Abstract

Terrestrial and solar neutrino experiments have a variety of anomalous data that has resisted clarification. Recently, it has appeared that measurements of neutrinos from intense sources on gallium have passed 5 and other hints from MicroBooNE and elsewhere remain interesting. I will present the latest update of these anomalies. I will then explain the primary reasons why these cannot be simply interpreted as a 1 eV sterile neutrino due to constraints from other experimental probes, notably solar neutrinos and cosmological data sets. I will present a novel, simple model that evades many of these constraints by adding in one new particle, which is the dark matter, beyond a sterile neutrino leading to shape-shifting sterile neutrinos.

Light Sterile Neutrinos:
A Modern Picture and a Model to Evade Cosmology

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April 25, 2023

Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

Overview

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

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2. Sterile neutrino experimental picture through 2020
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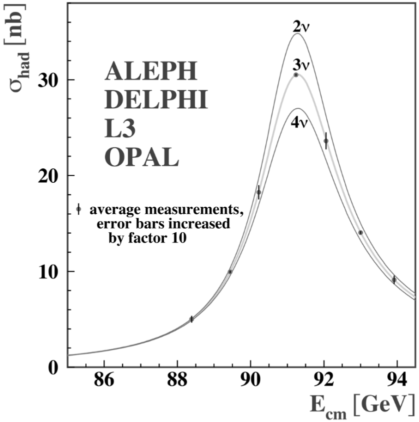
Data is confusing
Up to you to decide

Any new light neutrinos must be sterile: SM gauge singlets



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

Neutrinos have mass

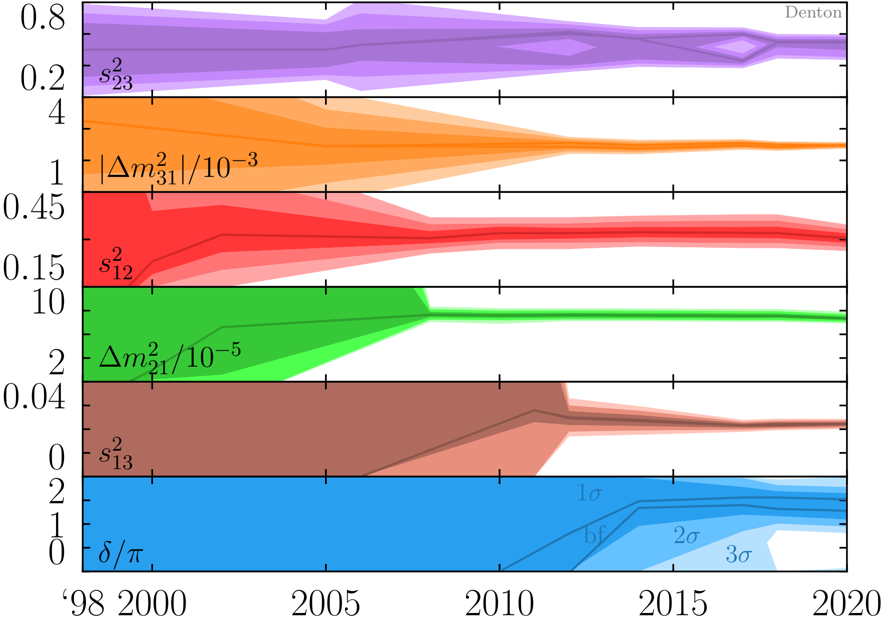
- Can get usual Dirac mass term via Higgs
  - $\Rightarrow$ three new right-handed neutrinos
- Steriles can have additional mass terms
  - Seesaw?

    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?

    L. Wolfenstein NPB 1981
    S. Bilenky, S. Petcov RMP 1987
- 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

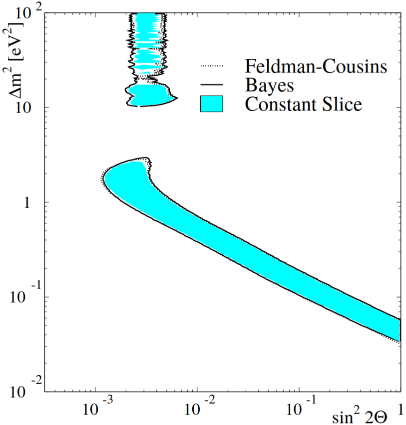
Three flavor oscillation picture: looks good

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

- MiniBooNE ran from 2002 to 2019
- 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

  - Not a problem for MiniBooNE

MiniBooNE 2006.16883

- 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

GALLEX: 1991-1997, GNO: 1998-2003 1001.2731
SAGE: 1989-2007 0901.2200

  - Consistent with KamLAND

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- 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
$\rightarrow > 5\sigma$: C. Giunti, et al. 2212.09722

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

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- Attempts to explain with standard physics: unsuccessful

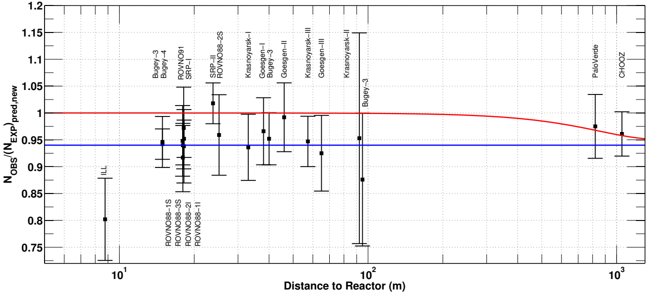
C. Giunti, et al. 2212.09722
V. Brdar, J. Gehrlein, J. Kopp 2303.05528
W. Haxton, et al. 2303.13623

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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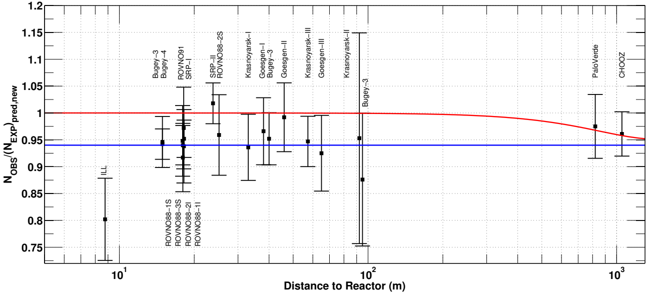

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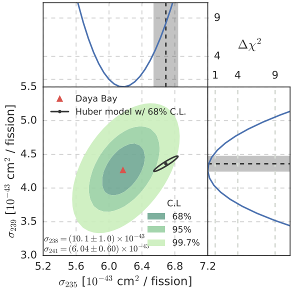

Daya Bay 1704.01082

RENO 1806.00574

Daya Bay, PROSPECT 2106.12251

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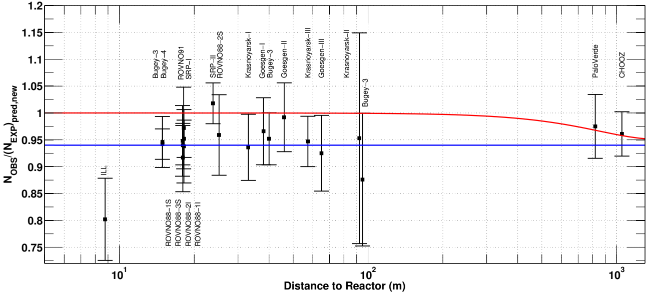

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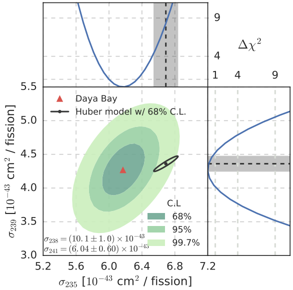

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RENO 1806.00574

Daya Bay, PROSPECT 2106.12251

Probably nuclear physics

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

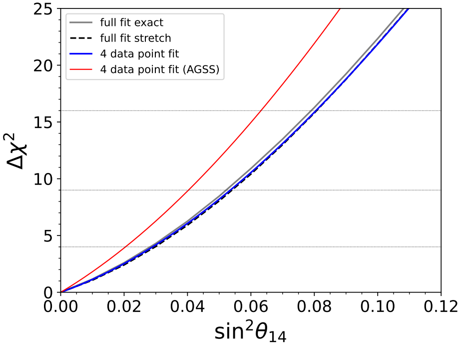
All hints in tension with cosmological data

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

So far:

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

LSND, MiniBooNE

Might have anomalous $\nu_e \to \nu_e$

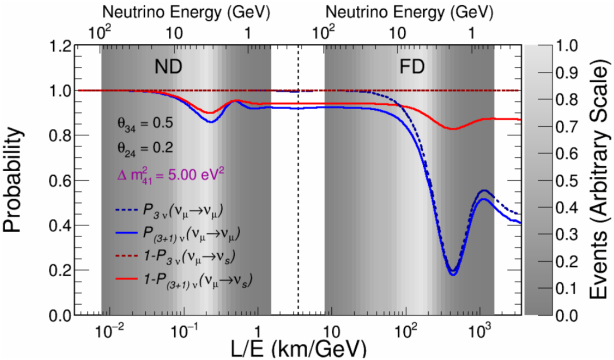
Yes: Gallium, ~~Reactor rate~~

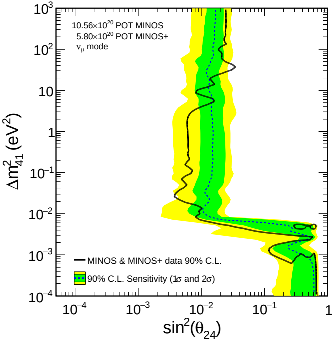
No: Reactor spectral, solar

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

MINOS/MINOS+

- MINOS ran from 2005-2012, MINOS+ (higher energy) ran from 2013-2016
- 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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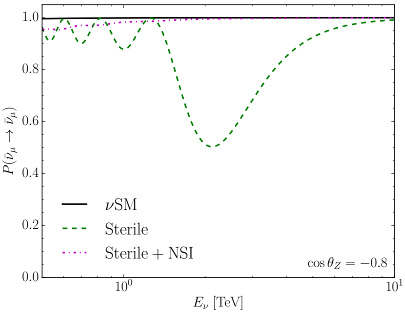
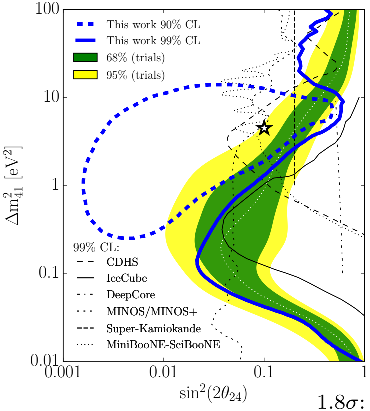


PBD, Y. Farzan, I. Shoemaker 1811.01310



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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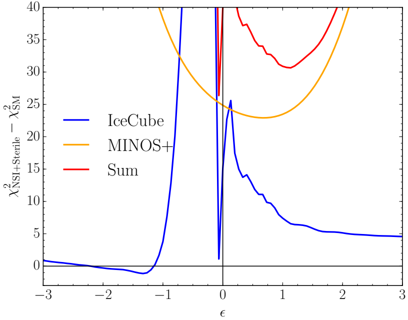
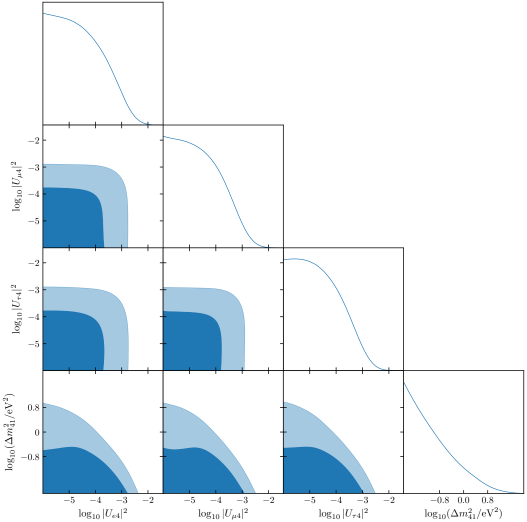


- Built UV complete model with ϵ_{ss}
- IceCube: 3+1+NSI is preferred over SM
- MINOS: No preference for 3+1 even with NSI

PBD, Y. Farzan, I. Shoemaker 1811.01310

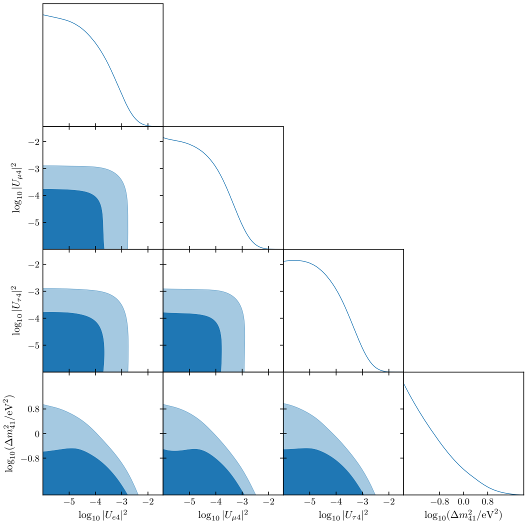
Cosmological bounds



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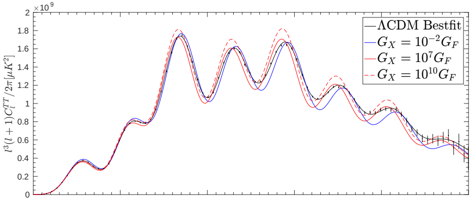
- To be consistent with data must have small mixing **and** small mass
- Much more than just $N_{\rm eff}$ and $\sum m_\nu$
- Just adding a new interaction is not straightforward



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

Cosmological bounds with an interaction

- Include H_0 and σ_8 tensions
- Data prefers: $N_{\text{eff}} = 4.02 \pm 0.29$ and $G_X \sim 10^8 G_F$

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 $m_X \sim 10$ MeV if the self interaction is in the ν_τ sector

N. Blinov, et al. 1905.02727

- Testable by IceCube looking for dips due to CνB

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

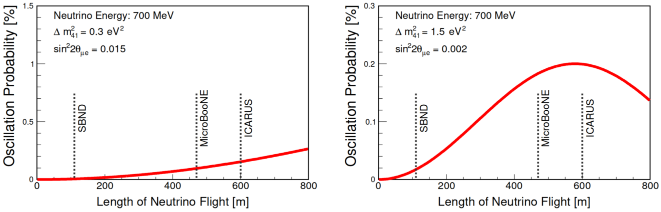
Let's resolve this terrestrially

Short baseline program

1. Leverage LAr to discriminate photons from electrons

MicroBooNE 1910.02166

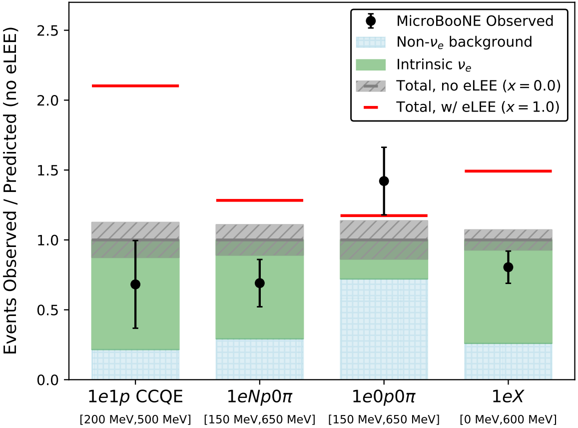
2. L is easier to measure than E



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

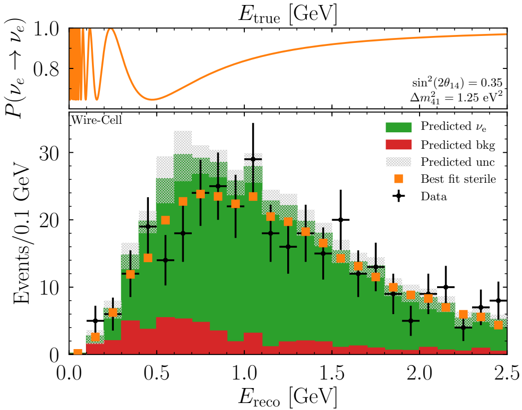
MicroBooNE is focused on ν_e appearance
Can do ν_μ and ν_e disappearance too!

See also D. Cianci, et al. 1702.01758

MiniBooNE backgrounds too big, plus anomaly

Dip hunting

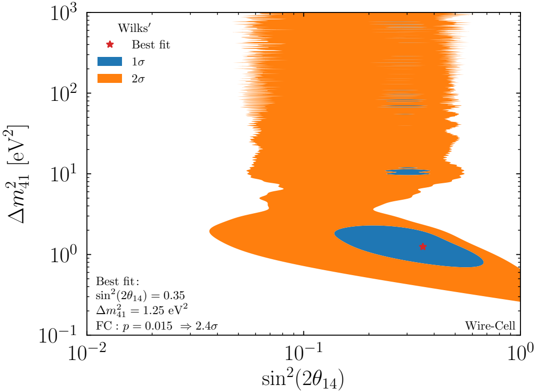
- 4 analysis channels
  - Wire cell has most statistics
  - Analyses not fully independent
- Dip appears in multiple analyses

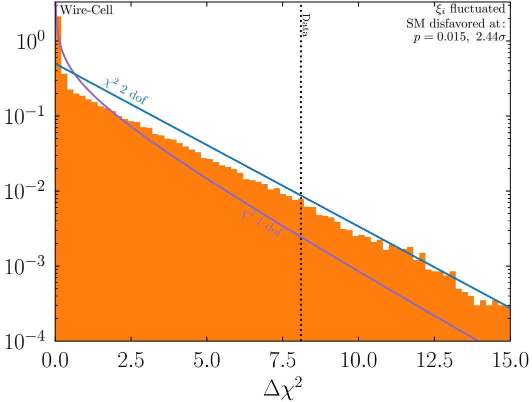


Analysis procedure

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



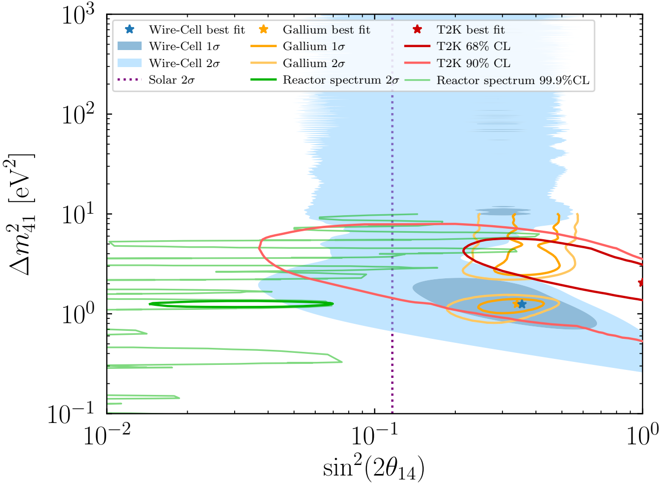


Other MicroBooNE analysis channels

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, ...
Constraints vary considerably among "global" analyses:

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

S. Parke, M. Ross-Lonergan 1508.05095

Z. Hu, et al. 2008.09730

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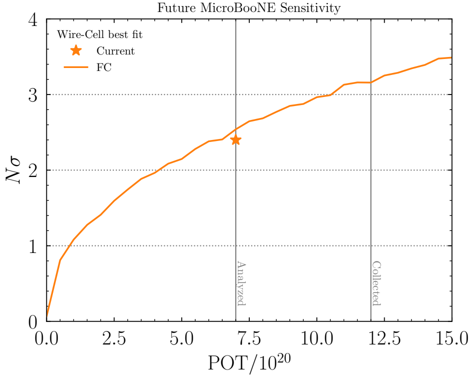
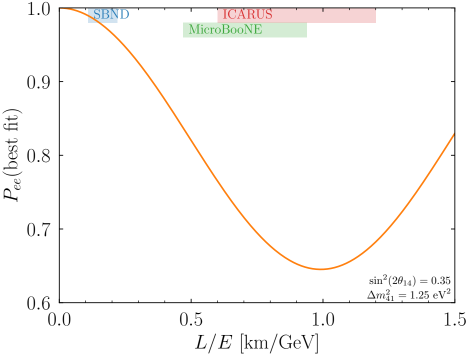
All analyses *assume* unitarity
Throw out LSND, MiniBooNE, RAA, gallium, etc.

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 high evidence for disappearance

MicroBooNE 2210.10216

None discuss cosmological constraints

What does it take to evade cosmology?

Shape-shifting sterile neutrinos

- Sterile neutrinos seem to act differently in different places:
  - Earth's surface
  - Sun
  - Early universe
- Suppose sterile neutrino talk to nucleons via long-range scalar ϕ
- $m_\phi \sim 5 \times 10^{-15}$ eV $\Rightarrow 1/m_\phi \sim 40,000$ km $\sim 6R_\oplus$

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- ϕ - nucleon coupling below fifth force limits: $g_n \sim 5 \times 10^{-25}$
- At Earth's surface, field has non-zero value:

$$\phi^\oplus \approx -\frac{g_n N_n^\oplus}{4\pi R_\oplus} e^{-m_\phi R_\oplus} = -4 \times 10^{12}\text{ eV}$$

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- At Earth's surface, field has non-zero value:

$$\phi^\oplus \approx -\frac{g_n N_n^\oplus}{4\pi R_\oplus} e^{-m_\phi R_\oplus} = -4 \times 10^{12} \text{ eV}$$

- Also need a bare mass term for the new mass state: $m_s(\vec{x}) = m_0 + g_s\phi(\vec{x})$

$m_0 \neq 0$ needed for cosmological $\sum m_\nu$

- Take $m_0 = 1$ eV and $g_s \sim 5 \times 10^{-14} \Rightarrow -g_s\phi^\oplus = 0.2$ eV

H. Davoudiasl, PBD 2301.09651

PBD 2301.11106

Shape-shifting sterile neutrinos

Dirac mass matrix:

$$M_\nu = \begin{array}{cc} & \begin{array}{cc} \nu_{e,\mu,\tau} & \nu_s \end{array} \\ & \begin{pmatrix} m_\nu & m_D \\ 0 & m_s(\vec{x}) \end{pmatrix} \begin{array}{c} \nu_{e,\mu,\tau} \\ \nu_s \end{array} \end{array}$$

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\end{array}
$$

$$\tan 2\theta_{14} \simeq \frac{2m_D m_s(\vec{x})}{m_s^2(\vec{x}) - m_D^2 - m_\nu^2}$$

$$m_1 \simeq m_\nu \frac{m_s(\vec{x})}{\sqrt{m_s^2(\vec{x}) + m_D^2}}$$

$$m_{2,3} \simeq m_\nu$$

$$m_4 \simeq \sqrt{m_s^2(\vec{x}) + m_D^2}$$

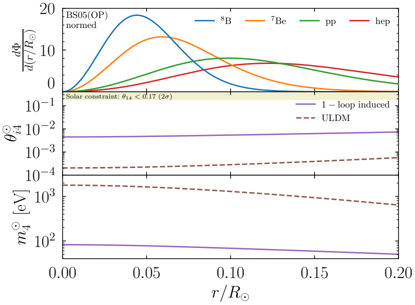
Set $m_\nu = 0.03$ eV and $m_D = 0.3$ eV

Shape-shifting sterile neutrinos

Behavior as density increases:

1. Vacuum of space: $m_4 \sim 1$ eV, $\theta_{14} \sim 0.3$
   Active neutrinos as expected
   - $\sum m_\nu$ comes mostly from $z \in [10, 100]$

   C. Lorenz, et al. 2102.13618
2. Earth's surface: nearly same
3. Center of sun: $m_4 \sim 10^3$ eV, $\theta_{14} \sim 3 \times 10^{-4}$
4. Early universe: set $\phi_i \gtrsim 10^{16}$ eV high enough so m_4, θ_{14} consistent at BBN



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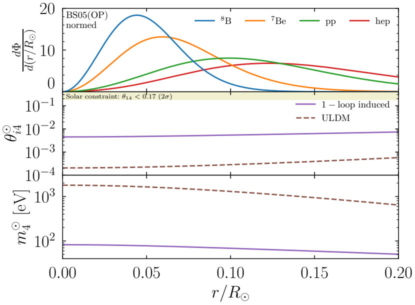


- Self interaction from loops: $\frac{\lambda_\phi}{4!}\phi^4$ with $\lambda_\phi \sim 10^{-56}$
  - Affects solar and cosmology
- If it is cancelled to $\lambda_\phi \sim 10^{-65}$ then ϕ is DM

Other phenomena of shape-shifting sterile neutrinos

- Self interact $\frac{\lambda_\phi}{4!}\phi^4$ makes calculations *vastly* harder
  - Exact in some cases; developed techniques for general numerical solutions
- ν_s's will be resonantly produced in the early universe in small bursts as ϕ oscillates past 0
  - Effect is small
- The sterile neutrino is too heavy to affect supernova dynamics

- The Sun's potential could lead to an annual (and daily) modulation in sterile signals
  - Depends on m_ϕ which is flexible
  - No such search has been performed
- Could lead to a modification of atmospheric constraints on steriles

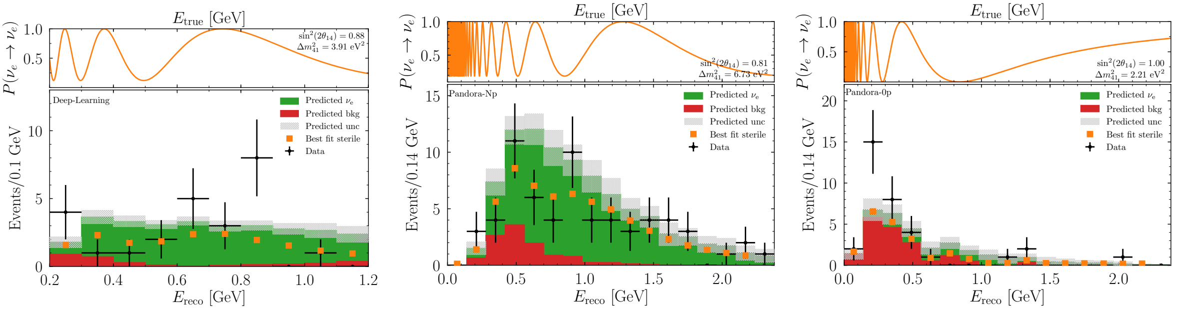
1 eV sterile summary

- 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
- Possible to evade cosmology with: 1 sterile neutrino and ultra-light DM

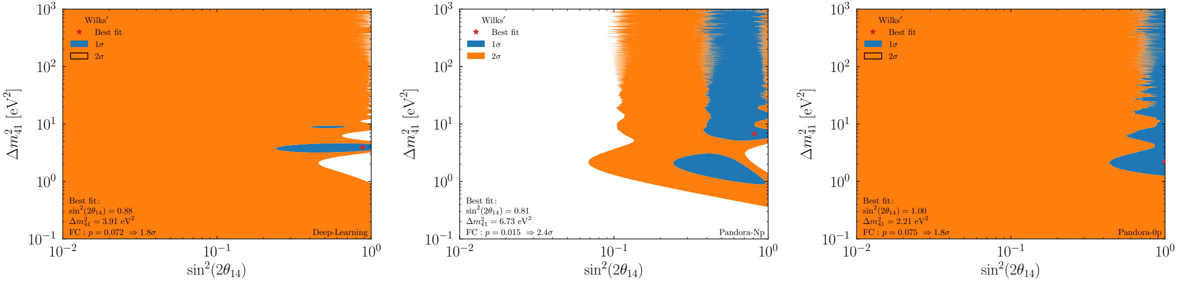
Thanks!

Backups

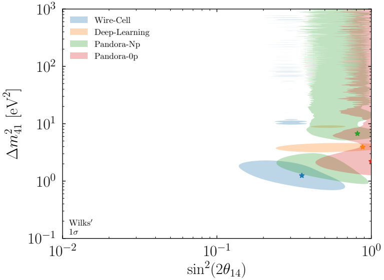
MicroBooNE data in other analyses



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