Lecture IV

- dark neutrinos+dark forces
- Apparent CPT violation
- Dark Energy
- Dark Energy from mass varying neutrinos

ν mixing with exotic fermion

- What happens when we add an exotic fermion coupled to a light boson?
- New force mainly affecting neutrinos
  - ➡ Apparent CPT violation in ν oscillations
  - ➡ ν Dark energy

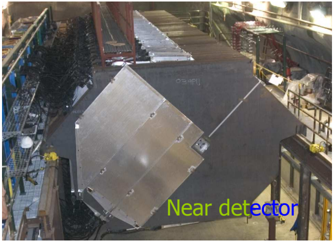
more ν

surprises?

CPT

- Prob($\nu_\mu \rightarrow \nu_\mu$)=Prob($\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$)
- absent matter effects, ν_μ and $\overline{\nu}_\mu$ disappearance should be the same
- In SM at baseline sensitive to atmospheric Δm^2, ν_μ disappearance is almost all into ν_τ and should have negligible matter effects

The MINOS Detectors



Near detector, 1.0 ktonne, 1km from source

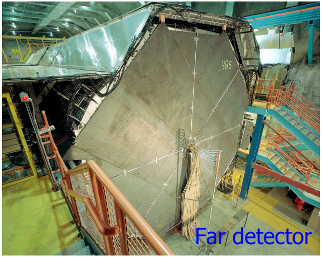
Far detector, 5.4 ktonne, 735 km from source

Tracking, sampling calorimeters

- Alternate steel and scintillator planes
- Functionally identical
- Magnetised to 1.3 T

Two detectors to mitigate systematics

- e.g. neutrino flux or cross section mismodelings



Minos antineutrinos

- central value of antineutrino mixing parameters about 2σ different from neutrino mixing

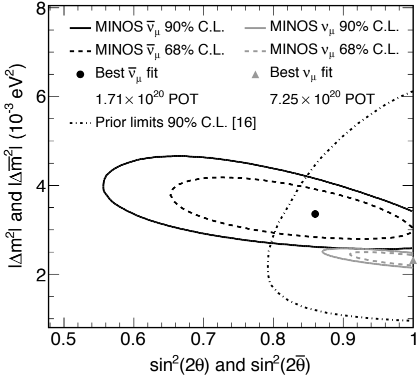
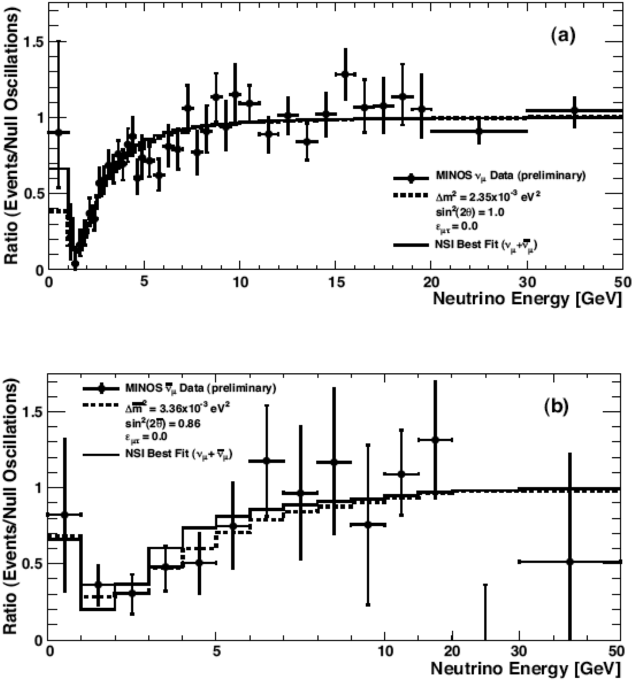


FIG. 4: Allowed regions for the $\overline{\nu}_\mu$ oscillation parameters from a fit to the data in Fig. 3, including all sources of systematic uncertainty. Indirect limits prior to this work [16] and the MINOS allowed region for ν_μ oscillation [3] are also shown.


(a)
Ratio (Events/Null Oscillations)
Neutrino Energy [GeV]
MINOS νμ Data (preliminary)
Δm² = 2.35x10⁻³ eV²
sin²(2θ) = 1.0
εμτ = 0.0
NSI Best Fit (νμ+ν̄μ)
(b)
MINOS ν̄μ Data (preliminary)
Δm̄² = 3.36x10⁻³ eV²
sin²(2θ̄) = 0.86
εμτ = 0.0
NSI Best Fit (νμ+ν̄μ)

CPT violation?

⇒standard CPT conserving fit has 2% probability

⇒CPTV implies Lorentz violation in local field theory

⇒implies rotational violation in some reference frame

⇒Lorentz violation extremely well tested in other contexts

Minos tests of CPT

⇒ Need a theory of CPT violation

⇒ e.g. Kostelecky Standard Model Extension

⇒background CPT (and Lorentz) violating field

⇒sidereal change in neutrino velocity relative to CPTV/LV field

⇒search for sidereal change in oscillation probability

⇒strong upper limits (arXiv:1007.2791)

Alternative to CPTV:
Matter effect from a new force

⇒MINOS neutrinos go through matter

⇒vector interaction with matter distinguishes neutrinos from antineutrinos

⇒similar to usual MSW effect, but could be larger?

⇒Non Standard interactions typically constrained to be much weaker than weak

“Apparent CPT Violation in Neutrino Oscillation Experiments”

Netta Engelhardt, Ann Nelson, and Jon Walsh
arXiv:1002.4452v3

- anomalous matter effect
- Sterile neutrinos to the rescue again!
- propose: gauged B-L, 3 sterile neutrinos

Effective Hamiltonian for (anti) neutrino flavor change in matter

$$H_{\text{eff}} = \text{terms} \ \propto \ \text{the identity} + \frac{(\text{mass})^2}{2p} + \begin{pmatrix} V+V_{nc}+V_{cc} & & & & & \\ & V+V_{nc} & & & & \\ & & V+V_{nc} & & & \\ & & & -V & & \\ & & & & -V & \\ & & & & & -V \end{pmatrix}$$

6 x 6 mass matrix

potential in matter, changes sign for neutrinos

resonance for anti neutrinos

for anti neutrino and sterile neutrino $$H_{\text{eff}} = \begin{pmatrix} V + V_{nc} + \frac{m^2}{2p} & \frac{mM}{2p} \\ \frac{mM}{2p} & -V + \frac{M^2+m^2}{2p} \end{pmatrix}$$

neutrino mass matrix = $\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$

$m =$ Dirac mass $\quad V =$ B-L potential

$M =$ sterile neutrino Majorana mass

NOTE RESONANCE at $2V + V_{nc} \approx \frac{M^2}{2p}$

Mixing with sterile neutrino suppressed for neutrinos, enhanced for antineutrinos

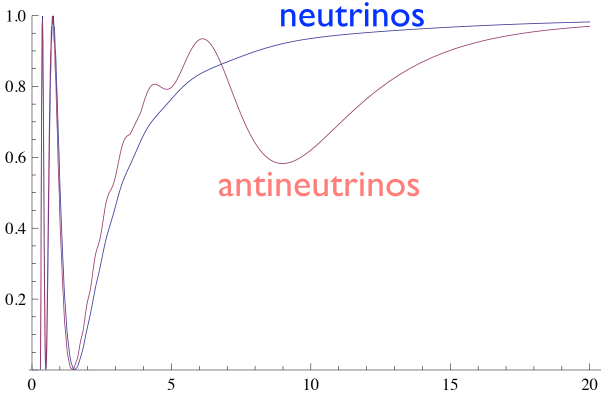
Effects of potential on ν_μ disappearance

eg: V= 1.2 10^{-12} eV in earths crust

linear combination ($s_{23}c_{13}\nu_\mu + c_{23}c_{13}\nu_\tau + s_{13}\nu_e$), s_{13}=.1, mixes with sterile neutrino with vacuum mixing angle θ=0.1

Vacuum mass^2 differences: .00008eV^2, .0025 eV^2, .05 eV^2

ν_μ disapearance probability at 735 km



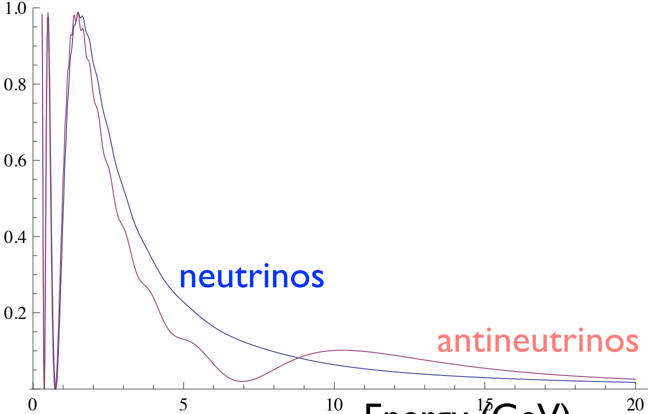
ν_τ appearance

eg: V= 1.2 10^{-12} eV in earths crust

linear combination ($s_{23}c_{13}\nu_\mu + c_{23}c_{13}\nu_\tau + s_{13}\nu_e$) mixes with sterile neutrino with vacuum mixing angle θ=0.1; s_{13}=.1

Vacuum mass^2 differences: .00008eV^2, .0025 eV^2, .05 eV^2

ν_τ appearance probability at 735 km



Energy (GeV)

oscillations into ν_s

eg: $V = 1.2\ 10^{-12}$ eV in earths crust

linear combination ($s_{23}c_{13}\nu_\mu + c_{23}c_{13}\nu_\tau + s_{13}\nu_e$) mixes with sterile neutrino with vacuum mixing angle θ=0.1; s_{13}=.1

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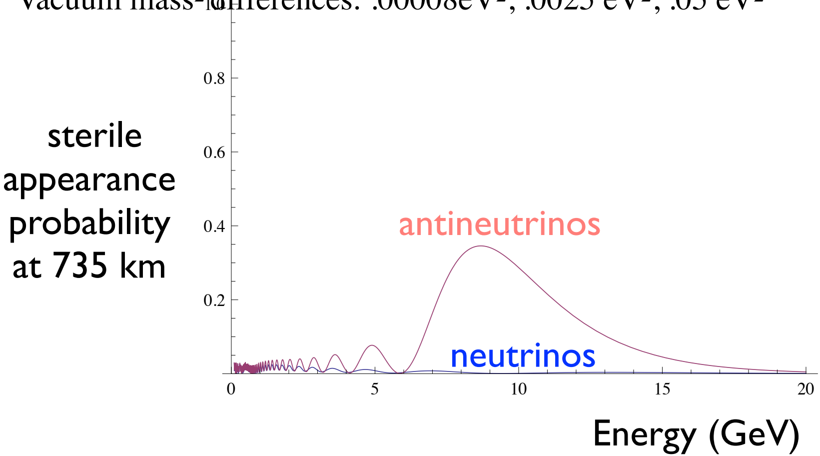
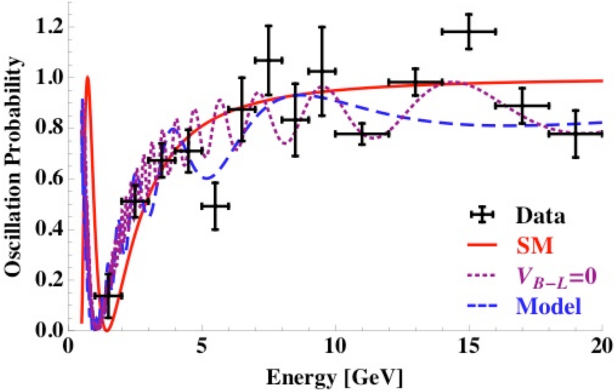


Model best fit to MINOS neutrino disappearance (only 1 sterile neutrino mixes significantly)



(a) neutrinos

Experimental Constraints

- MSW potential $\propto g^2/m_V^2$
- need $g^2/m_V^2 \sim$ of similar size to usual MSW effect from usual weak interactions for significant effect
- need $g/m_V \sim 1/(300\ \mathrm{GeV})$
- precision EW, neutrino electron scattering: $g<10^{-3} \Rightarrow m_V < 300\ \mathrm{MeV}$
- Note: weaker constraints on sterile neutrino couplings

Summary: new fermion + new light vector boson

- mixing with exotic fermions can affect neutrino oscillation sensitivity to new forces
- apparent CPT violation in ν_μ disappearance expts

Mass Varying Neutrinos (MaVaNs)

Rob Fardon, A.E.N., Neal Weiner; astro-ph/0309800, hep-ph/0507235

David **B**. Kaplan, A.E.N., Neal Weiner; hep-ph/0401099,

Kathryn Zurek, hep-ph/0405141

Weiner and Zurek, hep-ph/0509201

ν physics beyond the standard model at the meV scale?

- Dark Energy Density: $\rho_{DE}^{1/4} \sim 2\times10^{-3}$ eV
  - See Saw Scale: $M_W^2/M_{Pl} \sim 10^{-4}$ eV
- $m_{3/2}$ in one scale GMSB $\sim 10^{-3}$ eV
- Neutrino masses: $(\Delta m^2_{solar})^{1/2} \sim 9\times10^{-3}$ eV
  - $(\Delta m^2_{atmospheric})^{1/2} \sim 5\times10^{-2}$ eV
  - $(\Delta m^2_{LSND})^{1/2} \sim (0.1—2)$ eV

Coincidental Scales?

- Neutrino number density scale $n_\nu^{1/3} \sim 10^{-4}$ eV

  n_ν depends on redshift as $(1+z)^3$

- Dark Matter Density: $\rho_{DM}^{1/4} \sim 2\times10^{-3}$ eV

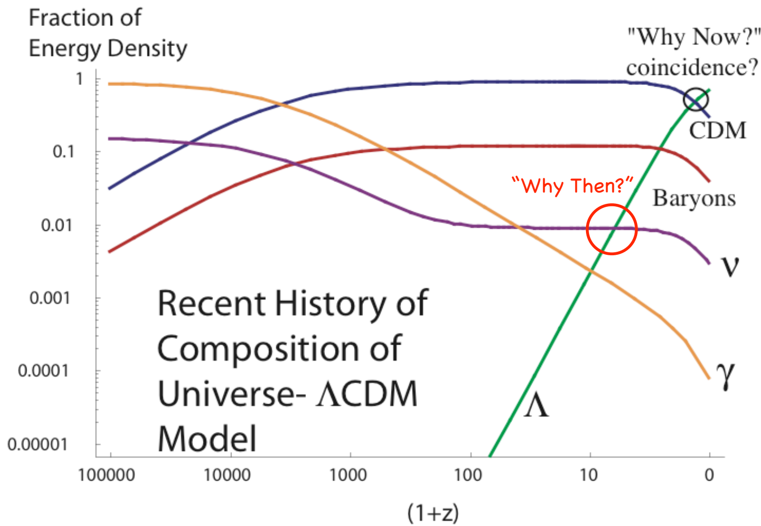
  ρ_{DM} depends on redshift as $(1+z)^3$

- Neutrino energy density 10^{-3} eV $\geq \rho_\nu^{1/4} \geq 5\times10^{-4}$ eV

  ρ_ν depends on redshift as $(1+z)^3$?

Why Now???

Recent History of the Energy Density of the Universe



Composition of universe

$$H^2 = (\dot{R}/R)^2 = (8\pi/3)\, G_N\, \rho$$

Type of ρ	dilution rate ($P = w\,\rho$)	clustering	Particle Physics
CDM, Baryons	$(1/R)^3$ ($w=0$)	Gravitationally Clumps	WIMPS Axions Etc.
radiation	$(1/R)^4$ ($w=1/3$)	Does not clump	Photons Light ν
Cosmological Constant	Does not dilute ($w=-1$)	Smooth	Vacuum Energy
quintessence	$(1/R)^{3(1+w)}$ $-1<w<-0.9$	Smooth (not perfect fluid)	Cosmon, MaVaNs

Looking through the Neutrino portal

- Neutrino number density scale $n_\nu^{1/3} \sim 10^{-4}$ eV

  n_ν scales as z^3

- Dark Energy Density: $\rho_{DE}^{1/4} \sim 2\times10^{-3}$ eV approximately constant

- Neutrino energy density 10^{-3} eV $\geq \rho_\nu^{1/4} \geq 5\times10^{-4}$ eV

  red shift dependent mass?

Can we relate dark energy to neutrinos? ($m_\nu \sim \varrho_\nu^{1/4}$ at z where $m_\nu \sim n_\nu^{1/3}$)

General considerations for varying parameters

Varying Parameter➡New Field

(e.g. varying mass➡Higgs)

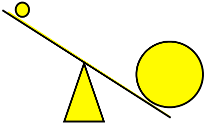
Significant effects require fields which are lighter than scale of affected physics—for cosmology, this means new sub-meV bosons
(not necessarily as light as H~10^{-33} eV)

Is a light, weakly coupled new sector
  natural?
  consistent with expt?

The 'mini-seesaw' MavaN Model

Assume "Dark Sector" (= unknown particles with no standard Model charges) contains light

- ☛ "Acceleron" scalar field A
- ☛ fermion fields n (aka 'sterile' or 'righthanded' ν)
- ☛ Yukawa couplings $\lambda A n n$
- ☛ Scalar potential $V(A)$



"Our sector" contains

- ☛ Active Neutrinos ν
- ☛ Higgs Field H

Allow tiny $(y = 0(10^{-11} \text{—} 10^{-15}))$ coupling $y H n \nu$

➠ Neutrino mass matrix

$$\begin{pmatrix} 0 & y\langle H\rangle \\ y\langle H\rangle & \lambda\langle A\rangle \end{pmatrix}$$

'Dirac' Mass

$m_D = y\langle H\rangle$

~1 eV-0.0001 eV

Neutrino Masses vary as A^{-1}

Neutrino mass matrix

$$\begin{array}{c} \\ \nu \\ n \end{array} \begin{pmatrix} \nu & n \\ 0 & \gamma H \\ \gamma H & \lambda A \end{pmatrix}$$

For large $\langle A \rangle$ light neutrino is mostly active, mass is $\sim (\gamma \langle H \rangle)^2 / \lambda A$

Heavier neutrino is mostly dark, mass is $\sim \lambda A$

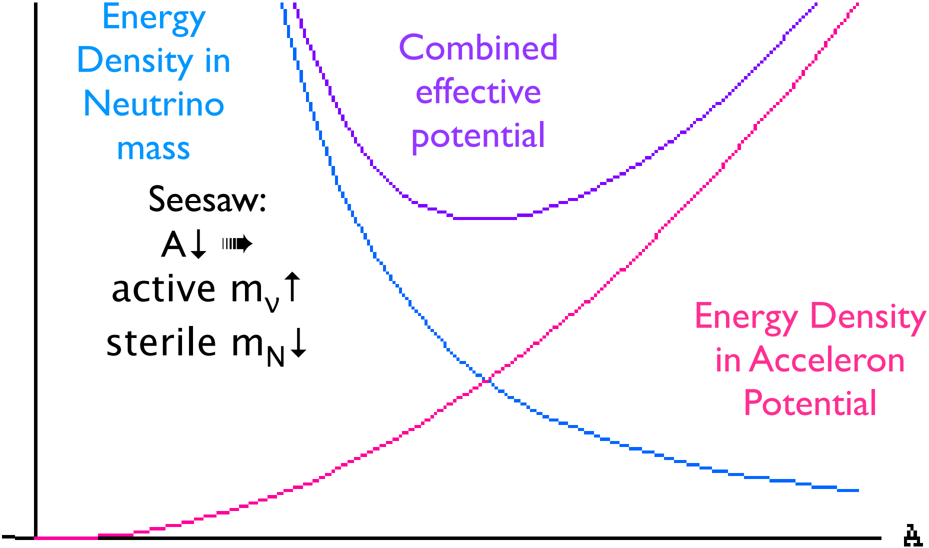
Assume $V(A)$ increasing function of A.

$$V_{eff}(A) = V(A) + (T^2 + m_\nu^2(A))^{1/2}\, n_\nu$$

Note: n_ν redshifts as $(1+z)^3$

temperature T redshifts as $(1+z)$

Varying Effective Potential for A as Neutrino density decreases



A Technically Natural Model

(except cosmological constant)

Gauge Mediated Susy Breaking Model with

$m_{3/2} \sim 10^{-3}$ eV

Nearly hidden nearly supersymmetric sector containing

A, n chiral superfields

$W \supset y\, H\nu n + \lambda\, Ann\ ,\ \lambda \sim 1,\ y \sim 10^{-11}$

susy breaking masses for A, ñ scalars

$\mathcal{M}_{\tilde{n}}, \mathcal{M}_A < 10^{-3}$ eV

$V \supset \lambda^2\, |\tilde{n}|^4 + 4\lambda^2\, |A\tilde{n}|^2 - \mathcal{M}_{\tilde{n}}^2\, |\tilde{n}|^2 +$

$y^2\, |H\tilde{n}|^2 + \mathcal{M}_A^2\, |A|^2 + \text{constant}$

Can we test MaVaN Dark Energy?

- Cosmological tests of neutrino mass from large scale structure: MaVaN mass was much lighter at high redshift.
- No terrestrial sources of high scalar neutrino density (neutrino density weighted by (m/E)), relative to cosmological, other than nuclear fireball.
- Main interesting astrophysical source of high scalar neutrino density is supernova.

Neutrino Mass and mixing Matter dependent?

- A, ñ could couple to other matter, e.g.
  $(1/\Lambda)\tilde{n}G^2$, $\xi\tilde{n}\, H_u H_d$

➡ A, ñ expectation values could be different in dense matter than air

➡ Neutrino mass and mixing parameters could be different in matter than air or vaccuum

(exotic MSW-type effect, **not** CP violating, energy independent)

Smoking Guns for MaVaNs

- Effects of environment in neutrino oscillations?
- Tritium endpoint searches for absolute ν mass depends on density of source?
- Cosmologically “impossible” sterile neutrinos?
- Cosmologically “inconsistent” neutrino masses?
- θ_{13} in long baseline search for ν_e appearance inconsistent with reactor constraint?
- energy spectrum of solar ν_e inconsistent with standard large mixing angle MSW?

Summary

- Effects of "dark sector" with new light fermion mixing with neutrinos and a new light boson
  - new vector boson: apparent CPT violation
  - new scalar boson: MaVaNs.
    - alternate explanation of dark energy
    - motivated by coincidence of neutrino mass and dark energy scales.
    - (Very)Anomalous matter effects