STUDYING THE POSSIBILITY
TO MEASURE $\sin^2 2\theta_{13}$
AT THE DAYA BAY NUCLEAR POWER REACTORS

Institute of High Energy Physics, CAS

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Current Status of Neutrino Oscillations (Theory)

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January 16, 2004

I. Introduction

The discovery of non-vanishing neutrino masses involves a series of spectacular events which started almost forty years ago by Ray Davis who wanted to see the neutrino from the sun. Davis' scientifically driven curiosity has led today to a more complete picture of the spectrum of fundamental particles and a convincing opening to the physics beyond the standard model. Despite their elusive nature neutrinos are as ubiquitous as the electromagnetic radiation. Few particles have played roles as prevalent as neutrinos do, starting from the early universe as in the Big Bang Nucleosynthesis, to the structures of the universe, and the modern day energy generation and radiation medicine.

The smoking guns of the discovery are provided by the SuperK atmospheric neutrino data and the SNO solar neutrino neutral current events. The kamLAND reactor neutrino experiment has greatly constrained the solar neutrino parameter space in such a way that massive neutrinos enable us to better peak into new physics, such as the lepton CP violation. The Los Alamos experiment which implies the existence of a sterile neutrino, if confirmed by the on-going MiniBooNE experiment, would open a domain of new physics with wide implications that ranges from possible drastic extension of the standard model to the tests of extra dimensions.

On the cosmological front, despite their finite masses, neutrinos 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. So, billions upon billions of neutrinos are streaming through each of us every second. Neutrinos are an important component of the inner-space/outer-space connection of particle physics, astrophysics, and cosmology. It is widely recognized that neutrinos are a new tool for discoveries in the future and the new field of neutrino astronomy has come into age.

Because of the smallness of the neutrino masses and their differences, oscillations in macroscopic distance are the appropriate way to investigate the neutrino structure. I will first review briefly the evidence of the neutrino mass, describe where we stand, outline a roadmap for future studies, and present you a list of issues in the neutrino frontiers in particle physics, astrophysics, and cosmology. As you can see, most of the issues are experimentally driven, and fruitful theory activities will come later. In the study of these issues a number of approaches would have to be adopted: reactors, accelerators, cosmic rays, and large detectors. A very useful facility is the deep underground laboratory of very large overburden to cut down the cosmic ray background. It can provide a clean environment under which interesting topics in other areas of science and even engineering can also be studied effectively.

It is interesting to note the crucial role of non-accelerator experiments, in particular nuclear reactor experiments, have played in the development of the neutrino physics, starting from the first observation of neutrino by Reines in 1956 from the Savannah River Plant reactor. It is appropriate for us to come to nuclear reactor again in the measuring of the neutrino mixing angle θ_{13}.

II Neutrino parameters from oscillation experiments

♣ From traditional short distand particle physics experiments, $d \approx= 1$ fm

- Three flavors of light neutrinos as SU(2) partners of charged leptons, and interact according to broken $SU(2) \times U(1)$ symmetry.
- Neutrinos being neutral offer the possibility of Majorana fermions.
- mass limit–absolute mass bounds from kinematic effects

  $m_{\rm e} < 2.2$ eV (@95% CL, Mainz and Troitsk, $^3H \rightarrow ^3 H_{\rm e} + e^- + \bar{\nu}_{\rm e}$)

  $m_\mu < 0.19$ MeV

  $m_\tau < 18.2$ MeV

♣ From oscillation experiments, $d \geq$ km

The long distance information of all sources, solar, atmospheric, reactors, and accelerators have observed disappearance of $\nu_{\rm e}/\nu_\mu$ which are interpreted as flavor transmutation. For small masses and

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

macroscopic oscillation in classic distance become manifested and 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 $E \sim$ MeV/GeV.

General properties

- 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.

- 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 Maki-Nakagawa-Sakata-Pontecorvo mixing matrix transforms the mass eigenstates (ν_1, ν_2 ν_3) to the flavor eigenstates (ν_e, ν_μ, ν_τ)

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

  $C_{\mathrm{jk}} = \cos\theta_{\mathrm{jk}}$, $S_{\mathrm{jk}} = \sin\theta_{\mathrm{jk}}$, $\hat{S}_{13} = e^{i\delta_{CP}}\sin\theta_{13}$; CP effect $\sim \sin\theta_{13}$.

- For 3 flavors, oscillation experiments only determine:
  3 mixing angles: θ_{12}, θ_{13}, θ_{23}; 2 mass-square differences, $\Delta m^2_{21} \equiv m^2_2 - m^2_1$, $\Delta m^2_{32} \equiv m^2_3 - m^2_2$, and 1 CP phase angle δ_{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**: SuperK μ-like events depletion increases with distance, while e-like events agree with expectation, Fig. 1.

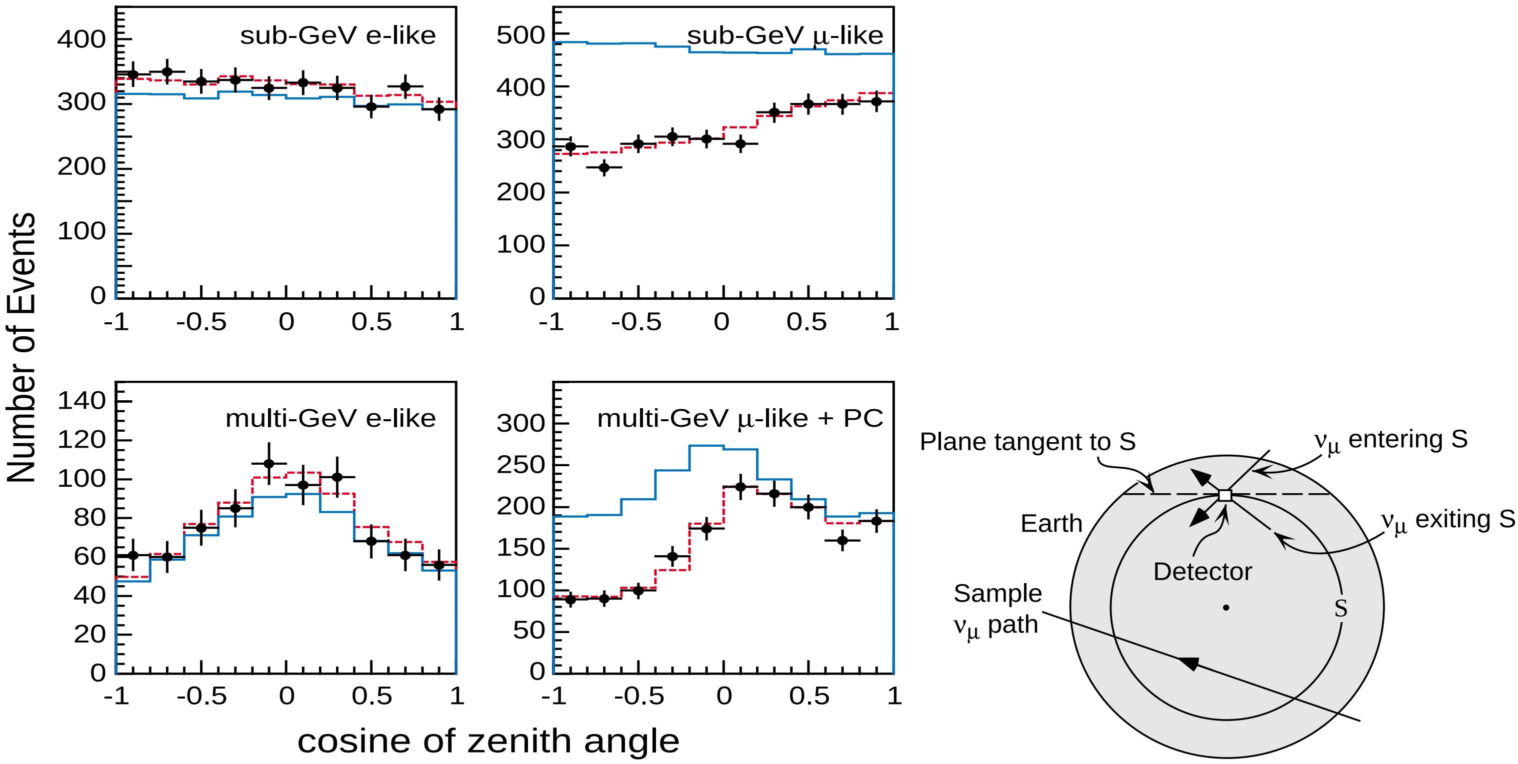


Figure 1: SuperK atmospheric neutrino results showing depletion of predicted μ-like events for increasing neutrino traveling distance while the agreement in e-like events is excellent. The fitting of the μ-like events with the assumption $\nu_\mu \to \nu_\tau$ and maximum mixing.

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

$$\begin{array}{lll} \mathrm{CC}(\phi_{CC}): & \nu_{\mathrm{e}} + d \longrightarrow p + p + e^- & {}^8\mathrm{B\ flux}\ (10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}) \\ \mathrm{NC}(\phi_{NC}): & \nu_{\mathrm{x}} + d \longrightarrow p + n + \nu_{\mathrm{x}} & \phi_{\mathrm{SSM}} = 5.05^{+1.01}_{-.81} \\ \mathrm{ES}(\phi_{ES}): & \nu_{\mathrm{e}} + e^- \longrightarrow \nu_{\mathrm{e}} + e^- & \phi^{\mathrm{unconstr}}_{\mathrm{SNO}} = 5.09^{+.44+0.46}_{-0.43-0.43} \end{array}$$

$\phi_{CC} = \phi_{\mathrm{e}}, \quad \phi_{NC} = \phi_{\mathrm{e}} + \phi_{\mu\tau} \Rightarrow \phi_{ES} = \phi_{\mathrm{e}} + 0.15\phi_{\mu\tau}$. Excellent agreement with the standard solar model ^{8}B neutrino flux, no-flavor-mixing rejected at 5.3σ; Fig.2

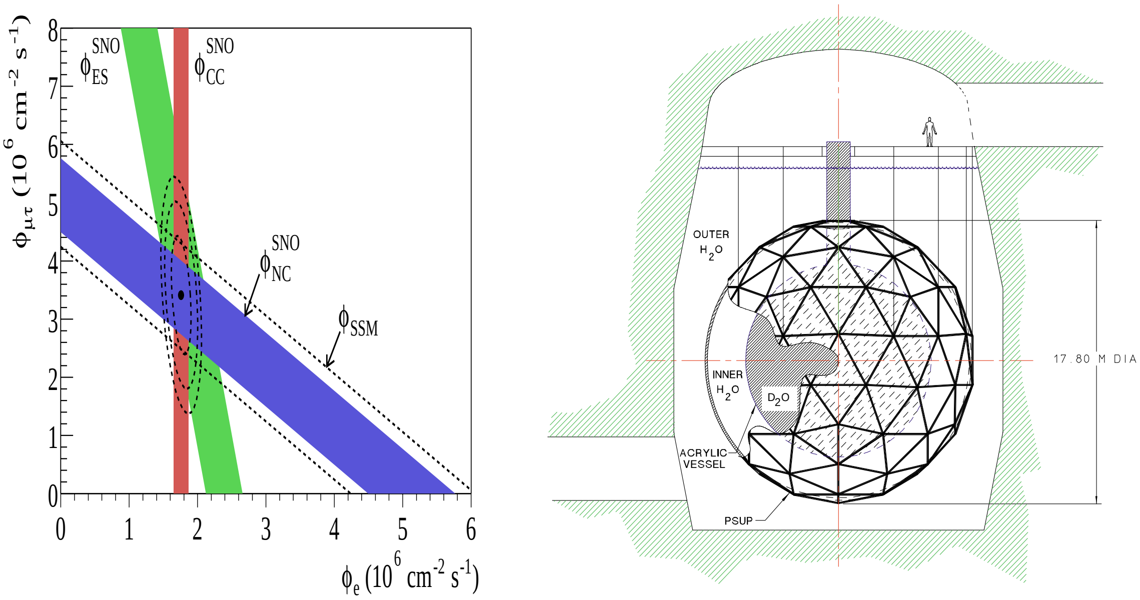


Figure 2: SNO Flux of ^{8}B high energy solar neutrino

- The total $\Delta m^2 - \sin^2 2\theta$ space including atmospheric, solar, reactors, long baseline (K2K), and Los Alamos short baseline (LSND) beam-stop experiments is give in Fig. 3.
- LSND: sterile neutrino, or anomalous muon decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$, or ν and $\bar{\nu}$ different mass spectra (CPT violation); but all strongly disfavored.

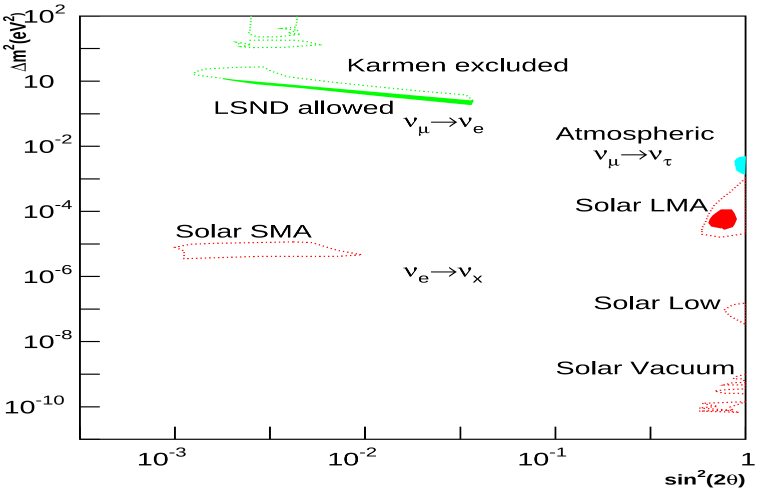


Figure 3: Oscillation parameter space showing all three indications of oscillation in two-flavor mixing approximation. With SNO and KamLAND, only the LMA solution is favored. The LSND will be studied by MiniBooNE which is running at Fermilab and results expected in early 2005.

- The best fit for 3 flavors from SuperK, SNO, KamLAND and CHOOZ:

Solar (LMA): $\Delta m^2_{21} = 7.1^{+1.2}_{-0.6} \times 10^{-5}$ eV^2, $\theta_{12} = 32.5^{+2.4}_{-2.3}$ $(\nu_e \to \nu_\mu, \nu_\tau)$
(SNO new salt phase data, θ_{12} being 5σ away from maximal).

Atmospheric: $|\Delta m^2_{32}| = 2.0 \times 10^{-3}$, $\sin^2 2\theta_{23} = 1.0$ $(\nu_\mu \to \nu_\tau)$
$(|\Delta m^2_{32}| = (1.3 - 3.0) \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = (0.9 - 1.0))$

CHOOZ: $\sin^2 2\theta_{13} < 0.1$ $(\theta_{13} < 9^\circ)$.
(Recent fit depending on $|\Delta m^2_{32}|$:
0.36 for 1.3×10^{-3} eV^2, 0.2 for 2×10^{-3} eV^2.)

- Two different mass spectra: normal hierarchy and inverted hierarchy:

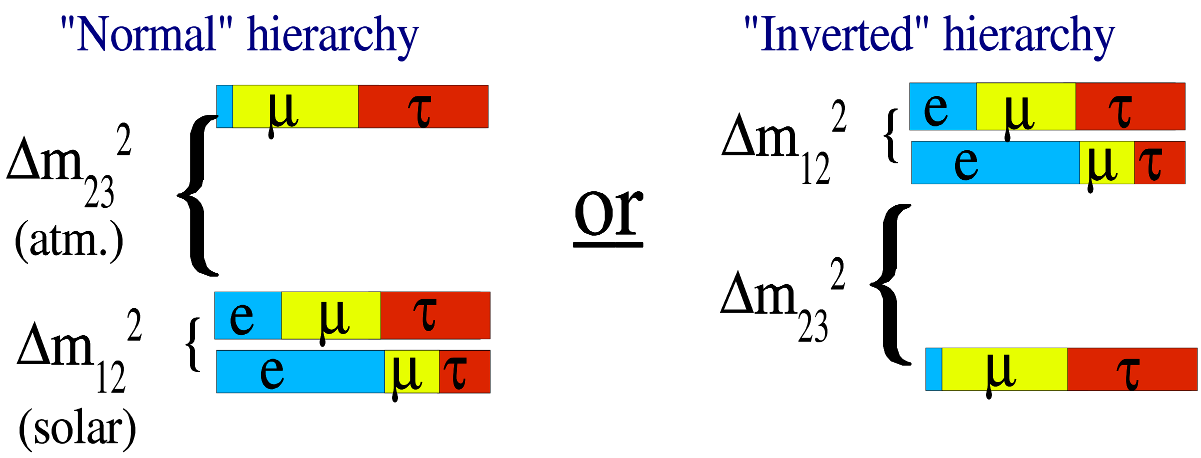


Figure 4: Normal and inverted spectra: normal $\Delta m^2_{32} > 0$; inverted $\Delta m^2_{32} < 0$.

- Include the LSND result and therefore a fourth neutrino.

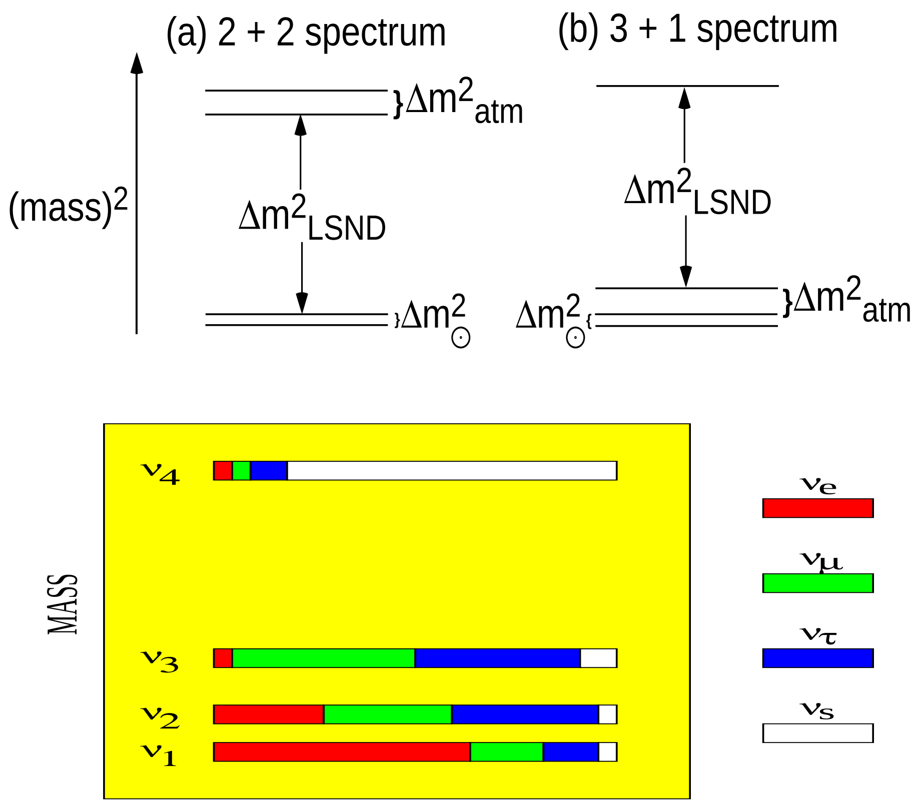


Figure 5: Level structures of four neutrinos. The 2+2 scenario is disfavored compared to the 3+1 scenario, but neither provides a good fit to existing data.

- **Absolute neutrino masses and number of neutrinos**

  Oscillation experiments do not provide information on masses of individual neutrinos, need model independent kinematic effect to determine individual masses.

  Extreme scenarios for 3 flavors:

  Small mass-hierarchical

  normal: $m_1 \approx 0$, $m_2 \approx 0.007$, $m_3 \approx 0.045$ eV, $\quad \sum m_\nu \approx 0.052$ eV

  inverted: $m_3 \approx 0$, $m_1 \approx 0.007$, $m_2 \approx 0.045$ eV.

  Large mass–degenerate

$$m_1 \approx m_2 \approx m_3 \begin{cases} \gg \sqrt{\Delta m^2_{\rm atm}} \approx 0.045 \text{eV}, \\ < \; 2.2 \text{eV} \end{cases} \qquad \sum m_\nu \leq 7 \text{ eV}$$

.

♣ Cosmological constraint: eV neutrino free streaming damps structure formations at scales smaller than $d_{\rm FS} \sim 1200/m_\nu({\rm eV})$ Mpc.

- Recent galaxy survey on the power spectrum of CMB: WMAP/2dFGRS + BBN

$$\sum_j m_{\nu_j} < 0.71 - 1.2 \text{ eV}, \quad 2 \leq N_\nu \leq 7 \quad (m_\nu < 0.23 \text{ eV for } N_\nu = 3)$$

  Future cosmological measurements on CMBR temperature and polarization, large structures, supernova surveys, and weak lensing will provide better constraints on $\sum m_\nu$. (Bound is model dependent and can be modified by nonstandard effect.)

III. Where do we stand?

- Massive neutrinos are the first evidence of physics beyond the SN, opening a window to new physics; revealing a hierarchy problem within the SM: 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.

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

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

U_{MNSP} will be determined more accurately than V_{CMK}.

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

- Theoretical status: Large freedom in constructing neutrino mass matrix. Renew interests in GUT + SUSY, and nucleon decays. Most promising models of m_ν are the see-saw mechanism and Zee model of radiative masses. See-saw requires Majorana neutrinos.

- Detailed studies of the neutrino sector, and implications of massive neutrinos to astrophysics and cosmology have just begun. But this is an experimentally driven forefront. The construction of a theoretical framework will follow.

IV. Some outstanding issues

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

♣ Issues in the neutrino sector:

1. Determine $|U_{e3}(\theta_{13}| = |\sin\theta_{13}|$, critical to the leptonic CP-violation study.
2. Verify oscillations: See the dip in atmospheric neutrino L/E distribution and measure the whole solar neutrino energy spectrum., See the $\nu_\mu \to \nu_\tau$ appearance
3. Determine Δm^2_{21}, Δm^2_{31}, θ_{12}, and θ_{23} more accurately.
4. Determine the mass hierarchy: normal or inverted.
5. Determine the absolute neutrino masses Why are they so small? Can the ν mass matrix be understood by some symmetry?
6. Study the electromagnetic properties of neutrinos. Do neutrinos have non-vanishing magnetic moments?
7. Measure the CP angle δ_{CP}. Is δ_{CP} large?
8. Settle the LSND question.

♣ Issues of a broader picture

1. Are the neutrinos Majorana or Dirac? If Majorana, what are ϕ_1 and ϕ_2.
2. If LSND is correct, is it sterile or something else? Are there more than one sterile?
3. Can massive ν help distinguish extensions of SM and probe extra dimensions?
4. 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 issues

1. Is lepton CP violation relevant to baryogenesis and makes it work?
2. Do neutrinos and antineutrinos obey CPT?
3. Why are leptonic mixing angles so large even maximal and different from those for the quarks?
4. What is the origin of the neutrino mass? Any relations with quark masses? Any implication to GUT, SUSY?
5. What is the origin of flavor, why are there more than one flavors and who ordered the extra ones?
6. Where do we go from here and how to extend the SM?

V. Road map for oscillation and related measurements

Experiments with ν_μ beams subject to 8-fold parameter degeneracies: sign(Δm^2_{31}), ($\delta_{\rm CP}$, $\theta 13$), (θ_{23}, $\pi/2 - \theta_{23}$). All future accelerator based 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: Experiments existing and under construction
  - K2K, OPERA, ICARUS, Minos: determine 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 a signal is observed.
- Stage 1: New facilities: (Measure or limit θ_{13}.)
  - NuMI/Minos, off-axis beam (low beam contamination and narrow energy spread): $\sin^2 2\theta_{13} < 0.06$, 90% CL.
  - Improve the $\sin^2 2\theta_{13}$ limit with super-beams at Minos, J-PARC-HyperK.
  - Two-detector reactor ($\bar{\nu}_{\rm e} \to \bar{\nu}_{\rm e}$, clean, no parameter degeneracy)/beta-beam ($\nu_{\rm e} \to \nu_\mu$) experiments: determine $\sin^2 2\theta_{13}$ to $0.02 - 0.01$, 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_{32}), search for CP, Fig. 6.

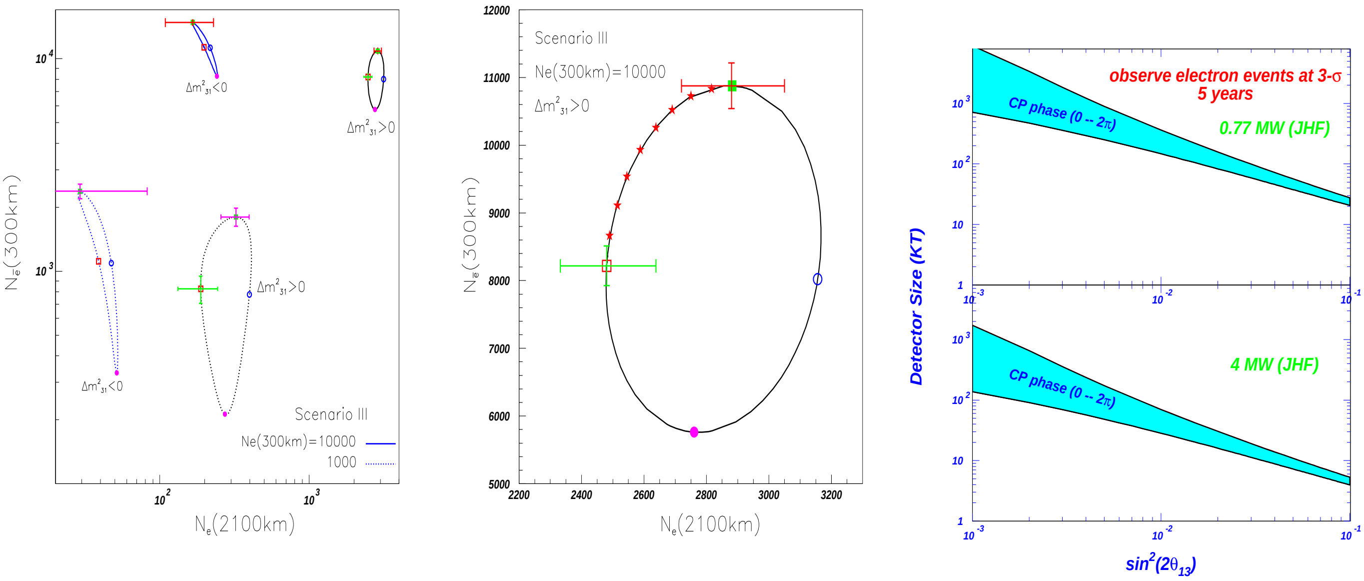


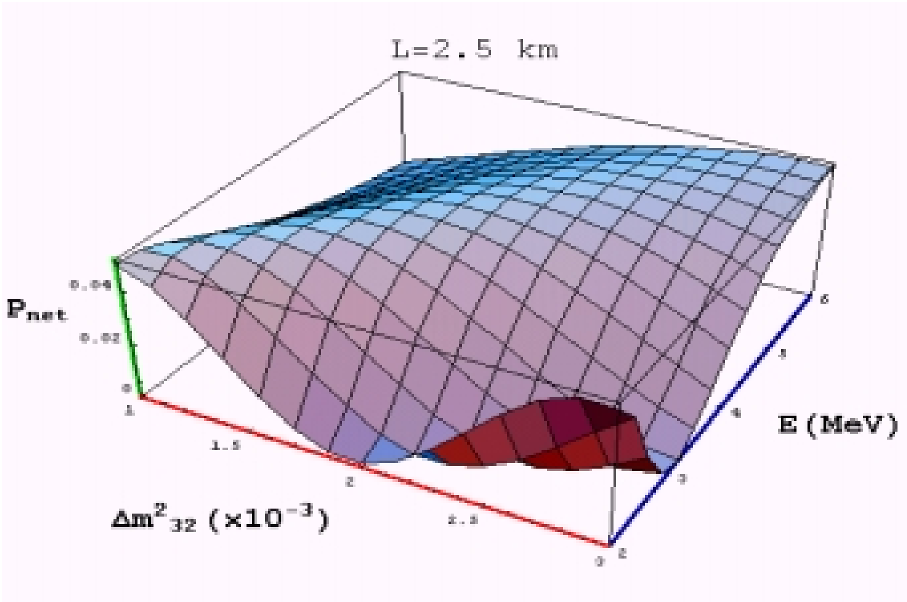
Figure 6: Combined analysis of J-PARC-SuperK (300 km) and J-PARC-Beijing (2100 km) (Whisnant, Yang and Young [21]).

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

♣ Advantages of reactor experiments for θ_{13}

θ_{13} and δ_{CP} are the remaining neutrino parameters to be determined.

- A survival experiment $\bar{\nu}_e \to \bar{\nu}_e$, independent of δ_{CP}, no parameter degeneracy.
- $E_\nu = \mathcal{O}(\text{MeV})$ and $L = \mathcal{O}(\sim \text{km})$, matter effect negligible, vacuum probability valid.
- Choice of baseline depends on Δm^2_{32}.
- Near the first oscillation max $1 - \text{P}(\nu_e \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32}$ good to $5 - 10\%$ $\Delta_{32} = 1.276 \Delta m^2_{32}(\text{eV}^2) \times 10^3 L(\text{km})/E(\text{MeV})$, $\Delta m^2_{32} \times 10^3 = 1.3 - 3.0$ eV^2 at 90% C.L. Reactors provide neutrinos of $2.5 - 6$ MeV, $L = 2.5$ is the optimal baseline.



♣ Several possible sits for reactor θ_{13} experiments

The determination of θ_{13} using nuclear reactors is within reach of existing HEP experimental technologies and will be the focus of neutrino physics in the next several years. With reactors to provide neutrino beams, the cost is moderate in the HEP standard.

- European initiative-1: P. Huber *et al.*, hep-ph/ 0303232, Fig. 7
- European initiative-2 (beta beam): M. Apollonio *et al.*, hep-ph/0210192.
- Japanese initiative: H. Minakata *et al.*, hep-ph/0211111, Fig. 8.
- American "initiative-1: Diablo Canyon Reactor Project K.M. Heeger, "*Reactor neutrino measurement of* θ_{13}", TAUP 2003, Seattle, USA, Sept. 7, 2003 and S.J. Freedman, "*Measuring* θ_{13} *with reactors*" HEAPEP July 24, 2003.
- American initiative-2: M.H. Shaevitz and J.M. Link, hep-ex/0306031. An Illinois initiative.
- Russian initiative (Kr2Det): V. Martemyanov *et al.*, hep-ex/0211070.
- Brazilian initiative: 4GW reactor surrounded by 400-600m hills. The civil construction cost would be half of that in US. Funding and construction could occur by 2006.
- Chinese initiative: Daya Bay Reactors, 4×2.7 GW_{th}, high neutrino flux, low construction cost, existing infrastructure, and high enthusiasm factor.

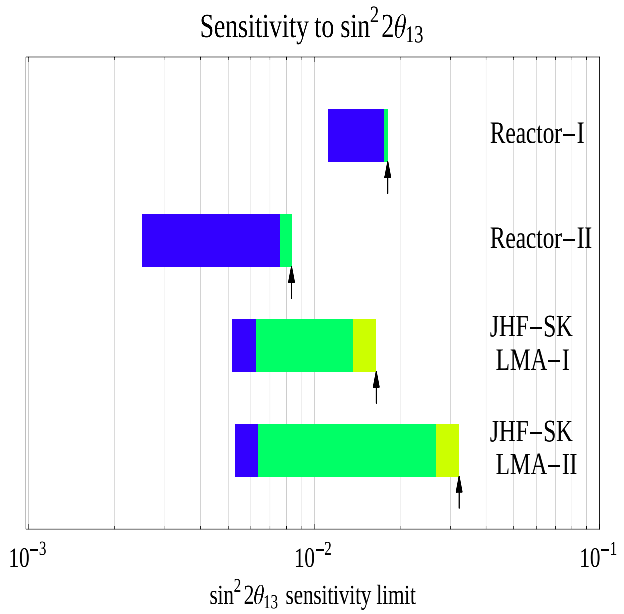


Figure 7: A European reactor ν proposal. The sensitivities to θ_{13} for Reactor I (400tGWy) and Reactor II (8000tGWy), JHF-SuperK at LMA-I ($\Delta m^2_{21} = 7 \times 10^{-5}$ eV^2) and JHF-SuperK LMA-II ($\Delta m^2_{21} = 1.4 \times 10^{-4}$ eV^2) at the 90% CL. The sensitivity limits for the reactor 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.

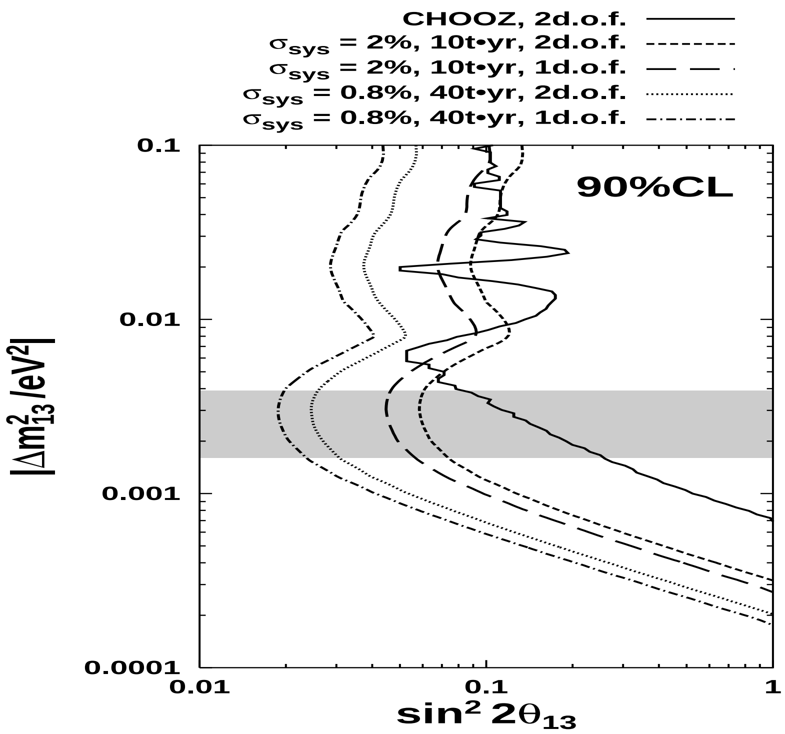


Figure 8: A Japanese reactor ν proposal. 90% CL exclusion limits on $\sin^2 2\theta_{13}$ which can be placed by reactor measurement of 24.3 GW_{th} thermal power of average neutrino energy 4 MeV, and two CHOOZ-like detectors (200 m and 1.7 km). 1 or 2 d.f. refers to with or without the knowledge of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

♣ Other particle physics measurements

- Neutrinoless double beta decay for Majorana neutrinos
  The rate is determined by the ee element of neutrino mass matrix:
  $$|m_{\rm ee}|^2 = |\sum U_{\rm ej}^2 m_{\rm j}|^2 \approx (1 - \sin^2\theta_{12}\sin^2\phi_2)m_1^2$$
  For $m_2 \approx m_1$ and neglecting $U_{\rm e3}$, $m_1^2\cos^2\theta_{12} \leq |m_{\rm ee}^2| \leq m_1^2$
  - Current bound: $m_{\rm ee} \leq 0.35 - 0.50$ eV (Heidelberg-Moscow).
  - Future reach: $m_{\rm ee} \sim 0.01$ eV (GENIUS, MAJORANA, EXO, XMASS,and MOON).
  - Good with degenerate and inverted mass spectra.
  - If m_1 is measured separately, can help determine one of the Majorana phases.

- Tritium beta decay for absolute masses of neutrinos
  End point of the decay spectrum of $^3H \longrightarrow ^3 H_{\rm e} + e^- + \bar{\nu}_{\rm e}$,
  $$m_{\nu_{\rm e}}^2 = \sum |U_{\rm ej}|^2 m_j^2$$
  For degenerate masses, $m_{\nu_{\rm e}}^2 \approx m_\nu^2$, present limit ~ 2.2 eV.
  - A large tritium experiment, KATRIN, can discover m_ν of 0.35 eV with 5σ, 0.30 eV with 3σ, and put an upper bound of 0.2 eV if m_ν is very small.

- Programs in low energy neutrino scatterings:
  (existing information in the low energy region is poor) DIS with large targets, nuclear structure functions, hadron structures, CKM and $\sin\theta_{\rm W}$.

VI. Neutrinos and Neutrino Astronomy

- Neutrinos play an important role in cosmological and astrophysical settings and are a good example of the so-called inner-space/outer-space connection.
- Joining γ rays and charged particles, neutrinos and gravitational waves are the new observational tools of high energy astrophysics.
  - Neutrinos: can reveal deep inside regions opaque to photons.
- For astronomical distance ($\geq$Mpc), oscillations probe down to $\Delta m^2 \sim 10^{-17}$ eV^2.

♣ 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- given in early discussions.

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

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

♣ Neutrinos from core collapse supernova–an exciting frontier

- 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 in a core collapse SN explosion.
- 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 of high density and high temperature.
- An Early Warning System of SN events and gravitational wave emission.

♣ Ultra-high energy neutrinos

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

- Sources of UHE neutrinos– Topological defects (10^{24} eV), AGN and GRB (10^{20} eV), the GZK mechanism (10^{18} eV).
- HENT (high energy neutrino telescope)– 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
  - Sources of UHE cosmic rays (AGN, GRB) are more than 100 Mpc away. So their energy can not exceed the GZK cutoff, $E_{\rm GZK} = 5 \times 10^{19}$ eV.
  - Puzzle: cosmic ray events (~ 20) over GZK-cutoff $E_{\rm GZK} = 5 \times 10^{19}$ eV observed.
  - 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.
  - Z-burst is a demonstration of the existence of cosmic background neutrinos.

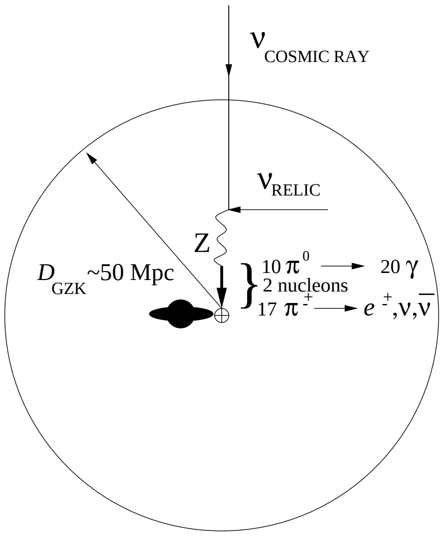


Figure 9: Z-burst productions from resonant scatterings of cosmic UHE ν against relic $\bar{\nu}$. If the Z-bust occurs within the GZK zone (50-100 Mpc) and is directed toward Earth, γ's and N's with energy above $E_{\rm GZK}$ may be detected on Earth as super-GZK air-showers.

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

Light primordial black holes evaporate and eventually explode due to Hawking radiation. HR contains neutrinos which can be used to constrain PBH. The absence of diffuse 100 MeV γ's limits the abundance of PBH's so that they cannot be a candidate of dark matter. The bound can be further strengthened by the search for diffuse cosmic neutrino flux of a few MeV.

♣ Cosmic τ neutrinos

High energy ν_τ cannot be produced directly from known astrophysical sources.

- Observation of high energy ν_τ is an evidence of ν oscillation, $\nu_\mu, \nu_{\rm e} \to \nu_\tau$.
- 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, $\eta_{\rm B} = 10^{-10}$, is a theoretical challenge, resisting explanation for many years, highlighting the necessity to extend the standard model. It serves as a strong testing ground for the theoretical ideas that extend the SM.
- Massive neutrinos make lepton CP-violation possible, reinject enthusiasm in leptogenesis: $L \neq 0$ can make $B \neq 0$ due to $B - L$ conservation.
- The theoretical status of Leptogenesis is still evolving, measurement of the lepton CP phase will be helpful.

VII. Underground laboratory–A new required facility

We have entered a new phase of extraordinary discoveries. Two new observational regimes, neutrinos and gravitational waves, are expected to be the new tools for discovery. But they require a very low background environment to be effective.

- 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.
- Many other important particle physics experiments (proton decay and dark matter searches), astrophysics experiments (supernova neutrinos, diffuse ν from primordial black holes), and nuclear astrophysics experimental (details of mechanism of low energy nuclear reactions that powers the star, effect of nuclear structure on stellar evolution and explosion) also require underground laboratories.
- Other branches of science can also benefit from an underground laboratory that provides low cosmic ray background and unusual/non-traditional conditions: geoscience, precision radioassay, and microbiology.

Deep underground laboratory together with high energy accelerators and large modern detectors are new facilities for discoveries in a new era of physics. The tremendous potentials of underground laboratories as a tool for fundamental discoveries in science and engineering have been extensively discussed.

VIII. Summary

The future neutrino physics and astrophysics involve a very long to-do list. For the near term priority, let us see a 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 end-point to constrain m_ν.
- Measuring Δm^2_{21} and Δm^2_{31} with sufficient accuracy.
- Distinguish 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 Neutrinos 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.

I have borrowed figures 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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