Lecture5: $\sim$ eV Sterile neutrinos

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Sterile neutrinos:

What is(are) sterile neutrino(s)?

- Hypothetical neutral leptons
- Sterile neutrinos are SU(2) singlet
- Do not interact via any of the fundamental interactions except *'gravity'*
- Relevant in neutrino oscillation experiments, astrophysics, dark matter, etc...

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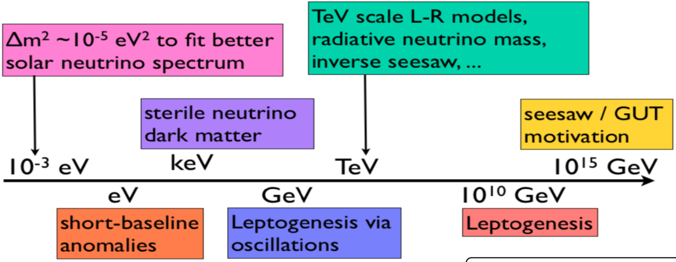
At what mass scale ?



Credits: T. Schwetz - GDR, 23 Nov 2020

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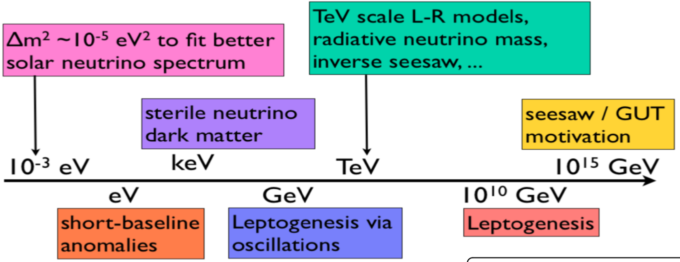


Credits: T. Schwetz - GDR, 23 Nov 2020

Our focus will be on '$\sim$ eV sterile neutrino' ?

Why '$\sim$ eV sterile neutrinos?

- Three flavor neutrino oscillations involve,

  * **The atmospheric mass squared difference:** $|\Delta m^2_{31}|$
  * **The solar mass squared difference:** Δm^2_{21}
  * **The atmospheric mixing angle:** θ_{23}
  * **The reactor mixing angle:** θ_{13}
  * **The solar mixing angle:** θ_{12}
  * **The CP-violating phase:** δ

- For two-flavor neutrino oscillations,

$$P_{e\mu} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

  when L is in meters, E is in MeV $\Rightarrow \Delta m^2 \sim eV^2$

- Standard three-flavor neutrino oscillations tell us,

$$\Delta m^2 \sim 10^{-5}\ \text{eV}^2 \text{ and } 10^{-3}\ \text{eV}^2$$

- Therefore, $\Delta m^2 \sim \text{eV}^2$ can not be explained by three-generation

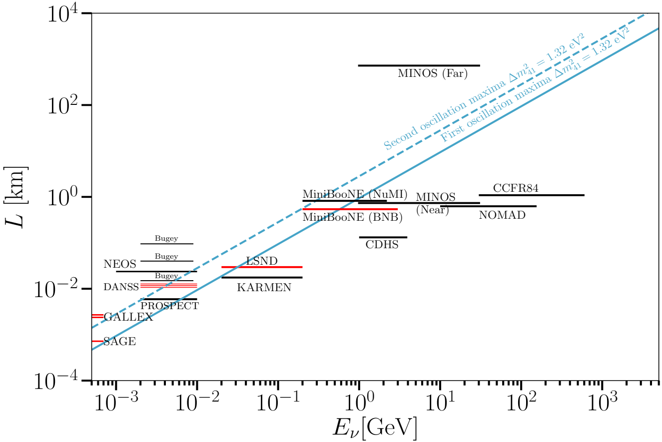
Short-baseline (SBL) experiments:

- $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance searches
  LSND, MiniBooNE, KARMEN, NOMAD
- $\bar{\nu}_e$ disappearance experiments (reactors)
  Bugey-3 (15, 40, 95), Bugey-4, Goessgen, Krasnoyarsk, Rovno, ILL, Chooz, Palo Verde
- ν_μ disappearance
  CDHS, MiniBooNE, atmospheric neutrinos, MINOS NC

SBL: $E/L \sim \mathrm{eV}^2$ $\quad\to\quad$ set $\Delta m^2_{21} \approx \Delta m^2_{31} \approx 0$

Credits: T. Schwetz - SNAC, 26 Sept 2011

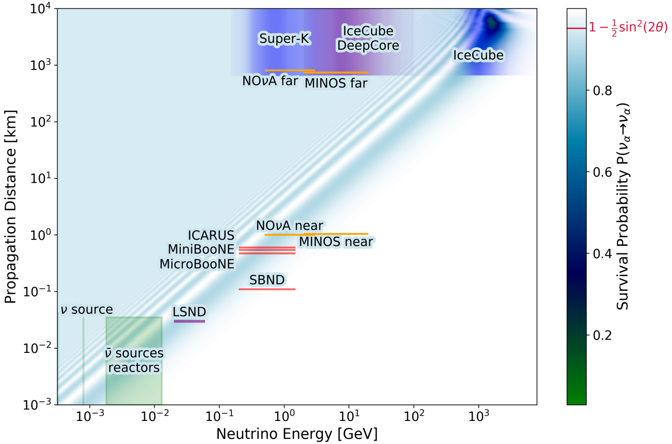
Experiments looking for light-sterile neutrino:



- Red those with $> 2\sigma$ preference for an additional neutrino state

Diaz, Argüelles, Collin, Conrad, Shaevitz, Phys. Rept. 884 (2020), arXiv: 1906.00045

Experiments looking for light-sterile neutrino:



- $P(\nu_\alpha \to \nu_\alpha)$ **for a simplified 2-flavor model with one active and one sterile neutrino mixing with a strength of** $\sin^2 2\theta = 0.1$ **at** $\Delta m_s = 1$ **eV**
- **For energies above** $E_\nu > 1\mathrm{TeV}$**, matter effects become important**

S. Böser et.al., arXiv: 1906.01739

Oscillations in 3+1 scenario:

Appearance $(\alpha \neq \beta)$

$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

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

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- Amplitude of ν_e disappearance:
  $$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$
- Amplitude of ν_μ disappearance:
  $$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \simeq 4|U_{\mu 4}|^2$$
- Amplitude of $\nu_\mu \to \nu_e$ transitions:
  $$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

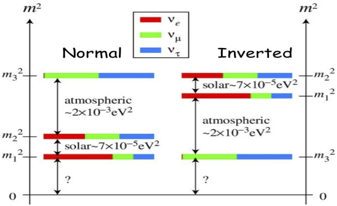
$\Downarrow$

Appearance-Disappearance Tension

Credits: S. Agarwalla - Neutrino 2020, Fermilab

Hierarchy?

Three-flavor scenario



Hierarchy?

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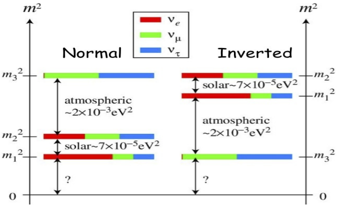
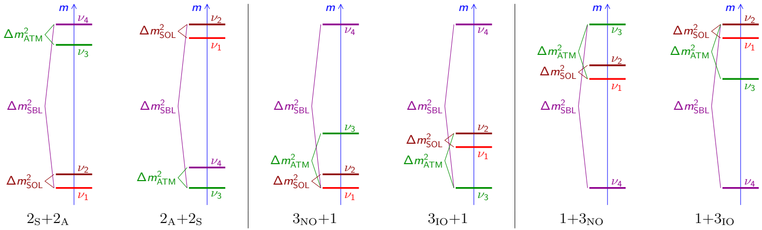


(3+1)-flavor scenario

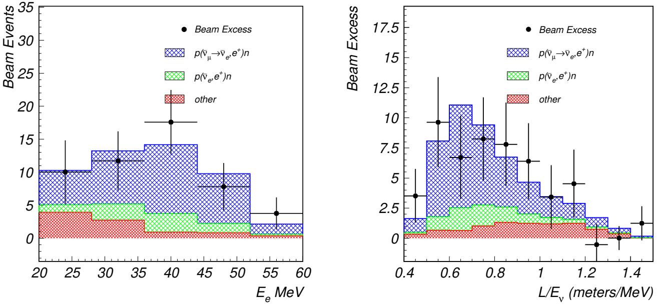


Disallowed by active+sterile mixings **Allowed by data** **Disallowed by cosmology**

Giunti, Lasserre, arXiv: 1901.08330

LSND experiment:

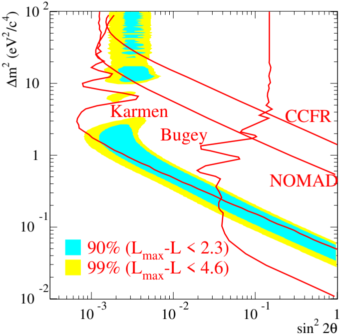
- Liquid Scintillator Neutrino Detector (LSND) experiment was designed to search for $\overline{\nu}_\mu \to \overline{\nu}_e$ at the Los Alamos Neutron Science Center, USA
- The LSND has $L = 30$ m, and E in $20 < E < 200$ MeV
- 798 MeV proton beam used to produce a large number of pions, mostly (π^+)
- Pions decay further to produce neutrinos, $\pi^+ \to \mu^+ \nu_\mu$ and $\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$
- A total excess of ~ 88 $\overline{\nu_e}$ events was observed in $\overline{\nu_\mu}$ beam



LSND Collab., Aguilar et. al., PRD64 (2001) 112007

Cont...

- LSND excess events can be explained by $\Delta m^2 \sim 1$ eV^2
- Results are shown in $(\sin^2 2\theta, \Delta m^2)$-plane for $20 < E_e < 200$ MeV



- Fit includes $\overline{\nu}_\mu \to \overline{\nu}_e$ and $\nu_\mu \to \nu_e$ oscillations
- The most favored allowed region: $0.2 - 2.0$ eV^2, also a region around 7 eV^2 is possible

LSND Collab., Aguilar et. al., PRD64 (2001) 112007

MiniBooNE experiment:

- The MiniBooNE experiment at Fermilab was designed to test LSND in both ν_e and $\bar{\nu}_e$ mode.
- The energy region is $200 < E < 1250\ MeV$

Table 1 Overview of the LSND and MiniBooNE experiments

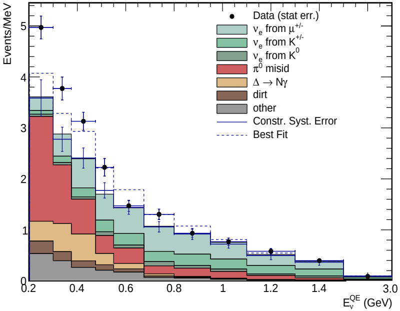
Property	LSND	MiniBooNE
Proton energy	798 MeV	8,000 MeV
Proton intensity	1,000 μA	4 μA
Proton beam power	798 kW	32 kW
Protons on target	28,896 C	284 C
Duty factor	6×10^{-2}	8×10^{-6}
Total mass	167 tons	806 tons
Neutrino distance	29.8 m	541 m
Events for 100% $\nu_\mu \rightarrow \nu_e$ transmutation	33,300	128,077

Conrad, Louis, Shaevitz, Annu. Rev. Nucl. Part. Sci. 2013. 63:4567

- Both LSND and MiniBooNE used $L/E \approx 1m/\mathrm{MeV}$ to probe $\Delta m^2 \approx 1eV^2$

Cont...

- MiniBooNE neutrino mode E_ν^{QE} distributions with 12.84×10^{20} POT, for ν_e CCQE data
- Background are displayed using histogram with systematic errors

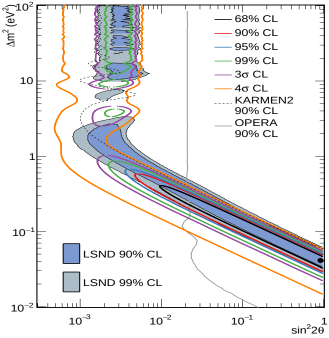


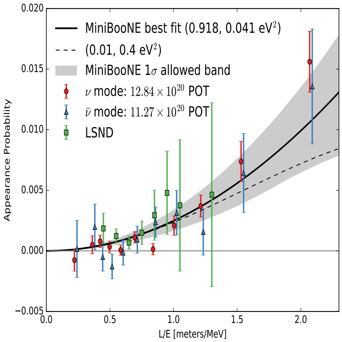
- A ν_e CCQE event excess of 381.2 ± 85.2 events (4.5σ) is observed for $200 < E_\nu^{QE} < 1250$ MeV

MiniBooNE Collab., Aguilar-Arevalo, et. al., PRL121 (2018) 221801

Cont...

- MiniBooNE allowed regions for a combined ν, and $\overline{\nu}$ data sets for events with $200 < E_{\nu}^{QE} < 3000$ MeV
- The best-fit occurs at $(\Delta m^2, \sin^2 2\theta) = (0.041\ \text{eV}^2, 0.92)$



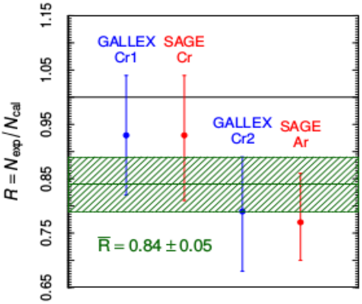


- A comparison between the MiniBooNE data excesses to the LSND data

MiniBooNE Collab., Aguilar-Arevalo, et. al., PRL121 (2018) 221801

Gallium anomaly:

- GALLEX , and SAGE were designed to detect solar neutrinos using $\nu_e + 71Ga \rightarrow 71Ge + e^-$ reaction
- Neutrino travels a distance of 1.9 m and 0.6 m with energy 0.8 MeV
- Figure shows the ratios of measured (N_{exp}) to the calculated (N_{cal}) event rate

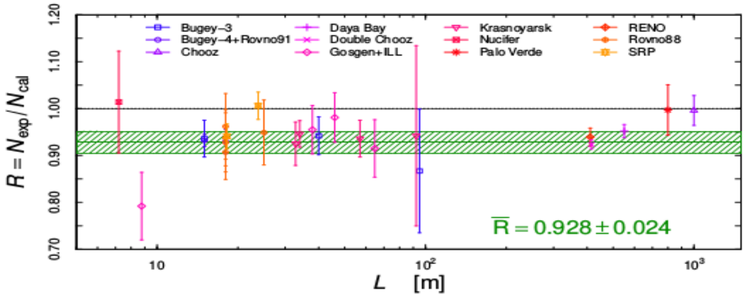


- Gallium anomaly shows about 2.9σ deficit
- As the L/E is similar to LSND, oscillation with $\Delta m^2 \sim$ eV^2 can explain the deficit

Giunti, Lasserre, arXiv: 1901.08330

Reactor anomaly:

- This result would imply reactors have observed a deficit of $\overline{\nu_e}$, at baselines of order 10 - 100 m
- Figure shows the ratios of observed to the expected event rate

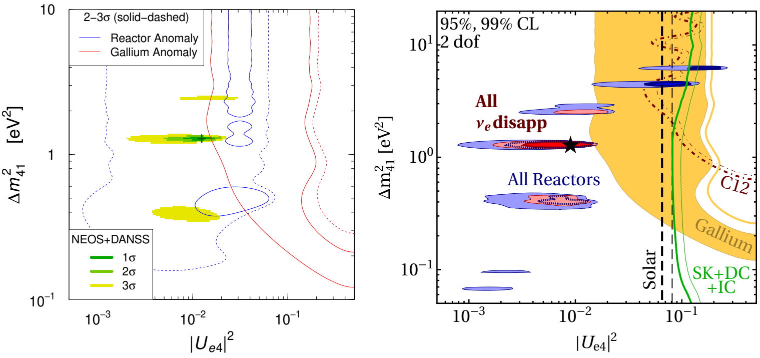


- Reactor $\bar{\nu}$ anomaly has significance of about 3σ
- The deficit can be explained by $\nu-$oscillations generated by a $\Delta m^2 \gtrsim 0.5$ eV^2

Giunti, Lasserre, arXiv: 1901.08330

SBL $\nu_e, \overline{\nu_e}$ disappearance:

- **Left: Best-fit region is shown around $\Delta m^2_{41} \simeq 1.3\,\mathbf{eV}^2$ and $|U_{e4}|^2 \simeq 0.01$**
- **Left: Tension between the model-independent NEOS+DANSS allowed regions and those indicated by the reactor and Gallium anomalies**



(a) (b)

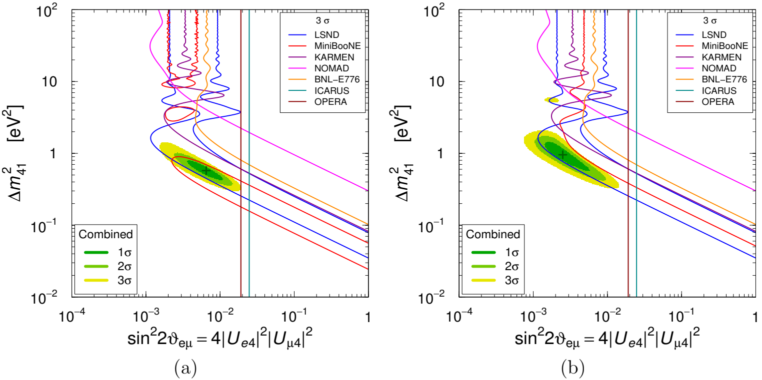
- **Right: Global-fit of the reactor neutrino data including the NEOS/Daya Bay and DANSS spectral ratio data in (blue)**

Giunti, Lasserre, arXiv: 1901.08330

- **Right: Red regions show Gallium, solar, $\nu_e - ^{12}C$ constraints**

SBL $\nu_e, \overline{\nu_e}$ appearance:

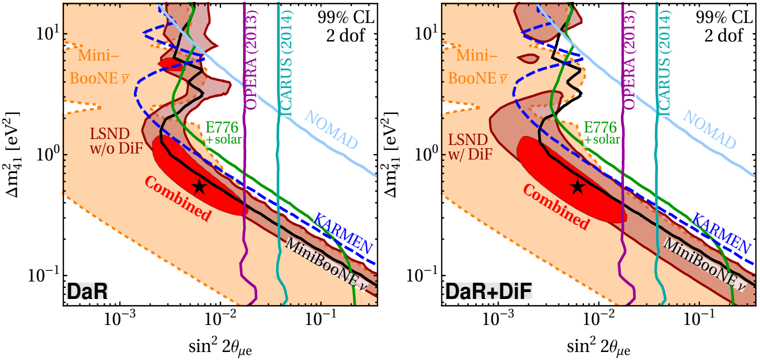
- **Left: Results of SBL $\overline{\nu_\mu} \to \overline{\nu_e}$ appearance with all MiniBooNE data**
- **Right: Results of SBL $\overline{\nu_\mu} \to \overline{\nu_e}$ appearance without the low-energy MiniBooNE data**



Giunti, Lasserre, arXiv: 1901.08330

SBL $\nu_e, \overline{\nu_e}$ appearance:

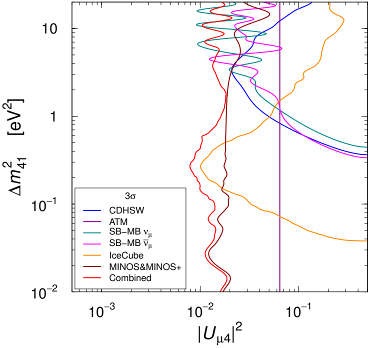
- **Left: Results of only decay-at-rest (DaR) data from LSND is included**
- **Right: Also decay-in-flight data (DiF) is used**



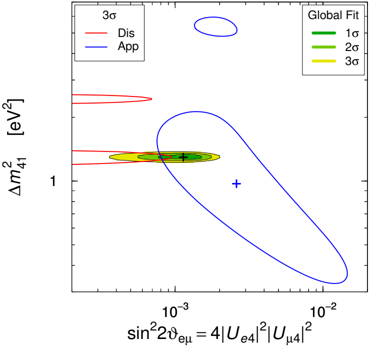
Dentler, Hernndez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv: 1803.10661

SBL $\nu_\mu, \overline{\nu_\mu}$ disappearance:

- **Left: Exclusion curves found in the $\nu_\mu, \overline{\nu_\mu}$ disappearance experiments**



(a)



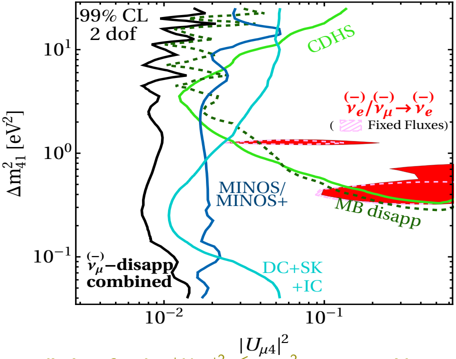
(b)

- **Right: One can see a strong tension between the appearance data and the disappearance data**

Giunti, Lasserre, arXiv: 1901.08330

SBL $\nu_\mu, \overline{\nu_\mu}$ disappearance:

- **Exclusion curves found in the $\nu_\mu, \overline{\nu_\mu}$ disappearance experiments**

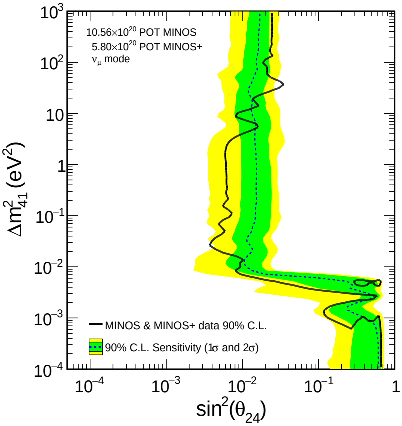


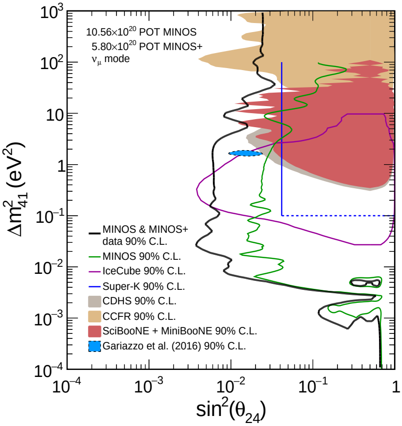
- **The plot shows strong limits of order $|U_{\mu 4}|^2 \lesssim 10^{-2}$ across a wide range of Δm^2_{41} values from $\sim 2 \times 10^{-1}$ eV^2 to ~ 10 eV^2**
- **The strong limit from atmospheric data at $\Delta m^2_{41} \lesssim 1$ eV^2 is dominated by IceCube**

Dentler, Hernndez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv: 1803.10661

MINOS and MIONS+

- MINOS experiment at Fermilab was designed to detect ν_μ and $\overline{\nu_\mu}$ disappearance channels
- The joint analysis of data from the MINOS and MINOS+ experiments sets stringent limits on mixing with sterile neutrinos in the 3+1 model for $\Delta m^2_{41} > 10^{-2}$ eV^2

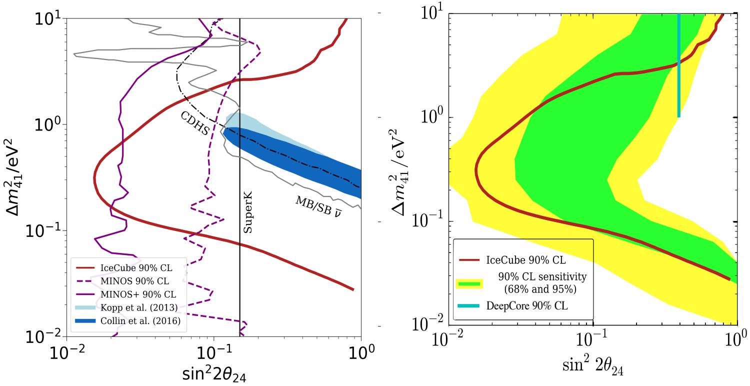




MINOS+ Collab., Adamson, et. al., PRL122(2019)

IceCube

- Constraints on sterile neutrino from IceCube ν_μ disappearance channel



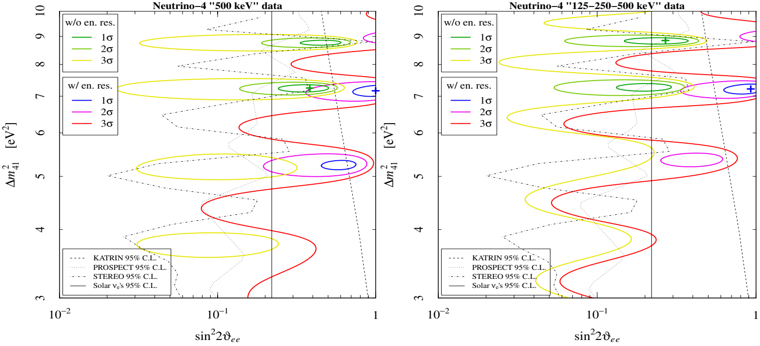
- Strong exclusion limits are obtained in the range of $\Delta m_s^2 \sim 0.02 - 0.3\ \mathrm{eV}^2$

S. Böser et.al., arXiv: 1906.01739

Neutrino-4

- Neutrino-4 experiment measure reactor $\overline{\nu_e}$ flux and spectrum dependence on the distance in the range 6-12 meters from the center of the reactor core.

NEUTRINO-4 Collab., arXiv: 1809.10561

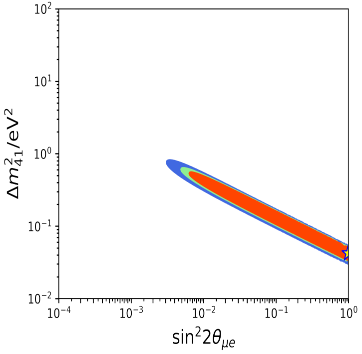


- Strong tension between the Neutrino-4 and the 90% C.L. exclusion curves of KATRIN, PROSPECT, STEREO and solar ν_es have been observed

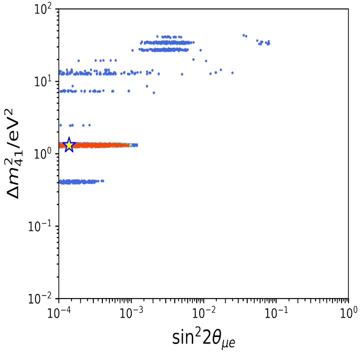
Giunti, Li, Ternes, Zhang, PLB 816 (2021)

Global-fit in 3+1 scenario:

Appearance channel



Disappearance channel



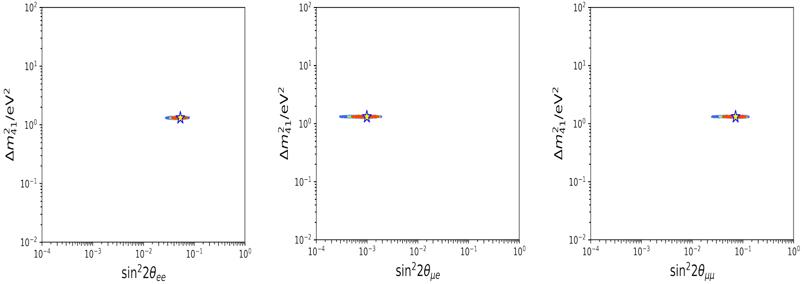
- Strong tension between appearance and disappearance channels

Diaz, Argüelles, Collin, Conrad, Shaevitz, Phys. Rept. 884 (2020), arXiv: 1906.00045

Cont...

Combined analysis:

Appearance + disappearance channels



Diaz, Argüelles, Collin, Conrad, Shaevitz, Phys. Rept. 884 (2020), arXiv: 1906.00045

Global-fit 3+1 scenario:

* The best-fit value of $\Delta m^2_{41} = 1.7$ eV^2

CL	$\|U_{e4}\|^2$	$\|U_{\mu 4}\|^2$	$\|U_{\tau 4}\|^2$
68.27% (1σ)	$0.016 - 0.024$	$0.011 - 0.018$	$\lesssim 0.0032$
95.45% (2σ)	$0.013 - 0.028$	$0.0083 - 0.022$	$\lesssim 0.018$
99.73% (3σ)	$0.0098 - 0.031$	$0.0060 - 0.026$	$\lesssim 0.039$

Gariazzo, Giunti, Laveder, Li, JHEP 1706 (2017) 135

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Efforts towards the search for $\sim$ eV sterile neutrinos have been constantly growing

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Gariazzo, Giunti, Laveder, Li, JHEP 1706 (2017) 135

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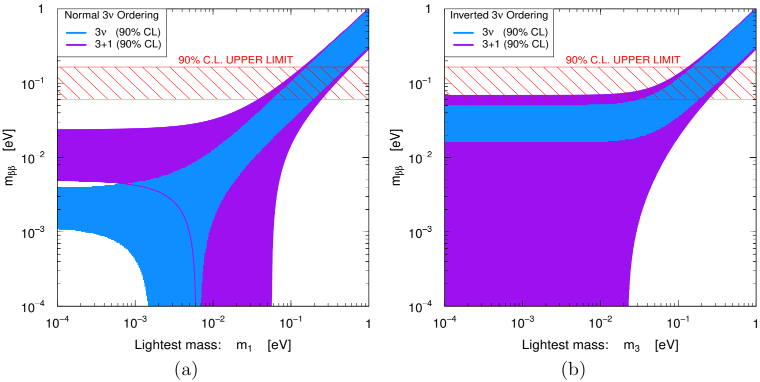
Current/Future Experiments: NEOS, STEREO, PROSPECT, DANSS, SoLid, BEST, KATRIN, ^{163}Ho experiments, The Fermilab SBN program, JSNS^2, ...

Sterile neutrino on $0\nu2\beta$ decay

- The rate of $0\nu2\beta$ decay is proportional to the effective Majorana mass $m_{\beta\beta}$ given by

$$m_{\beta\beta} = \left| |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3 + |U_{e4}|^2 \, e^{i\alpha_4} \, m_4 \right| ,$$

where, α^i's are combination of Dirac and Majorana phases



Giunti, Lasserre, arXiv: 1901.08330

Sterile Neutrino Phenomenology:

Texture zeros in M_ν in 3+1 framework

- The low energy neutrino mass matrix m_ν in the 3+1 scheme:

$$m_\nu^{(1)} = U m_\nu^{\text{diag}} U^T; \qquad m_\nu^{\text{diag}} = \text{diag}(m_1, m_2, m_3, m_4)$$

$$m_\nu^{(2)} = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} & m_{es} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} & m_{\mu s} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} & m_{\tau s} \\ m_{se} & m_{s\mu} & m_{s\tau} & m_{ss} \end{pmatrix};$$

- Here, $U = V.P$ is the (4×4) PMNS matrix and

$$V = R_{34}\tilde{R}_{24}\tilde{R}_{14}R_{23}\tilde{R}_{13}R_{12}, \qquad P = \text{diag}(1, e^{-i\alpha/2}, e^{-i(\beta/2-\delta_{13})}, e^{-i(\gamma/2-\delta_{14})})$$

- $R, \tilde{R}$ are the rotation matrices:

$$R_{34} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_{34} & s_{34} \\ 0 & 0 & -s_{34} & c_{34} \end{pmatrix}, \tilde{R}_{14} = \begin{pmatrix} c_{14} & 0 & 0 & s_{14}e^{-i\delta_{14}} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_{14}e^{i\delta_{14}} & 0 & 0 & c_{14} \end{pmatrix},$$

- # of parameters in $m_\nu^{(1)}$: 6- angles, 4-masses, 3-Dirac CP phases, and 3-Majorana phases
- # of parameters in $m_\nu^{(2)}$: 10 complex entries, 20 real parameters

Mismatch in # of parameters

Cont...

Assumptions: Consider m_ν has underlying symmetry, which helps to reduce # of parameters

Texture zeros in m_ν is one such scenarios

- m_ν has 10 parameters; # of texture-zeros = ${}^{10}c_n$, where n = # of zeros
- One-zero texture in m_ν : $m_{\alpha\beta} = 0$; 10 possibilities
- Two-zero texture in m_ν : $m_{\alpha\beta} = 0 = m_{\sigma\lambda}$; 45 possibilities
- For three-zeros: 120, four-zeros: 210, and five-zeros: 252 possibilities
- Note: All possibilities are not consistent phenomenologically
- More than 5-zeros in 3+1 scenario are phenomenologically disallowed

Borah, Ghosh, Gupta, Raut, PRD96 (2017)

One-zero and one-massless neutrino:

- One-zero texture:

$$m_1 U_{a1} U_{b1} + m_2 U_{a2} U_{b2} e^{2i\alpha} + m_3 U_{a3} U_{b3} e^{2i(\beta+\delta_{13})} + m_4 U_{a4} U_{b4} e^{2i(\gamma+\delta_{14})} = 0 \ ,$$

  here, $m_1(m_3) = 0$ for NH (IH)

- Phenomenologically allowed cases:

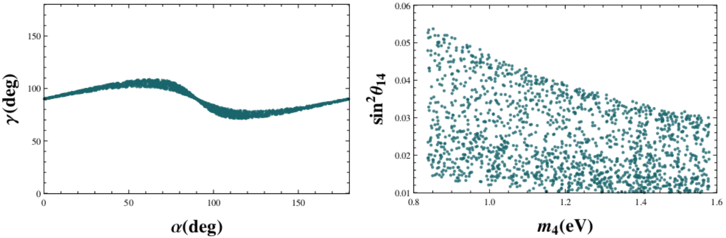
$\mathbf{M}_{\alpha\beta=0}$	NH($m_1 = 0$)	IH($m_3 = 0$)
M_{ee}	×	√
$M_{e\mu}$	√	√
$M_{e\tau}$	√	√
$M_{\mu\tau}$	√	√
$M_{\mu\mu}$	√	√
$M_{\tau\tau}$	√	√
M_{es}	×	×
$M_{\mu s}$	×	×
$M_{\tau s}$	√	√
M_{ss}	×	×

- For NH (IH): 6 (7) allowed cases

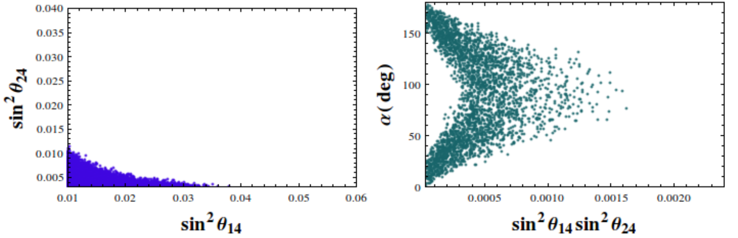
NN, Ghosh, Gupta, IJMPA31 (2016) 24

Cont...

- For $|M_{ee}| = 0$, IH



- For $|M_{e\mu}| = 0$, NH (IH) is shown in left (right) panel



NN, Ghosh, Gupta, IJMPA31 (2016) 24

Minimal extended type-I seesaw mechanism:

- **The SM is extended by 3-ν_R's and a gauge singlet field S**
- **The Lagrangian:**

$$-\mathcal{L}_{\mathcal{M}} = \overline{\nu_L} M_D \nu_R + \overline{S^c} M_S \nu_R + \frac{1}{2} \overline{\nu_R^c} M_R \nu_R + h.c..$$

- The neutrino mass matrix $M_\nu^{7\times7}$ in the basis (ν_L, ν_R^c, S^c)

$$M_\nu^{7\times7} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & M_R & M_S^T \\ 0 & M_S & 0 \end{pmatrix}$$

- Assumption: $M_R \gg M_S > M_D$
- The effective $M_\nu^{4\times4}$ in the basis (ν_L, S^c):

$$M_\nu^{4\times4} = -\begin{pmatrix} M_D M_R^{-1} M_D^T & M_D M_R^{-1} M_S^T \\ M_S (M_R^{-1})^T M_D^T & M_S M_R^{-1} M_S^T \end{pmatrix}$$

- **Assuming** $M_S > M_D$**:**

$$m_\nu^{3\times3} \simeq M_D M_R^{-1} M_S^T (M_S M_R^{-1} M_S^T)^{-1} M_S (M_R^{-1})^T M_D^T - M_D M_R^{-1} M_D^T$$
$$m_s \simeq -M_S M_R^{-1} M_S^T$$

- **Example:** $M_D \simeq 100$ **GeV,** $M_S \simeq 500$ **GeV,** $M_R \simeq 2 \times 10^{14}$ **GeV** $\Rightarrow m_\nu \simeq 0.05$ **eV, and** $m_s \simeq 1.3$ **eV**

Barry, Rodejohann, Zhang, JHEP07 (2011) 091, Zhang, PLB714 (2012) 262

Cont...

- The active-sterile neutrino mixing matrix is given by,

$$V \simeq \begin{pmatrix} (1-\frac{1}{2}RR^\dagger)U' & R \\ -R^\dagger U & 1-\frac{1}{2}R^\dagger R \end{pmatrix},$$

- $R_{3\times1}$ governs the strength of active-sterile mixing:

$$R_{3\times1} = M_D M_R^{-1} M_S^T (M_S M_R^{-1} M_S^T)^{-1}.$$

- Essentially, $R_{3\times1} = (V_{e4}, V_{\mu4}, 0)^T$, is suppressed by the ratio $\mathcal{O}(M_D)/\mathcal{O}(M_S)$
- **Assumption:**

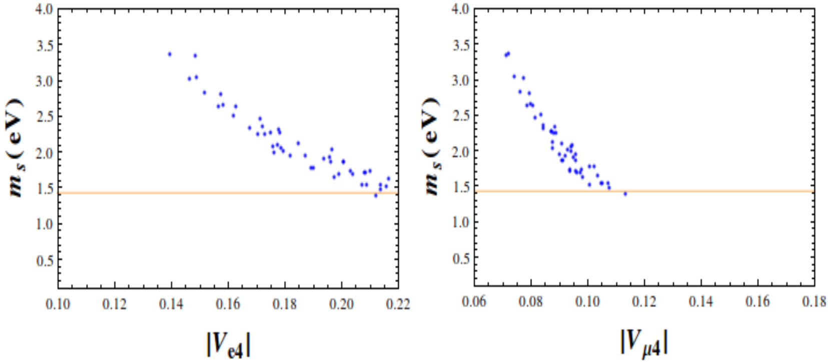
$$M_R = \begin{pmatrix} r_1 & 0 & 0 \\ 0 & r_2 & 0 \\ 0 & 0 & r_3 \end{pmatrix}; \begin{pmatrix} 0 & r_2 & 0 \\ r_2 & 0 & 0 \\ 0 & 0 & r_1 \end{pmatrix}; \begin{pmatrix} 0 & 0 & r_2 \\ 0 & r_1 & 0 \\ r_2 & 0 & 0 \end{pmatrix}; \begin{pmatrix} r_1 & 0 & 0 \\ 0 & 0 & r_2 \\ 0 & r_2 & 0 \end{pmatrix}$$

- **Five-zeros in M_D, and one-zero in $(M_S)_{1\times3}$**
- **Allowed texures: $m_{e\tau} = 0$, and $m_{\tau\tau} = 0$ for IH**

NN, Ghosh, Goswami, Gupta, JHEP 03 (2017) 075

Cont...

- **Correlation plots for the texture $m_{\tau\tau} = 0$ are**



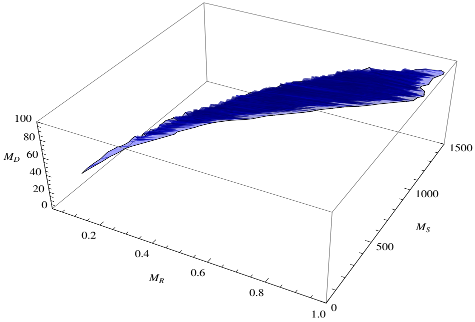
NN, Ghosh, Goswami, Gupta, JHEP 03 (2017) 075

NLO correction for MES model:

- **For $M_D/M_S \sim 0.1$, NLO corrections can be important**

Grimus, Lavoura, JHEP 11 (2000) 042

- **Here, NLO term is proportional to $M_D^4/M_R M_S^2$**
- **NLO correction: $m_\nu^{3\times3} = (m_\nu^{3\times3})_{lo} + M_D^4/M_R M_S^2$**
- **Allowed parameter space for which NLO correction term $\sim 10^{-5}$ eV**



NN, Ghosh, Goswami, Gupta, JHEP 03 (2017) 075

Symmetry Realization:

- To enforce texture zeros in fermions mass matrices by means of Abelian symmetry

[Grimus, Joshipura, Lavoura, Tanimoto, EPJC 36 (2004) 227]

- **Adopted Abelian symmetry group $Z_8 \times Z_2$ to realize texture $m_{e\tau} = 0$ and $m_{\tau\tau} = 0$**
- **For $m_{e\tau} = 0$:**

$$M_l = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, M_D = \begin{pmatrix} 0 & a_2 & 0 \\ b_1 & 0 & b_3 \\ c_1 & 0 & 0 \end{pmatrix}$$

$$M_R = Diag(r_1, r_2, r_3), \;\; M_S = \begin{pmatrix} 0 & s_2 & s_3 \end{pmatrix}$$

- **The fields transformation under $Z_8 \times Z_2$:**

Lepton doublet	$(Z_8 \times Z_2)$	RH Singlet	$(Z_8 \times Z_2)$	ν fields	$(Z_8 \times Z_2)$	Higgs doublet	$(Z_8 \times Z_2)$
$\bar{D}_{L_e}$	$(\omega^6, -1)$	e_R	$(\omega^2, -1)$	ν_{eR}	$(\omega^5, 1)$	ϕ	$(1, 1)$
$\bar{D}_{L_\mu}$	$(\omega^3, 1)$	μ_R	$(\omega^5, 1)$	$\nu_{\mu R}$	$(\omega^2, -1)$	ϕ'	$(\omega^3, 1)$
$\bar{D}_{L_\tau}$	$(\omega^5, 1)$	τ_R	$(1, 1)$	$\nu_{\tau R}$	$(1, 1)$	ϕ''	$(\omega^2, 1)$

- **S transform as $(\omega^6, -1)$ under $(Z_8 \times Z_2)$ forbids $\bar{S}^c S$ term**

Sterile neutrino at long baseline:

- **The $\nu_\mu \to \nu_e$ conversion probability in 'vacuum':**

$$P_{\alpha\beta}(L,E) = \delta_{\alpha\beta} - \underbrace{4\sum_{k>j} \mathrm{Re}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin^2(\Delta)}_{\text{CP conserving}} + \underbrace{2\sum_{k>j} \mathrm{Im}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin(2\Delta)}_{\text{CP violating}} ; \quad \Delta = \frac{\Delta m^2_{kj} L}{4E}$$

- **Considering $|U_{e4}| \sim |U_{\mu 4}| \sim |U_{e3}| \sim \varepsilon \sim 0.15$:**

$$\begin{aligned} P^{\rm LBL}_{\nu_\mu \to \nu_e} &= 4 \sin^2\vartheta_{13} \sin^2\vartheta_{23} \sin^2\Delta_{31} \\ &+ 2 \sin\vartheta_{13} \sin 2\vartheta_{12} \sin 2\vartheta_{23} (\alpha\Delta_{31}) \sin\Delta_{31} \cos(\Delta_{32} + \delta_{13}) \\ &+ 4 \sin\vartheta_{13} \sin\vartheta_{14} \sin\vartheta_{24} \sin\vartheta_{23} \sin\Delta_{31} \sin(\Delta_{31} + \delta_{13} - \delta_{14}) , \end{aligned}$$

where $\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}| \sim \varepsilon^2$

⊗ **The presence of δ_{14} can impact the search of CP violation**

- The probability in Matter:

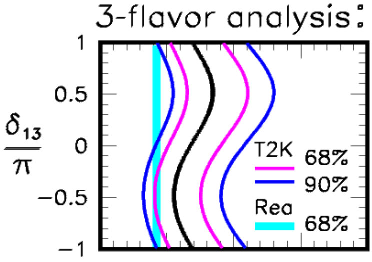
$$H = UKU^\dagger + V ; \quad K = \mathrm{diag}(0, k_{21}, k_{31}, k_{41}) ,$$

V is the matter potential

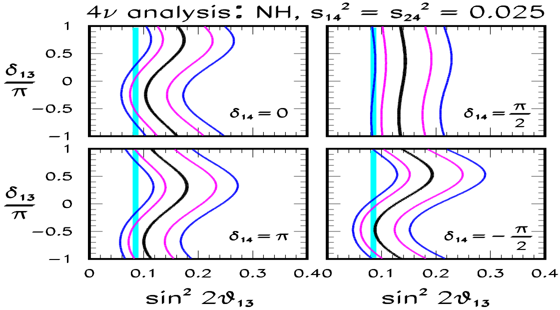
Klop, Palazzo, PRD91 (2015) 7, 073017

At T2K:

- 3-flavor formalism:

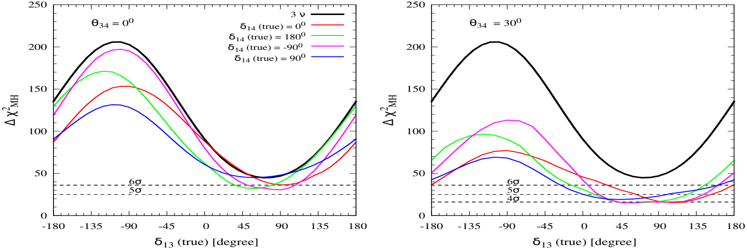


- (3+1)-flavor formalism:



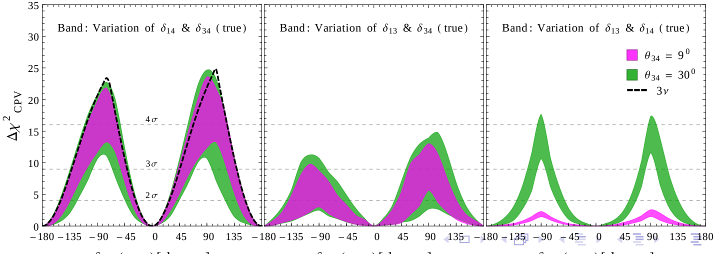
At DUNE:

- Mass hierarchy sensitivity:



- CP-violation sensitivity:

Agarwalla, Chatterjee, Palazzo, JHEP09(2016)016



Summary

- **A brief overview of $\sim$ eV sterile neutrino has been presented**
- **Various experimental results are discussed in support of sterile neutrino**
- **Possible phenomenology has been presented**

Summary

- A brief overview of $\sim$ eV sterile neutrino has been presented
- Various experimental results are discussed in support of sterile neutrino
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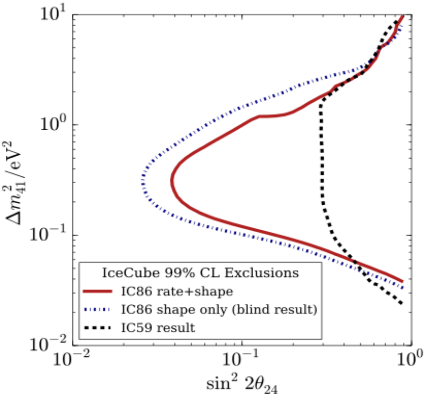
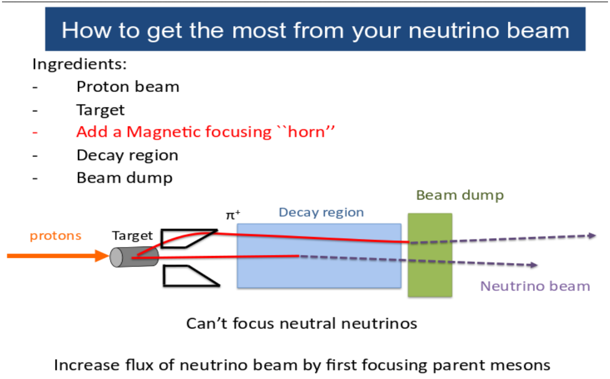
thank you

Back Up

Icecube result : arXiv[1605.01990]



Neutrino beam generation



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