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

Peter B. Denton

CETUP

July 4, 2023

Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

Overview

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

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    - Cosmology!
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Data is confusing
Up to you to decide

Neutrinos have mass

- Can get usual Dirac mass term via Higgs
  - ⇒ 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

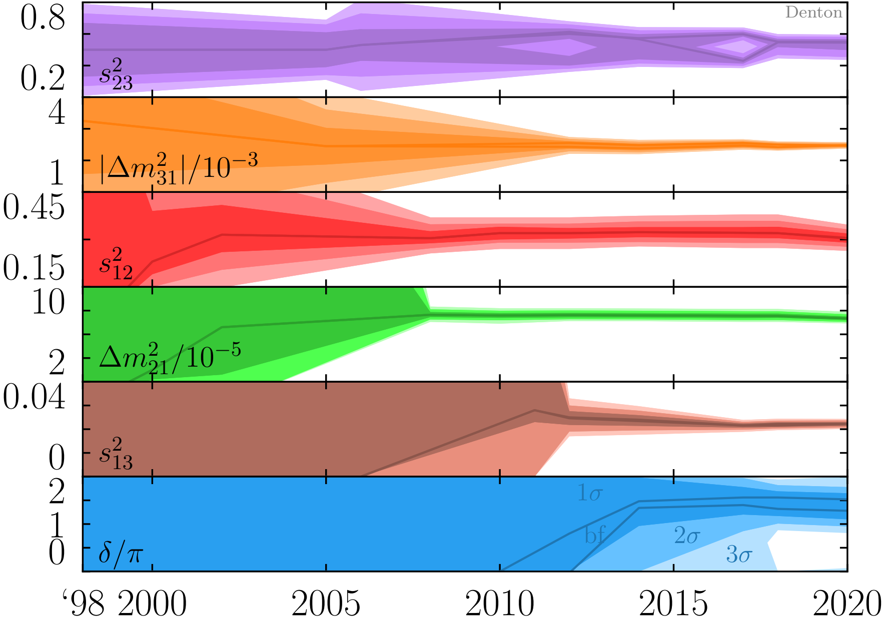
  - Pseudo-Dirac?

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_{23}^2
4
1
$|\Delta m_{31}^2|/10^{-3}$
0.45
0.15
s_{12}^2
10
2
$\Delta m_{21}^2/10^{-5}$
0.04
0
s_{13}^2
2
1
0
δ/π
1σ
bf
2σ
3σ
‘98
2000
2005
2010
2015
2020

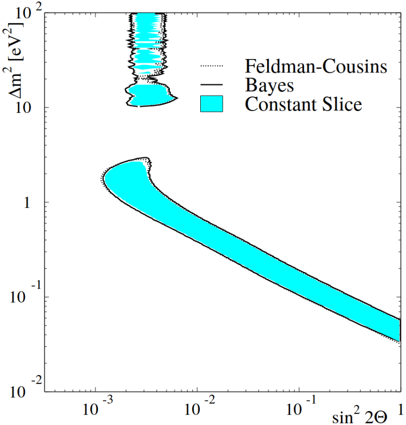
Three flavor oscillation picture: looks good

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
  - $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu4}|^2 \sim 0.002$

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`

See also Juergen's talk yesterday

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

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

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  - $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2) \sim 0.4$
- Attempts to explain with standard physics: unsuccessful

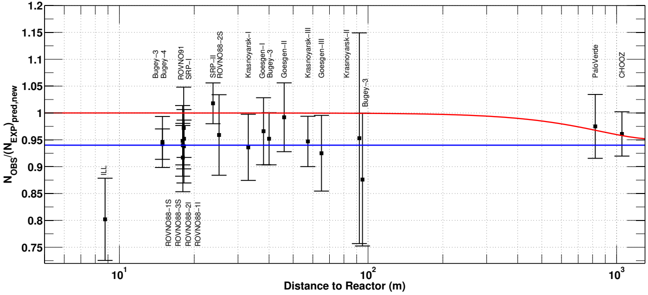
C. Giunti, et al. 2212.09722
V. Brdar, J. Gehrlein, J. Kopp 2303.05528
S. Elliott, V. Gavrin, W. Haxton 2303.13623

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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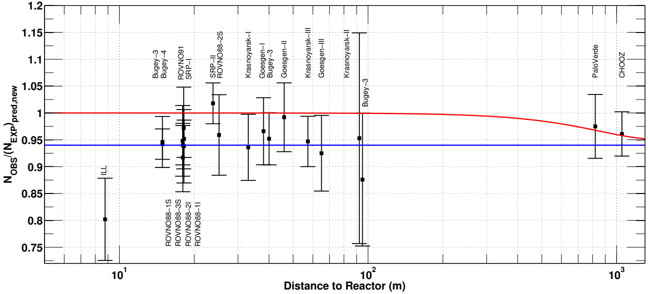

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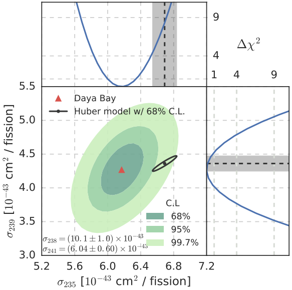

Daya Bay 1704.01082

RENO 1806.00574

Daya Bay, PROSPECT 2106.12251

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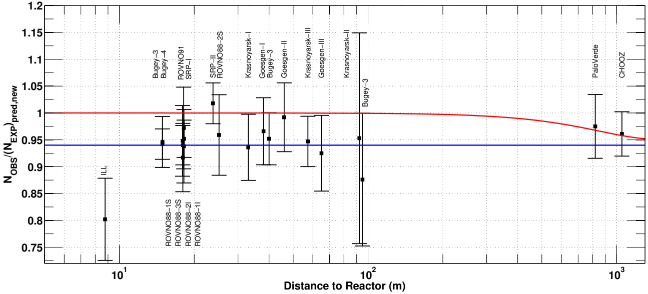

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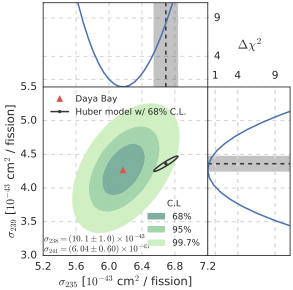

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Daya Bay, PROSPECT 2106.12251

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`

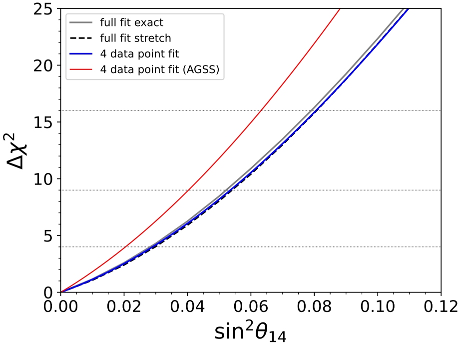
All hints in tension with cosmological data

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 $\nu_e \to \nu_e$

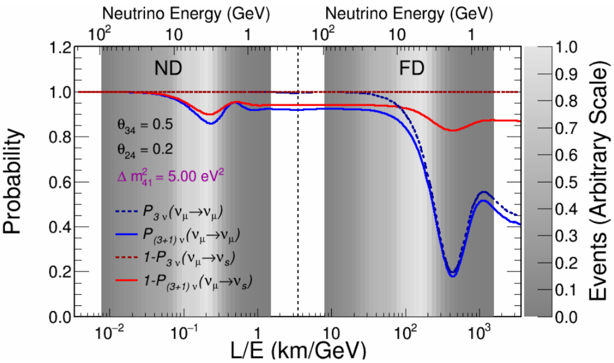
Yes: Gallium, ~~Reactor rate~~

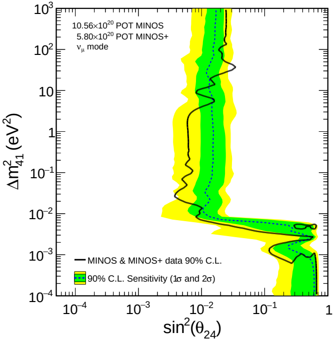
No: Reactor spectral, solar, *KARMEN*

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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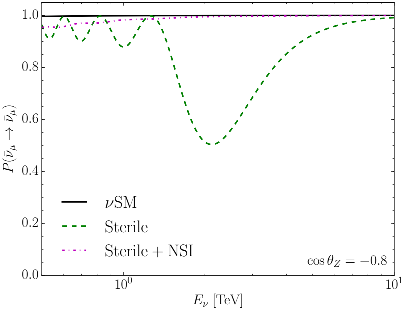
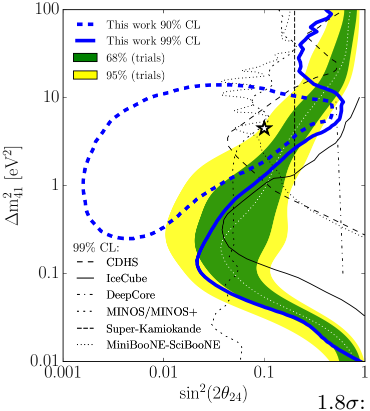
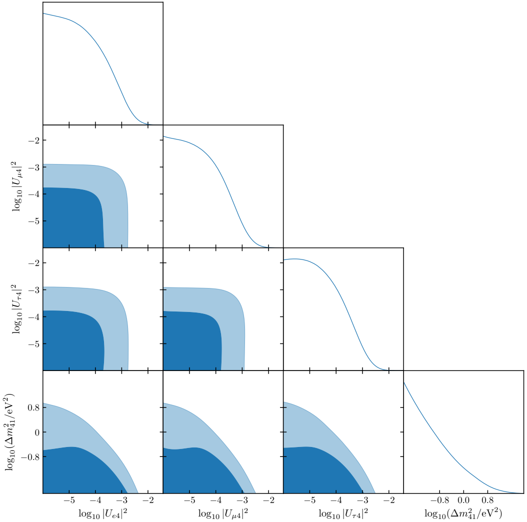


PBD, Y. Farzan, I. Shoemaker 1811.01310



1.8σ: IC 2005.12942

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

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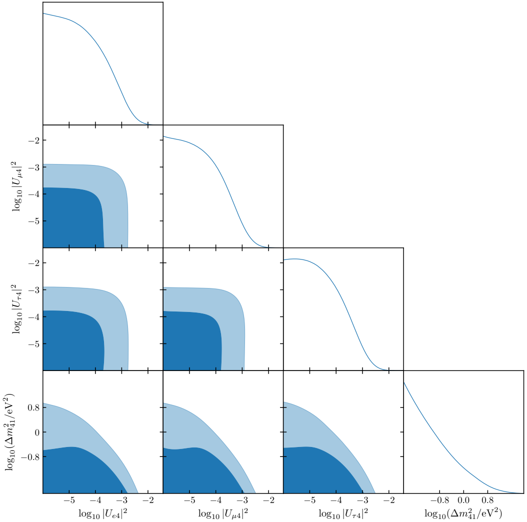

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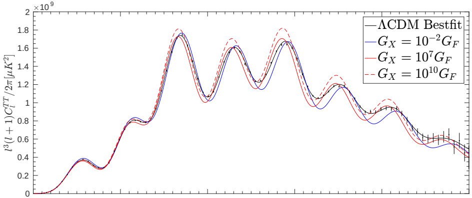
- To be consistent with data must have small mixing **and** small mass
- Much more than just N_{eff} and $\sum m_\nu$
- Just adding a new interaction is not straightforward



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 $G_X \sim 10^8 G_F$

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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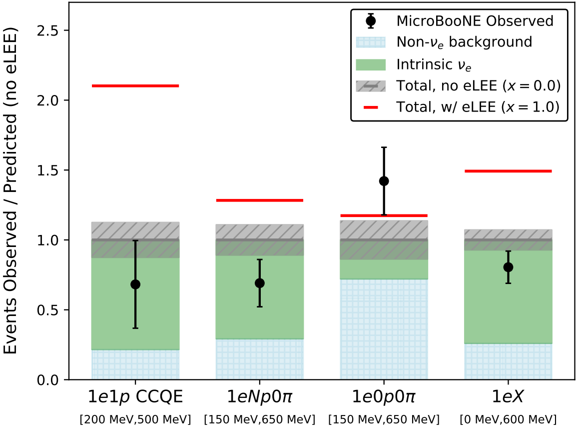
I. Esteban, et al. 2107.13568

Not a great fit to the cosmological data

Other new physics (cosmo) scenarios fit the data better

Let’s resolve this terrestrially

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

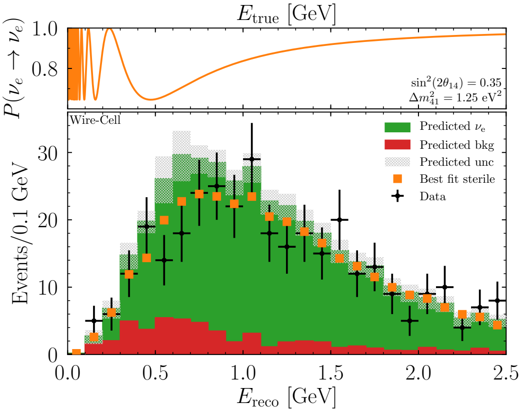
MicroBooNE is focused on ν_e appearance
Can do ν_μ and ν_e disappearance too!

See also D. Cianci, et al. 1702.01758

MiniBooNE backgrounds too big, plus anomaly

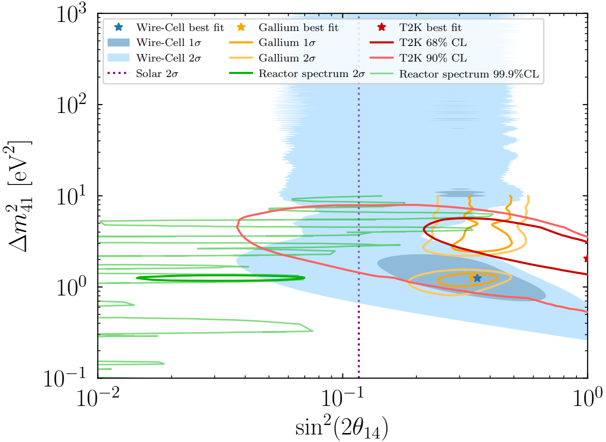
Dip hunting

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



Global ν_e disappearance picture

MicroBooNE prefers ν_e disappearance at $\sim 2.4\sigma$



Cosmology disfavors entire plane!

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
- Others handle fully-/partially-contained better
- Also doesn't see high evidence for disappearance

MicroBooNE 2210.10216

None discuss cosmological constraints

What does it take to evade cosmology?

2301.09651 with Hooman Davoudiasl

See also:
Y. Farzan 1907.04271
V. Brdar, J. Gehrlein, J. Kopp 2303.05528

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
- Suppose $m_\phi \sim 5 \times 10^{-15}$ eV $\Rightarrow 1/m_\phi \sim 40,000$ km $\sim 6R_\oplus$

A broad range of values works

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- ϕ - nucleon coupling below fifth force limits: $g_n \sim 5 \times 10^{-25}$

MICROSCOPE `2209.15487`

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

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

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

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

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

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

Self interacting scalar

Start with a potential:

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2$$

But loops will add in a term:

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\lambda}{4!}\phi^4$$

$$\delta\lambda \sim \frac{g_s^4}{16\pi^2} \sim 4 \times 10^{-56}$$

Call this the “1-loop induced” case

Shape-shifting sterile neutrinos in the early universe

To avoid cosmological constraints, need:

1. $m_s \gtrsim$ keV ($\theta_{14} \lesssim 10^{-3}$)
2. Thus $\phi_{\rm BBN} \gtrsim 10^{16}$ eV
3. At minimal reheating temp $T_{\rm rh} \sim 10$ MeV, need $\phi_i \gtrsim$ few$\times 10^{16}$ eV
4. Various ways to do this, e.g. thermal misalignment

D. Marsh 1510.07633

5. At $\lambda \sim 4 \times 10^{-56}$ ϕ is initially quartic dominated
6. Transitions to $m_\phi^2\phi^2$ dominated at ∼keV with $m_\phi^2\phi^2 \sim 0.2$ eV^2
7. Thus ϕ contributes $\sim 10^{-9}$ of DM

Ultralight dark matter

1. ϕ needs to transition to matter-like by $T \sim$ keV

S. Das, E. Nadler `2010.01137`

2. Need $\phi \sim 10^{19}$ eV at $T \sim$ keV to get the relic abundance

10^5 higher than before

3. Assuming quartic dominates before keV, need $\phi_i \sim 10^{23}$ eV at $T_{\text{rh}} \sim 10$ MeV
4. So $\lambda \sim 3 \times 10^{-66}$ (or smaller)

Fine tuning

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Fine tuning

Can have a shape-shifting sterile neutrino
that evades cosmology by adding one particle: dark matter

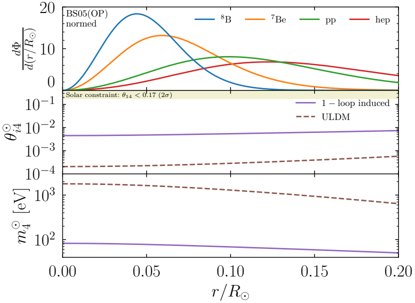
Shape-shifting sterile neutrinos in vacuum

Back to low energy pheno:

- Vacuum of space: $m_4 \sim 1$ eV, $\theta_{14} \sim 0.3$
- Active neutrinos as expected
- $\sum m_\nu \lesssim 0.1$ eV comes mostly from $z \in [10, 100]$

C. Lorenz, et al. `2102.13618`

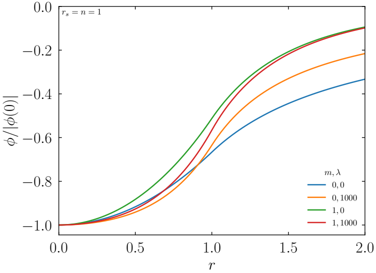
Shape-shifting sterile neutrinos at the Earth



1. Earth's surface:
   things are nearly the same as vacuum
2. Center of sun: $m_4 \sim 10^3$ eV, $\theta_{14} \sim 3 \times 10^{-4}$

Self interacting long range forces sourced by celestial objects

1. A general long range force will have a self interaction
2. Need to solve:
$$-2\frac{\phi'}{r}-\phi''+m^2\phi+\frac{1}{3!}\lambda\phi^3+n(r)=0$$
3. Analytic solutions don't exist, and is a boundary problem
$$\phi'(0)=0,\ \phi(\infty)=0$$
4. Need to employ shooting method to infer $\phi(0)$
5. Depending on shape of $n(r)$ and value of λ, can hit double precision limit



Other phenomena of shape-shifting sterile neutrinos

- 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
- Doesn't address surface constraints e.g. reactor spectral, KARMEN, etc.

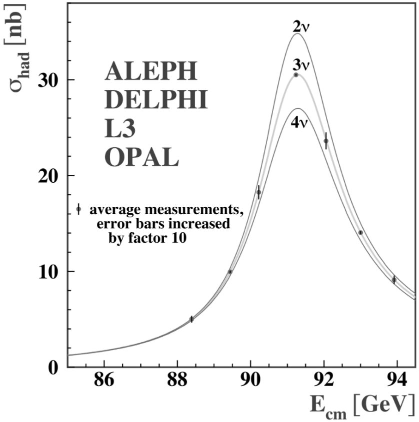
1 eV sterile summary

- 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

Any new light neutrinos must be sterile: SM gauge singlets



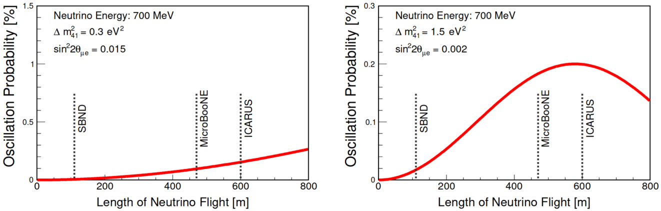
Fun fact: pre-LEP upper limit on $N_\nu \sim 6000$!

Short baseline program

1. Leverage LAr to discriminate photons from electrons

MicroBooNE 1910.02166

2. L is easier to measure than E



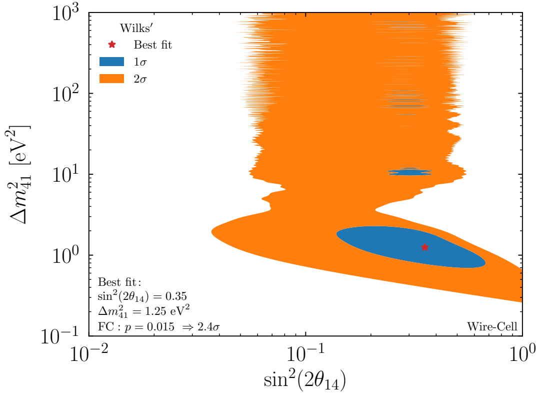
P. Machado, O. Palamara, D. Schmitz 1903.04608

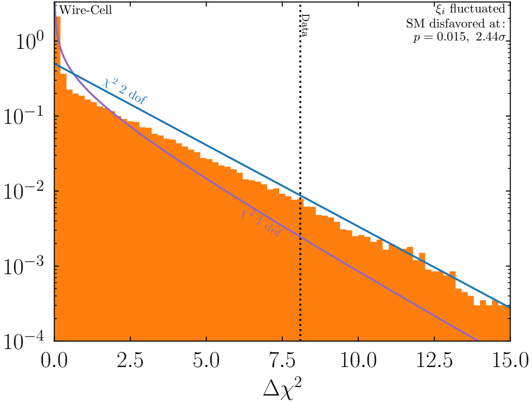
3. Beam is mostly ν_μ, but some ν_e too
4. Test bed for LAr technology

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



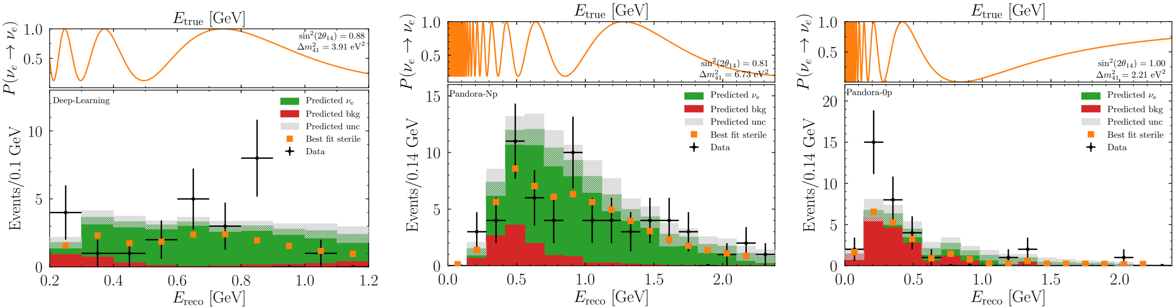


Other MicroBooNE analysis channels

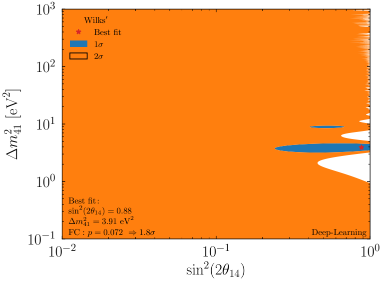
Analysis	$\sin^2(2\theta_{14})$	Δm^2_{41} (eV^2)	$N\sigma$ (FC)
Wire-Cell	$0.35^{+0.19}_{-0.16}$	$1.25^{+0.74}_{-0.39}$	2.4
Deep-Learning	$0.88^{+0.12}_{-0.41}$	$3.91^{+0.40}_{-0.40}$	1.8
Pandora-Np	$0.81^{+0.19}_{-0.47}$	[1.28,2.44] $6.73^{+1.75}_{-0.90}$ $\vdots$	2.4
Pandora-0p	$1_{-0.29}$	$2.21^{+0.82}_{-0.60}$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

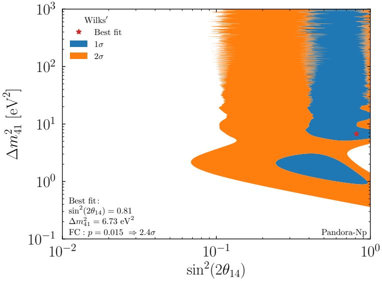
See backups for more plots

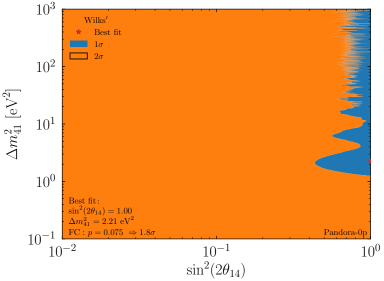
MicroBooNE data in other analyses



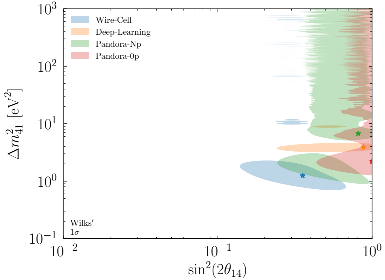
MicroBooNE contours in other analyses







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

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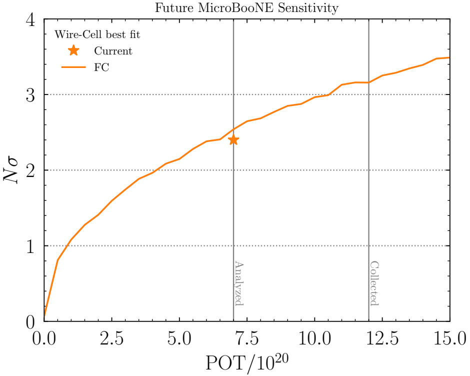
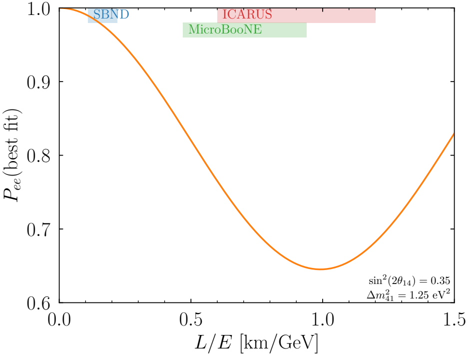
All analyses *assume* unitarity
Throw out LSND, MiniBooNE, RAA, gallium, etc.

S. Parke, M. Ross-Lonergan 1508.05095

Z. Hu, et al. 2008.09730

To the future





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?

3+1+NSI

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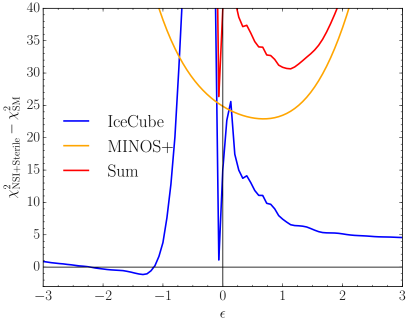

- Built UV complete model with ϵ_{ss}
- IceCube: 3+1+NSI is preferred over SM
- MINOS: No preference for 3+1 even with NSI

PBD, Y. Farzan, I. Shoemaker 1811.01310