Phenomenology with sterile neutrinos

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Fermilab

based on work done in collaboration with
Evgeny Akhmedov, Roni Harnik, Boris Kayser,
Pedro Machado, Michele Maltoni, Thomas Schwetz

Outline

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Theoretical motivation

- Standard Model singlet fermions are a very generic feature of "new physics" models
  - Leftovers of extended gauge multiplets (e.g. GUT multiplets) (typically heavy)
  - Dark matter (keV ... TeV or above)
- Neutrino–singlet mixing is one of the allowed "portals" between the SM and a hidden sector.
- SM singlet fermions can live at any mass scale
  - Here: Focus on $\mathcal{O}(\text{eV})$ sterile neutrinos (accessible to oscillation experiments)
  - Motivated experimentally
- Typical Lagrangian:

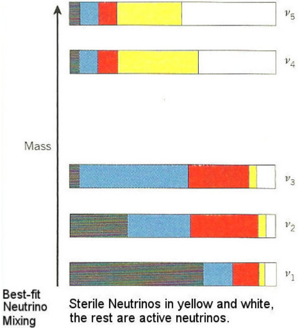
$$\mathcal{L}_{\text{mass}} \supset Y_\nu \, \bar{L} H^* N_R + m_s \, \bar{\nu}_s N_R + \frac{1}{2} M \, \overline{N_R^c} N_R + h.c.$$

$\Rightarrow$ mass mixing between active and sterile neutrinos

Experimental signatures of sterile neutrinos

- Disappearance of active neutrinos (e.g. $\nu_e \to \nu_s$ oscillations)
- Anomalous transitions Appearance among active neutrinos (e.g. $\nu_\mu \to \nu_s \to \nu_e$)
- Oscillation length $L^{\rm osc} = 4\pi E/\Delta m^2_{41}$ different from SM expectation (typically shorter)

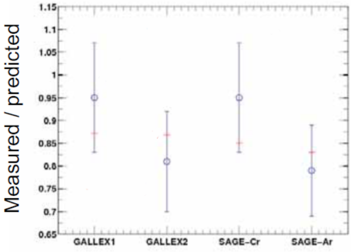
Notation: $\Delta m^2_{jk} = m^2_j - m^2_k$; $m_{4,5}$: mostly sterile, $m_{1,2,3}$: mostly active



Sterile Neutrinos in yellow and white, the rest are active neutrinos.

Experimental motivation 1: The Gallium anomaly

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

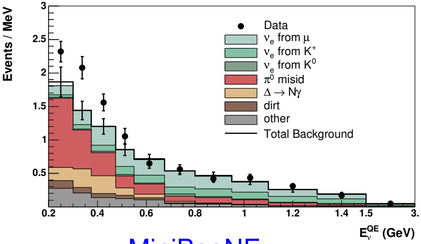


Giunti Laveder arXiv:1005.4599, arXiv:1006.3244
Mention et al. Moriond 2011 talk

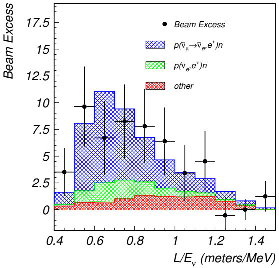
- Question: How well are efficiencies of the radiochemical method understood?

Experimental motivation 2: LSND and MiniBooNE

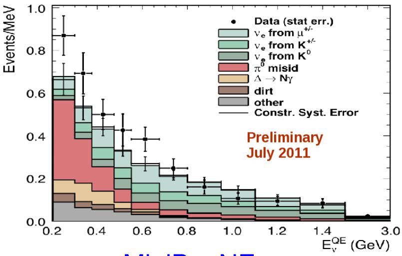
- LSND:
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source (3σ)
- MiniBooNE:
  - No significant ν_e or $\bar{\nu}_e$ excess in the LSND-preferred region
  - but $\bar{\nu}_e$ consistent with LSND
  - Low-E excess not understood



MiniBooNE ν_e



LSND $\bar{\nu}_e$



MiniBooNE $\bar{\nu}_e$

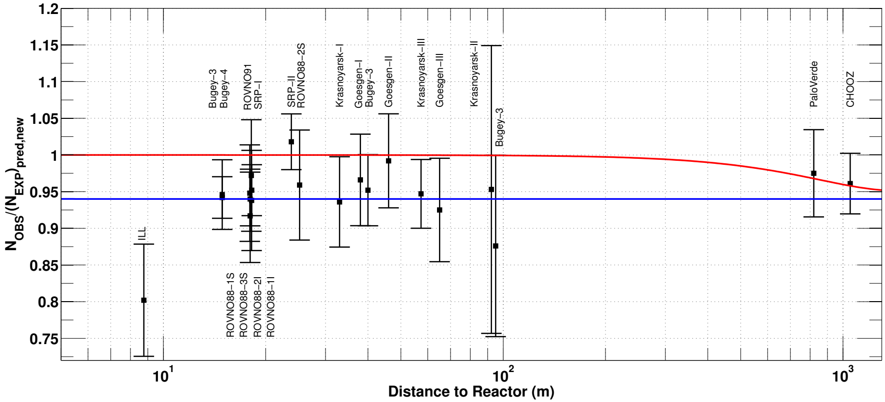
Experimental motivation 3: The reactor anomaly

- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ higher than previous prediction Mueller et al. arXiv:1101.2663, confirmed by P. Huber arXiv:1106.0687
- 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: $E_\nu = Q - E_e$)
- Problem: Requires knowledge of Q-values for all contributing decays. $\rightarrow$ take from nuclear databases where available, fit to data otherwise
- Cross check:
  - Simulate mock e^- spectra using few well-understood β-decays
  - Reconstruct $\bar{\nu}_e$ spectrum using old method: Result is 3% too low
  - Reconstruct $\bar{\nu}_e$ spectrum using new method: Result is exact.
- Possible problem: Poorly understood effects in nuclei with large log *ft*

Huber arXiv:1106.0687

The reactor anti-neutrino anomaly

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



Mention et al. arXiv:1101.2755

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

Sterile neutrino oscillations

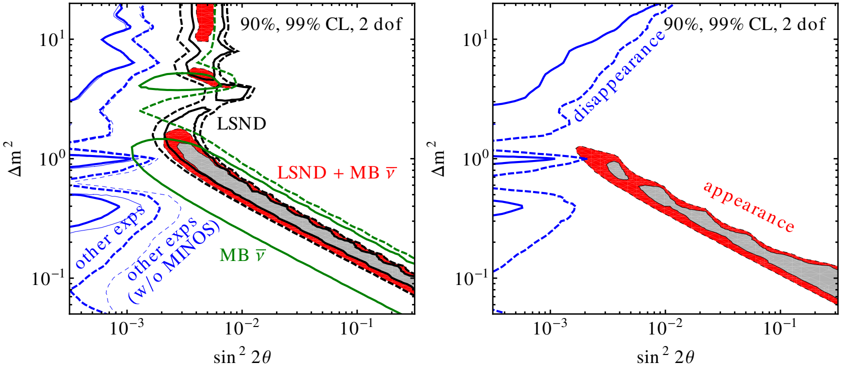
Idea:

- Introduce extra neutrino flavor ν_s, mixing with the active ones
- $\nu_e \to \nu_s$ oscillations explain Gallium anomaly
- $\bar{\nu}_e \to \bar{\nu}_s$ oscillations explain reactor anomaly
- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_s \to \overset{(-)}{\nu}_e$ oscillations explain LSND + MiniBooNE

A 3+1 model: 3 active neutrinos + 1 sterile neutrino

- Short baseline: Standard oscillations ineffective (Δm^2_{21}, Δm^2_{31} too small)
- Add extra (sterile) neutrino
- Fit shows: 3+1 neutrino scheme does not work well

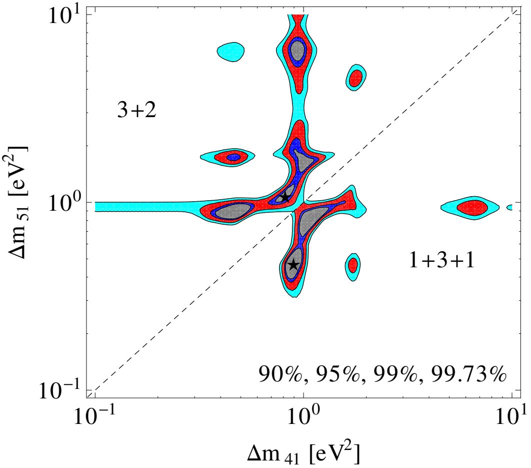
JK Maltoni Schwetz 1103.4570 and work in progress
see also Giunti Laveder 1107.1452 and 1109.4033; Mention et al. 1101.2755; Karagiorgi et al. 0906.1997 and 1110.3735



"other exps" = NOMAD, KARMEN, MB ν, SBL reactors, CDHS, atmospheric ν, MINOS
θ = effective mixing angle for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_s \to \overset{(-)}{\nu}_e$ oscillations

Global fit in a 5-flavor scheme

Check if more than one sterile neutrino improves the fit:



JK Maltoni Schwetz 1103.4570 and work in progress

Global fit in a 5-flavor scheme (2)

	$\lvert\Delta m^2_{41}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert\Delta m^2_{51}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+1	0.48	0.14	0.23					255.5/252
3+2	1.10	0.14	0.11	0.82	0.13	0.12	-0.31	245.2/247
1+3+1	0.48	0.13	0.12	0.90	0.15	0.15	0.62	241.6/247

	LSND+MB($\bar{\nu}$) vs rest		appearance vs disapp.	
	old	new	old	new
$\chi^2_{\mathrm{PG},3+1}$/dof	27.3/2	25.8/2	15.7/2	14.2/2
PG_{3+1}	1.2×10^{-6}	2.5×10^{-6}	3.9×10^{-4}	8.2×10^{-4}
$\chi^2_{\mathrm{PG},3+2}$/dof	30.0/5	24.8/5	24.7/4	19.5/4
PG_{3+2}	1.5×10^{-5}	1.5×10^{-4}	5.7×10^{-5}	6.1×10^{-4}
$\chi^2_{\mathrm{PG},1+3+1}$/dof	24.9/5	21.2/5	19.6/4	10.7/4
PG_{1+3+1}	1.5×10^{-4}	7.5×10^{-4}	6.0×10^{-3}	3.1×10^{-2}

Parameter goodness of fit: Test compatibility of 2 data sets
by comparing global $\chi^2_{\min}$ to $\chi^2_{\min}$ for separate fits

Sterile neutrinos in cosmology

Models with one or several $\mathcal{O}$(eV) sterile neutrinos are constrained by comsology:

Sum of neutrino masses

$\sum m_\nu \lesssim 0.5$ eV

# of relativistic species

$N_\nu > 3$ mildly preferred

Hamann Hannestad Raffelt Tamborra Wong, arXiv:1006:5276

Ways out:

- *Even* more relativistic degrees of freedom
- Dark energy equation of state parameter $w < -1$
- Neutrino chemical potential

Hamann Hannestad Raffelt Wong, arXiv:1108.4136

- Suppressed production of sterile neutrinos in the early universe for instance by coupling to a Majoron field

Bento Berezhiani, hep-ph/0108064

Global fits — take home message

Substantial tension in the global fit.

- Is one (or all) of the positive results not due to neutrino oscillations?
- Is one (or several) of the null results wrong?
- Are there more than 2 sterile flavors?
- Are there sterile neutrinos plus something else?

Outline

The standard lore on neutrino oscillations

Diagonalization of the mass terms of the charged leptons and neutrinos gives

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \left(\bar{e}_{\alpha L} \gamma^\mu U_{\alpha j} \nu_{jL}\right) W^-_\mu \; + \; \text{diag. mass terms} \; + \; h.c.$$

(flavor eigenstates: $\alpha = e, \mu, \tau$, mass eigenstates: $j = 1, 2, 3$)

Assume, at time $t = 0$ and location $\vec{x} = 0$, a flavour eigenstate

$$|\nu(0,0)\rangle = |\nu_\alpha\rangle = \sum_i U^*_{\alpha j} |\nu_j\rangle$$

is produced. At time t, location $\vec{x}$ it has evolved into

$$|\nu(t)\rangle = \sum_i U^*_{\alpha j} e^{-iE_j t + i\vec{p}_j \vec{x}} |\nu_i\rangle$$

Oscillation probability: ($L^{\rm osc}_{jk} = 4\pi E / \Delta m^2_{jk}$)

$$P(\nu_\alpha \to \nu_\beta) = \left| \langle \nu_\beta | \nu(t) \rangle \right|^2 = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} e^{-i(E_j - E_k)t + i(\vec{p}_j - \vec{p}_k)\vec{x}}$$

The standard lore on neutrino oscillations (2)

In the two-flavor approximation (working in one dimension and assuming $t = x \equiv L$):

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} e^{-i(E_j - E_k)t + i(\vec{p}_j - \vec{p}_k)\vec{x}} \\ &= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-2\pi i \frac{L}{L^{\text{osc}}_{jk}} \right] \\ &\simeq \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E} \end{aligned}$$

(θ = mixing angle, $\Delta m^2 = m_2^2 - m_1^2$, $\alpha \neq \beta$)

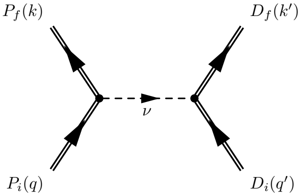
Going beyond the standard approach

Questions not answered by the standard approach:

- How does the Heisenberg uncertainty on E_j, $\vec{p}_j$ ($\sigma_E, \sigma_p \gg \Delta m^2/2E$) due to localization of the source and detector affect oscillations?
- How heavy can a sterile neutrino be before it can no longer interfere with the active neutrinos?
- Is the neutrino kinematically entangled with its interaction partners (e.g. the muon in $\pi \to \mu\nu$)?
- ...

Neutrino wave packets

One consistent solution: Feynman diagram approach to neutrino oscillations



Akhmedov Cohen Beuthe Cardall Giunti Glashow Grimus Jacob Kayser Keister Kiers Kim JK Lee Ligeti Lindner Nussinov Polyzou Rich Sachs Stockinger Smirnov Weiss, ...

Treat external particles as (Gaussian) wave packets:

	initial state	final state
Production vertex	$\phi_{Pi}(\vec{x}_1 - \vec{x}_P)e^{-iE_{Pi}t_1}$	$\phi_{Pf}(\vec{x}_1 - \vec{x}_P)e^{+iE_{Pf}t_1}$
Detection vertex	$\phi_{Di}(\vec{x}_2 - \vec{x}_D)e^{-iE_{Di}t_2}$	$\phi_{Df}(\vec{x}_2 - \vec{x}_D)e^{+iE_{Df}t_2}$

Transition amplitude

$$i\mathcal{A}_{\alpha\beta} = \int d^3x_1\, dt_1 \int d^3x_2\, dt_2\; \phi_{Pi}(\vec{x}_1 - \vec{x}_P)e^{-iE_{Pi}t_1}\; \phi_{Pf}(\vec{x}_1 - \vec{x}_P)e^{+iE_{Pf}t_1}$$

$$\times\, \phi_{Di}(\vec{x}_2 - \vec{x}_D)e^{-iE_{Di}t_2}\; \phi_{Df}(\vec{x}_2 - \vec{x}_D)e^{+iE_{Df}t_2}$$

$$\times \sum_j \mathcal{M}_P \mathcal{M}_D U^*_{\alpha j} U_{\beta k} \int \frac{d^4p}{(2\pi)^4} e^{-ip_0(t_2-t_1)+i\vec{p}(\vec{x}_2-\vec{x}_1)} \frac{i(\not{p} + m_j)}{p_0^2 - \vec{p}^2 - m_j^2 + i\epsilon}\,.$$

(assuming ϕ_{Pi}, ϕ_{Pf}, ϕ_{Di}, ϕ_{Df} to be spinors)

- $dt_1\; dt_2$-integrals $\rightarrow$ energy-conserving δ functions $\rightarrow$ p_0-integral trivial
- $d^3x_1\; d^3x_2$-integrals can be evaluated if wave packets are Gaussian
- d^3p-integral: Use Grimus-Stockinger theorem (limit of propagator for large $L = |\vec{x}_D - \vec{x}_S|$):

W. Grimus, P. Stockinger, Phys. Rev. **D54** (1996) 3414, hep-ph/9603430

$$\int d^3p\, \frac{\psi(\vec{p})\, e^{i\vec{p}\vec{L}}}{A - \vec{p}^2 + i\epsilon} \xrightarrow{|\vec{L}|\rightarrow\infty} -\frac{2\pi^2}{L}\psi(\sqrt{A}\tfrac{\vec{L}}{L})e^{i\sqrt{A}L} + \mathcal{O}(L^{-\frac{3}{2}}).$$

Oscillation probability

$$P_{\alpha\beta}(L) \propto \sum_{j,k} U^*_{\alpha j} U_{\alpha k} U^*_{\beta k} U_{\beta j} \ \exp\left[-2\pi i \frac{L}{L^{\mathrm{osc}}_{jk}} - \left(\frac{L}{L^{\mathrm{coh}}_{jk}}\right)^2 - \frac{(\Delta m^2_{jk})^2}{32\sigma_m^2 E^2} - 2\pi^2 \xi^2 \left(\frac{\sigma_x}{L^{\mathrm{osc}}_{jk}}\right)^2 - \frac{(m_j^2 + m_k^2)^2}{32\sigma_m^2 E^2} \right],$$

Five terms:

see e.g. Beuthe hep-ph/0109119

- Oscillation ($L^{\mathrm{osc}}_{jk} = 4\pi E/\Delta m^2_{jk}$)
- Decoherence during propagation (see below)
- Decoherence at production/detection (see below)
- Localization: Typically requires size of neutrino wave packet σ_x smaller than oscillation length (ξ = process-dependent parameter, can also be ~ 0)
- Approximate conservation of average energies/momenta

Oscillation probability

$$P_{\alpha\beta}(L) \propto \sum_{j,k} U^*_{\alpha j} U_{\alpha k} U^*_{\beta k} U_{\beta j} \ \exp\left[-2\pi i \frac{L}{L^{\rm osc}_{jk}} - \left(\frac{L}{L^{\rm coh}_{jk}}\right)^2 - \frac{(\Delta m^2_{jk})^2}{32\sigma_m^2 E^2} - 2\pi^2 \xi^2 \left(\frac{\sigma_x}{L^{\rm osc}_{jk}}\right)^2 - \frac{(m_j^2 + m_k^2)^2}{32\sigma_m^2 E^2} \right],$$

see e.g. Beuthe hep-ph/0109119

In two-flavor approximation, for not too large L and m_j, m_k, the well known formula

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}, \qquad \Delta m^2 = m_2^2 - m_1^2$$

is approximately recovered.

Decoherence due to wave packet separation

- The neutrino's mass eigenstate components separate spatially due to their different group velocities

$$P_{\alpha\beta}(L) \propto \exp\left[-\left(\frac{L}{L_{jk}^{\mathrm{coh}}}\right)^2\right] = \exp\left[-\left(\frac{L\,\Delta m_{jk}^2}{4\sqrt{2}\sigma_x E^2}\right)^2\right]$$

- Decoherence happens faster for short neutrino wave packets (small σ_x), large Δm^2, or low energy ($\rightarrow$ larger velocity difference)
- σ_x is an effective wave packet size which depends on the localization of the production process (Prod) and the detection process (Det)

$$\sigma_x^2 = \sigma_{x,\mathrm{Prod}}^2 + \sigma_{x,\mathrm{Det}}^2$$

(spatially delocalized detection process can restore coherence even if mass eigenstates are already separated)

- The difficult part: Estimate $\sigma_{x,\mathrm{Prod}}$, $\sigma_{x,\mathrm{Det}}$

Wave packet decoherence in the NuMI beam

- In the NuMI beam
  - 10^{-9} cm $\ll \sigma_x \lesssim 10$ cm
    lower limit: interatomic distance scale
    upper limit: timing resolution of experimental electronics
  - $E \sim 5$ GeV
  - $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

Coherence length

$$L^{\rm coh}_{jk} = 4\sqrt{2}\sigma_x E^2/\Delta m^2_{jk}$$
$$\simeq 6 \times 10^5 \text{ light years} \left(\frac{\sigma_x}{10\text{ cm}}\right)\left(\frac{E}{5\text{ GeV}}\right)^2\left(\frac{2.4 \times 10^{-3}\text{ eV}^2}{\Delta m^2_{jk}}\right)$$

…not relevant experimentally

Note: For supernova neutrinos (smaller σ_x, lower E), $L^{\rm coh}$ is *very relevant*

Decoherene in neutrino production and detection

$$P_{\alpha\beta}(L) \propto \exp\left[-\frac{(\Delta m^2_{jk})^2}{32\sigma_m^2 E^2} \right]$$

- This term accounts for two effects:
  - If the neutrino's parent particle (here: the pion) travels a long distance ($> L^{\text{osc}}$) while decaying, oscillations are averaged out.
  - If the experimental energy- and momentum resolutions are sufficient to determine the neutrino mass kinematically, oscillations will vanish.
- In the NuMI beam, the first effect dominates and precludes active–sterile oscillations for

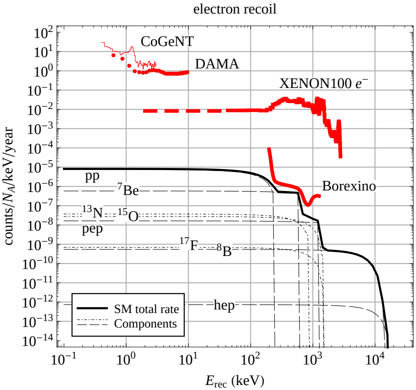
$$\Delta m^2_{41} \gtrsim 30 \text{ eV}^2$$

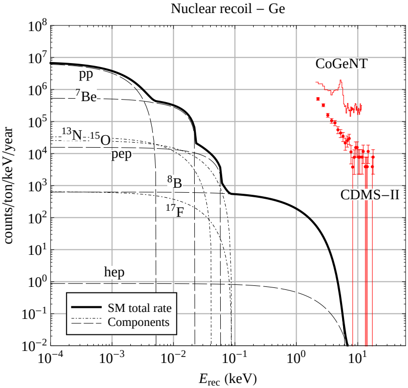
Outline

Neutrinos and direct dark matter detection

- Solar and atmospheric neutrinos are a well-known background to future direct dark matter searches

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





- If low-energy neutrino interactions are enhanced by new physics, this background can be significantly enhanced
  $\rightarrow$ Possible explanation of DM anomalies?

Pospelov arXiv:1103.3261, Harnik JK Machado (work in progress)

Enhanced neutrino scattering at low energies

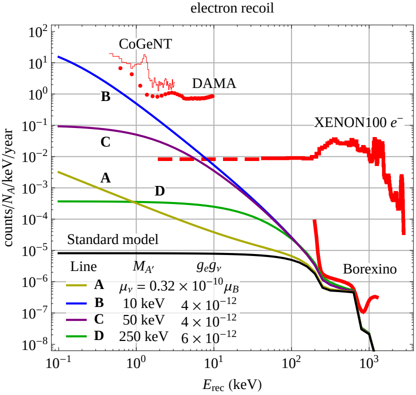
- Introduce new light (1 eV ... 1 GeV) force mediator A', e.g. a $B-L$ gauge boson, with small couplings g'
- Differential neutrino scattering cross section on target particle T (electron or atomic nucleus):

$$\frac{d\sigma_{\nu e}}{dE_r} \sim \frac{g'^4 m_T}{(M_{A'}^2 + 2E_r m_T)^2}, \qquad E_r = \text{recoil energy}$$

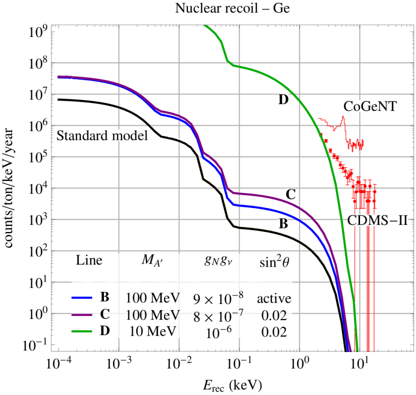
  - Enhanced at low E_r for light A'
  - Negligible compared to SM scattering ($\sim g^4 m_T / M_W^4$) at energies probed in dedicated neutrino experiments

Enhanced neutrino scattering at low energies

- Introduce new light (1 eV . . . 1 GeV) force mediator A', e.g. a $B - L$ gauge boson, with small couplings g'



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



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

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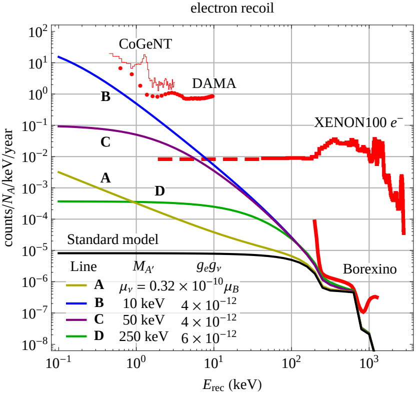
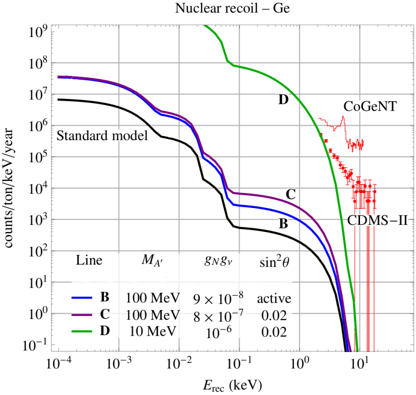


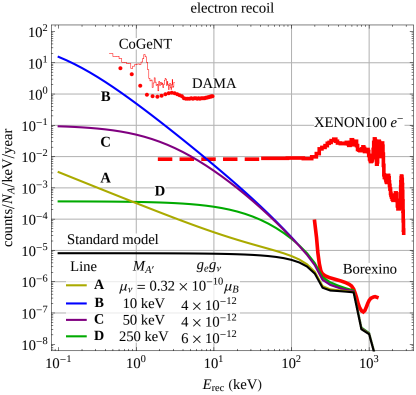


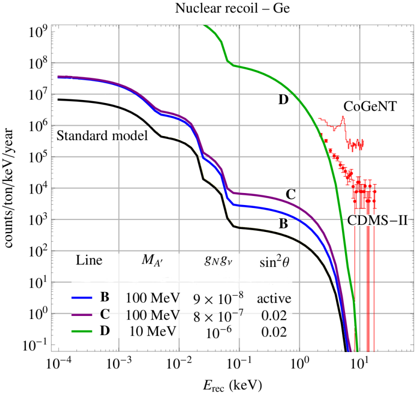
B, C, D: $U(1)_{B-L}$ boson
A: ν magnetic moment

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

Enhanced neutrino scattering at low energies

- Introduce new light (1 eV . . . 1 GeV) force mediator A', e.g. a $B - L$ gauge boson, with small couplings g'

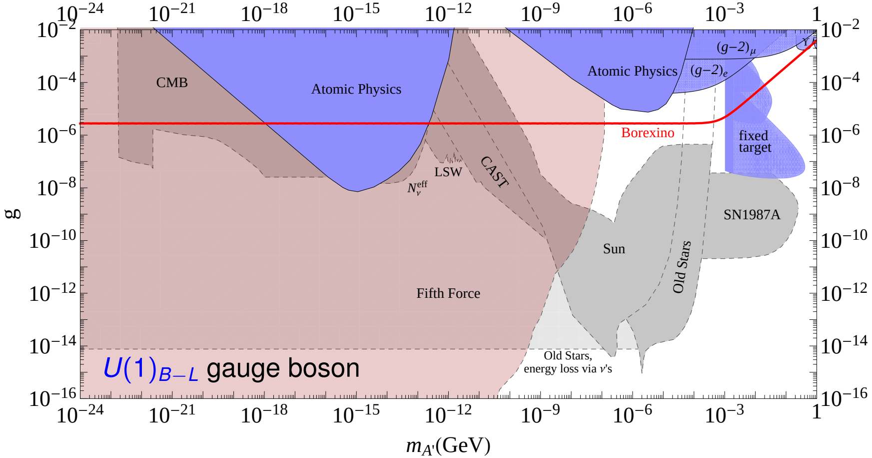




B, C, D: $U(1)_{B-L}$ boson
A: ν magnetic moment

B: $U(1)_{B-L}$ boson
C, D: kinetically mixed $U(1)'$ + sterile ν

Constraints on light gauge bosons



Harnik JK Machado (work in progress)

most limits taken from compilations by Jaeckel, Redondo, Ringwald;
Bjorken, Essig, Schuster, Toro;
and Bordag, Klimchitskaya, Mohideen, Mostepanenko

Neutrino model building with a light A' gauge boson

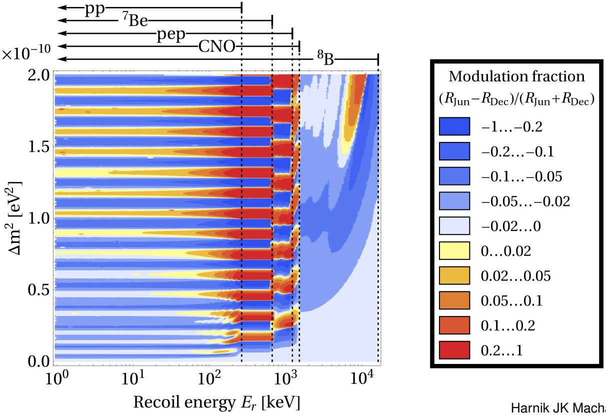
A rich toolbox of possibilities:

- Different types of gauge bosons:
  - Gauged $B - L$
  - A "dark photon" coupled to SM particles via kinetic mixing
  - Gauged baryon number
  - ...
- Sterile neutrinos ν_s:
  - A' can couple more strongly to ν_s than to SM particles
    (e.g. ν_s carries $U(1)'$ charge, SM particles couple only through small kinetic mixing)
  - $\mathcal{O}$(keV–MeV) sterile neutrinos make it easier to avoid certain bounds
- Neutrino magnetic moments:
  - Magnetic moment interactions also enhanced at low energy

Temporal modulation of neutrino signals

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

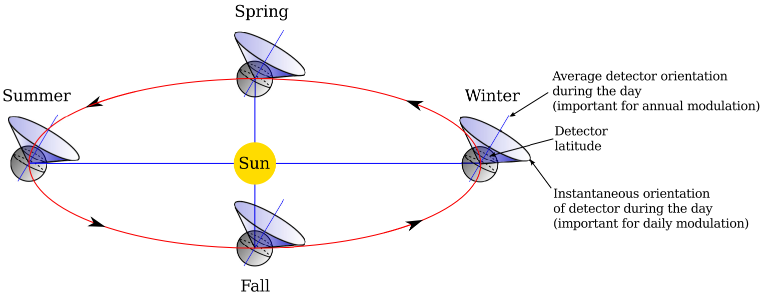
- The Earth–Sun distance: Solar neutrino flux peaks in winter.
- Active–sterile neutrino oscillations: For oscillation lengths $\lesssim$ 1 AU, sterile neutrino appearance depends on the time of year.



Harnik JK Machado, work in progress

Temporal modulation of neutrino signals (2)

- Sterile neutrino absorption: For strong ν_s–A' couplings and not-too-weak A'–SM couplings, sterile neutrino cannot traverse the Earth.
  $\rightarrow$ 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.
- Direction-dependent detection efficiencies: If channeling effects are important, detection rates depend on the position of the Sun.



Harnik JK Machado, work in progress

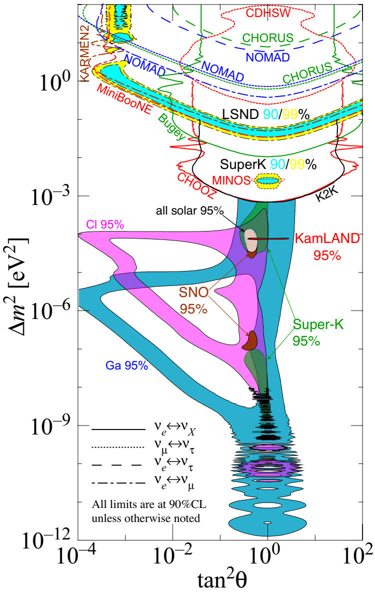
Outline

Conclusions

- Light sterile neutrinos are well motivated experimentally and theoretically
  - Two 3σ effects, several 2σ hints
  - But: In the simplest models, severe tension with null results
- Sterile neutrinos are a testing ground for the quantum mechanics of neutrino oscillations
- Rich and interesting neutrino phenomenology in dark matter detectors
  - Enhanced ν–e and ν–N scattering rates at low energy
  - Huge model-building toolbox: Various types of light gauge bosons, sterile neutrinos at different mass scales, magnetic moments, ...
  - Daily, semi-annual, and annual modulation signals possible

Thank you!

Experimental situation



http://hitoshi.berkeley.edu/neutrino

"Atmospheric oscillations:"

- $\nu_\mu \to \nu_\tau$ oscillations
- $\Delta m^2 = (2.50^{+0.09}_{0.16}) \times 10^{-3}$ eV^2
- Confirmed by Super-K, K2K, MINOS, T2K

"Solar oscillations:"

- $\nu_e \to \nu_\mu, \nu_\tau$ oscillations
- $\Delta m^2 = (7.59^{+0.20}_{0.18}) \times 10^{-5}$ eV^2
- Confirmed by solar neutrino detectors and KamLAND

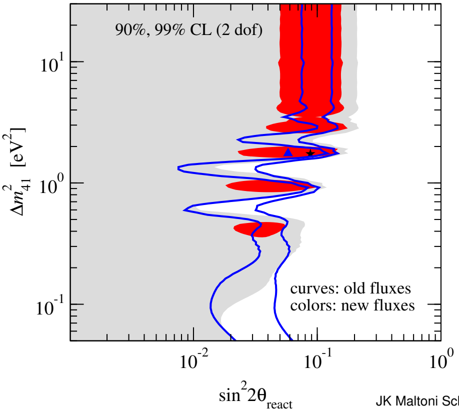
Anomalous effects:

- LSND: $\Delta m^2 \gtrsim 0.1$ eV^2
- Reactor anomaly: $\Delta m^2 \gtrsim$ few $\times$ 0.1 eV^2
- MiniBoone?
- Gallium anomaly?

Plot: Hitoshi Murayama, global fit: Schwetz Tórtola Valle 1108.1376

Fit to reactor anti-neutrino data in a 3+1 model

Assume 3 active neutrinos + 1 sterile neutrino
($\longrightarrow \bar{\nu}_e$ can oscillate into sterile neutrinos)



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θ_{react} = effective mixing angle for $\bar{\nu}_e \longrightarrow \bar{\nu}_s$ oscillations

Our fitting procedure

- Atmospheric neutrinos: Eight classes of events: Sub-GeV e, μ ($p < 400$ GeV/c), Sub-GeV e, μ ($p > 400$ GeV/c), Multi-GeV e, μ, Upward stopping μ, upward throughgoing μ, 10 zenith angle bins each
- MINOS: Include NC and CC disappearance search
  (based on 1001.0336 and Neutrino 2010 talk by P. Vahle)
- Reactor experiments: Bugey 3 (incl. spectrum), Bugey 4, Chooz (incl. spectrum), Goesgen 1–3, ILL, Krasnoyarsk 1–3, Palo Verde, Rovno
- SBL ν_e appearance experiments: LSND, KARMEN, MiniBooNE (ν (2010) and $\bar{\nu}$ data, consider only $E > 475$ MeV, i.e. low-E excess in ν_e sample not included)
- Gallium anomaly not included
- SBL ν_μ disappearance experiments: CDHS, NOMAD
- All codes reproduce the individual fits from the respective experiments.

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The Grimus-Stockinger theorem

Let $\psi(\vec{p})$ be a three times continuously differentiable function on $\mathbb{R}^3$, such that ψ itself and all its first and second derivatives decrease at least like $1/|\vec{p}|^2$ for $|\vec{p}| \to \infty$. Then, for any real number $A > 0$,

$$\int d^3p \, \frac{\psi(\vec{p}) \, e^{i\vec{p}\vec{L}}}{A - \vec{p}^2 + i\epsilon} \xrightarrow{|\vec{L}| \to \infty} -\frac{2\pi^2}{L} \psi(\sqrt{A}\tfrac{\vec{L}}{L}) e^{i\sqrt{A}L} + \mathcal{O}(L^{-\frac{3}{2}}).$$

$\Rightarrow$ Quantification of requirement of on-shellness for large $L = |\vec{L}|$.

W. Grimus, P. Stockinger, Phys. Rev. **D54** (1996) 3414, hep-ph/9603430

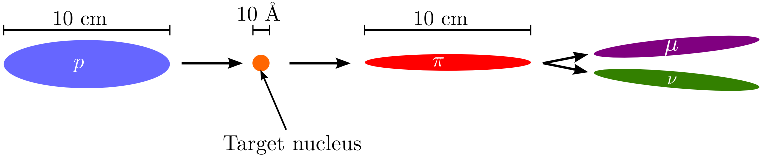
Neutrino wave packets in a long-baseline experiment

Consider neutrino production via $\pi \to \mu\nu$ in the NuMI beam.

- Length of proton, pion, muon, neutrino wave packets:

$$1 \text{ fm} \ll \sigma_{x,\text{Prod}} \lesssim 10 \text{ cm}$$

(localization of particle in accelerator: ~ 1 ns$\times c$)



Neutrino wave packets in a long-baseline experiment

Consider neutrino production via $\pi \to \mu\nu$ in the NuMI beam.

- Length of proton, pion, muon, neutrino wave packets:

$$1 \text{ fm} \ll \sigma_{x,\text{Prod}} \lesssim 10 \text{ cm}$$

(localization of particle in accelerator: $\sim 1 \text{ ns} \times c$)

Uncertainties in neutrino detection are much smaller:

- Interaction vertex localized to $\sim$1–10 Å.
- Duration of detection process: $\lesssim 1 \text{ ns} \sim 10 \text{ cm}$ (typical time resolution of detector electronics)

$\Rightarrow$ Spatial/Temporal uncertainty of ν detection process:

$$\sigma_{x,\text{Det}} < 10 \text{ cm}$$

Length of neutrino wave packet

$$\Rightarrow \sigma_x = \sqrt{\sigma^2_{x,\text{Prod}} + \sigma^2_{x,\text{Det}}} \lesssim 10 \text{ cm}$$