Status of LSND/MiniBooNE, Reactor and Gallium Anomalies and Sterile Neutrino Searches

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Definition

Sterile neutrino:

- name introduced by B.Pontecorvo in 1967
- neutral lepton that does not take part in the weak interactions
- theoretically well motivated (ν mass generation mechanism)
- can take part in neutrino oscillations

Probability of $\nu_\alpha \to \nu_\beta$ appearance in model with two neutrinos

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

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Neutrino oscillation matrix

Extended oscillation matrix:

$$|\nu_j\rangle = \sum_{\alpha=\mathrm{e},\mu,\tau} U_{\alpha j}|\nu_\alpha\rangle.$$

$$\mathrm{U} = \begin{pmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} & U_{\mathrm{e}4} & \dots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \dots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \dots \\ U_{\mathrm{s}1} & U_{\mathrm{s}2} & U_{\mathrm{s}3} & U_{\mathrm{s}4} & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}.$$

$|U_{\alpha j}|^2$, describe the neutrino flavour-α fraction of ν_j

Possible experimental signs of sterile neutrinos

- Anomalous disappearance of one flavour of neutrinos:
  $\nu_\alpha \to \nu_\alpha$
- Anomalous appearance of ν_β in a beam of ν_α:
  $\nu_\alpha \to \nu_\beta$

LSND/MiniBooNE puzzle

LSND - Liquid Scintillator Neutrino Detector

- LSND - experiment at Los Alamos Meson Physics Facility, 1993-1998
- Search for oscillations $\overline{\nu}_\mu \to \overline{\nu}_e$
- $\overline{\nu}_\mu$ from μ^+ decay at rest
- Detector: 167 t of liquid scintillator (mineral oil with a small admixture of butyl scintillant)
- Cherenkov and scintillation light

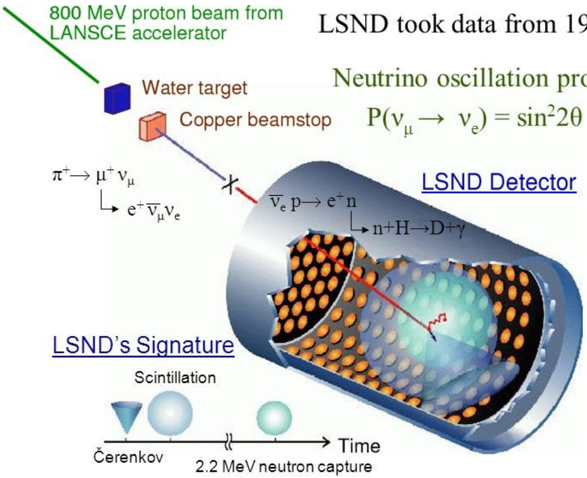
LSND anomaly

The LSND Experiment

LSND took data from 1993-98

Neutrino oscillation probability:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$



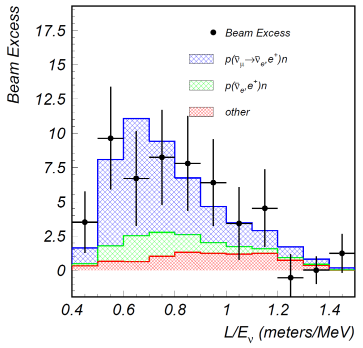
Baseline of 30 meters

Energy range of 20 to 55 MeV

L/E of about 1m/MeV

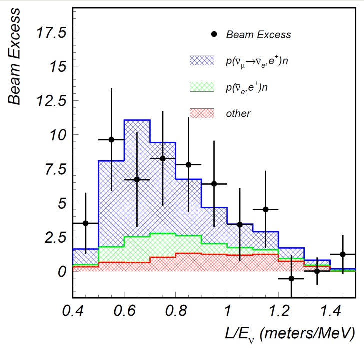
VirginiaTech *Invent the Future* — *Jonathan Link* — *4/19/2007*

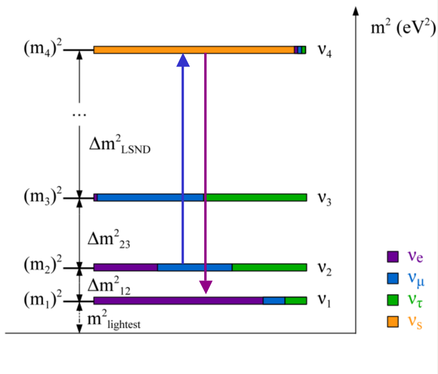
LSND anomaly – excess of $\overline{\nu}_e$ in a beam of $\overline{\nu}_\mu$



- Excess of $87.9 \pm 22.4 \pm 6.0$ events
- Corresponds to oscillation probability $(0.264 \pm 0.067 \pm 0.045)\%$
- 3.8σ evidence for oscillation

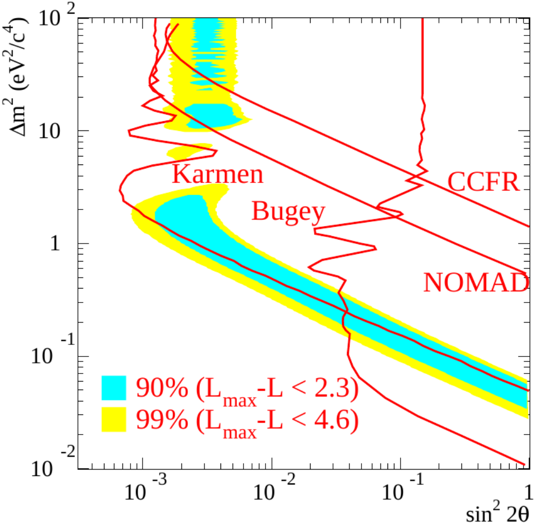
LSND anomaly- excess of $\overline{\nu}_e$ in a beam of $\overline{\nu}_\mu$





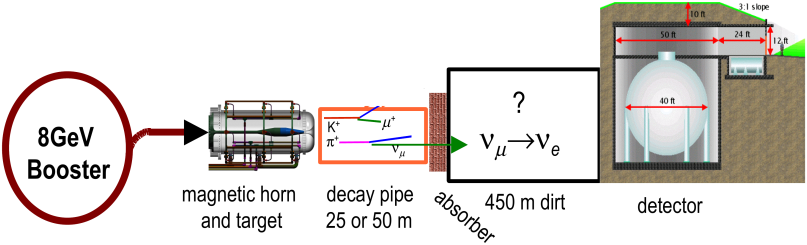
$\Rightarrow$ if mixing with sterile neutrinos then additional mass state is needed

LSND anomaly



LSND allowed regions(yellow and turquoise) vs excluded (red lines)

MiniBooNE – constructed to confirm or refute LSND result



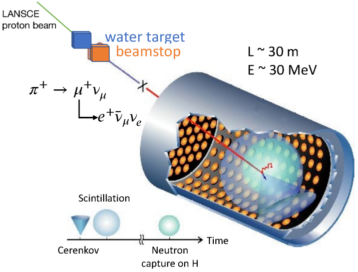
- MiniBooNE - experiment at Fermilab, 2002-2012 and 2016-2019
- Search for oscillations $\overline{\nu}_\mu \to \overline{\nu}_e$ and $\nu_\mu \to \nu_e$
- $\overline{\nu}_\mu$ and ν_μ from π decay in flight
- Detector: 800 t of mineral oil
- Cherenkov and scintillation light

Comparing MiniBooNE and LSND

LSND (1993-1998)

0.8 GeV proton beam

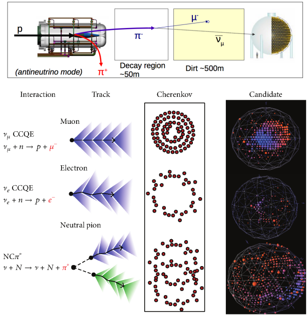
Decay At Rest neutrino flux



MiniBooNE (2002-2019)

8 GeV proton beam

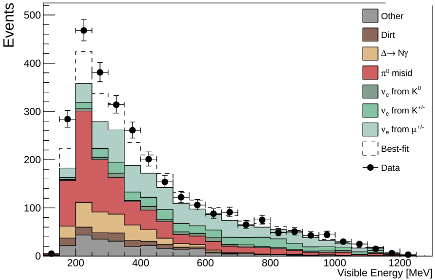
Decay In Flight beam

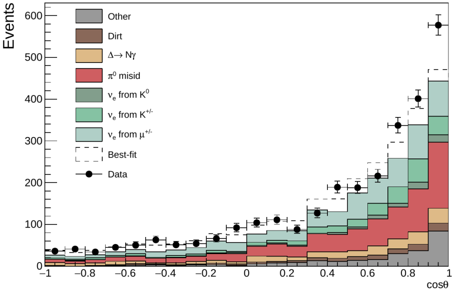


Different systematics. Same L/E baseline.

MiniBooNE ν_e sample

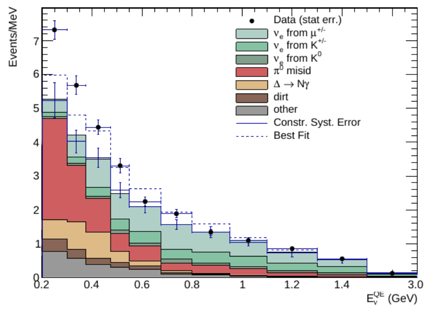
MiniBooNE anomaly- excess of ν_e in a beam of ν_μ:





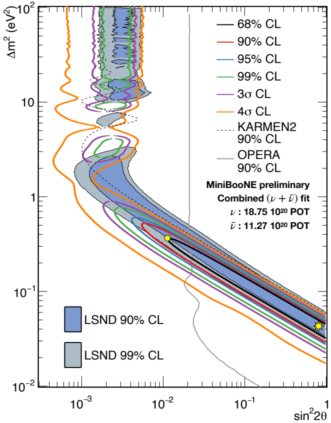
Hints for eV-scale neutrinos

Total excess (ν and $\overline{\nu}$ mode):
$638.0 \pm 52.1(\mathit{stat}) \pm 132.8(\mathit{syst})$
Overall significance 4.8σ

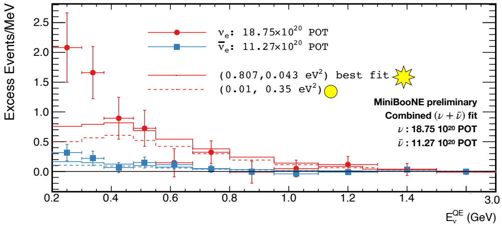


- Excess of 560.6 ± 119.6 events (neutrino mode)
- Significance 4.7σ in neutrino mode only

Preferred regions in sterile neutrino hypothesis



- Neutrino mode excess 4.7σ,
- **Neutrino+Anti-neutrino modes excess : 4.8σ**

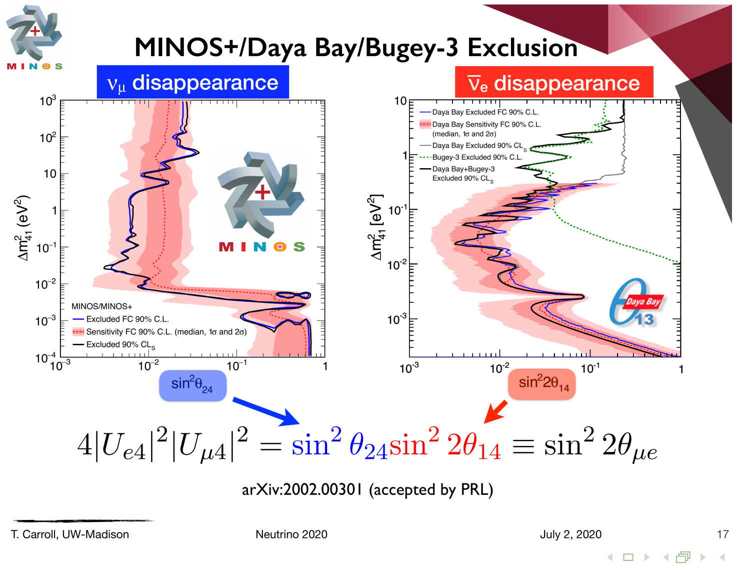


Neutrino + Anti-Neutrino Mode

$$(\Delta m^2, \sin^2 2\theta) = (0.043\ \text{eV}^2, 0.807)$$
$$\chi^2/ndf = 21.7/15.5\ (\text{prob} = 12.3\%)$$

Adrien Hourlier — The XXIX International Conference on Neutrino Physics and Astrophysics — July 2nd 2020 17

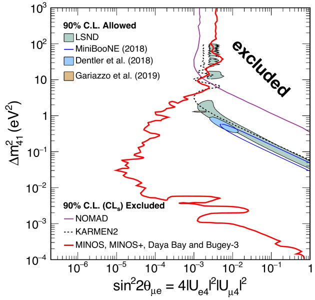
Exclusion plots from MINOS, MINOS+ and Daya Bay experiments



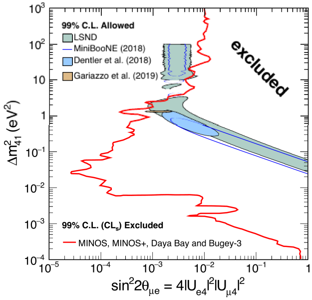
Exclusion plots from MINOS, MINOS+ and Daya Bay experiments

MINOS+/Daya Bay/Bugey-3 Exclusion

90%C.L.



99%C.L.



arXiv:2002.00301 (accepted by PRL)

T. Carroll, UW-Madison   Neutrino 2020   July 2, 2020   18

RAA (Reactor Antineutrino Anomaly)

Two methods to predict the reactor $\overline{\nu}_e$ flux:

Summation method

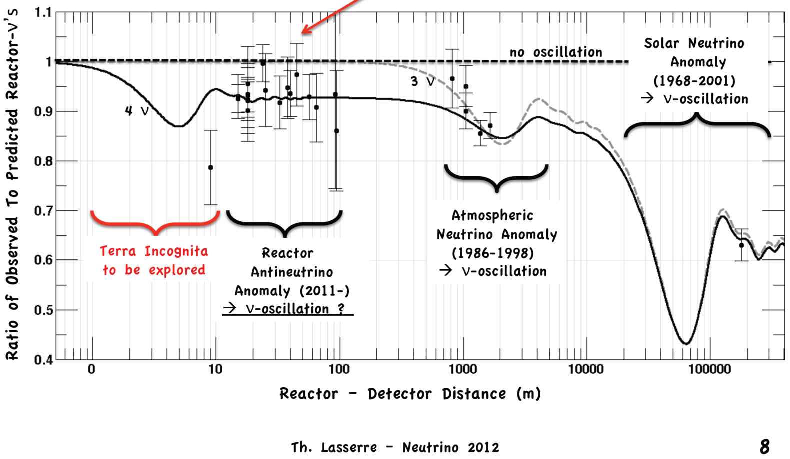
- Summing spectra of all decay branches of all fission isotopes
- Based on nuclear database
- Larger uncertainty (10-20%)

Conversion method

- Uses measured electron spectra associated with $^{235}\mathrm{U}$,$^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, $^{241}\mathrm{Pu}$.
- $\overline{\nu_e}$ spectra deduced from electron spectra
- Flux recalculated with this method $\rightarrow$ reactor anomaly

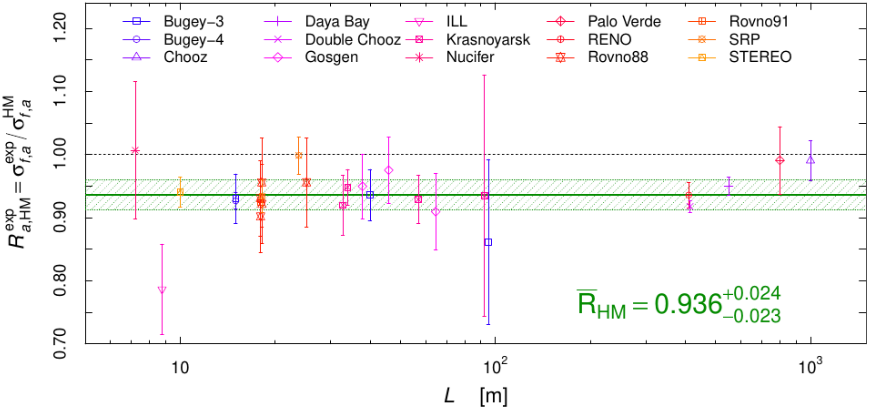
Hints for eV-scale neutrinos

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



Data vs theory. 3-flavour (dashed line) and 3+1 (solid line) neutrino oscillations.

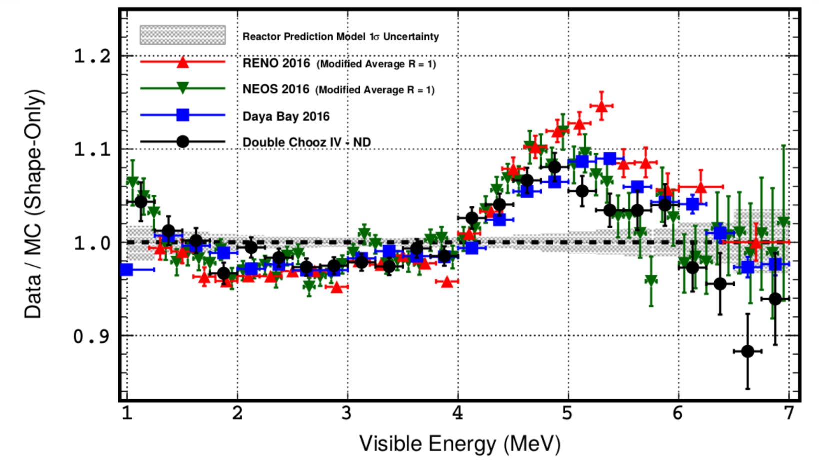
Reactor anomaly: deficit of $\overline{\nu}_e$ flux at short distances from reactors



HM = Huber (Phys.Rev.C84,024617 (2011)), Mueller et al. (Phys.Rev.C83,054615

Reactor anomaly - new questions

Origin of energy spectral distortion between 4 and 6 MeV ?

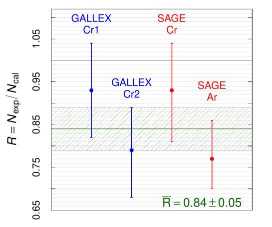


Gallium Anomaly

Hints for eV-scale neutrinos – radiochemical neutrino detection experiments

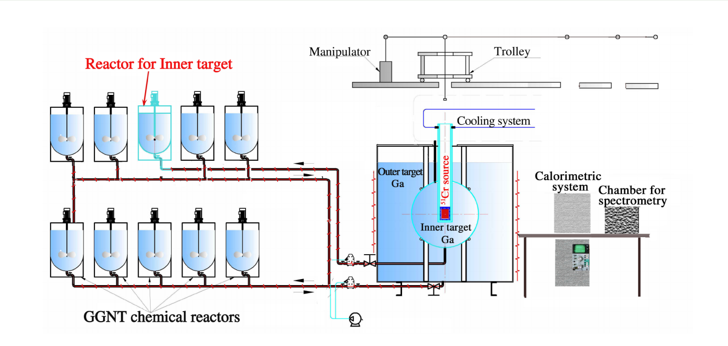
Gallium anomaly

- GALLEX (Gran Sasso, Italy), SAGE(Baksan, Russia)
- Experiments designed to study ν_e from the Sun.
  $\nu_\mathrm{e} + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$
- Tests with radioactive sources $^{51}\mathrm{Cr}$ and $^{37}\mathrm{Ar}$:
  $\mathrm{e}^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_\mathrm{e}$, $\quad \mathrm{e}^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_\mathrm{e}$



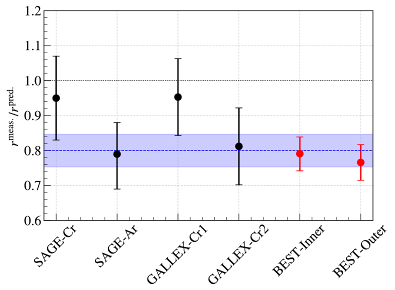
2021 results

Gallium anomaly - BEST experiment



- Baksan Neutrino Observatory in Caucasus mountains in Russia
- 2 containers with liquid Gallium (inner sphere, r=66.75cm; outer cylinder, radius 109cm)
- $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$

Gallium anomaly - BEST experiment



Assuming electron-sterile mixing, best fit oscillation parameters:

- BEST: $\Delta m^2 = 3.3 eV^2$, $\sin^2 2\theta = 0.42$
- BEST,GALLEX,SAGE: $\Delta m^2 = 1.25 eV^2$, $\sin^2 2\theta = 0.34$

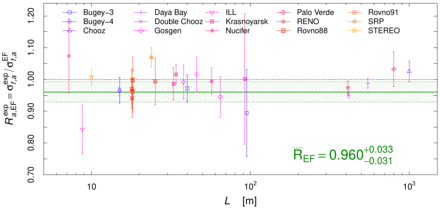
TABLE XII. Results of all six Ga source experiments.

Experiment	R
SAGE-Cr [24]	0.95 ± 0.12
SAGE-Ar [25]	0.79 ± 0.095 (+0.09 / -0.10)
GALLEX-Cr1 [27]	0.953 ± 0.11
GALLEX-Cr2 [27]	0.812 ± 0.11
BEST-Inner	0.791 ± 0.05
BEST-Outer	0.766 ± 0.05

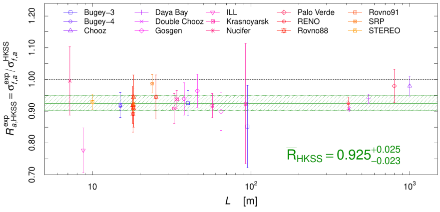
arXiv:2201.07364, arXiv:2109.11482

New reactor $\overline{\nu_e}$ flux predictions

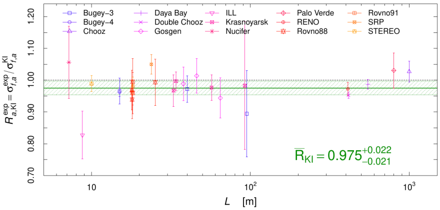
Reactor anomaly - various new theoretical predictions



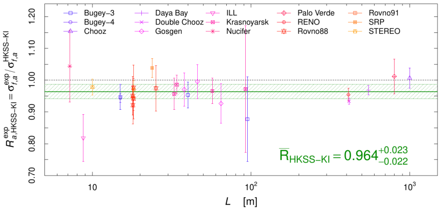
(a) EF model [18]: no RAA (1.2 σ).



(b) HKSS model [22]: RAA (2.9 σ).



(c) KI model [24]: no RAA (1.1 σ).

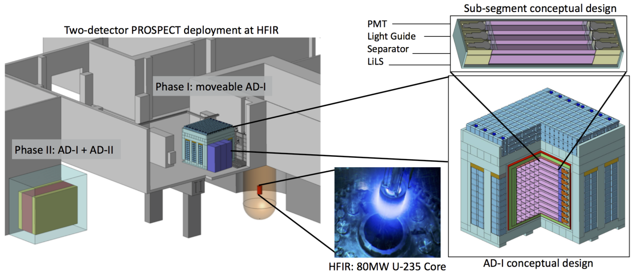


(d) HKSS-KI model: no RAA (1.5 σ).

KI – based on new measurements of the ratio of cumulative β spectra from $^{235}\mathrm{U}$ and $^{239}\mathrm{Pu}$ arXiv:2110.06820

Reactors at very short baselines (6-12m) – PROSPECT

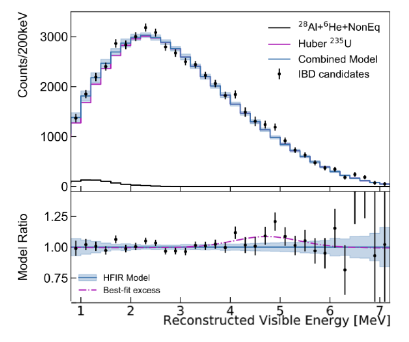
- Experiment at Oak Ridge National Laboratory, US
- 85 MW High Flux Isotope Reactor (HFIR)
- Fuel: $^{235}\mathrm{U}$



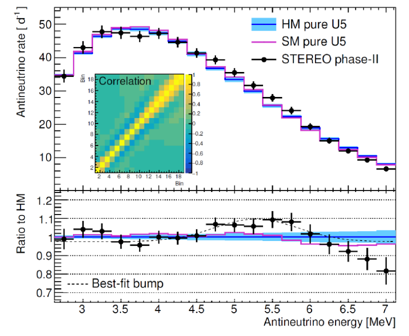
Segmented, 4-ton liquid scintillator detector. Current results with baselines between 6.7 and 9.2 meters.

Reactors at very short baselines (6-12m)

PROSPECT (Oak Ridge National Laboratory)

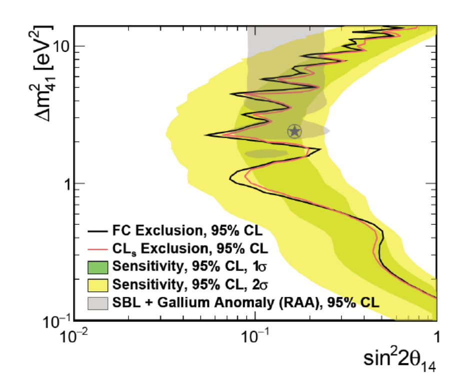


STEREO (ILL-Grenoble)

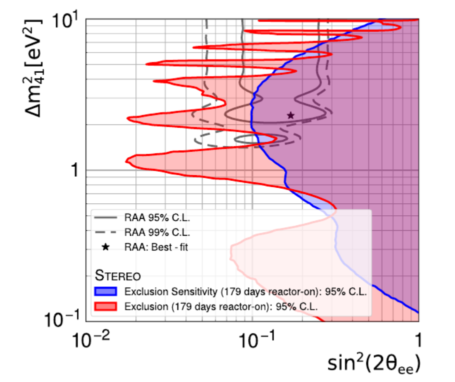


Reactors at very short baselines (6-12m)

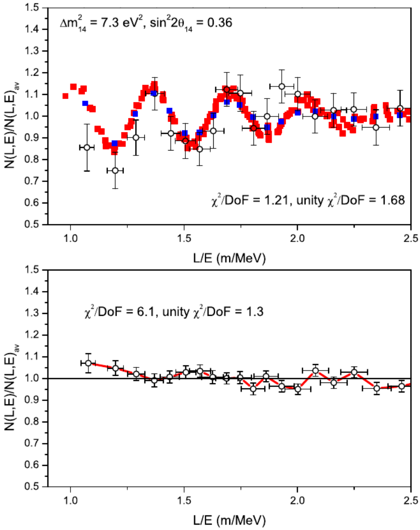
PROSPECT



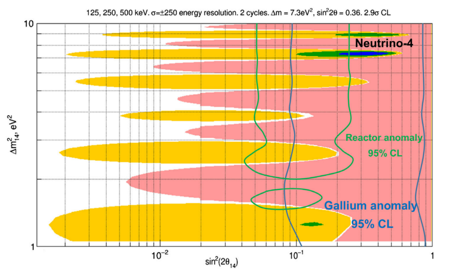
STEREO



Reactors at very short baselines



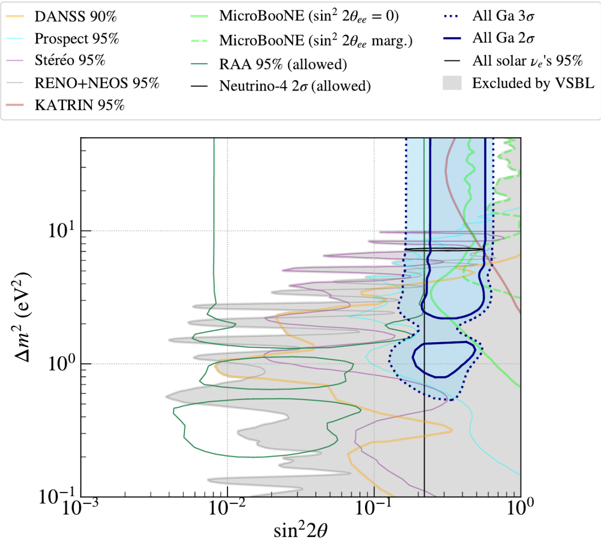
Neutrino-4 allowed regions



Baseline 6-12m

2.9σ evidence for oscillation

Gallium vs reactor experiments



arXiv:2201.07364, arXiv:2109.11482

Results from global analysis of gallium and reactor data

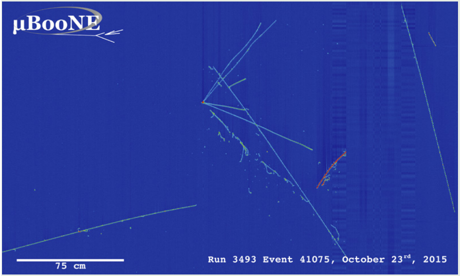
- Analysis based on DANSS, NEOS, PROSPECT, STEREO, Neutrino-4, SAGE, GALLEX and BEST data
- Very short baseline reactor data consistent with no-oscillations
- Gallium data - deficit $> 5\sigma$, compatible with Neutrino-4 result ($\Delta m^2 \simeq 7 - 12 eV^2$)
- Gallium data are in tension with solar data

J.M.Berryman,P.Coloma,P.Huber,T.Schwetz,A.Zhou, arXiv:2111.12530, Nov 2021

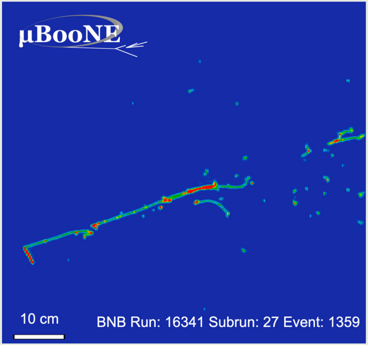
MicroBooNE - checks of MiniBooNE low energy excess

- 170-ton liquid argon TPC (LArTPC)
- located at the same beam (BNB) as MiniBooNE
- L=470m, $< E_\nu >= 0.8 GeV$

MicroBooNE - checks of MiniBooNE low energy excess



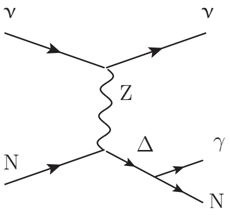
Much better particle identification. Can distinguish electrons from photons.



Electron neutrino event (electron shower + proton track)

MicroBooNE - checks of MiniBooNE low energy excess

Two samples: 1γ1p and 1γ0p

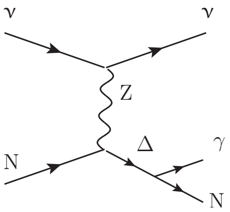


No excess in neutral-current delta radiative decay single photon channel

arXiv:2110.00409

MicroBooNE - checks of MiniBooNE low energy excess

Two samples: $1\gamma 1p$ and $1\gamma 0p$



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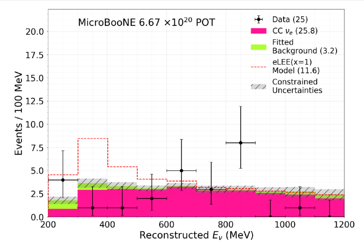
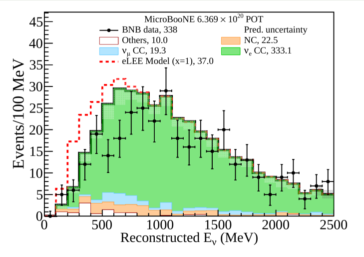
MicroBooNE - checks of MiniBooNE low energy excess

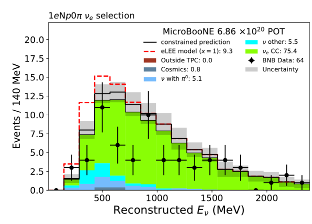
CCQE scattering (1e1p)

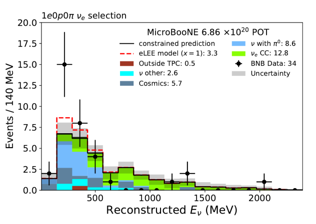


Inclusive ν_e scattering (1eX)



Pionless ν_e scattering (1eNp0π, 1e0p0π)



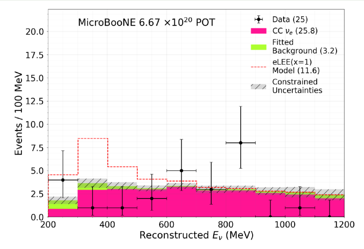


No excess in single-electron channels

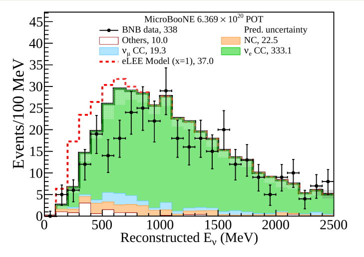
arXiv:2110.14054

MicroBooNE - checks of MiniBooNE low energy excess

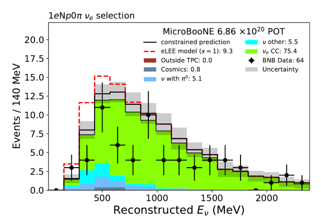
CCQE scattering (1e1p)

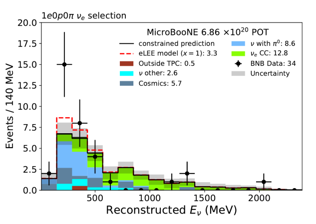


Inclusive ν_e scattering (1eX)



Pionless ν_e scattering (1eNp0π, 1e0p0π)





No excess in single-electron channels

arXiv:2110.14054

Hints for eV-scale neutrinos - summary from 2018

Experiment	Source	Channel	Significance
LSND	μ^+ decay at rest	$\overline{\nu}_\mu \to \overline{\nu}_e$	3.8σ
MiniBooNE	accelerator	$\nu_\mu \to \nu_e$	3.4σ
MiniBooNE	accelerator	$\overline{\nu}_\mu \to \overline{\nu}_e$	2.8σ
Reactors	beta-decays	$\overline{\nu}_e$ disapp.	3.0σ
GALLEX,SAGE	radioactive source, electron capture	ν_e disapp.	2.9σ

All anomalies could be explained by the existence of eV-scale neutrino

Hints for eV-scale neutrinos - summary from 2021

Experiment	Source	Channel	Significance
LSND	μ^+ decay at rest	$\overline{\nu}_\mu \to \overline{\nu}_e$	3.8σ
MiniBooNE	accelerator	$\nu_\mu \to \nu_e$	4.7σ
MiniBooNE	accelerator	$\overline{\nu}_\mu \to \overline{\nu}_e$	2.8σ
Reactors	beta-decays	$\overline{\nu}_e$ disapp.	1.1σ–2.9σ
BEST, GALLEX, SAGE	radioactive source, electron capture	ν_e disapp.	$> 5\sigma$

- Three experimental anomalies are still present
- Each of them can be explained by mixing with sterile neutrinos
- More new questions than answers

Instead of summary

Experiments interested in sterile neutrino physics

- 2021 results from MicroBooNE (Fermilab,US), PROSPECT (Oak Ridge, US), STEREO (ILL-Grenoble), BEST (Baksan, Russia), Neutrino-4 (Russia)
- Earlier sterile neutrino related results (>2017) from MINOS,MINOS+,NOvA (Fermilab,US), IceCube (South Pole), Daya Bay (China), RENO (Korea), T2K (Japan), NEOS (Korea), DANSS (Russia), KATRIN (Karlsruhe,Germany)
- Dedicated future experiments: SBN (Fermilab), nuPRISM (J-PARC), JSNS (J-PARC), KPipe (J-PARC), SoLid (Belgium), IsoDAR@KamLAND . . .
- Big future experiments that plan to search for sterile neutrinos: DUNE, HYPER-K, JUNO, ESSnuSB