Neutrino telescopes

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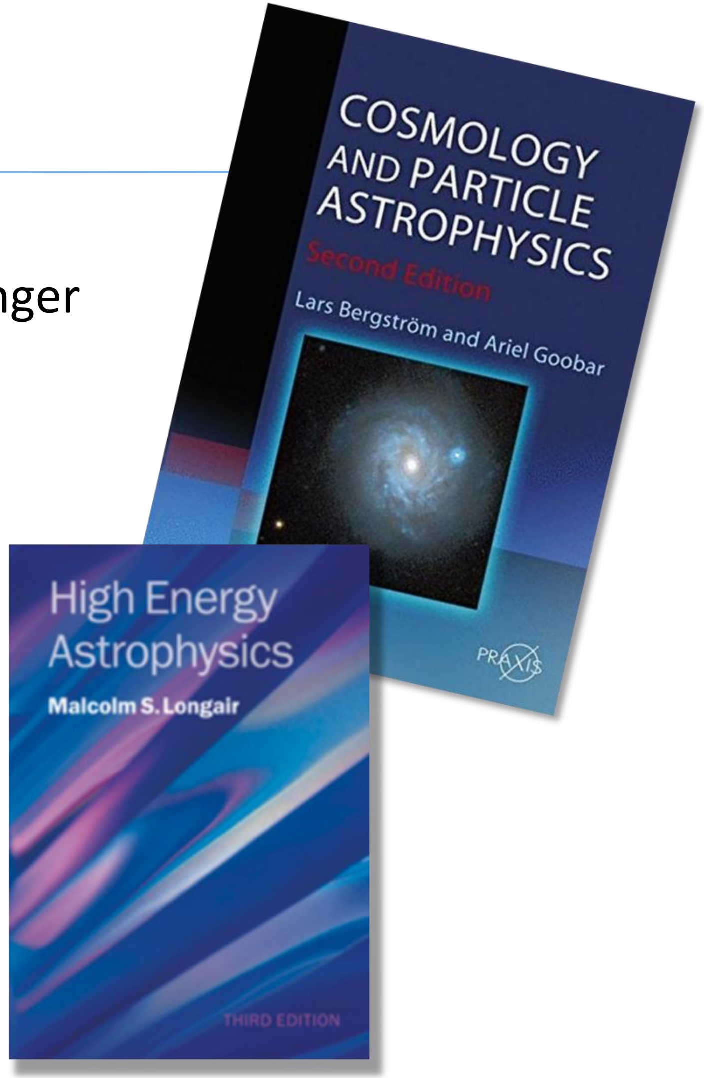
What’s the plan?

- Today’s lecture on telesccopes
- This afternoon a hands-on session
- A talk on the recent discovery with KM3NeT by Maarten on Wednesday

Literature

- L. Bergstrom and A. Goobar, “*Cosmology and Particle Astrophysics*”, Springer Verlag
- U. Katz and C. Spiering, “High-energy neutrino astrophysics: Status and perspectives”, arXiv:0801.4376
- M. Longair, *“High energy astrophysics”*, Cambridge University Press
- I. Bartos and M. Kowalski, “Multimessenger Astronomy”, IOP Publishing



Acknowledgements

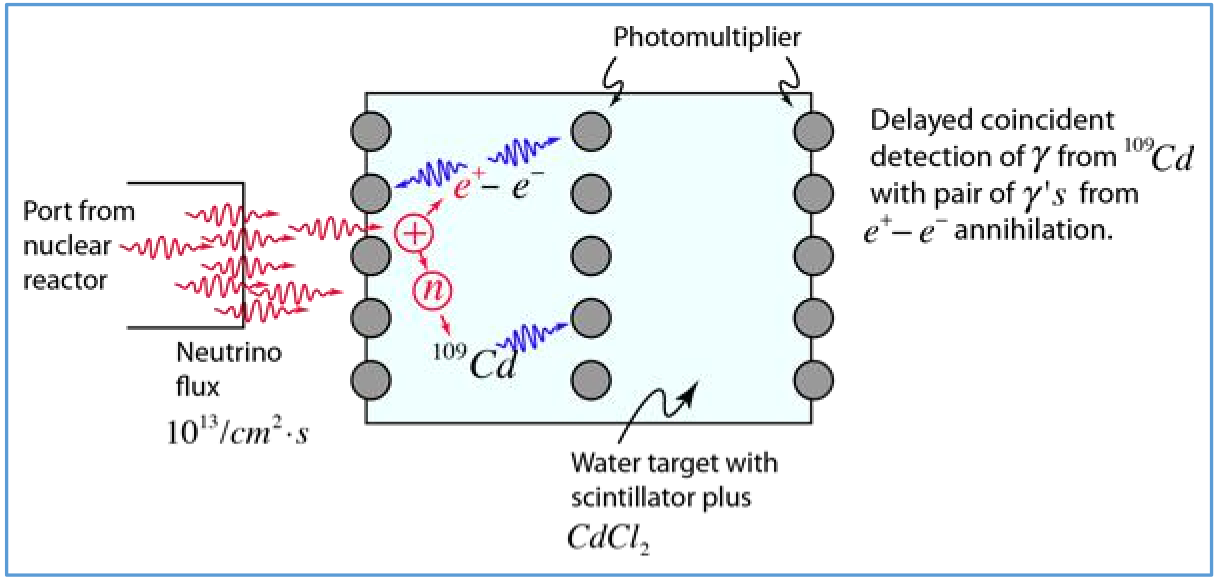
Maarten de Jong, Aart Heijboer, Carlos Argüelles, Rasa Muller, Daan van Eijk

Neutrino discovery

- Observation of neutrinos (*1956*) from nearby reactor through:

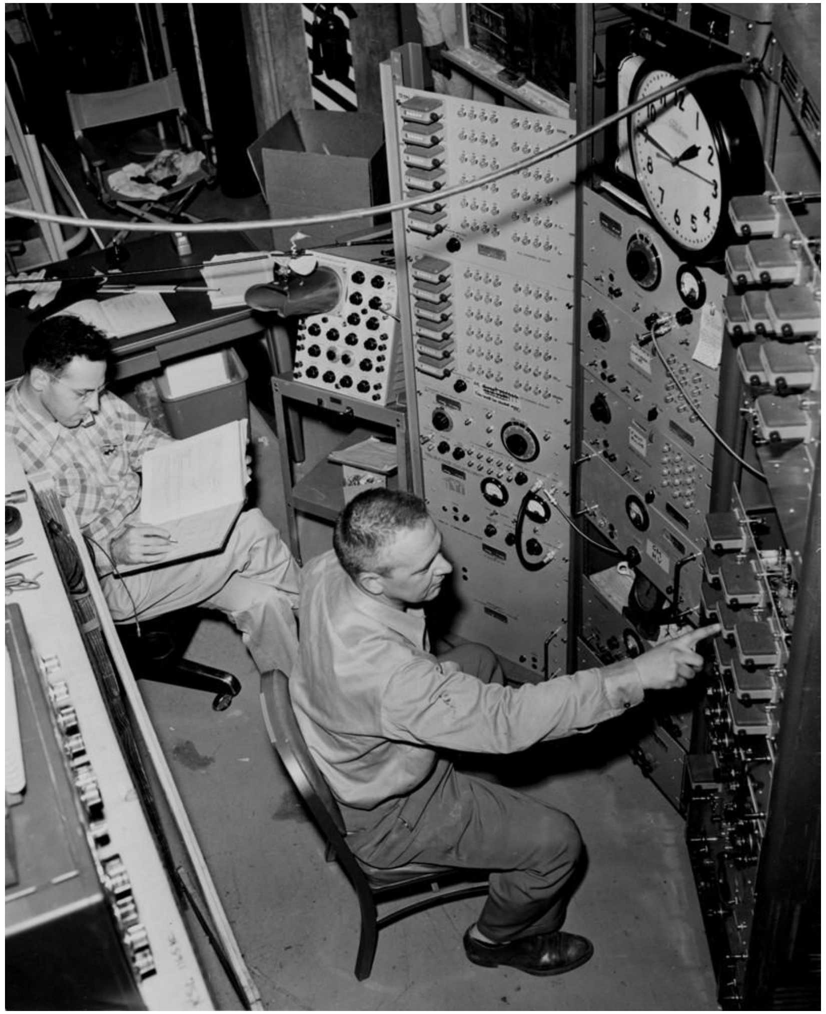
$$\bar{\nu}_e + p \rightarrow n + e^+$$

and $$n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$$



40 kg of $CdCl_2$

Los Alamos



8.B:9.A

Nuclear Physics **27** (1961) 385—394; © *North-Holland Publishing Co., Amsterdam*

ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

M. A. MARKOV and I. M. ZHELEZNYKH

P. N. Lebedev Physical Institute, Academy of Sciences, Moscow, USSR

Received 3 January 1961

Abstract: The paper is concerned with the problems of detecting high-energy cosmic neutrinos in underground experiments. Various kindred problems of high-energy neutrino physics are discussed, viz. (1) the magnitude of weak-interaction cut-off momentum, (2) muon and electron neutrinos and (3) intermediate boson. It is shown that a reasonable counting rate could be obtained with available equipment.

1. Introduction

Within a few years there will evidently appear a new branch of experimental physics — neutrino physics of medium and high energies — the results of which may prove fundamental in the elementary particle theory in general [1]).

8.B:9.A

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Search for a method to:

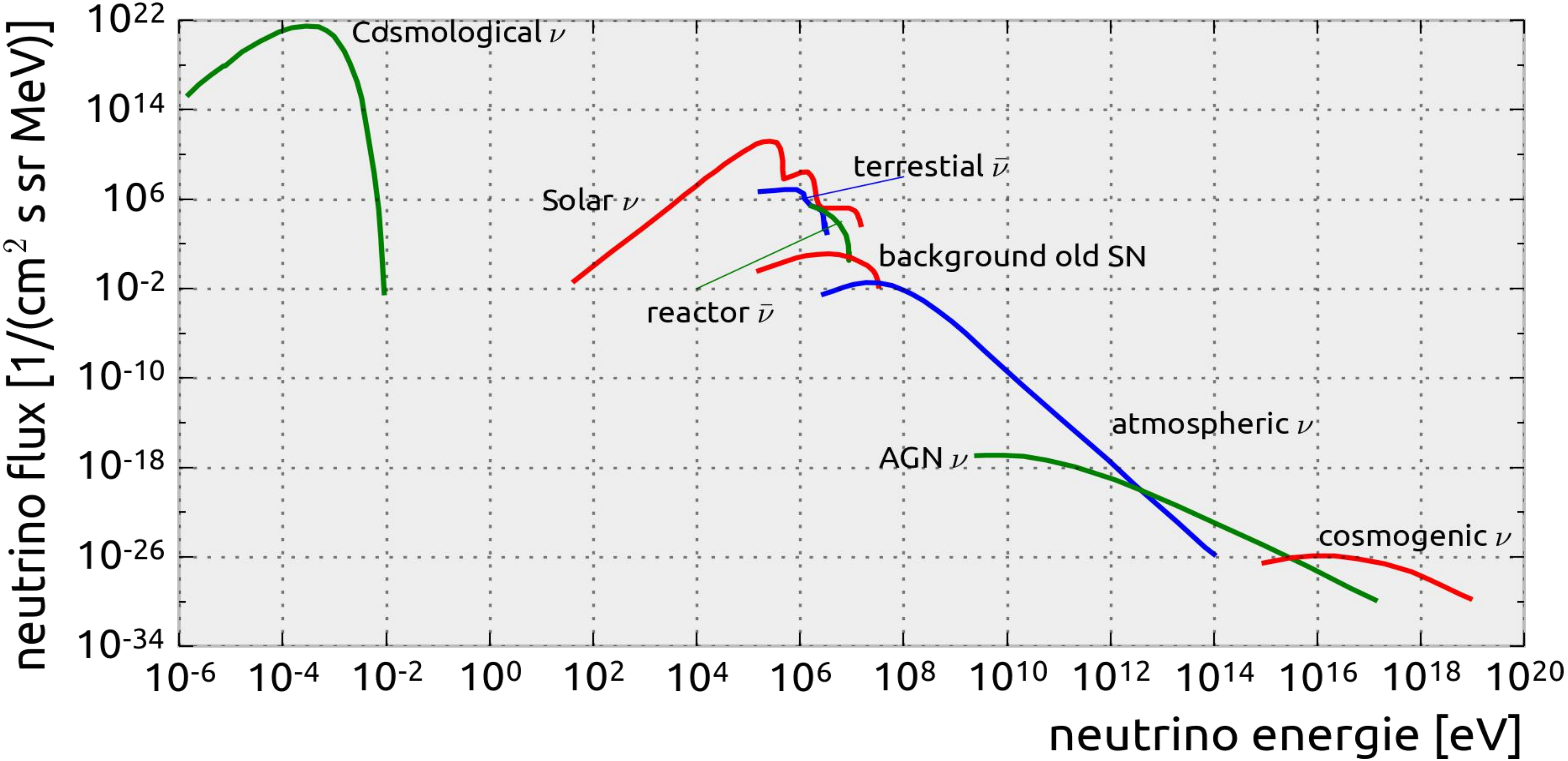
- investigate the existence of vector bosons
- to verify whether ν_e and ν_μ are different particles
- not (yet) interested in cosmic neutrinos

Wi

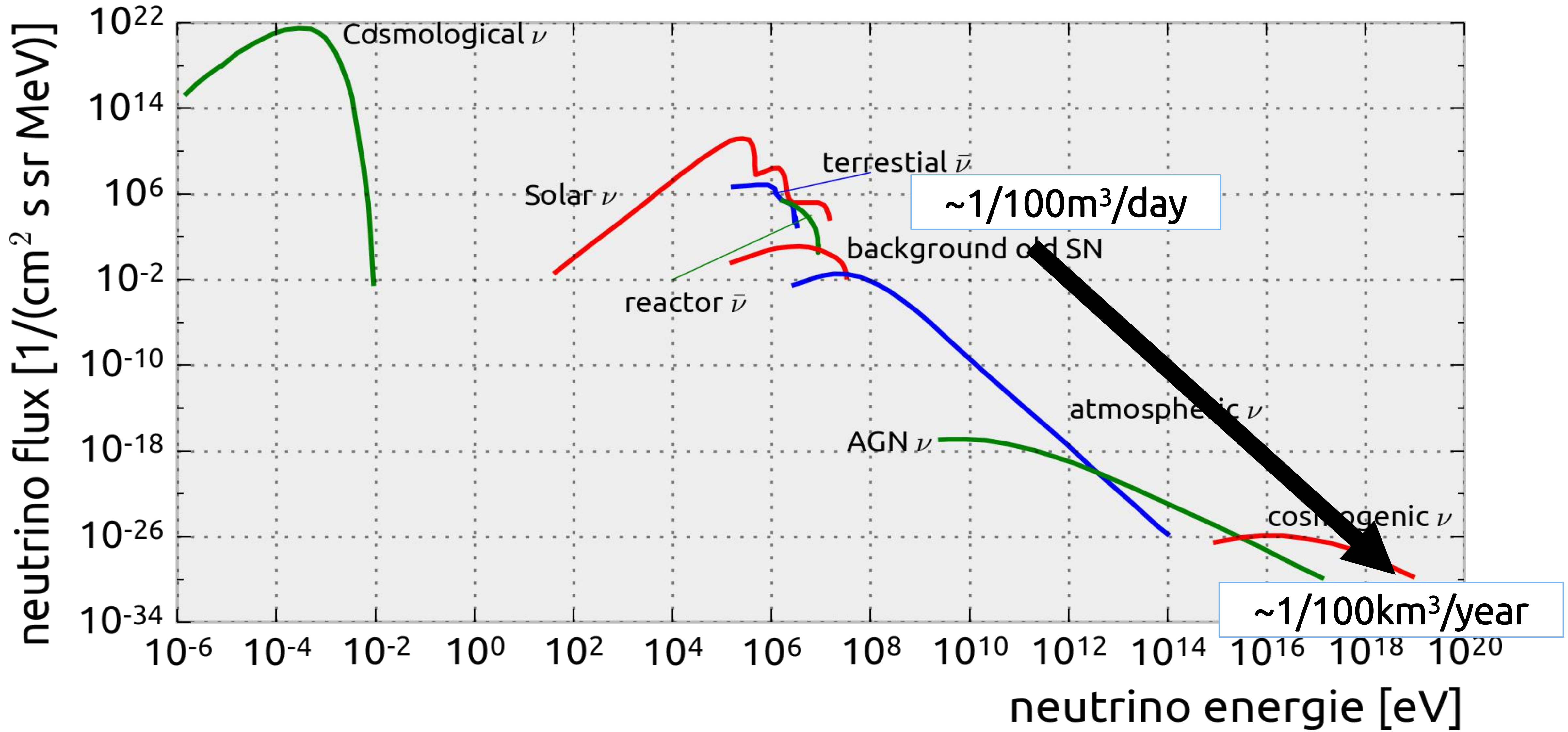
physi

which may prove fundamental in the elementary particle theory in general [1]).

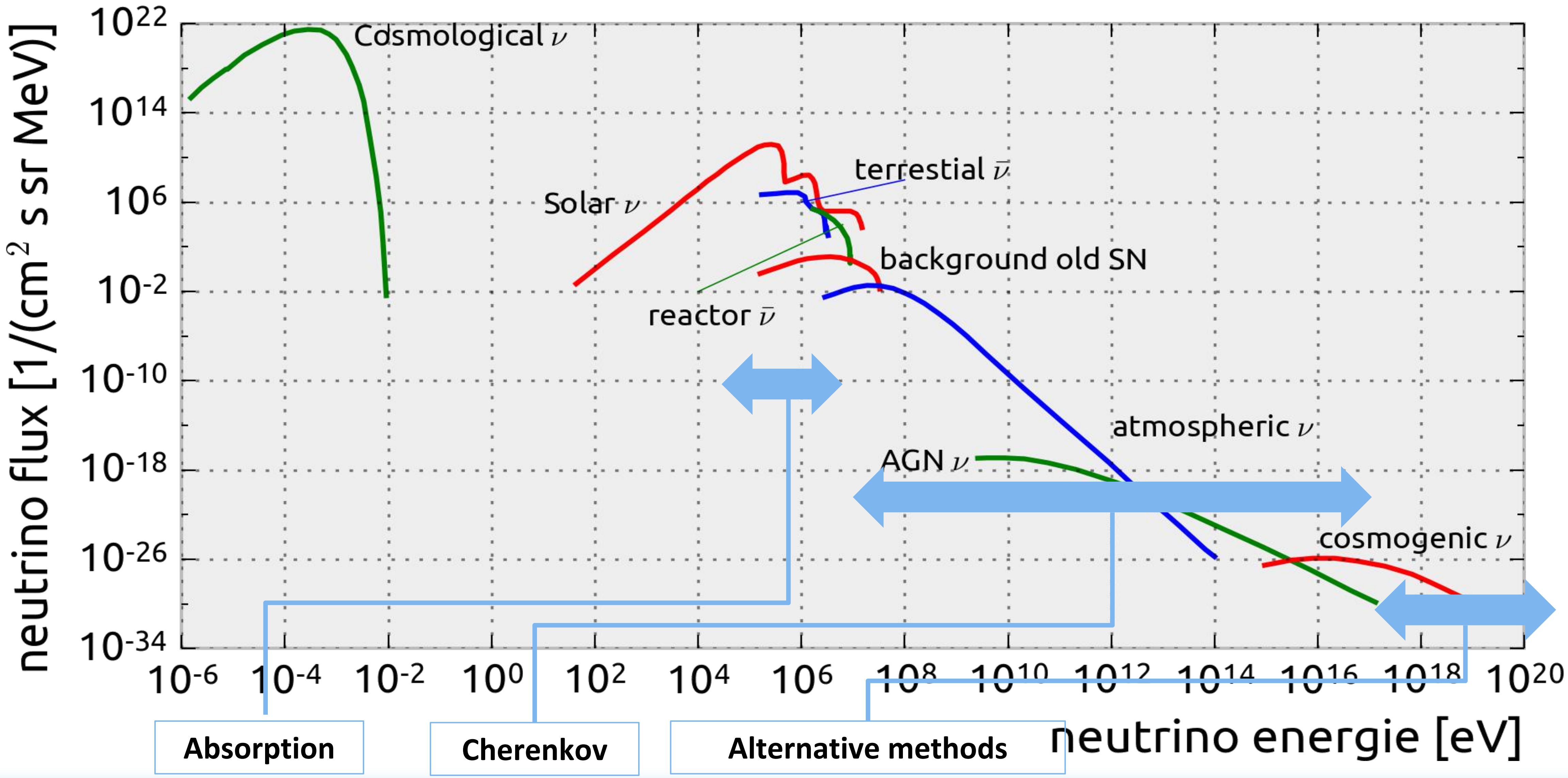
Neutrino sources and their fluxes



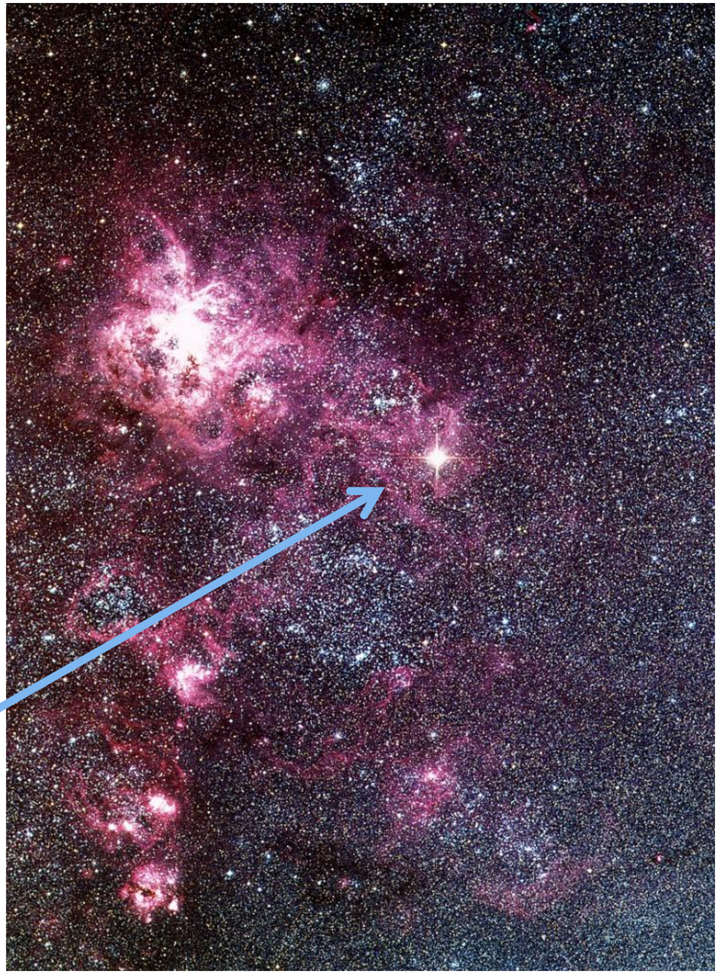
Neutrino sources and their fluxes



Neutrino sources and their fluxes

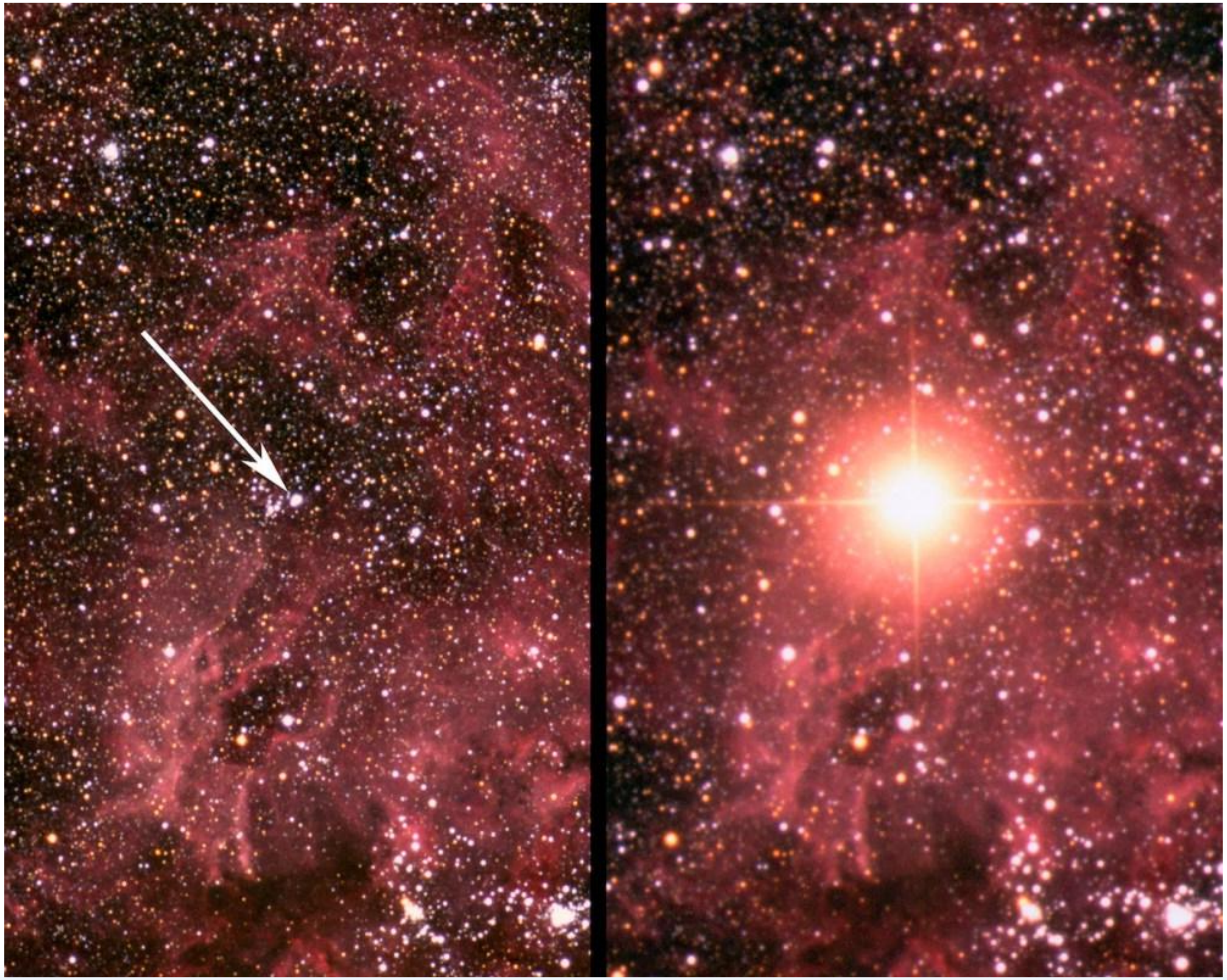


SN1987A in the Large Magellanic Cloud

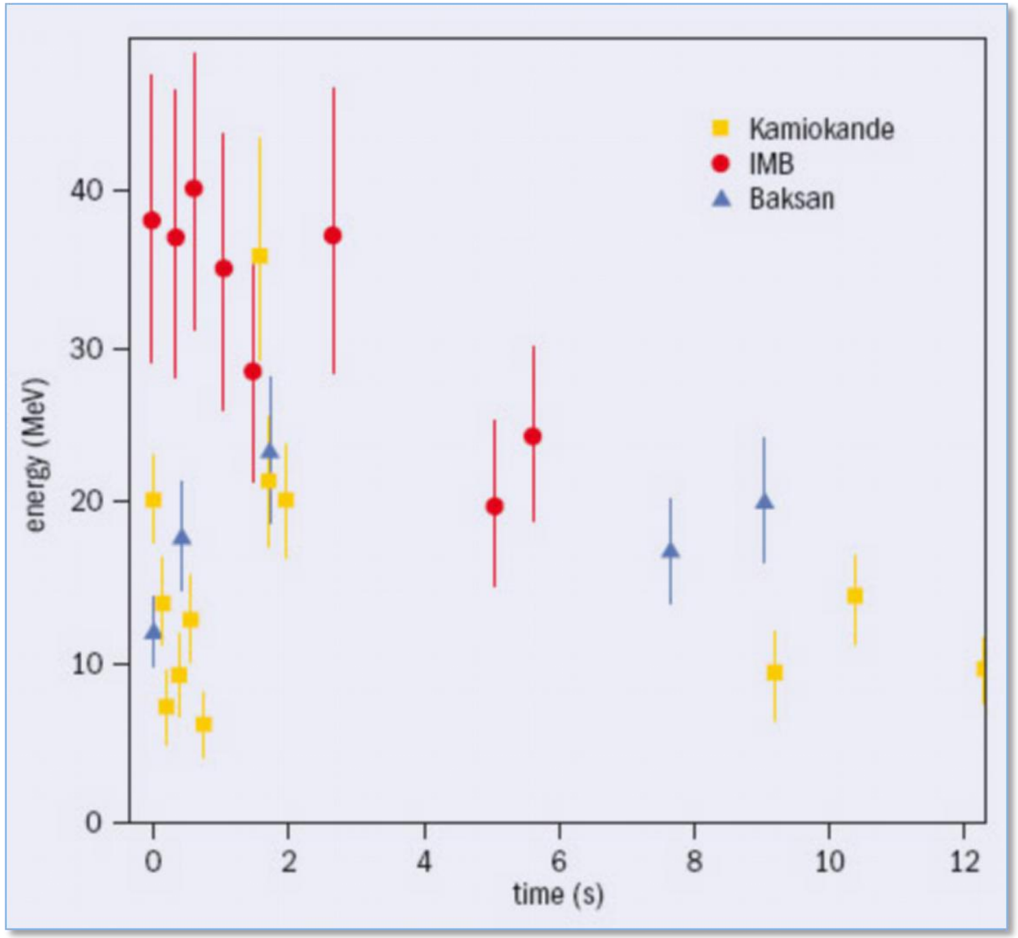


Februari 1987:
A bright spot near the Tarantula nebula!

SN1987A in the Large Magellanic Cloud

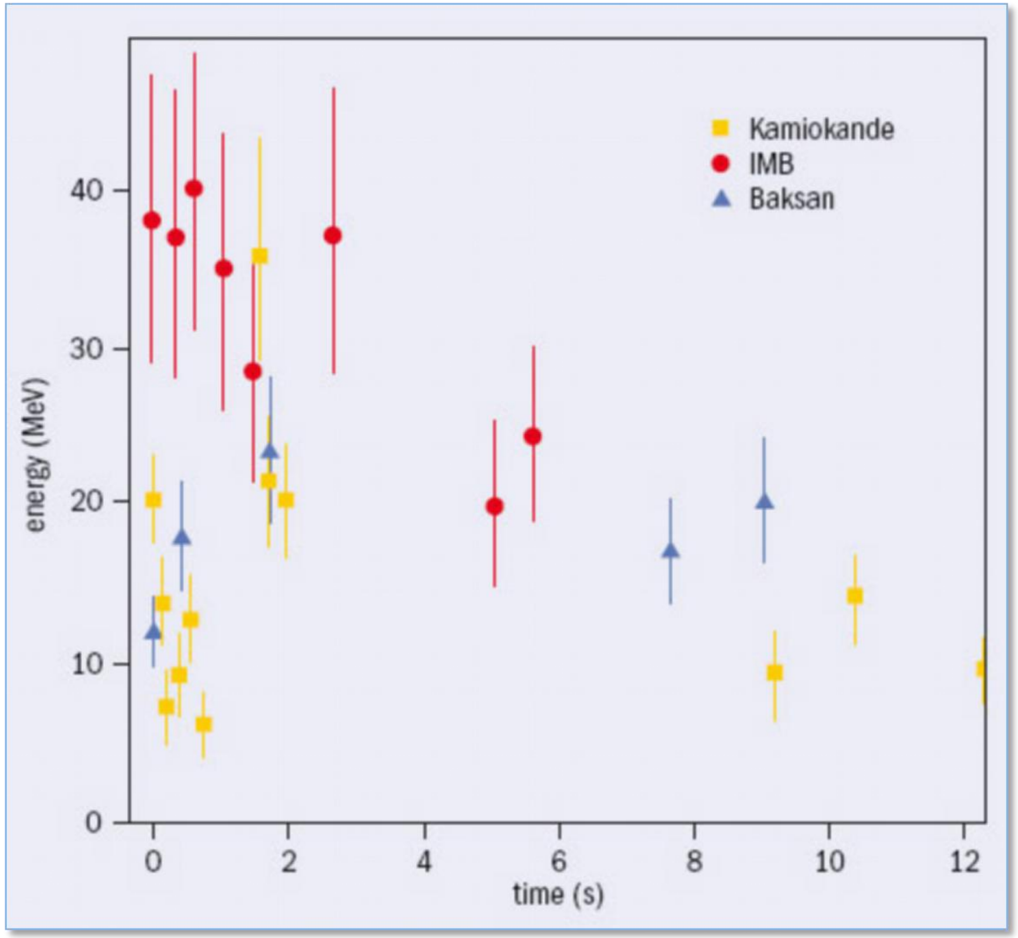


SN1987A: neutrino observations



- Supernova explosion in 1987
  in Large Magellanic Cloud
- First supernova visible by eye since 1604
- Second known cosmic neutrino source
- 25 neutrino events recorded
  by Kamiokande and IMB experiments
- Both time of arrival and energy have been recorded
- Assume all neutrinos created at the same time

SN1987A: neutrino observations



$$E_A = \gamma_A mc^2$$
$$E_B = \gamma_B mc^2$$

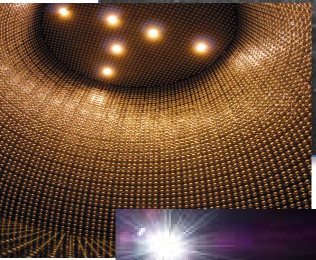
$$\Delta t = t_B - t_A = \frac{1}{2}\frac{D}{c}\left(\frac{1}{\gamma_B^2} - \frac{1}{\gamma_A^2}\right)$$

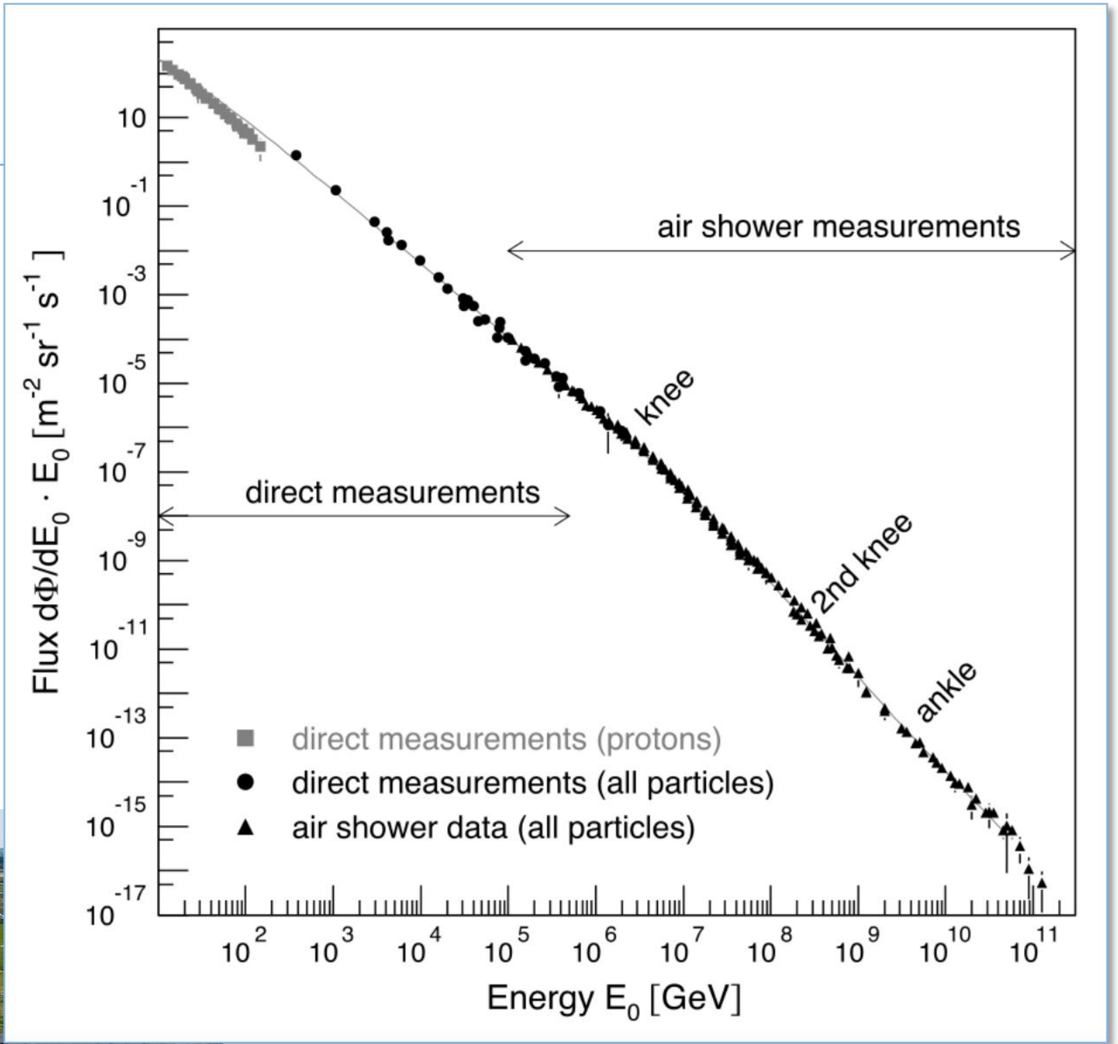
Difference between the time of arrival of high and low energetic neutrinos:

$m_\nu < 26$ eV

Assume D (distance) to supernova is known and that all neutrinos are produced at t_o

What is the origin of cosmic rays?



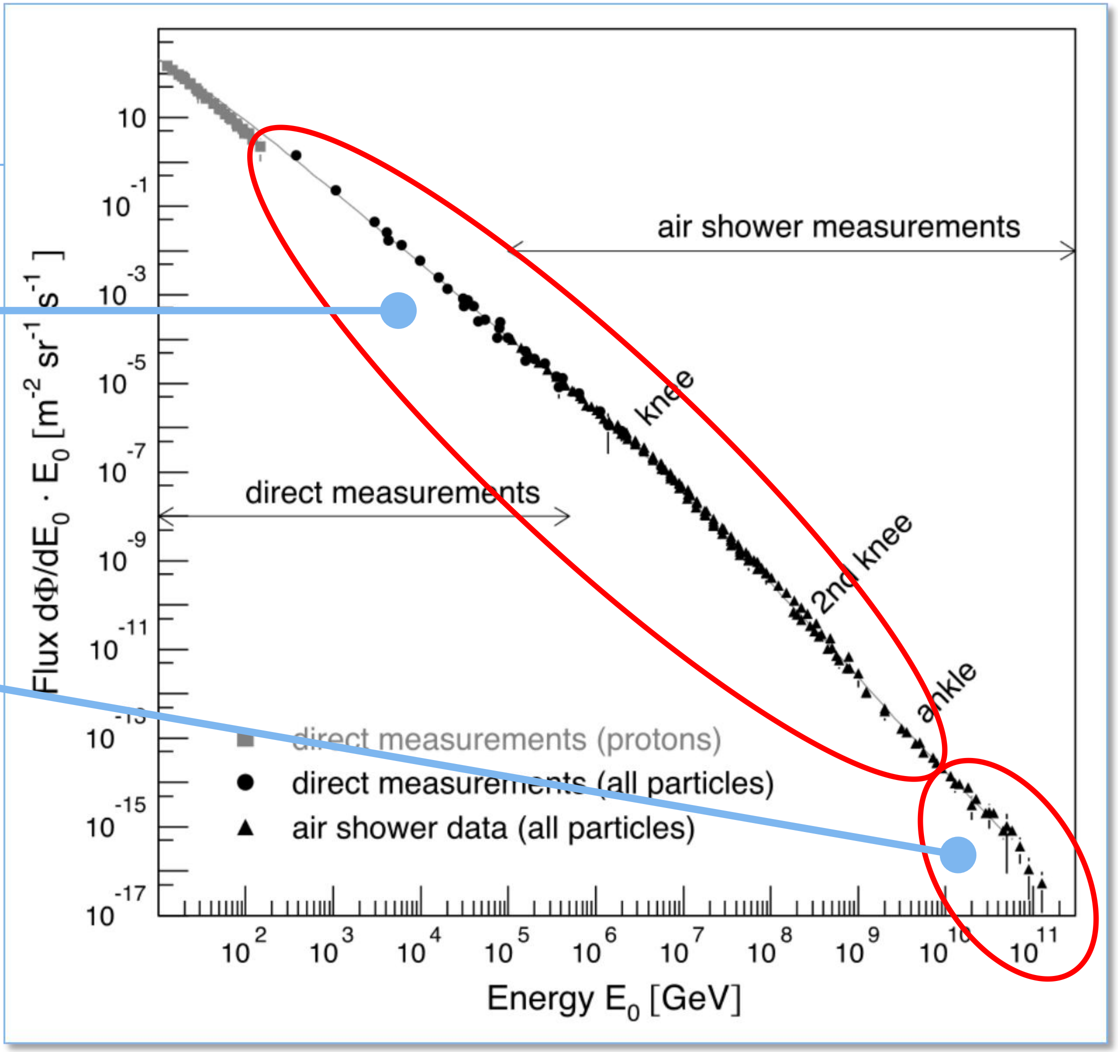


CR flux: $\Phi \sim E^{-\gamma}$

Spectral index $\gamma \epsilon [2.5, 5]$

What is the origin of cosmic rays?

- Potential **galactic** sources
  - Supernova remnants
- Potential **extragalactic** sources
  - Active galactic nuclei (AGNs)
  - Gamma ray bursts (GRB)
- Exotics:
  - Dark matter decay and annihilation

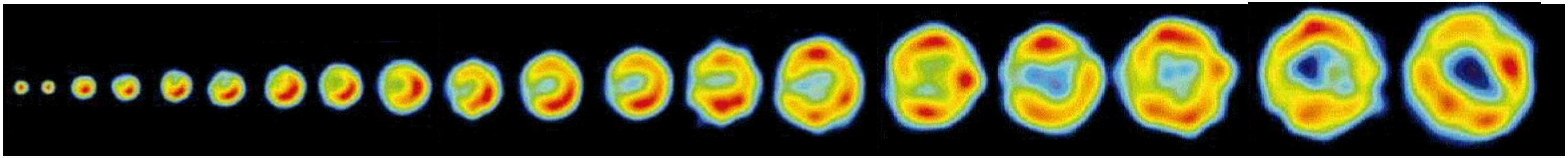


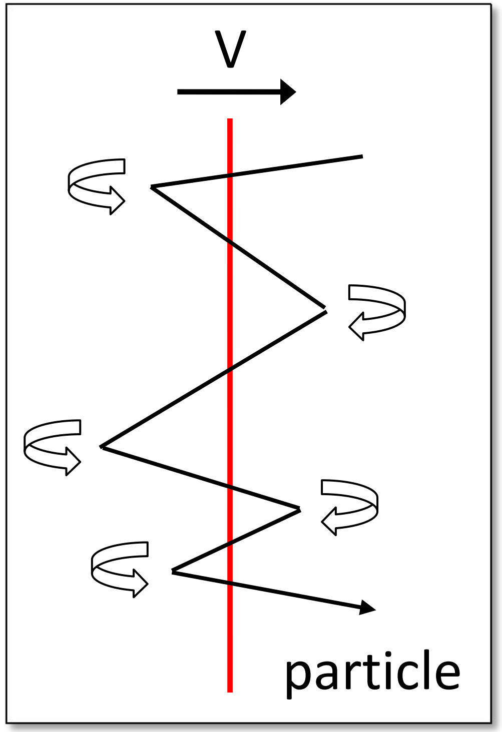
CR flux: $\Phi \sim E^{-\gamma}$

Spectral index $\gamma \in [2.5, 5]$

Fermi shock acceleration

Radio maps SN1993J – M81 April 1993–June 1998





Acceleration $\Delta E = \alpha E$

Probability β

k steps $E = E_0(1+\alpha)^k$

$N = N_0(\beta)^k$

Solve for k

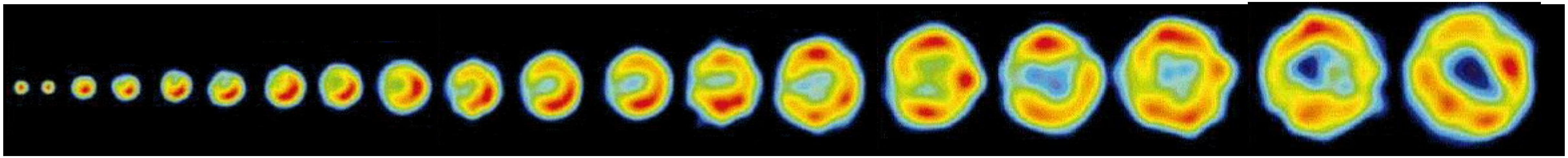
$$\frac{\ln(N/N_0)}{\ln(E/E_0)} = \frac{\ln(\beta)}{\ln(1+\alpha)}$$

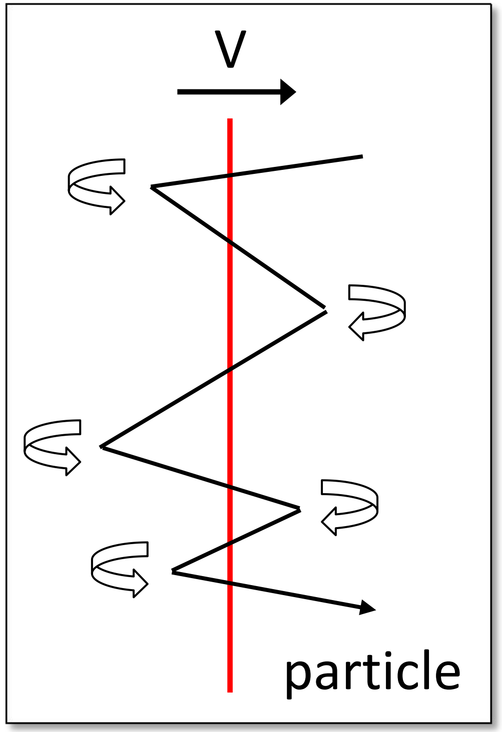
$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\frac{\ln(\beta)}{\ln(1+\alpha)}}$$

$$\frac{dN}{dE} \propto E^{\frac{\ln(\beta)}{\ln(1+\alpha)}-1}$$

Fermi shock acceleration

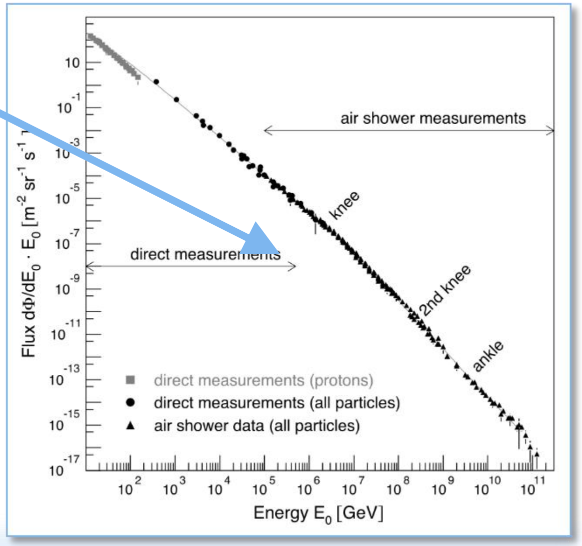
Radio maps SN1993J – M81 April 1993–June 1998





$$\frac{dN}{dE} \propto E^{\frac{\ln(\beta)}{\ln(1+\alpha)}-1} = E^{-2}$$

?



The gamma-ray - neutrino connection

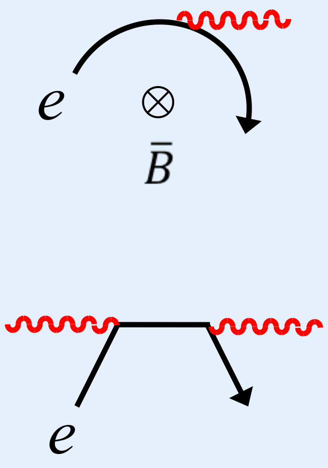
Gamma-ray production:

Both electromagnetic and hadronic processes

electro-magnetic

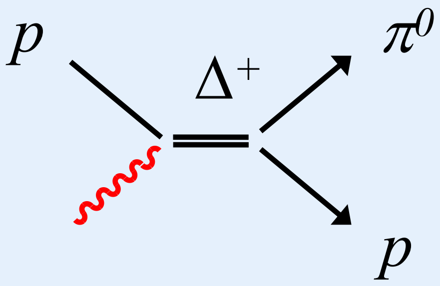
Synchrotron radiation

inverse Compton scattering



gamma rays

hadronic



$\pi^0 \longrightarrow \gamma\gamma$

gamma rays

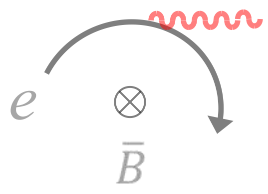
The gamma-ray - neutrino connection

Neutrino production:

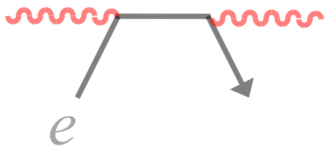
hadronic processes dominant

electro-magnetic

Synchrotron radiation

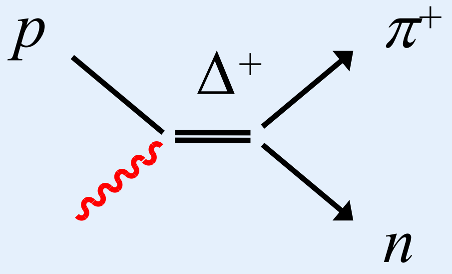


inverse Compton scattering



gamma rays

hadronic



$$\pi^\pm \longrightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$$

$$\mu^\pm \longrightarrow e^\pm + \bar{\nu}_\mu/\nu_\mu + \nu_e/\bar{\nu}_e$$

neutrinos

The gamma-ray - neutrino connection

Electromagnetic processes:

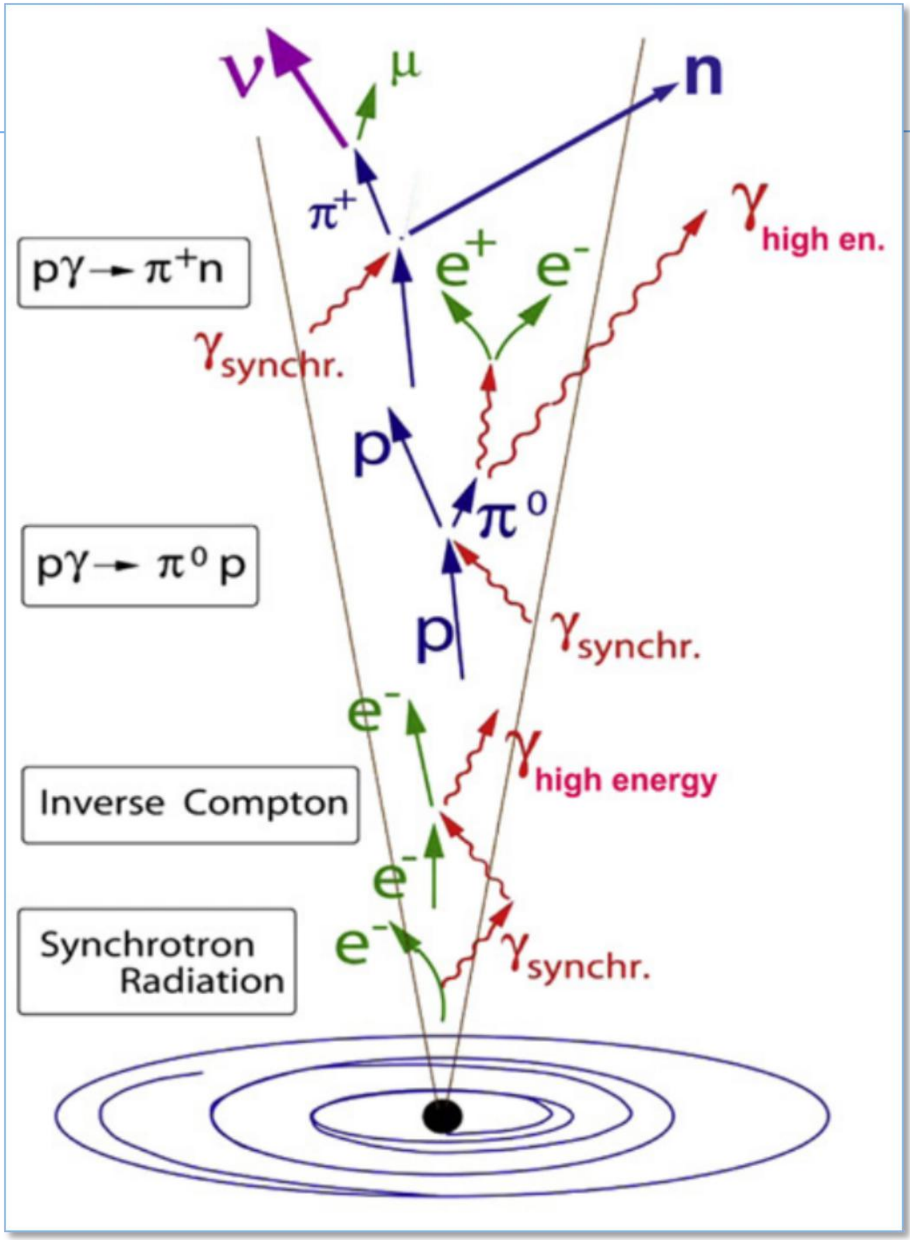
- synchrotron radiation
- inverse compton scattering

$$e^- + \gamma_{\text{low energy}} \rightarrow e^- + \gamma_{\text{high energy}}.$$

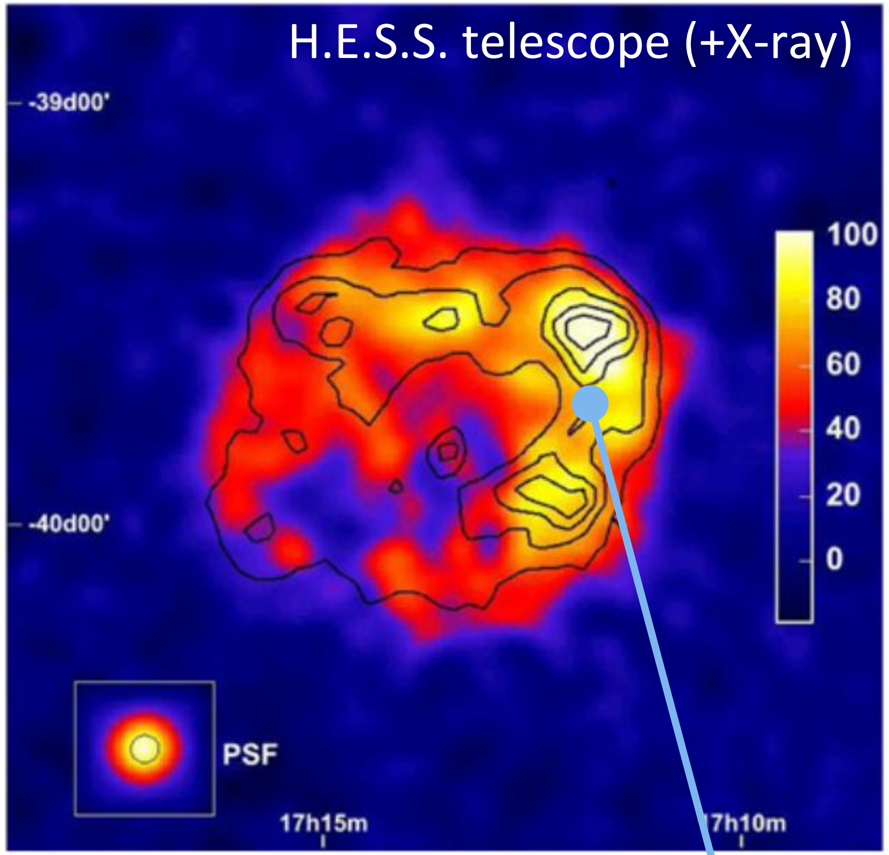
Hadronic reactions:

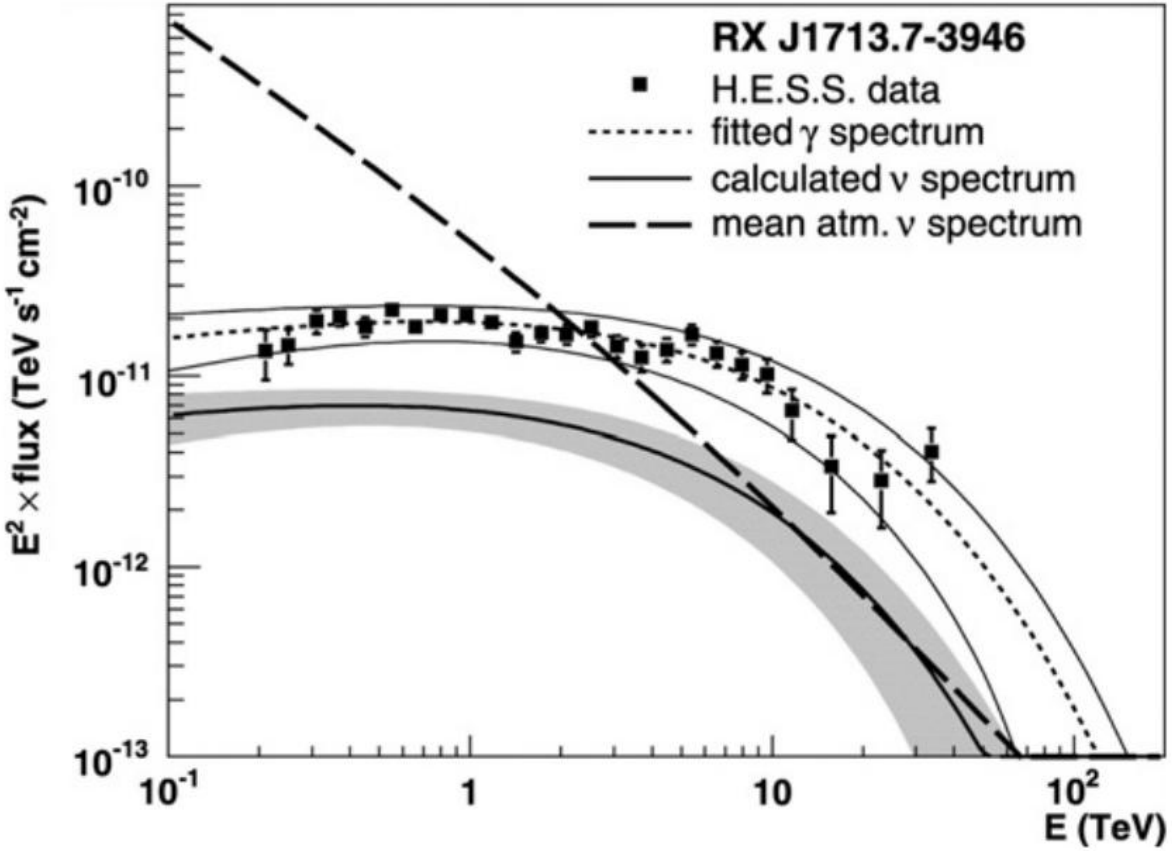
$$p + \text{nucleus} \rightarrow \pi + X \quad (\pi = \pi^{\pm}, \pi^0)$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^0 + p \\ \pi^+ + n, \end{cases}$$



Gamma rays from SNR RX J1713.7-3946



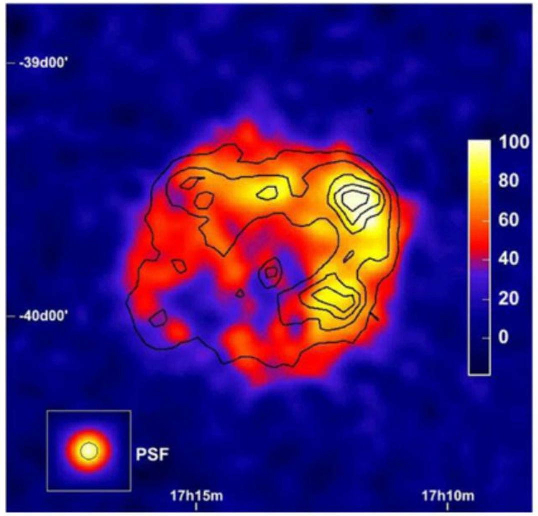


Observed gamma-rays compatible with pion π⁰ decay when accelerated protons interact with the molecular clouds

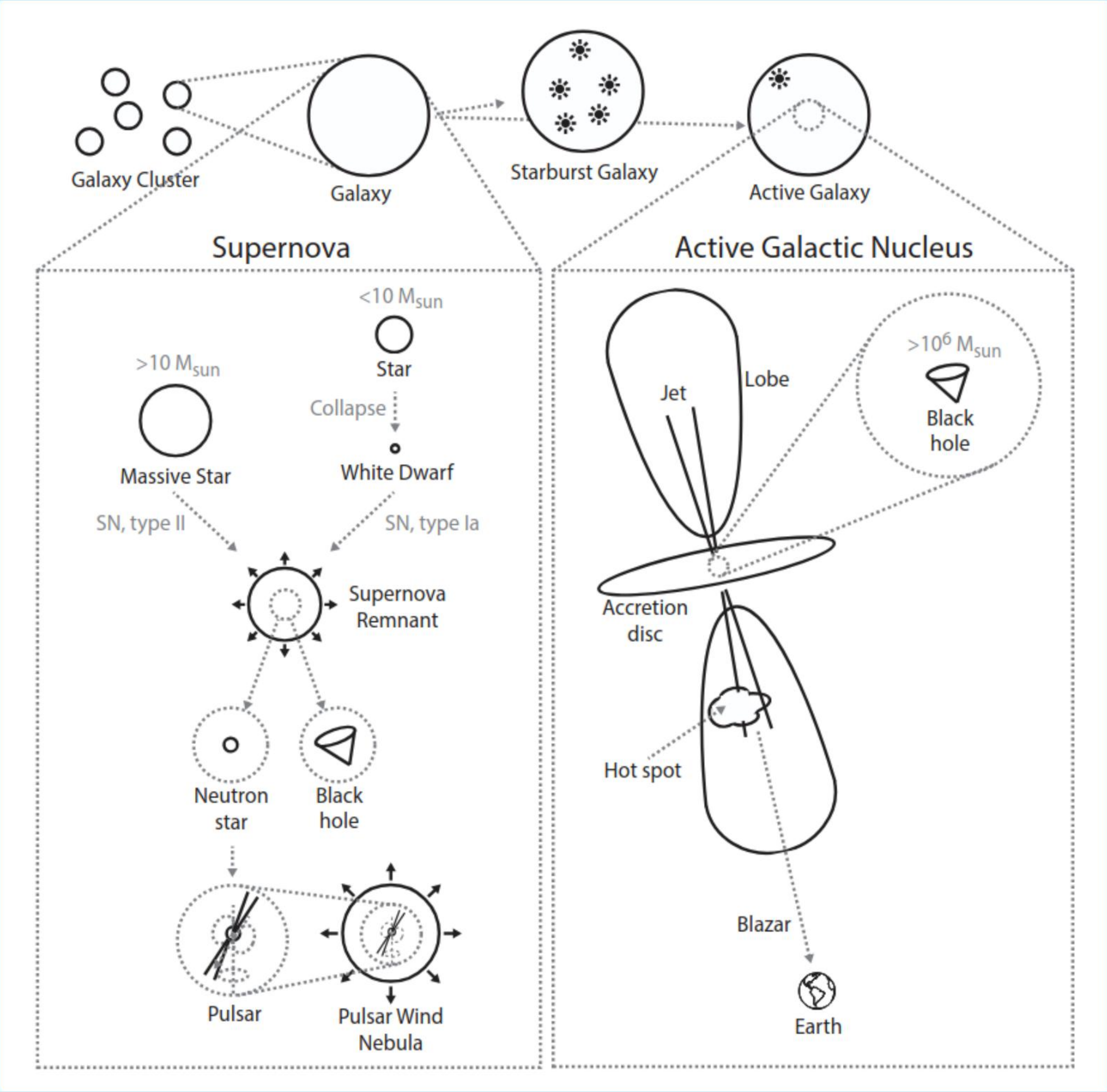
$$p + \text{nucleus} \rightarrow \pi + X \quad (\pi = \pi^{\pm}, \pi^0)$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^0 + p \\ \pi^+ + n, \end{cases}$$

Sites



RX J1713.7-3946



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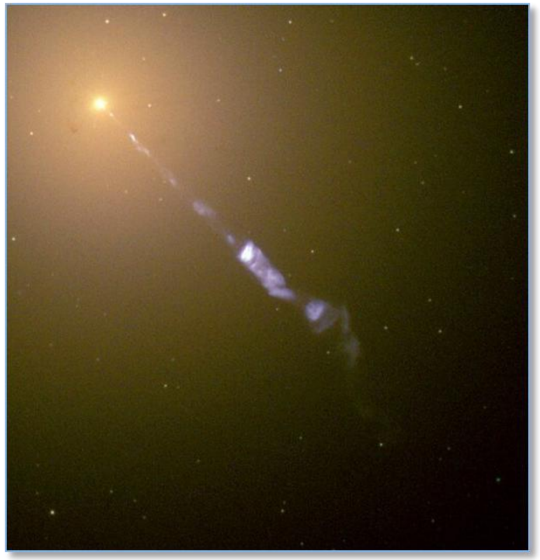
M87



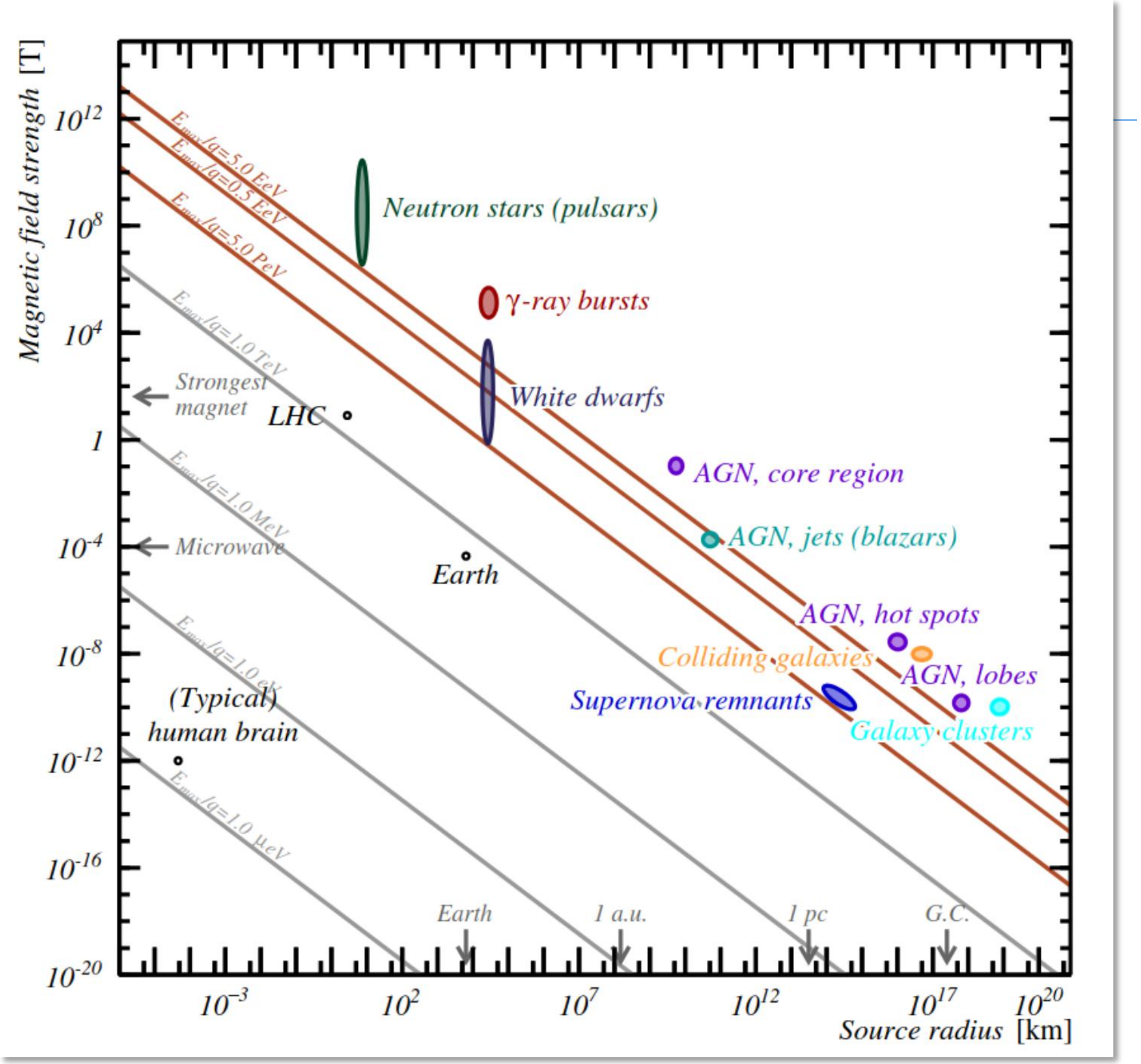
Sites

Hillas argument:
The Larmor orbit of accelerated particles has to fit inside the object

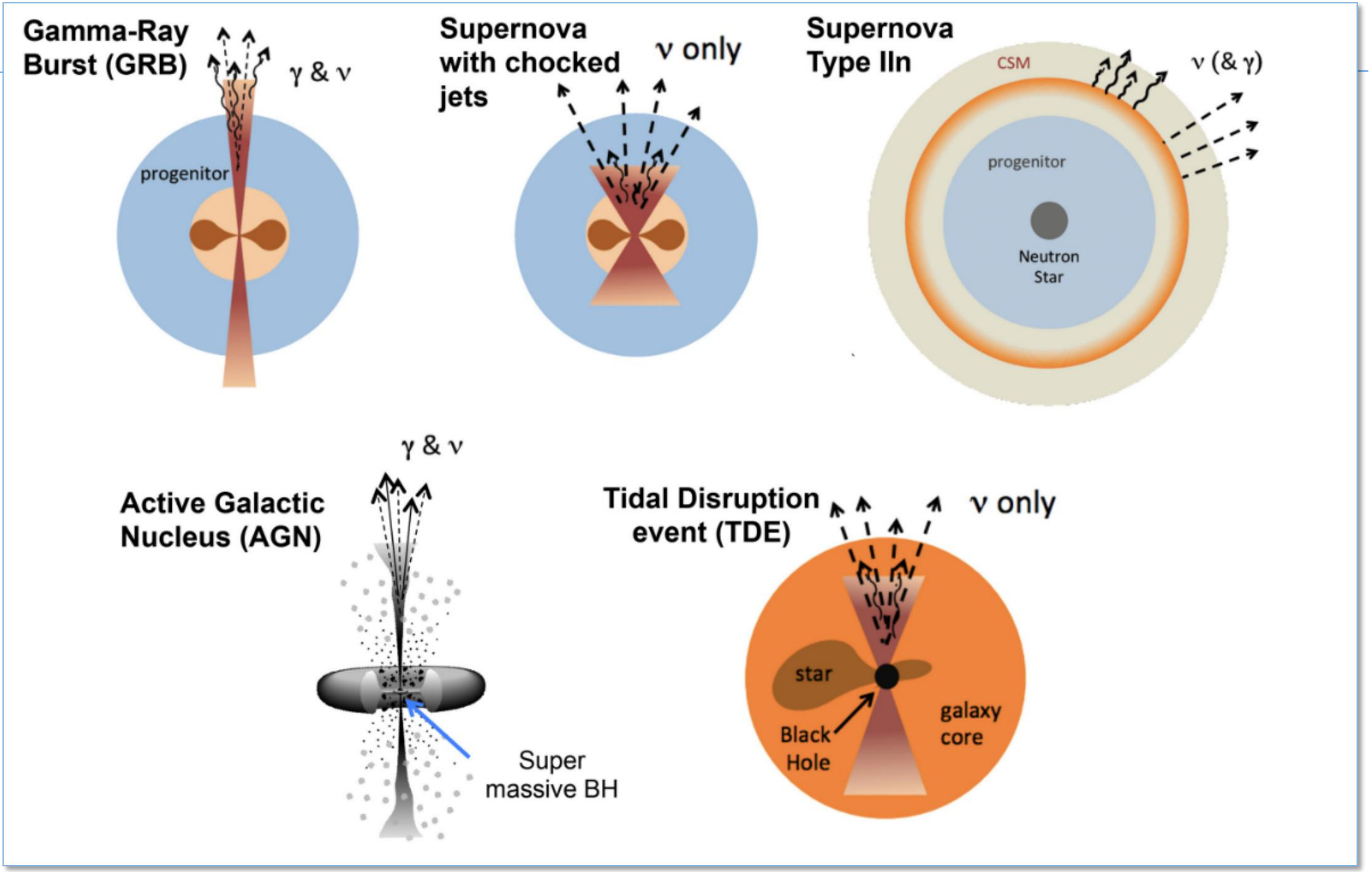
Larmor orbit:

$$R_L = \frac{E}{ZeB}$$

$$E_{max} = ZeBR_L$$



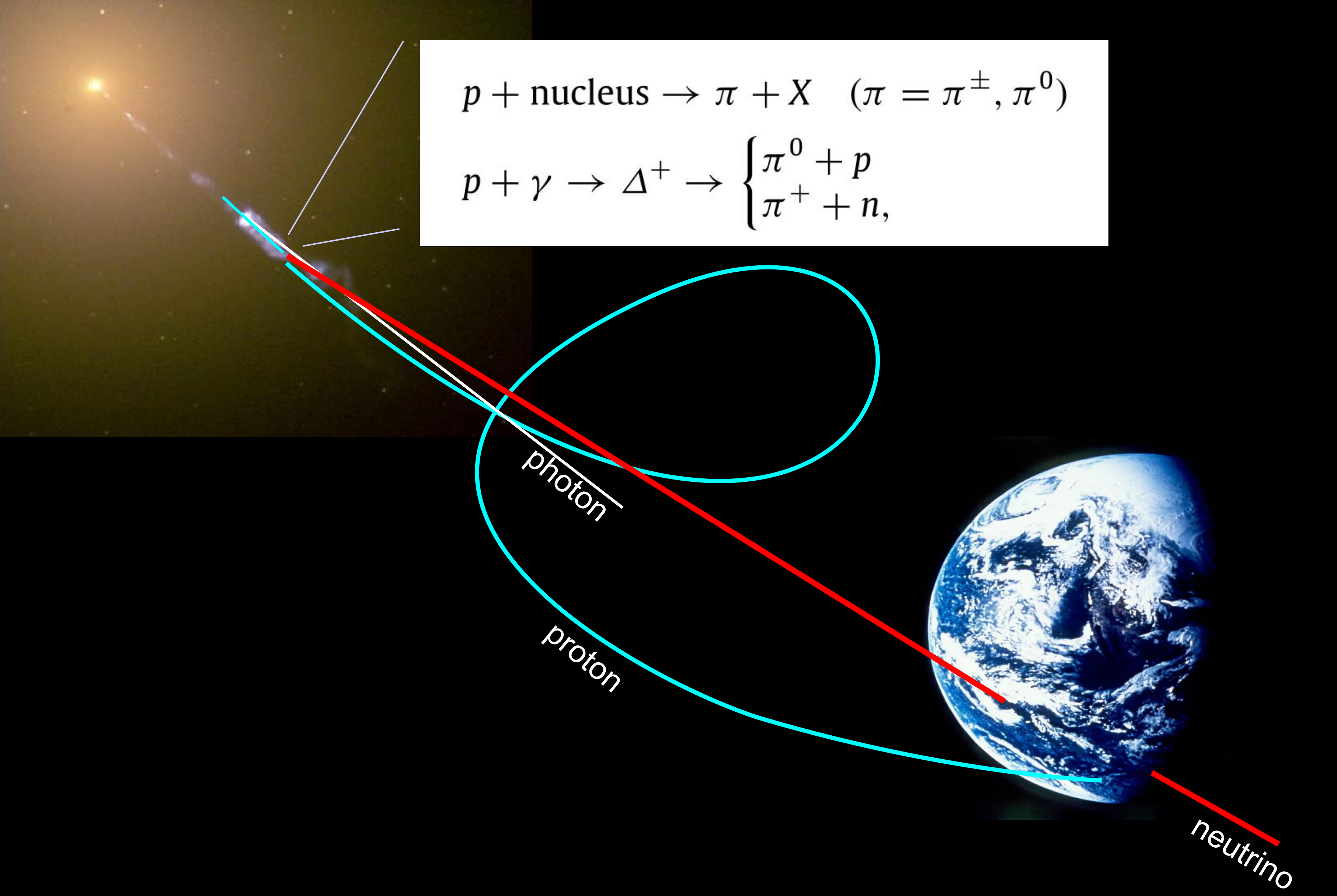
Summary



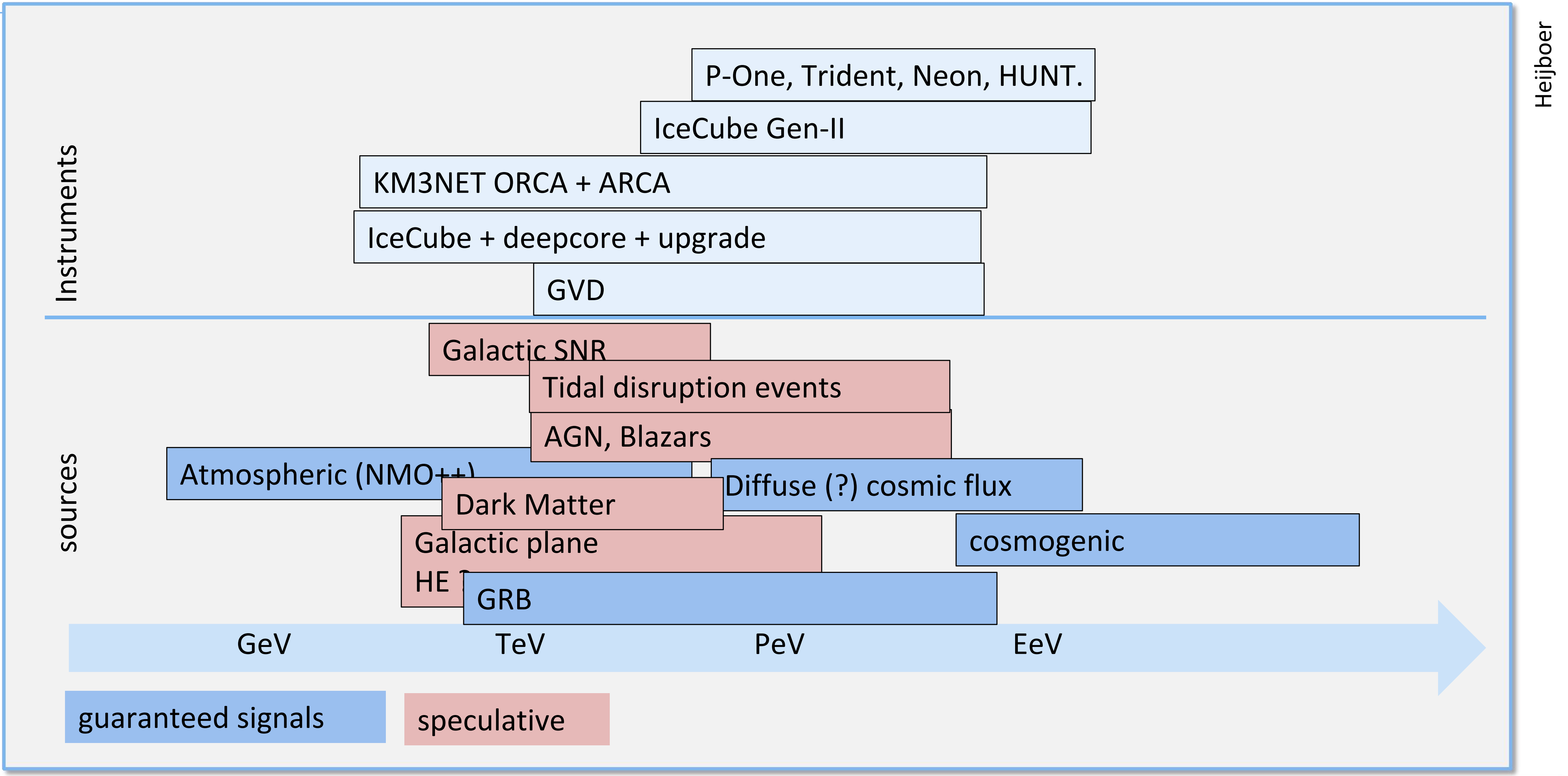
Bartos, Kowalski

$$p + \text{nucleus} \rightarrow \pi + X \quad (\pi = \pi^{\pm}, \pi^{0})$$

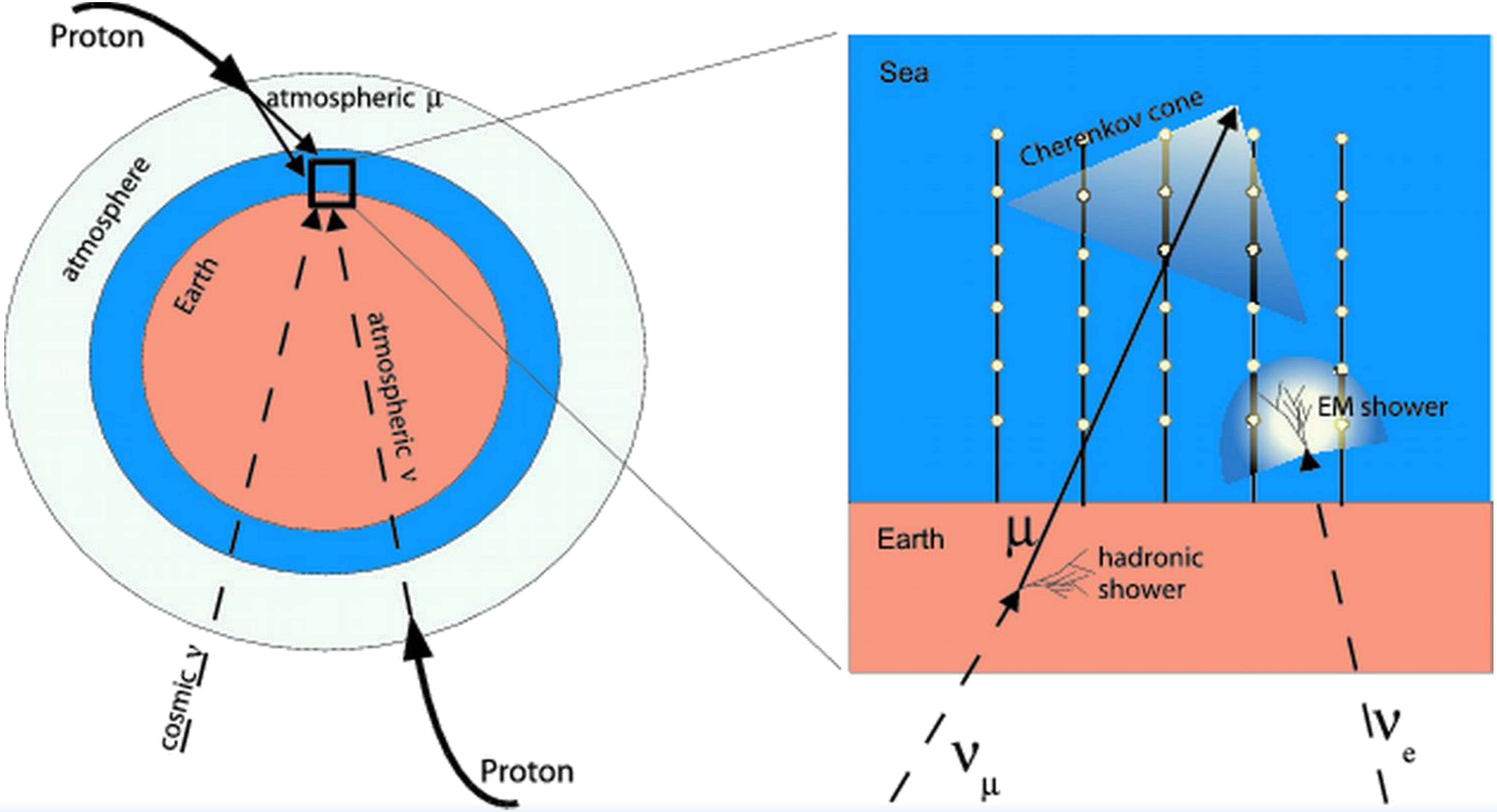
$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} \pi^{0} + p \\ \pi^{+} + n, \end{cases}$$



The cosmic neutrino landscape

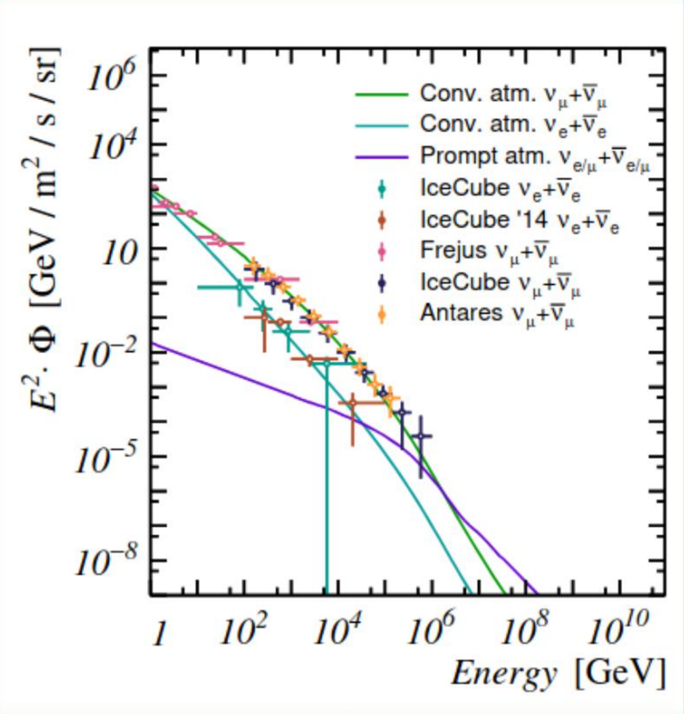


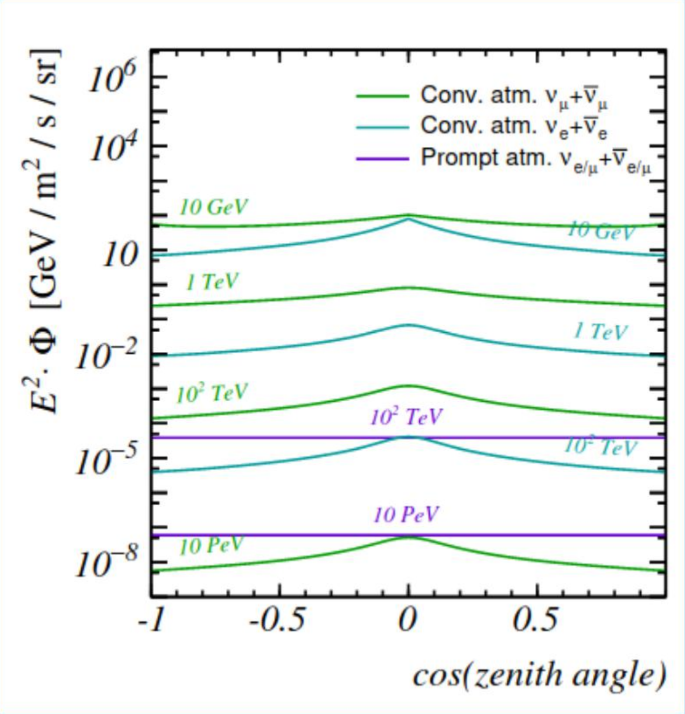
Neutrino telescope concept



Atmospheric neutrinos

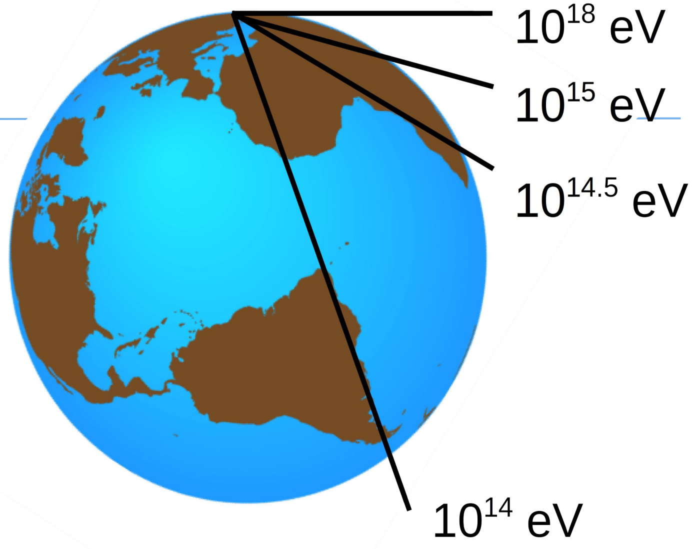
- Conventional neutrinos: Decay of pions and kaons. Neutrino flavour ratio: ν_e : ν_μ : ν_τ
- Prompt neutrinos

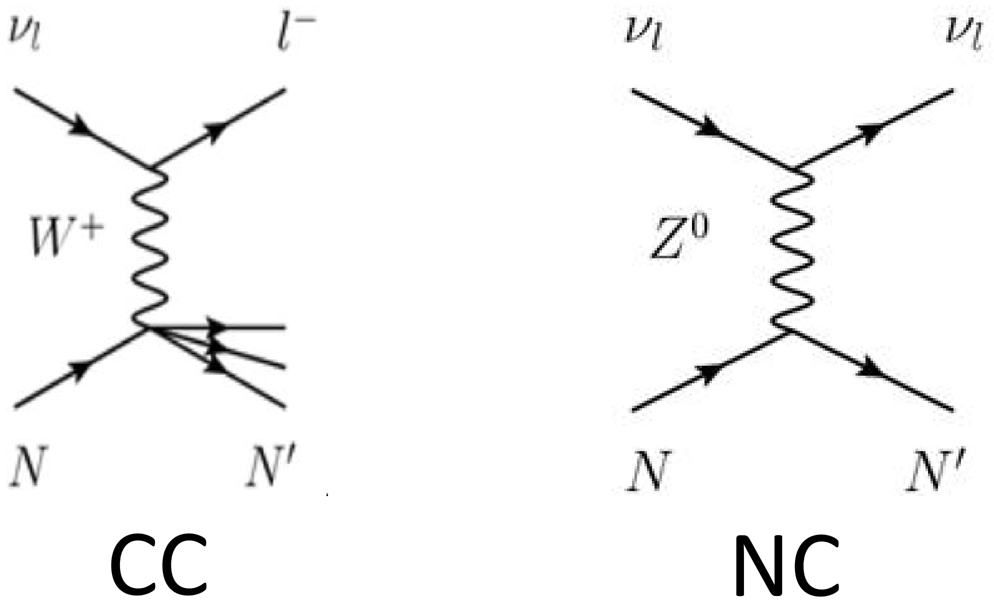


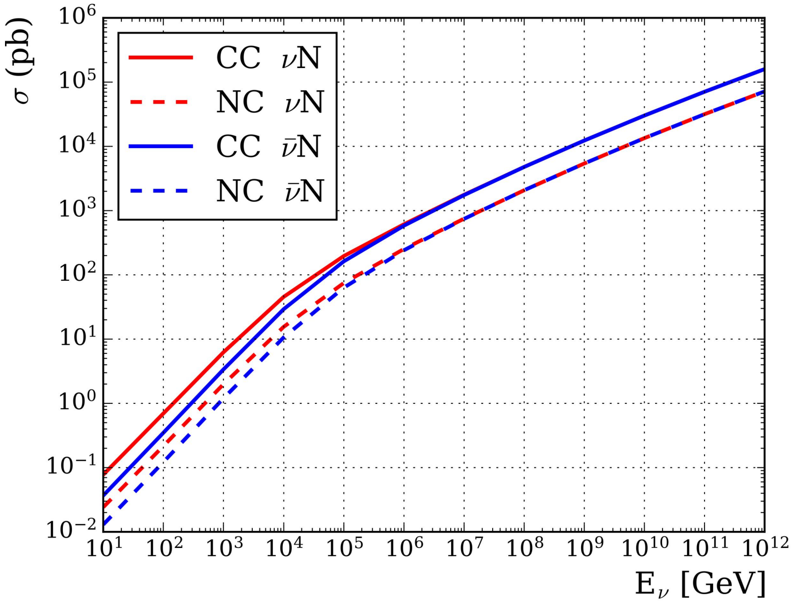


Neutrino interactions in water

- Both neutral and charge current interactions.
- Cross section increases with energy
  - Expect UHE neutrinos skimming or from zenith.

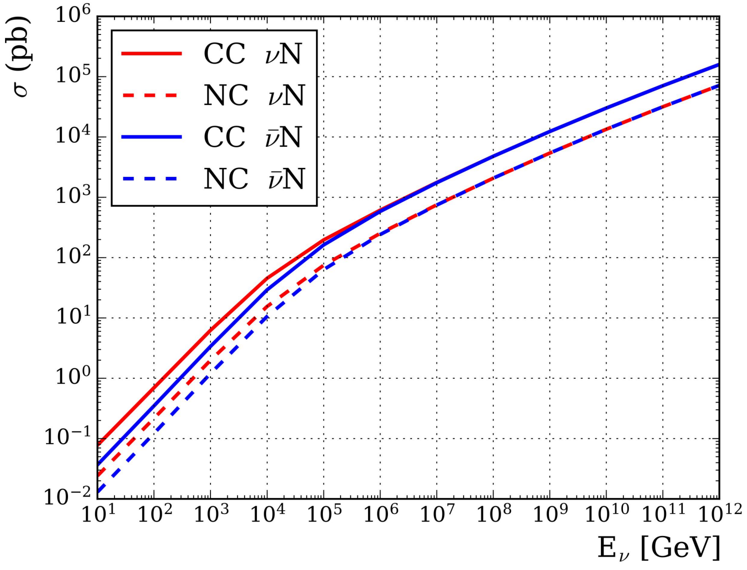


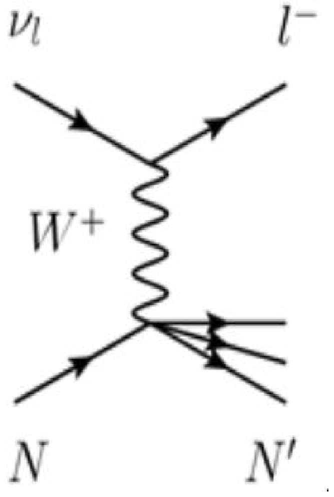




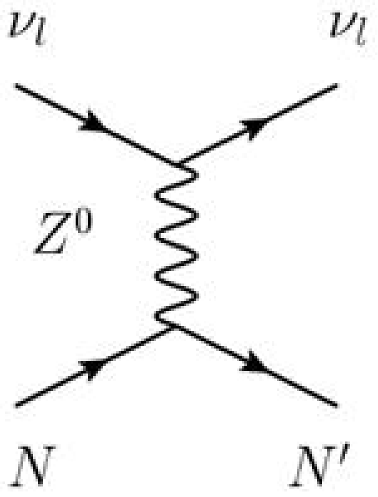
Neutrino interactions in water

In the high energy limit the Bjorken-y factor approaches 0.2.
A fraction (1 − y) of the initial energy E_ν of the neutrino will be carried by the lepton after the reaction, the rest is transferred to the nucleon.

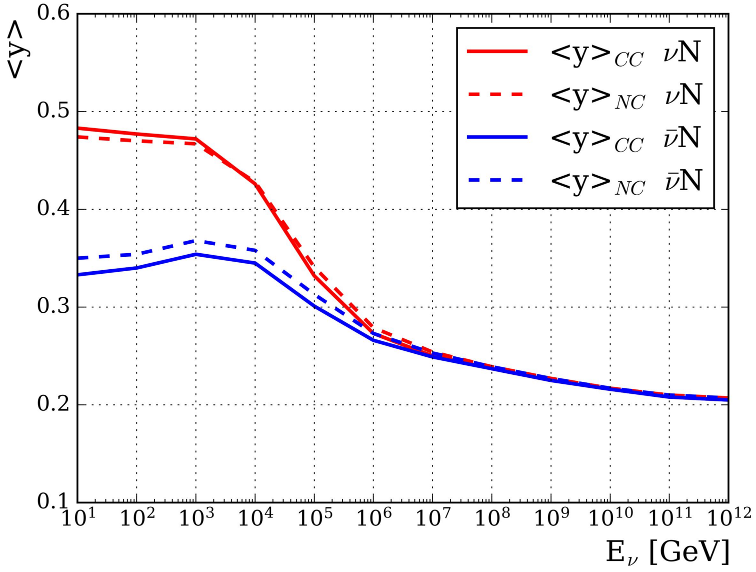




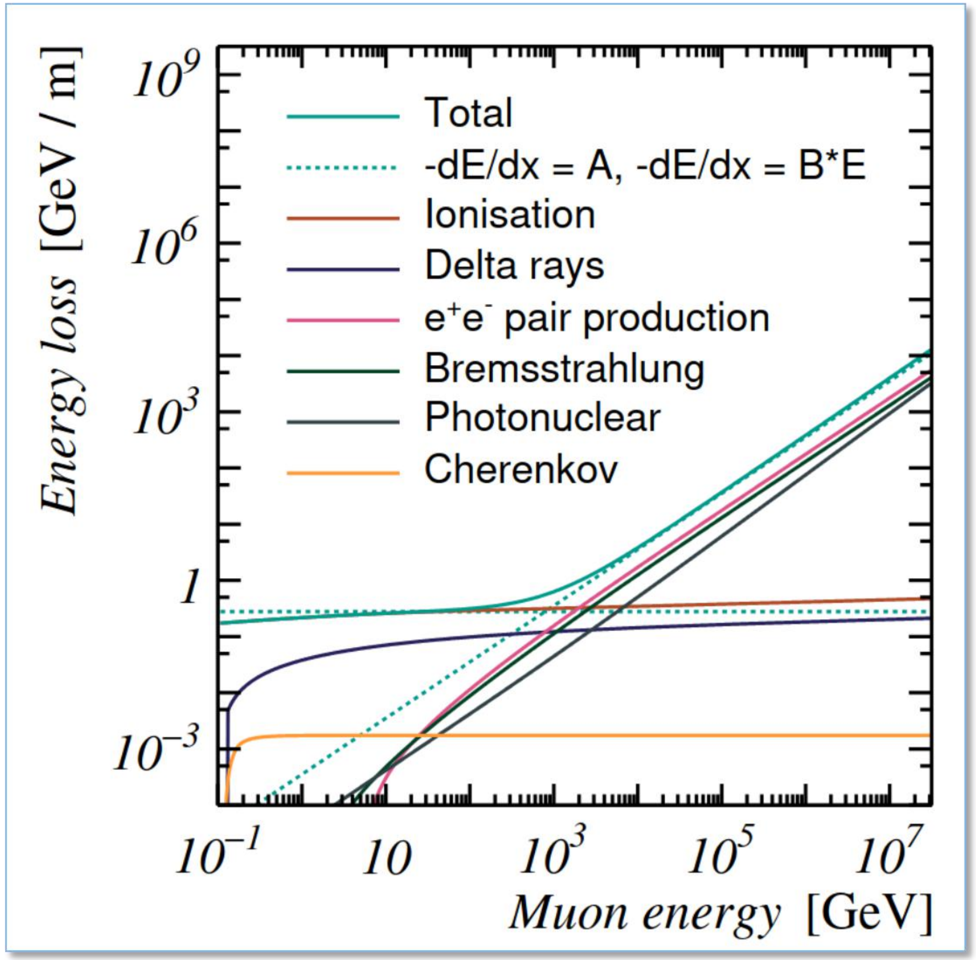
CC

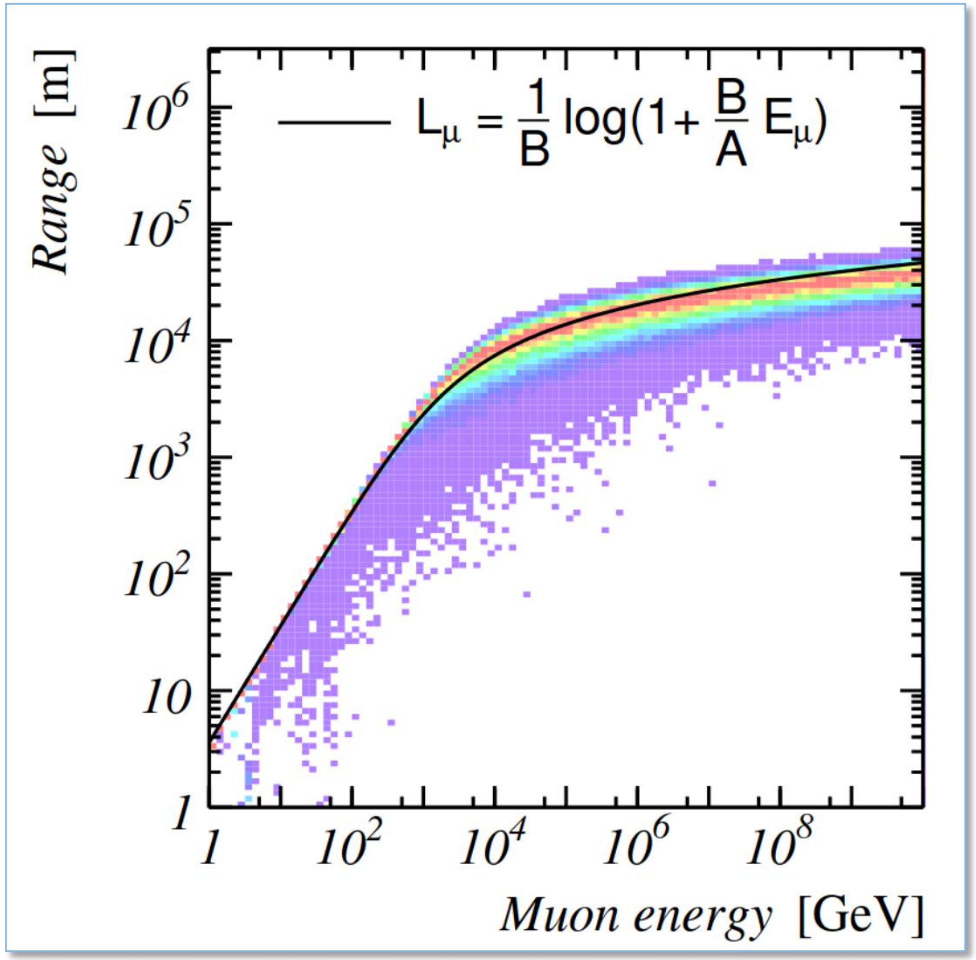


NC



Energy deposition in water





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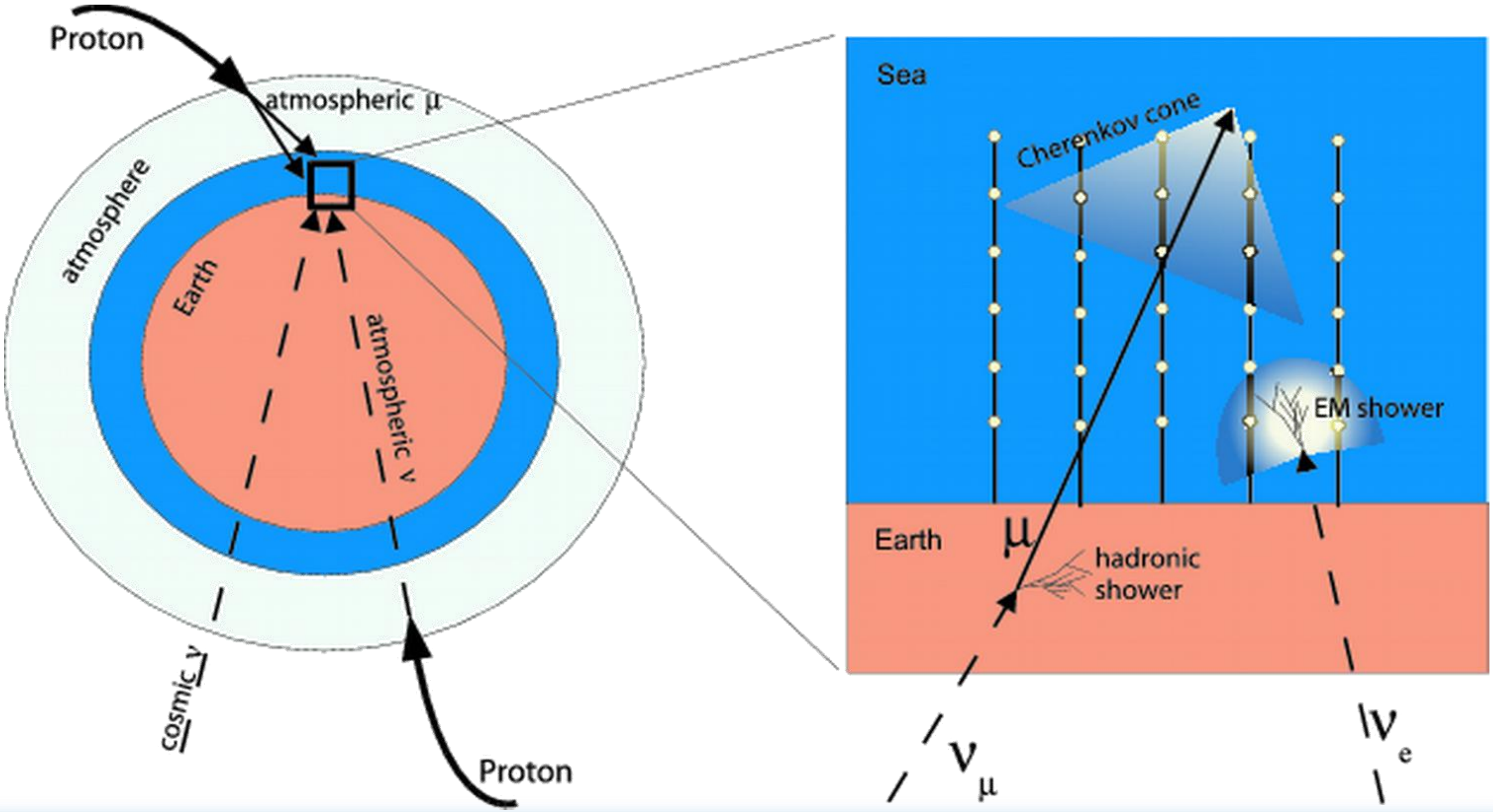
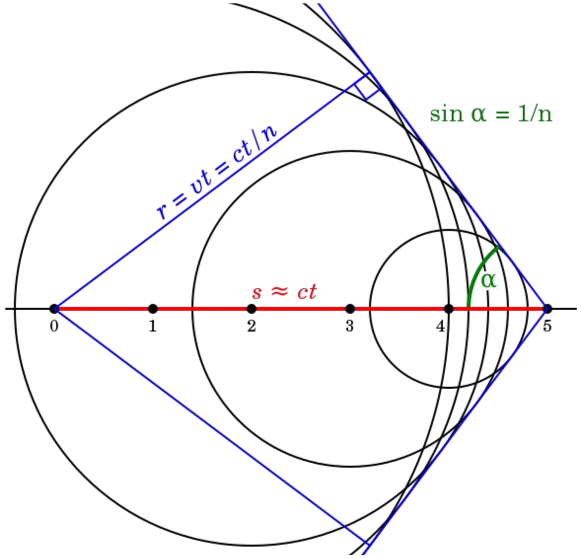
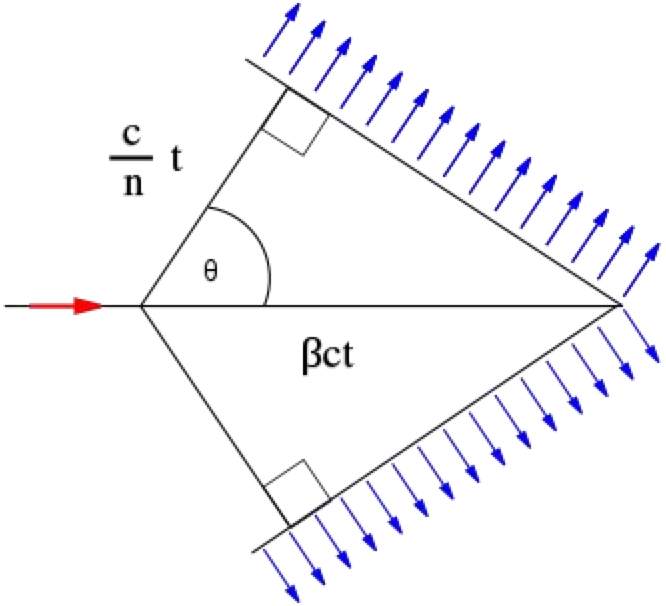
Neutrino telescope concept



Cherenkov radiation

Charged particle moves superluminally through a medium





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

Cone angle

$$v_{\mathrm{th}} \geq \frac{c}{n}$$

Threshold velocity

Number of photons/distance/wavelength

$$\frac{\partial N}{\partial x \partial \lambda} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n^2}\right)\frac{1}{\lambda^2}$$

Frank, Tamm

First ideas: DUMAND

DUMAND
Deep Underwater Muon and Neutrino Detector.

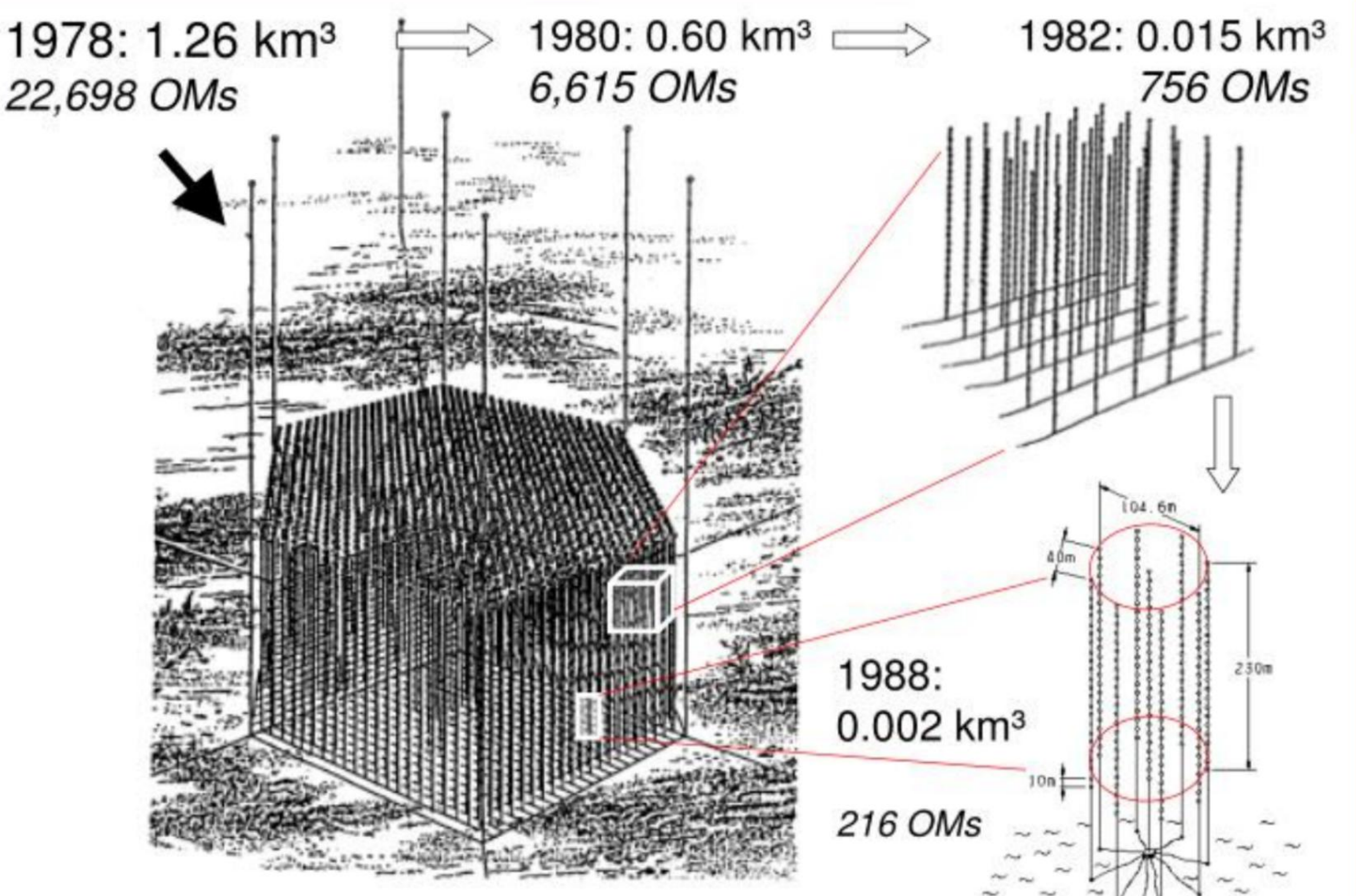
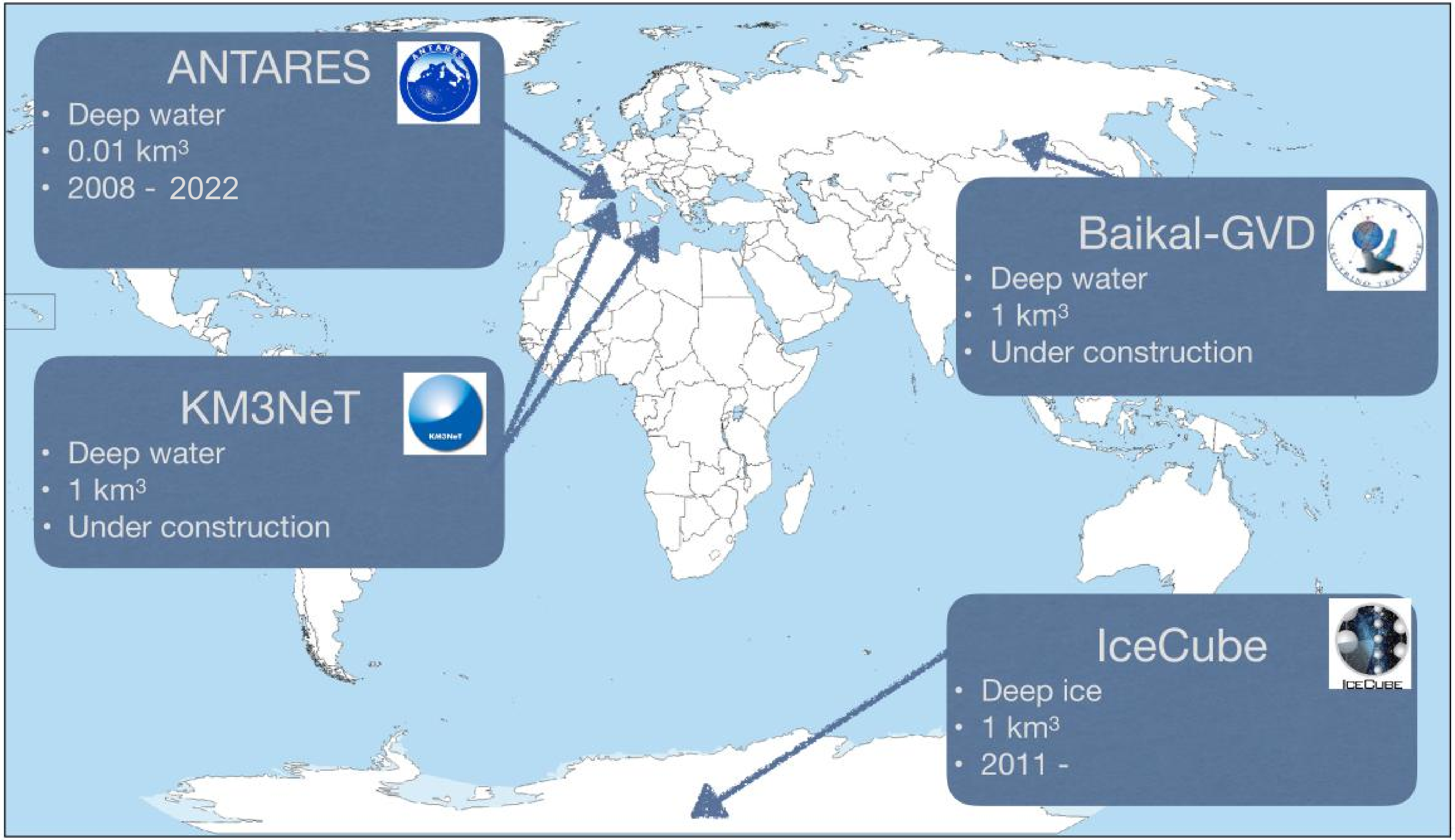


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

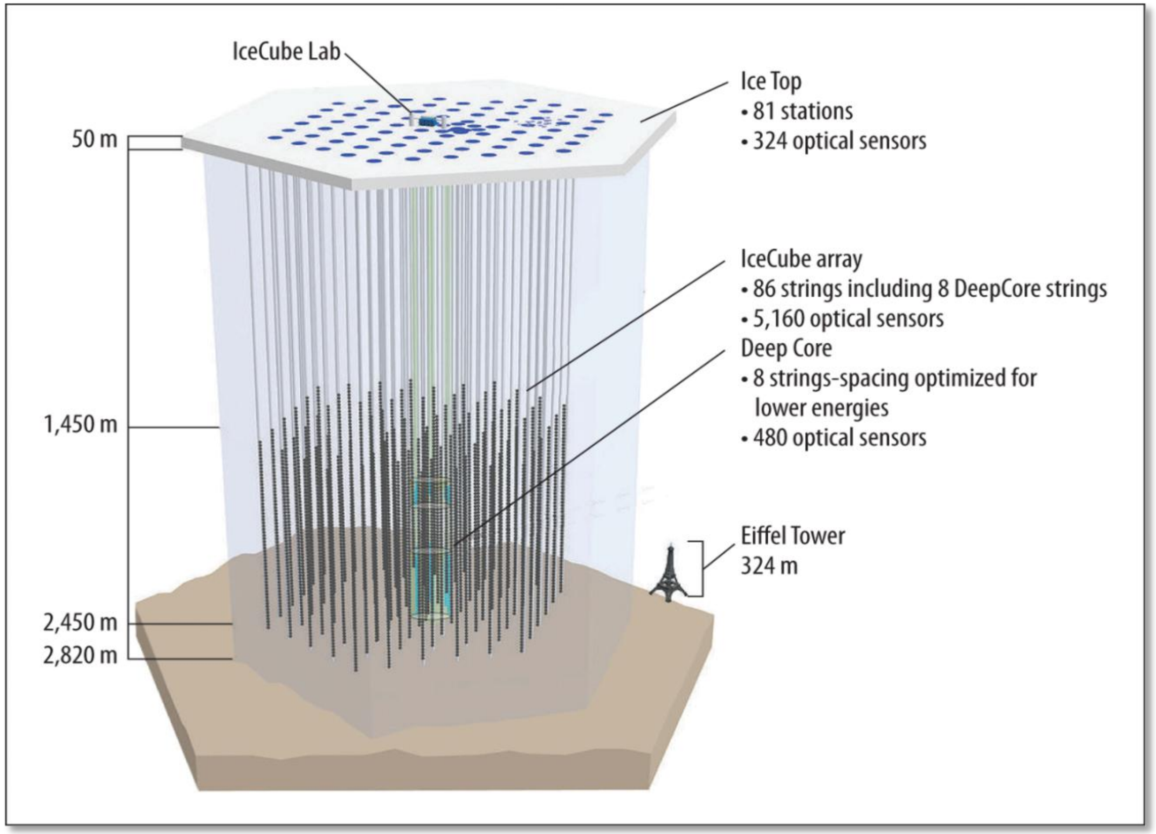
Ideas

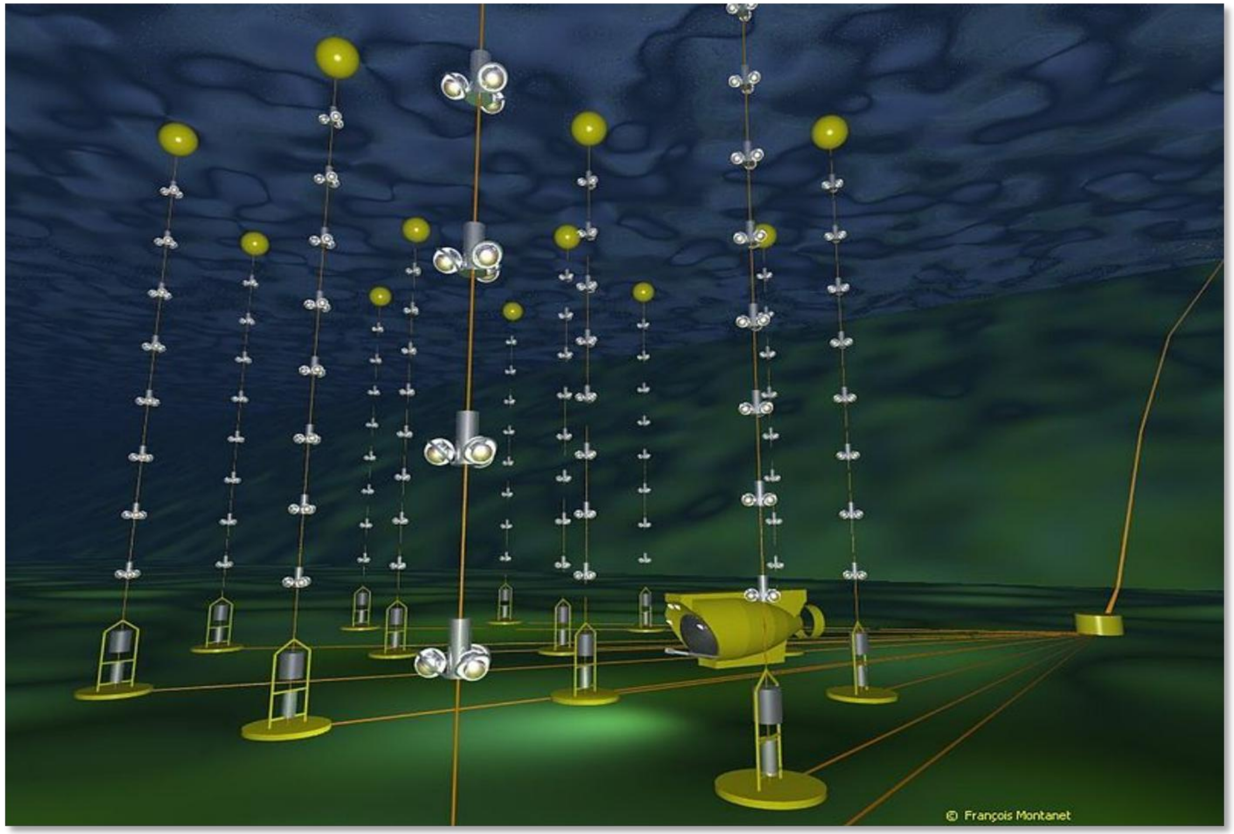
Realized

Second generation neutrino telescopes: IceCube, Antares, GVD



Second generation neutrino telescopes: IceCube, Antares, GVD



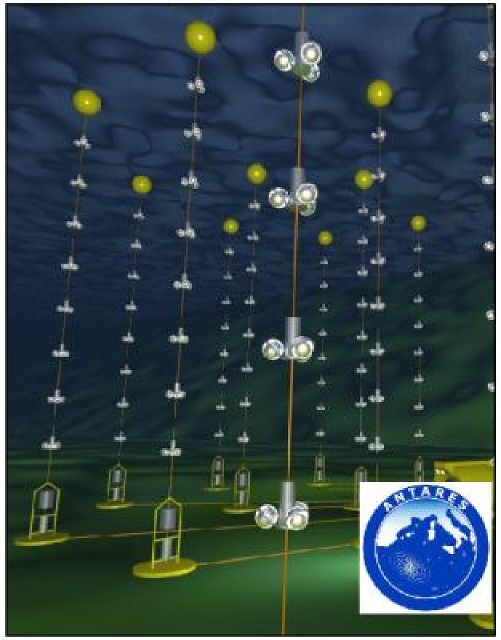


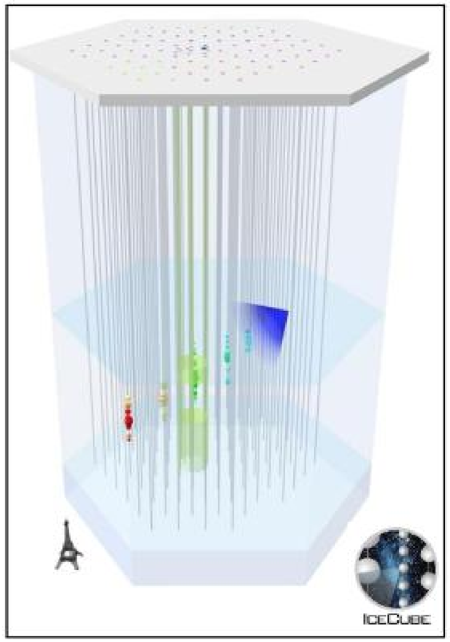
IceCube at the Southpole

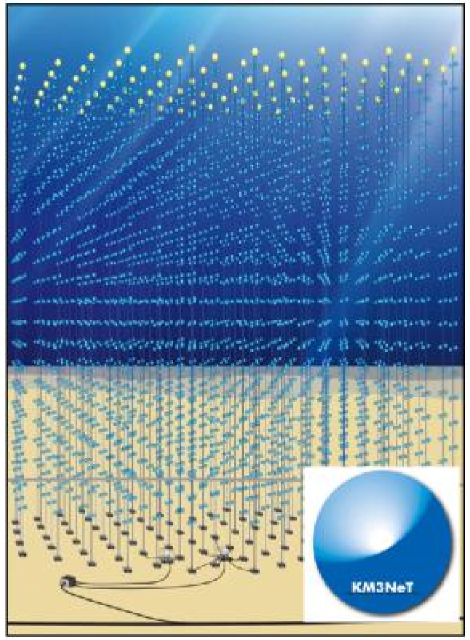
Antares in the Medditerranean Sea

GVD in Lake Baikal

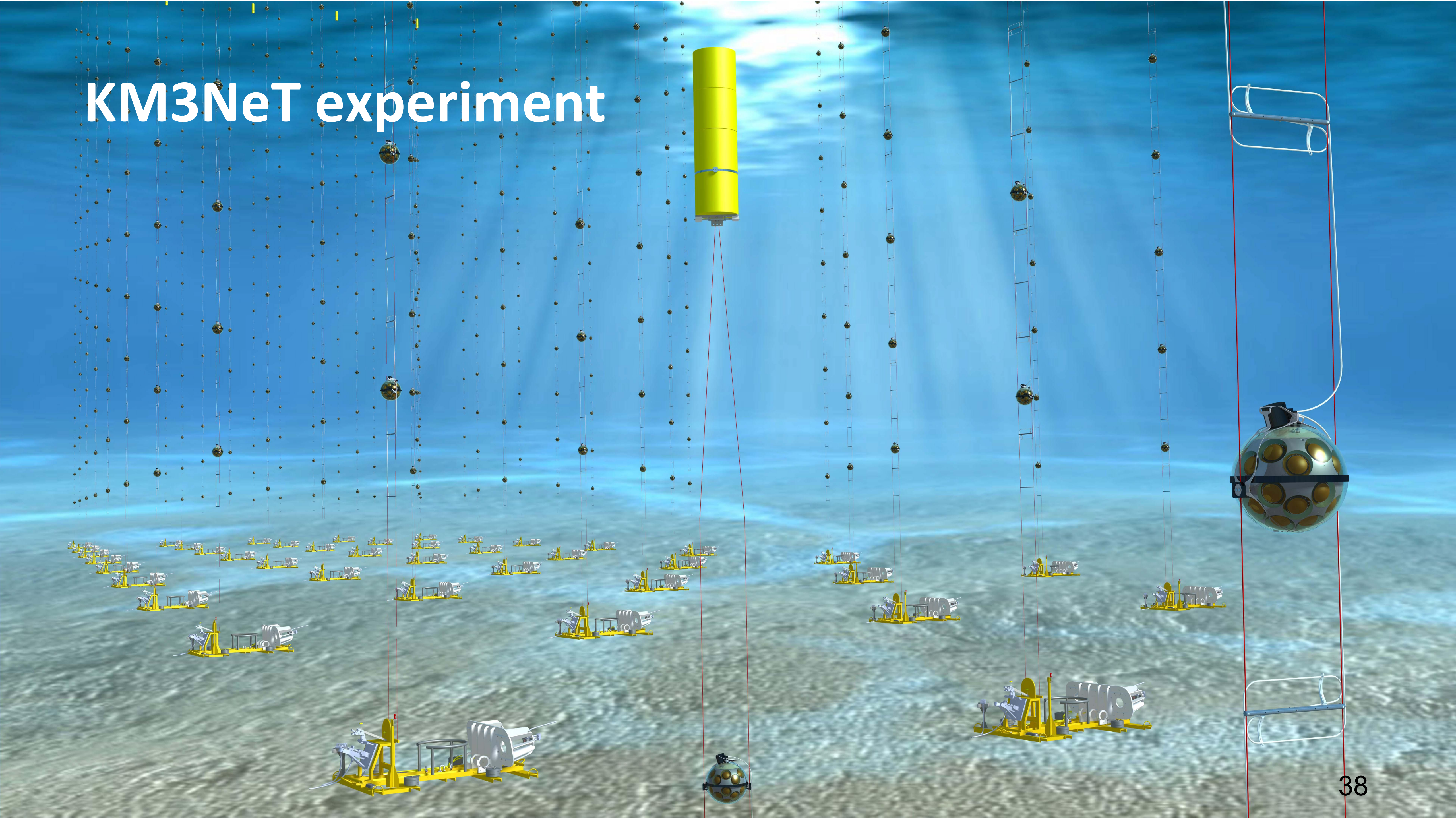
Second generation neutrino telescopes: IceCube, Antares, GVD





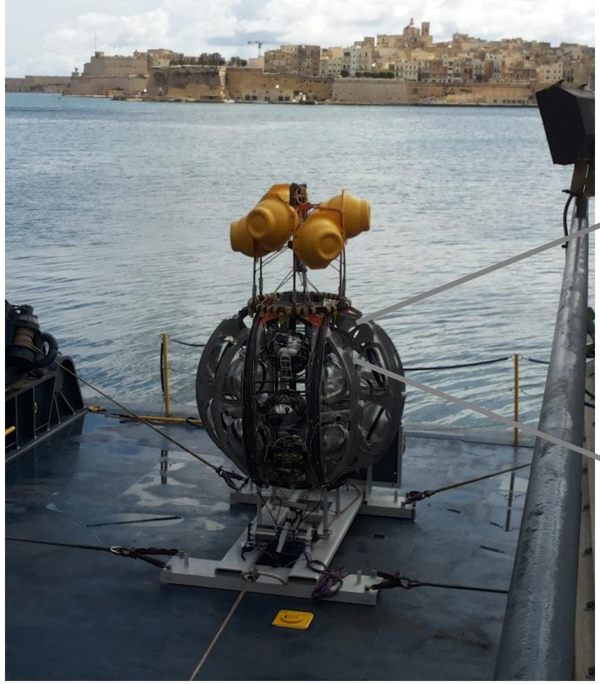


KM3NeT experiment



Next generation: KM3NeT

Launcher vehicle

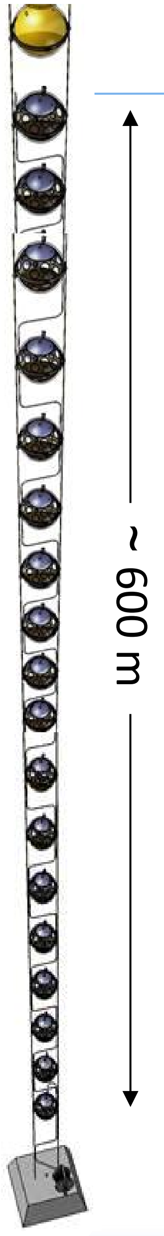


- *rapid deployment*
- *autonomous unfurling*
- *recoverable*

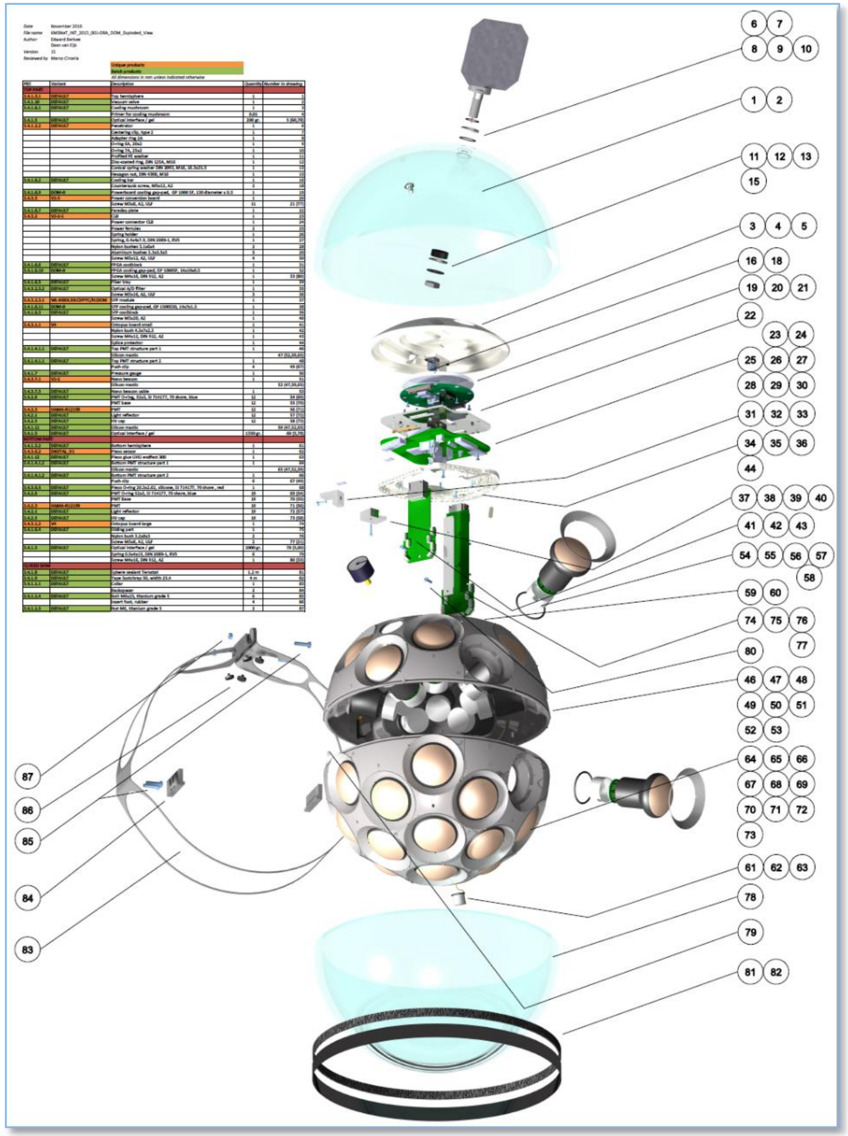
Optical module

← 17” →

- *31 x 3” PMTs*
- *low-power HV*
- *White Rabbit*
- *DWDM*



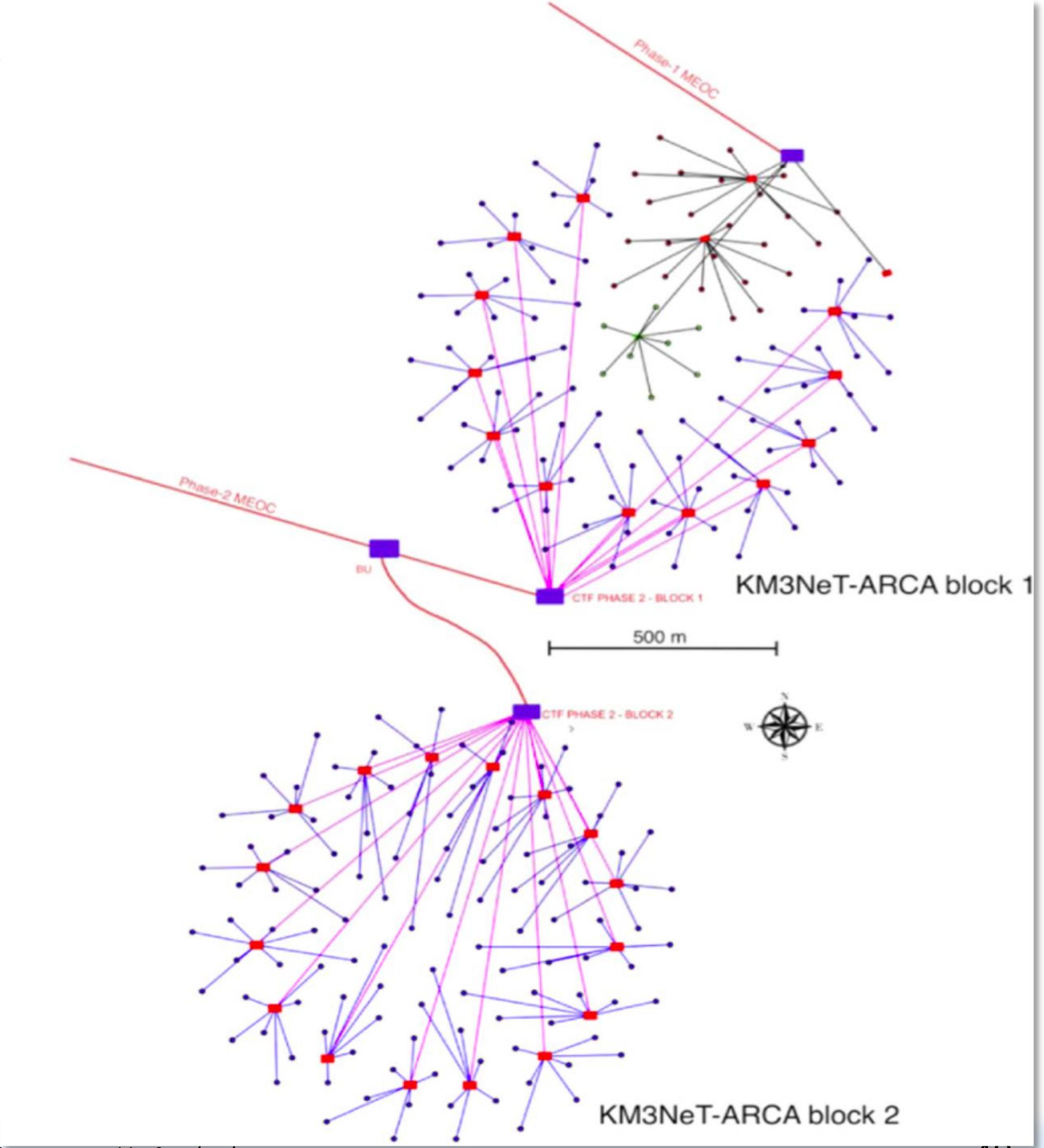
KM3NeT digital optical module



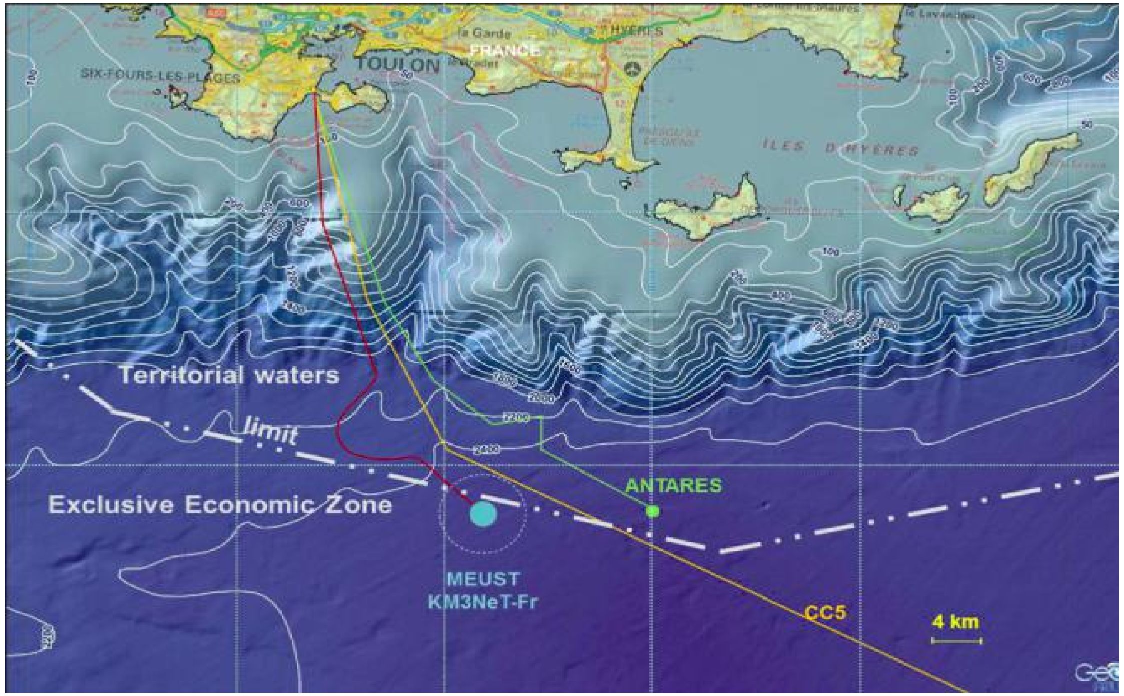
Neutrino telescope concept

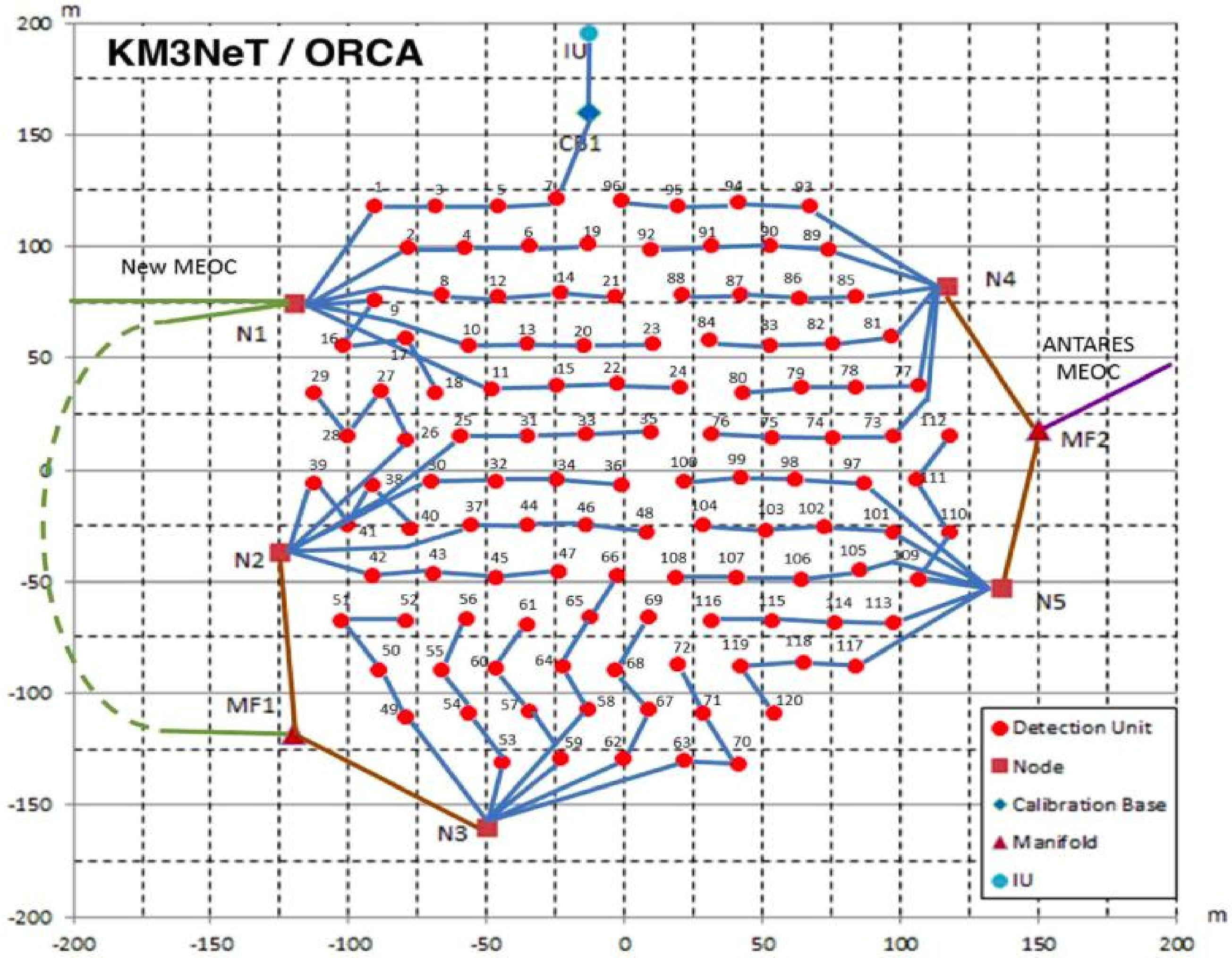
- Sensors:
  - 31 photo-multiplier tubes
  - Compass/tilt
  - Hydrophone
  - LED (nano beacon)
- Electronics:
  - Timing!
  - Optical fiber read-out

KM3NeT: Italian site



KM3NeT: French site





KM3NeT: French site

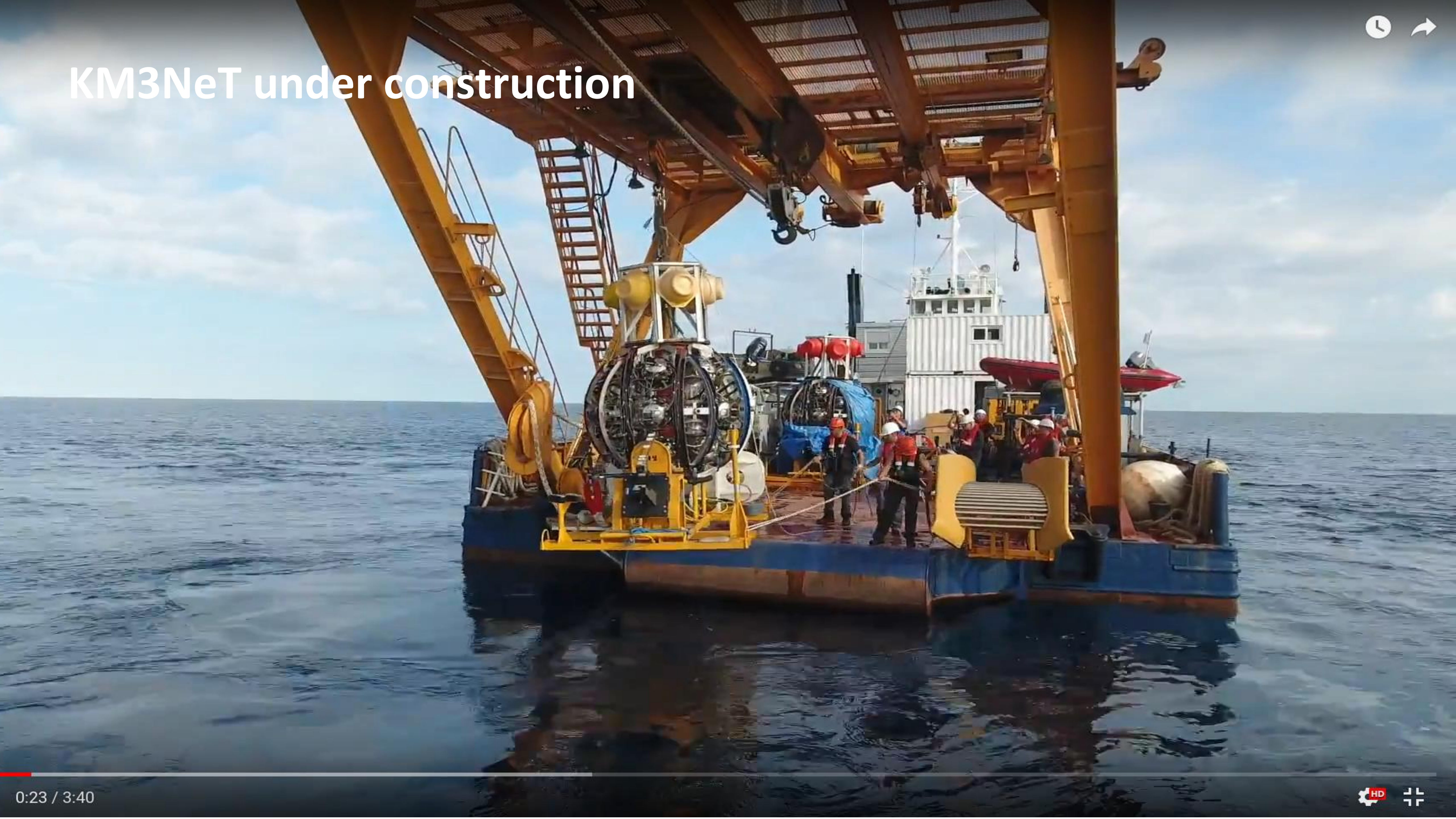
2014: Implementation of the main cable to shore

KM3NeT: numbers

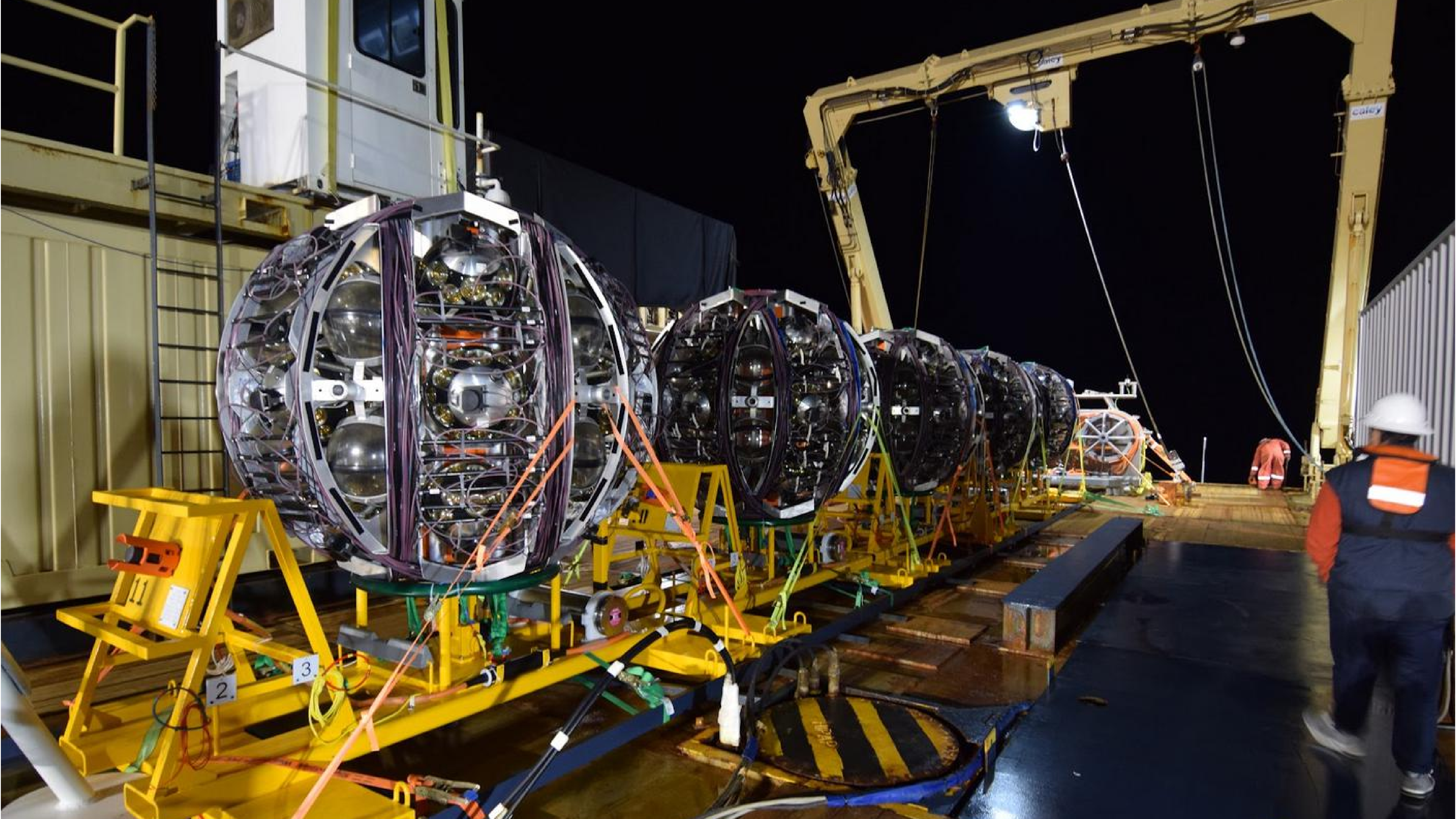
- Number of strings: ~300
- KM3NeT-Fr (Orca):
  - Relatively low energetic neutrino's (GeV): high density of modules.
  - Distance between the strings is 20 m. Distance between modules 9 m. Length of a string: 200 m
- KM3NeT-It (Arca):
  - High energetic neutrino's (TeV, PeV) : Need large volume!
  - Distance between strings is 95 m. Distance between modules 36 m. Length of a string is 700 m.

KM3NeT under construction

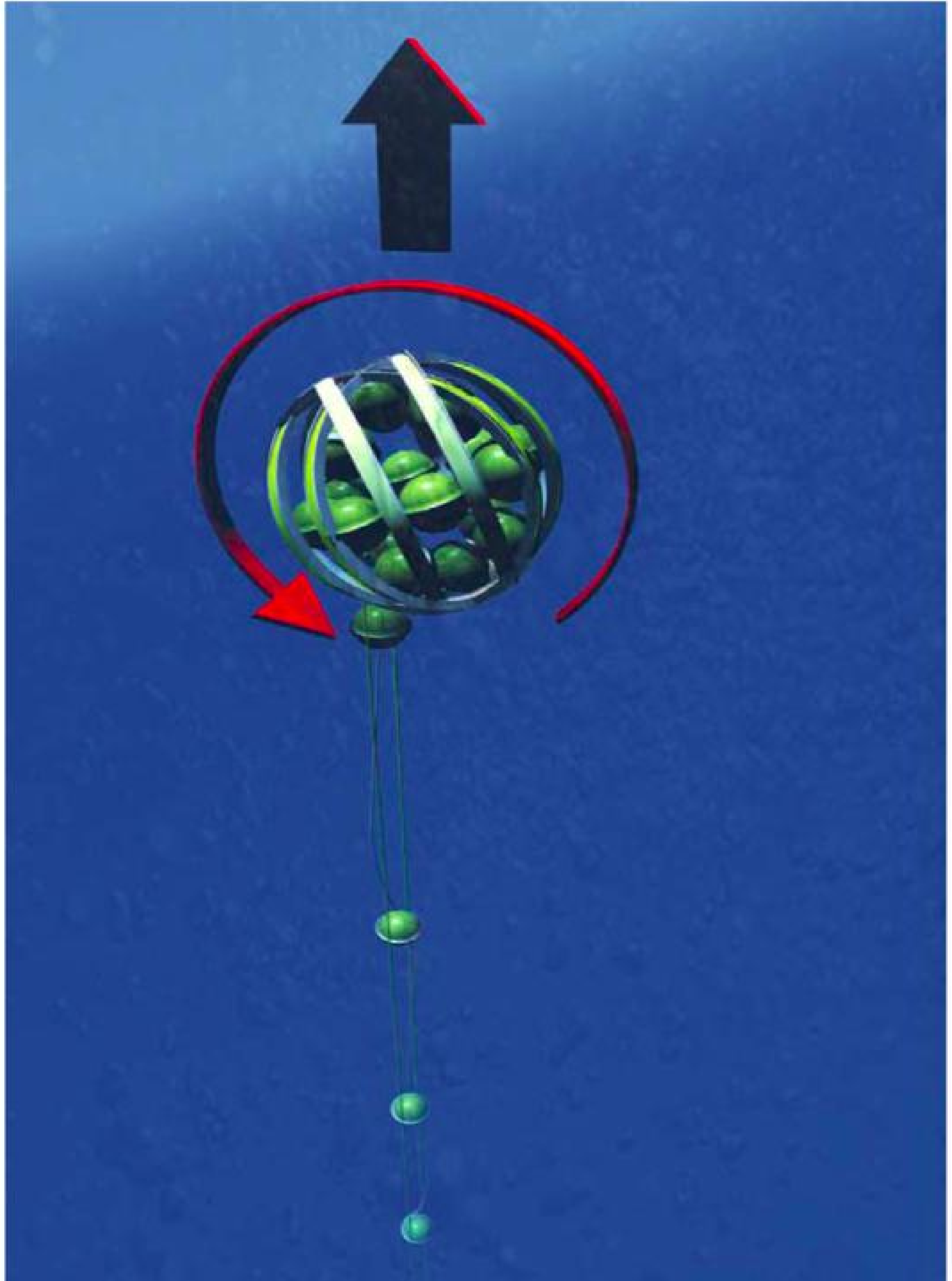
KM3NeT under construction

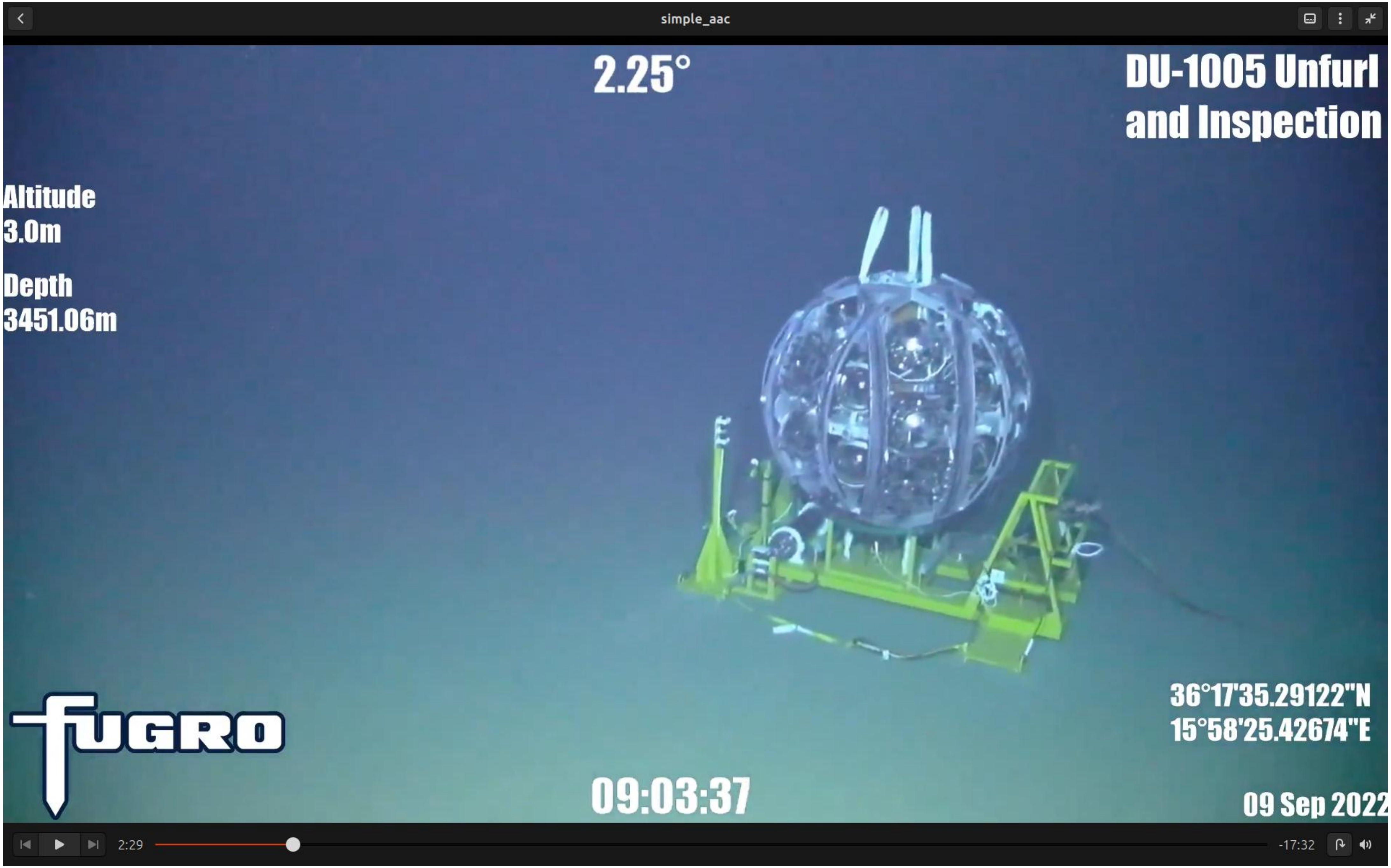


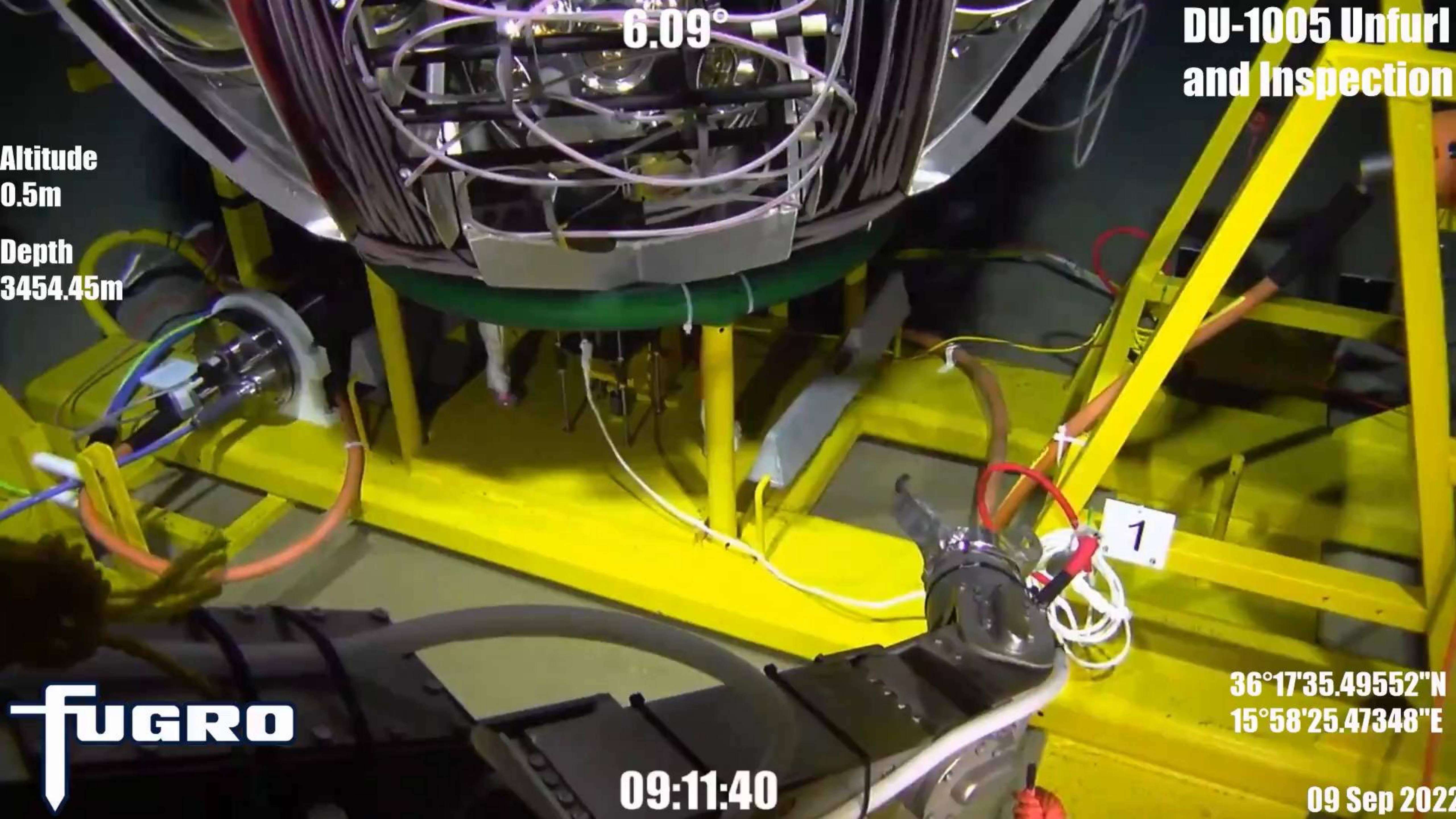

Remotely operated Submarine
Detection Units
Interlink cable
OPTIMUS PRIME
ISTANBUL


caley
caley
11
3
2

KM3NeT under construction




simple_aac
2.25°
DU-1005 Unfurl
and Inspection
Altitude
3.0m
Depth
3451.06m
FUGRO
36°17'35.29122"N
15°58'25.42674"E
09:03:37
09 Sep 2022
2:29
-17:32


6.09°
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and Inspection
Altitude
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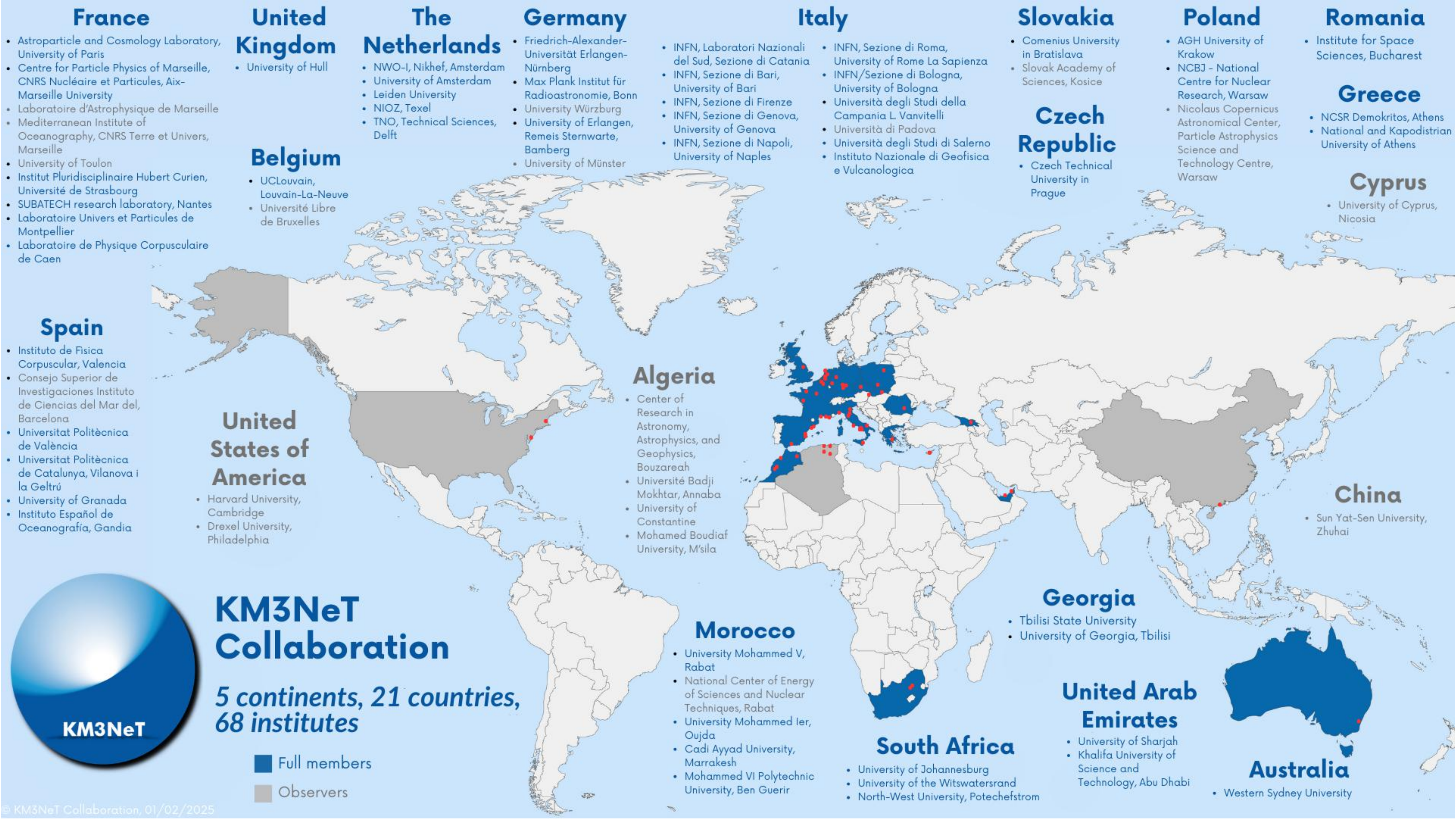
France
Astroparticle and Cosmology Laboratory, University of Paris
Centre for Particle Physics of Marseille, CNRS Nucléaire et Particules, Aix-Marseille University
Laboratoire d'Astrophysique de Marseille
Mediterranean Institute of Oceanography, CNRS Terre et Univers, Marseille
University of Toulon
Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg
SUBATECH research laboratory, Nantes
Laboratoire Univers et Particules de Montpellier
Laboratoire de Physique Corpusculaire de Caen
United Kingdom
University of Hull
The Netherlands
NWO-I, Nikhef, Amsterdam
University of Amsterdam
Leiden University
NIOZ, Texel
TNO, Technical Sciences, Delft
Belgium
UCLouvain, Louvain-La-Neuve
Université Libre de Bruxelles
Germany
Friedrich-Alexander-Universität Erlangen-Nürnberg
Max Plank Institut für Radioastronomie, Bonn
University Würzburg
University of Erlangen, Remeis Sternwarte, Bamberg
University of Münster
Italy
INFN, Laboratori Nazionali del Sud, Sezione di Catania
INFN, Sezione di Bari, University of Bari
INFN, Sezione di Firenze
INFN, Sezione di Genova, University of Genova
INFN, Sezione di Napoli, University of Naples
INFN, Sezione di Roma, University of Rome La Sapienza
INFN/Sezione di Bologna, University of Bologna
Università degli Studi della Campania L. Vanvitelli
Università di Padova
Università degli Studi di Salerno
Instituto Nazionale di Geofisica e Vulcanologica
Slovakia
Comenius University in Bratislava
Slovak Academy of Sciences, Kosice
Czech Republic
Czech Technical University in Prague
Poland
AGH University of Krakow
NCBJ - National Centre for Nuclear Research, Warsaw
Nicolaus Copernicus Astronomical Center, Particle Astrophysics Science and Technology Centre, Warsaw
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Spain
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Consejo Superior de Investigaciones Instituto de Ciencias del Mar del, Barcelona
Universitat Politècnica de València
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United States of America
Harvard University, Cambridge
Drexel University, Philadelphia
Algeria
Center of Research in Astronomy, Astrophysics, and Geophysics, Bouzareah
Université Badji Mokhtar, Annaba
University of Constantine
Mohamed Boudiaf University, M'sila
China
Sun Yat-Sen University, Zhuhai
KM3NeT
KM3NeT Collaboration
5 continents, 21 countries, 68 institutes
Full members
Observers
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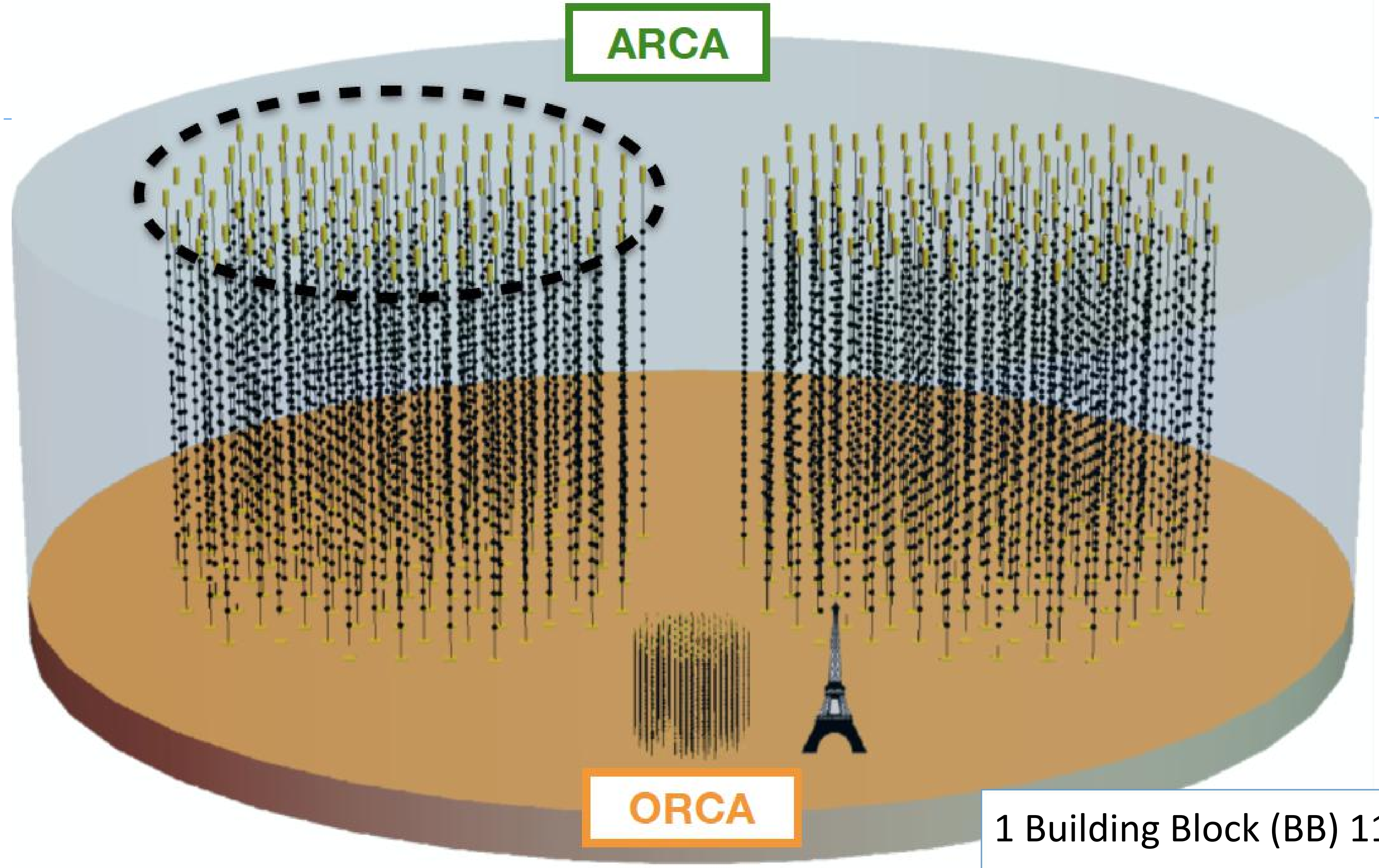
National Center of Energy of Sciences and Nuclear Techniques, Rabat
University Mohammed Ier, Oujda
Cadi Ayyad University, Marrakesh
Mohammed VI Polytechnic University, Ben Guerir
South Africa
University of Johannesburg
University of the Witswatersrand
North-West University, Potechefstrom
Georgia
Tbilisi State University
University of Georgia, Tbilisi
United Arab Emirates
University of Sharjah
Khalifa University of Science and Technology, Abu Dhabi
Australia
Western Sydney University
© KM3NeT Collaboration, 01/02/2025

ORCA

- Depth ~2500 m
- One block of 115 Detection Units
- Distance between Detection Units ~20 m
- Vertical distance between DOMs ~9 m

ARCA

- Depth ~3500 m
- Two blocks of 115 Detection Units each
- Distance between Detection Units ~90 m
- Vertical distance between DOMs ~36 m

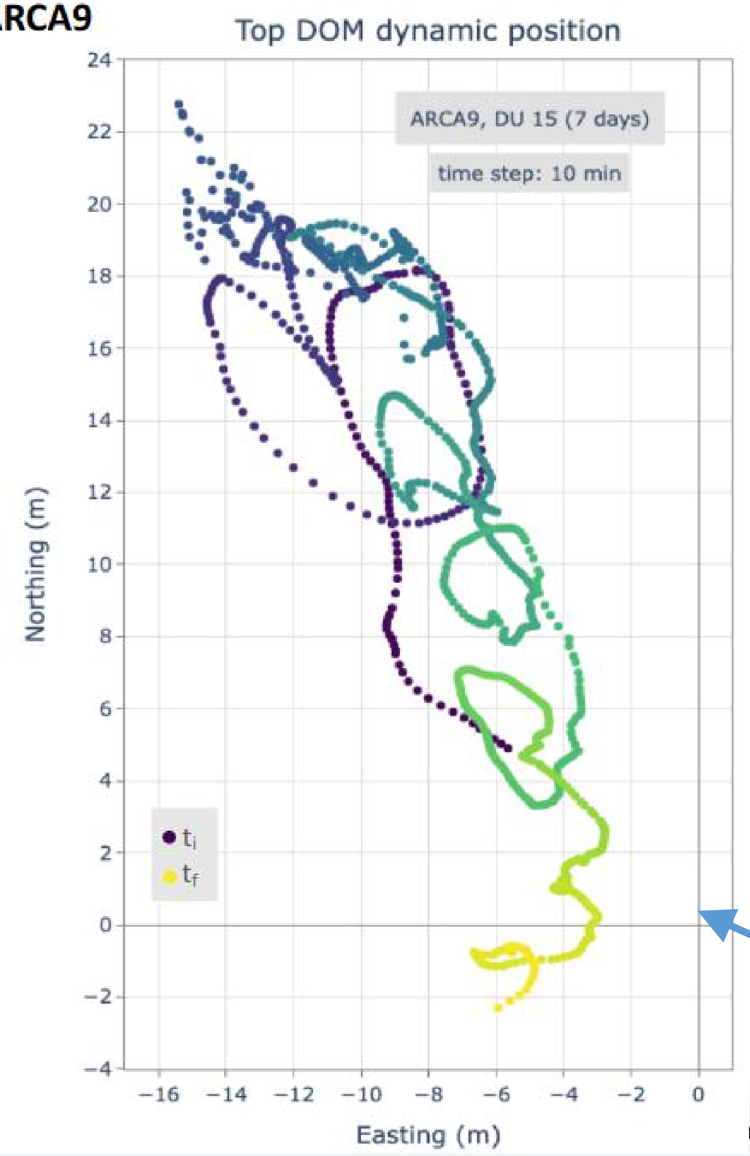


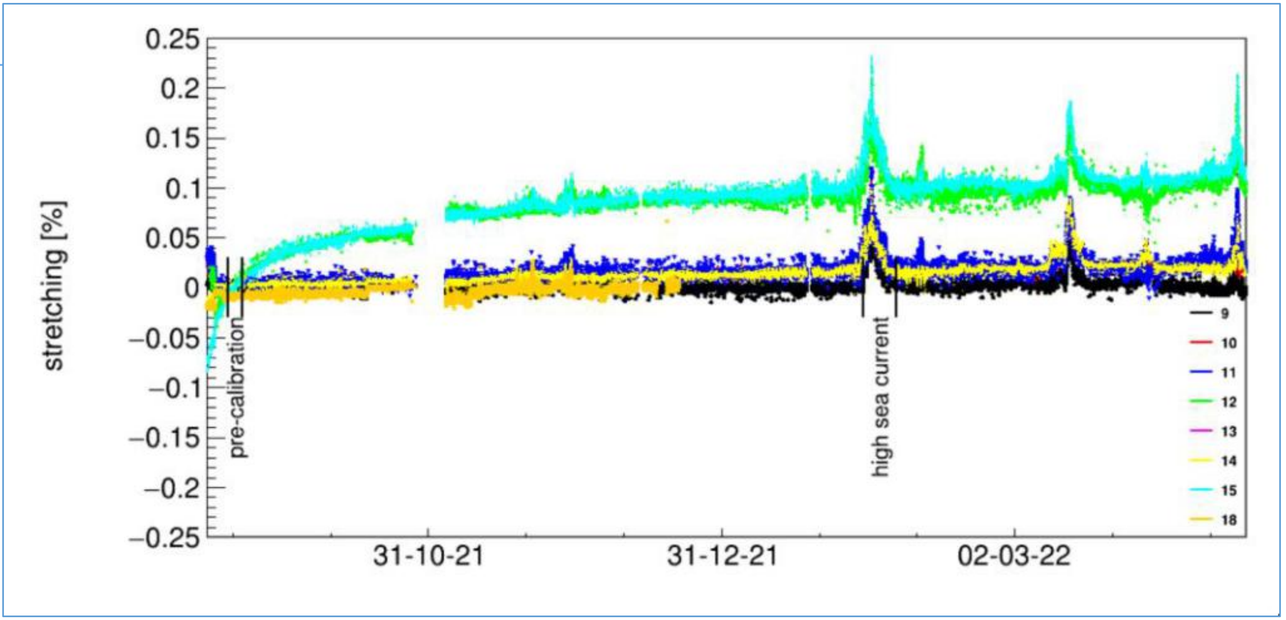
1 Building Block (BB) 115 Detection Units

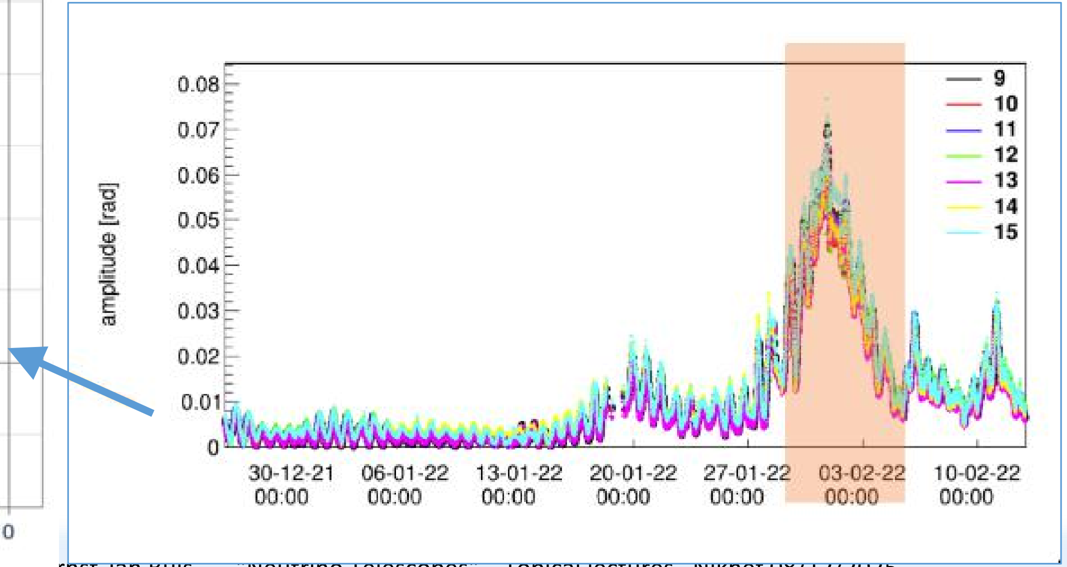
ARCA 2 BB (230 DUs)
ORCA 1BB (115DUs)

Positioning system

ARCA9





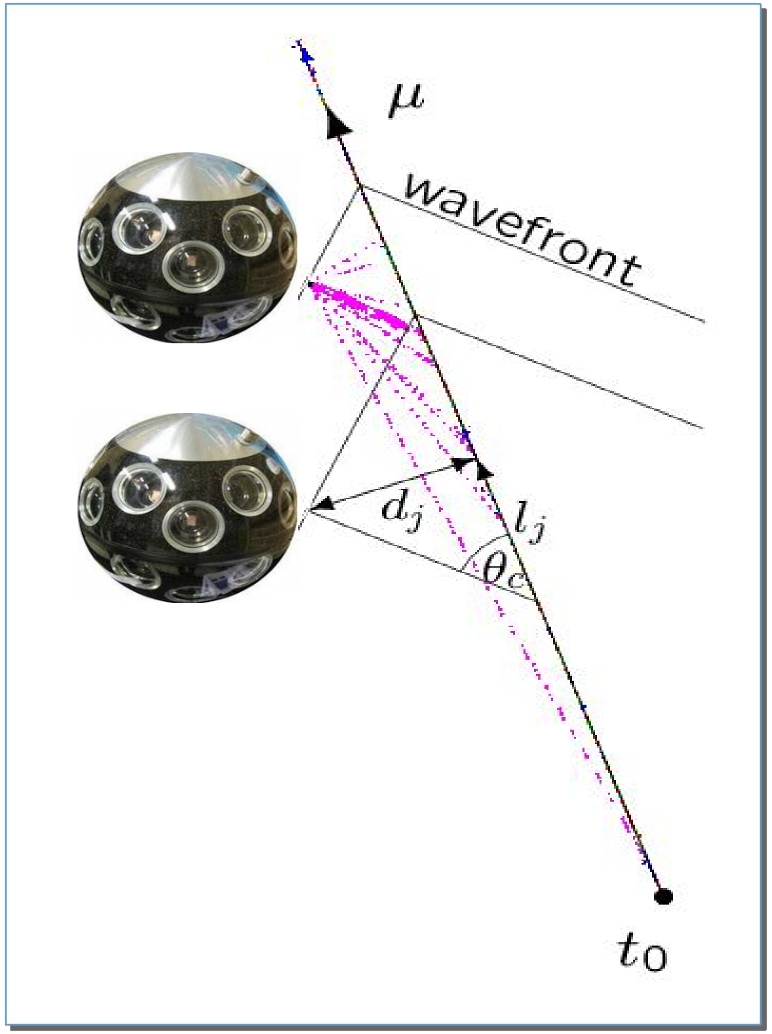


Streching measured in new deployed strings in ARCA

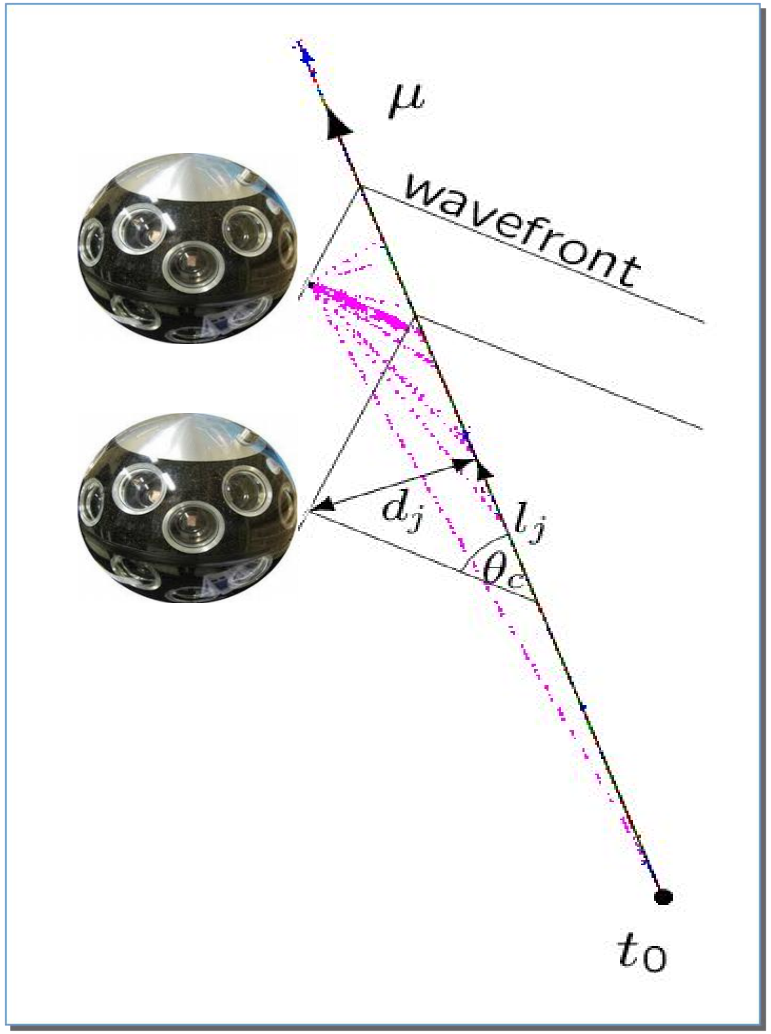
Digital Optical Module

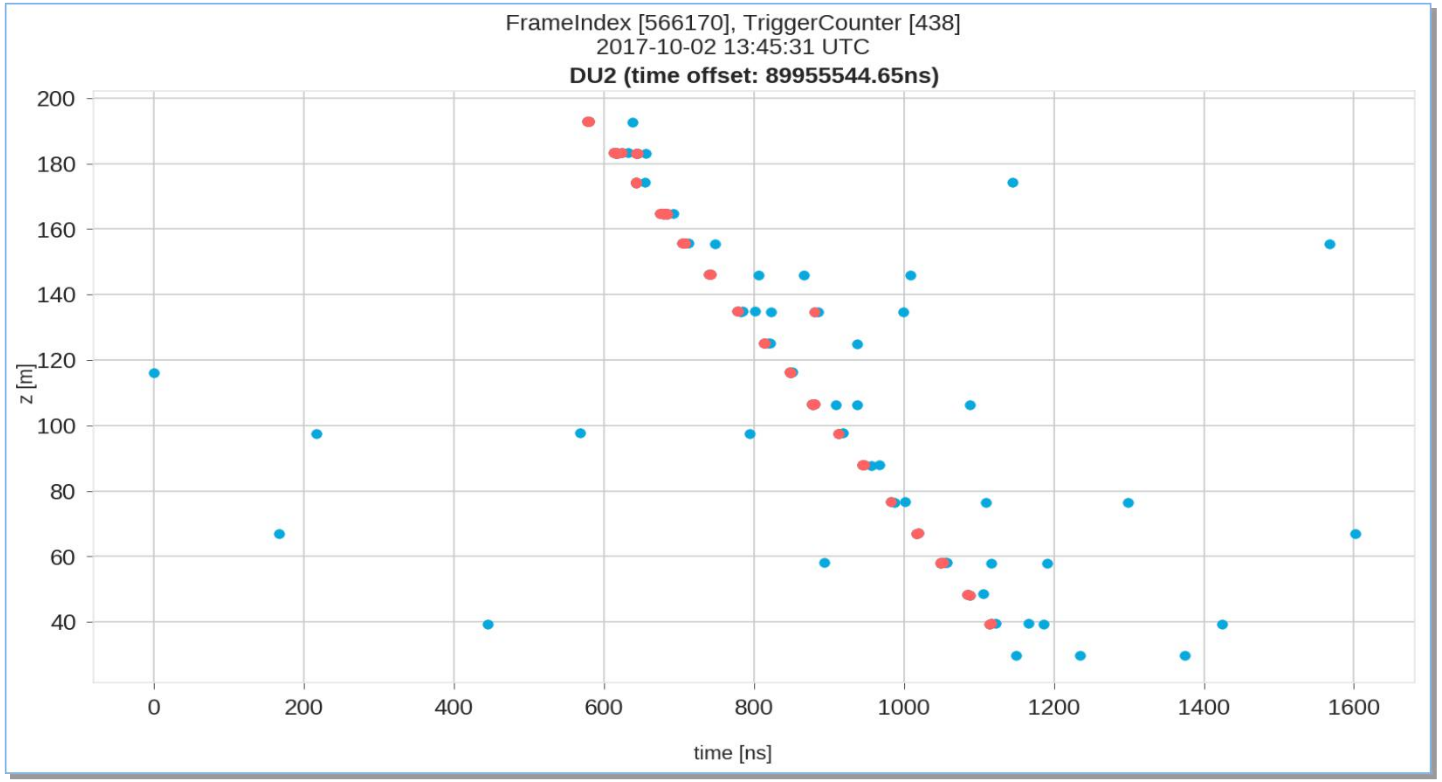
- Sensors:
  - 31 photo-multiplier tubes (3”)
    - Hamamatsu R14374
  - Compass/tilt
  - Hydrophone
  - LED (nano beacon)

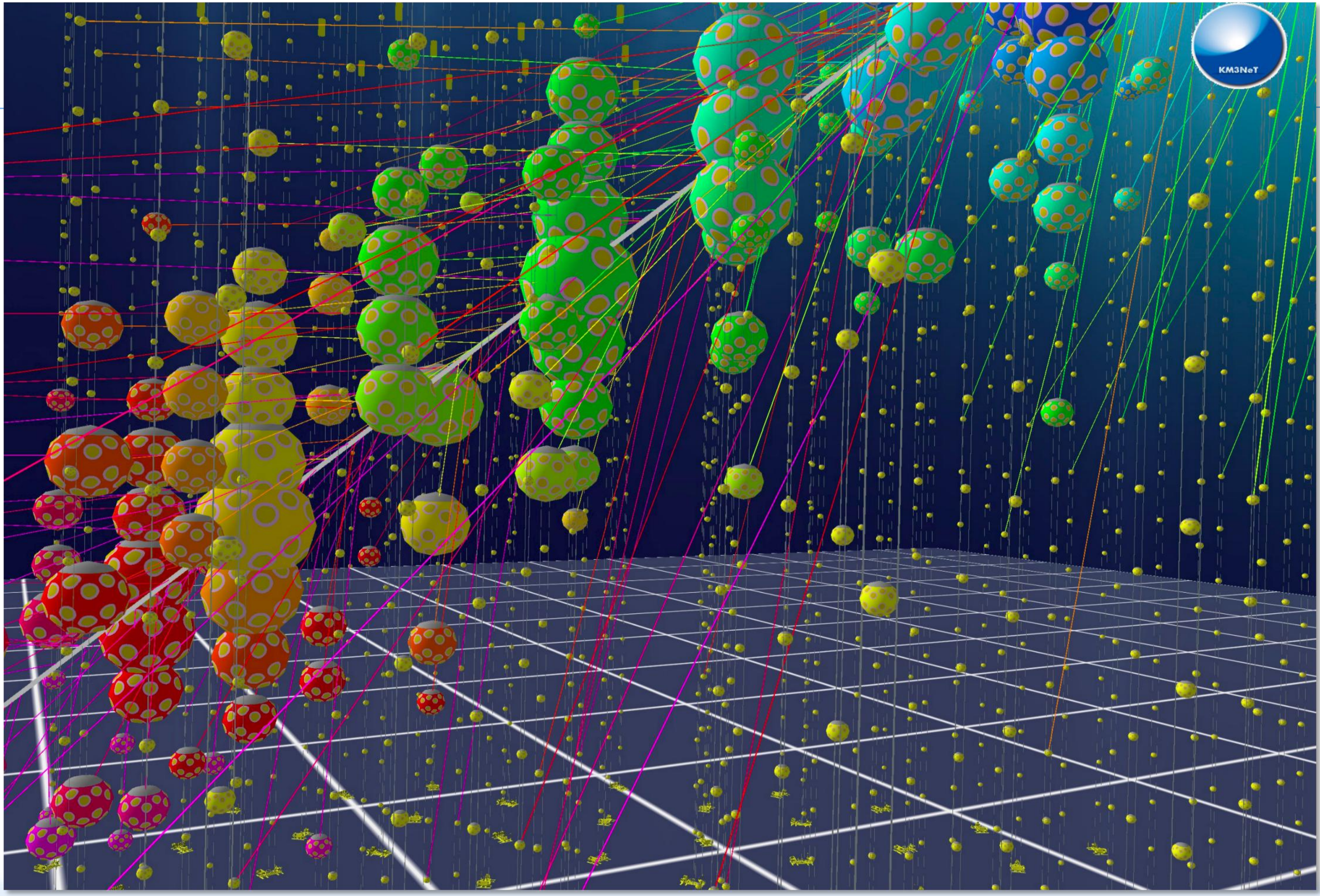
- Electronics:
  - Timing!
  - Optical fiber read-out

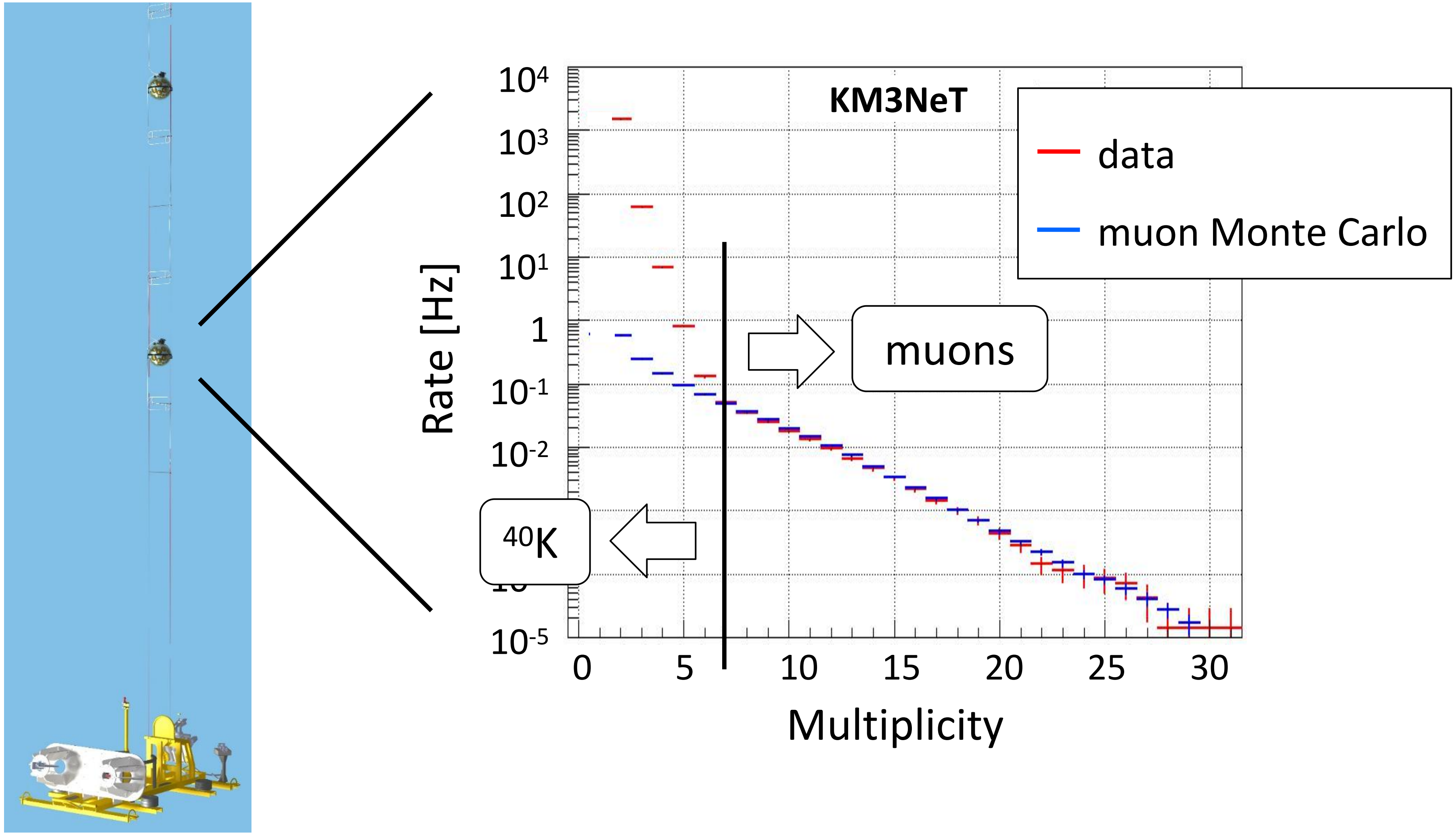


Event reconstruction

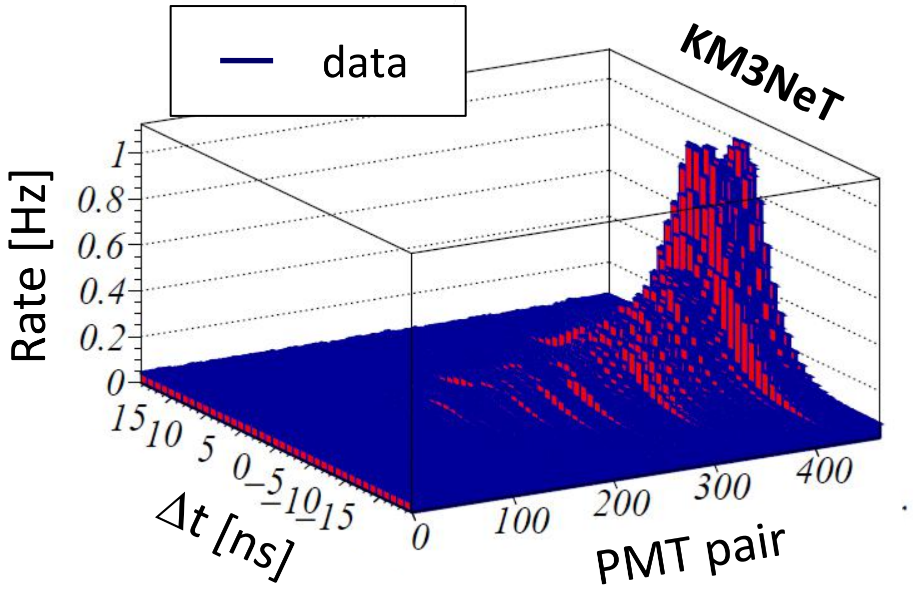





KM3NeT

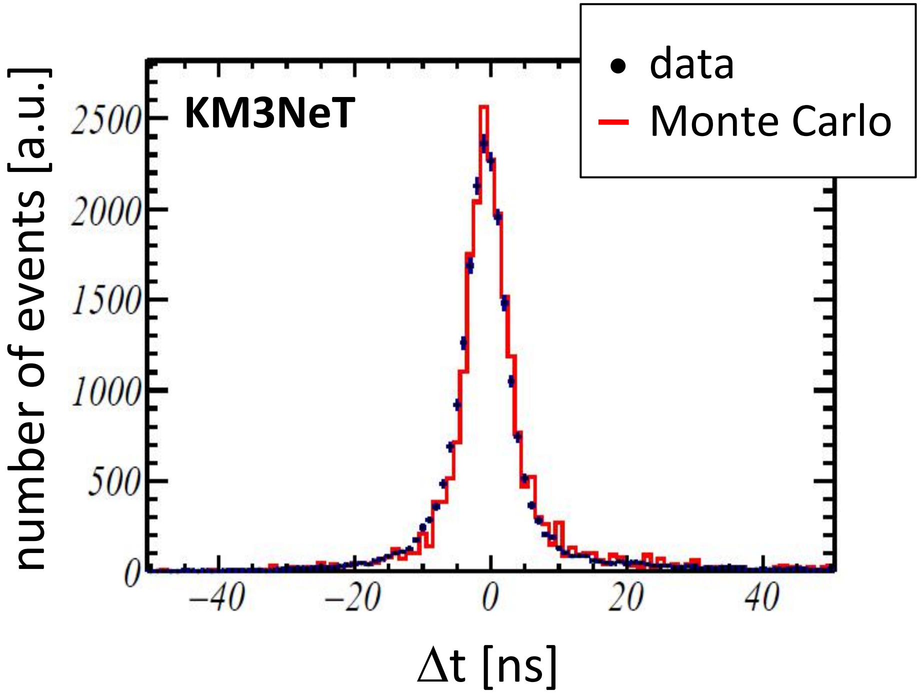

KM3NeT
data
muon Monte Carlo
muons
40K
Rate [Hz]
Multiplicity
10⁴
10³
10²
10¹
1
10-1
10-2
10-5
0
5
10
15
20
25
30

^{40}K decays



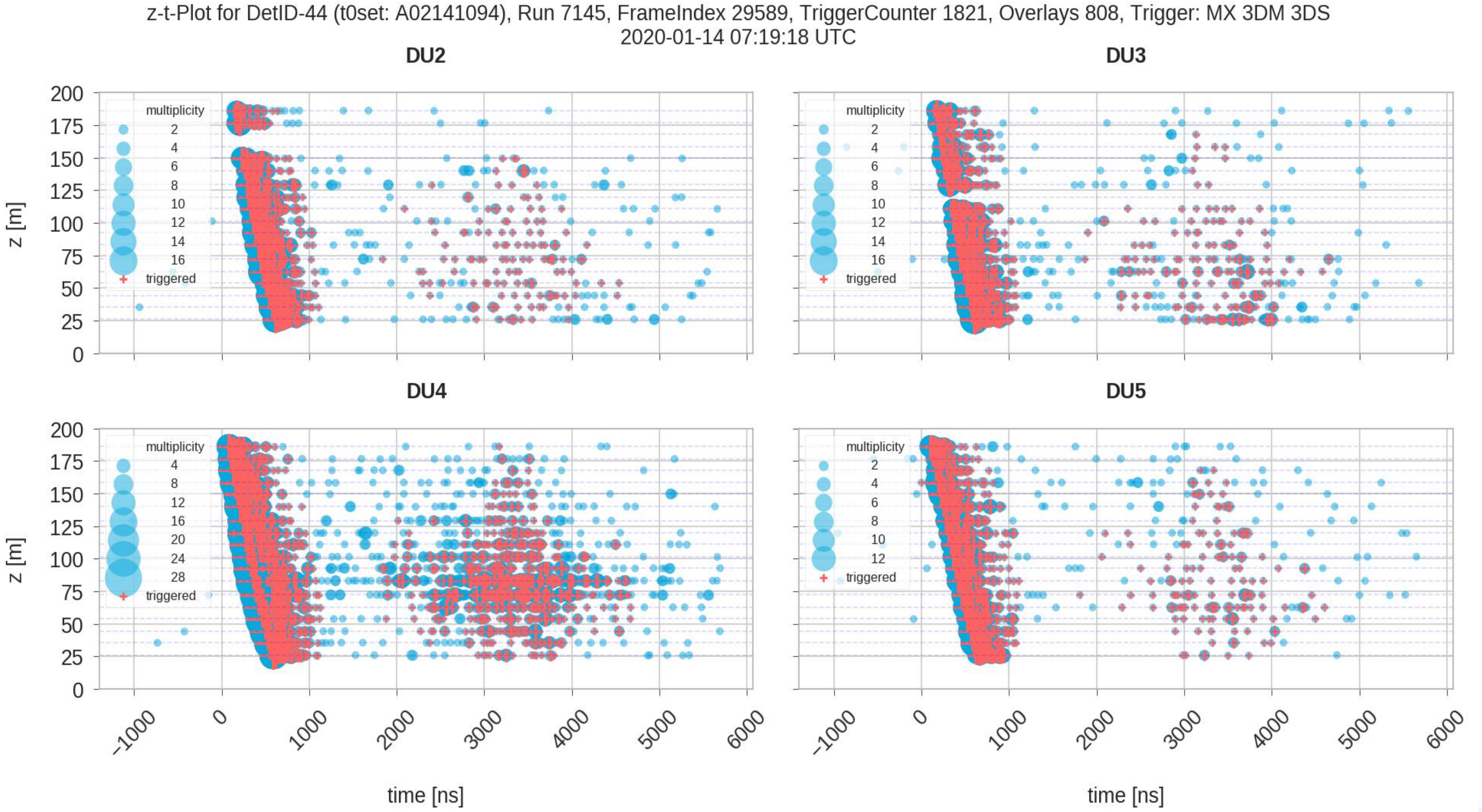
intra-optical module

Atmospheric muons



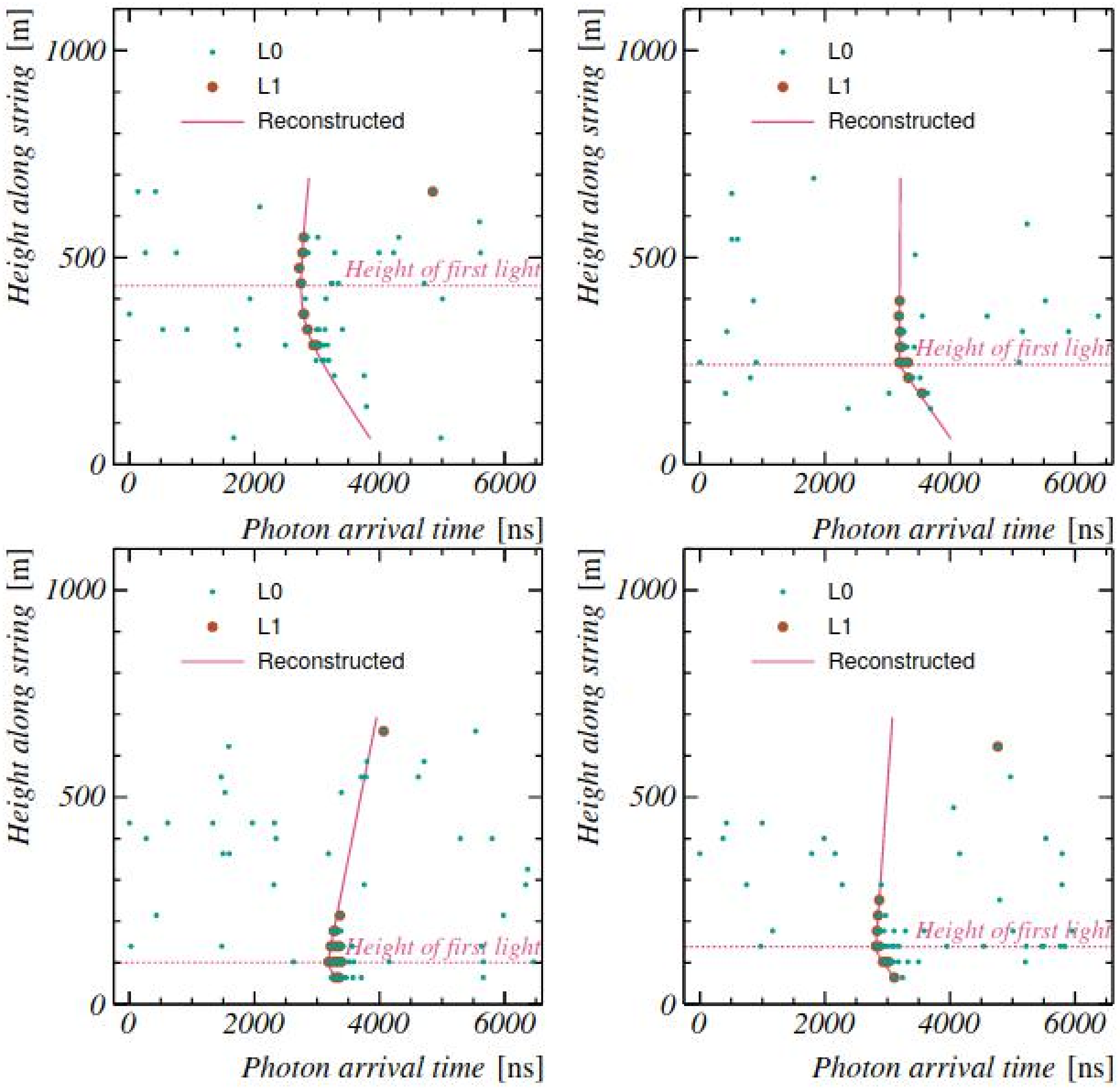
inter-optical module

Tracking



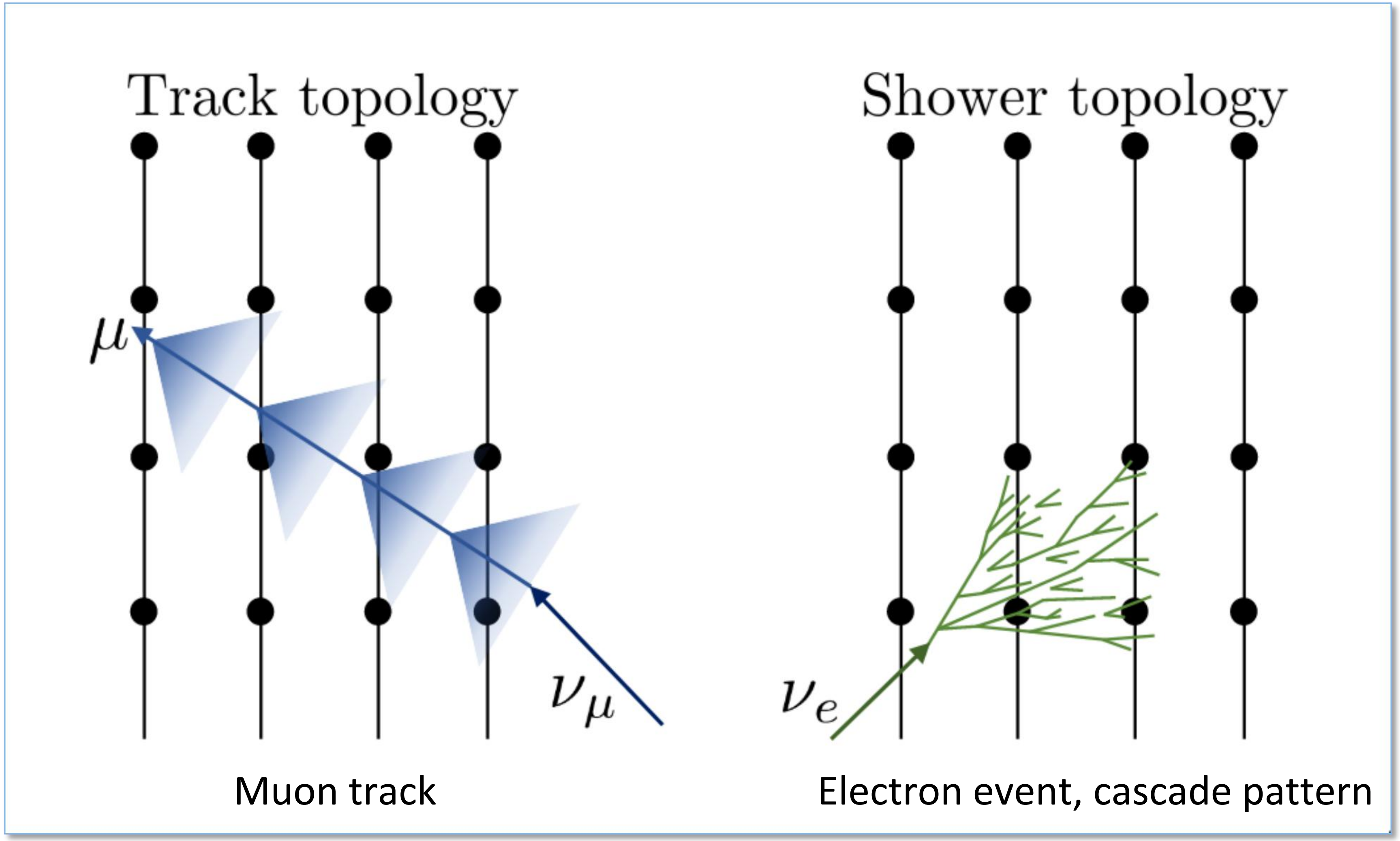
z-t-Plot for DetID-44 (t0set: A02141094), Run 7145, FrameIndex 29589, TriggerCounter 1821, Overlays 808, Trigger: MX 3DM 3DS
2020-01-14 07:19:18 UTC
DU2
DU3
DU4
DU5
multiplicity
triggered
z [m]
time [ns]

Tracking

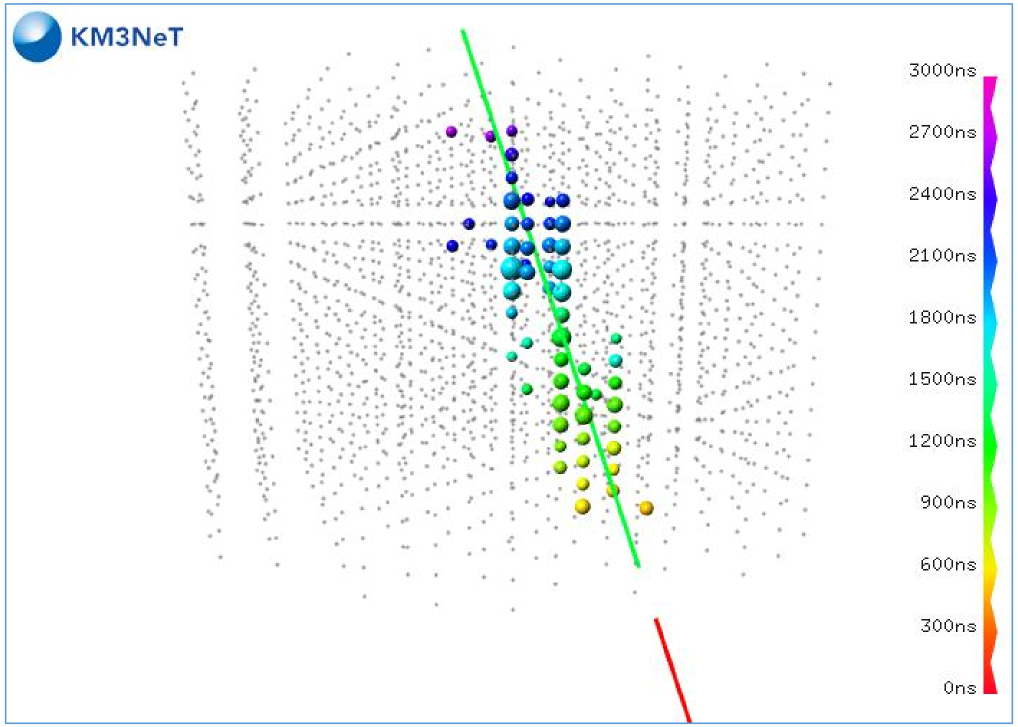


Thesis K. Melis, 2021

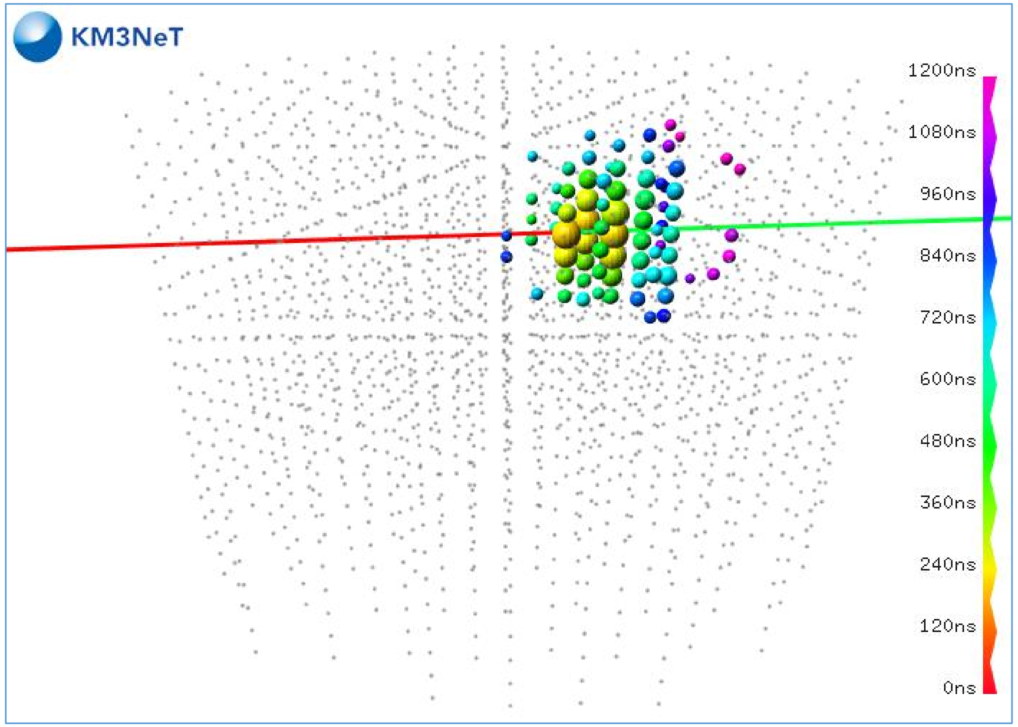
Event topology



Simulated events

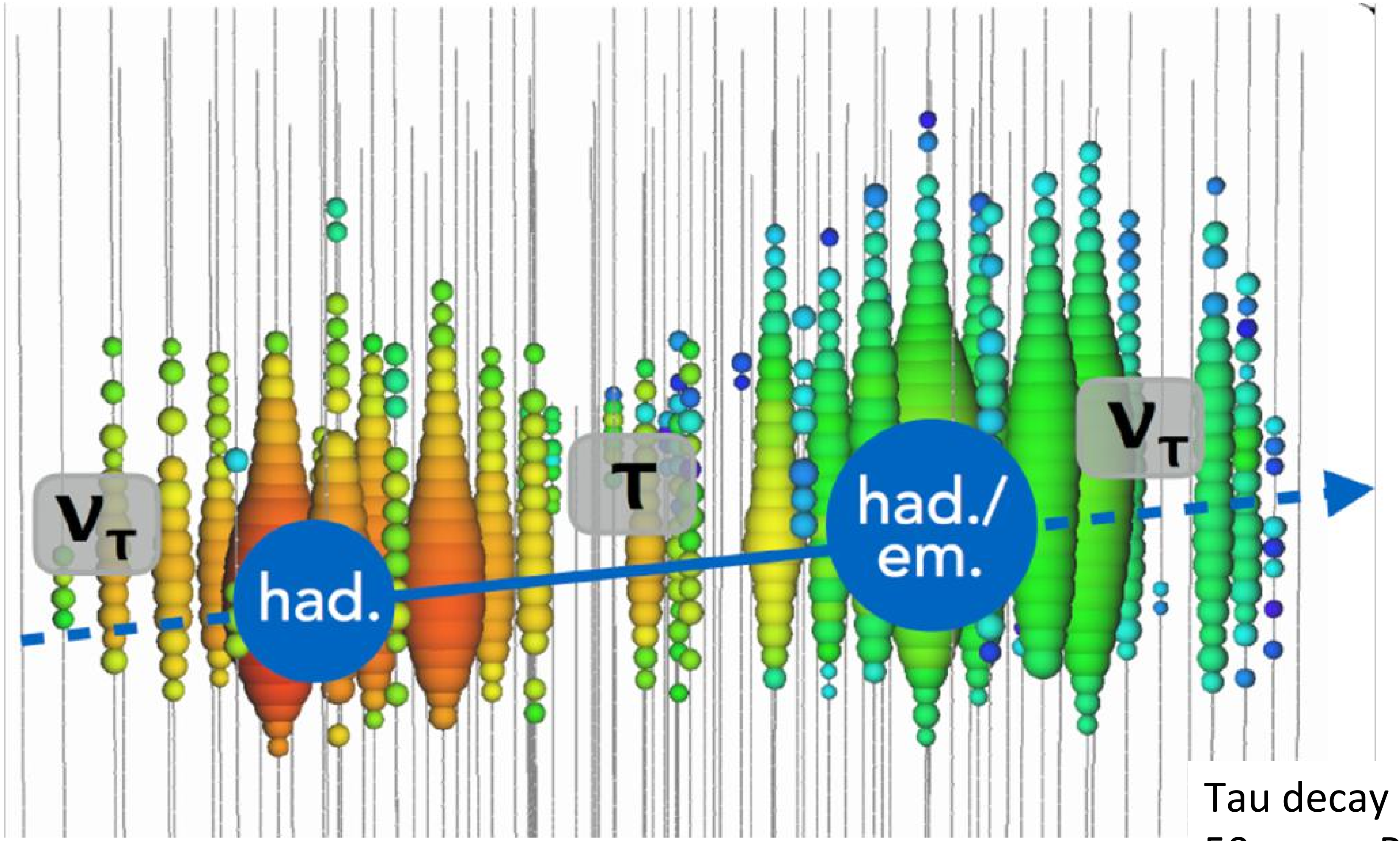


Upgoing muon event, track



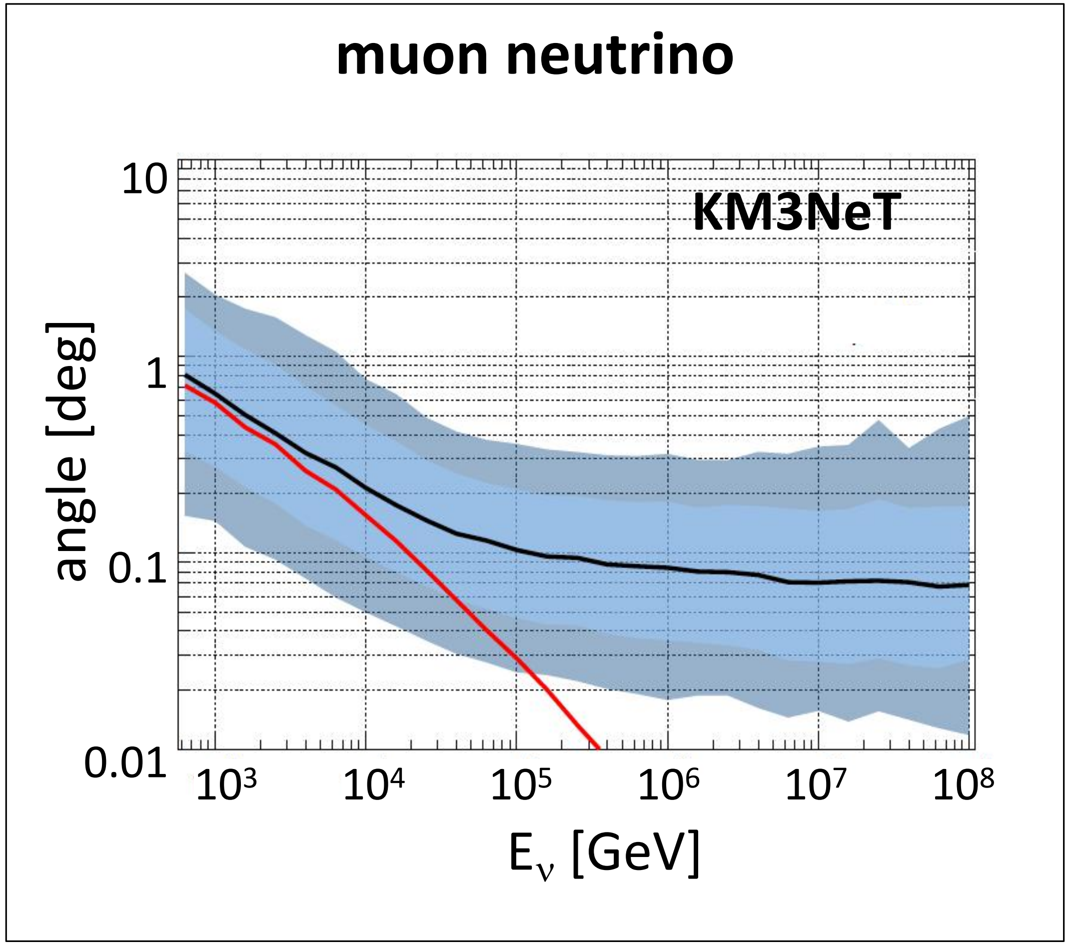
Electron event, cascade pattern

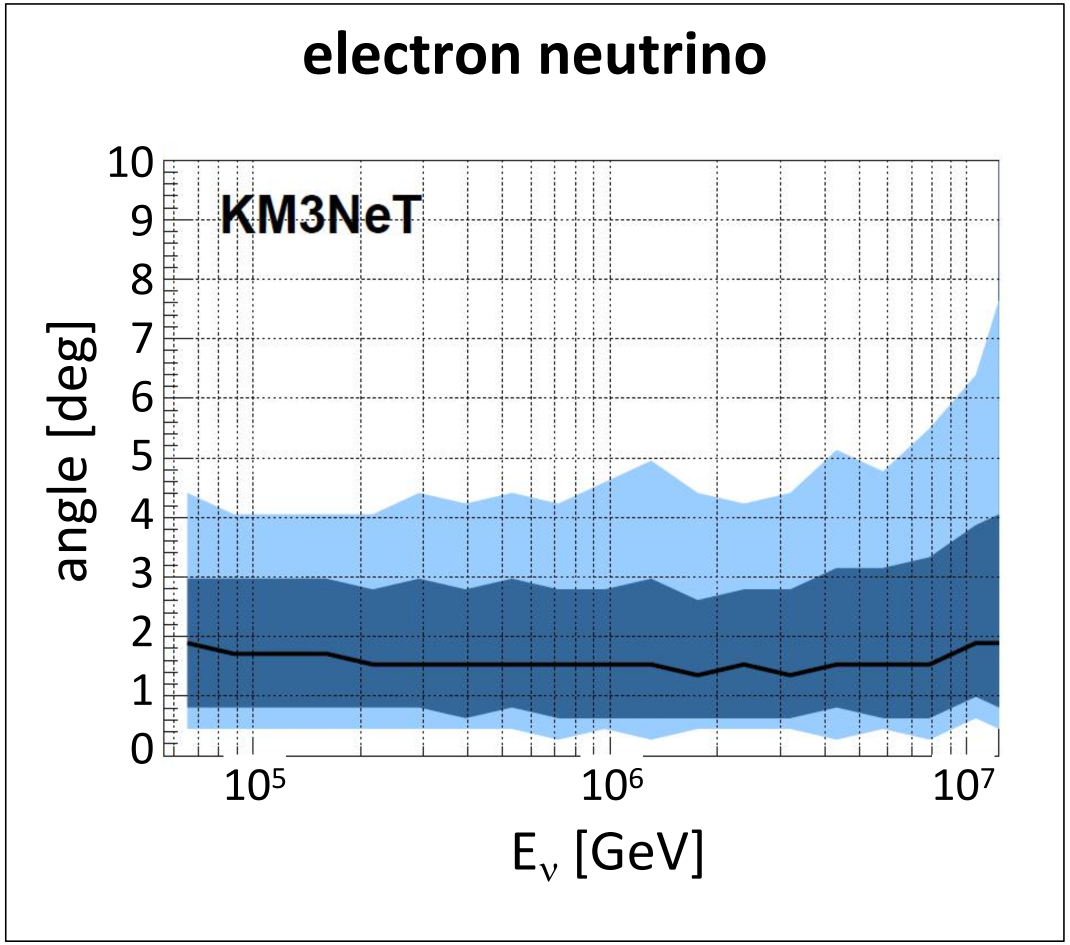
Tau production and decay



Tau decay length:
50 m per PeV

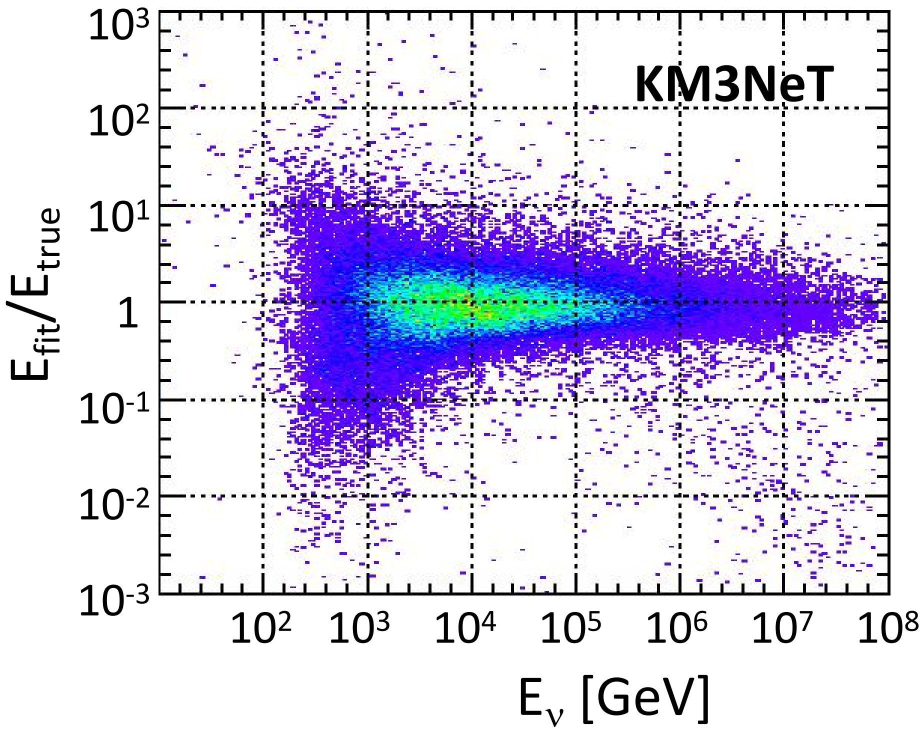
Angular resolution



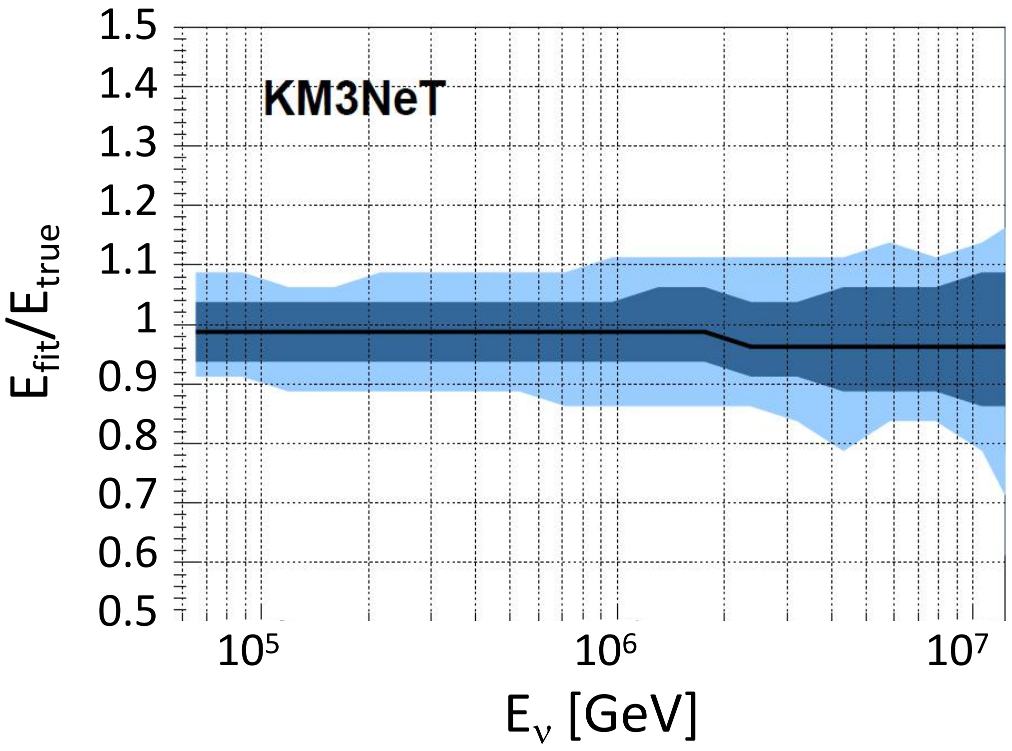


Energy resolution

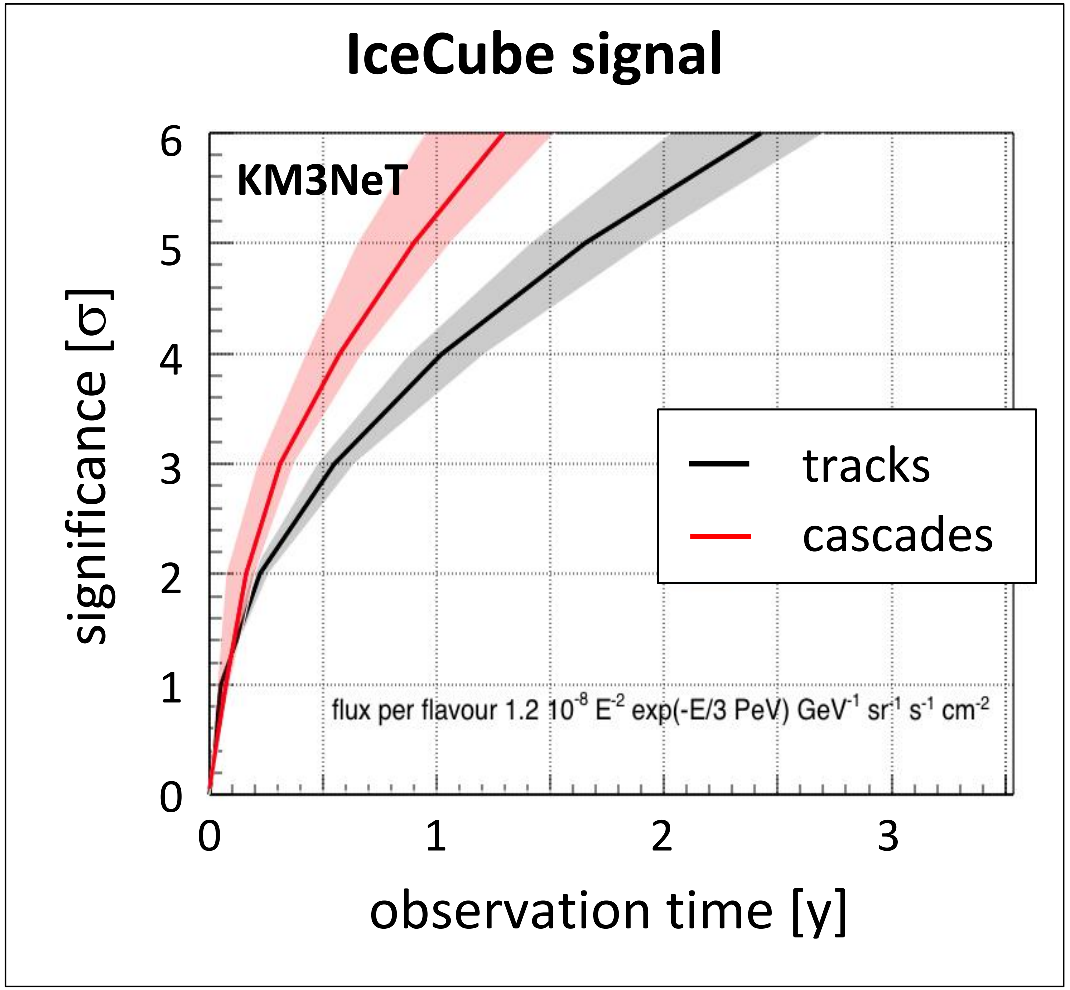
muon neutrino

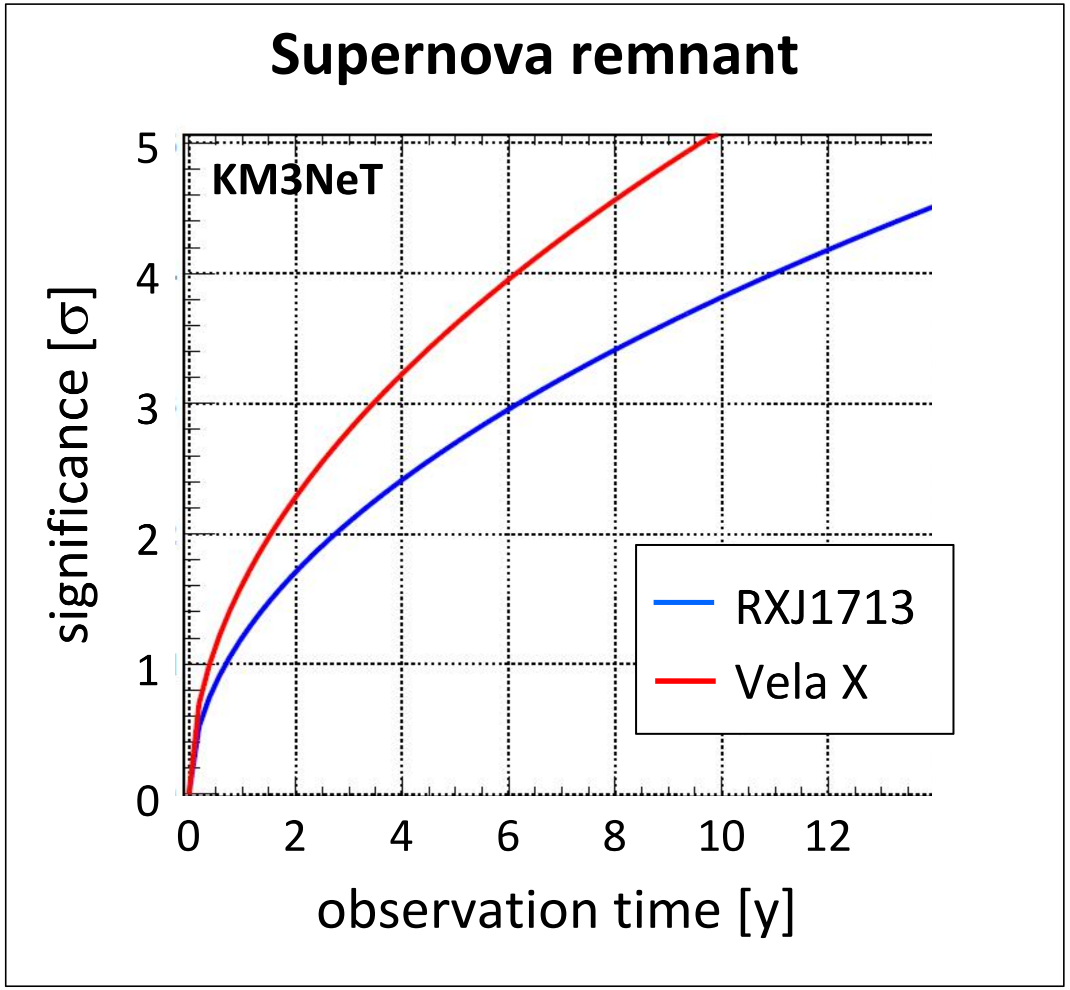


electron neutrino



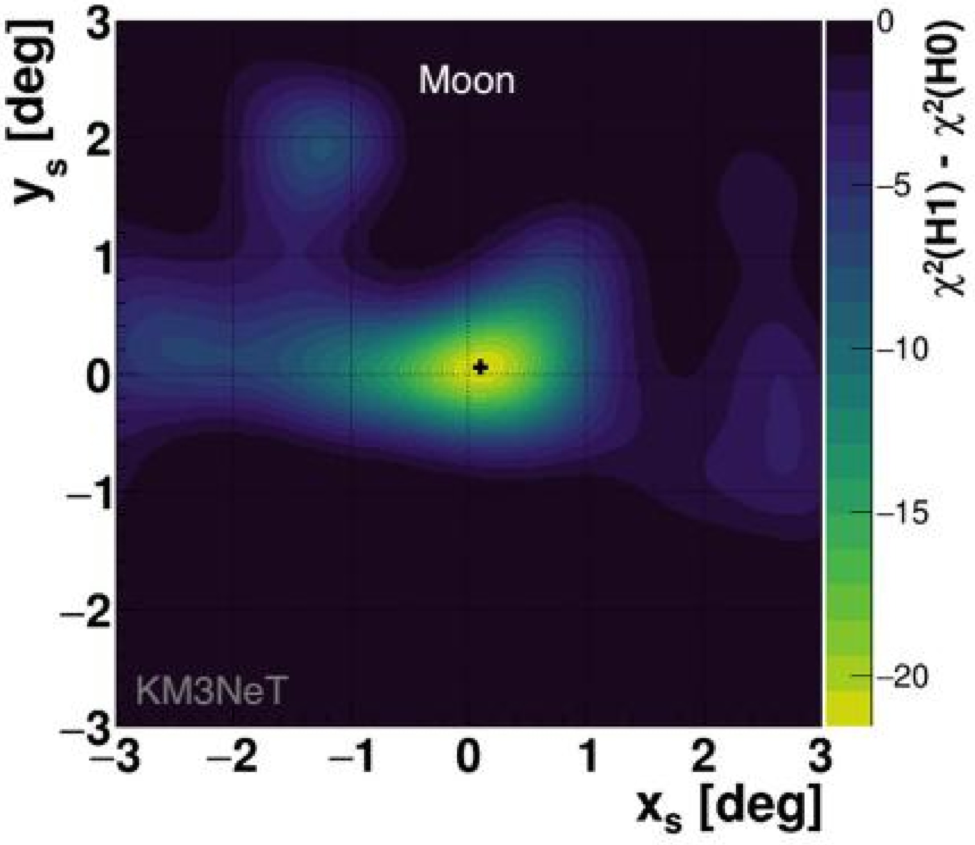
Sensitivity

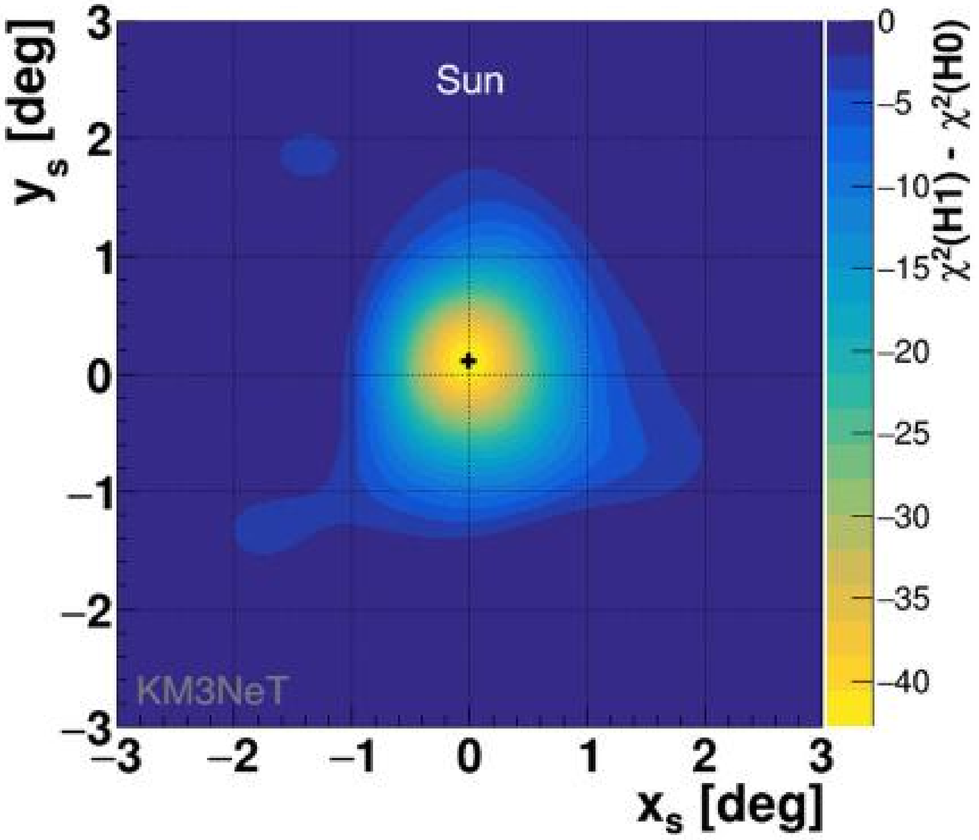




Direction measurement

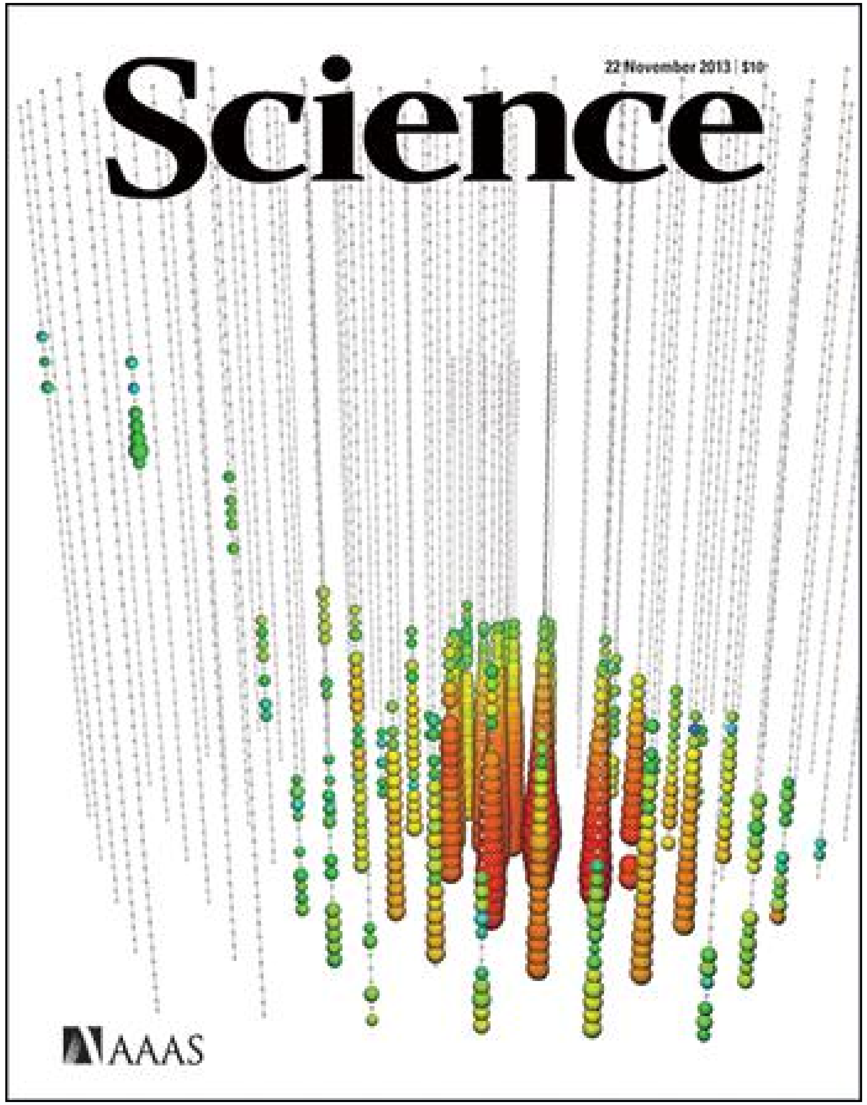
Sun shadow,
significance 6.0 σ,
resolution 0.68° +/- 0.15°



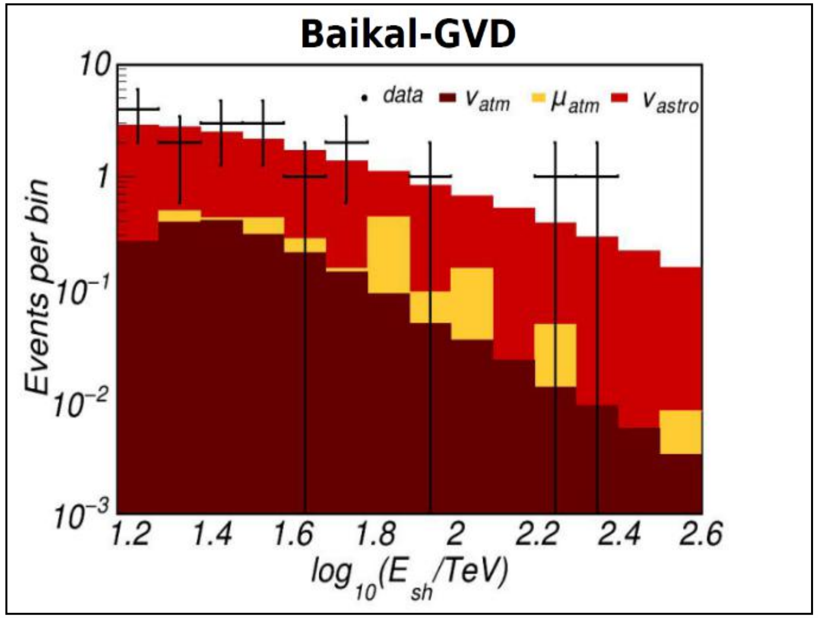


Highlights

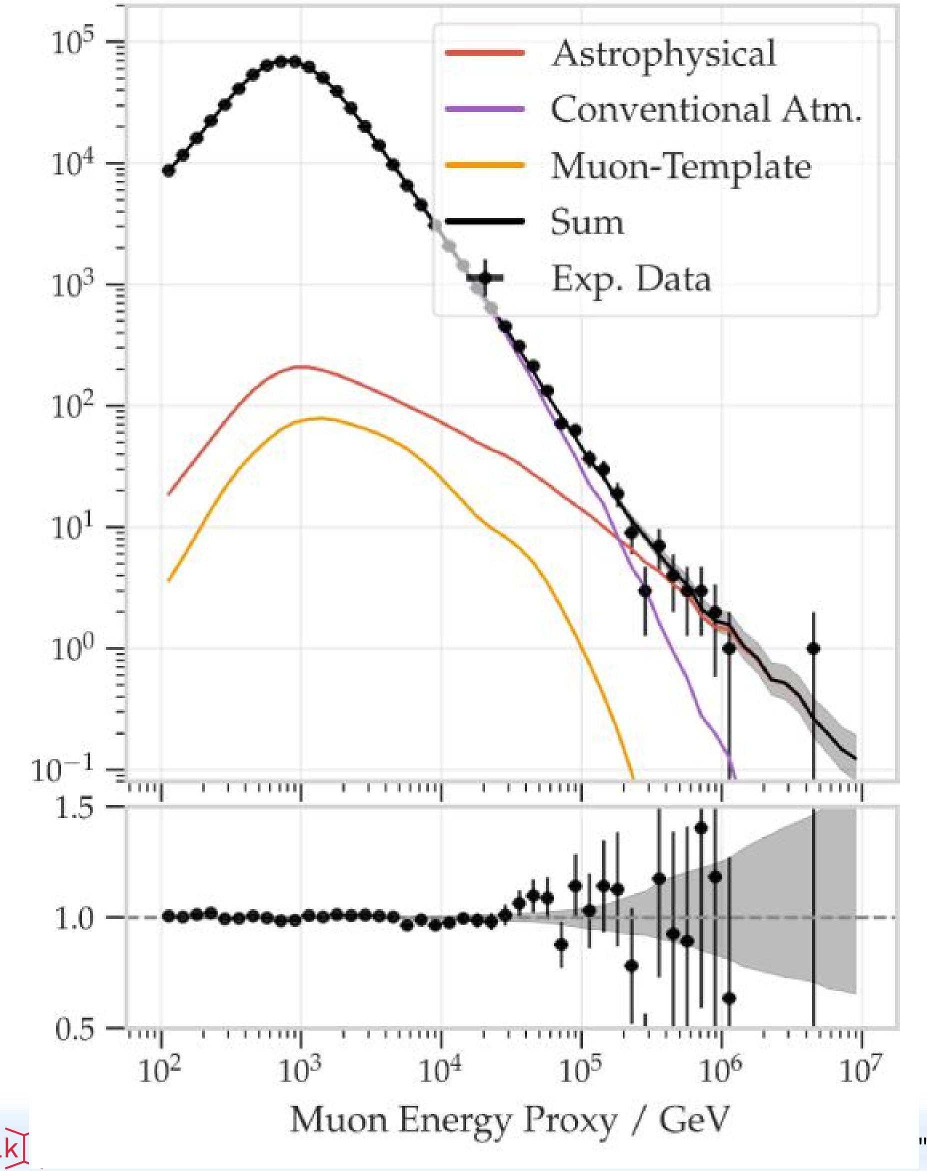
IceCube: Cosmic neutrinos exists



- 2013 publication of the first cosmic neutrino flux
- Confirmed by GVD & one very high energy neutrino from KM3NeT



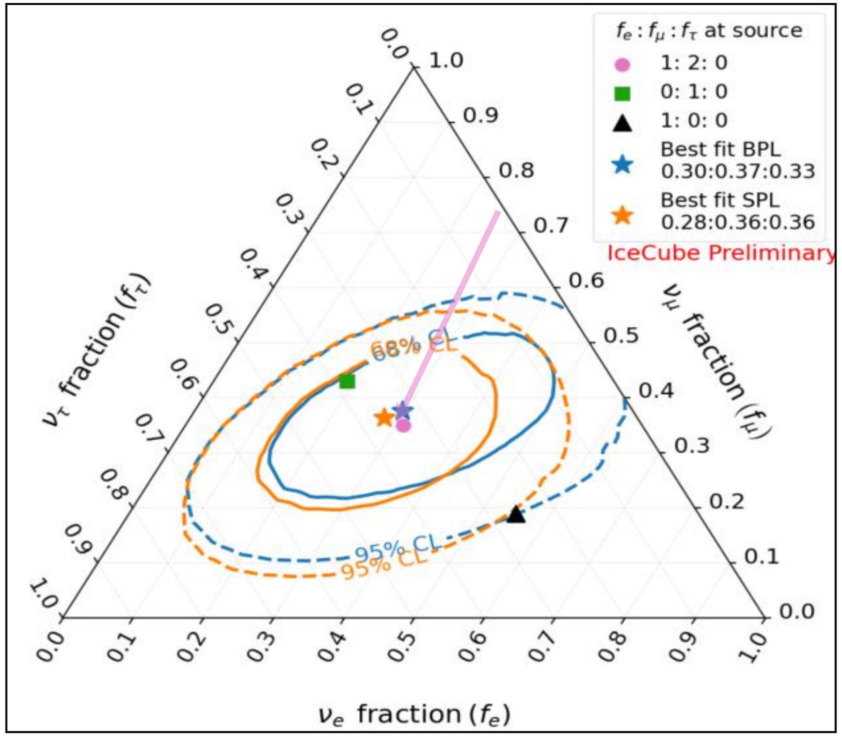
IceCube: Cosmic neutrinos exists

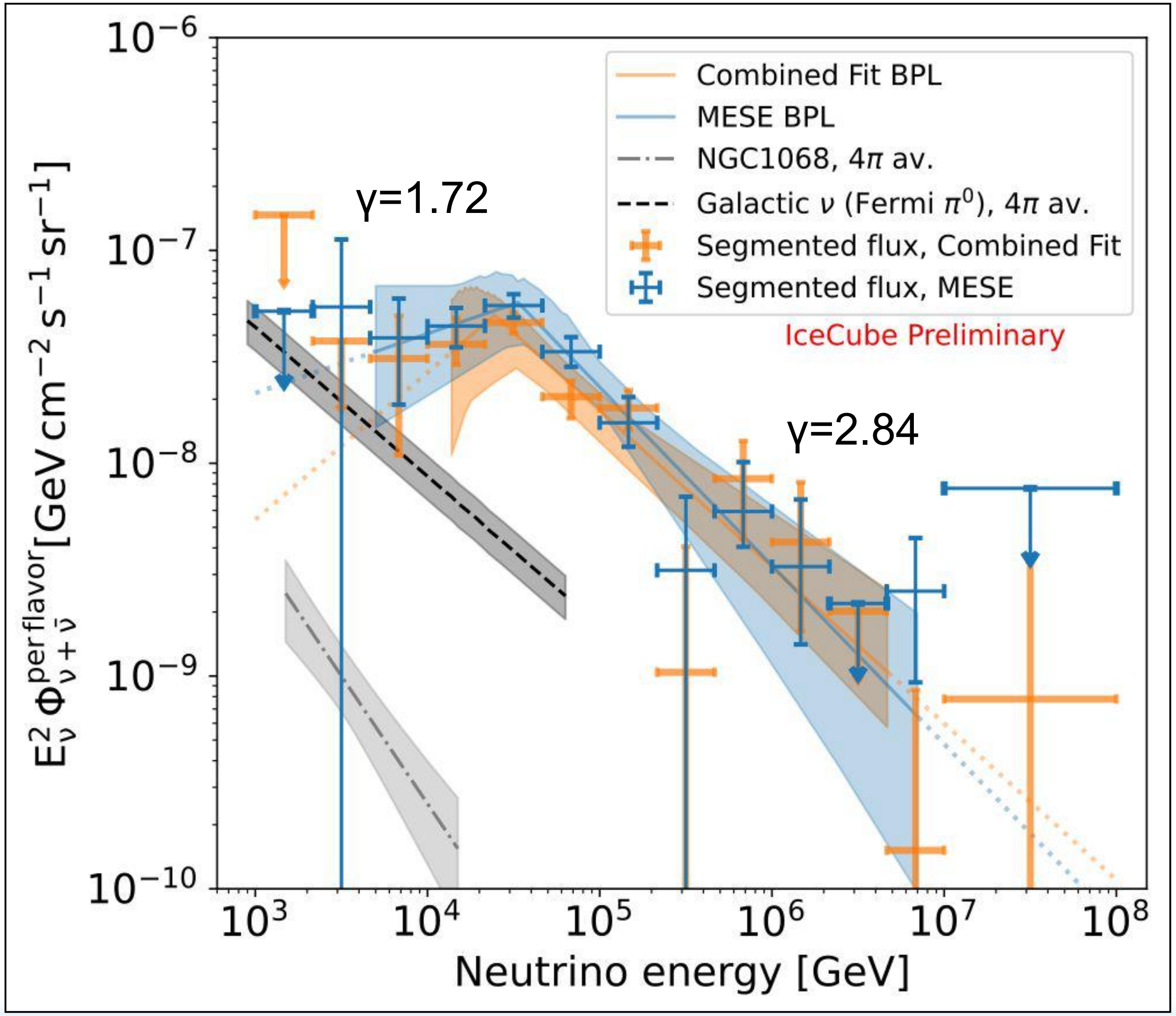


- 2013 publication of the first cosmic neutrino flux
- Confirmed by GVD & one very high energy neutrino from KM3NeT

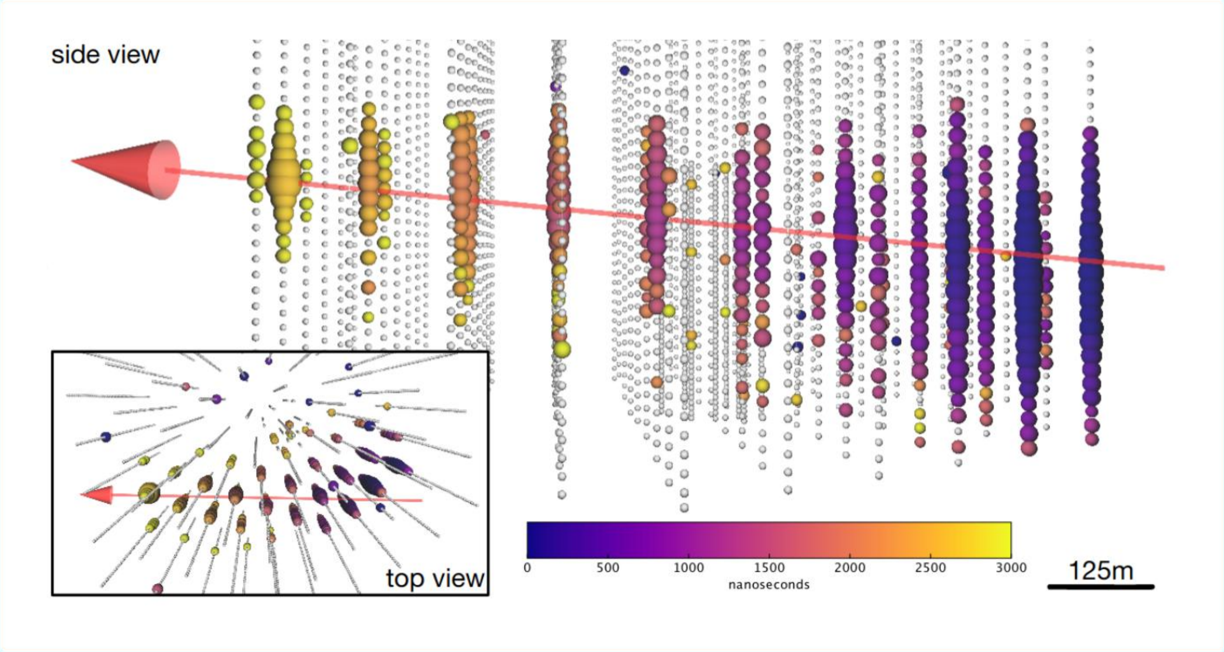
Cosmic neutrino flux measurement

- Diffuse, extragalactic
- Latest fit prefers broken power-law (4.7σ)
- Flavour ratio: 1:1:1





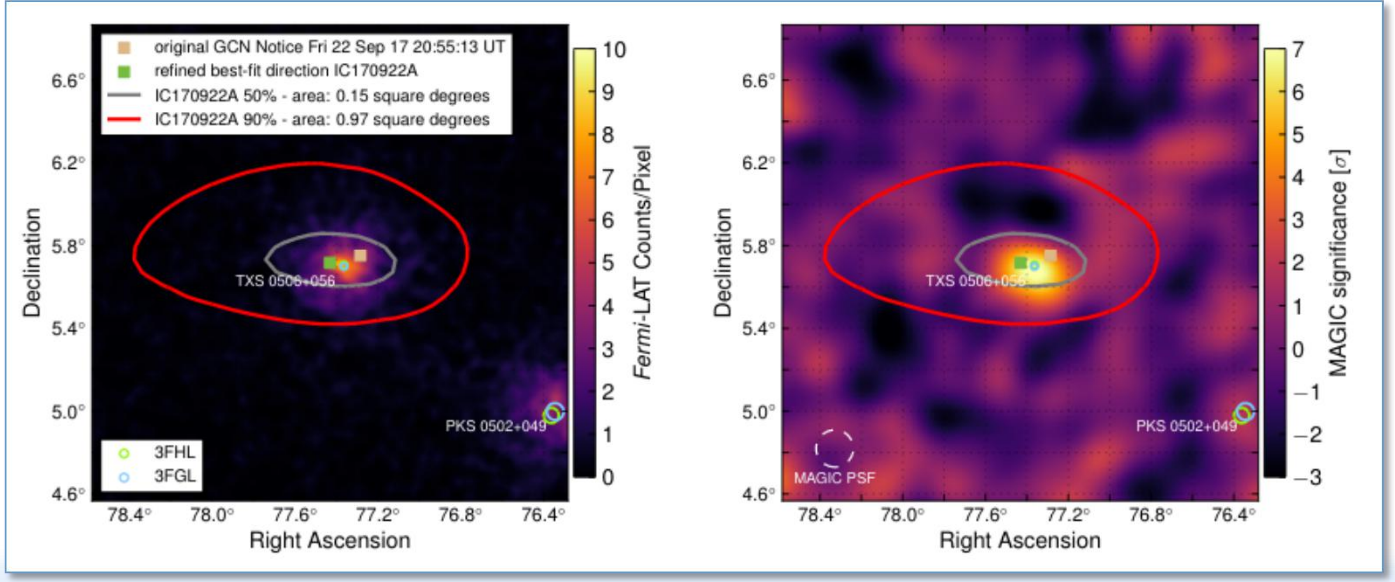
TXS 0506+056



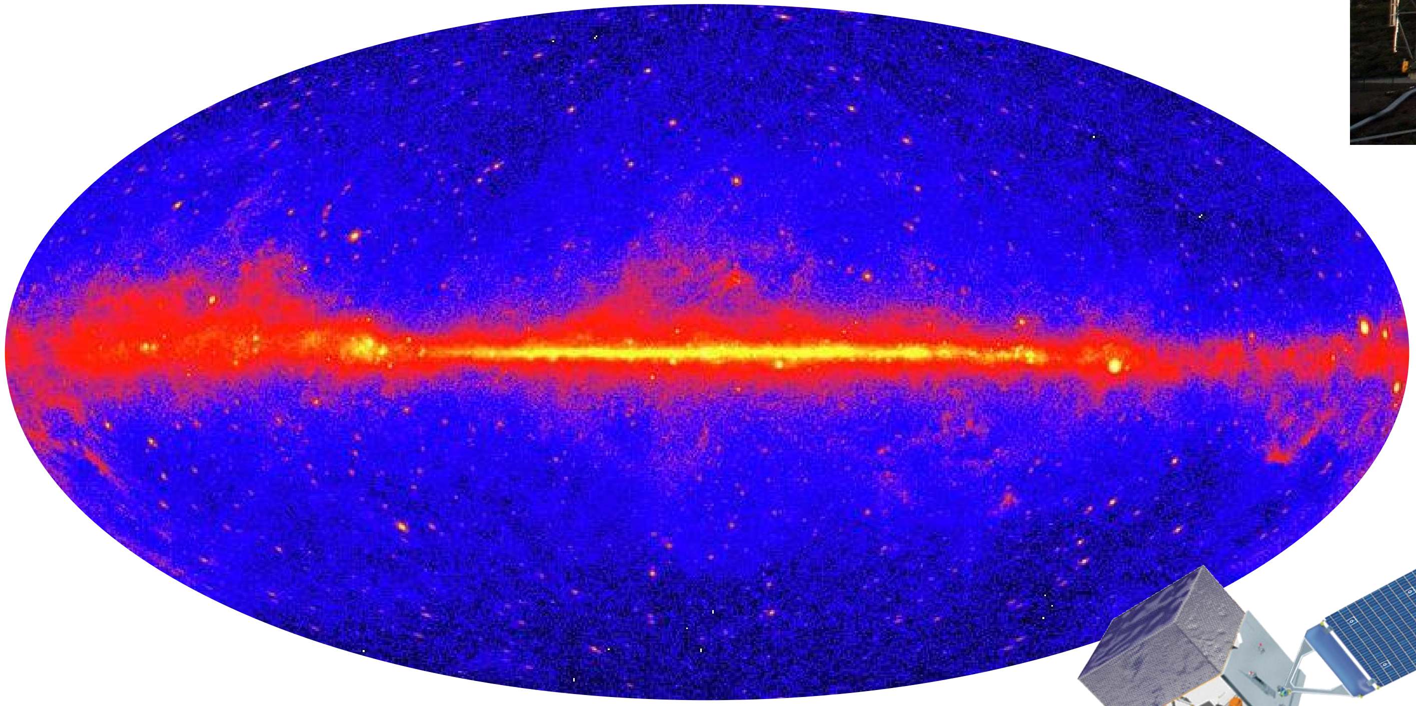
<u>22/9/2017, TXS 0506+056</u>:

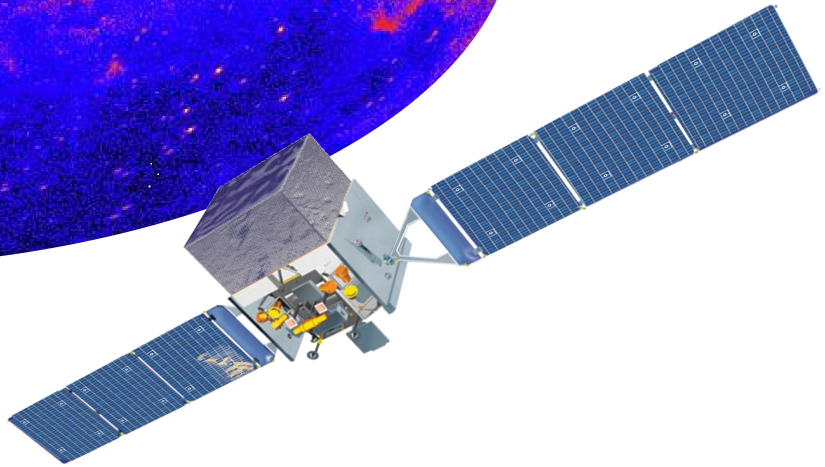
Blazer with first neutrino-gamma coincidence observation:

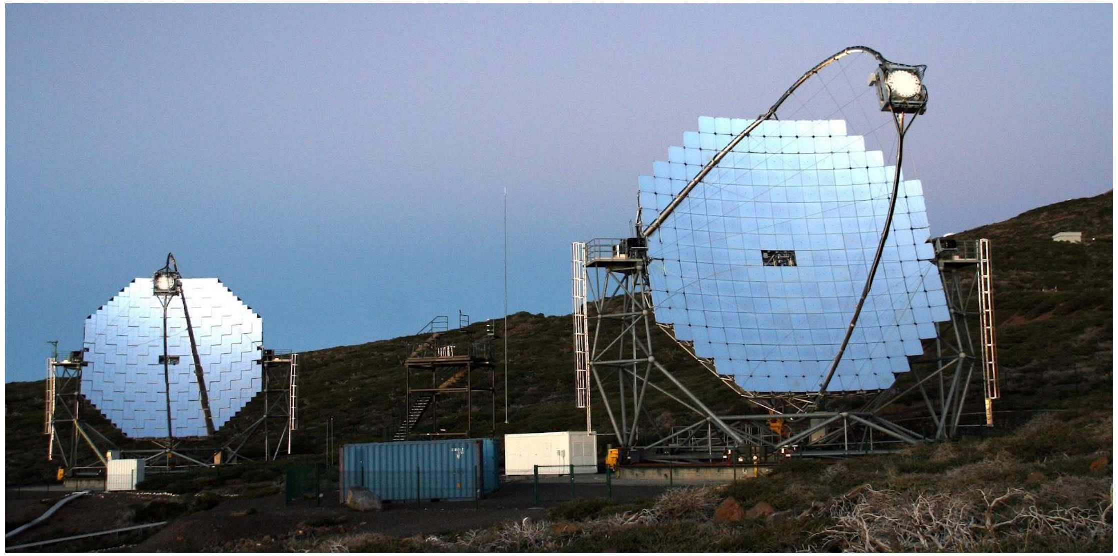
- Magic, Fermi
- IceCube



Fermi-LAT

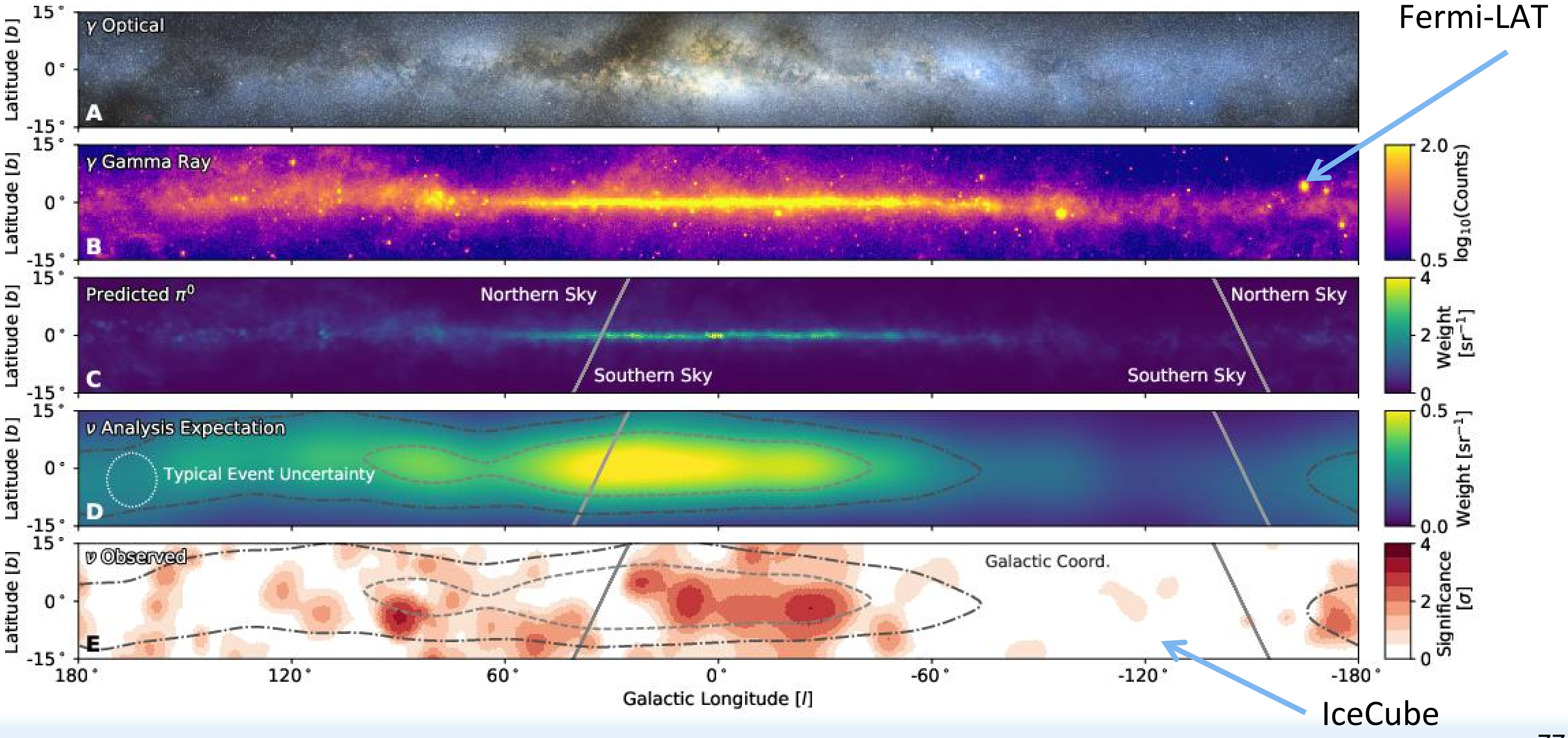






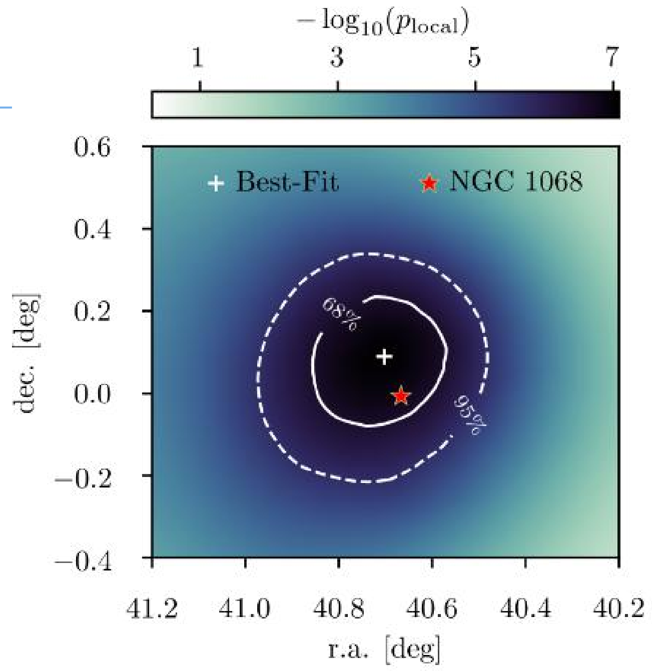
MAGIC

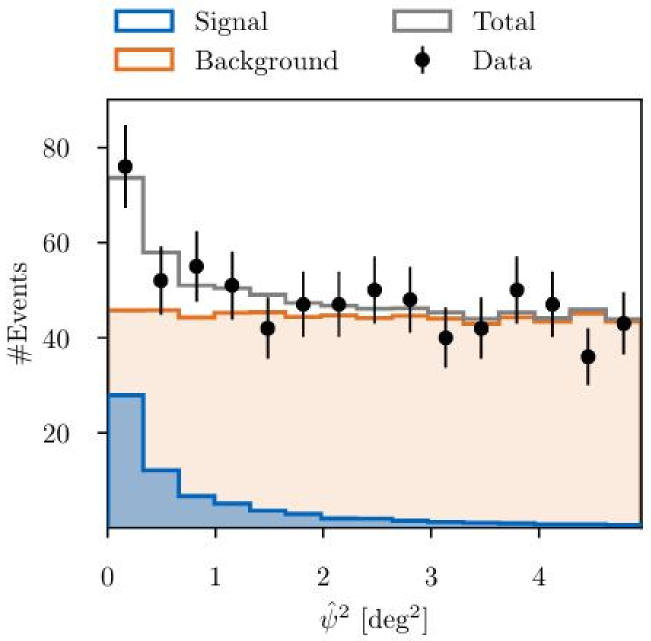
Neutrino sources

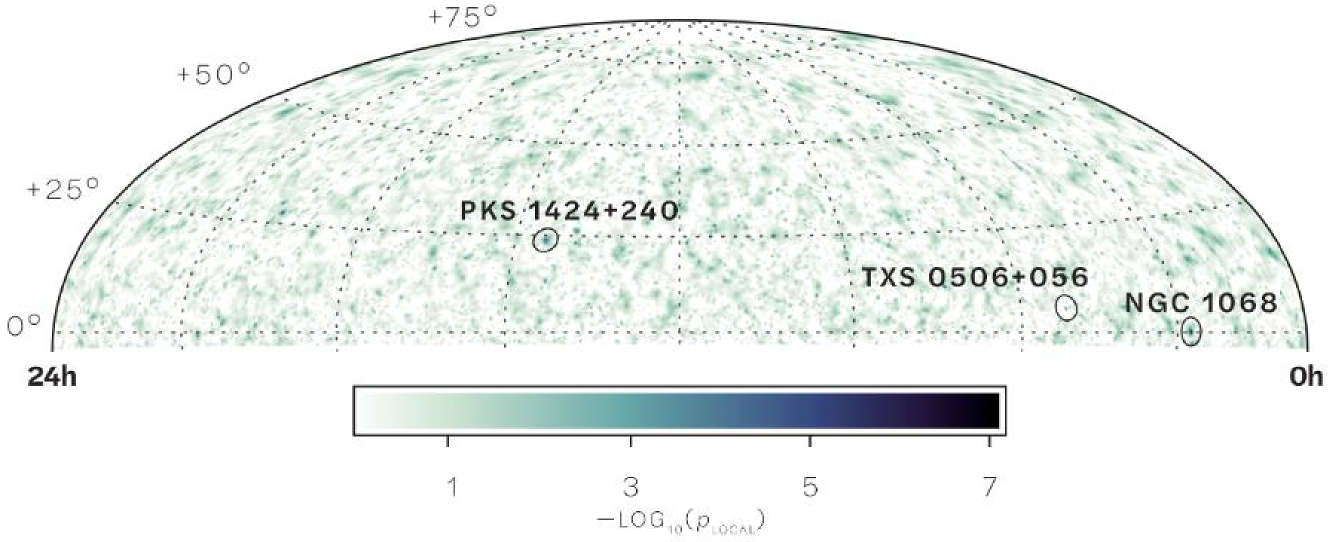


NGC 1068

- Integrated flux of over 10 years
- An excess of ~79 events (4.2 σ) in the vicinity of NCG 1068, which is an AGN

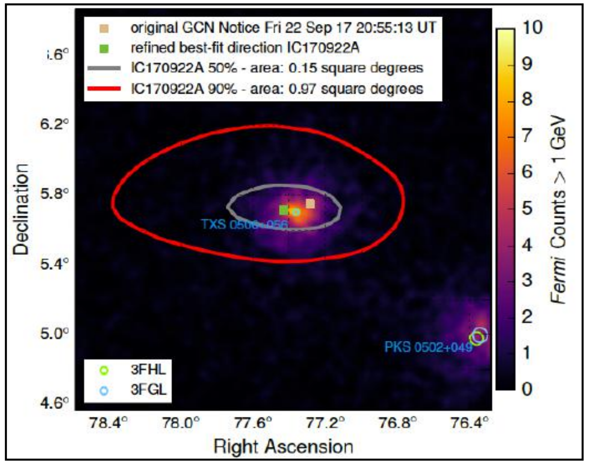






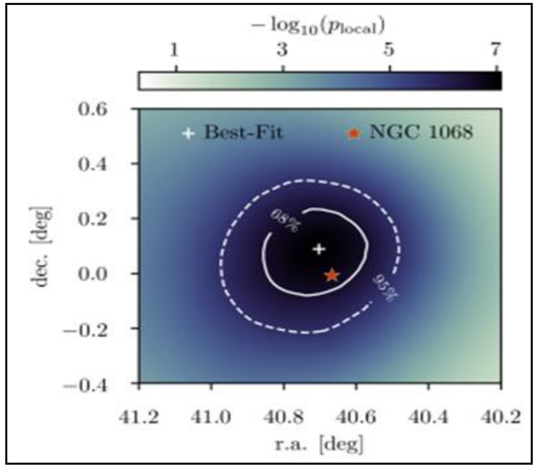
Cosmic neutrino sources

TXS 0506+056



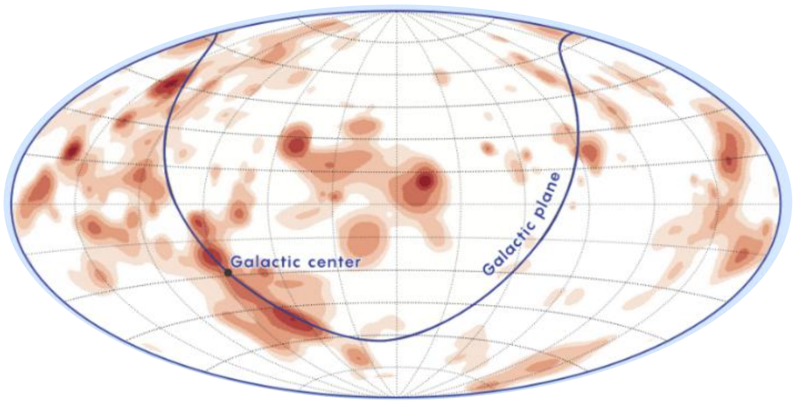
- High energy IceCube track from 2017
- Location: known Blazar, TXS 0506+056 also 'flaring' in X-rays at the time.
- Extensive Multi-messenger follow-up
- ν burst in 2015

NGC 1068



- Excess of upgoing neutrino candidates
  from direction of an Active Galaxy
- 10 years of data
- Very few gamma rays

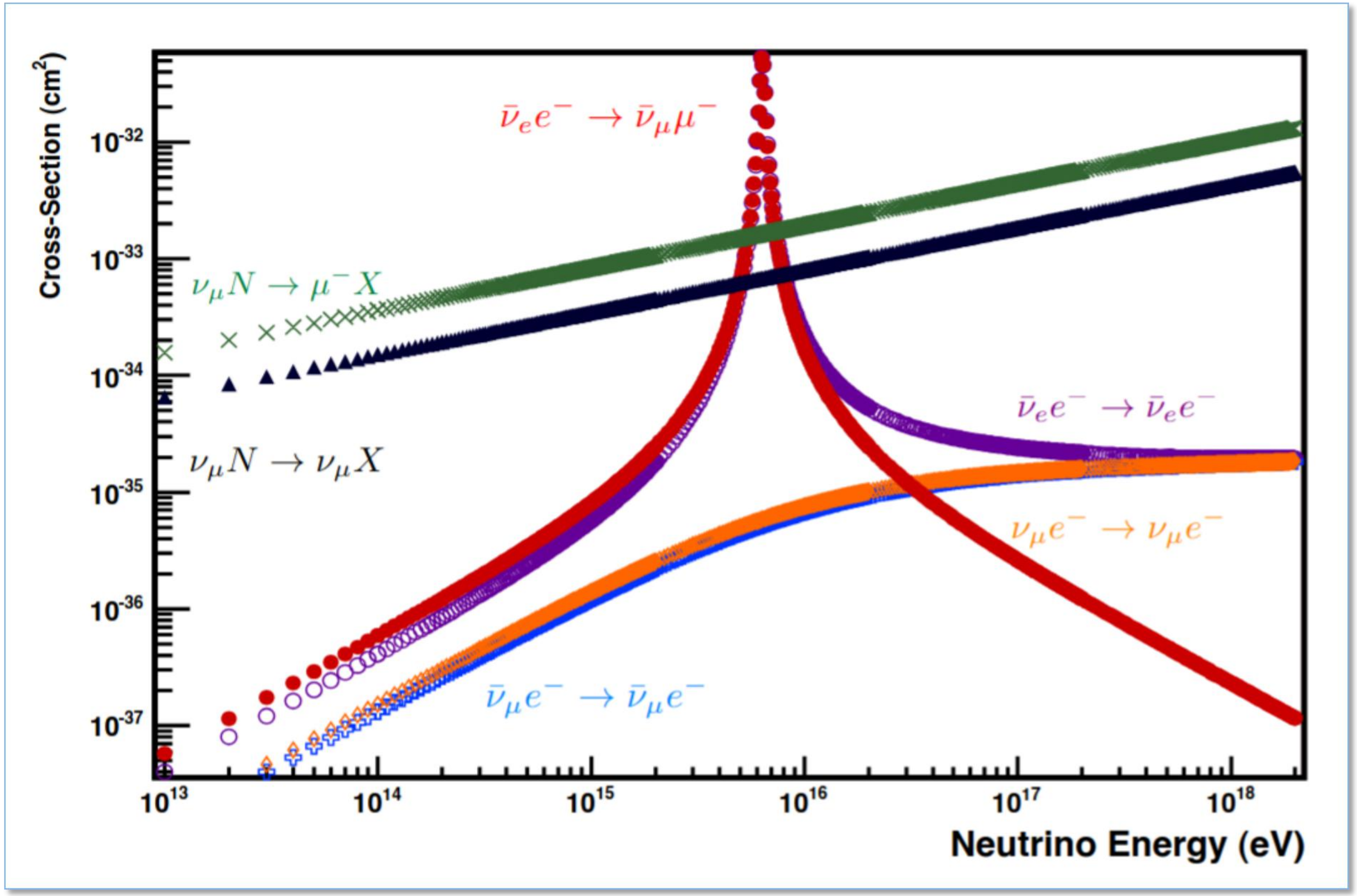
Galactic plane



- Diffuse / unresolved contribution from our Galaxy
- ~10% of all cosmic neutrinos

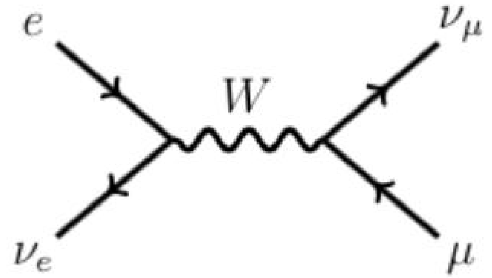
Vast majority of cosmic neutrinos has no known source…

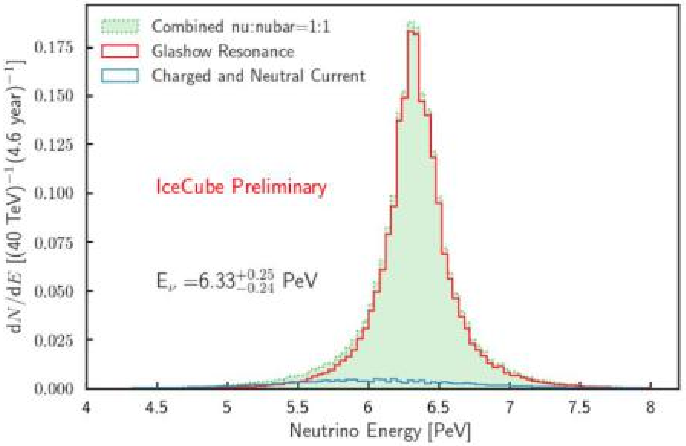
Neutrino sources and their fluxes



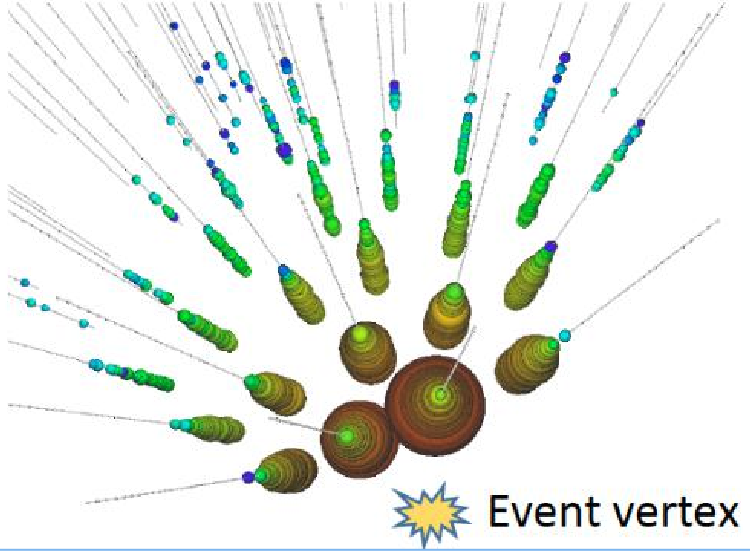
Glashow event

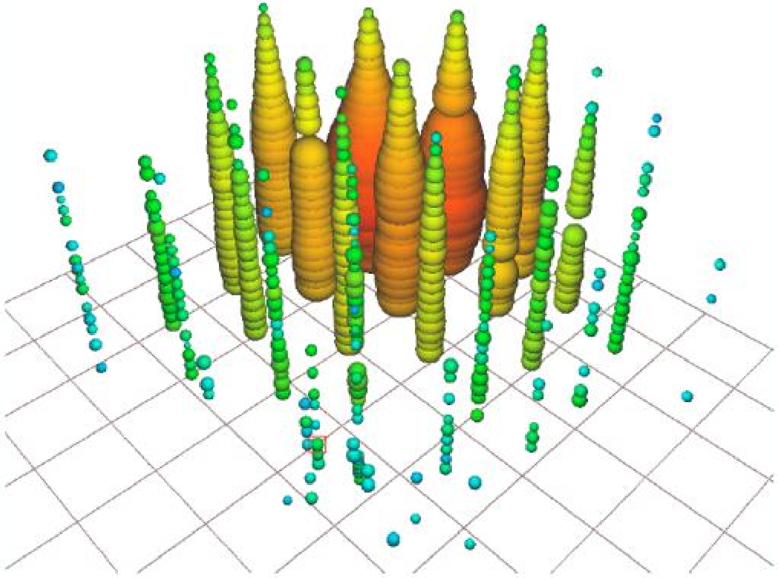
Resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron





Detection of anti neutrino in cosmic neustrino flux:
Test predictions from cosmic ray interactions with interstellar matter, such as pγ and pp





“Detection of a particle shower at the Glashow resonance with IceCube”, Nature, Vol 591 (2021), p

Glashow event

equal mixture of π^0, π^- and π^+, one expects the ratio $\bar{\nu}_e : \nu_e = 1:1$

Detection of anti neutrino in cosmic neustrino flux:
Test predictions from cosmic ray interactions with interstellar matter, such as pγ and pp

Counting the anti neutrinos in the total flux

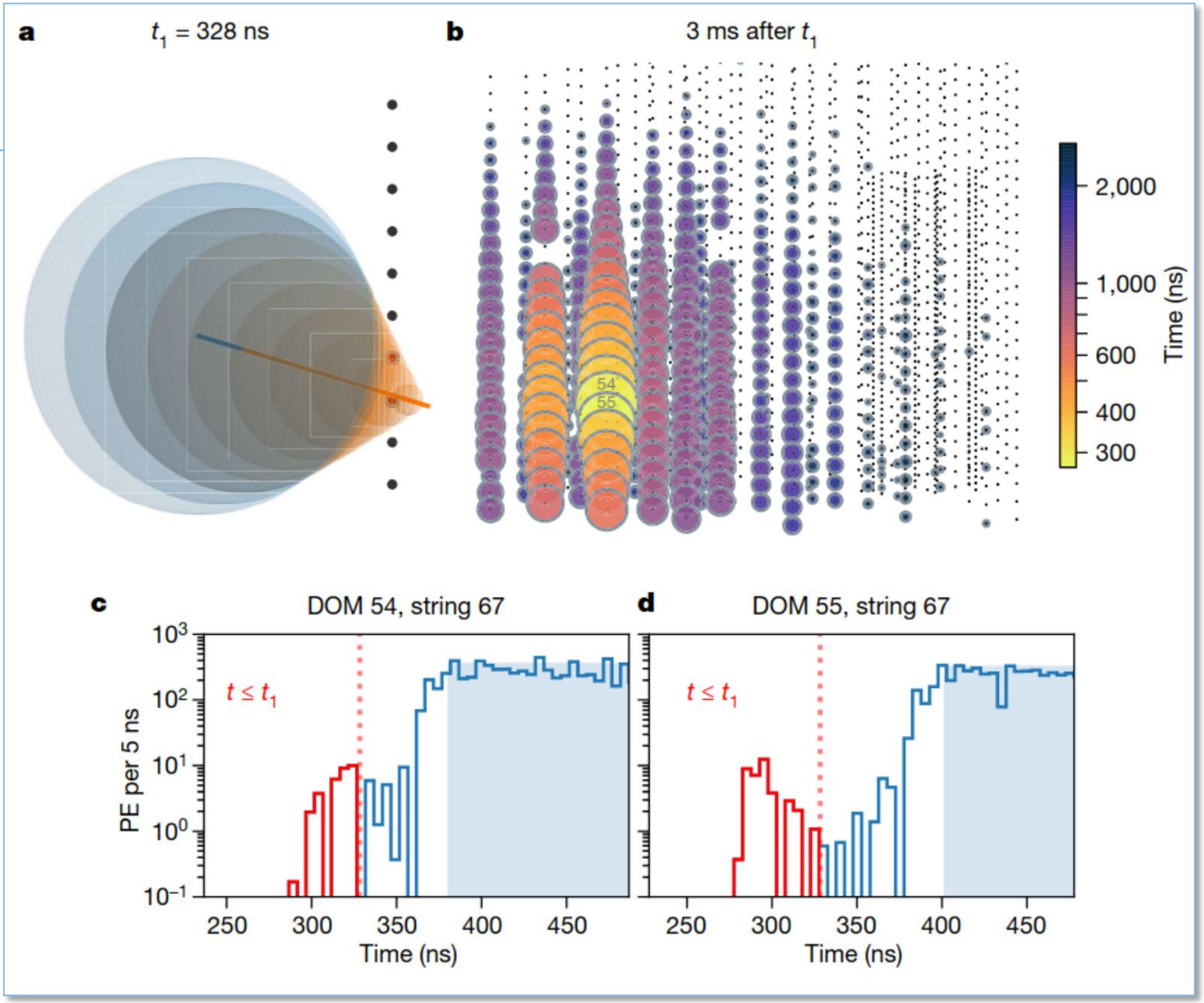
$\bar{\nu}_e : \nu_e = 1:3.5$ at Earth

We consider six possible source models:
(i) $pp \to \pi^\pm$ pairs $\to \nu_e + \bar{\nu}_e + 2\nu_\mu + 2\bar{\nu}_\mu$, referred to as the "$\pi^\pm$ *mode*";
(ii) $pp \to \pi^\pm$ pairs $\to \nu_\mu,\ \bar{\nu}_\mu$ only, referred to as the "*damped* $\mu^\pm$ *mode*";
(iii) $p\gamma \to \pi^+$ only, $\to \nu_e + \nu_\mu + \bar{\nu}_\mu$, referred to as the "$\pi^+$ *mode*";
(iv) $p\gamma \to \pi^+ \to \nu_\mu$ only, referred to as the "*damped* μ^+ *mode*";
(v) charm production and immediate decay to $\nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu$, referred to as the "*prompt mode*"; and
(vi) β-decay of cosmic neutrons to $\bar{\nu}_e$, referred to as the "*neutron decay (or* β *decay) mode*".

V. Barger et al, arxiv.1407.3255

Glashow event

- Detection of an early pulse of the high energy muon that ‘*outruns*’ the Cherenkov photons from the hadronic shower.
- The Cherenkov signal from the muon is observed as a early pulse in the DOMs



“Detection of a particle shower at the Glashow resonance with IceCube”, Nature, Vol 591 (2021), p

February 13 2023, 01:16:47 UTC

Lecture by Maarten on Wednesday

Article

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

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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[5].

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.

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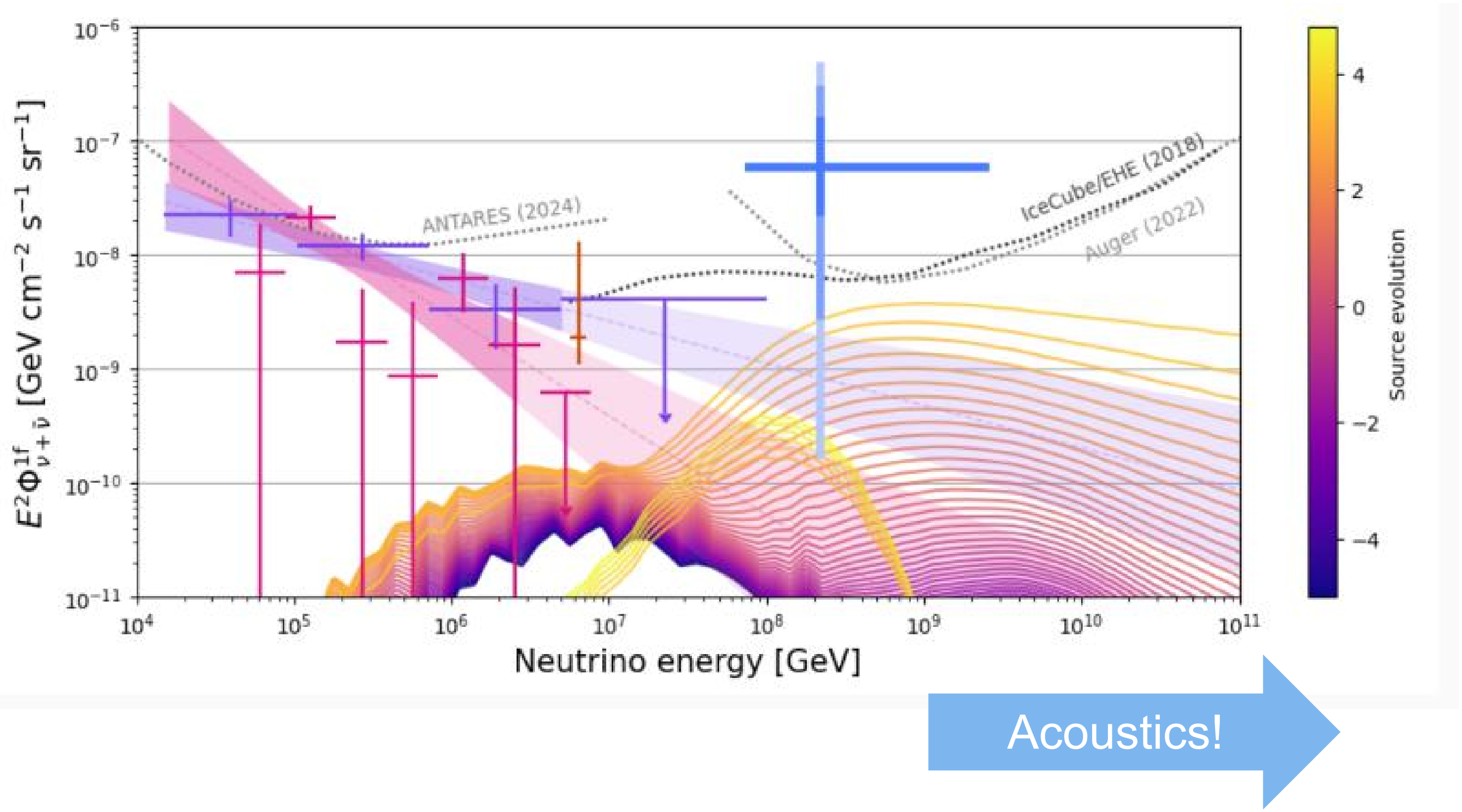
Alternative detection methods

A cosmic origin

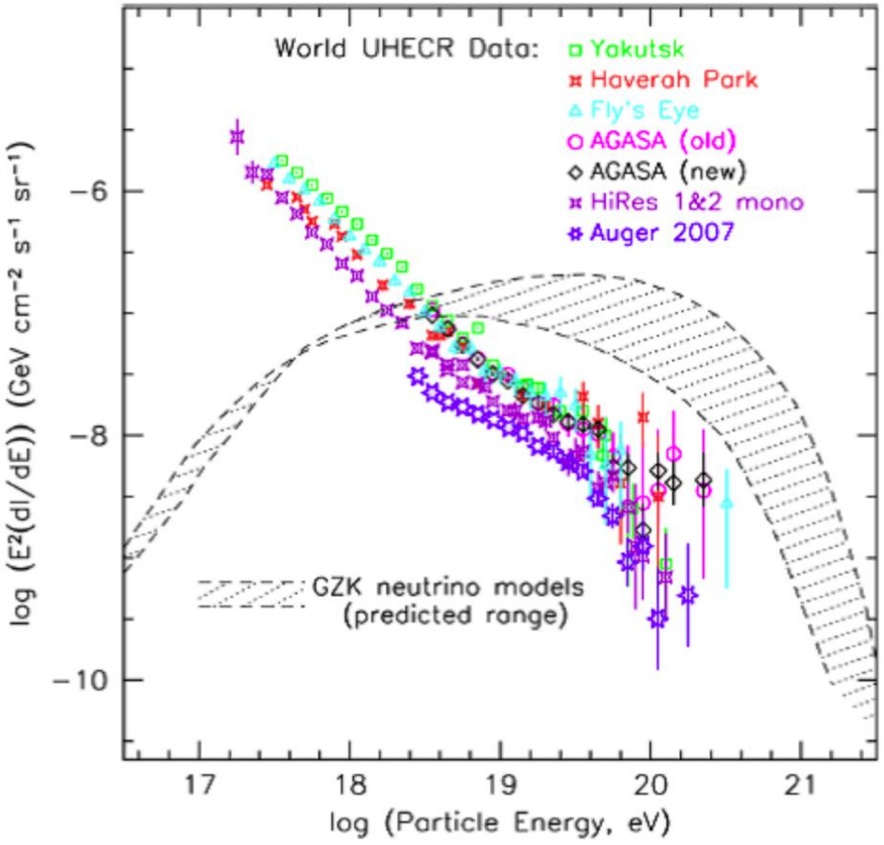
Adriani et al, 2025

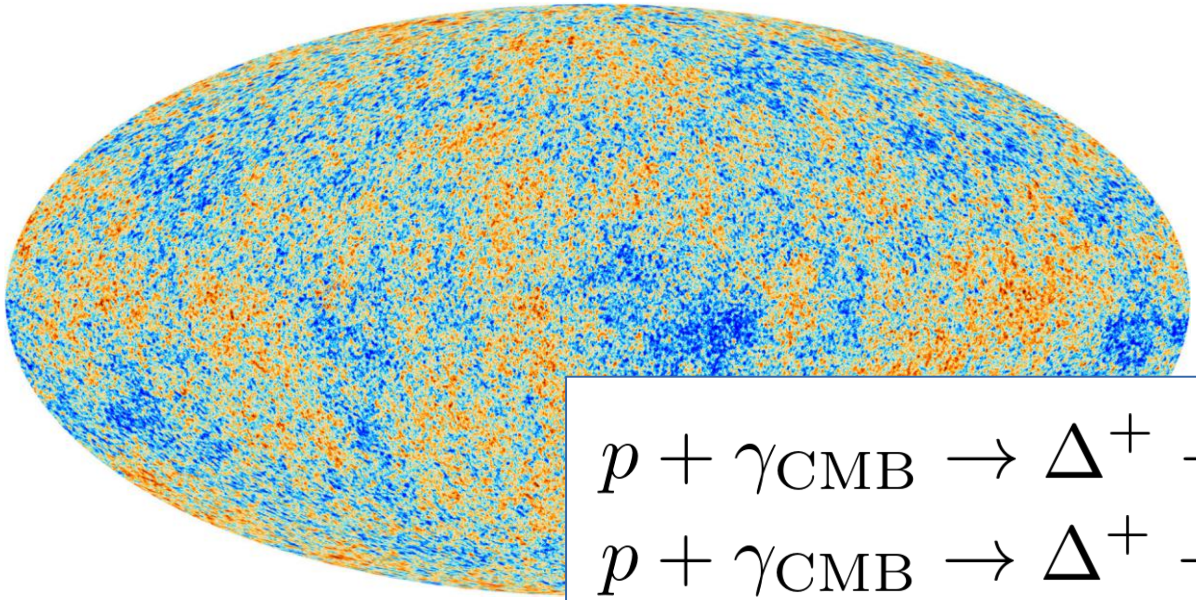


- Flux predictions, depends on the composition of the cosmic rays (Protons, ions)
- VHE event shows a preference for proton dominated cosmic flux
- (Flux prediction differs with more than 3 orders of magnitude)

The GZK cut-off

- Greisen, Zatsepin and Kuzmin (1966): Universe is not transparent for high energy protons and ions.
- Berezinsky and Zatsepin: first prediction of associated neutrino flux

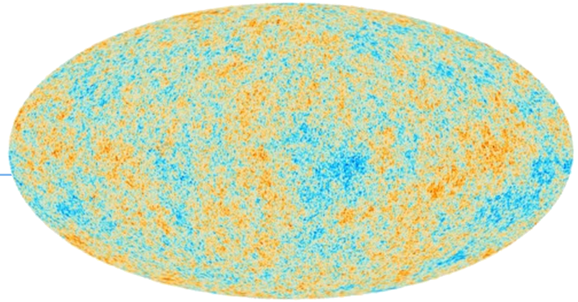




$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^o$$
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

… with subsequent decay to *neutrinos*

The GZK horizon



The universe is opaque for cosmic rays at resonances.

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p + \pi^{o}$$
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

Cross section for proton-photon reaction

$$\lambda = \frac{1}{n\sigma}$$

$$\sigma_{p\gamma} \approx 10^{-28} \text{ cm}^{-2}$$
$$n = 420(1+z)^{3} \text{ cm}^{-3}$$

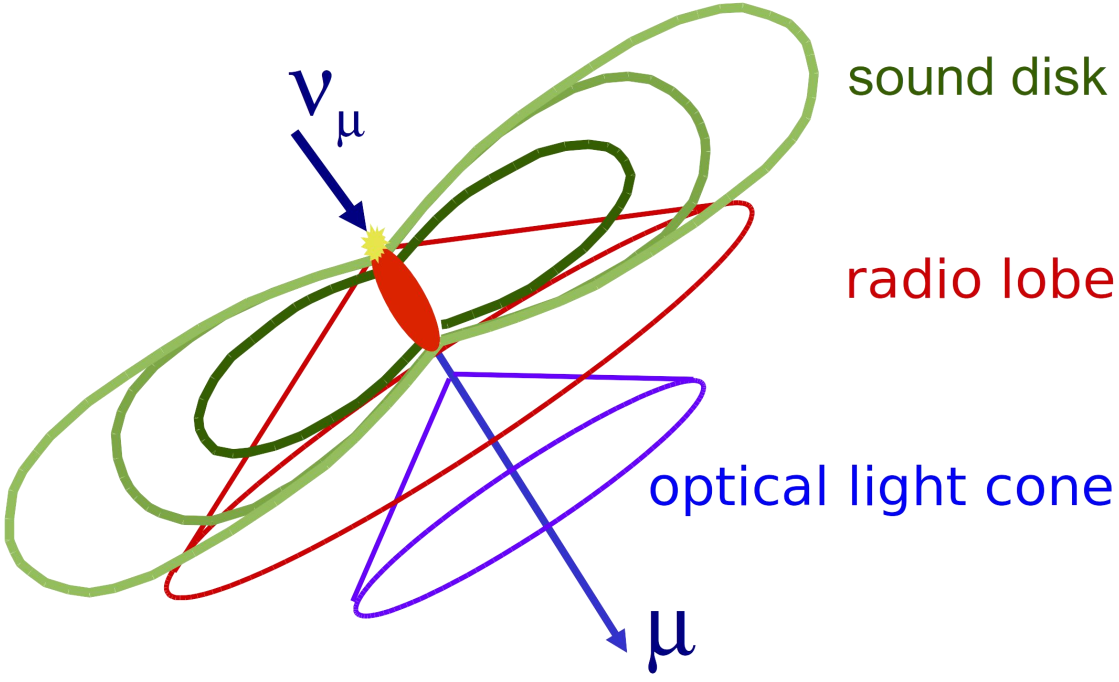
Density of CMB photons in the Universe

$$\lambda_{\text{GZK}} \approx 8Mpc$$

Mean free path. Total energy is absorbed around 100 Mpc

Detection of high energy neutrinos

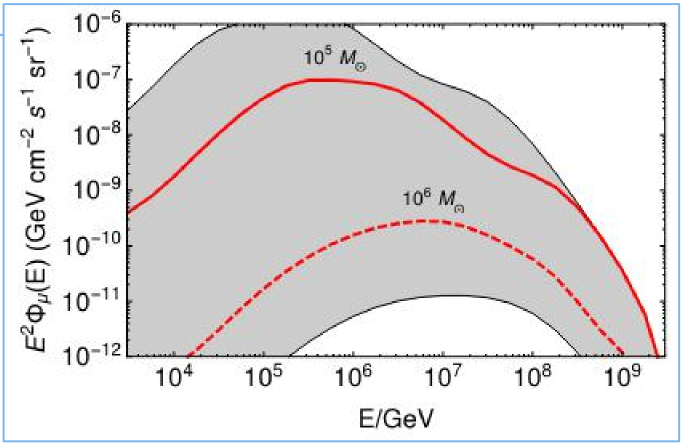
- Three methods of observing neutrinos in large scale telescopes
  - Optical, Cherenkov radiation
  - Coherent radio emission
  - *Acoustic signals*



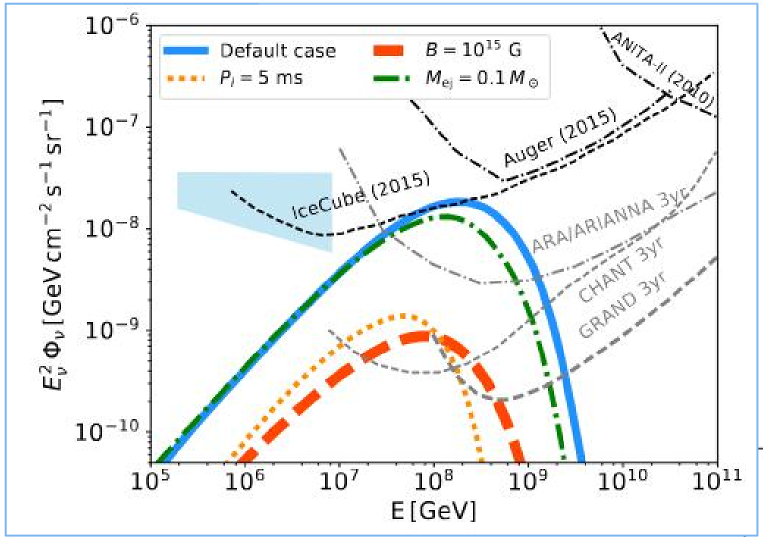
Scientific objectives of an acoustic telescope

- Astrophysical sources, origin of UHECR:
  - GZK neutrinos
  - AGNs, Blazars
  - Tidal Disuption Events (TDE)
  - Magnetars
- Exotics:
  - Superheavy dark matter
- Particle physics at energy scale presently unreachable
  - Cross section measurement
- Cosmic neutrino background
- Serendipity
  - Is there a fundamental end to the CR spectrum?

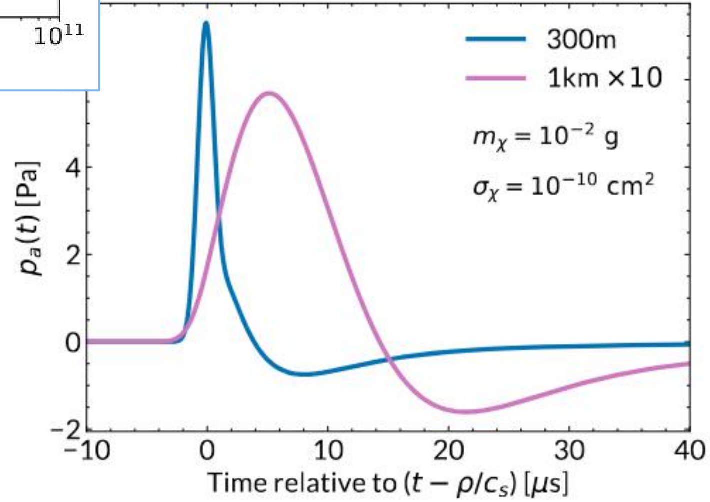
Lunardini, Winter 2017



Fang, Metzger 2017

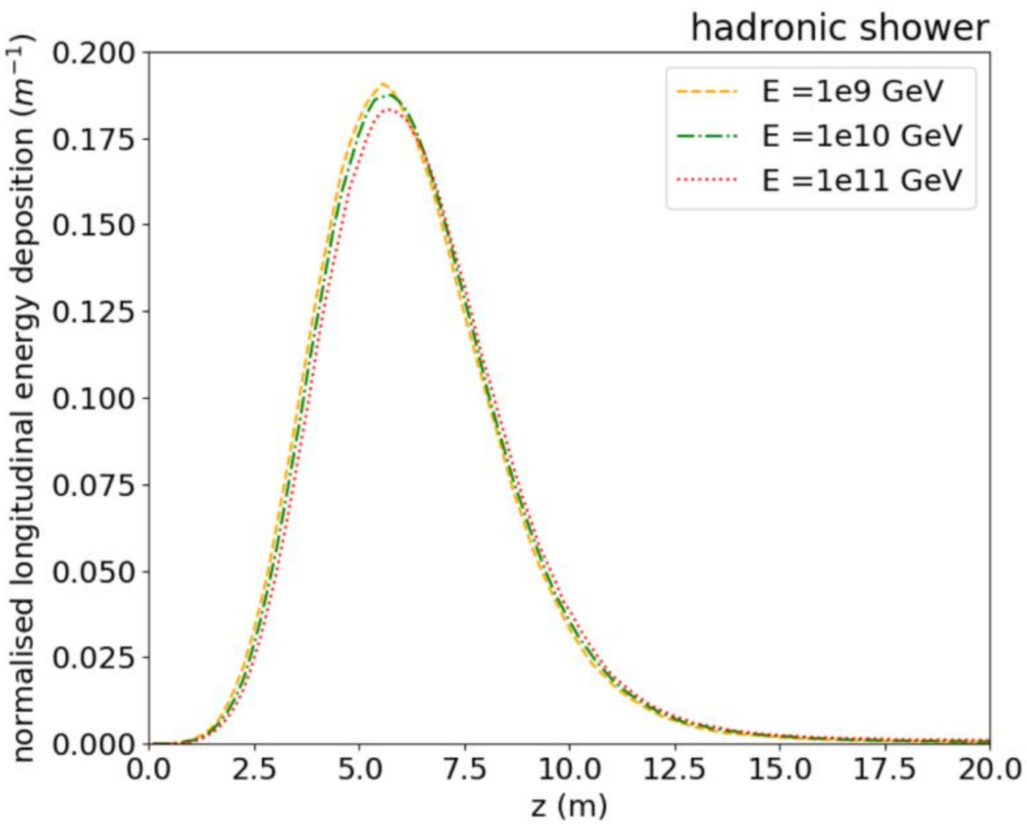


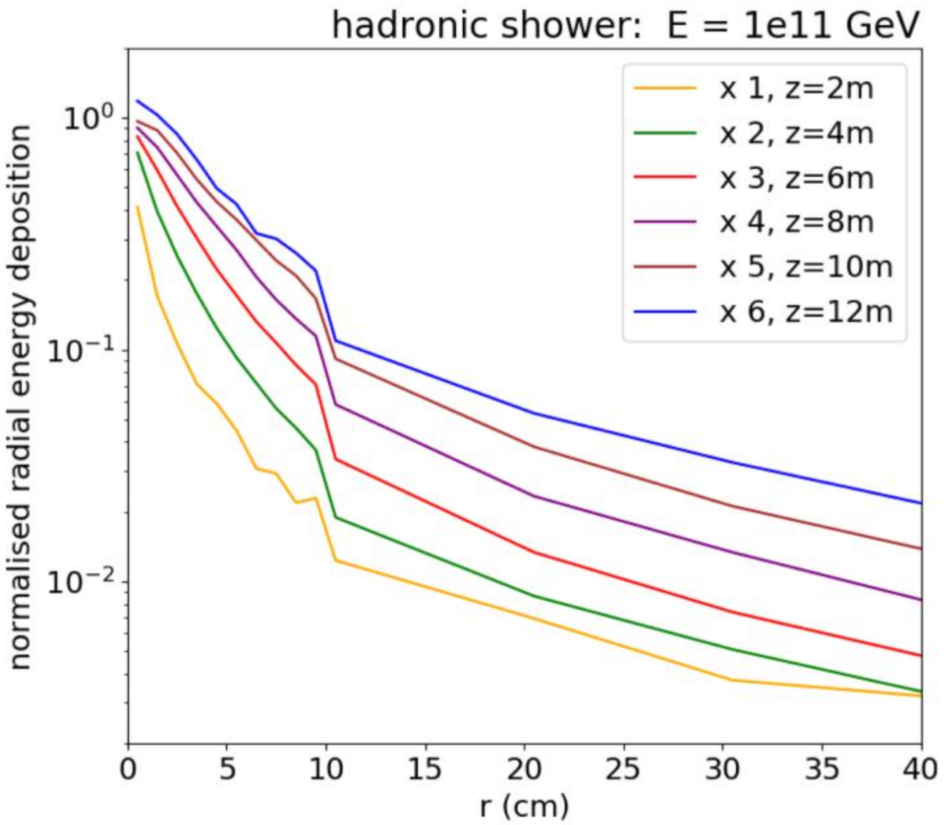
Cleaver et al, 2025



Particle showers in water

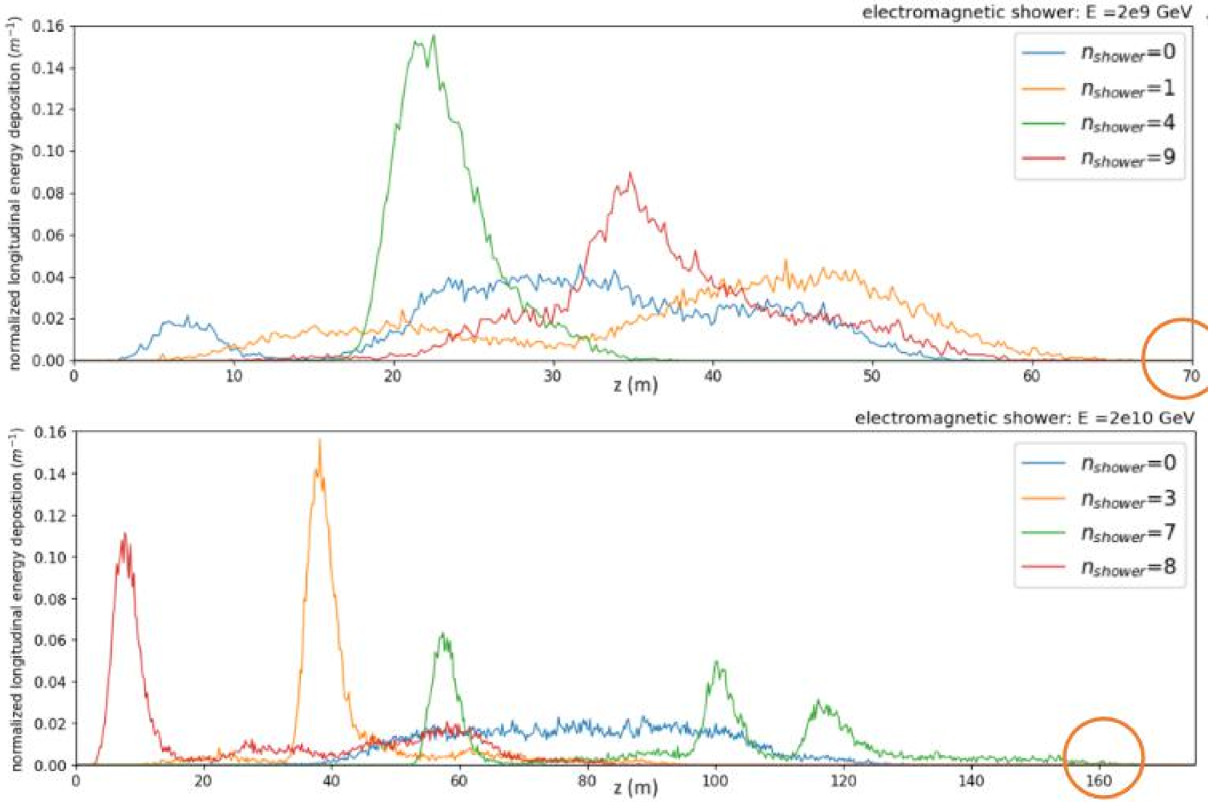
- Particle showers include of hadronic and electromagnetic showers
- Both longitudinal and radial energy deposition





Particle showers in water at the highest energies

- At energies above the shower geometries are affected by the LPM effect
  - Reduce cross sections for EM processes in the shower
- Extended longitudinal energy distribution, subshowers
- Pronounced in EM showers
- Corsika simulations



C. Gatius, MSc thesis

Acoustic neutrino signals

- First idea by Askaryan (1957)
- Wave equation **p** is given by energy deposition *ε*.

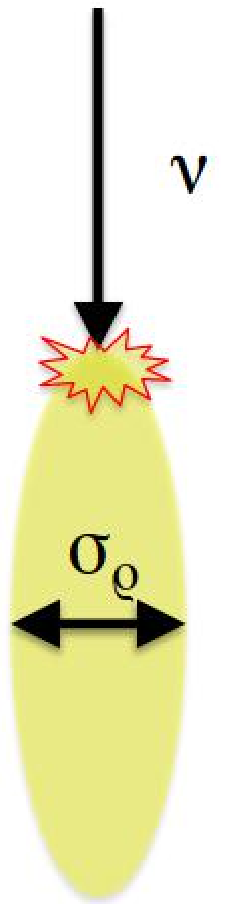
$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\alpha}{C_p}\frac{\partial^2 \varepsilon}{\partial t^2}$$

Water properties:

c = speed of sound

C_p = expansion coefficient

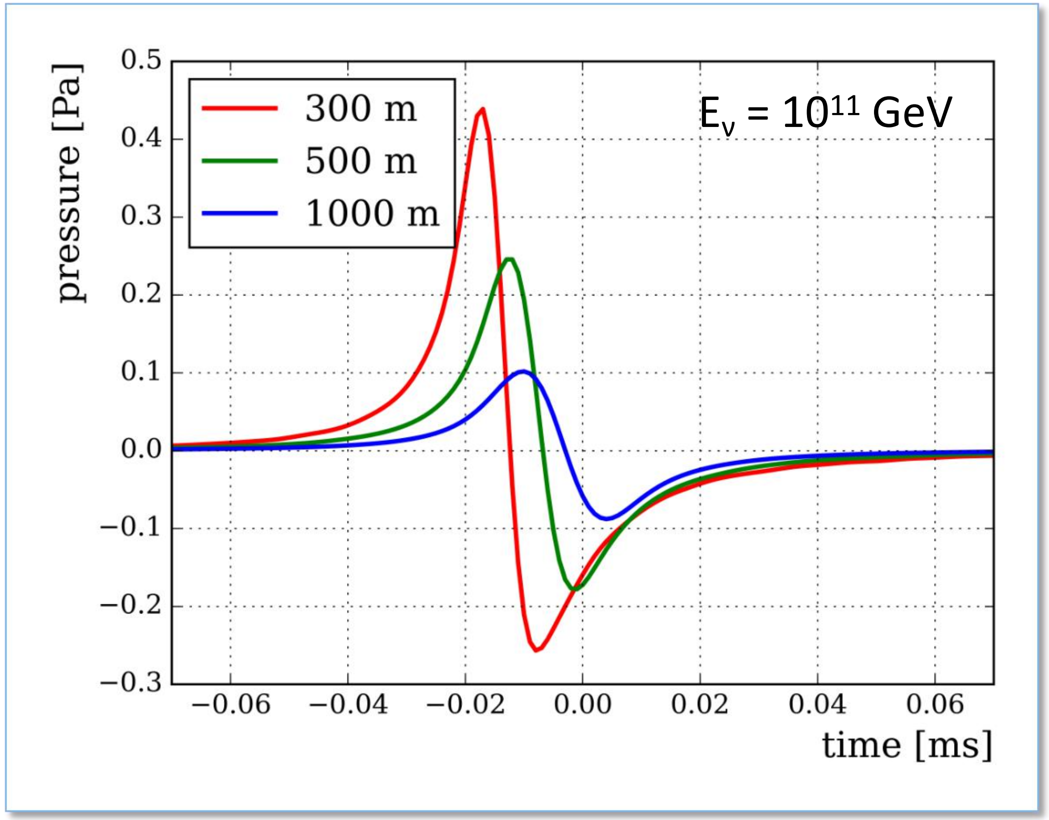
α = heat capacity



$$p_{\max} \propto \gamma_G \frac{E_0}{\sigma_\rho^2}$$

$$\gamma_G \equiv c_s^2 \alpha / c_p$$ Grüneisen parameter

Acoustic neutrino signals



- Pulse asymmetry
- Broad spectrum that peaks at 5-12 kHz.
- Near field effects
- Complex waveforms in case of LPM effect

-> Detect **mPa** pulses in a static pressure environment of **MPa**

Future telescope concept