

LIP Summer Internship 2026

Neutrinos: a short overview

Valentina Lozza

FCT Fundação
para a Ciência
e a Tecnologia



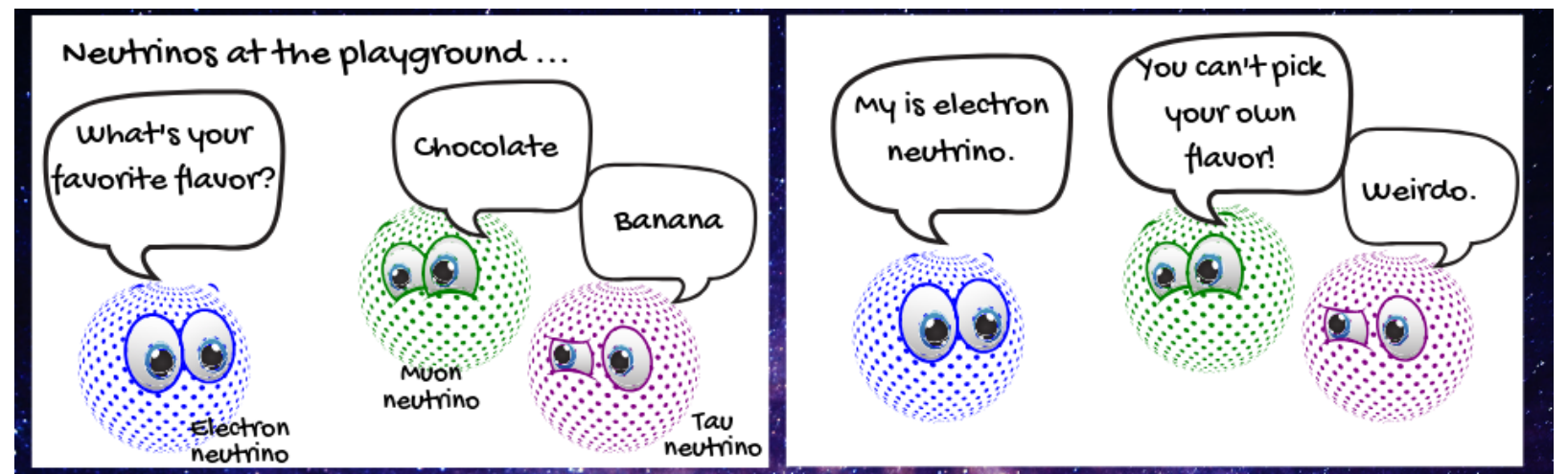
LIP Lisbon

09 July 2026, Lisbon

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 today

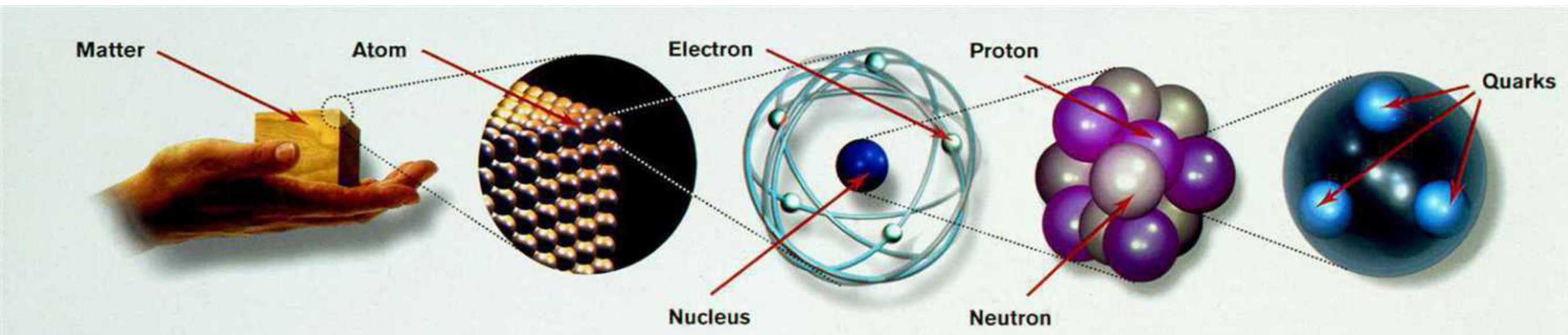


<https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf>

1. NEUTRINOS

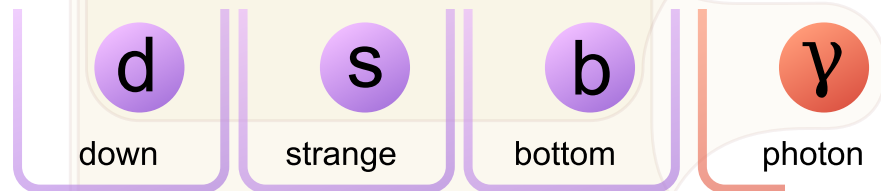
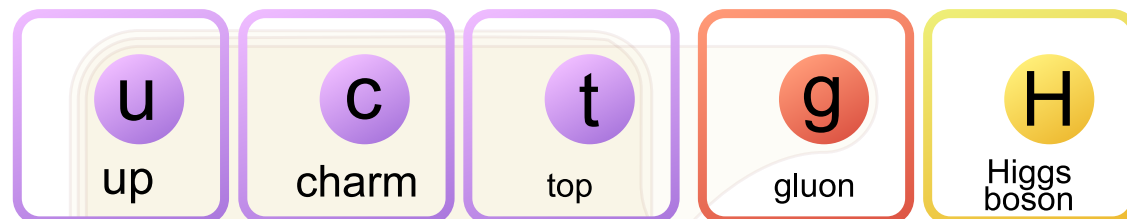


THE SCALE OF THINGS

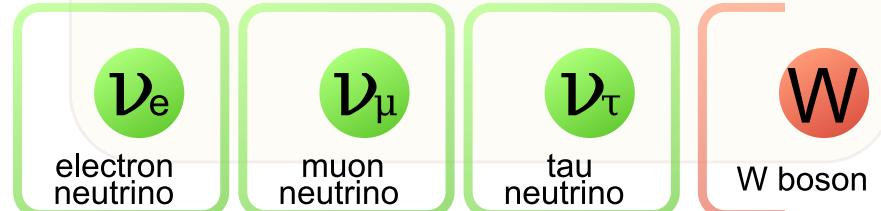
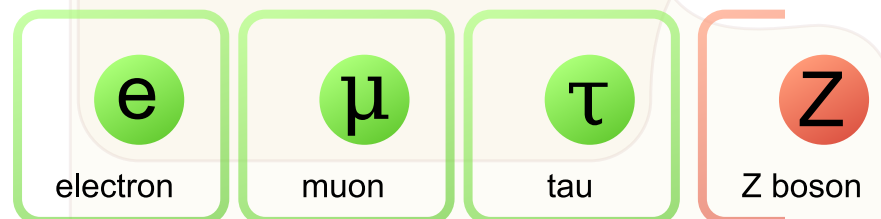


* = elementary particles

QUARKS



LEPTONS



GAUGE BOSONS

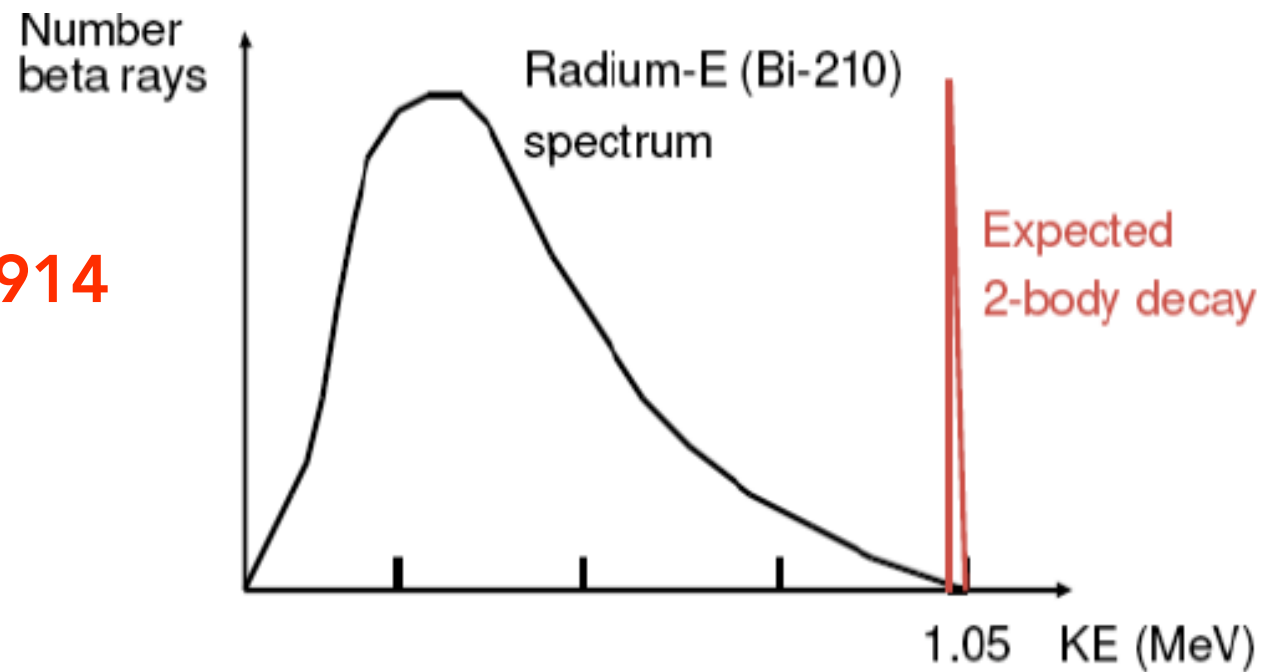
- Atoms
 - electrons*
 - nucleus
 - protons and neutrons
 - quarks u e d *
- photons *

} matter

And the neutrinos? Where they come from?

THE BETA DECAY

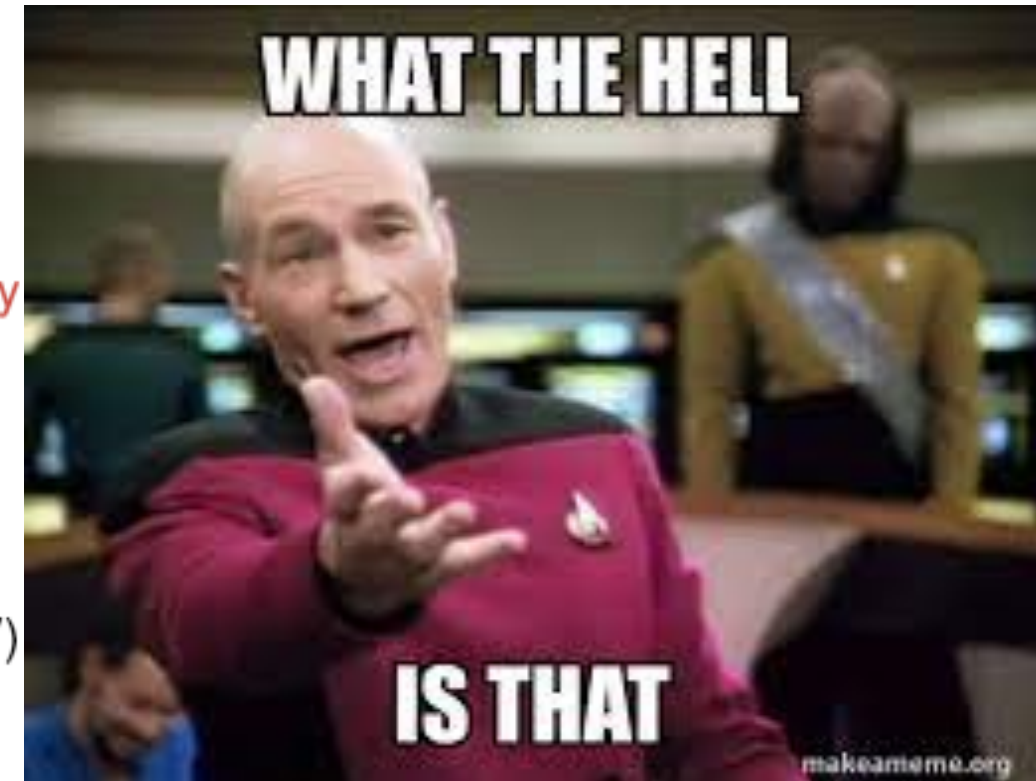
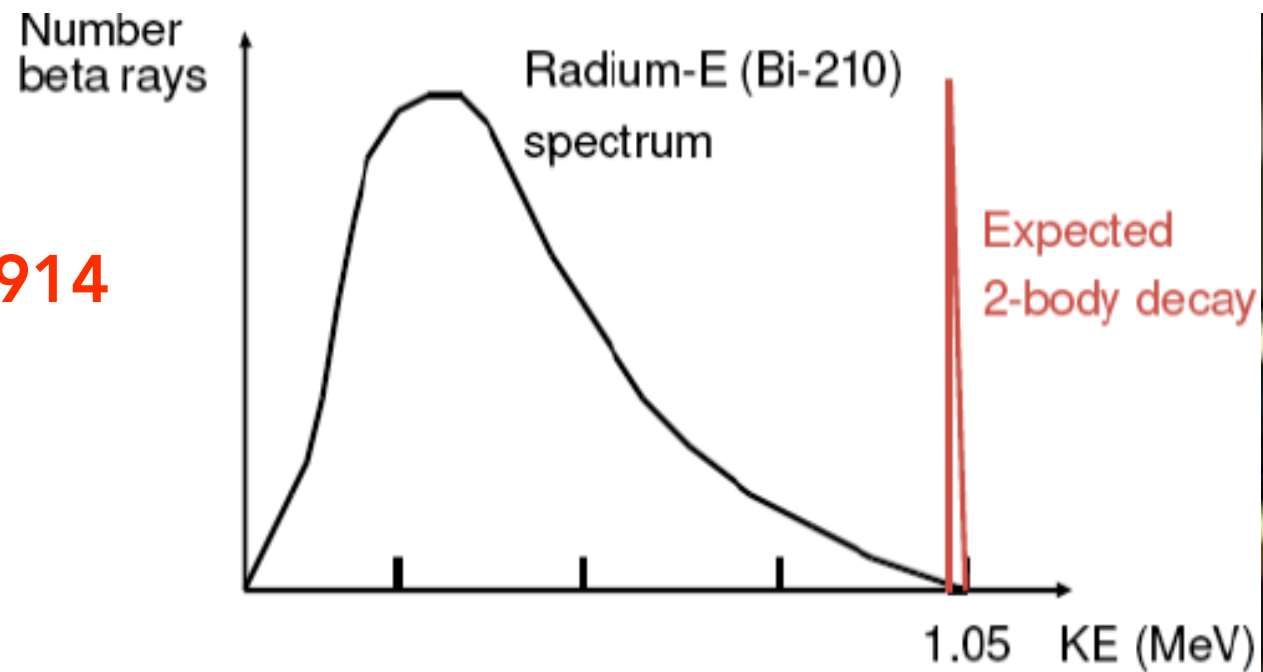
Chadwick, 1914



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

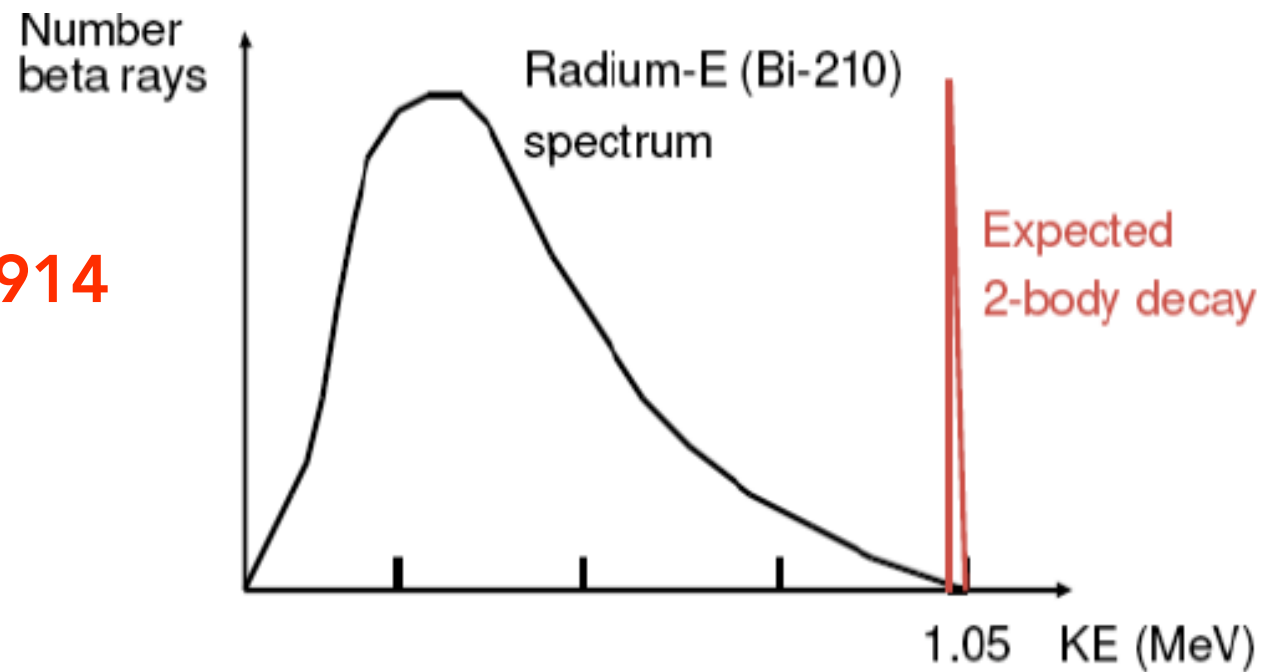
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Chadwick, 1914

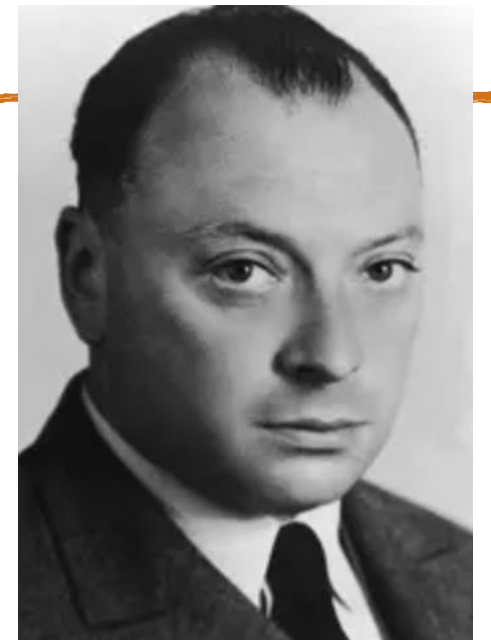


1932: THE IDEA OF NEUTRON-INO

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



1930: THE IDEA OF NEUTRON-INO

Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen

considering the
'false' statistics of N-14 and Li-6 nuclei as well as the
continuous β -spectrum, I have hit upon a desperate remedy
to save the "exchange theorem" of statistics and the energy
theorem. Namely [there is] 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 additionally differ from light quan-
ta in that they do not travel with the velocity of light:
The mass of the neutron must be of the same order of magni-
tude as the electron mass and, in any case, not larger than
0.01 proton mass. The continuous β -spectrum would then become
understandable by the assumption that in β decay a neutron
is emitted together with the electron, in such a way that
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Now, the next question is what forces act upon the neu-
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the bearer of these lines), that the neutron at rest is a
magnetic dipole of a certain moment μ . Experiment probably
required that the ionizing effect of such a neutron should
not be larger than that of a γ ray, and thus μ should prob-
ably not be larger than $e \cdot 10^{-13}$ cm.

But I don't feel secure enough to publish anything
about this idea, so I first turn confidently to you, dear
radioactives, with a question as to the situation concerning
experimental proof of such a neutron, if it has something
like about 10 times the penetrating capacity of a γ ray.

I admit that my remedy may appear to have a small a
priori probability because neutrons, if they exist, would
probably have long ago been seen. However, only those who
wager can win, and the seriousness of the situation of the
continuous β -spectrum can be made clear by the saying of my
honored predecessor in office, Mr. Debye, who told me a short
while ago in Brussels, "One does best not to think about
that at all, like the new taxes." Thus one should earnestly
discuss every way of salvation.—So, dear radioactives, put
it to test and set it right.—Unfortunately, I cannot
personally appear in Tübingen, since I am indispensable here
on account of a ball taking place in Zürich in the night
from 6 to 7 of December.—With many greetings to you, also to
Mr. Back, your devoted servant,

W. Pauli

Key points:

"False" statistics of the decays"

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The continuous beta spectrum would become understandable

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He named the particle NEUTRON

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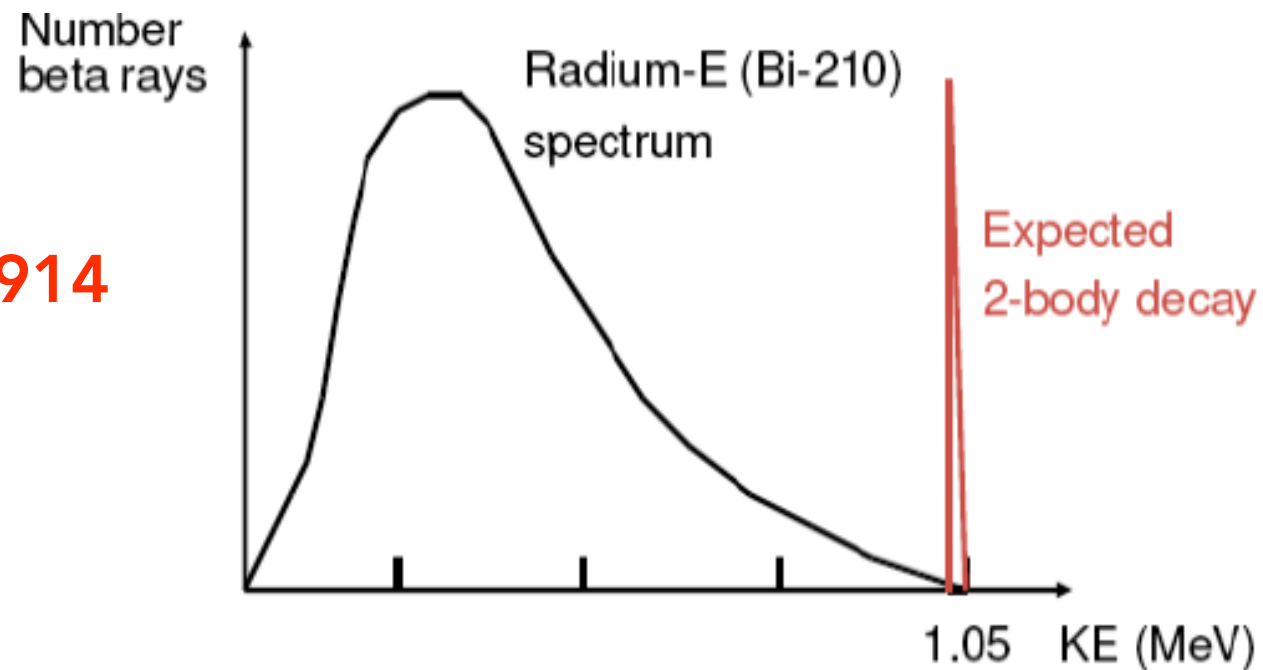
The continuous beta spectrum would become understandable

Doubt about the ability to detect it

The "actual" neutron was discovered in 1932

1934: THE NEUTRINO

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)

1934: A TERRIBLE MISTAKE



If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned—and it is not necessary to assume interaction in order to explain the function of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

Physical Laboratory,
University,
Manchester.
Feb. 20.

H. BETHE.
R. PEIERLS.

1946: A LIGHT AT THE END OF THE TUNNEL

Bruno Pontecorvo

Inverse β Process

(National Research Council of Canada, Division of Atomic Energy. Chalk River, 1946, Report PD-205.
This version was kindly provided by Prof. W.F.Davidson).

Inverse β Process

It is clear that inverse β transformations produced by neutrinos are processes of this type and certainly can be produced by neutrinos, if neutrinos exist at all. They consist of the concomitant absorption of a neutrino and emission of a β particle (positron or negatron) by a nucleus. It is obvious, on thermodynamical grounds, that such process must have an extreme low yield since their inverse, the β process, is so unlikely. It has been currently stated in the literature that an inverse process produced by neutrinos cannot be observed, due to the low yield. As it will be shown below, this statement seems to be too drastic. The object of this note is to show that the experimental observation of an inverse β process produced by neutrinos is not out of the question with the modern experimental facilities, and to suggest a method which might make an experimental observation feasible.

EVERYTHING WENT WELL

- In 1952-1959 two experiments finally detected neutrinos!

Detection of the Free Neutrino*

F. REINES AND C. L. COWAN, JR.

*Los Alamos Scientific Laboratory, University of California,
Los Alamos, New Mexico*

(Received July 9, 1953; revised manuscript received September 14, 1953)

AN experiment¹ has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_{-} + p \rightarrow n + \beta^{+}, \quad (1)$$

EVERYTHING WENT WELL

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Project Poltergeist



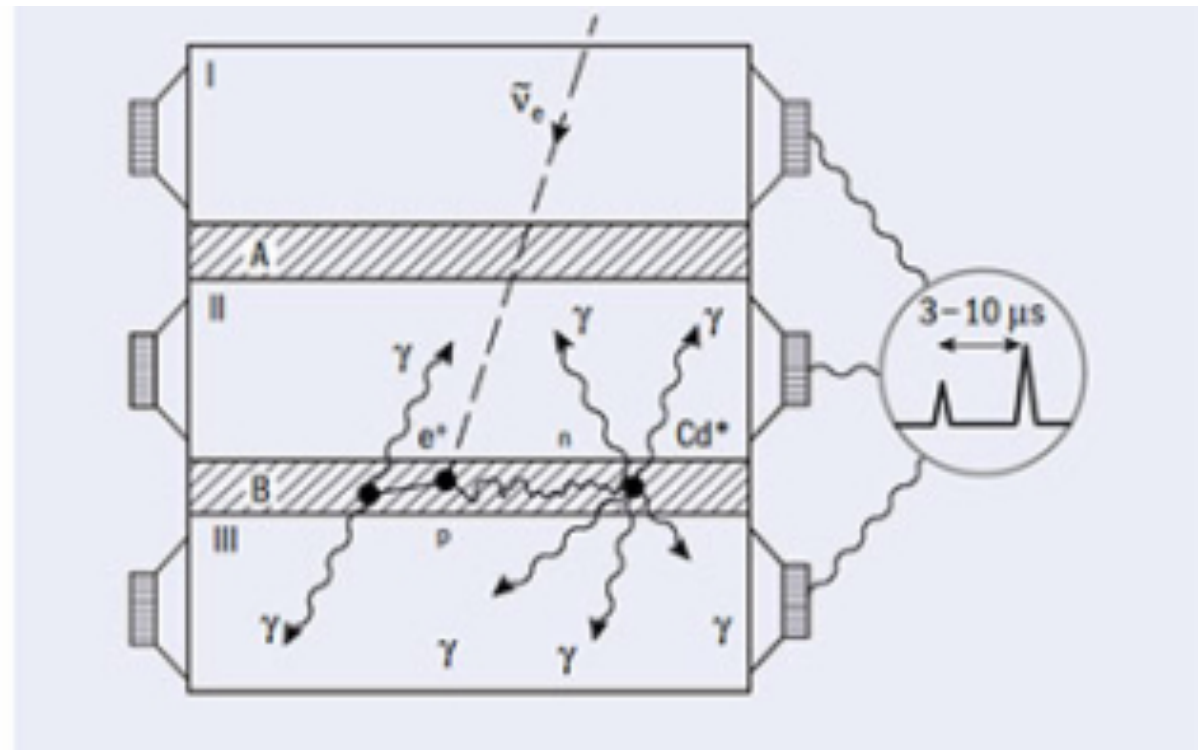
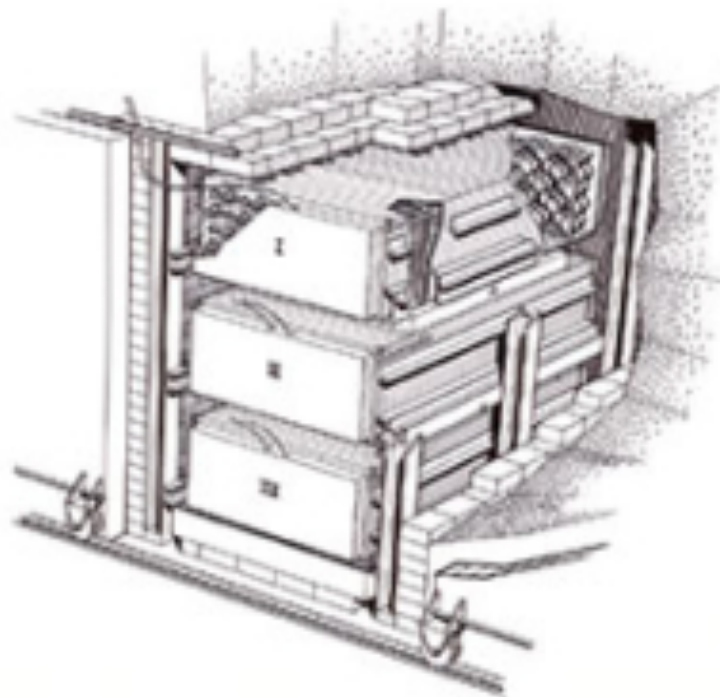
Herr Auge



Nobel prize Reines 1995

MAKE IT BIGGER

- 1956: The Savannah River Detector



- Clearly detect the coincidence between a positron (2 gammas of 511 keV) and a neutron capture in water+Cd (several high energy gammas) few μs apart.

MAKE IT BIGGER

- 1956: The Savannah River Detector

446

NATURE

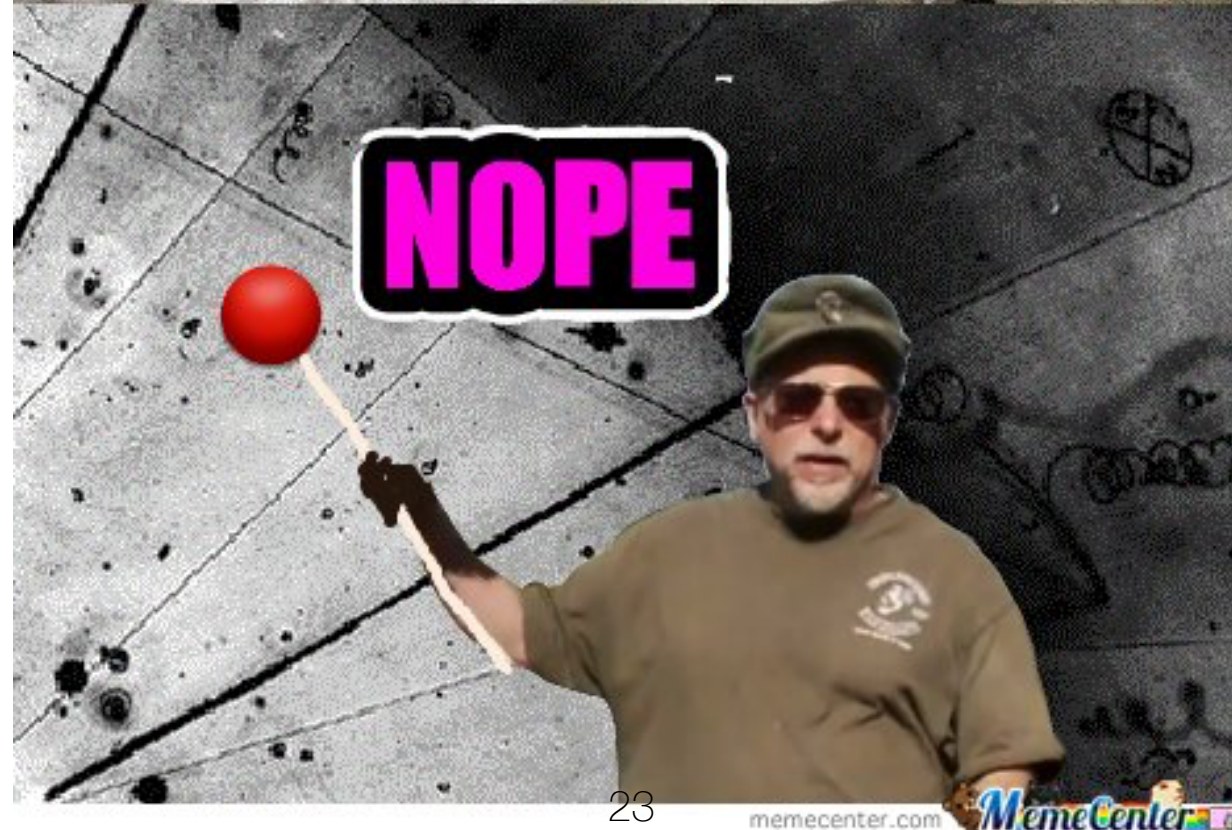
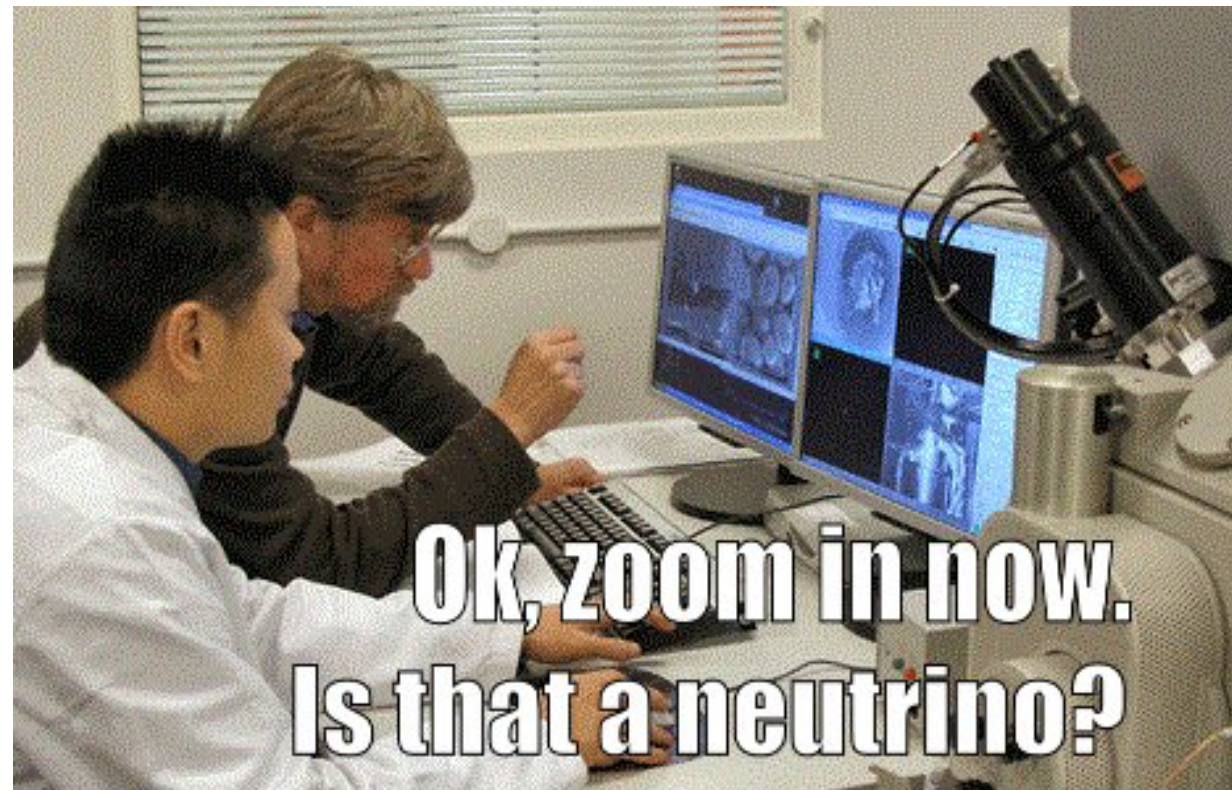
September 1, 1956 VOL. 178

THE NEUTRINO

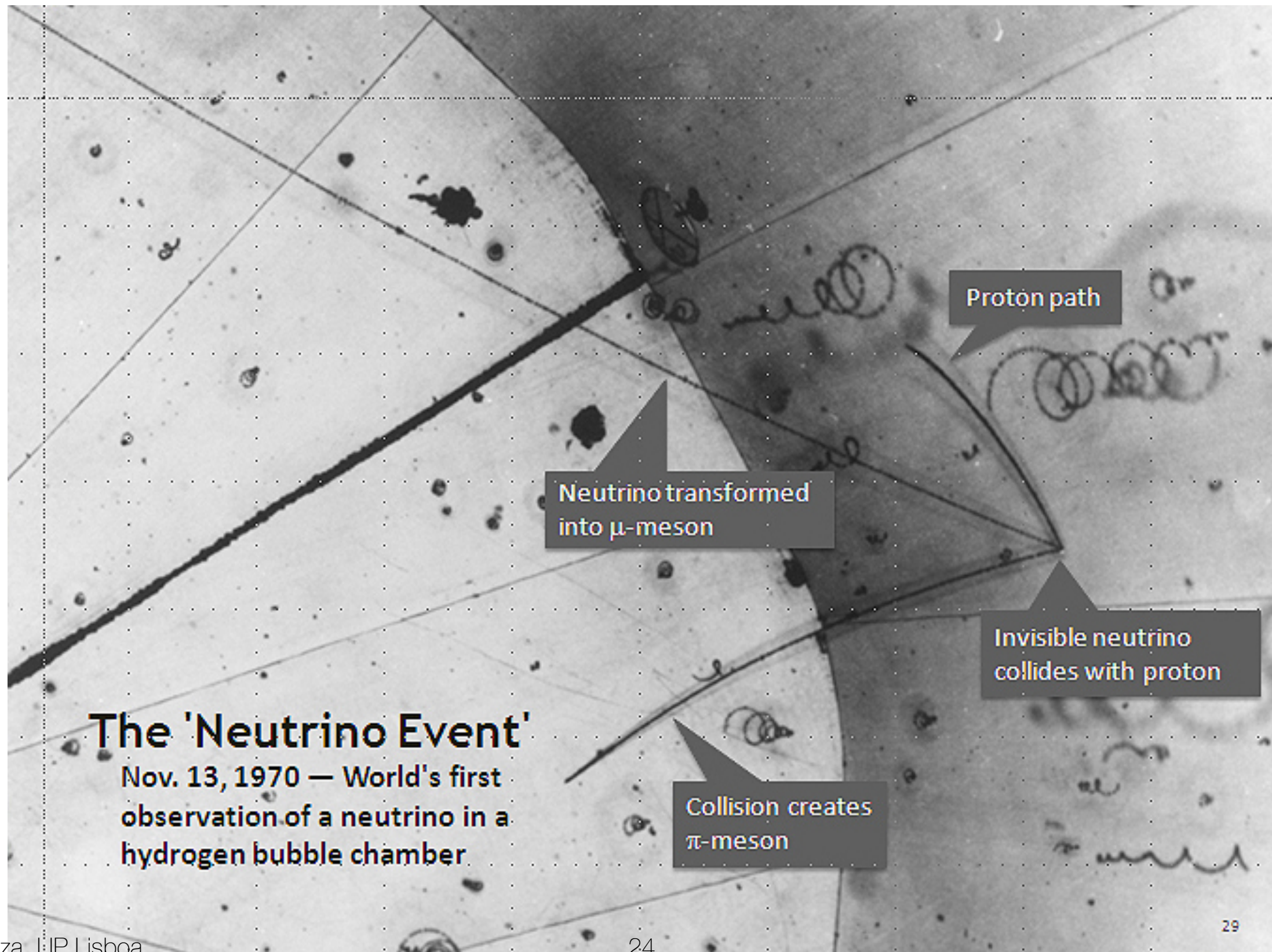
By DR. FREDERICK REINES and DR. CLYDE L. COWAN, jun.
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

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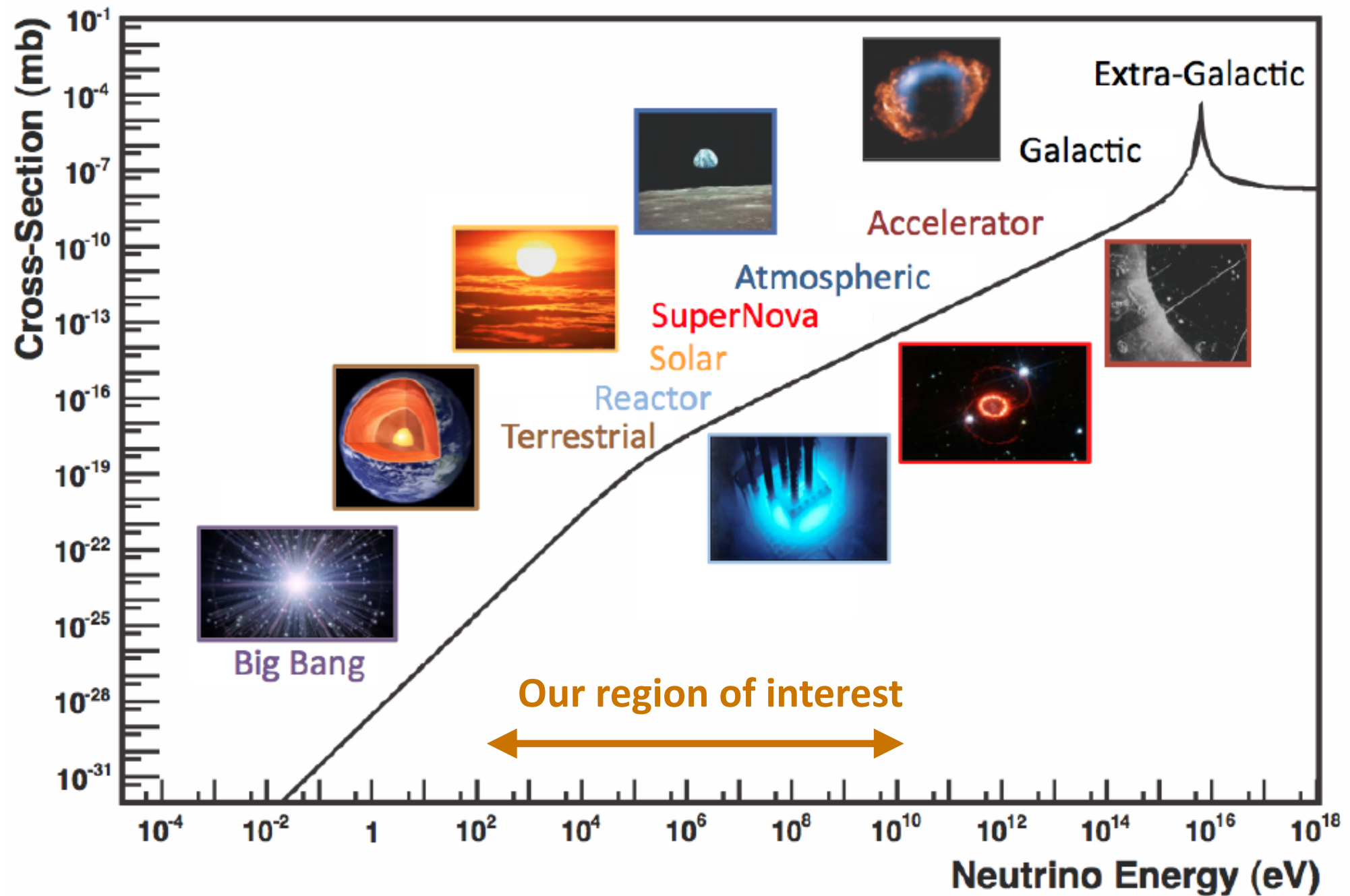
THE DETECTION



UNTIL



WHERE NEUTRINOS COME FROM?

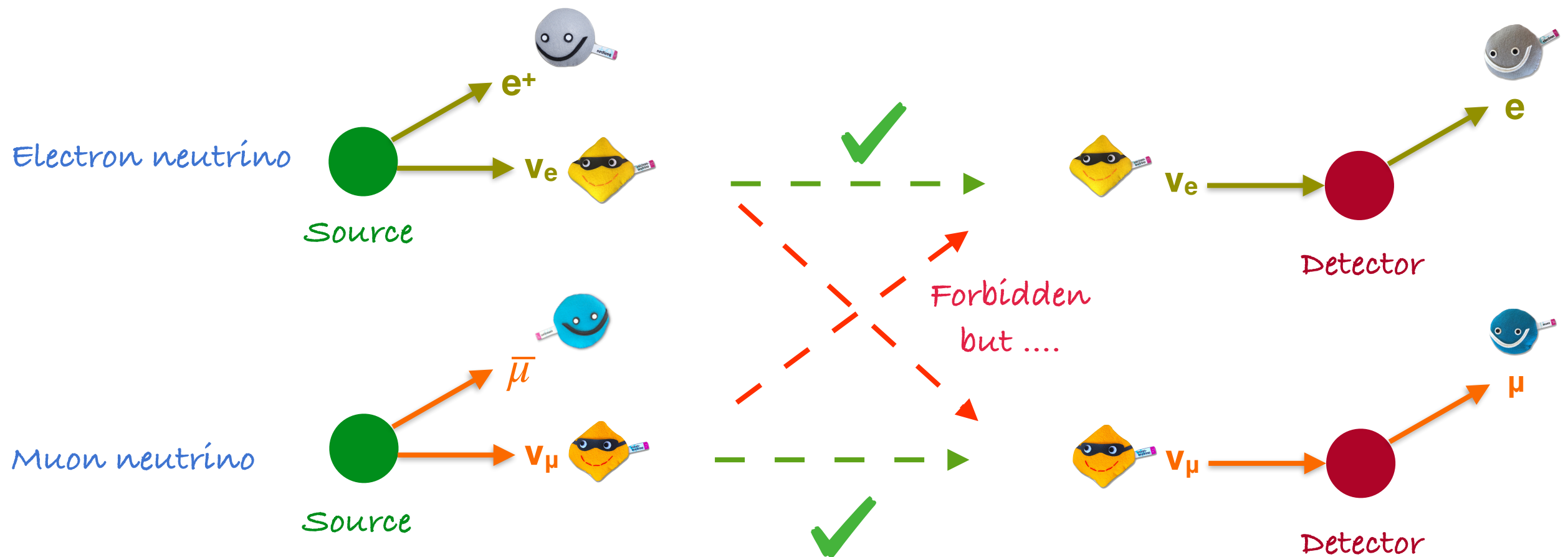
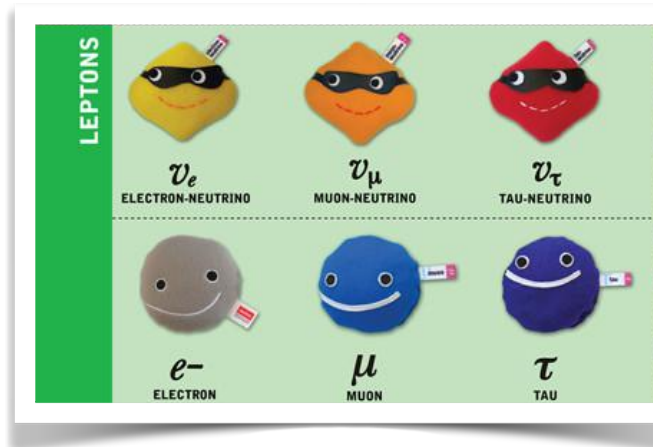


22 orders of magnitude!!!!

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

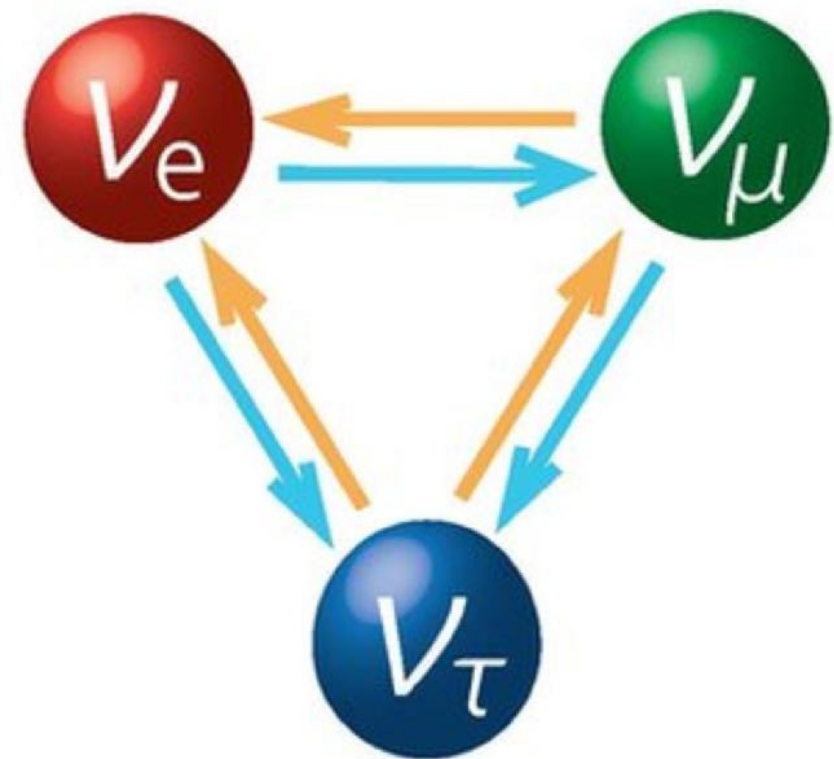
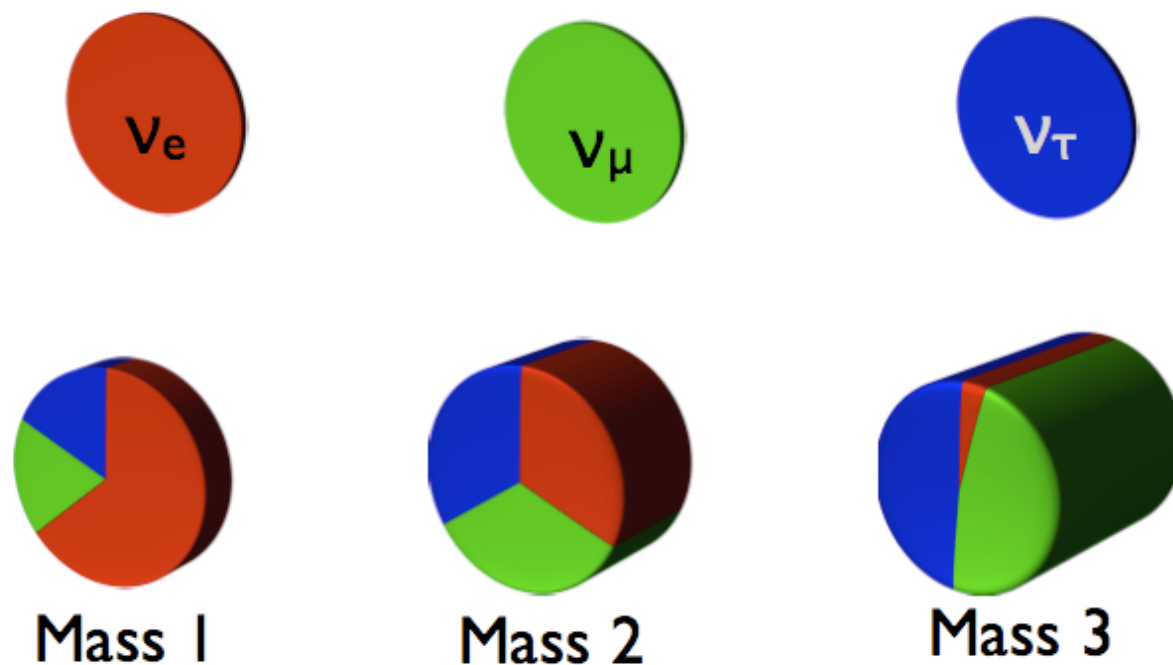


NEUTRINO STATES

CC Charged Current Reaction	$\nu_e + d \rightarrow p + p + e^-$
NC Neutral Current Reaction	$\nu_x + d \rightarrow \nu_x + p + n$
ES Elastic Scattering Reaction	$\nu_x + e^- \rightarrow \nu_x + e^-$

★ What we know about neutrinos:

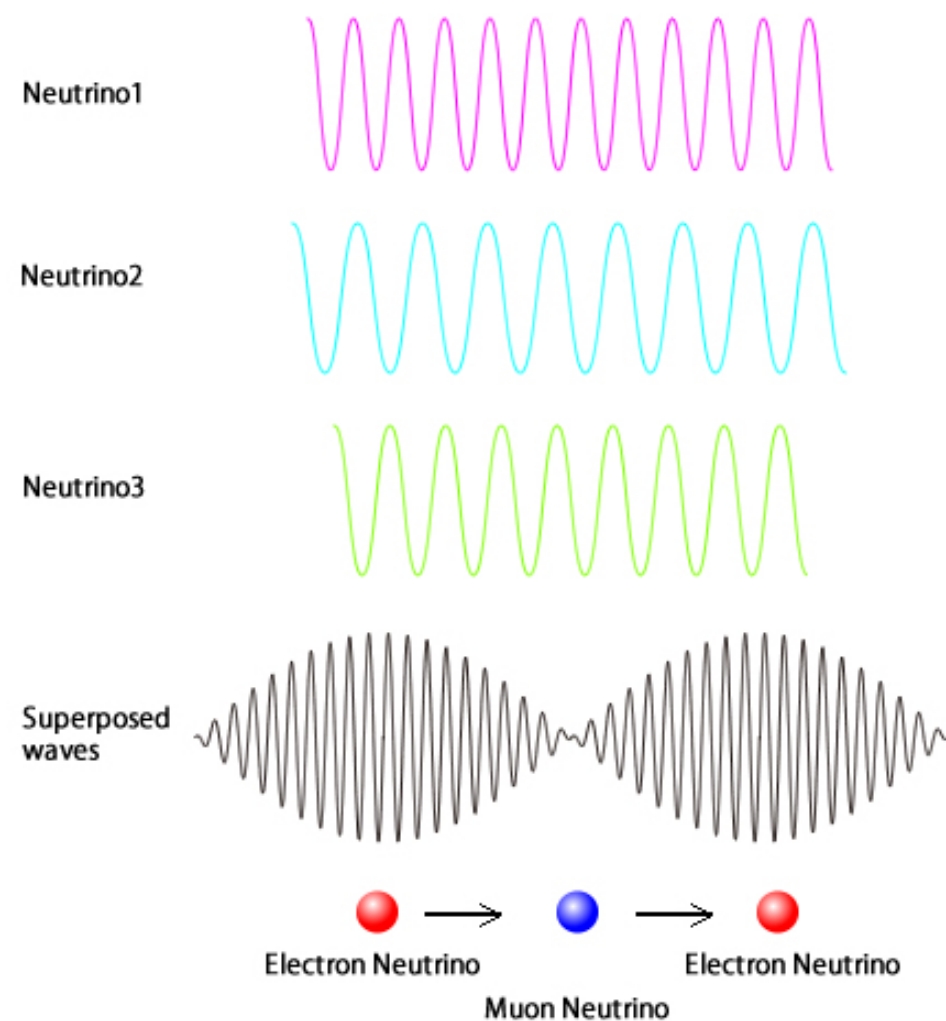
- No charge - do not participate in electromagnetism
 - Weak interactions
- They have a tiny but different from 0 mass
 - Mass eigenstates is different from the flavour eigenstates
 - Neutrino can change their flavour once they have been produced



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 ($\theta_{12}, \theta_{13}, \theta_{23}$) and an extra complex phase $e^{i\delta}$

$e^{i\delta}$
Responsible for the CP-violation part

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

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**

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

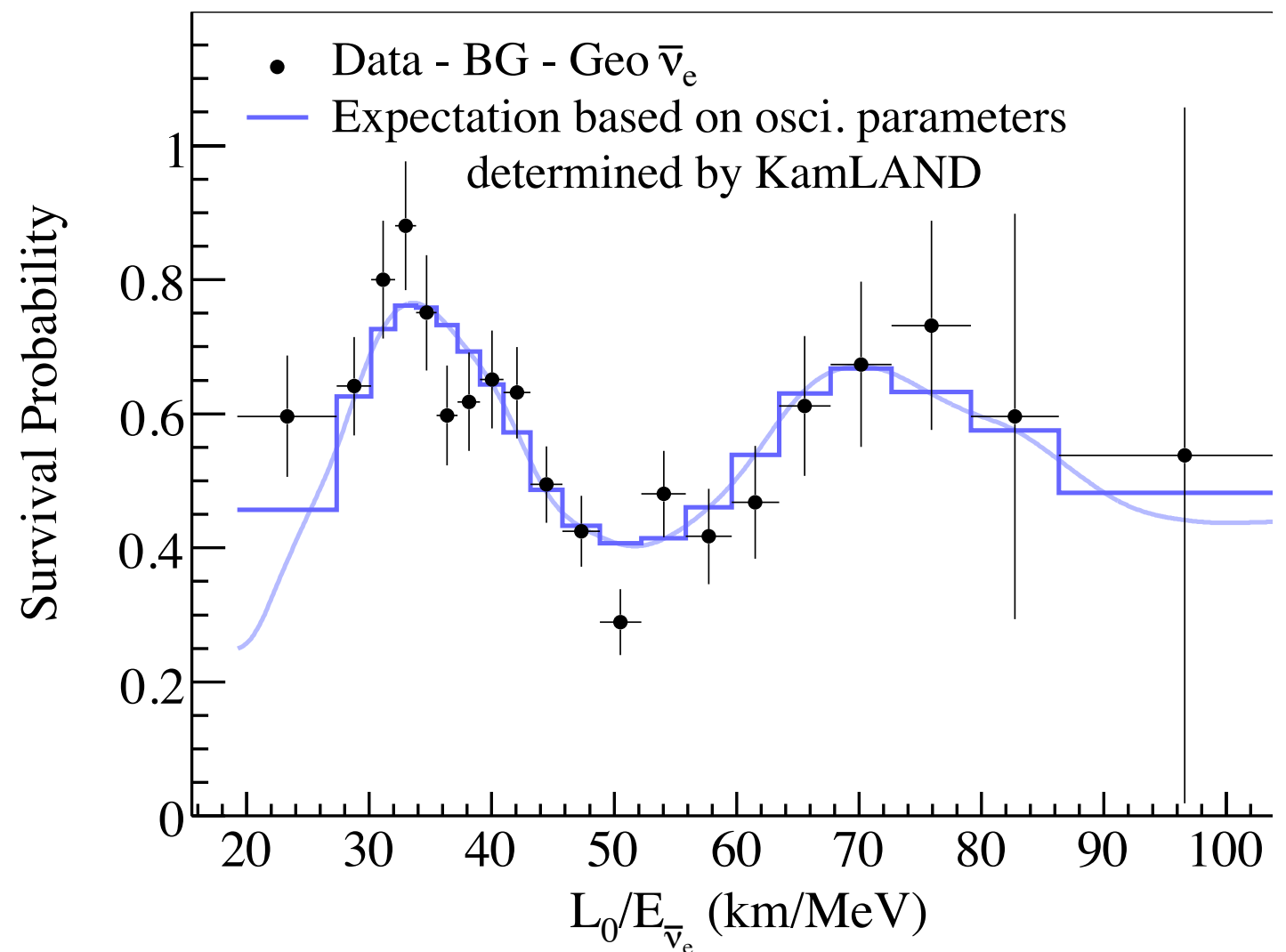
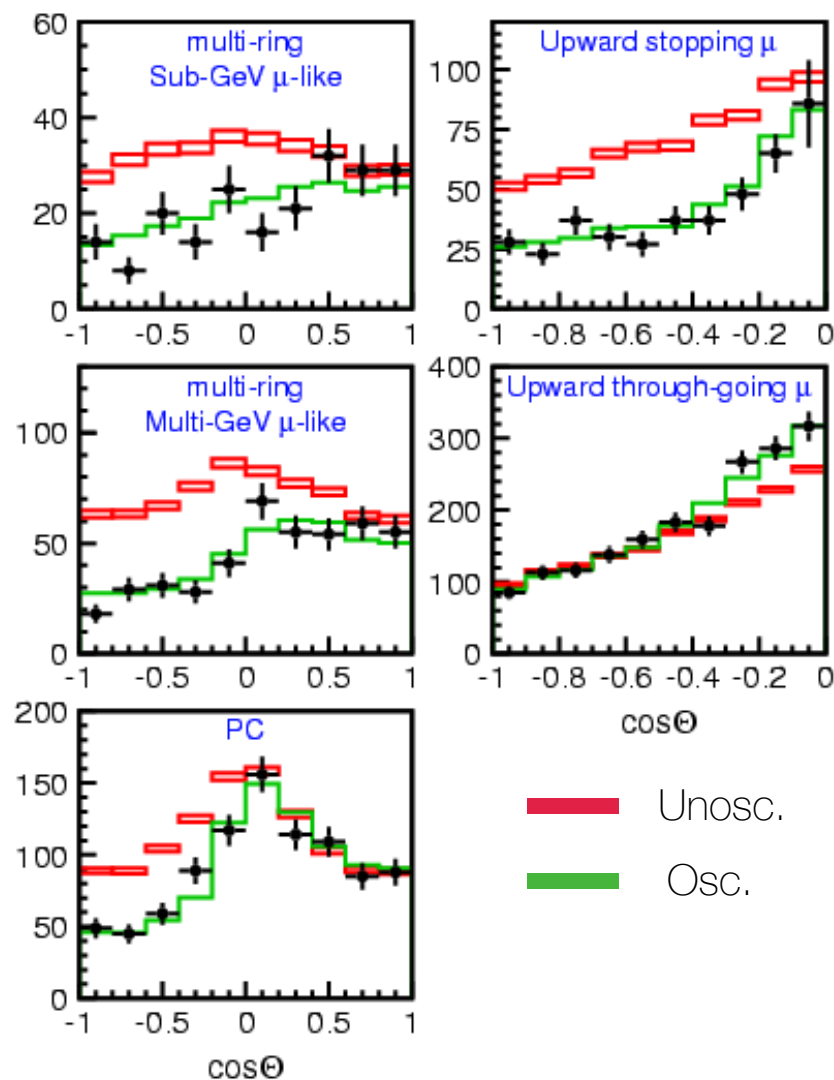
Simplified 2-neutrinos case

MEASURING OSCILLATIONS

Flavour
eigenstate

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

Mass
eigenstate



MASS ORDERING

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

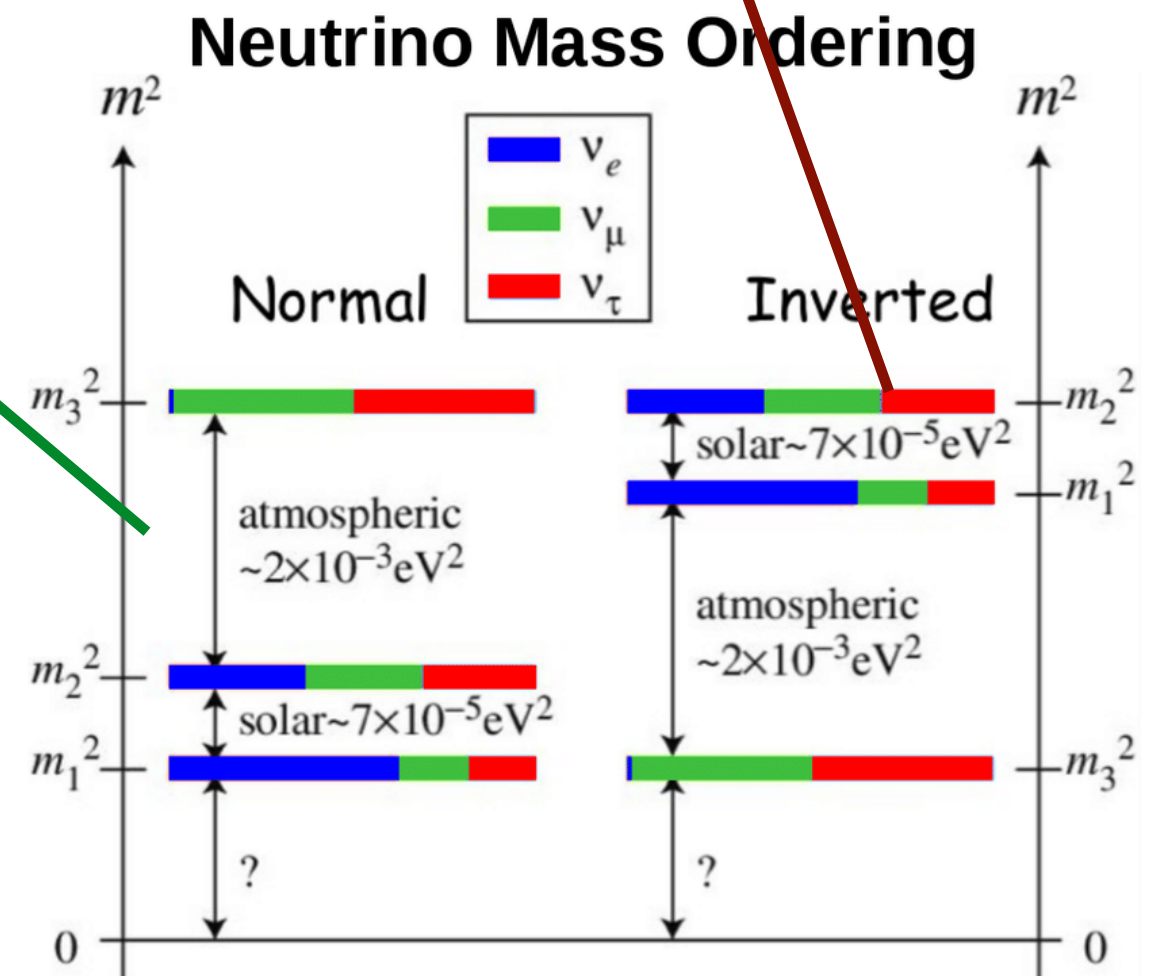
Accelerator and
Atmospheric

SBL reactor

Solar +
LBL reactor

parameter	best fit $\pm 1\sigma$	3σ range	Relative precision at 1σ	
Δm_{21}^2 [10^{-5}eV^2]	$7.50^{+0.22}_{-0.20}$	6.94–8.14	3%	Precision
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (NO)	$2.55^{+0.02}_{-0.03}$	2.47–2.63	1%	SIGN UNKNOWN
$ \Delta m_{31}^2 $ [10^{-3}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		

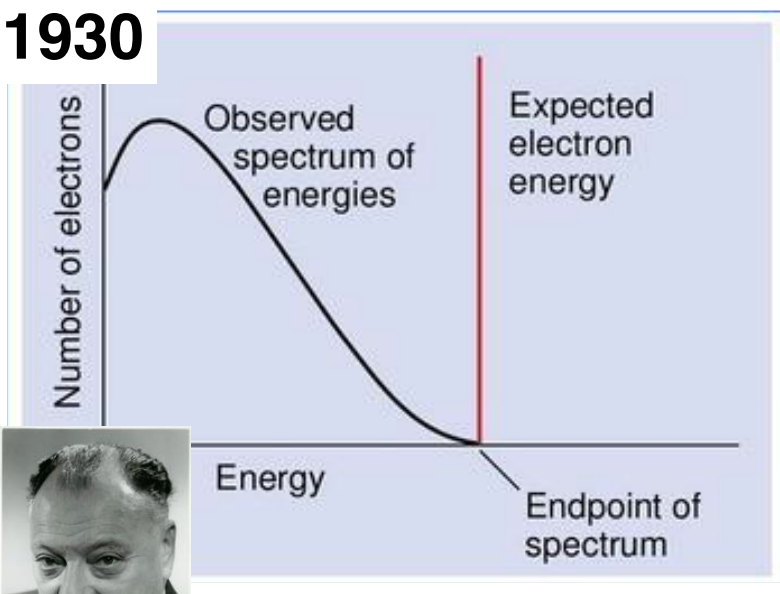
Neutrino measurements and plans - L IMFP/ XV CPAN 2023



NEUTRINO

MEMORY LN

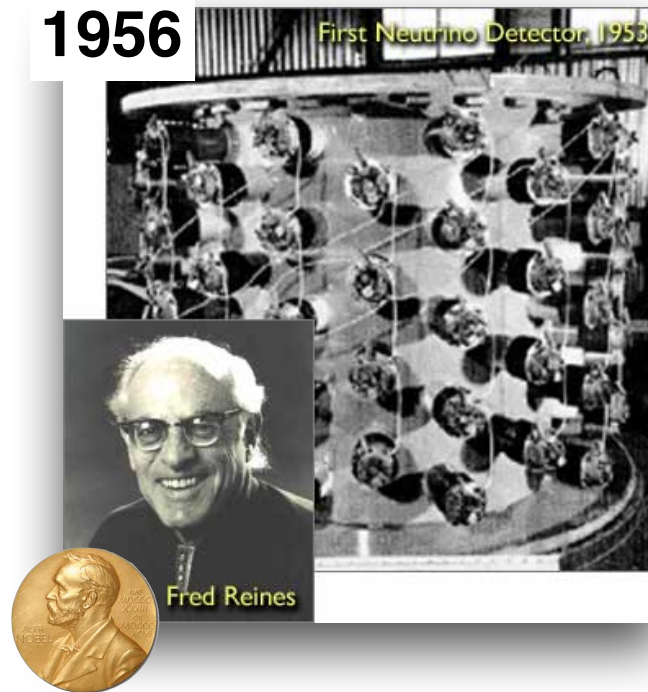
1930



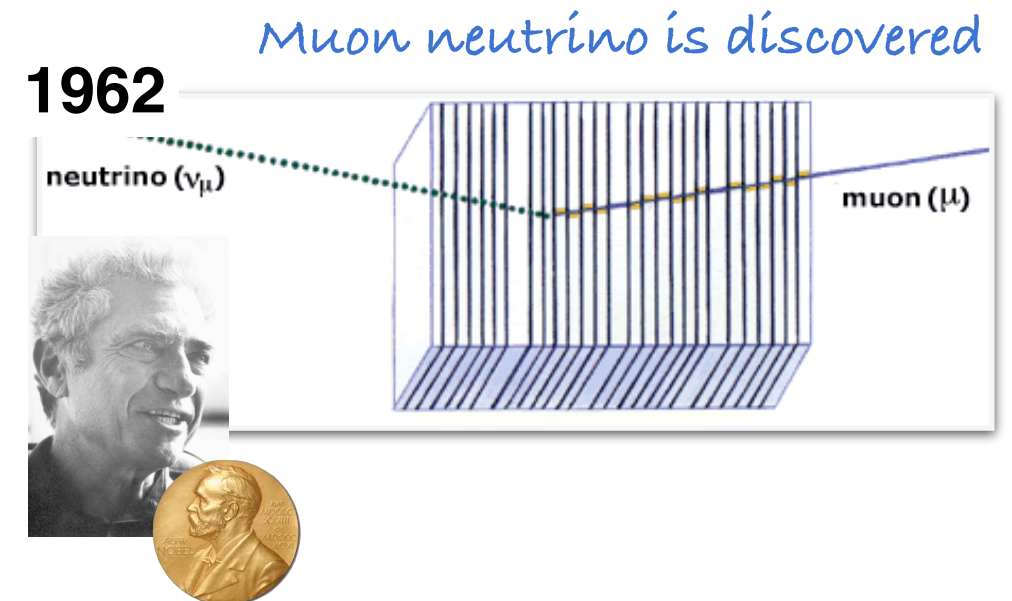
Neutrino is born

First observation of neutrinos

1956



1962



1968



The solar neutrinos problem

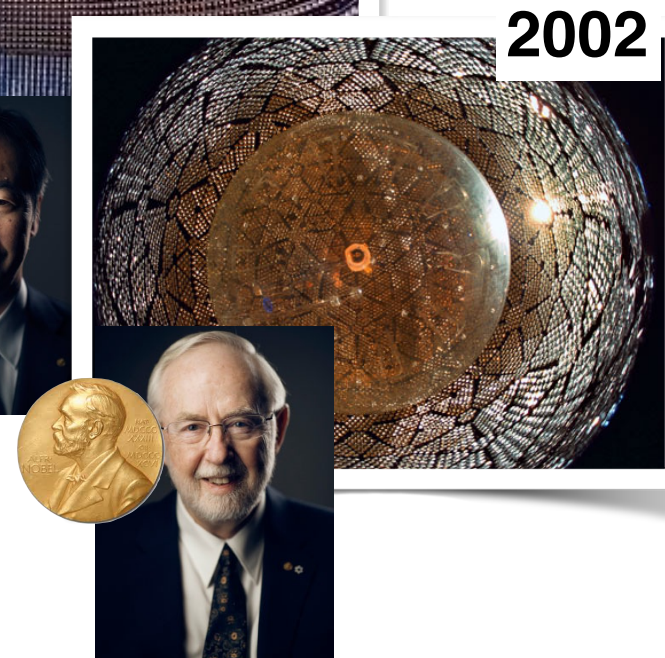
1987



1998



2002



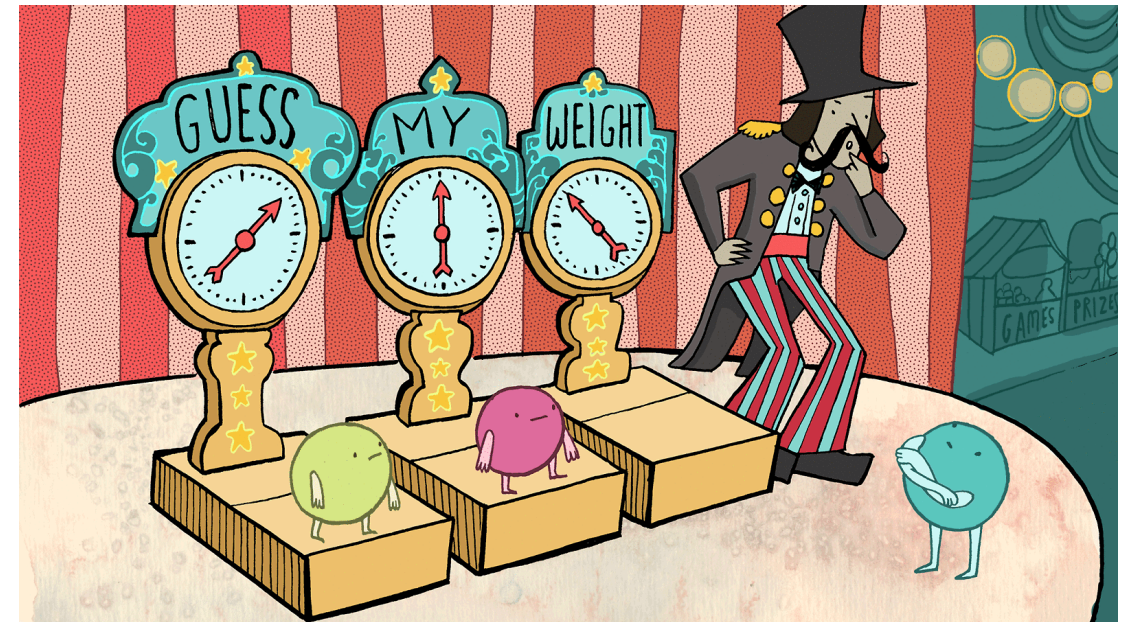
AND NOW?

We know that neutrinos change flavour



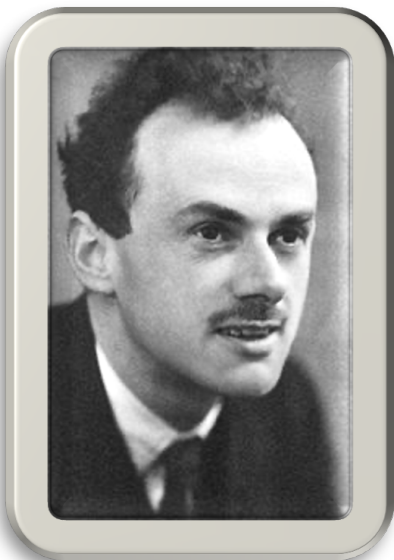
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

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.



2. Detecting neutrinos today

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!!!!!!



★ So how do we study neutrinos?

- We need large detectors



DETECTING NEUTRINOS

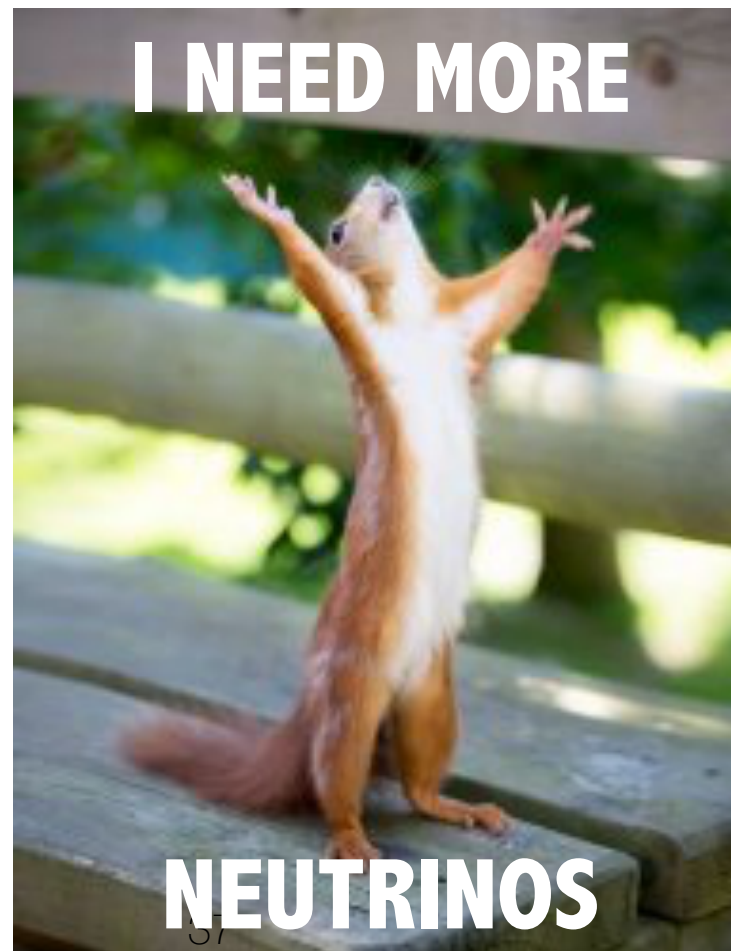
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- And large neutrinos fluxes



DETECTING NEUTRINOS

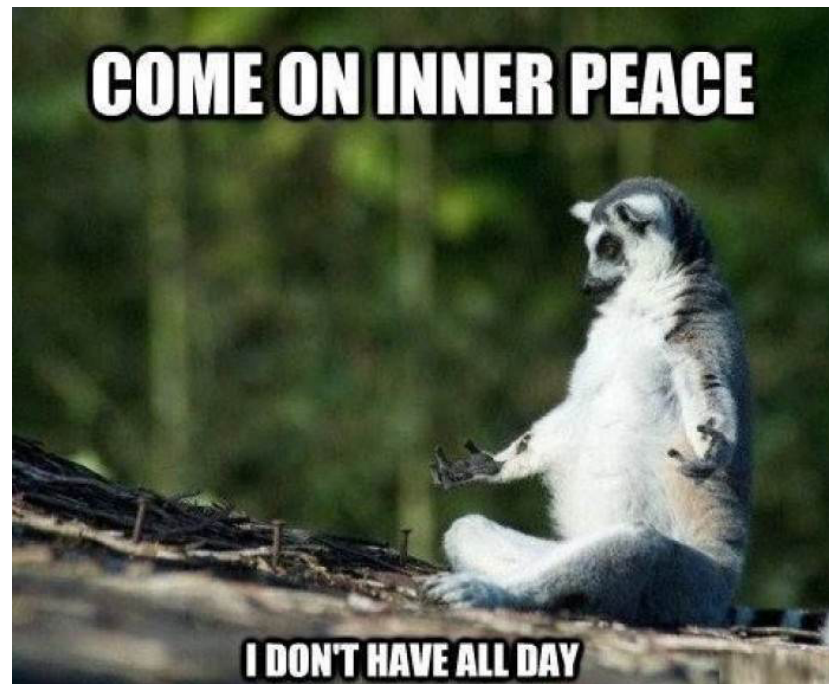
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- A loooooooot of time



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★ So how do we study neutrinos?

- We need large detectors
- And large neutrinos fluxes
- A loooooooot of time
- Reduce as much as possible other sources of contamination (cosmic radiation for example)



2. Detecting neutrinos with large scale experiments, few examples:

SNO+

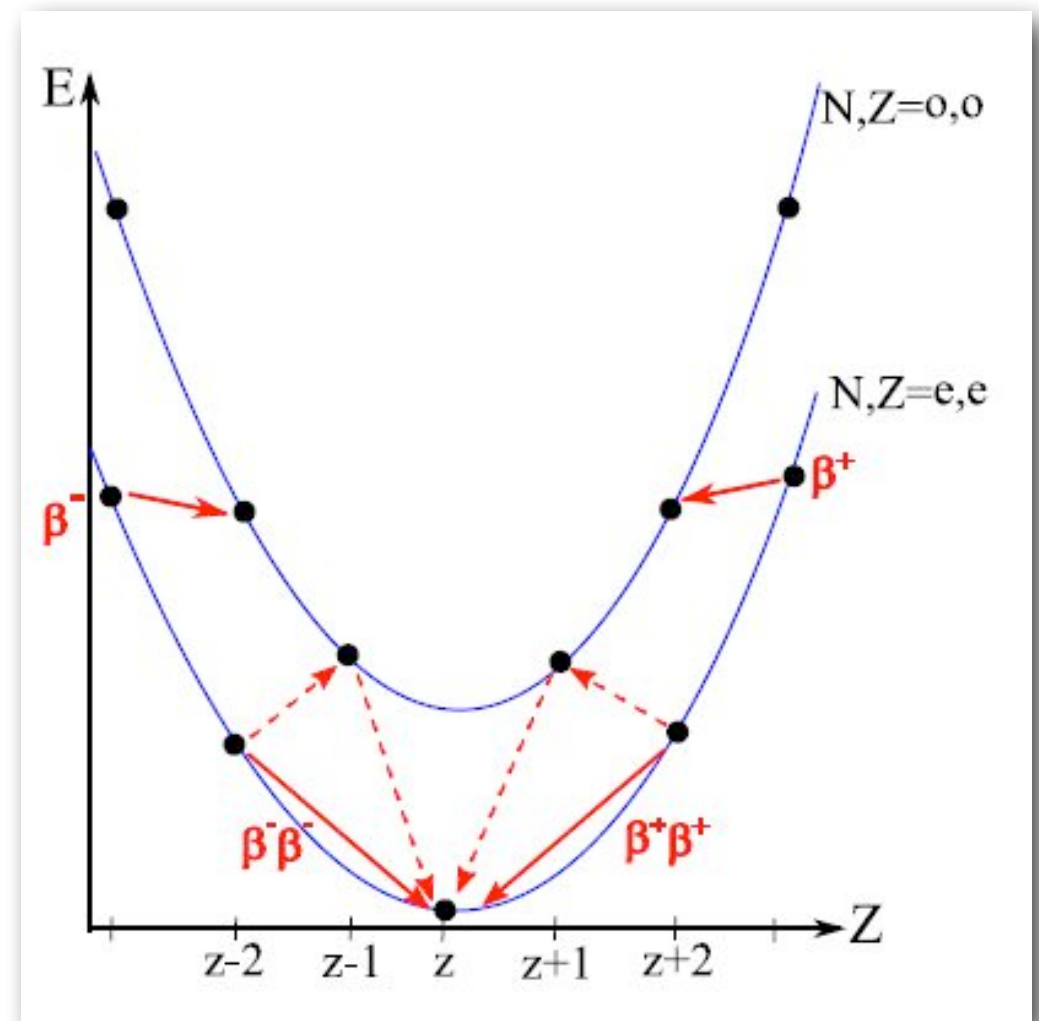
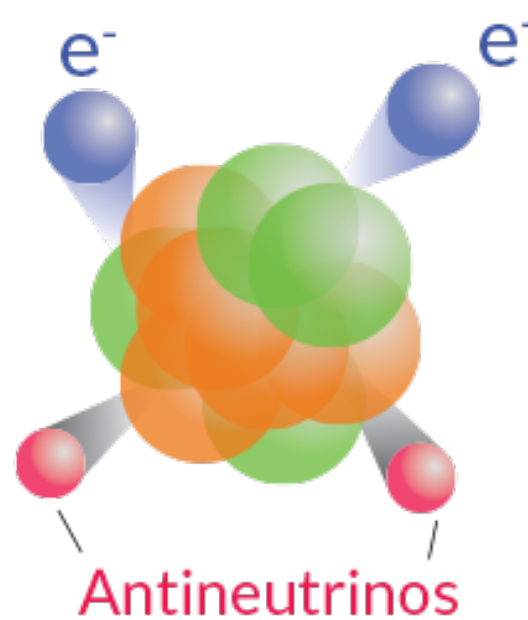
DETECTING THE DOUBLE-BETA DECAY WITH 0 NEUTRINOS

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

Beta decay



Double beta decay



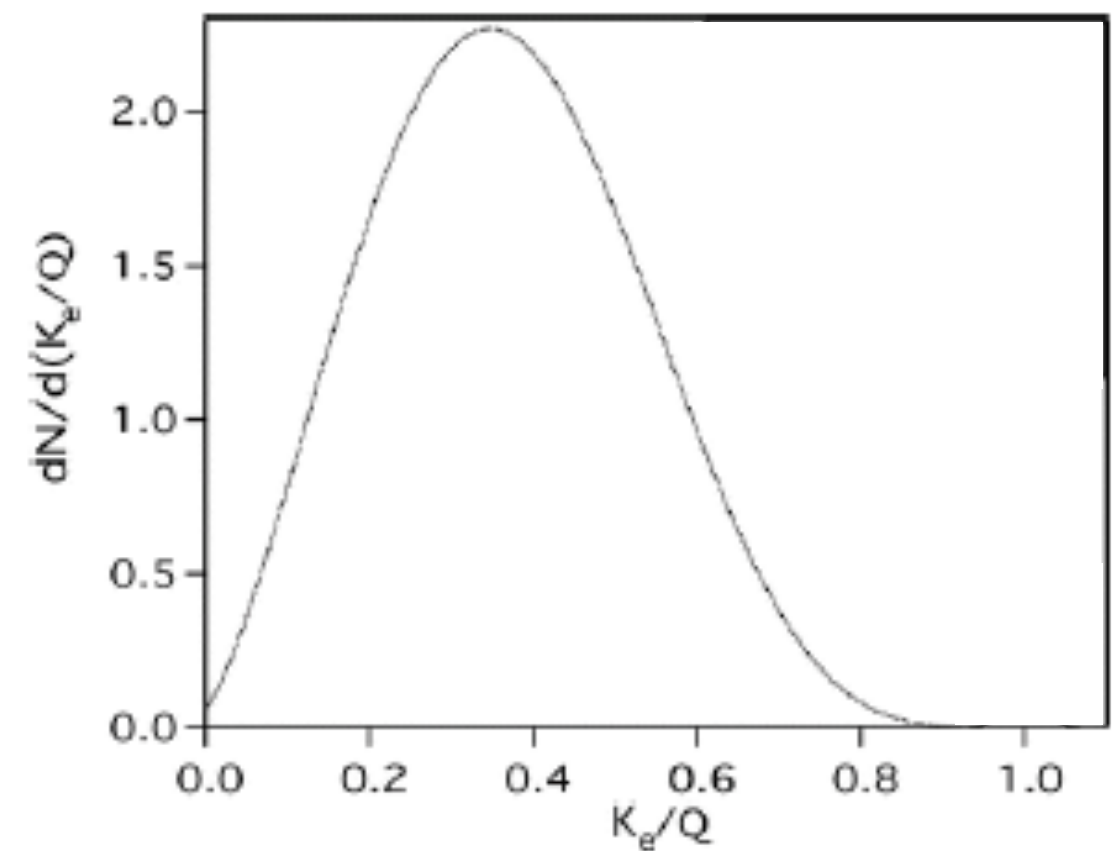
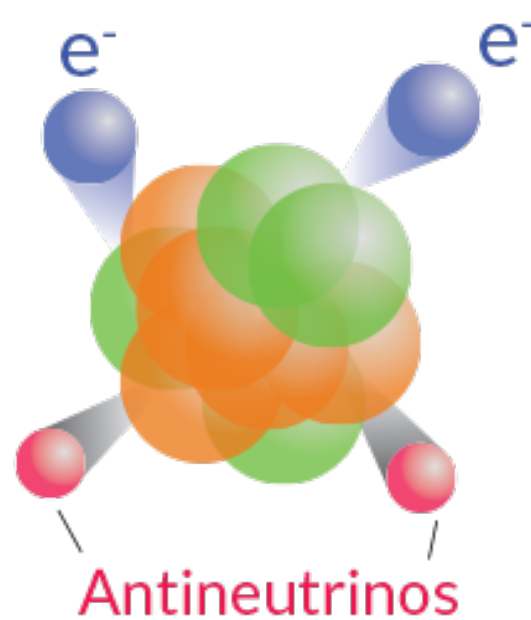
WHAT IS THE 0VBB DECAY?

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 - A double-beta decay happens

Beta decay



**Double
beta decay**



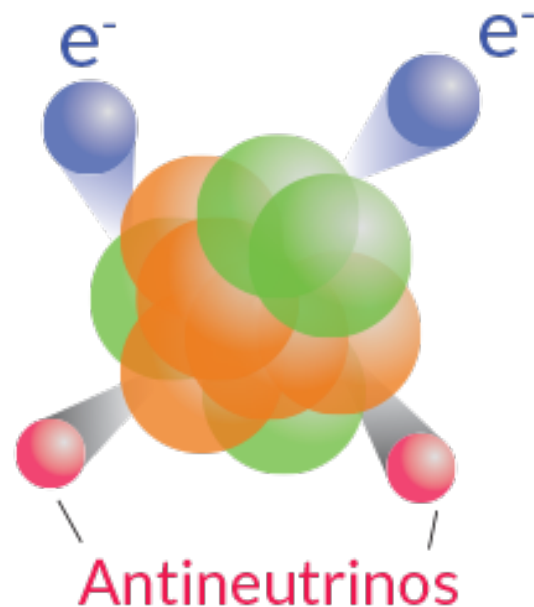
WHAT IS THE 0 ν BB DECAY?

★ Sometimes things get even more crazy (or maybe not)

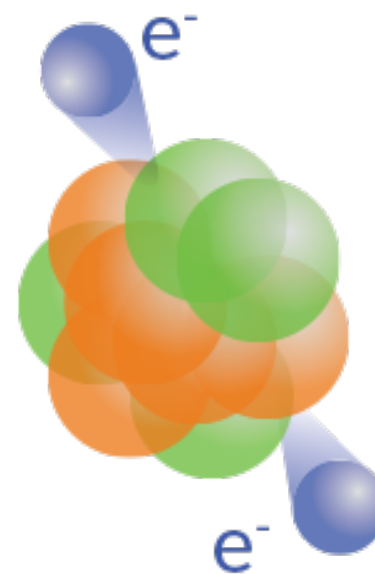
Beta decay



**Double
beta decay**



**Neutrinoless double
beta decay**



Only happens if
neutrinos are Majorana

Involves "internal" neutrino
annihilation
Only possible for Majorana
neutrinos

WHERE IS THE CATCH?

★ Only 35 isotopes in nature do double-beta decay and the process half-life is 10^{20} years

WHERE IS THE CATCH?

- ★ Only 35 isotopes in nature do double-beta decay and the process half-life is 10^{20} years
- ★ Currently no-one has seen the neutrinoless double-beta decay process and the expected half-life is larger than 10^{25} years

WHERE IS THE CATCH?

We need HUGE detectors with tonnes of material containing the candidate isotope



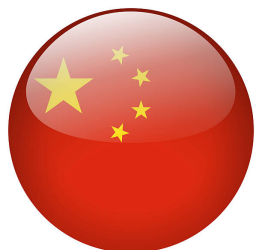
LIP Coimbra
LIP Lisboa



SNOLAB
TRIUMF
University of Alberta
Queen's University
Laurentian University



UNAM



Shandong University



TU Dresden

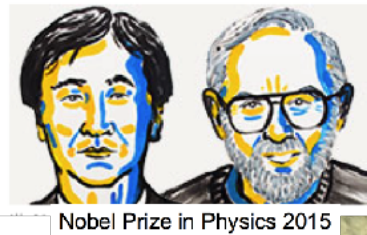


University of Chicago
Boston University
BNL
University of California Berkeley
LBNL
University of Pennsylvania
UC Davis

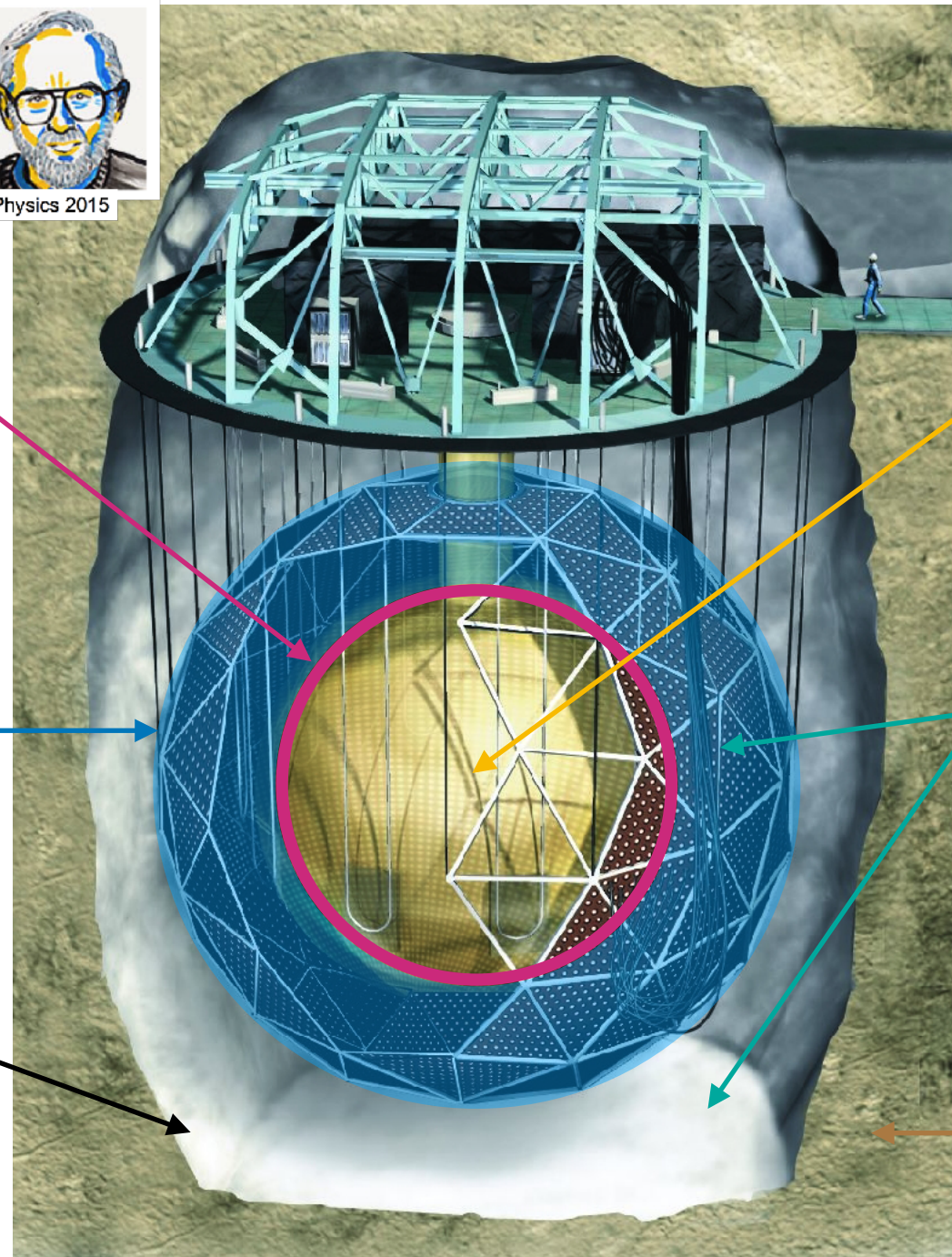


Oxford University
Kings College
University of Liverpool
University of Sussex
University of Lancaster

SNO+ DETECTOR



Deep Underground
~ 2 km



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

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

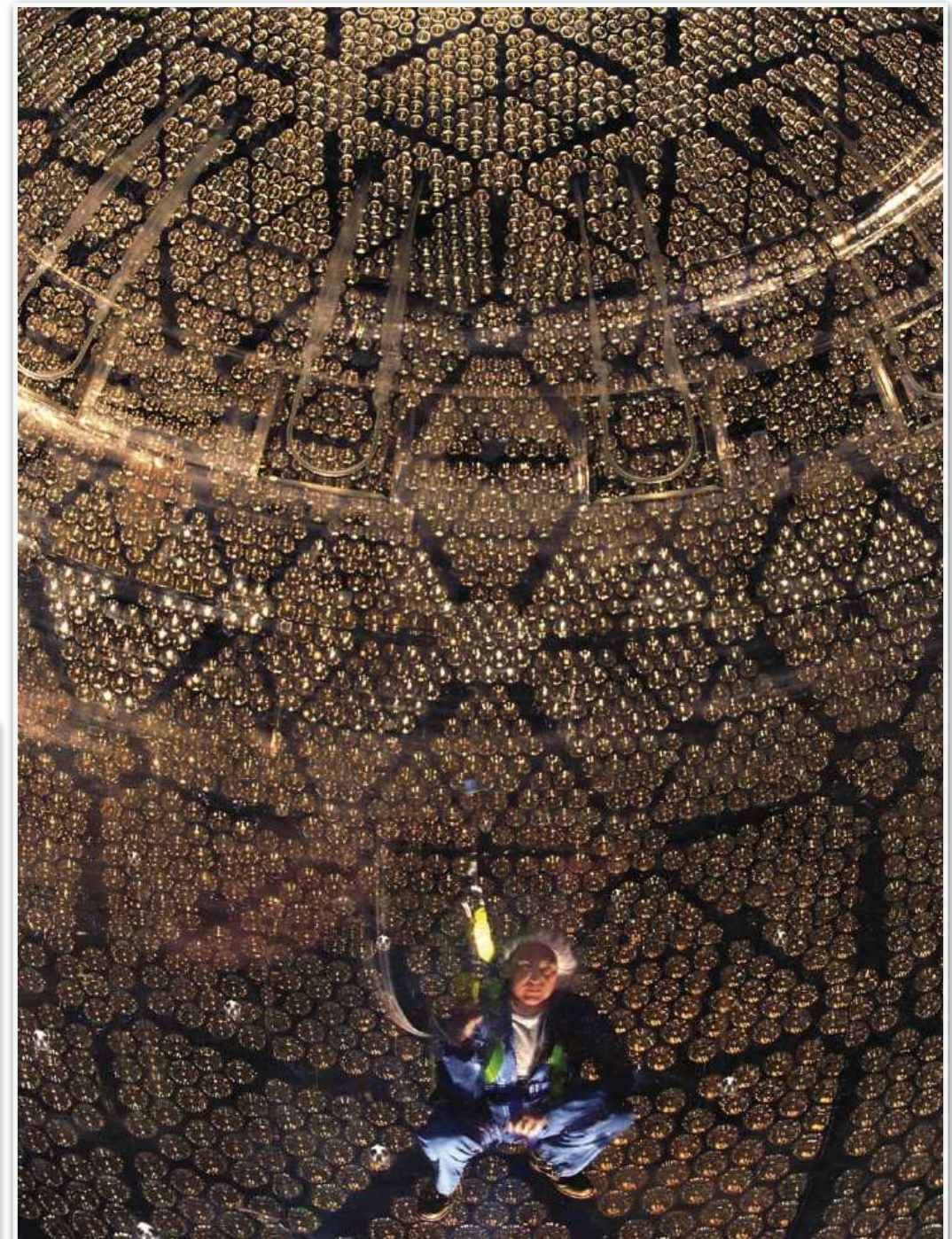
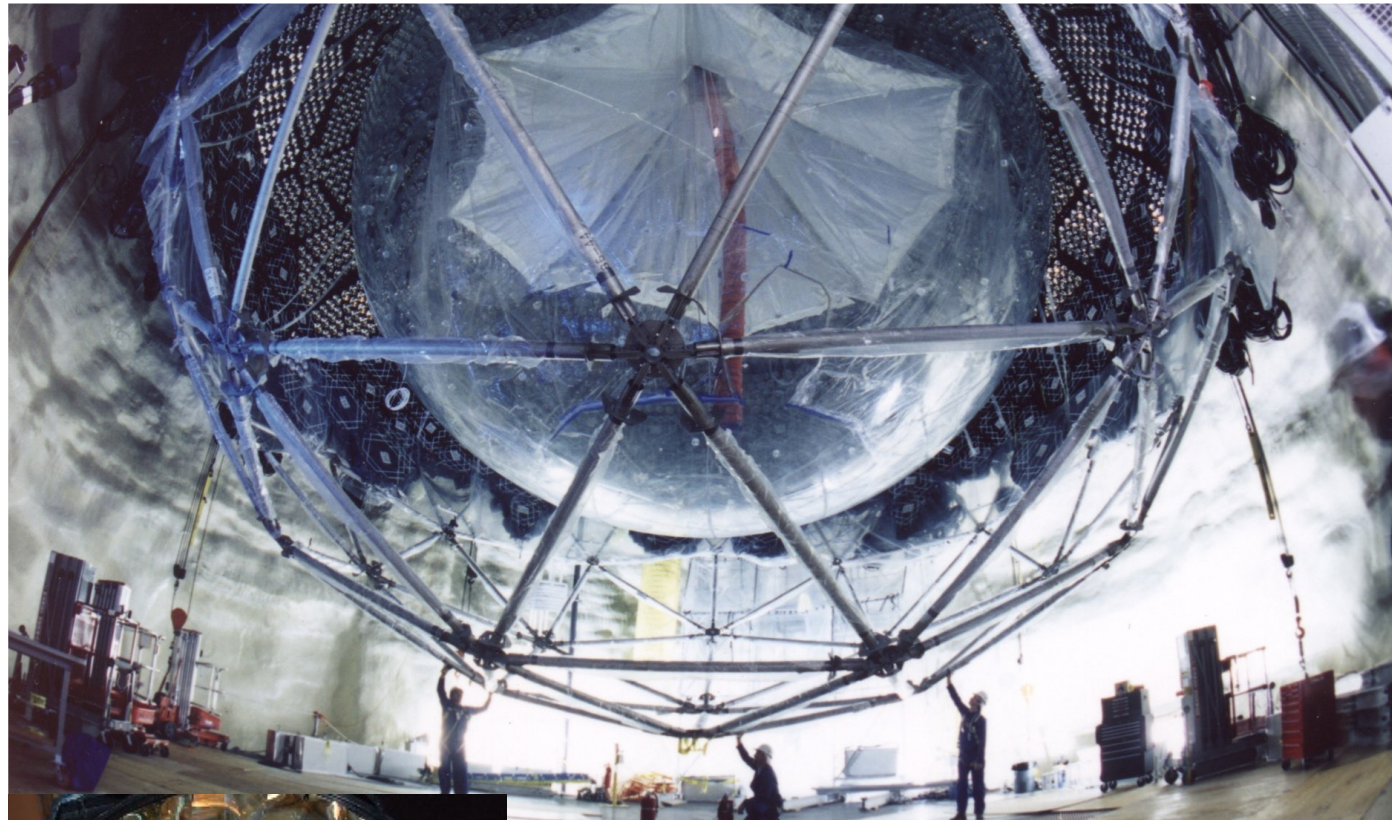
Urylon layer/Radon seal

Active medium

Light water (H₂O) shielding
- 1700t internal
- 5300t external

Norite Rock

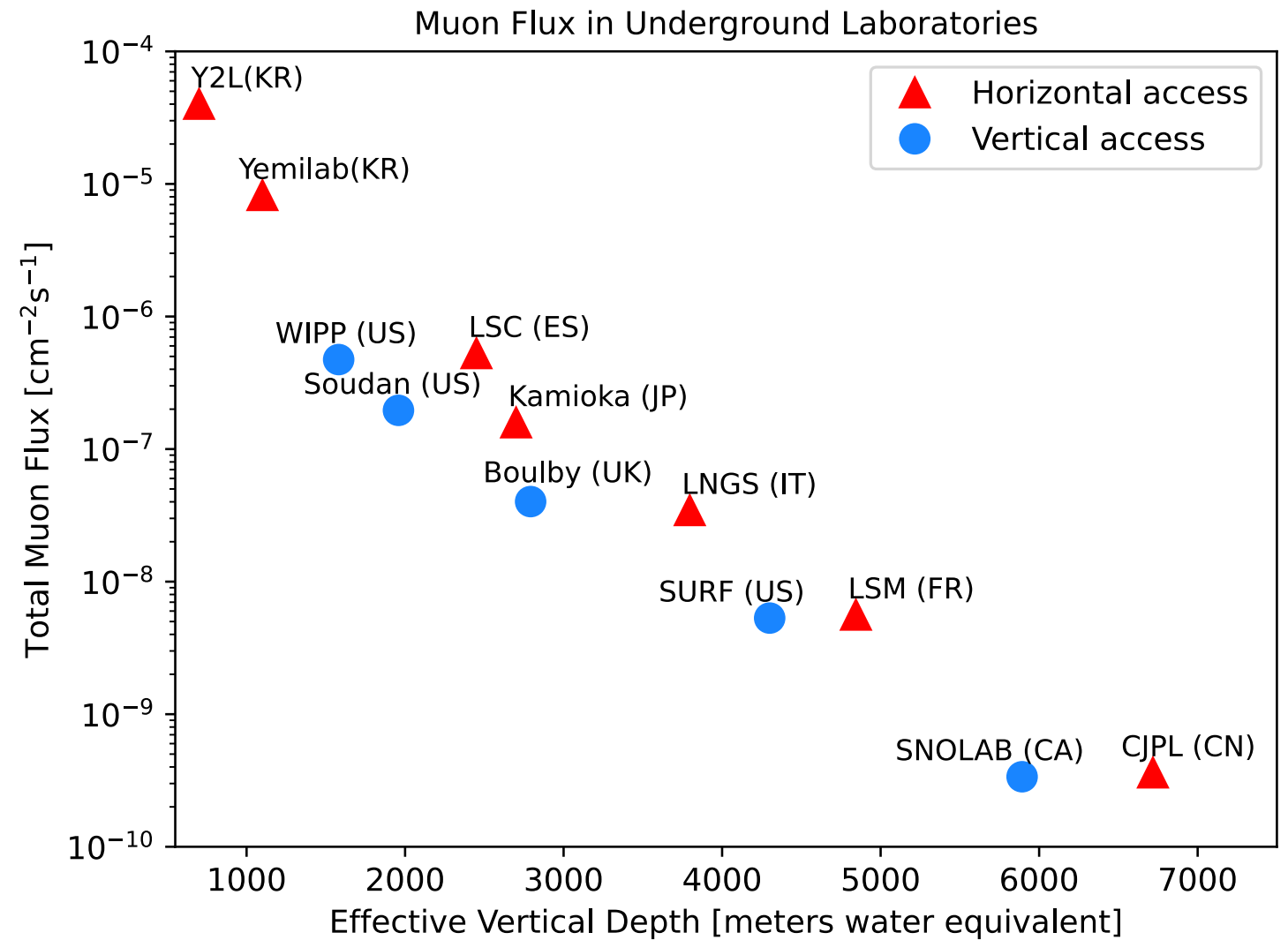
CONSTRUCTION



DEEP UNDERGROUND



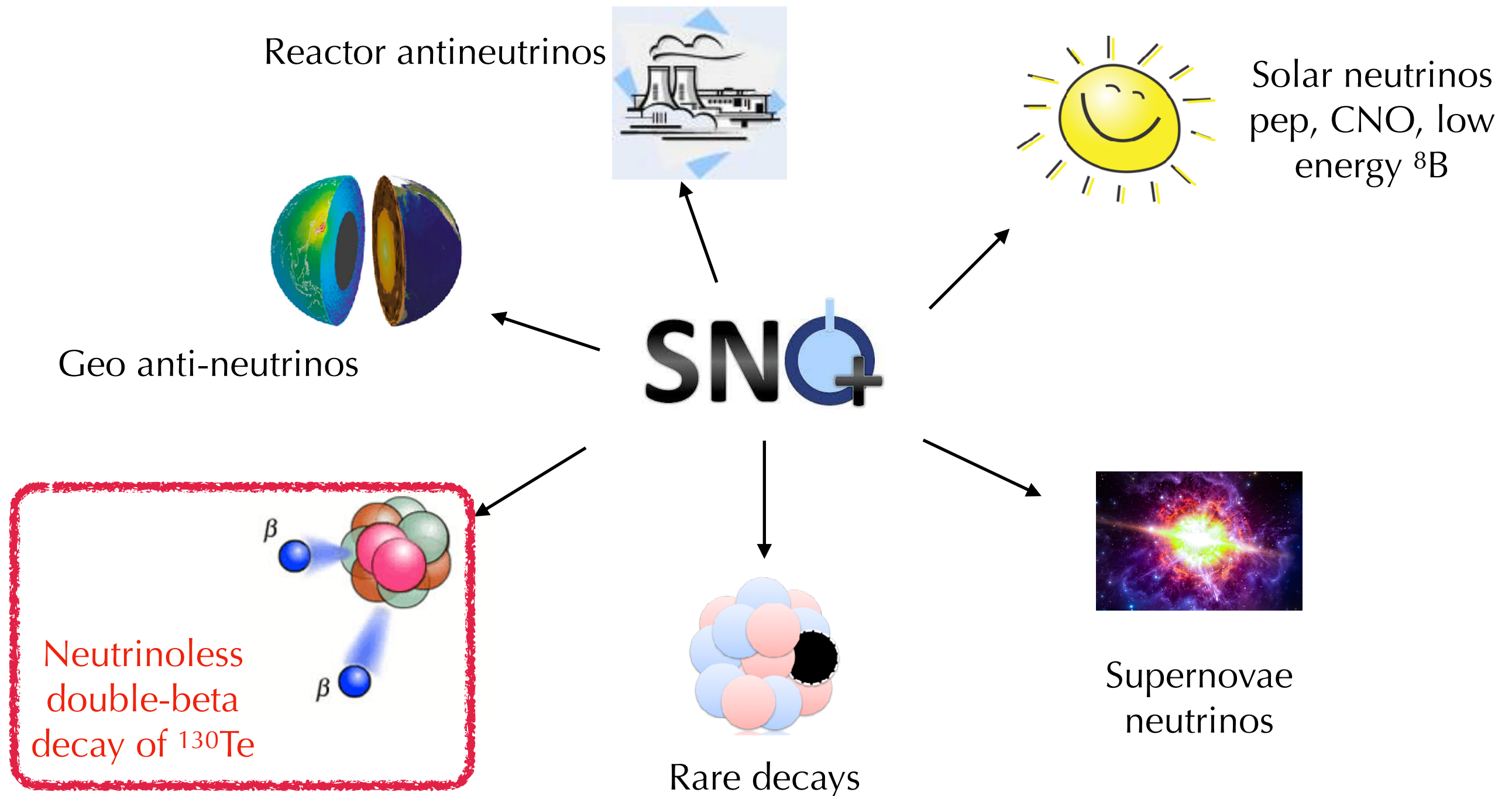
@SNOLAB, Sudbury, Canada



A MULTIPURPOSE DETECTOR



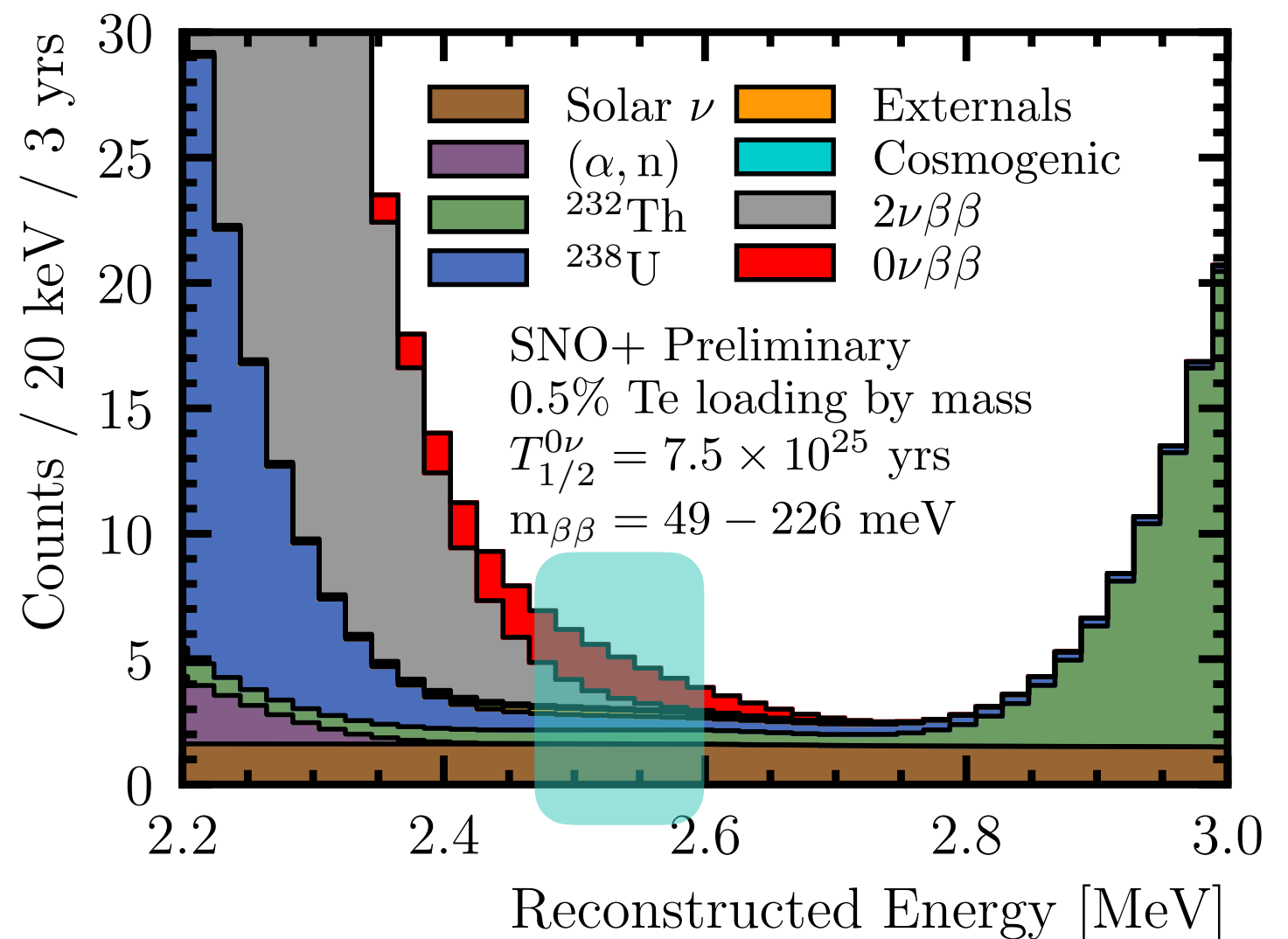
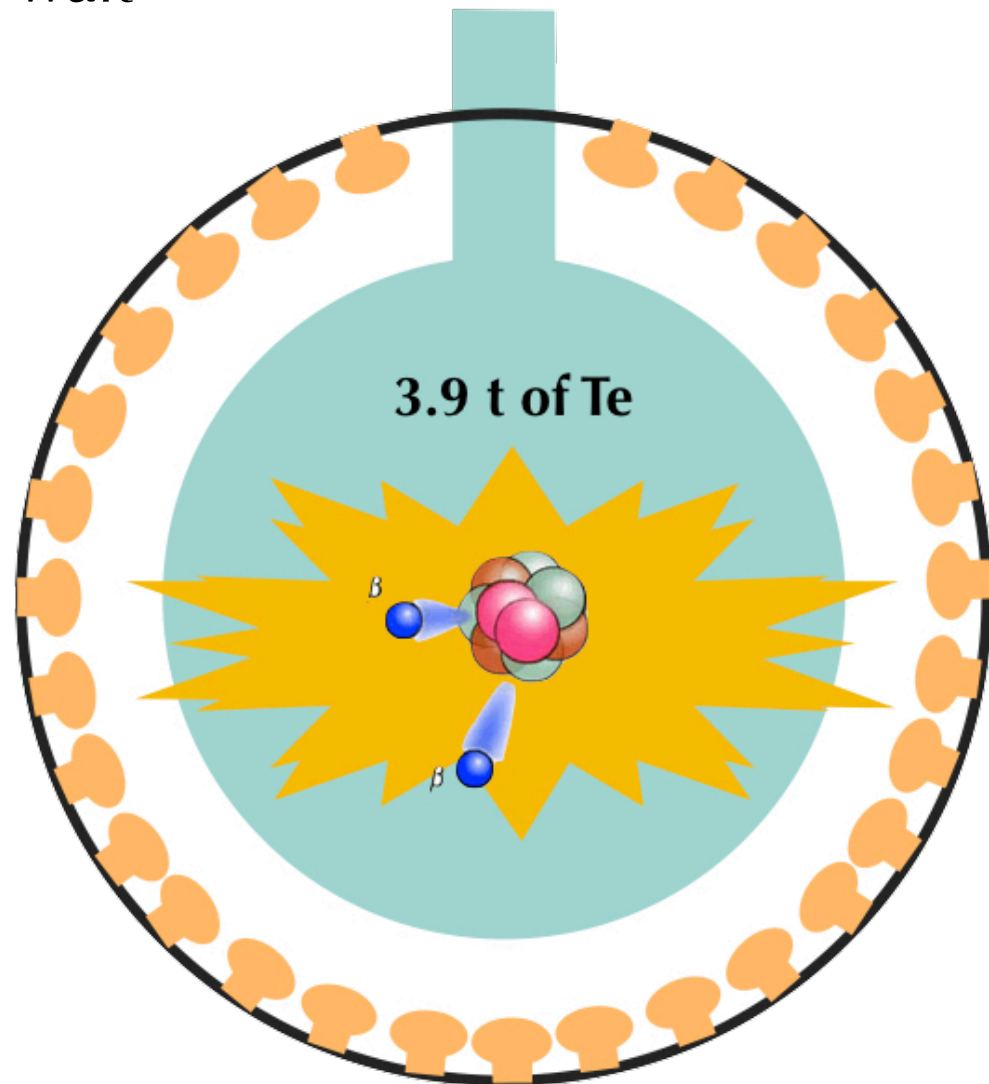
★ A very large detector that searches for the nature of neutrinos



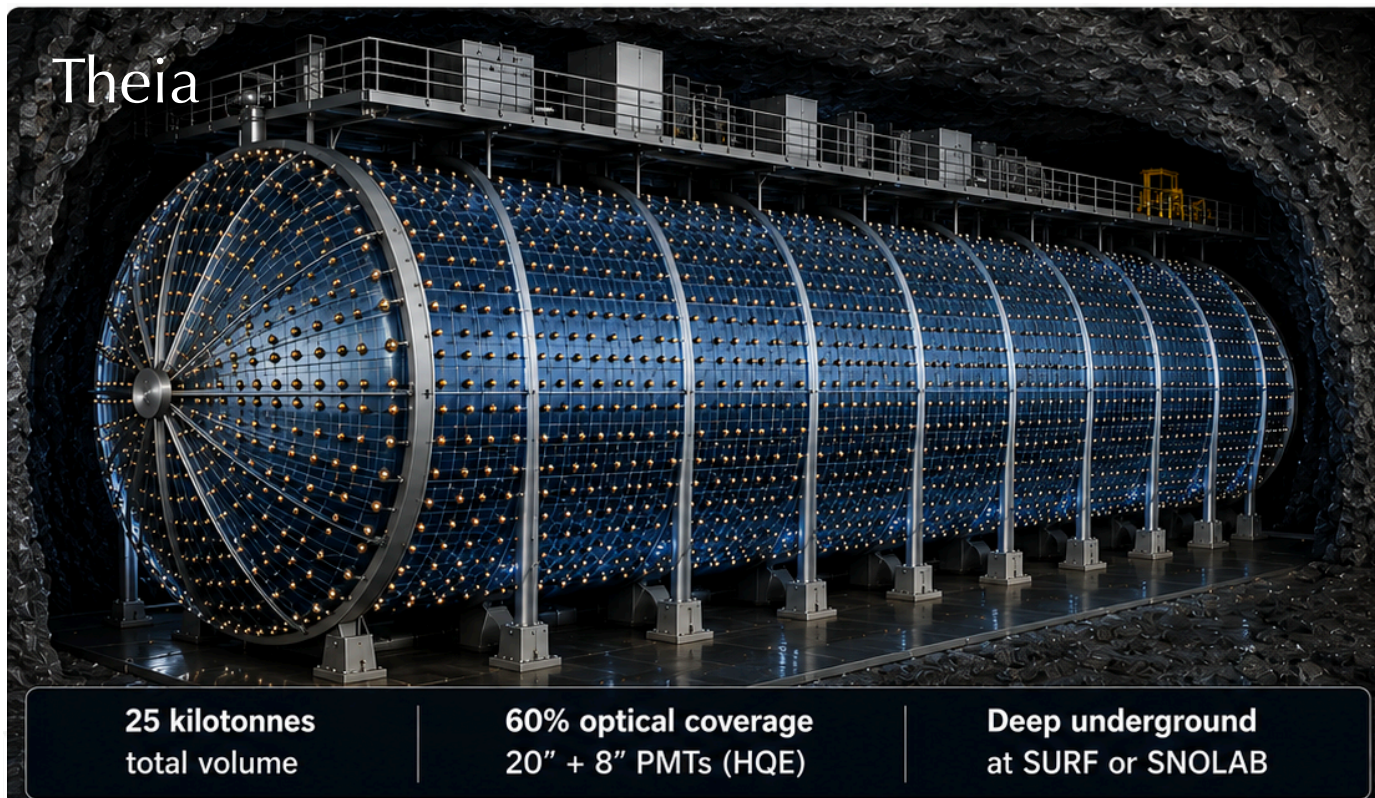
ONU DOUBLE-BETA DECAY WITH SNO+



★ Load 3.9 tonnes (or more) of Tellurium into a 780 tonnes liquid scintillator detector and then wait



EVEN LARGER DETECTORS IN THE HORIZON

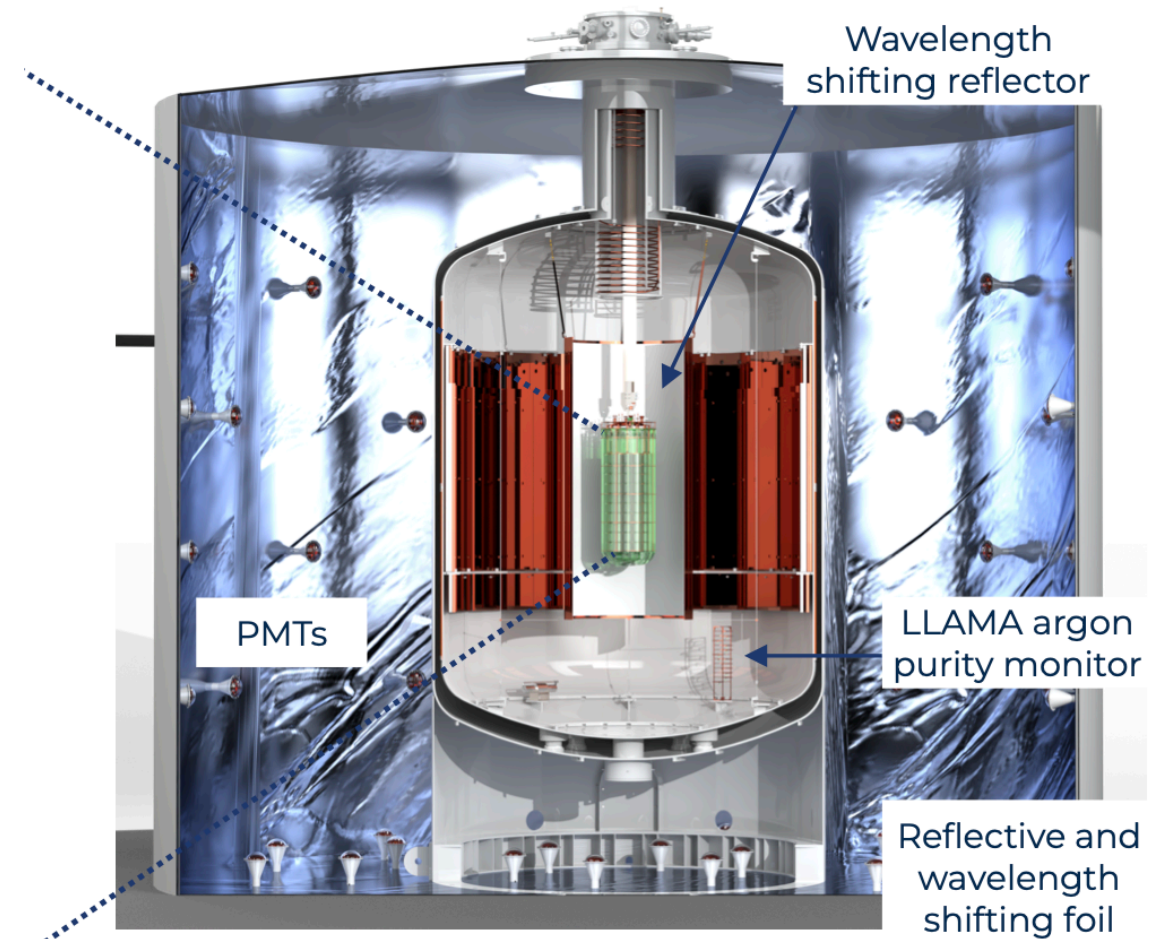


KamLAND2-Zen

1000 kg of Xe
Increase isotope mass

Legend-1000

Instrumented water tank



- 1 tonne 90%-enriched HPGe detectors deployed at LNGS.
- BI goal: $< 2 \times 10^{-5}$ cts/(keV kg yr) $\mapsto T_{1/2} > 10^{28}$ yr.
- Start data taking in early 2030's.

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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BACK UP SLIDES