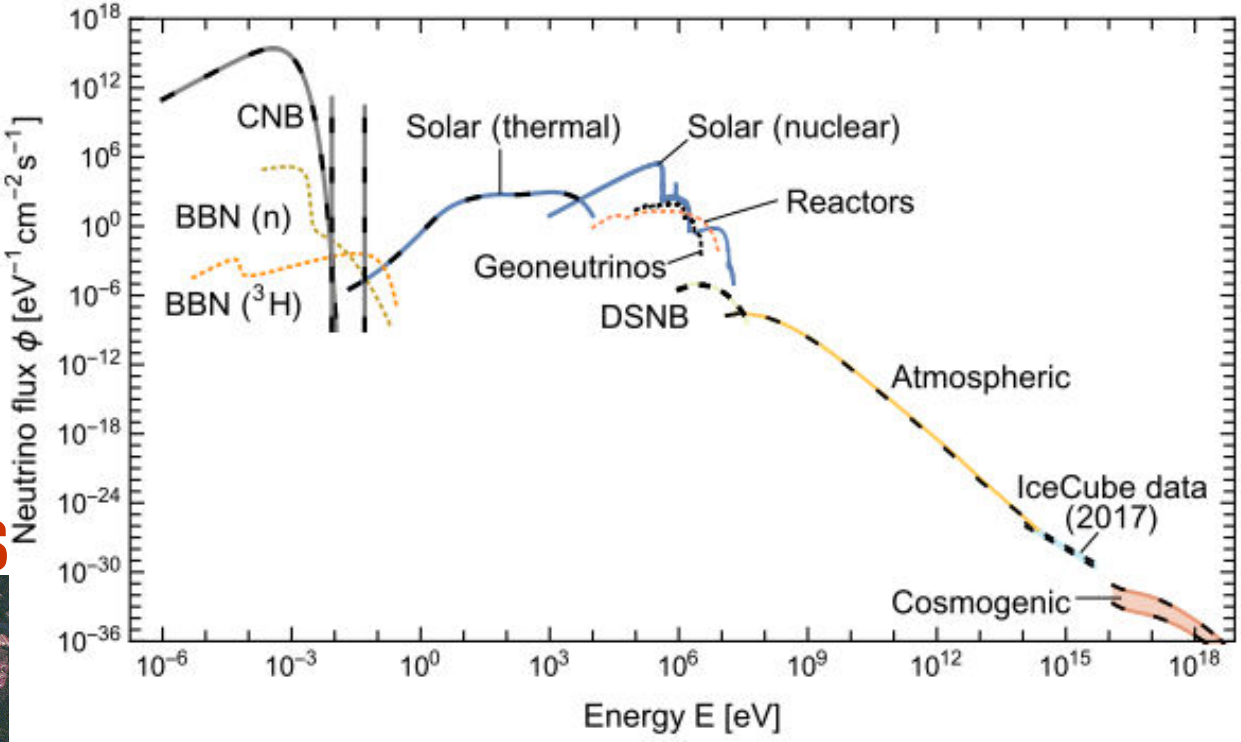
Sources of neutrinos



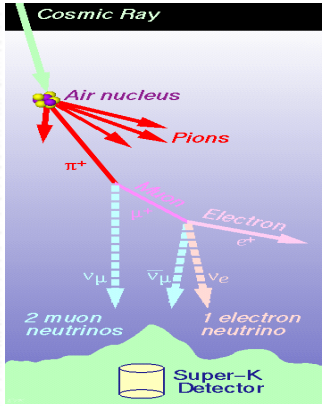


Reactors





Atmosphere





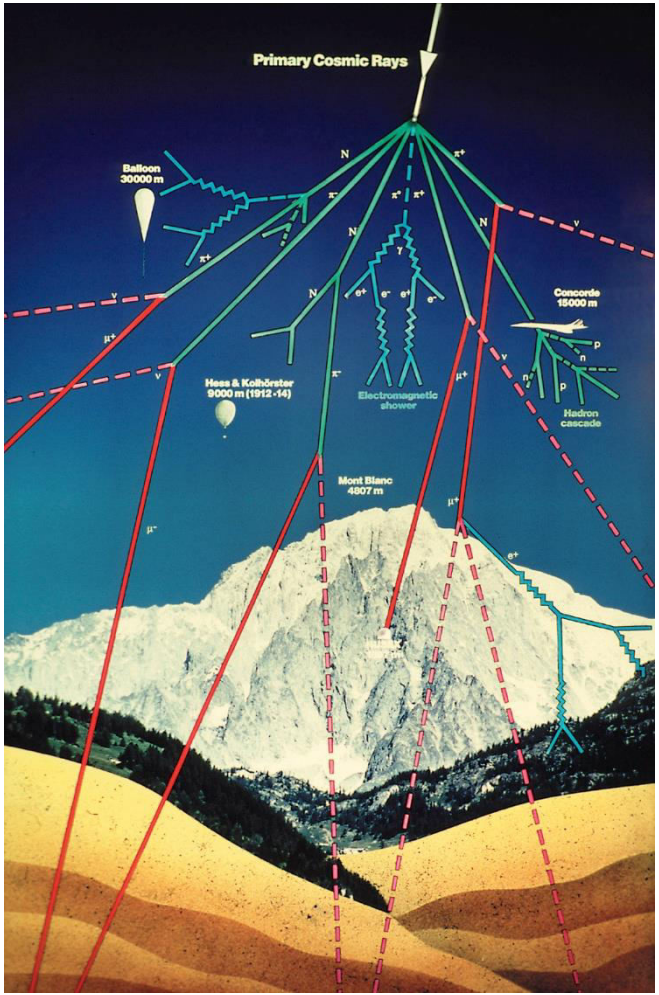
Overview:

- Neutrinos
- Cosmic rays

Cosmic rays

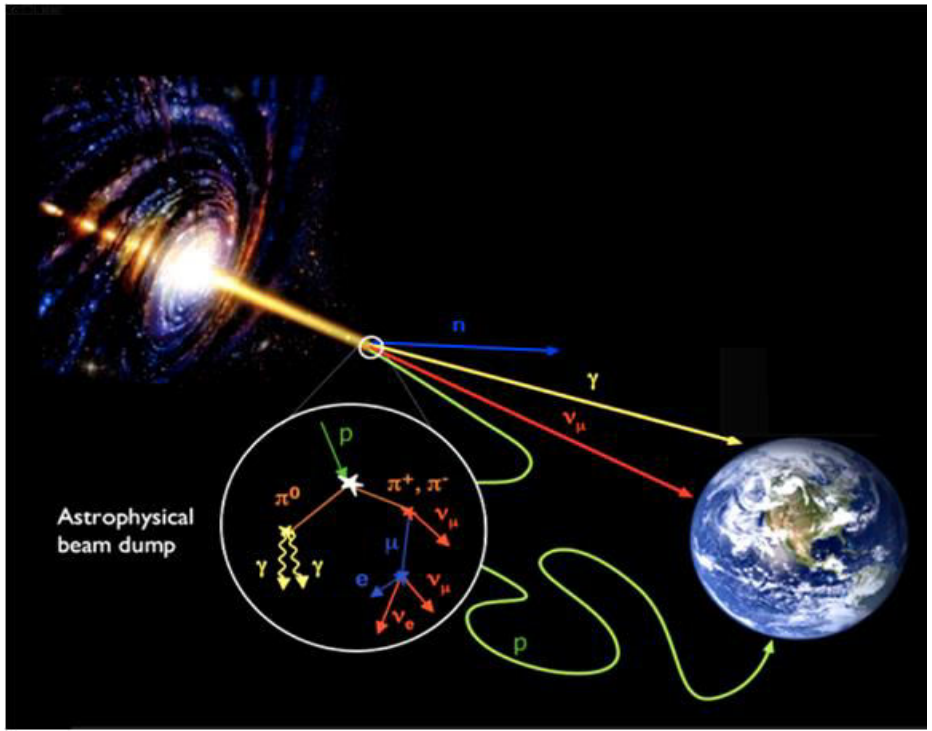


Victor Hess – balloon experiment (1912)



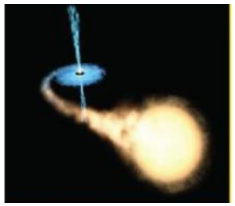
Cosmic rays

- Where do they come from?



Galactic sources: TeV – EeV ?

SNR, micro-quasars, pulsars

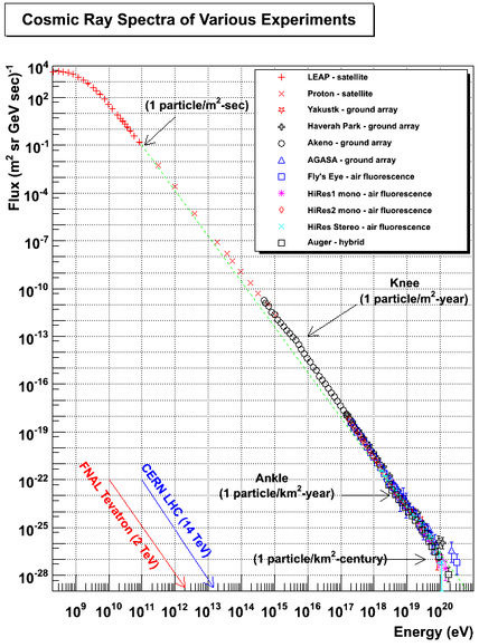

Extra-galactic sources: EeV–PeV…

AGN, GRB,…



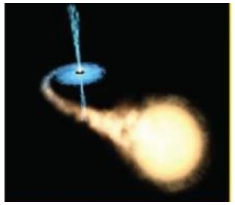

Cosmic rays

- Where do they come from?
- Acceleration mechanism



Galactic sources: TeV – EeV ?

SNR, micro-quasars, pulsars

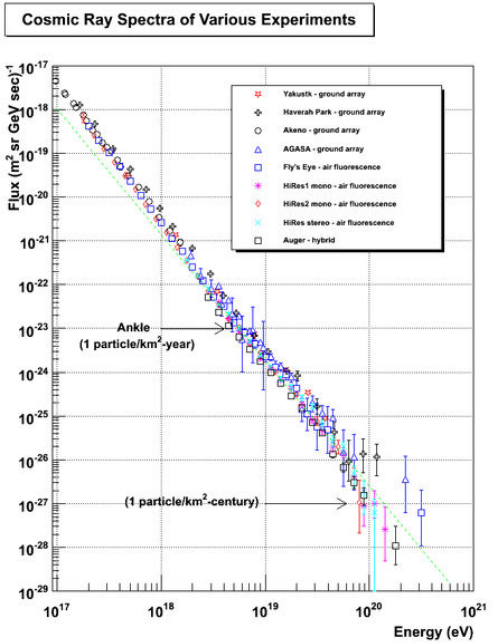

Extra-galactic sources: EeV–PeV…

AGN, GRB,…



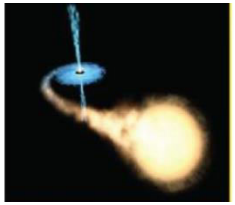

Cosmic rays

- Where do they come from?
- Acceleration mechanism



Galactic sources: TeV – EeV ?

SNR, micro-quasars, pulsars


Extra-galactic sources: EeV–PeV…

AGN, GRB,…




Cosmic rays

- Where do they come from?
- Acceleration mechanism

Visible light: 2-3 eV

Radioactivity: ~ MeV

= 1 000 000 eV

= 10^6 eV

CERN – LHC = 14 TeV

= 14 10^{12} eV

Galactic sources: TeV – EeV ?

SNR, micro-quasars, pulsars

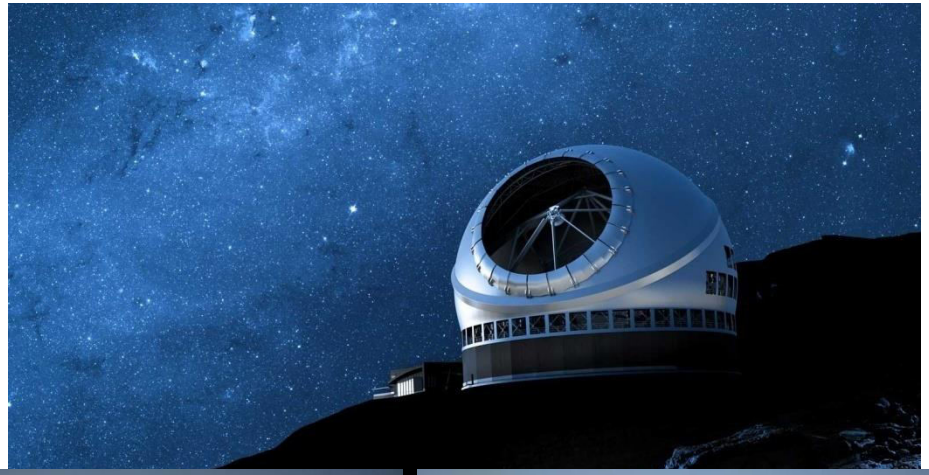
Extra-galactic sources: EeV–PeV…

AGN, GRB,…



Light

- Advantages:
  - Observations since Galilei (~ 4 centuries)



- Disadvantages
  - Absorption
  - Scattering

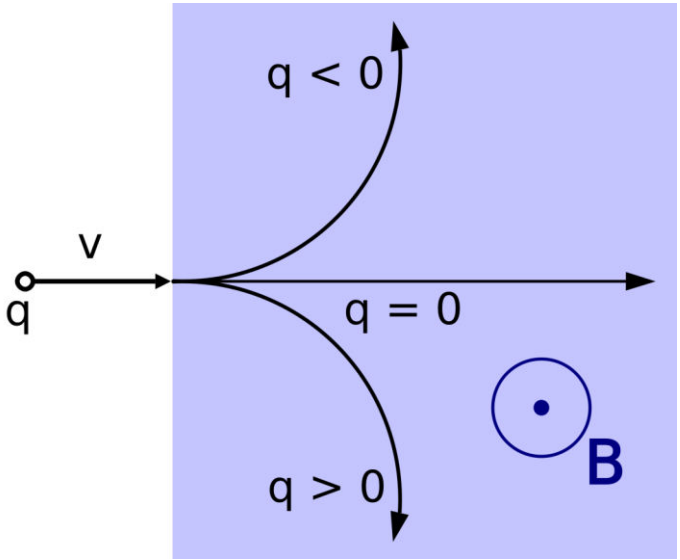


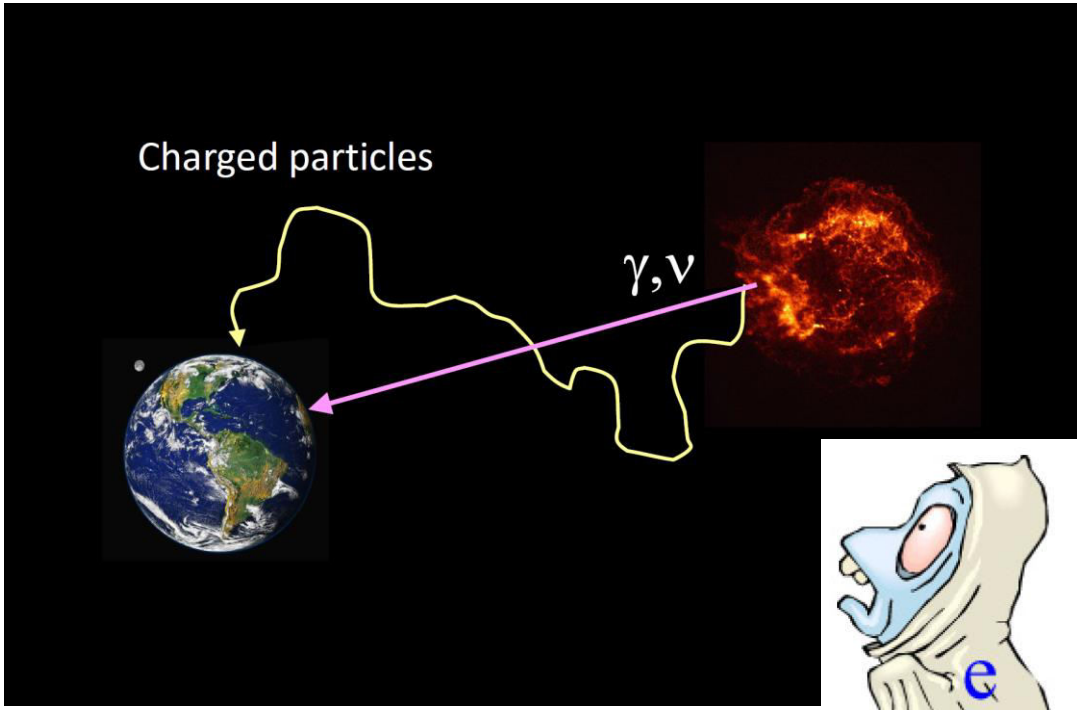


Charged particles

Deflection by magnetic field

$$\vec{F} = q\vec{v} \times \vec{B}$$





Neutrinos

- Extremely low chance to interact with matter:
  - Messenger from deep space
  - Detection method?

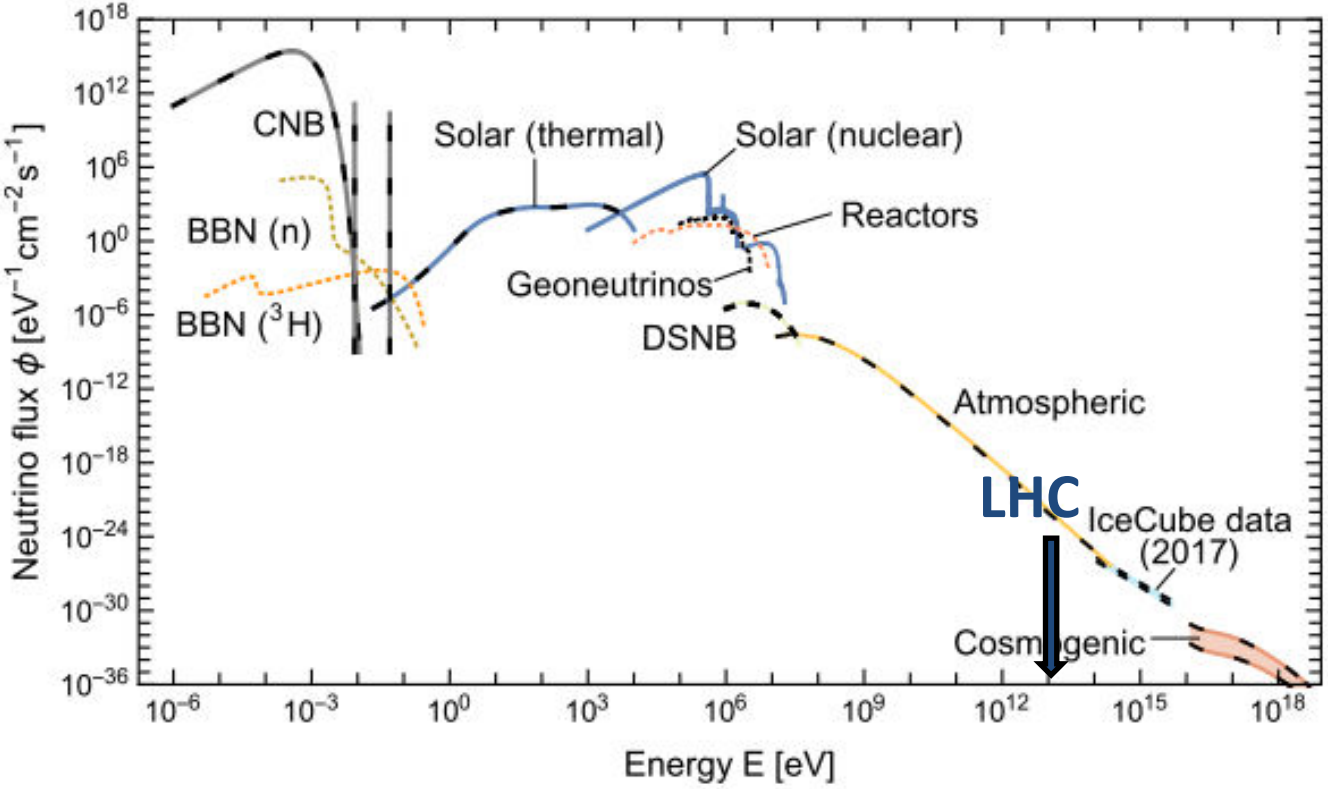


The most intense source on Earth is Sun:
6×10^{10} ν/cm^2s



Once in 70 years ν interacts with a human!

Neutrinos


CNB
BBN (n)
BBN (^{3}H)
Solar (thermal)
Solar (nuclear)
Reactors
Geoneutrinos
DSNB
Atmospheric
LHC
IceCube data
(2017)
Cosmogenic
Neutrino flux ϕ [eV^{-1} cm^{-2} s^{-1}]
Energy E [eV]
10^{18}
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-36}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}

Overview:

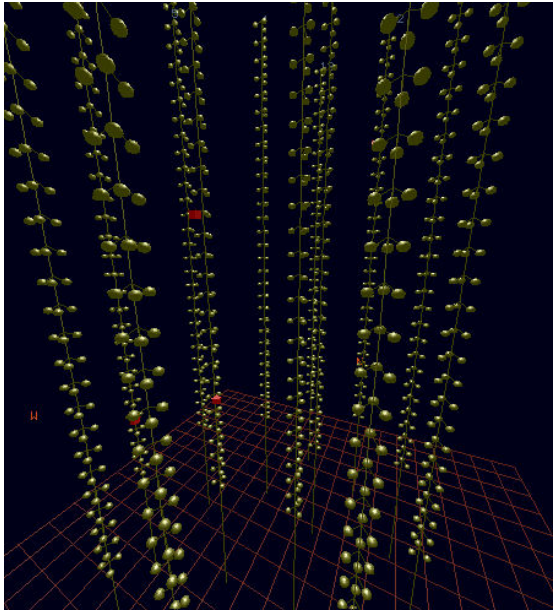
- Neutrinos
- Cosmic rays
- Principle of neutrino telescopes

Neutrino telescope scheme

Light sensors provides:

- Number of Cherenkov photons
- Time of arrival to the photo-sensor

$$\nu_l + N \rightarrow^{CC} \begin{cases} e^- + X \rightarrow cascades \\ \tau^- + X \rightarrow cascades \\ \mu^- + X \rightarrow track + cascades \end{cases}$$

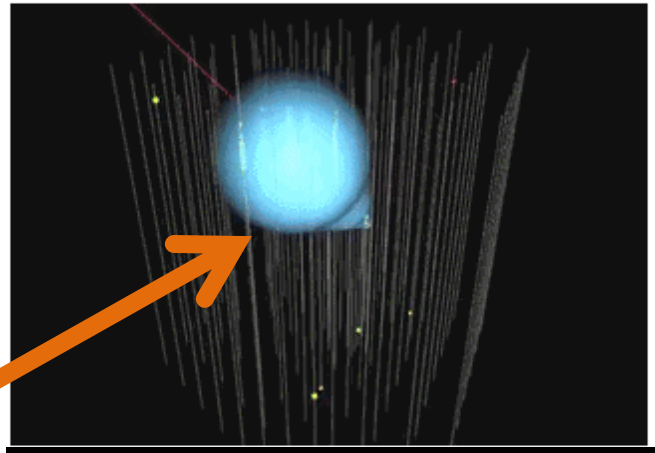


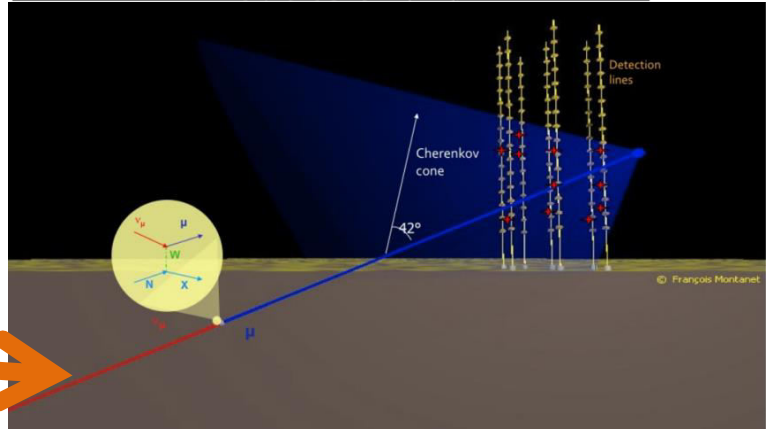
$$\nu_l + N \rightarrow^{NC} \nu_l + cascade$$



Detection principle

- Three-dimensional array of photo-sensors merged in transparent medium like water or ice
- Register Cherenkov light in space and time

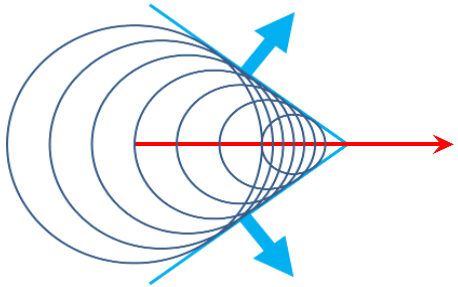




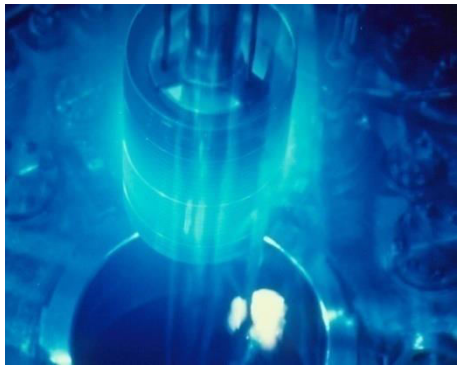
$$\nu_l + N \rightarrow \begin{cases} e^- + X \rightarrow cascades \\ \tau^- + X \rightarrow cascades \\ \mu^- + X \rightarrow track \end{cases}$$

Cherenkov light

•Charged particle travelling faster than the speed of light in a particular environment radiates Cherenkov light

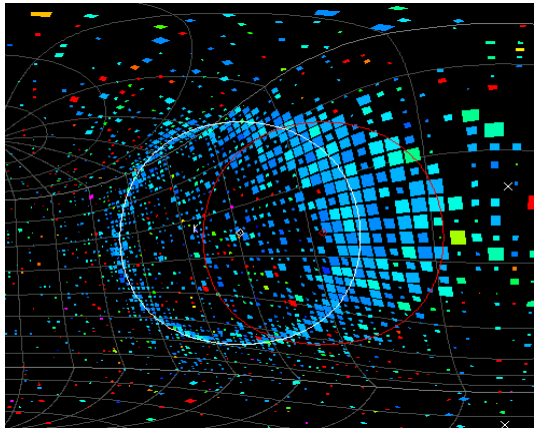


• Pale blue light



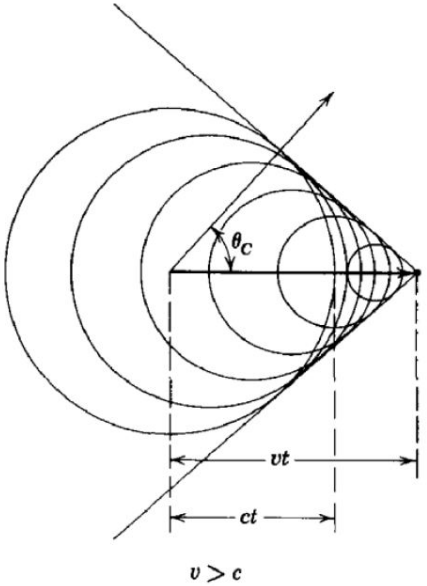


• Effect known for ultrasonic airplanes

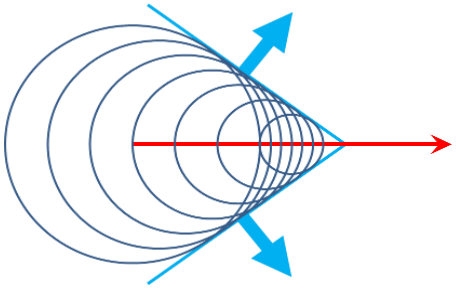


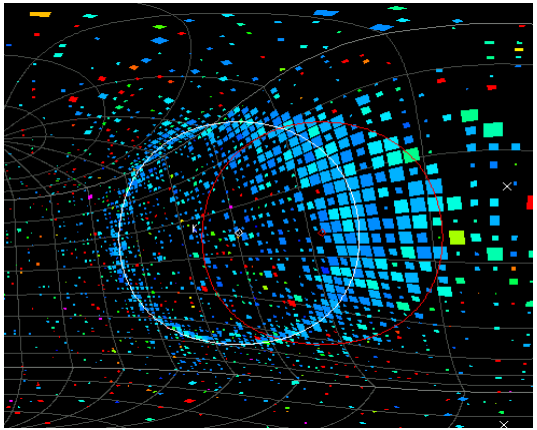
Cherenkov angle

- Charged particle travelling faster than the speed of light in a particular environment radiates Cherenkov light



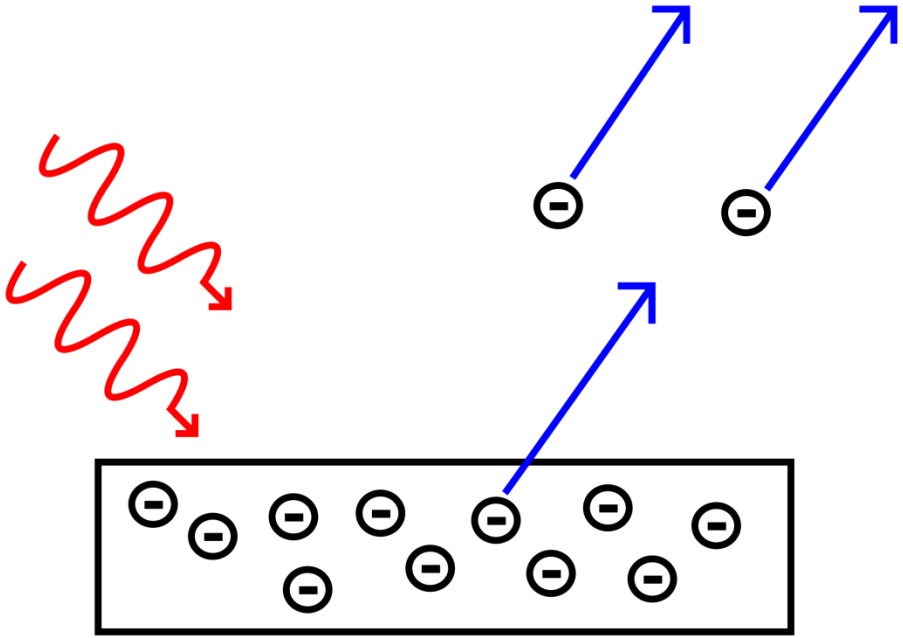
$$\cos\theta_C = \frac{c}{n}$$





Photon registration

Photo-Multiplier Tube exploits the photo-effect:



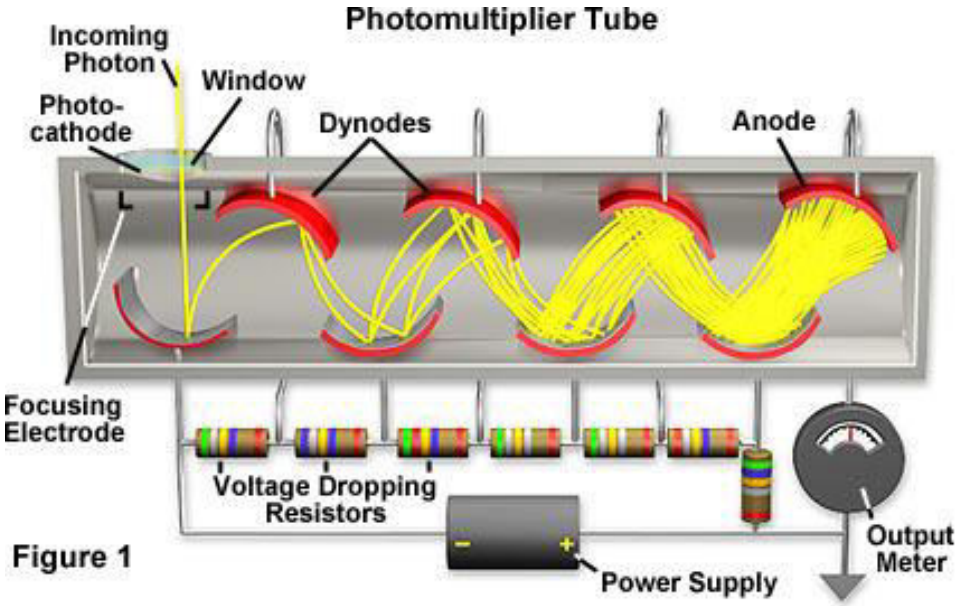


Figure 1

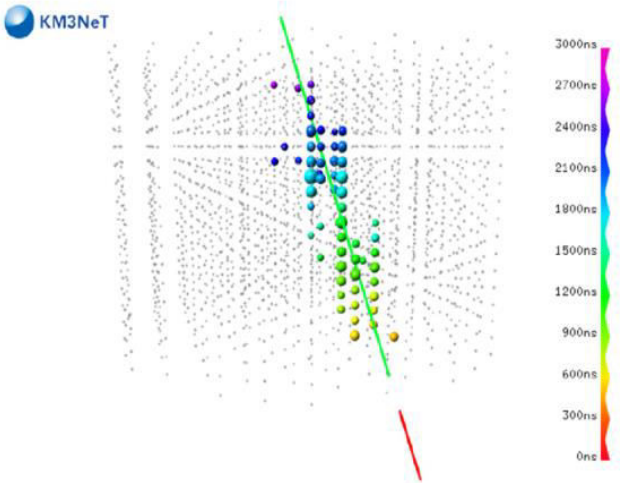
Light signatures

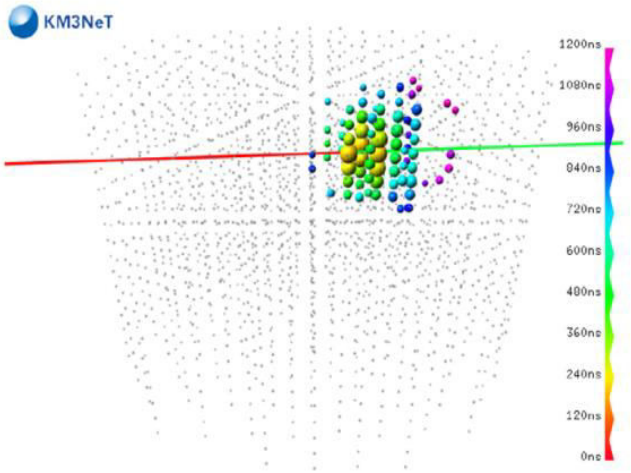
Cascade: point-like source

Muon: track-like source

$$\nu_l + N \rightarrow^{CC} \begin{cases} e^- + X \rightarrow cascades \\ \tau^- + X \rightarrow cascades \\ \mu^- + X \rightarrow track + cascades \end{cases}$$

$$\nu_l + N \rightarrow^{NC} \nu_l + cascade$$





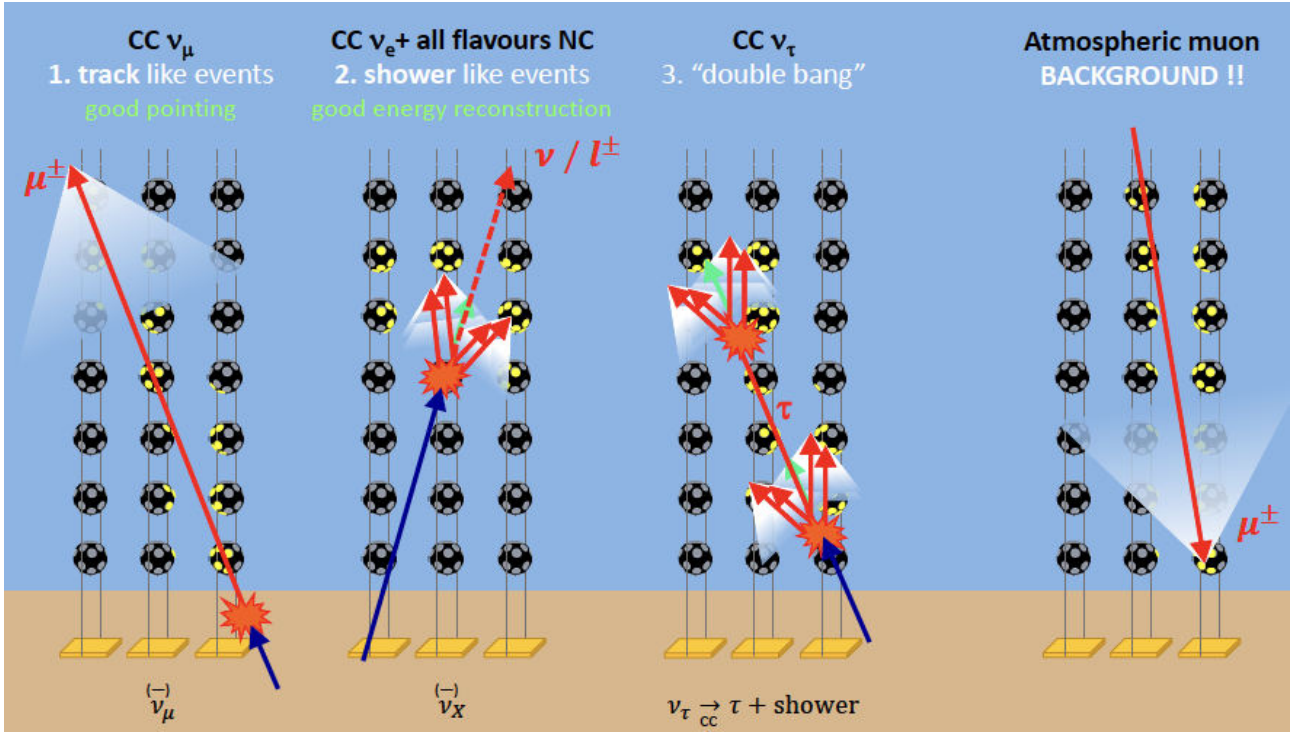
Event topologies

muons detected per year in km^3:

- atmospheric* μ ~ 10^{11}
- atmospheric** ν → μ ~ 10^5
- cosmic ν → μ > 200

* 3000 per second

** 1 every 6 minutes

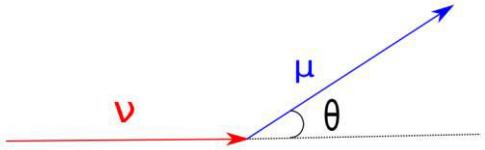


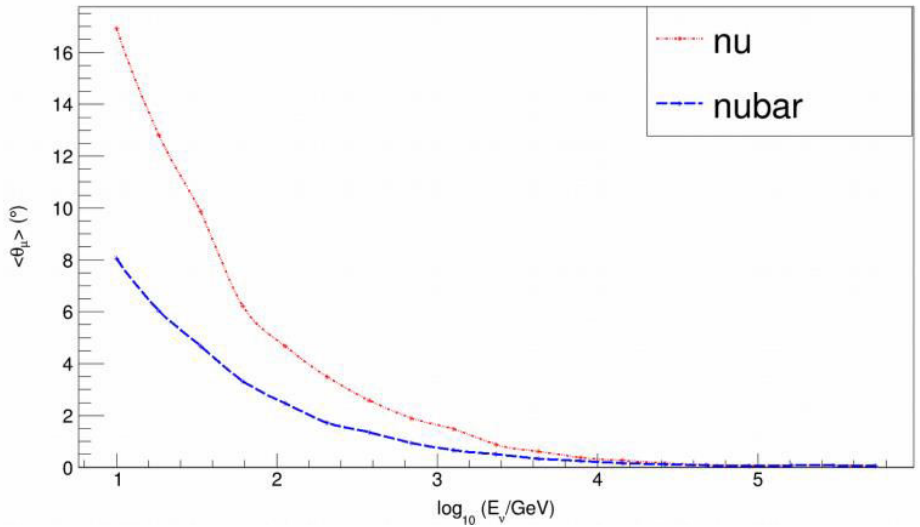
Tracks @E_ν>100 TeV ang. res. below 0.1° - energy res. ~ factor 2

Shower @E_ν>100 TeV ang. res. below 2° - energy res. ~6%

Muon: track-like light source

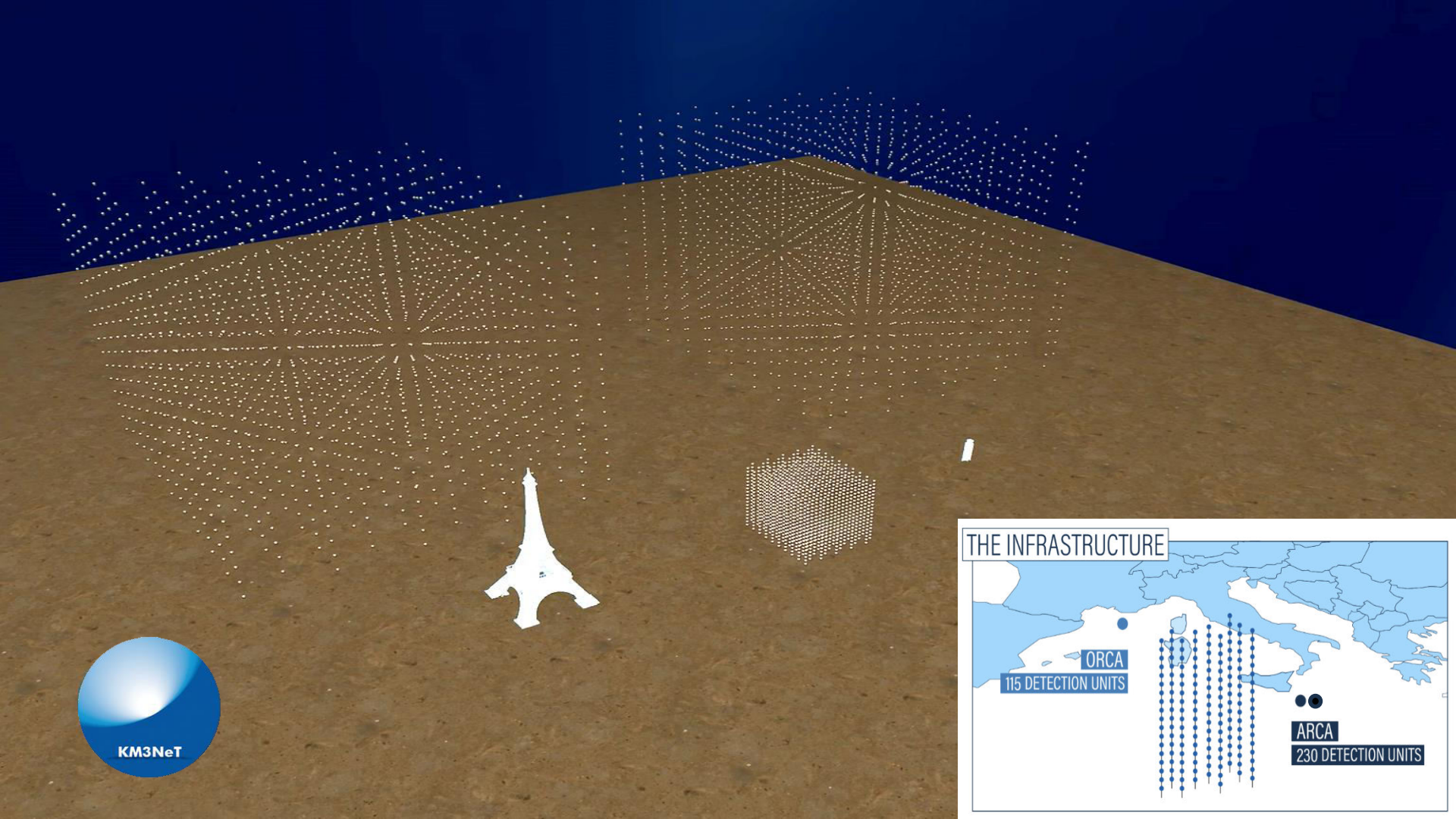
The angle between the incoming neutrino and outgoing muon





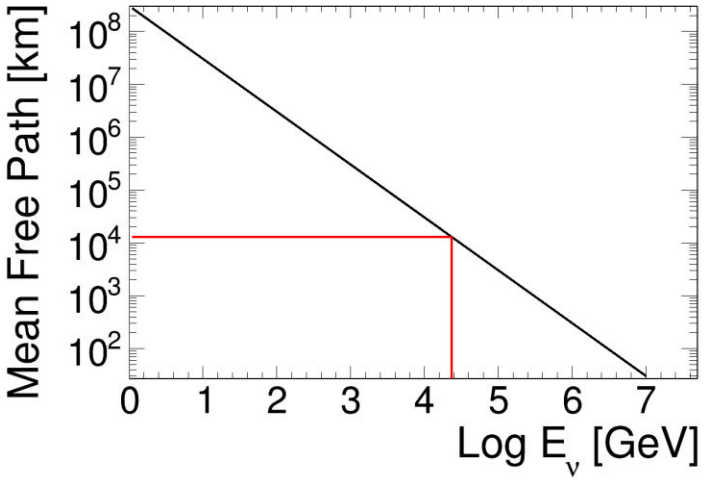
Muon range in water:

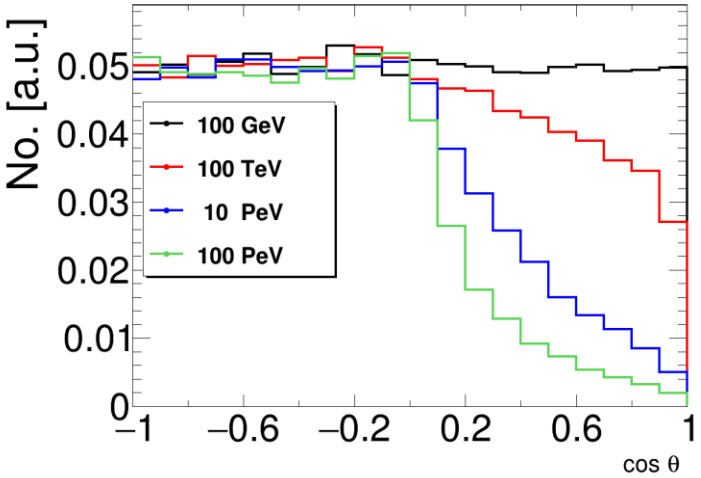
- 2 km for 1 TeV
- ~20 km for 1 PeV!!


KM3NeT
THE INFRASTRUCTURE
ORCA
115 DETECTION UNITS
ARCA
230 DETECTION UNITS

Mean free path

Mean distance for neutrino to interact in the Earth's interior

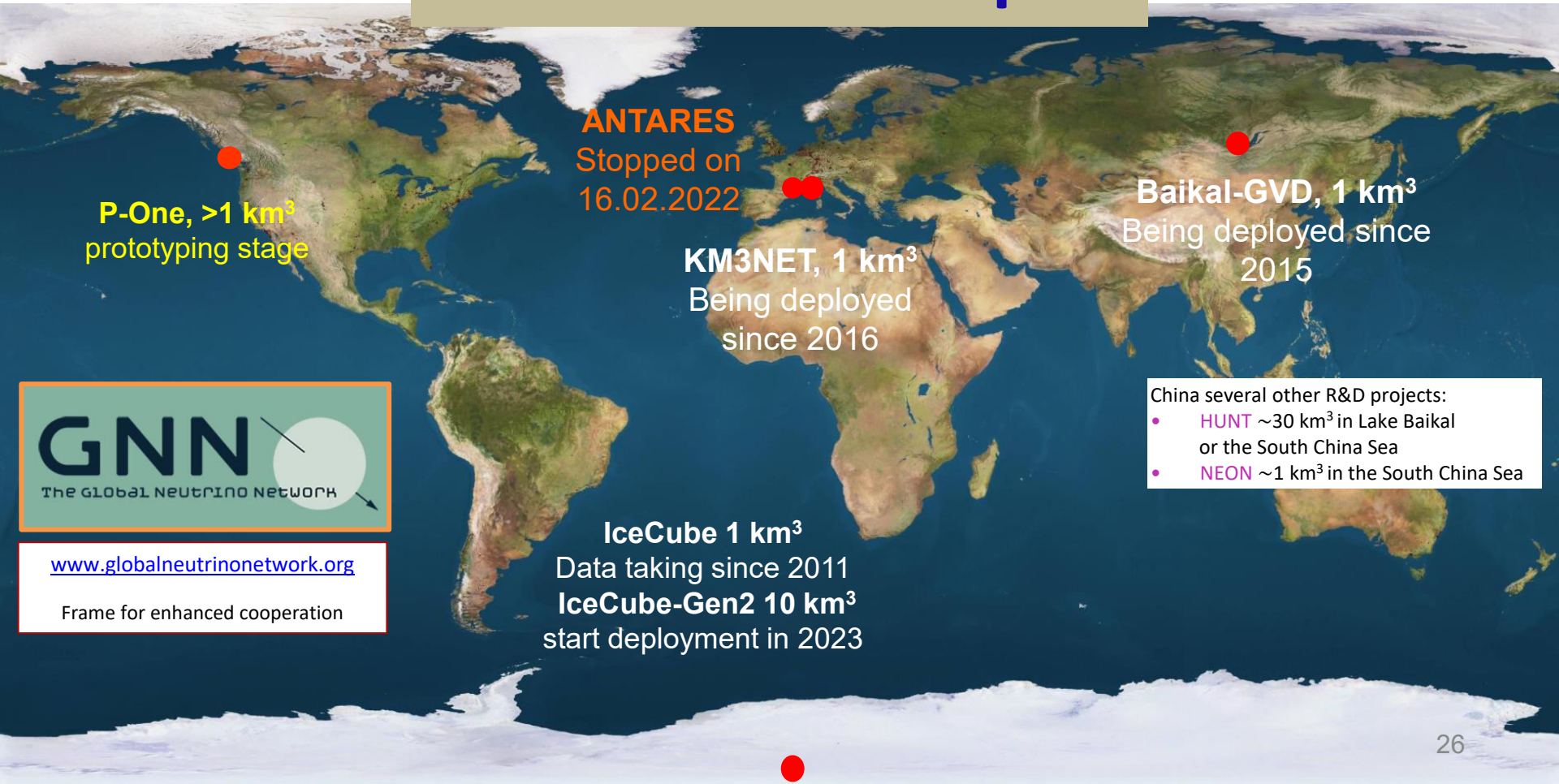




For Earth's diameter 12.7 km
it is about 30 TeV

down-going: cos θ= -1
up-going: cos θ= 1

Neutrino telescopes



Overview:

- Neutrinos
- Cosmic rays
- Principle of neutrino telescopes
- KM3NeT

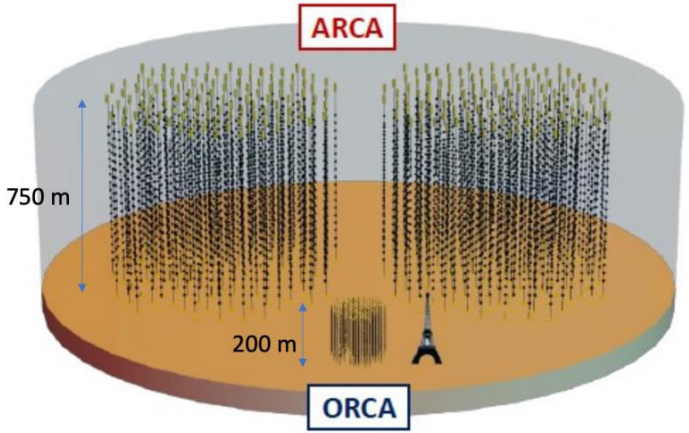
KM3NeT

KM3NeT is an experiment hosting two neutrino detectors in Mediterranean Sea:

- **ARCA** (**A**stroparticle **R**esearch with **C**osmics in the **A**byss) designed for observation of high energy (GeV-PeV) neutrino sources. A telescope offshore Capo Passero (Sicily) at a depth of 3 500 m.

- **ORCA** (**O**scillation **R**esearch with **C**osmics in the **A**byss) aimed at the neutrino mass hierarchy. A detector offshore Toulon (France) able to detect neutrinos of tens of GeV at a depth of 2 500 m.

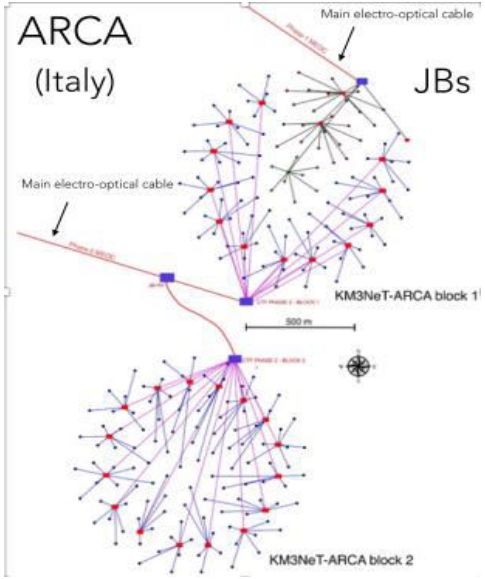




KM3NeT / ARCA

- Two blocks of 115 Detection Units each at a depth of 3 500 m
- Average distance between DUs 90 m
- Vertical spacing of DOMs 36 m
- **Volume (0.5 x 2) km^3 = 1 GTon**







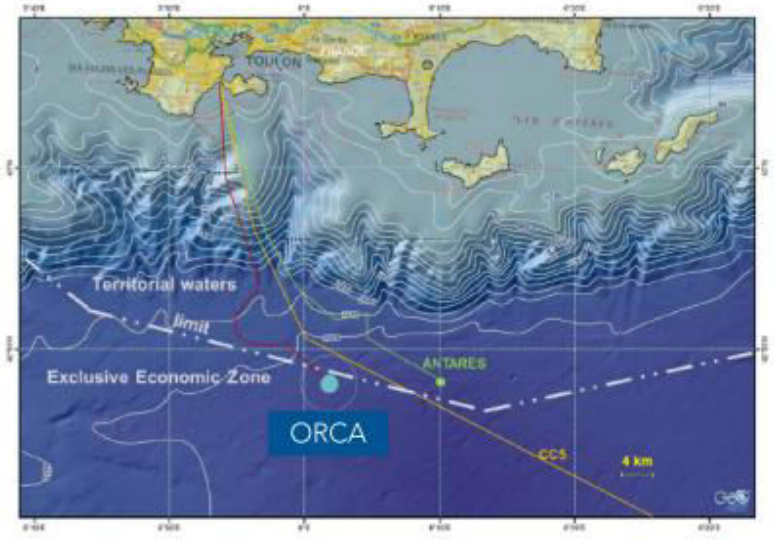
DU: 18 DOMs

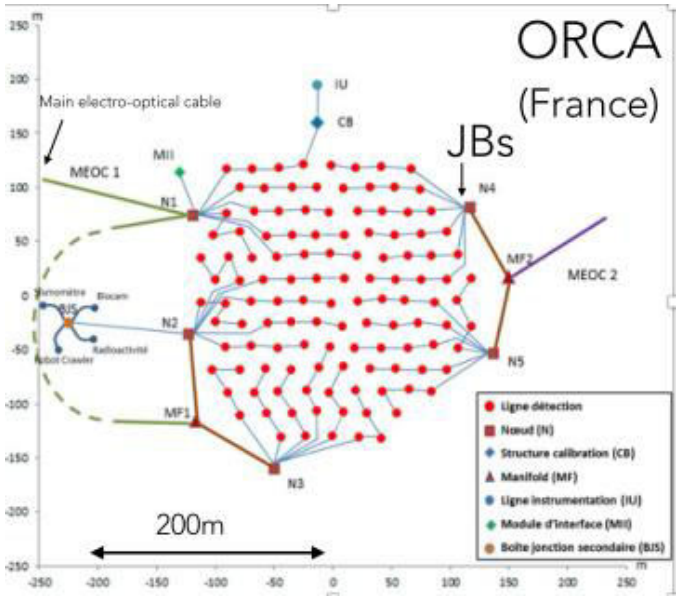


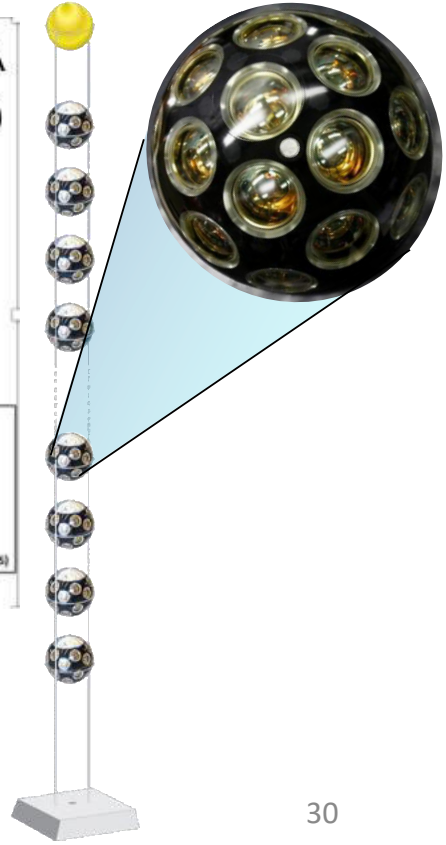
DOM: 31 photo-multiplier tubes

KM3NeT / ORCA

- One block of 115 Detection Units at a depth of 2 500 m
- Average distance between DUs 20 m
- Vertical spacing of DOMs 9 m
- **Volume = 7 MTon**

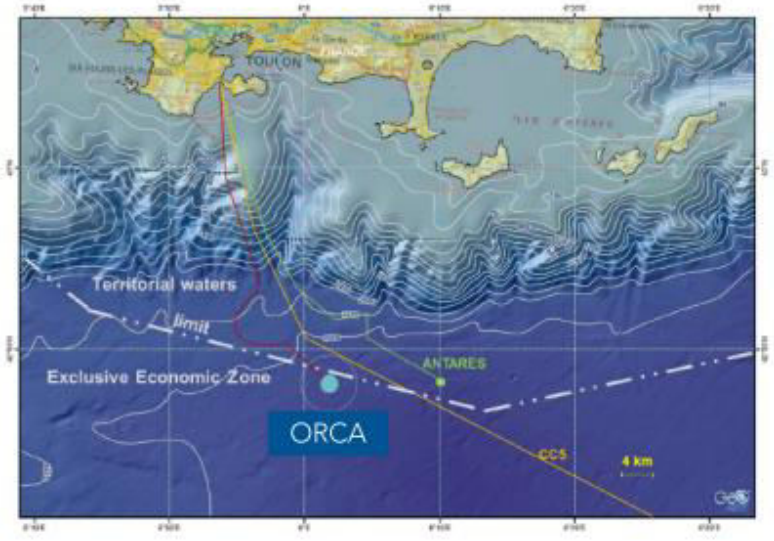


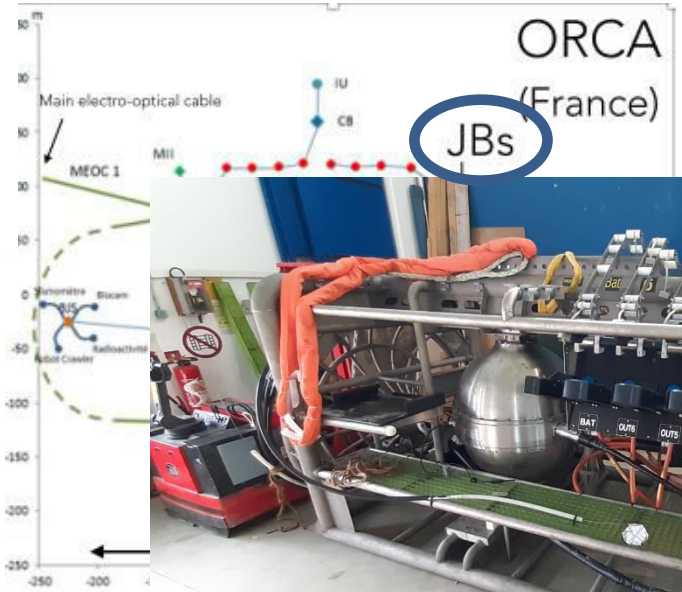




KM3NeT / ORCA

- One block of 115 Detection Units at a depth of 2 500 m
- Average distance between DUs 20 m
- Vertical spacing of DOMs 9 m
- **Volume = 7 MTon**



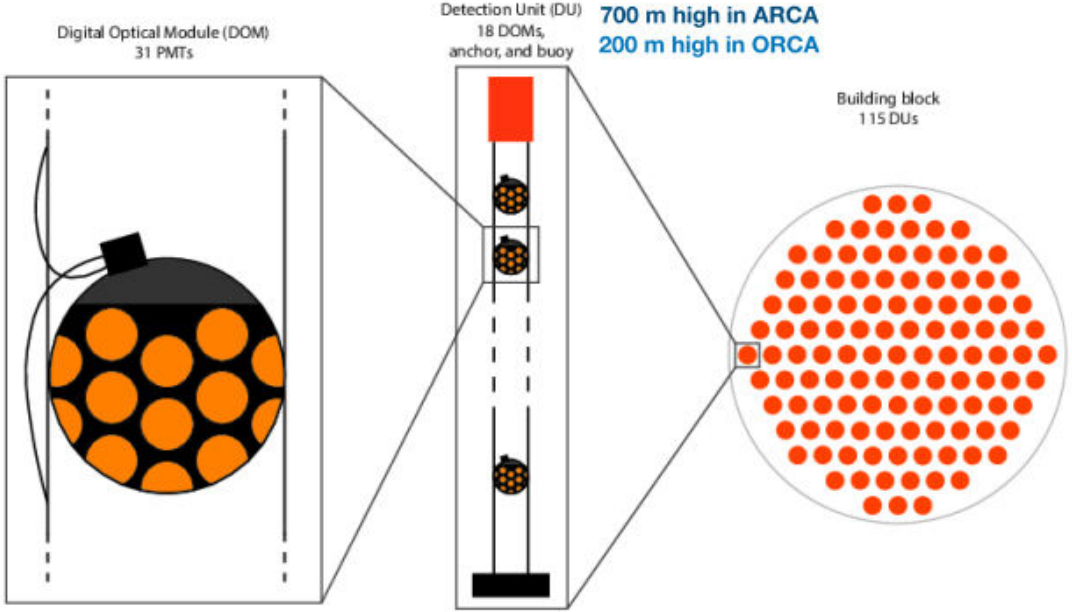


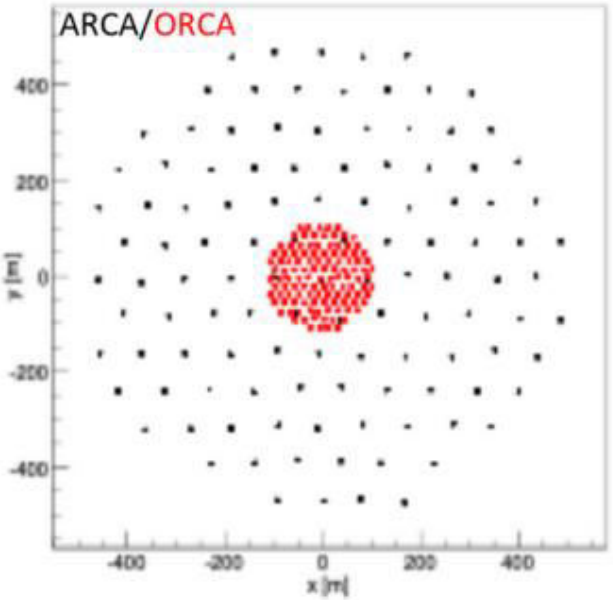
Junction Box: communication and power connection



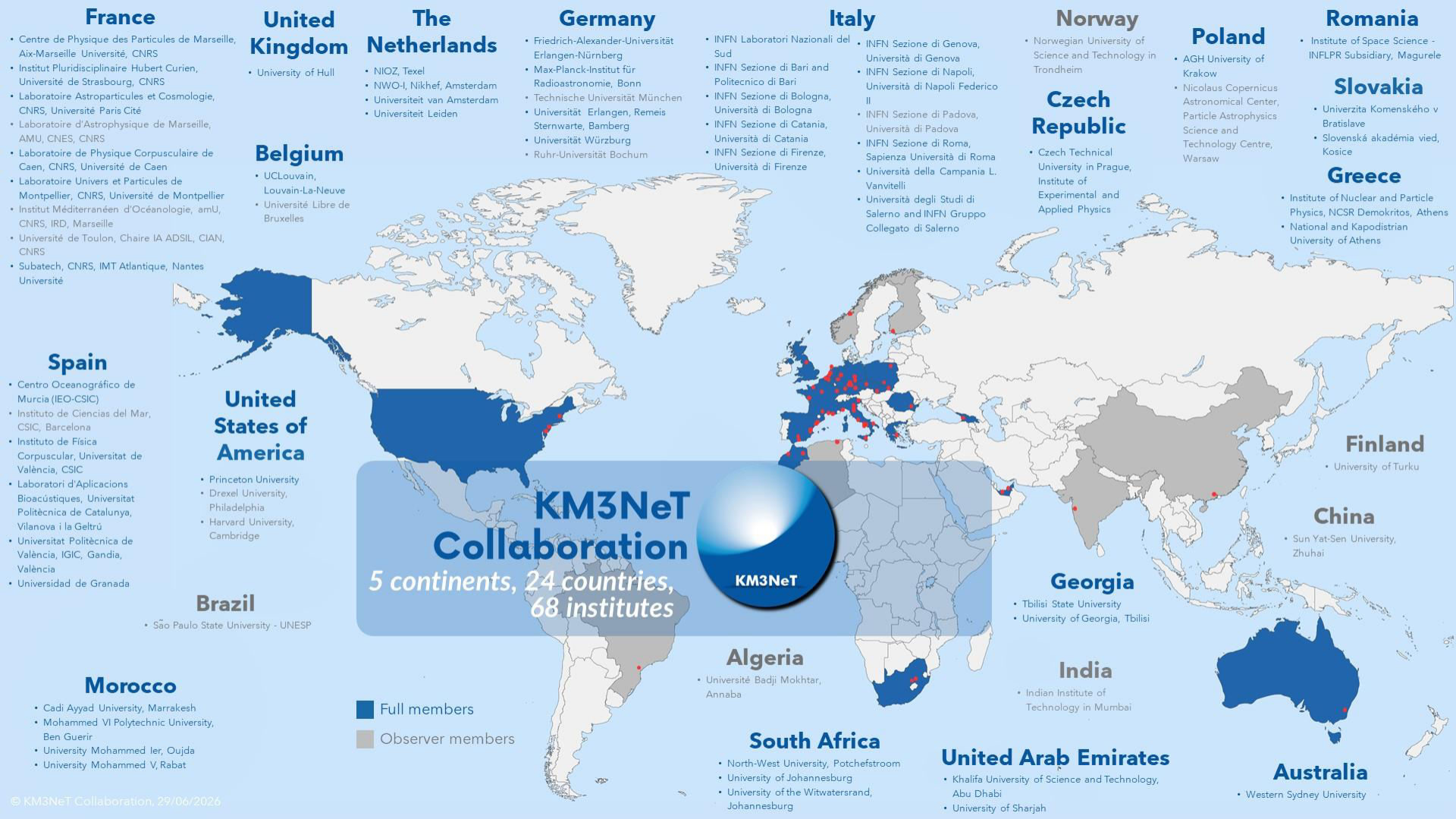
Current status

- ARCA – 62 detection units
- ORCA – 42 detection units





KM3NeT Collaboration, Eur.Phys.J.C 84 (2024) 9, 885


France
• Centre de Physique des Particules de Marseille, Aix-Marseille Université, CNRS
• Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, CNRS
• Laboratoire Astroparticules et Cosmologie, CNRS, Université Paris Cité
• Laboratoire d'Astrophysique de Marseille, AMU, CNES, CNRS
• Laboratoire de Physique Corpusculaire de Caen, CNRS, Université de Caen
• Laboratoire Univers et Particules de Montpellier, CNRS, Université de Montpellier
• Institut Méditerranéen d'Océanologie, amU, CNRS, IRD, Marseille
• Université de Toulon, Chaire IA ADSIL, CIAN, CNRS
• Subatech, CNRS, IMT Atlantique, Nantes Université
United Kingdom
• University of Hull
Belgium
• UCLouvain, Louvain-La-Neuve
• Université Libre de Bruxelles
The Netherlands
• NIOZ, Texel
• NWO-I, Nikhef, Amsterdam
• Universiteit van Amsterdam
• Universiteit Leiden
Germany
• Friedrich-Alexander-Universität Erlangen-Nürnberg
• Max-Planck-Institut für Radioastronomie, Bonn
• Technische Universität München
• Universität Erlangen, Remeis Sternwarte, Bamberg
• Universität Würzburg
• Ruhr-Universität Bochum
Italy
• INFN Laboratori Nazionali del Sud
• INFN Sezione di Bari and Politecnico di Bari
• INFN Sezione di Bologna, Università di Bologna
• INFN Sezione di Catania, Università di Catania
• INFN Sezione di Firenze, Università di Firenze
• INFN Sezione di Genova, Università di Genova
• INFN Sezione di Napoli, Università di Napoli Federico II
• INFN Sezione di Padova, Università di Padova
• INFN Sezione di Roma, Sapienza Università di Roma
• Università della Campania L. Vanvitelli
• Università degli Studi di Salerno and INFN Gruppo Collegato di Salerno
Norway
• Norwegian University of Science and Technology in Trondheim
Czech Republic
• Czech Technical University in Prague, Institute of Experimental and Applied Physics
Poland
• AGH University of Krakow
• Nicolaus Copernicus Astronomical Center, Particle Astrophysics Science and Technology Centre, Warsaw
Romania
• Institute of Space Science - INFLPR Subsidiary, Magurele
Slovakia
• Univerzita Komenského v Bratislave
• Slovenská akadémia vied, Kosice
Greece
• Institute of Nuclear and Particle Physics, NCSR Demokritos, Athens
• National and Kapodistrian University of Athens
Spain
• Centro Oceanográfico de Murcia (IEO-CSIC)
• Instituto de Ciencias del Mar, CSIC, Barcelona
• Instituto de Física Corpuscular, Universitat de València, CSIC
• Laboratori d'Aplicacions Bioacústiques, Universitat Politècnica de Catalunya, Vilanova i la Geltrú
• Universitat Politècnica de València, IGIC, Gandia, València
• Universidad de Granada
United States of America
• Princeton University
• Drexel University, Philadelphia
• Harvard University, Cambridge
Brazil
• São Paulo State University - UNESP
Morocco
• Cadi Ayyad University, Marrakesh
• Mohammed VI Polytechnic University, Ben Guerir
• University Mohammed Ier, Oujda
• University Mohammed V, Rabat
KM3NeT Collaboration
5 continents, 24 countries, 68 institutes
KM3NeT
Full members
Observer members
Algeria
• Université Badji Mokhtar, Annaba
South Africa
• North-West University, Potchefstroom
• University of Johannesburg
• University of the Witwatersrand, Johannesburg
United Arab Emirates
• Khalifa University of Science and Technology, Abu Dhabi
• University of Sharjah
India
• Indian Institute of Technology in Mumbai
Georgia
• Tbilisi State University
• University of Georgia, Tbilisi
China
• Sun Yat-Sen University, Zhuhai
Finland
• University of Turku
Australia
• Western Sydney University
© KM3NeT Collaboration, 29/06/2026

Overview:

- Neutrinos
- Cosmic rays
- Principle of neutrino telescopes
- KM3NeT
- Ultra-high energy neutrino with KM3NeT



Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

https://doi.org/10.1038/s41586-024-08543-1

Received: 19 August 2024

Accepted: 18 December 2024

Check for updates

The KM3NeT Collaboration*[+]

The detection of cosmic neutrinos with energies above a teraelectronvolt (TeV) offers a unique exploration into astrophysical phenomena[1–3]. Electrically neutral and interacting only by means of the weak interaction, neutrinos are not deflected by magnetic fields and are rarely absorbed by interstellar matter: their direction indicates that their cosmic origin might be from the farthest reaches of the Universe. High-energy neutrinos can be produced when ultra-relativistic cosmic-ray protons or nuclei interact with other matter or photons and their observation could be a signature of these processes. Here we report an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea[4], which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of 120^{+110}_{-60} petaelectronvolts (PeV). In light of its enormous energy and near-horizontal direction, the muon most probably originated from the interaction of a neutrino of even higher energy in the vicinity of the detector. The cosmic neutrino energy spectrum measured up to now[5–7] falls steeply with energy. However, the energy of this event is much larger than that of any neutrino detected so far. This suggests that the neutrino may have originated in a different cosmic accelerator than the lower-energy neutrinos or this may be the first detection of a cosmogenic neutrino[8], from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.

Cosmic neutrinos may be produced either in the vicinity of the cosmic-ray source or along the cosmic-ray propagation path, leading to the production of secondary unstable particles, which subsequently decay into neutrinos. Cosmic rays interacting in the Earth's atmosphere produce atmospheric neutrinos, which form an experimental background to cosmic neutrinos. To detect cosmic neutrinos, very-large-volume neutrino observatories monitor natural bodies of water or ice for the Cherenkov light induced by the passage of the charged particles that result from neutrino interactions in or near the detector. The KM3NeT research infrastructure comprises two detector arrays of optical sensors deep in the Mediterranean Sea[4]. The ARCA detector is located offshore Portopalo di Capo Passero, Sicily, Italy, at a depth of about 3,450 m and connected by means of an electro-optical cable to the shore station of the INFN, Laboratori Nazionali del Sud (LNS). The geometry of ARCA is optimized for the study of high-energy cosmic neutrinos. The ORCA detector is located at a depth of about 2,450 m, offshore Toulon, France, and is optimized for the study of neutrino oscillations. Both detectors are under construction but already operational. Once completed, they will comprise 345 (230 for ARCA and 115 for ORCA) vertical detection lines, each holding 18 optical modules. Each module hosts 31 3-inch photomultiplier tubes (PMTs) pointing in all directions and ensuring 4π coverage[9]. Both detectors can identify all flavours of neutrino interactions: those producing long-lived muons, denominated 'tracks', and those producing electromagnetic and hadronic cascades at the neutrino interaction vertex, denominated 'showers'.

Of interest in this article are neutrino interactions that produce high-energy muons, which can travel several kilometres in seawater before being absorbed. These muons lose energy as they propagate mainly because of stochastic radiative processes such as bremsstrahlung, pair production and photonuclear reactions. The average energy loss per unit path length is proportional to the muon energy. Electromagnetic cascades arise from these stochastic energy losses; the number of charged particles that produce Cherenkov radiation in the cascades is proportional to the amount of energy lost by the muon in the process. The recorded time of arrival and time-over-threshold of the signals on the PMTs (denoted as 'hits') are used to reconstruct the muon direction and energy.

Although atmospheric neutrinos are more abundant at lower energies (~TeV), cosmic neutrinos should become dominant at energies above 100 TeV. The neutrino energy is thus a crucial parameter for establishing a cosmic origin. The IceCube Collaboration announced the discovery of PeV cosmic neutrinos in 2013 (ref. 10). The most energetic neutrinos reported so far are a 6.05 ± 0.72 PeV electron antineutrino observed at the energy of the Glashow resonance[11] and a muon neutrino above 10 PeV from the observation of a 4.4-PeV muon[12].

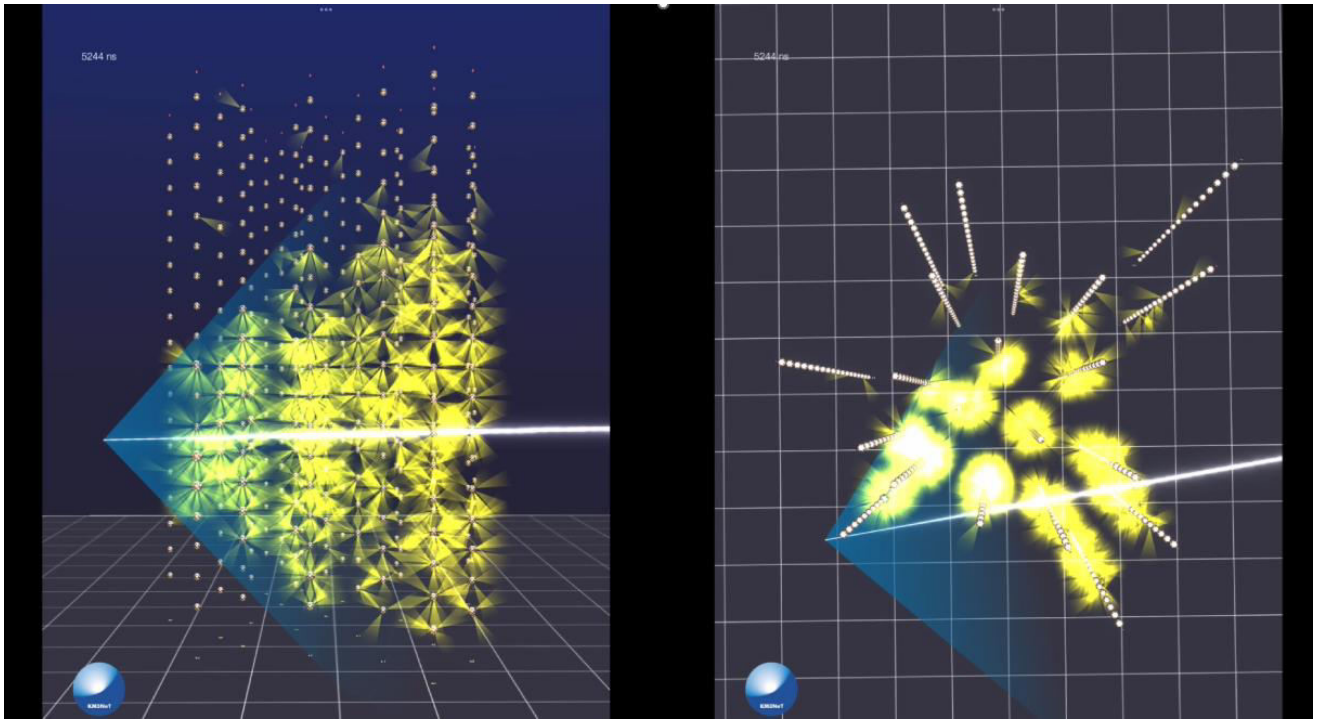
The neutrino event KM3-230213A

An extremely high-energy muon traversing the ARCA detector was observed on 13 February 2023 at 01:16:47 UTC. This event is referred to here as KM3-230213A. At that time, 21 detection lines were in operation.

*A list of authors and their affiliations appears at the end of the paper.

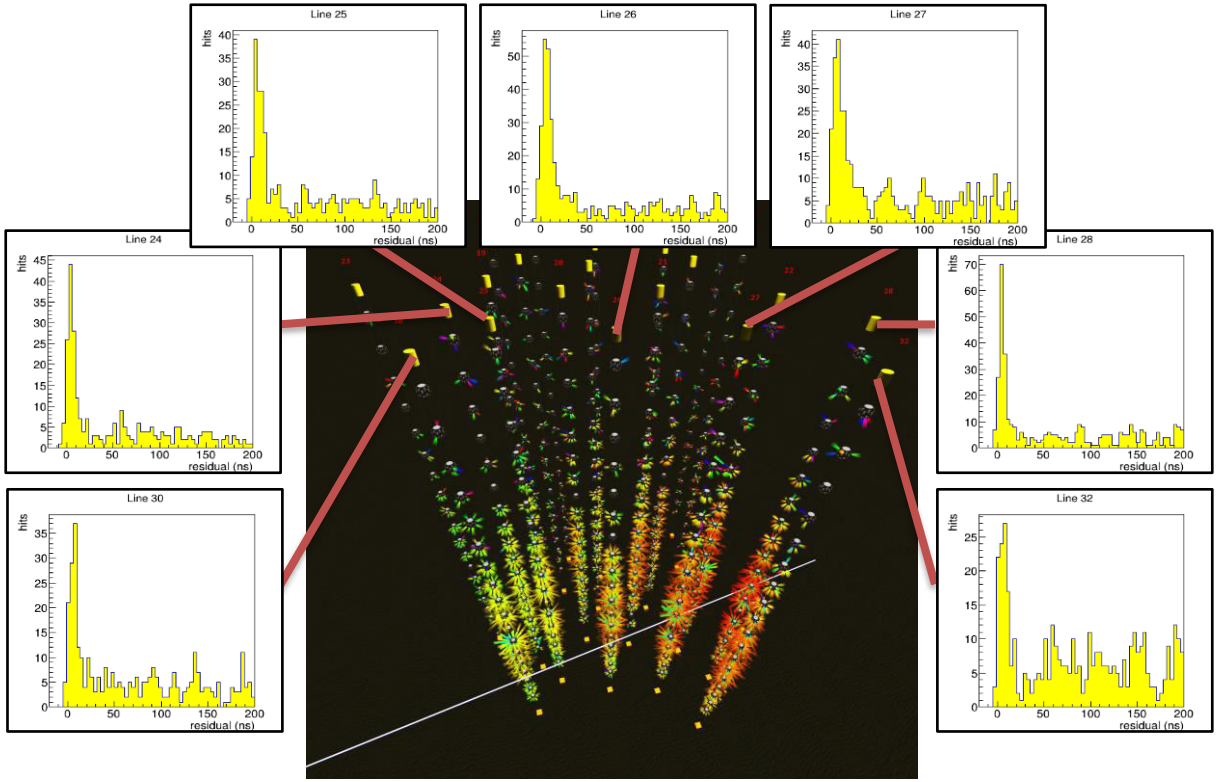
KM3-230213A event

- February 13, 2023 – ARCA detector consisted of 21 lines
- 1/3 of the detector was illuminated with light



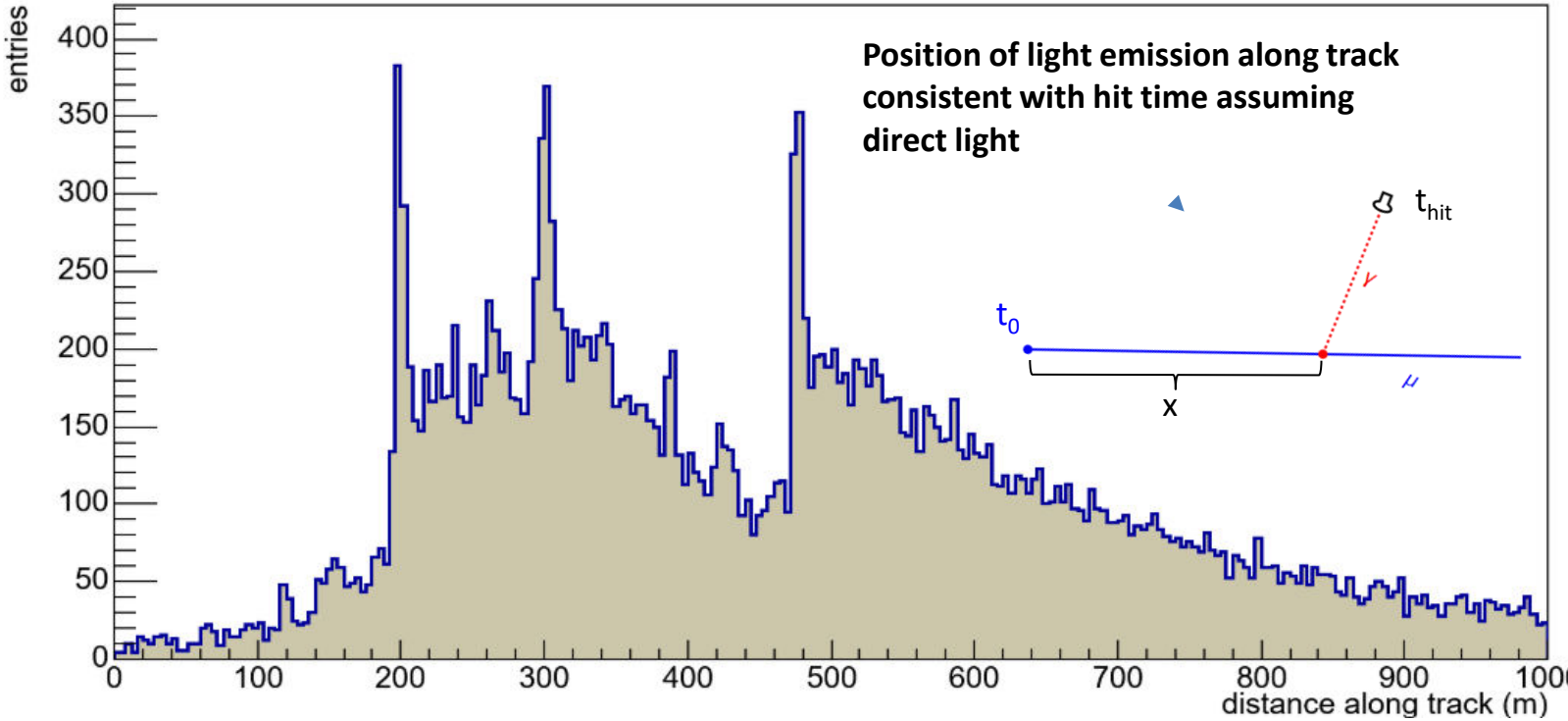
KM3-230213A event

- Signature - horizontal track crossing through the detector



KM3-230213A event

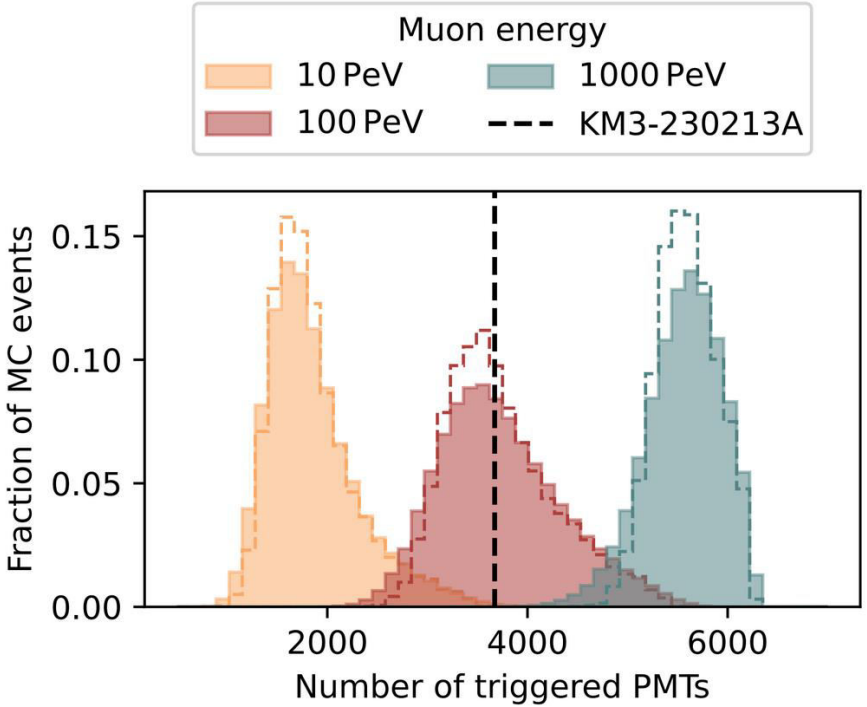
- Light profile – 3 large energy depositions characteristic for stochastic losses of high energy muons



Muon energy estimation

- Simulating muons passing through the detector with same direction and position
- Varying optical properties and PMT's efficiency

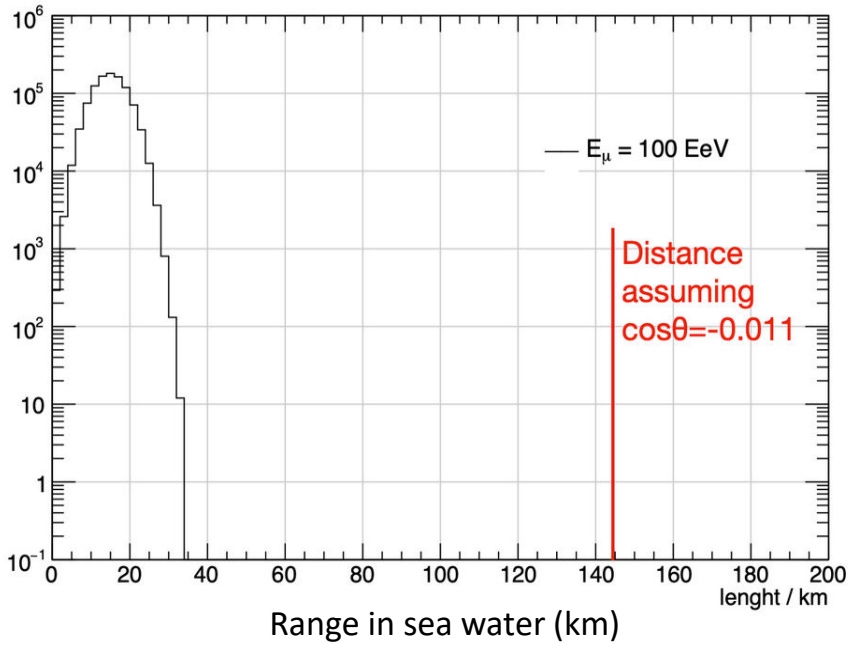
$$E_{\mu} = 120^{+110}_{-60}\ PeV$$

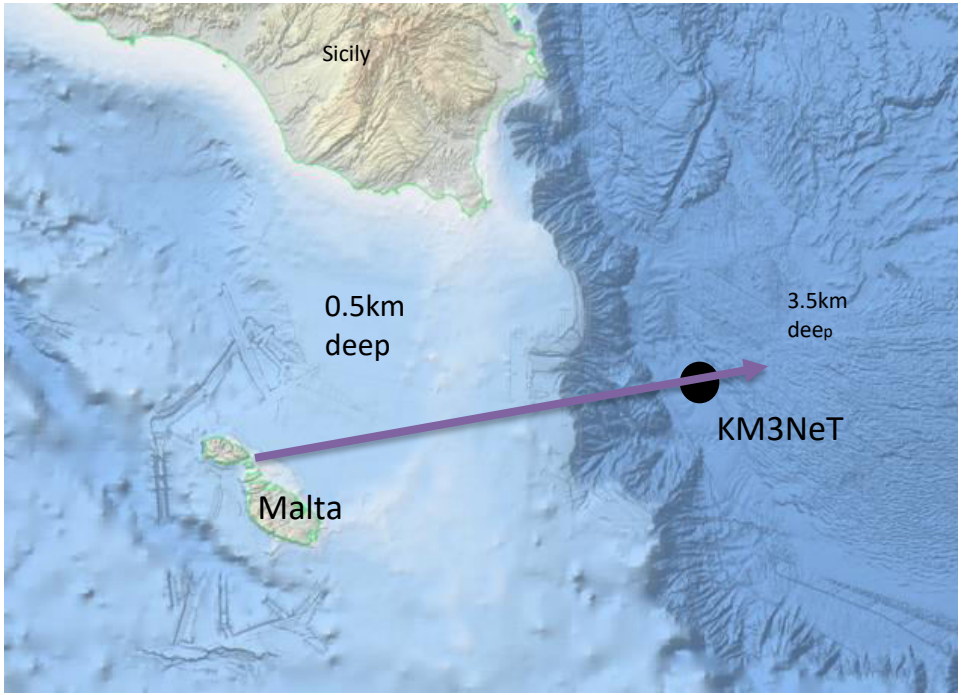


Nature **638**, 376-382 (2025)

KM3-230213A possible origin

- Atmospheric muons can reach 30-50 km only at hundreds PeV energies.
- Passage through continental shelf (Maltan) - actual amount of matter is even larger.



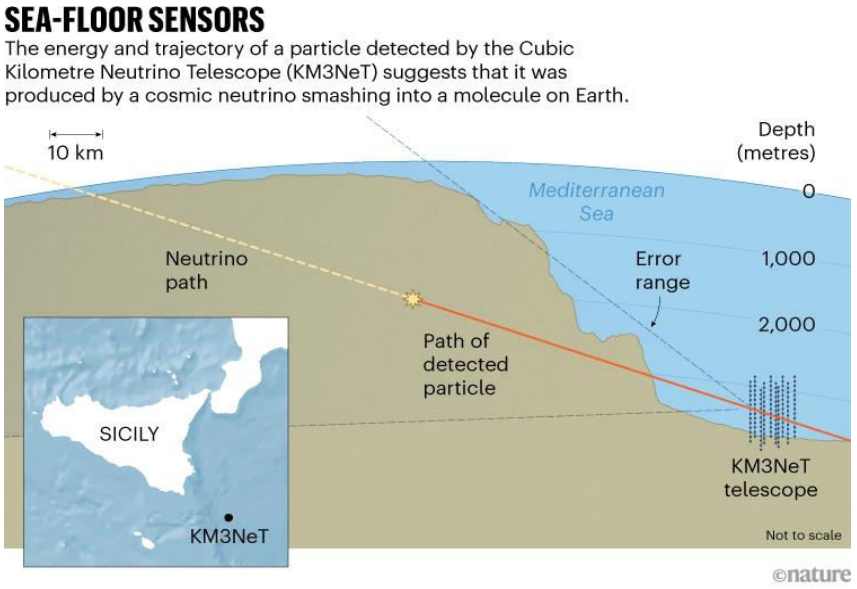


KM3-230213A possible origin

- Atmospheric muons can reach 30-50 km only at hundreds PeV energies.
- Passage through continental shelf (Maltan) - actual amount of matter is even larger.
- Atmospheric neutrinos are very rare at such high energies, 10^{-5} per year.

$$E_{\mu} = 120^{+110}_{-60}\ PeV$$

$$E_{\nu} = 220^{+570}_{-110}\ PeV$$



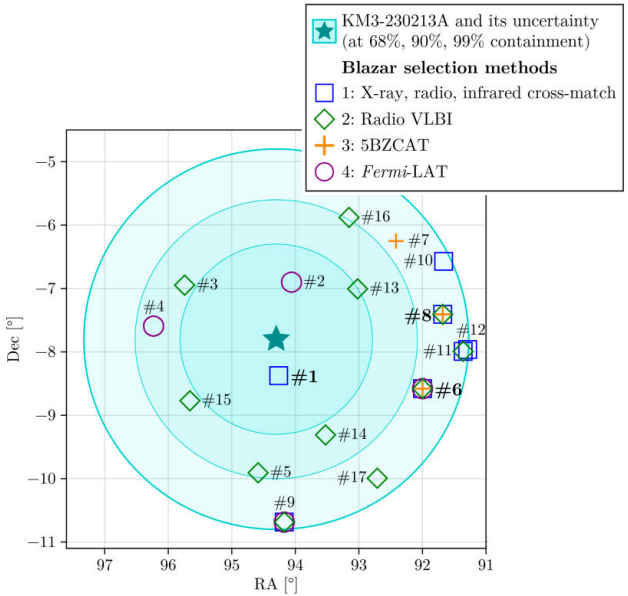
KM3-230213A possible origin

- Atmospheric muons can reach 30-50 km only at hundreds PeV energies.
- Passage through continental shelf (Maltan) - actual amount of matter is even larger.
- Atmospheric neutrinos are very rare at such high energies, 10^{-5} per year.
- Most likely the **neutrino** is of **cosmic** origin

$$E_\nu = 220^{+570}_{-110}\ PeV$$

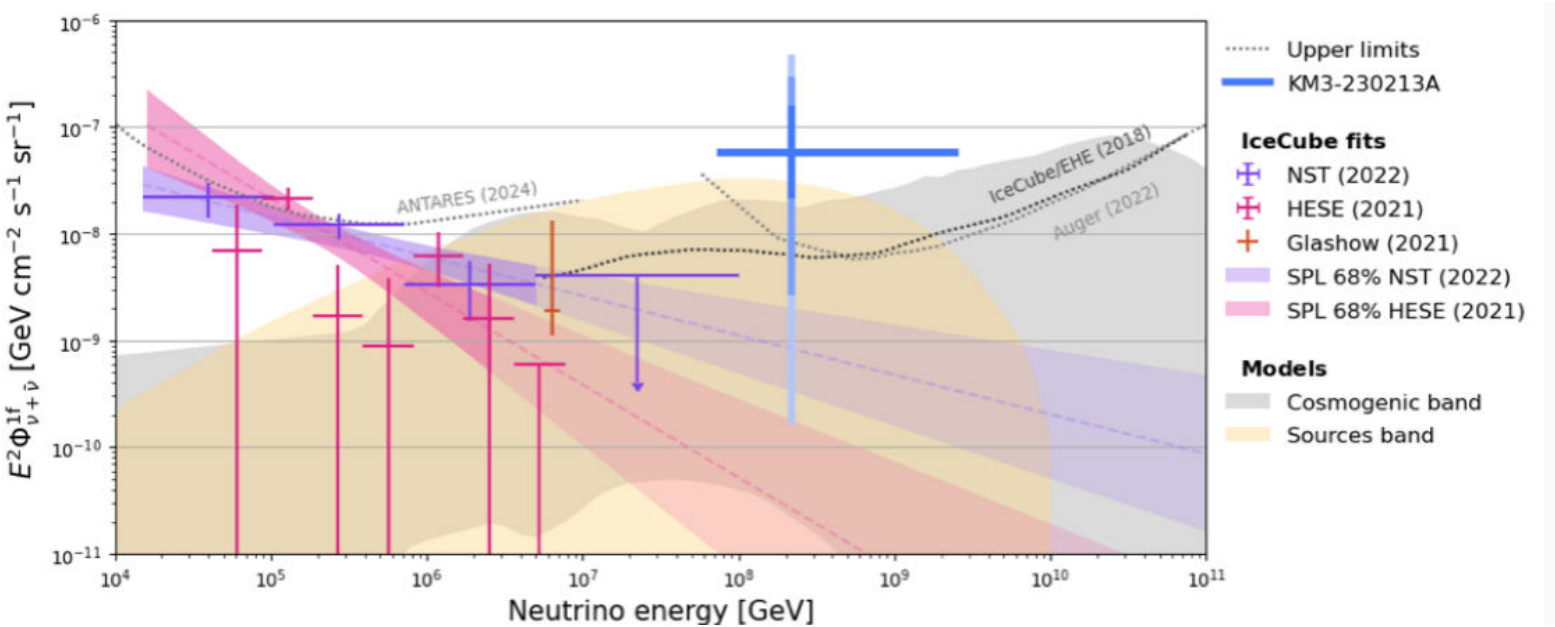
Celestial coordinates:
RA = 94.3◦, Dec= −7.8◦

Galactic coordinates:
l = 216,1 ◦, b = -11.1◦



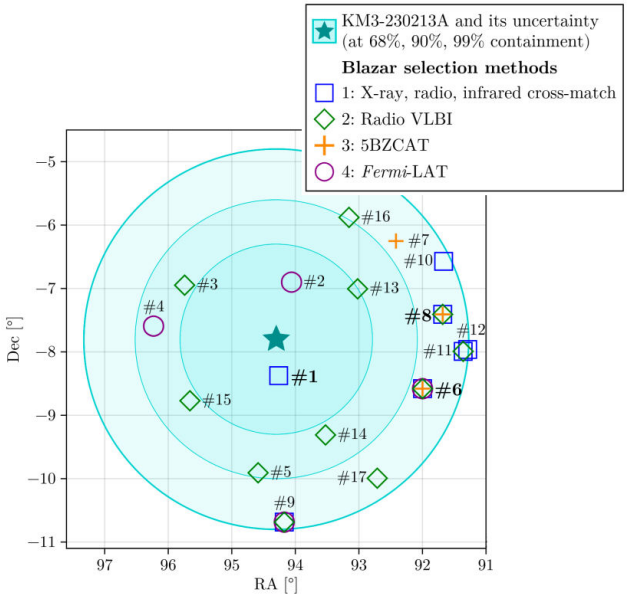
Astrophysical origin

- Tension with IceCube and Auger limits for high energy region.
- Assuming single power law spectrum: $\phi=(E/100\ \mathrm{TeV})^{\gamma}$ [GeV $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$]



KM3-230213A event possible origin

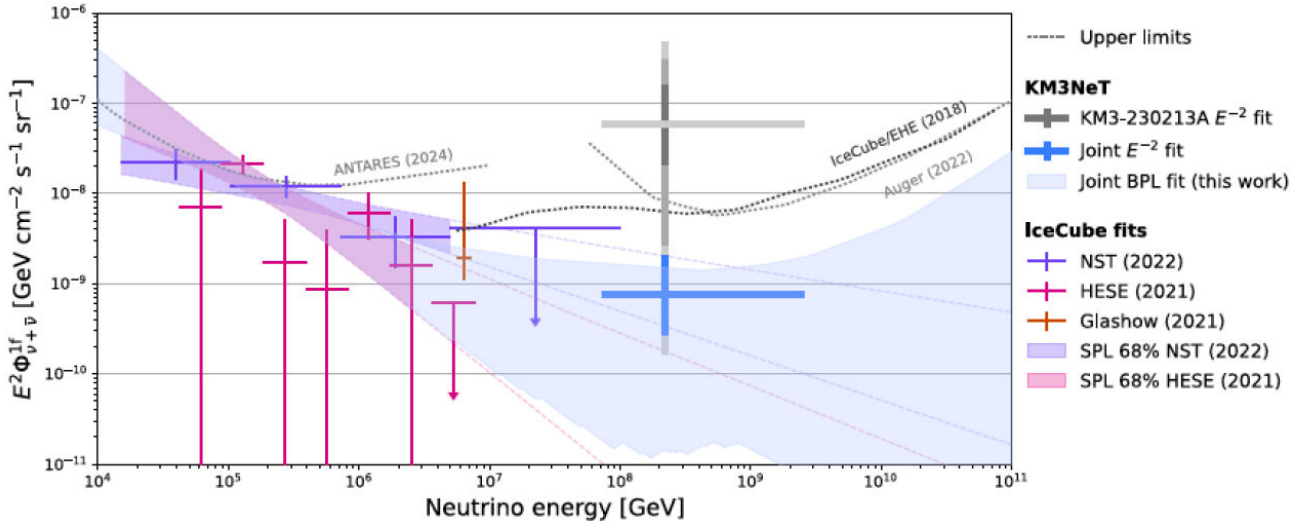
- Counterpart searches around the event direction.
- 17 blazar candidates found within the localization.
- 3 candidates with electromagnetic flares, but no conclusive association.
- No Galactic counterpart in this direction.



KM3-230213A event

Fit combining IceCube's ultra high energy neutrinos and KM3-230213A event:

- Single and broken power law hypotheses tested – no significance for a spectral break.
- The event is consistent with recent diffuse astrophysical flux.



Conclusions

- A single event opened new windows on astrophysics.
- KM3-230213A is the most energetic neutrino detected: 220 PeV.
- No convincing electromagnetic source has been identified. Most likely the origin is extragalactic.
- The event provides unique constraints on fundamental physics.

Conclusions

- A single event opened new windows on astrophysics.
- KM3-230213A is the most energetic neutrino detected: 220 PeV.
- No convincing electromagnetic source has been identified. Most likely the origin is extragalactic.
- The event provides unique constraints on fundamental physics.

Future data and analyses will clarify
the origin of the KM3-230213A event!

Ďakujem za pozornosť!





Rastislav Dvornický

Katedra jadrovej fyziky a biofyziky

dvornicky@fmph.uniba.sk

FACULTY OF MATHEMATICS, PHYSICS AND INFORMATICS

UNIVERZITA KOMENSKÉHO V BRATISLAVE