Abstract

Sterile neutrinos are a component of many extremely well motivated explanations of neutrino masses. While $m_4 \sim 1$ eV is not a mass range desired theoretically, it is one that is relatively straightforward to probe experimentally. In this talk I will review the existing hints and constraints on light sterile neutrinos. In particular I will show how cosmological constraints compare with terrestrial constraints and provide speculation on how these constraints might be different. Finally, I will discuss the latest results from MicroBooNE and the path forward.

Sterile neutrinos at 1 eV

Peter B. Denton

MPI Heidelberg

July 11, 2022

Speaking from Setauket land

Overview

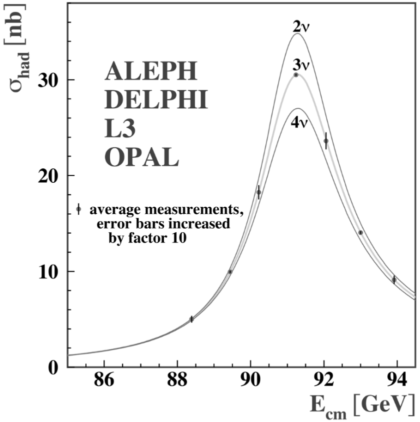
1. Sterile neutrino theory
2. Sterile neutrino experimental picture through 2020
   - Cosmology!
3. MicroBooNE

Overview

1. Sterile neutrino theory
2. Sterile neutrino experimental picture through 2020
   - Cosmology!
3. MicroBooNE

Data is confusing
Up to you to decide

Any new light neutrinos must be sterile: SM gauge singlets



Fun fact: pre-LEP upper limit on $N_\nu \sim 6000$!

Neutrinos have mass

- Can get usual Dirac mass term via Higgs
  - $\Rightarrow$ three new right-handed neutrinos
- Steriles can have additional mass terms
  - Seesaw?

H. Fritzsch, M. Gell-Mann, P. Minkowski PLB 1975
P. Minkowski PLB 1977
W. Konetschny, W. Kummer PLB 1977
D. Wyler, L. Wolfenstein NPB 1983
R. Foot, H. Lew, X. He, G. Joshi ZPC 1989

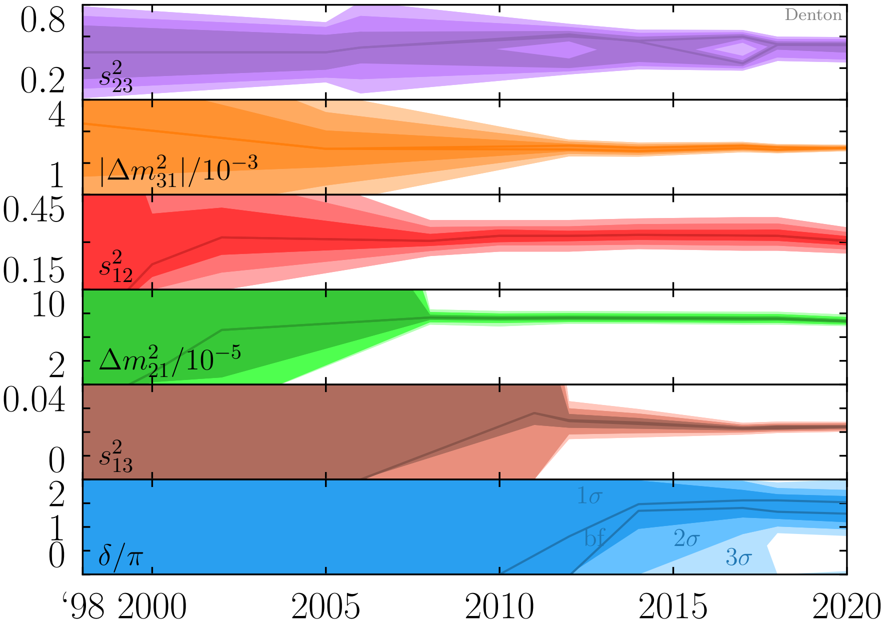
  - Pseudo-Dirac?

See e.g. J. Beacom, et al. hep-ph/0307151

- Some options have no sterile neutrinos, but other new particles
  - E.g. type-II seesaw

Interesting mass ranges are often 10^{13} GeV, 10^{3} GeV, or 10^{-26} GeV, not 10^{-9} GeV

Three flavor oscillation picture


Denton
0.8
0.2
s^2_{23}
4
1
$|\Delta m^2_{31}|/10^{-3}$
0.45
0.15
s^2_{12}
10
2
$\Delta m^2_{21}/10^{-5}$
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
'98 2000 2005 2010 2015 2020

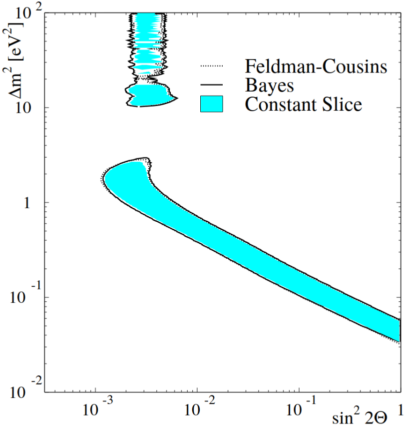
Three flavor oscillation picture: looks good

Let's check many Δm^2's!

Accelerator: LSND

- LSND ran from 1993-1998
- $E_{\bar{\nu}_\mu} \in [20, 53]$ MeV
- $L = 30$ m
- Looked for $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance
- Excess of: $87.9 \pm 22.4 \pm 6.0 \Rightarrow 3.8\sigma$ (1 dof)
- Interesting region:
  - $\Delta m^2_{41} \sim 1$ eV^2
  - $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sim 0.002$

OPERA, ICARUS disfavor $\sin^2 2\theta_{\mu e} \gtrsim 0.02$



LSND hep-ex/0104049

Accelerator: MiniBooNE

- Built to test LSND, higher energy, longer baseline, similar L/E, both $\nu,\bar{\nu}$
- $E_{\nu_\mu} \sim 500$ MeV
- $L = 541$ m
- Excesses:
  - ν_e: $381.2 \pm 85.2 \Rightarrow 4.5\sigma$ (1 dof)
  - $\bar{\nu}_e$: $79.3 \pm 28.6 \Rightarrow 2.8\sigma$ (1 dof)
  - Combined: 4.7σ (1 dof)
  - Excesses consistent with LSND under sterile hypothesis
  - Combined with LSND: $\Rightarrow 6.0\sigma$ (1 dof)

MiniBooNE 1805.12028

Accelerator experiment caveats

- Neither LSND nor MiniBooNE is particularly well fit by a sterile
  - The excess grows at lower energies faster than it should
  - Not necessarily a huge problem
- LSND result may not be robust under cut assumptions

J. Hill hep-ex/9504009

- ν_e appearance requires both ν_μ disappearance and ν_e disappearance
  - Since $|U_{\mu4}|^2|U_{e4}|^2>0$ and $|U_{\alpha i}|\in[0,1]$, $\exists$ lower limits on both $|U_{\mu4}|$ and $|U_{e4}|$

The Gallium Experiments

- Low energy solar neutrino experiments measure the *pp* flux
  - Consistent with KamLAND

SAGE 0901.2200

GALLEX 1001.2731

- Callibrate detectors with intense radioactive sources
- See fewer neutrinos than expected:

3.0σ: C. Giunti, M. Laveder 1006.3244

2.3σ: J. Kostensalo, et al. 1906.10980

$> 4\sigma$: BEST 2109.11482

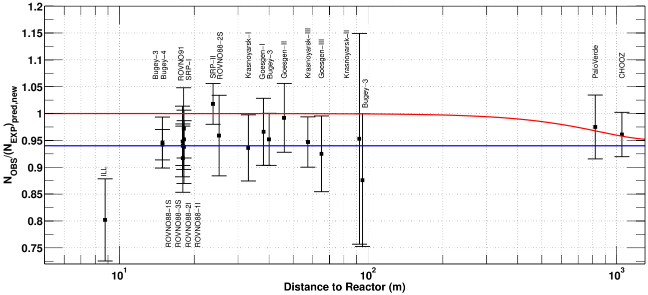
- Prefers:
  - $\Delta m_{41}^2 \gtrsim 0.5$ eV^2
  - $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2) \sim 0.4$

Reactor Rates

Deficit relative to prediction

P. Huber 1106.0687

T. Mueller, et al. 1101.2663



G. Mention, et al. 1101.2755

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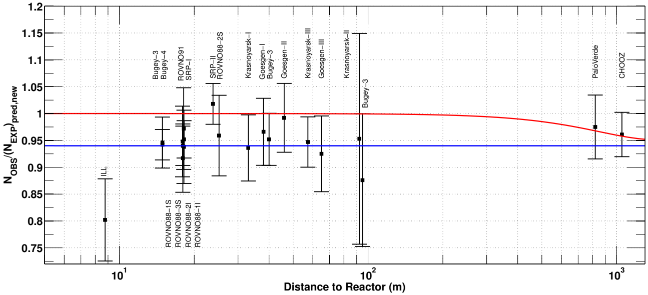

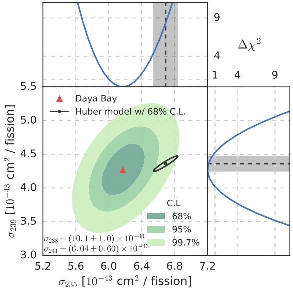

G. Mention, et al. 1101.2755

Daya Bay 1704.01082

Daya Bay, PROSPECT 2106.12251

Short baseline spectral

- NEOS, DANSS see some spectral anomalies
  - $\Delta m^2_{41} = 1.26$ eV^2 and $\sin^2 2\theta_{14} = 0.044$ at 3.3σ
- Mixings larger than $\sin^2 2\theta_{14} \sim 0.01$ disfavored by spectral data
- Neutrino-4 also sees spectral anomalies
  - $\Delta m^2_{41} = 7.32$ eV^2 and $\sin^2 2\theta_{14} = 0.31$
  - In tension with other reactor data
  - Analysis issues

J. Berryman, P. Huber 2005.01756

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J. Berryman, P. Huber 2005.01756

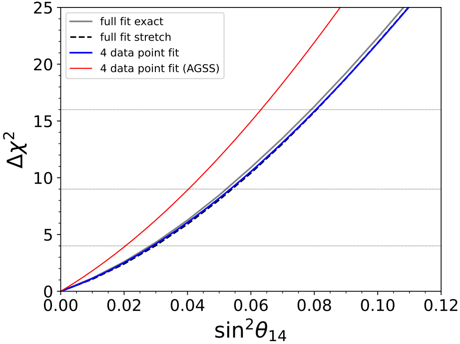
All in tension with cosmological data

Solar

1. Use gallium and Borexino for pp data
2. Use SNO and SK for ^{8}B data

No Borexino data?

3. Use KamLAND data to set Δm^2_{21}
4. Fix θ_{13} to best fit
5. Vary θ_{12} and θ_{14}
6. Consider impact on U_{e4} (θ_{14}) only
7. Applies for $\Delta m^2_{41} \gtrsim 10^{-3}$ eV^2
8. Is effectively a unitary violation analysis
9. Checked Wilks' theorem with MC



K. Goldhagen, et al. 2109.14898

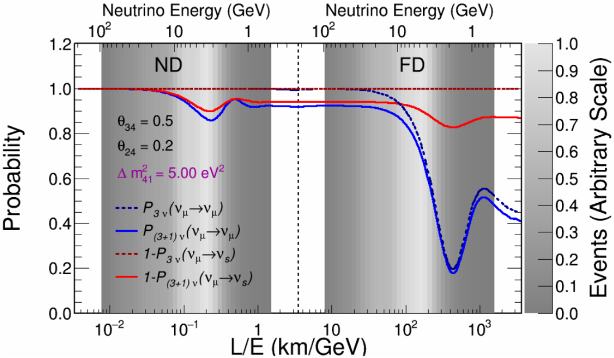
Have anomalous $\nu_\mu \to \nu_e$

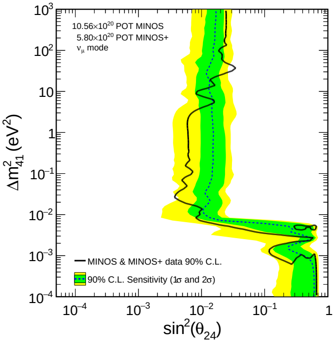
Might have anomalous $\nu_e \to \nu_e$

Do we have anomalous $\nu_\mu \to \nu_\mu$?

MINOS

Leverage near- and far-detectors simultaneously





MINOS 1710.06488

Some concerns, e.g. W. Louis 1803.11488

IceCube

At $E \sim 1$ TeV and $\Delta m^2_{41} \sim 1$ eV^2,
$\bar\nu_\mu \to \bar\nu_\mu$ experiences large disappearance through the Earth's core

H. Nunokawa, O. Peres, R. Funchal hep-ph/0302039

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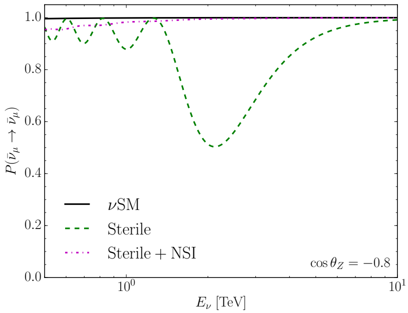
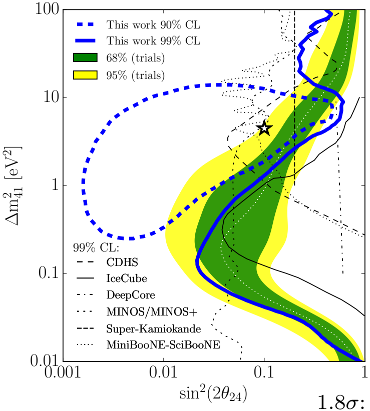


PBD, Y. Farzan, I. Shoemaker 1811.01310



1.8σ: IC 2005.12942

3+1+NSI

A new interaction can mitigate IceCube constraints

$\epsilon_{\mu\mu}$, $\epsilon_{\tau\tau}$: J. Liao, D. Marfatia 1602.08766

Can it also help with MINOS?

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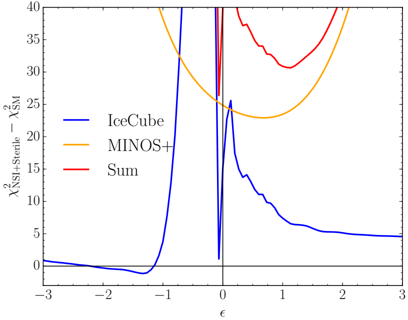
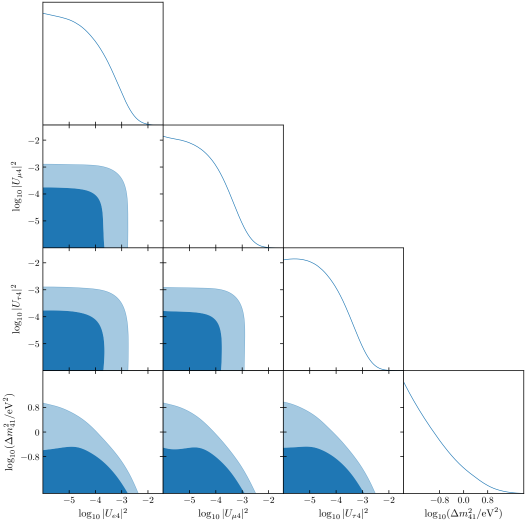


- Built UV complete model with ϵ_{ss}
- IceCube: 3+1+NSI is preferred over SM
- MINOS: No preference for 3+1 even with NSI

PBD, Y. Farzan, I. Shoemaker 1811.01310

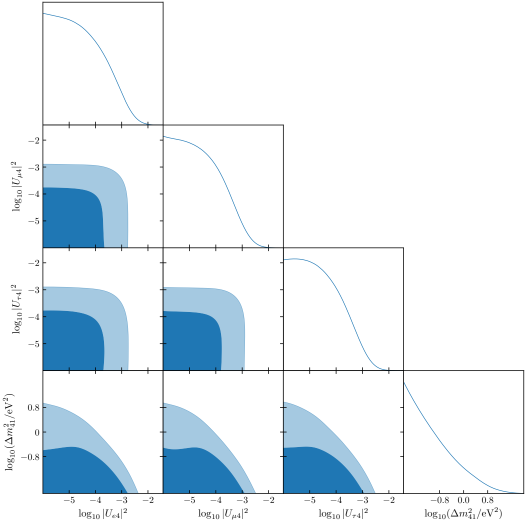
Cosmological bounds



1σ, 2σ S. Hagstotz, et al. 2003.02289

- Includes CMB temperature, polarization, and lensing, and BAO
- No local H_0 constraint
- Bounds independent of flavor
- To be consistent with data must have small mixing **and** small mass

Cosmological bounds



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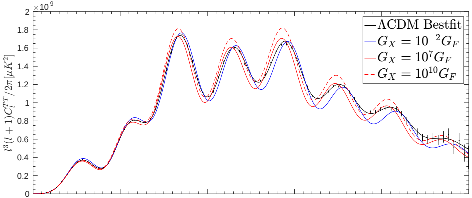
- Bounds independent of flavor
- To be consistent with data must have small mixing **and** small mass
- Much more than just $N_{\rm eff}$ and $\sum m_\nu$
- Just adding a new interaction is not straightforward



N. Song, M. Gonzalez-Garcia, J. Salvado 1805.08218

Cosmological bounds with an interaction

- Include H_0 and σ_8 tensions
- Data prefers: $N_{\rm eff} = 4.02 \pm 0.29$ and $G_X \sim 10^{-3}$ MeV^{-2}

C. Kreisch, F. Cyr-Racine, O. Doré 1902.00534

G. Barenboim, PBD, I. Oldengott 1903.02036

- Large self-interaction is constrained by:
  - $Z \to$invisible for large couplings
  - BBN+CMB for light masses
  - Kaon decays for all remaining parameter space for ν_e, ν_μ
- Viable space persists if the self interaction is in the ν_τ sector (or sterile?)

N. Blinov, et al. 1905.02727

- Testable by IceCube

G. Barenboim, PBD, I. Oldengott 1903.02036

C. Creque-Sarbinowski, J. Hyde, M. Kamionkowski 2005.05332

I. Esteban, et al. 2107.13568

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Not a great fit to the cosmological data

Other new physics (cosmo) scenarios fit the data better

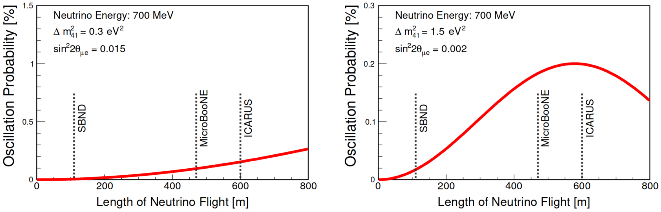
Let's resolve this terrestrially

Short baseline program

1. Leverage LAr to discriminate photons from electrons

MicroBooNE 1910.02166

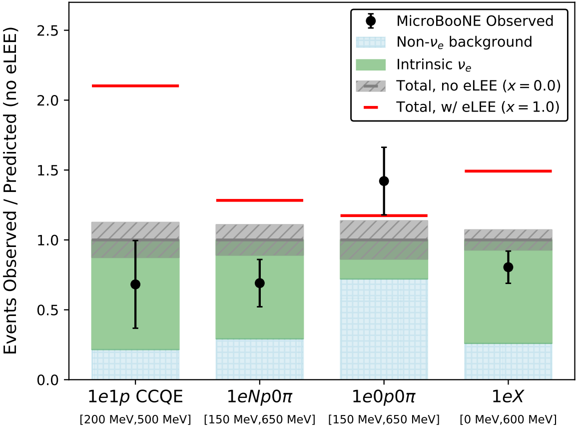
2. L is easier to measure than E



P. Machado, O. Palamara, D. Schmitz 1903.04608

3. Beam is mostly ν_μ, but some ν_e too
4. Test bed for LAr technology

MicroBooNE results



- Three analysis teams:
  1. Wire-Cell
  2. Deep Learning
  3. Pandora
     - With 0 protons
     - With 1+ protons
- Underfluctuation compared to no-oscillations
- Disfavors MiniBooNE's best fit LEE hypothesis at 3.75σ

MicroBooNE 2110.14054

MicroBooNE disappearance

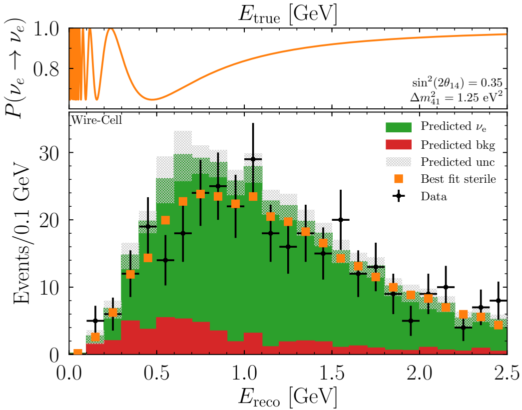
MicroBooNE is focused on ν_e appearance
Can do ν_μ and ν_e disappearance too!

See also D. Cianci, et al. 1702.01758

MiniBooNE backgrounds too big, plus anomaly

Dip hunting

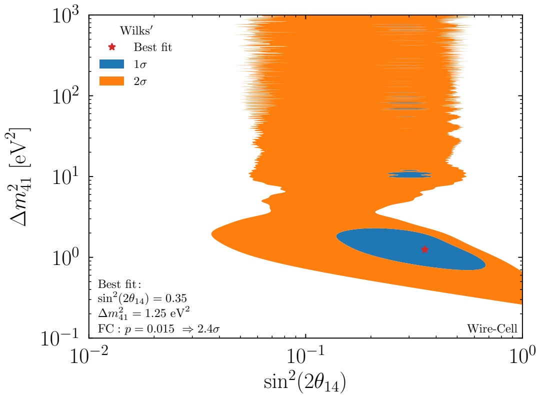
- 4 analysis channels
  - Wire cell has most statistics
  - Analyses not fully independent
- Dip appears in multiple analyses

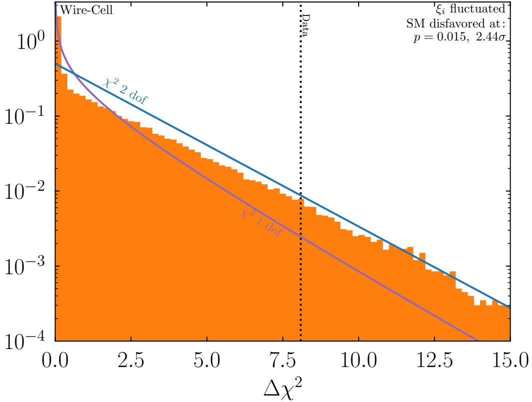


Analysis procedure

1. Take systematics as fully uncorrelated bin to bin
2. Unfold predicted spectrum to spectrum in true energy
   - Use a derivative regulator
3. Apply oscillation probability
4. Reapply energy smearing
5. Compare to data with LLR-Poisson with pull terms
6. Apply Feldman-Cousins
   - Fluctuate systematics
   - Literature suggests this is conservative
   - Verified that it is conservative in this case
7. Get contours via Wilks'
   - FC contours are very similar

Results and Monte Carlo significance



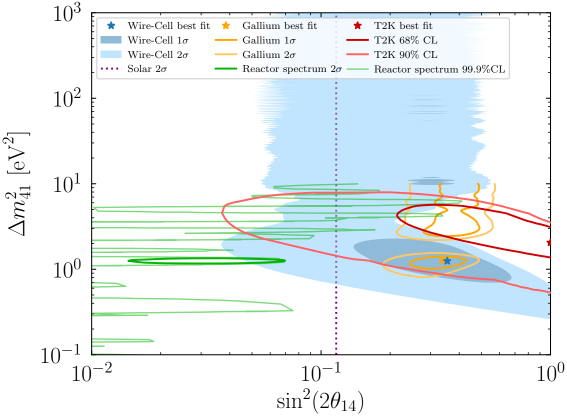


Other MicroBooNE analysis channels

Analysis	$\sin^2(2\theta_{14})$	Δm^2_{41} (eV^2)	$N\sigma$ (FC)
Wire-Cell	$0.35^{+0.19}_{-0.16}$	$1.25^{+0.74}_{-0.39}$	2.4
Deep-Learning	$0.88^{+0.12}_{-0.41}$	$3.91^{+0.40}_{-0.40}$	1.8
Pandora-Np	$0.81^{+0.19}_{-0.47}$	[1.28,2.44] $6.73^{+1.75}_{-0.90}$ $\vdots$	2.4
Pandora-0p	$1_{-0.29}$	$2.21^{+0.82}_{-0.60}$ $\vdots$	1.8

See backups for more plots

Global ν_e disappearance picture



Cosmology disfavors entire plane!

Unitarity constraints

Unitary violation: the study of how $U_{3\times3}$ is not unitary independent of $m_4, m_5, \ldots$
Constraints vary considerably in the literature:

$$1 - |U_{e1}|^2 - |U_{e2}|^2 - |U_{3e}|^2 < \begin{cases} 0.05 \\ 0.001 \end{cases} \quad \text{at } 2\sigma$$

S. Parke, M. Ross-Lonergan 1508.05095

Z. Hu, et al. 2008.09730

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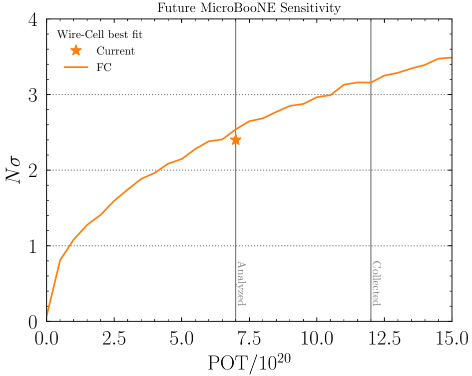
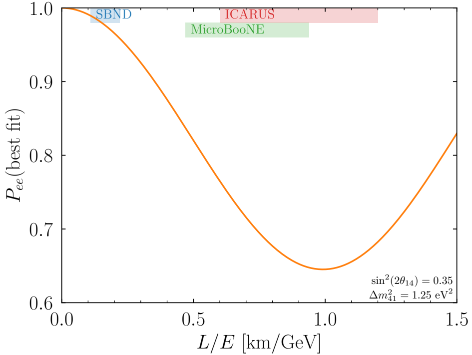
All analyses *assume* unitarity
Throw out LSND, MiniBooNE, RAA, gallium, etc.

S. Parke, M. Ross-Lonergan 1508.05095

Z. Hu, et al. 2008.09730

To the future





Other analyses

- Evidence for appearance is still there with MiniBooNE, but lower significance
- Don't see $> 2\sigma$ evidence for disappearance but very similar best fit

C. Argüelles, et al. 2111.10359

- Evidence for appearance is still there, but lower significance

MiniBooNE 2201.01724

- Analysis depends on whether focused on disappearance or both
- Also doesn't see evidence for disappearance

MicroBooNE NOTE-1116-PUB

All ignore cosmological constraints

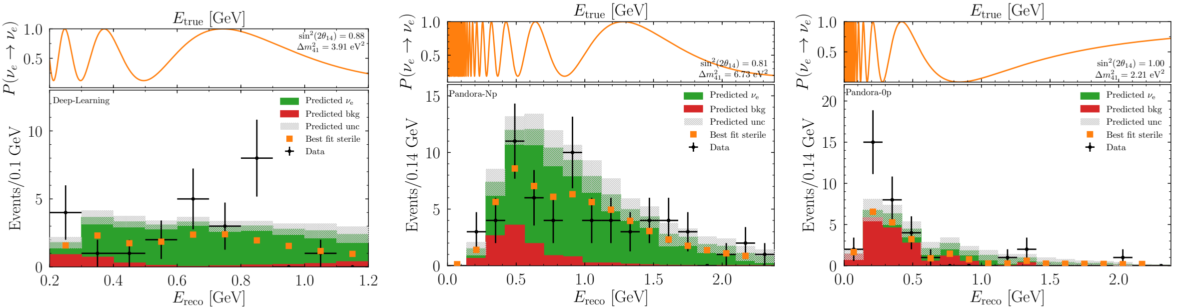
1 eV sterile summary

- Hints for ~ 1 eV steriles persist
  - RAA is essentially gone
  - Gallium is back
- Constraints for ~ 1 eV steriles persist
- Cosmological constraints are strong and robust
  - Maybe Hubble parameter tension?
  - Testable with IceCube upgrade
- MicroBooNE does not see appearance
- MicroBooNE might be seeing disappearance
  - Consistent with gallium
  - Inconsistent with other constraints

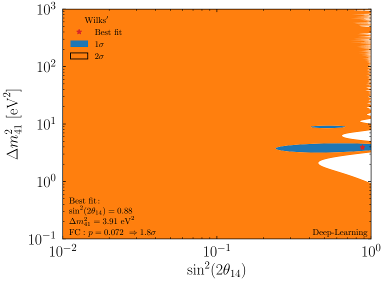
Thanks!

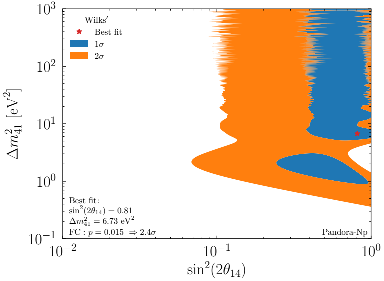
Backups

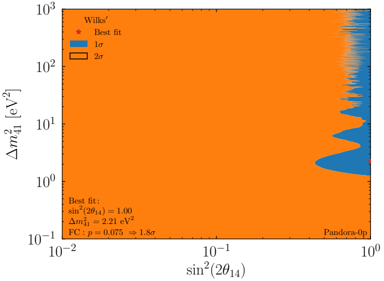
MicroBooNE data in other analyses



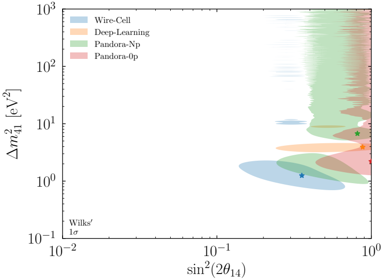
MicroBooNE contours in other analyses







MicroBooNE contours in other analyses



MicroBooNE analyses overlap

Events in multiple analyses:

Analysis	W-C	D-L	Pan-Np	Pan-0p
Wire-Cell	606	15	45	7
Deep-Learning	15	25	9	0
Pandora-Np	45	9	64	0
Pandora-0p	7	0	0	35