Neutrino Oscillation Experiments

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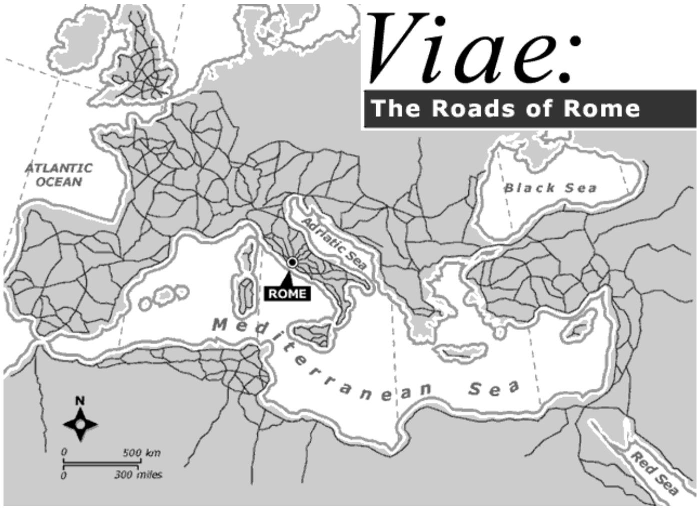
1. A Roadmap for Neutrino Oscillations
2. Neutrino Oscillation Phenomenology
3. The Experimental Situation
    - The Imminent Future
4. Experimental Ideas for Progress
5. The Roadmap Revisited

Roadmaps In Scientific Research

The recent US HEPAP sub-panel charged with charting a 20-year future of high energy physics in the US drew heavily upon the concept of
a Roadmap

A "roadmap" is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagine of the brightest drivers of change in that field
Robert Galvin
Former CEO, Motorola

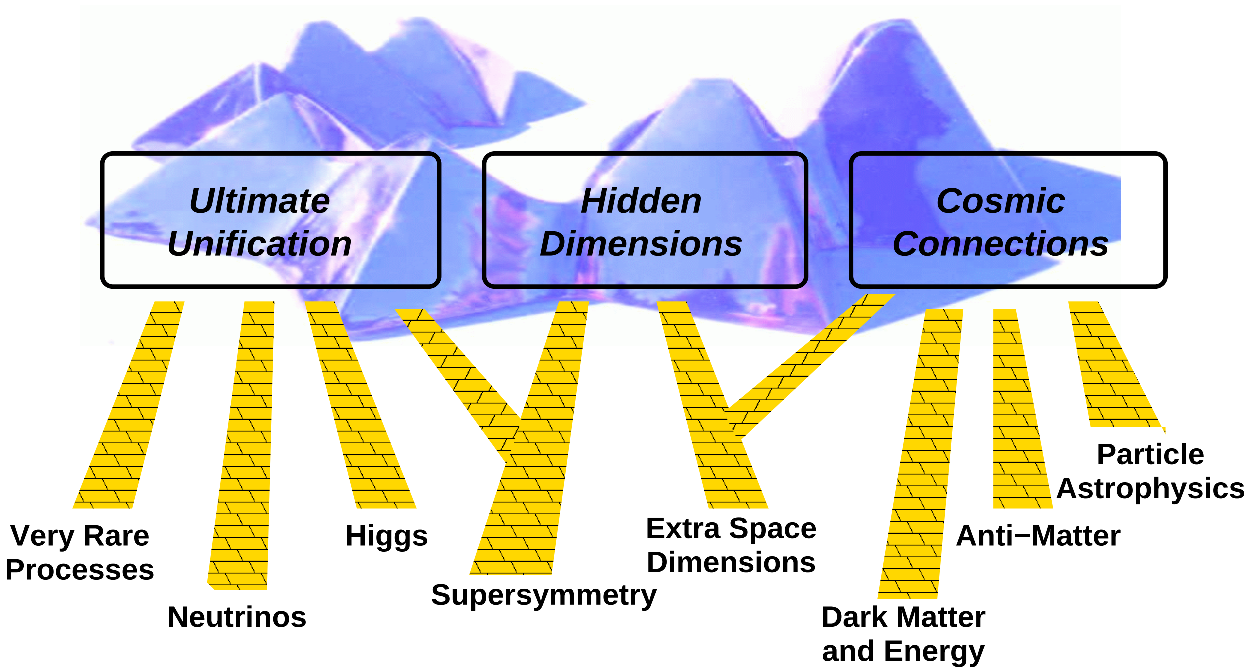


Why a "roadmap"?

map : because we have a broad sense of the goals of our exploration

road : because we can conceive of promising routes to reach our goals

Goals of the US Particle Physics Roadmap

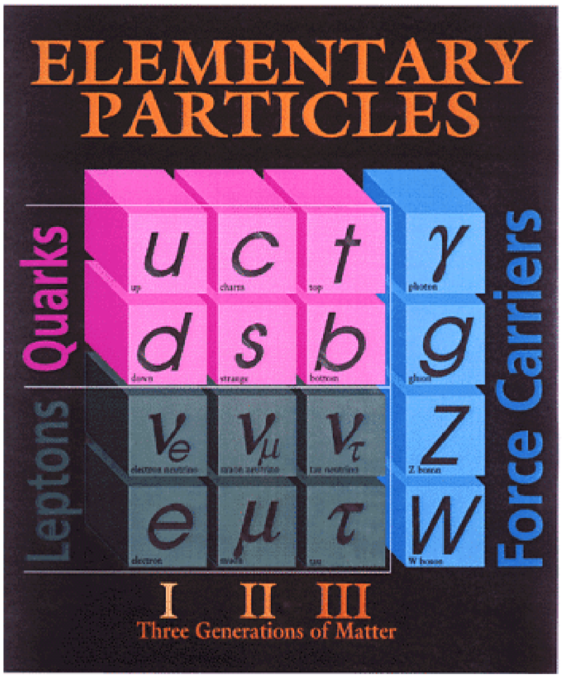


- Studies of neutrino oscillations play a key role in at least two of these concepts

Ultimate Unification: attempting to find a unified description of fundmental forces and particles

Cosmic Connections: using our description of fundamental particles and fields to draw inferences about the present, past and future of the Universe

Neutrinos and Unification

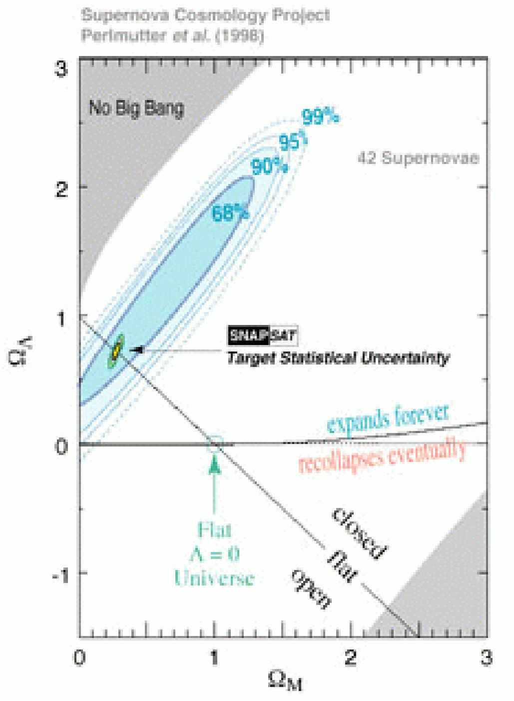


- Particle periodic table
  - ↪ Common structure of weak interactions in quark and lepton sector
  - ↪ No contact between quark and lepton sector
  - ↪ No explanation for generations
- An underlying cause for these patterns?
- Neutrino oscillation probes leptonic mixing
- Neutrino mass hierarchy can be tested
- Tests for Predictive Grand Unified Theories (extended gauge groups)

Neutrinos and the Cosmos

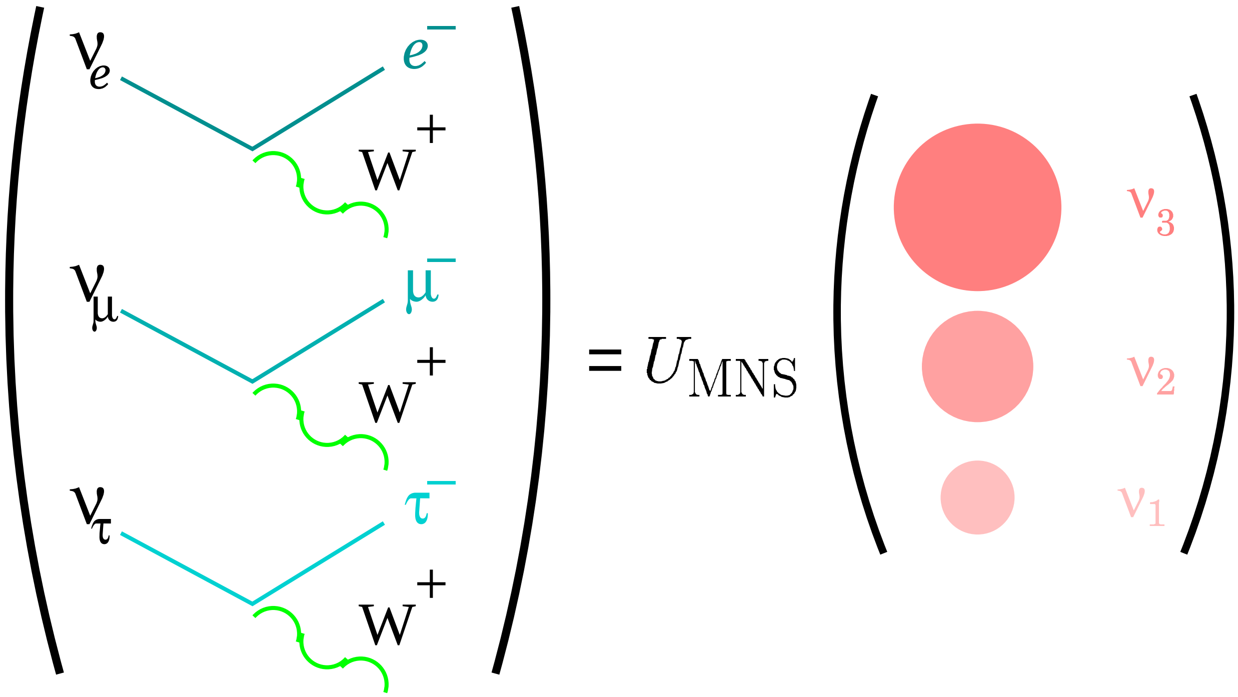
- Dark Matter
  - ↪ High-z Supernovae, cosmic microwave background measurements suggest a universe with $\Omega_M \sim 0.2$
  - ↪ However, “bright” baryonic matter is only a small fraction
  - ↪ Neutrinos may account for a fraction of the dark matter

$$\Omega_\nu \approx \sum_i m_{\nu_i}/(40 \text{ eV})$$



- Matter-Antimatter Asymmetry
  - ↪ The Universe appears to be overwhelmingly constructed of matter with little anti-matter
  - ↪ CP violation in the early Universe can lead to such asymetries
    - ⋆ But known CP violation (quark system) is insufficient
  - ↪ Leptogenesis from lepton sector CP violation?
    - ⋆ ν are the probe of this CP violation!

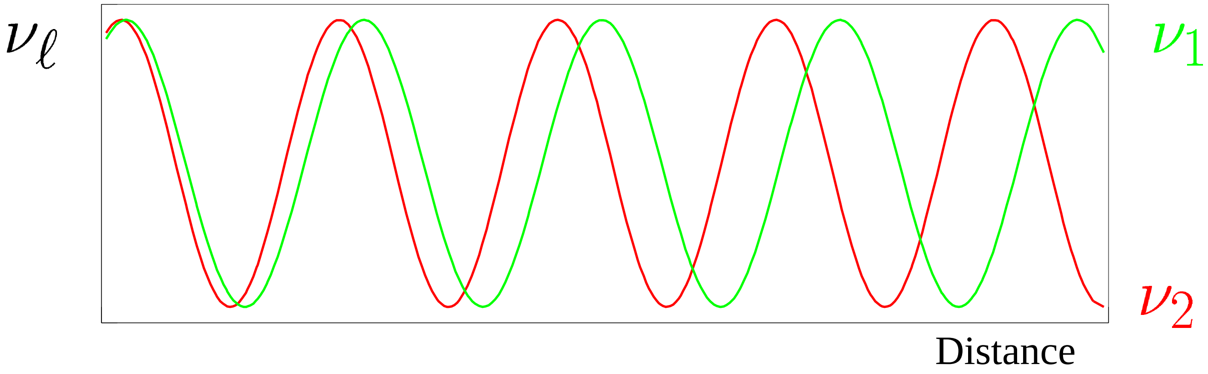
Neutrino Mixing



Neutrino Flavor Neutrino Mass

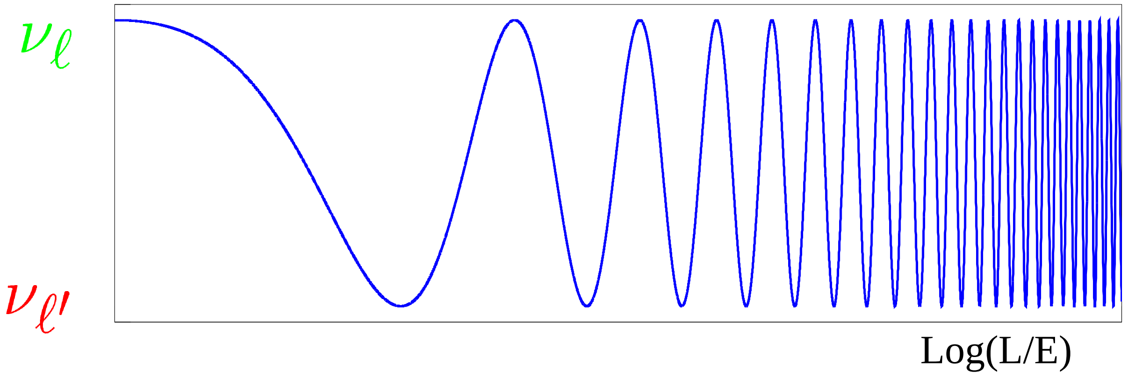
U_{MNS} = Maki-Nakagawa-Sakata Mixing Matrix

Two Generation Neutrino Oscillation



$$U_{MNS} = \begin{pmatrix} \cos\theta & e^{i\delta}\sin\theta \\ -e^{-i\delta}\sin\theta & \cos\theta \end{pmatrix}$$

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



Three Generation Mixing

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$U_{MNS} \approx \begin{pmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}S_{13}e^{i\delta} & C_{23}C_{13} \end{pmatrix}$$

$$E/L \gg \delta M^2_{23} \gg \delta M^2_{12}$$

$$\begin{aligned} P(\nu_\mu \to \nu_\tau) &\approx \sin^2 2\theta_{23} C^4_{13} \sin^2(\delta M^2_{23} L/4E) \\ P(\nu_\mu \leftrightarrow \nu_e) &\approx S^2_{23} \sin^2 2\theta_{13} \sin^2(\delta M^2_{23} L/4E) \\ P(\nu_\mu \to \nu_\mu) &= 1 - P(\nu_\mu \to \nu_e) - P(\nu_\mu \to \nu_\tau) \\ P(\nu_e \to \nu_\tau) &\approx C^2_{23} \sin^2 2\theta_{13} \sin^2(\delta M^2_{23} L/4E) \end{aligned}$$

"Standard" Scenario

- $\sin^2 2\theta_{23} C^4_{13}$ & $|\delta M_{23}|$ (atmospheric)
- $\sin^2 2\theta_{12}$ & $|\delta M_{12}|$ (solar)
- θ_{13} small (CHOOZ)

CP Violation in Neutrino Oscillation

CP Violation requires:

- Appearance measurements
  CPT conservation $\Rightarrow P(\nu \not\to \nu) = P(\overline{\nu} \not\to \overline{\nu})$
- At least two non-zero δM^2
  (two interfering amplitudes required)
- Non-zero U_{MNS} phase, δ

Observable is

$$A_{CP} = \frac{P(\nu_A \to \nu_B) - P(\overline{\nu}_A \to \overline{\nu}_B)}{P(\nu_A \to \nu_B) + P(\overline{\nu}_A \to \overline{\nu}_B)}$$

CP Violation Scenarios

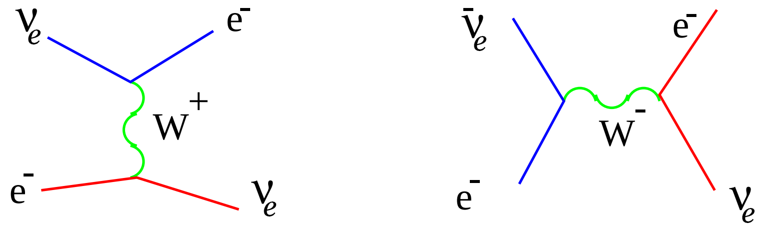
“Standard” Scenario for $\nu_e \to \nu_\mu$

- One amplitude with $\sin 2\theta_{13}$, δM^2_{23}
- Other amplitude with $\sin 2\theta_{12}$, δM^2_{12}
- Be a sunny optimist and assume LMA solar solution (Super-K)
  - $\hookrightarrow$ If $\sin 2\theta_{13} \gg \delta M^2_{12}/\delta M^2_{23}$,
    $P(\nu_e \to \nu_\mu)$ big and A_{CP} small
  - $\hookrightarrow$ If $\sin 2\theta_{13} \sim \delta M^2_{12}/\delta M^2_{23}$,
    $P(\nu_e \to \nu_\mu)$ small and A_{CP} may be big!
  - $\hookrightarrow$ If $\sin 2\theta_{13} \ll \delta M^2_{12}/\delta M^2_{23}\ldots$

Revenge of LSND, e.g. $\nu_e \to \nu_\tau$

- Two mass scales are now δM_{LSND}, $\delta M_{\mathrm{atmos}}$!
- CP violation at much shorter baselines!

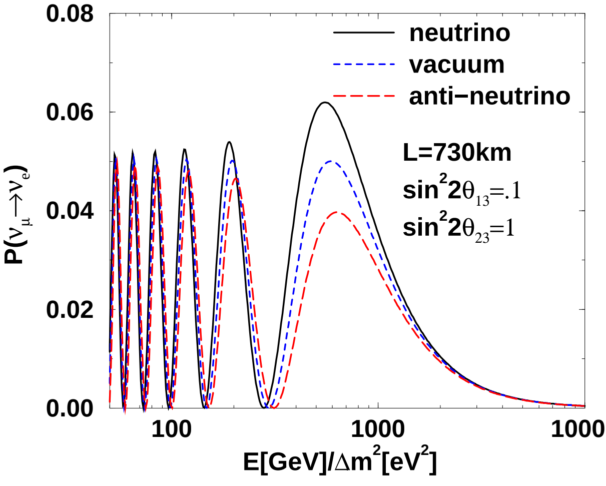
Matter Effects & ν Oscillation

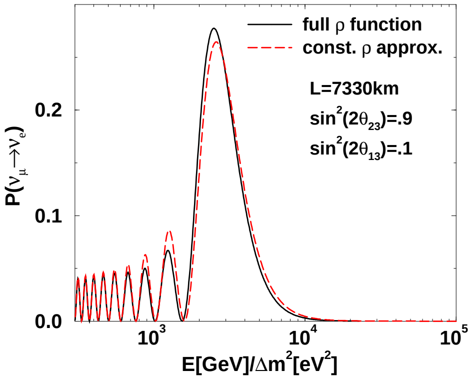


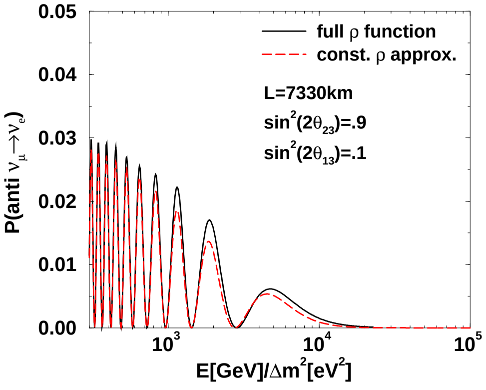
- Largest in ν_e, $\overline{\nu_e}$
- ν_e propagation ⇒Oscillations

$$\begin{aligned}\sin^2 2\theta_M(x) &= \frac{\sin^2 2\theta}{\sin^2 2\theta + (\pm x - \cos 2\theta)^2} \\ L_M &= L \times \sqrt{\sin^2 2\theta + (\pm x - \cos 2\theta)^2} \\ x &= \frac{2\sqrt{2} G_F n_e E_\nu}{\delta M^2}\end{aligned}$$

- $P(\nu_e \to \nu_x) \neq P(\overline{\nu}_e \to \overline{\nu}_x)$, sign of δM^2
- $L \gtrsim 1000$ km (Mocioiu and Shrock `hep-ph/0002149`)

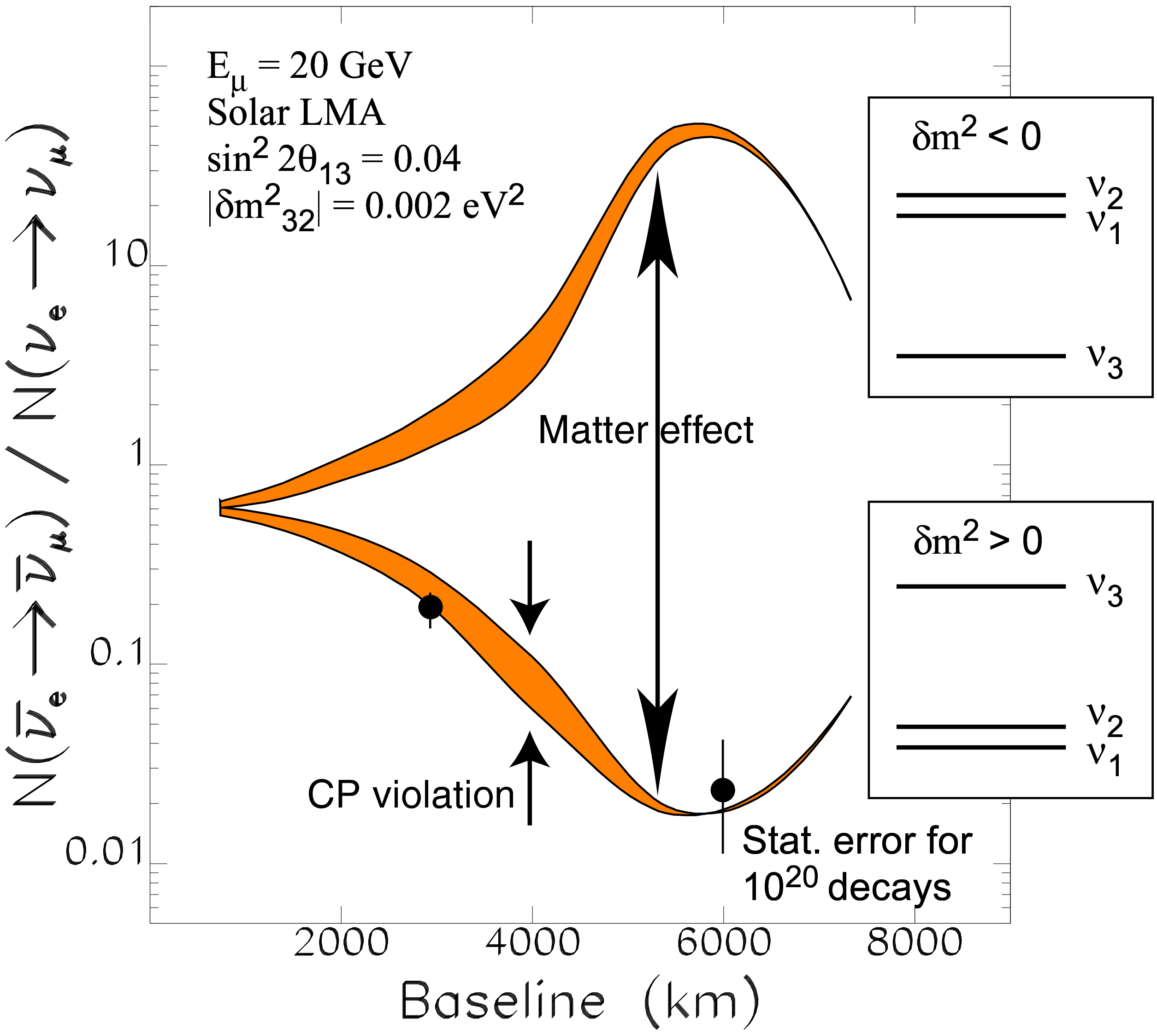






Matter Effects and CP at Long Baselines

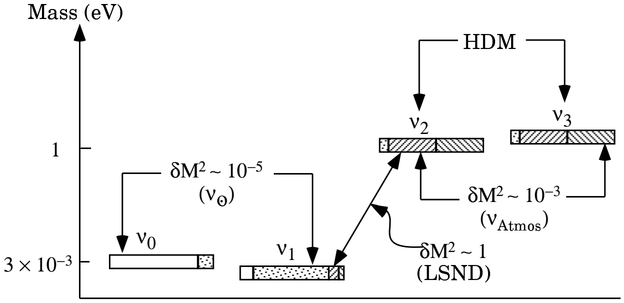
Wrong-Sign Muon Measurements



(Barger, Geer, Raja, Whisnant)

So, What Will We Know?

- K2K, MINOS, CERN-NGS will precisely probe atmospheric oscillations
  - ↪ δM^2_{23} known to 30%, $\sin^2 2\theta_{23}$ to 20%
  - ↪ Small, but not zero chance, we will have discovered $\nu_\mu \to \nu_e$ ($|U_{e3}|$)
- LSND will be confirmed/refuted (BooNE)
  - ↪ If confirmed, suggests 4 light neutrinos



Will know oscillation parameters δM_{12}, $\sin^2 2\theta_{12}$ to 10% or better

- SNO/KAMLAND will have determined solar oscillation parameters

The Lingering Questions

- Is that all there is?
  - ↪ Unitarity of 3-generation mixing matrix
  - ↪ Sterile neutrinos: how many and mixings?
- Measurement of small mixing ($|U_{e3}|$)
- Confirmation of Matter Effects in accelerator beam?
- Mass hierarchy: how many light,
  how many heavy?
- CP violation?

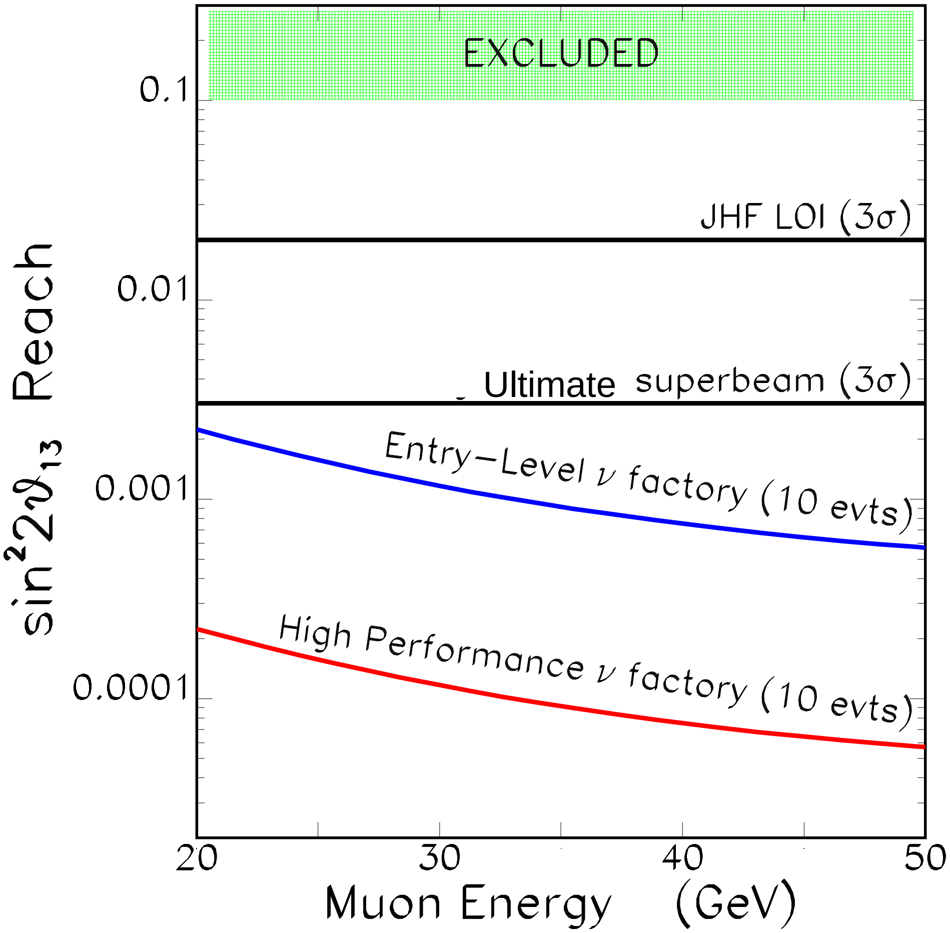
The "likely" key question for experiments:
What is the value of $|U_{e3}|$
(or, can I see $\nu_\mu \to \nu_e$ at $\delta m^2 \sim 10^{-3}$ eV^2?)

- $|U_{e3}|$ sets difficulty for measurements of mass hierarchy, CP violation
- This assumes: solar large mixing angle, large δ^2_m ("LMA"), LSND has not observed oscillation

Tools of the Future

1. Optimizing “conventional” (meson decay) neutrino beams
   - High power proton sources (megawatt)
   - Improved beam designs at low E_ν
   - Reducing detector backgrounds
2. Muon decays as a source of neutrinos
   - Source of ν_μ *AND* ν_e
   - Beam backgrounds negligible
   - Requires significant R&D
3. Megaton detectors
   - Will serve as next generation proton decay detectors as well

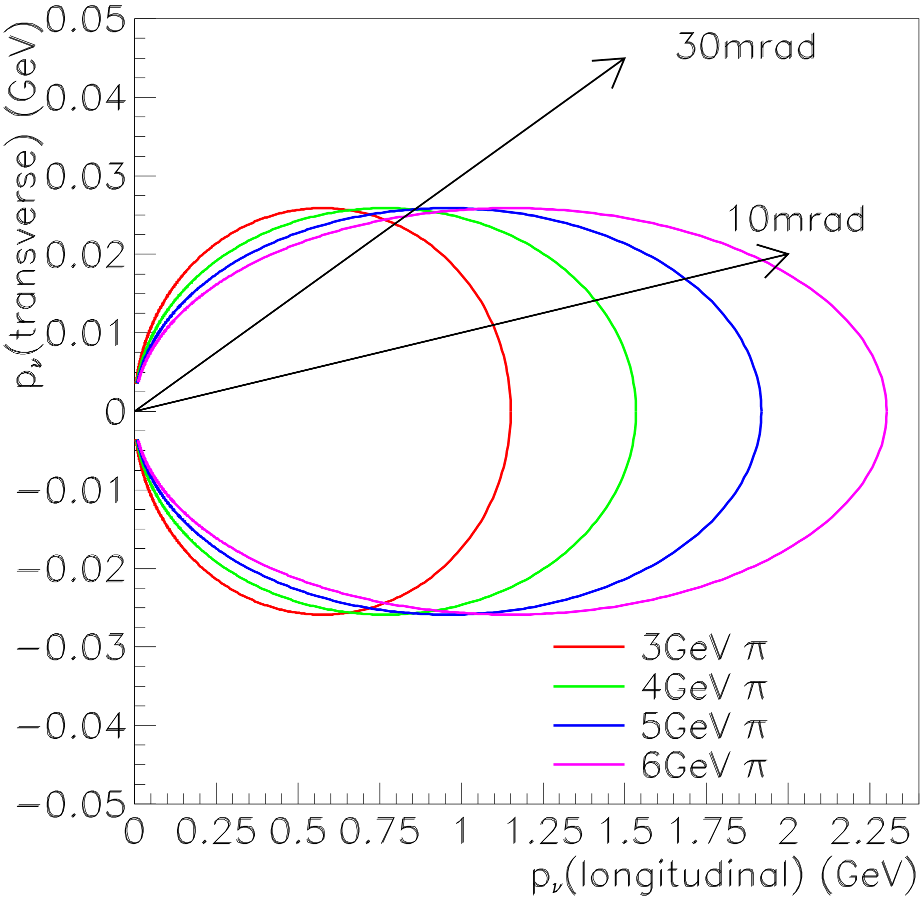
Progression of $|U_{e3}|$ Sensitivity



- Conventional "superbeams" based on high rate proton sources can make huge strides forward
  - ↪ "Ultimate" is 2 MW protons, 30kTon-yr in Liquid Ar
  - ↪ Much depends on controlling backgrounds
- But even first muon based neutrino sources do much better
  - ↪ *someday...*

Controlling Backgrounds With the Beam!

- Most problematic backgrounds to ν_e are higher energy ν_μ and ν_τ in beam

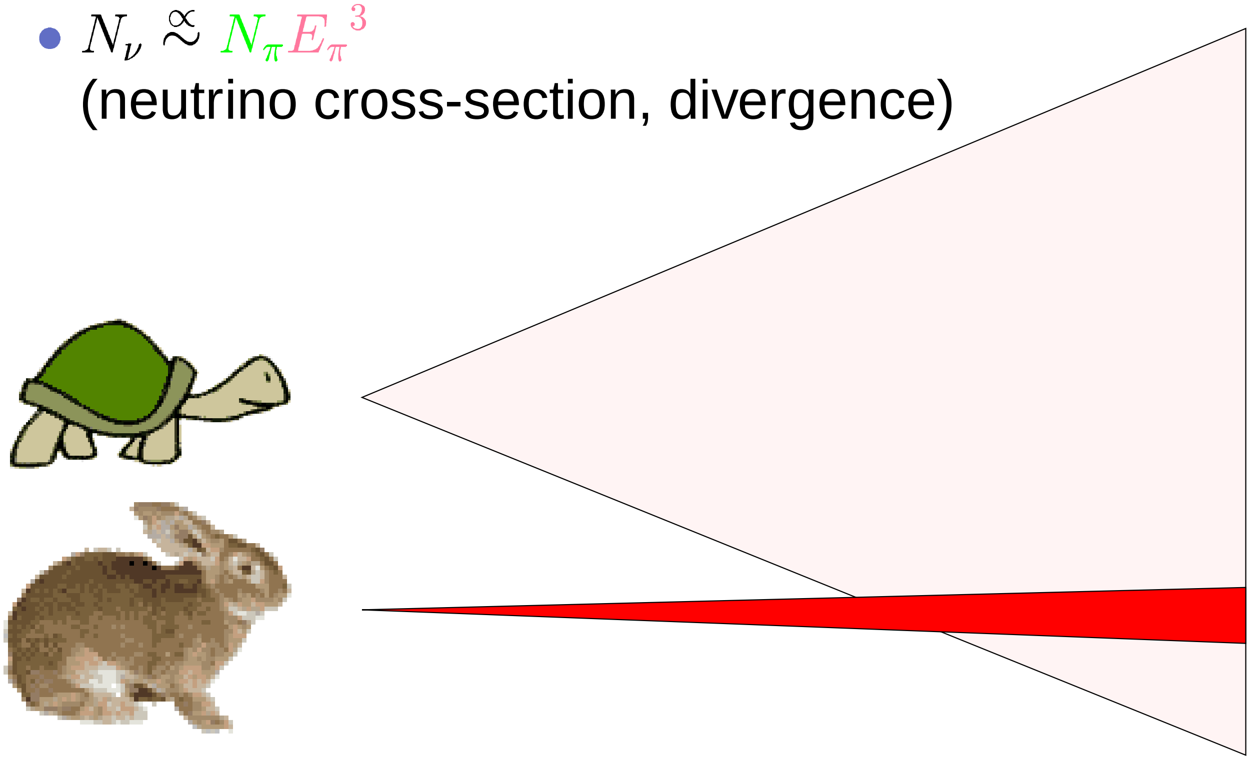


- “Off-axis” from π direction makes beam approximately monochromatic
(first proposed for BNL-889 beam)

Why Muon Sources?

Conventional ($\pi^{\pm}$) Beam Economics

- Production rates fall steeply with increasing E_π (production cross-section, proton acceleration)
- $N_\nu \underset{\sim}{\propto} N_\pi E_\pi{}^3$ (neutrino cross-section, divergence)



μ Beam Economics

- Produce and capture at low energies (large cross-section, higher p power)
- Accelerate parent beam after cooling $N_\nu \underset{\sim}{\propto} N_\mu E_\mu^3$

if only "produce", "capture", "accelerate" and "cool" were simple!

Snowmass Neutrino Oscillation Summary

Where do neutrino physicists in the U.S. see the focus of the field in the future?

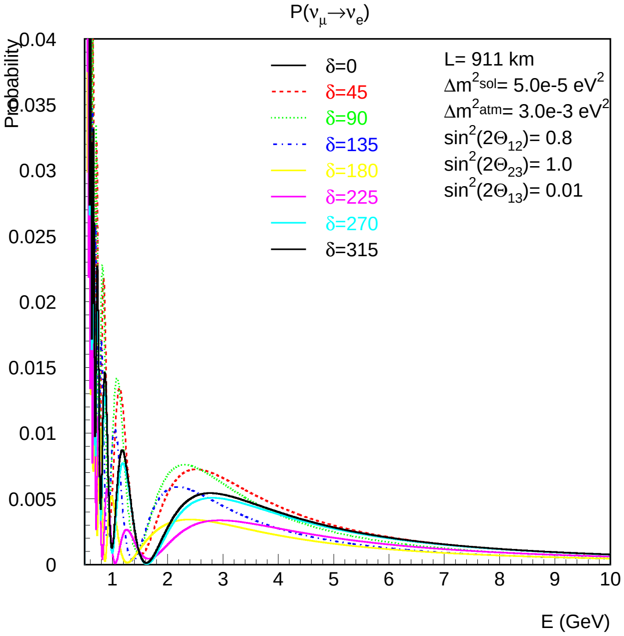
“The recent evidence for neutrino oscillations is a profound discovery. The US should strengthen its lepton flavor research program by expediting construction of a high-intensity conventional neutrino beam (”superbeam”) fed by a 1 - 4 MW proton source.

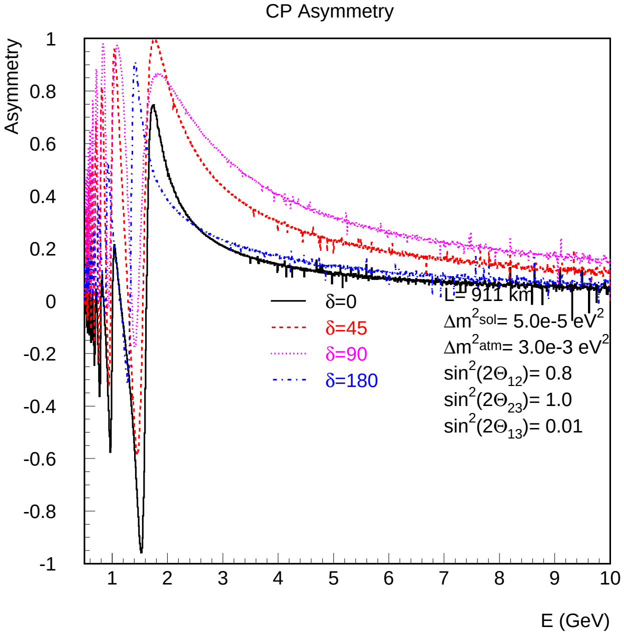
A superbeam will probe the neutrino mixing angles and mass hierarchy, and may discover leptonic CP violation. The full program will require neutrino beams at a number of energies, and massive detectors at a number of baselines. These facilities will also support a rich program of other important physics, including proton decay, particle astrophysics, and charged lepton CP- and flavor-violating processes.

The ultimate laboratory for neutrino oscillation measurements is a neutrino factory, for which the superbeam facility serves as a strong foundation. The development of the additional needed technology for neutrino factories and muon colliders requires a ongoing vigorous R&D effort in which the US should be a leading partner.”

Might the US Upgrade NUMI?

- 2 GeV ν beam, ~ 20 mr from FNAL to Soudan (NUMI) Axis
- $550 < L < 900$ km (US or Canada)





- At 900 km, the matter effects are large compared to the CP-violating effects
  - $\hookrightarrow$ Determine mass hierarchy with coarse measurement ν_e from ν_μ and $\overline{\nu}_\mu$ beams?
- Requires, of course, a high power proton source

“Imitation is the Most Sincere Form of Flattery”

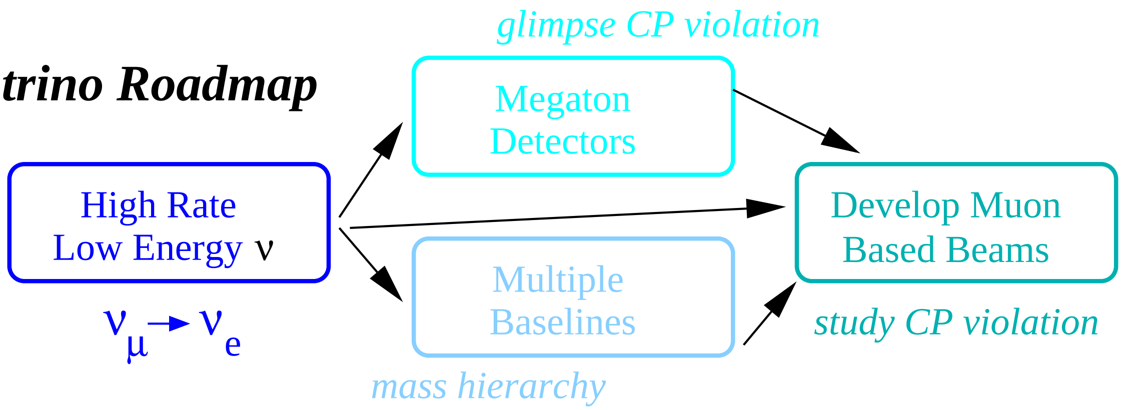
The rest of the ν world thinks so much of the potential of the JHF 50 GeV PS. . .

- Design studies at FNAL and CERN for high intensity proton sources that have serious costing and site layout
- Interest is great because ν physics motivation is great

Summary and Roadmap

- Neutrino physics is a rapidly expanding, exciting field
- In the short-term future we expect to learn much
  - ↪ Resolution of solar, LSND ν oscillations
  - ↪ Precision for atmospheric transition
- We know our next goal
  - ↪ A complete picture of mixing
  - ↪ Three (or more) generations participating
    - ⋆ $|U_{e3}|$
    - ⋆ Sterile ν?
- And ultimately…
  - ↪ Mass hierarchy, CP violation
- High power proton sources and large detectors are key tools

Neutrino Roadmap



glimpse CP violation

Megaton
Detectors

High Rate
Low Energy ν

$\nu_\mu \to \nu_e$

Develop Muon
Based Beams

study CP violation

Multiple
Baselines

mass hierarchy