Sterile neutrinos at the eV scale

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Hinchcliffe's theorem

"When a title is in the form of a question,
the answer is always NO."

see, however:

IS HINCHLIFFE'S RULE TRUE?

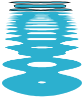
Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

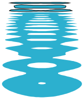
Recap: summary of neutrino oscillation results

- Established theoretical formalism
- Precise measurements of $_{23}$, $j\Delta m^2_{31}j$, $_{12}$, Δm^2_{21}, $_{13}$.



Recap: summary of neutrino oscillation results

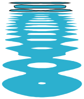
- sgn(Δm^2_{31}) unknown
- No sensitivity to $_{CP}$ yet
- Absolute neutrino masses not known
- Some open questions regarding coherence properties of neutrinos



Recap: summary of neutrino oscillation results

- LSND and MiniBoonE
  - Anomalous $\overset{(-)}{\nu}_e$ appearance at short baseline
- Reactor and gallium anomalies
  - Anomalous $\overset{(-)}{\nu}_e$ disappearance at short baseline

! Today's lecture



Oscillation anomalies: LSND and MiniBooNE

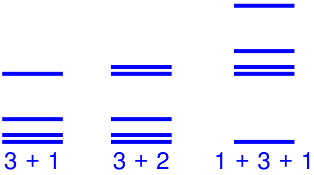
- LSND:
  - $_e$ appearance in $_\mu$ beam from stopped pion source (> 3) at $L{=}E$ 1 km/GeV
- MiniBooNE:
  - No significant $_e$ or $_e$ excess in the LSND-preferred region
  - but $_e$ consistent with LSND
  - Low-E excess not understood

ν ! ν_e oscillations at L/E 1 km/GeV?

- Remember: Oscillation maxima for standard oscillations expected at
  - $L{=}E$ 500 km/GeV (from m^2_{31} $2{:}4$ 10^{-3} eV^2)
  - $L{=}E$ 15 000 km/GeV (from m^2_{21} $8{:}1$ 10^{-5} eV^2)
- Explaining LSND and MiniBooNE requires an additional mass squared difference Δm^2_{41} 1 eV^2.
- This requires an additional neutrino species.
- LEP measurements of the invisible Z width constrain the number of active neutrinos to three.
- Only possibility: A sterile neutrino $_s$, not coupling to SM gauge interactions.
  - "3 + 1 scenario"
- Then: Possibility of $_\mu$! $_s$! $_e$ oscillations at $L{=}E$ 1 km/GeV

$\overset{(-)}{\nu}_e$ appearance in the 3+1 scenario and beyond

	$^{2}_{3+1}$/dof	$^{2}_{3+2}$/dof	$^{2}_{1+3+1}$/dof
LSND	11.0/11	8.6/11	7.5/11
MiniB	19.3/11	10.6/11	9.1/11
MiniB	10.7/11	9.6/11	12.7/11
E776	32.4/24	29.2/24	31.3/24
KARMEN	9.8/9	8.6/9	9.0/9
NOMAD	0.0/1	0.0/1	0.0/1
ICARUS	2.0/1	2.3/1	1.5/1
Combined	87.9/66	72.7/63	74.6/63

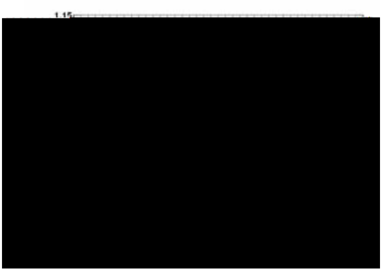


- Global fit to all appearance data is consistent
- Background oscillations important in MiniBooNE and E776
- Significant improvement in 3 + 2 and 1 + 3 + 1

JK Machado Maltoni Schwetz, 1303.3011

The Gallium anomaly

- Intense radioactive ν_e sources (^{51}Cr and ^{37}Ar) have been deployed in the GALLEX and SAGE solar neutrino detectors
- Neutrino detection via $^{71}\text{Ga} + \nu_e \to {}^{71}\text{Ge} + e^-$
- Result: Measurements consistently lower than expectation (2.7σ)



Giunti Laveder arXiv:1005.4599, arXiv:1006.3244
Mention et al. Moriond 2011 talk

- Question: How well are efficiencies of the radiochemical method understood?

The reactor anomaly

- Recent reevaluation of expected reactor ¯$_e$ flux is 3:5% higher than previous prediction Mueller et al. arXiv:1101.2663, confirmed by P. Huber arXiv:1106.0687
- Method: Use measured -spectra from ^{238}U, ^{235}U, ^{241}Pu fission at ILL and convert to ¯$_e$ spectrum (for single -decay: $E_\nu = Q \quad E_e$)
- Problem: Requires knowledge of Q-values for all contributing decays.
  ! take from nuclear databases where available, fit to data otherwise

Old method Schreckenbach 1985	New method Mueller et al. arXiv:1101.2663
30 effective decays	Uses nuclear databases (90% of ¯$_e$ flux)
(fit parameters to ILL data)	5 effective decays (remaining 10%)
	Error propagation, correlation matrix
	Corrections to the Fermi theory of decay
	Off-equilibrium corrections
	(not all -decay chains in equilibrium

- Cross check:
  - Simulate mock e^- spectra using few well-understood -decays
  - Reconstruct $_e$ spectrum using old method: Result is 3% too low
  - Reconstruct $_e$ spectrum using new method: Result is exact.

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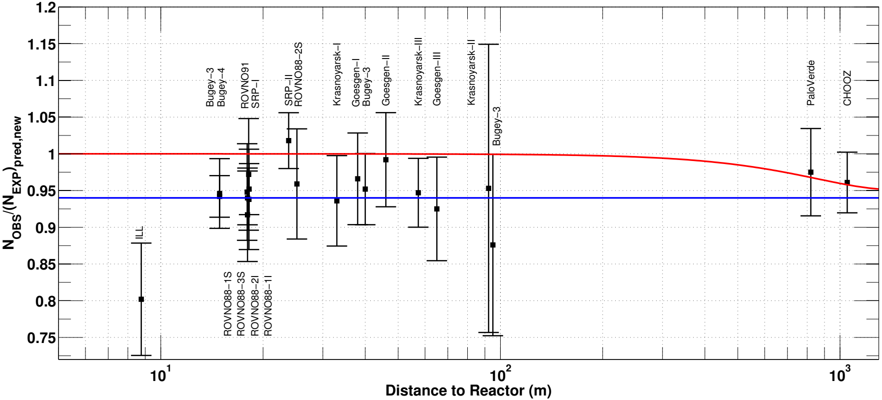
- Possible problems:
  - Poorly understood effects in nuclei with large log *ft*
    Huber arXiv:1106.0687
  - Large systematic uncertainties for non-unique forbidden decays
    Hayes et al. arXiv:1309.4146

The reactor anti-neutrino anomaly

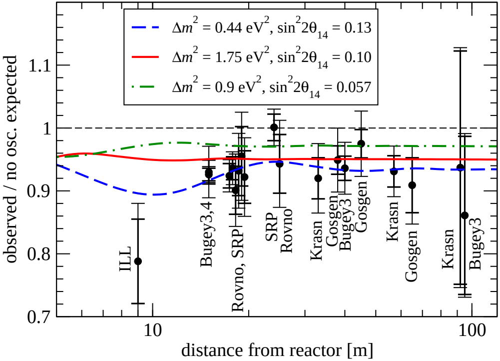
- Have short-baseline reactor experiments observed a $\bar{\nu}_e$ deficit?



Mention et al. arXiv:1101.2755

red = new reactor $\bar{\nu}_e$ flux prediction
blue = old reactor $\bar{\nu}_e$ flux prediction

$\overset{(-)}{\nu}_e$ disappearance in the 3+1 scenario



	sin^2 2 $_{14}$	m^2_{41} [eV^2]	$^2_{\text{min}}$/dof (GOF)	$^2_{\text{no osc}}$/dof (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)

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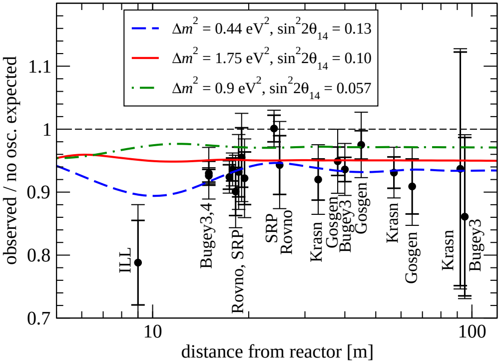

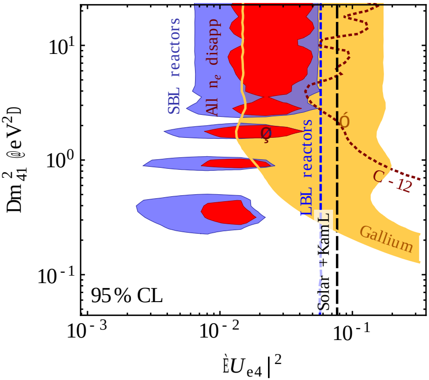

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SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
global $_e$ disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

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Relation between appearance and disappearance

We find: $^{(-)}{}_e$ disappearance experiments consistent among themselves, $^{(-)}{}_e$ appearance experiments consistent among themselves.

But:

$3 + 1$ neutrinos

At large baseline ($L \quad 4 \; E/\Delta m^2_{41}$, but $L \quad 4 \; E/\Delta m^2_{31}$

$$P_{ee} = 1 \quad 2|U_{e4}|^2(1 \quad |U_{e4}|^2)$$
$$P_{\mu\mu} = 1 \quad 2|U_{\mu 4}|^2(1 \quad |U_{\mu 4}|^2)$$
$$P_{e\mu} = 2|U_{e4}|^2|U_{\mu 4}|^2$$

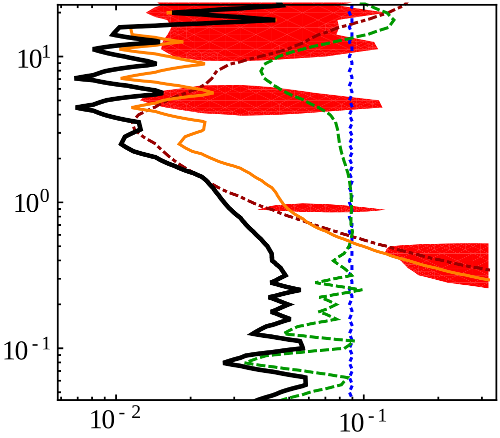
It follows

$$2P_{e\mu} \simeq (1 \quad P_{ee})(1 \quad P_{\mu\mu})$$

In the $3 + 1$ case, at large enough baseline, there is a one-to-one relation between the appearance and disappearance probabilities.

$\overset{(-)}{\nu}$ disappearance in the 3+1 scenario

- Parameter regions favored by tentative hints are in tension with null results from $\overset{(-)}{\nu}_\mu$ disappearance searches



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The global oscillation fit

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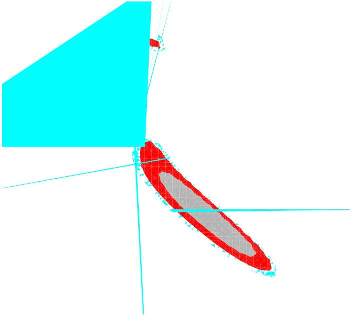

	$^{2}_{\text{min}}$/dof	GOF
3+1	712/(689 9)	19%

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$3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal

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Parameter goodness of fit (PG) test:

Compares $^{2}_{\rm min}$ from global and separate fits to test compatibility of 2 data sets

	$^{2}_{\rm min}$/dof	GOF	$^{2}_{\rm PG}$/dof	PG
3+1	712/(689 9)	19%	18.0/2	1:2 10^{-4}

The global oscillation fit

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- $3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal
- $3+2$ Fit improves considerably with two sterile neutrinos

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3+1	712/(689 9)	19%	18.0/2	1:2 10^{-4}
3+2	701/(689 14)	23%	25.8/4	3:4 10^{-5}

The global oscillation fit

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- $3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal
- $3+2$ Fit improves considerably with two sterile neutrinos
- $1+3+1$ Further improvement, especially in appearance fit

Parameter goodness of fit (PG) test:

Compares $^{2}_{min}$ from global and separate fits to test compatibility of 2 data sets

	$^{2}_{min}$/dof	GOF	$^{2}_{PG}$/dof	PG
3+1	712/(689 9)	19%	18.0/2	1:2 10^{-4}
3+2	701/(689 14)	23%	25.8/4	3:4 10^{-5}
1+3+1	694/(689 14)	30%	16.8/4	2:1 10^{-3}

Conclusion from oscillation fits:

severe tension

in all cases

Sterile neutrinos in cosmology

Models with $\mathcal{O}$(eV) sterile neutrino(s) constrained by cosmology:

Sum of neutrino masses

$$\sum m_\nu \lesssim 0.23 \text{ eV}$$

of relativistic species

$N_\nu = 4$ mildly disfavored

Ade et al. (Planck), arXiv:1303.5076
Gonzalez-Garcia Maltoni Salvado, arXiv:1006.3795
Hamann Hannestad Raffelt Tamborra Wong, arXiv:1006:5276

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Question:

What does is take to evade these constraints?

Are light sterile neutrinos ruled out by cosmology?

$_s$ production in the early Universe through $_{e,\mu,\tau}$! $_s$ oscillations at T & MeV

Dodelson Widrow 1994

Reconciling sterile neutrinos with cosmology

- Large lepton asymmetry (& 0:01) ! $_s$ production MSW-suppressed

  Foot Volkas hep-ph/9508275, Chu Cirelli astro-ph/0608206, Saviano et al. arXiv:1302.1200
- Very low reheating temperature

  Gelmini Palomares-Ruiz Pascoli, astro-ph/0403323
- Entropy production after neutrino decoupling (e.g. due to late decay of heavy sterile neutrinos or other particles) ! neutrinos diluted

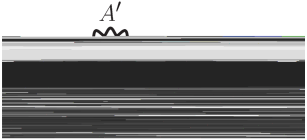
  Fuller Kishimoto Kusenko 1110.6479, Ho Scherrer 1212.1689
- Self-interacting $_s$

  ! $_s$ production MSW-suppressed

  Hannestad Hansen Tram arXiv:1310.5926; Dasgupta JK arXiv:1310.6337

Suppressed ν_s production from thermal MSW effect

- $_s$ production in the early Universe through $_{e,\mu,\tau}$! $_s$ oscillations
  Dodelson Widrow 1994
- Assume $_s$ couple to & MeV gauge boson A'
- Neutrino self energy:



- Leads to thermal MSW potential V / T^4
- At high T: mixing strongly suppressed

$$\sin 2 \ _{\text{eff}} = \frac{\sin 2}{\sqrt{\sin^2 2 \ + \left(\cos 2 \quad \frac{2EV}{\Delta m^2}\right)^2}}$$

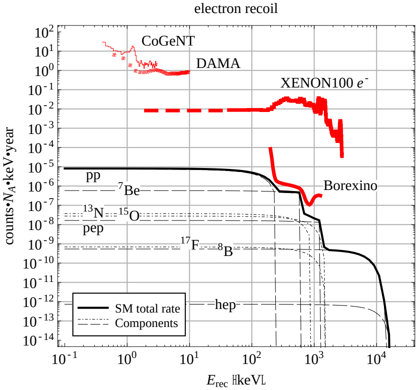
- No $_s$ production through oscillations
  ! no cosmological constraints

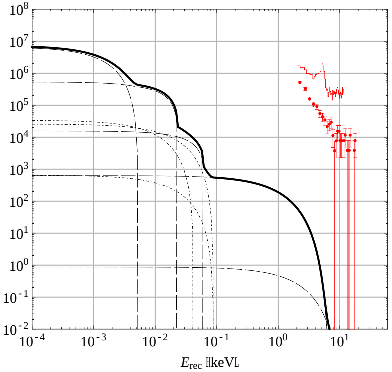
Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337

Neutrinos and direct dark matter detection

Solar neutrinos are a well-known background to future direct DM searches:

see e.g. Gütlein et al. arXiv:1003.5530





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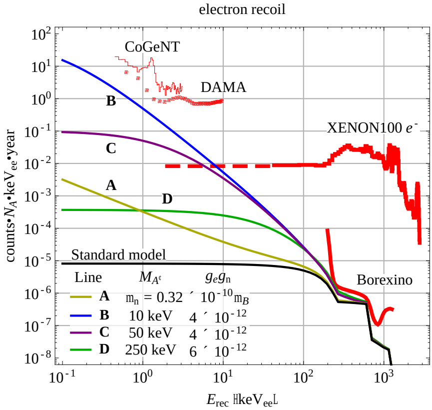
SM signal will only become sizeable in multi-ton detectors

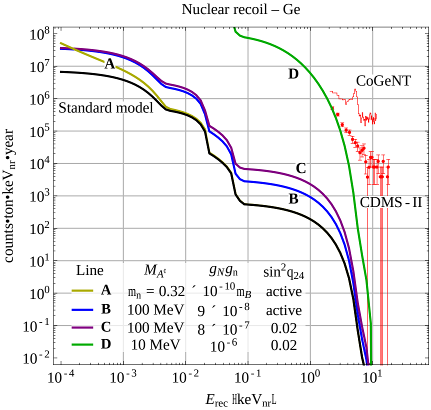
But: New physics can enhance the rate

Examples:

- Neutrino magnetic moments
- Sterile neutrinos + . GeV scale hidden sector gauge force

Low-energy scattering of neutrinos beyond the SM





A: magnetic moment
B, C, D: kinetically mixed A' + sterile ν_s

A: magnetic moment
B: $U(1)_{B-L}$ boson
C: kinetically mixed $U(1)'$ + sterile
D: $U(1)_B$ + sterile charged under $U(1)_B$
[Pospelov 1103.3261, Pospelov Pradler 1203.0545]

- Enhanced scattering at low E_r for light A'
- Negligible compared to SM scattering ($\sim g^4 m_T / M_W^4$) at energies probed in dedicated neutrino experiments

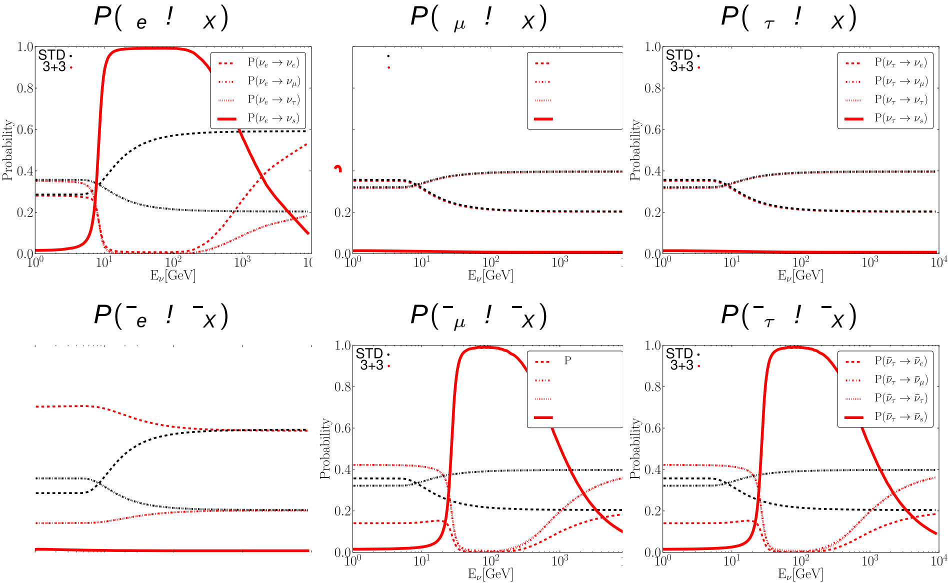
[Harnik JK Machado arXiv:1202:6073]

Sterile neutrinos and DM annihilation in the Sun

- Neutrino telescope limits on neutrinos from dark matter annihilation in the Sun depend crucially on oscillation physics.
- If sterile neutrinos exist, new MSW resonances can lead to strong conversion of active neutrinos into sterile neutrinos in the Sun.

Esmaili Peres, arXiv:1202.2869
Argüelles JK, arXiv:1202.3431

Oscillation probabilities for a 3+3 toy scenario



Thick red lines = active–sterile oscillations

plots from Argüelles JK, arXiv:1202.3431
see also Esmaili Peres, arXiv:1202.2869