Sterile Neutrinos on Earth and in the Skies

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MAX-PLANCK-GESELLSCHAFT

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Outline

Outline

Sterile neutrinos

from Merriam-Webster online dictionary

…so why do we talk about 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, $m \gg 100$ GeV)
  - Can explain dark matter ($m \sim$ keV)
  - Can explain various neutrino oscillation anomalies ($m \sim$ eV)
    $\rightarrow$ This talk

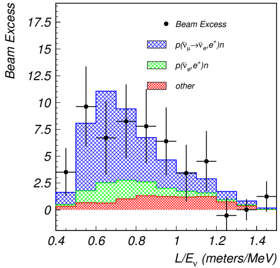
Outline

1. Motivation
2. Oscillation anomalies
   - ν_e appearance
   - ν_e disappearance
   - ν_μ disappearance
   - Sterile Neutrino Oscillations: The Global Picture
3. Sterile Neutrinos in Cosmology
4. Light sterile neutrinos and dark matter searches
   - Sterile neutrinos and direct dark matter searches
   - Sterile neutrinos and indirect dark matter searches
5. Summary

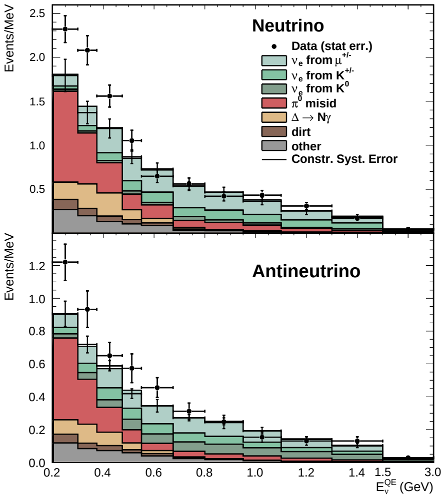
Outline

Oscillation anomalies: LSND and MiniBooNE

- LSND:
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$)
- MiniBooNE:
  - No significant ν_e or $\bar{\nu}_e$ excess in the LSND-preferred region
  - but $\bar{\nu}_e$ consistent with LSND
  - Low-E excess not understood



LSND hep-ex/0104049



MiniBooNE arXiv:1207.4809

eV-scale sterile neutrinos

Typical Lagrangian:

$$\mathcal{L} \supset \frac{1}{2} M_{ij}^{(a)} \overline{\nu_i^c} \nu_j + \frac{1}{2} M_{is}^{(s)} \overline{\nu_i^c} \nu_s + h.c.$$

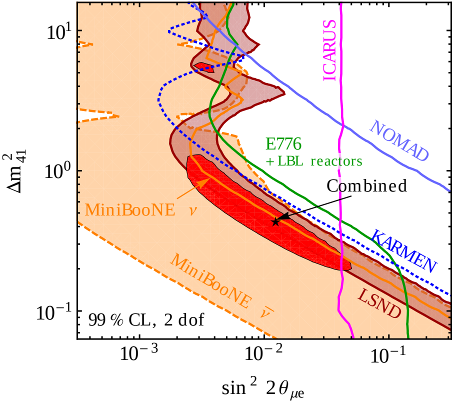
$\Rightarrow$ mass mixing between active and sterile neutrinos

Signatures in oscillation experiments

- Disappearance of active neutrinos
  (e.g. $\nu_e \to \nu_s$ oscillations)
  Atmospheric, Solar, Reactor, Pion decay beam, Radioactive source experiments
- Anomalous transitions among active neutrinos ("appearance")
  (e.g. "$\nu_\mu \to \nu_s \to \nu_e$")
  Pion decay beams
- Oscillation length $L^{\mathrm{osc}} = 4\pi E / \Delta m_{41}^2$ different from SM expectation
  (typically shorter)

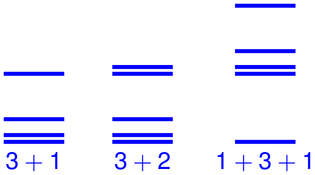
Notation: $\Delta m_{jk}^2 = m_j^2 - m_k^2$; $m_{4,5}$: mostly sterile, $m_{1,2,3}$: mostly active

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



	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 $1+3+1$

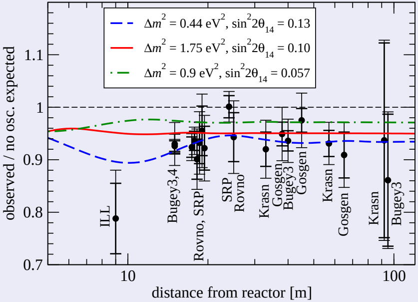


JK Machado Maltoni Schwetz, 1303.3011
other fits by Giunti Laveder et al.
Conrad Ignarra Karagiorgi Shaevitz Spitz Djurcic Sorel

Outline

Reactor and gallium experiments

- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim$ 3.5% higher than previous prediction
  Mueller et al. 1101.2663, P. Huber 1106.0687; see, however, Hayes et al. 1309.4146
- Method: Use measured β-spectra from ^{238}U, ^{235}U, ^{241}Pu fission at ILL and convert to $\bar{\nu}_e$ spectrum (for single β-decay: $E_\nu = Q - E_e$)
- Requires knowledge of Q-values for all contributing decays.
  $\rightarrow$ take from nuclear databases where available, fit to data otherwise



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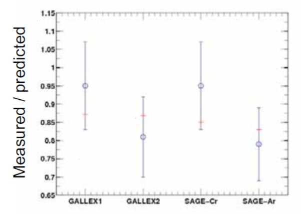
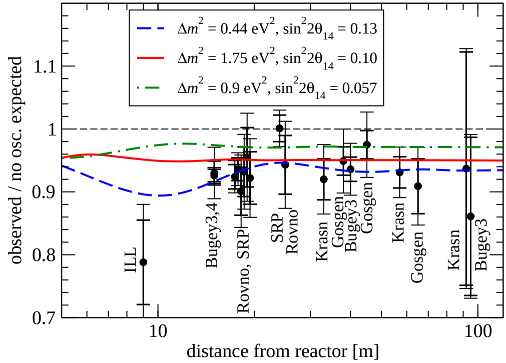
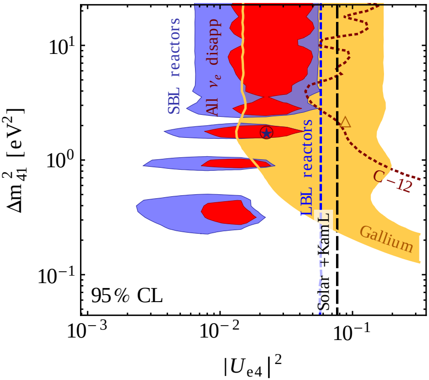
- Experiments with intense radioactive ν_e sources (^{51}Cr and ^{37}Ar)
- Neutrino detection via
  $^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^-$
- Observation: Neutrino deficit ($\sim 3\sigma$)

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

Outline

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.

Relation between appearance and disappearance

$3 + 2$ neutrinos

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

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

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

$$P_{e\mu} = 2\Big[|U_{e4}|^2|U_{\mu4}|^2 + |U_{e5}|^2|U_{\mu5}|^2 + \mathrm{Re}(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5})\Big]$$

Relation between appearance and disappearance

$3+2$ neutrinos

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

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

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

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

It follows

$$\begin{aligned} 2P_{e\mu} &\simeq (1-P_{ee})(1-P_{\mu\mu}) \\ &\quad + 4\Big[\mathrm{Re}(U^*_{e4}U_{\mu 4}U_{e5}U^*_{\mu 5}) + 4|U_{e4}|^2|U_{\mu 5}|^2 + 4|U_{e5}|^2|U_{\mu 4}|^2\Big] \\ &= (1-P_{ee})(1-P_{\mu\mu}) - 2\Big[|U_{e4}|^2|U_{\mu 5}|^2 + |U_{e5}|^2|U_{\mu 4}|^2\Big] \\ &\quad - 2\big|U_{e4}U_{\mu 5} - U_{e5}U_{\mu 4}\big|^2 \end{aligned}$$

Relation between appearance and disappearance

$3+2$ neutrinos

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

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

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

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

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.

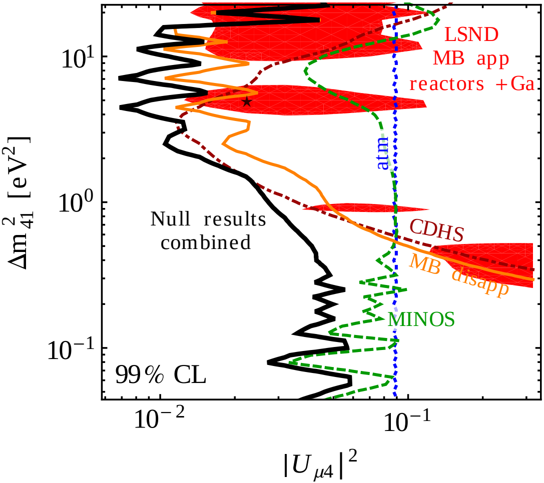
Combining different oscillation channels

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



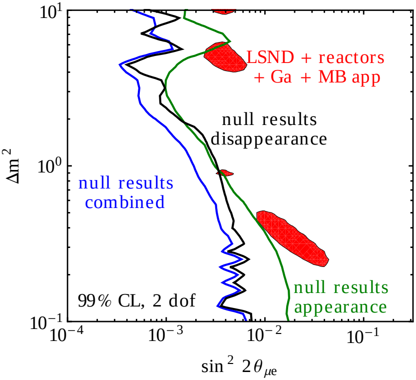
JK Machado Maltoni Schwetz, 1303.3011

Outline

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

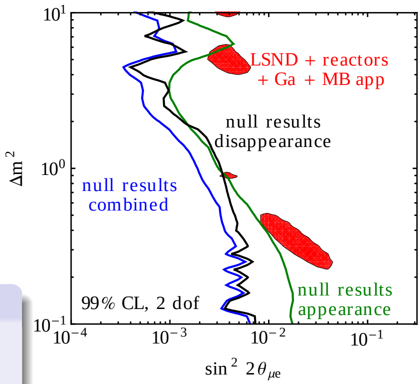


	χ^2_{min}/dof	GOF
3+1	712/(689 − 9)	19%

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



Parameter goodness of fit (PG) test:

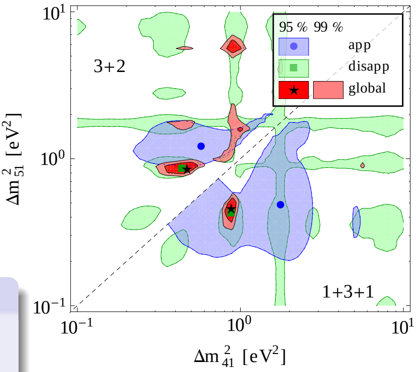
Compares χ^2_{min} from global and separate fits to test compatibility of 2 data sets

	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
- $3+2$ Fit improves considerably with two sterile neutrinos



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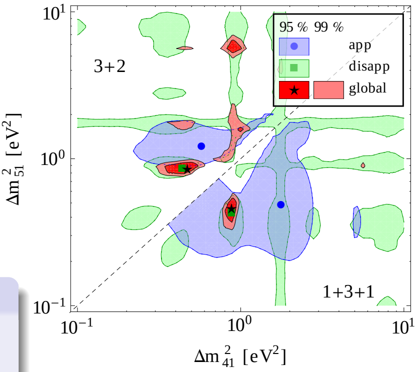
	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}
3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}

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
- $3+2$ Fit improves considerably with two sterile neutrinos
- $1+3+1$ Further improvement, especially in appearance fit



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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 data alone:

severe tension

in all cases

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?

Outline

Sterile neutrinos in cosmology

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

Sum of neutrino masses

$\sum m_\nu \lesssim 0.5$ eV

# of relativistic species

$N_\nu = 4$ mildly favored?

Giusarma Di Valentino Lattanzi Melchiorri Mena, arXiv:1403.4852
Dvorkin Wyman Rudd Hu, arXiv:1403.8049
Li Xia Zhang, arXiv:1404.0238
Zhang Li Zhang, arXiv:1403.7028, 1404.3598

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

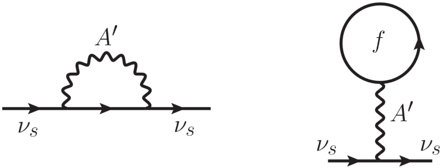
  Bento Berezhiani, hep-ph/0108064

- 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

Suppressed ν_s production from thermal MSW effect

- Assume sterile neutrinos are charged under a new gauge group $U(1)_s$
- Neutrino self energy:



- Thermal propagators:

$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

with

$$\Gamma_f(p) = 2\pi\delta(p^2 - m^2)n_f(p)\,, \qquad n_f(p) = [e^{|p\cdot u|/T_s} + 1]^{-1}\,,$$

$$\Gamma_b(p) = 2\pi\delta(p^2 - m^2)n_b(p)\,, \qquad n_b(p) = [e^{|p\cdot u|/T_s} - 1]^{-1}\,.$$

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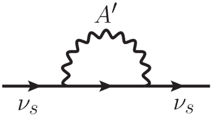
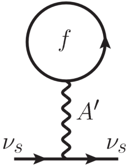




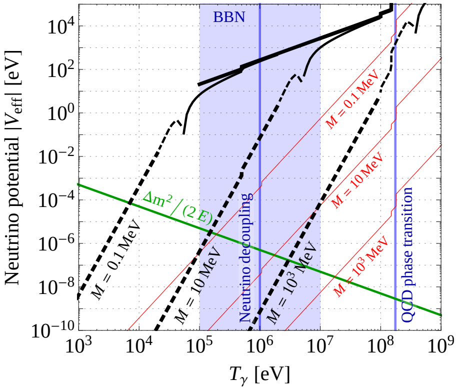
- Tadpole digagram: conventional MSW potential: $V \propto n_{\nu_s} - n_{\bar{\nu}_s}$
  Bubble digagram: thermal contribution $V \propto T^\alpha$
- Strong MSW-type potential even without lepton asymmetry

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

- ν_s production through oscillations suppressed in the early Universe
  $\rightarrow$ no cosmological constraints

Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337

Suppressed ν_s production from 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

Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv: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

Two further remarks

- If sterile and visible sectors have ever been in thermal equilibrium, ν_s will have been produced thermally very early on.
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  after the SM phase transitions.
  $\to$ 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)

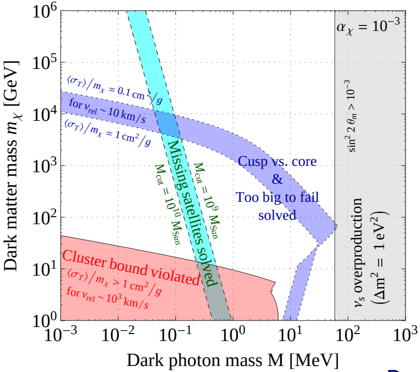
see e.g. Harnik JK Machado arXiv:1202.6073

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

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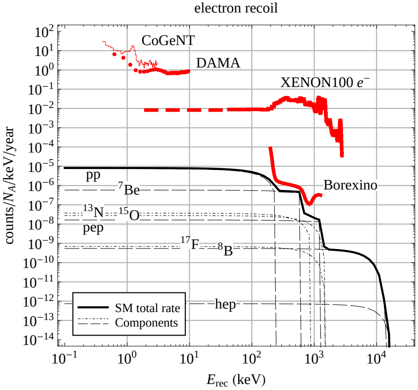
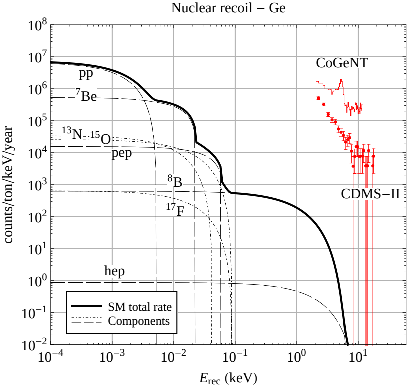
Neutrinos and direct dark matter detection

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

$\Rightarrow$ DM detectors can search for new physics in the ν sector

$\Rightarrow$ New ν physics can be confused with a dark matter signal

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

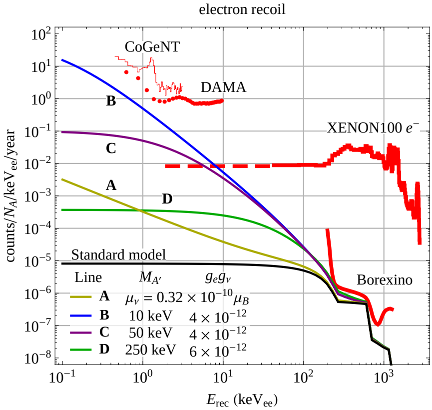
$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \epsilon F'_{\mu\nu} F^{\mu\nu} + \bar{\nu}_s i \partial\!\!\!/ \nu_s + g' \bar{\nu}_s \gamma^\mu \nu_s A'_\mu$$
$$- \overline{(\nu_L)^c} m_{\nu_L} \nu_L - \overline{(\nu_s)^c} m_{\nu_s} \nu_s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

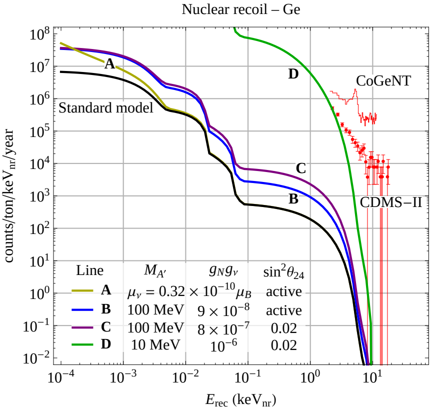
A small fraction of solar neutrinos can oscillate into ν_s

ν_s scattering cross section in the detector given by

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

Example: A not-so-sterile 4th neutrino





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 $U(1)_B$

proposed in Pospelov 1103.3261, details in 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

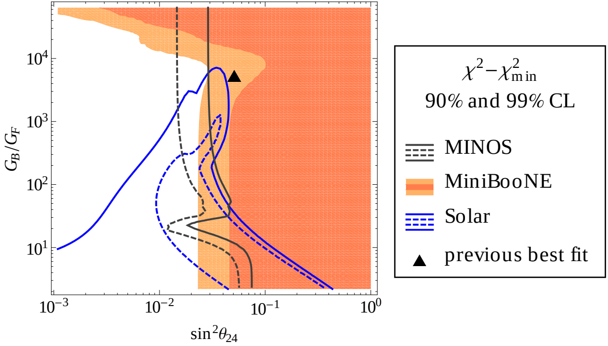
Harnik JK Machado arXiv:1202:6073

Interacting sterile neutrinos and SBL oscillations

If sterile neutrinos have new interactions with SM fermions, the associated MSW potentials will influence oscillations.

How does this affect the tension in the SBL data?

Karagiorgi Shaevitz Conrad, arXiv:1202.1024



JK, Johannes Welter, in preparation

Outline

Sterile neutrinos and DM annihilation in the Sun

- IceCube and Super-Kamiokande 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

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:

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

Mikheyev-Smirnov-Wolfenstein (MSW) potential:

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

n_e (n_n) = electron (neutron) number density

Oscillation probability:

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

Two-flavor approximation

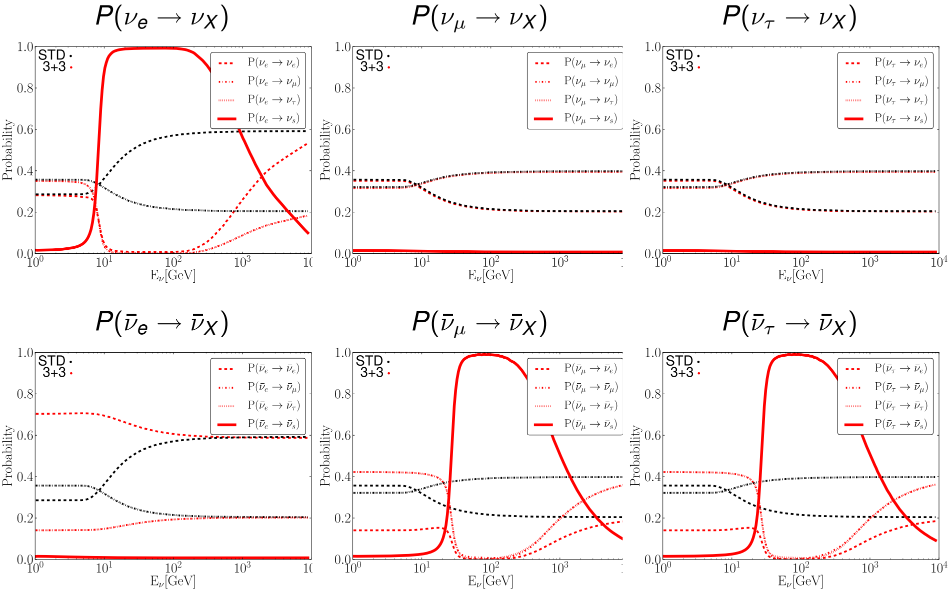
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{\text{eff}} \, \sin^2 \frac{\Delta m^2_{\text{eff}} L}{4E} \,,$$

with

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

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

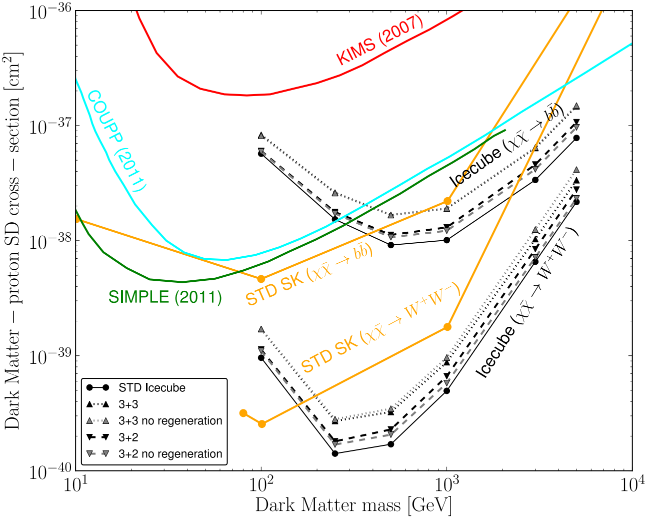
Oscillation probabilities



Thick red lines = active–sterile oscillations

Carlos Argüelles JK, arXiv:1202.3431

Impact on IceCube limits



Carlos Argüelles JK, arXiv:1202.3431

Outline

Summary

- Sterile neutrinos are theoretically well motivated and phenomenologically useful
- Global fits shows tension between appearance and disappearance searches
  - Note: Different groups come to somewhat different conclusions
- Cosmology after BICEP-2 seems to mildly favor sterile neutrinos with $m_s \sim 0.5$ eV (a little too light for the SBL anomalies)
- Many mechanisms for making sterile neutrinos fully consistent with cosmology
  - Example: new gauge interaction in the sterile sector
  - Can additionally solve small scale structure problem if coupled also to dark matter
- Sterile neutrinos and dark matter searches
  - Direct searches: Non-standard neutrino signals in DM detectors
  - Indirect searches: IceCube 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

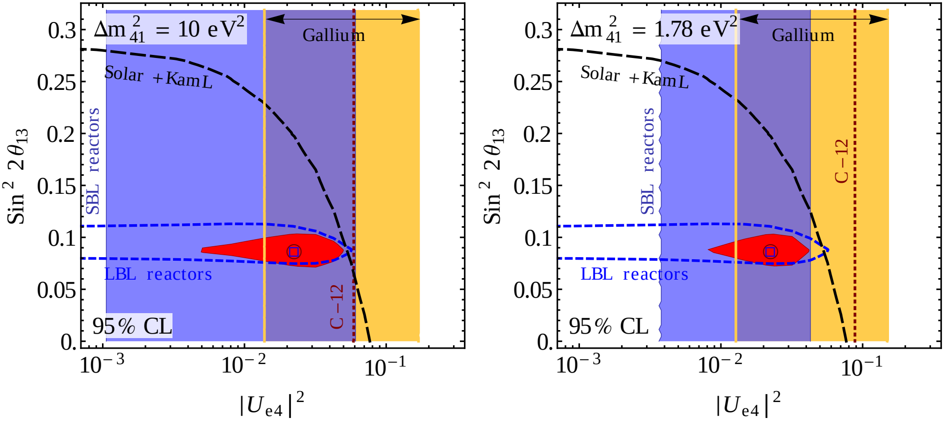
$\overset{(-)}{\nu}_e$ appearance

- 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

Impact of θ_{13}

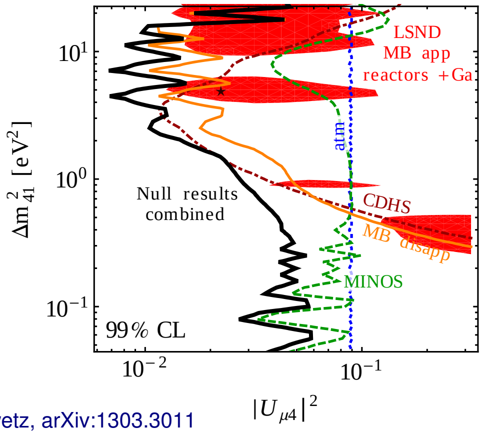


- Sterile neutrinos do not impact θ_{13} measurement
- $\theta_{13} \neq 0$ does not impact sterile neutrino search

JK Machado Maltoni Schwetz, arXiv:1303.3011

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

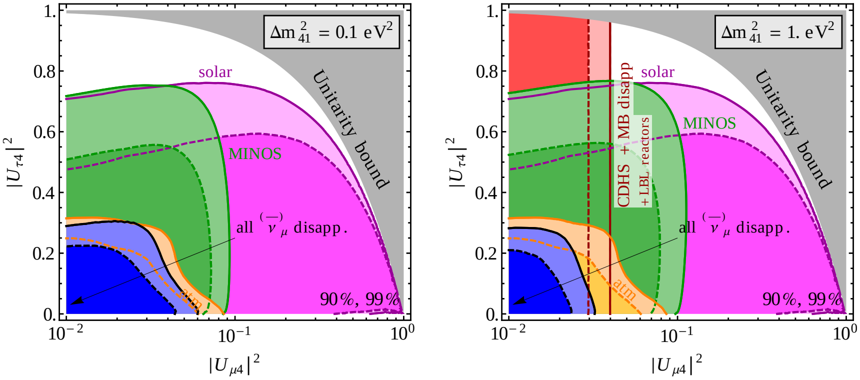
- Parameter regions favored by tentative hints are in tension with null results



JK Machado Maltoni Schwetz, arXiv:1303.3011

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

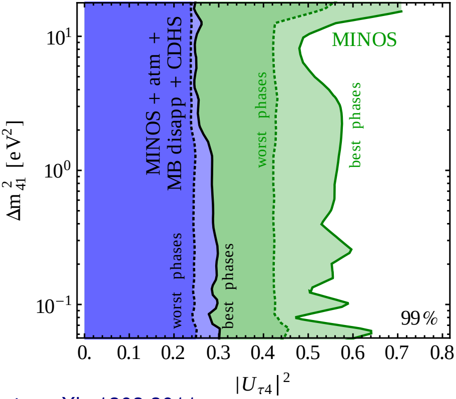
- Parameter regions favored by tentative hints are in tension with null results
- Constraints on $|U_{\tau 4}| \sim \sin\theta_{34}$ possible due to NC events and matter effects



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

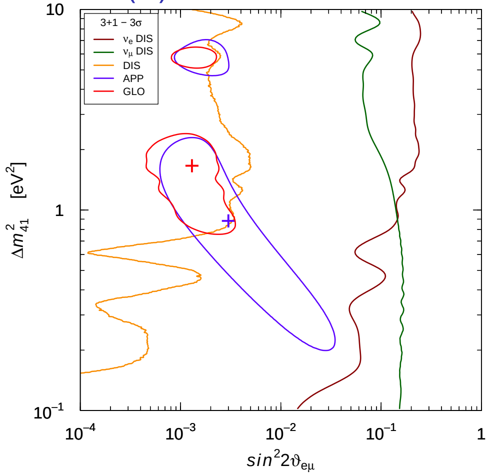
The Giunti et al. fit

Includes the following data sets:

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE ($E > 475$ MeV)
  - KARMEN
  - NOMAD
  - ICARUS
- $\overset{(-)}{\nu}_\mu$ disappearance data:
  - CDHS
  - MINOS bound on $|U_{\mu 4}|$
- $\overset{(-)}{\nu}_e$ disappearance data:
  - Reactor experiments
  - Gallium anomaly
  - Solar neutrinos
  - KamLAND
  - ν_e–^{12}C CC scattering in KARMEN and LSND

Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720
see also Giunti Laveder Li Liu Long arXiv:1210.5715
Giunti Laveder arXiv:1111.1069

The Giunti et al. fit (2)



APP/DIS curves: 3σ C.L.

Parameter goodness of fit (APP vs. DIS): 4%

Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720
see also Giunti Laveder Li Liu Long arXiv:1210.5715
Giunti Laveder arXiv:1111.1069

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

The Karagiorgi et al. fit

Conrad Ignarra Karagiorgi Shaevitz Spitz
arXiv:1207.4765
Karagiorgi arXiv:1110.3735
Karagiorgi Djurcic Conrad Shaevitz Sorel
arXiv:0906.1997

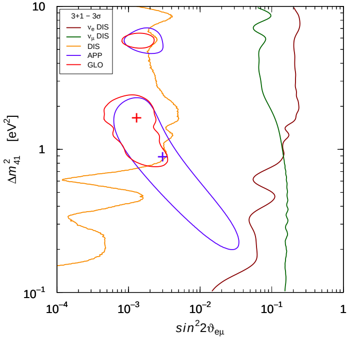
Includes the following data sets:

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD
- $\overset{(-)}{\nu}_\mu$ disappearance data:
  - MiniBooNE
  - Minos CC u_μ
  - CDHS
  - CCFR
  - Atmospheric neutrinos
- $\overset{(-)}{\nu}_e$ disappearance data:
  - Short baseline reactor experiments
  - Gallium experiments
  - ν_e–^{12}C CC scattering in KARMEN and LSND

Result

χ^2/dof and PG test results in qualitative agreement with ours

A combined fit of oscillation data and cosmology



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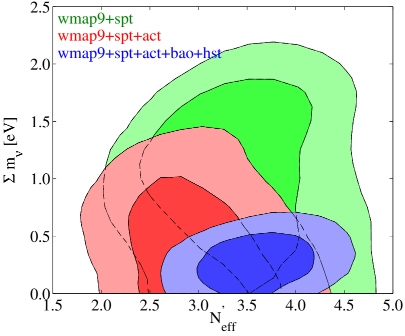
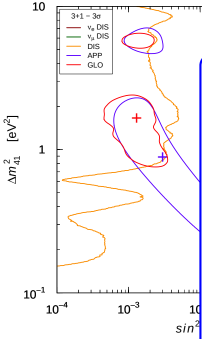
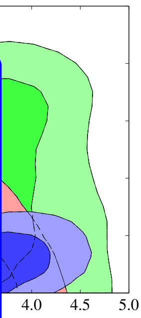


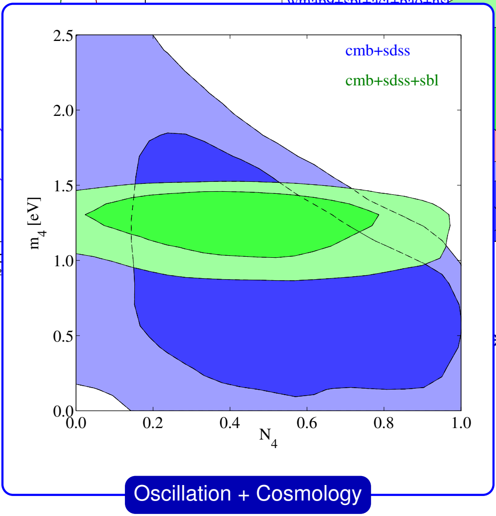
Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720

A combined fit of oscillation data and cosmology





elchiori arXiv:1302.6720



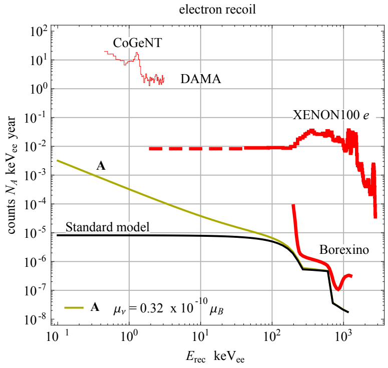
Example 1: Neutrino magnetic moments

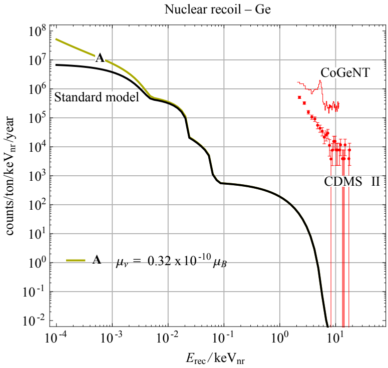
Assume neutrinos carry an enhanced magnetic moment

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

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

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





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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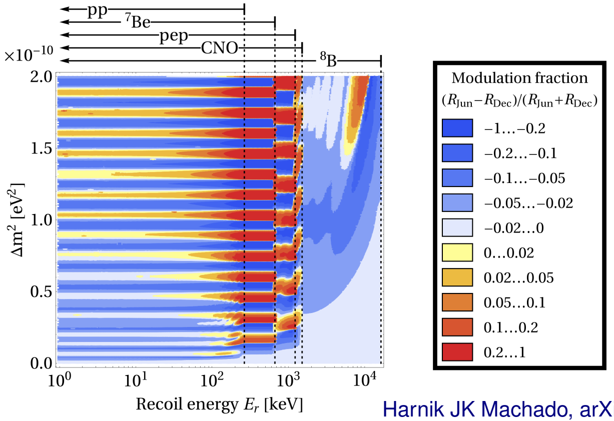

Harnik JK Machado, arXiv:1202.6073

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  $\rightarrow$ lower flux at night. And nights are longer in winter.

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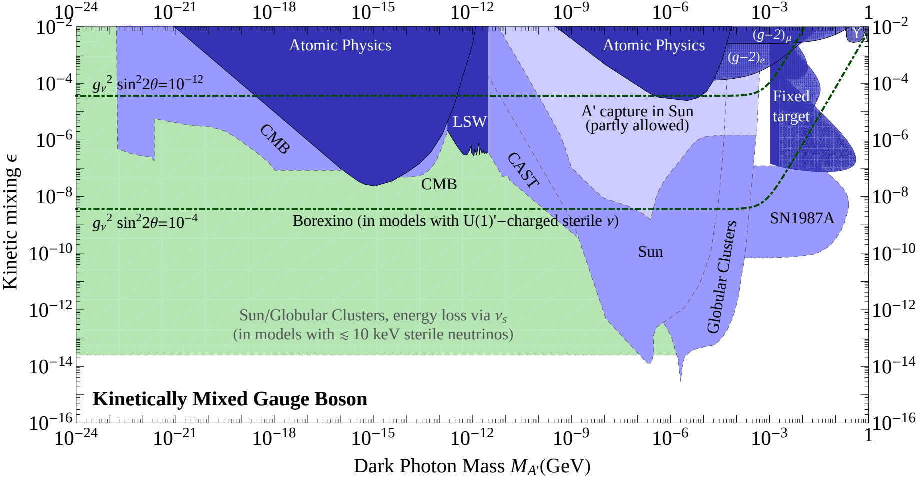
  $\rightarrow$ lower flux at night. And nights are longer in winter.
- Earth matter effects: An MSW-type resonance can lead to modified flux of certain neutrino flavors at night. And nights are longer in winter.

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