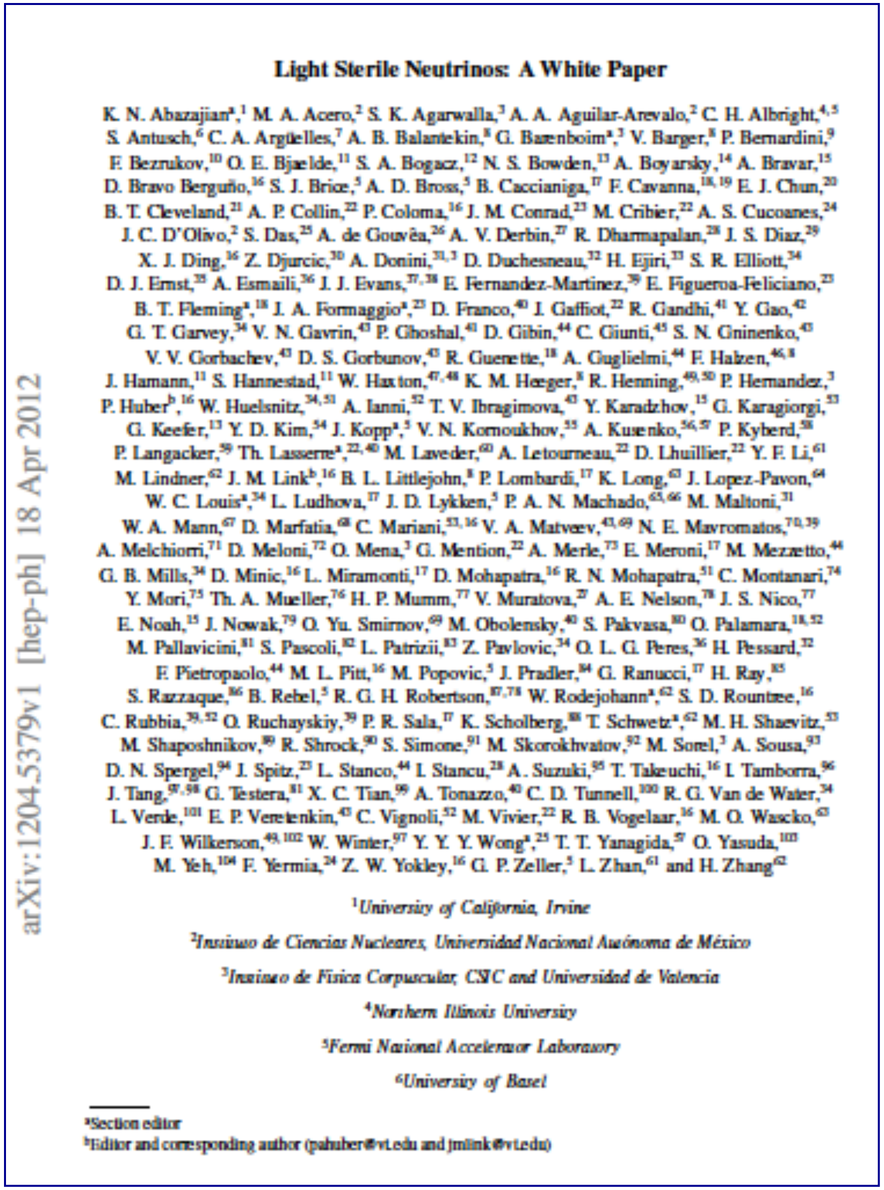
Present Status and Future Prospects of a Light eV-Scale Sterile Neutrino

Sanjib Kumar Agarwalla
sanjib@iopb.res.in and sagarwalla@icecube.wisc.edu

Institute of Physics (IOP), Bhubaneswar, India
Department of Physics and WIPAC, UW Madison, USA

Light Sterile Neutrinos: Huge Interest in the Community



Light Sterile Neutrinos: A White Paper

K. N. Abazajian[a],[1] M. A. Acero,[2] S. K. Agarwalla,[3] A. A. Aguilar-Arevalo,[2] C. H. Albright,[4,5]
S. Antusch,[6] C. A. Argüelles,[7] A. B. Balantekin,[8] G. Barenboim[a],[3] V. Barger,[8] P. Bernardini,[9]
F. Bezrukov,[10] O. E. Bjaelde,[11] S. A. Bogacz,[12] N. S. Bowden,[13] A. Boyarsky,[14] A. Bravar,[15]
D. Bravo Berguño,[16] S. J. Brice,[5] A. D. Bross,[5] B. Caccianiga,[17] F. Cavanna,[18,19] E. J. Chun,[20]
B. T. Cleveland,[21] A. P. Collin,[22] P. Coloma,[16] J. M. Conrad,[23] M. Cribier,[22] A. S. Cucoanes,[24]
J. C. D'Olivo,[2] S. Das,[25] A. de Gouvêa,[26] A. V. Derbin,[27] R. Dharmapalan,[28] J. S. Diaz,[29]
X. J. Ding,[16] Z. Djurcic,[30] A. Donini,[31,3] D. Duchesneau,[32] H. Ejiri,[33] S. R. Elliott,[34]
D. J. Ernst,[35] A. Esmaili,[36] J. J. Evans,[37,38] E. Fernandez-Martinez,[39] E. Figueroa-Feliciano,[23]
B. T. Fleming[a],[18] J. A. Formaggio[a],[23] D. Franco,[40] J. Gaffiot,[22] R. Gandhi,[41] Y. Gao,[42]
G. T. Garvey,[34] V. N. Gavrin,[43] P. Ghoshal,[41] D. Gibin,[44] C. Giunti,[45] S. N. Gninenko,[43]
V. V. Gorbachev,[43] D. S. Gorbunov,[43] R. Guenette,[18] A. Guglielmi,[44] F. Halzen,[46,8]
J. Hamann,[11] S. Hannestad,[11] W. Haxton,[47,48] K. M. Heeger,[8] R. Henning,[49,50] P. Hernandez,[3]
P. Huber[b],[16] W. Huelsnitz,[34,51] A. Ianni,[52] T. V. Ibragimova,[43] Y. Karadzhov,[15] G. Karagiorgi,[53]
G. Keefer,[13] Y. D. Kim,[54] J. Kopp[a],[5] V. N. Kornoukhov,[55] A. Kusenko,[56,57] P. Kyberd,[58]
P. Langacker,[59] Th. Lasserre[a],[22,40] M. Laveder,[60] A. Letourneau,[22] D. Lhuillier,[22] Y. F. Li,[61]
M. Lindner,[62] J. M. Link[b],[16] B. L. Littlejohn,[8] P. Lombardi,[17] K. Long,[63] J. Lopez-Pavon,[64]
W. C. Louis[a],[34] L. Ludhova,[17] J. D. Lykken,[5] P. A. N. Machado,[65,66] M. Maltoni,[31]
W. A. Mann,[67] D. Marfatia,[68] C. Mariani,[53,16] V. A. Matveev,[43,69] N. E. Mavromatos,[70,39]
A. Melchiorri,[71] D. Meloni,[72] O. Mena,[3] G. Mention,[22] A. Merle,[73] E. Meroni,[17] M. Mezzetto,[44]
G. B. Mills,[34] D. Minic,[16] L. Miramonti,[17] D. Mohapatra,[16] R. N. Mohapatra,[51] C. Montanari,[74]
Y. Mori,[75] Th. A. Mueller,[76] H. P. Mumm,[77] V. Muratova,[27] A. E. Nelson,[78] J. S. Nico,[77]
E. Noah,[15] J. Nowak,[79] O. Yu. Smirnov,[69] M. Obolensky,[40] S. Pakvasa,[80] O. Palamara,[18,52]
M. Pallavicini,[81] S. Pascoli,[82] L. Patrizii,[83] Z. Pavlovic,[34] O. L. G. Peres,[36] H. Pessard,[32]
F. Pietropaolo,[44] M. L. Pitt,[16] M. Popovic,[5] J. Pradler,[84] G. Ranucci,[17] H. Ray,[85]
S. Razzaque,[86] B. Rebel,[5] R. G. H. Robertson,[87,78] W. Rodejohann[a],[62] S. D. Rountree,[16]
C. Rubbia,[39,52] O. Ruchayskiy,[39] P. R. Sala,[17] K. Scholberg,[88] T. Schwetz[a],[62] M. H. Shaevitz,[53]
M. Shaposhnikov,[89] R. Shrock,[90] S. Simone,[91] M. Skorokhvatov,[92] M. Sorel,[3] A. Sousa,[93]
D. N. Spergel,[94] J. Spitz,[23] L. Stanco,[44] I. Stancu,[28] A. Suzuki,[95] T. Takeuchi,[16] I. Tamborra,[96]
J. Tang,[97,98] G. Testera,[81] X. C. Tian,[99] A. Tonazzo,[40] C. D. Tunnell,[100] R. G. Van de Water,[34]
L. Verde,[101] E. P. Veretenkin,[43] C. Vignoli,[52] M. Vivier,[22] R. B. Vogelaar,[16] M. O. Wascko,[63]
J. F. Wilkerson,[49,102] W. Winter,[97] Y. Y. Y. Wong[a],[25] T. T. Yanagida,[57] O. Yasuda,[103]
M. Yeh,[104] F. Yermia,[24] Z. W. Yokley,[16] G. P. Zeller,[5] L. Zhan,[61] and H. Zhang[62]

[1] *University of California, Irvine*

[2] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México*

[3] *Instituto de Física Corpuscular, CSIC and Universidad de Valencia*

[4] *Northern Illinois University*

[5] *Fermi National Accelerator Laboratory*

[6] *University of Basel*

---

[a] Section editor

[b] Editor and corresponding author (pahuber@vt.edu and jmlink@vt.edu)

According to INSPIRE: 971 Citations

Sterile neutrinos: singlets of SU(2) × U(1) gauge group, provide economical extension of the SM

Extensive study of sterile neutrinos at various energy scales

GUT: see-saw models of neutrino mass, leptogenesis

TeV: production at LHC and impact on electroweak precision observables

keV: (warm) dark matter candidates

eV: SBL and LBL oscillation experiments

sub-eV: θ_{13} - reactors and solar neutrinos

Light Sterile Neutrinos: Huge Interest in the Community

arXiv:2203.07323v2 [hep-ex] 18 May 2023

White Paper on Light Sterile Neutrino Searches and Related Phenomenology

M. A. Acero,[2,*] C. A. Argüelles,[23,*] M. Hostert,[58,59,70,*] D. Kalra,[13,*] G. Karagiorgi,[13,*]
K. J. Kelly,[11,*] B. R. Littlejohn,[31,*] P. Machado,[19,*] W. Pettus,[33,*] M. Toups,[19,*]
M. Ross-Lonergan,[13,*] A. Sousa,[12,*] P. T. Surukuchi,[106,*] Y. Y. Y. Wong,[66,*]

W. Abdallah,[108,†] A. M. Abdullahi,[19,41,†] R. Akutsu,[90,†] L. Alvarez-Ruso,[29,†] D. S. M. Alves,[51,†]
A. Aurisano,[12,†] A.B. Balantekin,[109,†] J. M. Berryman,[5,38,†] T. Bertólez-Martínez,[4,†] J. Brunner,[110,†]
M. Blennow,[48,53,68,†] S. Bolognesi,[79,†] M. Borusinski,[22,†] T.Y. Chen,[13,†] D. Cianci,[13,†] G. Collin,[1,†]
J.M. Conrad,[62,†] B. Crow,[22,†] P. B. Denton,[8,†] M. Duvall,[22,†] E. Fernández-Martinez,[53,†] C. S. Fong,[97,†]
N. Foppiani,[23,†] D. V. Forero,[56,†] M. Friend,[27,45,†] A. García-Soto,[23,29,†] C. Giganti,[40,†] C. Giunti,[36,†]
R. Gandhi,[111,†] M. Ghosh,[26,†] J. Hardin,[62,†] K. M. Heeger,[106,†] M. Ishitsuka,[89,†] A. Izmaylov,[32,37,†]
B. J. P. Jones,[100,†] J. R. Jordan,[3,†] N. W. Kamp,[62,†] T. Katori,[46,†] S. B. Kim,[83,†] L. W. Koerner,[25,†]
M. Lamoureux,[35,†] T. Lasserre,[79,†] K.G. Leach,[57,†] J. Learned,[22,†] Y. F. Li,[30,112,†] J. M. Link,[102,†]
W. C. Louis,[51,†] K. Mahn,[64,†] P. D. Meyers,[74,†] J. Maricic,[22,†] D. Markoff,[65,†] T. Maruyama,[27,†]
S. Mertens,[63,88,†] H. Minakata,[102,†] I. Mocioiu,[71,†] M. Mooney,[14,†] M.H. Moulai,[105,†] H. Nunokawa,[76,†]
J. P. Ochoa-Ricoux,[42,†] Y. M. Oh,[28,†] T. Ohlsson,[68,48,†] H. Päs,[15,†] D. Pershey,[17,†] R. G. H. Robertson,[104,†]
S. Rosauro-Alcaraz,[39,†] C. Rott,[83,99,†] S. Roy,[113,†] J. Salvado,[4,†] M. Scott,[32,†] S. H. Seo,[28,†] M. H. Shaevitz,[13,†]
M. Smiley,[5,52,†] J. Spitz,[3,†] J. Stachurska,[62,†] M. Tammaro,[114] T. Thakore,[12,†] C.A. Ternes,[36,†] A. Thompson,[61,†]
S. Tseng,[86,†] B. Vogelaar,[102,†] T. Weiss,[106,†] R. A. Wendell,[49,87,†] R.J. Wilson,[14,†] T. Wright,[102,†]
Z. Xin,[30,112,†] B. S. Yang,[81,†] J. Yoo,[81,†] J. Zennamo,[19,†] J. Zettlemoyer,[19,†] J. D. Zornoza,[29,†] J. Zupan,[12]

S. Ahmad,[72] E. Arrieta-Diaz,[54] V. S. Basto-Gonzalez,[69] N. S. Bowden,[50] B. C. Cañas,[69] D. Caratelli,[93]
C. V. Chang,[84] C. Chen,[84] T. Classen,[50] M. Convery,[115] G. S. Davies,[60] S. R. Dennis,[9] Z. Djurcic,[116]
R. Dorrill,[31] Y. Du,[117] J.J. Evans,[55] U. Fahrendholz,[88] J. A. Formaggio,[62] B. T. Foust,[106] H. Frandini
Gatti,[19] D. Garcia-Gamez,[21] S. Gariazzo,[36] J. Gehrlein,[8] C. Grant,[7] R. A. Gomes,[20] A. B. Hansell,[82]
F. Halzen,[105] S. Ho,[47] J. Hoefken Zink,[6,34] R. S. Jones,[80] P. Kunkle,[7] J.- Y. Li,[18] S. C. Li,[102,77] X. Luo,[5]
Yu. Malyshkin,[37,44] C.J. Martoff,[85] D. Massaro,[6,95,34] A. Mastbaum,[78] R. Mohanta,[26] H.P. Mumm,[67]
M. Nebot-Guinot,[18] R. Neilson,[16] K. Ni,[94] J. Nieves,[29] G. D. Orebi Gann,[5,52] V. Pandey,[96] S.
Pascoli,[6,34] G. Paz,[103] A. A. Petrov,[103,98] X. Qian,[8] M. Rajaoalisoa,[12] S. H. Razafinime,[12] C. Roca,[50]
G. Ron,[24] B. Roskovec,[73] E. Saul-Sala,[29] L. Saldaña,[106] D. W. Schmitz,[91] K. Scholberg,[17] B. Shakya,[118]
P. L. Slocum,[106] E.L. Snider,[19] H. Th. J. Steiger,[43,75,88] A. F. Steklain,[101] M. R. Stock,[88] F. Sutanto,[50]
V. Takhistov,[87] R. Tayloe,[33] Y.-D. Tsai,[92] Y.-T. Tsai,[115] D. Venegas-Vargas,[21] M. Wallbank,[12]
E. Wang,[107] P. Weatherly,[16] S. Westerdale,[74] E. Worcester,[8] W. Wu,[19] G. Yang,[5] and B. Zamorano[21]

[1] *Department of Physics, University of Adelaide, Adelaide, SA, Australia*
[2] *Universidad del Atlántico, Puerto Colombia, Atlántico, Colombia*
[3] *University of Michigan, Ann Arbor, MI, 48109, USA*
[4] *Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain*
[5] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[6] *Dipartimento di Fisica e Astronomia, Università di Bologna, via Irnerio 46, 40126 Bologna, Italy*
[7] *Department of Physics, Boston University, Boston, MA 02215, USA*
[8] *Physics Department, Brookhaven National Laboratory, Upton, NY, USA*
[9] *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[10] *Department of Physics, Case Western Reserve University, Cleveland, OH 44106, USA*
[11] *CERN, Esplanade des Particules, 1211 Geneva 23, Switzerland*
[12] *Department of Physics, University of Cincinnati, Cincinnati, OH 45221, USA*
[13] *Columbia University, New York, NY, USA*
[14] *Colorado State University, Fort Collins, CO, USA*
[15] *TU Dortmund, Department of Physics, D-44221, Dortmund, Germany*
[16] *Department of Physics, Drexel University, Philadelphia, Pennsylvania 19104, USA*
[17] *Department of Physics, Duke University, Durham, NC 27708, USA*
[18] *University of Edinburgh, Edinburgh EH8 9YL, United Kingdom*
[19] *Fermi National Accelerator Laboratory, Batavia, IL, USA*

Snowmass White Paper
Acero et al., arXiv:2203.07323 [hep-ex]

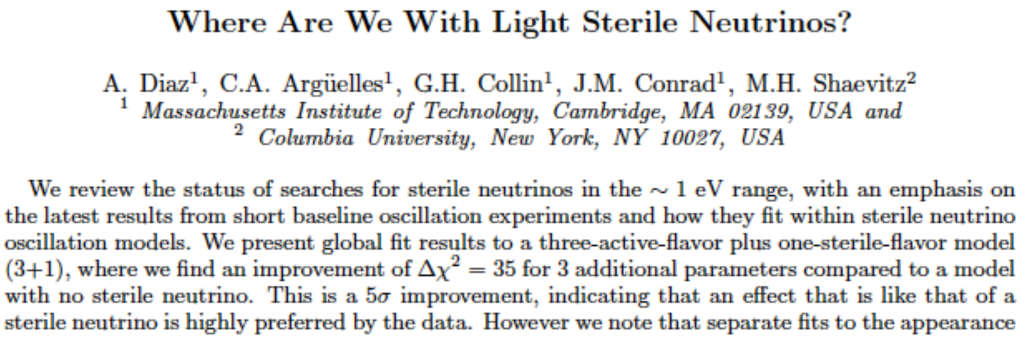
According to INSPIRE: **42** Citations

eV-scale Sterile Neutrinos

Carlo Giunti[1] and Thierry Lasserre[2]

[1]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino,
Via P. Giuria 1, I–10125 Torino, Italy; email: carlo.giunti@to.infn.it
[2]Commissariat à l'énergie atomique et aux énergies alternatives,
Centre de Saclay, DRF/IRFU, 91191 Gif-sur-Yvette, France;
email: thierry.lasserre@cea.fr

Giunti, Lasserre, arXiv:1901.08330 [hep-ph]
According to INSPIRE: **149** Citations

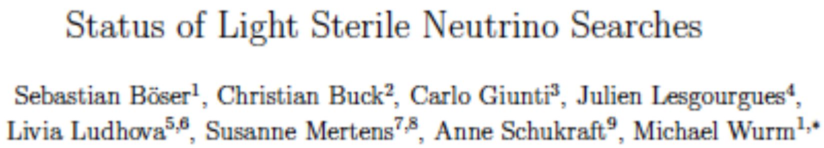


Where Are We With Light Sterile Neutrinos?

A. Diaz[1], C.A. Argüelles[1], G.H. Collin[1], J.M. Conrad[1], M.H. Shaevitz[2]
[1] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA and*
[2] *Columbia University, New York, NY 10027, USA*

We review the status of searches for sterile neutrinos in the $\sim$ 1 eV range, with an emphasis on the latest results from short baseline oscillation experiments and how they fit within sterile neutrino oscillation models. We present global fit results to a three-active-flavor plus one-sterile-flavor model (3+1), where we find an improvement of $\Delta\chi^2 = 35$ for 3 additional parameters compared to a model with no sterile neutrino. This is a 5σ improvement, indicating that an effect that is like that of a sterile neutrino is highly preferred by the data. However we note that separate fits to the appearance

Diaz et al., arXiv:1906.00045 [hep-ex]
According to INSPIRE: **179** Citations

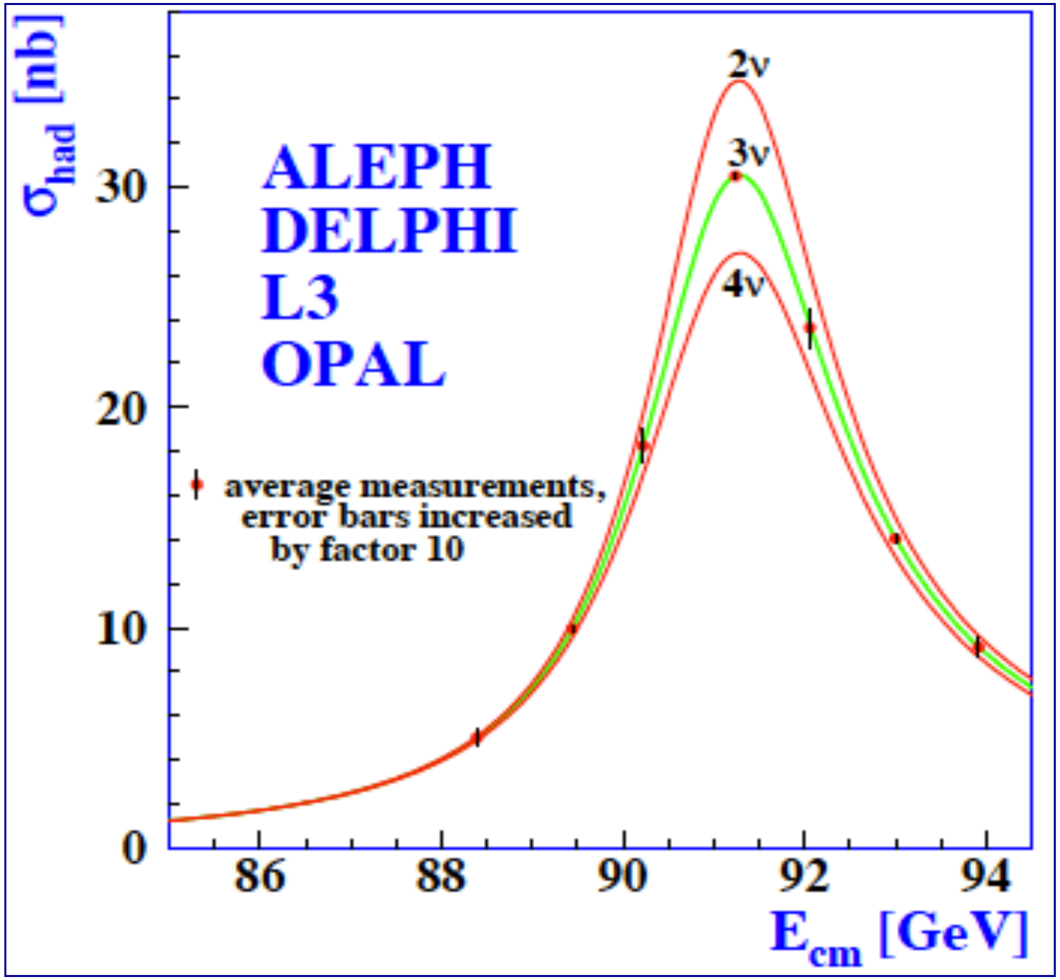


Status of Light Sterile Neutrino Searches

Sebastian Böser[1], Christian Buck[2], Carlo Giunti[3], Julien Lesgourgues[4],
Livia Ludhova[5,6], Susanne Mertens[7,8], Anne Schukraft[9], Michael Wurm[1,*]

Böser et al., arXiv: 1906.01739 [hep-ex]
According to INSPIRE: **188** Citations

Why 3 Weak Flavor States?



Precision data on the Z-decay width at the e^+e^- collider at LEP

$$e^+e^- \rightarrow Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a\bar{\nu}_a$$

$$N_{\nu_{\text{active}}} = 2.9840 \pm 0.0082$$

[LEP, Phys. Rept. 427 (2006) 257, hep-ex/0509008]

3 light active flavor neutrinos

$\nu_e \ \nu_\mu \ \nu_\tau$

http://pdg.lbl.gov/2016/reviews/rpp2016-rev-light-neutrino-types.pdf

Why do we need light sterile neutrinos?

Several Anomalies at Short-Baseline Experiments

Long-standing saga of eV-scale anomalies!

1995 LSND Anomaly: $\sim 3.8\sigma$	**[PRD 64 (2001) 22, 112007]**
2008 MiniBooNE Anomaly (combined ν & antineutrino): $\sim 4.8\sigma$	**[PRL 121 (2018) 22, 221801]**
2011 Reactor Antineutrino Anomaly: $\sim 3\sigma$	**[PRD 83 (2011) 073006, PRC 84 (2011) 024617]**
2005 Gallium Neutrino Anomaly: $\sim 2.9\sigma$	**[PRC 83 (2011) 065504, PLB 795 (2019) 542]**
NEOS: $\sim 3\sigma$	**[PRL 118, 121802 (2017)]**
DANSS: $\sim 2.8\sigma$	**[PLB 787 (2018) 56]**
Neutrino-4: $\sim 2.8\sigma$	**[JETP Lett. 109 (2019) 4, 213]**

Anomalous Results

The Liquid Scintillator Neutrino Detector

The "LSND Anomaly"

(1993 - 1998)

Los Alamos National Lab (LANL)

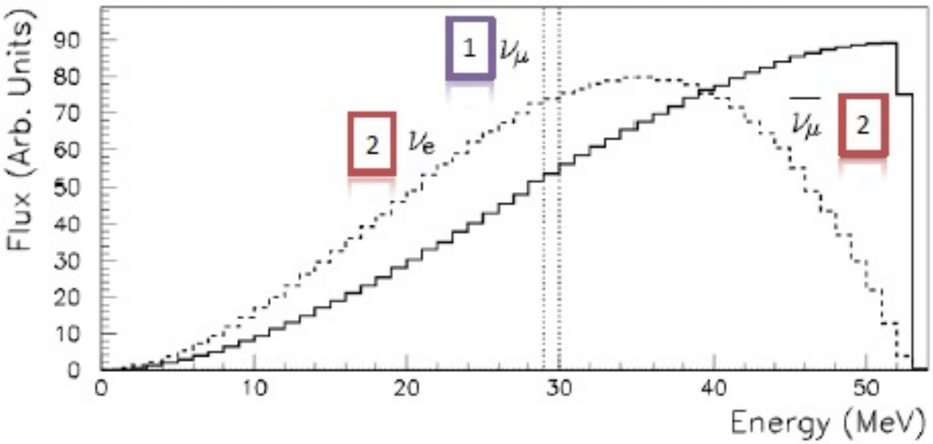
Liquid Scintillator Neutrino Detector (LSND)

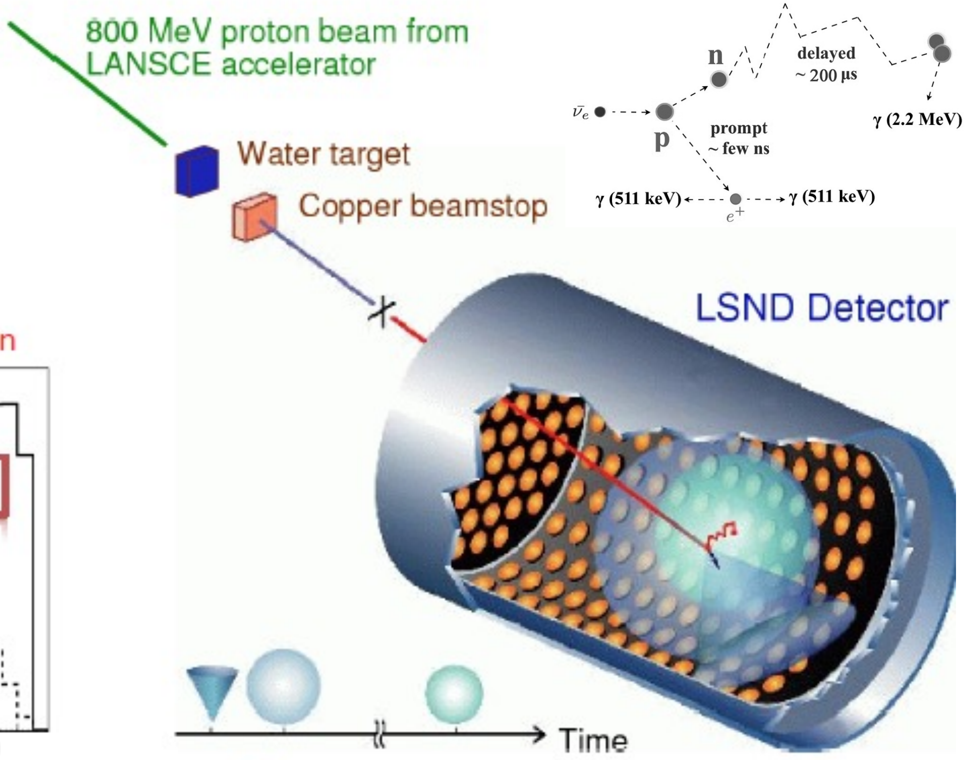
1 $\pi^+ \to \mu^+ \nu_\mu$

2 $\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

$\xrightarrow{?} \bar{\nu}_e$

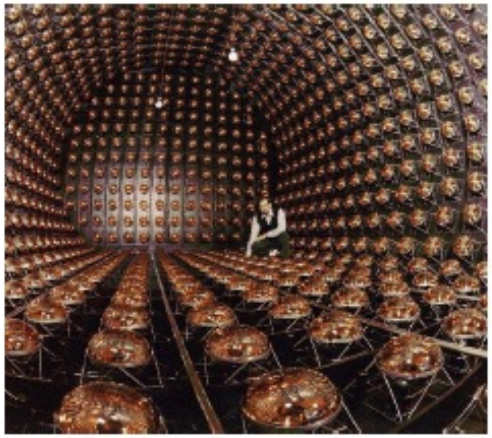
Beam produced by decays *at rest* is precisely known





neutron captures to produce a 2.2 MeV gamma

Look for electron anti-neutrinos in a beam with well-predicted fluxes and small electron anti-neutrino background

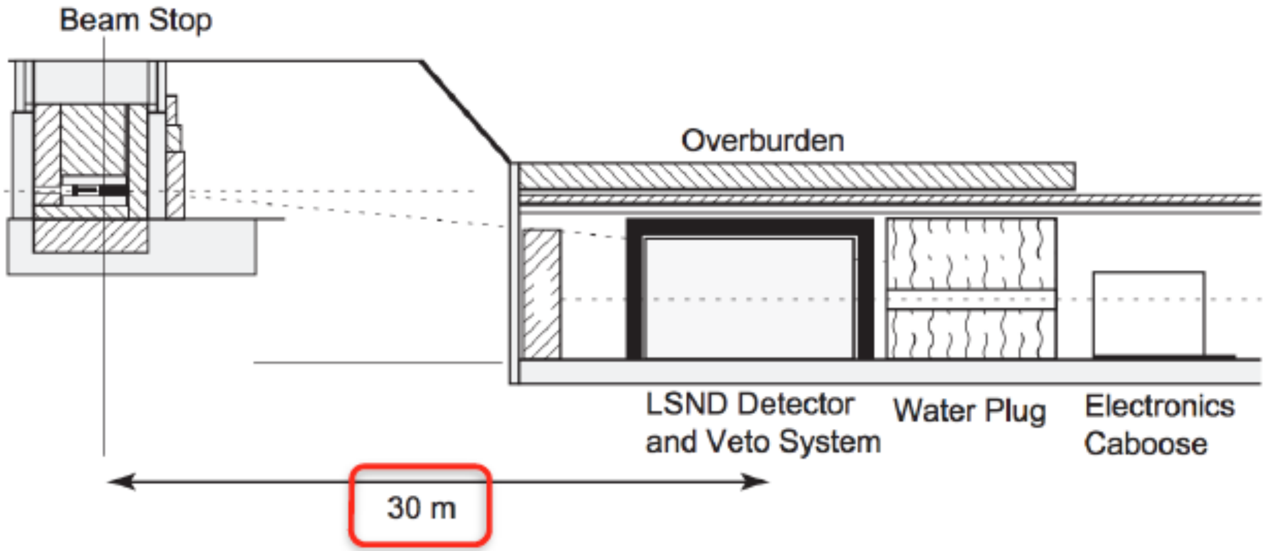


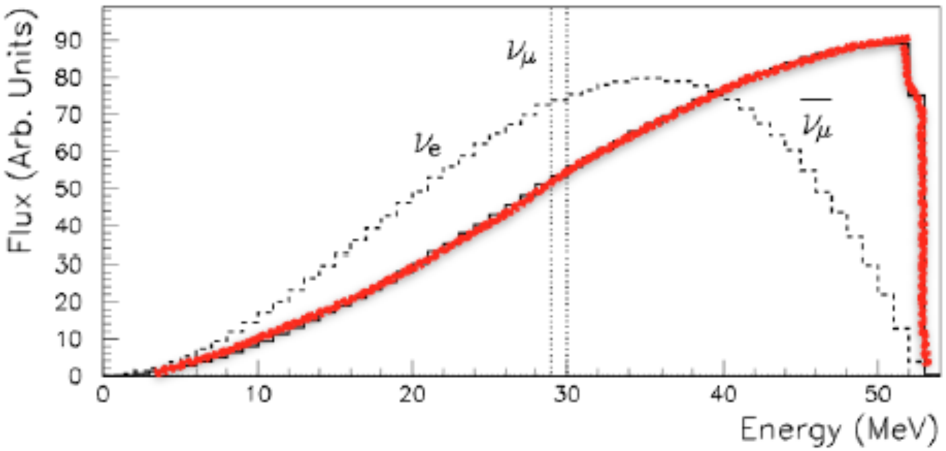
$\bar{\nu}_e$ **detection via inverse-beta-decay:** $\bar{\nu}_e + p \to e^+ + n$

(coincidence signal)

Phys. Rev. D64 (2001) 112007

Liquid Scintillator Neutrino Detector (LSND)





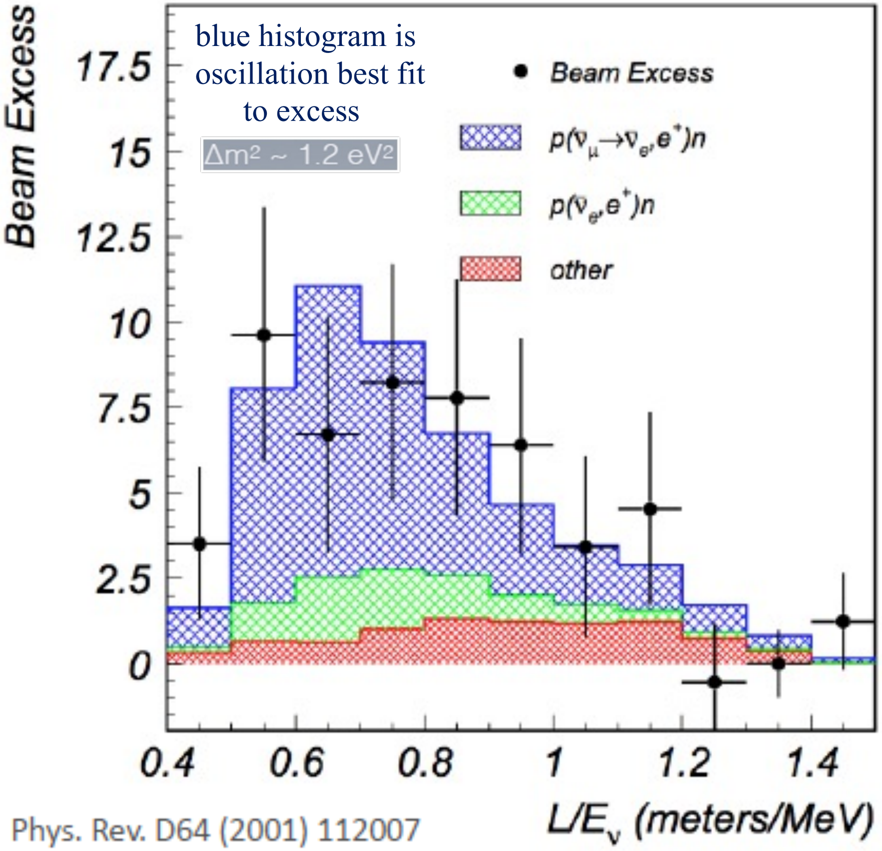
L

E

$$L/E \sim 1 \ \ \mathrm{m/MeV}$$

Courtesy David Schmitz

Liquid Scintillator Neutrino Detector (LSND)



Phys. Rev. D64 (2001) 112007

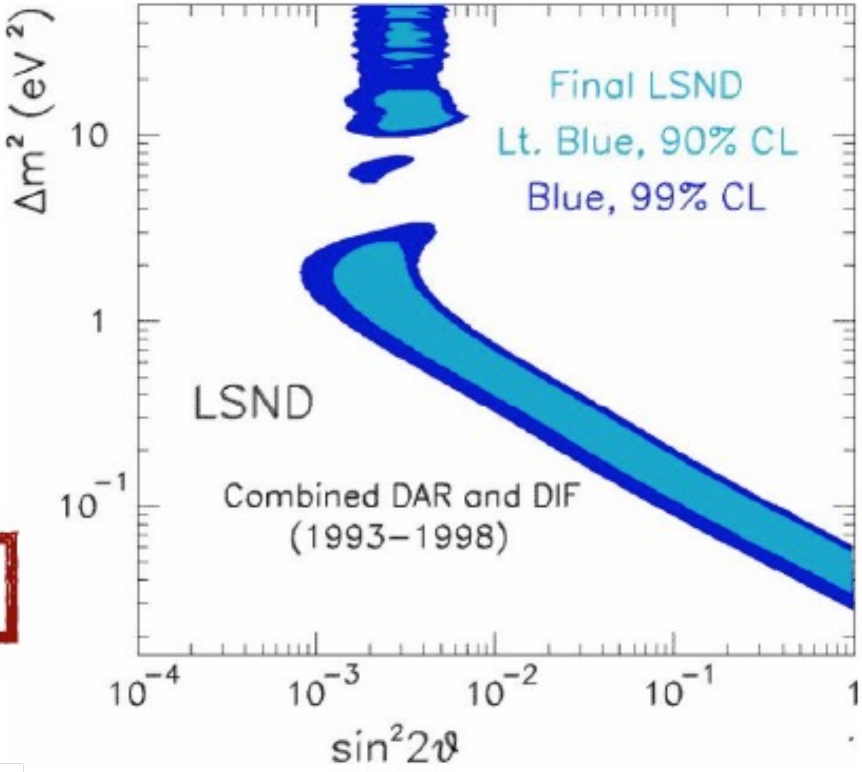
L/E distribution of the most signal-like events

Saw an excess of 87.9 ± 22.4 ± 6.0 events

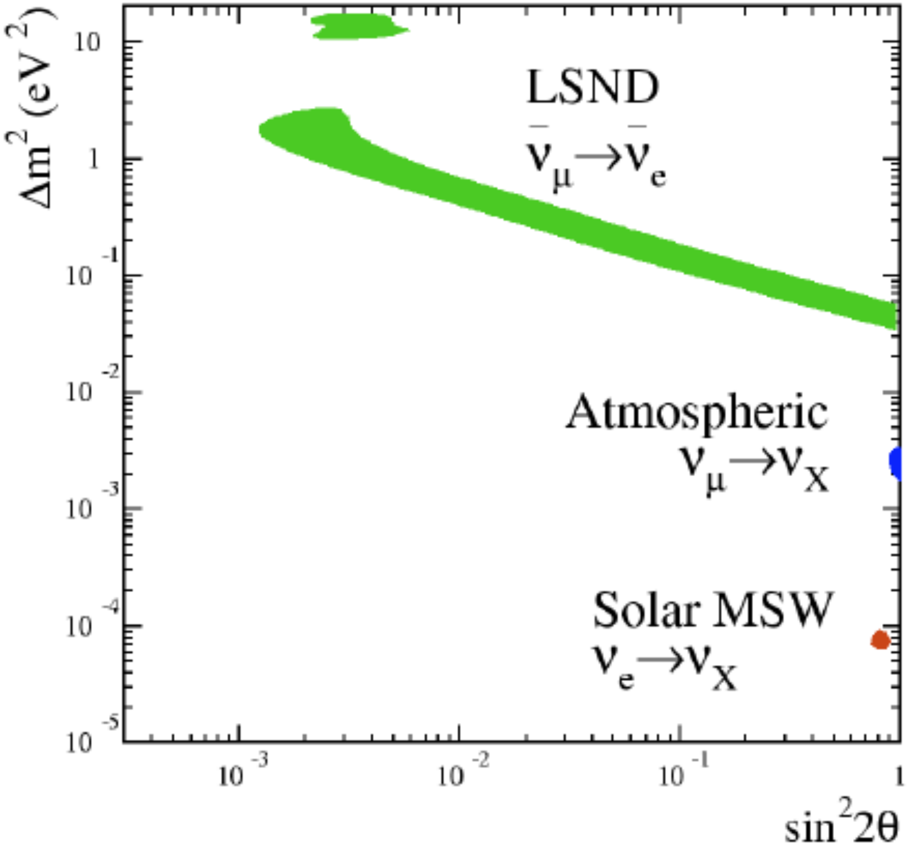
$3.8\,\sigma$ excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$

Observed excess described by best fit oscillation probability:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$



How to accommodate the LSND result?

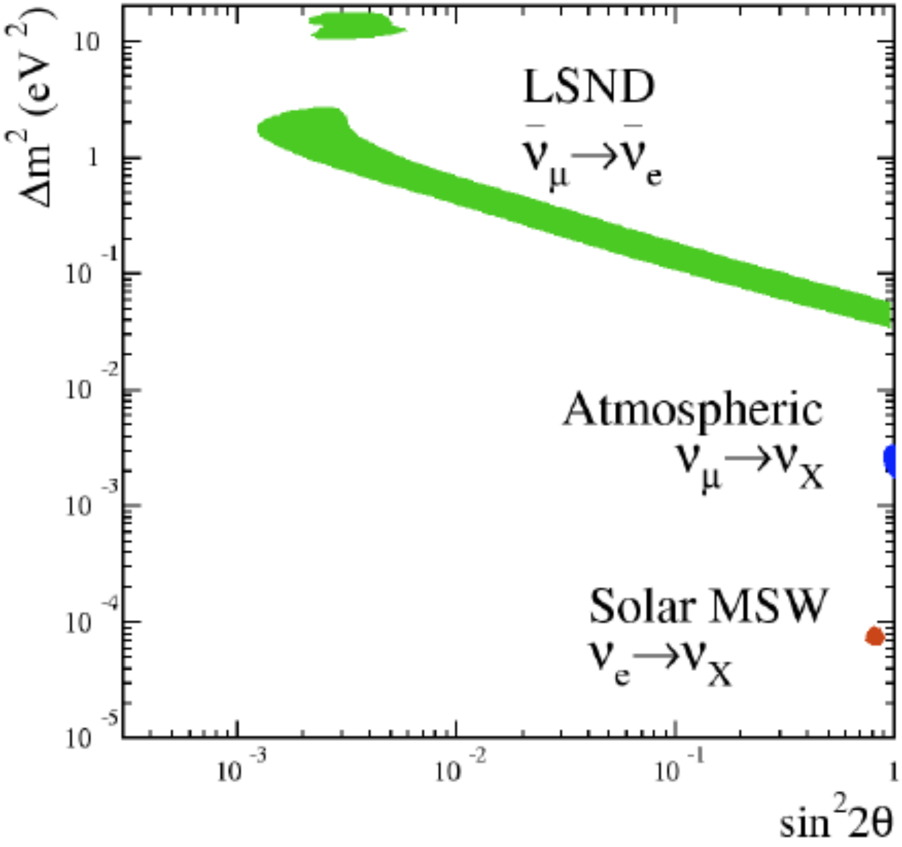


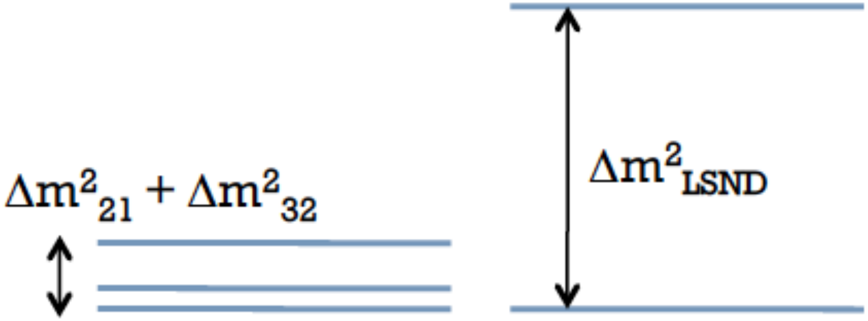
Δm^2_{LSND} $L/E \sim 1$ km/GeV

$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$ $L/E = 500$ km/GeV

$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$ $L/E = 15,000$ km/GeV

How to accommodate the LSND result?





$\Delta m^2_{LSND} >> \Delta m^2_{21} + \Delta m^2_{32}$

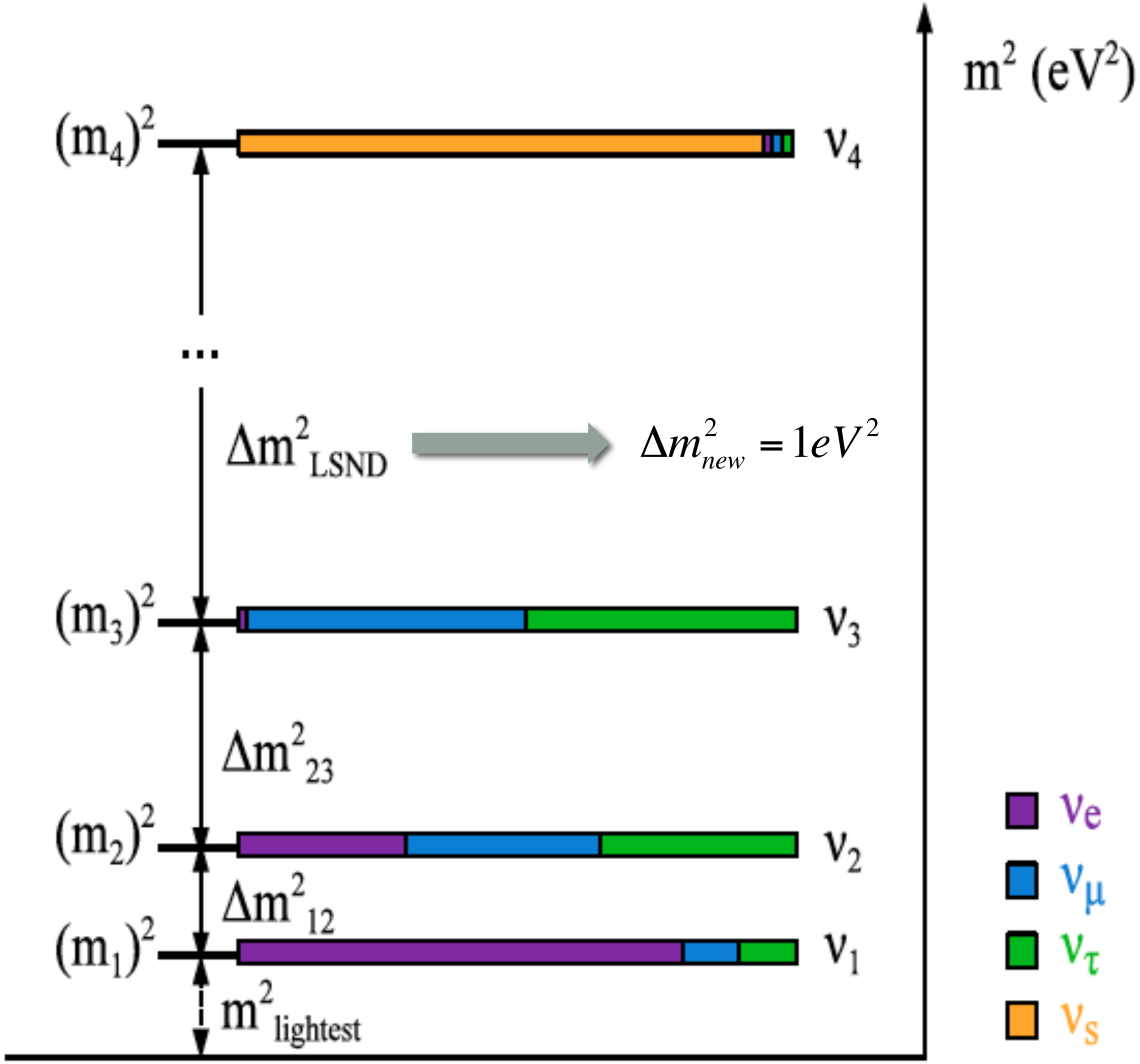
How to accommodate the LSND result?

Sterile neutrino

Additional neutrino flavor and mass state that has no weak interactions through the standard W/Z bosons

Mass state accessed only through mixing with standard model neutrinos

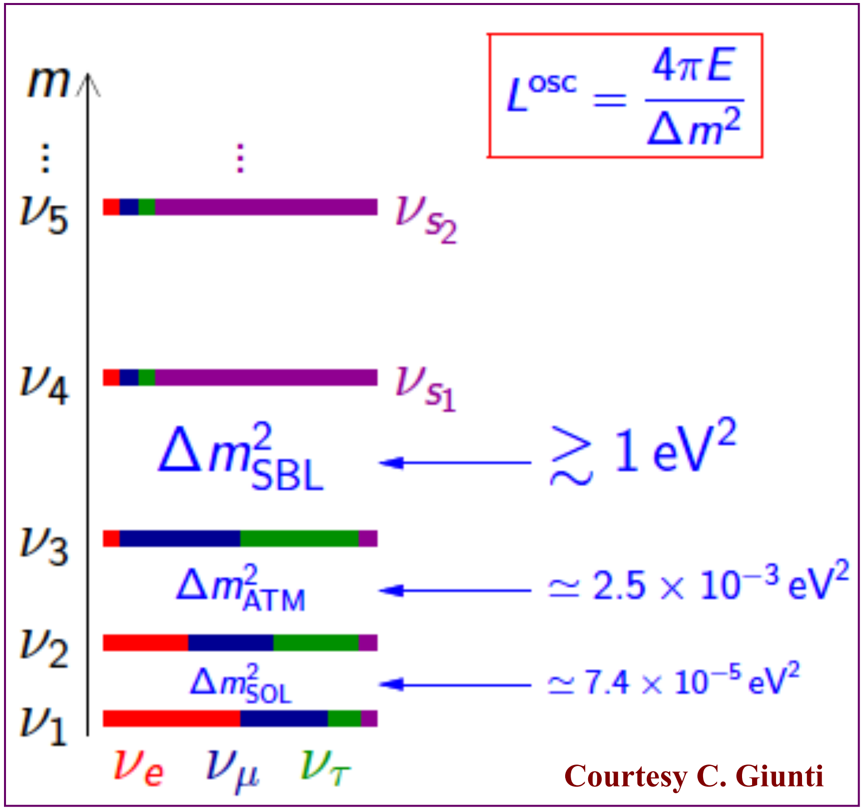
Sterile neutrinos: singlets of $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group and provide economical extension of the Standard Model



LSND data point towards a light eV-Scale Sterile Neutrino

LSND results hint towards high $\Delta m^2 \approx 0.1 - 10$ eV^2 oscillation

Require additional neutrinos with masses at eV-scale



Courtesy C. Giunti

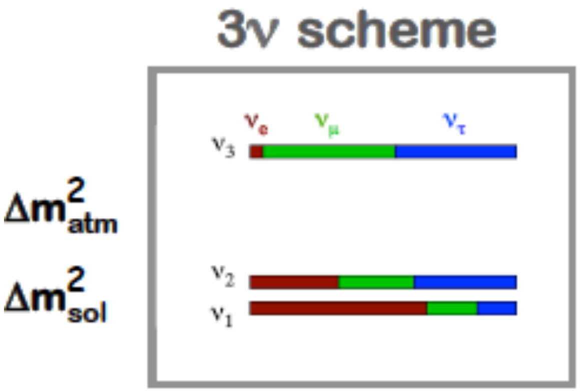
- ν_s : Sterile states (no weak interactions)
- Can feel gravity
- Can affect oscillations through mixing
- Well postulated in see-saw models
- In all these models, sterile neutrinos couple to active neutrinos via Yukawa couplings

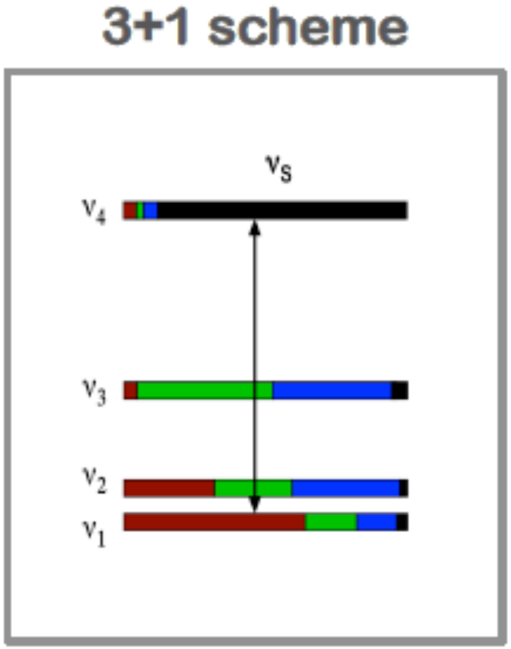
Introduce ν_R in the SM: $\boxed{\text{Dirac mass } m_D \overline{\nu_R} \nu_L + \text{Majorana mass } m_M \overline{\nu_R^c} \nu_R}$

6 massive Majorana neutrinos : $(\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}) + (\nu_{eR}, \nu_{\mu R}, \nu_{\tau R})$

Light left-handed anti-ν_R = Light left-handed sterile neutrino : $\nu_R^c \rightarrow \nu_{sL}$

One Light eV-Scale Sterile Neutrino





$\Delta m^2_{41} \sim 1\ \mathrm{eV}^2$

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

↑
SBL

Add one sterile ν with three active ones at the eV-scale

Small perturbation of 3ν mixing

$|U_{e4}|^2 << 1, |U_{\mu 4}|^2 << 1, |U_{\tau 4}|^2 << 1, |U_{s4}|^2 \approx 1$

3+1 Short-Baseline Oscillation

Appearance ($\alpha \neq \beta$)

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

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

Disappearance

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

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

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

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:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

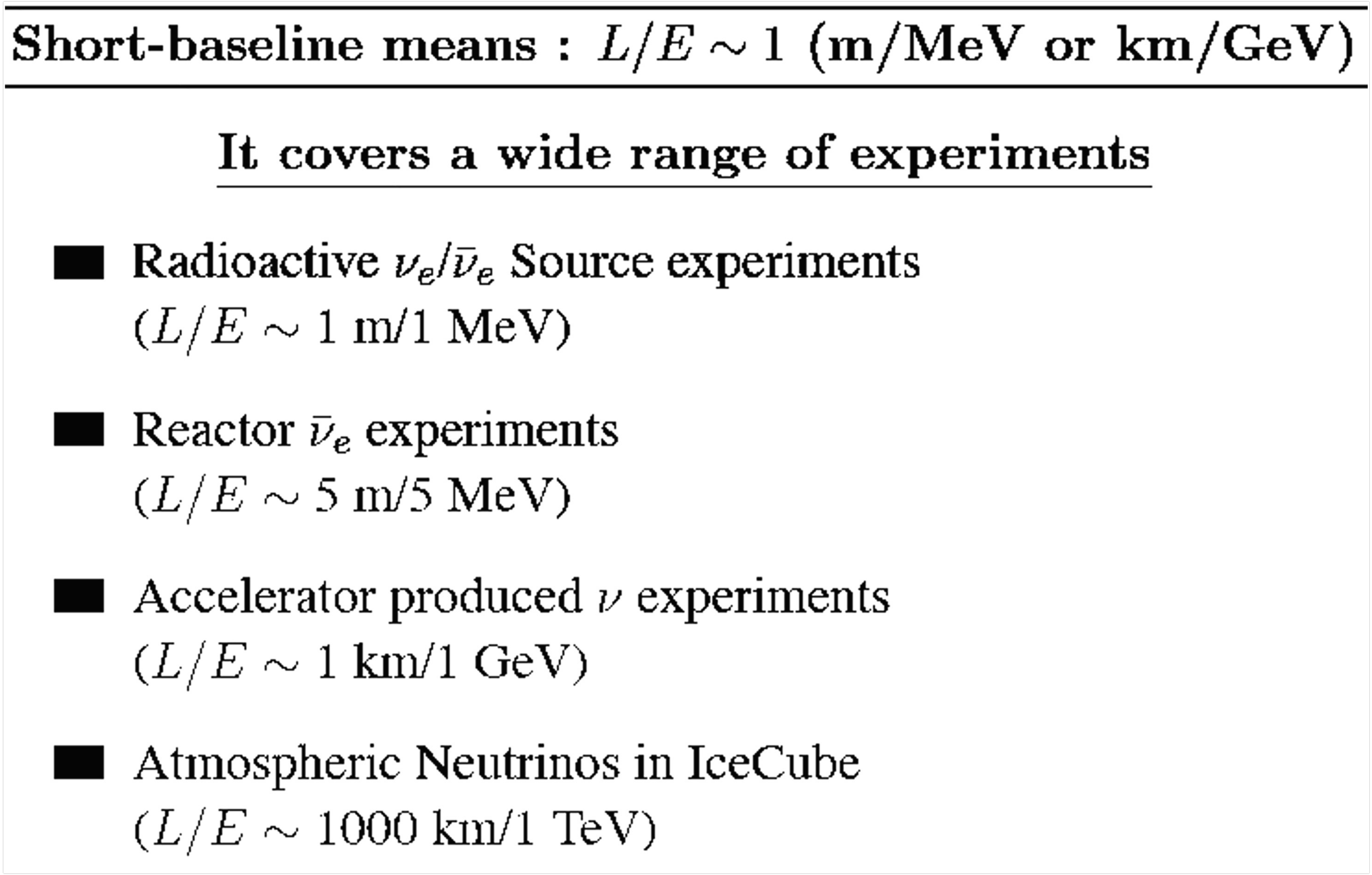
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

⇓

Appearance-Disappearance Tension

See reviews by C. Giunti

Where to look for eV-scale active-sterile oscillation?

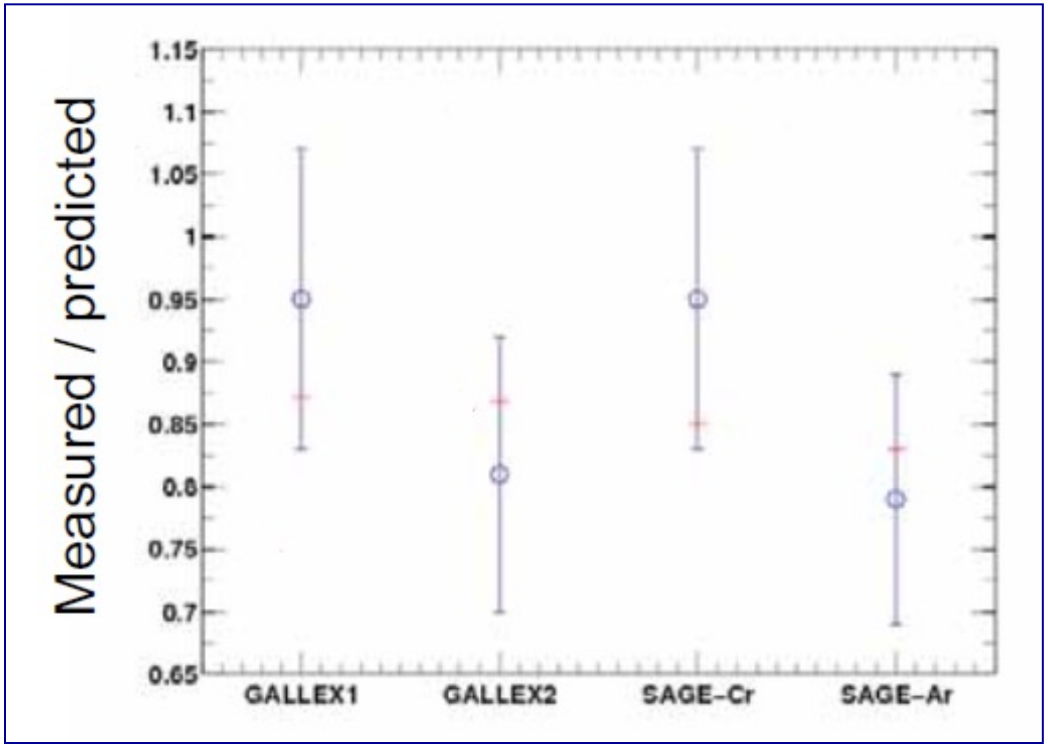


Short-baseline means : $L/E \sim 1$ (m/MeV or km/GeV)

It covers a wide range of experiments

- Radioactive $\nu_e/\bar{\nu}_e$ Source experiments
  ($L/E \sim 1$ m/1 MeV)
- Reactor $\bar{\nu}_e$ experiments
  ($L/E \sim 5$ m/5 MeV)
- Accelerator produced ν experiments
  ($L/E \sim 1$ km/1 GeV)
- Atmospheric Neutrinos in IceCube
  ($L/E \sim 1000$ km/1 TeV)

Gallium Neutrino Anomaly



Calibration measurements for the GALLEX & SAGE solar neutrino detectors using intense radioactive ν_e fluxes from ^{51}Cr & ^{37}Ar

^{51}Cr : 747 KeV (82%)
^{37}Ar: 811 KeV (90%)

Detection process:

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$$

Measurements consistently lower than expectation

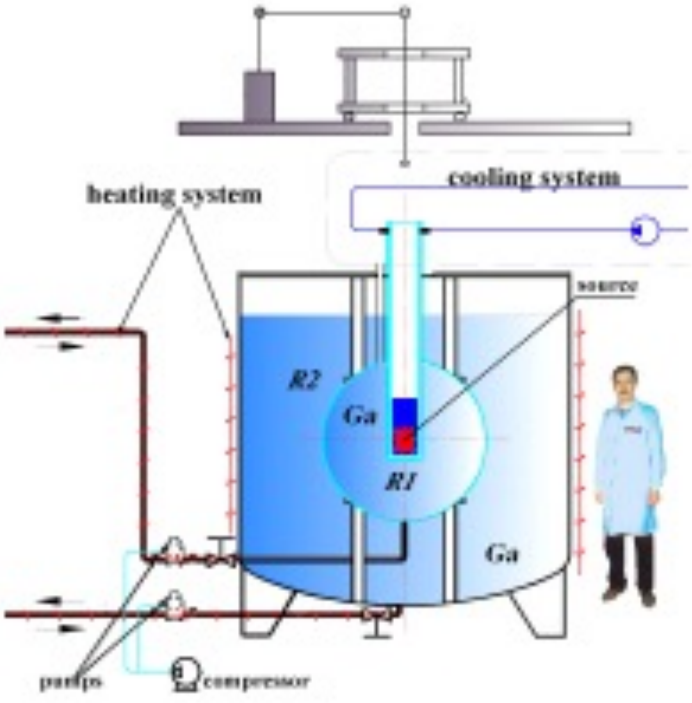
Suggests possible ν_e disappearance at 2.7σ due to active – sterile oscillation

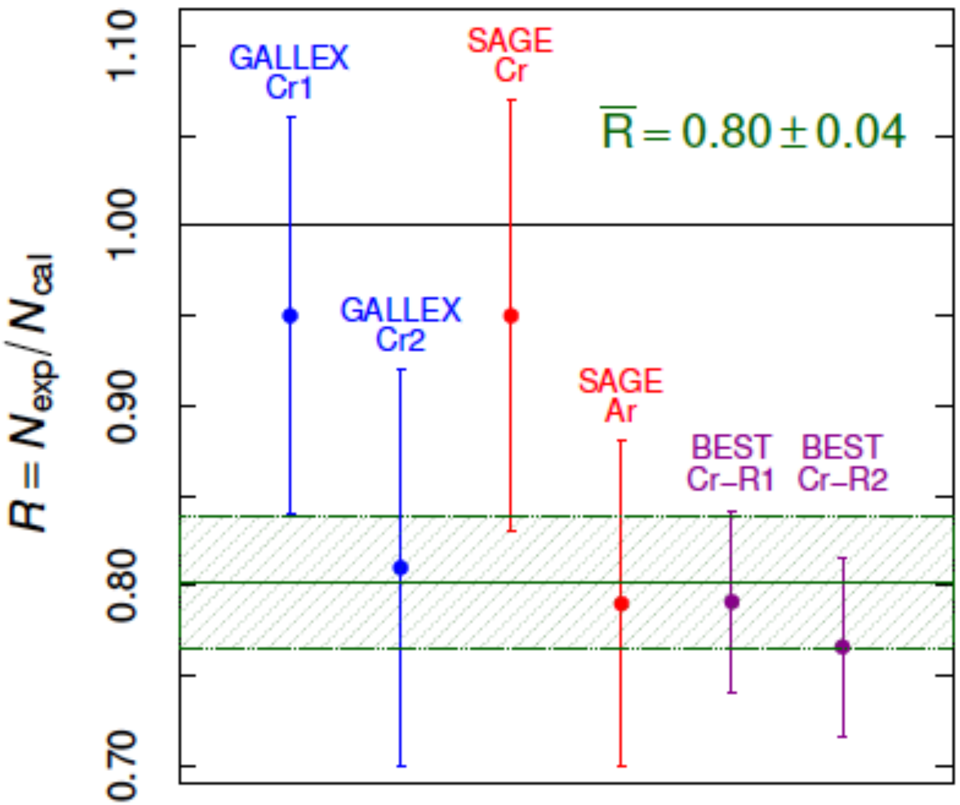
How well do we know the cross sections of the radiochemical detection processes?

New Measurements from BEST Experiment

Baksan Experiment on Sterile Transitions (BEST)

arXiv:2109.11482 and arXiv:2109:14654





$$\langle L \rangle_{\rm GALLEX} \simeq 1.9\,{\rm m} \qquad \langle L \rangle_{\rm SAGE} \simeq 0.6\,{\rm m}$$

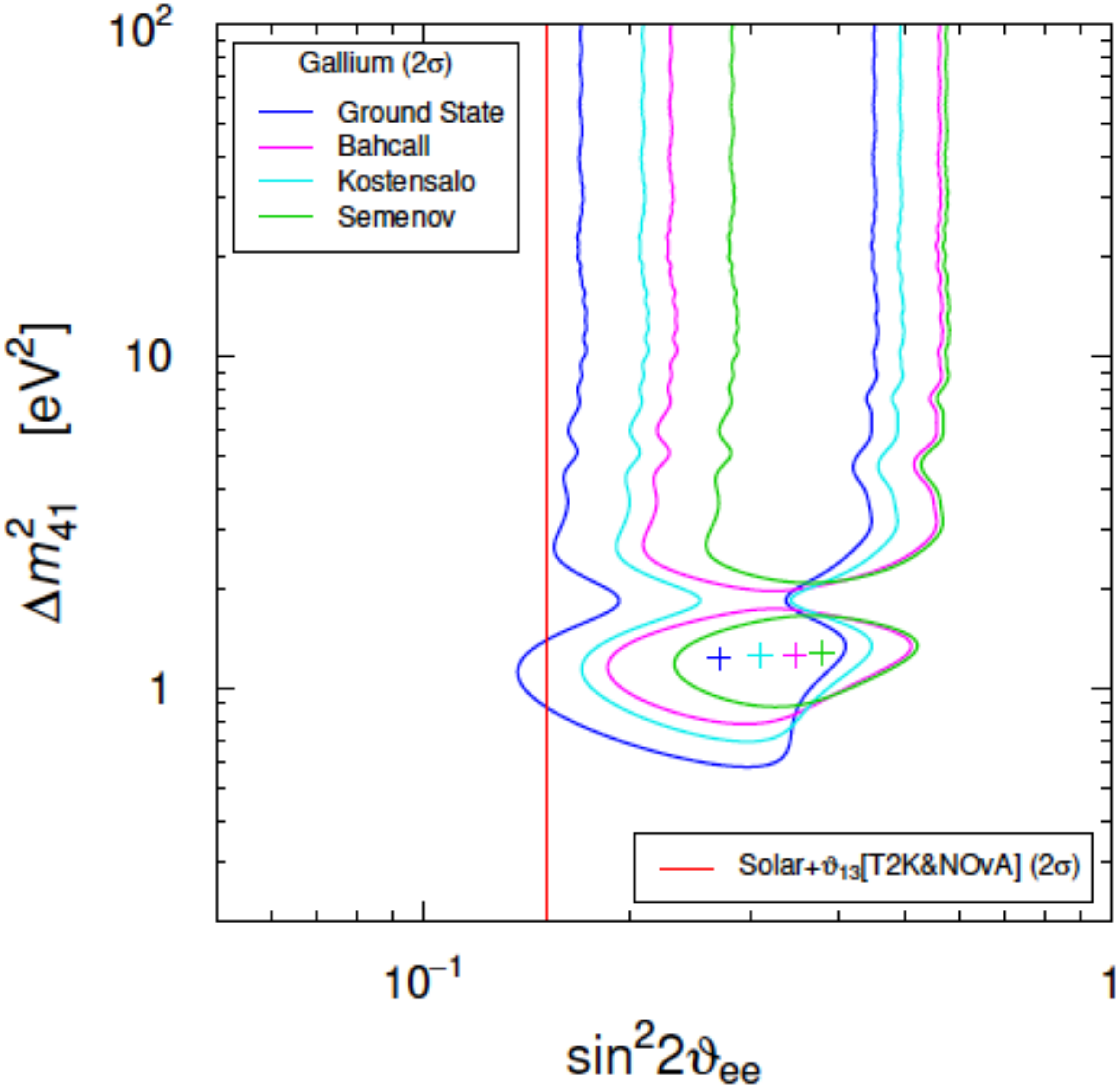
$$\langle L \rangle_{\rm BEST}^{\rm R1} \simeq 0.7\,{\rm m} \qquad \langle L \rangle_{\rm BEST}^{\rm R2} \simeq 1.1\,{\rm m}$$

$$\Delta m^2_{\rm SBL} \gtrsim 1\,{\rm eV}^2 \gg \Delta m^2_{\rm ATM}$$

Gallium neutrino anomaly has been reinforced after the new measurements from BEST

More than 5σ deficit of ν_e

Gallium Anomaly vs. Solar Neutrino Bound



Both Gallium and Solar Neutrino Experiments detect ν_e

Gallium anomaly is in strong tension with the solar neutrino bound

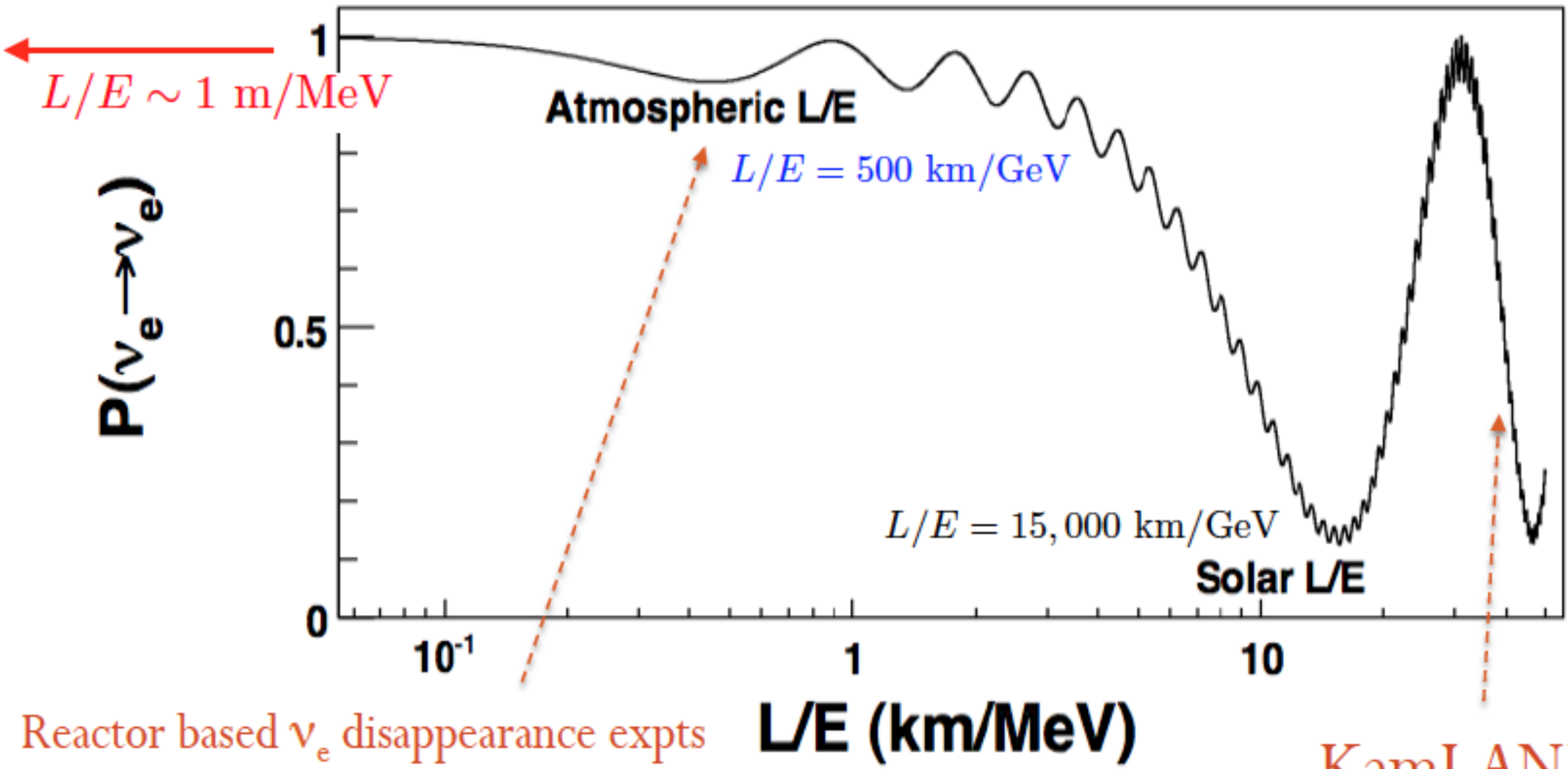
Giunti, Li, Ternes, Tyagi, Xin, arXiv:2209.00916

Reactor Antineutrinos at very Short-Baselines

The Evolution of

"Reactor Antineutrino Anomaly"

Oscillations with Reactor Antineutrinos



Reactor based ν_e disappearance expts such as Double Chooz and Daya Bay

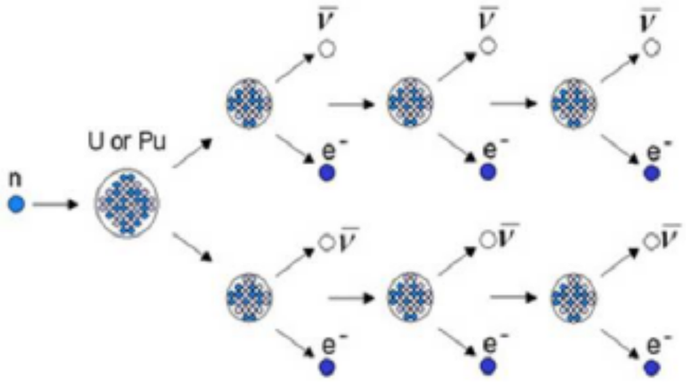
KamLAND

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27 \cdot \Delta m^2_{23} \cdot L/E)$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{12} \cdot \sin^2(1.27 \cdot \Delta m^2_{12} \cdot L/E)$$

Reactor Antineutrino Experiments

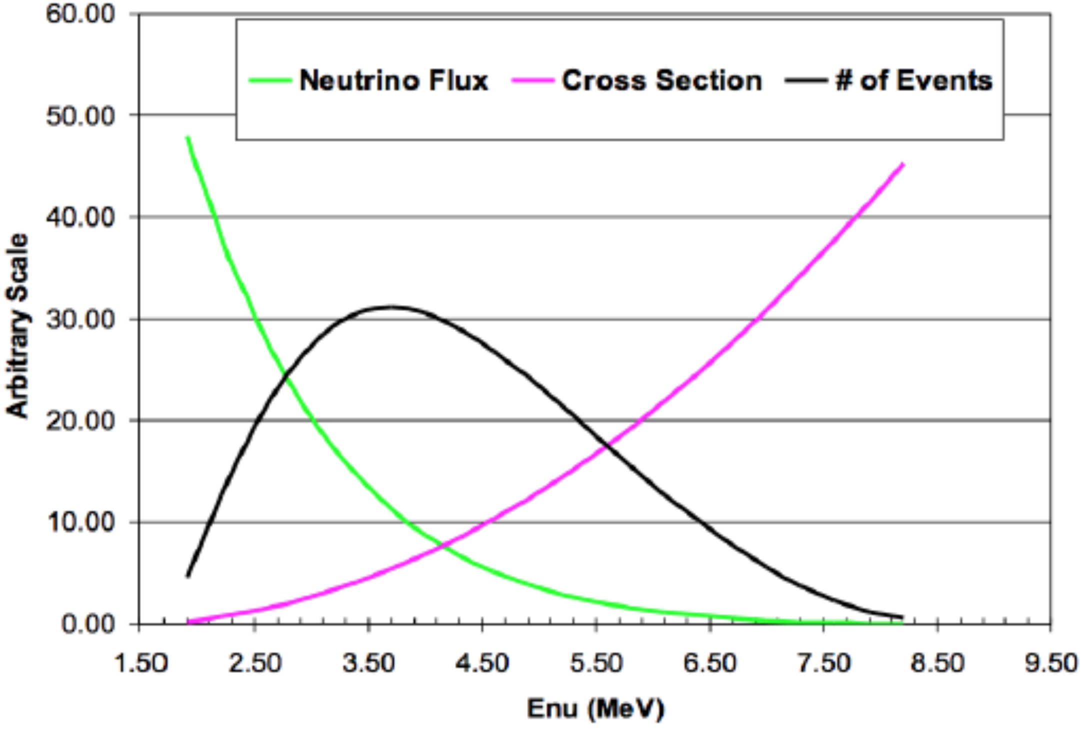
Reactor $\bar{\nu}_e$ production



β^- decay of neutron rich fission fragments of U and Pu

Detection through inverse β Decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

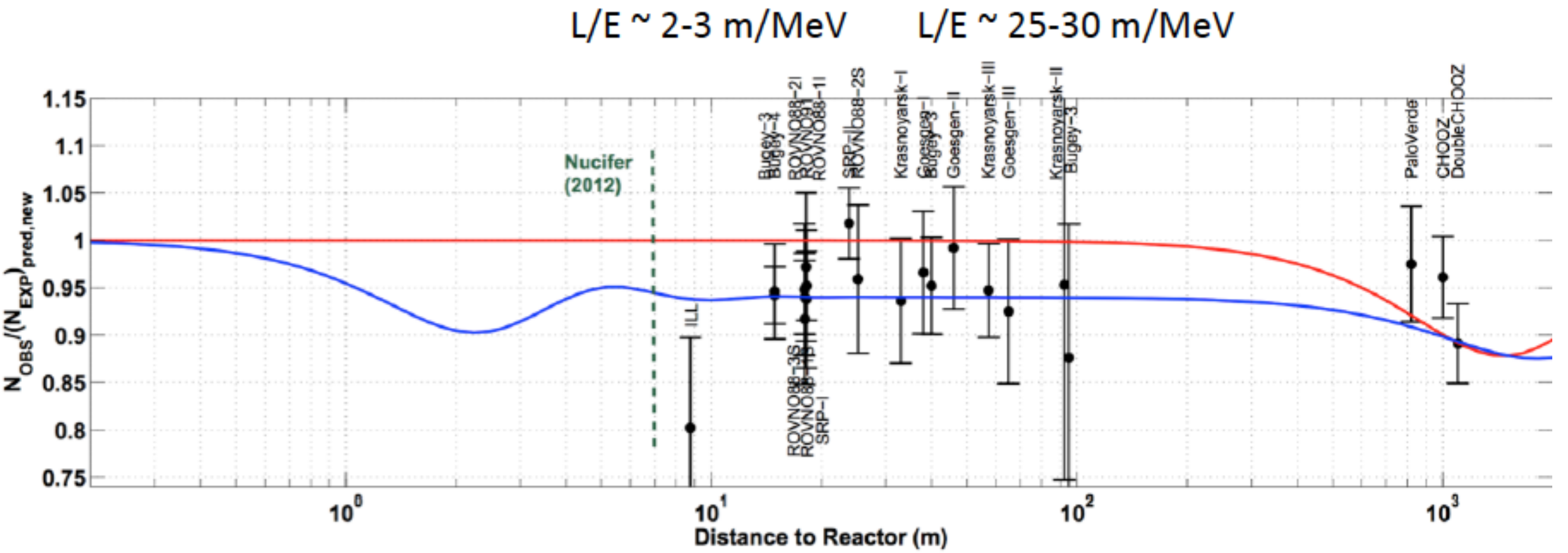


$E_{prompt} = E_\nu - 0.8$ MeV

Reactor Antineutrino Anomaly

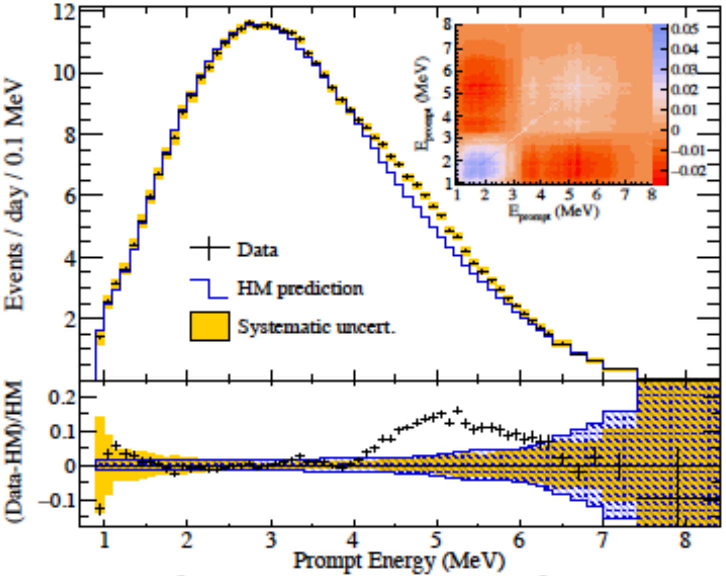
- In preparation for Double Chooz analysis with a single far detector, Mueller et al. applied an improved procedure to go from measured ^{235}U, ^{239}Pu, and ^{241}Pu β^- spectra (at ILL) to neutrino spectra.
  - Th. A. Mueller et al. "Improved Predictions of Reactor Antineutrino Spectra" Phys. Rev. C83 (2011) 054615; arXiv:1101.2663.
- Result was a net 3% increase in the estimated fluxes relative to previous predictions, reanalysis of past reactor experiments
  - G. Mention et al. "The Reactor Antineutrino Anomaly", Phys. Rev. D83 (2011) 083006; arXiv:1101.2755.
- P. Huber, using a different method to go from β- to neutrino spectra, finds a similar shift
  - P. Huber, "On the determination of anti-neutrino spectra from nuclear reactors"; arXiv:1106.0687.

Reactor Antineutrino Anomaly

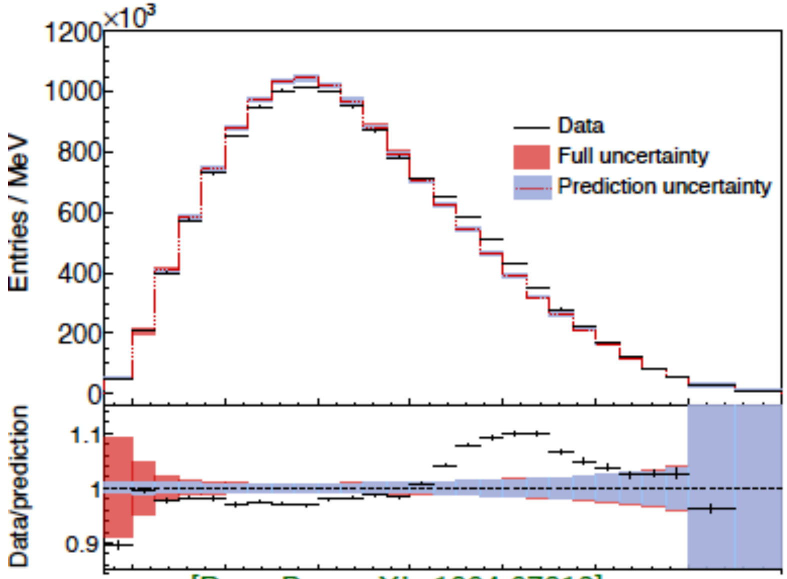


- Looked back at ratio of the observed to predicted $\overline{\nu}_e$ event rate for 19 different reactor neutrino experiments at baselines less that 100 m.
- Mean average ratio including correlations is 0.927 ± 0.023, indicating a 7.3% deficit at short baseline.
- Curves show fits to data assuming standard 3 neutrino oscillations and assuming oscillations with one additional sterile neutrino

Reactor Antineutrino 5 MeV Bump (Shoulder)



[RENO, arXiv:2010.14989]

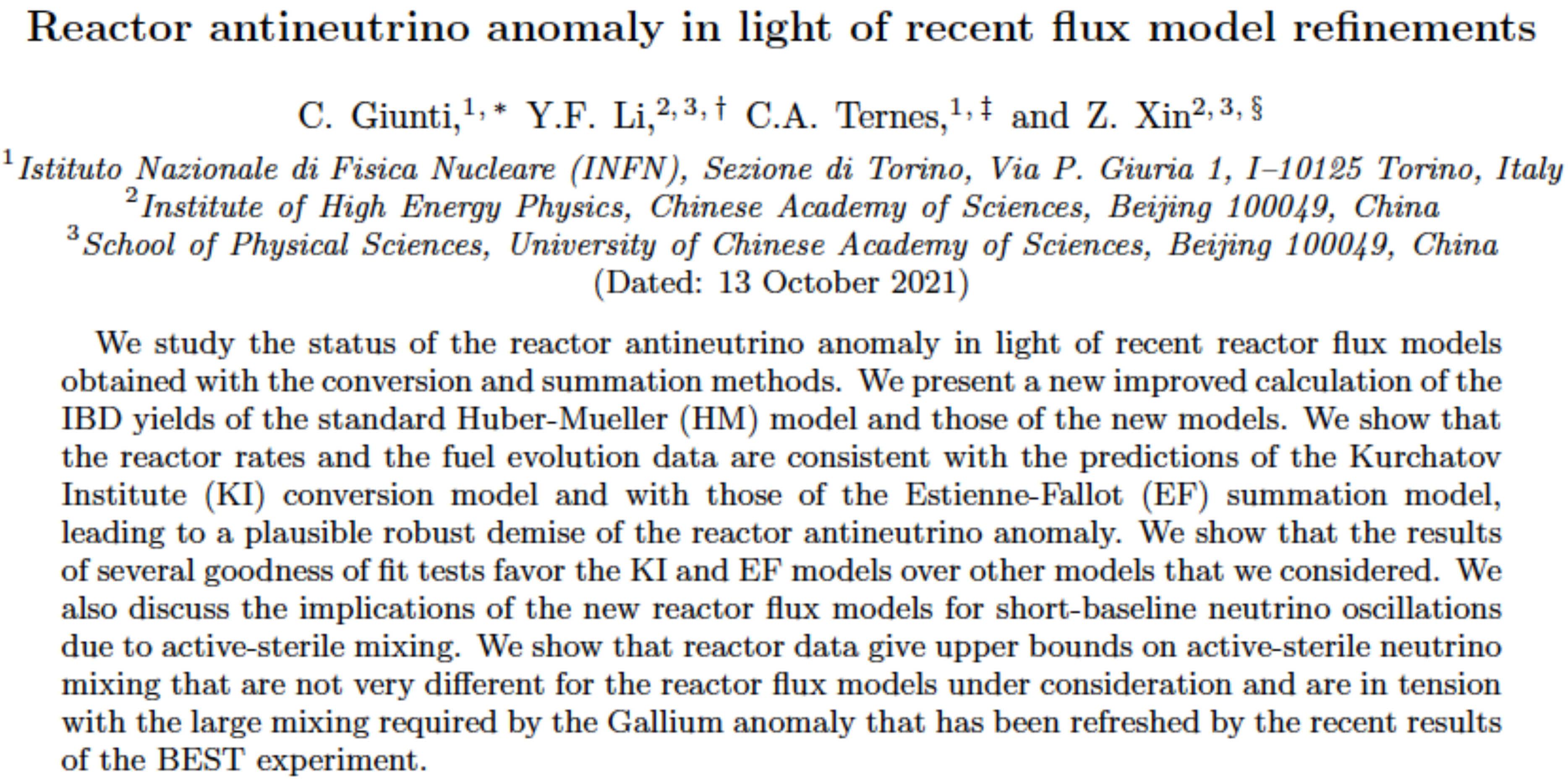


[Daya Bay, arXiv:1904.07812]

- Discovered in 2014 by RENO, Double Chooz, Daya Bay.
- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in RENO, DC, DB).
- Most likely it is due to a theoretical miscalculation of the spectrum.
- A recalculation of the spectrum can have opposite effects on the anomaly:
  - A 4-6 MeV increase of the predicted flux which explains the bump increases the anomaly.
  - A 1-4 MeV decrease of the predicted flux decreases the anomaly.

Talk by C. Giunti in NOW 2022

Reactor Antineutrino Anomaly



Reactor antineutrino anomaly in light of recent flux model refinements

C. Giunti,[1,*] Y.F. Li,[2,3,†] C.A. Ternes,[1,‡] and Z. Xin[2,3,§]

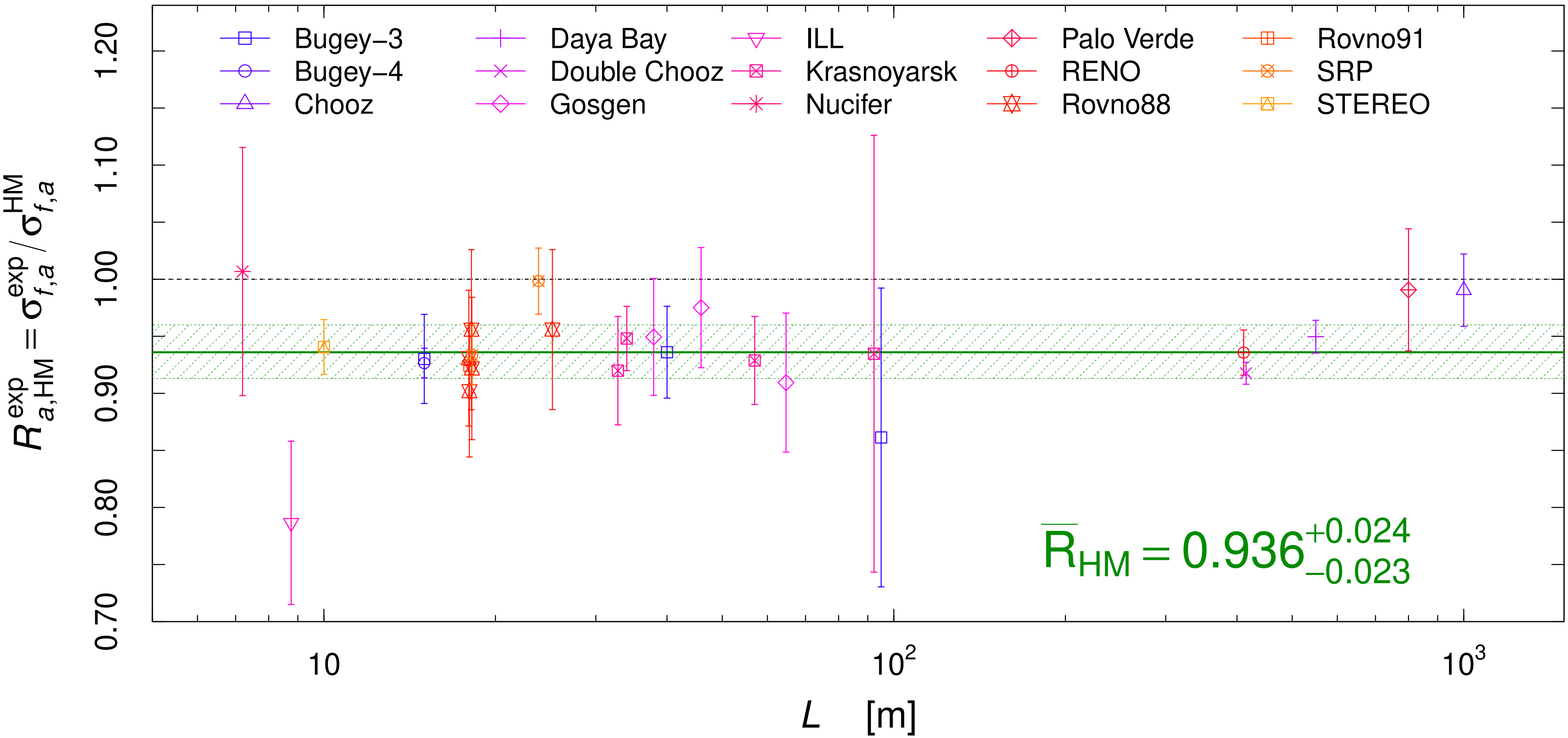
[1] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I–10125 Torino, Italy*
[2] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[3] *School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*

(Dated: 13 October 2021)

We study the status of the reactor antineutrino anomaly in light of recent reactor flux models obtained with the conversion and summation methods. We present a new improved calculation of the IBD yields of the standard Huber-Mueller (HM) model and those of the new models. We show that the reactor rates and the fuel evolution data are consistent with the predictions of the Kurchatov Institute (KI) conversion model and with those of the Estienne-Fallot (EF) summation model, leading to a plausible robust demise of the reactor antineutrino anomaly. We show that the results of several goodness of fit tests favor the KI and EF models over other models that we considered. We also discuss the implications of the new reactor flux models for short-baseline neutrino oscillations due to active-sterile mixing. We show that reactor data give upper bounds on active-sterile neutrino mixing that are not very different for the reactor flux models under consideration and are in tension with the large mixing required by the Gallium anomaly that has been refreshed by the recent results of the BEST experiment.

Giunti, Li, Ternes, Xin, PLB 829 (2022) 137054

Reactor Antineutrino Anomaly

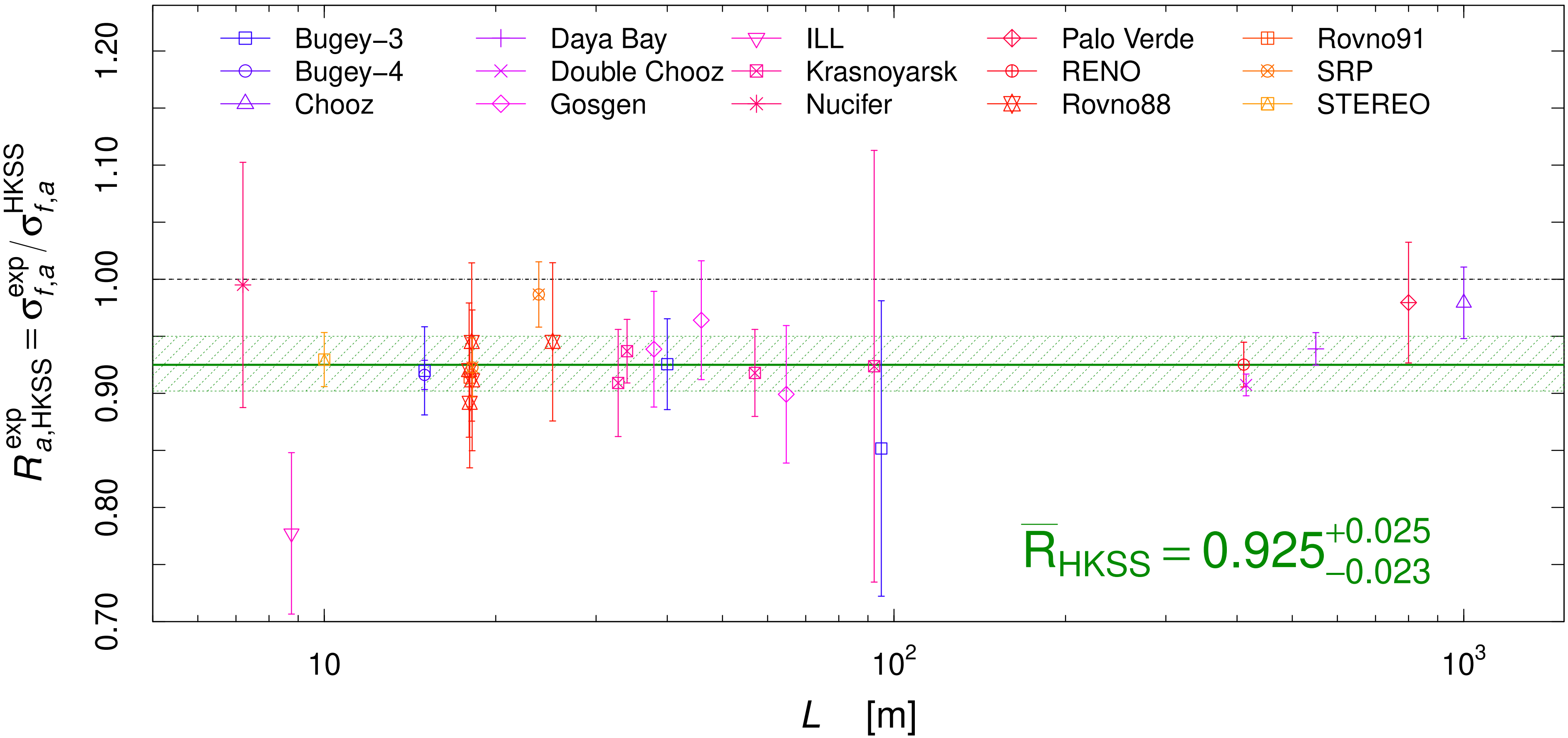


Mueller et al., arXiv:1101.2663; Huber, arXiv:1106.0687; Giunti, Li, Ternes, Xin, arXiv:2110.06820

New improved calculation of the IBD yields of the standard Huber-Mueller (HM) flux model using conversion method (new β spectra from ^{235}U fission)

Reactor Antineutrino Anomaly (RAA) is around 2.5σ

Reactor Antineutrino Anomaly

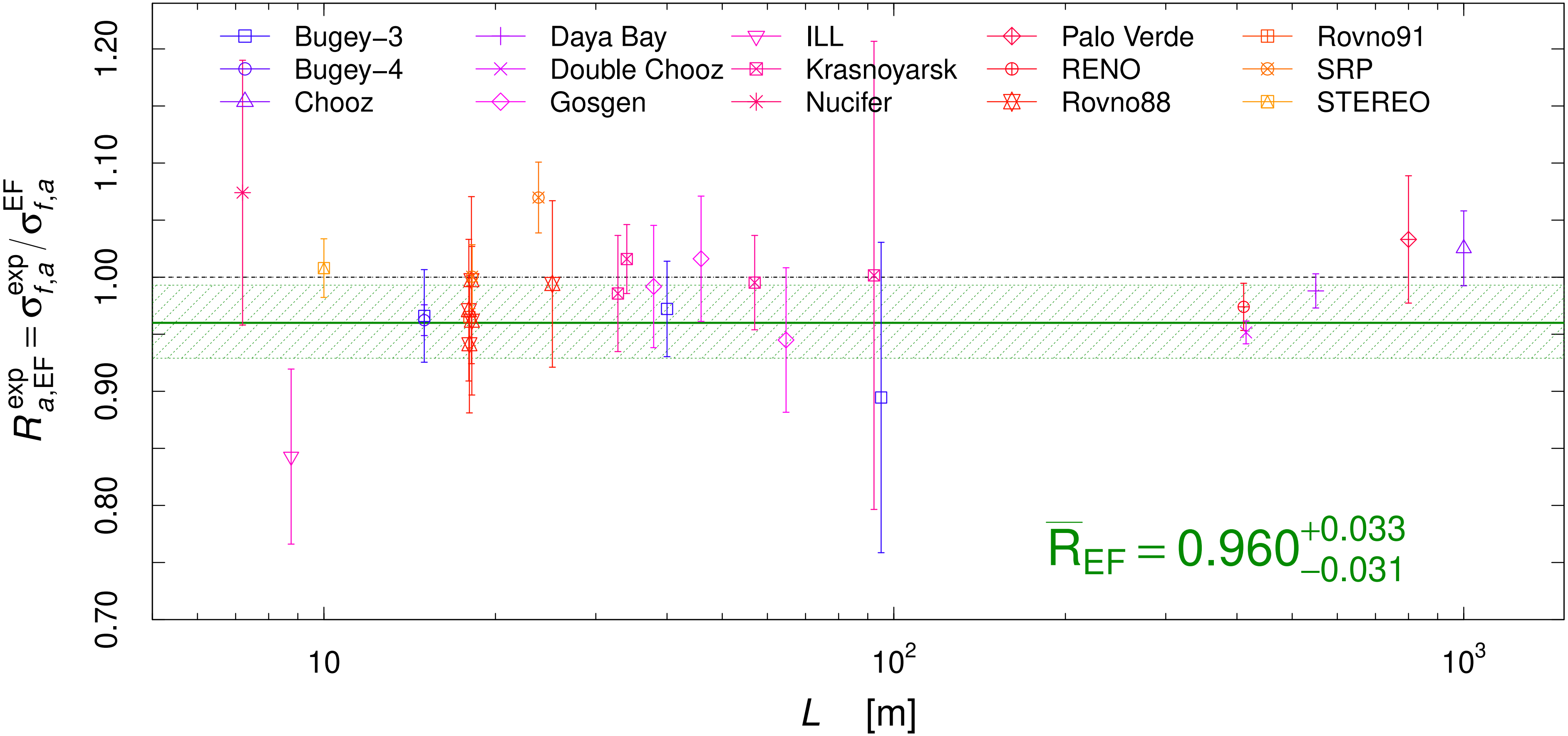


Hayen, Kostensalo, Severijns, Suhonen, arXiv:1908.08302; Giunti, Li, Ternes, Xin, arXiv:2110.06820

New HKSS fluxes in 2019 using conversion method (HM + HKSS uncertainties)

Reactor Antineutrino Anomaly (RAA) is around 2.9σ

Reactor Antineutrino Anomaly

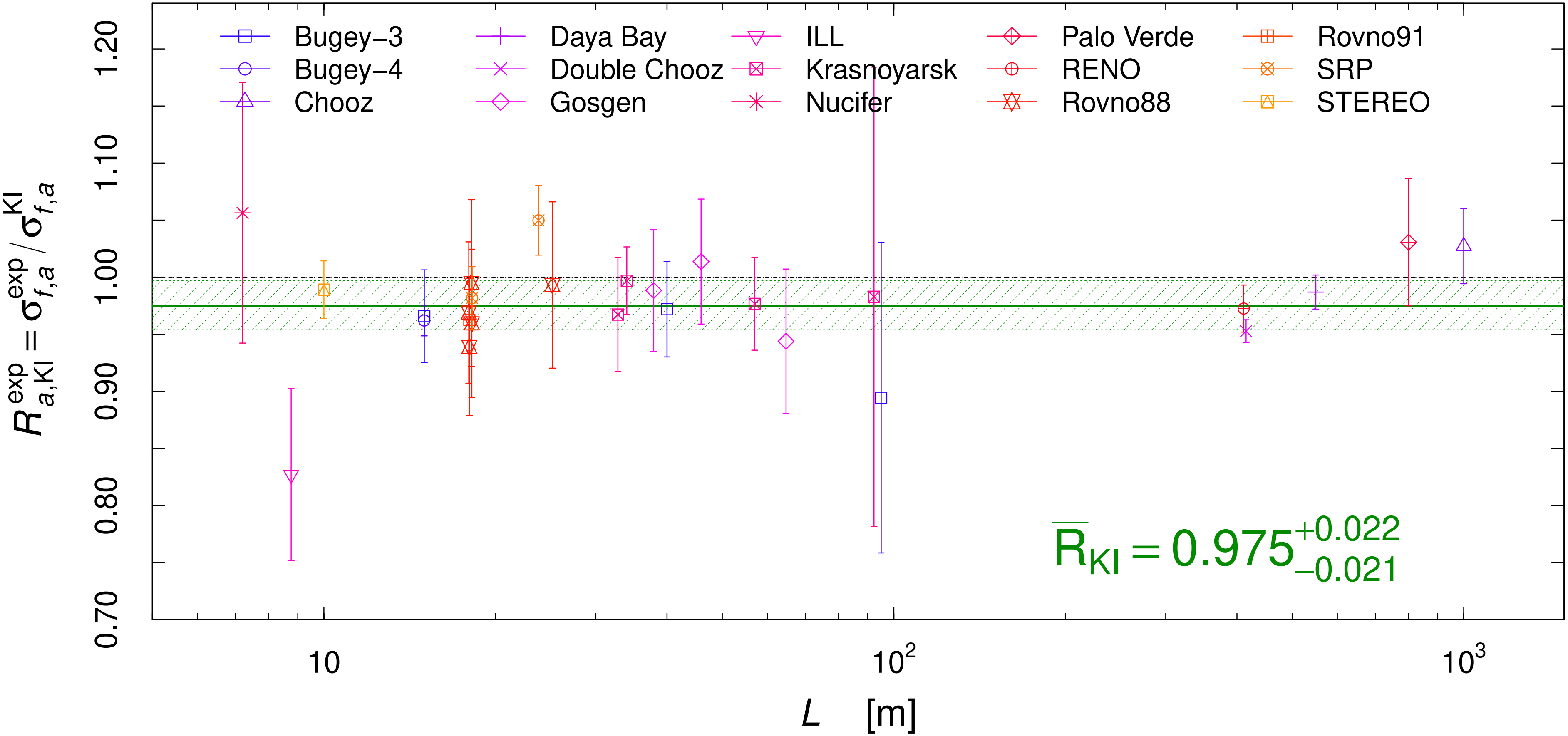


Estienne, Fallot, et al., arXiv:1904.09358; Giunti, Li, Ternes, Xin, arXiv:2110.06820

New EF fluxes in 2019 using summation method
(5% uncertainties for ^{235}U, ^{239}Pu, ^{241}Pu and 10% for ^{238}U)

Reactor Antineutrino Anomaly (RAA) is around 1.2σ

Reactor Antineutrino Anomaly

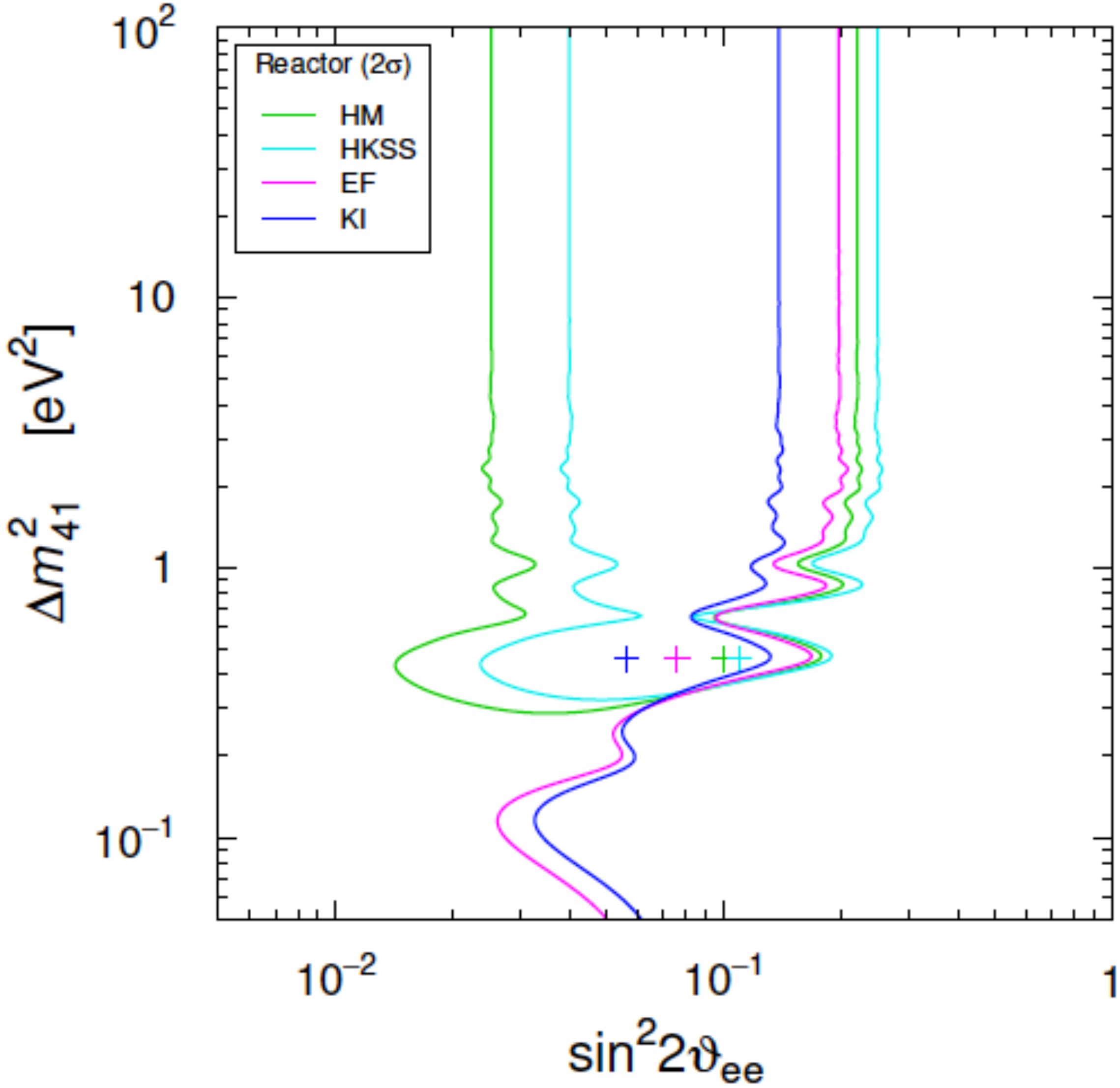


Kurchatov Institute: Kopeikin, Skorokhvatov, Titov, arXiv:2103.01684; Giunti, Li, Ternes, Xin, arXiv:2110.06820

New KI fluxes in 2021 using conversion method (HM + KI uncertainties)
Approximate agreement with ab initio (summation method) EF fluxes

Reactor Antineutrino Anomaly (RAA) is around 1.1σ

Take Home Message



The favored KI and EF models are compatible with no active-sterile oscillations at short baselines

Independently from the reactor antineutrino flux model, we have an upper bound on

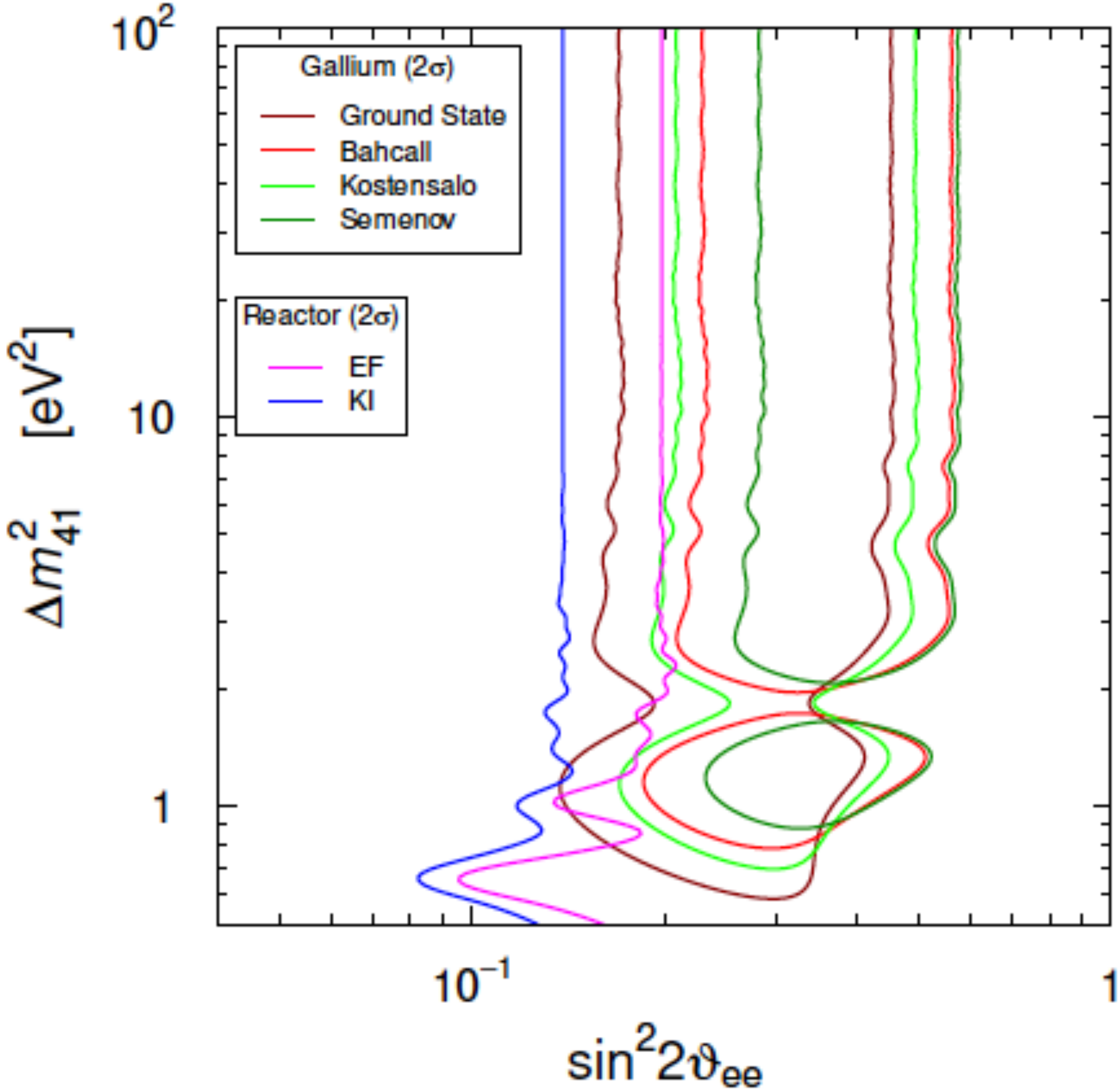
$$\sin^2 2\theta_{ee} \lesssim 0.25 \ (2\sigma)$$

Take Home Message

The reactor rates and the fuel evolution data are consistent with the predictions of the Kurchatov Institute (KI) conversion model and with those of the Estienne-Fallot (EF) summation model, leading to a plausible robust demise of the reactor antineutrino anomaly

Giunti, Li, Ternes, Xin, PLB 829 (2022) 137054

Reactor Anomaly vs. Gallium Anomaly



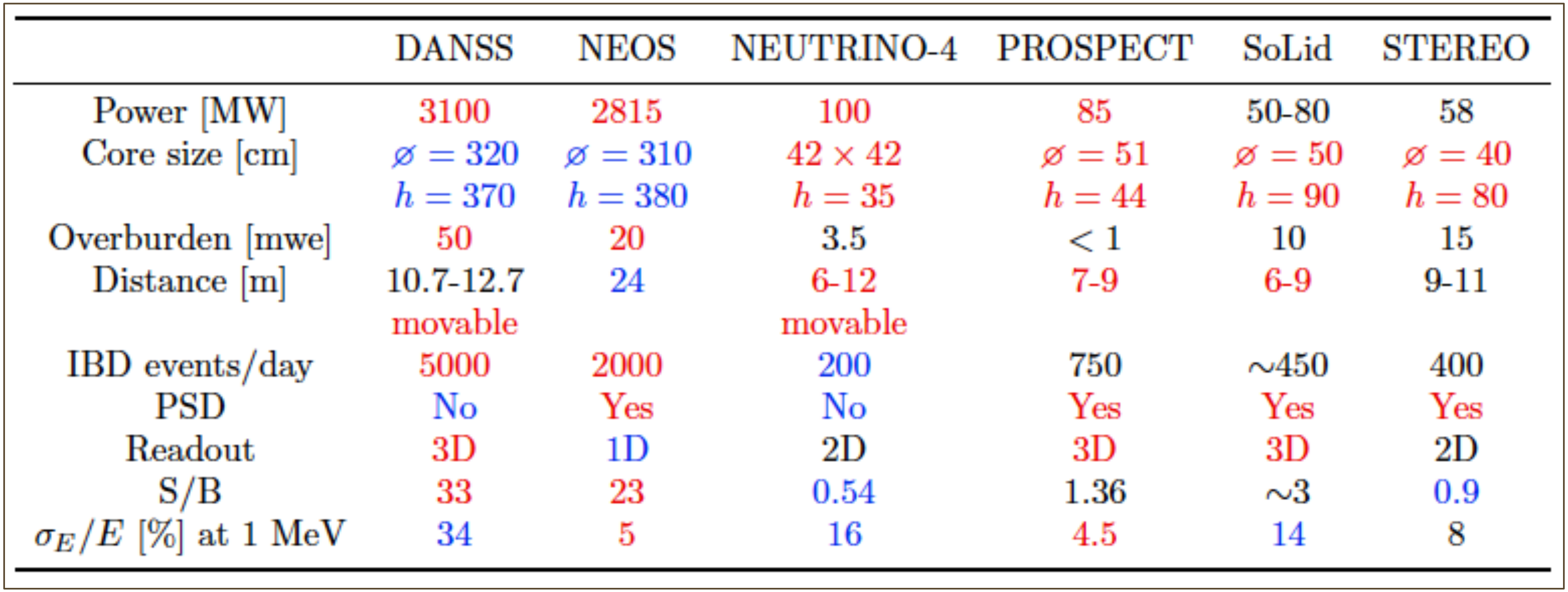
Another Tension!

Note:

Reactor Anomaly deals w/ electron antineutrinos, whereas Gallium Anomaly deals w/ electron neutrinos

Giunti, Li, Ternes, Tyagi, Xin, arXiv:2209.00916

Very Short-Baseline Reactor Experiments

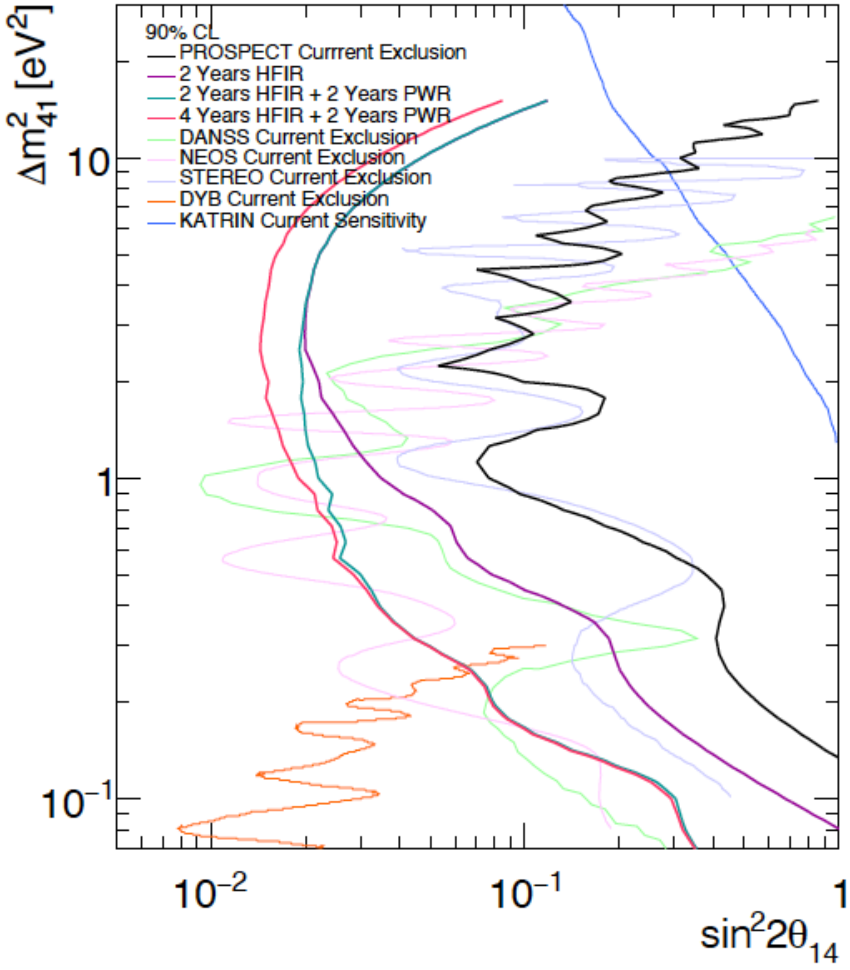


	DANSS	NEOS	NEUTRINO-4	PROSPECT	SoLid	STEREO
Power [MW]	3100	2815	100	85	50-80	58
Core size [cm]	$\varnothing = 320$ $h = 370$	$\varnothing = 310$ $h = 380$	42×42 $h = 35$	$\varnothing = 51$ $h = 44$	$\varnothing = 50$ $h = 90$	$\varnothing = 40$ $h = 80$
Overburden [mwe]	50	20	3.5	< 1	10	15
Distance [m]	10.7-12.7 movable	24	6-12 movable	7-9	6-9	9-11
IBD events/day	5000	2000	200	750	∼450	400
PSD	No	Yes	No	Yes	Yes	Yes
Readout	3D	1D	2D	3D	3D	2D
S/B	33	23	0.54	1.36	∼3	0.9
σ_E/E [%] at 1 MeV	34	5	16	4.5	14	8

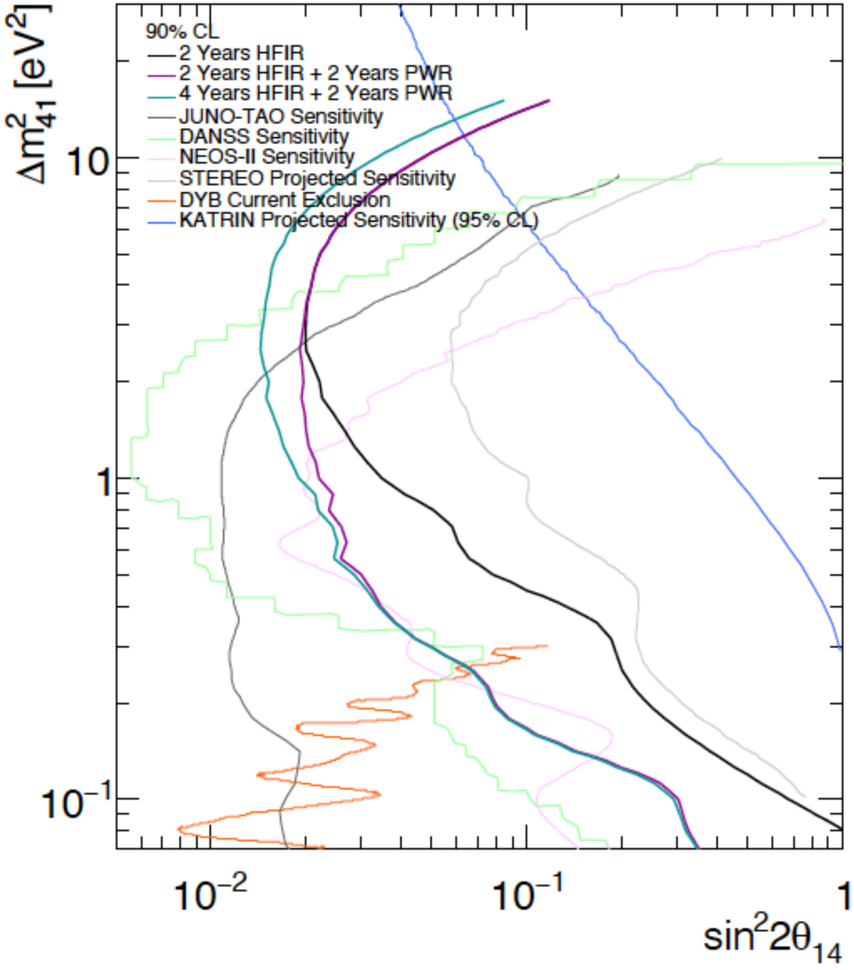
DANSS: Kalinin Nuclear Power Plant (KNPP), Moscow, Russia
Neutrino-4: SM-3 Research Reactor at Dmitrovgrad, Russia
SoLid: SCK-CEN BR2 Research Reactor in Belgium

NEOS: Hanbit Nuclear Power Complex in Yeong-gwang, Korea
PROSPECT: High Flux Isotope Reactor (HFIR) at ORNL, USA
STEREO: High Flux Reactor of the Institute Laue-Langevin, France

Present and Future Sensitivity from Very SBL Reactor Experiments



Present Sensitivity

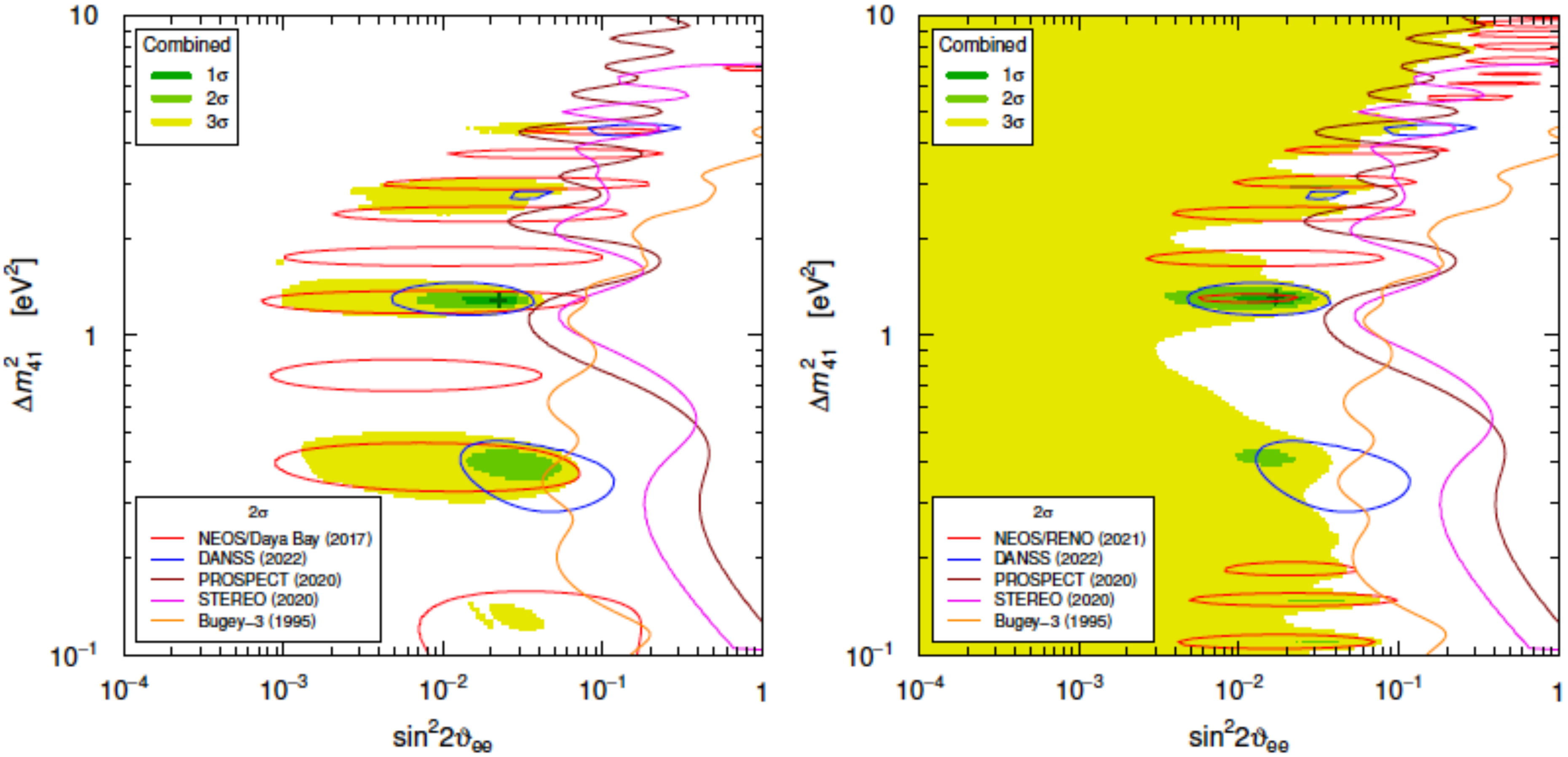


Future Sensitivity

PWR = Pressurized Water Reactor
HFIR: High Flux Isotope Reactor

Courtesy Bryce Littlejohn

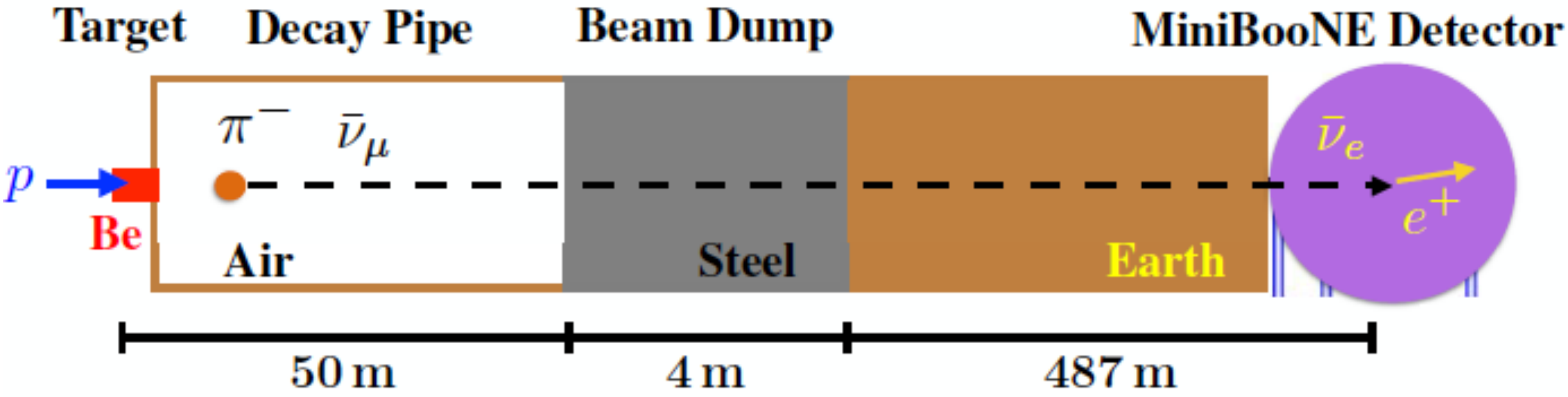
Global Fit of Existing Data

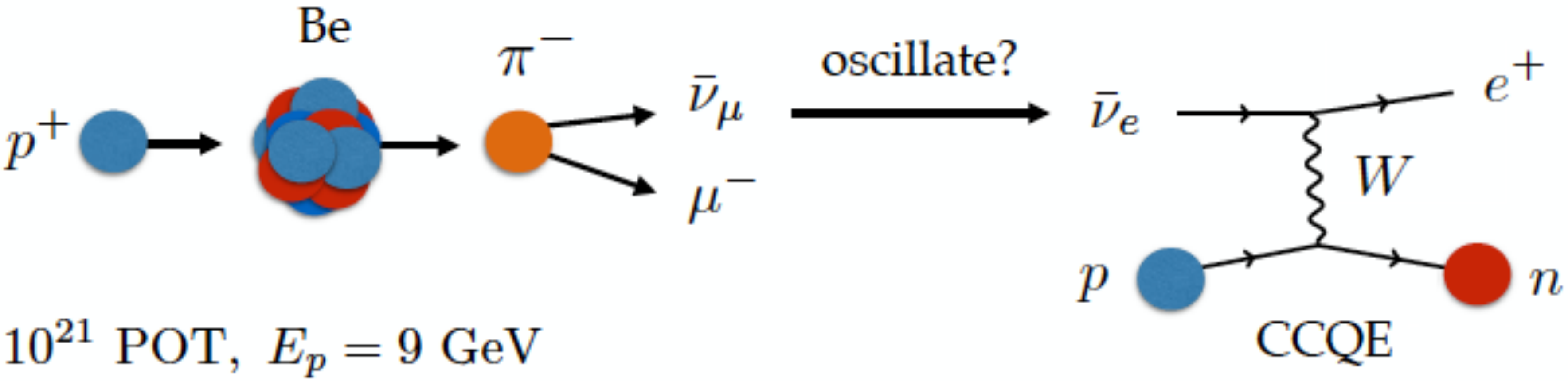


- Fit with NEOS/Daya Bay: $\Delta\chi^2_{3\nu-4\nu} = 12.6 \Longrightarrow 3.1\ \sigma$
- Fit with NEOS/RENO: $\Delta\chi^2_{3\nu-4\nu} = 9.1 \Longrightarrow 2.6\ \sigma$

Giunti, Li, Ternes, Tyagi, Xin, arXiv:2209.00916

MiniBooNE Experiment





10^{21} POT, $E_p = 9$ GeV

Energy and baseline chosen to test LSND

Comparable oscillation probabilities

MiniBooNE Collaboration 1805.12028

Courtesy Gordan Krnjaic

MiniBooNE Data Analysis

	neutrino mode	antineutrino mode
Luminosity	12.84×10^{20} POT	11.27×10^{20} POT
Reconstructed Neutrino Energy	$200 < E_\nu^{QE} < 1250$ MeV	
Excess events BG subtracted	381.2 ± 85.2	79.3 ± 28.6

Possibly Important Caveat

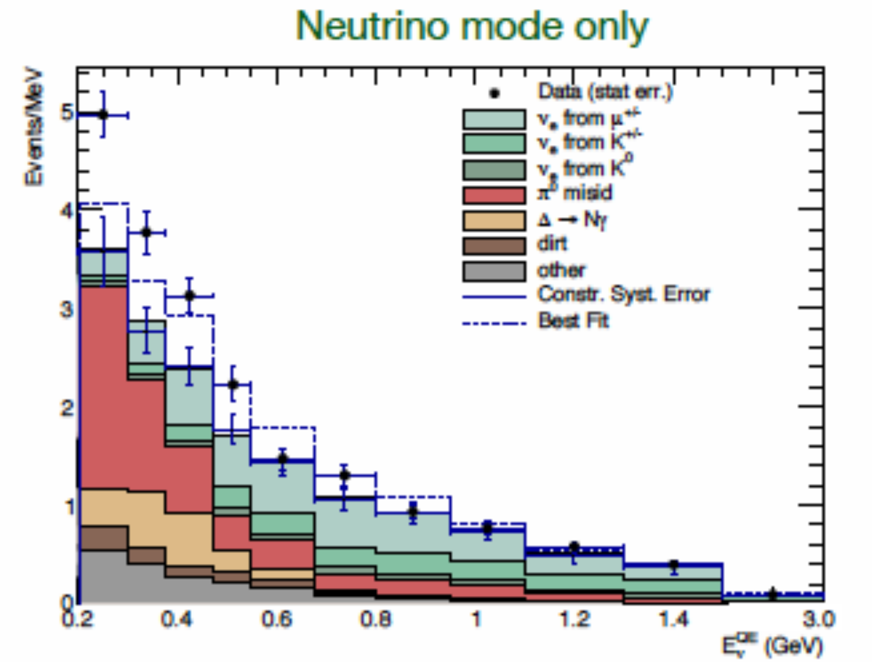
Mild tension ~ 2+ sigma between neutrino and antineutrino modes

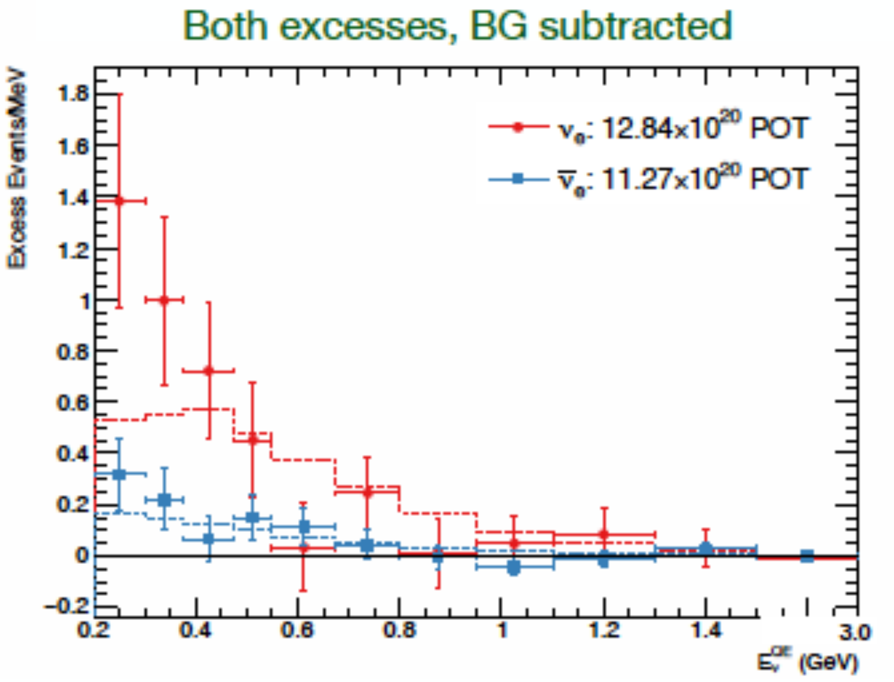
Updated Neutrino Mode Analysis
MiniBooNE Collaboration1805.12028

Complements earlier antineutrino
results collected 2002-2010

Courtesy Gordan Krnjaic

MiniBooNE Anomaly


Neutrino mode only


Both excesses, BG subtracted

$$E_\nu^{(\text{reconst.})} = \frac{2m_n E_e + m_p^2 - m_n^2 - m_e^2}{2(m_n - E_e + \cos\theta_e \sqrt{E_e^2 - m_e^2})}.$$

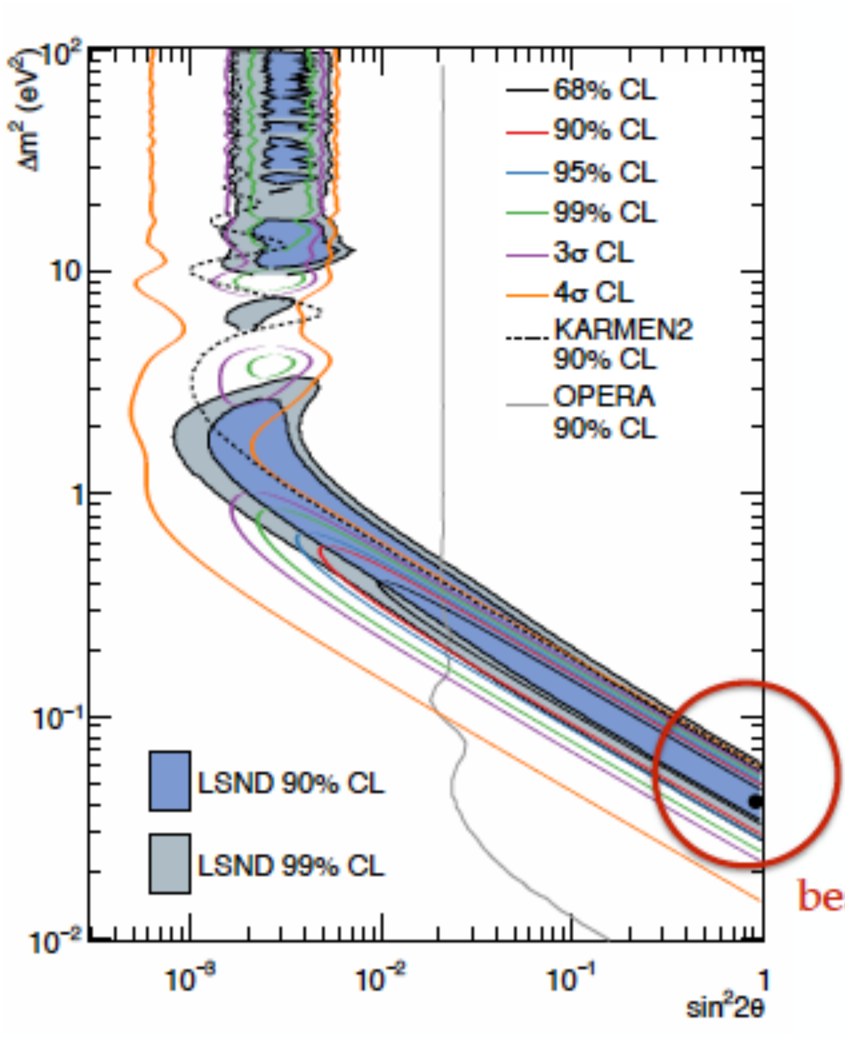
Measure charged lepton energy/angle

Observed ~ 400 events, PMNS predicts 0

Combined $\nu/\bar{\nu}$ modes : 4.8σ excess

MiniBooNE Collaboration 1805.12028

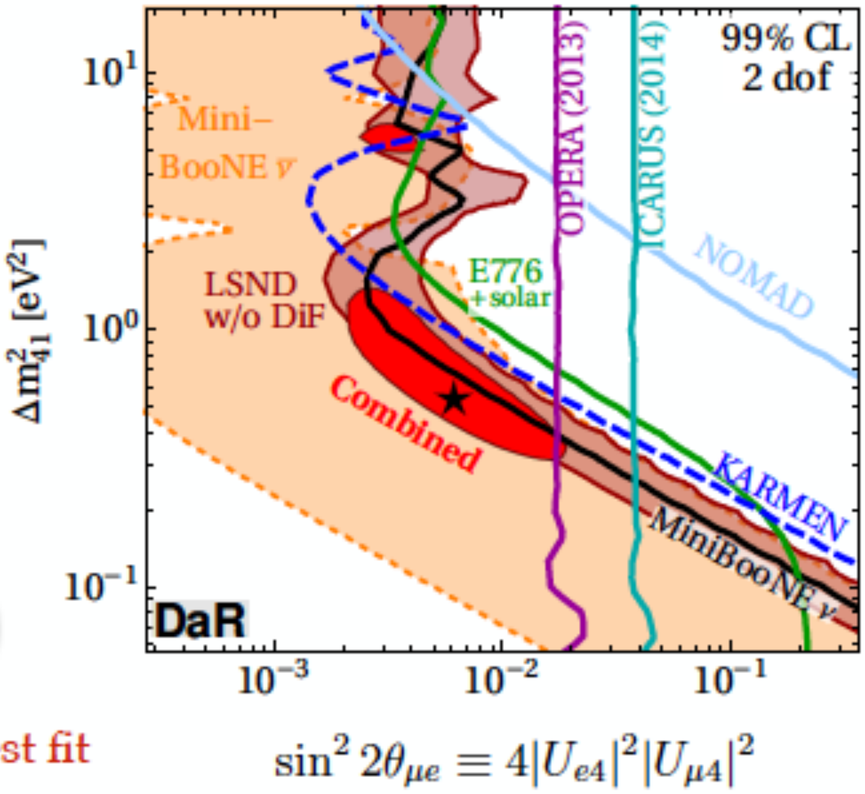
Can eV-scale Sterile Neutrino explain LSND+ MiniBooNE Anomaly?



best fit

MiniBooNE Collaboration 1805.12028

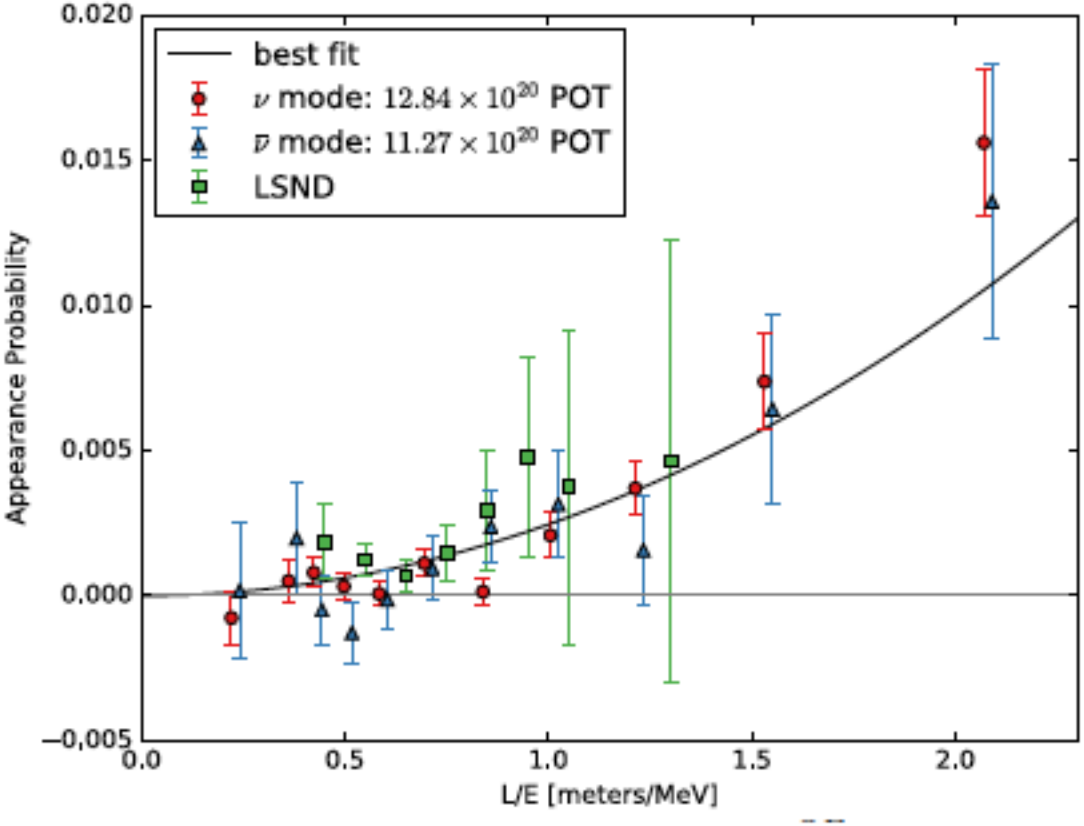
Best fits [appearance only]



Combined 6.1 sigma excess!

Dentler et. al. 1803.10661

Can eV-scale Sterile Neutrino explain LSND+ MiniBooNE Anomaly?

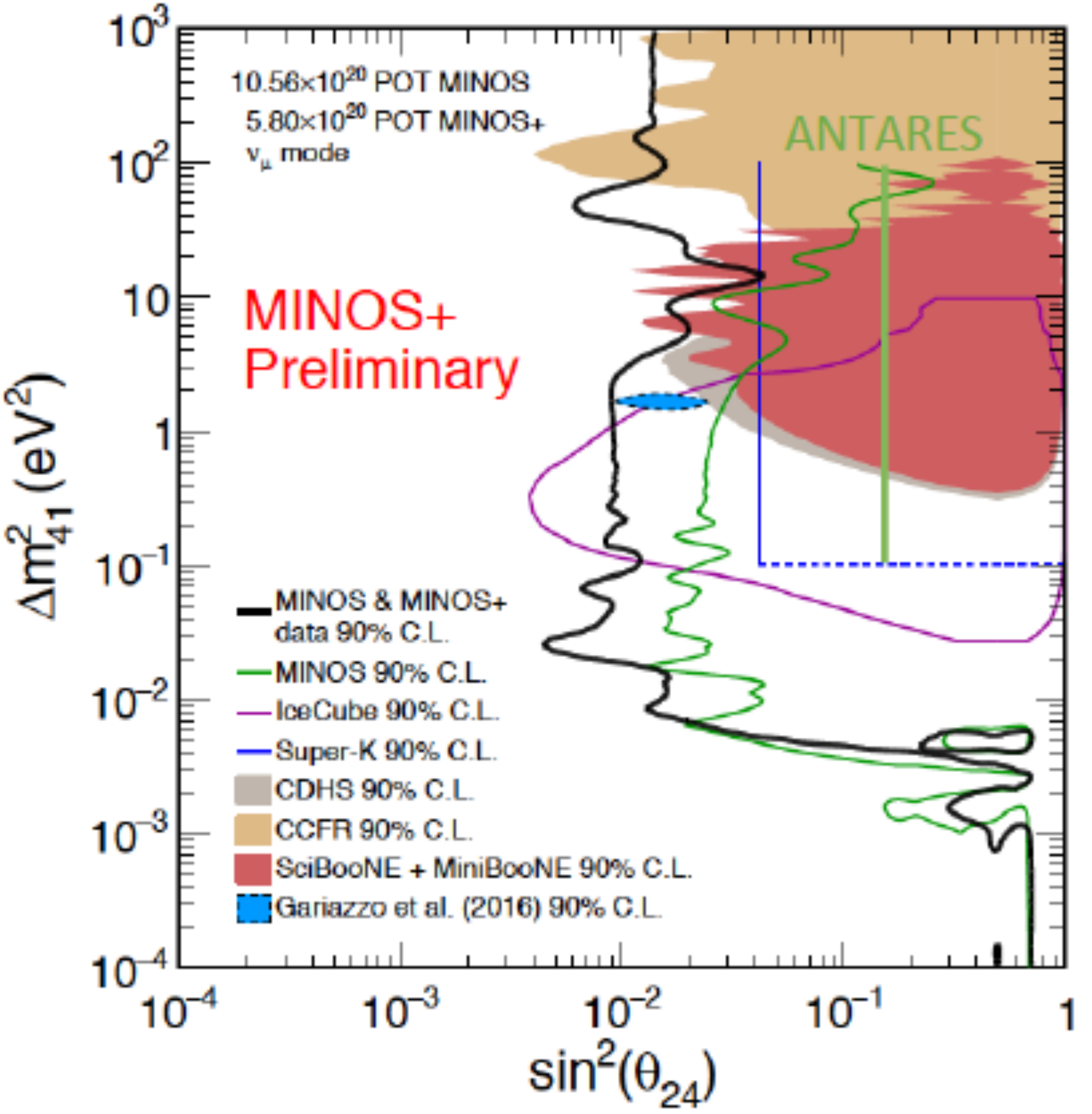


@ face value the scaling seems to support LSND / MB compatibility

MiniBooNE Collaboration 1805.12028

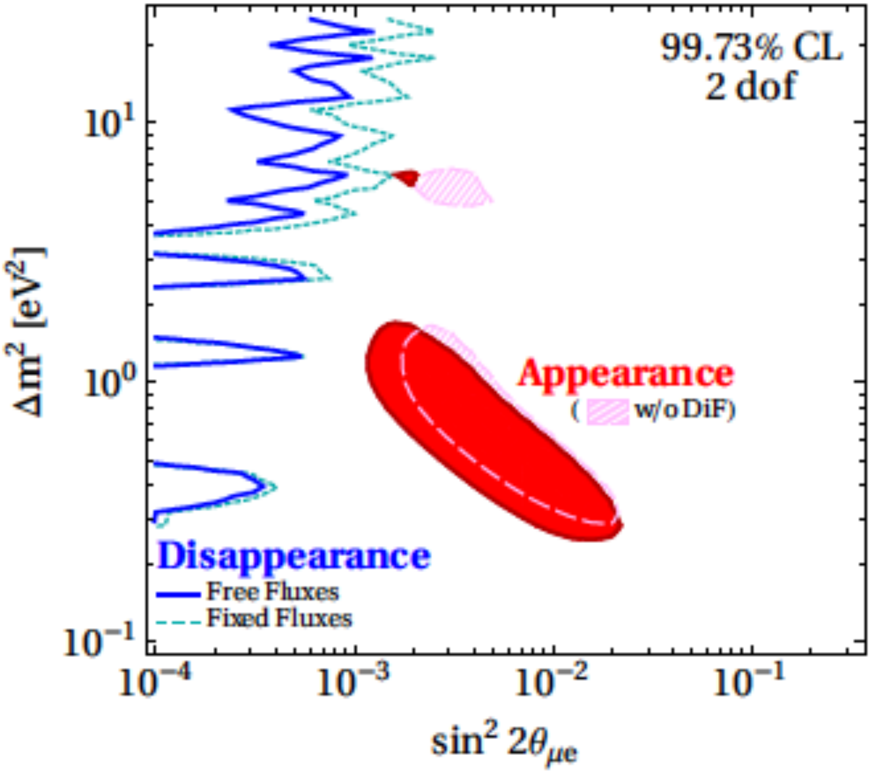
Courtesy Gordan Krnjaic

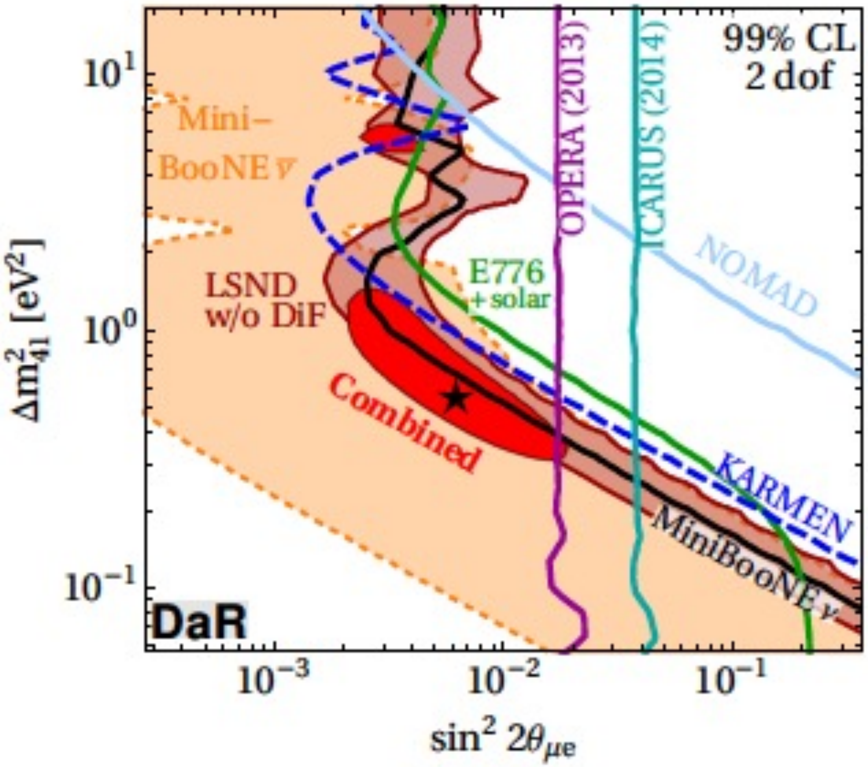
Let us Zoom the Muon Disappearance Results



No anomaly!
No evidence!
Only constraints!

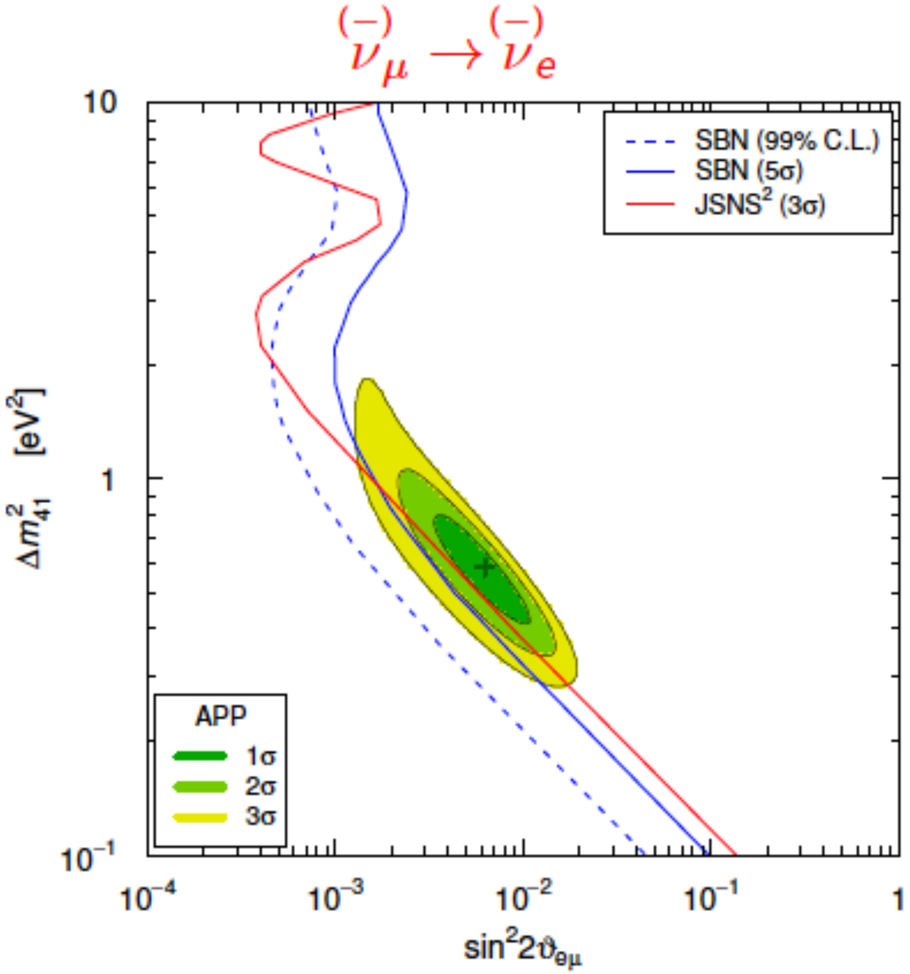
Significant tension between appearance and disappearance results

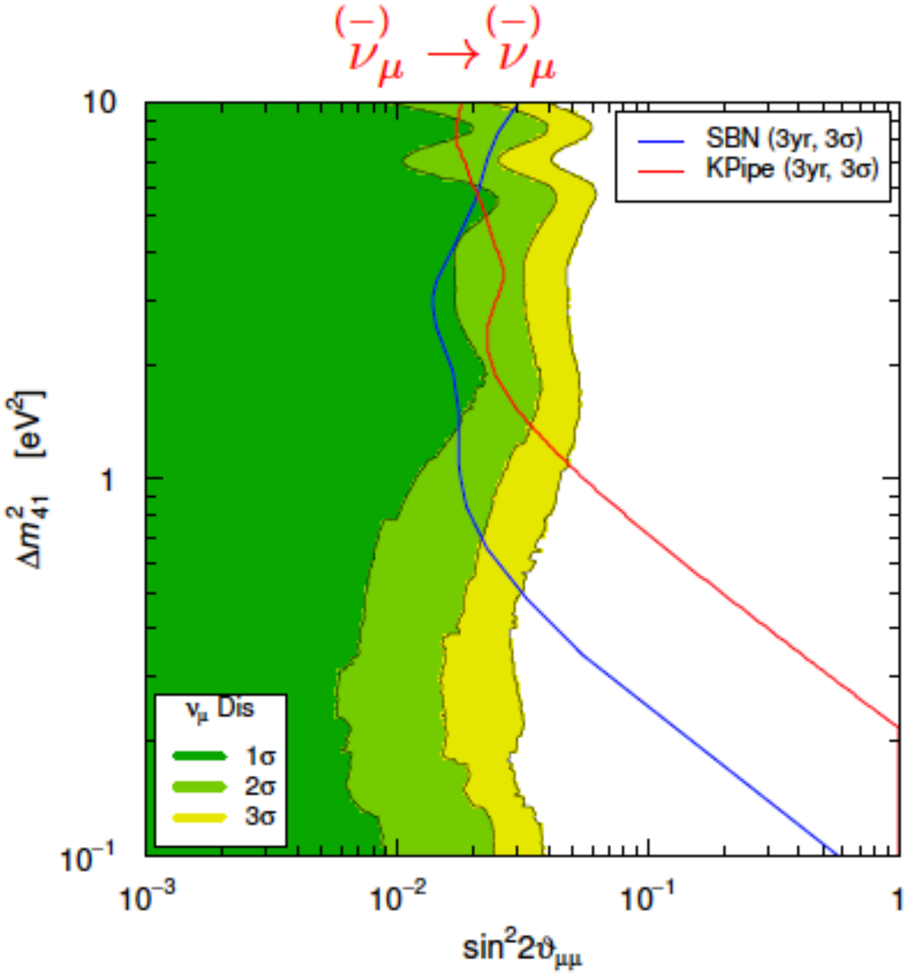




Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, JHEP 08 (2018) 010

New Dedicated Experiments





Fermilab SBN Program: See Talk by Miquel Nebot-Guinot

Status of JSNS^2 and JSNS^2 – II: See Talk by ChangDong Shin

Attend the Topical Discussion on this topic

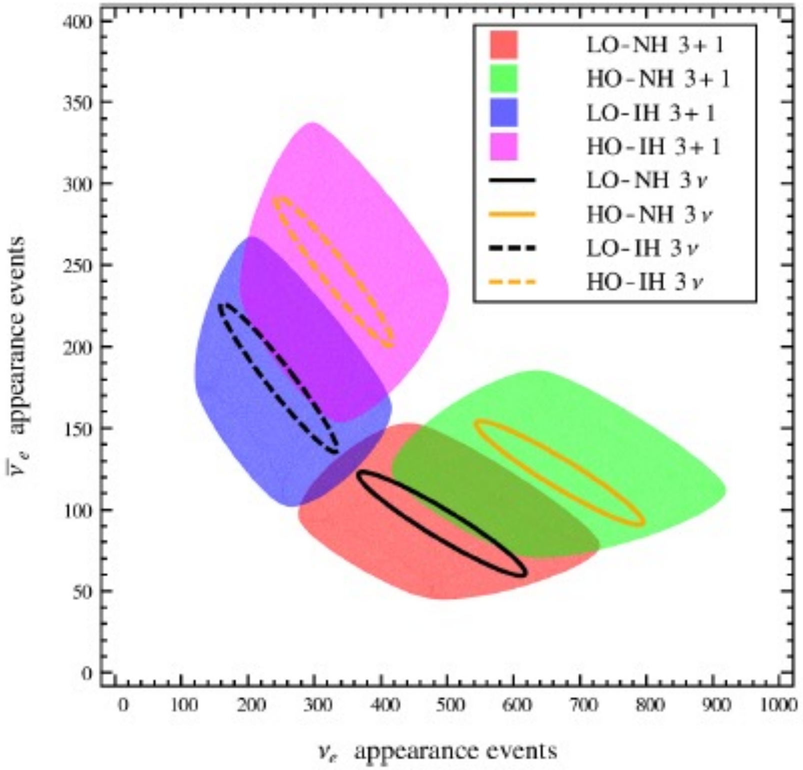
First Study on θ_{23} Octant with Light Sterile Neutrino

PRL 118, 031804 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

Octant of θ_{23} in Danger with a Light Sterile Neutrino

Sanjib Kumar Agarwalla,[1,2,*] Sabya Sachi Chatterjee,[1,2,†] and Antonio Palazzo[3,4,‡]
[1]*Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India*
[2]*Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400085, India*
[3]*Dipartimento Interateneo di Fisica "Michelangelo Merlin", Via Amendola 173, 70126 Bari, Italy*
[4]*Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Via Orabona 4, 70126 Bari, Italy*

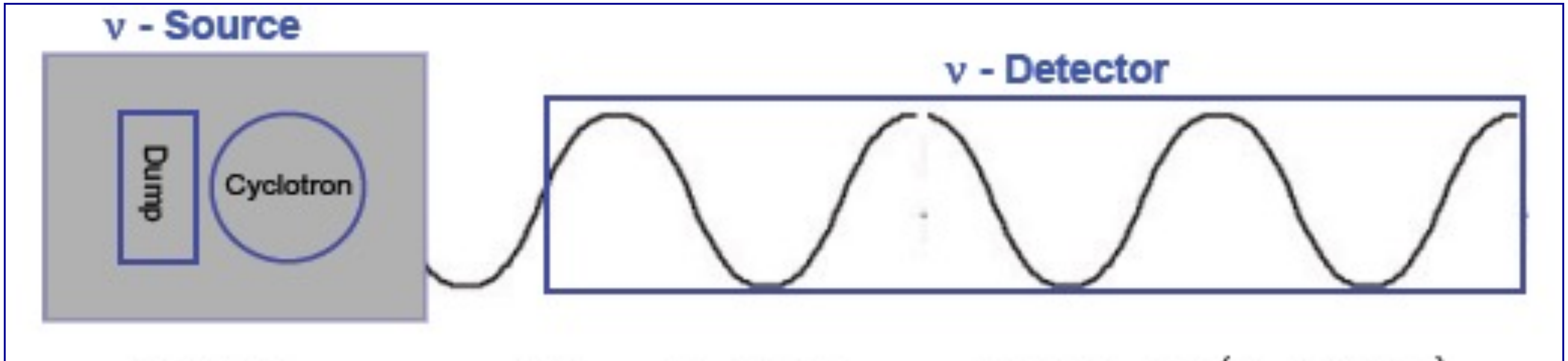
(Received 23 May 2016; revised manuscript received 5 December 2016; published 20 January 2017)



$\sin^2\theta_{23}$ = 0.42 (LO) and 0.58 (HO)

- Three-flavor ellipses due to variation in δ_{13} in [-π to π]
- Four-flavor blobs due to variation in δ_{13} and δ_{14} in [-π to π]
- Due to new CP phases, sensitivity towards octant lost in DUNE

Short-Baseline Neutrino Oscillation Wave



$1/L^2$ flux rate modulated by $\text{Prob}_{osc} = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L/E\right)$

Agarwalla, Conrad, Shaevitz, arXiv:1105.4984 [hep-ph]; Agarwalla, Huber, arXiv:1007.3228 [hep-ph]

Neutrino Sources

- **Decay-at-rest beam from proton beam dump**
- **Small core reactor source**
- **Very high activity radioactive source**

- Observe the L/E dependence of the event rates within a long ν detector
- Background distribution is either independent of L or goes like $1/L^2$
- Powerful verification of the short-baseline oscillation/new physics

What Cosmology can infer about Light Sterile Neutrino?

- One eV-scale sterile neutrino is in severe tension with cosmology
- In standard scenario, sterile neutrino is produced via oscillations at T $\gtrsim$ MeV
- There are two key measurements from cosmology on massive neutrinos

❑ **$N_{\text{eff}} \lesssim 3.16$**

- **Measure the energy density due to relativistic particles**
- **Presence of an extra neutrino species would imply $N_{\text{eff}} \sim 4$**

❑ **$\sum m_\nu \lesssim 0.12$ eV**

- **Sum of neutrino masses**
- **It affects structure formation and one light eV-scale sterile neutrino compatible with anomalies would suggest $\sum m_\nu \sim 1$ eV**

Planck TT, TE, EE + low E + lensing + BAO, arXiv:1807.06209 [11053 Citations]

Concluding Remarks

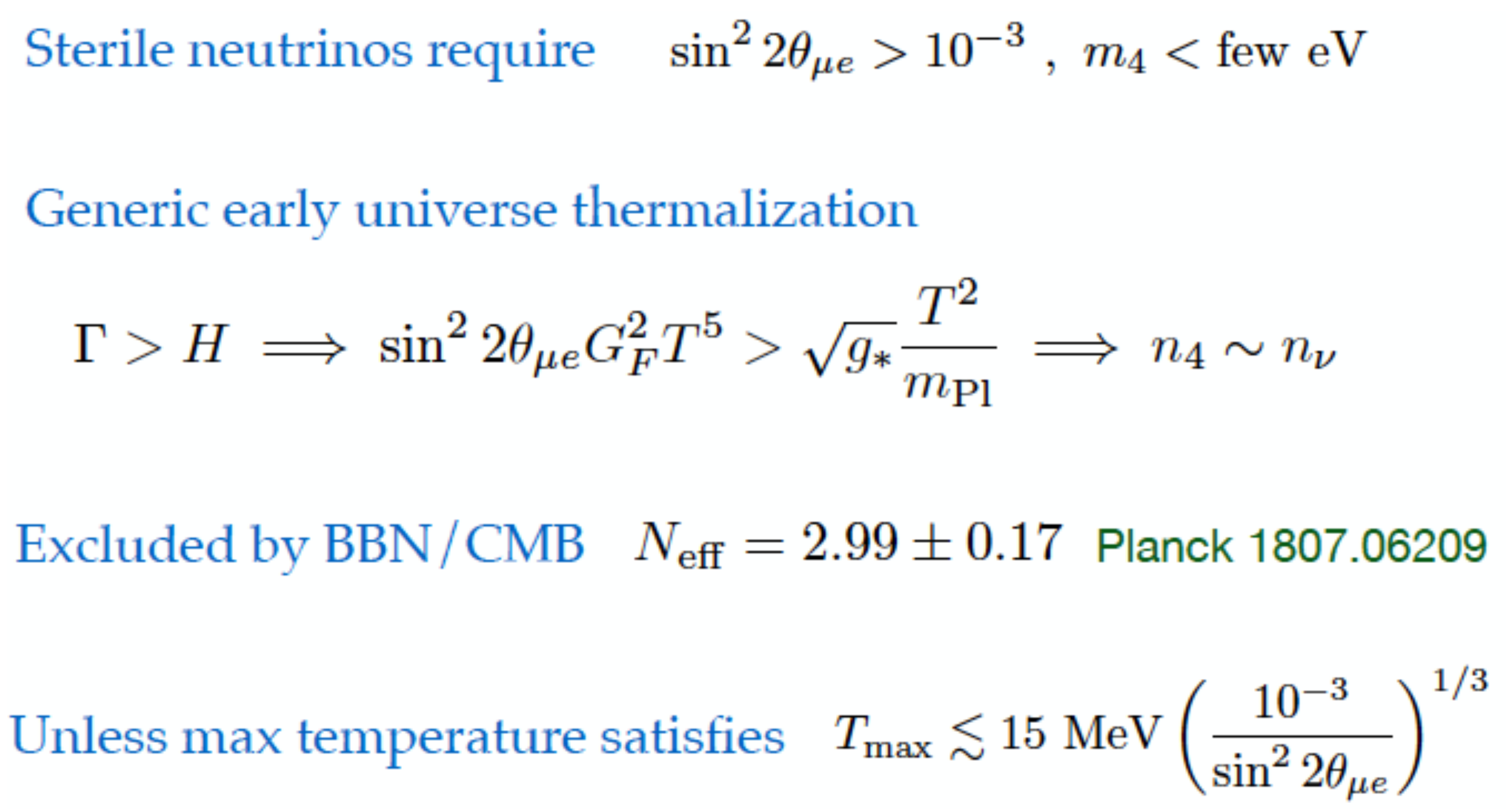
Light sterile neutrinos were interesting, are still interesting, and will remain interesting in near future as well………

Discovery of a light sterile neutrino would prove that there is new physics beyond the SM at low energies, which is completely orthogonal to new physics searches at high energies at the LHC……

Let us continue our effort to look for them at any mass scale and at any energies……

Thank you

What Cosmology can infer about Light Sterile Neutrino?



Sterile neutrinos require $\sin^2 2\theta_{\mu e} > 10^{-3}$, $m_4 <$ few eV

Generic early universe thermalization

$$\Gamma > H \implies \sin^2 2\theta_{\mu e} G_F^2 T^5 > \sqrt{g_*}\frac{T^2}{m_{\rm Pl}} \implies n_4 \sim n_\nu$$

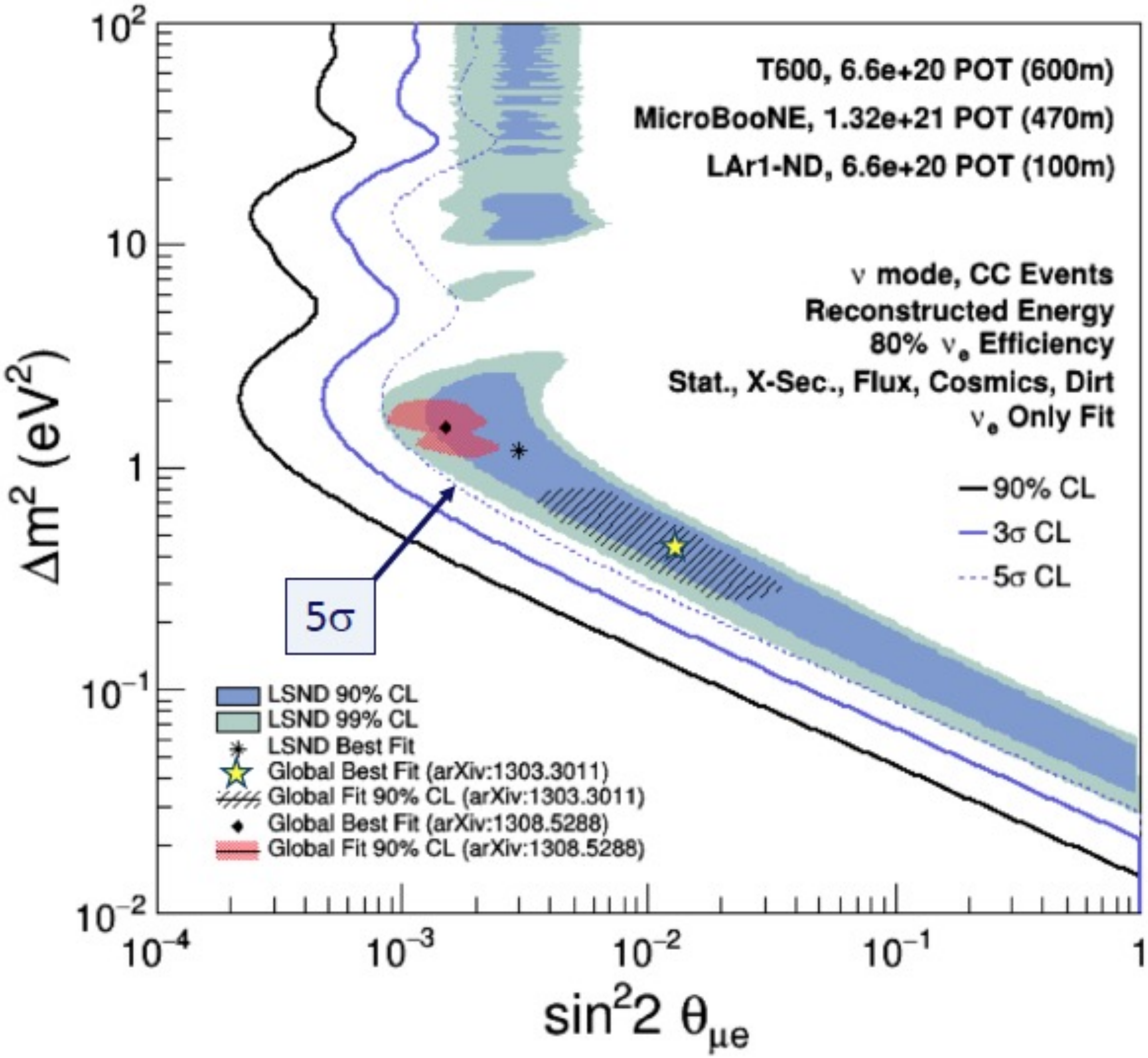
Excluded by BBN / CMB $N_{\rm eff} = 2.99 \pm 0.17$ Planck 1807.06209

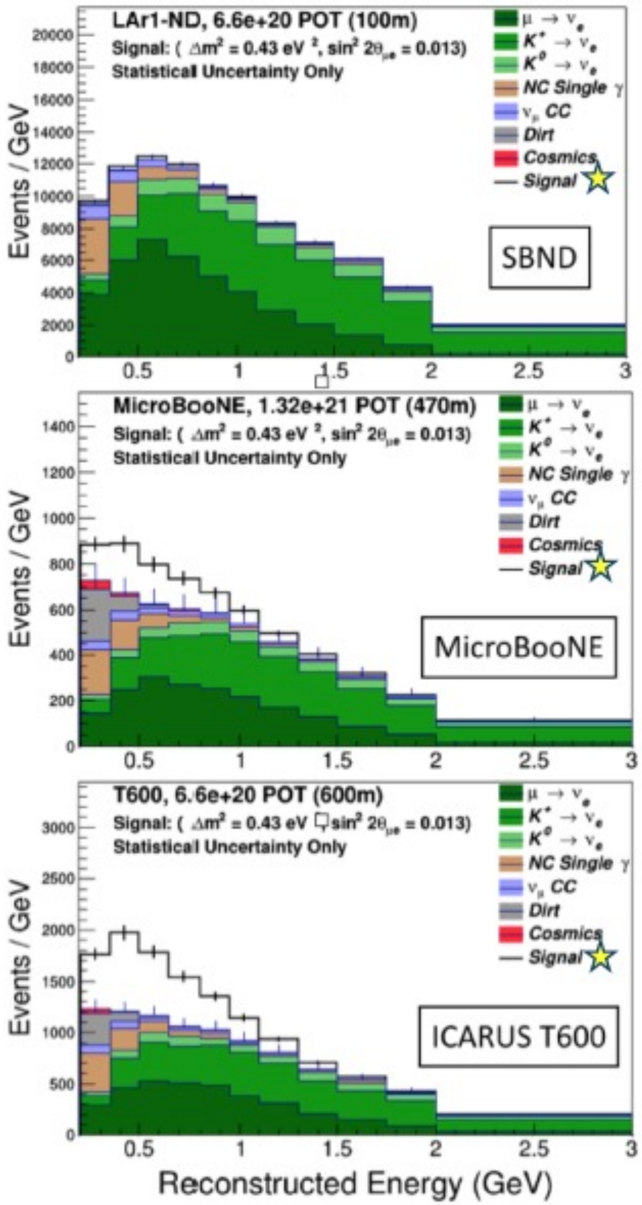
Unless max temperature satisfies $T_{\rm max} \lesssim 15 \text{ MeV} \left(\frac{10^{-3}}{\sin^2 2\theta_{\mu e}}\right)^{1/3}$

Courtesy Gordan Krnjaic

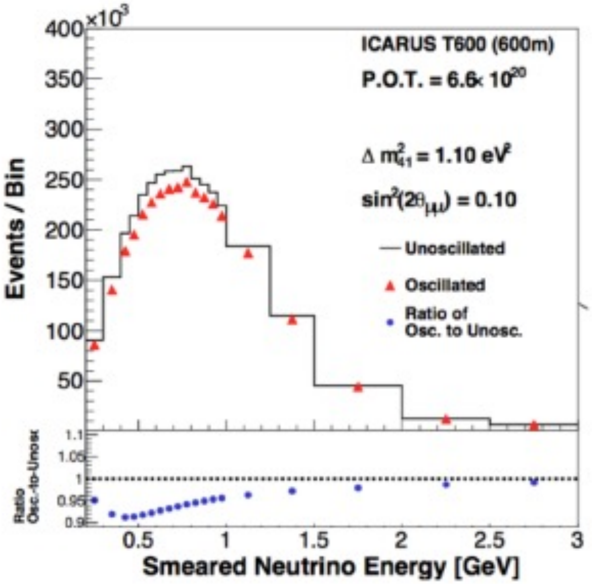
Interesting discussion in arXiv:1806.10629v1 by Chu, Dasgupta, Dentler, Kopp, Saviano

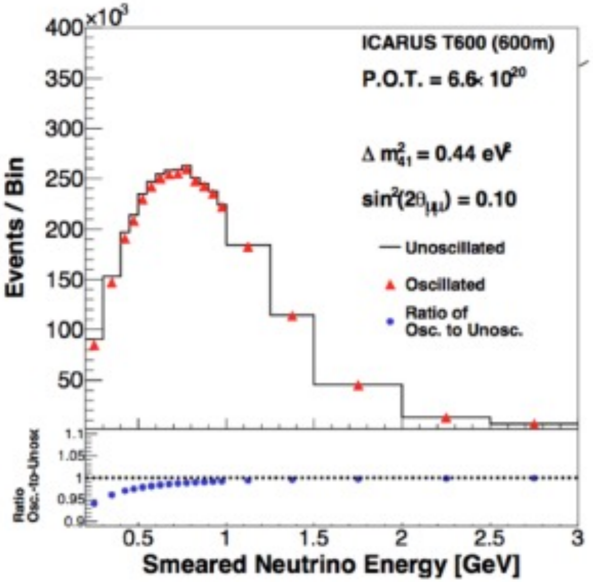
Fermilab: Short-Baseline Neutrino Appearance Oscillation Sensitivity

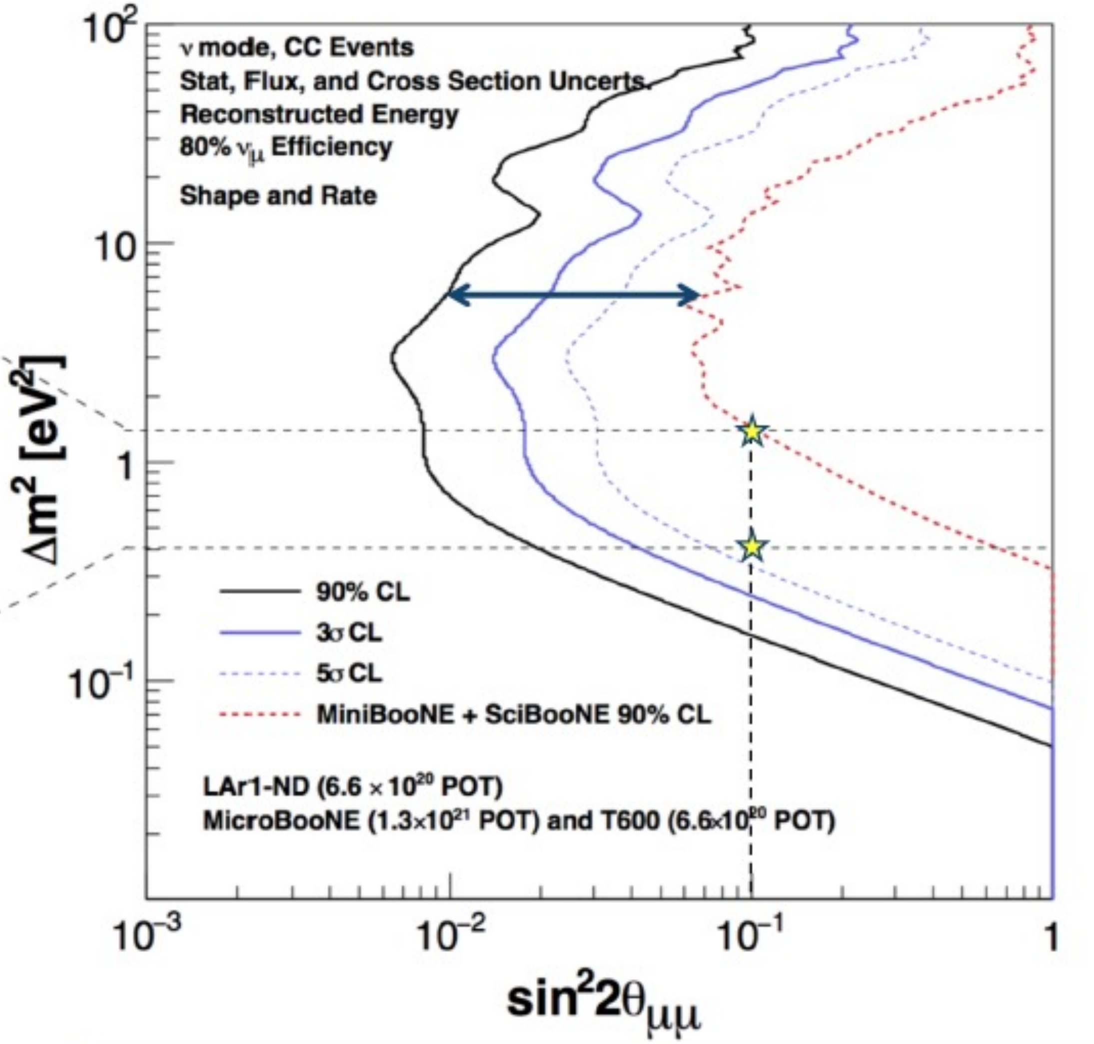




Fermilab: Short-Baseline ν Disappearance Oscillation Sensitivity







Very little background. Near detector key to controlling flux and cross-section uncertainties.