Neutrino physics

9th mini-school on Particle and Astroparticle Physics

5 February 2024

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

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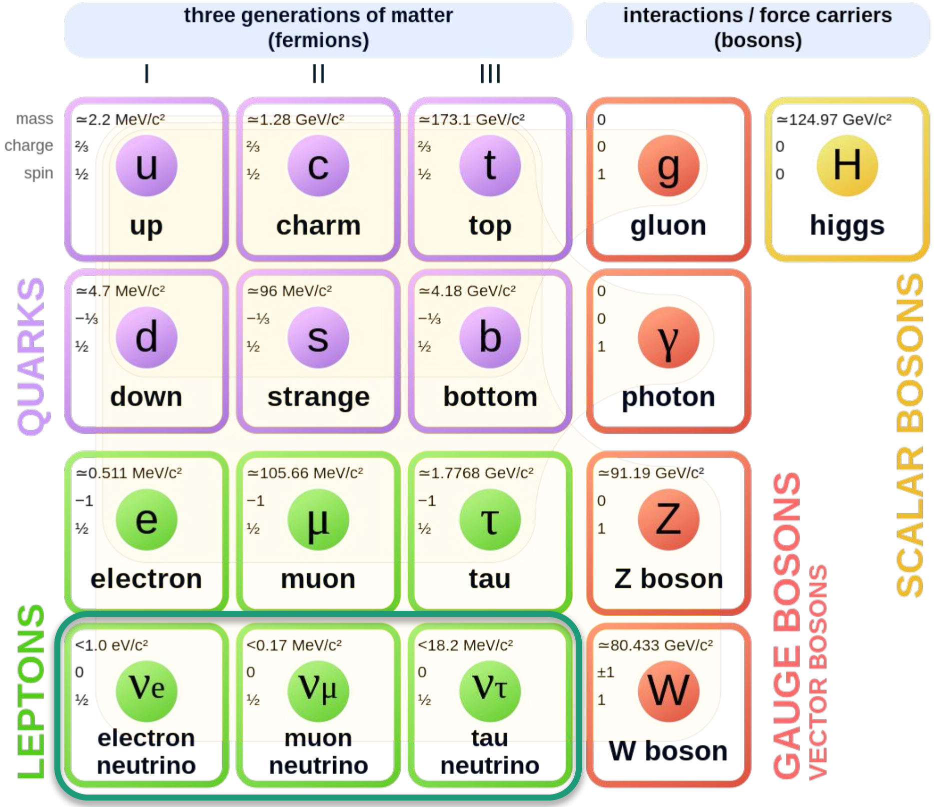
The Standard Model

- Neutrinos are *special*:
  - Electrically neutral fermions.
    - Only weak interactions.
  - Tiny (but non-zero!) masses.

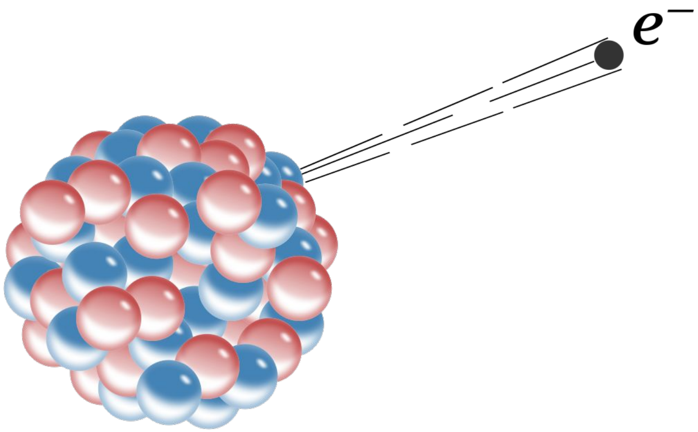
- Neutrinos play important roles in our understanding of nature:
  - Matter-antimatter (a)symmetry?
  - Why three generations of matter?
  - What is the nature of mass?



Neutrino pre-history

- A radioactive puzzle: the continuous spectrum of "beta-rays".
  - Transition between two stable isotopes via the emission of a beta ray.
  - Radiation energy should be **equal to the difference** of the isotope **masses**.

> At the present stage of atomic theory, however, we may say that we have **no argument**, either empirical or theoretical, **for upholding the energy principle** in the case of β-ray disintegrations.
>
> Niels Bohr



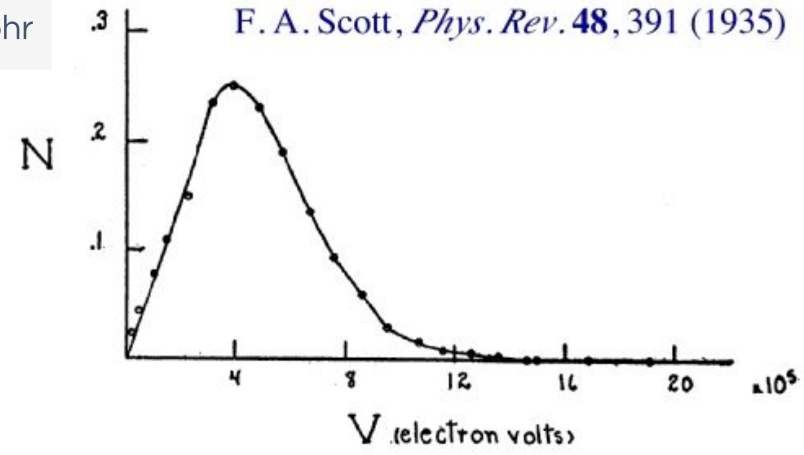
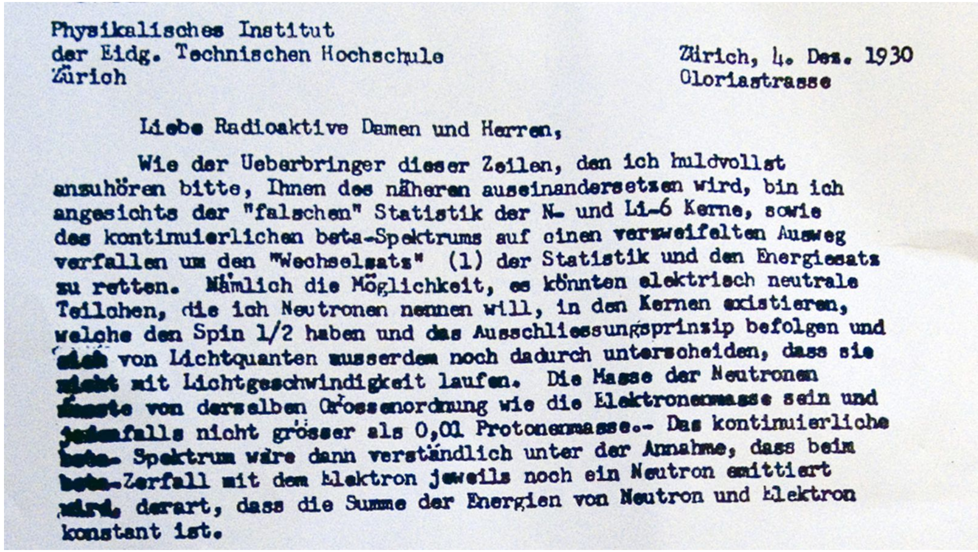


FIG. 5. Energy distribution curve of the beta-rays.

A desperate remedy (1930)

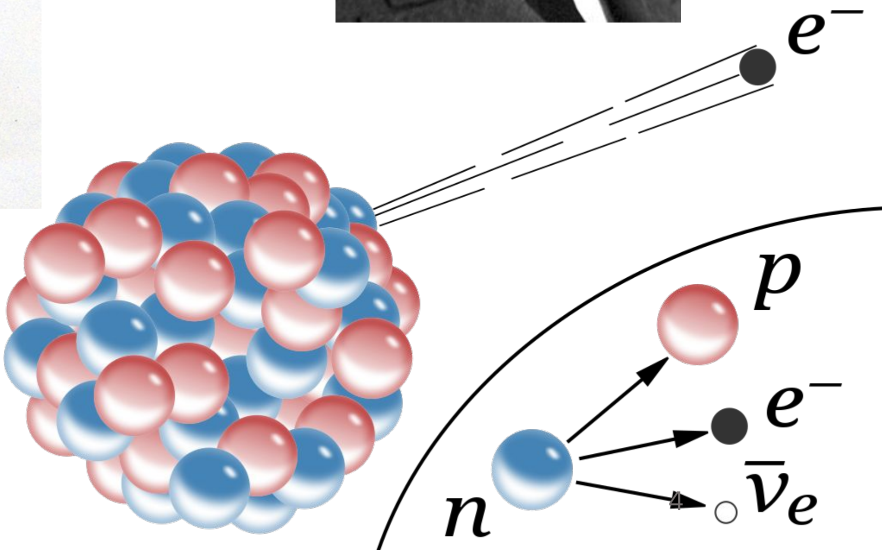


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

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 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.



A desperate remedy (1930)

Dear Radioactive Ladies and Gentlemen,

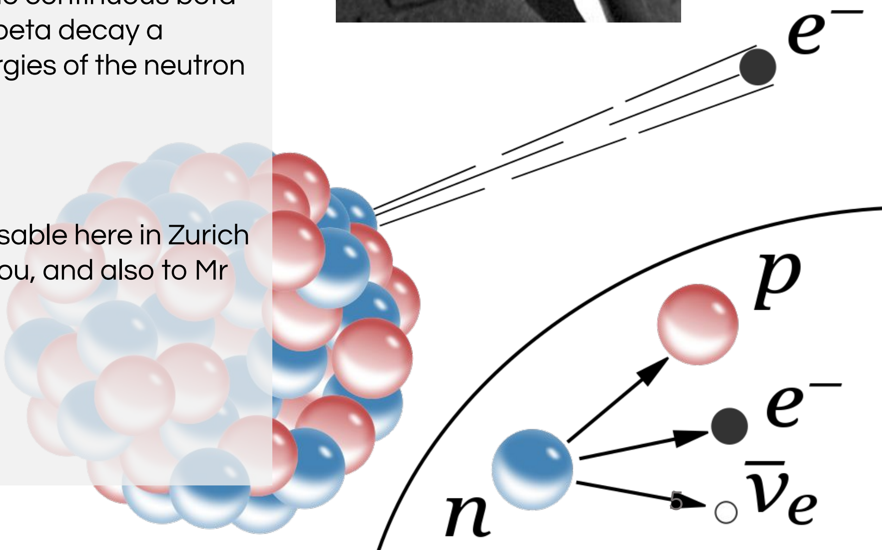
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, **I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy.** Namely, the possibility that **there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle** and which further differ from light quanta in that they do not travel with the velocity of light. The **mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.** The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

...

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,

W. Pauli



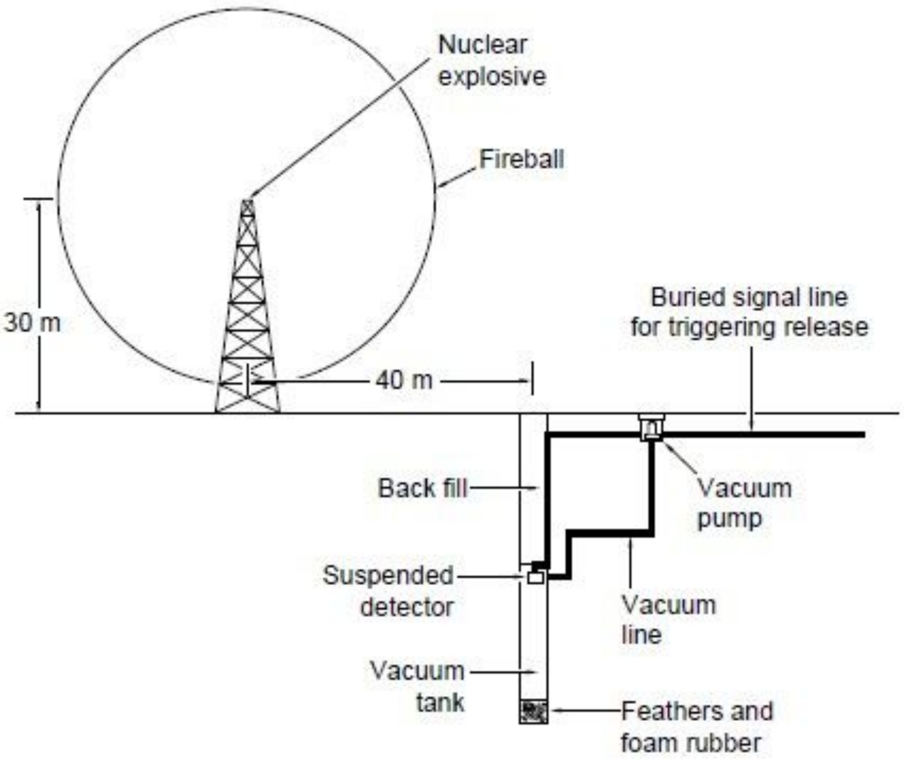
The discovery of neutrinos

- Experiment proposed by F. Reines and C. Cowan in 1951.

- Need a large flux of (anti)neutrinos:
    - Get as close as possible to a **nuclear explosive detonation.**

- Detector needs to be protected from the shockwave:
    - Dig a whole.
    - Create a **vacuum.**
    - **Drop the detector** in the vacuum when the nuclear explosive is detonated.

- This idea didn't materialise...

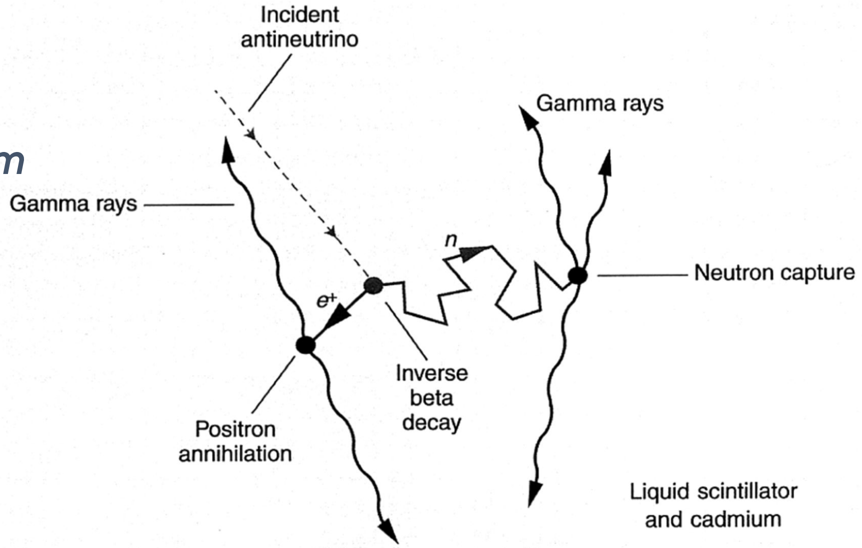


The discovery of neutrinos (1956)

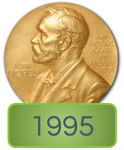
- Following the initial proposal, Reines and Cowan changed their strategy.

- Place detector very close to **nuclear reactor**: intense antineutrino flux.
- Large target tanks filled with water and ***cadmium*** chloride.
- Antineutrinos interact via inverse beta decay: $\overline{\nu} + p \rightarrow e^{+} + n$.
  - **e^{+}** annihilates to produce **pair of γ**
  - Capture of **n** on Cd produces ***delayed*** γ.

- Measured cross-section: **$\sim 10^{-44}$cm^{2}**.
  - Proton-proton collisions at LHC: $\sim 10^{-25}$ cm^{2}
  - Probability of 1 MeV ν interacting traversing the earth: 10^{-11}



The discovery of neutrinos (1956)



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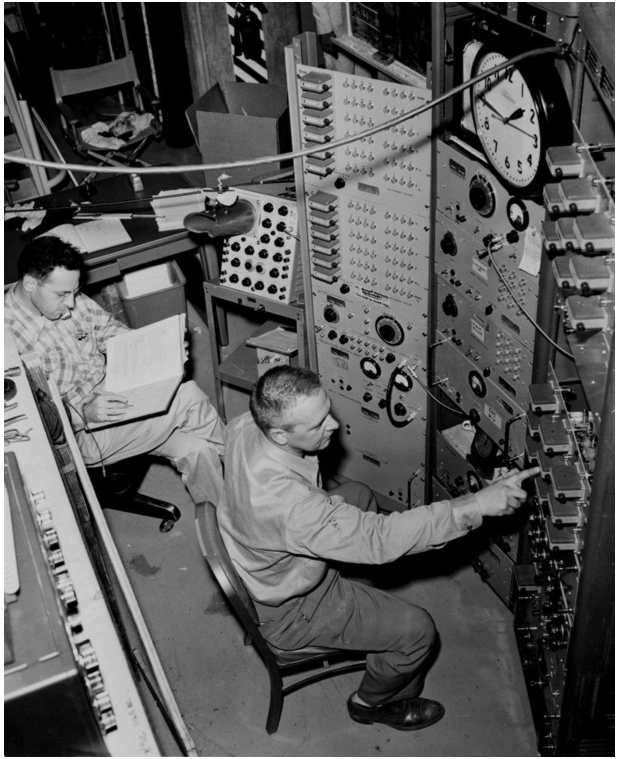
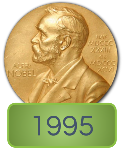


The disc 1956)



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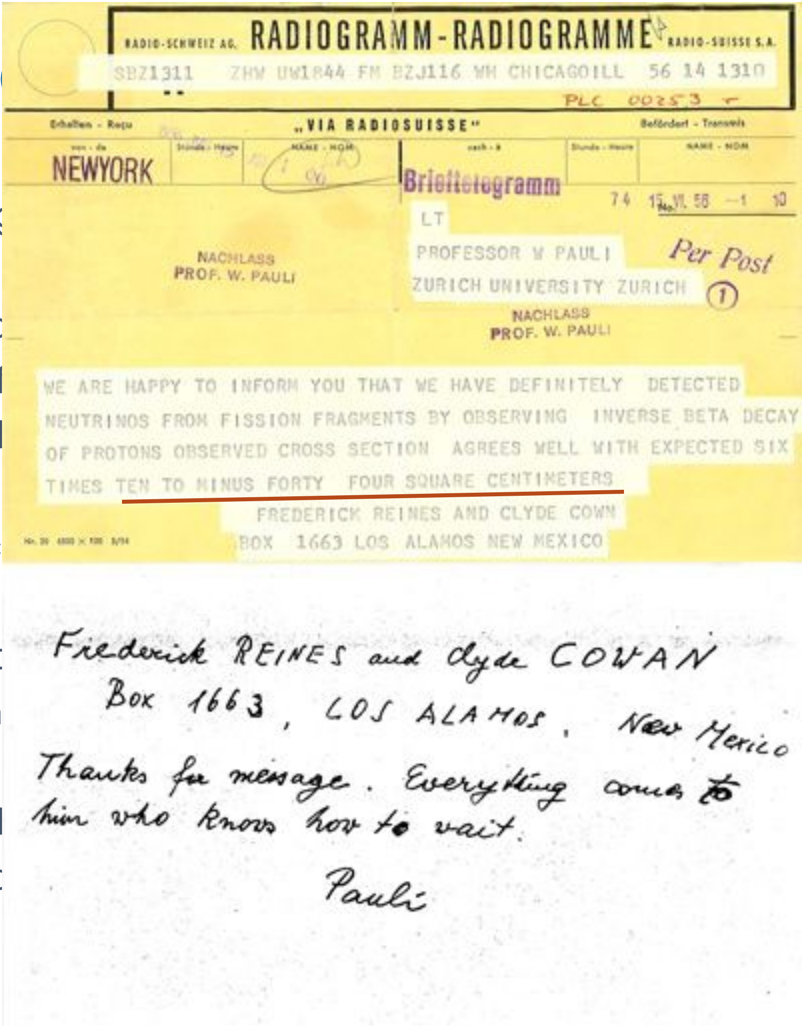

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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWAN

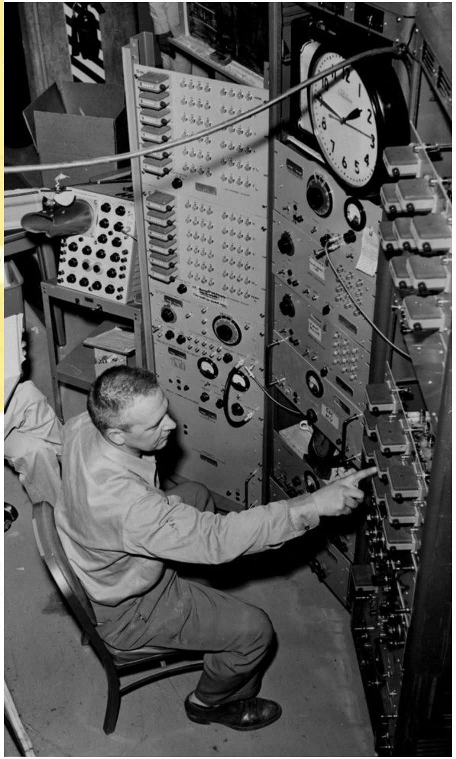
BOX 1663 LOS ALAMOS NEW MEXICO

Frederick REINES and Clyde COWAN

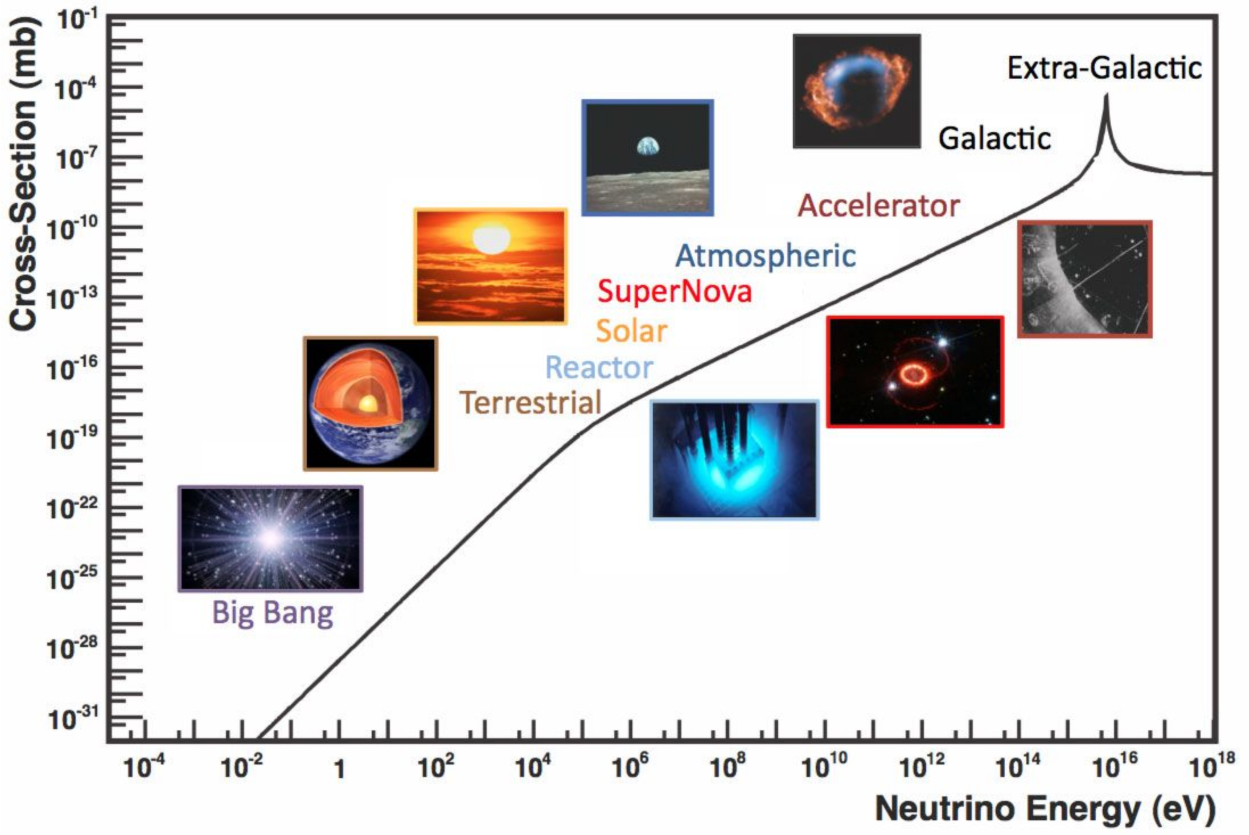
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

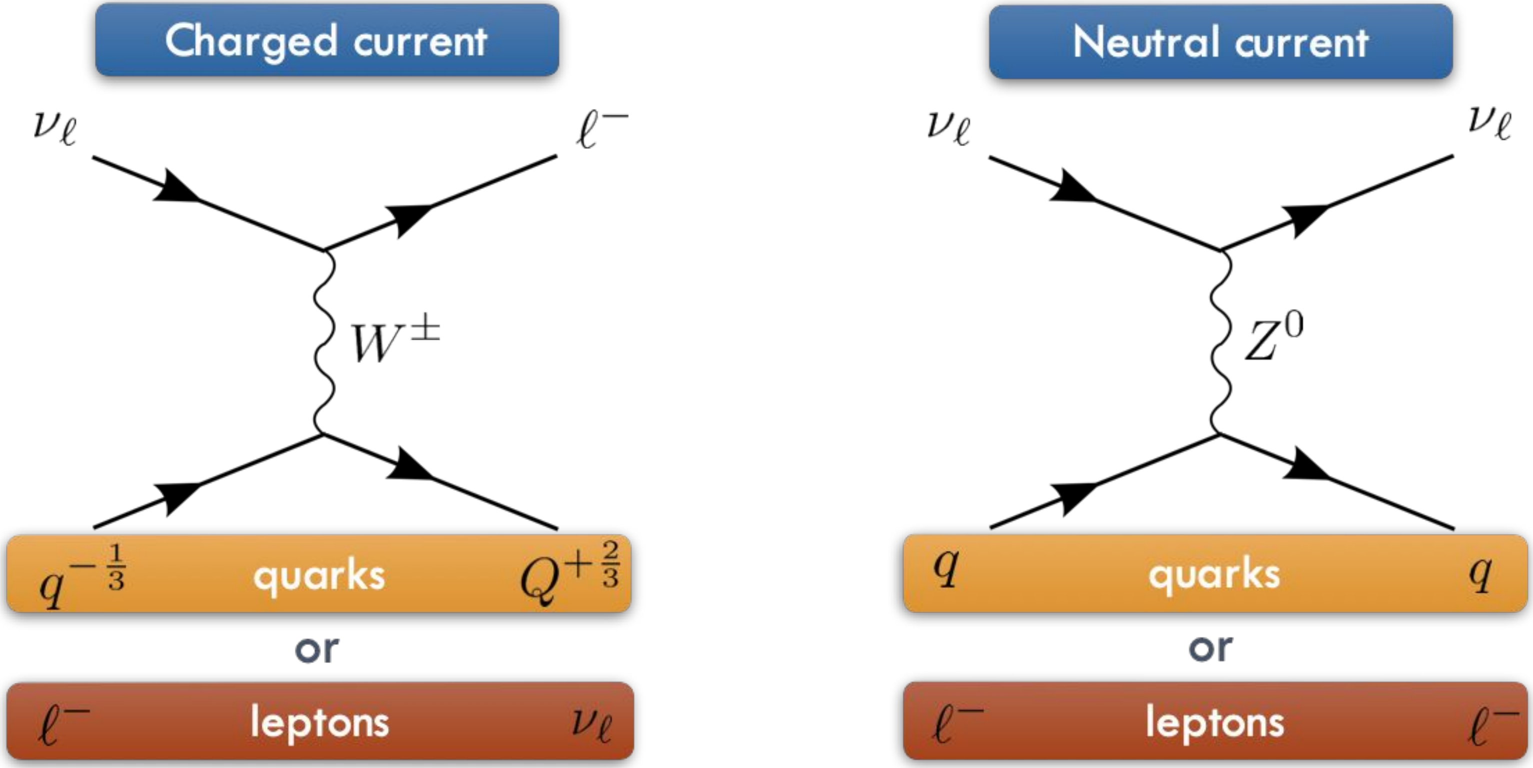
Pauli



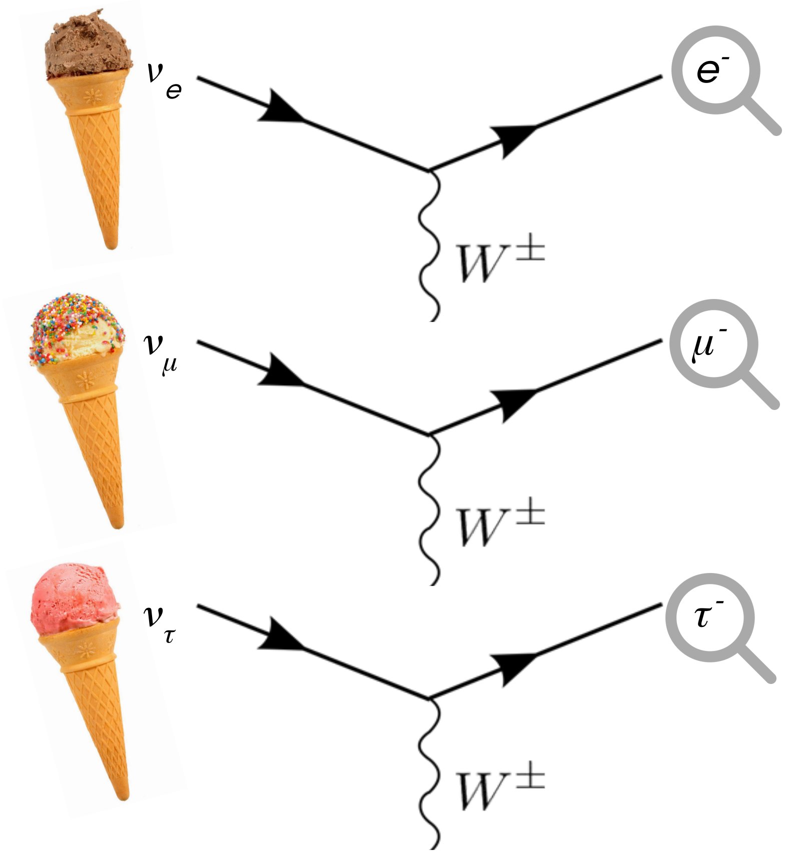
Where do neutrinos come from?



Neutrino interactions

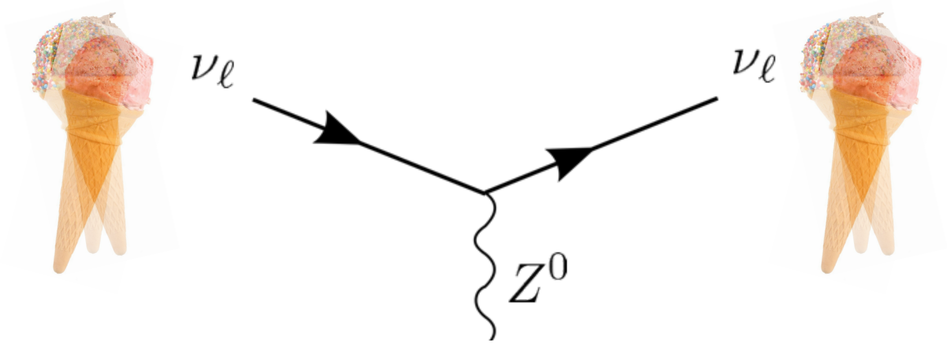


Neutrino interactions

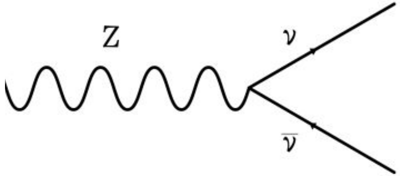


- Charged current:
  - Charged leptons of the **same generation** as the neutrino are produced.
  - This allows for the identification of the neutrino flavour by identifying the charged lepton generation.

- Neutral current:
  - **Does not allow** for the identification of neutrino flavour.



How many neutrinos?

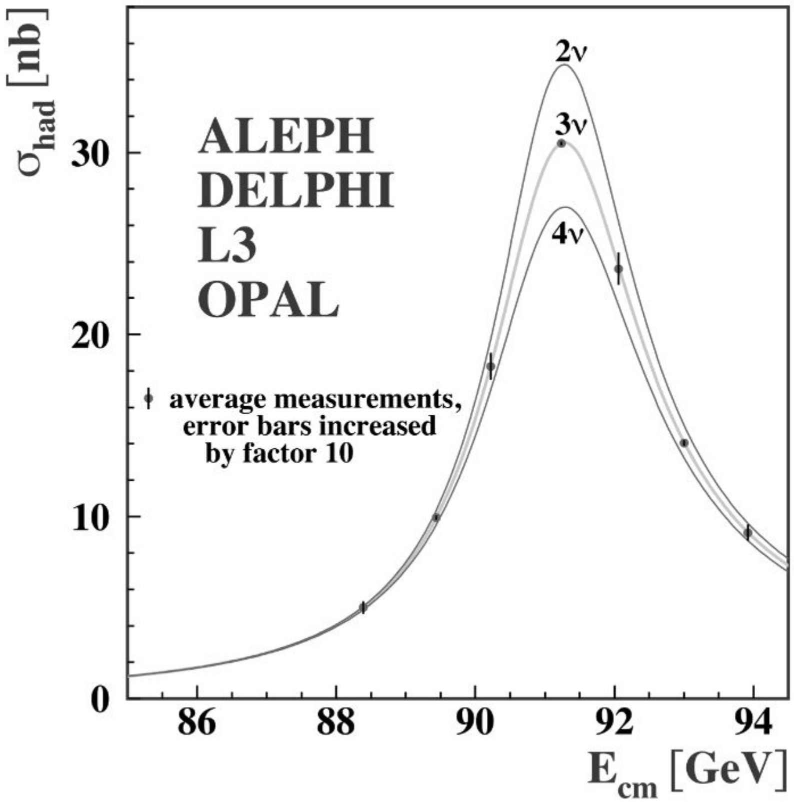


- In the early 90s, the large electron-positron collider (**LEP**) at CERN made very precise measurements of the **Z-boson width.**

- The width is related to the particle lifetime by the uncertainty principle.
  - The **more decay final states**, the faster the decay, the **wider the resonance.**
  - **Each neutrino flavour** corresponds to **one** decay final state.

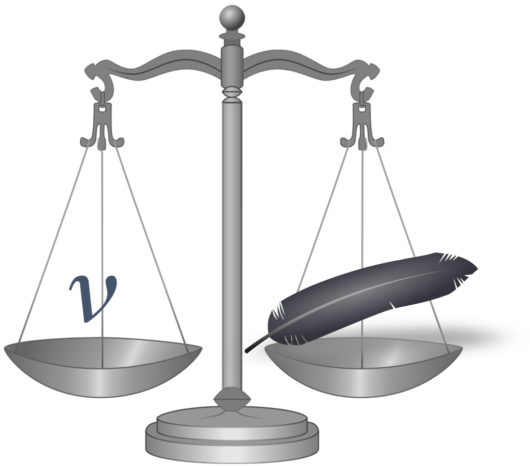
- Number of neutrinos: 2.9840 ± 0.0082.
  - **Three fermion generations!**

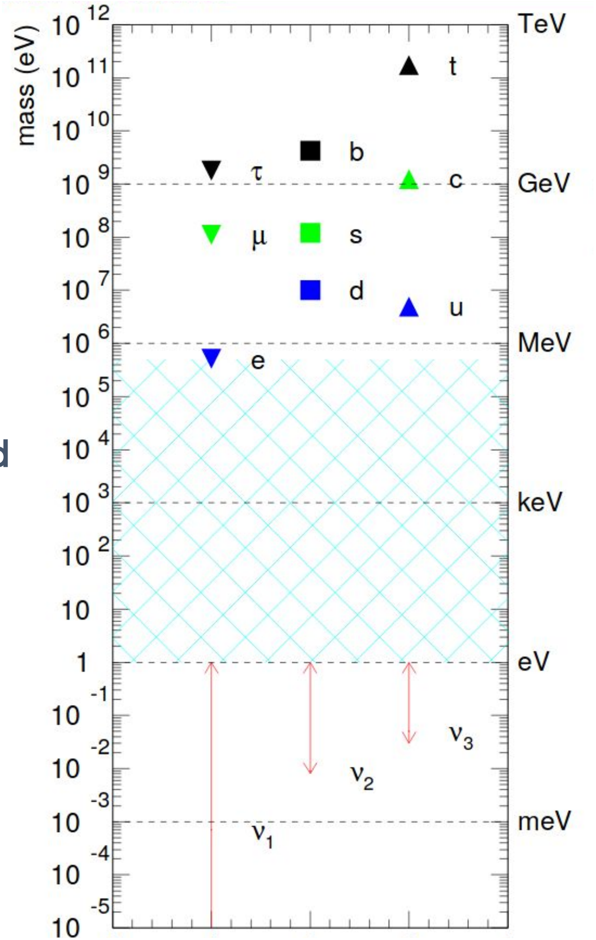
- Smallprint: only counts "**light**" neutrinos ($m \ll m_Z$) that **couple** to the Z boson.



Neutrino mass

- What is the mass of a neutrino?
  - We don't know... yet!
- However, we know neutrinos must be **six orders of magnitude** less massive than the electron.
- This huge difference suggests the origin of neutrino mass is qualitatively different from the other fermion masses.
- Can be seen as an indication of new physics **Beyond the Standard Model.**



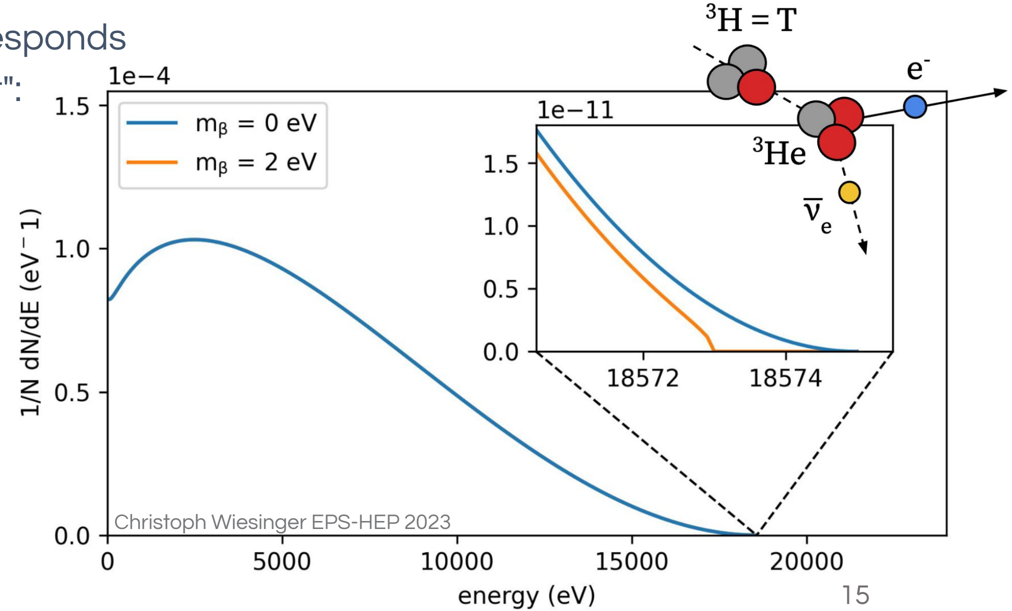


de Gouvêa, Neutrino 2016

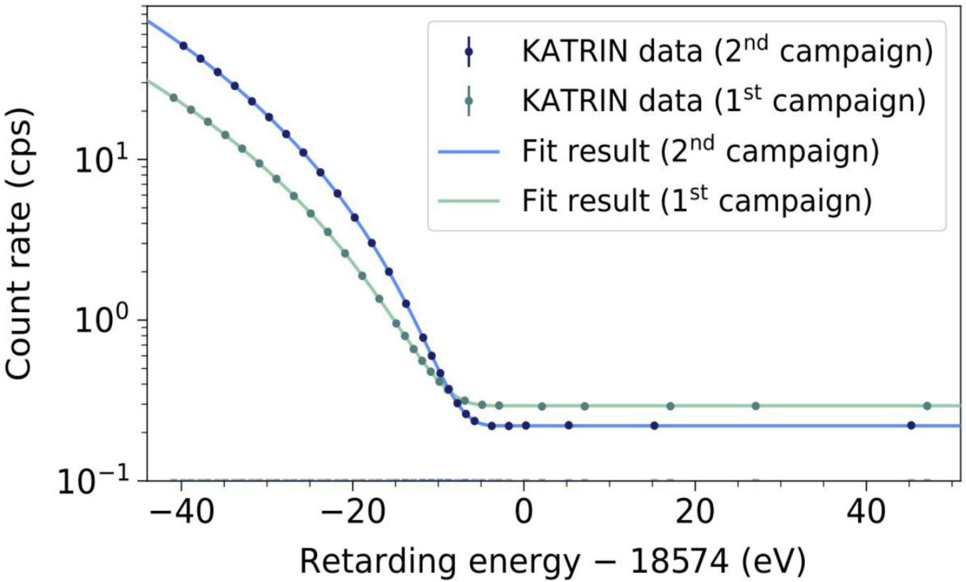
How to measure neutrino mass?

- Let's go back to energy conservation in beta decay.
  - Before the decay, the total energy is the mass of the initial isotope.
    - $E = m_i$
  - After the decay, the total energy is the mass of the initial isotope plus the sum of the electron and neutrino energies.
    - $E = m_f + E_e + \mathbf{E_\nu}$
  - The maximum electron energy corresponds To the emission of a neutrino "at rest":
    - $E_e < m_i - m_f - m_\nu$

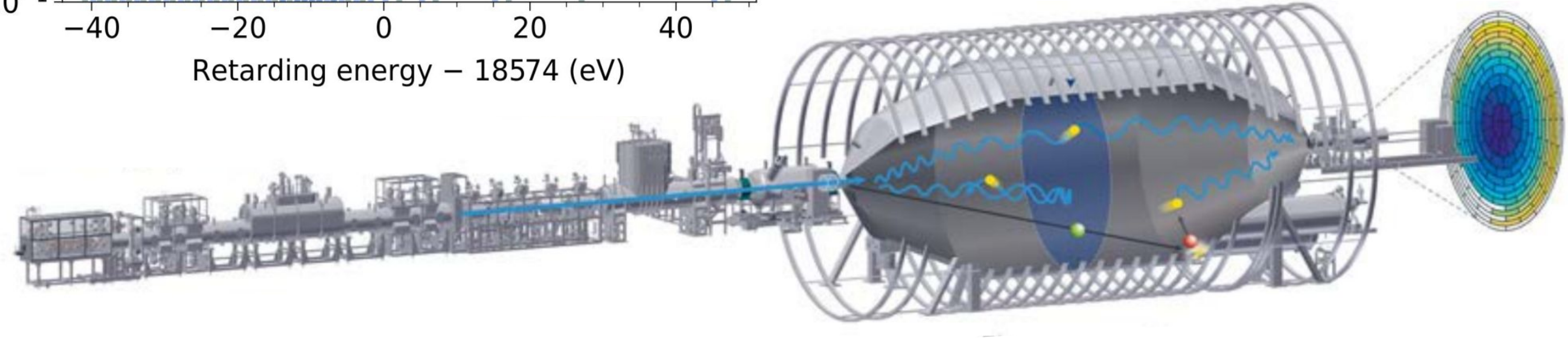
It is possible to infer the neutrino mass from the beta decay electron spectrum!



The KATRIN experiment



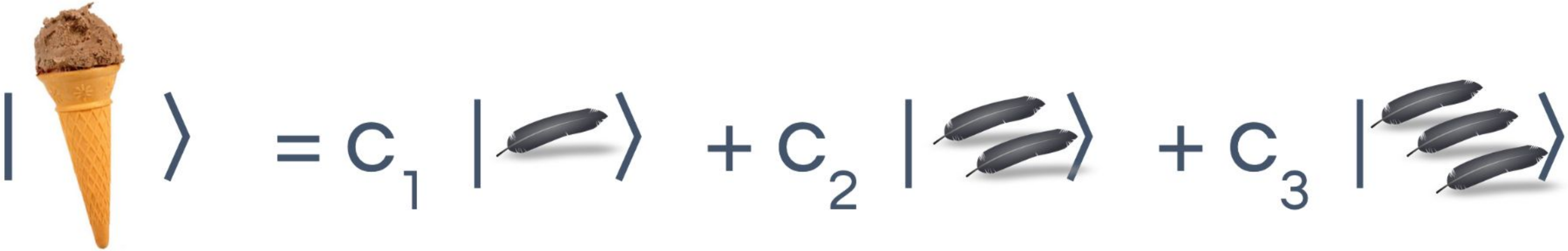
- Measurement of the tritium beta decay.
- Result:
  - The neutrino mass is **smaller than 0.8 eV!**



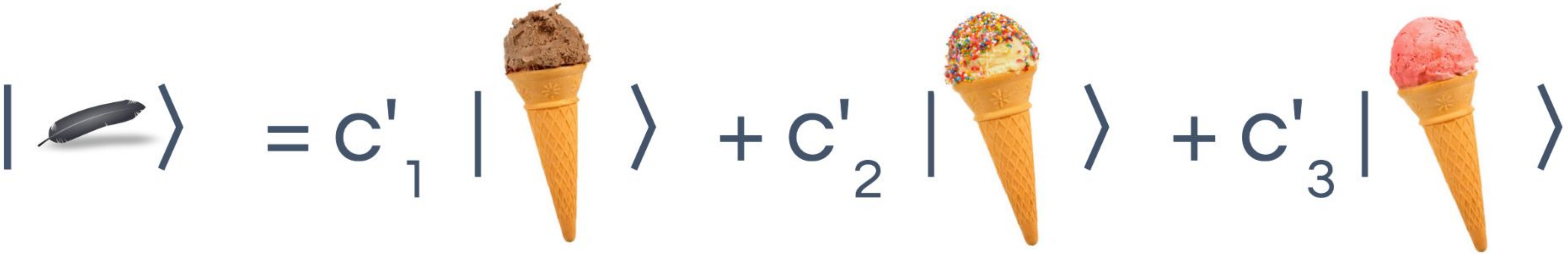
KATRIN's spectrometer arriving "home".

After a long journey…

Mass states and flavour states

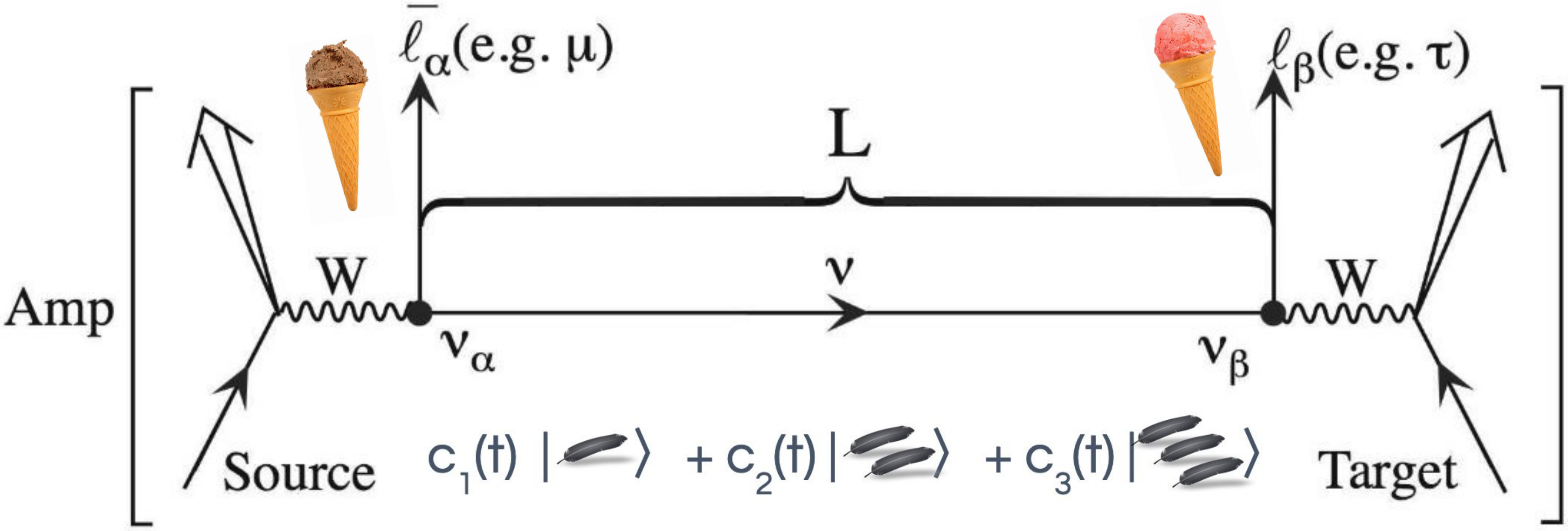


Each flavour state corresponds to a superposition of mass states.



Each mass state corresponds to a superposition of flavour states.

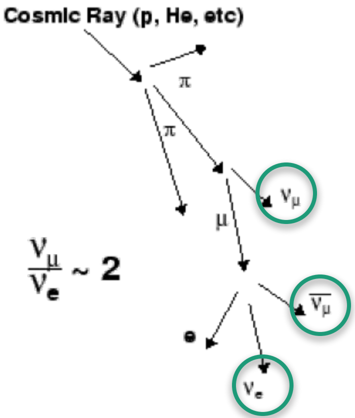
Neutrino oscillations

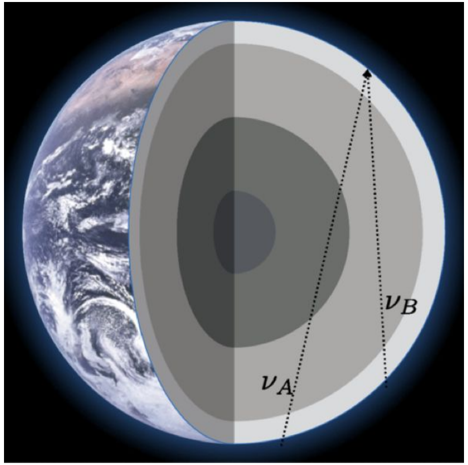


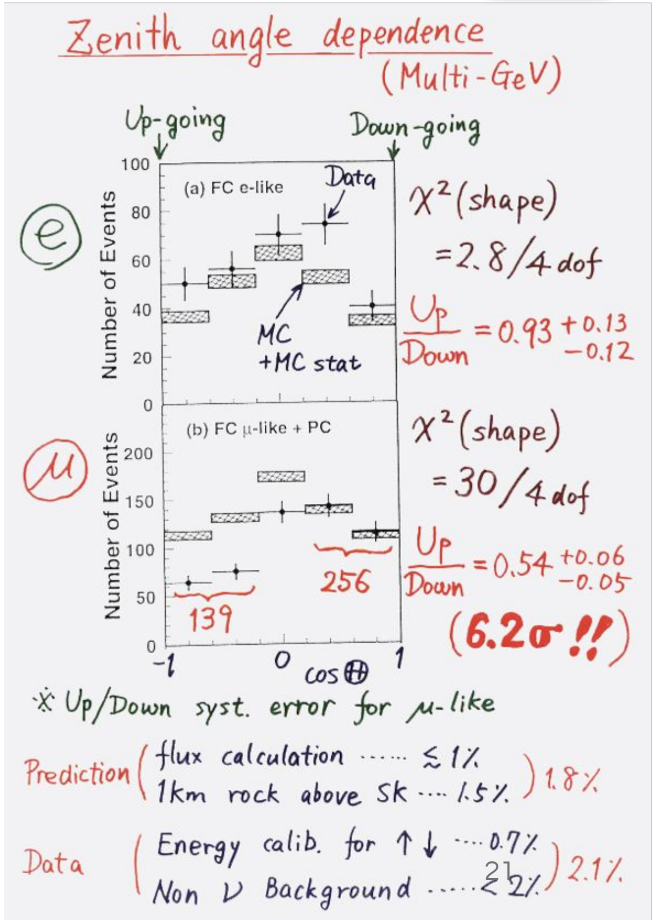
- The mixture of mass states **evolves** with the passage of **time**, as neutrinos traverse **space**.
- After travelling a distance *L*, neutrinos may be observed in a **different flavour**!
- The probability to observe a neutrino in a different flavour state depends on the ratio of *L* to the neutrino energy: ***L/E***

Discovery of neutrino oscillations

- Super-Kamiokande experiment (1998, Japan)
  - Measurement neutrinos produced in the atmosphere.
  - "Downward-going" neutrinos:
    - Propagate through part of the atmosphere before reaching the detector: **short *L*.**
  - "Upward-going" neutrinos:
    - Propagate through the Earth: **long *L*.**
  - Only "upward-going" neutrinos change flavour!







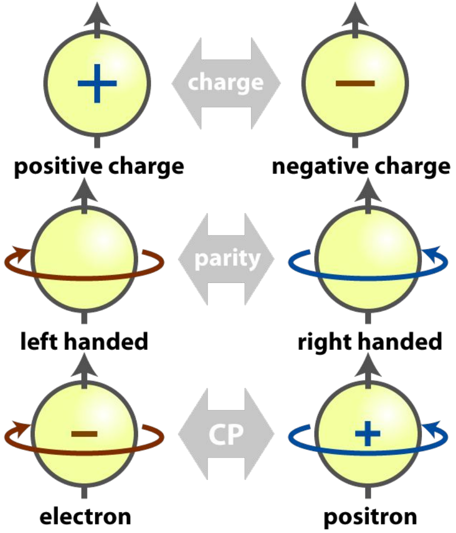
Matter and antimatter

- Where has all the **antimatter** gone?!
- The ratio of matter particles to photons in the universe suggests a slight excess of matter over antimatter.
  - Everything we see around us is that "slight excess".

- To transform matter into antimatter:
  - Charge-parity conjugation (CP)

- There is CP-symmetry violation in the interactions of quarks But it is too small to explain the "slight excess".

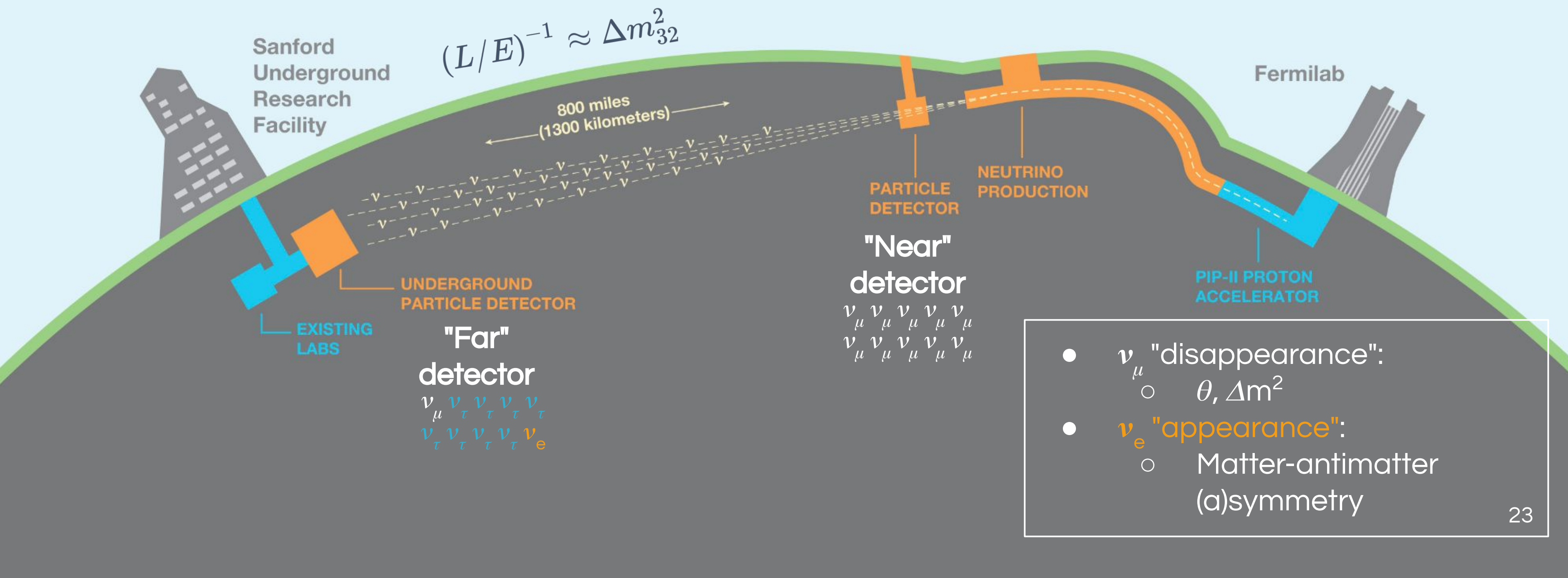
- Neutrino oscillations are the last opportunity to find large CP violation in the Standard Model.
  - $\mathrm{P}\left(\nu_\mu \rightarrow \nu_e\right) = \mathrm{P}\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)?$
  - This is one of the main goals of the next generation Of neutrino experiments!



Flip Tanedo, Symmetry Magazine

DUNE

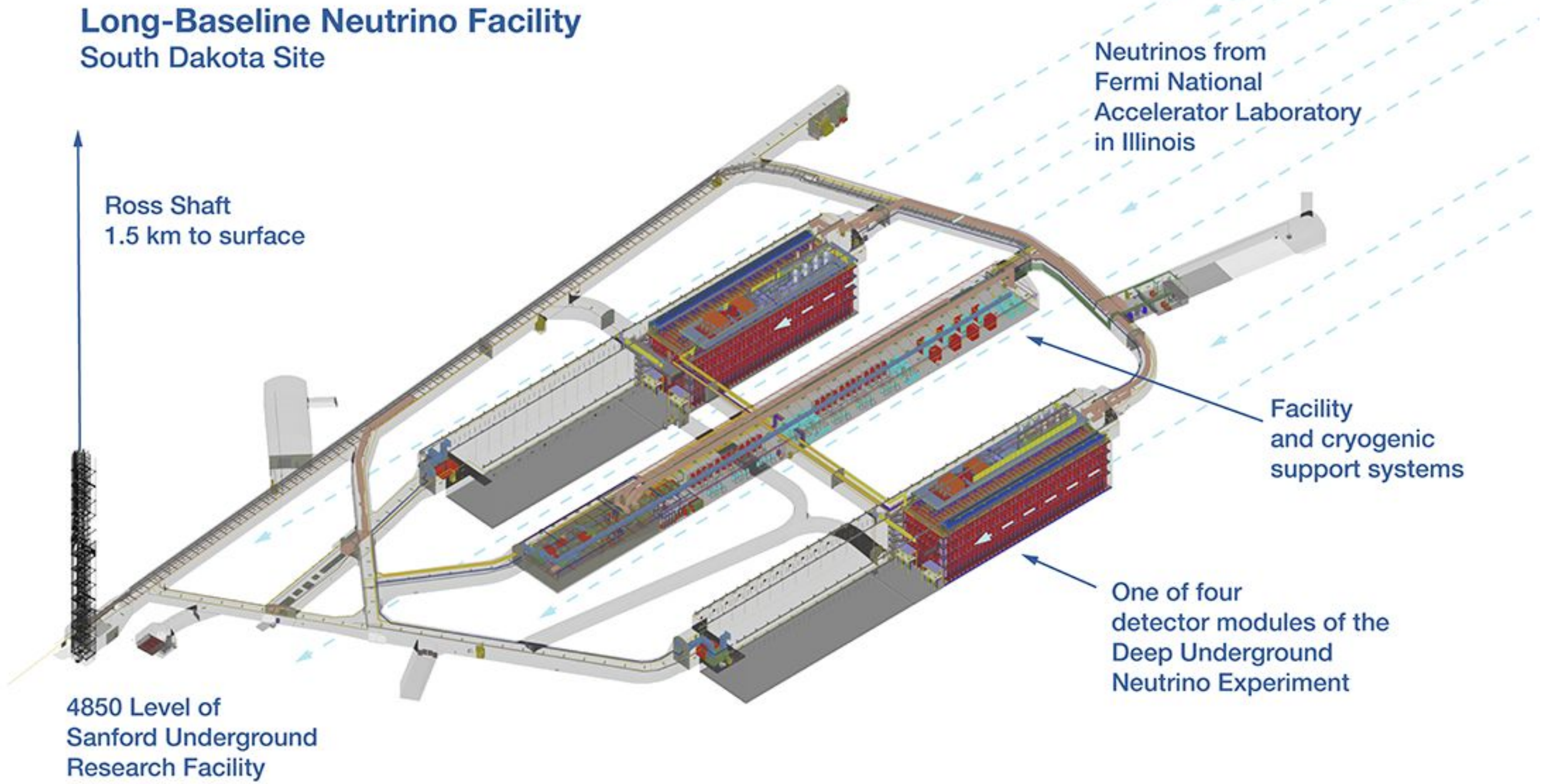
DEEP UNDERGROUND NEUTRINO EXPERIMENT



- ν_μ "disappearance":
  - θ, Δm^2
- ν_e "appearance":
  - Matter-antimatter (a)symmetry

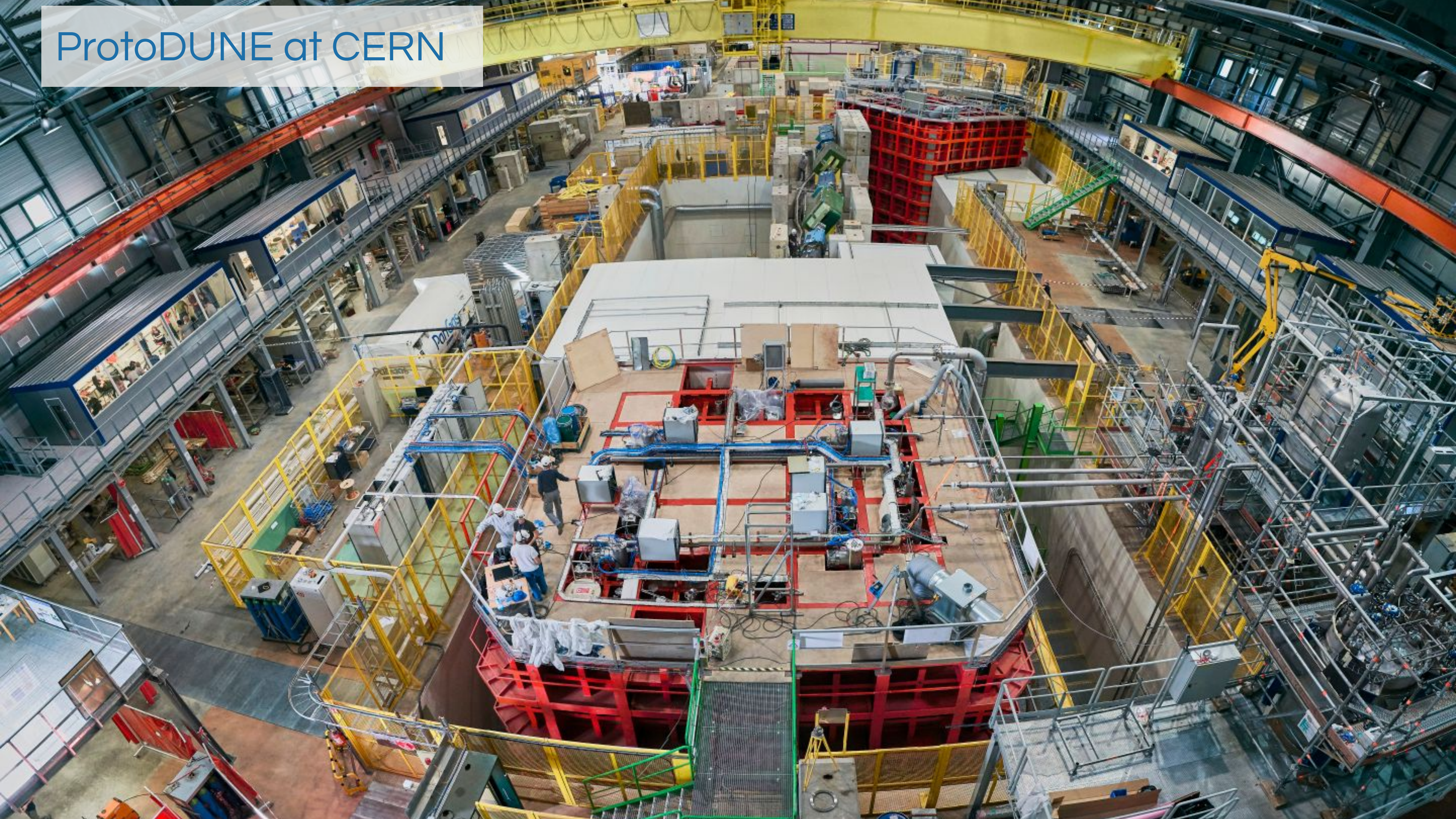
DUNE's very large detectors

- Under construction 1.5 km underground in a South Dakota mine.
    - Very close to Ray Davis' experiment.
- Up to four large detectors, each with 17 kton of liquid argon.



Excavation complete 1/2/2024!

ProtoDUNE at CERN



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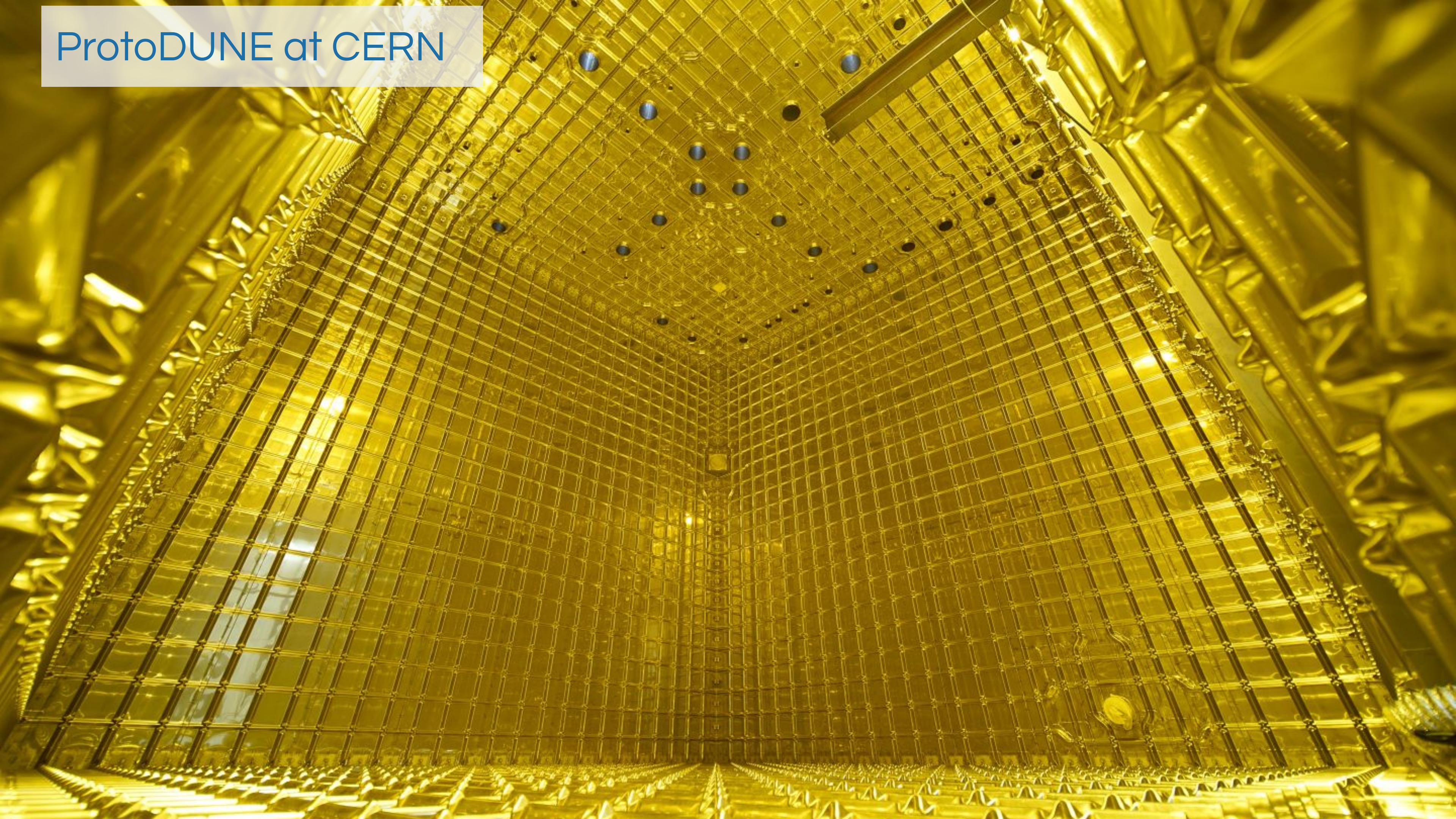
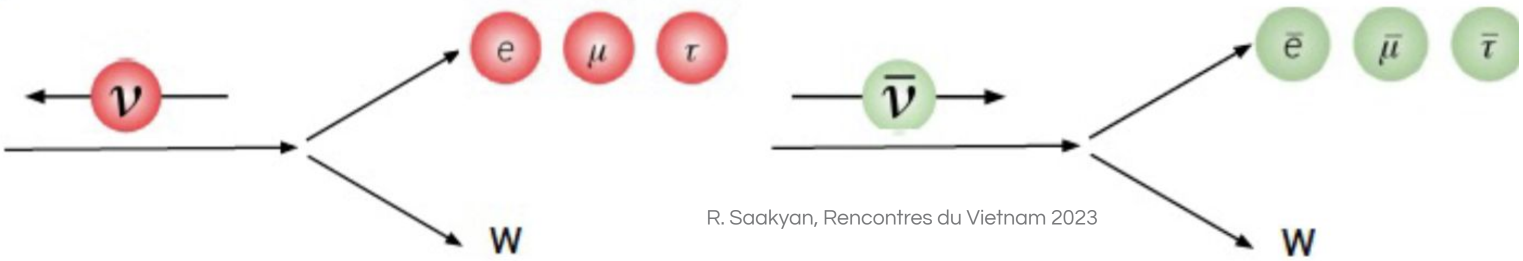
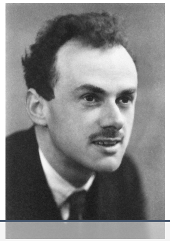


How to tell a neutrino from an antineutrino?

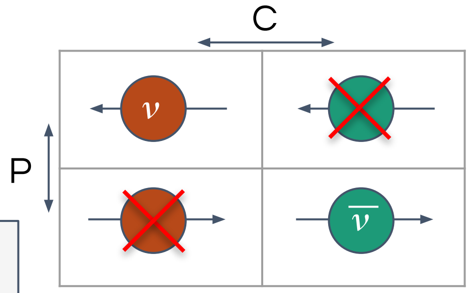
- What is the meaning of charge conjugation for neutral particles?!
- Experiment tells us:
  - "Left-handed" neutrinos produce particles.
  - "Right-handed" neutrinos produce antiparticles.
- Majorana's hypothesis:
  - Neutrinos and antineutrinos are the same particle in a different helicity state.

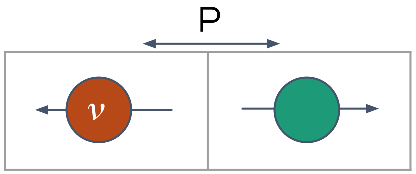


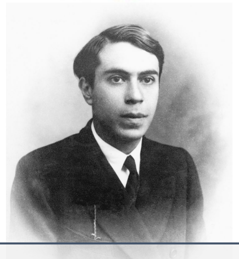
R. Saakyan, Rencontres du Vietnam 2023



Dirac





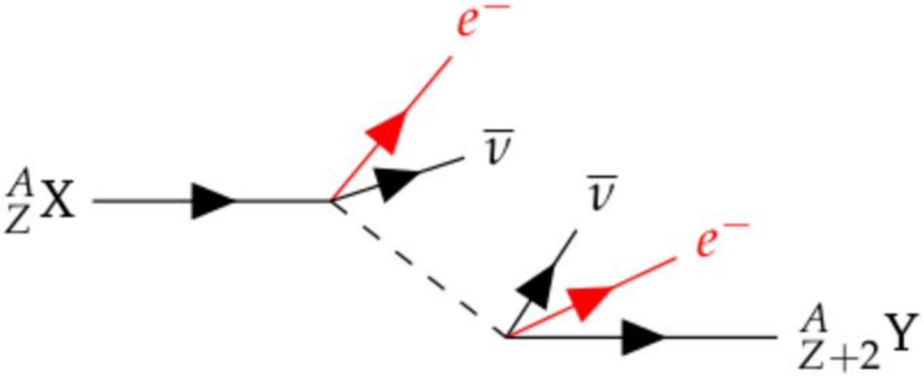


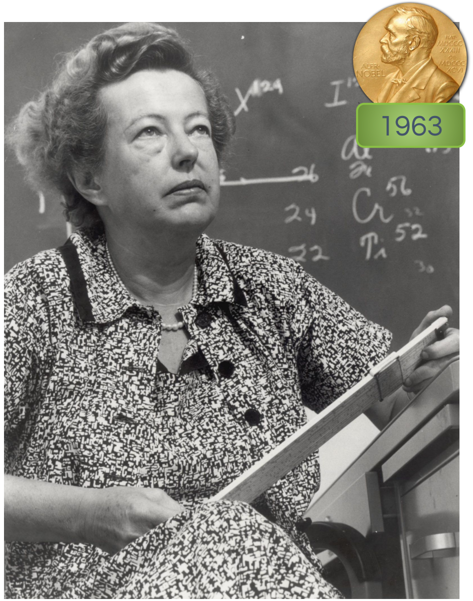
Majorana

Neutrinoless double-beta decay

- Two simultaneous beta-decays in a single process.
    - Extremely rare.
- Half-life around 10^{21} years!
    - Much longer than the age of the universe.
    - Experimentally observed in about 10 isotopes.

- Conservation of energy: the **sum** of the electrons' energies has a continuous spectrum, like beta-decay.
- What if neutrinos are their own antiparticles (Majorana)?



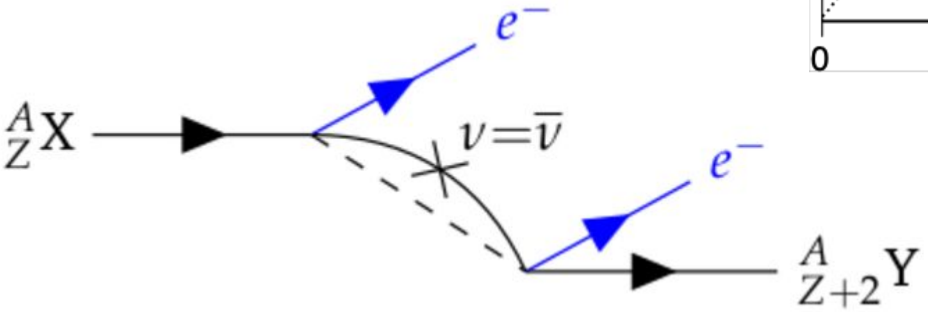


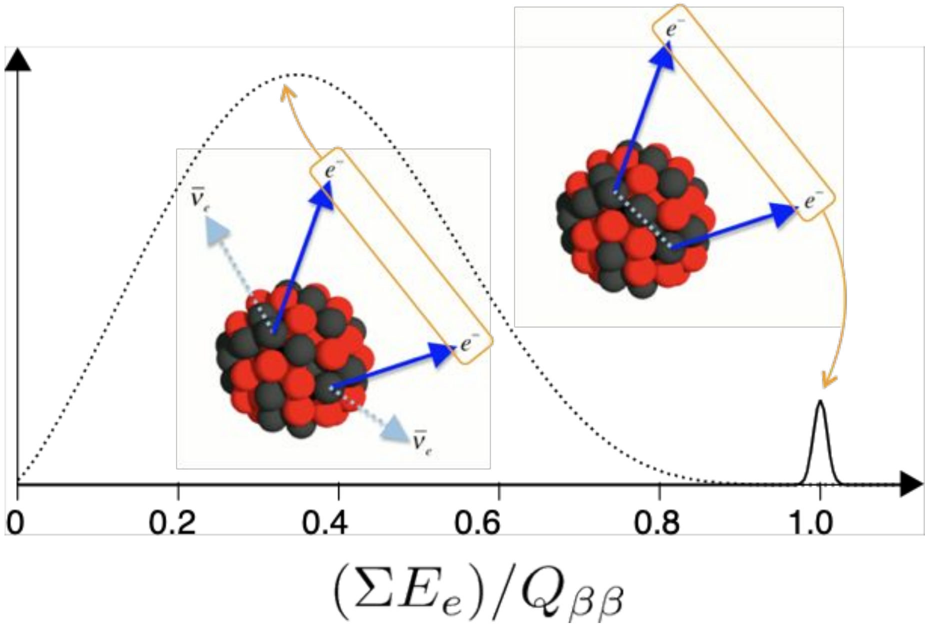
Maria Goeppert-Mayer

[C. Wiesinger](#)

Neutrinoless double-beta decay

- **Only if neutrinos are their own antiparticles,** a similar process may exist: double-beta decay **without neutrino emission.**
- In this case, the **sum** of the electrons' energies is **always the same.**
- This is the **only** experimentally accessible **process** that can tell us if neutrinos are **Dirac** or **Majorana** particles!

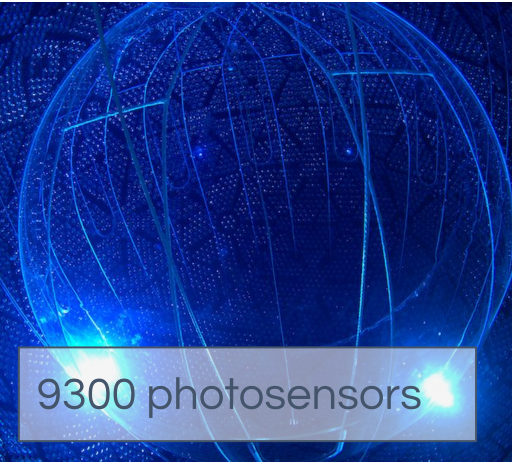


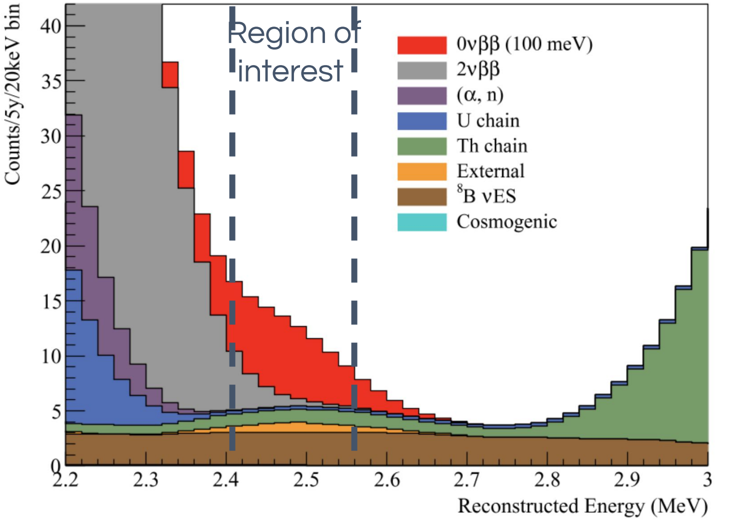


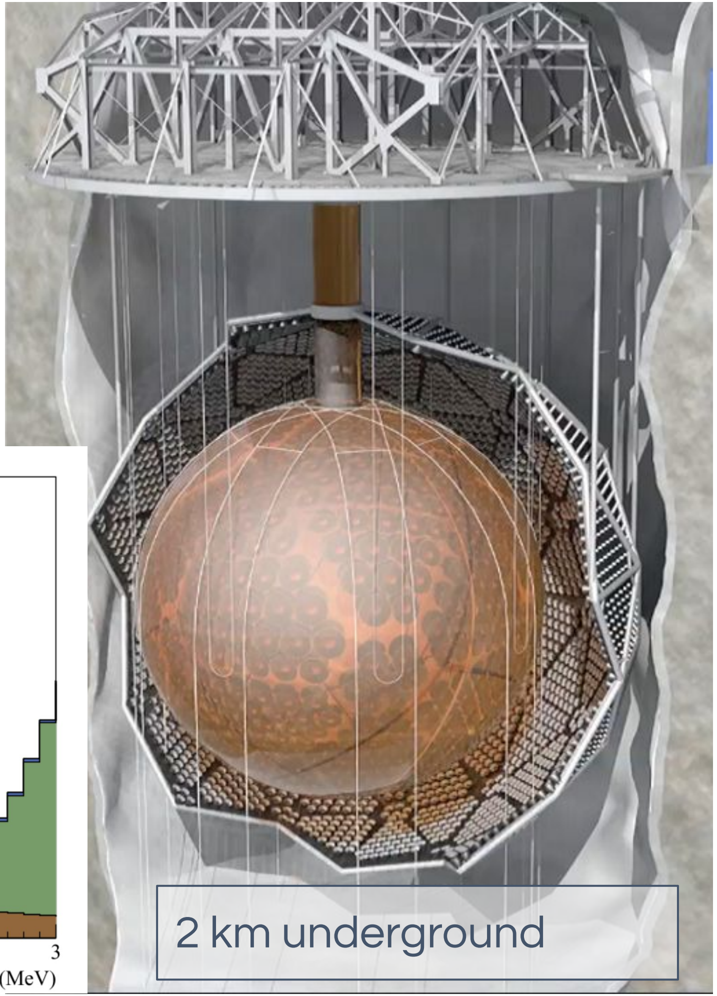
[C. Wiesinger]

The SNO+ experiment

- Reuses part of the SNO experiment's infrastructure.
- Contains a large acrilic sphere with 790 tons of liquid scintillator.
- Double-beta decay isotope ^{130}Te will be dissolved in the liquid.
- The goal is to find (or exclude) a **tiny excess** of decays with the summed electron energy at the expected value.







Summary

- Neutrinos interact only through the weak interaction.
  - Very small cross-sections.
    - Challenging experiments!
  - May be responsible for the observed asymmetry between matter and antimatter in the Universe.

- The discovery of neutrino oscillations implies:
  - **Non-zero neutrino masses**
  - A new source of **CP violation** in the Standard Model.

- Neutrinos **may be their own antiparticles.**
  - Search for Majorana neutrinos with neutrinoless double-beta decay experiments.

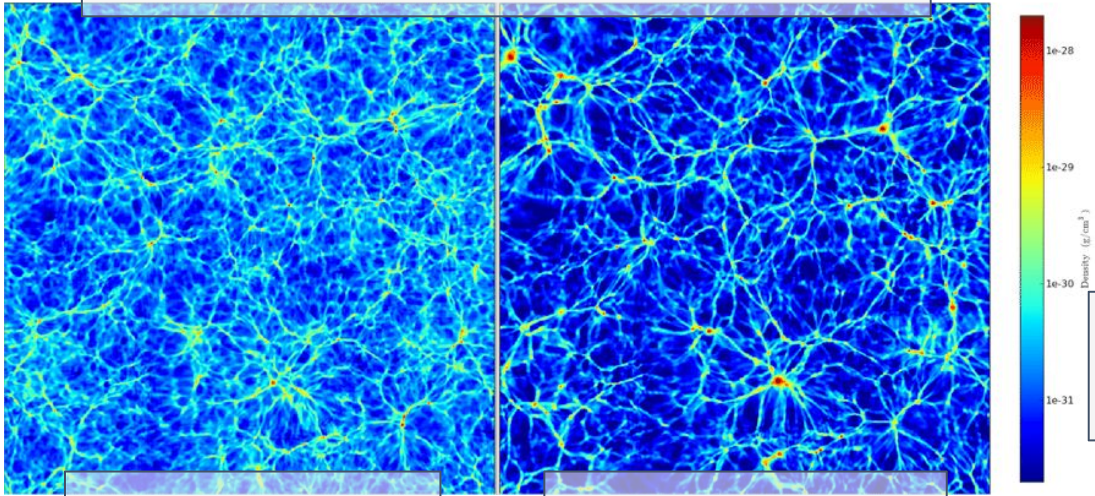
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Extra

What does the cosmos say about neutrinos?

- Neutrinos are the second most abundant (Standard Model) particle in the universe.
  - Dark matter → not in the Standard Model!
- The presence of neutrinos affects the evolution of the universe.
- We can infer neutrino properties by observing the cosmos.

Distribution of matter in the universe



With neutrinos

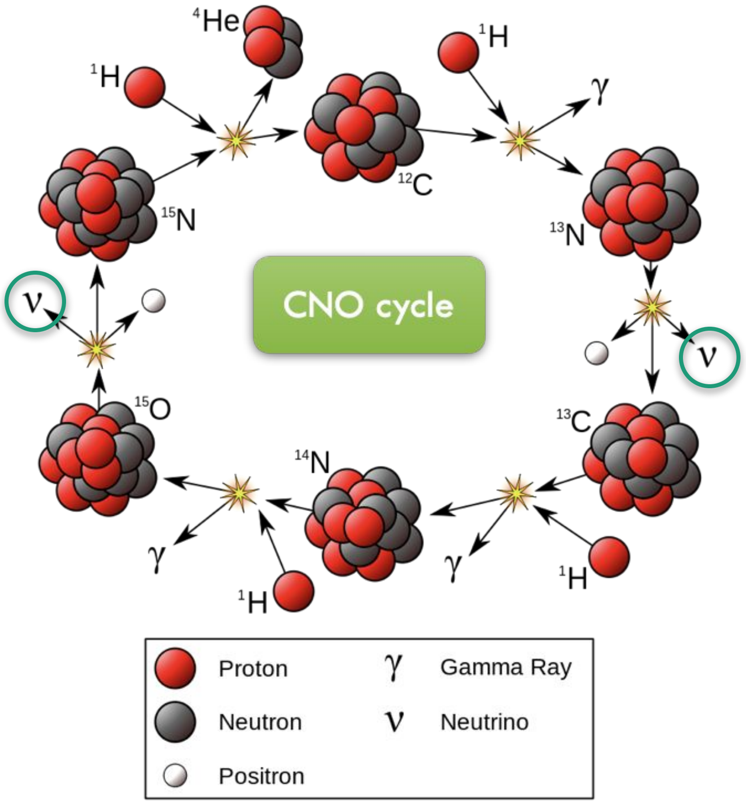
Without neutrinos

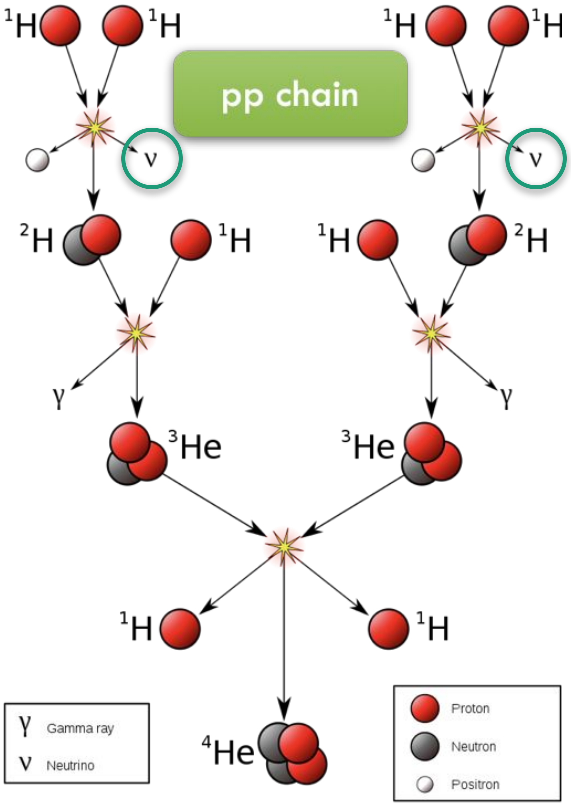
- Number of neutrinos: 2.99 ± 0.34
- Neutrino mass: **< 0.5 eV**
- In agreement with laboratory experiments!

But how do we know neutrinos are **not massless**?!

The Standard Solar Model

- Precise prediction of the number of electron neutrinos produced in the Sun.





The solar neutrino puzzle

2002

- In the late 1960's, Ray Davis and John Bachall proposed an experiment to try to detect these solar neutrinos.
- The measured flux of **electron** neutrinos was about ⅓ of the Standard Solar Model expectation...

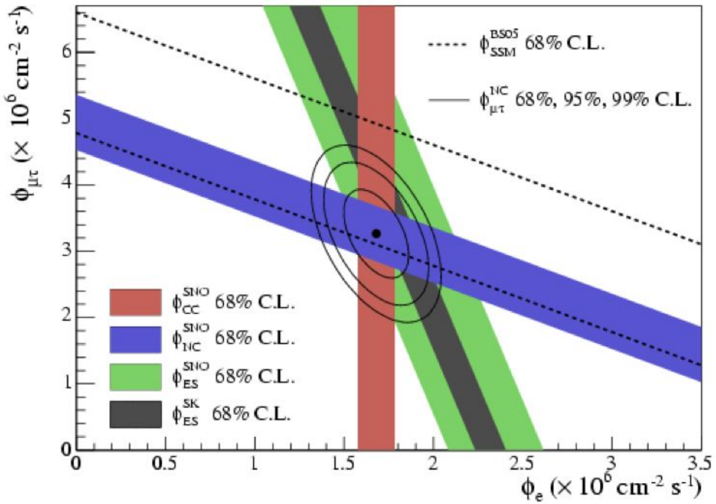
The Homestake experiment
1970 – 1994!

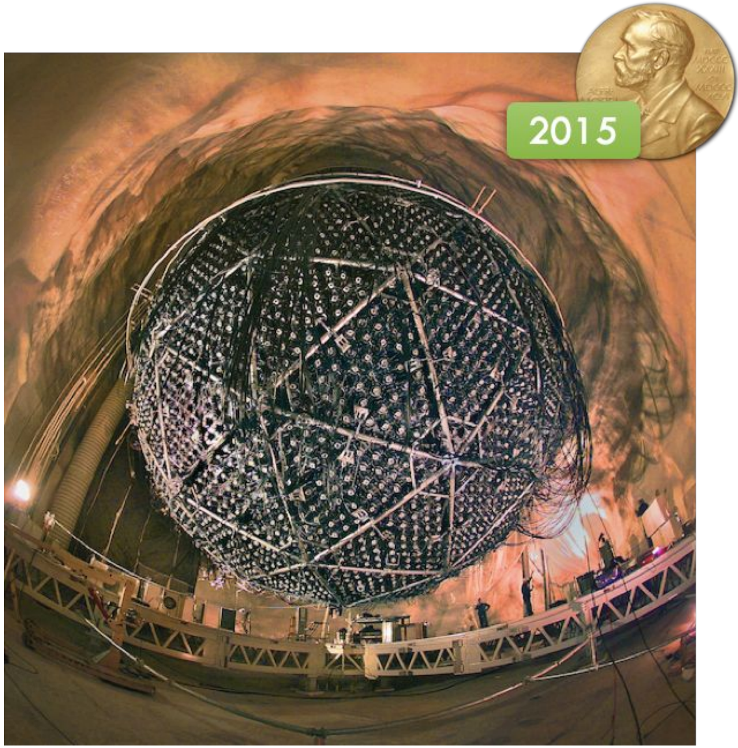
Ray Davis

The solar puzzle solution

- Electron neutrinos produced in the sun **change to different flavours** before they reach the Earth!
- SNO experiment (2001, Canada):
  - Measure total neutrino flux in **agreement with the Standard Solar Model – neutral current.**
  - Measure the electron neutrino flux in agreement with **Ray Davis – corrente carregada.**

⇒ Neutrinos oscillate and therefore are massive!



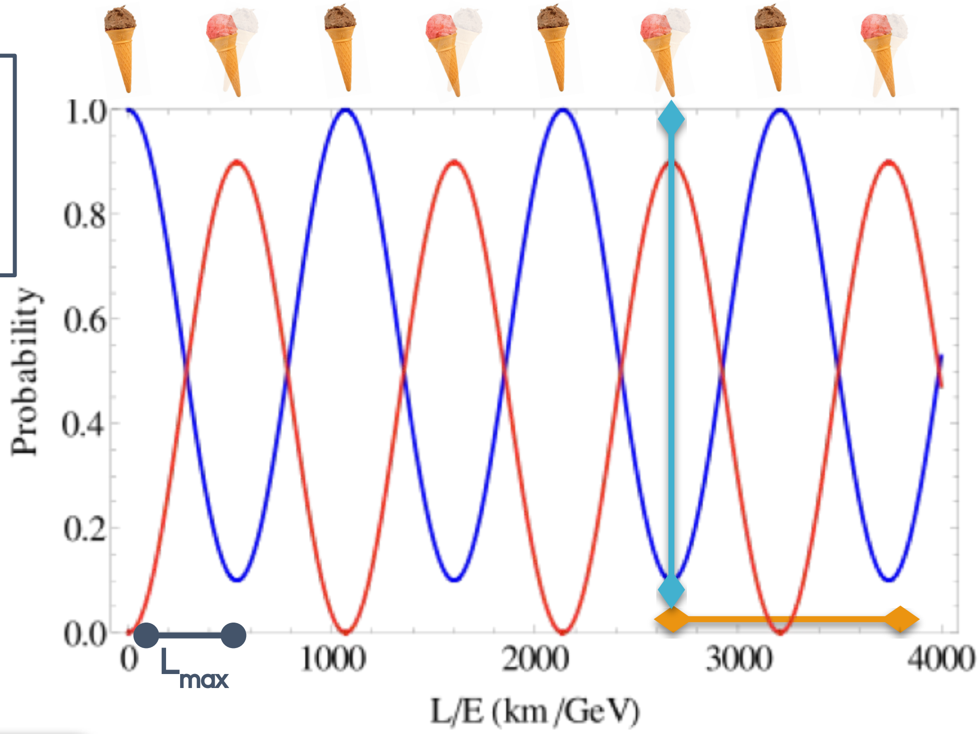


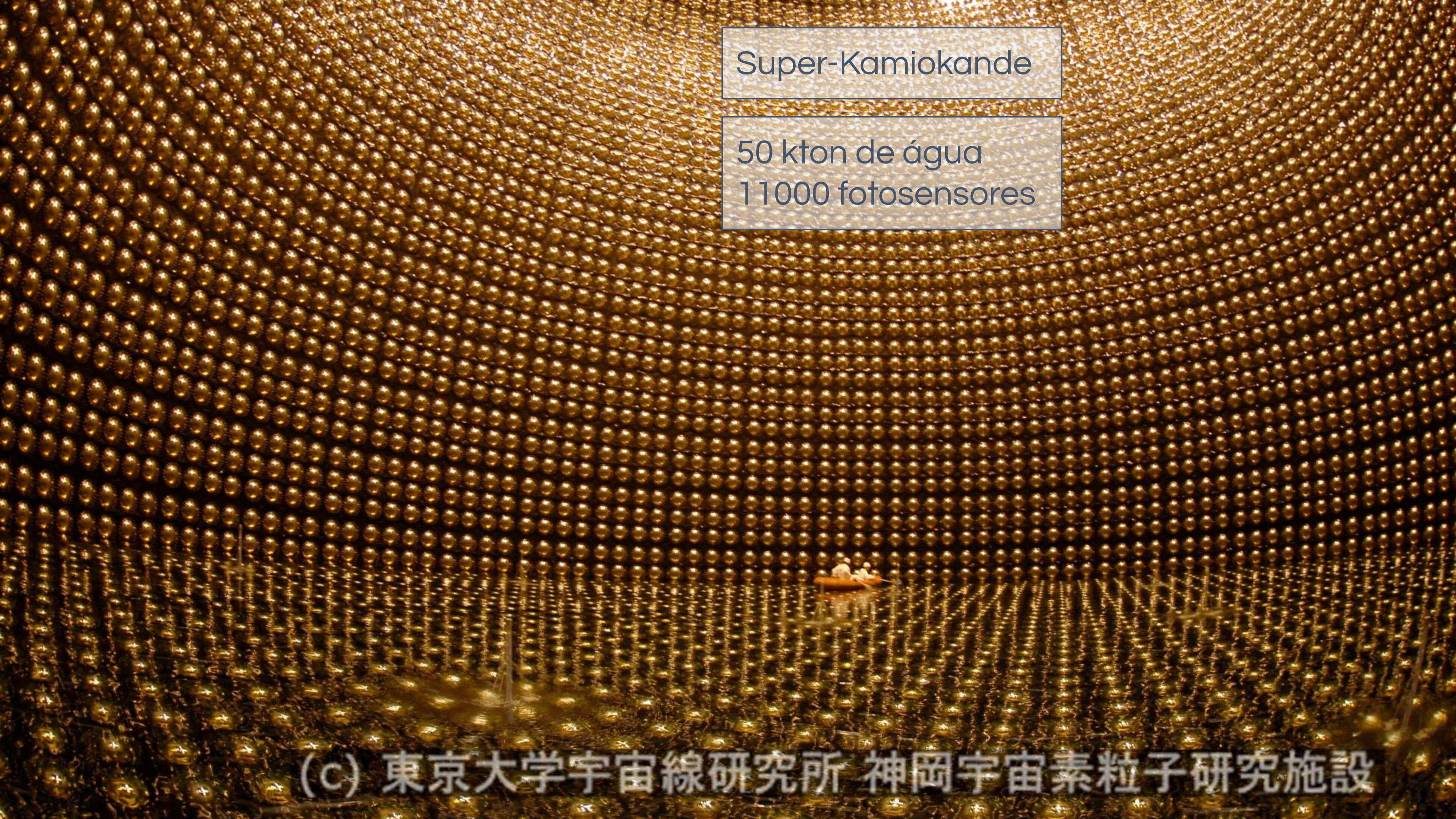
Neutrino oscillations

Measuring the propagation distance at which a neutrino of energy E is most likely to change flavour, Lmax, allows us to infer the squared-mass difference.

$$\Delta m^2\,[\mathrm{eV}^2] = \frac{\pi}{2}\,\frac{E[\mathrm{GeV}]}{1.27 \times L_{max}\,[\mathrm{km}]}$$

$$P(\nu_e \to \nu_\mu) = \underbrace{sin^2(2\theta)}_{\text{Oscillation amplitude}}\, sin^2(1.27\underbrace{\Delta m^2 \frac{L}{E_\nu}}_{\text{Oscillation frequency}})$$





Super-Kamiokande

50 kton de água
11000 fotosensores

Pontecorvo-Maki-Nakagawa-Sakata

- **Three-flavour** neutrino mixing is described by the PMNS matrix.
  - Includes complex phase that **violates CP symmetry** if different from zero or pi.

Weak / Flavor states

"Atmospheric" parameters

Neutrinos may hold the key to explain how **matter** came to dominate over **antimatter** in the history of the Universe!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{\boxed{-i\delta_{CP}}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{\boxed{+i\delta_{CP}}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Reactor" parameters

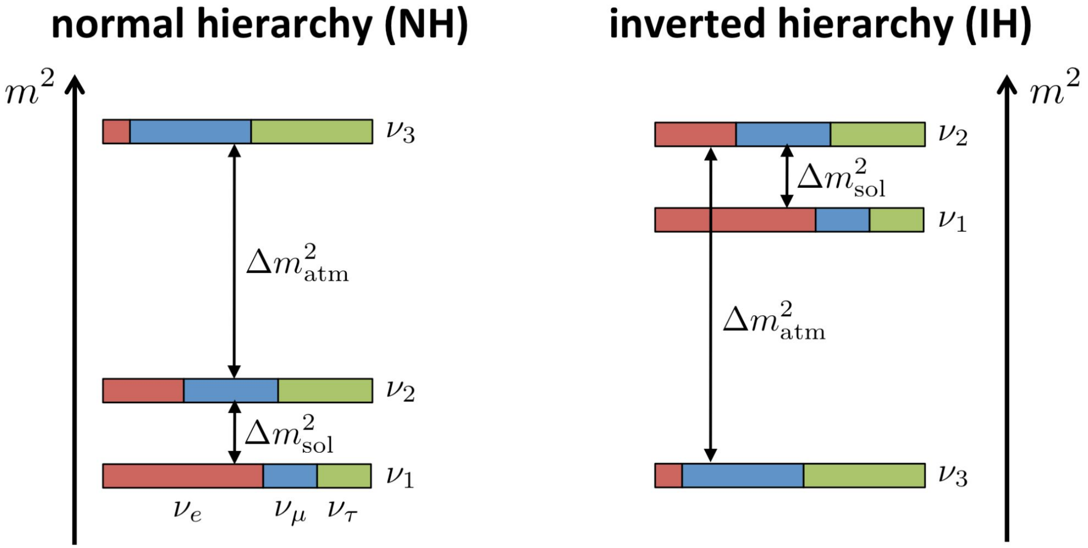
CP violating phase

"Solar" parameters

Mass states

Neutrino mass ordering

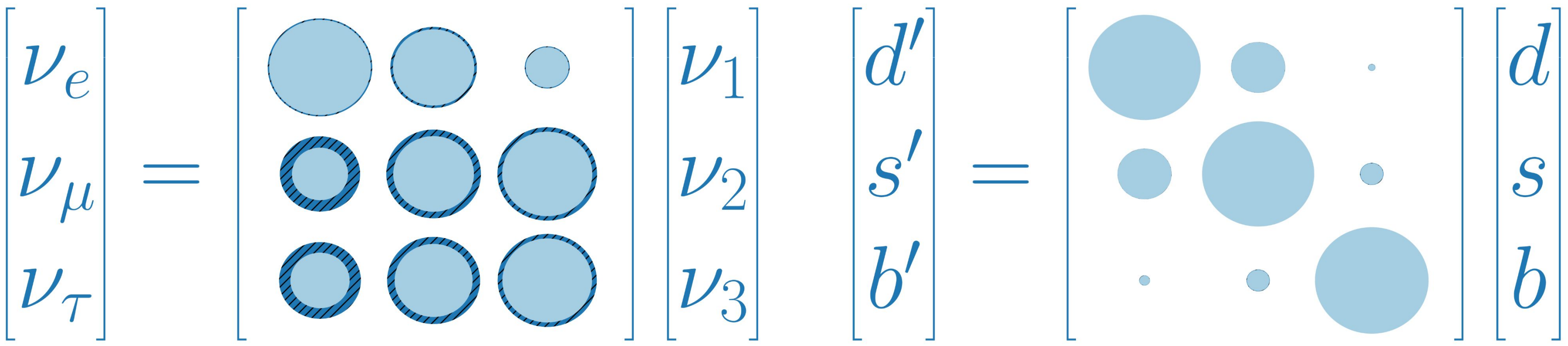
- To **first order**, neutrino oscillation experiments are not sensitive to the sign of the squared-mass differences...
    - Currently, we do not know if $m_1 < m_3$ (**normal ordering**) or if $m_3 < m_1$ (**inverted ordering**).
- However, at **high energies**, coherent interactions with **matter** have an effect on **electron (anti)neutrinos**, but not on the other flavours!

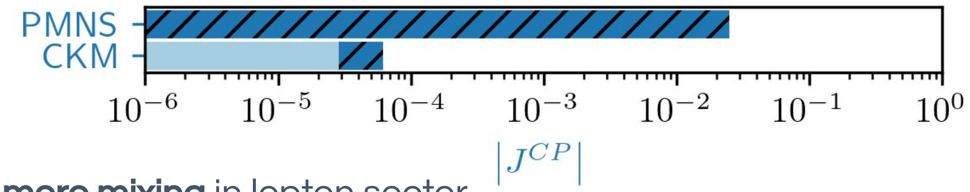


Lepton *vs* quark mixing

PMNS NuFit 5.1 (2021)

CKM CKMfitter Spring 21

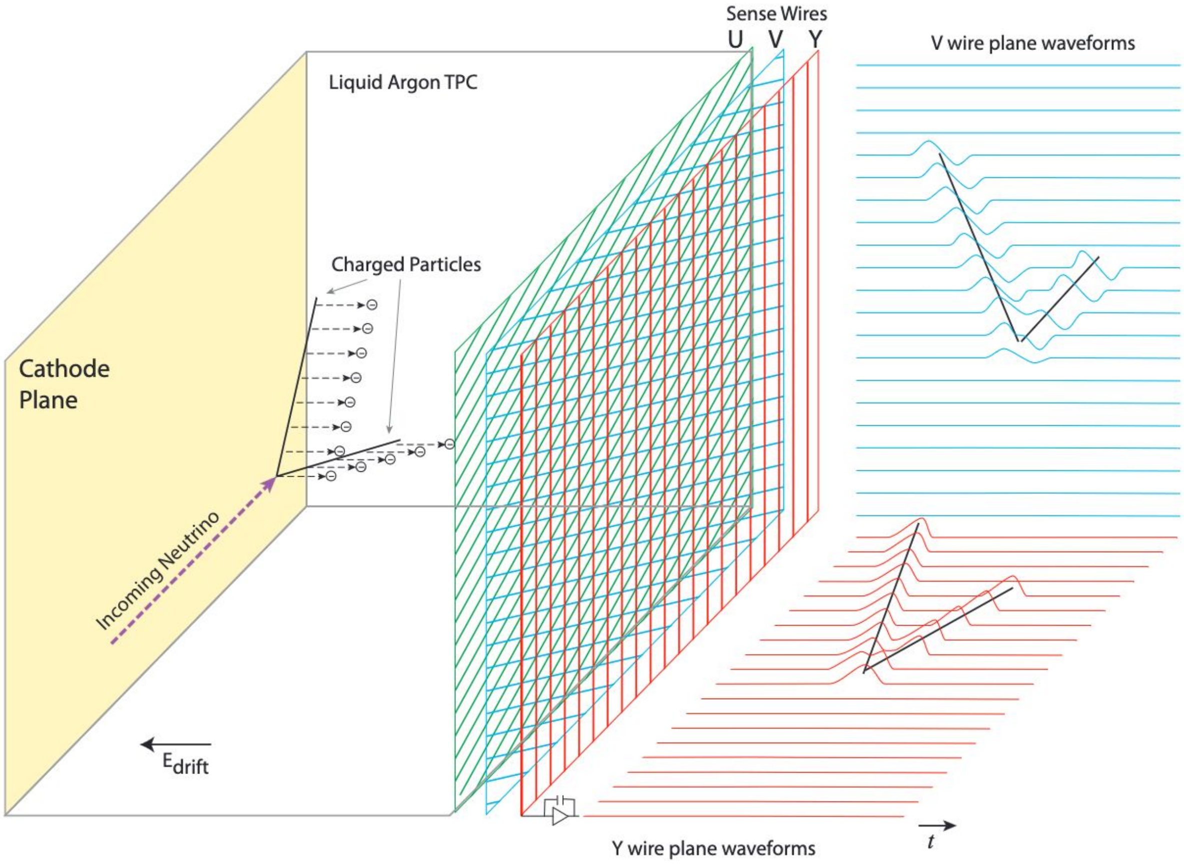


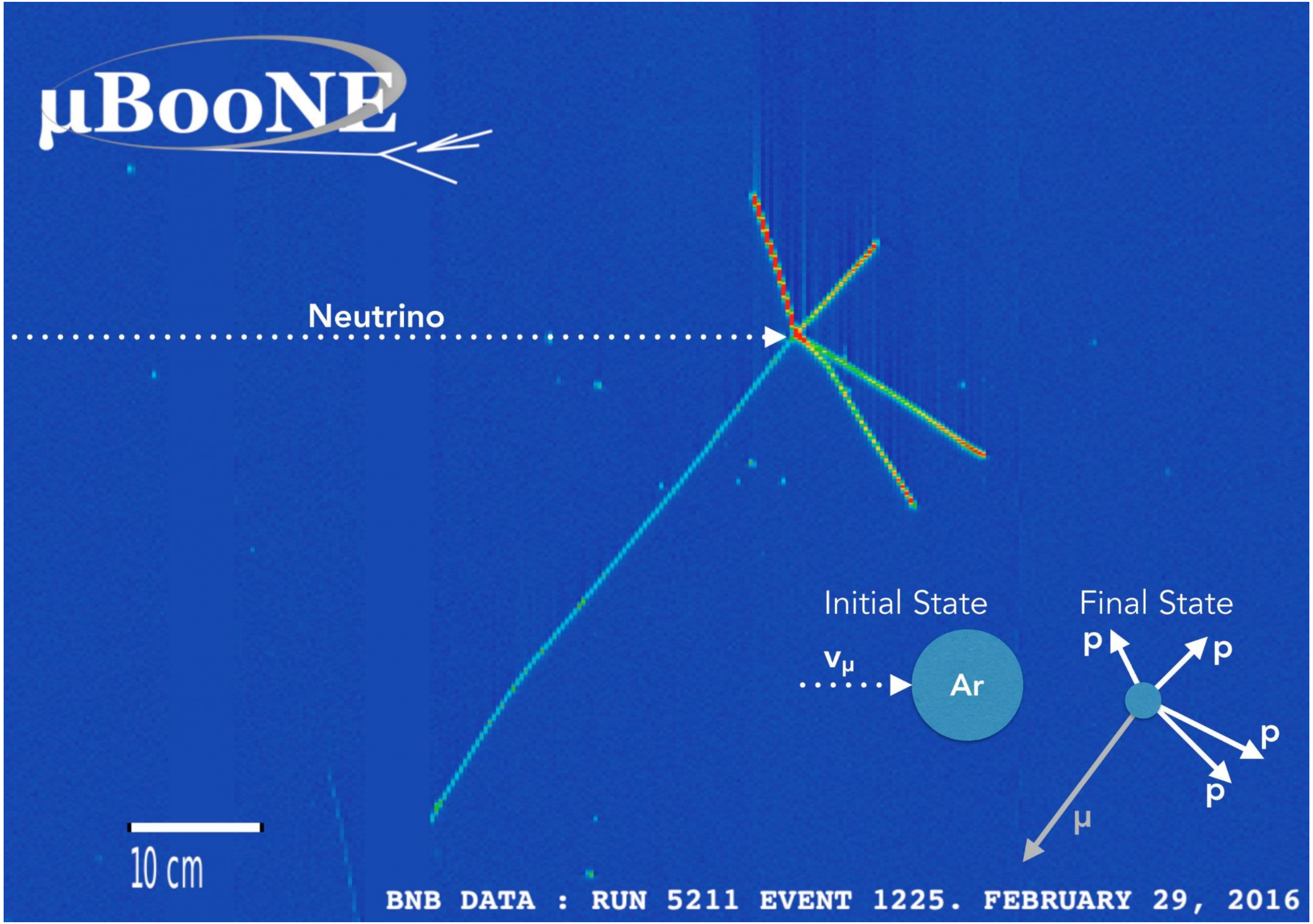


- Much **more mixing** in lepton sector.
- **CP violation** can be up to three orders of magnitude larger!

Liquid-argon time-projection chamber

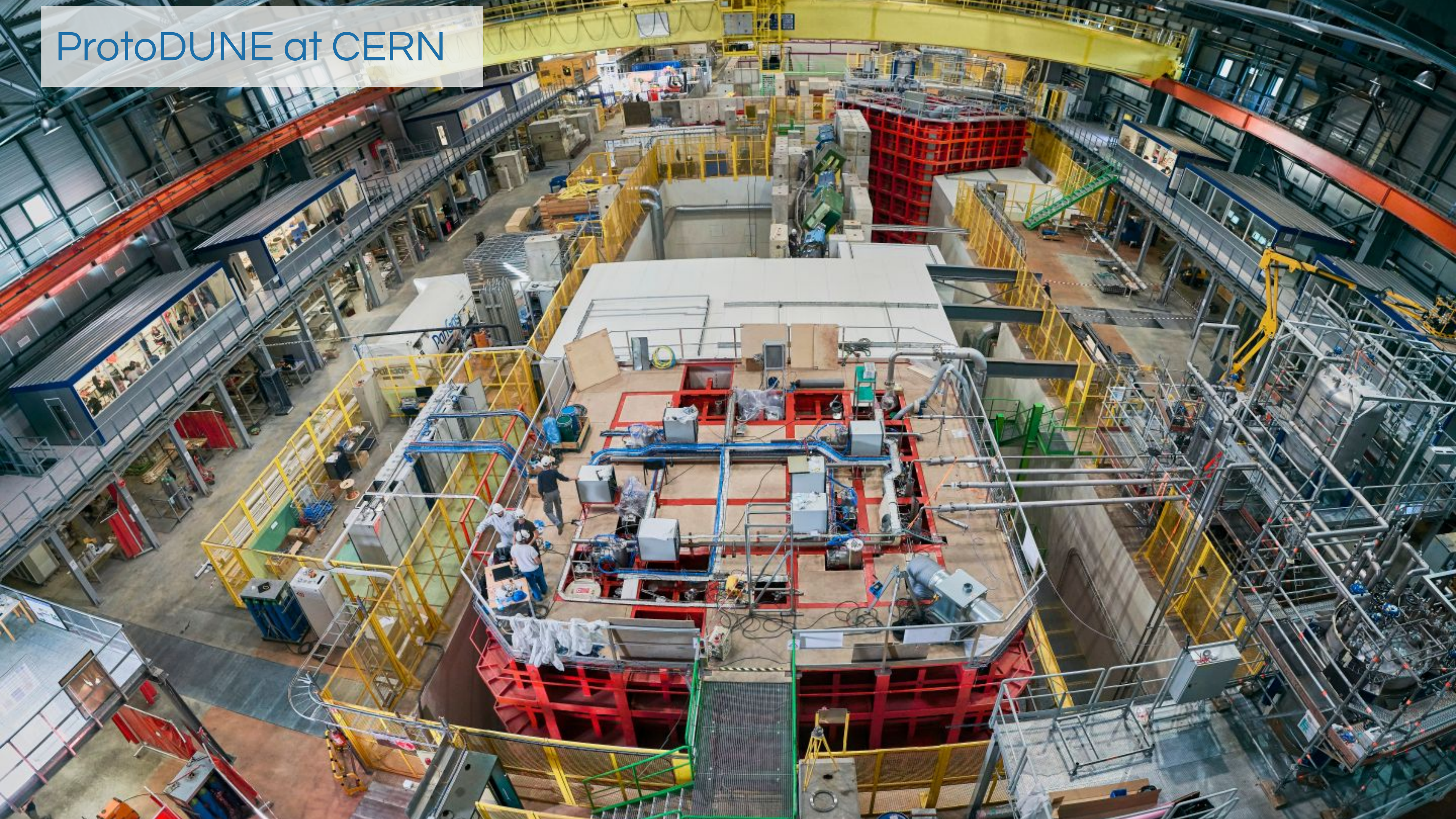
Advanced detector technology to meet DUNE's high-precision requirements.



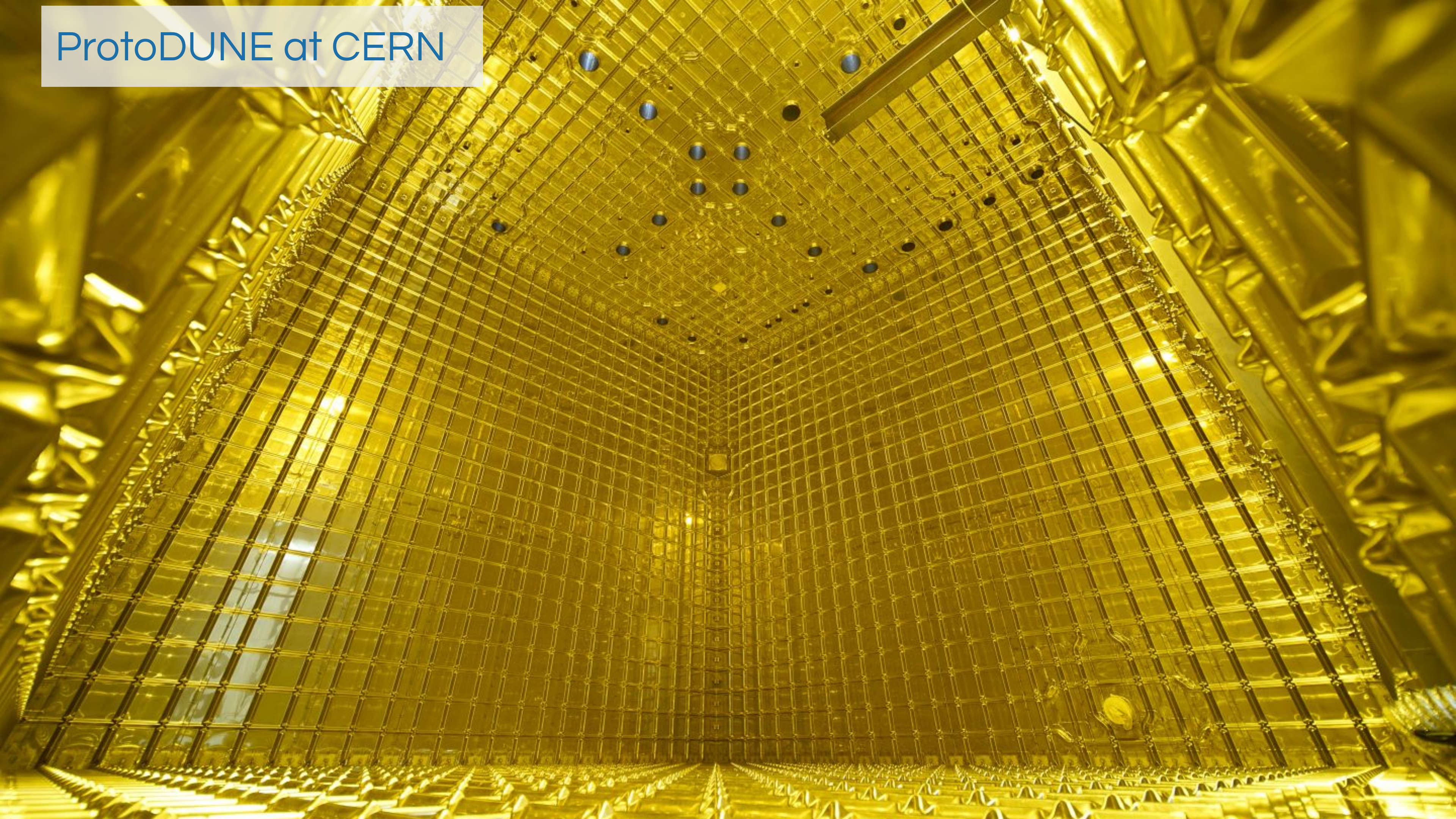


Credit: Fermilab

ProtoDUNE at CERN

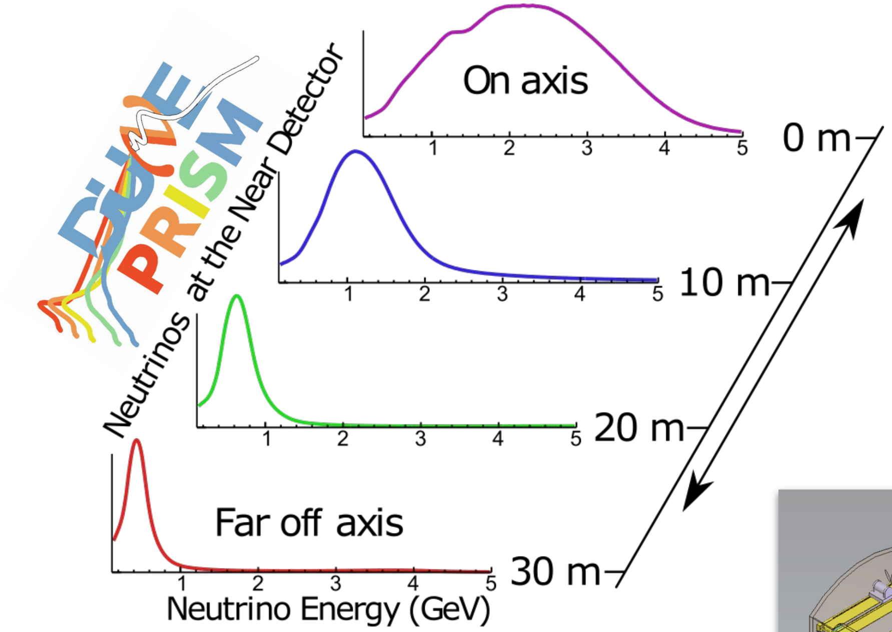


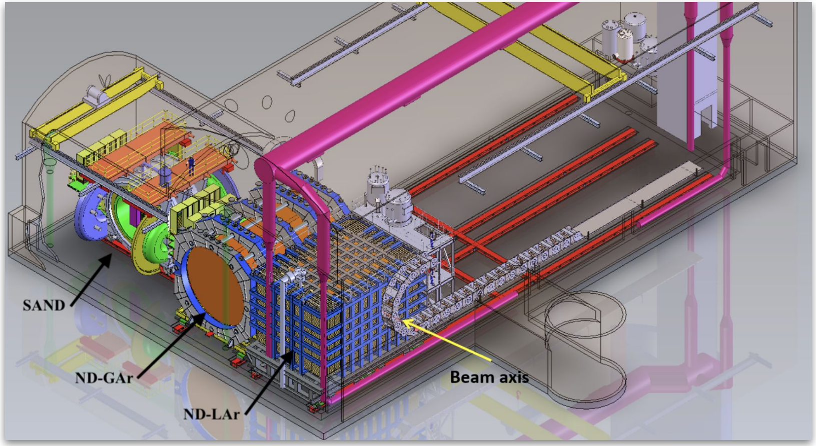
ProtoDUNE at CERN

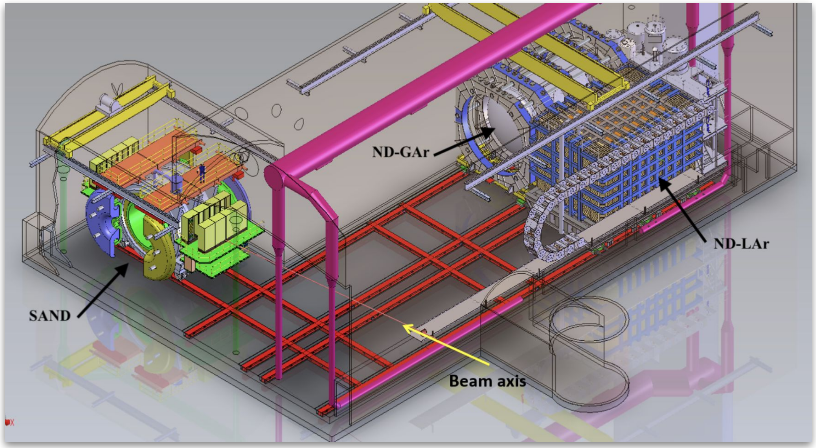


ProtoDUNE no CERN

DUNE near detectors

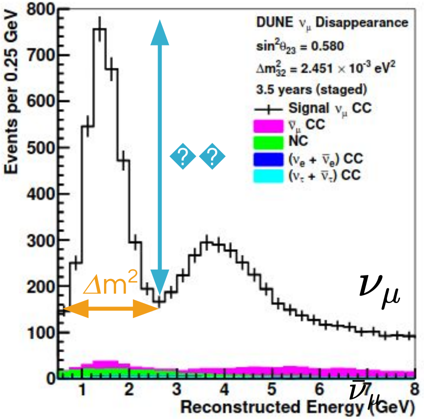


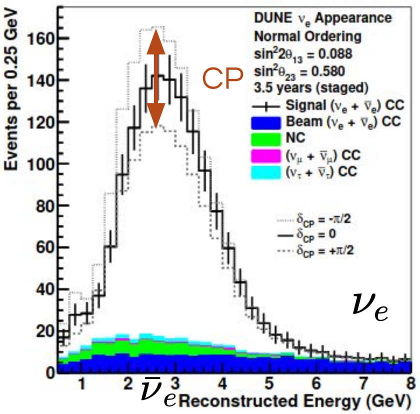




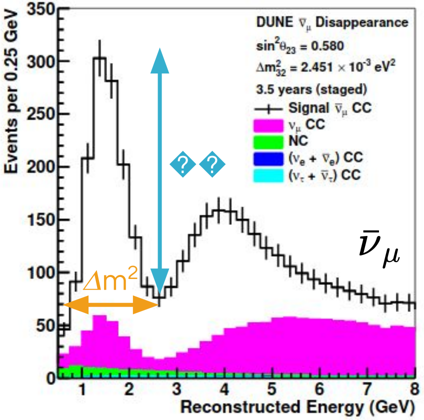
- Liquid and gaseous argon TPCs.
- **Moveable!**
    - "PRISM" effect allows for precise measurements of neutrino interactions.

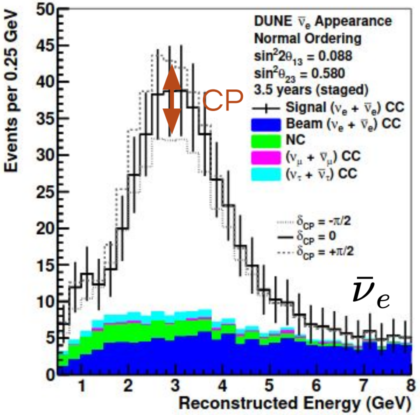
Neutrino oscillations with DUNE





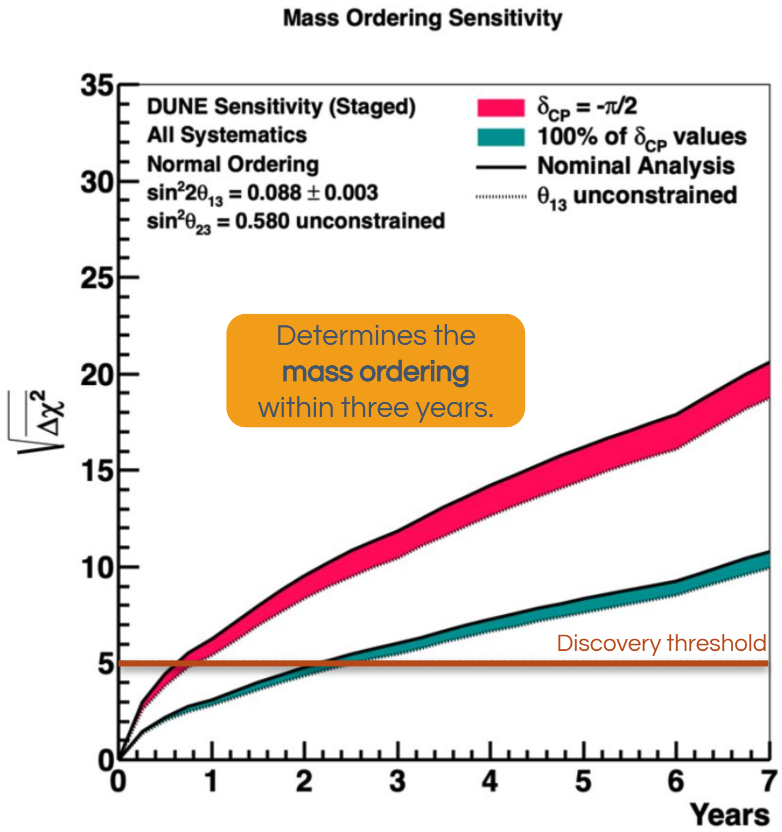
Neutrinos



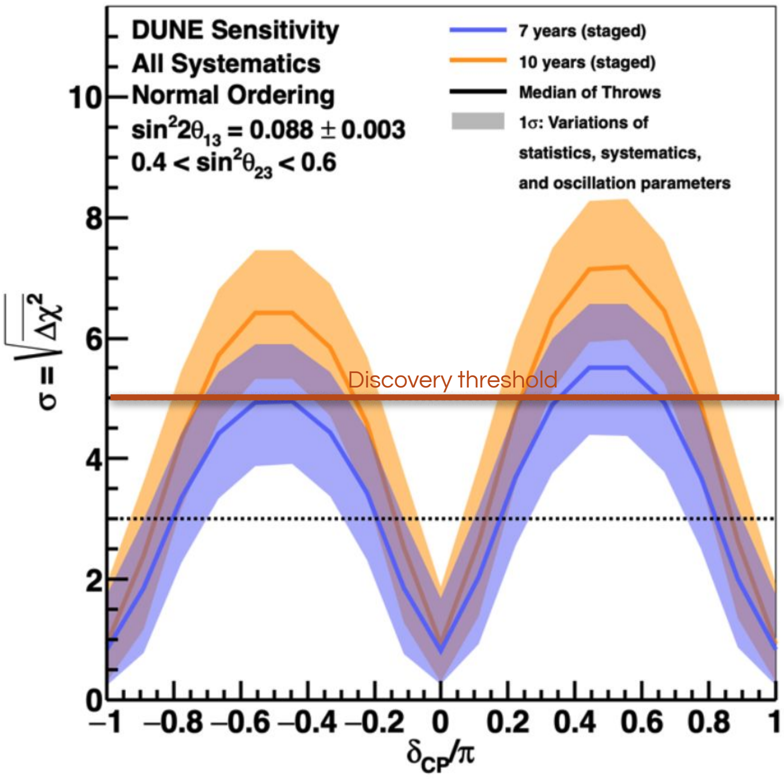


Antineutrinos

DUNE sensitivity



Discovers **CP** violation unless it is very small



The see-saw mechanism

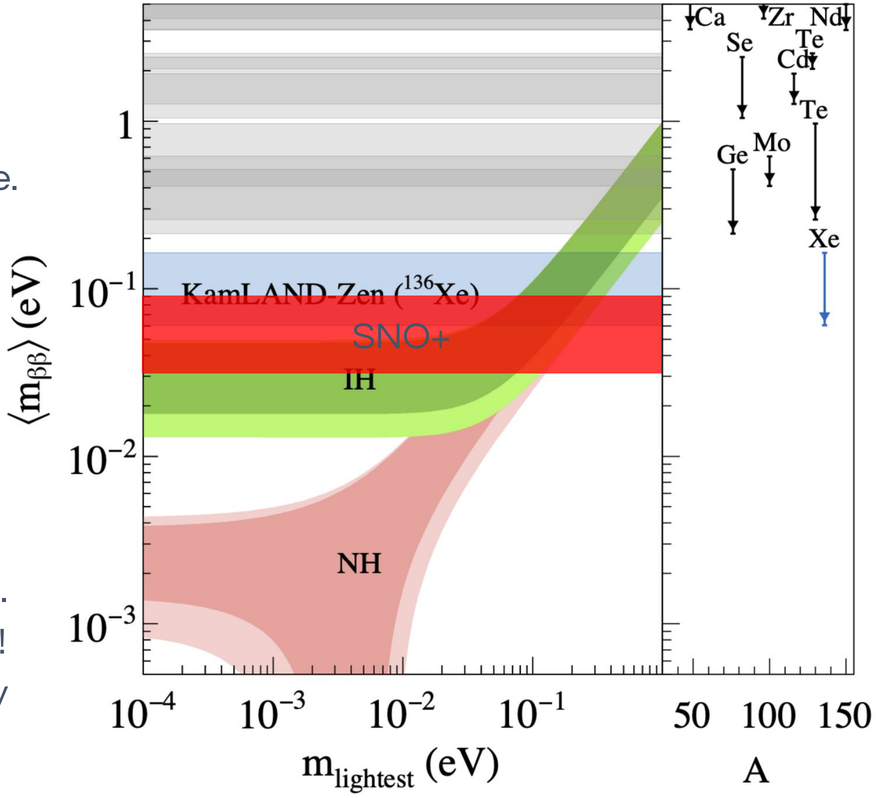
- Two **"active"** neutrino states (per generation) are sufficient to explain all known neutrino interactions.
- We can **speculate** the existence of two additional states.
  - In analogy to the four states necessary to describe the charged fermions.
  - These additional **"sterile"** states **do not interact** with the Standard Model.
  - **However**, the masses of the **sterile** and **active** neutrinos **mix**.
    - **Large** sterile neutrino **masses** would result in the **very small** active **neutrino masses we observe**.
    - Requires neutrinos to be **Majorana** particles!

Putting it all together

- No observation of neutrinoless double-beta decay so far...
  - But we have upper limits on the decay rate.

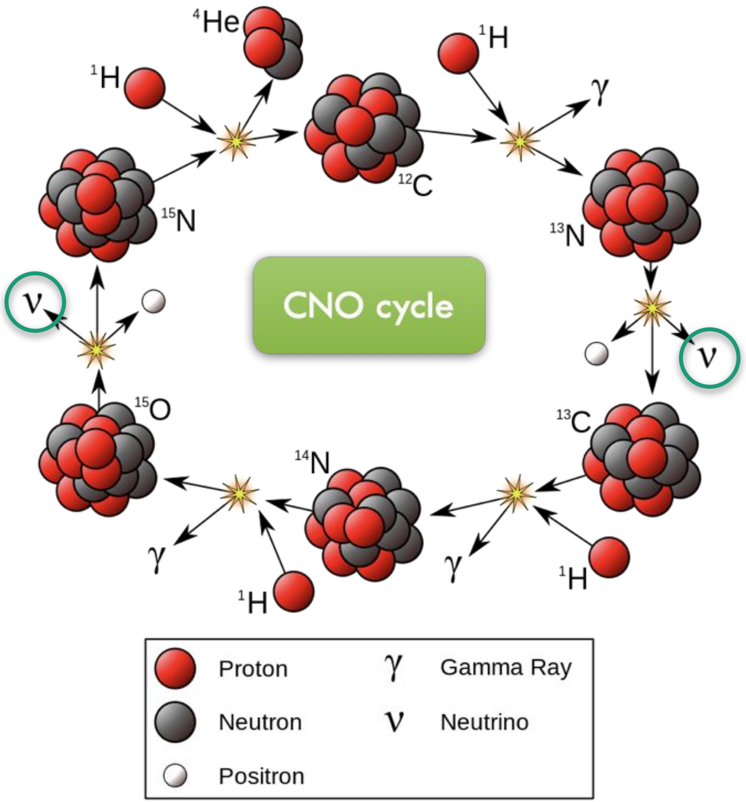
- Connection between neutrinoless double-beta decay rates and neutrino mass depends on:
  - Neutrino **mixing** parameters.
  - Neutrino **mass ordering**.

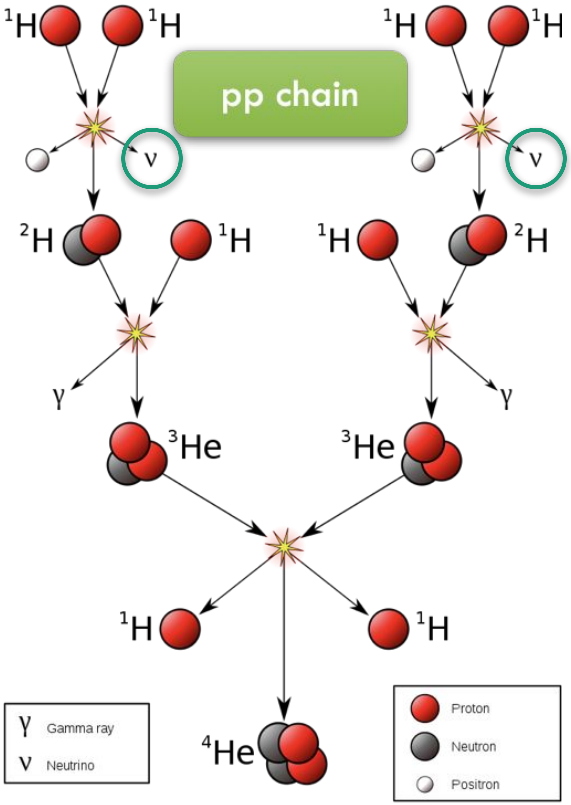
- It may be that neutrinos are Majorana particles and neutrinoless double-beta decay rate is zero.
  - In this case we will never know the answer!
- If the neutrino mass ordering is **inverted**, we may know the answer *soon* (few of decades?).



Neutrino mixing and oscillations

The Standard Solar Model





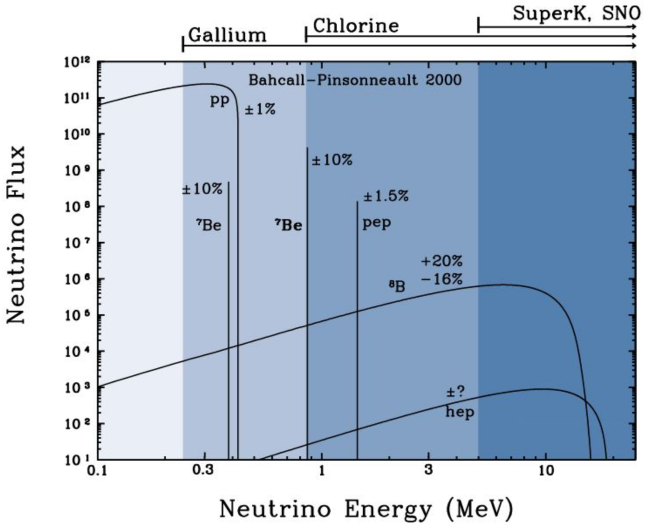
Solar neutrino puzzle

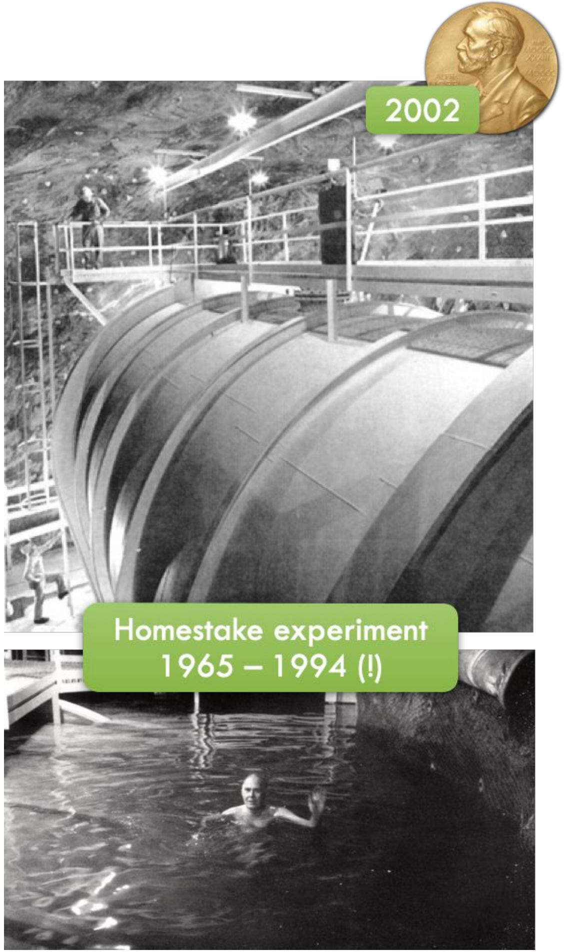
- In the late 1960s Ray Davis and John Bahcall set up an experiment to try to detect these solar neutrinos.

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

- They detected the neutrinos, but not as many as they expected.
- This was soon confirmed by a number of other experiments.
    - Kamiokande, SAGE, GALLEX.

Problem with the Standard Solar Model?

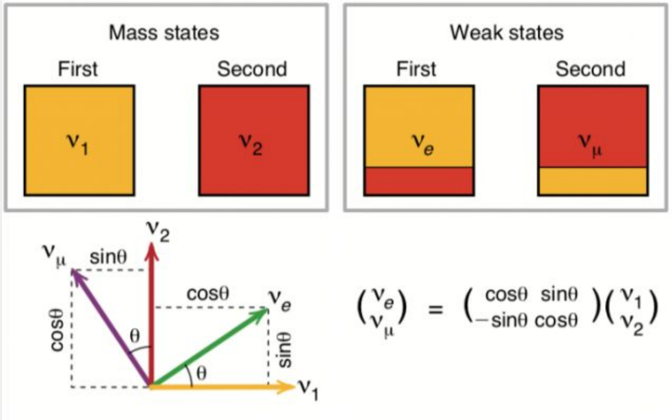


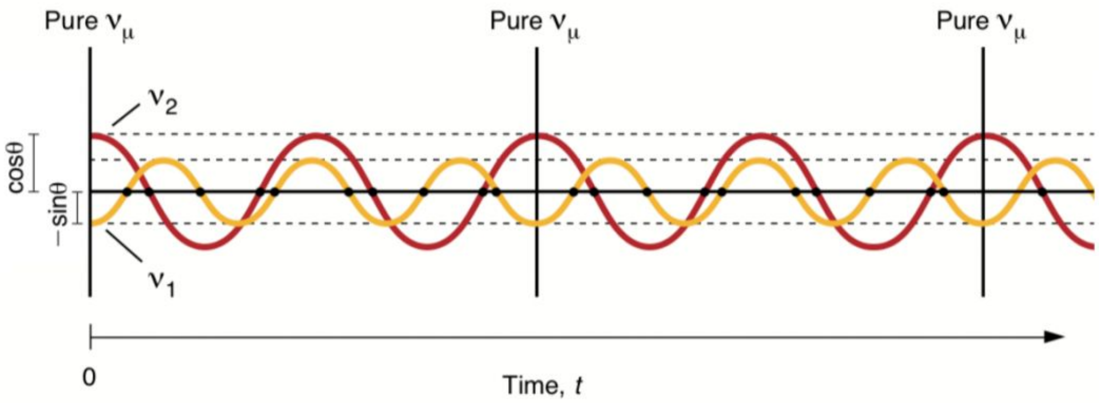


Neutrino mixing

- Neutrinos:
  - **Evolve** in (space-)time, obeying the Schrödinger equation (and relativistic counterparts).
  - **Interact** weakly with the other Standard Model fermions.

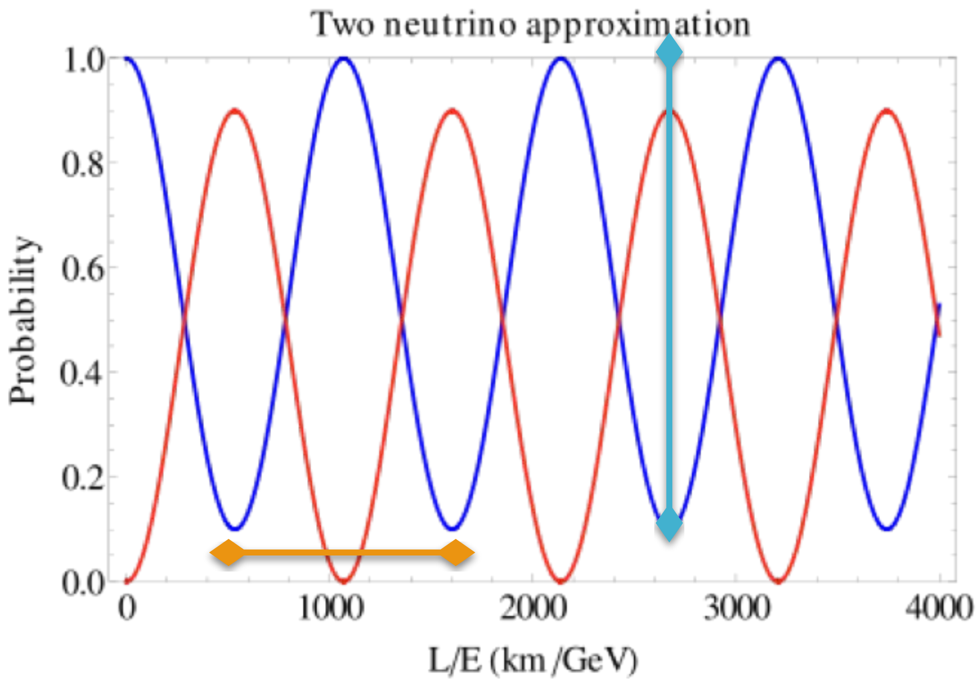
- The basis for describing the time-evolution of neutrinos and their weak interactions need not be the same.
  - **Mass** *vs* **Weak** interaction eigenstates.
  - **Consequence: neutrino oscillations!**





Credit: SLAC neutrino group; "Celebrating the neutrino", Los Alamos Science, 1997.

Neutrino oscillations

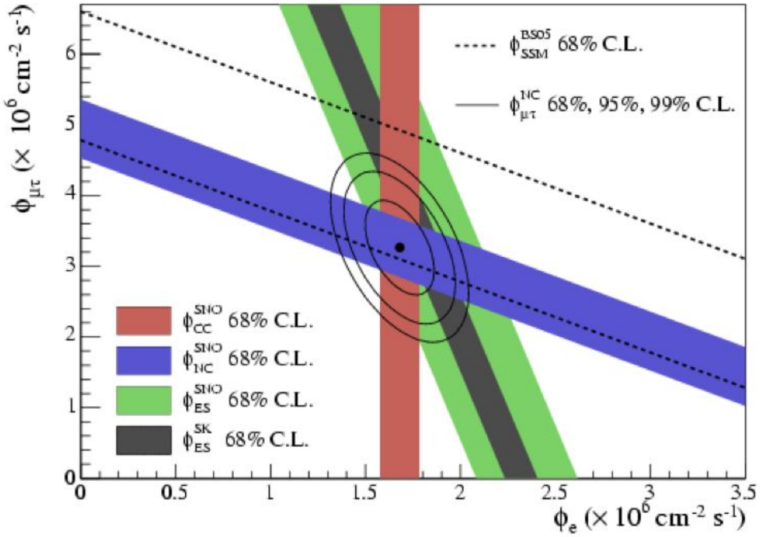


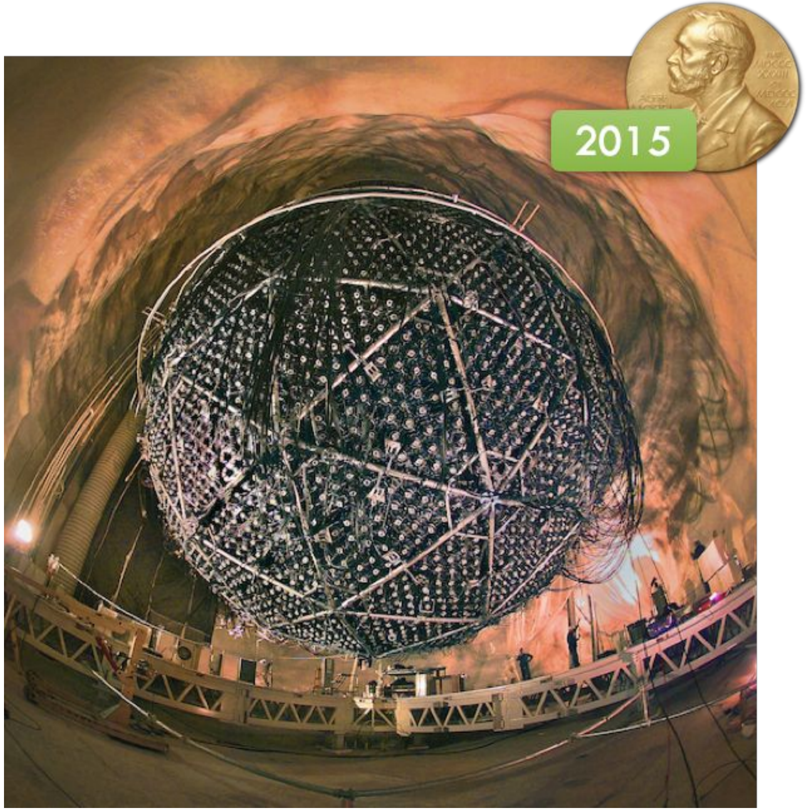
- **Mixing angle** determines the **amplitude.**
- **Squared-mass difference** determines the **frequency.**

$$P(\nu_e \rightarrow \nu_\mu) = sin^2\underbrace{(2\theta)}_{\text{Oscillation amplitude}} sin^2(1.27\underbrace{\Delta m^2 \frac{L}{E_\nu}}_{\text{Oscillation frequency}})$$

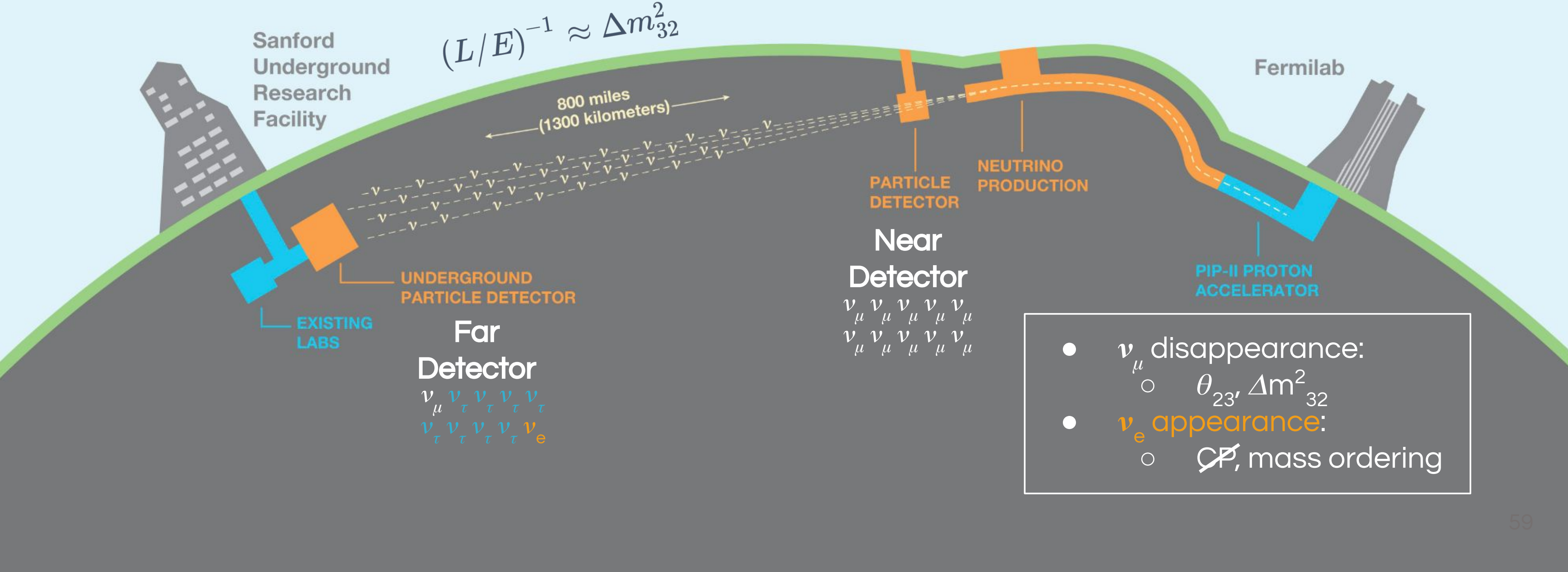
The solar neutrino solution

- Two experiments provided confirmation of Ray Davis' observations: **Super-Kamiokande** and **SNO.**
- **SNO** measured **total neutrino flux** and **electron neutrino flux** independently.
- Confirmation that **total neutrino flux** from Standard Solar Model is **correct.**
- **Electron neutrinos** really are disappearing!



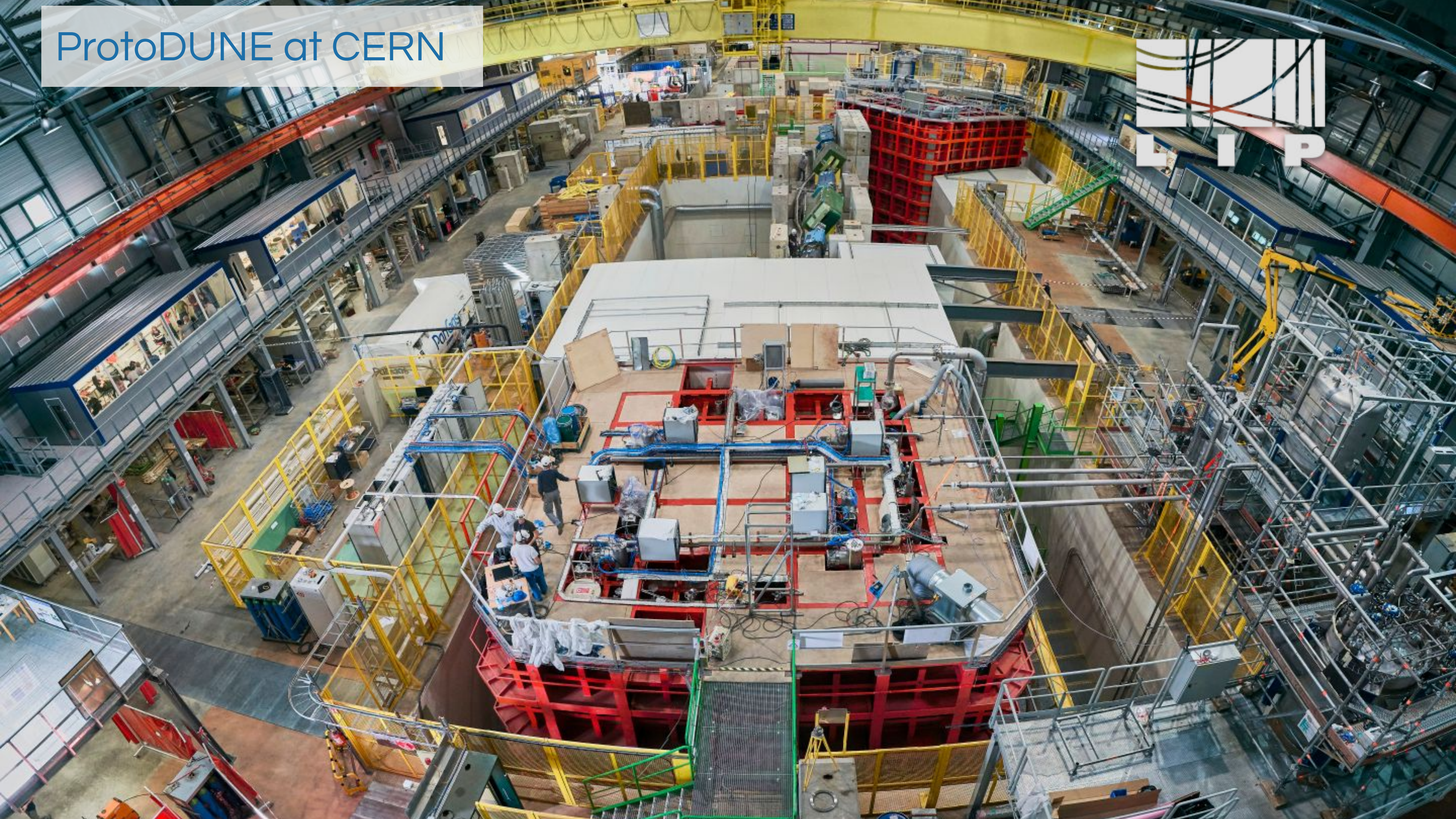


DEEP UNDERGROUND
NEUTRINO EXPERIMENT

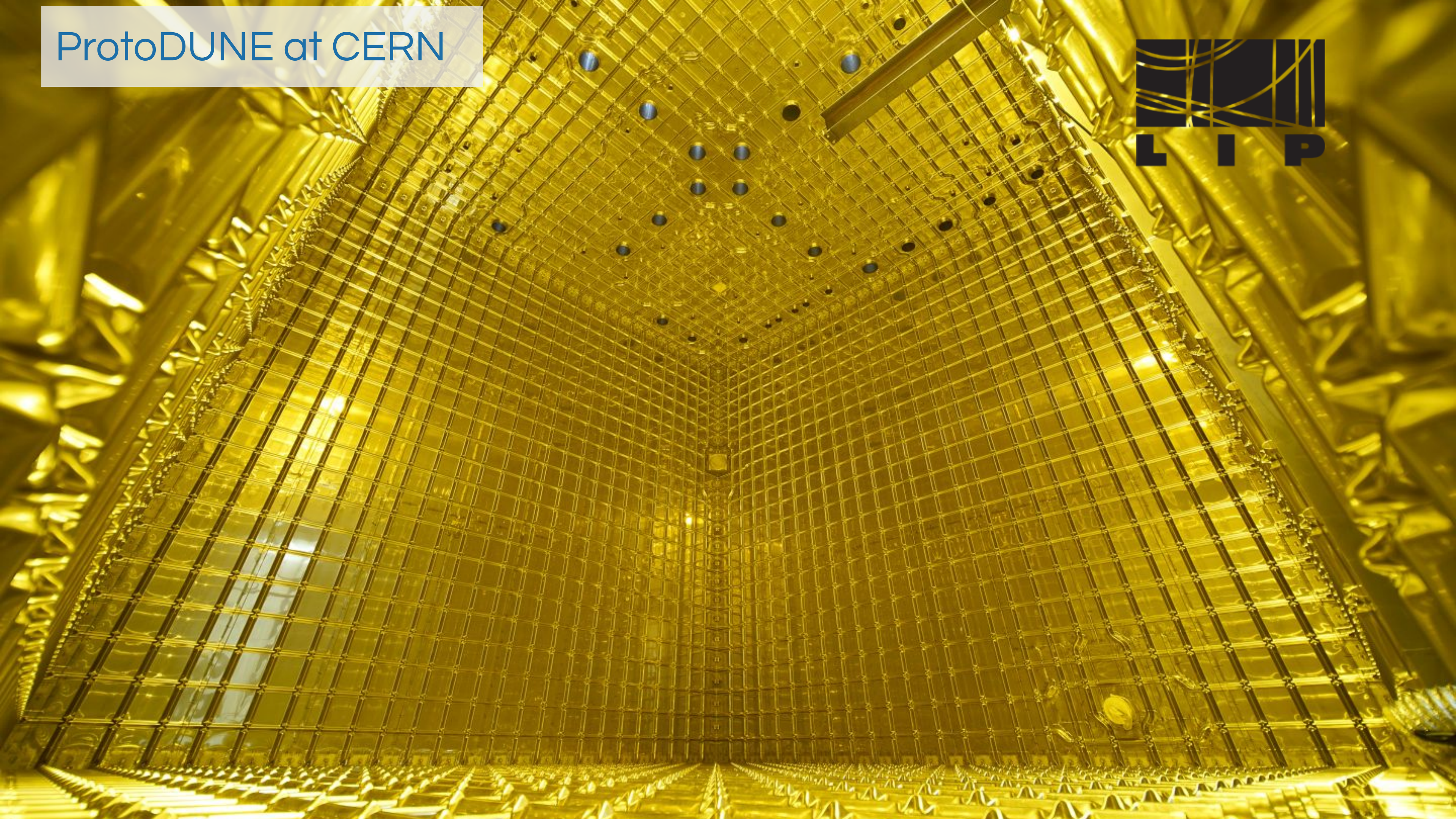


- ν_μ disappearance:
  - θ_{23}, Δm^2_{32}
- ν_e appearance:
  - ~~CP~~, mass ordering

ProtoDUNE at CERN



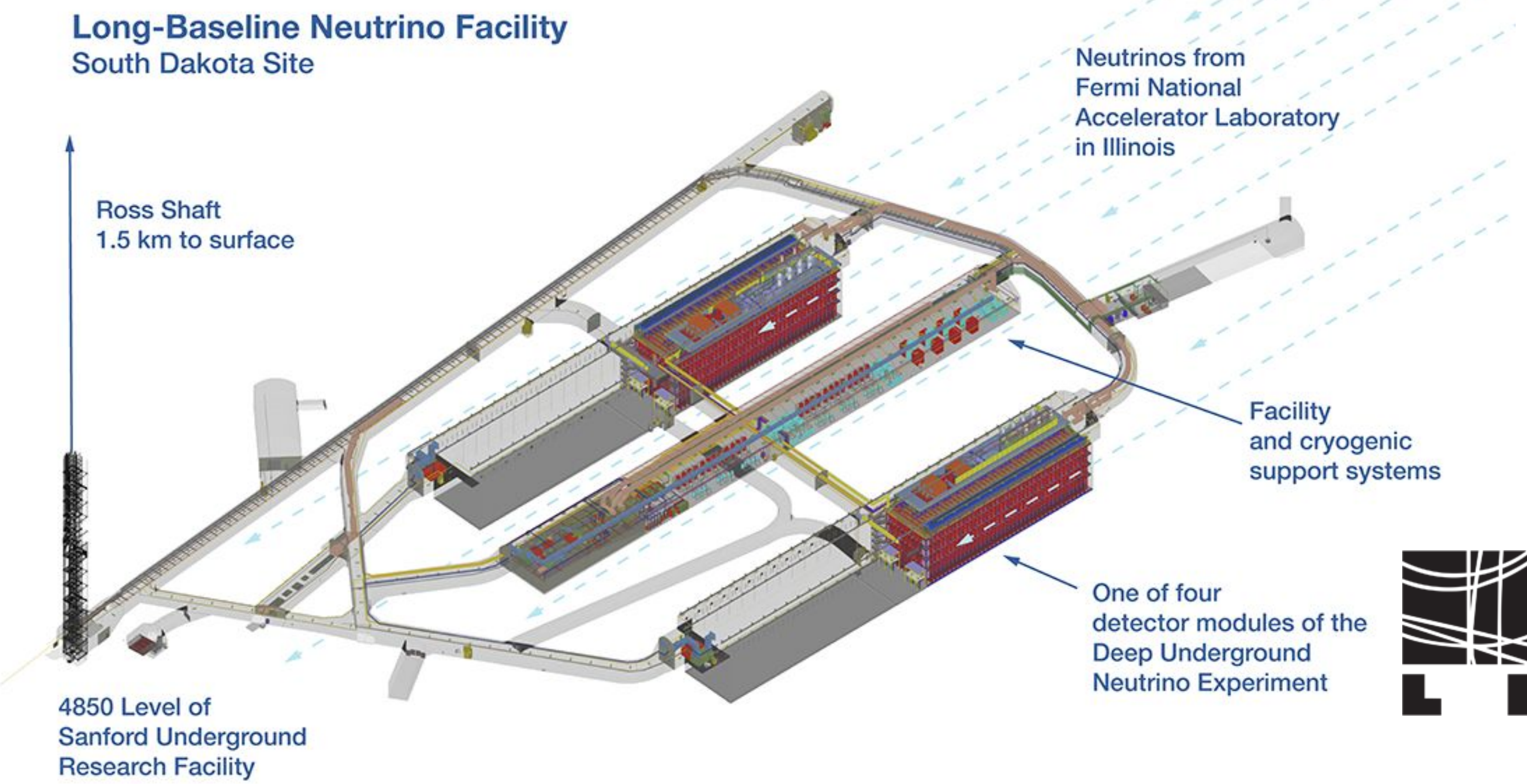
ProtoDUNE at CERN



ProtoDUNE at CERN

The DUNE far detectors

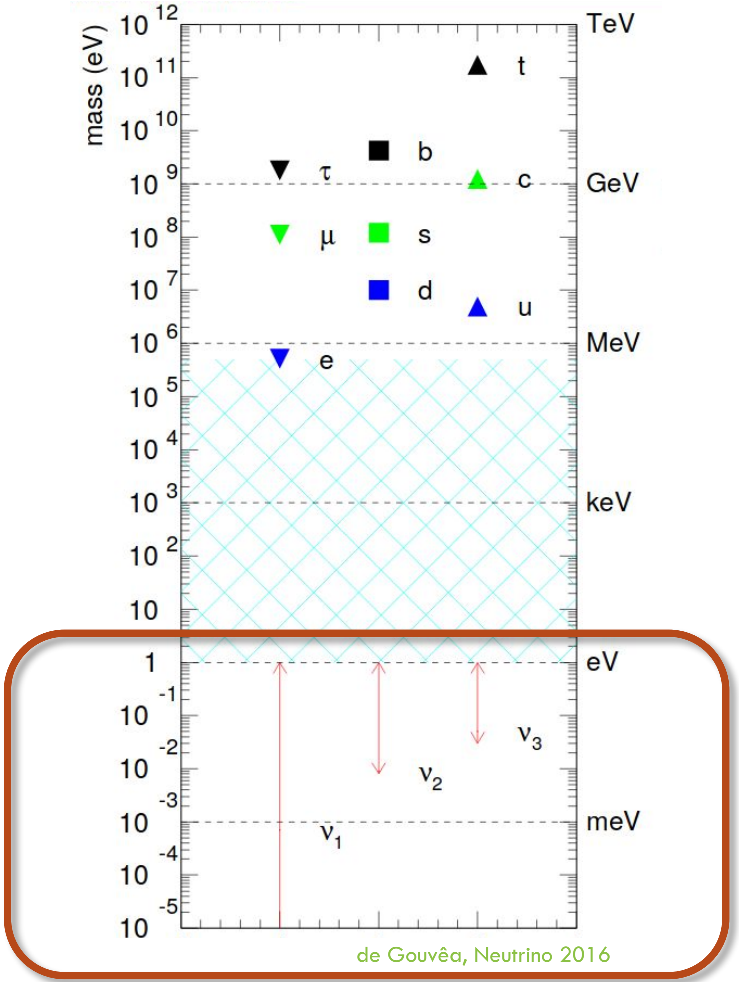
- 1.5 km underground in South Dakota.
- Four LArTPC modules with **17 kton** of liquid argon each.



Neutrino mass and double-beta decay

Neutrino mass

- There are **six orders of magnitude** between the **electron** mass and the **upper limit** on **neutrino** mass.
- The Higgs mechanism explains **how** particles get mass but it **doesn't predict their masses.**
- The **very large difference** between the masses of neutrinos and that of other particles hints at a **different mechanism** for neutrino mass.
- The mass of the charged fermions is described by **Dirac mass** terms.
- Because they are neutral, neutrinos may be described by **Majorana mass** terms.

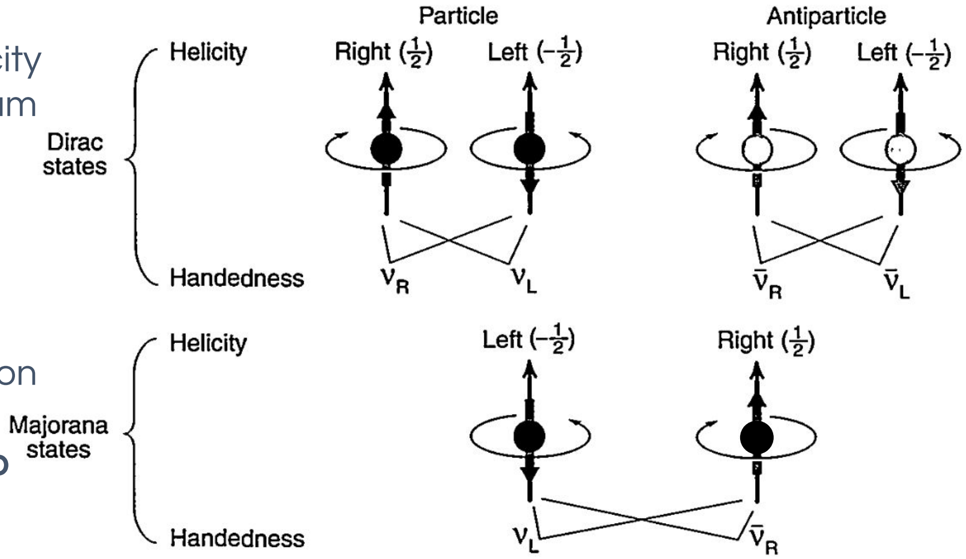


de Gouvêa, Neutrino 2016

Dirac or Majorana?

- To turn a particle into an antiparticle:
  - Flip its charge (**C**)
  - Flip its direction (**P**), resulting in opposite helicity
    - Helicity: "alignment" between momentum and spin.
- But what does it mean to "flip the charge" of a neutrino?!
- Neutrinos can have a more economic representation than the other fermions.
  - Instead of four **Dirac** states, we only need **two Majorana states.**
  - The only difference between Majorana neutrinos and antineutrinos is the direction of their spin!

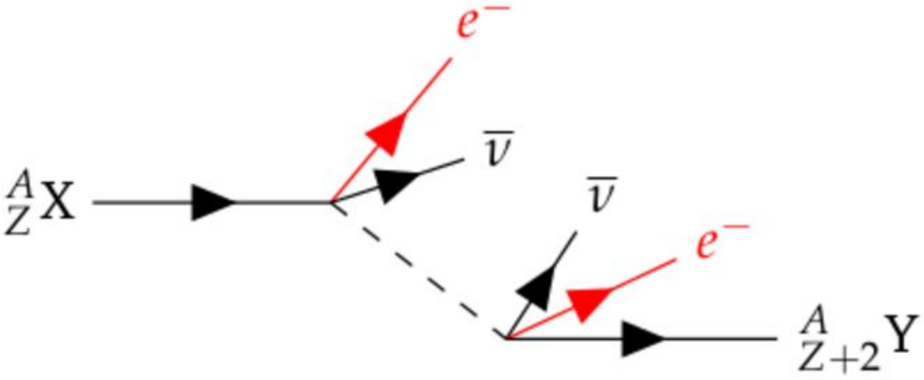
→ Neutrinos may be their own antiparticles!

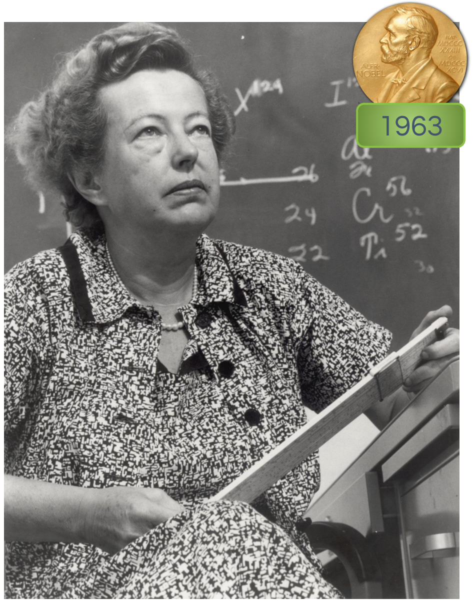


Credit: "Celebrating the neutrino", Los Alamos Science, 1997.

Double-beta decay

- Second order weak interaction process.
  - Extremely rare.
- Typical half-life is around 10^{21} years!
  - Much, much longer than the age of the Universe!
  - Process observed for 12 nuclei.
- Sum of the electrons' energies has similar distribution to beta-decay spectrum.



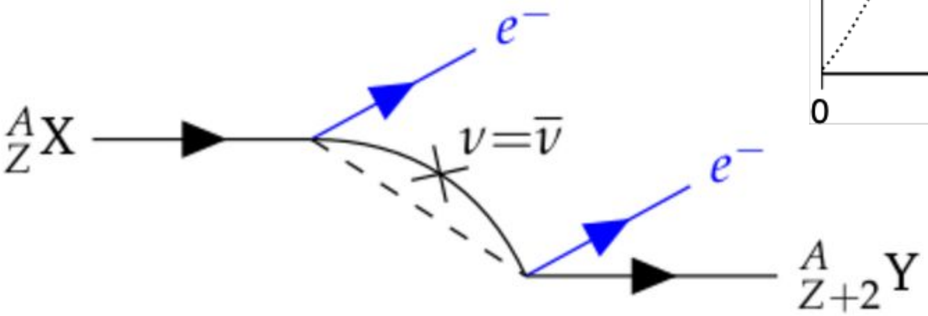


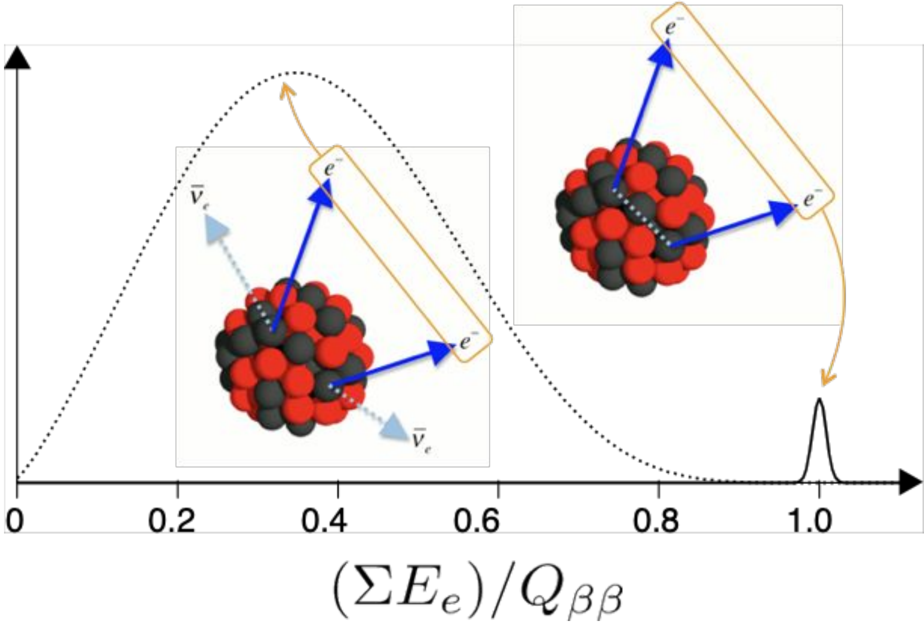
Maria Goeppert-Mayer

C. Wiesinger

Neutrinoless double-beta decay

- **Only if** neutrinos are their own antiparticles:
  - **Neutrinoless** double-beta decay!
- No neutrinos in the final state.
  - Electron energies add up to $Q_{\beta\beta}$
- This is the only experimental method to search for Majorana neutrinos.
- Decay rate depends on neutrino mass.
  - Bonus: neutrino **mass measurement**.



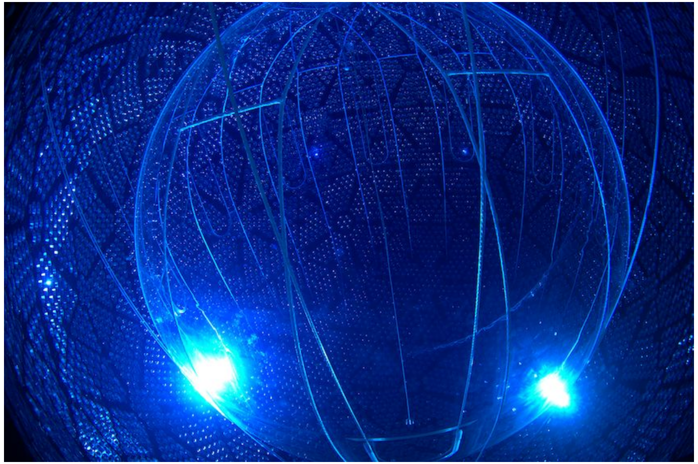


SNO+

- Large acrylic sphere filled with **790 tons** of **liquid scintillator**.
  - Scintillator emits light when traversed by charged particles.
  - About 9300 photomultiplier tubes detect the scintillation photons.
- 2 km underground in SNOLAB, Canada.

- **Double-beta decay isotope** ^{130}Te will be diluted in the scintillator.
  - Extremely challenging process.

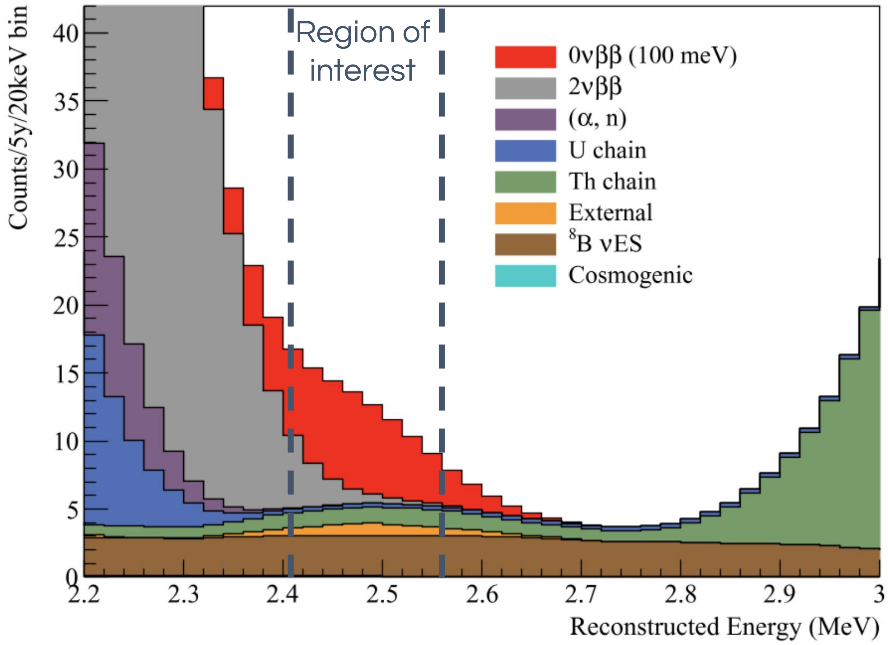
LIP is a founding member of the experiment.



SNO+

- Main physics program is the **search for neutrinoless double-beta decay**.
  - In 5 years, will be able to exclude decay half-lives shorter than **2 x 10^{26} years**.
  - Corresponds to neutrino mass of **37 to 89 meV.**

- Will also measure:
  - Solar neutrinos
    - Oscillations, solar metallicity
  - Geoneutrinos.
  - Reactor antineutrinos.



SNO+ News

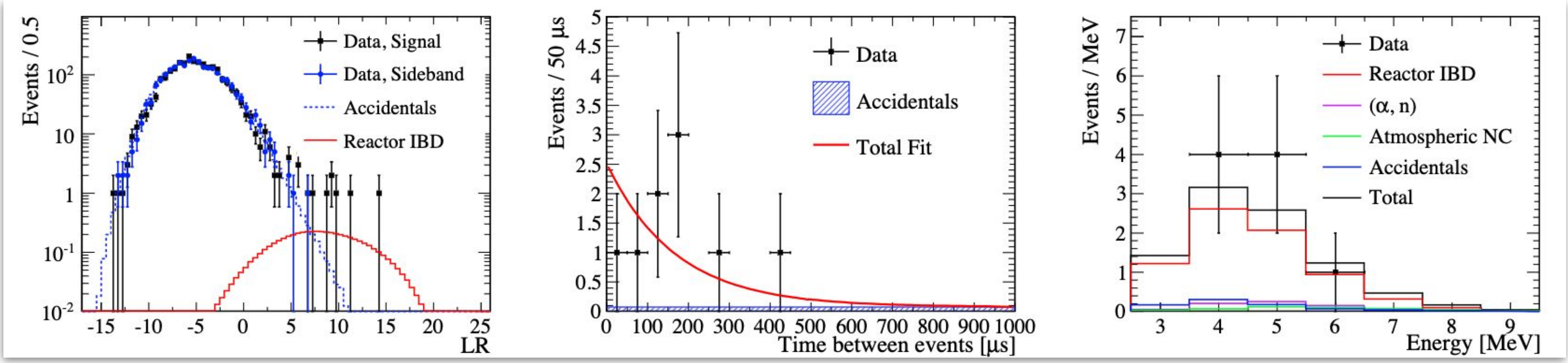
Antineutrinos from nuclear reactors detected by water

LIP-ECO/SNO+ | 01 Março, 2023

"The SNO+ collaboration has captured the signal of antineutrinos from nuclear reactors using a water-filled neutrino detector, a first for such a device. The result was selected as Editor's Suggestion in PRL. LIP researcher Sofia Andringa co-coordinates the SNO+ group that performed the analysis."

- Data collected with detector filled with pure water.
  - Before scintillator loading.
- First detection of reactor antineutrinos with **pure water** experiment!

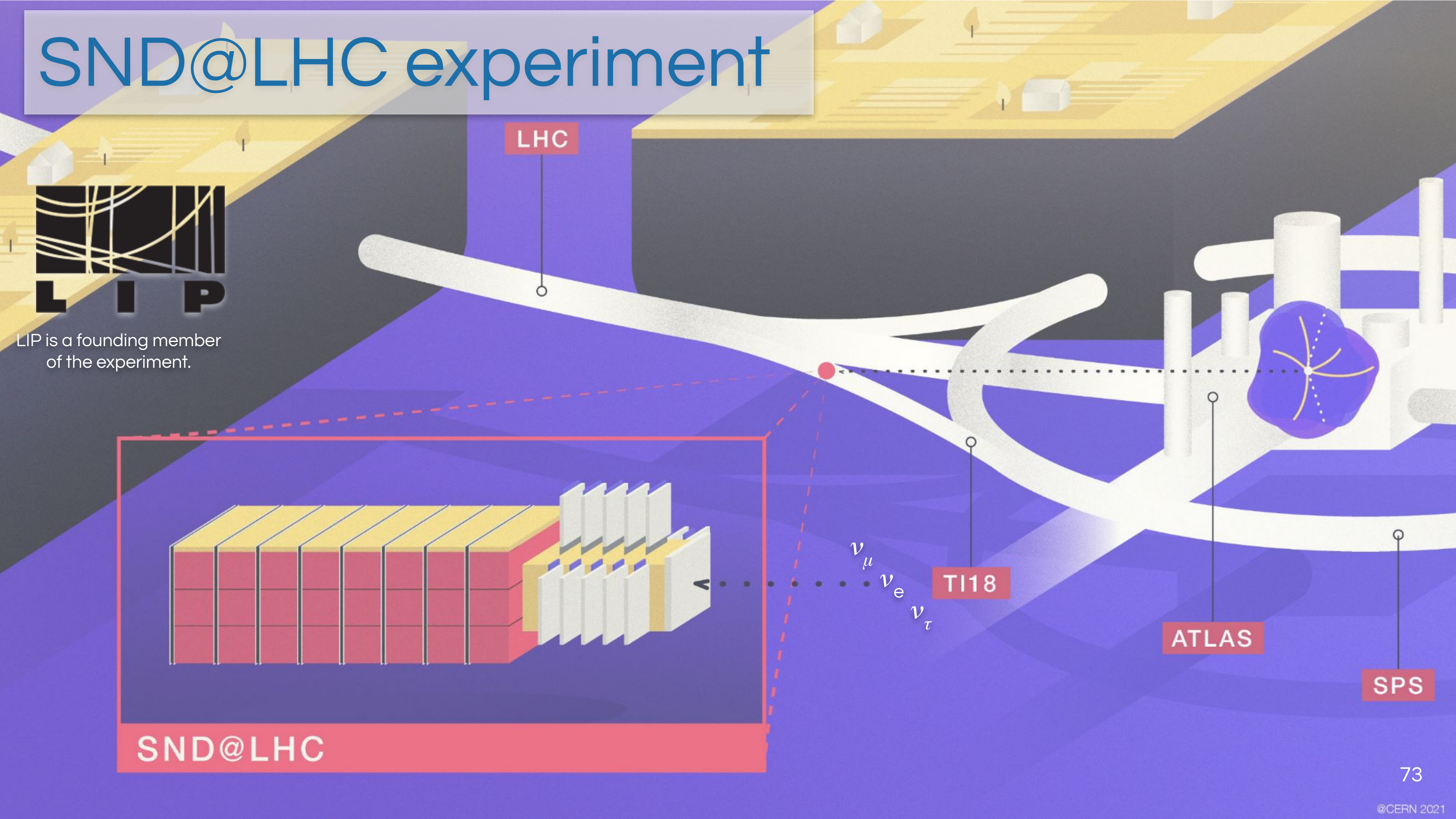
Data analysis led by LIP.



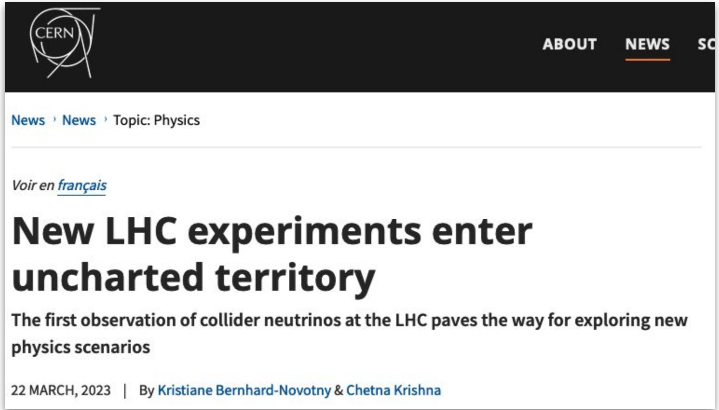
Neutrinos at the LHC

SND@LHC experiment

LIP is a founding member of the experiment.



Observation of collider neutrinos at the LHC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Voir en français

New LHC experiments enter uncharted territory

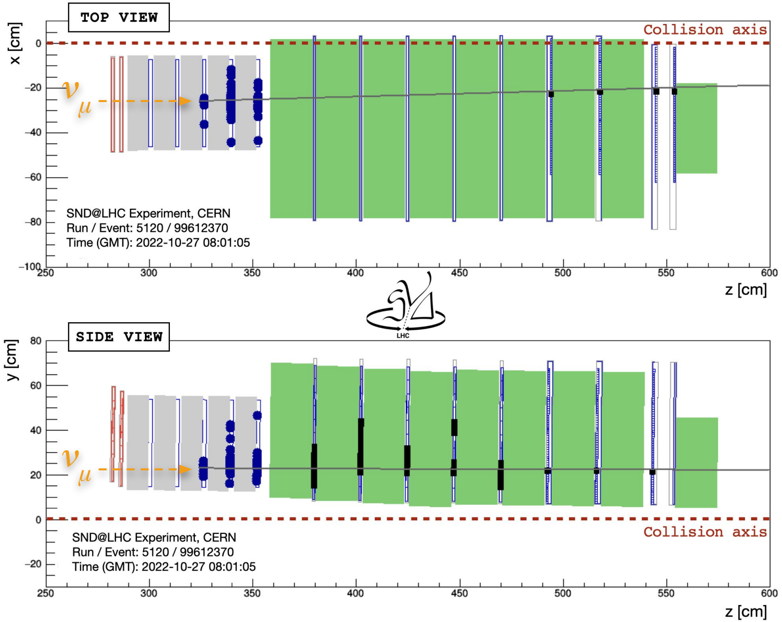
The first observation of collider neutrinos at the LHC paves the way for exploring new physics scenarios

22 MARCH, 2023 | By Kristiane Bernhard-Novotny & Chetna Krishna


First observation of collider neutrinos by SND@LHC and FASER

LIP-ECO/CERN/N.Leonardo | 23 Março, 2023

"The new LHC experiments SND@LHC and FASER reported the first-ever observation of neutrinos produced in a particle collider. The results were announced at the Rencontres de Moriond taking place this week in La Thuile, Valle d'Aosta, Italy. "

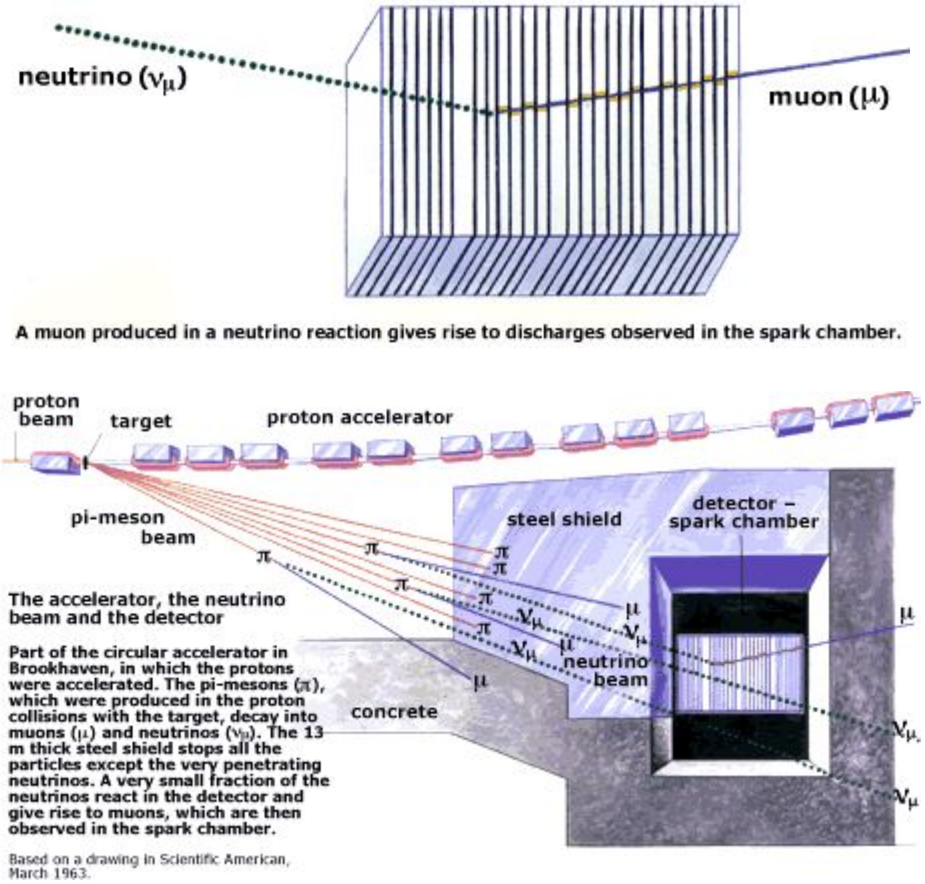


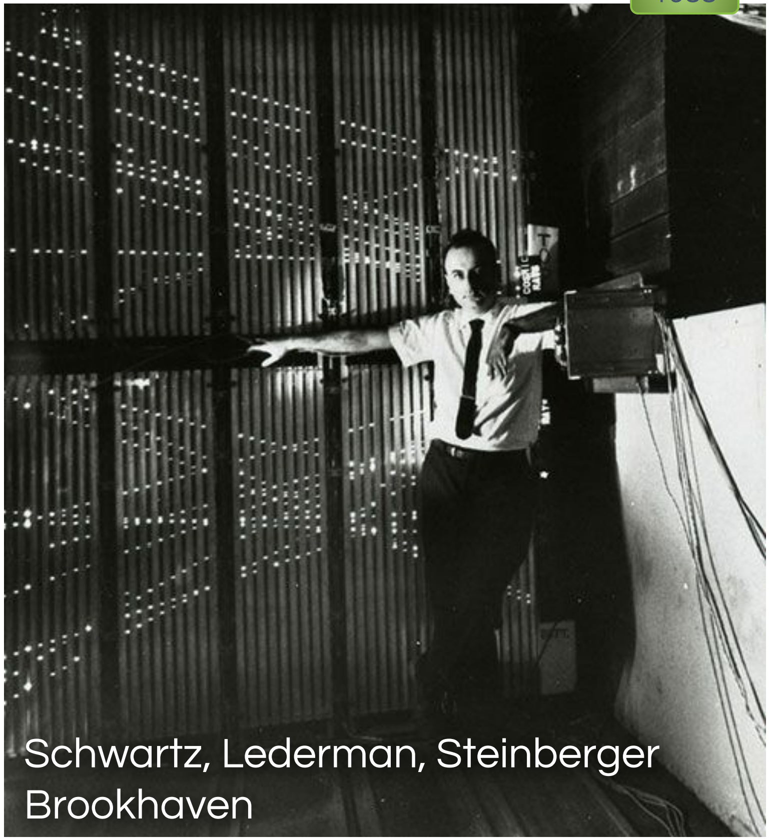
Data analysis led by LIP.

Extra

The muon neutrino (1962)

1988



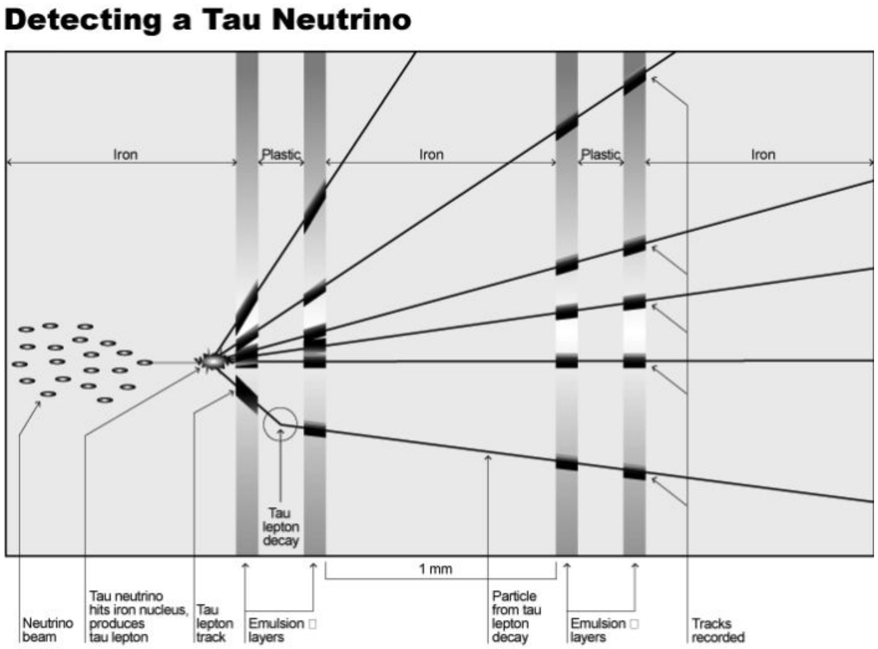

Schwartz, Lederman, Steinberger
Brookhaven

The tau neutrino (2000)

- Discovered by the DONUT experiment at Fermilab's Tevatron.
  - Proton collider with 800 GeV per beam.

- Identify the tau by its short lifetime.
  - Short track with a "kink" (secondary vertex).
- Need micrometric precision:
  - Nuclear emulsion detector.

- **Observed 9 ν_τ events!**



Neutrino mixing

- Neutrinos:
  - **Evolve** in (space-)time, obeying the Schrödinger equation (and relativistic counterparts).
  - **Interact** weakly with the other Standard Model fermions.
- The basis for describing the time-evolution of neutrinos and their weak interactions need not be the same.
  - In fact, they are not the same for quarks, which explained CP violation observations and predicted a 3rd generation of particles. Nobel prize for Kobayashi and Maskawa of C**KM**.
- Let's start with two neutrinos:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix}$$

$$\begin{aligned} \begin{pmatrix} |\nu_1(x,t)> \\ |\nu_2(x,t)> \end{pmatrix} &= \begin{pmatrix} e^{-i\phi_1} & 0 \\ 0 & e^{-i\phi_2} \end{pmatrix} \begin{pmatrix} |\nu_1(0,0)> \\ |\nu_2(0,0)> \end{pmatrix} \\ &= \begin{pmatrix} e^{-i\phi_1} & 0 \\ 0 & e^{-i\phi_2} \end{pmatrix} \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} |\nu_\alpha(0,0)> \\ |\nu_\beta(0,0)> \end{pmatrix} \end{aligned}$$

$$\boxed{P(\nu_\alpha \to \nu_\beta) = sin^2(2\theta) sin^2(\frac{\phi_2 - \phi_1}{2})}$$

Neutrino oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2(2\theta)sin^2(\frac{\phi_2 - \phi_1}{2})$$

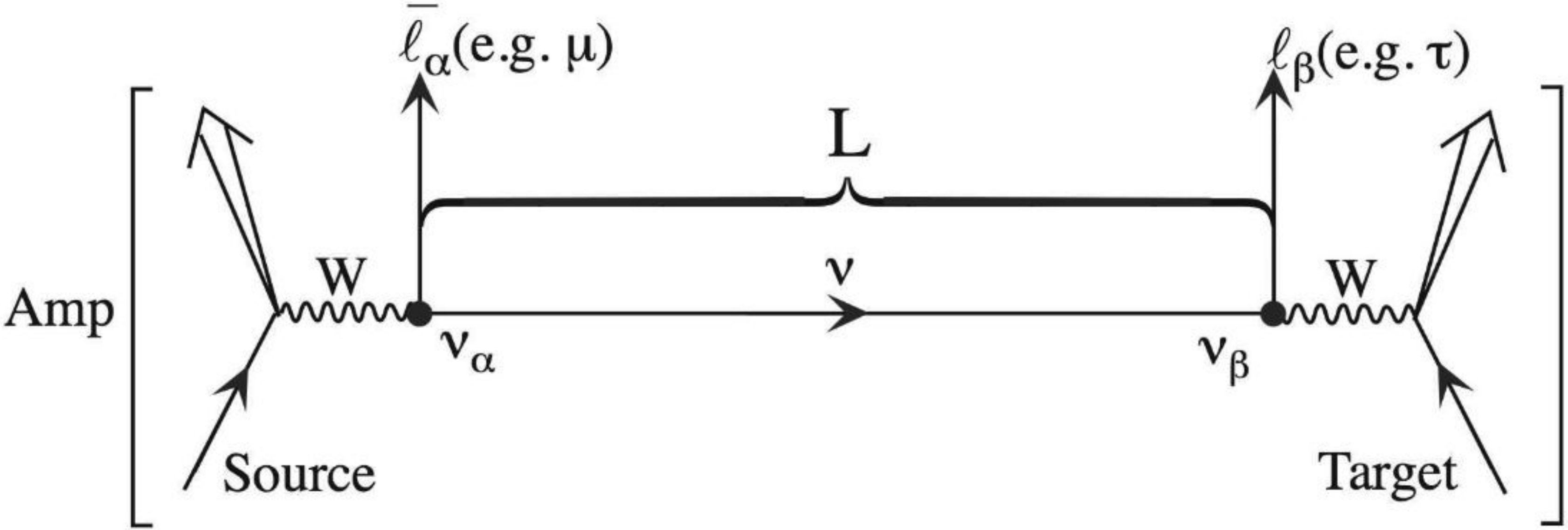
- The time evolution is determined by the energy of the state. If we assume* the two superimposed mass states are produced with the same energy, we get:

$$\phi_2 - \phi_1 = (\frac{m_1^2}{2E_1} - \frac{m_2^2}{2E_2})L = \frac{\Delta m^2 L}{2E}$$

$$P(\nu_e \rightarrow \nu_\mu) = sin^2\underbrace{(2\theta)}_{\text{Oscillation amplitude}}sin^2(1.27\underbrace{\Delta m^2 \frac{L}{E_\nu}}_{\text{Oscillation frequency}})$$

* Assumption not necessary if more detailed wavepacket formulation is used.

Neutrino oscillations



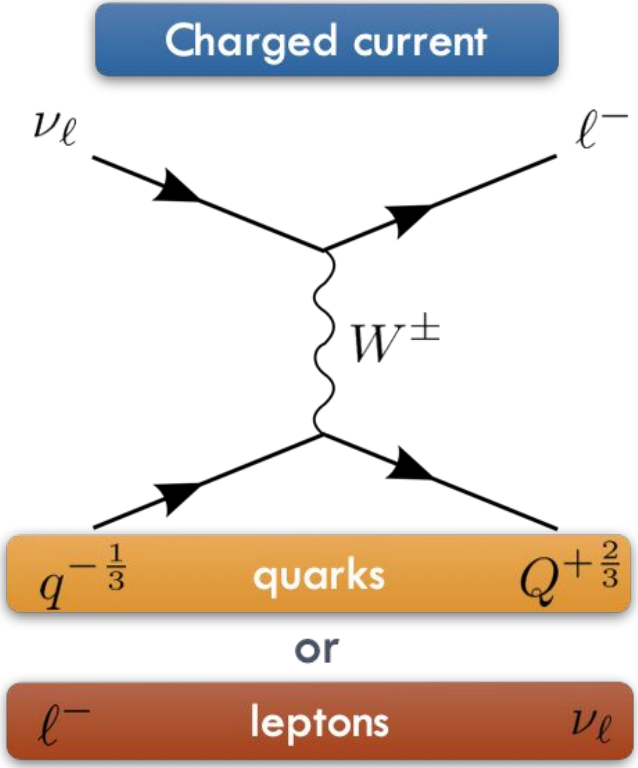
$$P(\nu_e \rightarrow \nu_\mu) = sin^2\underbrace{(2\theta)}_{\text{Oscillation amplitude}} sin^2(1.27\underbrace{\Delta m^2 \frac{L}{E_\nu}}_{\text{Oscillation frequency}})$$

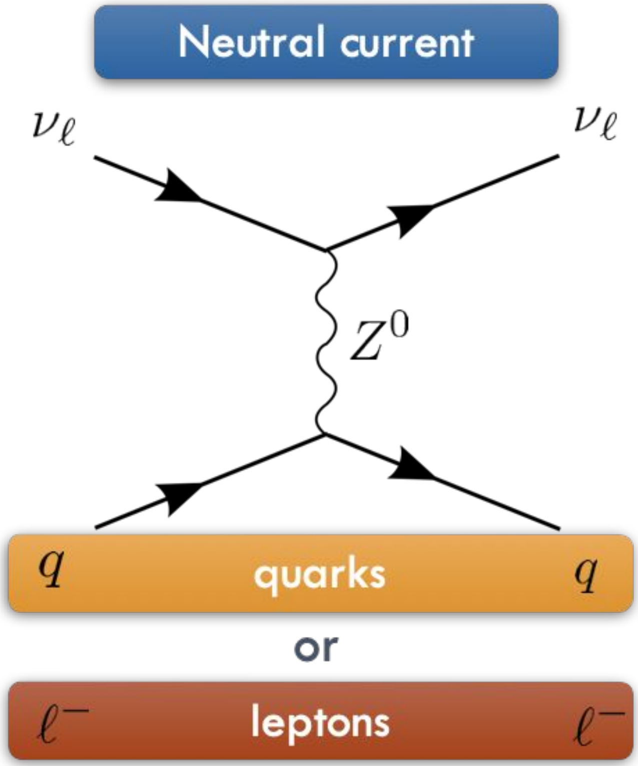
Consequences of neutrino oscillations

- **Neutrinos have mass!**
    - This was not foreseen in the original formulation of the Standard Model.
    - We observe two mass-squared splittings, so there are at least two non-zero neutrino mass states.
    - Neutrino mass provides an opportunity to discover new physics Beyond the Standard Model.
- Neutrino flavours **mix**!
    - The **lepton flavour is not conserved**, as assumed in the original Standard Model.
    - Neutrino mixing is much larger than in the quark sector.
    - Neutrino mixing provides an opportunity for large "CP violation".

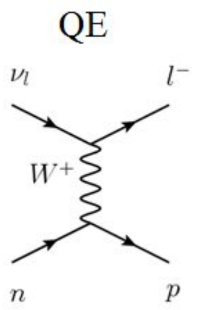
- **Open questions**:
    - How large is the CP violation in neutrino oscillations?
        - Could this explain the observed asymmetry between matter and antimatter in the Universe?
            - "Leptogenesis".
    - Does the neutrino mixing pattern hint at potential symmetries underlying the three generations?
    - What is the order of the neutrino masses?
    - What is the nature of neutrino mass?

Neutrino interactions



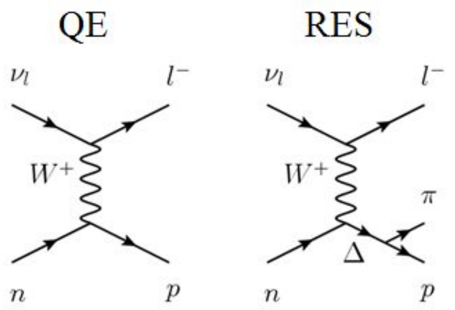


Neutrino interactions



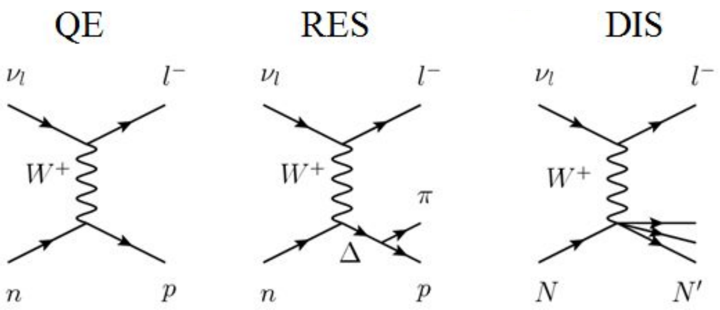
- Neutrino interactions with nuclei up to a **few hundred MeV** are "quasi-elastic".
    - Nucleon does not "break up"

Neutrino interactions



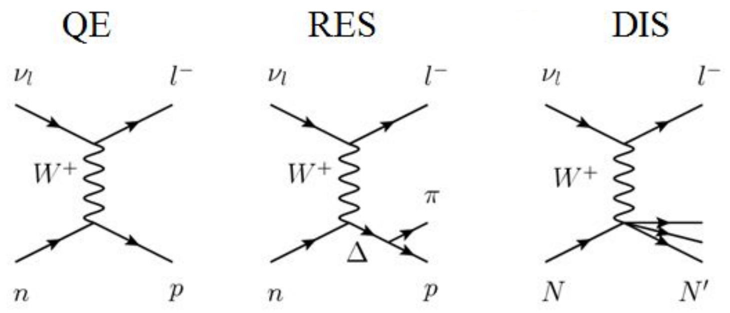
- **Above around 1 GeV** the energy transferred by the neutrino to the nucleon is enough to "excite" it into the delta-resonance (m_{Δ}=1323 MeV/c^2).
  - The delta baryon decays instantly to a pion and a nucleon.

Neutrino interactions

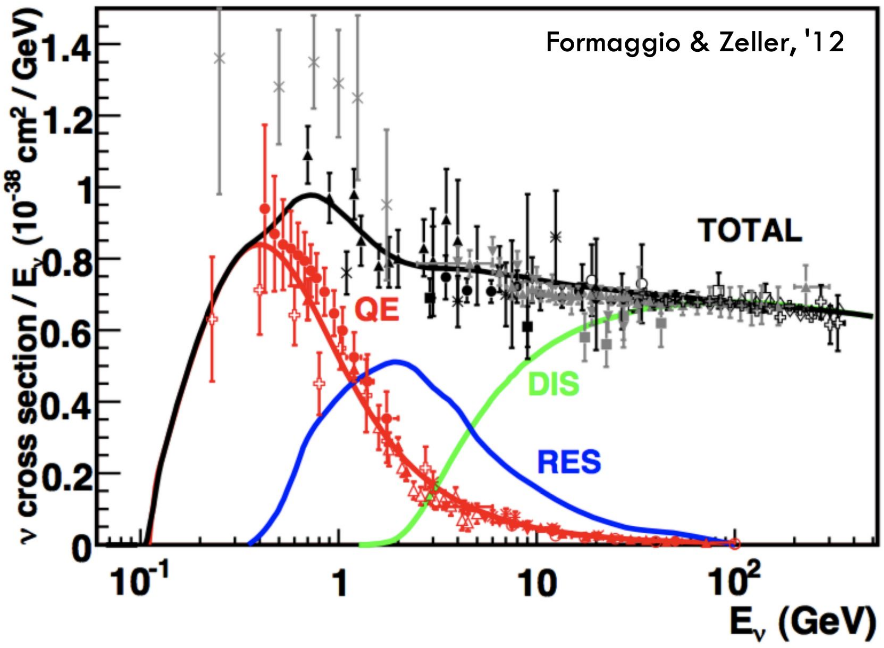


- **Above a few tens of GeV**, neutrinos "see" the quark structure of the nucleon.
- Energy transferred to the nucleon breaks it up into a collection of hadrons.
- This process is called Deep Inelastic Scattering.

Neutrino interactions

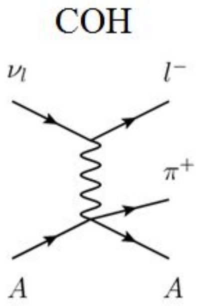


Increasing momentum transfer



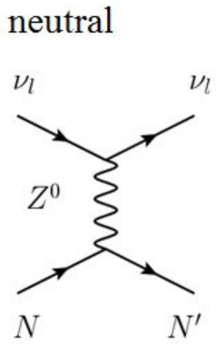
Neutrino interactions

- At **very low momentum transfers**, neutrinos can interact **coherently** with the **nucleus**.
- No nucleon ejection.



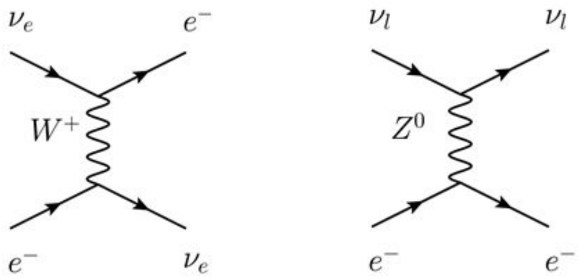
Neutrino interactions

- All these interaction modes can also occur in **neutral current** interactions.
  - Neutrino, instead of charged lepton in the final state.



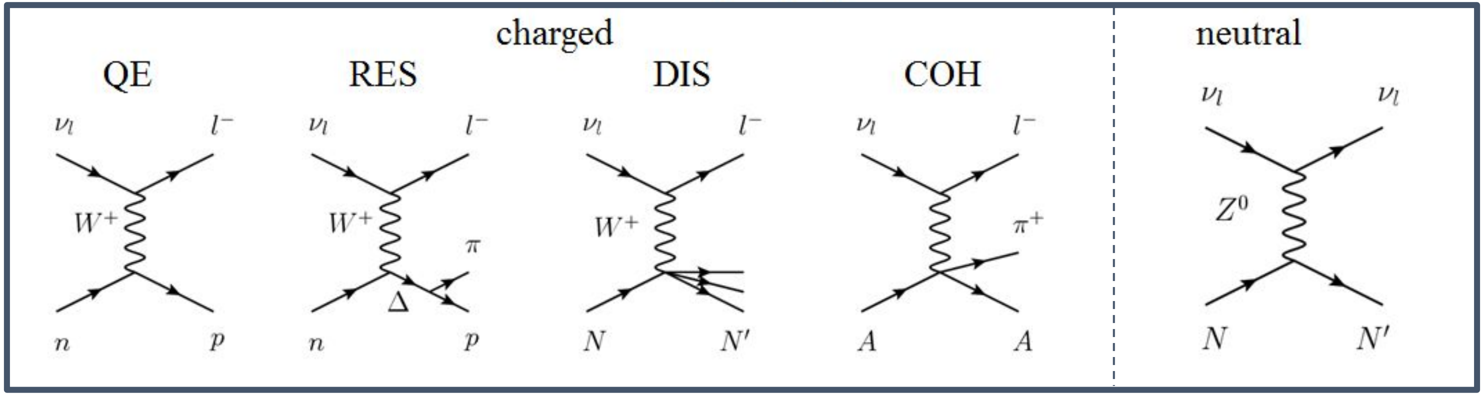
Neutrino interactions

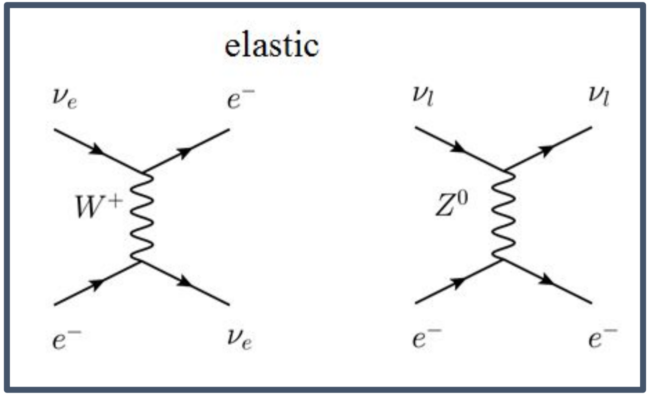
- Finally, neutrinos can interact **elastically with electrons.**
- Both **charged** and **neutral** currents contribute to the process!



Neutrino interactions

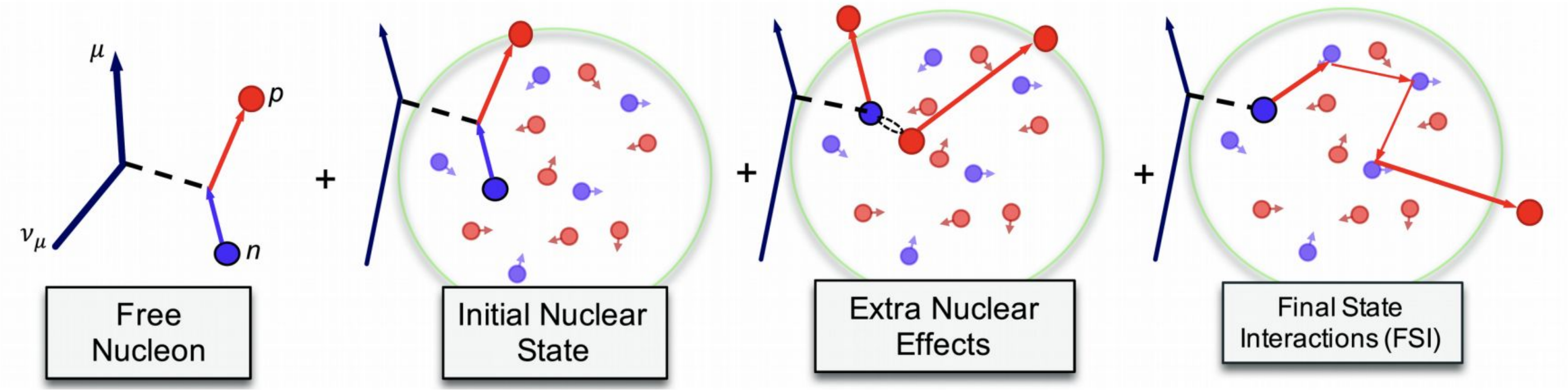
non elastic





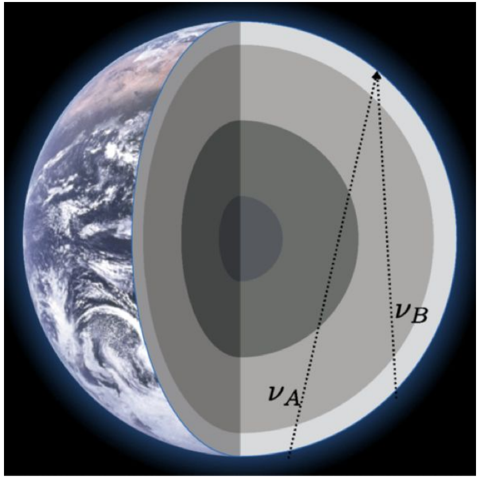
Neutrino interactions

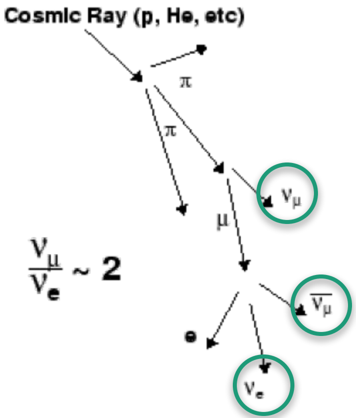
- Neutrino detection experiments often rely on neutrino interactions with nuclei.
- In practice, these interactions are very difficult to model.
    - Large theoretical effort to produce reliable neutrino interaction models.
    - Large experimental effort to measure neutrino-nucleus cross sections.

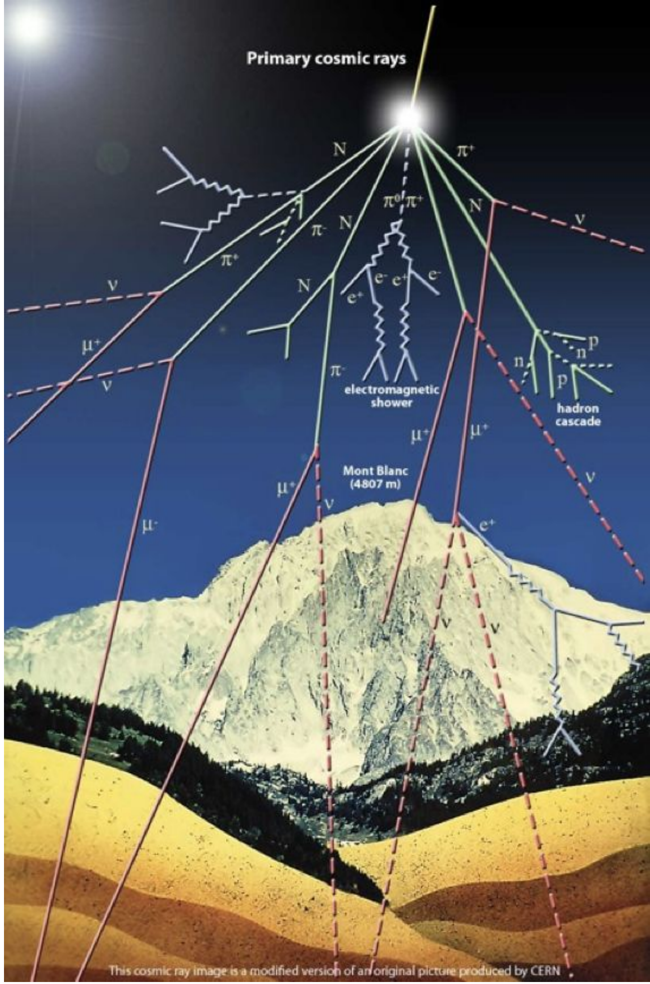


Atmospheric neutrinos

- Large flux of neutrinos **produced** in the atmosphere.
- Naïvely expect **2:1 ratio** of muon to electron neutrinos.
- Super-Kamiokande:
  - Water Cherenkov experiment (excellent **directionality**) to compare flux of neutrinos which have travelled a **different distances** through the earth.
  - Following a hint from previous generation experiment designed to search for proton decay.
    - Atmospheric neutrinos are a background to proton decay searches.

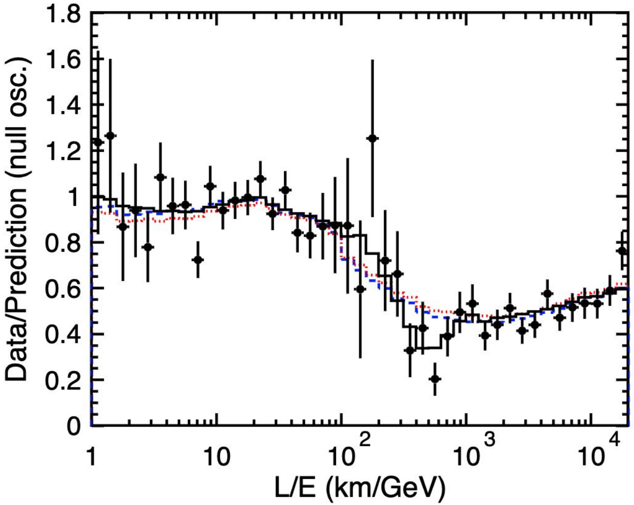


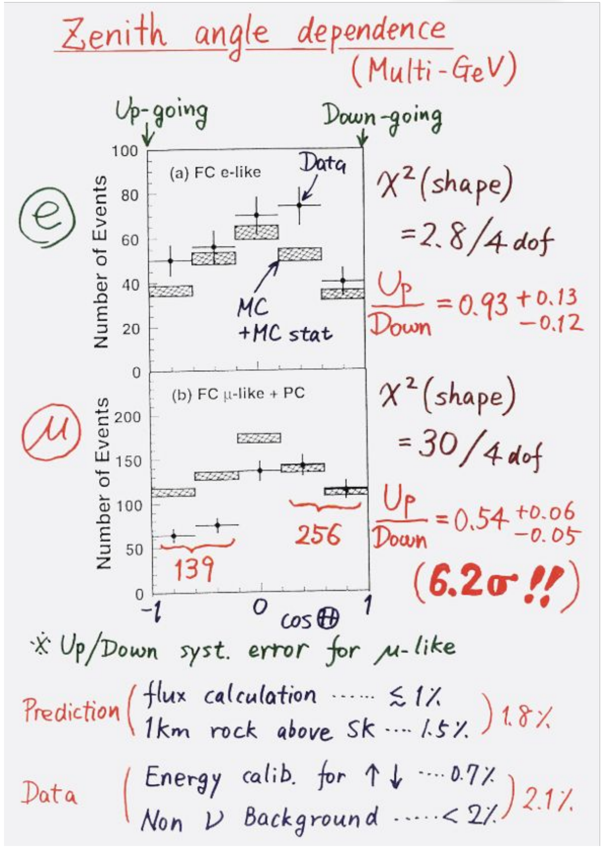




Neutrino oscillation discovery

- Super-Kamiokande announced its discovery of neutrino oscillations in 1998.
- Muon to electron neutrino ratio changes as a function of distance traveled by the neutrino.
    - Inferred from the angles of the neutrino interaction final-state particles.
- At oscillation maximum, most muon neutrinos oscillate into tau neutrinos.



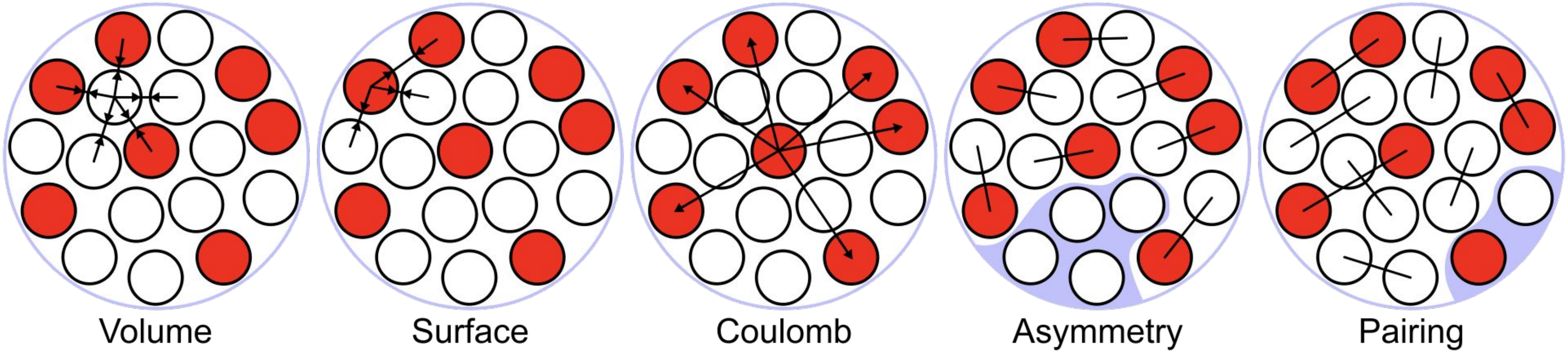


A deeper look at beta-decay

- Mass of nuclei described by the semi-empirical mass formula

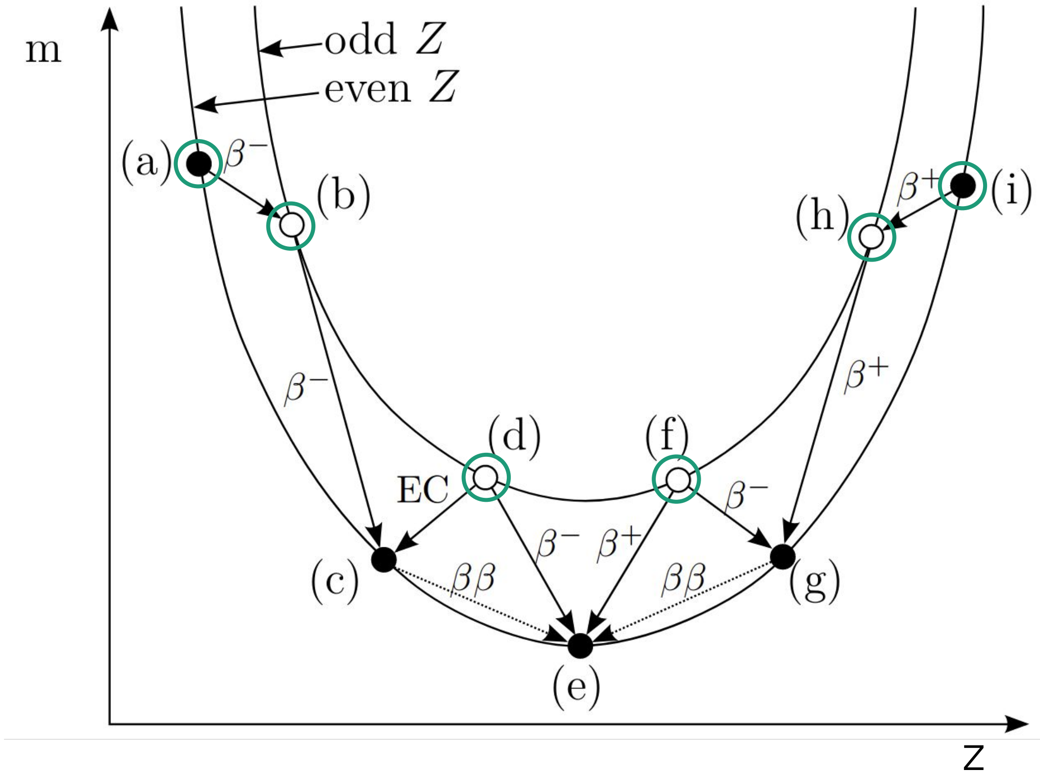
$$M(A,Z) = Z\,m_p + (A-Z)m_n - E_B$$

$$E_B = a_V A - a_s A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_A \frac{(A-2Z)^2}{A} - \delta(A,Z), \quad \textit{with} \quad \delta(A,Z) = \begin{cases} -a_p/A^{\frac{1}{2}} & \textit{even } Z \textit{ and } A \\ 0 & \textit{odd } A \\ +a_p A^{\frac{1}{2}} & \textit{odd } Z \textit{ even } A \end{cases}$$



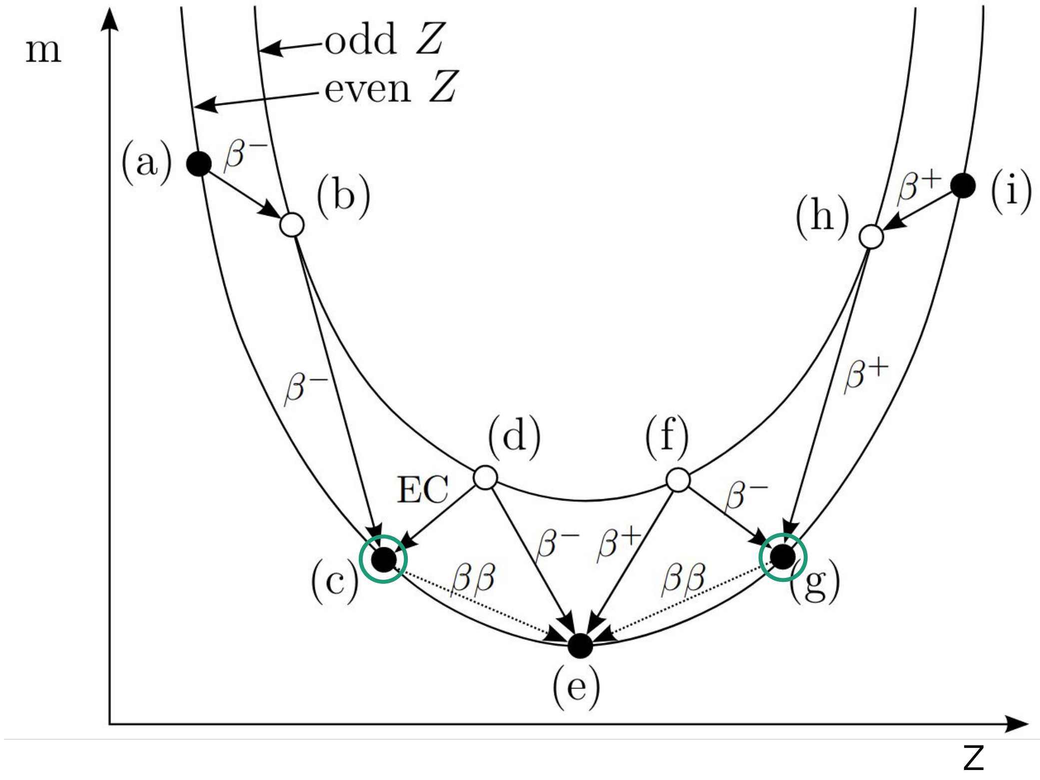
Allowed and forbidden decays

- Beta-decays change Z by one unit.
  - Allowed if M(A, Z±1) < M(A,Z)
    - a, b, d, f, h and i



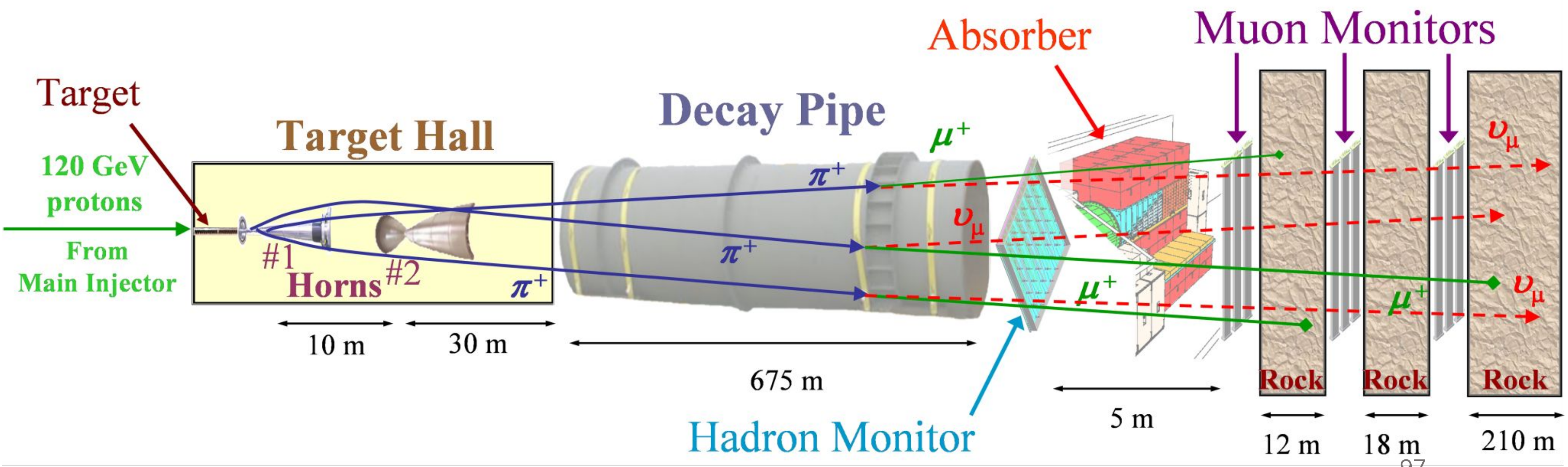
Allowed and forbidden decays

- Beta-decays change Z by one unit.
    - Allowed if M(A, Z±1) < M(A,Z)
        - a, b, d, f, h and i
- A very special situation occurs when:
    - M(A, Z±1) > M(A,Z)
    - AND M(A, Z±**2**) > M(A,Z)
    - Beta-decay is forbidden.
    - **But double-beta decay is allowed!**
        - c, g

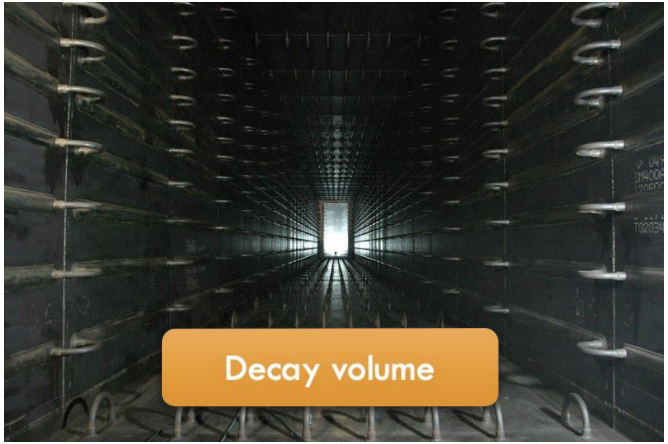


How to produce a neutrino beam

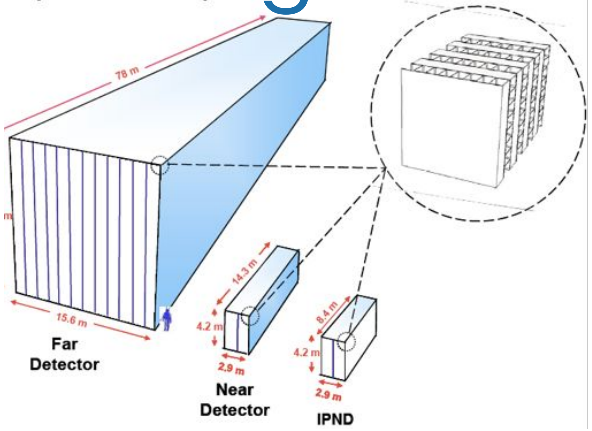
1. Accelerate protons and aim them at a target.
2. Focus the resulting pions using magnetic "horns".
   - Toroidal field can be reversed to focus positive of negative pions for neutrino or antineutrino beam.
3. Allow pions to decay to muon neutrinos and muons in empty (or He filled) volume.
4. Leave enough material to absorb muons upstream of the neutrino detectors.

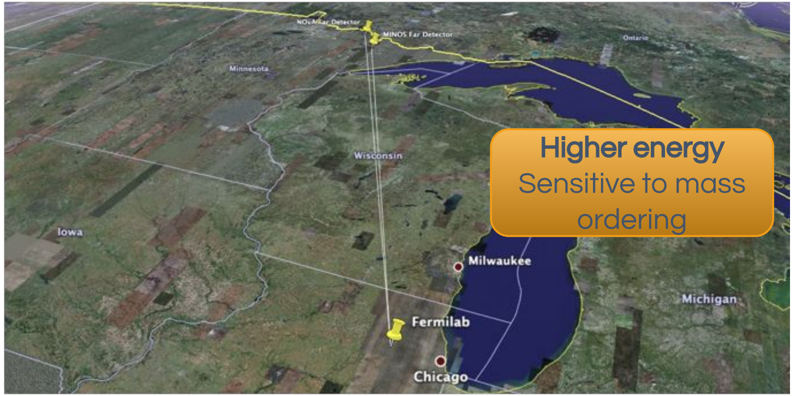


Neutrino beamline



Current long baseline experiments





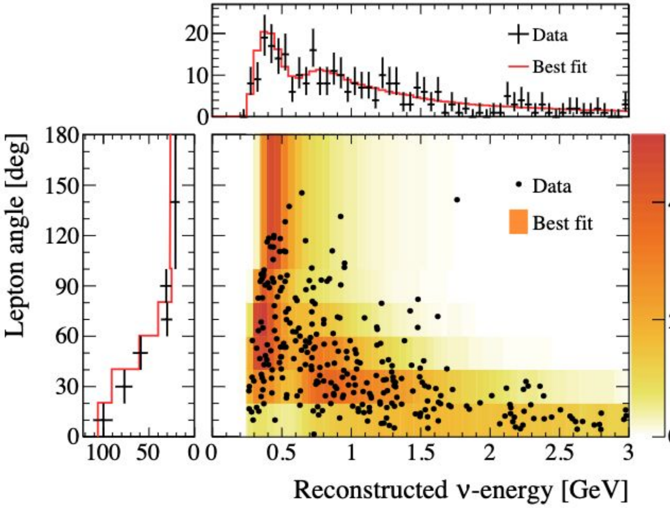
Higher energy
Sensitive to mass ordering

Lower energy
Cleaner CP violation signal

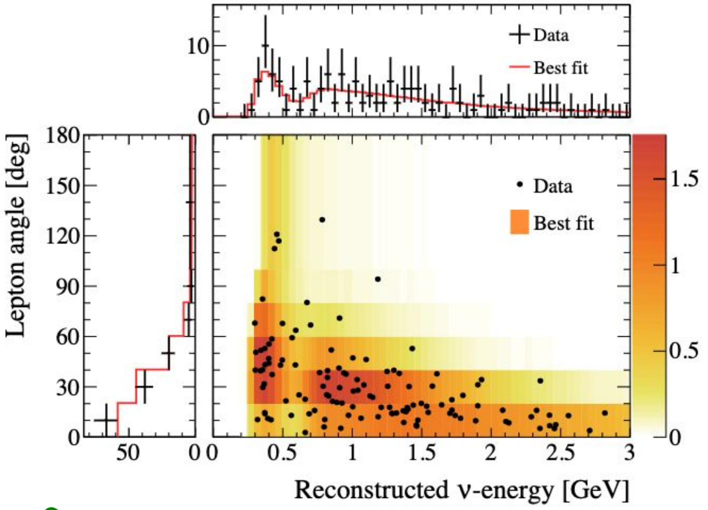
T2K

T2K and NOvA Far detectors' data

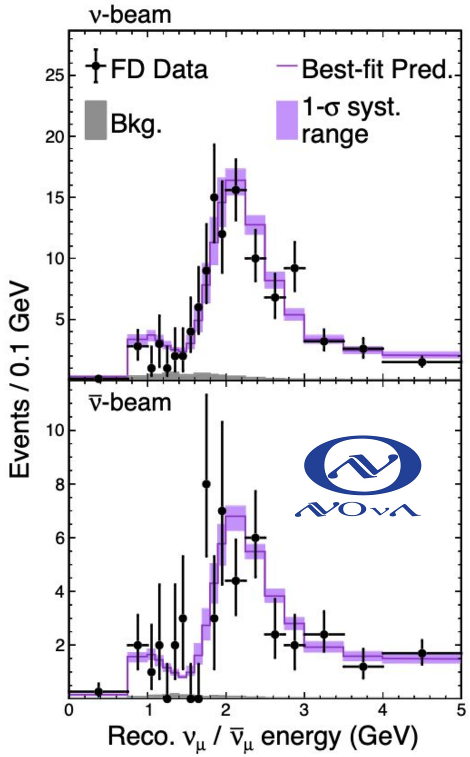
- Muons neutrinos disappear!
    - They oscillate to tau neutrinos.
- Mixing angle 23 is close to maximal.
- No difference between neutrino and antineutrino disappearance.



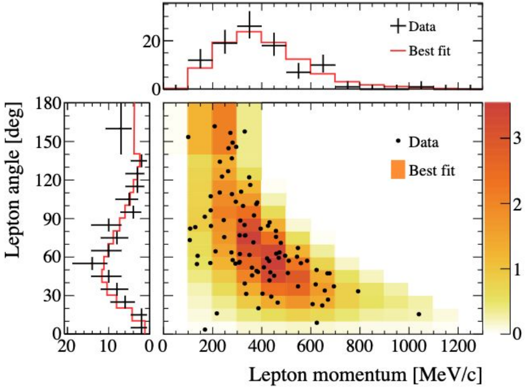
(a) ν-mode 1Rμ



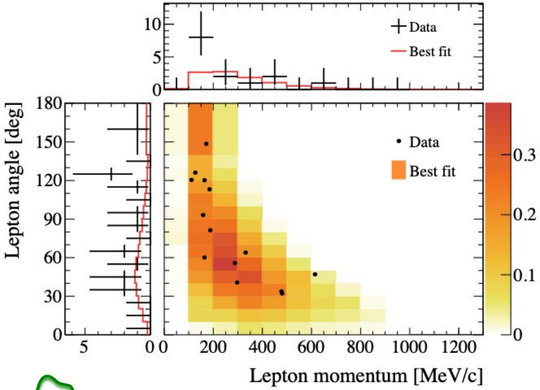
(d) $\bar{\nu}$-mode 1Rμ



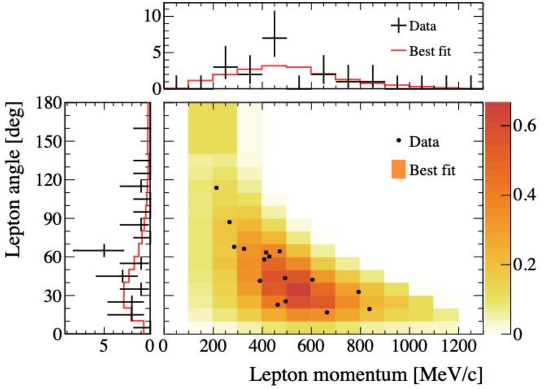
T2K and NOvA Far detectors' data



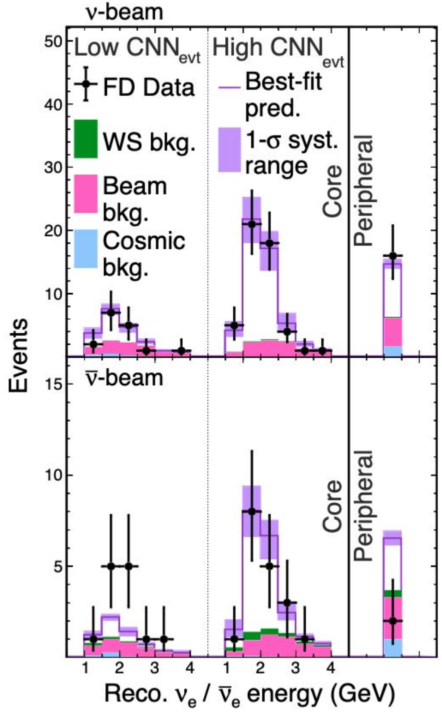
(b) ν-mode 1Re



(c) ν-mode 1Re1de



(e) $\bar{\nu}$-mode 1Re

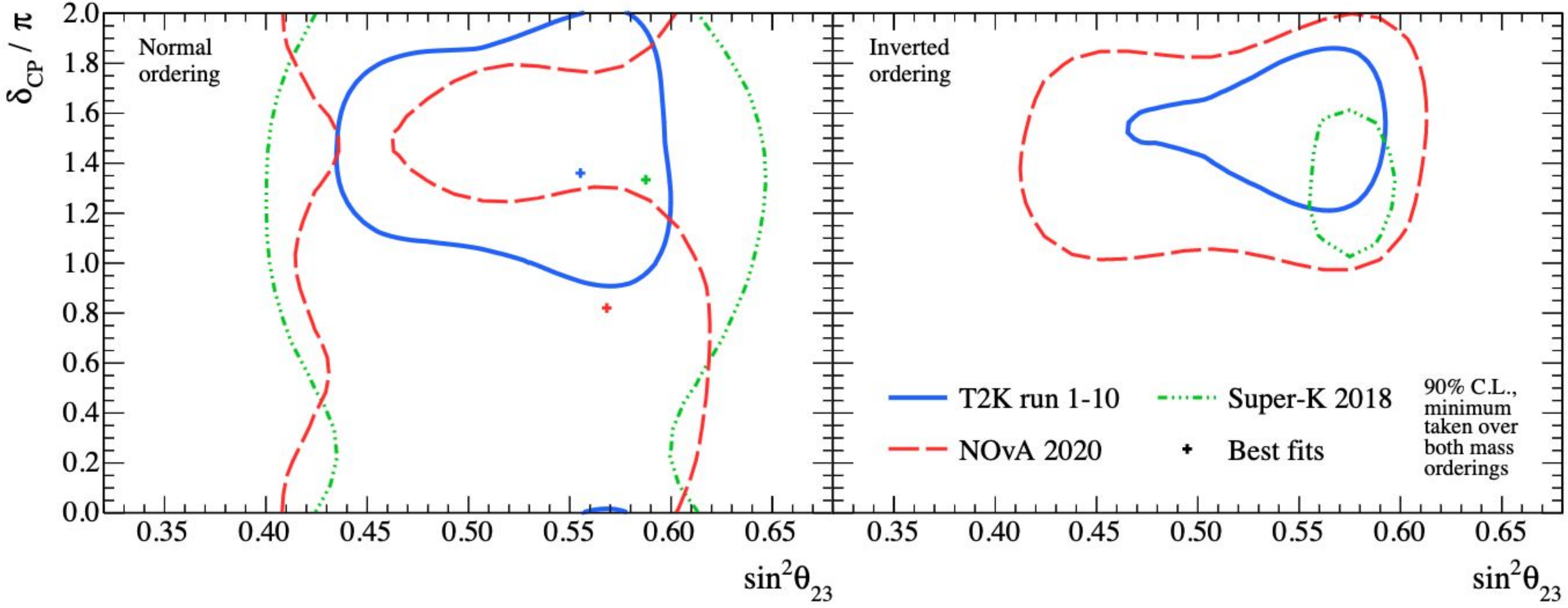


- Electron neutrinos appear!
- To early to tell if neutrinos and antineutrinos appear with the same probability.
- But we can still draw interesting conclusions from the comparison with the reactor experiments...

Where do we stand?

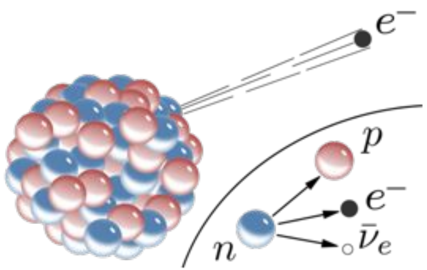
- Independently, both experiments prefer the **normal mass ordering**, but quite **different** values of the **CP-violating phase**.
- When taken together, the preference flips to the **inverted mass ordering** and **consistent CP-violating phase**.
- We're going to need a bigger experiment...

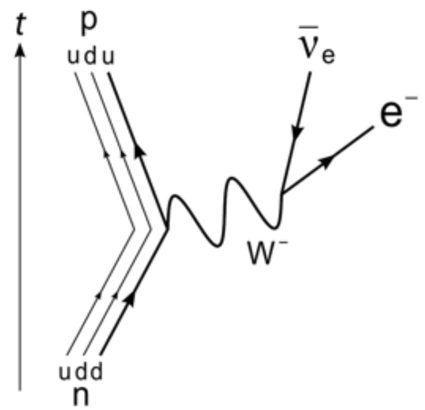
  → **DUNE**, scheduled to start at the end of the decade.

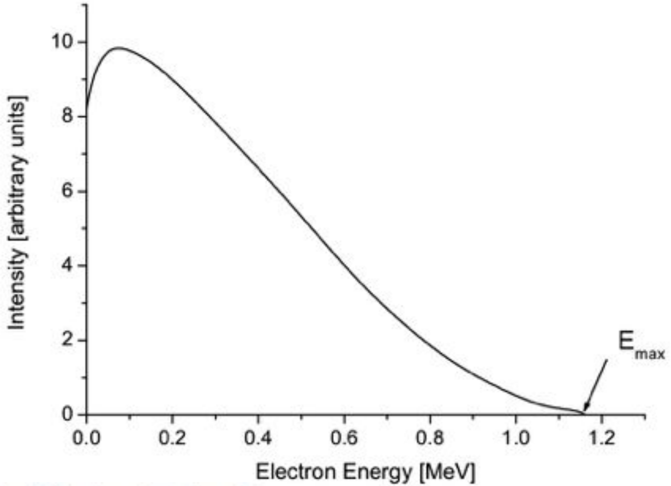


Let's go back to beta-decay

- Beta-decay provides an opportunity to try to measure neutrino masses.



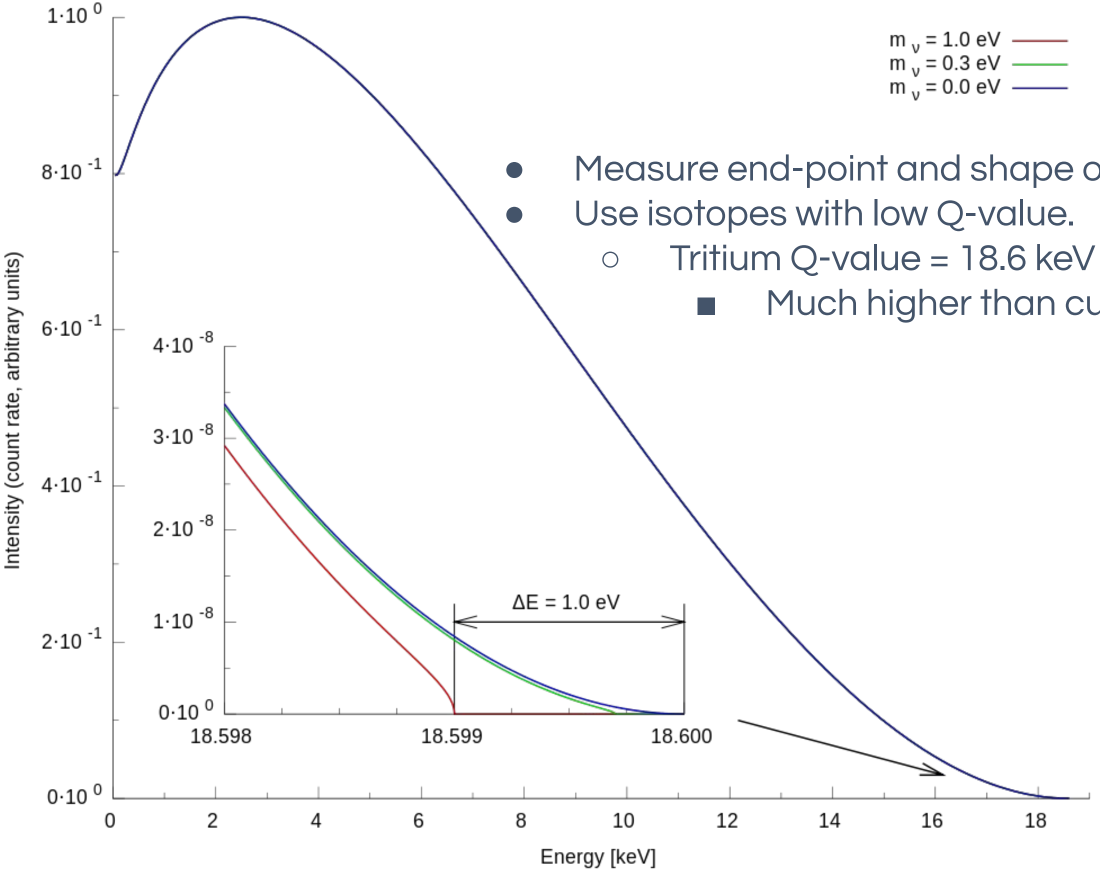




$$n \to p + e^- + \bar{\nu}_e \;\; or \;\; (A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$$
$$p \to n + e^+ + \nu_e \;\; or \;\; (A, Z) \to (A, Z-1) + e^+ + \nu_e$$

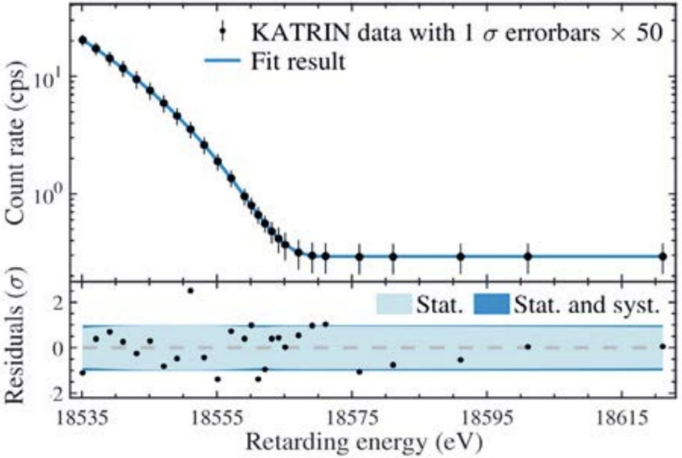
- Beta-decays can only occur when the total mass of the decay products is smaller than the mass of the initial nucleus.
  - $E_{max} = Q = M(A,Z) - M(A, Z\pm1) - m_e - \boxed{m_\nu}$

Direct m_ν measurements

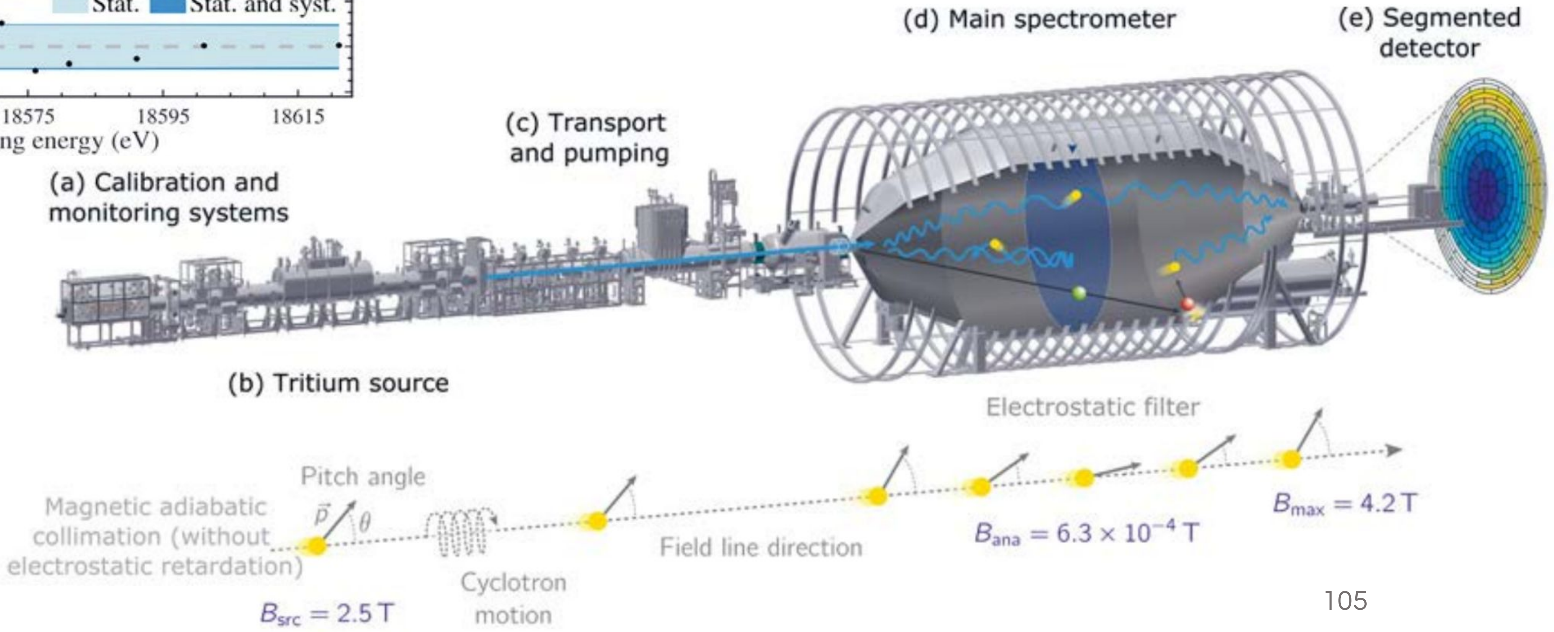


- Measure end-point and shape of the spectrum of beta-decay electrons.
- Use isotopes with low Q-value.
  - Tritium Q-value = 18.6 keV
    - Much higher than current limits on neutrino mass

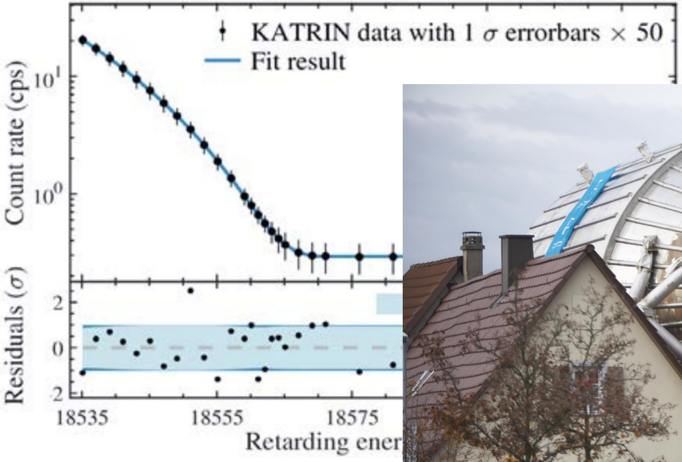
The KATRIN experiment



- State-of-the-art: $m_\nu < 0.8$ eV
- Huge spectrometer.

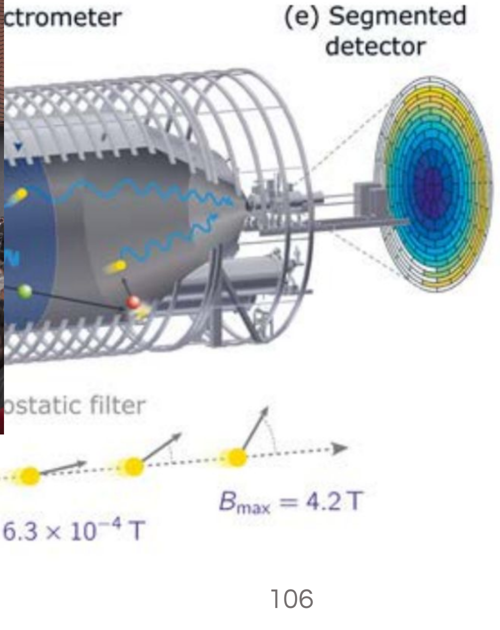


The KATRIN experiment



eV

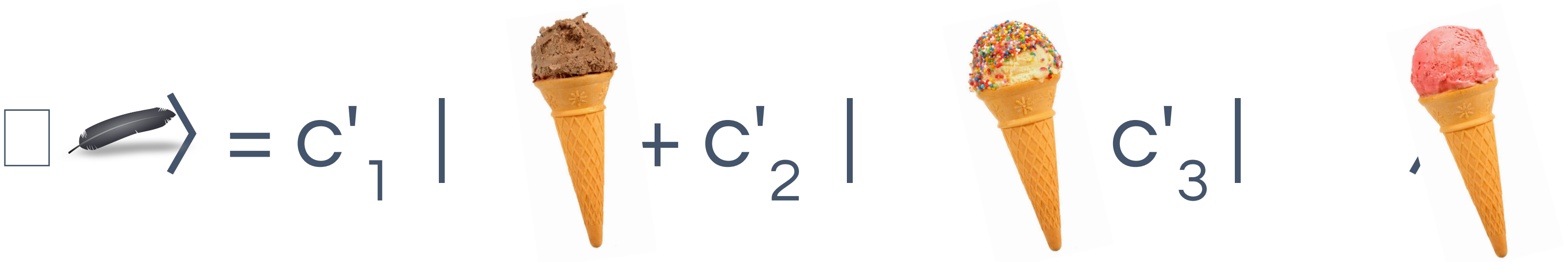
require new technology.
chrotron radiation!




300 km
50
40
0
10
20
Atlantik
Mittelmeer
Rhein
Donau
Karlsruhe
Deggendorf

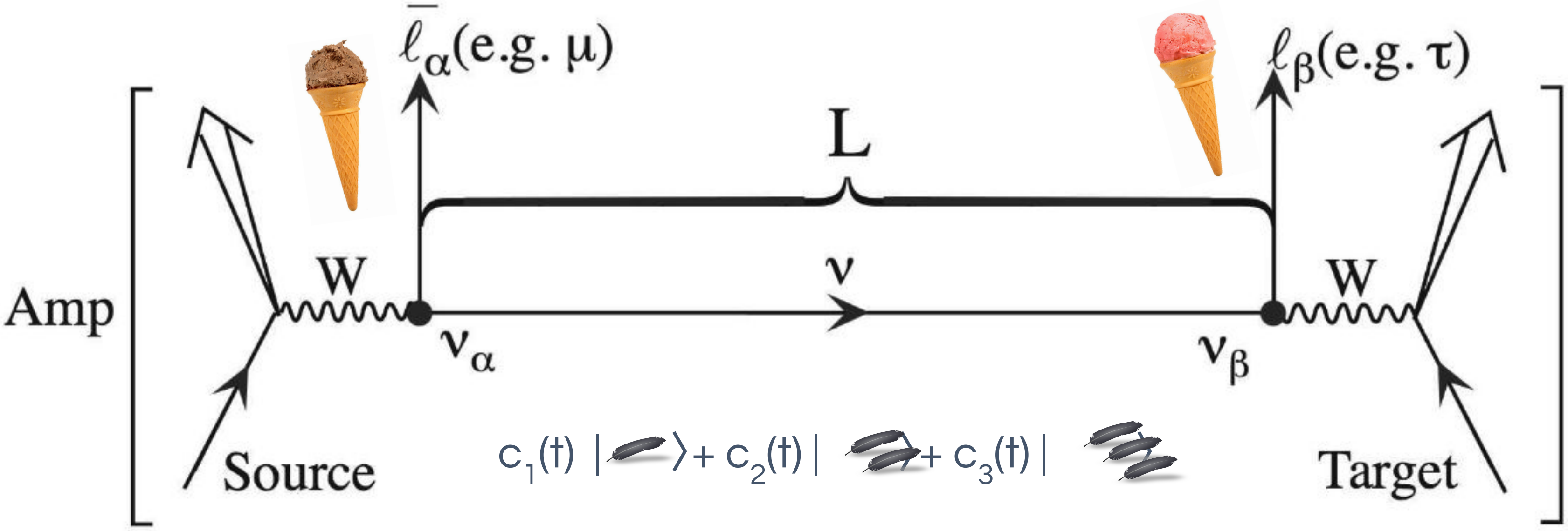
Mass states and flavour states

Each flavour state corresponds to a superposition of mass states.



Each mass state corresponds to a superposition of flavour states.

Neutrino oscillations



- The mixture of mass states **evolves** with the passage of **time**, as neutrinos traverse **space**.
- After travelling a distance *L*, neutrinos may be observed in a **different flavour**!
- The probability to observe a neutrino in a different flavour state depends on the ratio of *L* to the neutrino energy: ***L/E***