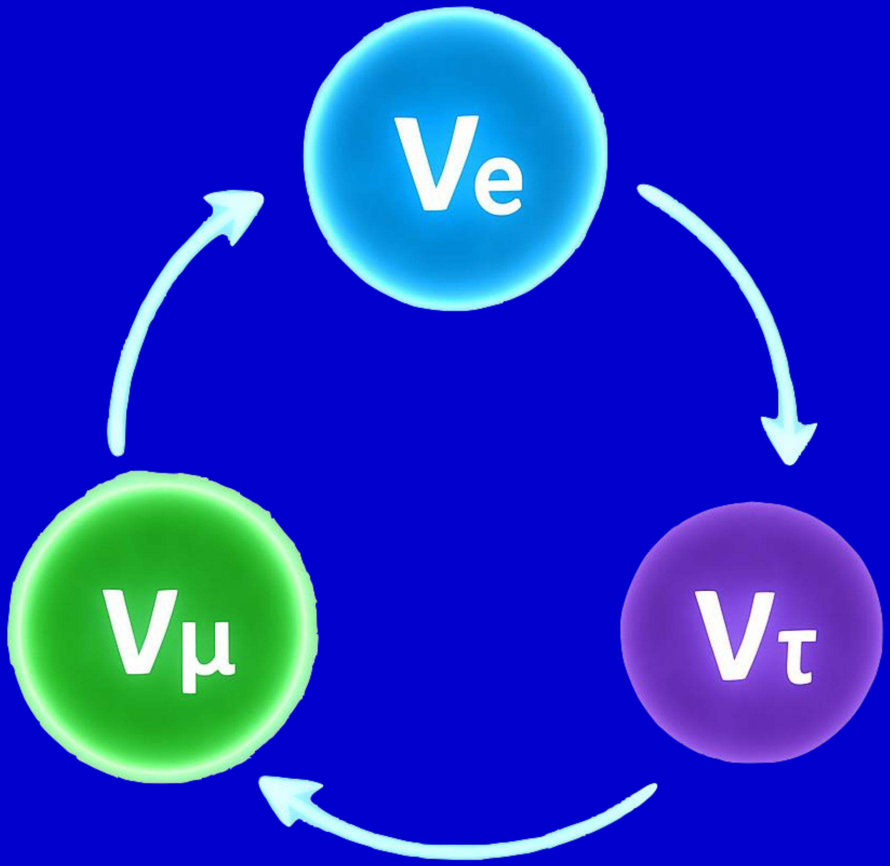
IMPERIAL

Neutrinos

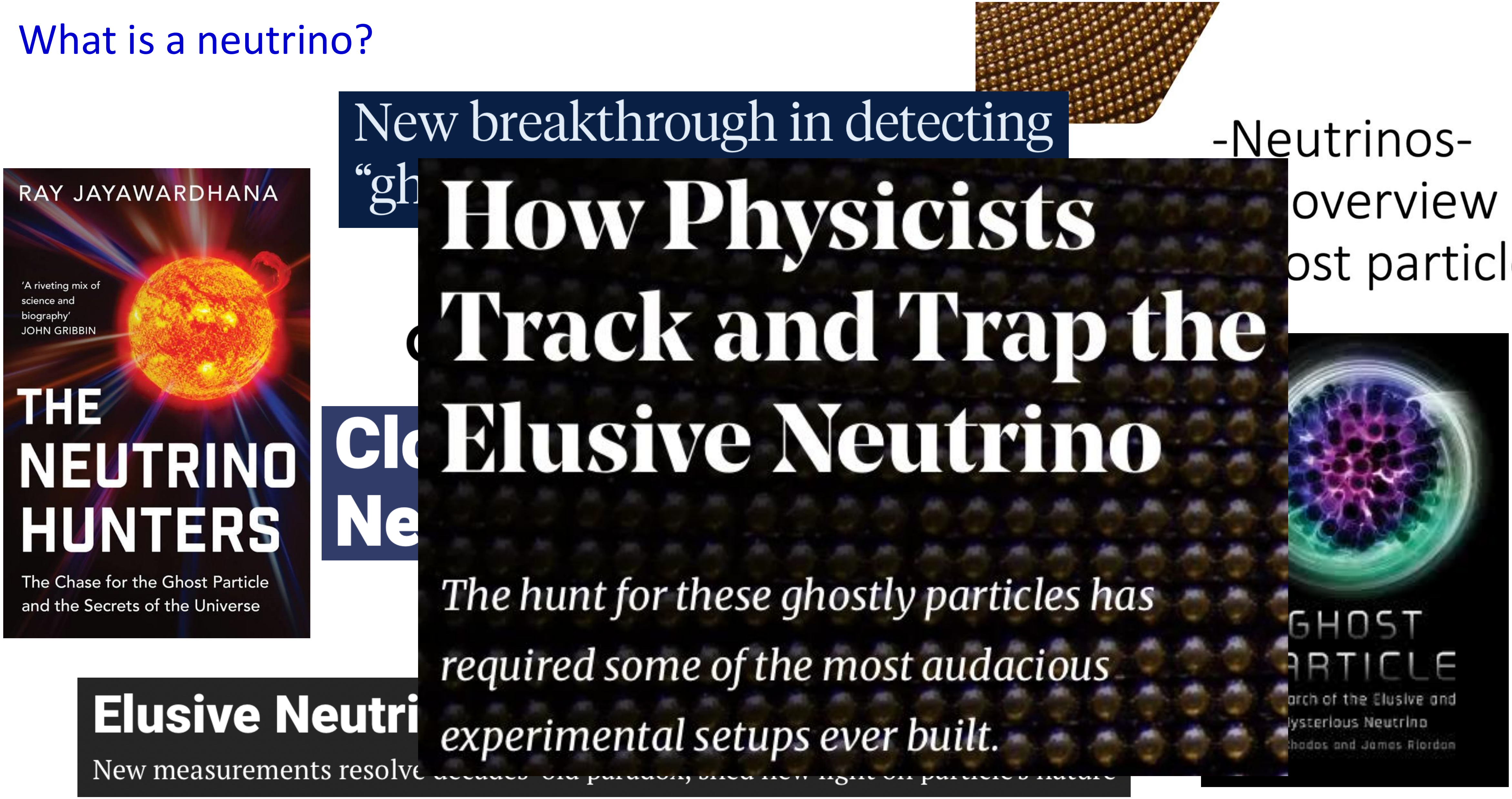


Anyssa Navrer-Agasson
Imperial HEP Masterclass - 17/07/2026

What we know

What is a neutrino?

-Neutrinos-
overview of
ost particle'.

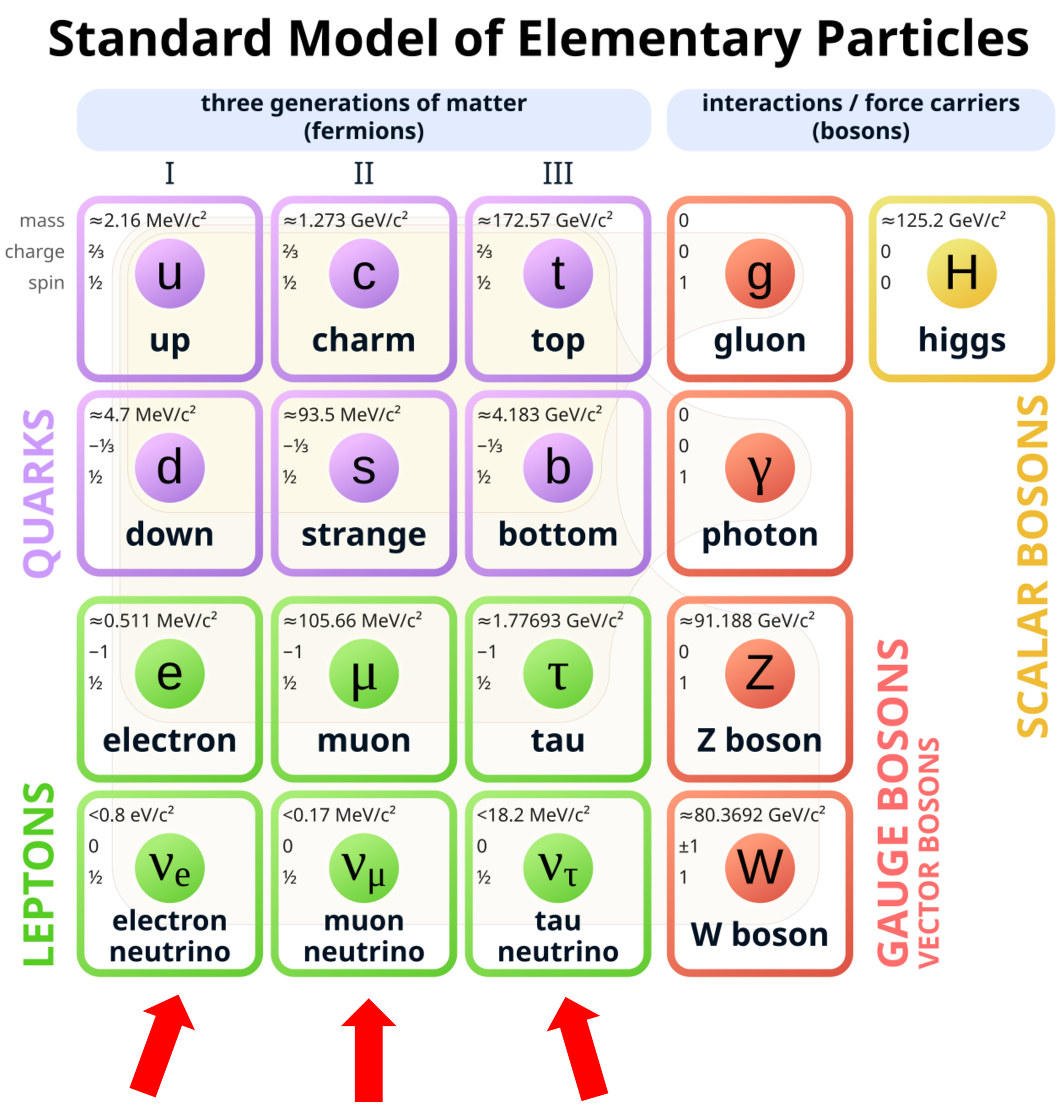


What is a neutrino?

- It's a particle, part of the standard model
- There are three types (flavours) of neutrinos

  Each associated with a specific lepton
- They are neutral (no electric or colour charge)
- Only interact via weak force (and gravity)
- Produced in nuclear processes
- There are **A LOT** of them:

  ~65 billion pass through every cm^2 of your body every second!



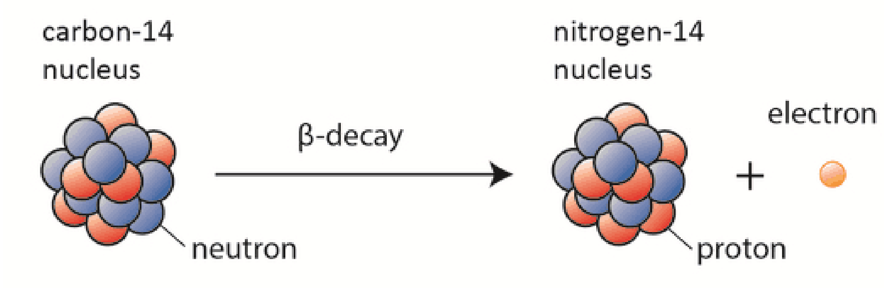
A little history
How did we even figure out neutrinos existed?

Meitner & Hahn

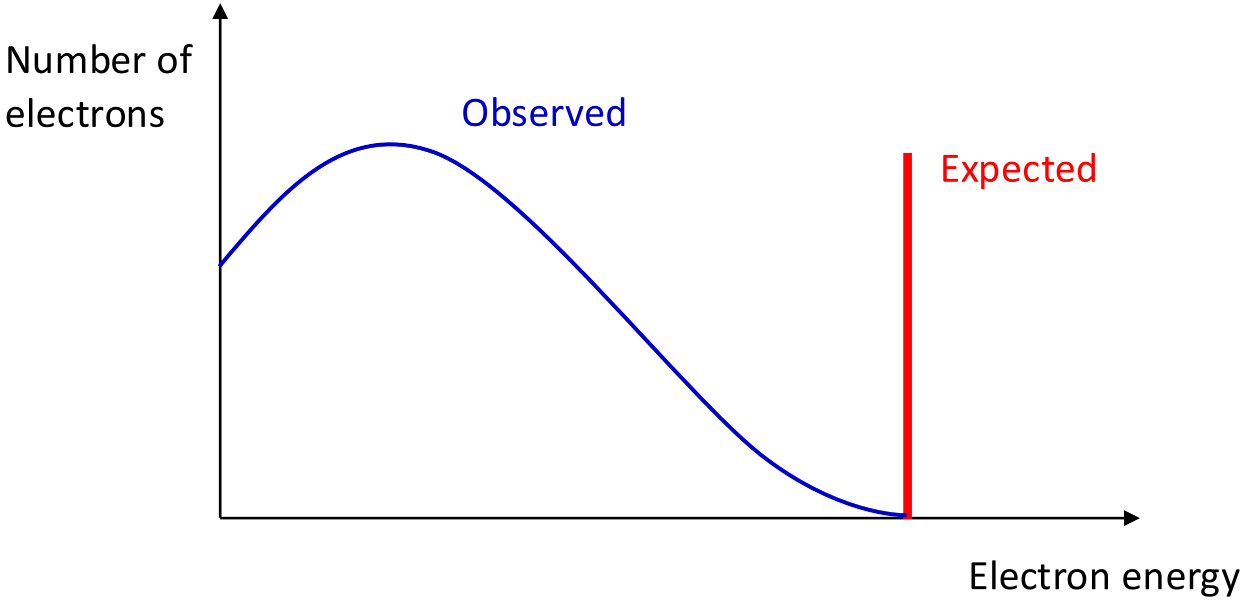
Ellis

Chadwick

- Story begins with beta decays



Neutron transforms into a proton, emits an electron



Conservation of energy

→ daughter nucleus mass + electron energy = parent nucleus mass

→ electron carries away the “missing mass”

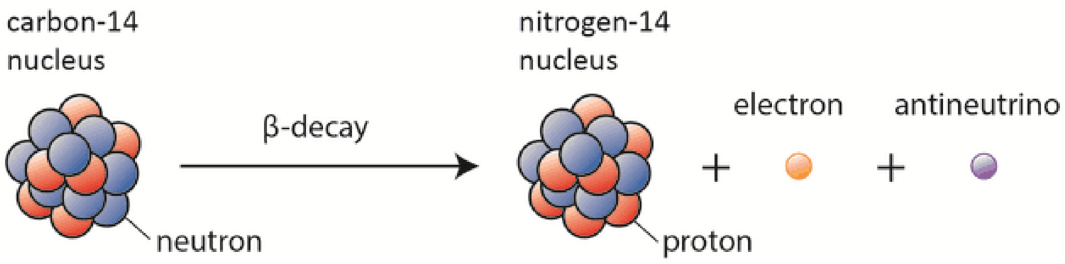
→ electron has a fixed energy for each atom

How do we explain this?!

A little history

Two solutions:

- Throw energy conservation out the window
- Beta decay is a 3-body decay and there's something else we didn't see!



Correct beta decay

Wolfgang Pauli

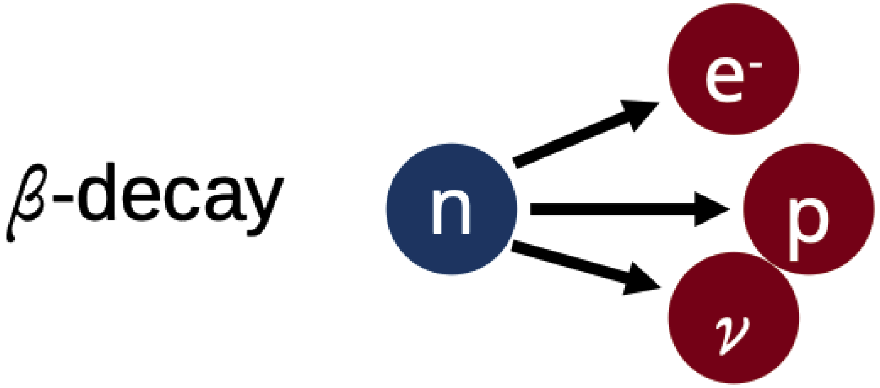
"I have done a terrible thing: I have postulated a
particle that cannot be detected. "

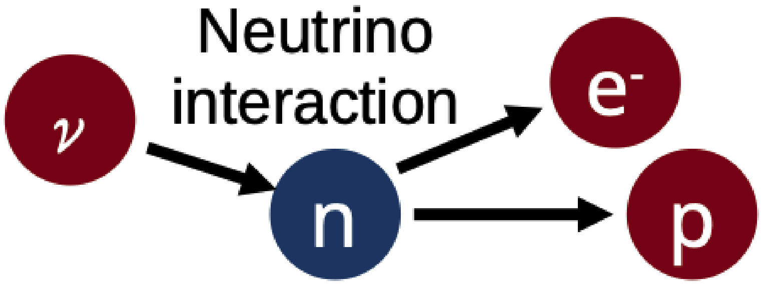
How to catch a neutrino

As we've said before, neutrinos do not interact much with anything

- 1 light-year of lead would have a 50% chance to stop a neutrino.

In 1934, Enrico Fermi wrote a mathematical description of the β-decay with a neutrino





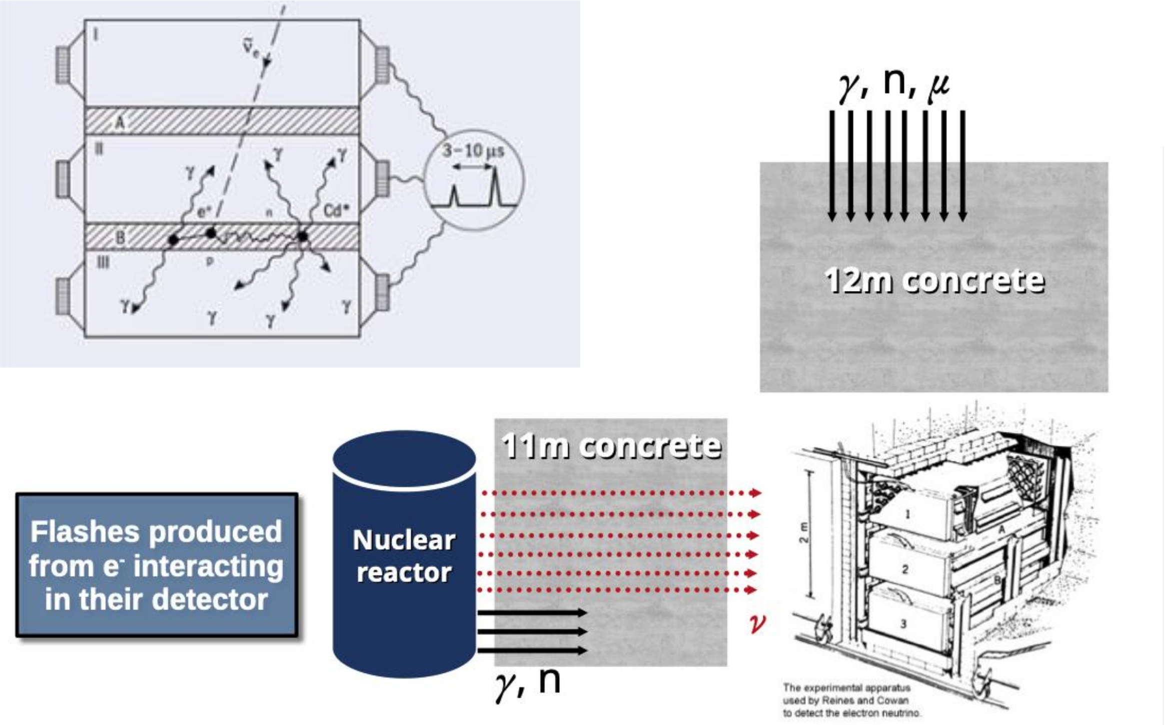
- Able to infer the neutrino interaction probability from properties of β-decay
- Neutrinos can create charged, detectable particles

How to catch a neutrino

How do you detect a particle that nearly never interacts?
By creating a lot of them!!

What creates a lot of neutrinos?
Nuclear reactors!!

Brilliant idea:
Rely on the -decays of uranium isotopes in nuclear reactors to observe the first neutrinos



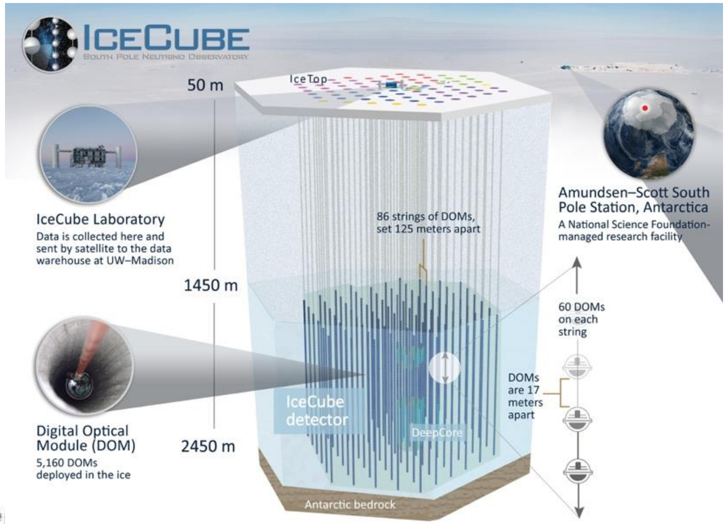
In 1956, Reines & Cowan put a detector near a nuclear reactor (Savannah River experiment)
What they saw:

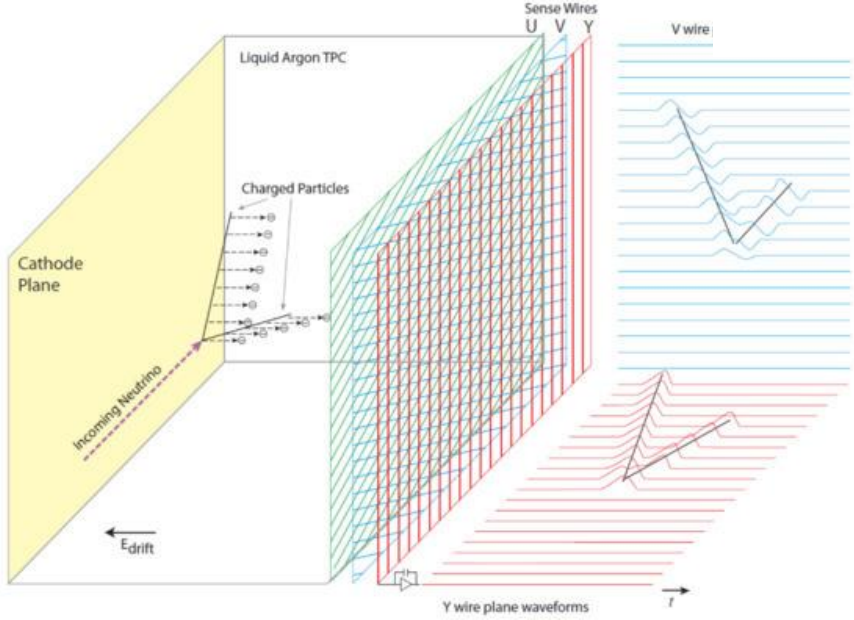
- Reactor ON: flashes
- Reactor OFF: no flashes

Discovery won the Nobel prize in 1995

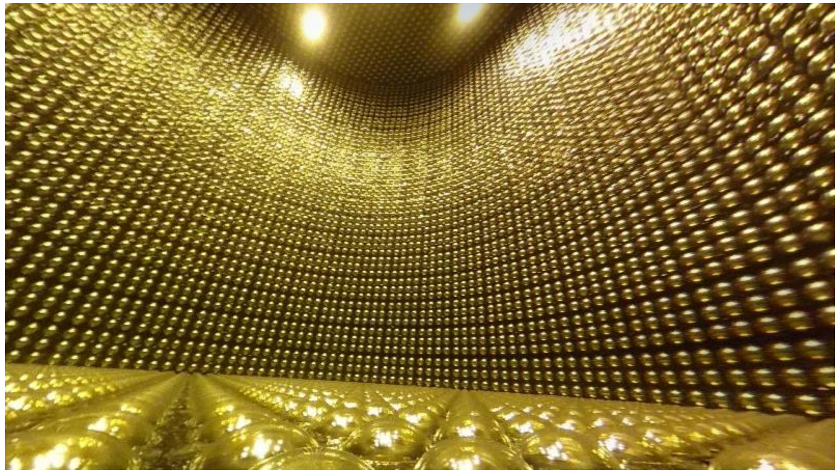
How to catch a neutrino

Modern detectors





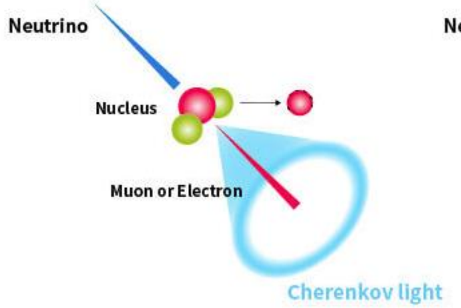
Common feature: they are very large!

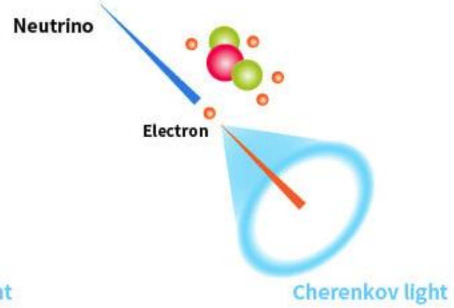


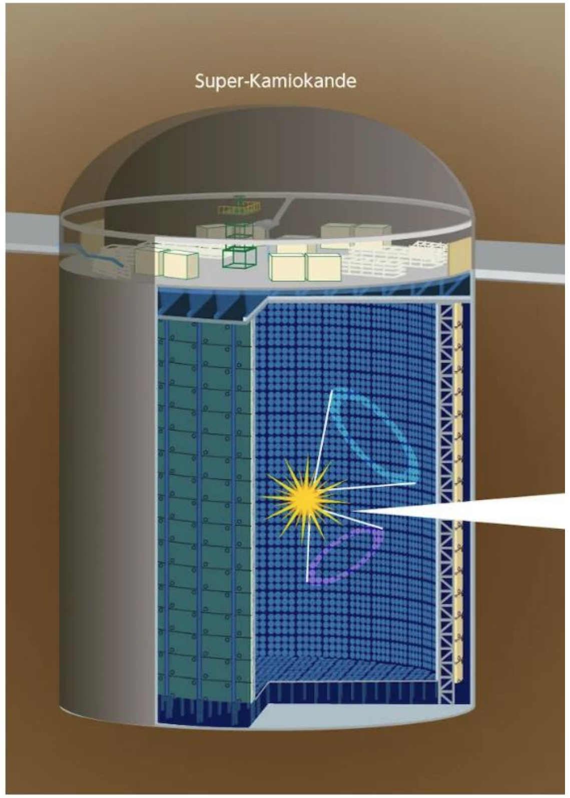
How to catch a neutrino
Modern detectors

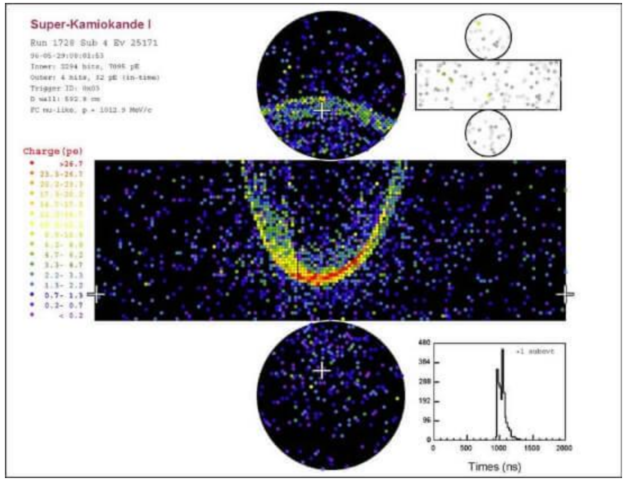
Water Cherenkov detectors

Principle:
- Large ultra pure water tank
- When a charged particle traverses the water, Cherenkov light is emitted
- Then collected on photon detectors placed on the walls

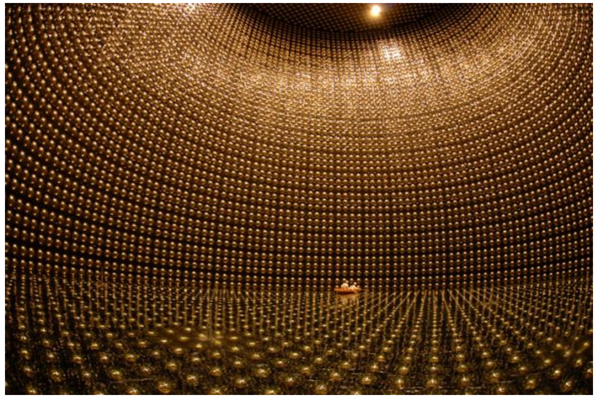








Example: **Super-Kamiokande**
- Located in Japan
- 50, 000 tons of water



Anybody here watched
The three-body problem?

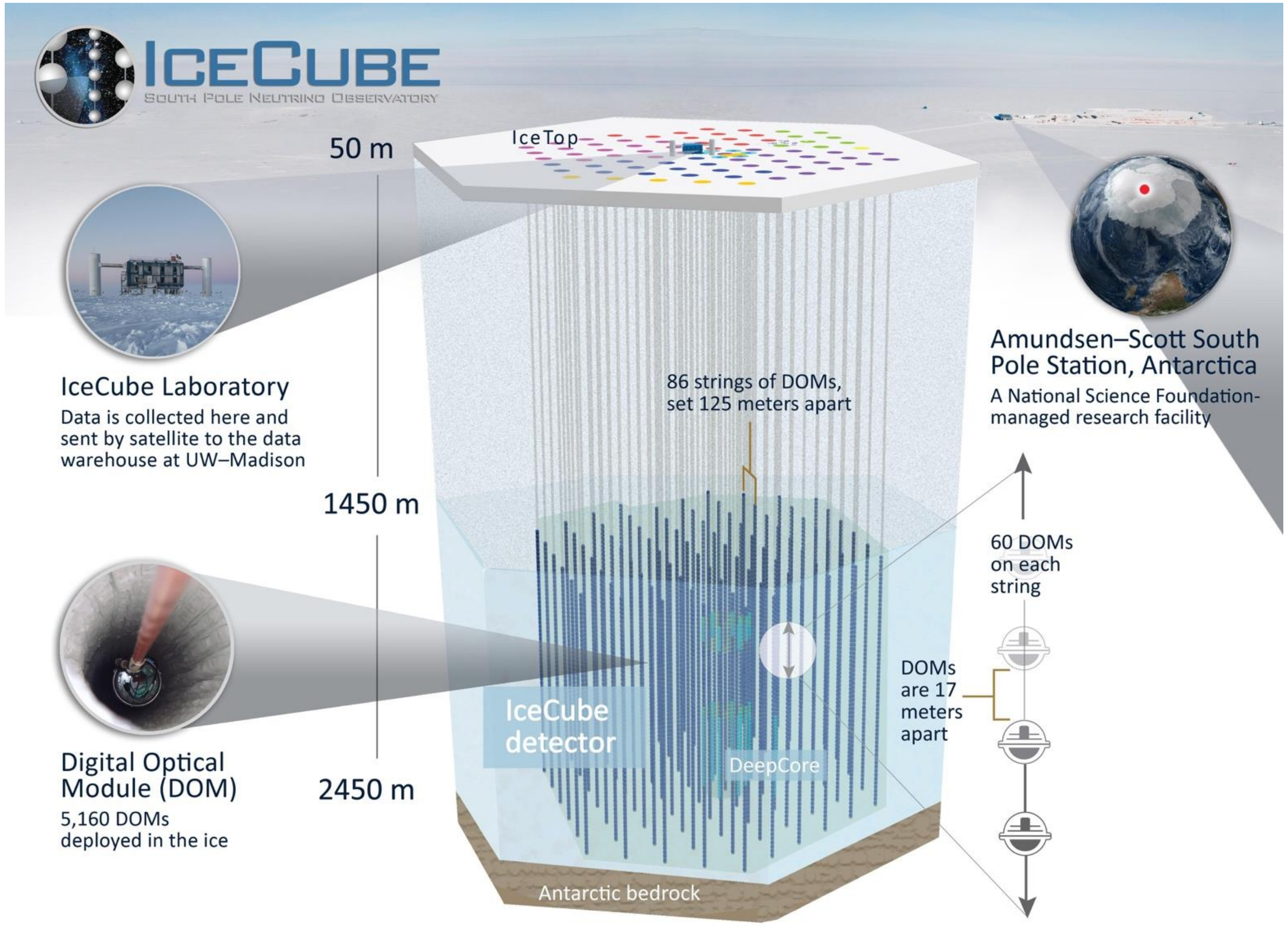
How to catch a neutrino
Modern detectors

"Natural" detectors

Principle:

- Instead of a water tank, put light detectors into large bodies of water/ice

- Same detection principle as before

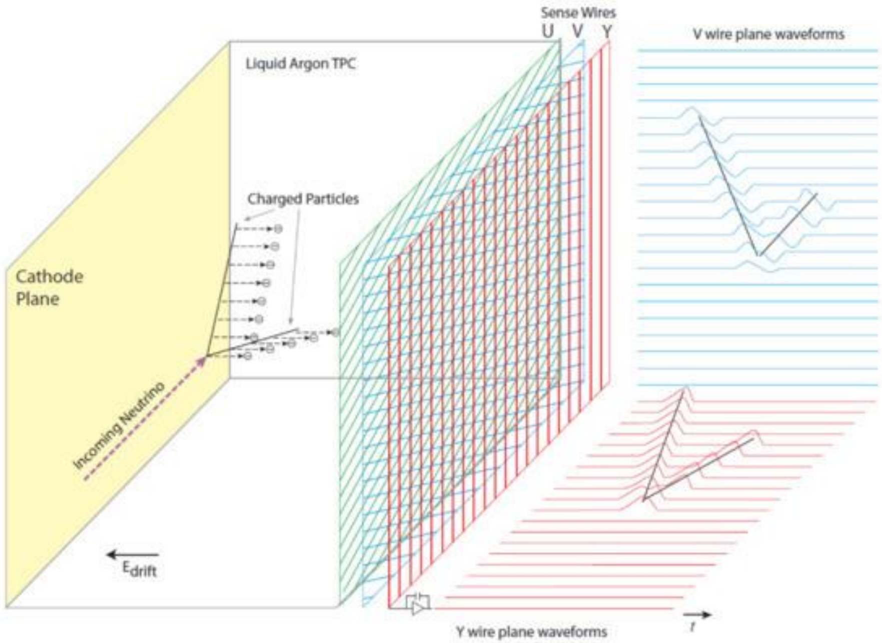


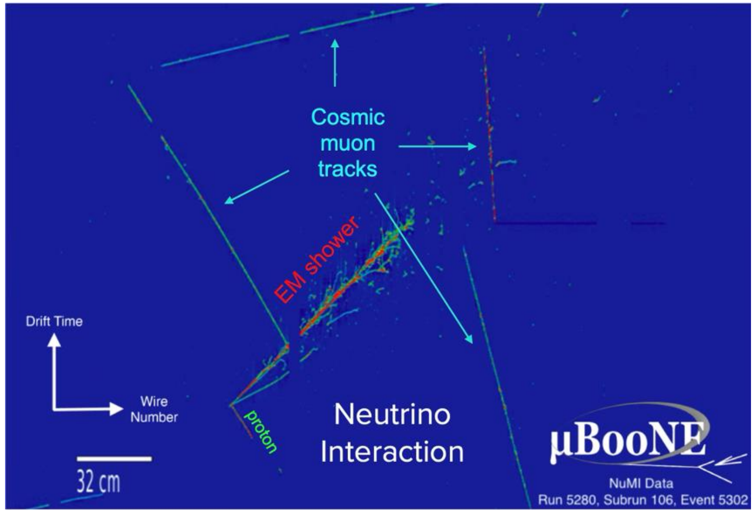
Example: **IceCube**

- Located at the South Pole
- Spans roughly 1 square-kilometer

How to catch a neutrino
Modern detectors

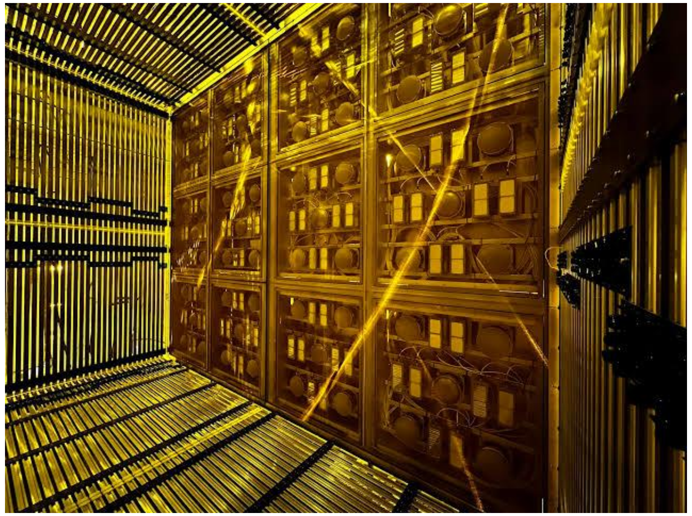
Liquid argon time projection chambers
(LArTPCs)





Principle:

- Large tank of liquid argon with ambient electric field
- When charged particles cross the medium, they create secondary electrons
- Electric field drifts the electrons to an anode place where they are collected

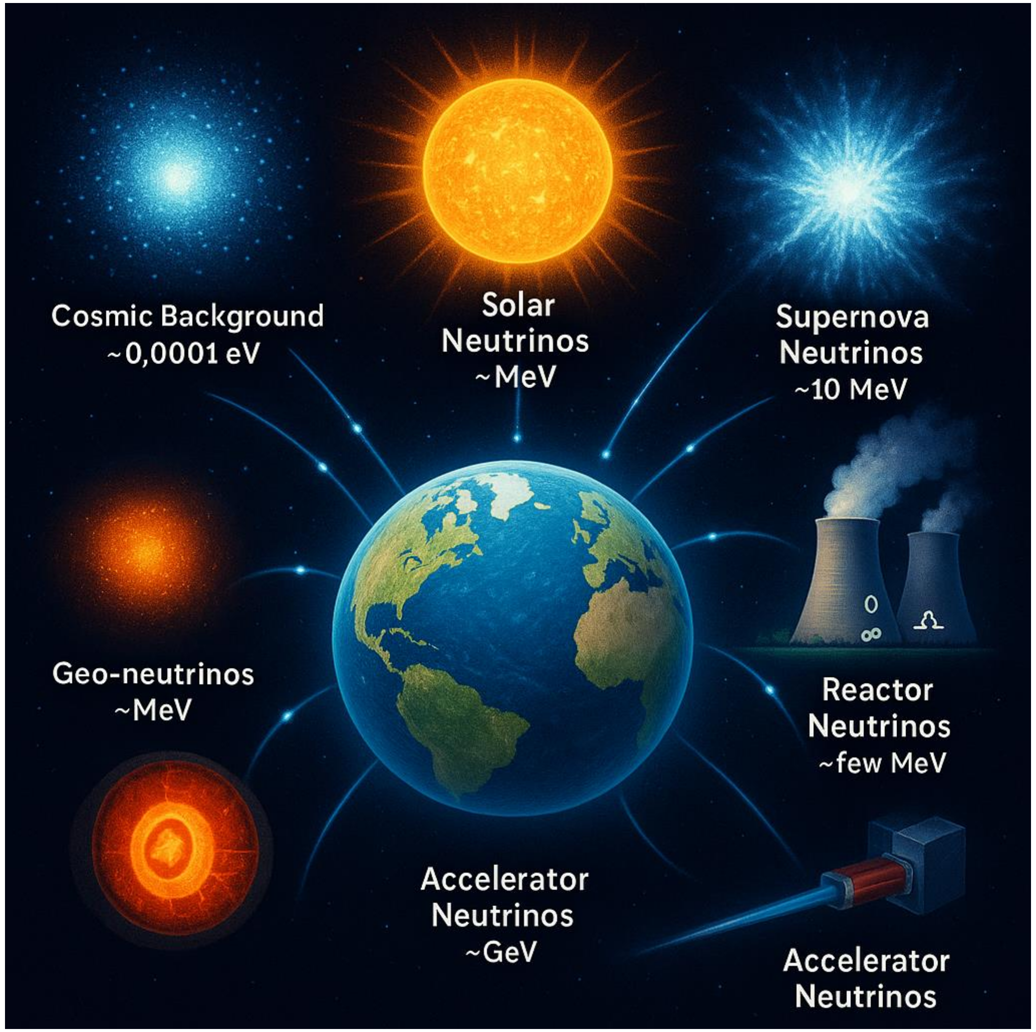


Example: **SBND**

- Located at Fermilab (USA)
- 112 tons of argon

Where do they come from?

- Already talked about nuclear reactors!
- Cosmic Microwave Background is the largest source, but extremely low energy
- Earth has many unstable materials with decays involving neutrinos
- Cosmic ray interactions in the atmosphere also create neutrinos
- We've learned how to make very intense neutrino beams from particle accelerators
- Now let's talk a little bit about the Sun!



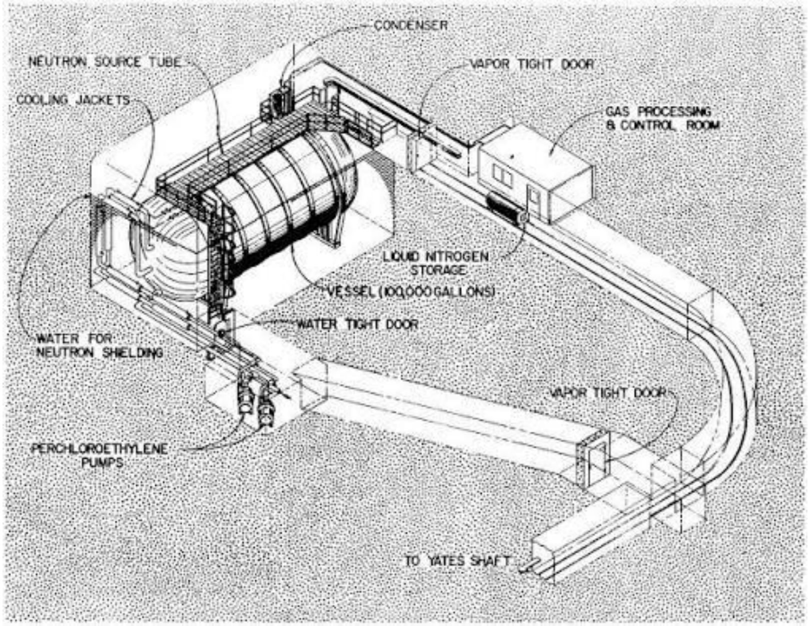
Neutrino Mystery nº1
The missing solar neutrinos

- In the 60, the Homestake experiment tried to detect electron neutrinos from the Sun.

- Problem: only saw 1/3 of what model of the Sun's nuclear reactions predicted?

- **Where are the missing neutrinos?**
  Is the solar model wrong?

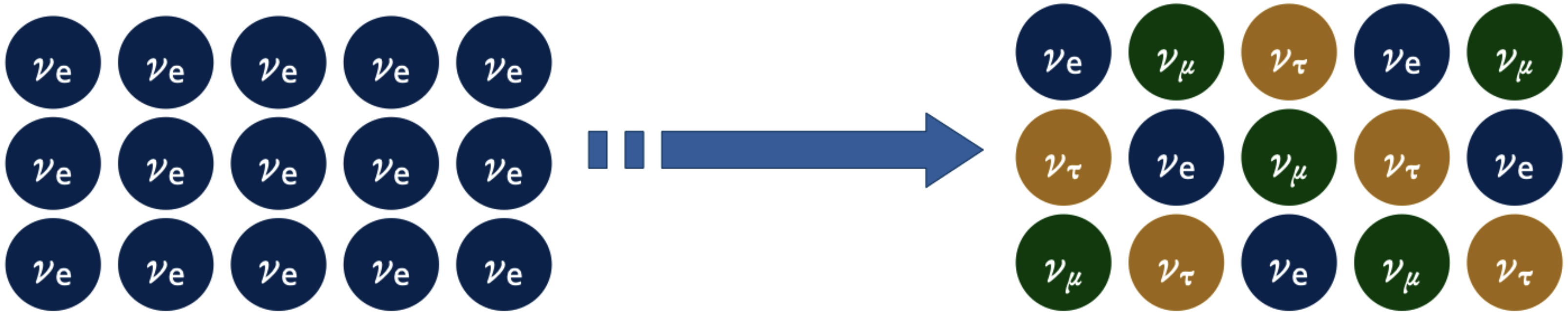
- Actual explanation is much weirder!



Neutrino oscillations

2015 Nobel Prize for discovery of Neutrino Oscillations!

- It turns out neutrinos can change flavour as they travel!



- The process is called **neutrino oscillation**

- In the 90s, experiments that could count the 3 flavours of neutrinos were built
  - And they saw the correct number of neutrinos!

- **Tells us that Neutrino mass ≠ 0 !**

Neutrino oscillations

How do they work?

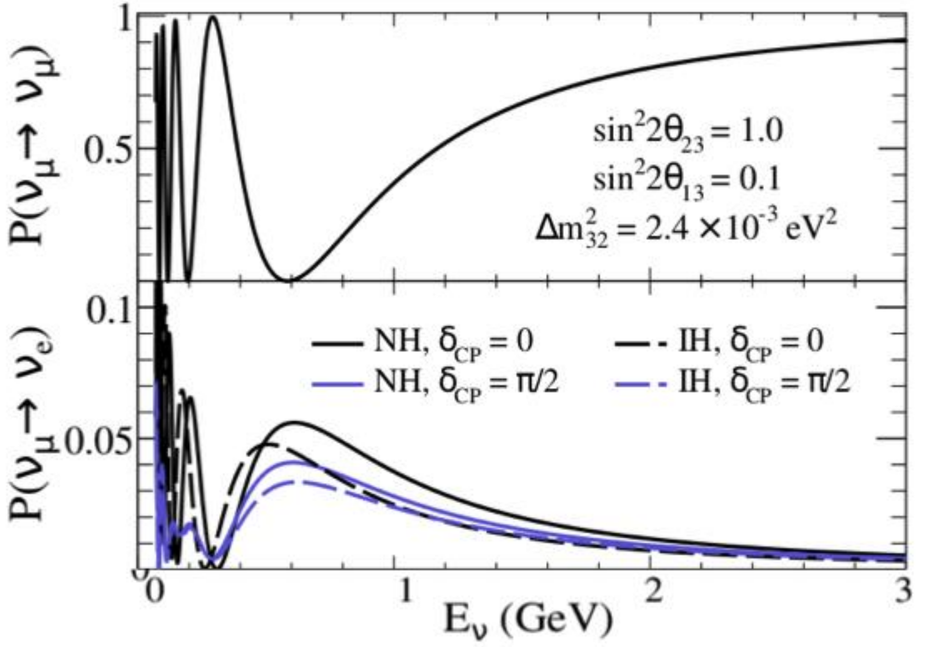
- Formula governing the probability of transition from one flavour to another

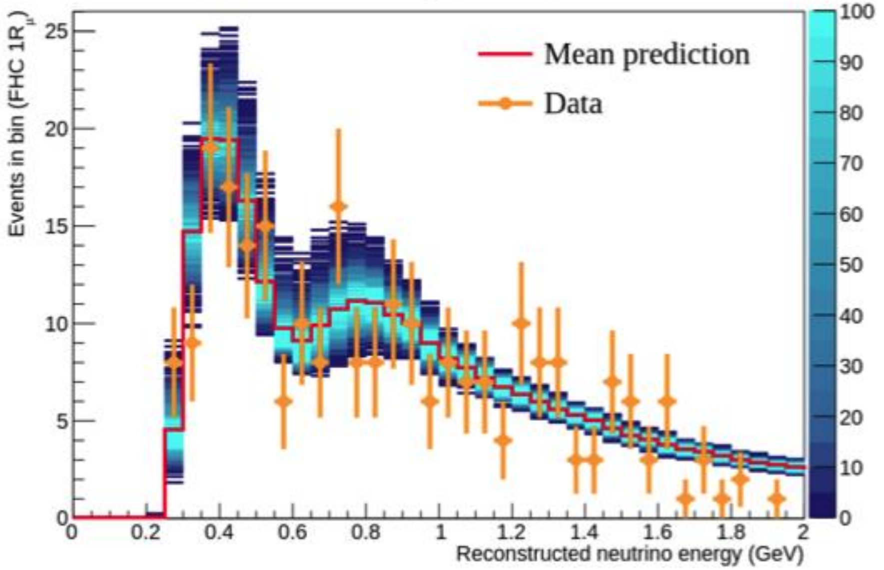
$$P_{\alpha\to\beta,\alpha\neq\beta} \simeq \sin^2(2\theta)\ \sin^2\left(1.27\,\frac{\Delta m^2 L}{E}\,\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

- Called “oscillations” because lots of sines and cosines in the equations!

- Depends on distance traveled and difference between neutrino masses

- Knowing the oscillation parameters = predict the number of each flavour of neutrinos at any distance from the source





Neutrino oscillations
Measuring the parameters

- Oscillation parameters summarized in the PMNS matrix

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor/Interference}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

Atmospheric	Reactor/Interference	Solar
$\mu \to \tau$	$\mu \leftrightarrow e$	$\mu \to e$
500 Km/GeV	500 Km/GeV	15,000 Km/GeV

- To measure a specific parameter, you “just” need to tune L (distance between source and detector) and E (neutrino energy)
  - Short (low-L) and Long (high-L) experiments
  - Can tell you about mass differences

Summary 1
What we know about neutrinos

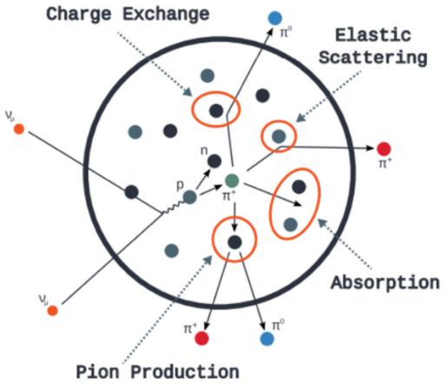
What we don’t know

Open questions about neutrinos

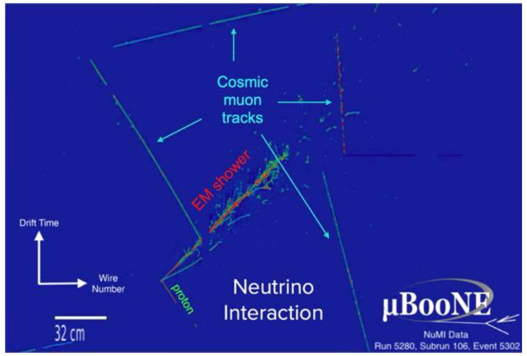
- What are the absolute masses of neutrinos?
- Do we even know which is the heaviest?
- How do they get their masses?
- Why are they so light?
- Are there only three neutrino types?
- Do neutrinos and antineutrinos oscillate in the same way?

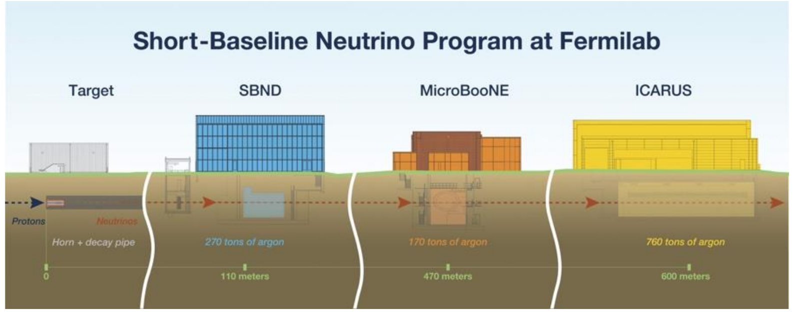
Neutrino interactions
What happens when neutrino meets something else?

- Neutrino interactions are complicated processes
- Involves a lot of nuclear physics
- Need to be understood to reduce uncertainties on oscillation measurements



- Current liquid argon experiments at Fermilab (USA) are exploring neutrino interactions using high-intensity neutrino beams

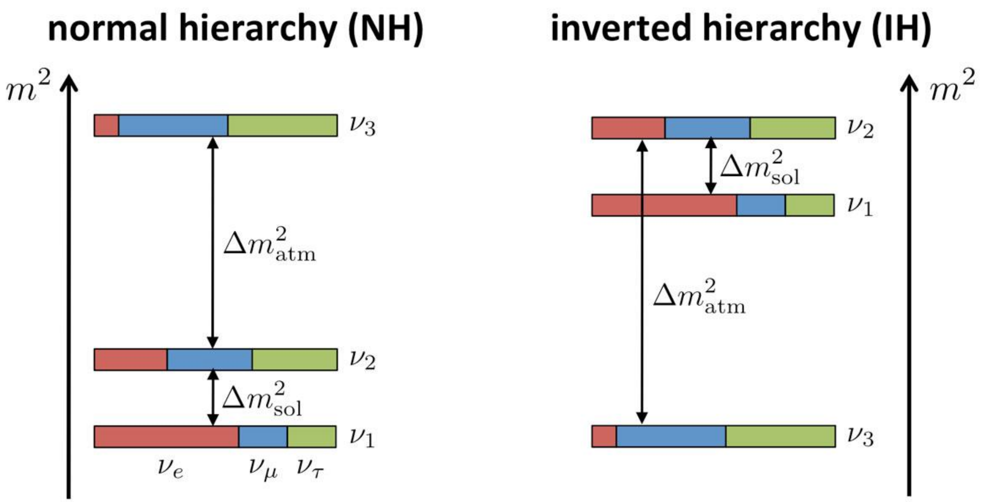




- Detailed images from LArTPCs help reconstruct what happened during the neutrino interaction

Neutrino masses

- We don't know much about neutrino masses beyond "they're non-zero"
- Neutrino "mass" states (ν_1, ν_2, ν_3) are different from their "flavour" states $(\nu_e, \nu_\mu, \nu_\tau)$
- We don't know what the masses m_1, m_2, m_3 are
- We don't yet know which of 1, 2, 3 is the heaviest
  - Two options, called "normal" and "inverted" ordering
- Future long baseline oscillation experiments will have an answer on the mass ordering



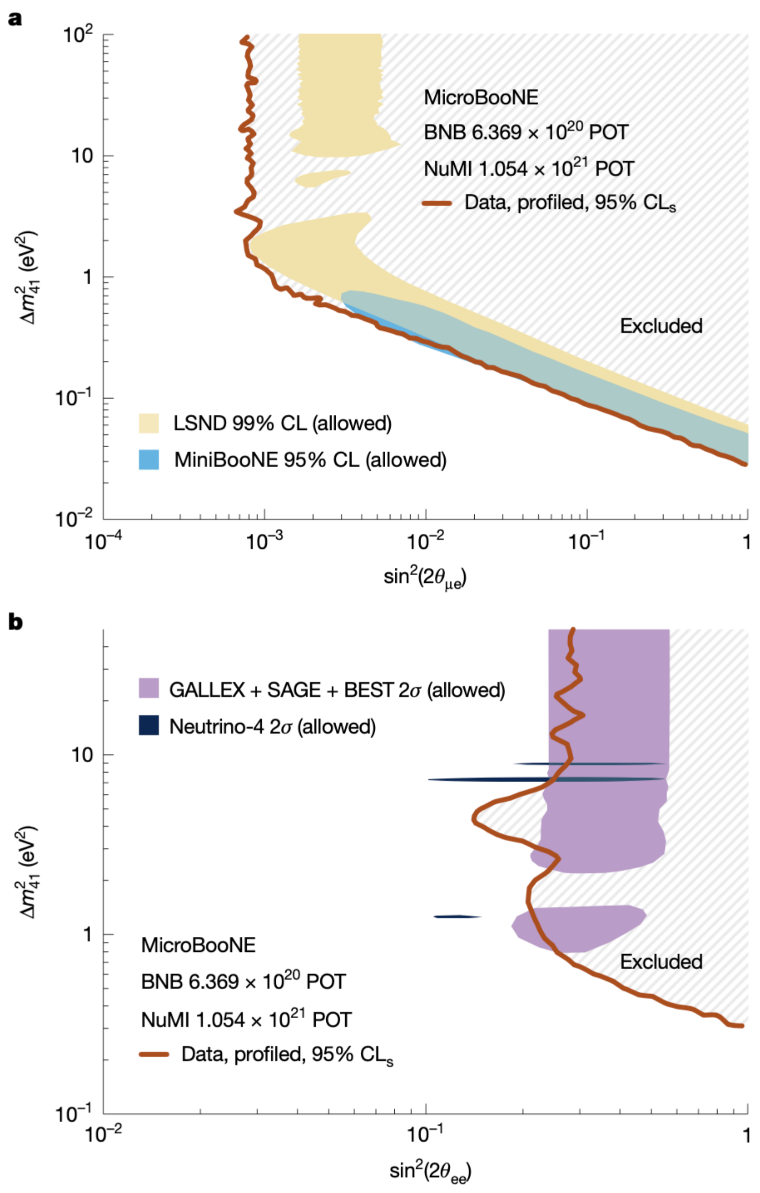
Matter-antimatter asymmetry

- Why is there only matter around?
  - When matter is created, so is antimatter
  - **Where did all the antimatter go?**
- Neutrinos may have the answer!
- In the PMNS matrix, there is a special parameter called δ_{CP}, which may create differences between neutrinos and anti-neutrinos
- By measuring this δ_{CP} parameter, we get hints on what happened to the antimatter

Sterile neutrino(s)?

Another neutrino mystery

- Some short baseline experiments saw anomalies that could be explained by the existence of a 4th type of neutrino, ν_4
- Would have to be "sterile", i.e. only interact via mixing with active neutrinos
- Minimal models predicting only one sterile neutrinos are less and less likely
- More complex picture with several steriles??



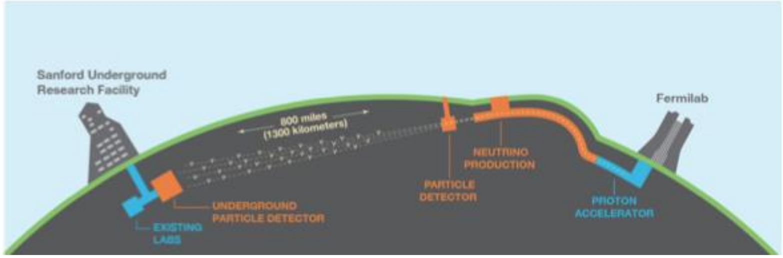
Future of neutrino experiments

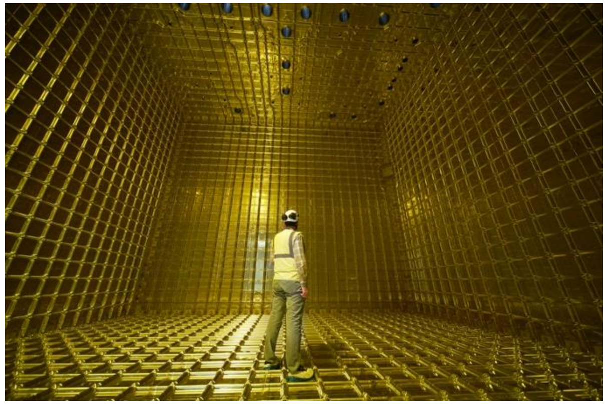
Even. Bigger. Detectors.

- Two giant experiments on the horizon:
  - DUNE (liquid argon) and Hyper-K (water Cherenkov)

- Bigger detectors, higher intensity neutrino beams, more precise measurements!

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

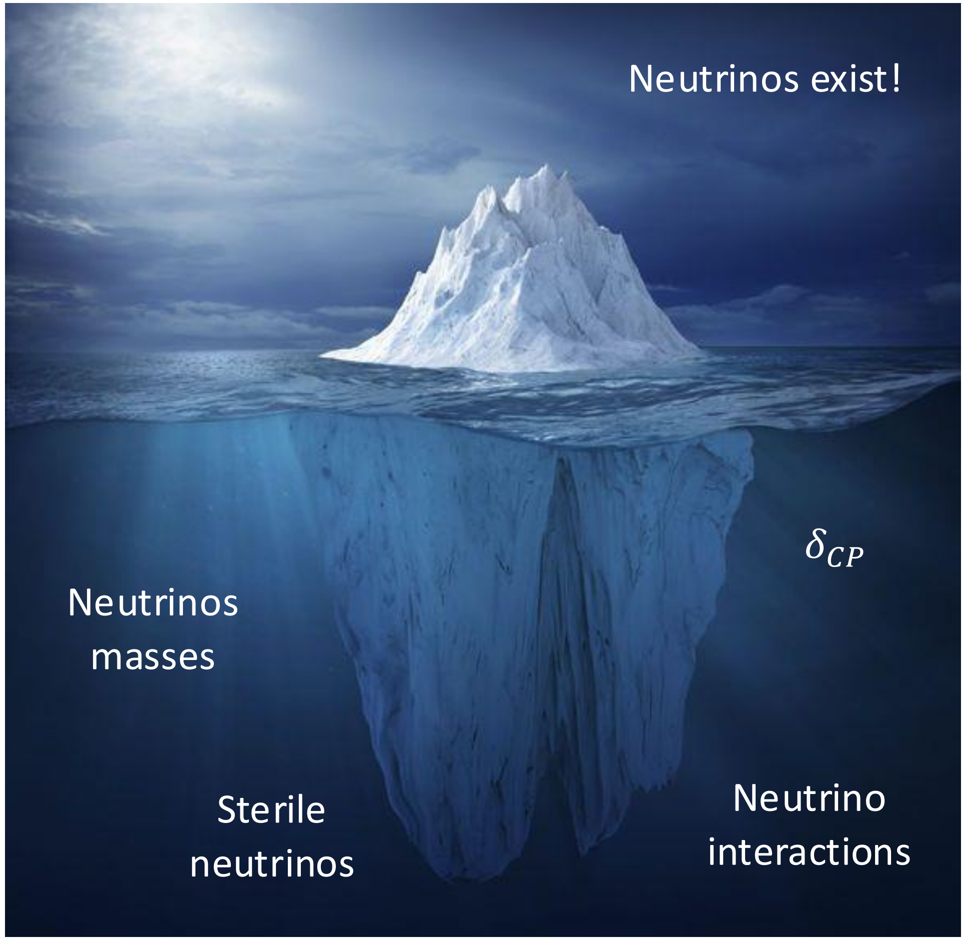




Hyper-Kamiokande

Neutrinos
What you should remember!

- **Neutrinos are everywhere but very hard to detect!**
- There are 3 kind of neutrinos (flavours)
- As they travel, neutrinos oscillate between flavours
- Despite their ghostly nature, neutrinos may explain why there is more matter than anti-matter in the Universe
- Measuring neutrino oscillations allows us to understand why the Universe has more matter than antimatter
- **Experiments currently under construction will answer many of the current open questions!**



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Any questions?