LIP Summer Internship 2025

Neutrinos: a short overview

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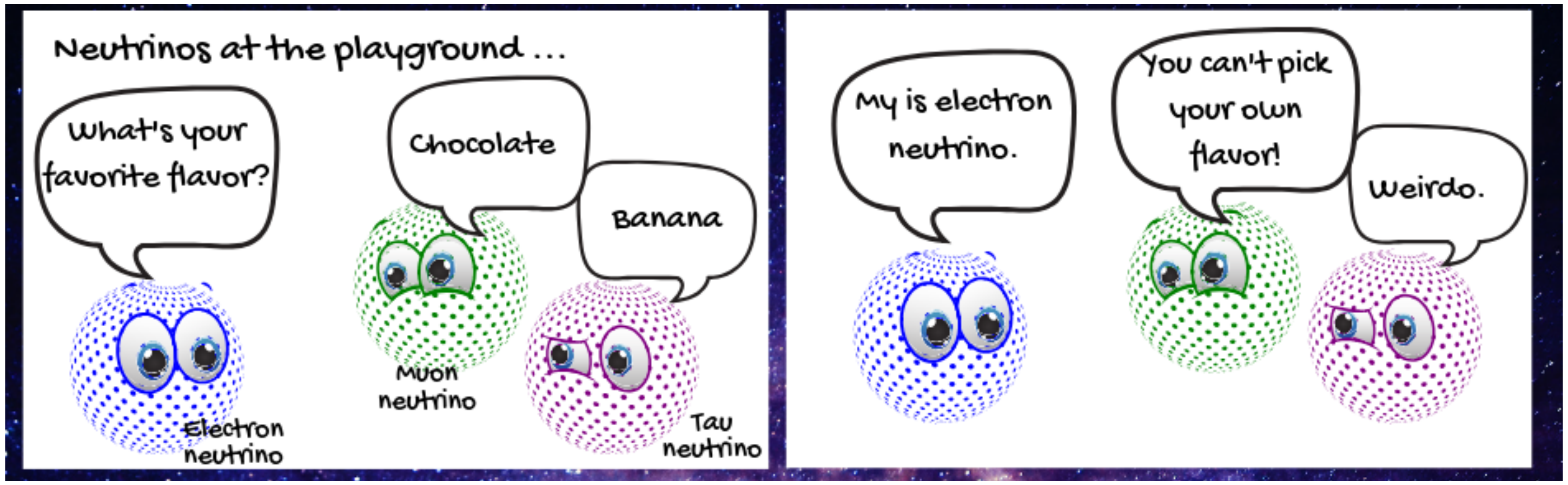
Overview

In this talk we will discuss two main topics

1. Neutrinos properties:
status of the art



elementary-comic.com

Overview

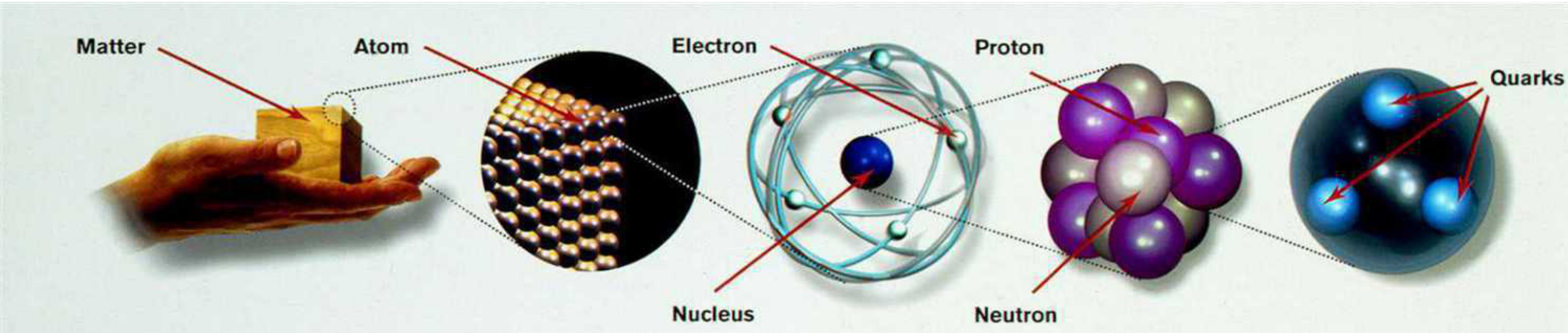
In this talk we will discuss two main topics

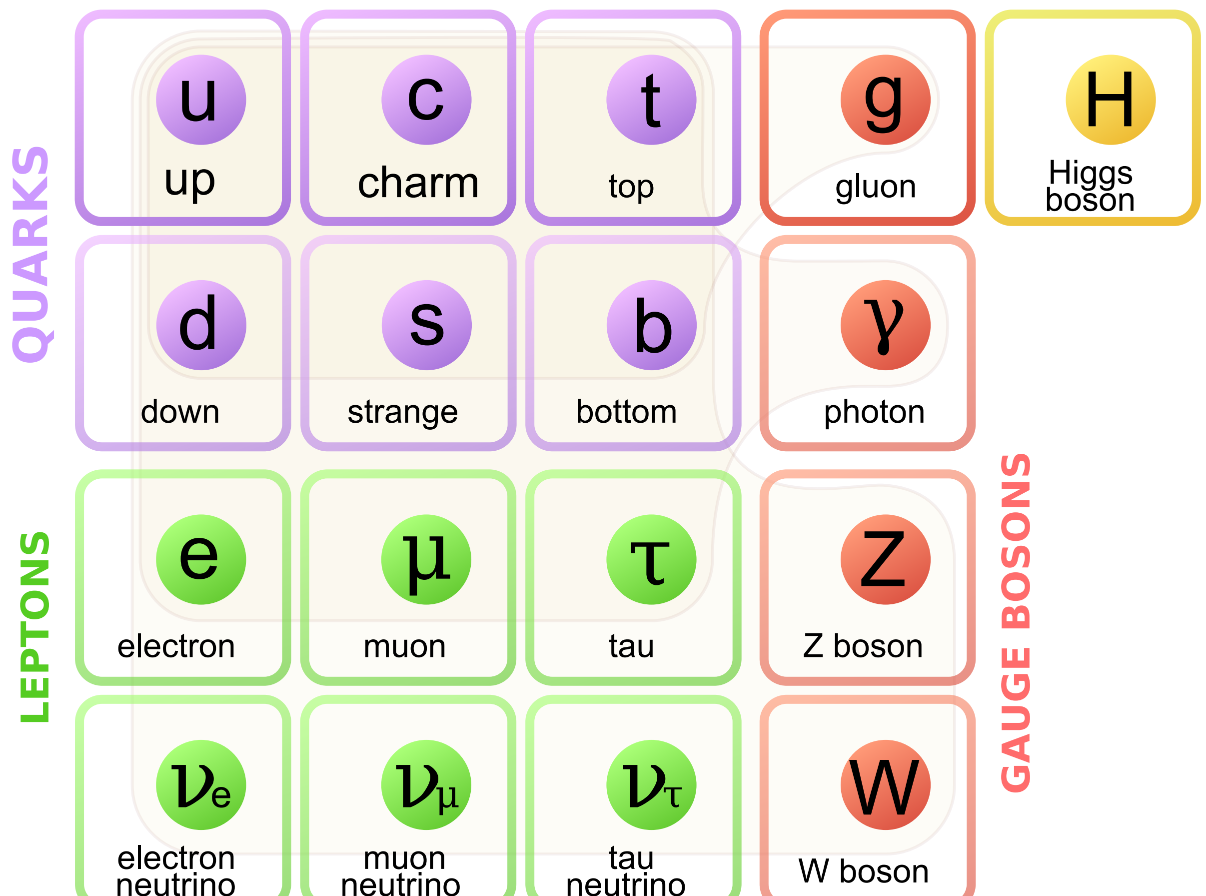
2. Detecting neutrinos with large scale experiments:
SNO+ & DUNE

https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf

1. Neutrinos

The Scale of things





* = elementary particles

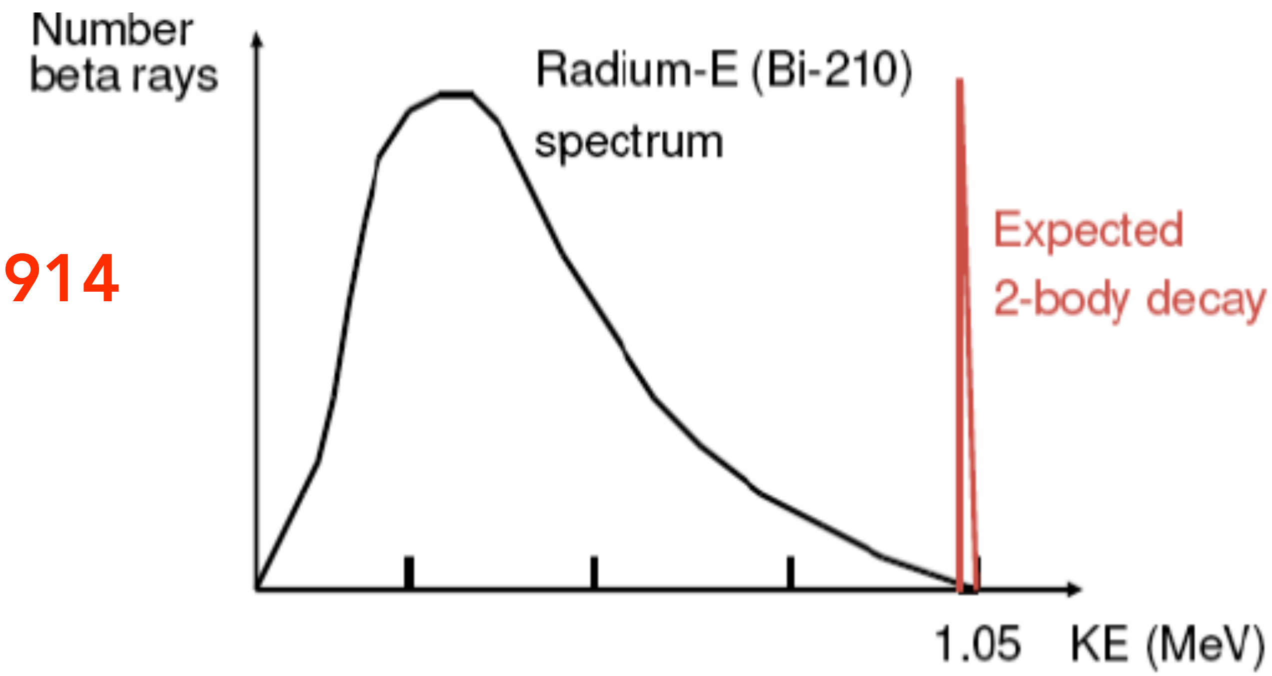
- Atoms
  - electrons
  - nucleus
    - protons and neutrons
      - quarks u e d *
- photons *

} matter

And the neutrinos? Where they come from?

The Beta decay

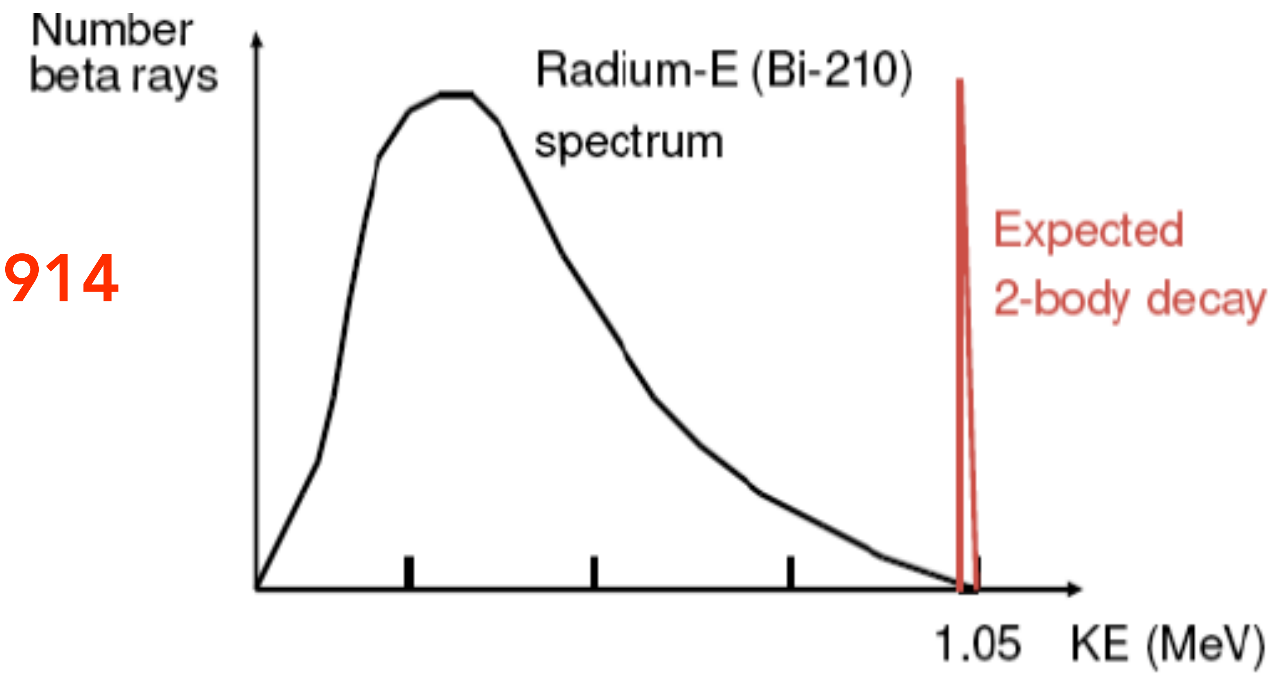
Chadwick, 1914

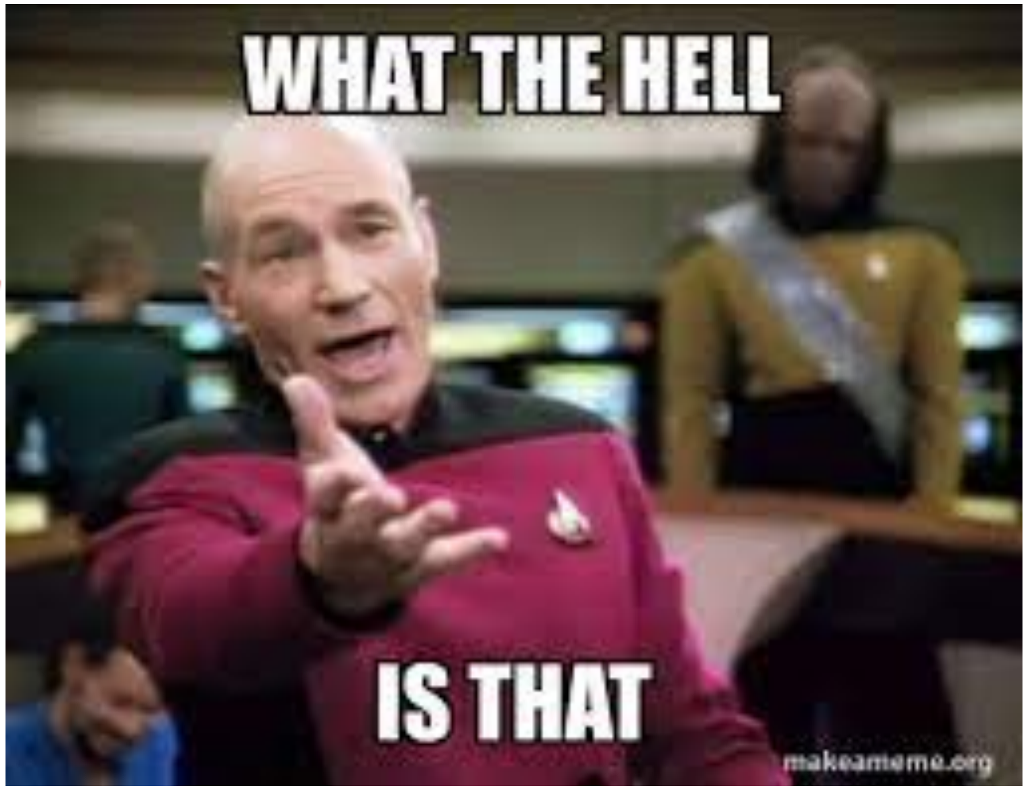


This spectrum was very different from that of alpha and gamma decays.

The Beta decay

Chadwick, 1914





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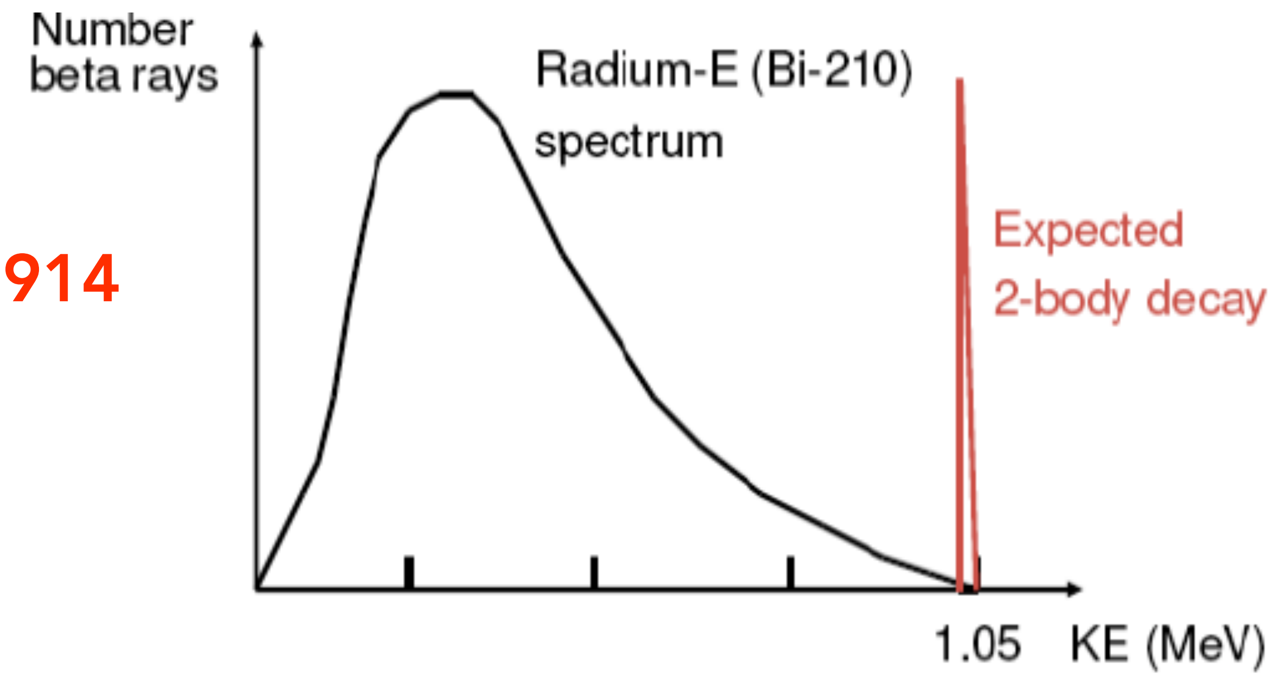


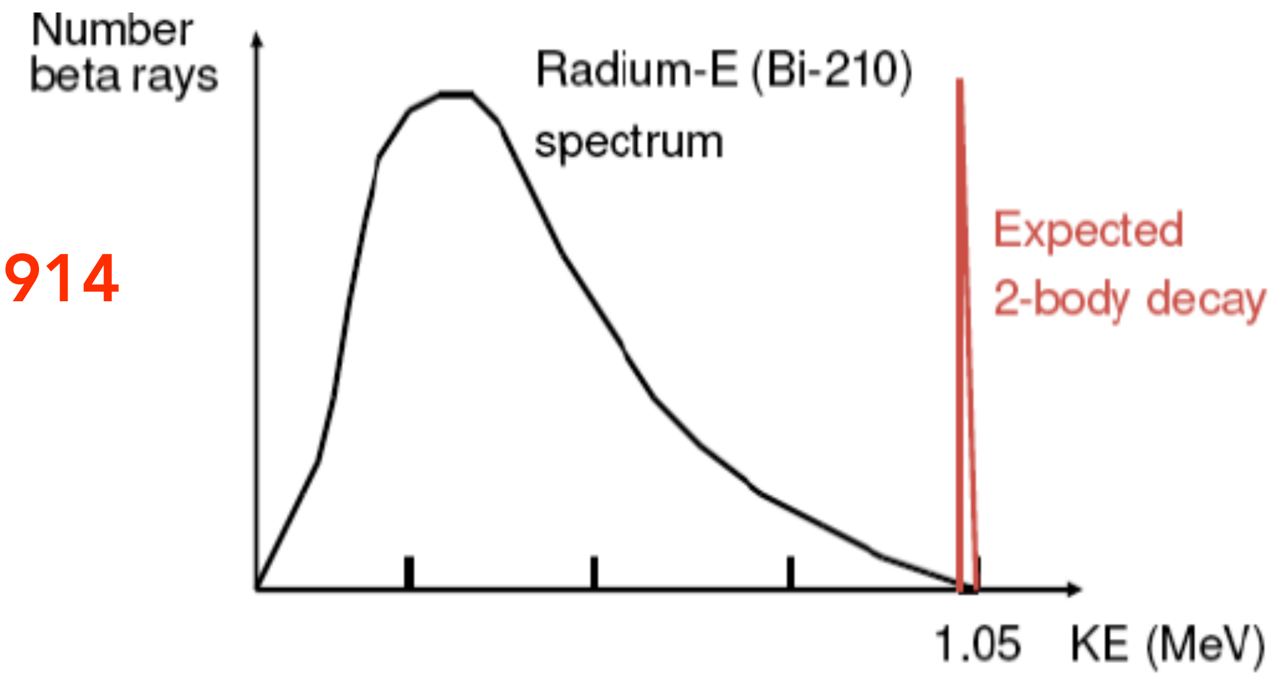
W. Pauli in 1930 proposed the existence of a third particle in the decay, which was carrying part of the energy, but didn't have charge and an extremely small mass

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

The Beta decay

Chadwick, 1914



W. Pauli in 1930 proposed the existence of a third particle in the decay, which was carrying part of the energy, but didn't have charge and an extremely small mass

Enrico Fermi gives it the name of **neutrino** (from Italian, little neutral one) and includes in his beta decay theory (1934)

A terrible mistake

Everything went Well

- In 1952-1959 two experiments finally detected neutrinos!

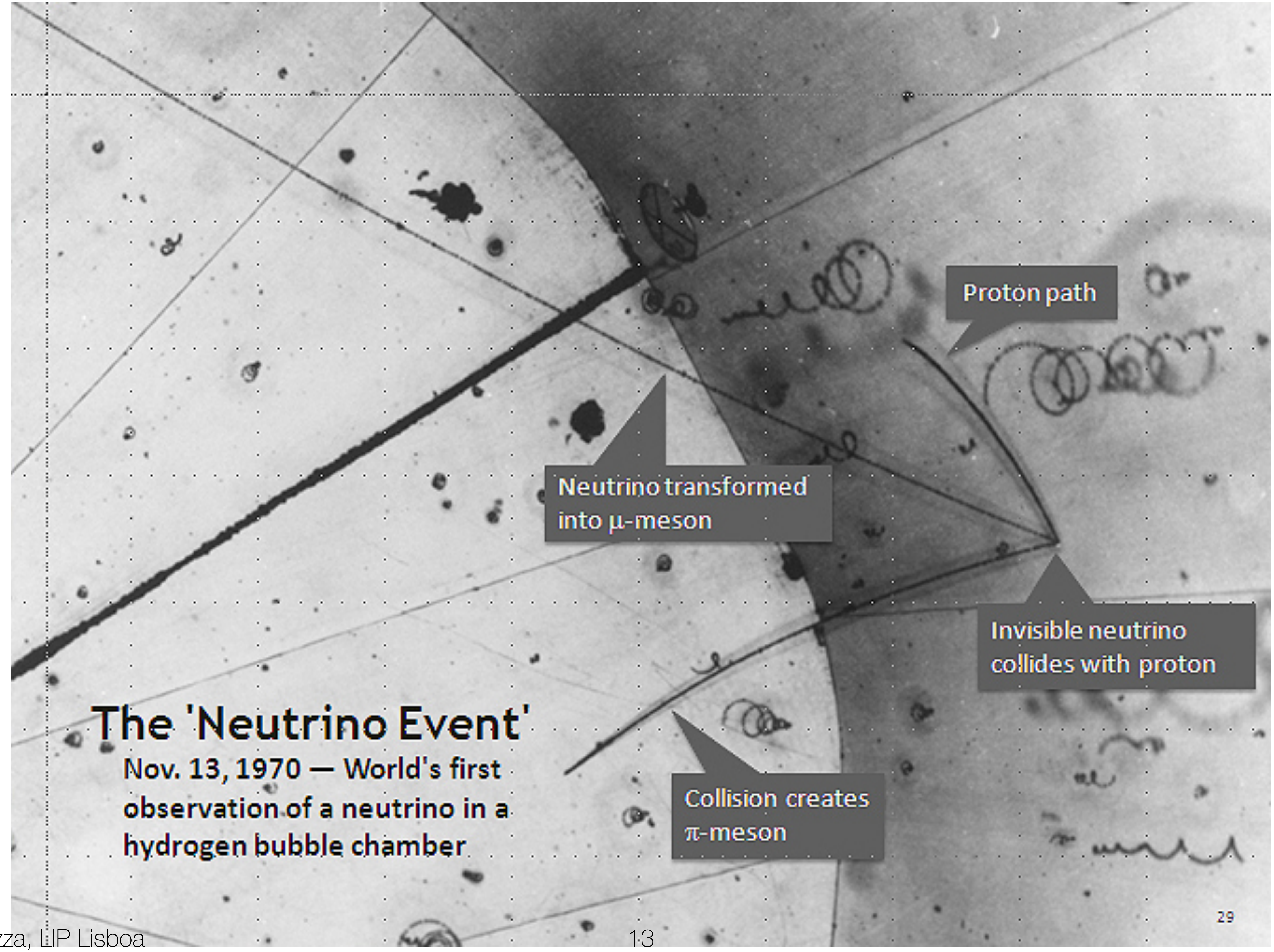
Project Poltergeist

Herr Auge

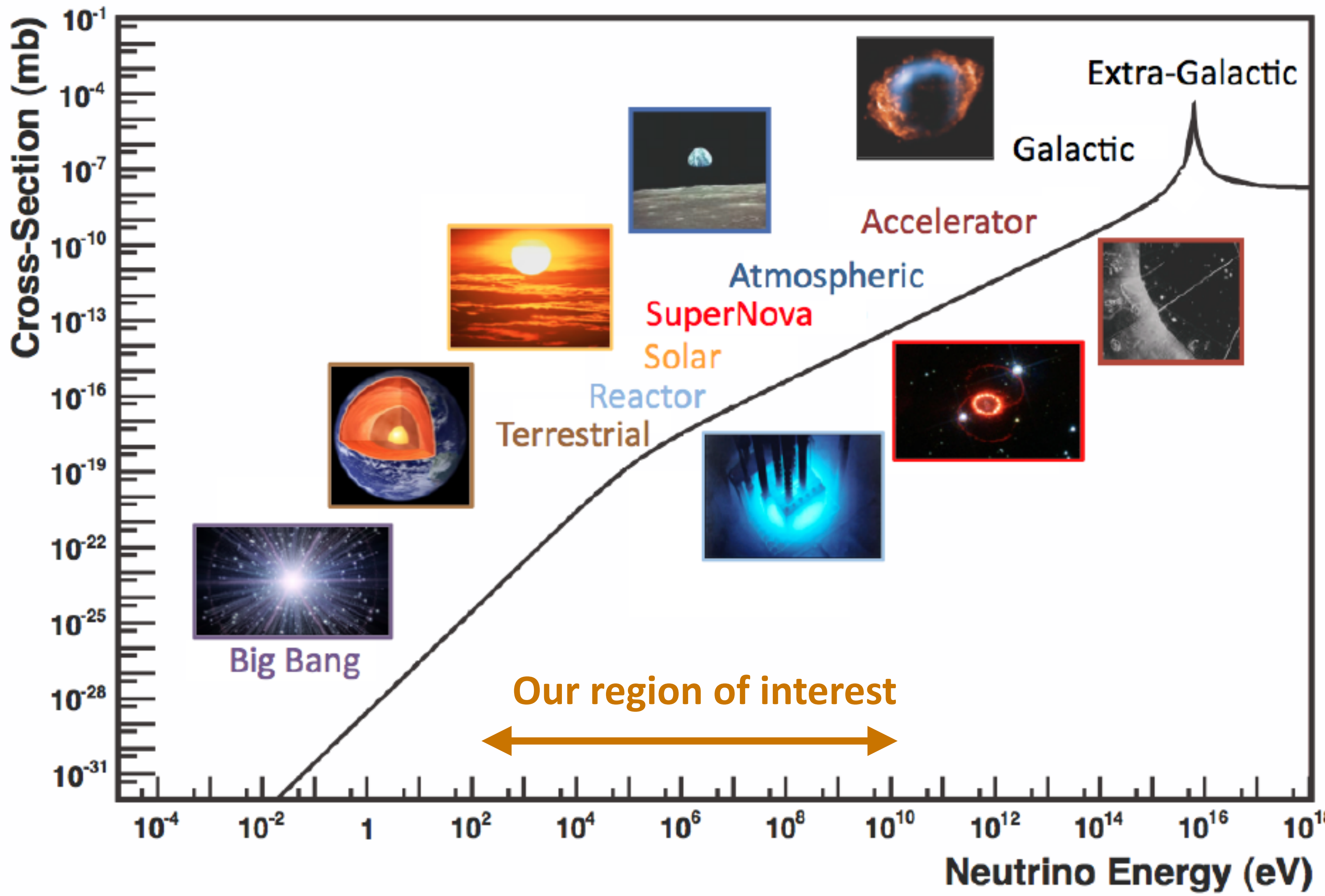
Nobel prize Reines 1995

The detection

Until ....


Proton path
Neutrino transformed
into μ-meson
Invisible neutrino
collides with proton
The 'Neutrino Event'
Nov. 13, 1970 — World's first
observation of a neutrino in a
hydrogen bubble chamber
Collision creates
π-meson
29

Where neutrinos come from?

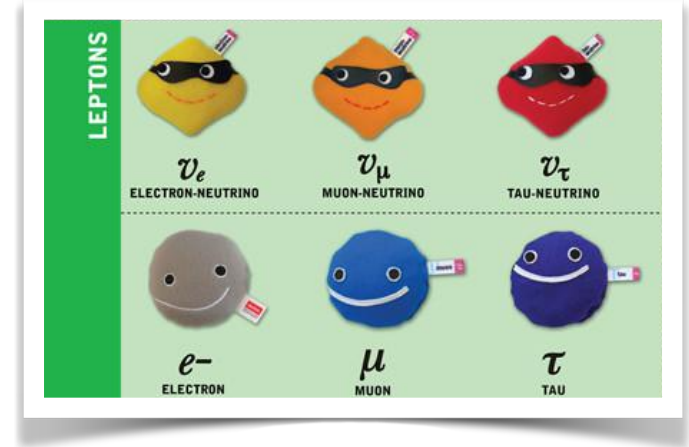


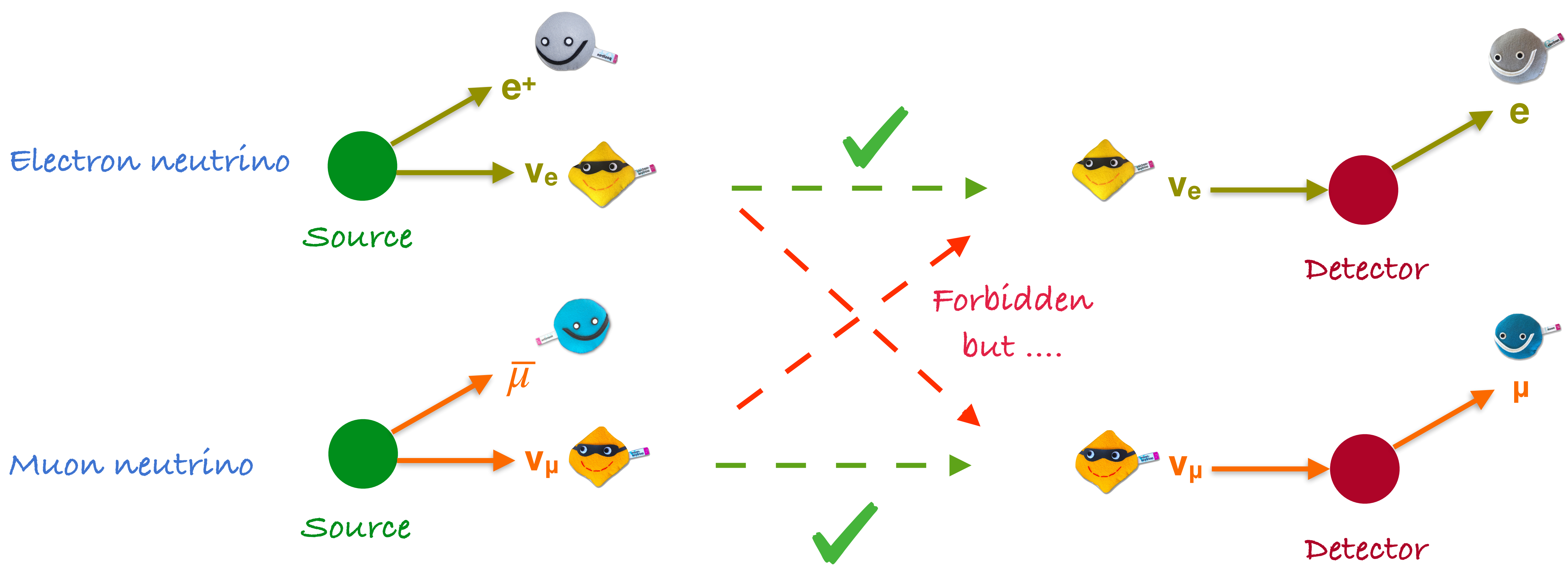
22 orders of magnitude!!!!

Neutrino Basics

★ What we know about neutrinos:

- 3 types (= *flavours*) of neutrinos exist = electron, muon, tau
    - According to the lepton they produce when they have weak CC interactions

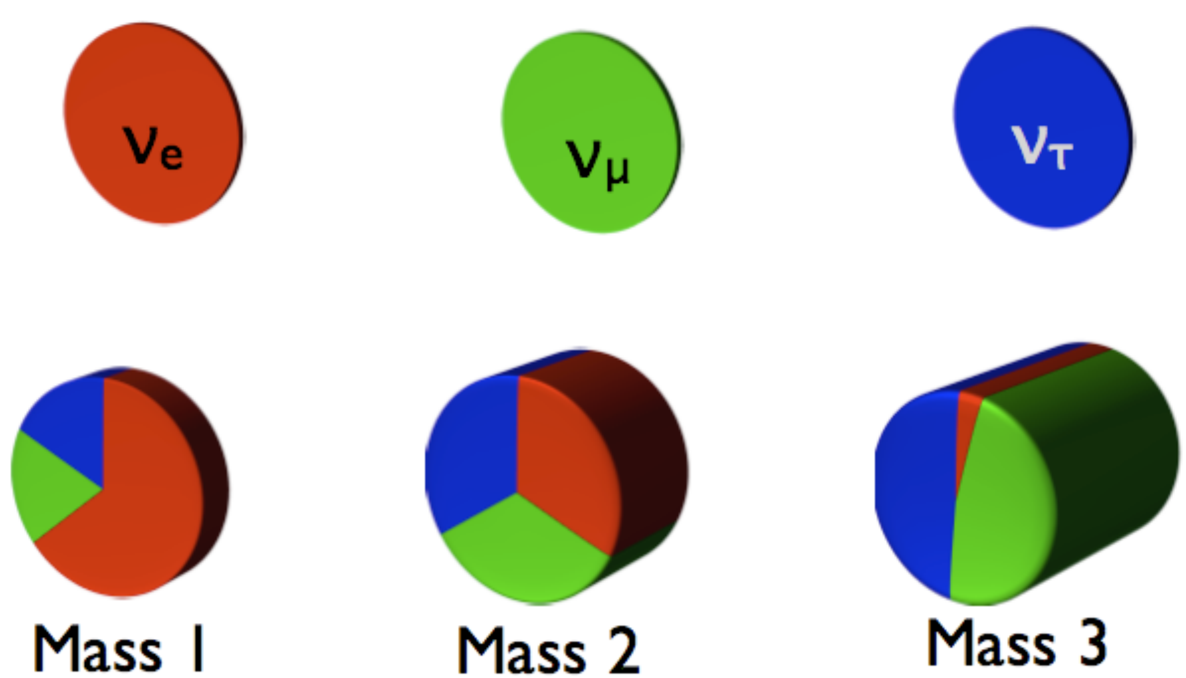


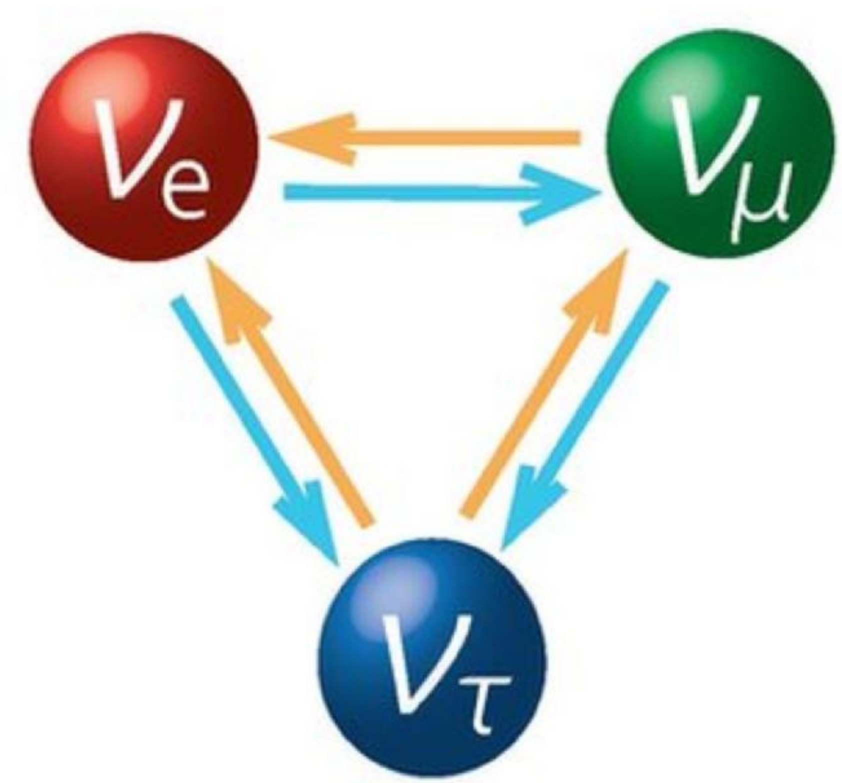


Neutrino States

★ What we know about neutrinos:

- No charge - do not participate in electromagnetism
  - Weak interactions
- They have a tiny but different from 0 mass
  - Mass eigenstates is different from the flavour eigenstates
  - Neutrino can change their flavour once they have been produced

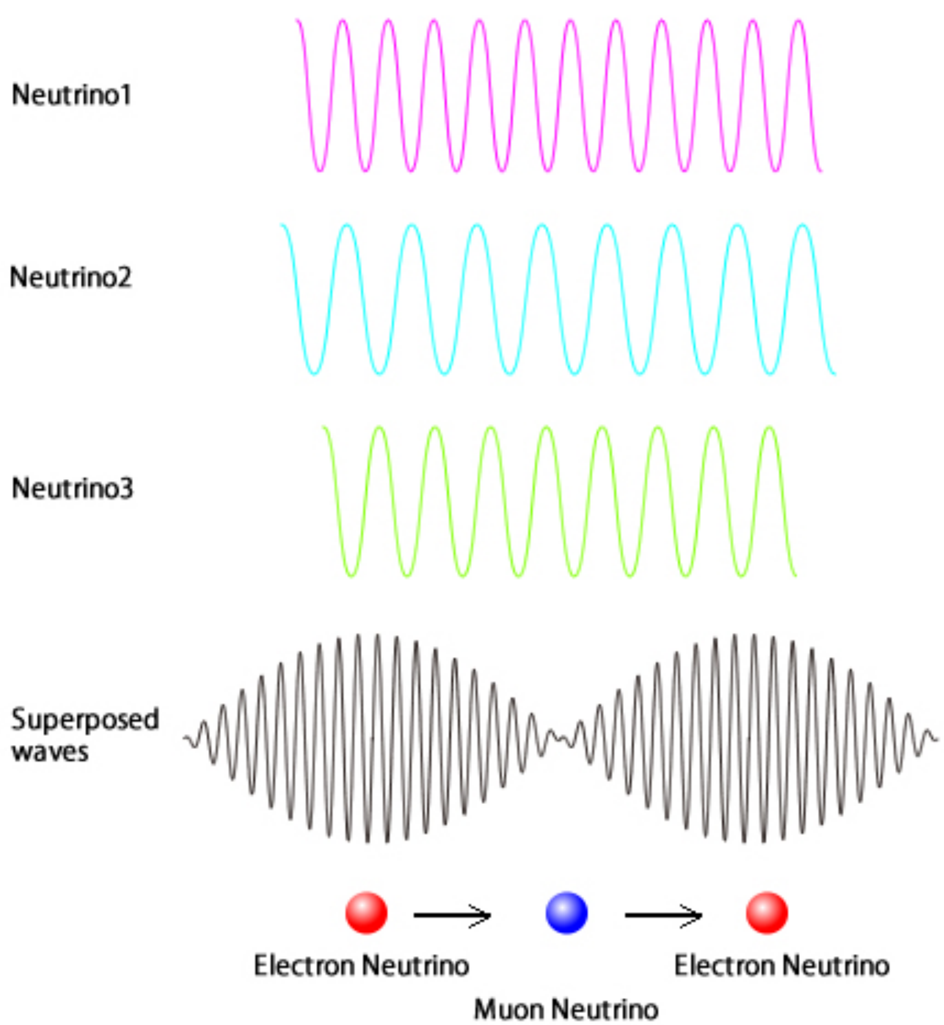




NEUTRINO OSCILLATIONS

★ Neutrino can change their flavour once they have been produced =

Neutrino's oscillations



Artwork by Sandbox Studio, Chicago with Corinne Mucha

Parametrize the Oscillations

★ Oscillations are parametrized by 3 masses *(m_1, m_2, m_3)*, 3 angles *(θ_{12},θ_{13},θ_{23})* and an extra complex phase $e^{i\delta}$

Responsible for the CP-violation part

Flavour eigenstate **Mass eigenstate**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Accelerator and Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{SBL reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar + LBL reactor}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Accelerator and Atmospheric

SBL reactor

Solar + LBL reactor

Dedicated experiments search for the different sectors in neutrino oscillations

The probability of an electron neutrino to be detected in the same flavour depends on the **mass difference** squared and the **distance source-detector**

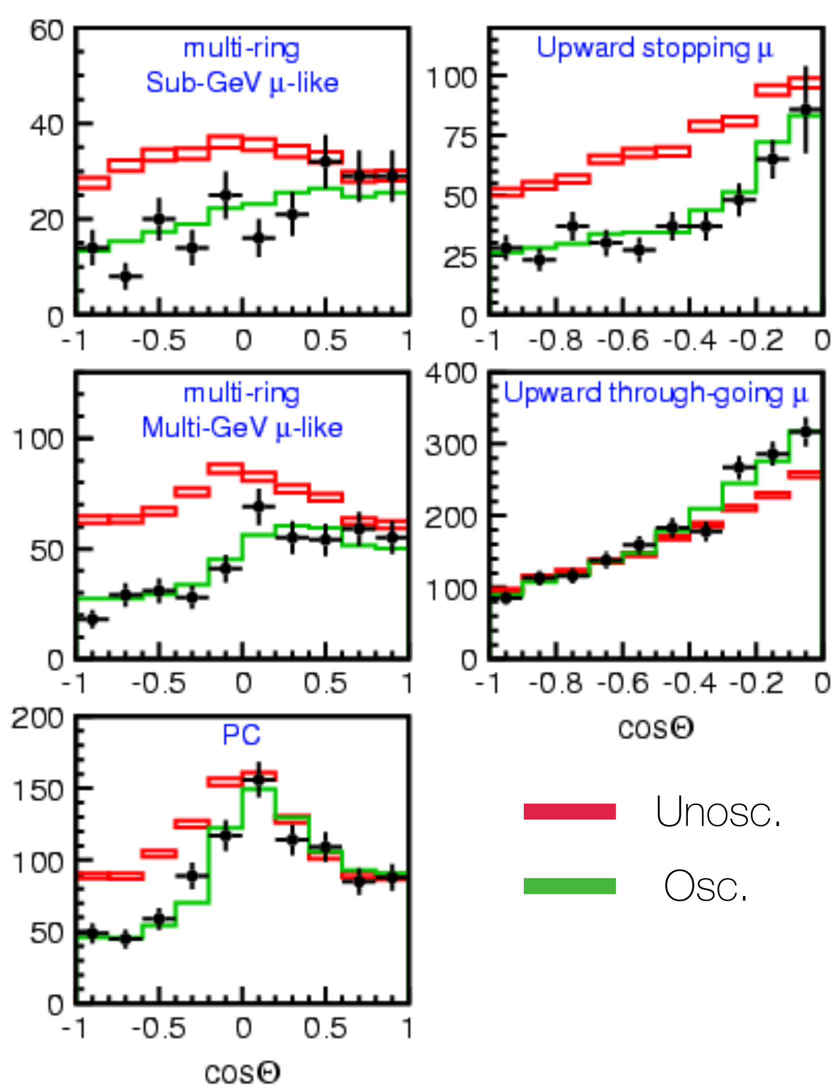
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

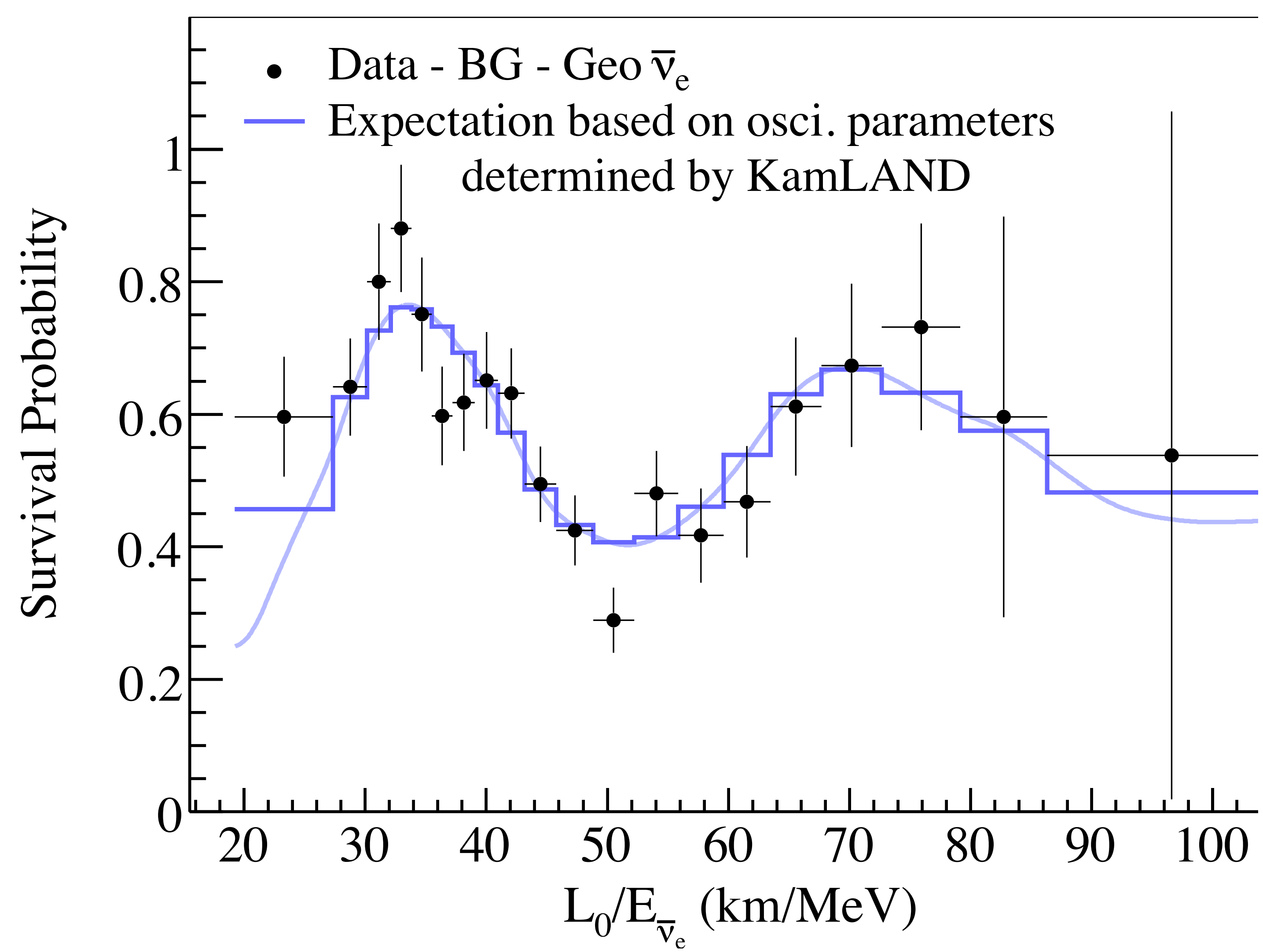
Simplified 2-neutrinos case

Measuring Oscillations

Flavour eigenstate | **Mass eigenstate**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$





Mass Ordering

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Accelerator and Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{SBL reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar + LBL reactor}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

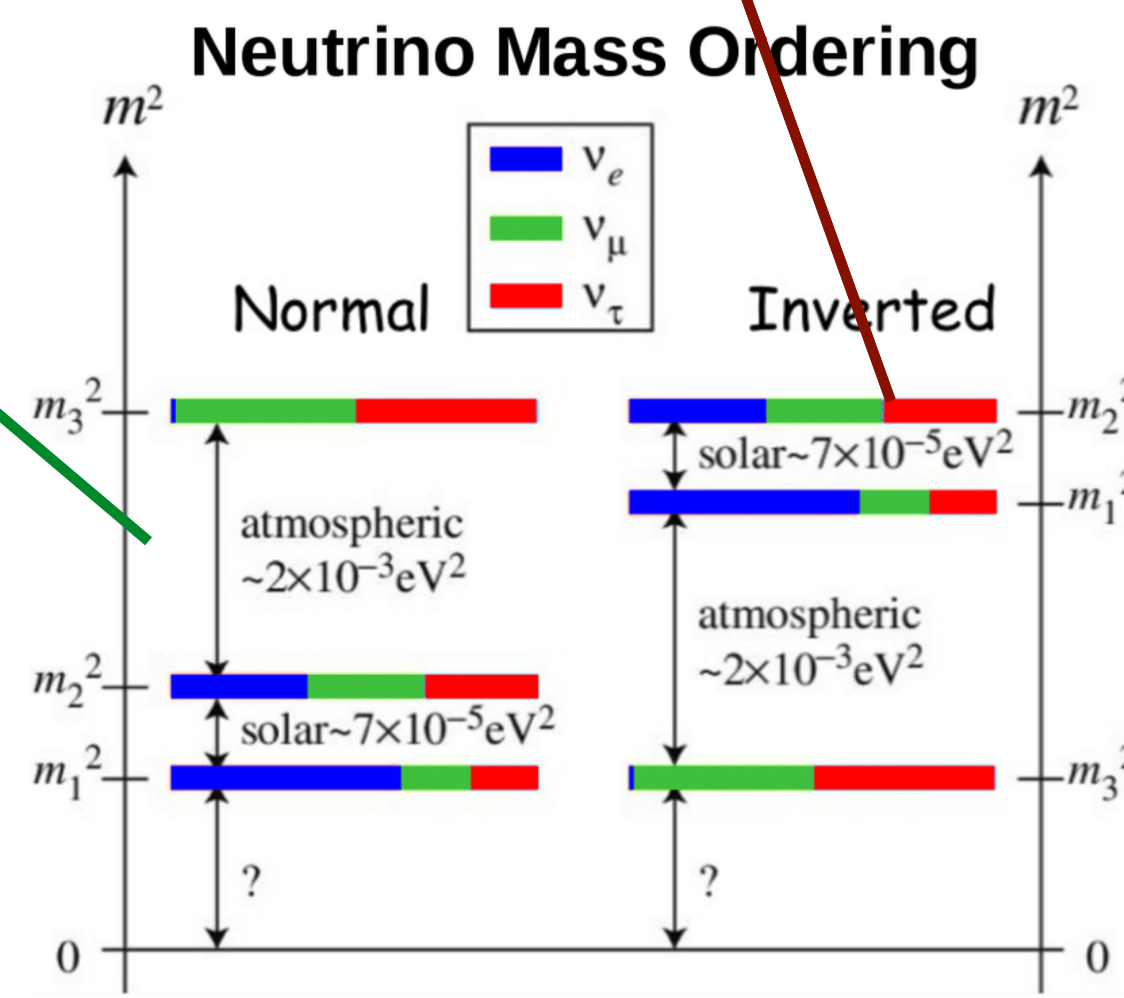
Accelerator and Atmospheric

SBL reactor

Solar + LBL reactor

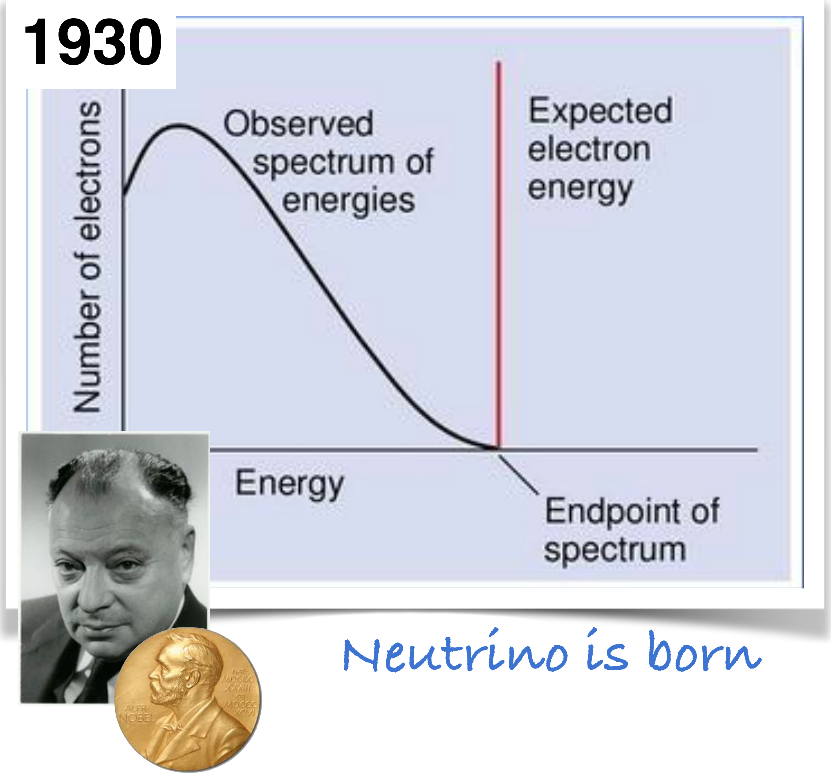
parameter	best fit $\pm 1\sigma$	3σ range	*Relative precision at 1σ*	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	3%	Precision
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.47–2.63	1%	**SIGN UNKNOWN**
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.37–2.53		
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.69	5%	Precision
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	5.74 ± 0.14	4.34–6.10	5%	**OCTANT UNKNOWN**
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	4.33–6.08		
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.000–2.405	3%	Precision
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.018–2.424		
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.71–1.99		**CP VIOLATION**?
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.11–1.96		

Neutrino measurements and plans - L IMFP/ XV CPAN 2023



Neutrino MEMORY LN

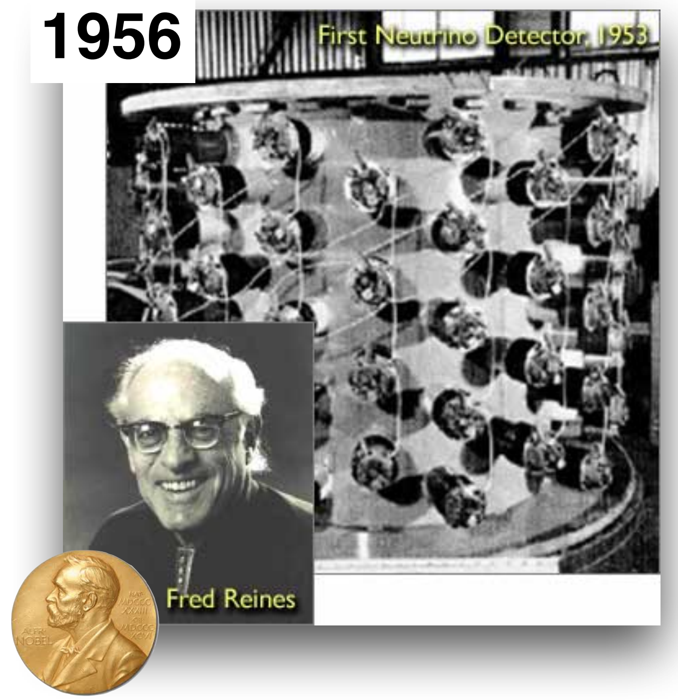
1930



Neutrino is born

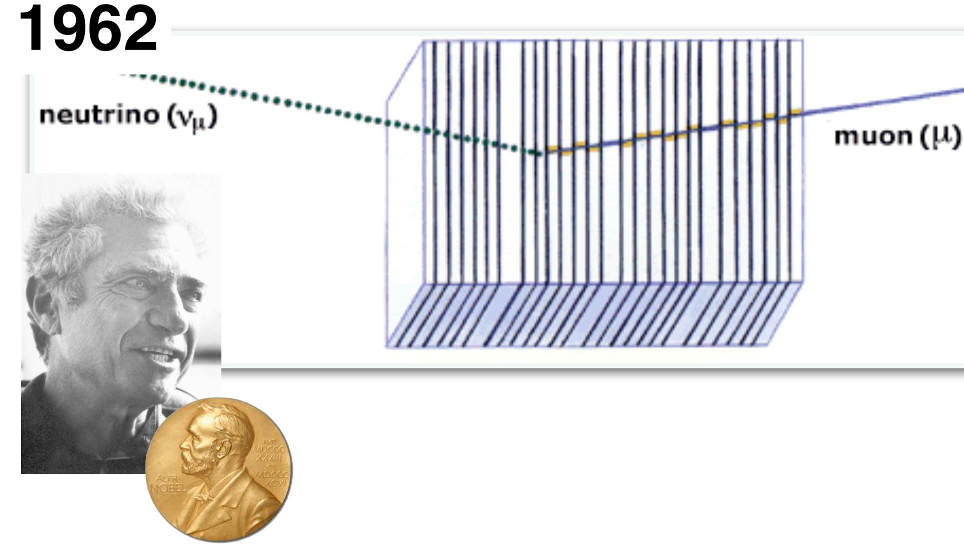
First observation of neutrinos

1956

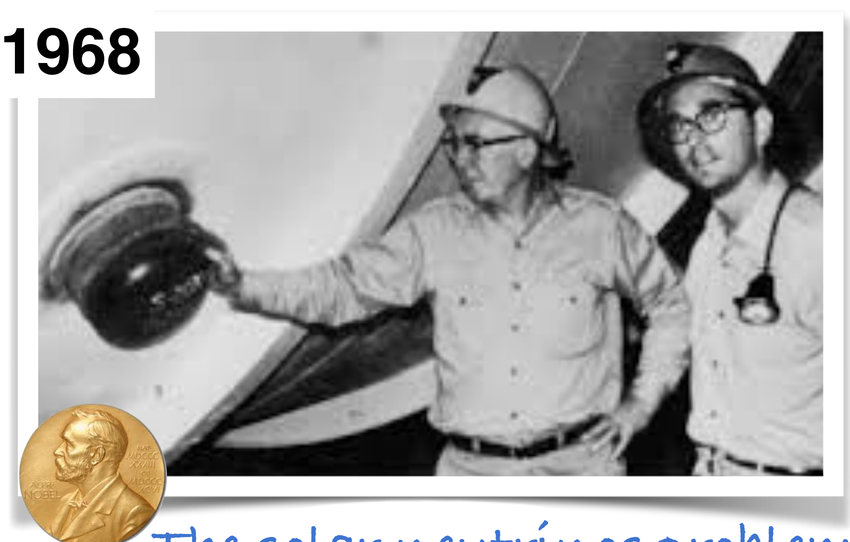


Muon neutrino is discovered

1962



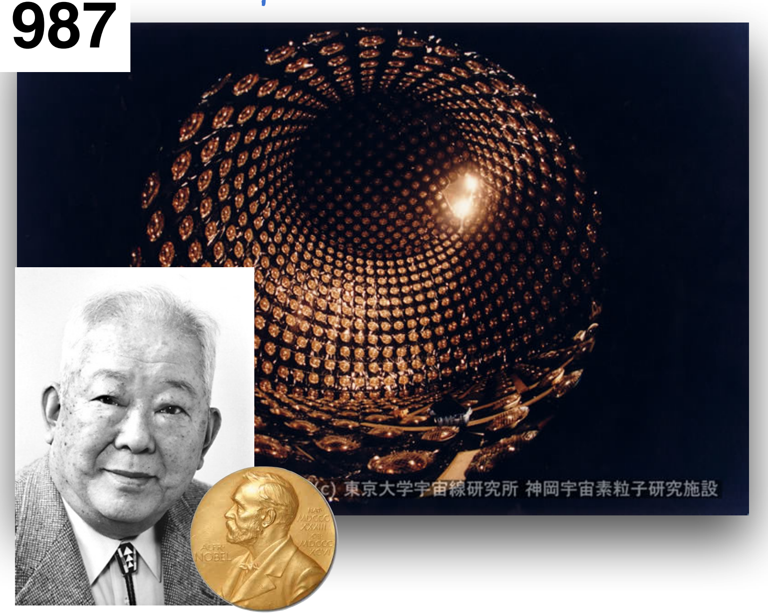
1968



The solar neutrinos problem

Supernova neutrinos

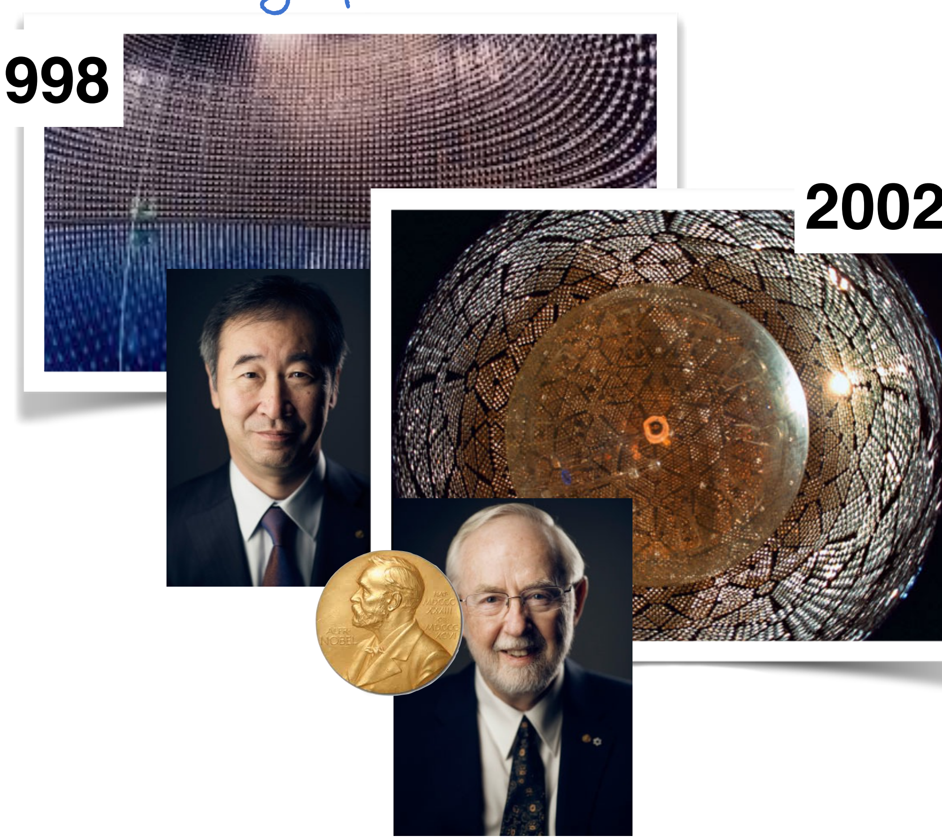
1987



Discovery of neutrino's oscillations

1998

2002

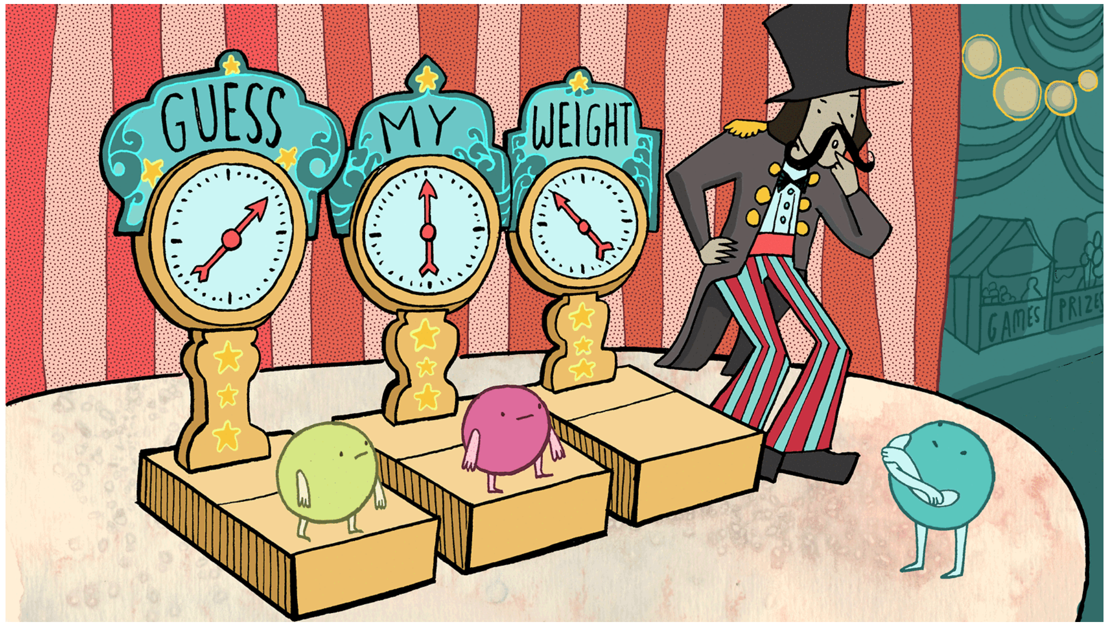


AND NOW?

We know that neutrinos change flavour

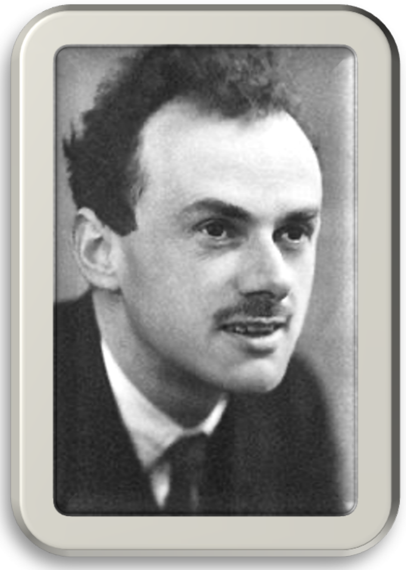
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

We still don't know their mass



Artwork by Sandbox Studio, Chicago with Corinne Mucha

What is the origin of the neutrino mass?



Dirac

Majorana

Majorana and Dirac proposed two different answers to the question of whether neutrinos and antimatter neutrinos are different particles or a single particle masquerading as two. As of today the topic remains an open question.


NEXT BIG THING
AHEAD

2. Detecting neutrinos with large scale experiments:

Detecting Neutrinos

★ Neutrinos have a very small interaction probability:

- The probability for a neutrino to interact in the Sun is extremely small: 10^{-41} cm^2
  - You need more than 10^{16} neutrinos/s emitted to observe 1 neutrino/s in 1 m^3 of water
- Important: We don't observe neutrinos directly (weak interaction and no charge), we observe the product of their reactions!!!!!!

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

★ So how do we study neutrinos?

  - We need large detectors

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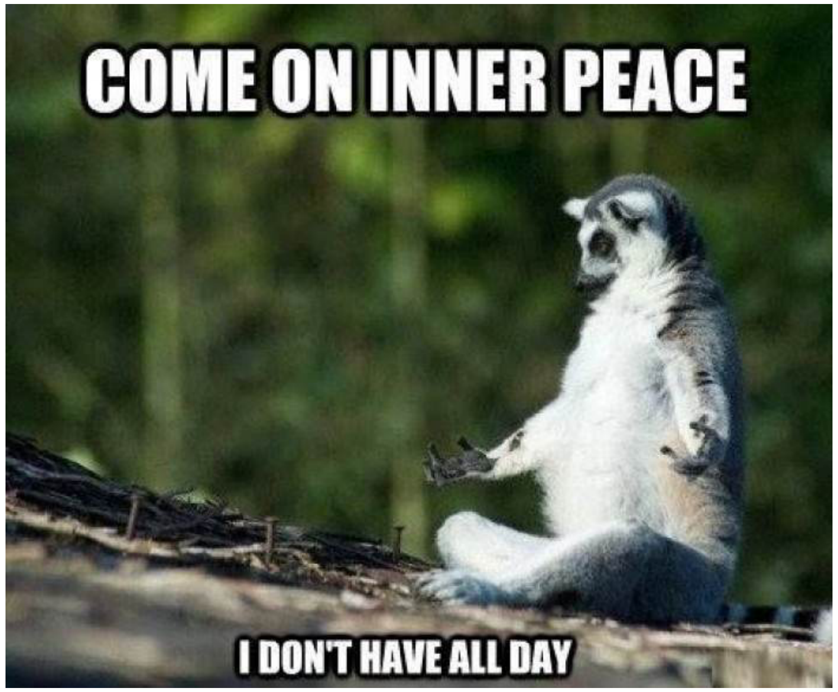
- A looooooot of time



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- ★ So how do we study neutrinos?
  - We need large detectors
  - And large neutrinos fluxes
  - A looooooot of time
  - Reduce as much as possible other sources of contamination (cosmic radiation for example)

2. Detecting neutrinos with large scale experiments:

SNO+

The nature of neutrinos

An understanding of the nature of neutrino mass is connected to the charge conjugation nature – Dirac or Majorana – of neutrinos. An observation of $0\nu\beta\beta$ would answer the following questions:

Are neutrinos their own antiparticles?

Is lepton number is violated?

What is the absolute value of the mass of neutrinos?

Why the Universe contains more matter than antimatter?

Results will have a profound impact across research areas

Neutrino physics

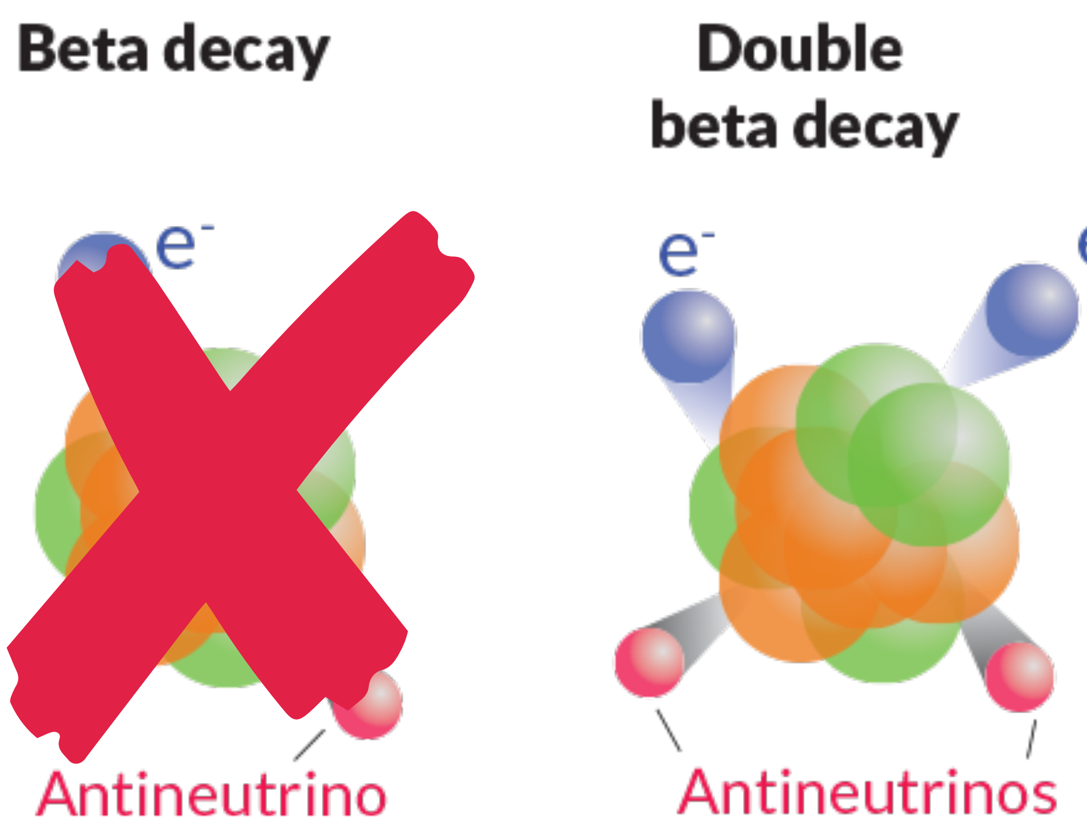
Standard Model of particle physics

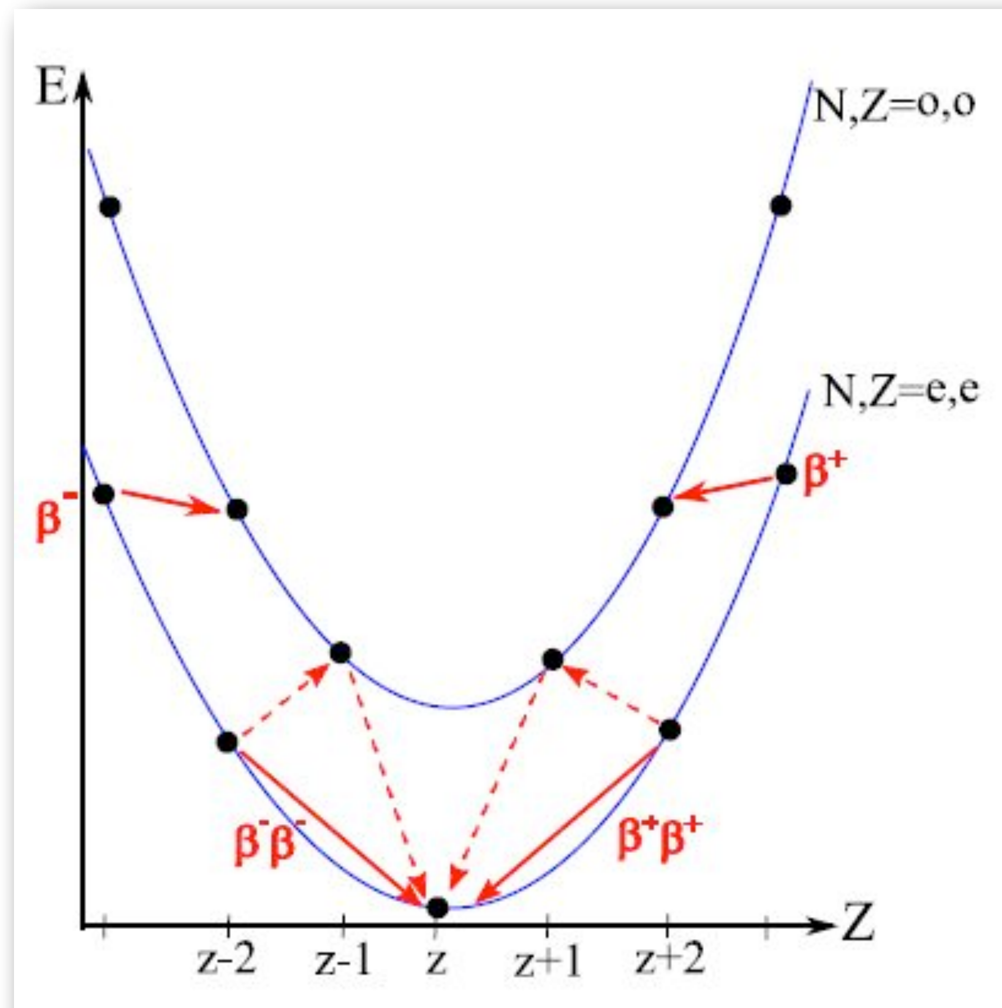
Cosmology

The 0νββ Decay

★ A radioactive decay is a way the nucleus becomes more stable by loosing one or more particles. We have seen that in nature there exist 3 main decay modes: alpha, beta, and gamma

- Sometimes a nucleus is unstable but cannot decay by a simple beta decay
  - A double-beta decay happens





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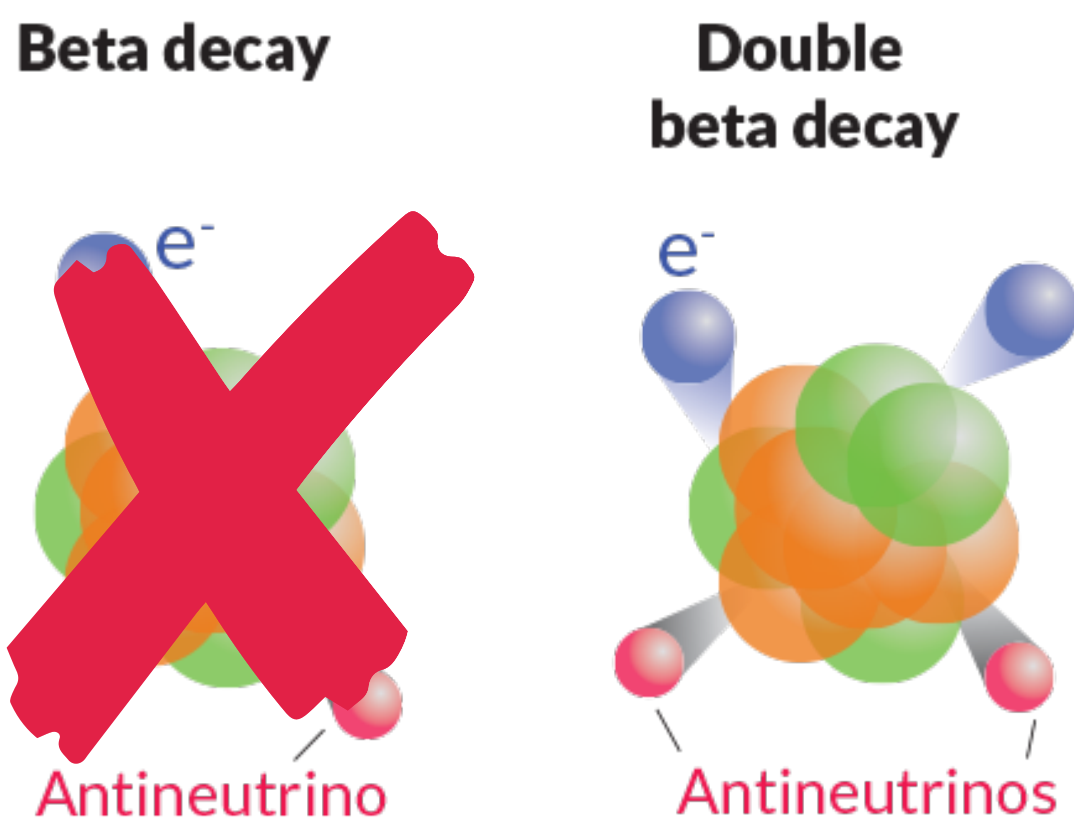

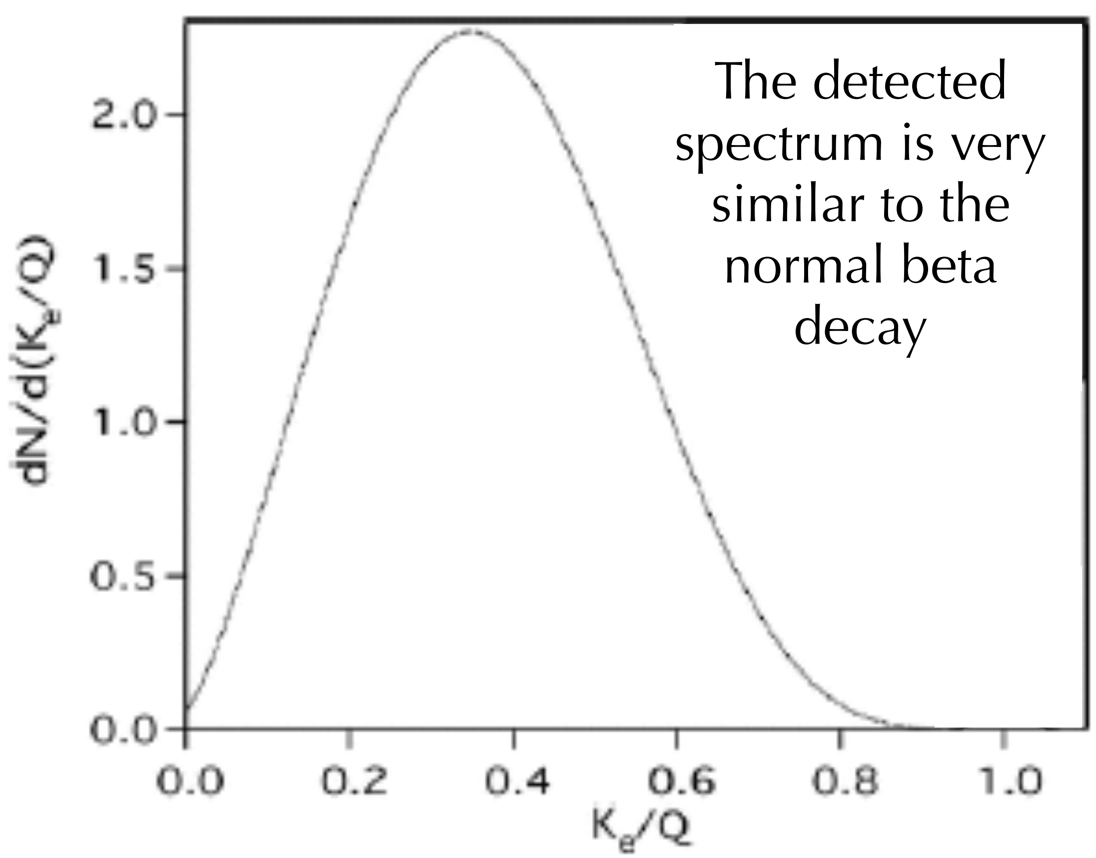

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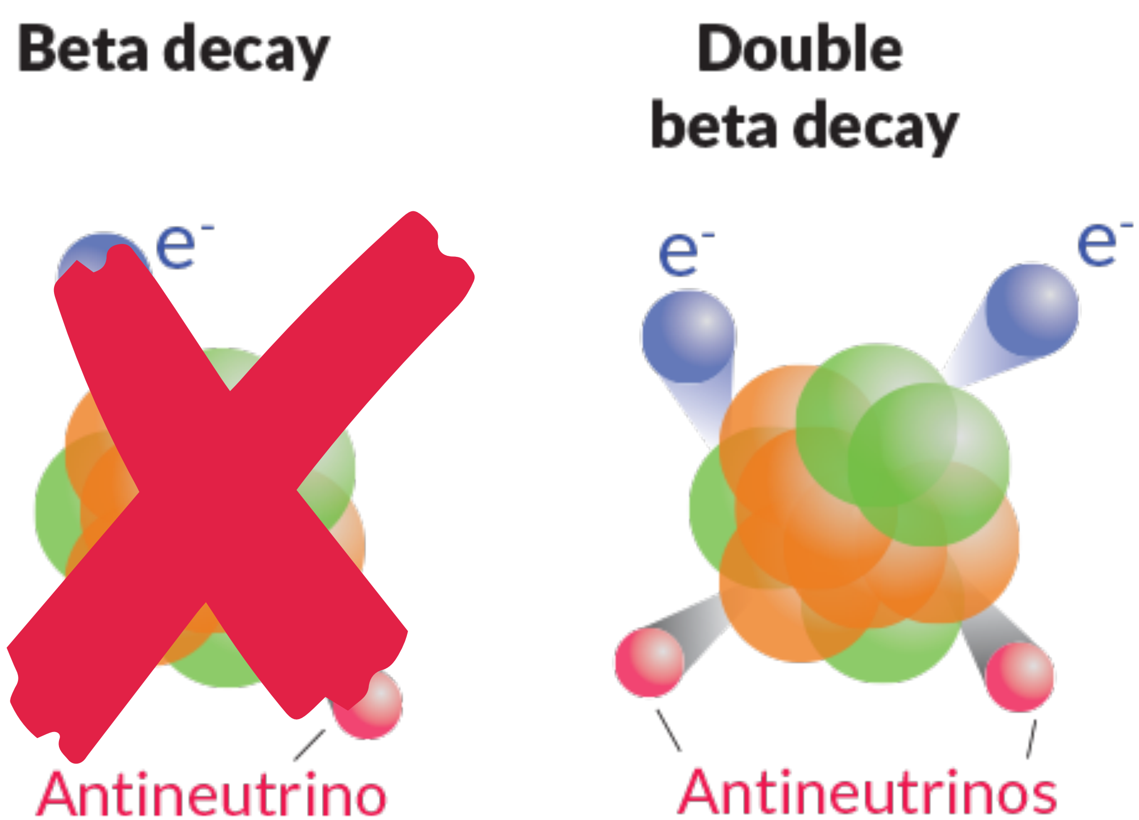

Only ~35 isotopes do this!!!!!
Decay scale is 10^{20} yrs

The 0νββ Decay

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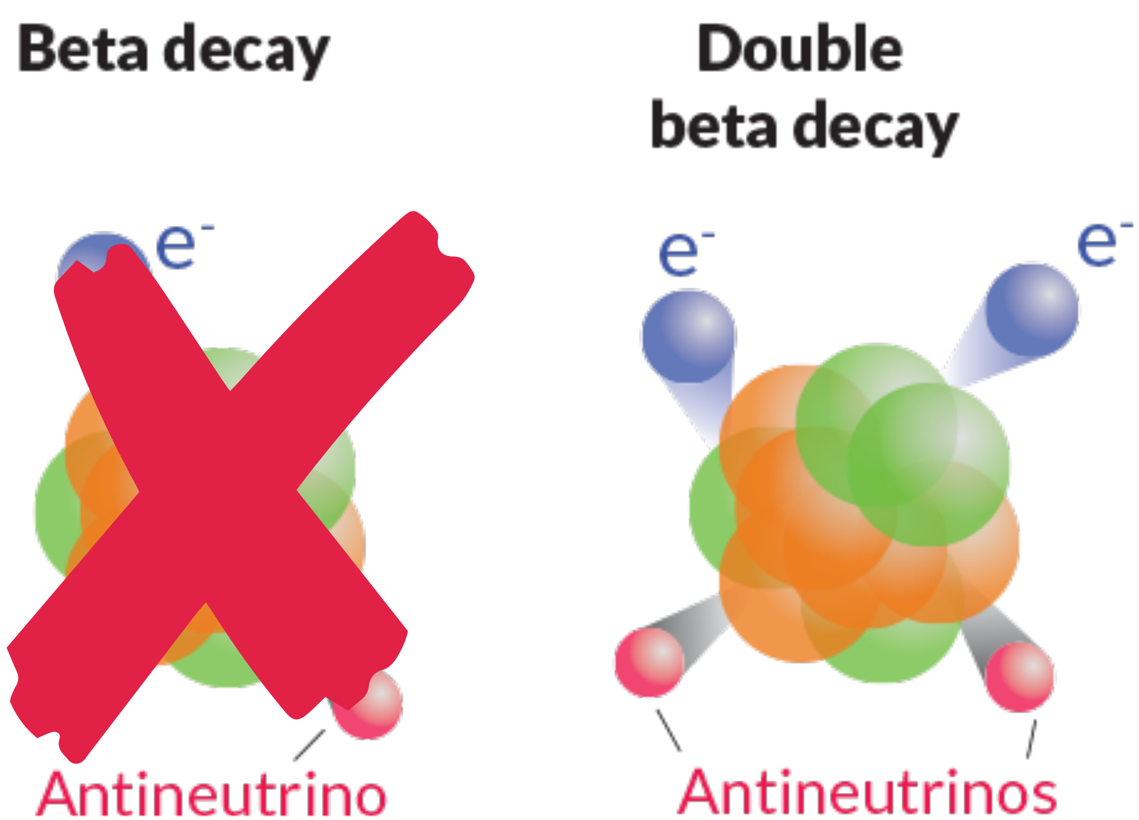

Only ~35 isotopes do this!!!!!
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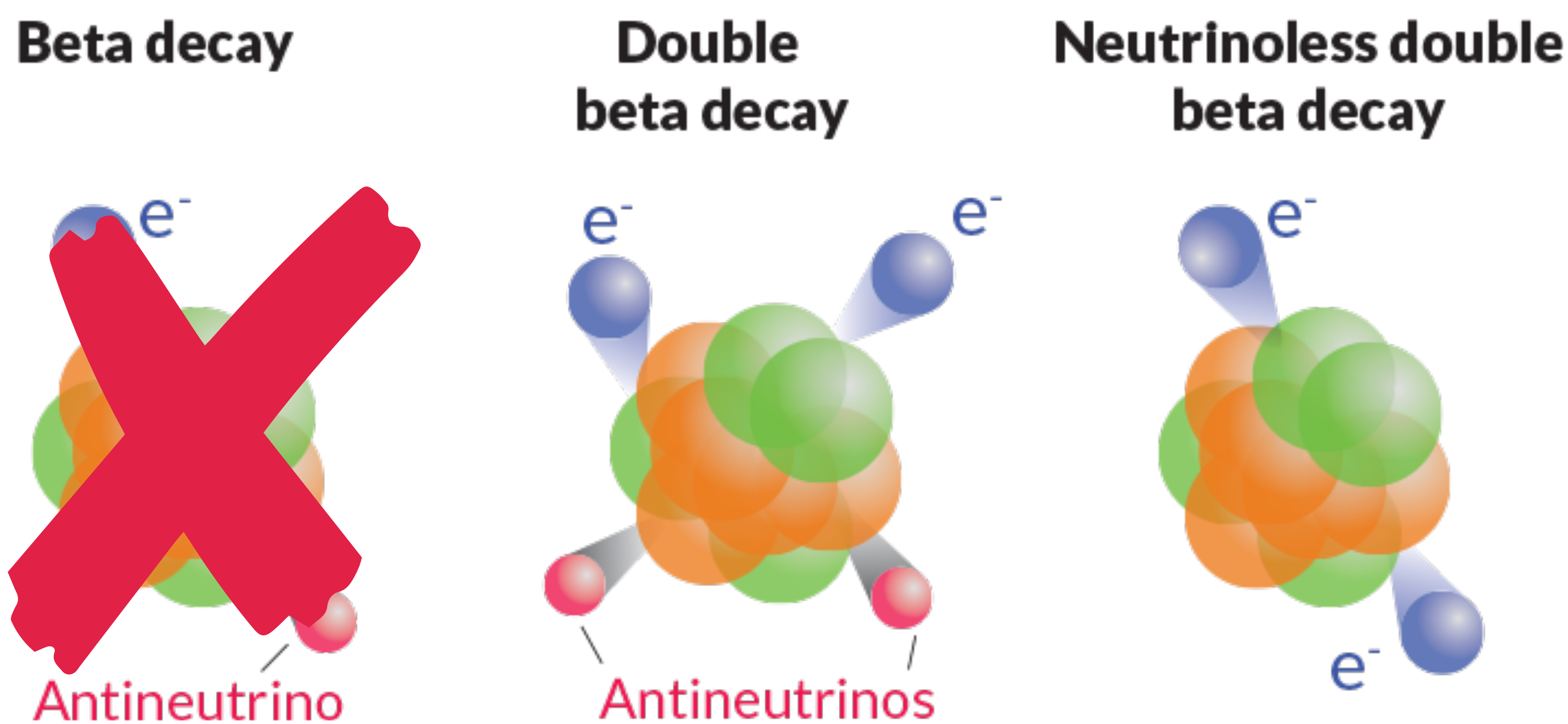
The 0νββ Decay

★ But we want to go further:

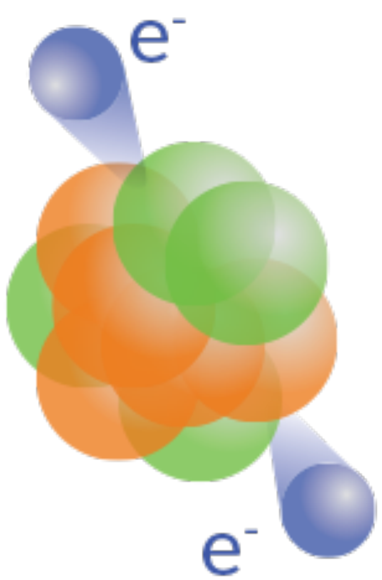


Only happens if neutrinos are Majorana

Involves "internal" neutrino annihilation
Only possible for Majorana neutrinos

The 0νββ Decay

Neutrinoless double beta decay



Phase-space factor $\sim Q_{\beta\beta}^5$

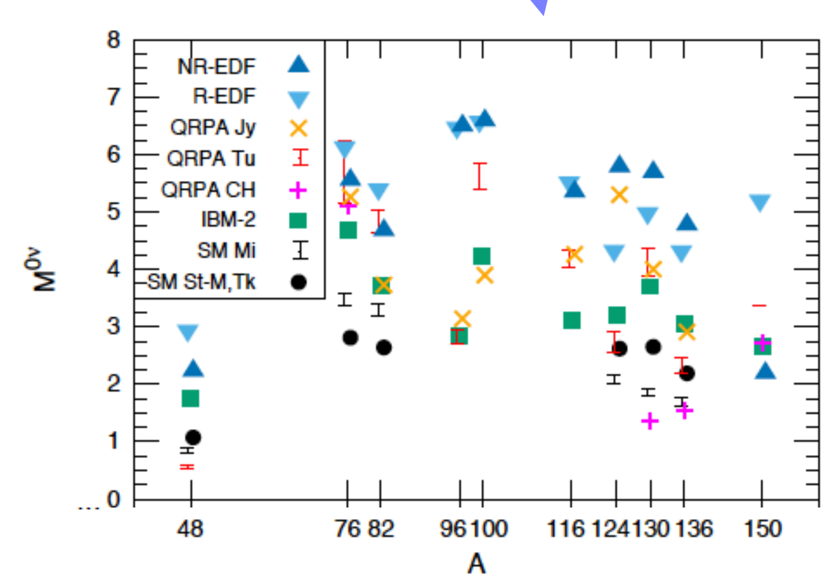
Nuclear Matrix Element, depends on the nuclear level distribution of the initial and final state
Largest theoretical uncertainty

$$\frac{1}{\boxed{T_{1/2}^{0\nu}}} = \boxed{G_{0\nu}}\boxed{|\mathcal{M}|^2}\left|\frac{\boxed{m_{ee}^{\nu}}}{m_e}\right|^2$$

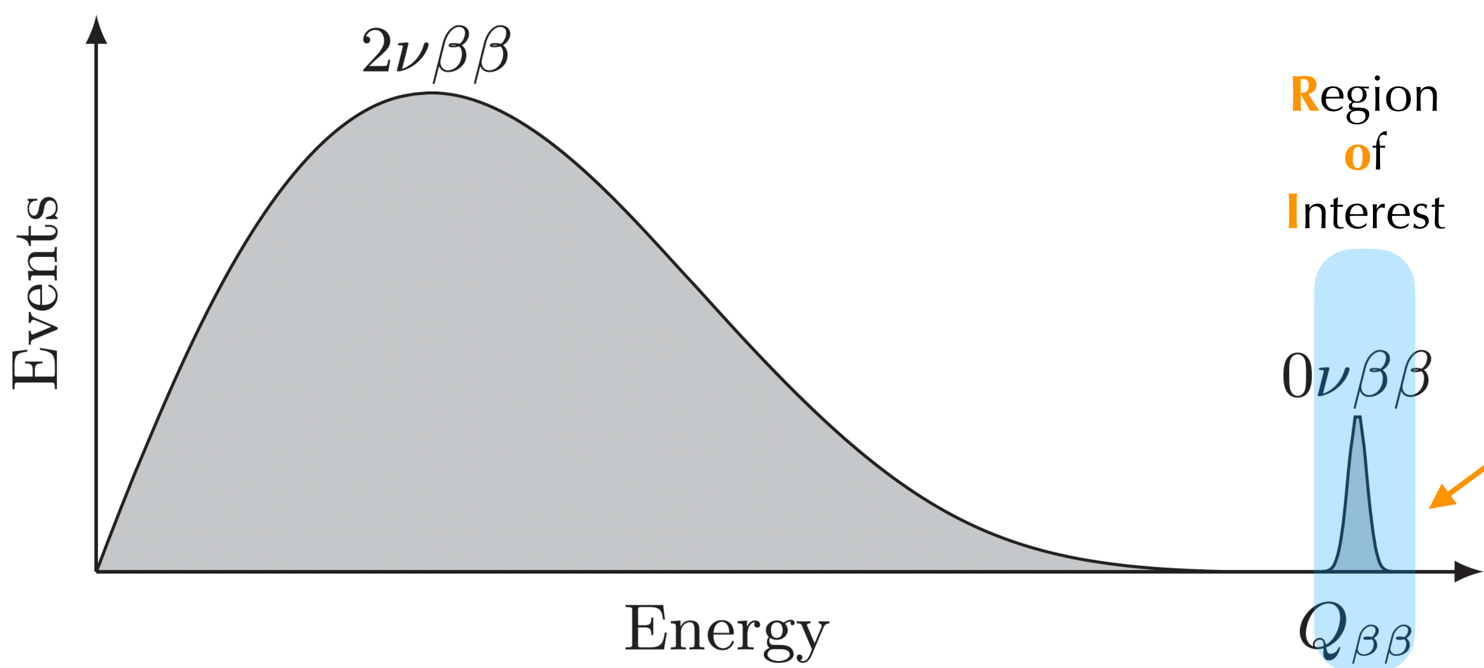
Half-life of the decay

Effective Majorana neutrino mass
Depends on m_1, m_2, m_3 and the mixing angles

$$\boxed{m_{ee}^{\nu} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3 s_{13}^2 e^{2i(\alpha_3+\delta)}}$$



The 0νββ Decay: Experiment



Count/Fit the number of events at the Q-value of the reaction

0ν efficiency

mass within the fiducial volume

$$T^{0\nu}_{1/2} \propto \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Background index
events/kev/kg/yr
SNO+ (expected) = 2.9e-4
GERDA = 5.4e-4
CUORE = 1.5e-2
KamLAND-Zen = 1.3e-4

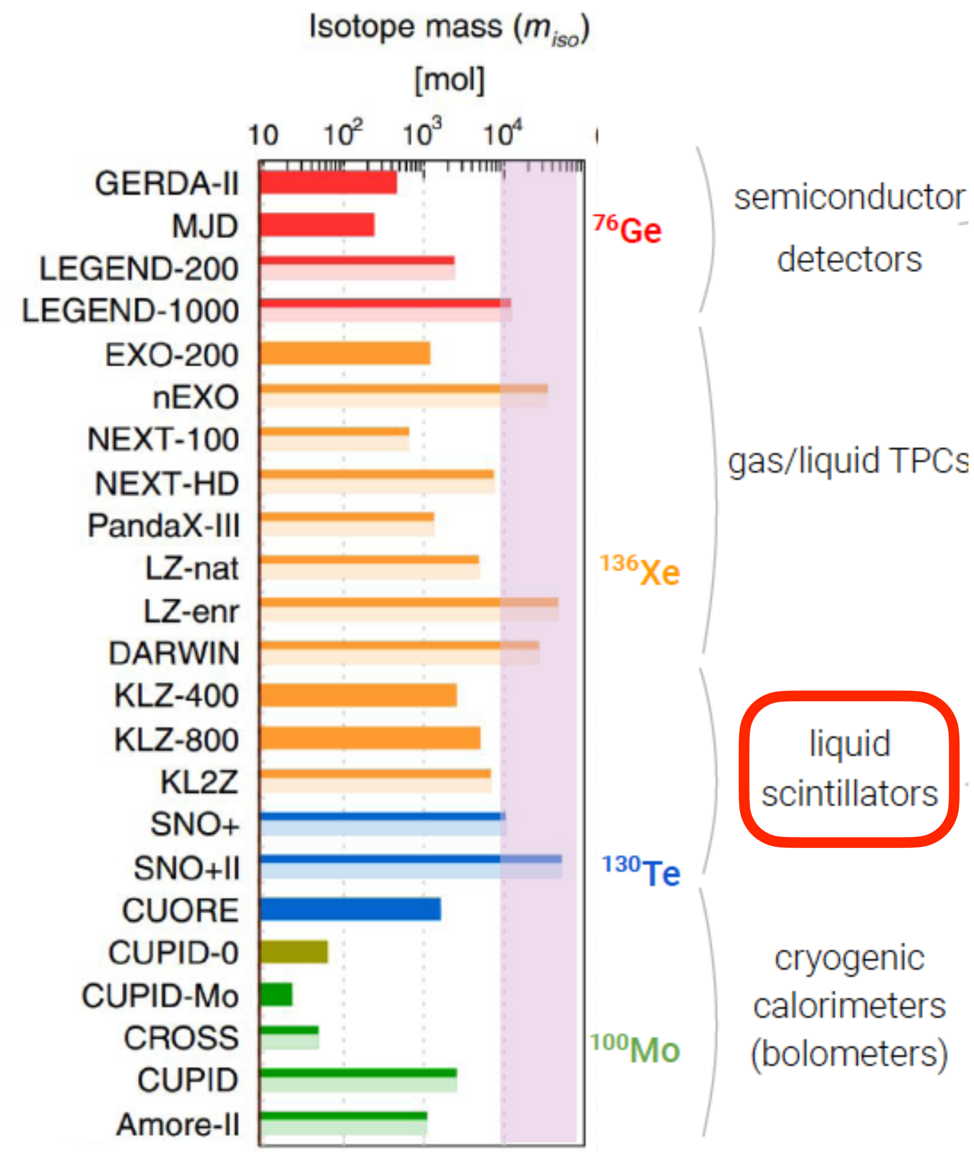
To improve the sensitivity on the Majorana mass by a factor 2, requires an improvement of the half-life by a factor of 4, hence 16x on the square root terms

Large mass
High radiopurity
Good energy resolution

Not seen yet!
Decay scale is >10^{25} yrs

THE 0VBB DECAY: TECHNIQUES

1. Liquid scintillator detectors (Xe/Te):
   I. Good resolution
   II. High mass
   III. Low background
   IV. Event's ID discrimination
2. Bolometers/semiconductors:
   I. Great resolution but relative low size.
   II. Requires cooling at cryogenic temperatures
3. Tracking or topology detectors:
   I. Gas/Liquid TPC.
   II. Good topology reconstruction.
   III. Low mass



M. Agostini, Neutrinoless $\beta\beta$ Decay - Status & Prospects
XX International Workshop on Neutrino Telescopes, Venice

The 0vBB Decay: Techniques

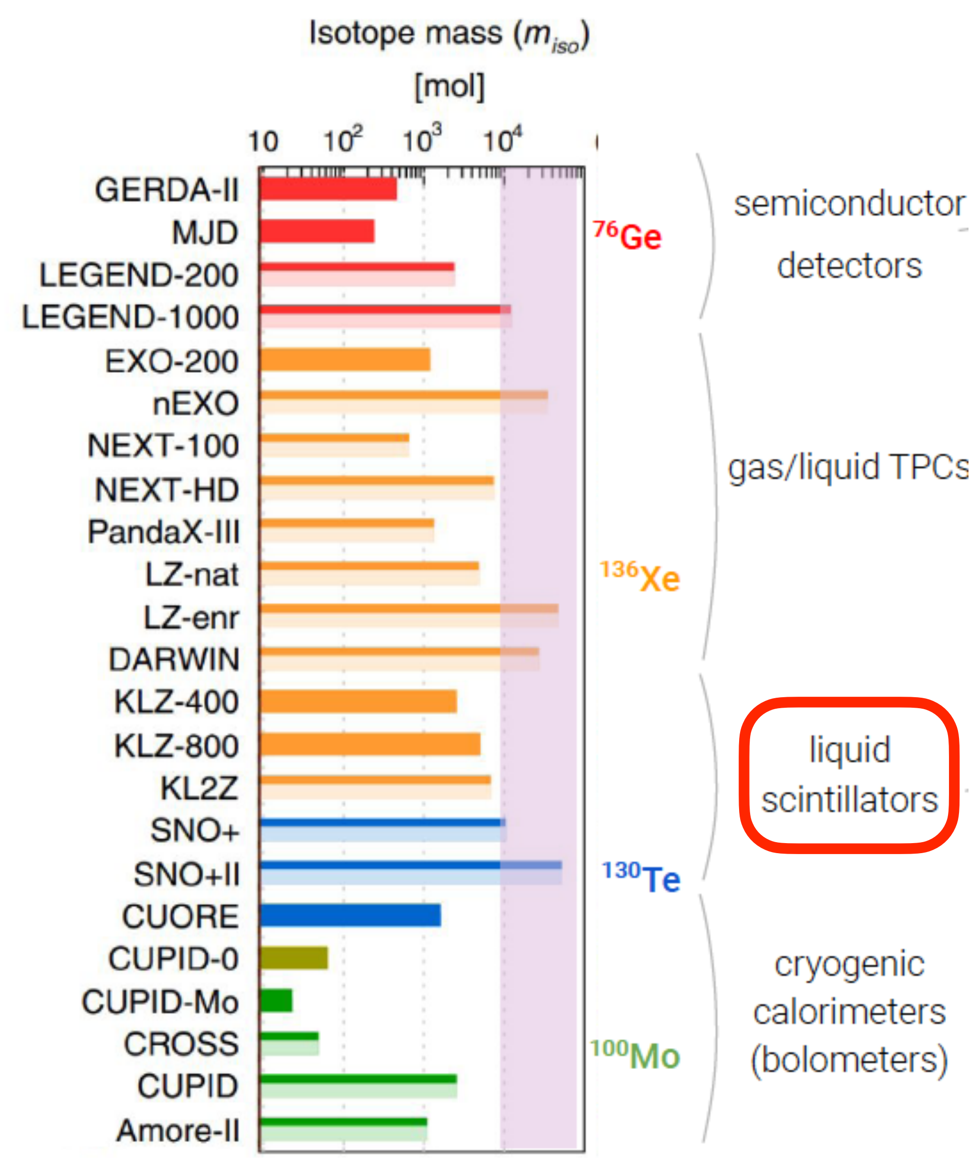
1. Liquid scintillator detectors (Xe/Te):

KL-Zen =BEST RESULT FOR 0νBB $T_{1/2}$

3.8×10^{26} yrs (combined 400-800)

2. Bolometers/semiconductors:
   I. Great resolution but relative low size.
   II. Requires cooling at cryogenic temperatures

3. Tracking or topology detectors:
   I. Gas/Liquid TPC.
   II. Good topology reconstruction.
   III. Low mass



M. Agostini, Neutrinoless $\beta\beta$ Decay - Status & Prospects
XX International Workshop on Neutrino Telescopes, Venice

SNO+

LIP Coimbra
LIP Lisboa

SNOLAB
TRIUMF
University of Alberta
Queen's University
Laurentian University

UNAM

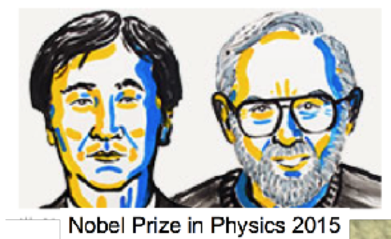
Shandong University

TU Dresden

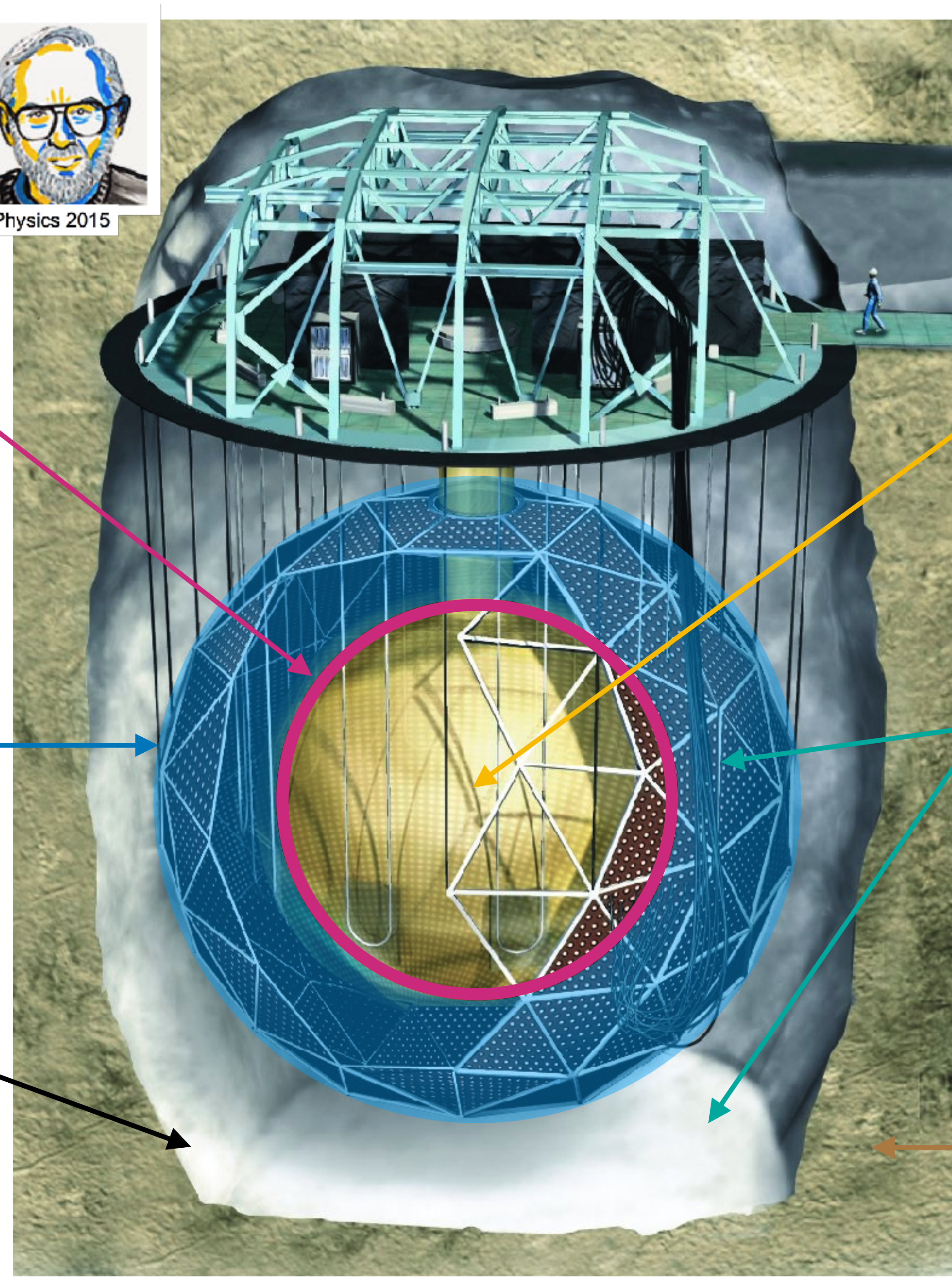
University of Chicago
Boston University
BNL
University of California Berkeley
LBNL
University of Pennsylvania
UC Davis

Oxford University
Kings College
University of Liverpool
University of Sussex
University of Lancaster

SNO+ DETECTOR



Deep Underground
~ 2 km



Acrylic Vessel (AV)
12 m diam., 5 cm thick

Active medium

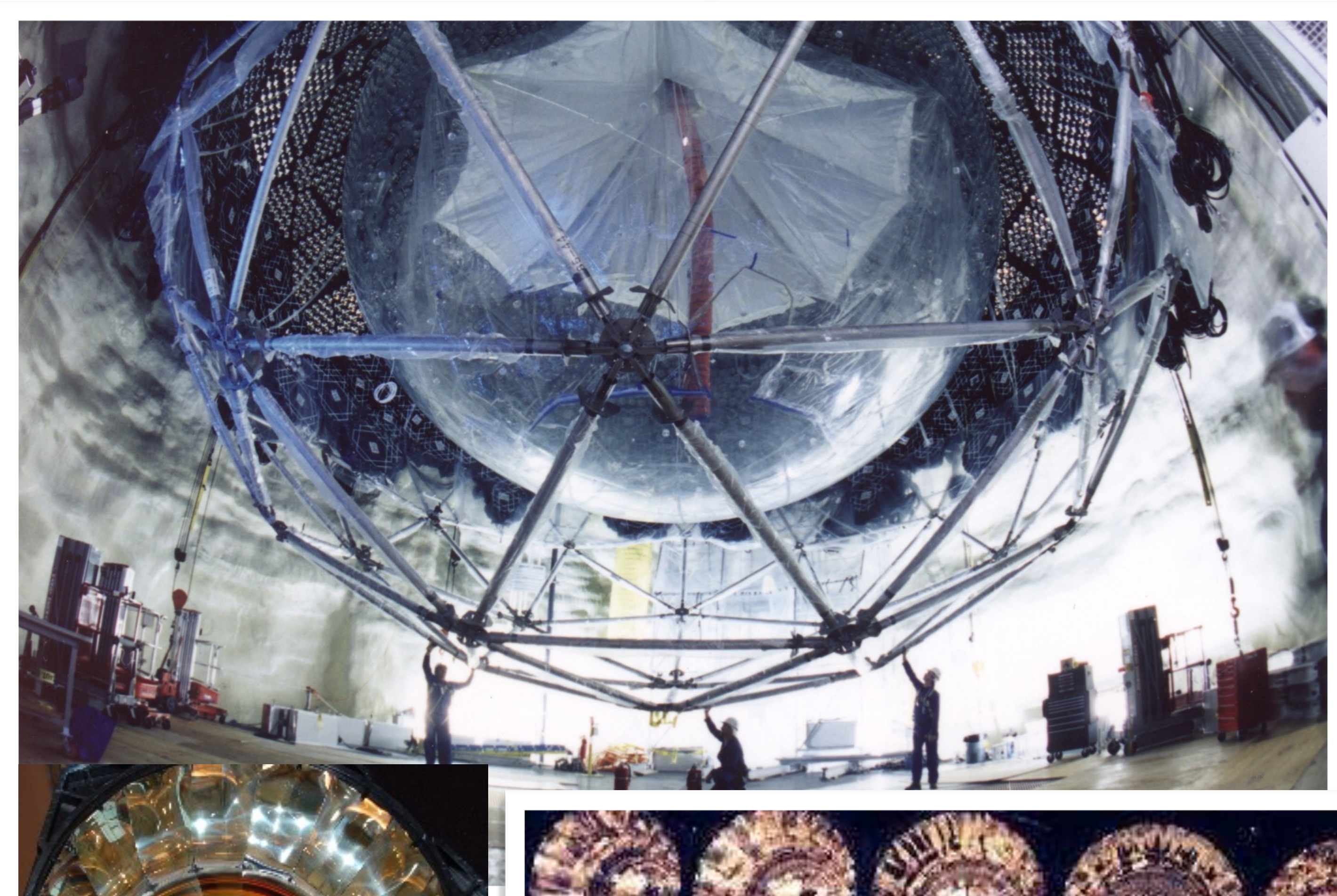
PSUP (PMT Support Structure)
~ 9300 PMTs
54% Coverage

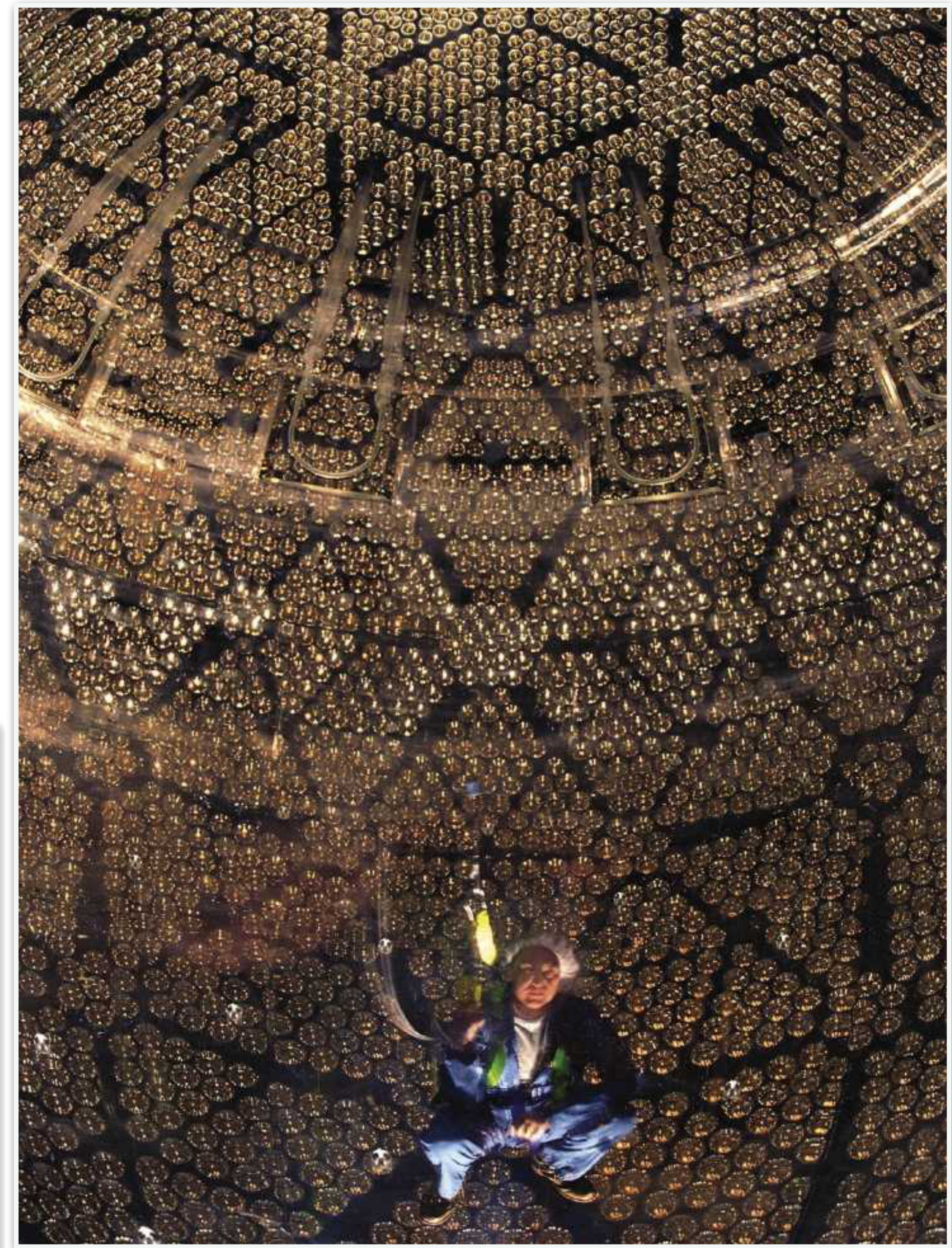
Light water (H_2O) shielding
- 1700t internal
- 5300t external

Urylon layer/Radon seal

Norite Rock

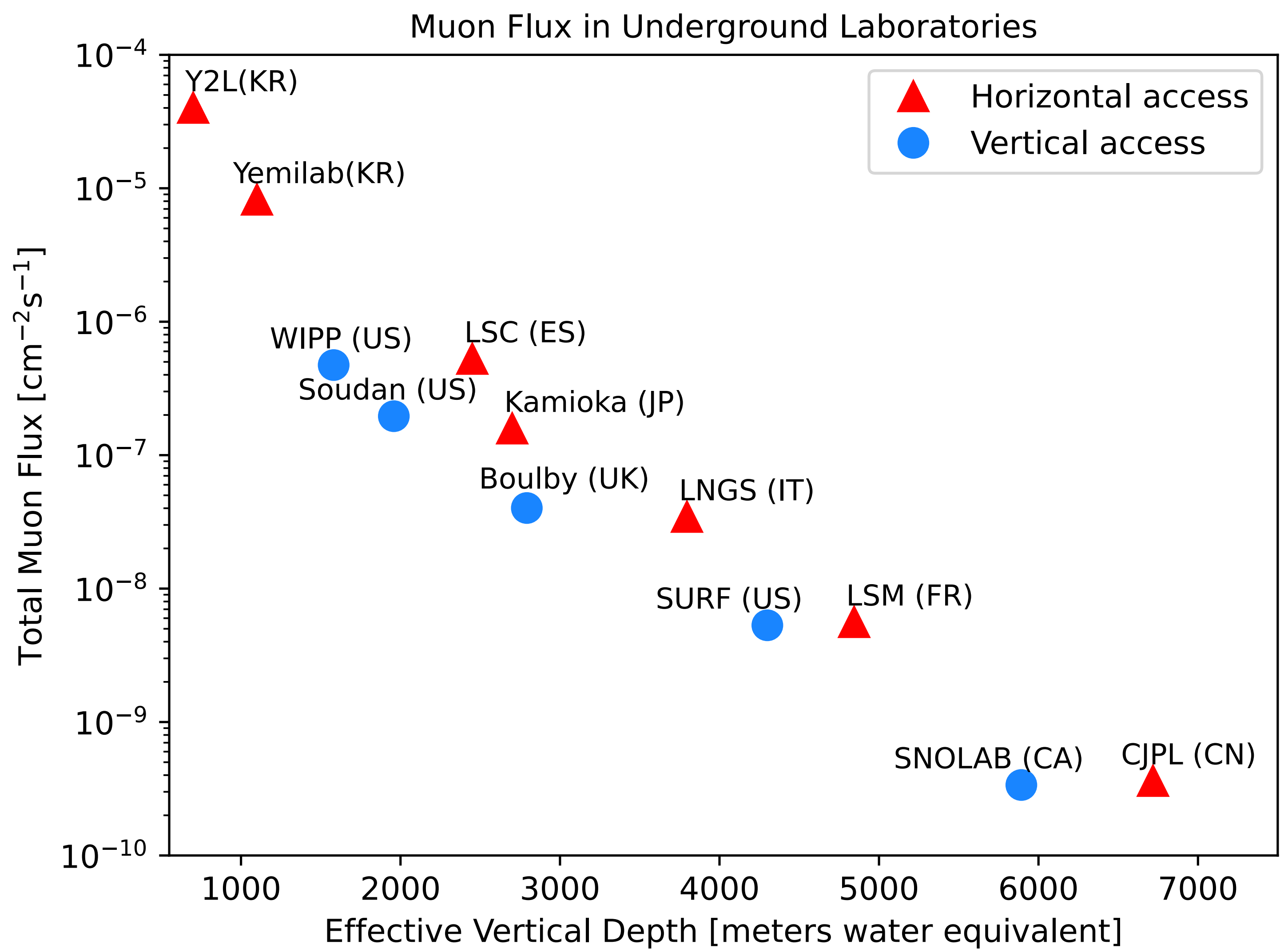
Construction





SNO+ Location

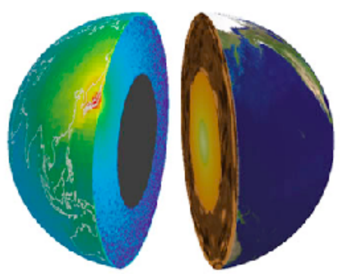
@SNOLAB, Sudbury, Canada



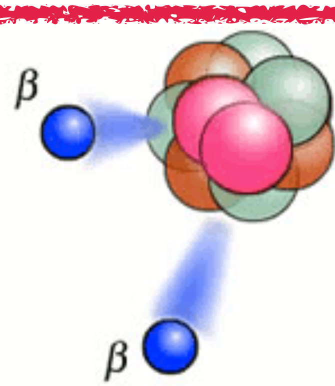
★ A very large detector that searches for the nature of neutrinos

Reactor antineutrinos

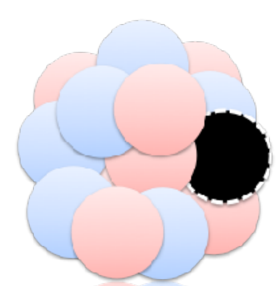
Solar neutrinos
pep, CNO, low
energy ^{8}B



Geo anti-neutrinos



Neutrinoless
double-beta
decay of ^{130}Te

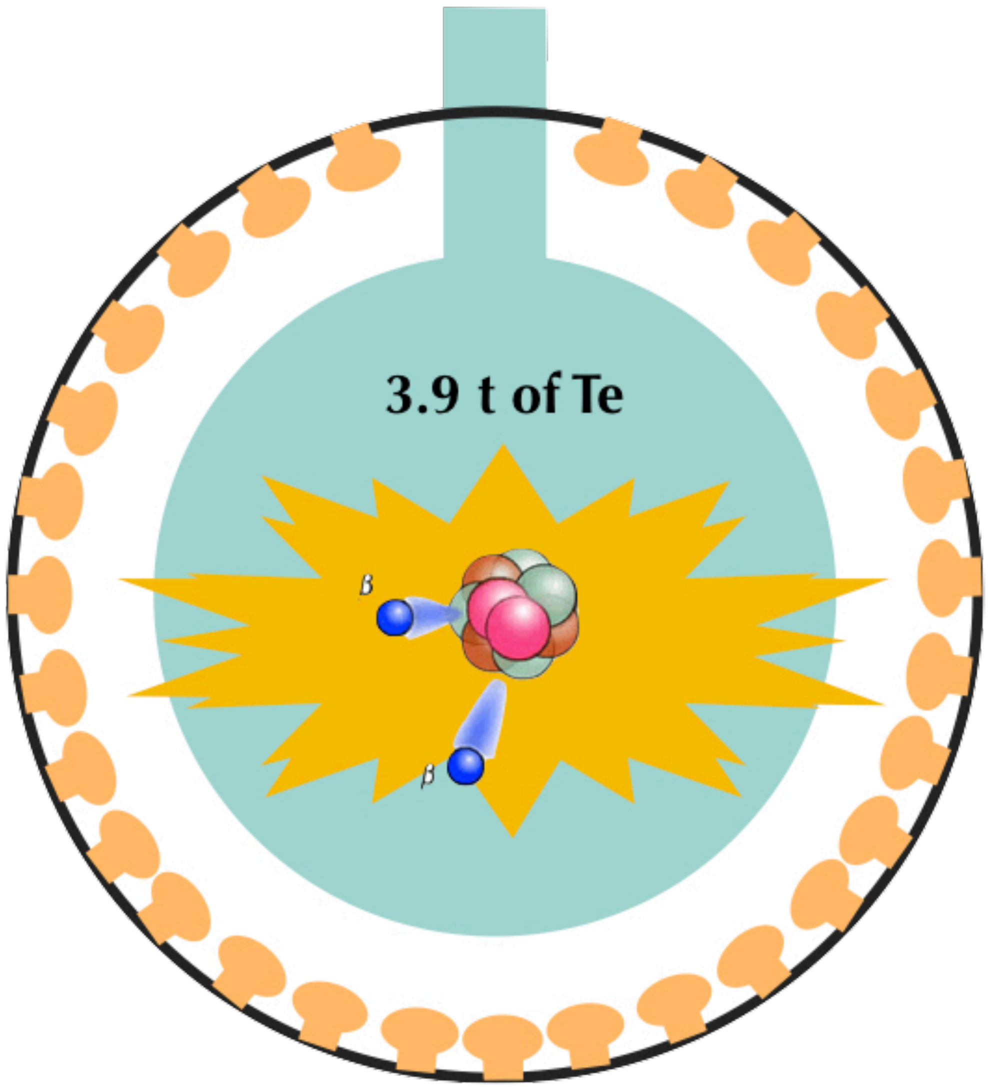


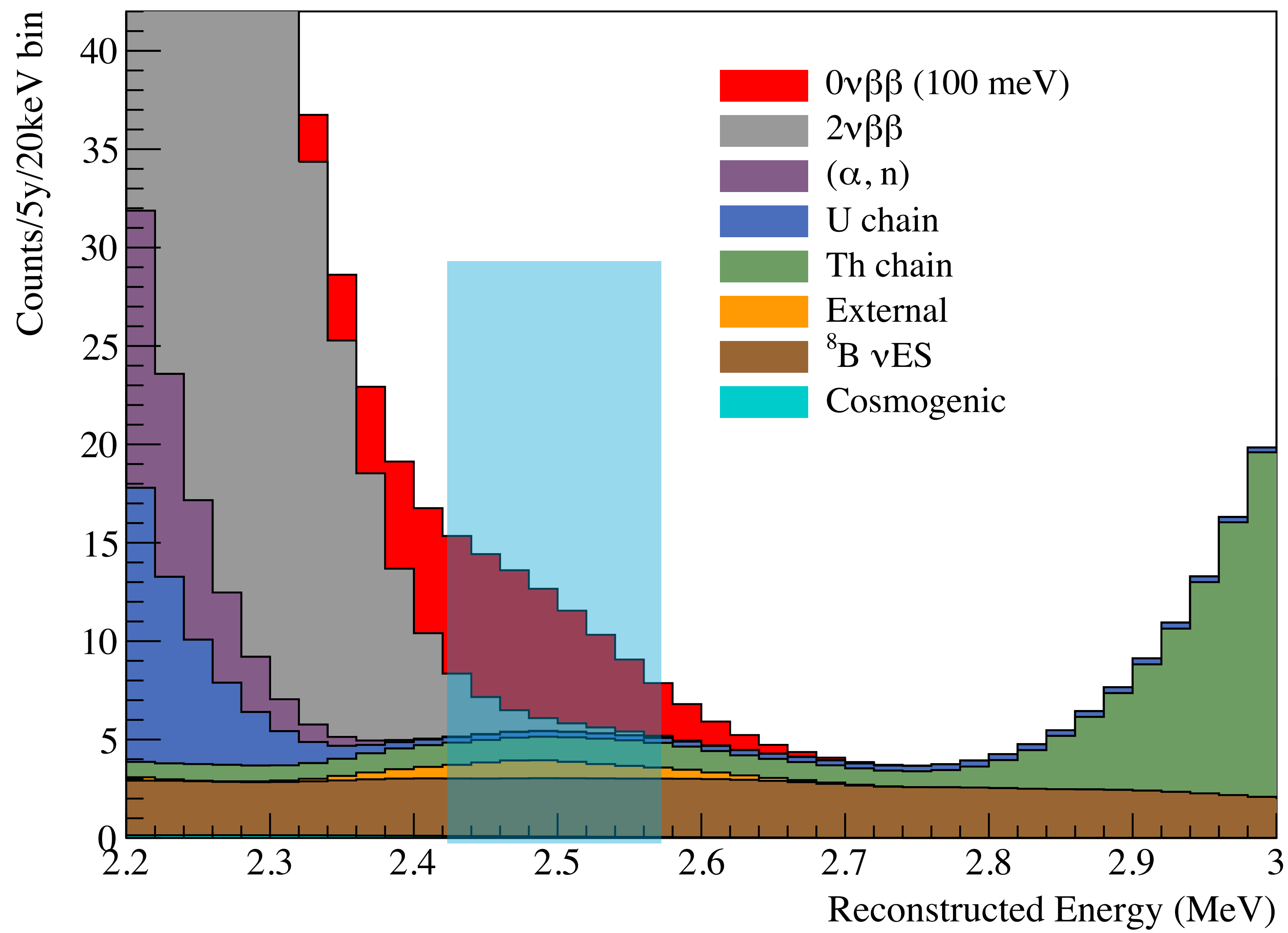
Rare decays

Supernovae
neutrinos

Double-beta decay with SNO+

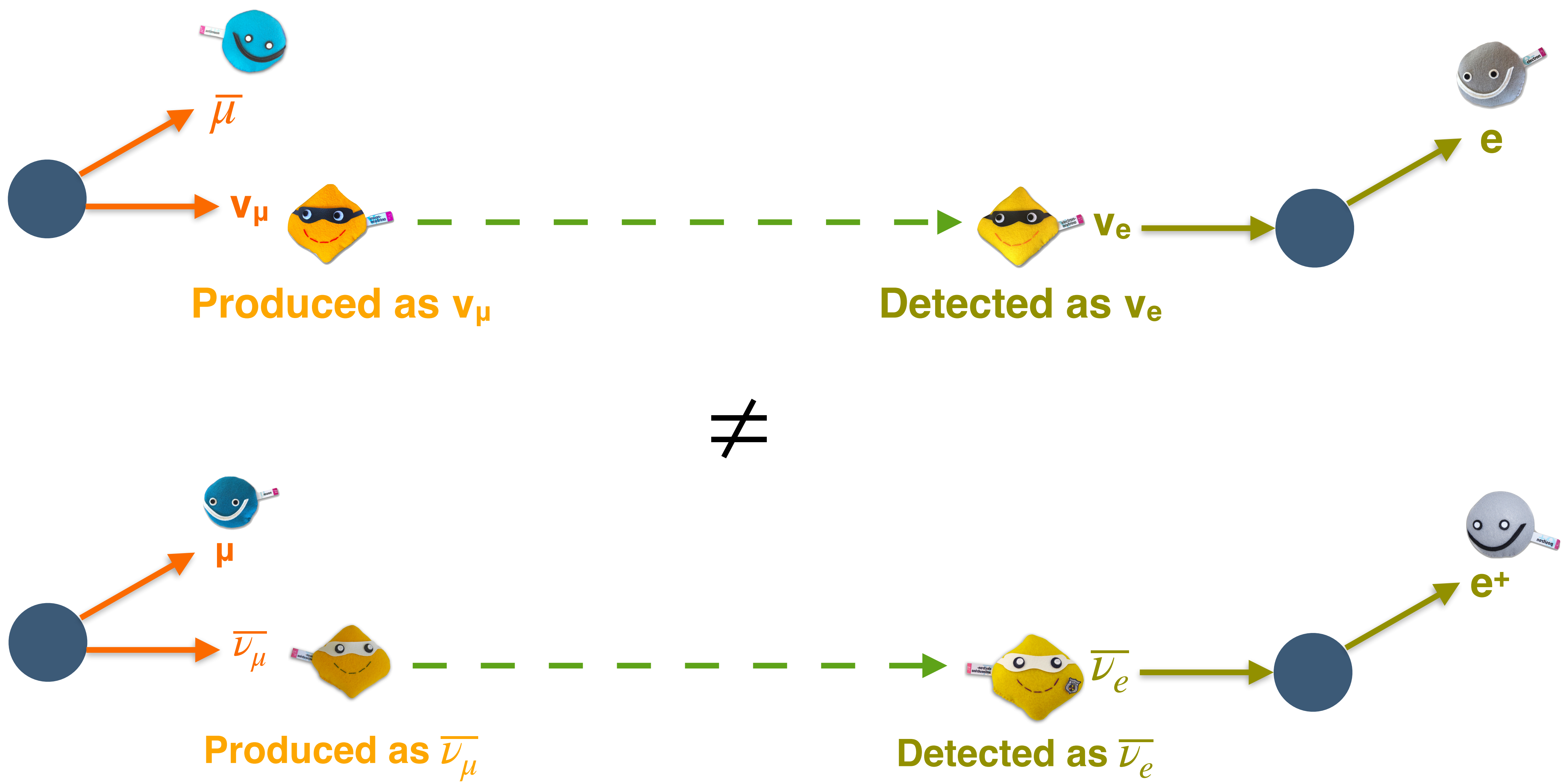
★ Add a large mass of the isotope of interest and then count





CP - Violation

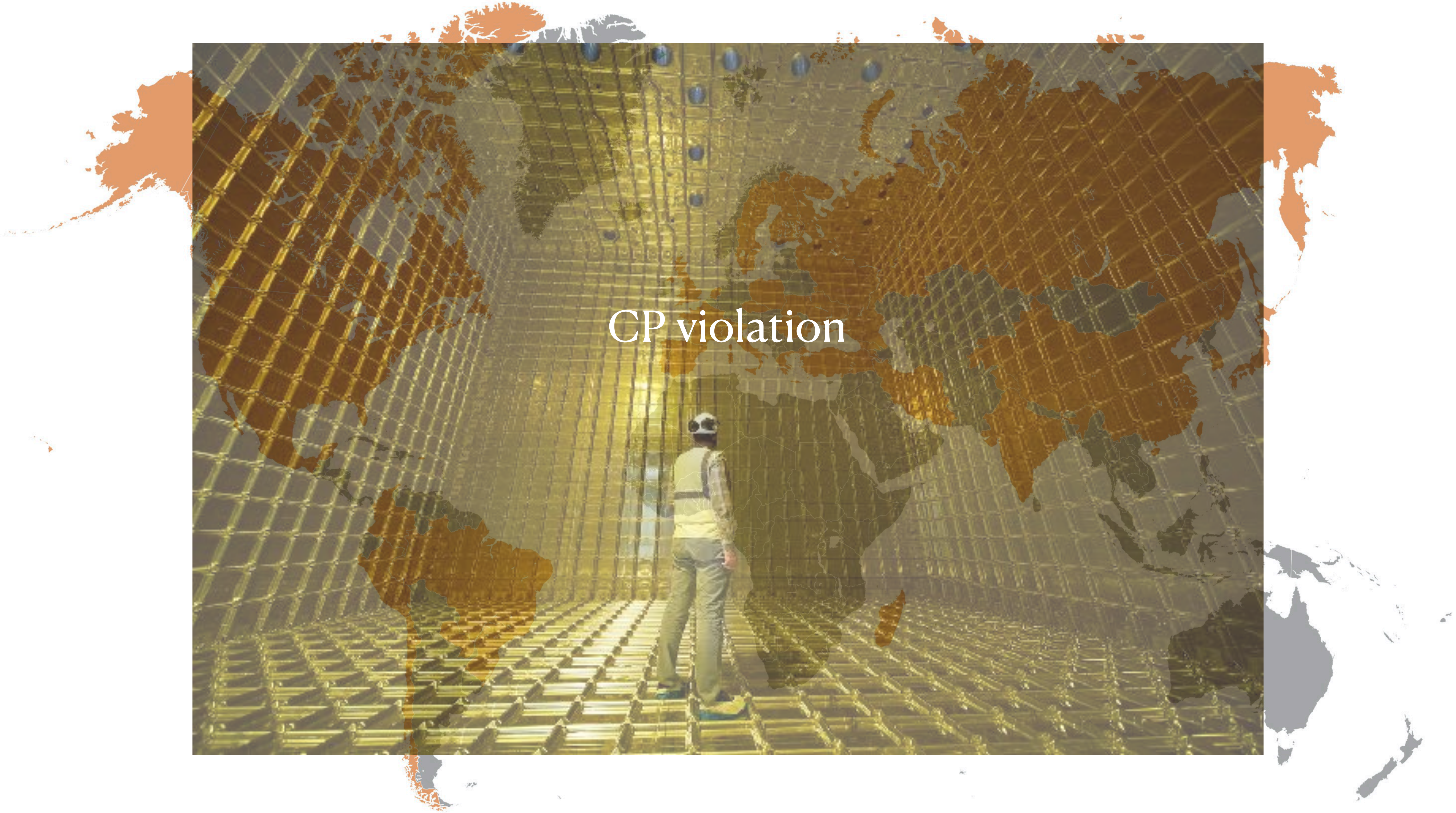
★ If neutrino's interactions DO NOT conserve CP, neutrino and antineutrinos oscillations are different!



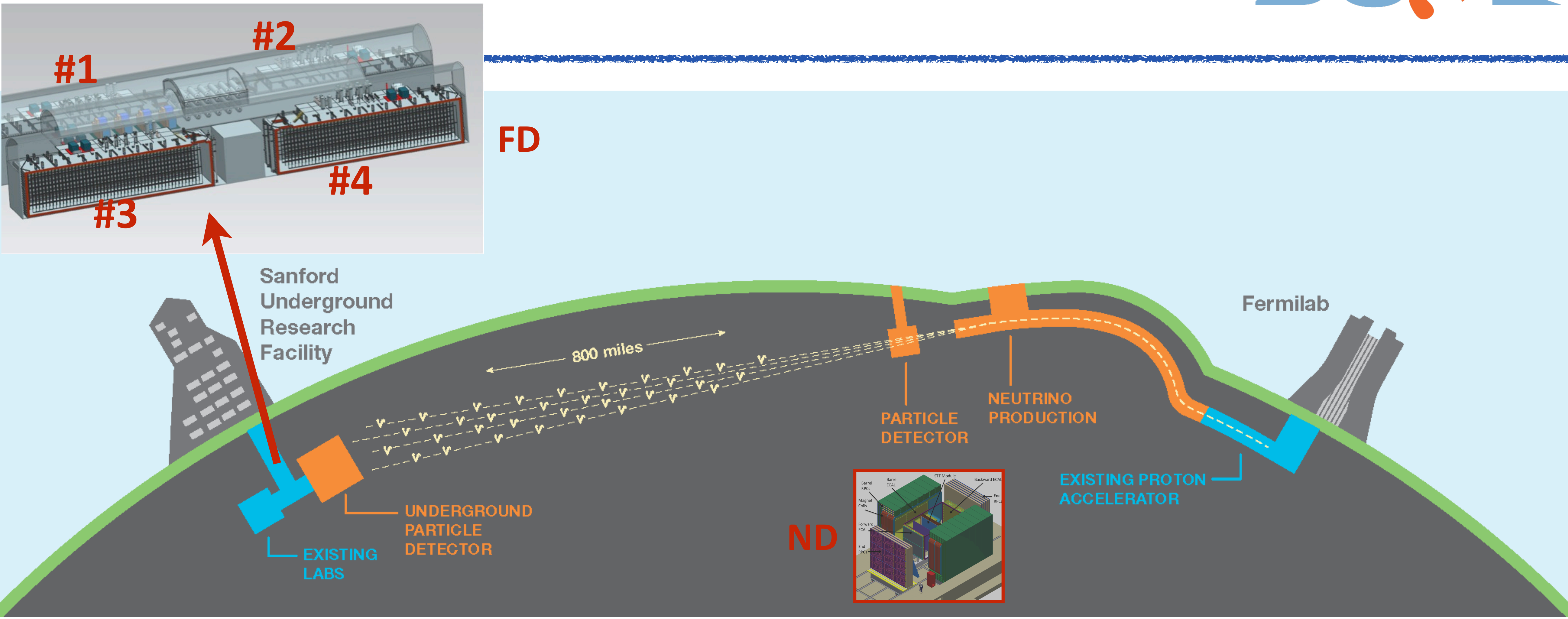
2. Detecting neutrinos with large scale experiments:

DUNE

DUNE



Physics



- ★ **<u>Neutrino Oscillation Physics</u>**
  - High sensitivity for leptonic CP violation
  - Identify the neutrino mass hierarchy
  - Precision oscillation physics
- ★ **<u>Proton Decay</u>**
  - Target SUSY-favored mode p —> K+ ν
- ★ **<u>SN burst physics and astrophysics</u>**
  - Galactic core collapse supernova
  - unique sensitivity to νe
- ★ **<u>Atmospheric Neutrinos</u>**
- ★ **<u>Solar neutrinos (similar approach as SN)</u>**
- ★ **<u>Neutrino Interaction Physics (Near Detector)</u>**

Physics

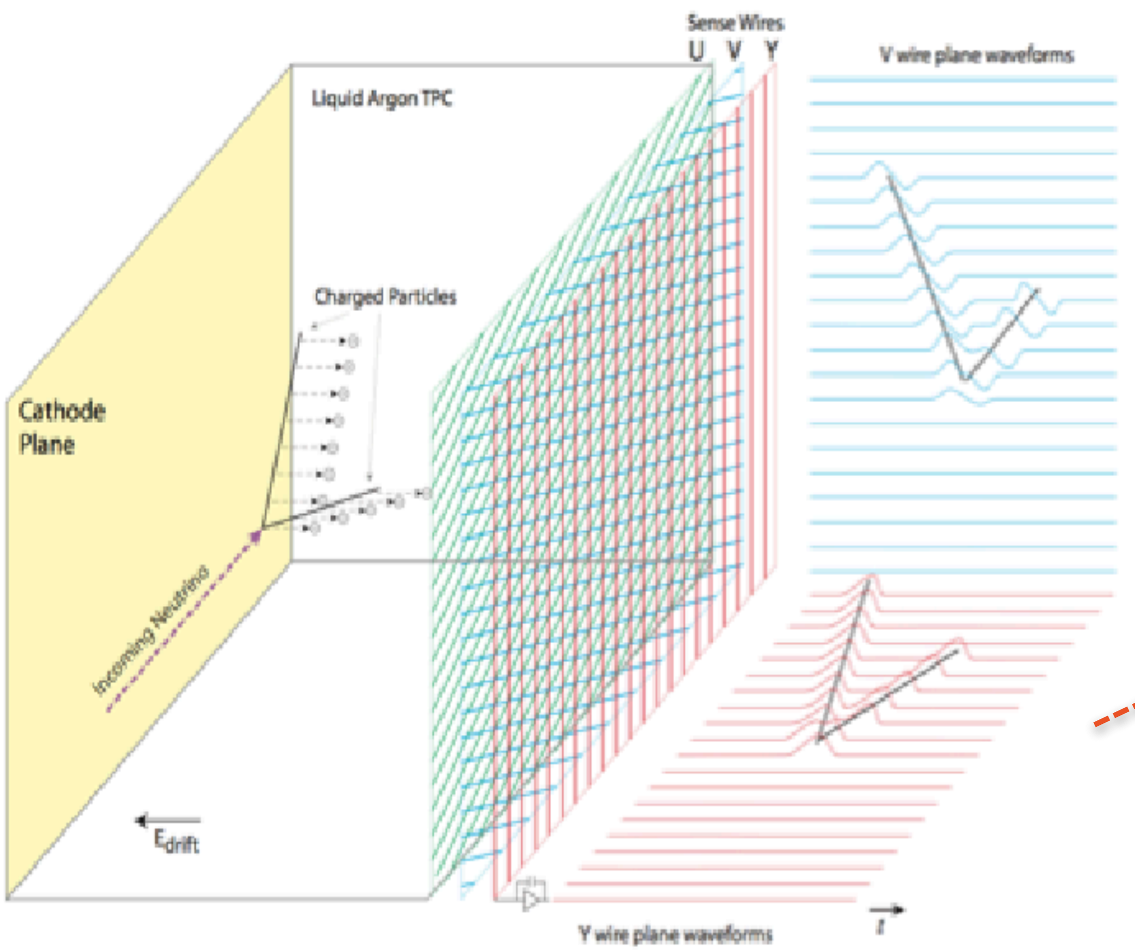
DUNE Far Detector: LAr TPCs

★ **<u>Technology advantages:</u>**

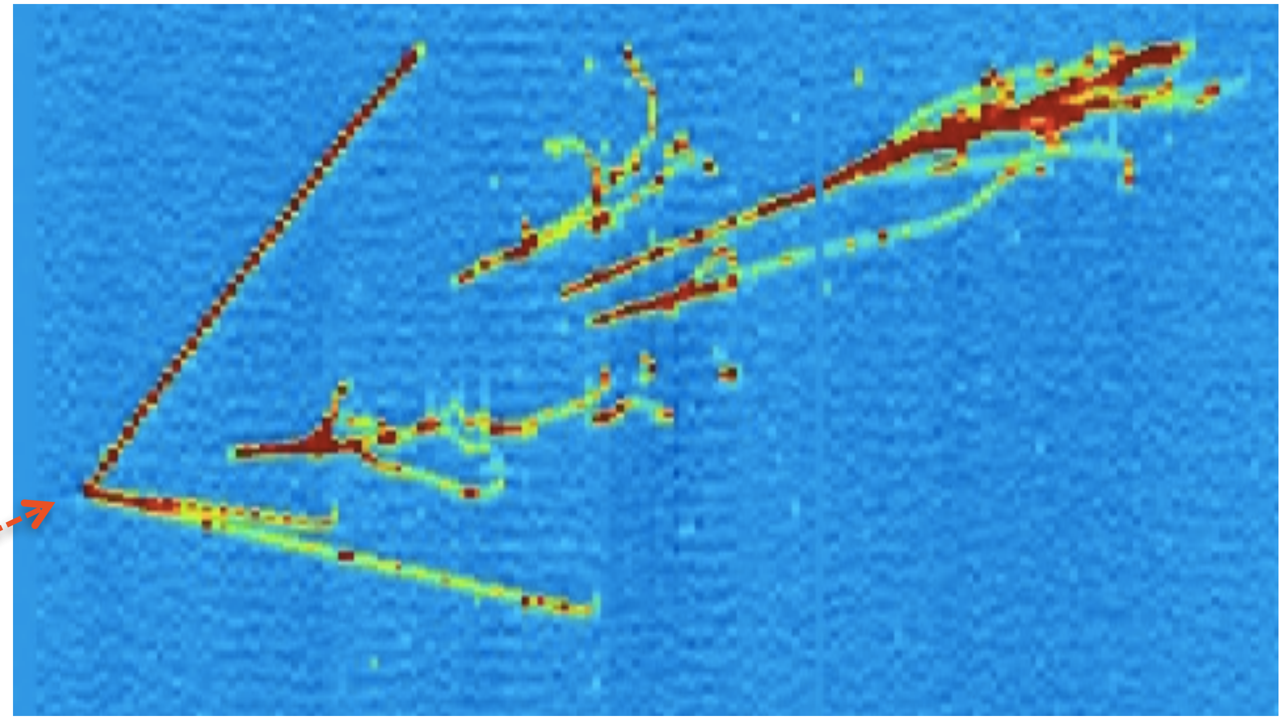
- 3D imaging (use image processing technology for event classification)
- Full event topology

★ **<u>Major Challenges:</u>**

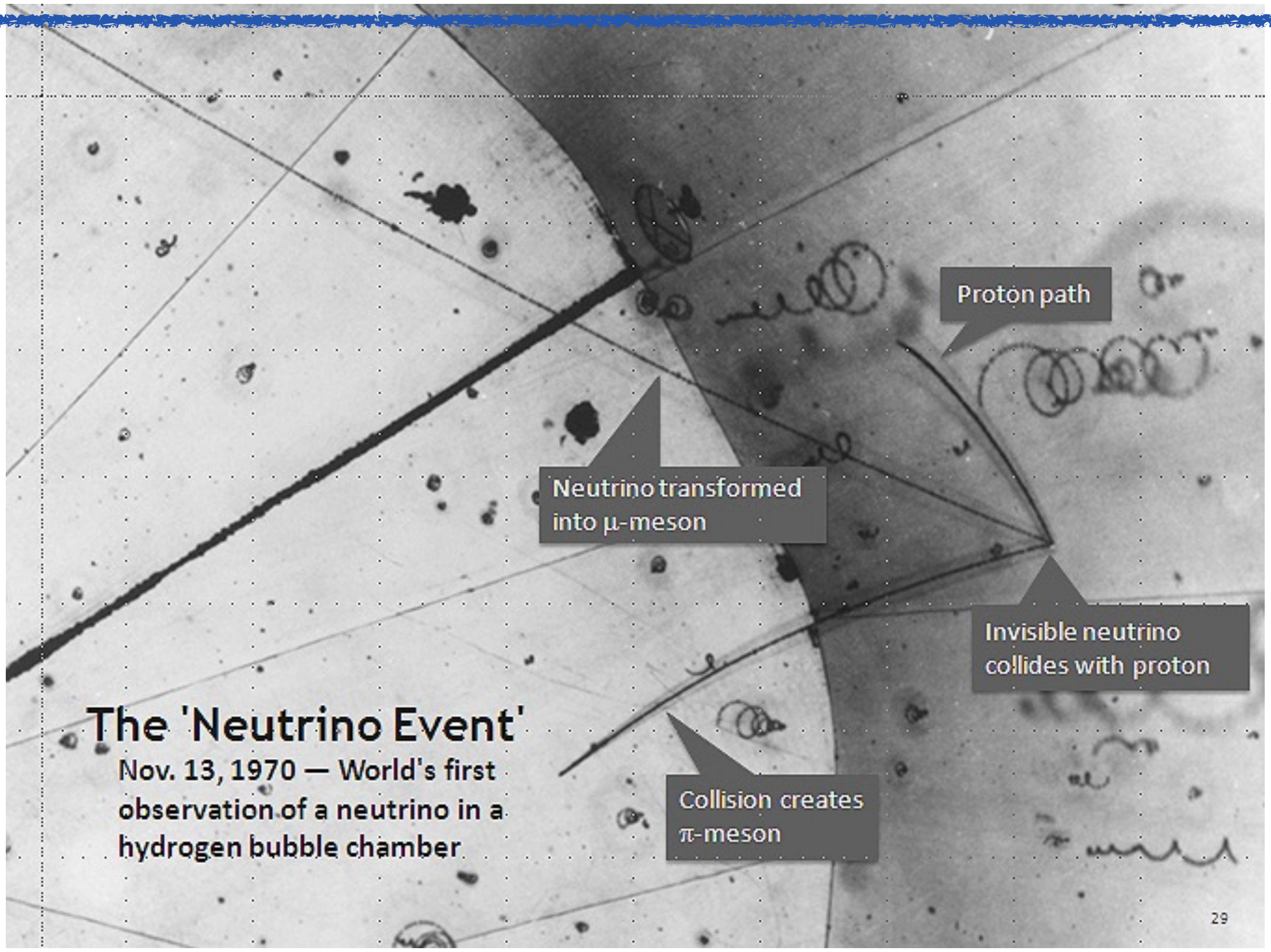
- Event reconstruction (monolithic detector)
- Strong activity in ML algorithms
  - **Scaling of technology**
- Understanding the detector

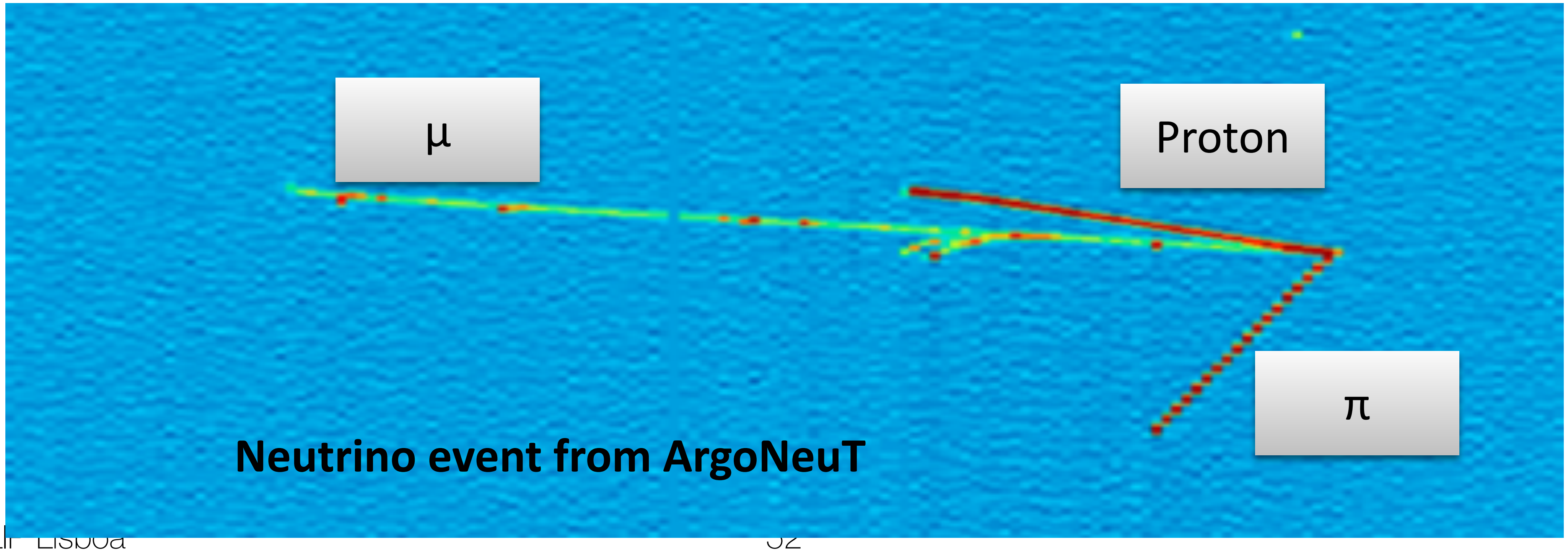


ν



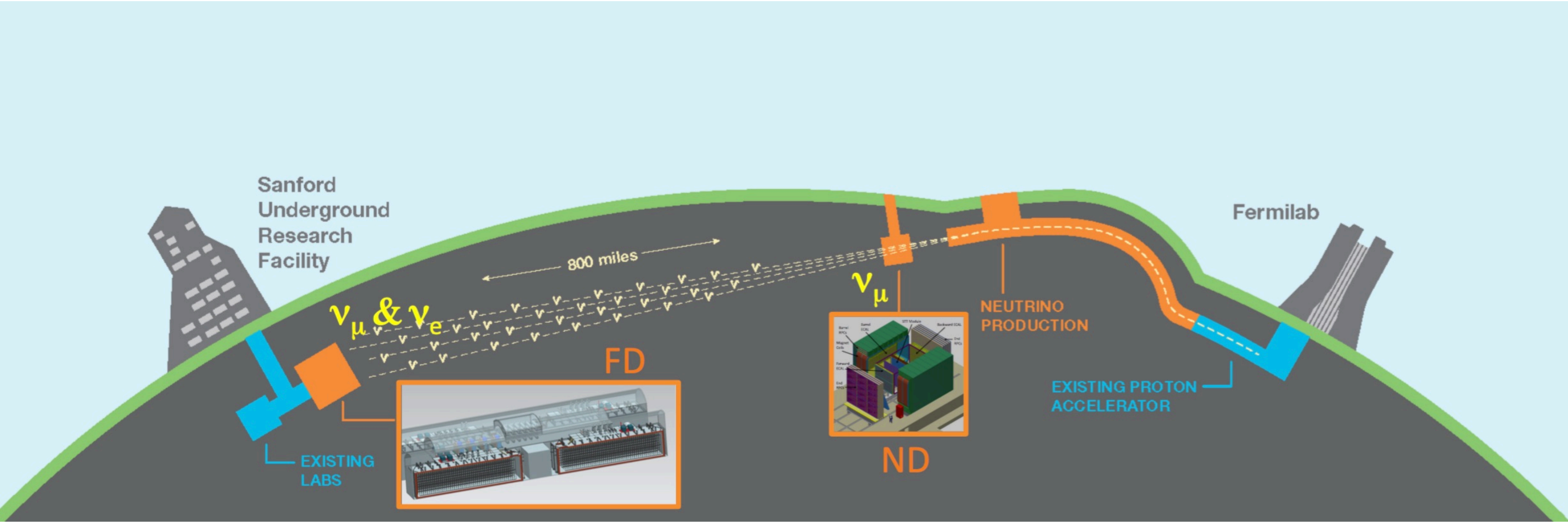
A Neutrino Event





Long Baseline Oscillations

Measure a neutrino beam at long distance…

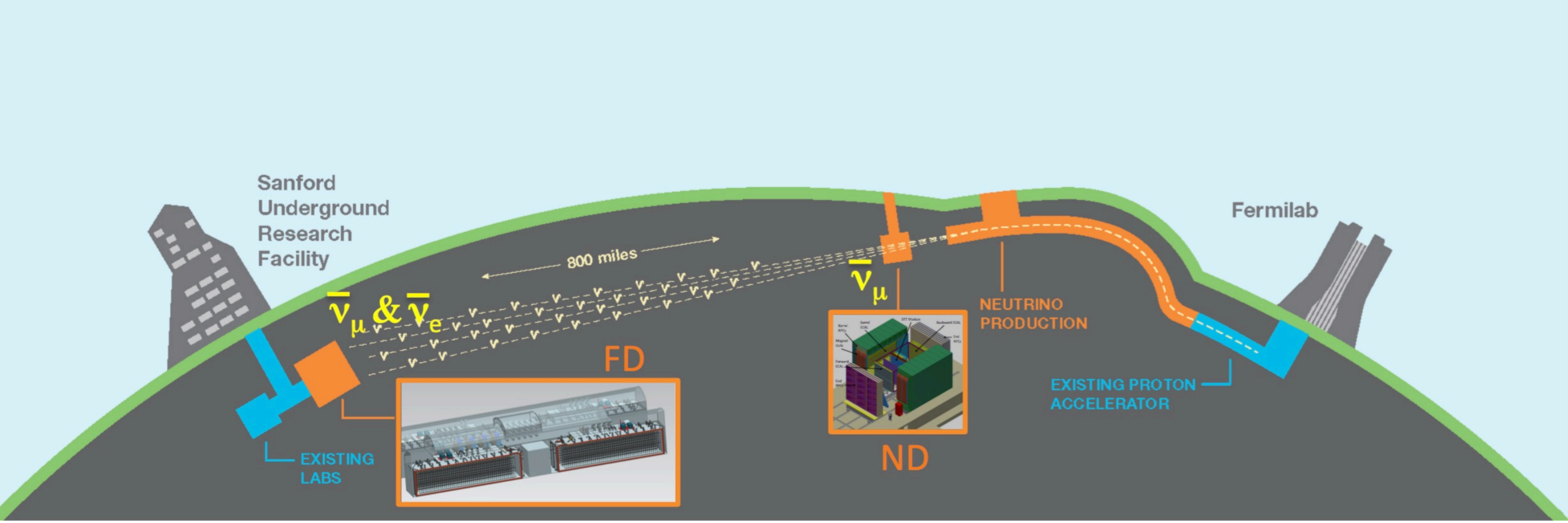


★ **Measure neutrino spectra at 1300 km in a wide band beam**

- Near detector at Fermilab: measurement of ν_μ unoscillated beam
- Far detector at SURF: measure oscillated ν_μ and ν_e

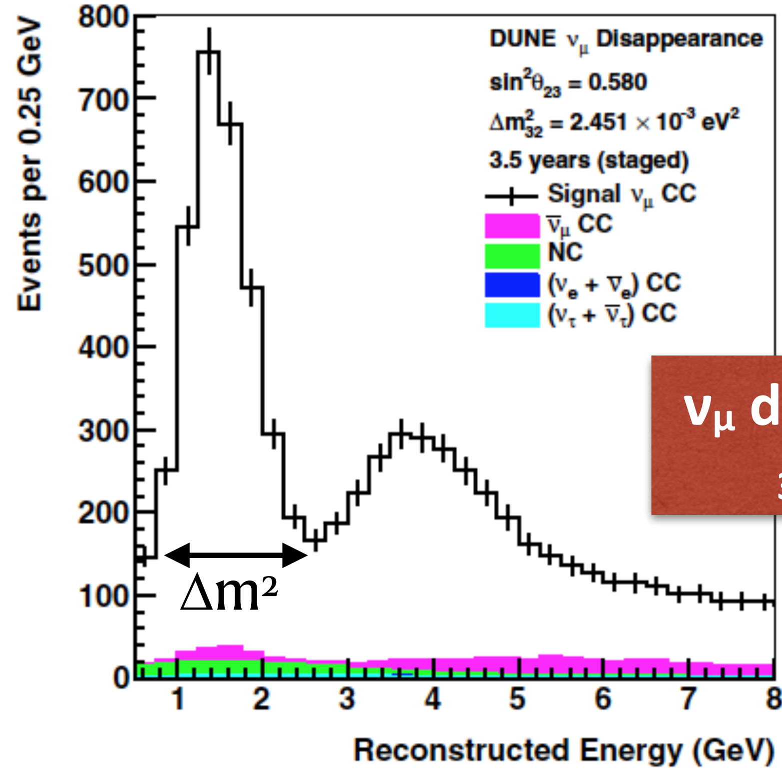
Long Baseline Oscillations

...and then repeat for antineutrinos

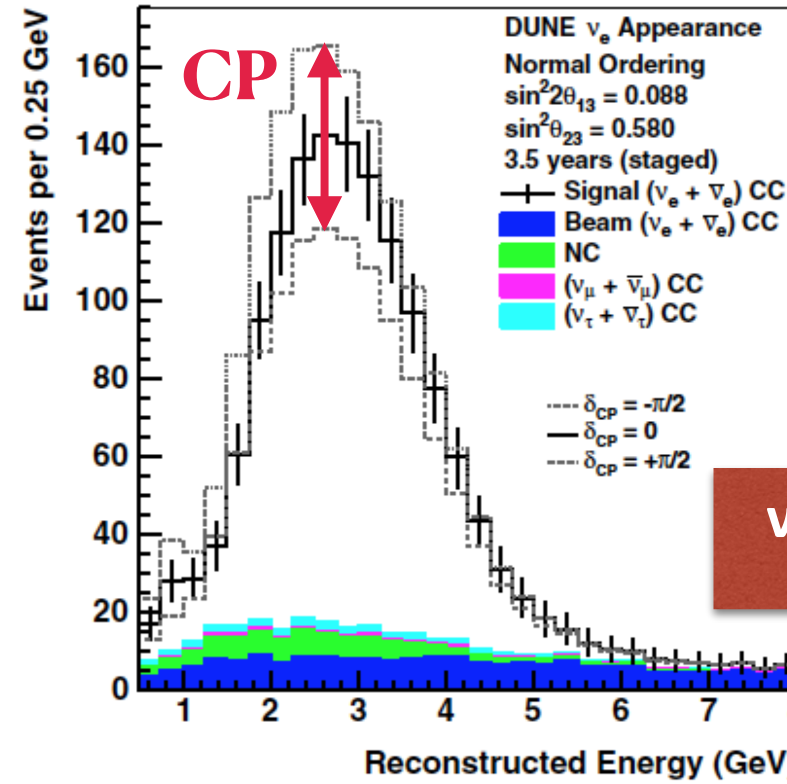


- ★ **Measure antineutrino spectra at 1300 km in a wide band beam**
  - Compare oscillations of neutrinos and antineutrinos
  - Direct probe of CP violation in the neutrino sector

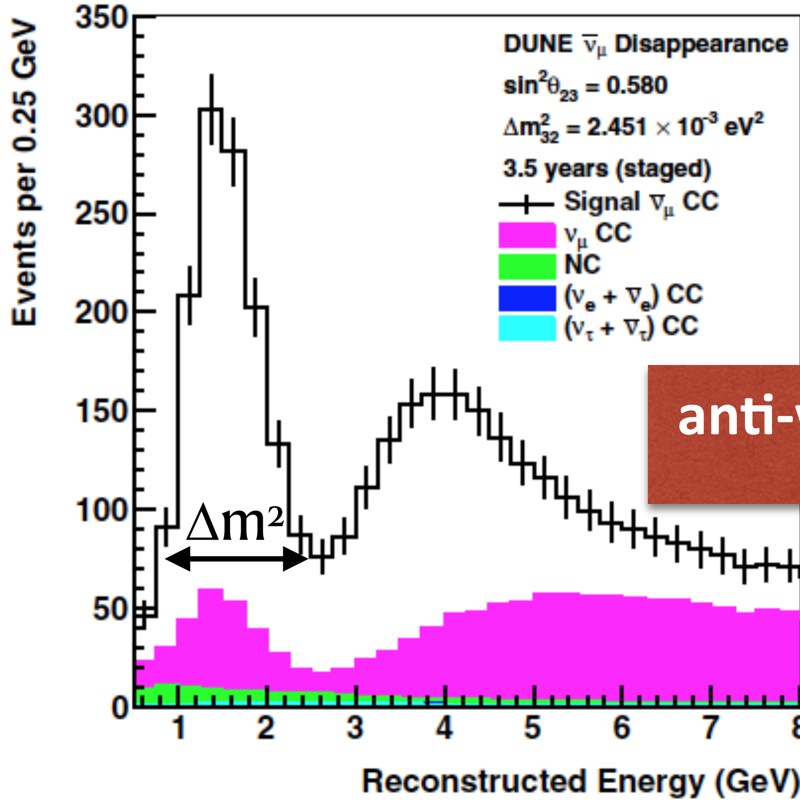
Event's type



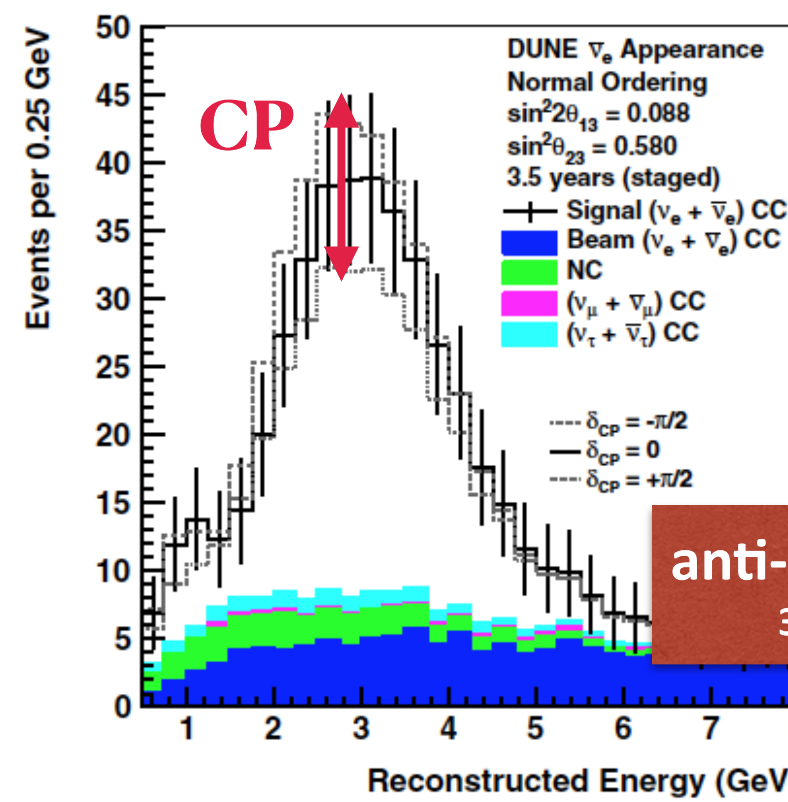
ν_μ disappearance
3.5 yrs running



ν_e appearance
3.5 yrs running



anti-ν_μ disappearance
3.5 yrs running



anti-ν_e appearance
3.5 yrs running

Summary

Neutrinos

- ★ They oscillate (and we know how)
- ★ They are massive (but we don't know how much)
- ★ Are neutrinos their own antiparticles?
- ★ What is the absolute mass scale?
- ★ What is the CP violation phase?
- ★ What is the mass hierarchy?
- ★ A whole zoo of experiments are trying to address these questions
- ★ A rich field of opportunities is in place

INFO

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The presenter Valentina Lozza is funded by FCT

Back up Slides

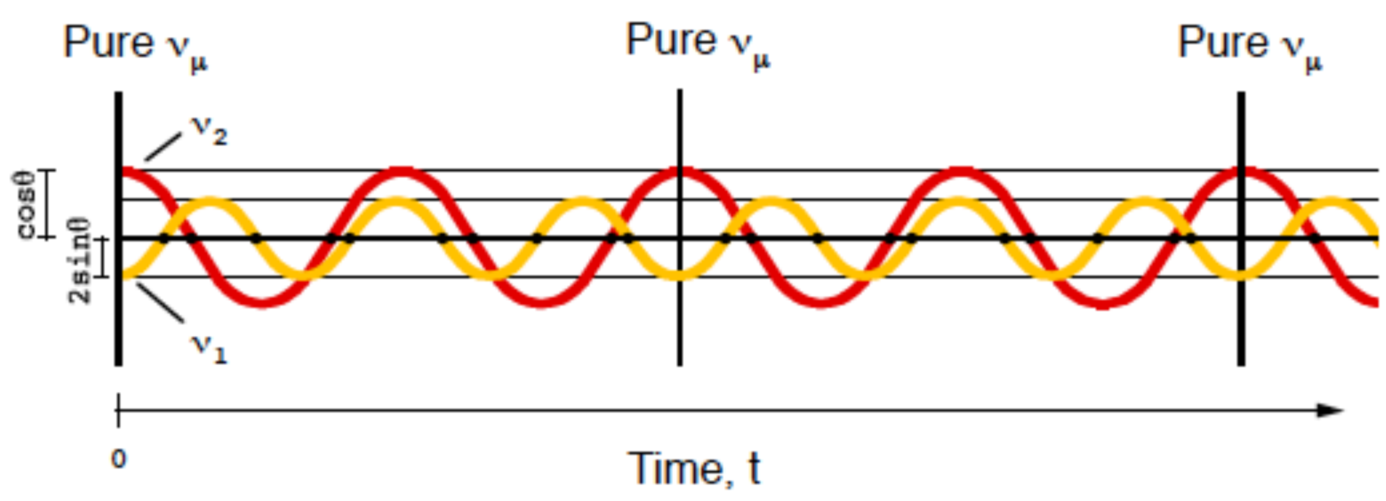
Parametrize the Oscillations: 2ν case

★ Oscillations are parametrized by 2 masses (m_1, m_2), 1 angle (θ)

Flavour eigenstate **Mass eigenstate**

$$\begin{bmatrix}\nu_e \\ \nu_\mu\end{bmatrix} = \begin{bmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix}\nu_1 \\ \nu_2\end{bmatrix}$$

The flavour composition changes with time, because the mass states have slightly different velocities



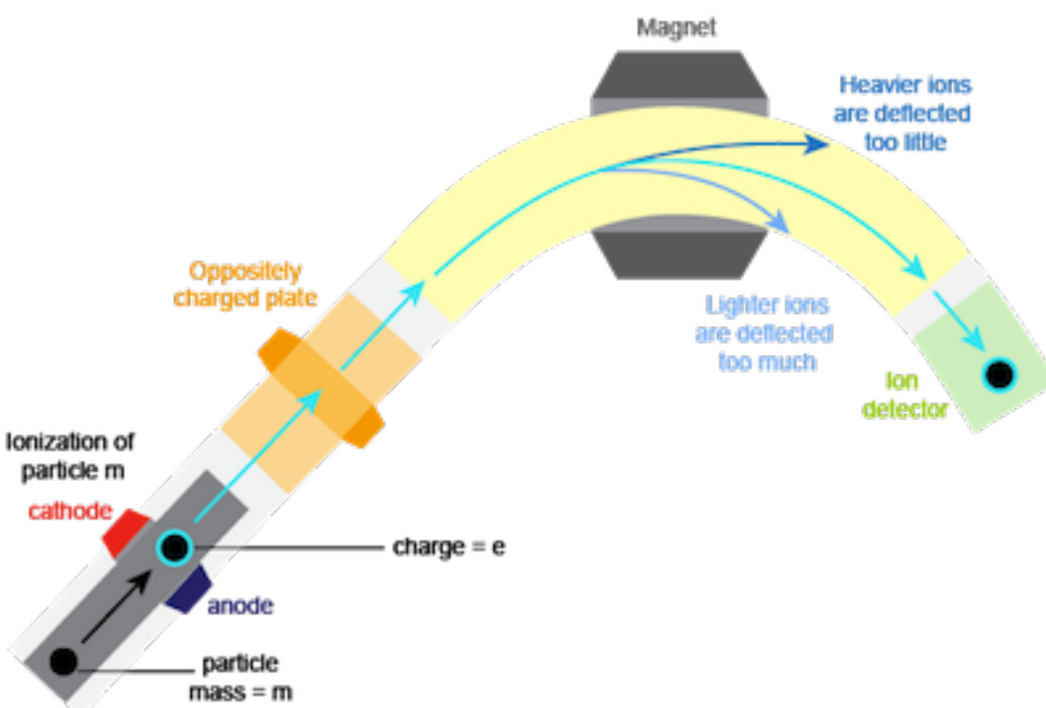
The probability of an electron neutrino to be detected in the same flavour depends on the mass difference and the distance source-detector

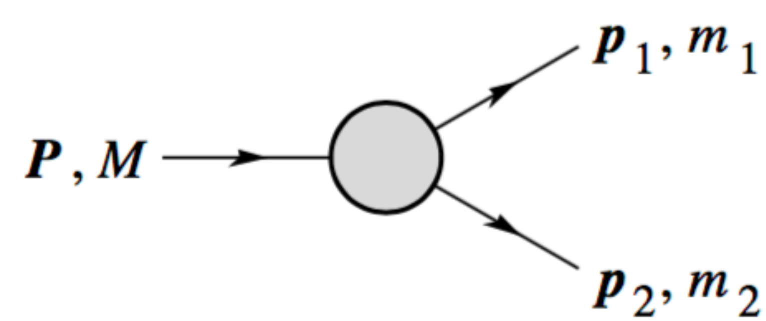
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\boxed{\Delta m^2}\,\boxed{L}}{4E}\right)$$

Can we measure the mass directly

★ Yes, but it is not easy!

- Measure their track curvature in a magnetic field **doesn't work**
    - neutrinos are neutral, not affected by EM fields
- Measure energy and momentum of daughter particles ?
    - Neutrinos are the lightest particles, **don't decay in others**
- Use quantum interference to probe neutrino mass ✓





$$M^2=(E_1+E_2)^2-(\mathbf{p_1}+\mathbf{p_2})^2$$

Where we operate