STUDYING NEUTRINO OSCILLATION BY USING DAYA BAY NUCLEAR POWER PLANT AS THE NEUTRINO SOURCE

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NEUTRINO PHYSICS

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I. Introduction

The discovery of neutrino masses involves a spectacular series of events. It emerged more than thirty years after a "simple" curiosity attempt wanting to see the neutrino from the sun. The smoking guns of the discovery are provided by the Super-K atmospheric neutrino data and the SNO solar neutrino neutral current events. The Los Alamos experiment which has seen excess beam-stop antielectrons, if verified, would require the existence of an $SU(2)$ singlet sterile neutrino. Neutrinos despite their masses are not the dark matter we once thought they would be. They are the fermionic relic left from the early universe and permeate all over the cosmos with more than 300 of them per cubic centimeter. They are an important part of the inner-space/outer-space connection of particle physics, astrophysics, and cosmology. They can be the new tools for discoveries in the future.

What I would like to do is to first review briefly the evidences of the neutrino masses, describe where we stand now, and present you a list of issues of what can be called the neutrino frontiers in particle physics and astrophysics. In dealing with these frontiers a number of approaches to study them would have to be adopted: reactors, accelerators cosmic rays, and large detectors. A particularly useful laboratory setting is the underground laboratory which is deep enough to have a large overburden to provide very low cosmic ray background. It is also a clean environment under which interesting topics in other areas of science and even engineering can be effectively studied.

II What do we know about neutrino parameters?

♣ From traditional particle physics, $d < 1$ fm.

- Three flavors of light neutrinos.
- SU(2) partners of charged leptons:
- mass limit–absolute mass bounds from end-point experiments:

  $m_{\mathrm{e}} < 3$ eV (Mainz and Troitsk: 2.2 eV @95% CL)

  $m_\mu < 0.19$ MeV

  $m_\tau < 18.2$ MeV
- Neutrinos interact according to broken $SU(2) \times U(1)$ symmetry.
- Neutrinos being neutral offer the possibility of Majorana fermions.

♣ From oscillation experiments, $d \geq$ km

The long distance information of all sources, solar, atmospheric, reactors, and accelerators have observed disappearance of ν_{e} and ν_μ. They can be interpreted as flavor mixing and oscillation. Oscillations become manifested for

$$\Delta E \Delta t = \Delta m^2 \frac{L}{2E} \approx 1,$$

Oscillations can probe a wide range of Δm^2 by varying L/E, very small $\Delta m^2 \sim$ sub-eV^2 requires large $L \sim$ km, for MeV and GeV energy neutrinos.

General properties and smoking guns

- For N flavors, the ν mass matrix consists of:
  N mass values, $N(N-1)/2$ mixing angles, $N(N-1)/2$ phases for Majorana ν or $(N-1)(N-2)/2$ phases for Dirac ν.

- The oscillation experiments can only measure $N-1$ mass-square differences, $N(N-1)/2$ mixing angles and $(N-1)(N-2)/2$ phases.

- For 3 flavors, the mixing (Pontecorvo, Maki, Nakagawa, Sakata) matrix which transforms the mass eigenstates (ν_1, ν_2 ν_3) to the flavor eigenstates ($\nu_{\rm e}$, ν_μ, ν_τ)

$$\begin{pmatrix} C_{12}C_{13} & C_{13}S_{12} & \hat{S}^*_{13} \\ -S_{12}C_{23} - C_{12}\hat{S}_{13}S_{23} & C_{12}C_{23} - S_{12}\hat{S}_{13}S_{23} & C_{13}S_{23} \\ S_{12}S_{23} - C_{12}\hat{S}_{13}C_{23} & -C_{12}S_{23} - S_{12}\hat{S}_{13}C_{23} & C_{13}C_{23} \end{pmatrix} \times \begin{pmatrix} e^{i\phi_1} & & \\ & e^{i\phi_2} & \\ & & 1 \end{pmatrix}$$

  $C_{\rm jk} = \cos\theta_{\rm jk}$, $S_{\rm jk} = \sin\theta_{\rm jk}$, $\hat{S}_{13} = exp(i\delta_{\rm CP})\sin\theta_{13}$.

- For 3 flavors, oscillation experiments can only determine: 3 mixing angles θ_{12}, θ_{13}, θ_{23}, 2 mass-square differences, $\Delta m_{21} = m_2^2 - m_1^2$, $\Delta m_{31} = m_3^2 - m_1^2$, and 1 CP phase angle $\delta_{\rm CP}$.

- To date only disappearance experiments have been convincingly performed. But there are strong evidences for flavor mixing from solar, atmospheric, reactors and accelerator experiments.

- Smoking guns: **Atmospheric**: Super-K depletion of μ-like events increases with distance while e-like events agree with expectation, Fig. 1.

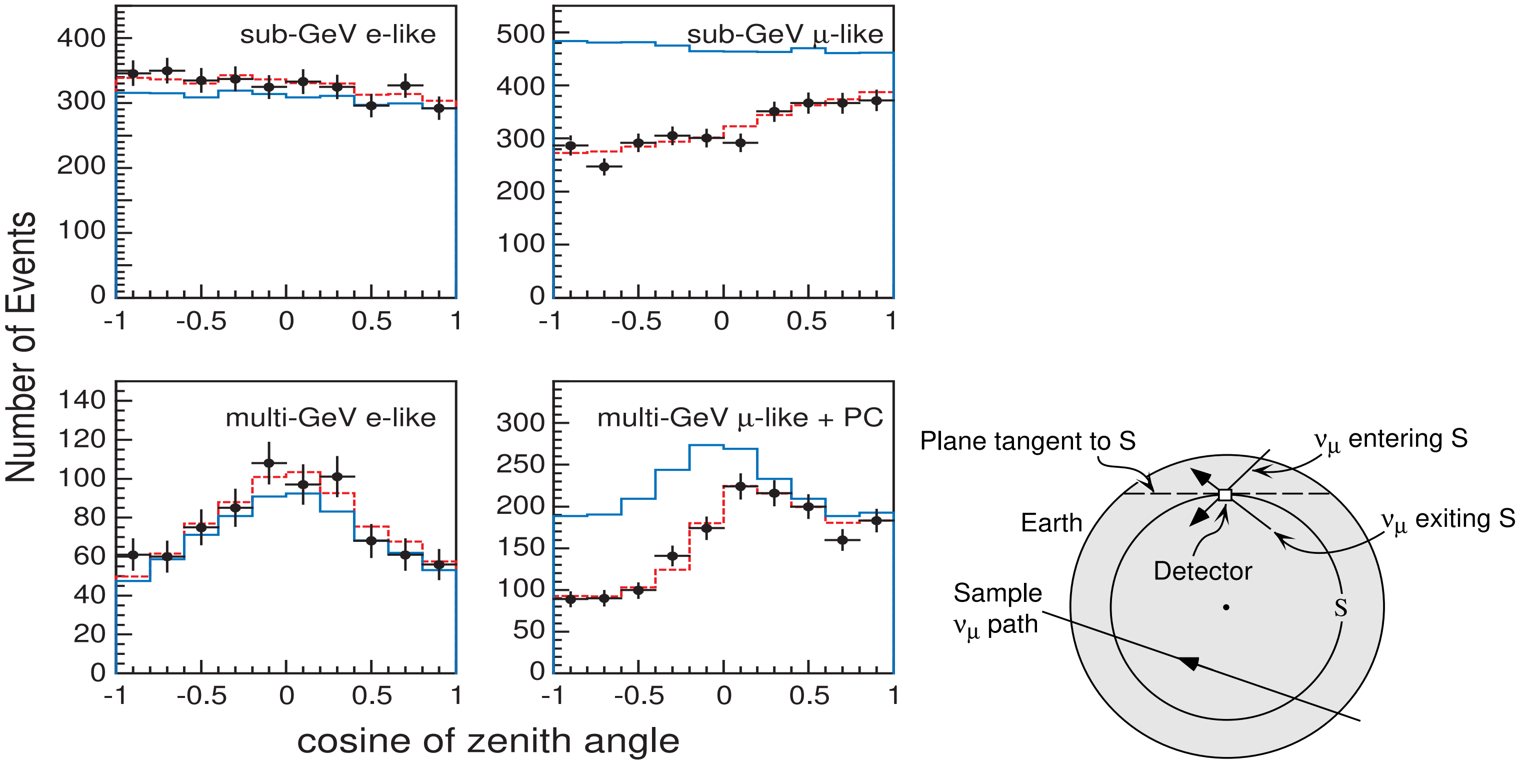

Figure 1: Super-K atmospheric neutrino results showing depletion of predicted μ-like events for increasing neutrino traveling distance while the agreement in e-like events is excellent. The fitting of the μ-like events with the assumption $\nu_\mu \to \nu_\tau$ with maximum mixing.

- Smoking gun: **Solar**: SNO neutral and charge currents.

$$
\begin{aligned}
\mathrm{CC}(\phi_{CC}): &\quad \nu_{\mathrm{e}} + d \longrightarrow p + p + e^- \\
\mathrm{NC}(\phi_{NC}): &\quad \nu_{\mathrm{x}} + d \longrightarrow p + n + \nu_{\mathrm{x}} \\
\mathrm{ES}(\phi_{ES}): &\quad \nu_{\mathrm{e}} + e^- \longrightarrow \nu_{\mathrm{e}} + e^-
\end{aligned}
$$

$$\phi_{CC} = \phi_{\mathrm{e}} \quad \phi_{NC} = \phi_{\mathrm{e}} + \phi_{\mu\tau} \Rightarrow \phi_{ES} = \phi_{\mathrm{e}} + 0.15\phi_{\mu\tau}$$

Excellent agreement with the standard solar model ^{8}B neutrino flux, Fig.2

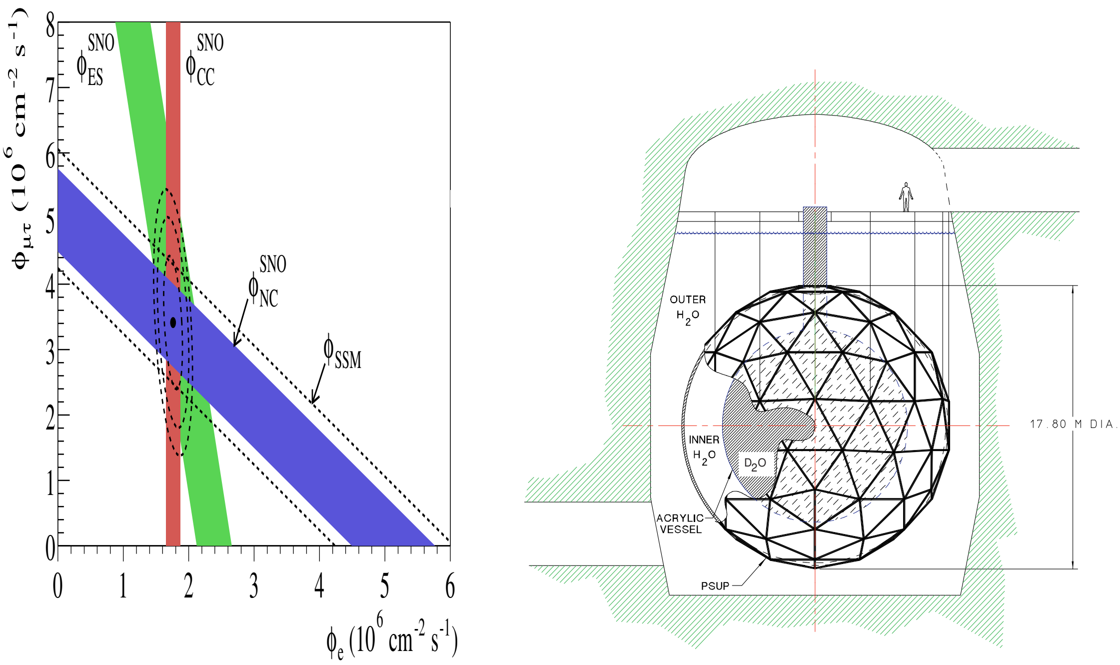

Figure 2: SNO Flux of ^{8}B high energy solar neutrino

- The total experimental $\Delta m^2 - \sin^2 2\theta$ space including atmospheric, solar, and Los Alamos LSND short baseline beam-stop experiment requiring $\Delta m^2 \approx 1$ eV.
- LSND: sterile neutrino, or anomalous muon decay $\mu^+ \longrightarrow \bar{\nu}_e \bar{\nu}_i$, or ν and $\bar{\nu}$ different mass spectra (CPT violation); but all strongly disfavored.

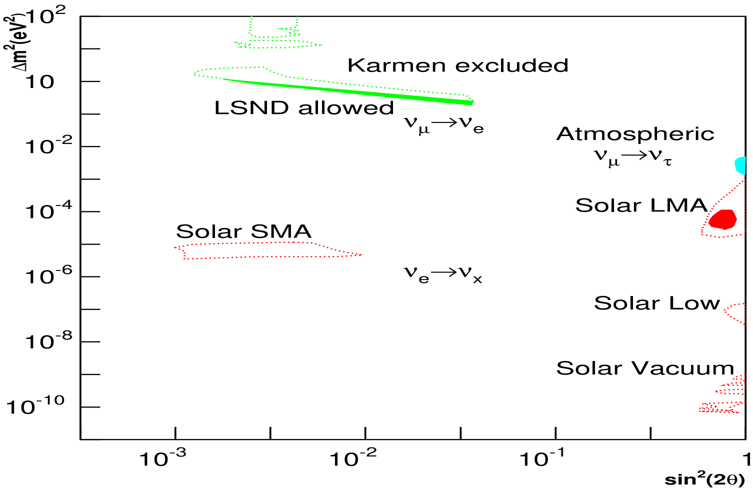

Figure 3: Oscillation parameter space showing all three indications of oscillation in two-flavor mixing approximation. With SNO and KamLAND, only the LMA solution is favored. The LSND will be studied by MiniBooNE which is running at Fermilab and results expected in early 2005.

- The best fit for 3 flavors from Super-K, SNO, KamLAND and CHOOZ:
  Solar (LMA): $\Delta m^2_{21} = 7 \times 10^{-5}$, $0.75 < \sin^2 2\theta_{12} < 0.96$ (30°,39.2°).
  Atmospheric: $|\Delta m^2_{32}| = 2.0 \times 10^{-3}$, $\sin^2 2\theta_{23} = 1.0$.
  CHOOZ: $\sin^2 2\theta_{13} < 0.1 \quad (\theta_{13} < 9°)$.
- New SNO (with salt): $\Delta m^2_{21} = 7.1^{+12}_{-0.6}$ eV^2, $\theta 32.5^{+2.4}_{-2.3}$, 5σ away from maximal.
- Two different mass spectra: normal hierarchy and inverted hierarchy:

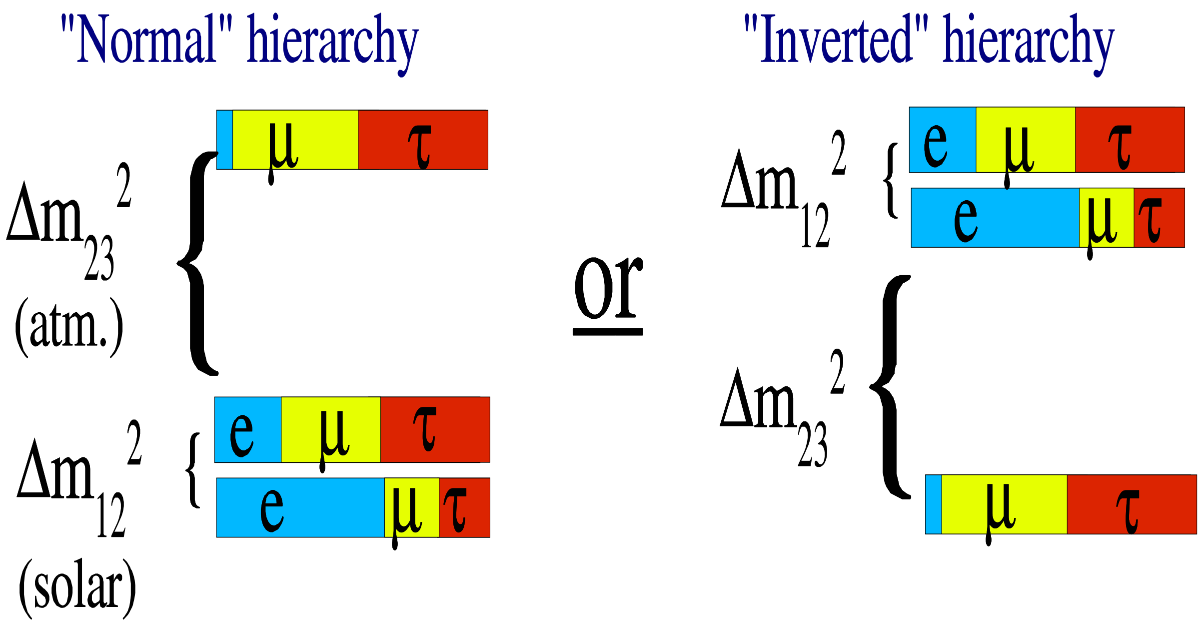

Figure 4: Normal and inverted spectra: normal $\Delta m^2_{32} > 0$; inverted $\Delta m^2_{32} < 0$.

- Include the LSND result and therefore a fourth neutrino.

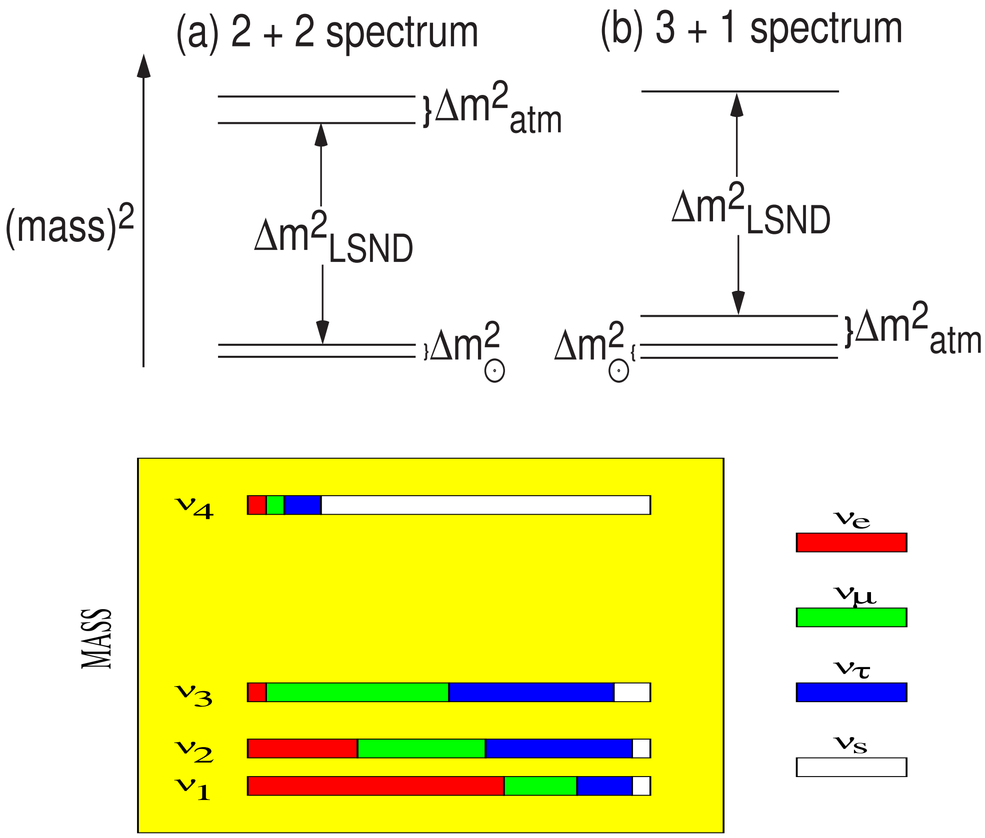

Figure 5: Level structures of four neutrinos. The 2+2 scenario is disfavored compared to the 3+1 scenario, but neither provides a good fit to the data.

- What are the absolute neutrino masses?
  Extreme scenarios for three neutrino flavors:
  Small mass
  normal: $m_1 \approx 0$, $m_2 \approx 0.007$, $m_3 \approx 0.045$ eV.
  inverted: $m_3 \approx 0$, $m_1 \approx 0.007$, $m_2 \approx 0.045$ eV.
  Large mass–degenerate

$$m_1 \approx m_2 \approx m_3 \begin{cases} \gg \sqrt{\Delta m^2_{\rm atm}} \approx 0.045 \text{eV} \\ < \ 2.2 \text{eV (Mainz and Troitsk)} \end{cases}$$

♣ Cosmological constraint:

- Most recent galaxy survey on the power spectrum of CMB: WMAP + 2dFGRS

$$\sum_j m_{\nu_j} < 0.71 \text{ eV}, \qquad m_\nu < 0.23 \text{ eV}$$

III. Where do we stand?

- Massive neutrinos are the first experimental evidence of physics beyond the SN, opening a window to new physics; SM has an hierarchy problem, mass spectrum extending 11 orders of magnitude: $\mathcal{O}(\leq 1\ \text{eV}) - \mathcal{O}(10^{11}\ \text{eV})$.

- Small mass and large mixing in the lepton sector in contrast to the quark sector, neutrino and quarks may have different origins for their masses.

$$U_{\text{PMNS}} = \begin{pmatrix} Ce^{i\phi_1} & Se^{i\phi_2} & \hat{S}^*_{13} \\ -Se^{i\phi_1}/\sqrt{2} & Ce^{i\phi_2}/\sqrt{2} & 1/\sqrt{2} \\ Se^{i\phi_1}/\sqrt{2} & -Ce^{i\phi_2}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \qquad \begin{array}{l} C = \cos\theta_\odot \\ S = \sin\theta_\odot \\ \hat{S}^*_{13} = \sin\theta_{13}e^{-i\delta_{\text{CP}}} \end{array}$$

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \qquad \begin{array}{l} A,\ \rho,\ \eta \sim \mathcal{O}(1) \\ \lambda \approx 0.22 \end{array}$$

- 1-2 and 2-3 generations large-large or large-maximal mixing, 1-3 small or very small mixing.

- Large freedom in constructin of neutrino mass matrix subjedt to diverse physical interpretations. Most promising models of m_ν are the see-saw mechanism and Zee model of radiative masses. See-saw requires Majorana neutrinos.

- Detailed study of the neutrino sector, the implications to astrophysics and cosmology have just begun, an experimentally driven forefront. Theoretical Construction of a consistent theoretical framework will follow.

IV. What are the outstanding issues?

Accepting massive neutrinos, a range of outstanding issues, both experimental and theoretical, have to be studied. Presently most of the answers will be experimentally driven.

♣ Neutrino sector:

1. See the dip in atmospheric neutrino L/E distribution.
2. Measure the whole solar neutrino energy spectrum.
3. Determine the value of $U_{e3}(\theta_{13})$, critical to leptonic CP-violation.
4. Determine Δm^2_{21}, Δm^2_{31}, θ_{12}, and θ_{23} more accurately.
5. Can we see the $\nu_\mu \to \nu_\tau$ oscillation?
6. Is the mass hierarchy normal or inverted?
7. What are the absolute neutrino masses? Why are they so small? Can a ν mass matrix be constructed and the parameters understood by some symmetry?
8. What are the electromagnetic properties of neutrinos? Do neutrinos have non-vanishing magnetic moments?
9. What is the CP angle δ_{CP}? Is it large?
10. Can we settle the LSND question?

♣ Issues in the broader picture

1. Are the neutrinos Majorana or Dirac?
2. If neutrinos are Majorana, what are ϕ_1 and ϕ_2.
3. If LSND is right, how do we interpret it? ν_s or something else?
4. Can massive neutrinos help probe extra dimensions?
5. Are there connections between lepton and quark flavors?

♣ Issues related to astrophysics and cosmology

1. Are there astrophysical sources of TeV neutrinos?
2. What can neutrinos tell us about astrophysics and cosmology?
3. What can astrophysics and cosmology tell us about neutrinos?

♣ Some fundamental questions

1. Can lepton CP violation make baryogenesis to work?
2. Do neutrinos and antineutrinos obey CPT?
3. What is the origin of the neutrino mass? Any relations with quark masses and dark energy?
4. Why leptonic mixing angles so large even maximal and different from those the quark? any implication to GUT?
5. What is the origin the flavor? Who ordered the extra flavors?
6. Where do we go from here and how to modify the SM?

V. Road map for oscillation and related measurements

Experiments with ν_μ beams subject to 8-fold parameter degeneracy: sign(Δm^2_{31}), ($\delta_{\rm CP}$, $\theta 13$), (θ_{23}, $\pi/2-\theta_{23}$). All experiments require a large detector (ton), high beam intensity (MW/GW), and long running time (year). Most experiments may best be done at underground labs with large overburden.

♣ Road maps for neutrino oscillation experiments

- Stage 0: Existing experiments
  - K2K, CNGS (OPERA,ICARUS), NuMI/Minos: Δm^2_{23} to 10%. See $\nu_\mu \to \nu_\tau$?
  - KamLAND determines $\sin^2 2\theta_{12}$ to ± 0.1.
  - MiniBooNE: Determine LSND and the associated Δm^2 if signals are observed.
- Stage 1: New facilities (Measuring or limiting θ_{13}.)
  - NuMI/Minos, off-axis beam (better sensitivity): $\sin^2 2\theta_{13} > 0.06$, 90% CL.
  - Improve $\sin^2 2\theta_{13}$ by off-axis super-beams at MuNI/Minos and JHF-HyperK.
  - Two-detector reactor($\bar{\nu}_{\rm e} \to \bar{\nu}_\mu$)/beta-beam($\nu_{\rm e} \to \nu_\mu$) experiments: no parameter degeneracy, determine $\sin^2 2\theta_{13}$ to about 0.02, check CPT.
- Stage 2: New facilities–Superbeam and very large detectors ($>$ 500 kt)
  - One long baseline (300 km) and the other very long baseline (2100 km).
  - Determine matter effect and sign(Δm^2_{31}), and search for CP, Fig. 6.

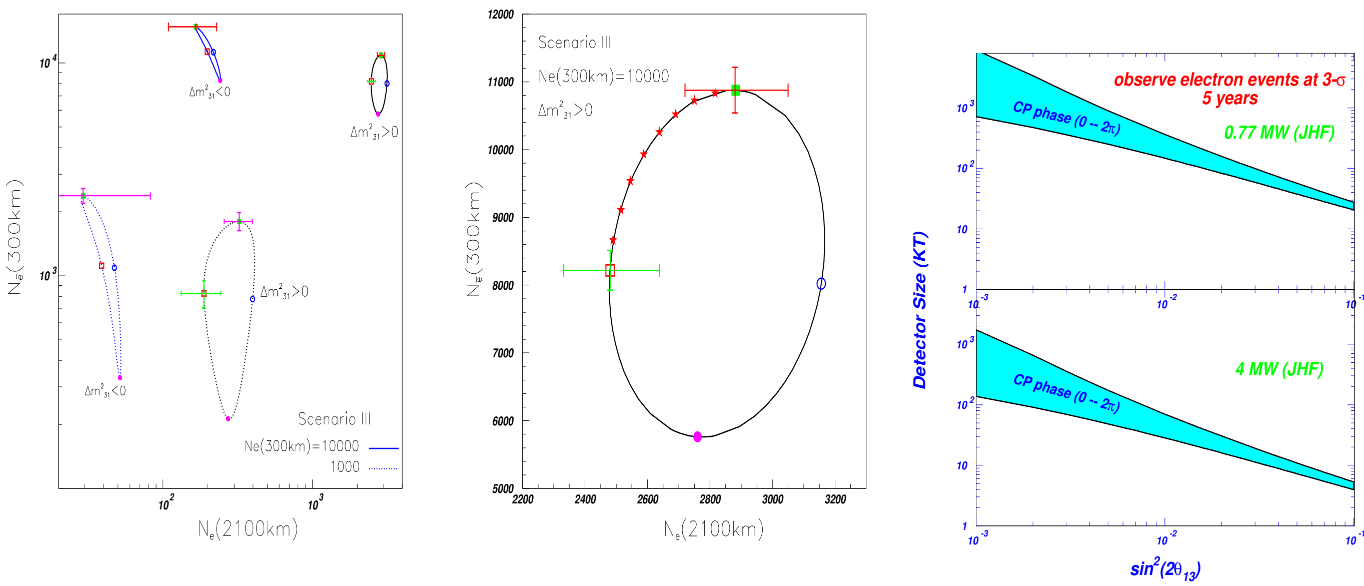

Figure 6: Combined analysis of JPARC-SuperK (300 km) and JPARC-Beijing (2100 km) (Whisnant, Yang and Young [21]).

- Stage 3: Neutrino factory with muon storage ring, large detector
  - Performing $\nu_\mu \to \nu_\tau$ appearance experiments.
  - Performing $\nu_e \to \nu_\tau$ appearance experiments.
  - Precision of 1% for Δm^2_{32} and 10% on $\sin^2 2\theta_{23}$ from $\nu_\mu \to \nu_\tau$.
  - Precision down to 10^{-5} for $\sin^2\theta_{13}$, only limited by backgrounds.

♣ Reactor experiments for θ_{13}

Important to know the value of θ_{13} in the study of lepton CP-violation $\sim \sin\theta_{13}\sin\delta_{C}$

Advantages of reactors experiments:

- A survival experiment $\bar{\nu}_e \to \bar{\nu}_e$, independent of δ_{CP}.
- $E_\nu = \mathcal{O}(\mathrm{MeV})$ and $L = \mathcal{O}(\sim \mathrm{km})$, matter effect negligible, independent of $\mathrm{sign}(\Delta m^2_{31})$.
- vacuum probability valid: $\mathrm{P}(\nu_e \to \nu_e) \simeq 1 - \sin^2 2\theta_{13}\sin^2\Delta_{31} - \cos^2\theta_{13}\sin^2\Delta_{21}$
- But have to know Δm^2_{31} well, statistics $\sim$ detector size $\times$ reactor power $\times$ running time.

♣ Seven possibilities

- European "proposal"-1 (reactor): P. Huber *et al.*, hep-ph/ 0303232, Fig. 7
- Japanese "proposal": H. Minakata *et al.*, hep-ph/0211111, Fig. 8.
- American "proposal": M.H. Shaevitz and J.M. Link, hep-ex/0306031.
  A group (spearheaded by Jonathan Link) is developing a reactor experiment proposal supported by the directors of Fermilab and Argonne.
- European "proposal"-2 (beta beam): M Apollonio *et al.*, hep-ph/0210192.
- Russian "proposal" (Kr2Det): V. Martemyanov *et al.*, hep-ex/0211070.
- Brazilian "proposal": On the Angra dos Reis coast, Brazil (3 hours south of Rio), a 4GW reactor surrounded by 400-600m hills. A proposal and cost estimate are being made. The civil construction cost would be half of that in US. Funding and construction could occur by 2006.
- Asian Pacific Collaboration: Daya Bay Reactors, 4×2.7 $\mathrm{GW_{th}}$.

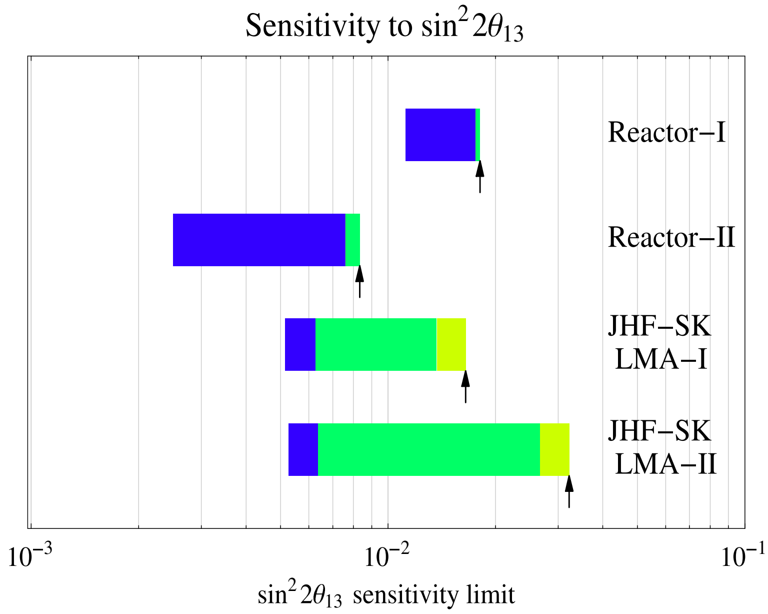

Figure 7: A European reactor ν proposal. The sensitivities to θ_{13} for Reactor I (400tGWy) and Reactor II (8000tGWy), JHF-SuperK at LMA-I ($\Delta m^2_{21} = 7 \times 10^{-5}$ eV^2) and JHF-SuperK LMA-II ($\Delta m^2_{21} = 1.4 \times 10^{-4}$ eV^2) at the 90% CL. The sensitivity limits for the reactor experiments hardly depend on the true value of the solar parameters. The left edges of the bars correspond to the sensitivity limits from statistics only. The right edges are the realistic limits by taking into account of the various uncertainties: systematics, correlations, and parameter degeneracy.

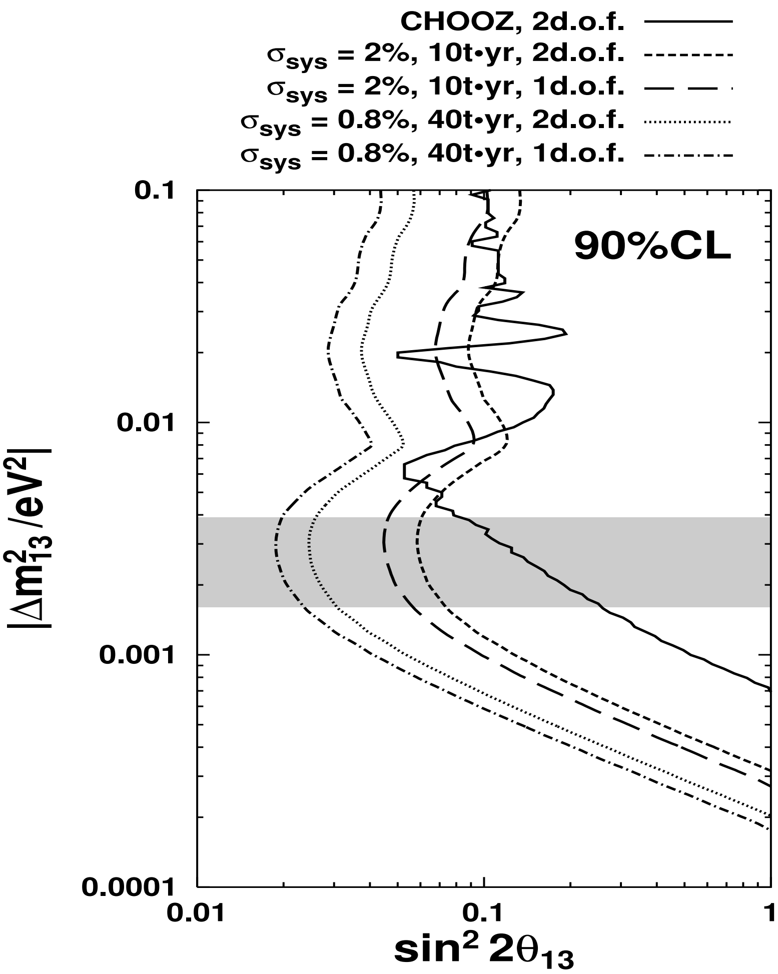

Figure 8: A Japanese reactor ν proposal. 90% CL exclusion limits on $\sin^2 2\theta_{13}$ which can be placed by reactor measurement of 24.3 GW_{th} thermal power of average neutrino energy 4 MeV, and two CHOOZ-like detectors (200 m and 1.7 km). 1 or 2 d.f. refers to with or without the knowledge of Δm^2_{31}. Sensitivity of Russian Kr2Det is about the same.

♣ Other particle physics measurements

- Neutrinoless double beta decay

  This is critical in determining whether or not neutrinos are Majorana. The rate is determined by the ee element of neutrino mass matrix (a physical quantity):

  $$|m_{\mathrm{ee}}|^2 = |\sum U_{\mathrm{ej}}^2 m_{\mathrm{j}}|^2 \approx (1 - \sin^2\theta_{12}\sin^2\phi_2)m_1^2$$

  i.e., $m_1^2\cos^2\theta_{12} \leq |m_{\mathrm{ee}}^2 \leq m_1^2$ (for $m_2 \approx m_1$ and neglecting U_{e3}).

  – A favored approach for the inverted mass spectrum.
  – Current bound: $m_{\mathrm{ee}} \leq 0.35 - 0.50$ eV (Heidelberg-Moscow).
  – Future reach: $m_{\mathrm{ee}} \sim 0.01$ eV (GENIUS, MAJORANA, EXO, XMASS,and MOON).
  – If m_1 is measured separately, can help determine one of the Majorana phases.

- Tritium beta decay

  This is to look at the end point of the decay spectrum with

  $$m_{\nu_{\mathrm{e}}}^2 = \sum |U_{\mathrm{ej}}|^2 m_j^2$$

  In the case of degenerate masses, $m_{\nu_{\mathrm{e}}}^2 \approx m_j^2$, present limit ~ 2.2 eV.

  – A large tritium experiment in design, KATRIN, can discover m_μ of 0.35 eV with 5σ, 0.30 eV with 3σ, and put an upper bound of 0.2 eV if μ_μ is zero.

- Extensive programs in low energy ν scattering (existing information in the low energy region is poor), DIS with large targets, nuclear structure functions, hadron structures, CKM and $\sin\theta_{\mathrm{W}}$.

VI. Neutrinos and Neutrino Astronomy

- Neutrinos play important roles in cosmological and astrophysical settings and are a good example of the so-called inner-space/outer-space connection.
- Joining the high energy γ rays and high energy charged particles, neutrinos and gravitational waves are the new observational regimes of high energy astrophysics.
  - Neutrinos: emerging from deep inside regions opaque to photons.

♣ Neutrino as dark matter

- Neutrinos do not congregate well and disfavor as a (hot) dark matter.
- Recent WMAP/2dFGRS:

$$\Omega_\nu h^2 = \frac{\sum m_{\nu_j}}{93.5\text{eV}} < 0.0076 \Longrightarrow \Omega_\nu < 1.5\% \quad @95\%\ \text{CL} \quad \text{while} \quad \Omega_{\text{DM}} \approx 23\%$$

.

♣ Cosmological constraint on neutrino masses

The above limit on the neutrino mass density leads to

$$\sum \nu_j < 0.71\ \text{eV}, \qquad m_\nu \leq 0.23\ \text{eV}$$

♣ Constraints on sterile neutrino from Cosmology–WMAP/2dFGSR á la LSND

- 3+1 scenario: one isolated "heavy" neutrino $\Delta m^2_{\text{LSND}} \leq 0.5\ \text{eV}^2$.
- 2+2 scenario: 2 "heavy" neutrinos $\Delta m^2_{\text{LSND}} \leq 0.2\ \text{eV}^2$.
- Big Bang nucleosynthesis of light elements places a stronger constraint on ν_{s}.

♣ Core collapse supernova neutrino–an exciting frontier with SN ν's

- SN1987A demonstrated that SN is a source of cosmic neutrinos.
- About 99% of the gravitational energy ($\sim 3 \times 10^{53}$ ergs) is released by neutrinos.
- Average E_ν: 12 MeV for $\nu_{\rm e}$, 15 MeV for $\bar{\nu}_{\rm e}$, and 18 MeV for ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$.
- The ν emission occurs hours before γ emission and lasts for about 10 second.
- Neutrino physics with SN ν's: Matter effect, ν magnetic moment, new physics under extreme conditions: high density and high temperature.
- An Early Warning System for SN events and can corrlate with gravitational wave emission.

♣ Ultra-high energy neutrinos

UHE ν's may reveal: behavior of a massive young galaxy, physics of high density and very high energy, physics of cosmic rays, possibility of violation of Lorentz which may occur in the early universe, and neutrino electromagnetic properties and possible nonstandard interactions.

- Sources of UHE neutrinos– Topological defects (10^{24} eV), AGN and GRB (10^{20} eV), the GZK mechanism (10^{18} eV).

- HENTs (high energy neutrino telescopes)– Many experimental programs: IceCube, NT-200, NESTOR, ANTARES, RICE, GLUE, etc. Some are already in operation. HENTs can also observe possible high energy neutrino production from the annihilation of neutralinos in the core of Earth and the sun.

- Z-burst
  - 20 cosmic ray events over GZK-cutoff $E_{\rm GZK} = 5 \times 10^{19}$ eV observed.
  - Source of UHE cosmic rays (AGN, GRB) are more than 100 Mpc away. So their energy can not exceed the GZK cutoff.
  - Z-burst model: UHE ν's scattered off relic cosmic background $\bar{\nu}$'s to produce Z^0's which decay to form the observed UHE cosmic rays.
  - This also demonstrates the existence of cosmic background ν.

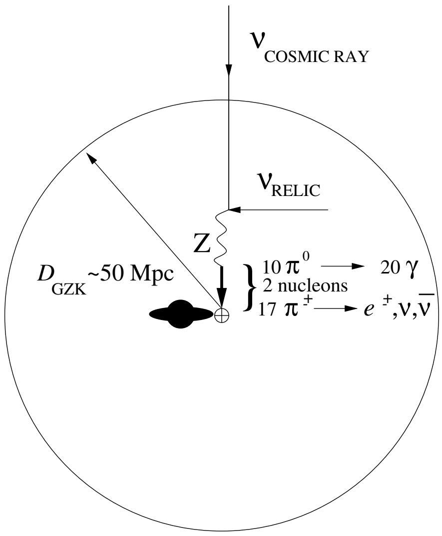

Figure 9: Z-burst productions from resonant scatterings of cosmic UHE ν against relic $\bar{\nu}$. If the Z-bust occurs within the GZK zone (50-100 Mpc) and is directed toward Earth, γ's and N's with energy above $E_{\rm GZK}$ may be detected on Earth as super-GZK air-showers.

♣ Neutrinos from primordial black hole (PBH, $M_{\rm PBH} \sim 5 \times 10^{-8} - 10^{25}$ kg)

Light primordial black holes evaporate and evetually explode due to Hawking radiation which contains neutrinos. The Hawking radiation has detectable astrophysics consequences. The absence of diffuse 100 MeV γ's limit the abundance of PBH's so that they cannot be a candidate of dark matter. The bound can be strengthened by the search for diffuse cosmic neutrino flux of a few MeV.

♣ Cosmic τ neutrinos

No high energy ν_τ can be produced directly from known astrophysical sources.

- Observation of high energy ν_τ is a direct proof of ν oscillation.
- For astronomical distances (>Mpc), oscillations probe down to $\Delta m^2 \sim 10^{-17}\ eV^2$.
- ν_τ can be regenerated by τ decays (μ's tend to be absorbed). A significant amount of ν_τ's should be detectable with large detectors.

♣ Leptogenesis

- Baryon asymmetry, $\eta_{\rm B} = 10^{-10}$, resisting theoretical explanation for many years.
- Massive neutrino with CP-violation reinject excitment in leptogenesis: $L \neq 0$ can make $B \neq 0$ because $B - L$ conservation.
- The theoretical status of Leptogenesis is still evolving and awaits for the measurement of CP phase.
- The baryon number problem is a theoretical challenge, highlighting the necessity to extend the standard model. It serves as a strong testing ground for the theoretical ideas that extend the SM.

VII. Underground laboratory–A new required facility

- We are entering a new phase of extraordinary discoveries. Two new observational regimes, neutrinos and gravitational waves, are expected to be the new tools for discovery.

- General experiments in neutrino oscillation and neutrinoless double beta decays have low rates, required to be performed in an underground laboratory to shield against the cosmic ray background.

- Some other important particle physics experiments (proton decay, dark matter), astrophysics experiments (supernova neutrinos, diffuse ν from primordial black holes), and nuclear astrophysics experimental (low energy nuclear reactions powering the star, effect of nuclear structure on stellar evolution and explosion) also require an underground laboratory.

- Other branches of science can also benefit from an underground laboratory to provide low cosmic ray background and unusual/non-traditional conditions: geoscience, precision radioassay, and microbiology.

- Underground laboratory together with high energy accelerators and large modern detectors are parts of new facilities for discoveries in a new era of physics. The building of underground laboratories of deep overburden has great science engineering potentials and been extensively discussed.

VIII. Conclusion

the above is essentially a long shopping list. With limited resources let us see another list given by Sheldon Glashow:

- Pinning down the leptonic mixing angles: bound θ_{23} away $\pi/4$ with sufficient accuracy, bound θ_{12} away from $\pi/4$ with 5σ, bound θ_{13} away from 0 with 5σ.
- Searching for neutrinoless double beta decay.
- Studying the tritium endpoint to constrain m_ν.
- Measuring Δm^2_{21} and Δm^2_{31} with sufficient accuracy.
- Distinguishing the normal from the inverted neutrino mass spectrum.
- Resolving the LSND anomaly and confirming the 3 active ν scenario.
- Testing CPT for neutrinos, e.g., comparing solar and KamLAND data.
- Improving the cosmological limit on $\Sigma_{\rm j}\, m_{\nu_{\rm j}}$.

"A study on the Physics of ν's" has recently been initiated jointly by the APS Divisions of P&F, NP, Astrophysics, and the Physics of Beams. Topics include:

- Solar and atmospheric neutrino experiments.
- Reactor neutrino experiments.
- Superbeam experiments and development.
- Neutrino factory and beta beam experiments and development.
- Neutrinoless double beta decay and direct searches for ν mass.
- What cosmology/astrophysics and ν physics can teach each other.

Most of the above programs, plus some others, have to be done in a deep underground laboratory. A recommendation to this group: Think also about "Underground Laboratory" which may enhance this **MTH13** project.

I have borrowed graphics from various papers and benefited from the discussions presented in many additional papers. Below is a list of them. I don't claim completeness and apologize for any omissions.

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