LIP Summer Internship 2023

Neutrinos
a short overview

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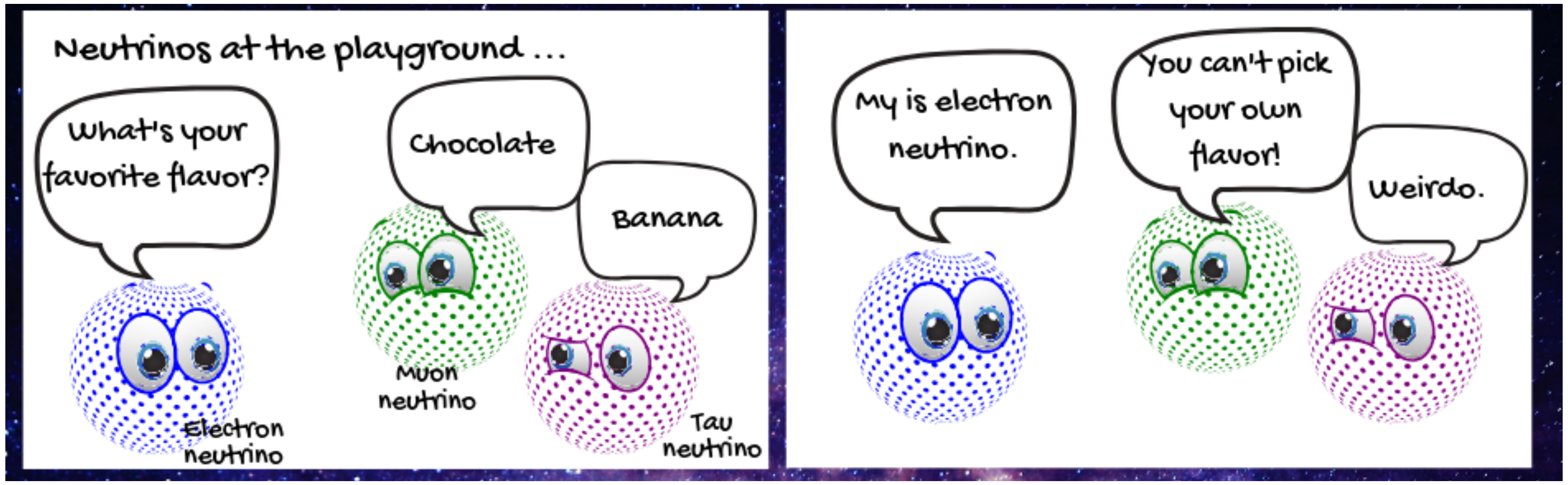
LIP Lisbon

05 July 2023, Lisbon

In this talk we will discuss two main topics

1. Neutrinos properties:
status of the art



elementary-comic.com

Overview

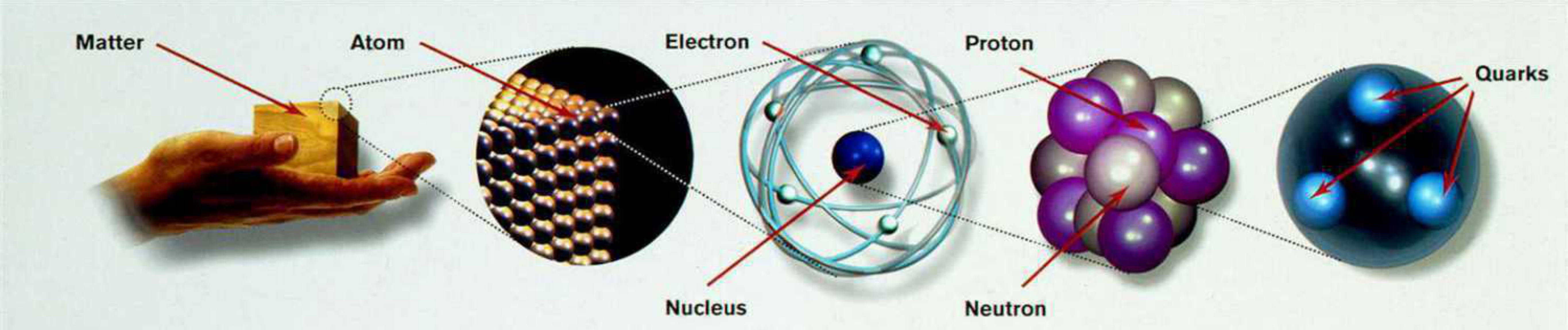
In this talk we will discuss two main topics

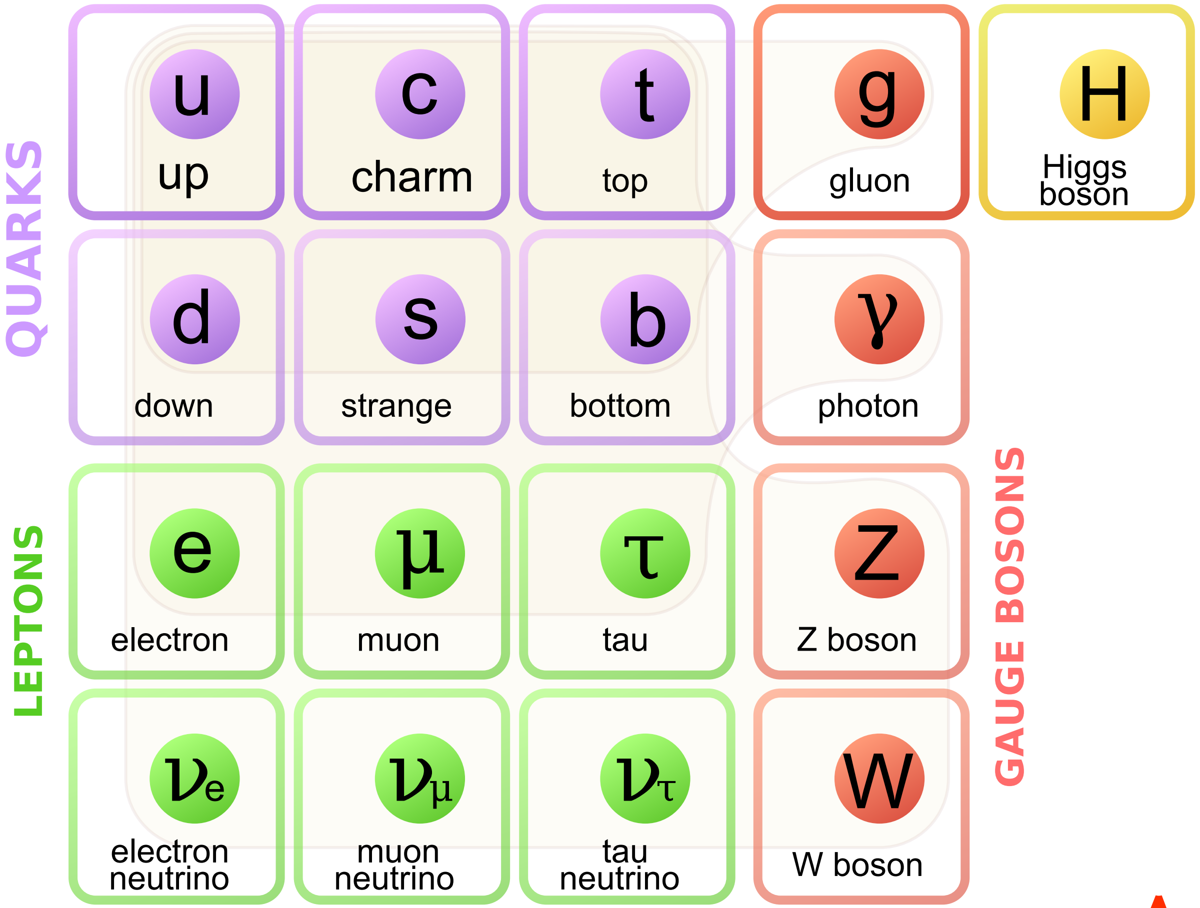
2. Large Scale experiments looking for neutrinos:
SNO+ & DUNE

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


NEUTRINOS
NEUTRINOS EVERYWHERE
imgflip.com

The Scale of things





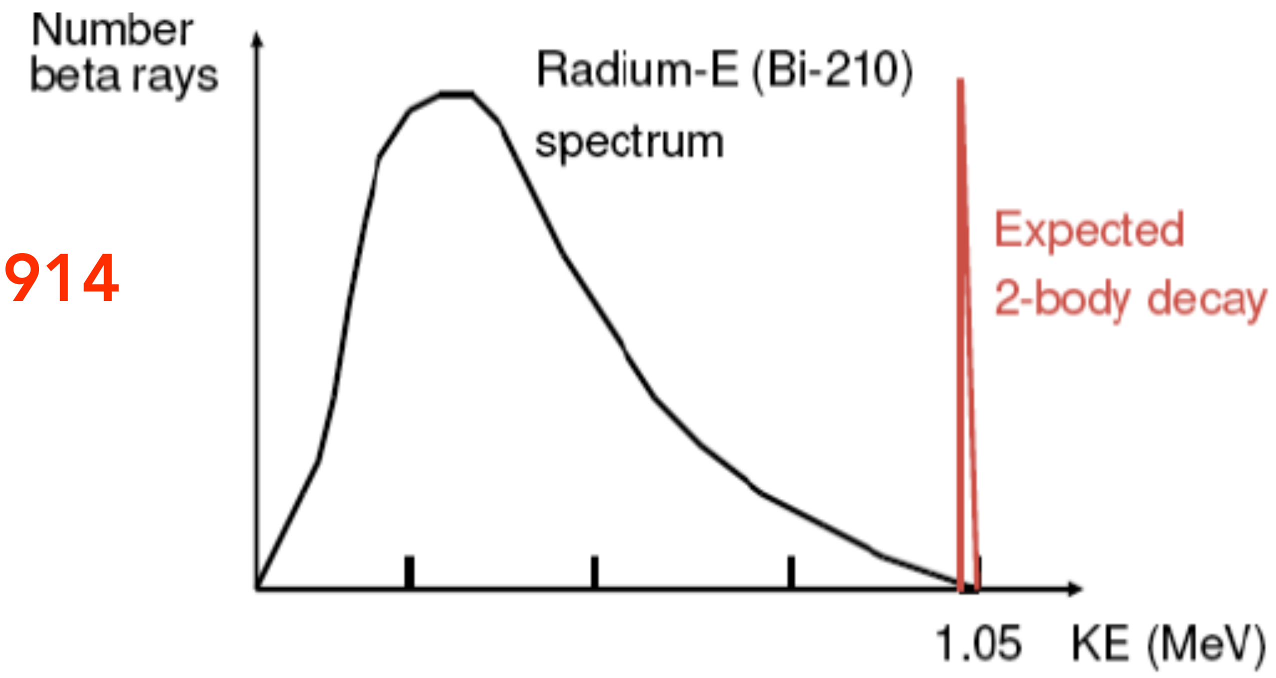
* = elementary particles

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

} matter

And the neutrinos? Where they come from?

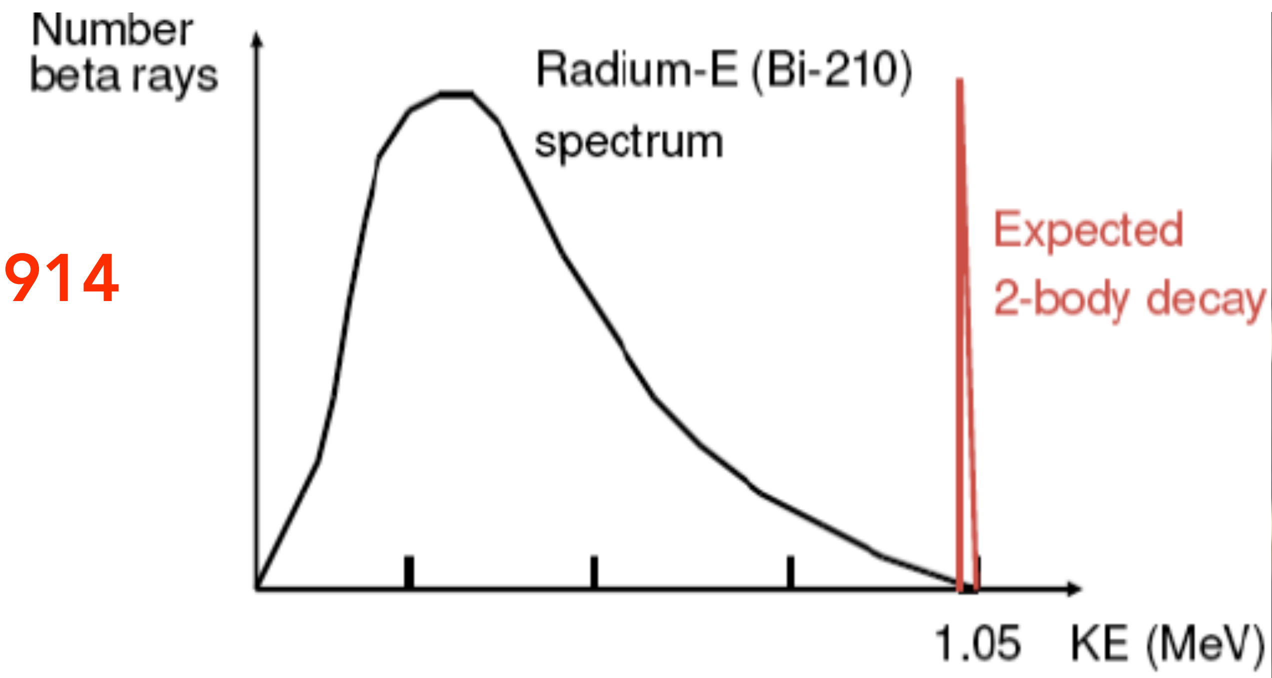
Chadwick, 1914

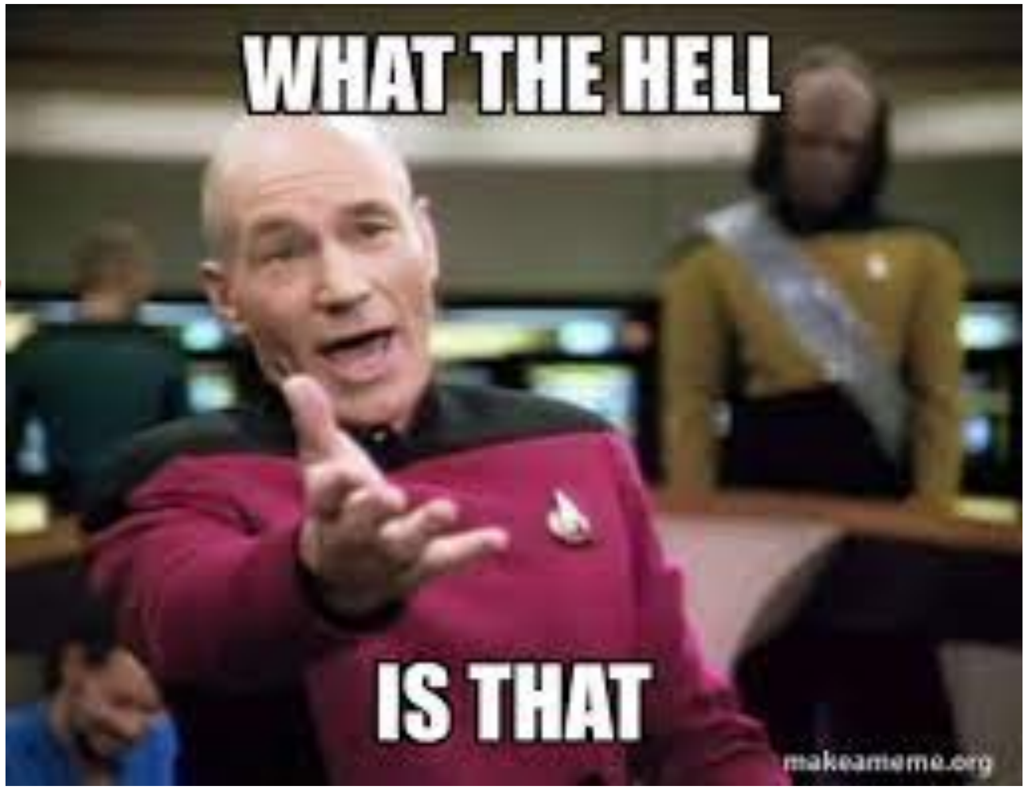


This spectrum was very different from that of alpha and gamma decays.

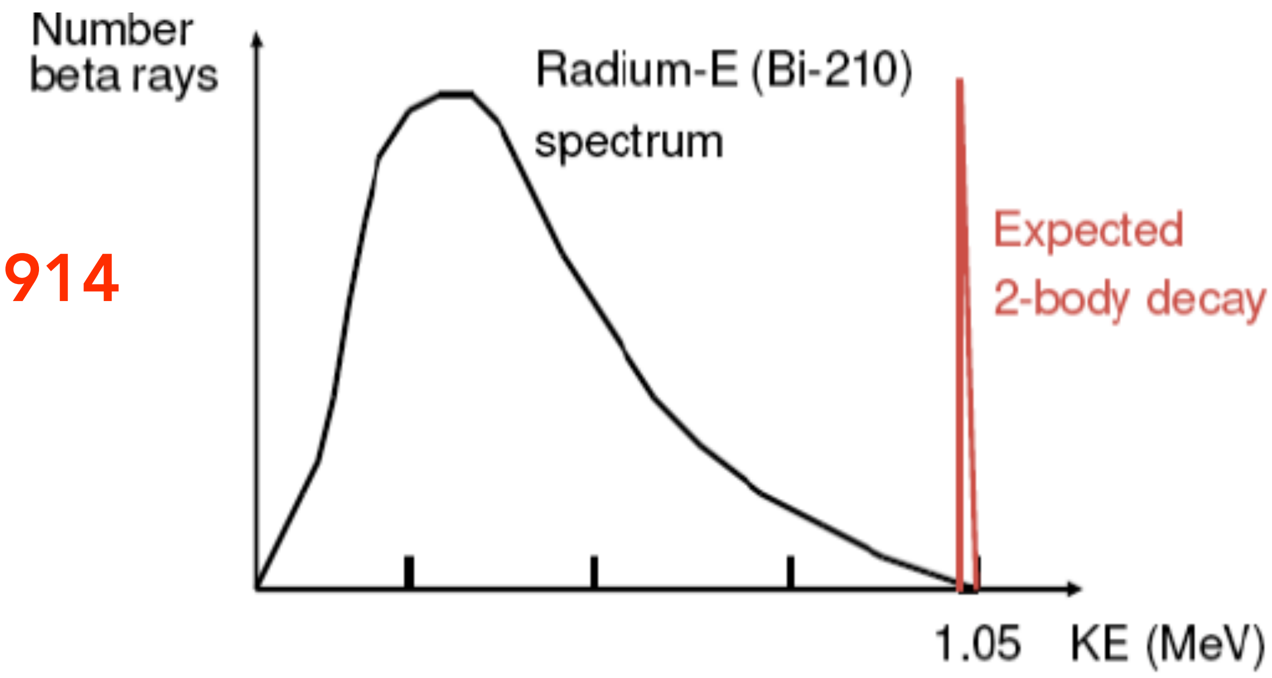
The Beta decay

Chadwick, 1914





Chadwick, 1914

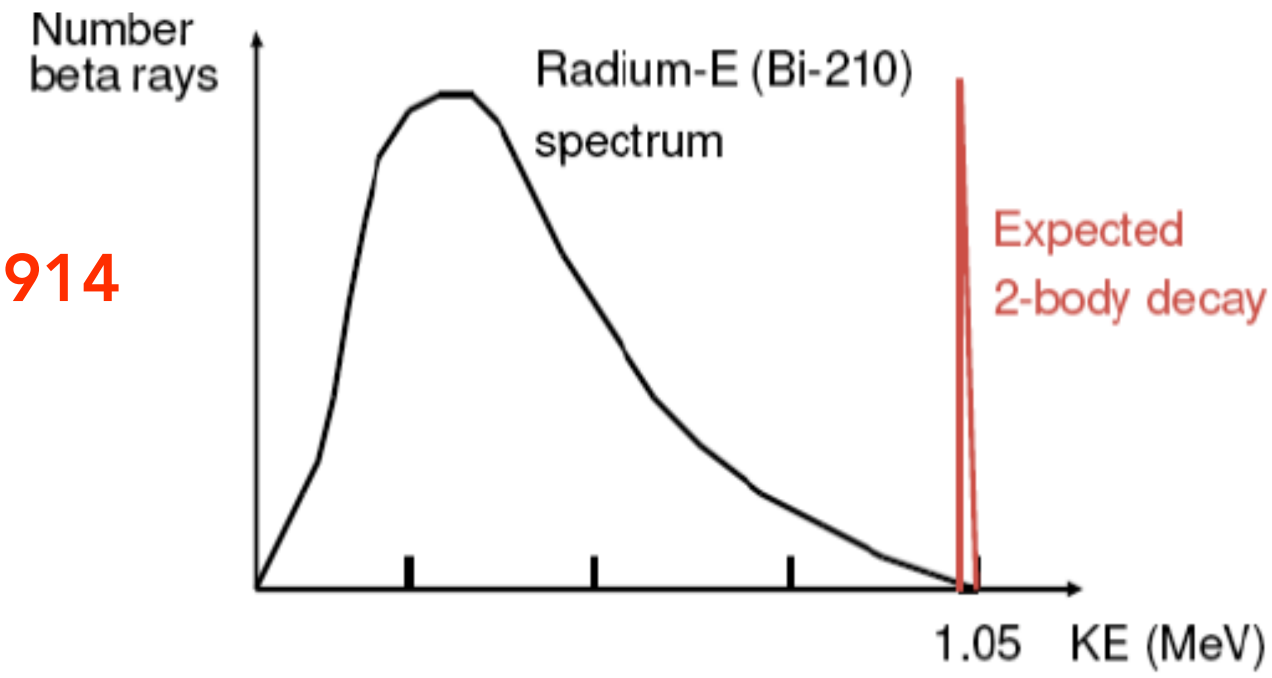


W. Pauli in 1930 proposed the existence of a third particle in the decay, which was carrying part of the energy, but didn't have charge and an extremely small mass

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

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!

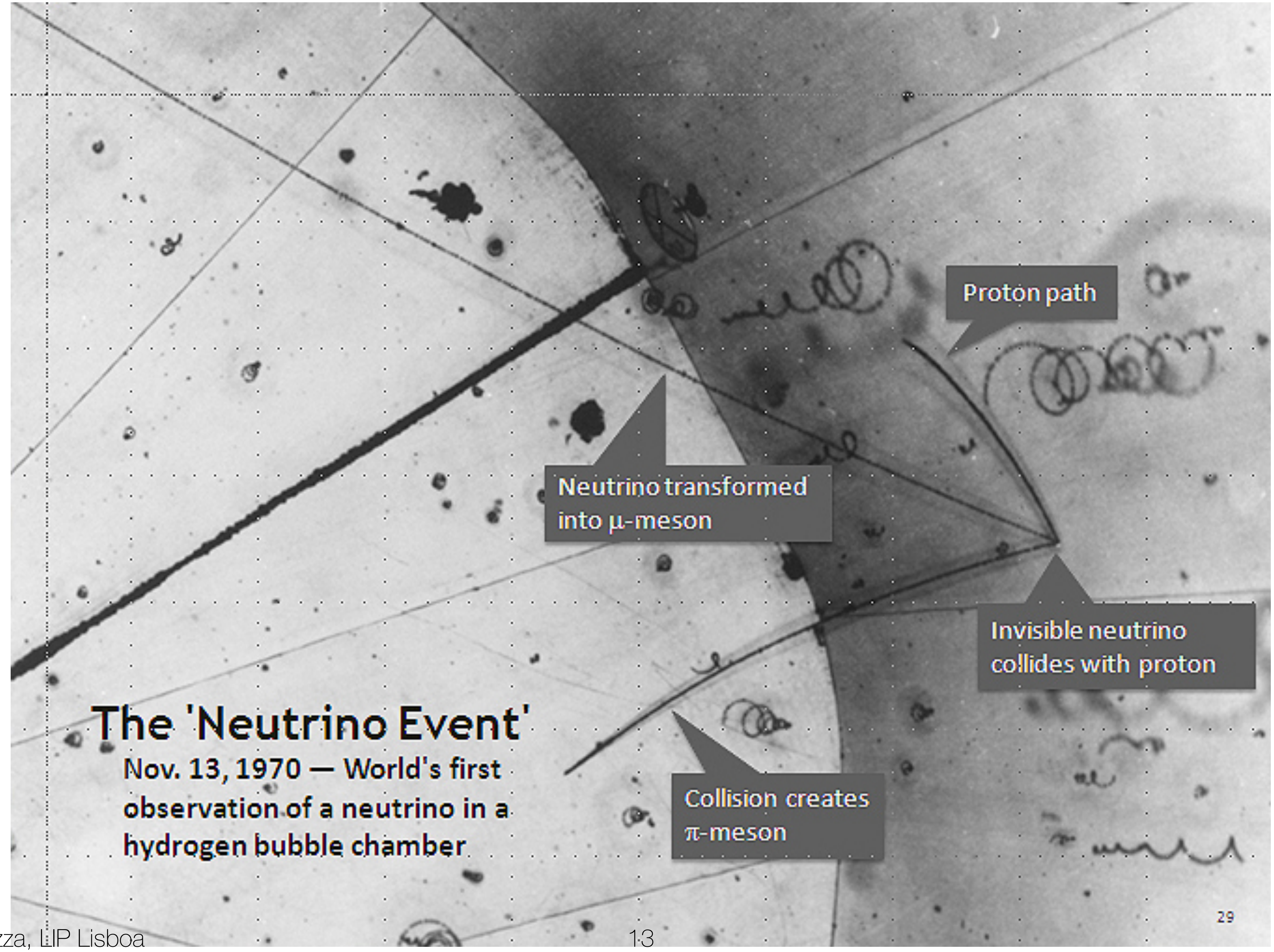
Project Poltergeist

Herr Auge

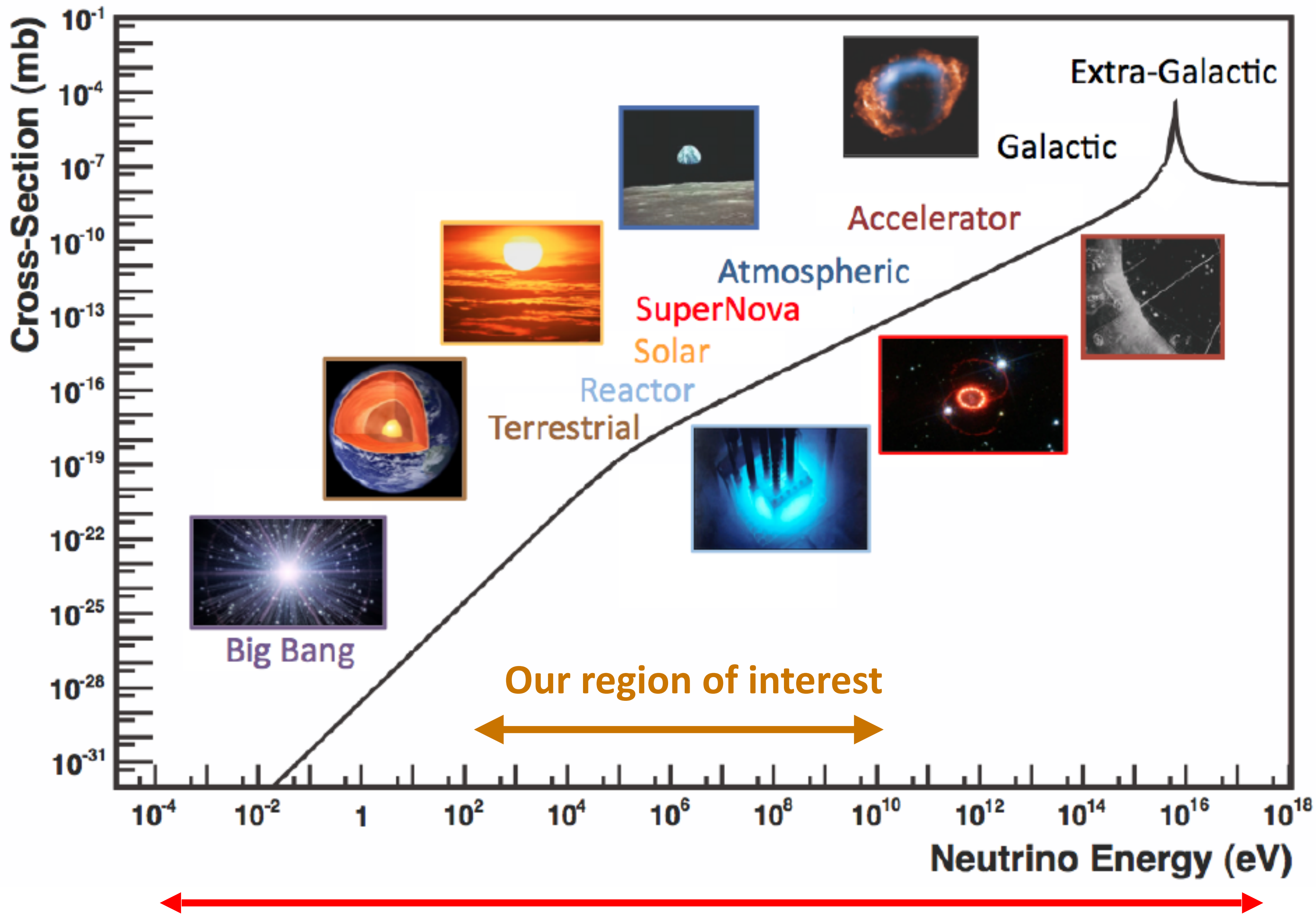
Nobel prize Reines 1995

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

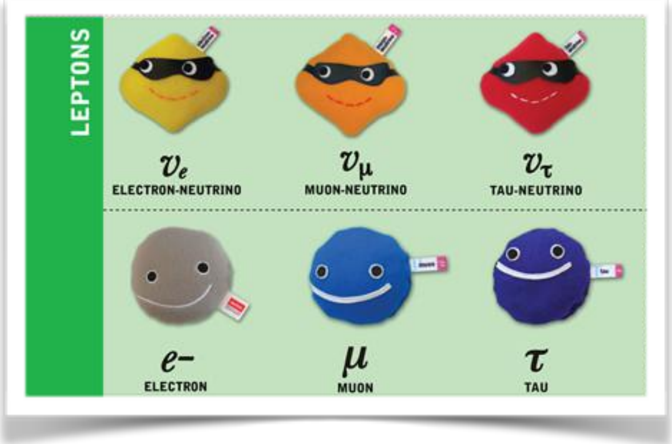
Where neutrinos come from?

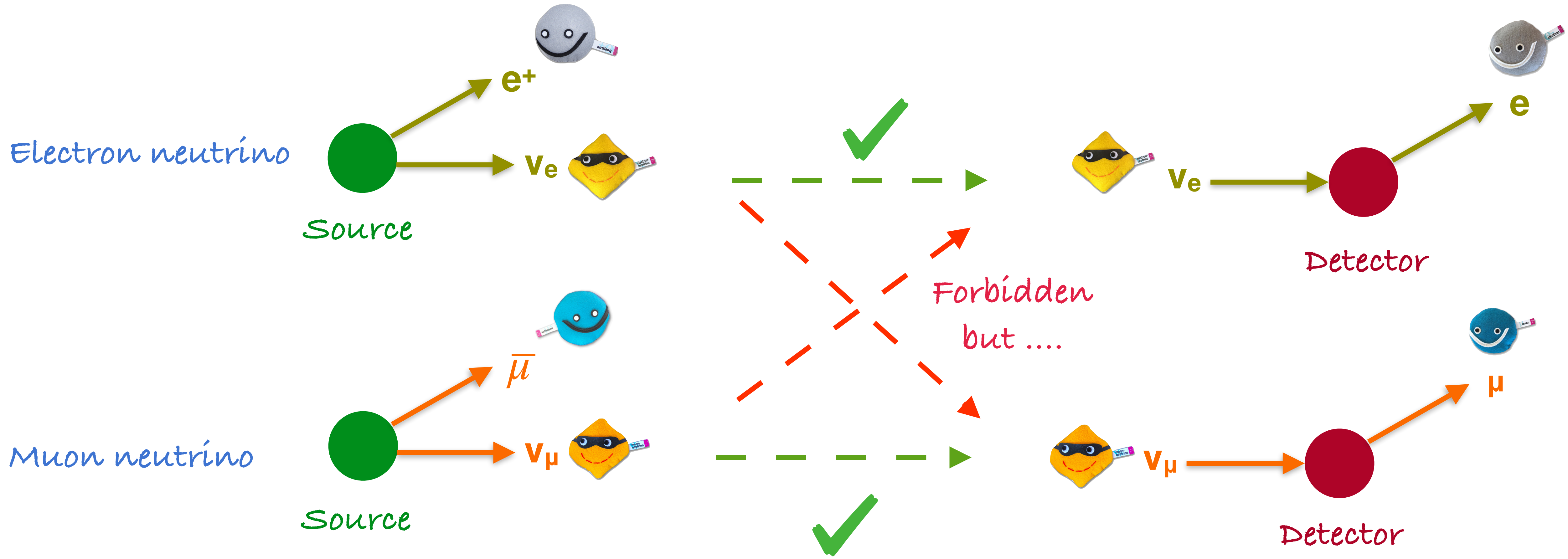


22 orders of magnitude!!!!

★ 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

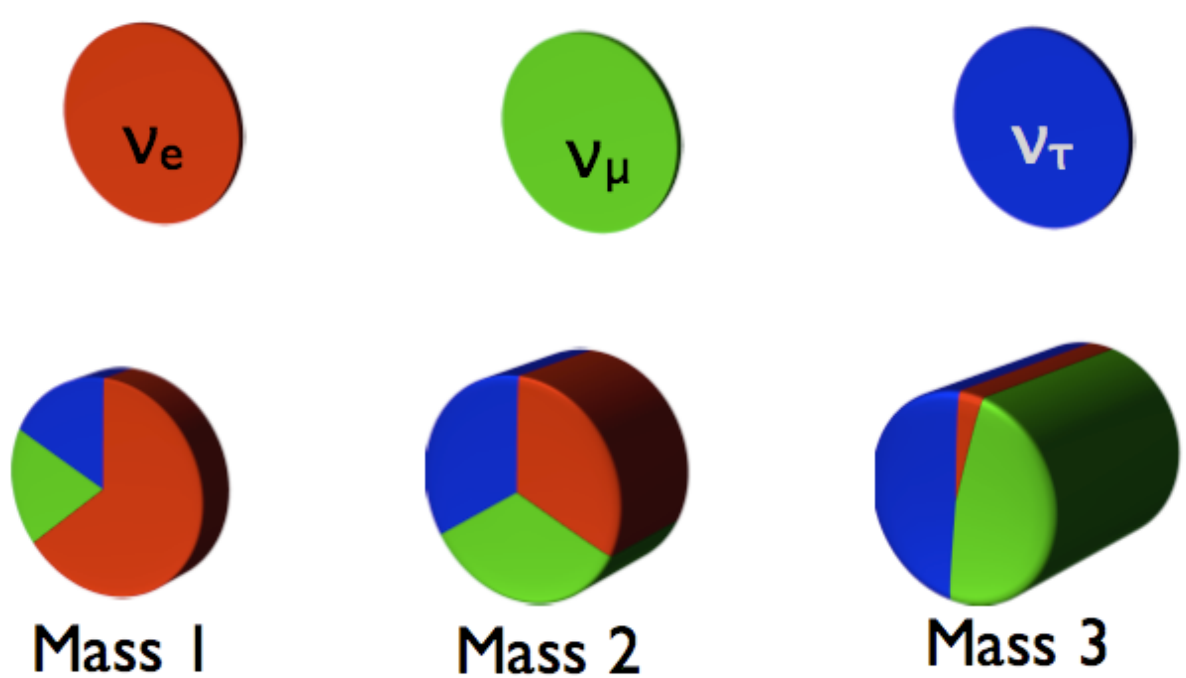


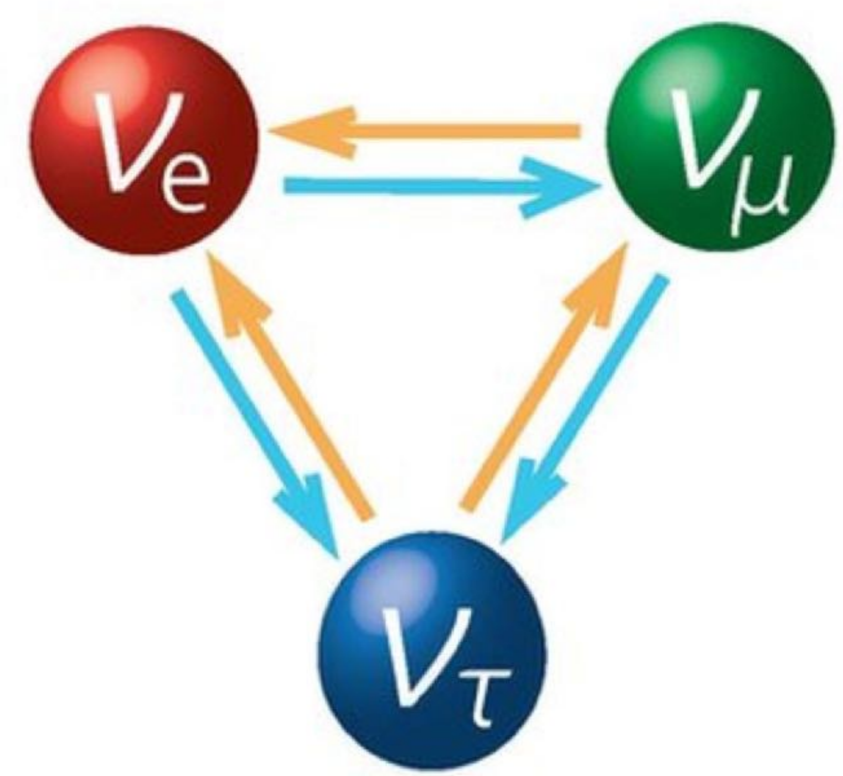


Neutrino States

★ 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

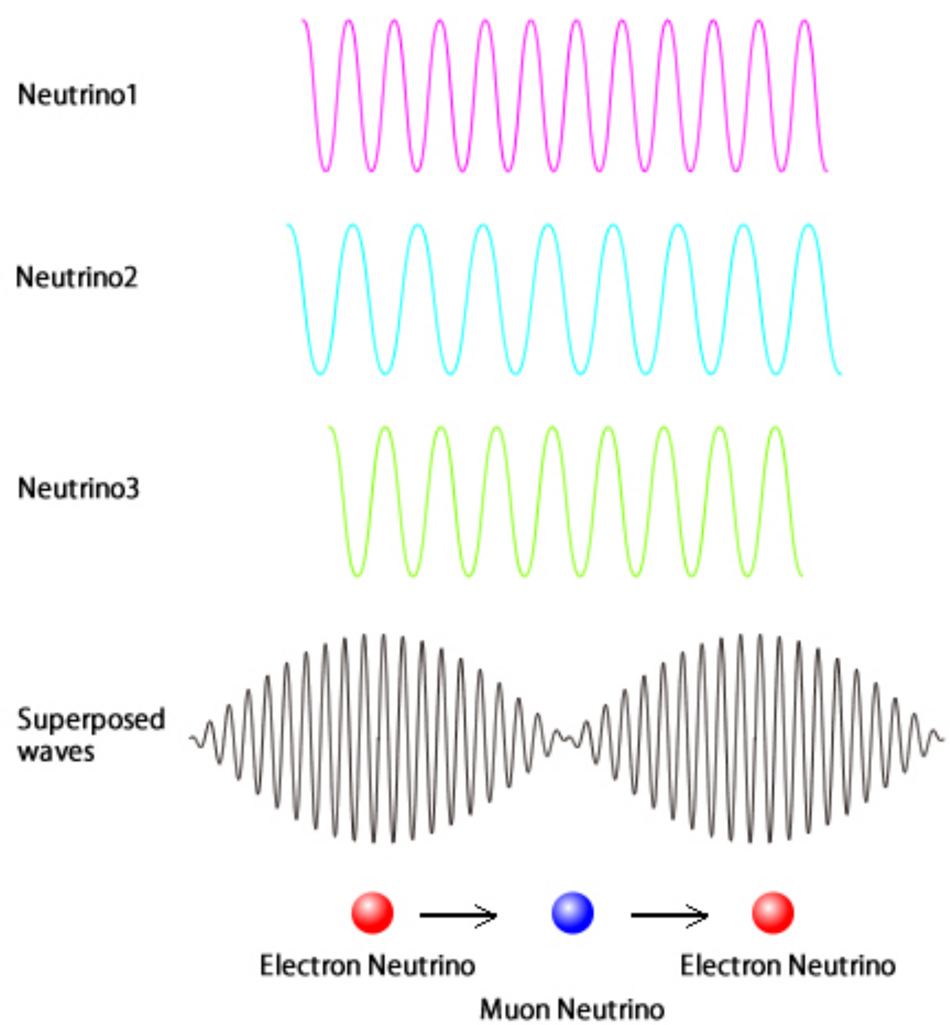




Neutrino oscillations

★ 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**

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

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**

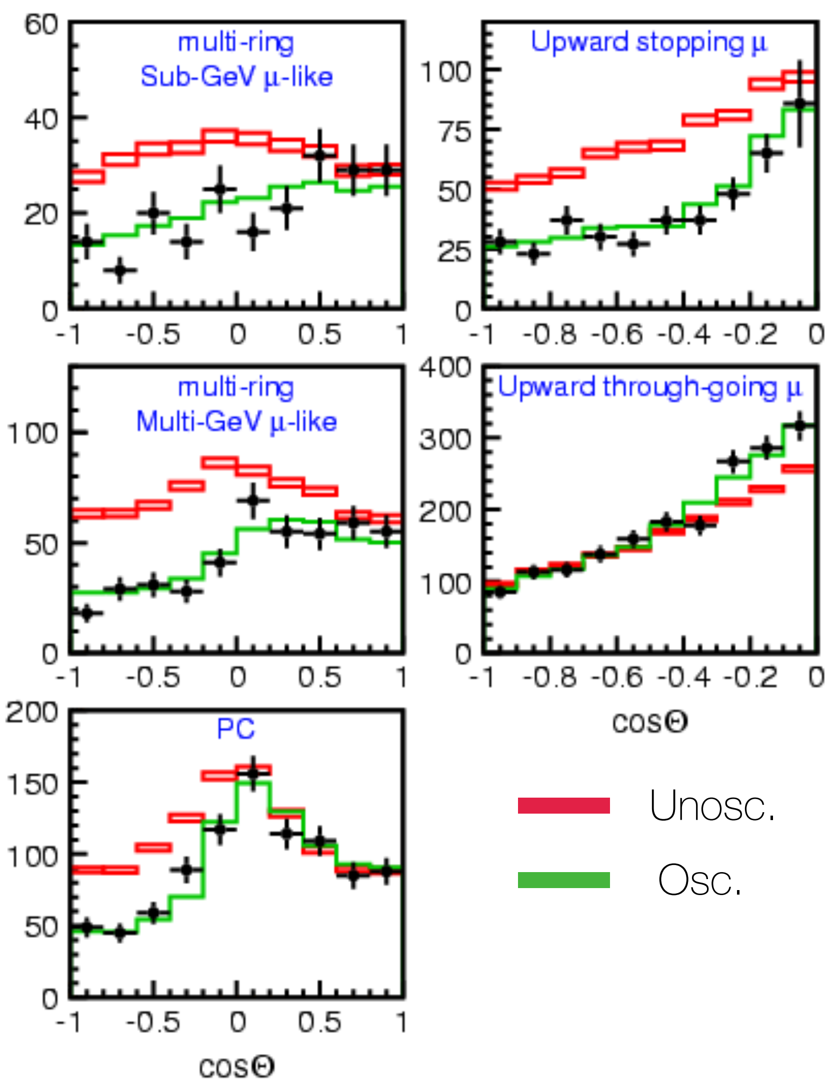
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

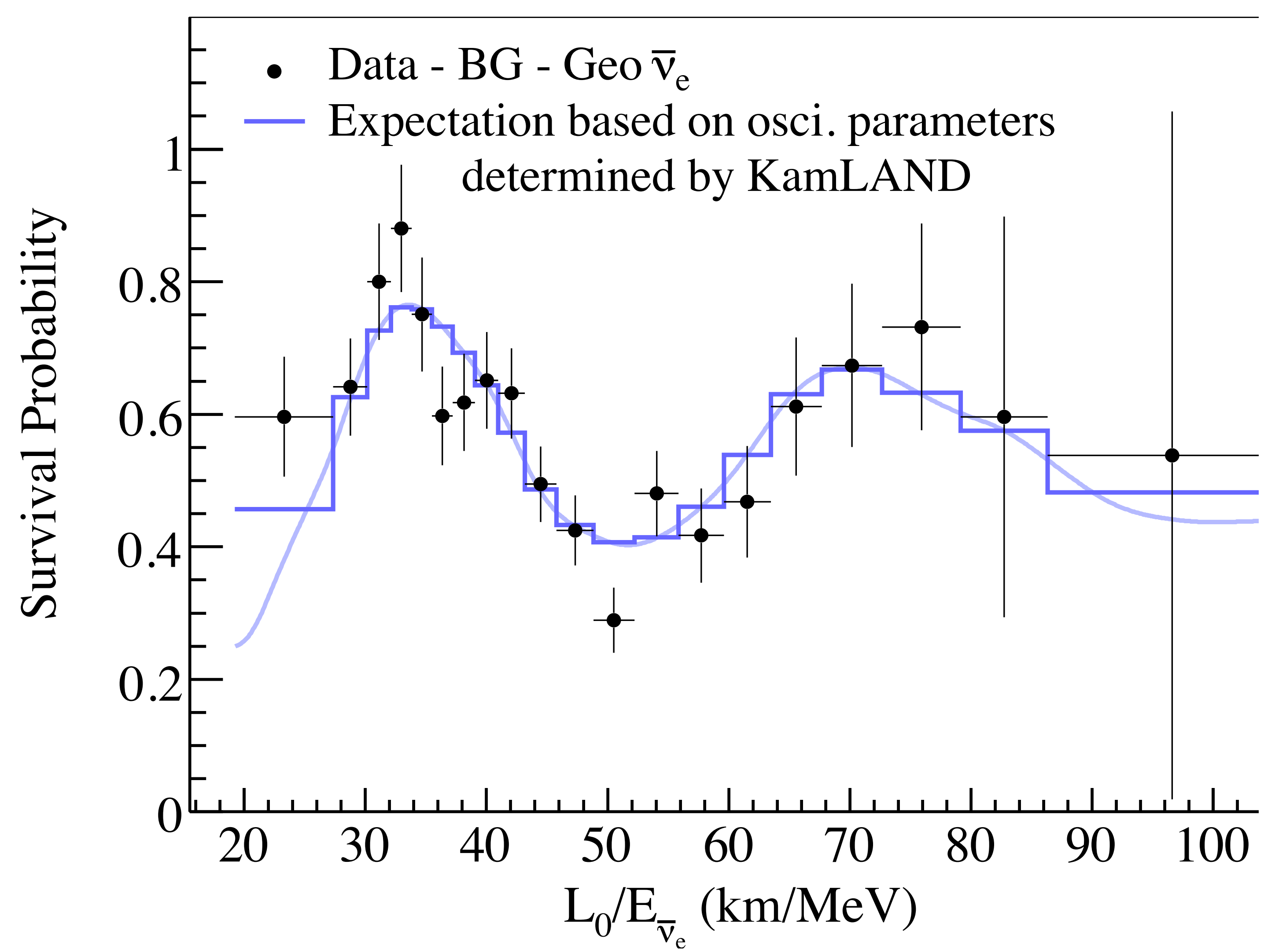
Simplified 2-neutrinos case

Measuring Oscillations

Flavour eigenstate **Mass eigenstate**

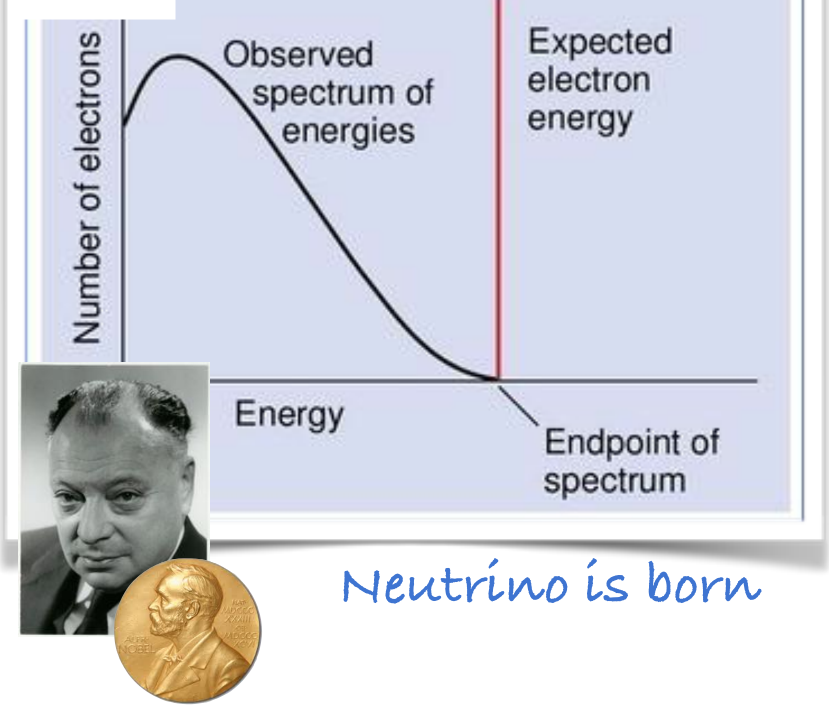
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12}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





Neutrino MEMORY LN

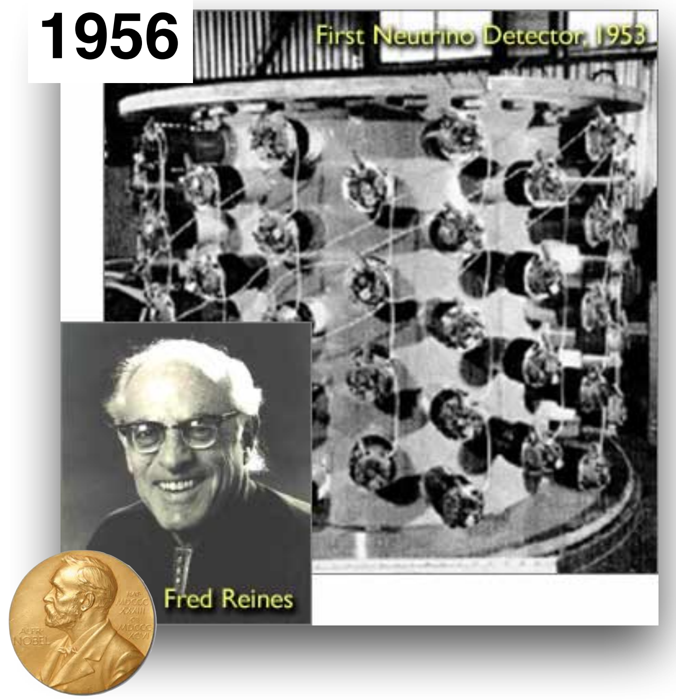
1930



Neutrino is born

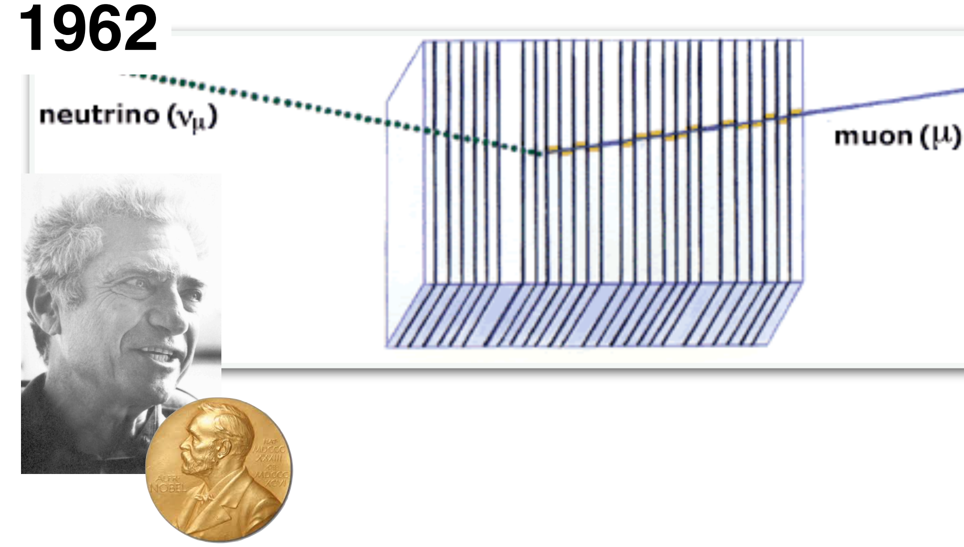
First observation of neutrinos

1956



Muon neutrino is discovered

1962

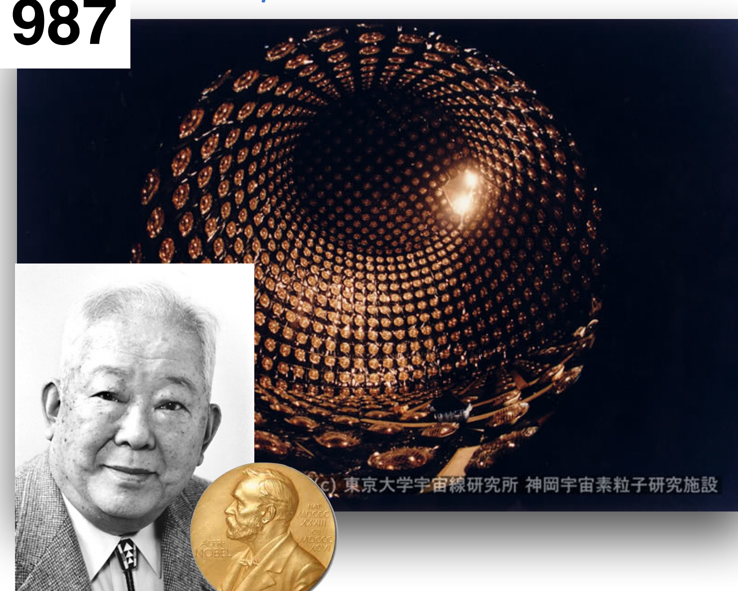


1968

The solar neutrinos problem

Supernova neutrinos

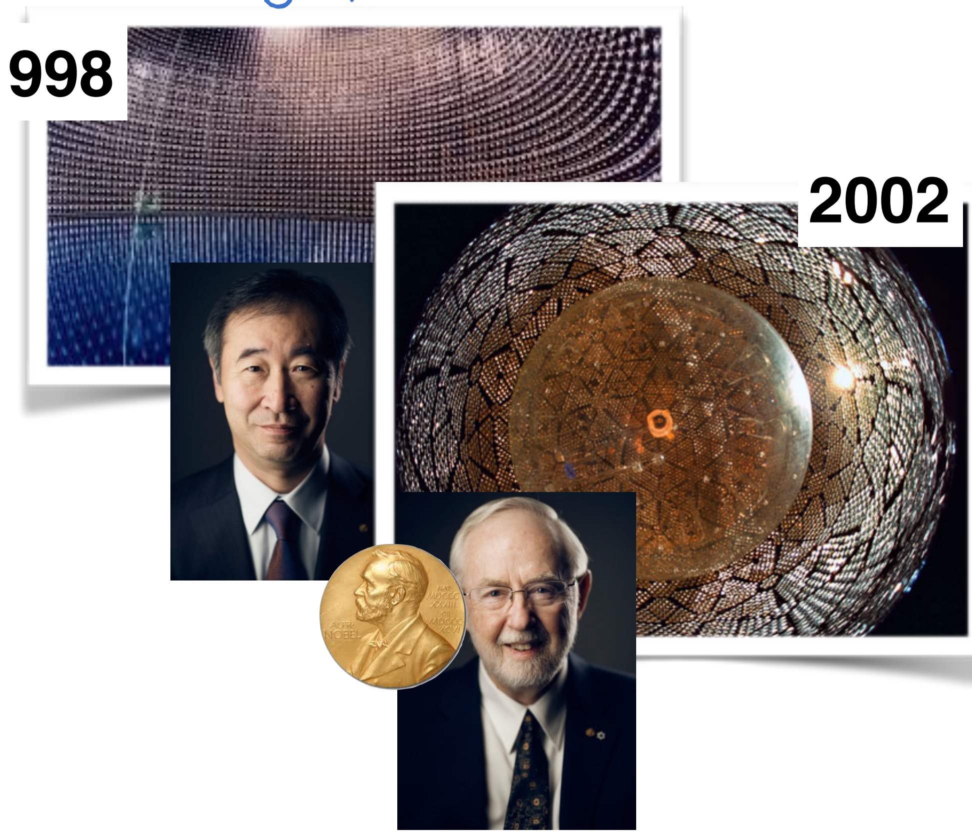
1987



Discovery of neutrino's oscillations

1998

2002

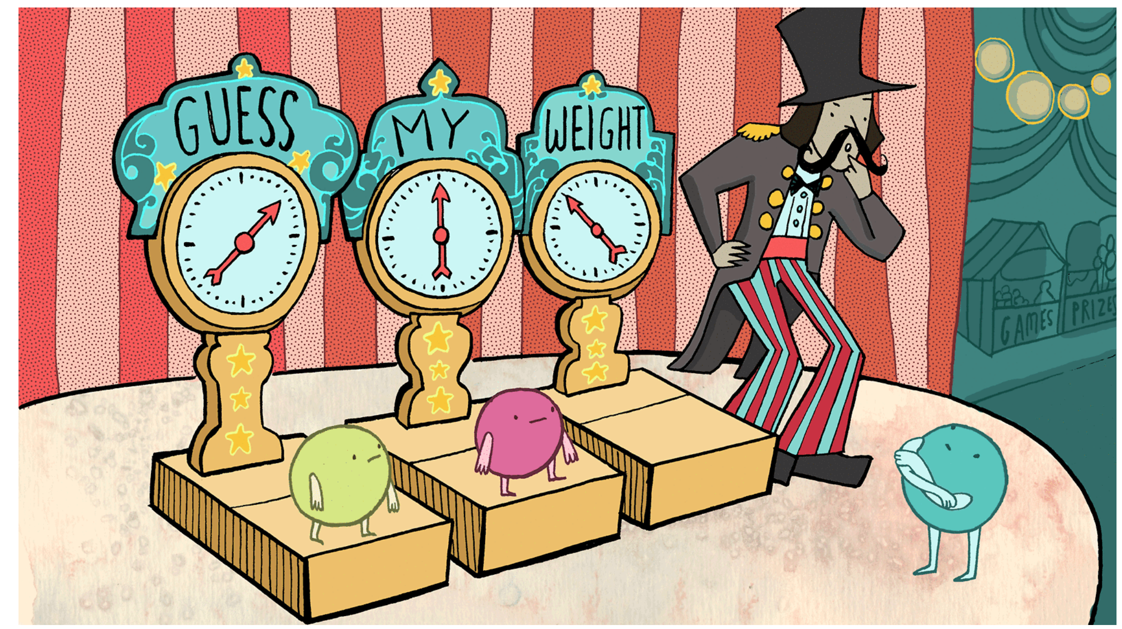


And now?

We know that neutrinos change flavour

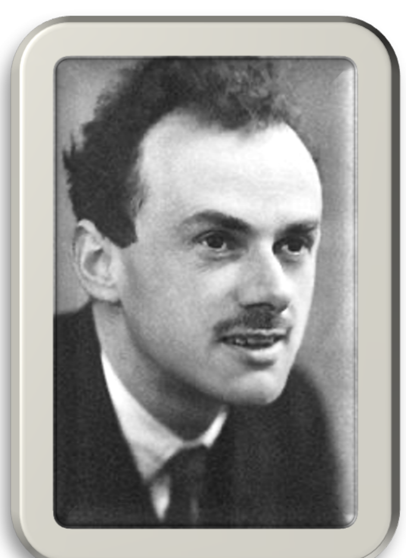
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

We still don't know their mass



Artwork by Sandbox Studio, Chicago with Corinne Mucha

What is the origin of the neutrino mass?



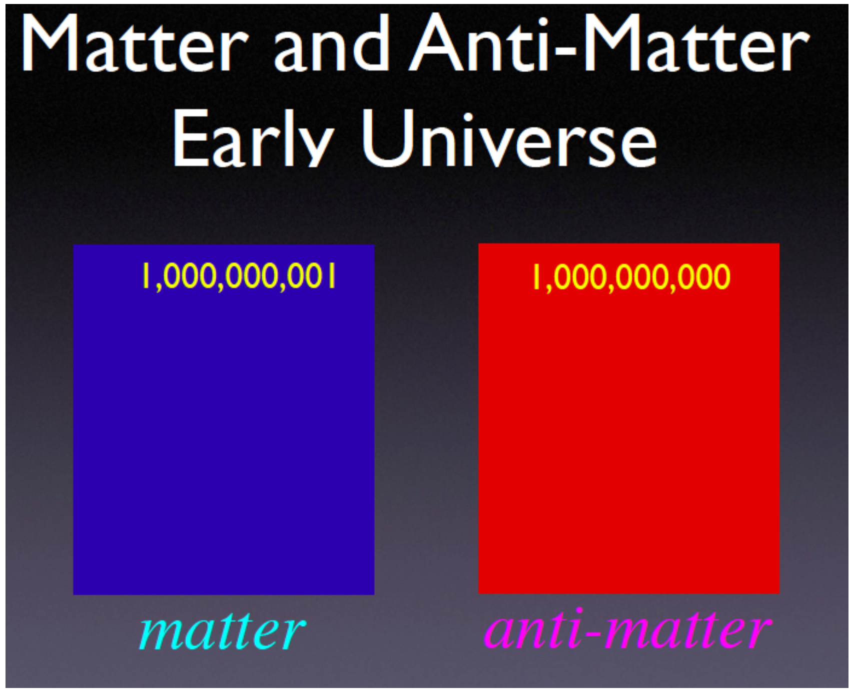
Dirac

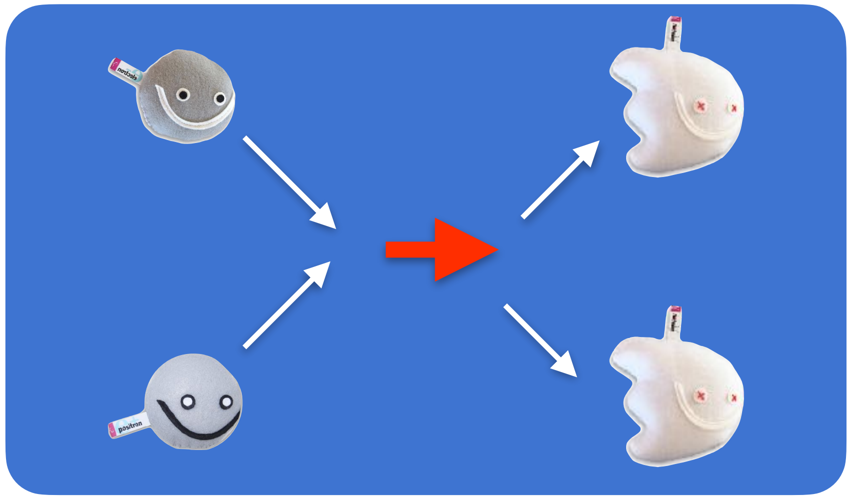
Majorana

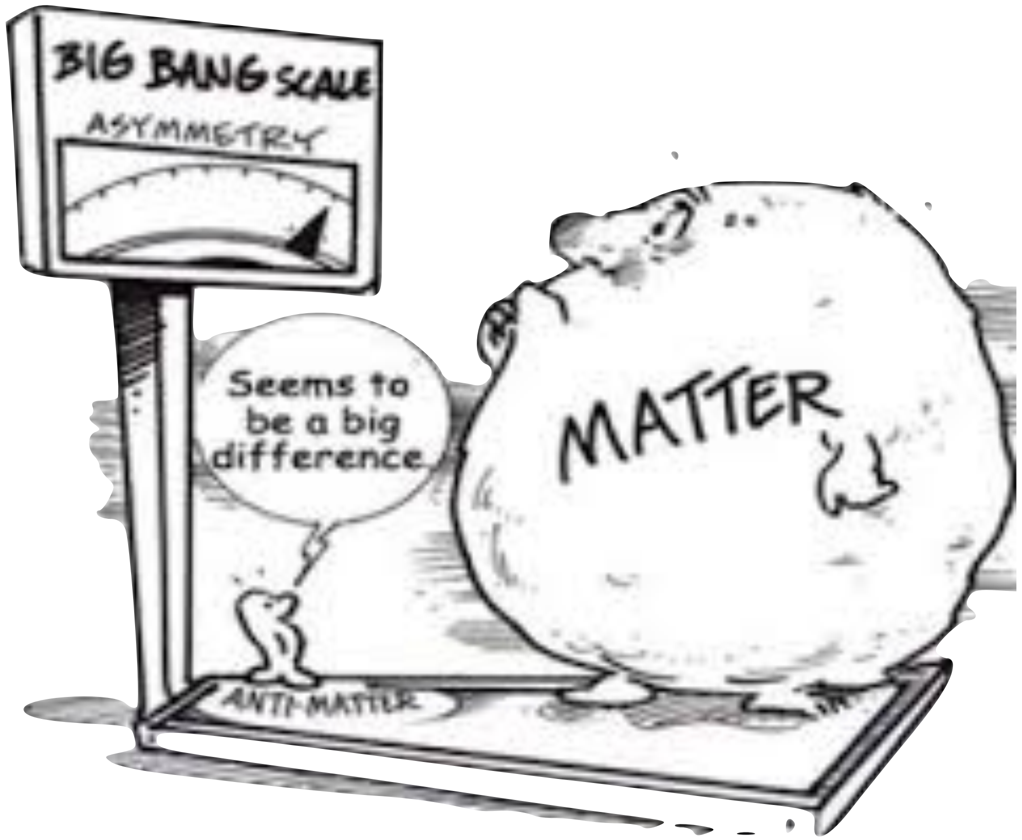
Majorana and Dirac proposed two different answers to the question of whether neutrinos and antimatter neutrinos are different particles or a single particle masquerading as two. As of today the topic remains an open question.

Majorana

Majorana neutrinos might explain the matter antimatter asymmetry of the Universe








NEXT BIG THING
AHEAD

2. Large Scale experiments looking for neutrinos:

SNO+ & DUNE

★ Neutrinos have a very small interaction probability:

- The probability for a neutrino to interact in the Sun is extremely small: 10^{-42} cm^2
  - You need more than 10^{16} neutrinos to observe 1 neutrino/s in 10 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

Detecting Neutrinos

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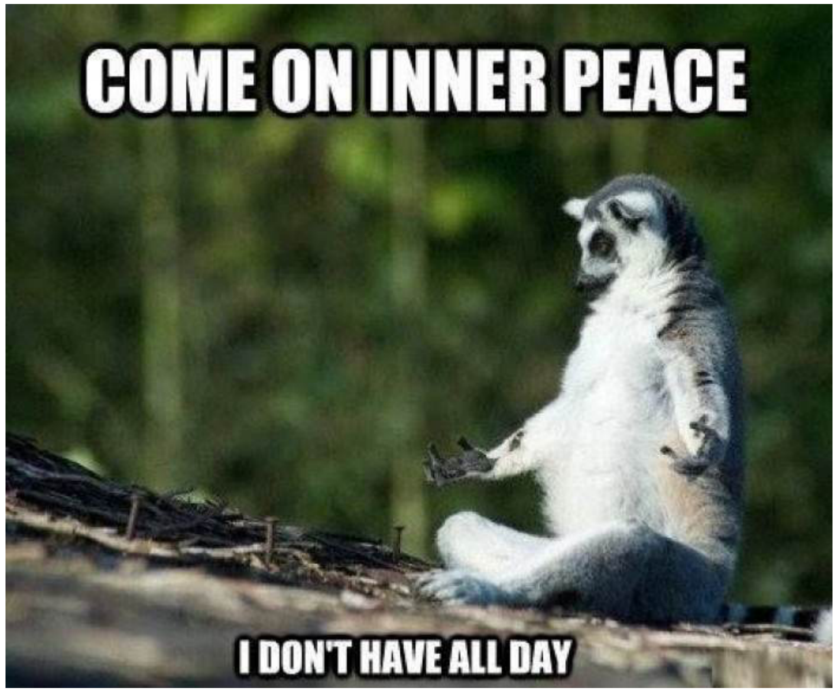

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★ So how do we study neutrinos?

- 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)

Where we operate

SNO+

LIP Coimbra
LIP Lisboa

SNOLAB
TRIUMF
University of Alberta
Queen's University
Laurentian University

UNAM

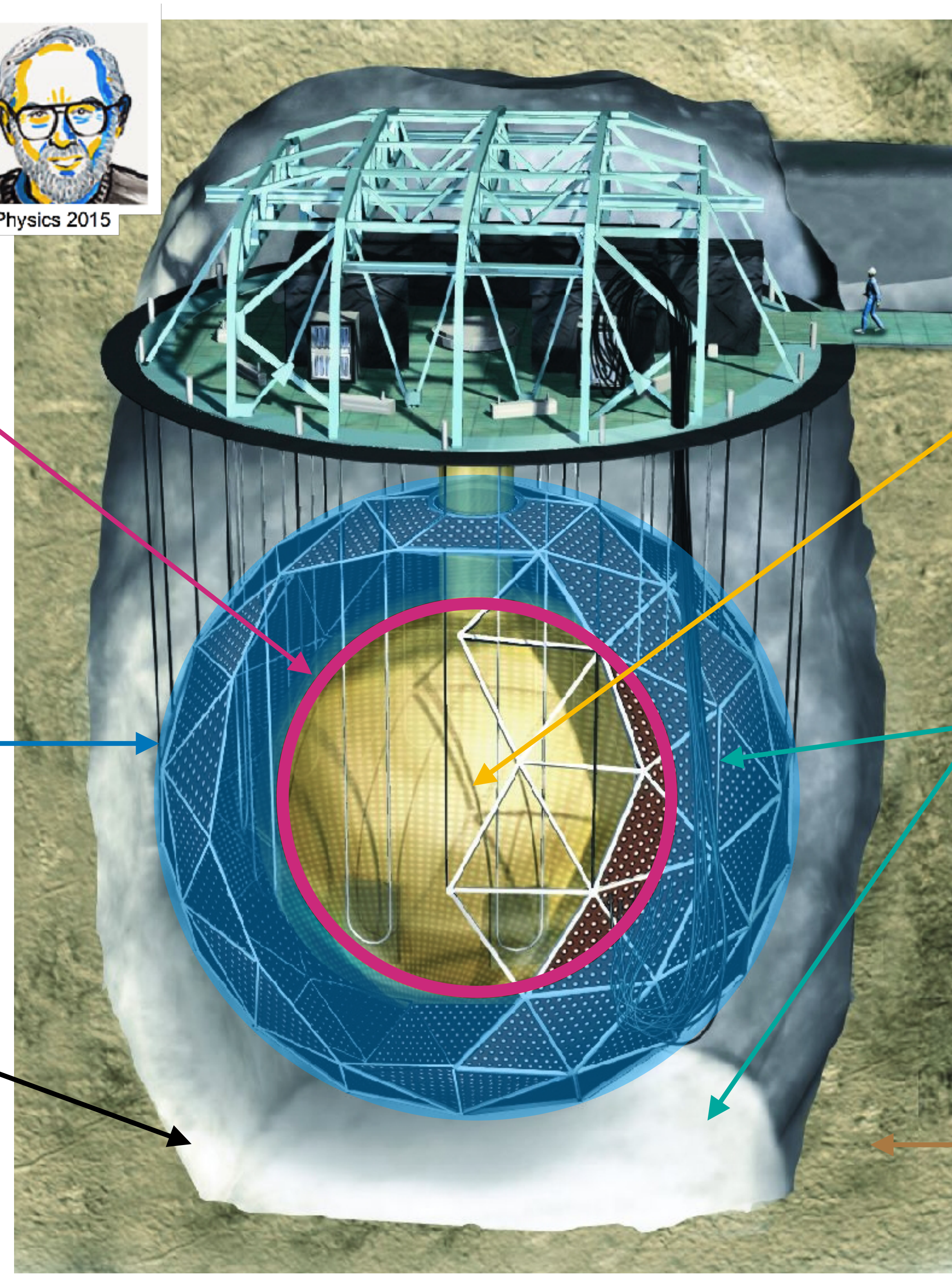
TU Dresden

Boston University
BNL
University of California Berkeley
LBNL
University of Chicago
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

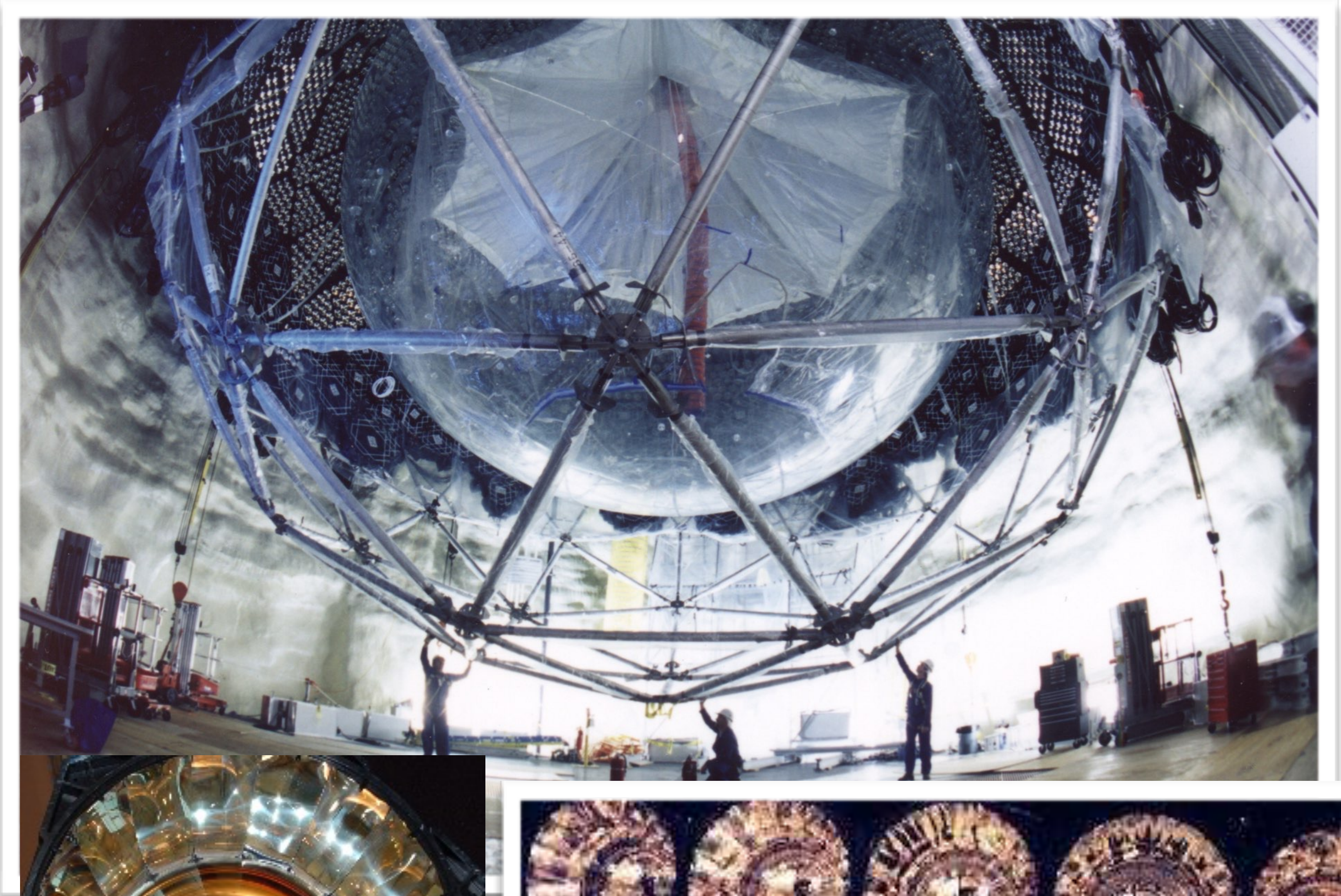
PSUP (PMT Support Structure)
~ 9300 PMTs
54% Coverage

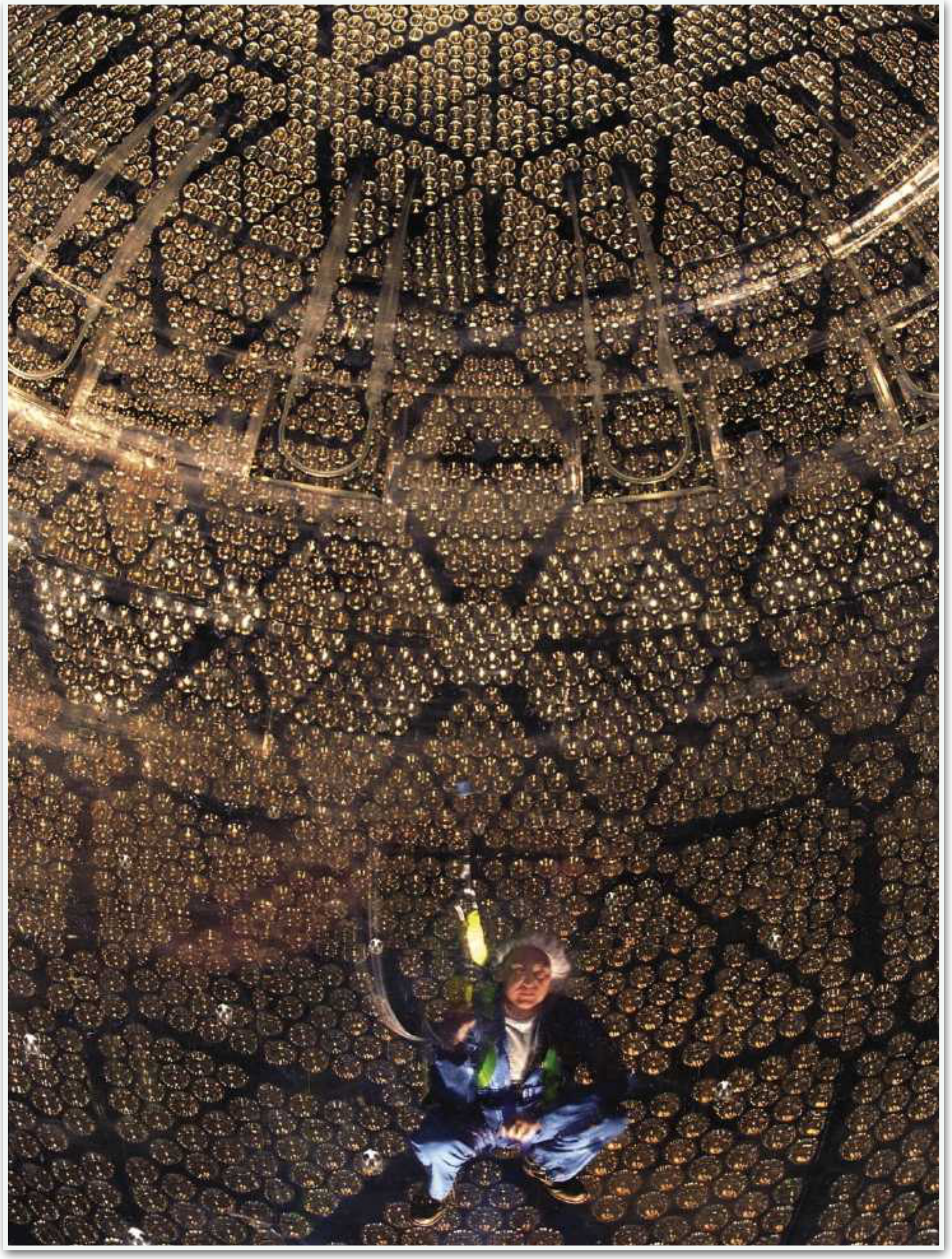
Light water (H2O) shielding
- 1700t internal
- 5300t external

Urylon layer/Radon seal

Norite Rock

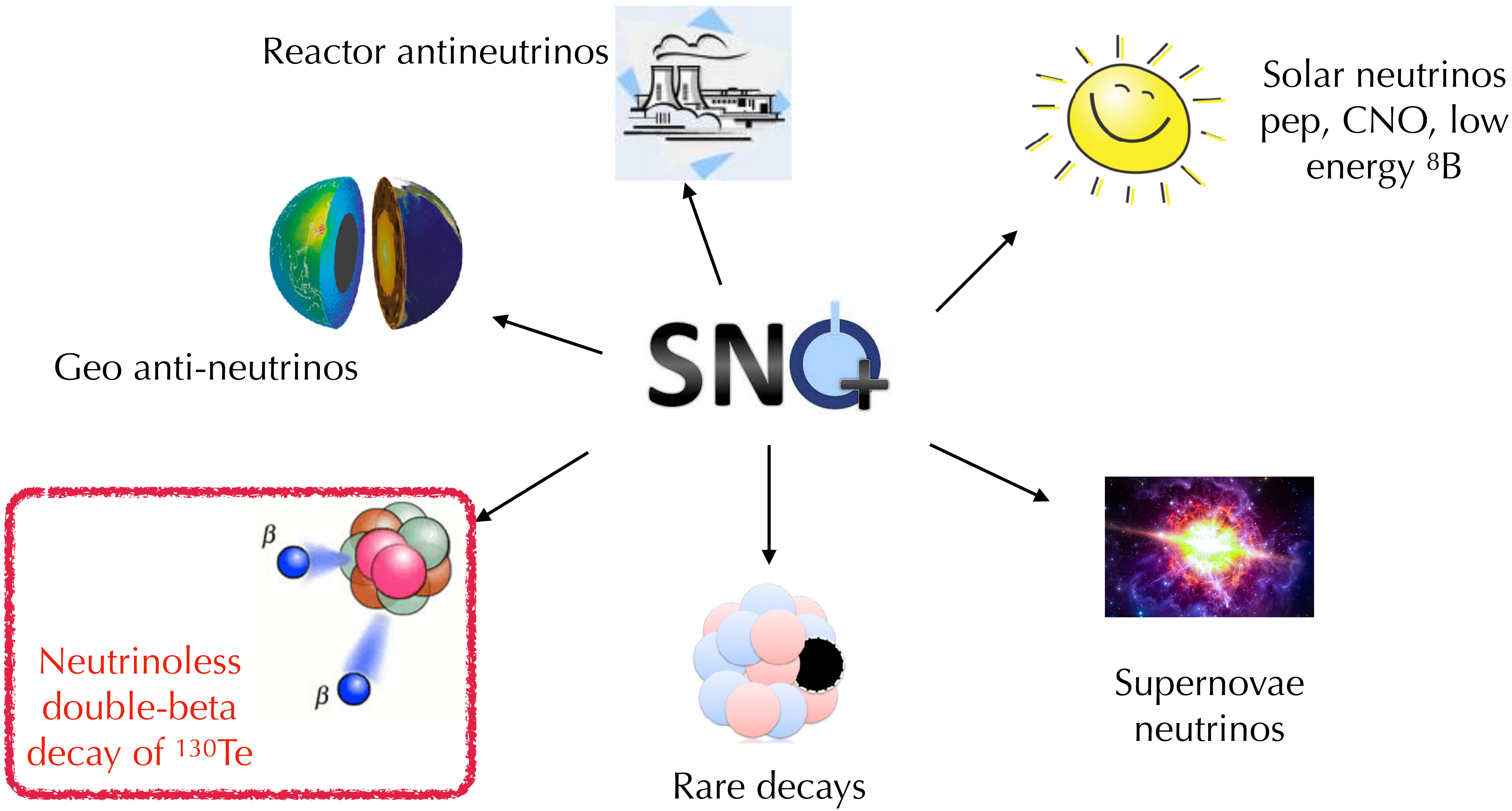
Construction





WHAT IS SNO+?

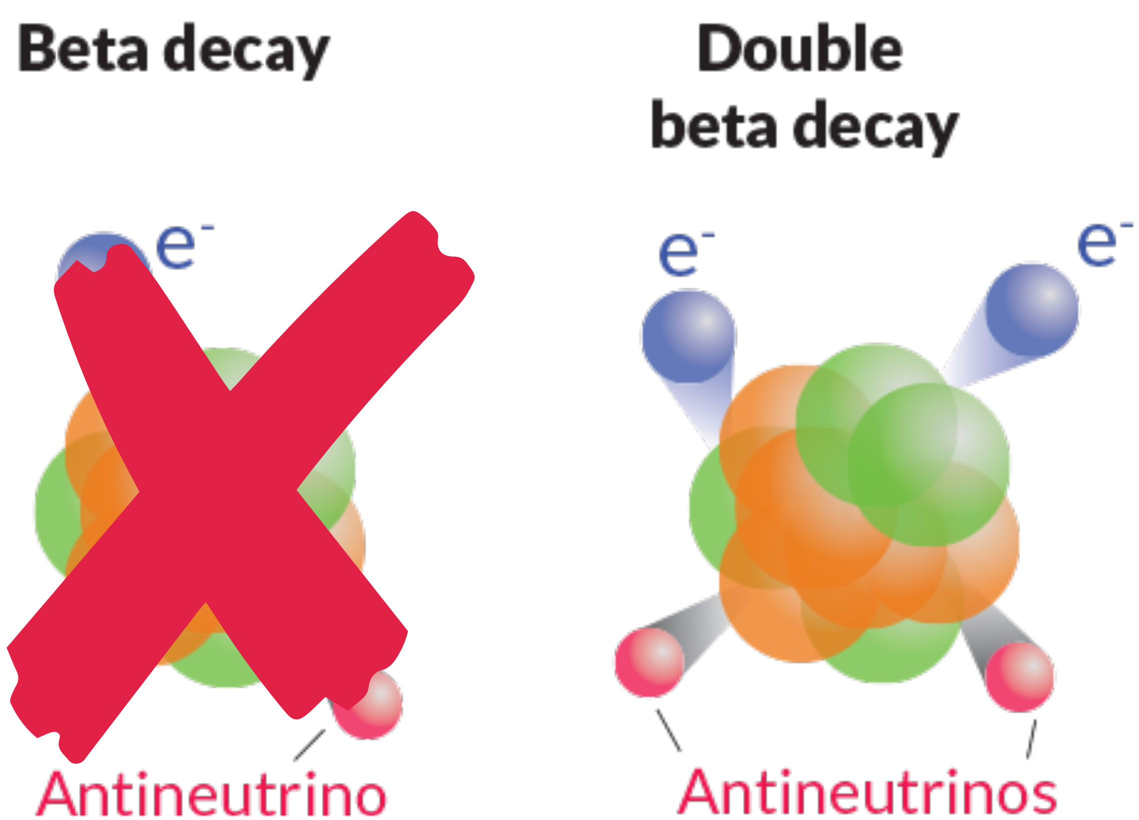
★ A very large detector that searches for the nature of neutrinos

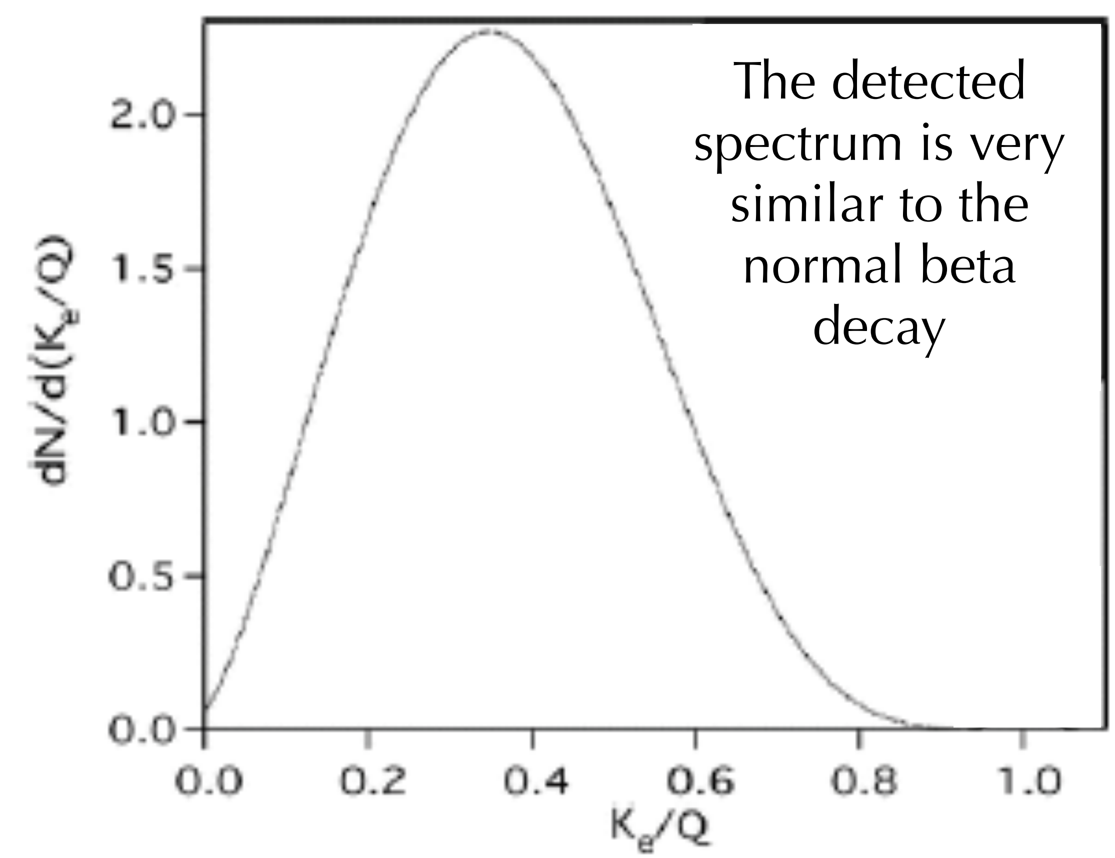


The 0vbb Decay

★ 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





The 0νββ Decay

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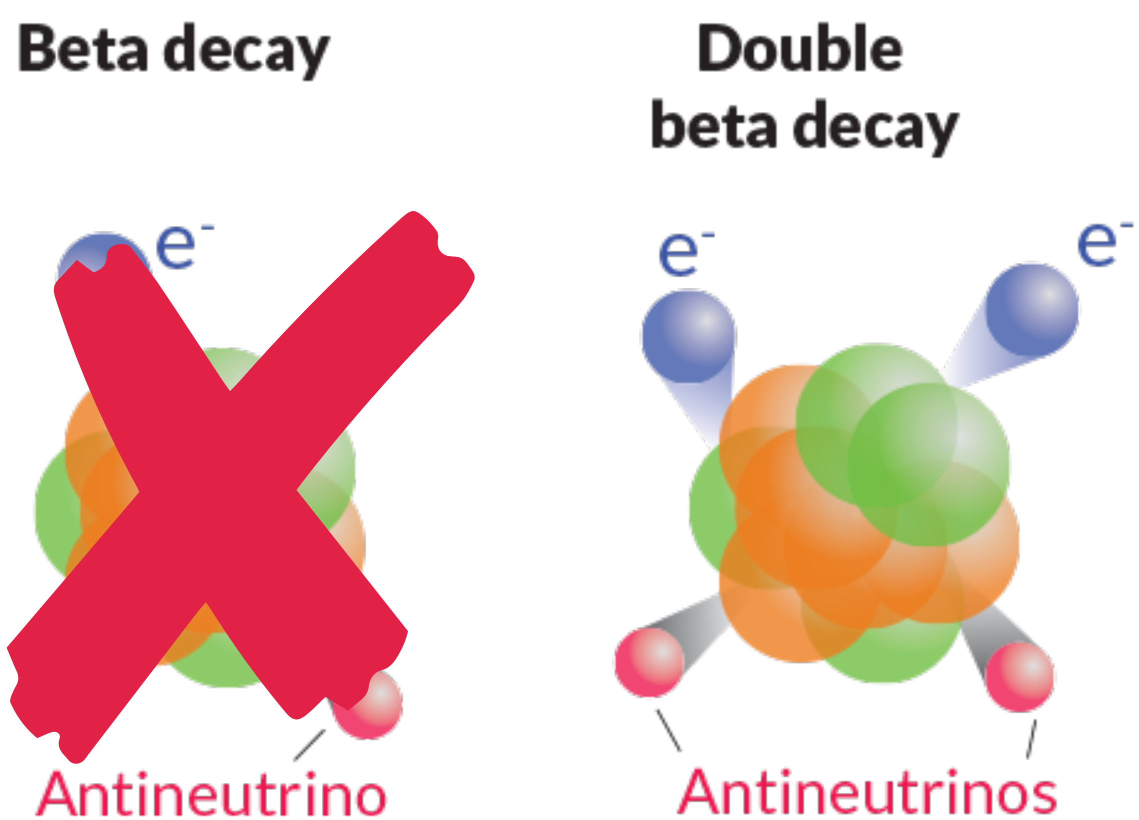

Only ~35 isotopes do this!!!!!
Decay scale is 10^{20} yrs

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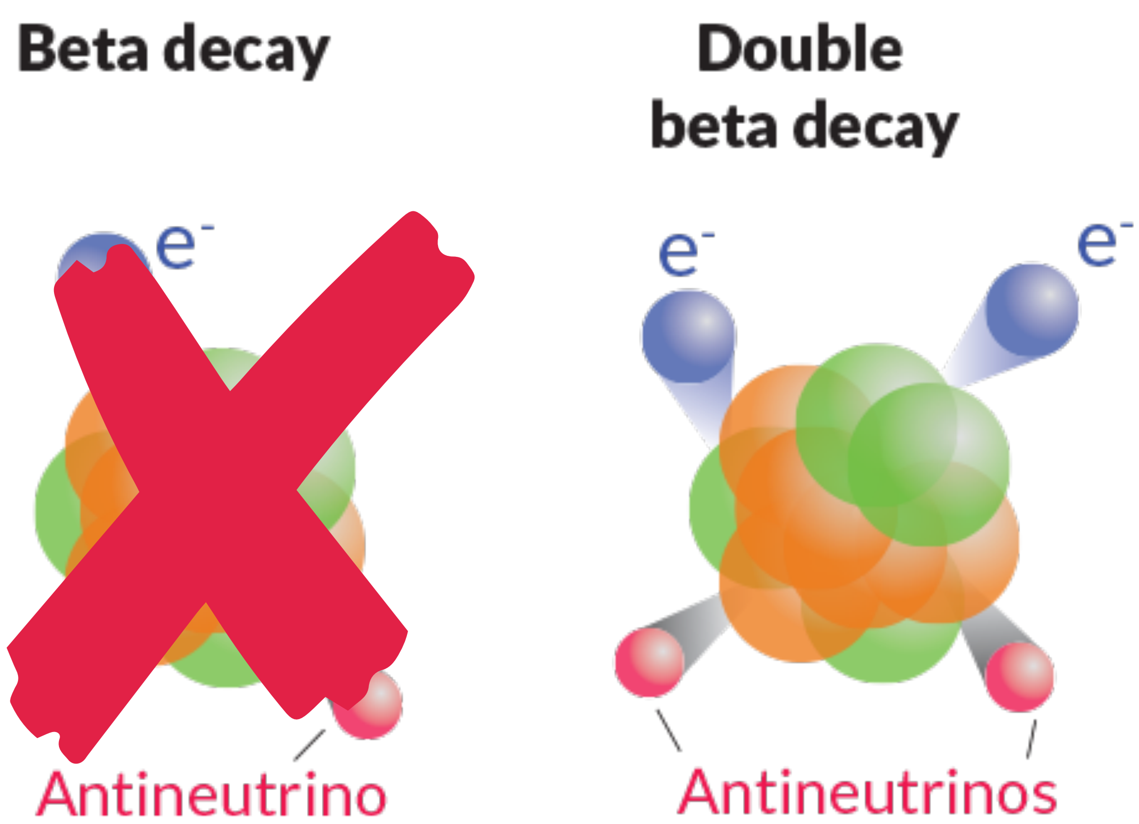
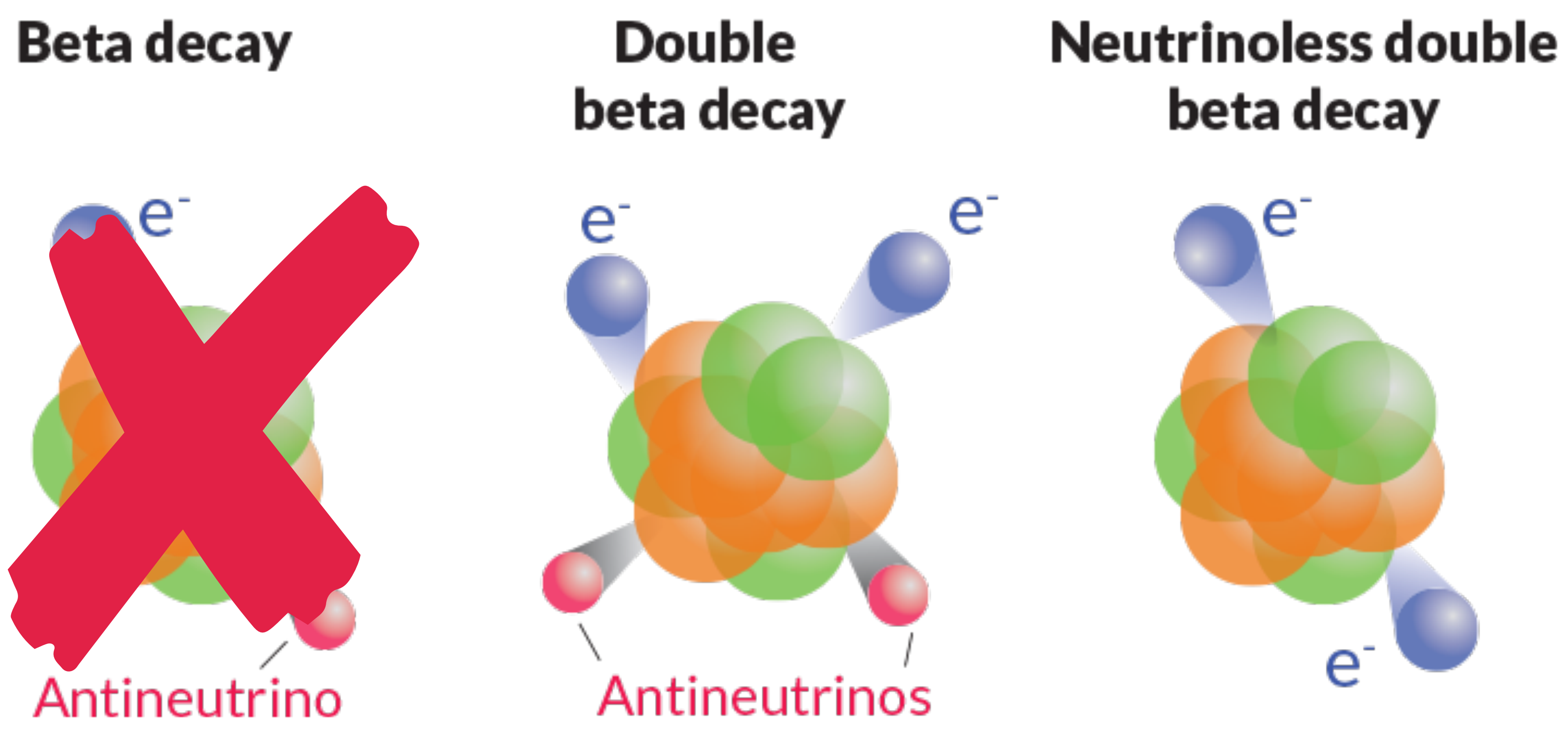


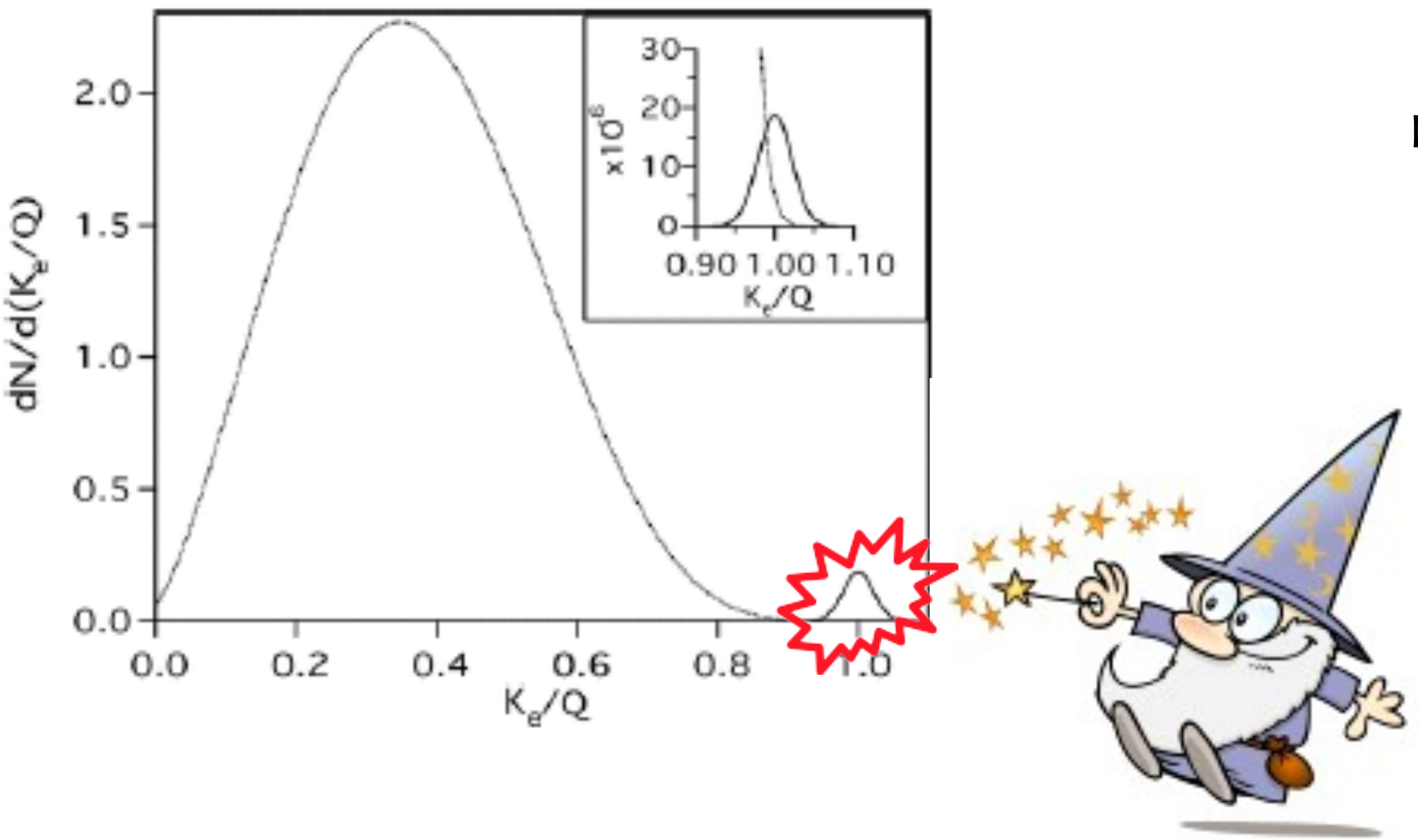
Only ~35 isotopes do this!!!!!
Decay scale is 10^{20} yrs

★ But we want to go further:



Only happens if neutrinos are Majorana

★ In this case the decay spectrum is very different and looks like the 2 body-decay



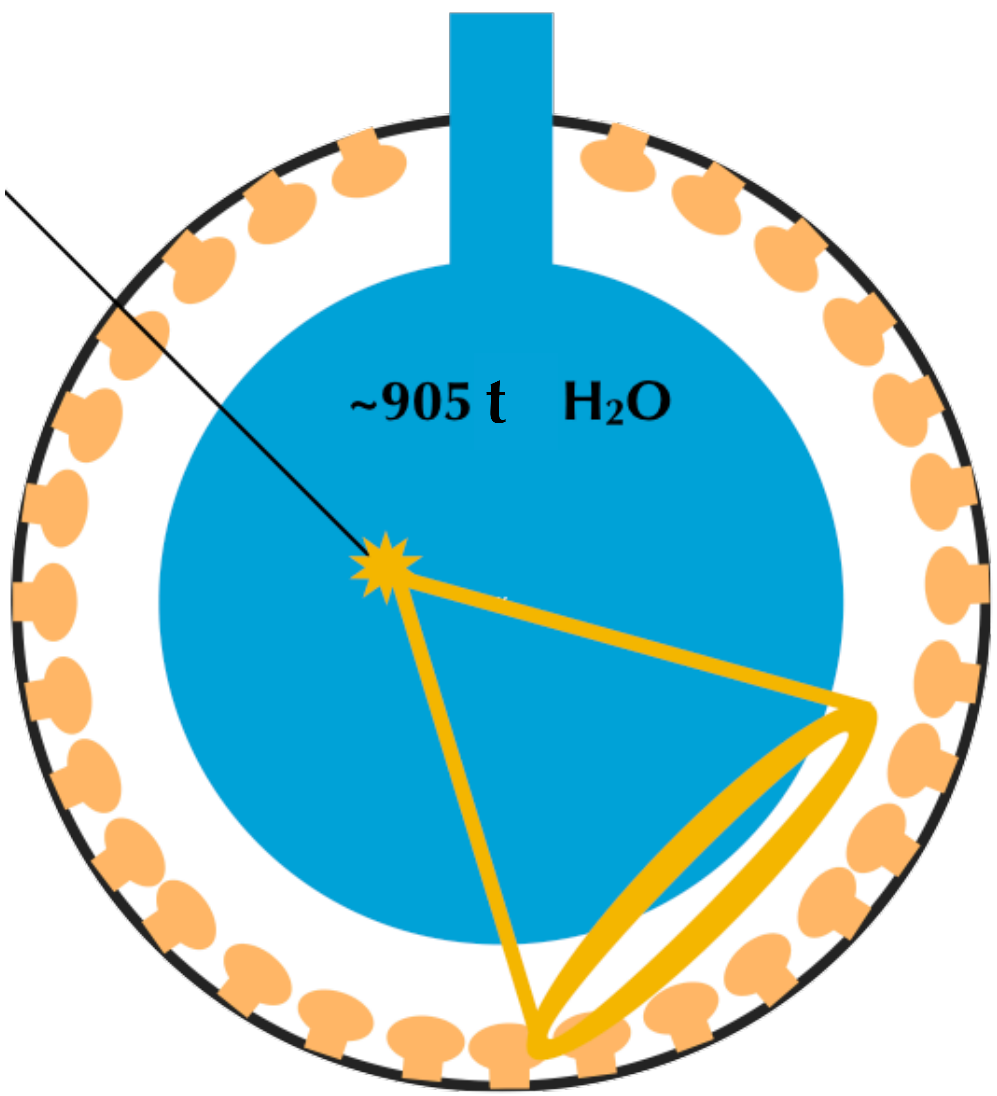
Not seen yet!
Decay scale is >10^{25} yrs

This is what we search for in SNO+

Timeline

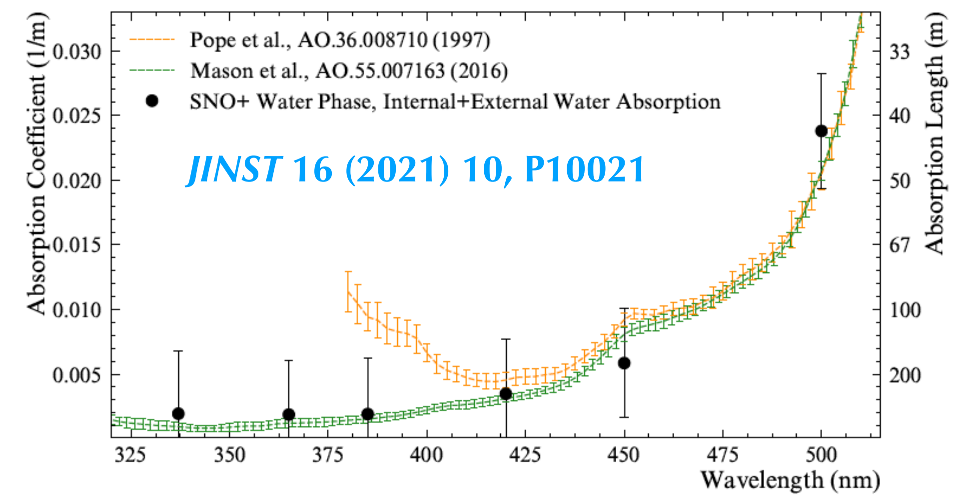
2016 2017 2018 2019 2020 2021 2022 2023

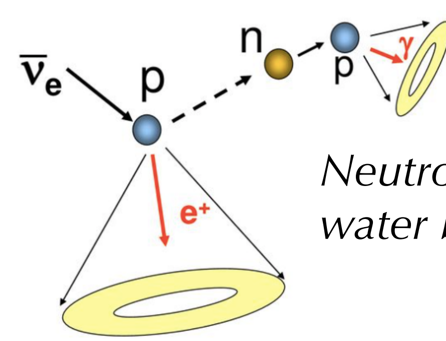
Water Phase



Several publications:

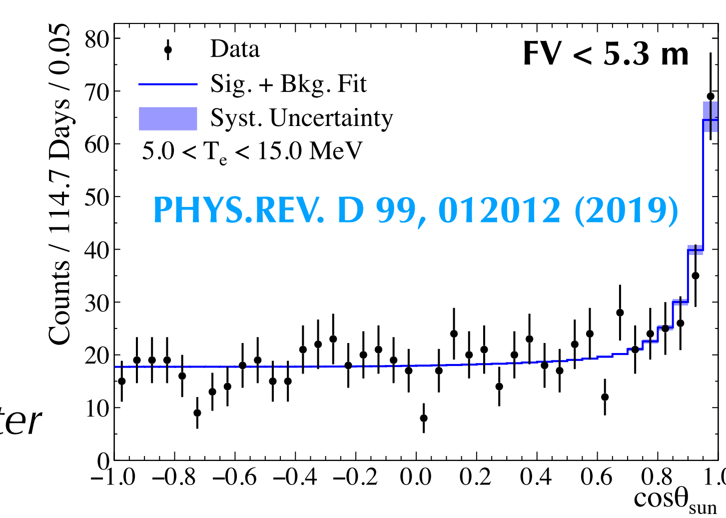
Optical properties of water and acrylic





Phys. Rev. C 102, 014002 (2020)

Neutron capture efficiency: best for a water based detector!

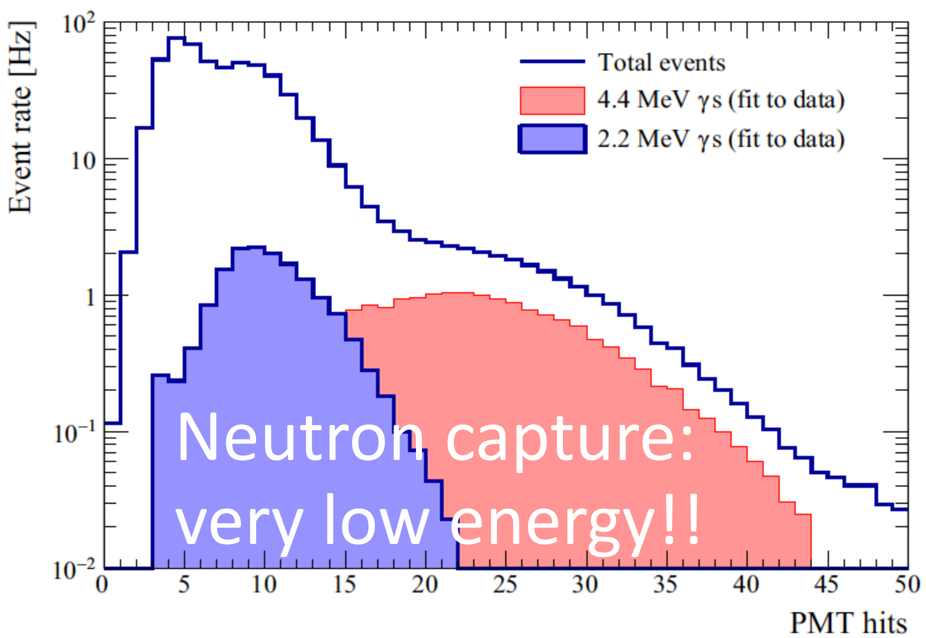


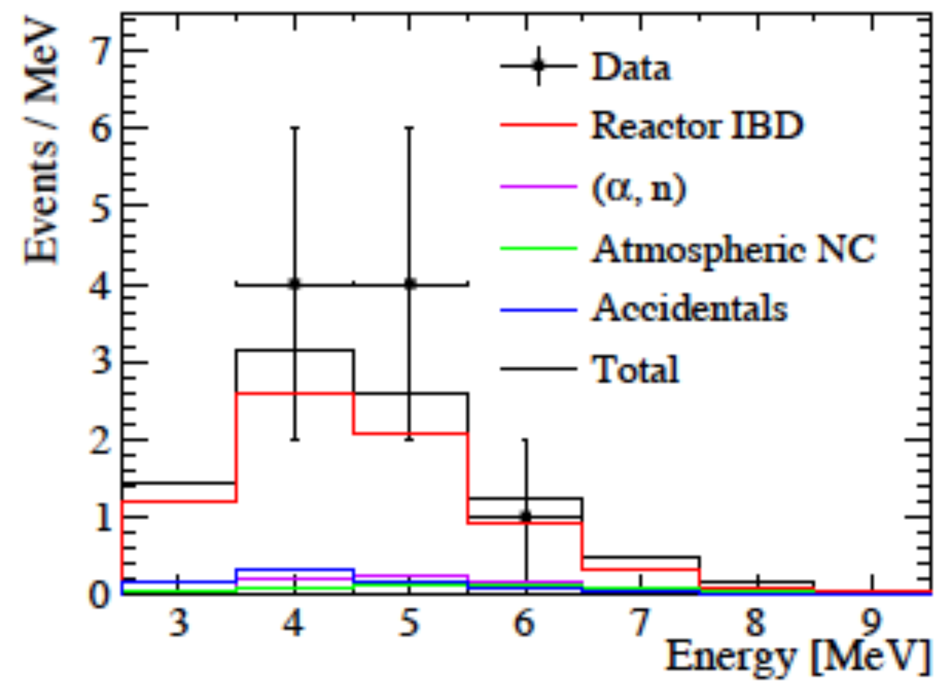
Solar neutrinos in water

Timeline

2016 2017 2018 2019 2020 2021 2022 2023

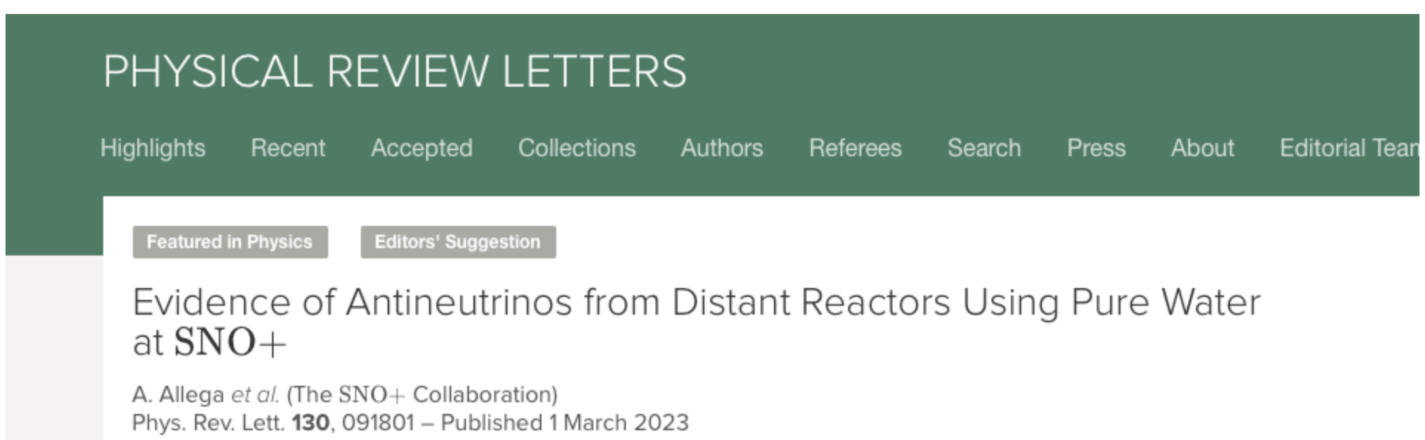
Several publications: Water Phase





First evidence of reactor antineutrinos in a Cherenkov detector (featured article!)

Best neutron response of any H_2O Cherenkov detectors (crucial to anti-neutrino signal)



PHYSICAL REVIEW LETTERS

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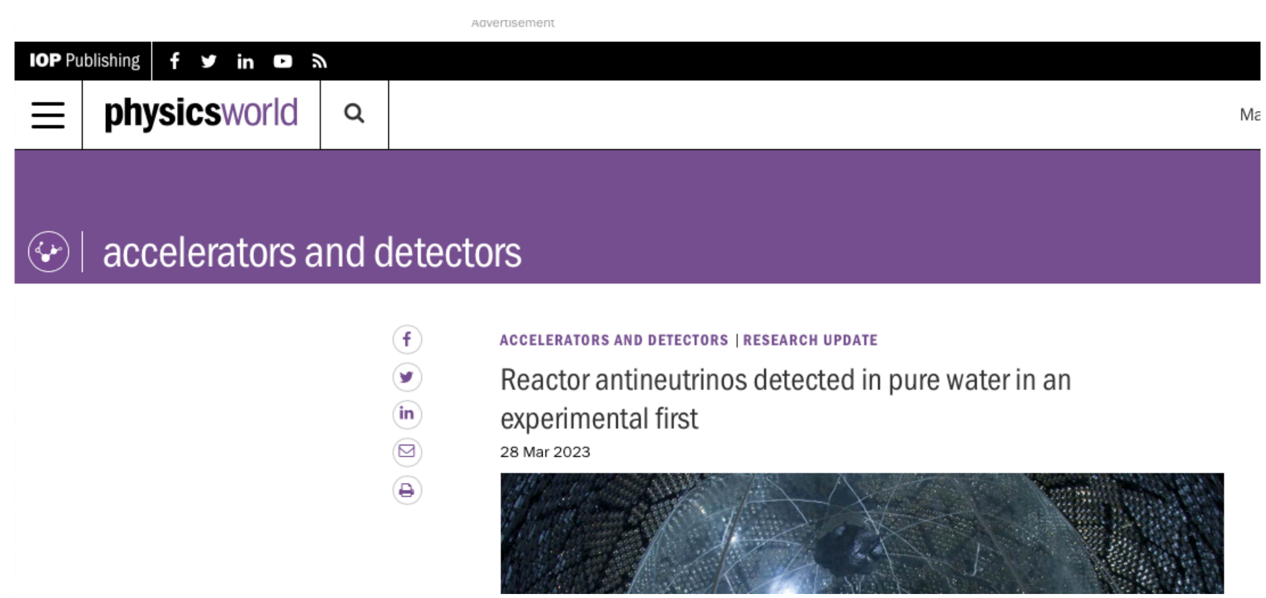
Featured in Physics Editors' Suggestion

Evidence of Antineutrinos from Distant Reactors Using Pure Water at SNO+

A. Allega *et al.* (The SNO+ Collaboration)
Phys. Rev. Lett. **130**, 091801 – Published 1 March 2023



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physicsworld

accelerators and detectors

ACCELERATORS AND DETECTORS | RESEARCH UPDATE

Reactor antineutrinos detected in pure water in an experimental first

28 Mar 2023

Timeline

2016 2017 2018 2019 2020 2021 2022 2023

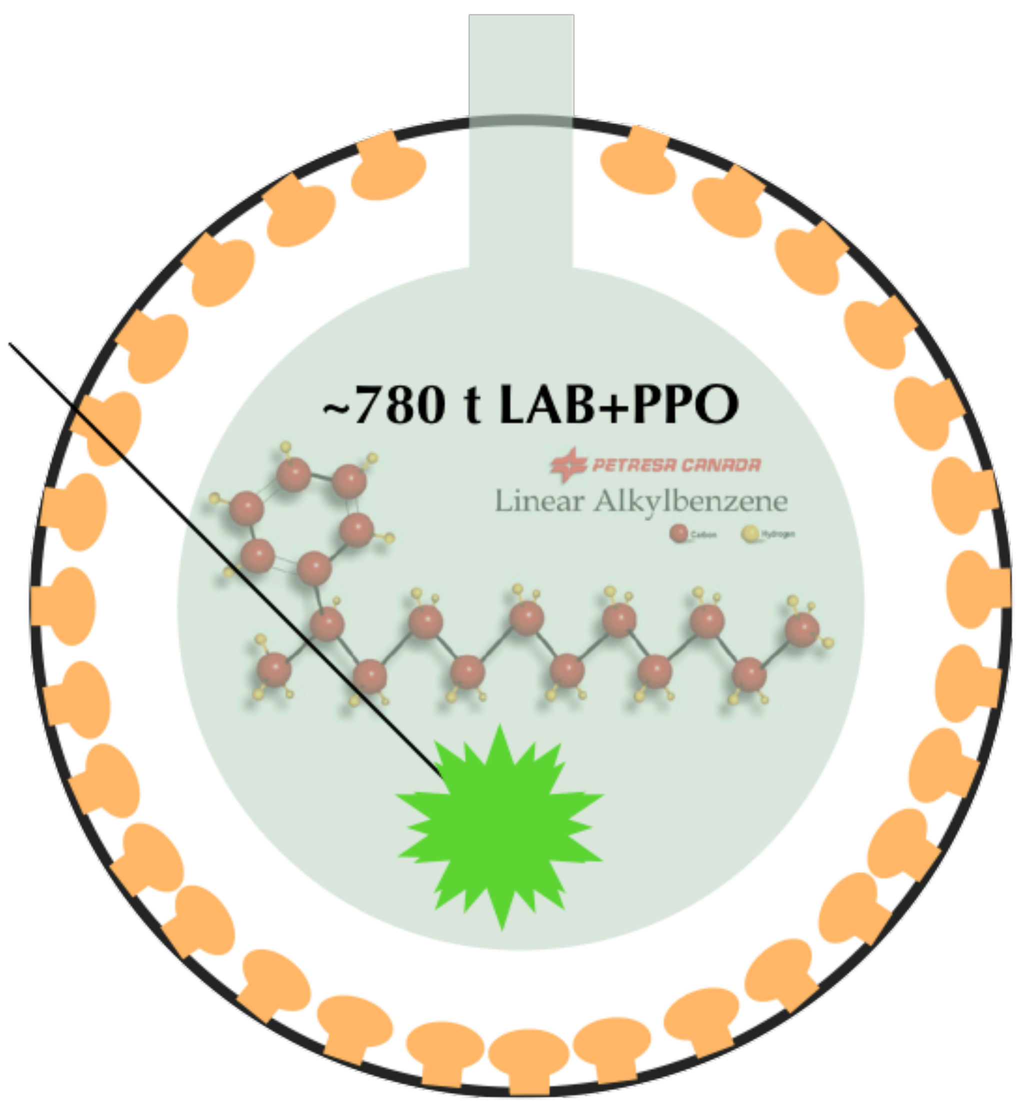
Scintillator Phase

We are here

2020

March-October 2020
"Partial fill" data phase

April 2022
Full PPO concentration
Official start of the scintillator phase



Timeline

2016 2017 2018 2019 2020 2021 2022 2023

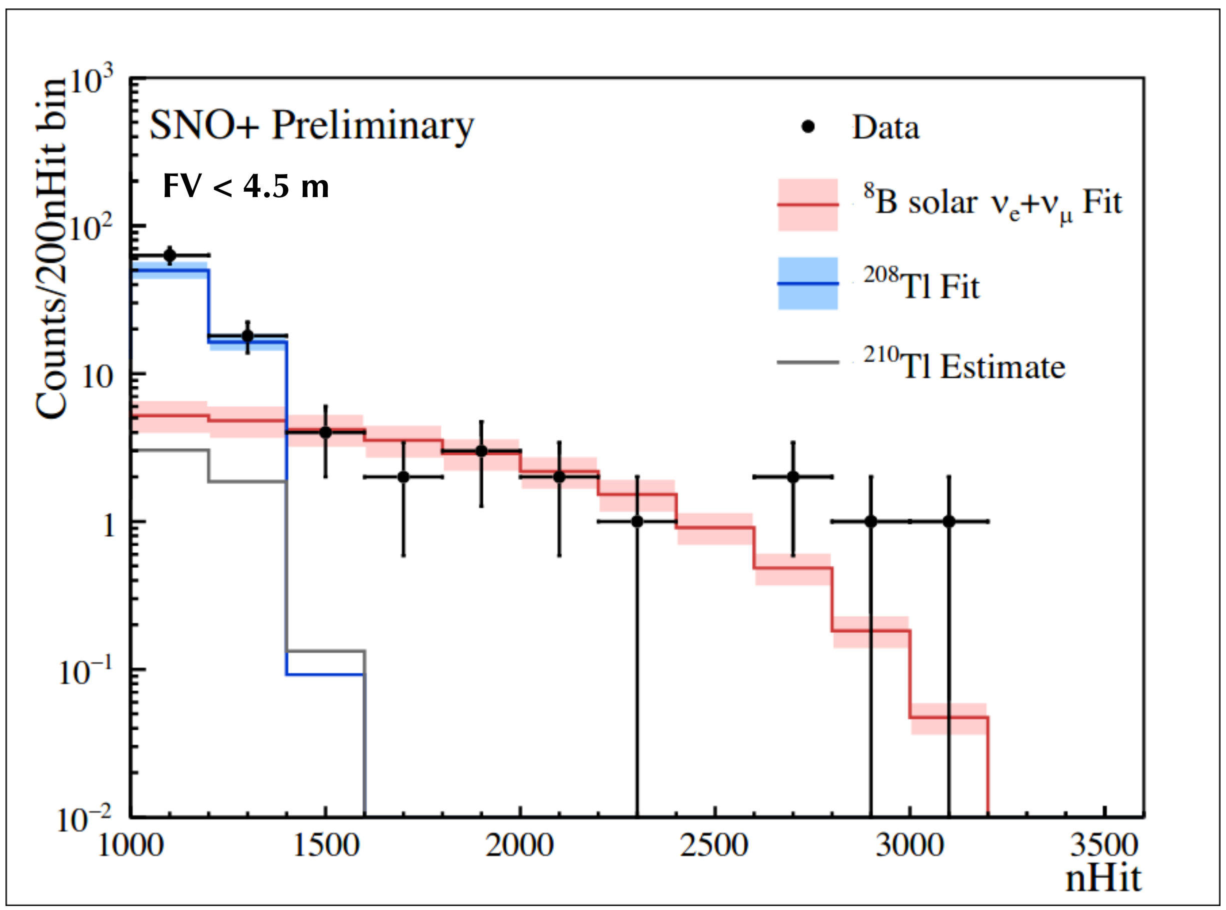
Scintillator Phase

2020

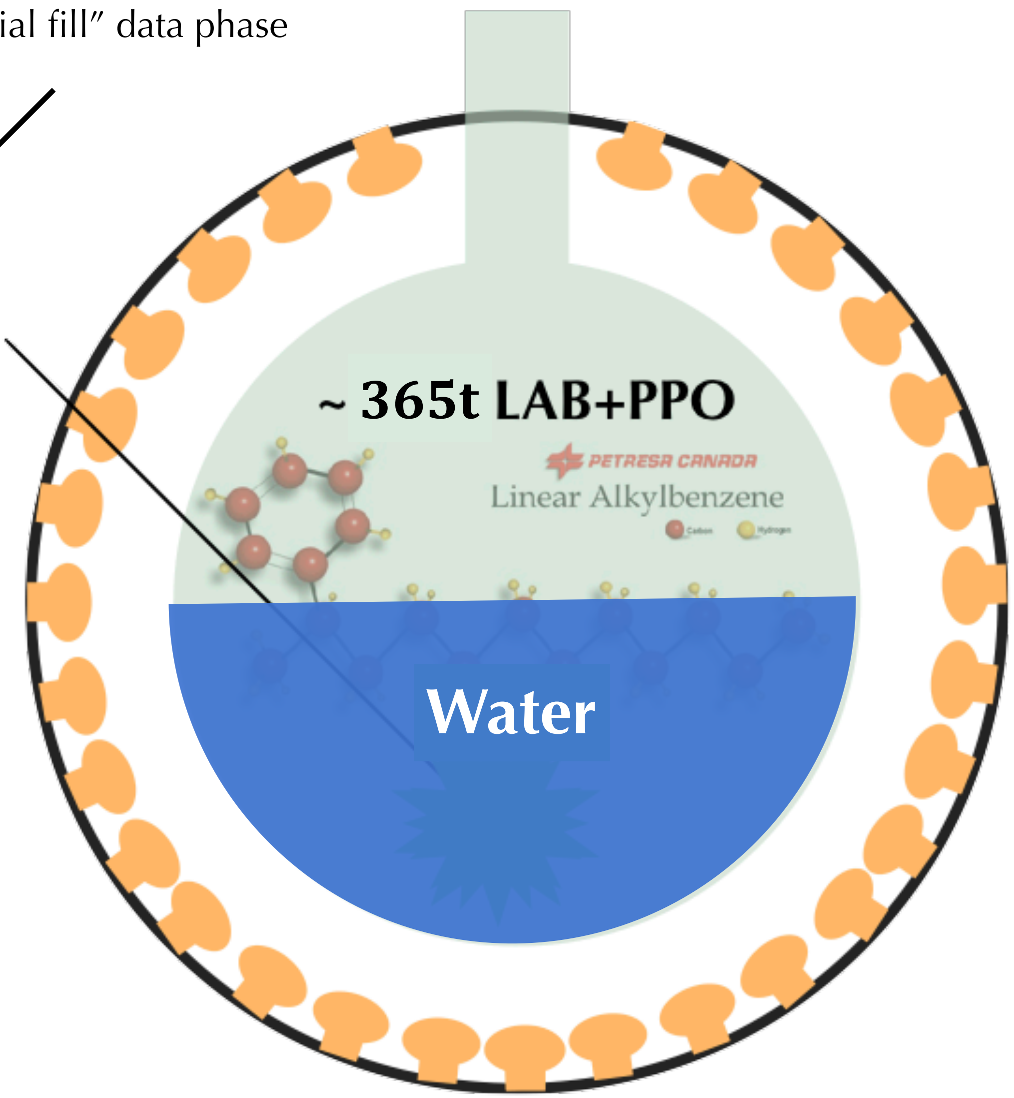
We are here

	$\Phi_{^8B}$
R = 4.5 m	$6.45\times10^{6}\ ^{+26.2\%}_{-22.4\%}(stat.)\ ^{+8.8\%}_{-11.5\%}(syst.)$ cm^{-2} s^{-1}

March-October 2020
“Partial fill” data phase



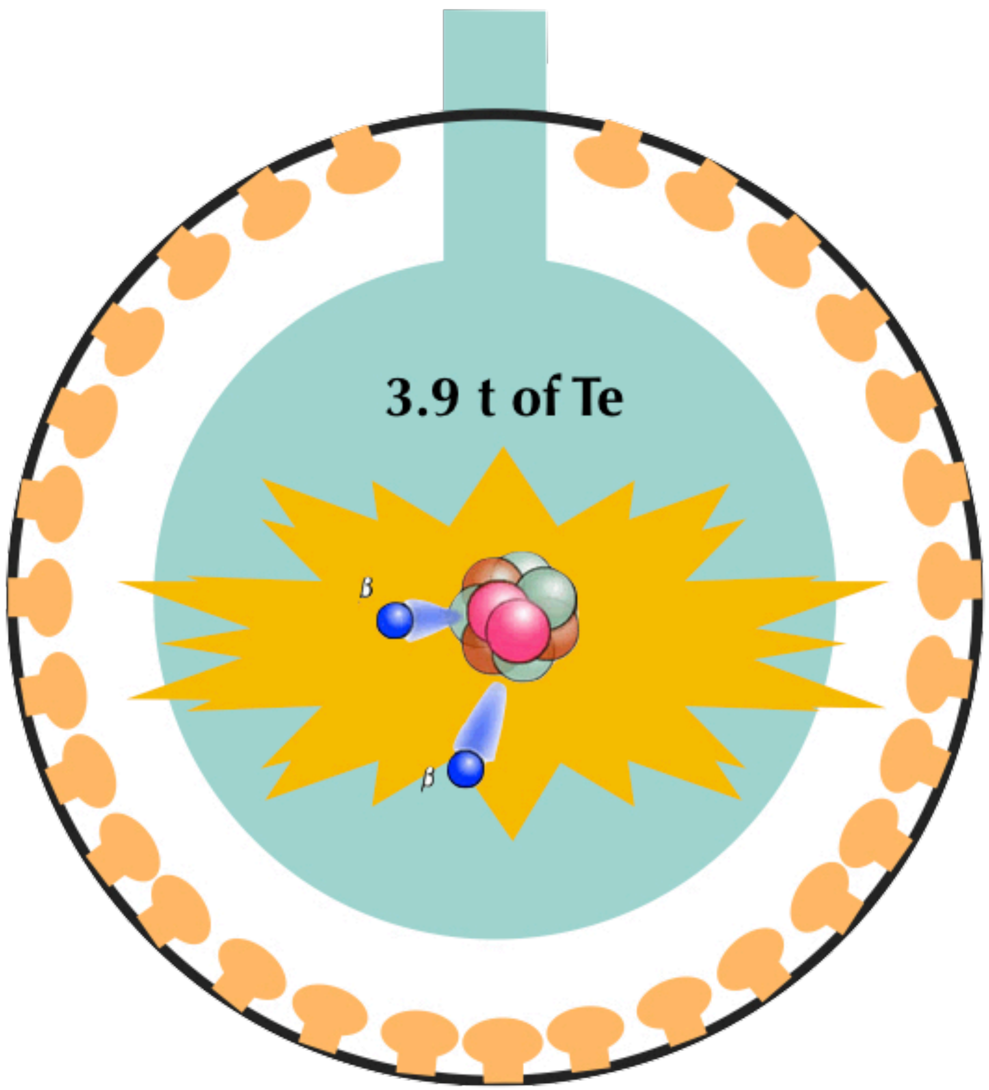
Solar neutrinos is scintillator

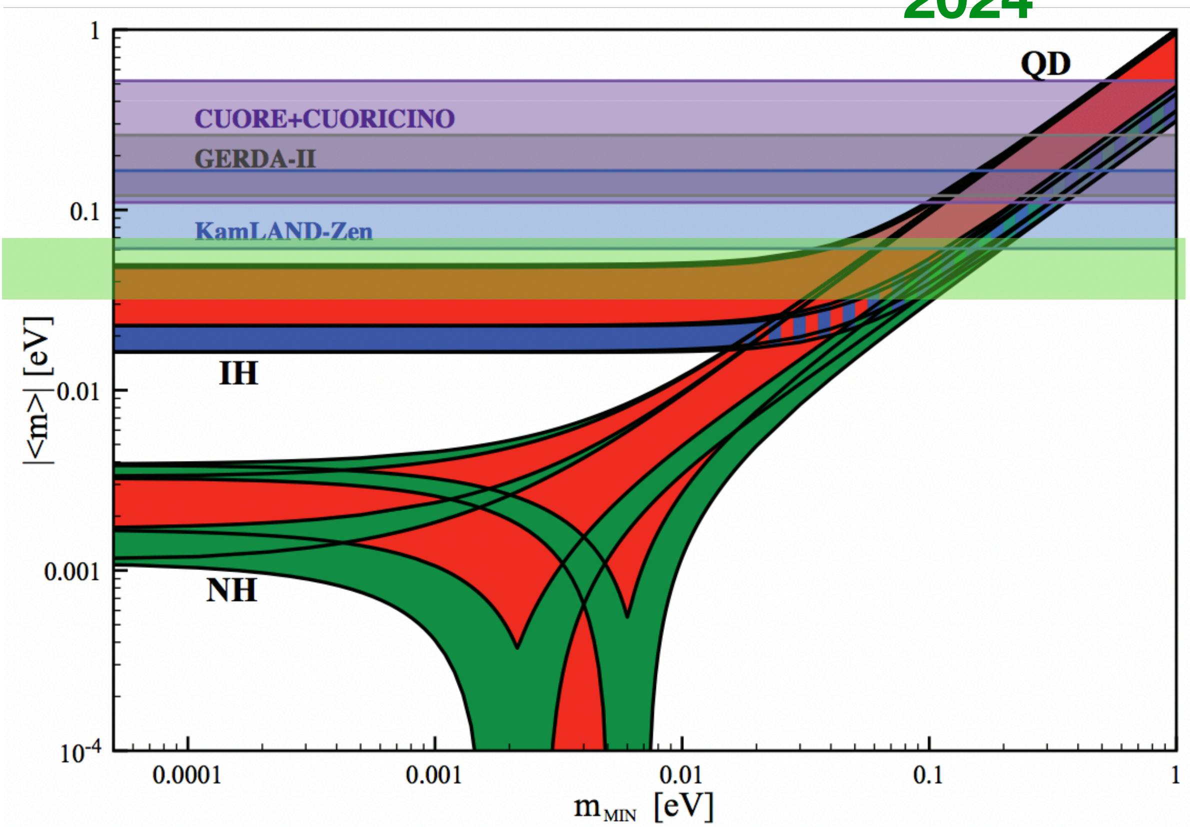


Timeline

2016 · 2017 · 2018 · 2019 · 2020 · 2021 · 2022 · 2023 · towards Te loading 2024

Neutrinoless Double-Beta Decay Phase



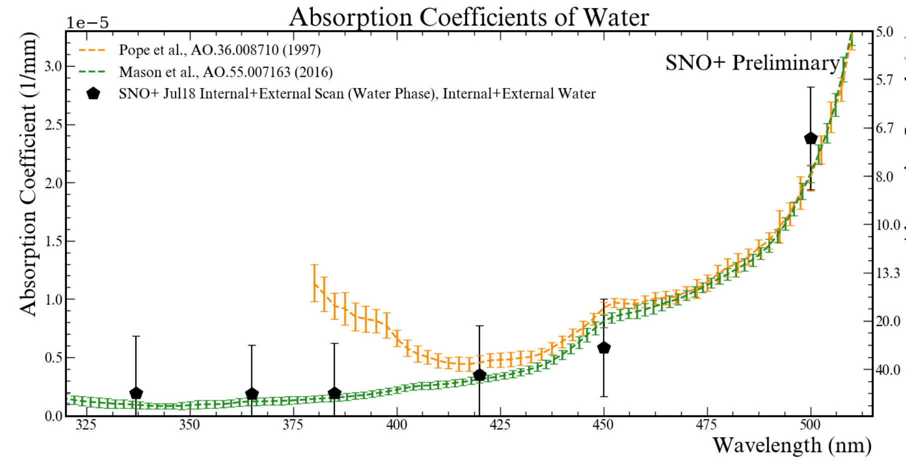


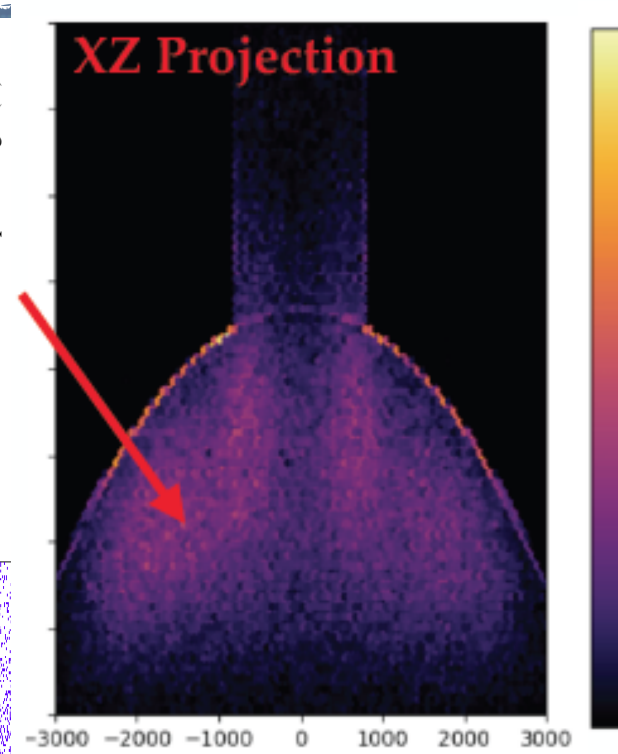
SNO+ Expectation after 5 years data taking:

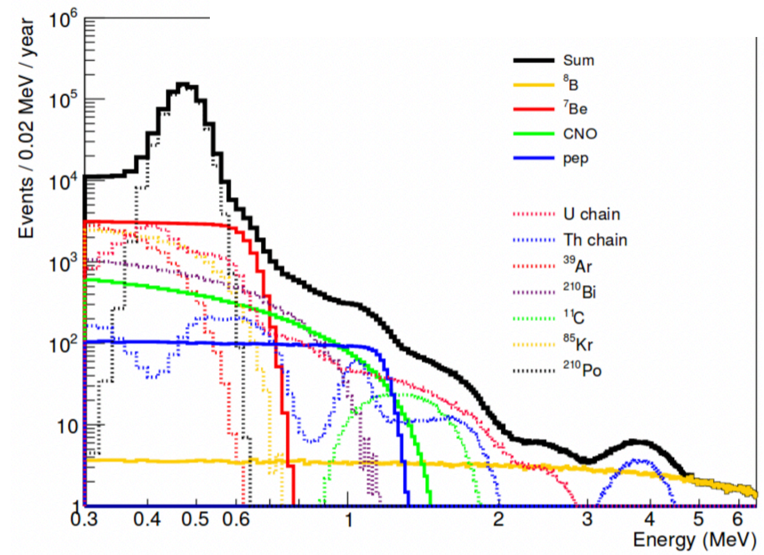
T1/2 > 2.1×10^{26} years
37 meV < $m_{\beta\beta}$ < 89 meV

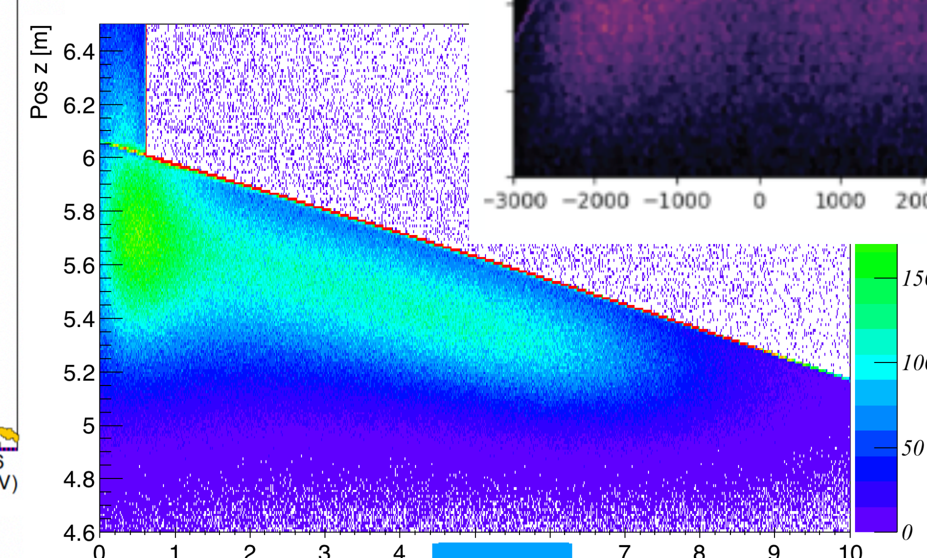
SNO+ Activities @ LIP

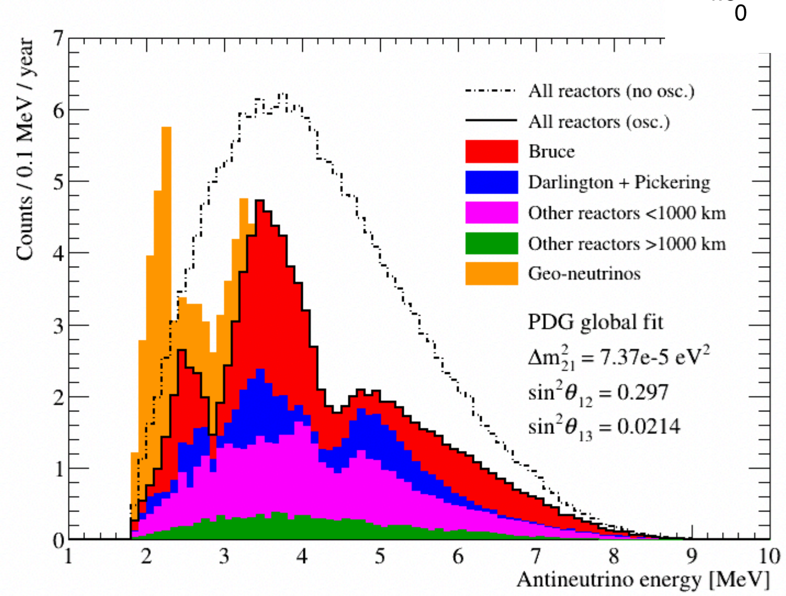
- ★ **Detector calibration**
  - Optical and Radioactive sources
- ★ **Background events**
  - Water/Scintillator characterisation
- ★ **Data analysis**
  - Cosmic muons in SNO+
  - Solar neutrinos
  - Reactor anti-neutrinos
  - 0vbb

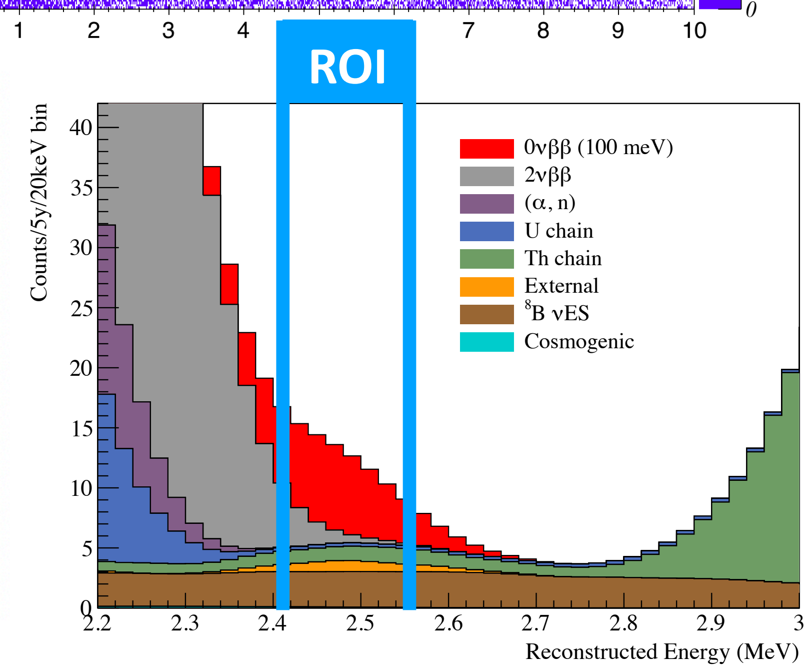




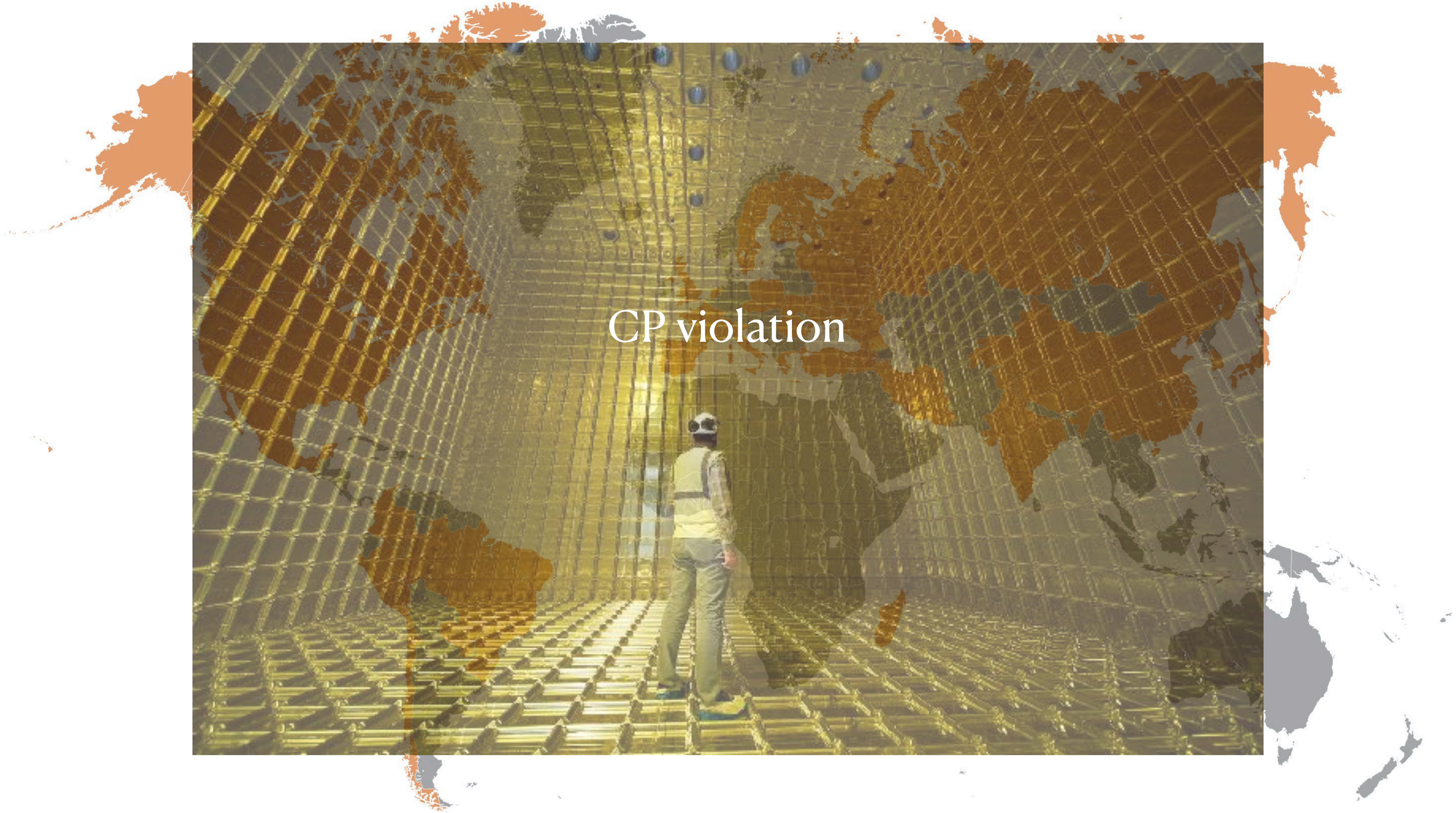




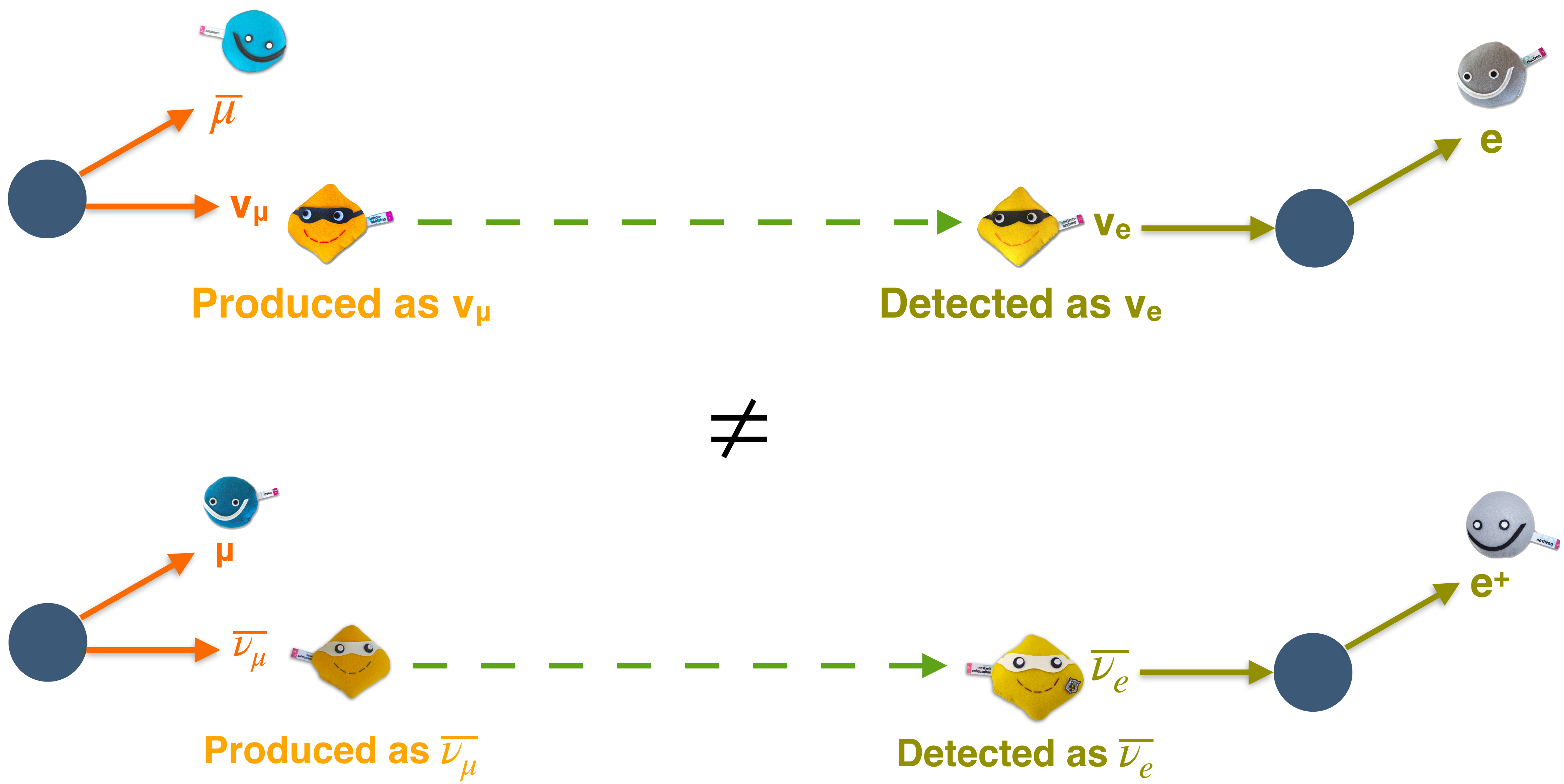




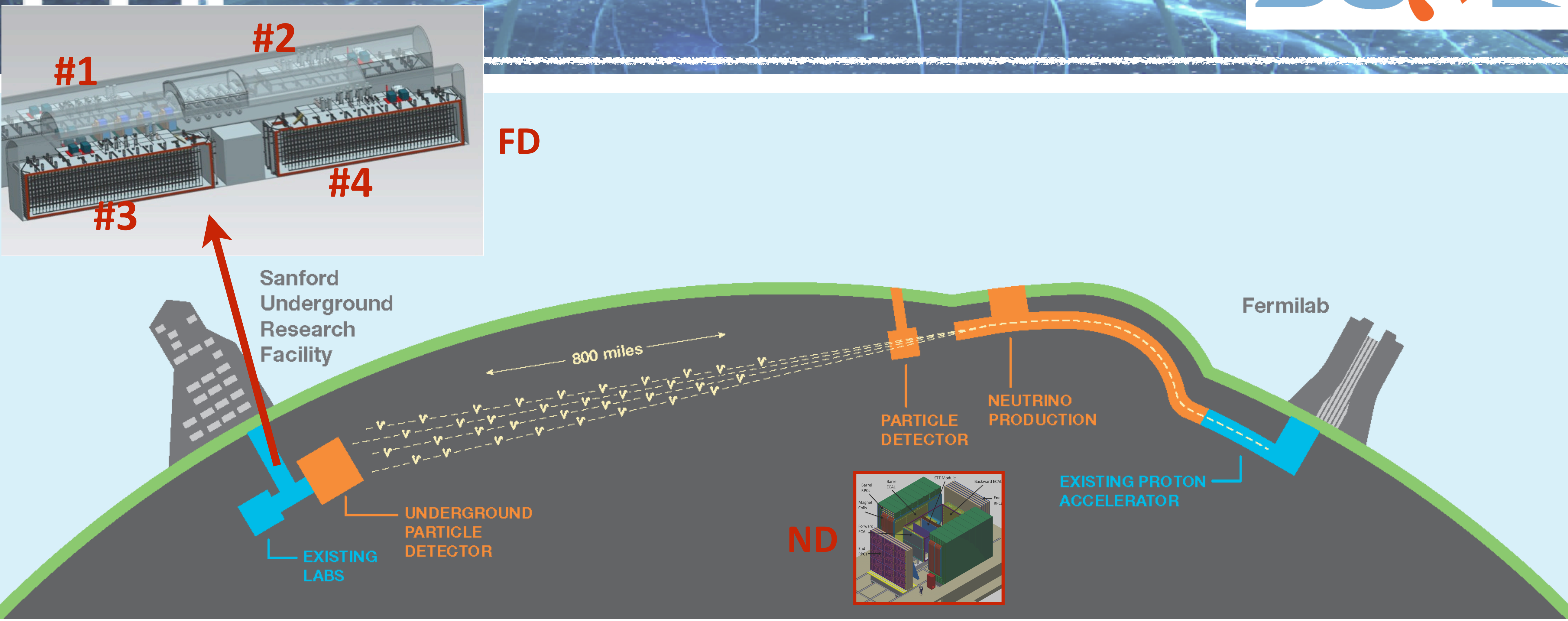
DUNE



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



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>

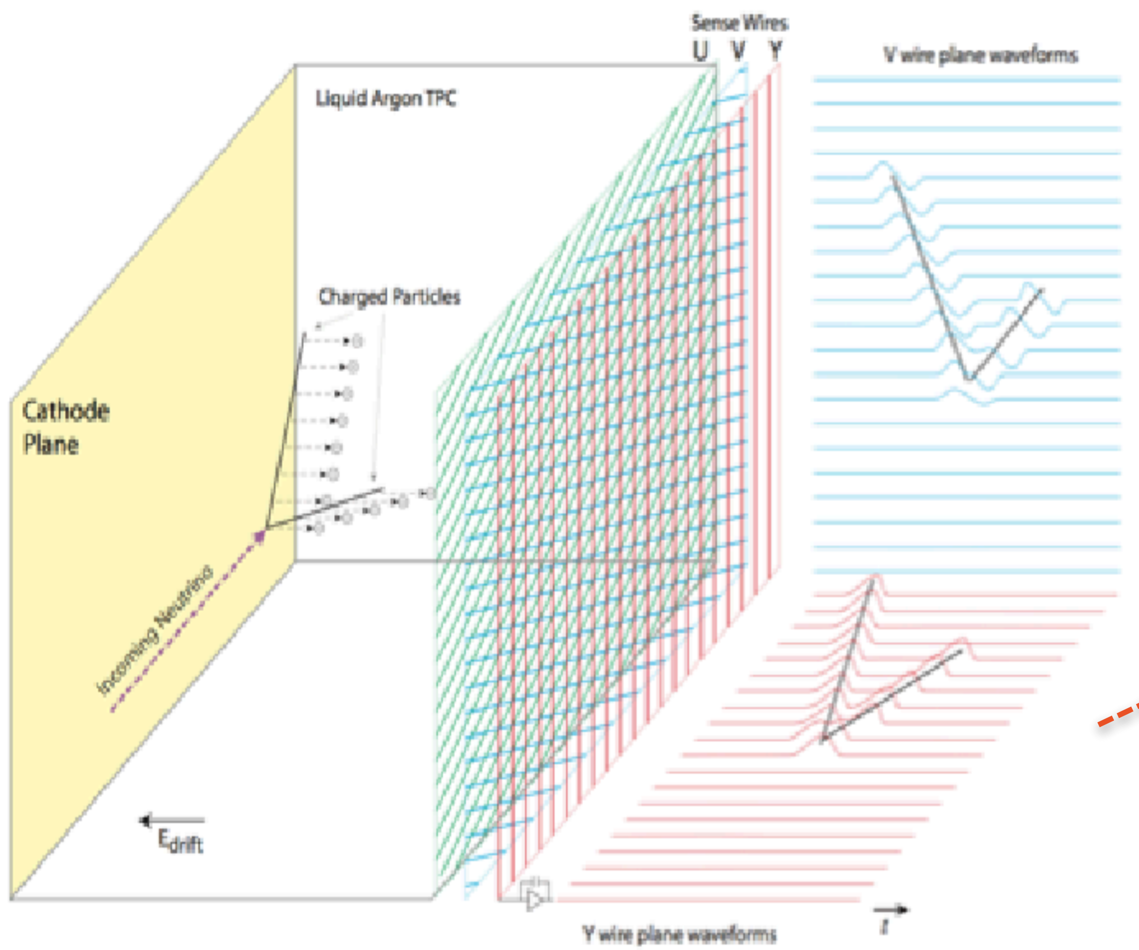
DUNE Far Detector: LAr TPCs

★ **Technology advantages:**

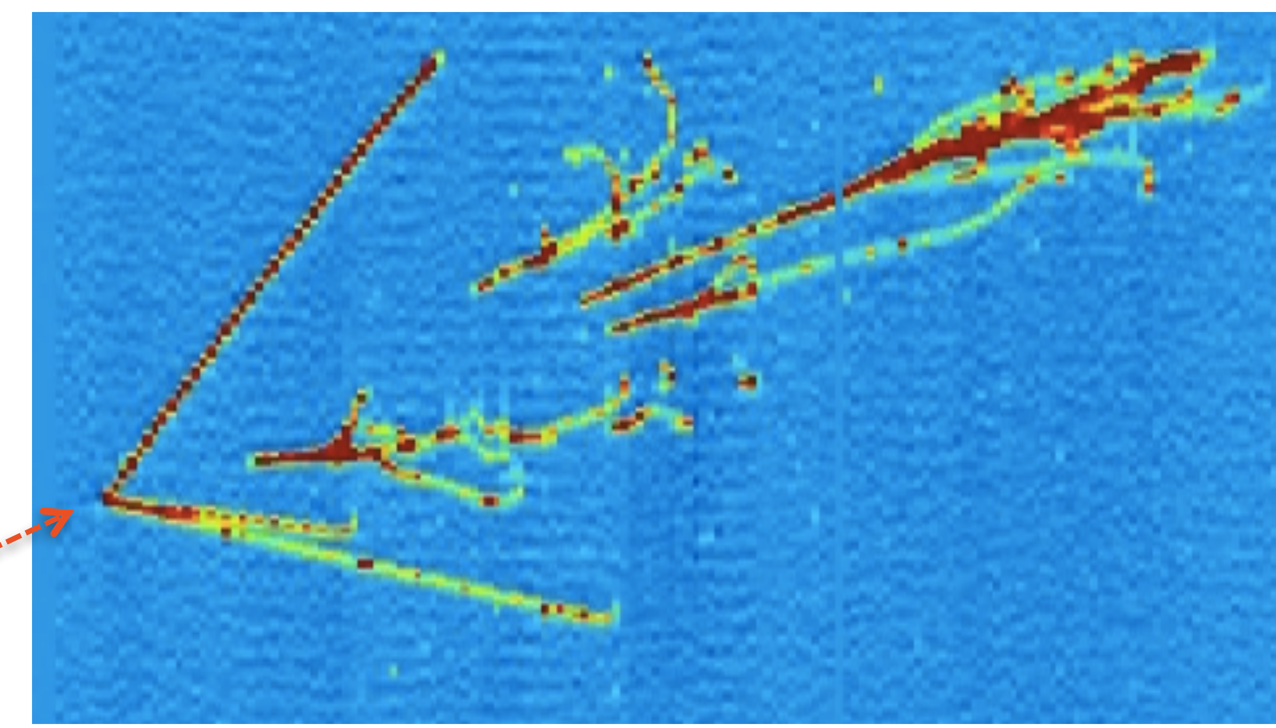
- 3D imaging (use image processing technology for event classification)
- Full event topology

★ **Major Challenges:**

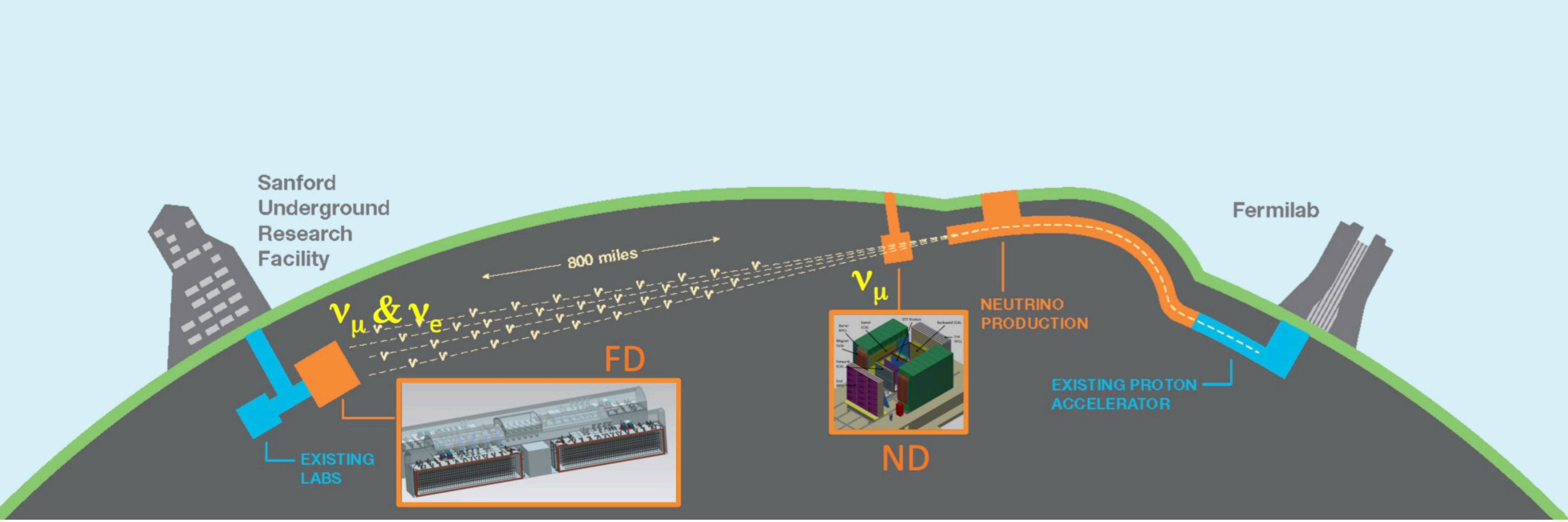
- Event reconstruction (monolithic detector)
- Strong activity in ML algorithms
  - **Scaling of technology**
- Understanding the detector



ν



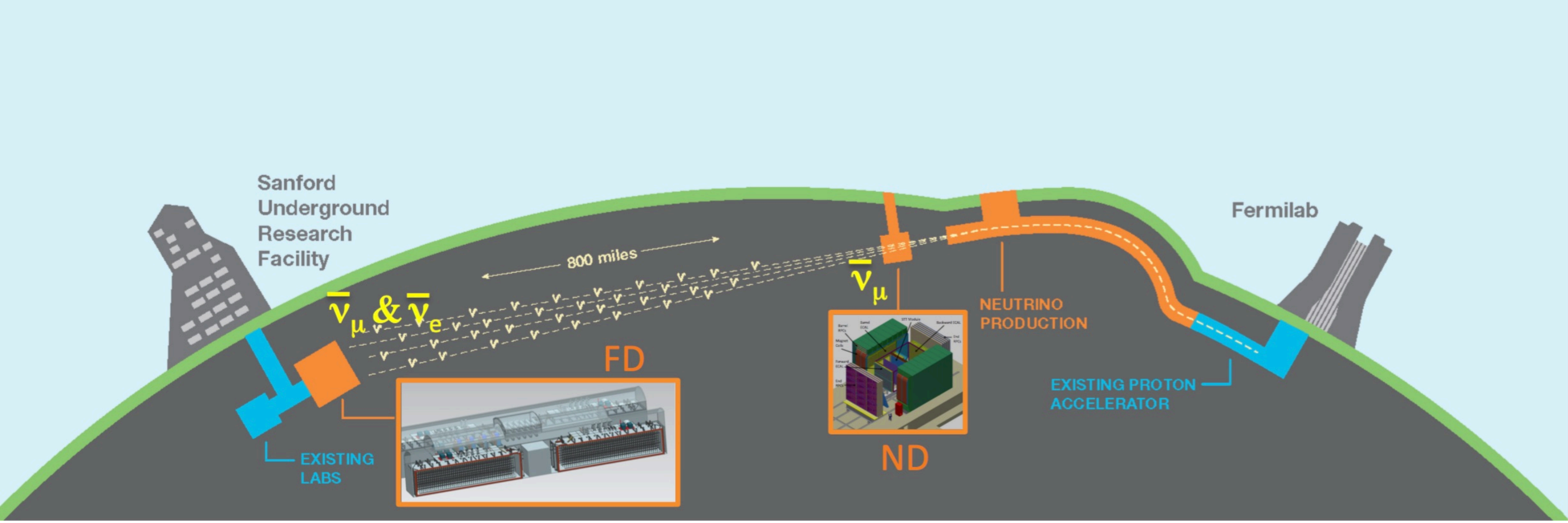
Measure a neutrino beam at long distance…



★ **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

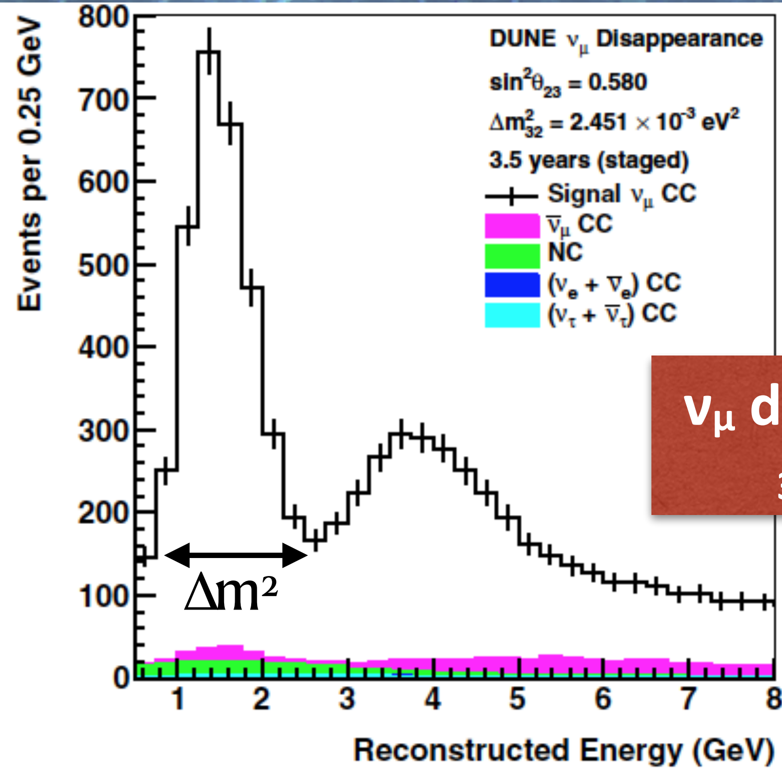
...and then repeat for antineutrinos



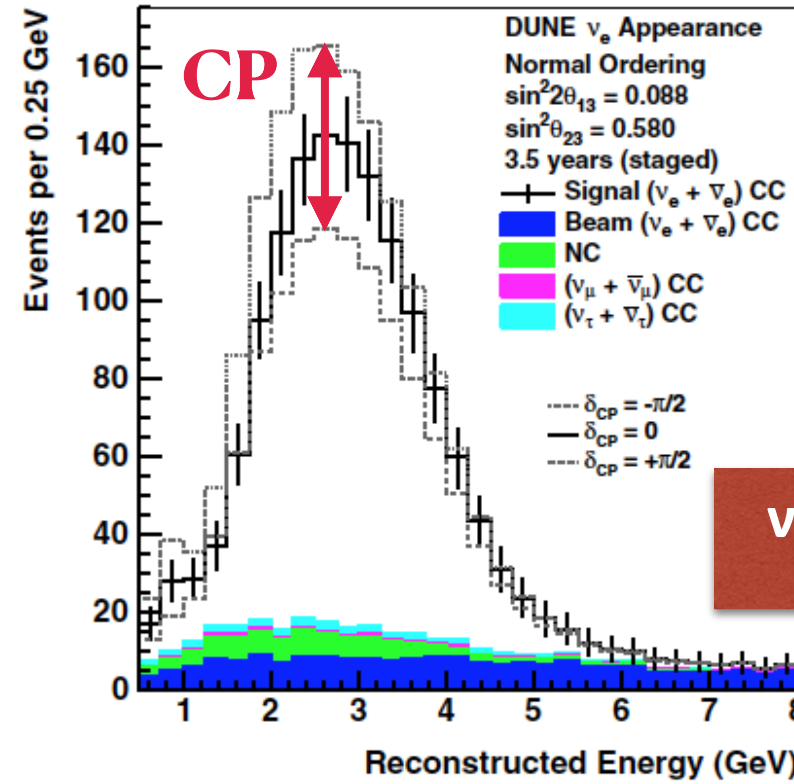
★ **Measure antineutrino spectra at 1300 km in a wide band beam**

- Compare oscillations of neutrinos and antineutrinos
- Direct probe of CP violation in the neutrino sector

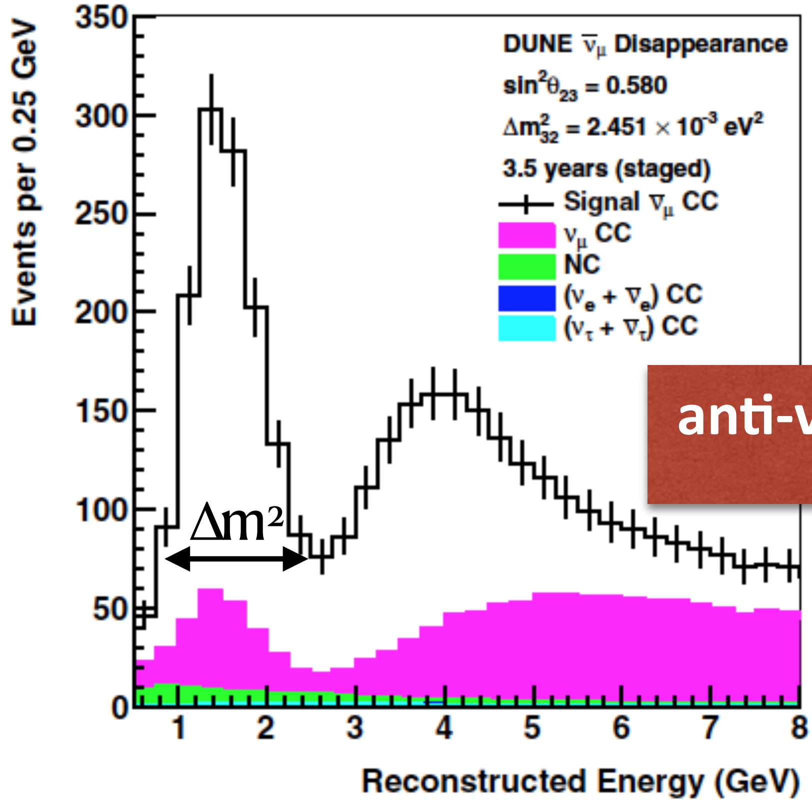
Event's type



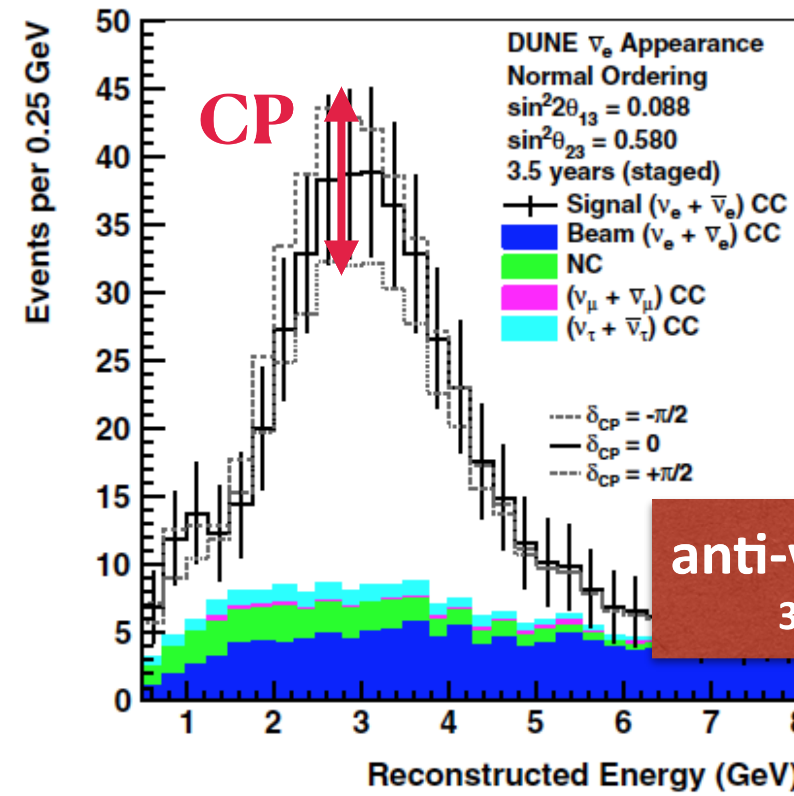
ν_μ disappearance
3.5 yrs running



ν_e appearance
3.5 yrs running



anti-ν_μ disappearance
3.5 yrs running



anti-ν_e appearance
3.5 yrs running

DUNE Activities @ LIP

★**Detector calibration**

- Hardware design (laser, n-source)
- Analysis of calibration data

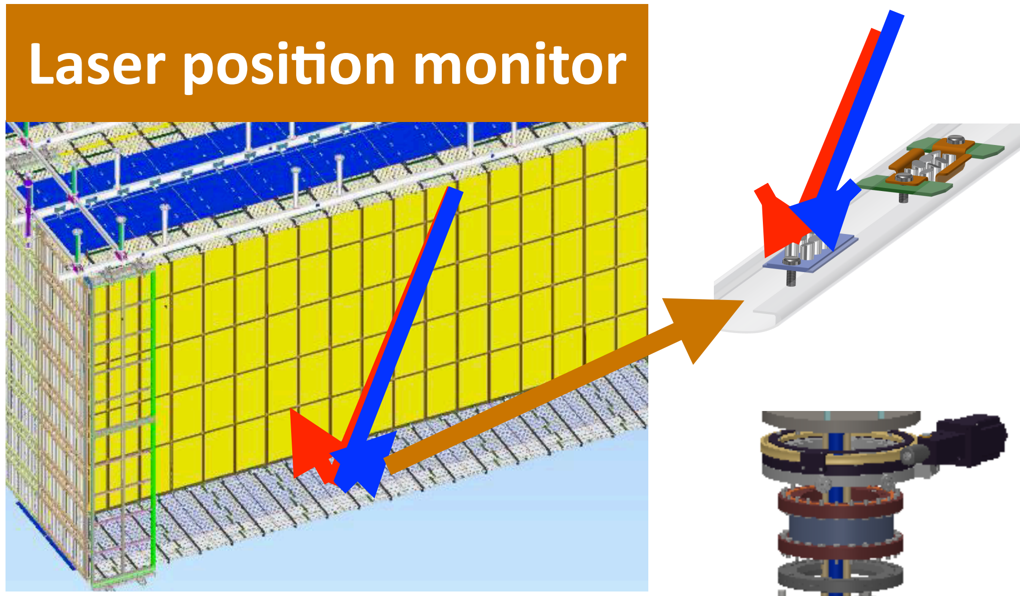
★**DAQ**

- Electronics design
- Data quality

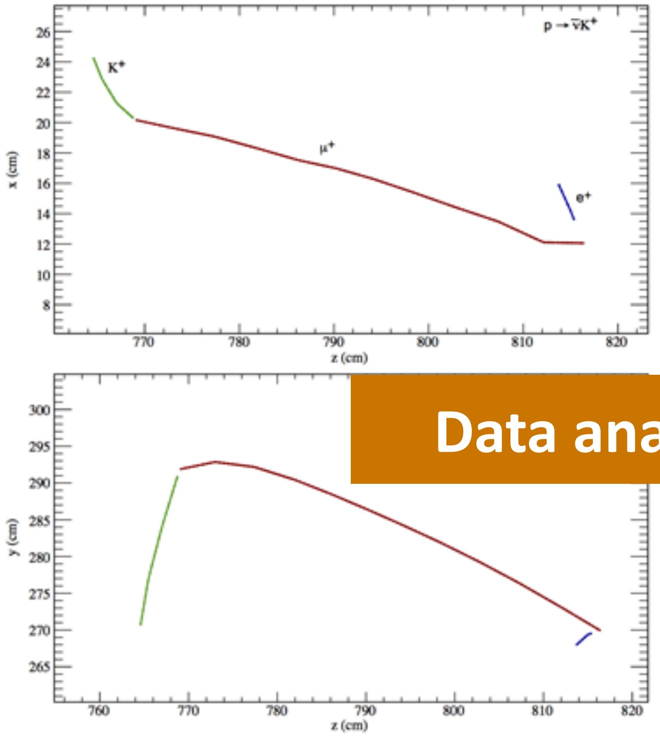
★**Data analysis**

- Cosmic rays
- Beam data

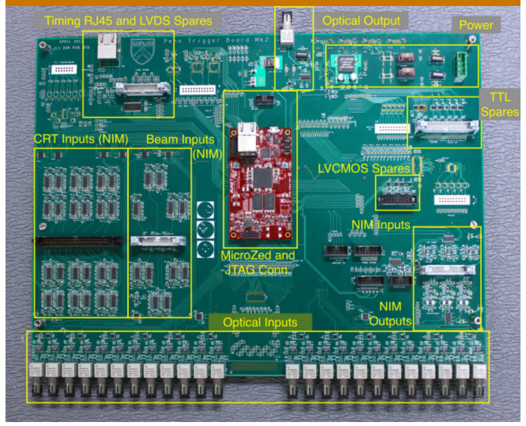
Laser position monitor

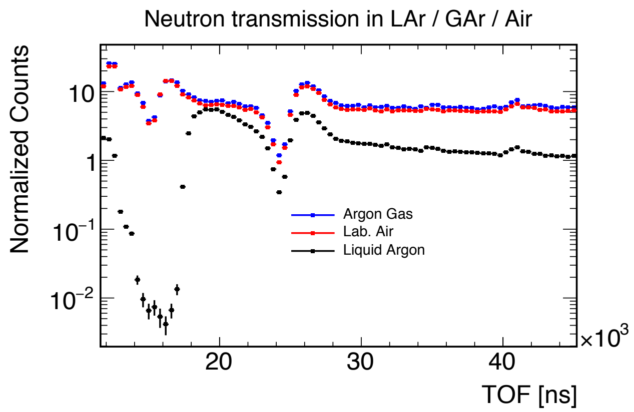


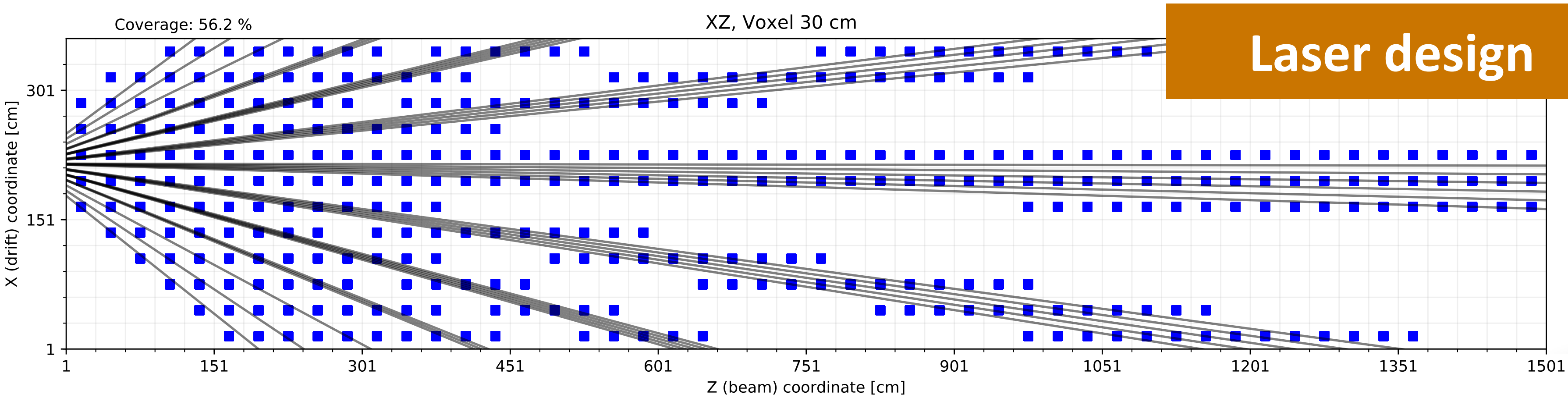
Data analysis



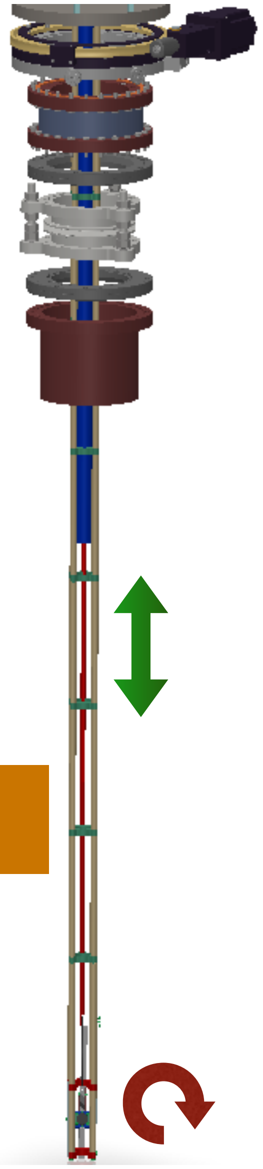
Cal/DAQ interface







Laser design



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

Neutrino group @LIP

For thesis/summer projects/general info: maneira@lip.pt

The presenter Valentina Lozza is funded by FCT

Back up Slides

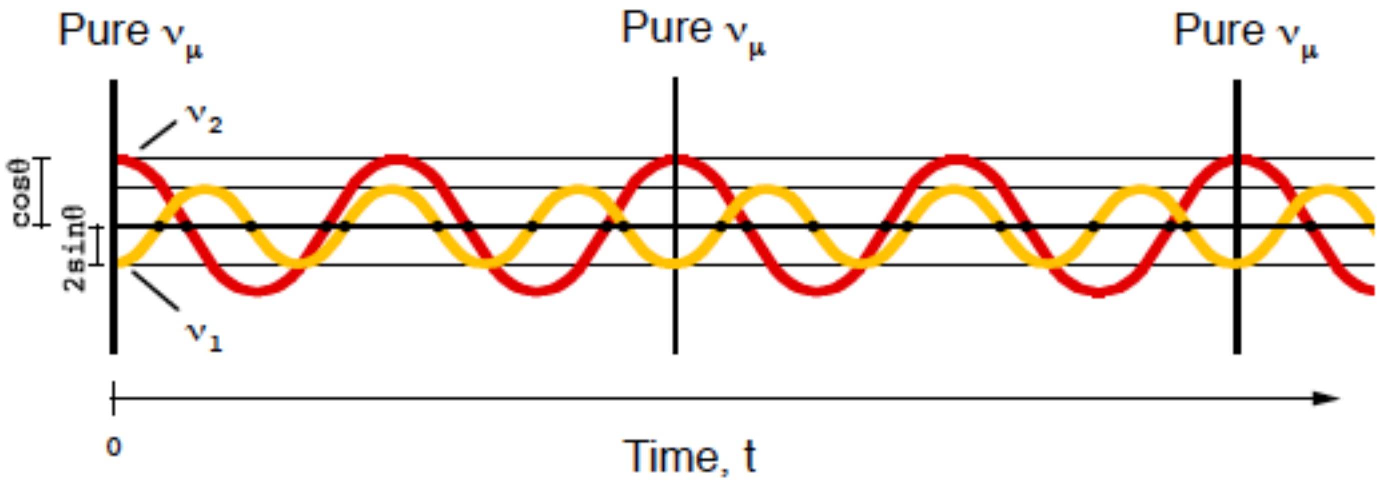
Parametrize the Oscillations: 2ν case

★ 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



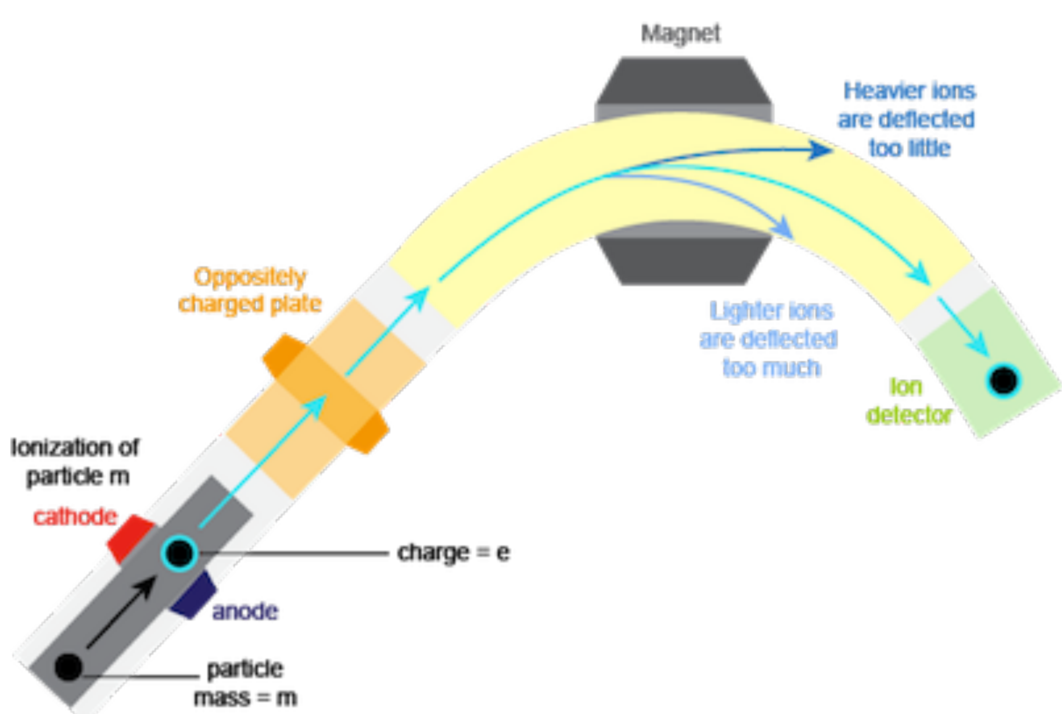
The probability of an electron neutrino to be detected in the same flavour depends on the mass difference and the distance source-detector

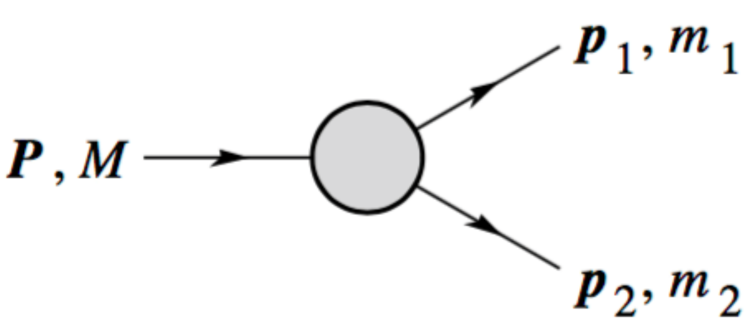
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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 ✓





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

It's All About Purity

Meters and meters of pipes