Symphony Of Neutrinos

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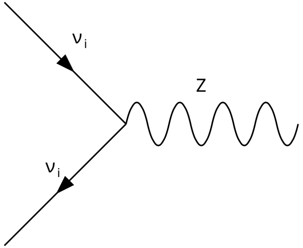
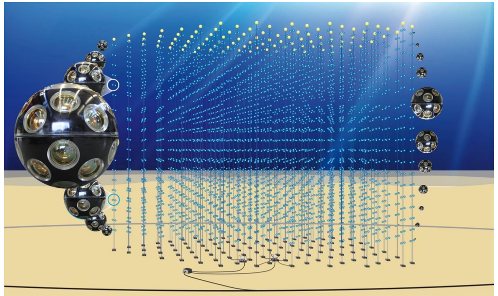
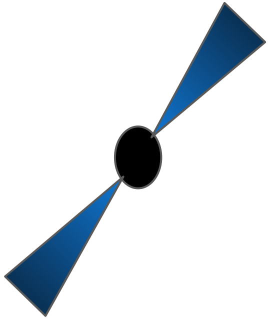
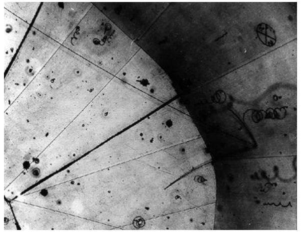
Overview

- Brief History Of Neutrinos
- Introduction To Neutrinos
- Properties
- Detection And Detectors
- Astrophysical Origins



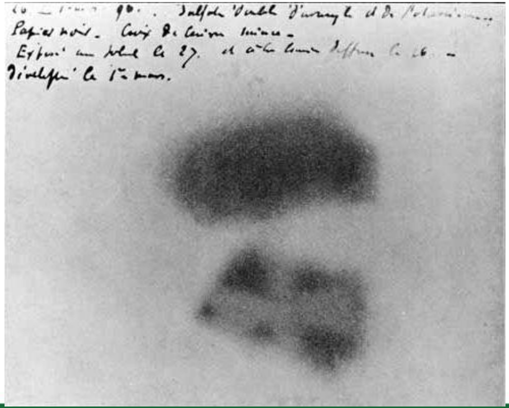






Brief History Of Neutrinos

1) **1896**: Henri Becquerel discovered natural radioactivity while studying
   - phosphorescent properties of uranium salts.
   - α rays: easy to absorb, hard to bend, positive charge, mono-energetic;
   - β rays: harder to absorb, easy to bend, negative charge, **spectrum?**
   - γ rays: no charge, very hard to absorb.
2) **1897:** J.J. Thompson discovers the electron.
3) **1914:** Chadwick presents definitive evidence for a continuous β-ray spectrum. Origin unknown, different options include several different energy loss mechanisms.



Brief History Of Neutrinos

- Beta decay problem: When studying beta decay, scientists looked at nuclear reactions like:

$$\text{Neutron} \rightarrow \text{Proton} + \text{Electron}$$

- They assumed this was a two-body decay: The neutron inside the nucleus decays into a proton and an electron.

  According to the law of conservation of energy and momentum, if only two particles are involved, the electron should always be emitted with a specific, fixed energy — just like how throwing a ball gives it a predictable speed based on how hard you throw it.

Brief History Of Neutrinos

- If the total energy available in a decay was 1 MeV, some electrons had 0.2 MeV, others 0.5 MeV, and some up to 1 MeV — but not always the same.

🤯 Why ???

- **Big Deal**

This continuous energy distribution violated what physicists expected before 1930s:

If only the proton and electron were involved, energy and momentum couldn't be properly accounted for.

It looked like some energy was simply disappearing, which broke the fundamental law of energy conservation — a core principle in physics.

"Either conservation of energy is wrong… or something else is happening."

This led to a crisis in theoretical physics. Some scientists even considered abandoning conservation laws at the subatomic level — a radical idea.

Brief History Of Neutrinos

- Fun fact:
  - It took 15+ years to decide that the “real” β-ray spectrum was really continuous.
  - Reason for continuous spectrum was a total mystery:
  - QM: Spectra are discrete;
  - Energy-momentum conservation: $N \to N' + e^-$ — electron energy and momentum well-defined

- Neutrino era hide and seek. . .

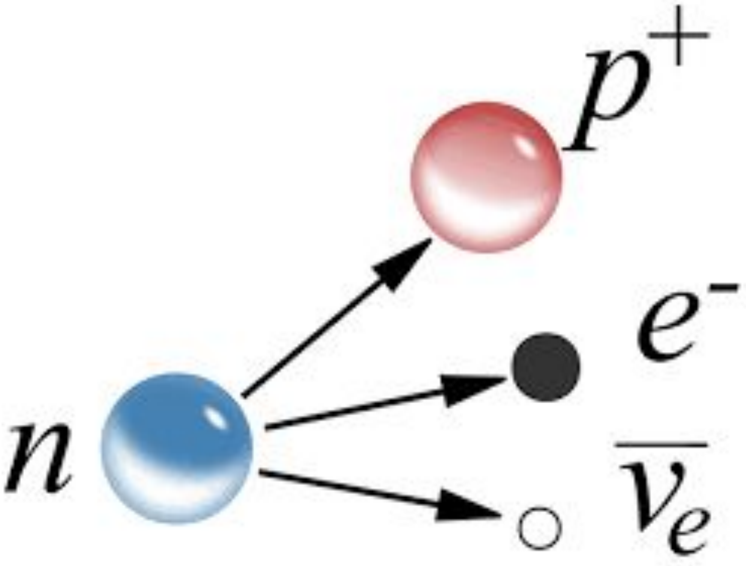
- **1930:** Postulated by Pauli to (a) resolve the problem of continuous β-ray spectra, and (b) reconcile nuclear model with spin-statistics theorem. ⇒
- **1932:** Chadwick discovered the neutron. neutron 6 = Pauli’s neutron = neutrino (Fermi);

Brief History Of Neutrinos

Wolfgang Pauli's solution:

- He hypothesized that an invisible, neutral particle must also be emitted during beta decay, carrying away the "missing" energy and momentum. He called it a "neutron" at the time, but it was later renamed the neutrino after the discovery of the (massive) neutron by Chadwick in 1932.

- A light, neutral, and weakly interacting particle (now called the neutrino) is emitted in beta decay to conserve energy and momentum.



Brief History Of Neutrinos

Dear Radioactive Ladies and Gentlemen,

I have come upon a desperate way out regarding the wrong statistics of the ^{14}N and ^{6}Li nuclei, as well as the continuous β-spectrum, in order to save the "alternation law" statistics and the energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call "neutrons," and satisfy the exclusion principle... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any case not larger than 0.01 times the proton mass. The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant...

For the time being I dare not publish anything about this idea and address myself to you, dear radioactive ones, with the question how it would be with experimental proof of such a neutron, if it were to have the penetrating power equal to about ten times larger than a γ-ray.

I admit that my way out may not seem very probable *a priori* since one would probably have seen the neutrons a long time ago if they exist. But only the one who dares wins, and the seriousness of the situation concerning the continuous β-spectrum is illuminated by my honored predecessor, Mr Debye who recently said to me in Brussels: "Oh, it is best not to think about this at all, as with new taxes." One must therefore discuss seriously every road to salvation. Thus, dear radioactive ones, examine and judge. Unfortunately, I cannot appear personally in Tübingen since a ball... in Zürich... makes my presence here indispensible....

Your most humble servant, W. Pauli

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

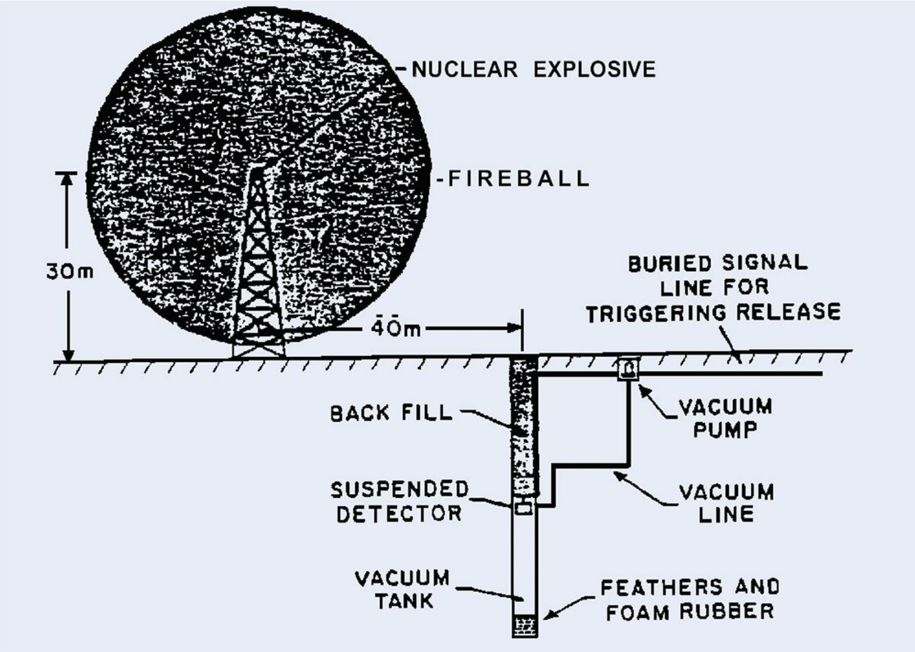
Zürich, 4. Dez. 1930
Gloriastrasse

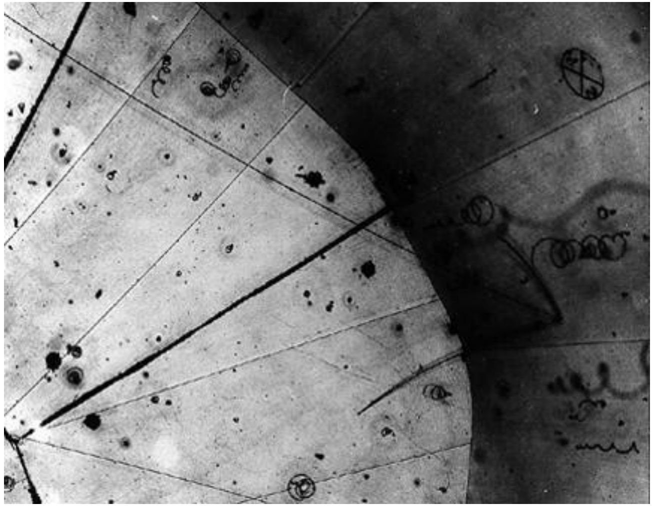
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen 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 Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Brief History Of Neutrinos

- Since the neutron was discovered two years later by J. Chadwick, Fermi, following the proposal by E. Amaldi, used the name “neutrino” (little neutron) in 1932 and later proposed the Fermi theory of beta decay.





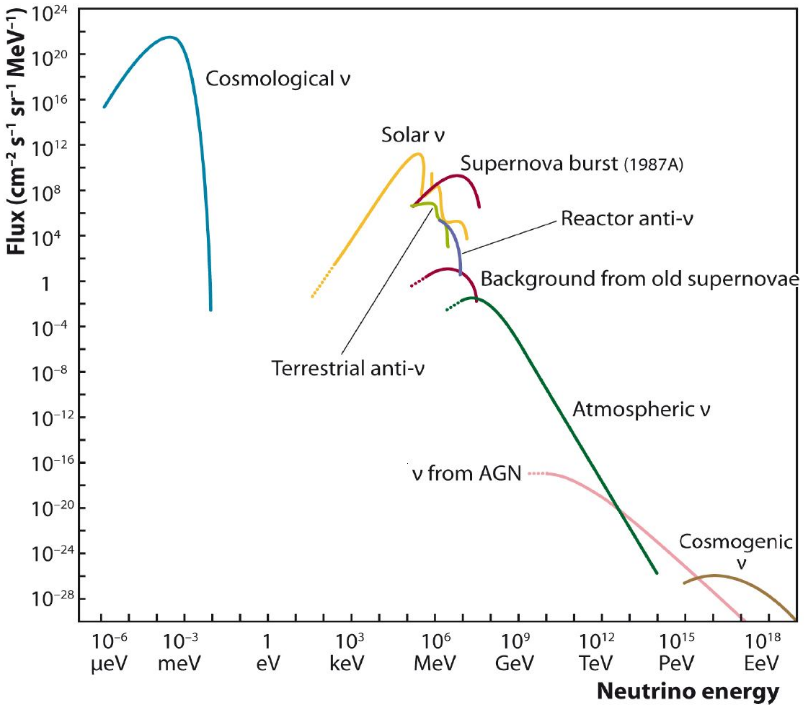
Brief History Of Neutrinos

Fermi's Theory (1934):

- He proposed that beta decay is caused by a new type of fundamental force (later called the weak nuclear force). In beta decay:
- A neutron turns into a proton.
- It emits an electron and an antineutrino (the antiparticle of the neutrino).
- This theory was one of the first attempts to describe particle interactions using quantum field theory, similar to how electromagnetic interactions are described by quantum electrodynamics.

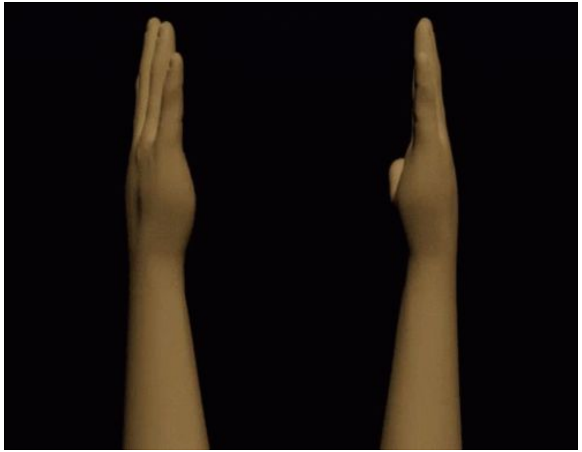
Brief History Of Neutrinos

- **1936/37:** ("Meson" discovered in cosmic rays. Another long, tortuous story. Turns out to be the muon…)



Brief History Of Neutrinos

- What we know until by the until now!



Brief History Of Neutrinos

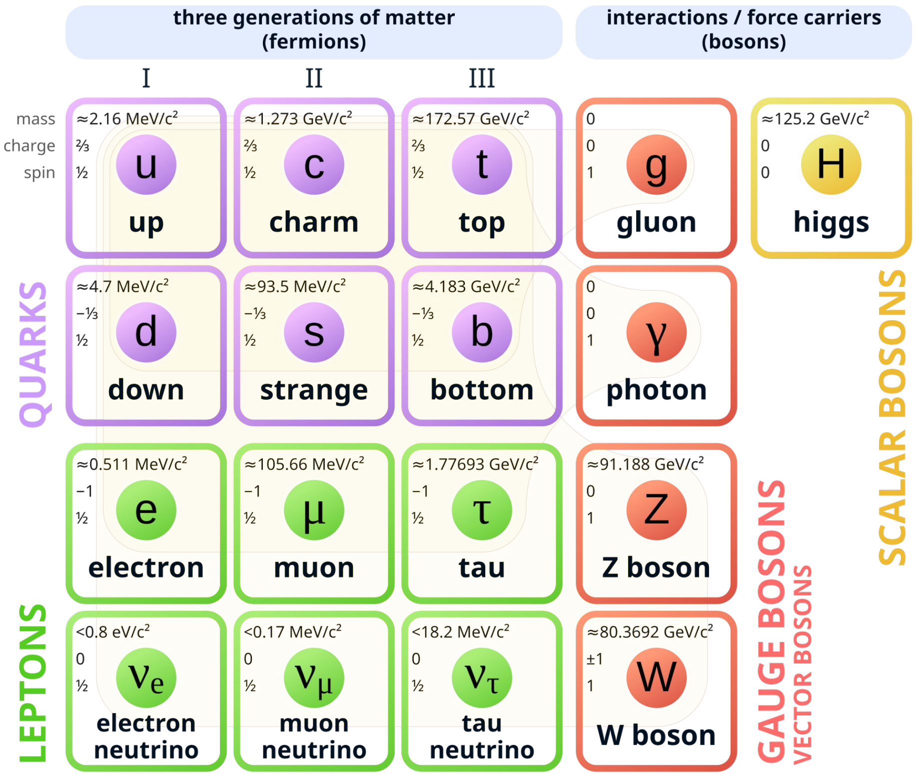
- What we know until by the end 20th century:
  - Three flavors
  - Interact only via weak interactions (W ±, Z0);
- Have ZERO mass – helicity good quantum number;
- νL field describes 2 degrees of freedom:

  – left-handed state ν,

  – right-handed state $\bar{\nu}$ (CPT conjugate);
- Neutrinos carry lepton number:

– L(ν) = +1; – L($\bar{\nu}$) = −1.

Standard Model of Elementary Particles



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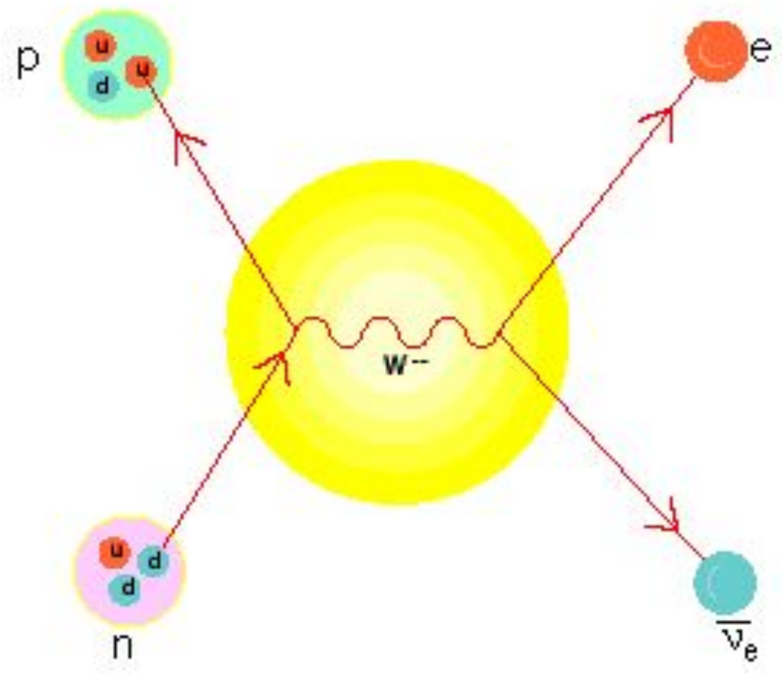
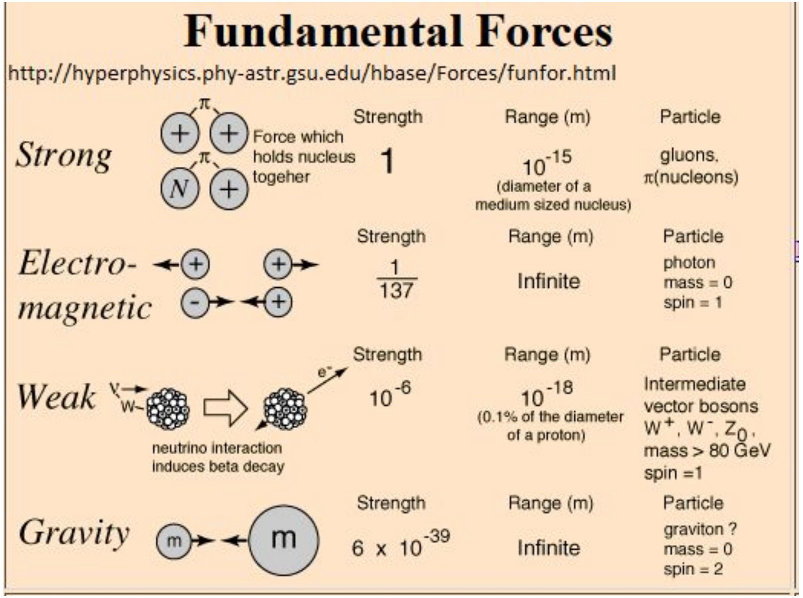
Introduction To Neutrinos

- Neutrino: Fundamental particles in the Standard Model of particle physics.
    - Symbol: ν (Greek letter "nu")
    - Electrically neutral and have tiny mass
    - Travel nearly at the speed of light
    - Come in three types (flavors):
        - Electron neutrino (ν_e)
        - Muon neutrino (ν_μ)
        - Tau neutrino (ν_τ)



Properties

- No electric charge → Do not interact via electromagnetic force
- Interact only via the weak nuclear force and gravity
- Pass through matter almost undisturbed — billions pass through your body every second!
- Have very small mass, but not zero (confirmed by neutrino oscillation experiments)



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Properties

- Weak Interaction with neutrinos:

- Neutral Current (NC) Interaction:

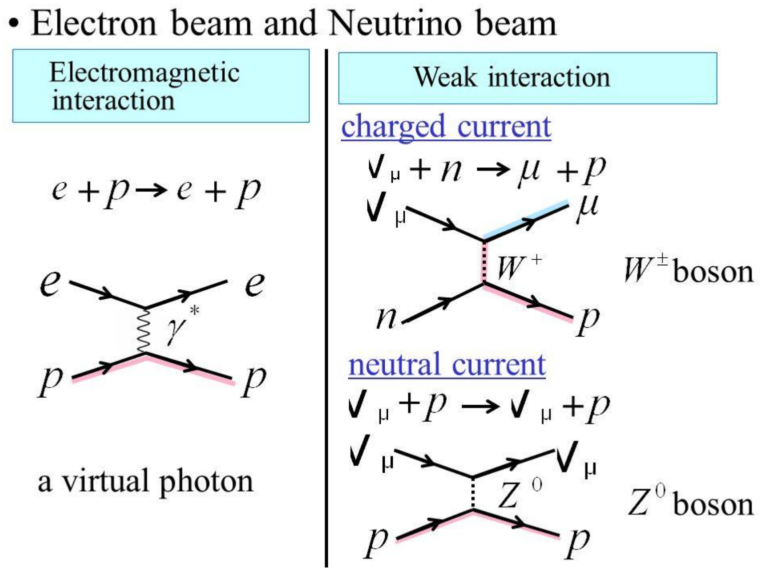
  Involves the exchange of Z bosons, which are neutral (no electric charge).

- Charged Current (CC) Interaction:

  Involves the exchange of W bosons (W^+ or W^-), which carry electric charge.

  Changes the charge of the participating particles.

- The lepton (e.g., electron, muon, tau) or quark involved changes flavor due to the exchange of a W boson.

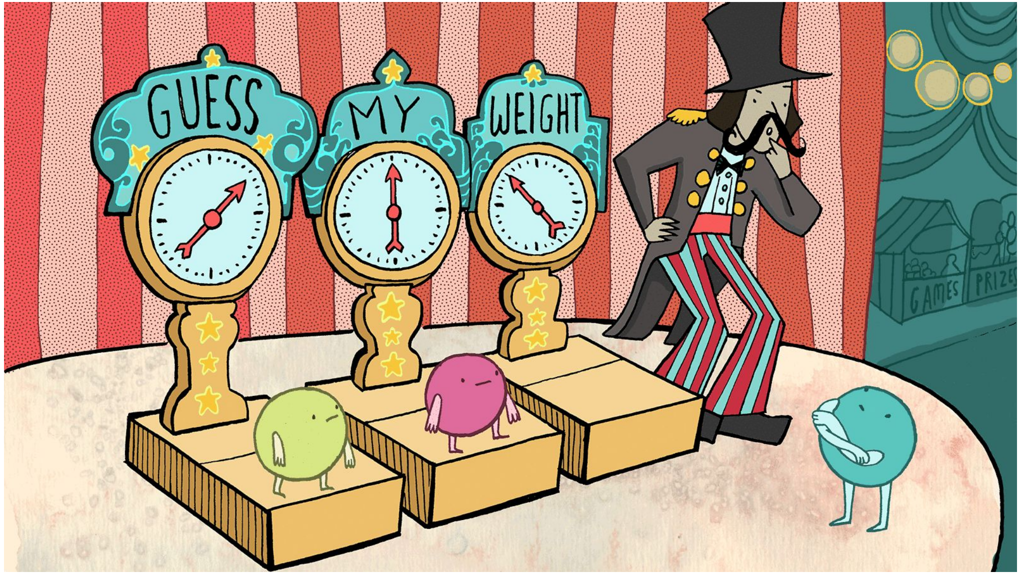


Properties

- Mass of neutrino: Initially massless Neutrino Assumption: For decades, neutrinos were assumed to be massless based on the Standard Model of particle physics.

- However, this assumption faced challenges from experiments in the late 20th century.

- Neutrino Oscillations: A key breakthrough



Discussion Time

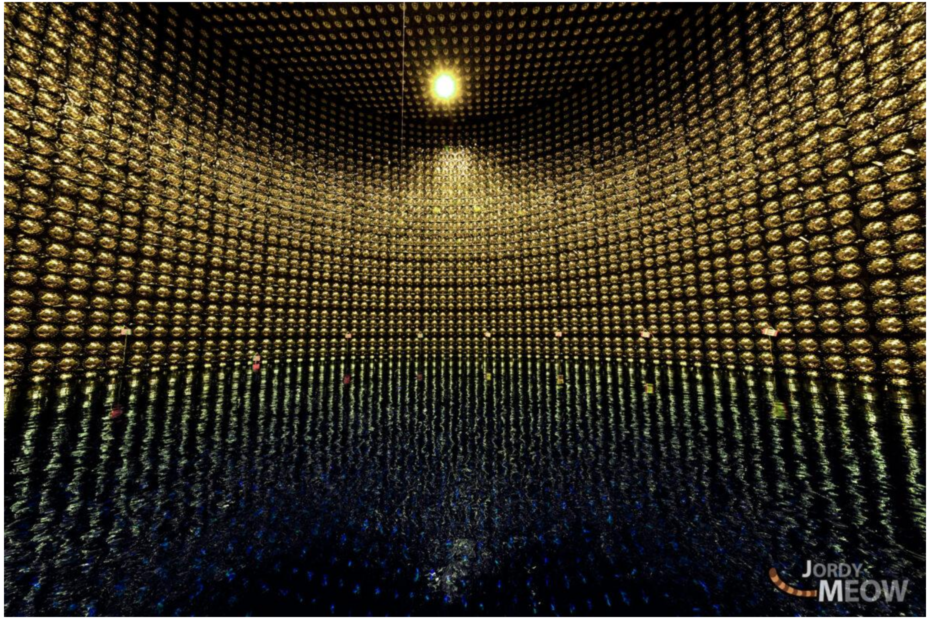
Detection And Detectors

Detector Type	Detection Medium	Detection Method	Best For	Energy Range	Example Experiment
Cherenkov Detectors	Water or Ice	Detect **Cherenkov light** from charged particles moving faster than light in the medium	Directional detection of medium/ high-energy neutrinos	~10 MeV – PeV+	Super-Kamiokande, IceCube
Scintillator Detectors	Organic Liquid Scintillator	Detect **scintillation light** from ionizing radiation	Low-energy neutrinos (solar, reactor)	~MeV	KamLAND, Borexino
Liquid Argon TPCs (LArTPCs)	Liquid Argon	Use **ionization tracks** and drift them through an electric field for 3D imaging	Precise reconstruction of interactions	MeV – GeV	DUNE (planned), ICARUS
Solid-State Detectors	Crystals, Semiconductors	Measure tiny ionization or nuclear recoil from neutrino interactions	Low-energy neutrinos, coherent scattering	keV – MeV	COHERENT, CONNIE
Radiochemical Detectors (Historic)	Chlorine, Gallium targets	Neutrino converts atom → different isotope; chemical extraction used to count	Historic solar neutrino measurements	Sub-MeV	Homestake, GALLEX

Detection And Detectors

Super-Kamiokande (Japan)

- Type: Water Cherenkov detector.
- Significance: Discovery of neutrino oscillations in 1998. This led to the Nobel Prize in Physics in 2015 for Takaaki Kajita and Arthur B. McDonald.
- Development: It uses 50,000 tons of ultrapure water to detect Cherenkov radiation produced by high-energy particles. The detector has played a key role in studying atmospheric and solar neutrinos.



Detection And Detectors

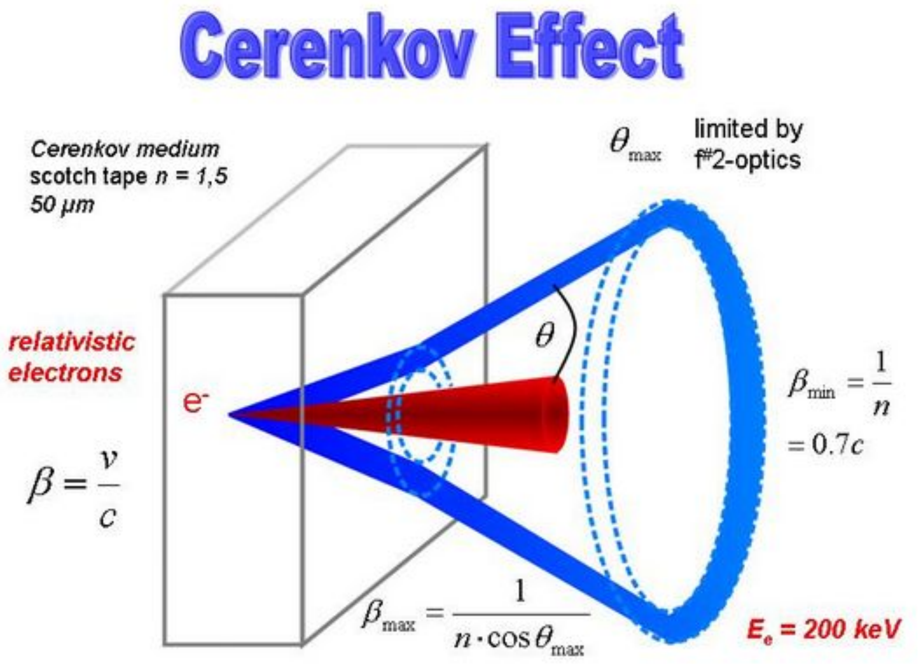
- Working principle: water Cherenkov detector

- Cherenkov radiations: electromagnetic radiation emitted when charged particles, such as electrons, travel through a dielectric medium (such as water, glass, or air) at a speed greater than the speed of light in that medium

- Detector design: a) pure water

  b) a large cylindrical tank

  c) 1,000 meters underground



Detection And Detectors

Discovery of Neutrino Oscillations (1998)

- detected that muon neutrinos (ν□) were disappearing as they traveled through the Earth

- First strong evidence that neutrinos have mass, contradicting the Standard Model of particle physics, which assumed neutrinos massless

- Neutrino oscillations in 2015, Takaaki Kajita (Super-Kamiokande) and Arthur McDonald (Sudbury Neutrino Observatory) were awarded the Nobel Prize in Physics

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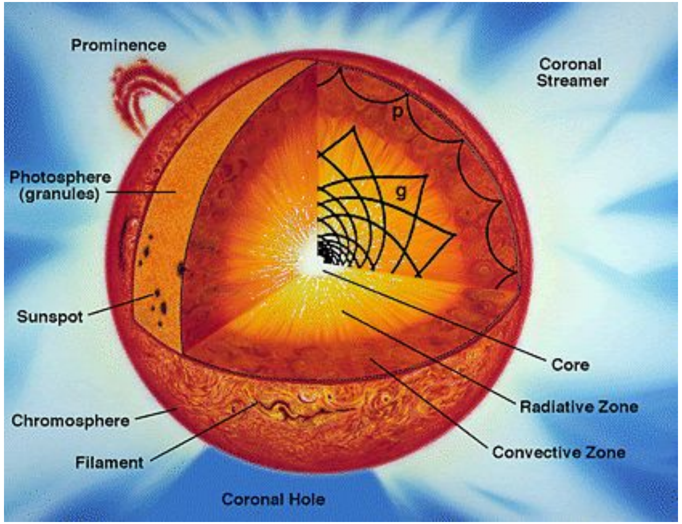
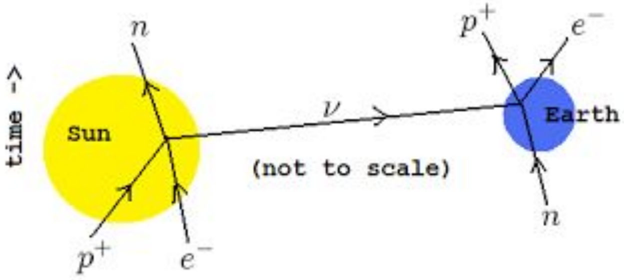
Detection And Detectors

- It detected fewer muon neutrinos coming from the opposite side of the Earth (upward) than from above (downward).

- These were atmospheric neutrinos created when cosmic rays hit the atmosphere.

- The missing muon neutrinos had transformed into tau neutrinos, which the detector couldn't see directly.





Detection And Detectors

- A neutrino produced in one flavor (say, muon) would be a superposition of mass states.

- As it travels, each mass state evolves differently over time.

- This causes the neutrino to "oscillate" into other flavors with a probability that depends on the distance traveled and the energy of the neutrino.

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \cdot \sin^2\left(\frac{1.27\,\Delta m^2\,L}{E}\right)$$

θ = mixing angle (how strongly flavors are mixed)

Δm^2 = difference in the squares of neutrino masses (in eV²)

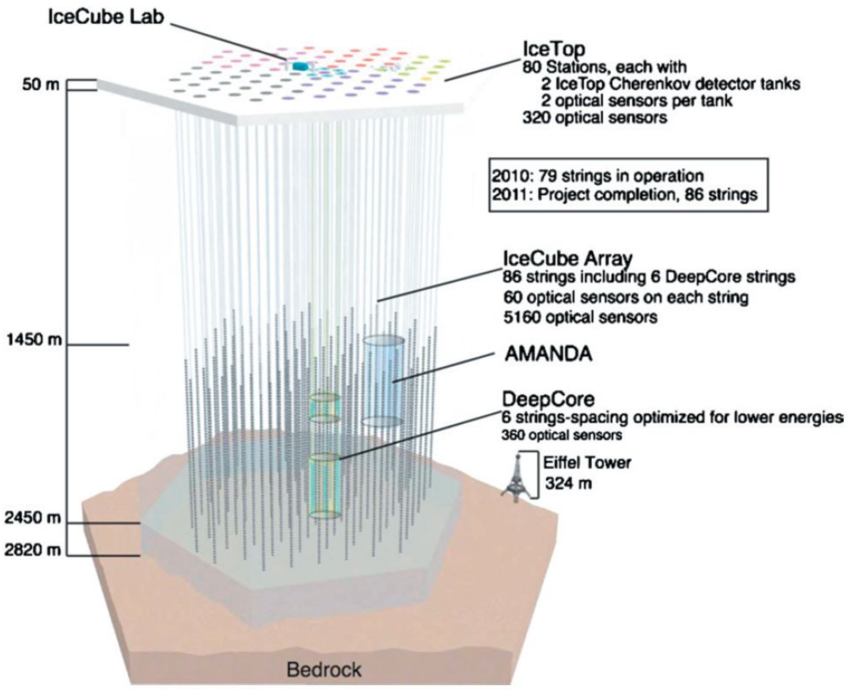
L = distance traveled by the neutrino (in km)

E = neutrino energy (in GeV)

Detection And Detectors

IceCube Neutrino Observatory (Antarctica)

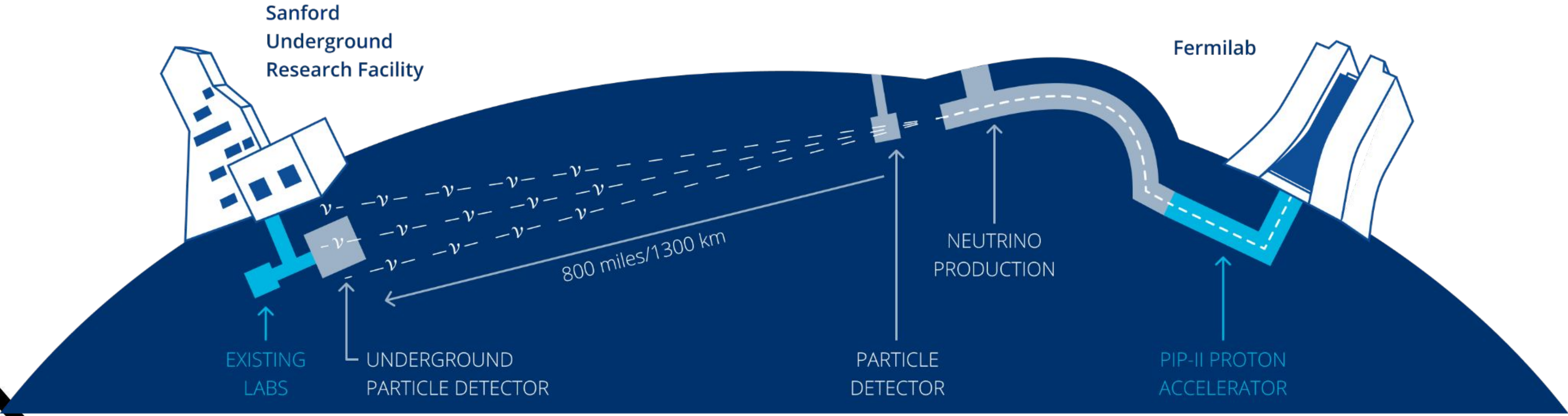
- Detects high-energy neutrinos; contributions to astrophysics, such as detecting high-energy cosmic neutrinos.
- Development: It consists of over 5,000 basketball-sized optical sensors embedded in a cubic-kilometer of ice.
- IceCube helps researchers study high-energy processes in the universe, including those related to black holes and supernovae.



Detection And Detectors

DUNE (Deep Underground Neutrino Experiment): Study neutrino oscillations

- Fermi National Accelerator Laboratory (Fermilab), USA.
- Type: Liquid Argon Time Projection Chamber (LArTPC).
- Two main components: the near detector at Fermilab and the far detector at the Sanford Underground Research Facility in South Dakota.



Detection And Detectors

At LHC

1. FASERν (FASERnu)

- Location: 480 meters from the ATLAS interaction point in a service tunnel.
- Goal: Detect collider-produced neutrinos and measure their interactions.
- Detector Type: Emulsion detector (like a photographic plate that tracks particles).
- Status: Took data in Run 3 (2022+); successfully detected LHC neutrinos in 2023 — a first!
- Importance: First direct detection of neutrinos produced in a collider.

2. SND@LHC (Scattering and Neutrino Detector at LHC)

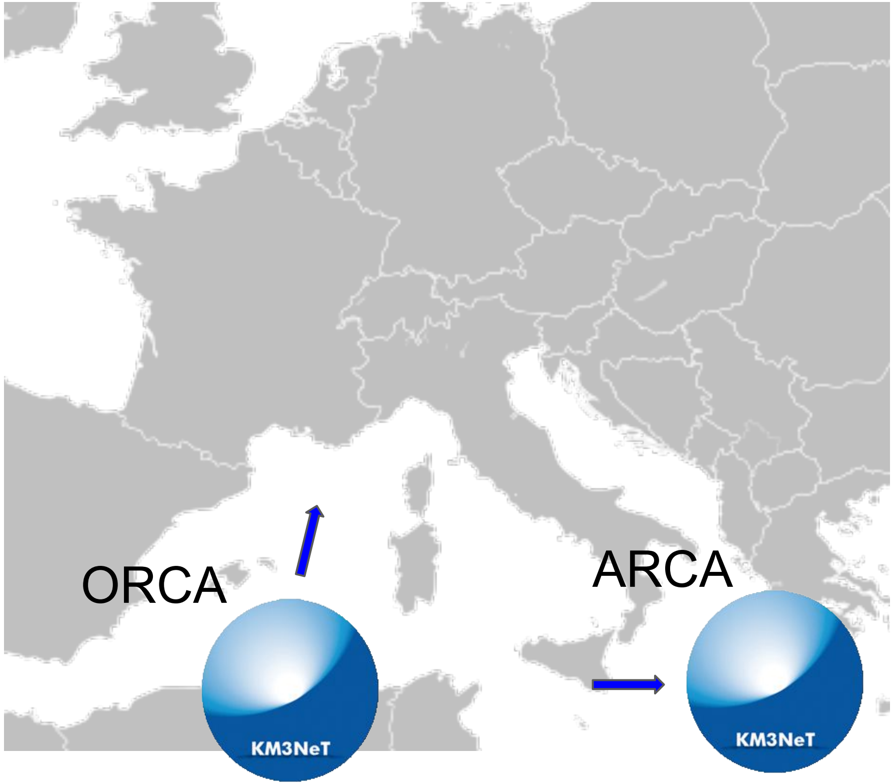
- Location: Near the LHC's interaction point (IP1).
- Goal: Measure neutrino interactions and properties, including tau neutrinos.
- Design: Hybrid detector (emulsion + electronic trackers + calorimeter).
- Status: Started running in 2022.

Detection And Detectors

- KM3NeT: Kilometre cubic neutrino telescope at meditaterian sea

- ORCA: Oscillation Research with Cosmics in the Abyss
  - Off the coast of Toulon, France depth of 2.5 km
  - Purpose: Study neutrino oscillations and measure the neutrino mass hierarchy
  - Energy Range: ~1–100 GeV

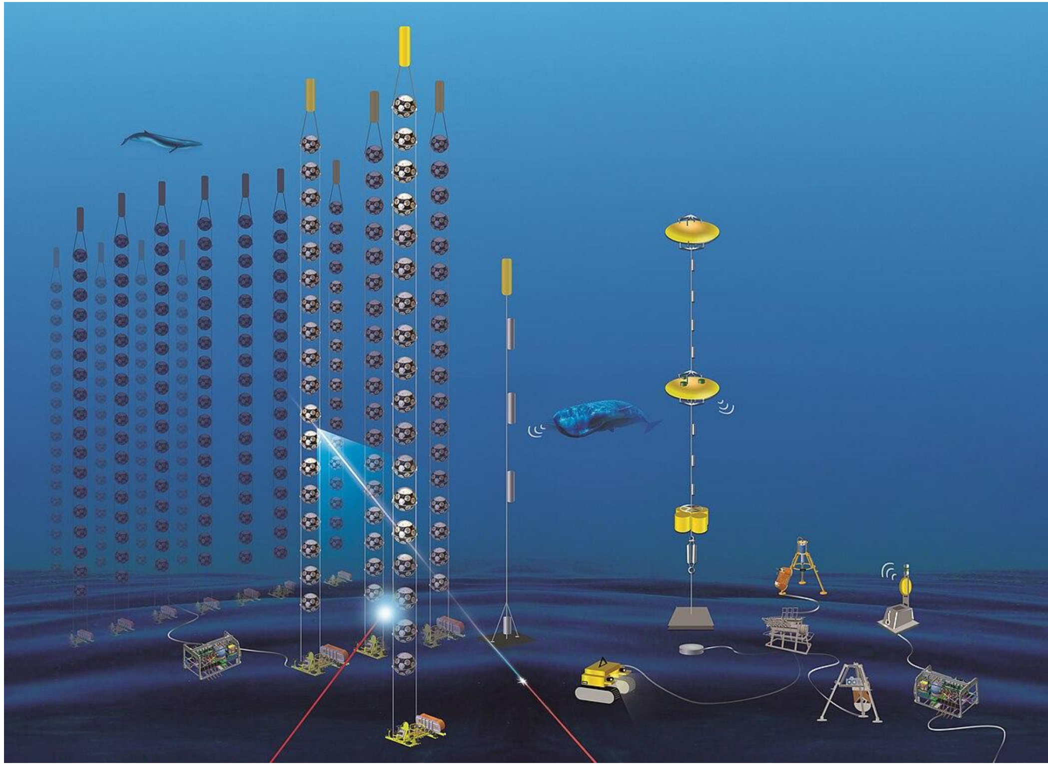
- ARCA: Astroparticle Research with Cosmics in the Abyss
  - Off the coast of Capo Passero, Sicily (Italy) depth: ~3.5 km
  - TeV–PeV and beyond



Detection And Detectors

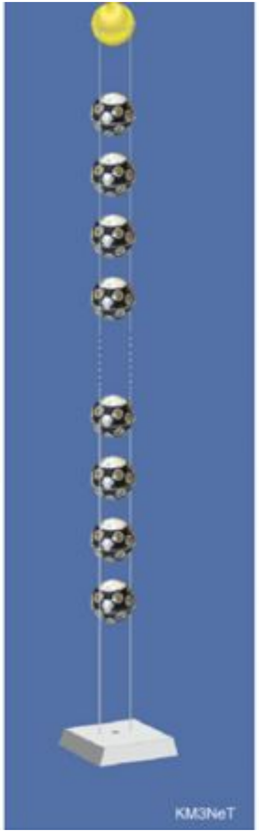
Engineering brilliance:

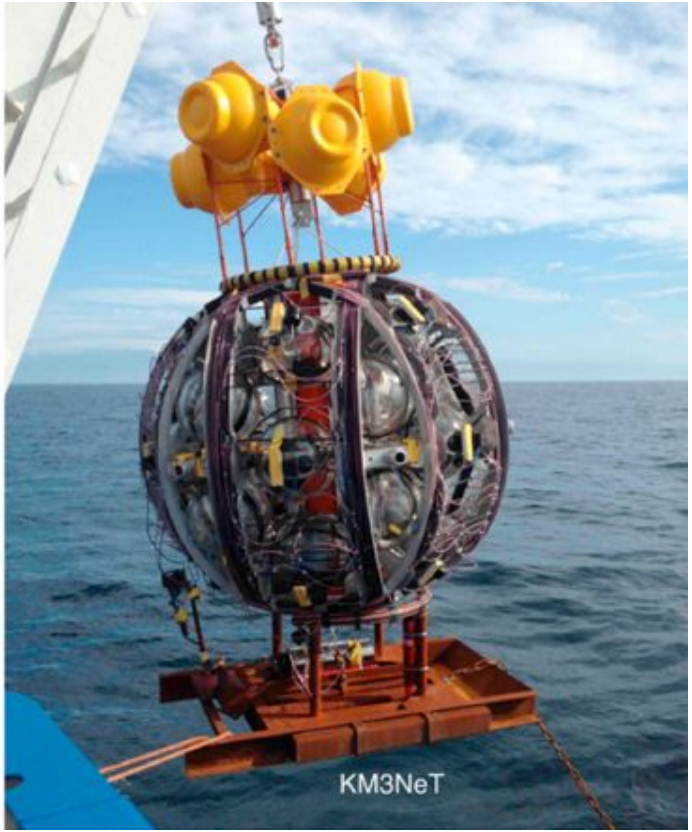
- Built-in directional sensitivity
- Digital optical modules: Survive extreme deep-sea pressure (~350 bar)
- Real-time, high-speed data transmission over hundreds of km underwater.
- Time Synchronization with Sub-Nanosecond Accuracy



Detection And Detectors

Nature approved: https://www.youtube.com/watch?v=omlFkdCkbYk





Detection And Detectors

Feature	KM3NeT	Other Detectors
Multi-PMT DOMs	✅ Yes (31 per module)	❌ No (usually 1 large PMT)
Deep-sea self-deployable units	✅ Yes	❌ Rare or absent
Smart DOMs with onboard logic	✅ Yes	❌ Minimal/centralized processing
Nanosecond timing underwater	✅ White Rabbit tech	❌ Less precise or surface-based
Real-time, modular deep-sea ops	✅ Yes	❌ Usually static, dry environments
Two detectors with shared tech	✅ ORCA + ARCA	❌ Single site/single focus

Detection And Detectors

Highest energy neutrino ever detected!

Article

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

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

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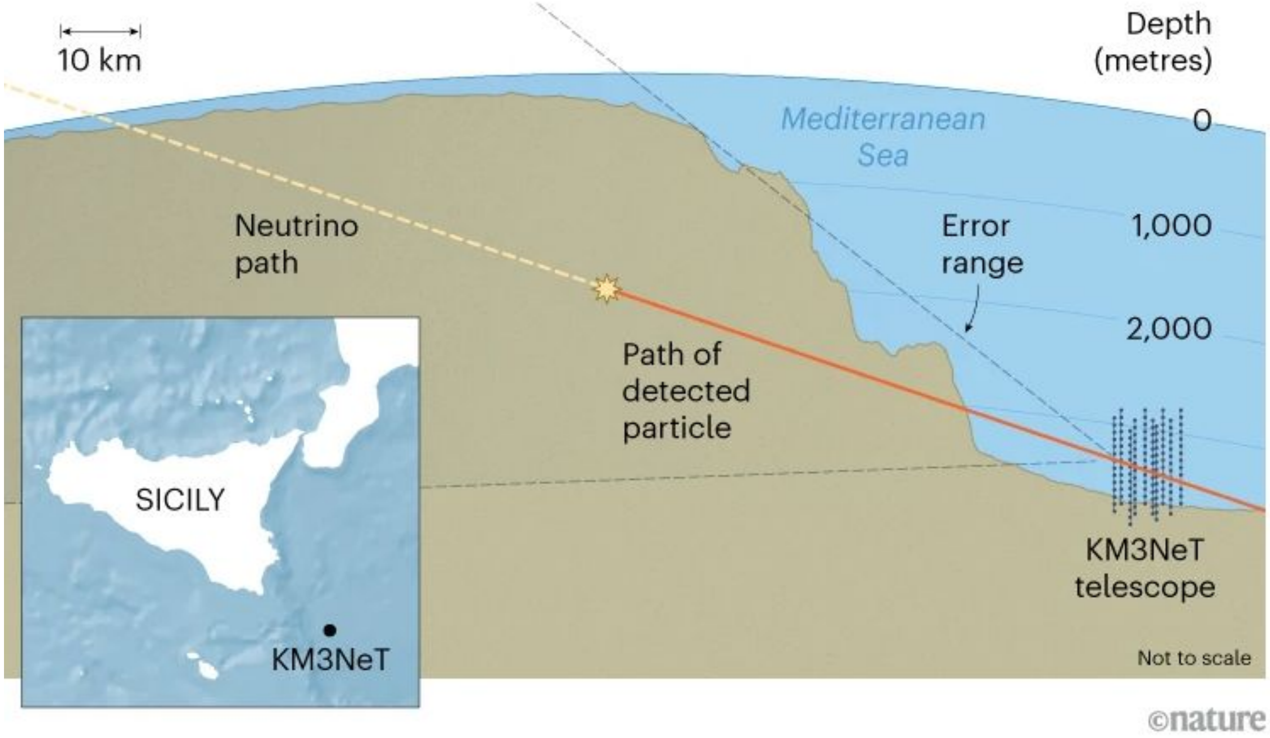
Check for updates

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

Detection And Detectors



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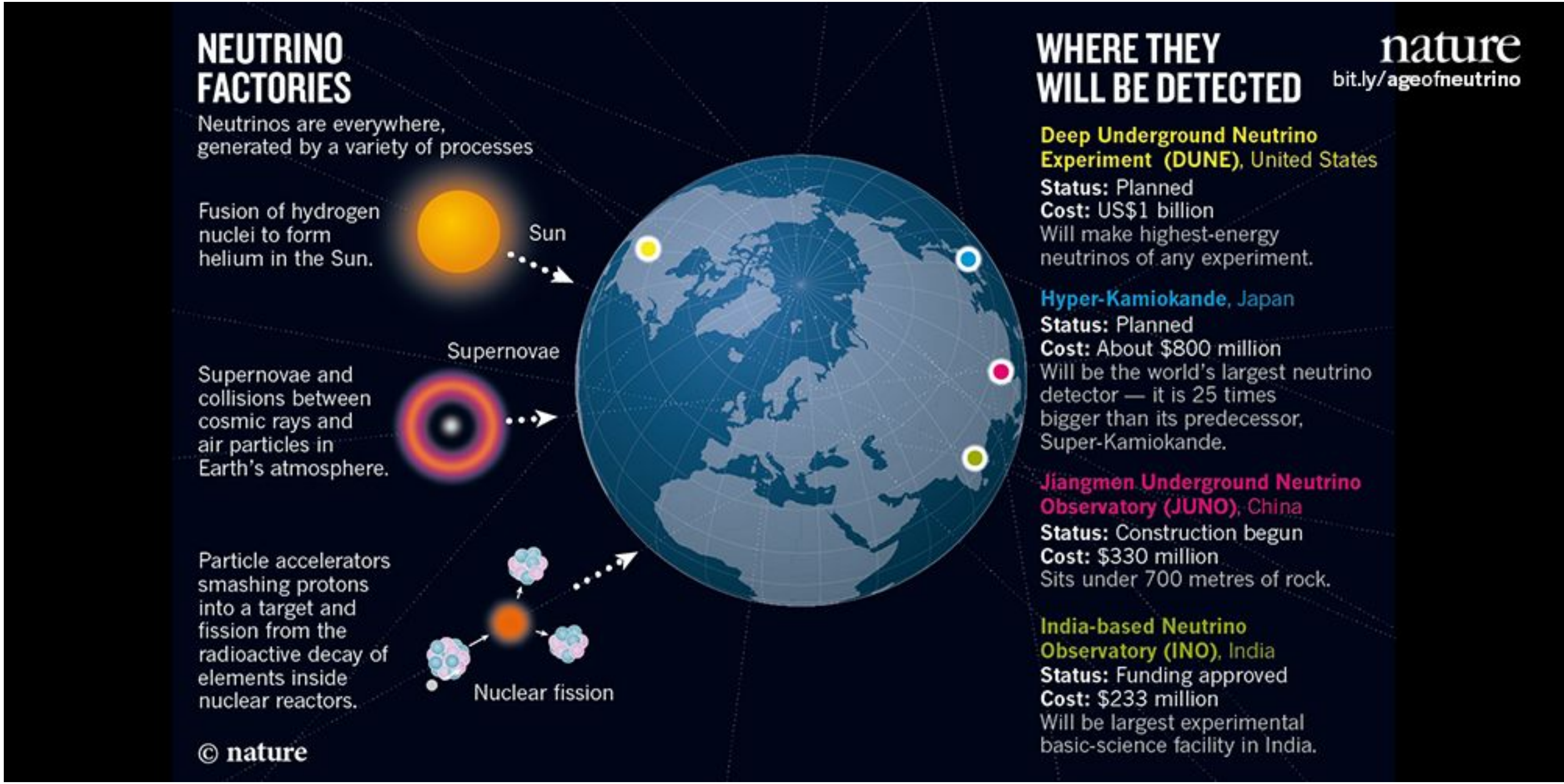
Detection And Detectors



Astrophysical Origins

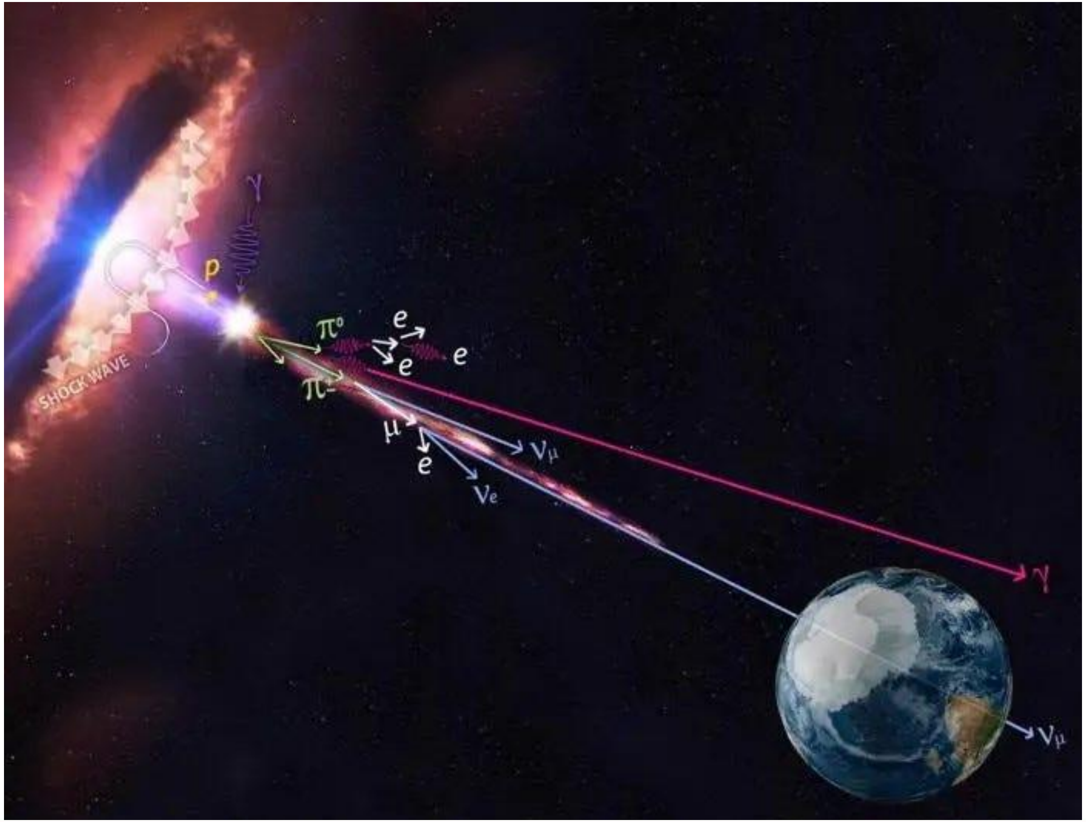
- Active Galactic Nuclei (AGN): Supermassive black holes at galaxy centers with energetic jets.

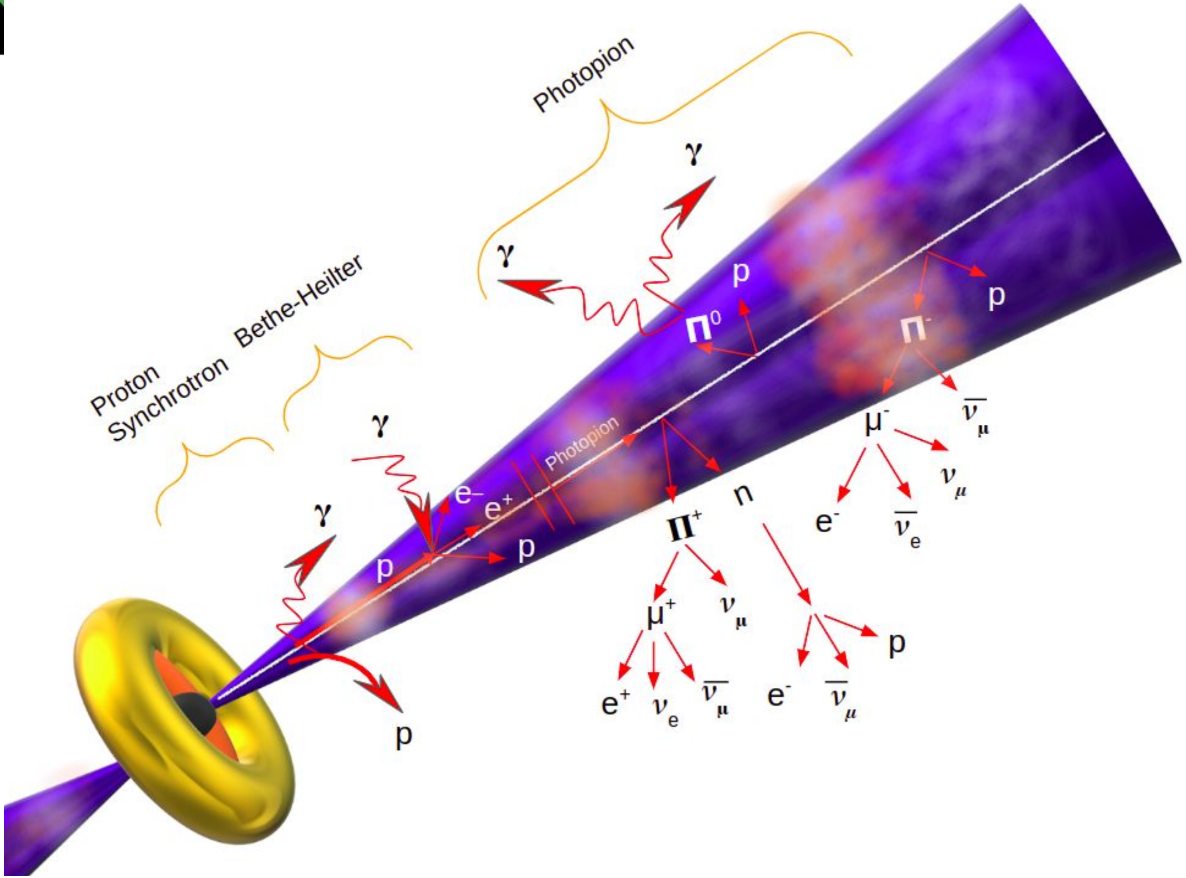
- Gamma-Ray Bursts (GRBs): Extremely energetic cosmic explosions, possibly from neutron star mergers or collapsing massive stars.

- Proton-photon (pγ) or proton-proton (pp) interactions.

- Secondary particles (pions) decay to produce neutrinos.

Astrophysical Origins





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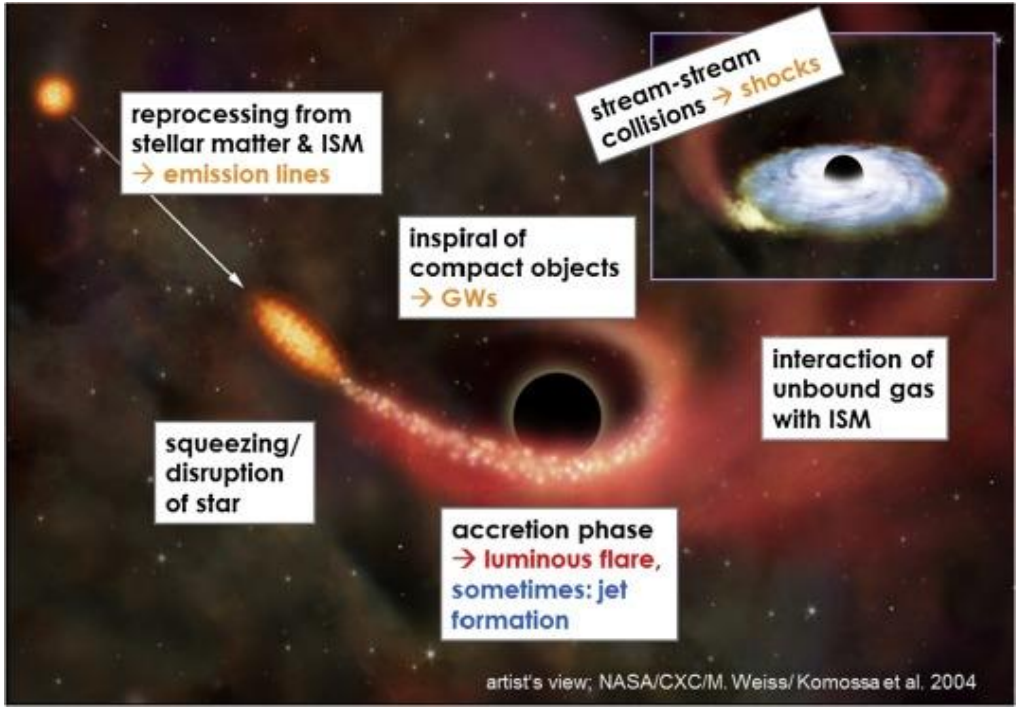
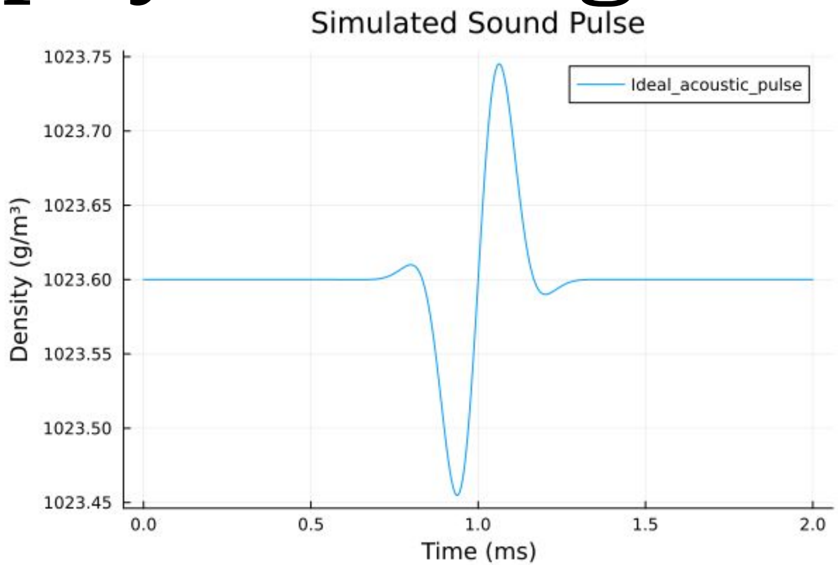
Astrophysical Origins

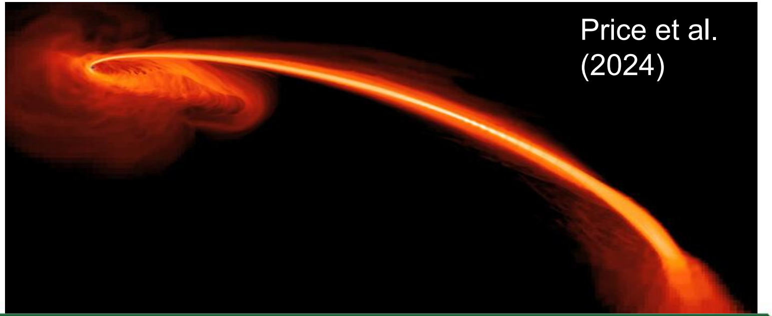
- Origins Tidally disrupted events (TDE):



Astrophysical Origins

- What we do at AGH!





Join Us :)


KM3NeT


Thank you

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