PDG
Collaboration meeting

October26, 2018

Double beta decay
Searches beyond three neutrinos
Light, heavy neutral leptons
Neutrino mixing review

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Flavour states ≠ mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{U_D} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i(\beta+\delta)} \end{pmatrix}}_{U_M} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

9 quantities to be measured: 3 masses, 3 angles, 3 phases

Known

1 square mass difference

1 square mass difference in absolute value

3 angles

Partially known

1 sign (NO favoured at 3.5 sigma)

1 Dirac phase

Unknown

Absolute mass scale

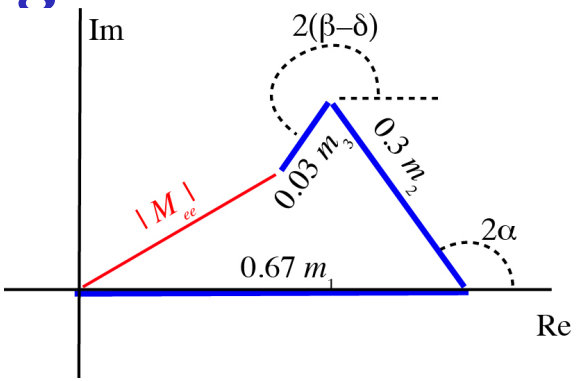
Dirac or Majorana?

2 Majorana phases (irrelevant for oscillations and matter effects)

See Maury Goodman

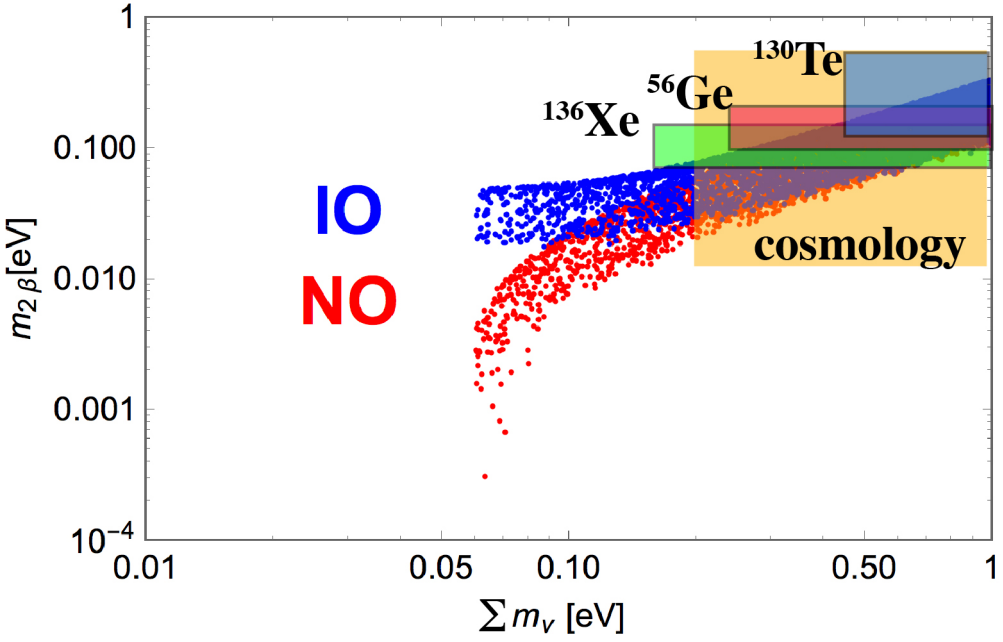
The stage

$$M_{ee} \text{ or } m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 \, m_{\nu_i} \right|$$



Best limits
^{136}Xe: 61-165 meV
^{76}Ge: 99-215 meV
^{130}Te: 110-520 meV

Bands in the diagram correspond to Majorana phases 0-2π assuming random distribution of the phases. Thanks to A. Ianni



Double-beta decay nodes

< 2018 edition: NODE = S076HDB $0\nu\beta\beta$ (limits) and $2\nu\beta\beta$ (values) decays.
Very old results present, less precise than more recent data
Quite confusing

In 2018 edition: Split in

NODE=S076NDB $2\nu\beta\beta$ $T_{1/2}$ measured values in 10^{21} yr units (nuclear physics)

NODE=S076HDB $0\nu\beta\beta$ Limits $T_{1/2}>10^{23}$ yr in 10^{23} yr units
Only the best or comparable limits for the half-lives of each transition are reported and only those with about $T_{1/2}>10^{23}$ yr that are relevant for particle physics.

NODE=S076MW Effective Majorana mass
Uncertainties due to Nuclear Matrix Elements

More than three neutrinos?

Neutrino Mixing.

Section A) on fluxes and B) on mixing angles OK

C) Other neutrino nixing results

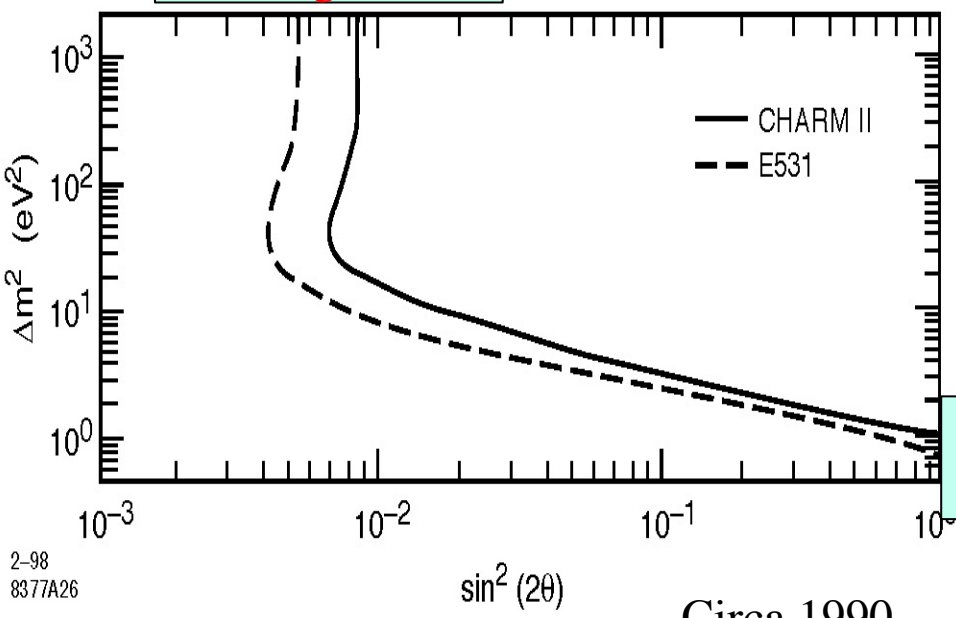
The node description and structure are obsolete.

Once upon a time, before the discoveries, the results of searches for oscillations were reported as an exclusion plot of Δm^2 (to represent the oscillation **frequency**) vs oscillation **amplitude** called $\sin^2 2\theta$ (folding around 45°)

For $\nu_\mu \rightarrow \nu_\tau$, $\sin^2 2\theta = \sin^2(2\theta_{23})\cos^4(\theta_{13})$

PDG encodes

Limit on $\sin^2 2\theta$ for "large" Δm^2



Limit on Δm^2 for $\sin^2 2\theta$=1

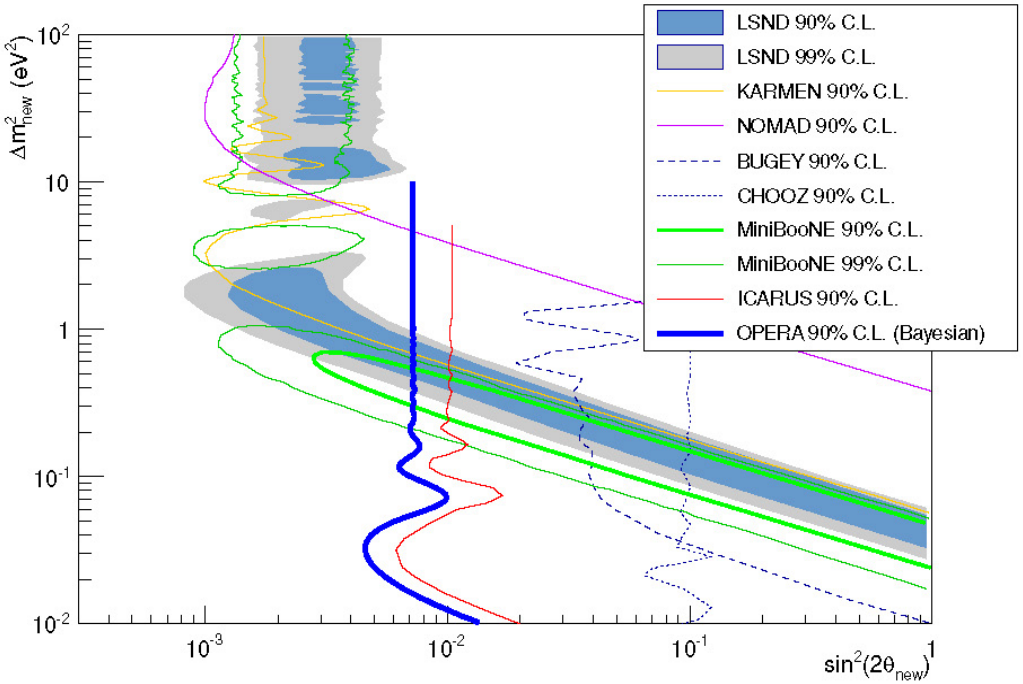
Circa 1990

"Anomalies"

JHEP07 (2013) 004

Starting since several years experiments past, running and approved look to clarify possible "anomalies" around $\Delta m^2 = 1$eV, from

LSND
Reactor. 3% effect with >5% systematics.
Ga. 10 %, 2 σ stat. + unknown systematics on cross section



Exclusion lines do not extend to $\sin^2 2\theta_{new}$

Anomalies

Hide section

C) Other neutrino mixing results

Hide the section, and its nodes (from NODE=S067D1 to NODE=S067NUS).
Move the limits in last two nodes (S076CPT, S076CP2) to the CPT Invariance table under the **Test of discrete space-time symmetries.**

Create new section under **Searches not in other sections** (SUSY, WIMP, Magnetic monopoles,...). Two alternatives

Light sterile neutrinos

eV mass scale unknown neutrinos having very small mixing with normal ones, sterile.
Simplest extension, one light sterile neutrino: **3+1 scheme**.

OR

Neutrino anomalies

Most recent claims for anomalies, taken together, are inconsistent with light sterile oscillations

Experimental searches

ν_μ, $\bar{\nu}_\mu$ disappearance
$\bar{\nu}_e$ disappearance
ν_e appearance in ν_μ beams
neutral currents appearance in ν_μ beams
"new" matter effects with atmospheric neutrinos (SK)

Light sterile neutrino searches

In 3+1 scheme, the limited, or measured, oscillation amplitudes of the different processes are different functions of the mixing matrix elements $|U_{e4}|$, $|U_{\mu 4}|$ and $|U_{t4}|$ or, in an equivalent manner, of the mixing angles θ_{14}, θ_{24} and θ_{34}.

$$P(\nu_e \to \nu_e) \propto |U_{e4}|^2 = \sin^2\theta_{14}$$

$$P(\nu_\mu \to \nu_\mu) \propto |U_{\mu 4}|^2 = \cos^2\theta_{14}\sin^2\theta_{24}$$

$$P(\nu_\mu \to \nu_e) \propto |U_{e4}|^2|U_{\mu 4}|^2 = \sin^2\theta_{14}\cos^2\theta_{14}\sin^2\theta_{24}$$

Joint analyses of solar and reactor: 90% cl upper limit $|U_{e4}|^2 = \sin^2\theta_{14} < 0.041$
"no ν_e-ν_s mixing approximation": $|U_{e4}|^2 = \sin^2\theta_{14} \sim 0$, by some experiments

$$P(\nu_\mu \to \nu_\mu) \propto |U_{\mu 4}|^2 \approx \sin^2\theta_{24}$$

$$P(\nu_\mu \to \nu_e) \propto |U_{e4}|^2|U_{\mu 4}|^2 \approx \sin^2\theta_{14}\sin^2\theta_{24}$$

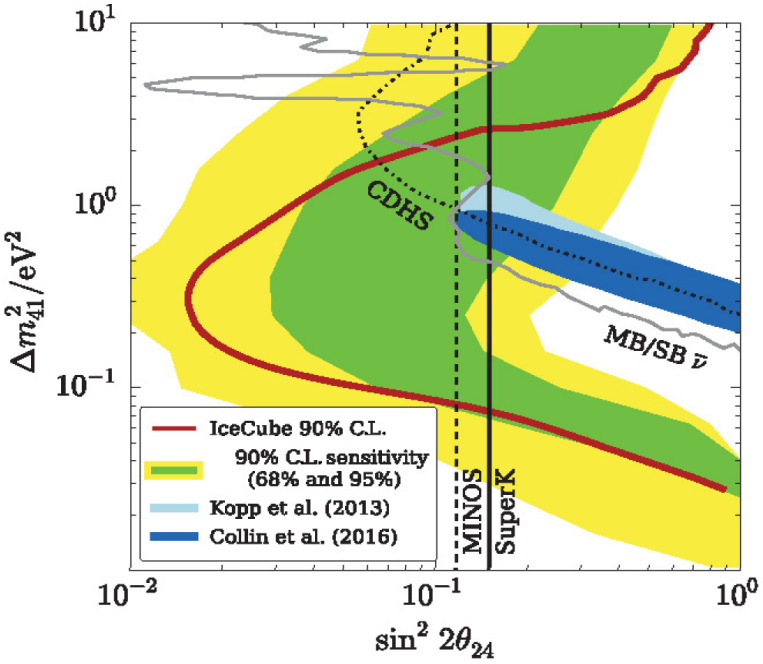
Caveat. Maltoni @ Neutrino2018

⇒ sterile neutrino models **fail to simultaneously account** for **all** the $\nu_e \to \nu_e$ data, the $\nu_\mu \to \nu_e$ data and the $\nu_\mu \to \nu_\mu$ data. This conclusion is robust;

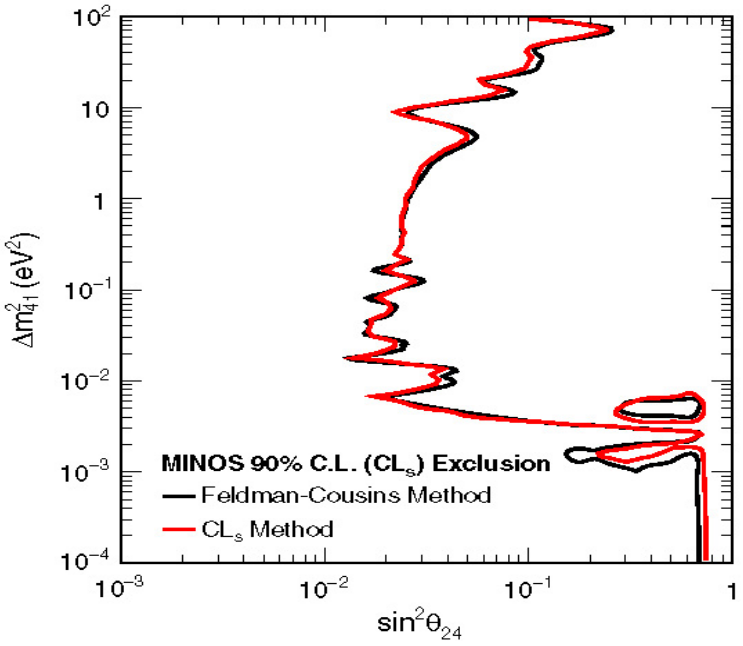
ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \propto |U_{\mu 4}|^2 \approx \sin^2\theta_{24}$$

IceCube PRL 117, 071801 (2016)



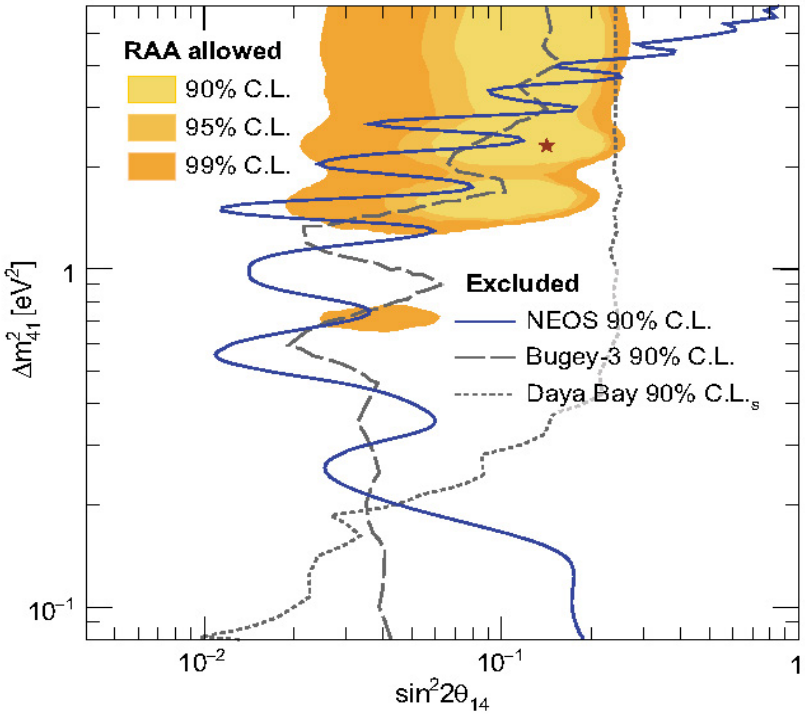
MINOS PRL 117 151801(2016)



ν_e disappearance (reactors)

$$P(\nu_e \to \nu_e) \propto |U_{e4}|^2 = \sin^2\theta_{14}$$

NEOS PRL 118 121802 (2017)

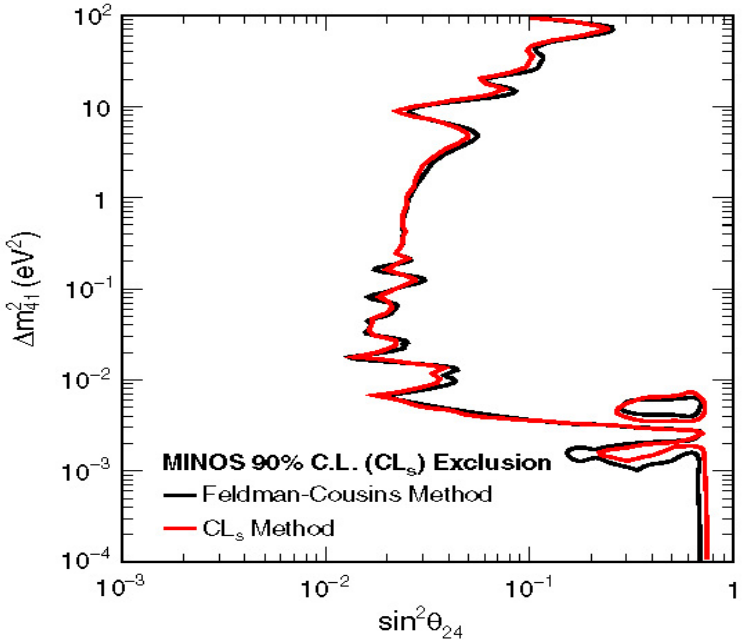


Notice that the exclusion line does not reach $\sin^2\theta$=1

Neutral Currents searches

MINOS, NOvA, T2K
Look at Far Detector and Near Detector
MINOS, e. g., fit θ_{22}, θ_{24}, θ_{23}, Δm^2_{32} and Δm^2_{41}, fixing θ_{12}, θ_{13}, Δm^2_{21} to values from other experiments.

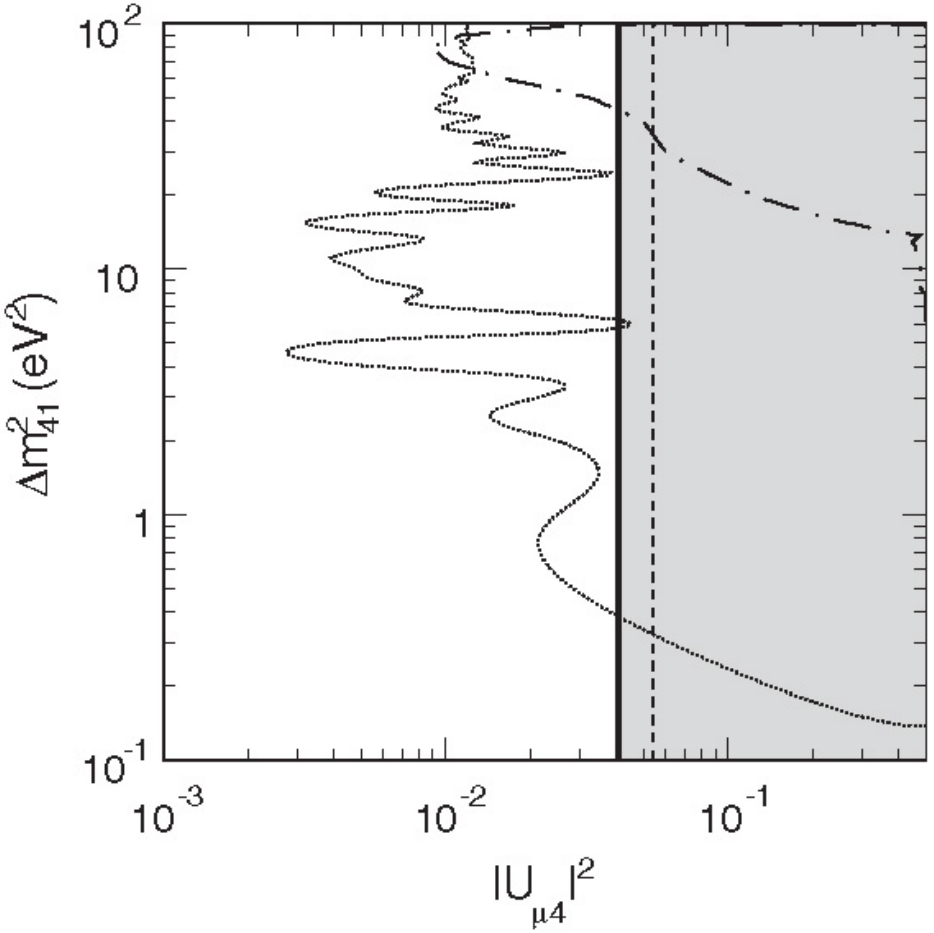
Exclusion plot
$|U_{\tau 4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$.



Matter effects SK

SuperK, Abe PRD 91 052019 (2015), use matter effects on atmospheric neutrinos, to give upper limits on upper limits on $|U_{e4}|$, $|U_{\mu 4}|$ and $|U_{\tau 4}|$.

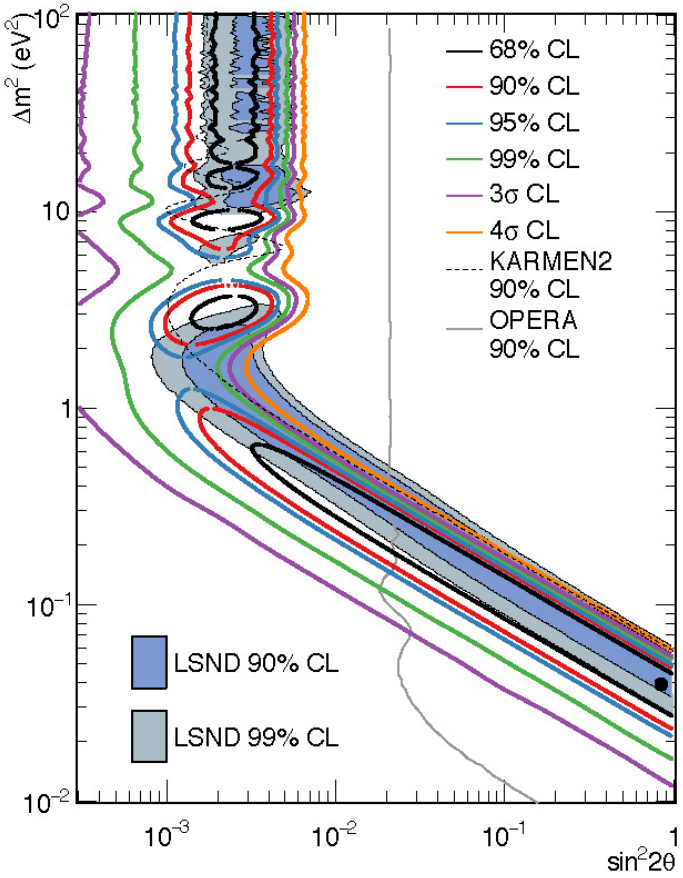
Dotted line limit from MiniBooNE + SciBooNE
Dot dashed line limit form CCFR

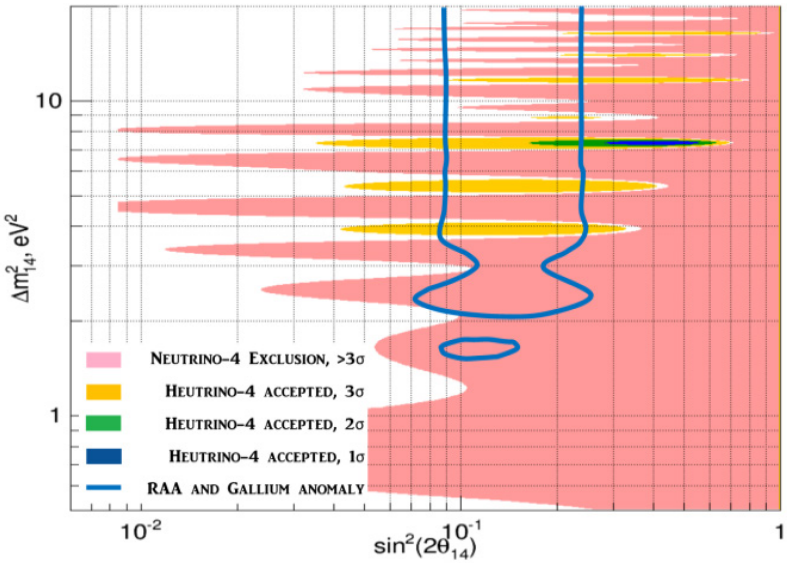


Other results

MiniBoone on LSND “oscillation”
2007. excluded 1%
2012. may be 6%
2018. yes 15%, elsewhere 1805.12028

Neutrino-4 1809.10561
Yes, still elsewhere





Possible encoding schemes

A minireview on light neutrinos?
Probably not necessary, if

1. A paragraph in the Neutrino mixing review is included (as in the present one)
2. An introduction to this section describes the criteria of the following encodings

Encoding option A
3+1 Model: give limit (value) for $|U_{e4}|^2$, $|U_{\mu 4}|^2$, $|U_{\tau 4}|^2$ for two, or three, values of Δm^2_{new} (e.g. 0.5 and 5 eV^2 or 0.1, 1, 10 eV^2)

Encoding option B
Model independent:
limits or values for oscillation probability amplitude, Δm^2_{new} in a comment
Similarly to DM searches DAMA case

Encoding option C
Do not encode at all. Have a minireview

NODE=S077. Heavy neutral leptons

Vast majority of entries is very old
e.g. kink search in nuclear β decay still mentions the 17 keV neutrino!
But few kink searches might be still active for sterile neutrinos, with mass, say > 10 eV

Include new section
Introduction.
Searches for neutral leptons heavier then hypothetical sterile neutrinos, namely with mass > 10 eV are included.

Move here
NODE=S077MNS Limits on stable heavy neutral lepton (last measurement in 1992)
NODE= S077MN Heavy Neutral Lepton Mass Limits (last measurement in 1995)

Hide the rest. Available in the past edition anyway.
Or, hide completely

14. Review on Neutrino masses, mixing and oscillations

Following the guideline of the Advisory Committee to periodically have a change in the authorship, we have been searching for two new authors, a theorist and an experimentalist.

The review is also meant to be useful to students, post docs and physicists not fully updated on neutrino mixing and masses.

An effort will be requested to the authors to substantially reduce the present length of 80 pages.

The three-neutrino mixing scheme is well established experimentally and, by now, it should be assumed since the start.

A brief discussion on hints for light sterile neutrinos should be included.

The structure and organisation of the review will be, as usual, responsibility of the authors.

Summary

- Listings of half-lives for 2ν2β and (limits) for 0ν2β separated since 2018 edition
- Increasing confusion with neutrino "anomalies"
  - Define encoding criteria in the listings
- Eliminate "Heavy neutral lepton search" section partially or completely?
- General criteria for the new review of neutrino masses, mixing and oscillations?

THANKS