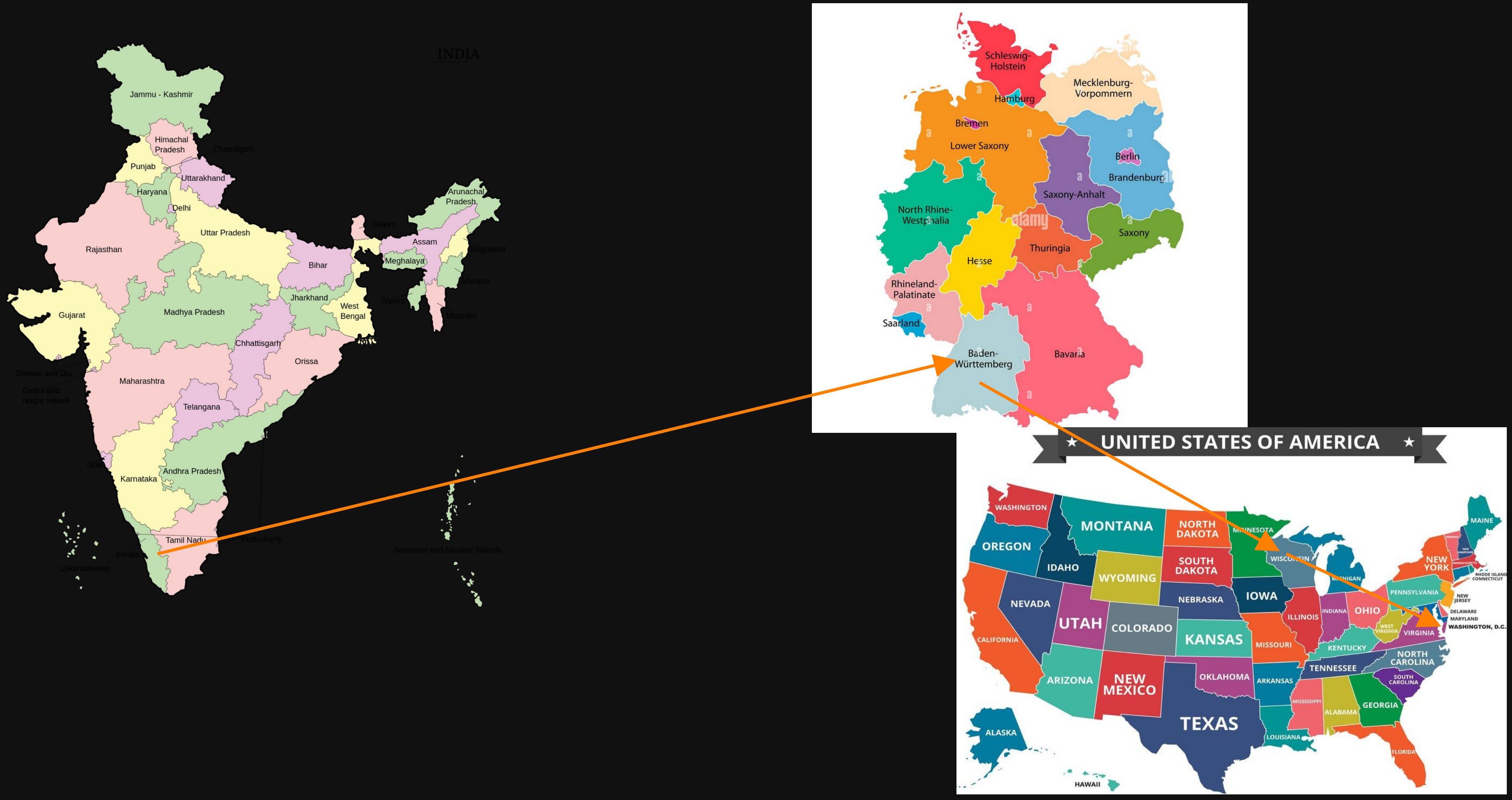
Neutrino Telescope Basics, Data Analysis, and Current Measurements

Aswathi Balagopal V.
Day 1, Cosmic Neutrino Practicum 2026

UNIVERSITY OF DELAWARE
BARTOL RESEARCH INSTITUTE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Content of the three lectures

Day 1

- A bit of history, connection between messengers
- Neutrinos at different energy scales
  - μeV to EeV energy scales
  - Measurements relevant at each energy scale

Day 2

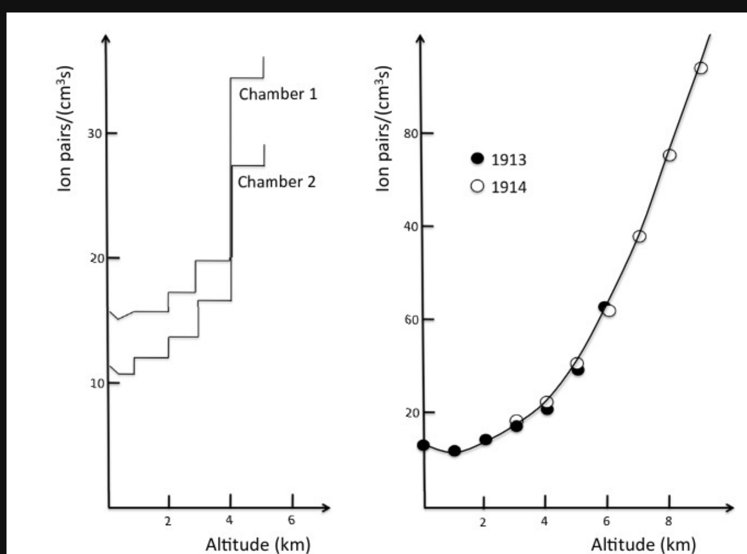
- Atmospheric neutrinos
  - Cosmic ray interactions in the atmosphere
  - Types of atm neutrino fluxes
  - Oscillations in atm neutrinos
- Astrophysical neutrinos
  - Event selections, diffuse measurements
  - Data analysis methods

Day 3

- Sources of astrophysical neutrinos
  - Latest measurements
  - Data analysis methods
- EHE neutrinos
- Future detectors

The birth of particle astrophysics

- Originated from the discovery of cosmic rays (CR)
- They are ionized nuclei, most having high energies
- In 1912 Victor Hess ascends on a balloon to measure the amount of "ionizing radiation" within an electroscope
- Found radiation to increase with height, which means that it comes from outer space



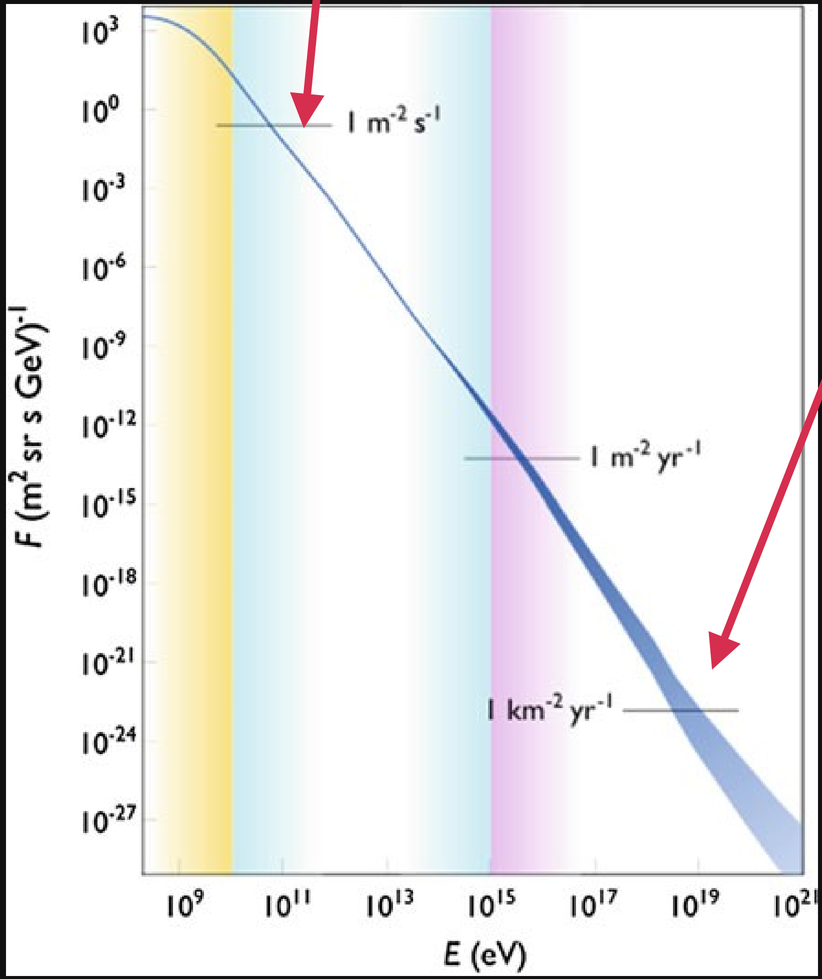
Cosmic-ray flux

They are nuclei from the different cosmic accelerators in the Universe!

Flux = counts for the observed events standardized to the same units of collection area and time across all energies

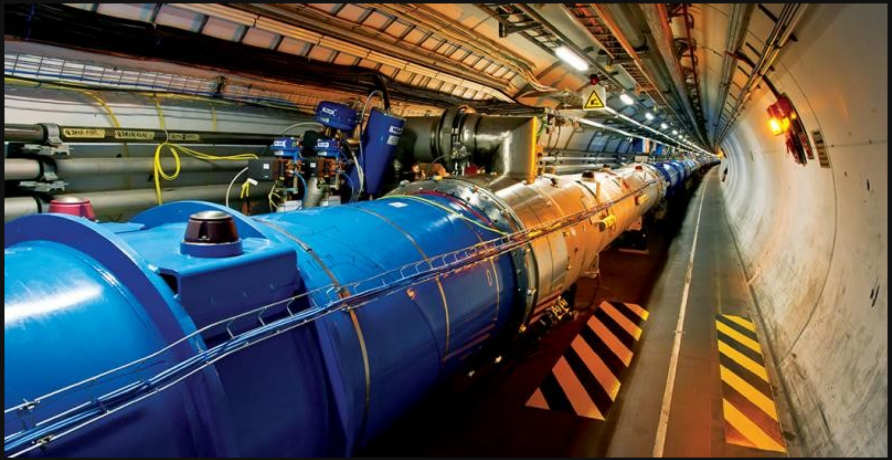
Measured with space-based experiments

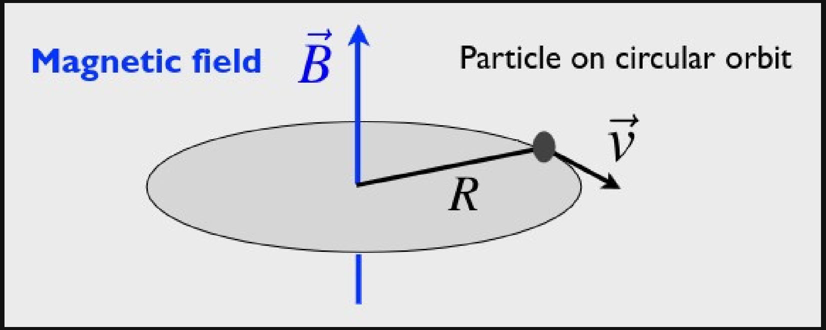
Measured with ground-based experiments



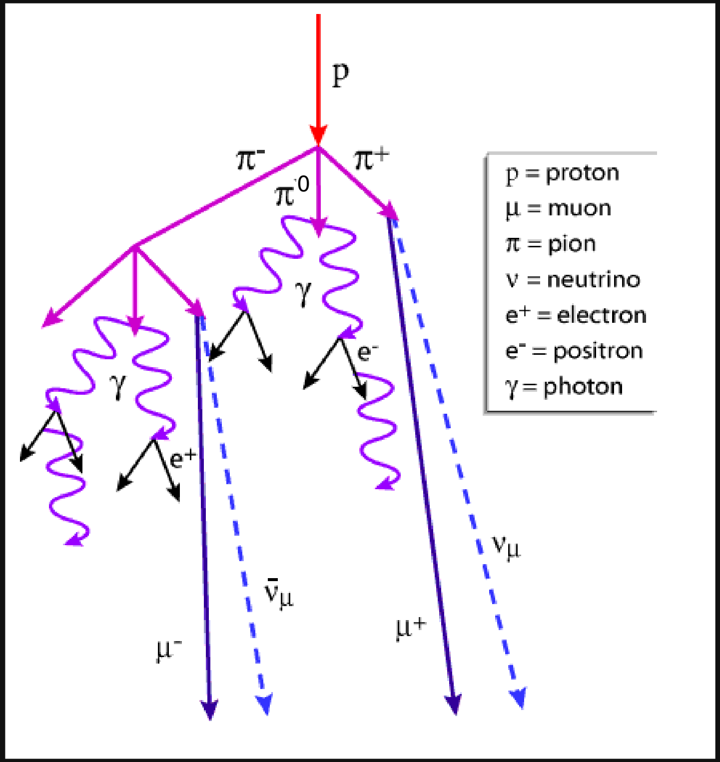
We see cosmic rays from all directions with energies as large as 10^{21} eV

Highest energy cosmic rays





Extensive air showers: measuring CRs at Earth



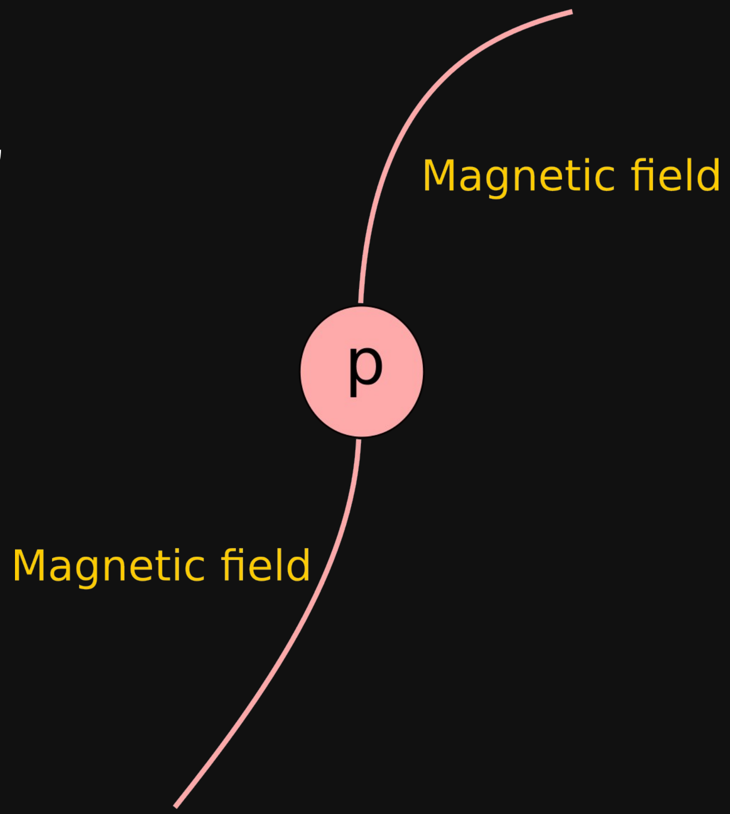
- Cosmic rays interact with the Earth's atmosphere
- They produce a shower of particles known as "air shower"
- Daughter particles include pions, muons, electrons, photons
- We can observe these shower of particles on the ground with detectors
- This is the principle used to detect cosmic rays of higher energies (and lower fluxes)

What produces them?

Our Universe is filled with such extremely high energy particles travelling almost at the speed of light!!

We are trying find out what produces them, and how they are produced

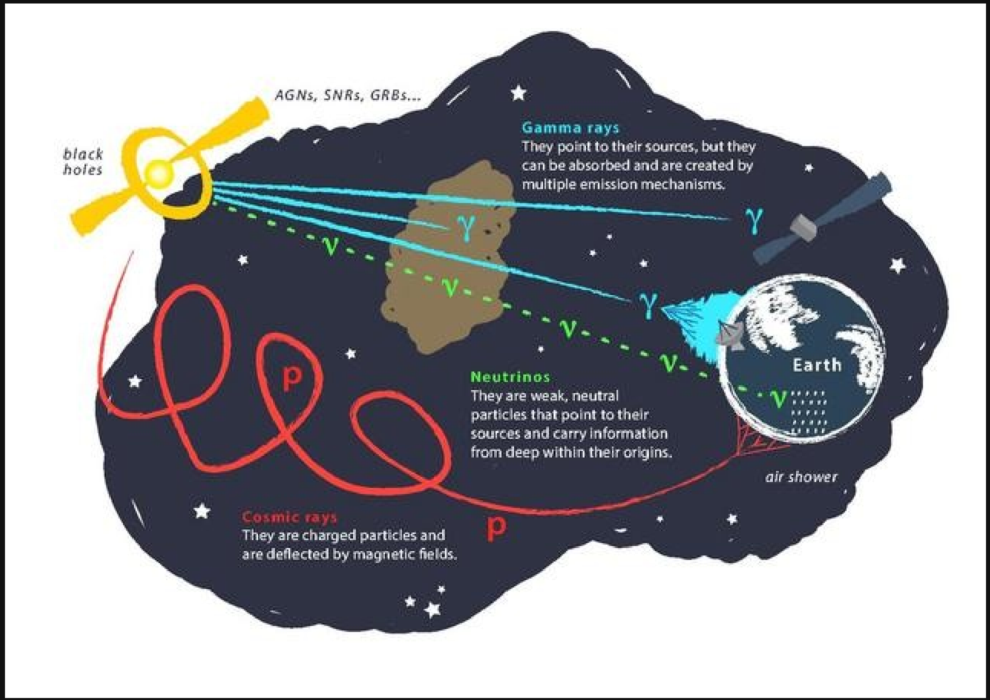
But cosmic rays are hard!
They get deflected by magnetic fields and cannot point to where they are coming from :(



Multiple Messengers

Nature's accelerators produce CR's, gamma rays and neutrinos

- CRs, being charged particles, bend in intergalactic magnetic fields
- Neutrinos and gamma rays (photons) are neutral particles, also produced in these accelerators



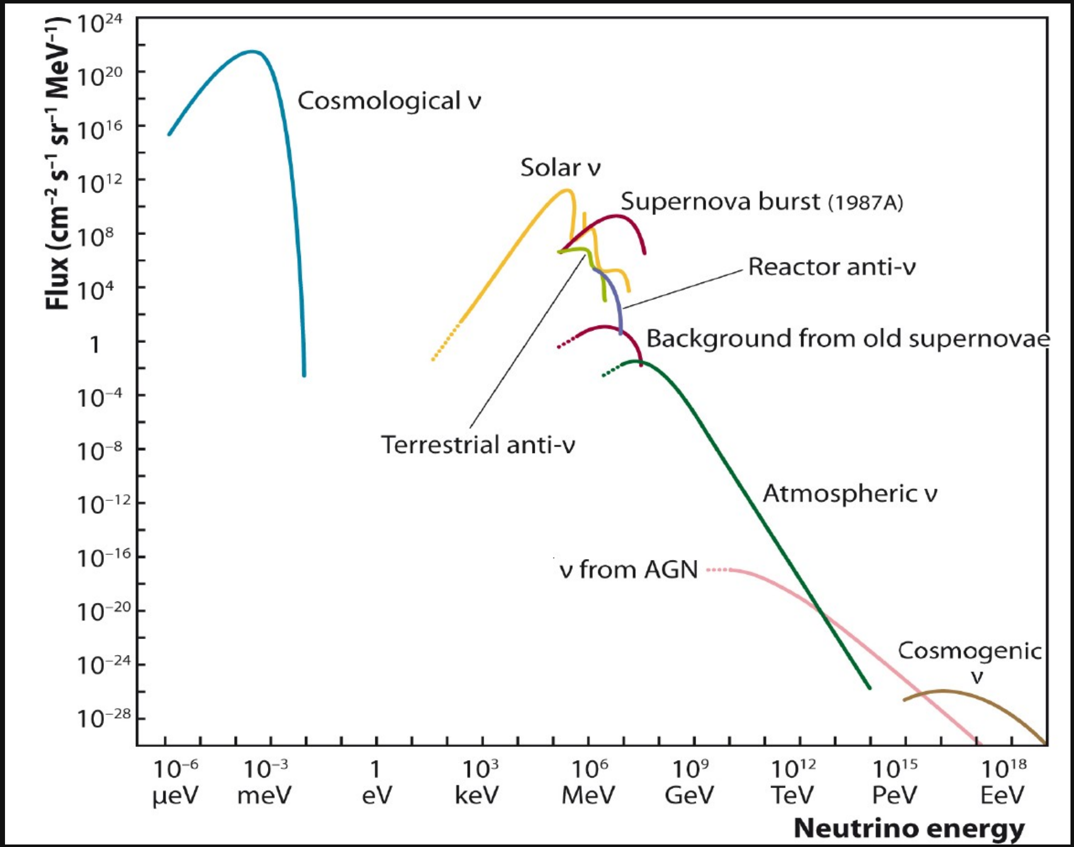
Check in

- CRs are charged particles produced in astrophysical sources
- Accompanied by neutrinos and gamma rays
- We are still trying to find the sources of these cosmic rays

Are you on board?

Neutrinos in the Universe

Neutrinos are everywhere!

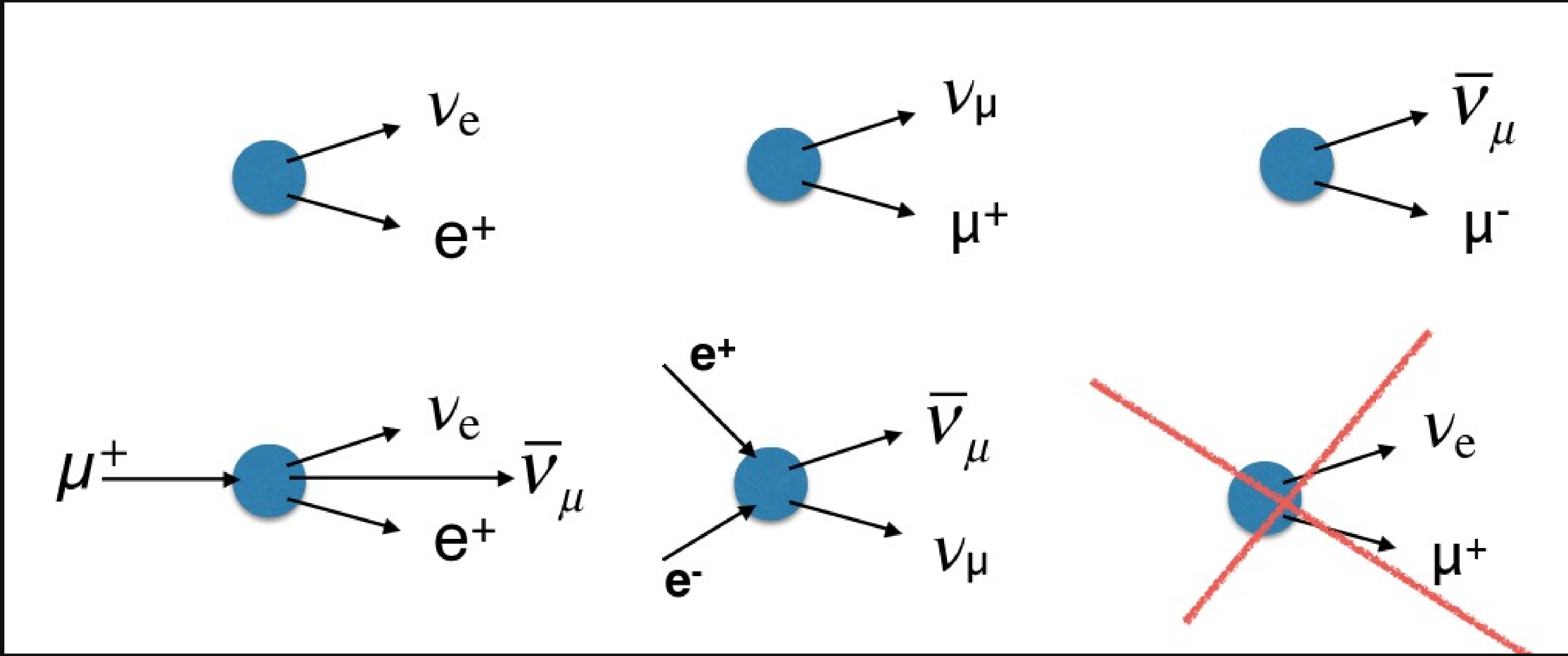


Neutrinos are neutral particles, point directly to their source, travel large distances

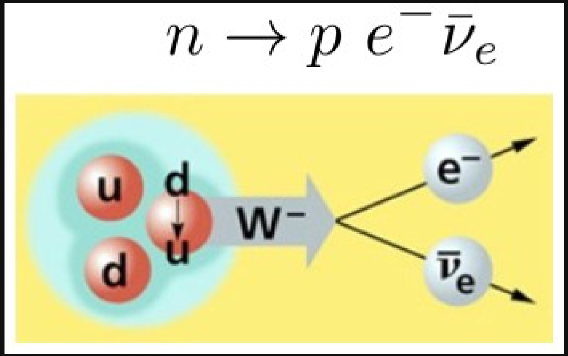
- They come from remnants of the Big Bang
- From the Sun
- From CR air showers
- From nuclear reactors
- From astrophysical sources

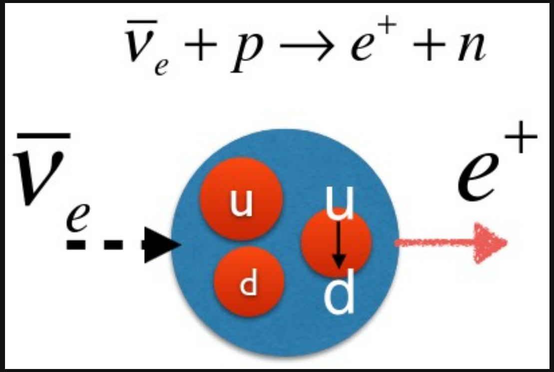
Neutrino Creation

- Lepton number needs to be preserved
- Le, Lμ and Lτ needs to be conserved in an interaction
- Particles get +1 and antiparticles get -1

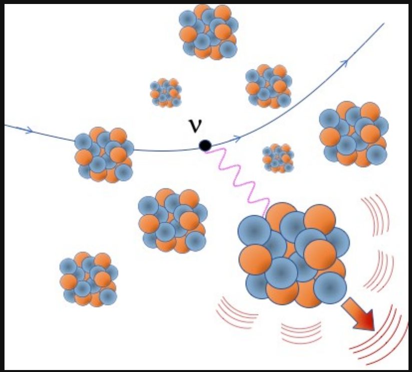


Neutrino Interactions

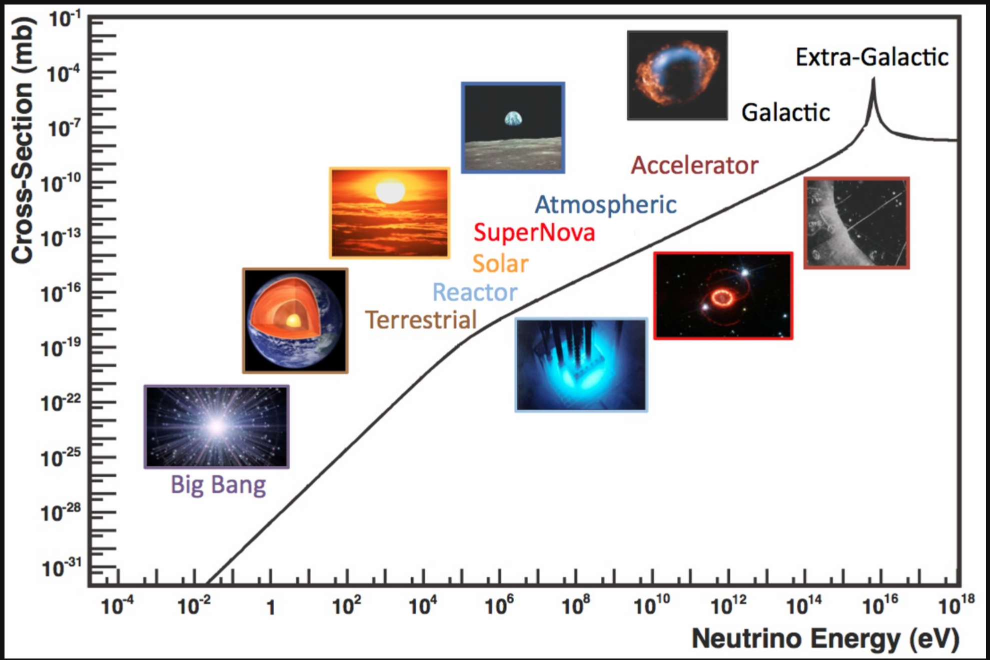




- Radio activity (beta decay) converts nuclei into neutrinos
- Inverse beta decay converts neutrinos into charged particles
- Both are called "weak interactions"
- They are rare processes
- Neutrinos can undergo scattering
- Neutrino-nucleus scattering causes the nucleus to recoil



Neutrino-Nucleon Cross sections



- The effective area with which the interacting particles see each other: "cross section", units: barn
- Cross section of neutrinos tell us how many incident particles will interact with the neutrino
- The neutrino-nucleon cross section grows with energy

$1\,\mathrm{MeV} \lesssim E \lesssim 10\,\mathrm{TeV}$

$$\sigma_{\nu N} \simeq (0.67 \times 10^{-38} E)\ \mathrm{cm}^2 = (6.7\,E)\ \mathrm{fb}$$

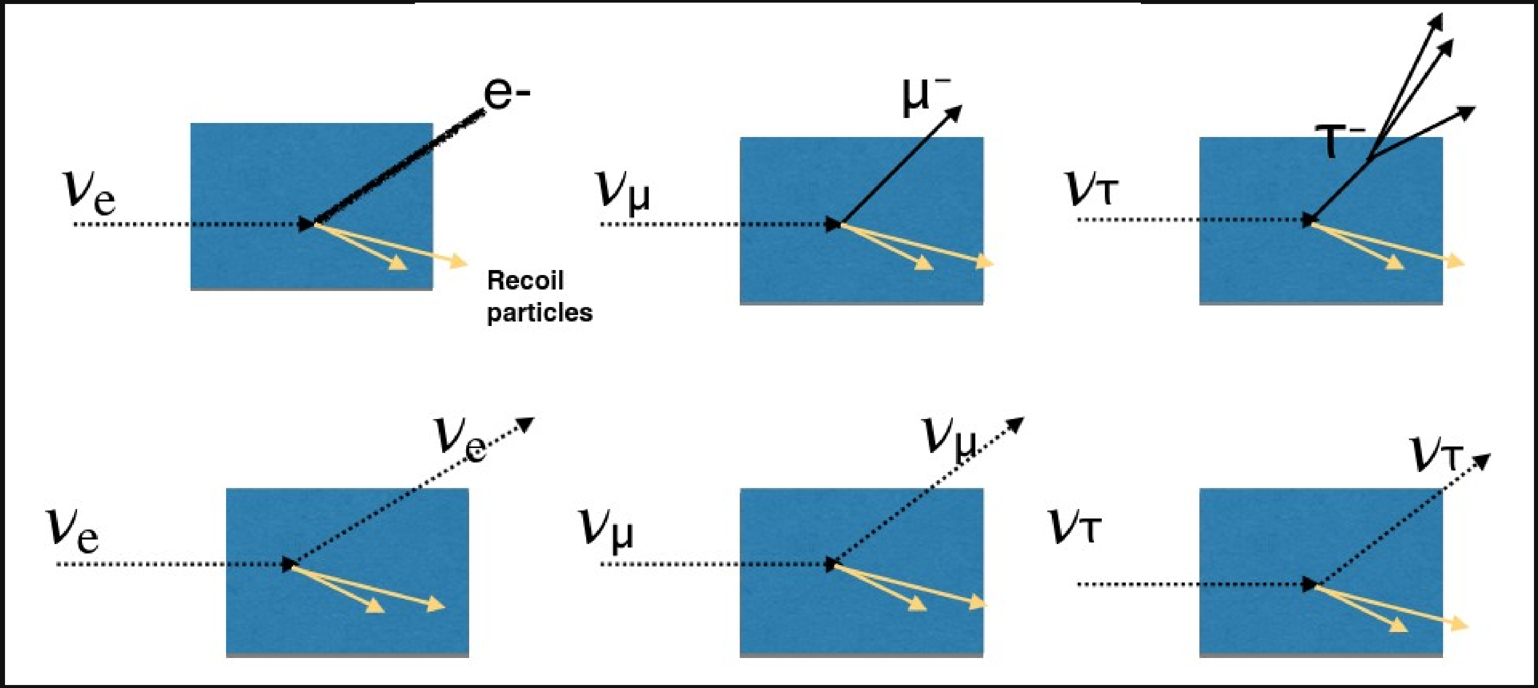
E is in GeV

$$\sigma_{\nu N} \simeq \left(0.67 \times 10^{-34} \sqrt{\frac{E}{10\,\mathrm{TeV}}}\right) \mathrm{cm}^2$$

10 and 10^7 TeV (10^{19} eV)

Neutrino Detection

- Neutrinos are charged and hence appear invisible as it enters a detector
- It interacts rarely and leaves charged particles that can be detected (charged current)
- It can also scatter and leave observable energy (neutral current)



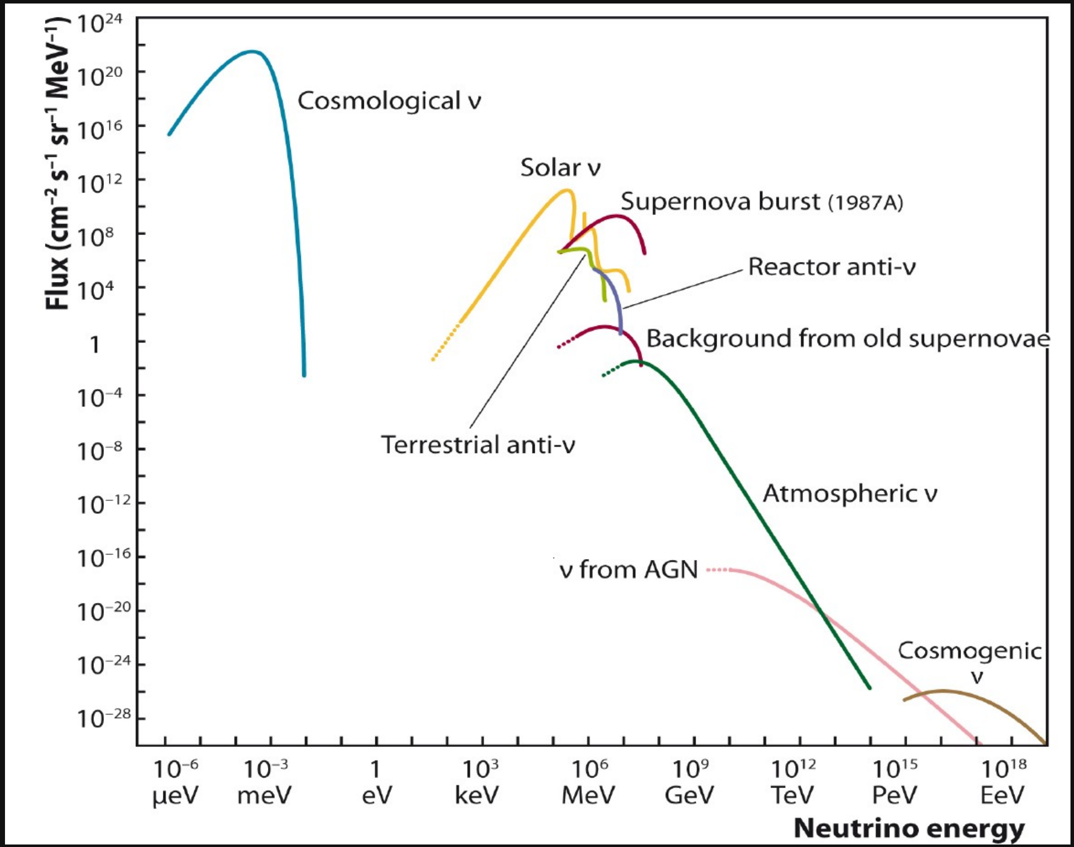
Check in

- We discussed neutrino interactions and cross sections
- These are necessary to detect neutrinos in your detector

Are you on board?

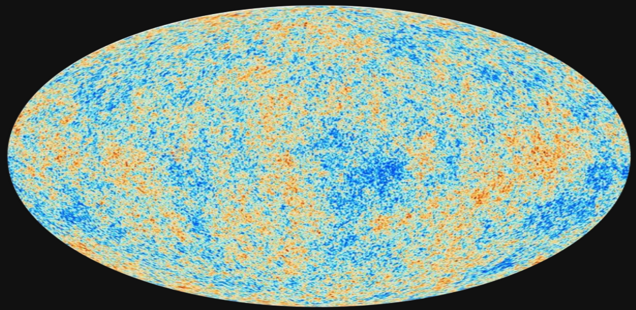
Neutrinos in the Universe

Neutrinos are everywhere!



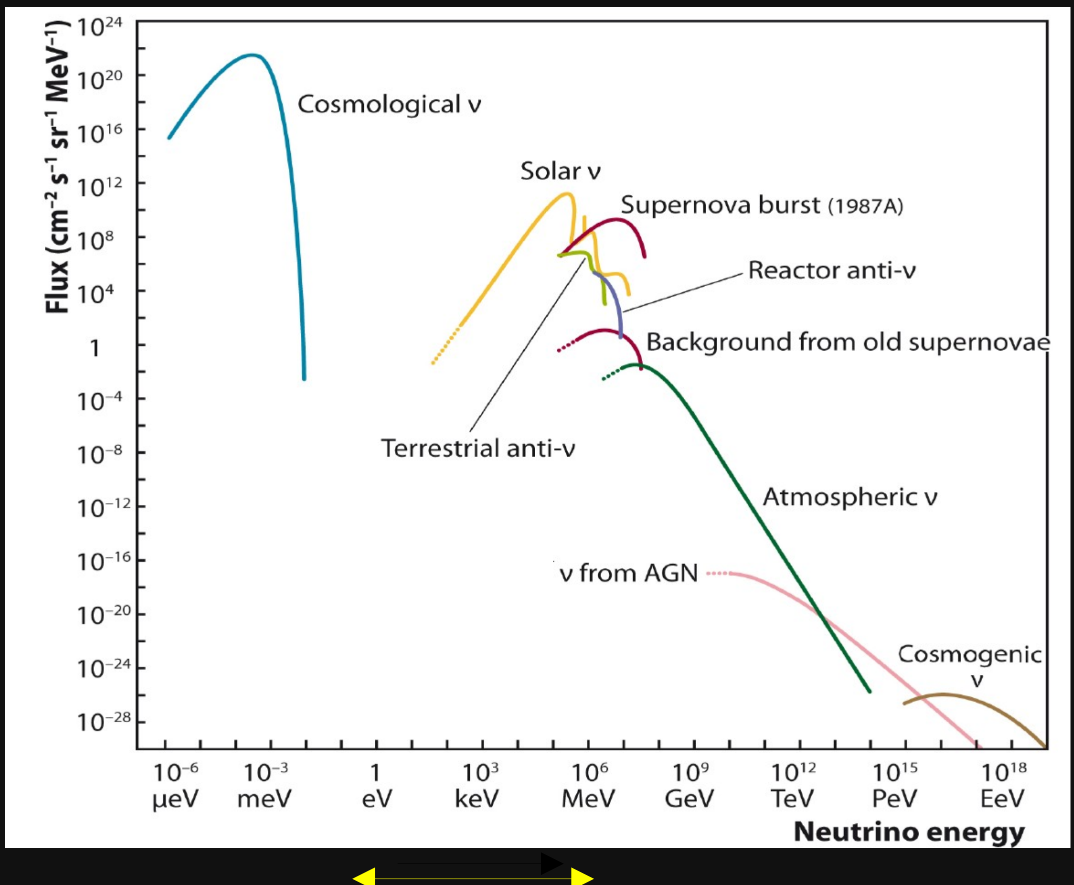
Neutrino capture on unstable nucleus
Eg: PTOLEMY

- Starting at the lowest energies, we have remnant neutrinos from the Big Bang (relic neutrinos), like the cosmic microwave background radiation
- Low prob of detection



CMB $\lambda = 10^{-3} \Rightarrow$ energy = 10^{-4} eV

Neutrinos in the Universe

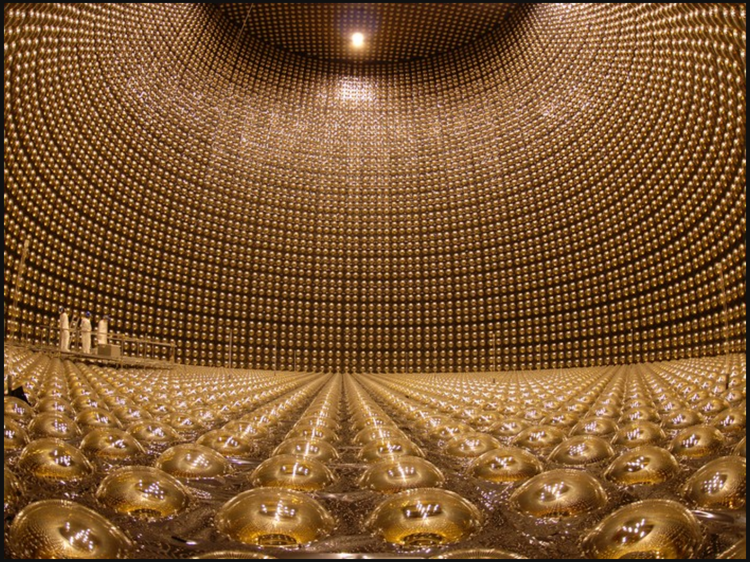


Neutrino capture on stable nucleus (chlorine, gallium) Eg: Homestake

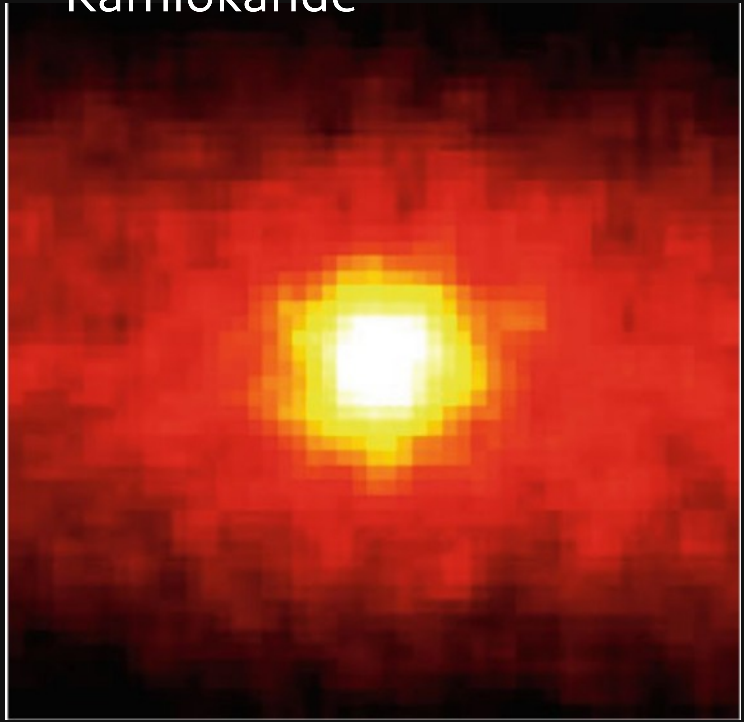
- Stellar/solar neutrinos, famously detected by several experiments
- At MeV energies, the sun outshines the cosmos
- Gave rise to the solar neutrino problem

The Solar Neutrino Problem

- The fusion reactions in the Sun cause electron neutrinos to be produced which we can detect on Earth
- Experiments found a deficit in the number of electron neutrinos with respect to expectations

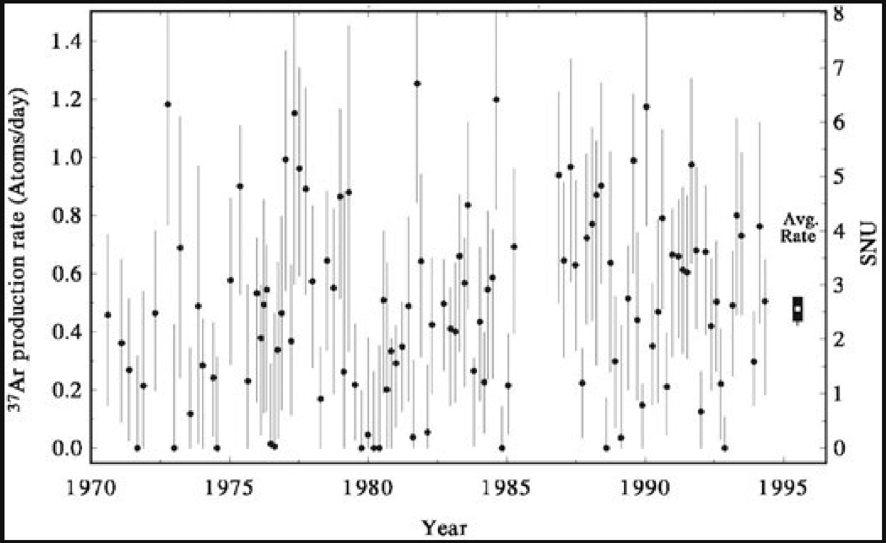


The Sun observed via neutrinos with Super Kamiokande

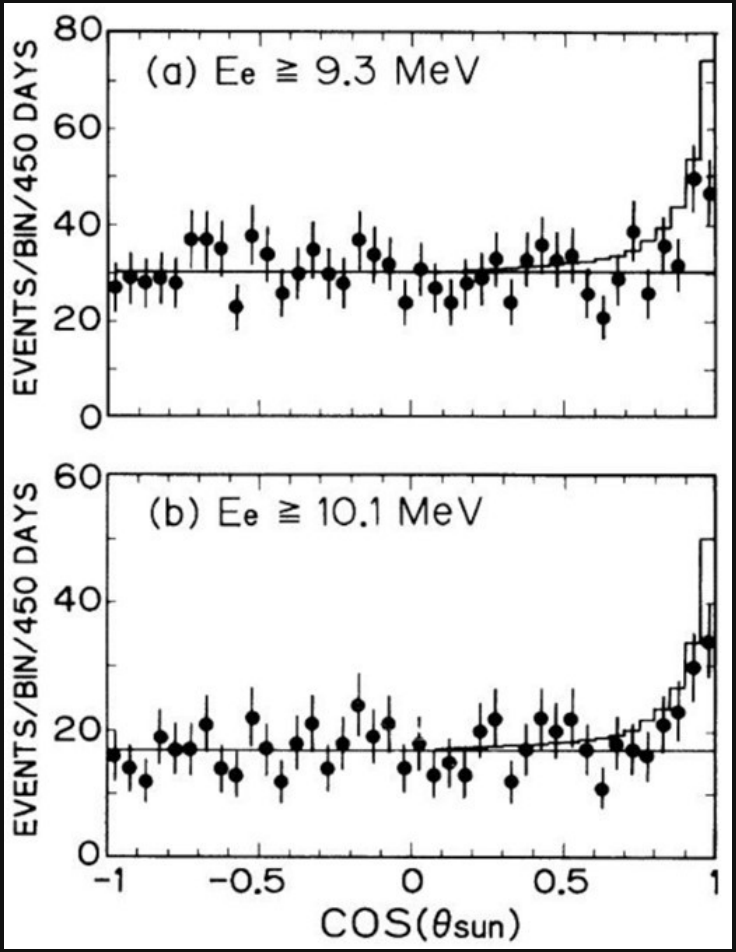


The Solar Neutrino Problem

Observed rate of Solar neutrinos in the Homestake expt. was 30% less than predicted



Observed rate of Solar neutrinos from Kamiokande in the direction of the Sun was 50% less than predicted



Neutrino Oscillations

- The final answer to this problem was solved by neutrino oscillations (discovered by SNO)
- Electron neutrinos were changing its flavor to muon and tau neutrinos as they travelled to the Earth

The Sudbury Neutrino Experiment (SNO)

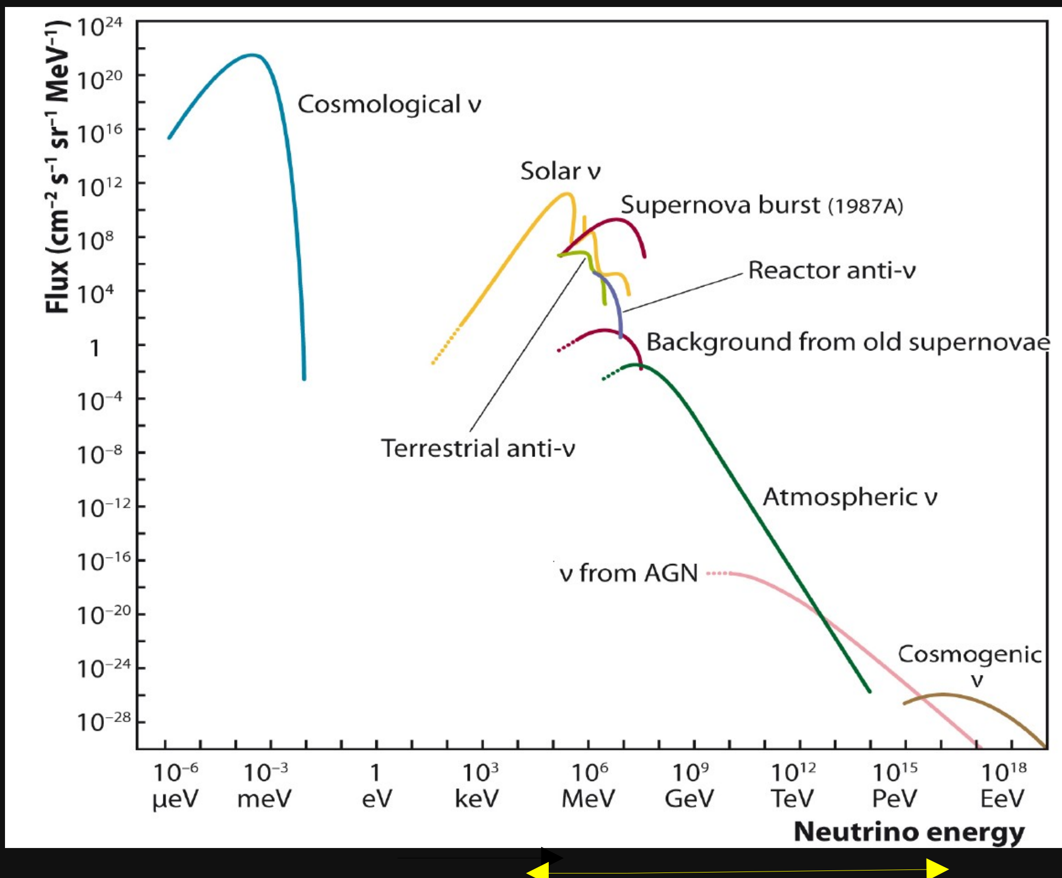
Oscillations are flavor transformations of neutrinos as they travel. Like chocolate ice cream becomes vanilla ice cream and/or strawberry ice cream

Check in

- Solar neutrinos- keV to MeV energies
- Revealed neutrino oscillations

Are you on board?

Neutrinos in the Universe

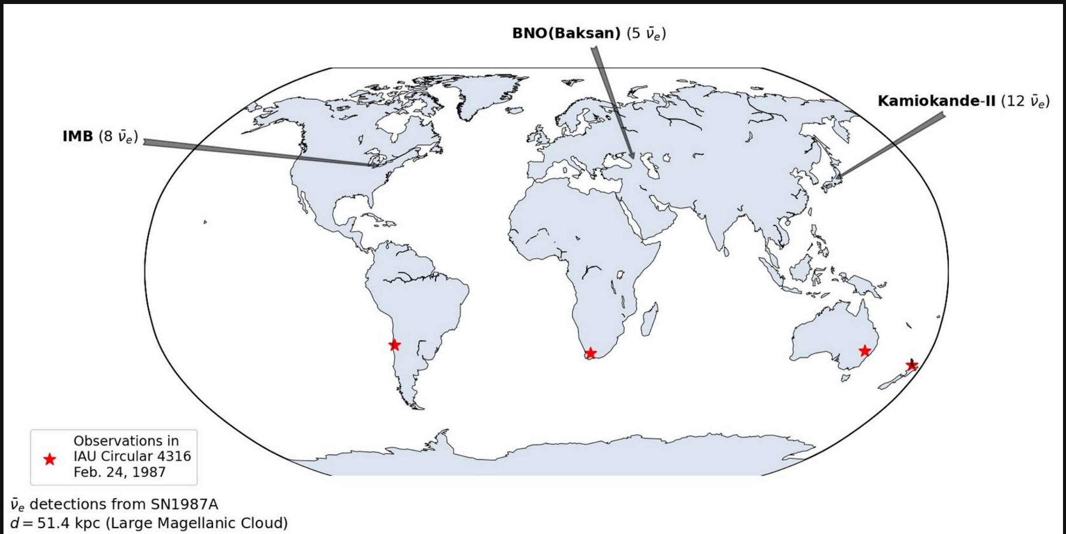


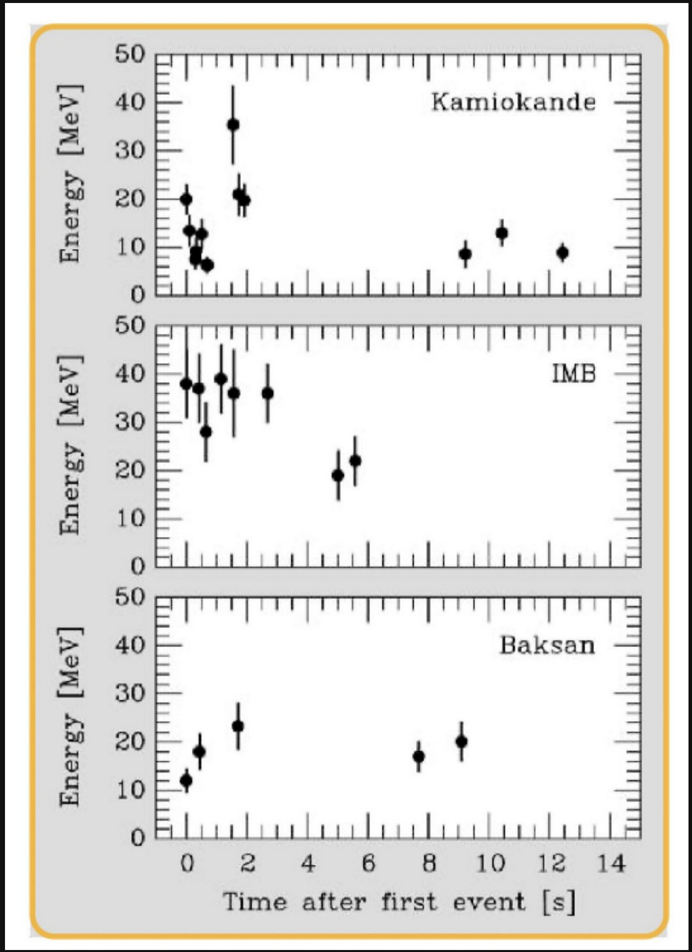
Water/ice cherenkov detectors

- Supernovae, a known source of neutrinos (several MeV)
- Supernova: massive stars at the end of their life explode into a supernova
- Neutrinos are produced in supernovae and carry ~ 99% of its energy

Supernova neutrinos

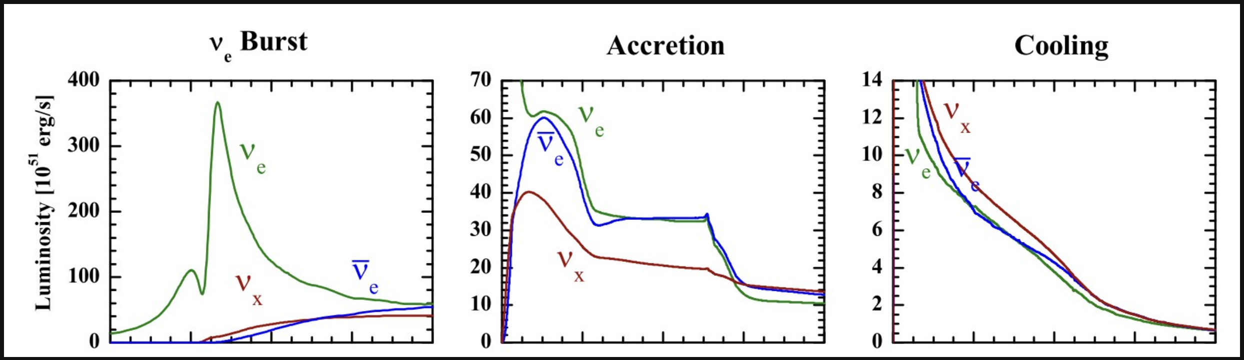
- On 23 Feb 1987, seen in several detectors, recorded a total of 25 neutrinos over 13 seconds.
- 2.5 hrs later, supernova observed by astronomers (visible with eye)
- Occurred in the Large Magellanic Clouds at a distance of ~ 50 kpc





Supernova neutrinos

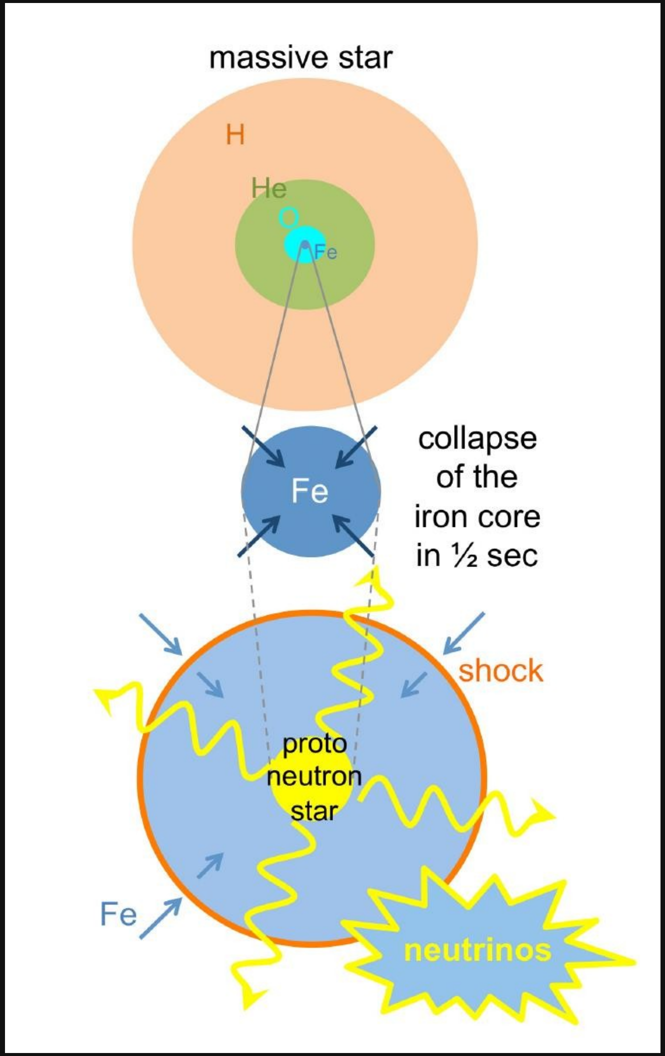
- Supernova burst seen during the core collapse of a massive star
- Forms black hole/neutron star
- Neutronization burst: $e^- + p \rightarrow n + \nu_e$
- ~10^{58} neutrinos in ~10s
- 99% gravitational energy released
- Typical energy: 10-20 MeV



Initial neutronization burst
$e^- + p \rightarrow n + \nu_e$

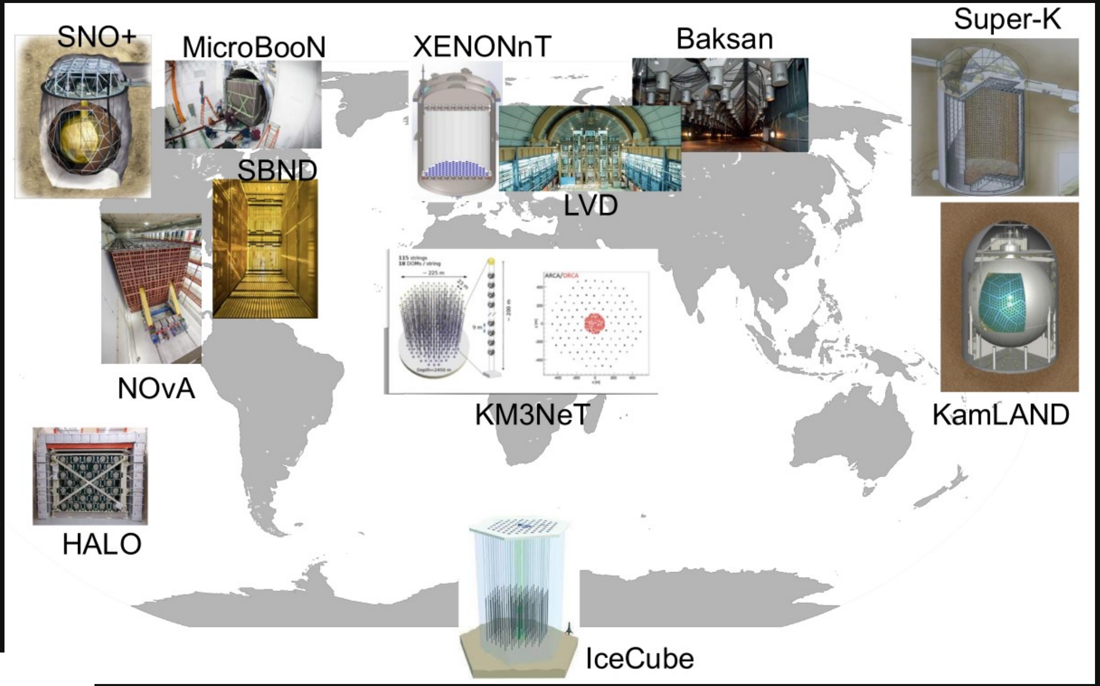
Material falls into proto neutron star
$e^- + p \rightarrow n + \nu_e$
$e^+ + n \rightarrow p + \bar{\nu}_e$

proto neutron star loses trapped thermal energy
$e^- + e^+ \rightarrow \bar{\nu} + \nu$

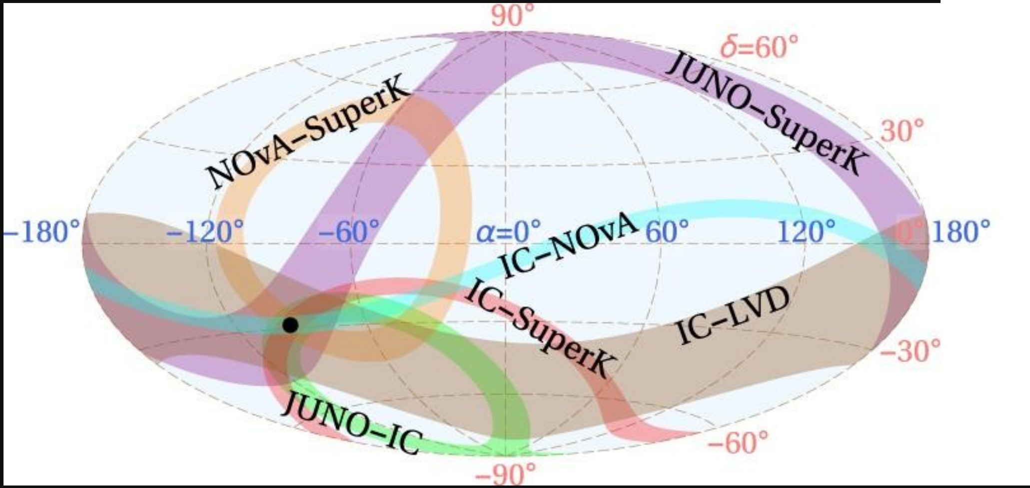


Supernova Early Warning System (SNEWS)

- MeV neutrino burst as trigger for electromagnetic supernovae observations
- Coordinated follow-up helps localize the event

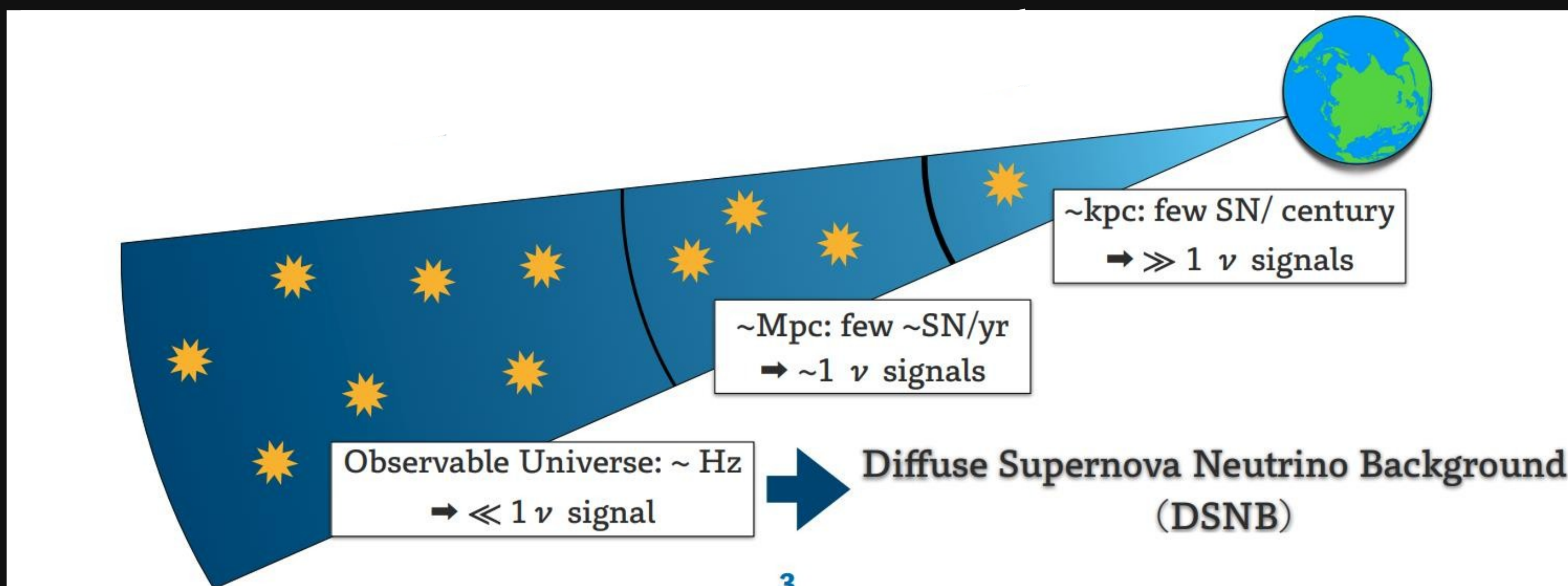


Detectors participating in SNEWS

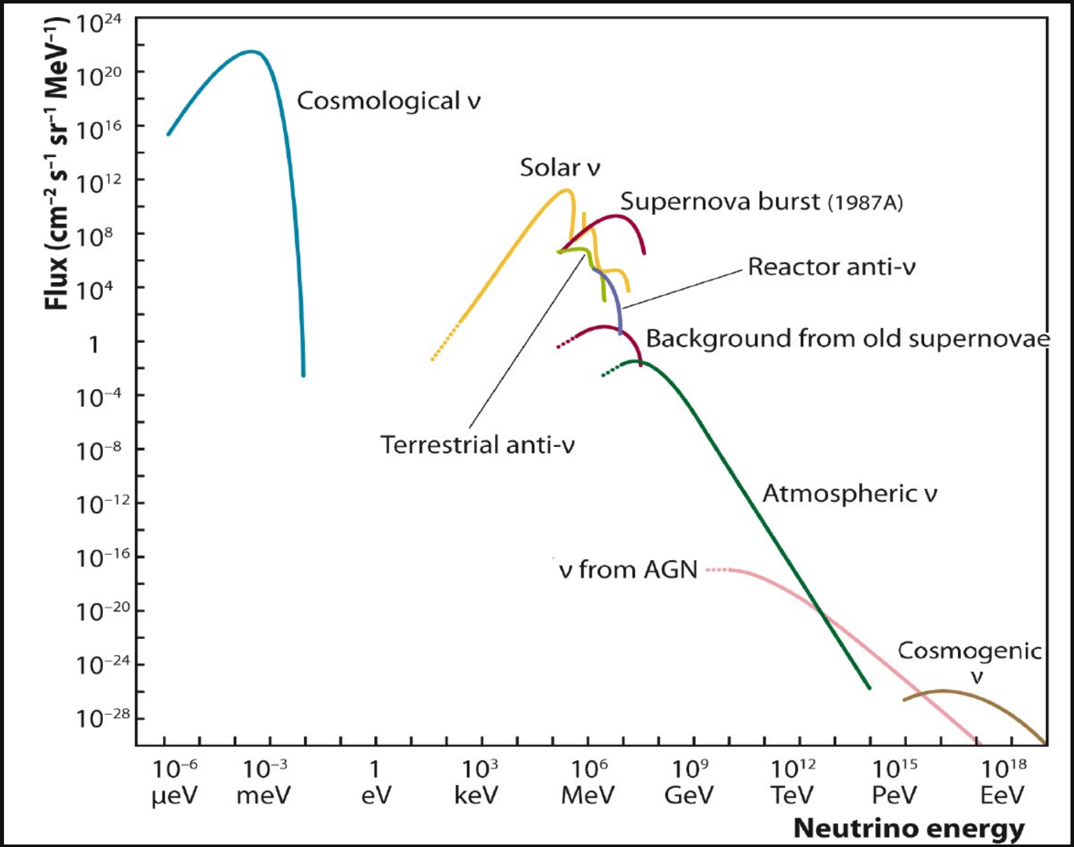


Diffuse Supernova Neutrino Background

- Core collapse supernovae (CCSNe) release 10^{53} erg in neutrinos
- Nearby CCSNe are very rare; diffuse supernova neutrino background: better chance to observe
- Addition of Gadolinium to SuperK to help neutron capture (helps distinguish signals from $\bar{\nu}_e$
- Current data: 2.6 σ tension with no DSNB hypothesis



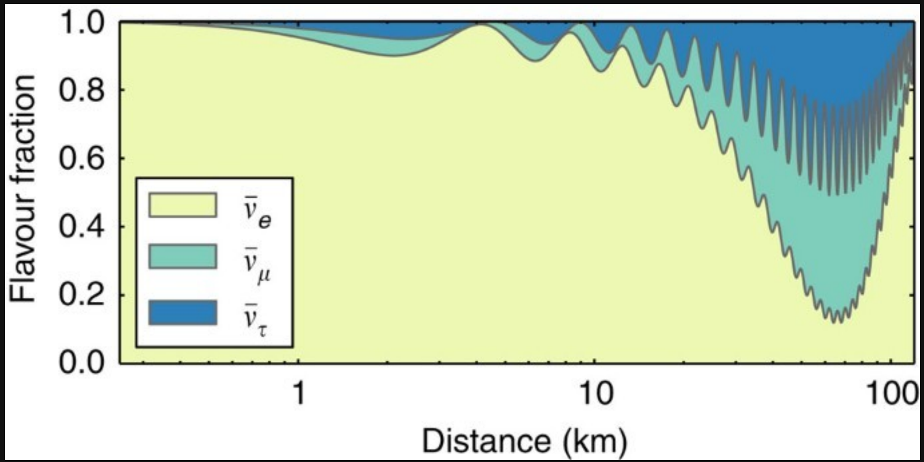
Neutrinos in the Universe



- Reactor neutrinos help study the properties of neutrinos, neutrino oscillations
- Atmospheric neutrinos: abundant at GeV-TeV energies, help study oscillations

Reactor neutrinos

- A majority of the properties of neutrinos have been studied with neutrinos from nuclear reactors
- Detectors placed at short or long distances from reactors can study different stages of oscillations of neutrinos
- Oscillations are a function of L/E (L is distance travelled and E is the neutrino's energy)
- Reactor neutrinos have ~ MeV energies, similar to solar neutrinos



E = 4 MeV

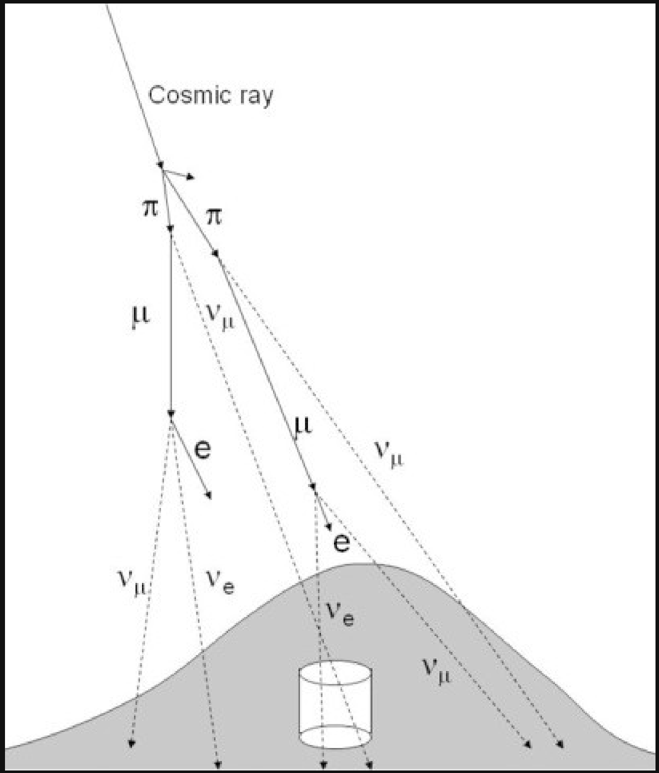
Check in

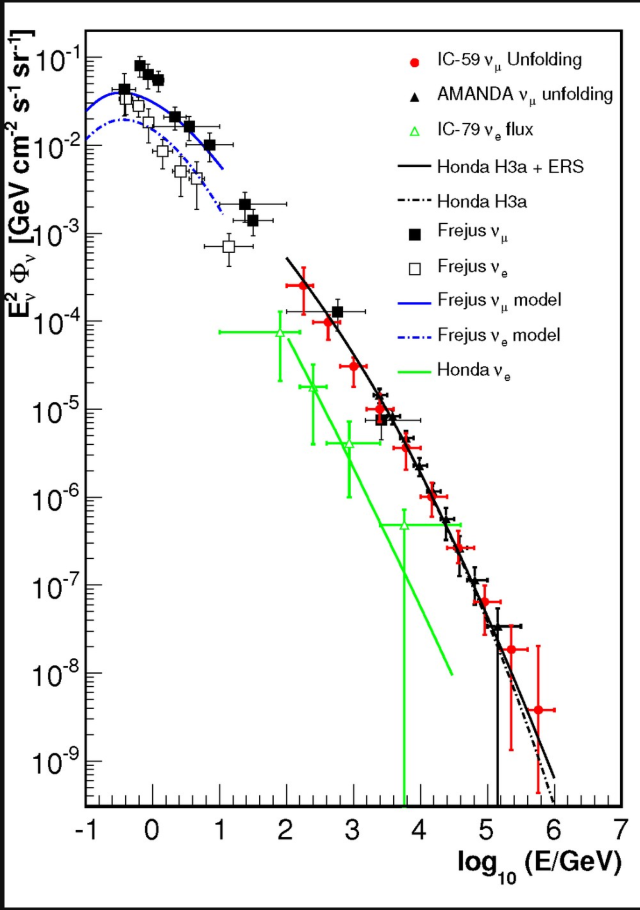
- Supernova neutrinos- confirmed astrophysical source!
- Very rare, ongoing efforts to detect the next one
- Reactor neutrinos- help determine properties of neutrinos, mixing parameters

Are you on board?

Atmospheric neutrinos

- They are produced in CR air showers
- Pions decay to muons, which further decay to produce neutrinos
- 2/3rds of atmospheric neutrinos are produced with muon flavor and 1/3rd with electron flavor

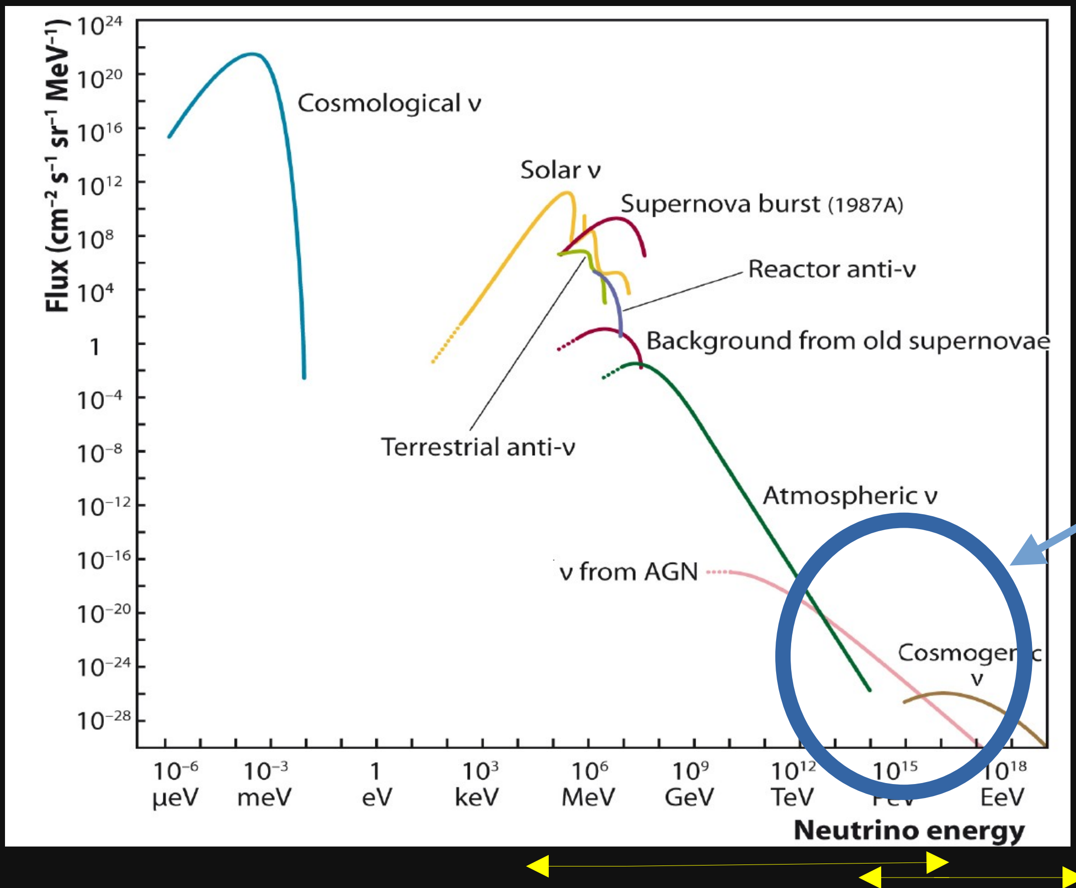




Atmospheric neutrino flux from IceCube

We will discuss atmospheric neutrinos again tomorrow

Astrophysical & Cosmogenic Neutrinos



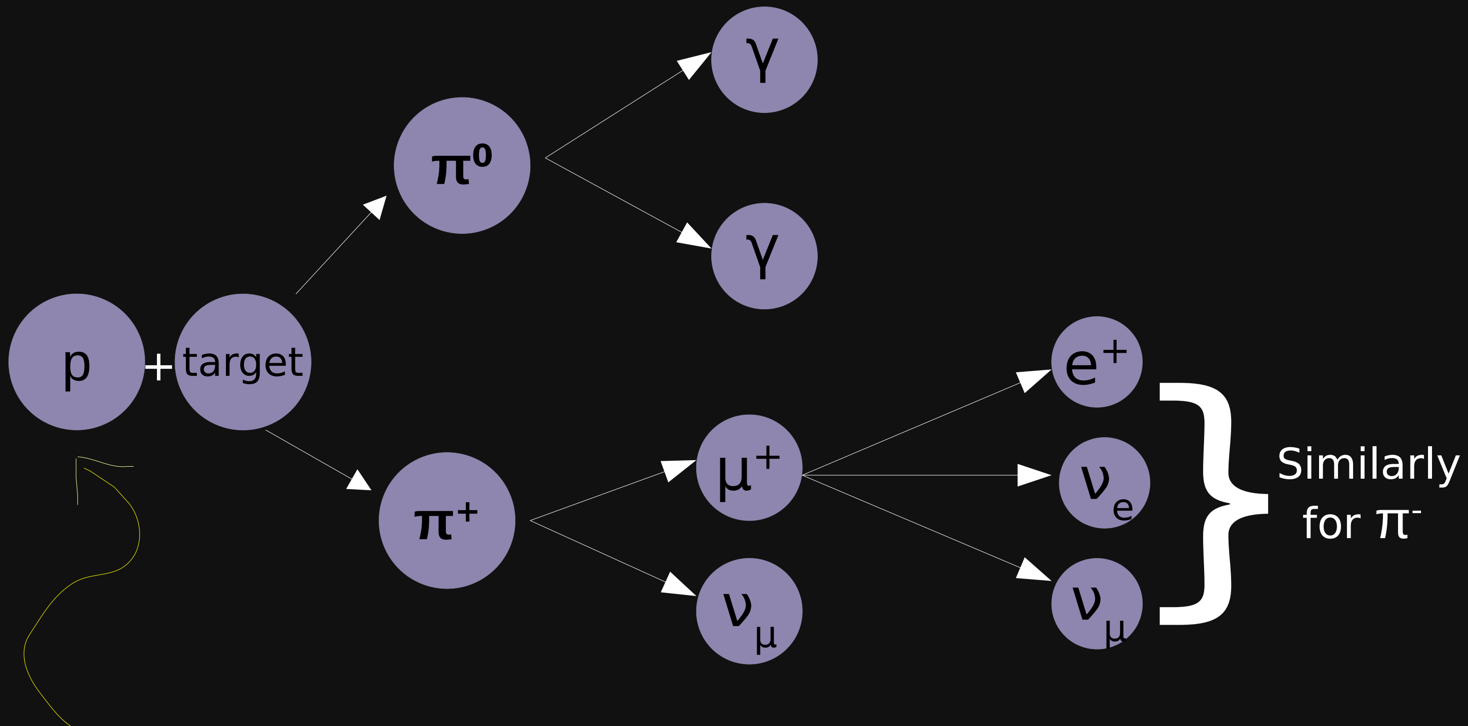
Neutrino telescopes built to observe this. IceCube discovered astrophysical neutrinos after 2 years of operation

Radio detectors

Water/ice cherenkov detectors

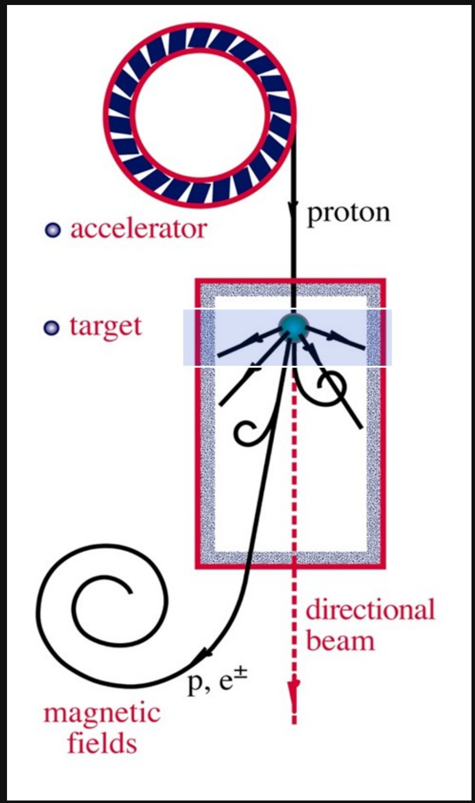
Production Mechanism of Astrophysical Neutrinos

- Neutrinos (and gamma rays) are produced by the interactions of cosmic rays with target material in cosmic accelerators
- We can use neutrinos to look for cosmic-ray sources!



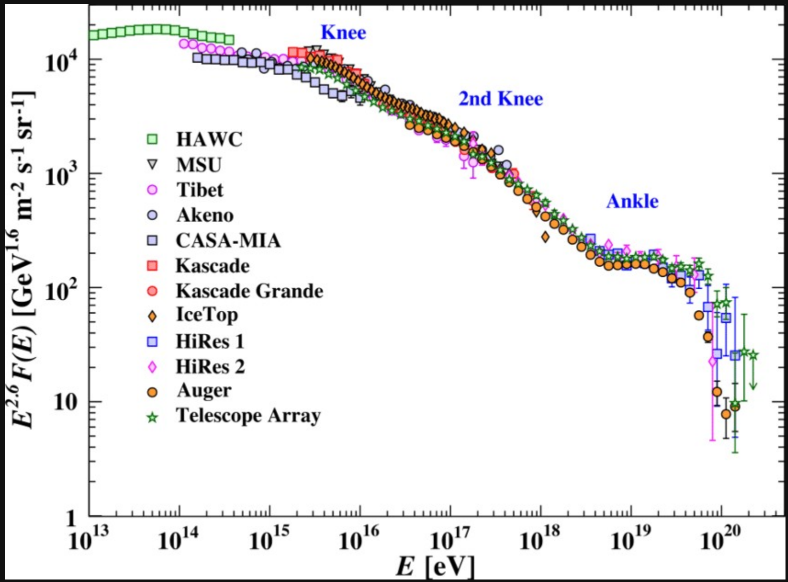
Cosmic ray

Target = p/γ



Maximum flux of extragalactic neutrinos

- Protons are accelerated in the sources according to Fermi acceleration
- Energy spectrum α $dN_{CR} / dE_{CR} \propto E^{-2}$
- Energy production rate in CRs between 10^{19} eV and 10^{21} eV is 5×10^{44} erg Mpc^{-3} yr^{-1}
- All protons undergo photohadronic interactions (pγ), producing neutrons, gamma rays and neutrinos
- The sources are optically thin to neutrons, which leave the sources and subsequently decay into protons, accounting for the UHECR flux observed at the Earth
- Energy flux of neutrinos cannot be greater than that of CR



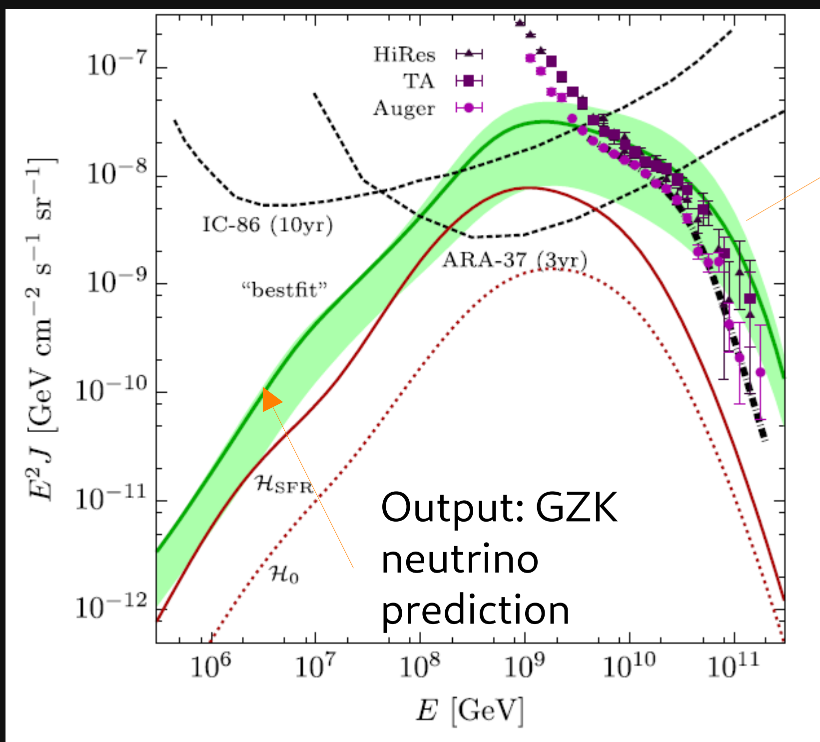
$E^2\Phi < 2 \times 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2} Waxman-Bahcall bound

Cosmogenic Neutrinos

- Neutrinos produced by the interaction of cosmic rays with CMB
- Called GZK (Greisen–Zatsepin–Kuzmin) effect

$$p + \gamma \rightarrow n + \pi^{+}\nu$$
$$\rightarrow p + \pi^{0}\nu$$

- Cosmic rays disappear, neutrinos with EeV (10 6 TeV) energy appear



Input: cosmic ray flux and CMB photons (400 cm^{-3})

Kilometer-cube volume detector needed to observe this flux!

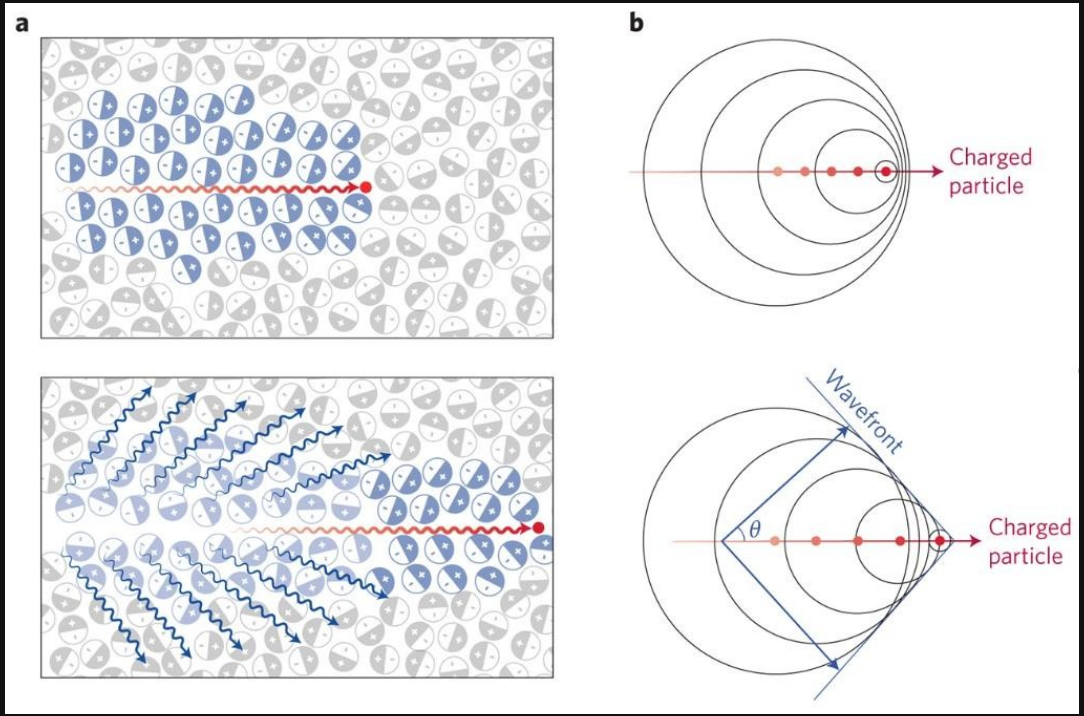
Check in

- Atmospheric neutrinos- interaction of CRs with atm
- Astrophysical neutrinos- produced by CR interactions in sources
- Cosmogenic neutrinos- interaction of CRs with CMB photons

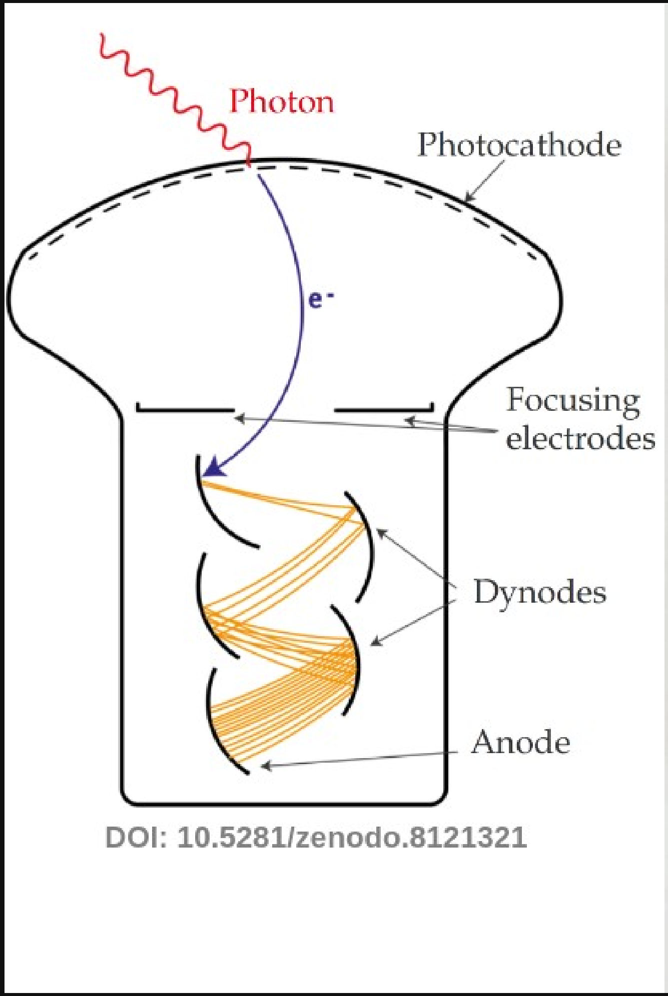
Are you on board?

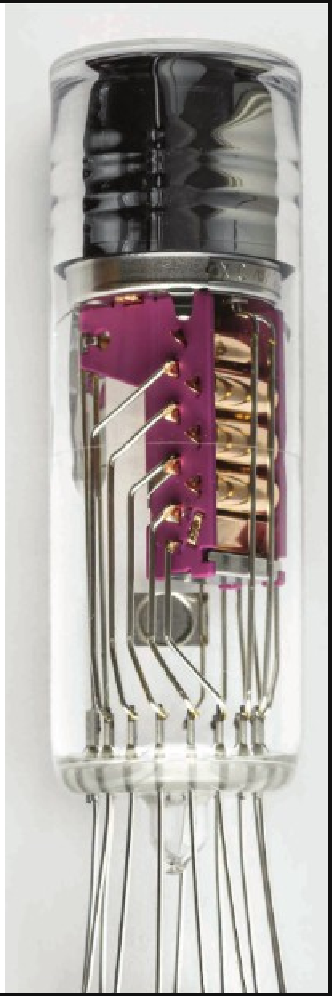
Neutrino Telescopes

- Detection done via ice or water at these energy scales
- Large transparent medium to detect Cherenkov radiation
- We use PMTs to measure the light



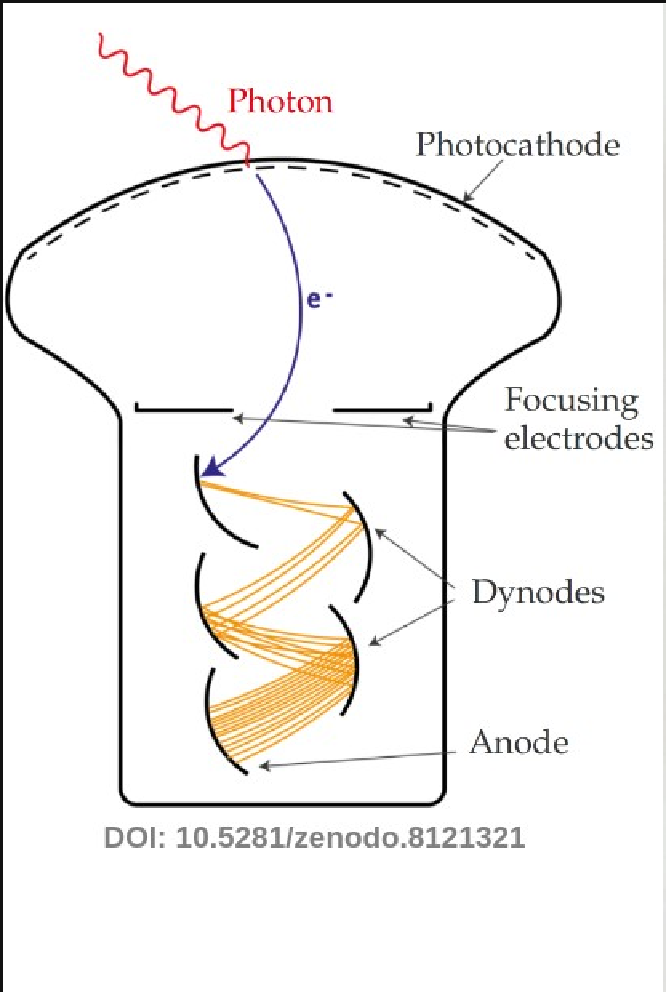
Photomultiplier Tubes (PMTs)

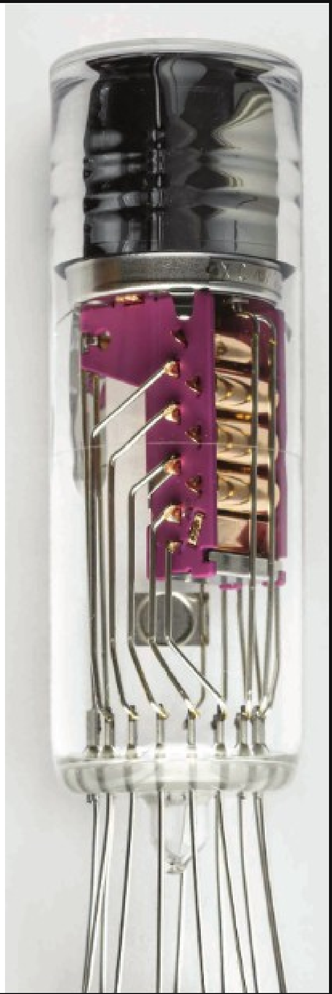




- Glass envelope with a high vacuum inside housing a photocathode
- Has several intermediate electrodes called dynodes, and an anode.
- Incident photon hits the photocathode material and electrons are produced by photoelectric effect
- Electrons are multiplied by secondary emission in the electron multiplier chain

Quantum Efficiency of PMTs

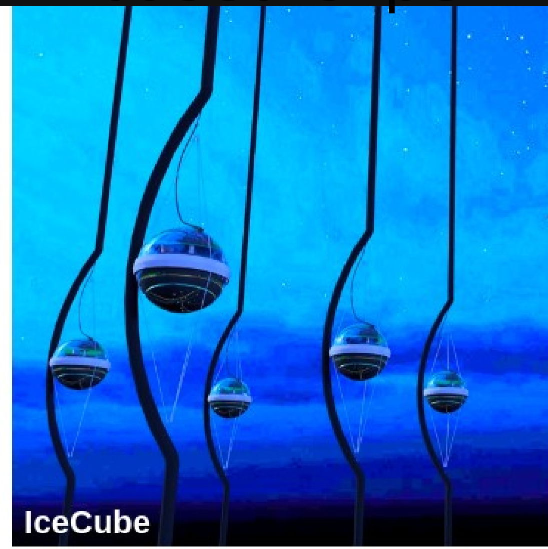




- Photocathode composition
  - Semiconductor material made of antimony (Sb) and one or more alkalai metals (Cs, Na, K)
  - Thin, so ejected electrons can escape
- Quantum efficiency $\eta(\lambda) = \dfrac{\text{Number of photoelectrons released}}{\text{Number of incident photons on cathode}}$

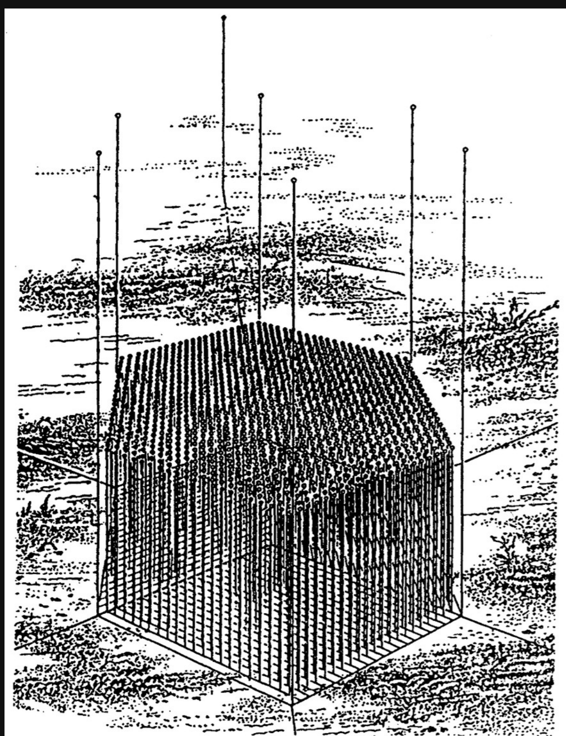
PMTs in particle astrophysics

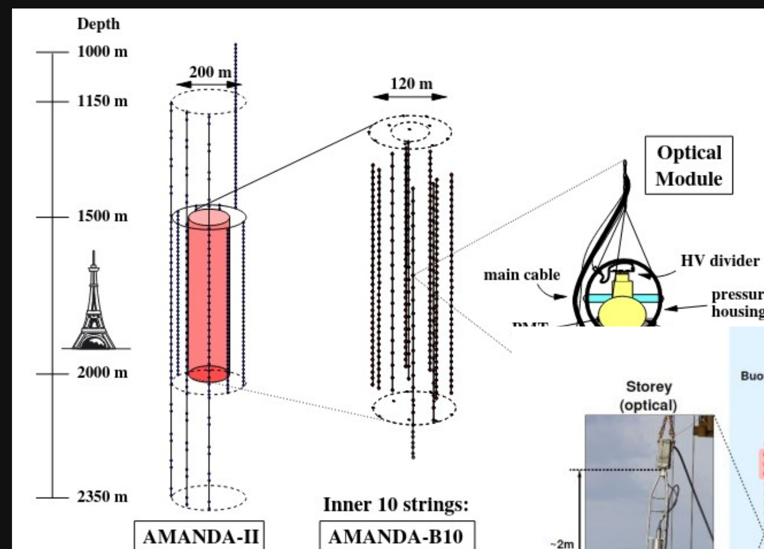
Used in most light-based experiments

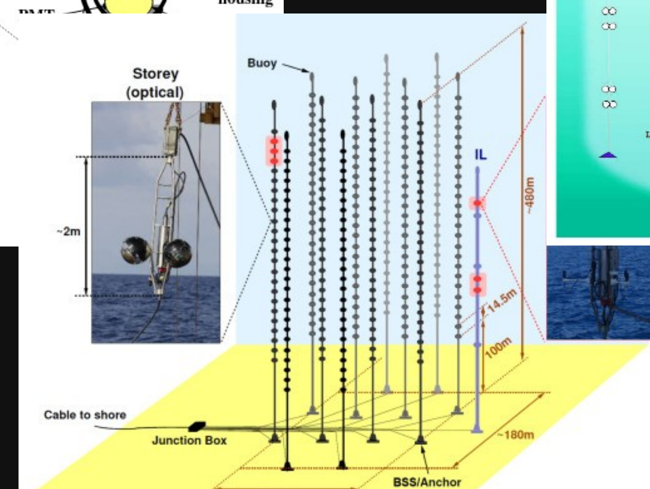


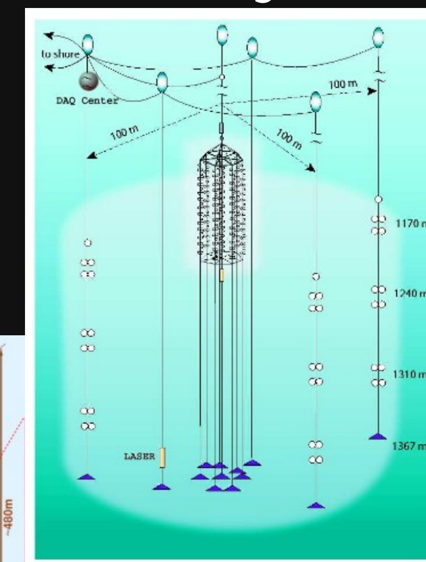
Early High-Energy Neutrino Telescopes

- DUMAND: early detector in Hawaii (80's); strings holding optical detectors proposed, cancelled project
- ANTARES, AMANDA, Baikal experiments (next generation) with strings deployed in ice/water demonstrated the principle of neutrino detection with these technologies









Lessons Learnt

DUMAND	AMANDA	ANTARES
Pioneered the concept of using deep ocean water as a Cherenkov medium — proved the basic detection principle was sound	First telescope to **successfully detect atmospheric neutrinos** from a sub km-scale medium (South Pole ice)	Confirmed that the Mediterranean deep sea (~2500 m depth) has excellent **optical clarity** — absorption lengths ~60 m, far better than Antarctic ice for some wavelengths
Demonstrated that deep-sea deployment of photomultiplier strings was **technically feasible,** though plagued by engineering failures (water leaks, cable issues)	Showed that **Antarctic glacial ice,** despite scattering from dust layers, could serve as an **effective detector medium** — but scattering lengths were shorter than hoped, limiting angular resolution	Demonstrated that **bioluminescence** backgrounds, while variable and sometimes intense, are manageable with time-filtering techniques
Established that **optical noise from bioluminescence** and radioactive decay (mainly ^{40}K) in seawater is a serious background that must be managed	Identified that **dust layers** at certain depths significantly degrade photon propagation; optimal ice depth is below ~1400 m	Showed sea-floor current and biofouling are engineering challenges but not dealbreakers
Never reached full operation, but its failures directly informed better engineering in later projects	Demonstrated that **drilling with hot water** was a practical deployment method for strings in ice	Achieved **better angular resolution** than AMANDA due to water's superior scattering properties, pointing toward KM3NeT's design
Retrieve/redeploy	Proved that IceCube was worth building	Detected atmospheric neutrinos, proved that KM3Net was viable

Lessons Learnt

- Different challenges for ice vs water
- Atmospheric muon rates, deeper detectors lowers the background
- Deployment technology (drilling, underwater cables)
- ~0.01 km^3 is insufficient to detect astrophysical neutrinos; ~1 km^3 is the minimum viable scale
- Both ice and water work; water wins on scattering/angular resolution, ice wins on stability and noise floor
- Atmospheric muons and neutrinos dominate
- Pressure housings, connectors, and long-term reliability in extreme environments are as important as physics design
- Upper limits from all confirmed the neutrino sky is faint — require large exposures

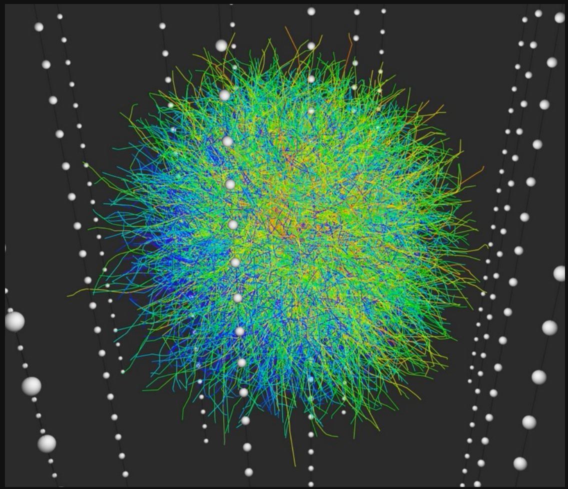
Check in

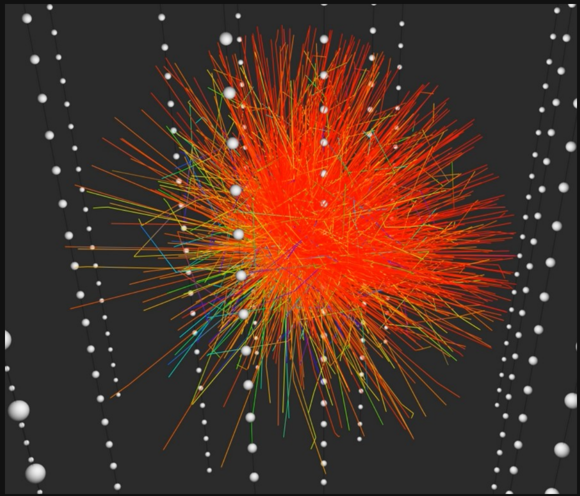
- Neutrino telescopes use Cherenkov light for detection
- Measurements with PMTs
- Early experiments helped establish basic principles needed for detection

Are you on board?

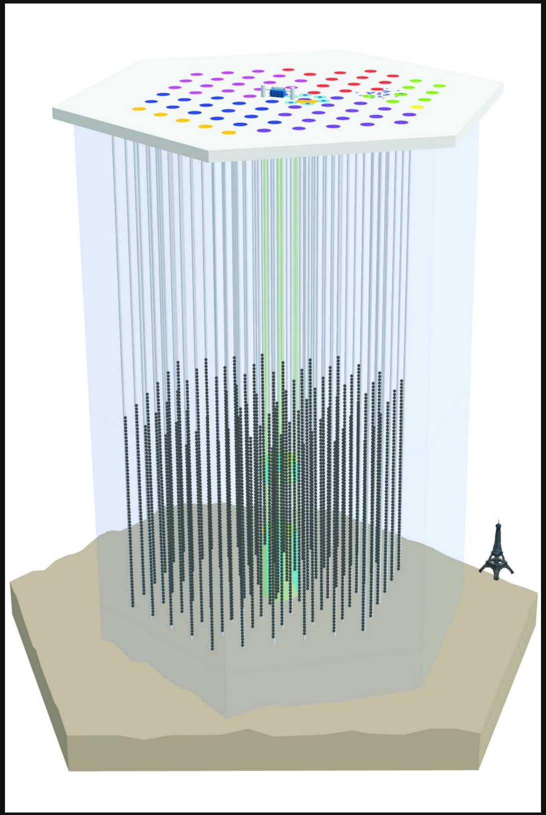
Ice vs Water

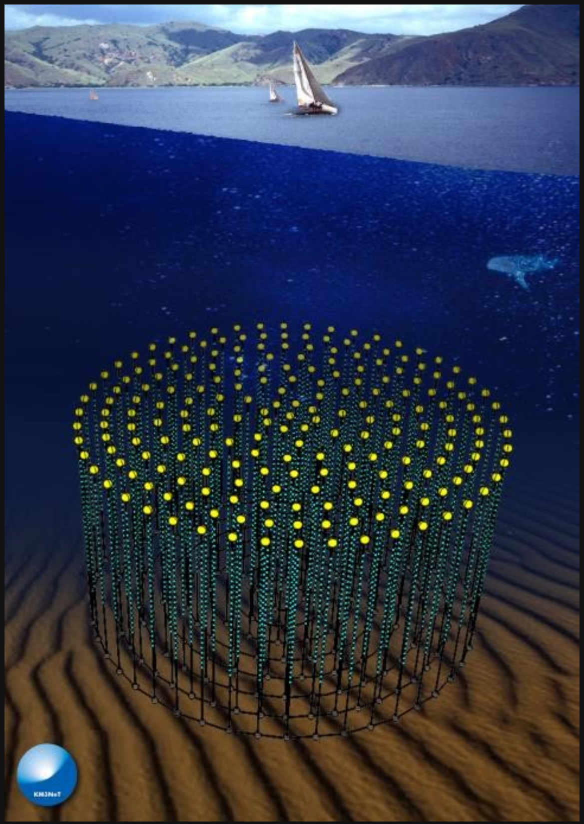
Property	Lake Baikal (water)	Mediterranean (water)	Antarctica (ice)
Absorption length (m)	22	60	100
Effective scattering (m)	480	265	25
Depth	1370	2475	2450
Noise	Quiet	^{40}K, bioluminescence	Quiet
Retrieve/redeploy	Yes	Yes	No

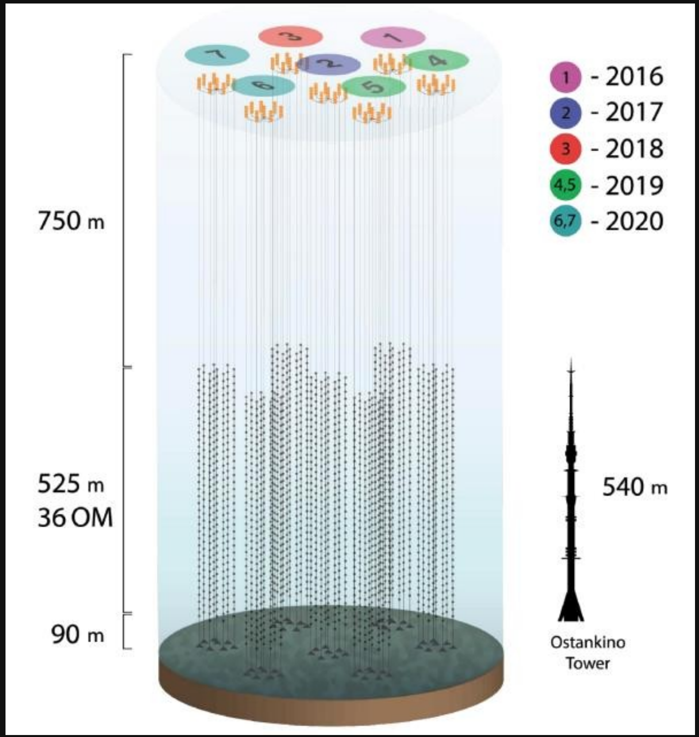




High-Energy Neutrino Telescopes







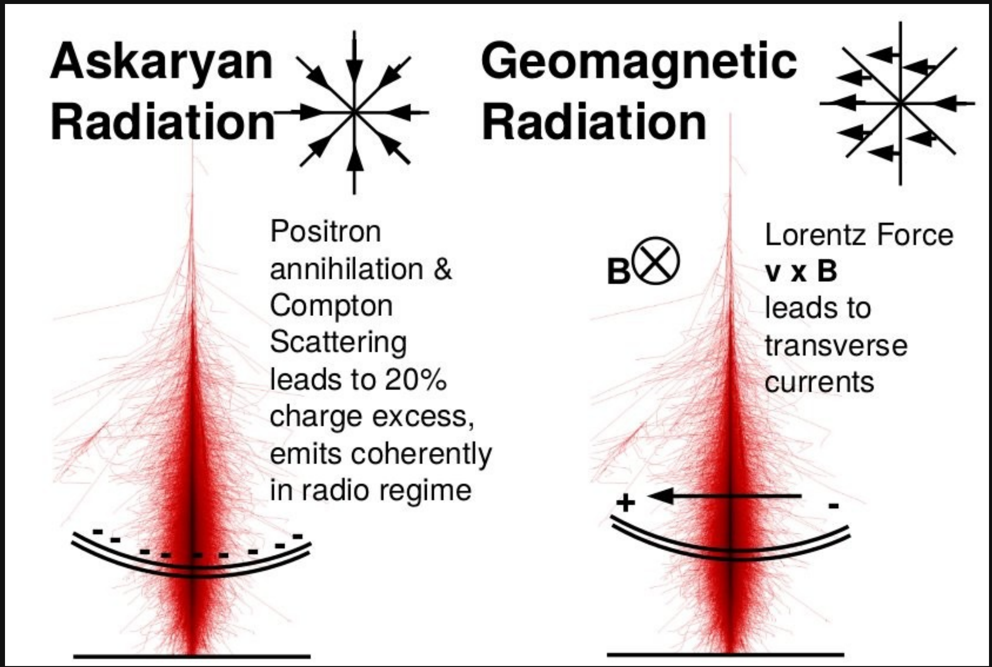
IceCube; operational 1 km^3
IceCube-Gen2; planned 8 km^3

KM3Net; under construction
2 x 0.5 km^3
ARCA for HE and ORCA for LE

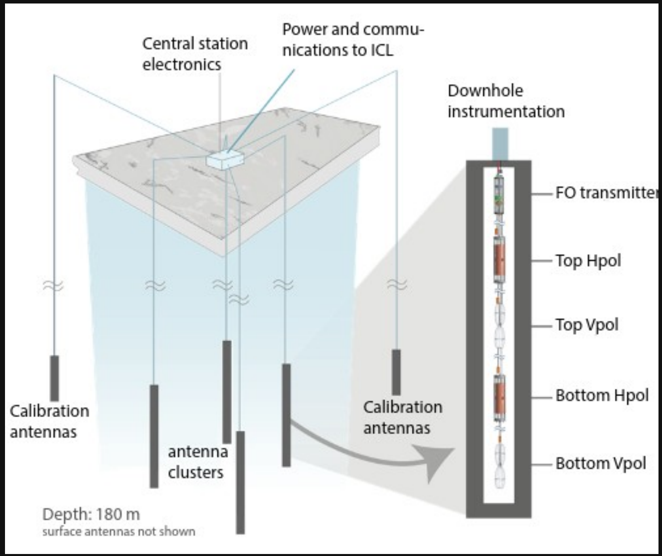
Baikal-GVD; under construction 1 km^3

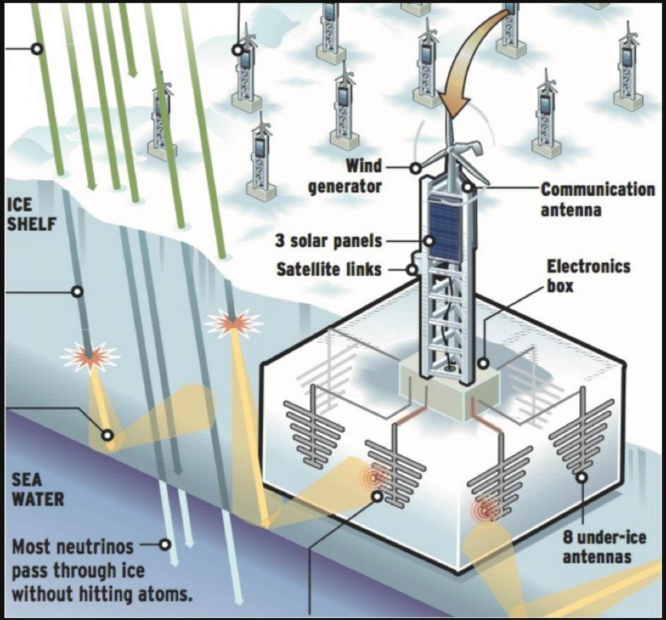
Ultra High-Energy Neutrino Telescopes

- At extremely high energies, optical detectors are no longer efficient for neutrino detection
- Radio detectors (technology tested with air shower detectors) can enter here
- Only Askaryan emission in ice; air shower-based radio neutrino detectors rely on geomagnetic emission



Radio Neutrino Telescopes





ANITA (1-4); first flight 2006
Over 1 million km^3 of ice visible

ARA; deep-ice radio antennas

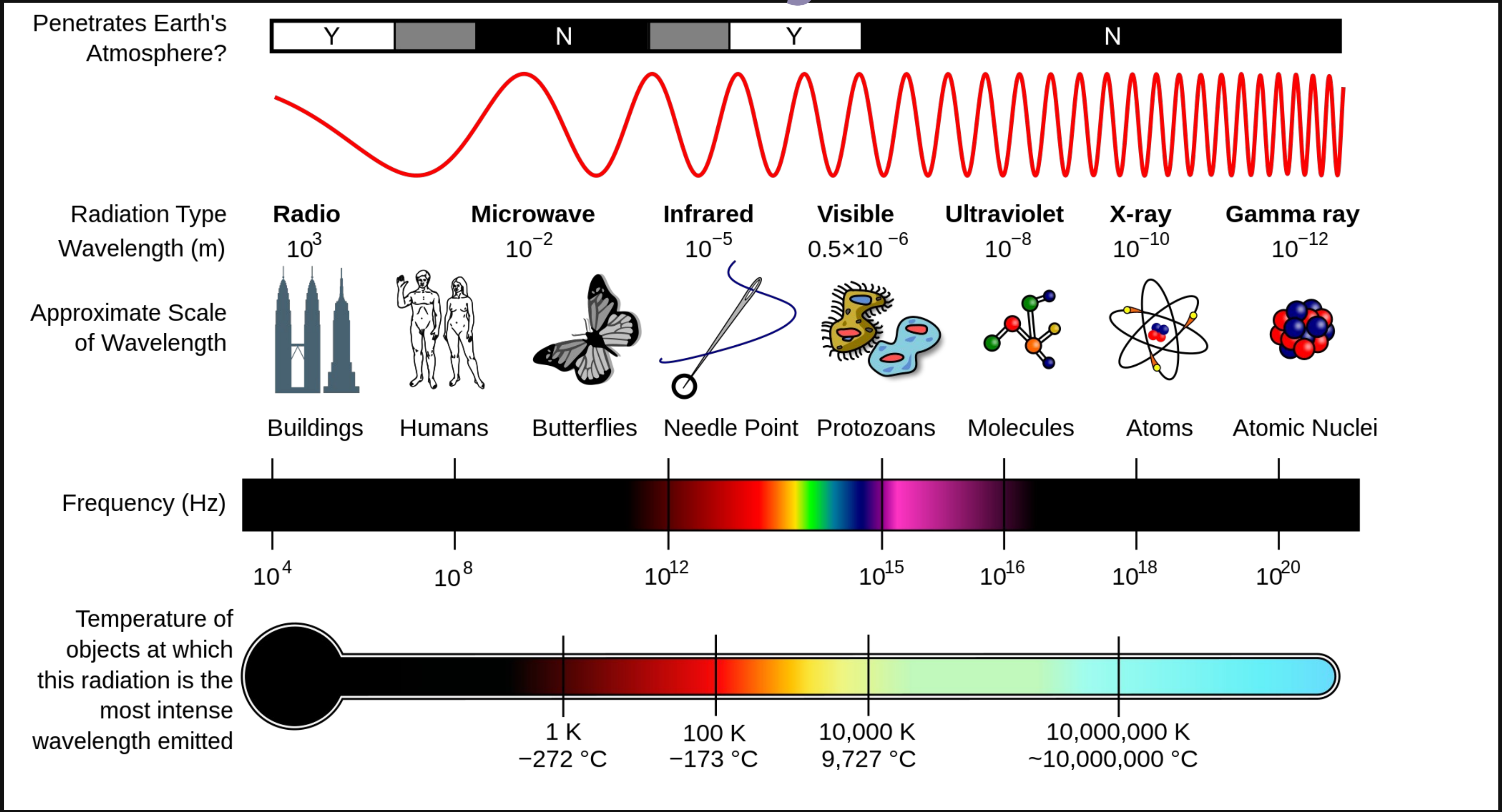
ARIANNA: Shallow-ice radio detectors

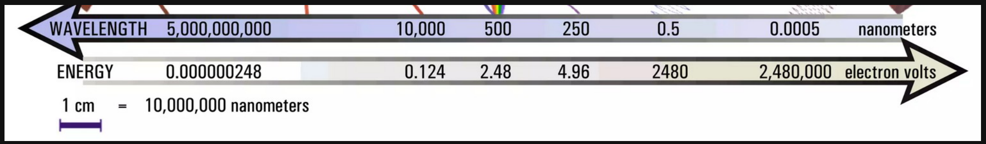
Take Home Messages

- Sources of cosmic rays can also be sources of photons and neutrinos
- Can use multiple messengers to understand astrophysical sources
- Remaining questions:
  - A majority of the observed cosmic rays and neutrinos have unknown sources. What exactly are these?
  - How are the produced?
  - How does the Universe accelerate particles to such extreme energies?
- Neutrino sources from lowest to highest energies, and how to detect them

Backup

Photons/ Electromagnetic radiation

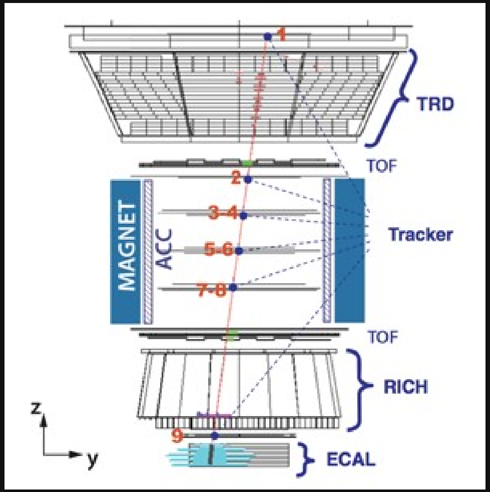




We have spent decades looking at astrophysical sources with photons

Cosmic-ray detection

- At lower energies, we need only small detectors due to high fluxes
- We use space-based experiments for low-energy detection
- Space experiments use direct detection techniques
- At high energies, low fluxes means large detectors
- We use ground-based experiments
- Ground experiments use indirect detection techniques



Example: AMS experiment on the International Space Station (ISS)