# Neutrinos

## 16ª Escola de Professores no CERN em Língua Portuguesa

6/9/2024

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
*partículas e tecnologia*

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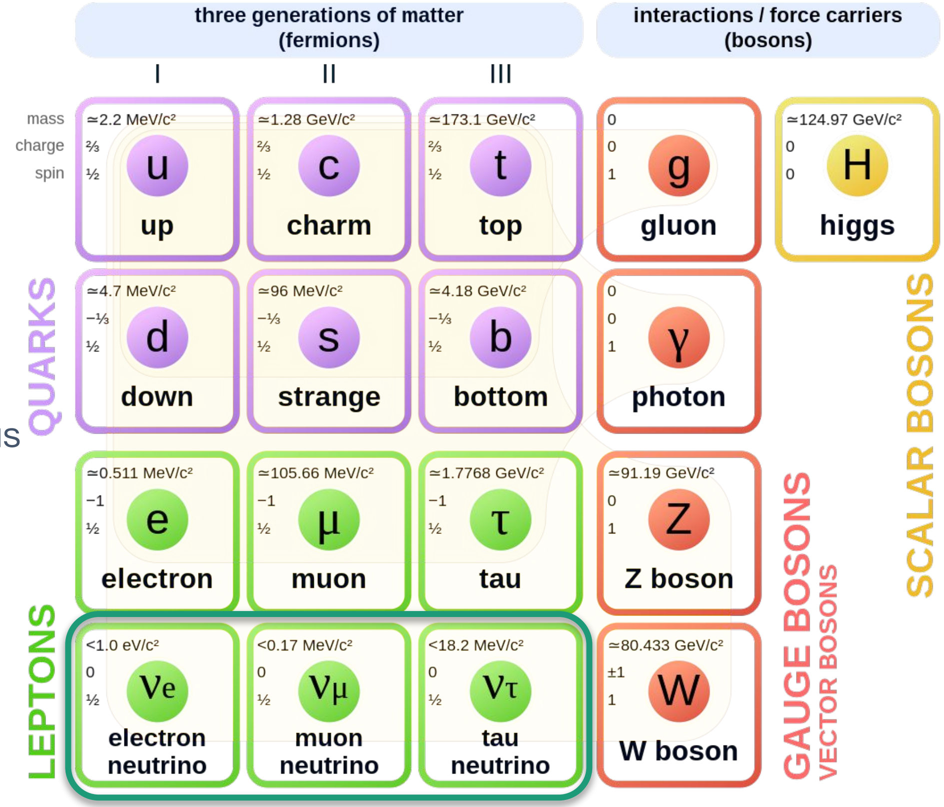
# Porque são interessantes os neutrinos?

- Os neutrinos são partículas *especiais*:
  - São os únicos fermiões sem carga eléctrica.
    - Interagem apenas através da força *fraca* e da gravidade.
  - Têm massa muito pequena.
    - Mas não nula!

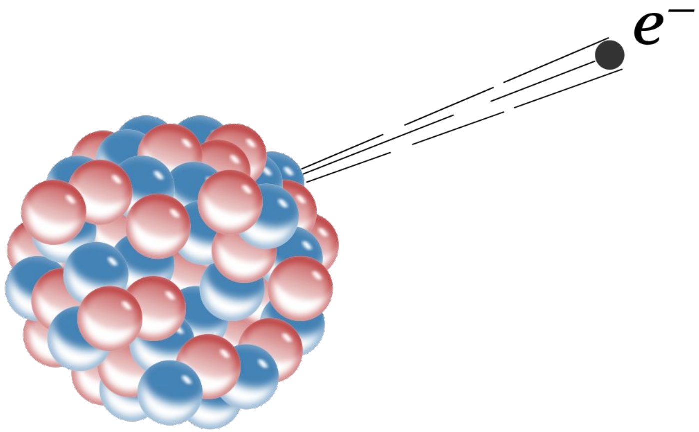
- Os neutrinos têm um papel importante em algumas das grandes questões:
  - Como é gerada a assimetria entre matéria e antimatéria no universo?
  - Porquê três gerações de fermiões?
  - Qual é a origem da massa?



# Pré-história dos neutrinos

- Um *puzzle* radioactivo: o espectro contínuo dos raios beta.
  - A emissão de raios beta resulta de uma transição entre dois isótopos nucleares.
  - A energia da radiação emitida deveria ser **igual à diferença das massas** dos isótopos

> 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



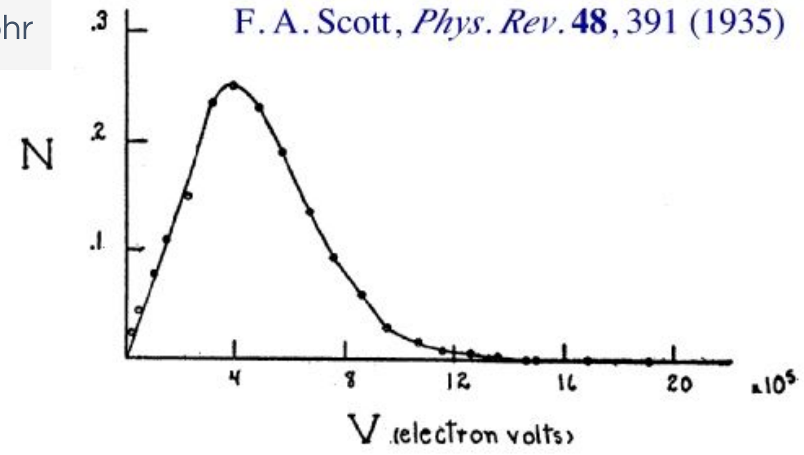
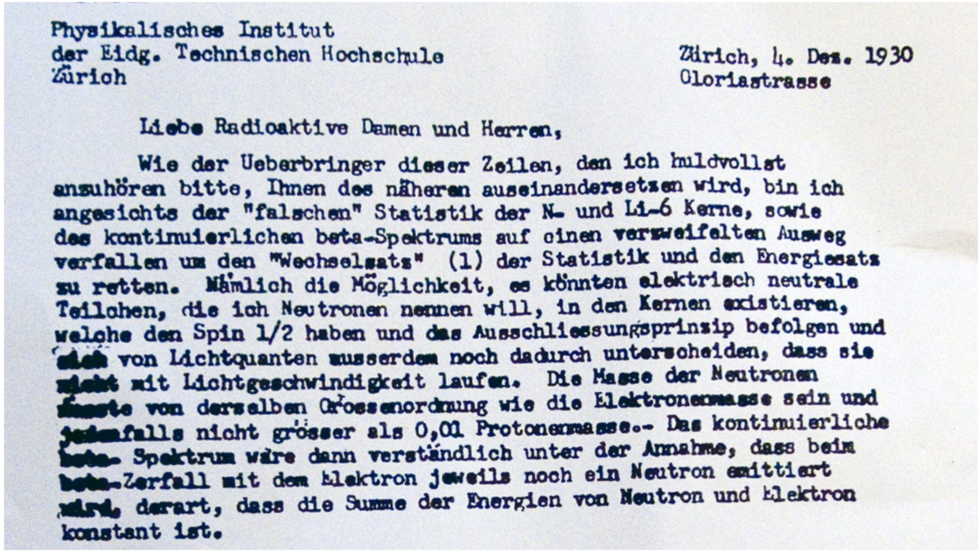




FIG. 5. Energy distribution curve of the beta-rays.

# Uma medida desesperada

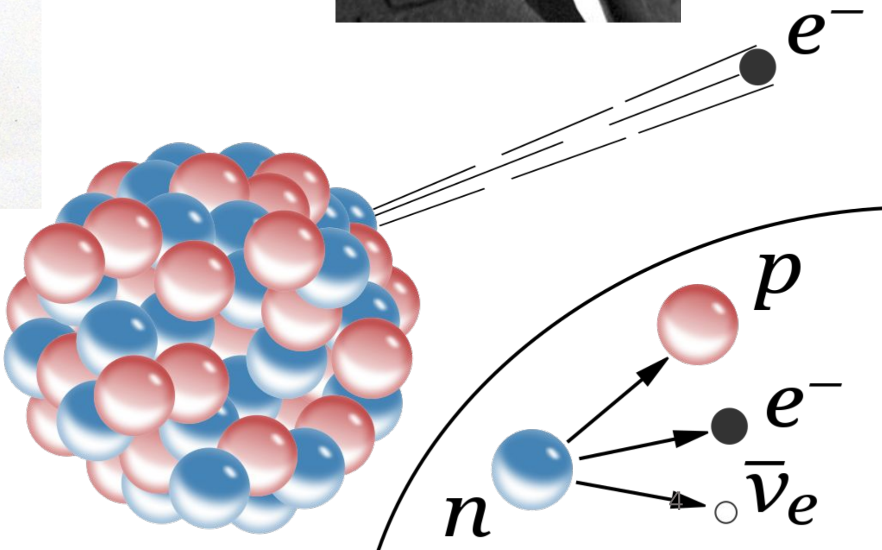


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

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 könnte 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.



# Uma medida desesperada

Dear Radioactive Ladies and Gentlemen,

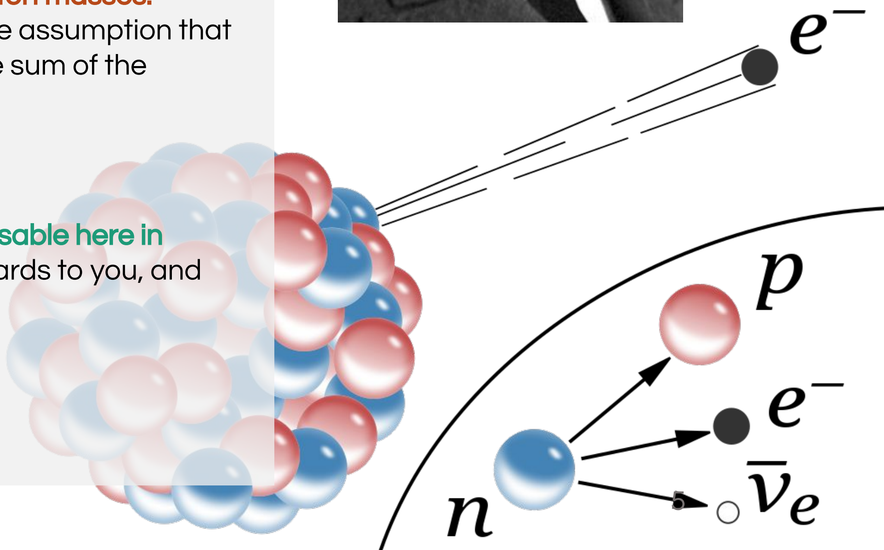
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and $Li^6$ nuclei and the continuous beta spectrum, **I have hit upon a desperate remedy to save** the "exchange theorem" of statistics and **the law 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



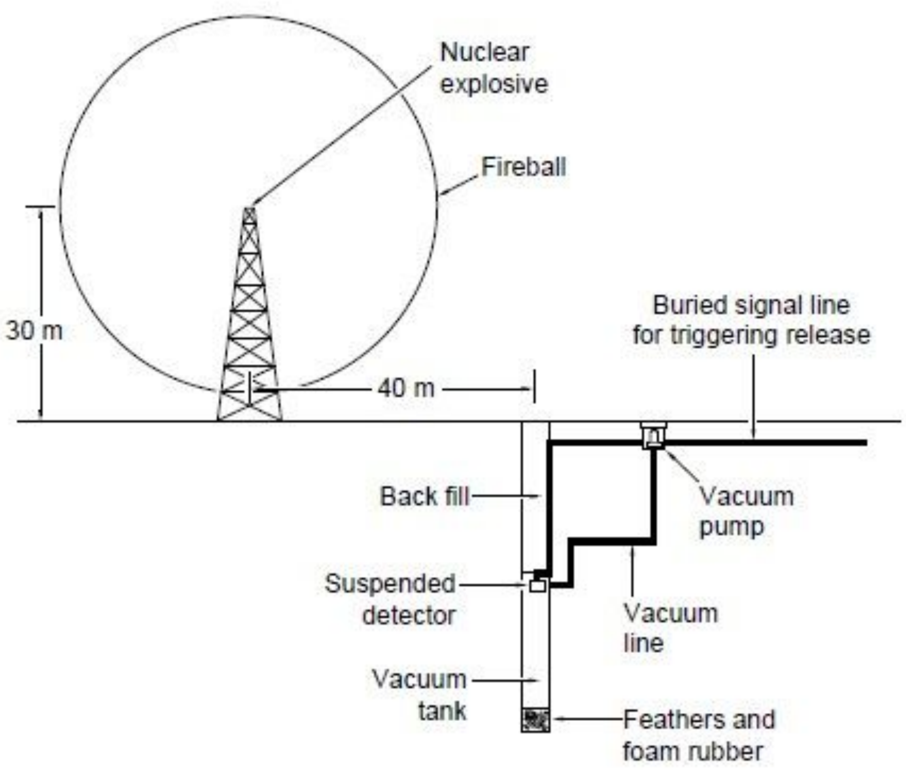
# Um plano para descobrir o neutrino

- Experiência proposta por F. Reines e C. Cowan em 1952.

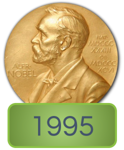
- Para obter um enorme fluxo de neutrinos:
  - Colocar o detector o mais próximo possível da **detonação de uma bomba nuclear** .

- Para proteger o detector da onda de choque:
  - Suspender o detector num grande tanque de vácuo subterrâneo.
  - **Largar o detector no vácuo** quando a bomba for detonada.

- Este plano não se concretizou...



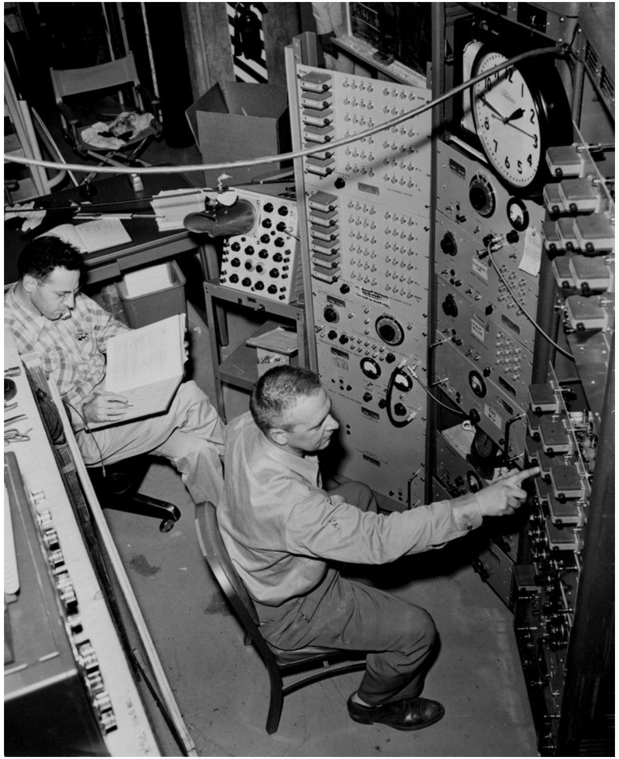
# A descoberta do neutrino (1956)




- Após a proposta inicial, Reines e Cowan alteraram a sua estratégia.

- Colocaram o detector muito próximo de um reactor nuclear, onde o fluxo de neutrinos é muito elevado.
- O detector continha grandes tanques cheios de água com cloreto de **cádmio** .
- Observaram interacções de neutrinos através da reacção: $\overline{\nu} + p \rightarrow e^{+} + n$.
    - $e^{+}$ e $e^{-}$ na água aniquilam produzindo um **par de** $\gamma$
    - O **neutrão** é capturado no cádmio produzindo um $\gamma$.

- Secção eficaz medida por Reines e Cowan: **~$10^{-44}$cm$^{2}$**.
    - Colisões protão-protão no LHC: ~$10^{-25}$ cm$^{2}$

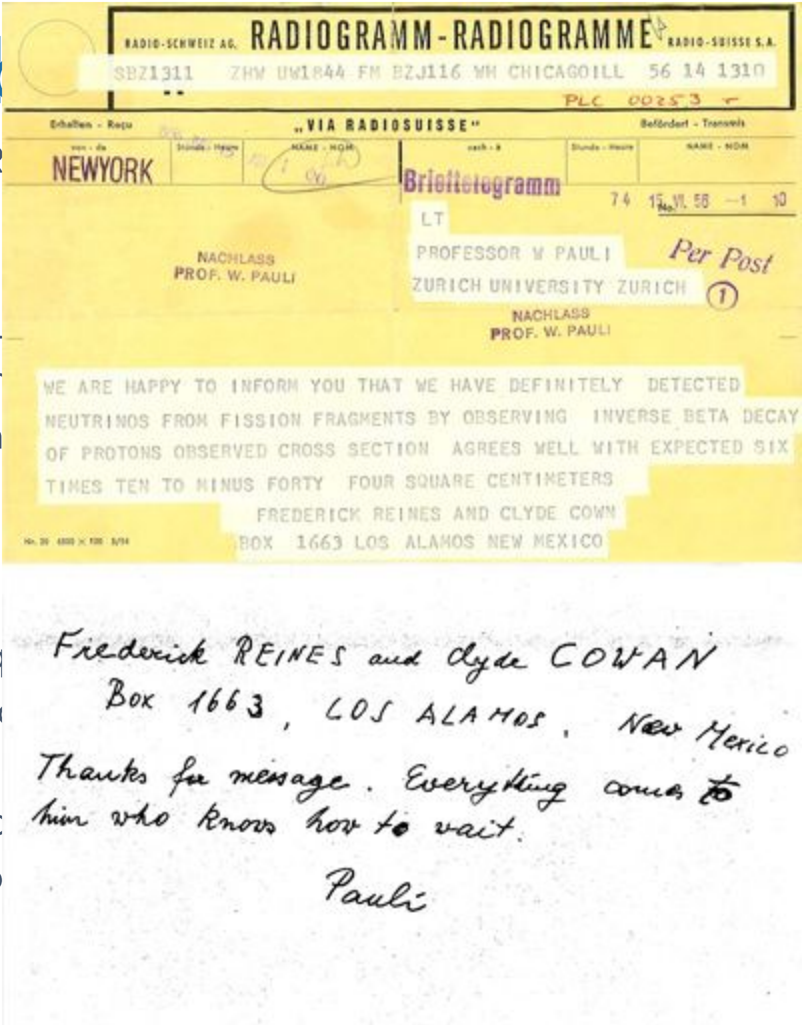


# A descob 1956)

- Após a proposta inicial, R
  estratégia.

- Colocaram o detector mu
  nuclear, onde o fluxo de n
- O detector continha gran
  cloreto de **cádmio** .
- Observaram interacções
  $\overline{\nu} + p \rightarrow e^+ + n$.
  - $e^+$ e $e^-$ na água aniq
  - O **neutrão** é captur

- Secção eficaz medida po
  - Colisões protão-pro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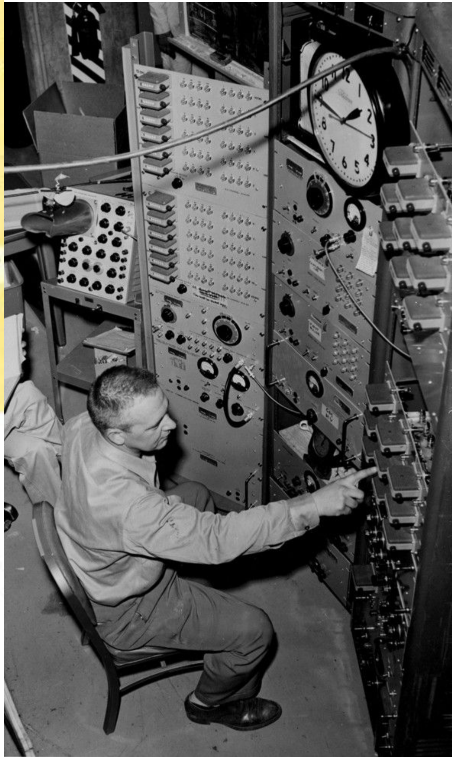
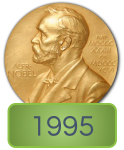
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
NACHLASS PROF. W. PAULI
NACHLASS PROF. W. PAULI

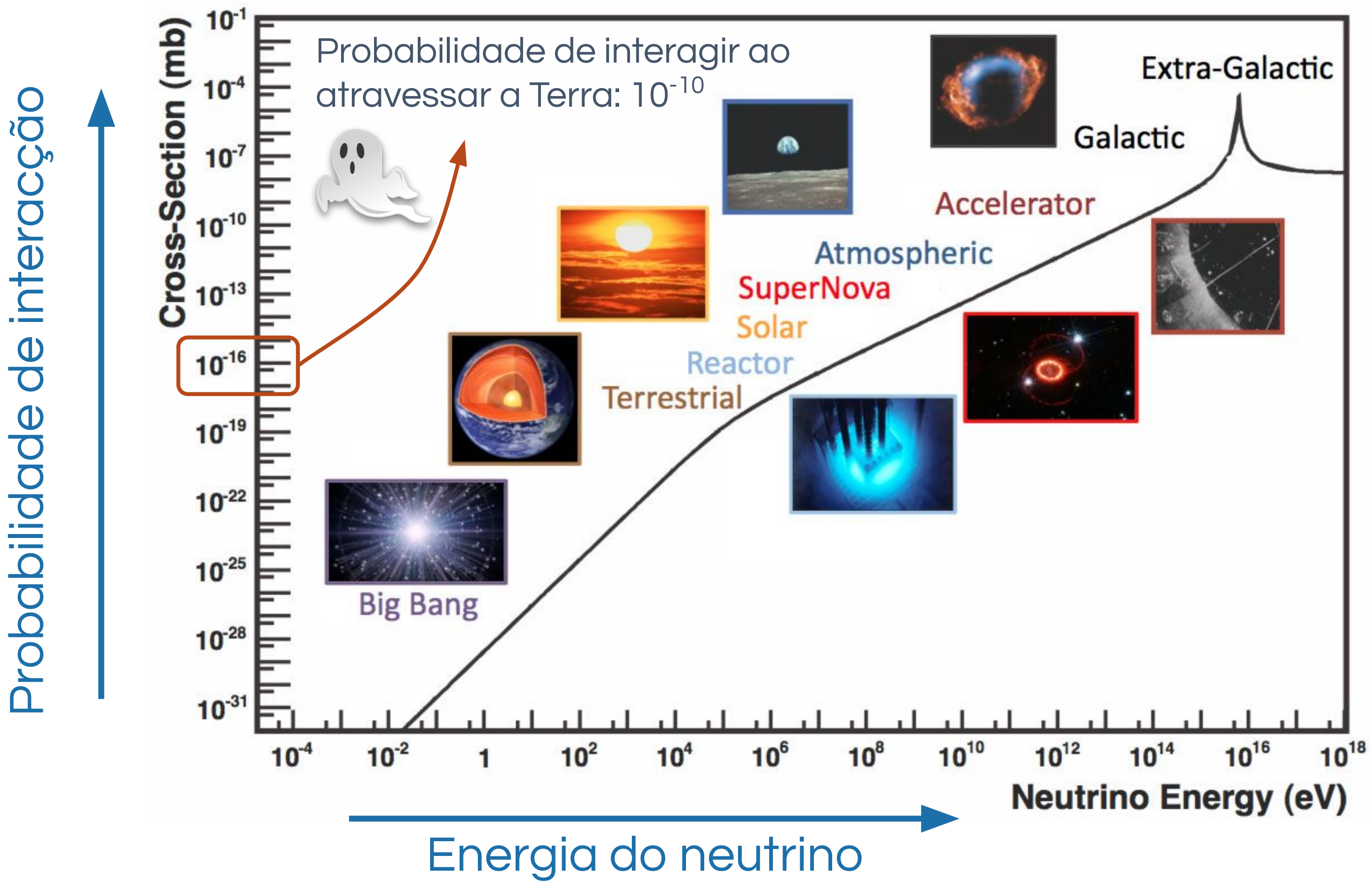
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

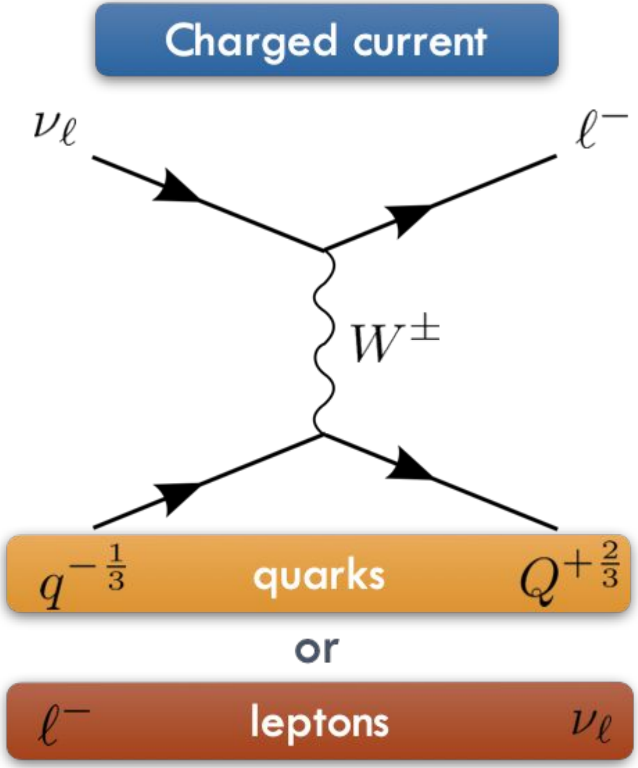


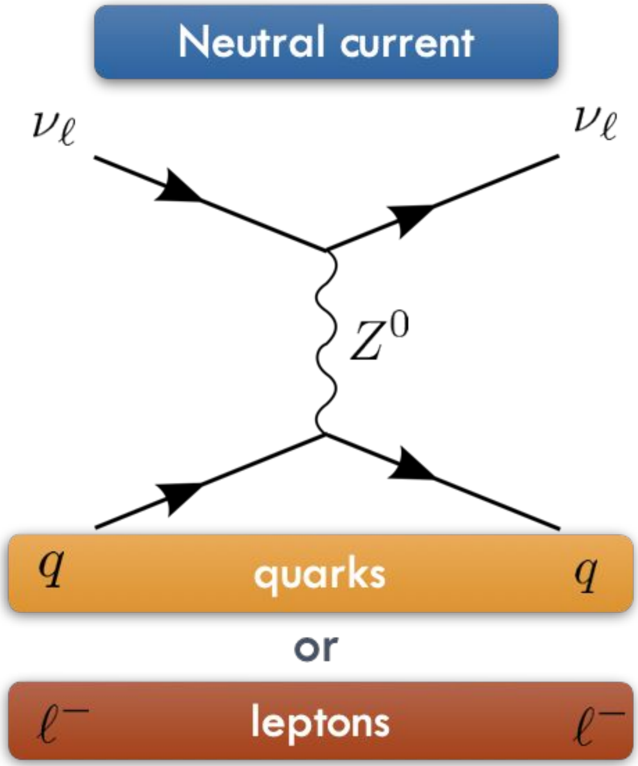


# Fontes de $\nu$s e probabilidade de interacção

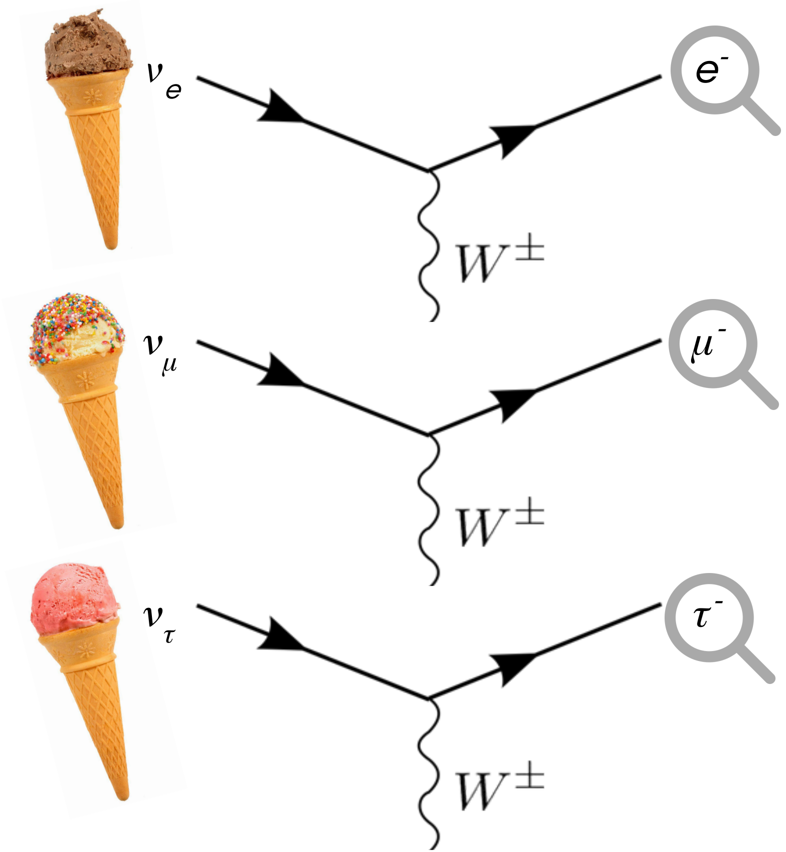


# Como interagem os neutrinos?

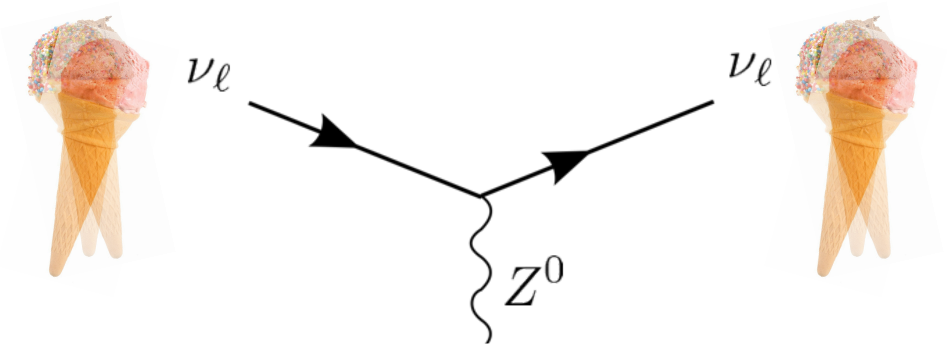


# Interacções de neutrinos




- Corrente carregada:
  - Os neutrinos produzem leptões carregados **da mesma geração** .
  - Permitem a **identificação** do **sabor** do neutrino através da identificação do leptão carregado.
- Corrente neutra:
  - **Não permite** a identificação do sabor do neutrino.

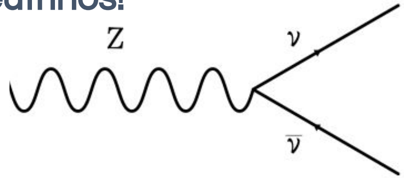


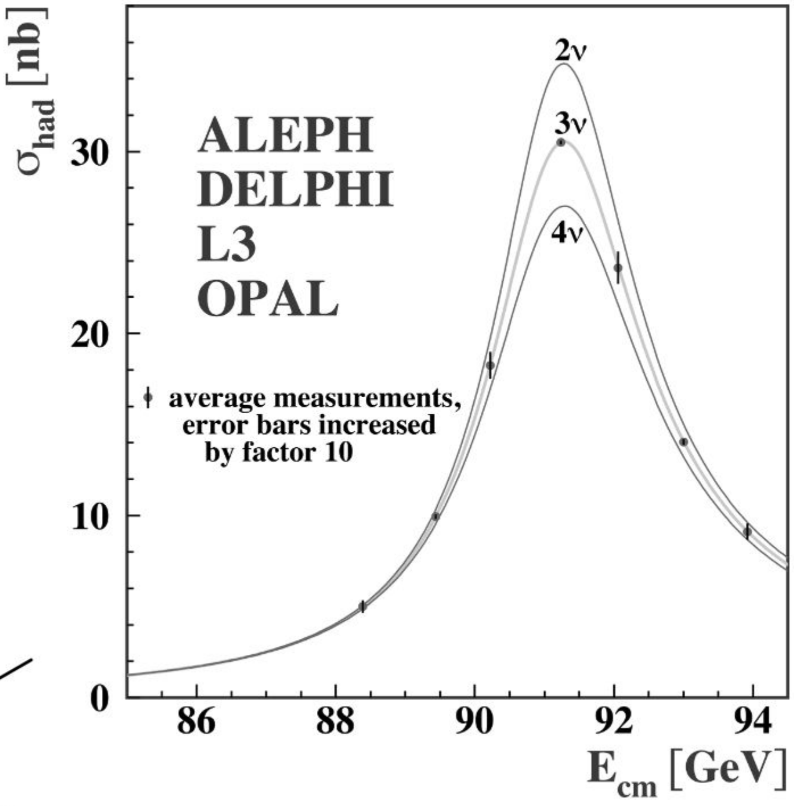
# Quantos sabores de neutrinos?

- A largura do pico de ressonância do bosão Z foi medida com enorme precisão pelas experiências do LEP nos anos 90.

- A largura do pico depende do número de decaimentos possíveis do bosão Z.
- O bosão Z pode decair para um par de neutrino-antineutrino do mesmo sabor.
- Portanto, a largura do pico permite-nos contar o número de sabores de neutrinos.

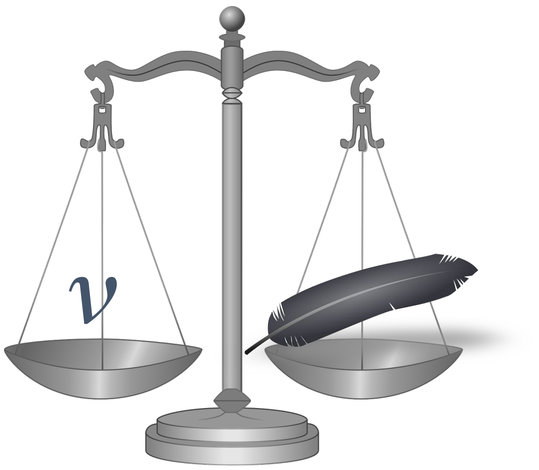
- Número de sabores medido: 2.9840 ± 0.0082.
    - **Apenas três sabores de neutrinos!**

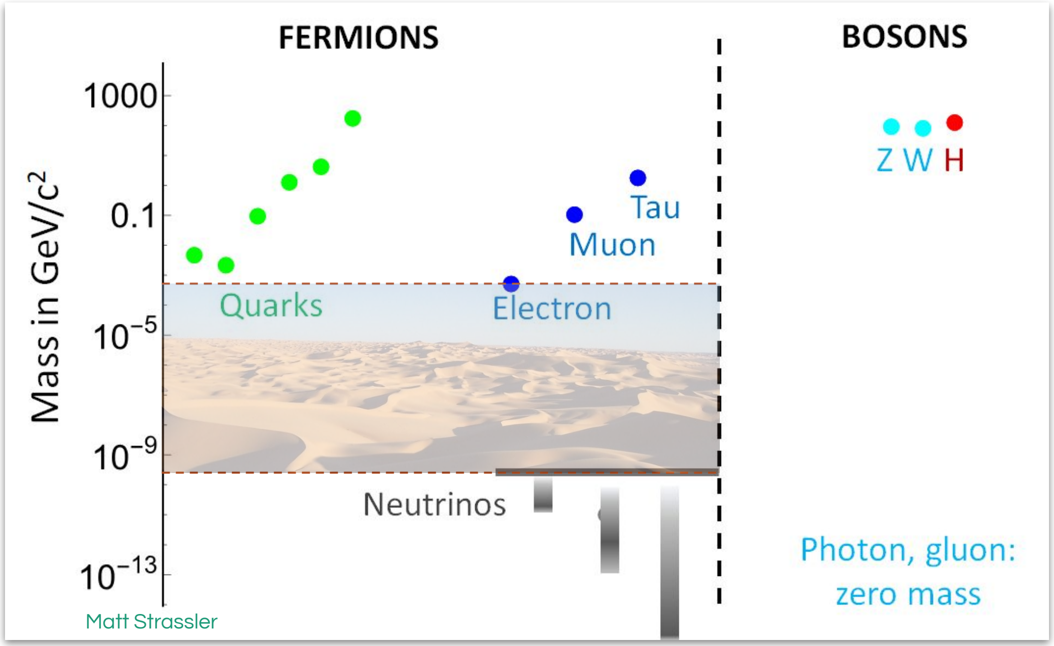


# Massa dos neutrinos

- Qual é a **massa** dos neutrinos?
  - Não sabemos... ainda!
- Mas sabemos que tem de ser pelo menos **6 ordens de grandeza** menor que a do electrão!
- Esta enorme diferença sugere que a massa do neutrino poderá ter uma origem diferente.
- Pode ser vista como uma indicação de nova física para além do Modelo Padrão.

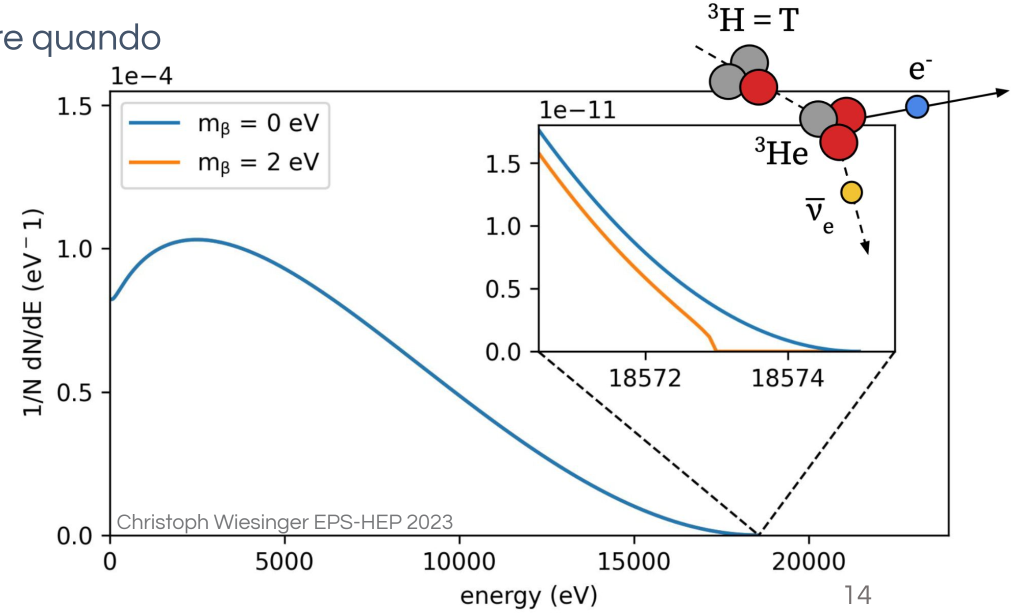


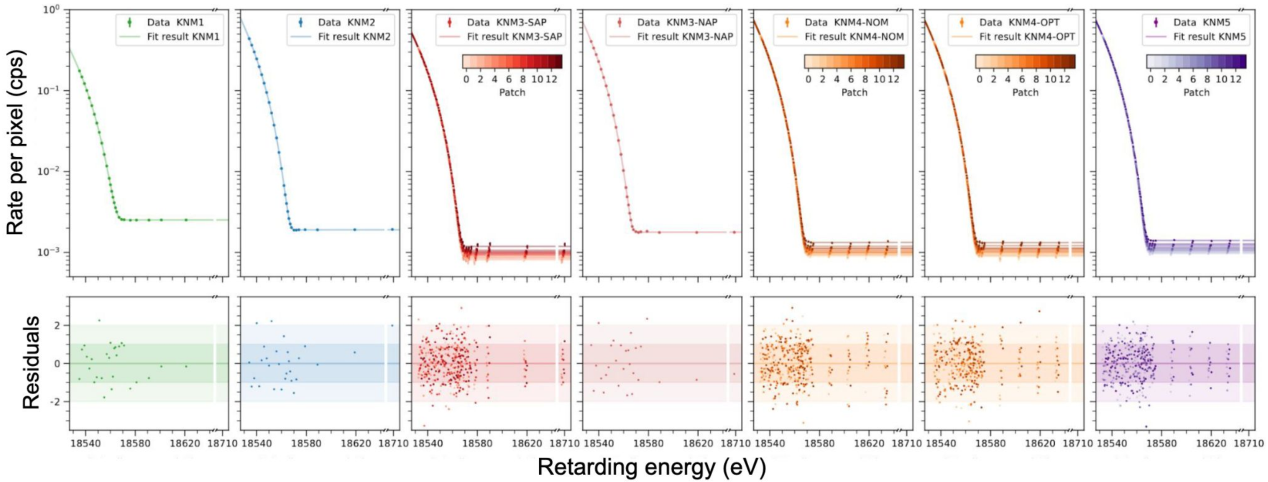
# Como medir a massa do neutrino?

- Voltemos à conservação de energia no decaimento beta.
  - Antes do decaimento a energia do sistema é igual à massa do isótopo inicial:
    - $E = m_i$
  - Depois do decaimento a energia é igual à soma da massa do isótopo final e das energias do electrão e do **neutrino** :
    - $E = m_f + E_e + \mathbf{E_\nu}$
  - A energia máxima do electrão ocorre quando o neutrino é produzido em repouso:
    - $E_e < m_i - m_f - m_\nu$

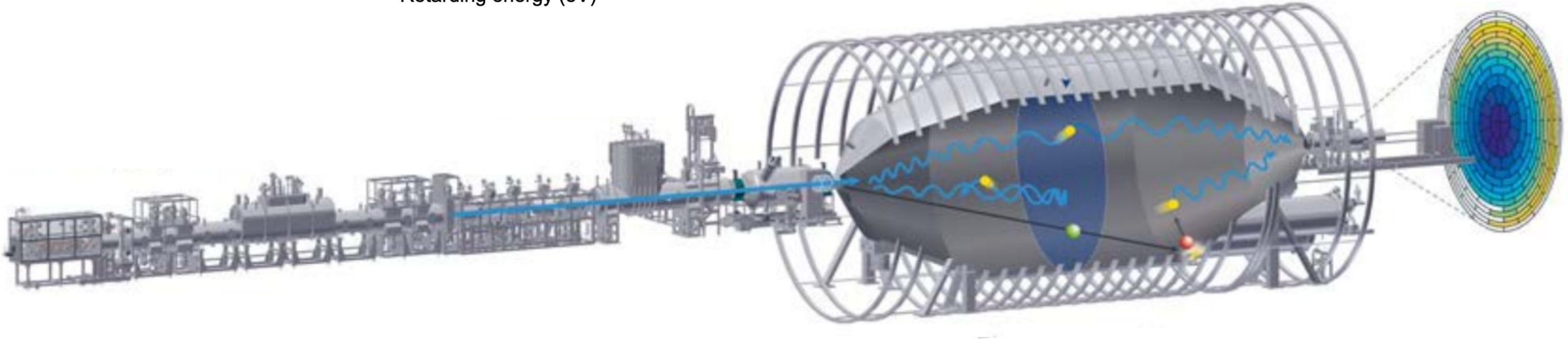
É possível inferir a massa do neutrino através da medição do espectro de energia do electrão!



# A experiência KATRIN




- Medição do decaimento beta de trítio.
- Resultado:
  - A massa do neutrino é **inferior a 0.45 eV** !



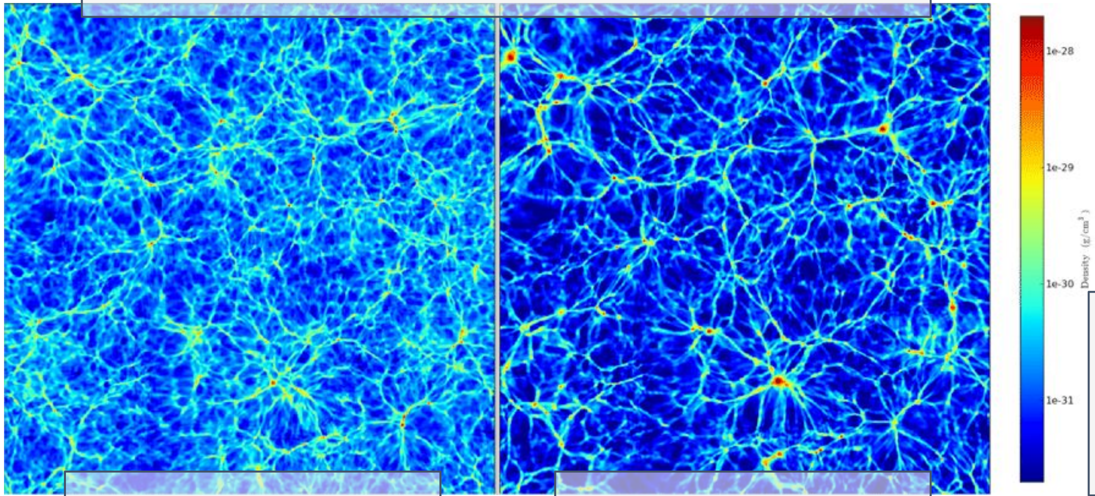
Espectrómetro KATRIN a chegar a "casa"

Após uma longa viagem...

# O que nos diz o cosmos sobre os neutrinos?

- Os neutrinos são a segunda partícula, do Modelo Padrão, mais abundante no universo.
  - Matéria escura!
- A sua presença tem efeitos na evolução do universo.
- Podemos inferir propriedades dos neutrinos a partir de observações do cosmos.

Distribuição de matéria no universo




Com neutrinos

Sem neutrinos

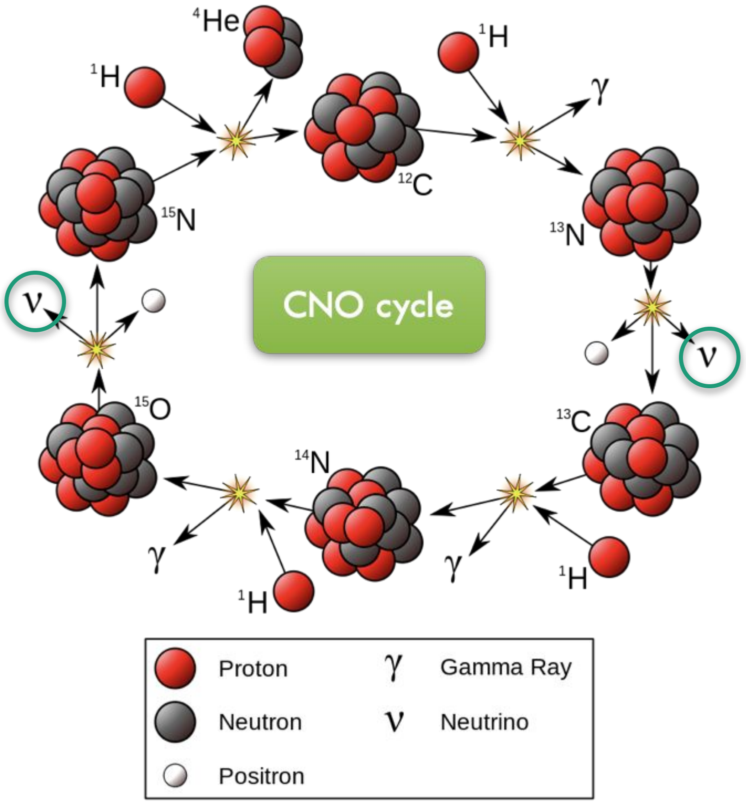
- Número de neutrinos: 2.99 ± 0.34
- Massa do neutrino: **< 0.5 eV**
- Em **concordância** com as experiências "terrestres"!

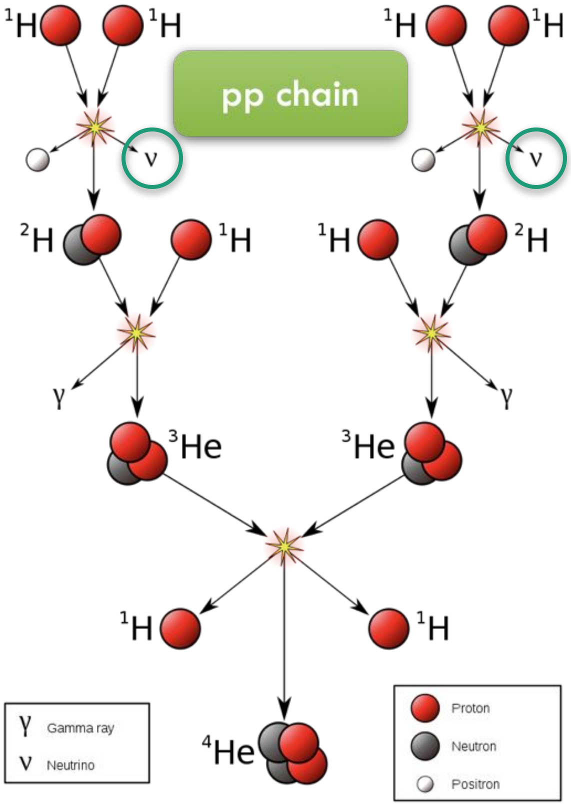
Mas como sabemos que a massa do neutrino não é **zero**?!

# Oscilação de neutrinos

# O modelo solar padrão

- Permite-nos calcular com precisão o fluxo de neutrinos produzidos no Sol.



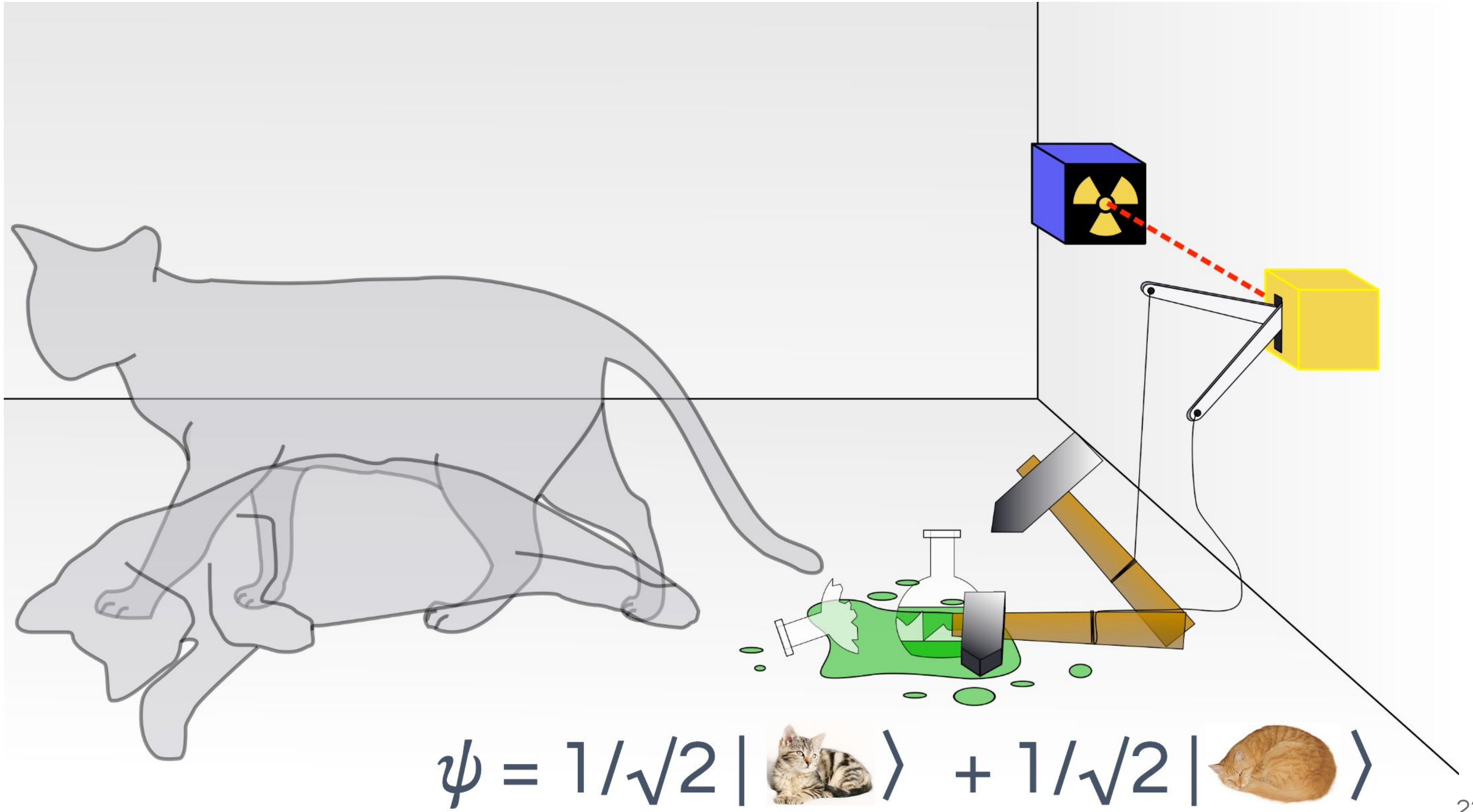
# O puzzle dos neutrinos solares


- No final dos anos 60, Ray Davis e John Bahcall propuseram uma experiência para medir o fluxo de **neutrinos do electrão** produzidos no Sol.
- O resultado da medição foi cerca de ⅓ do fluxo calculado a partir do modelo solar padrão.
    - Estaria o modelo solar errado?

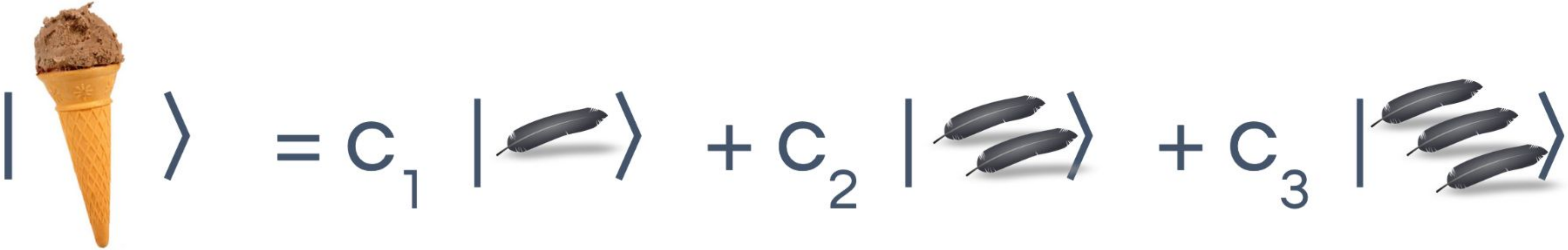
A experiência Homestake
1970 – 1994

Ray Davis

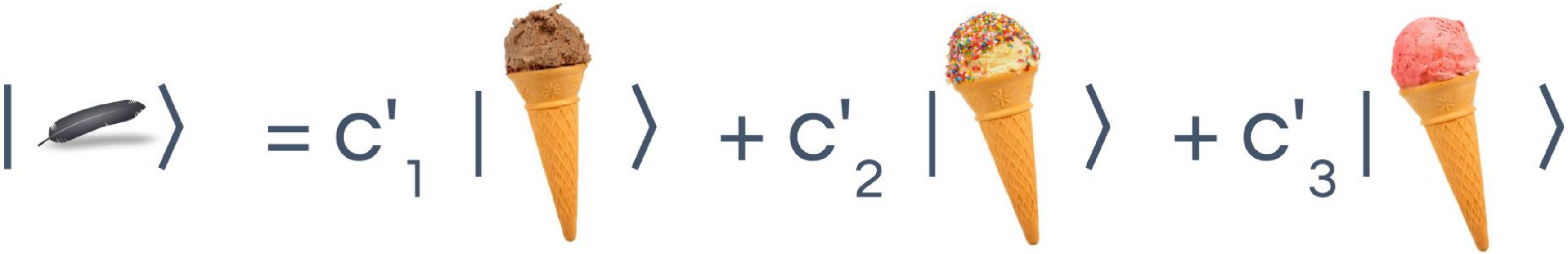
# Sobreposição de estados



# Estados de massa e estados de sabor

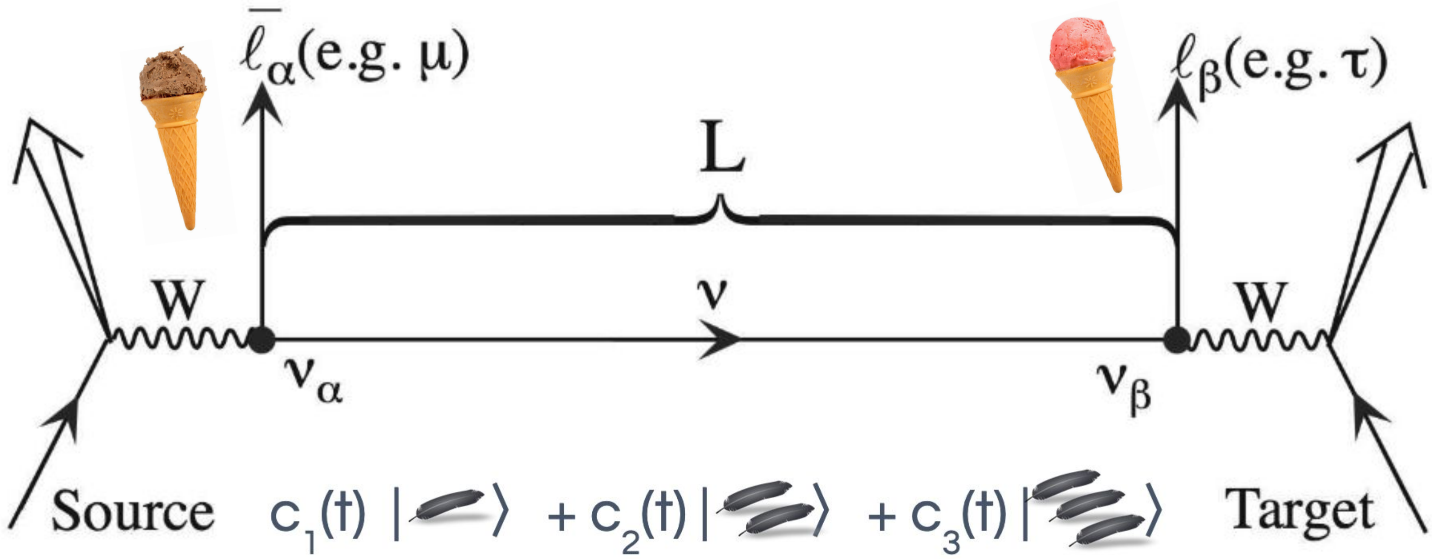



Cada estado de sabor corresponde a uma sobreposição de estados de massa.




Cada estado de massa corresponde a uma sobreposição de estados de sabor.

# Oscilação de neutrinos




- A mistura dos estados de massa **evolui com a passagem do tempo** , à medida que o neutrino atravessa o espaço.
- Após uma distância *L* o neutrino pode ser observado com um **sabor diferente** !

# Oscilação de neutrinos

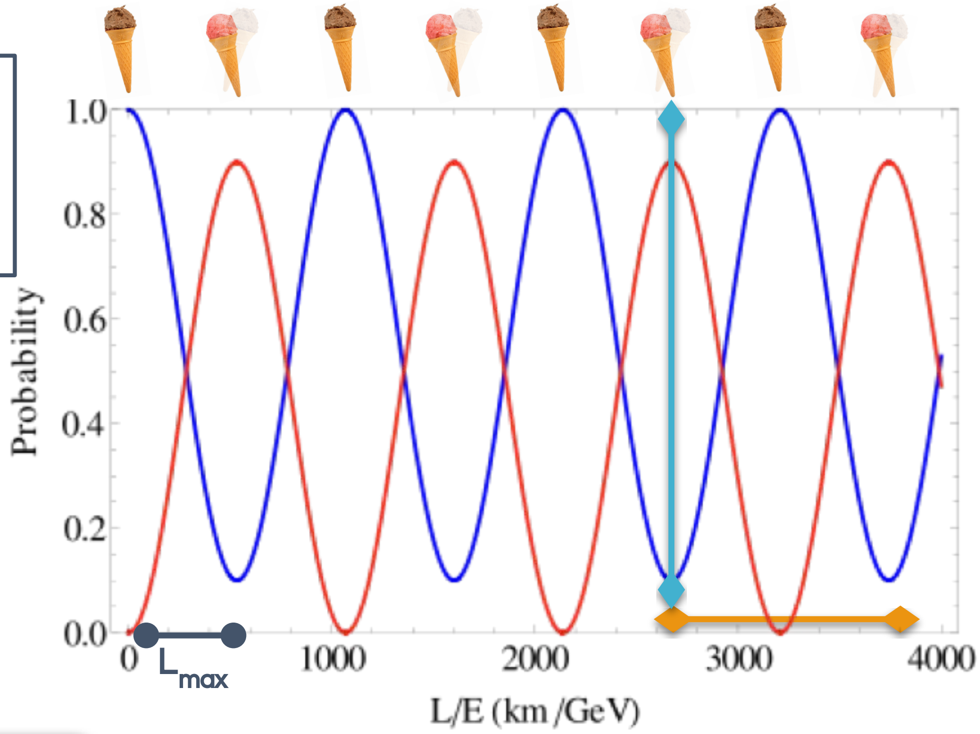
A medição da distância de propagação em que a oscilação atinge o primeiro máximo, $L_{max}$, para um neutrino de energia E permite-nos inferir a diferença entre o quadrado das massas.

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

$$P(\nu_e \rightarrow \nu_\mu) = sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L}{E_\nu})$$

Oscillation amplitude

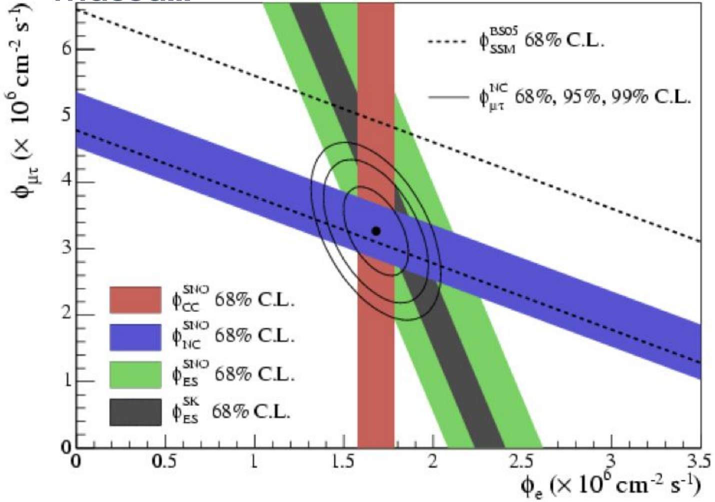
Oscillation frequency

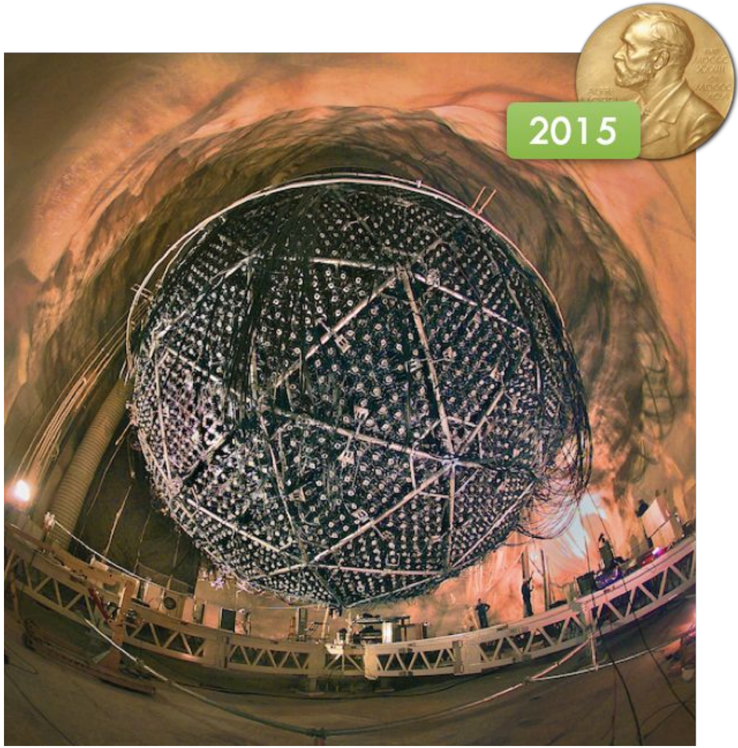


# A solução do puzzle solar

- Os neutrinos do electrão produzidos no Sol **mudam de sabor** no seu caminho até à Terra!
- Experiência SNO (2001, Canadá):
  - Medição do fluxo total de neutrinos de **acordo com o modelo solar** – corrente neutra.
  - Medição do fluxo de neutrinos do electrão **de acordo com Ray Davis** – corrente carregada.

**⇒ Os neutrinos oscilam, portanto têm massa!!!**

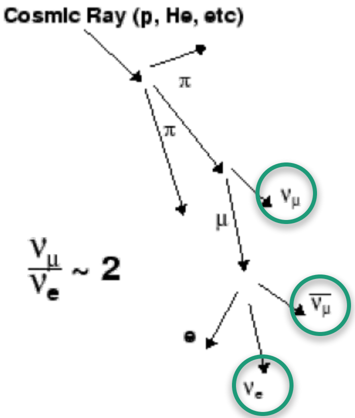


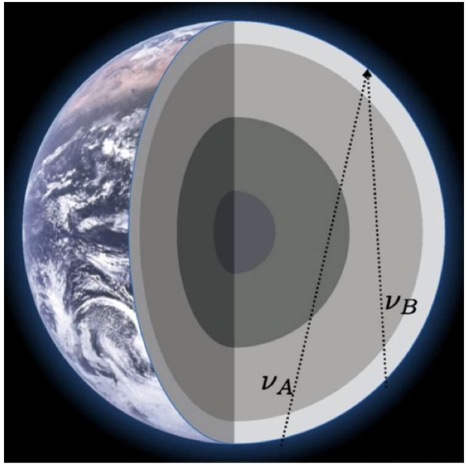



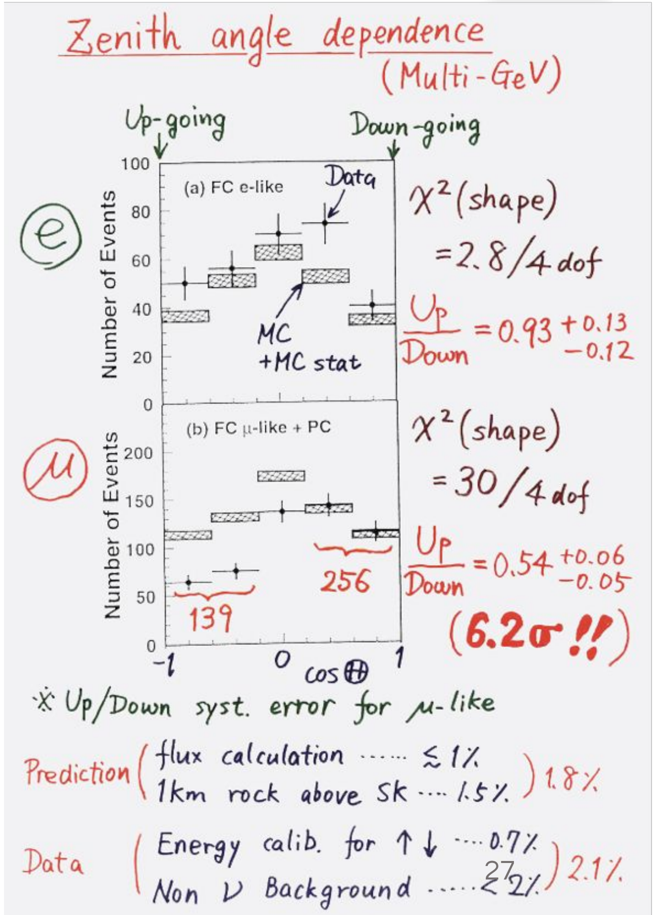
# Descoberta da oscilação de neutrinos

2015

- Experiência Super-Kamiokande (1998, Japão):
  - Medição do fluxo de neutrinos produzidos na atmosfera.
  - Neutrinos vindos de "cima" para "baixo":
    - Atravessam parte da atmosfera para chegar ao detector: L curto.
  - Neutrinos vindos de "baixo" para "cima":
    - Atravessam a Terra para chegar ao detector: L longo.
    - Só estes "desaparecem"!

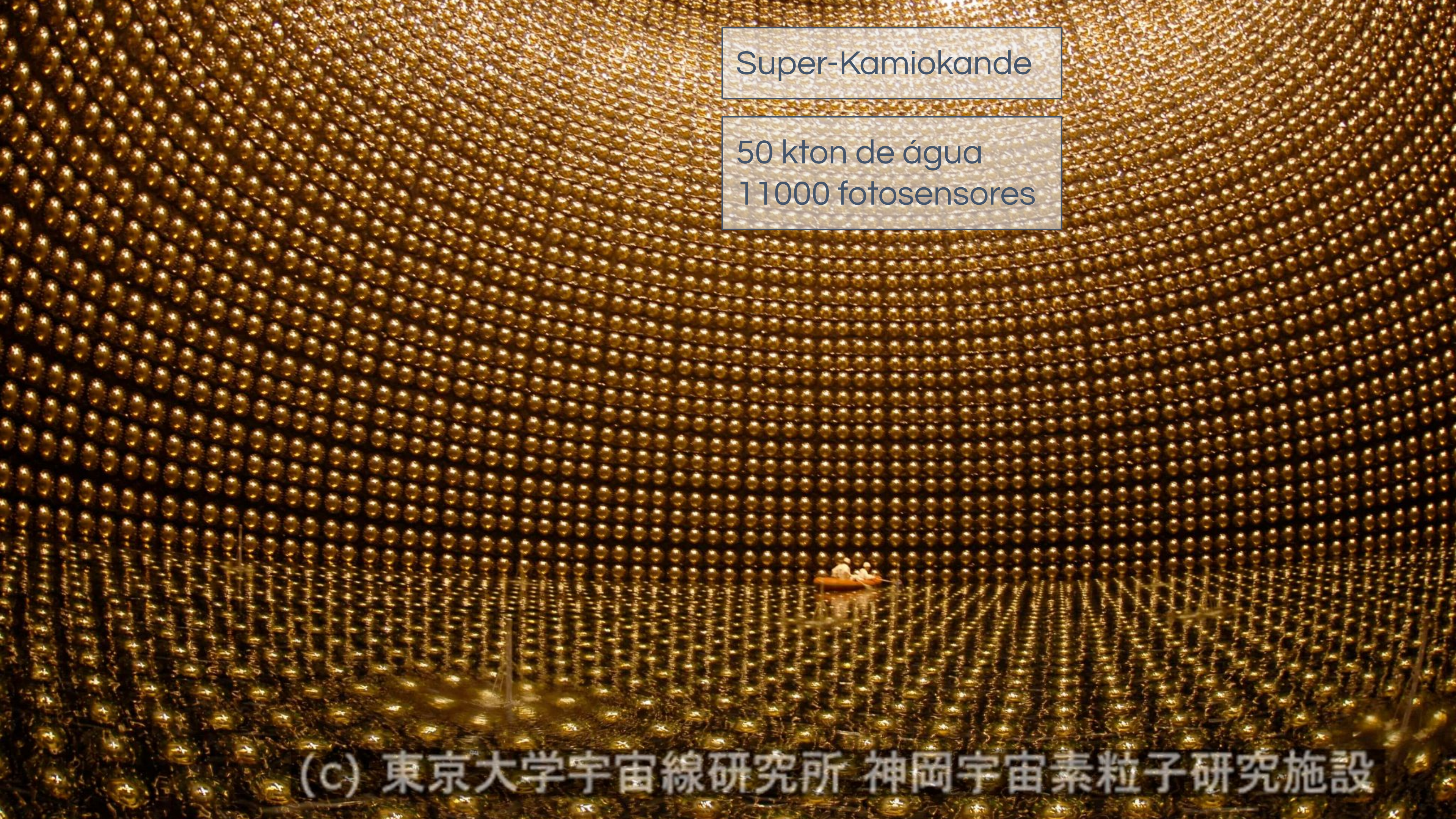


Super-Kamiokande

50 kton de água
11000 fotosensores

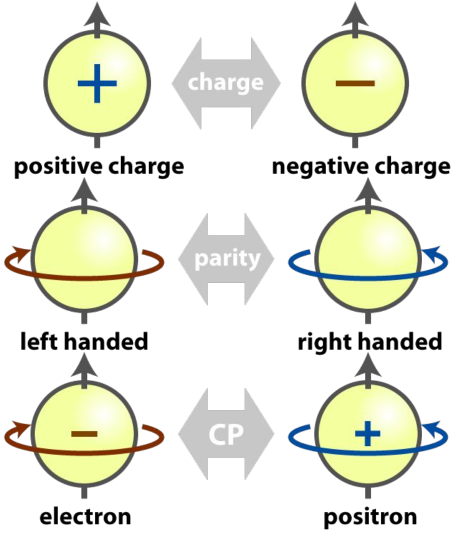


# Matéria e antimatéria

- Para onde foi toda a antimatéria?
- Rácio entre abundância de partículas de matéria e fotões no universo sugere que se tenha surgido um ligeiro excesso de matéria sobre antimatéria durante a evolução do universo.
    - Esse ligeiro excesso somos nós e tudo aquilo que vemos à nossa volta!

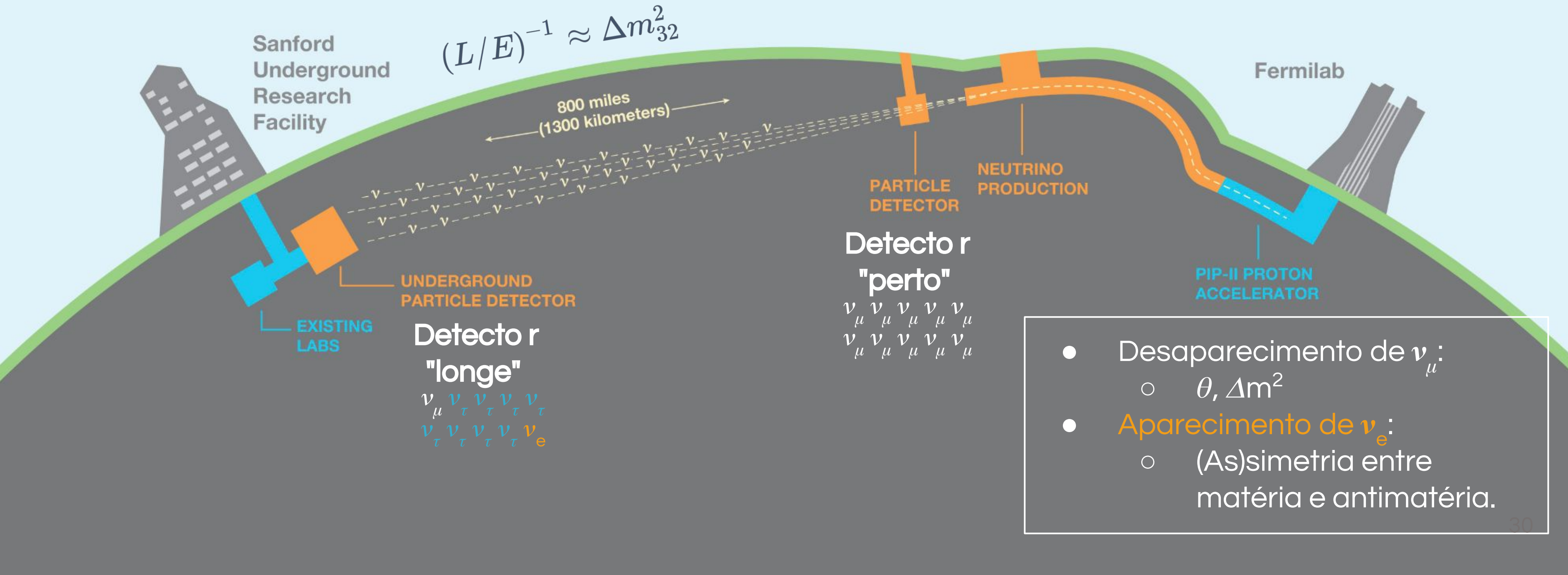
- Para "transformar" matéria em antimatéria:
    - Conjugação carga-paridade (CP)

- Existe "violação de CP" nas interacções fracas dos quarks
    - Mas é demasiado pequena para explicar a assimetria do universo.
- A oscilação de neutrinos é a **última oportunidade** para encontrar violação de CP no Modelo Padrão!
    - $\mathrm{P}\left(\nu_\mu \to \nu_e\right) = \mathrm{P}\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)?$
    - Este é o principal objectivo da próxima geração de experiências de oscilação de neutrinos!




Flip Tanedo, Symmetry Magazine

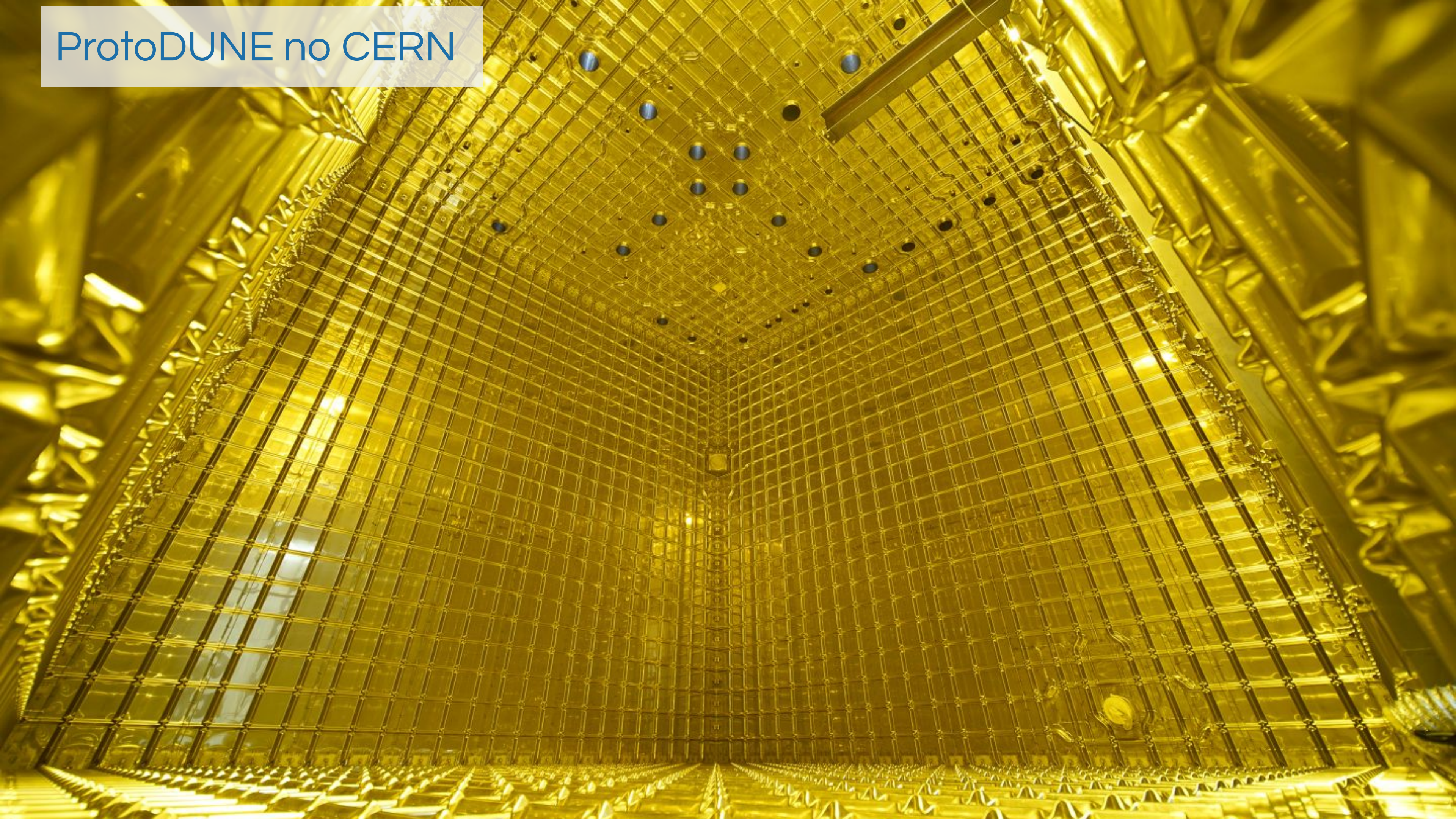
DEEP UNDERGROUND NEUTRINO EXPERIMENT



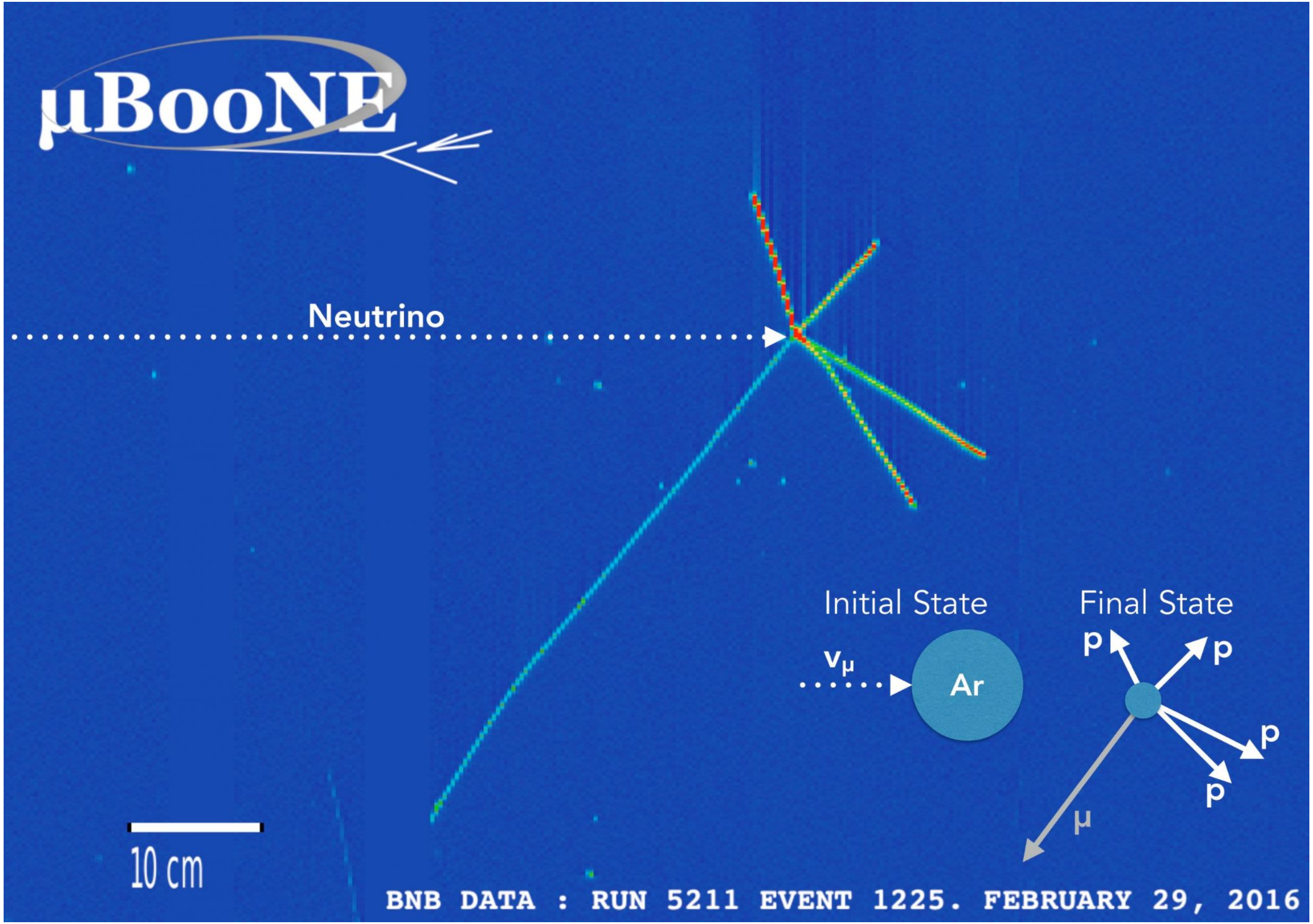

- Desaparecimento de $\nu_\mu$:
  - $\theta$, $\Delta m^2$
- Aparecimento de $\nu_e$:
  - (As)simetria entre matéria e antimatéria.

# ProtoDUNE no CERN

# ProtoDUNE no CERN



# ProtoDUNE no CERN





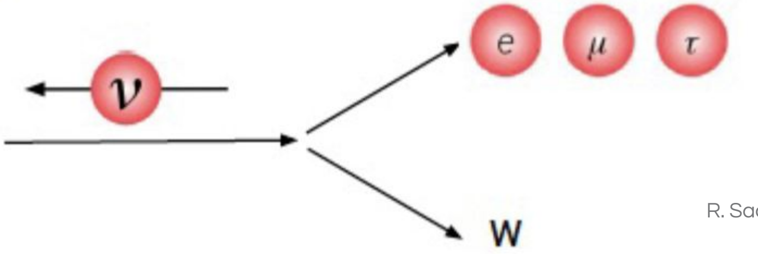

Credit: Fermilab

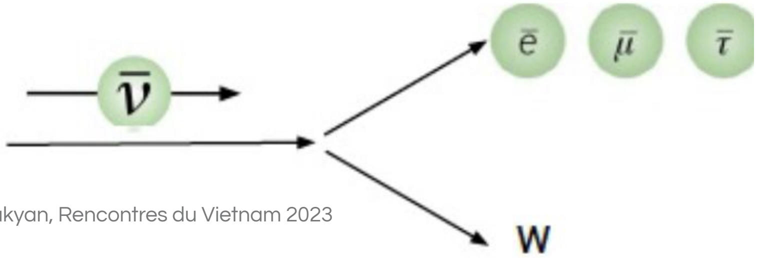
Cavernas para os detectores de DUNE finalizadas em Agosto de 2024

# Neutrinos de Majorana

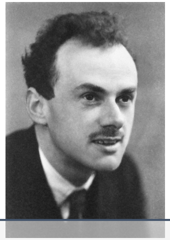
# Como se distingue um $\nu$ de um anti-$\nu$?

- O que significa a conjugação de carga em neutrinos?
- Sabemos que:
  - Neutrinos "esquerdos" produzem partículas.
  - Neutrinos "direitos" produzem antipartículas.
- Hipótese de Majorana:
  - O neutrino e o antineutrino são a mesma partícula, em estado de helicidade diferente.

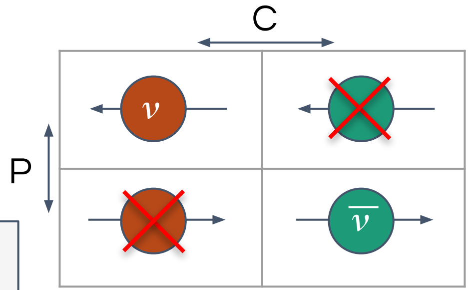


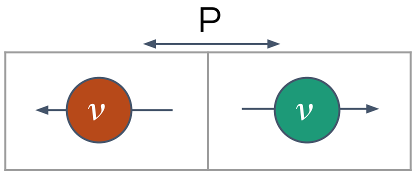




R. Saakyan, Rencontres du Vietnam 2023



Dirac

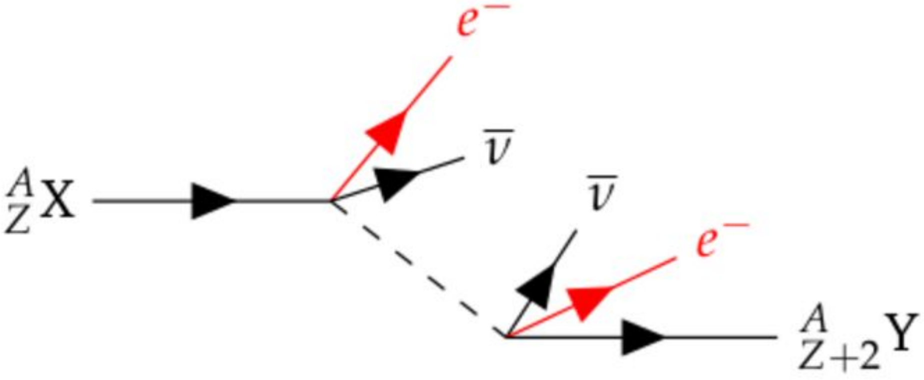


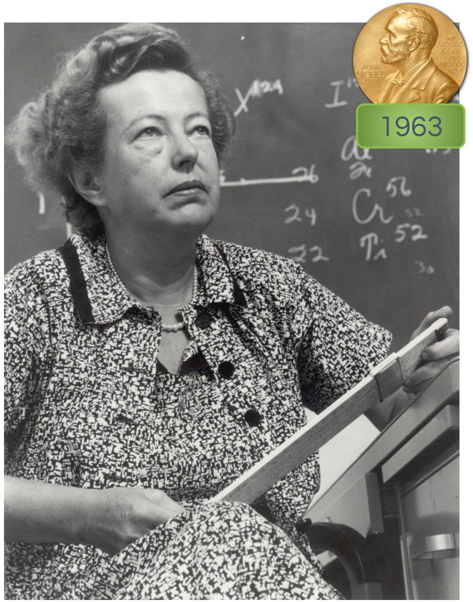




Majorana

# Decaimento beta duplo

- Dois decaimentos beta em simultâneo.
  - Um único processo.
  - Extremamente raro.
- Tempo de vida média à volta de $10^{21}$ anos!
  - Muito mais longo do que a idade do universo.
  - Já foi observado em cerca de 10 isótopos.
- Conservação de energia: a **soma** da energia dos electrões tem um espectro parecido ao do decaimento beta.
- E se os neutrinos forem a sua própria antipartícula (Majorana)?



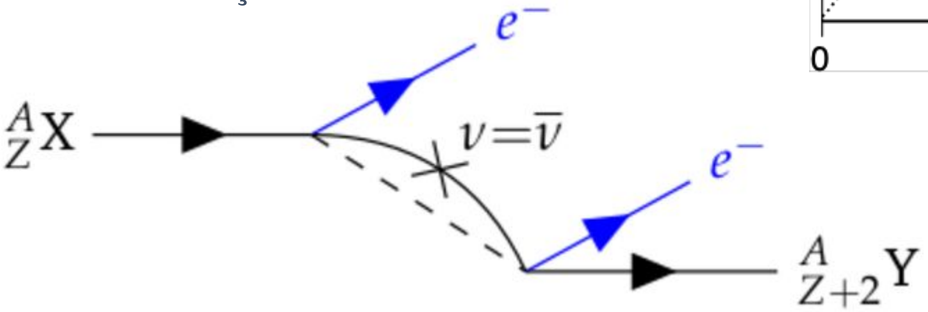



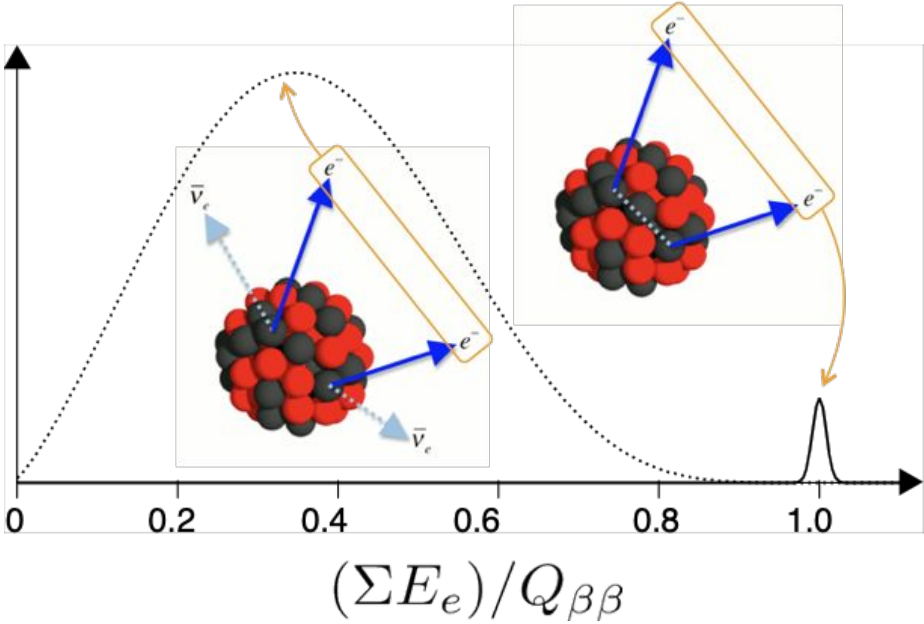

Maria Goeppert-Mayer

C. Wiesinger

# Decaimento beta duplo sem neutrinos

- Um processo semelhante ocorre apenas se os **neutrinos forem a sua própria antipartícula:**
  - Decaimento beta duplo **sem neutrinos.**
- Sem neutrinos emitidos no decaimento, a soma das energias dos electrões é constante.
- Este é o único processo que nos permite determinar a natureza dos neutrinos: Dirac vs Majorana
- O tempo de vida média depende da massa do neutrino.
  - Bónus: medição da massa.

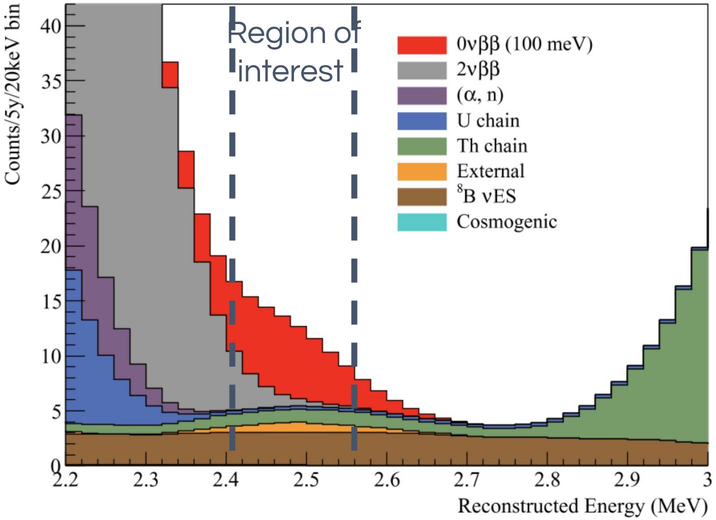


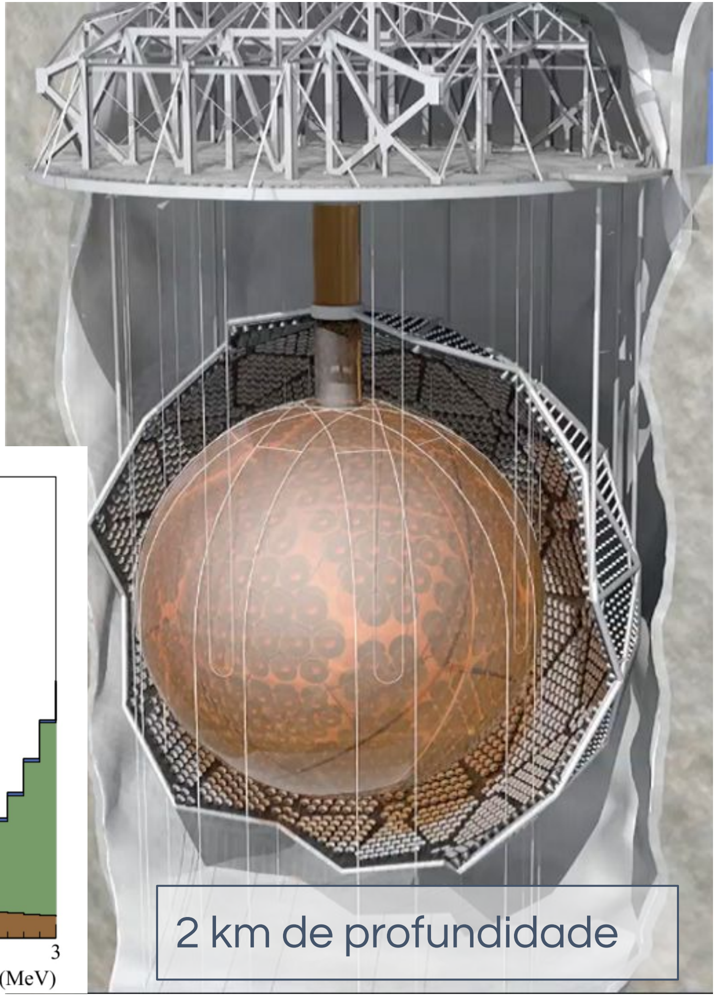




C. Wiesinger

# A experiência SNO+

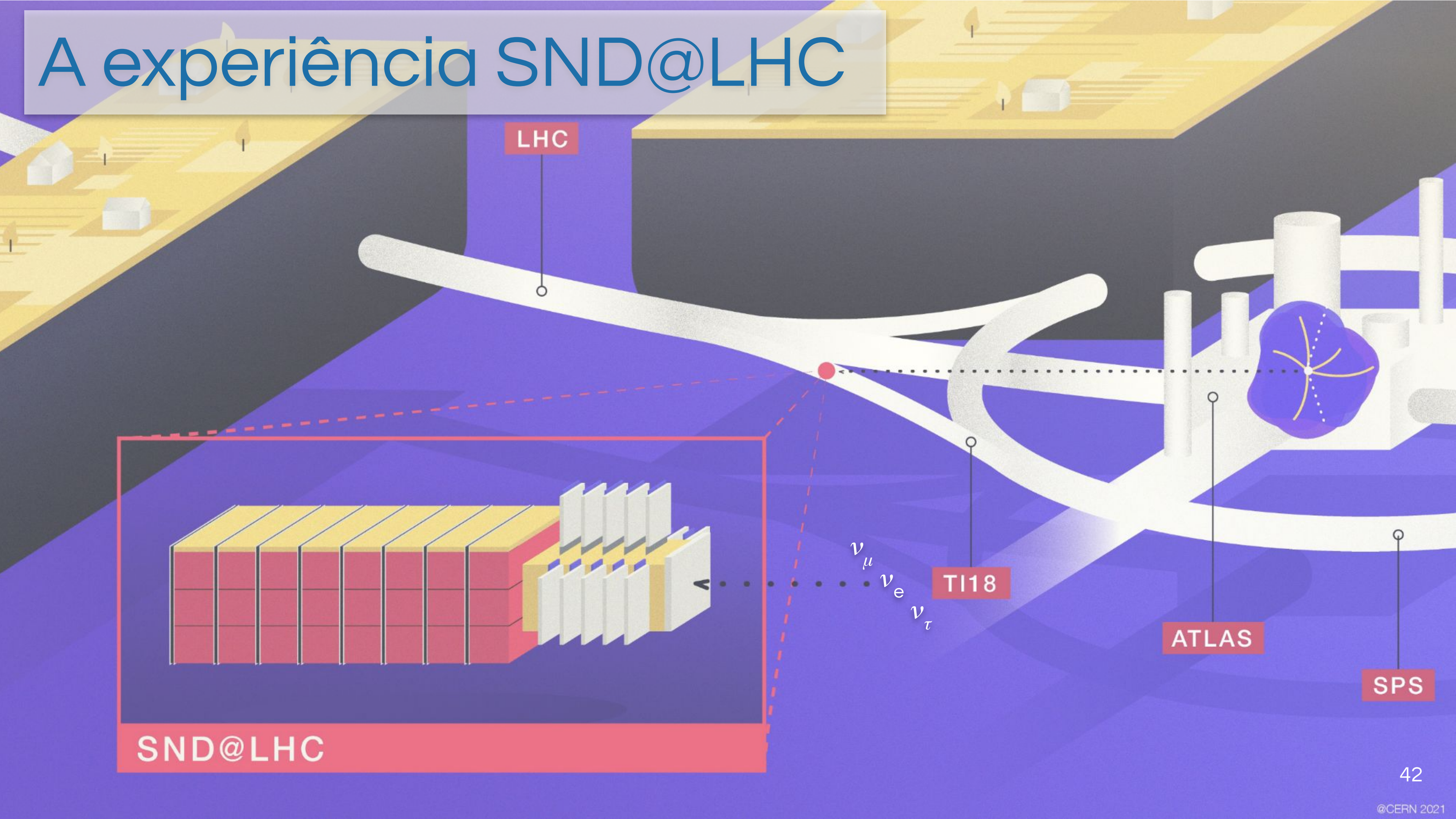
- Reutiliza parte da infraestrutura da experiência SNO.
- Grande esfera de acrílico com 790 toneladas de cintilador líquido.
- O isótopo de decaimento beta duplo $^{130}Te$ será diluído no líquido.
- Objectivo: encontrar um pequeníssimo excesso de decaimentos com a soma das energias dos electrões esperada.

# Neutrinos no LHC

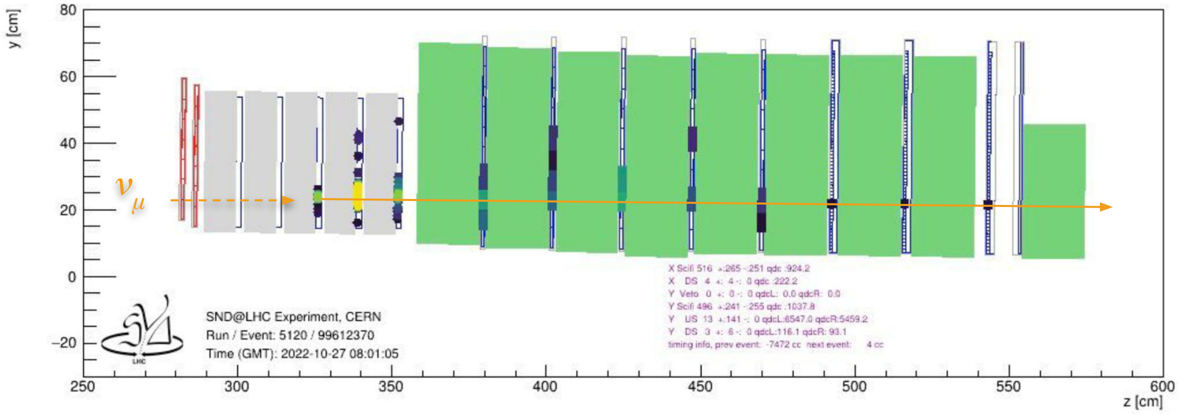
# A experiência SND@LHC



PHYSICAL REVIEW LETTERS **131**, 031802 (2023)

**Editors' Suggestion**

# Observation of Collider Muon Neutrinos with the SND@LHC Experiment




**Primeira observação de neutrinos produzidos em colisões de partículas num acelerador por SND@LHC e FASER** / 2023-03-23

Investigação

As novas experiências SND@LHC e FASER apresentaram a primeira observação de neutrinos produzidos em colisões de partículas num acelerador. Os resultados foram anunciados nos Rencontres de Moriond que estão a decorrer esta semana em La Thuile, Vale d'Aosta, Itália.

LER MAIS ›

Physics — VIEWPOINT

## The Dawn of Collider Neutrino Physics

**The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.**

By **Elizabeth Worcester**

# SND@LHC

Uma pequena experiência num grande acelerador!

# Resumo

- Os neutrinos são partículas especiais, sendo os únicos fermiões que interagem apenas através da força fraca (e da gravidade).

- Interagem em estados de sabor.
- "Viajam" em estados de massa.

- A mistura entre os estados de massa e os de sabor dá origem a oscilações de neutrinos.
    - Pode ajudar a explicar a assimetria entre matéria e antimatéria no universo!

- A massa dos neutrinos é extremamente pequena a comparar com a das outras partículas.
    - Exige uma explicação, provavelmente para além do Modelo Padrão.

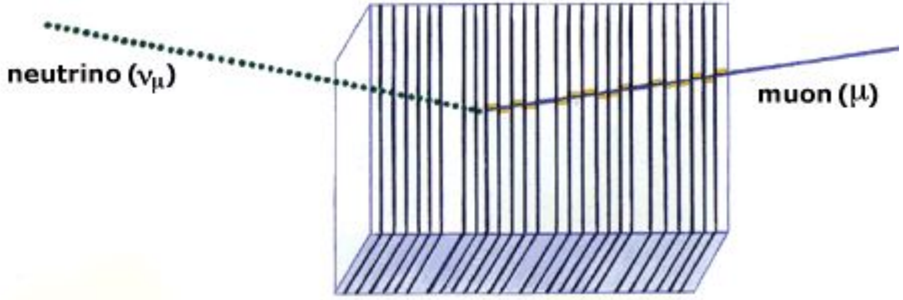
- Os neutrinos podem ser a sua própria antipartícula!

- Um vasto programa de experiências com neutrinos procura responder a estas questões.

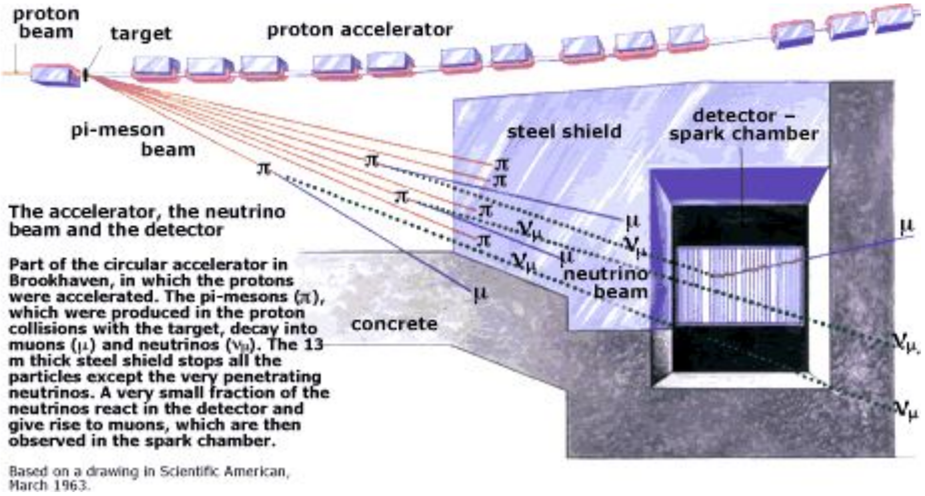
## Obrigado pela vossa atenção

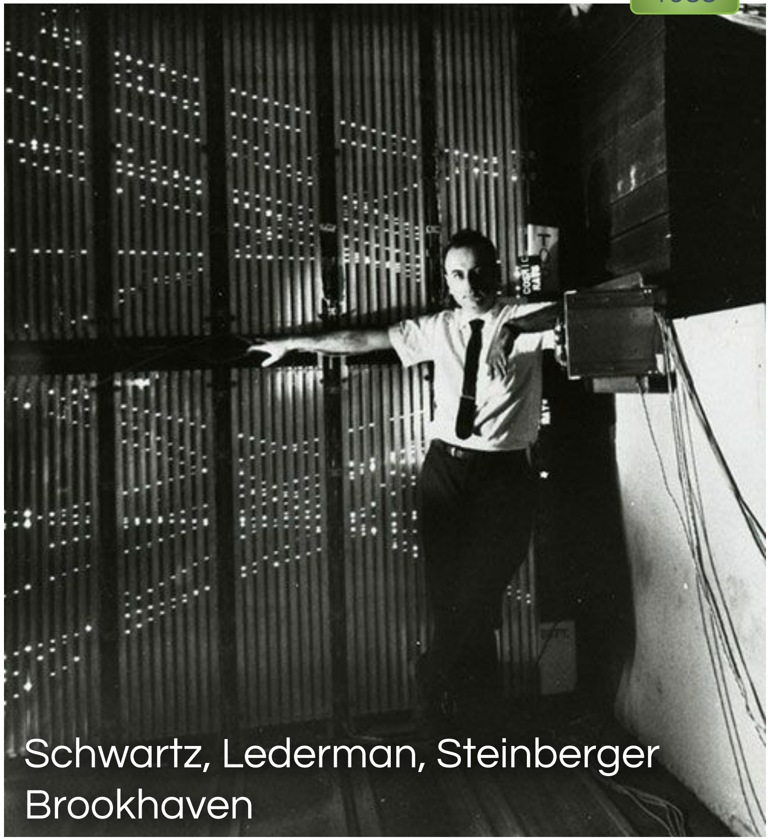
# Extra

# The muon neutrino (1962)


A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.



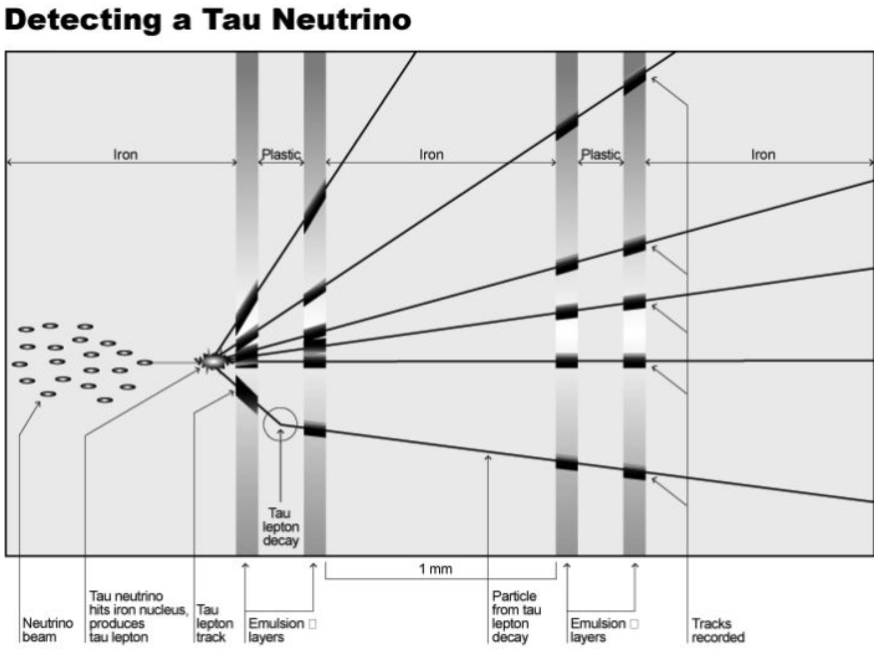



Schwartz, Lederman, Steinberger
Brookhaven

# The tau neutrino (2000)

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

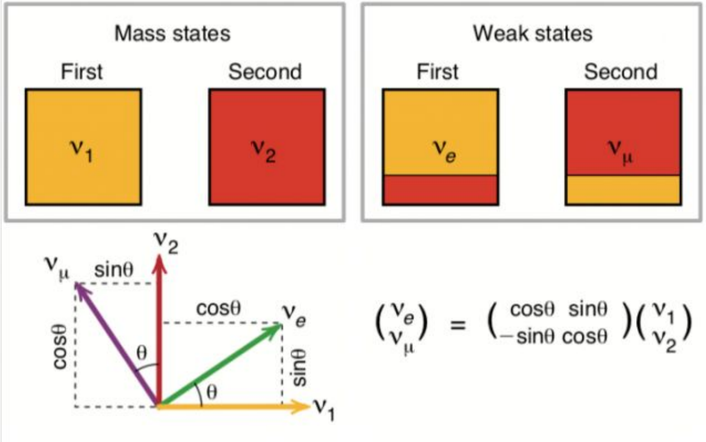
- Identify the tau by its short lifetime.
  - Short track with a "kink" (secondary vertex).
- Need micrometric precision:
  - Nuclear emulsion detector.

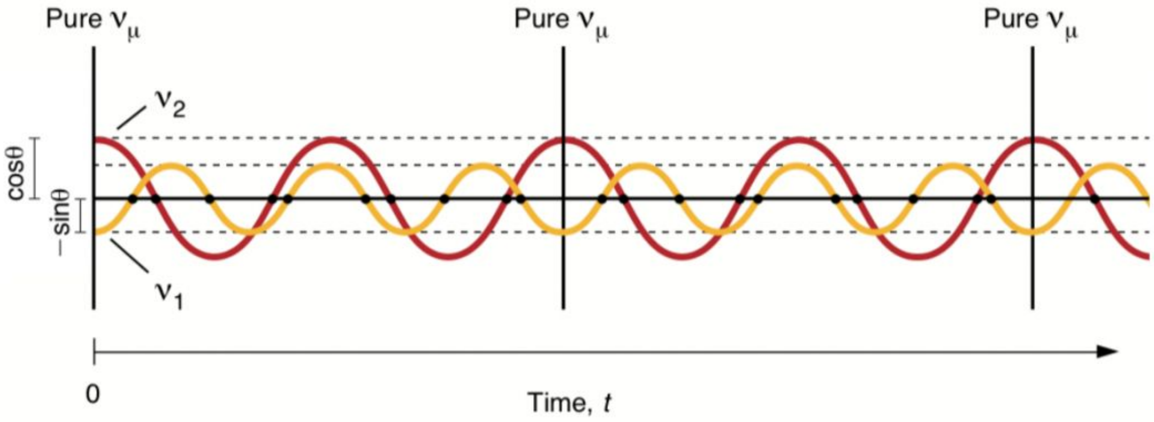




- **Observed 9 $\nu_\tau$ events!**

# Oscilação de neutrinos

- A **propagação** dos neutrinos através do **espaço-tempo** é determinada pelo seu **estado de massa** .
- A **interacção** dos neutrinos com as outras partículas é determinada pelo seu **estado de sabor** .
- A **mistura** entre os estados de massa e os estados de sabor dá origem à oscilação de neutrinos!




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

# 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!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{+i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Reactor" parameters

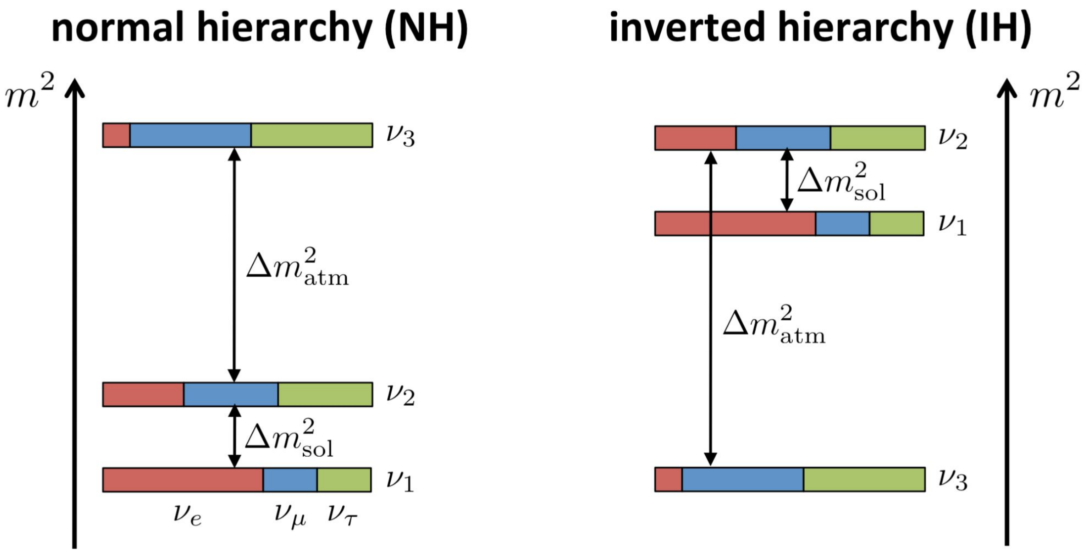
CP violating phase

"Solar" parameters

Mass states

# Neutrino mass ordering

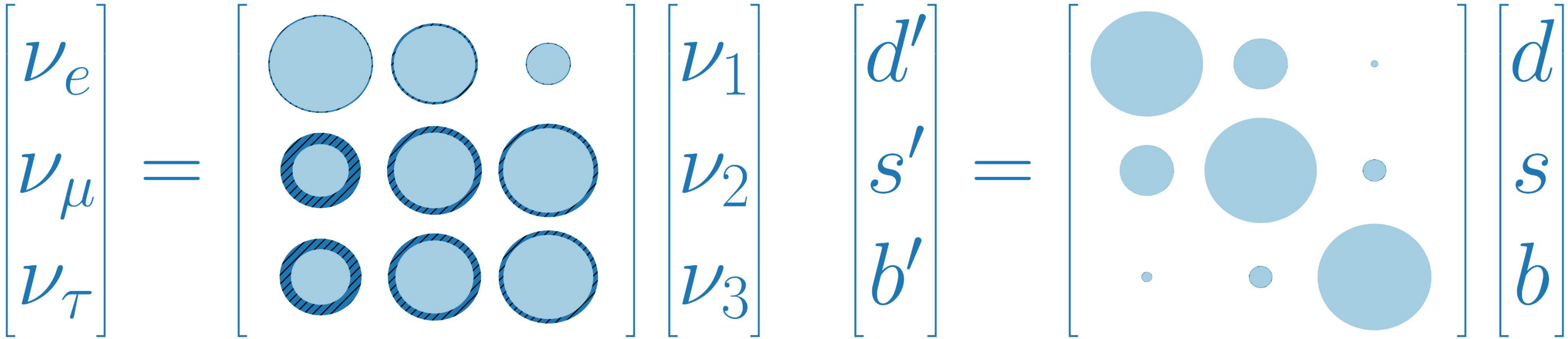
- To **first order**, neutrino oscillation experiments are not sensitive to the sign of the squared-mass differences...
  - Currently, we do not know if $m_1 < m_3$ (**normal ordering**) or if $m_3 < m_1$ (**inverted ordering**).
- However, at **high energies**, coherent interactions with **matter**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

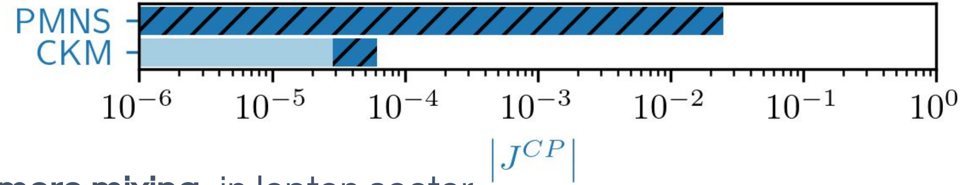


# Lepton *vs* quark mixing

PMNS NuFit 5.1 (2021)

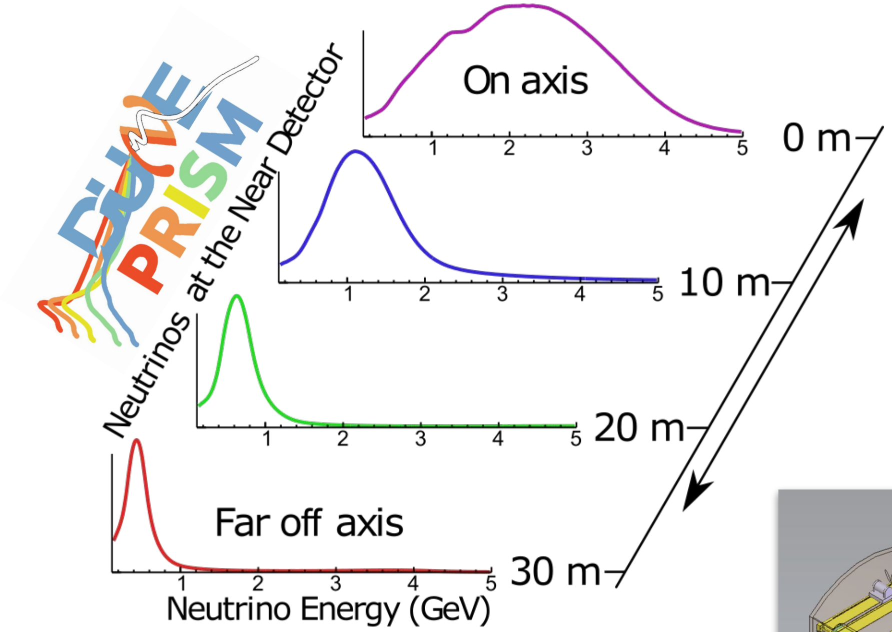
CKM CKMfitter Spring 21



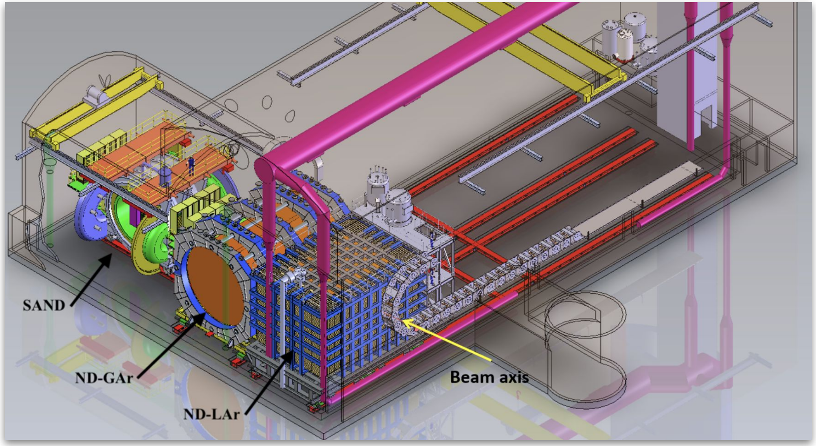


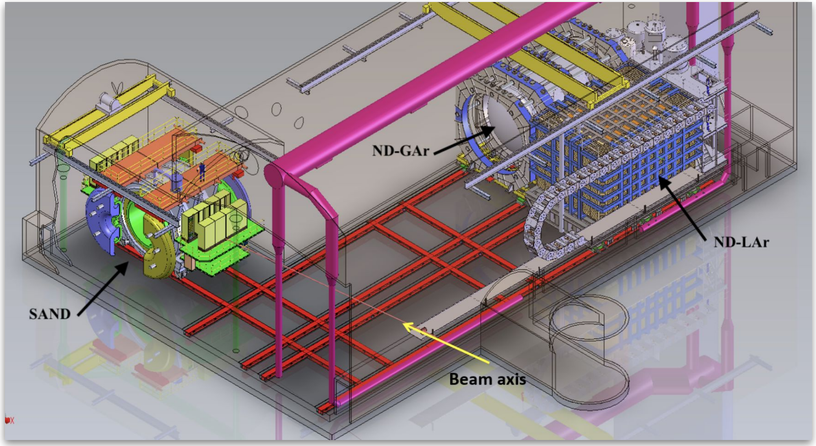

- Much **more mixing** in lepton sector.
- **CP violation** can be up to three orders of magnitude larger!

# DUNE near detectors

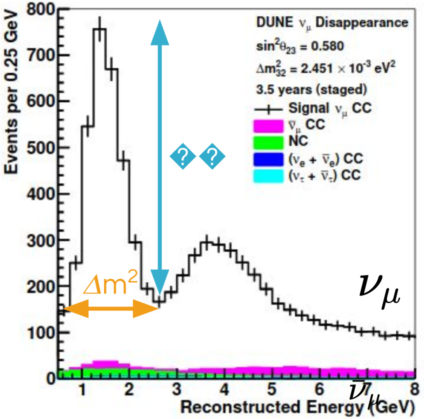


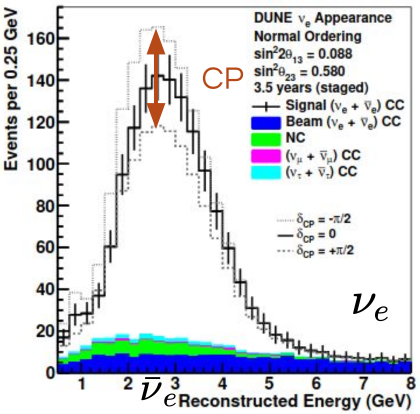

- Liquid and gaseous argon TPCs.
- **Moveable!**
  - "PRISM" effect allows for precise measurements of neutrino interactions.



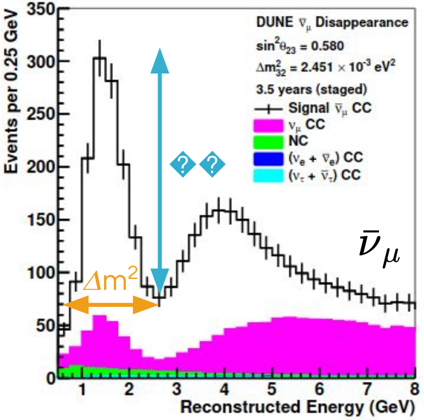



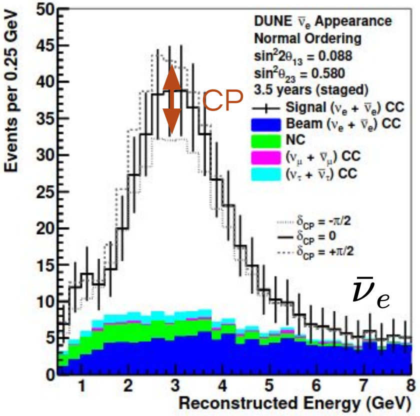
# Neutrino oscillations with DUNE



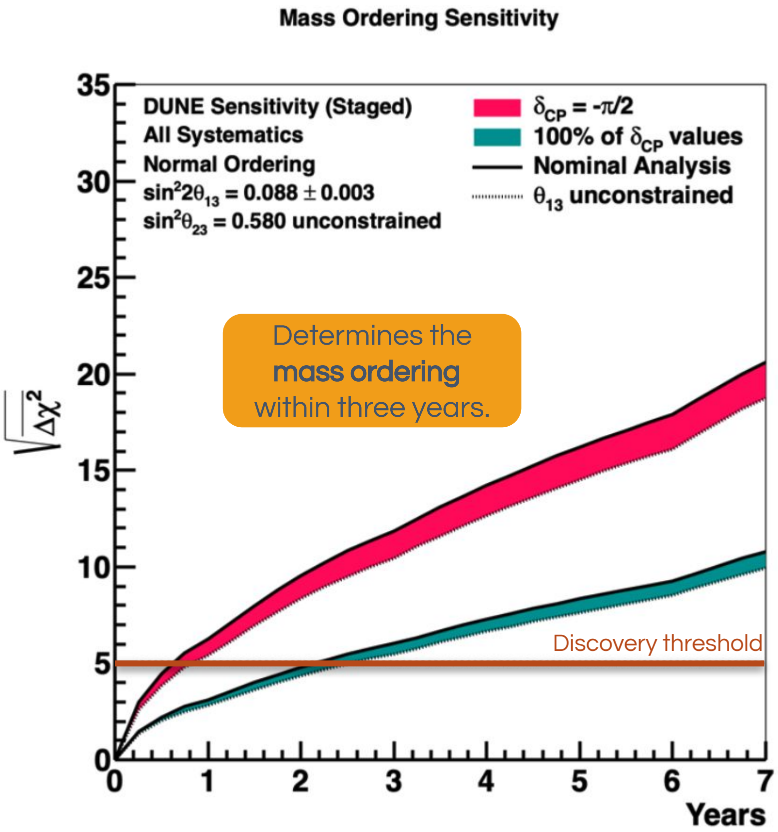

Neutrinos

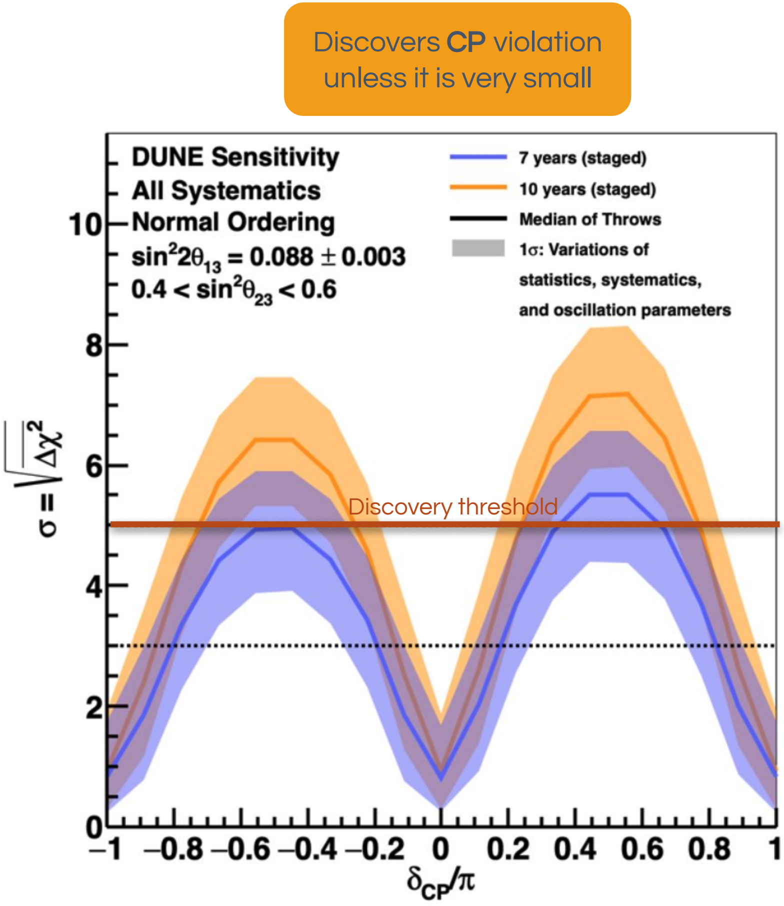



Antineutrinos

# DUNE sensitivity



# 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:

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

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

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

# 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:

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

$$P(\nu_e \rightarrow \nu_\mu) = sin^2(2\theta) sin^2(1.27 \Delta m^2 \frac{L}{E_\nu})$$

Oscillation amplitude

Oscillation frequency

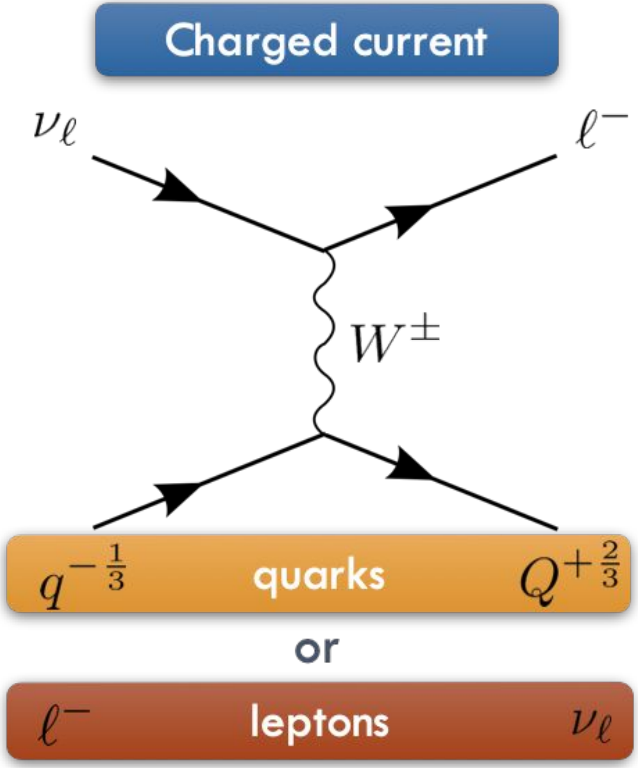
* Assumption not necessary if more detailed wavepacket formulation is used.

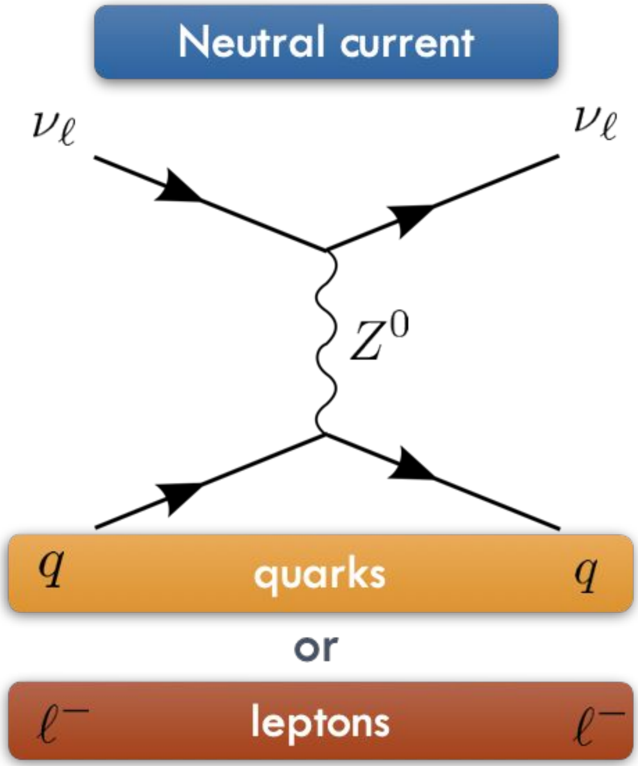
# Consequences of neutrino oscillations

- **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".

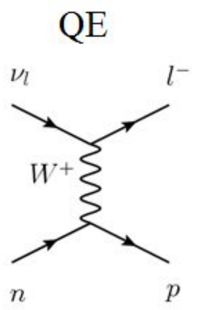
- **Open questions**:
  - How large is the CP violation in neutrino oscillations?
    - Could this explain the observed asymmetry between matter and antimatter in the Universe?
      - "Leptogenesis".
  - Does the neutrino mixing pattern hint at potential symmetries underlying the three generations?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

# Neutrino interactions



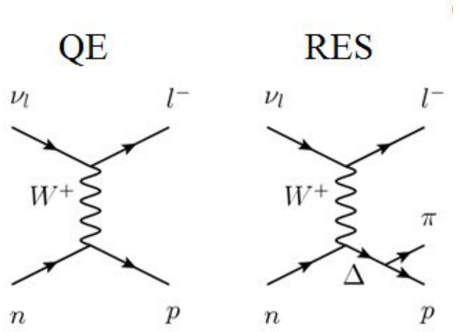



# Neutrino interactions



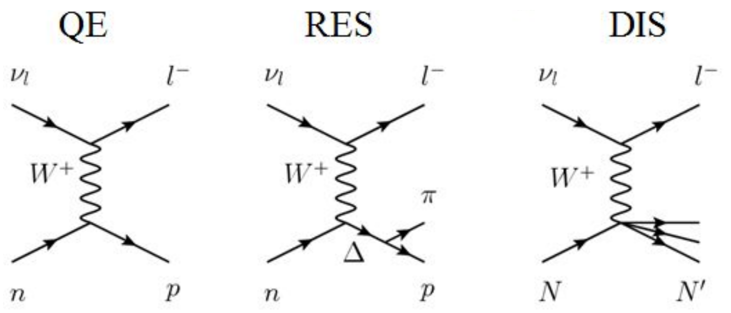

- Neutrino interactions with nuclei up to a **few hundred MeV** are "quasi-elastic".
  - Nucleon does not "break up"

# Neutrino interactions



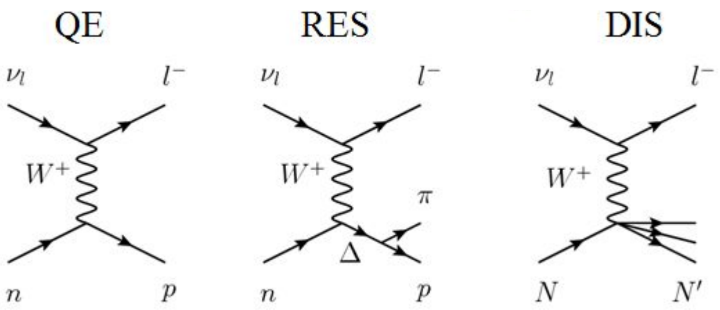

- **Above around 1 GeV** the energy transferred by the neutrino to the nucleon is enough to "excite" it into the delta-resonance ($m_{\Delta}$=1323 MeV/$c^2$).
    - The delta baryon decays instantly to a pion and a nucleon.

# Neutrino interactions

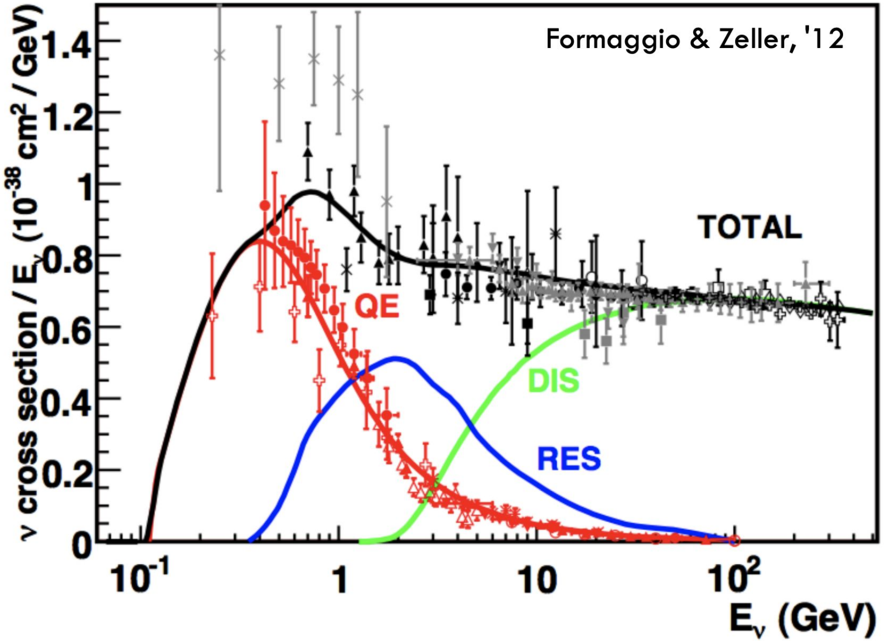



- **Above a few tens of GeV** , neutrinos "see" the quark structure of the nucleon.
- Energy transferred to the nucleon breaks it up into a collection of hadrons.
- This process is called Deep Inelastic Scattering.

# Neutrino interactions

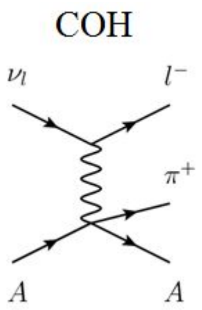



Increasing momentum transfer



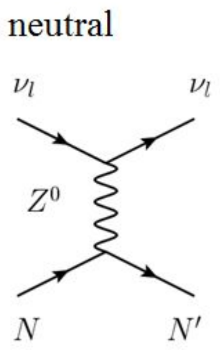
# Neutrino interactions

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



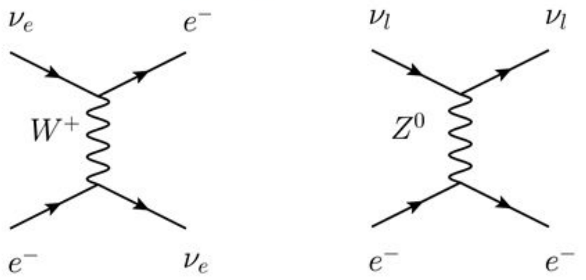
# Neutrino interactions

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

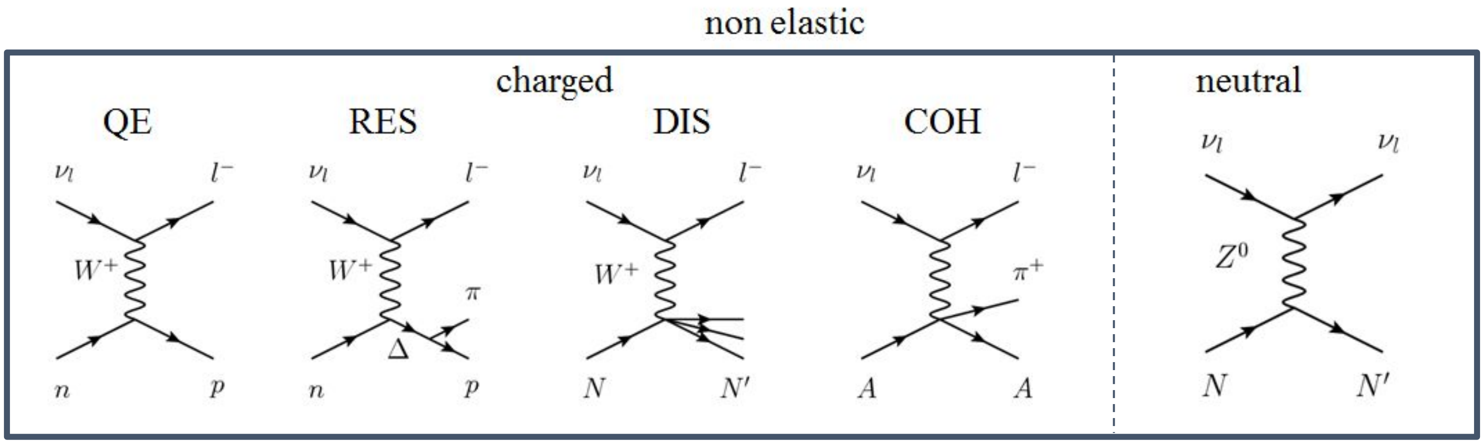


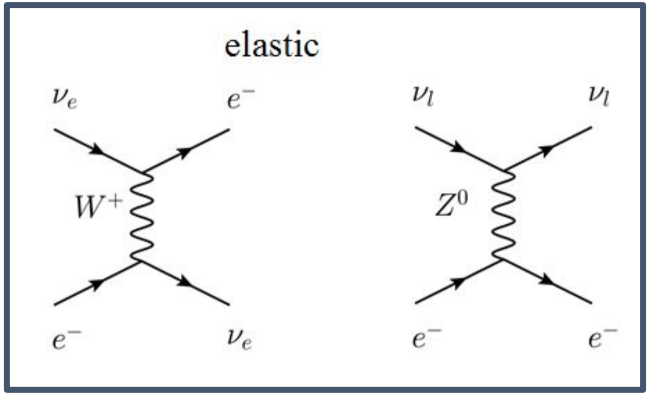
# Neutrino interactions

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



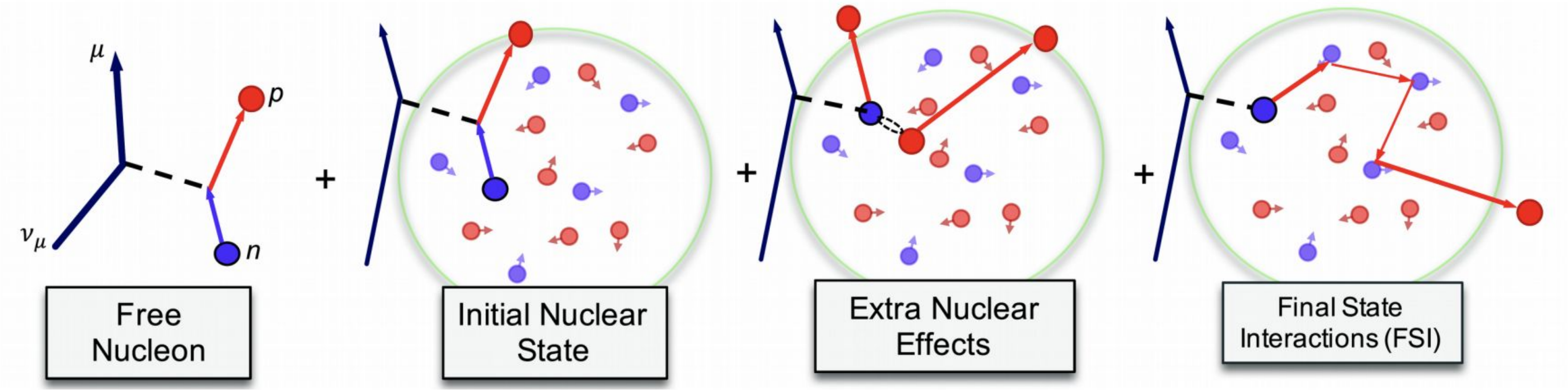
# Neutrino interactions



# 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.

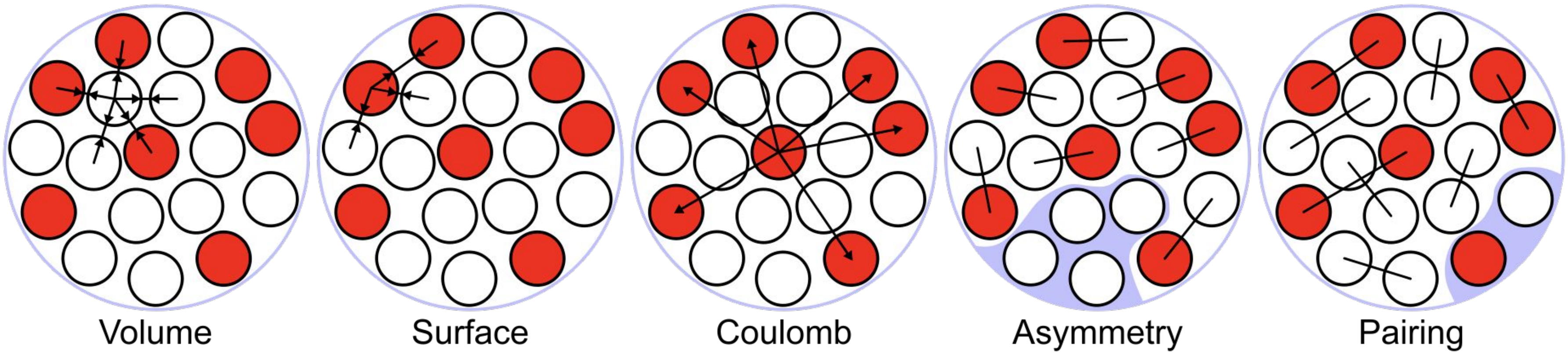


# A deeper look at beta-decay

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

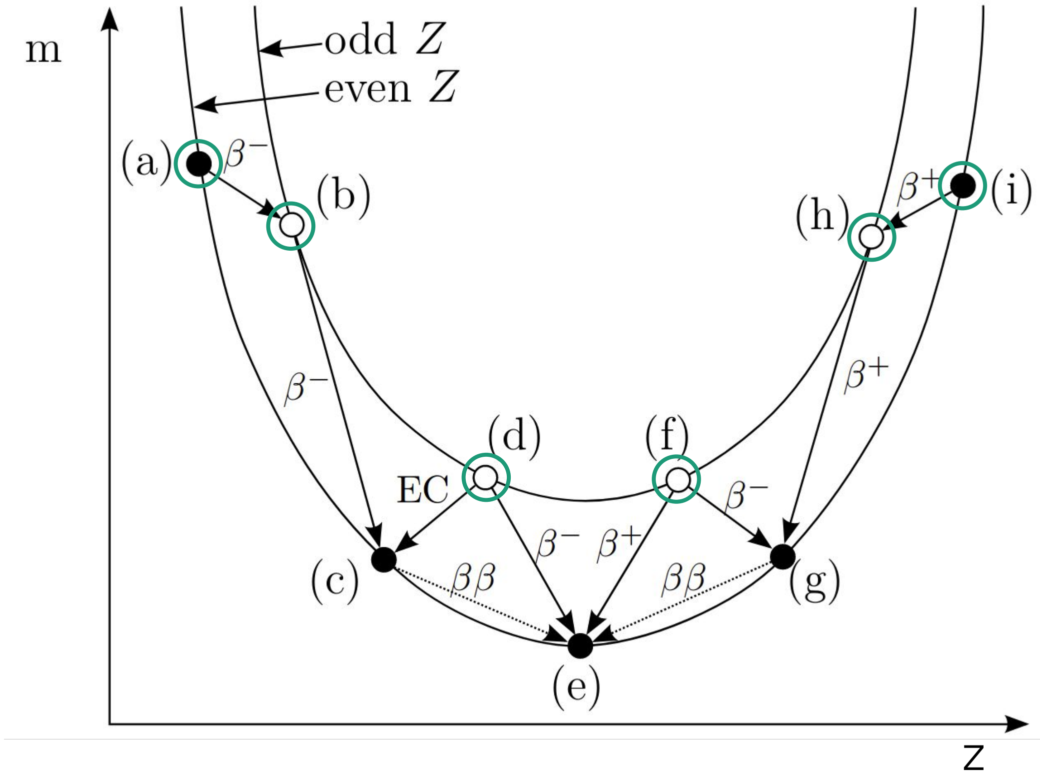
$$M(A,Z) = Z\,m_p + (A-Z)m_n - E_B$$

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



# Allowed and forbidden decays

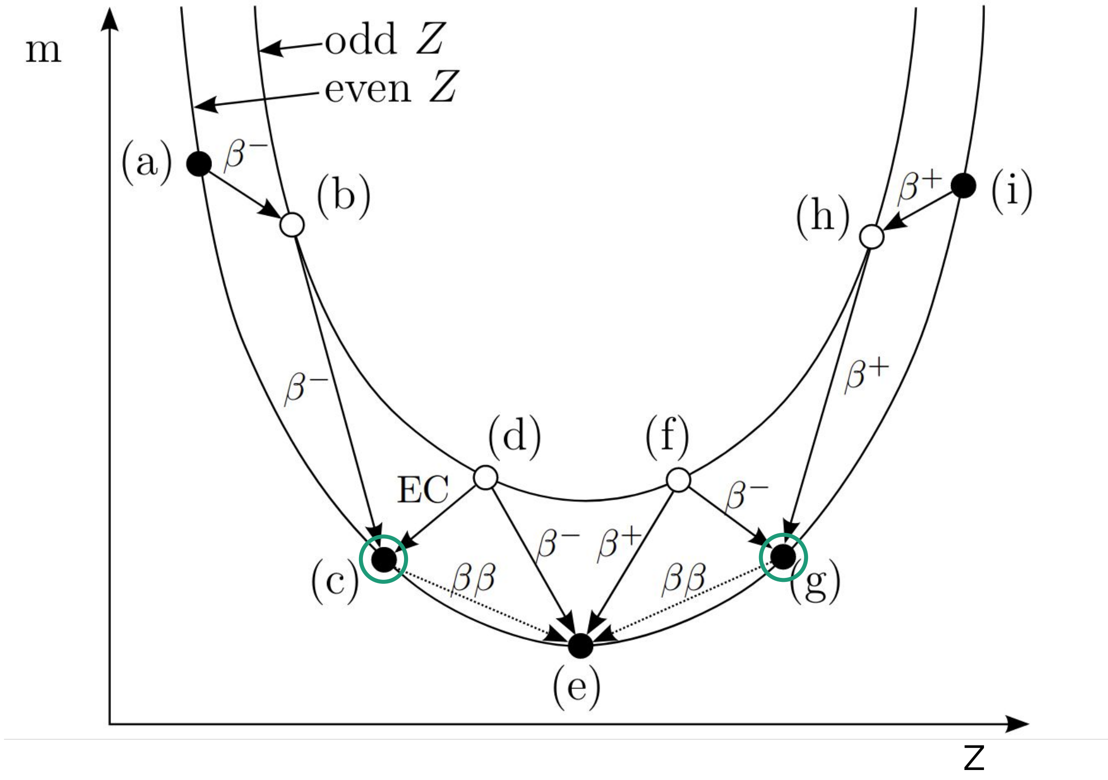
- Beta-decays change Z by one unit.
  - Allowed if M(A, Z±1) < M(A,Z)
    - a, b, d, f, h and i



# Allowed and forbidden decays

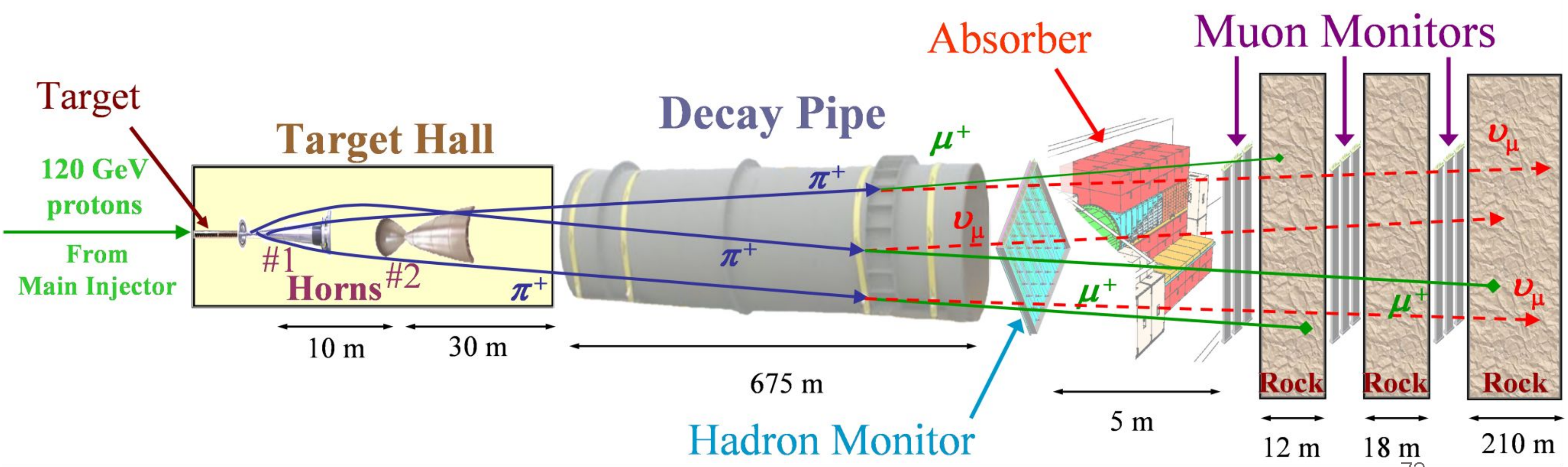
- Beta-decays change Z by one unit.
  - Allowed if M(A, Z±1) < M(A,Z)
    - a, b, d, f, h and i

- 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

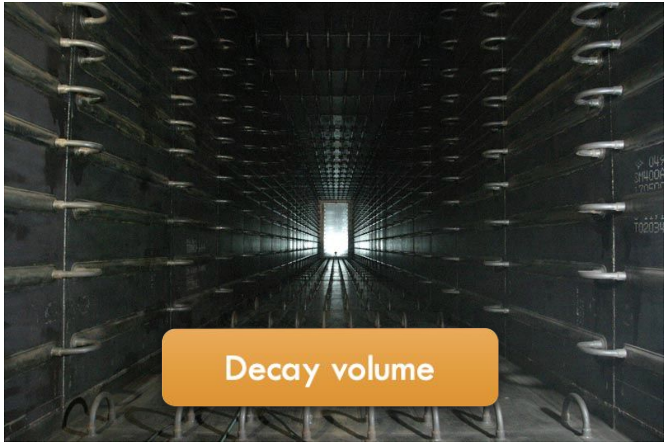


# How to produce a neutrino beam

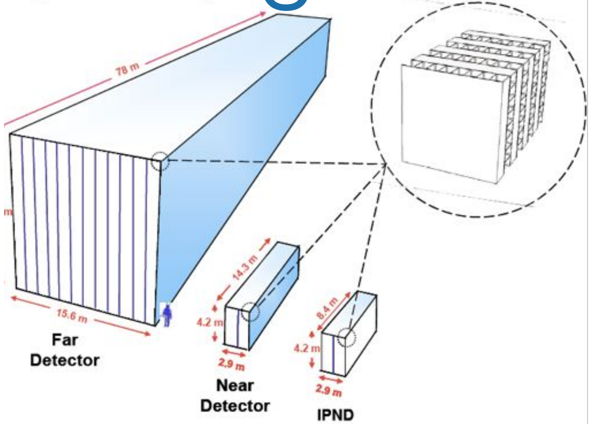
1. Accelerate protons and aim them at a target.
2. Focus the resulting pions using magnetic "horns".
   - Toroidal field can be reversed to focus positive of negative pions for neutrino or antineutrino beam.
3. Allow pions to decay to muon neutrinos and muons in empty (or He filled) volume.
4. Leave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

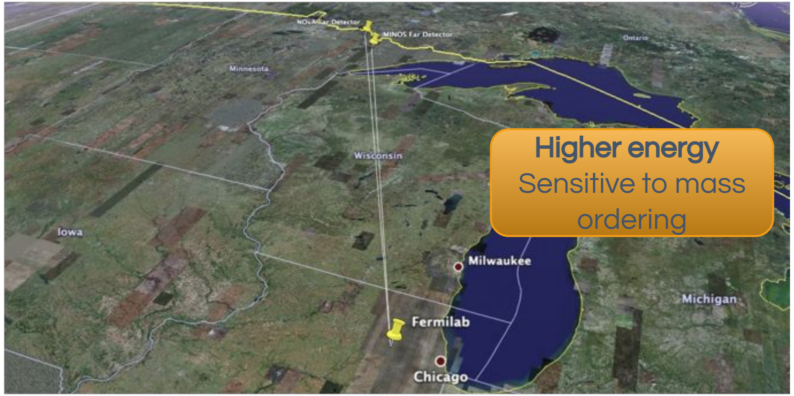


# Neutrino beamline


# Current long baseline experiments



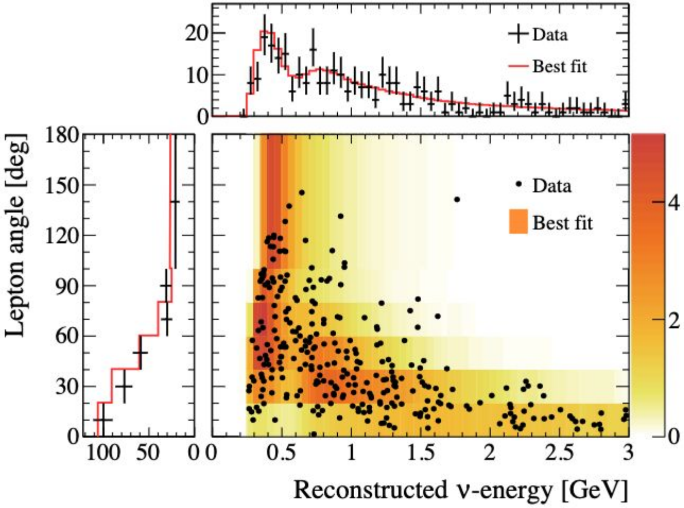




**Higher energy**
Sensitive to mass ordering

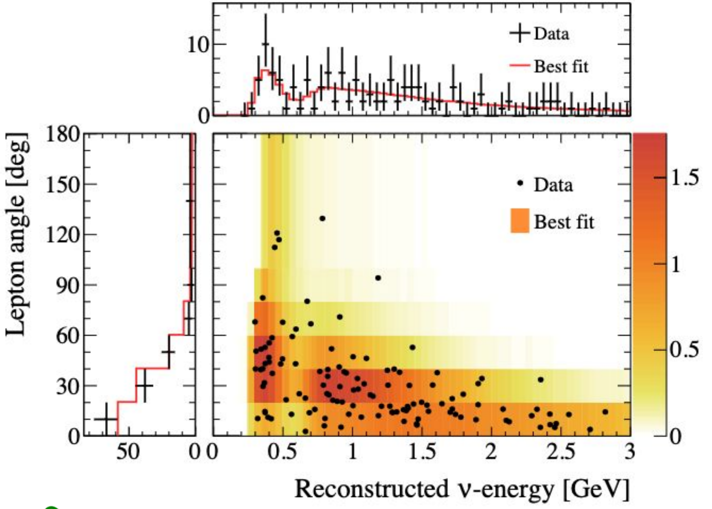

**Lower energy**
Cleaner CP violation signal

# T2K and NOvA Far detectors' data

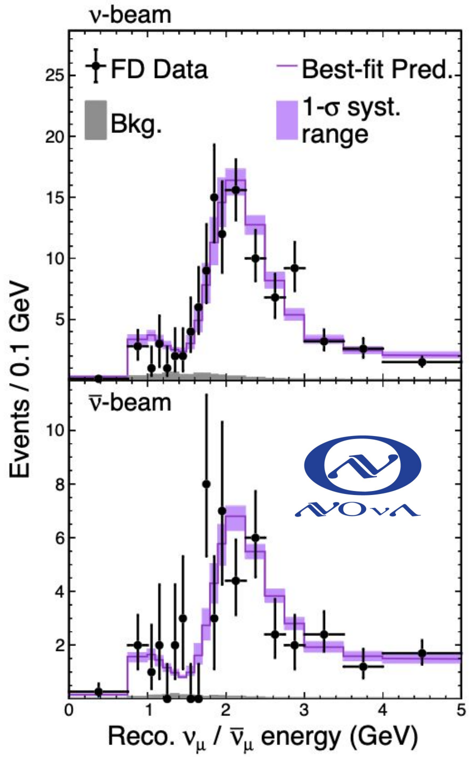
- Muons neutrinos disappear!
  - They oscillate to tau neutrinos.
- Mixing angle 23 is close to maximal.
- No difference between neutrino and antineutrino disappearance.



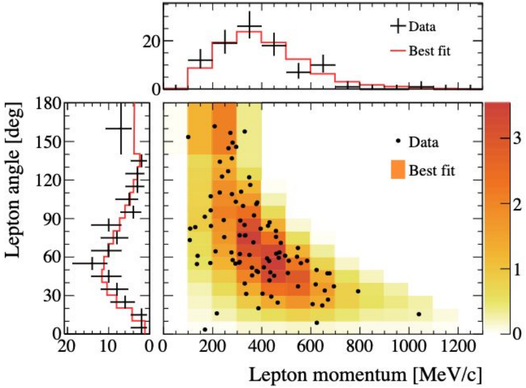

(a) ν-mode 1Rμ



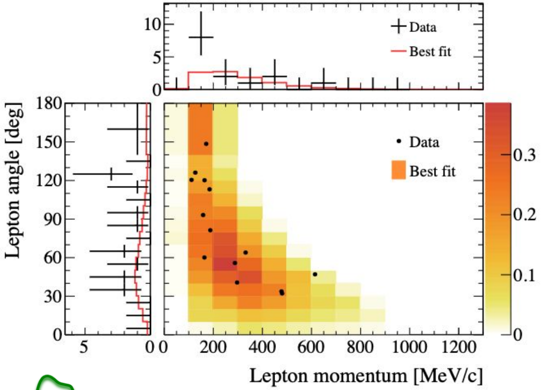

(d) $\bar{\nu}$-mode 1Rμ



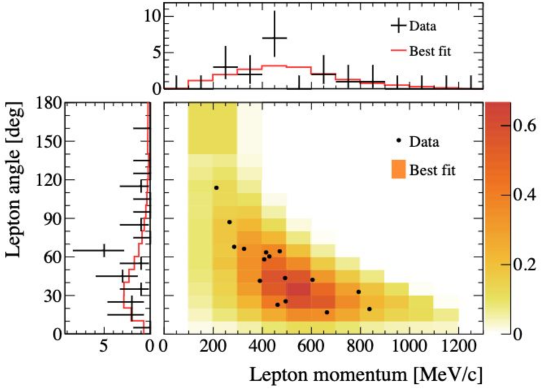
# T2K and NOvA Far detectors' data




(b) $\nu$-mode 1R$e$

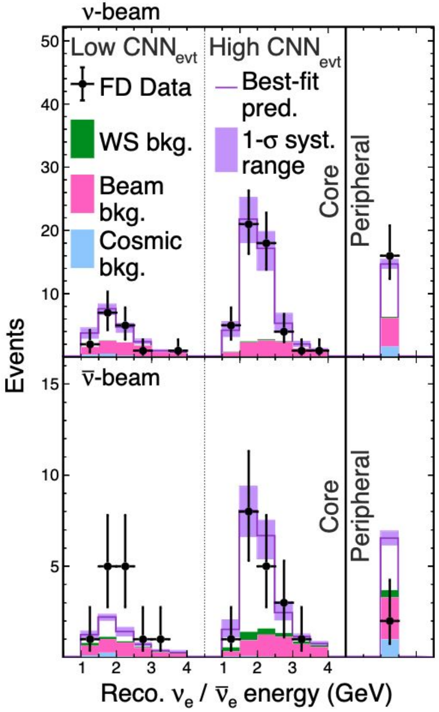



(c) $\nu$-mode 1R$e$1d$e$




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

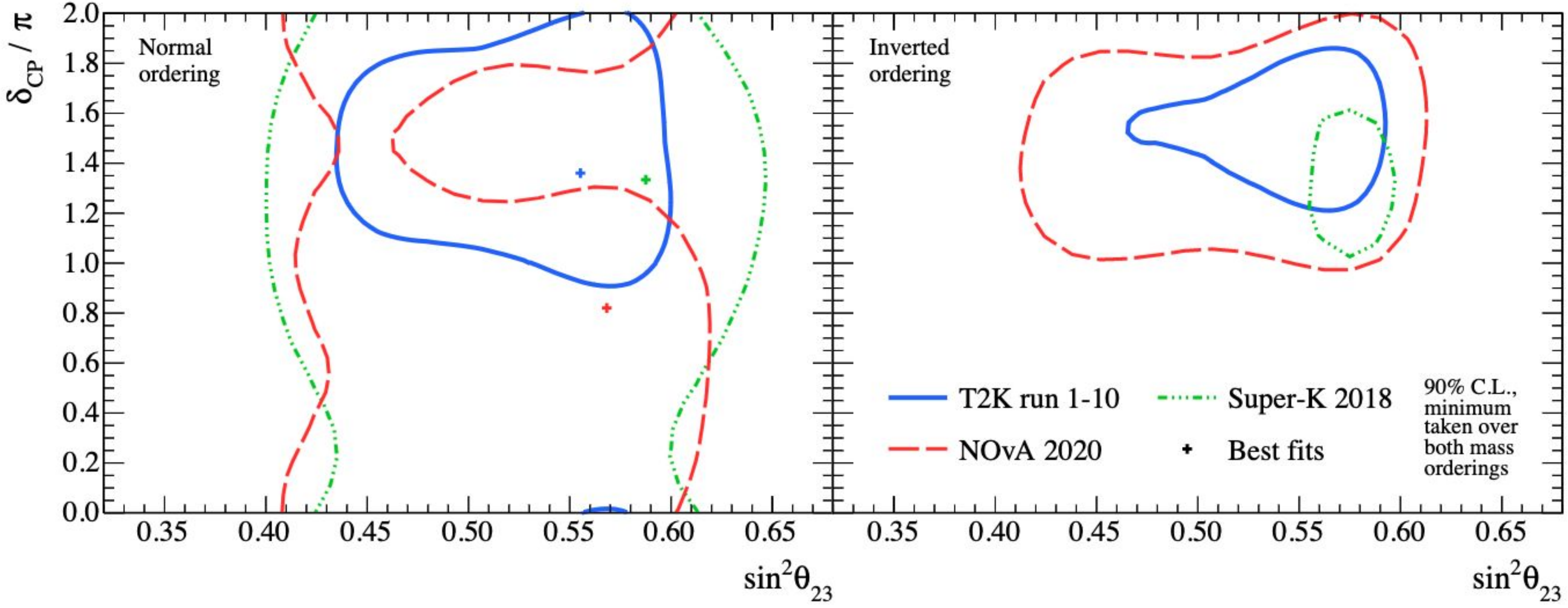
- Electron neutrinos appear!
- To early to tell if neutrinos and antineutrinos appear with the same probability.
- But we can still draw interesting conclusions from the comparison with the reactor experiments...



# Where do we stand?

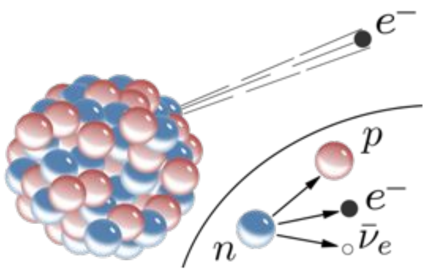
- Independently, both experiments prefer the **normal mass ordering** , but quite **different** values of the **CP-violating phase** .
- When taken together, the preference flips to the **inverted mass ordering** and **consistent CP-violating phase** .
- We're going to need a bigger experiment...

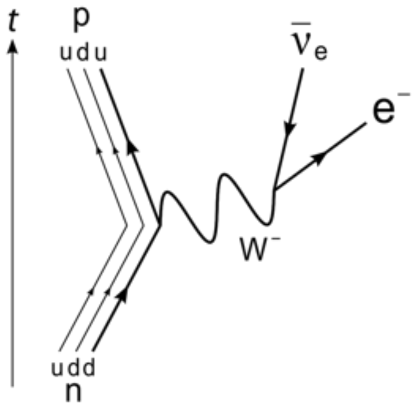
  → **DUNE**, scheduled to start at the end of the decade.

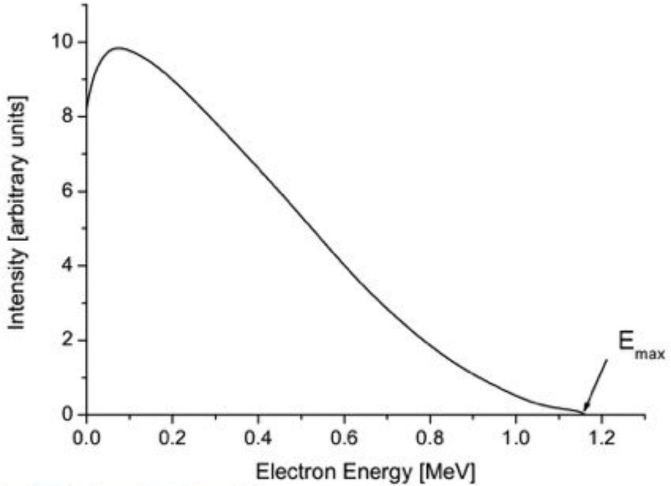


# Let's go back to beta-decay

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



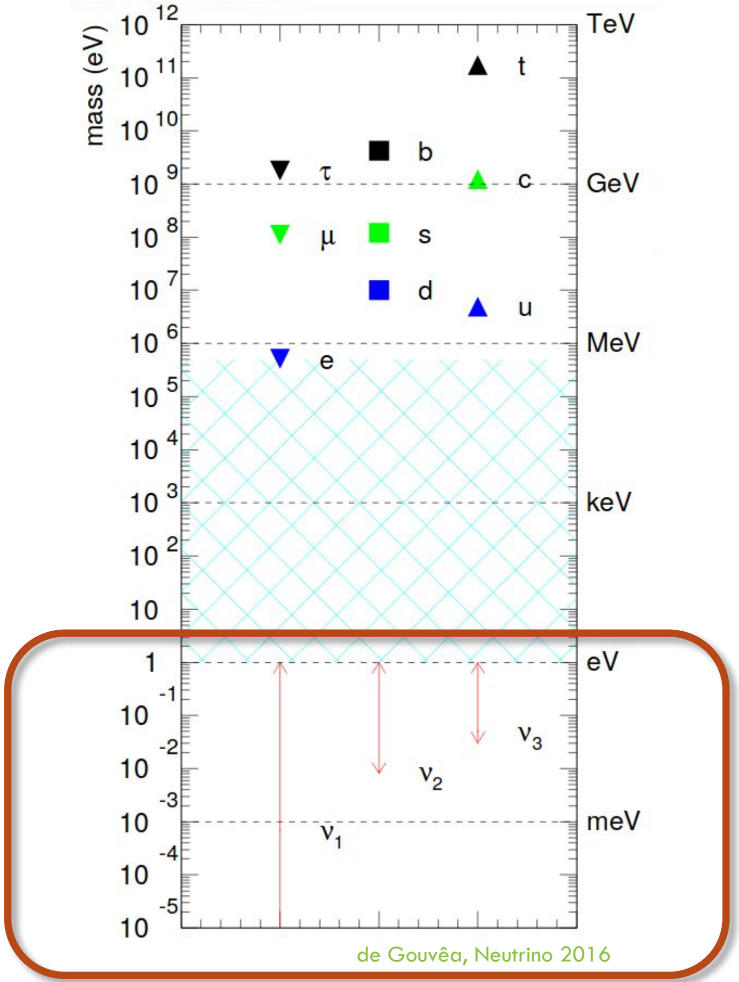




$$n \rightarrow p + e^- + \bar{\nu}_e \quad or \quad (A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$
$$p \rightarrow n + e^+ + \nu_e \quad or \quad (A, Z) \rightarrow (A, Z-1) + e^+ + \nu_e$$

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

# 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

# SNO+ News

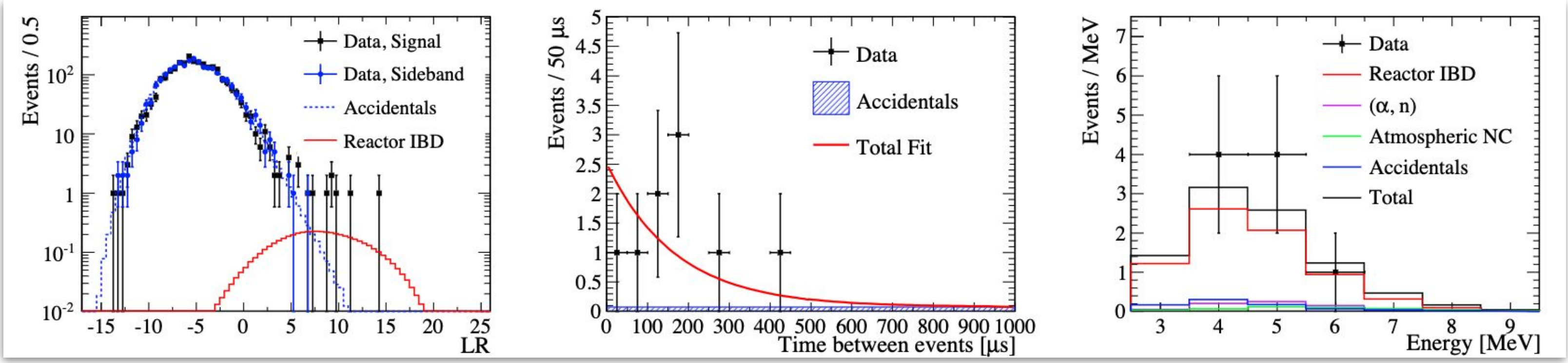
## Antineutrinos from nuclear reactors detected by water

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.**

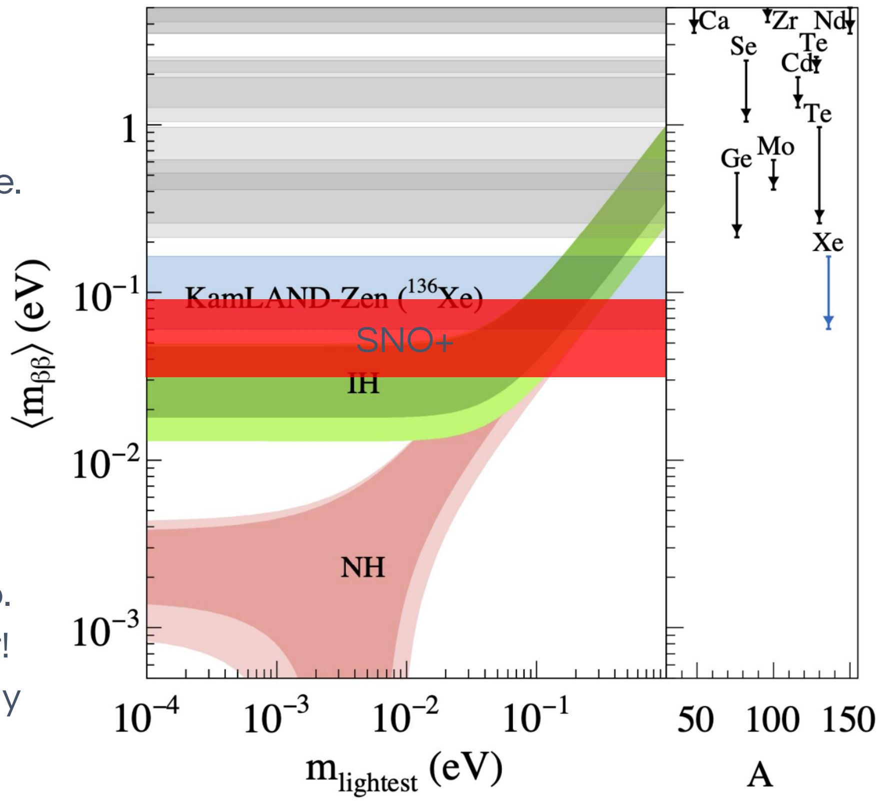


# Putting it all together

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

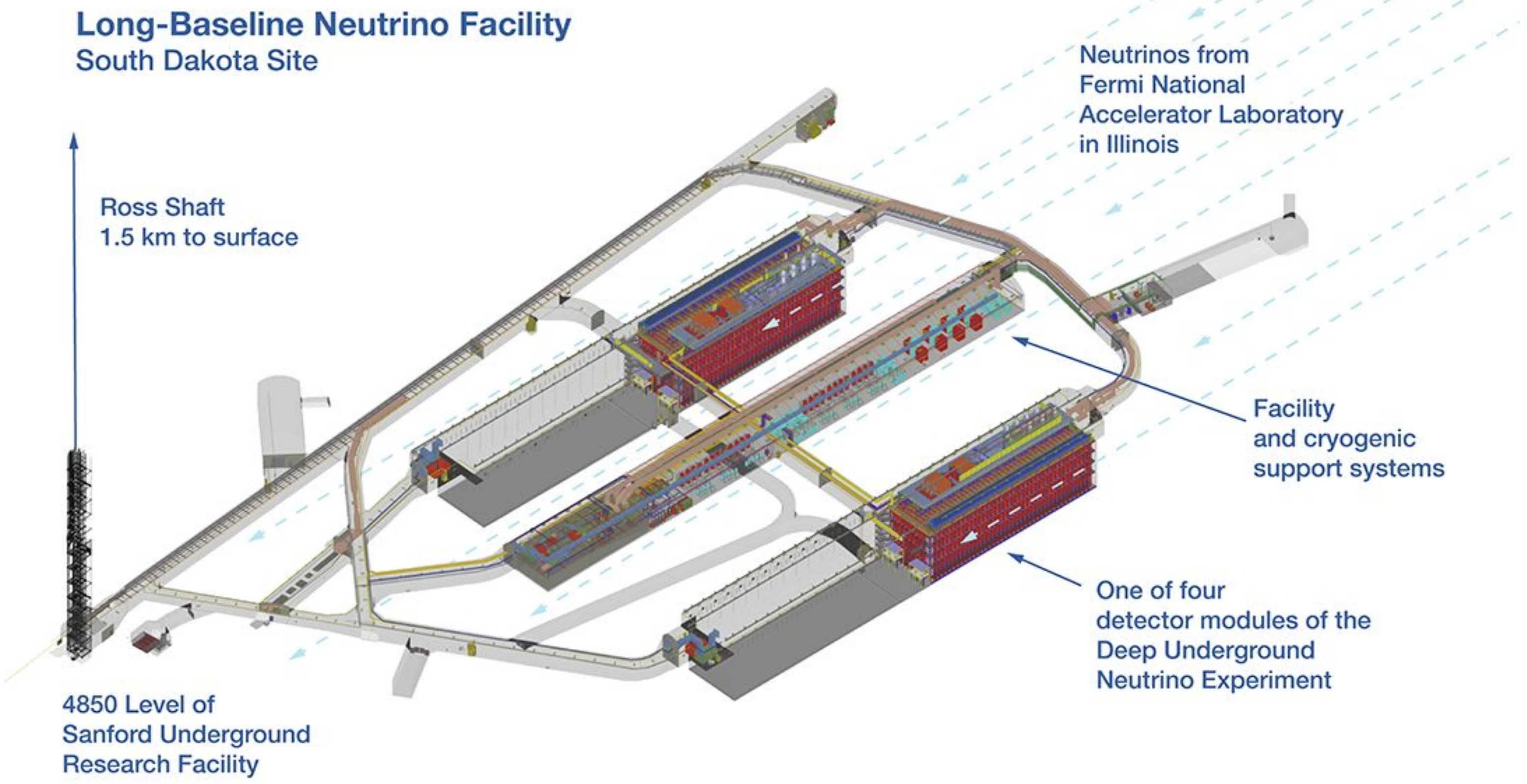
- Connection between neutrinoless double-beta decay rates and neutrino mass depends on:
  - Neutrino **mixing** parameters.
  - Neutrino **mass ordering** .

- 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?).



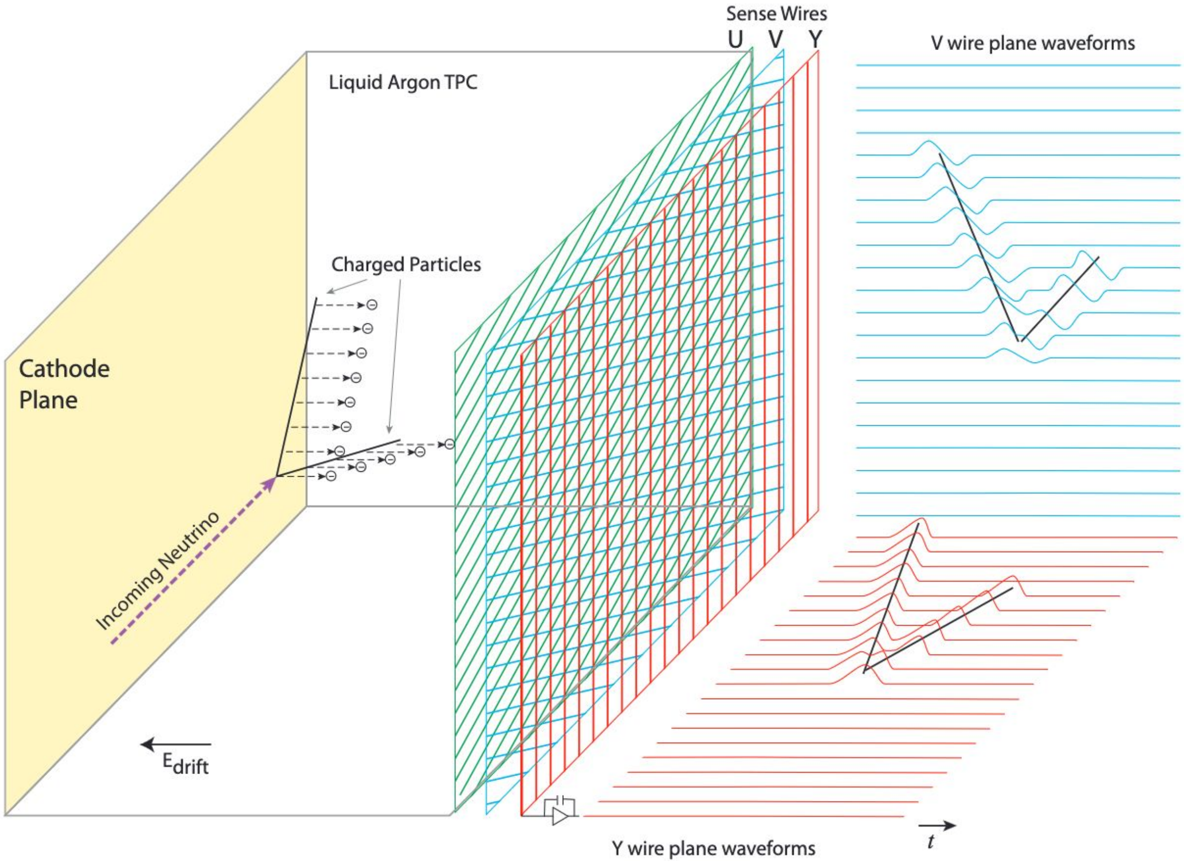
# Os grandes detectores de DUNE

- Vão ser instalados a 1.5 km de profundidade numa mina no Dakota do Sul.
  - Muito perto da antiga experiência de Ray Davis.
- Quatro grandes módulos de árgon liquido, cada um com 17 kton (17 x protoDUNE x 4)



# Liquid-argon time-projection chamber

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



# 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!