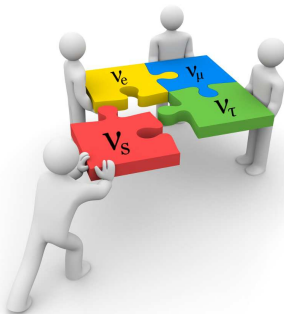


Theory and Phenomenology of Sterile Neutrinos

Joachim Kopp (University of Mainz)

June 7, 2014 @ Neutrino 2014, Boston



Outline

- 1 Sterile Neutrinos
- 2 Oscillation Anomalies: A Global Fit
 - ν_e Appearance
 - ν_e Disappearance
 - ν_μ Disappearance
 - Sterile Neutrino Oscillations: The Global Picture
- 3 Sterile Neutrinos in Cosmology: Robustness of Constraints
- 4 Light Sterile Neutrinos and Dark Matter Searches
 - Sterile Neutrinos and Direct Dark Matter Searches
 - Sterile Neutrinos and Indirect Dark Matter Searches
- 5 Summary



Sterile Neutrinos

Sterile neutrinos

Definition

Sterile neutrino = SM singlet fermion

- Very generic extension of the SM
 - ▶ can be leftovers of **extended gauge multiplets** (e.g. GUT multiplets)
- Very useful in phenomenology:
 - ▶ Can explain **smallness of neutrino mass** (seesaw mechanism, $m \sim \text{TeV} \dots M_{\text{Pl}}$)
 - ▶ Can explain **baryon asymmetry of the Universe** (leptogenesis, $m \gg 100 \text{ GeV}$)
 - ▶ Can explain **dark matter** ($m \sim \text{keV}$)
 - ▶ Can explain various **neutrino oscillation anomalies** ($m \sim \text{eV}$)



Example: The ν MSM

- SM + ≥ 3 sterile neutrinos N_j

$$\mathcal{L} \supset Y_{ij} \bar{L}_i H N_j + \frac{1}{2} M_{ij} \bar{N}_i^c N_j$$

- Two of the sterile neutrino masses $> 10^{10}$ GeV
 - ▶ Seesaw mechanism
 - ▶ Leptogenesis
- One sterile neutrino at $\sim$ keV
 - ▶ Warm Dark Matter Candidate

Asaka Blanchet Shaposhnikov, hep-ph/0503065
Asaka Shaposhnikov, hep-ph/0505013
Asaka Eijima Ishida, arXiv:1101.1382

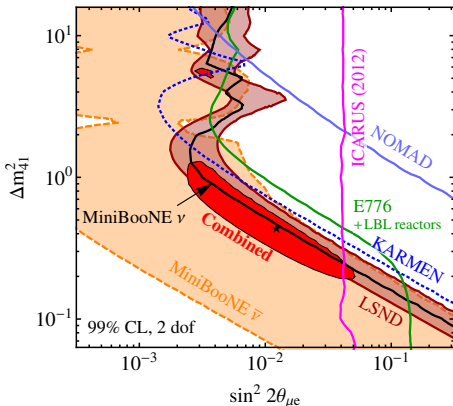
- Possible extensions
 - ▶ More sterile neutrinos $\rightarrow$ eV-scale neutrinos for short-baseline anomalies?
 - ▶ Left-right symmetric extension: sterile neutrinos charged under $SU(2)_R$
Duerr Fileviez-Perez Lindner, arXiv:1306.0568



Oscillation Anomalies: A Global Fit

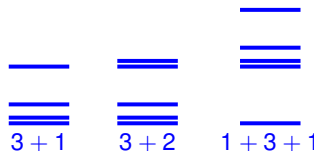
$\bar{\nu}_e$ appearance in the 3+1 scenario and beyond

Motivated by LSND and MiniBooNE: excess of $\bar{\nu}_e$ events in $\bar{\nu}_\mu$ beam.



	χ^2_{3+1}/dof	χ^2_{3+2}/dof	$\chi^2_{1+3+1}/\text{dof}$
LSND	11.0/11	8.6/11	7.5/11
MiniB ν	19.3/11	10.6/11	9.1/11
MiniB $\bar{\nu}$	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

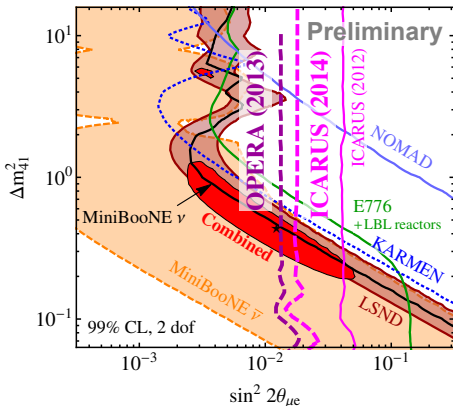


JK Machado Maltoni Schwetz, 1303.3011
see also fits by Giunti Laveder et al.

Conrad Ignarra Karagiorgi Shaevitz Spitz Djurcic Sorel

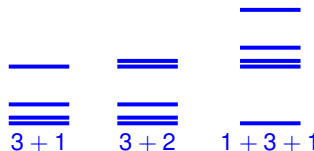
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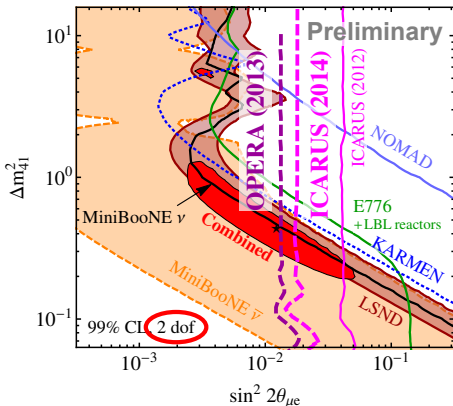


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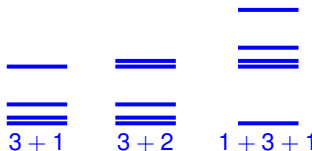
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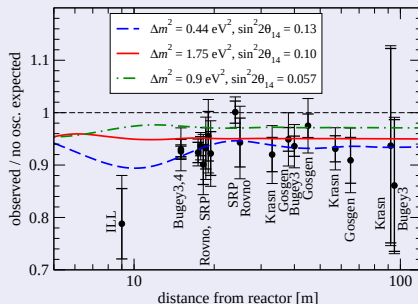
Conrad Ignarra Karagiorgi Shaevitz Spitz Djurcic Sorel

$\bar{\nu}_e$ disappearance: reactor and gallium experiments

The reactor anomaly

- Reevaluation of reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ above previous prediction
→ systematic uncertainties or new physics?

Mueller et al. 1101.2663, Huber 1106.0687, Hayes et al. 1309.4146 & talk by G. Garvey



$\bar{\nu}_e$ disappearance: reactor and gallium experiments

The reactor anomaly

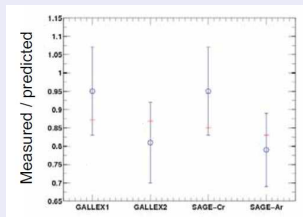
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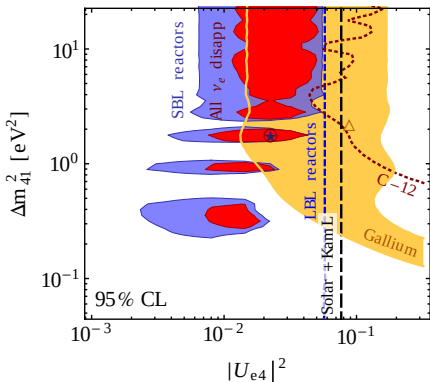
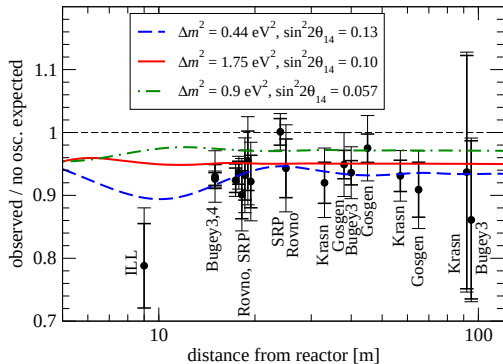
The gallium anomaly

- Experiments with intense radioactive ν_e sources (^{51}Cr and ^{37}Ar)
- Neutrino detection via
 $^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$
- Observation: Neutrino deficit ($\sim 3\sigma$)

Giunti Laveder 1006.3244



$\bar{\nu}_e$ disappearance in the 3+1 scenario



	$\sin^2 2\theta_{14}$	$\Delta m_{41}^2 [\text{eV}^2]$	$\chi_{\min}^2/\text{dof}$ (GOF)	$\Delta\chi_{\text{no osc}}^2/\text{dof}$ (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%)
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
global ν_e disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

JK Machado Maltoni Schwetz, 1303.3011

Relation between appearance and disappearance

We find: $\bar{\nu}_e$ disappearance experiments consistent among themselves,
 $\bar{\nu}_e$ appearance experiments consistent among themselves.

But:

3 + 1 neutrinos

At $L \gg 4\pi E/\Delta m_{41}^2$, but $L \ll 4\pi E/\Delta m_{31}^2$

$$P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

$$P_{\mu\mu} = 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$$

$$P_{e\mu} = 2|U_{e4}|^2|U_{\mu4}|^2$$

It follows

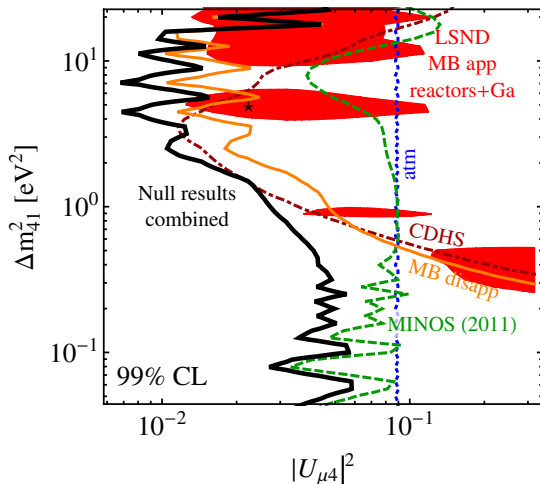
$$2P_{e\mu} \simeq (1 - P_{ee})(1 - P_{\mu\mu})$$

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

Combining different oscillation channels
provides the **strongest, most robust**
constraints on sterile neutrinos

$\bar{\nu}_\mu$ disappearance in the 3+1 scenario

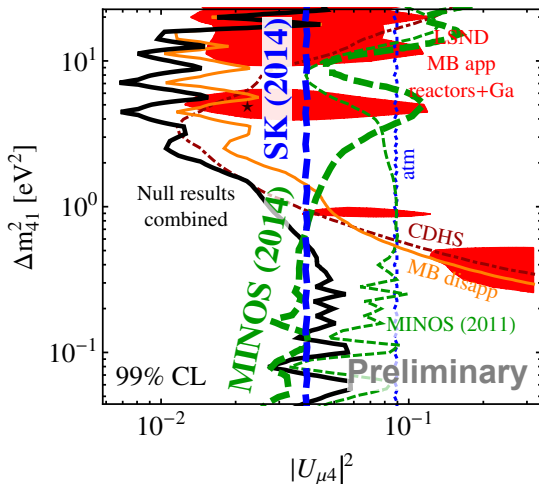
- Parameter regions favored by **tentative hints** are in **tension with null results** from $\bar{\nu}_\mu$ disappearance searches



JK Machado Maltoni Schwetz, 1303.3011

$\bar{\nu}_\mu$ disappearance in the 3+1 scenario

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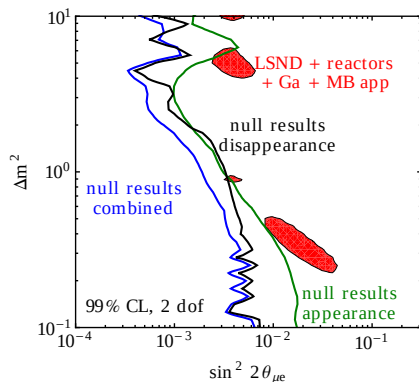


JK Machado Maltoni Schwetz, 1303.3011

The global oscillation fit

JK Machado Maltoni Schwetz, arXiv:1303.3011

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

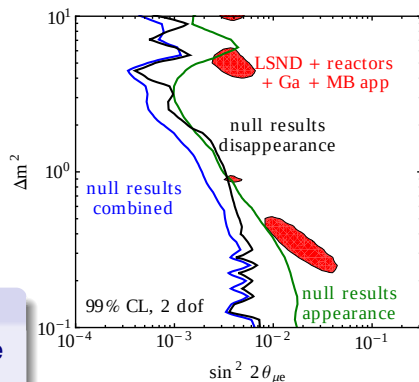


	$\chi^2_{\min}/\text{dof}$	GOF
3+1	712/(689 - 9)	19%

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JK Machado Maltoni Schwetz, arXiv:1303.3011

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Parameter goodness of fit (PG) test:

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

	$\chi^2_{\min}/\text{dof}$	GOF	$\chi^2_{\text{PG}}/\text{dof}$	PG
3+1	712/(689 - 9)	19%	18.0/2	1.2×10^{-4}

The global oscillation fit

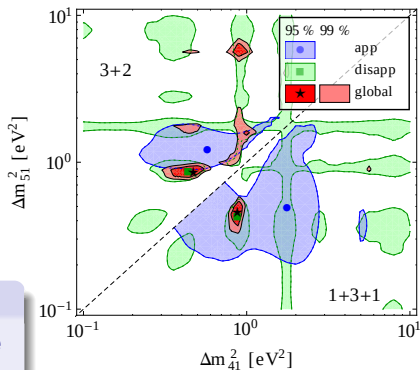
JK Machado Maltoni Schwetz, arXiv:1303.3011

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3 + 2 **Tension remains** for **two sterile neutrinos**

Parameter goodness of fit (PG) test:

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



	$\chi^2_{\min}/\text{dof}$	GOF	$\chi^2_{\text{PG}}/\text{dof}$	PG
3+1	712/(689 - 9)	19%	18.0/2	1.2×10^{-4}
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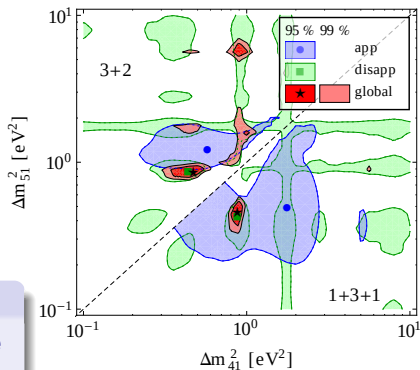
The global oscillation fit

JK Machado Maltoni Schwetz, arXiv:1303.3011

- 3 + 1 Severe **tension** between appearance and disappearance and between exp's with and without a signal
- 3 + 2 **Tension remains** for **two sterile neutrinos**
- 3 + 3 No significant improvement expected

Parameter goodness of fit (PG) test:

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



	$\chi^2_{\min}/\text{dof}$	GOF	$\chi^2_{\text{PG}}/\text{dof}$	PG
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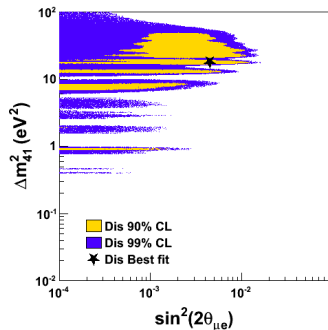
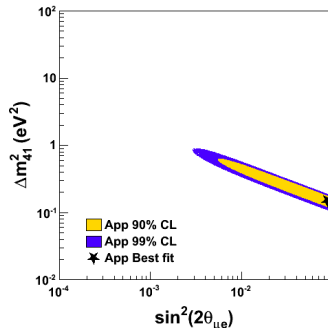
The MIT/Columbia fit

- $(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e)$ appearance data:
 - ▶ LSND
 - ▶ MiniBooNE
 - ▶ KARMEN
 - ▶ NOMAD
- $(\bar{\nu}_{\mu})$ disappearance data:
 - ▶ MiniBooNE
 - ▶ Minos CC ν_{μ}
 - ▶ CDHS
 - ▶ CCFR
 - ▶ Atmospheric neutrinos
- $(\bar{\nu}_e)$ disappearance data:
 - ▶ Short baseline reactor experiments
 - ▶ Gallium experiments
 - ▶ ν_e - ^{12}C CC scattering in KARMEN, LSND

Conrad Ignarra Karagiorgi Shaevitz Spitz, arXiv:1207.4765

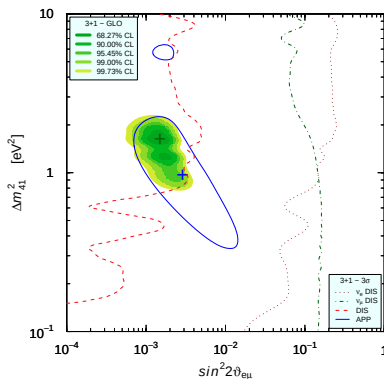
Poster by [Gabriel Collin](#)

χ^2/dof and PG test results in **qualitative agreement** with ours $\rightarrow$ **tension confirmed**



The GL^4 fit

- $(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ appearance data:
 - ▶ LSND
 - ▶ MiniBooNE
 - ▶ E776
 - ▶ KARMEN
 - ▶ NOMAD
 - ▶ ICARUS
 - ▶ OPERA
- $(\bar{\nu}_\mu)$ disappearance data:
 - ▶ MiniBooNE/SciBooNE
 - ▶ Minos NC+CC ν_μ
 - ▶ CDHS
 - ▶ CCFR
 - ▶ Atmospheric neutrinos
- $(\bar{\nu}_e)$ disappearance data:
 - ▶ Reactor experiments
 - ▶ Gallium experiments
 - ▶ Solar neutrinos
 - ▶ ν_e - ^{12}C scattering in KARMEN, LSND



Giunti Laveder Li Long arXiv:1308.5288
Giunti Laveder Li Liu Long arXiv:1210.5715
Giunti Laveder arXiv:1111.1069

Conclusion

NO tension found

Conclusion from oscillation data:

severe tension

My personal point of view

Anomalies are definitely interesting enough to be checked

- If **mundane explanations** are found, we will learn **important lessons for future neutrino experiments**
- If **sterile neutrinos** exist, this would be the **discovery of the decade**.

Questions for the future

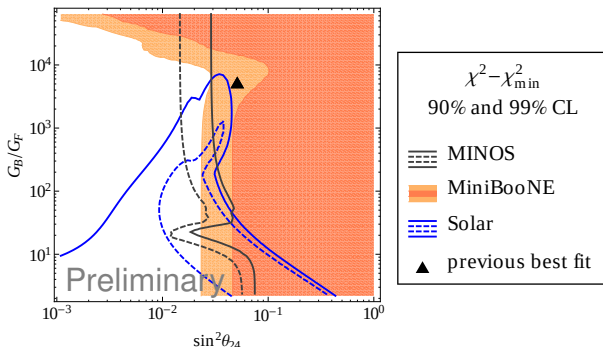
- Is one (or all) of the **positive results** not due to sterile neutrinos?
- Are some of the **exclusion limits** too strong?
(removing one from the fit is not enough!)
- Does **new physics beyond the simple $3 + X$ scenarios** help?

Hidden sector gauge forces and SBL oscillations

If sterile neutrinos have new interactions with SM fermions
(e.g. in models with “baryonic sterile neutrinos”),
new MSW potentials will influence oscillations.

How does this affect the tension in the SBL data?

Karagiorgi Shaevitz Conrad, arXiv:1202.1024
Pospelov, arXiv:1103.3261



JK, Johannes Welter, in preparation



Sterile Neutrinos in Cosmology: Robustness of Constraints

Sterile neutrinos in cosmology

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

Sum of neutrino masses

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

of relativistic species

$$N_\nu = 4 \text{ mildly disfavored}$$

(This would change if BICEP-2 is included.)

Talks by [Marta Spinelli](#), [Daniel Eisenstein](#)

[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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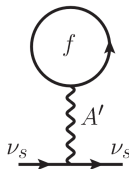
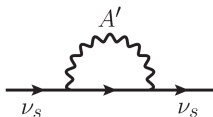
[Hamann Hannestad Raffelt Tamborra Wong](#), [arXiv:1006.5276](#)

Question:

What does it take to **evade** these constraints?

Suppressed ν_s production from thermal MSW effect

- ν_s production in the early Universe through $\nu_{e,\mu,\tau} \rightarrow \nu_s$ oscillations
Dodelson Widrow 1994
- Assume ν_s charged under a **hidden sector gauge group** $U(1)_s$
- Neutrino **self energy**:

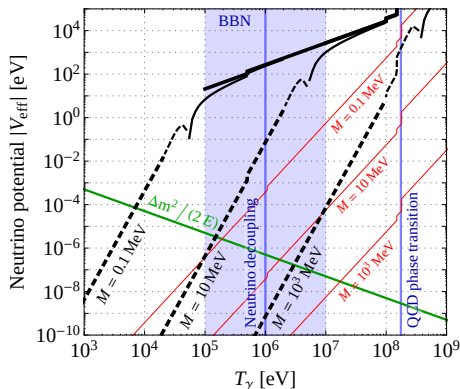


- Tadpole digraph**: conventional MSW potential: $V \propto n_f - n_{\bar{f}}$
Bubble digraph: thermal contribution $V \propto T^\alpha$
- At high T : strong MSW-type potential **even without lepton asymmetry**

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

- ν_s production through oscillations **suppressed** in the early Universe
→ **no cosmological constraints**
Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337

Suppression of ν_s production by thermal MSW effect



- For $\alpha' \sim 10^{-3}$ and $M_{A'} \lesssim 10$ MeV:

effective potential $V_{\text{eff}} \gg$ oscillation frequency $\Delta m^2 / (2E)$

until neutrino decoupling.

$\Rightarrow$ **sterile neutrino production suppressed**, no cosmological constraints

Hannestad Hansen Tram arXiv:1310.5926

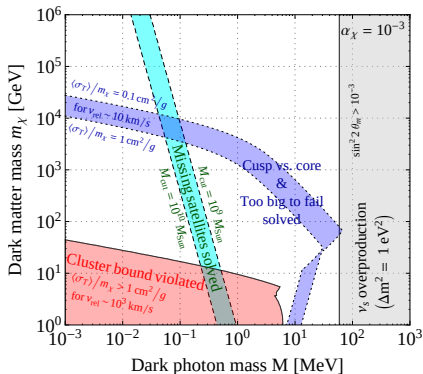
Dasgupta JK arXiv:1310.6337

Hidden sector gauge forces and dark matter

Interesting connection to dark matter physics:

The **same gauge force** that suppressed sterile neutrino production can also **solve small scale structure problems**:

- Too big to fail problem
- Cusp vs. core problem
- Missing satellites problem



Dasgupta JK arXiv:1310.6337



Dark Matter|

Google Search

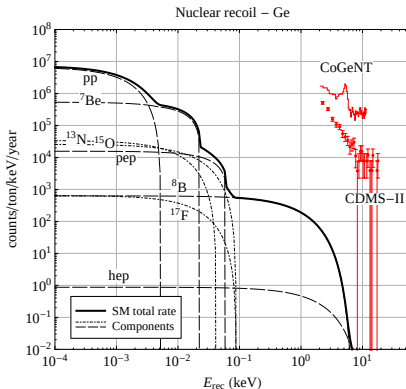
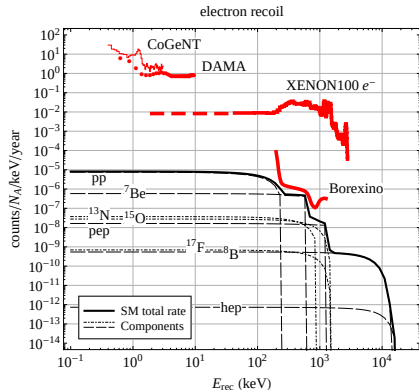
I'm Feeling Lucky

Light Sterile Neutrinos and Dark Matter Searches

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

$$\frac{d\sigma_{\text{SM}}(\nu N \rightarrow \nu N)}{dE_r} = \frac{G_F^2 m_N F^2(E_r)}{2\pi E_\nu^2} \left[A^2 E_\nu^2 + 2AZ(2E_\nu^2(s_w^2 - 1) - E_r m_N s_w^2) \right. \\ \left. + 4Z^2(E_\nu^2 + s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_N)) + s_w^2(E_r m_N - 2E_\nu^2)) \right],$$



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SM signal will only become sizeable in **multi-ton detectors**

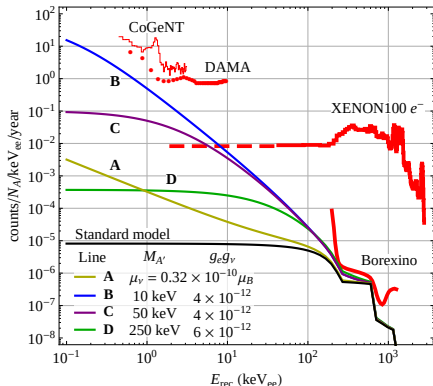
But: New physics can **enhance** the rate

Examples:

- **Neutrino magnetic moments**
- **Sterile neutrinos** + $\lesssim$ **GeV** scale **hidden sector gauge force**

Low-energy scattering of neutrinos beyond the SM

electron recoil

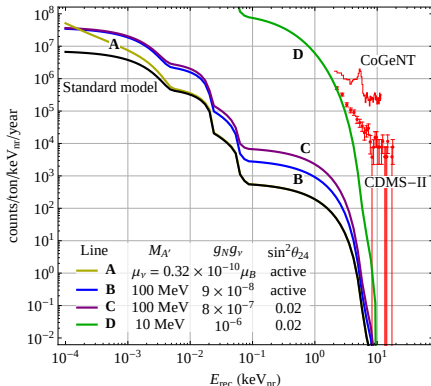


A: ν magnetic moment

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

- 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

Nuclear recoil – Ge



A: ν magnetic moment

B: $U(1)_{B-L}$ boson

C: kinetically mixed $U(1)'$ + sterile ν

D: $U(1)_B$ + sterile ν charged under $U(1)_B$

[Pospelov 1103.3261, Pospelov Pradler 1203.0545]

[Harnik JK Machado arXiv:1202.6073]

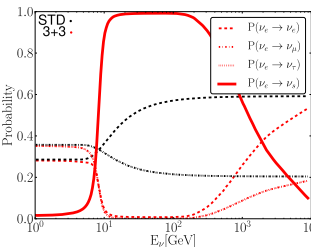
Sterile neutrinos and DM annihilation in the Sun

- 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.

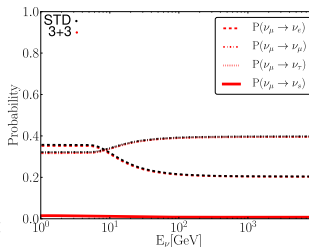
Esmaili Peres, arXiv:1202.2869
Argüelles JK, arXiv:1202.3431

Oscillation probabilities for a 3+3 toy scenario

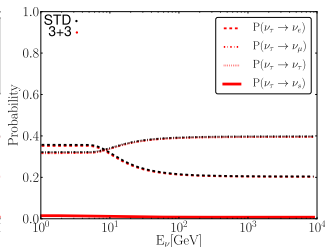
$$P(\nu_e \rightarrow \nu_X)$$



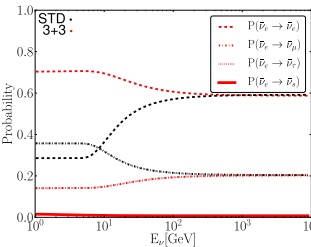
$$P(\nu_\mu \rightarrow \nu_X)$$



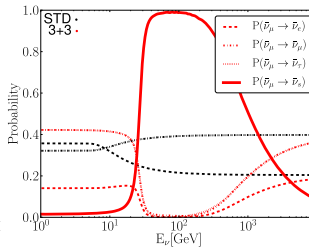
$$P(\nu_\tau \rightarrow \nu_X)$$



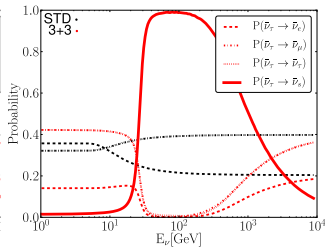
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_X)$$



$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_X)$$



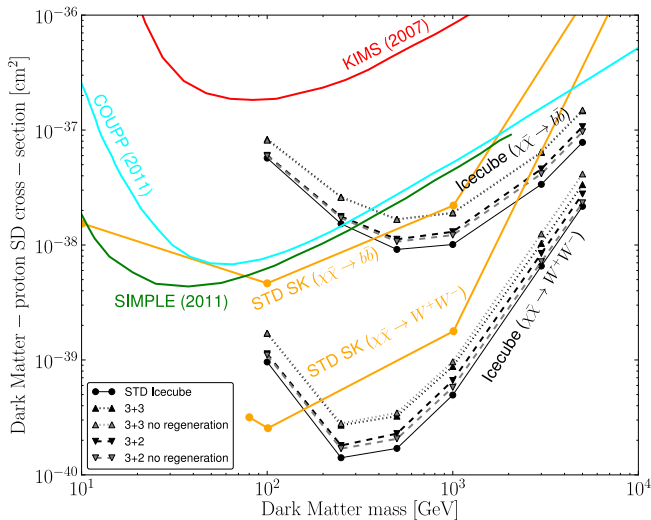
$$P(\bar{\nu}_\tau \rightarrow \bar{\nu}_X)$$



Thick red lines = active–sterile oscillations

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

Impact on IceCube limits



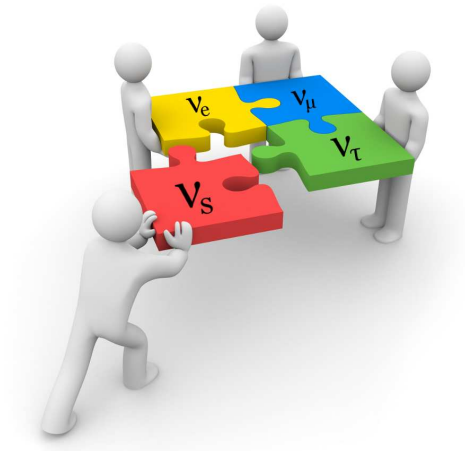
plot from Carlos Argüelles JK, arXiv:1202.3431
see also Esmaili Peres, arXiv:1202.2869



Summary

Summary

- Sterile neutrinos are theoretically well motivated and phenomenologically useful
- Tension between appearance and disappearance searches
- Neutrino 2014: several interesting new limits
 - ▶ Will increase the tension
 - ▶ Qualitative conclusions strengthened
- Cosmology disfavors $N_\nu \geq 4$, especially for $m_{\nu_s} \gtrsim 0.23$ eV.
(if BICEP-2 is included, this conclusion would change)
- Many mechanisms for making sterile neutrinos fully consistent with cosmology
 - ▶ Example: hidden sector gauge force
 - ▶ Can additionally solve small scale structure problems if coupled also to dark matter
- Sterile neutrinos and dark matter searches
 - ▶ Direct searches: non-standard neutrino signals in DM detectors
 - ▶ Indirect searches: limits on DM annihilation in the Sun modified by active–sterile oscillations



Thank you!

Data sets included in our fit

$\bar{\nu}_e$ disappearance

- SBL reactor experiments
- LBL reactor experiments
- KamLAND
- Radioactive source (Ga) experiments
- Solar neutrinos
- Atmospheric neutrinos
- ν_e - ^{12}C scattering in KARMEN, LSND

$\bar{\nu}_e$ appearance

- LSND
- MiniBooNE
- KARMEN
- NOMAD
- ICARUS
- E776

$\bar{\nu}_\mu$ disappearance

- Atmospheric neutrinos (includes *either* $\bar{\nu}_e$ disapp. *or* full matter effects)
- MiniBooNE (includes oscillations of backgrounds)
- MINOS CC+NC (full n -flavour oscillations in matter)
- CDHS

Relation between appearance and disappearance

3 + 2 neutrinos

At $L \gg 4\pi E/\Delta m_{41}^2$, but $L \ll 4\pi E/\Delta m_{31}^2$

$$P_{ee} = 1 - 2 \left[|U_{e4}|^2(1 - |U_{e4}|^2) + |U_{e5}|^2(1 - |U_{e5}|^2) - |U_{e4}|^2|U_{e5}|^2 \right]$$

$$P_{\mu\mu} = 1 - 2 \left[|U_{\mu4}|^2(1 - |U_{\mu4}|^2) + |U_{\mu5}|^2(1 - |U_{\mu5}|^2) - |U_{\mu4}|^2|U_{\mu5}|^2 \right]$$

$$P_{e\mu} = 2 \left[|U_{e4}|^2|U_{\mu4}|^2 + |U_{e5}|^2|U_{\mu5}|^2 + \text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*) \right]$$

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It follows

$$\begin{aligned} 2P_{e\mu} &\simeq (1 - P_{ee})(1 - P_{\mu\mu}) \\ &\quad + 4 \left[\text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*) + 4|U_{e4}|^2 |U_{\mu5}|^2 + 4|U_{e5}|^2 |U_{\mu4}|^2 \right] \\ &= (1 - P_{ee})(1 - P_{\mu\mu}) - 2 \left[|U_{e4}|^2 |U_{\mu5}|^2 + |U_{e5}|^2 |U_{\mu4}|^2 \right] \\ &\quad - 2 |U_{e4} U_{\mu5} - U_{e5} U_{\mu4}|^2 \end{aligned}$$

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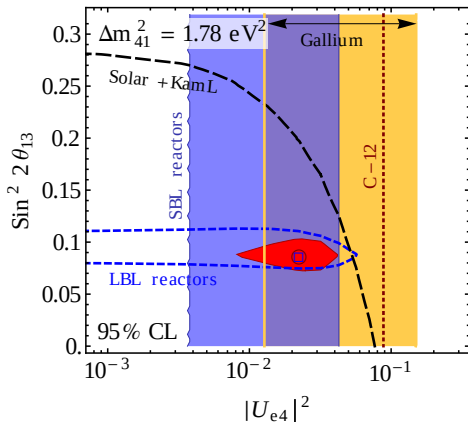
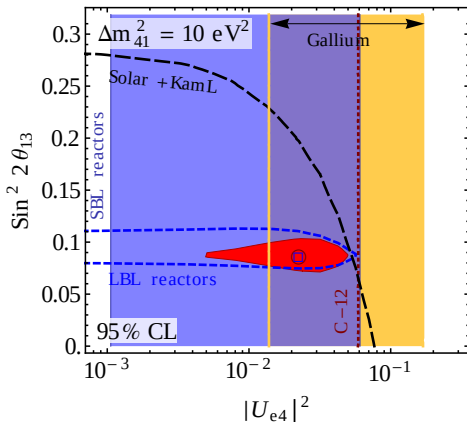
It follows

$$2P_{e\mu} \leq (1 - P_{ee})(1 - P_{\mu\mu})$$

Unlike in the 3 + 1 case, for 3 + 2 models, there is **NO one-to-one relation** between the appearance and disappearance probabilities.

However, there is an **inequality**, which can be used to set meaningful constraints.

Impact of θ_{13}

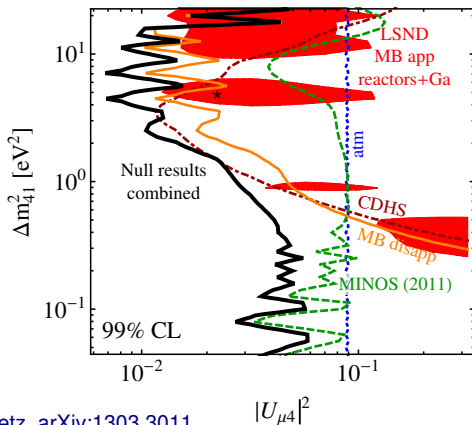


- Sterile neutrinos do not impact θ_{13} measurement
- $\theta_{13} \neq 0$ does not impact sterile neutrino search

JK Machado Maltoni Schwetz, arXiv:1303.3011

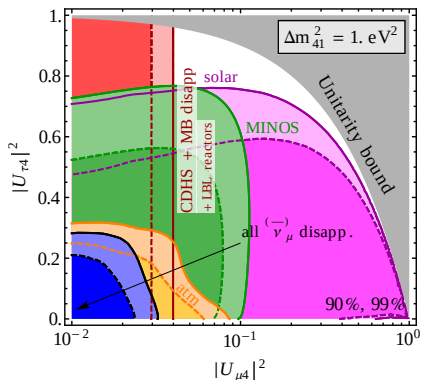
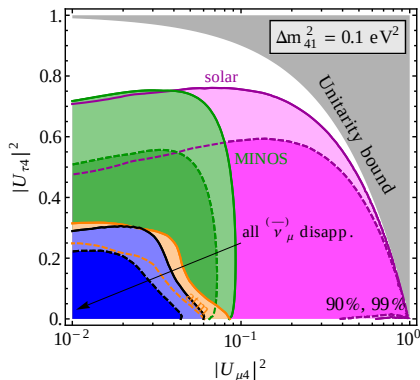
$\bar{\nu}_\mu$ disappearance in the 3+1 scenario

- Parameter regions favored by **tentative hints** are in **tension with null results**



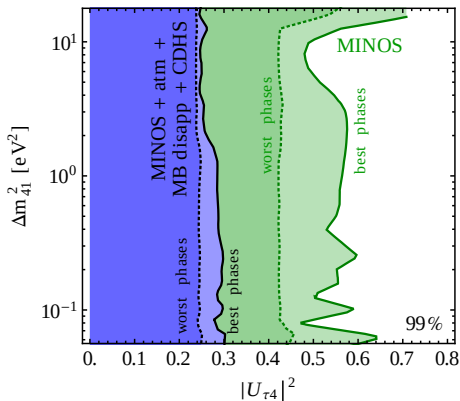
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- Parameter regions favored by **tentative hints** are in **tension with null results**
- Constraints on $|U_{\tau 4}| \sim \sin \theta_{34}$ possible due to NC events and matter effects



$\bar{\nu}_\mu$ disappearance in the 3+1 scenario

- Parameter regions favored by **tentative hints** are in **tension with null results**
- Constraints on $|U_{\tau 4}| \sim \sin \theta_{34}$ possible due to NC events and matter effects
- Complex phases important



Differences between our fit and Giunti et al.

- **MiniBooNE fit**

we use MB analysis based on official MC events, include BG oscillation

- **MINOS fit**

we fit CC+NC data, including ND and FD, detector response matrices based on official MINOS MC

- **Reactor fit**

minor differences in the data set, possibly different treatment of correlations among systematic uncertainties

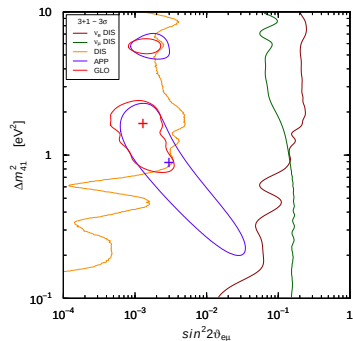
- **LSND fit**

Note that LSND spectral data is more constraining than the total count rate. We use this information; our fit is consistent with the numbers reported in hep-ex/0203023 (Church, Eitel, Mills, Steidl, combined LSND+KARMEN analysis)

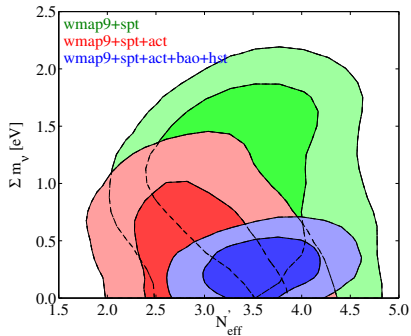
- **Atmospheric neutrinos**

Full fit vs. tabulated χ^2

A combined fit of oscillation data and cosmology

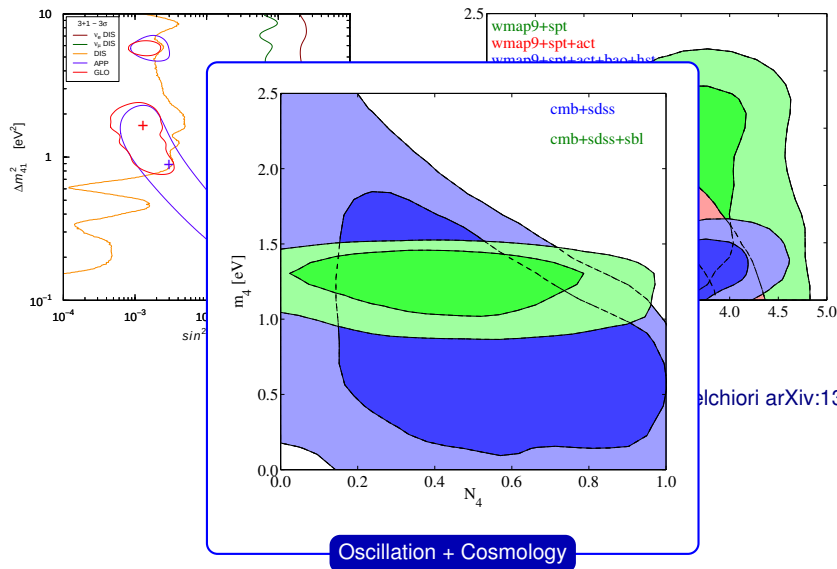


+



Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720

A combined fit of oscillation data and cosmology



Delchiori arXiv:1302.6720

Are light sterile neutrinos ruled out by cosmology?

ν_s production in the early Universe through $\nu_{e,\mu,\tau} \rightarrow \nu_s$ oscillations at $T \gtrsim \text{MeV}$

Dodelson Widrow 1994

Making sterile neutrinos fully consistent with cosmology

- > 1 new relativistic degrees of freedom + $w < -1$ + $\mu_\nu \neq 0$
Hamann Hannestad Raffelt Wong, arXiv:1108.4136
- **Entropy production** after neutrino decoupling (e.g. due to late decay of heavy sterile neutrinos or other particles) $\rightarrow$ neutrinos diluted
Fuller Kishimoto Kusenko 1110.6479, Ho Scherrer 1212.1689
- Very low reheating temperature
Gelmini Palomares-Ruiz Pascoli, astro-ph/0403323
- Large **lepton asymmetry** ($\gtrsim 0.01$) $\rightarrow \nu_s$ production MSW-suppressed
Foot Volkas hep-ph/9508275, Chu Cirelli astro-ph/0608206, Saviano et al. arXiv:1302.1200
- Couplings to a **Majoron field** $\rightarrow$ suppressed production
Bento Berezhiani, hep-ph/0108064
- **New gauge interaction** in the ν_s sector
 $\rightarrow \nu_s$ production **suppressed** by thermal potential
Hannestad et al. 1310.5926
Dasgupta JK 1310.6337

Two further remarks

- If **sterile** and **visible** sectors have ever been in **thermal equilibrium**, ν_s will have been **produced thermally** very early on.
- But **temperatures** of the two sectors are very different:

$$T_{\text{visible}} > T_{\text{sterile}}$$

after the SM phase transitions.

→ ν_s **abundance** $\ll$ active neutrino abundance

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→ ν_s **abundance** $\ll$ active neutrino abundance

Mixing of $U(1)_s$ -charged ν_s with active neutrinos:

$$\mathcal{L} \supset -\bar{L} Y_\nu \tilde{H} \nu_R - \bar{\nu}_s Y_s H_s \nu_R - \frac{1}{2} \overline{(\nu_R)^c} M_R \nu_R + h.c. ,$$

($\tilde{H}$ = SM Higgs, H_s = sterile sector Higgs)

see e.g. Harnik JK Machado arXiv:1202.6073

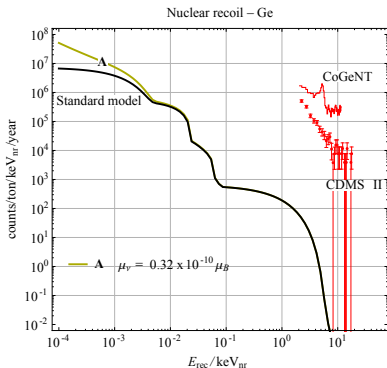
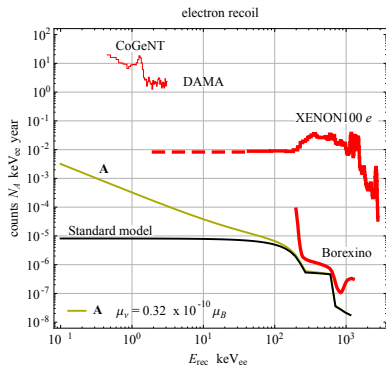
Example 1: Neutrino magnetic moments

Assume neutrinos carry an enhanced **magnetic moment**

$$\mathcal{L}_{\mu\nu} \supset \mu_\nu \bar{\nu} \sigma^{\alpha\beta} \partial_\beta \mathbf{A}_\alpha \nu, \quad \mu_\nu \gg \mu_{\nu, \text{SM}} = 3.2 \times 10^{-19} \mu_B$$

Cross section **large** at low energies due to photon propagator $\propto q^{-2}$

$$\frac{d\sigma_\mu(\nu e \rightarrow \nu e)}{dE_r} = \mu_\nu^2 \alpha \left(\frac{1}{E_r} - \frac{1}{E_\nu} \right),$$



Example: A not-so-sterile 4th neutrino

Introduce a new $U(1)'$ gauge boson A' (hidden photon) and a light sterile neutrino ν_s

Related model with gauged $U(1)_B$ first discussed in Pospelov 1103.3261
detailed studies in Harnik JK Machado 1202.6073 and Pospelov Pradler 1203.0545

- ν_s charged under $U(1)' \rightarrow$ direct coupling to A'
- SM particles couple to A' only through kinetic mixing

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \epsilon F'_{\mu\nu} F^{\mu\nu} + \bar{\nu}_s i \not{\partial} \nu_s + g' \bar{\nu}_s \gamma^\mu \nu_s A'_\mu \\ - (\overline{\nu_L})^c m_{\nu_L} \nu_L - (\overline{\nu_s})^c m_{\nu_s} \nu_s - (\overline{\nu_L})^c m_{\text{mix}} \nu_s$$

A small fraction of solar neutrinos can oscillate into ν_s

ν_s scattering cross section in the detector given by

$$\frac{d\sigma_{A'}(\nu_s e \rightarrow \nu_s e)}{dE_r} = \frac{\epsilon^2 e^2 g'^2 m_e}{4\pi p_\nu^2 (M_{A'}^2 + 2E_r m_e)^2} [2E_\nu^2 + E_r^2 - 2E_r E_\nu - E_r m_e - m_\nu^2]$$

Temporal modulation of neutrino signals

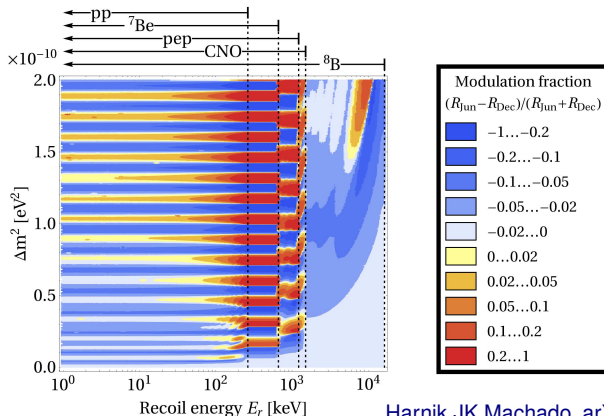
Signals of **new light force mediators** and/or **sterile neutrinos** can show **seasonal modulation**:

- The **Earth–Sun distance**: Solar neutrino flux **peaks in winter**.

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Harnik JK Machado, arXiv:1202.6073

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- **Sterile neutrino absorption**: For **strong ν_s – A' couplings** and **not-too-weak A' –SM couplings**, sterile neutrino **cannot traverse the Earth**.
→ lower flux **at night**. And **nights are longer in winter**.

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- The **Earth–Sun distance**: Solar neutrino flux **peaks in winter**.
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- **Sterile neutrino absorption**: For **strong ν_s – A' couplings** and **not-too-weak A' –SM couplings**, sterile neutrino **cannot traverse the Earth**.
→ lower flux **at night**. And **nights are longer in winter**.
- **Earth matter effects**: An **MSW-type resonance** can lead to modified flux of certain neutrino flavors **at night**. And **nights are longer in winter**.

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_s i \not{\partial} \nu_s + g' \bar{\nu}_s \gamma^\mu \nu_s A'_\mu$$


3+3 flavor toy model

Consider toy model with 3 sterile neutrinos, each of them mixing with only one of the active flavors:

$$U = R_{14}(\theta) R_{25}(\theta) R_{36}(\theta) U_{PMNS}, \quad R_{ij} = \text{rotation in } ij\text{-plane}.$$

Hamiltonian:

$$\mathcal{H} \simeq E + \frac{1}{2E} U \mathcal{D} U^\dagger + V_{MSW}, \quad \mathcal{D} = \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2, \Delta m_{41}^2, \Delta m_{51}^2, \Delta m_{61}^2)$$

Mikheyev-Smirnov-Wolfenstein (MSW) potential:

$$V_{MSW} = \sqrt{2} G_F \text{diag}(n_e - n_n/2, -n_n/2, -n_n/2, 0, 0, 0),$$

n_e (n_n) = electron (neutron) number density

Oscillation probability:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | e^{-i\mathcal{H}t} | \nu_\alpha \rangle \right|^2$$