Status and Prospects of Neutrino Oscillations: Terrestrial Sources

D. Markoff
North Carolina State University
Triangle Universities Nuclear Laboratory

Oscillation Evidence From What Nature Provides

TYPE	MIXING	δm^2	$\sin^2 2\theta$
Atmospheric	$\nu_\mu \rightarrow \nu_\tau (\text{not}\, \nu_e)$	$\sim 10^{-3}$ eV^2	~ 1
Solar	$\nu_e \rightarrow \nu_\mu, \nu_\tau$	10^{-5}-10^{-4} eV^2	~ 0.8

Atmospheric Anomaly

Solar Neutrino Deficit

Can we develop a consistent and complete description of neutrino oscillations?

Consider 3 ν mixing: $\Sigma\delta m^2 = \delta m_{12}^2 + \delta m_{23}^2 + \delta m_{23}^2 = 0$

What are the mixing parameters? (δm, θ)

Be clever with terrestrial sources to dial-in measurement conditions – probe the (δm^2, $\sin^2 2\theta$) parameter space

Neutrino Oscillation Parameters

Mixing Matrix, U

Flavor eigenstates → ← Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$U_{\alpha i}$ matrix elements mixing flavor (α=e,μ,τ) and mass (i=1,2,3) eigenstates.

$U_{\alpha i}$ depend on pairwise mixing angles (θ_{12}, θ_{23}, θ_{13}) between mass states.

(Mixing matrix, U also depends on phase(s), δ, producing CP odd terms.)

Assume decoupling of solar and atmospheric oscillations ($\theta_{13} = 0$):

$$\sin^2 2\theta_{solar} \approx \sin^2 2\theta_{12} \approx 0.8$$

$$\sin^2 2\theta_{atmos} \approx \cos^4 \theta_{13} \sin^2 \theta_{23} \approx 1$$

$$\sin^2 2\theta_{react} \approx \sin^2 2\theta_{13} < 0.1 \text{ (CHOOZ)}$$

Design detectors to measure θ_{solar} and θ_{atmos} (θ_{12}, θ_{23}, θ_{13}) .

Complementary Properties of
Reactors and Accelerators

E_ν~few MeV

- **Can probe very small Δm^2**

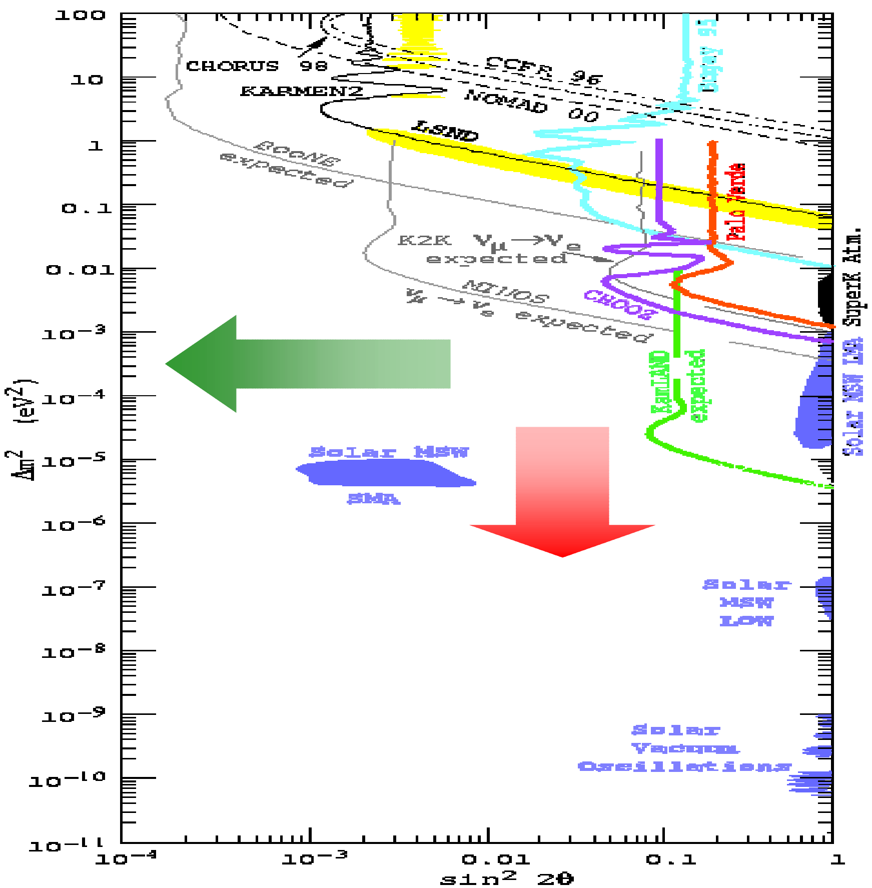
  With E_n~5MeV, probe Δm^2~10^{-3} with L~1km

- **Disappearance only**

  fair $\sin^2 2\theta$ sensitivity

- **4π source**

  → detector mass grows with L^2



E_ν~few GeV

- **Good mass sensitivity requires very large L**

  With E_n~5GeV, probe Δm^2~10^{-3} with L~1000km

- **Produce μ and τ**
- **Appearance measurement possible**
- **(More) collimated beam**

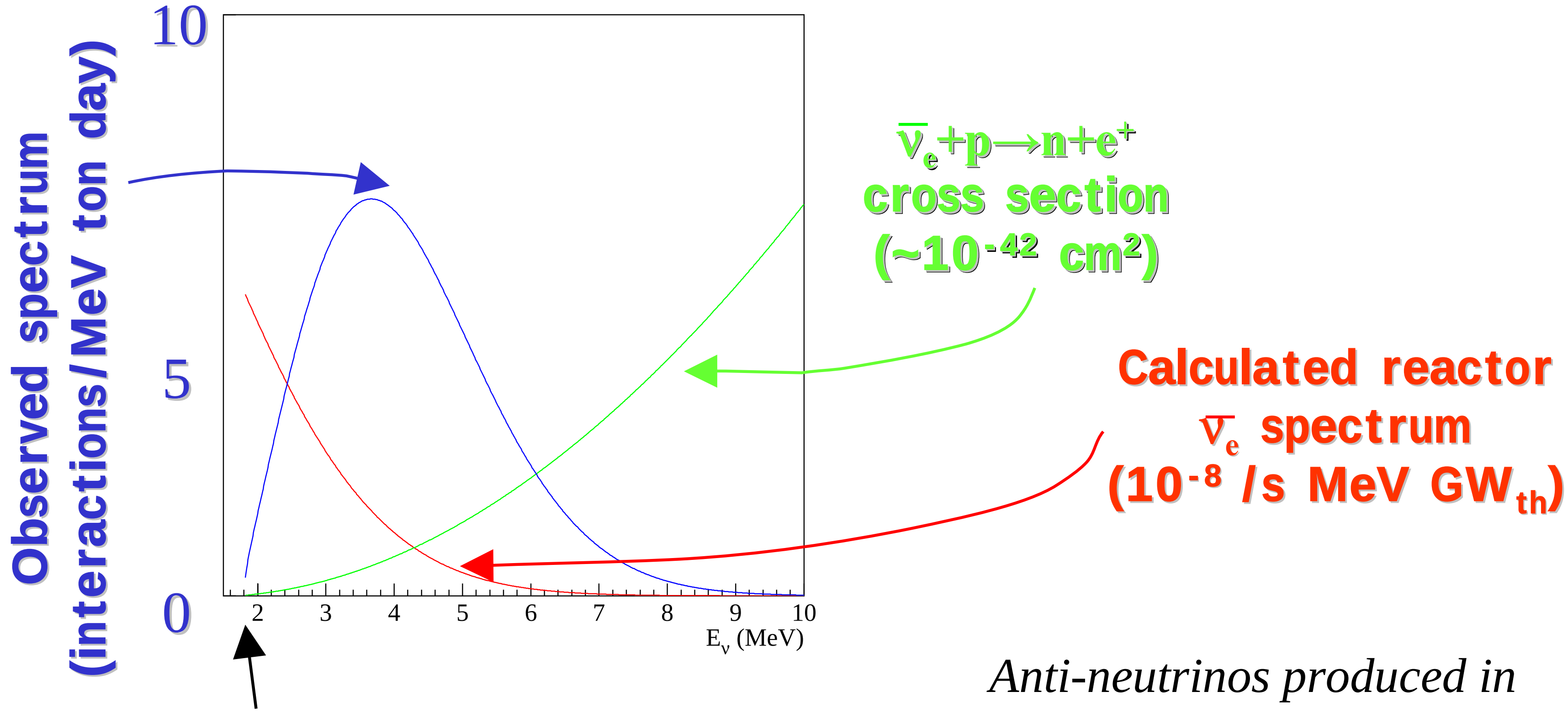
Reactor Based Experiments

- Isotropic source of $\bar{\nu}_e$ (**3 GW$_{thermal}$ - 6•10^{20} $\bar{\nu}$/s**)

  >99.9% of ν are produced by decay chains from fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

- Calculations of anti-neutrino spectrum well developed: simulations and measurements
  - **Flux calculations to few percent.**
- Measure inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Cross section 100 x neutrino scattering
  - Characteristic signature including coincidence measurement
- Backgrounds from radioactivity are a challenge
- Careful calibrations needed for detector efficiency

The Anti-neutrino Spectrum

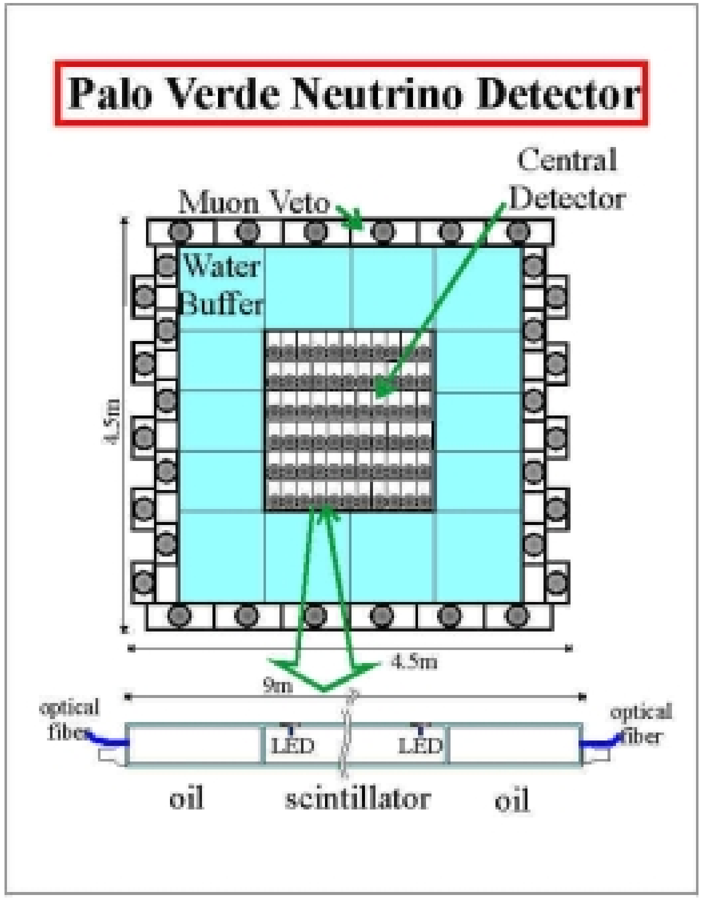


Neutrinos with E<1.8 MeV are not detected

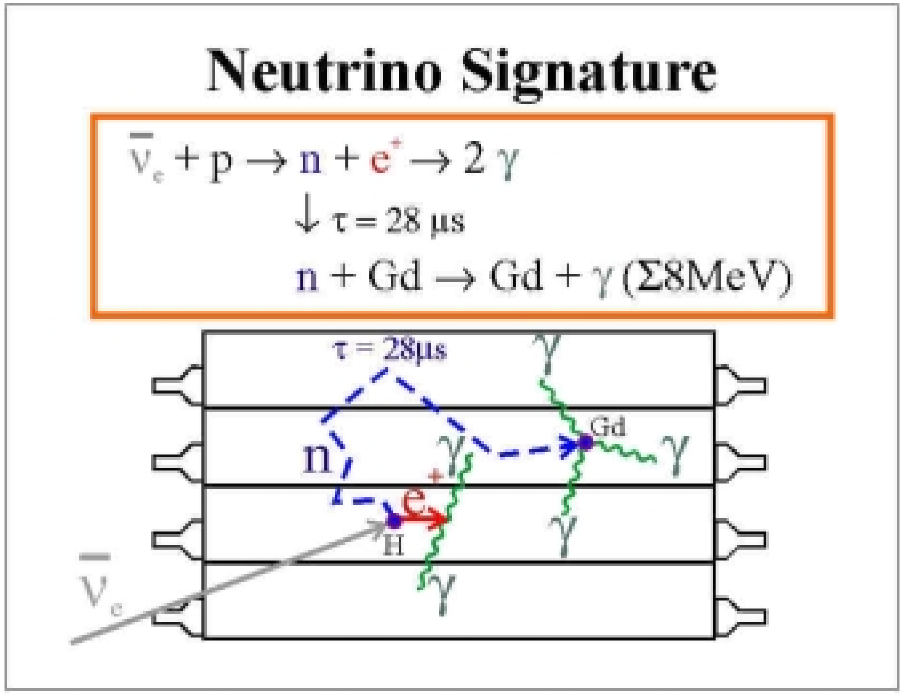
Anti-neutrinos produced in high-Q, short-lived reactions thus tracks well with the reactor power.

So in practice only ~1.5 neutrinos/fission can be detected above threshold

Palo Verde Reactor Experiment



Investigate ν_e-ν_x oscillations
Fiducial volume 12 tons
Gd loaded liquid scintillator
Reactor 1, 3: L=890 m
Reactor 2: L=750 m



Segmented detector
study ν_e- *n* angular correlations

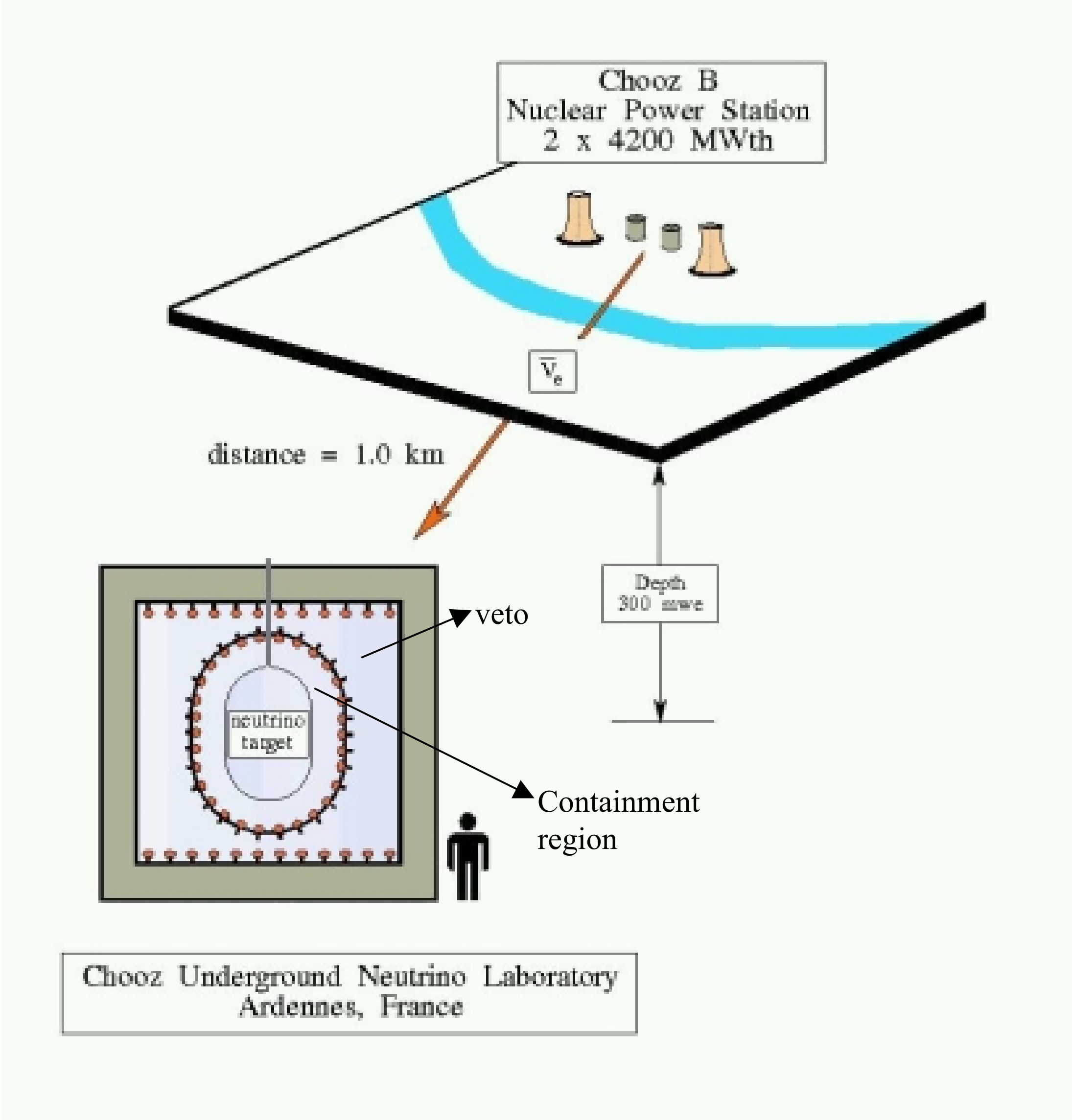
CHOOZ Reactor Experiment

Investigate ν_e-ν_x oscillations

1 km baseline
  Reactor 1: 998 m
  Reactor 2: 1115 m
Compare spectrum for independent analysis.

Inner region: 5 ton Gd loaded liquid scintillator (e^+ and n signals)

Containment region: 17 tons liquid scintillator (n signal)



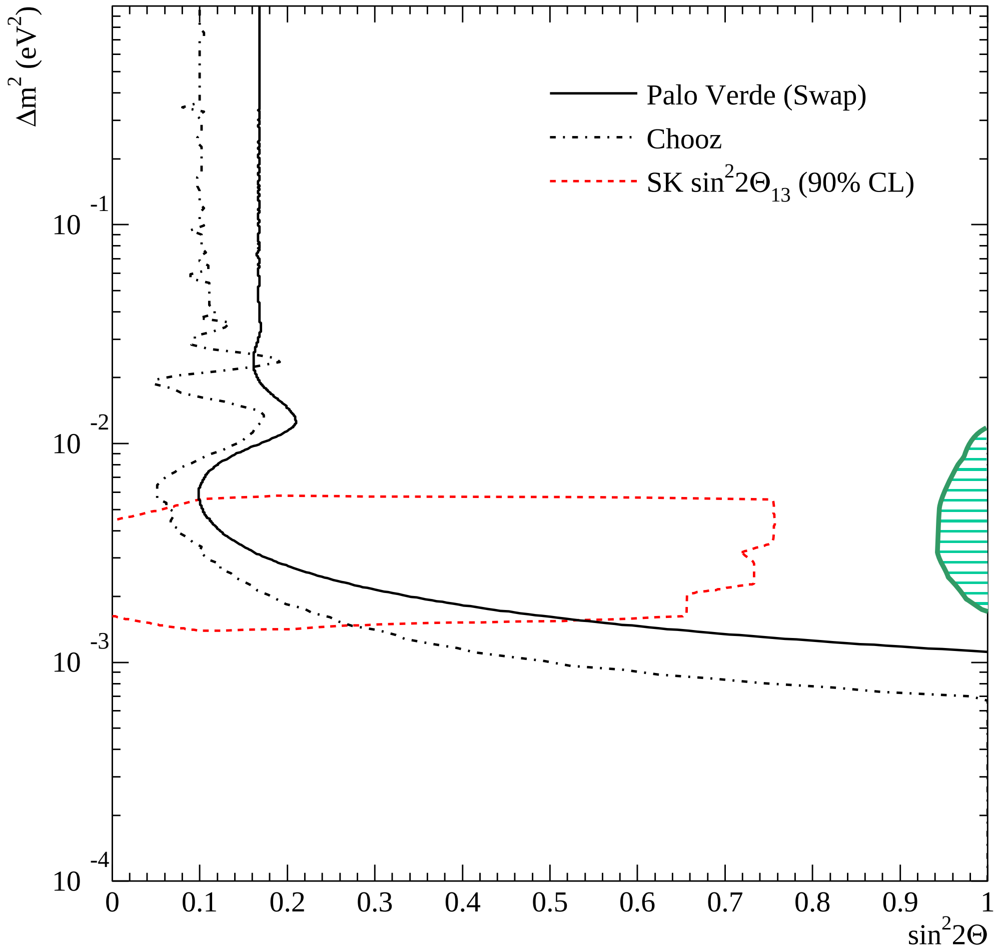
Reactor Results

$$\frac{\text{neutrinos detected}}{\text{neutrinos expected}}$$

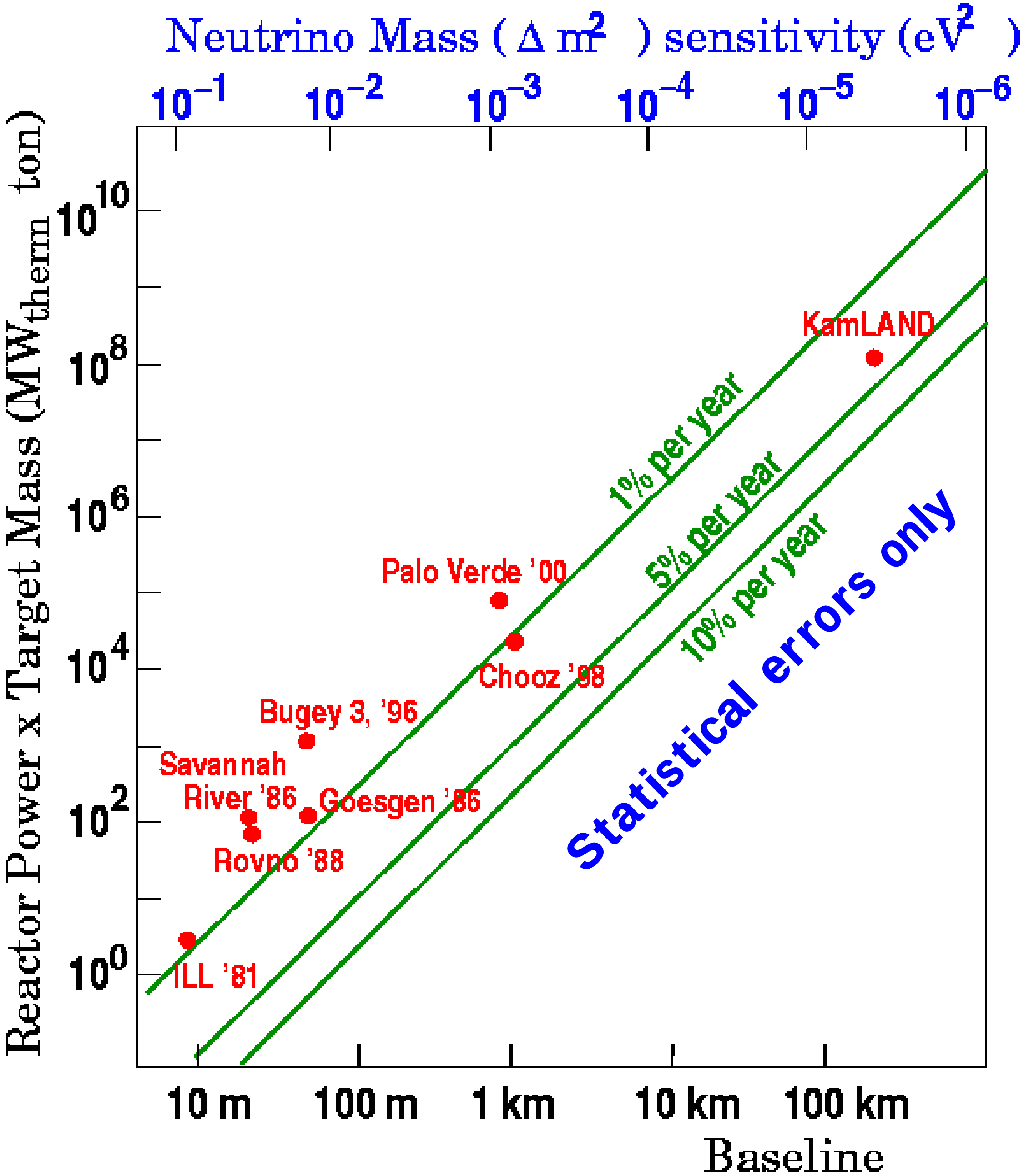
1.01±0.04 Chooz
1.04±0.08 Palo Verde

Conclusion:

Chooz and Palo Verde saw no evidence for neutrino oscillations involving $\bar{\nu}_e$ down to 10^{-3} eV^2
→ Atmospheric neutrino oscillations are mainly $\nu_\mu - \nu_\tau$

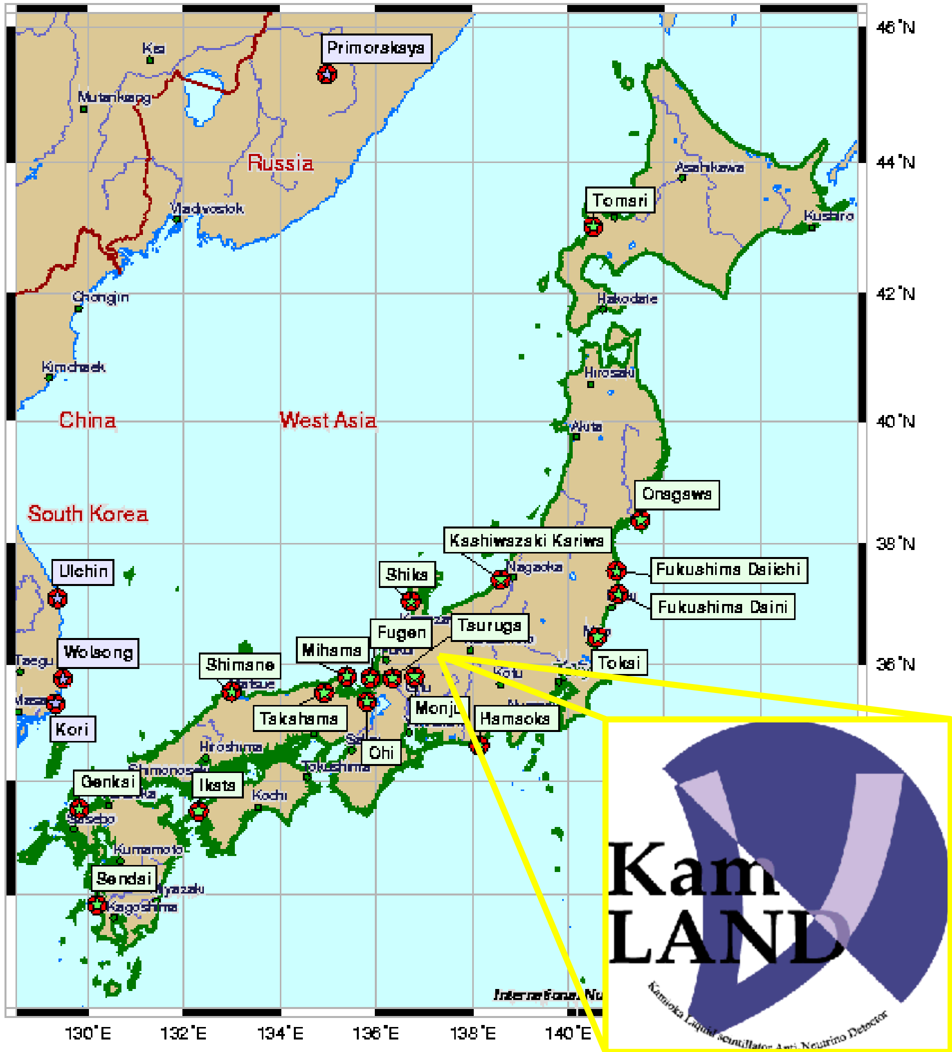


Phys Lett B 466, 415 (1999)
Phys Rev D **62**, 072002 (2002)



Bemporad, Gratta, and Vogel Reviews of Modern Physics v 74, April 2002

KamLAND: Good Position and Timing



Kamioka Liquid-scintillator
Anti-Neutrino Detector

Large flux from 20 reactors stations (70 reactor cores)

Sensitive to LMA MSW parameter space indicated by SNO results for ν_e-ν_x :

$\langle L \rangle \sim 190$ km

$\Delta m^2 \sim 10^{-5}$ eV^2

$\sin^2 2\theta \sim 1$

$(\Delta m_{12}^2, \theta_{12})$

Probe solar neutrino matter enhanced mixing parameters with vacuum oscillation conditions.

KamLAND Detector Design

•Scintillator
 80% Mineral Oil
 20% pseudocumine
 1.5 g/l PPO

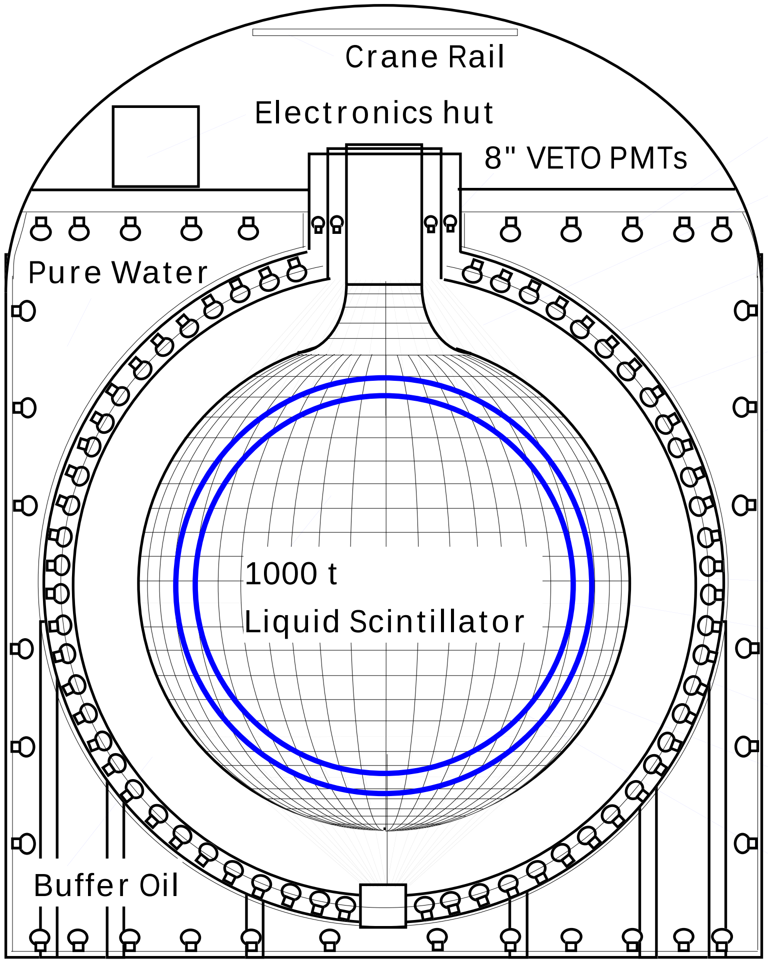
•30% photocathode coverage

1325 fast 17″ PMTs
544 large area 20″ PMTs

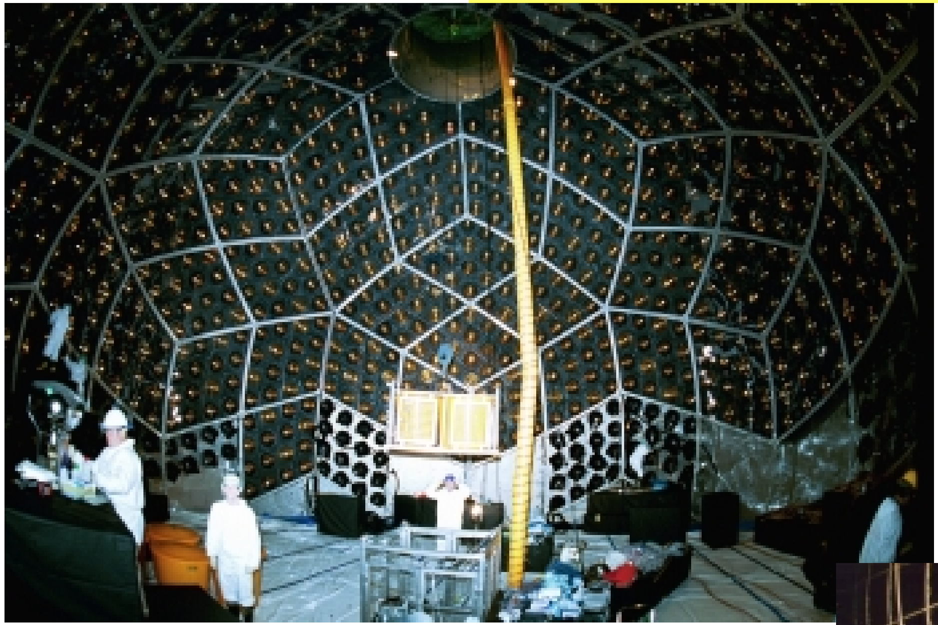
•Water Čerenkov veto detector

225 large area 20″ PMTs

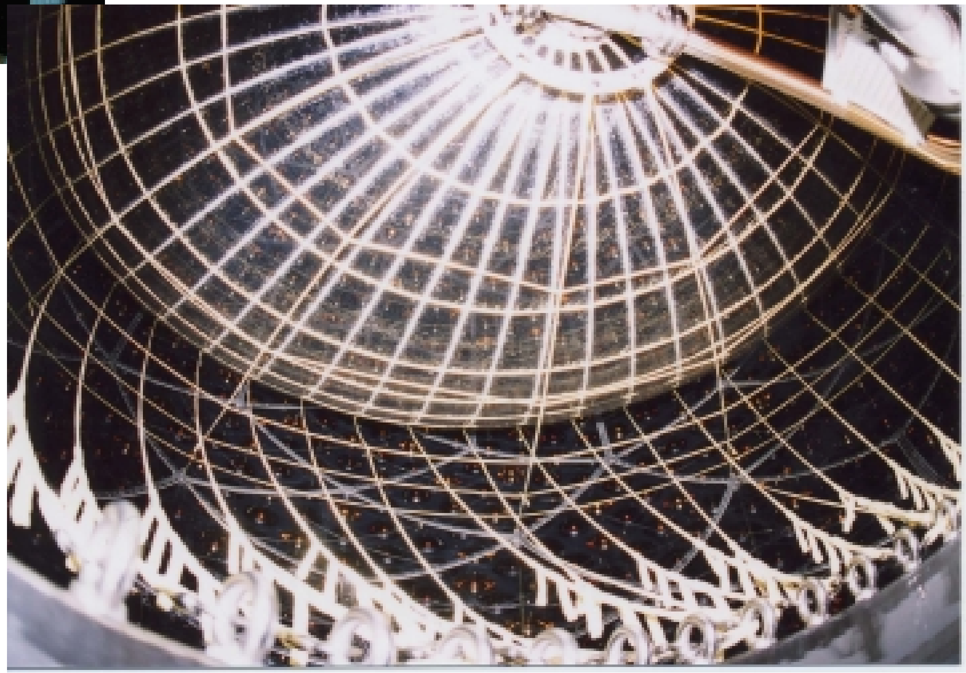
•Multi-hit, deadtime-less electronics



KamLAND Construction

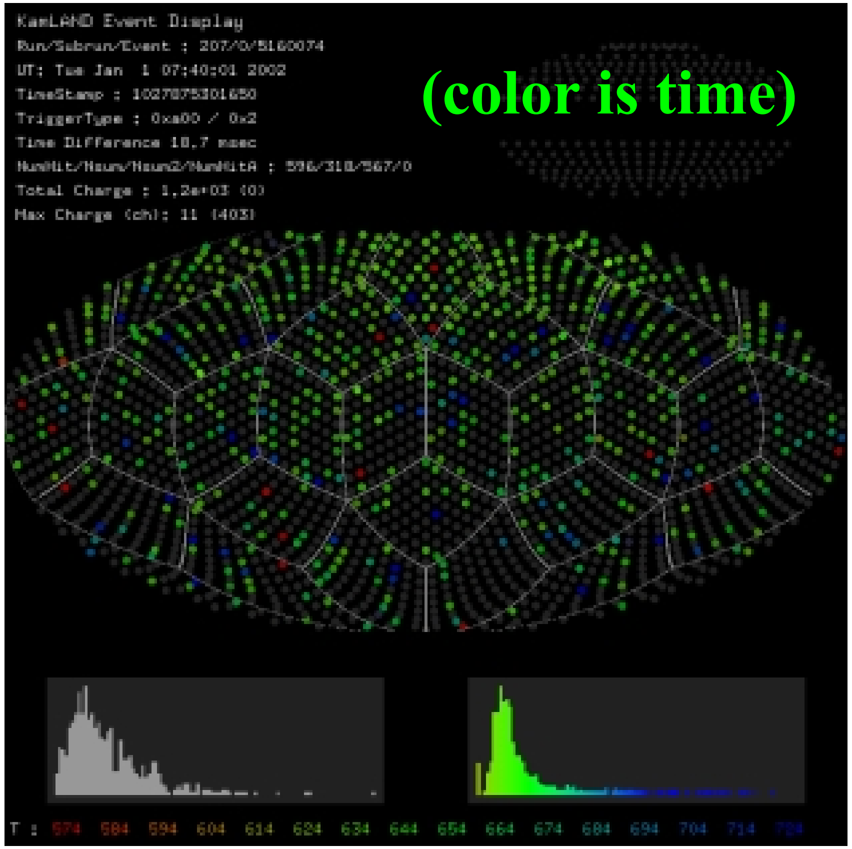


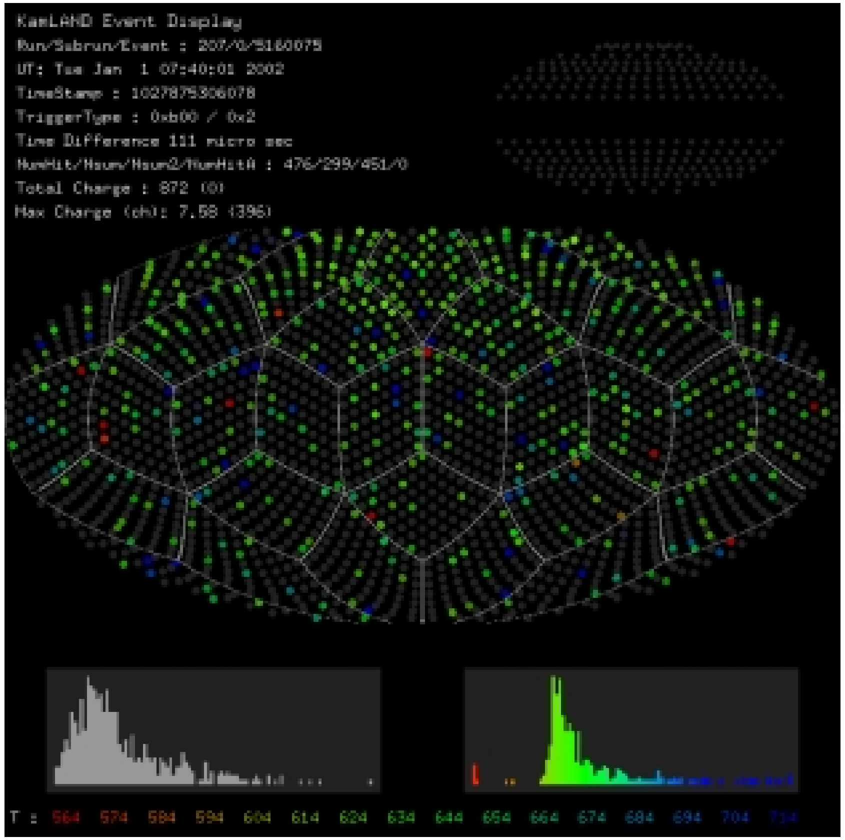
Installation of the Inner Detector



View of the balloon supported by kevlar ropes.

KamLAND Neutrino Event Candidate





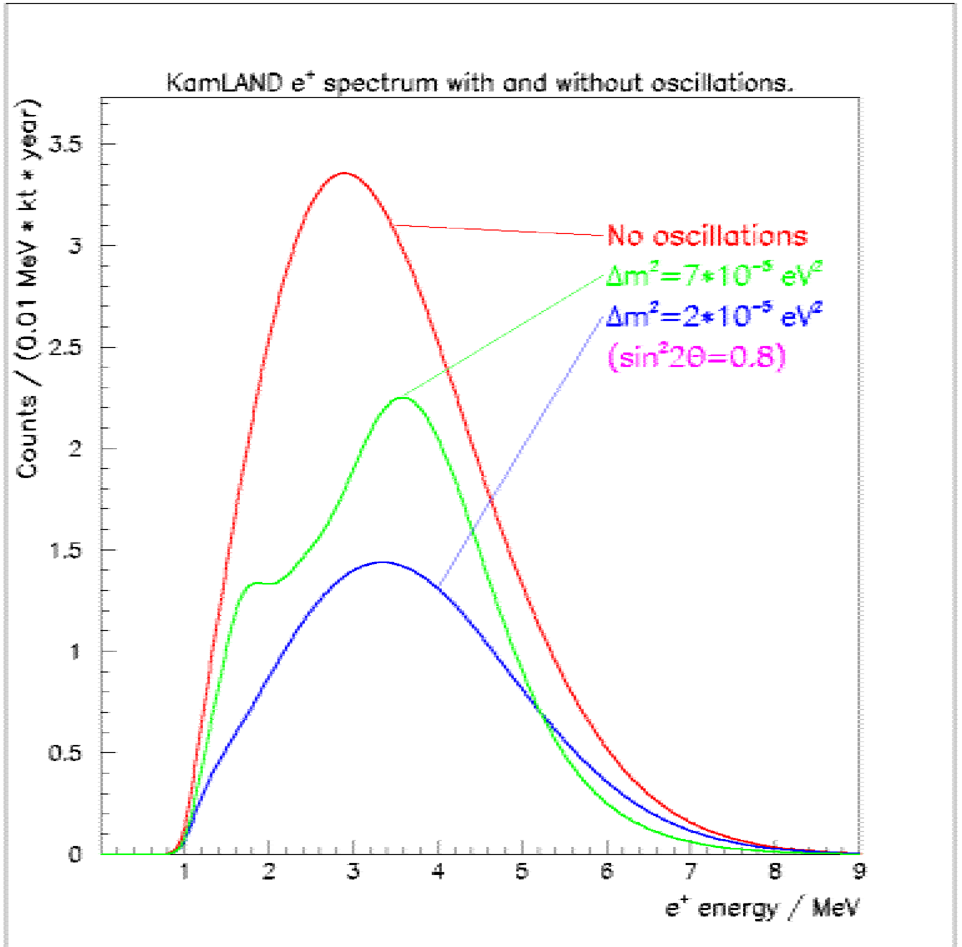
Prompt (e^{+}) Signal
E = 3.20 MeV

$\Delta t = 111\ \mu s$
$\Delta R = 34$ cm

Delayed (neutron) Signal
E = 2.22 MeV

Spectrum Distortion

Neutrino oscillations change both the rate and energy spectrum of the detected events.



Heilbronn Proposal

If KamLAND does not see oscillations……

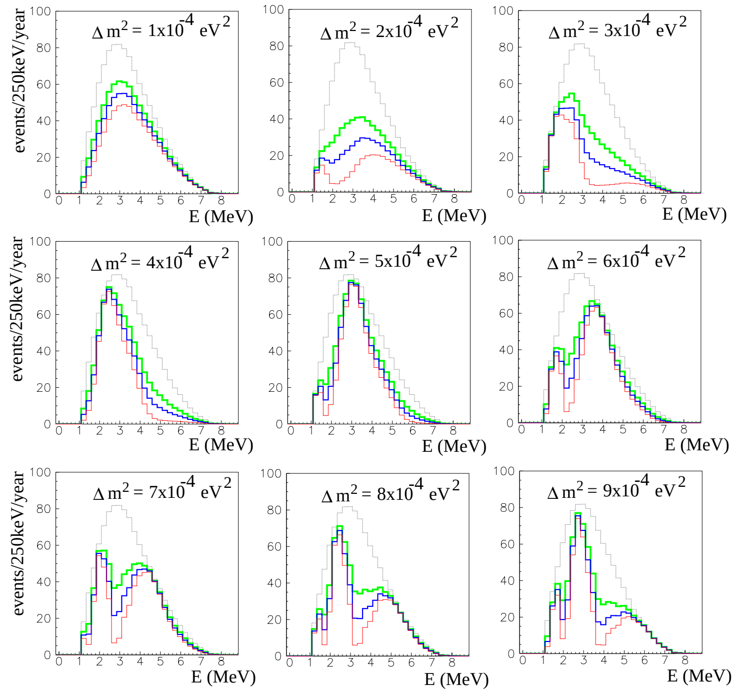
Sensitivity to "HLMA"
High LMA region with
$2x10^{-4}$ eV^2 < Δm^2 < 10^{-3} eV^2

Saltmine: 480-640 mwe

Select baseline to 2 reactors
14 to 20 km

Liquid scintillator
100-1000 kton, depending on needed sensitivity

Spectrum distortion for proposed HLMA project



hep-ex/0203013

Accelerator Based Experiments

- High intensity neutrino beams

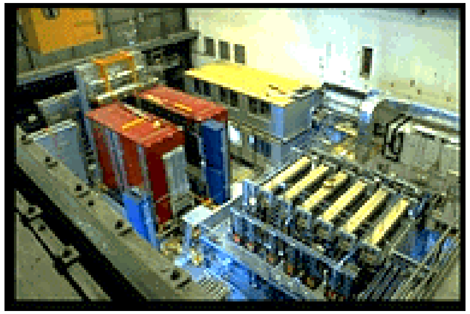
$$p + \text{target} \rightarrow \pi, K \rightarrow \nu_{\mu}, \bar{\nu}_{\mu}, (< 1\% \, \nu_{\text{e}})$$

- Detect by charged current weak interaction

$$\nu_i + N \rightarrow i + X \text{ where } i \equiv e, \mu, \tau$$

- Sensitivity to ν_τ through τ decay
  - track kinks or kinematics
- Near and far detectors
- Large spectrometers and calorimeters for momentum, energy and track reconstruction

NOMAD and CHORUS



Neutrinos from CERN (SPS protons on Be)
Average E_ν = 26 GeV
L~800 m - Search in large Δm^2 region.

Neutrino Oscillation MAgnetic Detector

Target and drift chamber: fiducial mass 2.7 tons
Identify τ events using kinematic criteria
Requires particle ID and momentum of secondaries

CERN Hybrid Oscillation Research apparatUS

Identify τ events through track "kinks"
770 kg emulsion and scintillating fiber trackers
Measure track momenta with spectrometers
Energy from Pb scintillating fiber calorimeter

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

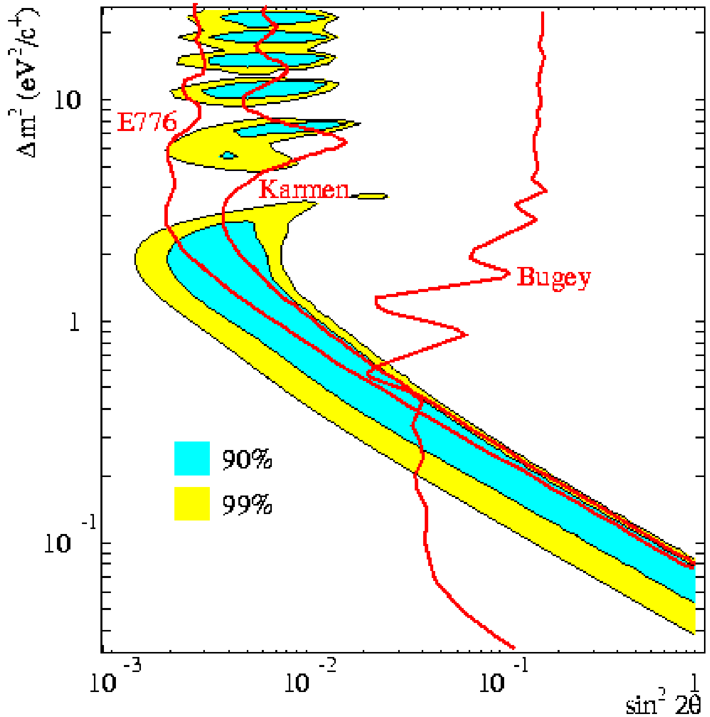
NOT SEEN
at large Δm^2
$P_{\mu\tau} < 4\times10^{-4}$

LSND and KARMEN

Appearance measurement of ν_e-bar.

LSND ν from LAMPF accelerator.

KARMEN ν from ISIS synchrotron.



Decay in flight: $\nu_\mu : \pi^+ \rightarrow \mu^+ + \nu_\mu$

Decay at rest: $\bar{\nu}_\mu : \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

LSND Result

Signal above background:

87.9±22.4 ±6.0 events

Oscillation probability:

(0.264 ±0.067 ±0.045)%

(Phys Rev D **64** 112007)

Evidence for ν_μ-ν_e oscillation at large Δm^2 and small $\sin^2 2\theta$. Some consistency with KARMEN results.

.3 eV^2<Δm^2<2 eV^2

Oscillation Evidence

TYPE	MIXING	δm^2	$\sin^2 2\theta$	
Atmospheric	$\nu_\mu \rightarrow \nu_\tau (\text{not}\, \nu_e)$	$\sim 10^{-3}$ eV^2	~ 1	Atmospheric Anomaly
Solar	$\nu_e \rightarrow \nu_\mu, \nu_\tau$	10^{-5}-10^{-4} eV^2	~ 0.8	Solar Neutrino Deficit
Reactor (limit)	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$	$> 10^{-3}$ eV^2 $< 10^{-3}$ eV^2	< 0.1 LMA	Oscillations Not Seen
LSND	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	~ 1 eV^2	~ 0.01	Observed Oscillations

Can we develop a consistent and complete description of neutrino oscillations?

Consider 3 ν mixing: $\Sigma\delta m^2 = \delta m_{12}{}^2 + \delta m_{23}{}^2 + \delta m_{23}{}^2 = 0$

But: $\delta m_{solar}{}^2 + \delta m_{atmos}{}^2 + \delta m_{LSND}{}^2 \neq 0$

Consider 4 ν mixing: sterile neutrino? Consider CPT violation?

What are the mixing parameters?

Be clever with terrestrial source experiments to check parameters.

K2K: Long Baseline Neutrino Experiment (KEK E362)

- Beam energy: E_ν = 1~2 GeV
- Beam: ~$6x10^{12}$ protons/2.2 sec, 1.1 μsec spill time
- Path length: 250 km,
- Beam aiming accuracy: ~1 mrad
- Beam half-width: ~3 mrad
- Rate: ~200 events at SK for 10^{20} protons on target at KEK
  - → $2.4x10^{-5}$ events/full-intensity spill
- Background: 5 atmospheric neutrino events/day in SK
  - → $P(BG)=6x10^{-11}$ per spill

<u>Near Detector Hall:</u>

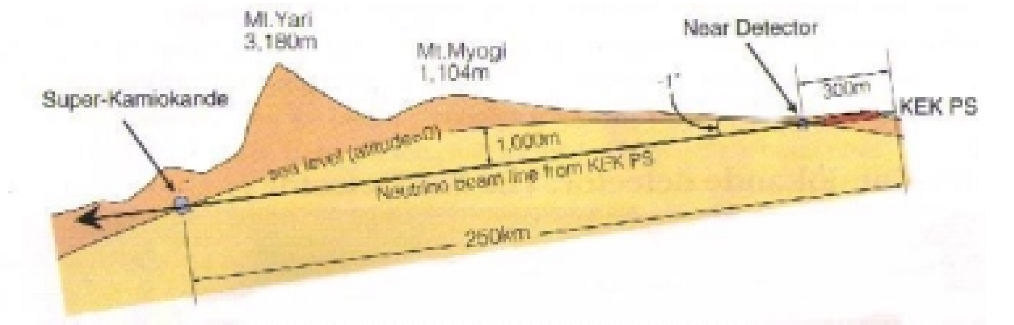
1 kT Water Cherenkov detector

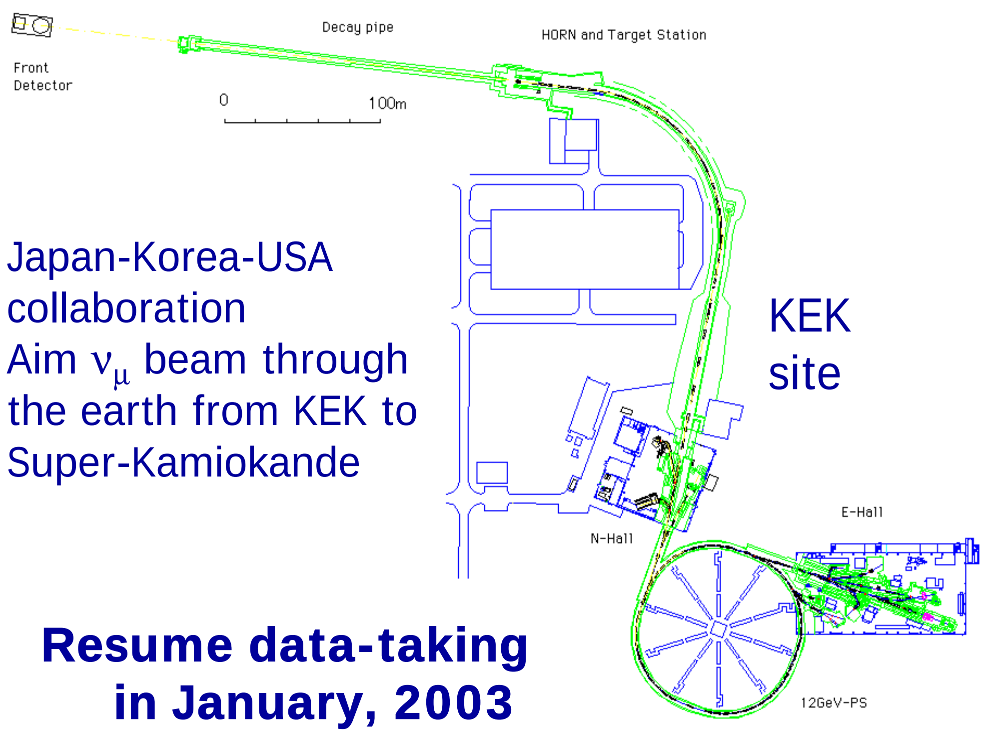
Fine-grained detector (FGD):

Sci-Fi detector (SciFi)

Pb Glass (PBG)/ Veto walls

Muon Range Detector (MRD)





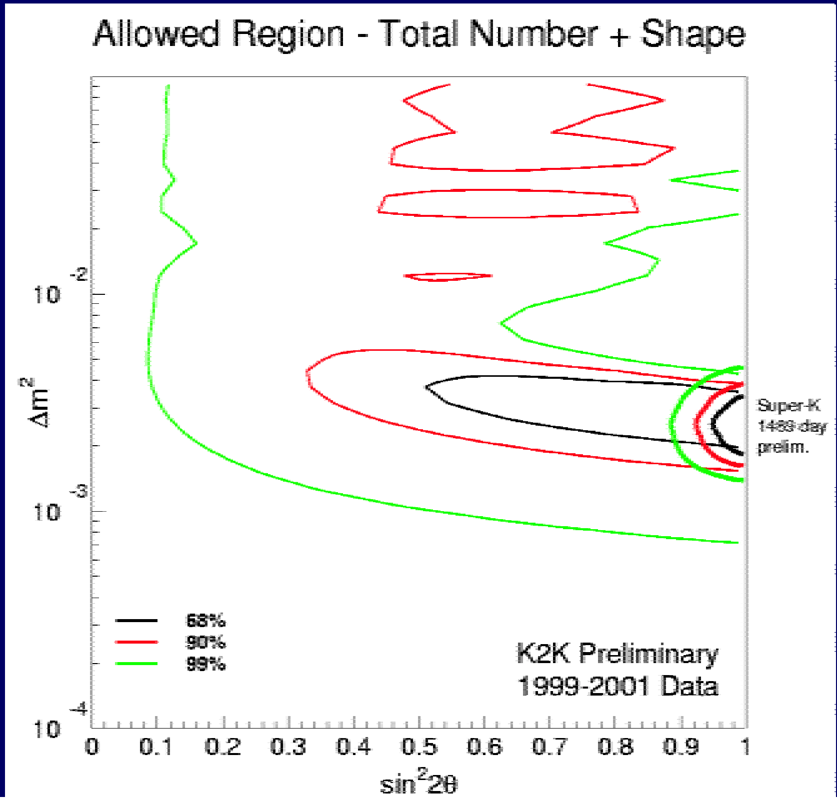
- Japan-Korea-USA collaboration
- Aim ν_μ beam through the earth from KEK to Super-Kamiokande

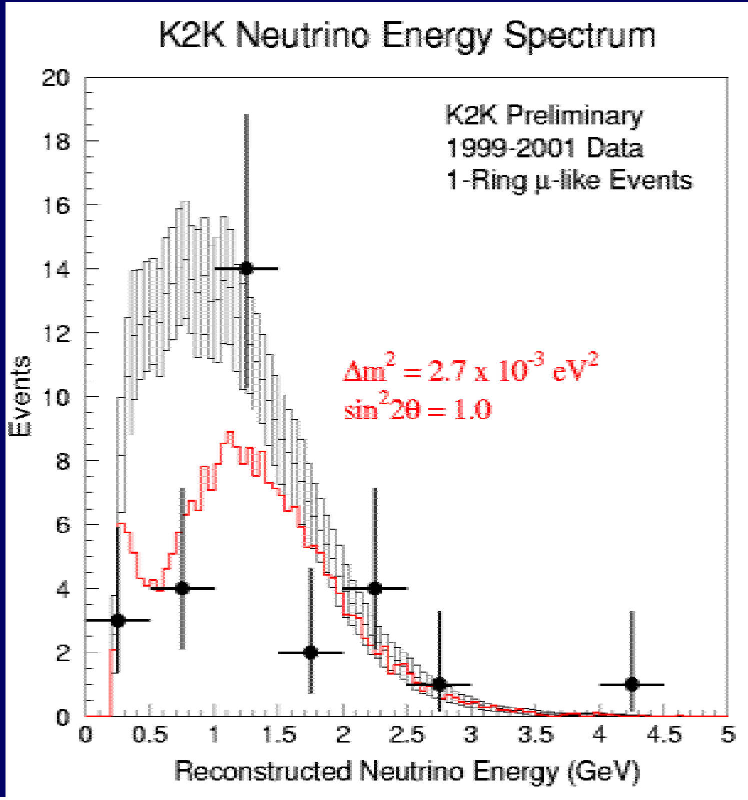
KEK site

Resume data-taking in January, 2003

K2K results

- Inconsistent with no-oscillations (~99% CL)
  - Events observed in SK: 56   Expected (no-osc): 80.1 (+6.5/-5.4)
- Generally consistent with Super-K best-fit oscillation parameters
  - Best-fit point : $\Delta m^2 = 2.7\text{x}10^{-3}\ \text{eV}^2$, $\sin^2 2\theta = 1.0$
  - Starting to have enough statistics to see spectrum distortion





K2K Status and Future

- Need more data to reach high confidence levels
- Rearrange surviving tubes + on-hand spares to provide ~50% of original coverage (July-Sept 02)

  Reduced coverage is OK for K2K and atmospheric ν

  Hamamatsu can supply sufficient PMTs for full coverage over ~3 years
- Begin data taking again in January, 2003
  - Additional K2K beam time planned for '04, perhaps early '05
  - KEK PS will shut down in '05: move HEP to JHF
    - JHF ν beam line (design effort underway)
    - JHF2K collaboration (organization underway)
  - Super-K upgrade (replacement of missing PMTs): '05?

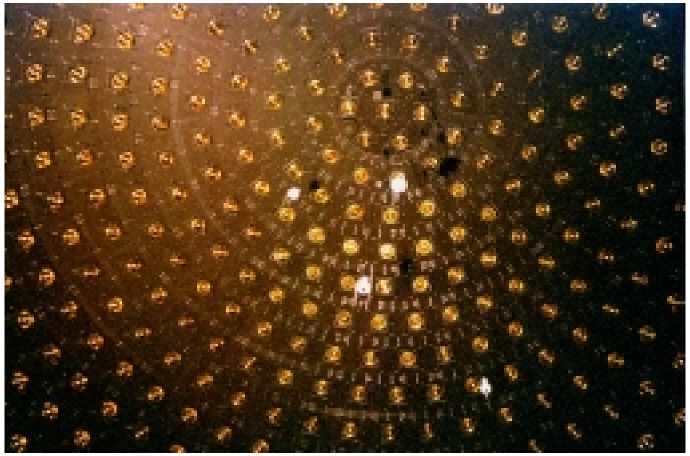
BooNE: Booster Neutrino Experiments

Designed to measure same parameter space as LSND.

MiniBooNE at FNAL
$\nu_\mu - \nu_e$ appearance search
$\bar{\nu}_\mu - \bar{\nu}_e$ appearance search

E_ν 300 MeV – 1.5 GeV
440 m dirt path

1220 PMTs from LSND
330 PMTs new for veto



Detector filled with oil
Calibrations in progress…
Beam on detector soon?

Accelerator Projects (Long Baseline)

Sensitive to Δm_{23}^2, θ_{23}

ν_e appearance: $\sin^2\theta_{13}$

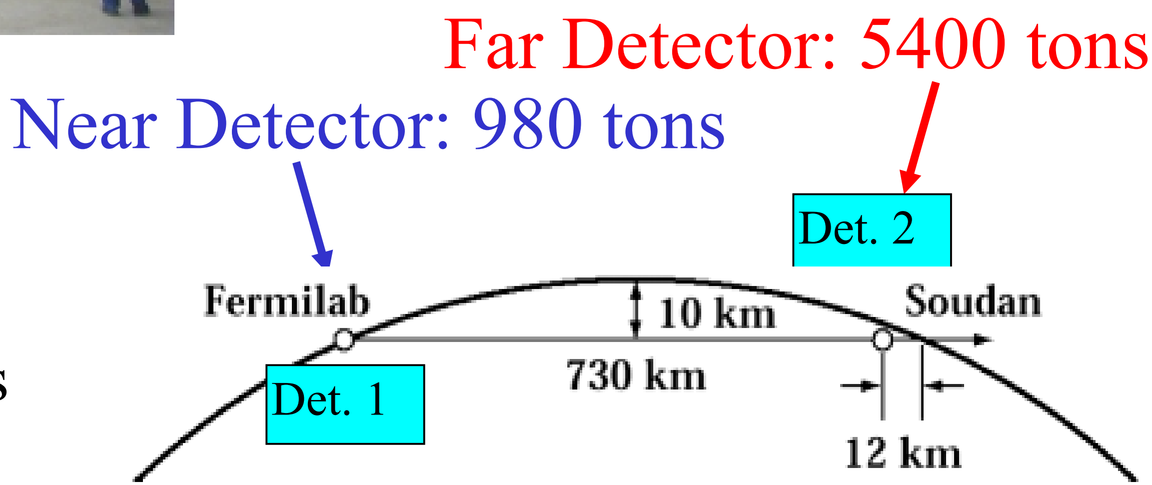
- FermiLab to Soudan (NuMI - MINOS)
  - $<E_n> = 3,6,12$ GeV L~730 km
- CERN to Gran Sasso Neutrino Beam (CNGS)
  - OPERA and ICARUS
  - Sensitive to ν_μ-> ν_e, ν_τ appearance
- JHF2K (SuperK)
  - beam ν_μ, ν_e, ν_e-bar, Emean~0.51 GeV
- BNL Proposal (Superbeam Project)
  - Send ν beam to Homestake (3000 km) study sign of Δm_{23}^2

Fermilab NuMI and MINOS - 2004

Identify: CC ν_μ, ν_e events
NC ν_μ events

(Direct measurement of ν vs ν-bar oscillations.)

NuMI tunable beam: adjust horns and target to change energy spectra for oscillation parameters of interest.

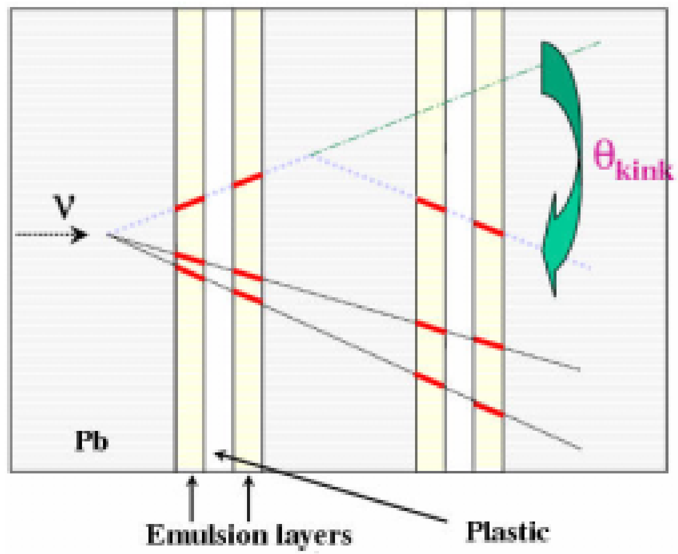


CNGS: OPERA and ICARUS – 2006 (CERN to Gran Sasso)

Measure τ appearance events: $\Delta m^2 \sim 2 \times 10^{-3}$ eV^2 sensitivity 10%. (ν_μ-ν_τ)
Highly grained detectors: ν_e appearance measurement – θ_{13}. (ν_μ-ν_e)

ICARUS: Imaging Cosmic and Rare Underground Signals (ICANOE)
Liquid argon imaging detector and
fine-grained magnetized calorimeter

OPERA: Oscillation Project with
Emulsion tRacking Apparatus
Emulsion cloud chamber concept:
detect τ by decay topology



How do we extend the current limits?

The next step in terrestrial neutrino sources:

Look to Neutrino Factories!