Neutrino Mass

The neutrino mass search technique sensitive to the smallest ν masses is the search for ν oscillation.

Under a number of circumstances,

$$P(\nu_\ell \rightarrow \nu_{\ell' \neq \ell}) = \sin^2 2\theta \, \sin^2\left[1.27\,\delta M^2(eV^2)\,\frac{L(km)}{E_\nu(GeV)}\right].$$

- ℓ: e, μ, τ
- θ: Mixing angle
- δM^2: $M_2^2 - M_1^2$
- L: Distance ν travels
- E_ν: ν energy

Neutrino Oscillation

There are 3 pieces of evidence that neutrinos oscillate, which implies that they have mass.

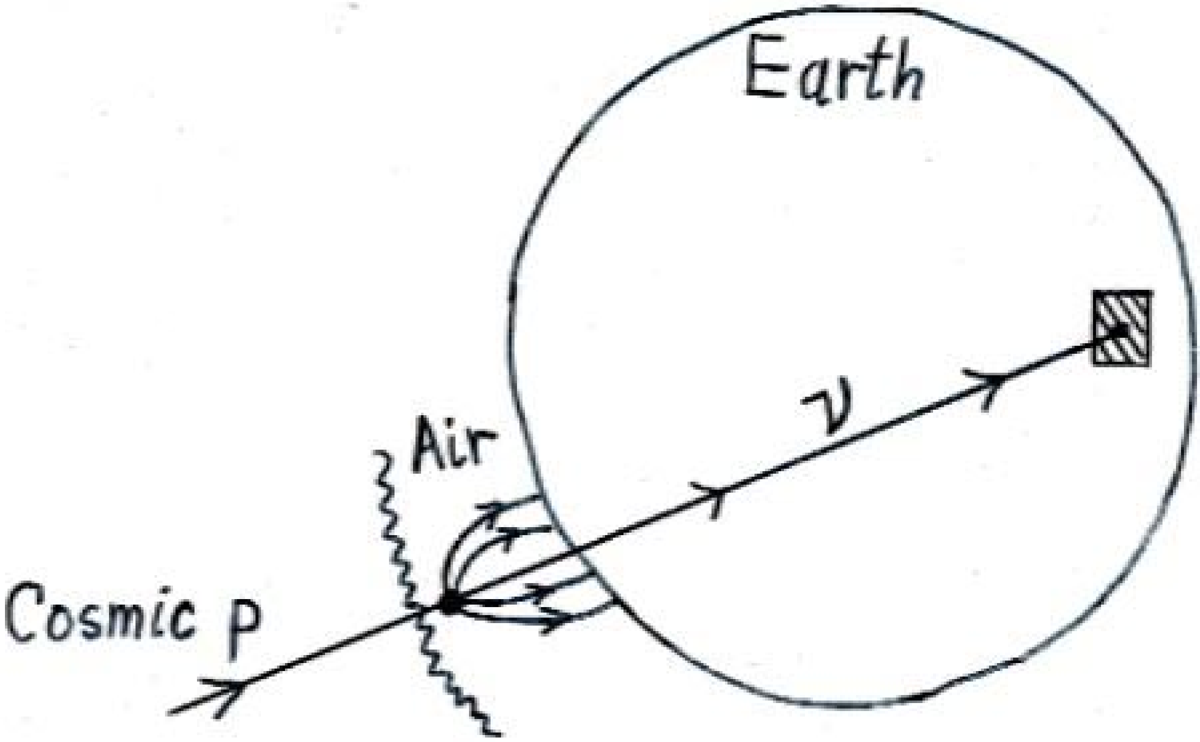
Neutrinos	Evidence of Oscillation
Atmospheric	Compelling
Solar	Strongish
LSND	Unconfirmed

Recent review of the current situation:

hep-ph/9906244

(Fisher, B.K., McFarland)

Evidence for Neutrino Mass From the Atmospheric Neutrinos



$$p + \text{Air} \longrightarrow \pi + \ldots$$
$$\pi \longrightarrow \mu\, \nu_\mu$$
$$\mu \longrightarrow e\, \nu_e\, \nu_\mu$$

$\therefore\ \nu_\mu : \nu_e = 2:1$ [with corrections]

Try to measure something that is as independent of theoretical flux calculations as possible:

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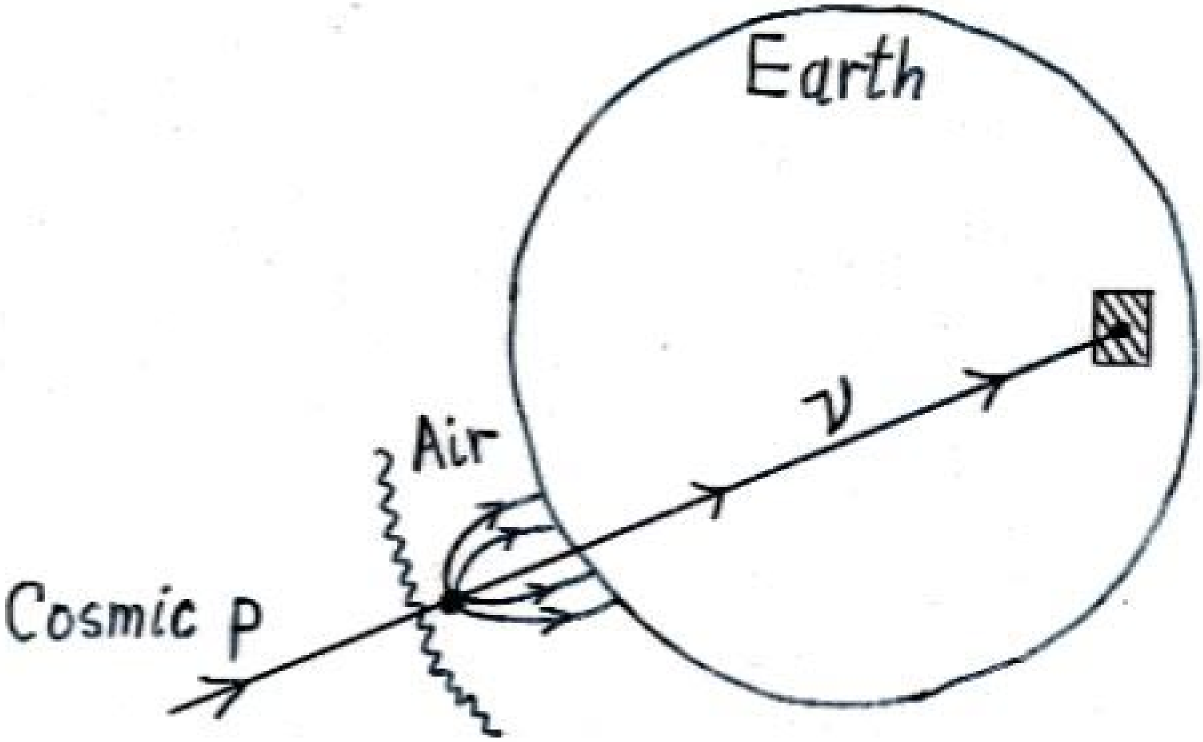

$$p + \text{Air} \longrightarrow \pi + \ldots$$
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$\therefore\ \nu_\mu : \nu_e = 2:1$ [with corrections]

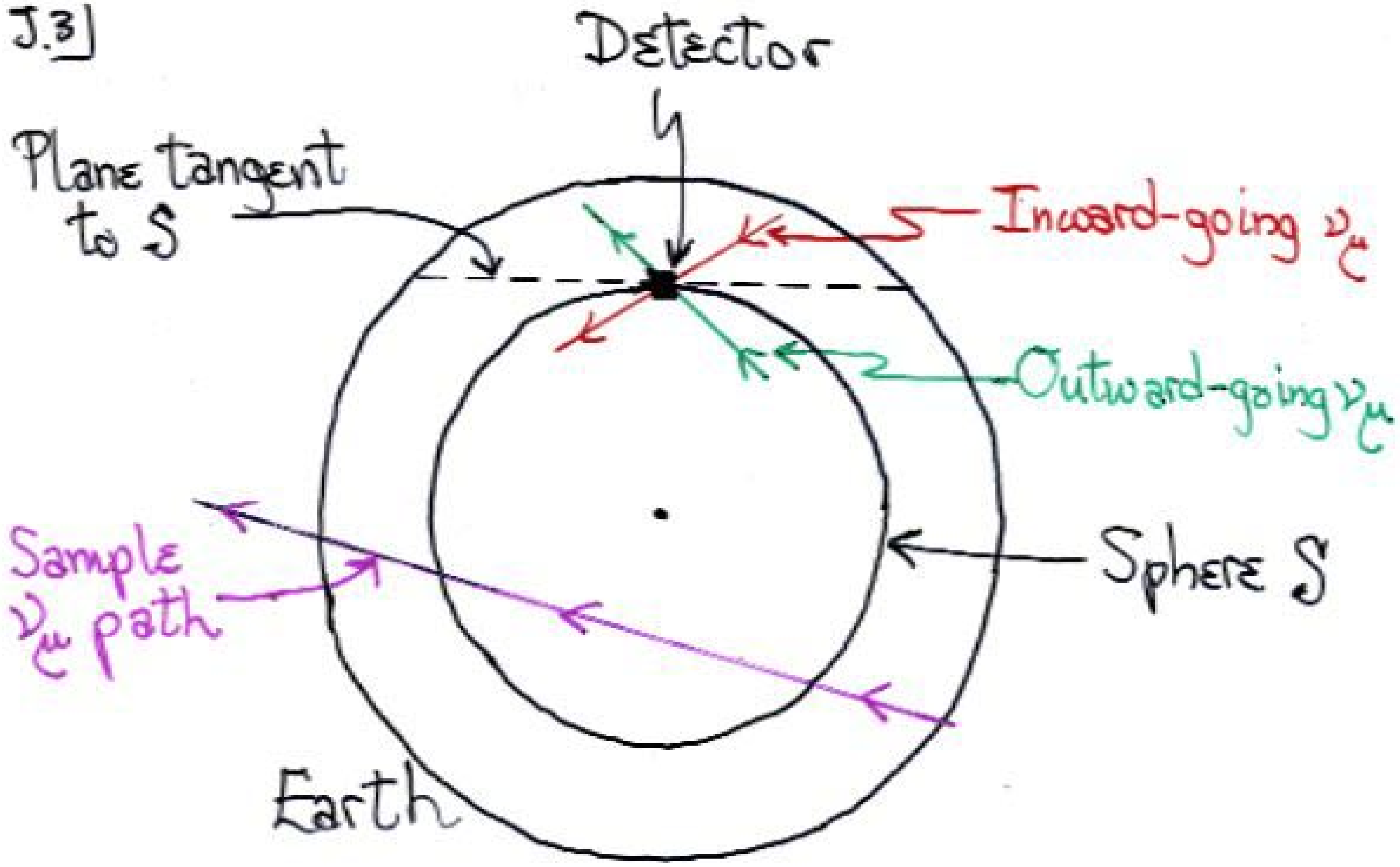
Try to measure something that is as independent of theoretical flux calculations as possible:

Flux Down vs. Flux Up

Suppose nothing increases or decreases the atmospheric ν_μ flux during earth traversal.

Then, for $E_\nu >$ a few GeV, where the cosmic ray flux is $\cong$ isotropic,

$$\nu_\mu \text{ Flux Down} \cong \nu_\mu \text{ Flux Up}$$



Any ν_μ that enters S later exits S.

∴ In a steady state—

Total ν_μ flux into S = Total ν_μ flux out of S.

Cosmic-ray isotropy ⇒ Spherical symmetry.

⇒ At each point of S—

ν_μ flux into S = ν_μ flux out of S

∴ ν_μ Flux Down = ν_μ Flux Up

With just a bit more work —

$\nu_\mu \text{ Flux}(\theta_z) = \nu_\mu \text{ Flux}(\pi - \theta_z)$.

SuperK Down vs. Up

Down : $+0.2 < \cos\theta_z < +1.0$

Up : $-1.0 < \cos\theta_z < -0.2$

In the Multi-GeV data,

$$\frac{\nu_\mu(\text{Up})}{\nu_\mu(\text{Down})} = 0.53 \pm 0.05.$$

(Learned)

Something is adding or removing muon neutrinos within the earth.

$\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_{\text{sterile}}$ oscillation?

Not $\nu_\mu \to \nu_e$ because $\nu_e(\text{Up})/\nu_e(\text{Down}) = 0.92 \pm 0.11$.

The zenith-angle distributions are well described by

$\nu_\mu \rightarrow \nu_\tau$ with $\delta M^2 = 3.5 \times 10^{-3}\, eV^2$, $\sin^2 2\theta = 1.0$

Combined analysis of all SuperK ν_{Atmos} data $\Longrightarrow$

$\nu_\mu \rightarrow \nu_\tau$ with

$$2 \times 10^{-3}\, eV^2 \lesssim \delta M^2 \lesssim 6 \times 10^{-3}\, eV^2$$

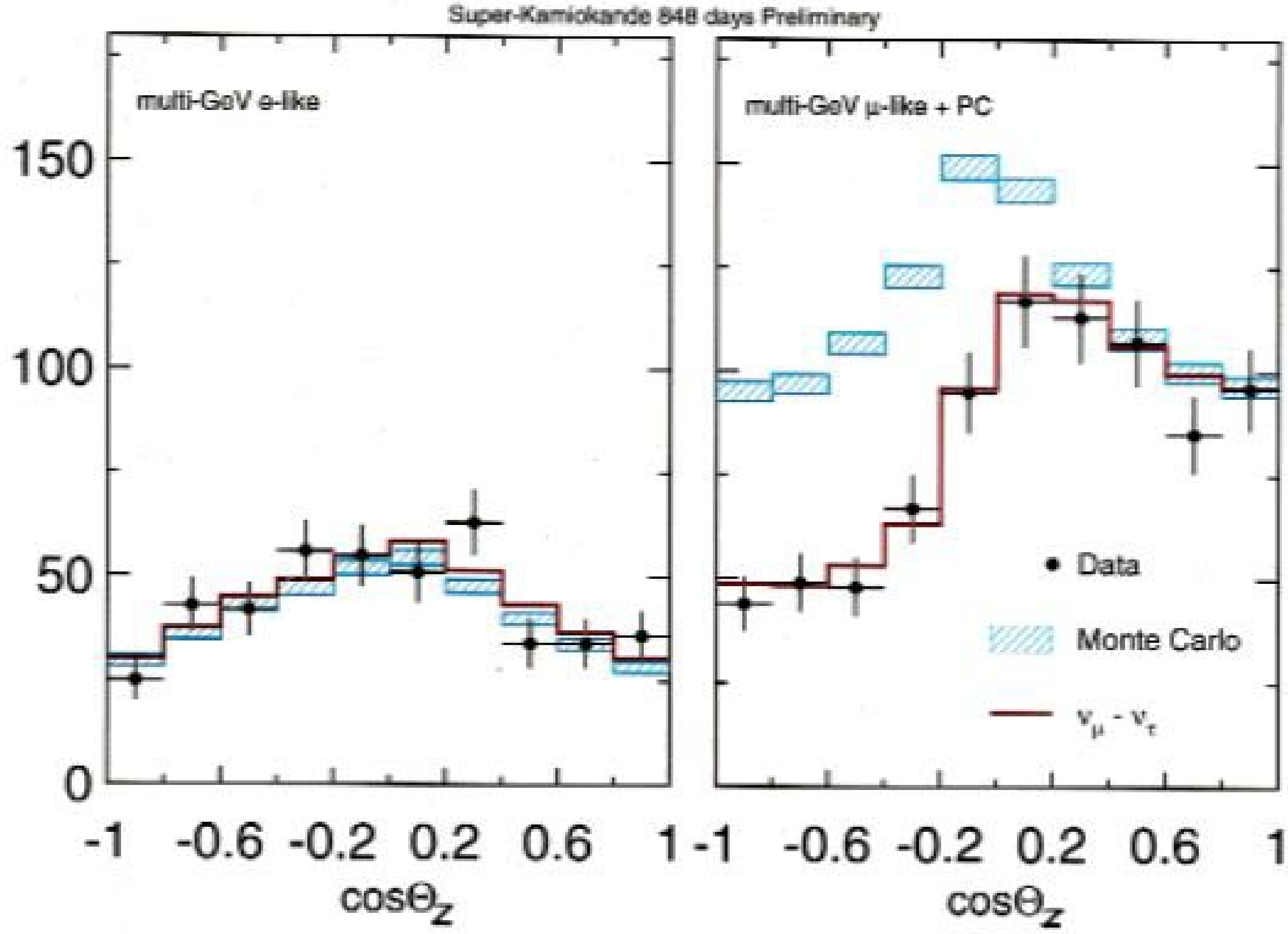
and

$$\sin^2 2\theta \simeq 1 .$$

Similar favored regions from MACRO, Soudan 2, and KAM.

When all data are considered, ν decay and ν–matter interaction do not work.

(Barger, Learned, Pakvasa, Weiler; Gonzalez–Garcia et al.; Lipari, Lusignoli; Fogli et al.)



[hatched box], hence —, does depend on theory.

S.1)

Oscillation	Matter Effect in the Earth
$\nu_\mu \to \nu_s$	Yes
$\nu_\mu \to \nu_\tau$	No

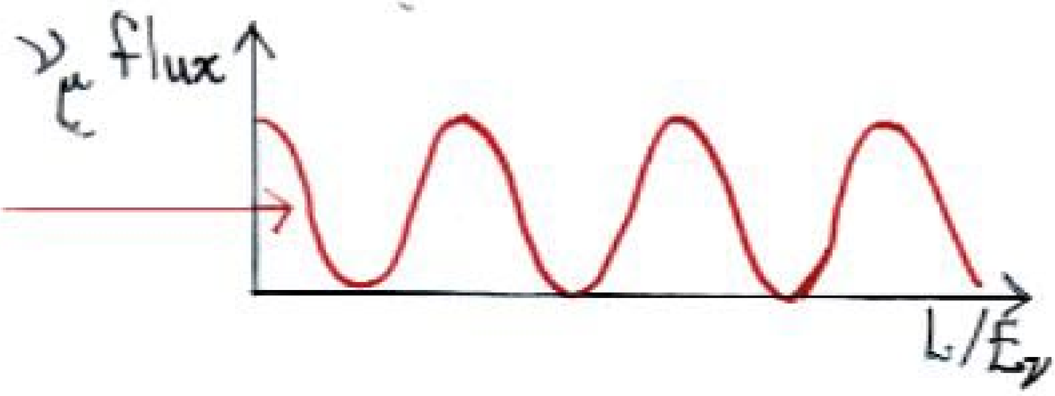
Higher energy ν_{Atmos} data (upward-going muons, and partially-contained events) disfavor $\nu_\mu \to \nu_s$ at $\sim 2\sigma$.

(Learned)

Some key experiments

Test the $\nu_\mu \to ?$ oscillation interpretation of the ν_{Atmos} data by seeking $\nu_\mu \to ?$ in long-baseline accelerator-generated ν_μ beams.

- Try to see



$$\left\{ P(\nu_\mu \to ?) \propto \sin^2\left[1.27\, \delta M^2\, L/E_\nu\right] \right\}$$

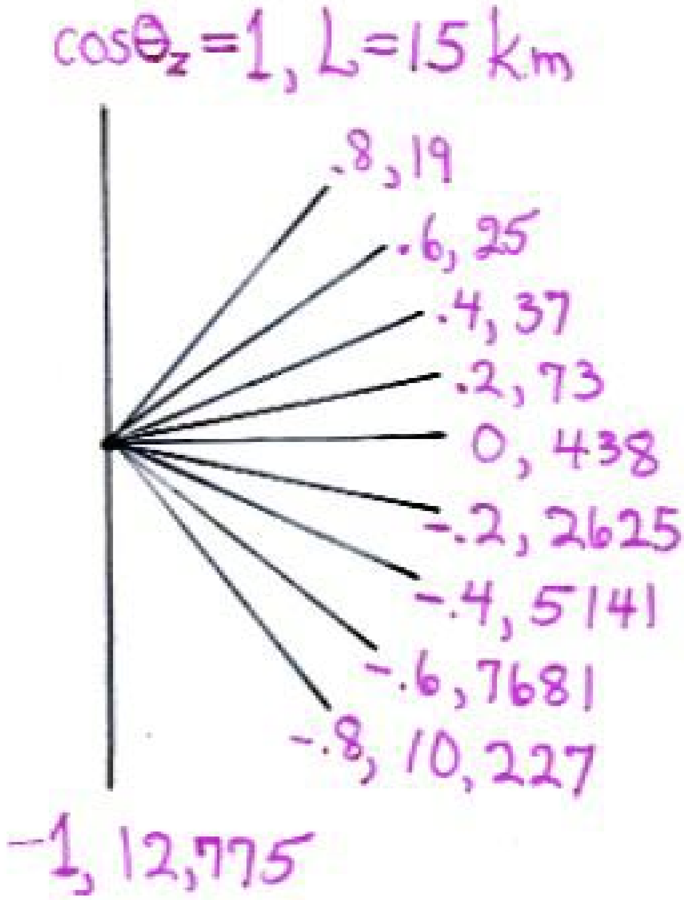
- Try to see if $? = \nu_\tau$ by seeking ν_τ appearance.

Near term: Conventionally produced ν beams
Long term: ν beams from muon facilities

[W] For $\delta M^2 = 3.5 \times 10^{-3}\ eV^2$, and $E_\nu = 1\ GeV$,

$$\lambda_{osc} = 707\ km.$$

Then –



(Di Lella)

I.2) # The hints of neutrino mass

Solar Neutrinos

Experimental reports:

Target	Exp.	E_ν Threshold (MeV)	$\frac{\text{Event Rate}}{\text{Std. Solar Model*}}$
$H_2O(e)$	KAM	~7	.54 ± .12
"	SuperK	~6	.47 ± .07
^{37}Cl	HMSTK	0.8	.33 ± .06
^{71}Ga	SAGE	0.2	.52 ± .07
"	GALLEX	0.2	.60 ± .07

*Bahcall & Pinsonneault, 1998

It has proved very difficult to explain these departures from theory via solar and nuclear physics, without invoking neutrino mass.

(Updated analysis: Hata & Langacker)

$\nu_e \to \nu_{\mu,\tau,\text{ or } s}$ [which implies ν mass] explains all the $\nu_\odot$ event rates.

[MSW]

Flavor Conversion Mechanism	Requirements $\delta M^2\,(eV^2)$	$\sin^2 2\Theta$
MSW Effect	$(0.4\text{–}1.0)\times 10^{-5}$	$10^{-3}-10^{-2}$
" "	$(2\text{–}8)\times 10^{-5}$	$0.7-0.9$
Vacuum Oscillation	$10^{-11}-10^{-9}$	$0.7-1.0$

(Hata & Langacker
Krastev & Petcov)

If $P(\nu_e \rightarrow \nu_{\mu,\tau}) = \frac{1}{2}$ At All E_ν, We Expect
.57
.57
.50
.50
.50

$P(\nu_e \to \nu_{\mu,\tau}) = \frac{1}{2}$, independent of E_ν, could be explained by vacuum oscillation with δM^2 as large as $\sim 10^{-3}\ eV^2$.

Some key experiments

Seek a ν_μ or ν_τ component in the solar neutrino flux, produced by

$$\nu_e \xrightarrow[\text{Vac. Osc.}]{\text{MSW or}} \nu_\mu \text{ or } \nu_\tau$$

Caution: If $\nu_e \rightarrow \nu_{\text{Sterile}}$, there is no $\nu_{\mu,\tau}$ component in the solar flux.

Continue to probe the dependence of the solar ν_e flux on —

- Neutrino Energy
- Whether it is Day or Night
- The Season of the Year

LSND

A so-far unconfirmed further hint of ν mass.

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

From $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ ($\bar{\nu}_\mu$) ← Appearance ($\bar{\nu}_e$)

$L/E_\nu \sim 30\,m / 30\,MeV$, so $\delta M^2 \gtrsim 1\,eV^2$.

Taking into account constraints from other experiments (KARMEN, Bugey, NOMAD, ...):

$$0.2\,eV^2 \lesssim \delta M^2 \lesssim 10\,eV^2$$

$$0.002 \lesssim \sin^2 2\theta \lesssim 0.03$$

E.3

Some key experiments

Confirm or disprove the $\bar{\nu}_\mu \to \bar{\nu}_e$ interpretation of the LSND data in experiments at other facilities.

A Cosmological Constraint on ν Mass

There are 115 neutrinos/species/cm^3 in the universe.

Even with tiny masses, neutrinos can contribute significantly to

$$\frac{\text{Mass Density}}{\text{Critical Density}} \equiv \Omega .$$

Evidence from several sources implies

$$\Omega_{\text{All matter}} \lesssim 0.4.$$

To allow the observed galactic structure to have formed,

$$\Omega_{\nu} \lesssim 0.2.$$

(N. Bahcall, Primack, Steigman)

[C.2] If ν mass eigenstate ν_m has mass M_{ν_m},

$$\Omega_\nu = (M_{\nu_1} + M_{\nu_2} + M_{\nu_3})/40\,\text{eV}.$$

$$\therefore \quad M_{\nu_1} + M_{\nu_2} + M_{\nu_3} \lesssim 8\,\text{eV}.$$

F.11

Where Does the ν Oscillation Evidence Point?

$\nu_\odot$, ν_{Atmos}, and ν_{LSND} oscillations cannot all be explained in terms of just 3 neutrinos:

With only 3 neutrinos,

$$\Sigma \delta M^2 = (M^2_{\nu_3} - M^2_{\nu_2}) + (M^2_{\nu_2} - M^2_{\nu_1}) + (M^2_{\nu_1} - M^2_{\nu_3}) = 0.$$

$\uparrow$ Mass eigenstates

But—

Oscillating Neutrinos	Required $\lvert\delta M^2\rvert$ (eV^2)
Solar	10^{-10} or 10^{-5}
Atmospheric	10^{-3}
LSND	1
	$\Sigma \delta M^2 \neq 0$

$\therefore$ Must add a sterile neutrino ν_s.

Must not contribute to Γ_{Z^0}

There is a loophole in this argument. No attempt to exploit the loophole has succeeded in fitting __all__ the data.

(Cardall & Fuller; Teshima, Sakai, Inagaki; Thun & McKee; Barenboim & Scheck; Ohlsson & Snellman)

Even if we disregard HMSTK, and suppose δM^2_{solar} can be large, it is still very hard to make 3 neutrinos work.

(Giunti)

Confirmation of a ν_s would be groundbreaking.

∴ We need to check each of the 3 reported signals of neutrino oscillation.

$\not{CP}$ in Neutrino Oscillation

$$P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'} ; U) \underset{CPT}{=} P(\nu_\ell \to \nu_{\ell'} ; U^*)$$

↑ Neutrino mixing matrix

If U is not real, we can have $\not{CP}$ differences

$$\Delta_{\not{CP}}(\ell\ell') \equiv P(\nu_\ell \to \nu_{\ell'}) - P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) \neq 0 .$$

Such differences would cleanly establish that U contains a complex phase.

$$CPT \Rightarrow P(\nu_\ell \to \nu_\ell) = P(\bar{\nu}_\ell \to \bar{\nu}_\ell)$$

∴ No $\not{CP}$ in a disappearance neutrino oscillation experiment.

It takes at least 3 non-degenerate neutrino mass eigenstates ν_m to produce $\not{CP}$.

F.4

To see $\not{CP}$, an experiment must have L/E_ν big enough so that

$$\delta M^2_{mm'}(eV^2)\,\frac{L(km)}{E_\nu(GeV)} \gtrsim 1$$

for at least 3 $\delta M^2_{mm'} \equiv M^2_m - M^2_{m'}$.

Mass of ν_m ↑

If there are only 3 neutrinos,

$$\delta M^2(\text{MSW for } \nu_\odot) \sim 10^{-5}\ eV^2$$

$\Longrightarrow$ We need $\frac{L(km)}{E_\nu(GeV)} \gtrsim 10^5$.

Physics for a ν Factory?

(3ν)

$\not{CP}$ analyses:

Arafume & Sato; Fisher, B.K., McFarland; Bernabéu; Schubert; Dick, Freund, Lindner, Romanino; Gago, Pleitez, Funchal

$\not{CP}$

If there are only 3 neutrinos, then for $\ell\ell' = e\mu, \mu\tau$, or τe,

$$\Delta_{\not{CP}}(\ell\ell') = -16\, J\, s_{12} s_{23} s_{31} \;.$$

Here $J \equiv \Im m(U_{e1} U_{e2}^* U_{\mu 1}^* U_{\mu 2})$,

and $s_{mm'} \equiv \sin\left[1.27\, \delta M^2_{mm'}(eV^2) \frac{L\,(km)}{E_\nu(GeV)}\right]$,

where $\delta M^2_{mm'} \equiv M^2_m - M^2_{m'}$.

(Arafune & Sato
Fisher, B.K., McFarland)

$\Delta_{\not{CP}}(\ell\ell')$ is the same for $\ell\ell' = e\mu, \mu\tau$, and τe.

Questions

Q: How do we test/falsify the various ν mass scenarios?

A: LSND confirmation $\Rightarrow$ ~~3ν (No LSND)~~

$\nu_{\mu,\tau}$ from the sun $\Rightarrow$ ~~$\nu_{\odot} \to \nu_{sterile}$~~

Q: Are sterile neutrinos unnatural?

A: Heavy ones are common in a see-saw picture.

Even light ones can be natural in some schemes. But if one, maybe three.
(Foot & Volkas
Berezhiani & Mohapatra)

But: Ockham's razor.

Q: Is ~ maximal mixing of ν_μ^{Atmos} with some other neutrino unnatural?

A: No, ν_μ may be maximally mixed with a ν_s. This has no quark analogue.

Or, large mixing may arise from a family symmetry, or from the details of the see-saw mechanism.

(Foot & Volkas; Ramond; Smirnov)

Q: How do we measure ν masses, and not just their splittings?

A: Good question.

Conclusion

This is an exciting time in neutrino physics.

We have lots of interesting work to do.