Introducing Neutrino Astronomy

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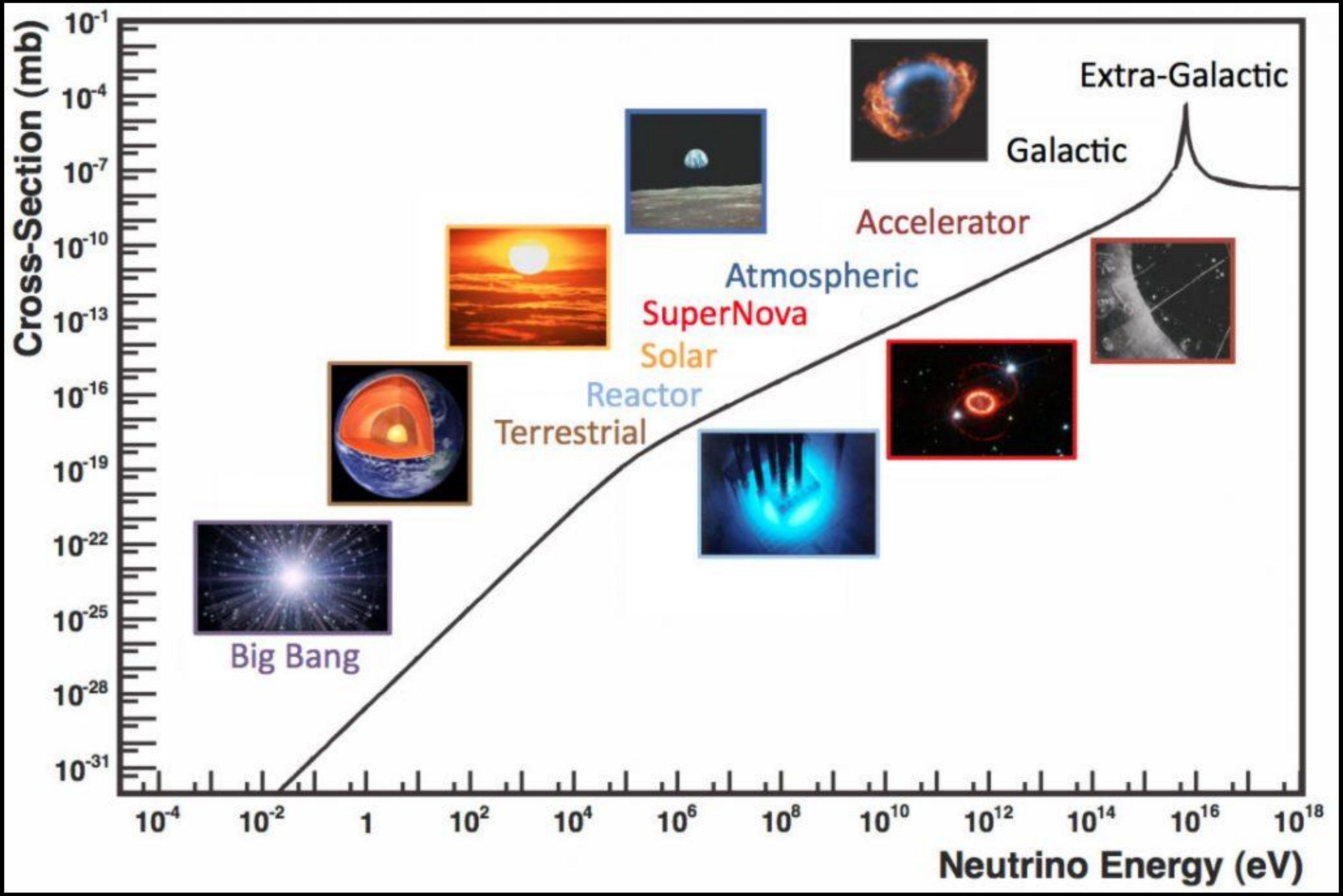
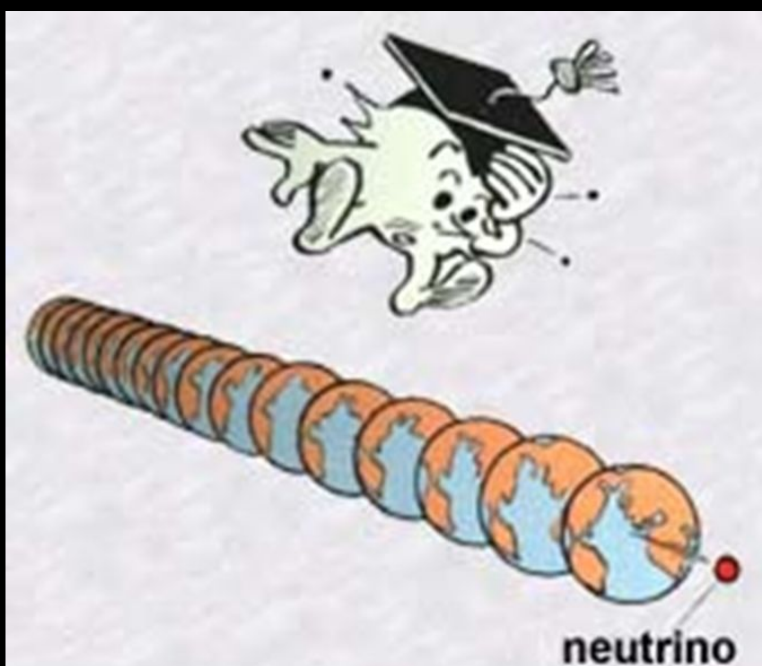
WHAT IS THE NEUTRINO?

- Almost massless elementary particle
- Lepton (no internal structure –so far)
- Interacts very weakly with matter through weak interactions
- Is produced in elementary processes where the weak interaction is at play: Supernova explosions, cataclysmic cosmic events, nuclear reactors, particle accelerators..

Sources of neutrinos



Did you know that… *about 65 million neutrinos from the sun pass through our fingernail every second?*



Interaction probability with matter: Infinitessimal! A 1 MeV neutrino may travel for a distance of 50 light years in water before it interacts!

As the neutrino energy increases, its interaction probability increases. The more “targets” we have in our disposal, the more probable it is to detect a neutrino

WHY SHOULD AN ASTRONOMER CARE?

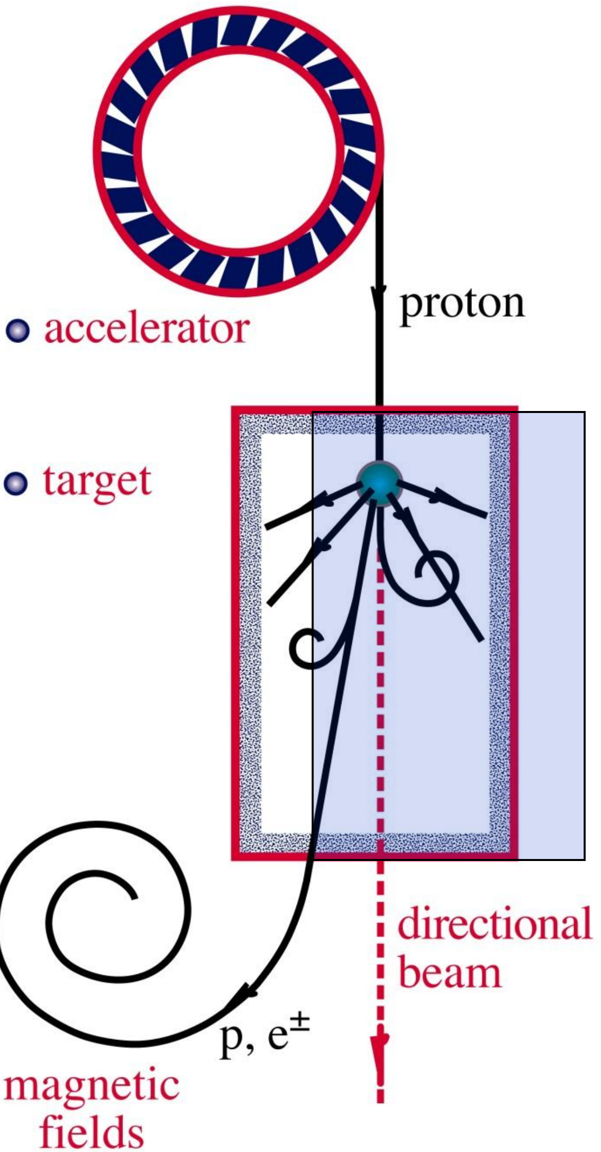
Astrophysics is the science of unexpected discoveries

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

What about neutrinos?

- All stars produce neutrinos in the hadronic interactions taking place in their cores.
- Violent, cataclysmic events in the Universe such as Supernova explosions (SN1987 A) produce neutrinos!
- Cataclysmic cosmic events are expected to produce neutrinos of high energy (AGNs, Blazars - confirmed)
- Dark matter annihilations, interactions of exotic particles existing since the infancy of the Universe etc could produce neutrinos!
- If we can use neutrinos to do astronomy, we can open a new window to the Universe! And when we do that, we expect.. The unexpected.

Cosmic Accelerators



Cataclysmic cosmic phenomena

AGNs, Blazars

Interstellar dust and matter

$p + \gamma$ □ $n + \pi^+$

$\sim$ *cosmic ray + neutrino*

□ $p + \pi^0$

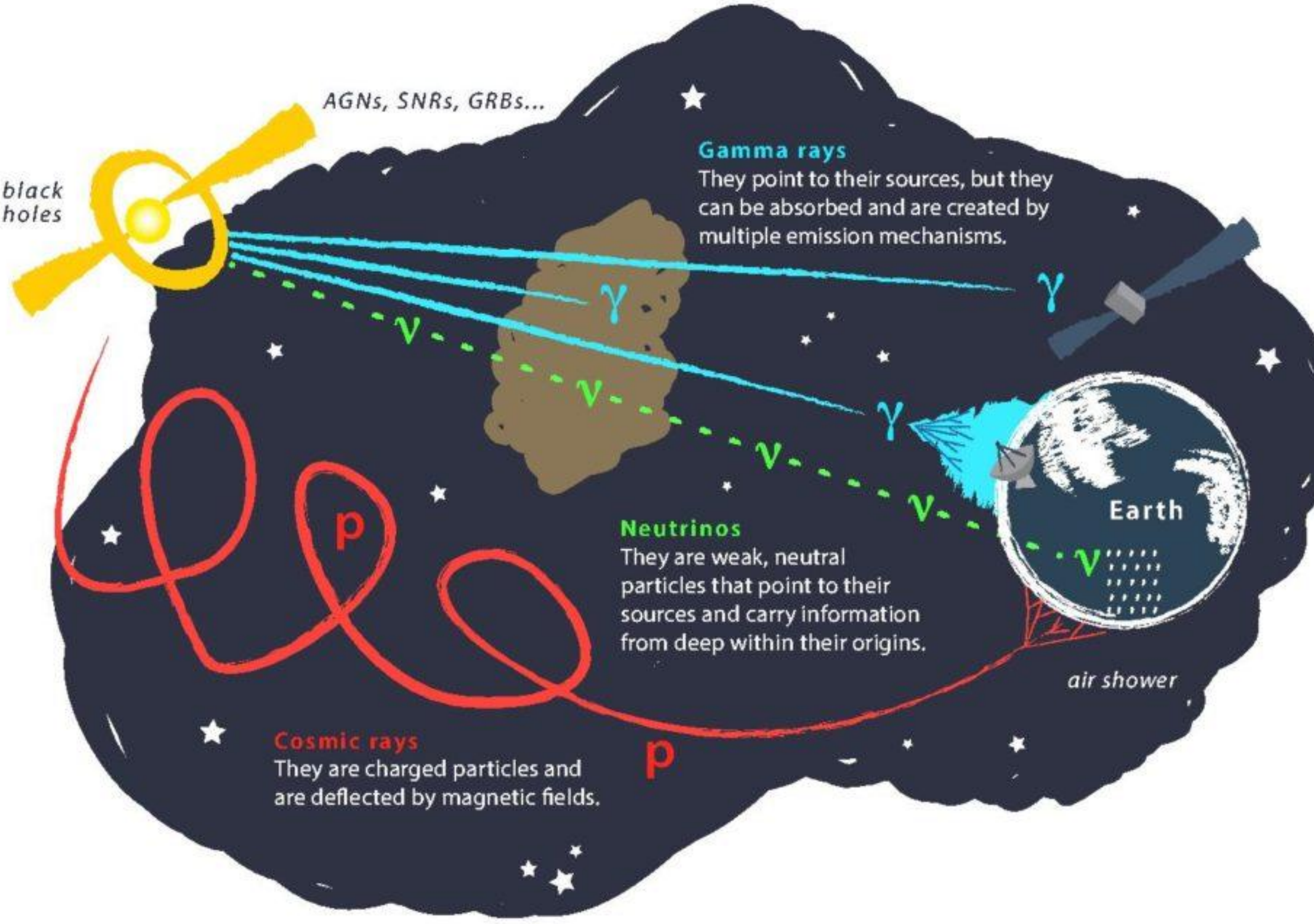
$\sim$ *cosmic ray + gamma*

Neutrino: The cosmic messenger

- Zero electric charge. Their trajectories are not curved by galactic magnetic fields we can use them to point back to their sources

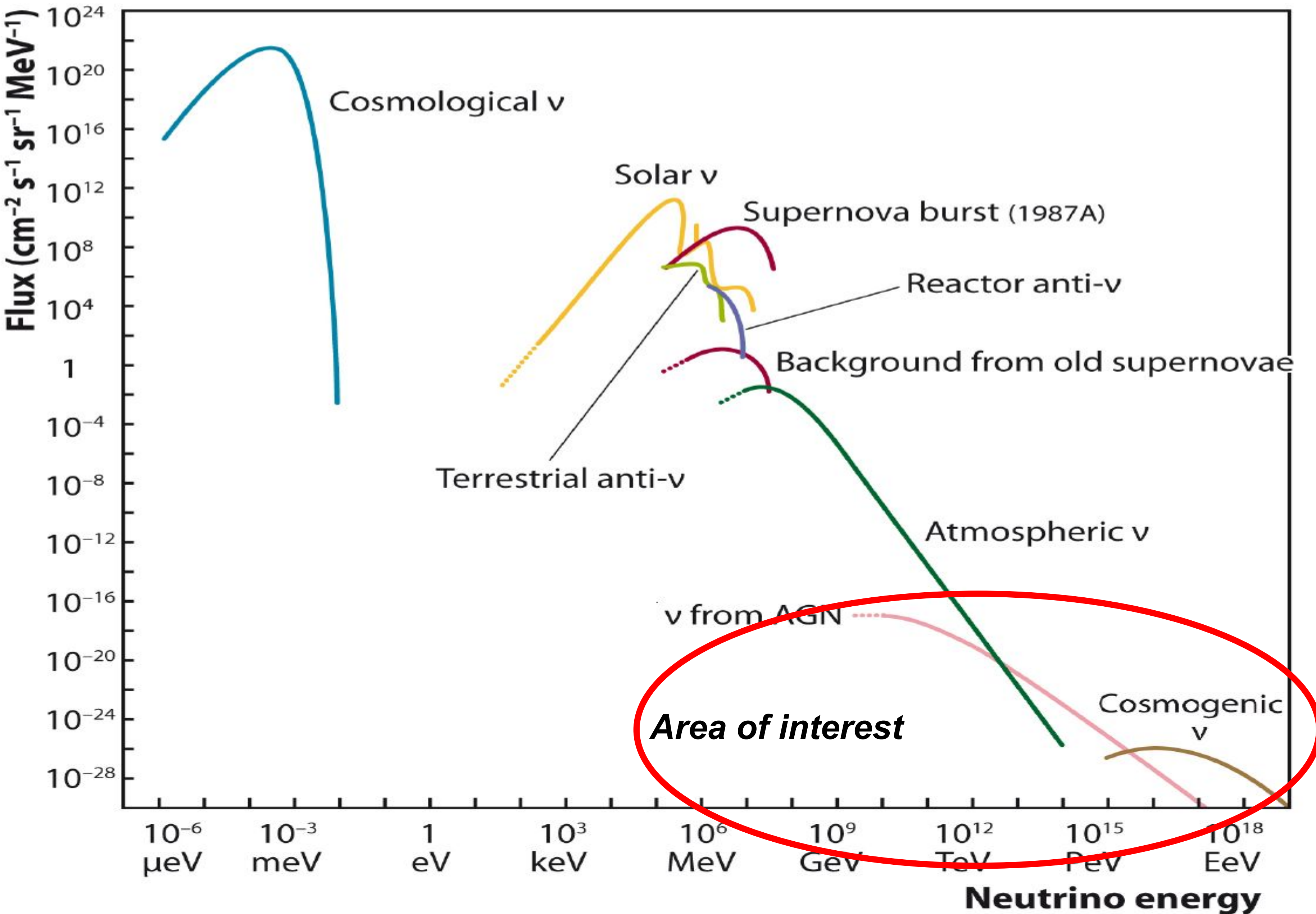
- They don't decay

- They rarely interact with matter we can use them to point back to their sources and probe the innards of astrophysical objects otherwise inaccessible to us.



AGNs, SNRs, GRBs...
black holes
Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.
γ
γ
γ
ν
ν
ν
ν
ν
Earth
Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.
p
p
air shower
Cosmic rays
They are charged particles and are deflected by magnetic fields.

PROBLEM: TOO FEW NEUTRINOS



Neutrinos are ideal cosmic messengers, but their detection is a challenge.

Their property to interact very rarely with matter makes it very difficult to "catch" the few high energy neutrinos that Astrophysical Events may produce.

A very big detector, with many "targets" for the interaction of neutrinos may see only a few dozen neutrinos per year.

We need a huge detector!

HIGH ENERGY NEUTRINO TELESCOPES

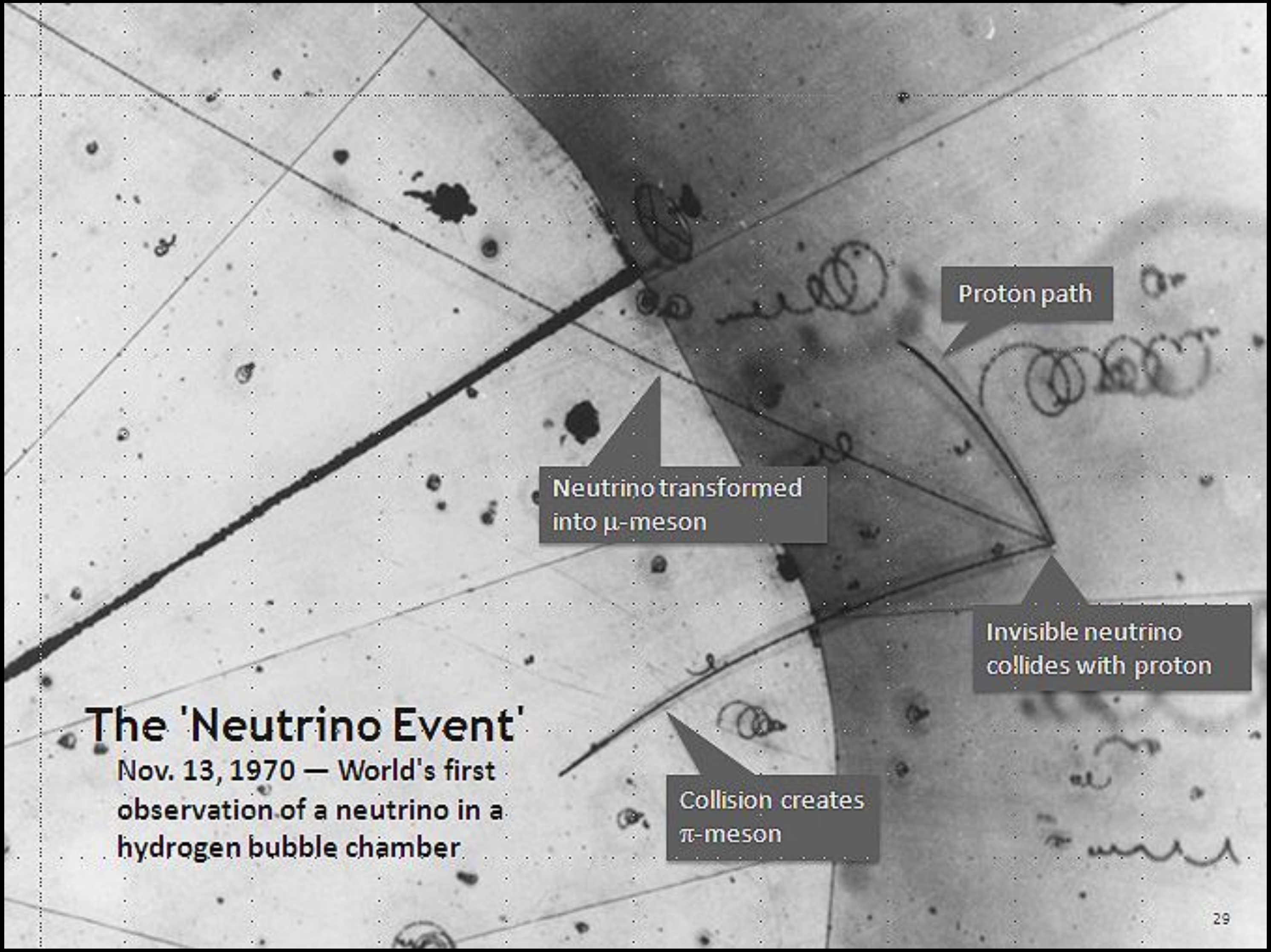
Volume of at least 1 cubic kilometer

- High costs, take a lot of space

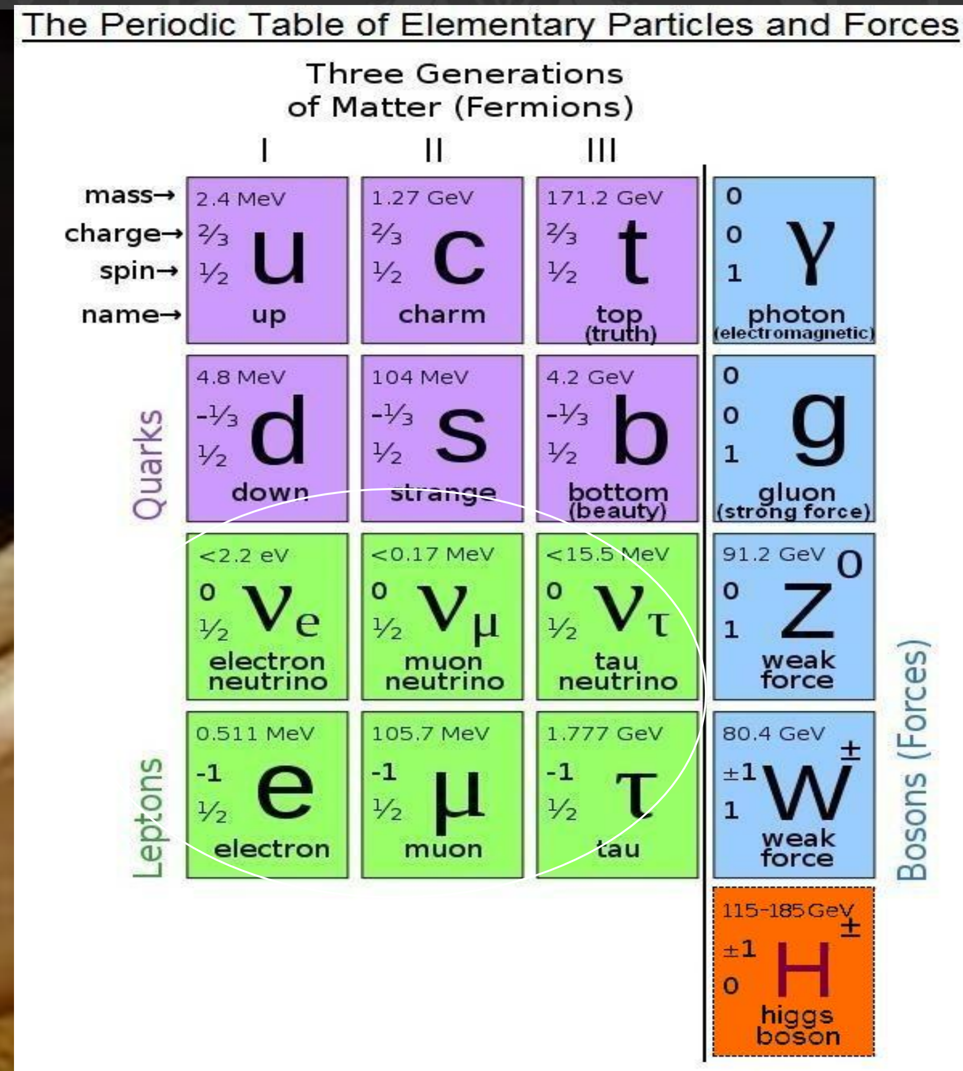
- We need to submerge them in deep sea or ice that allow us to install detectors of such volume!

How do neutrinos interact?

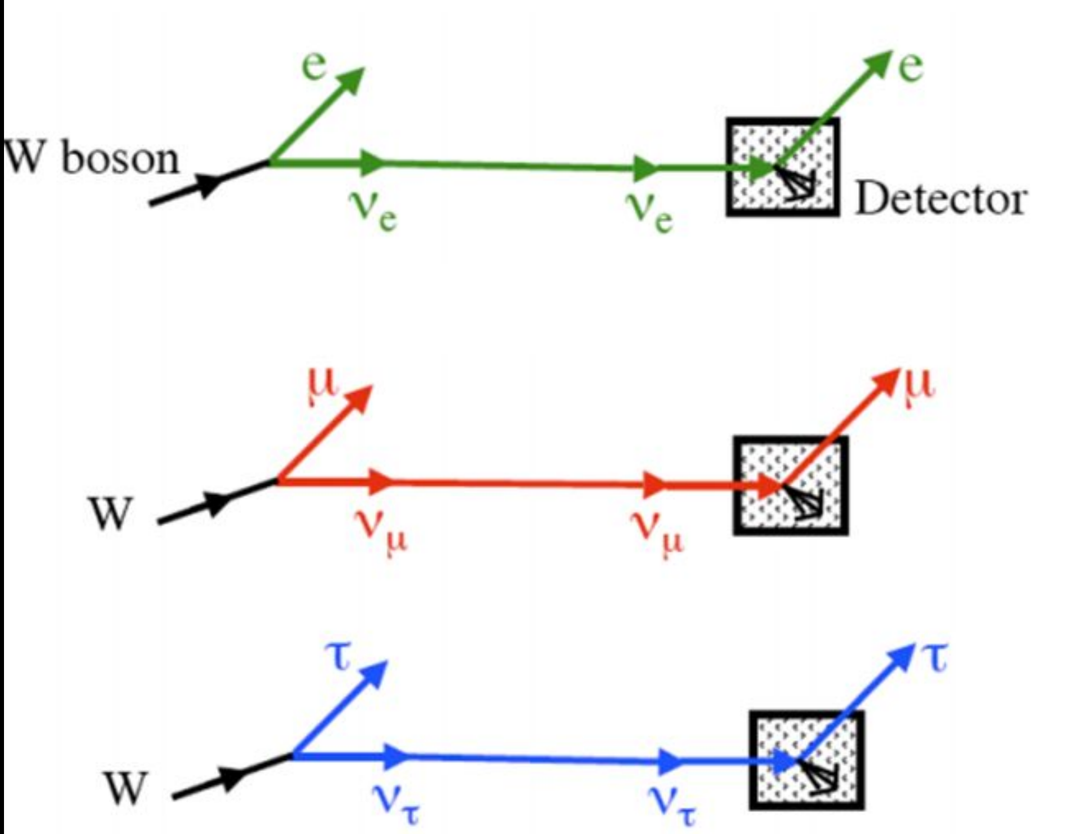
We cannot observe neutrinos themselves: only the products of their interactions!

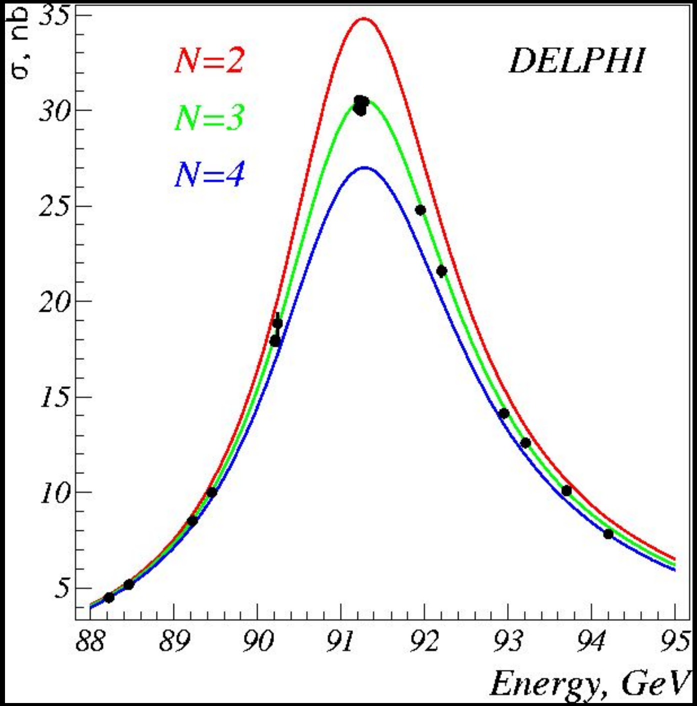


Neutrinos appear in 3 different flavors



The three different types of neutrinos





NOW WE KNOW THAT..

Neutrinos can be detected through the detection of the products of their interactions.

There are three "flavours" of neutrinos": τo ν_τ, ν_μ, ν_e with different experimental signatures in our detectors: when they interact, they produce charged leptons (e,μ,τ).

Therefore, to detect cosmic neutrinos we need to measure the product charged leptons!
How?

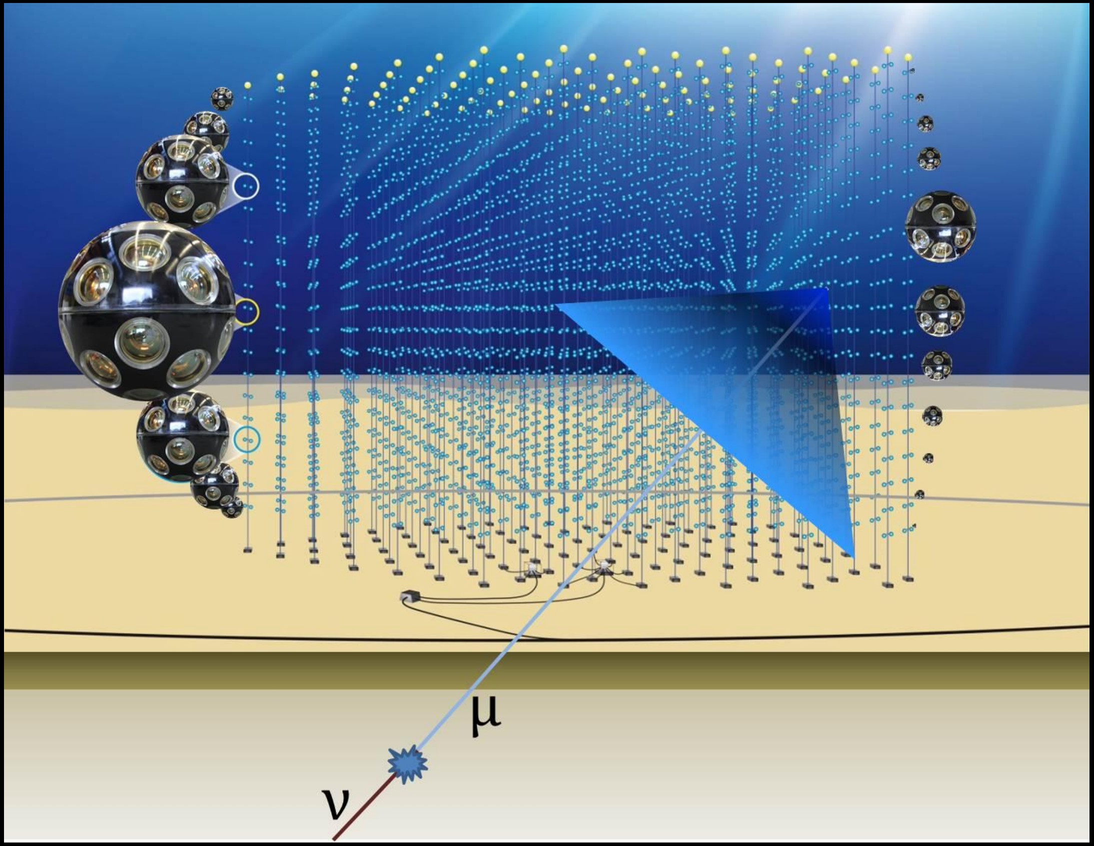
Charged leptons produced in neutrino interactions from neutrinos of astrophysical origin can travel faster than light in water! ($C_{water} \sim 0.75$ c)

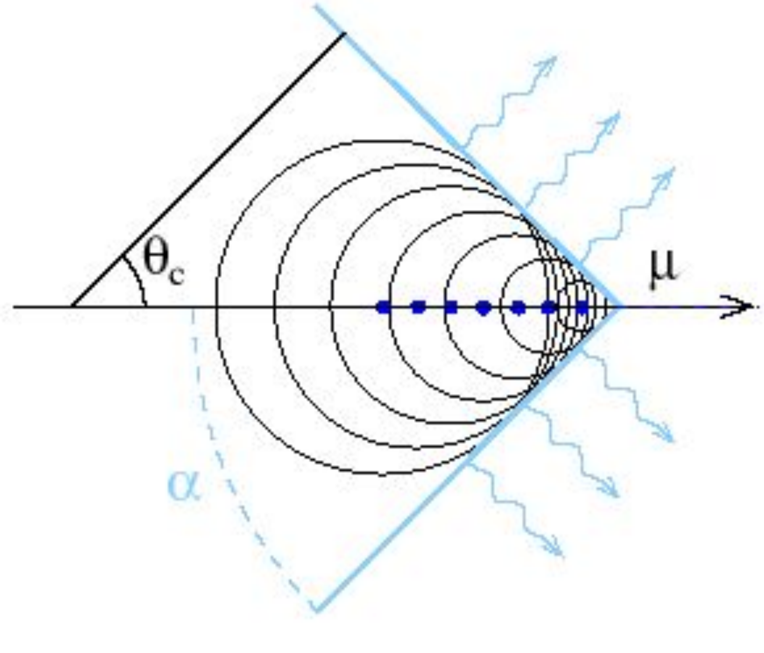
When charged particles travel faster than the speed of light in water (or any medium), a characteristic bluish light is produced: Cherenkov radiation. By measuring this radiation we can reconstruct the track of the secondary particles as well as estimate their energy (with logarithmic sensitivity). This way we can understand where the neutrinos came from and how energetic they are!

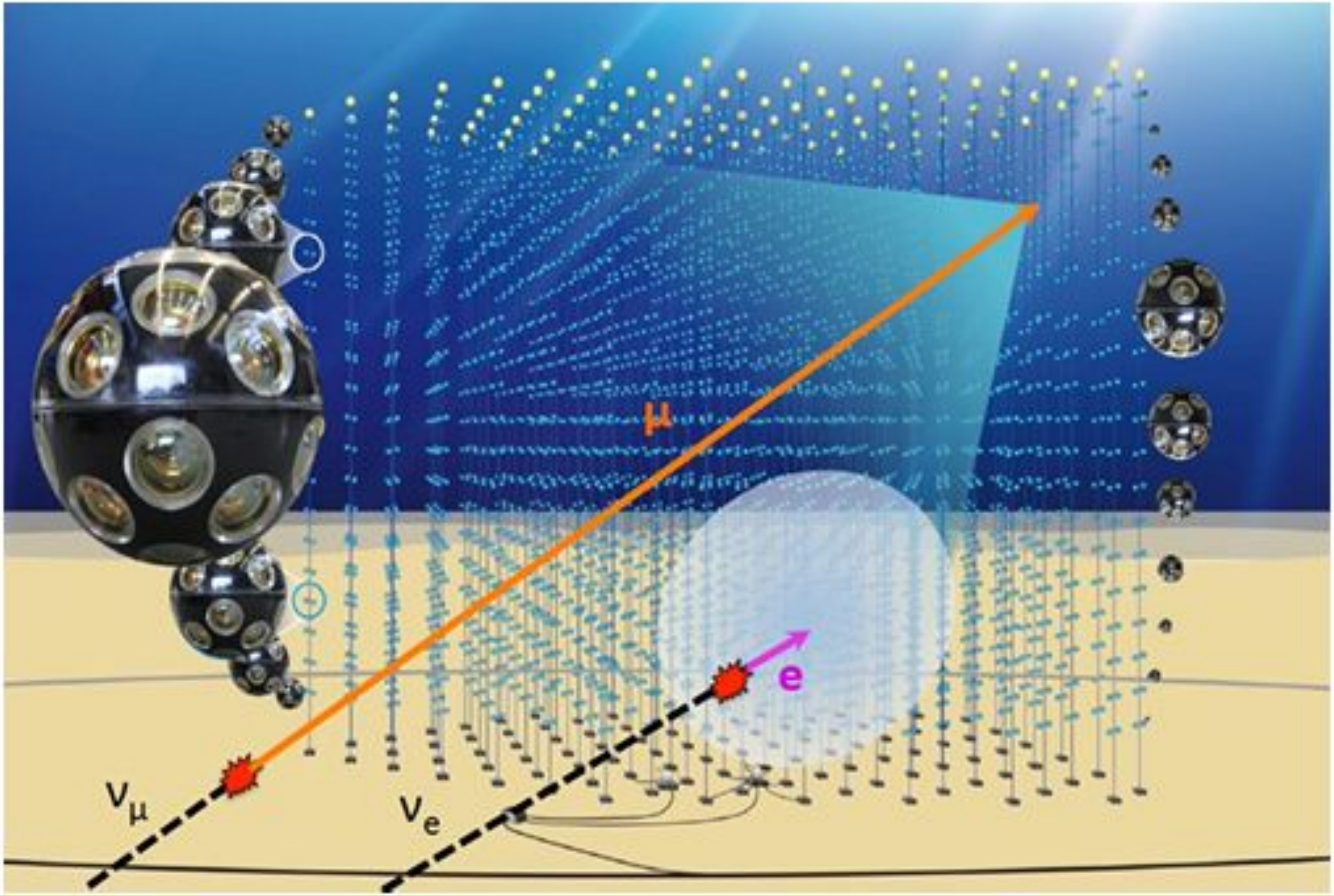
High velocity charged particles in a nuclear reactor produce the characteristic blue light of the Cherenkov radiation.

Moissey Markov

Cherenkov Radiation







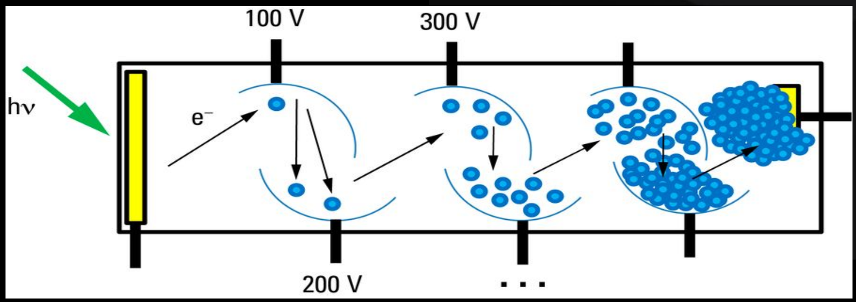
μ
e
ν$_μ$
ν$_e$

HOW DO WE DETECT CHERENKOV RADIATION?

We use photosensitive devices called "photomultipliers" (PMTs) that can detect even single photons through the photoelectric effect:

When a photon of specific frequency interacts with their photosensitive surface an electron is produced. The electron is accelerated through a high voltage and is "multiplied" in a system of dynodes. As a result we have a measurable electric pulse in the anode.

PMTs transform light into electric current. Like inverse lamps!



http://quarknet.fnal.gov/projects/pmt/student/dynodes.shtml

HIGH ENERGY NEUTRINO TELESCOPES

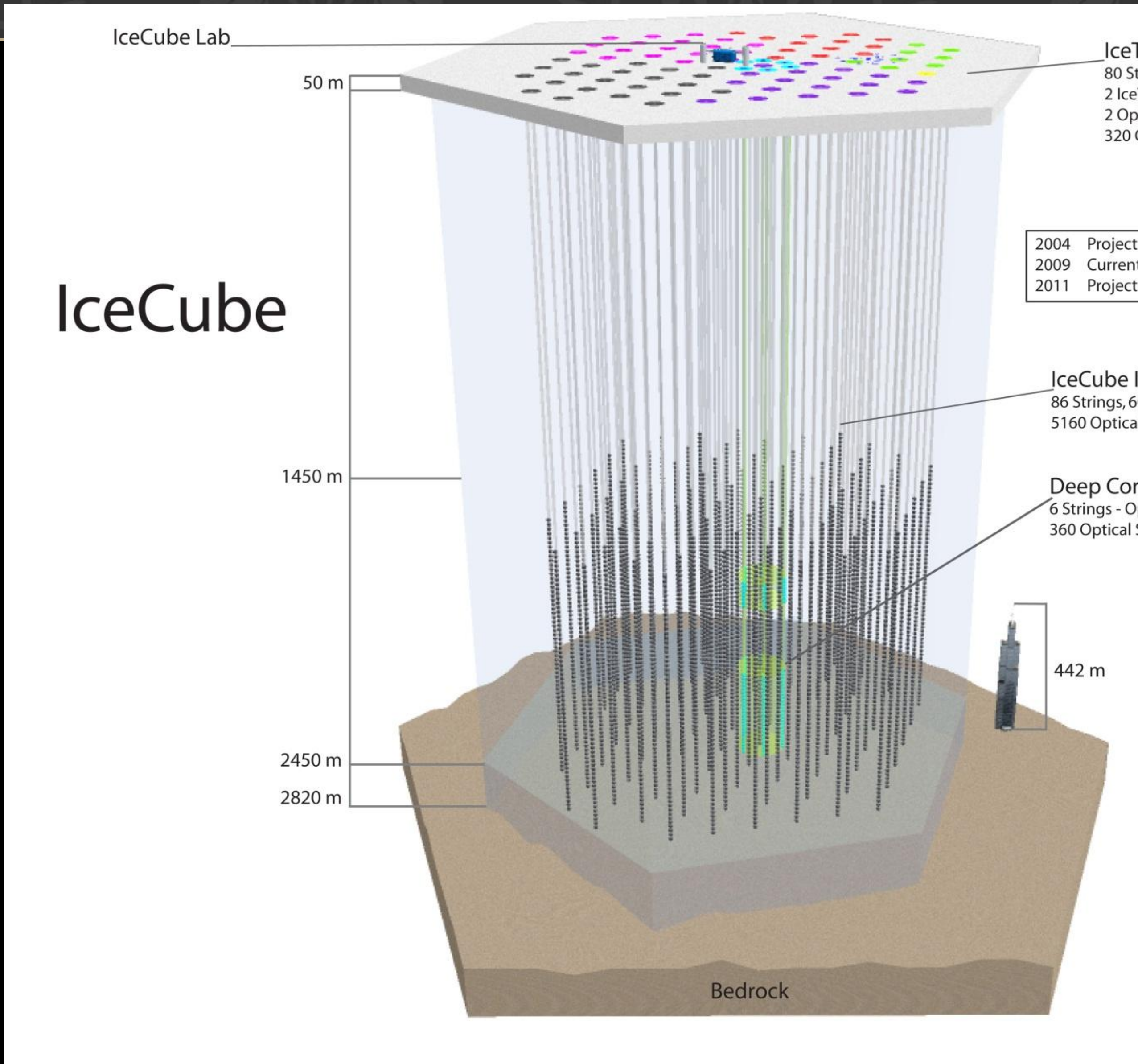
Big volume(~1 km3)

Optical modules (eyes) consisting of photomultipliers submerged in the very deep sea or ice to reduce the “noise” of cosmic rays (muons) that come from the atmosphere .

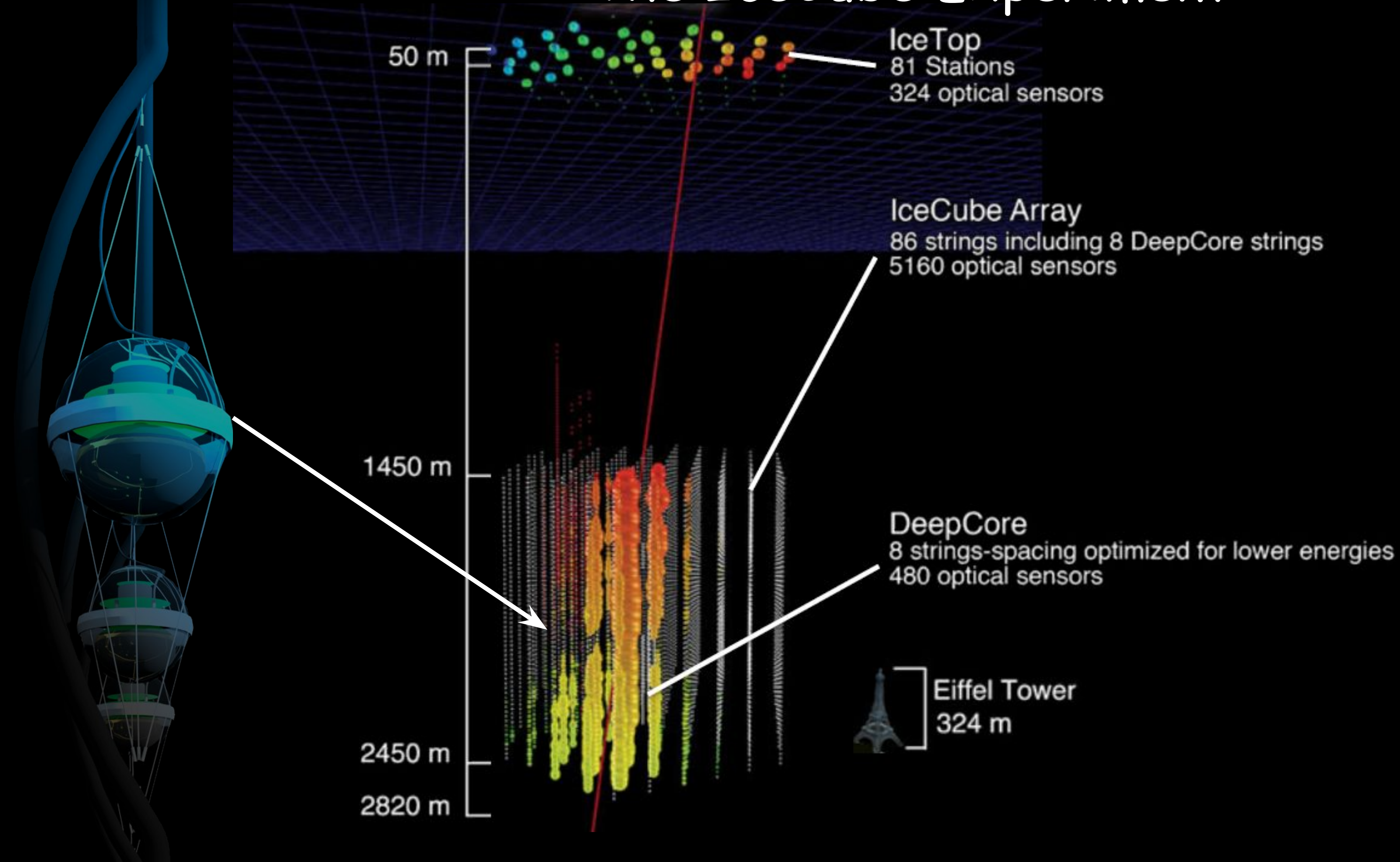
They require an optical medium with long transmission length (water/ice), low levels of contamination and optical backgrounds.

They measure neutrinos coming from the other side of the Earth!

The IceCube experiment

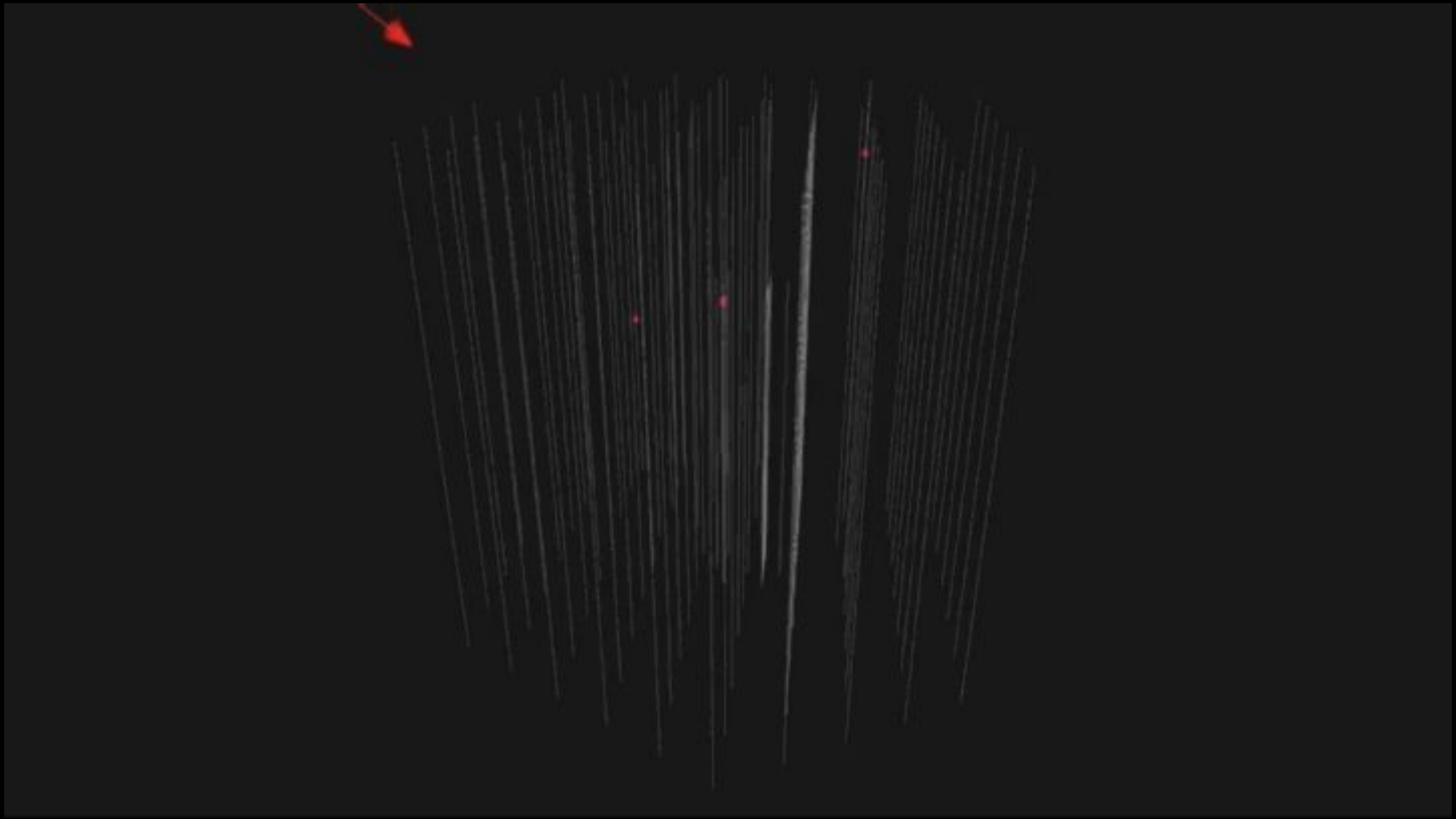


The IceCube Experiment

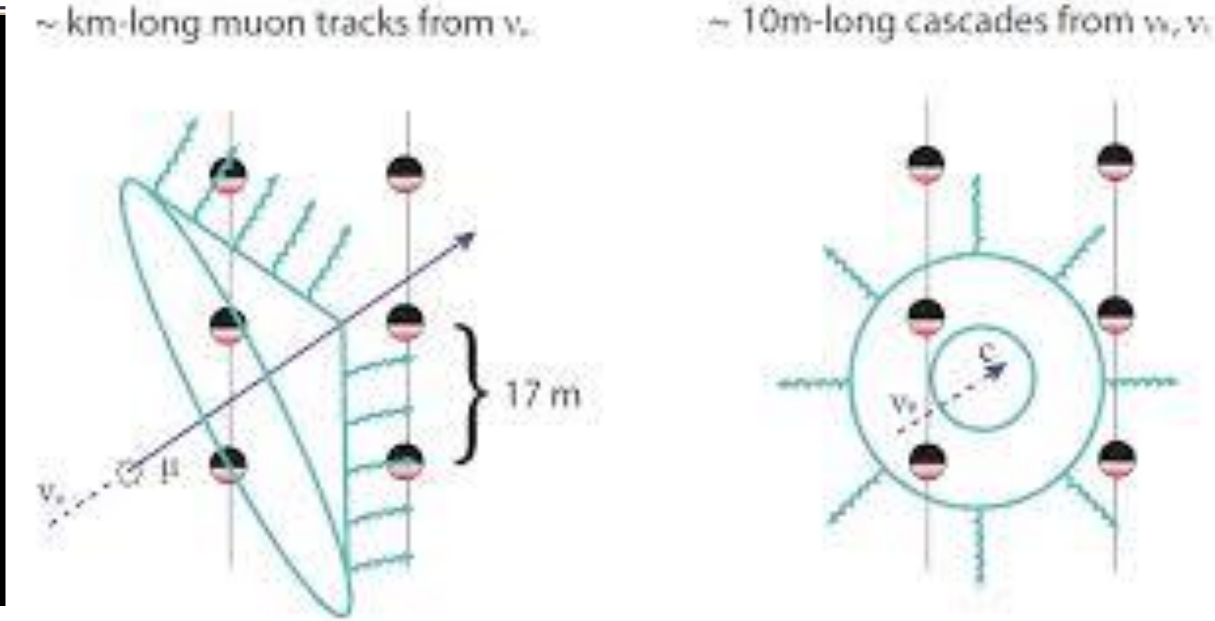


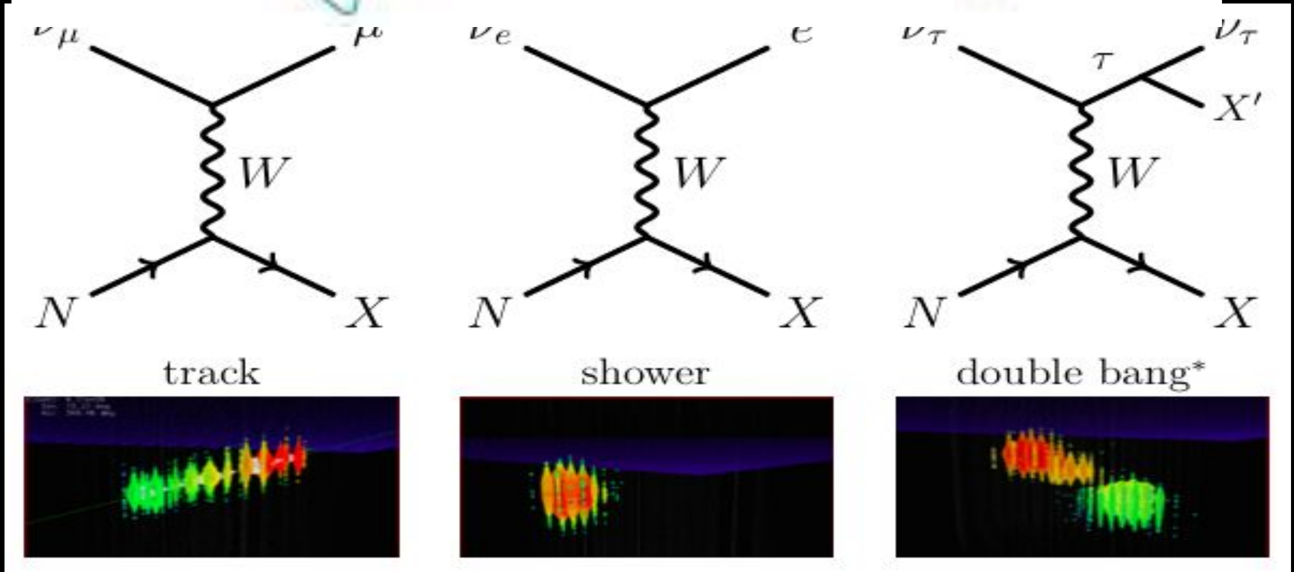
5160 φωτοπολλαπλασιαστέςσε 1 km^3

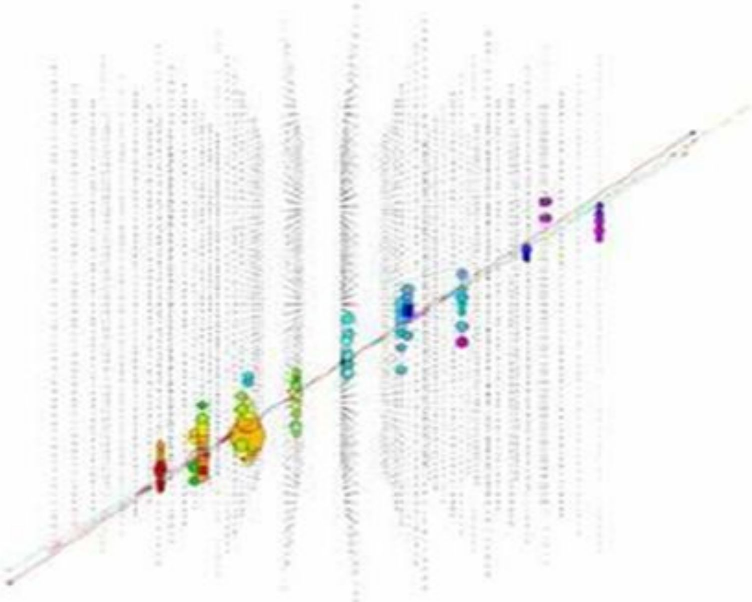
DETECTING NEUTRINOS (ICECUBE EXPERIMENT)



EXPERIMENTAL SIGNATURES

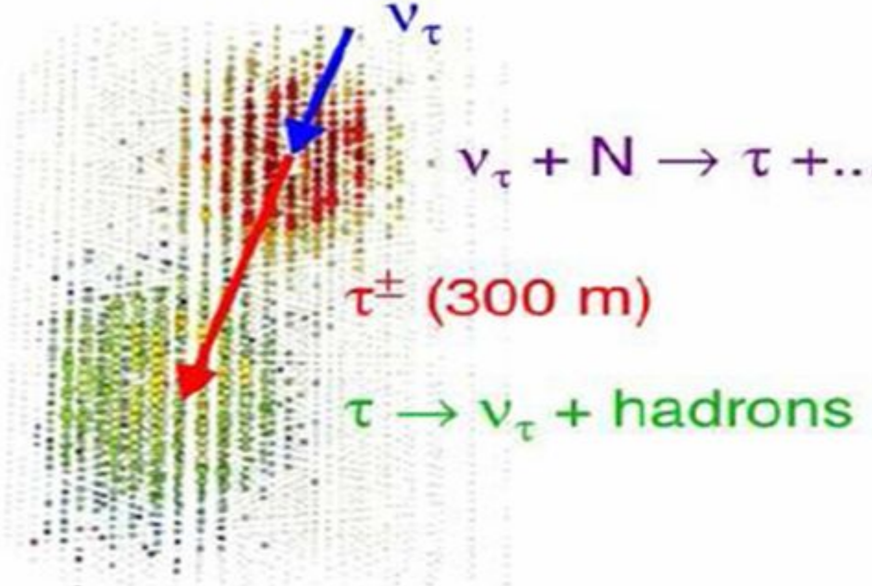






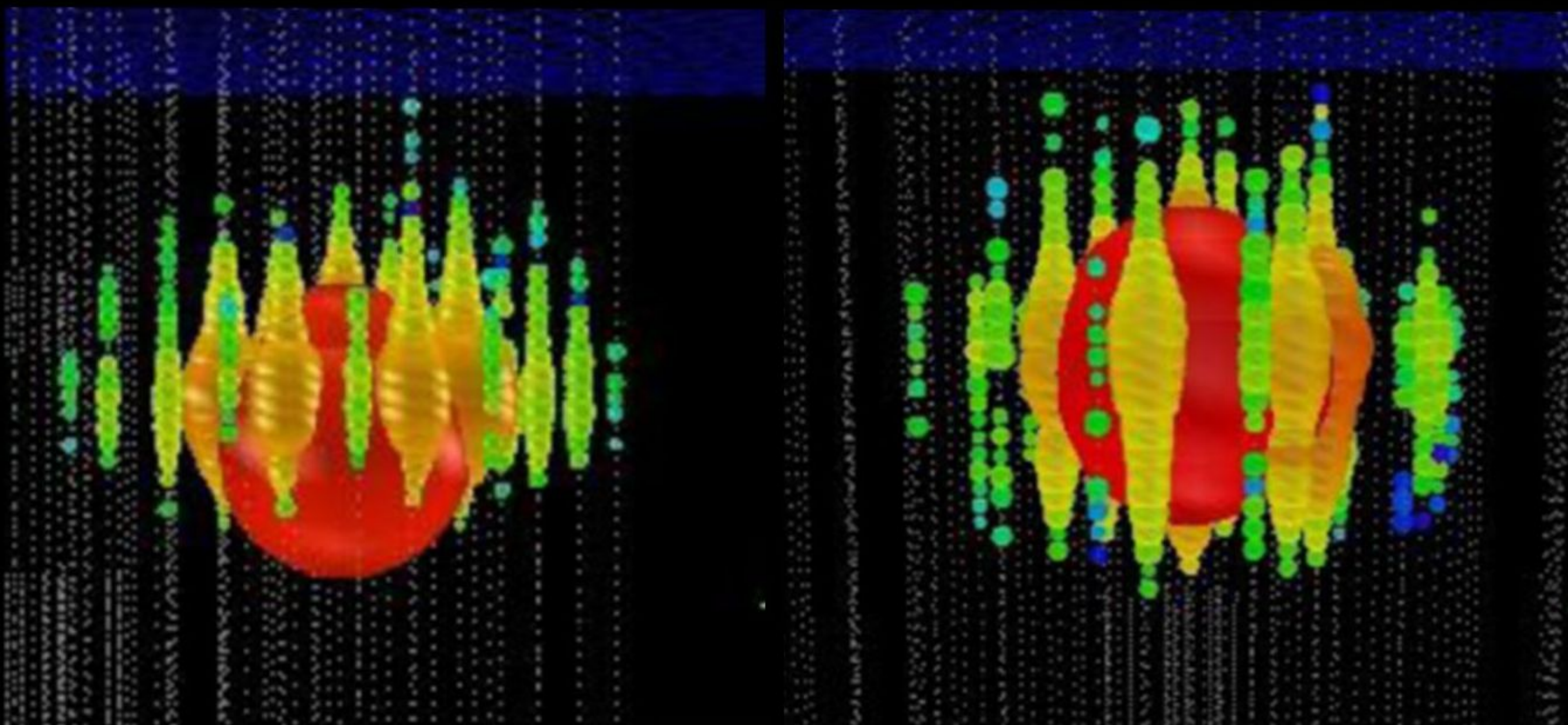
(a) 10 TeV ν_μ

(b) 375 TeV ν_e



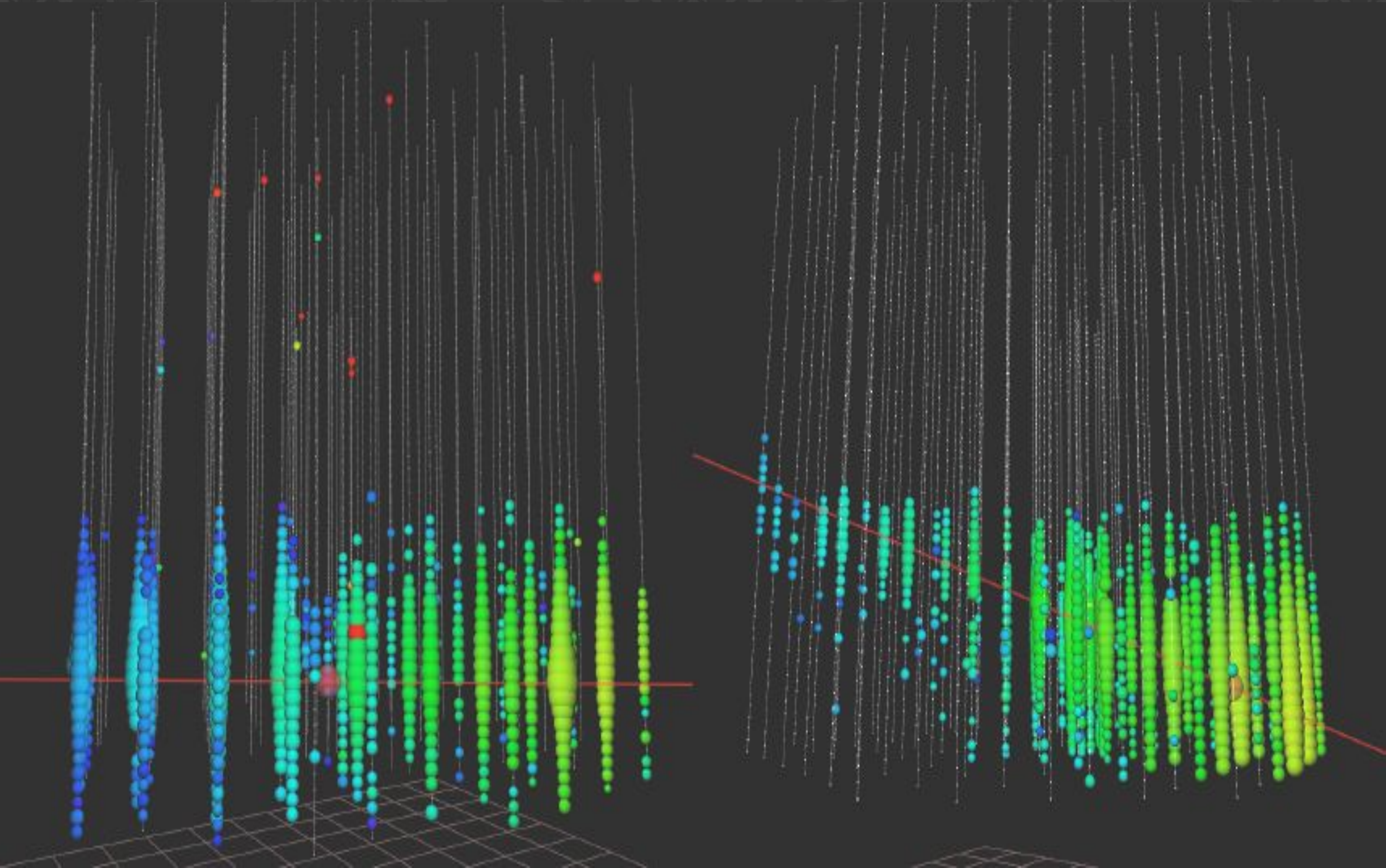
The first detections of High Energy Astrophysical Neutrinos (IceCube)

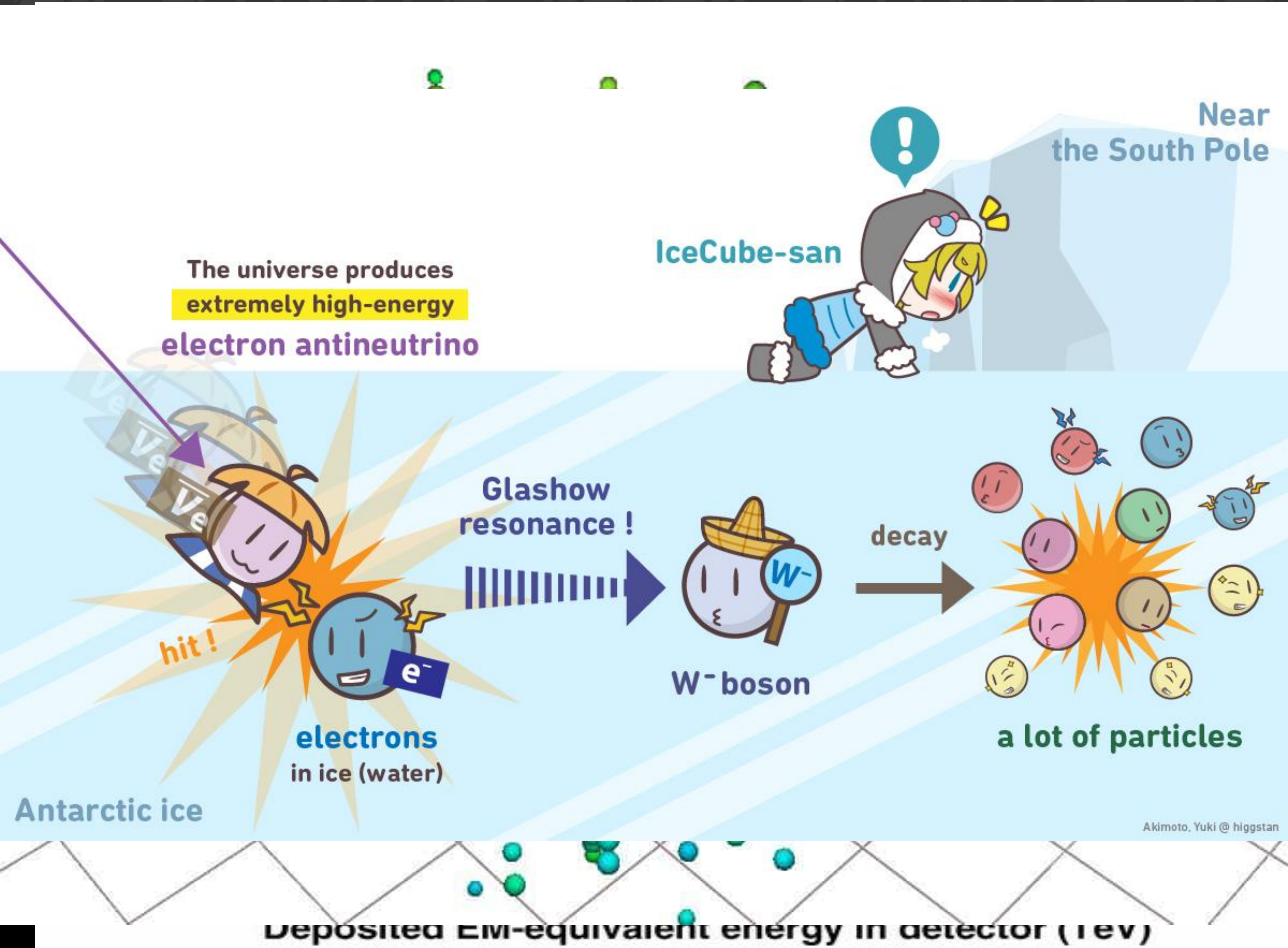
Ernie | Bert



~1.100 000 GeV | ~1.000 000 GeV

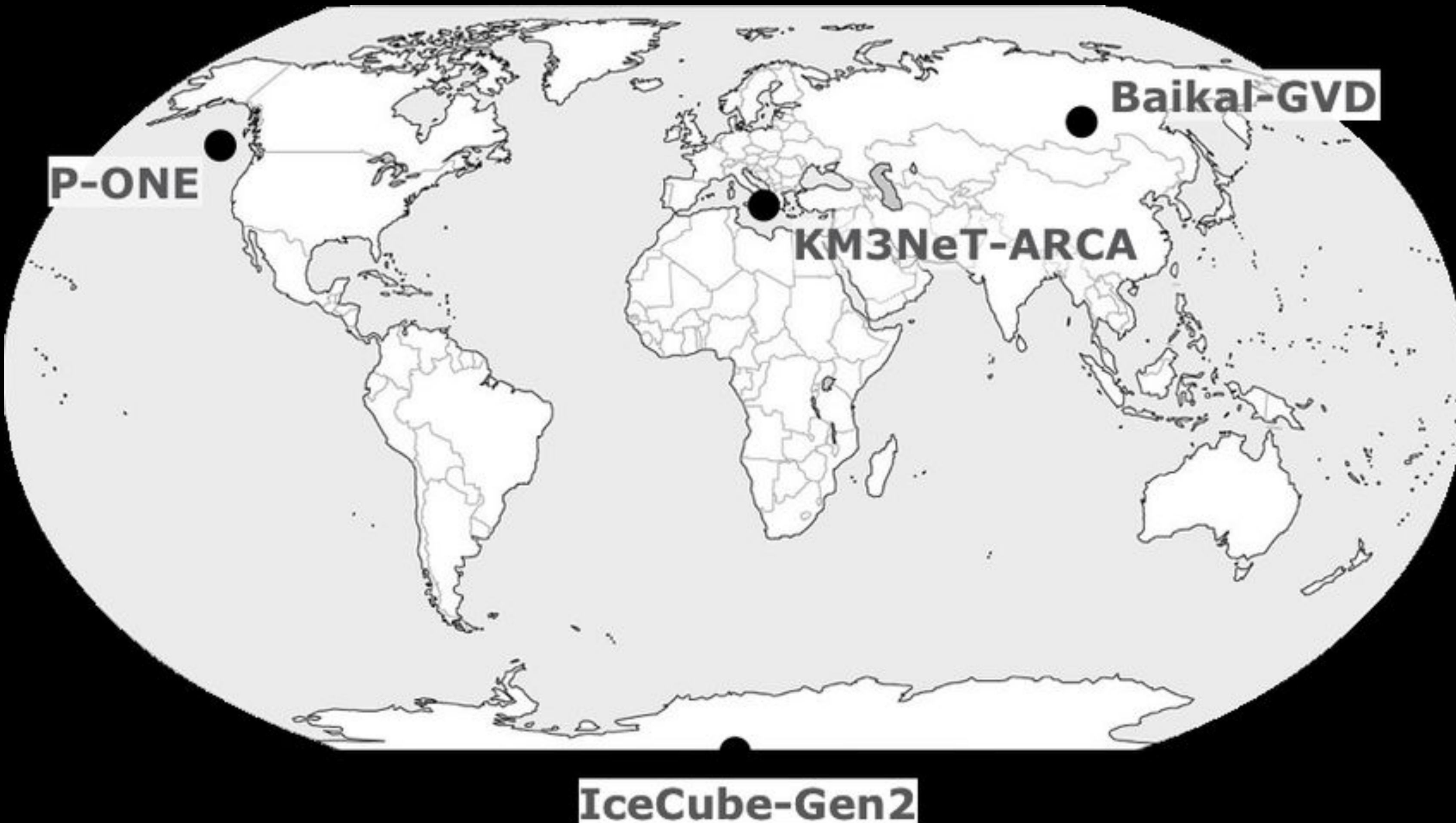
560 TeV muon in IceCube (compare with LHC energies of 6.5 TeV/proton) !!





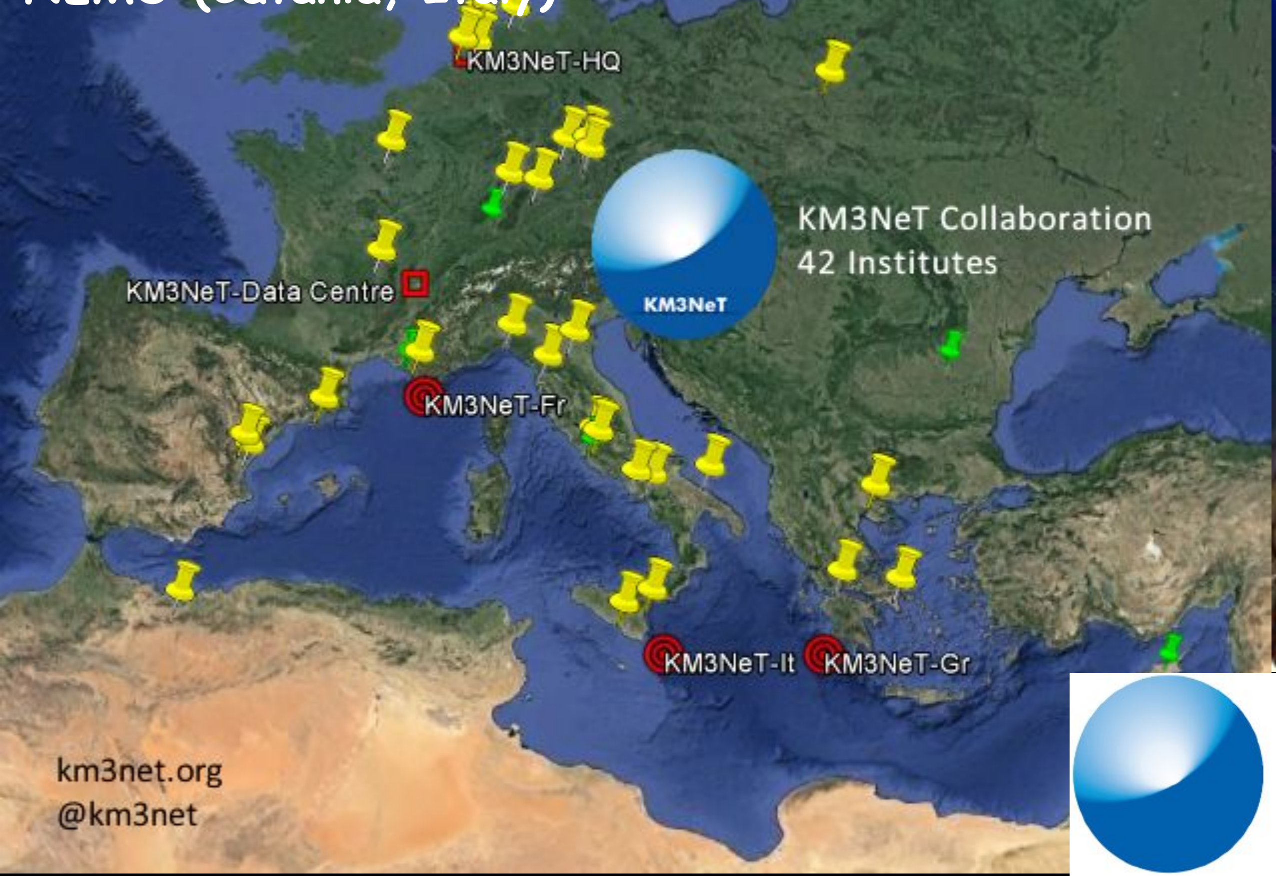
Near
the South Pole
IceCube-san
The universe produces
extremely high-energy
electron antineutrino
hit !
Glashow
resonance !
W⁻
W⁻ boson
decay
e⁻
electrons
in ice (water)
a lot of particles
Antarctic ice
Akimoto, Yuki @ higgstan
Deposited EM-equivalent energy in detector (TeV)

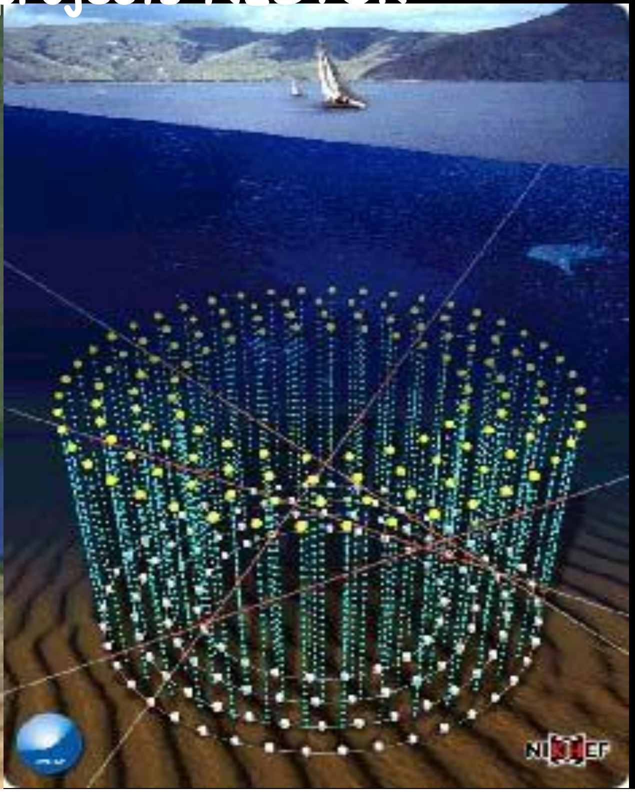
HOW MANY NEUTRINO TELESCOPES DO WE NEED?



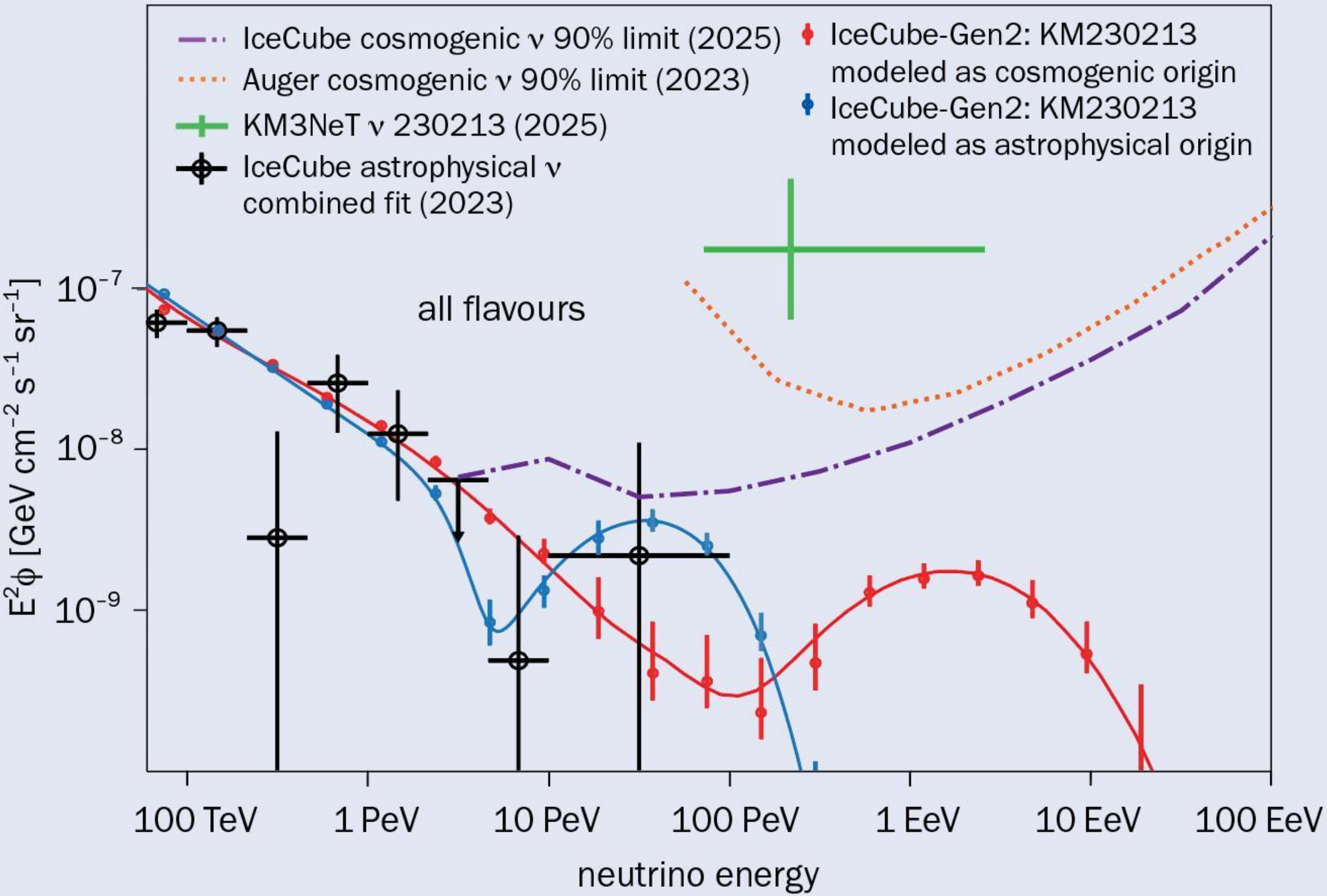
THE KM3NET EXPERIMENT

Collaboration of institutions in Europe to build a >1km3 experiment in the Mediterannean. Based on the work done in the pilot projects NESTOR (Pylos, Greece),ANTARES (Toulon, France), NEMO (Catania, Italy)





KM3NeT
Opens a new window on our universe


IceCube cosmogenic ν 90% limit (2025)
Auger cosmogenic ν 90% limit (2023)
KM3NeT ν 230213 (2025)
IceCube astrophysical ν combined fit (2023)
IceCube-Gen2: KM230213 modeled as cosmogenic origin
IceCube-Gen2: KM230213 modeled as astrophysical origin
all flavours
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
100 TeV
1 PeV
10 PeV
100 PeV
1 EeV
10 EeV
100 EeV
neutrino energy

EPILOGUE

The neutrino is the "ghost" of particle Physics: very hard to detect. Its properties allow it to be an ideal cosmic messenger allowing us to observe the universe in new "eyes".

Their detection requires very large volume detectors (>1km3) in sea or ice to detect the Cherenkov radiation from their byproducts.

So far we have managed to detect the first neutrinos of cosmic origin (IceCube), the first neutrino point source (Blazars) as well as measure the atmospheric neutrino flux in high energies.