NEUTRINO PHYSICS

THE HUNDRED YEAR QUEST

J. Schneps
Tufts University

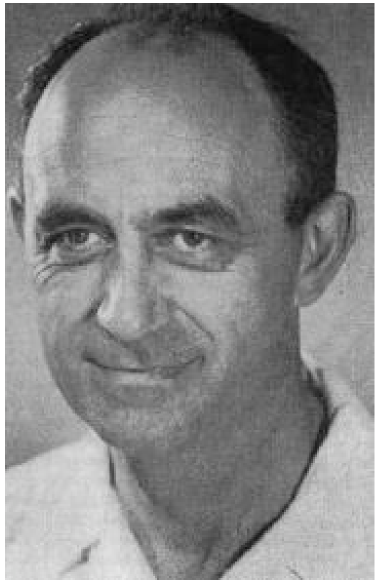
DESY
12/13 April 2011

The First ~50 years

In December AD 1930
Pauli proposed the
"neutron" as a solution
to the β-decay continuous
spectrum problem.

For neutrino physics
I will designate this year
as AP 0 (AP=Anno Pauli).

In the period 10 to 0 BP (note 0 BP = AP 0) there was much ferment over the β-decay problem, but by AP 4 (1934) the problem was essentially solved. Enrico Fermi invented the weak interaction,and modified the name of Pauli’s particle to ‘neutrino’.



By AP 9(1939), thanks to Hans Bethe, we could understand how the sun burns.

By AP 20(1950) nuclear β-decay was quite well understood ($n \rightarrow p e^{-} \nu$). There were some ambiguities about the interaction form:

S,T,P,V,A

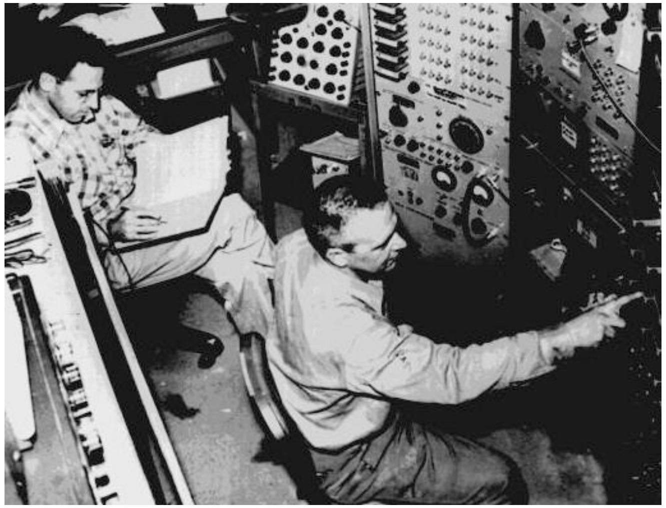
Meanwhile, other things were happening. The “muon” was discovered in AP 06(1936), and by AP 17(1947) was understood to be a weakly acting particle, the product of pion decay, $\pi \rightarrow \mu\nu$.

From AP 4(1934) to ~AP 20(1950) it was considered that the interaction of a neutrino would never be observed because of the minuscule cross section (~10^{-43} m^2)

However, about that time it was realized nuclear reactors are a prolific source of antineutrinos. Cowan and Reines took advantage of this and in AP 26(1956) were able to detect

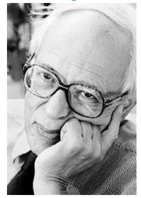
$$\bar{\nu} p \rightarrow e^+ n$$

The neutrino was “discovered”.

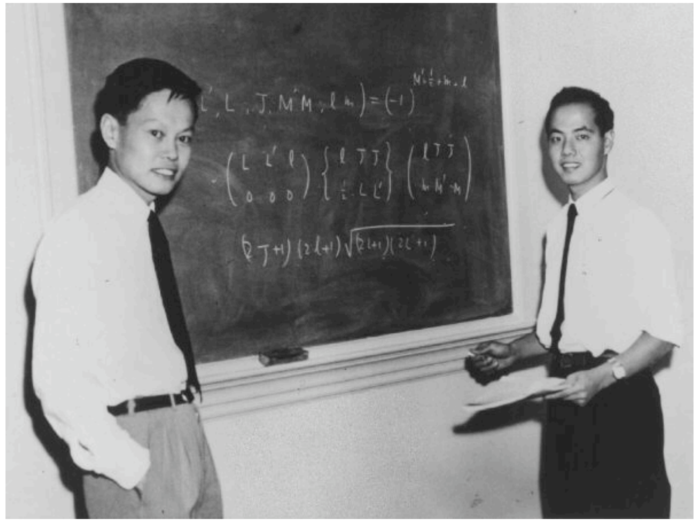


(And in AP 25-26(1955-56) $K^0,\overline{K^0}$ mixing was predicted, and found.)

BUT, perhaps these weren't the greatest events in particle physics in AP 26(1956), for in that year

(Gell-Mann & Pais)



Yang and Lee proposed Parity Violation!

AP 27(1957)

Confirmed experimentally by C.S. Wu et.al.

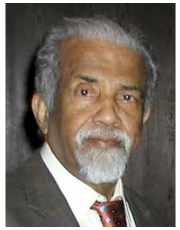
AP 28(1958)

V-A Theory of the Weak interaction

P violated - C violated

CP conserved ?

Marshak & Sudarshan, Feynman & Gell-Mann

Could the ν from pion decay, be different from the ν of beta decay ?

AP 32(1962)

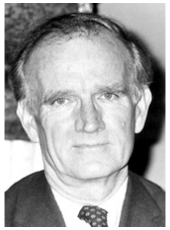
The first accelerator neutrino beam from decaying pions at the Brookhaven AGS (Lederman, Schwartz,Steinberger)

$\nu N \rightarrow \mu N$

Now there are two neutrinos; ν_μ and ν_e

AP 31-40(1961-70)

AP 34(1964) Quark model and CP violation in K^0 system



Cronin & Fitch

Electroweak Theory is developed (Glashow,Salam,Weinberg).

There are doubts. It predicts unobserved neutral currents, W's, Z's.

AP 40(1970)

GIM mechanism - explains suppressed FCNC - predicts charmed quark

AP 43(1973)

Neutral Currents discovered by Gargamelle collaboration - (including of course D. Haidt)

$$\nu_\mu e^- \to \nu_\mu e^-$$

$$\nu_\mu N \to \nu_\mu N$$

AP 44(1974) charm discovered ; AP 45 tau lepton (suggests a 3rd neutrino, ν_τ)

AP 47(1977) bottom quark; AP 53 (1983) W's and Z's

The Standard Model is "In"

AP 33(1963)-present - neutrinos are used as probes, e.g., cross sections, structure functions, m_A, θ_W , etc.

The first ~50 years - one discovery after another

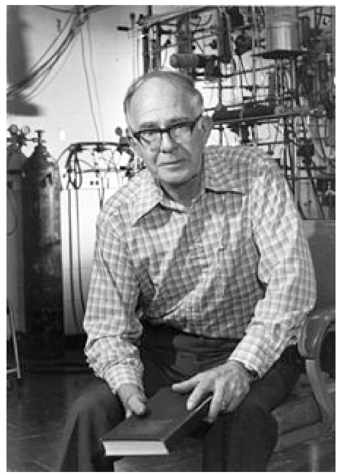
But we left out a few things

AP 7(1937) - Majorana : Is the neutrino its own antiparticle? - (neutrinoless double β-decay)

AP 20(1950) - present - neutrino mass from H^3 β-decay

AP 28(1958) - Pontecorvo ; Are there ν-$\bar{\nu}$ oscillations (analogous to K^0-$\overline{K^0}$)?

AP 35-50(1965-80) - Ray Davis detects solar neutrinos ~1/2 expected number. Common opinion: Either the experiment or the Standard Solar Model is wrong.This became the solar neutrino problem.(both were okay) Could ν-$\bar{\nu}$ or ν_e-ν_μ oscillations explain it??

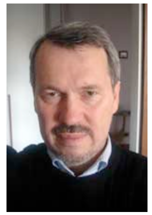
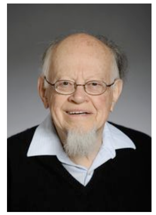


AP 50 - 70(1980-2000)

Solar, Reactors, Atmospheric, Accelerators
Things are heating up

Solar Neutrino "deficit" confirmed by gallium experiments, GALLEX, GNO (Gran Sasso) and SAGE(Russia), also by Kamiokande and later Superkamiokande. If oscillations and the MSW effect (matter effect) are taken into account

it requires $m_2^2 - m_1^2 = \Delta m^2_{21} \sim 10^{-4}$ eV^2

AP 57(1987)

Neutrino burst from Supernova 1987A observed by Kamiokande and IMB.

Neutrino Astronomy is born.

Around 1987 a new idea became attractive, neutrinos as the missing Dark Matter. The mass had to be ~ 20 ±10 eV.

The leading candidate is ν_τ .

Look in accelerator beams for $\nu_\mu \rightarrow \nu_\tau$ oscillations

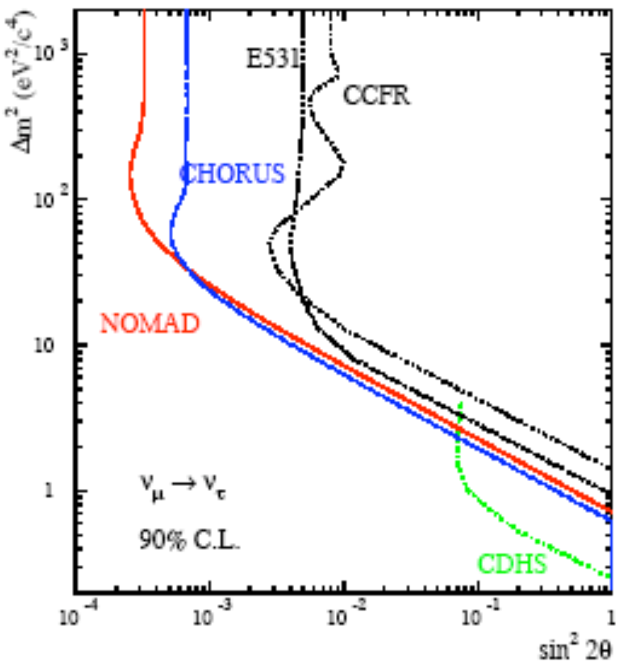
Wide band ν_μ beams around 10-100 GeV with pion decay tunnels of ~500m and the detector at ~1 km were just right for $\Delta m^2 \sim 100$ -1000 eV^2.

CHORUS and NOMAD at CERN.

By AP 70(2000) no evidence for oscillations, but limits were set

$P_{\mu\tau} \rightarrow \sin^2 2\theta \, \sin^2[1.27(L/E)\Delta m^2]$

L(m),E(MeV), Δm^2(eV^2)



Atmospheric Neutrinos

AP 58(1988) - Atmospheric neutrinos, the background for nucleon decay experiments - The ratio $(\nu_\mu + \bar{\nu}_\mu) / (\nu_e + \bar{\nu}_e)$ is observed to be significantly below the expected value of ~2 ($\pi \rightarrow \mu\nu_\mu$; $\mu \rightarrow e\nu_\mu\nu_e$) by the Kamiokande and IMB experiments.

Kamioka<u>nde</u> notes the effect is mainly a deficit of ν_μ . They propose missing ν_μ have oscillated into ν_τ.
'<u>nde</u>' for Nucleon Decay Experiment →Neutrino Detection Experiment

As we saw, the two neutrino oscillation hypothesis leads to the simple formula for ν_μ disappearance

$$P\mu\mu = 1 - P\mu\tau$$

$$P\mu\tau = \sin^2 2\theta_{23} \sin^2[1.27(L/E)\Delta m^2_{32}]$$

With L in km, E in GeV, $\Delta m^2_{32} = m_3^2 - m_2^2$ in eV^2

$$|\nu_\mu\rangle = \cos\theta_{23}|\nu_2\rangle + \sin\theta_{23}\,|\nu_3\rangle$$

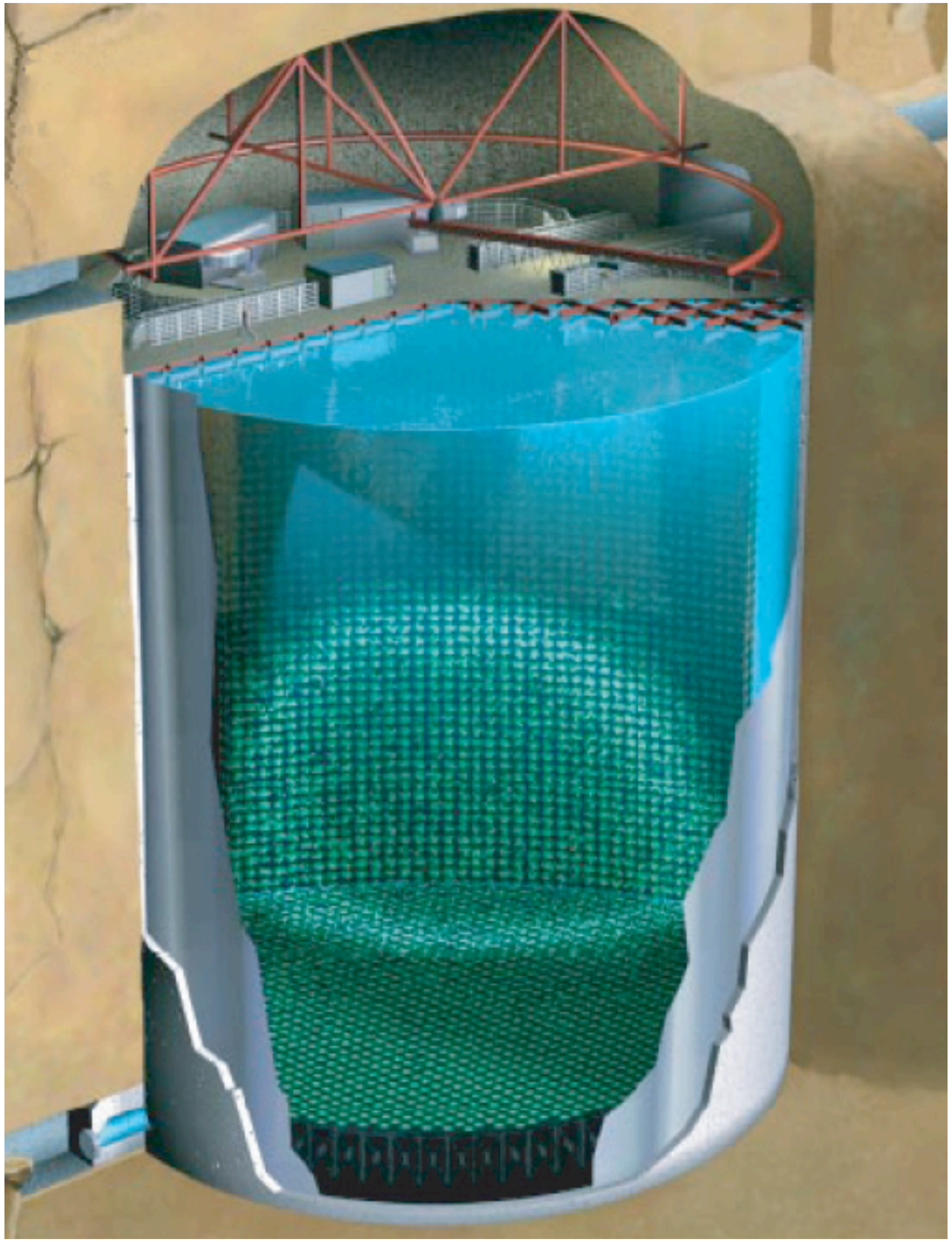
$$|\nu_\tau\rangle = -\sin\theta_{23}|\nu_2\rangle + \cos\theta_{23}\,|\nu_3\rangle$$

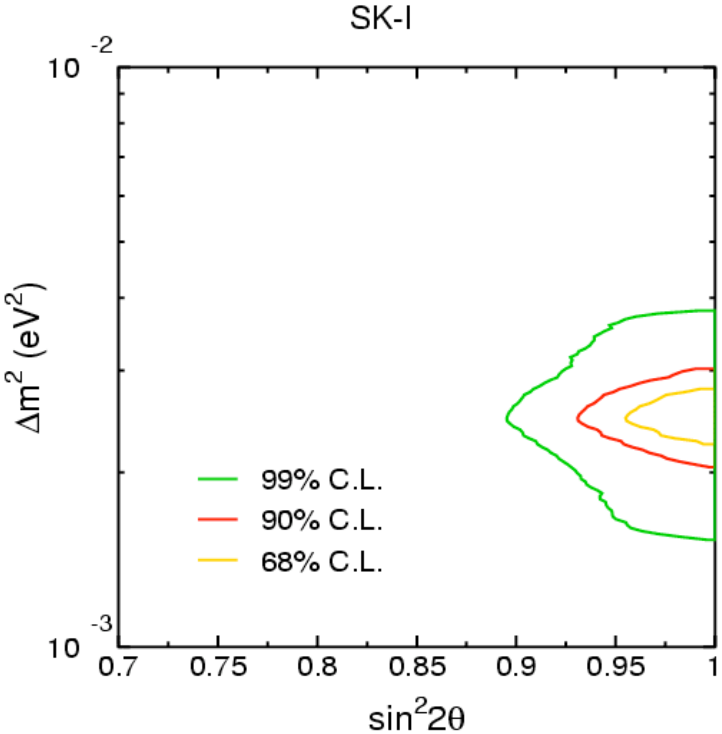
θ_{23} is called the atmospheric mixing angle

Note Δm_{32}^2 can be positive or negative

Superkamiokande is built (50 ktons H_2O) and by measuring zenith angle (essentially L) and E, in

AP 68(1998) oscillations of atmospheric neutrinos are confirmed. $\sin^2 2\theta_{23} \sim 1$, $|\Delta m^2_{32}| = 2.5 \times 10^{-3}$ eV^2





SK-I
10^{-2}
10^{-3}
Δm^2 (eV^2)
0.7
0.75
0.8
0.85
0.9
0.95
1
$\sin^2 2\theta$
99% C.L.
90% C.L.
68% C.L.

AP 65-68(1995-98) LSND , Los Alamos

$\pi^+ \to \mu^+ \nu_\mu$; $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ (π^+ stopped or in flight)

No $\bar{\nu}_e$ produced, but observe $\bar{\nu}_e + p \to e^+ + n$

All backgrounds are carefully studied

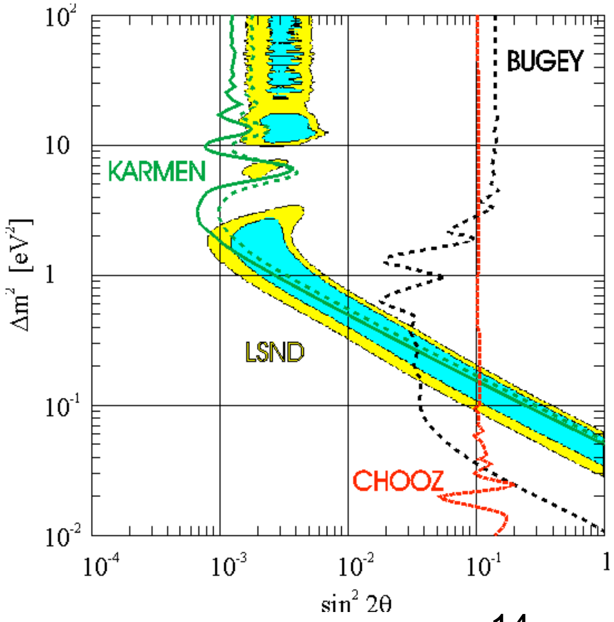
Their hypothesis - neutrino oscillations

$$\bar{\nu}_\mu \to \bar{\nu}_e$$

For two-neutrino oscillations

$P \to \sin^2 2\theta \sin^2[1.27(L/E)\Delta m^2]$

Data require $\Delta m^2 \sim 1\ eV^2$



Now we have to introduce the standard 3 ν formalism - the MSNP matrix connects flavor to mass states

3 mixing angles θ_{12}(solar), θ_{23}(atmospheric), θ_{13} (sub-dominant) and the CP phase δ - allows for two Δm^2 's (LSND?)

Mixing Matrix:

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ | Atmos. L/E $\mu \leftrightarrow e$ | Solar L/E $e \to \mu,\tau$ | $0\nu\beta\beta$ decay

500km/GeV | 15km/MeV

SNO/KamLAND $|U_{e2}|^2$

Reactor/LBL $|U_{e3}|^2(1-|U_{e3}|^2)$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Atm Nus/LBL $|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

$$\frac{CC}{NC}|_{sno} \approx |U_{e2}|^2$$

S. Parke, NEUTRINO 2010

Reactor Experiments AP62-69(1992-99)

PALO VERDE and CHOOZ

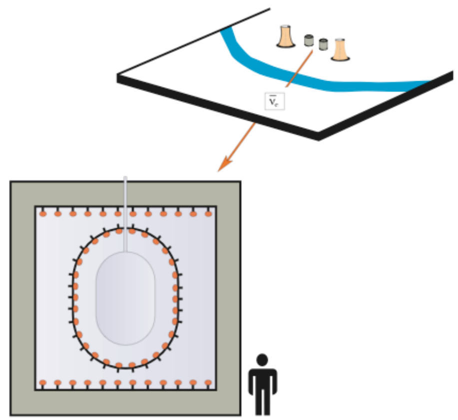
The object was to see $\bar{\nu}_e$ disappearance.
Earlier experiments had source to detector distances, L ~ 100 m. They saw no effect.
The new proposals had baselines of L ~ 1 km

$$P_{ee}=1-\sin^2 2\theta \sin^2[1.27L(m)\Delta m^2(eV^2)/E(MeV)]$$

1999 Result: no evidence for disappearance, but limits obtained

$\sin^2 2\theta_{13} < 0.15$ if $|\Delta m^2_{31}| \approx 2.5 \times 10^{-3}\ eV^2$

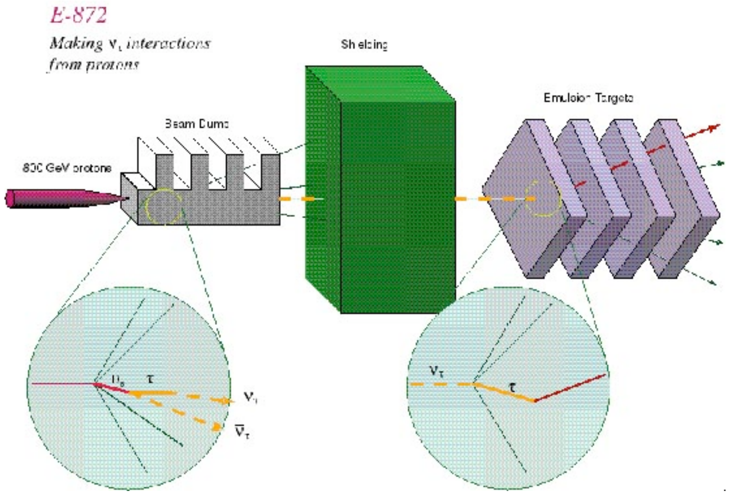
CHOOZ



AP 70(2000) ν_τ

The τ lepton was discovered in 1975. From experiments at LEP, the Z^0 width indicates 3 active neutrinos as the Standard Model requires. Study of τ decays indicates the emitted neutrino is different from ν_e and ν_μ. But still, we want to observe it directly. Start (or end) a new (old) millenium with the DONuT experiment at Fermilab.<u>D</u>irect <u>O</u>bservation of <u>N</u>e<u>u</u>trino <u>T</u>au

$$D_s^+ \rightarrow \tau^+ + \nu_\tau \;;\; \nu_\tau + n \rightarrow \tau^- + p \;;\; \tau^- \rightarrow \nu_\tau + X$$

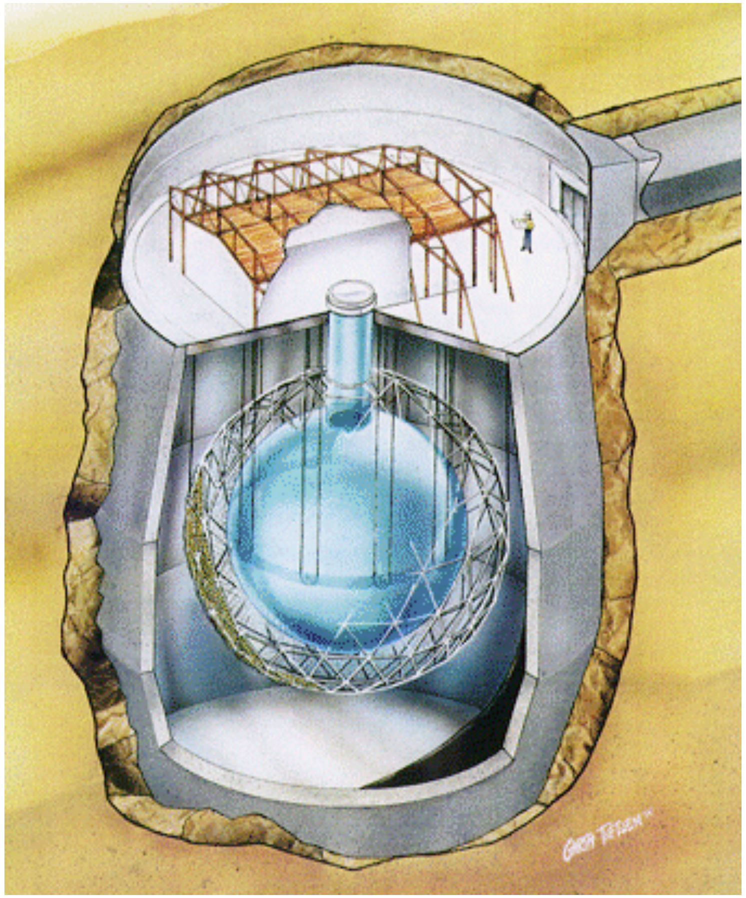


All three neutrinos have been “observed”.

AP 72(2002) SNO -Sudbury Neutrino Observatory

1000 tons of D_2O
2 km underground

SuperKamiokande - ν_e + e- $\rightarrow \nu_e$ + e-



SNO(2002) - ES: ν_x + e- $\rightarrow \nu_x$ + e-

CC: $\nu_e + d \rightarrow p + p +$ e-

NC: $\nu_x + d \rightarrow p + n + \nu_x$

(ν_x= all neutrinos)

All experiments showed too few ν_e compared to SSM, but SNO NC was the clincher. Rate of ν_x agrees with SSM. Interpretation, $\nu_e \rightarrow \nu_\mu$, ν_τ

Oscillations, enhanced by MSW (matter) effect in the sun.

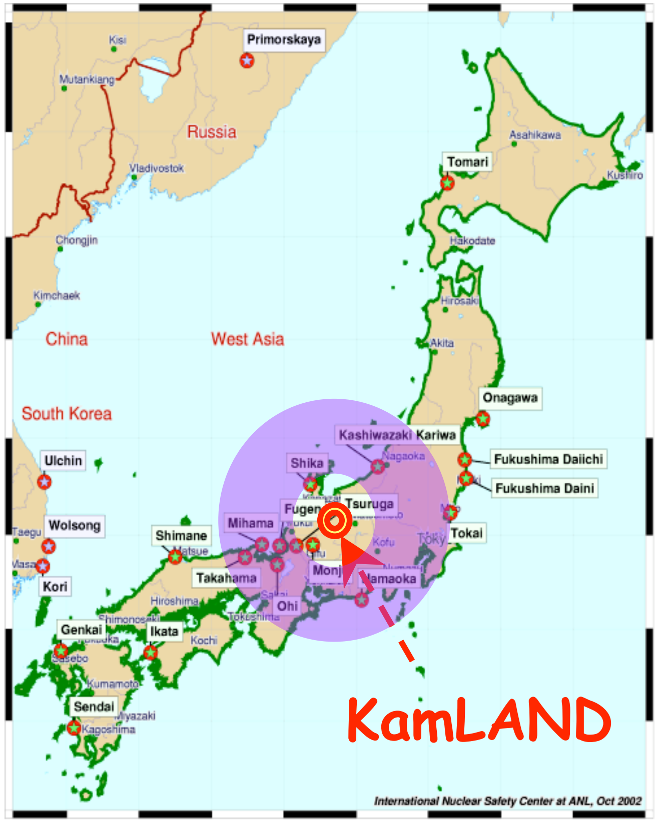
Result: $\Delta m^2_{21} \approx 10^{-4}$ eV^2 ; $\sin^2 2\theta_{12} \approx 0.8$

AP 68-78(1998-2008) KamLAND

With the large solar mixing angle favored, $\sin^2 2\theta_{12}$~0.8, it was evident that this solution could be tested terrestrially, using reactor $\bar{\nu}_e$ at L ~ 100 km.
Problem of low flux resolved by using many reactors.
L = 180 km (ave. distance)

2008 Result: KamLAND alone
$\tan^2\theta_{12}=0.56$; $\Delta m^2_{21}=7.58 \times 10^{-5}$ eV^2

Solar + KamLAND
$\tan^2\theta_{12}=0.47$; $\Delta m^2_{21}=7.59 \times 10^{-5}$ eV^2
$\sin^2 2\theta_{12}$ =0.87



~ 5 x 10^6 $\bar{\nu}_e$ / cm2 / sec

Few evts/day detected

Long baseline accelerator experiments to test atmospheric neutrino results K2K, NuMI/MINOS, CNGS(OPERA,ICARUS)

Recall, $P_{\mu\tau} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$ for ν_τ appearance

$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$ for ν_μ disappearance

Oscillation peak (or dip) at $1.27\Delta m^2 L/E = \pi/2$

With $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, L/E ~ 500 km/GeV

1990 - P822 proposal, Fermilab → Soudan mine ,735 km

Main Injector wide band ν_μ beam,

became NuMI/MINOS (E875) in 1995, Started running, January 2005,

ν_μ beam peak ~ 2-3 GeV

1995 - K2K proposal, KEK to SuperK, 250 km,

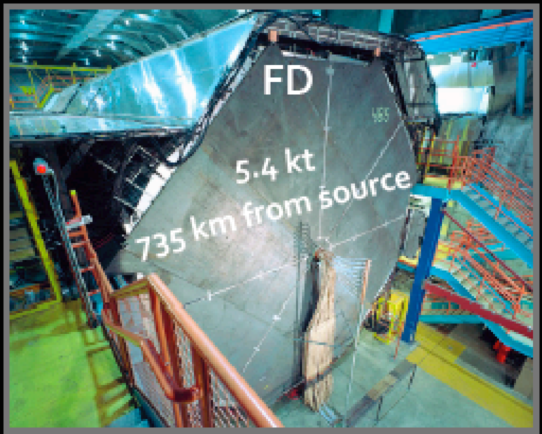
ν_μ beam ~ 1 GeV, Started running 1999, finished 2002.

1998 - CNGS, experiments OPERA and ICARUS, 730 km, ν_μ beam ~15 GeV, will start in 2006

From J.Schneps DESY 2006

The MINOS Experiment

Main Injector Neutrino Oscillation Search



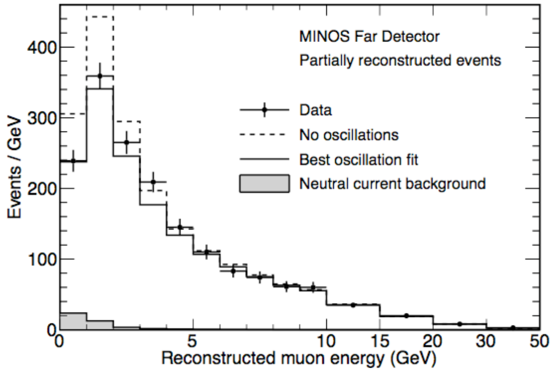
- Detectors are planar steel/ scintillator calorimeters
  - Functionally equivalent
  - Magnetized with <B>~1.3 T
  - Cancellation of ν flux and cross-section uncertainties

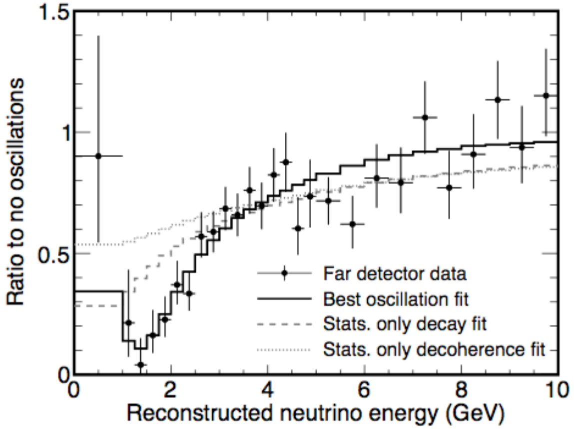
- 735 km baseline from Fermilab to Soudan Mine
- Uses NuMI ν_μ beam
  - 2.5×10^{13} protons/pulse
  - 320 kW beam power
  - 3.3 GeV average E_ν

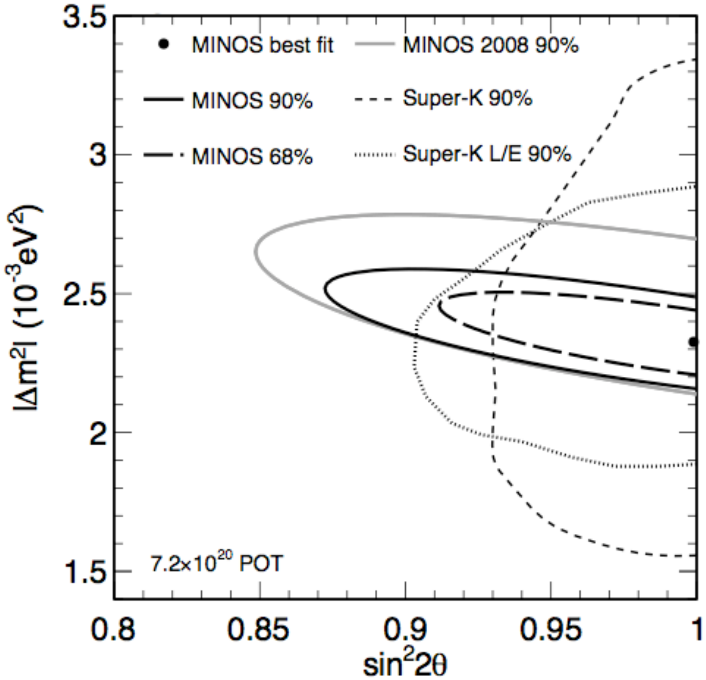
- Compare prediction from ND with FD observation to make precision measurements of neutrino oscillation parameters

MINOS RUN - AP 75-80

‘Atmospheric’ parameters from ν_μ disappearance







$\Delta m^2_{32}=2.32\ ^{+0.12}_{--0.08} \times 10^{-3}\ eV^2$

$\sin^2 2\theta_{23}>0.9$ (90% CL)

arXiv:1103.0340

$\sin^2 2\theta_{12}$ and Δm^2_{21} measured in solar experiments and KamLAND

$\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$ measured with atmospheric neutrinos and long baseline accelerator beams, still some

BIG QUESTIONS

- What is θ_{13}? All we know is the CHOOZ limit $\sin^2 2\theta_{13} < 0.15$
- MASS HIERARCHY. Is $m_3 > m_2$ (Normal) or $m_3 < m_2$ (Inverted)?
- Is θ_{23} exactly 45^0? A little greater? A little smaller?
- What is the CP phase δ? Is CP conservation violated ($\delta \neq 0,\pi$)? (If so, could it support the leptogenesis idea to explain baryon-antibaryon asymmetry in the universe?)

$\nu_\mu \rightarrow \nu_e$ oscillations could provide some answers

They depend on $\Delta m^2_{31} \approx \Delta m^2_{32}$ such that long baseline experiments could be sensitive to $\sin^2 2\theta_{13}$. In addition, the matter effect on ν_e as the beam passes through the earth gives rise to differences in $\nu_e(\overline{\nu_e})$ appearance for $\nu_\mu(\overline{\nu_\mu})$ beams which depend on δ and the Mass Hierarchy.

Standard 3-ν Phenomenology for $\nu_\mu \rightarrow \nu_e$ with matter effects

Normal Hierarchy, h = 1 ; Inverted Hierarchy, h = -1.

$$\Delta = 1.27\Delta m_{31}^2 L(km)/E(GeV)$$

$$x = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$$

or

$$x = E(GeV)/11GeV$$

$$P_1(\nu) = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \frac{\sin^2[(1-hx)\Delta]}{(1-hx)^2}$$

$$P_2(\nu) = (\frac{\Delta m_{21}^2}{\Delta m_{31}^2})^2 \sin^2 2\theta_{12} \sin^2 2\theta_{23} \frac{\sin^2[x\Delta]}{x^2}$$

$$P_3(\nu) = -(\frac{\Delta m_{21}^2}{\Delta m_{31}^2})^2 \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(x\Delta)}{x} \frac{\sin[(1-hx)\Delta]}{(1-hx)} \sin\delta$$

$$P_4(\nu) = h(\frac{\Delta m_{21}^2}{\Delta m_{31}^2})^2 \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(x\Delta)}{x} \frac{\sin[(1-hx)\Delta]}{(1-hx)} \cos\delta$$

$$\Delta m_{31}^2 = 2.35 \times 10^{-3} eV^2$$

$$\Delta m_{21}^2 = 7.59 \times 10^{-5} eV^2$$

$$\theta_{23} = \frac{\pi}{4} rad$$

$$\theta_{12} = 0.58 rad$$

$$P_1(\bar{\nu}) = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \frac{\sin^2[(1+hx)\Delta]}{(1+hx)^2}$$

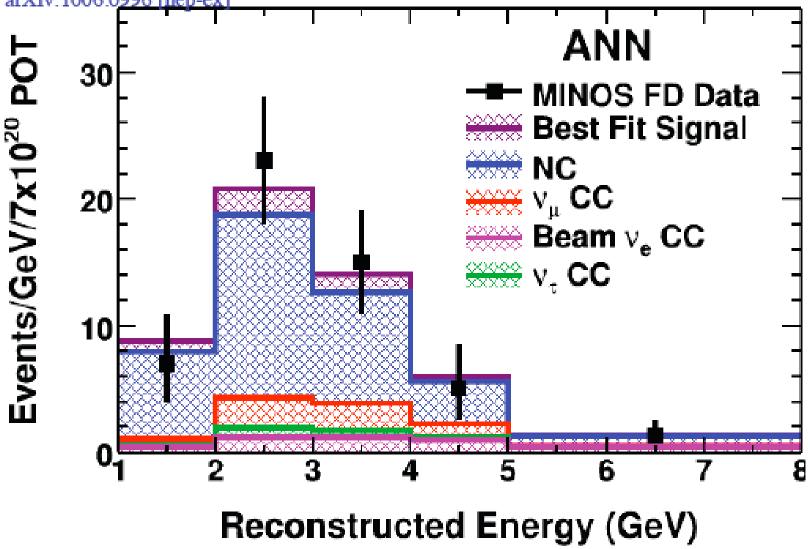
$$P_2(\bar{\nu}) = (\frac{\Delta m_{21}^2}{\Delta m_{31}^2})^2 \sin^2 2\theta_{12} \sin^2 2\theta_{23} \frac{\sin^2[x\Delta]}{x^2}$$

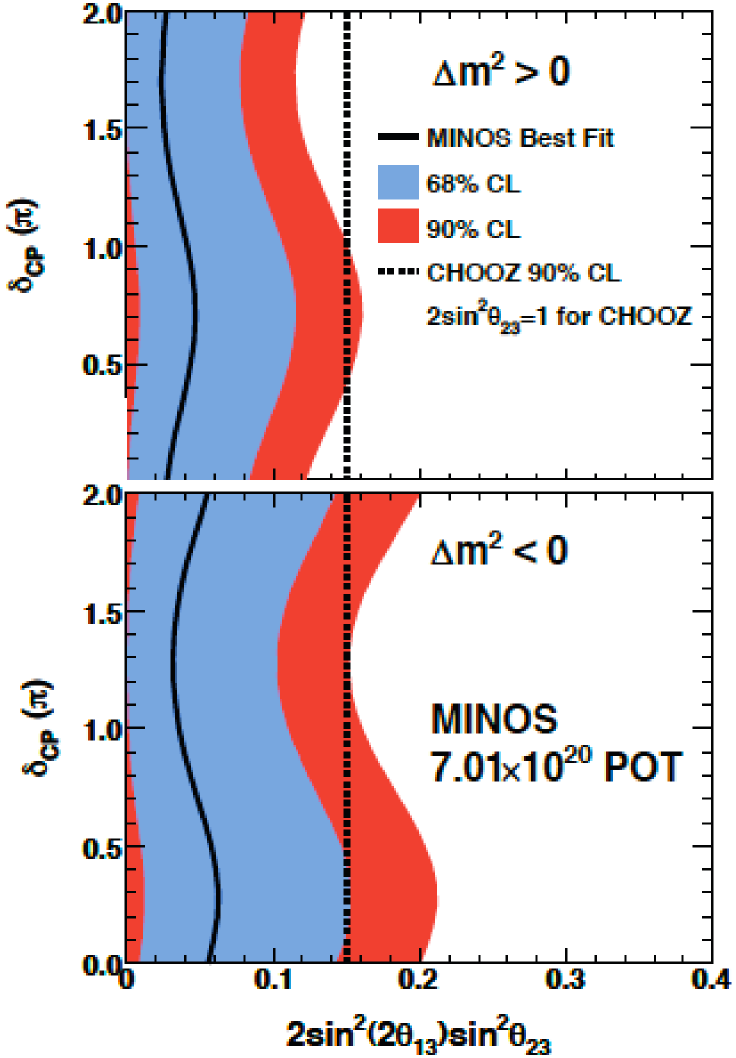
$$P_3(\bar{\nu}) = (\frac{\Delta m_{21}^2}{\Delta m_{31}^2})^2 \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(x\Delta)}{x} \frac{\sin[(1+hx)\Delta]}{(1+hx)} \sin\delta$$

$$P_4(\bar{\nu}) = h(\frac{\Delta m_{21}^2}{\Delta m_{31}^2})^2 \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(x\Delta)}{x} \frac{\sin[(1+hx)\Delta]}{(1+hx)} \cos\delta$$

AP 80(2010)MINOS - ν_e Appearance

arXiv:1006.0996 [hep-ex]





54 events observed. For no oscillations expect 49.1±7.0(stat)±2.7(sys) from Near Detector extrapolation.

The limitations are event rate and background.

MINOS was designed in 1995 to measure the 'atmospheric' parameters. The resolution is such that NC events with $\pi^0 \rightarrow$ em shower are a serious background. Nevertheless we can reach the CHOOZ limit for normal hierarchy (NH).

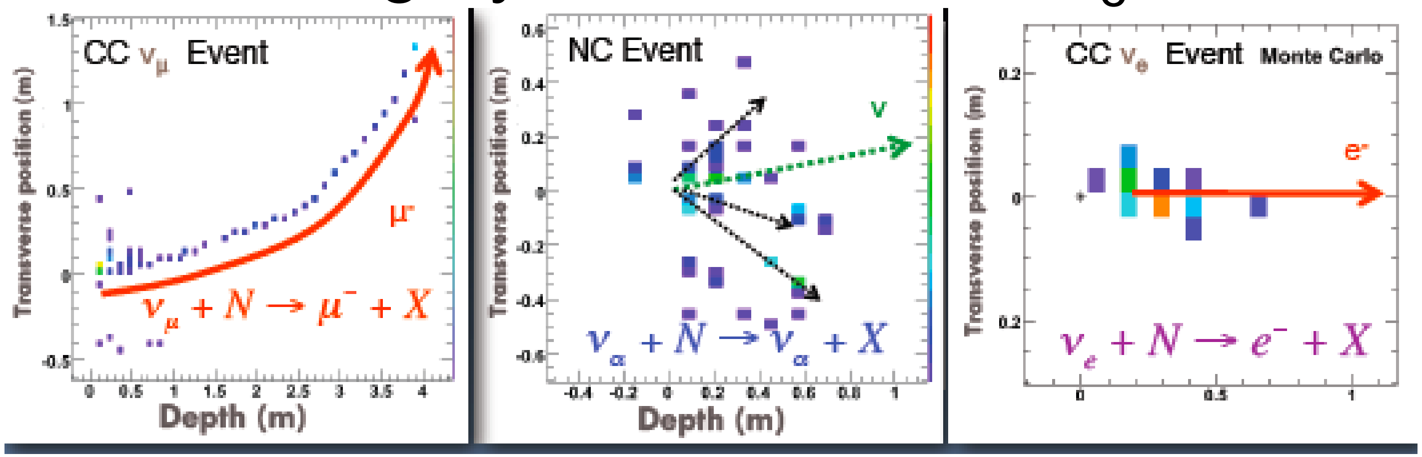
For δ=0 we find: $\sin^2 2\theta_{13} < 0.12$ for NH

$\sin^2 2\theta_{13} < 0.2$ for IH at 90% CL

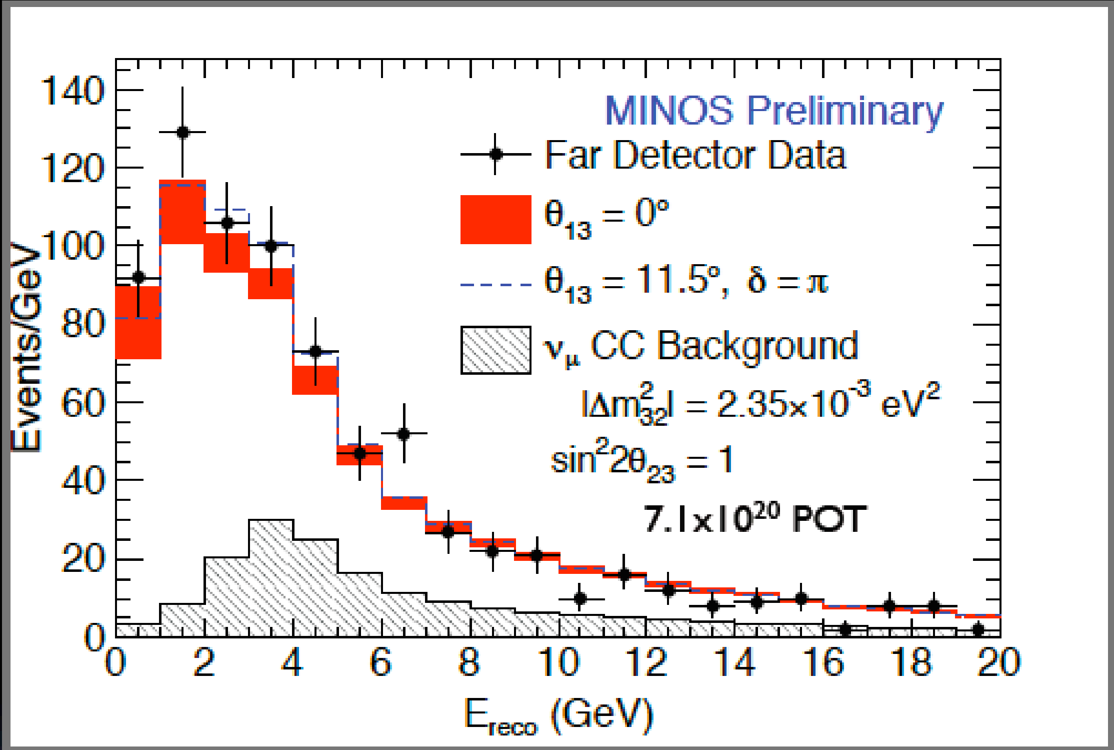
(New MINOS results coming in a few months)

AP 75-80(2005-10) Some mysteries from M&M*

If LSND is correct it indicates a 4th neutrino. But Z^0 width indicates 3 active neutrinos. Thus a 4th neutrino should be ‘sterile’ (no SM interaction). How can MINOS look for this? The cross section for neutral current interactions is the same for ν_e, ν_μ, ν_τ. Therefore, with 3-ν oscillations, the NC rate remains constant. However, if oscillations into ν_S occur, the rate will decrease. There are serious BG’s from high-y CC events and ν_e .



Neutral Current Events



Observed: 802 events

Expected: 757 events

- No depletion of neutral current events observed
  - No evidence of oscillations into sterile neutrinos
  - ν_μ change into ν_τ and ν_e

- Set a limit on fraction of ν_μ that may oscillate into sterile neutrinos

$$f_s \equiv \frac{P_{\nu_\mu\to\nu_s}}{1 - P_{\nu_\mu\to\nu_\mu}} < 0.22(0.40) \text{ at } 90\% \text{ C.L.}$$

no (with) ν_e appearance

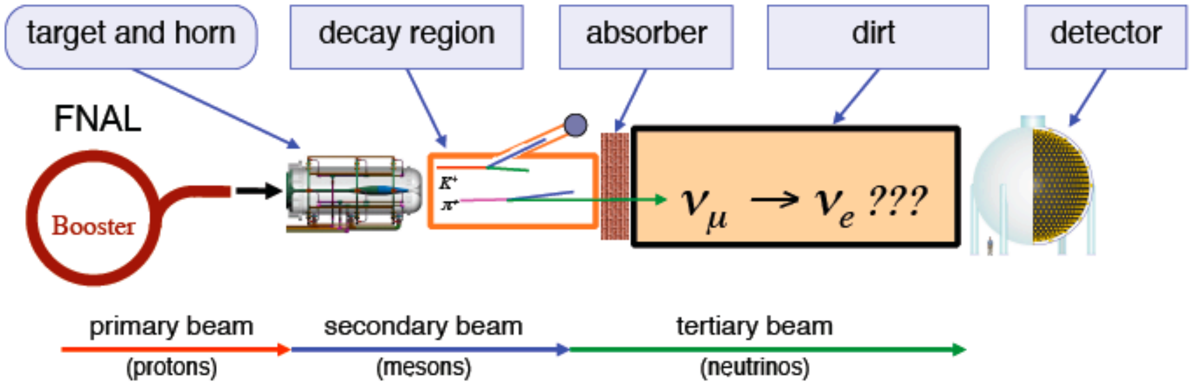
AP 77-80(2007-10) MiniBooNE

MiniBooNE was designed to test the LSND signal

Keep L/E same as LSND
while changing systematics, energy & event signature

$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$ ➔ Two neutrino fits

LSND:	E ~30 MeV	L ~30 m	L/E ~1
MiniBooNE:	E ~500 MeV	L ~500 m	L/E ~1



Neutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with 6.5E20 POT ➔ assumes CP/CPT conservation
Antineutrino mode: search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance with 5.66E20 POT ➔ direct test of LSND

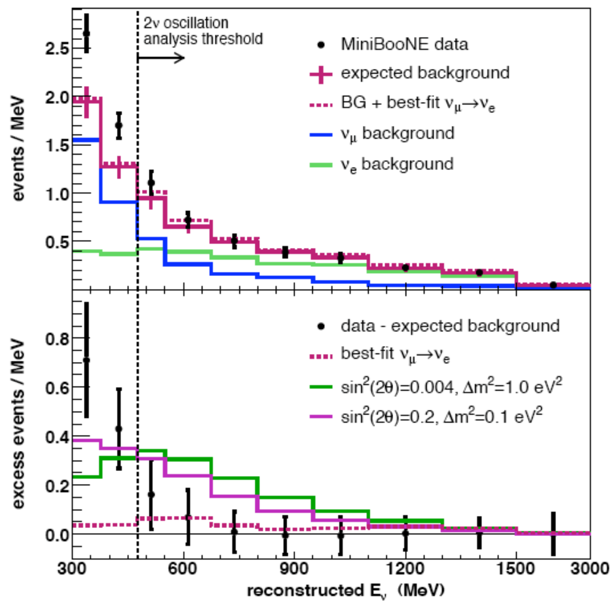
FNAL has done a great job delivering beam!

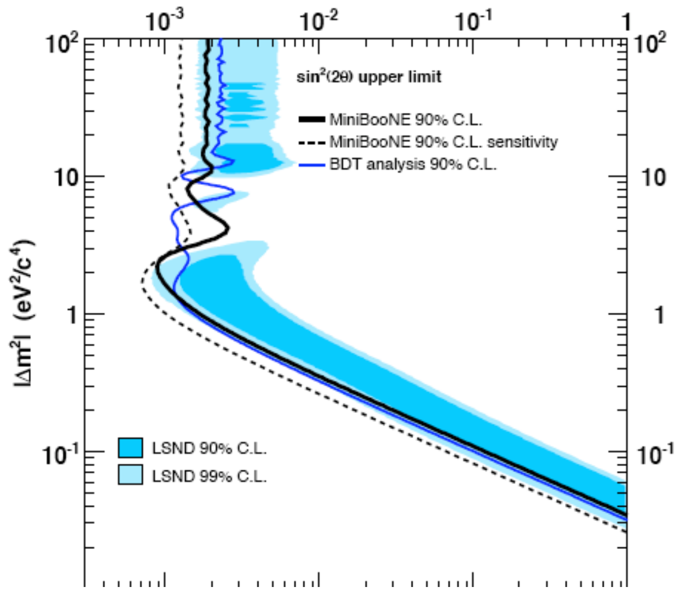
Look for the LSND effect in a ν_μ beam produced by 8 GeV protons from the Fermilab Booster. The region $475 < E_\nu < 3000$ MeV would be sensitive to $\nu_\mu \rightarrow \nu_e$ oscillations with $\Delta m^2 \sim 1$ eV^2 .

Result for 6.5×10^{20} pot:

ν_e excess above BG is $22 \pm 19 \pm 35$ events. That is, no evidence for LSND effect.

But wait !





Phys.Rev.Lett.98:231801,2007

MiniBooNE $\bar{\nu}_\mu$

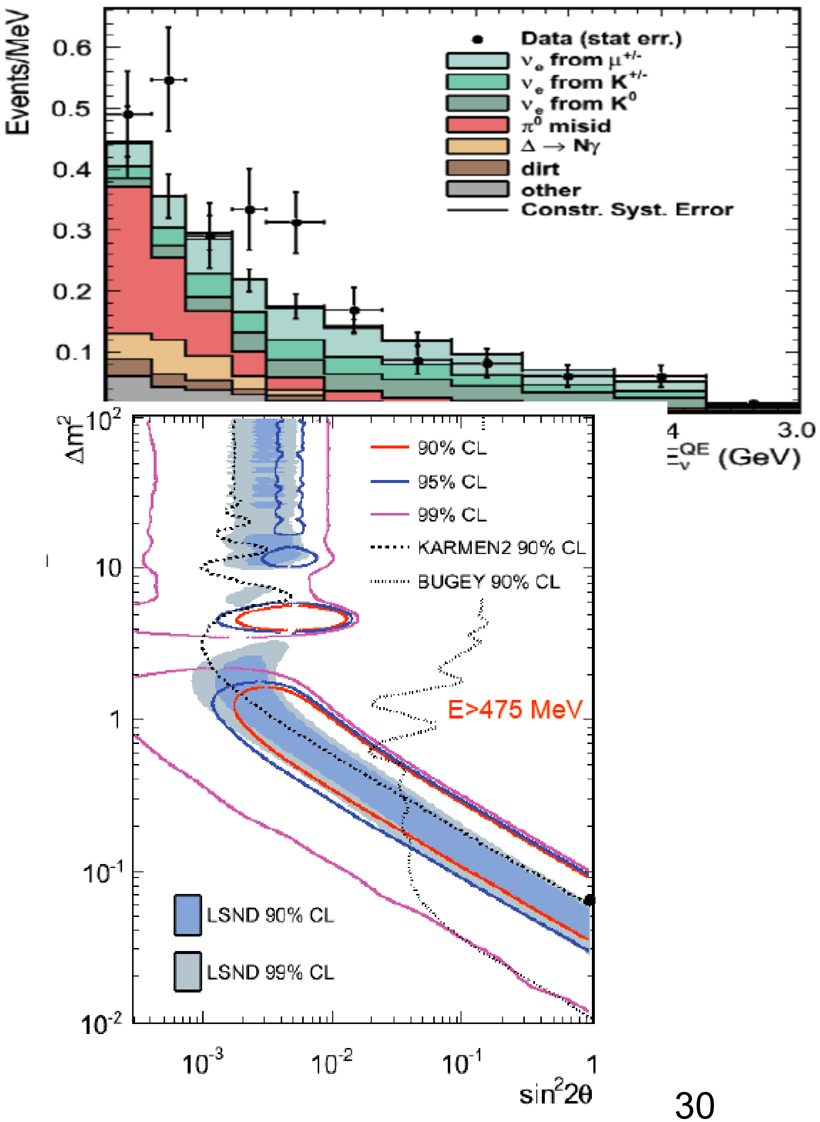
$\bar{\nu}_\mu$ beam exposure; 5.66 x 10^{20} pot. Excess for 475<E<1250 MeV is 20.9±12.9 and for 1250<E<3000 MeV is 3.8±5.8.

A 1.3 σ effect. The fit is shown in the contour plot. It is consistent with LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

Also noted is a 3σ excess of events in ν_μ for E<475 MeV. What could this be?

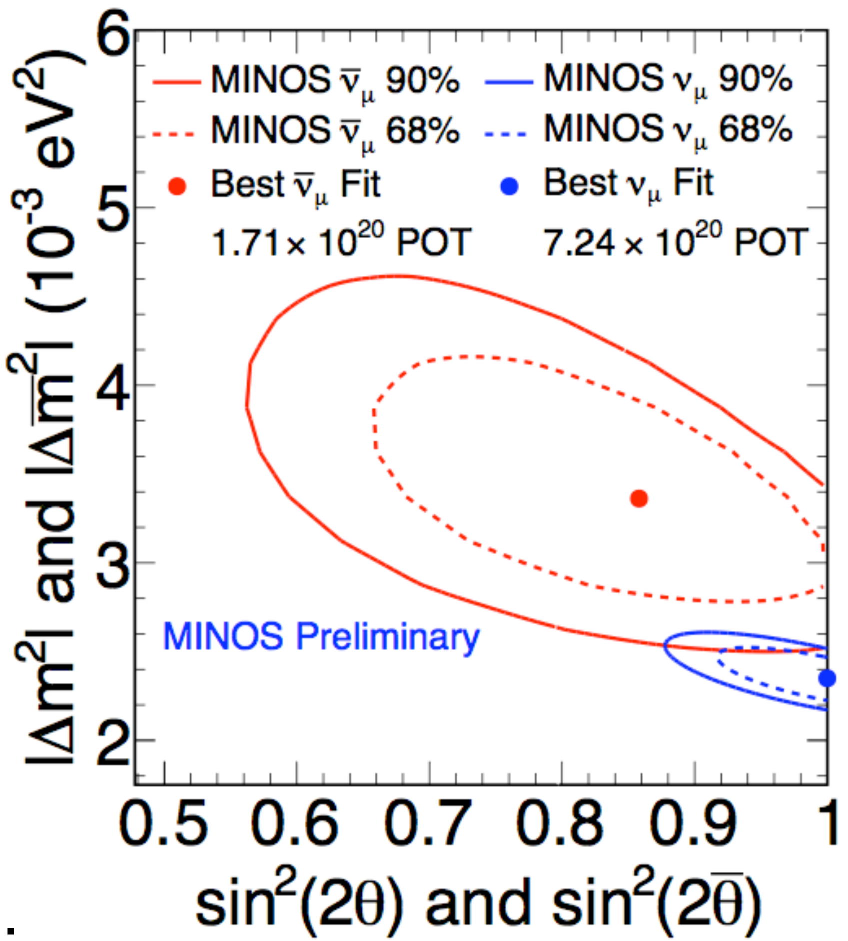
A much smaller excess for $\bar{\nu}_\mu$ in this region. Clearly more statistics are needed, But,

Could ν_μ differ from $\bar{\nu}_\mu$??



AP 79(2009) MINOS $\bar{\nu}_\mu$

The MINOS detector is unique in having a magnetic field. It can separate μ^+ from μ^- and thus ν_μ from $\bar{\nu}_\mu$. During the long ν_μ run we analyzed the small number of $\bar{\nu}_\mu$ events. But beginning in 2009 the horn currents were reversed and a $\bar{\nu}_\mu$ beam was achieved. First results are quite interesting.



For 1.7×10^{20} pot we find

$|\overline{\Delta m^2}| = 3.36 \times 10^{-3}\ \mathrm{eV}^2$

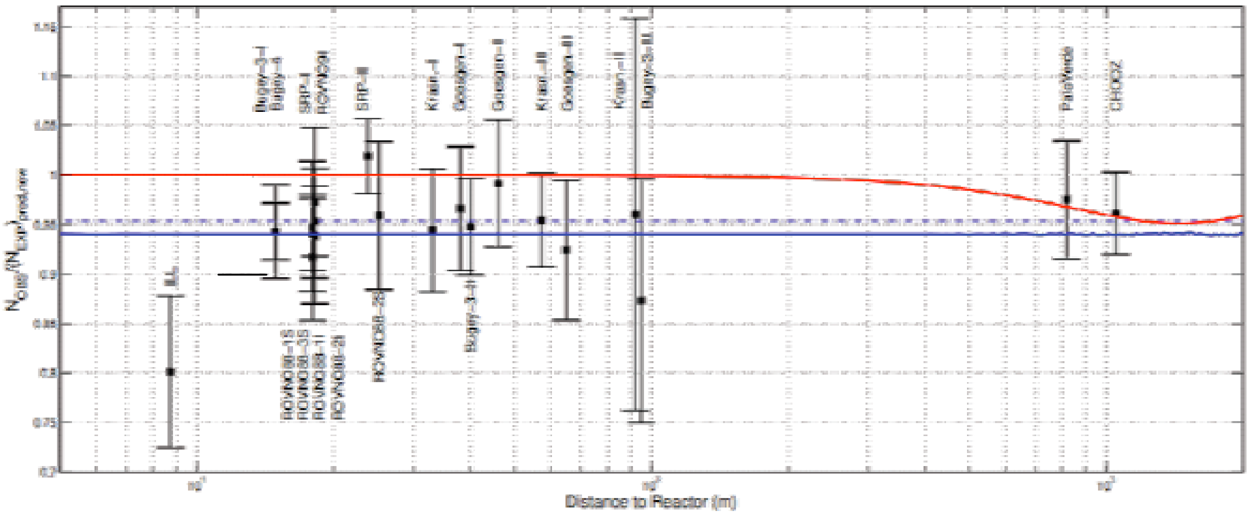
$\overline{\sin^2 2\theta_{23}} = 0.86$

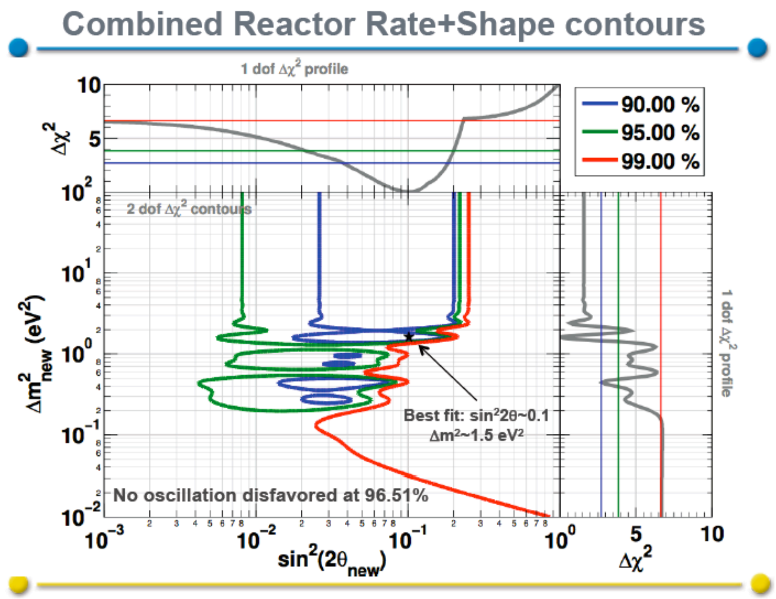
The antineutrino run is continuing.

But wait. There is more.

AP 81(2011) Reactor Antineutrino Anomaly

French collaboration announces new, more precise calculation of neutrino flux from reactors. The result is expected event rates should be ~ 3% higher than what has previously been used. So now, 18 of 19 early reactor experiments have rates below the prediction. What could this be? A possible explanation is $\overline{\nu}_e$ oscillation to a 4th sterile neutrino with mixing angle θ, $\Delta m^2 \sim 1\ eV^2$





See T. Laserre, Neutel 2011

It looks like all the hints for something surprising come from antineutrino experiments

LSND, MiniBooNE, MINOS, Reactor Anomaly

Difference with neutrino experiments could hint at CPT violation, existence of a hidden (almost) sterile neutrino sector, NSI (non-standard neutrino interactions)

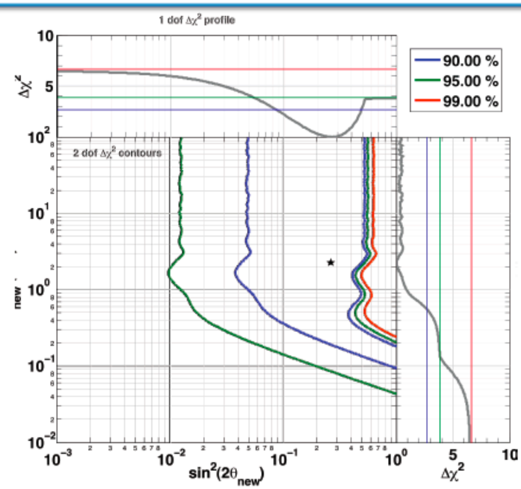
But wait,there is

The Gallium Neutrino Anomaly

The Gallium anomaly

- **4 calibration runs with intense MCi neutrino sources:**
  - 2 runs at Gallex with a ^{51}Cr source (750 keV ν_e emitter)
  - 1 run at SAGE with a ^{51}Cr source
  - 1 run at SAGE with a ^{37}Ar source (810 keV ν_e emitter)
  - **All observed a deficit of neutrino interactions compared to the expected activity. Hint of oscillation ?**

The Gallium anomaly



- Effect reported in C. Giunti & M. Laveder in PRD82 053005 (2010)
- Significance reduced by additional correlations in our analysis
- No-oscillation hypothesis disfavored at 97.7% C.L.

So, neutrinos are giving hints too.

The Future: AP 81-100(2011-2030)

All these hints have caused great excitement in the neutrino community - theorists thinking beyond the SM: CPT violation, NSI, sterile neutrino sectors, leptogenesis, etc. Phenomenologists do global fits to all the experiments (e.g., $\sin^2 2\theta_{13}$ could be ~0.07 but is consistent with 0.0; 3 active + 2 sterile neutrinos fits better than 3 + 1). And we still don't know the masses of neutrinos and whether they are Majorana or Dirac.

We need experiments! The hints need to be clarified. There may even be new surprises.

So, what is coming up?

Low Energy

ν mass (^3H)

The KATRIN experiment

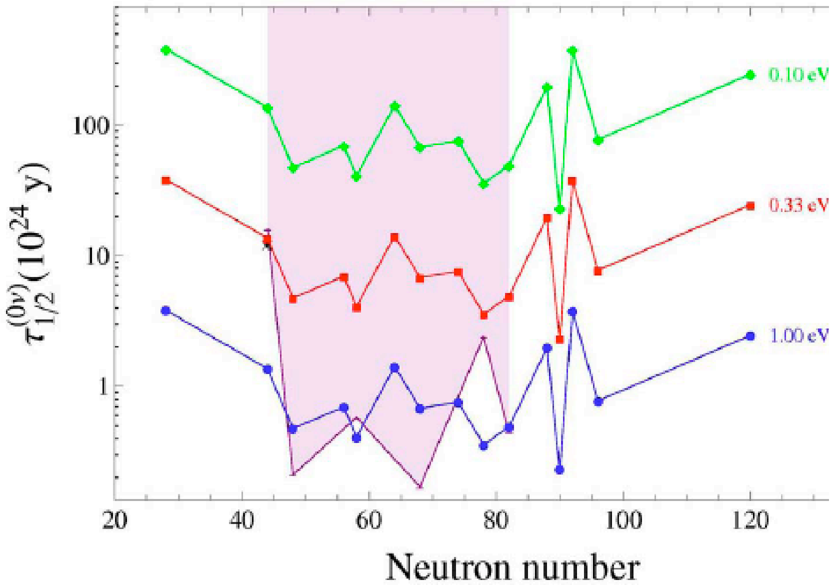
Measure the mass down to 0.2 eV. Results expected in a few years.

Neutrinoless Double β-decay

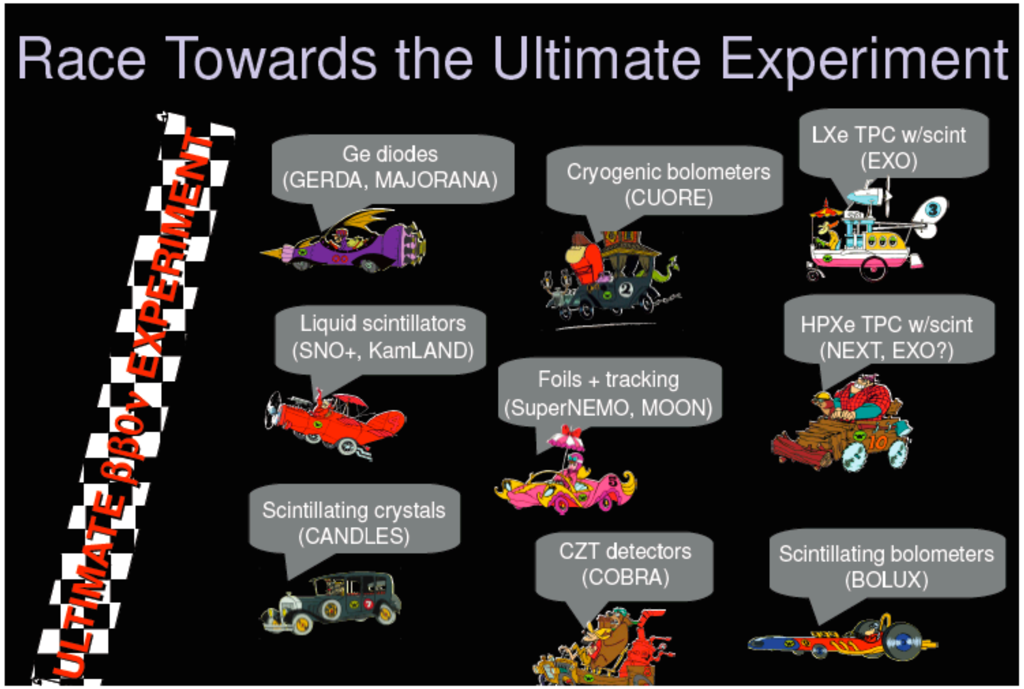
Can occur only if neutrinos are Majorana: $\nu \equiv \overline{\nu}$

Half-lives are very long and depend on neutrino mass. Thus, require very low BG --> Deep underground, high sensitivity and resolution. Detection would also give neutrino mass estimate. Present limit ~ 1-2 eV. Many experiments will run in this decade.

Good luck to us all!



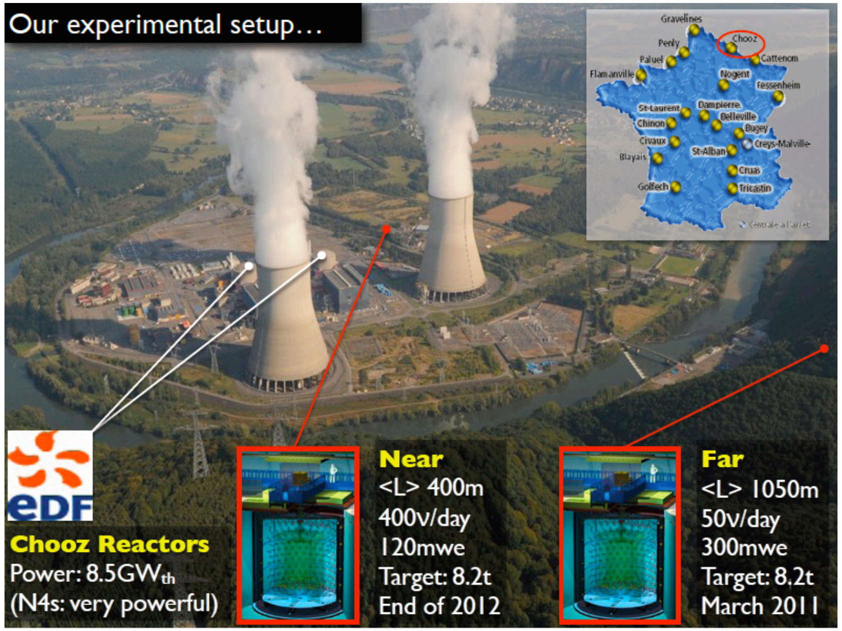
From Iachello and Gomez-Cadenes, Neutel 2011

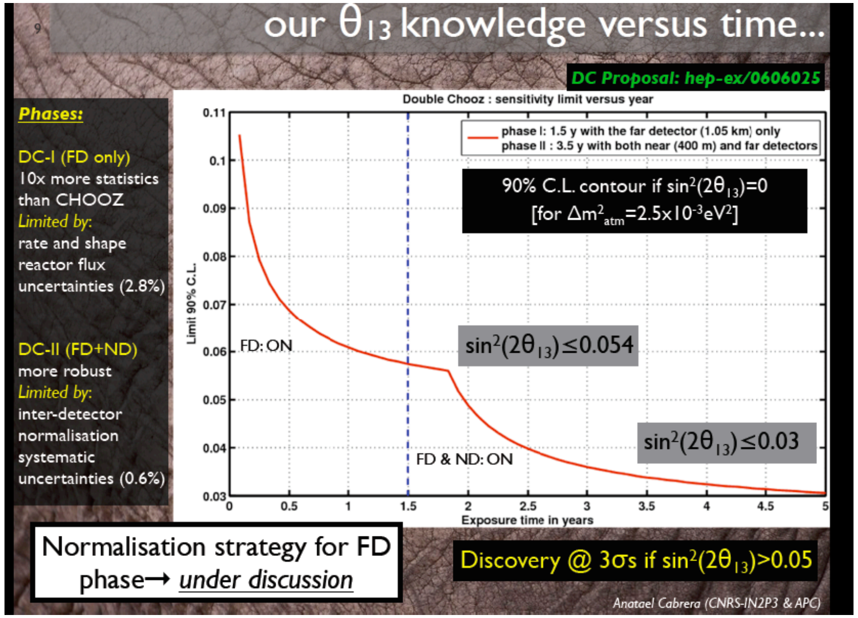


Reactors

Three new experiments are building and will be starting within the next few years. The main aim: To measure $\sin^2 2\theta_{13}$ or improve on the present limit: $\sin^2 2\theta_{13} < 0.15$.

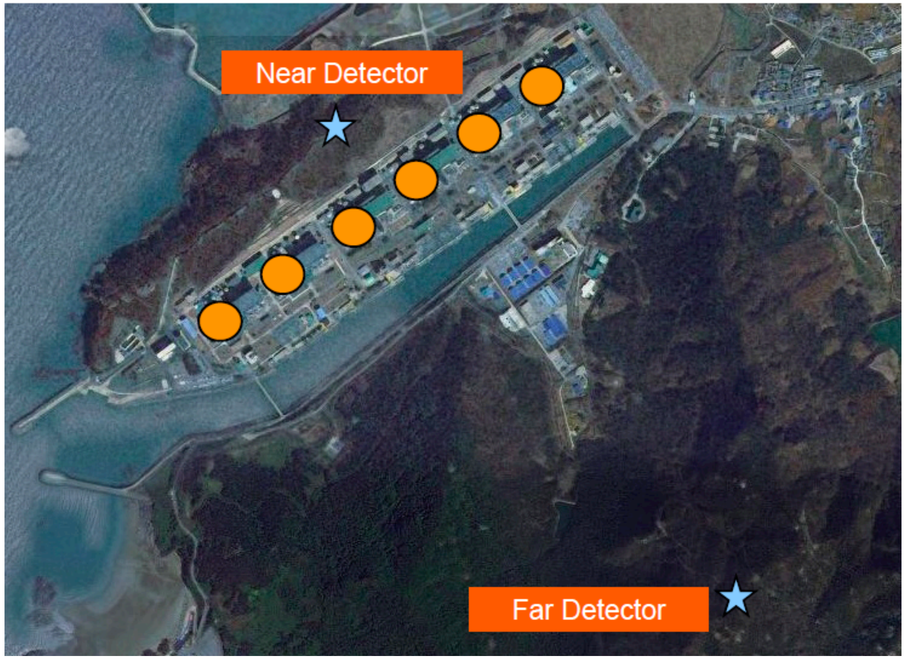
DOUBLE CHOOZ - Two detector experiment. About to begin. Will reach $\sin^2 2\theta_{13} < 0.03$ (90% CL) in < 3-5 years.

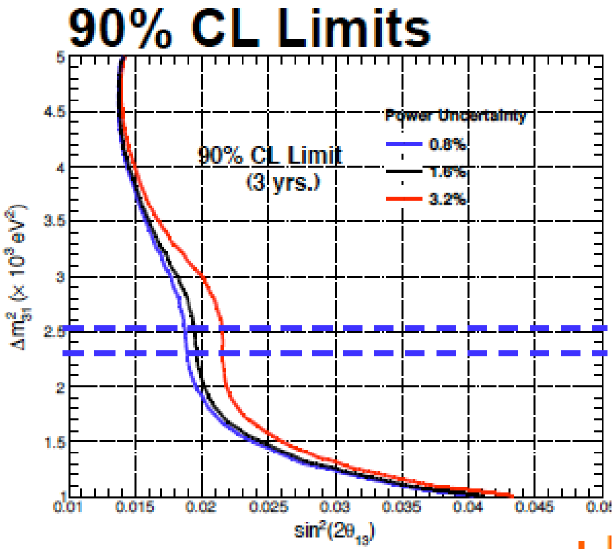




RENO - in South Korea

Six reactor - two detector experiment. Goal $\sin^2 2\theta_{13} < 0.02$ (90% CL) in 3 years. Start data taking this year.

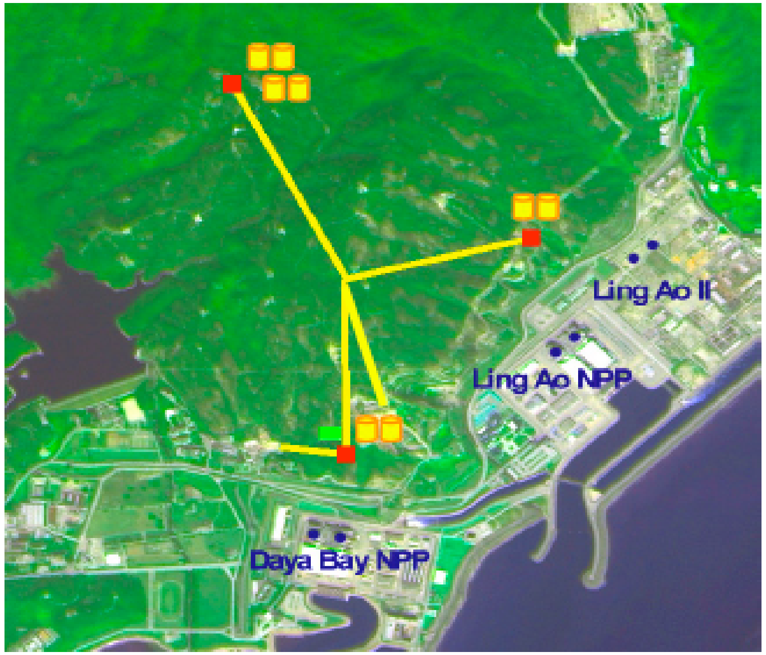


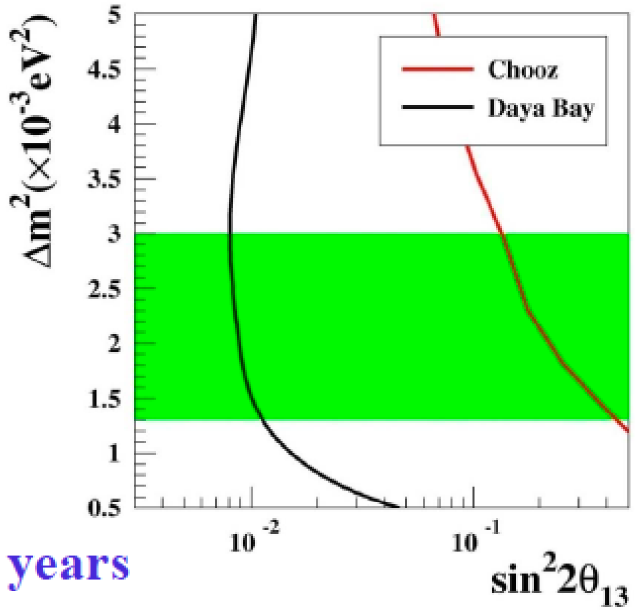


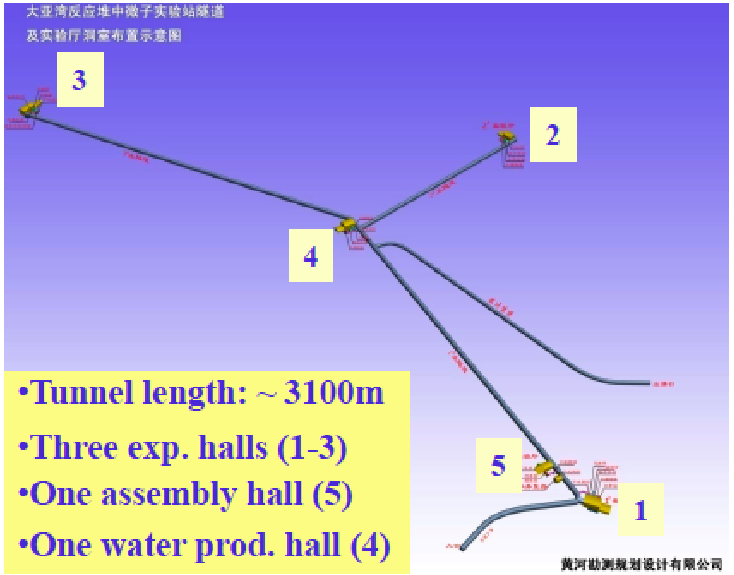
Soo-Bong Kim, Neutel 2011

Daya Bay - in China (the most ambitious)

Six reactor - three detector experiment (2 Near, 1 Far). Goal $\sin^2 2\theta_{13} < 0.01$ (90% CL) in 3 years. Start data taking next year.







Medium Energy

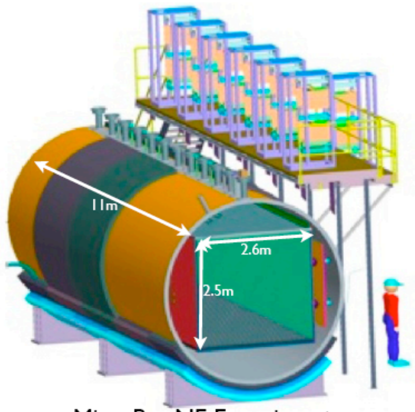
MicroBooNe at Fermilab

•MicroBooNE* is a LArTPC experiment that will operate in the on-axis Booster neutrino beam and off-axis NuMI neutrino beam on the surface at Fermilab.
•Combines timely physics with hardware R&D necessary for the evolution of LArTPCs.
- MiniBooNE low-energy excess
- Low-Energy Cross-Sections
- Cold Electronics
- Long-drift operation (strict demands on LAr purity)

Cryostat Volume	150 Tons
TPC Volume	90 Tons
# Electronic Channels	~9000
Wire Pitch	3 mm
Electronics Style (Temp.)	JFET (120 K)
Max. Drift Length (Time)	2.5m (1.5ms)
Light Collection	~30 8" Hamamatsu PMTs

★Stage 1 approval from Fermilab directorate in June 2008
★CD-0 (Mission Need) in October 2009
★CD-1 (reviewed early March)
★CD-2/CD-3a (Fall 2010)
★Turn On (2012-2013)

*See poster from Vassili Papavassiliou

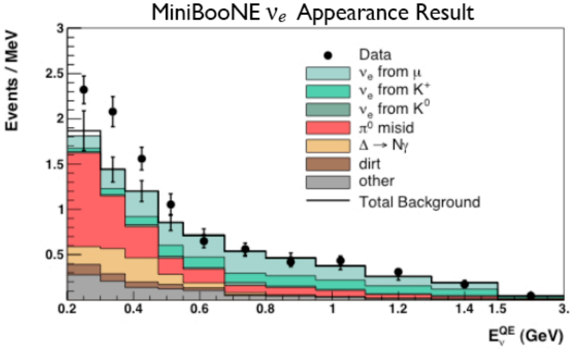


MicroBooNE Experiment
(DOE/NSF Supported)

•Address the MiniBooNE* low energy excess
- Does MicroBooNE confirm the excess?
- Utilize dE/dx + topology to determine if it is an electron-like or gamma-like process

•Low Energy Cross-Section Measurements (CCQE, NC π^o, $\Delta \rightarrow N\gamma$, Photonuclear, ...)
•Study processes relevant for proton-decay searches in a large LArTPC
•Fully implement automated reconstruction (building on ArgoNeuT's effort)

MiniBooNE ν_e Appearance Result



MiniBooNE Neutrino-Mode Excess
200-300MeV: 45.2±26.0 events
300-475MeV: 83.7±24.5 events

MicroBooNE will have >5σ significance for electron-like excess, >3.3σ for photon-like excess.

*See talks by:
Richard Van deWater
and
Georgia Karagiorgi
on Monday.

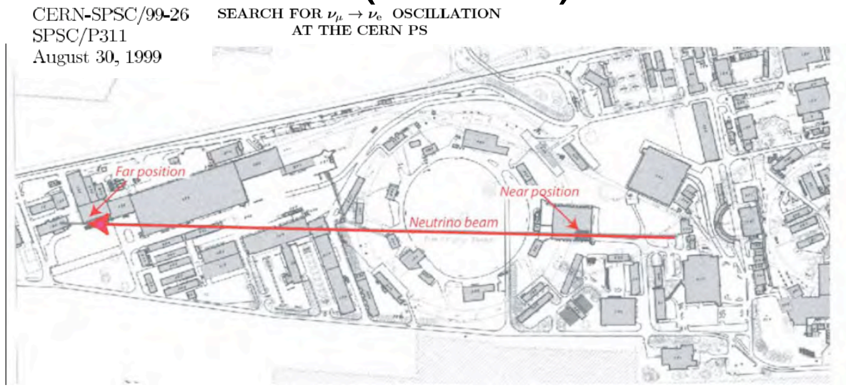
Refs:
1.) *Unexplained Excess of Electron-Like Events From a 1-GeV Neutrino Beam* MiniBooNE Collaboration, Phys. Rev. Lett. 102, 101802 (2009)

~ 100 ton LArTPC to test the MiniBooNe low energy Excess (is it e's or γ's ?) and the LSND hint.
Also a step toward more massive LAr detectors.
Turn-on 2012-13.

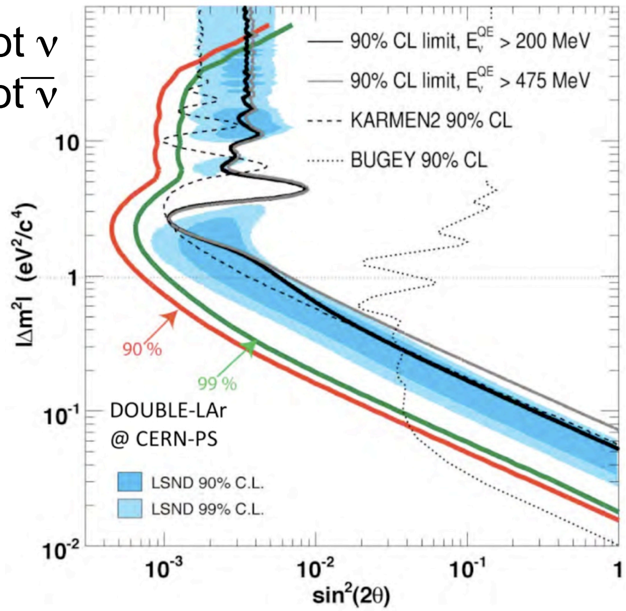
Double LAr proposal (sterile ν's)

- The LSND/+MiniBooNe both antineutrino and neutrino $\nu_\mu \rightarrow \nu_e$ oscillation anomalies;
- The Gallex + Reactor oscillatory disappearance of the initial ν_e signal, both for neutrino and antineutrinos
- An oscillatory disappearance may be present in the ν_μ signal, so far unknown.
- Accurate comparison between neutrino and antineutrino related oscillatory anomalies

Bring 600 ton ICARUS to CERN PS as far detector (850 m)
New 150 kton near (127 m)



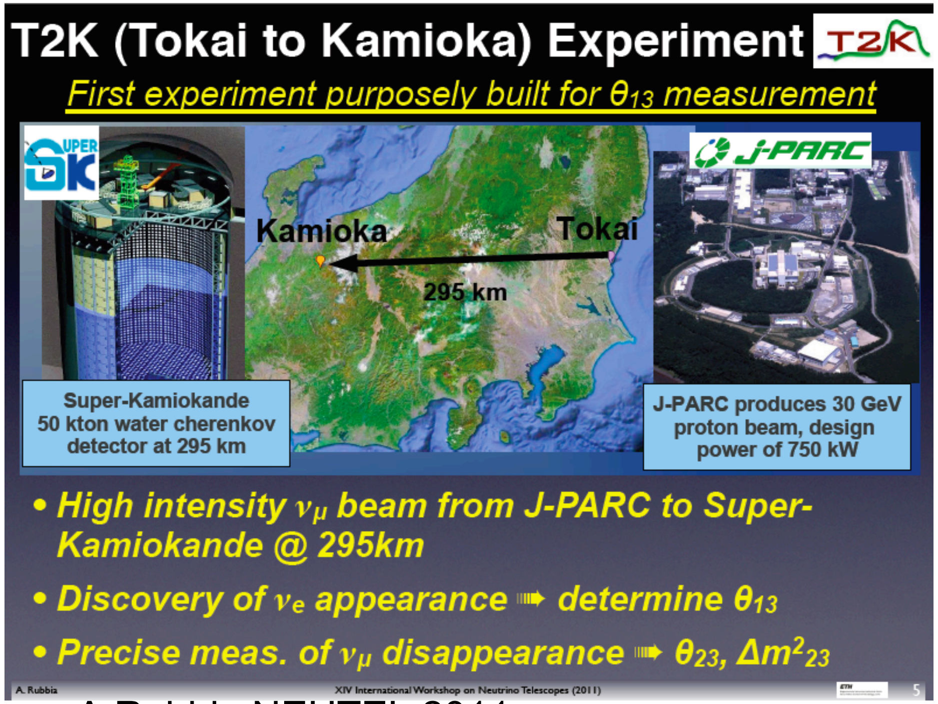
2.5e20 pot ν
5.0e20 pot $\bar{\nu}$

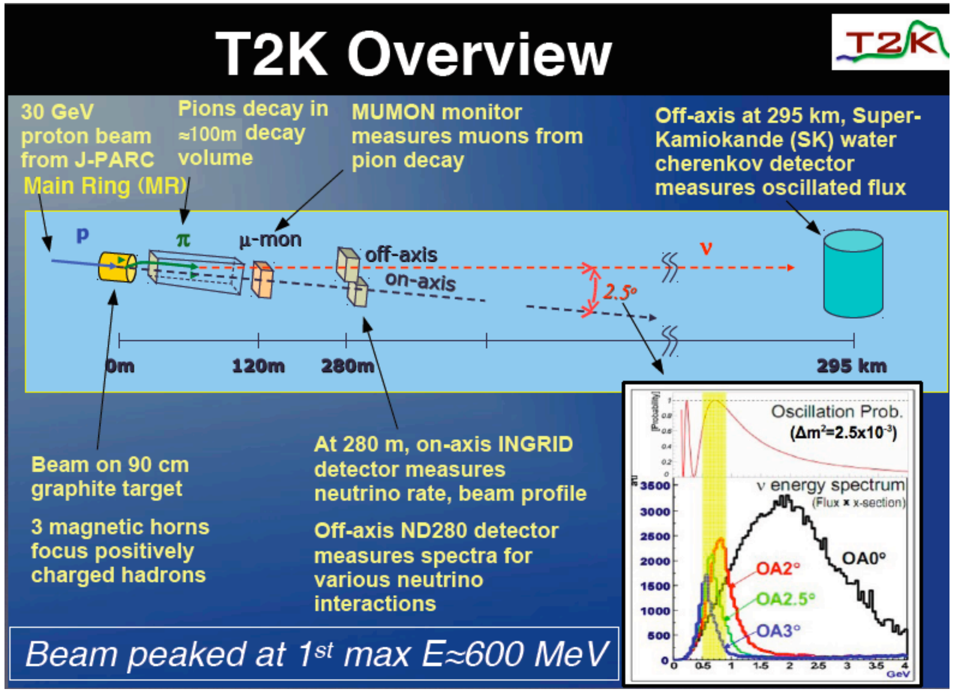


C. Rubbia Neutel 2011

Long Baseline - Near Future
T2K, NOνA

T2K - ~ 0.6 GeV ν_μ beam, 295 km baseline, startup in January AP 80(2010) - θ_{13}





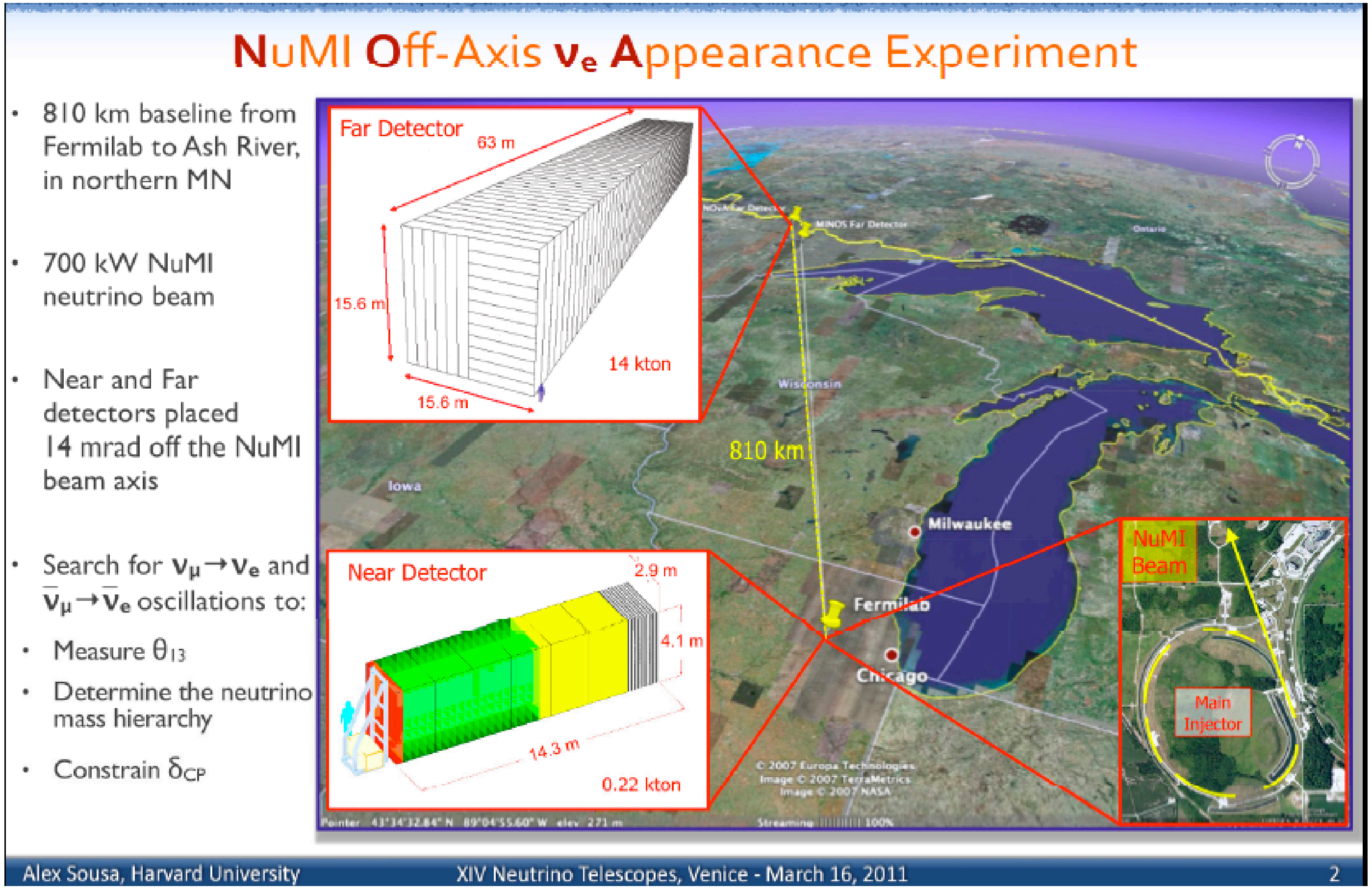
Conclusions

- T2K searches for $\nu_\mu \rightarrow \nu_e$ & $\nu_\mu \rightarrow \nu_x$ oscillations and aims at determining the atmospheric sector parameters
- T2K started physics running from Jan. 2010.
- We reported results from the first $\nu_\mu \rightarrow \nu_e$ oscillation analysis based on 3.23×10^{19} p.o.t. (2010 Jan.~ Jun):
  - # of observed events surviving all cuts = 1
  - # of expected background = 0.30 ± 0.07 (w/ θ_{13}=0)
- The observed ν_μ CC candidates are consistent with the neutrino oscillation parameters measured by SK, K2K and MINOS.
- The total integrated proton intensity accumulated until the earthquake is 1.45×10^{20} p.o.t. and events are being analyzed. With this increased statistics, we expect a θ_{13} sensitivity better than that of CHOOZ. In addition, the analysis strategy will be improved.
- The full extent of the impact of the earthquake on future T2K running is at present unknown.

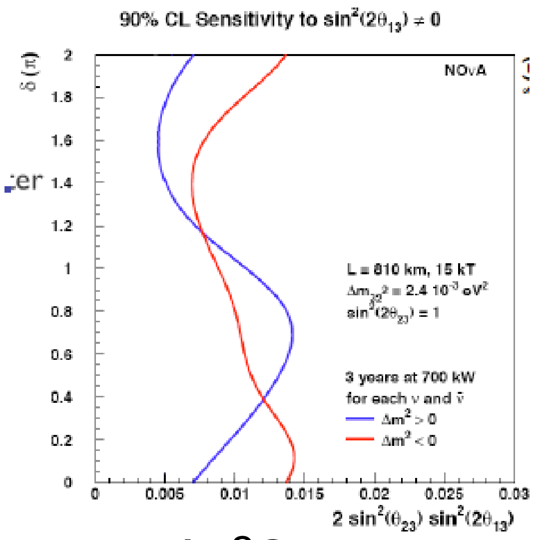
NOνA, AP 83-90(2013-20)

~ 2GeV off-axis $\nu(\bar{\nu})$ 700 kw beams; baseline 810 km; liquid scintillator far (14 ktons) and near detectors.

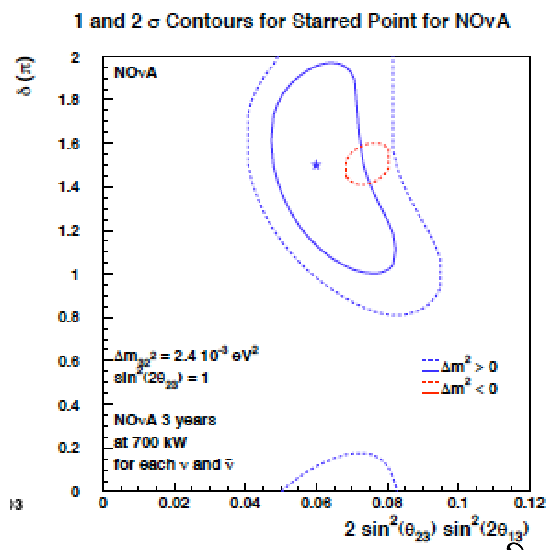
Startup October 2013 (maybe 31 Dec).Run until 2020.



NOνA
ν_e app.
limits

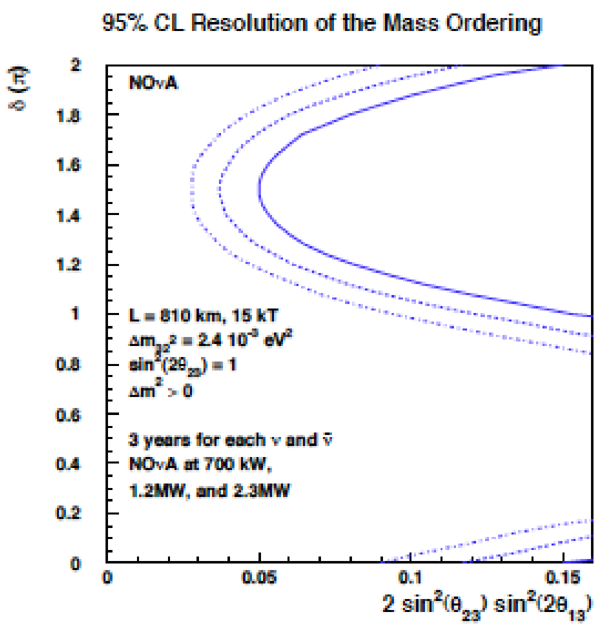


$\sin^2 2\theta_{13}$

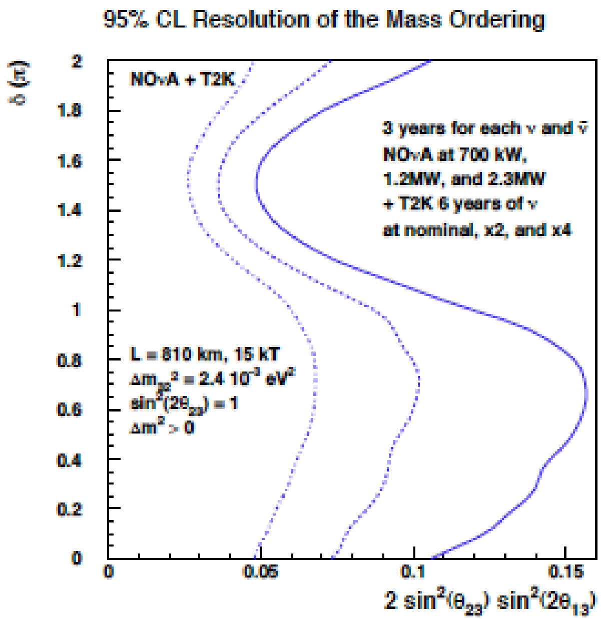


δ_{CP}

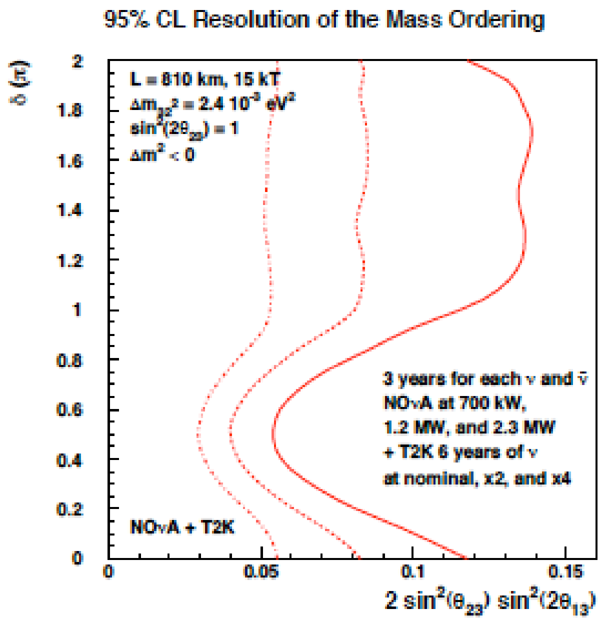
NOνA will also measure ν_μ dis-appearance precisely, ν_μ-$\bar{\nu}_\mu$ differences, as well as search for sterile ν's



Normal Hierarchy
NOνA alone



Normal Hierarchy
NOνA+T2K



Inverted Hierarchy
NOνA+T2K

AP 90-100(2020-30) and Beyond

Reactors, T2K, NOvA will determine $\sin^2 2\theta_{13}$ if it is > ~0.01. But if it is below ~0.06 they are unlikely to resolve δ_{CP} or Mass Hierarchy, nor small NSI's or ν-$\bar{\nu}$ differences.

Superbeam Proposals (to run ~2020-2030)

LBNE - USA (Fermilab to DUSEL?)

LAGUNA- Europe (CERN to ?? 7 poss. sites)

HyperKamiokande- Japan (JPARC to ?)

Beyond Superbeams

Neutrino Factory

Superbeams - ν_e Appearance

Choose baseline L, energy E, to maximize matter effects for δ_{CP} , MH determination. Maximize beam intensity, build massive detectors.

(Note: The massive detectors will do much more than the neutrino beam studies: proton decay and solar, atmospheric, supernova, and geo - neutrinos, etc)

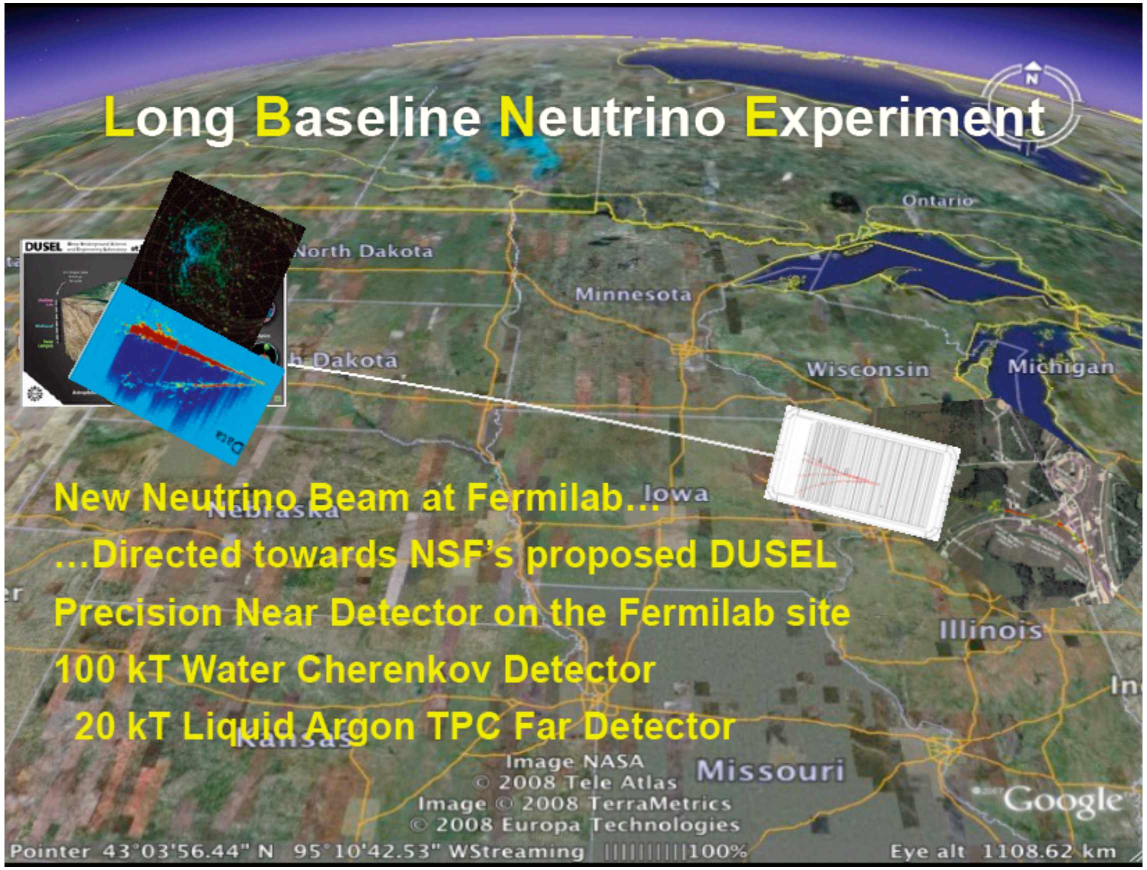
LBNE - Fermilab's future is the 'intensity frontier' : Neutrino physics, rare phenomena (e.g., Mu2e)

With Tevatron turn-off beam power for NOvA doubles (compared to MINOS) to 700 kW.

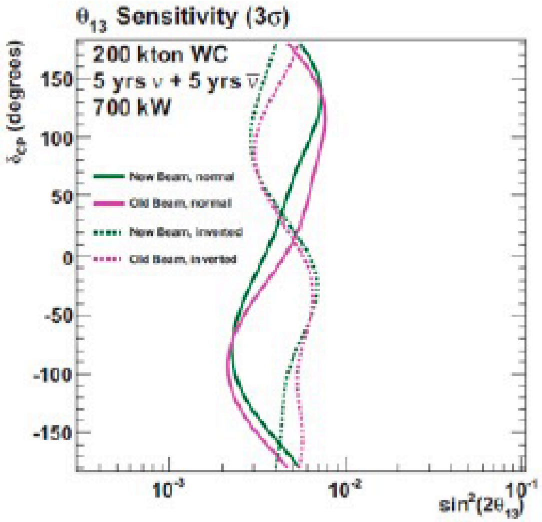
Planning for LBNE assumes this beam, but Project X at Fermilab aims at 2.3 MW on a similar time scale.

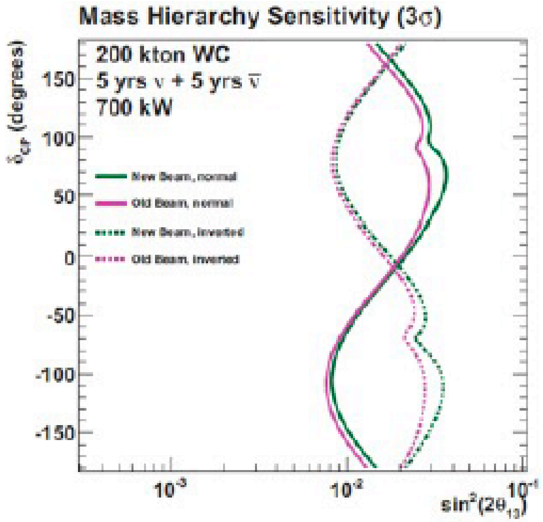
Present proposal - Fermilab to Homestake Mine in South Dakota, L=1300 km - AP 90-100 (2020-30)

Early cost estimates with ~1 Mton H_2O + 100 kton LAr were
~$2 b. After much reworking present beam + detectors+ caverns and shafts in mine somewhat
> $ 1 billion.
DOE limit is $ 1 billion (not including Project X)

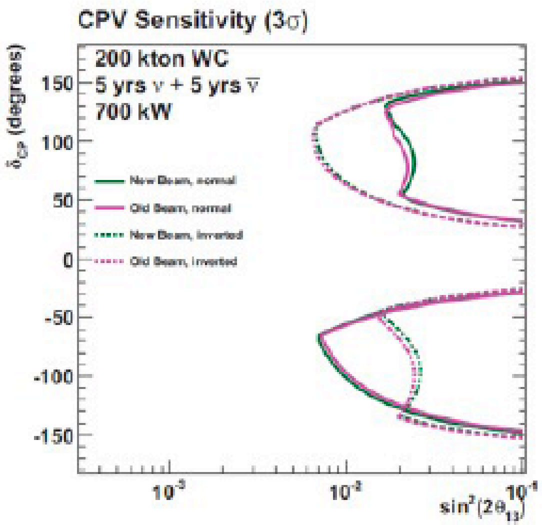


LBNE Sensitivities:





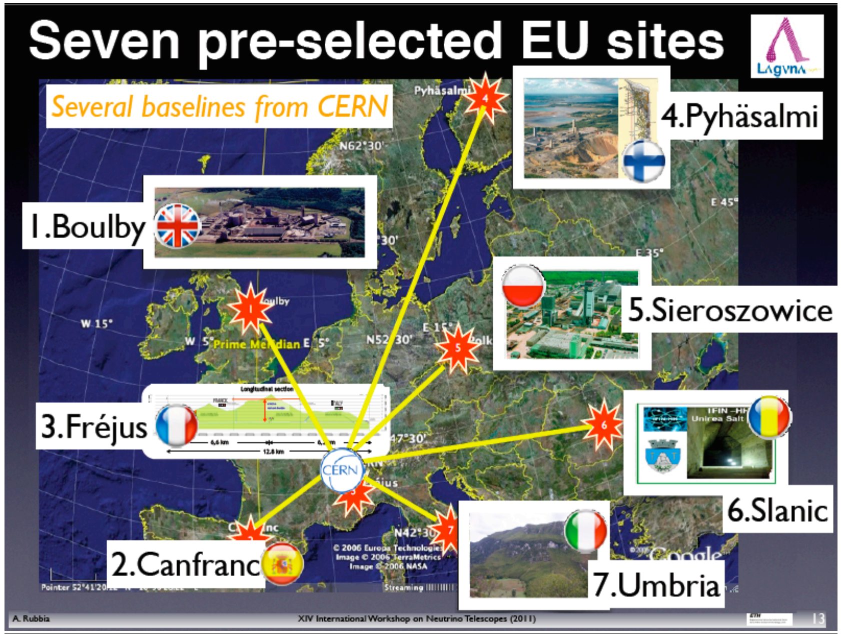
Sensitivities shown are for 200 ktons WCD.
With 34 ktons LAr, the sensitivities are equivalent.

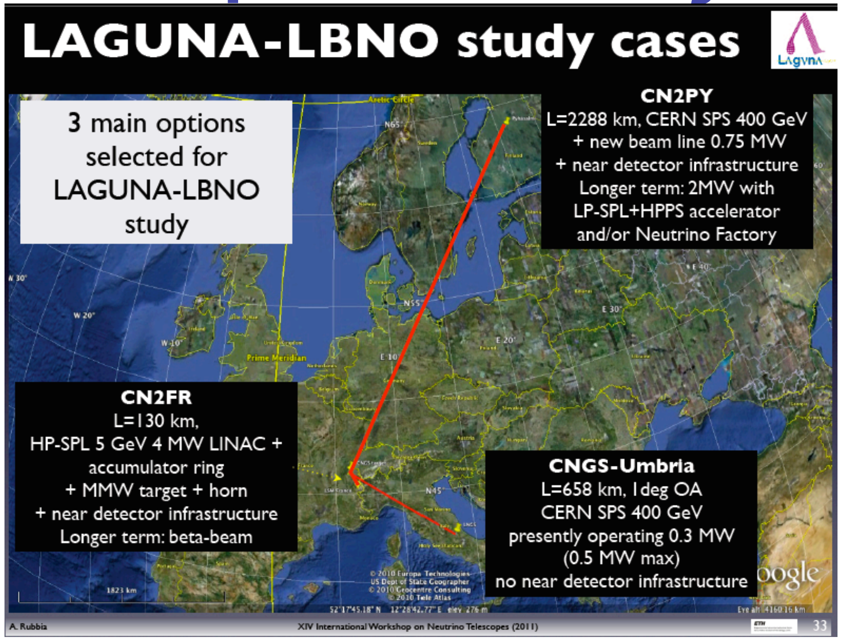


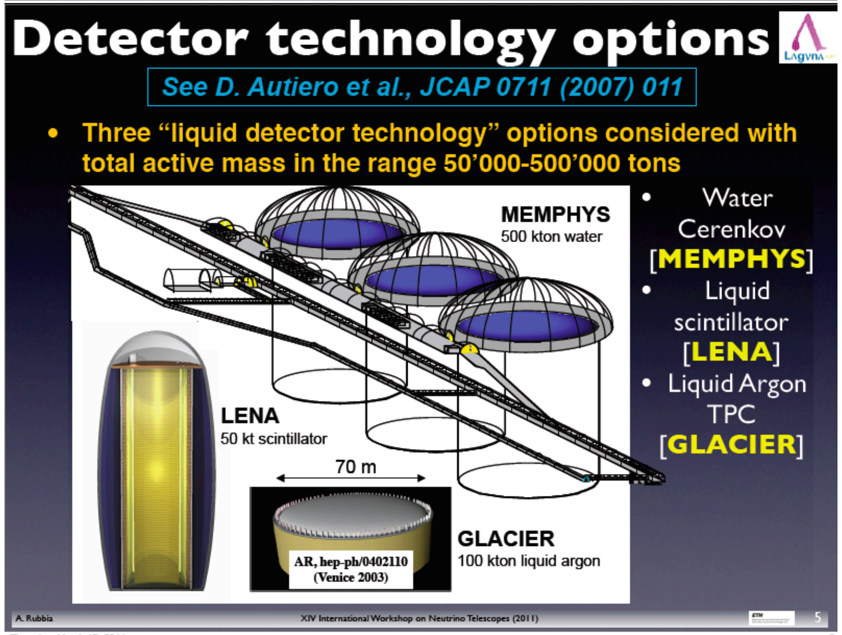
Sensitivities shown are for 10 years with 700 kW proton beam.
With Project X ($\geq$2 MW), the same sensitivity would be reached in 1/3 the time … or ~$\sqrt{3}$ greater sensitivity for the same running period.

Fall 2010 Report from the LBNE Physics Working Group

LAGUNA-LBNO European Project







The physics goals are essentially the same as for LBNE and the achievable sensitivities are similar for comparable beam power.

LAGUNA Time Lines

ν beams at CERN – future possibilities

Short timescale (~2015)

- Conventional LBL ν-beams from SPS (400 GeV)
  - Exploit the CNGS technology, sub-MW class facility, **CNGS+**
    - Intensity upgrade, new focusing scheme for low ν-beam energies
- Conventional SBL ν-beam from PS (20 GeV) – **PSNF**
  - Dedicated experiment on sterile neutrinos
  - Test bed for detector and targetry R&D, x-section measurements

Medium timescale (~2020)

- Conventional LBL ν-beams from SPS (400 GeV)
  - CNGS+ beam to a new site (**CN2?**)
- Upgrade using LP-SPL as proton driver, new HPPS (30-50 GeV)
  - ~MW class facility (**CN2?-HP**)

The BIG picture – ultimate facilities (~2030)

- Super beams, β-beams, Neutrino Factory
  - HP-SPL and new accelerators, MMW class facilities

Ilias Efthymiopoulos - CERN NNN10 - Toyama, December 15, 2010 9

Cost estimates: Not yet determined. It's going to be HIGH!

LAGUNA - Milestones

LAGUNA Design Study funded for site studies:	2008-2011
Categorize the sites and down-select:	Sept. 2010
LAGUNA-LBNO: funded for detector design and beam options	2011-2014
Critical decision (and $\theta_{13}\neq0$?)	2014 ?
Phase 1 excavation-construction:	2015-2020 ?
Phase 2 excavation-construction:	>2020 ?

Timeline matched to new potential CERN neutrino (super)beams in >2016

A. Rubbia XIV International Workshop on Neutrino Telescopes (2011) 38

Japan -JPARC to Okinoshima

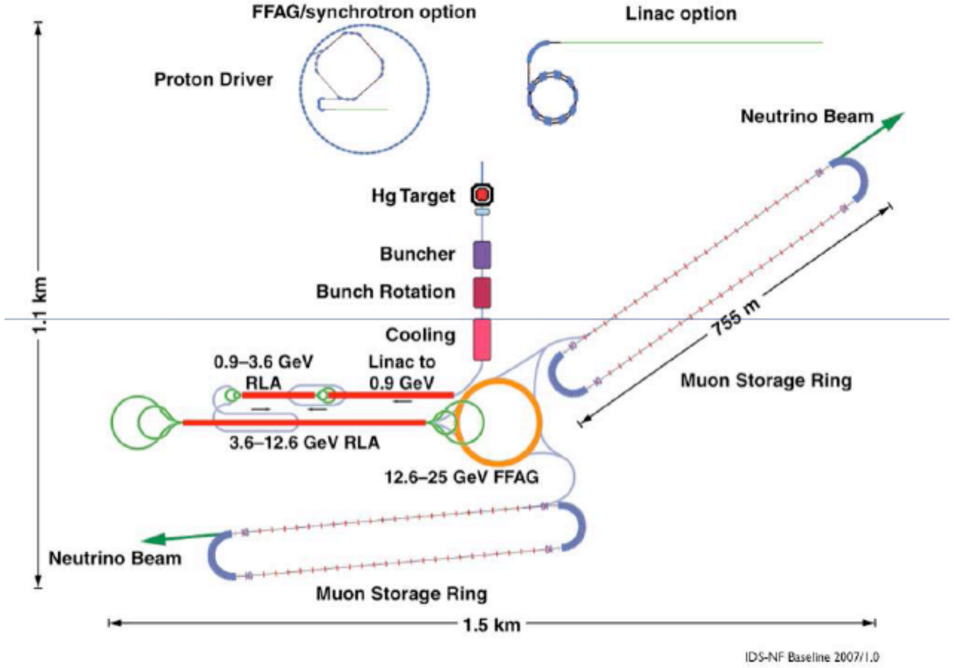
Upgrade the JPARC beam.

Detector would be 100 kton LarTPC similar to LAGUNA proposal.Sensitivities for CPV similar to LBNE and LAGUNA.

Alternate option: 540 kton H_2O Cerenkov at Kamioka.

AP 100 & Beyond- Neutrino Factory

Stored $\mu^- \to e^- \nu_\mu \bar{\nu}_e$	
Disappearance	**Appearance**
$\bar{\nu}_e \to \bar{\nu}_e \to e^+$	$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$ $\bar{\nu}_e \to \bar{\nu}_\tau \to \tau^+$
$\nu_\mu \to \nu_\mu \to \mu^-$	$\nu_\mu \to \nu_e \to e^-$ $\nu_\mu \to \nu_\tau \to \tau^-$



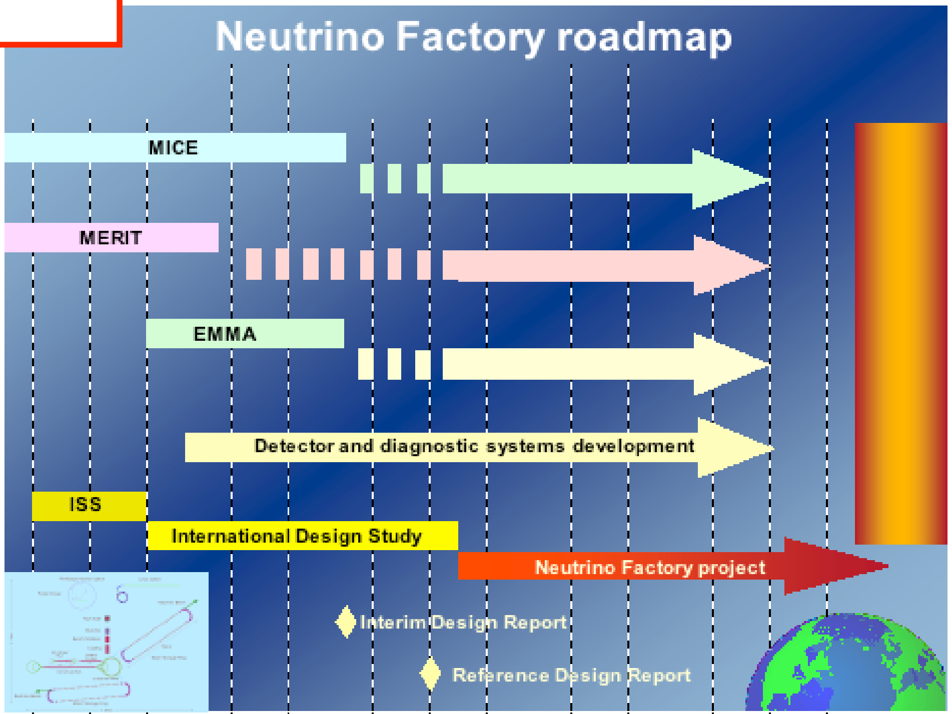
~25 GeV muons,
large ν_e and $\bar{\nu}_e$ fluxes. Makes very long baselines possible, e.g., 7500 km ‘magic’ baseline for ‘pure’ $\sin^2 2\theta_{13}$ down to 10^{-4} and ~2540 km ‘bimagic’ baseline for ‘pure’ mass hierarchy determination. All other parameters measurable to great accuracy by varying beam energy, and better sensitivity to non-standard phenomena. K.Long, NEUTEL 2011 and NEUTRINO 2010

International Design Study - Neutrino Factory (IDS-NF)

Bulgaria	Sofia
France	IPHC Strasbourg
Germany	MPI Heidelberg, MPI Munich, Würzburg
India	HCRI Allahabad, SINP Kolkata, TIFR Mumbai
Italy	Milano Bicocca, Napoli, Padova, Roma III
Japan	Kyoto, Osaka, Tokyo Met.
Spain	Madrid, Valencia
Russia	INRR Moscow
Switzerland	CERN, Geneva
UK	Brunel, DL, Glasgow, Imperial, IPPP Durham, Oxford, RAL, Sheffield, Warwick
USA	BNL, FNAL, JLab, LBNL, Mississippi, MSU, Muons Inc., Northwestern, ORNL, Princeton, Riverside, Stony Brook, South Carolina, Virginia Tech., UCLA

Note: Much of the R&D overlaps with that for a Mu-mu collider. Particular interest at Fermilab and CERN.

Time scale - put years on the vertical lines. If it's decided to go ahead physics by mid-2020's could be possible.



Summary & Conclusions

1. What we didn't cover:

a. Neutrino interactions, cross sections (e.g.,MINERvA at Fermilab)

b. Astrophysical neutrinos; solar, supernova, galactic, relic. Experiments like Borexino, ICECUBE, KM3NeT(ANTARES,NESTOR,NEMO).

c. Geoneutrinos, neutrino applications

2. In 80 years we have come from table-top experiments to billion(s) $ experiments. In the process neutrinos played a crucial role in reaching the state of our present knowledge and giving first hints of beyond the SM. We learned a lot about them; flavors, oscillations. We have Known knowns: $\sin^2 2\theta_{12}$, $\sin^2 2\theta_{23}$, Δm^2_{21}, $|\Delta m^2_{32}|$; Known unknowns: masses, Majorana/Dirac, θ_{13}, CPV, MH; Semi-Known unknowns; sterile neutrinos, CPT violation; and Unknown unknowns*. These last are the surprises, and given past experience, we should expect a few in the next 20 years.

3. Funding! Is society going to pay for all these proposed projects. It's important that we collaborate internationally and economize.

*See A. McDonald, Neutel 2011, quoting Donald Rumsfeld

Neutrinos have still a lot to teach us and are going to keep us busy for a long time to come, so you are all invited to

NEUTRINO 2030

in Zurich, the Pauli Centennial.

For details go to NEUTRINO 2010 (http://www.neutrino2010.gr)
and NEUTRINO TELESCOPES 2011(http://neutrino.pd.infn.it/Neutel2011/)