Neutrinos: a window into the **future**

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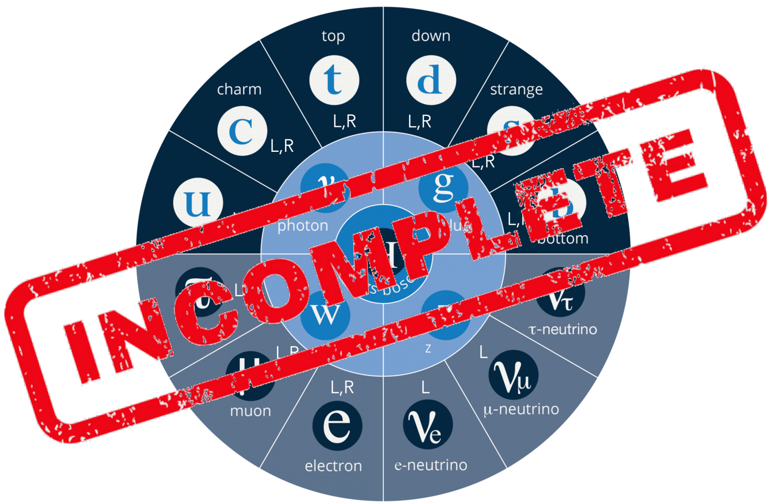
European Strategy Update

Particle Physics for the Future of Europe (28 Sept. 2020, IST)

The only SM I know of…



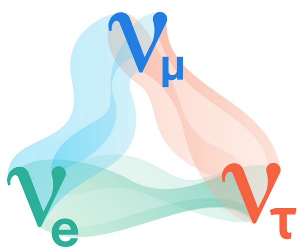
THE SM IS A REMARKABLE THEORY BUT…

How do we know the SM is incomplete?

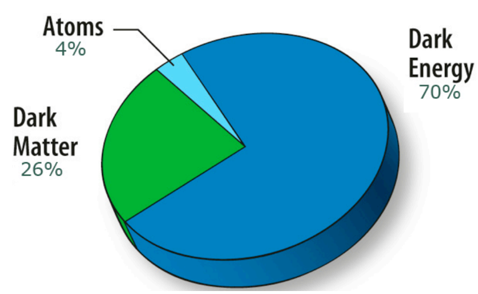
Experimental observation!

(although from the theory point of view some aspects of the SM are "not elegant")

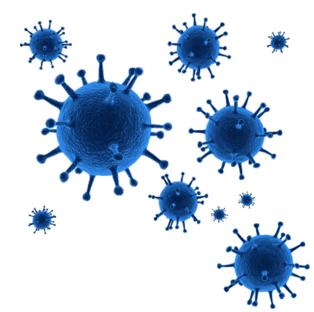
NEUTRINO MASSES AND MIXING



DARK MATTER



CORONA VIRUS



6.1 Introduction

The discovery of neutrino oscillation proves that neutrinos have non-zero masses. This is one of the few solid experimental proofs of physics beyond the Standard Model, as new interactions or new elementary particle states are needed to introduce this mass term in the Lagrangian.

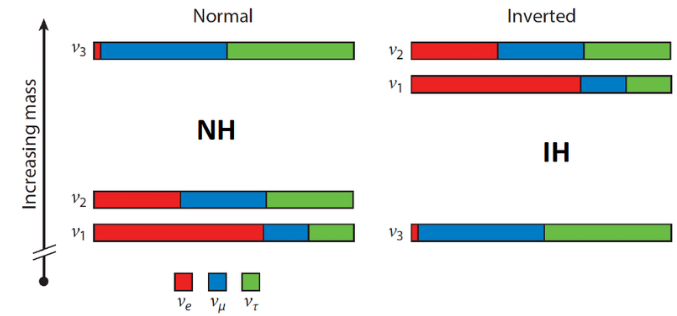
Big questions

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

MIXING MASS PROPAGATION

THE 3 NEUTRINO PICTURE:

$$\mathbf{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$



Although this is introductory QM…

It opens a window (or actually the front door) to physics beyond the SM

What do we know?

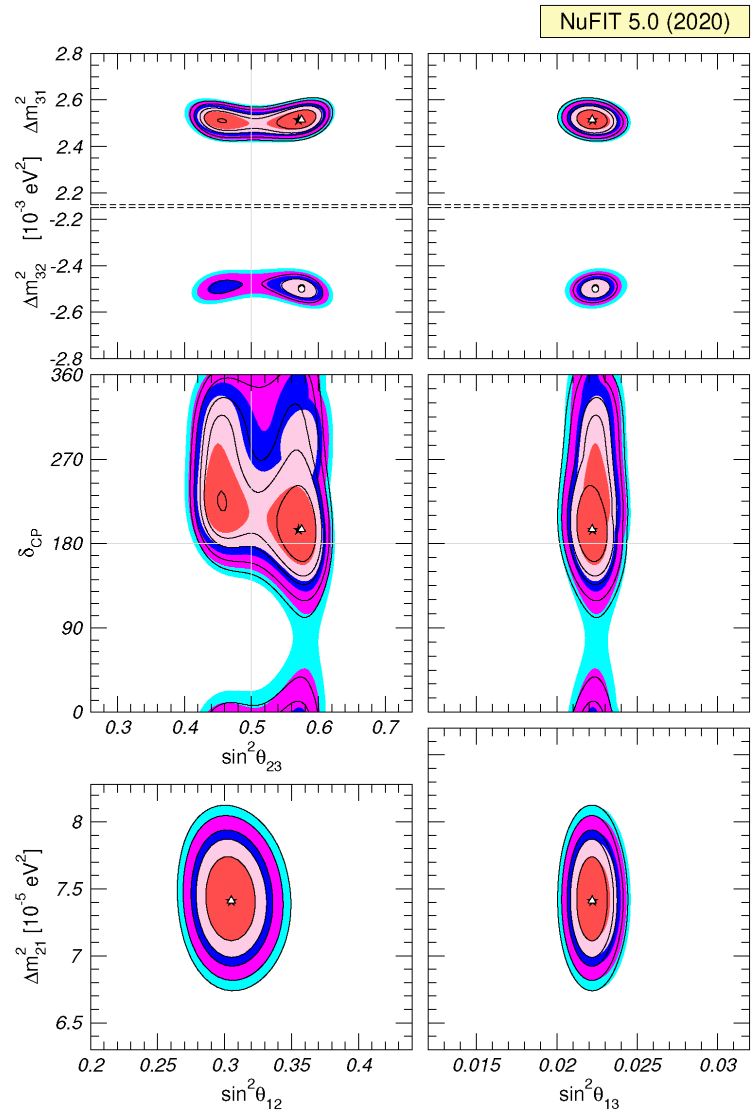
NO or IO?

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

6.1.1 The big questions related to the neutrino masses

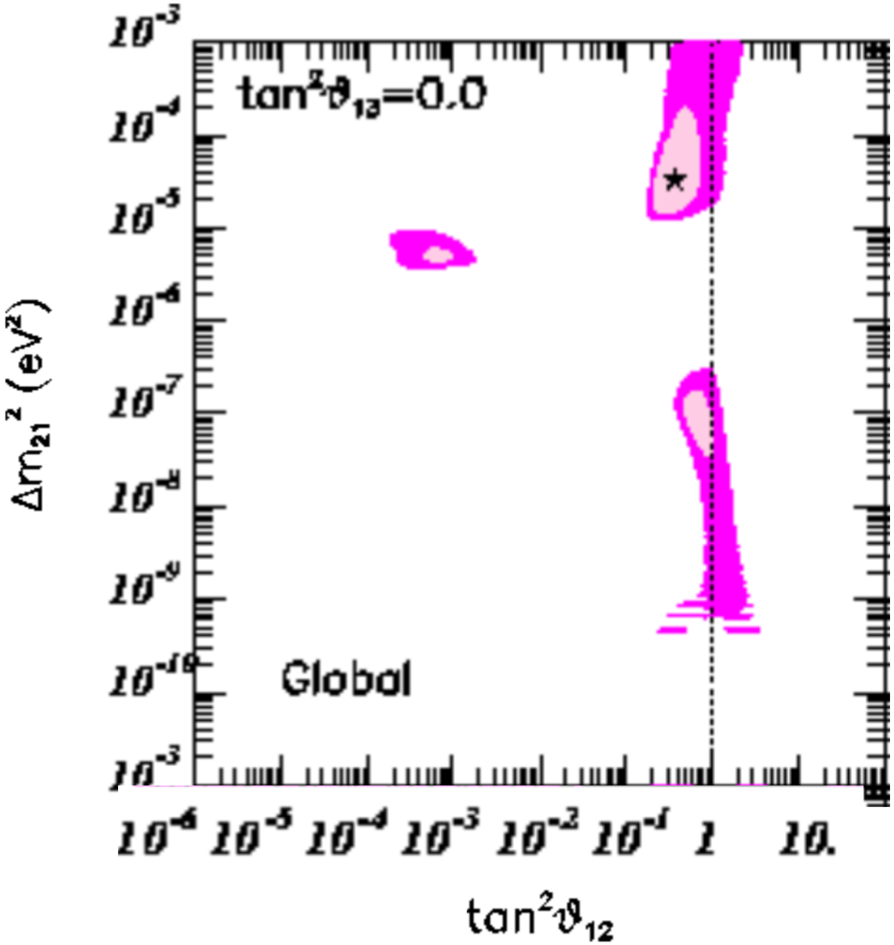
Thanks to the recent discoveries in the sector of neutrino oscillations we have now a clear zeroth-order picture of neutrino properties, which however, raises a number of theoretical and phenomenological questions: Why are neutrino masses many orders of magnitude smaller than any other fermion mass in the Standard Model? Are neutrinos their own antiparticles? What are the actual values of neutrino masses (absolute mass scale and mass ordering)? Is the CP symmetry violated in lepton mixing? What are the precise values of the mixing angles and why is lepton mixing so much different than quark mixing? Are there observable deviations from the standard three-neutrino picture (e.g., non-standard interactions or non-unitarity of the mixing matrix)? Answering these questions is the main focus of the present and future neutrino experimental program. It is of paramount importance as it offers a unique window on the physics

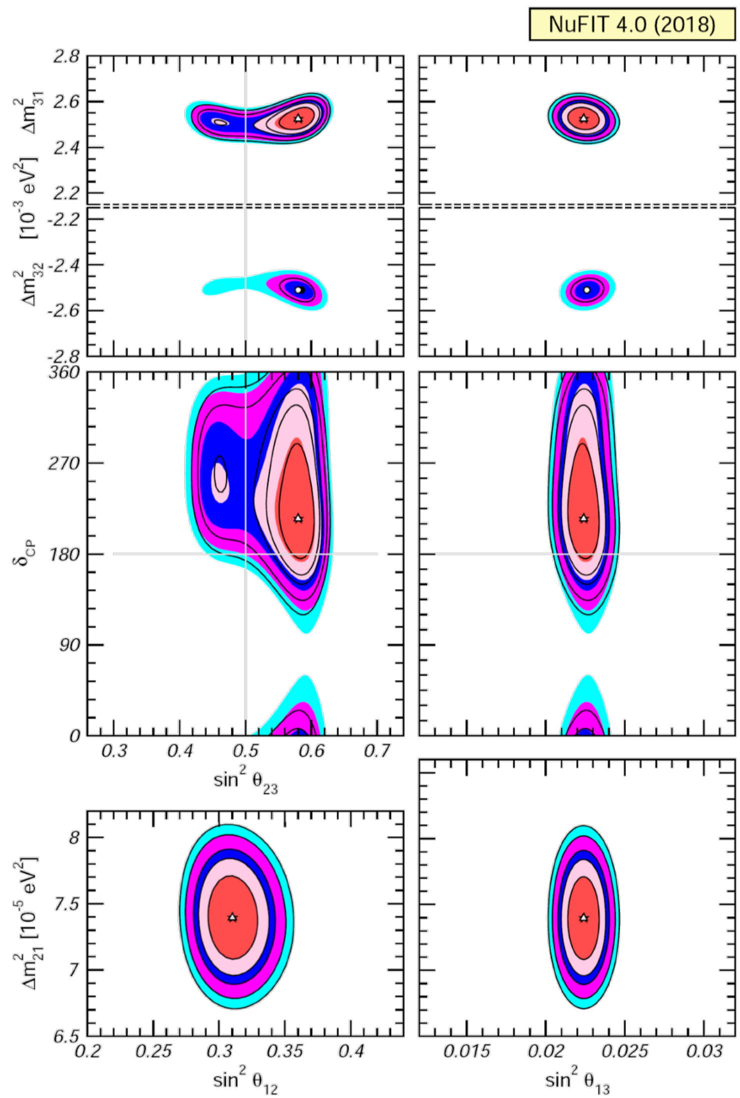
Physics briefing book, Input for the European Strategy for Particle Physics Update



Valle et al.; Gonzalez-Garcia et al; Lisi et al.

Gonzalez-Garcia, Maltoni, Peña-Garay, Vale'00





Remarkable measurement of neutrino oscillation parameters

European Strategy Update

CERN-ESU-004
1 October 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

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“A unique window to BSM Physics”

European Strategy Update

6.1 Introduction

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Moreover, the extremely low mass of the neutrinos, well below the eV scale, sets them far apart from the other fermions. This extraordinary lightness might be related to new physics at a very high scale, as proposed by the see-saw models. There is the tantalizing possibility suggested by the leptogenesis hypothesis that the phenomena at these high scales could explain the baryon asymmetry in the Universe. Moreover neutrinos could be a completely new kind of particle, a Majorana fermion, identical to its antiparticle. If this is realised in nature, new processes violating the conservation of the lepton number are possible. For all these reasons, neutrinos are therefore widely considered as a unique window to BSM physics.

These considerations have triggered a very vibrant experimental program world-wide that has made rapid progress in the last years. With the discovery of the third mixing angle θ_{13} the three neutrino mixing framework has been established.

A new exciting phase of experiments and discoveries opens up, that will be covered in this chapter. Moreover, as neutrinos are also a special probe of dense astrophysical systems, there is a strong synergy at many levels with astroparticle physics that will be covered in Chapter 7.

Physics briefing book, Input for the European Strategy for Particle Physics Update

DIRAC

$$Y_{ij} L \nu_R \Phi$$

- L is conserved
- Tiny couplings required

$y \sim 10^{-11}$

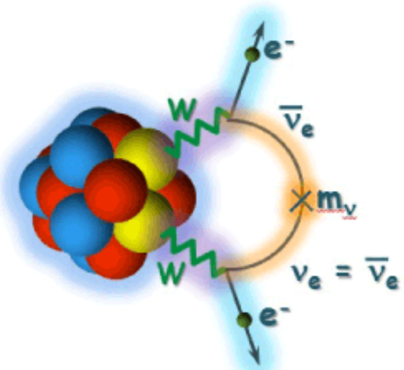
for eV neutrinos

MAJORANA

$$\frac{\kappa_{ij}}{\Lambda} L_i L_j \Phi\Phi$$

- L is broken
- Naturally small ν masses
- Nice effective description
- Simple realizations

NEUTRINOLESS DOUBLE BETA DECAY



Neutrinoless double beta decay

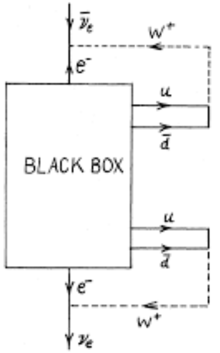
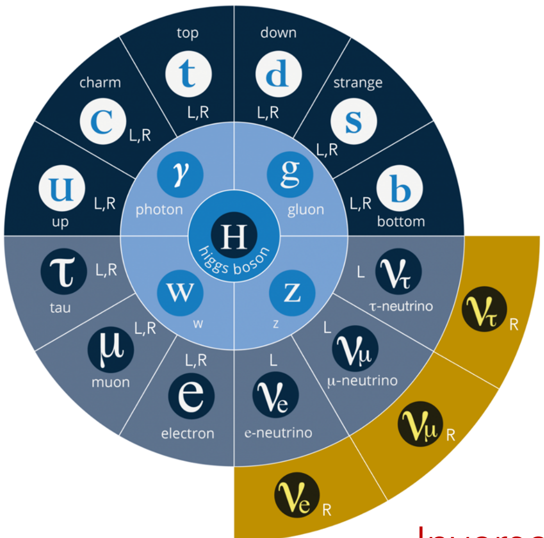


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

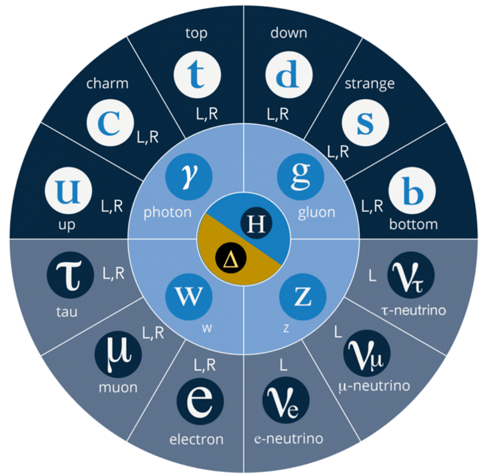
Schechter & Valle' 82

BSM Neutrino mass models

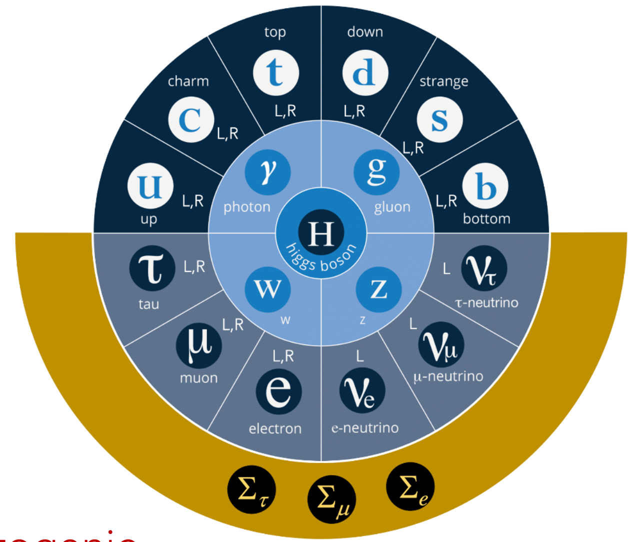
Type I seesaw



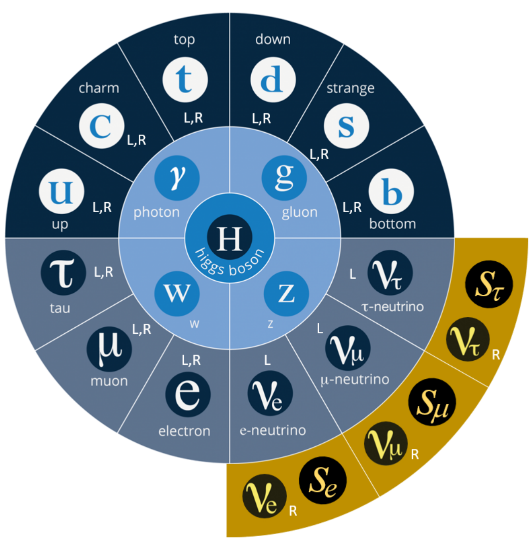
Type II seesaw



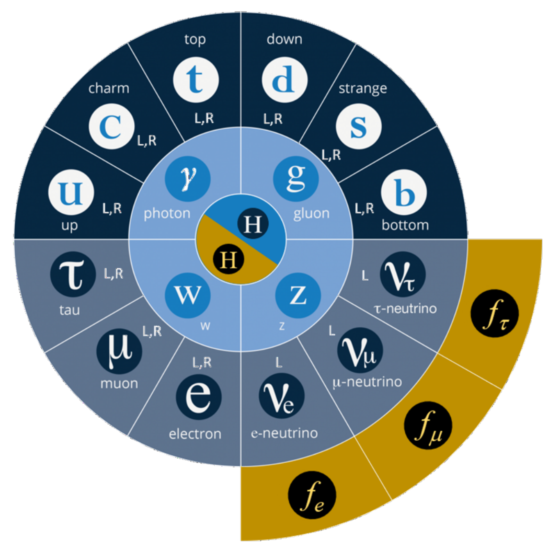
Type III seesaw



Inverse seesaw



Scotogenic

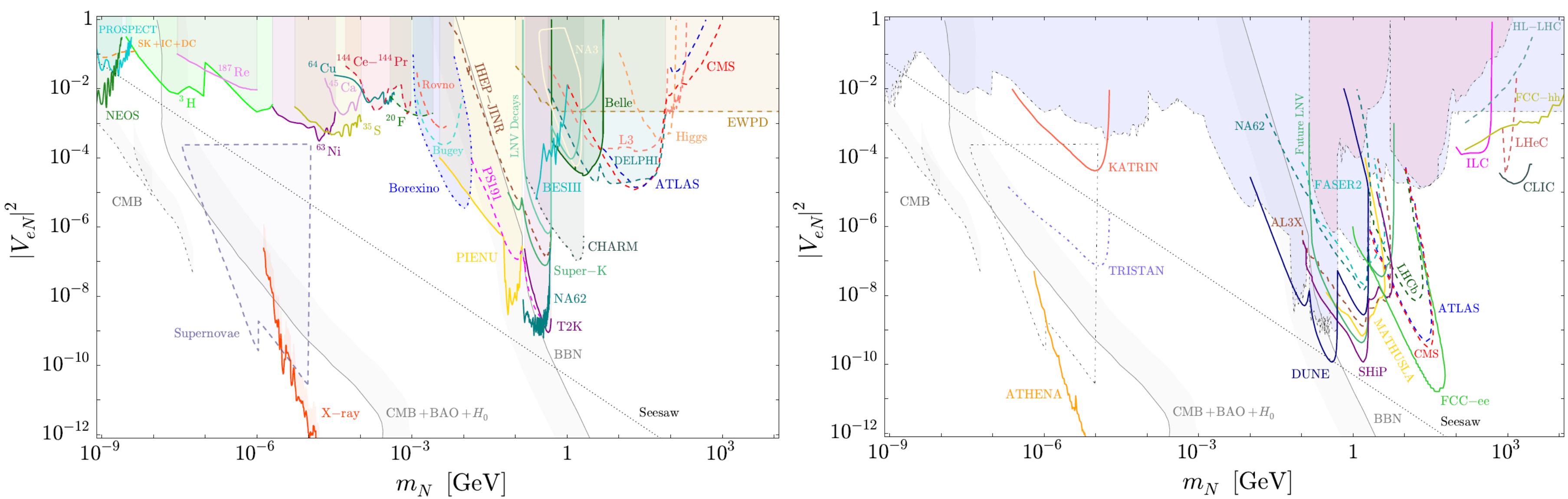


Complementary neutrino studies

European Strategy Update

Neutrino masses by themselves do not provide guidance towards the energy scale of new physics responsible for generating them. There is a vast range for the scale of new physics extending from sub-eV up to the GUT scale of 10^{16} GeV. In order to make progress in view of this multitude of possibilities a wide range of complementary observables needs to be explored. These include (i) the search for sterile neutrinos at various different mass scales including oscillations at the eV scale and heavy neutral leptons at collider and beam dump experiments, (ii) lepton number violation in neutrinoless double-beta decay or at high-energy colliders, (iii) charged lepton-flavour violation, (iv) precision measurements in the neutrino sector, and (v) search for non-standard neutrino properties such as exotic interactions or non-unitarity of the 3×3 mixing matrix.

Physics briefing book, Input for the European Strategy for Particle Physics Update



Bolton et al., JHEP 03 (2020) 170

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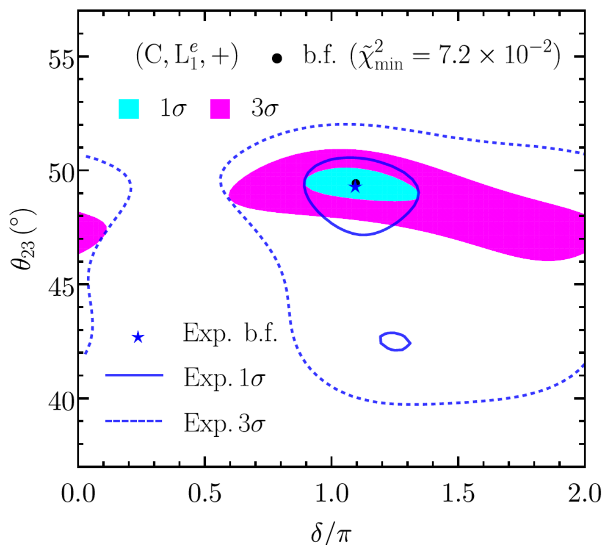

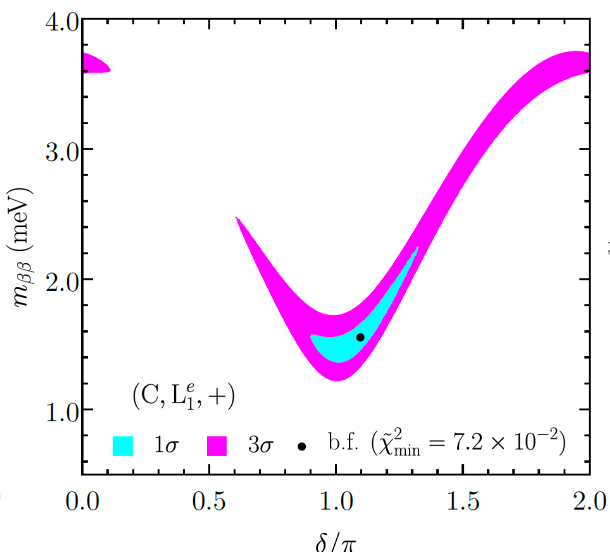

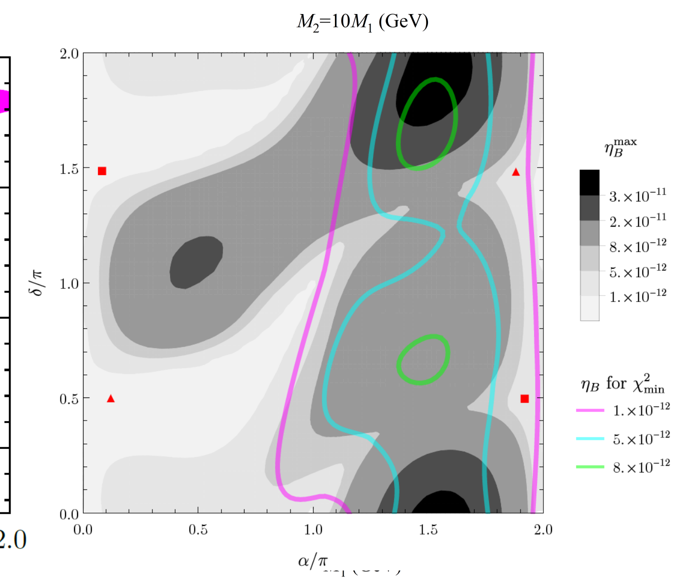

D. Barreiros, FRJ & T. T. Yanagida, PRD'20

H. Camara, R.G. Felipe & FRJ, PRD'18
D. Barreiros, R.G. Felipe & FRJ, hep-ph/2010.XXXX

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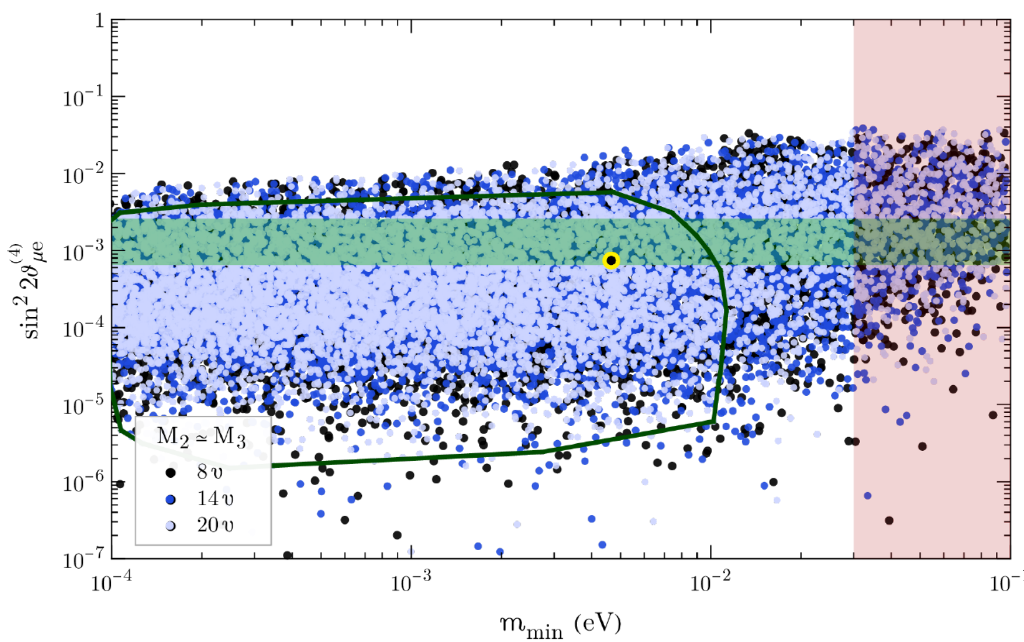
Physics briefing book, Input for the European Strategy for Particle Physics Update

	90% C.L. range	origin	Ref.
	NSI with quarks		
$\epsilon^{qL}_{e\mu}$	$[-0.023, 0.023]$	accelerator	[112, 165]
$\epsilon^{qR}_{e\mu}$	$[-0.036, 0.036]$	accelerator	[112, 165]
$\epsilon^{uV}_{e\mu}$	$[-0.073, 0.044]$	oscillation data + COHERENT	[127]
$\epsilon^{dV}_{e\mu}$	$[-0.07, 0.04]$	oscillation data + COHERENT	[127]
$\epsilon^{qL}_{e\tau}$, $\epsilon^{qR}_{e\tau}$	$[-0.5, 0.5]$	CHARM	[128]
$\epsilon^{uV}_{e\tau}$	$[-0.15, 0.13]$	oscillation data + COHERENT	[127]
$\epsilon^{dV}_{e\tau}$	$[-0.13, 0.12]$	oscillation data + COHERENT	[127]
$\epsilon^{qL}_{\mu\tau}$	$[-0.023, 0.023]$	accelerator	[165]
$\epsilon^{qR}_{\mu\tau}$	$[-0.036, 0.036]$	accelerator	[165]
$\epsilon^{qV}_{\mu\tau}$	$[-0.006, 0.0054]$	IceCube	[143]
$\epsilon^{qA}_{\mu\tau}$	$[-0.039, 0.039]$	atmospheric + accelerator	[165]
	NSI with electrons		
$\epsilon^{eL}_{e\mu}$, $\epsilon^{eR}_{e\mu}$	$[-0.13, 0.13]$	reactor + accelerator	[162]
$\epsilon^{eL}_{e\tau}$	$[-0.33, 0.33]$	reactor + accelerator	[162]
$\epsilon^{eR}_{e\tau}$	$[-0.28, -0.05]$ & $[0.05, 0.28]$ [-0.19, 0.19]	reactor + accelerator TEXONO	[162] [163]
$\epsilon^{eL}_{\mu\tau}$, $\epsilon^{eR}_{\mu\tau}$	$[-0.10, 0.10]$	reactor + accelerator	[128, 162]
$\epsilon^{eV}_{\mu\tau}$	$[-0.018, 0.016]$	IceCube	[143][a]

[a] Bound adapted from $\epsilon^{qV}_{\mu\tau}$.

TABLE III. Bounds on Flavor changing NC NSI couplings

Farzan & Tortola'18



Branco et al.'20

Neutrino Physics @ CFTP

- The role of **symmetries** (predictions for neutrino oscillations, neutrinoless double beta decays,…)
- **Non-unitarity** effects in the neutrino sector
- Neutrinos and **LFV** (SUSY, seesaw frameworks, …)
- **Sterile neutrinos** and oscillations
- Neutrino physics at **colliders** (LR models, seesaw messengers,…)
- The role of neutrinos in the early Universe (**leptogenesis**, connection high-low energy CPV)
- Neutrinos and **Dark Matter** in the context of neutrino mass generation mechanisms – **multi-Higgs models**

Neutrinos at the intensity, energy and cosmic frontiers

The physics involved in neutrino mass generation explores synergies among the three frontiers of particle physics:

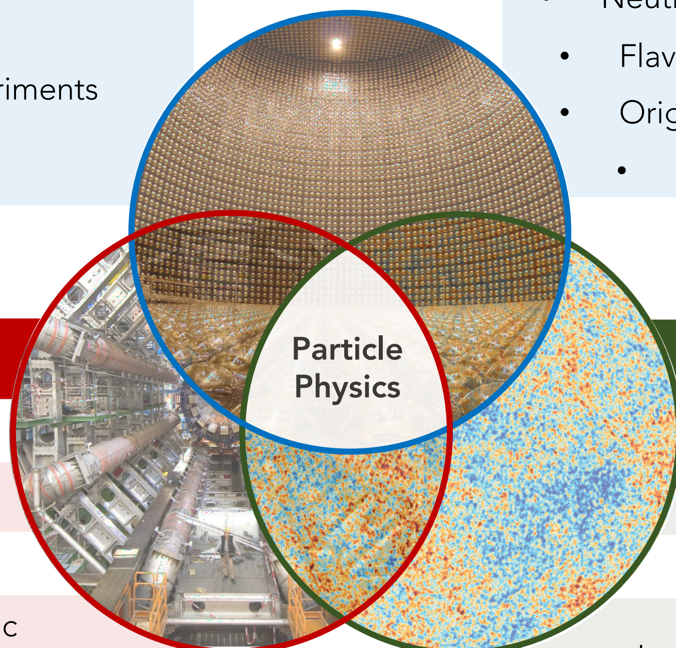
Intensity Frontier

Experiment

- $0\nu2\beta$ decay searches
- Neutrino oscillation experiments
- LFV searches

Theory

- Neutrino nature (Dirac/Majorana)
- Flavour symmetries
- Origin of leptonic CP violation
- New sources of flavour



Energy Frontier

Experiment

- LHC searches

Theory

- Models with new fermionic and/or scalar content
- New interactions resulting from extended gauge groups

Cosmic Frontier

Experiment

- Cosmological observations

Theory

- Leptogenesis
- New leptonic CP violating effects
- New dark matter candidates

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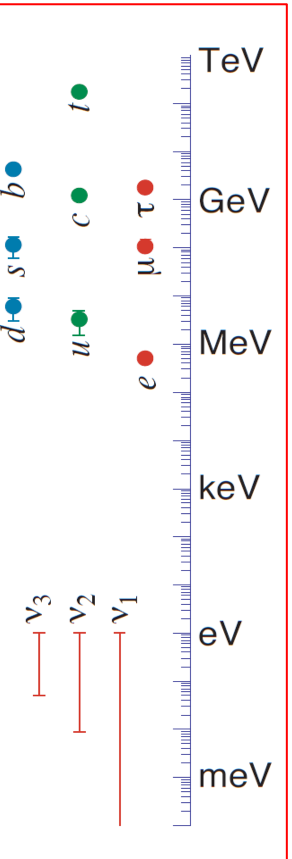
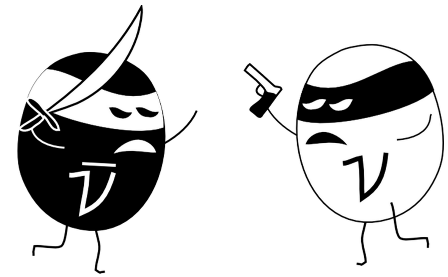


1. What are the absolute neutrino masses ?
2. Are neutrinos Dirac or Majorana ?
3. Measure the full 3-flavor mixing matrix
4. Is there new-new physics in oscillations?
5. Use neutrinos in astro and geo-physics



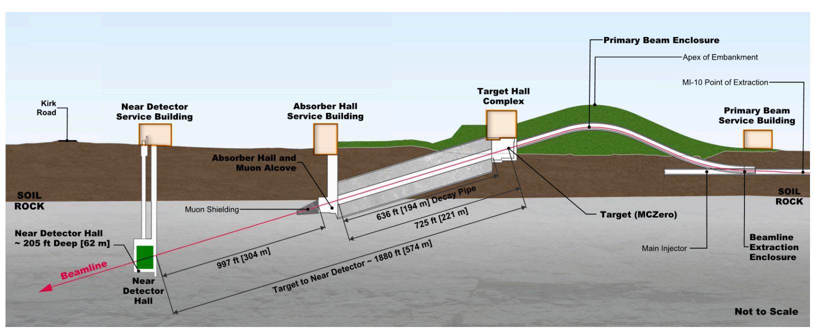
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

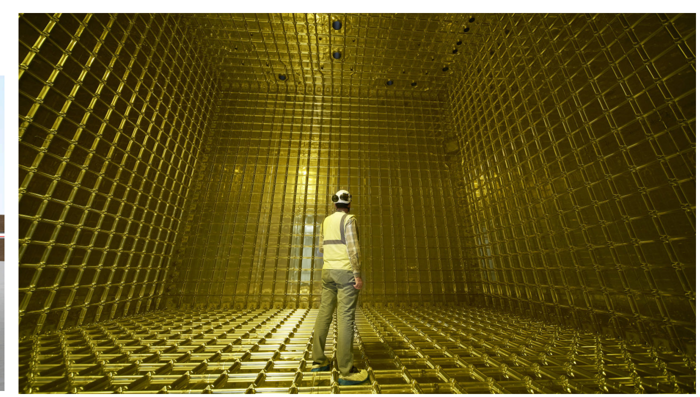
Our tools: Sources:

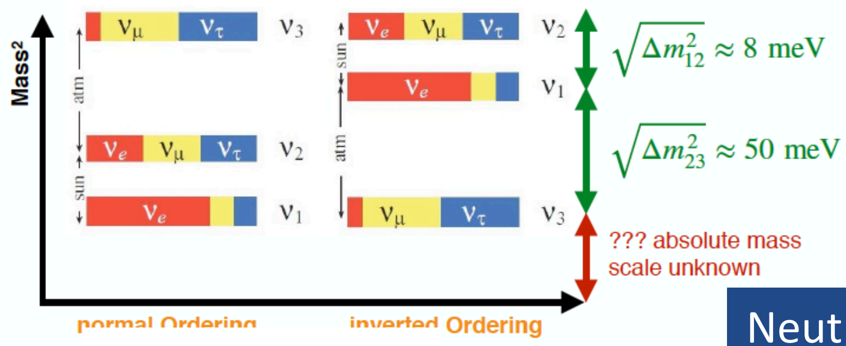
- Accelerators and Nuclear Reactors
- Nuclear decays
- Astronomical objects

Our tools: Detectors

- Dedicated small detectors
- Mid-range liquid scintillator detectors (~ kton scale)
- Massive H_2O or LAr detectors (> 40 kton)



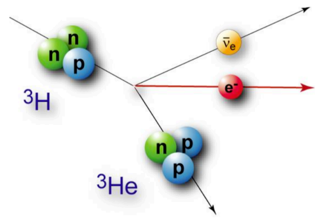


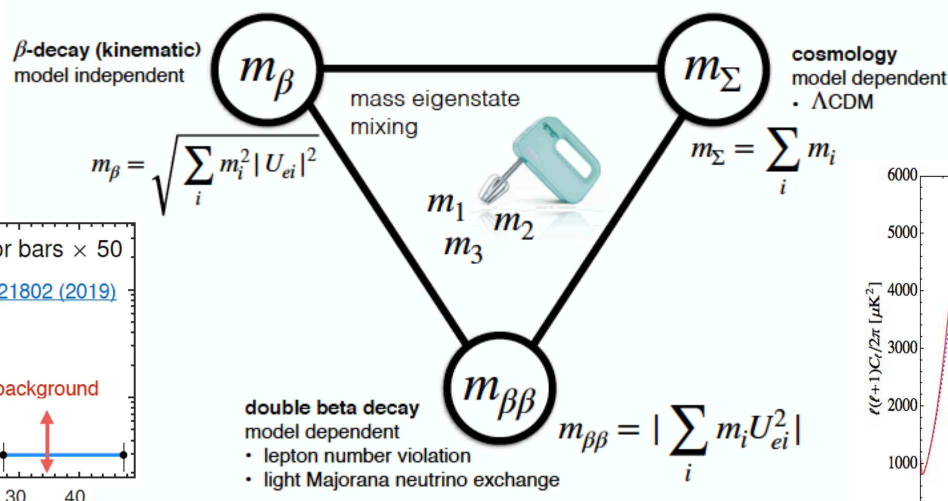


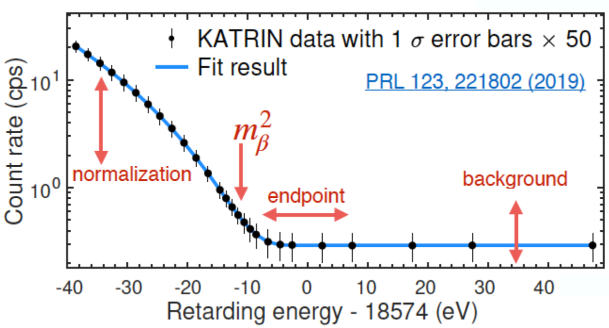
[B. Lehnert, ICHEP2020]

- We know: Neutrino state mass differences
- We don't know: Which is lightest, ν_1 or ν_3 ?
- We don't know: The absolute mass scale ?

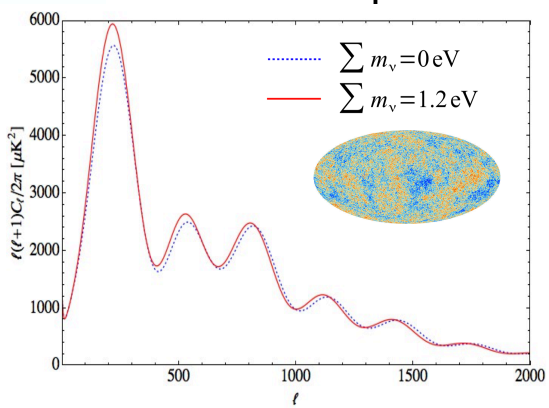
Neutrino Mass Observables







CMB Anisotropies



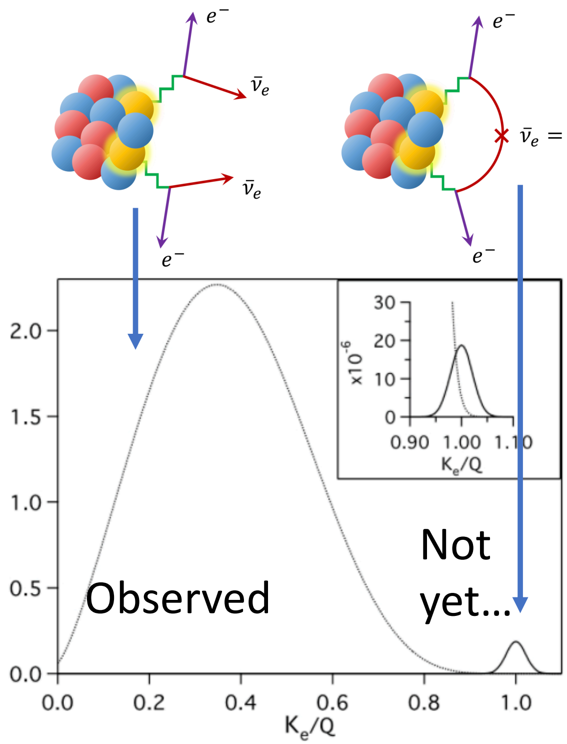
Tritium beta decay endpoint

- KATRIN first results: m_β **< 1.1 eV** (90% CL)
- Sensitivity goal (5yr): m_β < 0.2 eV (90% CL)
- New ideas: Cyclotron radiation emission spectroscopy. Project 8 sensitivity: 40 meV

Cosmology

- Current bound: Σm < 0.12 eV
- Future prospects: : Σm < 20 meV
- Far future: direct detection of CνB ??

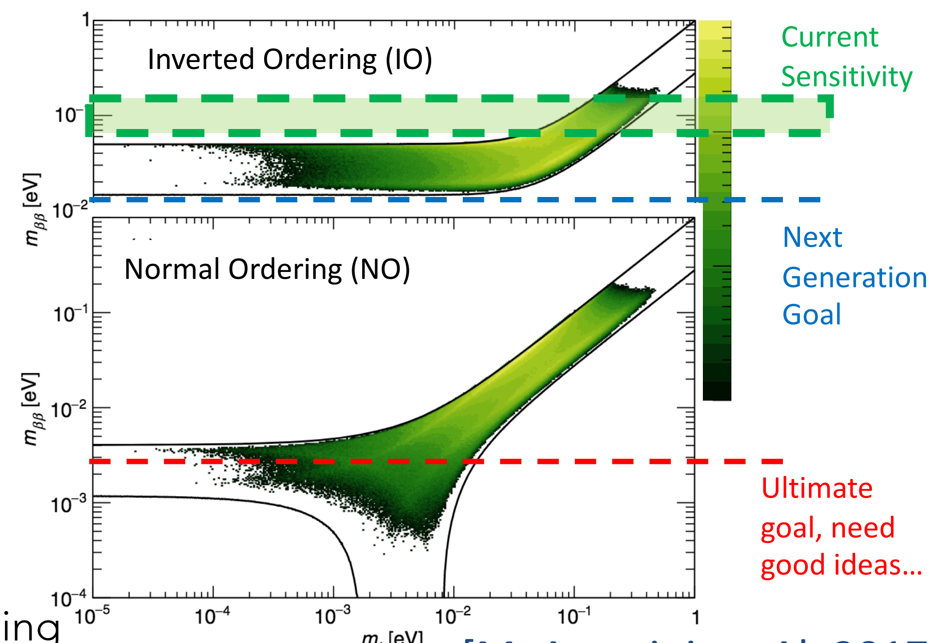
2 – Is the neutrino Dirac or Majorana ?



Neutrinoless Double Beta Decay

- Implies Lepton number violation, can only happen if neutrinos are Majorana
- Rate depends on effective Majorana mass, i.e.
  - Absolute neutrino masses
  - Neutrino mixing matrix, incl. Majorana phases

$$|m_{\beta\beta}| = \left| m_1 |U_{ei}^2| + m_2 |U_{e2}^2| e^{i(\alpha_2-\alpha_1)} + m_3 |U_{e3}^2| e^{-i(\alpha_1+2\delta)} \right|$$



[M. Agostini et. Al, 2017]

Experimental Search for DBD

- Very long half-lives (>10^{26} yr), very rare decay
- Many experiments worldwide
  - Cryogenic (good resolution)
  - Liquid Scintillators (high mass)
- Next generation aiming to cover IO region
- NO region a big challenge (~ 10^{29} yr)
  - My bias: big LS detectors with high loading

3 - Complete the 3-flavor mixing matrix

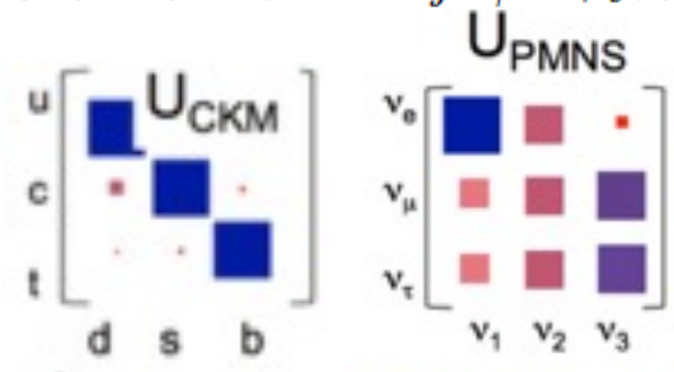
$$|\nu_{\text{flavor}}> = \sum_i U^*_{\alpha i} \cdot |\nu_{\text{mass}}>$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

PDG 2020

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23}) = 0.547 \pm 0.021$ (Inverted order)
$\sin^2(\theta_{23}) = 0.545 \pm 0.021$ (Normal order)
$\Delta m^2_{32} = (-2.546^{+0.034}_{-0.040}) \times 10^{-3}$ eV^2 (Inverted order)
$\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3}$ eV^2 (Normal order)
$\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2}$
δ, *CP* violating phase $= 1.36 \pm 0.17\ \pi$ rad
$\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle < 1.1 \times 10^{-4}$ eV^2, CL $= 99.7\%$
$\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle = (-0.12 \pm 0.25) \times 10^{-3}$ eV^2

$$|J| = |\mathrm{Im}(U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j})|$$



$J_{\text{quarks}} = 3\text{x}10^{-5}$ $J_{\text{leptons}} = 0.03 \sin \delta_{CP}$

- Least well-known is δ_{CP} phase
- CP effects, possibly leading to baryogenesis, measured by Jarlskog invariant
- Can be much bigger for neutrinos
- Crucial goal for upcoming experiments

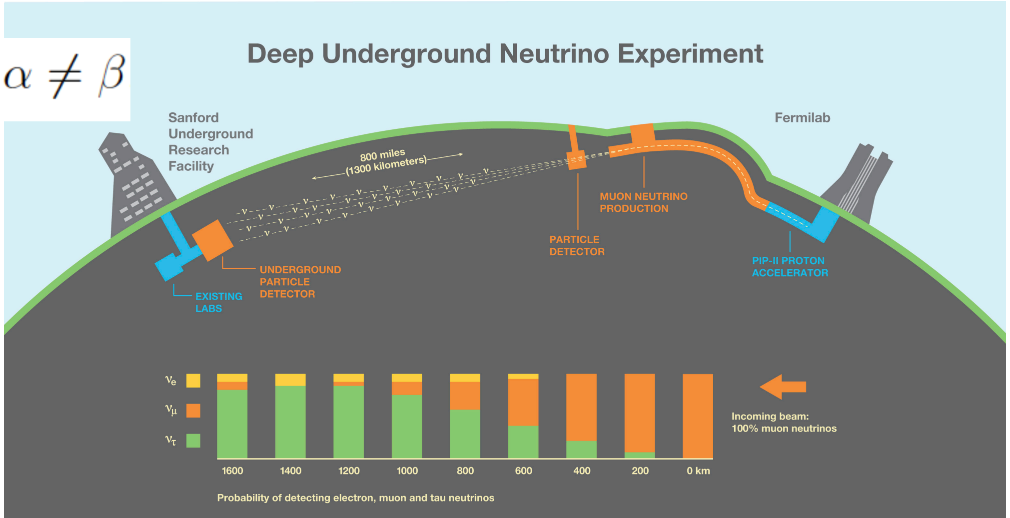
$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta),\ \alpha, \beta = e, \mu, \tau,\ \alpha \neq \beta$$

If $\delta_{CP} \neq 0, \pi$

- Oscillations for **neutrinos and antineutrinos** are different

How to measure ?

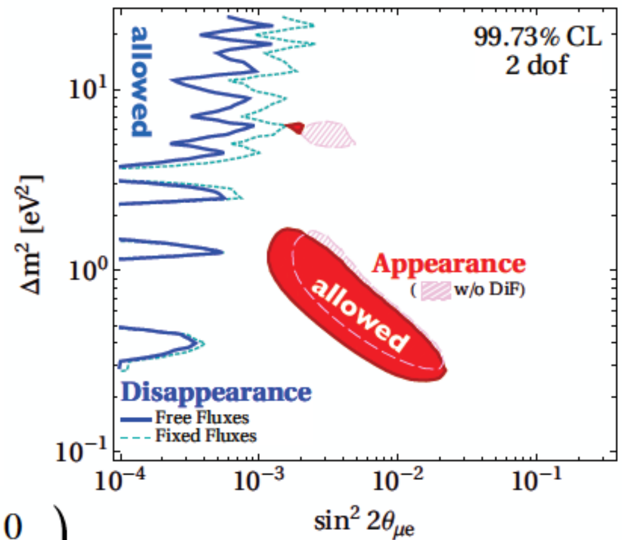
- Make beams of muon nu and anti-nu
- Make detector 1300 km away
- Observe appearance of nu and anti-nu



European Strategy Update

Sterile neutrinos

- Anomalies in electron neutrino appearance (LSND and MiniBooNE) and disappearance (reactor, Ga solar) results can be explained by oscillations with a fourth "sterile" state with ~eV mass difference
- But other muon neutrino disappearance results are strongly incompatible
- Unclear picture -> many new experiments looking for this



[P. Machado, Neutrino2020]

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c\Theta_{23} & s\Theta_{23} \\ 0 & -s\Theta_{23} & c\Theta_{23} \end{pmatrix} \begin{pmatrix} c\Theta_{13} & 0 & s\Theta_{13}\cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -s\Theta_{13}\cdot e^{-i\delta} & 0 & c\Theta_{13} \end{pmatrix} \begin{pmatrix} c\Theta_{12} & s\Theta_{12} & 0 \\ -s\Theta_{12} & c\Theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{pmatrix}$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

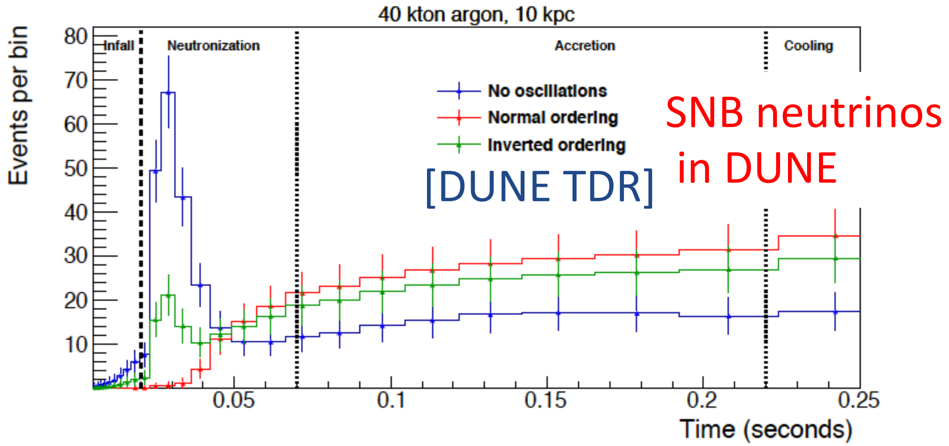
Non-unitarity

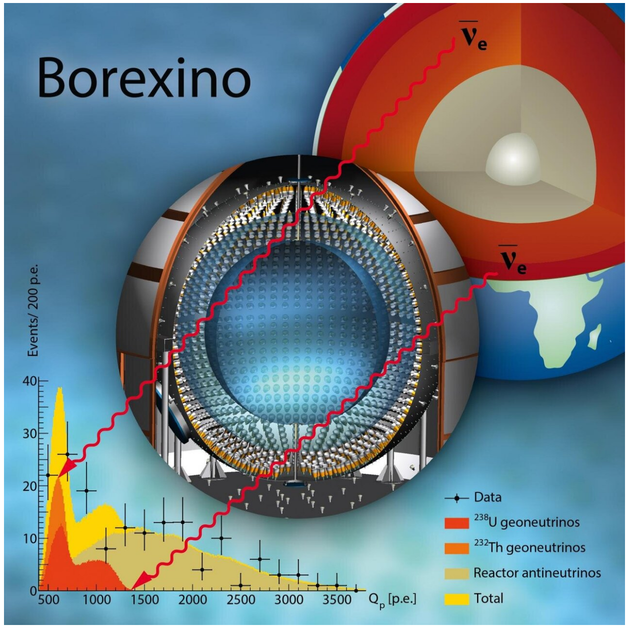
- Above parametrization assumes 3x3 PMNS matrix is unitary
- What if PMNS is a subset of a larger dimension matrix ?
- Searching for non-unitarity in the neutrino mixing matrix is searching for new physics at a higher energy scale
  - Need to measure Uαi elements independently
  - High precision is needed: measure oscillation with O(1%) uncertainties. DUNE and HK needed.

5 – Neutrino spectroscopy

Neutrinos from Stars and the Earth

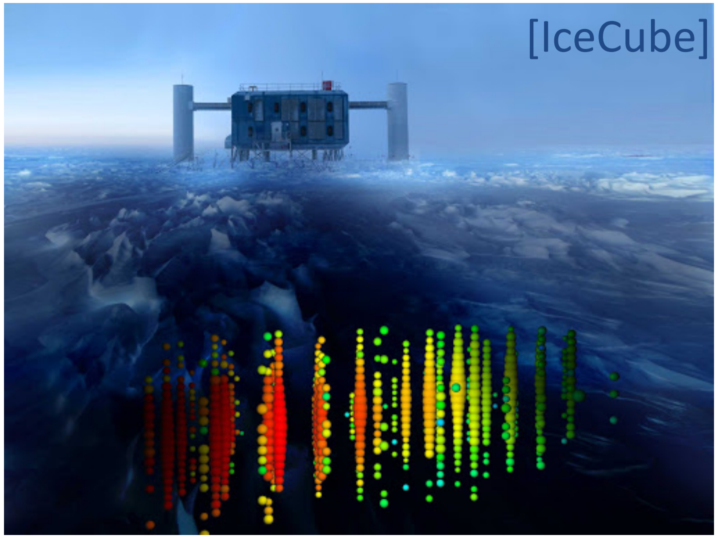
- Solar neutrinos gave the first hints of oscillations. All fluxes measured now and constraining solar models.
- Geo-neutrinos observed in Italy and Japan, prove that a large fraction of Earth's heat is radiogenic
- Observation of Supernova Bursts with modern detectors would provide a wealth of data on neutrinos and SN





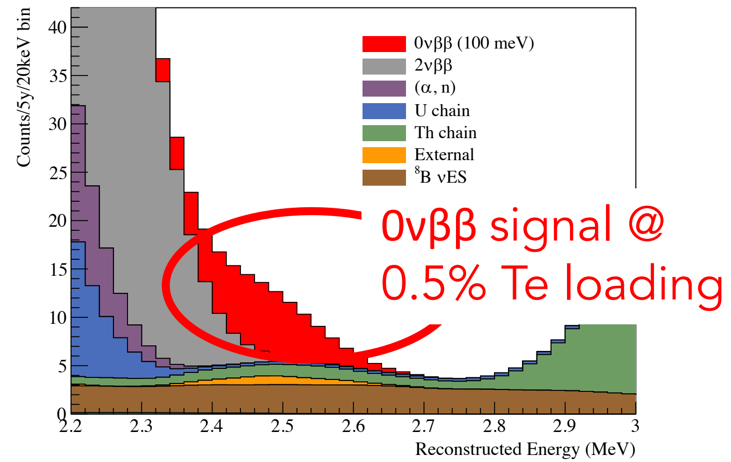
Neutrino Astronomy

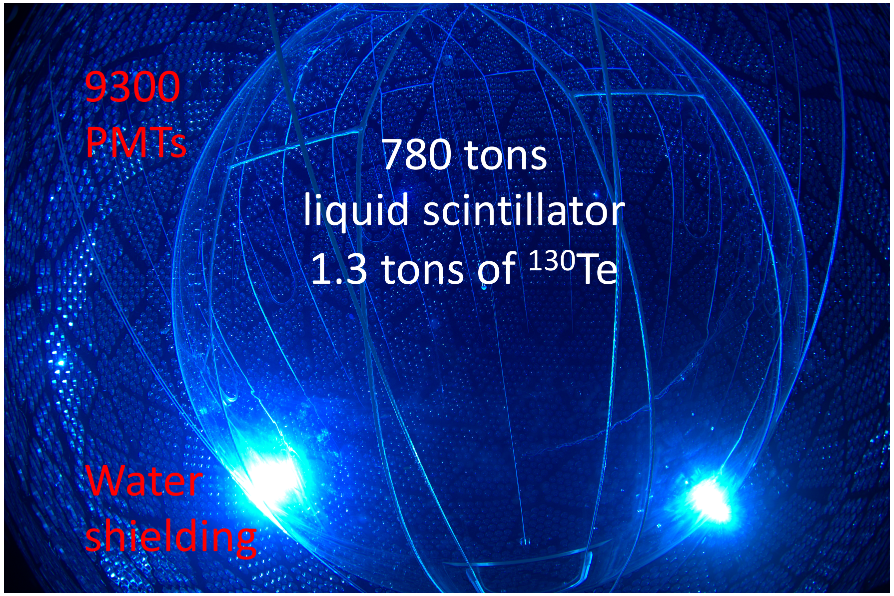
- IceCube detector in Antartica observed high-energy (PeV) astronomical neutrinos
- Some correlated with gamma, X-ray, telescope observations – *multi-messengers*
- New observatories in the Mediterranean and lake Baikal

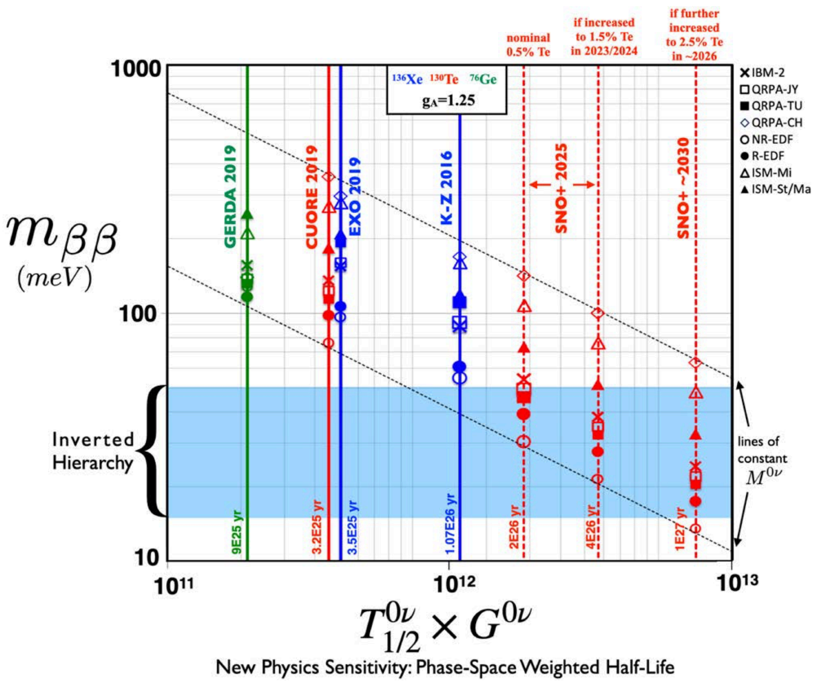


2.1 – SNO+

- Re-furbishing the SNO solar neutrino detector
- New purification, hold-down ropes, calibration systems, trigger and DAQ
  - Repairs in cavity, PMTs, electronics
- Currently half-filled with liquid scintillator. Te to be loaded early 2021. Sensitivity 2×10^{26} yr
- Loading DBD isotope in LS allows very large masses: 0.5% Te-loading now, can increase to 2.5%
- Very promising technique for future experiments aiming smaller nu masses: Theia? JUNO ?



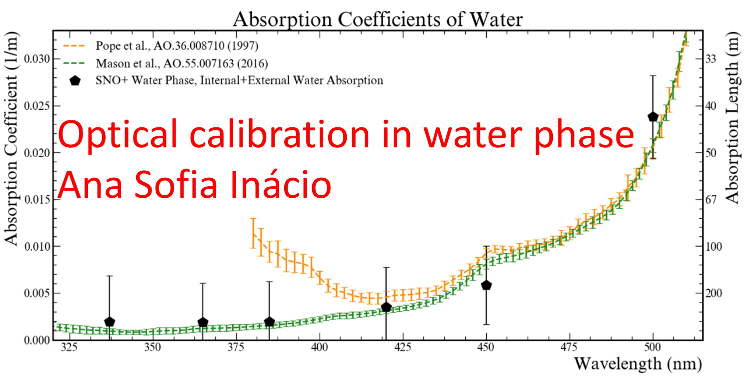


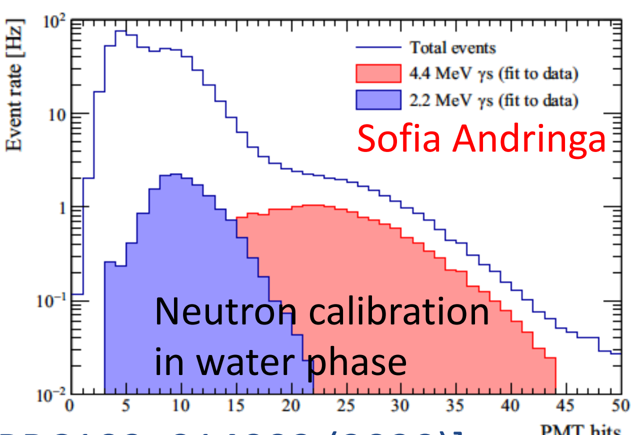


2.2 – Portugal in SNO+

European Strategy Update

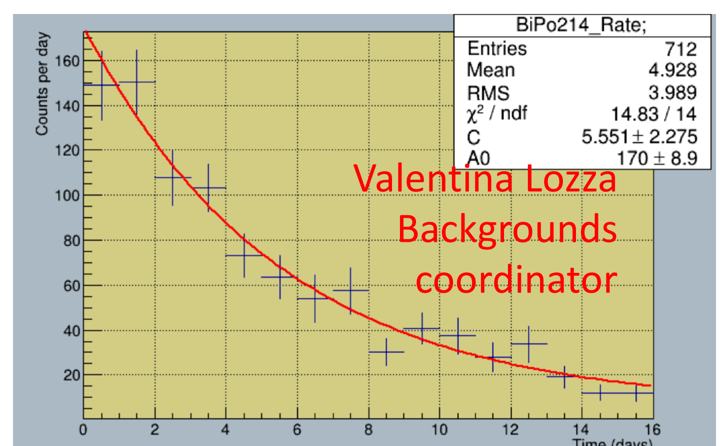
- LIP a founding member of SNO+
  - Signed the 2004 LOI, participated in first meeting, hosted 2010 meeting
- Detector calibrations
  - Hardware: optical fiber array for PMT calibration, internal deployment mechanism
  - Analysis of optical and neutron sources
- Data analysis and Physics
  - Anti-neutrinos from reactors (oscillations) and the Earth (Geophysics)
  - Measure the radioactivity backgrounds, crucial for all analyses



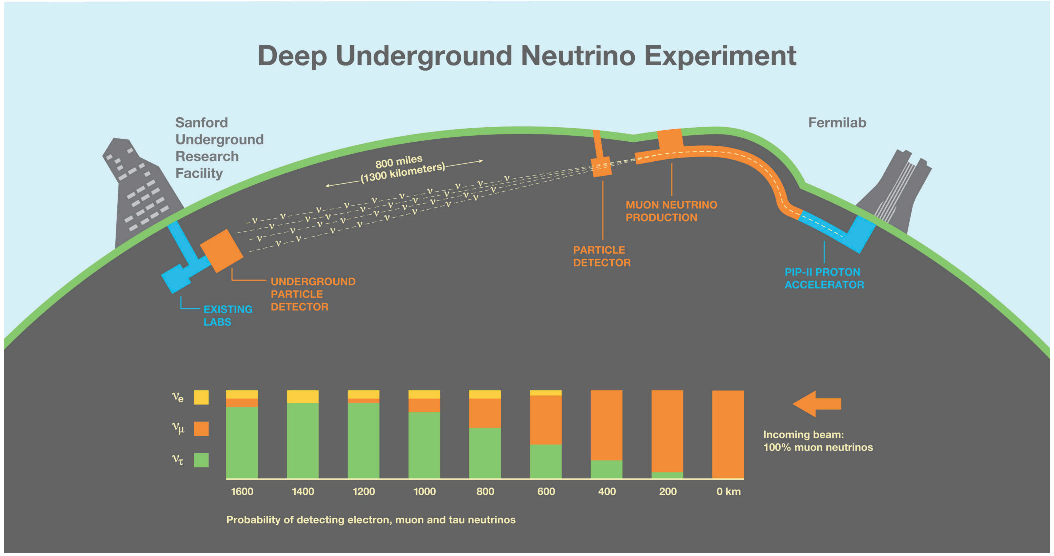


[PRC102, 014002 (2020)]

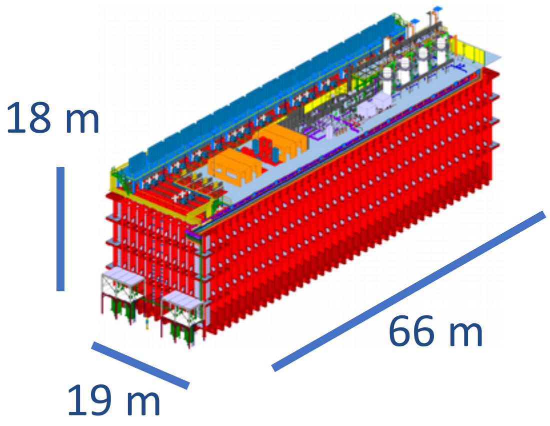
Radon decreasing in LS run



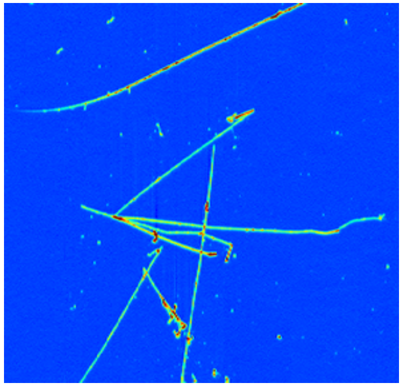
3.1 - DUNE



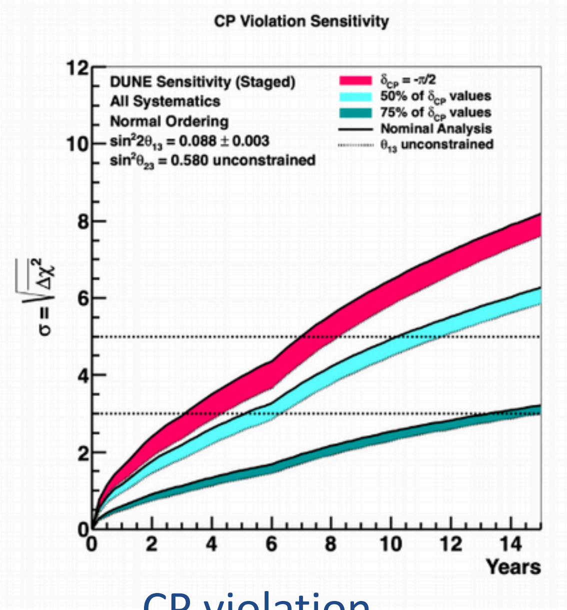
- Neutrino oscillation experiment with most intense beam from Fermilab
- Deep underground location allows rich program of non-beam Physics
- Complementary to HK in Japan.
  - Higher energy, wide-band beam
  - LAr TPC technology instead of water Cherenkov



One (of 4) 17 kton far detector module



Beam event display from ProtoDUNE @CERN



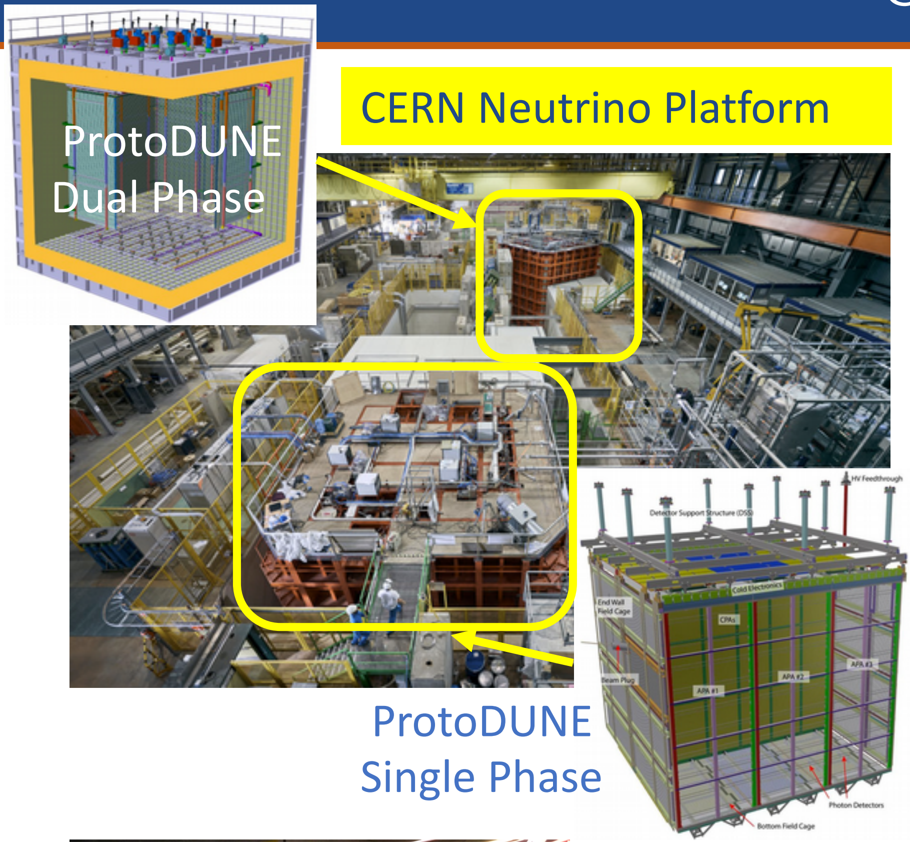
CP violation sensitivity

1

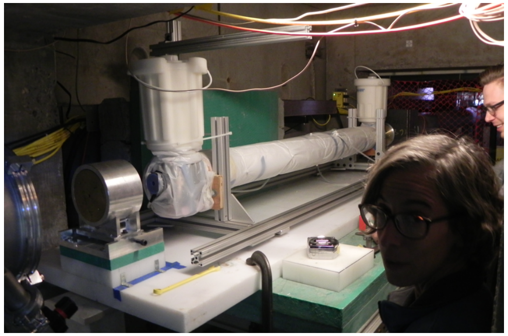
Major developments from the 2013 Strategy

B. The existence of non-zero neutrino masses is a compelling sign of new physics. The worldwide neutrino physics programme explores the full scope of the rich neutrino sector and commands strong support in Europe. Within that programme, the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe. ***Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).***

3.2 – Portugal in DUNE



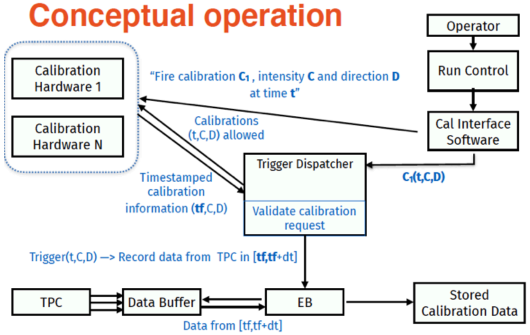
- Two 1 kton prototypes built and exposed to test beam at the Neutrino Platform
- ProtoDUNEs -I stopped operations this summer, PD-II will follow in 2022
- Great opportunity to strengthen CERN connection
- We contributed to trigger of PD-SP-I and purity monitor analysis of PD-DP-I
- We are developing the calibration systems that will be tested at ProtoDUNE-II soon, strong collaboration with Los Alamos

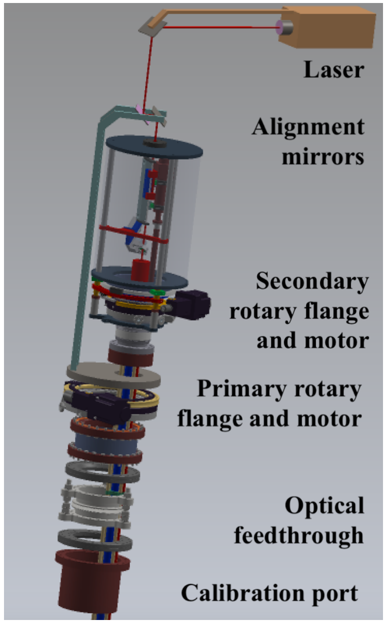


Neutron transmission experiment @ Los Alamos

Ionisation Laser
Design of "periscope"
DAQ and Slow Controls Interface

Conceptual operation

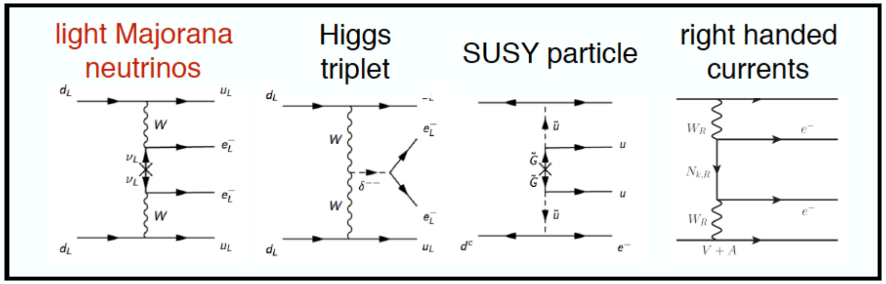




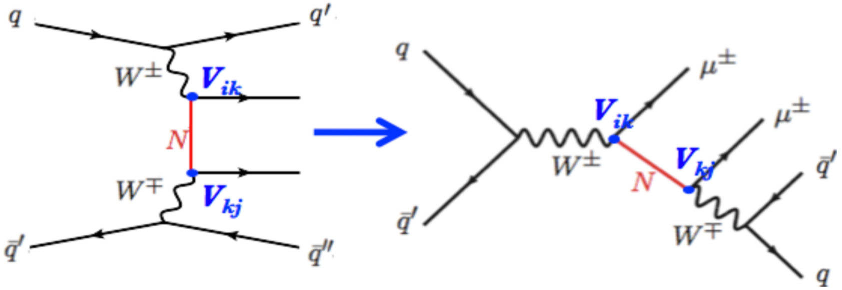
Outlook

- Double beta decay discovery ?
    - If Normal Ordering, will need a new generation of experiments
    - Will need a check with different isotopes/techniques (Theia, JUNO?)
    - Opens a rich phenomenology to be searched for at future colliders too
- Neutrino oscillations after CPV
    - Next would be search for non-unitarity and new-new Physics
- Interesting Technology to explore
    - Better light detectors for LS/water experiments. Ex.: LAPPDs: "flat wall" of very fast PMTs
    - Pixel readout for LAr TPCs
    - Machine Learning in event reconstruction and analysis
    - Open to surprises!

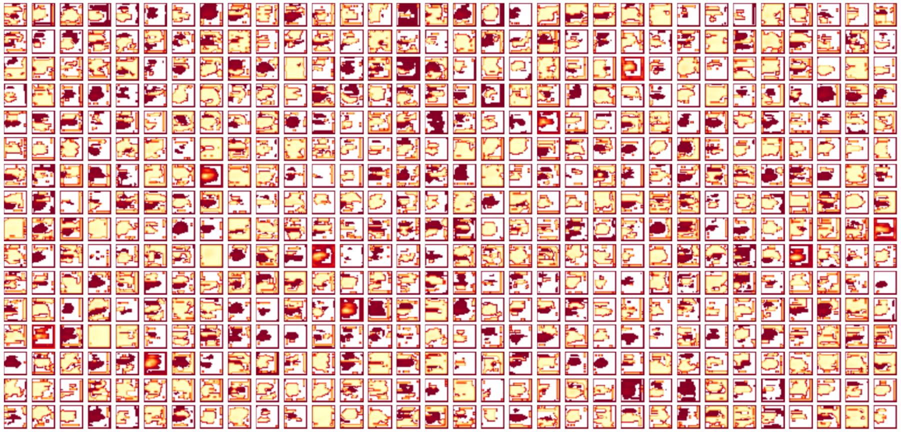
Underlying mechanism of DBD ?



Same-sign leptons at hadron colliders



Convolutional Neural Networks at DUNE



Thank you for your attention!