Sterile Neutrinos I

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Lecture Outline

- Sterile I: Theory and Phenomenology
  - Properties of sterile neutrinos in the standard model.
  - Sterile neutrinos and beyond the standard model, LRSM as an example.
  - Sterile neutrinos and extra dimensions.
  - Sterile neutrinos in cosmology/astrophysics.
  - 3+2 models, fits to the data.
- Sterile II: Measurements
  - How to make a smoking gun active-sterile neutrino oscillation measurement. A primer!

Sterile Neutrinos, Who needs them!

- Discovery of Sterile neutrinos would rank in importance with discovery of charm, bottom, and tau.
- These discoveries was presaged by theory to solve problems of tree-level flavor changes and the need for a third generation to introduce CP violations that were observed in experiments.
- May point to physics beyond the standard model.

Sterile Neutrinos in the Standard Model Gauge Group
(see R.R. Volkas, hep-ph/0111326)

- SM gauge group as constructed,

$$G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

- One generation/family of quarks and leptons forms the reducible representation,

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3,2)(1/3), \qquad d_R \sim (3,1)(-2/3), \qquad u_R \sim (3,1)(4/3);$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1,2)(-1), \qquad e_R \sim (1,1)(-2), \qquad \text{? MISSING ENTRY ?}$$

For massless neutrinos, right handed states do not exist, i.e. handed-ness is conserved.

$$\upsilon_L = \frac{(1-\gamma)}{2}\upsilon, \text{ helicity} = \text{-1 for m= 0}$$

$$\upsilon_R = \frac{(1+\gamma)}{2}\upsilon, \text{ helicity} = \text{+1 for m= 0}$$

- Parity violation put into SM by hand, i.e. (1- γ) coupling only, (1+ γ) coupling not observed.
- For minimal SM (no neutrino mass), mismatch between quark and lepton degrees of freedom!

Generating Dirac Neutrino Mass

- Quark and charged lepton (Dirac) mass generated through Yukawa coupling.

$$\mathcal{L}_{\text{Yuk}} = h_d \overline{Q}_L d_R \Phi + h_u \overline{Q}_L u_R \tilde{\Phi} + h_e \overline{\ell}_L e_R \Phi + \text{H.c.}$$

- With spontaneous symmetry breaking, Dirac neutrino mass terms of type,

$$\mathrm{m}_D \bar{\nu}_L \nu_R$$

- If ν_R are absent, and the Higgs sector remains minimal, then neutrinos are massless.
  - ➔ neutrino mass implies ν_R exists!
- ν_L and ν_R are building blocks of the neutrino mass Lagrangian.

Sterile Neutrinos in the Standard Model Gauge Group

- Missing right handed neutrino state should be,

  $\nu_R \sim (1,1)(0)$.
- where (color,weak)(hypercharge = 2*(Q - I_L)).
- ν_R has the quantum numbers of the vacuum, thus sterile with respect to the standard model gauge interactions!
- SM with neutrino mass now looks like,

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3,2)(1/3), \quad d_R \sim (3,1)(-2/3), \quad u_R \sim (3,1)(4/3);$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1,2)(-1), \quad e_R \sim (1,1)(-2), \quad \nu_R \sim (1,1)(0)$$

Sterile Neutrinos in the Standard Model Gauge Group

- Presence of ν_r would enhance two aesthetic qualities:
  - Left-right similarity, i.e. for each left handed fermion, there is a right handed one.
  - Quark-lepton similarity, i.e. For each quark of a given chirality (handedness), there is an associated chiral lepton.
- Family structure of a quark-lepton family provides strong motivation for one sterile fermion per family.
- Historically, quark-lepton similarity used to predict charm.

Majorana Neutrino Mass

- Because Quarks/Leptons have charge, they only have Dirac masses which are equivalent between left and right components.
- But only the neutrino can have Majorana mass terms of the type,

$$\mathrm{M}\ \bar{\nu}^c_R \nu_R$$

- With the full mass matrix given by,

$$\begin{pmatrix} \bar{\nu}_L & \overline{(\nu_R)^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix}.$$

- m_D is the Dirac mass ~ EW symmetry breaking.
- M is the Majorana mass ~ unknown value.

Sterile Neutrino Mass: See Saw Model

- If we assume M >> m_D, eigenvalues (m_L and m_R) become approximately,

$$\frac{m_D^2}{M} \quad \text{and} \quad M,$$

- If we assume M ~ GUT scale (~10^{15}GeV), and m_D ~ M_{EW} (~10^2 GeV), then:

$$m_L = 10^{-2}\text{ eV}, \quad m_R = \text{MGUT}$$

- And active-sterile mixing angle $\tan\theta << 1$.
- We explain smallness of neutrino mass, and lack of active-sterile couplings.
- But why M ~ GUT scale???

Sterile Neutrino Mass: Pseudo Dirac

- Interesting limits $M << m_D$ (pseudo-Dirac), eigenvalues (m_L and m_R) become approximately,

$$m_D \pm \frac{M}{2}$$

- As M -> 0 we end up with,
  - Nearly degenerate pair with a mass gap m_D above zero, i.e. $m_L \sim m_R \sim m_D$
- With mixing between the eigenstates given by,

$$\tan 2\theta = -\frac{2m_D}{M} \Rightarrow |\theta| \simeq \frac{\pi}{4}.$$

- Nearly maximal active(L)-sterile(R) mixing.
- Light sterile neutrinos implies large mixing!!!

Implications of Sterile Neutrino Mass

- Thus, non observations of sterile neutrinos implies m_R ~ MGUT, which begs the question,
  - Why is the Majorana mass at such a large symmetry breaking scale??
- Observations of sterile neutrinos with small mass (m_R ~ M_{EW}) and large coupling to active neutrinos, can be accommodated by the SM,
  - How would we explain smallness of neutrino Dirac mass?
- Searching for sterile neutrinos is important for under-standing source of fermion masses and new physics!

Sterile Neutrinos Beyond the SM

- Examples of extensions to the SM;
  - Mirror matter model (weakly sterile).
  - Pati-Salam model (weakly sterile).
  - SU(5) grand unification (fully sterile).
  - SO(10) grand unification (weakly sterile).
  - Left-right symmetric models (weakly sterile).
  - Unusual left-right sysmmetric (fully sterile).
- Notes,
  - "Fully sterile" feels no gauge interactions, including those beyond the SM.
  - "Weakly sterile" does not feel standard model gauge interactions (strong, EM, and weak).
  - Fully/Weakly sterile neutrinos do couple to gravity. Fully sterile can interact via Higgs exchange and partake in mass mixing.

Sterile neutrinos beyond the SM
Left-Right Symmetric Model

- Basic motivation of LRSM is to treat left and right handed fermions more symmetrically. Parity violation is induced spontaneously (> few TeV) rather than engineered explicitly.
- The gauge group is now given by,

$$G_{\mathrm{LR}} = \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L},$$

- ν_r is now explicitly put into the model and participate in right handed weak interactions mediated by exotic W-like bosons and an additional Z' boson (weakly sterile).

Sterile neutrinos beyond the SM
Left-Right Symmetric Model

- LRSM completed by specifying the Higgs sector, which is constructed to yield a see-saw structure for neutrinos and breaks G_{LR} in two stages.
- The resulting VEV hierarchy results,

$$\langle \Delta_R \rangle \sim v_R \gg \langle \Phi \rangle \sim v_{ew} \gg \langle \Delta_L \rangle \sim v_L$$

- At the scale v_R, right handed weak isospin is spontaneously broken and the W_R and Z' acquire mass.
- This symmetry breaking automatically generates large see-saw Majorana masses within the theory (not added ad hoc) and connects with see-saw limit.
- Nice idea, but not established. Example of neutrino mass as a window onto higher symmetries.

Neutrino Handedness
A Question??

- Dave Griffiths “There is a danger in carrying handedness too far”, D. Griffiths, Intro to Elementary Particles (1987).
- When particles have non zero mass, handed-ness is not conserved in the propagation of a free particle. This means left-right handed states are not well defined.
  - Can boost to a frame where a left handed state will become right handed.
- Does this mean sterile neutrinos states are not real, or at least there mass is not different from left handed states??

Sterile neutrinos and Extra Dimensions. A cool idea!

- See H. Pas, et al, PRD 72, 095017 (2005) for details.
- Definitions;
  - Brane -- our space-time universe
  - Bulk ---- extra dimensions. The Brane is embedded in the bulk.
- Idea, assume active-sterile neutino mixing at the ~1 eV^2 region (LSND oscillations).
- Sterile neutrinos have the same gauge quantum numbers of the vacuum and the graviton.
- Theories which include gravity usually involve extra dimensions. Thus, sterile neutrinos can in principle follow the graviton into the extra dimensions.

Sterile neutrinos and Extra Dimensions: Brane Fluctuations

- Theories show that branes embedded in higher dimensional spacetime possesses fluctuations or buckles on a microscopic scale from gravity, thermal and/or quantum fluctuations.
- Construct simple 1 + 1 dimensional space time embedded in a 1+2 space-time “toy” model with Minkowski metric,

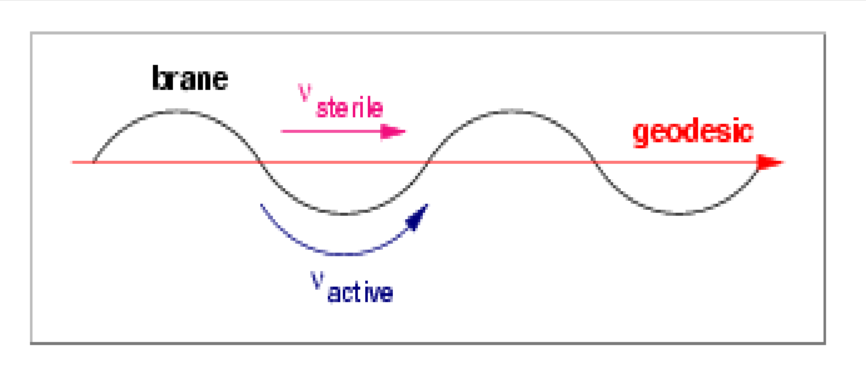
$$ds^2 = dt^2 - dx^2 - dy^2.$$

- Assume the brane exhibits the following spatial variations (no claim to realism),

$$y = A \sin kx;$$

Sterile neutrinos and Extra Dimensions: Geodesics

- Schematically...



- With travel distance for the sterile neutrino of,

$$D_g = x.$$

- And the geodesic for active states on the brane,

$$D_b = \int_{\text{brane}} \sqrt{dx^2 + dy^2} = \int^x \sqrt{1 + A^2 k^2 \cos^2 kx}\, dx.$$

Sterile neutrinos and Extra Dimensions: Shortcuts

- After some math, the shortcut distance is given by,

$$\epsilon = \left(\frac{Ak}{2}\right)^2.$$

- Where A is the amplitude and k the wave number of brane fluctuation, with Ak being the aspect ratio.
- The neutrino evolution equation in the brane is given by,

$$i\frac{d}{dt}\begin{pmatrix} \nu_a(t) \\ \nu_s(t) \end{pmatrix} = H_F \begin{pmatrix} \nu_a(t) \\ \nu_s(t) \end{pmatrix},$$

- The shorter distance traveled by the sterile neutrino will be added in as an effective potential,

$$H_F = +\frac{\delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + E\frac{\epsilon}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

Sterile neutrinos and Extra Dimensions: Energy Resonance

- Similar to MSW oscillation except more pronounced energy dependence with Δm^2 varying as E^2.
- Bulk term beats against the brane term to give resonant mixing at energy,

$$E_{res} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\epsilon}}.$$

- Assuming $\varepsilon << 1$, then $\Delta m^2 << E^2_{res}$
- Oscillation probability given by,

$$P_{as} = \sin^2 2\tilde{\theta} \sin^2(\delta H D/2),$$

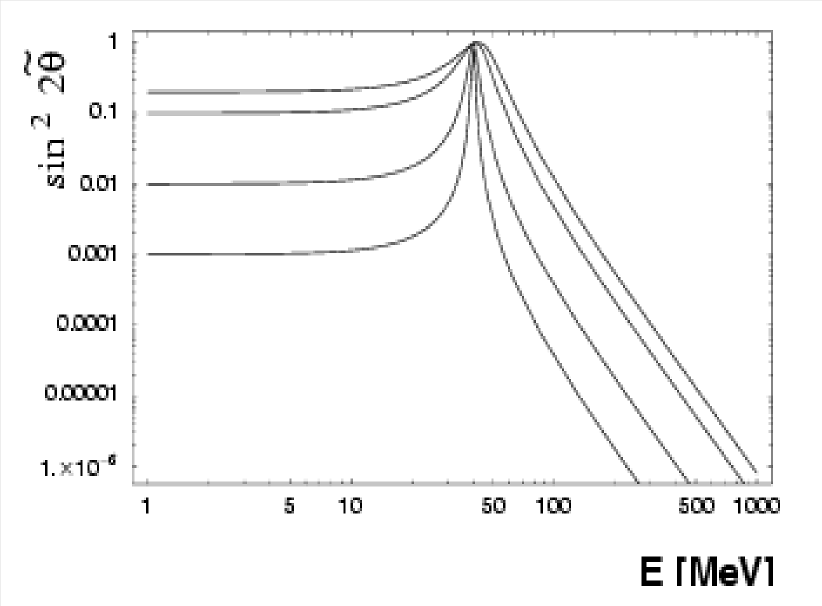
- With the new values given in terms of standard ones,

Sterile neutrinos and Extra Dimensions: Energy Resonance

$$\sin^2 2\tilde{\theta} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \cos^2 2\theta\left[1 - \left(\frac{E}{E_{res}}\right)^2\right]^2},$$

$$\delta H = \frac{\delta m^2}{2E}\sqrt{\sin^2 2\theta + \cos^2 2\theta\left[1 - \left(\frac{E}{E_{res}}\right)^2\right]^2}.$$

- For $E_\nu < E_{res}$, standard oscillations
- For $E_\nu = E_{res}$, resonant oscillations
- For $E_\nu > E_{res}$, oscillations die away.



E_{res} = 40 MeV

Sterile neutrinos and Extra Dimensions. Pre-MB predictions!

- Short baseline experiments, values of E_{res} allowed.

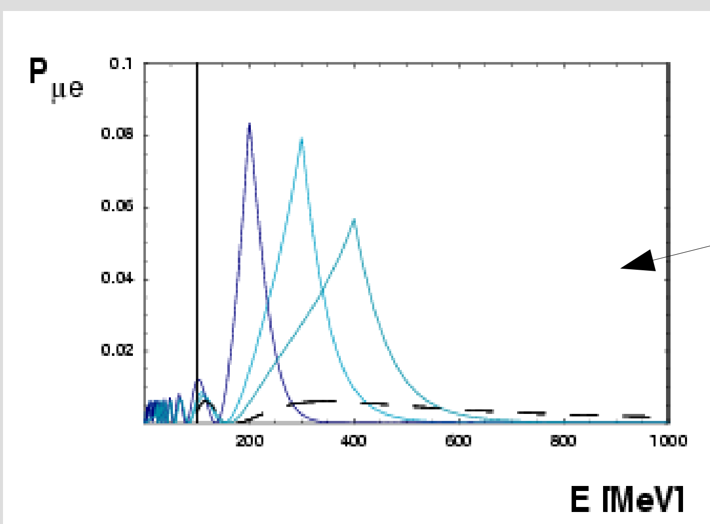
	$\alpha\beta$	E_ν	D	$\sin^2 2\tilde{\theta}_{\alpha\beta}$
LSND	μe	20–52.8 MeV	30 m	>0.003
KARMEN	μe	20–52.8 MeV	17.7 m	<0.002
MiniBooNE	μe	0.1–1.0 GeV	540 m	~0.0006
BUGEY	$e\not{e}$	1–6 MeV	25 m	<0.15
CDHS	$\mu\not{\mu}$	>1 GeV	755 m	<0.1

Standard oscillations sets lower limits above ~50 MeV.

oscillation suppressed below ~400 MeV

$$\sin^2 2\tilde{\theta}_{\mu\not{\mu}} \simeq \cos^2\theta_* \sin^2 2\tilde{\theta} \simeq \cos^2\theta_* \tan^2 2\theta \left(\frac{E}{E_{\rm res}}\right)^{-4} .$$

- Predictions for MinibooNE,



No high energy oscillations, enhanced oscillations at low energy (100-400MeV)!

Needless to say, extraD authors are working on fits to MiniBooNE low energy excess.

Sterile neutrinos in Cosmology

- Light sterile neutrinos can have important effects in big bang nucleosynthesis (BBN), the process thought responsible for generating the light isotopes ^{4}He, ^{3}He, D, and ^{7}Li.
- BBN epoch occurs shortly after neutrinos decouple from e/gamma plasma at T ~1 MeV.
- The plasma contain nucleonic contamination which are being intra-converted through the process,

$$\nu_e n \leftrightarrow e^- p, \quad \bar{\nu}_e p \leftrightarrow e^+ n, \quad n \leftrightarrow p e^- \bar{\nu}_e.$$

with $n/p = exp[\frac{(m_p - m_n)}{T}]$ for zero lepton number

- Ratio of elements determined by relative rates of above reactions, and expansion rate of the universe during relevant period.

Sterile neutrinos in Cosmology

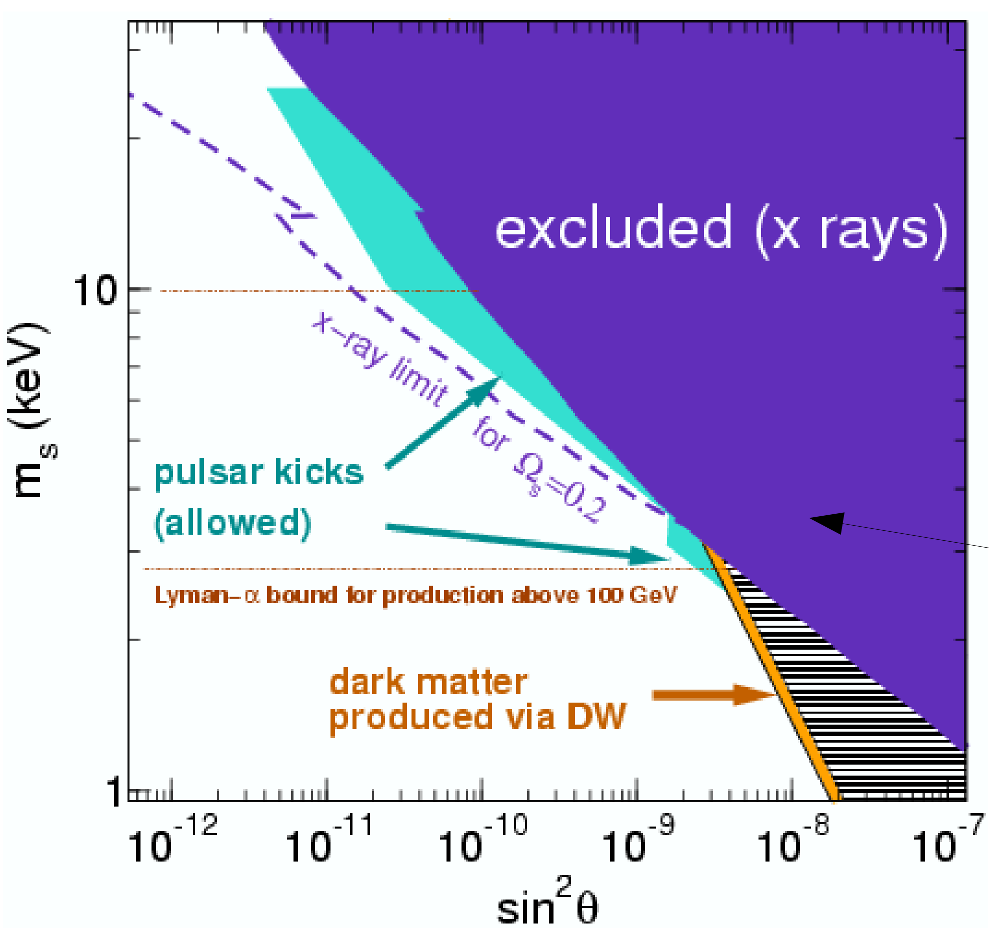
- Expansion during BBN determine by the relativistic component of the plasma. In standard BBN, the relativistic species are active (anti)neutrinos, electrons, positrons, and photons.
- A significant light sterile neutrino component would increase the expansion rate. Thus, decreasing the weak freeze-out period, increasing T, which changes the n/p ratio, resulting in an unacceptably high ^{4}He yield.
- Have assumed neutrino-antineutrino number density asymmetry is zero (zero lepton number).
  - However, active-sterile oscillations can induce large neutrino flavor asymmetries.

Sterile neutrinos in Cosmology

- Current BBN without sterile neutrinos work. However, the presence of sterile neutrinos can act to alter the n/p ratio.
  - There are many factor that can act to increase or decrease the effects.
- Cosmology with light sterile neutrinos requires careful analysis, with the outcome determined by the model and choice of parameters.
  - ➢ Successful cosmologies can result!

Sterile Neutrinos in Astrophysics

- Dark matter candidate.
- Pulsar Kicks (ν_s carries away energy asymmetry)



Limits from various astrophysics sources:

-pulsar kicks.

-relic sterile neutrino decays produce x-rays.

-ν_s dark matter below Ω_s dotted line.

m_s ~few keV, and mixing ~ 10^{-10}

A. Kusenko, hep-ph/0703116

Sterile Neutrinos in Astrophysics

- Super Nova explosions (R-process).

Reactions in the neutrino wind,

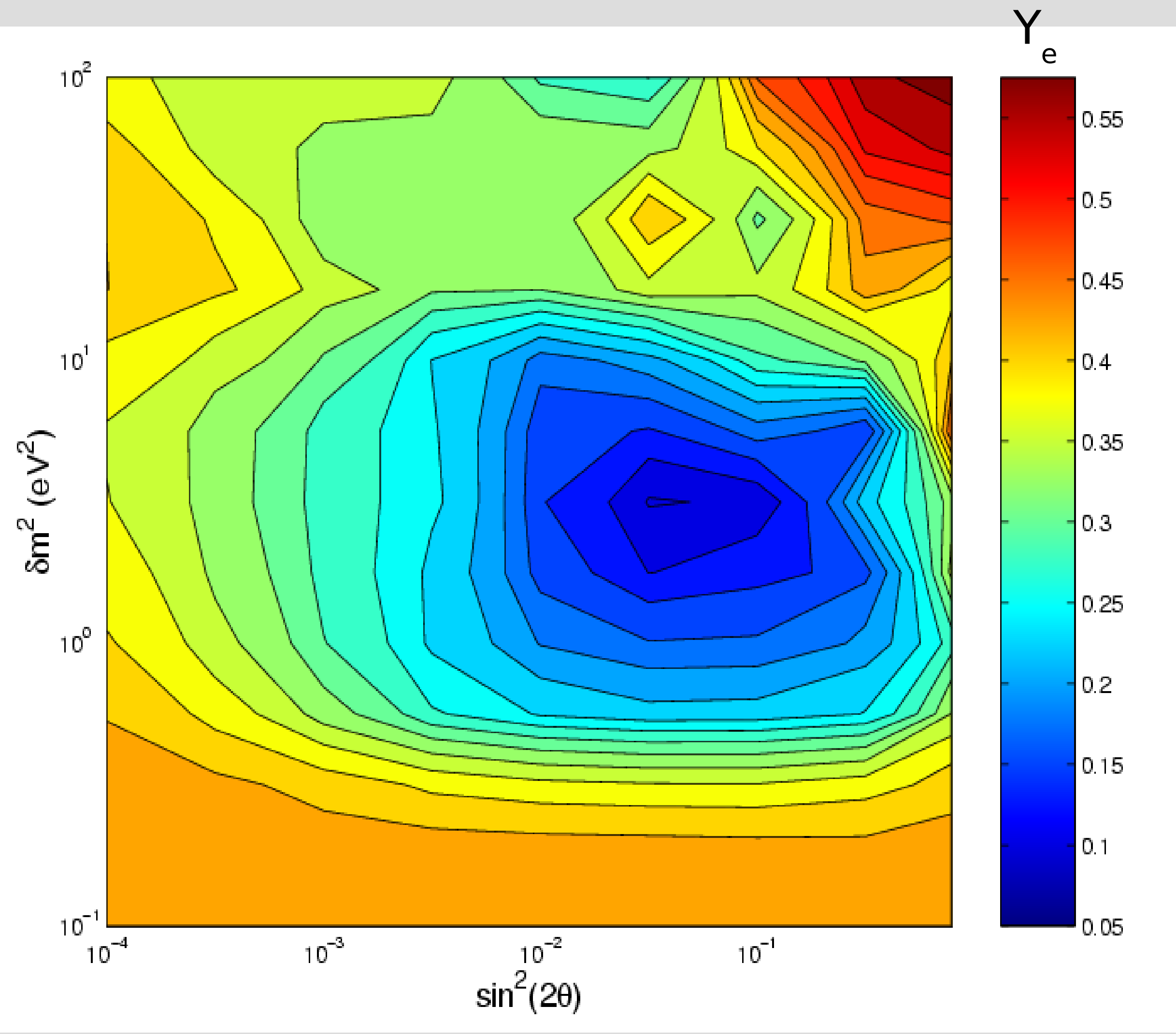
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

with $Y_e = 1/(1+n/p)$

-Values of $Y_e < 0.3$ yield neutron rich environment which is required for heavy element production.

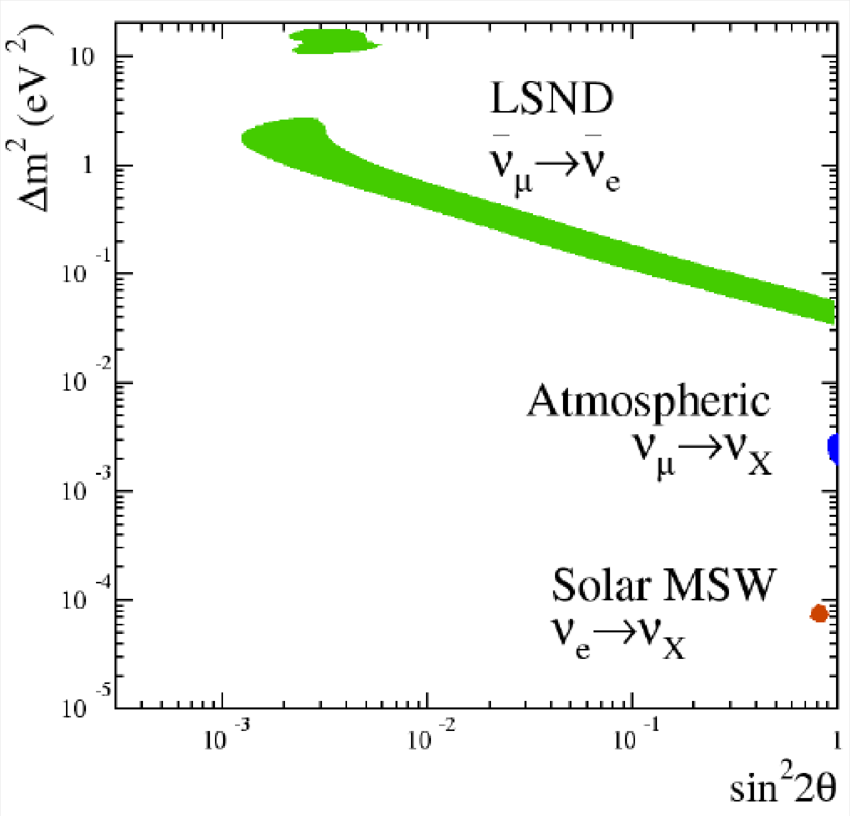
-Presence of sterile neutrinos can reduce Y_e.

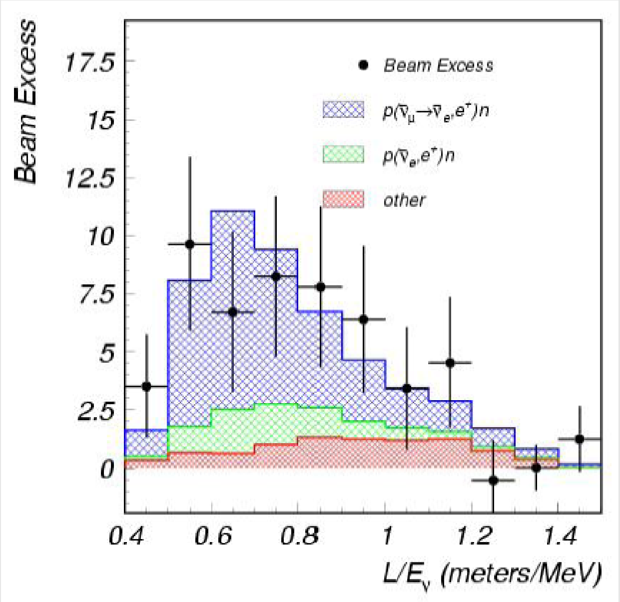
Neutrino background not included.



Fuller, hep-ph/0003034

Terrestrial Hints for Sterile Neutrinos
The LSND Signal





Δm^2_{LSND} ~ 0.1- 10 eV^2 + small mixing

$\Delta m^2_{LSND} >> \Delta m^2_{atm} >> \Delta m^2_{sol}$

→**one option: 3 active + n "sterile" neutrinos**

→other options: neutrino decay, extra-D, etc.

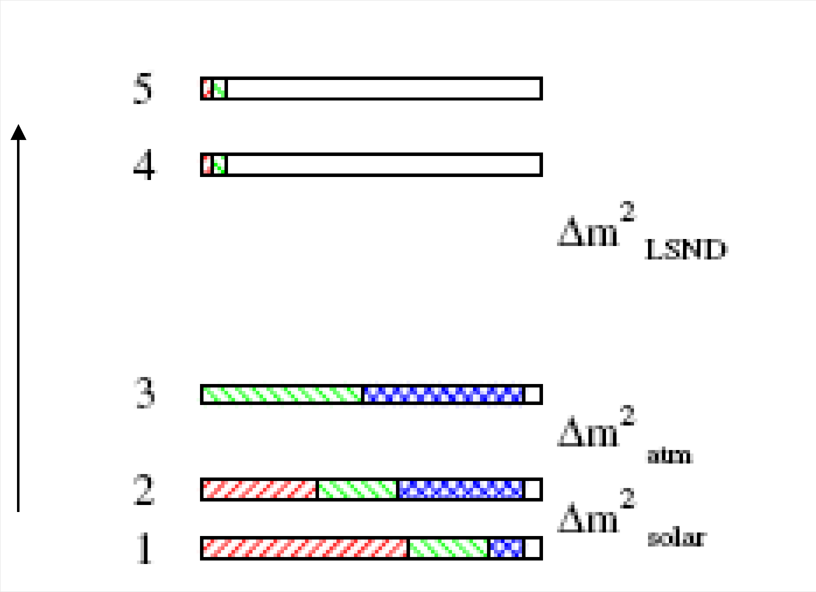
3+2 Model Phenomenology

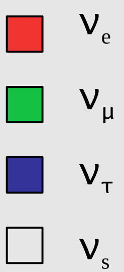
3 active + 2 **sterile** neutrinos

- ***light*** sterile neutrinos
- they can interact thru non-standard weak couplings
- they have very small active flavor content (U_{e4},..., U_{e5},...)

  → can participate in neutrino oscillations

increasing m²
(not to scale)





Why n=2?
3+1 models: SBL and LSND marginally consistent with each other
3+2: next natural step... *[M. Sorel, et al. hep-ph/0305255]*

The Mass Matrix: Adding One Sterile Neutrino
(see R.R. Volkas, hep-ph/0111326)

- In absence of Higgs triplets, the general 3+1 neutrino mass matrix is given by,

$$\begin{pmatrix} 0 & 0 & 0 & m_1 \\ 0 & 0 & 0 & m_2 \\ 0 & 0 & 0 & m_3 \\ m_1 & m_2 & m_3 & M \end{pmatrix}$$

- But this has two zero and two non-zero eigenvalues
  - Only two distinct Δm^2 values.
  - Cannot fundamentally motivate 3+1 models to explain LSND anomaly.

M. Sorel, et. al. hep-ph/0305255

3+2 Analysis

Idea: If light sterile neutrinos (ν_s) exist, then:

Includes CP phase; ϕ = -ϕ for antineutrinos

$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$

$$P(\nu_\alpha \rightarrow \nu_\beta) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2|U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{54})$$

$\nu_\mu \rightarrow \nu_s$

$\nu_e \rightarrow \nu_s$

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2 x_{54}]$$

With SBL approximation Δm_{solar}=0, Δm_{ATM}=0, and x_{ij}= $\delta m_{ij} L/4E$

Experimental constraints from:

LSND, KARMEN, NOMAD, MB, CCFR, CDHS, CHOOZ, BUGEY (+ atm constraint)

appearance experiments ($\nu_\mu \rightarrow \nu_e$): LSND, KARMEN, NOMAD, MB

disappearance experiments ($\nu_\mu \rightarrow \not\nu_\mu$ or $\nu_e \rightarrow \not\nu_e$): CCFR, CDHS, CHOOZ, BUGEY

(+ atm constraint): (ν_μ disappearance Constraint)

3+2 models can produce differences between neutrino and antineutrino appearance rates!

SBL Combined Analysis

Short-baseline (SBL) experiments on ν_μ and ν_e disappearance, and on $\nu_\mu \rightarrow \nu_e$ appearance, probe the same Δm^2 range and matrix elements

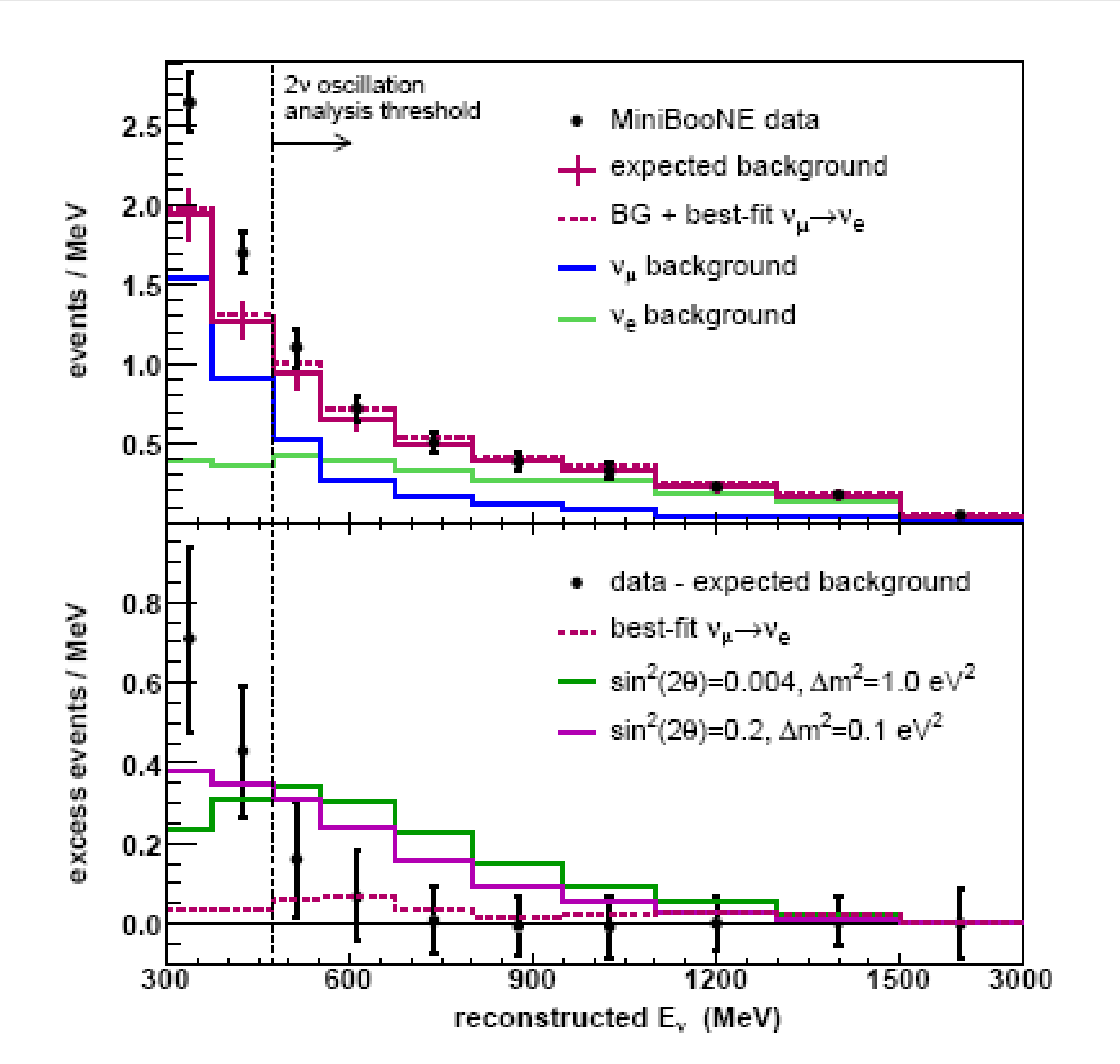
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

Channel	Experiment	Lowest Δm^2 Reach (90% CL)	$\sin^2 2\theta$ Constraint (90% CL)	
			High Δm^2	Optimal Δm^2
$\nu_\mu \rightarrow \nu_e$	LSND	$3 \cdot 10^{-2}$	$> 2.5 \cdot 10^{-3}$	$> 1.2 \cdot 10^{-3}$
	KARMEN	$6 \cdot 10^{-2}$	$< 1.7 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
	NOMAD	$4 \cdot 10^{-1}$	$< 1.4 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
$\nu_e \rightarrow \nu_{\not e}$	Bugey	$1 \cdot 10^{-2}$	$< 1.4 \cdot 10^{-1}$	$< 1.3 \cdot 10^{-2}$
	CHOOZ	$7 \cdot 10^{-4}$	$< 1.0 \cdot 10^{-1}$	$< 5 \cdot 10^{-2}$
$\nu_\mu \rightarrow \nu_{\not\mu}$	CCFR84	$6 \cdot 10^{0}$	none	$< 2 \cdot 10^{-1}$
	CDHS	$3 \cdot 10^{-1}$	none	$< 5.3 \cdot 10^{-1}$

Only LSND demands non-zero $U_{e4} U_{\mu 4}$, $U_{e5} U_{\mu 5}$, etc.

Is this consistent with upper limits derived from null short-baseline (NSBL) experiments?

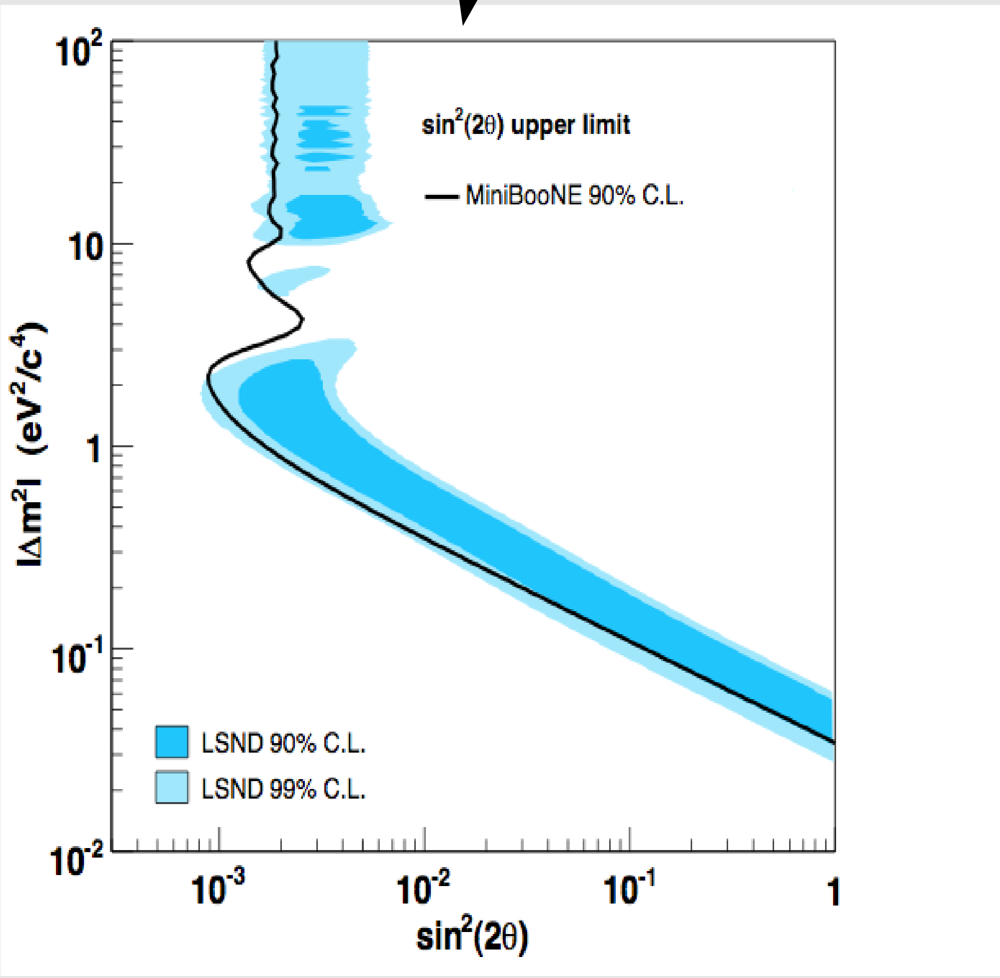
First Results from MiniBooNE

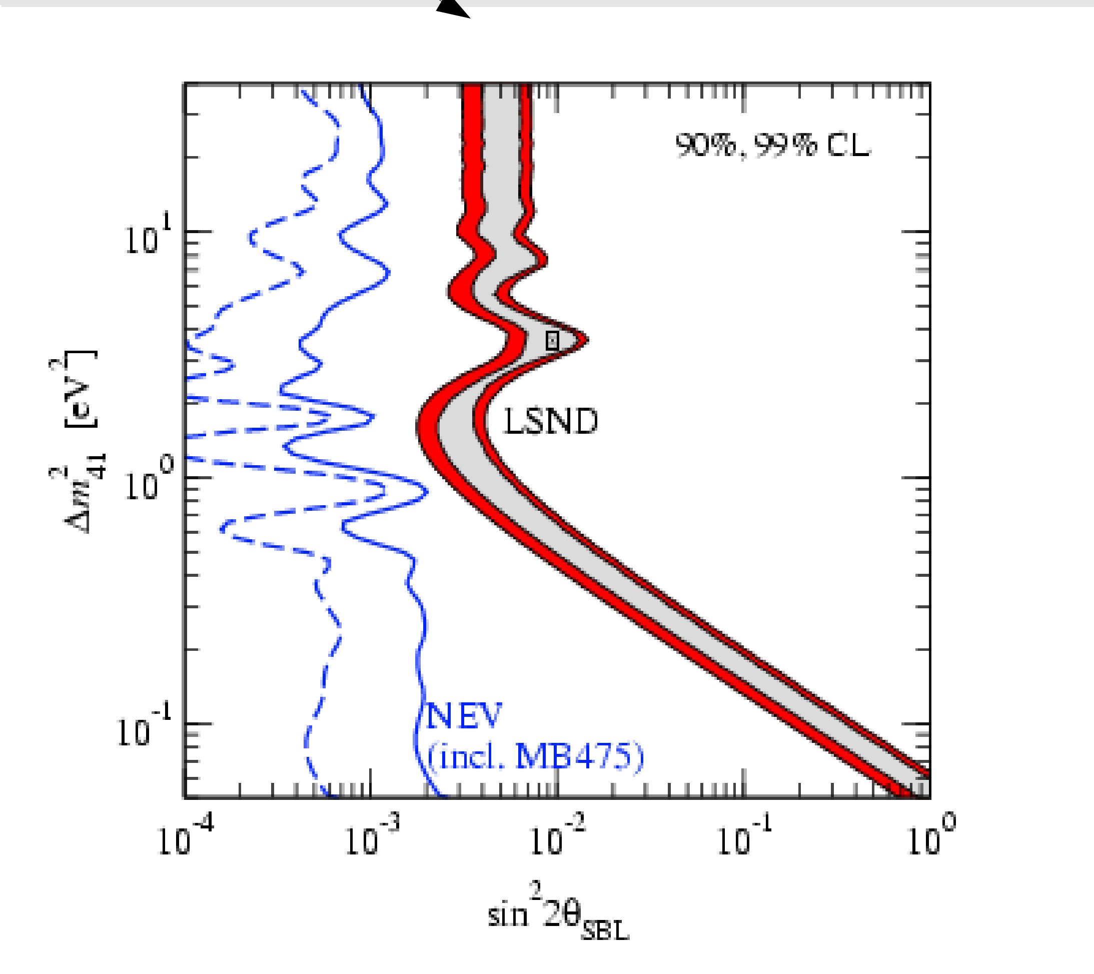


MiniBooNE result **excludes** the LSND 90%CL allowed region **at > 90% CL**…

Counting Expt :
300 MeV < E ^{QE}< 475 MeV
Excess over background : 3.7

MiniBooNE (E>475MeV) only, and (3+1) Global Fits





LSND ruled out with new MB results and within 3+1 models

First Results from MiniBoonE

…MiniBooNE result assumes:

CP-conserving, 2-neutrino oscillation scenario

E > 475 MeV

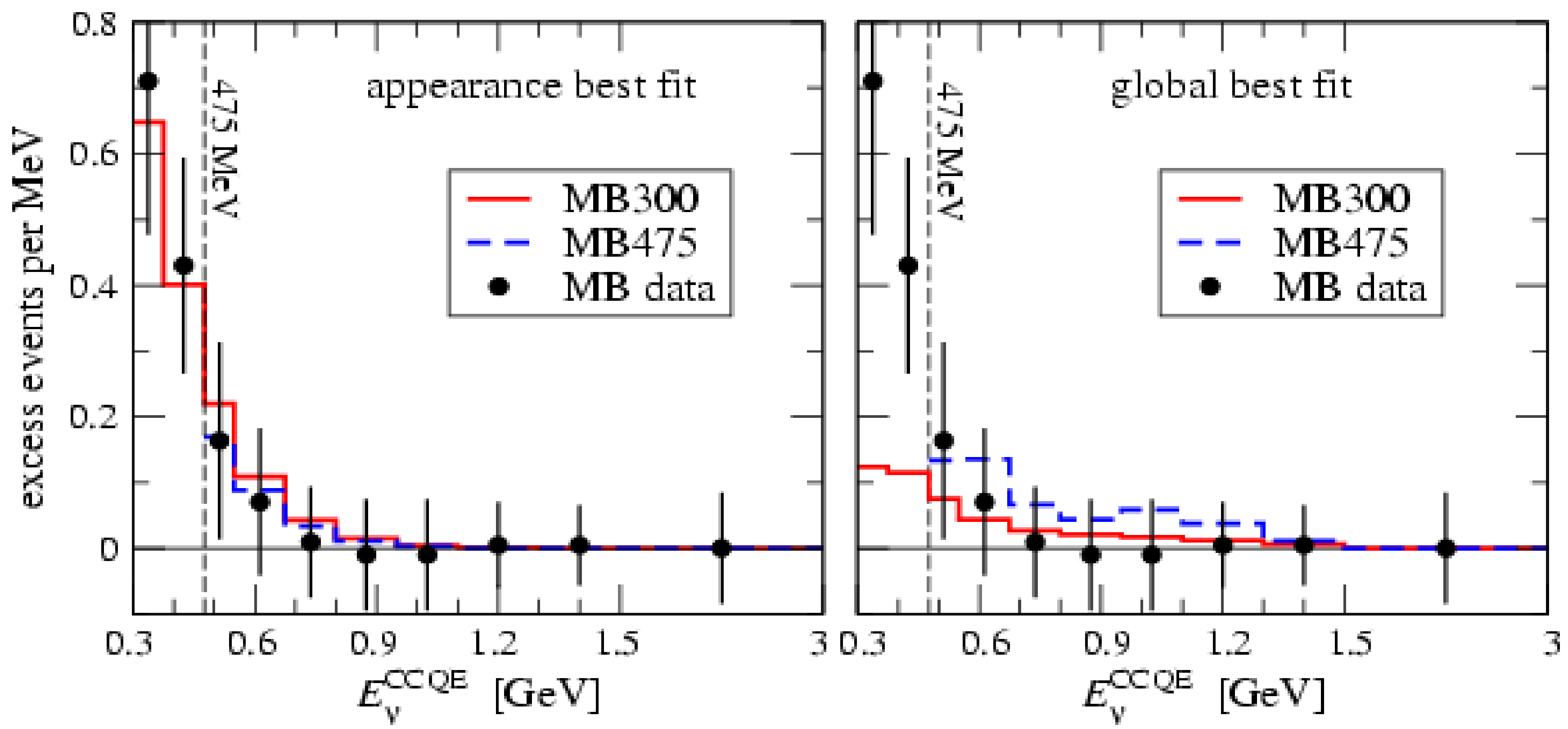
Excess of ν_e events at low energies:

Currently investigating if this is a detector effect, or SM background…

Could be a manifestation of beyond the SM physics…

Analysis by Maltoni & Schwetz
[hep-ph/0705.0107]

3+2 Global Fit Results



3+2 neutrino models:

- provide a **good fit** to LSND and the recent MB data
- can **account for the low energy** event **excess in MB**

However:

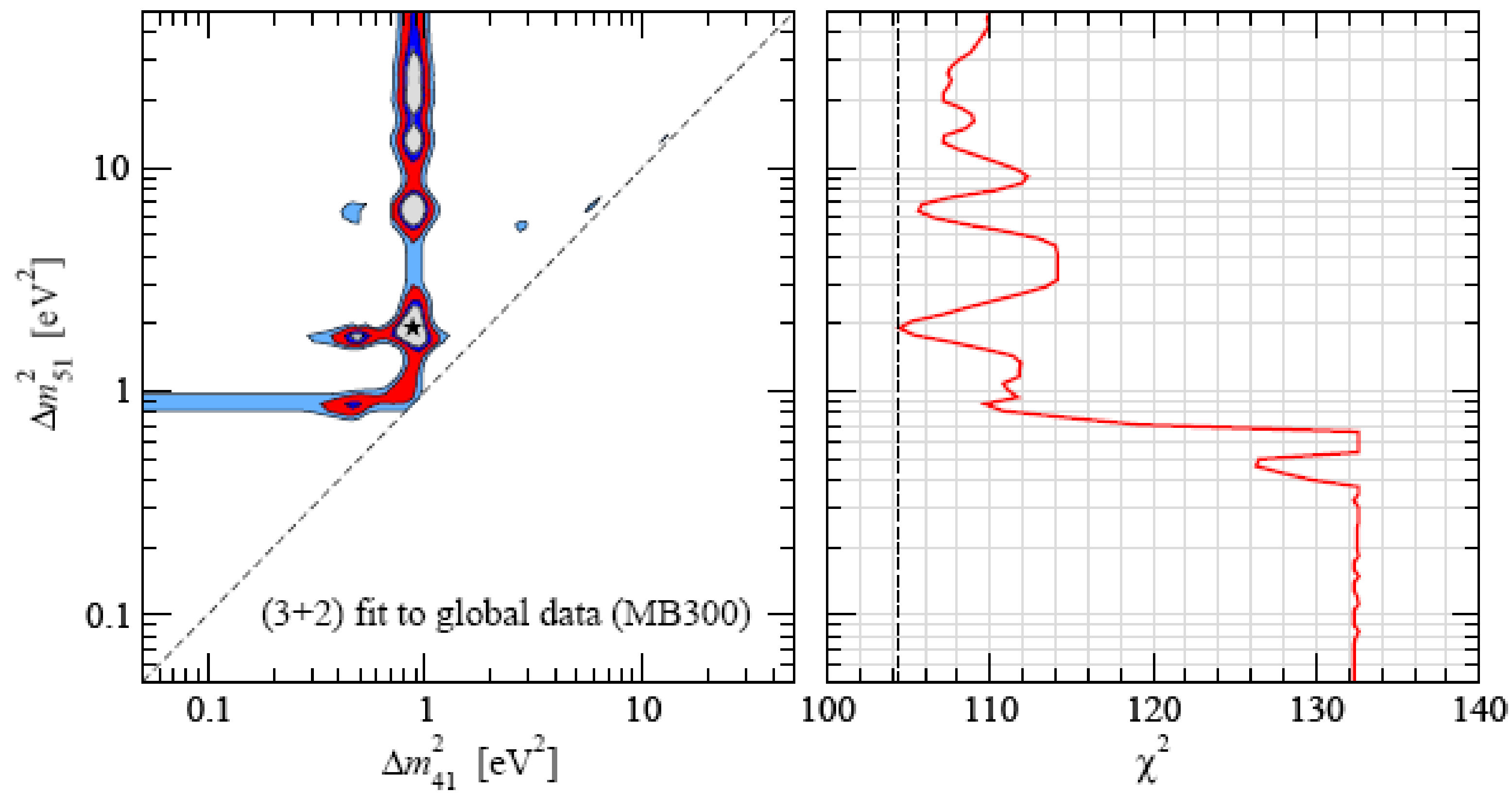
- there is significant **tension between appearance and disappearance data**

Note: analysis done without full MiniBooNE error matrix

MB will perform full analysis, G. Karagiorgi.

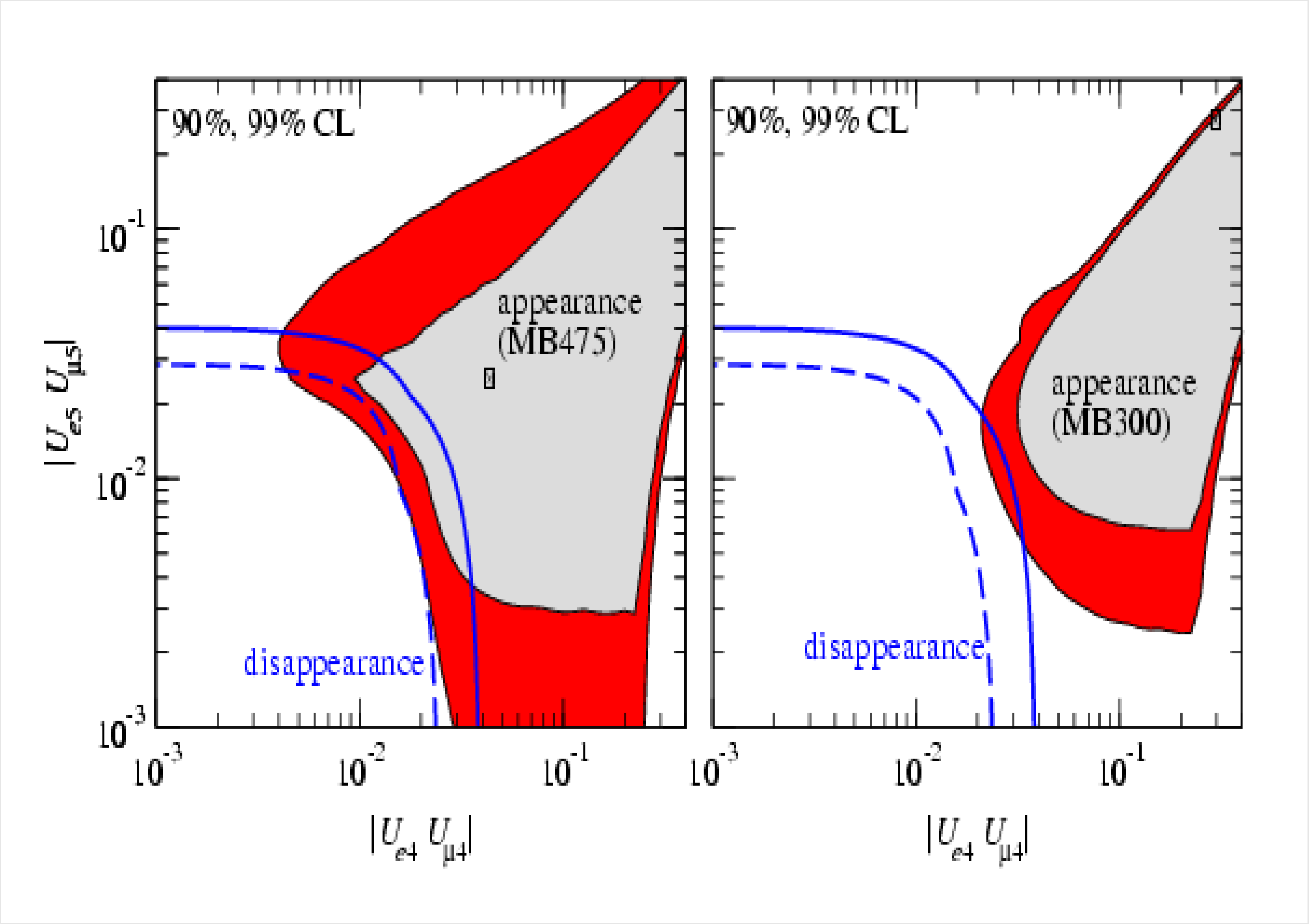
Analysis by Maltoni & Schwetz [hep-ph/0705.0107]

3+2 Global Fit Results



data set	$\lvert U_{e4}U_{\mu4}\rvert$		Δm^2_{41}	$\lvert U_{e5}U_{\mu5}\rvert$		Δm^2_{51}	δ	χ^2_{min}/dof	gof
appearance (MB475)	0.044		0.66	0.022		1.44	1.12π	16.9/(29 − 5)	85%
appearance (MB300)	0.31		0.66	0.27		0.76	1.01π	18.5/(31 − 5)	85%
	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$		$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$				
global data (MB475)	0.11	0.16	0.89	0.12	0.12	6.49	1.64π	94.5/(107 − 7)	63%
global data (MB300)	0.12	0.18	0.87	0.11	0.089	1.91	1.44π	104.4/(109 − 7)	41%

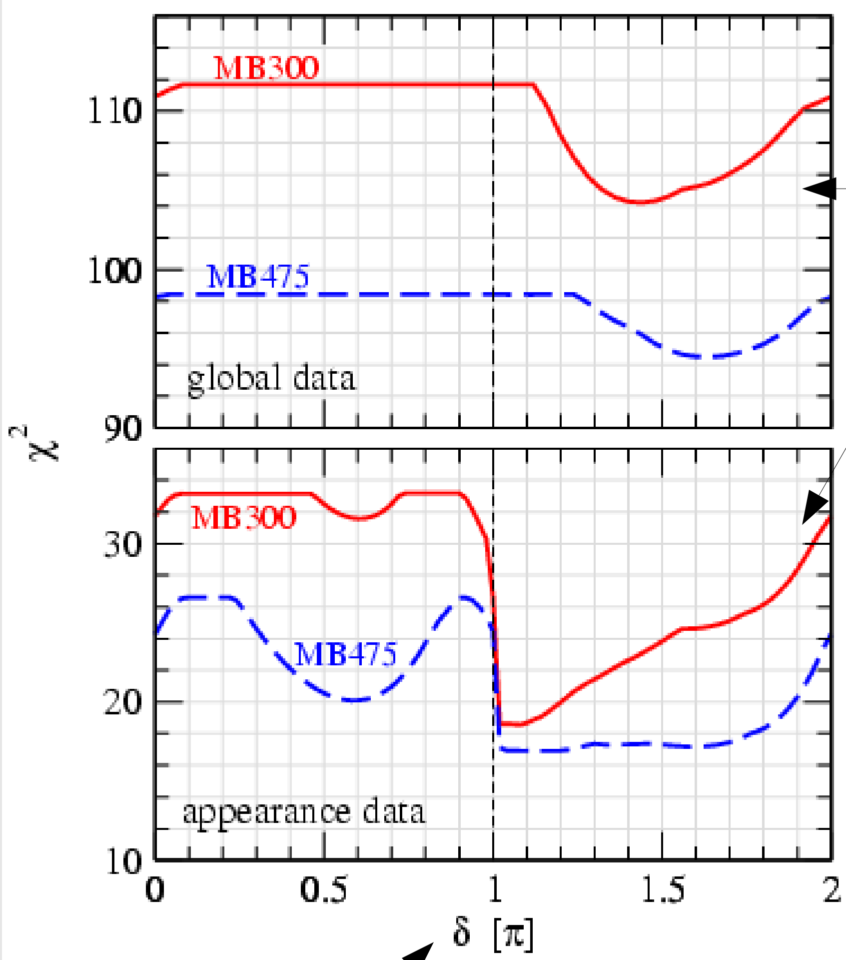
3+2 Tension with Disappearance Data



Large values of 3+2 appearance mixing amplitudes are inconsistent with disappearance amplitudes

3+2 Model CP Phase Fits

Has CP violation been observed?



Improved fits with CP phase included!

MiniBooNE antineutrino oscillation analysis will be interesting.
-could see LSND oscillations
-may need more antineutrino data for decent sensitivity!

CP conserving value $\delta = \pi$

Conclusions

- Standard Model does not tell us a whole lot about sterile neutrino properties, only gives some general guidance,
  - Given neutrinos have mass, there are right handed singlets, but number of flavors and mass spectrum unknown.
  - They can have Dirac and/or Majorana mass terms.
  - See-saw mechanism may or may not be relevant.
- Sterile neutrinos have interesting properties/effects,
  - Sterile neutrinos may interact with extra D's.
  - Sterile neutrinos have measurable consequences in cosmology and astrophysics.
  - 3+2 models, with CP, can be constructed to fit SBL data.
- Up to future experiments to nail down neutrino properties,
  - Wouldn't it be nice to have a smoking gun measurement of active-sterile oscillations...