lecture III

Outline of lectures

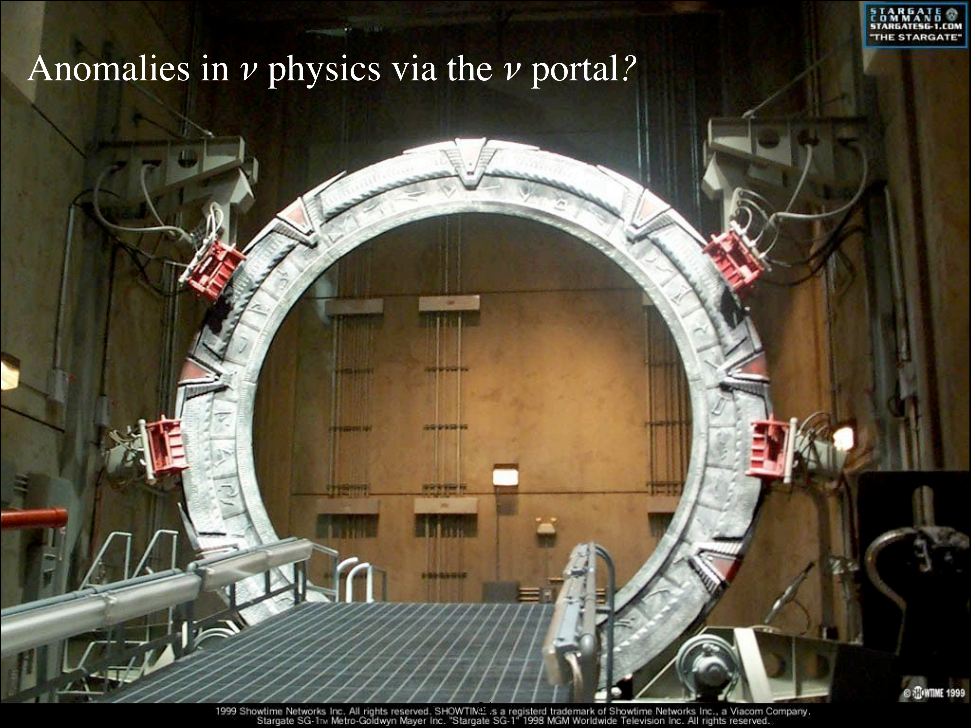
- introduction to what we know about neutrinos
  - ➡ mass ✓
  - ➡ mixing ✓
    - ★ lepton flavor violation ✓
  - ➡ oscillation ✓
  - ➡ matter effects ✓
- critical open experimental questions ✓

} yesterday more introductory

- ***the neutrino portal***
- neutrinos in cosmology and astrophysics
  - ➡ effects of sterile neutrinos
  - ➡ dark energy coincidence and MaVaNs

} today more advanced

Anomalies in ν physics via the ν portal?



Review of last part of lecture II

- Unknown territory for new discoveries is not just the high energy frontier
  - ➡ Are there new light particles, longer range forces?
    - ★ they must be weakly coupled to us!
      - in some cases constraints are very strong
      - in others not so much
  - ➡ vast landscape of possibilities to consider
    - ☺ avoids “limited palette” of small number of renormalizable interactions consistent with sacred principles
    - ☹ also avoids being predictive

Review of last part of lecture II continued

- How to organize our thinking about possible new sectors containing relatively light particles and long range forces?

  ➡ Portals!

★ low dimension gauge invariant operators of Standard Model

☺ these don't have to be Lorentz scalars

★ interaction between visible and hidden sector of form:

$$\xi \vartheta_{SM} \vartheta_{hidden}$$

whose effects are visible at relatively low energy

Dimensional Analysis of Portal

$$\xi \vartheta_{SM} \vartheta_{hidden}$$

- assume 3+1=4 spacetime dimensions for SM particles
  - ➡ ϑ_{SM} has dimension d_{SM}
    - ★ *e.g.* $\vartheta_{SM} = \ell\, h$ has $d_{SM}=5/2$
  - ➡ ϑ_{hidden} has dimension d_{hidden}
    - ★ *e.g.* $\vartheta_{hidden}=\psi$ has $d_{hidden}=3/2$
  - ➡ dimension of ξ is 4-d_{SM}-d_{hidden}
    - ★ *e.g.* coefficient of $\ell\, h\psi$ *is* dimensionless
    - ★ $\ell\, h\psi$ is renormalizable operator

Condensed Matter terminology

- Relevant Operator (in QFT we say superrenormalizable)
  - ➡ operator with scaling dimension $d<4$
    - ★ becomes more important at low energy/long distance
    - ★ If the operator can create massless particles it is always important at long distance
- Marginal Operator (in QFT we say renormalizable)
  - ➡ operator with scaling dimension $d=4$
    - ★ equally important at all distance/energy scales
- Irrelevant operator (in QFT we say nonrenormalizable)
  - ➡ operator with scaling dimension $d>4$
    - ★ important at high energy/short distance
    - ★ difficult to detect the effects at low energy

Dimensional Analysis continued

$$\xi \vartheta_{SM} \vartheta_{hidden}$$

- In standard model the scaling dimension of some operators changes below the weak scale
  - ➡ *e.g.* $\vartheta_{SM} = \ell\, h$ has $d_{SM}=5/2$ above the weak scale
    - ★ $\vartheta_{SM} = \ell < h >$ has effective $d_{SM}=3/2$ below the weak scale
  - ➡ $\ell <h> \psi$ operator becomes more important at low energy
    - ★ (below the weak scale: the operator is relevant with $d=3$)
      - ☺ no matter how small the coefficient, the operator becomes more important at low energy/long distance
      - ☺ light particles like neutrinos allow us to see the effects of relevant operators with tiny coefficients

relevant irrelevant operators

- An irrelevant operator at some scale can be relevant at low energy
- Weinberg operator $\vartheta_{Weinberg} = (h^2/M)\ \ell\ \ell$ has d=5, is irrelevant
- Below weak scale $h \to \langle h \rangle$
- Below weak scale $\vartheta_{Weinberg} \to\ \langle h \rangle^2/\mathrm{M})\ \ell\ \ell$ has d=3, is relevant
- We understand why $\vartheta_{Weinberg}$ is unimportant at weak scale:

  ➡ $M >> \langle h \rangle$
- Far below weak scale $\vartheta_{Weinberg}$ becomes important again

  ➡ without it neutrinos would have no mass

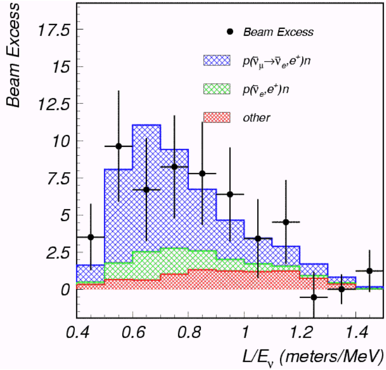
Popular Portals

- Scalar: $h^\dagger h\, \phi$, $h^\dagger h\, \phi^2$
  - Higgs mixing with exotic scalars
  - Higgs decay to exotics, Higgs production
  - new force if ϕ is light
- Vector: $B_{\mu\nu} X_{\mu\nu}$, $J^\mu X_\mu$
  - exotic vector coupling to electromagnetic charge, B, L
  - Z decay to exotics
  - new force
- Spin 1/2: $hl\psi$
  - neutrino mixing with exotic fermions
  - new force, strongest for neutrinos, if ψ experiences dark force

Where are all the anomalies in the neutrino sector?

- Are there no exotic light fermions?
- *Z* boson decays: "there are only 3 neutrinos lighter than $m_Z/2$"
  - ➡ possible to have light "sterile" neutrinos that don't couple to the *Z*
  - ➡ these could be related to the known quarks and leptons in some unified scheme
  - ➡ or simply part of a hidden sector
  - ➡ they could be massless or light composite fermions
  - ➡ they could live in extra dimensions….

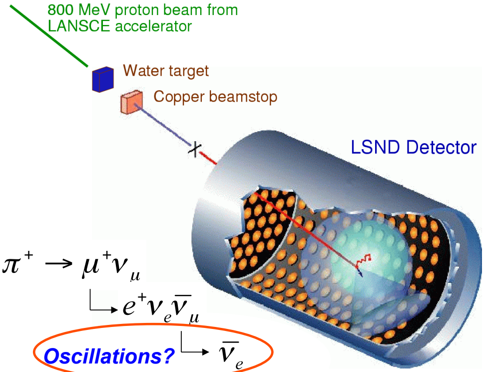
LSND: the Effect that Refuses to Die



$\bar{\nu}_e$ appearance at ~30 m in ~30 MeV $\bar{\nu}_\mu$ beam

3.8 σ excess

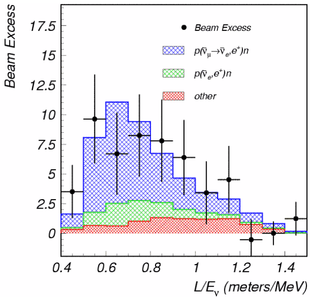
The LSND Experiment: Evidence for Oscillations



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
Oscillations? $\hookrightarrow \bar{\nu}_e$

Signal: $\bar{\nu}_e\ p \rightarrow e^+ n$

$\hookrightarrow n\ p \rightarrow\ d\ \gamma(2.2\text{MeV})$



LSND took data from 1993-98

- 49,000 Coulombs of protons
- L = 30m and 20 < E_ν < 53 MeV

Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

HARP recently announced measurements that confirm LSND $\bar{\nu}_e$ background estimate

from R. Van de Water talk, 2010

ν oscillation interpretation

$$P_{\mu\to e} = \sin^2(2\theta)\sin^2\left(\frac{(m_1^2 - m_2^2)L}{4E}\right)$$

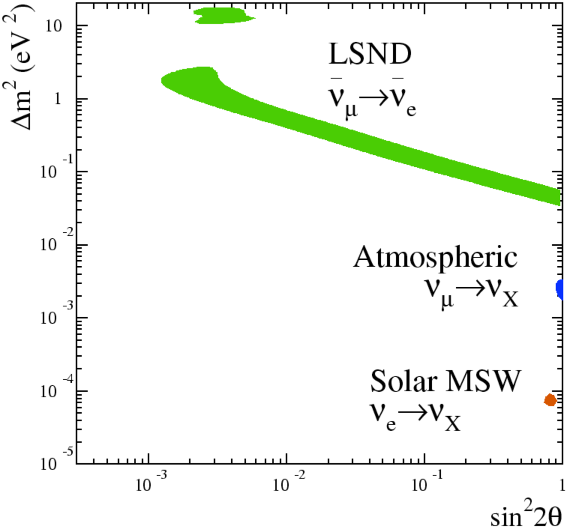
$$= \sin^2(2\theta)\sin^2\left(1.27\frac{\left(\frac{(m_1^2 - m_2^2)}{eV^2}\right)\left(\frac{L}{meters}\right)}{\left(\frac{E}{MeV}\right)}\right)$$

- LSND studied antineutrino oscillations
- L~ 30 m
- 20 MeV < E < 53 MeV
- sensitive to Δm^2~eV^2

(In)compatibility of LSND with Other Oscillation Signals

three oscillation signals have 3 different Δm^2
$\Rightarrow$ need ≥ 4 ν's,
3 active + n sterile

3.8σ evidence for physics beyond the ν standard model



MiniBooNE

$$P_{\mu\to e} = \sin^2(2\theta)\sin^2\left(\frac{(m_1^2 - m_2^2)L}{4E}\right)$$

$$= \sin^2(2\theta)\sin^2\left(1.27\frac{\left(\frac{(m_1^2 - m_2^2)}{eV^2}\right)\left(\frac{L}{meters}\right)}{\left(\frac{E}{MeV}\right)}\right)$$

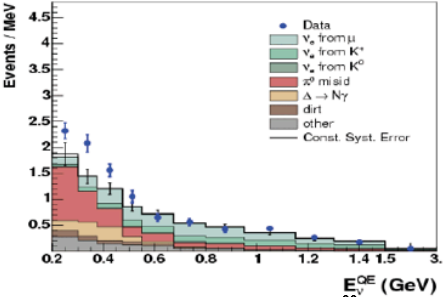
- initial run with muon neutrino beam
- L=541m
- 200 MeV < E < 3 GeV
- similar L/E to LSND, sensitive to $\Delta m^2 \sim eV^2$

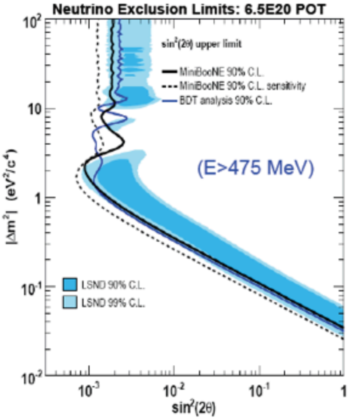
from R. Van de Water Neutrino 2010

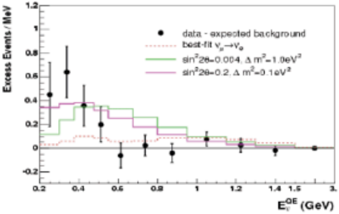
Neutrino mode MB results (2009)

- 6.5E20 POT collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction
  - energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.
  - A two neutrino fit rules out LSND at the 90% CL assuming CP conservation.
- E < 475 MeV, statistically large (6σ) excess
  - Reduced to 3σ after systematics, shape inconsistent with two neutrino oscillation interpretation of LSND. Excess of 129 +/- 43 (stat+sys) events is consistent with magnitude of LSND oscillations.

Published PRL 102,101802 (2009)







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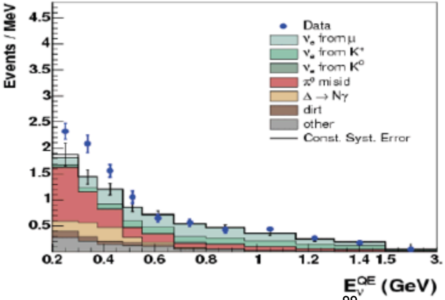
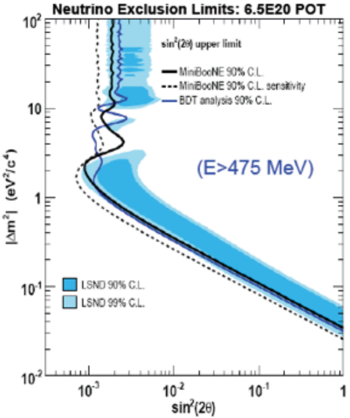
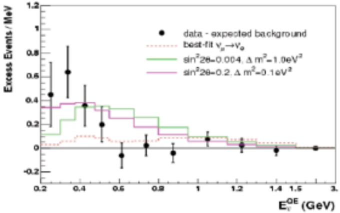


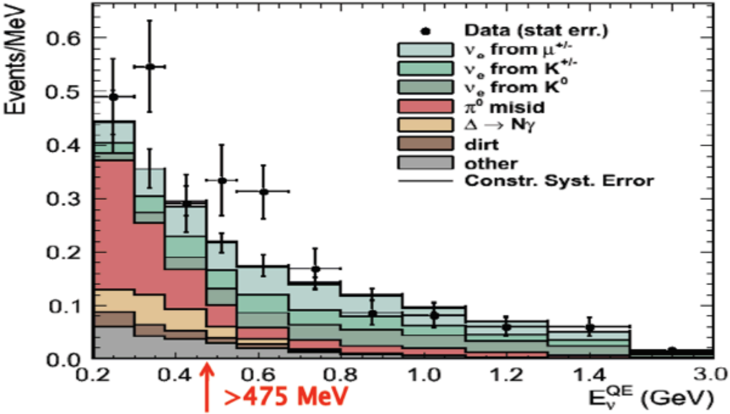




from R. Van de Water Neutrino 2010

New Antinuetrino Result with 5.66E20 POT

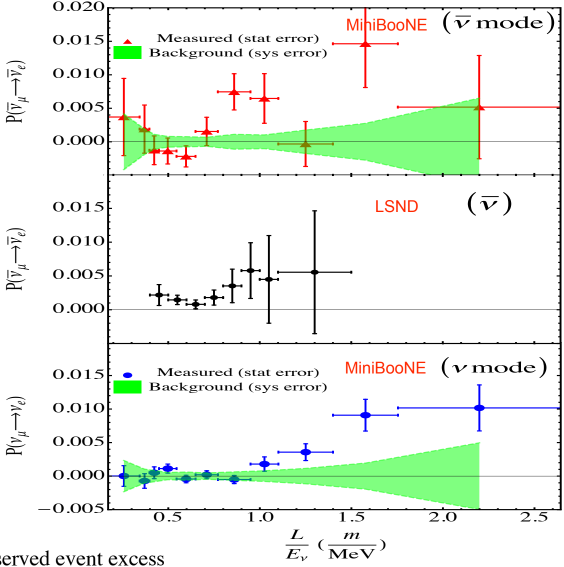
	200-475 MeV	475-1250 MeV	200-3000 MeV
Data	119	120	277
MC (stat+sys)	100.5 ± 14.3	99.1 ± 13.9	233.8 ± 22.5
Excess (stat)	18.5 ± 10.0 (1.9σ)	20.9 ± 10.0 (2.1σ)	43.2 ±15.3 (2.8σ)
Excess (stat+sys)	18.5 ± 14.3 (1.3σ)	20.9 ± 13.9 (1.5σ)	43.2 ± 22.5 (1.9σ)



New MiniBooNE result

Data plotted vs L/E

New!
5.66E20 POT

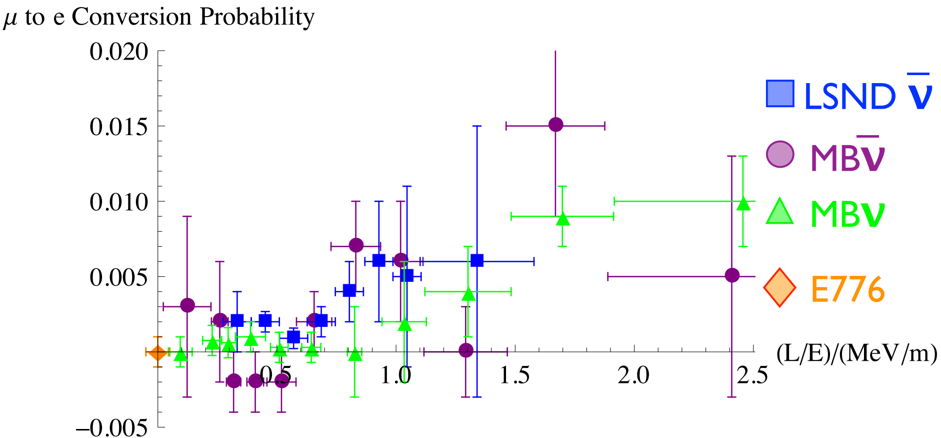


- MiniBooNE L/E bins match the standard MB energy bins, just recast in L/E

- MB 2007: neutrino data does not confirm LSND (but low energy ν_e excess)

$$P(\alpha \to \beta) \equiv \frac{\text{observed event excess}}{\text{number expected for full transmutation of } \nu_\mu \text{ or } \bar{\nu}_\mu}$$

LSND and MiniBooNE:
same L/E conversion prob for $\bar{\nu}$?



Are LSND/MB discovering CP Violation from new ν ?

ν effects on neutrino oscillations

new ultralight fermion: new mass eigenstates in oscillations

$$P_{\mu e} = \left| \sum_i U^*_{ei} U_{\mu i} e^{-i2x_{ij}} \right|^2 \qquad P_{\bar{\mu}\bar{e}} = \left| \sum_i U_{ei} U^*_{\mu i} e^{-i2x_{ij}} \right|^2$$

$$P_{\mu e} \equiv P(\nu_\mu \to \nu_e) \qquad P_{\bar{\mu}\bar{e}} = P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

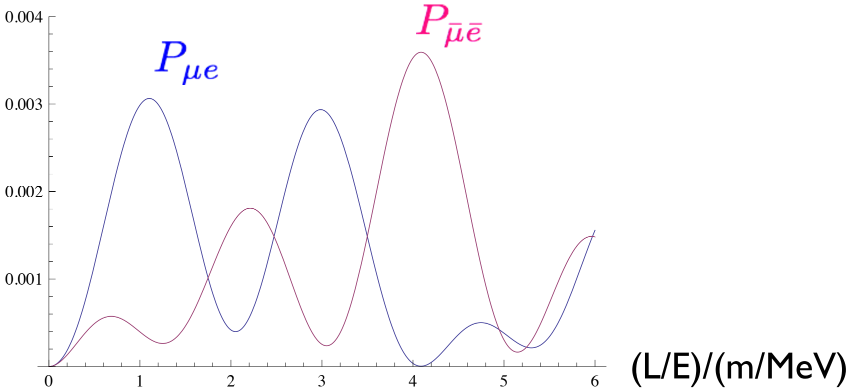
$$x_{ij} \equiv 1.27 \frac{|m_i^2 - m_j^2|}{eV^2} \frac{\frac{L}{E}}{\frac{km}{GeV}}$$

How many neutrinos for CPV?

- 3, with 2 mass squared differences
- with 3+1=4 ν we have more than enough?
- At short baseline we can neglect solar, atmospheric mass squared differences
- with 3+1 we only have 1 nonnegligible mass squared difference

  ➡ NO CPV observable at LSND/MB with 3+1
- for CPV at LSND/MB we need 3+2=5 ν

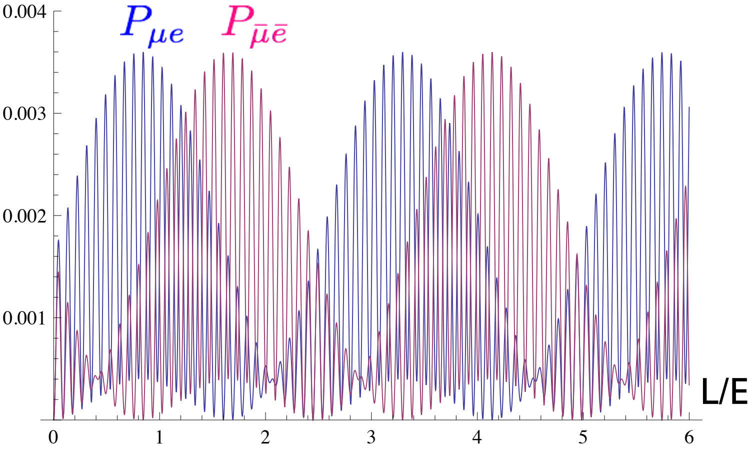
3+2, ultralight ν



$m_4^2 - m_1^2 = 1\ eV^2, \quad m_5^2 - m_1^2 = 1.4\ eV^2 \quad \delta_{CPV} = -2.1 \quad |U_{e4}U_{\mu 4}| = |U_{e5}U_{\mu 5}| = .02$

Other mass squared differences negligible at this L/E

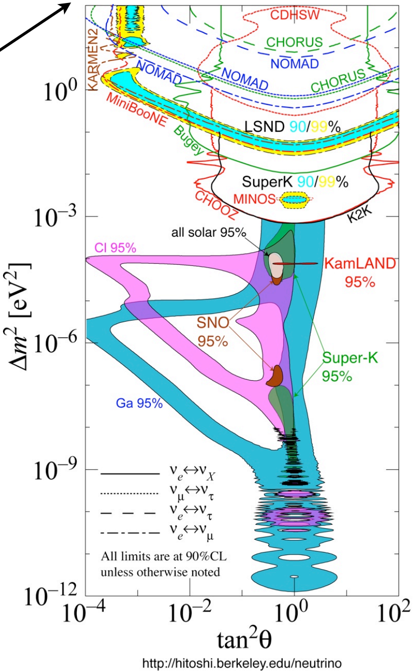
3+2 ultralight



$$m_4^2 - m_1^2 = 1\ eV^2, \quad m_5^2 - m_1^2 = 28\ eV^2 \quad \delta_{CPV} = -2.1 \quad |U_{e4}U_{\mu 4}| = |U_{e5}U_{\mu 5}| = .02$$

Above $\Delta m^2/\mathrm{eV}^2=100$
Oscillations rapid, can
Average over them
(Same results from
decoherence)
Some constraints remain
but mostly on **appearance.**

Disappearance constraints go
away (CDHS) or weaken
(Bugey, CHOOZ)



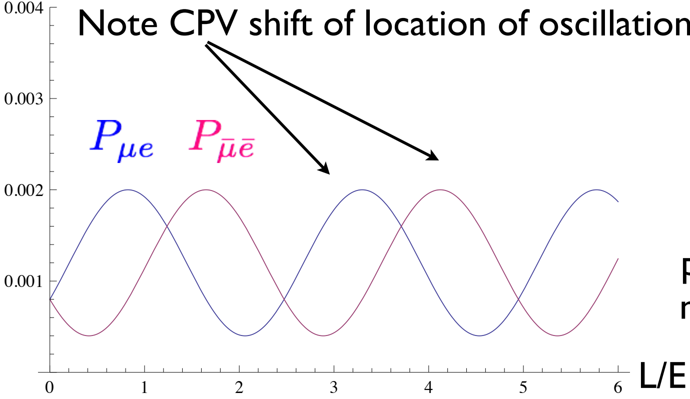
Effects of light sterile neutrinos

light: new mass eigenstates in oscillations (either masses large enough that wavepackets do separate spatially, or oscillations so rapid they must be averaged over, but small enough so mass has no affect on phase space factor) 10^{12} eV^2>>Δm^2 > 1000 eV^2

$$P_{\mu e} = \left| \sum_{i=ultralight} U^*_{ei} U_{\mu i} e^{-i2x_{ij}} \right|^2 + \sum_{i=light} |U^*_{ei} U_{\mu i}|^2$$

large CPV requires at least one x_{ij} of order one

3+1, ultralight + 1 light



Note probability never zero

$$m_4^2 - m_1^2 = 1\ eV^2 \quad m_5^2 \gg m_4^2 \quad \delta_{CPV} = -2.1 \quad |U_{e4}U_{\mu 4}| = |U_{e5}U_{\mu 5}| = .02$$

Other mass squared differences negligible at this L/E

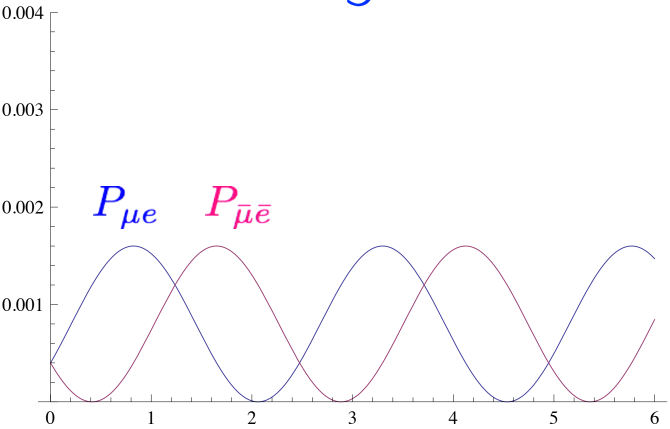
Effects of nonlight ν 's on oscillations

nonlight: new mass eigenstates, too heavy to be produced with same phase space as light states 10^{12} eV^2<Δm^2

$$P_{\mu e} = \left| \sum_{i=ultralight} U^*_{ei} U_{\mu i} e^{-i2x_{ij}} \right|^2 + \sum_{i=light} |U^*_{ei} U_{\mu i}|^2 + PSF \sum_{i=nonlight} |U^*_{ei} U_{\mu i}|^2$$

PSF=Phase Space factor, <1, Can be 0 (for neutral fermion which is too heavy to produce)

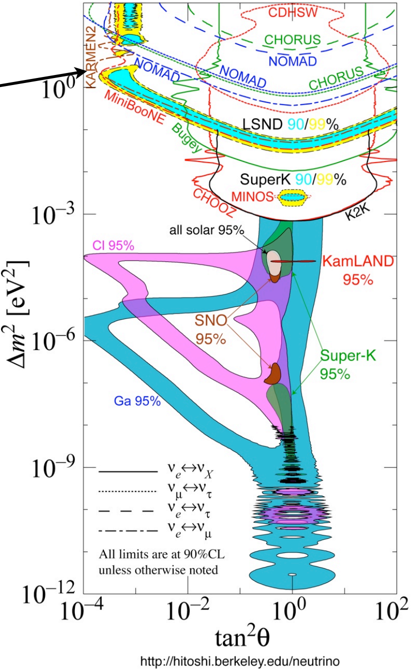
3+1 ultralight neutrinos + 1 nonlight neutrino



note oscillation prob can reach 0, but not at L/E=0 with CPV

$m_4^2 - m_1^2 = 1\ eV^2 \quad m_5^2 \gg 10^{10} eV^2 \quad \delta_{CPV} = -2.1 \quad |U_{e4}U_{\mu 4}| = |U_{e5}U_{\mu 5}| = .02$

Note any 1 laboratory experiment typically has wiggles (sensitive to L/E dependence of oscillations) only over a decade or so, likely sensitive to at most 1 Δm^2 .



General formula for vacuum (anti) neutrino oscillation appearance

- Assume *1* x_{ij} is of order *1*
- neglect all $x_{ij} << 1$
- For $x_{ij} >> 1$, neglect interference
- allow for nonunitarity from mixing with nonlight fermion

$$P_{\mu e} = \sin^2(2\theta_{eff})\sin^2(1.27\Delta m^2 L/E + \beta_{CP}) + \sin^2\alpha\cos^2(2\theta_{eff})$$
$$P_{\bar{\mu}\bar{e}} = \sin^2(2\theta_{eff})\sin^2(1.27\Delta m^2 L/E - \beta_{CP}) + \sin^2\alpha\cos^2(2\theta_{eff})$$

only 2 new parameters

CPV from interference with short distance

constant term from short distance

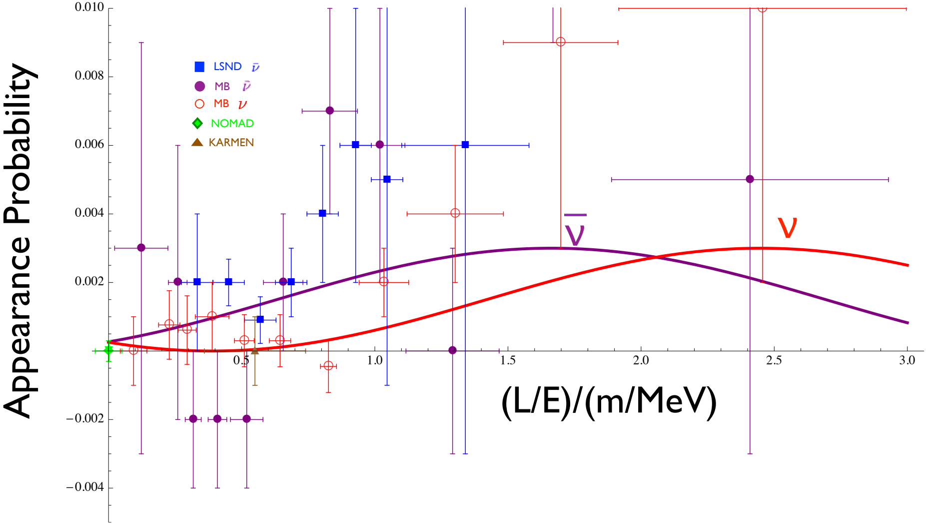
Can this formula fit short baseline data?

Minimal fit to short baseline ν oscillations

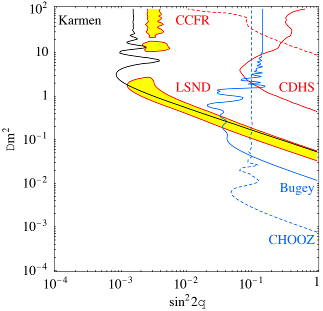
- 3 active + 1 light sterile neutrinos
- CP violation in mixing
  - requires nonunitary mixing matrix
    - 3 active +1sterile +1 heavy neutrino

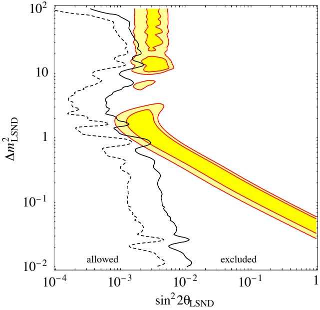
Effects of CP violation from Neutral Heavy Fermions on Neutrino Oscillations, and the LSND/MiniBooNE Anomalies
A. E. N., arXiv:1010.3970v1 [hep-ph]

Fit Example: Δm^2_{41}=0.6 eV^2, $\sin^2(2\theta)$=0.003, α=0, β=-0.3, χ^2=26.4/24 d.o.f



What about disappearance?





from
A. Strumia

Figure 2: 90% *CL regions from Karmen, CDHS, CCFR,* Bugey, Chooz *and LSND (shaded). The mixing angle θ on the horizontal axis is different for the different experiments.*

Figure 3: *The LSND region at* 90% *and* 99% *CL, compared with the* 90% *(dashed line) and* 99% *CL (continuous line) combined exclusion bounds from data in fig.* 2 *and SK.*

Disappearance vs appearance, large m_5 limit

$P_{e\to e} = \quad 4|U_{e4}|^2(1-|U_{e4}|^2-|U_{e5}|^2)\sin^2 x_{41} + 2|U_{e5}|^2(1-|U_{e5}|^2)$

Define $\quad x_{ij} \equiv 1.27\frac{(m_i^2-m_j^2)}{\mathrm{eV}^2}\frac{L/E}{\mathrm{km/GeV}}\ . \qquad \phi \equiv \arg\left(\frac{U_{e5}U_{\mu5}^*}{U_{e4}U_{\mu4}^*}\right)$

$$r \equiv \frac{|U_{e5}U_{\mu5}^* + U_{e4}U_{\mu4}^*|}{|U_{e4}U_{\mu4}^*|} \qquad \beta \equiv \frac{1}{2}\tan^{-1}\left(\frac{\sin\phi|U_{e5}||U_{\mu5}|}{|U_{e4}||U_{\mu4}| + \cos\phi|U_{e5}||U_{\mu5}|}\right)$$

Large m_5 gives constant term which is not well constrained ⇒ r can be fairly large

$$P_{\nu_\mu\to\nu_e} \;=\; 2|U_{e4}|^2|U_{\mu4}|^2[(1-r)^2 + 2r\sin^2\beta + 2r\sin^2(x_{41}-\beta)]\ .$$

Disappearance vs appearance, very large m_5 limit

Define $$x_{ij} \equiv 1.27 \frac{(m_i^2 - m_j^2)}{\mathrm{eV}^2} \frac{L/E}{\mathrm{km/GeV}} \, . \qquad \phi \equiv \arg\left(\frac{U_{e5}U_{\mu 5}^*}{U_{e4}U_{\mu 4}^*}\right)$$

$$r \equiv \frac{|U_{e5}U_{\mu 5}^* + U_{e4}U_{\mu 4}^*|}{|U_{e4}U_{\mu 4}^*|} \qquad \beta \equiv \frac{1}{2}\tan^{-1}\left(\frac{\sin\phi |U_{e5}||U_{\mu 5}|}{|U_{e4}||U_{\mu 4}| + \cos\phi |U_{e5}||U_{\mu 5}|}\right)$$

$$P_{\nu_\mu \to \nu_e} = |U_{e4}|^2 |U_{\mu 4}|^2 [(1-r)^2 + 4r \sin^2(x_{41} - \beta)] \, .$$

large r gives enhancement of μ→e oscillations, not constrained by disappearance in large m_5 limit

Evidence for neutrino mixing with heavy fermion?

- 3+2 +CPV with all $\Delta m^2 < 100$ eV^2 fits MB/LSND appearance, does not fit disappearance well
- 3+1 (+ 1) can fit MB/LSND appearance and all disappearance well, CPV improves fit

What about cosmology?

“Cosmology seeking friendship with sterile neutrinos”
arXiv1006.527v6
Jan Hamann, Steen Hannestad, Georg G. Raffelt, Irene Tamborra, and Yvonne Y. Y. Wong

Precision cosmology and big-bang nucleosynthesis mildly favor extra radiation in the universe beyond photons and ordinary neutrinos, lending support to the existence of low-mass sterile neutrinos. We use the WMAP 7-year data release, small-scale CMB observations from ACBAR, BICEP and QuAD, the 7th data release of the Sloan Digital Sky Survey, and measurement of the Hubble parameter from Hubble Space Telescope observations to derive credible regions for the assumed common mass scale ms and effective number Ns of thermally excited sterile neutrino states. Our results are compatible with the interpretation of the LSND and MiniBooNE anomalies in terms of 3 active + 2 sterile neutrinos if ms is in the sub-eV range.

Cosmology and sterile ν's

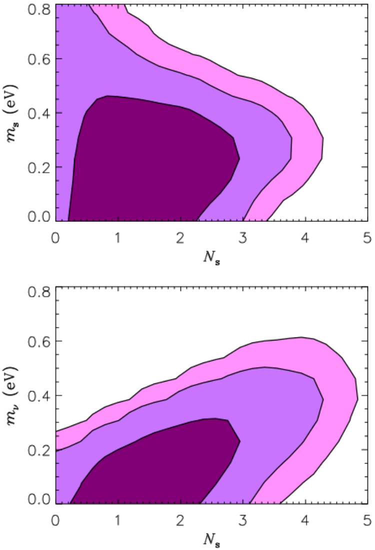


FIG. 1: 2D marginalized 68%, 95% and 99% credible regions for the neutrino mass and thermally excited number of degrees of freedom N_s. *Top:* The $3 + N_s$ scheme, in which ordinary neutrinos have $m_\nu = 0$, while sterile states have a common mass scale m_s. *Bottom:* The $N_s + 3$ scheme, where the sterile states are taken to be massless $m_s = 0$, and 3.046 species of ordinary neutrinos have a common mass m_ν.

from arXiv1006.527v6

- CMB, structure formation consistent with up to 4 light sterile ν's in thermal equilibrium
- primordial Helium now consistent with up to 2 sterile ν's
- stable sterile ν's in thermal equilibrium should be lighter than ~1 eV

Summary

- Neutrino portal is sensitive to new sectors containing fermions
- Is there any evidence?
- surprising LSND/MB results
  - ➡ LSND may be systematic, not compelling
  - ➡ MB is statistics limited
- more MB antineutrino data will be interesting
- CMB, Helium, structure now seem consistent with a few additional light states in thermal equilibrium

- propose analyzing short baseline ν flavor appearance expts with 2 new parameters

$$P_{\mu e} = \sin^2(2\theta_{eff})\sin^2(1.27\Delta m^2 L/E + \beta_{CP}) + \sin^2\alpha\cos^2(2\theta_{eff})$$
$$P_{\bar{\mu}\bar{e}} = \sin^2(2\theta_{eff})\sin^2(1.27\Delta m^2 L/E - \beta_{CP}) + \sin^2\alpha\cos^2(2\theta_{eff})$$