ν 2002

From the Theory/Phenomenology Perspective

The Neutrino World:

What do we know?

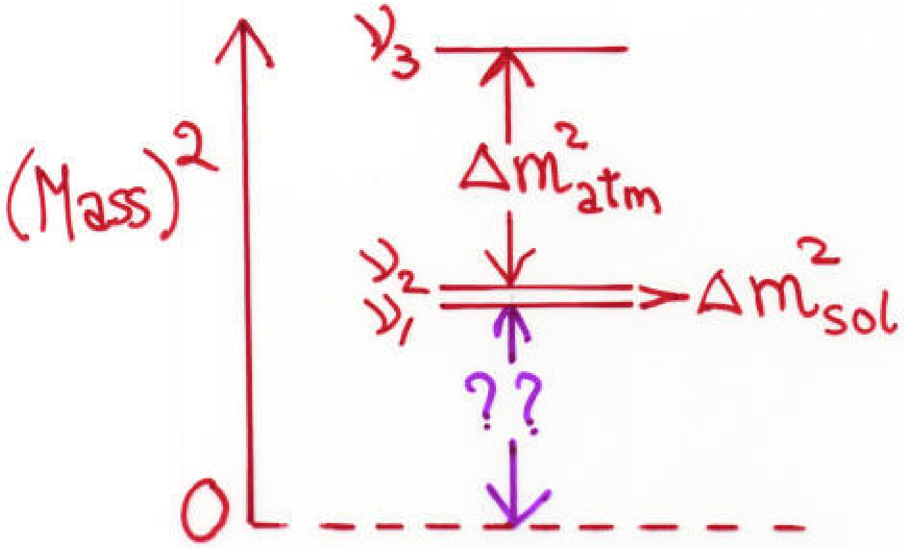
What would we like to find out?

Questions

- Do neutrinos truly oscillate/change flavor?

- How many neutrino species are there?
  Are there sterile neutrinos?

- What are the $(\text{Mass})^2$ splittings between the mass eigenstates ν_i? How far above zero does the whole pattern lie?

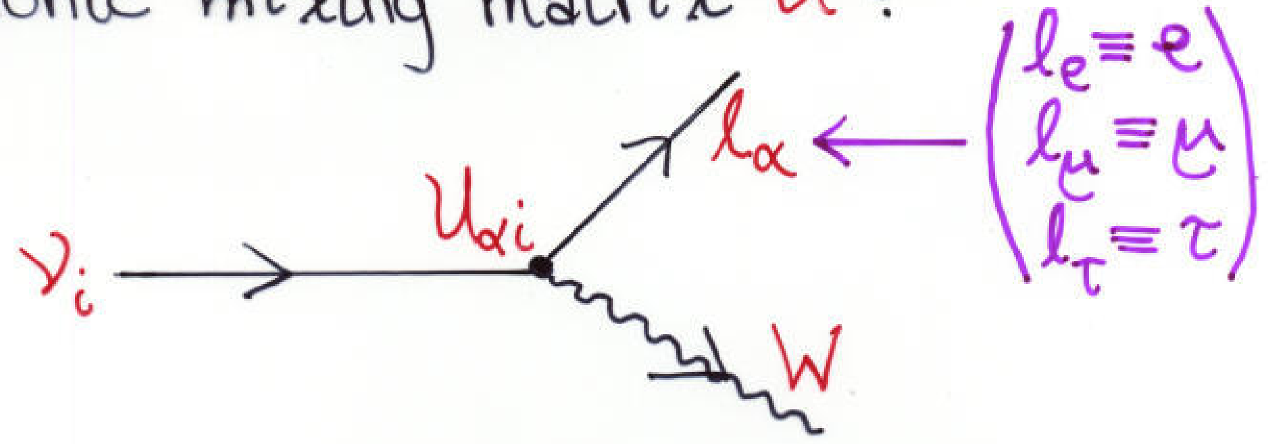


- Is each mass eigenstate—
  - A Majorana particle $(\bar{\nu}_i = \nu_i)$

or

  - A Dirac particle $(\bar{\nu}_i \neq \nu_i)$?

* What are the elements $U_{\alpha i}$ of the leptonic mixing matrix U?



What are the mixing angles in U?
What are the $\cancel{CP}$ phases ” ” ?

* Do neutrino interactions violate CP?

- In ν oscillation?

  How big are the effects ($\propto$ the small mixing angle θ_{13}) likely to be?

- In ν-less $\beta\beta$ decay?

  Can we see $\cancel{CP}$ there?

- Was early-universe baryogenesis made possible by leptonic $\cancel{CP}$?

- Do neutrinos break CPT?

- What can neutrinos tell us about astrophysics and cosmology?

- Can neutrinos serve as probes of extra dimensions?

- What are the electromagnetic properties of neutrinos? What are their dipole moments?

- How fast do neutrinos decay? Into what?

* What is the origin of neutrino flavor physics?

- Is it new physics at a high mass scale? Where? What's there?
- Does the see-saw mechanism generate ν masses?
- Do symmetries play a role in ν masses and mixing?
- What is the connection between ν flavor physics and quark flavor physics?

Do Neutrinos Truly Change Flavor?

S(uper)K, SNO, MACRO, Soudan 2:

YES!

Solar Neutrinos

SNO (Hallin)

The nuclear processes that power the sun make only ν_e.

But the solar neutrino flux arriving at earth includes ν_μ and/or ν_τ.

For the ^8B (high-energy) solar neutrinos, SNO studies —

NC $\nu_\odot d \rightarrow \nu n p \Longrightarrow \phi_e + \phi_{\mu\tau}$

ES $\nu_\odot e \rightarrow \nu e \Longrightarrow \phi_e + 0.15\,\phi_{\mu\tau}$

CC $\nu_\odot d \rightarrow e p p \Longrightarrow \phi_e$

$$\phi_{\mu\tau} = (3.41^{+0.66}_{-0.64}) \times 10^6 / \mathrm{cm}^2\,\mathrm{sec}$$

(5.3σ from zero)

Including SK $\nu_\odot e \rightarrow \nu e$ data,

$$\phi_{\mu\tau} = (3.45^{+0.65}_{-0.62}) \times 10^6 / \mathrm{cm}^2\,\mathrm{sec}$$

(5.5σ from zero)

Neutrinos do change flavor.

SNO : $\phi_{\mathrm{active}}(\mathrm{NC}) = (5.09^{+0.64}_{-0.61}) \times 10^6 / \mathrm{cm}^2\mathrm{sec}$

Bahcall : $\phi_{\mathrm{total}}(\mathrm{BP00}) = (5.05^{+1.01}_{-0.81}) \times 10^6 / \mathrm{cm}^2\,\mathrm{sec}$

SNO : $\phi_e(CC)/\phi_{active}(NC) \simeq 0.34$.

Barring non-Standard-Model flavor-changing ν-matter interactions (but see Smirnov & Valle),

$$\nu \text{ Flavor Change} \Rightarrow \left\{ \begin{matrix} \nu \text{ Mass} \\ \text{and Mixing} \end{matrix} \right\}$$

∴ The leptons, including the neutrinos, are much like the quarks.

Unitary quark mixing matrix : V

Unitary lepton mixing matrix : U

Complex phases in U, as in V, can lead to $\not{CP}$.

Several analyses of candidate mechanisms for solar $\nu_e \rightarrow \nu_\mu / \nu_\tau$.

[A.S. list]

There is general agreement that –

Most-favored mechanism for solar $\nu_e \longrightarrow \nu_\mu / \nu_\tau$ is the —

Large Mixing Angle –

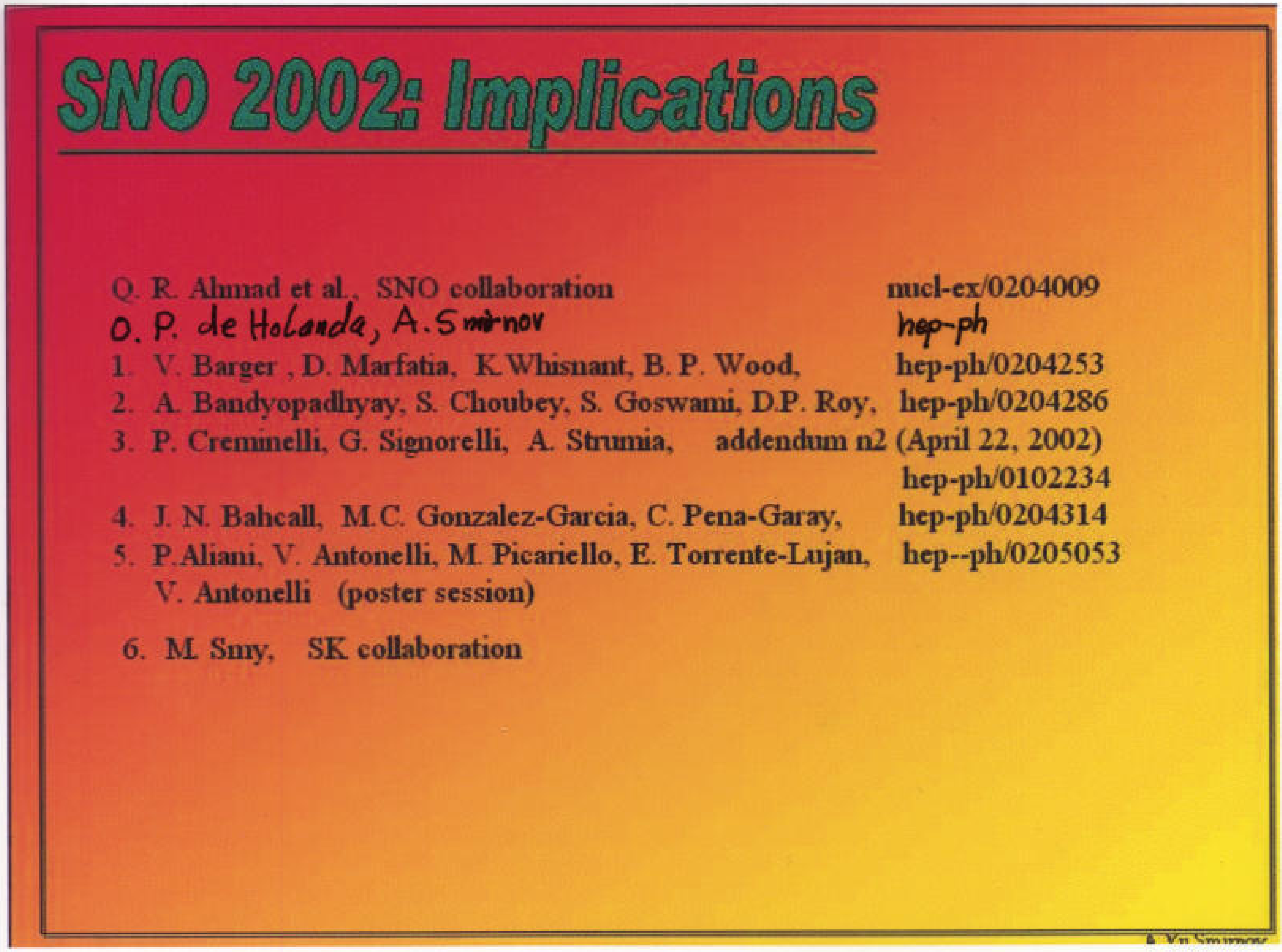
Mikheyev Smirnov Wolfenstein

– Effect

(LMA – MSW)

[E.L. plot]

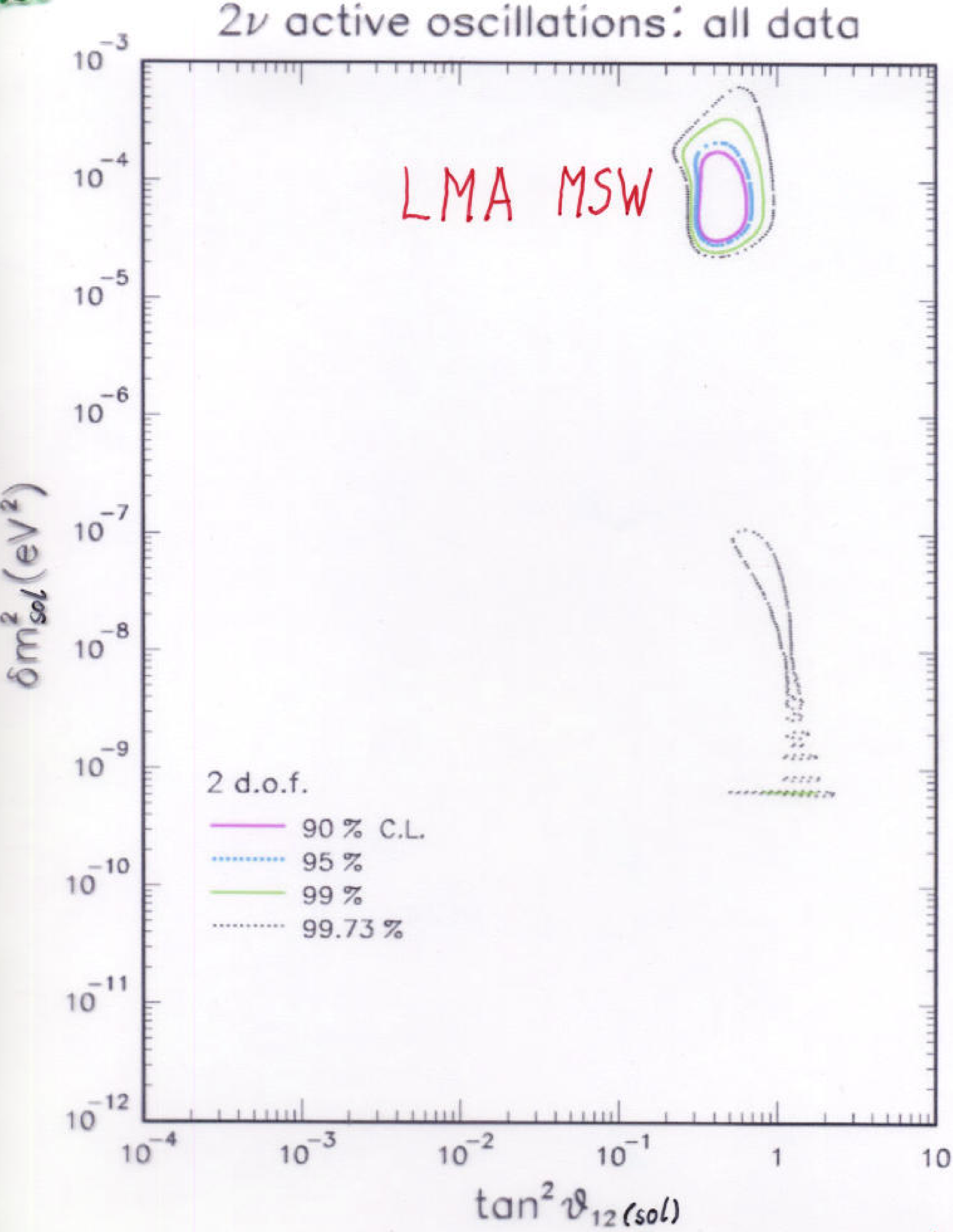
Smirnov



SNO 2002: Implications

Q. R. Ahmad et al., SNO collaboration	nucl-ex/0204009
O. P. de Holanda, A. Smirnov	hep-ph
1. V. Barger , D. Marfatia, K.Whisnant, B. P. Wood,	hep-ph/0204253
2. A. Bandyopadhyay, S. Choubey, S. Goswami, D.P. Roy,	hep-ph/0204286
3. P. Creminelli, G. Signorelli, A. Strumia, addendum n2	(April 22, 2002) hep-ph/0102234
4. J. N. Bahcall, M.C. Gonzalez-Garcia, C. Pena-Garay,	hep-ph/0204314
5. P.Aliani, V. Antonelli, M. Picariello, E. Torrente-Lujan, V. Antonelli (poster session)	hep--ph/0205053
6. M. Smy, SK collaboration	

Lisi



Global results

Cl, Ga, SK, SNO data
Analysis in terms of pulls

LMA - MSW is the candidate with the largest $\Delta m^2_\odot$ and with a large $\theta_\odot$.

Assuming only 3 neutrinos, LMA MSW is the only candidate whose ν parameters would make $\not{C}\not{P}$ observable in terrestrial ν oscillation.

Lisi et al. analysis assumed 2ν.

There are at least 3ν.

The 3rd one couples only feebly to e: $|U_{e3}|^2 < 0.03$. So it plays little role here.

It may play some role (Akhmedov).

$P(\nu \to \nu) \sim (1-|U|^2)^2 P(\nu \to \nu) + |U|^4$ (de Holanda)

III

Atmospheric Neutrinos

Compelling evidence for atmospheric

$\nu_\mu \longrightarrow \nu_?$

$\nu_?$ mostly ν_τ

Mixing ~ Maximal

$\Delta m^2_{atm} \sim 3 \times 10^{-3} eV^2$

(Shiozawa
Goodman)

Observation of expected geomagnetic effects verifies understanding of ν flux.

(Gaisser)

Verify atmospheric $\nu_\mu \rightarrow \nu_?$ by seeing same oscillation in accelerator ν_μ that travel a L(ong) B(ase) L(ine).

K2K: Low ν_μ rate, and E_{ν_μ} spectrum, in far detector are best fit by—

$$\Delta m^2_{atm} = 2.8 \times 10^{-3} eV^2, \ \sin^2 2\theta_{atm} = 1.0$$

Atmospheric oscillations are best fit by—

$$\Delta m^2_{atm} = 2.5 \times 10^{-3} eV^2, \ \sin^2 2\theta_{atm} = 1.0$$

(Nishikawa)

Future

Confirm $\nu_\odot$ LMA–MSW flavor change by seeing implied reactor $\bar{\nu}_e$ oscillation.

(KamLAND; Shirai)

Observe the undulation at $\sin^2(\Delta m^2 \frac{L}{4E})$ vs. 1/E for $\bar{\nu}_e$ oscillation.

Further confirm the $\nu_\mu \rightarrow \nu_\tau$ oscillation of atmospheric neutrinos in LBL experiments. Observe the undulation.

(K2K, MINOS, CNGS)
(Michael, Katsanevas)

Observe the undulation in atmospheric ν oscillation.

(MONOLITH, UNO, MIND)
(Tabarelli de Fatis)

How Many Neutrino Species Are There?

If

Flavor Change/ Oscillation	Δm^2 (eV^2)
Solar	$\sim (5-6) \times 10^{-5}$
Atmospheric	$\sim 3 \times 10^{-3}$
LSND	0.2 to 1, or 7*

are all genuine, nature must contain

- At least 4 neutrino masses
- Correspondingly, ν_e, ν_μ, ν_τ, $\nu_{s(terile)}$

  [Or, $m_{\bar{\nu}_i} \neq m_{\nu_i}$ (~~CPT~~)]

If there are only 3 masses, then

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

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*Drexlin

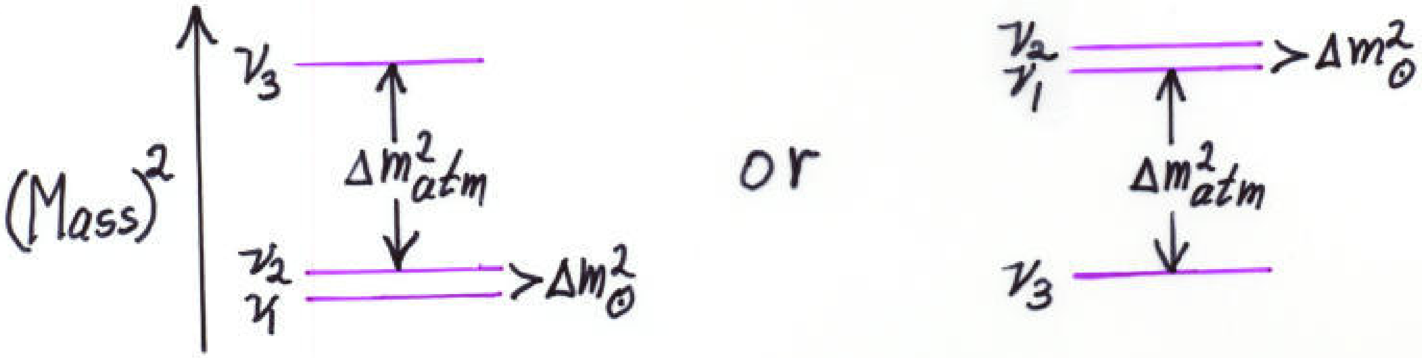
Future

Carry out MiniBooNE to confirm or refute LSND.

What is the Neutrino Mass Spectrum? What is U?

If only the Atm and Sol flavor changes prove to be genuine, nature may contain only 3 neutrinos.

Then the spectrum can look like —



Earth matter effects in LBL experiments can tell which.

Suppose there are only 3 neutrinos, and the behavior of solar neutrinos is due to the Large Mixing Angle MSW effect. Then—

$$U \approx \begin{array}{c|ccc|} & \nu_1 & \nu_2 & \nu_3 \\ \nu_e & c\,e^{i\frac{\alpha_1}{2}} & s\,e^{i\frac{\alpha_2}{2}} & s_{13}e^{-i\delta} \\ \nu_\mu & -\frac{s}{\sqrt{2}}e^{i\frac{\alpha_1}{2}} & \frac{c}{\sqrt{2}}e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \\ \nu_\tau & \frac{s}{\sqrt{2}}e^{i\frac{\alpha_1}{2}} & -\frac{c}{\sqrt{2}}e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \end{array}$$

$c \equiv \cos\theta_\odot$, $s \equiv \sin\theta_\odot$, $s_{13} \equiv \sin\theta_{13}$

With Large-Mixing MSW,

$$0.20 < \sin^2\theta_\odot < 0.30 \quad (90\%\,CL).$$

(SNO)

From bounds on reactor $\bar{\nu}_e$ oscillation,

$$\sin^2\theta_{13} \lesssim 0.03 \quad (90\%\,CL).$$

(CHOOZ; Palo Verde)

Note the contrast between $\mathcal{U}$ and the quark mixing matrix, V.

With B ≡ Big and s ≡ small,

$$V_{(\text{quarks})} = \begin{bmatrix} 1 & s & s \\ s & 1 & s \\ s & s & 1 \end{bmatrix},$$

but

$$\mathcal{U}_{(\text{leptons})} = \begin{bmatrix} B & B & s \\ B & B & B \\ B & B & B \end{bmatrix}.$$

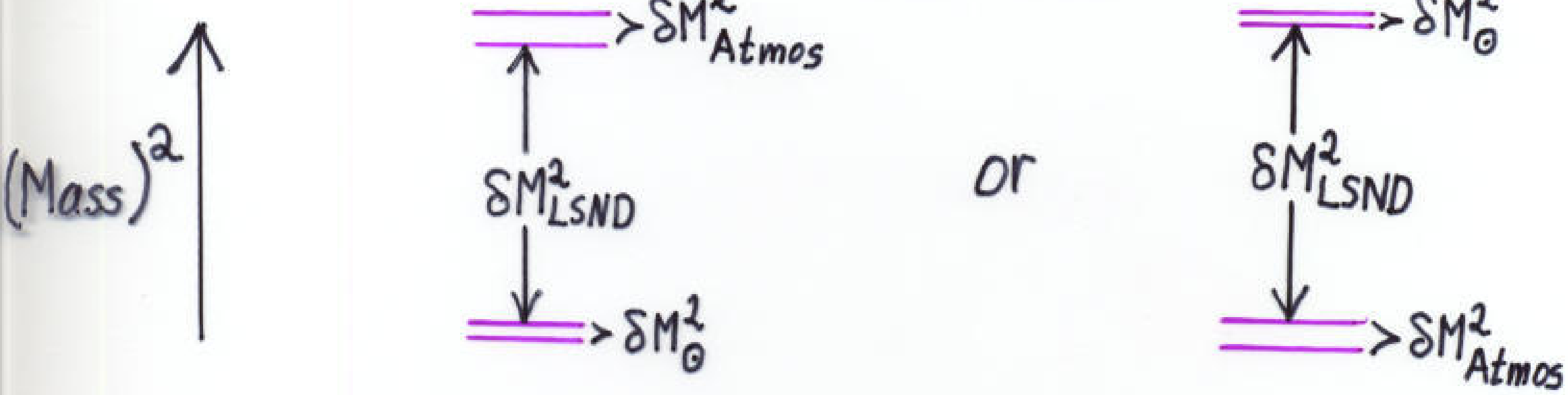
Are big leptonic mixings due to a symmetry, perhaps broken so that the mixings are not quite maximal?

If LSND is included

Four mass eigenstates are required.

The spectrum can look like —

2 + 2

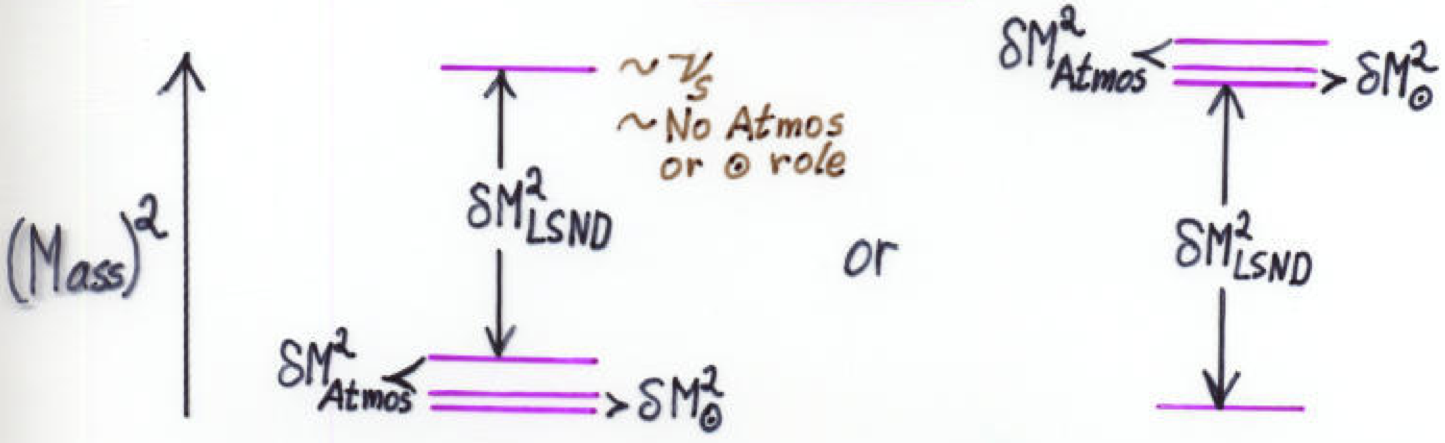


The ν_e content is >97 % in the solar pair. (Bugey, CHOOZ)

The ν_μ content is ≳97% in the atmos. pair. (CDHS)

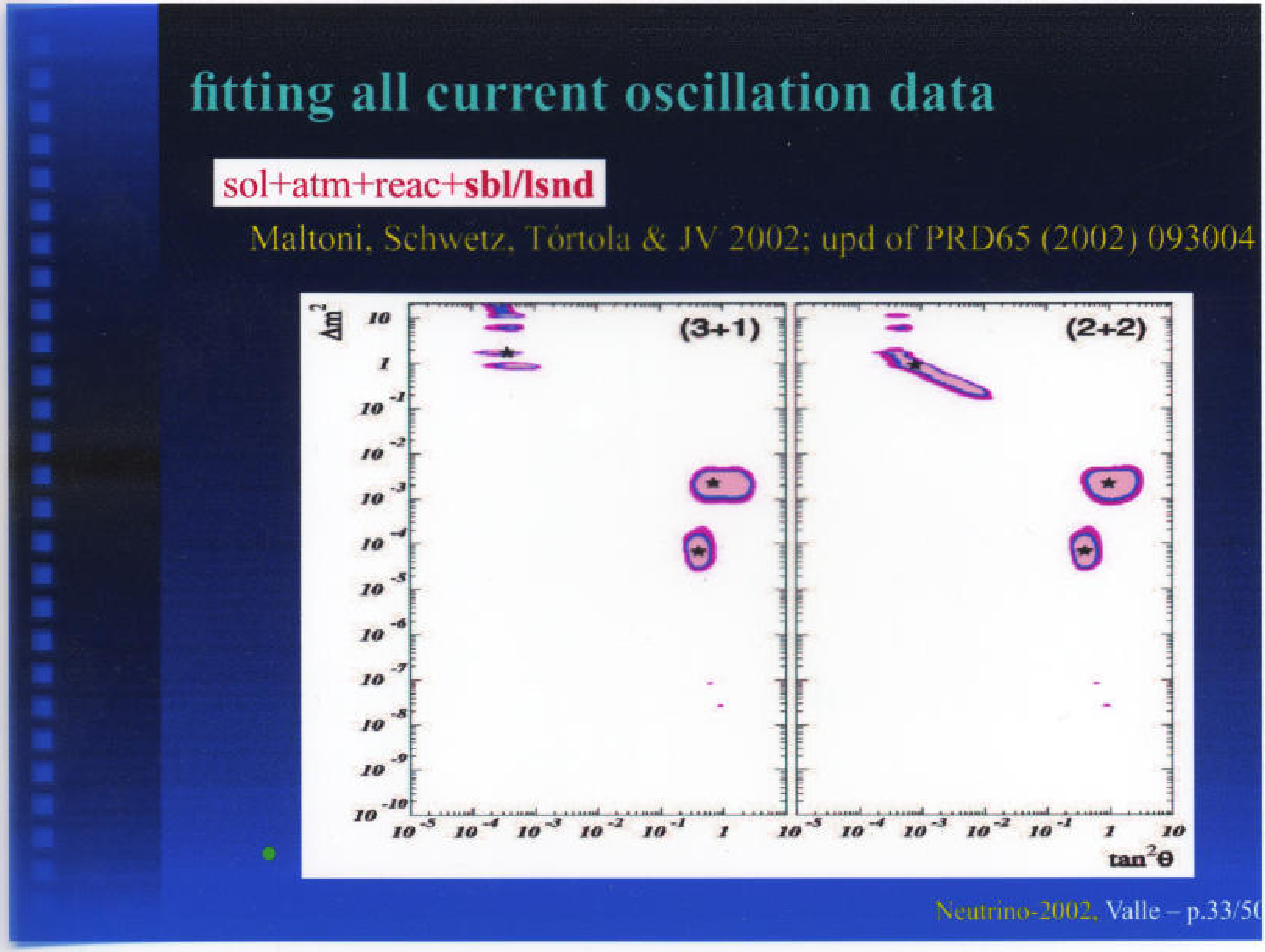
or

3 + 1



The ν_e content is >97% in the close-spaced trio. Similarly for ν_μ. (CDHS, Bugey, CHOOZ)

Valle



fitting all current oscillation data

sol+atm+reac+**sbl/lsnd**

Maltoni, Schwetz, Tórtola & JV 2002; upd of PRD65 (2002) 093004

2+2

Either Atm ν_μ or Sol ν_e flavor changes, or both, must produce a sterile ν with significant probability.

Peres & Smirnov:

$$\underbrace{\left(\frac{\nu_s}{\nu_e+\nu_\tau+\nu_s}\right)_{Atm}}_{<0.19\ @\ 90\%} + \underbrace{\left(\frac{\nu_s}{\nu_\mu+\nu_\tau+\nu_s}\right)_{Sol}}_{<0.25\ @\ 1\sigma} \simeq 1$$

(Shiozawa)

(Bahcall, Gonzalez-Garc
Peña-Garay

3+1

Neither Atm nor Sol flavor changes need produce much ν_s.

The "1" of
3+1

But $P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e)\Big|_{LSND} \propto |U_{\mu \overset{\downarrow}{4}} U_{e \overset{\downarrow}{4}}|^2$

is fighting against $U_{\mu 4}$ and U_{e4} upper bounds.

But perhaps there are —

$3(\text{active}) + 3(\text{sterile}) = 6$

neutrinos. Then constraints are loosened.

LSND is alive.

MiniBooNE is crucial.

Future

Determine the splittings and mixings:

$\Delta m^2_\odot \quad , \quad \theta_\odot$

$\Delta m^2_{atm} \quad , \quad \theta_{atm} \qquad [1 - \sin^2 2\theta_{atm}]$

$\Delta m^2_{LSND} \quad , \quad \text{``}\theta_{LSND}\text{''}$

Dear Colleagues: How precisely need these be known?

Maximal or near-maximal mixing suggests the presence of a symmetry.

The atmospheric oscillation connects mainly ν_μ and ν_τ.

If the $\nu_\mu - \nu_\tau$ mass matrix looks like—

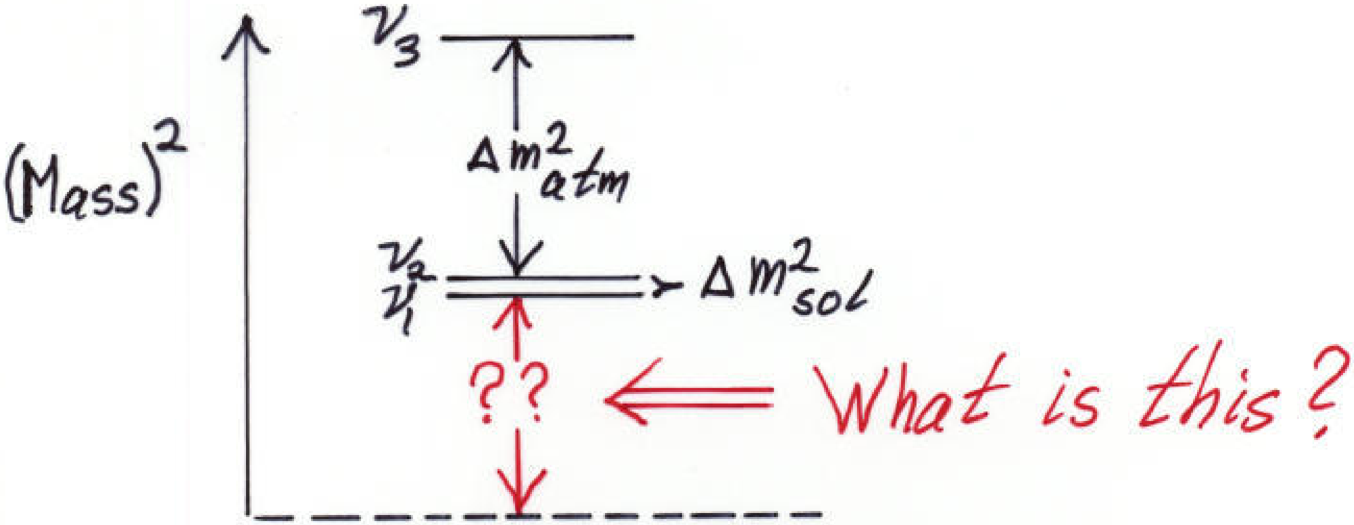
$$M = \underbrace{\begin{array}{c|cc} & \nu_\mu & \nu_\tau \\ \hline \nu_\mu & m & x \\ \nu_\tau & x & m \end{array}}_{\Longrightarrow\ \text{Max. Mixing}} + \underbrace{\begin{array}{c|cc} & \nu_\mu & \nu_\tau \\ \hline \nu_\mu & \delta & 0 \\ \nu_\tau & 0 & -\delta \end{array}}_{\text{Symmetry Breaking}} , \quad \delta \ll m, x;$$

then

$1 - \sin^2 2\theta_{Atm} \simeq \left(\frac{\delta}{x}\right)^2$ measures the scale of symmetry breaking.

* Workshop at Fermilab May 2-4 '02 *

How High Is the Whole Pattern?



Would it be enough to know $m_\tau^2 - m_\mu^2$ and $m_\mu^2 - m_e^2$, but not m_τ, m_μ, m_e?

Approaches

β spectrum in tritium decay

KATRIN to ~ 0.35 eV (Weinheimer)

If LSND is right, there is a ν_i with $m_{\nu_i} \gtrsim \sqrt{\Delta m^2_{LSND}} \simeq 0.4$ eV.

Does this ν_i couple to the e appreciably?

Cosmology – Perhaps $\sum_i m_{\nu_i}$ to ~0.3eV from ν– mass influence on Large Scale Structure formation.

(Hannestad)

There is a ν_i with

$$m_{\nu_i} \gtrsim \sqrt{\Delta m^2_{atm}} \simeq 0.05 \text{ eV},$$

Can we reach that range?

Does $\bar{\nu} = \nu$?

$\bar{\nu} = \nu$ is a generic prediction of the see-saw mechanism.

(Yanagida)

Assuming CPT invariance —

$$\beta\beta_{0\nu}\,[\text{Nucl} \rightarrow \text{Nucl}' + 2e^-] \Rightarrow \overline{\nu_i} = \nu_i$$

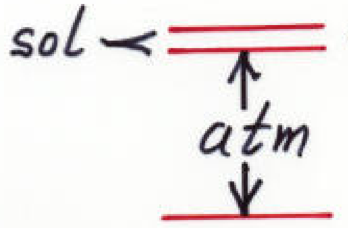
(Valle)

$$\text{Amp}\,[\beta\beta_{0\nu}] \propto m_{\beta\beta} \equiv \left| \sum_i m_{\nu_i} U_{ei}^2 \right|$$

$m_{\beta\beta}$ is a measure of the ν mass scale,

Desirable sensitivity: $m_{\beta\beta} \lesssim 0.05$ eV.

If the spectrum looks like —



$\leftarrow m_0 \gtrsim \sqrt{\Delta m^2_{atm}} \simeq 0.05\,\text{eV}$

then —

$$m_{\beta\beta} \cong m_0 \sqrt{1 - \sin^2 2\theta_0 \sin^2\left(\frac{\alpha_2 - \alpha_1}{2}\right)} \geq m_0 \cos 2\theta_0$$

Solar ν data and LMA-MSW fit $\Rightarrow \theta_\odot$ is strictly less than 45°.

With generous allowance for uncertainties,

$$m_{\beta\beta} \gtrsim 0.0085 \text{ eV}.$$

(Pascoli + Petcov)

Best fit LMA-MSW $\theta_\odot$ (SNO) and Δm^2_{atm} (SK)

$$\Longrightarrow m_{\beta\beta} \gtrsim 0.025 \text{ eV}.$$

Several proposed searches in this general range. (Cremonesi)

A hint of $\beta\beta_{0\nu}$ already?

(Klapdor-Kleingrothaus, Dietz, Harney, Krivosheina)

Does Neutrino Behavior Violate CP?

- Is expected if baryogenesis came through leptogenesis (Yanagida)

- Would establish that $\not{CP}$ is not a pecularariaty of quarks

If there are only 3 neutrinos,

U can contain 3 $\not{CP}$ phases:

$$\delta, \alpha_1, \alpha_2 . \qquad [U]$$

δ, and only δ, can lead to $\not{CP}$ in ν oscillation:

$$P(\underset{\uparrow}{\bar{\nu}_\ell} \rightarrow \underset{\uparrow}{\bar{\nu}_{\ell'}}) \neq P(\nu_\ell \rightarrow \nu_{\ell'}).$$

(Lindner)
(Akhmedov)

Let $P(\nu_\ell \to \nu_{\ell'}) - P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) \equiv \Delta_{\cancel{CP}}(\ell\ell')$.

If there are only 3 neutrinos,

$$\Delta_{\cancel{CP}}(e\mu) = \Delta_{\cancel{CP}}(\mu\tau) = \Delta_{\cancel{CP}}(\tau e)$$

$$= 16\,J\,k_{12}\,k_{23}\,k_{31}\ ,$$

where

$$J \equiv \mathrm{Im}(U_{e1}^{*}U_{e3}U_{\mu 1}U_{\mu 3}^{*}) \cong \frac{1}{4}\sin 2\theta_\odot \sin\theta_{13} \sin\delta ,$$

and

$$k_{ij} \equiv \sin\left[1.27\,\overbrace{\Delta m_{ij}^2}^{m_{\nu_i}^2 - m_{\nu_j}^2}(\mathrm{eV}^2)\,\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right] .$$

- Just one $\cancel{CP}$ difference
- No hadronic uncertainties
- But, small due to $\sin\theta_{13}$ and $\Delta m_\odot^2$

All effects of δ are $\propto \sin\theta_{13}$.

[U]

Crucially important:

Is $\theta_{13} \neq 0$?

How big is it?

Measuring θ_{13} is a major goal of future L(ong) B(ase) L(ine) experiments.

- Experiments under construction
- Super Beams
- Neutrino Factory

Extensive reviews of θ_{13}, $\not{CP}$, and other capabilities:

Lindner, Nakaya, Michael

24)

Where can the phases $\alpha_{1,2}$ play a role?

If $\bar{\nu}_i \neq \nu_i$, nowhere!

These Majorana phases have consequences only for Majorana particles.

If $\bar{\nu}_i = \nu_i$, $\alpha_{1,2}$ influence the rate for $\beta\beta 0\nu$ through –

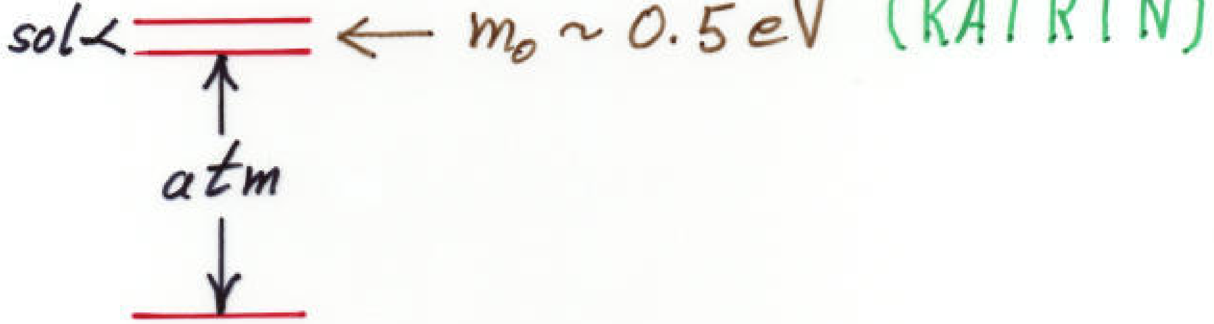
$$m_{\beta\beta} = \left| \sum_i m_{\nu_i} U_{ei}^2 \right|.$$

[U]

Can we measure $\alpha_{1,2}$?

An optimistic scenario:

The ν spectrum is



Then $m_{\beta\beta} \simeq m_0 \sqrt{1 - \sin^2 2\theta_\odot \sin^2\left(\frac{\alpha_2 - \alpha_1}{2}\right)}$,

or —

$$\sin^2\left(\frac{\alpha_2-\alpha_1}{2}\right) = \csc^2 2\theta_\odot \left[1 - \left(\frac{m_{\beta\beta}}{m_0}\right)^2\right]$$

$m_{\beta\beta}$ will be found from $\Gamma_{\beta\beta_{0\nu}}$ and nuclear m.e..

Barger, Glashow, Langacker, Marfatia : Impossible

Was Baryogenesis Made Possible by Leptonic $\cancel{CP}$?

Perhaps there was —

$$\Gamma[N(\text{Heavy Majorana}) \longrightarrow \ell^- + \text{Higgs}^+]$$

$$> \Gamma[N(\text{Heavy Majorana}) \longrightarrow \ell^+ + \text{Higgs}^-] .$$

This $\cancel{CP}$ would have produced a lepton (ℓ^-) excess that would then have resulted in a baryon excess.

(Yanagida)

The $\cancel{CP}$ phases required are Majorana phases, like the ones in $\beta\beta 0\nu$.

Do Neutrinos Violate CPT?

Gravitons and right-handed neutrinos may be the only particles that travel in extra spatial dimensions.

There, they might see CPT effects from stringy structure. Unlike field theories, string theories could break CPT.

The consequences:

$$m_{\overline{\nu}_i} \neq m_{\nu_i}$$

$\Longrightarrow$ $\overline{\nu}$ oscillation $\neq$ ν oscillation

(Murayama, Yanagida
Borissov, Lykken, Smirnov)

Big $\cancel{CPT}$ can easily be excluded:

KamLAND($\bar{\nu}_e$) vs. Solar (ν_e)

MiniBooNE($\bar{\nu}_\mu$) vs. MiniBooNE(ν_μ)

What Can Neutrinos Tell Us About Astrophysics and Cosmology?

Total energy and temperature of $\overset{(-)}{\nu}_{\mu,\tau}$ from supernovae using $\overset{(-)}{\nu}p \to \overset{(-)}{\nu}p$.

(Beacom)

ν masses play a role in Large Scale Structure formation.

(Hannestad)

The information could flow either way.

What is the Origin of Neutrino Flavor Physics?

Simple arguments suggest Majorana ($\nu \leftrightarrow \overline{\nu}$) masses are involved.

The see-saw relation

$$m_\nu = \frac{m_{quark}^2}{M_?}$$

$\Longrightarrow$ $M_?$ is very large, suggesting that physics at a high mass scale is involved.

But maybe ν mass is small because-

$$\nu \text{ mass} \sim \overline{\nu}_L \, \nu_R$$

↑ Lost in an extra dimension

(Valle

One, and very probably two, neutrino mixing angles are big.

Are symmetries behind this?

The roles of naturalness and symmetries in ν mass + mixing models were reviewed by King.

Models were also explored by Valle.

What are the Connections Between ν Flavor Physics and Quark Flavor Physics?

In G(rand) U(nified) T(heories), where quarks and leptons are in the same family, one expects connections.

An interesting example —

(Chang, Masiero, Murayama)

In SU(5) GUTS, for each generation, one has a family like

$$(\nu_\tau, \tau^-, \bar{b}, \bar{b}, \bar{b})_L \; .$$

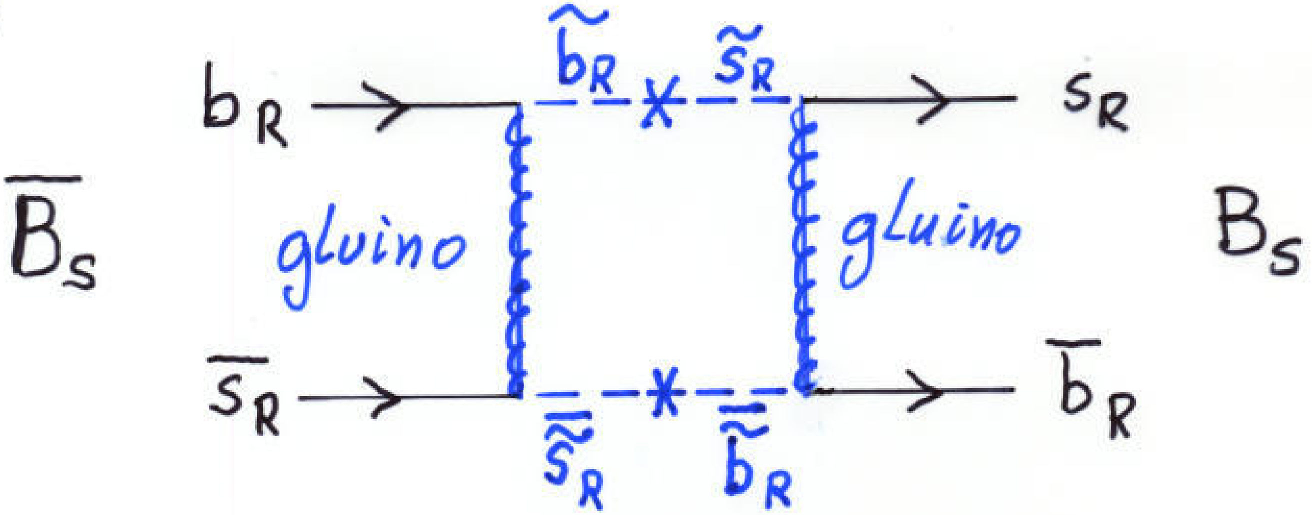
Atm ν oscillation $\Longrightarrow$

~ Maximal $\nu_{\mu L} - \nu_{\tau L}$ mixing.

∴ ~ Maximal $\bar{s}_L - \bar{b}_L$ $(s_R - b_R)$ mixing.

Then SUSY $\Longrightarrow$ Large $\underbrace{\tilde{s}_R - \tilde{b}_R}_{\text{squarks}}$ mixing.

Big squark mixing leads to —



⟹ Potentially large non-Standard-Model contribution to $\overline{B}_s - B_s$ meson mixing.

⟹ B-factory/Tevatron/LHC test of Standard Model picture of B physics mixing and $\not{CP}$ will fail, revealing —

New physics related to ν mixing.

C

Conclusion

Compelling evidence for atmospheric ν oscillation has now been joined by—

Compelling evidence for solar ν flavor change.

We already know a lot:

- $\sim \Delta m^2_{atm}$
- $\sim \Delta m^2_{\odot}$
- General character of the mixing matrix

But there is a lot we do not know:

- Individual ν_i masses
- Whether $\overline{\nu_i} = \nu_i$
- How large the small θ_{13} is
- Whether neutrinos violate CP
- ...
- The physics behind it all

Interesting years lie ahead in ν physics!