Lectures on Neutrino Physics

Lake Louise School

February, 2002

Mike Shaevitz

Lecture 1:

Neutrino Interactions

Example: NuTeV $\sin^2\theta_W$ Measurement

Direct Neutrino Mass Measurements

Neutrino Oscillation Phenomenology

Solar Neutrinos (part 1)

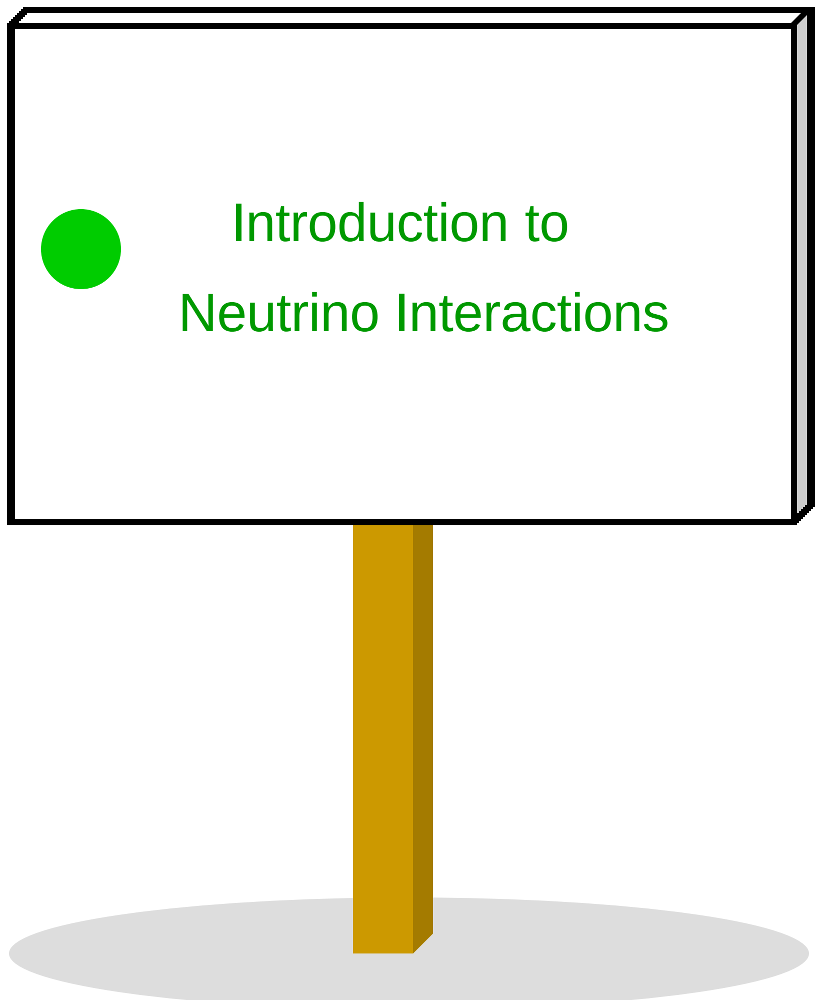
Lecture 2:

Solar Neutrinos (part 2)

Atmospheric and Longbaseline Exps.

LSND Region Experiments

Summary and Conclusions


Introduction to
Neutrino Interactions

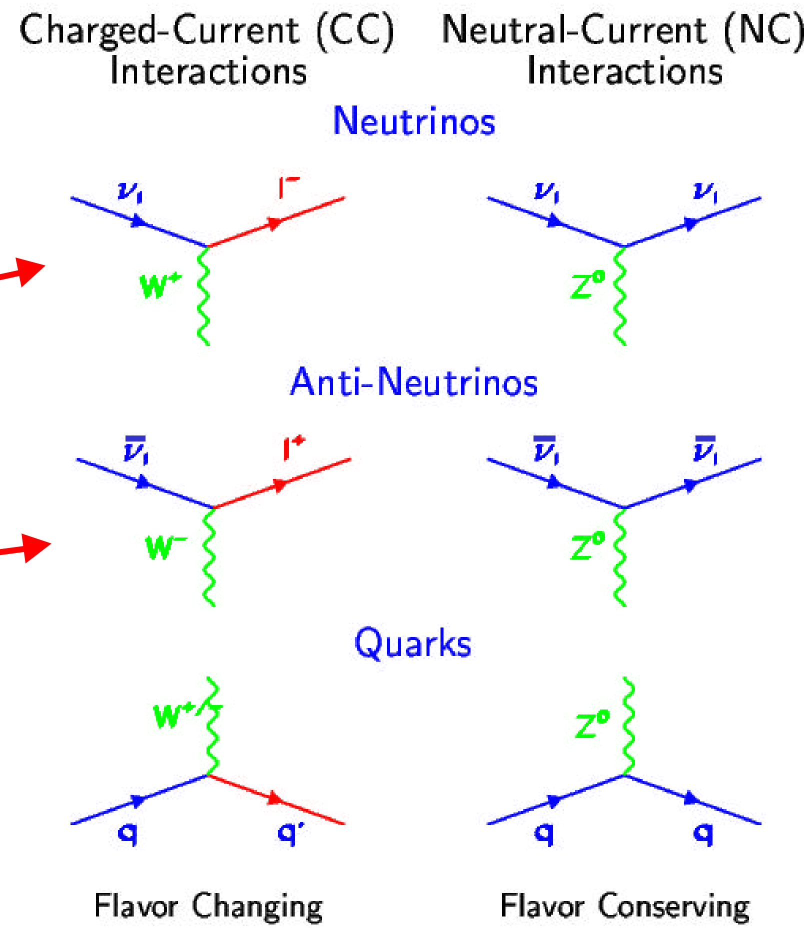
Neutrino Interactions

- W exchange gives Charged-Current (CC) events and
  Z exchange gives Neutral-Current (NC) events

In CC events the outgoing lepton determines if neutrino or antineutrino

$$l^- \rightarrow \nu$$

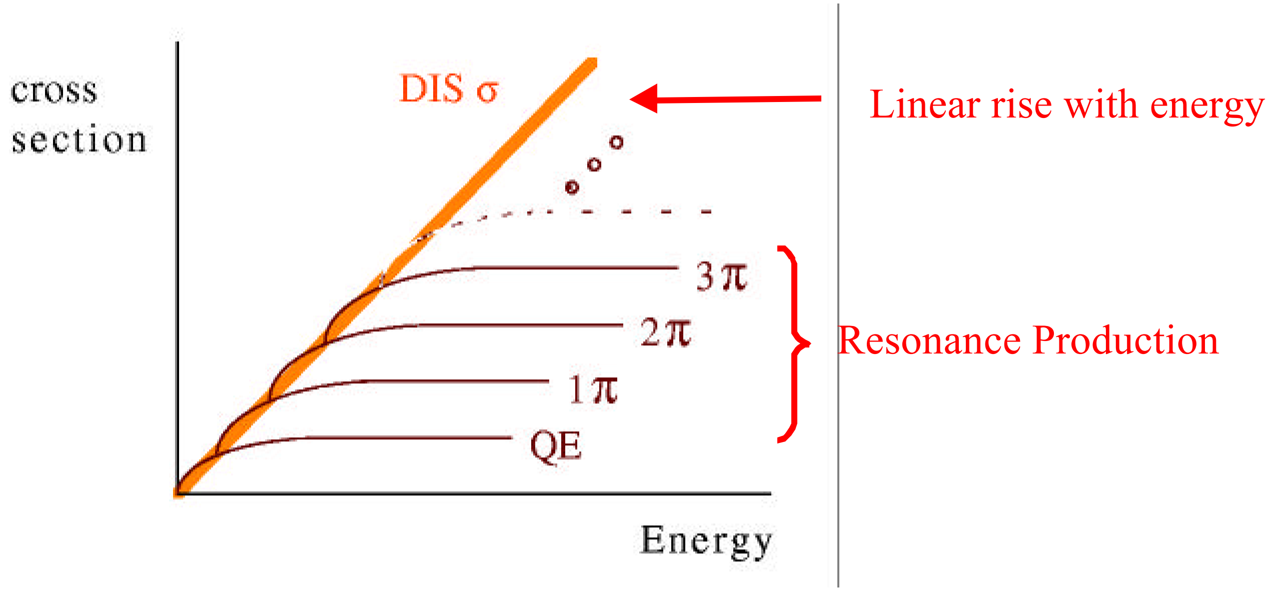
$$l^+ \rightarrow \bar{\nu}$$



Neutrino-Nucleon Processes

- Charged - Current: $W^{\pm}$ exchange
  - Quasi-elastic Scattering:
    (Target changes but no break up)
    $\nu_\mu + n \rightarrow \mu^- + p$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ (N^* or Δ)
    $n + \pi^+$
  - Deep-Inelastic Scattering:
    (Nucleon broken up)
    ν_μ + quark $\rightarrow \mu^-$ + quark'

- Neutral - Current: Z^0 exchange
  - Elastic Scattering:
    (Target doesn't break up or change)
    $\nu_\mu + N \rightarrow \nu_\mu + N$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$ (N^* or Δ)
  - Deep-Inelastic Scattering
    (Nucleon broken up)
    ν_μ + quark $\rightarrow \nu_\mu$ + quark



Neutrinos Are Left-Handed
(Helicity and Handedness)

- Helicity is projection of spin along the particles direction
  - Frame dependent (if massive)

The operator: $\sigma \cdot \mathbf{p}$

- Neutrinos only interact weakly with a (V-A) interaction
  - All **neutrinos** are **left-handed**
  - All **antineutrinos** are **right-handed**

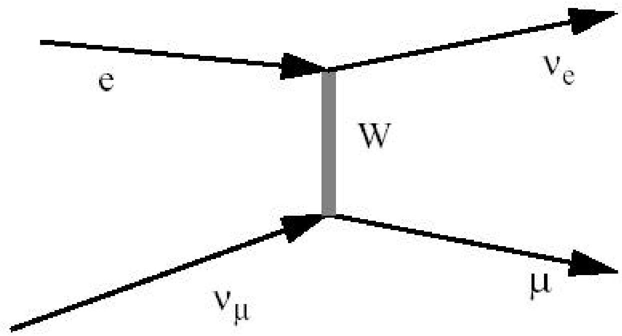
- If neutrinos have mass then left-handed neutrino is:
  - Mainly left-helicity
  - But also small right-helicity component $\propto m/E$

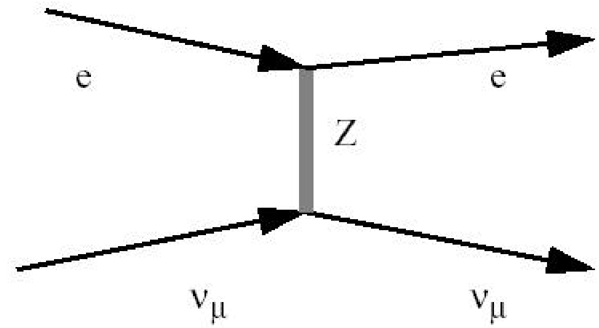
- Handedness (or chirality) is Lorentz-invariant
  - Only same as helicity for massless particles.

- Only left-handed charged-leptons (e^-,μ^-,τ^-) interact weakly but mass brings in right-helicity:

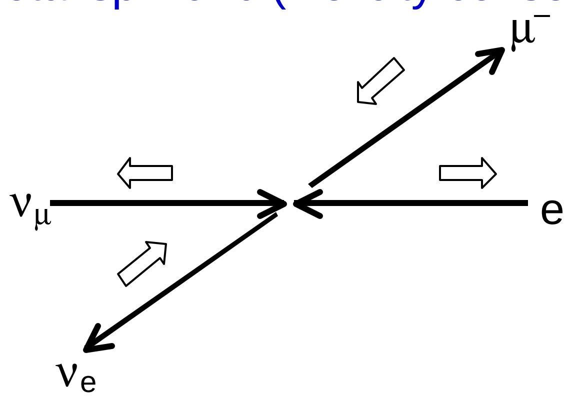
$$R_{theory} = \frac{\Gamma(\pi^\pm \to e^\pm \nu_e)}{\Gamma(\pi^\pm \to \mu^\pm \nu_\mu)} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi{}^2 - m_e{}^2}{m_\pi{}^2 - m_\mu{}^2}\right)^2 = 1.23 \times 10^{-4}$$

Neutrino-Electron Scattering





- Inverse μ–decay: $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$
  - Total spin J=0 (Helicity conserved)



  - Point scattering $\Rightarrow \sigma \propto s = 2m_eE_\nu$

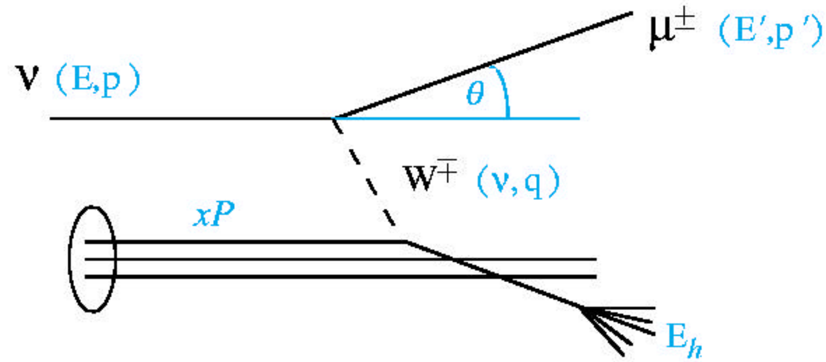
$$s_{TOT} = \frac{G_F^2 s}{p} = 17.2 \pm 10^{-42} cm^2 / GeV \cdot E_n (GeV)$$

- Elastic Scattering: $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$
  - Point scattering $\Rightarrow \sigma \propto s = 2m_eE_\nu$
  - Electron coupling to Z^0
    - (V-A): $-1/2 + \sin^2\theta_W$ J = 0
    - (V+A): $\sin^2\theta_W$ J = 1

$$s_{TOT} = \frac{G_F^2 s}{p}\left(\frac{1}{4} - \sin^2 q_W + \frac{4}{3}\sin^4 q_W\right)$$

Scattering: Scaling Variables

DEEP INELASTIC NEUTRINO SCATTERING



Measured quantities: E_h , E', θ

KinematicQuantities (Use 4 - vector inv ariants)

4 - momentum Transfer^2 : $Q^2 = -(p_l - p_n)^2 \approx \left(4E_n E_l \sin^2(q/2)\right)_{Lab}$

Energy Transfer : $n = ((p_l - p_n)\cdot p_T)/M_T = (E_n - E_l)_{Lab} = (E_h - M_T)_{Lab}$

FractionalEnergy Transfer : $y = ((p_l - p_n)\cdot p_T)/(p_n \cdot p_T) = (E_h - M_T)/(E_h + E_l)_{Lab}$

FractionalMomentum of Struck Quark : $x = Q^2 / 2M_T n$

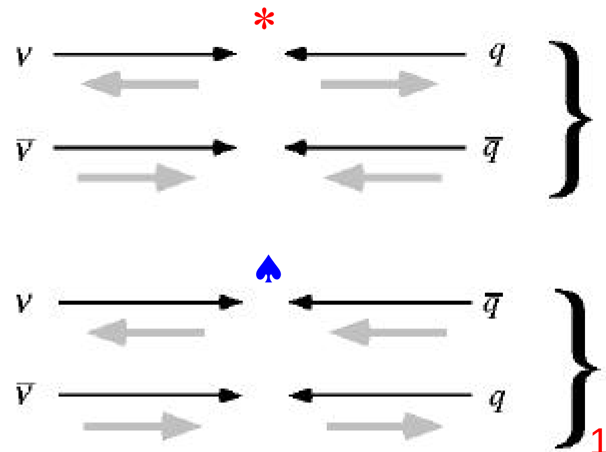
Neutrinos Probe Quark Structure

(Nucleon Structure Functions)

$$\frac{ds^{np}}{dxdy} = \frac{G_F^2 s}{p}\left(xd^{p}(x) + x\bar{u}^{p}(x)(1-y)^2 \right)$$

$$\frac{ds^{nn}}{dxdy} = \frac{G_F^2 s}{p}\left(xd^{n}(x) + x\bar{u}^{n}(x)(1-y)^2 \right)$$

(The xd terms are marked * and the $x\bar{u}$ terms are marked ♠.)



Total Spin = 0
νq or ν̄q̄
Flat in y

Total Spin = 1
νq̄ or ν̄q
1/4(1+cosθ*)^2 = (1-y)^2

– Need to add scattering off strange s(x) and charm c(x)

- For an isoscalar target (# protons = # neutrons):

$$\frac{d^2 s^{n(\bar{n})N}}{dxdy} = \frac{G_F^2 s}{2p}\left\{ \left(1+(1-y)^2\right) F_2(x) \pm \left(1-(1-y)^2\right) xF_3^{n(\bar{n})}(x) \right\}$$

$$F_2^{n(\bar{n})N}(x) = x(u(x)+d(x)+\bar{u}(x)+\bar{d}(x)+s(x)+\bar{s}(x)+c(x)+\bar{c}(x) = xq(x)+x\bar{q}(x)$$

$$xF_3^{n(\bar{n})N}(x) = xu_{Val}(x) + xd_{Val}(x) \pm 2x(s(x)-c(x))$$

where $u_{Val}(x) = u(x) - \bar{u}(x)$

Neutrino Cross Section is Very Small

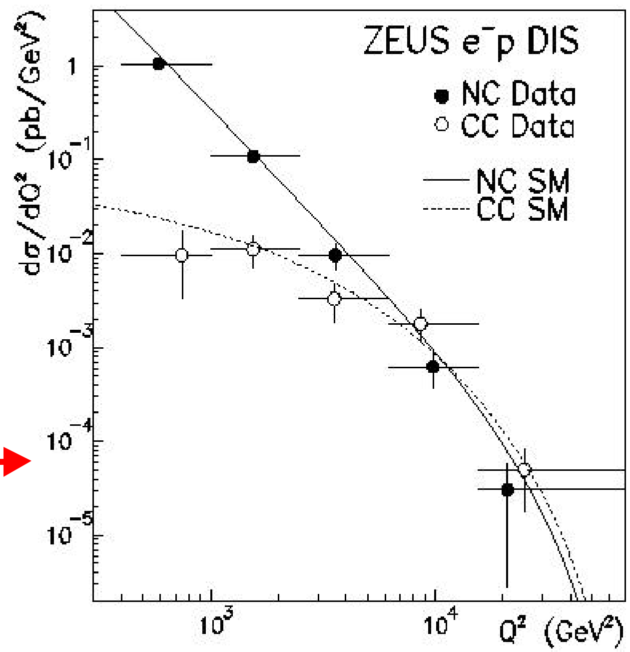
- Weak interactions are weak because of the massive W and Z boson exchange $\Rightarrow \sigma^{\text{weak}} \propto (1/M_W)^4$

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2 = 1.166\times10^{-5}/GeV^2 \quad (g_W \approx 0.7)$$

- For 100 GeV Neutrinos:
  - $\sigma(\nu e) \sim 10^{-40}$ and $\sigma(\nu N) \sim 10^{-36}$ cm^2
    vs. $\sigma(pp) \sim 10^{-26}$ cm^2
  - ***Mean free path length in Steel***
    ~ 3 ´10^9 meters!
    (Need big detectors)

$\sigma^{\text{EM}} \propto 1/Q^4$

At Hera see W and Z propagator effects
- Also weak ~ EM strength



Neutrino Physics Topics

- Nucleon structure
  - Structure Functions – F_2 , xF_3
  - Strange sea – s(x)
  - Tests of QCD and measure α_s

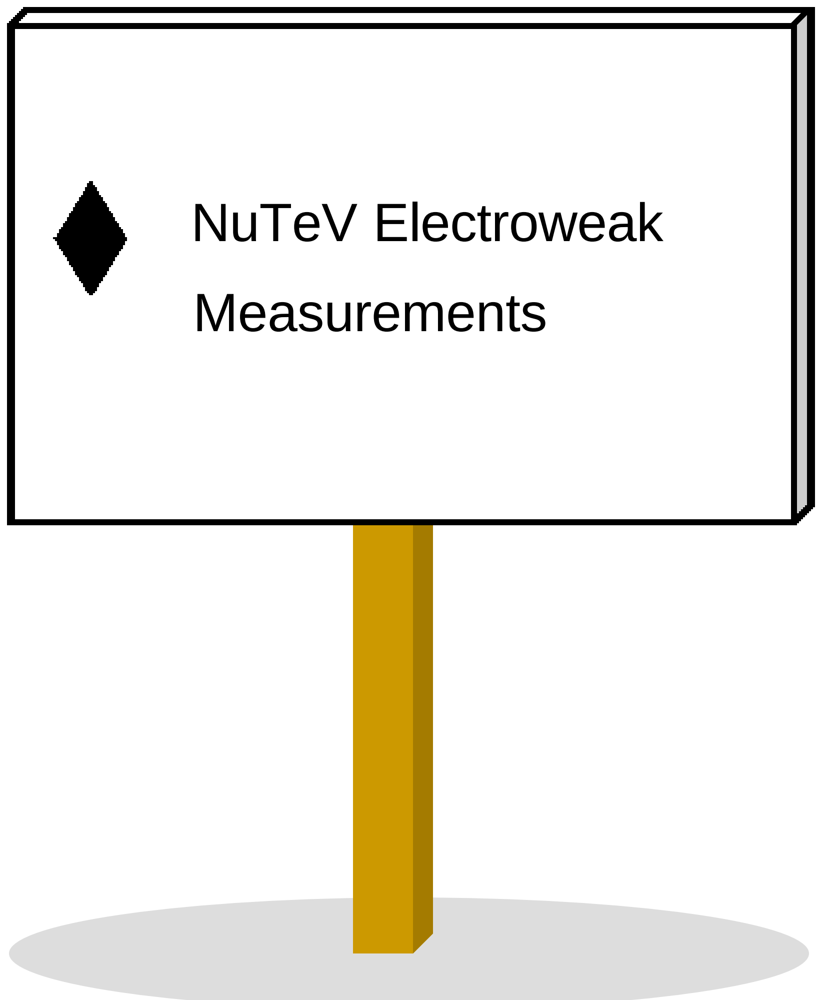
See various review articles: (Conrad,Shaevitz,Bolton; RMP 70 (1998) 1341)

- Electroweak Measurements
  - Measure $\sin^2\theta_W$
  - Test GWS SU(2)xU(1) theory

Brief Discussion Today about new NuTeV measurement (example of high-energy ν exp.)

- Neutrino Properties
  - Neutrino mass
    - Direct measurements
    - Double beta decay
    - Neutrino Oscillations

Talk about direct mass measurements and then neutrino oscillations


NuTeV Electroweak
Measurements

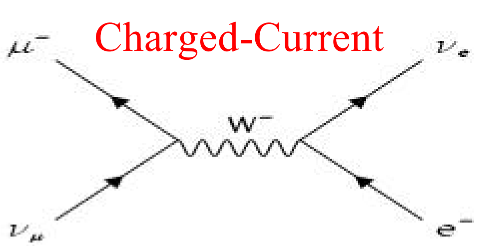
Electroweak Theory

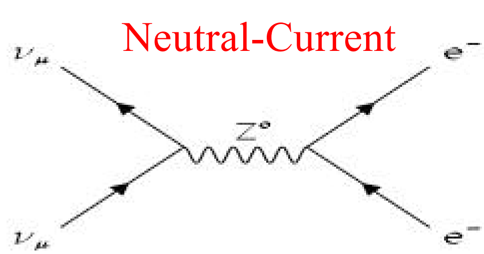
- Standard Model
  - SU(2) ⊗ U(1) gauge theory unifying weak/EM
    - ⇒ weak Neutral Current interaction
  - Measured physical parameters related to mixing parameter for the couplings, $g' = g \tan\theta_W$

Z Couplings	g_L	g_R
ν_e , ν_μ , ν_τ	1/2	0
e , μ , τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u , c , t	$1/2 - 2/3 \sin^2\theta_W$	$-2/3 \sin^2\theta_W$
d , s , b	$-1/2 + 1/3 \sin^2\theta_W$	$1/3 \sin^2\theta_W$

$$e = g \sin\theta_W , \; G_F = \frac{g^2\sqrt{2}}{8M_W^2} , \; \frac{M_W}{M_Z} = \cos\theta_W$$

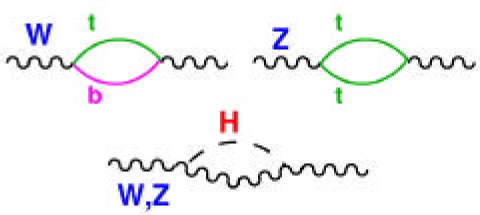
- Neutrinos are special in SM
  - Only have left-handed weak interactions
    - ⇒ $W^\pm$ and Z boson exchange



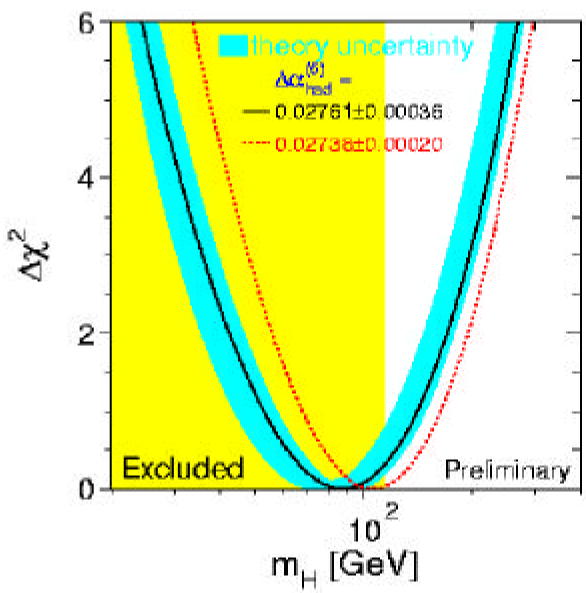


Current Era of Precision EW Measurements

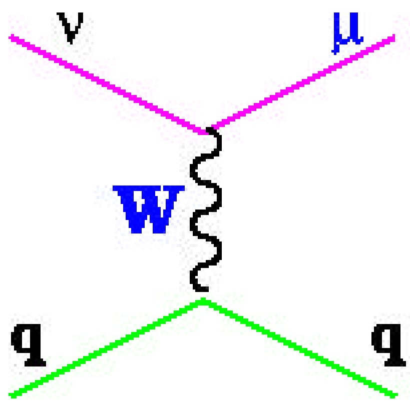
- Precision parameters define the SM:
  - $\alpha_{EM}^{-1} = 137.03599959(40)$ 45ppb (200ppm@M_Z)
  - $G_\mu = 1.16637(1)\times10^{-5}$ GeV^{-2} 10ppm
  - $M_Z = 91.1871(21)$ 23ppm
- Comparisons test the SM and probe for new physics
  - LEP/SLD (e+e-), CDF/D0 (p-pbar), νN , HERA (ep) , APV



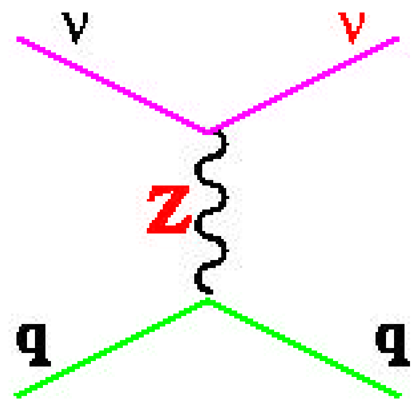
- Radiative corrections are large and sensitive to m_{top} and m_{Higgs}
  - *M_{Higgs} constrained in SM to be less than 196 GeV at 95%CL*



NuTeV Experimental Technique



$$Coupling \propto J^{(3)}_{weak}$$



$$Coupling \propto \left(J^{(3)}_{weak} - Q_{em}\sin^2\theta_W\right)$$

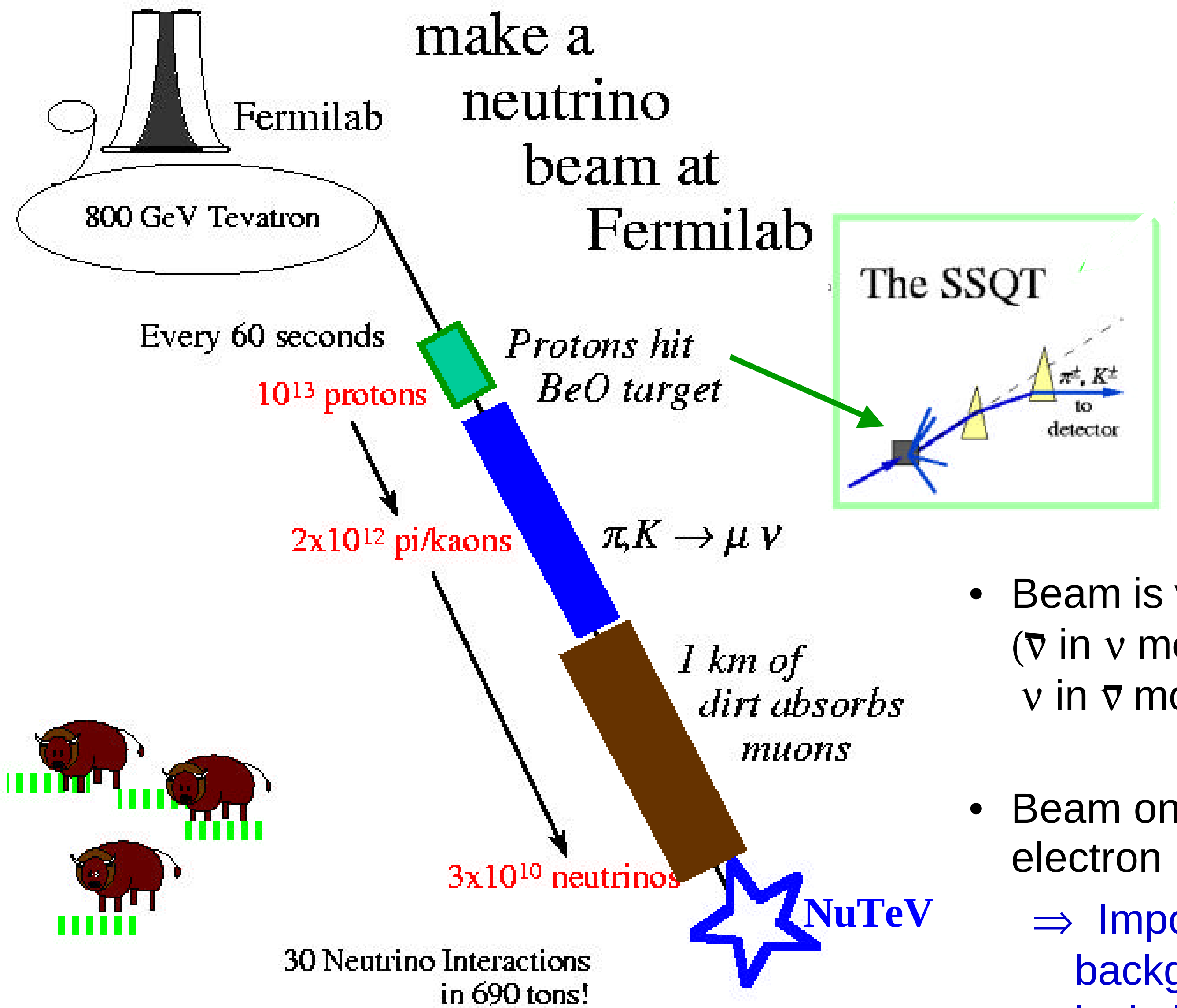
- For an isoscalar target composed of u,d quarks:

Llewellyn Smith Relation :

$$R^{\nu(\bar{\nu})} = \frac{\sigma^{\nu(\bar{\nu})}_{NC}}{\sigma^{\nu(\bar{\nu})}_{CC}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\,(1 + \frac{\sigma^{\bar{\nu}(\nu)}_{CC}}{\sigma^{\nu(\bar{\nu})}_{CC}})\right)$$

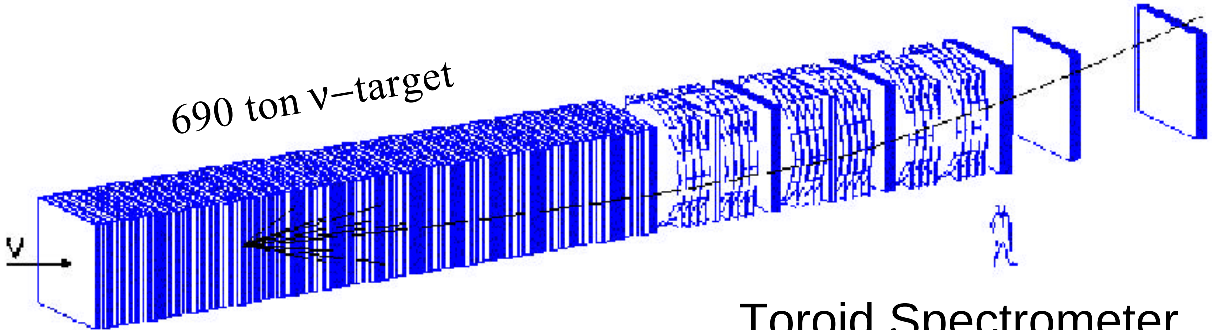
- *NC/CC* ratio easiest to measure experimentally
  but need separate neutrino and antineutrino running

How to make a neutrino beam at Fermilab



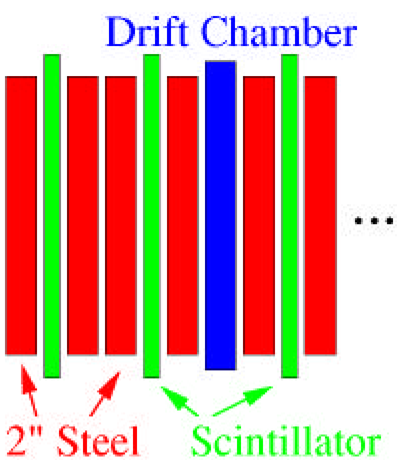
- Beam is very pure ($\bar{\nu}$ in ν mode 3×10^{-4}, ν in $\bar{\nu}$ mode 4×10^{-3})
- Beam only has ~1.6% electron neutrinos
  - $\Rightarrow$ Important background for isolating true NC event

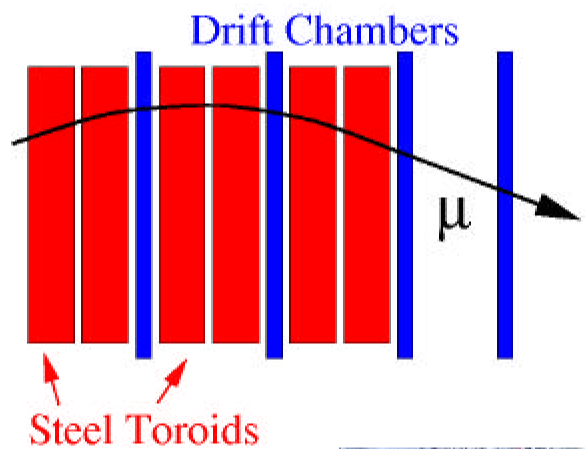
NuTeV Detector



Toroid Spectrometer

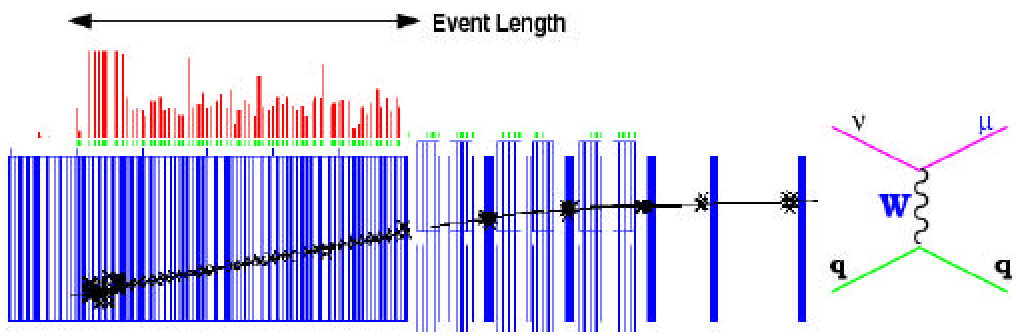
Target / Calorimeter

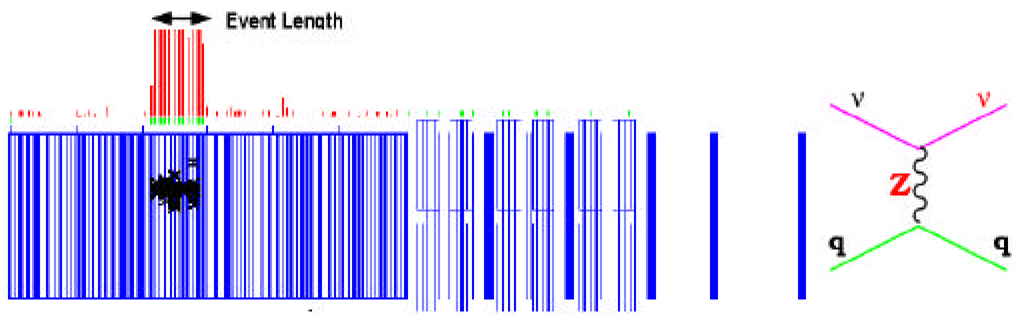




Neutral Current / Charged Current Event Separation

- Separate NC and CC events statistically based on the "event length" defined in terms of # counters traversed

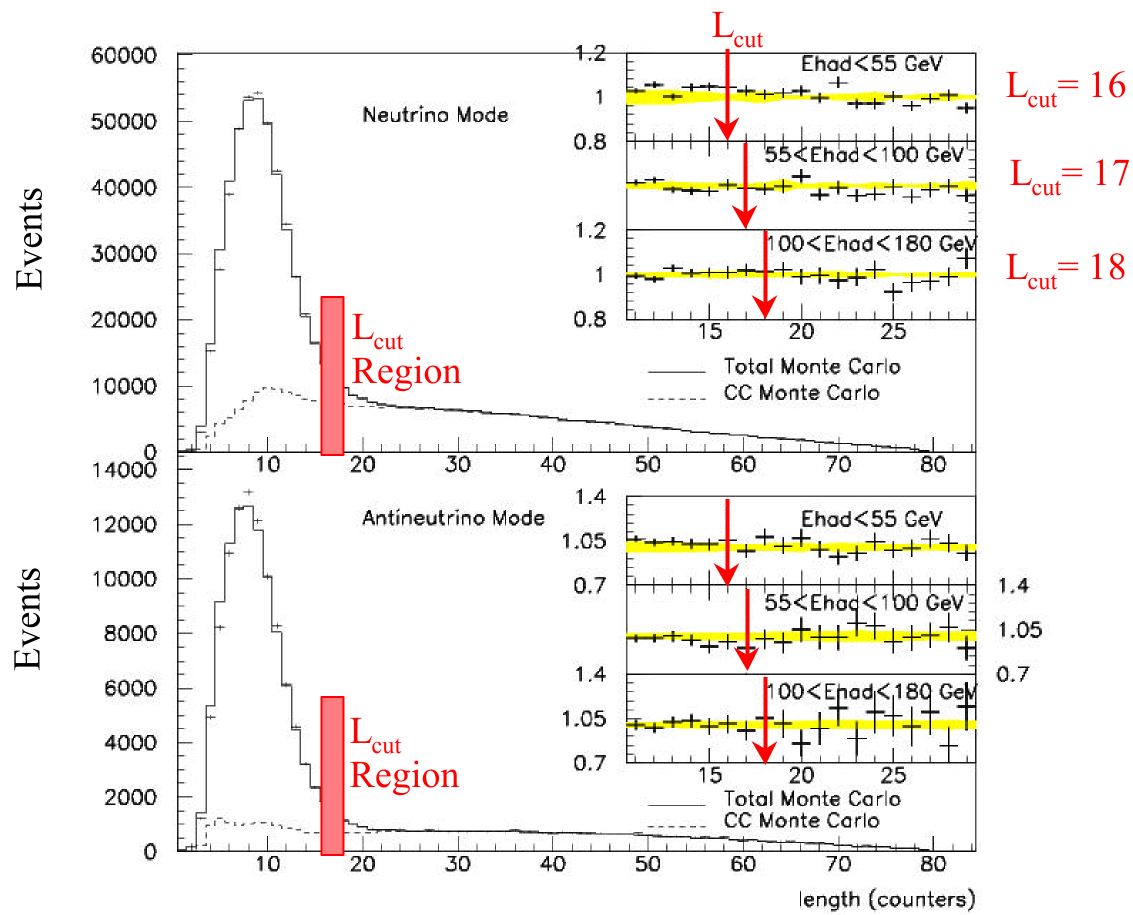




$$R_{\exp} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{L \le L_{cut}}{L > L_{cut}} = \frac{\text{NC Candidates}}{\text{CC Candidates}}$$

(measure this ratio in both n and $\bar{n}$ modes)

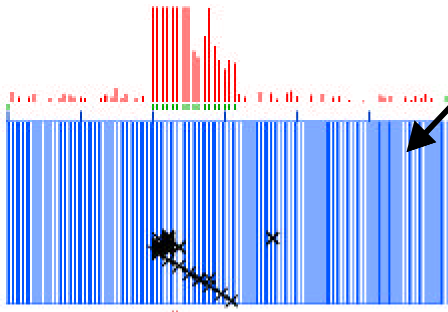
Determine R_{exp}: The Short to Long Ratio:

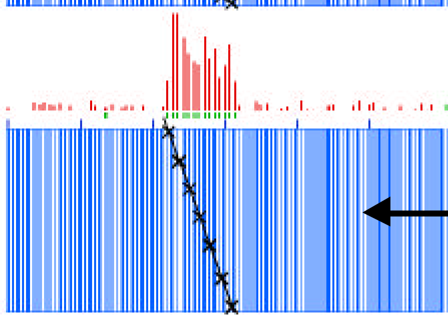


	Short (NC) Events	Long (CC) Events	R_{exp}=Short/Long
Neutrino	457K	1167K	**0.3916 ± 0.0007**
Antineutrino	101K	250K	**0.4050± 0.0016**

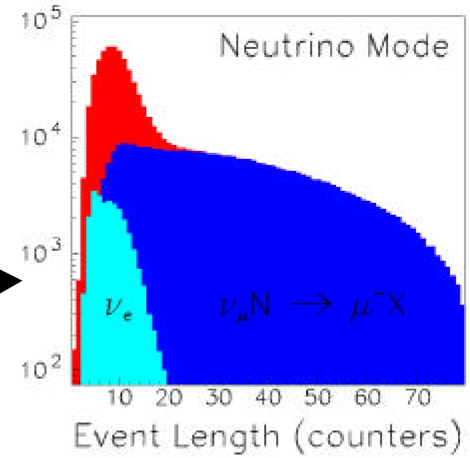
From R_{exp} to R^n

Need detailed Monte Carlo to relate R_{exp} to R^n and $sin^2 q_W$

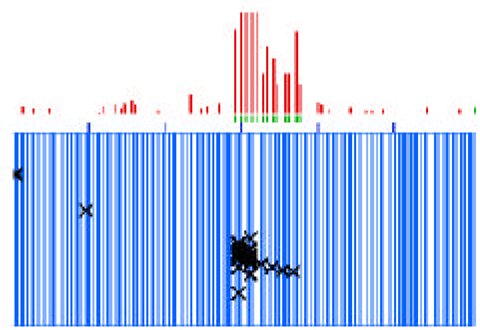




- Short ν_μ CC's (20% ν , 10% ν)
  - muon exits, range out at high y
- Short ν_e CC's (5%)
  - n_e *N ® e X*
- Cosmic Rays (0.9%/4.7%)



- Long ν_μ NC's (0.7%)
  - punch-through effects



Result from Fit to R^n and $R^{\bar{n}}$

- NuTeV result:

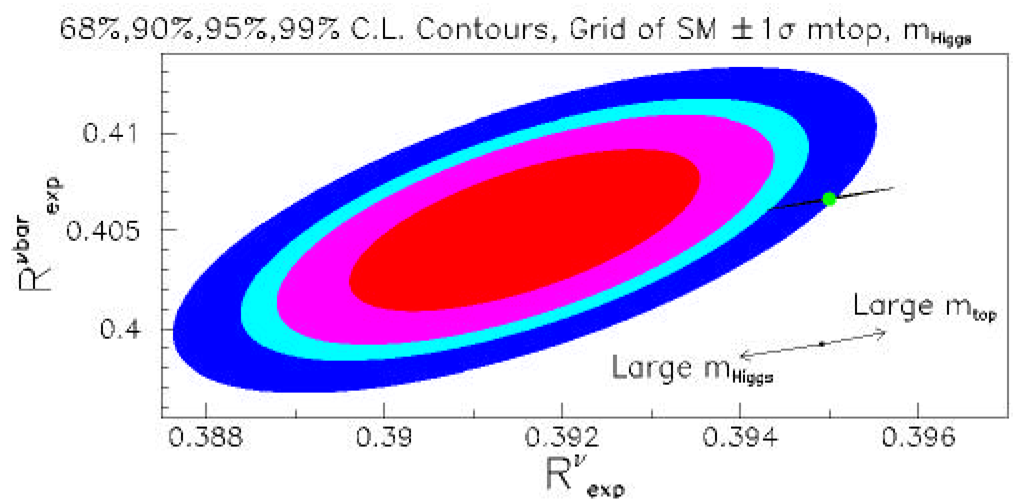
$$\sin^2 q_W^{(on-shell)} = 0.2277 \pm \pm 0.0013(stat.) \pm 0.0009(syst.)$$
$$= 0.2277 \pm 0.0016$$

(Previous neutrino measurements gave 0.2277 ± 0.0036)

- Standard model fit (LEPEWWG): 0.2227 ± 0.00037

  A 3σ discrepancy ....

$$R^n_{\exp} = 0.3916 \pm 0.0013$$
$$(SM : 0.3950) \quad \Leftarrow 3s \ \ difference$$
$$R^{\bar{n}}_{\exp} = 0.4050 \pm 0.0027$$
$$(SM : 0.4066) \quad \Leftarrow Good \ \ agreement$$



Possible Interpretations

- Changes in Standard Model Fits
  - Change PDF sets
  - Change M_{higgs} $\Rightarrow$ Need > 1000 TeV !
- "Old Physics" Interpretations: QCD
  - Violations of "isospin" symmetry
  - Strange vs anti-strange quark asymmetry
- Are ν's Different?
  - Special couplings to new particles
  - Majorana neutrino effects
  - Neutrino oscillations – ν_e disappearance
- "New Physics" Interpretations
  - New Z' or lepto-quark exchanges
  - New particle loop corrections

Two parameter fit to R^{ν}_{exp} and $R^{\bar{\nu}}_{exp}$:

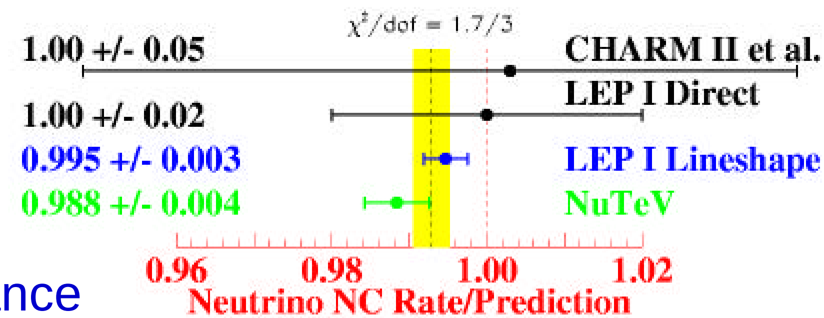
$g_L^2 = 0.3005 \pm 0.0014$

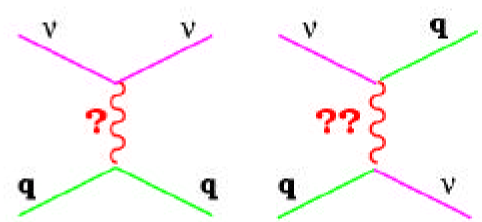
$(SM: 0.3042) \quad \Leftarrow 2.6s \;\; difference$

$g_R^2 = 0.0310 \pm 0.0011$

$(SM: 0.0301) \quad \Leftarrow agreement$

Discrepancy is left-handed coupling to u and d quarks



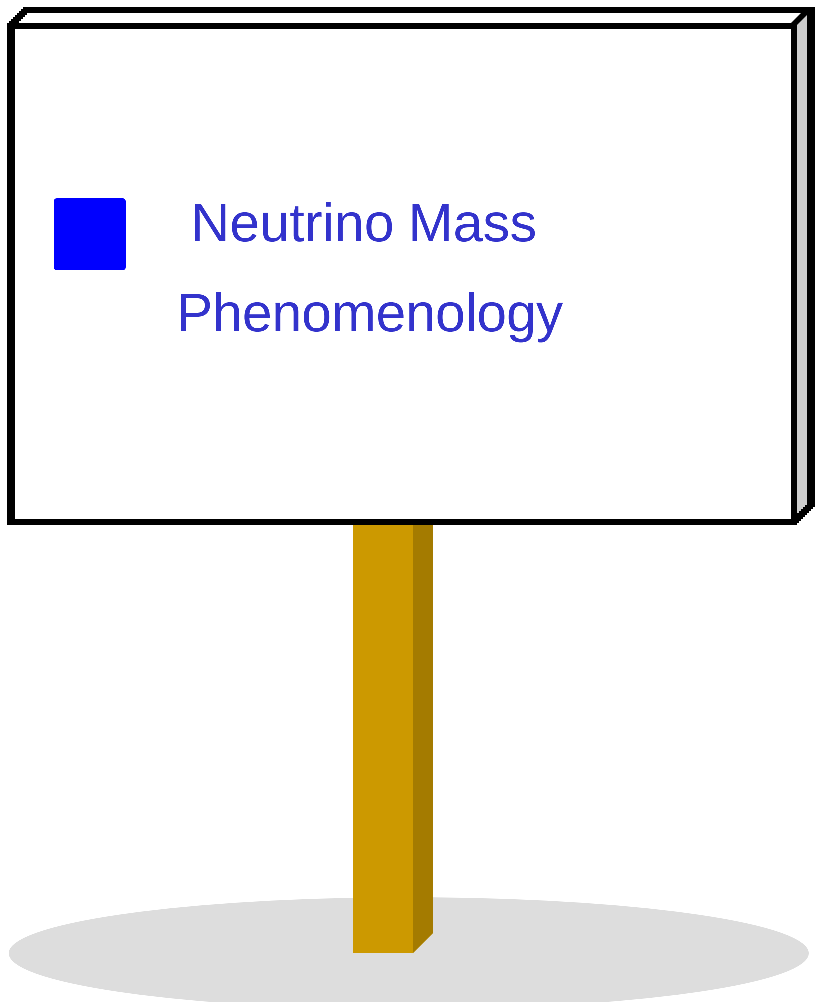


Neutrino Properties

- Neutrino Mass Phenomenology
- Direct Neutrino Mass Experiments
- Double Beta Decay Experiments
- Neutrino Oscillations

Bottom Line:

- ***No Direct evidence of neutrino mass***
- ***Neutrinos almost certainly oscillate from one flavor to another***
    - ***Þ Neutrinos have mass and mix***


Neutrino Mass
Phenomenology

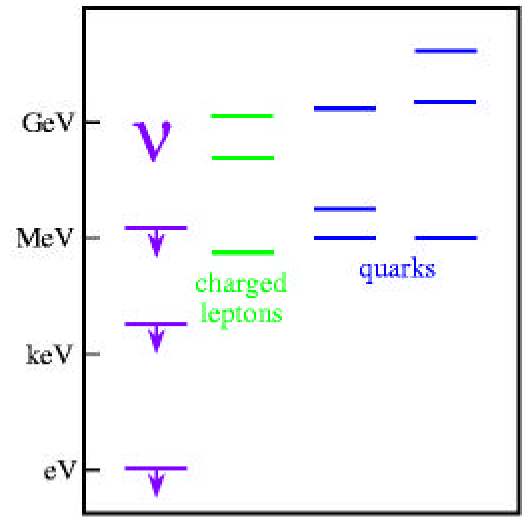
Neutrino Mass: Theoretical Ideas

- No fundamental reason why neutrinos must be massless
  - – But why are they much lighter than other particles?

➢ **Grand Unified Theories**
  - – Dirac and Majorana Mass
    $\Rightarrow$ See-saw Mechanism

➢ **Modified Higgs sector to accommodate neutrino mass**

➢ **Extra Dimensions**
  - – Neutrinos live outside of 3 + 1 space



Many of these models have at least one Electroweak isosinglet ν
- – Right-handed partner of the left-handed ν
- – Mass uncertain from light (< 1 eV) to heavy (>10^{16} eV)
- – Would be "sterile" – Doesn't couple to standard W and Z bosons

Dirac and Majorana Neutrinos

- Dirac Neutrinos
  - Neutrino and Antineutrino are distinct particles
  - Lepton number conserved
    - Neutrino → μ^-
    - Antineutrino → μ^+
  - Dirac Mass Term

$$-m_D\left(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L\right)$$

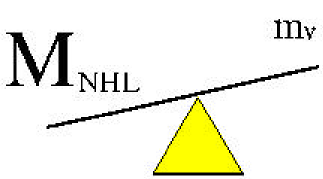
- Majorana Neutrinos
  - Neutrinos and Antineutrinos are the same particle
    ⇒ Only difference is "handedness"
    - Neutrinos are left-handed ν → μ^-
    - Antineutrinos are right-handed ν → μ^+
  - Lepton number not conserved
    - Neutrino ⇔ Antineutrino with spin flip
  - Majorana Mass Term

$$-\frac{1}{2}m_M^L\left(\overline{\nu_L}(\nu_L)^c + \overline{(\nu_L)^c}(\nu_L)\right) - \frac{1}{2}m_M^R\left(\overline{\nu_R}(\nu_R)^c + \overline{(\nu_R)^c}(\nu_R)\right)$$

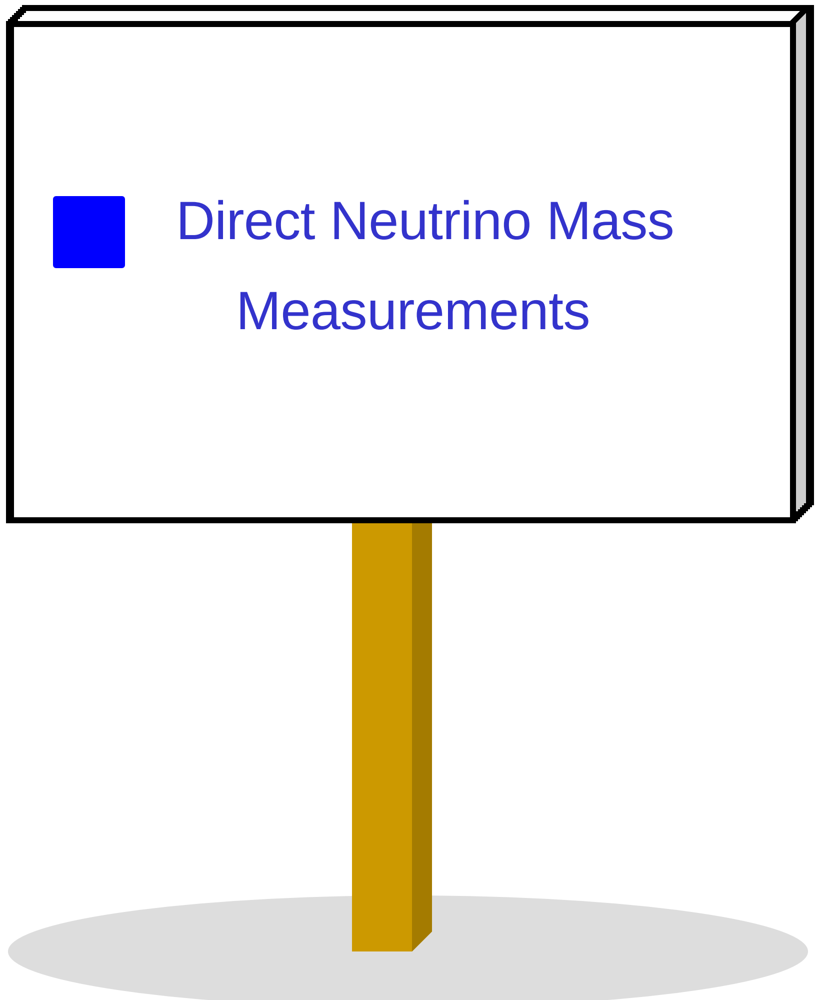
See-Saw Mechanism with Both Majorana and Dirac Terms:

$$\mathcal{M} = \begin{pmatrix} m_M^L & m_D \\ m_D & m_M^R \end{pmatrix} \qquad m_M^R = M \gg m_D \gg m_M^L = \mu$$

$$\mathcal{L}_{mass} = -\frac{1}{2}\left(\overline{\nu_L}\,\overline{(\nu_R)^c}\right)\mathcal{M}\begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix} + h.c.$$



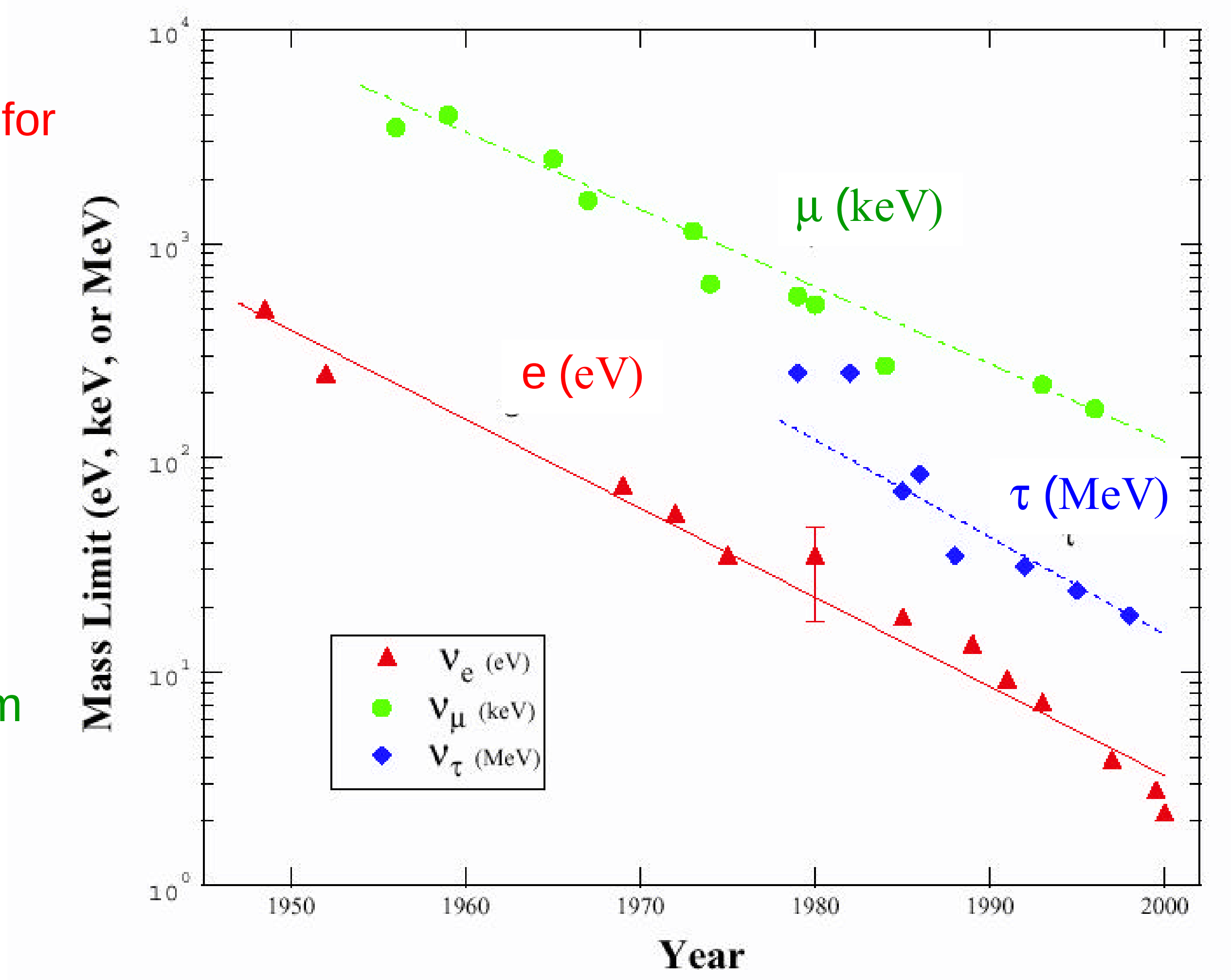
$$m_N \approx M, \quad m_\nu \approx \left|\mu - \frac{m_D^2}{M}\right|$$


Direct Neutrino Mass
Measurements

Direct Neutrino Mass Experiments

- Techniques
  - Electron neutrino:
    - Study E_e end point for $^3H \rightarrow {}^3He + \nu_e + e^-$
  - Muon neutrino:
    - Measure P_μ in $\pi \rightarrow \mu\nu_\mu$ decays
  - Tau neutrino:
    - Study $n\pi$ mass in $\tau \rightarrow (n\pi)\, \nu_\tau$ decays

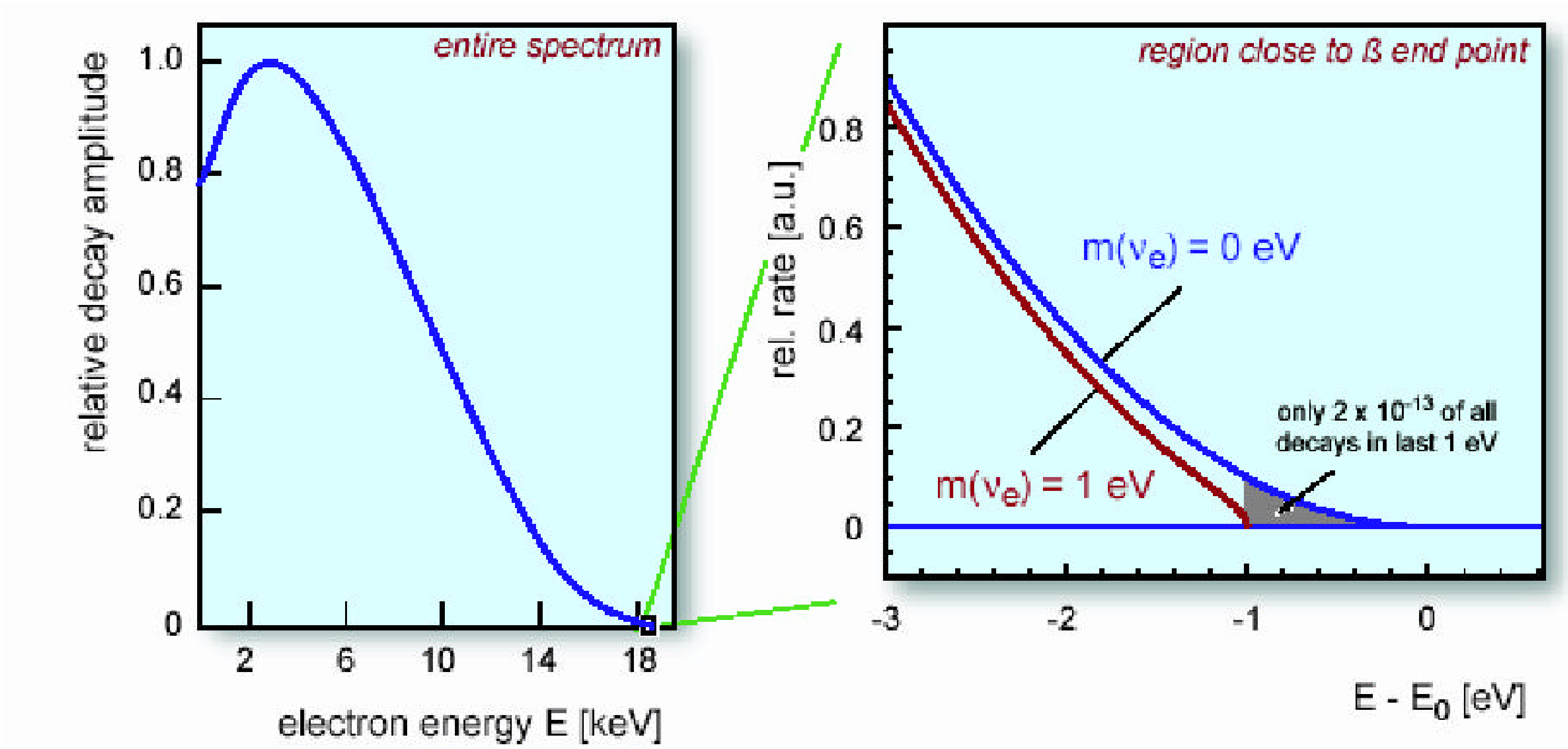
(Also, information from Supernova time-of-flight)



n_e Mass Measurements (Tritium b-decay Searches)

- Search for a distortion in the shape of the β-decay spectrum in the end-point region.

$^3H \rightarrow {}^3He + \nu_e + e^-$



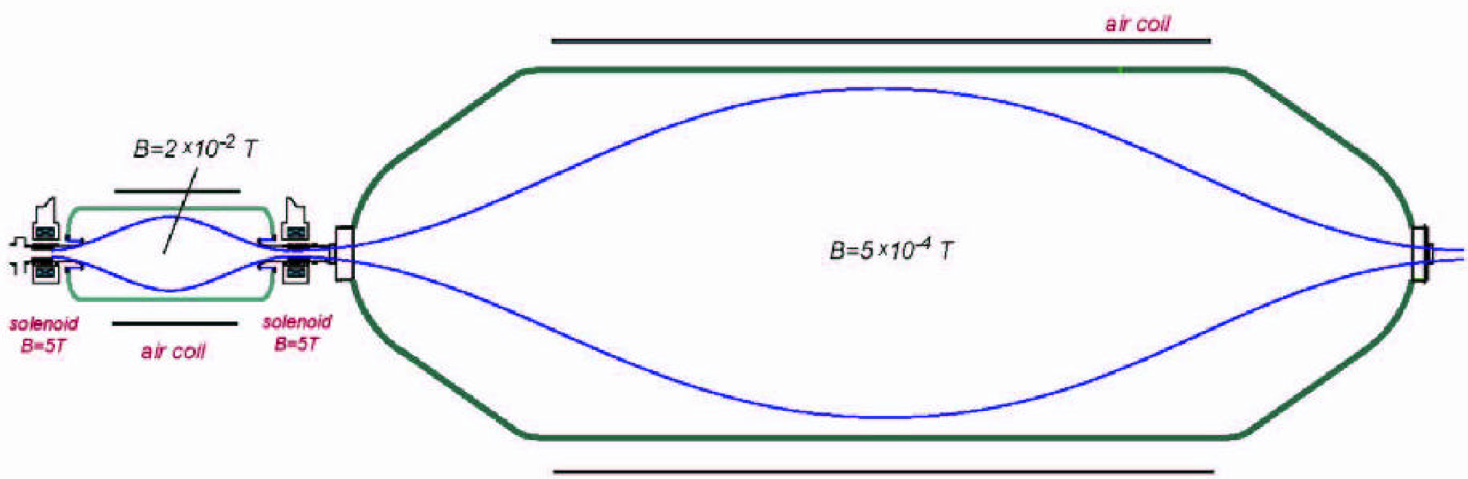
$$dN(E) = K|M|^2F(Z,R,E)\ p_eE\ (E_0\text{-}E)\ \{(E_0\text{-}E)^2\text{-}m^2_{\nu_e}c^4\}^{1/2}\ dE$$

Next Generation b-decay Experiment (dm»0.35 eV)

Karlsruhe Tritium Neutrino Experiment (KATRIN)

next-generation experiment with sub-eV neutrino mass sensitivity

FH Fulda - FZ & U Karlsruhe - U Mainz - INP Prague - U Seattle - INR Troitsk



pre-spectrometer

fixed retarding potential 18.4 kV

Ø = 1.7 m / L = 4.0 m

ΔE = 80 eV

main spectrometer

variable retarding potential 18.5-18.6 kV

Ø = 7 m / L = 20 m

ΔE = 1 eV

Muon Neutrino Mass Studies

- Current best limit from studies of the kinematics of $\pi \rightarrow \mu\, \nu$ decay

$$p_m^2 + m_m^2 = (m_p^2 + m_m^2 - m_n^2)^2 / 4m_p^2$$

- Can use π-decay:
  - **At Rest:**
    Mass of π is dominate uncertainty
  - **In Flight:**
    Resolution on p_π-p_μ limited experimentally

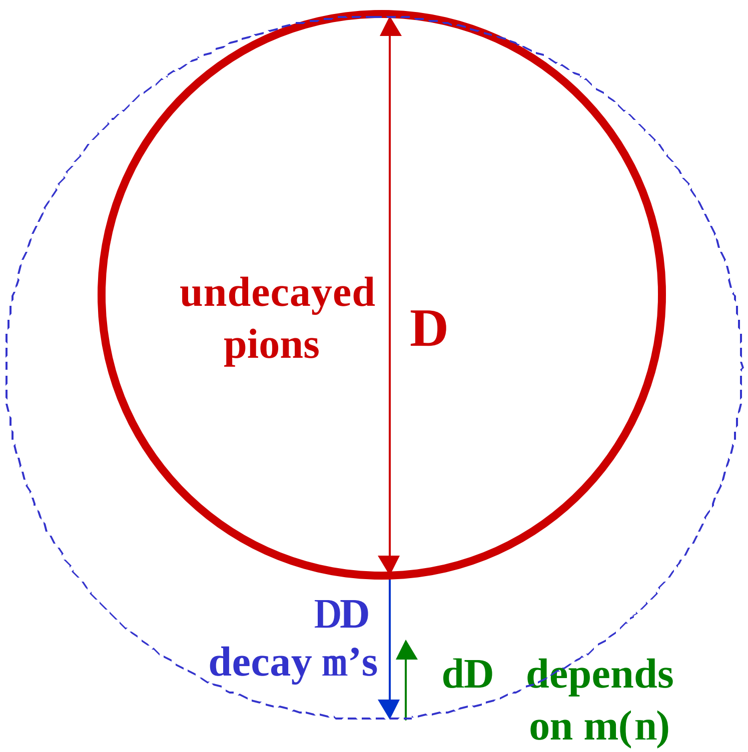
- Best mass limit is from π-decay at rest
  < 170 keV at 95% CL
  (Assamagan *et al*., PRD 1996)

- New BNL Experiment using *g*-*2* setup (sensitivity for > 8 keV)

Proposed BNL “NuMass” Experiment

BNL g-2 Neutrino Mass Experiment

$m(\nu_\mu) < 8$ keV/c^2



Forward-going decay muons orbit a larger diameter by DD

CM

$n_m \longleftarrow \quad p \quad \longrightarrow m$

q = 29.7 MeV/c

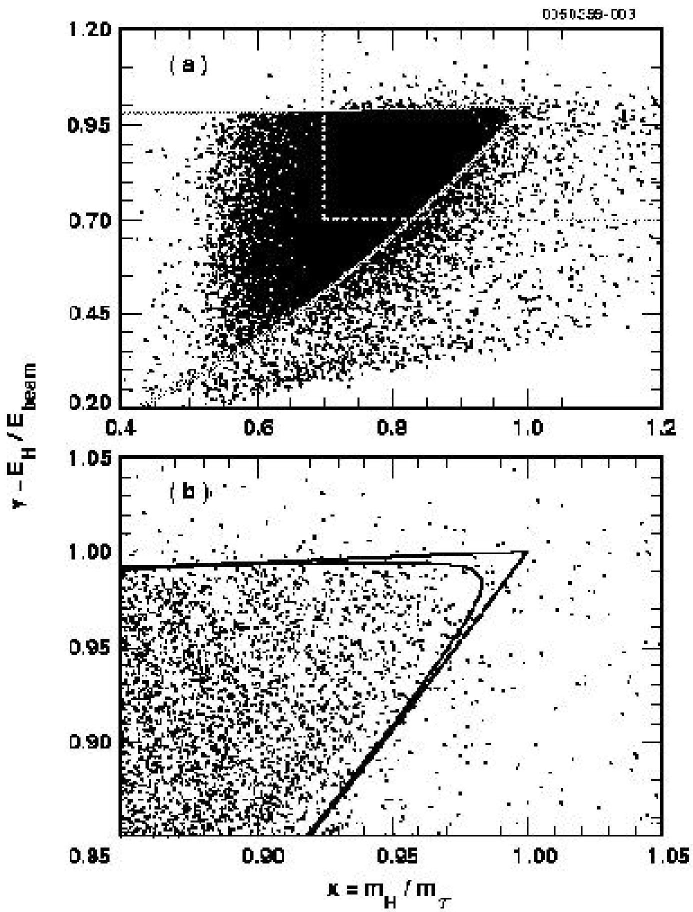
$$\frac{DD}{D} = \frac{p_m - p_p}{p_p} = \frac{0.7\ \text{MeV/c}}{3\ \text{GeV/c}} = \frac{3.26\ \text{mm}}{14\ \text{m}}$$

non-zero m_n shrinks DD

$$\frac{dD}{D} = \frac{-m_n^2}{2\, q\, m_p}$$

0.04 mm for current limit

Direct n_t Mass Limits



- Look at tau decays near the edge of the allowed kinematic range

  $\tau^- \to 2\pi^- \pi^+ \nu_\tau$ and
  $\tau^- \to 3\pi^- \ 2\pi^+ (\pi^0) \nu_\tau$

- Fit to scaled visible energy vs. scaled invariant mass (e.g. hep-ex/9906015, CLEO)

- Best limit is $m(\nu_\tau) < 18.2$ MeV at 95% CL (Aleph, EPJ C2 395 1998)

massive ν_τ
shifts the edge
of the distribution

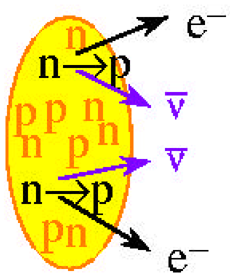
(Outer lines, mass=0;
inner lines, mass=30 MeV)

Double Beta Decay: Are Neutrinos Majorana Particles?

2νββ Decay

- Double-beta decay is transition:
  $(Z,A) \rightarrow (Z+2,A) + (e^- e^- \nu_e \nu_e)$
  Double weak transition $\propto G_F^4$

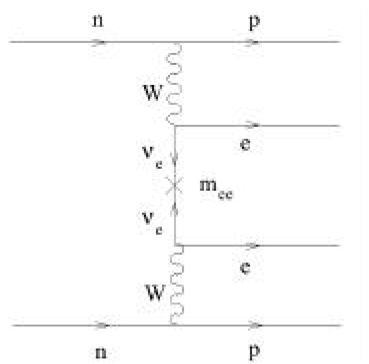
- In certain nuclei, single β–decay is energetically not allowed
  ($^{136}Xe \rightarrow ^{136}Ba$, $^{76}Ge \rightarrow ^{76}Se$, etc.

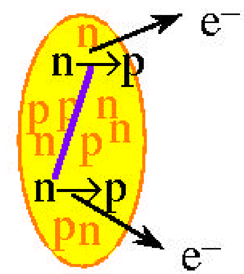


2νββ

0νββ Decay

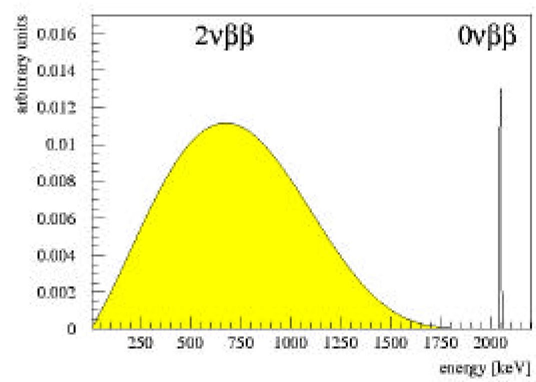
- If neutrinos are Majorana then can have 0ν transitions





0νββ

- Look for 0ν signal beyond the 2ν end point

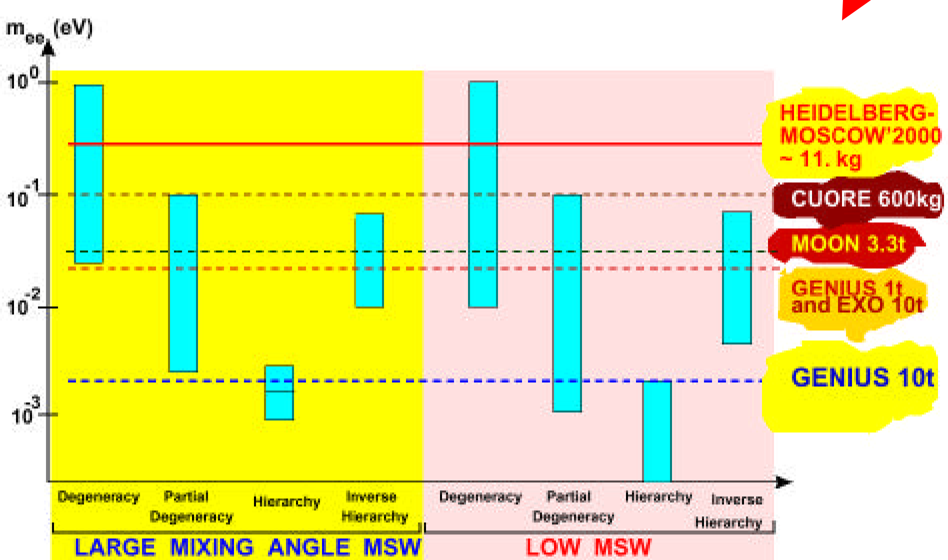


Determine neutrino mass from rate which $\propto (m_\nu/m_e)^2$

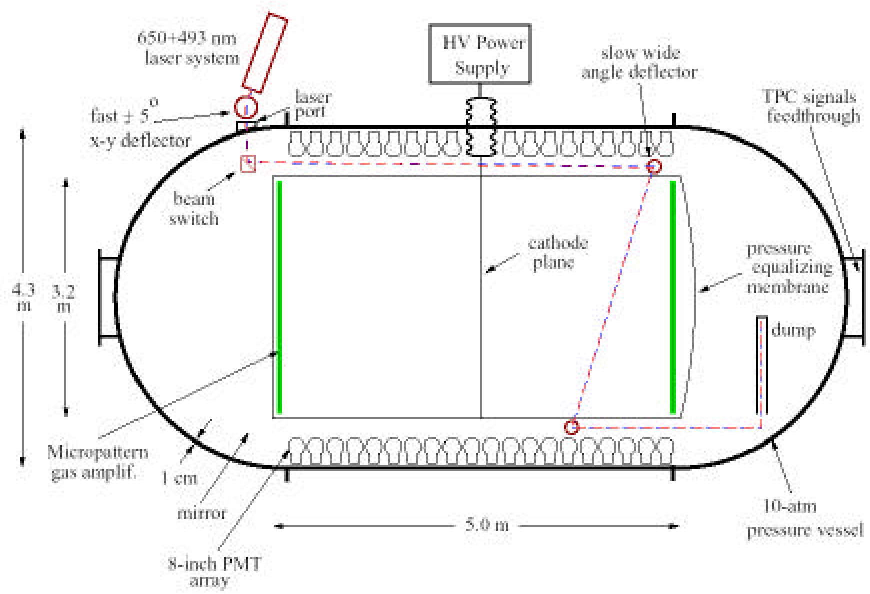
Double Beta Decay Neutrino Mass Searches

- Current best limit comes from Heidelberg-Moscow Experiment using ^{76}Ge

  $m_\nu < 0.2$ eV

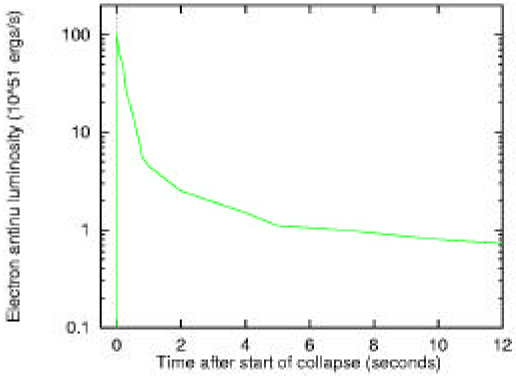


- Proposed next steps:
  - New ^{76}Ge experiments
    increase from kg to tons!
    (GENIUS, ….) ~few x 10^{-3} eV
  - New TPC technique
    $^{136}Xe \rightarrow ^{136}Ba$
    Track both $e^- e^-$ and Ba atom!
    EXO Experiment ~0.01 eV

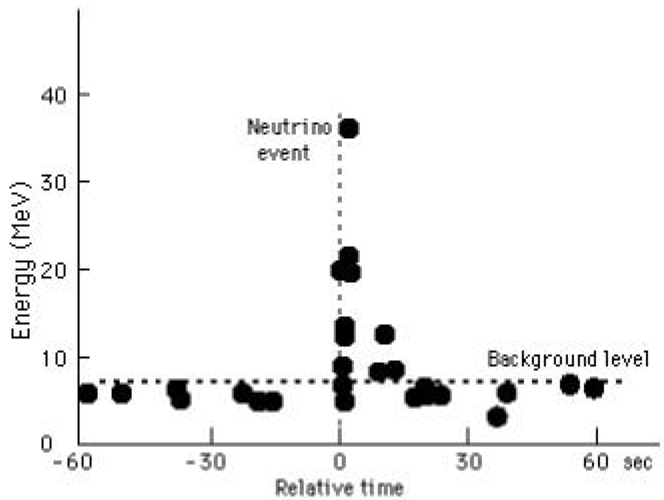


Supernova Neutrinos

- In a super nova explosion
  - Neutrinos escape before the photons
  - Neutrinos carry away ~99% of the energy
  - The rate of escape for ν_e is different from ν_μ and ν_τ (Due extra ν_e CC interactions with electrons)



- Neutrino mass limit can be obtained by the spread in the propagation time
  - $t_{obs}-t_{emit} = t_0 (1 + m^2/2E^2)$
  - Spread in arrival times if $m \neq 0$ due to ΔE



  - For SN1987a assuming emission time is over 4 sec
    $m_\nu < \sim 30$ eV

(All arrived within about ~13 s after traveling 180,000 light years with energies that differed by up to a factor of three. The neutrinos arrived about 18 hours before the light was seen)

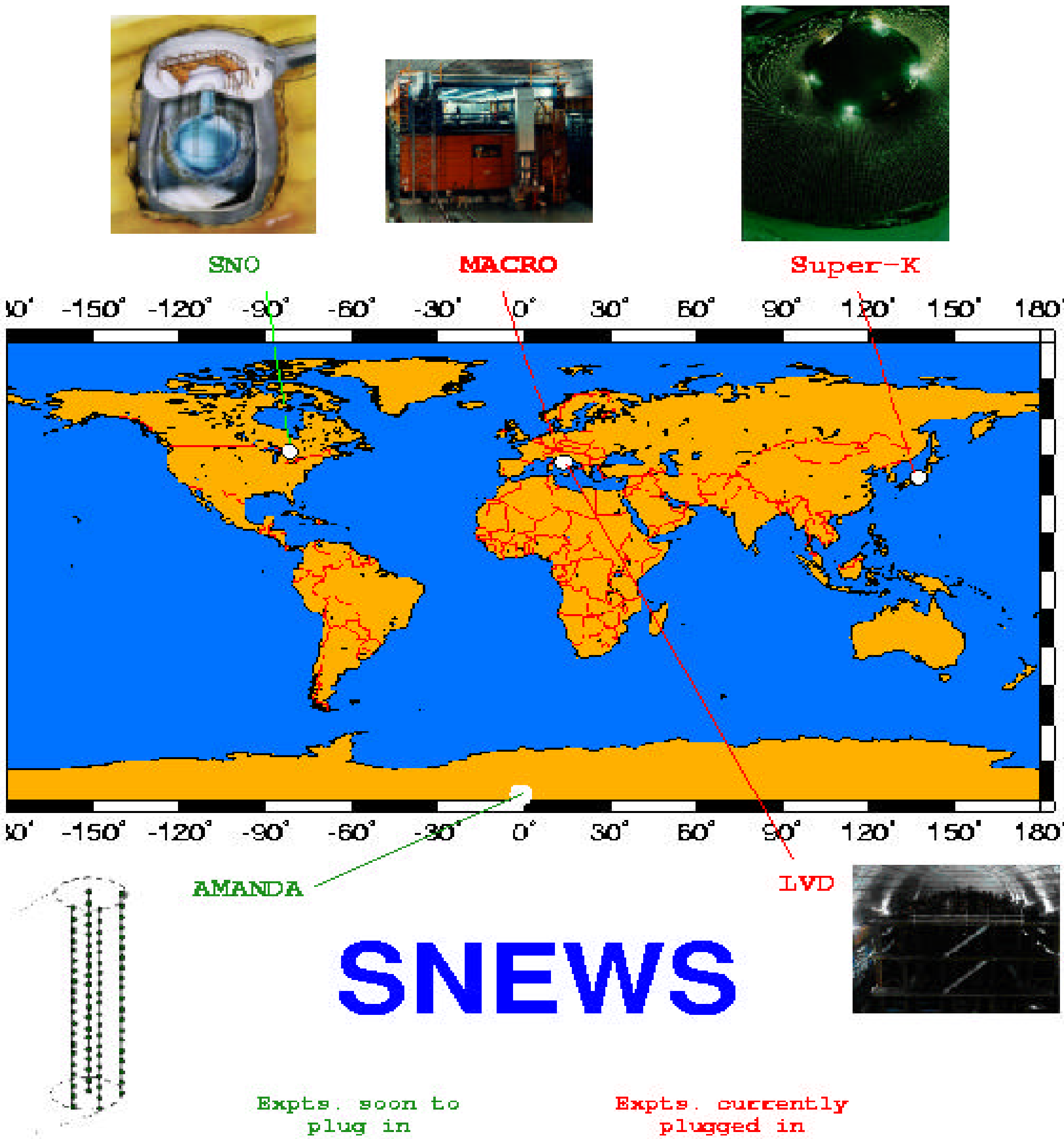
SNEWS
The SuperNova Early Warning Sytem

SNEWS –

- Coincidence trigger between world's ν observatories eliminates instrumental false alarms
- Confidence in such an automated signal allows for FAST enough alarm to beat the photons
- Running in test mode for $\gtrsim 1$ year, will release automated alarms sometime in 2000

What is to be gained from an early warning?

- UV/soft X-ray flash at shock breakout predicted.
- Environment near progenitor star is probed by the initial stages of the collapse.
- Possible unknown early effects. Who knows what we're missing when observing SN at Mpc distances starting days after the explosion?



Neutrino Oscillation Phenomenology

Neutrino Oscillations

- Direct measurements have difficulty probing small neutrino masses

  ⇒ *Use neutrino oscillations*

- If we postulate:
  - Neutrinos have (different) mass
  - The ***Weak Eigenstates*** are a mixture of ***Mass Eigenstates***

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Then a pure ν_μ beam at t=0, will develop a ν_e component with time.

The Probability for Oscillations...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

Derivation of Oscillation Formula

(A favorite graduate exam problem)

Take the mixing matrix to be:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

At production $(t = 0:)$

$$|\nu_\mu(0)\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

At a later time:

$$\begin{aligned} |\psi(t)\rangle &= -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle \\ &= (\cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t})|\nu_e\rangle + \\ &\qquad \sin\theta\cos\theta(e^{-iE_2 t} - e^{-iE_1 t})|\nu_\mu\rangle \end{aligned}$$

And the probability is:

$$\begin{aligned} P_{osc} &= |\langle\nu_e|\psi(t)\rangle|^2 \\ &= \frac{1}{2}\sin^2 2\theta[1 - cos(E_2 - E_1)t] \end{aligned}$$

Use $E_1 = \sqrt{p^2 - m_1^2} \approx p + m_1^2/2p$ (and same for E_2)
and $(t/p) = (tc)/(pc) = L/E$; then convert to "real" units

$$\begin{aligned} P_{osc} &\approx \frac{1}{2}\sin^2 2\theta\left(1 - cos\left(\frac{(m_2^2 - m_1^2)L}{E}\right)\right) \\ &= \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E) \end{aligned}$$

See if you can derive the 1.27 factor in the formula by recovering from the hbar = c =1.

Neutrino Oscillation Formalism

- Most analyses assume 2-generation mixing

$$\begin{pmatrix} n_e \\ n_m \end{pmatrix} = \begin{pmatrix} \cos q & \sin q \\ -\sin q & \cos q \end{pmatrix} \begin{pmatrix} n_1 \\ n_e \end{pmatrix} \qquad P(n_m \rightarrow n_e) = \sin^2 2q \, \sin^2(1.27\Delta m^2 L / E)$$

- But we have 3-generations: ν_e , ν_μ, and ν_τ (and maybe even more ….. the sterile neutrino ν_s's)

$$\begin{pmatrix} n_e \\ n_m \\ n_t \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-id} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{id} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{id} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{id} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix}$$

CKM-like Mixing Matrix for Leptons

(In this 3-generation model, there are 3 Δm^2's but only two are independent.) $\Delta m_{12}^2 = m_1^2 - m_2^2$, $\Delta m_{23}^2 = m_2^2 - m_3^2$, $\Delta m_{31}^2 = m_3^2 - m_1^2$

- At each Δm^2, there can be oscillations between all the neutrino flavors with different mixing angle combinations.

For example:
(3 sets of 3 equations like these)

$$P(n_m \rightarrow n_t) = \cos^4 q_{13} \sin^2 2q_{23} \sin^2(1.27\Delta m_{32}^2 L / E_n)$$
$$P(n_m \rightarrow n_e) = \sin^2 q_{23} \sin^2 2q_{13} \sin^2(1.27\Delta m_{32}^2 L / E_n)$$
$$P(n_e \rightarrow n_t) = \cos^2 q_{23} \sin^2 2q_{13} \sin^2(1.27\Delta m_{32}^2 L / E_n)$$

$\nu_\mu \rightarrow \nu_e$ at the same Δm^2 as $\nu_\mu \rightarrow \nu_\tau$

CP Violation in Neutrino Oscillations

- Disappearance measurements cannot see CP violation effect
- $$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$
- Very, very hard to see CP violation effects in exclusive (appearance) measurements. (From B. Kayser)
  - Only can see CP violation effects if an experiment is sensitive to oscillations involving at least three types of neutrinos.

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4\,\mathrm{Im}\left(U_{\mu 1} U^*_{e1} U^*_{\mu 3} U_{e3}\right)(s_{12} + s_{23} + s_{31})$$

where $s_{ij} = \sin\left(\delta m^2_{ij} L/2E\right)$ and $\delta m^2_{ij} = m_i^2 - m_j^2$

  - All the terms (s_{12}, s_{13}, s_{23}) must not be <<1 or effectively becomes only two component oscillation
    - For example, if $s_{31} \approx 0$ then $s_{12} \approx -s_{23} \Rightarrow s_{12} + s_{31} + s_{23} \approx 0$

⇒ **To see CP violation must be sensitive to all three neutrino oscillations**
i.e. the hardest is usually the lowest (solar neutrino)
$\Delta m^2 \approx 10^{-4} - 10^{-10}$ eV^2

Oscillation Formula Parameters

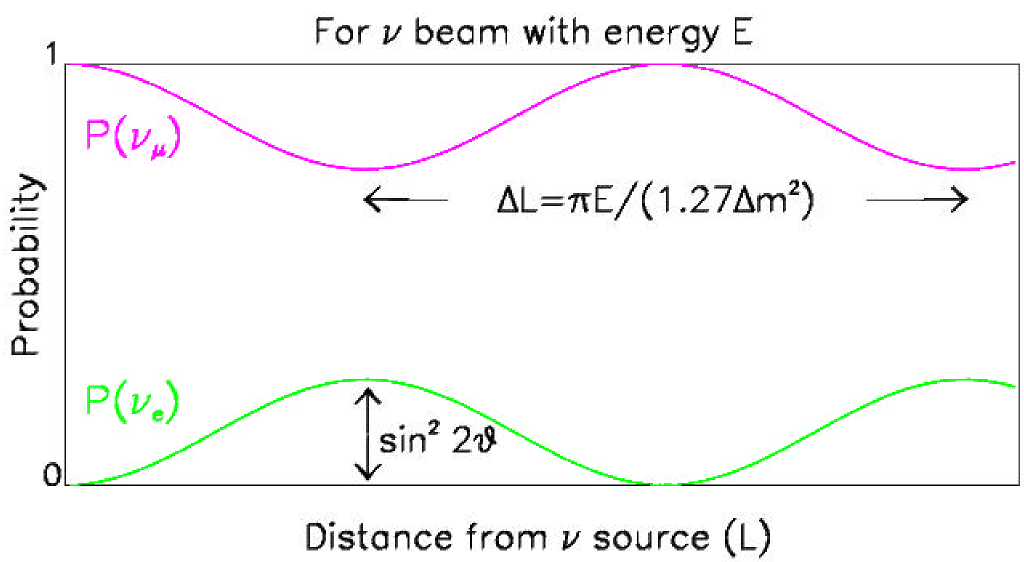
$$P_{Osc} = \sin^2 2q \ \sin^2\left(1.27\Delta m^2 L / E\right)$$

...Depends Upon Two Experimental Parameters:

- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:

- $\Delta m^2 = m_1^2 - m_2^2 \quad (eV^2)$
- $\sin^2 2\theta$

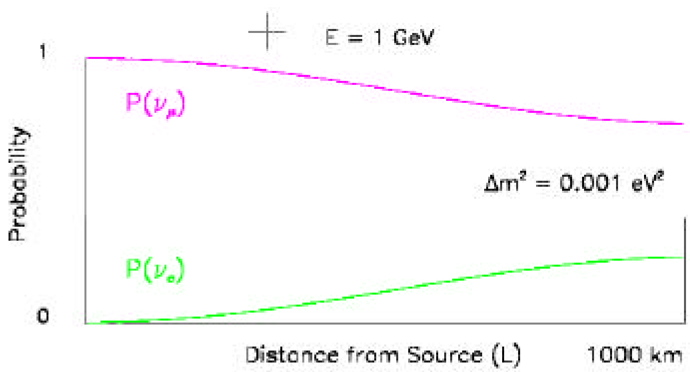


Oscillation Phenomenology

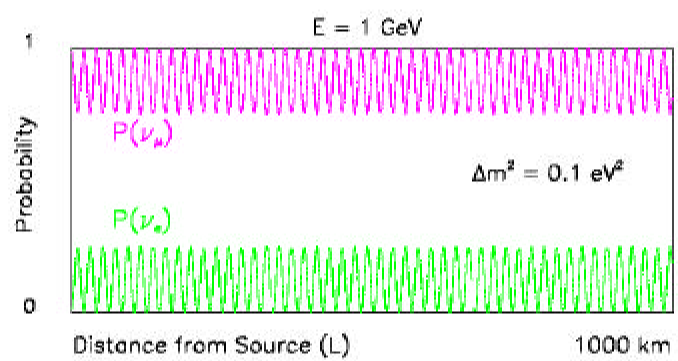
- Two types of oscillation searches:
  - ***Appearance Experiment:***
    Look for appearance of ν_e or ν_τ in a pure ν_μ beam vs. L and E
    - Need to know the backgrounds
  - ***Disappearance Experiment:***
    Look for a change in ν_μ flux as a function of L and E
    - Need to know the flux and cross sections

- $P_{osc} = \sin^2 2\theta \sin^2(1.27\ \Delta m^2\ L/E)$ sets the details of search
  - Mixing angle $\sin^2 2\theta$ sets the needed statistics

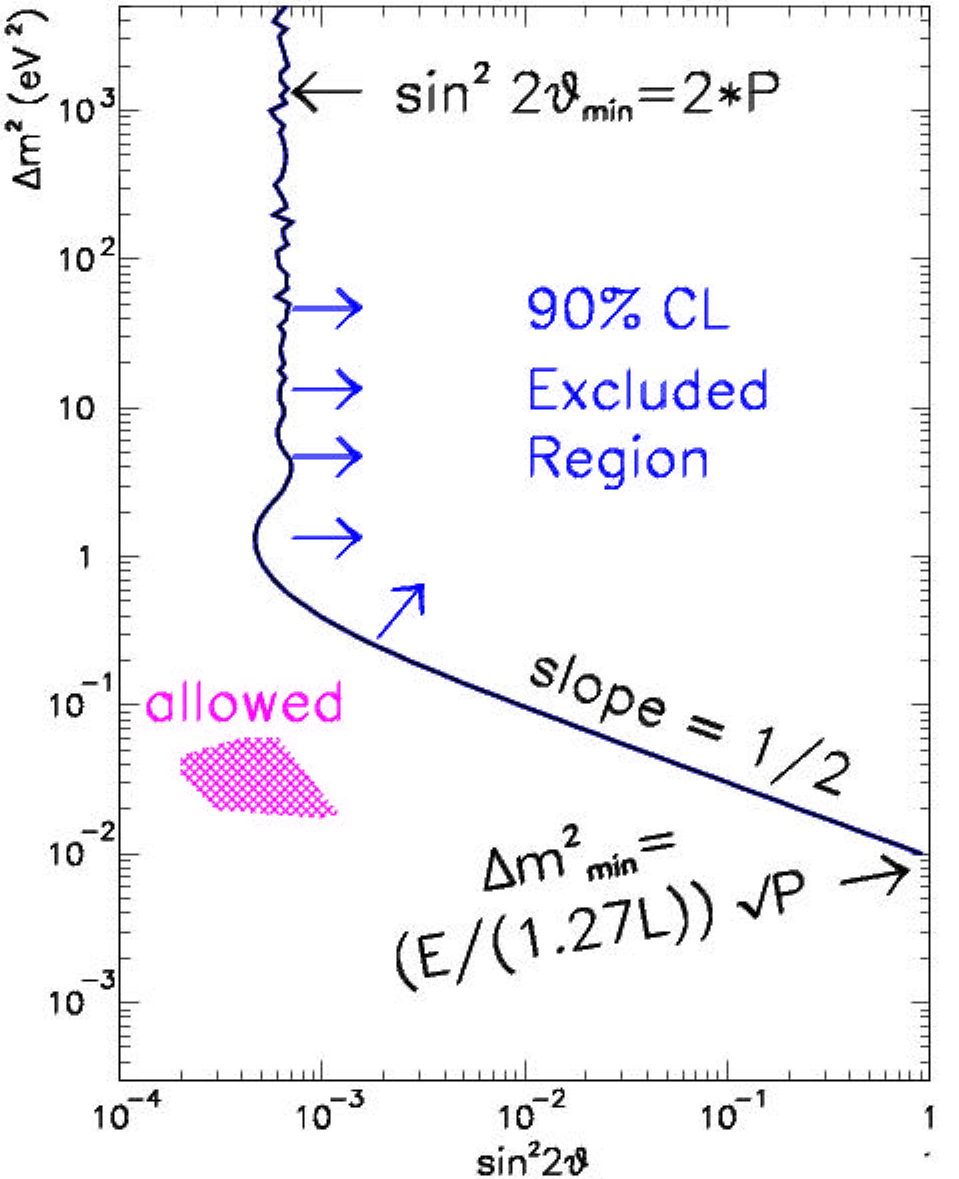
Small Dm^2 (Need large L/E)



Large Dm^2: <sin^2(1.27 Dm^2 L/E)>=1/2



Oscillation Plots



- If you see an oscillation signal with

  $P_{osc} = P \pm dP$

  then carve out an **allowed region** in (Δm^2,$\sin^2 2\theta$) plane.

- If you see no signal and limit oscillation with

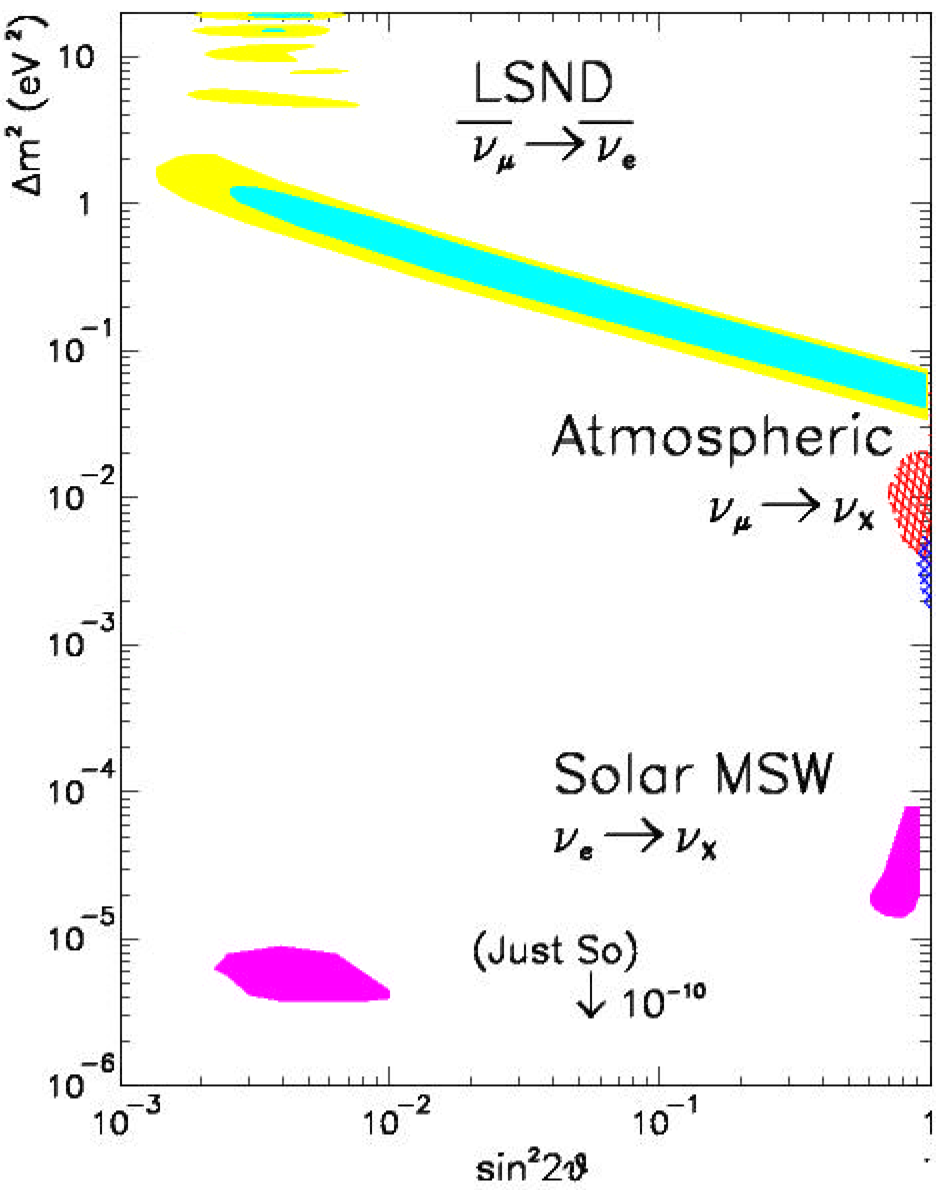
  $P_{osc} < P$ @ 90% CL

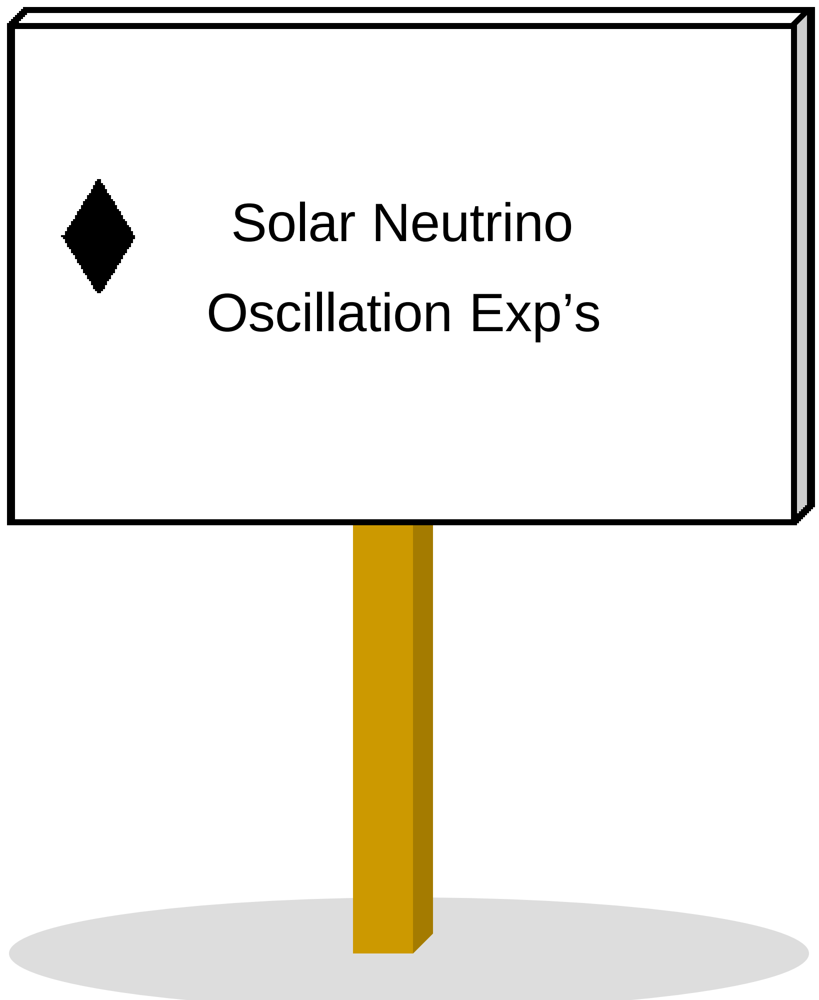
  then carve out an **excluded region** in the (Δm^2,$\sin^2 2\theta$) plane.

Current Neutrino Oscillation Signals

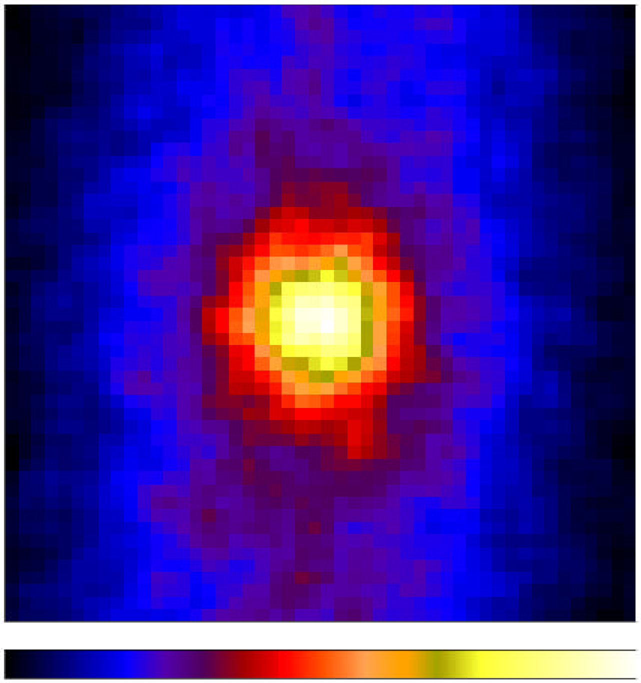
- Three Positive Signals
  - Solar Neutrinos
  - Atmospheric Neutrinos
  - Low-E Accelerator Neutrinos
- Many negative searches

Go thru results of each area and try to fit things together




♦ Solar Neutrino
Oscillation Exp's

Solar Neutrino Deficit



Super- K (Japan) image of the sun using neutrinos

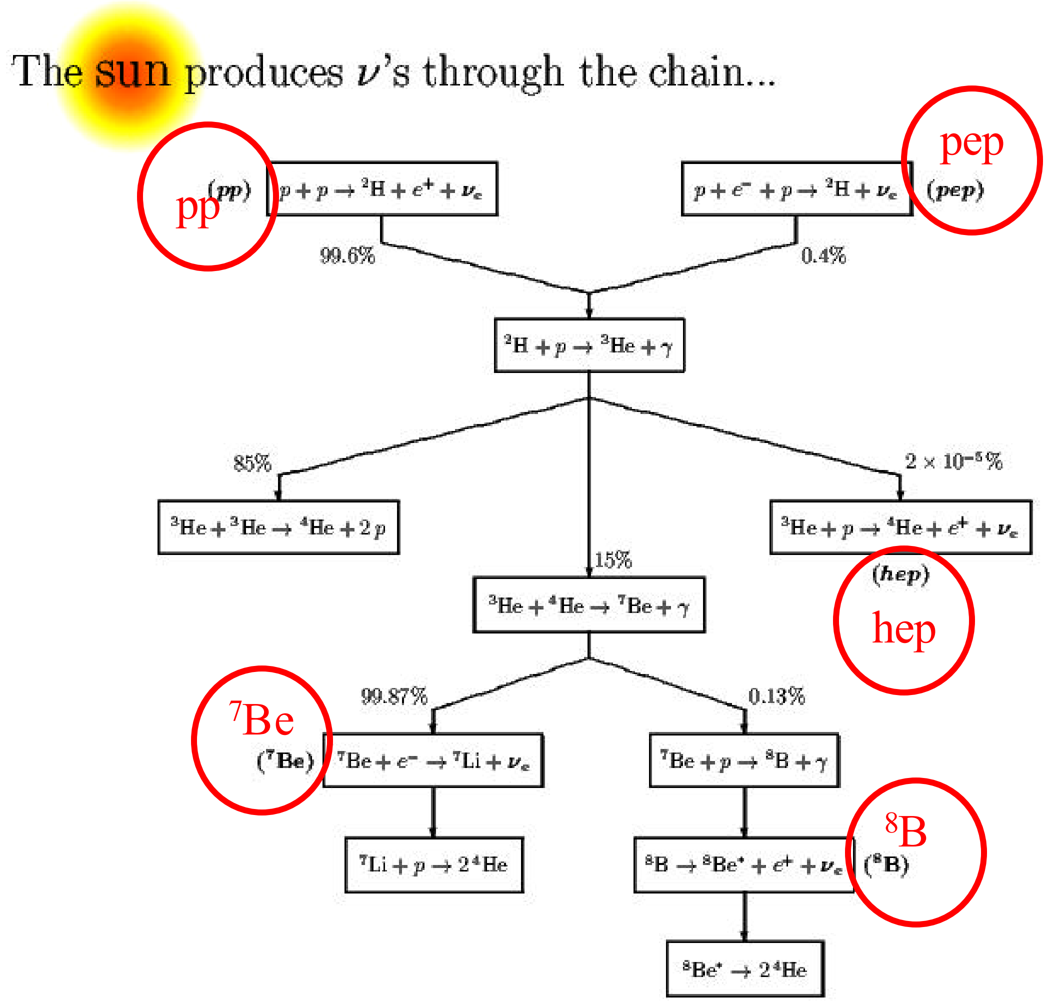
Flux of solar neutrinos detected at the earth is much less than expected

⇒ Is it due to neutrino oscillations?

- The "Standard Solar Model"
- Wide range of measurement techniques
- How does it fit into a oscillation hypothesis?
  - Several possible oscillation scenarios fit data
- Remaining questions and future plans

Standard Solar Model

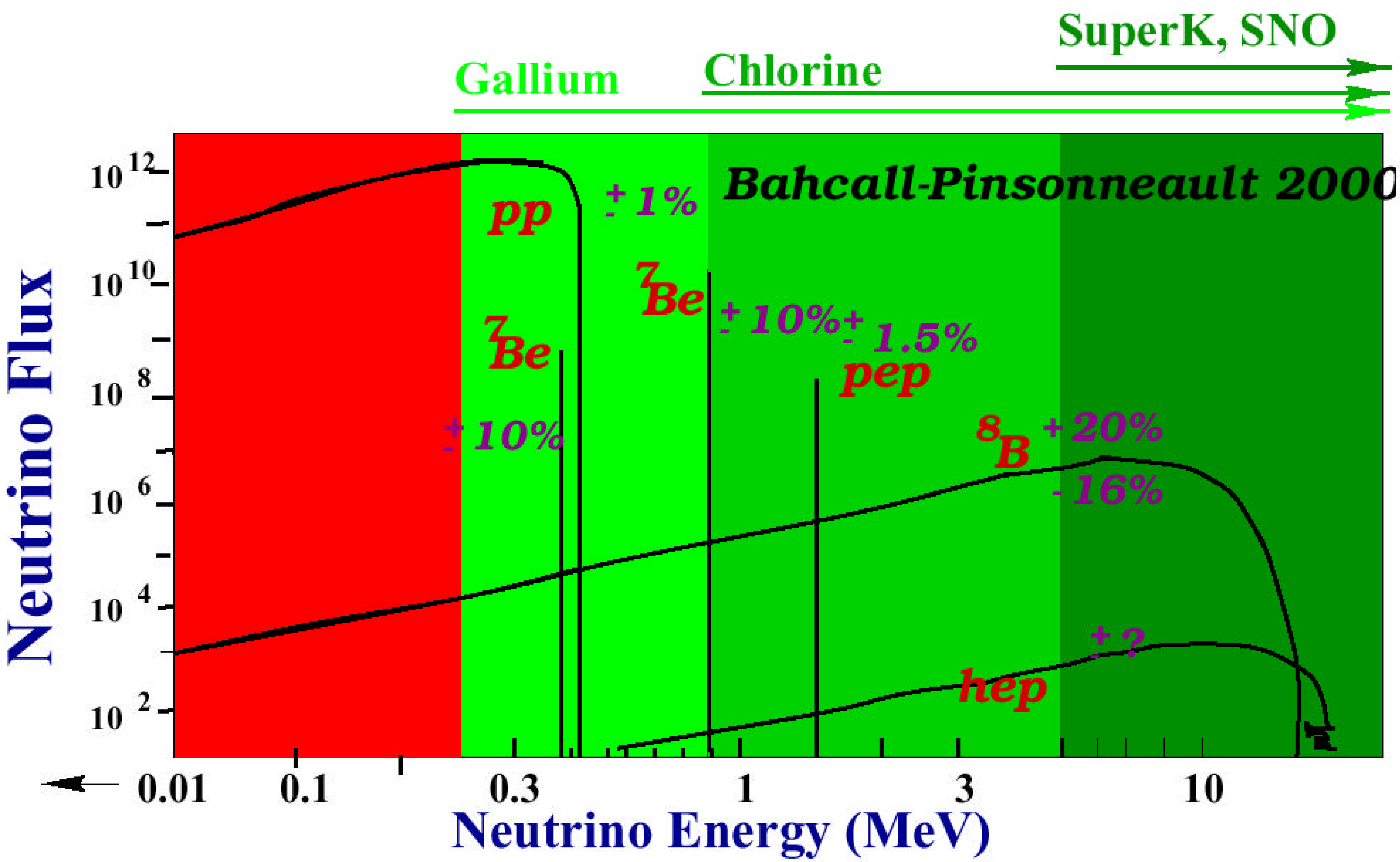
- Stellar evolution models:
  - Hydrodynamic equilibrium between pressure and gravity
  - Energy transport by radiation and convection
  - Energy production by nuclear reactions
    - Can produce ν's here
- Many experimental and theoretical inputs:
  - Age, luminosity, opacity, abundances, radius, surface temp, core temp, core density, diffusion parameters.
- Ouput:
  - Temp(r), density(r)
  - ***Neutrino Flux***



But how big are the uncertainties

Solar Neutrino Spectrum

- Many fusion processes in the sun lead to neutrinos
- Solar model predicts flux
  - From solar luminosity, main pp neutrino flux known to 1%
  - ^{7}Be and ^{8}B neutrinos 10% to 20% uncertainties



Solar Neutrino Experiments

- Solar neutrino cross sections

  …… are very, very small

  - At these energies $\sigma_\nu \sim 10^{-45}$ cm^2
  - With flux of 10^{10}/cm^2/s and 10^{30} atoms $\rightarrow$ 1 event / day

  – Introduce new unit …… ***"The SNU"***

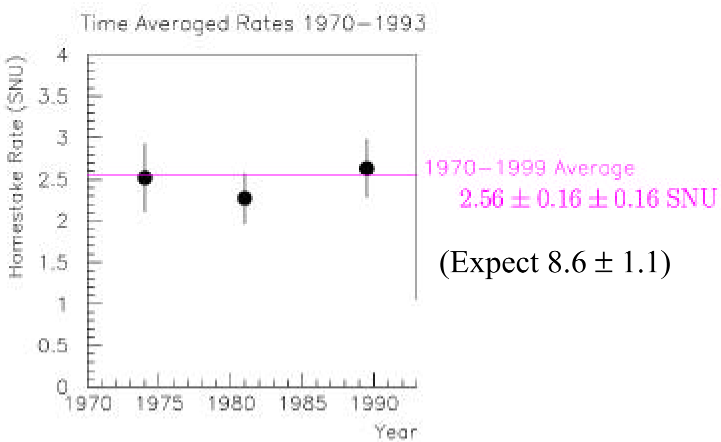
  - 1 SNU = 10^{-36} captures / target atom / s

- Two types of experiments:
  – Chemical Extraction experiments
  - Homestake ("Chlorine") $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
  - Sage and Gallex ("Gallium") $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

  – Scattering experiments
  - SuperKamioka (Kamioka) (Light water) $\nu_x + e^- \rightarrow \nu_x + e^-$
  - SNO (Heavy water) $\nu_e + d \rightarrow e^- + p + p$
    $\nu_x + d \rightarrow \nu_x + n + p$

Chemical Extraction Experiments

- Homestake: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
  - Located in Lead, SD
  - 615 tons of C_2Cl_4 (Cleaning fluid)
  - Extraction method:
    - Pump in He that displaces Ar
    - Collect Ar in charcoal traps
    - Count Ar using radioactive decay
  - Systematic errors ~ 7%



- Gallium Exps: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
  - GALLEX (Gran Sasso, Italy) uses aqueous gallium chloride (101 tons)
  - SAGE (Baksan,Russia) uses metallic gallium (57 tons)
  - Extraction method:
    - Synthesized into GeH_4
    - Inserted into Xe prop. Counters
    - Detect x-rays and Auger electrons

Sage : 67 ± 8 SNU

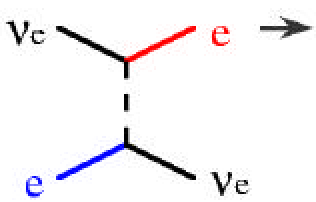
Gallex: 78 ± 6 SNU

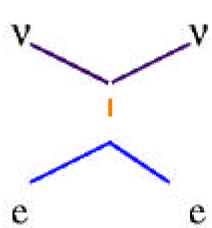
(Expect 130 ± 1.1)

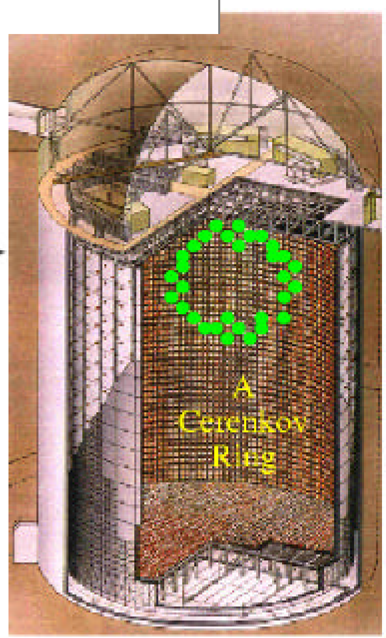
Super-K Experiment
H_2O Cerenkov Detectors

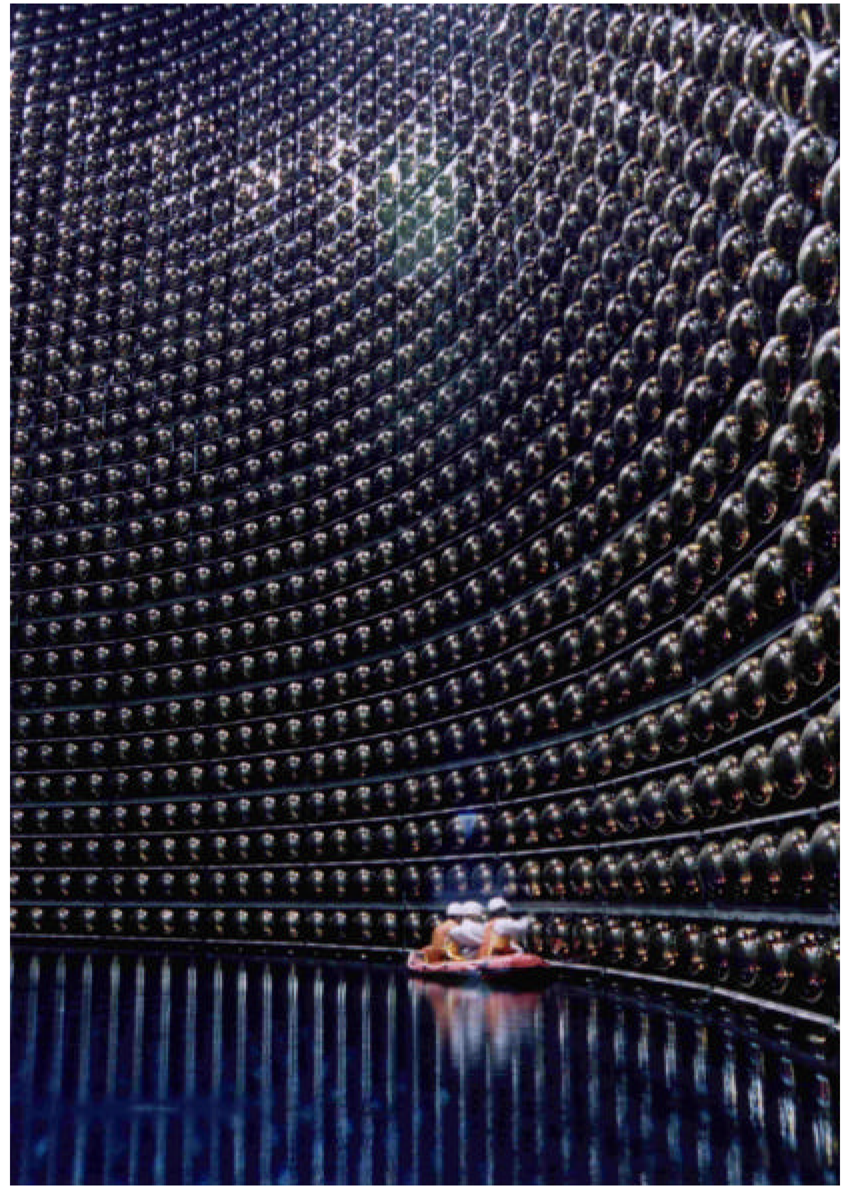
- SuperK
  - 22.5 kton fiducial volume
  - 36 m high, 34 m diam.
  - 11,146 phototubes (50 cm)
  - Energy threshold: 6.5 MeV
  - Linac (5 – 16 MeV) for in-situ calibration

Both NC & CC scatters



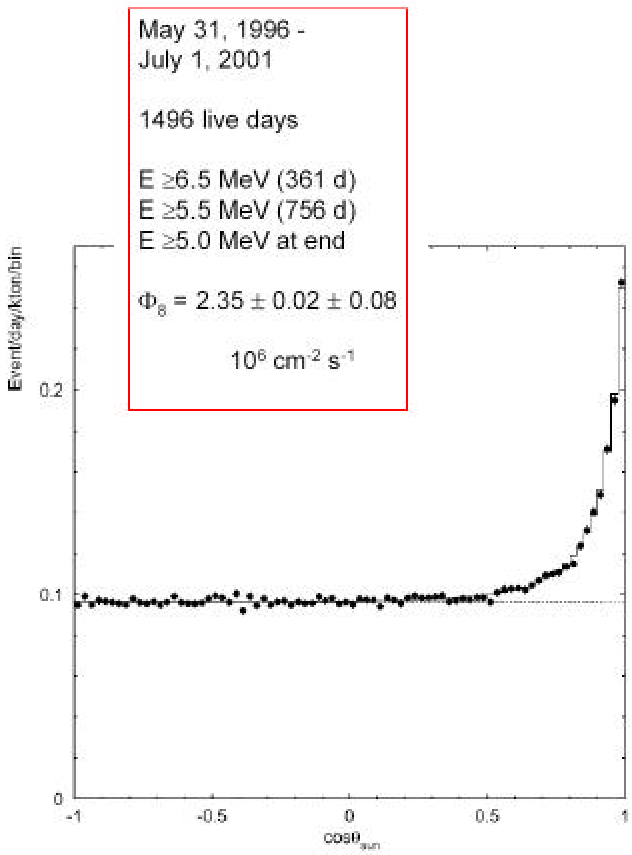


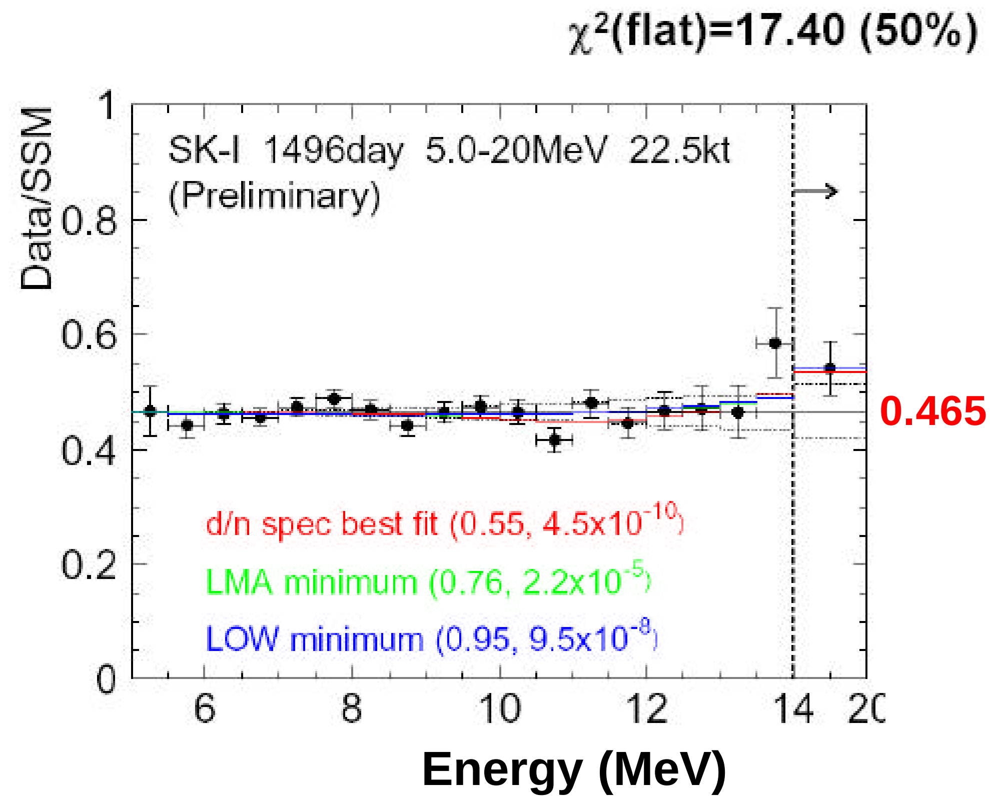




Super-K Results

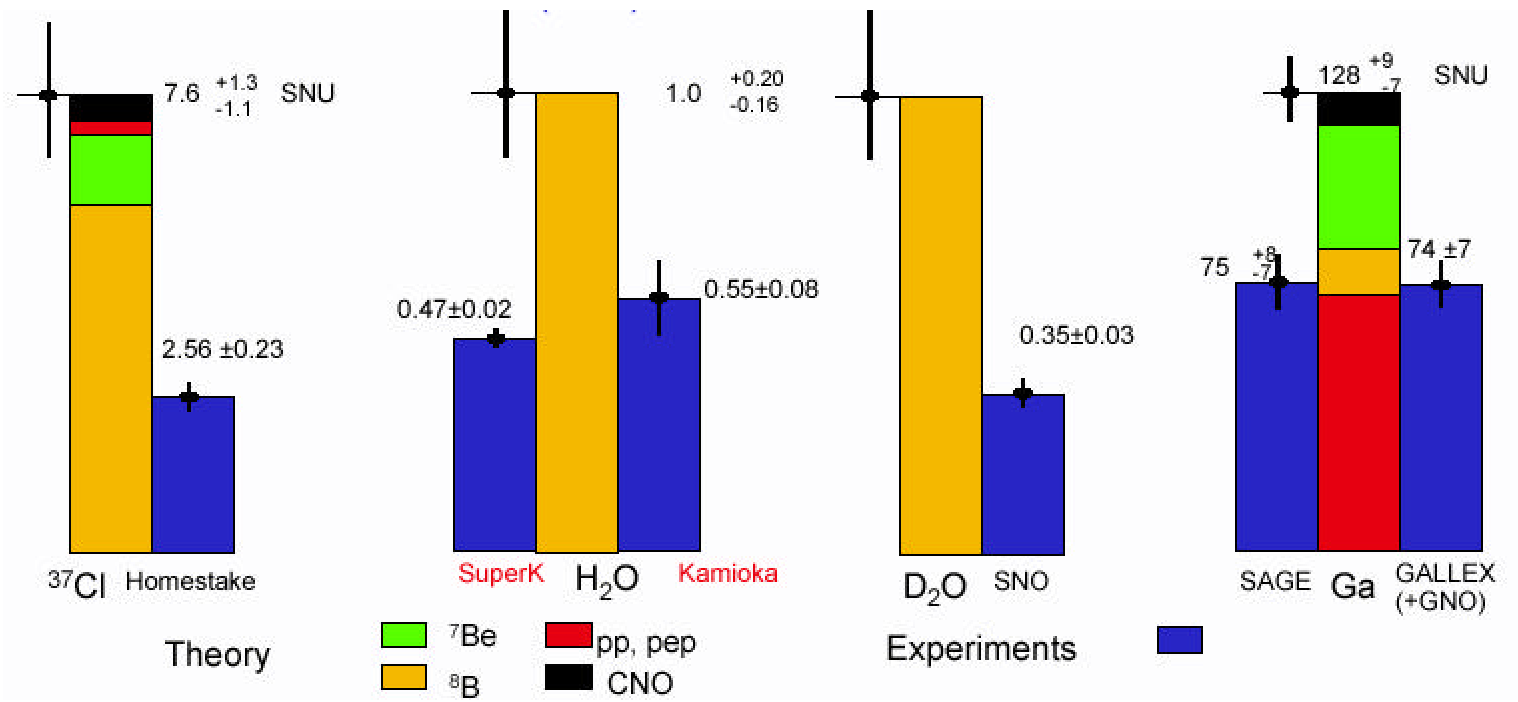
- Super-K has good angular, energy, and time resolution
  - Sensitivity to seasonal variations
  - Sensitive to day/night variations
  - Ability to “see” the sun



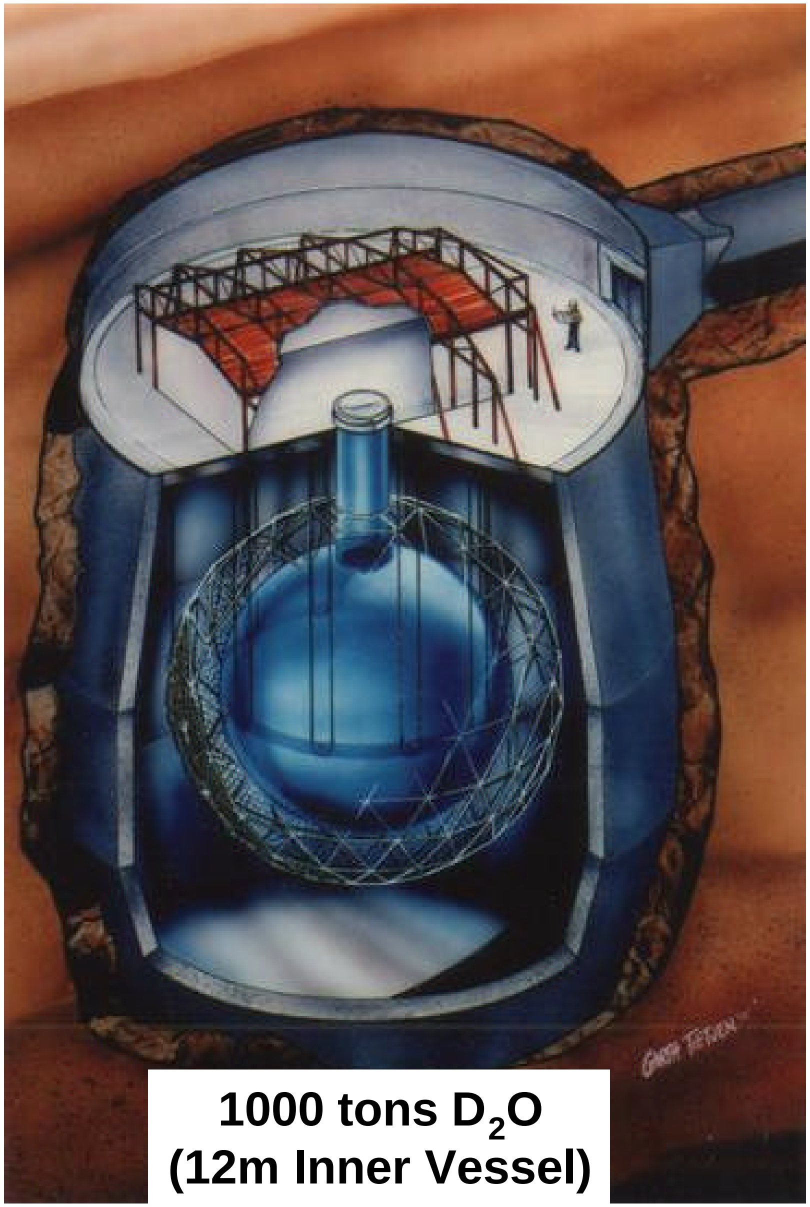


Solar Neutrino Experiments

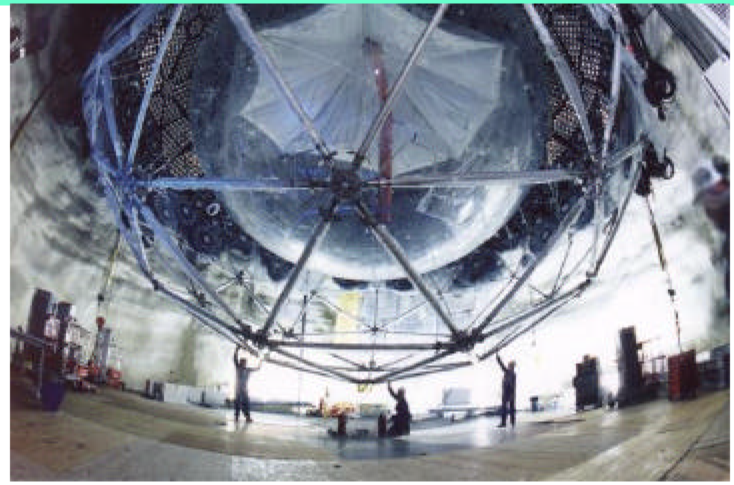
Rate measurement	Reaction	Obs / Theory
• Homestake (US)	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
• SAGE (Russia)	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.59 ± 0.06
• Gallex+GNO (Italy)	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.58 ± 0.05
• Super-K (Japan) H_2O	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.46 ± 0.02
• SNO (Canada) D_2O	$\nu_e + d \rightarrow p + p + e^-$	0.35 ± 0.03



Sudbury Neutrino Observatory (SNO)



1000 tons D_2O
(12m Inner Vessel)



- Advantages of Heavy vs Light Water
  - $\nu_e + d \rightarrow p + p + e^-$ (D_2O)
  - $\nu_e + e^- \rightarrow \nu_e + e^-$ (H_2O or D_2O)
  - Cross section $\propto (E_{cm})^2 = s$
    - $s = 2\, m_{target}\, E_\nu$
      $\Rightarrow s_N/s_{e-} = M_p/M_e \approx 2000$
  - But x5 more electrons in H_2O than n's

SNO (1kton) 8.1 CC events/day
SuperK (22ktons) 25 events/day

SNO Results

ν Reactions in Heavy Water

CC $\nu_e + d \Rightarrow p + p + e^-$

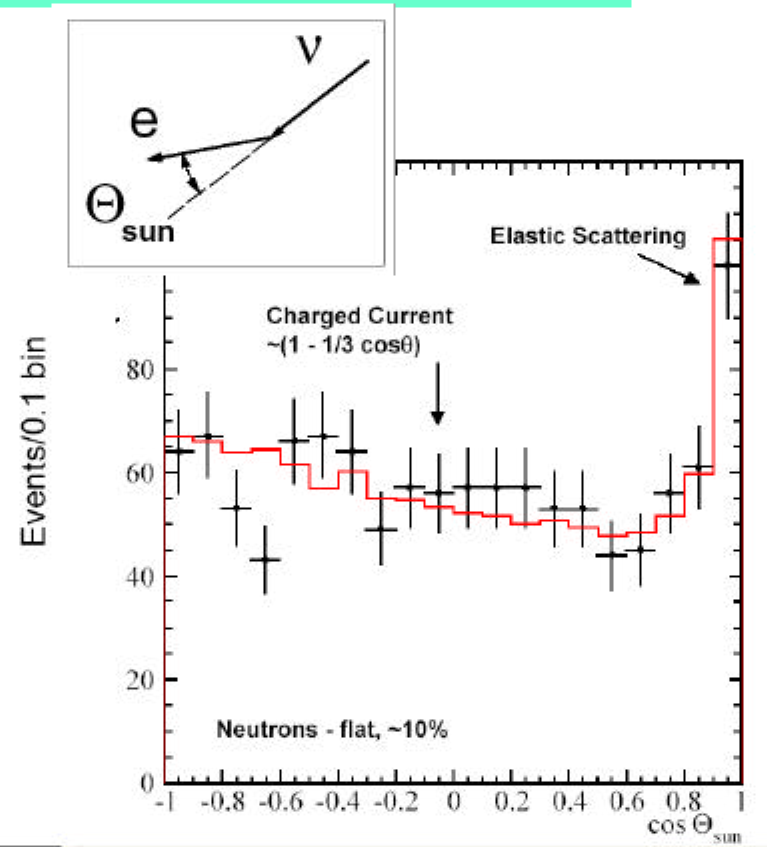
- "Charged Current"
- ν_e only.

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- "Neutral Current"
- Equal cross section for all active ν types

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

- "Elastic Scattering"
- Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ



Measure total flux of solar neutrinos vs. the pure ν_e flux

Charged-Current to Neutral Current ratio is a direct signature for oscillations

$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

CC/ES Could also show significant effects

$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.15(\nu_\mu + \nu_\tau)}$$

ES = Elastic Scattering

- **ν_e = NC + CC**
- **ν_μ or ν_τ = NC only**

SNO Physics

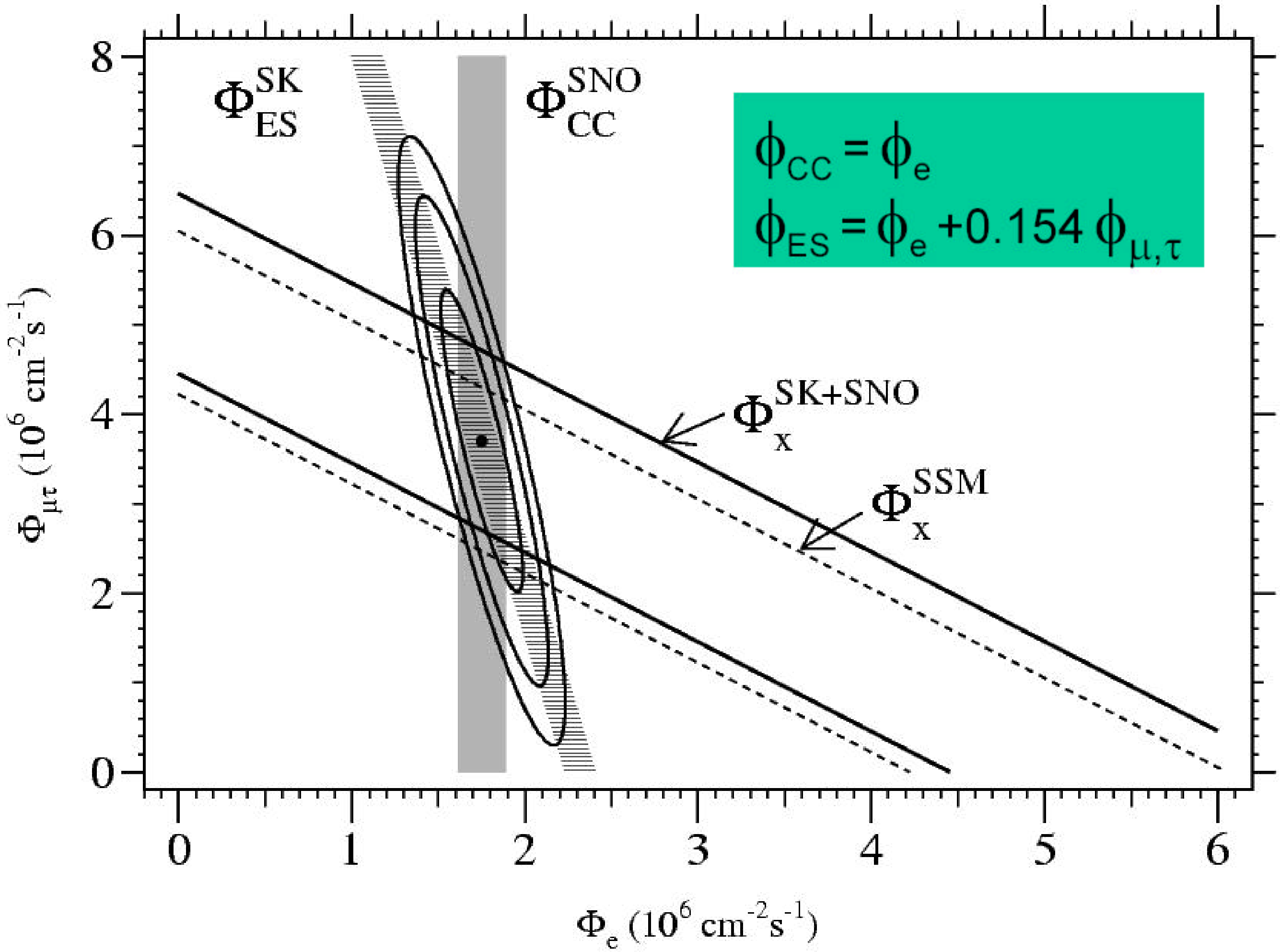
- First measurement of the total flux of ^{8}B neutrinos:

$\phi_{total}(^8B) = 5.44 \pm 0.99 \times 10^6\ cm^{-2}\ s^{-1}$

Agrees well with solar models:

$\phi_{SSMI}(^8B) = 5.05 \pm 0.80 \times 10^6\ cm^{-2}\ s^{-1}$ (BPB01)

Þ **Solar Oscillations not totally to sterile neutrinos**



Solar Neutrino Experiments

Rate measurement	Reaction	Obs / Theory
• Homestake (US)	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
• SAGE (Russia)	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.59 ± 0.06
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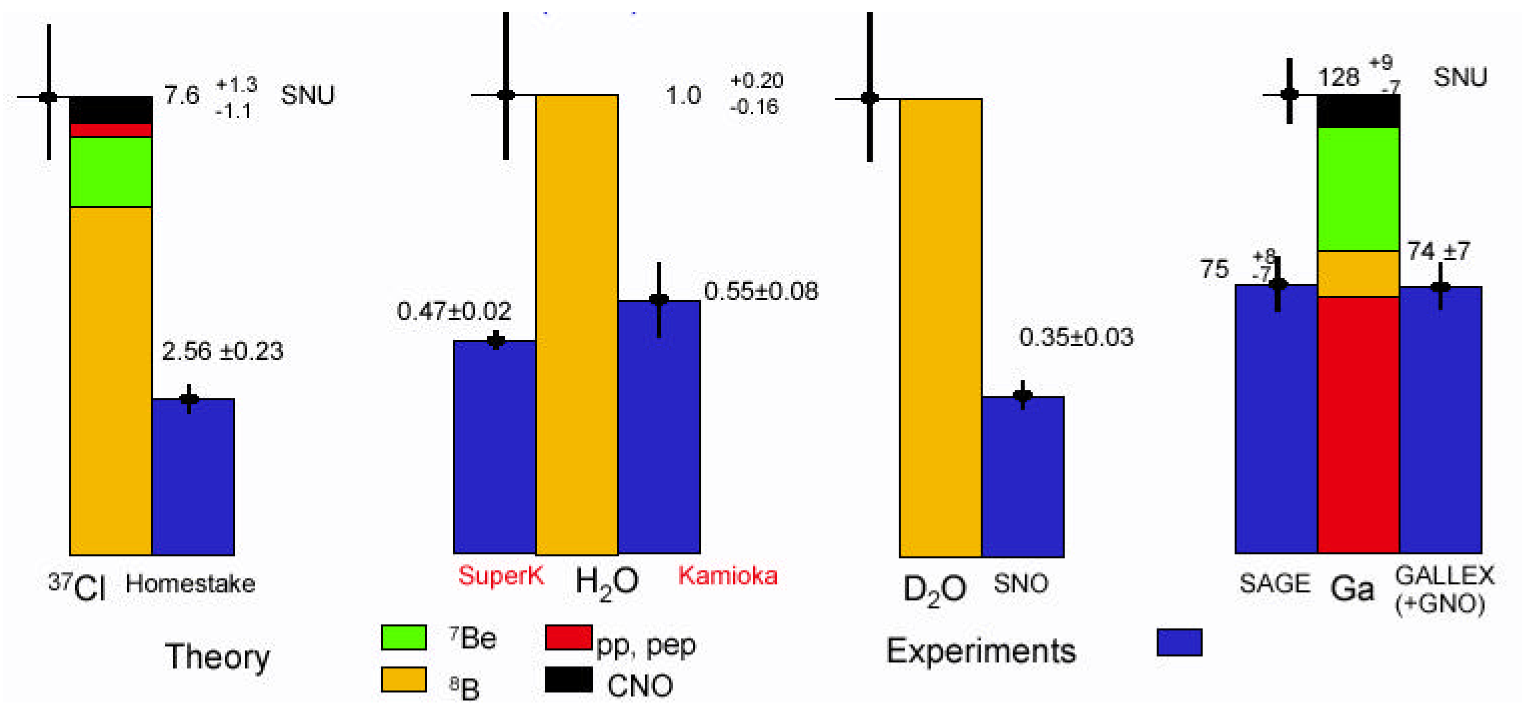
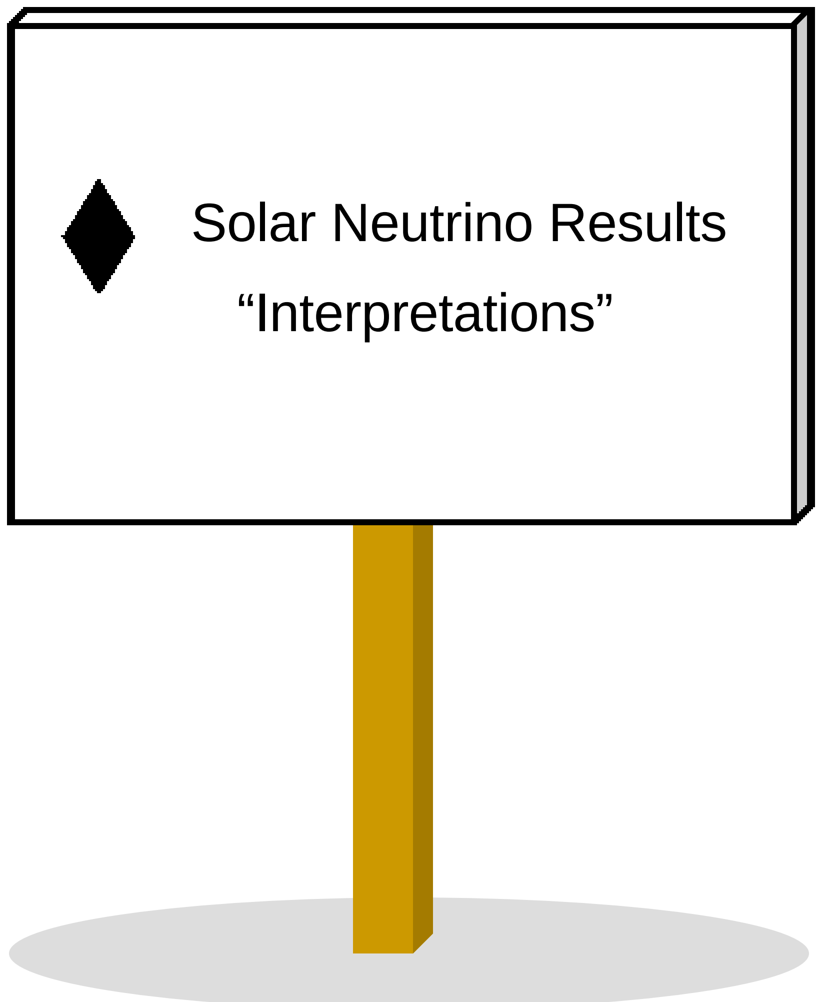
• Super-K (Japan) H_2O	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.46 ± 0.02
• SNO (Canada) D_2O	$\nu_e + d \rightarrow p + p + e^-$	0.35 ± 0.03

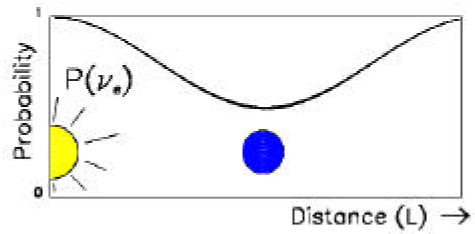
Limits osc to ν_s <50% @ 90%CL



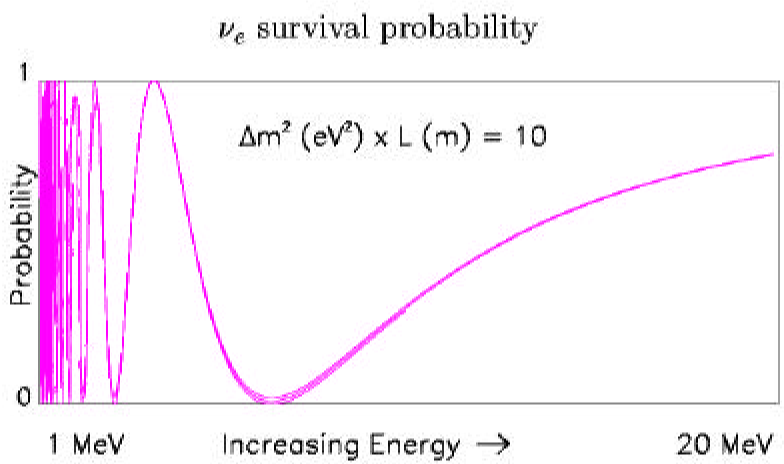

Solar Neutrino Results
“Interpretations”

Oscillation Interpretations

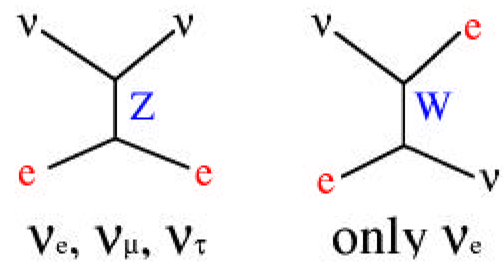
- "Just-So" or Vacuum Oscillations



  – Try to fit the results into the the oscillation formula
    $P_{osc} = sin^2 2q\ sin^2\ (1.27\ Dm^2 L/E)$
    for L ≈ 10^{11}(m)



- MSW or Matter Effects in Sun
(Mikheyev-Smirnov-Wolfenstein)
  – Mass eigenstates propagate
  – But these are mixtures of flavor eigenstates
    • They have different interactions with e's in sun



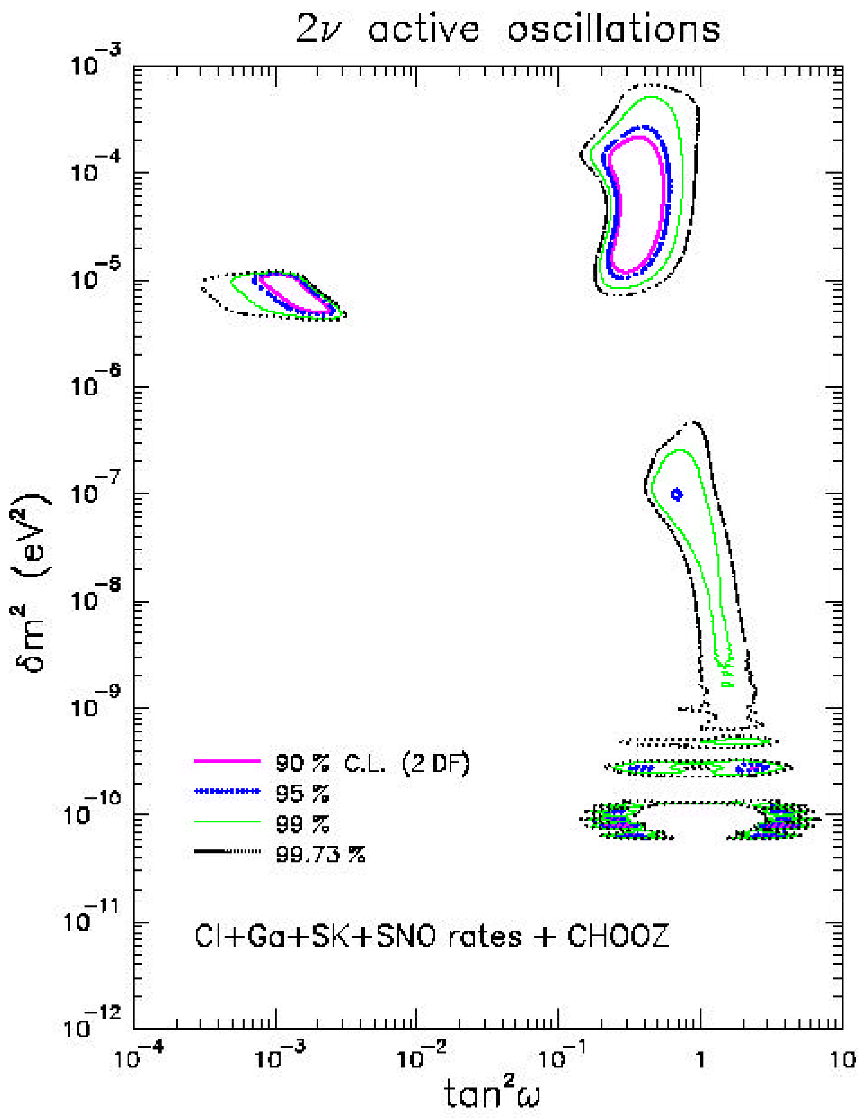
  – If N = electron density then

$$\text{Prob}\,(\nu_e \to \nu_\mu) = \left(\sin^2 2\theta / W^2\right)\ \sin^2\left(1.27 W \Delta m^2 L/E\right)$$

$$\text{where } W^2 = \sin^2 2\theta + \left(\sqrt{2} G_F N (2E/\Delta m^2) - \cos 2\theta\right)^2$$

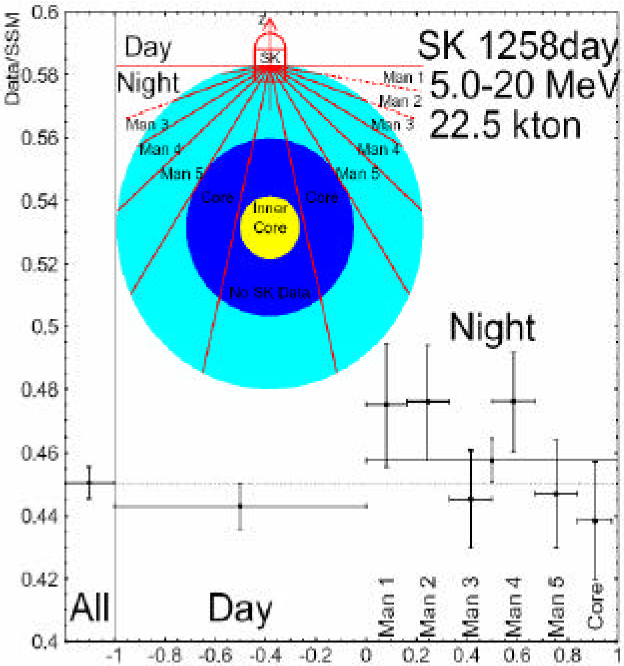
Resonance Condition:
$sin^2 2q_{eff} = 1$ *if* $W^2 = sin^2 2q$

Allowed Regions

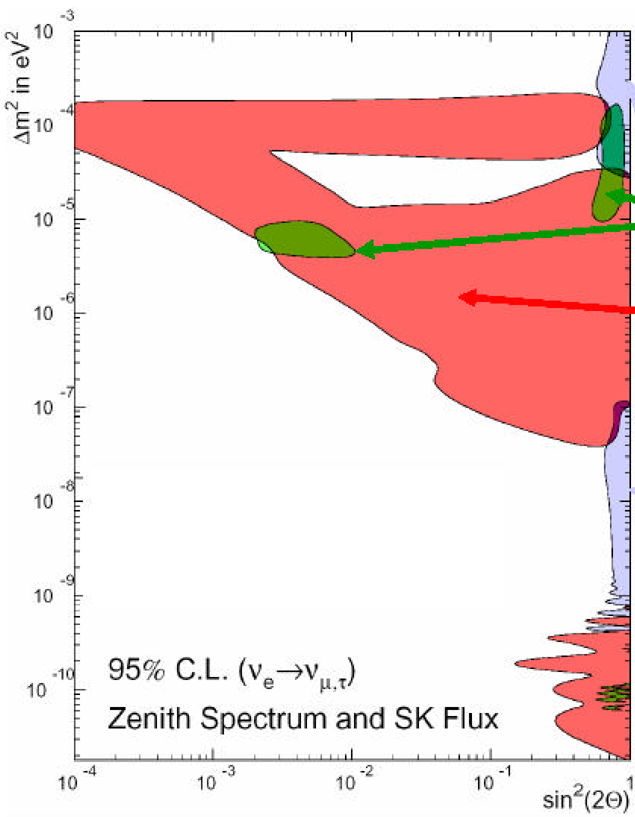


Fogli et al. hep-ph/0106247; Bahcall et al. hep-ph/0106258

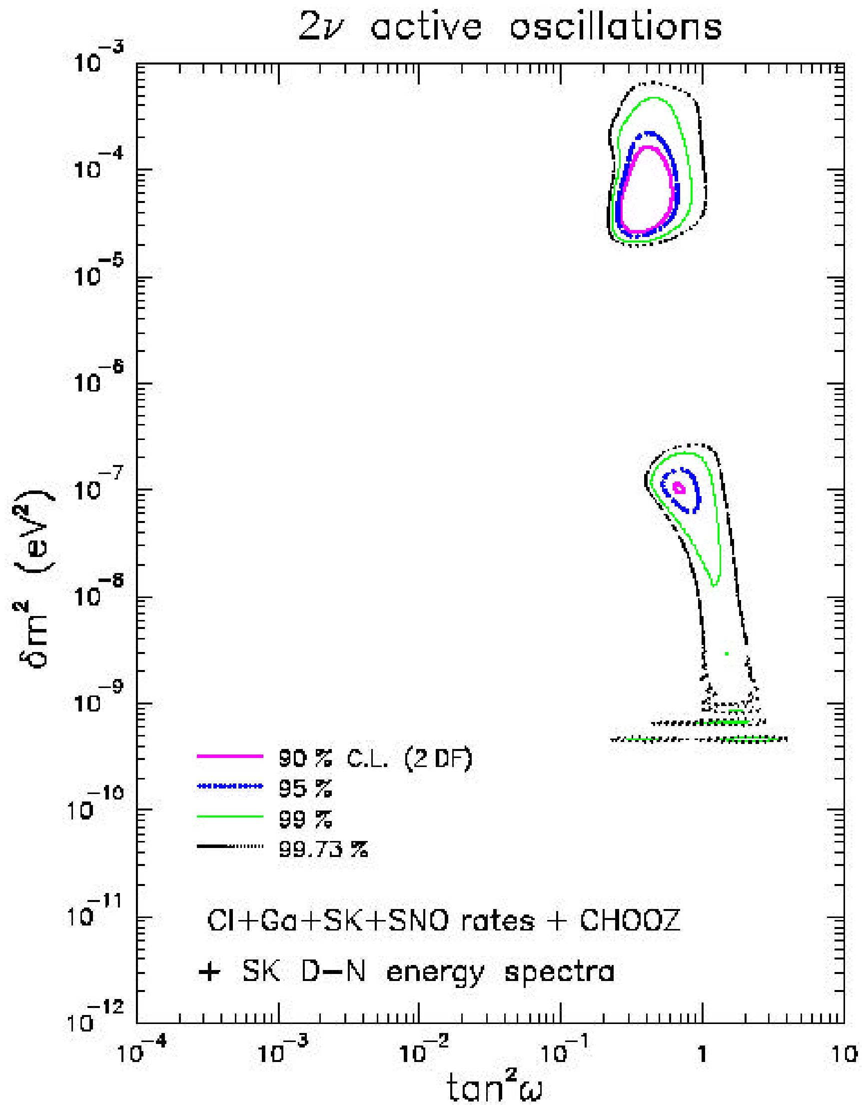
- Matter effects can also occur in the electrons in the earth
  - Would cause a ***day/night*** effect in the Super-K data



Oscillation Interpretations (Preliminary Super-K)



Putting It All Together



Fogli et al. hep-ph/0106247; Bahcall et al. hep-ph/0106258

What’s Coming Up in Solar n’s

- Kamland

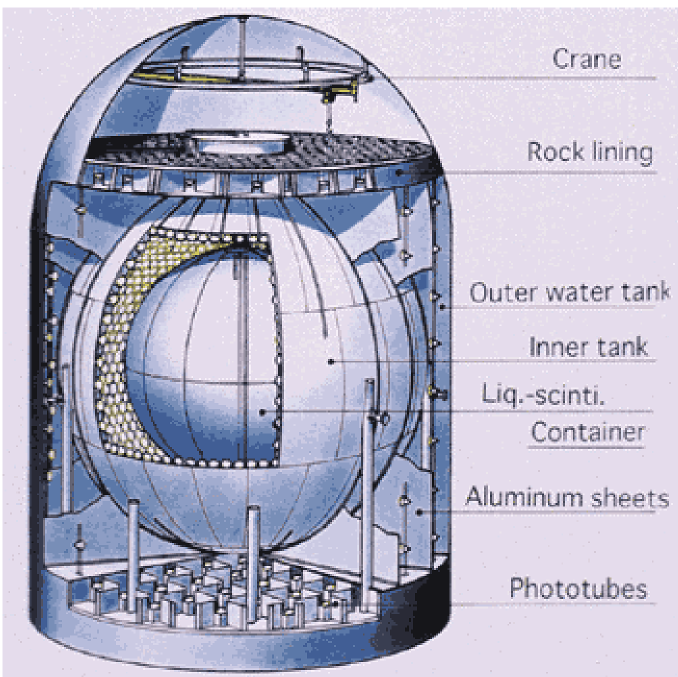
Reactor neutrino exp. In solar region

  - 1000 m^3 liquid scintillator
  - 2000 17-inch phototubes

$\bar{n}_e$ from reactors (L ~ 170 km)

Detect e^+ from $\bar{n}_e + p \rightarrow e^+ + n$

$(E_{threshold} = 1.8$ MeV$)$

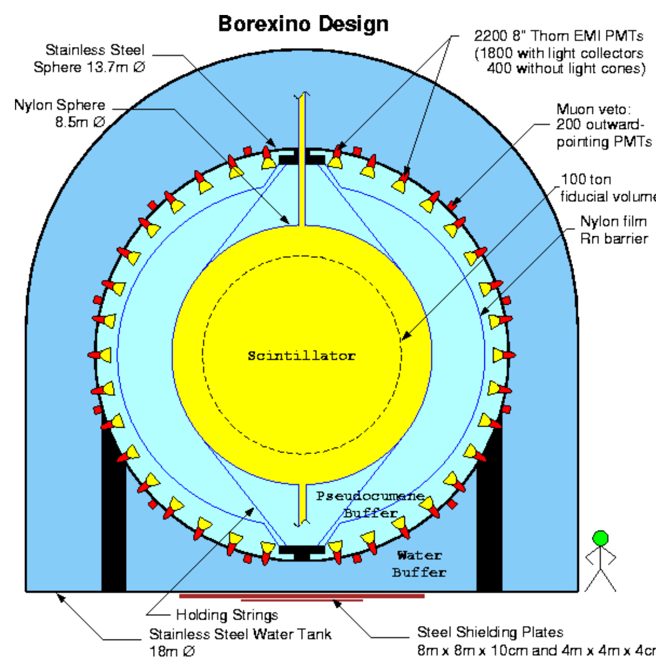


- Borexino

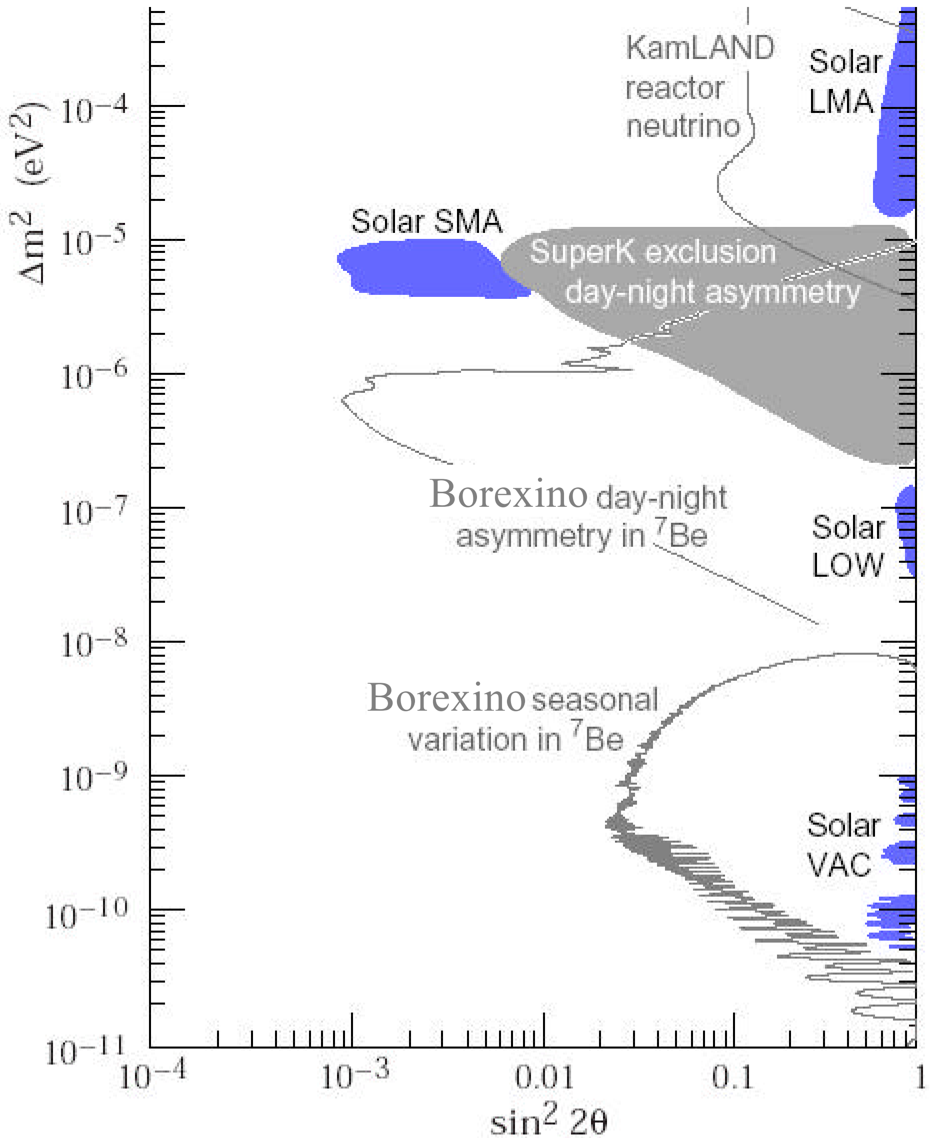
Go after ^{7}Be n’s

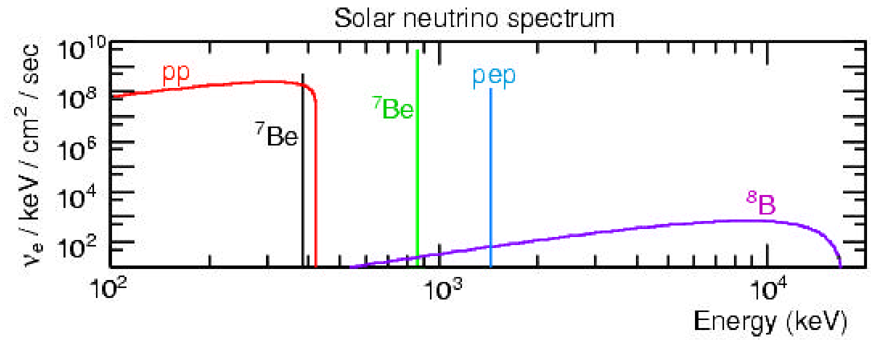
  - 300 ton liquid scintillator
  - 2200 8-inch phototubes
  - E_e > 250 keV

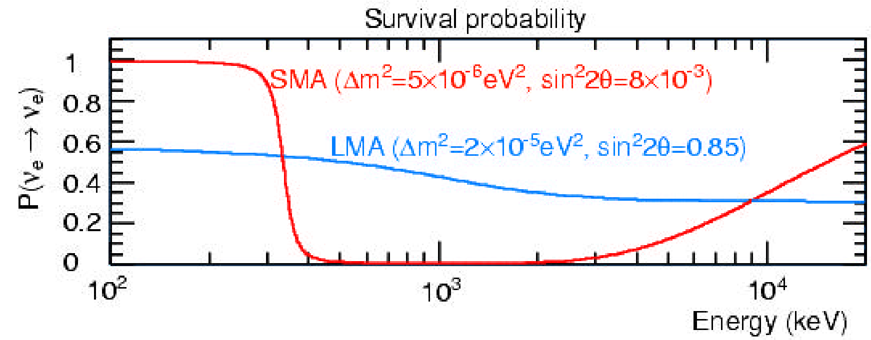
- Detect $\nu_e + e^- \rightarrow \nu_e + e^-$
  - 55 events/day for SSM

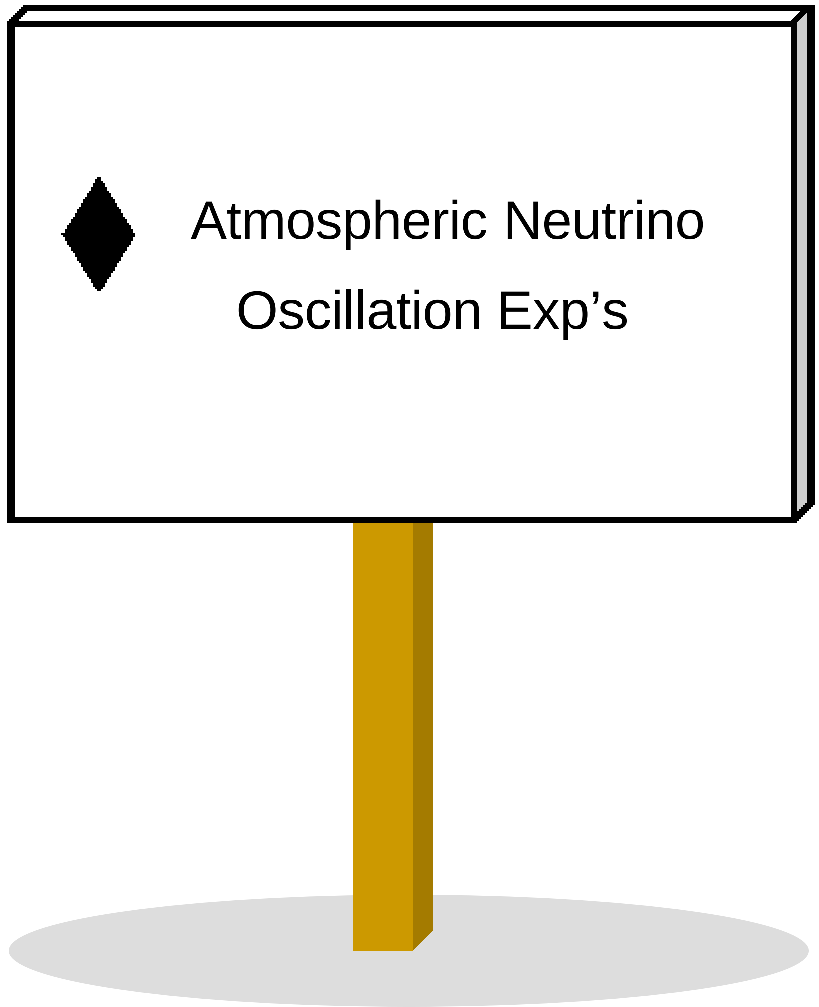


Kamland and Borexino Sensitivity

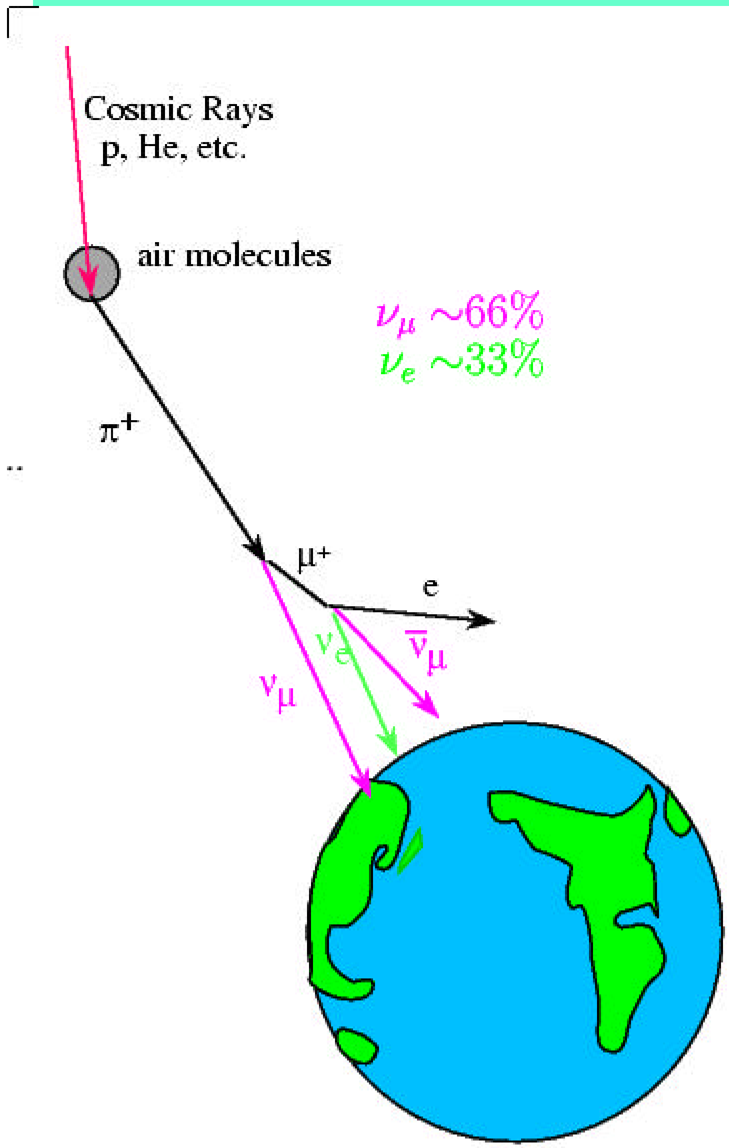







♦ Atmospheric Neutrino
Oscillation Exp’s

Atmospheric Neutrino Oscillations



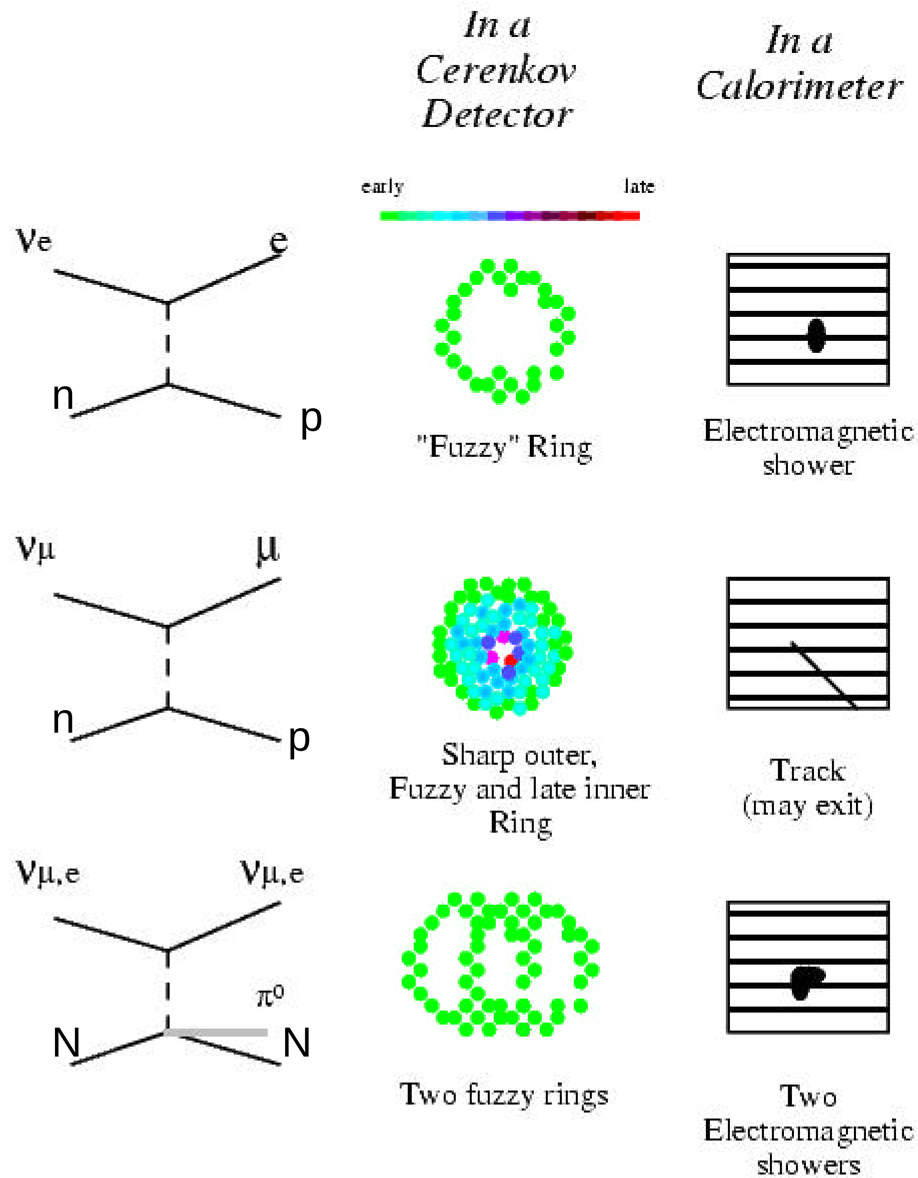
- Atmospheric Neutrino Flux
  - From π and μ decay from cosmic-ray hadronic showers in the atmosphere
  - Flux modeled using:
    - Measured cosmic-ray fluxes
    - Accelerator cross section measurements
    - Include geomagnetic effects
    - Some disagreements with atmospheric muon measurements (~20% level)

Experimental Techniques

Atmospheric Neutrinos > 0.1 GeV

Þ **Interactions on protons and neutrons in target**

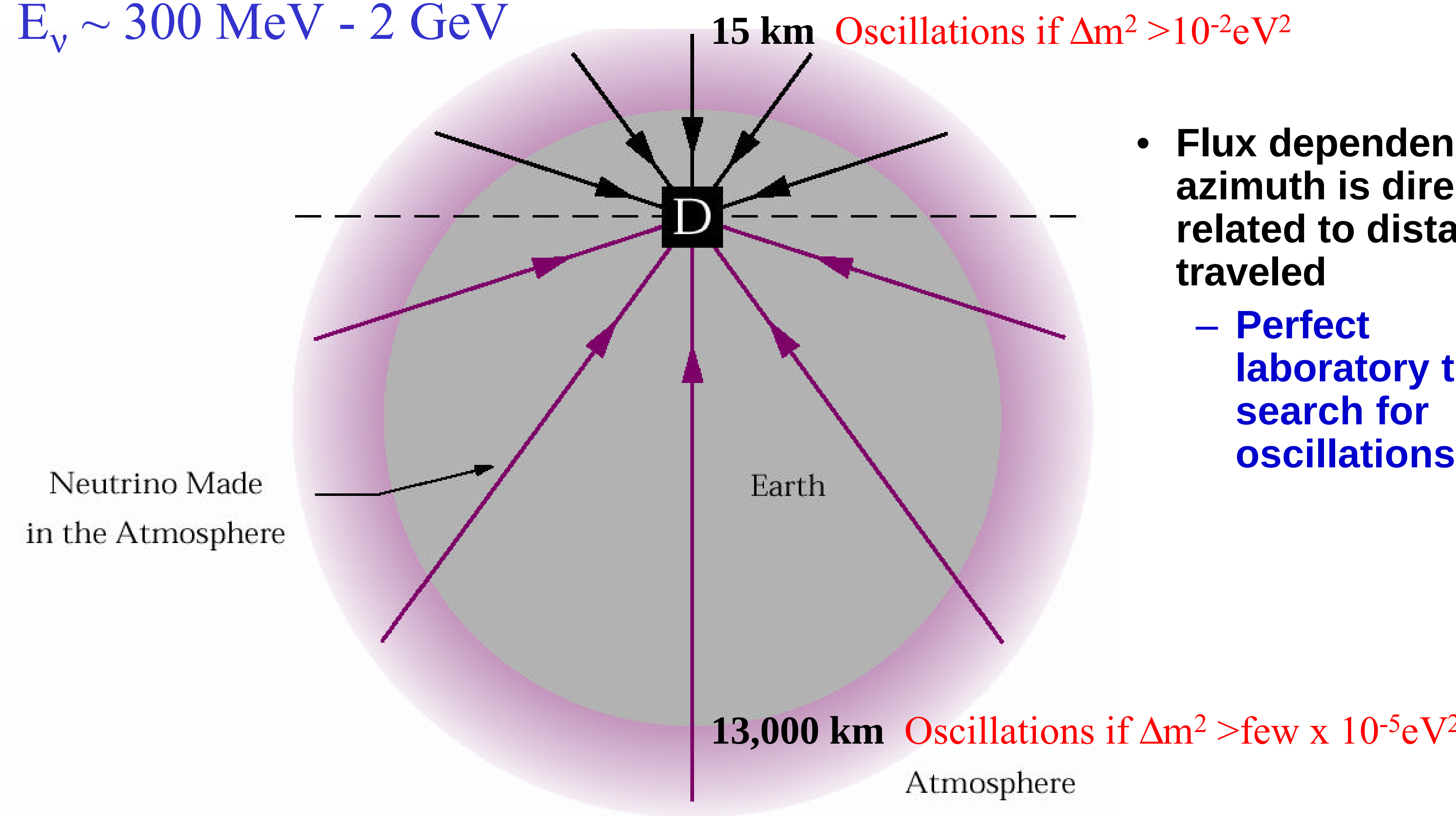
- Water Cerenkov Detectors (Super-K)
  - Identify various event types by the Cerenkov ring configurations (single-ring e's or μ's multi-ring NC and CC)
- Sampling Calorimeters and Trackers (Sudan II and MINOS like NuTeV)
  - Electrons have short showers
  - Muons have penetrating tracks
  - Multi-particle events



Atmospheric Neutrino Studies

$\cos\theta_{Zenith} = 1.0$

$E_\nu \sim 300$ MeV - 2 GeV



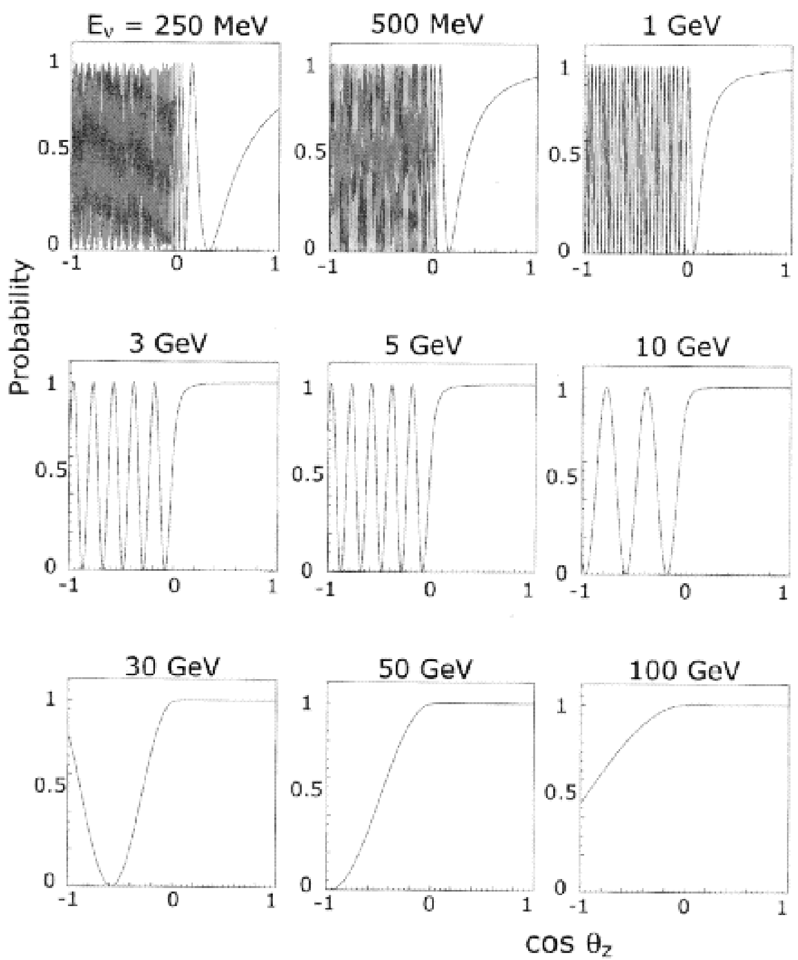
- **Flux dependence on azimuth is directly related to distance traveled**
  - **Perfect laboratory to search for oscillations**

$\cos\theta_{Zenith} = -1.0$

Oscillation Survival Probability for n_m®n_t

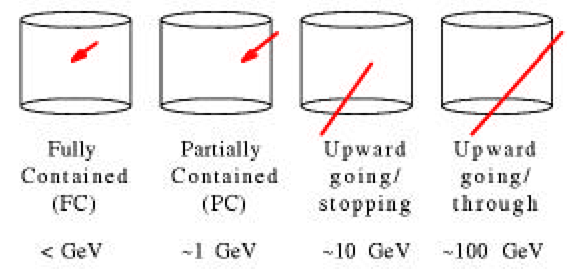
- $\cos\theta_{Zenith}$ distributions for various neutrino energies, E_ν (Rapid change in behavior for $\cos\theta_Z < 0$)

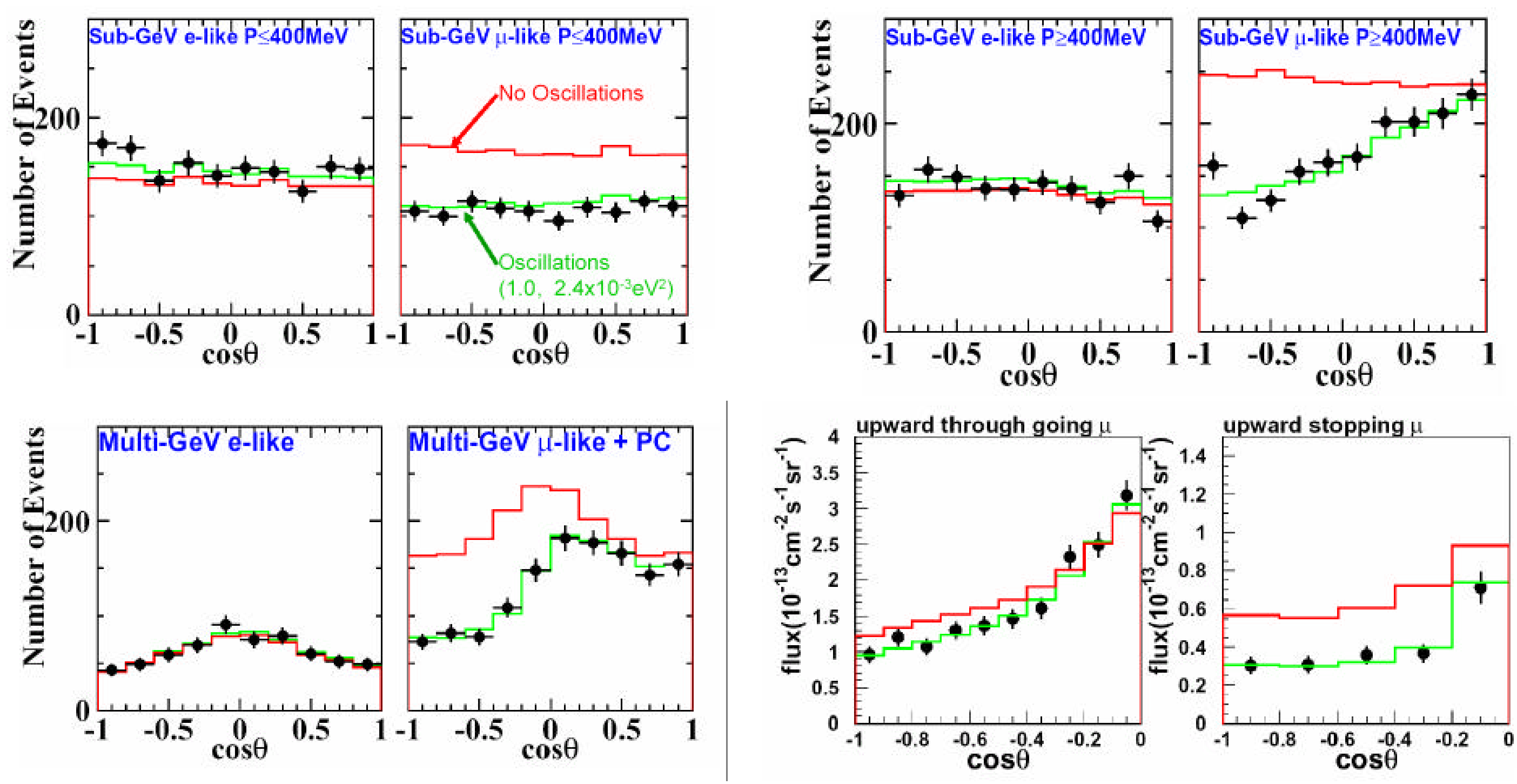
- $\Delta m^2 = 5\times10^{-3}$ eV^2 $\sin^2 2\theta = 1.0$



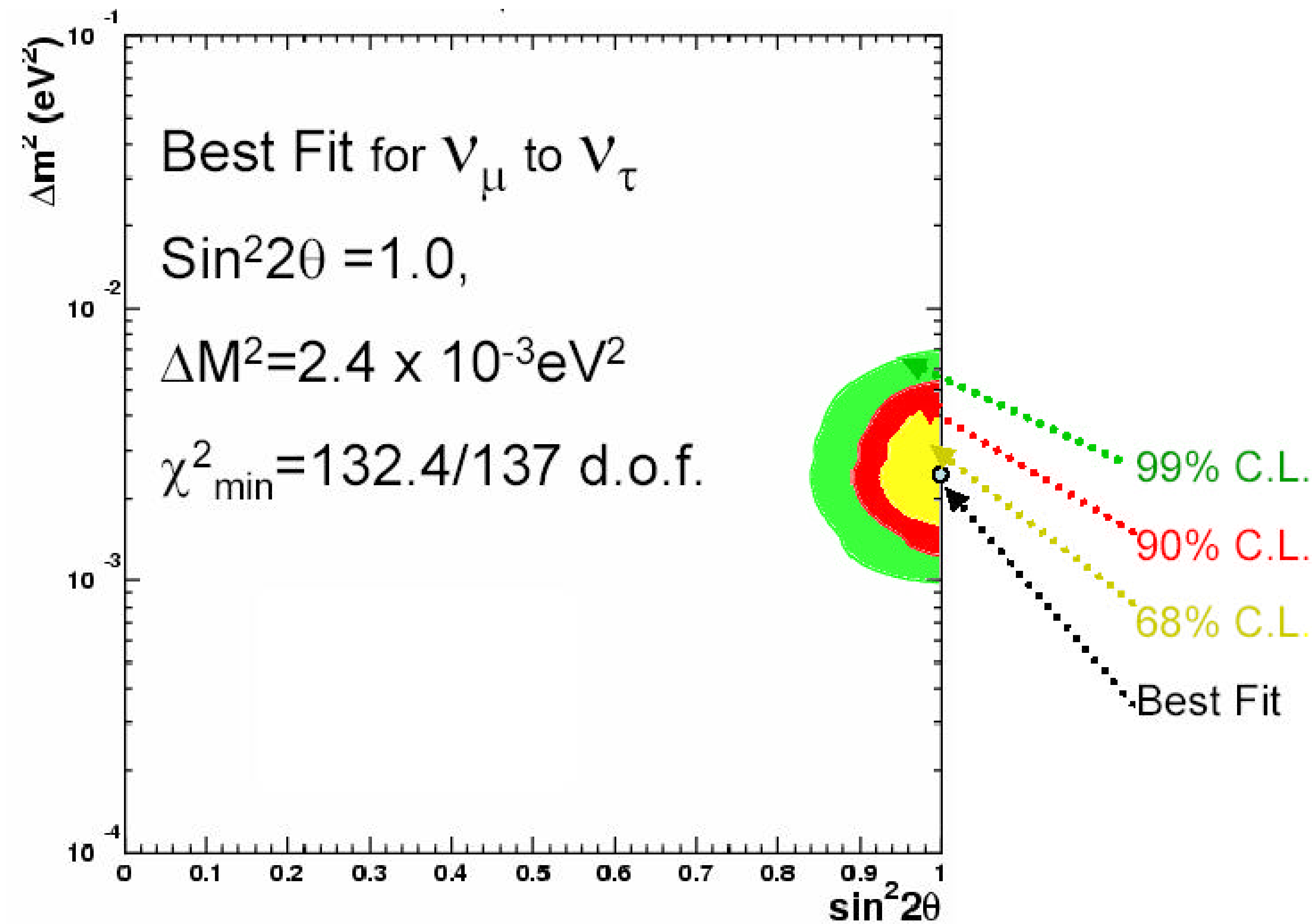
Note: Detector resolution will integrate over rapid oscillations and average to ½ .

Super-K Atmospheric Results
(1290 days)



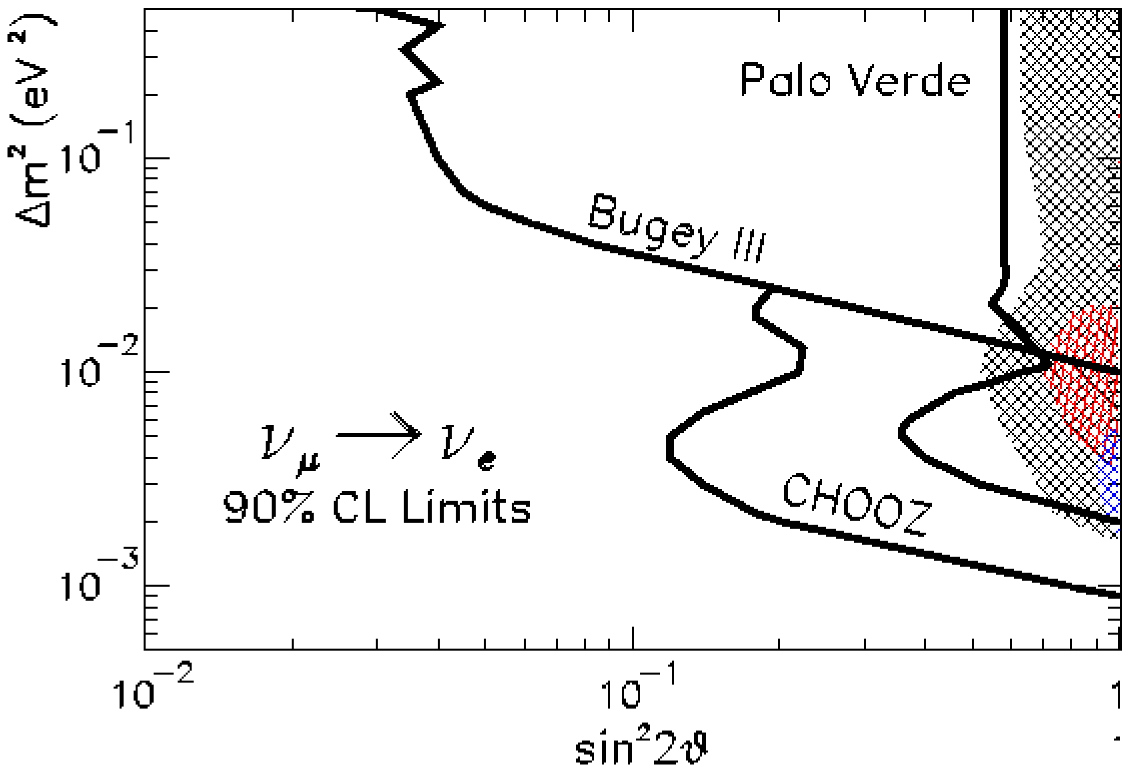


Super-K Fits to n_m®n_t



Reactor Experiments Limit Atmospheric n_m ® n_e Possibilities

- CHOOZ, Bugey, and Palo Verde Reactor Experiments
  - $\langle E_\nu \rangle \sim 3$ MeV and L ~ 1 km
- Dominant $\nu_\mu \rightarrow \nu_e$:
  - Ruled out by CHOOZ reactor ν experiment
  - Sub-dominant osc. possible at the $\sin^2 2\theta < 0.10$ level

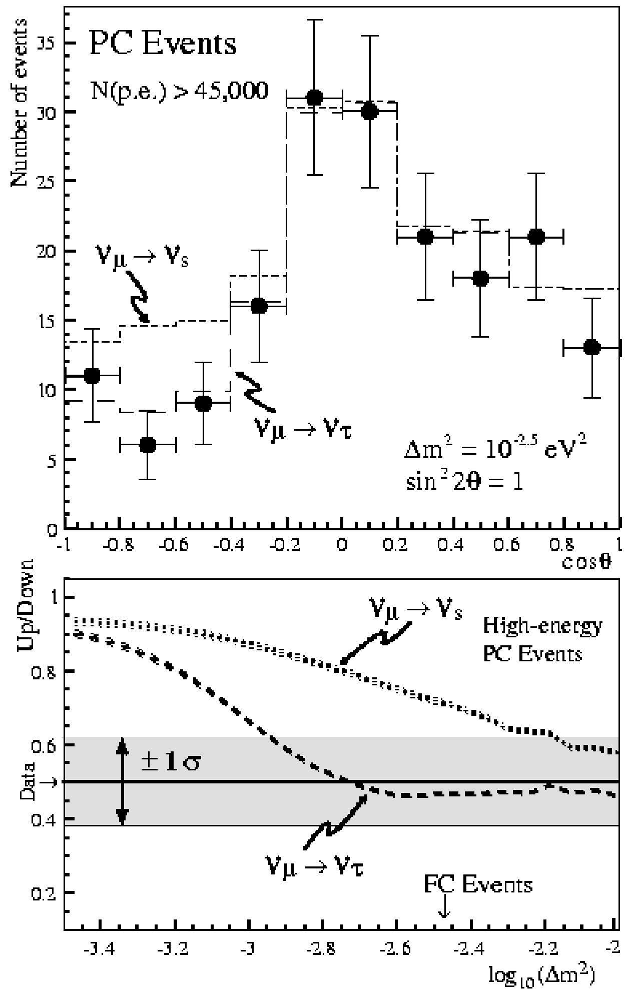


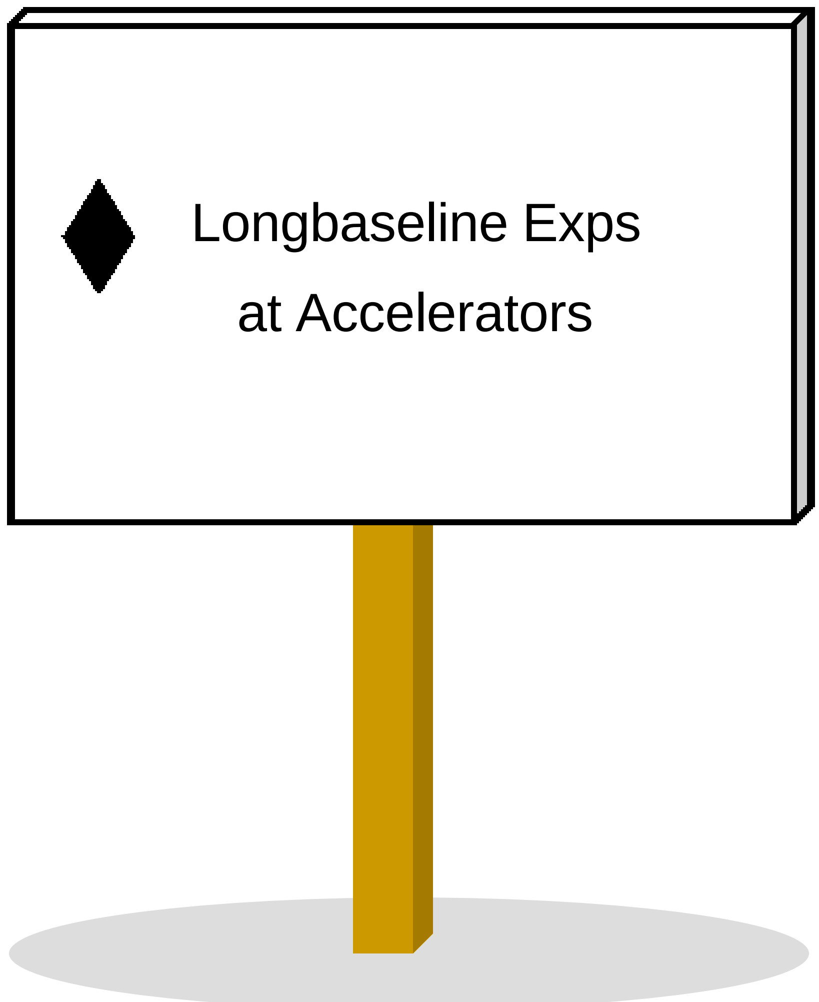
Can atmospheric result be due to n_m ® n_s oscillations ?

- Interactions with matter in earth different for $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_{sterile}$
  - $\nu_{sterile}$ has no NC interactions with quarks
  - Mainly near cosθ = -1.0

- Also, differences for:
  - NC enriched multi-ring events
  - Upward-going thru-μ events

- Exclude
  - Complete $\nu_\mu \rightarrow \nu_{sterile}$ ruled out at 99% CL
  - $\nu_\mu \rightarrow \nu_{sterile}$ fraction < 25% at 90% CL




Longbaseline Exps
at Accelerators

Long-Baseline Experiments

- Long-baseline experiments can be used to check atmospheric results with a well controlled accelerator produced ν beam

- With high statistics and good control of systematics can:
  - Measure oscillation parameters Δm^2, $\sin^2 2\theta$ more accurately
  - See oscillatory behavior with energy
  - Measure $\nu_\mu \rightarrow \nu_e$ at the atmospheric Δm^2
  - Directly observe ν_τ events from $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - Do further checks of possible $\nu_\mu \rightarrow \nu_{sterile}$

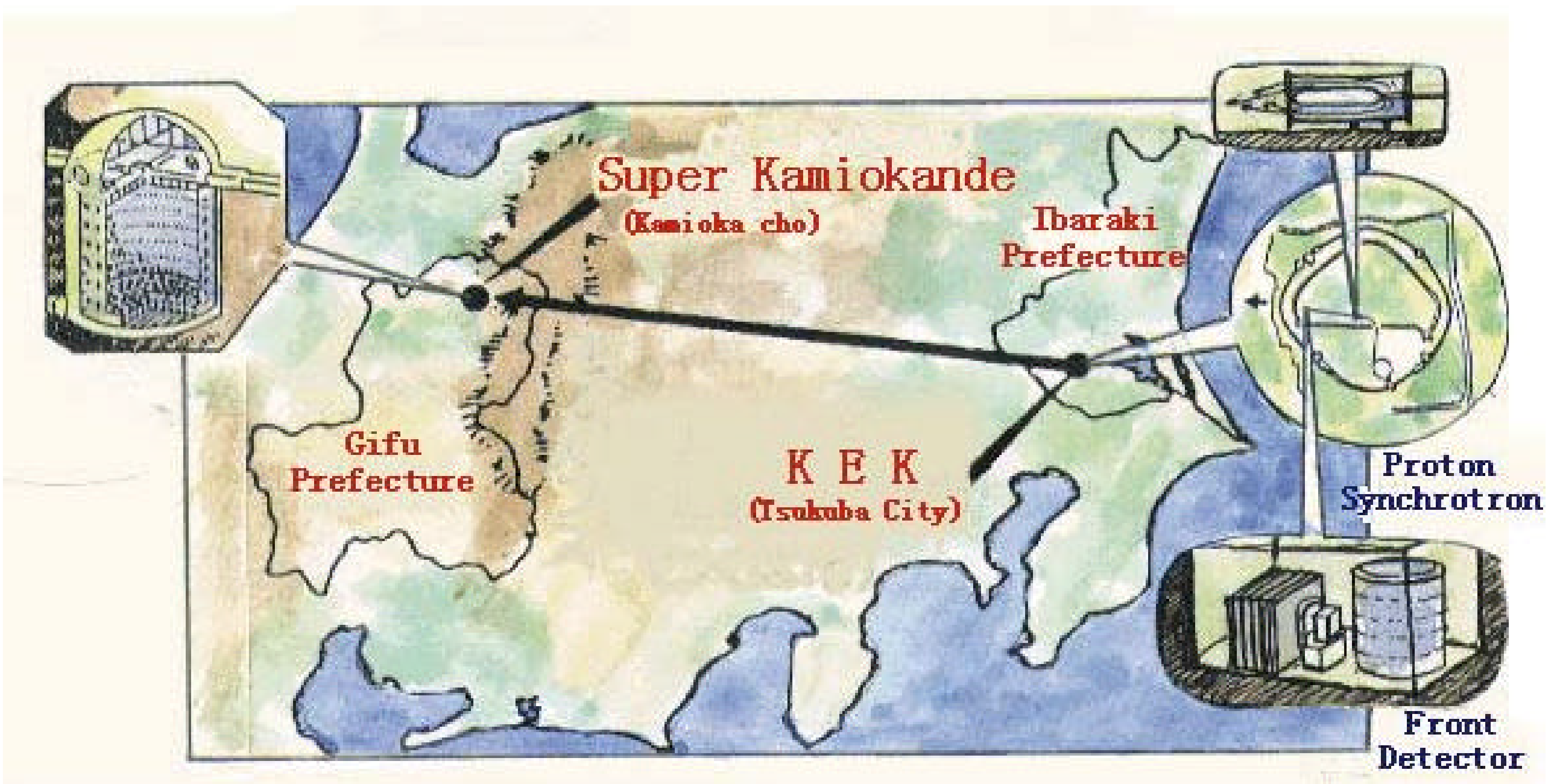
- Having a near monitoring detector along with far detector is best

- Current and near future experiments: K2K, MINOS, CNGS

KEK to SuperK (K2K) Experiment

See C. Walters Talk

- Low energy, $<E_\nu>=1.4$ GeV, beam sent from KEK to SuperK (250 km)
- Several front detectors at 100m and beam monitors

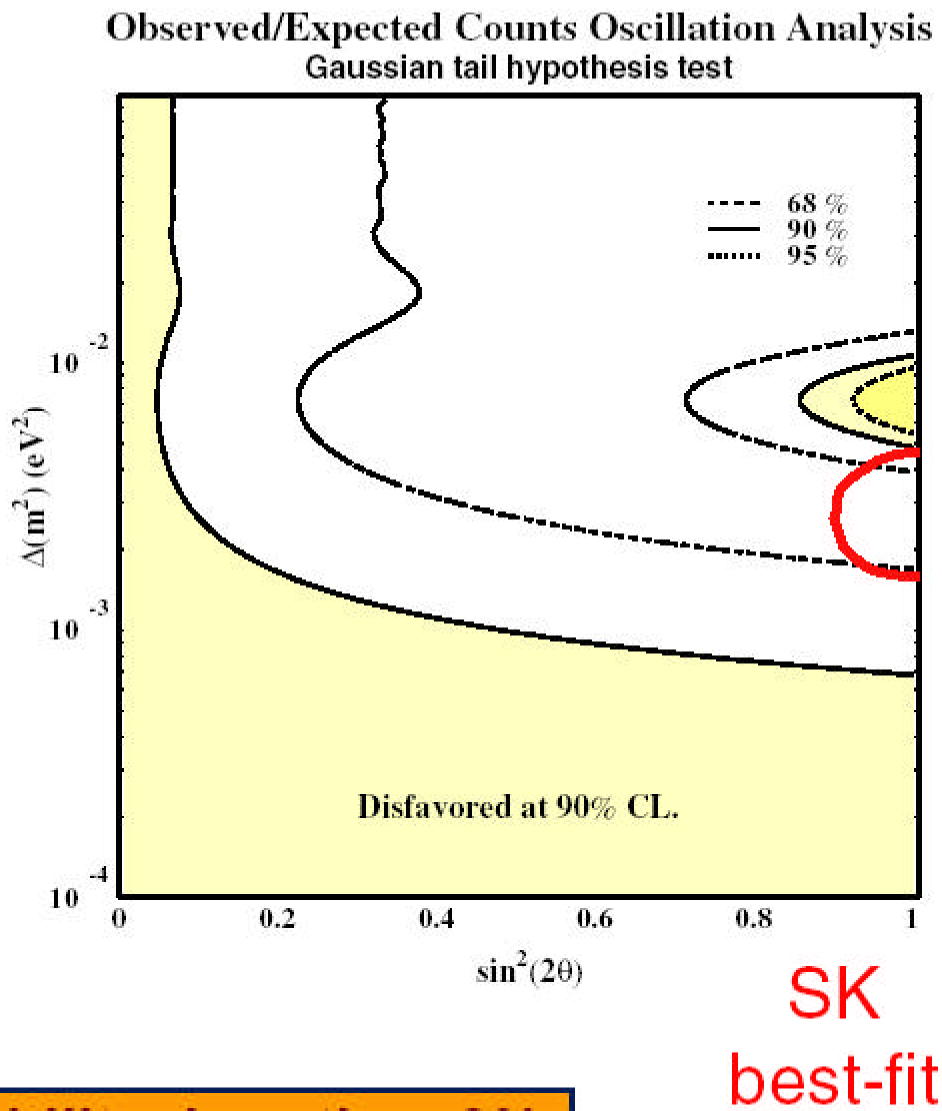


K2K Results (Events)

5.6 x 10^{19} POT delivered, through July 2001

Event Summary:

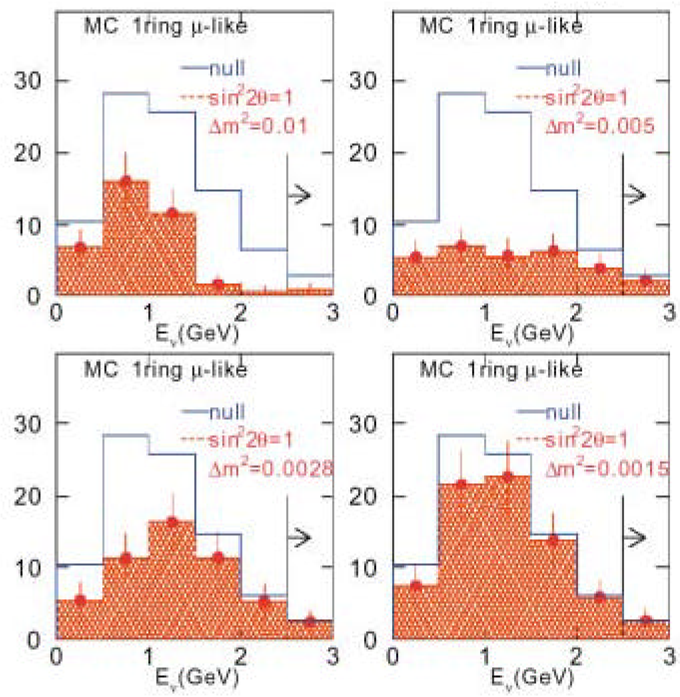
	detected	no osc	3x10^{-3}
FC	56	80.6±8.0	52.0
1-ring μ	30	43.6±6.9	24.2
1-ring e	2	4.4±1.7	3.7
multiring	24	31.9±5.3	24.1

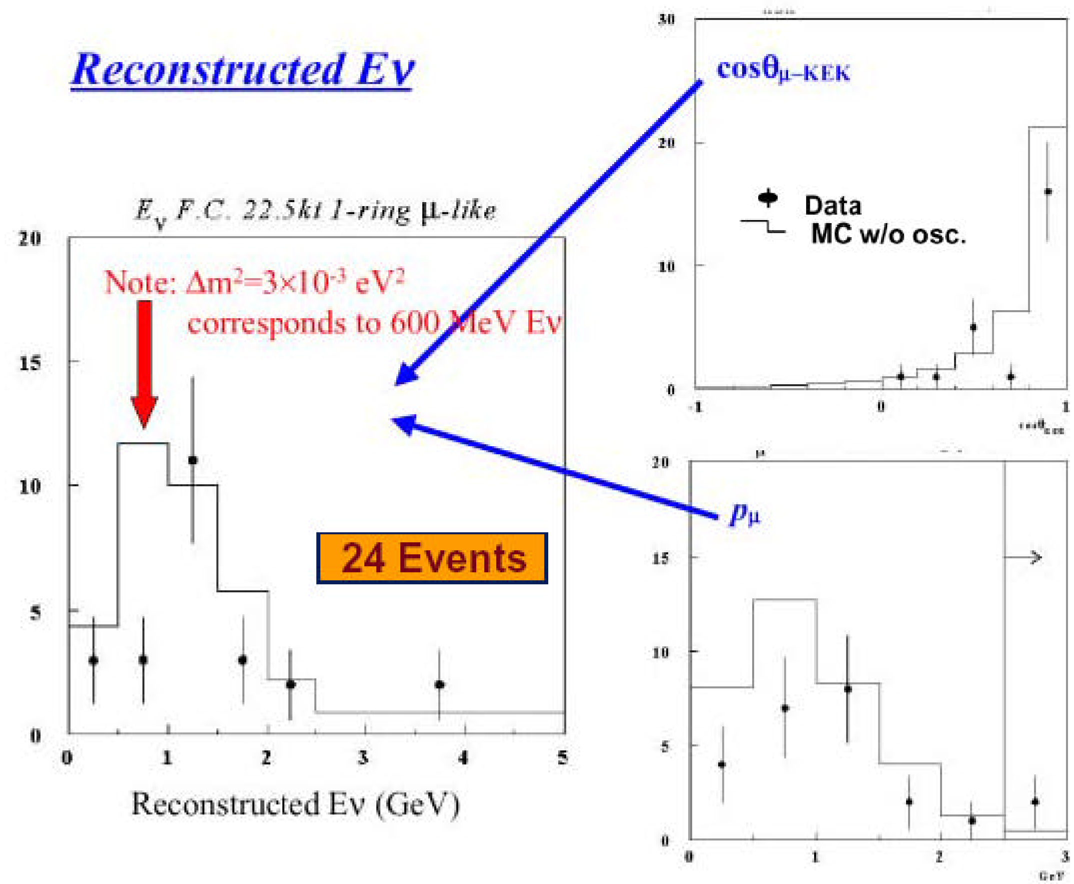


==> Null Oscillation probability: less than 3%

K2K Results (Energy Spectrum)

Monte Carlo Prediction for various oscillation scenarios





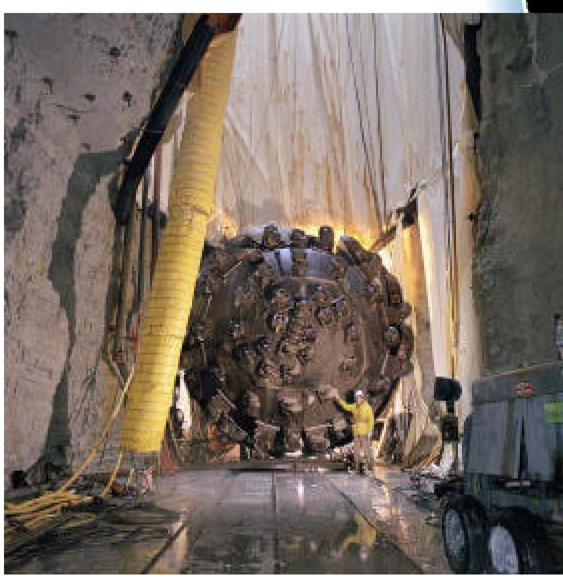
Conclude: Event deficit consistent with oscillations

but no oscillatory behavior and information on Dm^2

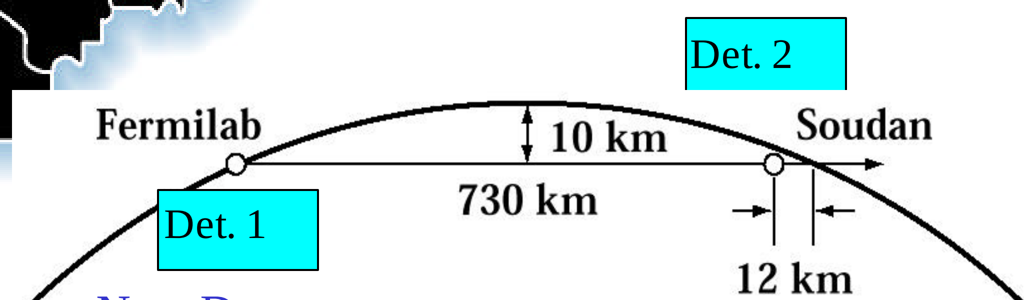
NuMI / MINOS Experiment

"Neutrinos at the Main Injector"

Two Detector Neutrino Oscillation Experiment



Far Detector:
5400 tons

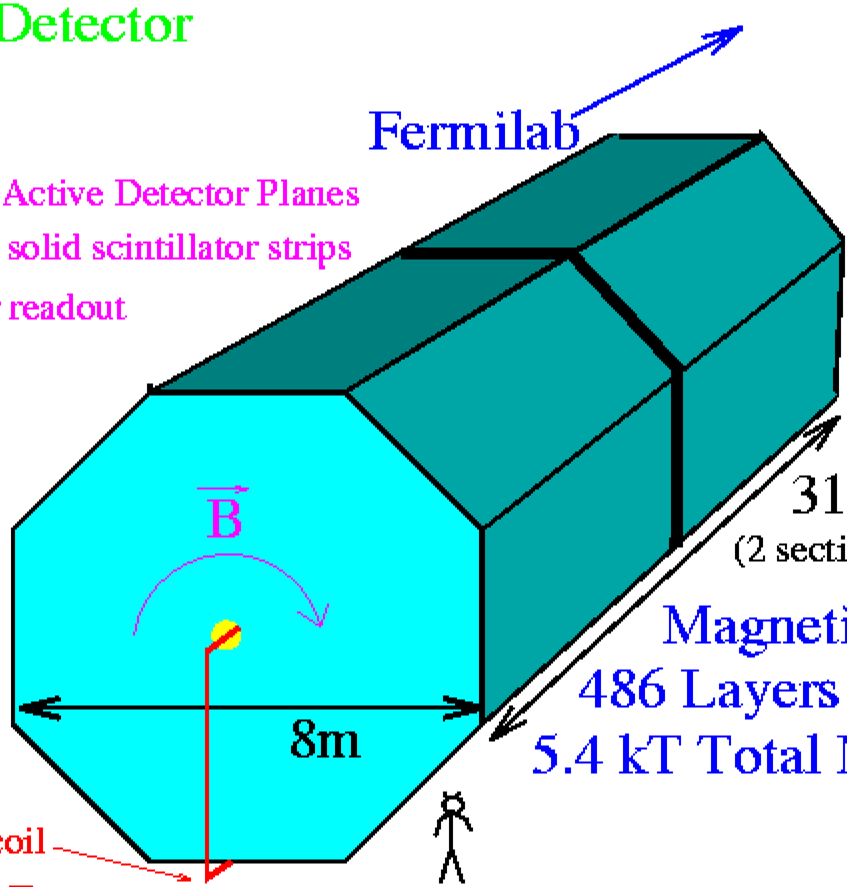


Near Detector:
980 tons

MINOS Far Detector

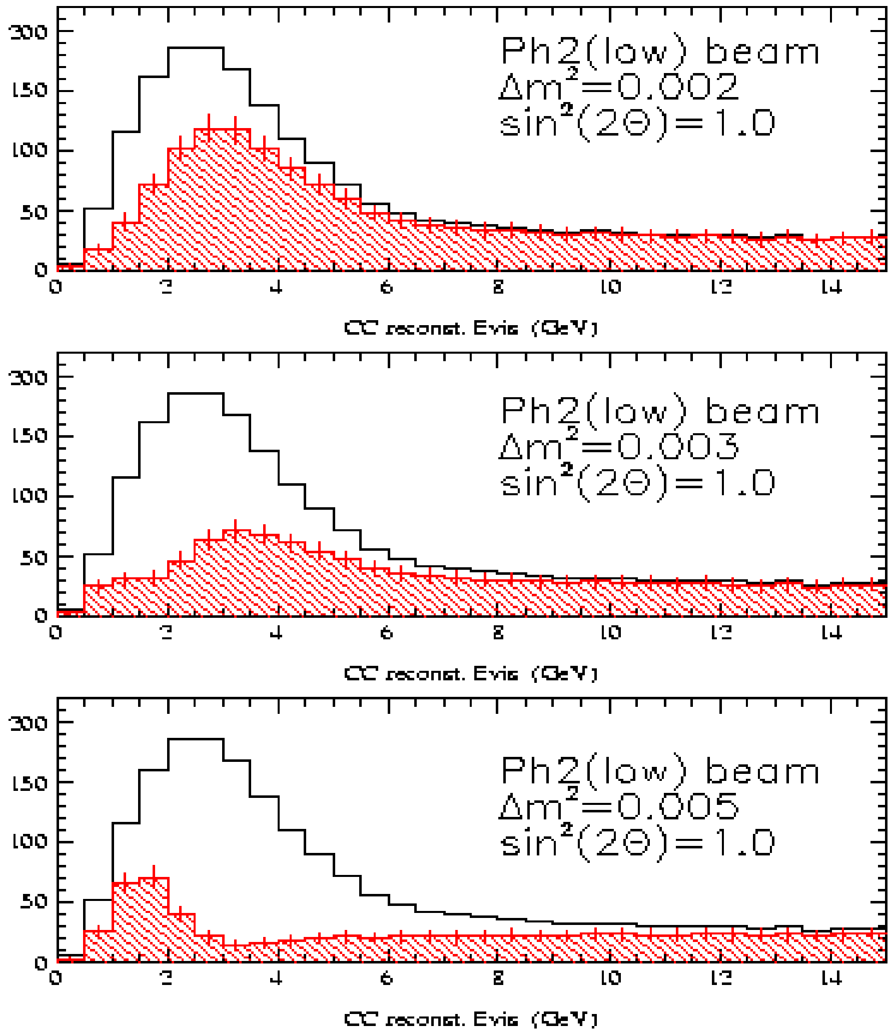
Far Detector

25,800 m² Active Detector Planes
4 cm wide solid scintillator strips
WLS fiber readout



Magnetized Fe Plates
486 Layers x 2.54 cm Fe
5.4 kT Total Mass

MINOS Energy Spectra



10 kt-yr Exposure
(~700 CC events/yr)

Solid lines - energy spectrum without oscillations

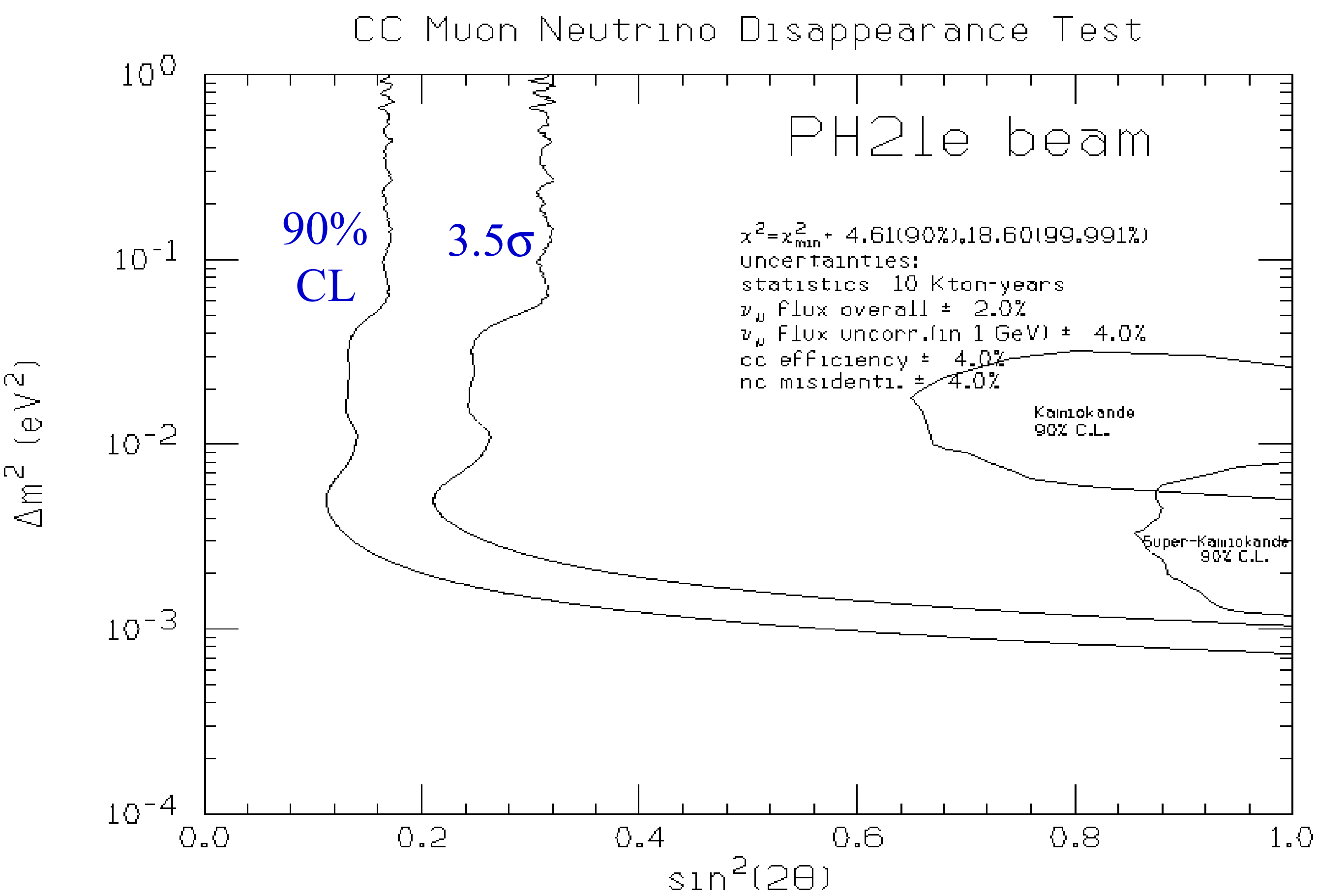
Dashed histogram - spectrum in presence of oscillations

Can measure:

Δm^2 to ~10 - 20%

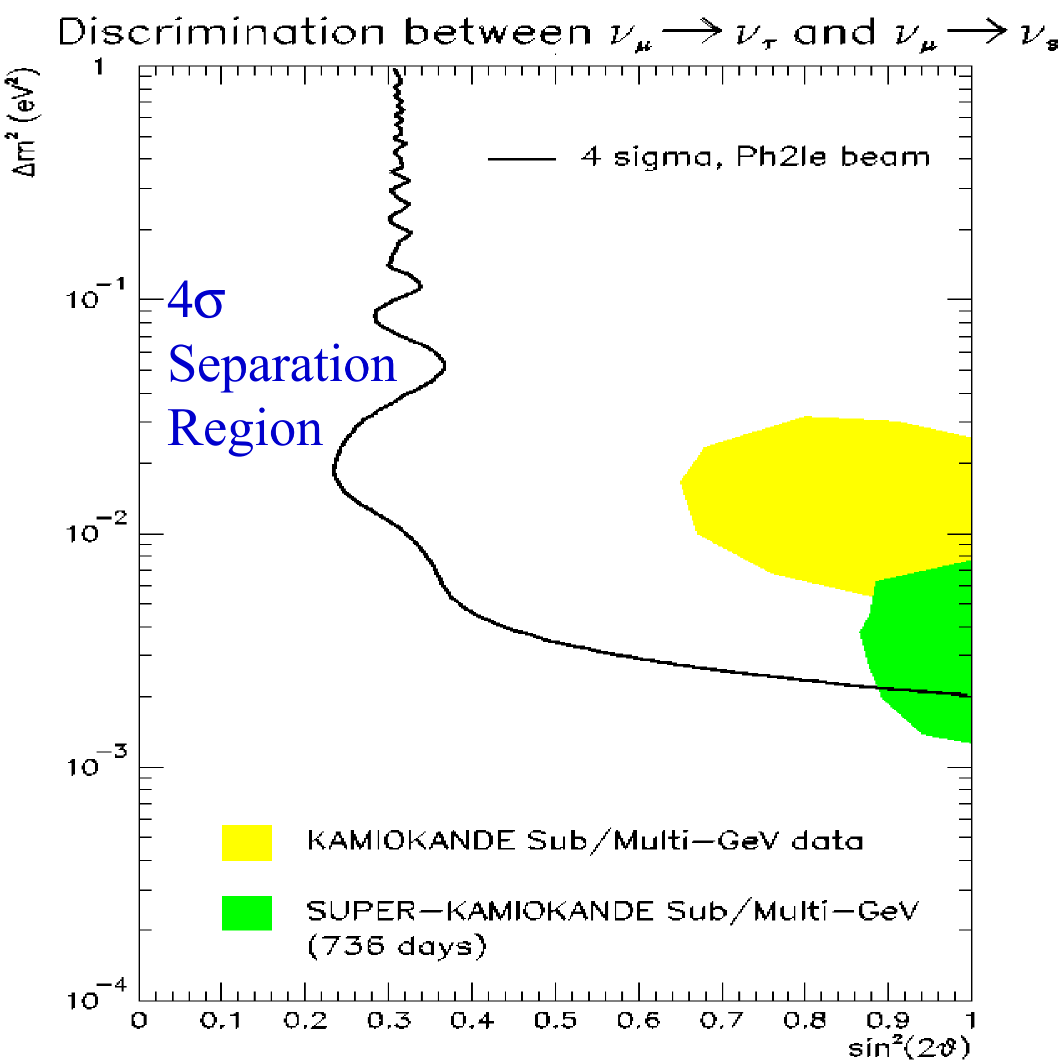
$\sin^2 2\theta$ to ~ 0.10

MINOS Dm^2 Sensitivity



MINOS Oscillation Mode Sensitivity

(Discriminate n_m®n_t vs. n_m®$n_{sterile}$)



- Use CC/NC Ratio to distinguish between oscillations to ν_τ or $\nu_{sterile}$

- For $\nu_\mu \rightarrow \nu_\tau$, CC production of τ's will look like NC ~80% of the time

  CC/NC $\rightarrow$ down

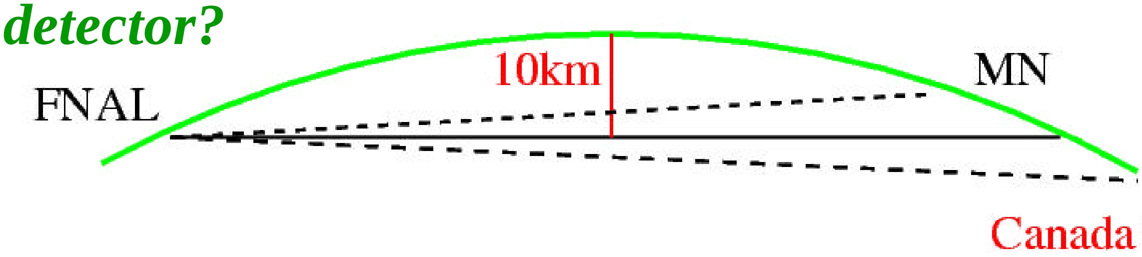
- For $\nu_\mu \rightarrow \nu_{sterile}$, both CC and NC will be suppressed.

  CC/NC stays ~ constant

Possible New Potential for NuMI Program
Off-Axis "Minos" Detector

- Goal: Measure $\nu_\mu \rightarrow \nu_e$ at the atmospheric $\Delta m^2 \Rightarrow \sin^2 2\theta_{13}$
  (Current CHOOZ Limit: $\sin^2 2\theta_{13} \approx 0.10$ @ 90% CL)
  - Backgrounds and identification are main problems
    - Intrinsic ν_e's in the beam, NC/CC π^0 production
    - Electron decays of τ's from $\nu_\mu \rightarrow \nu_\tau$
  - Key is to use energy constraint beam
    - Need a sharp energy distribution
    - Need little high energy tail
  - Answer is the normal NuMI beam to Minos ***but***
    - Put your detector offaxis (at ~15 mr)

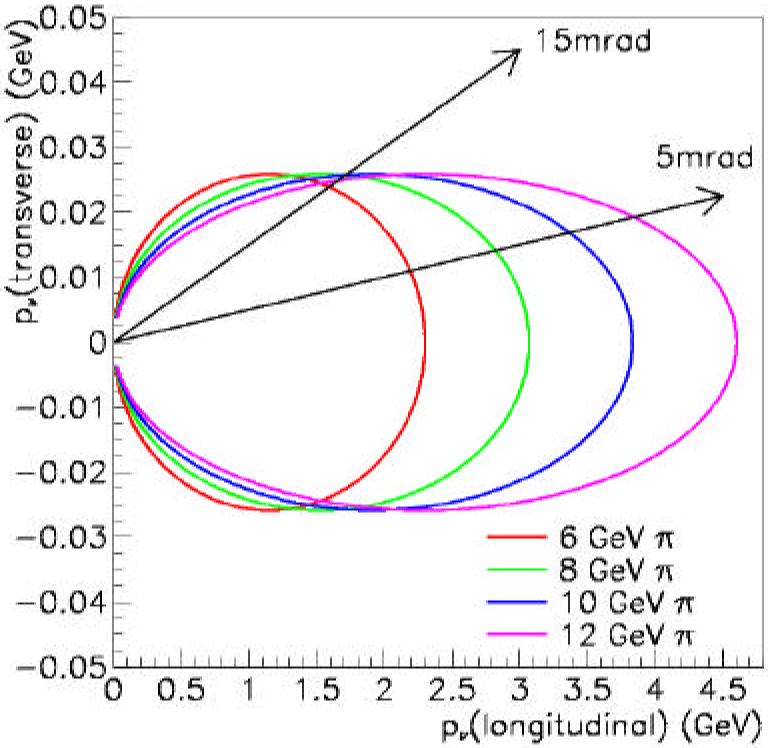
Where does this put the detector?
… Maybe Canada!

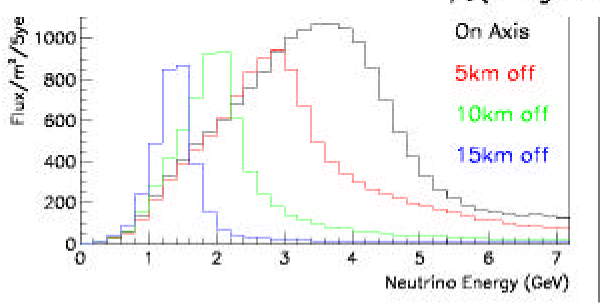



MAPQUEST™
Winnipeg
Kenora
Dryden
0
100mi
100km
Fort Frances
Thunder Bay
St. Paul
Green Bay
Sioux Falls
Madison
Grand Rapids
Rockford
Chicago
Des Moines
South Bend

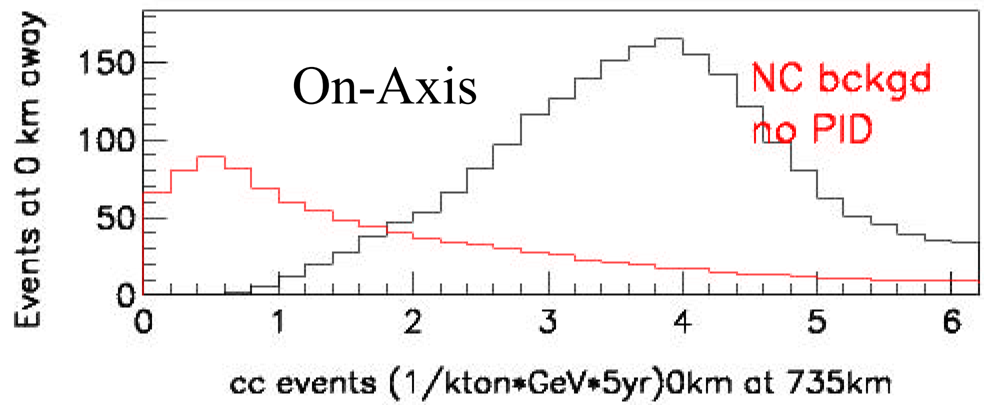
How/Why Does an Offaxis Beam Work?

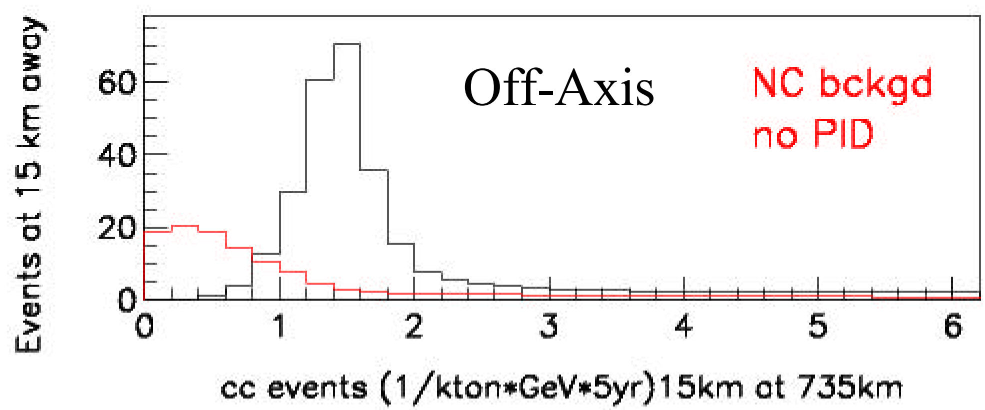
- Neutrinos produced from π-decay
  – Kinematics give mono-energetic beam at 15 mrad





- Energy cuts much more effective in reducing NC background with offaxis beam
  – NC tail from high E_ν on-axis events

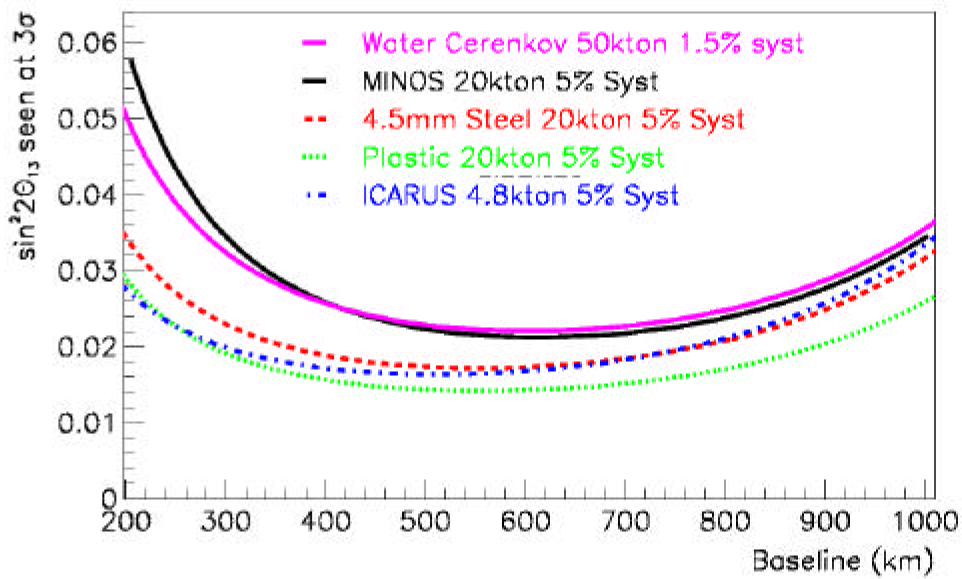




Estimates of Sensitivity

- Need to optimize:
  - Baseline
  - Detector
    - Mass and Technology (Signal and Bckgnd efficiency)
- Electron appearance requirements for detector
  - Good segmentation
    - Identify outgoing electrons
  - Good energy resolution
    - Separate ν_e and NC events
  - Particle identification
    - At the 1% or better level

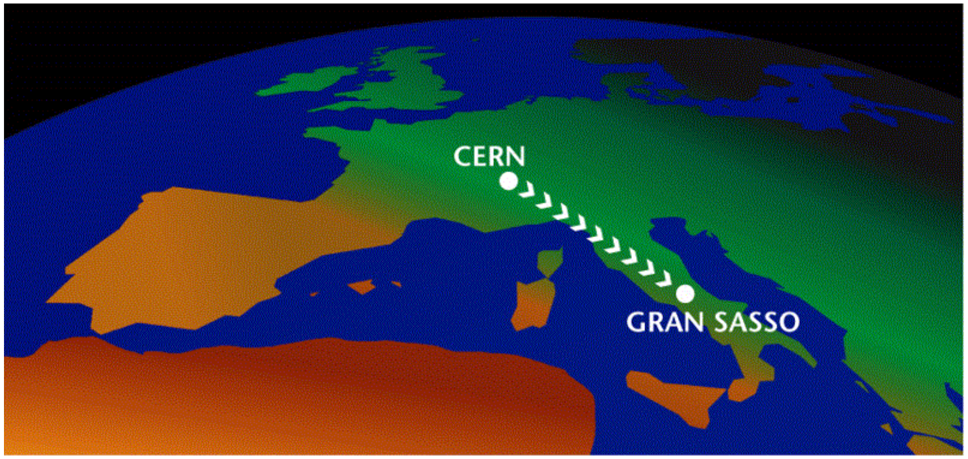
- Study of capabilities of various detector technologies



Conclusion:

- With reasonable detector can reach
  $\sin^2 2\theta_{13} \approx 0.02$ at 3σ
  (about x10 better than CHOOZ)

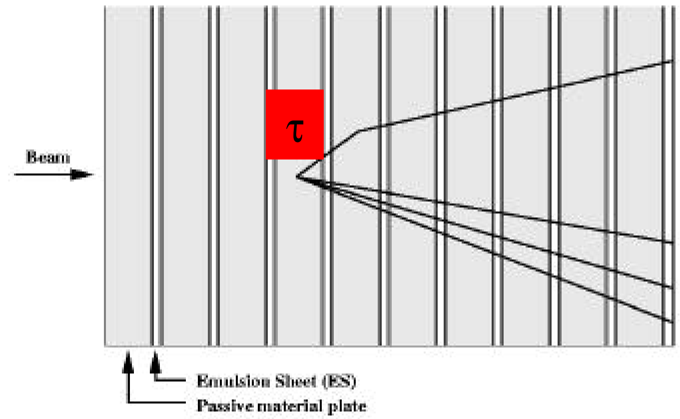
CERN to Gran Sasso n Osc. Program (CNGS)



- CERN has approved a program for a neutrino beam from CERN to Gran Sasso
  - Beam similar to Minos with ν_τ rate factor of two lower
  - Unlikely that a near detector hall would be built
- Emphasis on appearance experiments with ν_τ and ν_e identification
  - ***Opera Experiment***: Emulsion detector
  - ***ICARUS Experiment***: Liquid argon

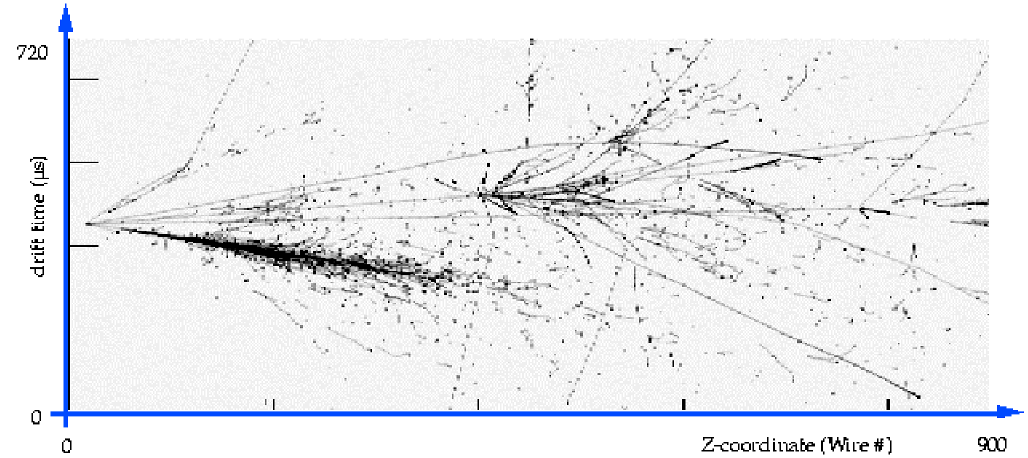
OPERA Hybrid Emulsion Experiment
(Oscillation Project with Emulsion-tRacking Apparatus)

- Emulsion bricks interspersed with electronics trackers
  - See τ decay in emulsion
- Goal: 1.5 kton hybrid target
  - ~ 3,600 ν_μ CC events/yr × eff.
  - ~ 45 ν_τ events/yr × efficiency
    - efficiency: ~10 % ?



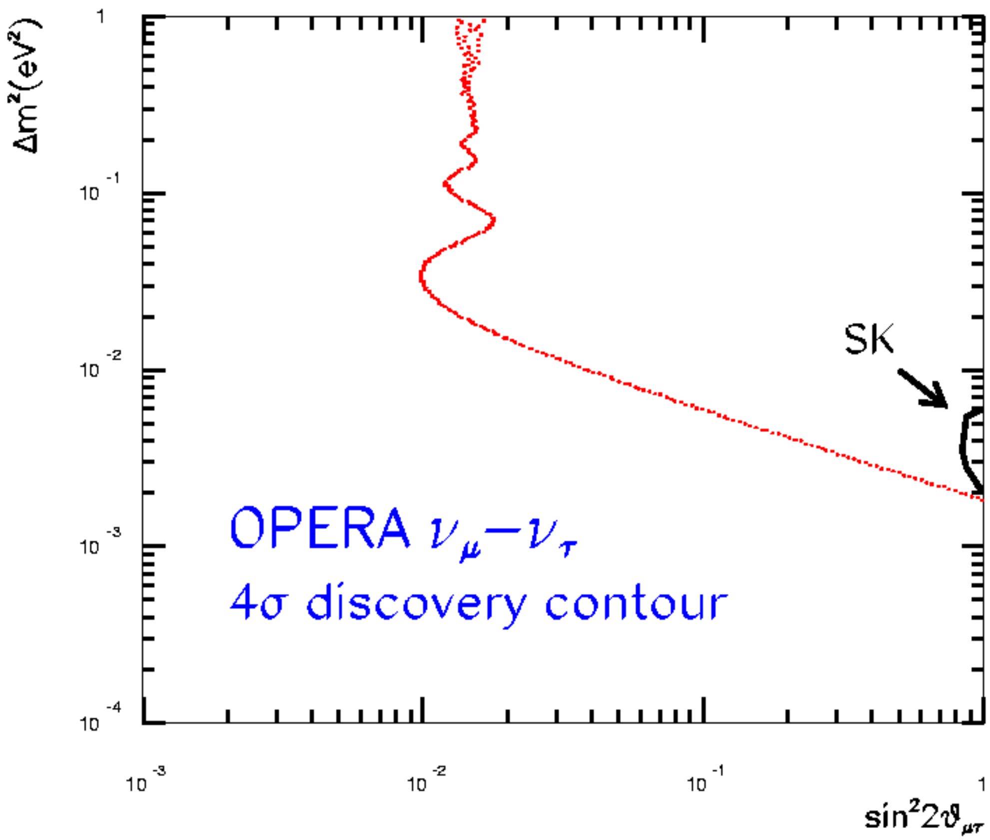
ICARUS Experiment

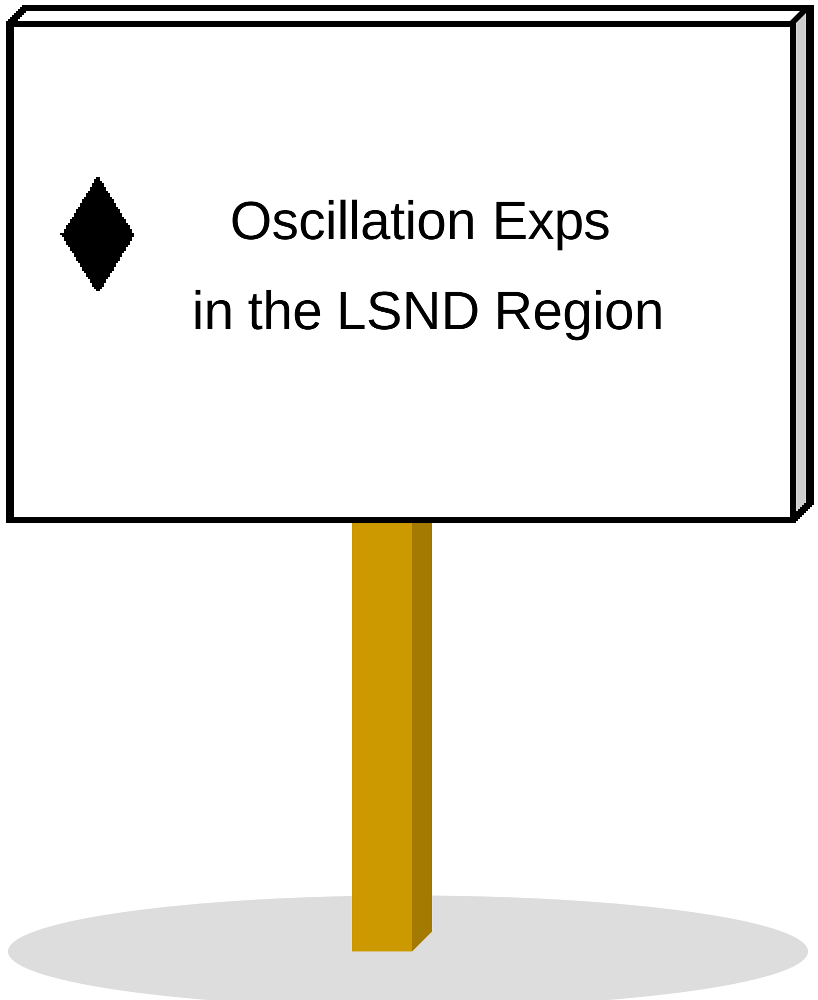
- Use liquid argon calorimeter
  - Liq Ar: 4 @ 1250 = 5000 tons
- Detect and identify all neutrino species



OPERA Sensitivity

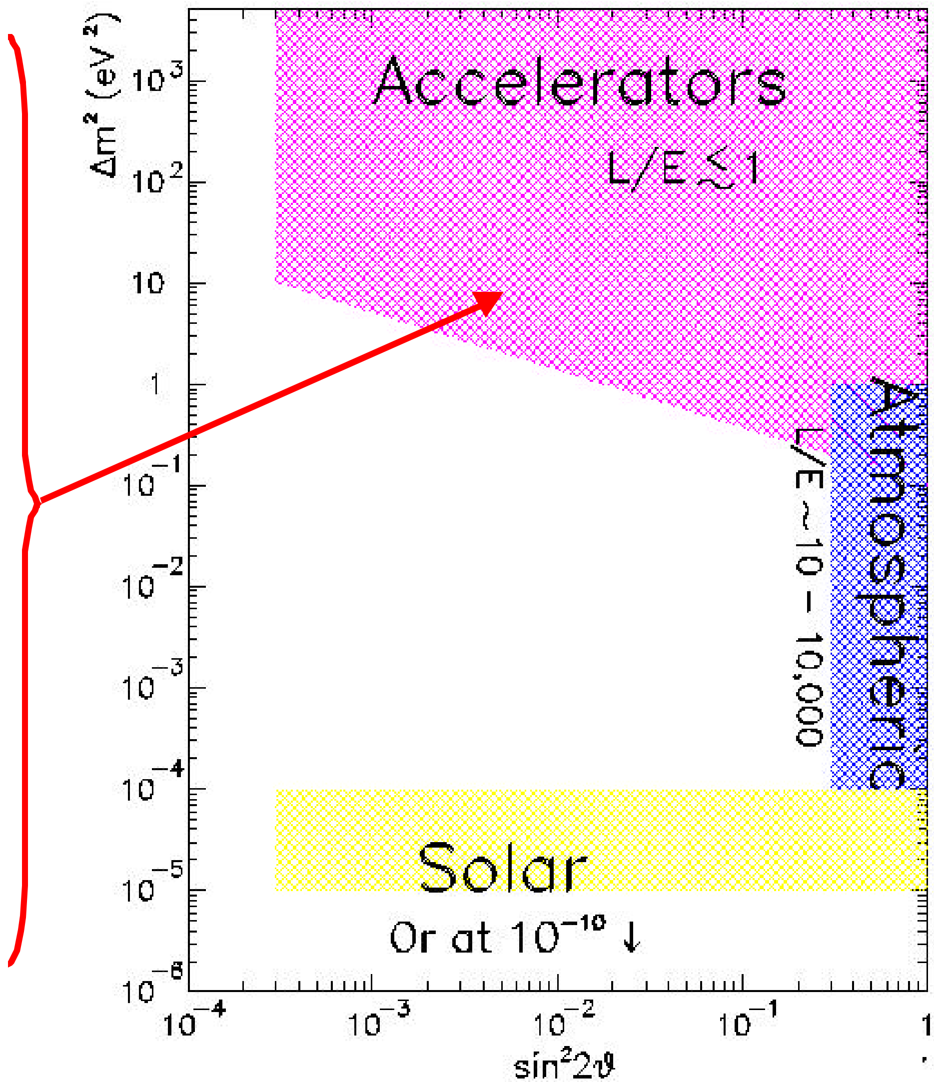
- Very low background
  - Can confirm oscillations to ν_τ with a few events
- For five year exposure (2.25×10^{20} pot)
  - ~ 25 $\nu_\mu \rightarrow \nu_\tau$ osc. events @ Δm^2=3.5×10^{-3} eV^2
  - ~ 0.5 events background




Oscillation Exps
in the LSND Region

LSND, Karmen, and MiniBooNE
n_m®n_e at high Dm^2

- LSND (LANCE) sees positive indication of oscillations
  – Final results
- Karmen II (RAL, England) experiment sees no excess and limits the allowed LSND region
  – Almost final results
- MiniBooNE (Fermilab) will make a definitive search for oscillations in this region



The LSND Experiment (1993-98)

See G. Mills Talk

$$p^+ \to m^+ n_m$$
$$\hookrightarrow e^+ n_e \bar{n}_m$$

Oscillations? $\hookrightarrow \boxed{\bar{n}_e}$

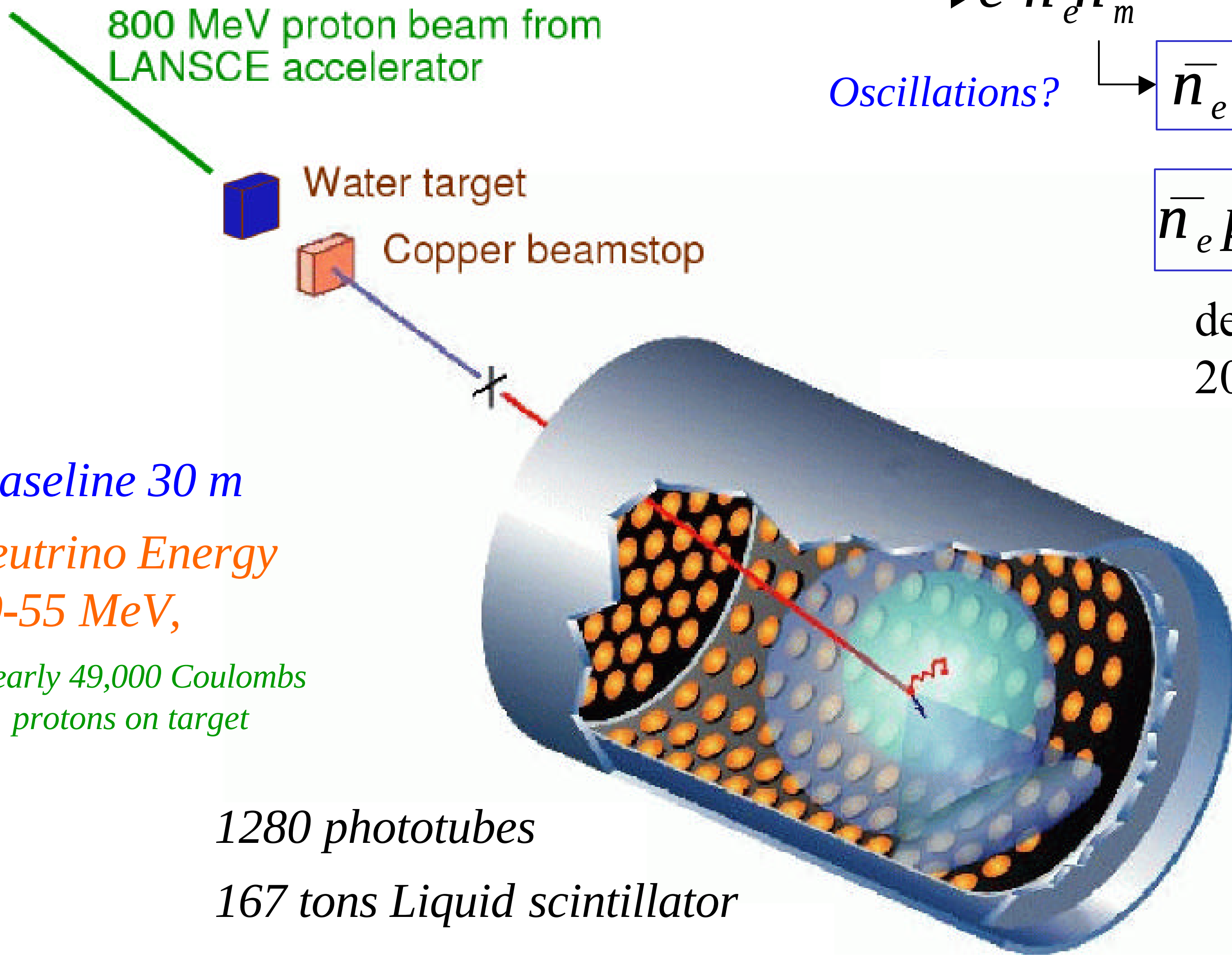
$$\boxed{\bar{n}_e p \to e^+ n}$$

detect prompt *e* track,
20<E_e<60 MeV

neutron capture:

$$\boxed{np \to dg}$$

2.2 MeV



Baseline 30 m

Neutrino Energy
20-55 MeV,

Nearly 49,000 Coulombs
of protons on target

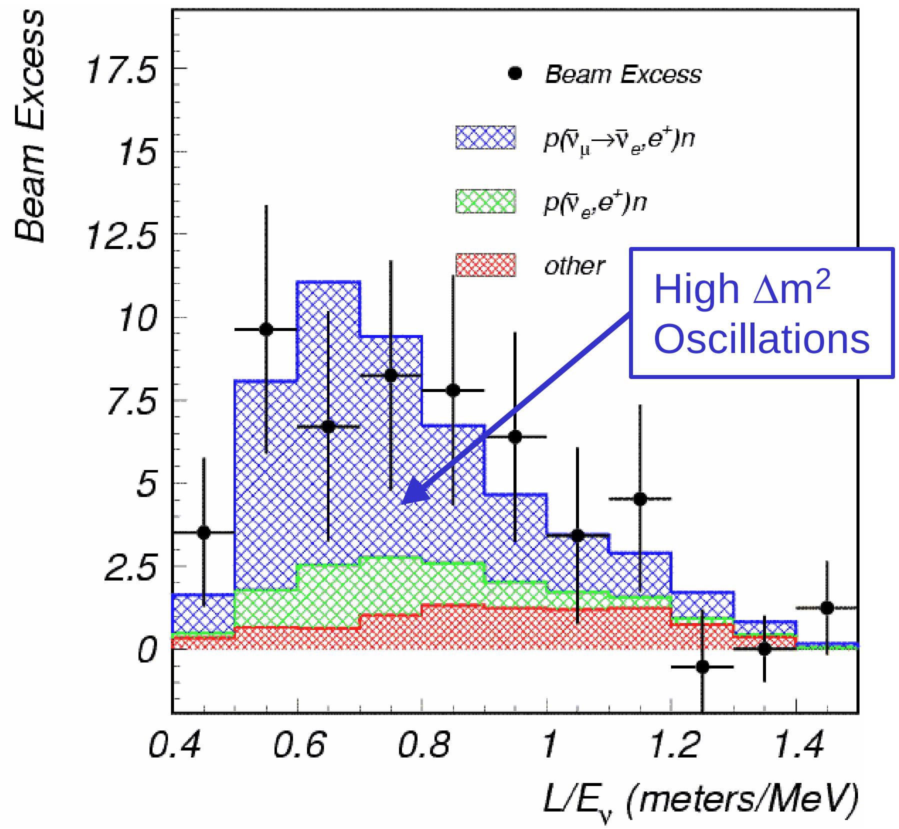
1280 phototubes

167 tons Liquid scintillator

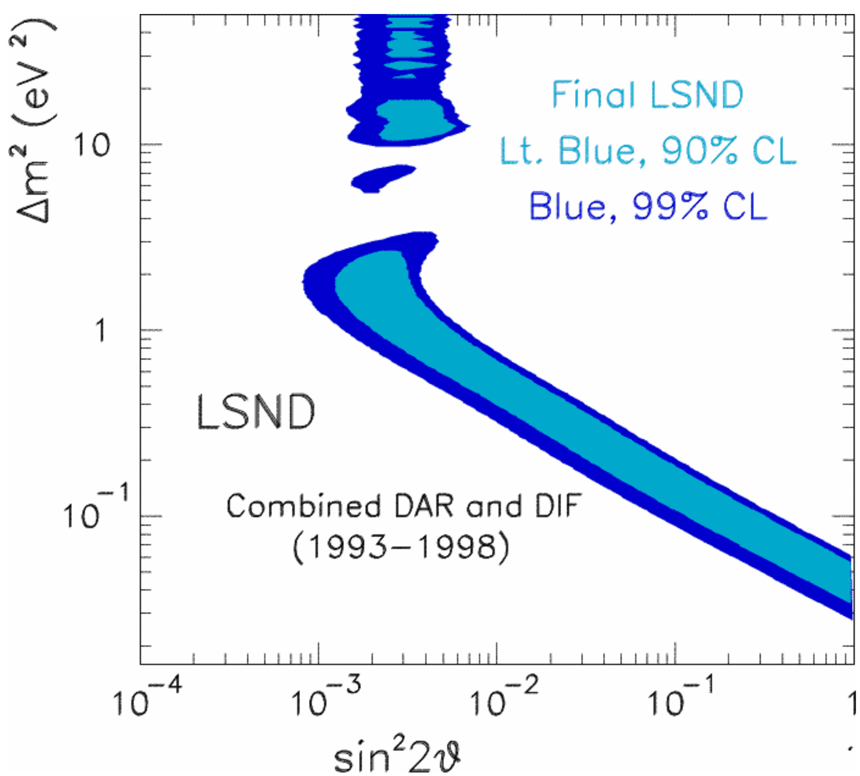
LSND Final Result

LSND sees excess above backgrounds

- Excess: 87.9 ± 22.4 ± 6.0 evts.

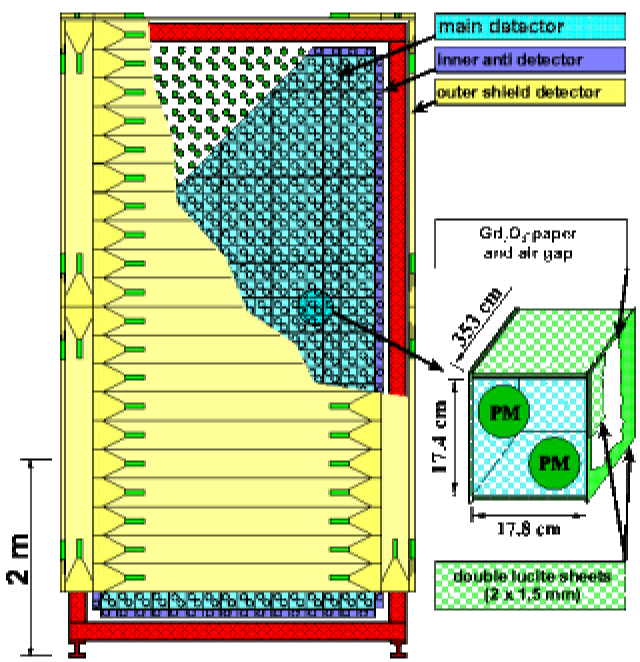


- Corresponding osc. probability: (0.264 ± 0.067 ± 0.045)%
- 3.3 σ evidence for oscillation.

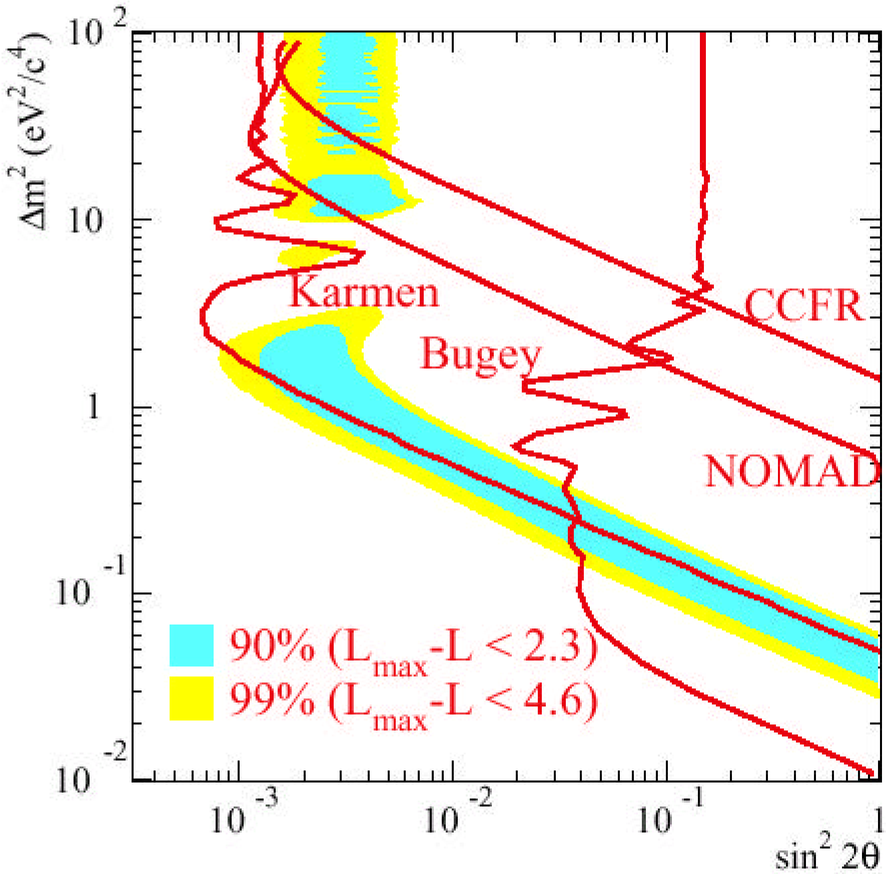


Karmen II (1997-2001)

- Pulsed 800 MeV pot (ISIS)
  - DAR beam (90º to target)
  - 17.6 m baseline
- 56 tons of liquid scintillator
  - 512 modules
  - Gd-doped (8 MeV γ)
- ×10 less statistics than LSND (less intensity & size)

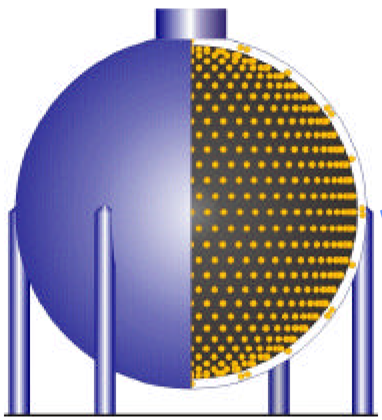


- Almost final results
  - 11 events observed
  - 12.3 ± 0.6 events expected

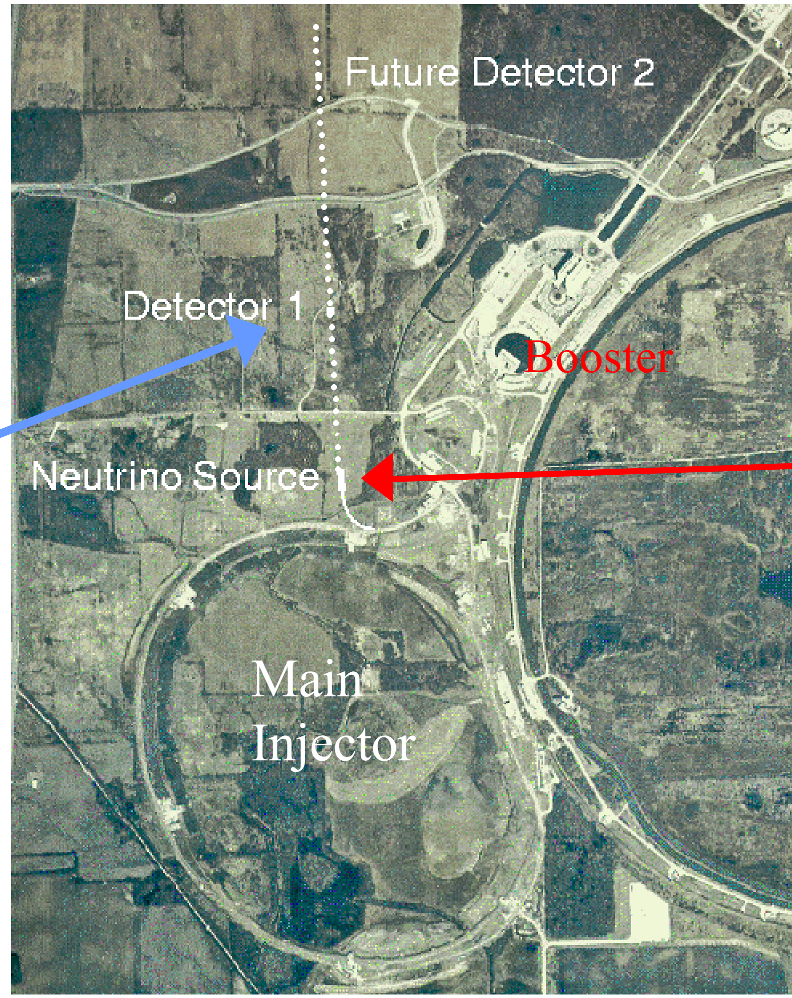


MiniBooNE Experiment

Need definitive study of n_m®n_e at high Dm^2 … MiniBooNE



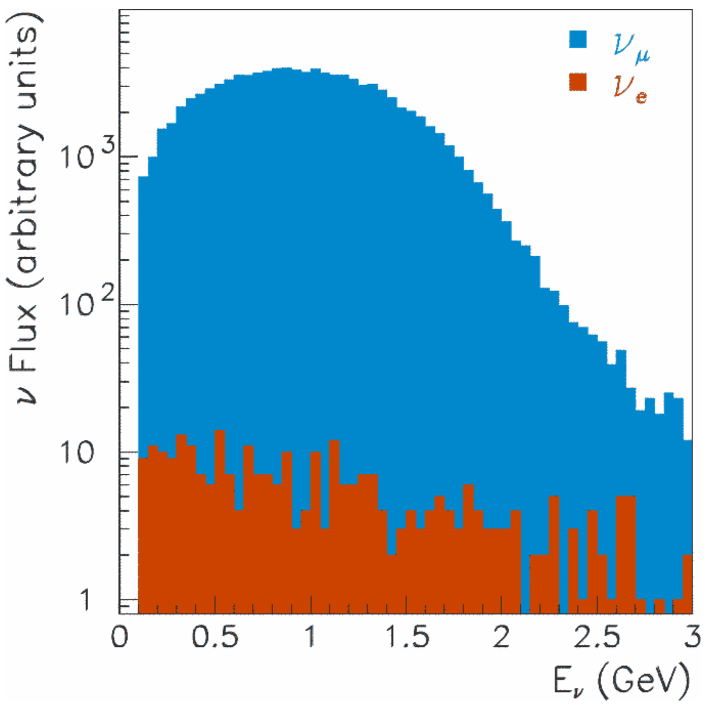
12m sphere filled with mineral oil and 1500 PMTs located 500m from source



Use protons from the 8 GeV booster
⇒ Neutrino Beam
$\langle E_\nu \rangle \sim 1$ GeV

MiniBooNE Neutrino Flux and Expected Events

The L/E is designed to be a good match to LSND at ~1 m/MeV.



Expected intrinsic ν_e flux is small compared to the ν_μ flux.

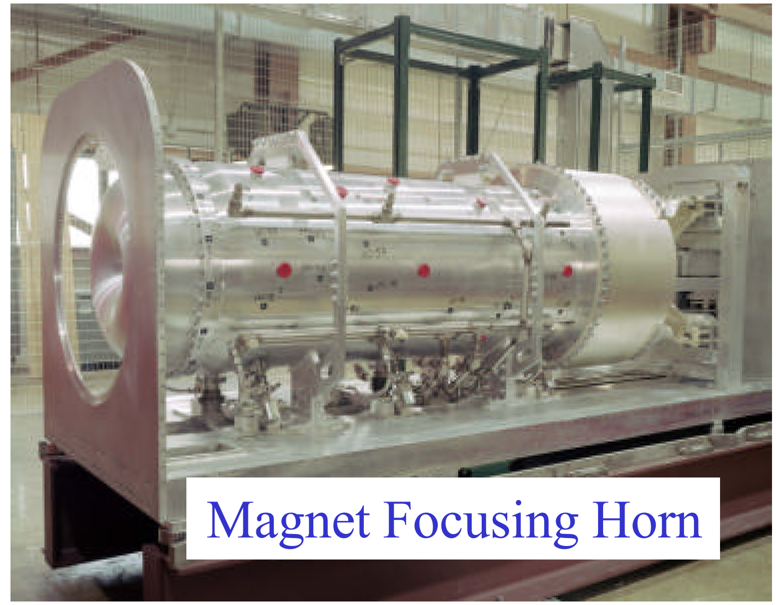
Expectation for electron-like events/2yrs

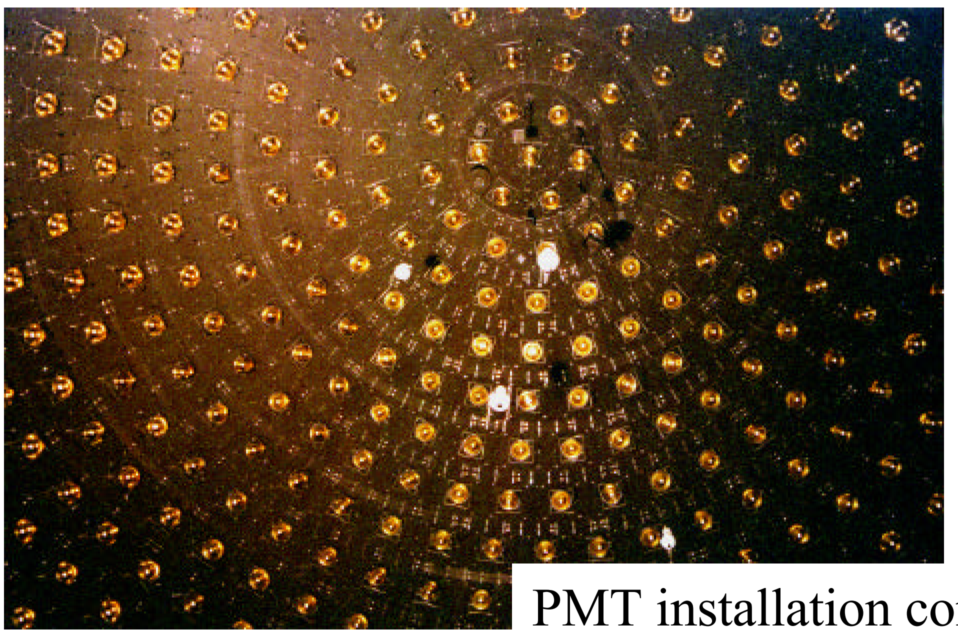
- Intrinsic ν_e background: 1,000 events
- μ mis-ID background: 500 events
- π^0 mis-ID background: 500 events
- **LSND-based n_m®n_e: 1,000 events**

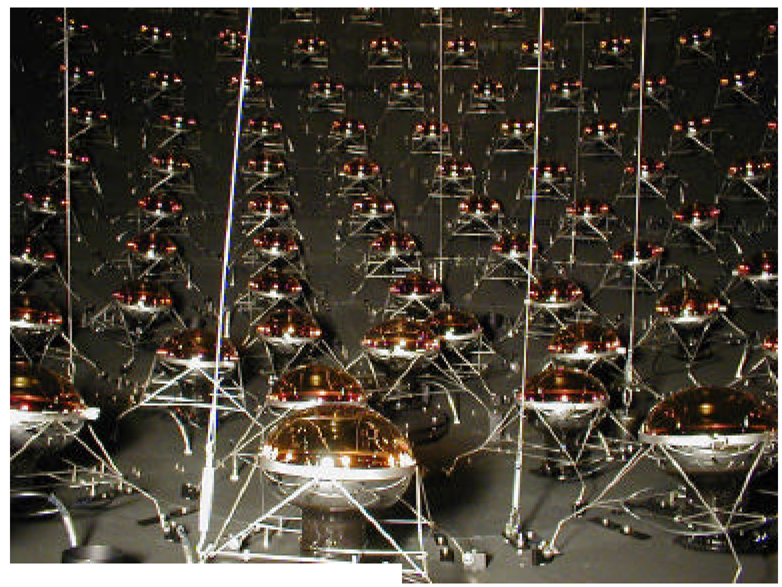
- **Backgrounds can be separated from signal**
  - Osc. signal has different energy spectrum than intrinsic ν
  - Experimental determinations of all backgrounds.

MiniBooNE is about to Start

- Everything on schedule for *June, 2002 Start*
  - Detector half filled with oil
  - Horn tested (10^7 pulses)
  - Proton extraction ready


Magnet Focusing Horn

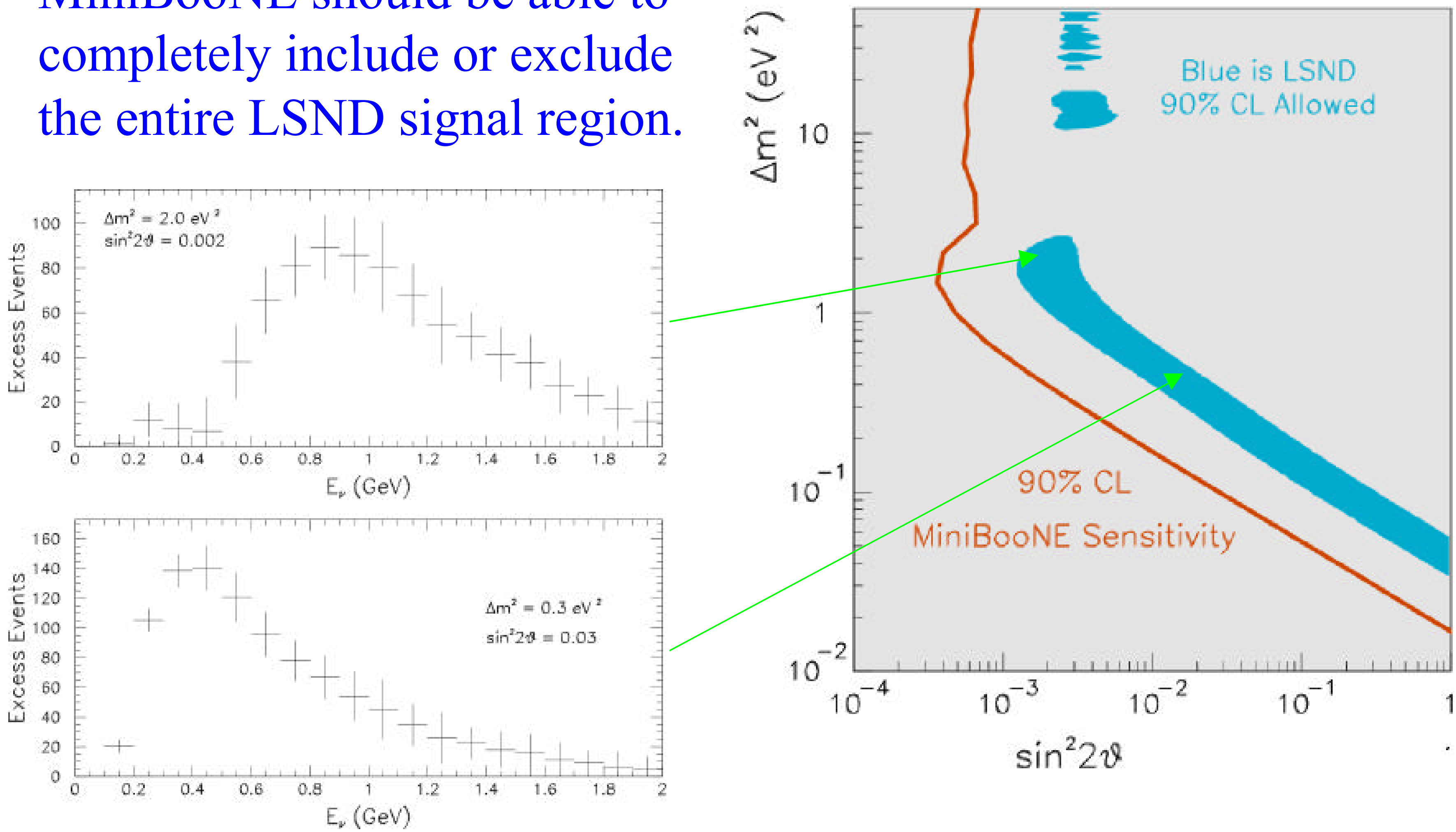




PMT installation completed in October.

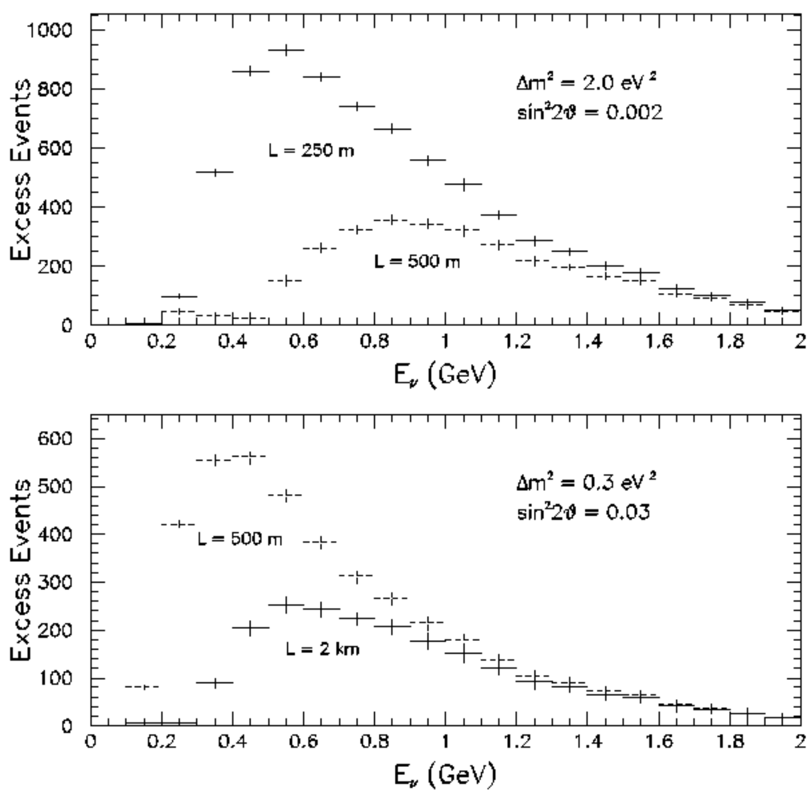
MiniBooNE Sensitivity to LSND

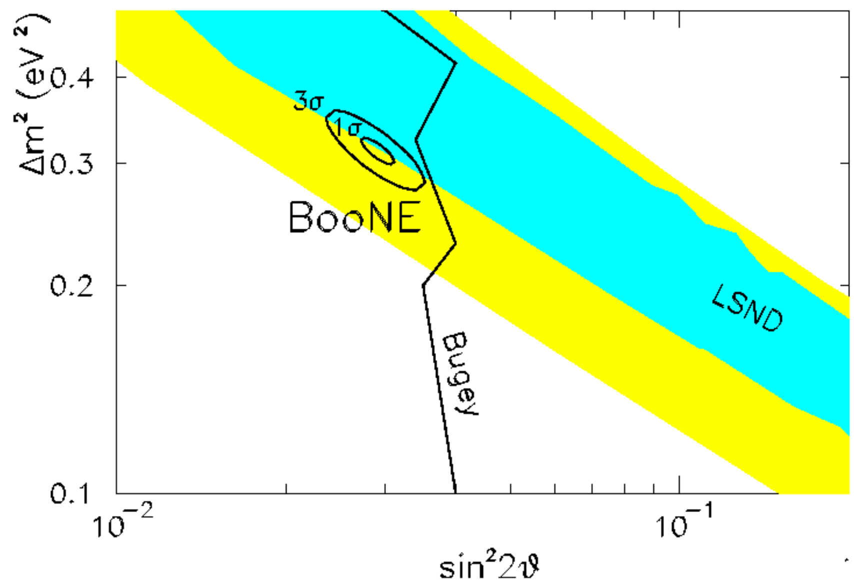
With two years of running MiniBooNE should be able to completely include or exclude the entire LSND signal region.



MiniBooNE Þ BooNE

- If signal is observed in MiniBooNE, then add second detector at appropriate distance Þ **Two detector BooNE experiment**

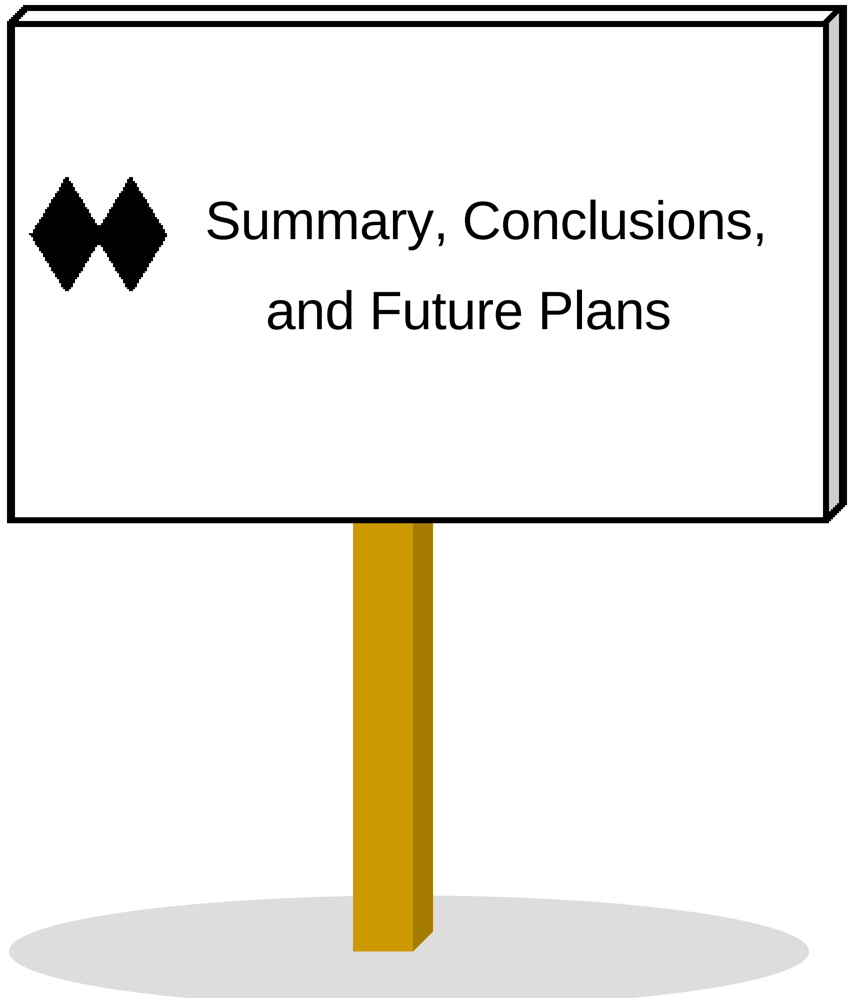




Measure:

Δm^2 to $\pm$ 0.014 eV^2

$\sin^2 2\theta$ to $\pm$ 0.002


Summary, Conclusions,
and Future Plans

Summary
Expectations for the Next ~5 years

- LSND Δm^2
  - Definitive determination if osc.
  - Measure $\Delta m^2/\sin^2 2\theta$ to 5-10%
  - If positive $\Rightarrow$ New round of experiments: $\nu_{\mu \text{ and } e} \rightarrow \nu_\tau$

Ü ***Results from MiniBooNE***

- Atmospheric Δm^2
  - Know if $\nu_\mu \rightarrow \nu_\tau$ or ν_s
  - Measure $\Delta m^2/\sin^2 2\theta$ to 10% if $\Delta m^2 > 2\times10^{-3}$ eV^2
  - Maybe see $\nu_\mu \rightarrow \nu_e$

Ü ***Results from K2K, MINOS , CNGS***

Ü ***MINOS Off-axis?***

- Solar Δm^2
  - Restrictions to one solar solution
  - Know if $\nu_e \rightarrow \nu_{\mu,\tau}$ or ν_s

Ü ***Results from Kamland, Borexino, SNO***

Next Step Driven by Near Term Results

- If MiniBooNE sees $\nu_\mu \rightarrow \nu_e$ oscillations then
  - Investigate the oscillation phenomenology at high Δm^2
    - Need at least 4 mass eigenstates … **Sterile Neutrinos!** What is the pattern … 2+2 , 3+1

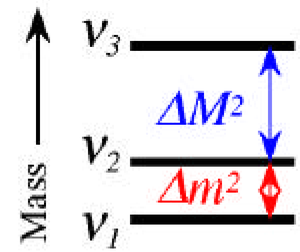
- If MiniBooNE refutes LSND then Minos/CNGS
  - Push to measure oscillation parameters with best precision
  - Search/measure $\nu_\mu \rightarrow \nu_e$ at the atmospheric Δm^2

- If MINOS/CNGS fail to measure $\nu_\mu \rightarrow \nu_e$ then
  - Design new exp's to measure θ_{13} (also sign of Δm^2)
    - Long-baseline "Superbeams" or ν–factory sources will be needed

- If parameters are reasonable, then move to a CP violation experiment
  - Experiment must be sensitive to
    - Δm^2_{23} and Δm^2_{12} $\Rightarrow$ requires the LMA
    - mixing at the θ_{13} level $\Rightarrow$ requires θ_{13} large enough to see

Scenario: MiniBooNE Confirms LSND
Three Dm^2_{solar} , Dm^2_{atm} , Dm^2_{LSND}

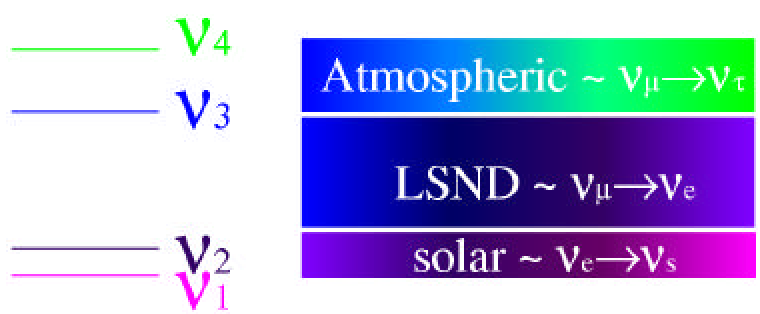
Possible explanations



- Atmospheric result is a mixture of Δm^2_{solar} and Δm^2_{LSND}
  - Difficult to fit all data with this model (hep-ph/000416)

- Introduce a 4th (or more) sterile neutrino
  - 2+2 Model:
    - Atmospheric or Solar (or both) have oscillation fractions to ν_s such that $f_{Solar} + f_{Atmos} = 1$

      Super-K Atmospheric:
      $f_{Atmos} < 0.25$ @ 90%CL
      SNO + Super-K Solar:
      $f_{Solar} < 0.50$ @ 90%CL
    - Model still possible but at the edge
      (Extension: 3active +3sterile model can work)

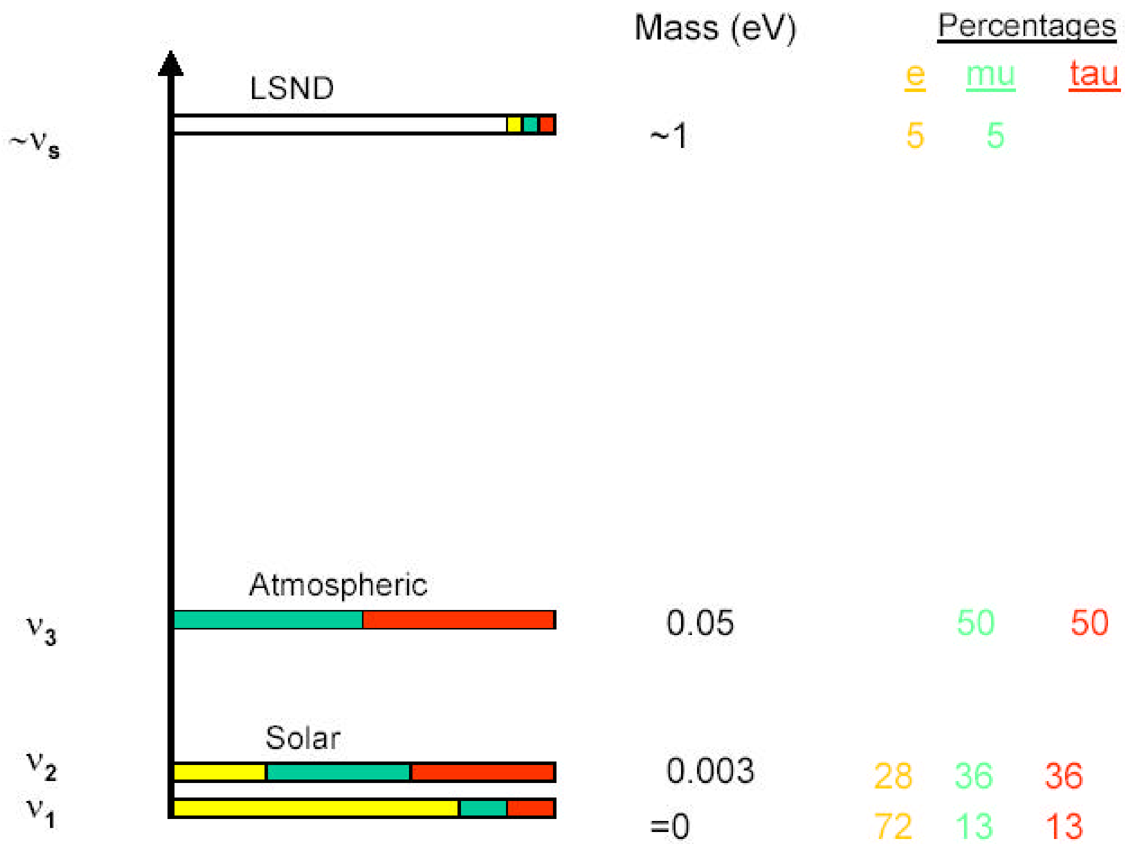


3+1 Model

- 3+1 Model:
  - Atmospheric: $\nu_\mu \rightarrow \nu_\tau$
  - Solar: LMA $\nu_e \rightarrow \nu_{\mu,\tau}$
  - LSND: $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$

- Solar oscillations are to a 50%/50% mixture of ν_μ and ν_τ

- LSND $\nu_\mu \rightarrow \nu_e$ oscillations are through high mass, mainly ν_s state with small admixture of ν_μ and ν_e



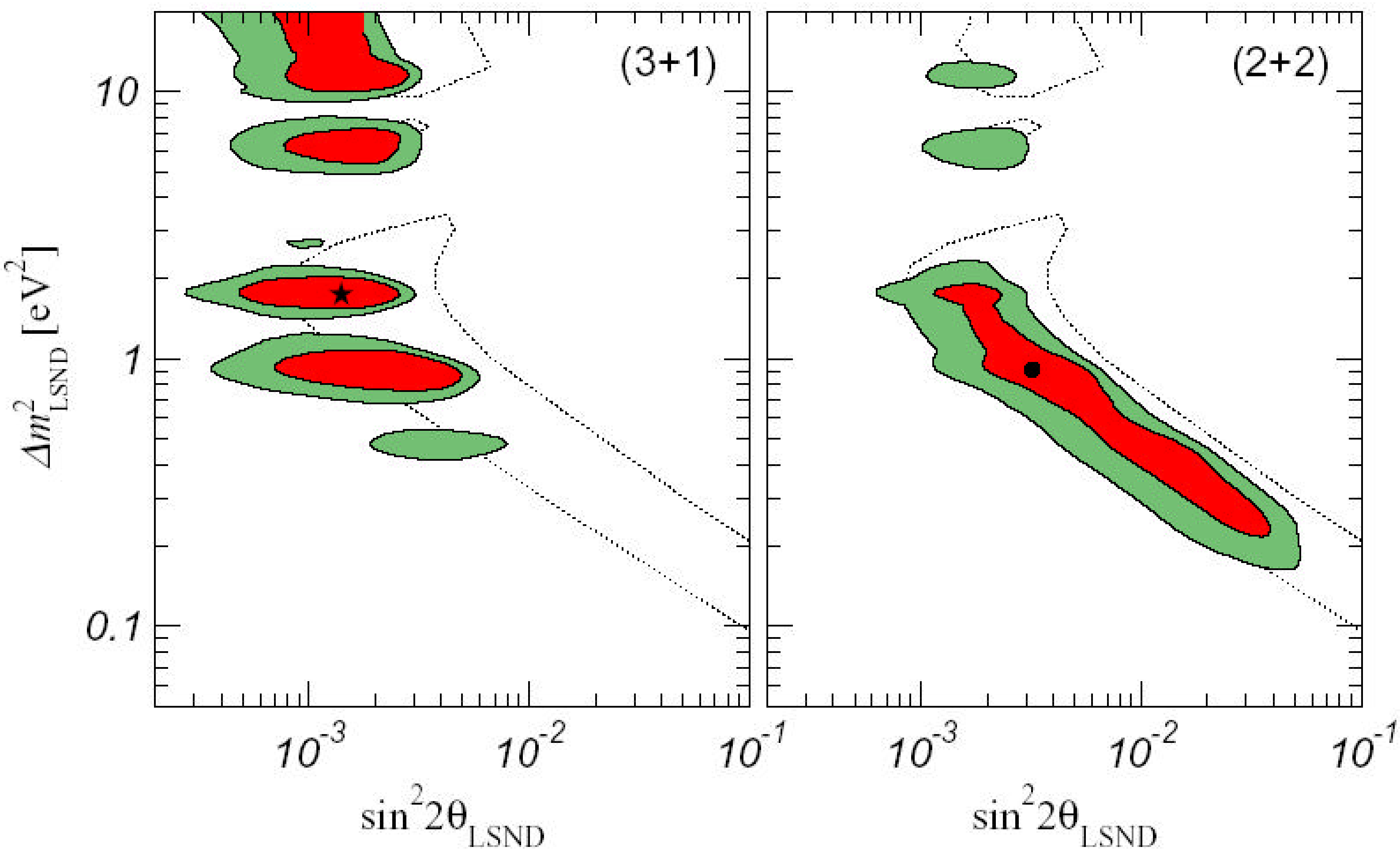
$$\nu_e = 0.85\nu_1 + 0.51\nu_2$$

$$\nu_\mu = -0.36\nu_1 + 0.60\nu_2 + 0.71\nu_3$$

$$\nu_\tau = 0.36\nu_1 - 0.60\nu_2 + 0.71\nu_3$$

Global Analysis

- Global analysis: Solar, Atmospheric, LSND/Karmen, Reactor
  (Maltoni, Schwetz,and Valle hep-ph0112103)



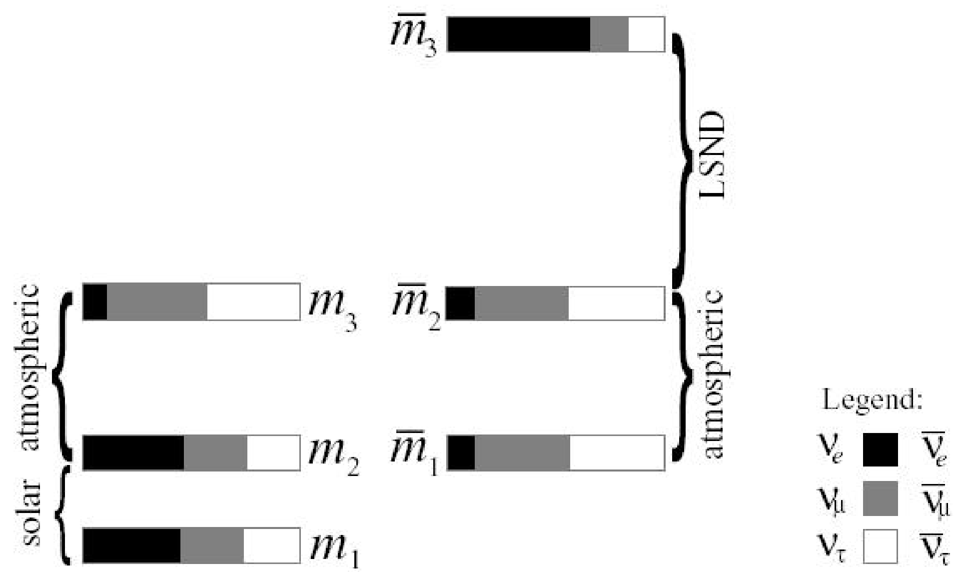
CPT Violation

- If CPT is violated the

$$Mass(n_i) \neq Mass(\bar{n}_i)$$

$\Rightarrow$ Now LSND sees $\bar{n}_m \rightarrow \bar{n}_e$

but Solar sees $n_e \rightarrow n_m$



(Barenboim, Borissov, Lykken, Smirnov, Murayama, Yanagida; hep-ph 0201080)

- Model accommodates solar, atmospheric, and LSND without sterile neutrinos
  - Just allow the antineutrino Δm^2 to be bigger than the neutrino

- Leptogenesis
  - After the EW phase transition since the neutrinos are lighter than antineutrinos

$$number(n) > number(\bar{n})$$

  - B-L processes then convert neutrino excess to baryon excess.
    - Sign and magnitude ~correct to generate baryon asymmetry in the universe.

Scenario: MiniBooNE Refutes LSND

- 3-generation Mixing

Atmospheric: θ_{23}

Solar: θ_{12}

$$\begin{pmatrix} n_e \\ n_m \\ n_t \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-id} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{id} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{id} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{id} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{id} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix}$$

Need to measure:

Sign of Δm_{23}^2

CP phase δ

θ_{13} ($\nu_e \rightarrow \nu_\mu$)

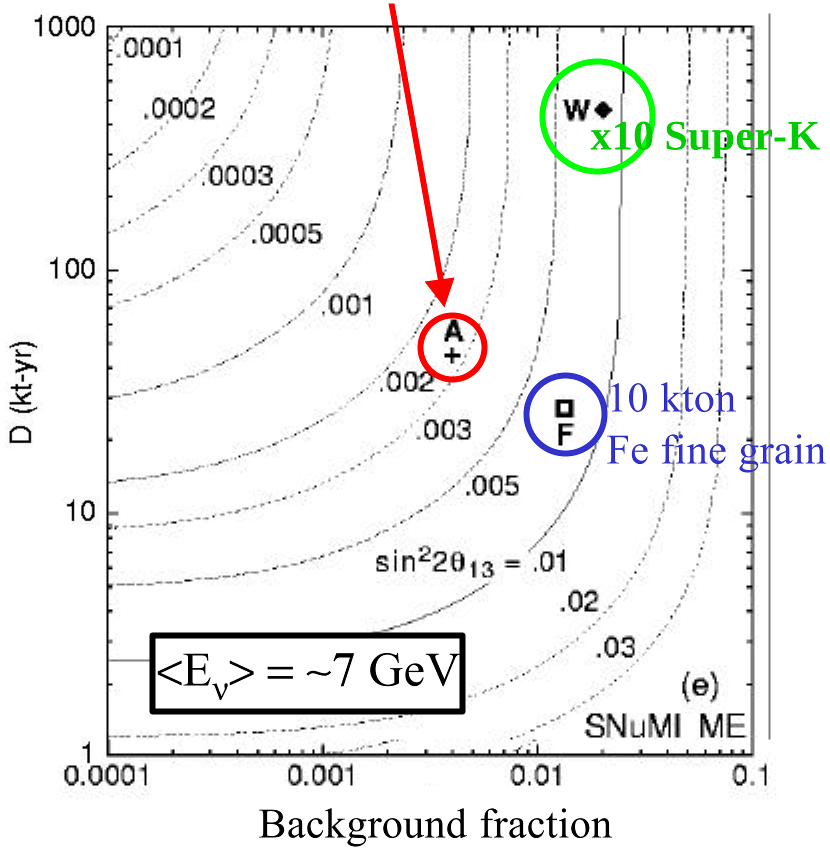
- Measurements of $n_m \rightarrow n_e$ and $\bar{n}_m \rightarrow \bar{n}_e$ yields q_{13} and d
  - θ_{13} key parameter for osc. phenomenolgy since θ_{12} and θ_{23} are both large
    - Determines whether CP violation is accessible

High Intensity Conventional Beam As Next Step "Superbeams"

- Need high intensity proton source
  - Upgraded FNAL/AGS booster, JHF, new Proton Drivers (FNAL/CERN)
- Need to construct high intensity neutrino beam pointed at long-baseline detector about 3000 km away.
  - Reduce background
  - Sensitivity to matter effects
- Need a massive (30 - 50 kton) detector
  - Need good backgrnd rejection (10^{-3}) (Liquid argon may be best)

sin²2q13 at 3 s vs. Size & Bkgnd

Super (×4) NuMI beam for 3yrs
30 kton Liq. Argon Detector
Baseline = 2900 km
Reach $\sin^2 2\theta_{13} \approx 0.003$ at 3σ



Possible Future Step:
Muon Storage Ring n-Factory

- Muon storage ring
  - Provides a super intense neutrino beam with a wide range of energies.
  - High intensity, mixed beam allows investigation of all mixings (n_e ® $n_{m \text{ or } t}$)

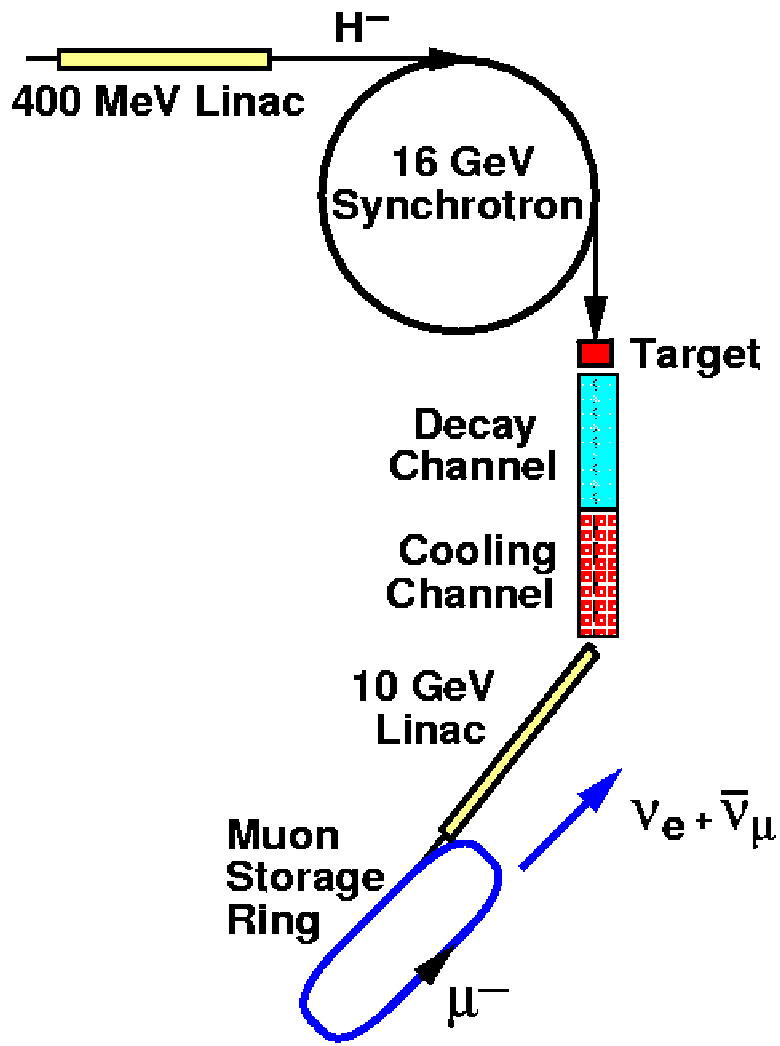
- Flavor composition/energy selectable and well understood:

$$m^- \rightarrow e^- + n_m + \bar{n}_e \quad \text{or}$$

$$m^+ \rightarrow e^+ + \bar{n}_m + n_e$$

- Highly collimated beam
  - Very long baseline experiments possible

    i.e. Fermilab to California

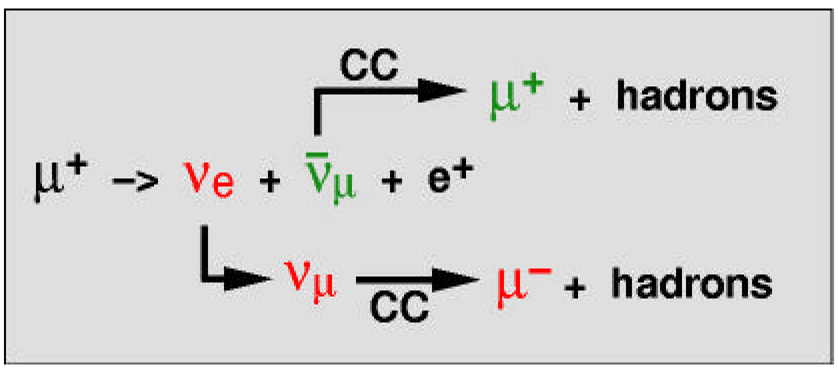


$\nu_e \to \nu_\mu$ Oscillation Measurements at a ν-Factory

- For the atmospheric Δm^2 region, use $\nu_e \to \nu_\mu$ to determine $\sin^2 2\theta_{13}$

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{32} L/E_\nu)$$

- By using $\nu_e \to \nu_\mu$, signal becomes a search for wrong-sign muons which allows good sensitivity to low $\sin^2 2\theta_{13}$

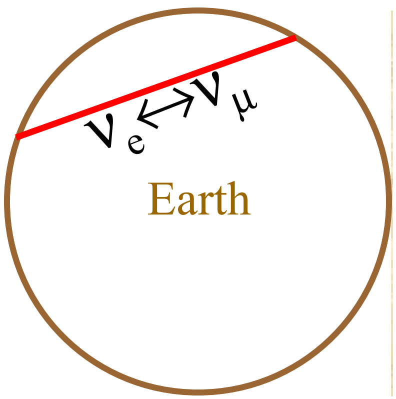


Background is low (few $\times 10^{-4}$)

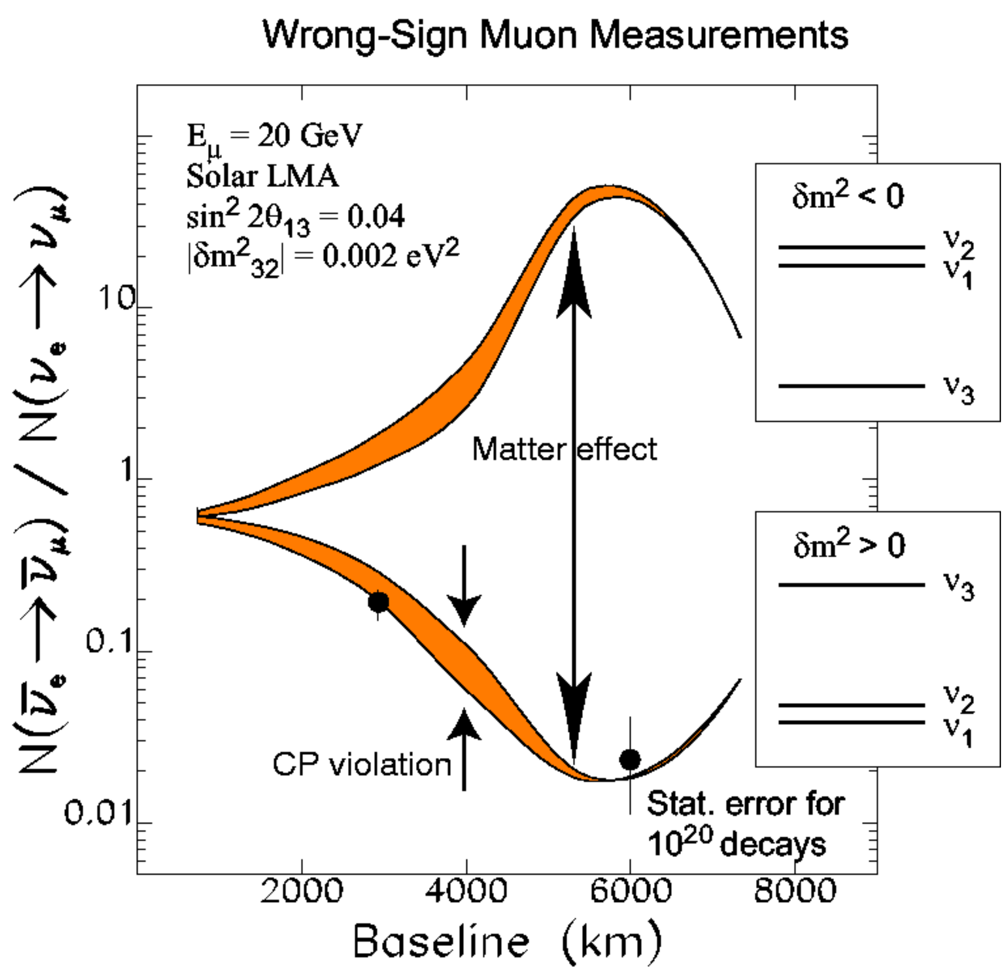
- Can reach $\sin^2 2\theta_{13} \approx 0.001$ for 2×10^{20} μ-decay

Matter (and CP) Effects for n_e ® n_m

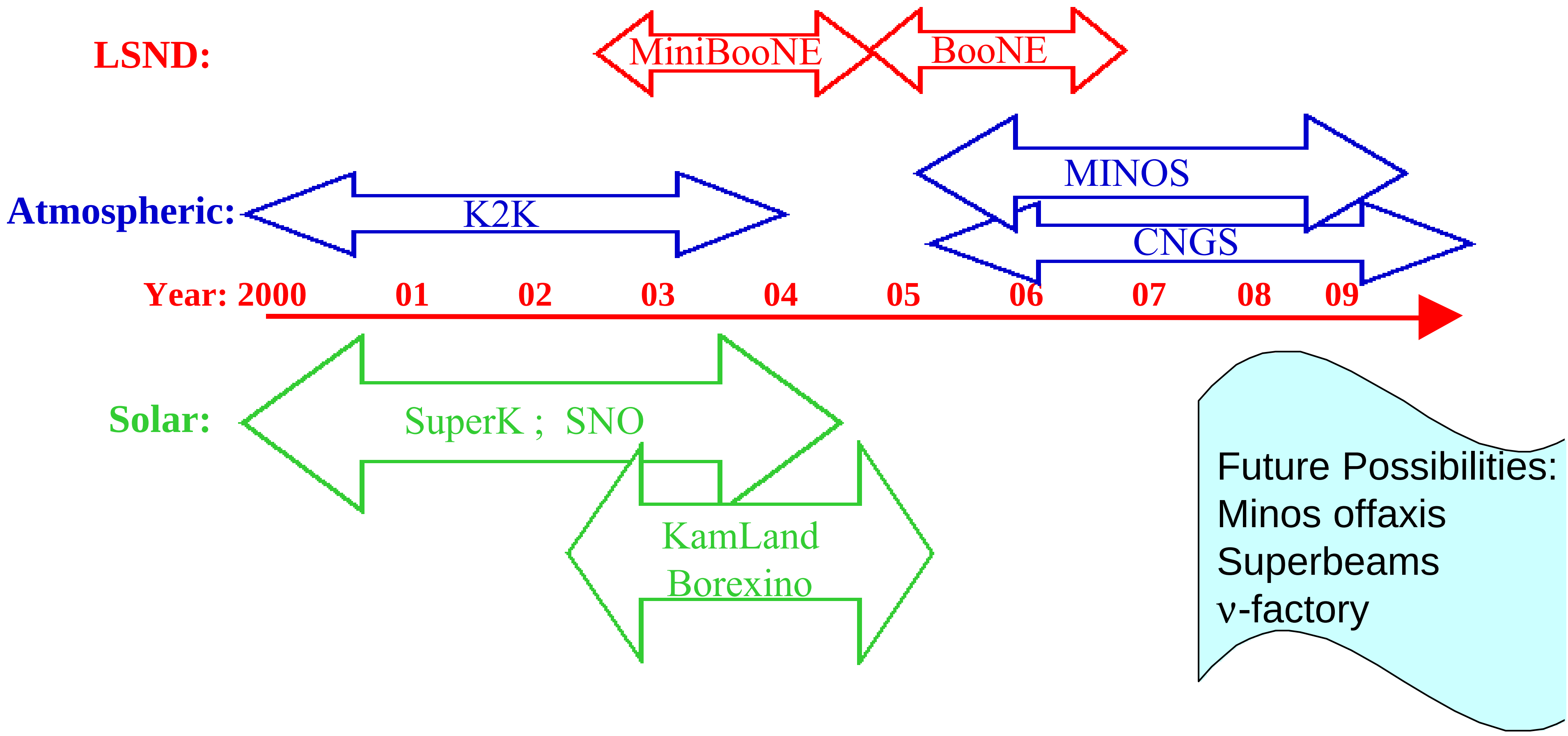
- For long baseline experiments, matter effects change the oscillation formula:
  - $\nu_e\ e \rightarrow \nu_e\ e$ NC and CC
  - $\nu_\mu\ e \rightarrow \nu_\mu\ e$ NC only



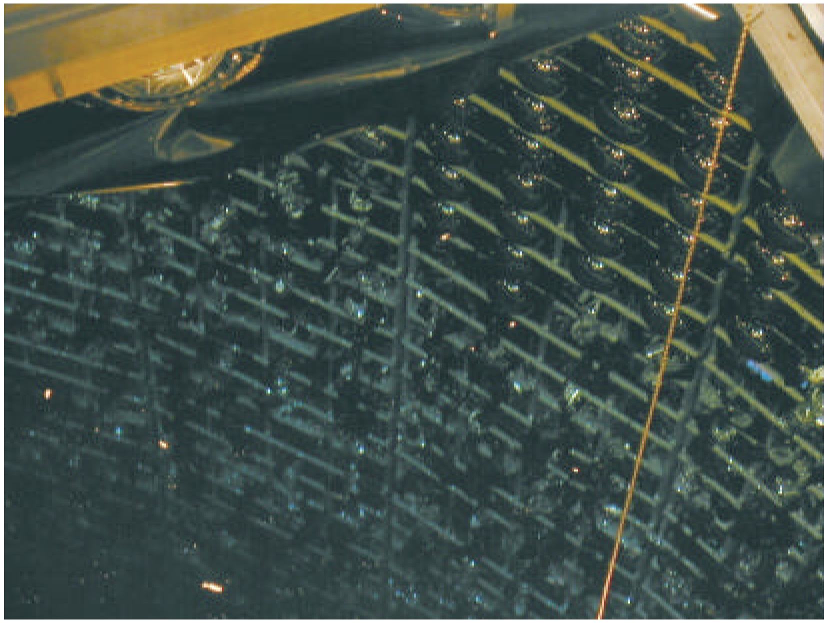
- Oscillation probability is modified depending on sign of $\Delta m^2 = m_3^2 - m_2^2$
  - Measure sign of Δm_{32}^2 to determine if $m_3^2 > m_2^2$

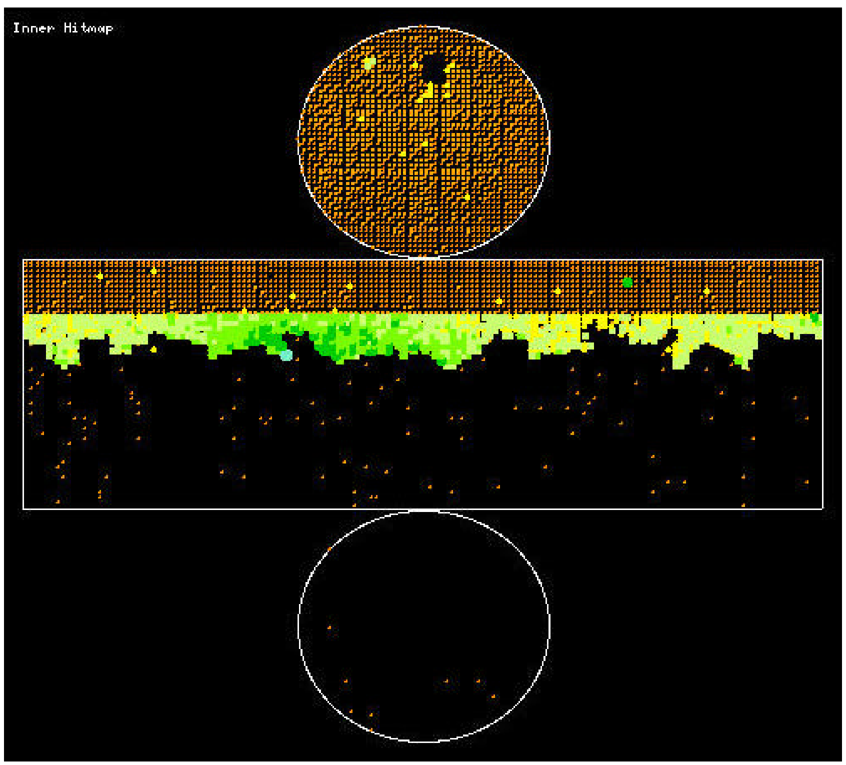


Oscillation Experiment Timeline



Exciting Times for Neutrino Experimentation over the next decade !!





Super-K Accident

- On Nov. 12, after refilling Super-K to the 80% level
  - Chain reaction happened started by the implosion of one tube at the bottom of the tank.

6777 (out of 11146) 20-inch tubes destroyed

1149 (out of 1849) 8-inch veto tubes destroyed

- Developed methods to stop future chain reaction
  - Plan to replace tubes for 50% coverage and restart K2K in January, 2003
  - Detector will be fully repaired for running with JHF beam
    (Take 3 to 4 years & $30M)