Theory and Phenomenology of Sterile Neutrinos

Joachim Kopp (University of Mainz)

June 7, 2014 @ Neutrino 2014, Boston

PRISMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

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, $m \sim \text{TeV} \ldots M_{\text{Pl}}$)
  - Can explain baryon asymmetry of the Universe (leptogenesis, $m \gg 100$ GeV)
  - Can explain dark matter ($m \sim$ keV)
  - Can explain various neutrino oscillation anomalies ($m \sim$ eV)

Example: The νMSM

- SM + ≥ 3 sterile neutrinos N_j

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

- 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

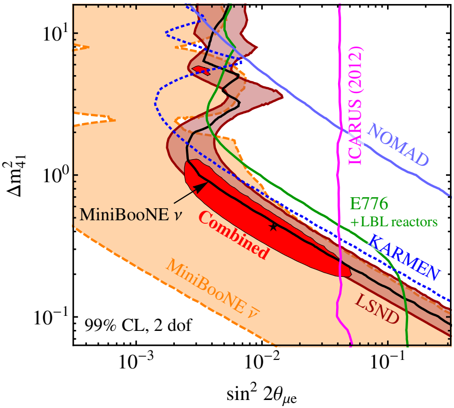
- Possible extensions
  - More sterile neutrinos $\rightarrow$ eV-scale neutrinos for short-baseline anomalies?
  - Left-right symmetric extension: sterile neutrinos charged under $SU(2)_R$

Duerr Fileviez-Perez Lindner, arXiv:1306.0568

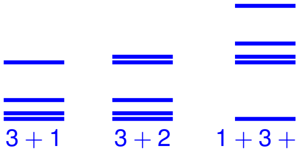
Oscillation Anomalies: A Global Fit

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

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



	χ^2_{3+1}/dof	χ^2_{3+2}/dof	χ^2_{1+3+1}/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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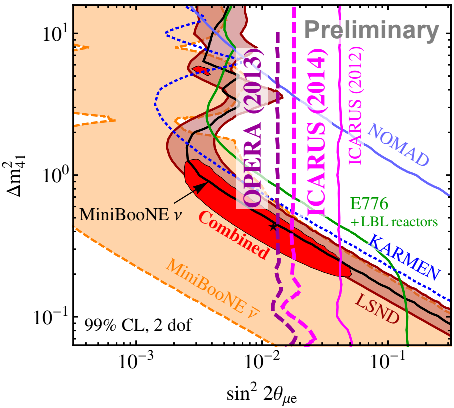

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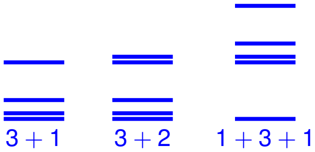

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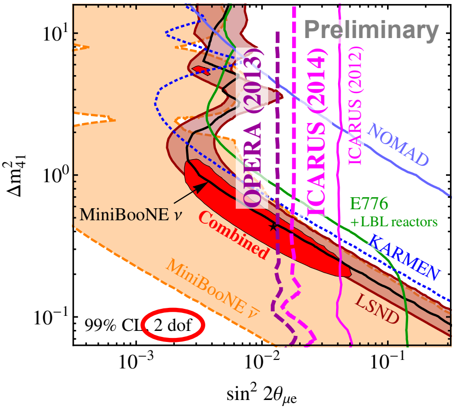

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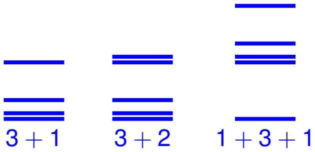

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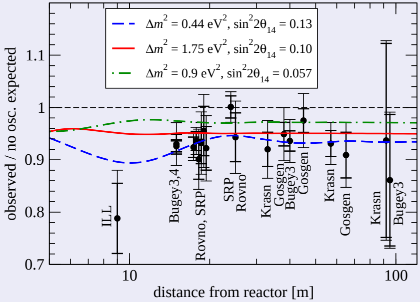
$\overset{(-)}{\nu}_e$ disappearance: reactor and gallium experiments

The reactor anomaly

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

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



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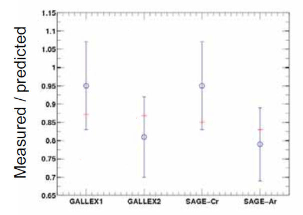
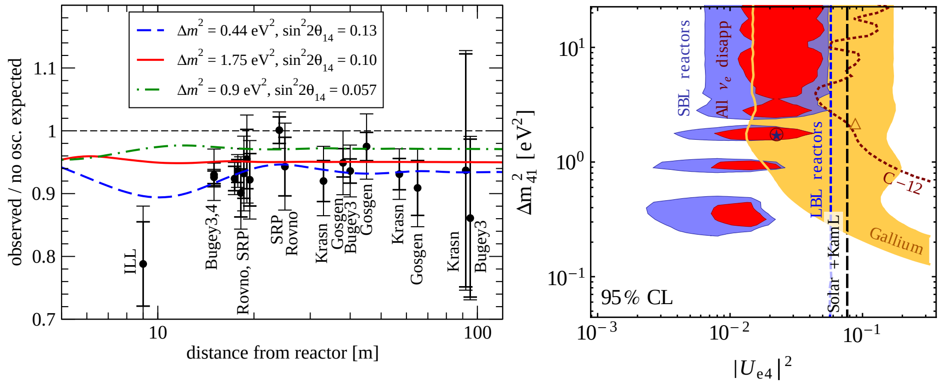
The gallium anomaly

- 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

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



	$\sin^2 2\theta_{14}$	Δm^2_{41} [eV^2]	χ^2_{min}/dof (GOF)	$\Delta\chi^2_{no\ osc}$/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%)
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: $\overset{(-)}{\nu}_e$ disappearance experiments consistent among themselves,
$\overset{(-)}{\nu}_e$ appearance experiments consistent among themselves.

But:

$3+1$ neutrinos

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

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

It follows

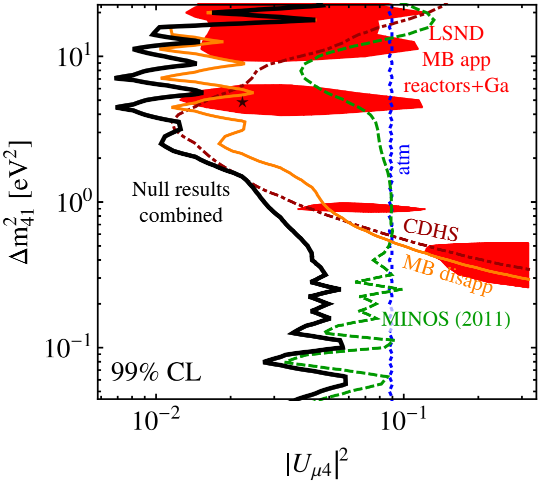
$$2P_{e\mu} \simeq (1 - P_{ee})(1 - P_{\mu\mu})$$

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

$\overset{(-)}{\nu}_\mu$ 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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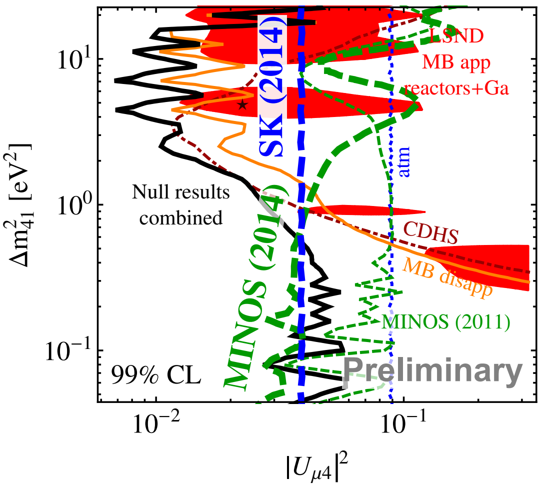
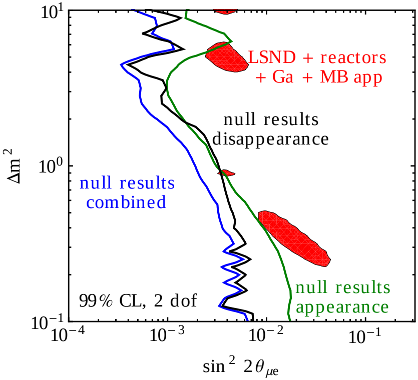


JK Machado Maltoni Schwetz, 1303.3011

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



	χ^2_{min}/dof	GOF
3+1	712/(689 − 9)	19%

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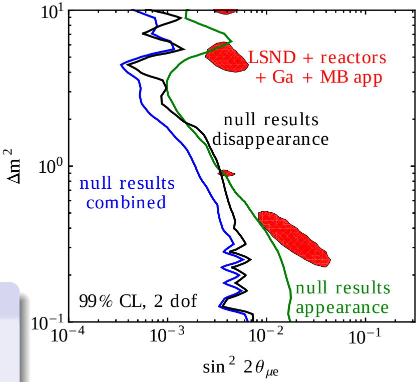


Parameter goodness of fit (PG) test:

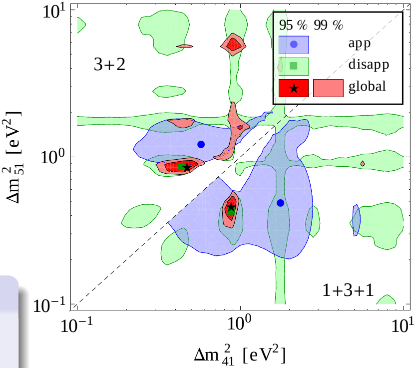
Compares χ^2_{min} from global and separate fits to test compatibility of 2 data sets

	χ^2_{min}/dof	GOF	χ^2_{PG}/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

- $3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal
- $3+2$ Tension remains for two sterile neutrinos



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The global oscillation fit

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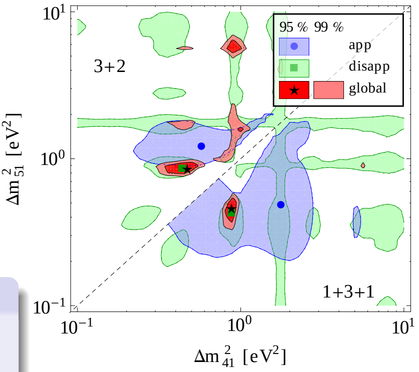
- **3 + 1** Severe tension between appearance and disappearance and between exp's with and without a signal
- **3 + 2** Tension remains for two sterile neutrinos
- **3 + 3** No significant improvement expected



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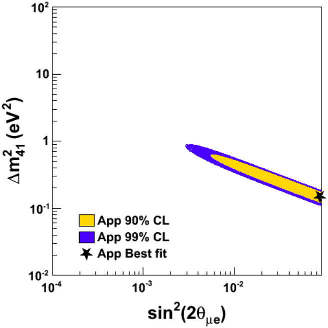
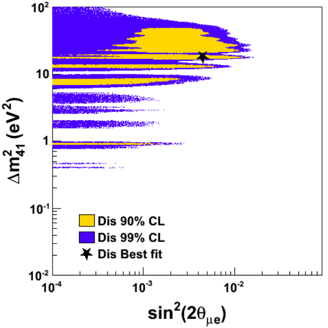
The MIT/Columbia fit

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD
- $\overset{(-)}{\nu}_\mu$ disappearance data:
  - MiniBooNE
  - Minos CC ν_μ
  - CDHS
  - CCFR
  - Atmospheric neutrinos
- $\overset{(-)}{\nu}_e$ 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

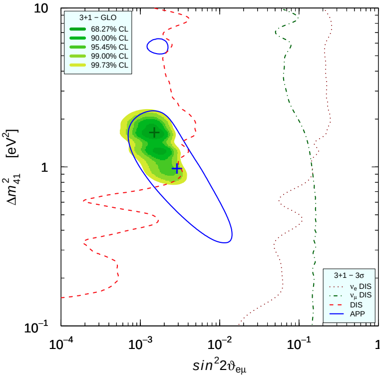
χ^2/dof and PG test results in qualitative agreement with ours $\to$ tension confirmed





The GL^4 fit

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - E776
  - KARMEN
  - NOMAD
  - ICARUS
  - OPERA
- $\overset{(-)}{\nu}_\mu$ disappearance data:
  - MiniBooNE/SciBooNE
  - Minos NC+CC ν_μ
  - CDHS
  - CCFR
  - Atmospheric neutrinos
- $\overset{(-)}{\nu}_e$ 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

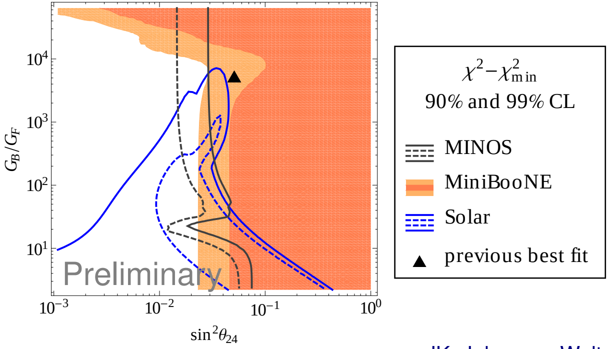
- Is one (or all) of the positive results not due to sterile neutrinos?
- Are some of the exclusion limits too strong? (removing one from the fit is not enough!)
- Does new physics beyond the simple $3 + X$ scenarios help?

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 $\mathcal{O}$(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

(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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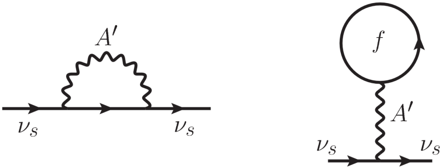
Question:

What does is take to evade these constraints?

Suppressed ν_s production from thermal MSW effect

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

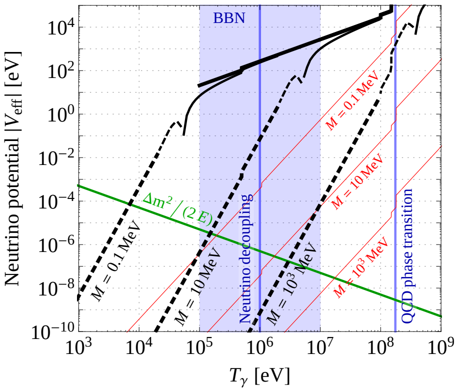


- Tadpole digagram: conventional MSW potential: $V \propto n_f - n_{\bar{f}}$
  Bubble digagram: thermal contribution $V \propto T^\alpha$
- At high T: strong MSW-type potential even without lepton asymmetry

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

- ν_s production through oscillations suppressed in the early Universe
  $\to$ 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 $V_{\rm eff}$ $\gg$ oscillation frequency $\Delta m^2/(2E)$

  until neutrino decoupling.

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

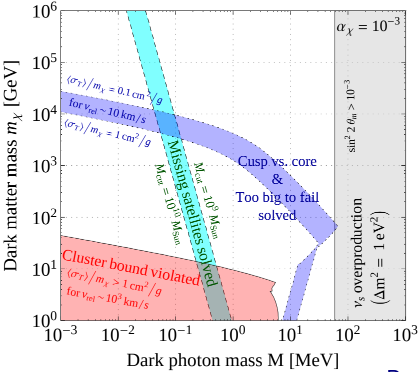
Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337

Hidden sector gauge forces and dark matter

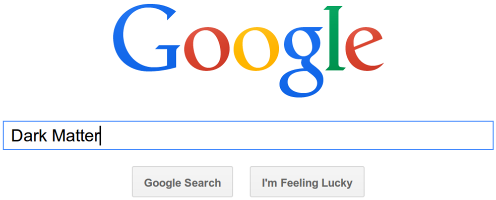
Interesting connection to dark matter physics:

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



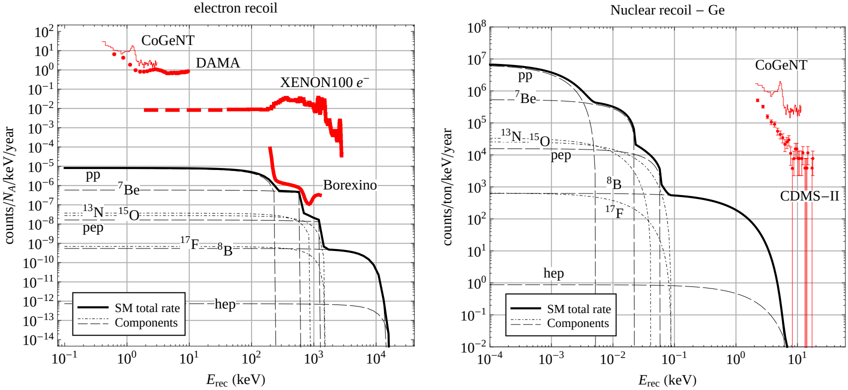
Light Sterile Neutrinos and Dark Matter Searches

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

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



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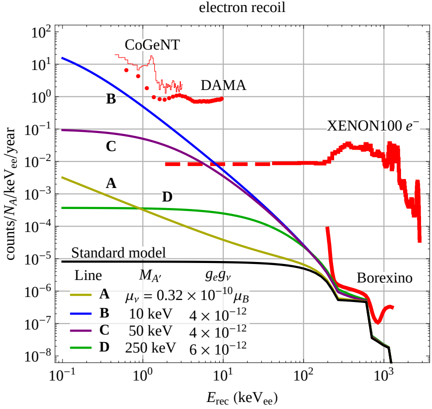
SM signal will only become sizeable in multi-ton detectors

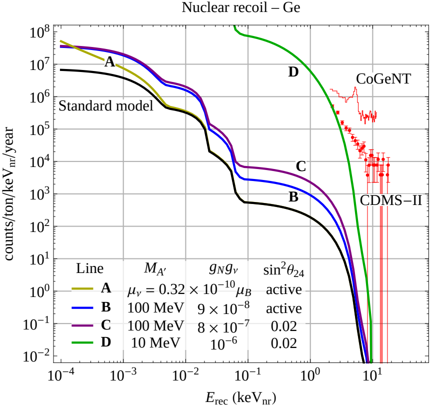
But: New physics can enhance the rate

Examples:

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

Low-energy scattering of neutrinos beyond the SM





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

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]

- 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

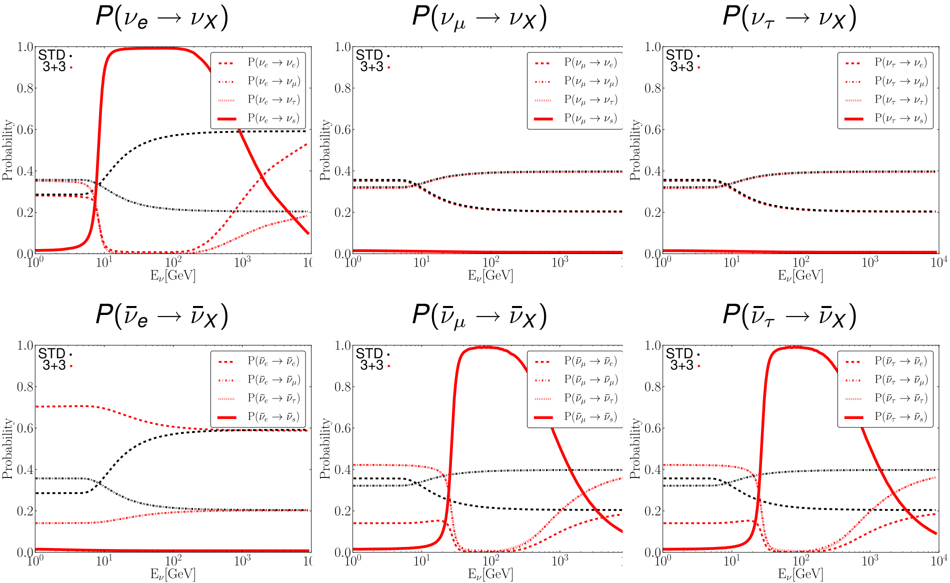
[Harnik JK Machado arXiv:1202:6073]

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

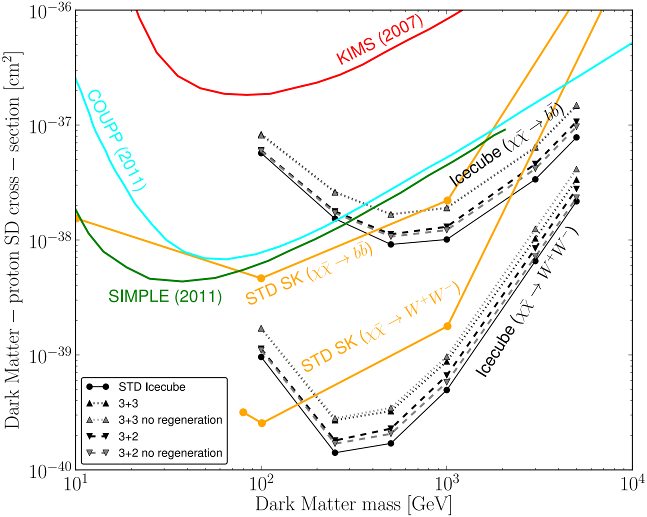
Oscillation probabilities for a 3+3 toy scenario



Thick red lines = active–sterile oscillations

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

Impact on IceCube limits

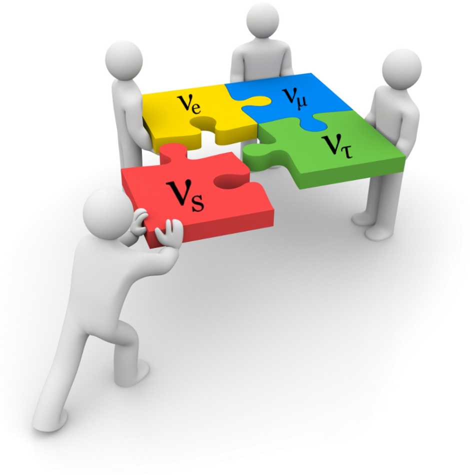


plot from Carlos Argüelles JK, arXiv:1202.3431
see also Esmaili Peres, arXiv:1202.2869

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

$\overset{(-)}{\nu}_e$ disappearance

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

$\overset{(-)}{\nu}_e$ appearance

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

$\overset{(-)}{\nu}_\mu$ disappearance

- Atmospheric neutrinos (includes *either* $\overset{(-)}{\nu}_e$ 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 $L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

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

$$P_{\mu\mu} = 1 - 2\Big[|U_{\mu 4}|^2(1-|U_{\mu 4}|^2) + |U_{\mu 5}|^2(1-|U_{\mu 5}|^2) - |U_{\mu 4}|^2|U_{\mu 5}|^2\Big]$$

$$P_{e\mu} = 2\Big[|U_{e4}|^2|U_{\mu 4}|^2 + |U_{e5}|^2|U_{\mu 5}|^2 + \mathrm{Re}(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)\Big]$$

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It follows

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

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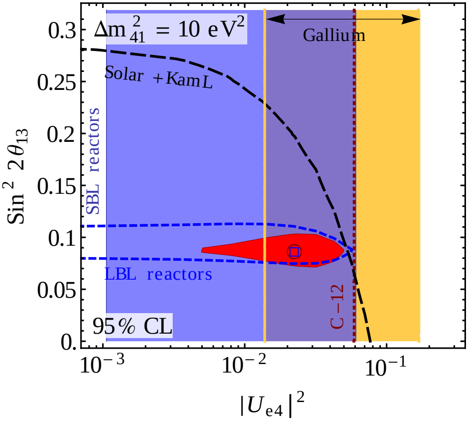
It follows

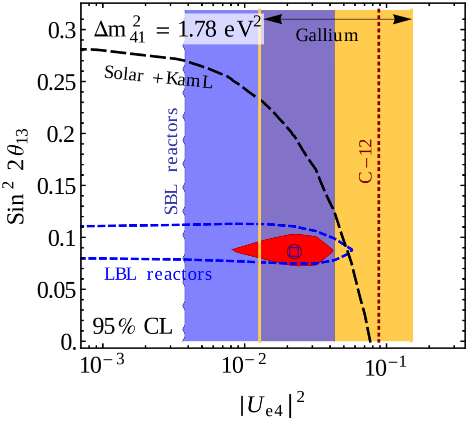
$$2P_{e\mu} \leq (1 - P_{ee})(1 - P_{\mu\mu})$$

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}



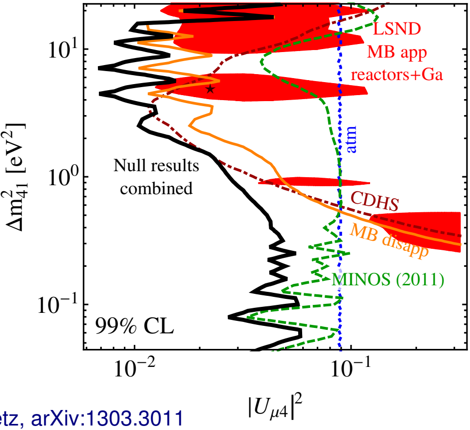


- Sterile neutrinos do not impact θ_{13} measurement
- $\theta_{13} \neq 0$ does not impact sterile neutrino search

JK Machado Maltoni Schwetz, arXiv:1303.3011

$\overset{(-)}{\nu}_\mu$ disappaearance in the 3+1 scenario

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



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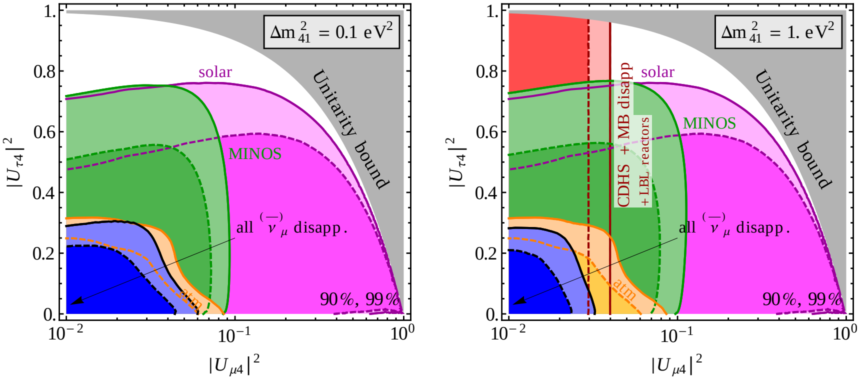
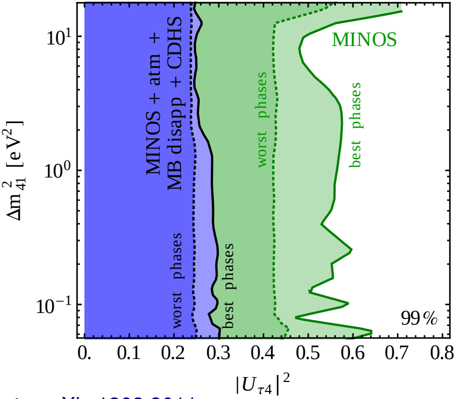
- Constraints on $|U_{\tau 4}| \sim \sin\theta_{34}$ possible due to NC events and matter effects



JK Machado Maltoni Schwetz, arXiv:1303.3011

$\overset{(-)}{\nu}_\mu$ disappaearance 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

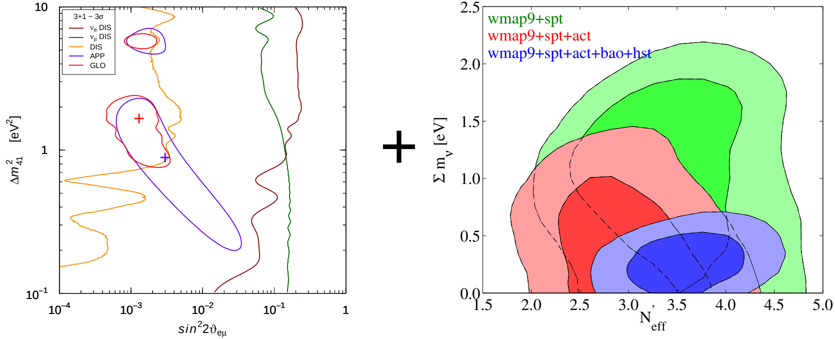


JK Machado Maltoni Schwetz, arXiv:1303.3011

Differences between our fit and Giunti et al.

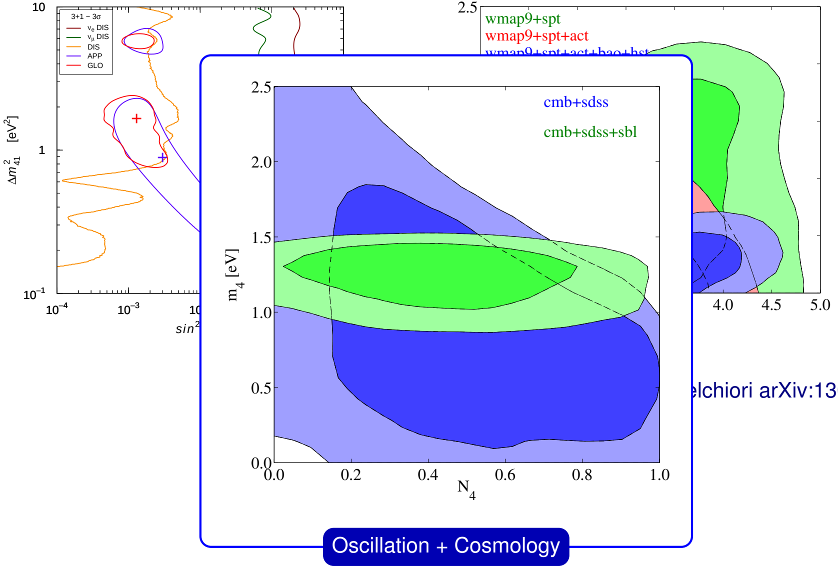
- MiniBooNE fit
  we use MB analysis based on official MC events, include BG oscillation
- MINOS fit
  we fit CC+NC data, including ND and FD, detector response matrices based on official MINOS MC
- Reactor fit
  minor differences in the data set, possibly different treatment of correlations among systematic 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



elchiori arXiv:1302.6720

Are light sterile neutrinos ruled out by cosmology?

ν_s production in the early Universe through $\nu_{e,\mu,\tau} \to \nu_s$ oscillations at $T \gtrsim$ 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) $\to$ 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 ($\gtrsim 0.01$) $\to$ ν_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 $\to$ suppressed production

  Bento Berezhiani, hep-ph/0108064

- New gauge interaction in the ν_s sector $\to$ ν_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 equilbrium, 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.
$\rightarrow$ ν_s abundance $\ll$ active neutrino abundance

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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

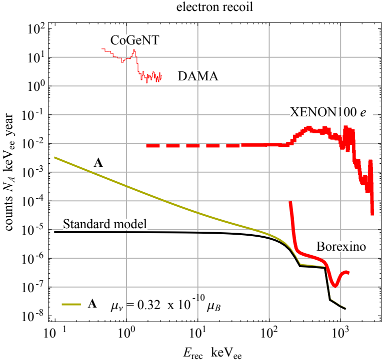
Example 1: Neutrino magnetic moments

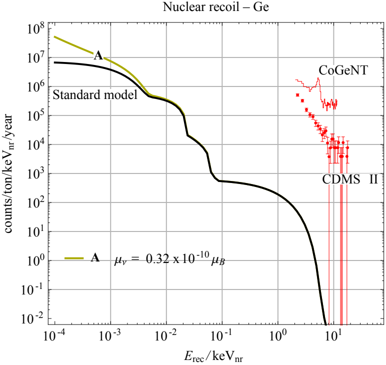
Assume neutrinos carry an enhanced magnetic moment

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

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

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





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

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_s i\partial\!\!\!/ \nu_s + g'\bar{\nu}_s\gamma^\mu\nu_s A'_\mu$$
$$- \overline{(\nu_L)^c} m_{\nu_L}\nu_L - \overline{(\nu_s)^c} m_{\nu_s}\nu_s - \overline{(\nu_L)^c} m_{\text{mix}}\nu_s$$

A small fraction of solar neutrinos can oscillate into ν_s

ν_s scattering cross section in the detector given by

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

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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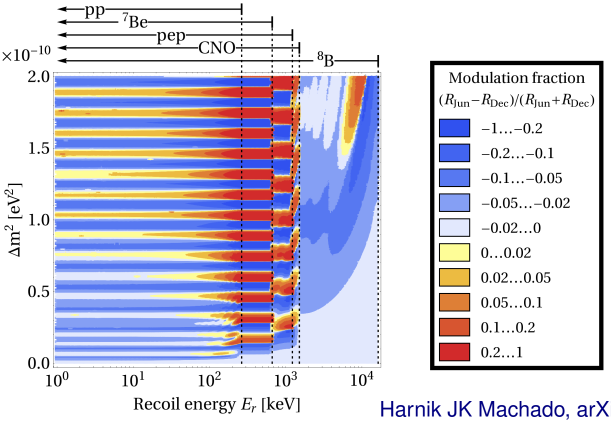

Harnik JK Machado, arXiv:1202.6073

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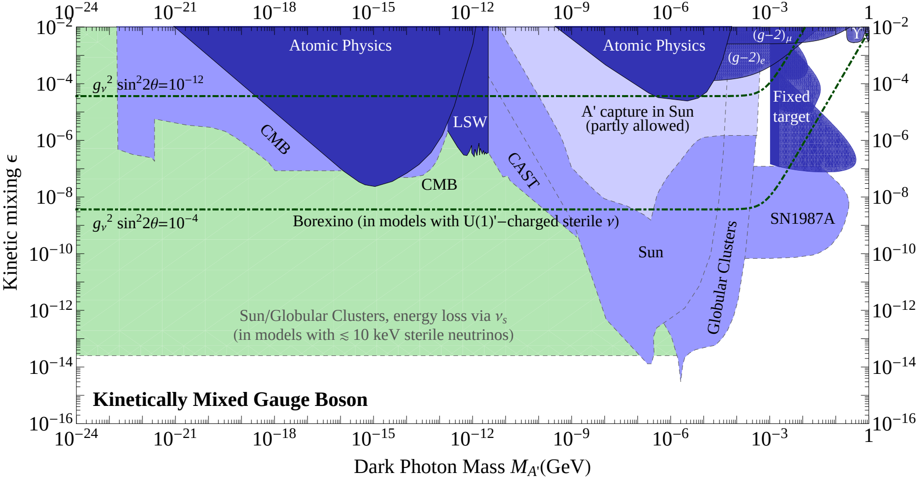
- Earth matter effects: An MSW-type resonance can lead to modified flux of certain neutrino flavors at night. And nights are longer in winter.

Hidden photons

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_s i\partial\!\!\!/ \nu_s + g'\bar{\nu}_s\gamma^\mu\nu_s A'_\mu$$



Constraints from Jaeckel Ringwald 1002.0329, Redondo 0801.1527,
Bjorken Essig Schuster Toro 0906.0580, Dent Ferrer Krauss 1201.2683, Harnik JK Machado

3+3 flavor toy model

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

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

Hamiltonian:

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

Mikheyev-Smirnov-Wolfenstein (MSW) potential:

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

n_e (n_n) = electron (neutron) number density

Oscillation probability:

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