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Probing extreme astrophysics with the 220-PeV neutrino observed by KM3NeT-ARCA

The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences, 5th March 2026

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Menu

Motto: **from the deep cosmos to the deep sea**

1. Mysterious neutrinos
2. Neutrino sources
3. KM3NeT telescopes
4. Cosmic messenger – looking behind the curtain of the universe
5. Plans: innovative acoustic detection of neutrinos
6. Conclusions

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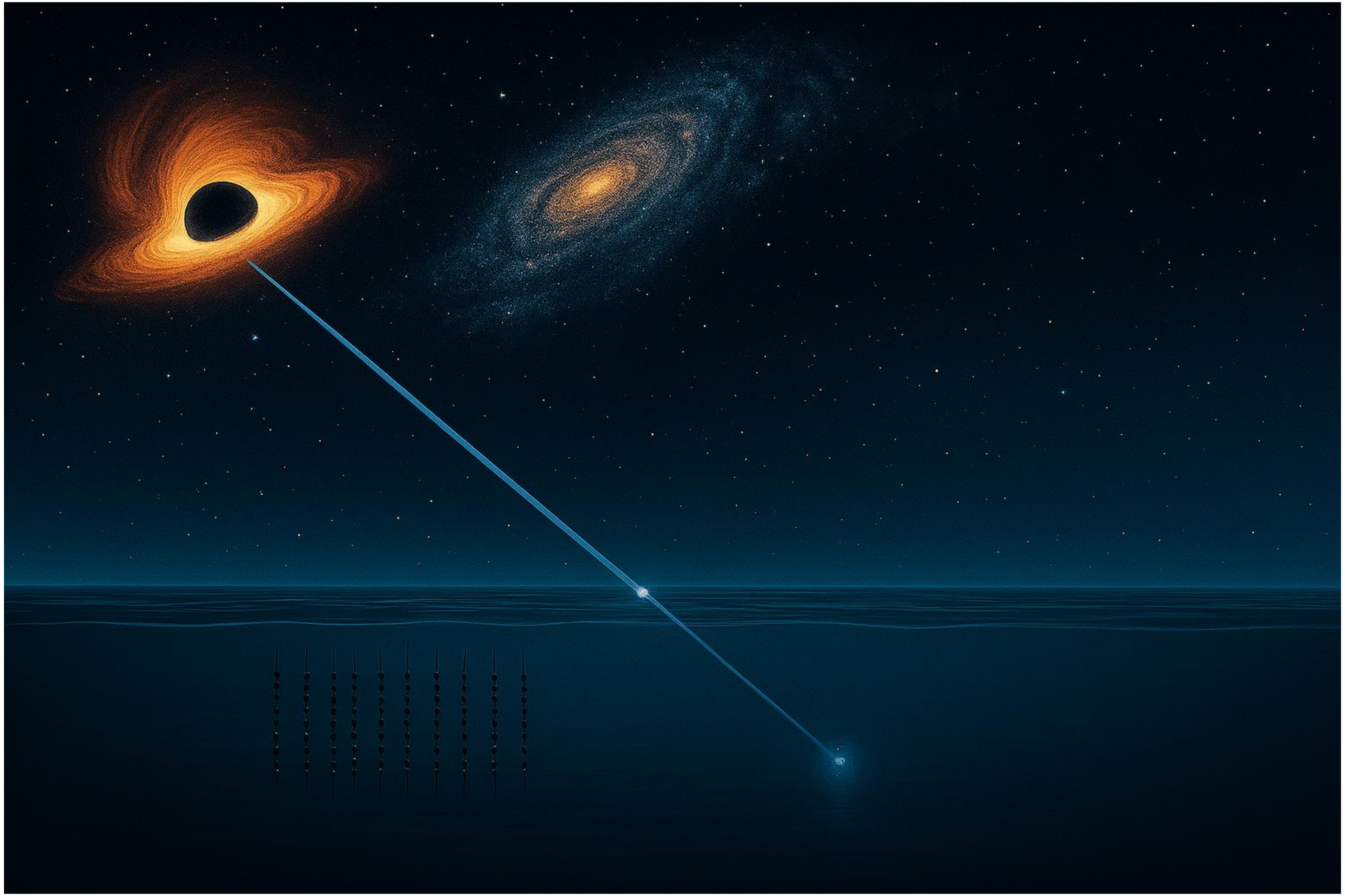
From the deep cosmos to the deep sea, an expedition to the frontiers of physics

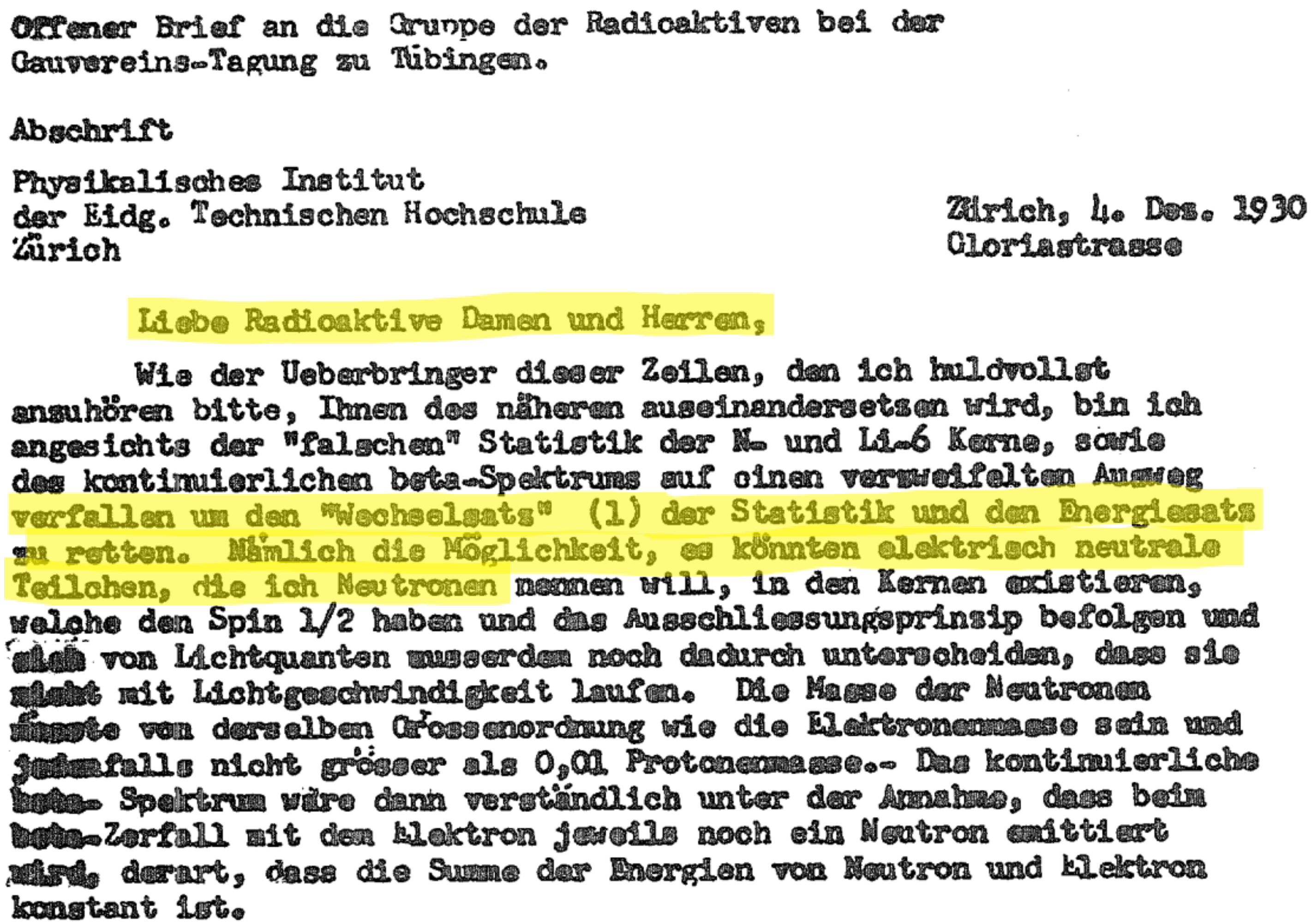


History

4 December 1930 – in the letter to Lise Meitner and nuclear physicists in Tübingen Wolfgang Pauli writes about desperation regarding the β decay problem

Dear Radioactive Ladies and Gentlemen,
[…]
I came up with a desperate idea to save the 'exchange principle' of statistics and the law of energy conservation. Namely, the possibility of electrically neutral particles existing in the atomic nucleus, which I called neutrons
[…]

[*later he proclaims famous words*]
I committed a terrible sin against the sacred principles of theory: I proposed a particle that cannot be detected.


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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren 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 Grossenordnung 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.

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History

1932 – James Chadwick discovers heavy neutral neutron (chaos with name)

1933-1934 – Enrico Fermi gives names to Pauli particle
he says: they are not heavy neutrons, there are piccole (wrt. small mass)
using Italian word

neutrino (Italian neutro + diminutive -ino)

1950 – Reines and Cowan are preparing to detect ν
(developing reactor experiment)
1956 – confirmed detection of ν_e
Savannah River Plant, South Carolina, USA
(Phys. Rev. 92, 830)

reversed β decay $\overline{\nu}_e + p \rightarrow n + e^+$
e^+ anihilates with e^- and two photons created

1995 – Reines obtains Noble prize

History

Till 1962 – known ν_e only (called neutrino)

1962 – Schwartz, Steinberger and Lederman present ν_μ evidence building the first neutrino beam

1998 – Super-Kamiokande confirms neutrino mixing
Deficit of atmospheric ν_μ relative to expectations

- ν coming from above (short path) – then in the expected numer
- upward-going ν (traveling the entire Earth) – observed in deficyt

2000 – discovery of ν_τ

2015 – Takaaki Kajita (Super-Kamiokande) and Arthur B. McDonald (SNO) obtain Noble prize for neutrino mixing discovery

Phys.Rev.Lett. 81 (1998) 1562-1567

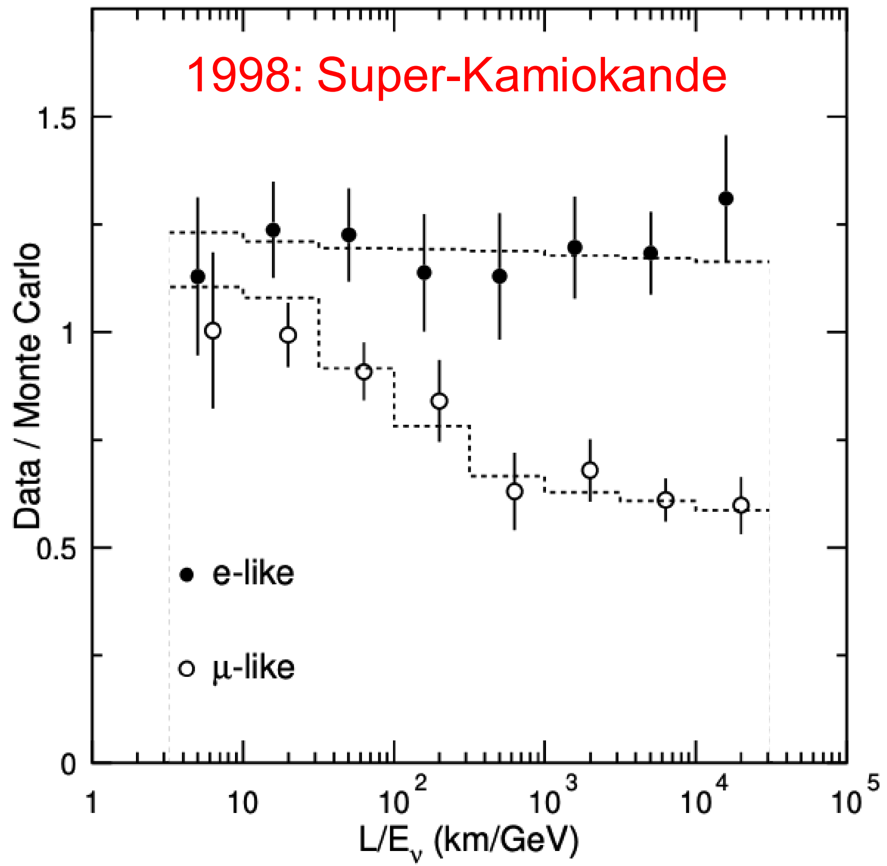

FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2-7%) of ν_μ CC interactions.

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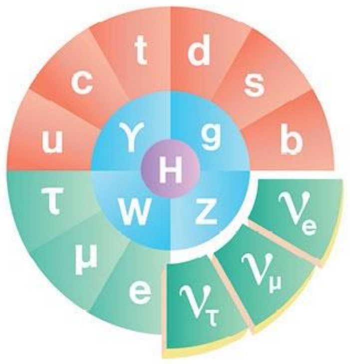
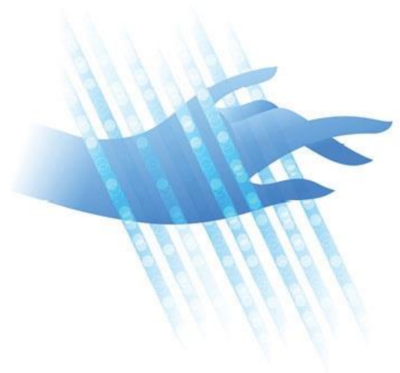
Mysterious neutrinos and goal of expedition

i.e. smashing the Standard Model barier and looking behind the curtain of the universe



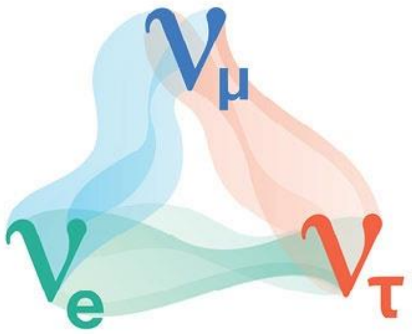
Elementary particles
(3 lepton generations)



abundant

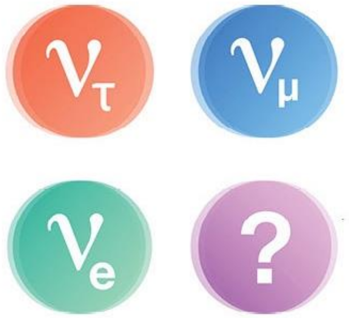
elusive

neutral and lightweight



three flavours and oscillating (like three types of ice-creams changed in time)

a lot of and elsewhere



3 is a minimum digit to describe data

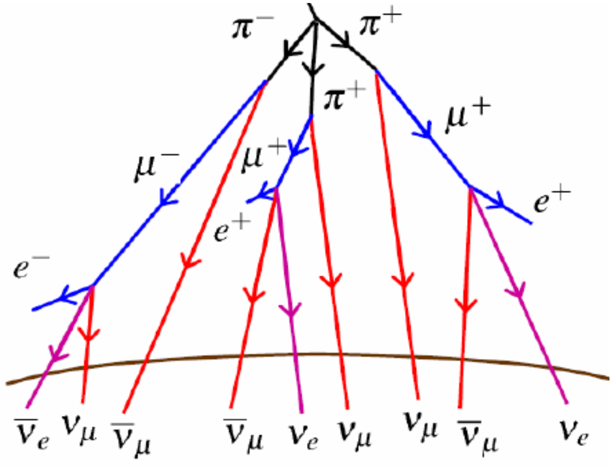
very mysterious

Borrowed: Symmetry Magazine / Sandbox Studio, Chicago

Neutrino sources

Natural (atmospheric, cosmic):

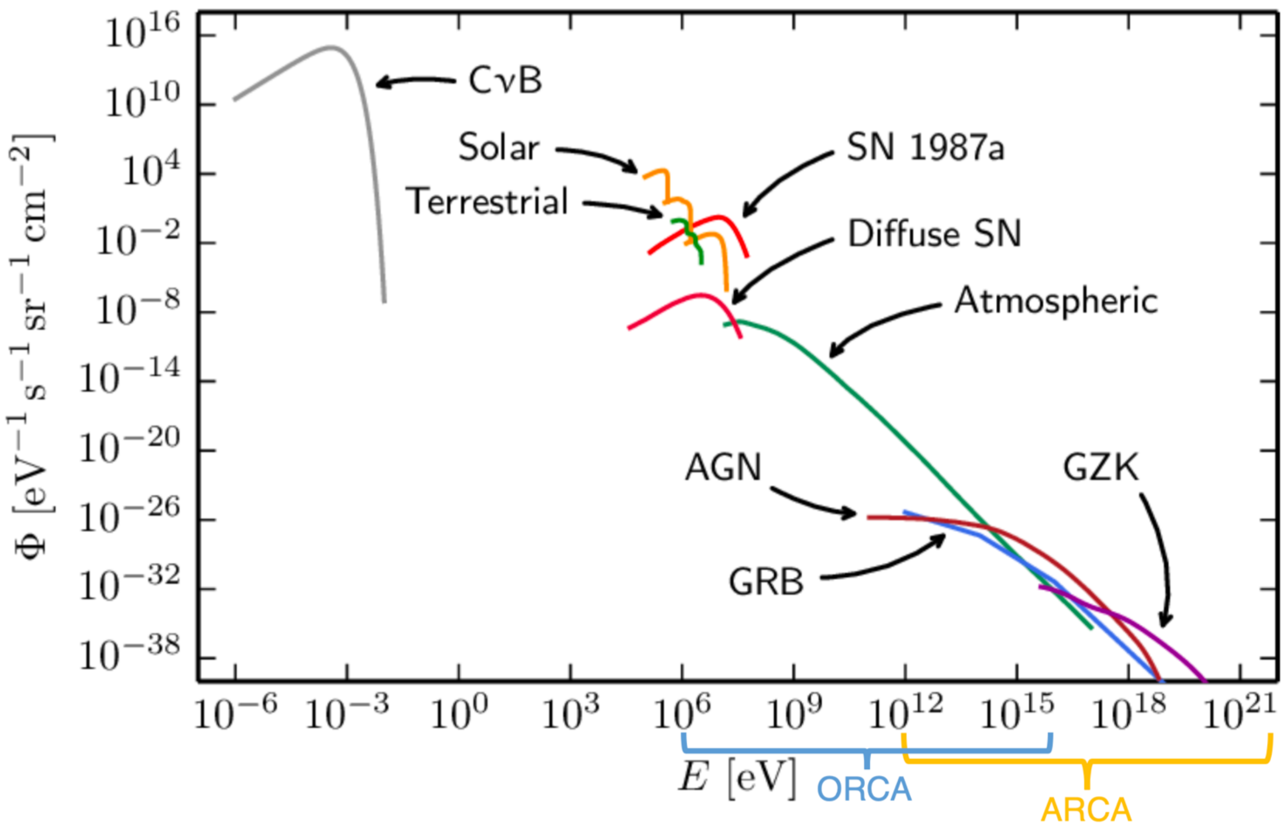
- Big Bang
- Sun
- interactions in atmosphere



- star explosions (Supernovae)
- Blazars
- far galactic (E>PeV)
- cosmic rays

Artificial – human created:

- nuclear reactors
- particle accelerators



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First ideas early 60's…science

Multi-messenger astronomy

Ann.Rev.Nucl.Sci
10 (1960) 1

NEUTRINO INTERACTIONS[1]

By Frederick Reines[2]

IV. COSMIC AND COSMIC RAY NEUTRINOS

As we have seen, interactions of high-energy particles with matter produce neutrinos (and antineutrinos). The question naturally arises whether the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems from the weak interaction of neutrinos with matter, which means that they propagate essentially unchanged in direction and energy from their point of origin (except for the gravitational interaction with bulk matter, as in the case of light passing by a star) and so carry information which may be unique in character. For example, cosmic neutrinos can reach us from other galaxies whereas the charged cosmic ray primaries reaching us may be largely constrained by the galactic magnetic field and so must perforce be from our own galaxy. Our more usual source of astronomical information, the photon, can be absorbed by cosmic matter such as dust. At present no acceptable theory of the origin and extraterrestrial diffusion of cosmic rays exists so that the cosmic neutrino flux can not be usefully predicted. An observation of these neutrinos would provide new information as to what may be one of the principal carriers of energy in intergalactic space.

The situation is somewhat simpler in the case of cosmic-ray neutrinos: they are both more predictable and of less intrinsic interest. Cosmic-ray

Greisen, 1960, Proc. Int. Conf on Instrum for HE physics

One may even anticipate eventual high-energy neutrino astronomy, since neutrino travel in straight lines, unlike the usual primary cosmic rays, and the neutrinos will convey a new type of astronomical information quite different from that carried by visible light and radio waves

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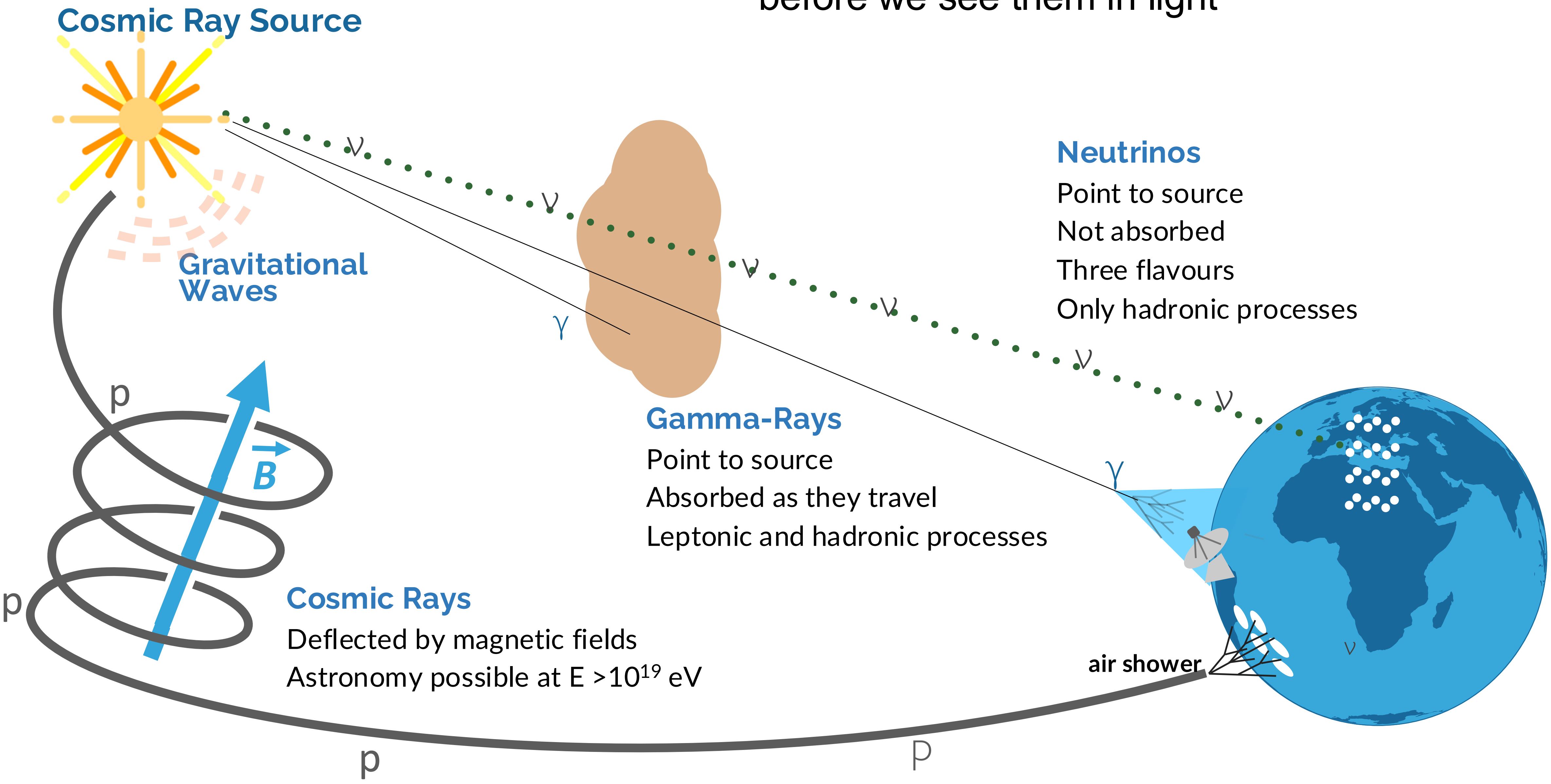
Role of neutrinos in multi-messenger astronomy

First messengers from cosmos, informing us about dramatic events in stars before we see them in light



Borrowed: Paschal Coyle, From the deep cosmos to the deep sea, 12 February 2025, 16:50, Paris

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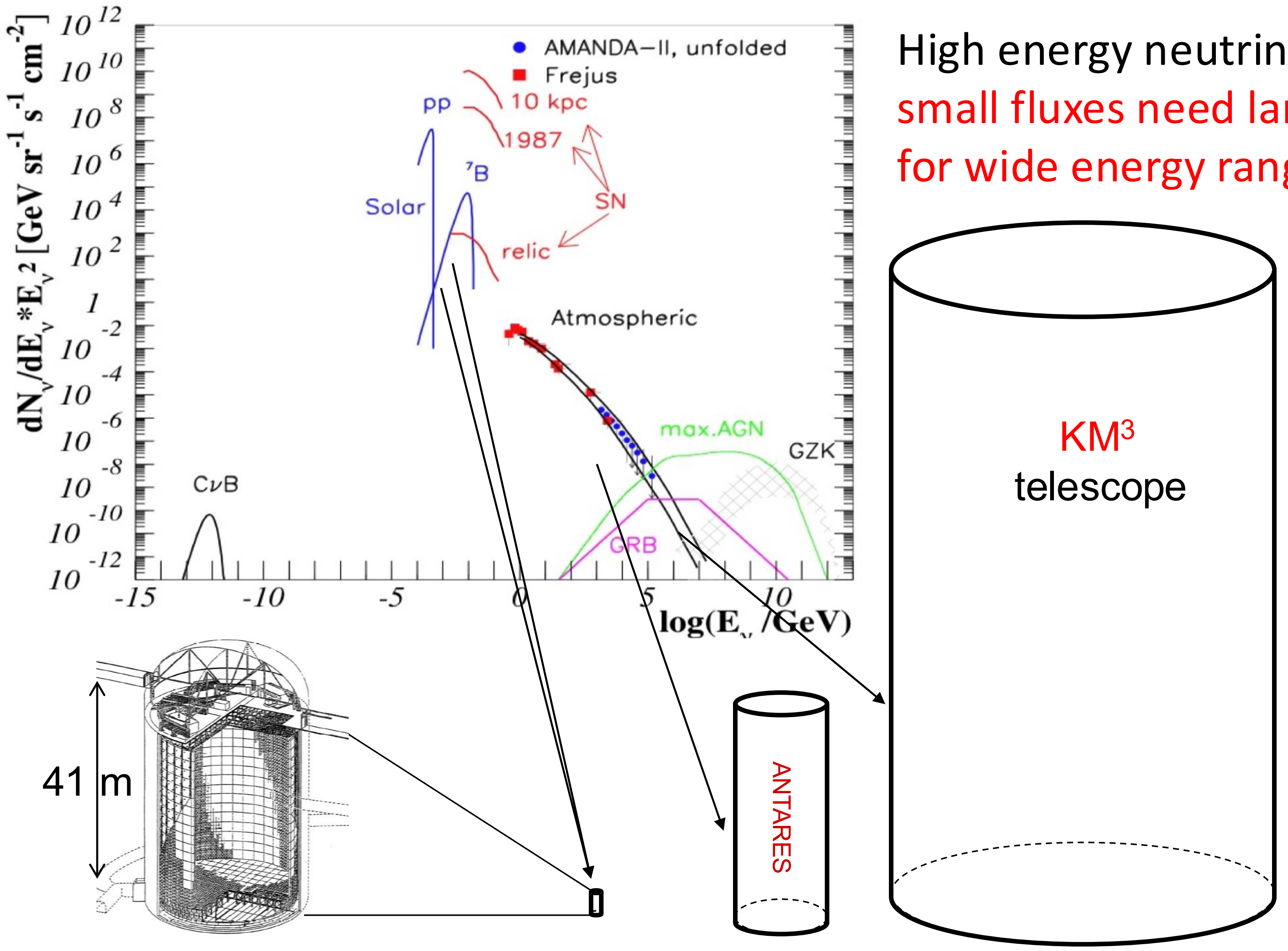
From MeV to PeV neutrinos

High energy neutrino:
small fluxes need large detectors
for wide energy range



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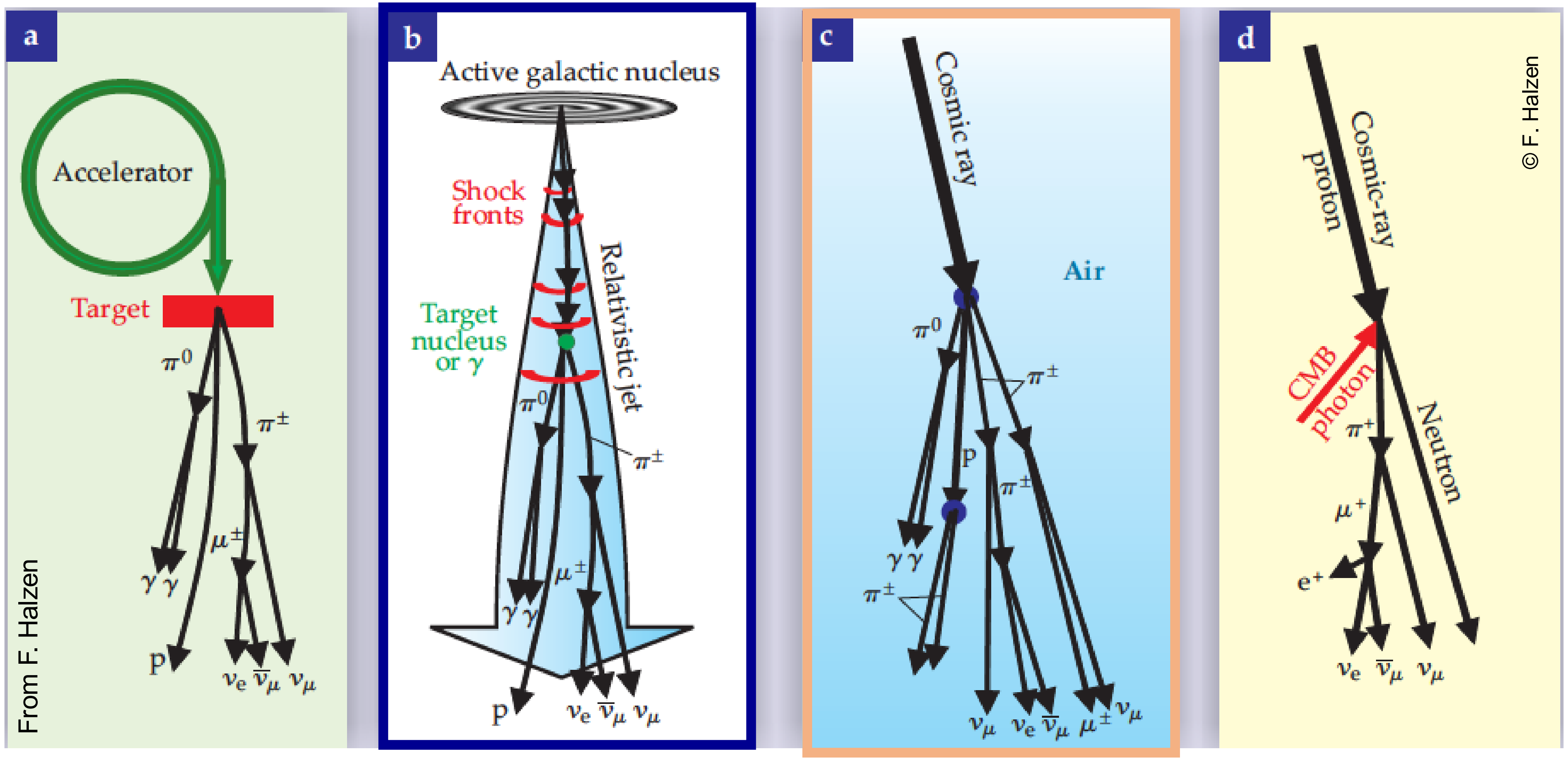
Common production mechanism



Neutrino beam cosmic neutrinos atmospheric neutrinos cosmogenic ν

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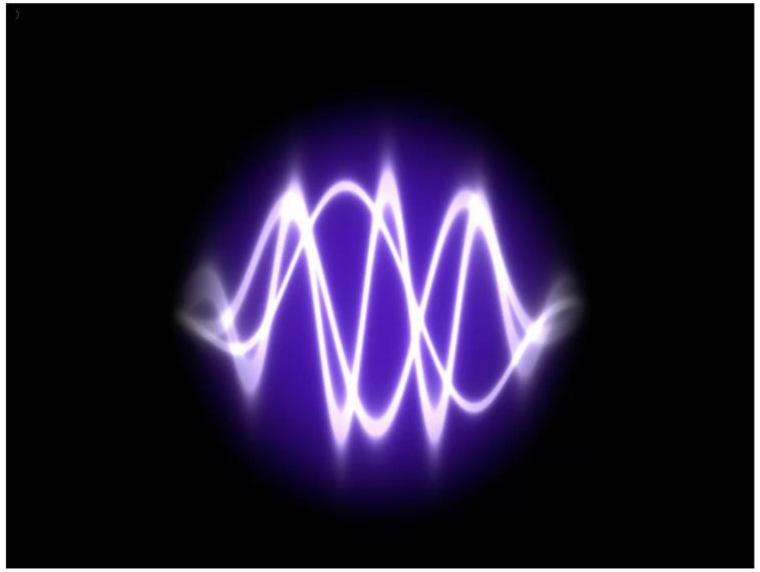
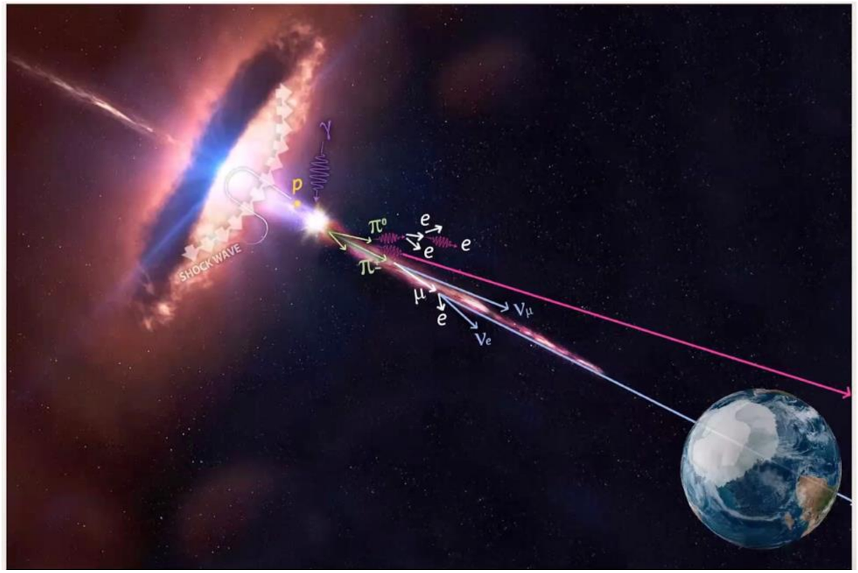
Science in km^3 neutrino telescope

Research on the properties of neutrinos



Exploration of the Universe (today)



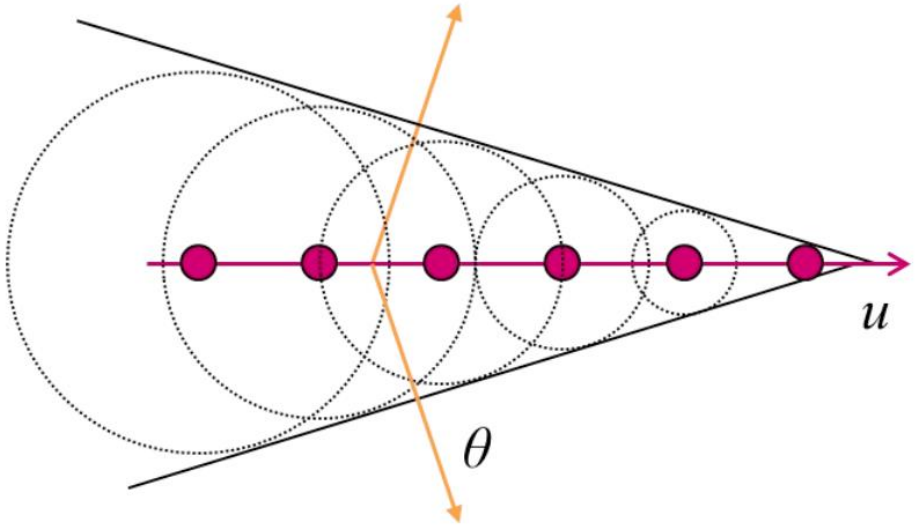
Exploration of the depths of the Mediterranean Sea

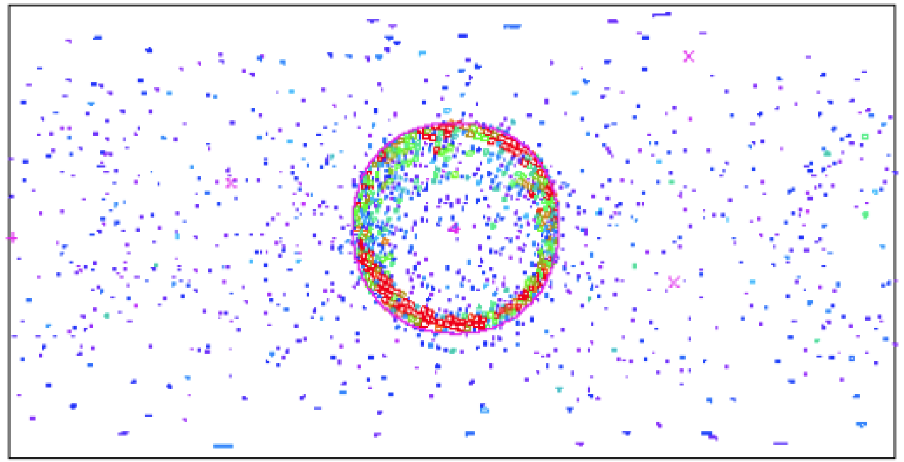
KM3NeT – Cubic Kilometre Neutrino Telescope

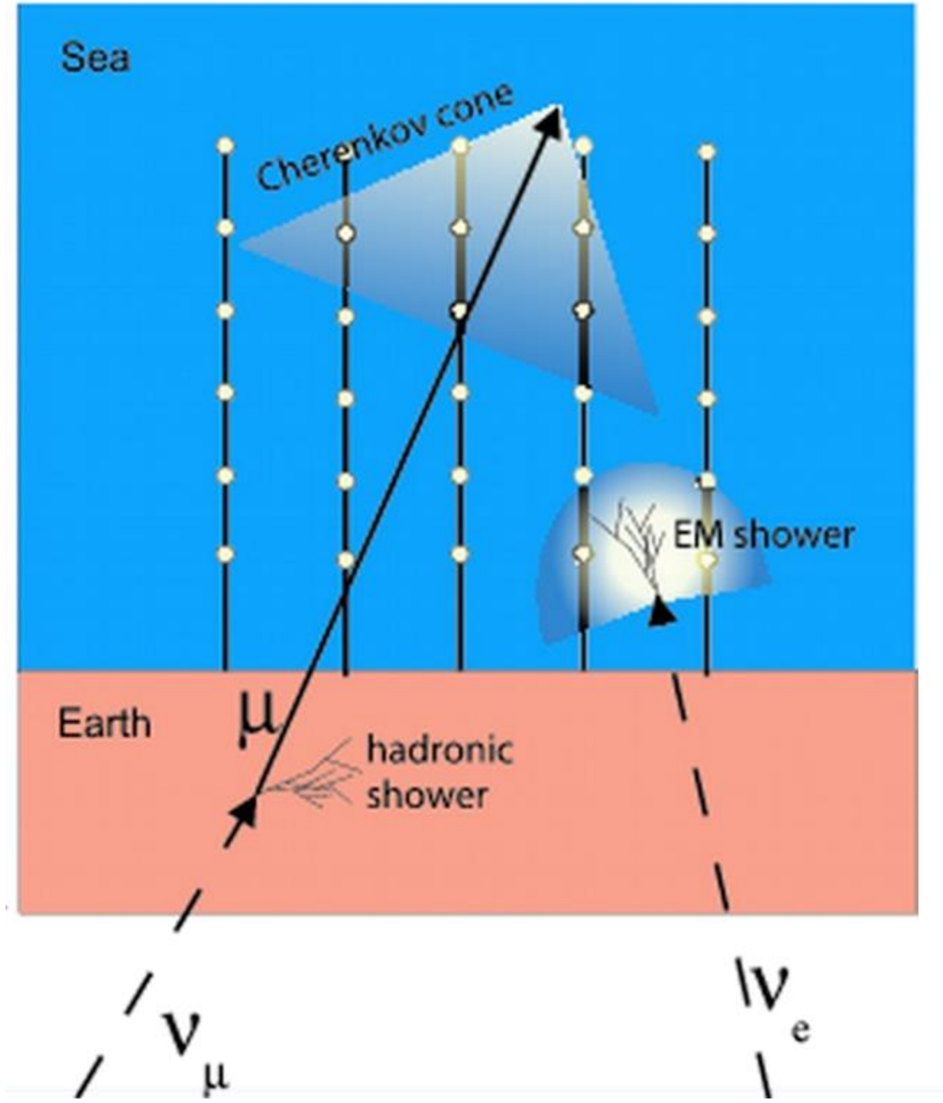
https://www.km3net.org/

Concept of optic detection

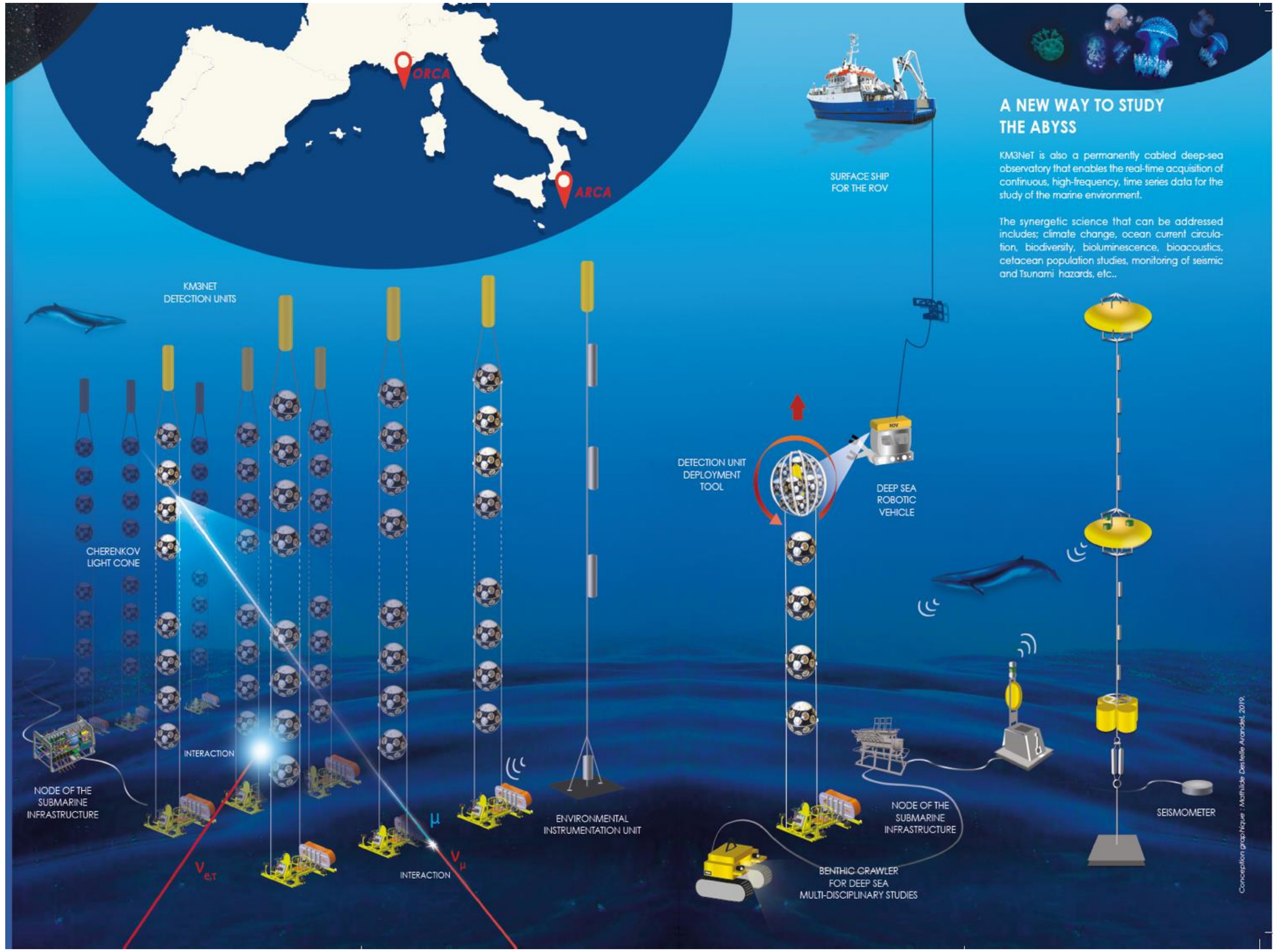
A particle (e.g., a muon) can travel through water faster than light (Cherenkov radiation)







KM3NeT, next generation neutrino telescopes



In the deepest Mediterranean Sea

- ARCA (Advanced Research in Cosmology and Astrophysics)

  close to Portopalo di Capo Passero Sicily, Italy

- ORCA (Oscillation Research with Cosmics in the Abyss)

  close to Toulon shore, France

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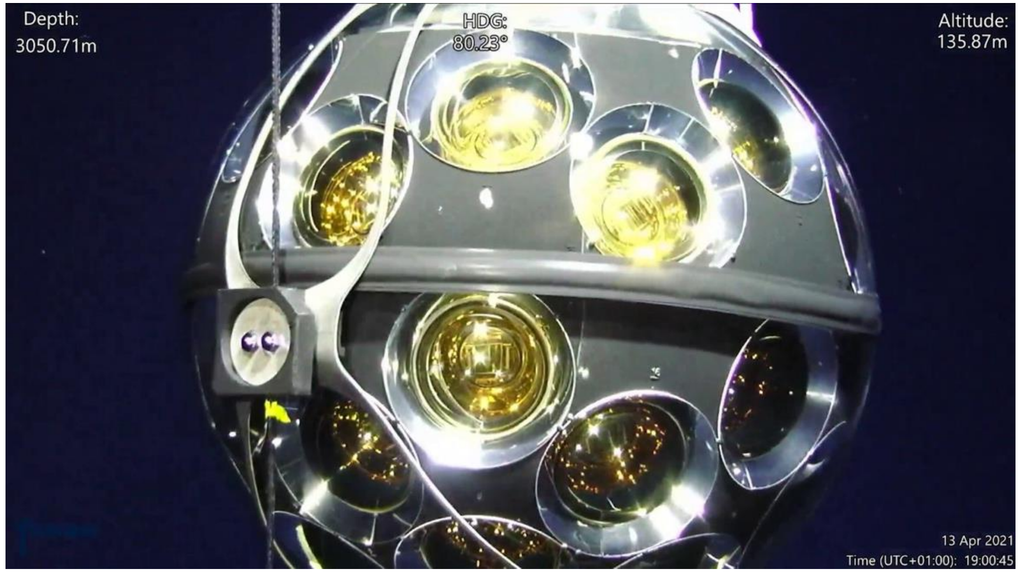
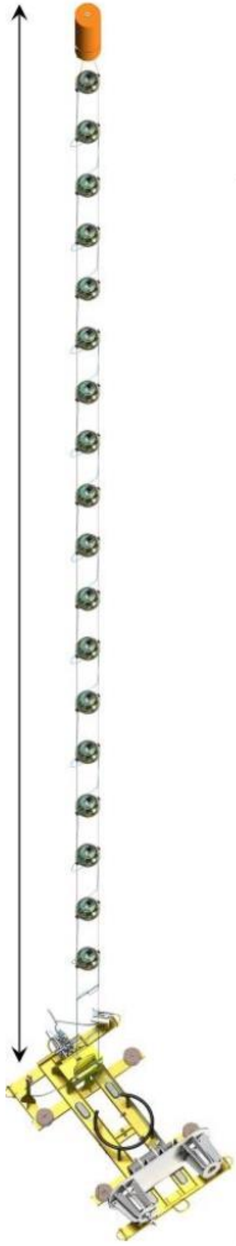
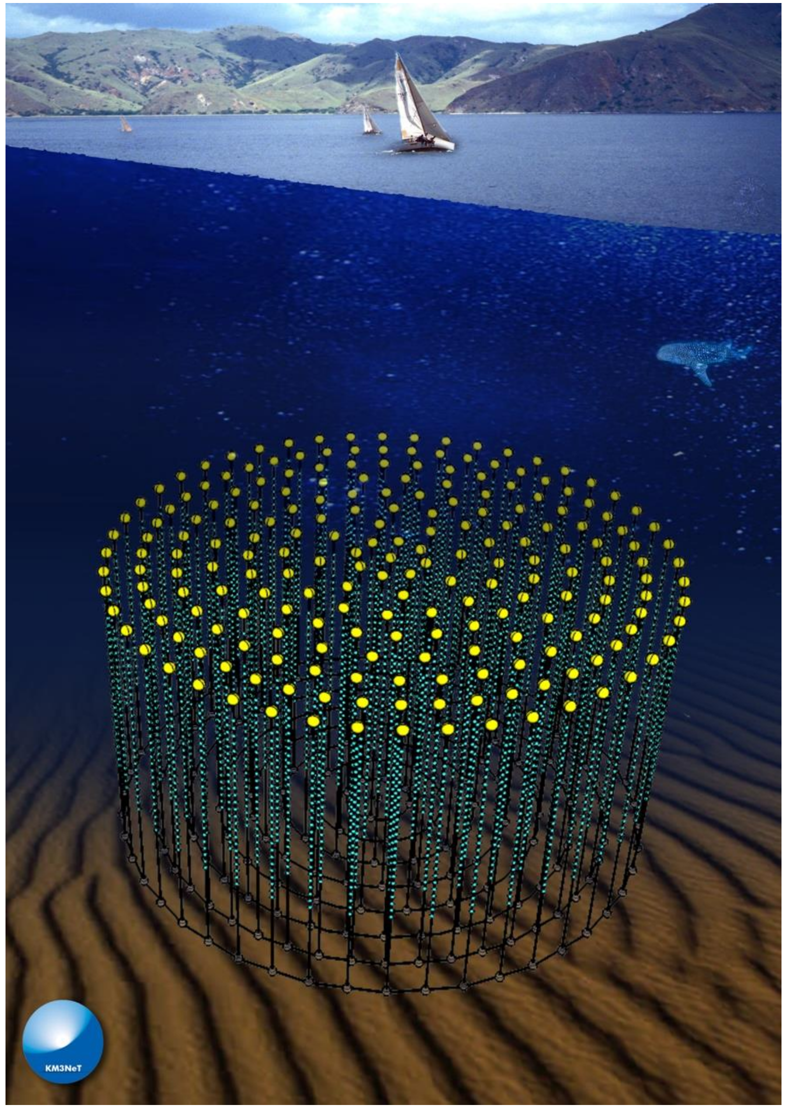
Optical modules are installed along the string

DU (Detection Unit – detection string)
18 DOMs along vertical line/string

DOM (Digital Optical Module) – 31 PMTs







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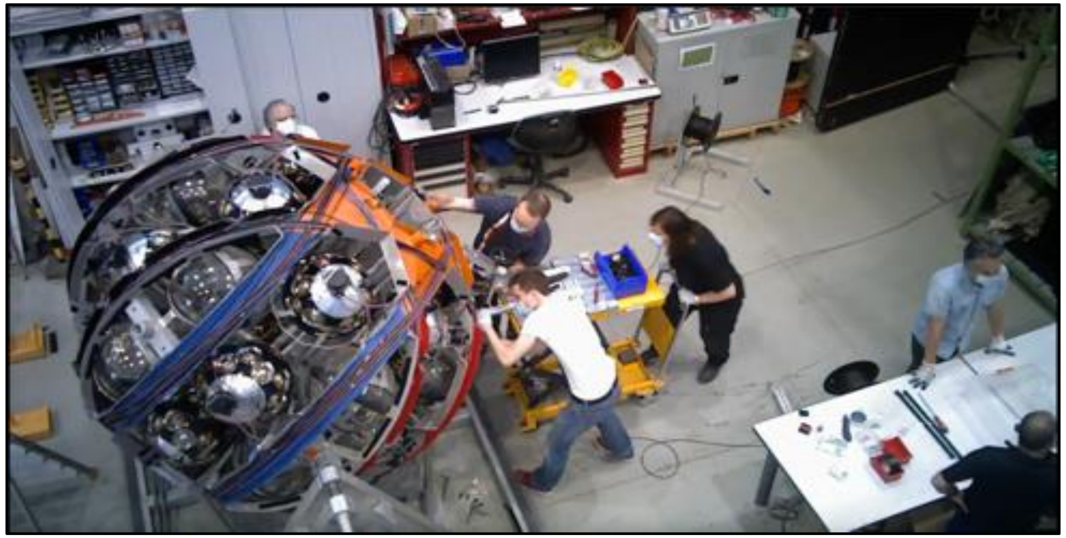
Optical modules

Genova

Marseille



Catania

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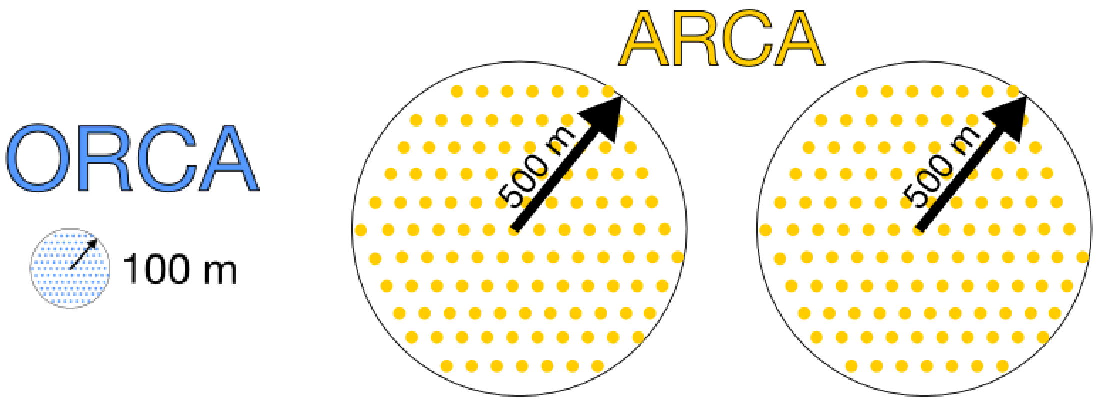
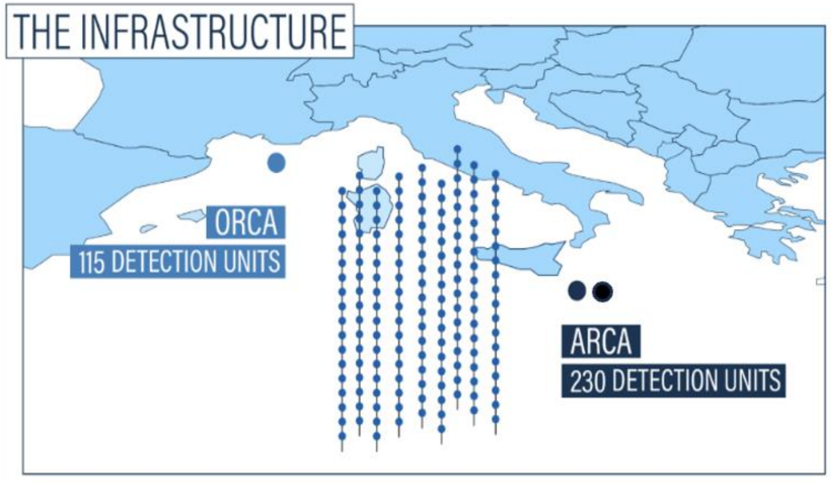
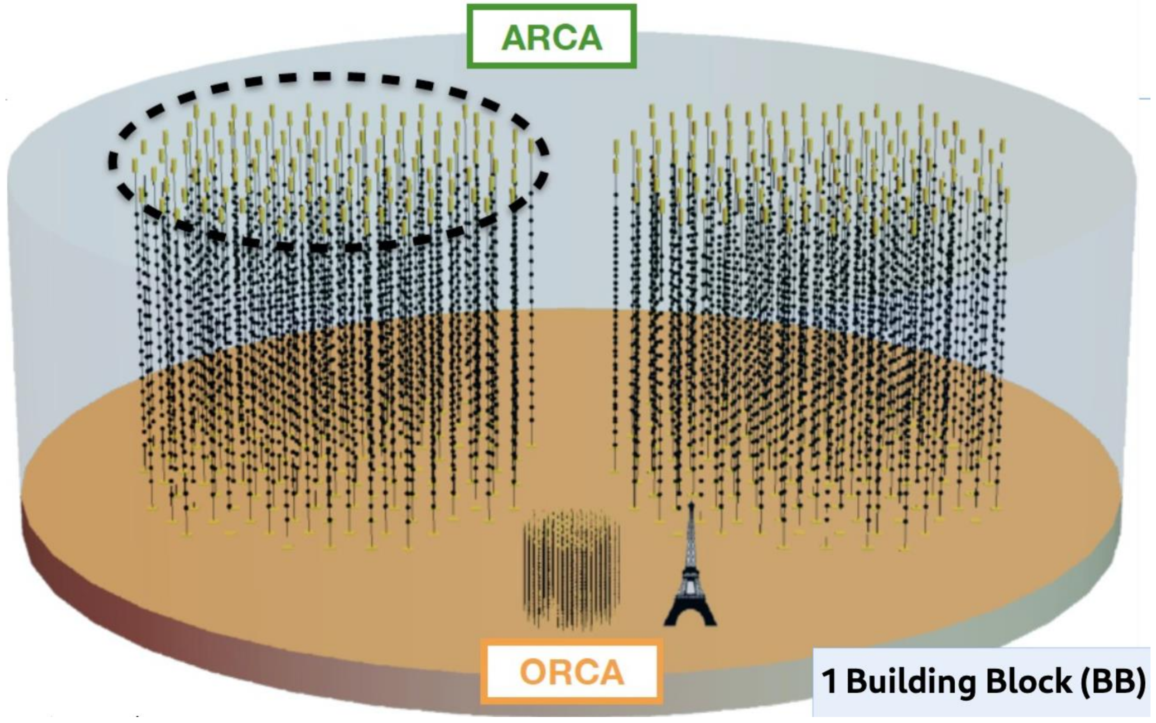
KM3NeT

KM3NeT: ARCA and ORCA







Detektor	ARCA	ORCA
deepest	3.5 km	2.45 km
volume	$1\ km^3$ (1Gton)	$0.007\ km^3$ (7Mton)
# lines	51 / 2x115	33 / 115
subject	Astroparticle RCA*	Oscillation RCA*
Cel	ν_{astro}	m_ν mass hierarchy

*RCA : Research with Cosmics in the Abyss

The third acoustic telescope is planned in Greek's Mediterranean Sea

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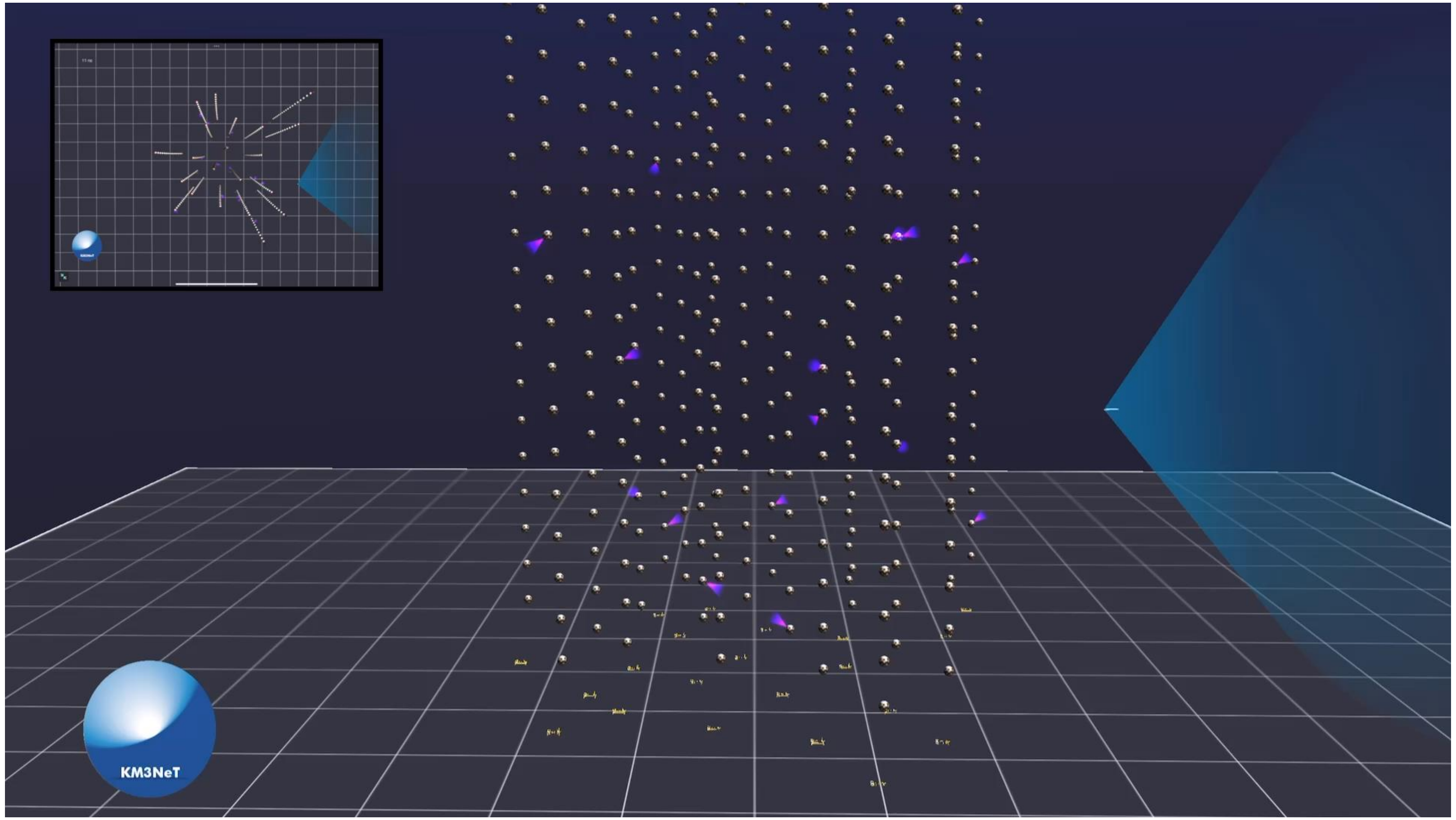
Mysterous messenger from deep cosmos to deep sea

13 February 2023, middle of night, hour 01:16:47 UTC
ARCA telescope, Portopalo di Capo Passero, Sicily, Italy



KM3-230213A

Active 21 detection strings
(only 9% of infrastructure)

378 DOMs, 12k PMTs

Signal from detector:

- 28 086 photons
- 35% active PMTs

Time of visit: less than 2 μs

Power failure?
Remember lesson from LEP: day-night effect – only train de Genève vers la France in Bellegarde direction

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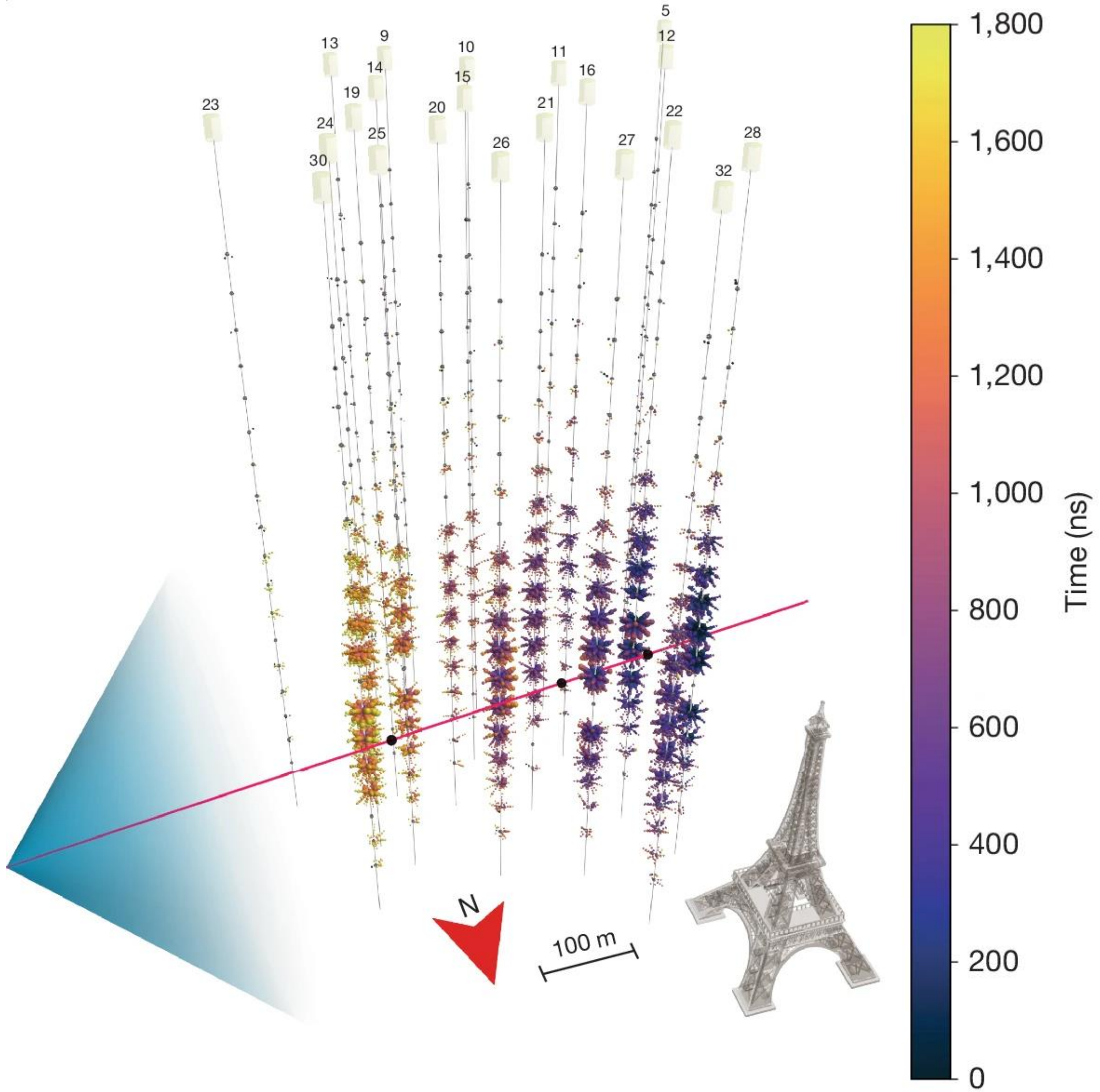
Mysterous messenger from deep cosmos to deep sea



Nature 638:376-382(2025)

21 detection strings (only 9% of infrastructure)

- In this configuration telescope worked from 23 Sep. 2022 till 11 Sep. 2023
- 287.4 days of data taking
- ~110 million of events, but the only one UHE KM3-230213A in a telescope

Highly relativistic μ travels a few hundred metres throughout the ARCA detector

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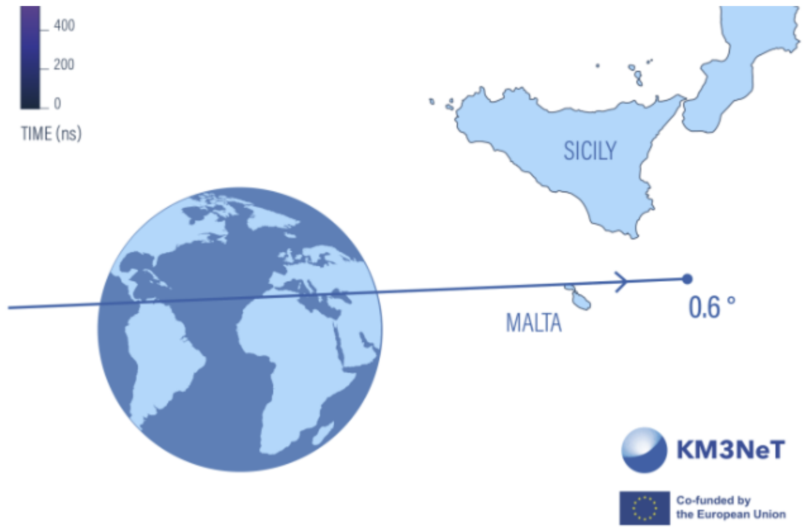
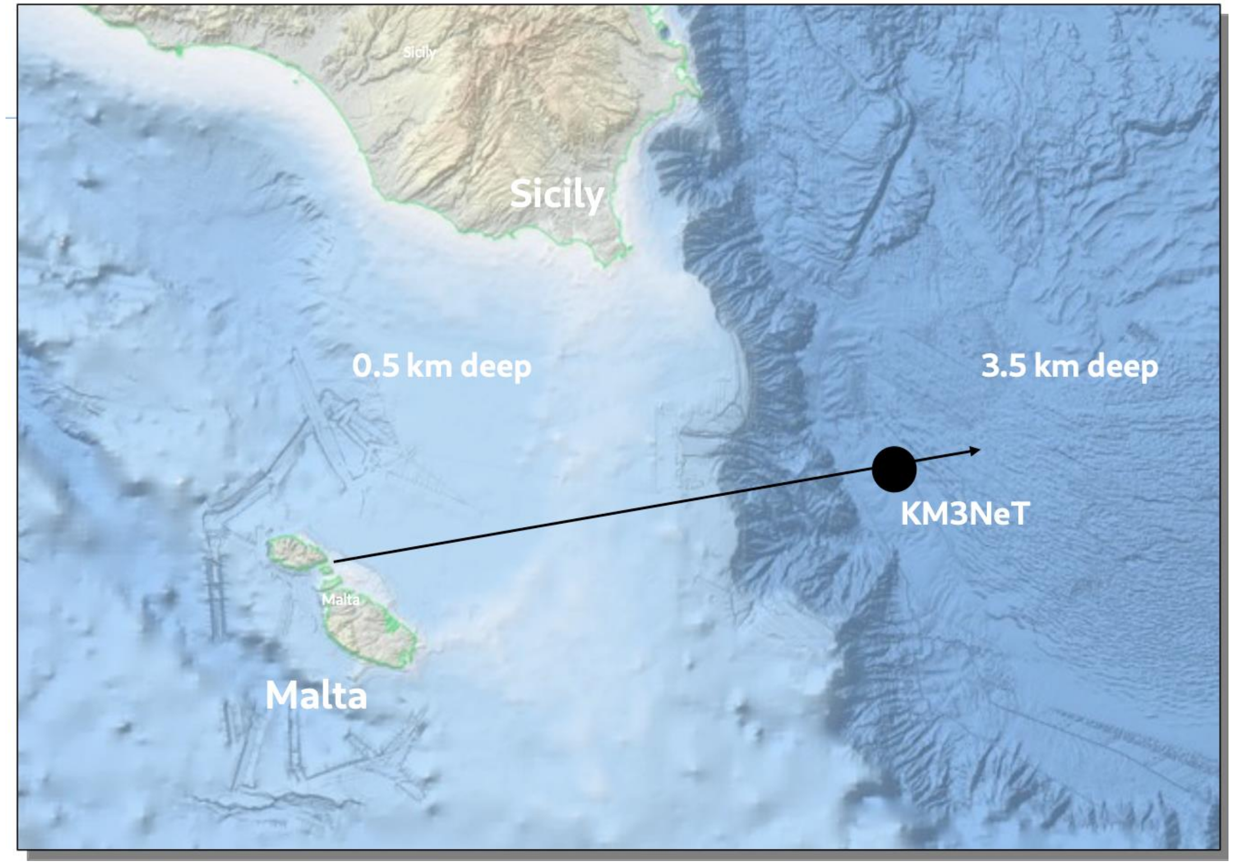
Highly relativistic μ with extremely high energy

Nature 638:376-382(2025)

In ARCA μ is registered with:

- energy: 120^{+110}_{-60} PeV
- horizontal direction 0.6°
- azimuth 259.8° (angles increase with clockwise, north is 0°)
- direction uncertainties:
  - statistical 0.12°
  - systematic 1.5°





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Highly relativistic μ travels a few hundred metres

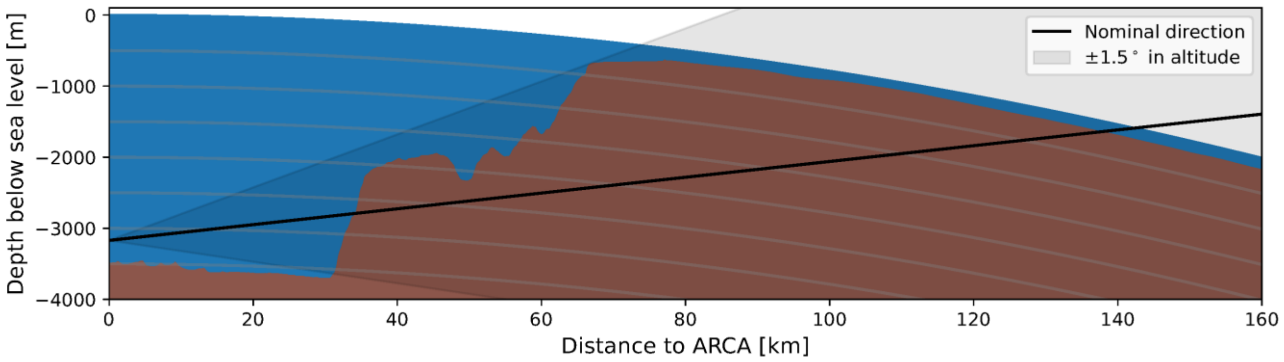
3 672 activated PMTs (35% of total)

Measured μ energy: 120^{+110}_{-60} PeV

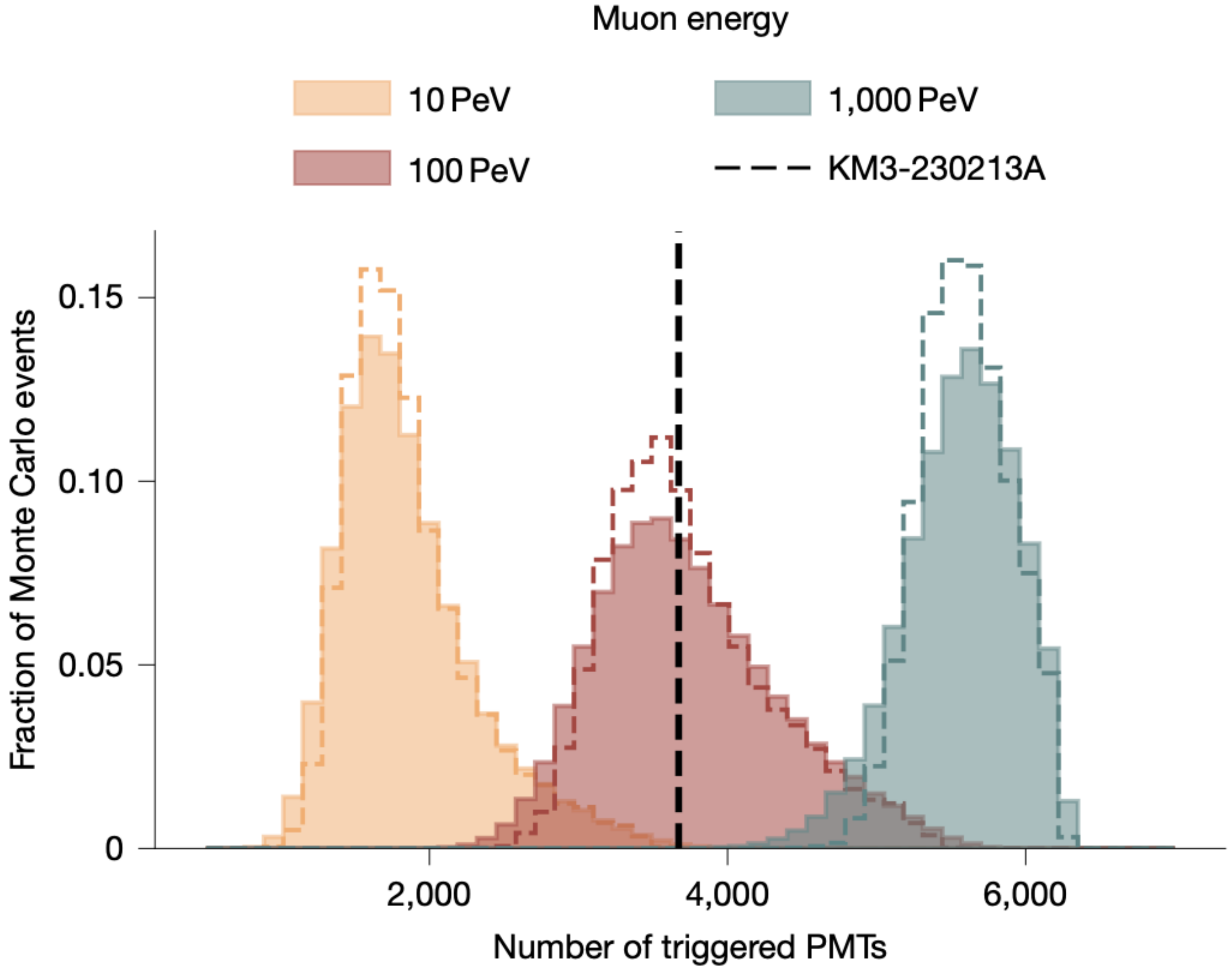
uncertainty dominated via limited knowledge of light absorption length in sea water

μ with high energy and horizontal direction travelled 300 km in water

This exceeds the maximum range of any atmospheric muon (≤60 km for E=100 EeV)



Nature 638:376-382(2025)



Simulated distributions of the number of activated PMTs for a muon at given energies: 10, 100 and 1000 PeV

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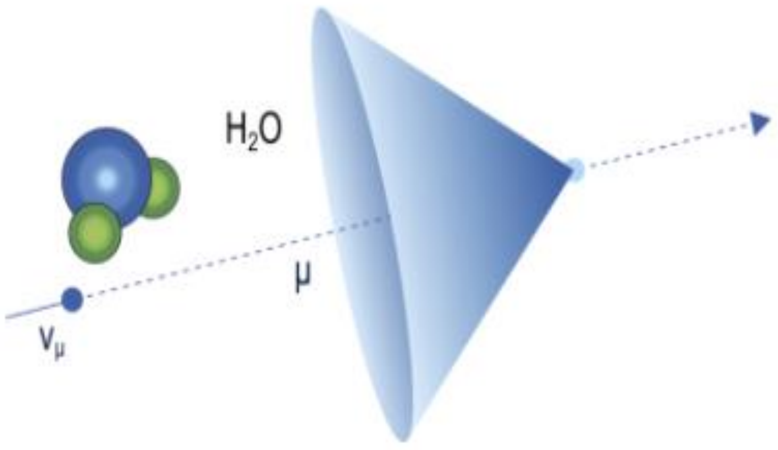
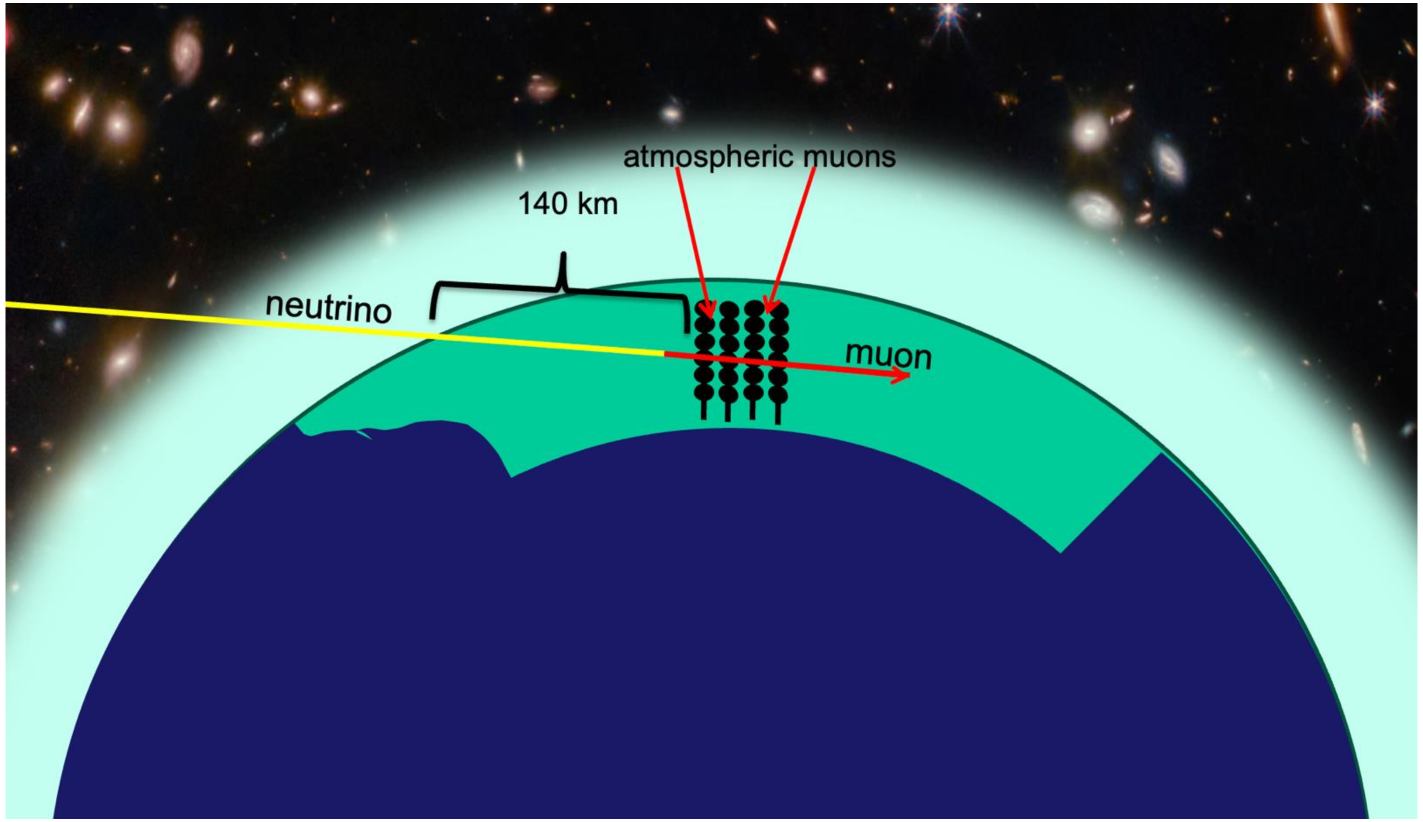
Highly relativistic μ with extremely high energy

Nature 638:376-382(2025)

The μ most likely originated from the interaction near the detector of a ν with an even higher energy





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A cosmic neutrino with an energy never observed before

KM3-230213A

Till 2025 the most energetic neutrinos:

- ν_e: IceCube, Science 342 (2013) 1242856: 6.05 ± 0.72 PeV
- ν_μ: IceCube, Astrophys. J. 928 (2022) 50: ~10 PeV

2025, ν_μ, KM3NeT, Nature 638:376-382(2025)

220^{+570}_{-100} PeV (millions of billions of electronvolts)

The opening of a new energy region previously beyond reach

only one UHE ν in Europe

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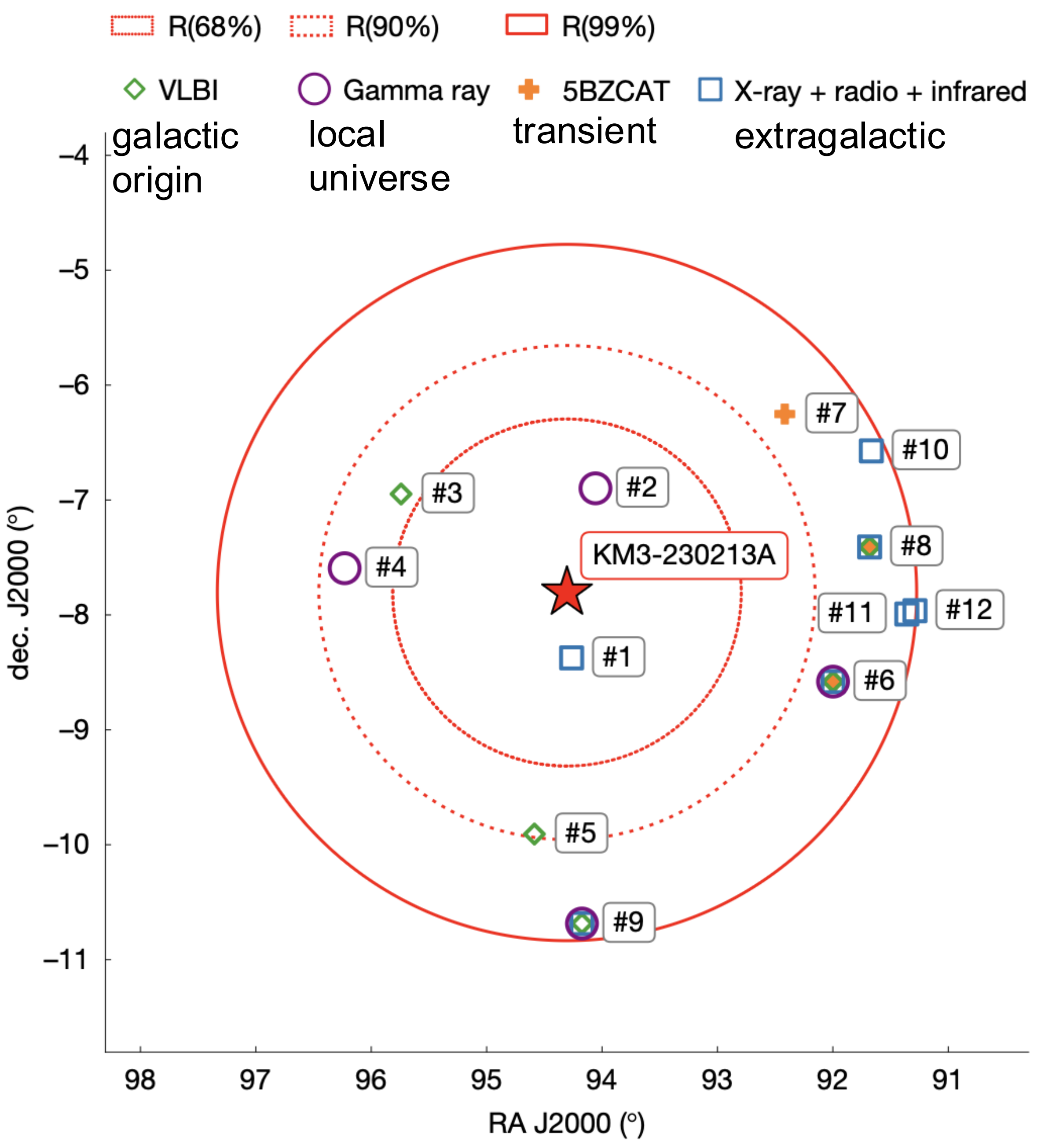
Possible origin

Nature 638:376-382(2025)

High energy 220^{+570}_{-100} PeV suggests:

1. the ν may have originated from a different cosmic accelerator than the lower-energy ν,
2. or that this is the first detection of a cosmogenic ν produced by interactions of ultra-high-energy cosmic rays with background photons in the universe

Multi-messenger astronomy



Potential sources corresponding to the KM3-230213A event within a 3° radius around its location

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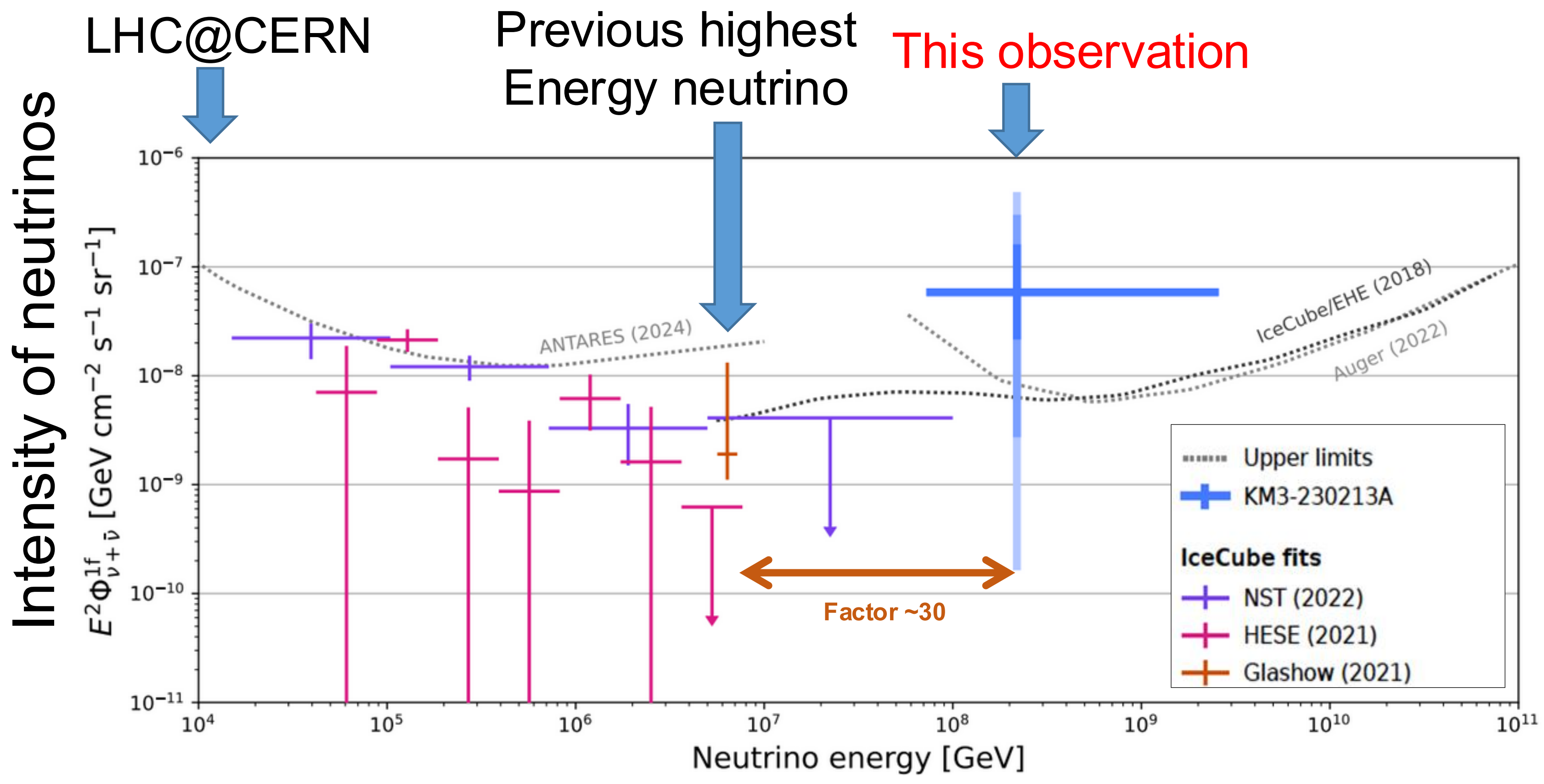
Unexplored energy regime

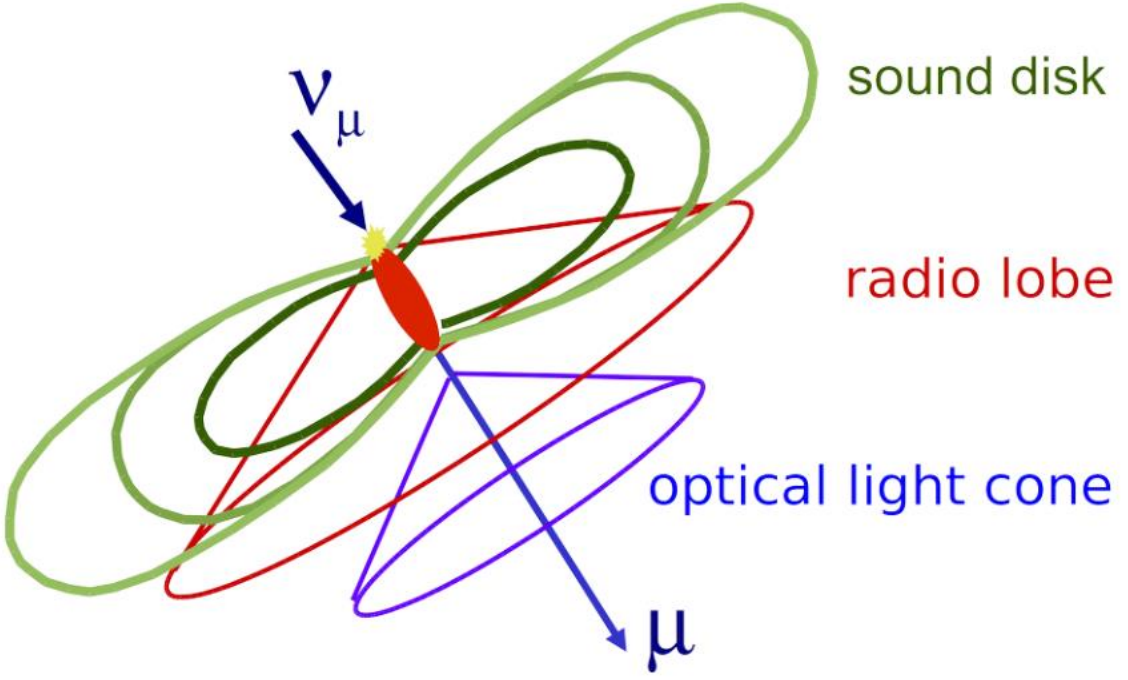


How do we measure neutrinos?

Multi-messenger astronomy

There are three methods of ν detection in large-scale telescopes:

1. optical, based on Cherenkov radiation
2. coherent radio emission
3. acoustic signal detection



In KM3NeT we aim to combine optical detection with acoustic detection, this will reduce uncertainties

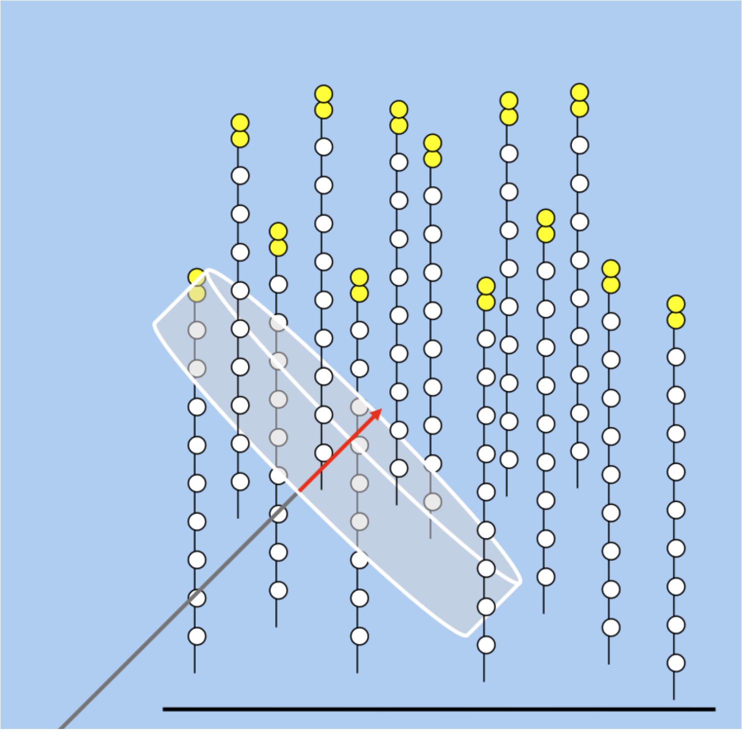
Acoustic neutrino signal

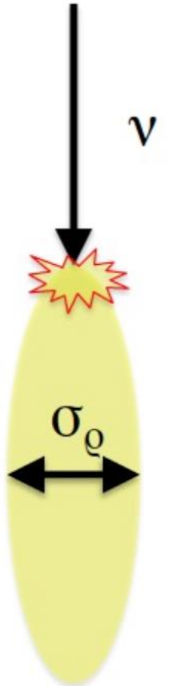
Thermoacoustic effect

- the first idea, Askaryan (1957)
- rapid expansion of the medium due to fast heating after energy deposition
- expansion leads to the formation of a preasure wave in water
- the pressure wave equation p is determined by energy deposition ε

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

c – speed of sound
C_p – coefficient of thermal expansion
α – head capacity
γ_G – Grüneisen parameter





$$p_{max} \propto \gamma_G \frac{E_0}{\sigma_\varrho^2} \quad ; \quad \gamma_G \equiv c^2\,\alpha/C_p$$

Water properties and cascade geometry influence the signal amplitude

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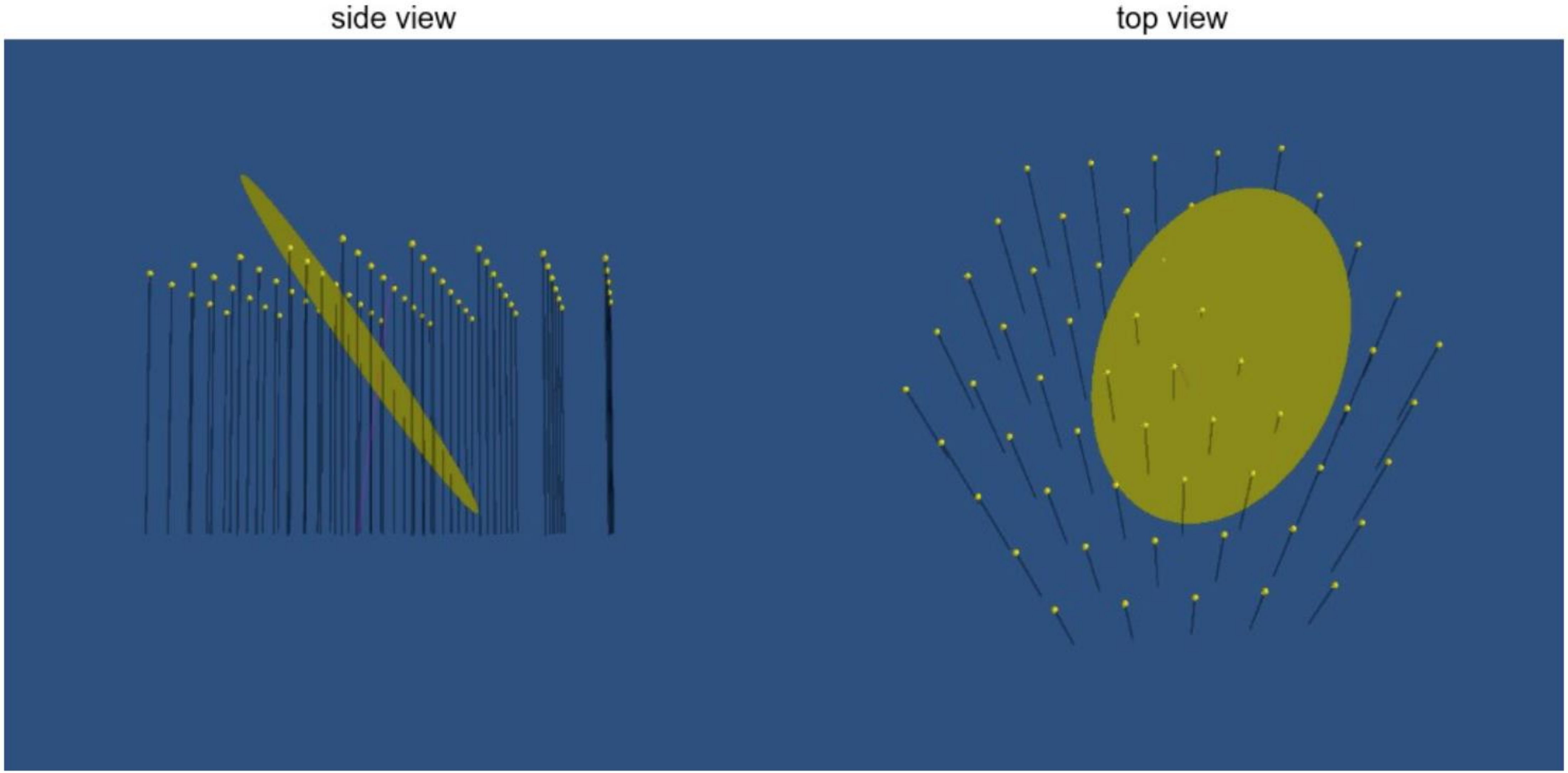
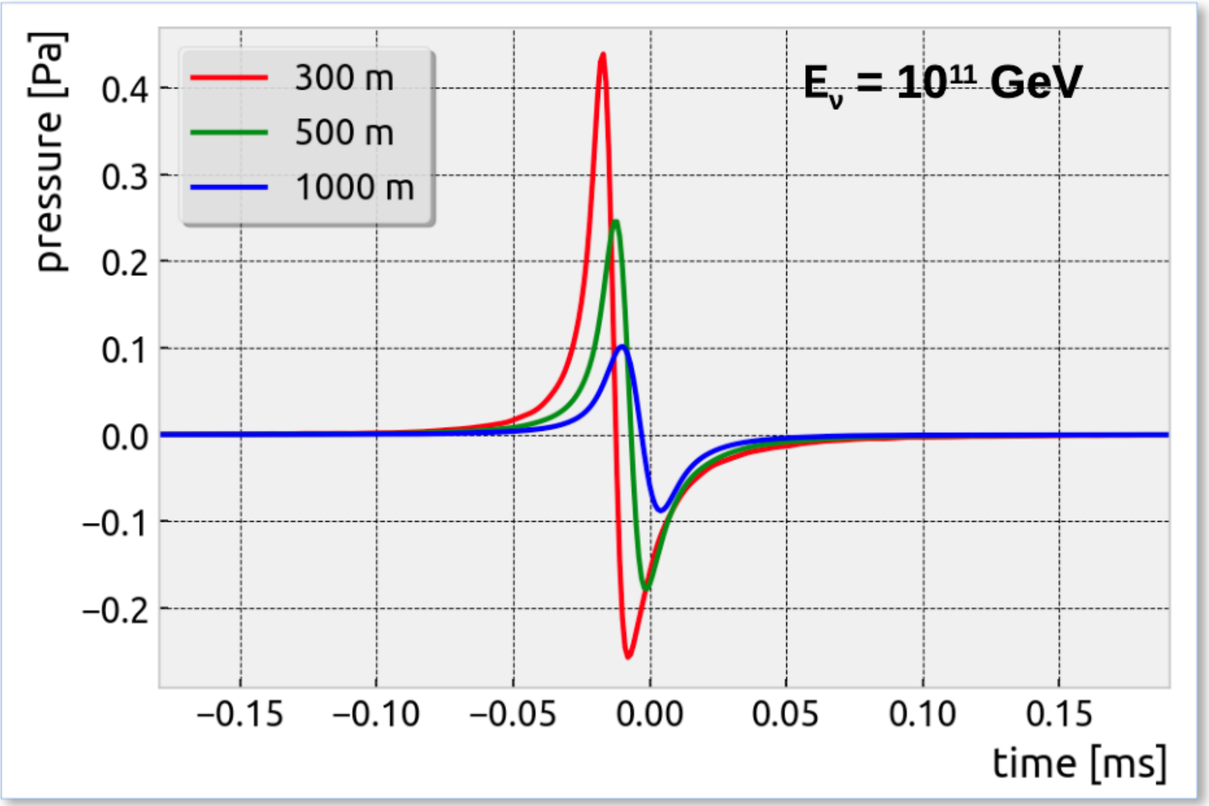
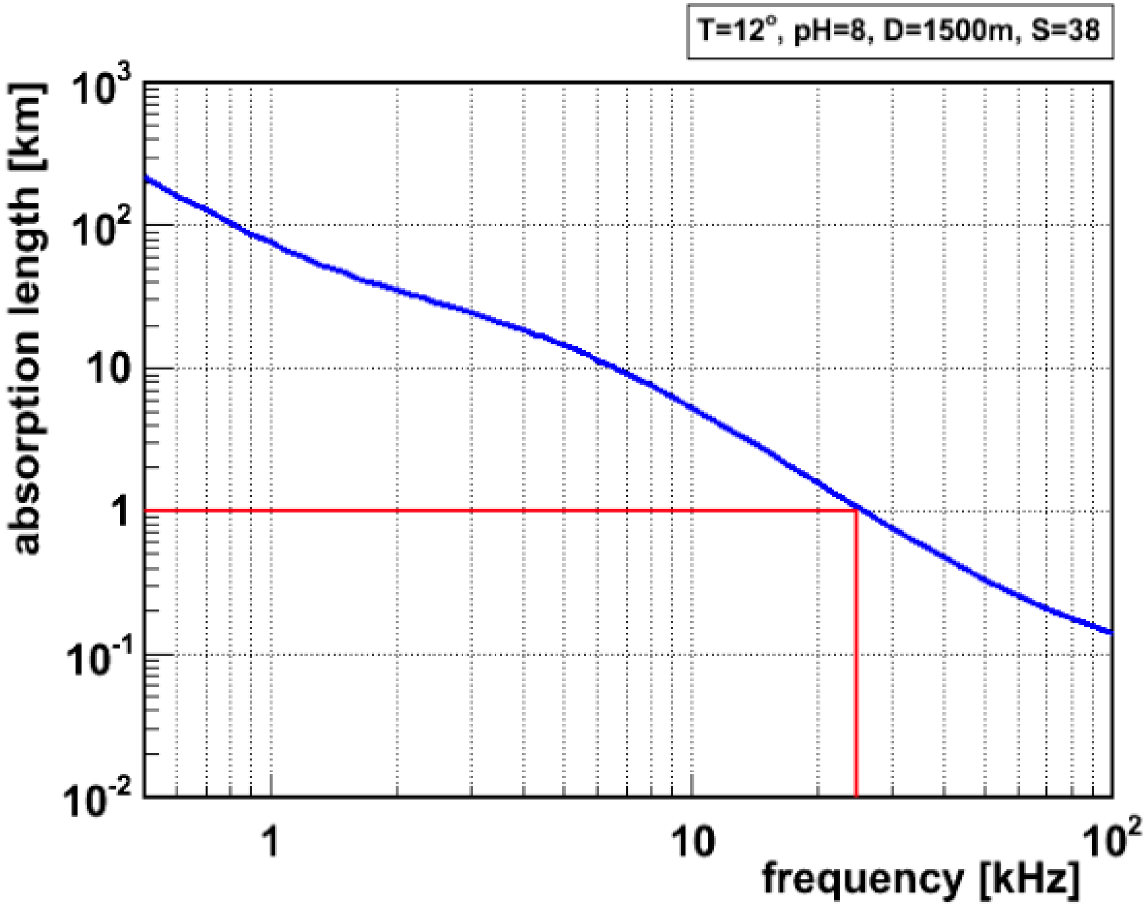
Expected event topology – sound from an UHE neutrino



Magnitude of the acoustic signal generated by an UHE neutrino

1 km → puls of 100 mPa, broad spectrum with a maximum in the range 5–12 kHz



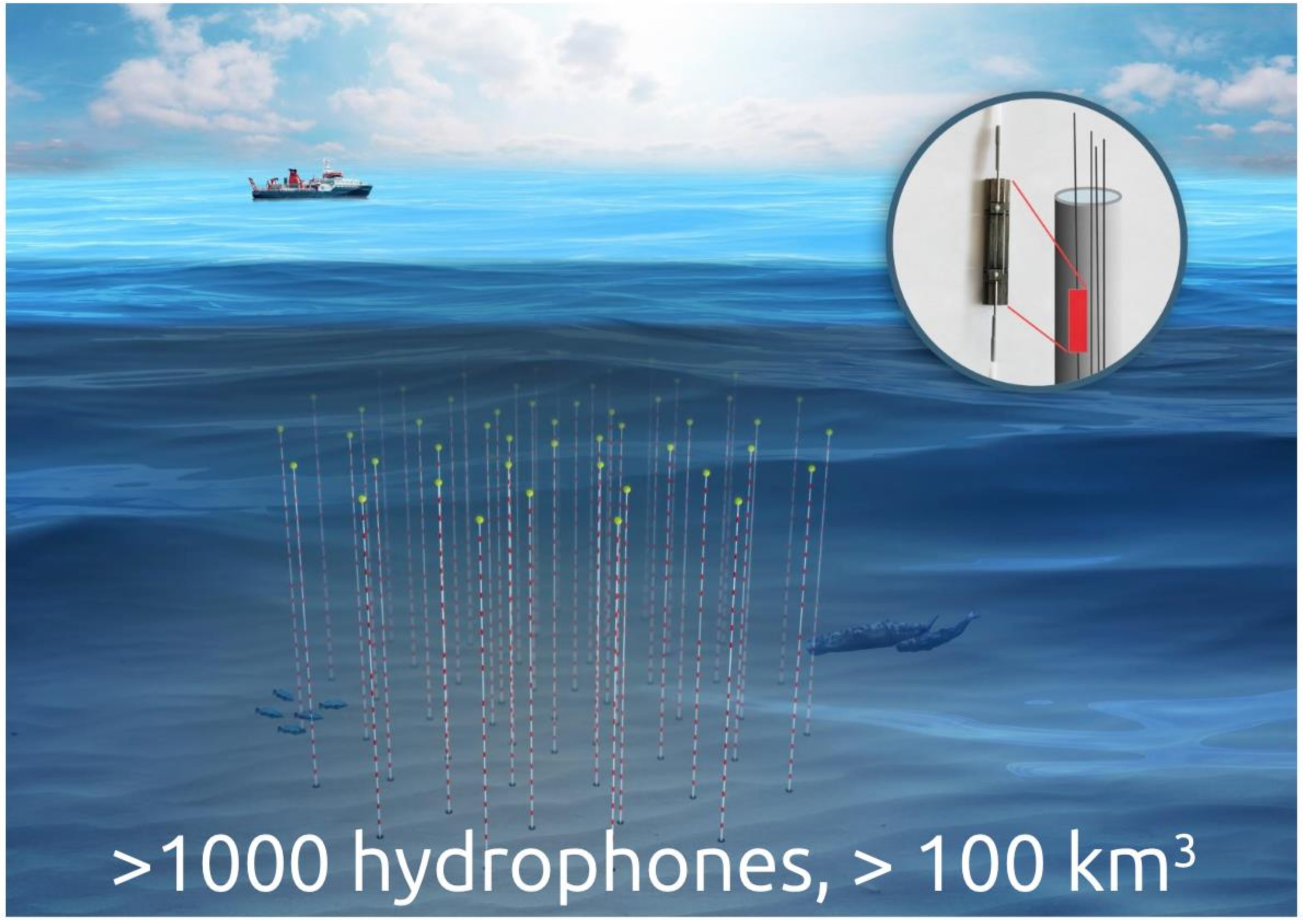


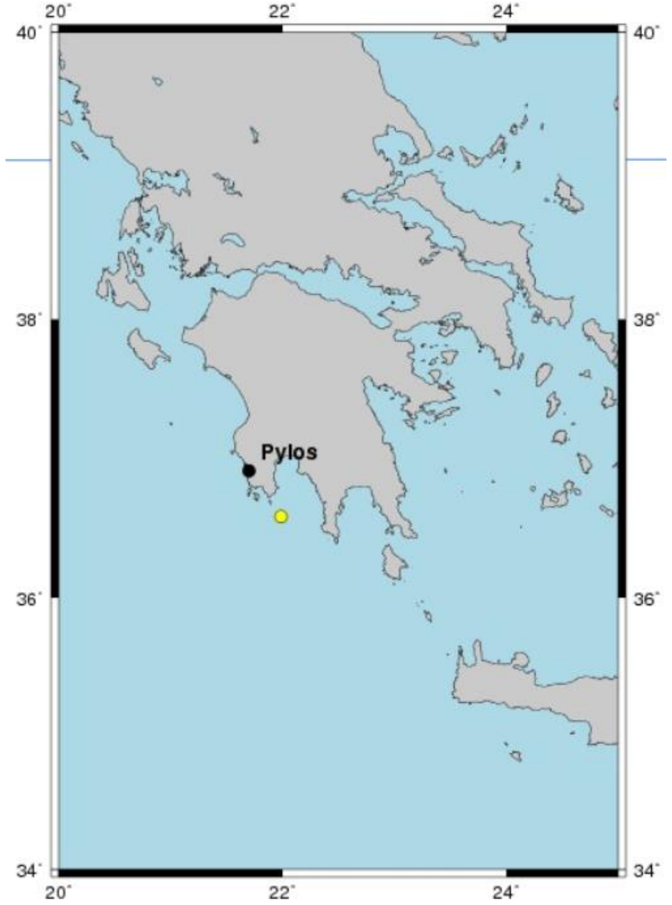
Challenge: measurement of mPa-scale pulses in an environment with MPa-level static pressure!

Concept of building an acoustic telescope prototype

To test the proposed new technology, we aim to participate in building a prototype acoustic detector – we have applied for a ministerial grant

This is important for the construction of the third acoustic telescope in Greek waters





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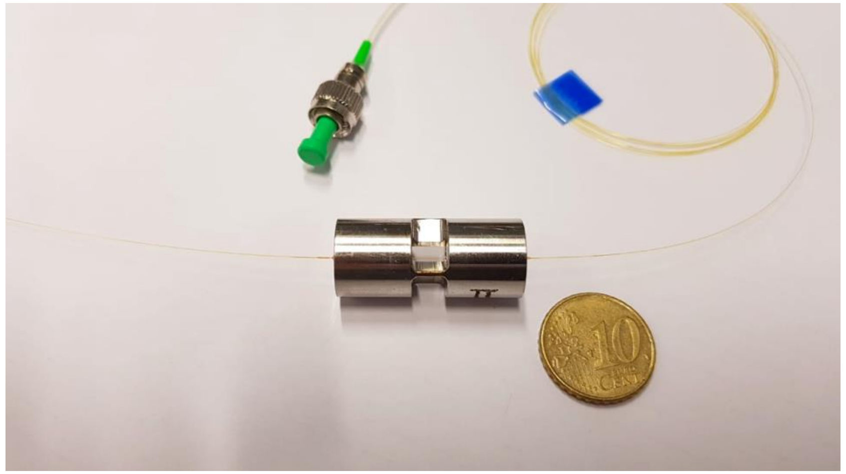
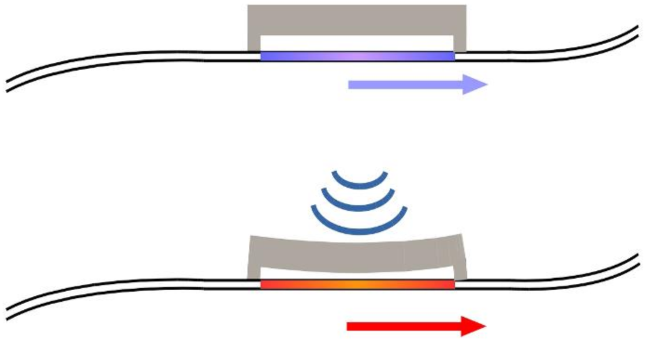
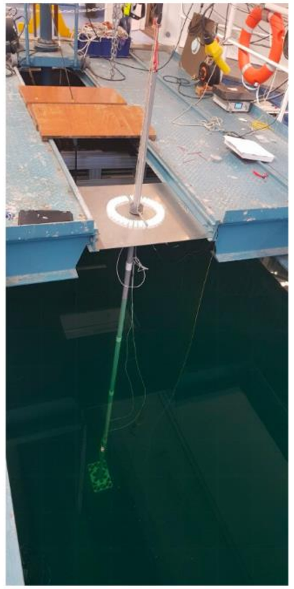
Innovative hydrophones based on fiber-optic technology

Collaboration with Nikhef and TNO-Innovation for Life

arXiv:2501.12999







- the transducer converts pressure into a wave
- it operates mechanically, requires no power supply, and is small (~2cm)
- its durability has been tested up to 250 bar
- the proposed hydrophones can revolutionize existing acoustic systems

Summary

Nature 638:376-382(2025)

Pre-starter: the most energetic UHE neutrino (9% of infrastructure) $220^{+570}_{-100}\ \mathrm{PeV}$

It is 15 714 times more than maximum energy at LHC → LHC circling the Earth

With the progress of the build, we will record more visitors from deep cosmos

Cosmic catchers are in Krakow, join us!

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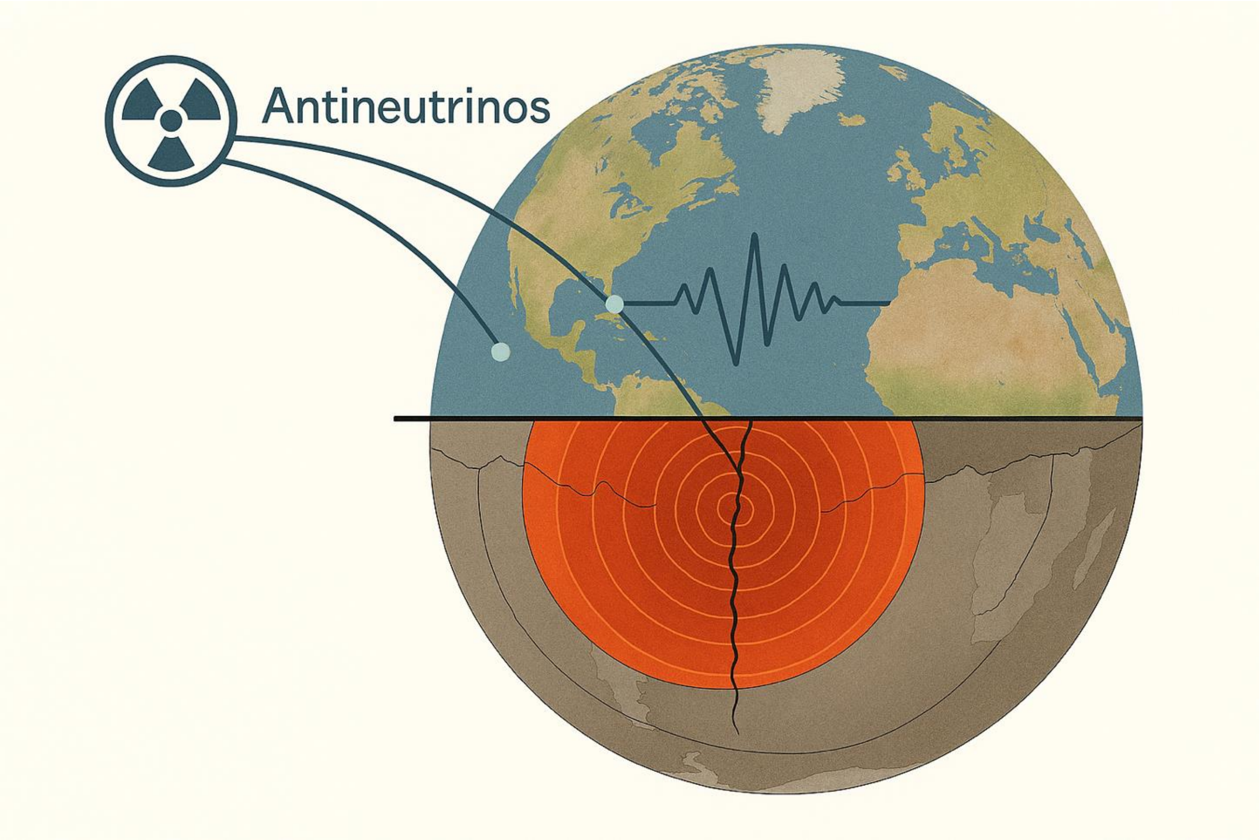
Do we know that…?

- Earthquake early-warning systems rely primarily on seismic data and on articial-inteligence technologies to identify early seismic signals

- There is a hypothesis suggesting that changes in the oscillations of antineutrinos (emitted by nuclear reactors) passing through an earhquake-prone region may be observable and could provide a form of tomography of that area



Neutrinos as probes of an impending earthquake

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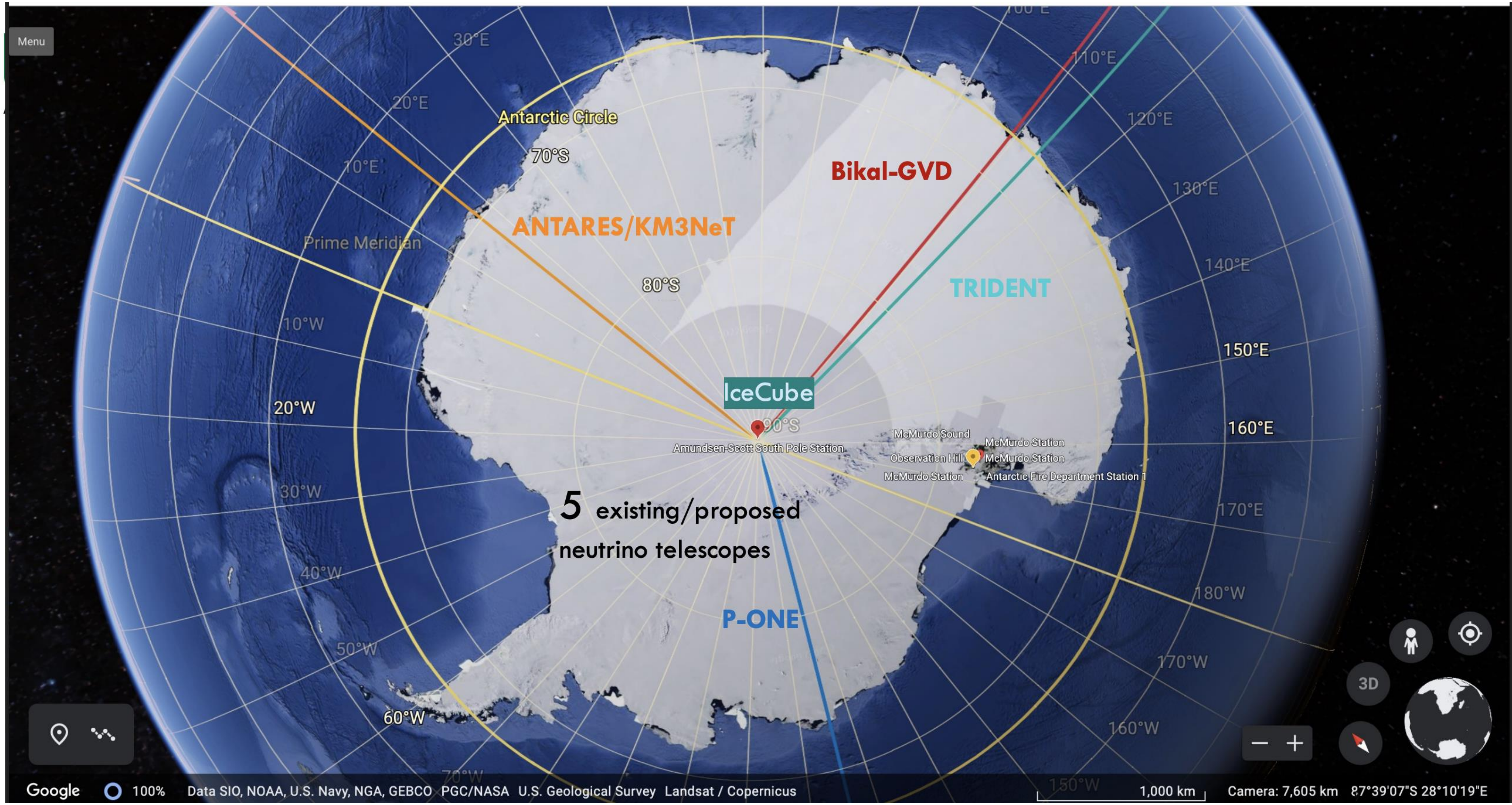
Thank for you attention

Back-up



Menu
Antarctic Circle
70°S
80°S
90°S
30°E
20°E
10°E
Prime Meridian
10°W
20°W
30°W
40°W
50°W
60°W
70°W
110°E
120°E
130°E
140°E
150°E
160°E
170°E
180°W
170°W
160°W
150°W
Bikal-GVD
ANTARES/KM3NeT
TRIDENT
IceCube
P-ONE
Amundsen-Scott South Pole Station
McMurdo Sound
McMurdo Station
Observation Hill
McMurdo Station
McMurdo Station
Antarctic Fire Department Station 1
5 existing/proposed
neutrino telescopes
3D
Google
100%
Data SIO, NOAA, U.S. Navy, NGA, GEBCO PGC/NASA U.S. Geological Survey Landsat / Copernicus
1,000 km
Camera: 7,605 km 87°39'07"S 28°10'19"E

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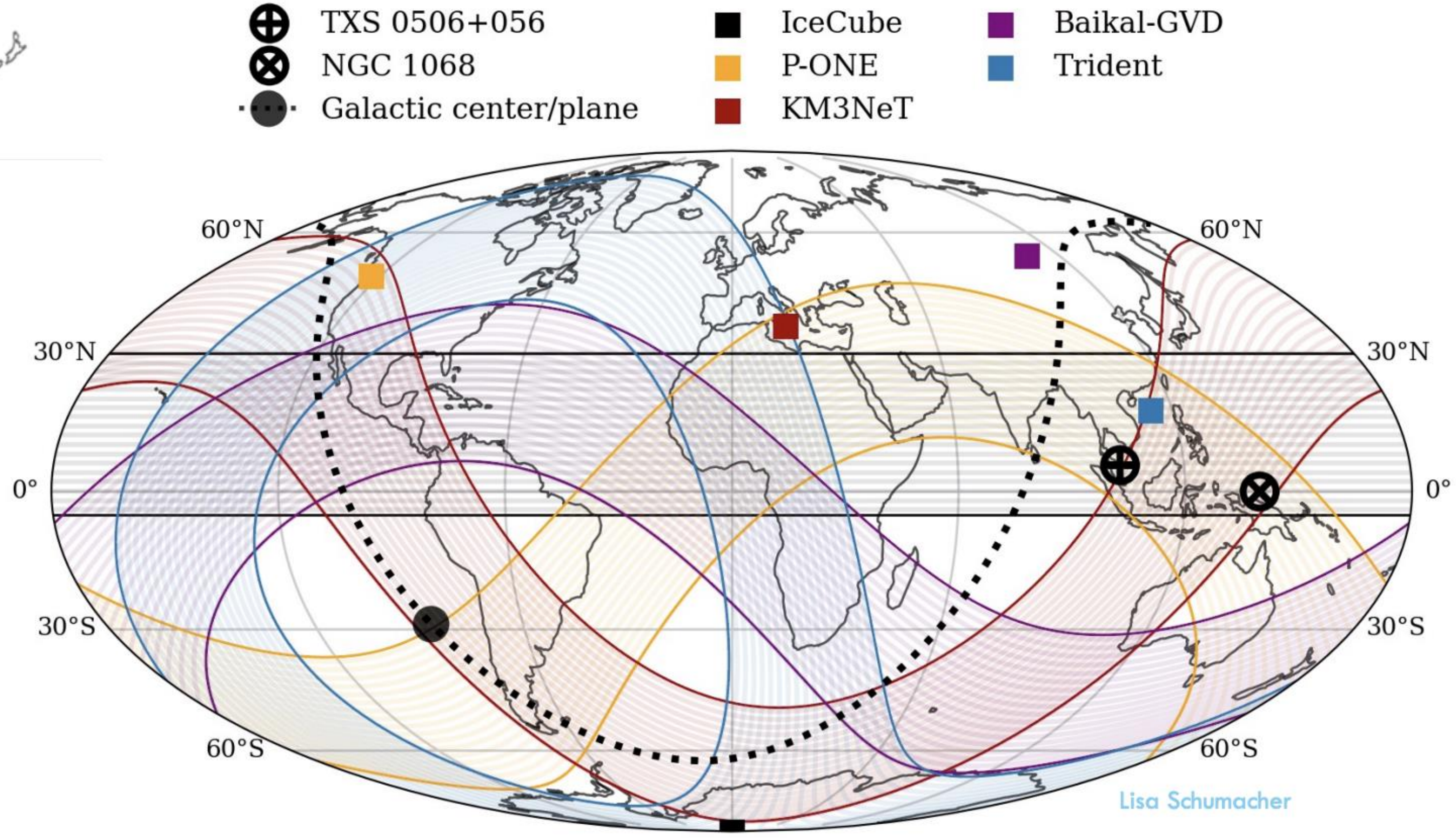
SKY COVERAGE

A global neutrino network to cover the full sky



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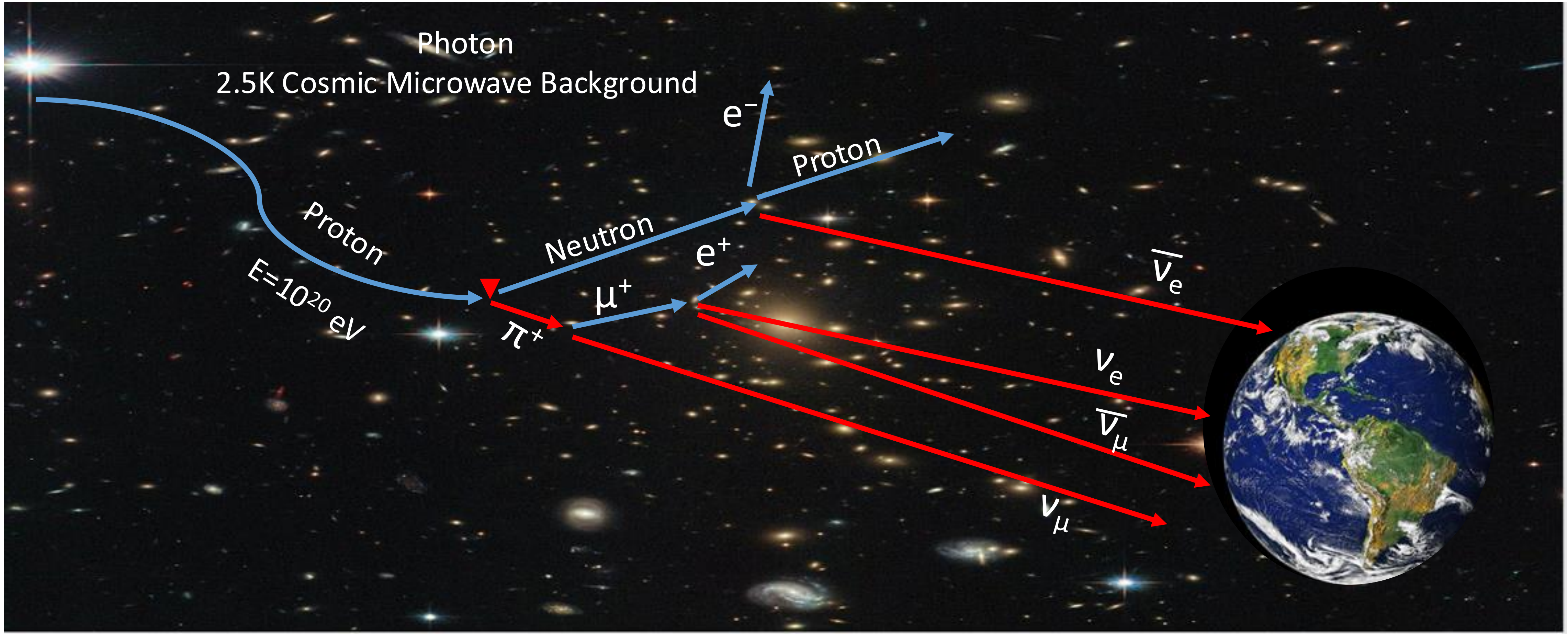
Cosmogenic neutrino contra UHE cosmic rays



Cosmogenic high-energy ν can be produced when ultra-relativistic protons or cosmic-ray nuclei interact with matter or background photons

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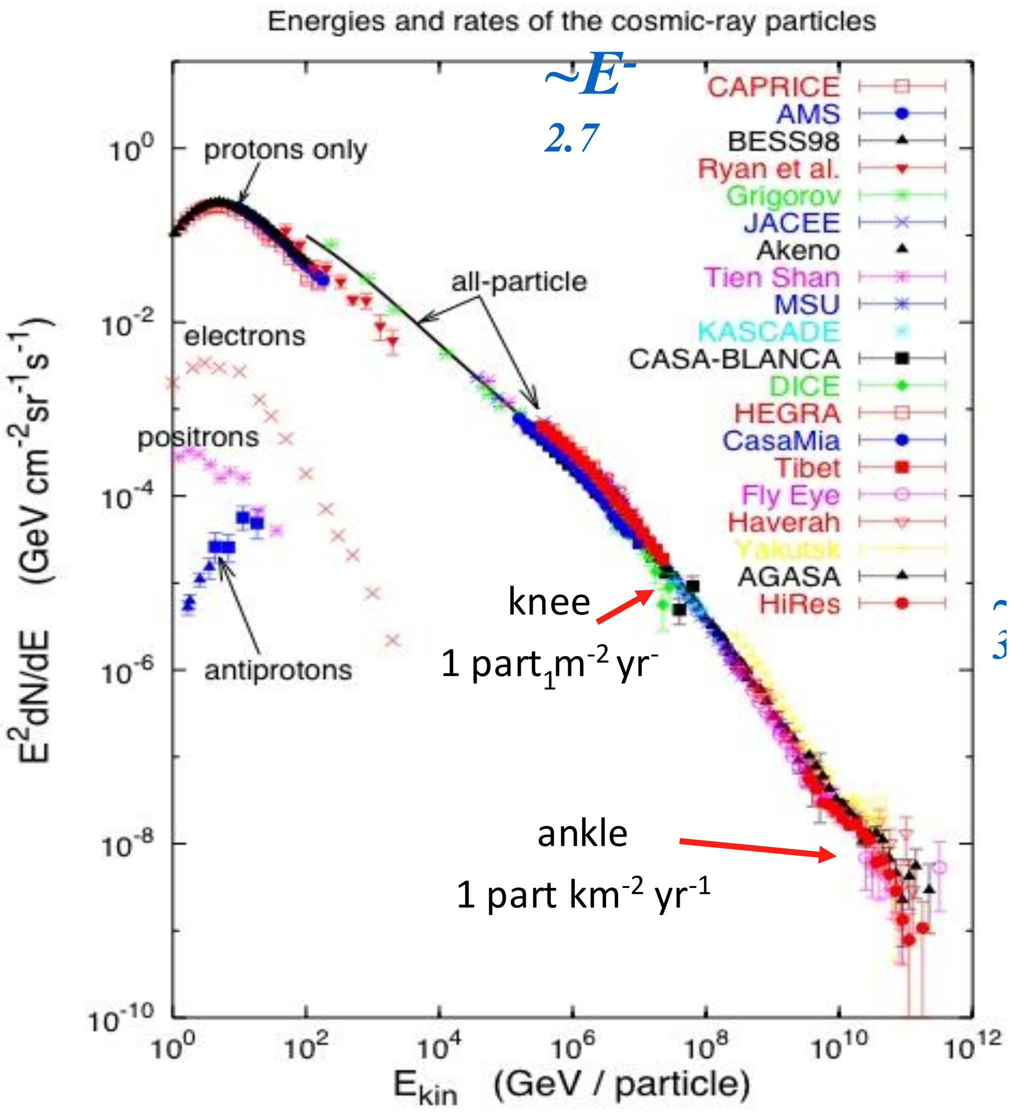
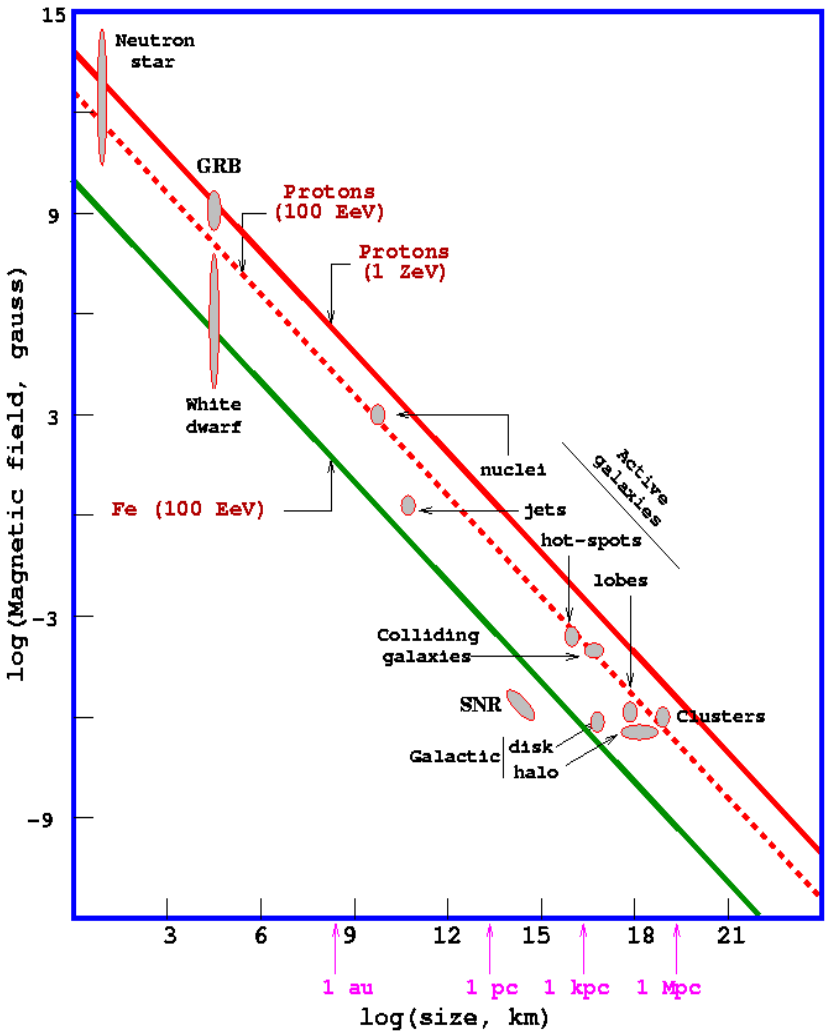

Energies and rates of the cosmic-ray particles
~E-2.7
protons only
all-particle
electrons
positrons
antiprotons
knee
1 part m-2 yr-1
ankle
1 part km-2 yr-1
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
E2dN/dE (GeV cm-2sr-1s-1)
Ekin (GeV / particle)


Neutron star
GRB
Protons (100 EeV)
Protons (1 ZeV)
White dwarf
nuclei
Active galaxies
Fe (100 EeV)
jets
hot-spots
lobes
Colliding galaxies
SNR
Clusters
Galactic disk halo
log(Magnetic field, gauss)
1 au
1 pc
1 kpc
1 Mpc
log(size, km)

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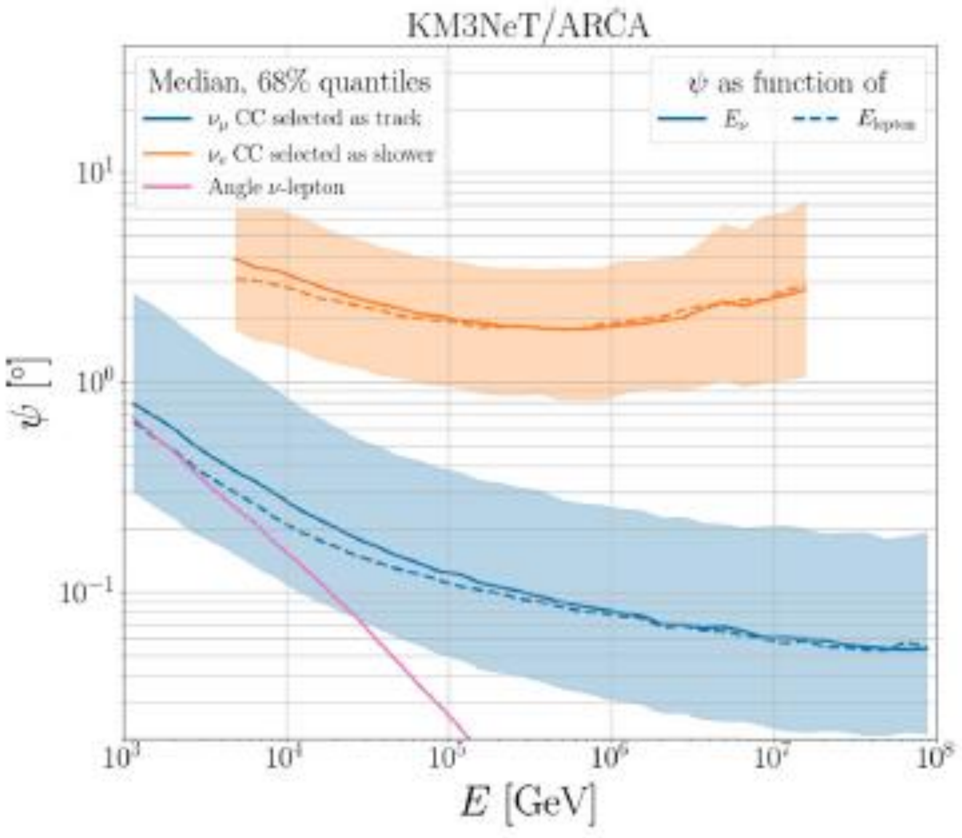
Expected resolution



Eur. Phys. J. C 84, 885 (2024)

Neutrinos very rare interact with matter

- Cross-section for interaction (from Fermi theory):

  $\sigma \approx 10^{-38}\ \mathrm{cm}^2$ (i.e. 1 femtobarn) for $E(\nu)$ in MeV range

- The mean lenght to interact with matter is looooooong $\lambda = \frac{1}{n\sigma}$

  for $E(\nu) \sim \mathrm{MeV}$ λ could be 10^{16} km,

  it is much higher than radius of our galactic (100 000 light-years ~ 946 billions km)

- Probability for interaction:

$$P = \sigma \cdot n \cdot d$$

  n numer of particles for volume unit (i.e. number of nuclei)

  d droga przebyta przez neutrino w materii

  for example. in $1\ \mathrm{m}^3$ of water vasel: $P \sim 10^{-42}\ \mathrm{m}^3$

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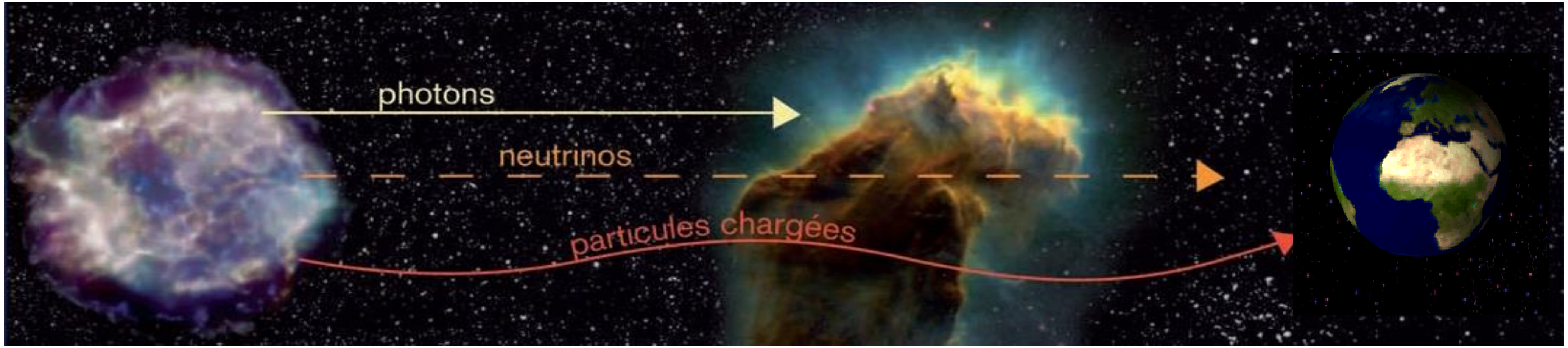
Plethora neutrinos around us

- In each second of our life, neutrinos pass throughout our bodies without any interaction, even 100 trillion (10^{12})
- A chance that neutrino interacts inside us is 1 over 1 trillion trillion
- This digit is such extremely small that difficult to imagine it
- We are very lucky if at least one neutrino interacts inside us during our life

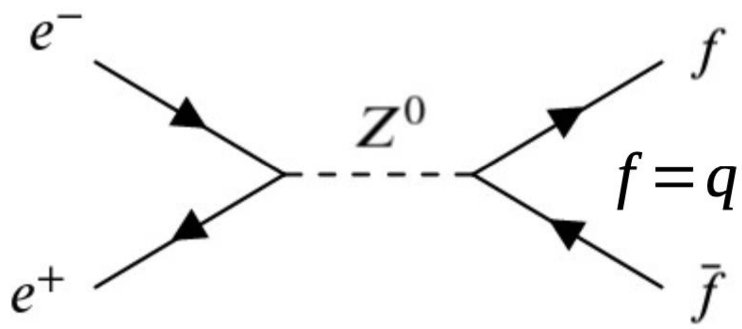
First messengers from cosmos



Neutrinos from supernovae reach Earth earlier than light, since:

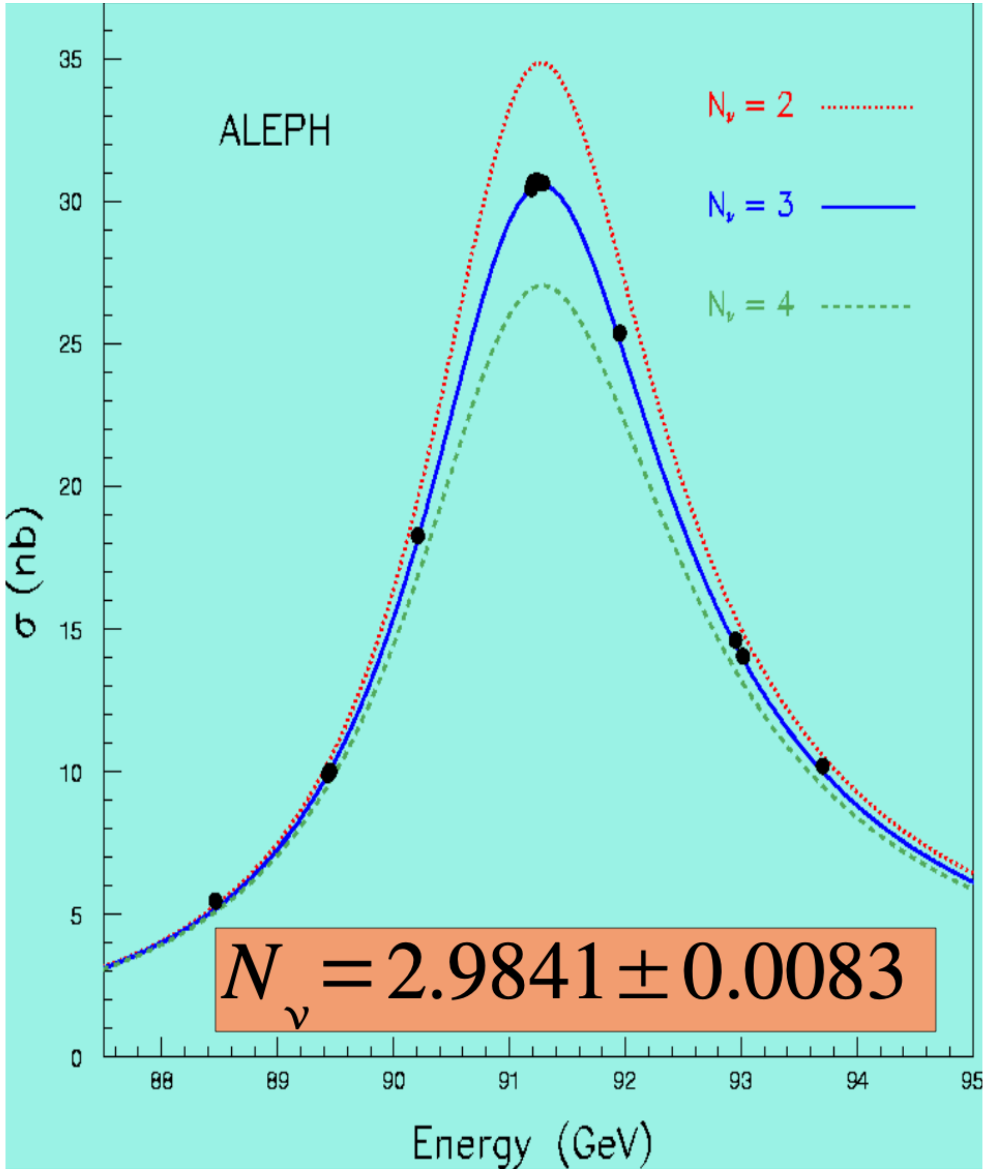
- they are emitted immediately after the collapse of the star's core, within a few seconds
- light takes more time to escape the dense layers of the star – it can take hours or even days before the shock wave breaks through the stellar envelope and releases visible radiation

Neutrinos act as a cosmic early warning system, informing us about dramatic events in stars before we see them in light



$f = q, l, \nu$

$$\Gamma_z = \sum \Gamma_{q\bar{q}} + 3\,\Gamma_{l\bar{l}} + N_\nu\,\Gamma_{\nu\bar{\nu}}$$



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https://git.km3net.de/acoustics/SUNSET.jl

SUNSET

SUNSET (**S**imulation of **U**nderwater **N**eutrino-induced **S**ound **E**mission and **T**ransport) is a code designed to generate and process underwater acoustic pulses emitted by calibration hardware as well as UHE neutrinos.

docs stable | docs dev | pipeline failed | coverage 11.97%

Documentation

Check out the **Latest Documention** which also includes tutorials and examples.

Installation

`SUNSET.jl` is not (yet) an officially registered Julia package but it's available via the KM3NeT Julia registry. To add the KM3NeT Julia registry to your local Julia registry list, follow the instructions in its README or simply do

```
git clone https://git.km3net.de/common/julia-registry ~/.julia/registries/KM3NeT
```

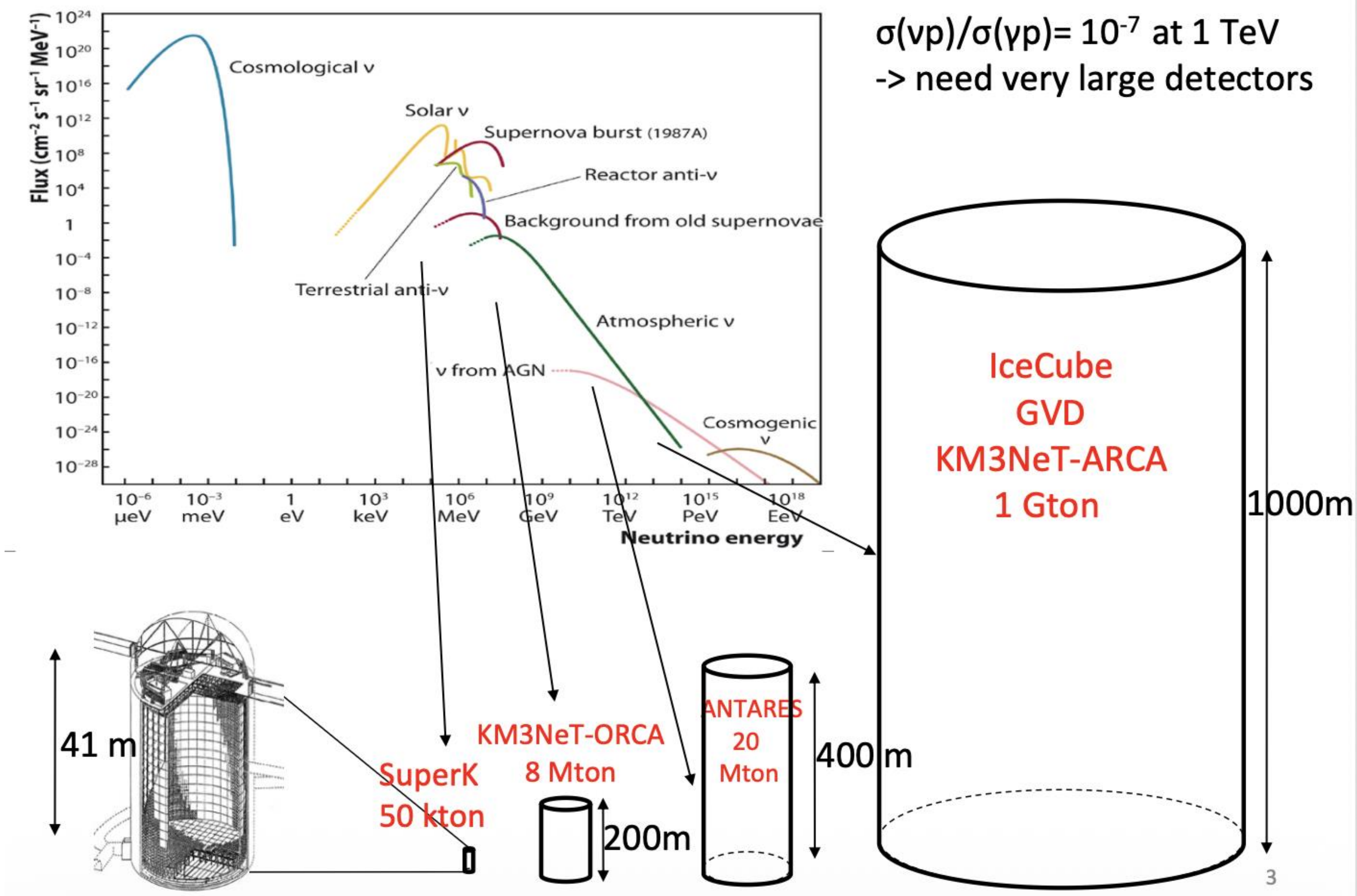
After that, you can add `SUNSET.jl` just like any other Julia package:

```
julia> import Pkg; Pkg.add("SUNSET")
```

Quickstart and usage

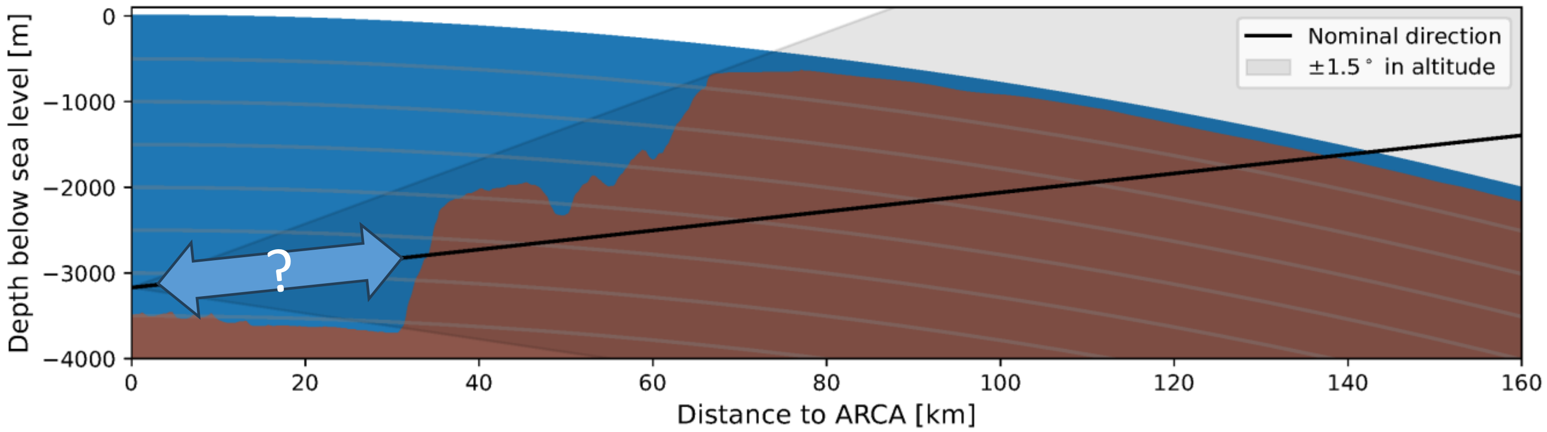
```
julia> using SUNSET
```

$\sigma(\nu p)/\sigma(\gamma p) = 10^{-7}$ at 1 TeV
-> need very large detectors



Atmospheric muons

Exceedingly unlikely for atmospheric muon to travel through that much water/column depth -> neutrino



100 PeV muon → **maximum 45 km in water**

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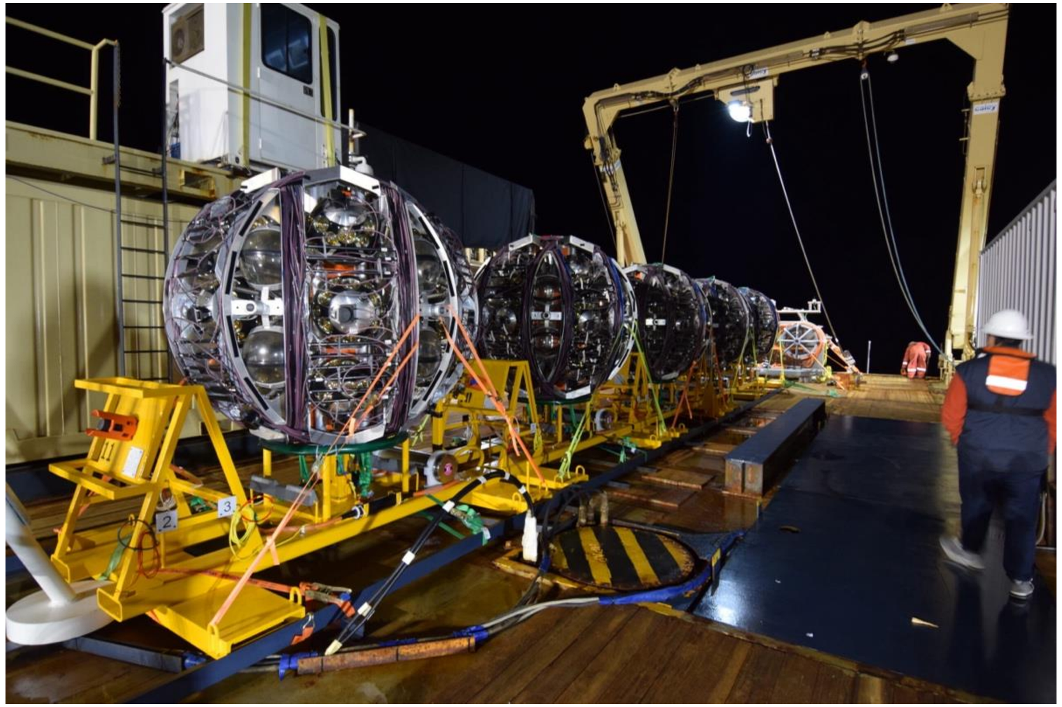
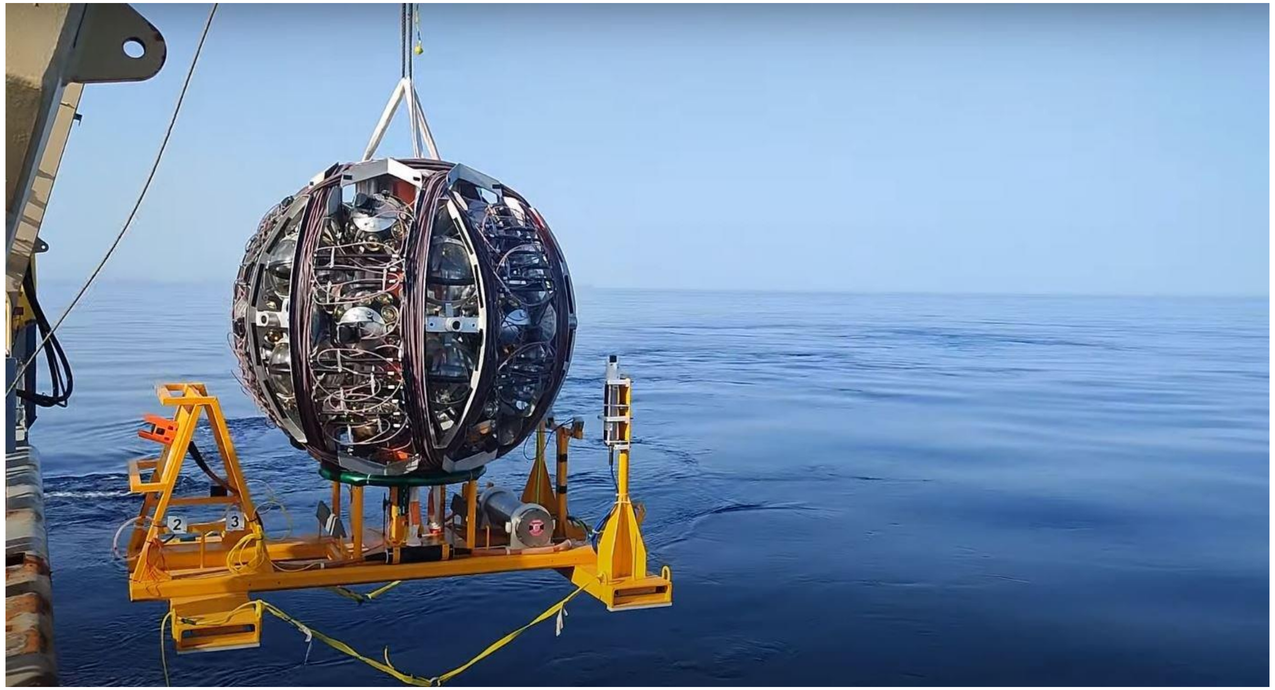
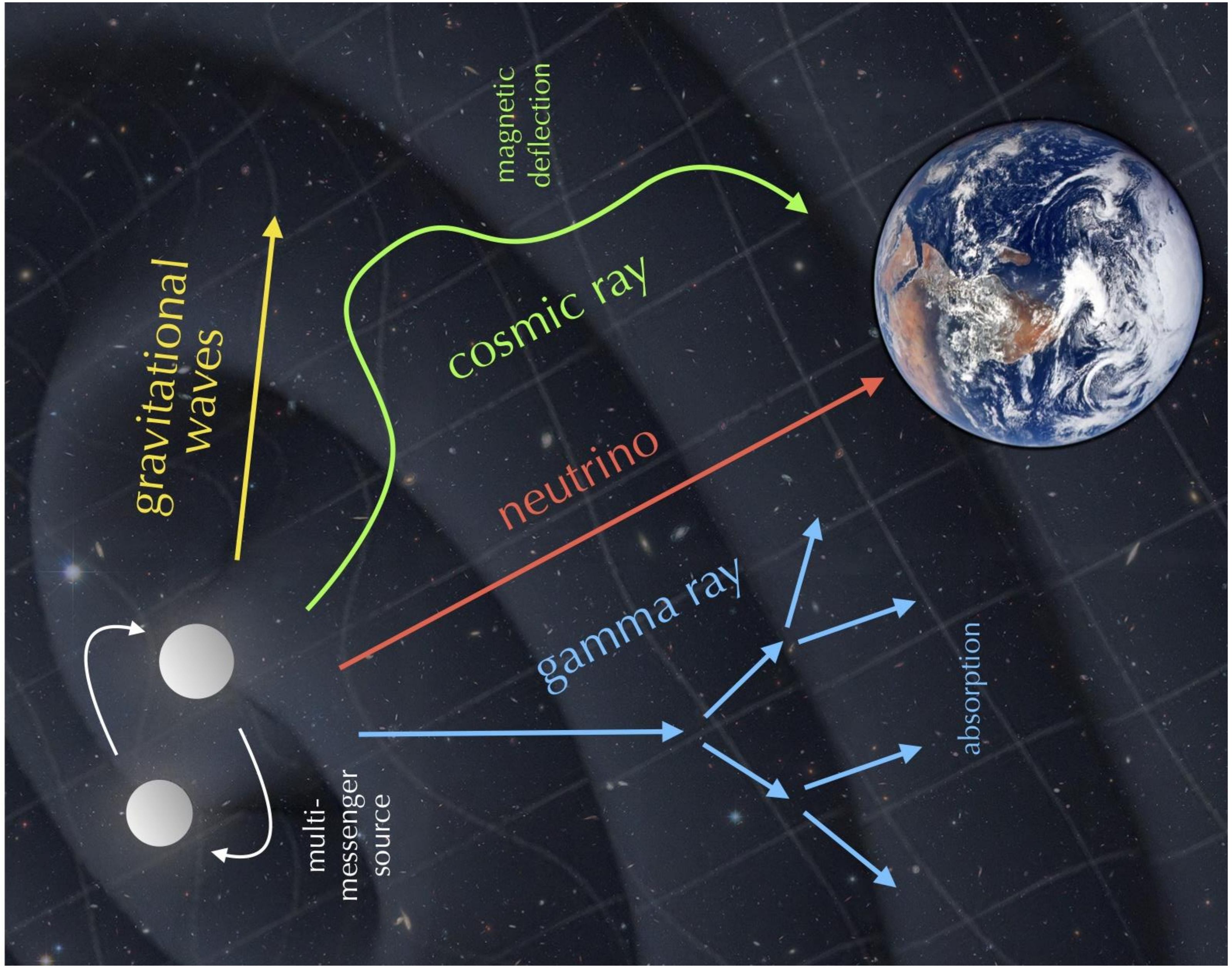
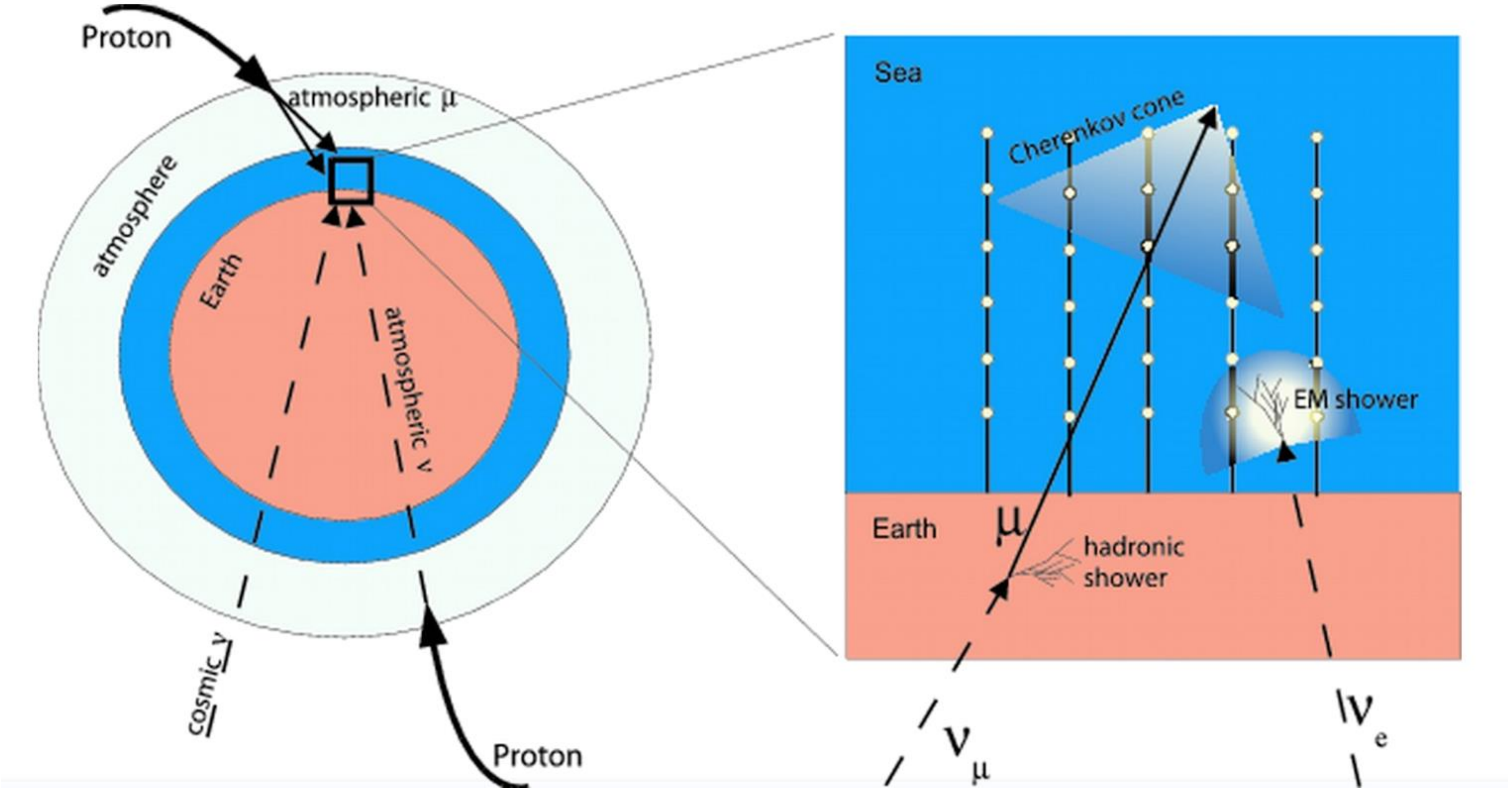





magnetic deflection
gravitational waves
cosmic ray
neutrino
gamma ray
absorption
multi-messenger source

Concept of optic detection



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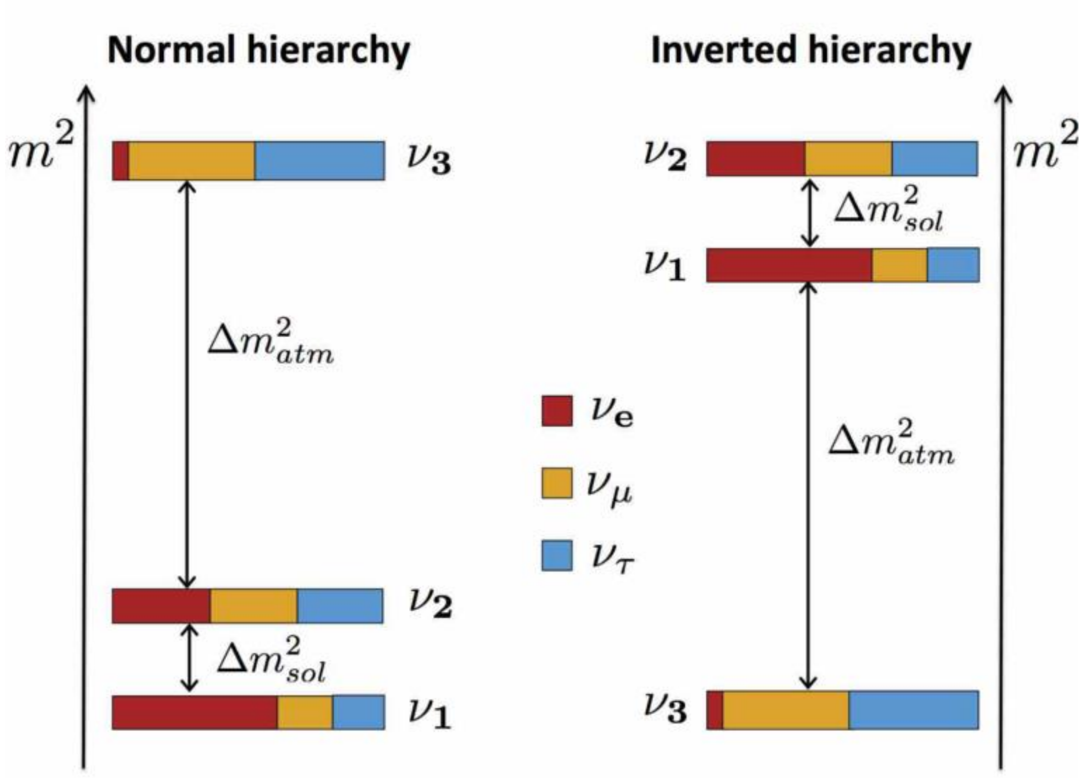
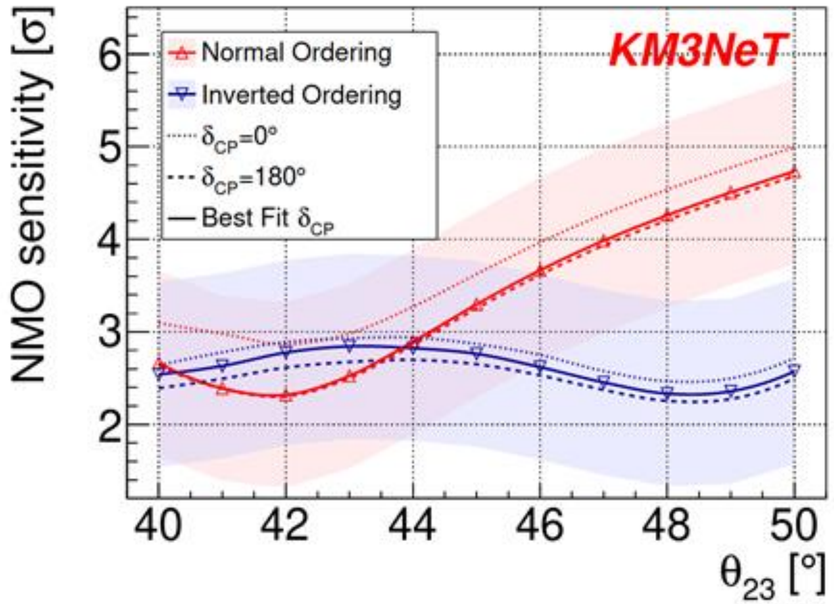
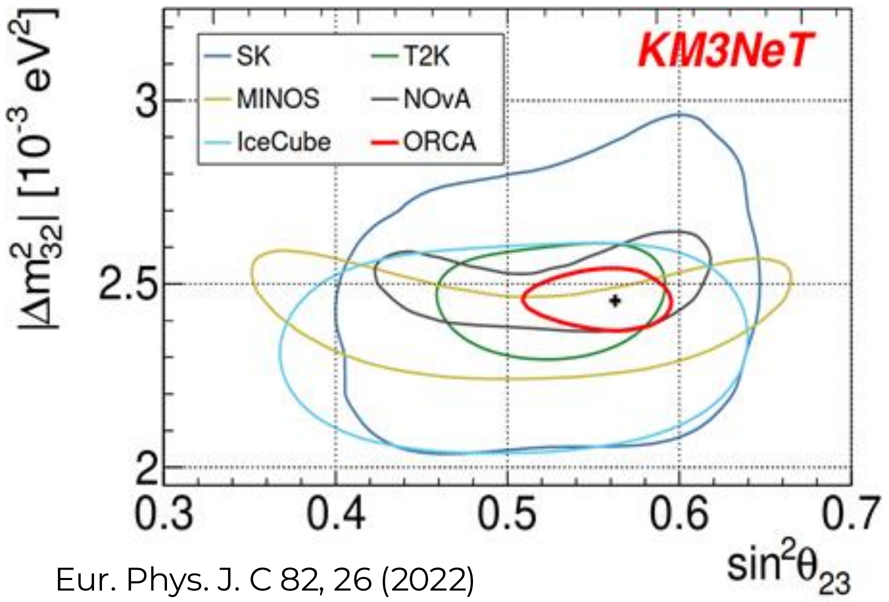


Today, one of the key question

Prospects for the mass ordering



Expected results for 3 years exposure, full detector.



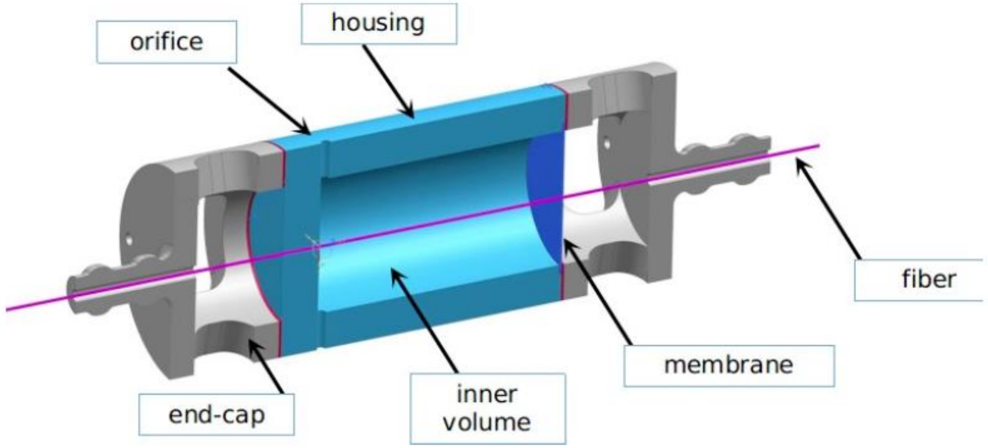
Eur. Phys. J. C 82, 26 (2022)

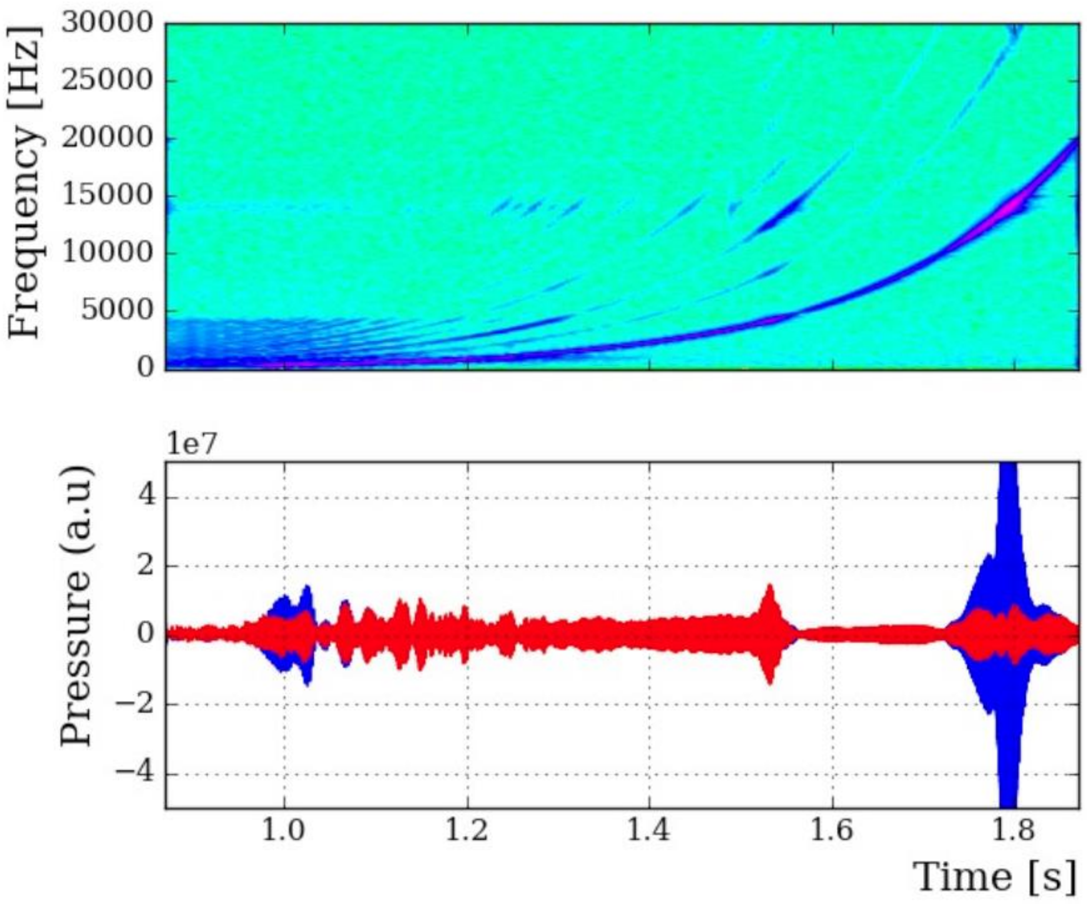
Competitive sensitivity to $\Delta m^2{}_{32}$, θ_{23}

Instrument response

- Mechanical resonance peak ~15 kHz
- Helmholtz resonance peak at 600 Hz

- Two types:
  - single membrane
  - double membrane





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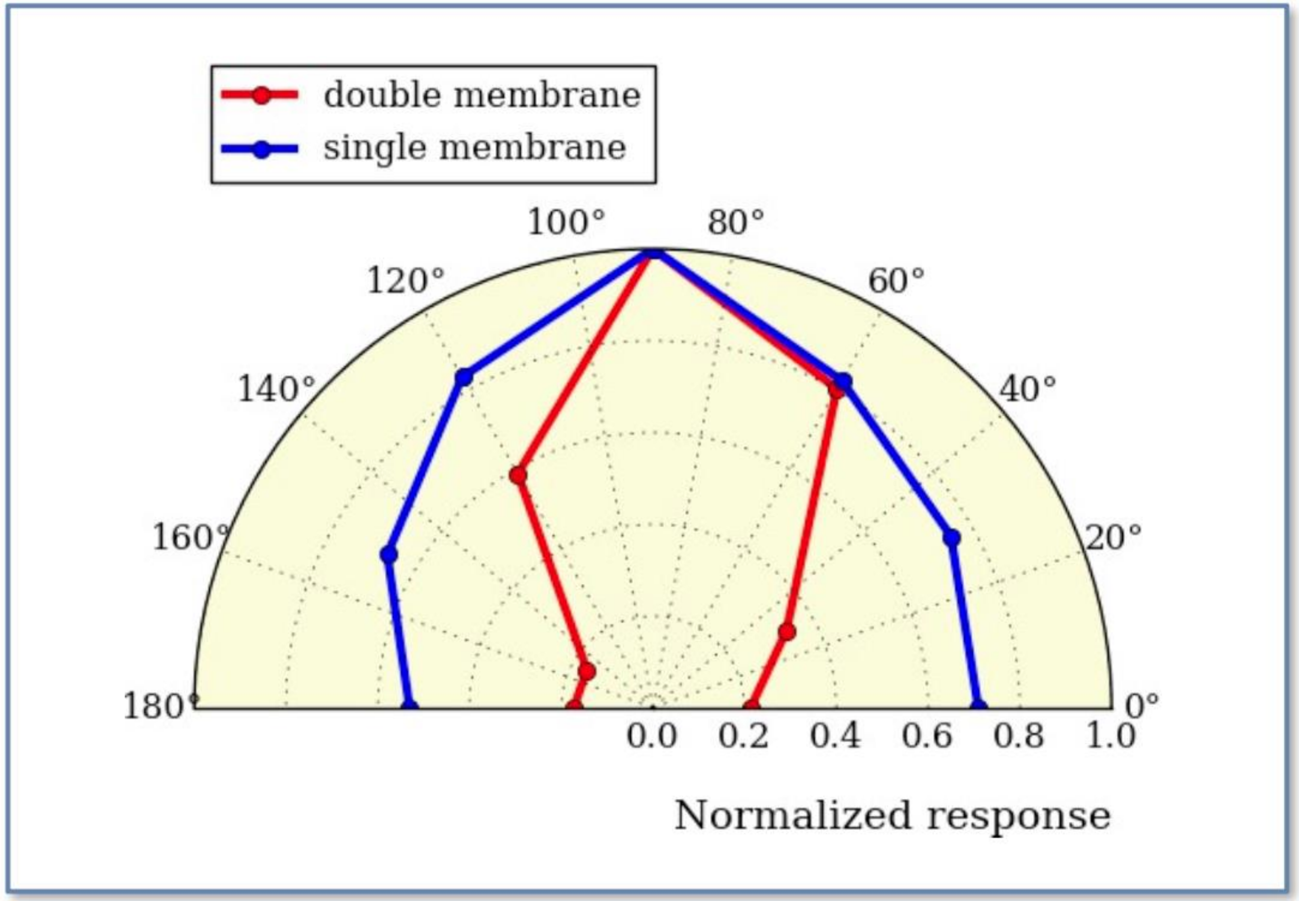
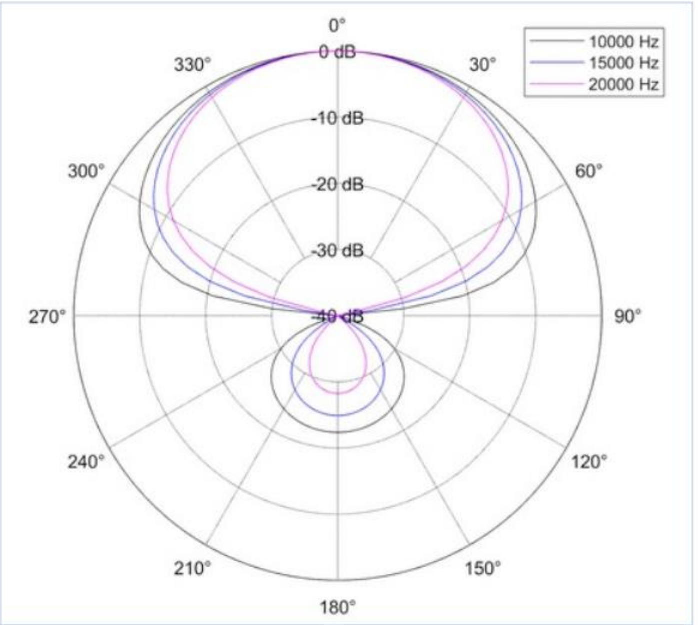
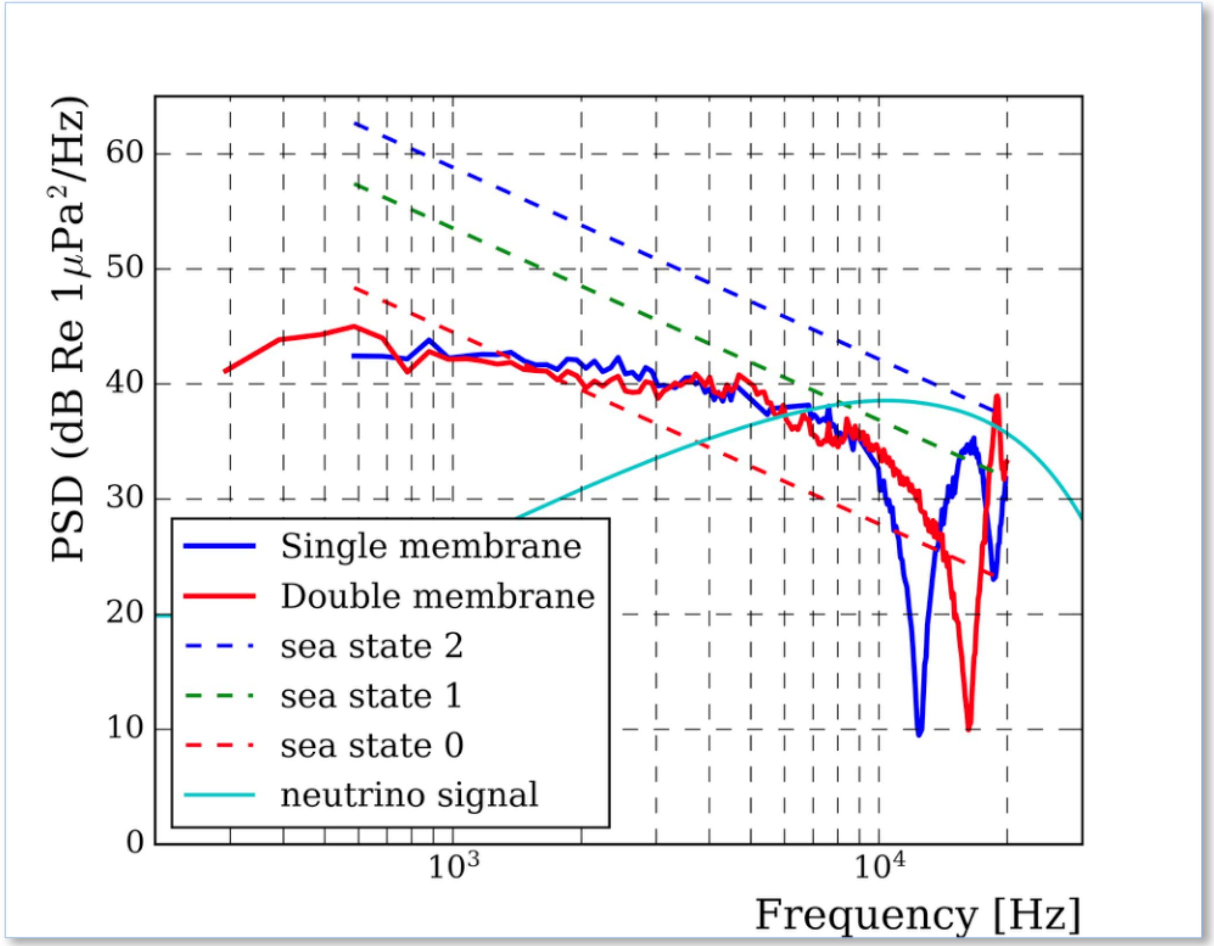
Instrument response: directionality

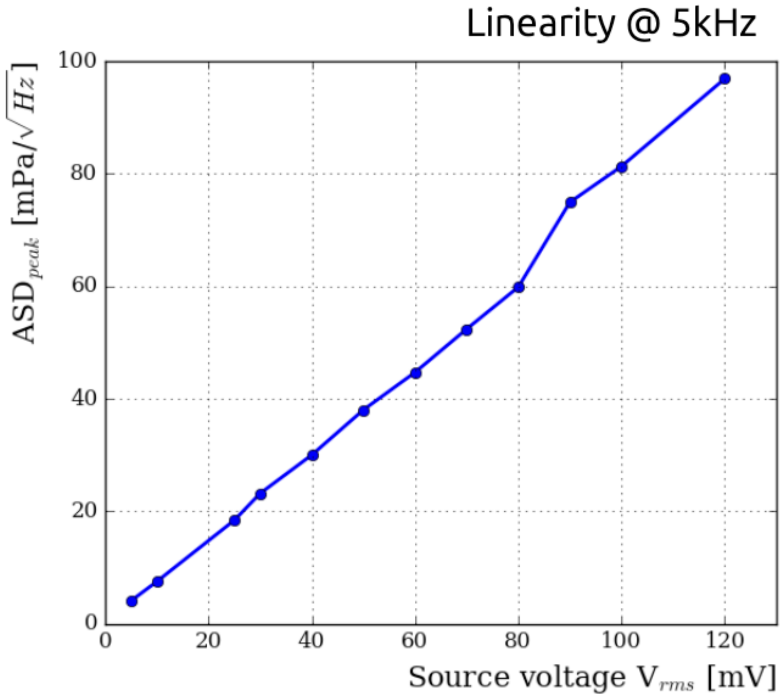




Theoretical deep-sea noise vertical angle distribution

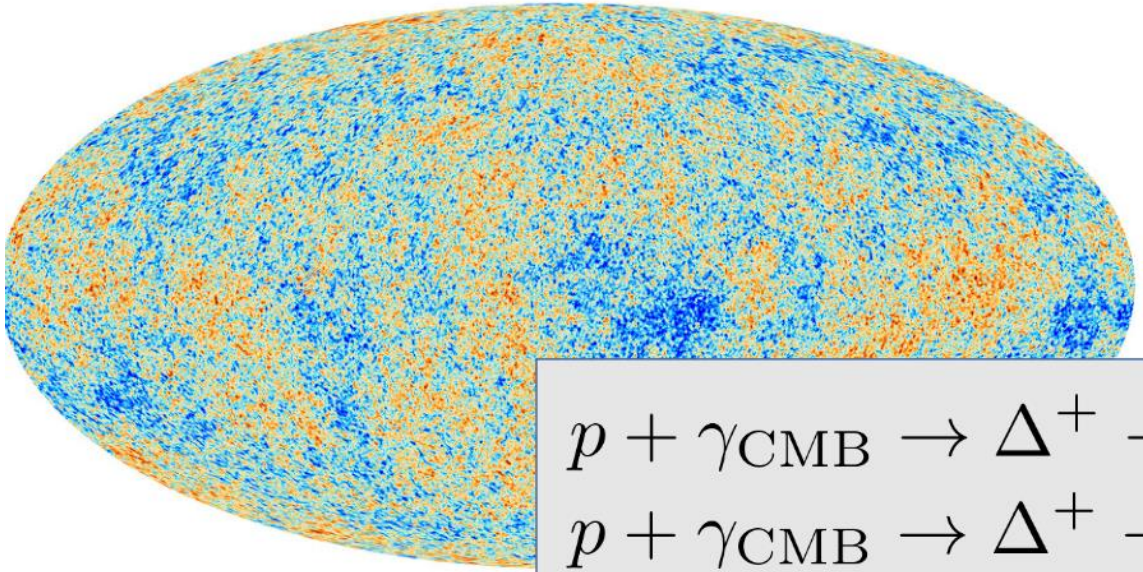
Hydrophone sensitivity

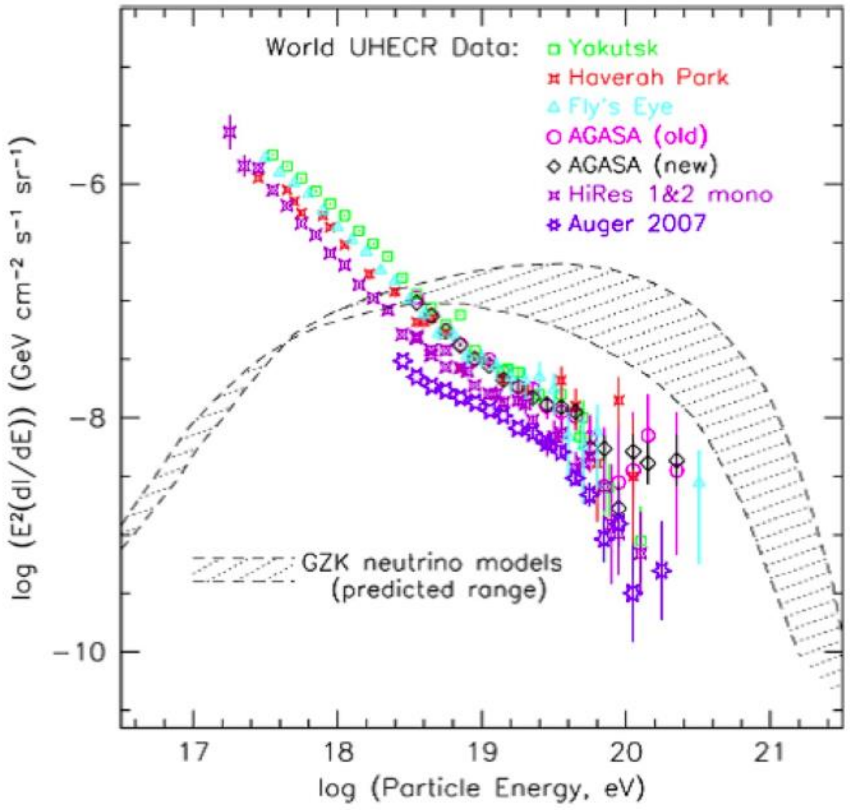




The GZK cut-off

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





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

… with subsequent decay to *neutrinos*

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