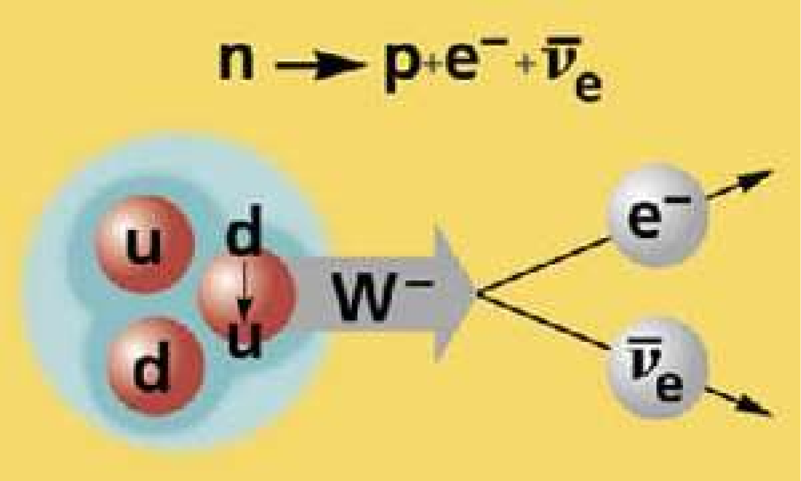
B.T.Fleming
PHENO 07
May 6, 2007

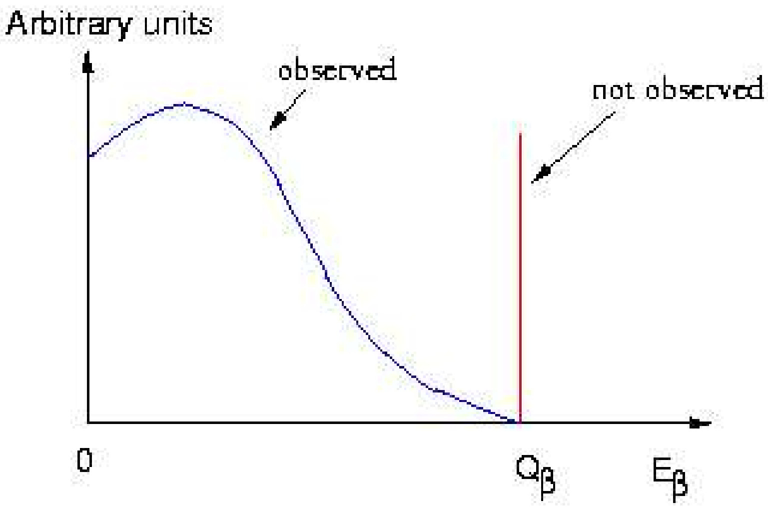
Neutrino Oscillations

Recent Results
from ~ last year

Pressing Questions in the near and farther future

The beginnings of the neutrino: Experiment drives Theory -> Desperate Remedies





Bohr was ready
to abandon
Conservation of Energy
to explain this missing
energy phenomena until Pauli
proposed this
"desperate remedy":
the neutrino

1930: Pauli

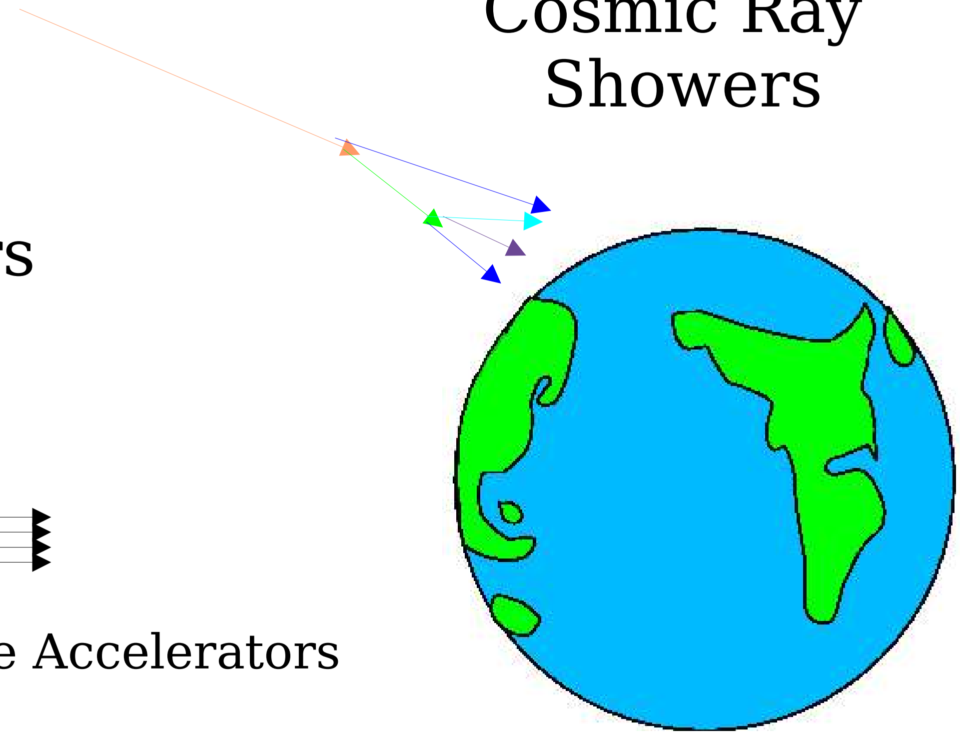
"...I have predicted
something which
shall never be detected
experimentally!"

Took another 26 years
just to detect the electron
neutrino!

To see neutrino interactions, you need:

1) **lots of neutrinos**
2) lots of detector
3) fine-grained
or specialized detectors
4) some combination
of the above

Cosmic Ray Showers

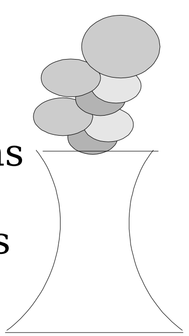


Neutrino Beams made from Particle Accelerators

ν's from cosmos:

our sun
supernovae
relic neutrinos

Neutrino Beams made from Reactors



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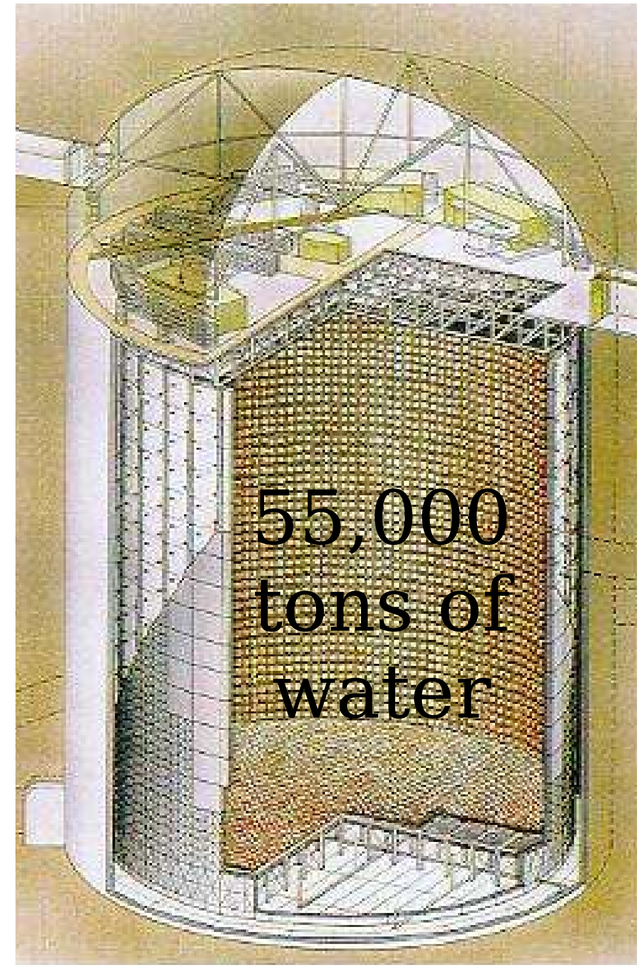
Super-K



MINOS far detector
5.4 ktons of steel to STOP
neutrinos

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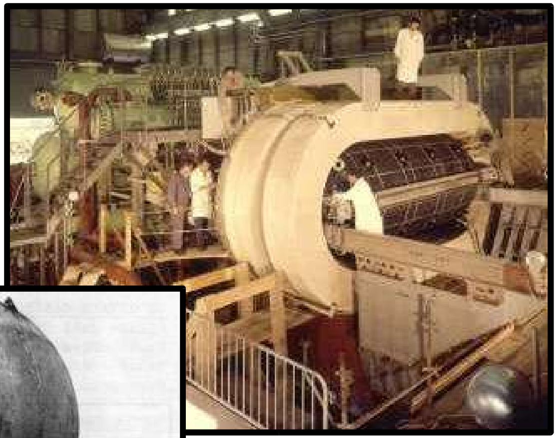
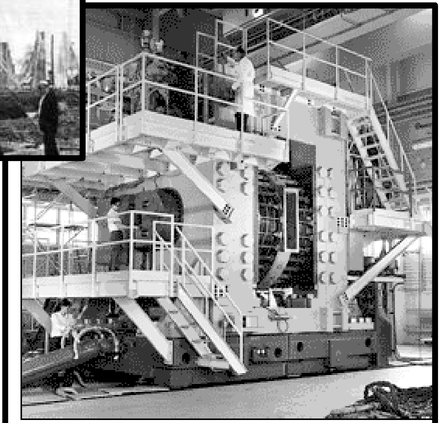
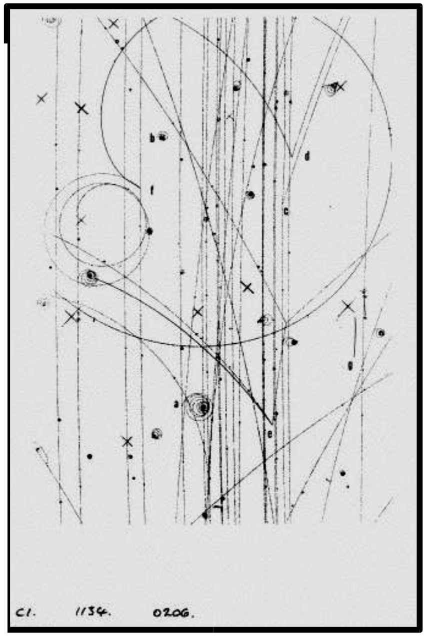
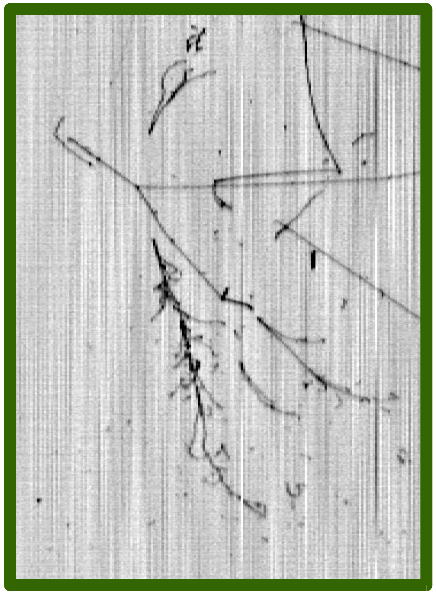


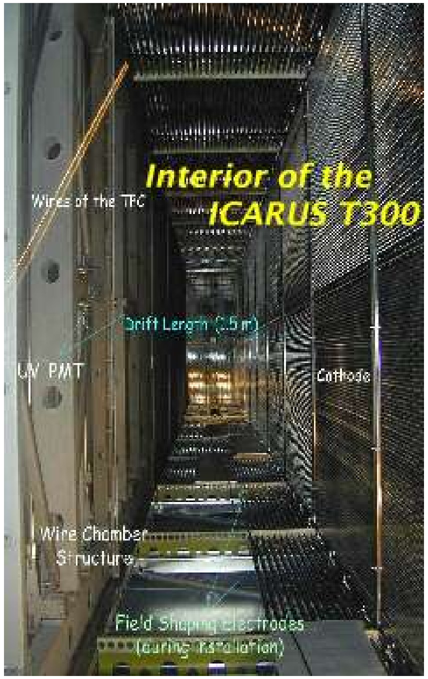


The 80-inch Bubble Chamber



Bubble chambers: limited size....





Liquid Argon
time projection chambers

To see neutrino interactions, you need:

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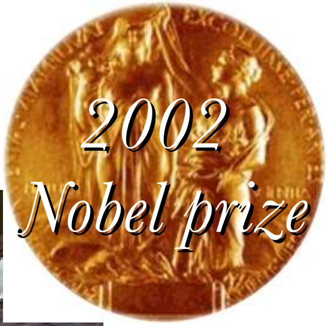
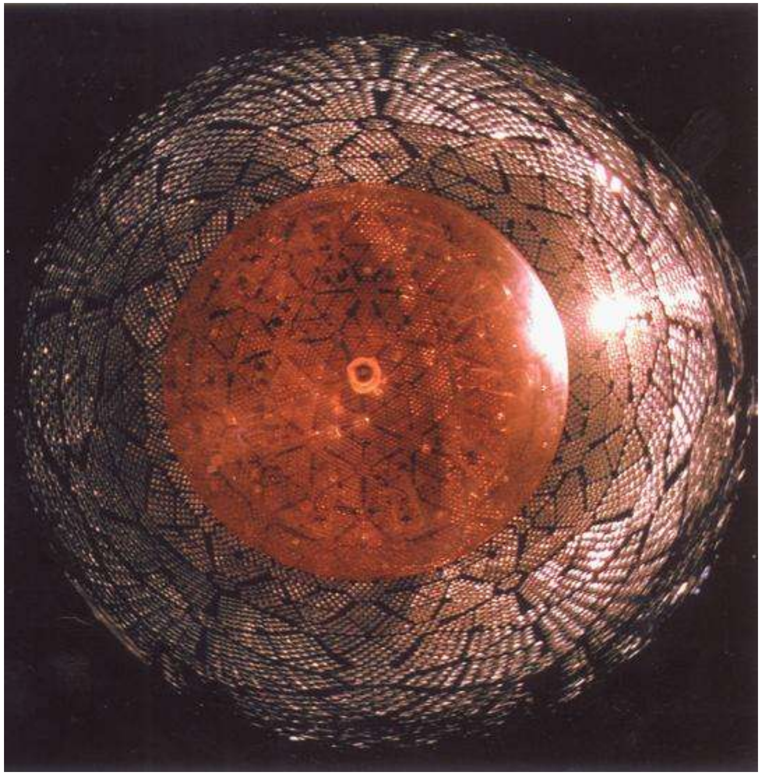


Homestake detector



SNO: tags neutral current
for all flavors vs.
charged current for electrons

To see neutrino interactions, you ne

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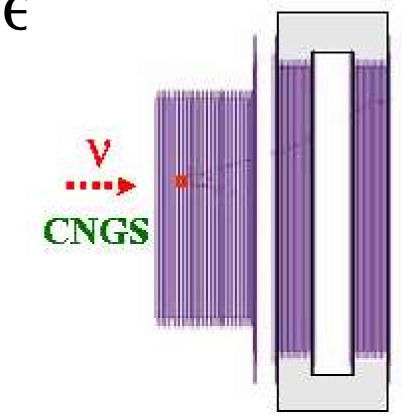
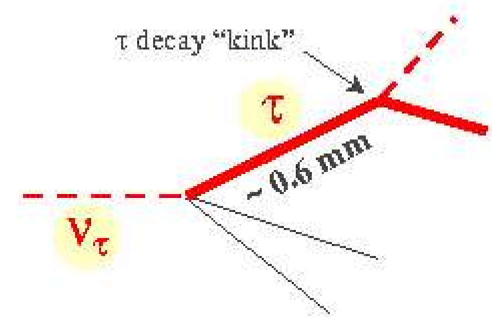
   or specialized detectors
4) **some combination of the above**



Detector module:
lead/emulsion stack
electronic tracking detector



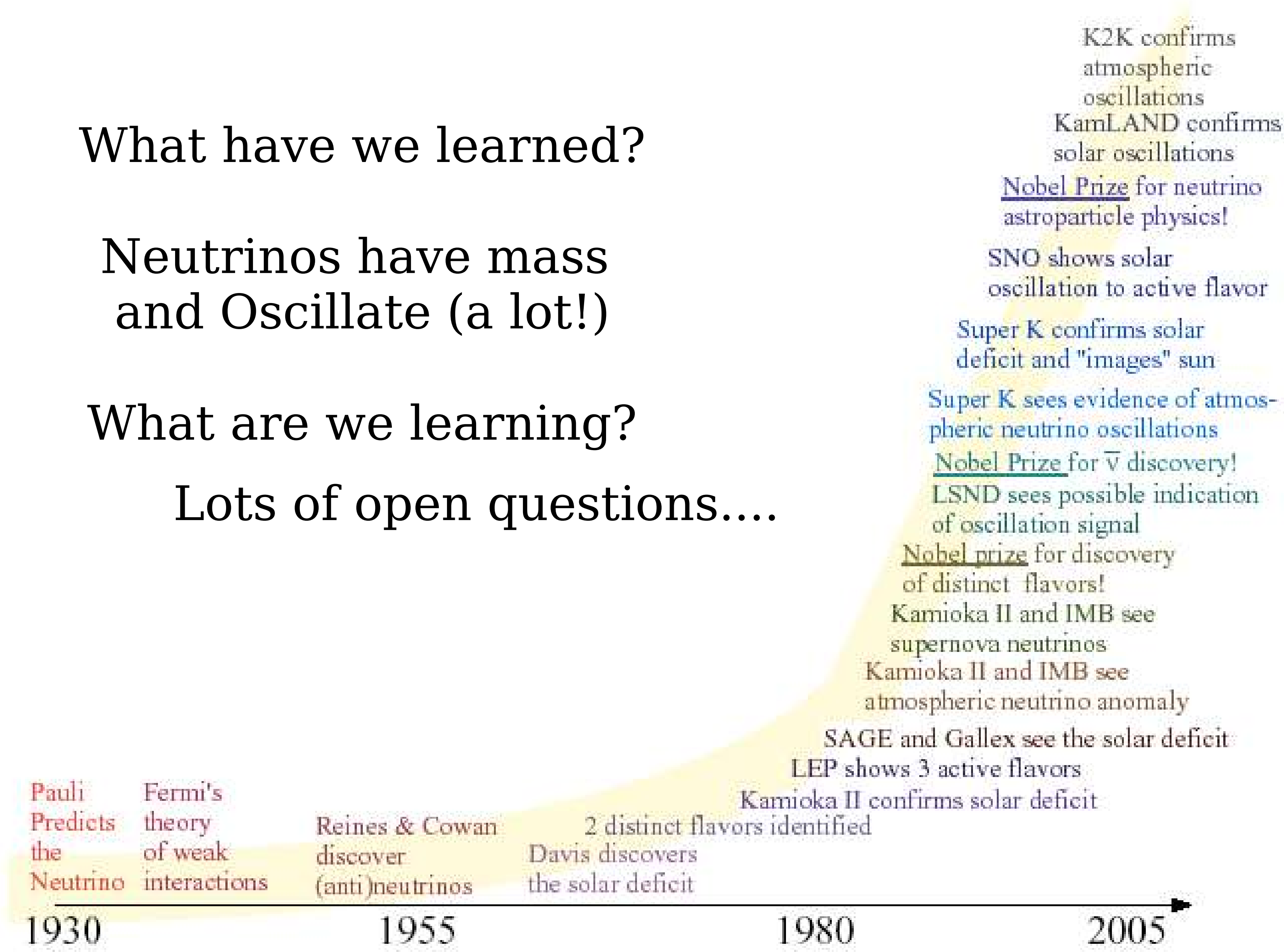
look for τ decay kink
in emulsion bricks!

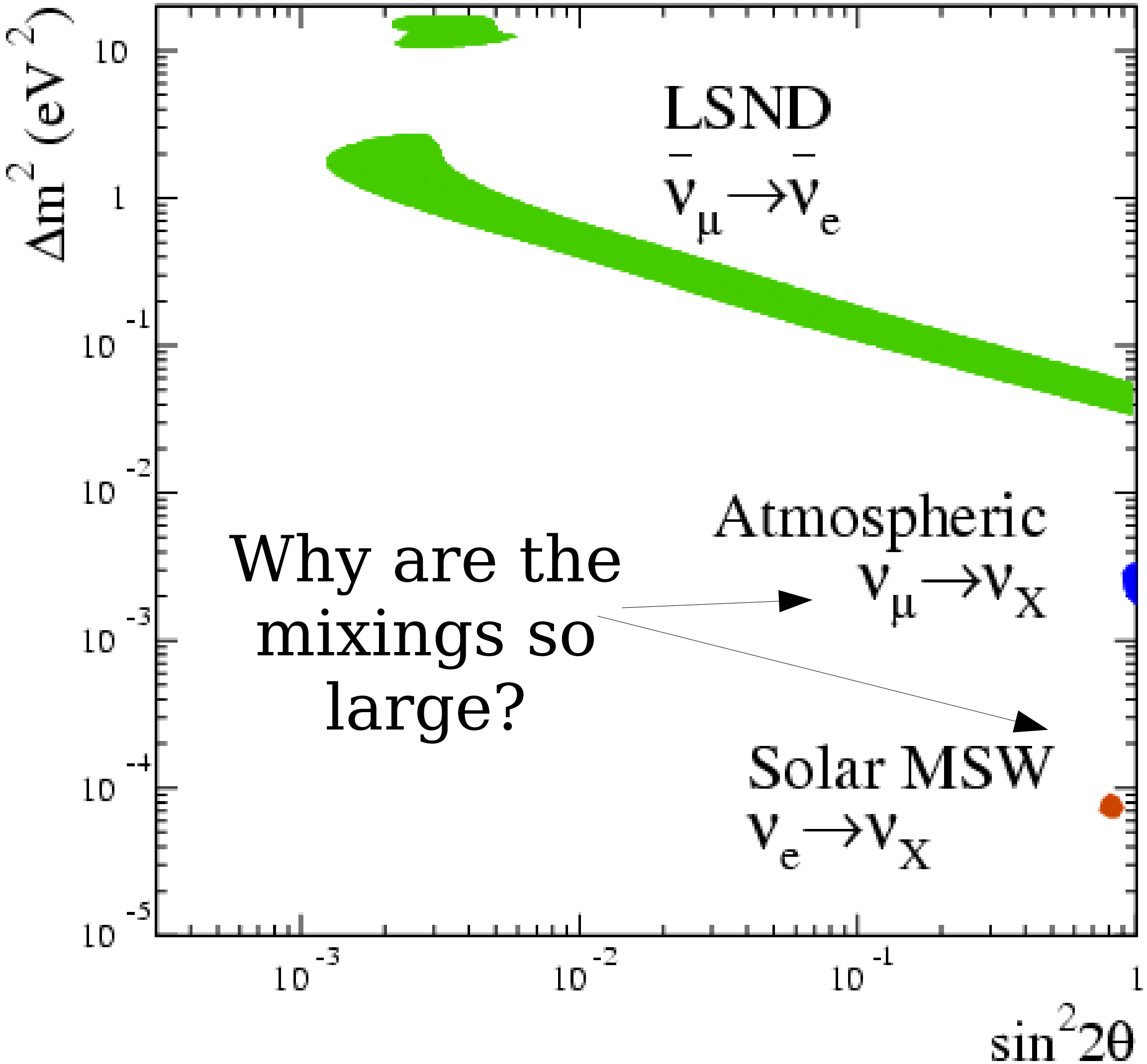
What have we learned?

Neutrinos have mass
and Oscillate (a lot!)

What are we learning?

Lots of open questions....





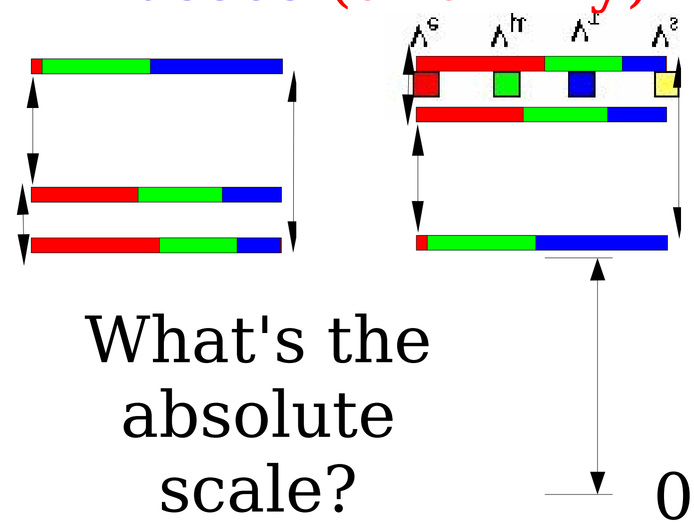
Why are the mixings so large?

There are too many signals!

ν_1
$\Delta m_{12}{}^2$
ν_2
$\Delta m_{23}{}^2$
ν_3

$\Delta m_{13}{}^2 = \Delta m_{12}{}^2 + \Delta m_{23}{}^2$

What's the pattern of masses (and why)

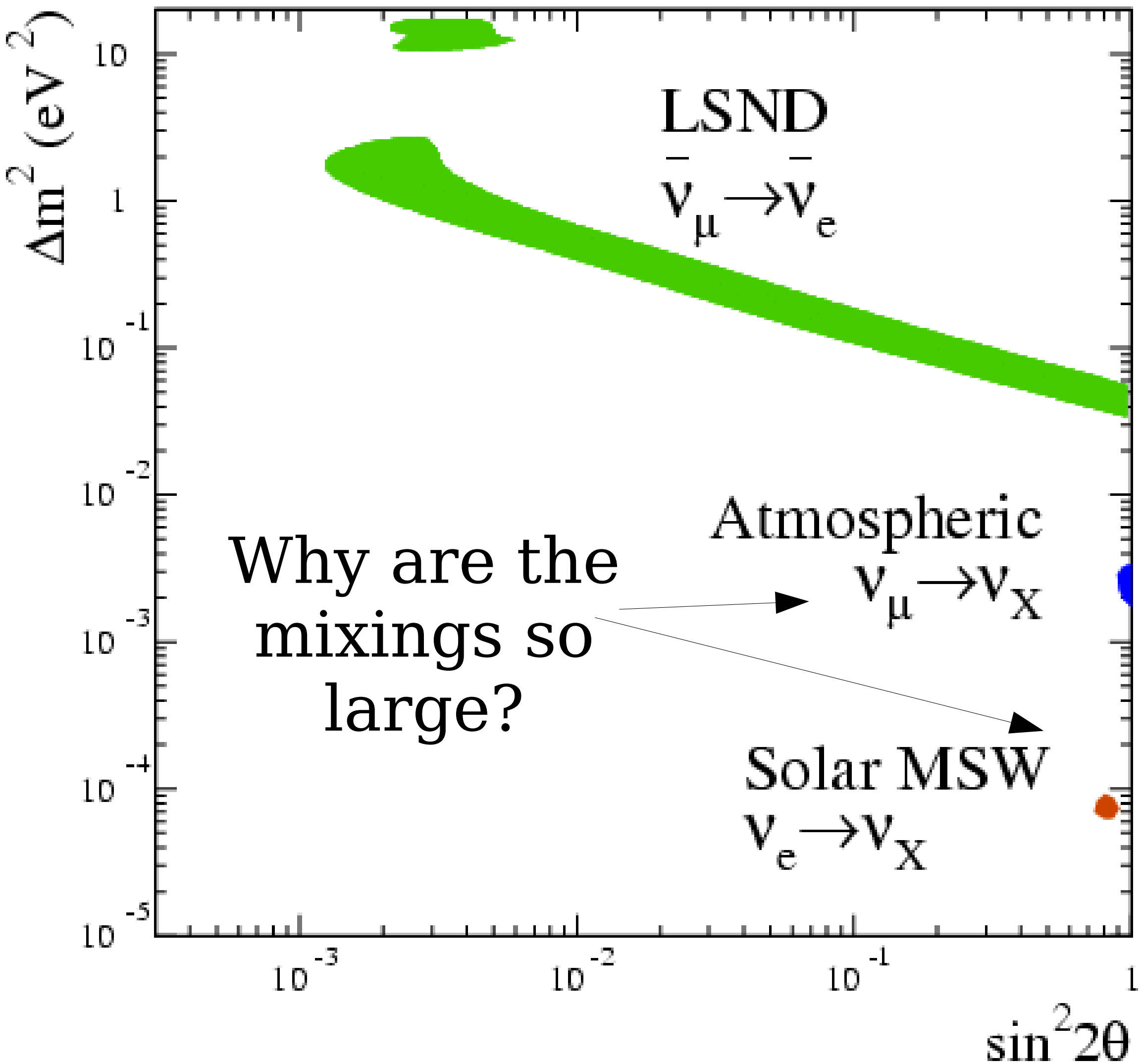


What's the absolute scale?

need direct mass mmnts: Katrin!

Are neutrinos Dirac or Majorana?

What about anti-neutrino oscillations? Do neutrinos CP?



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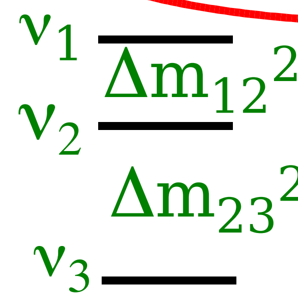

$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$

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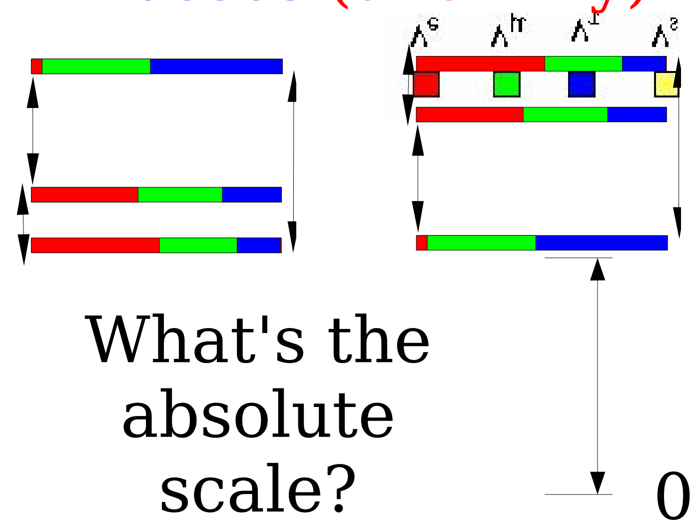

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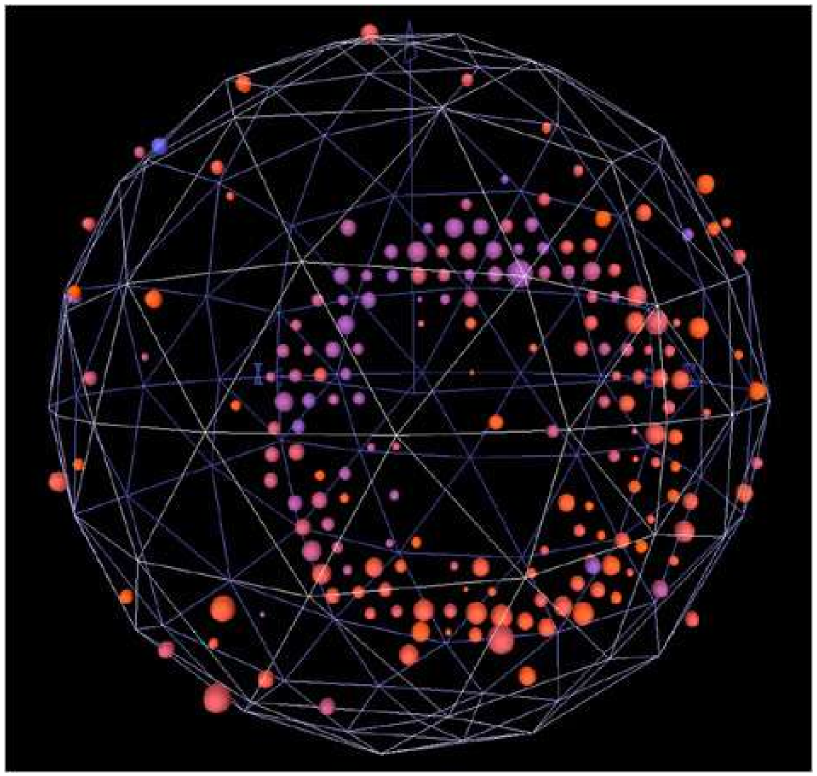
The New York Times April 12, 2007

"How Did the Universe Survive the Big Bang? In This Experiment, Clues Remain Elusive"



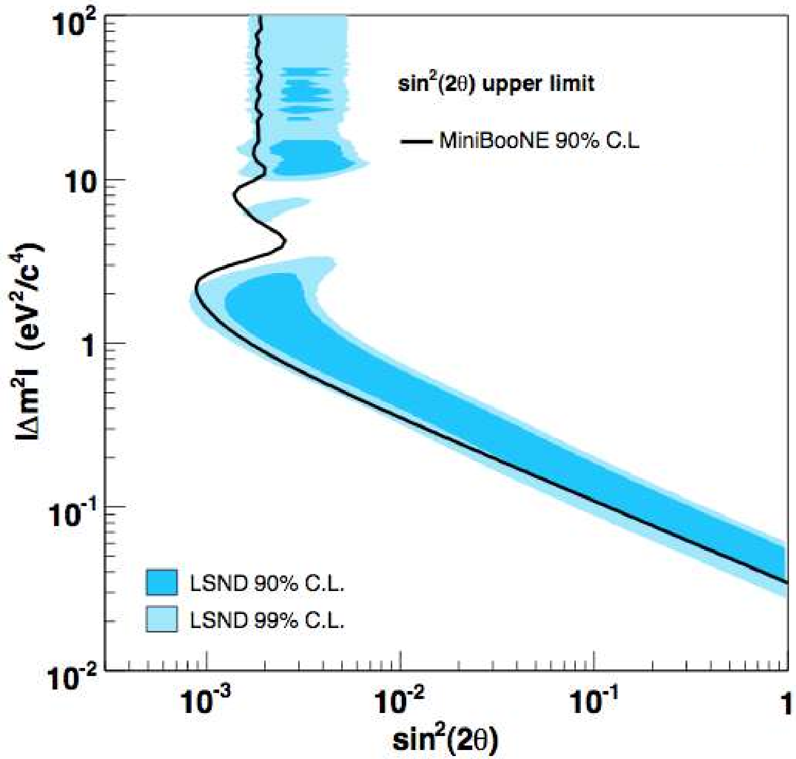
Chris Polly presented MiniBooNE's first results earlier today...

MiniBooNE looked for ν_e appearance in a ν_μ beam to address LSND's $\bar{\nu}_e$ appearance result...

Rule out two neutrino ν_e appearance as LSND reported

See a discrepancy at low energies which is not yet understood

•An analysis of the data within an LSND $\nu_\mu \rightarrow \nu_e$ appearance context

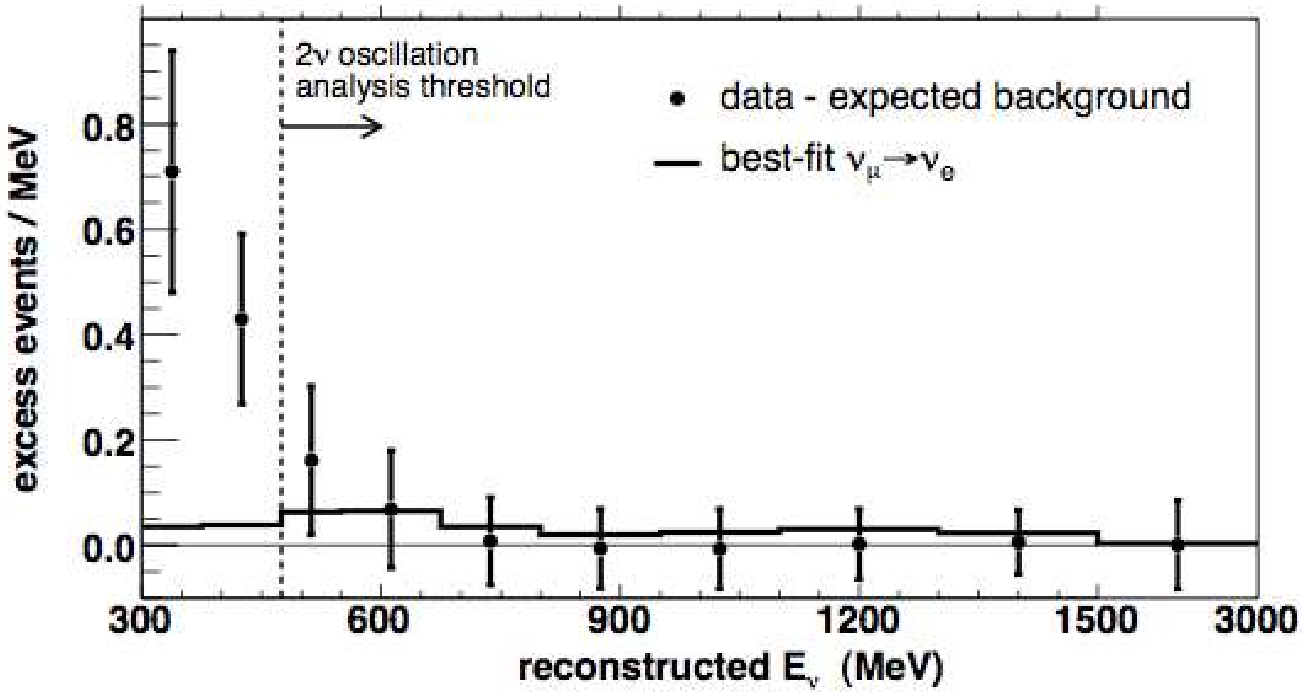


Two independent blind analyses observe event rate consistent with background above 475 MeV

Set a limit on $\nu_\mu \rightarrow \nu_e$ appearance:

Incompatible with LSND at 98% CL.

•A generic search for a ν_e excess in the ν_μ beam



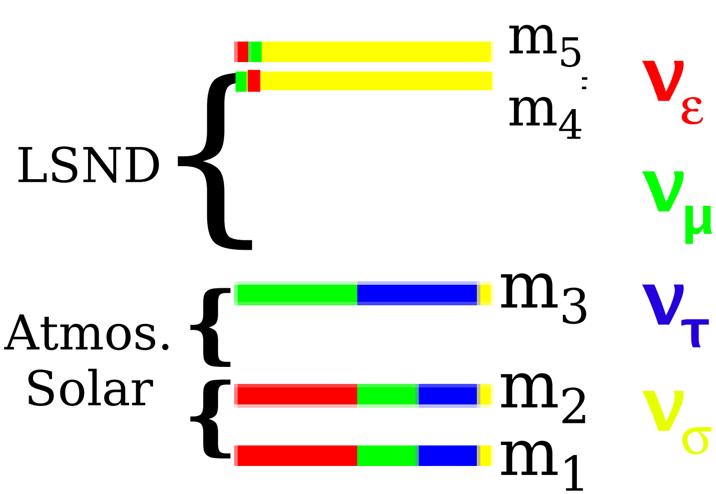
Discrepancy -> excess above background below 475 MeV…

MiniBooNE actively working to understand the low energy discrepancy (background, xsecs, physics?)

see G. Karagiorgi's talk tomorrow afternoon

Recent work by Maltoni et al. considers:
If these are really oscillation events, what does this mean? Sterile neutrinos?

MiniBooNE combined with other SBL experiments in the context of 3+1, 3+2, and 3+3 models



Then these are the main mixing matrix elements

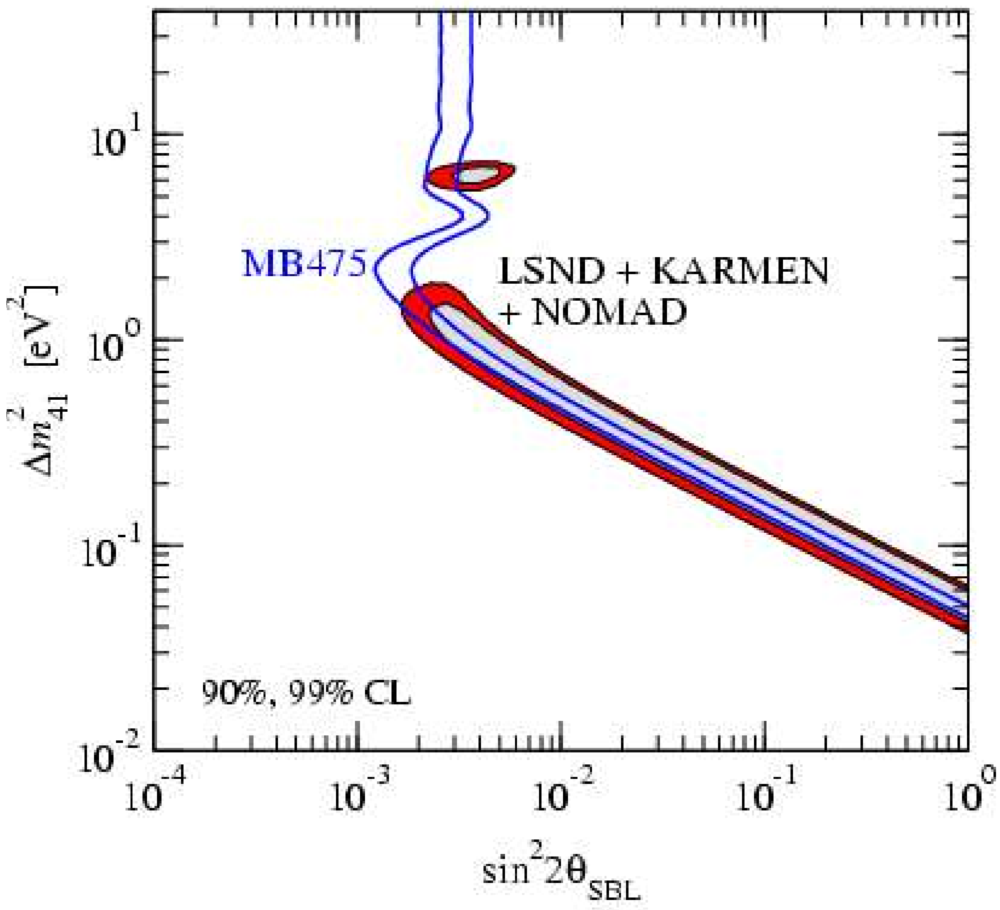
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4} \quad U_{e5} \quad \cdots} & & \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

Maltoni et al. cont.:

3+1 models ~
2 ν appearance

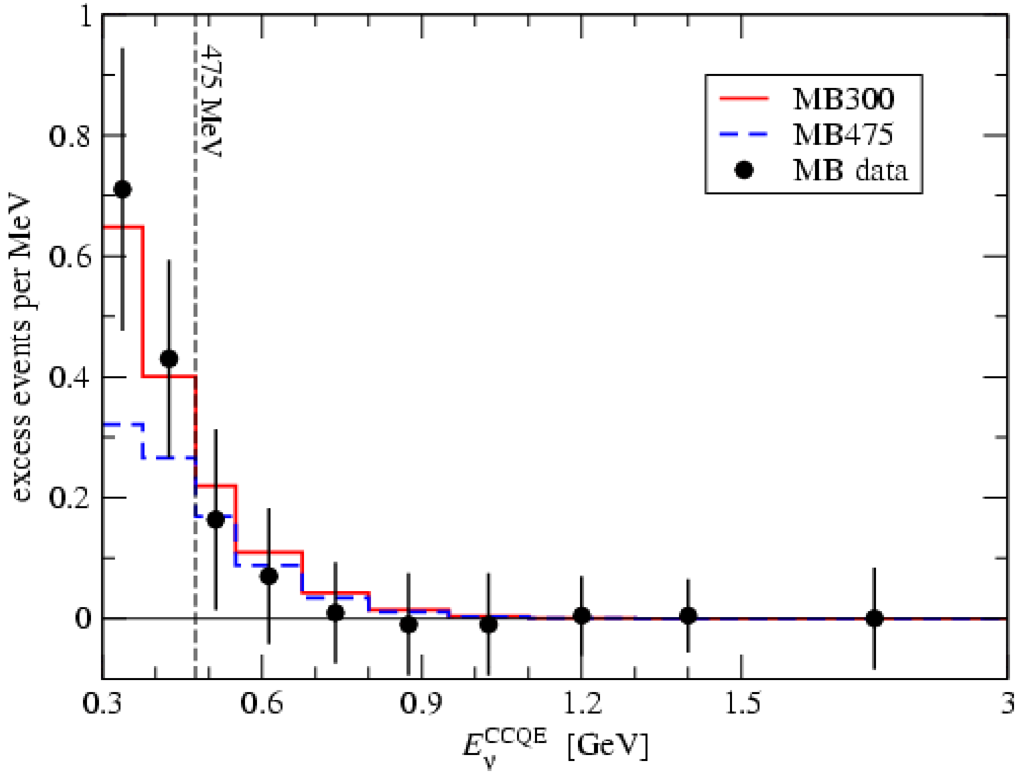
MiniBooNE
incompatible
with LSND, Karmen
and NOMAD

Including low energy
region in fit
-> quality of fit
drastically worsens



hep-ph/0705.0107v1

3+2 models include CP Violation: more flexibility to accommodate MiniBooNE with LSND, Karmen and NOMAD



hep-ph/0705.0107v1

→ However, there is significant tension between the appearance expts, and disappearance expts (Bugey, CDHS)

→ tension with standard cosmological constraints

→ 3+3 models: no significant improvement

For the 3x3 PMNS matrix:
$\sin^2 2\theta_{13}$, sign(Δm_{23}^2), δ?

The CP Violation Parameter

Three Neutrino Mixing Matrix:

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

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

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From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

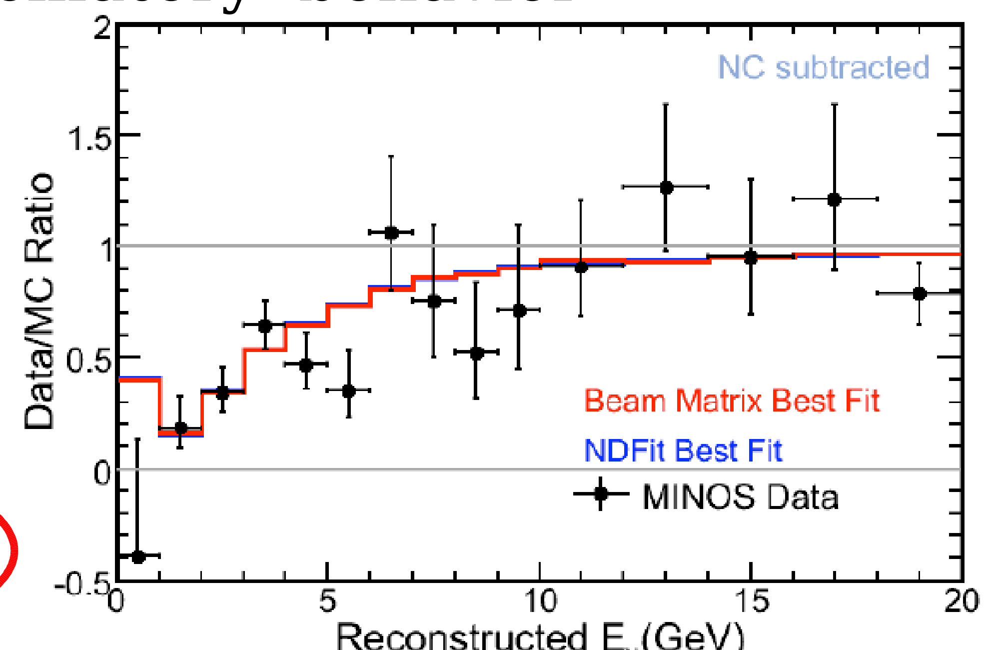
New measurements on the way!

First results from MINOS in March 2006 are terrestrial confirmation of the Atmospheric neutrino deficit.

Long Baseline ν_μ disappearance in beam traveling from Fermilab to Soudan shows beautiful oscillatory behavior

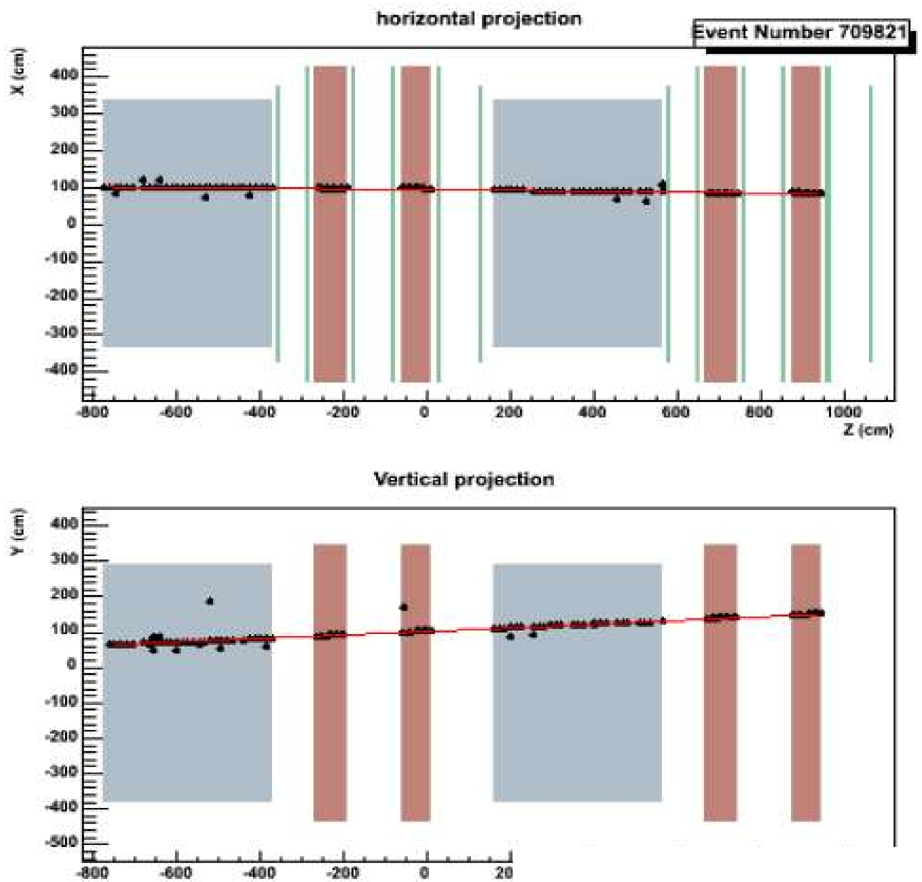
- $\Delta m^2_{32} = 2.74^{+.44}_{-.26} 10^{-3}$ eV^2
- 1.27 10^{20} pot collected
- Statistics limited

new results expected soon



CNGS first beam:
Opera looks for tau neutrino appearance

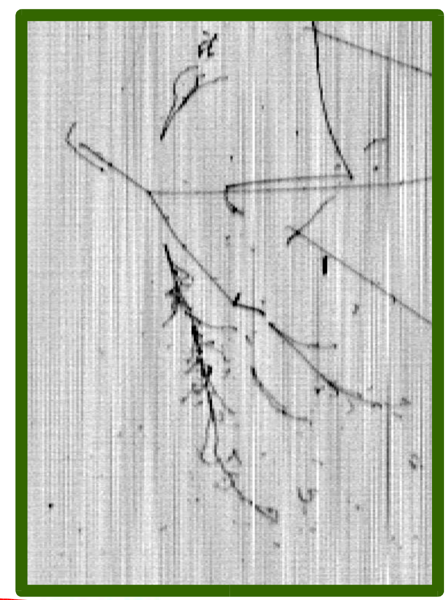
OPERA



Proposal: July 2000,
installation at LNGS started in May 2003
First observation of CNGS beam neutrinos : August 18th, 2006

ICARUS LArTPC:
expected to be operational by late 2007

One of the two T300 modules



For the 3x3 PMNS matrix:
$\sin^2 2\theta_{13}$, sign($\Delta m_{23}{}^2$), δ?

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From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

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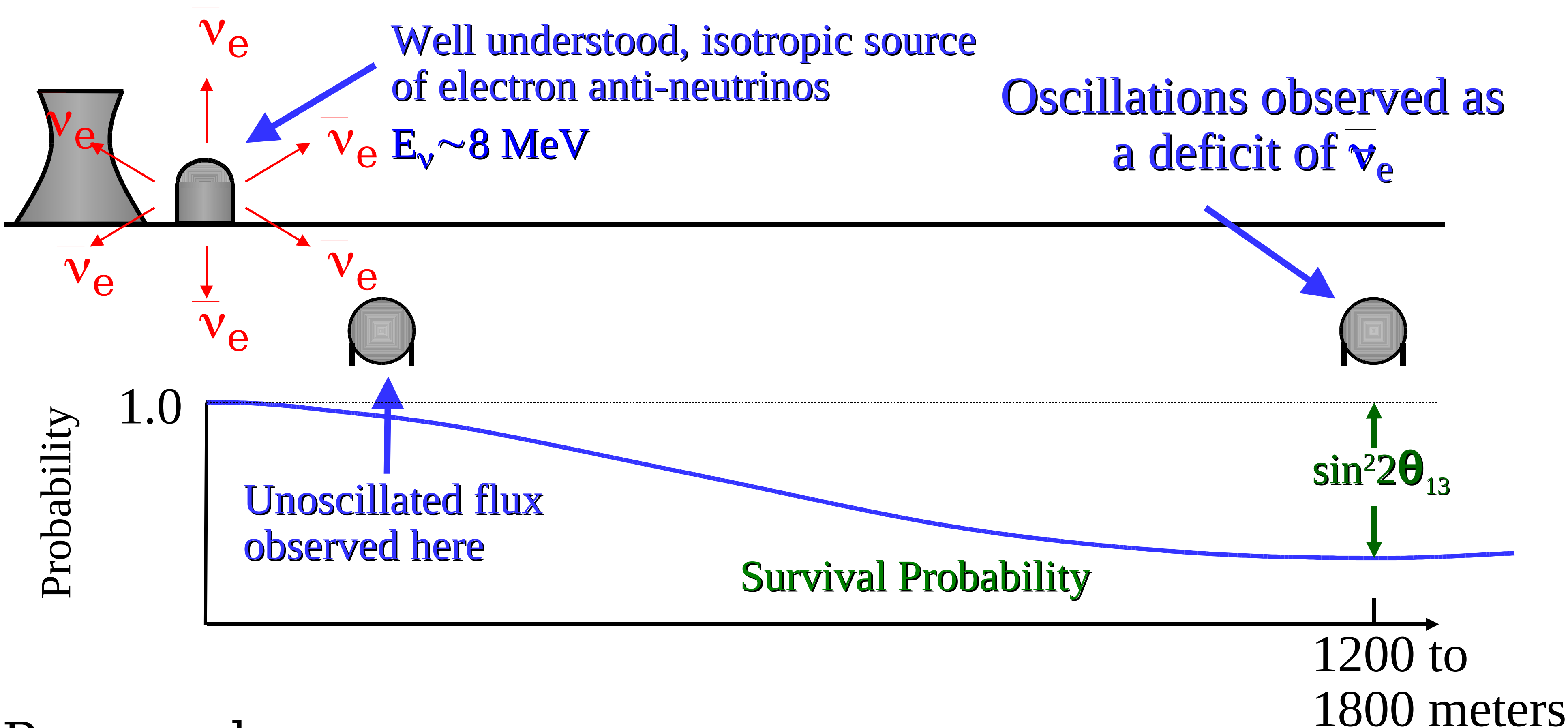
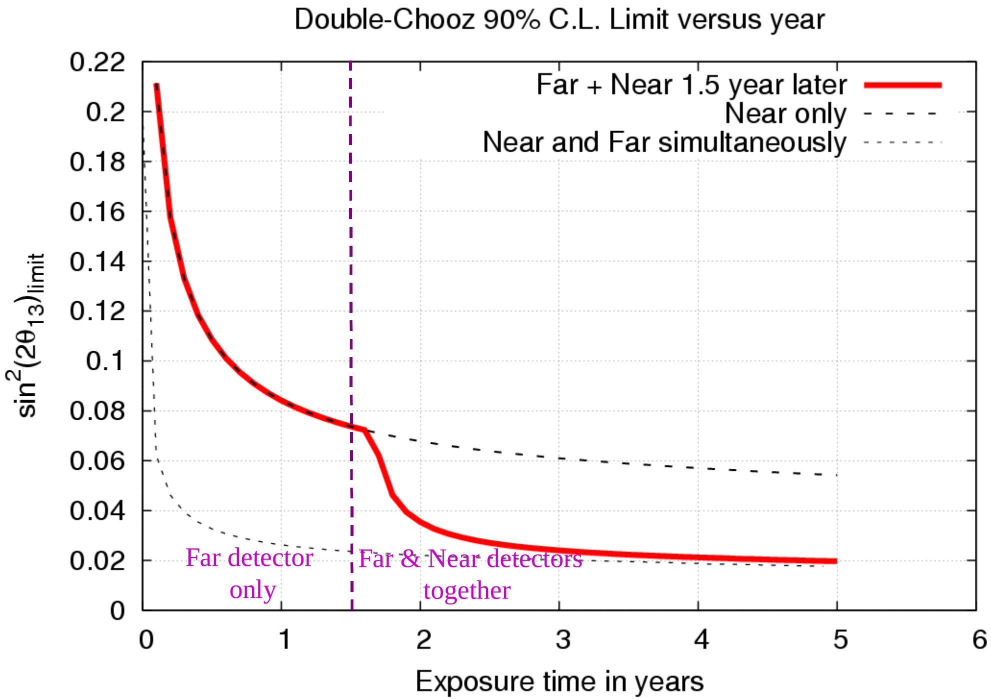
In order to measure CP Violation, θ_{13} must be large enough.....

θ_{13} Reactor Experiments



Proposed sites around the world

	start date	sensitivity($\sin^2 2\theta_{13}$)
Double Chooz	'07	.025
Daya Bay	'09	.008
Reno	late '09	.03
Angra	'13	.006



11/2007 11/2008 11/2009 11/2010

Double Chooz far detector turns on in 2007

with near detector 16 months later

→ jump in sensitivity

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From Atmospheric and Long Baseline Disappearance Measurements

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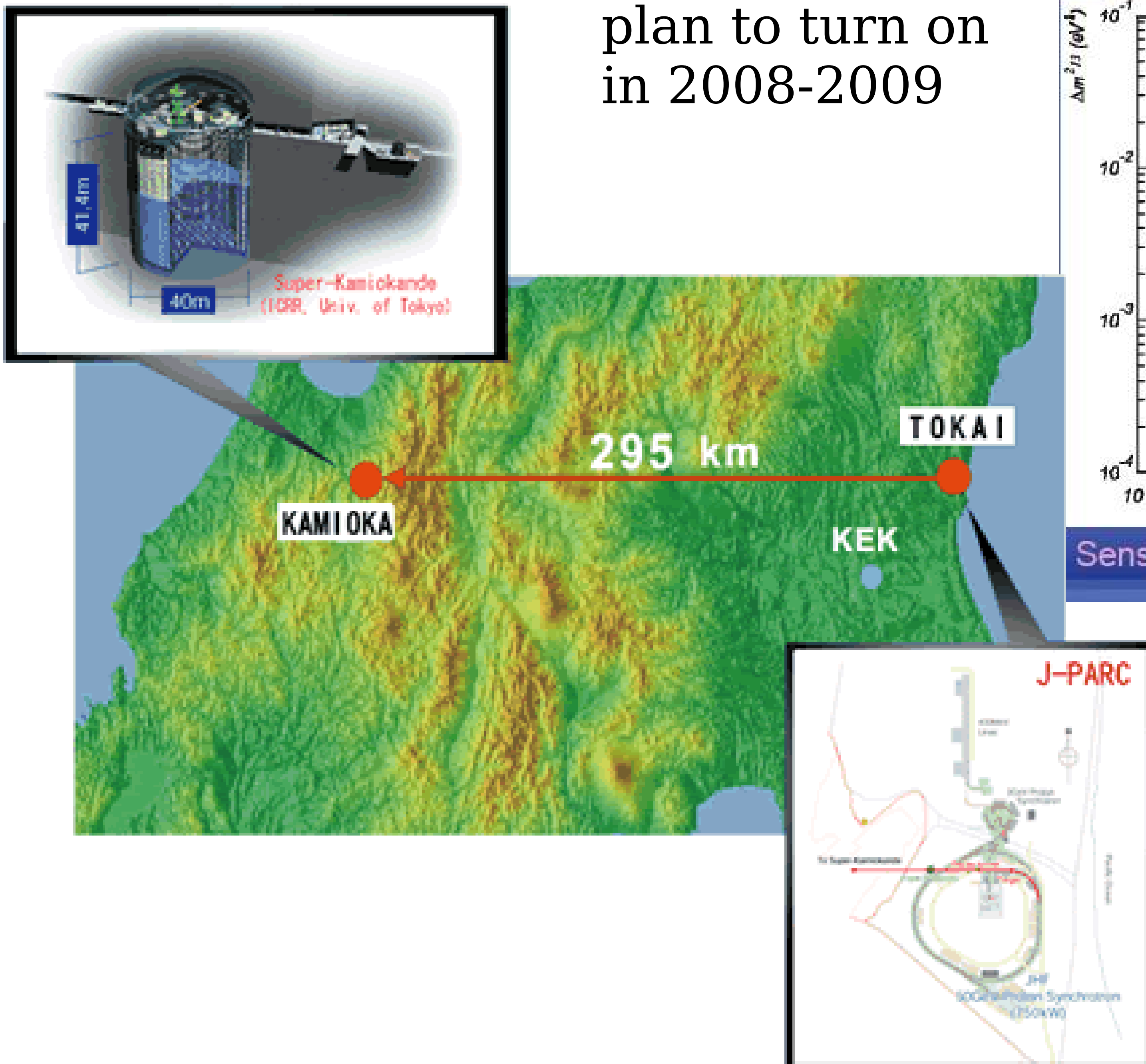
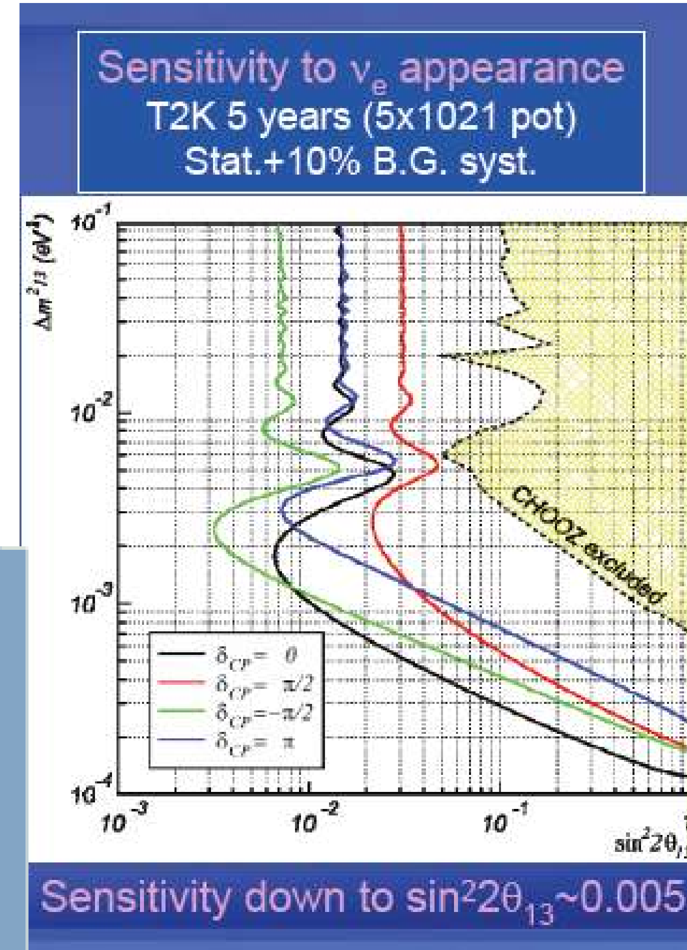
Measure θ_{13}, CP violation,
and mass hierarchy (with enough matter)

T2K: Tokai to Kamioka
ν_e appearance over 295 km

plan to turn on in 2008-2009

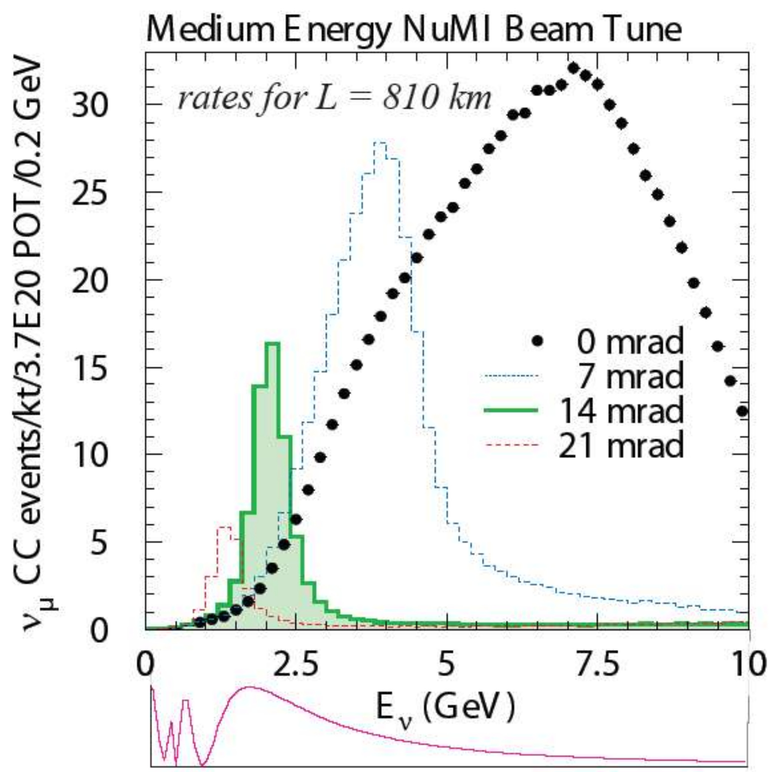


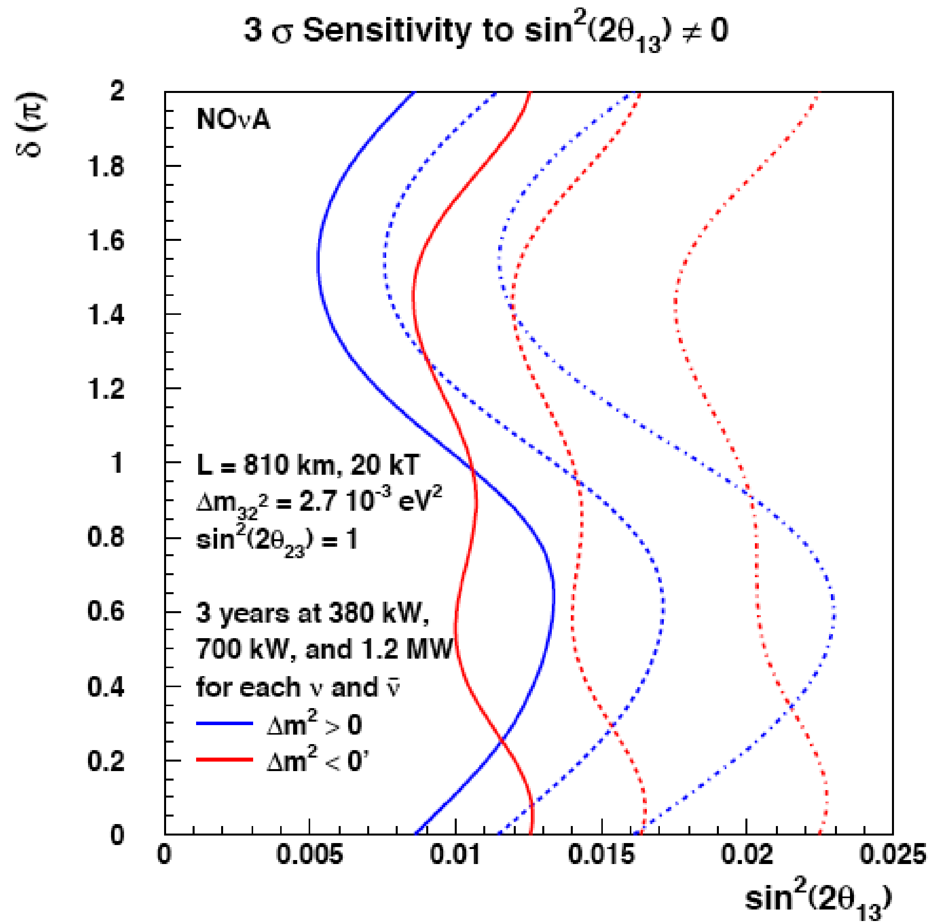


Sensitivity down to $\sin^2 2\theta_{13} \sim 0.005$ (if nature is kind)

no matter effects

NOvA -> Fermilab's NuMI beam: off axis over ~810 km baseline from FNAL to Ash River, MN

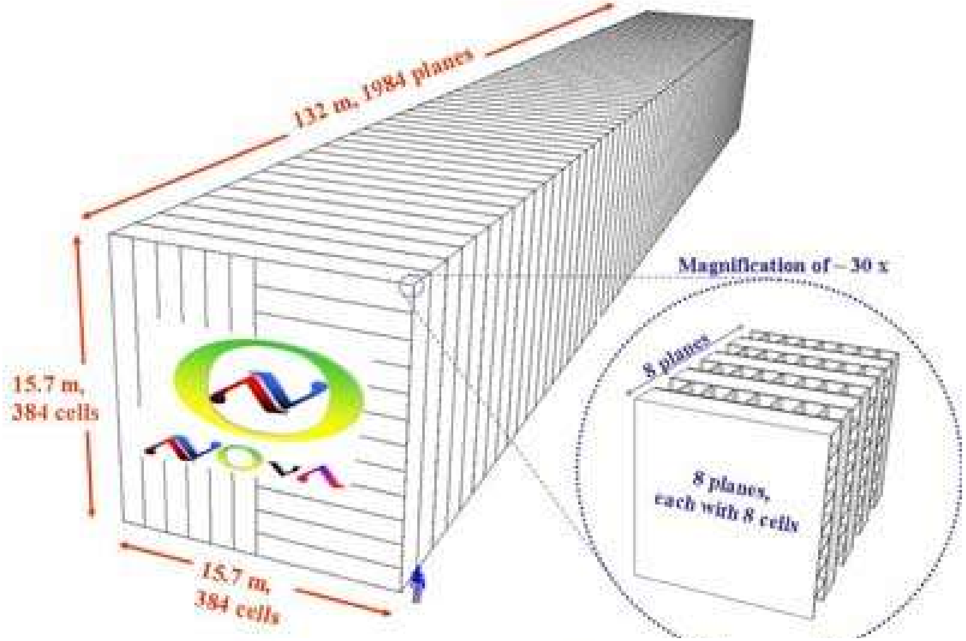




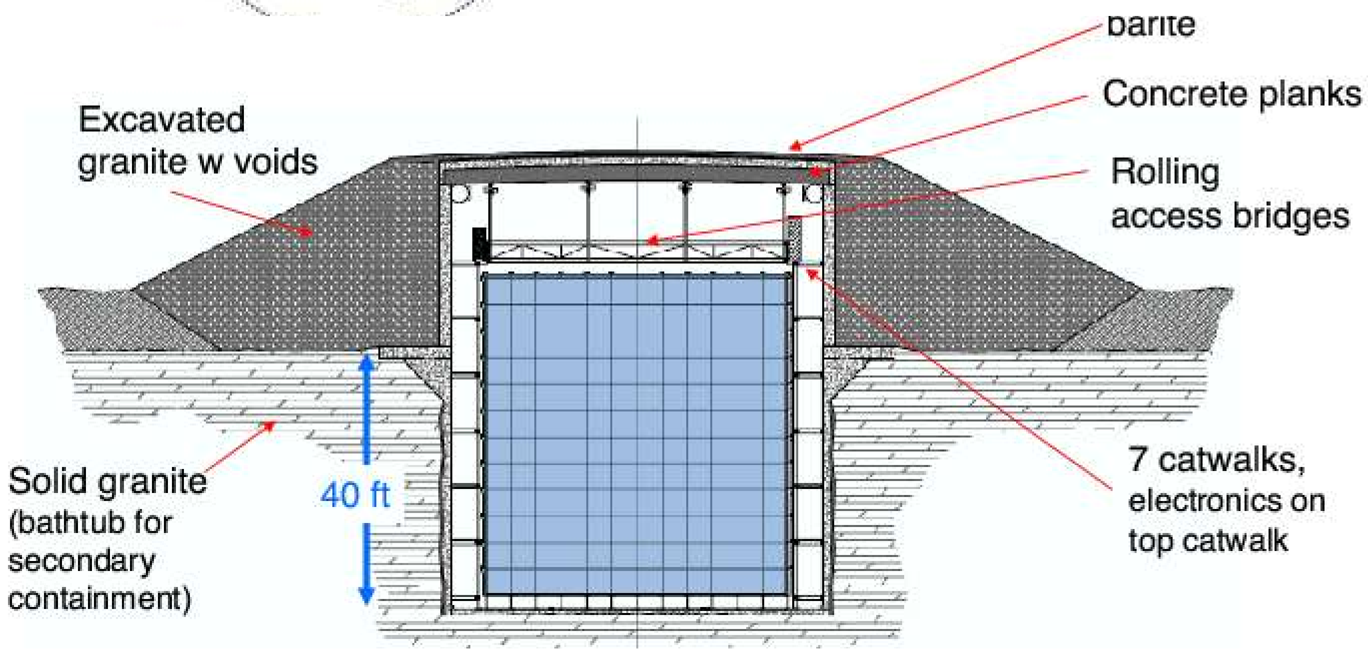
$\sin^2 2\theta_{13}$
mass hierarchy...

→ sensitivity down to ~0.005
(if nature is kind)

NOvA → ν_e appearance in liquid scintillator detector



- alternating xy cells of liquid scintillator
- cells: 15.7m x 3.87cm x 6.0 cm
- 0.8mm looped WLS fiber in each cell for light collection
- WLS fibers read-out by APDs
- 80% active material



Searches for $\sin^2 2\theta_{13}$ at reactors and long baseline (LB) experiments. LB measurements also have potential for CP violation searchs and mass hierarchy (NOvA)

↓

If we see something at these experiments
(if nature is kind...):
Want to pursue next generation LB measurements
to look for CP Violation!

If we don't -- want to pursue next generation
LB measurements to push on $\sin^2 2\theta_{13}$

Next generation LB measurements in the planning stages in US, Europe, Japan

look for CP Violation in neutrino sector!

In the US:

- FNAL/BNL Long Baseline Study almost complete
- DOE's NuSAG committee's charge -> next generation LB experiments
- FNAL re-evaluating near/far term program in context of timescales for ILC and neutrino program (Lab Steering Committee)
- International Scoping Study via NuFACT

In Europe and Japan:

- T2KK as next generation T2K
- Ideas to upgrade CNGS beam
  - MODULAr
  - Cern to Frejus

New prospects and new ideas to push towards CP Violation in n sector!

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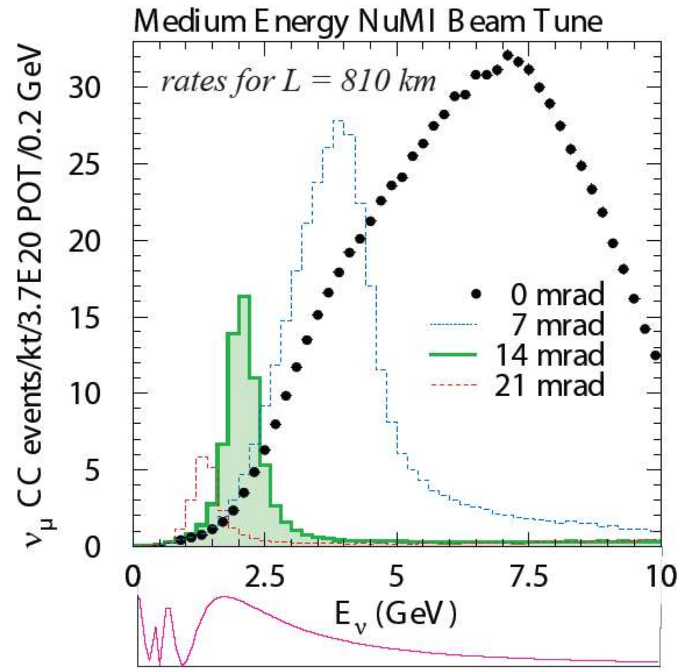
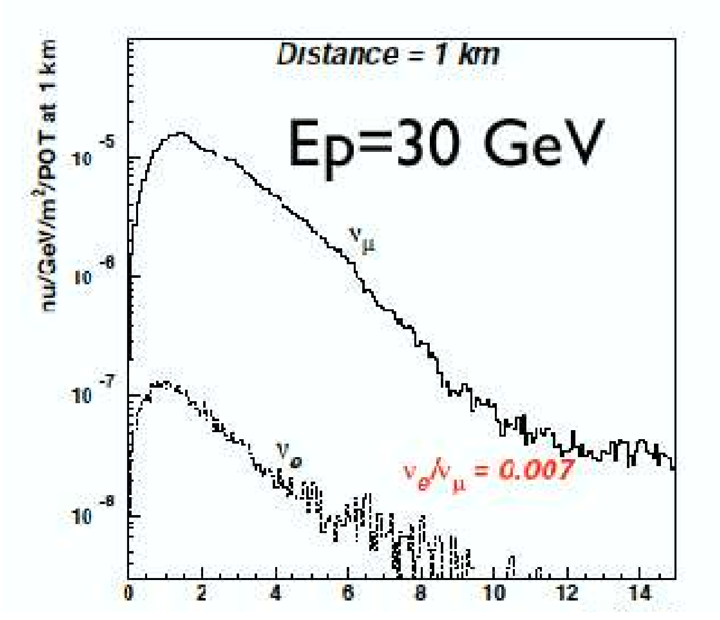
FNAL/BNL Long Baseline Study:
Two approaches to $\nu_\mu \rightarrow \nu_e$ long baseline searches

Off axis beams:
NOvA and T2K

Beyond NOvA (NuMI Off-Axis)
T2KK

primarily counting experments
-narrow band beams, surface det.

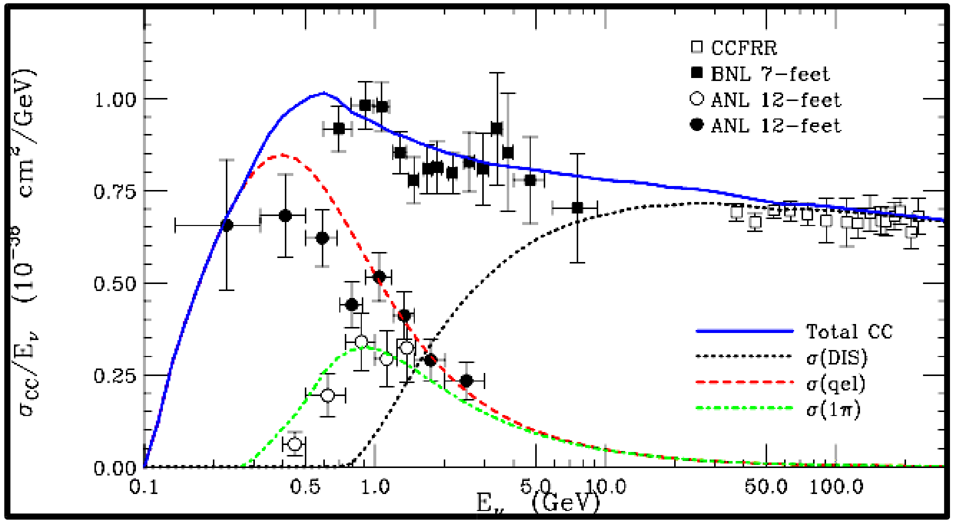




Wide Band, on axis beams:
Look for shape change in
wide band spectra:
Fermilab to DUSEL

Both span the 0.5-5GeV neutrino energy range

For both: need ***intense*** beams, and excellent detectors…..

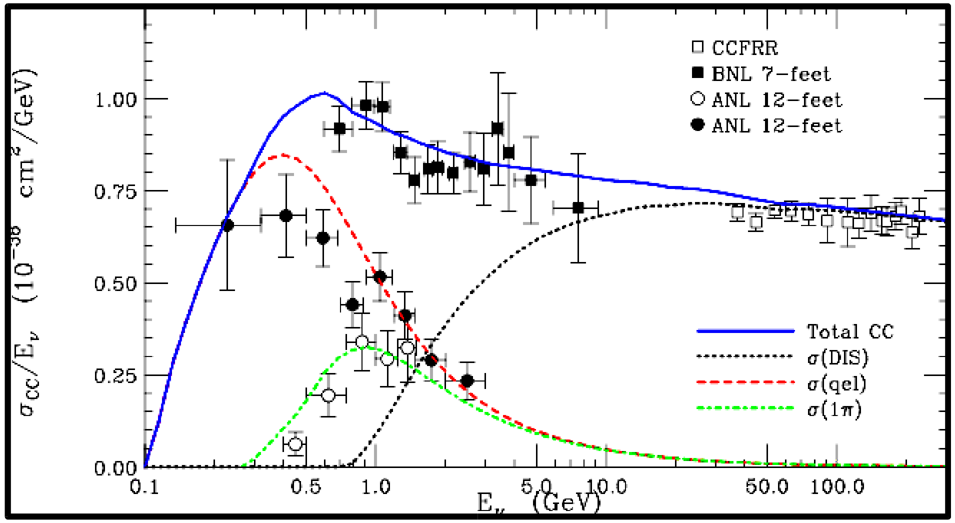


Detector requirements:

- maximize ν_e efficiency
- minimize backgrounds from misIDs
  primarily NC π° interactions

- Water Cerenkov
- Liquid Scintillator
- Liquid Argon TPCs

For both: need ***intense*** beams, and excellent detectors…..



Detector requirements:

- maximize ν_e efficiency
- minimize backgrounds from misIDs
  primarily NC π° interactions

- Water Cerenkov
- Liquid Scintillator
- Liquid Argon TPCs

- *known technology:*
  - *construction and operation*
  - *reconstruction and systematics*
- *must be sited deep underground*
  (for DUSEL program only)

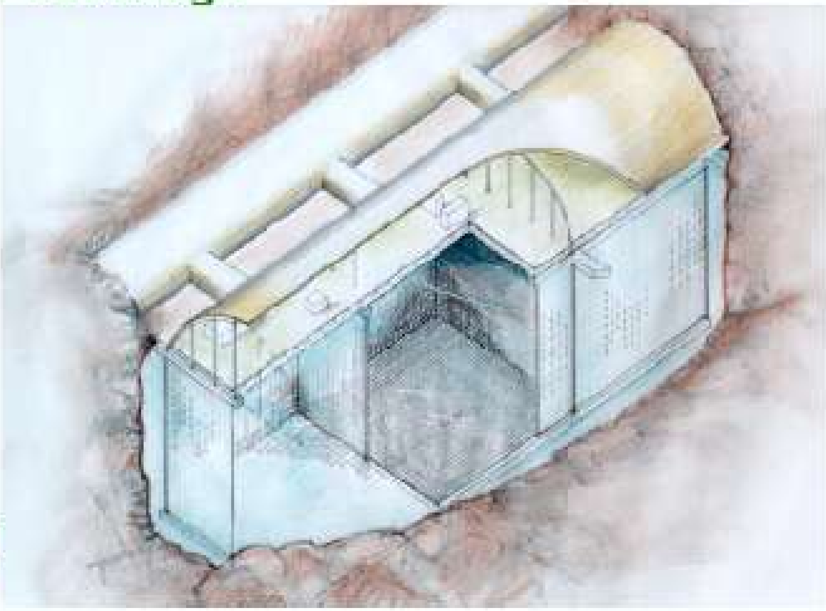
For example:

Detector at Henderson

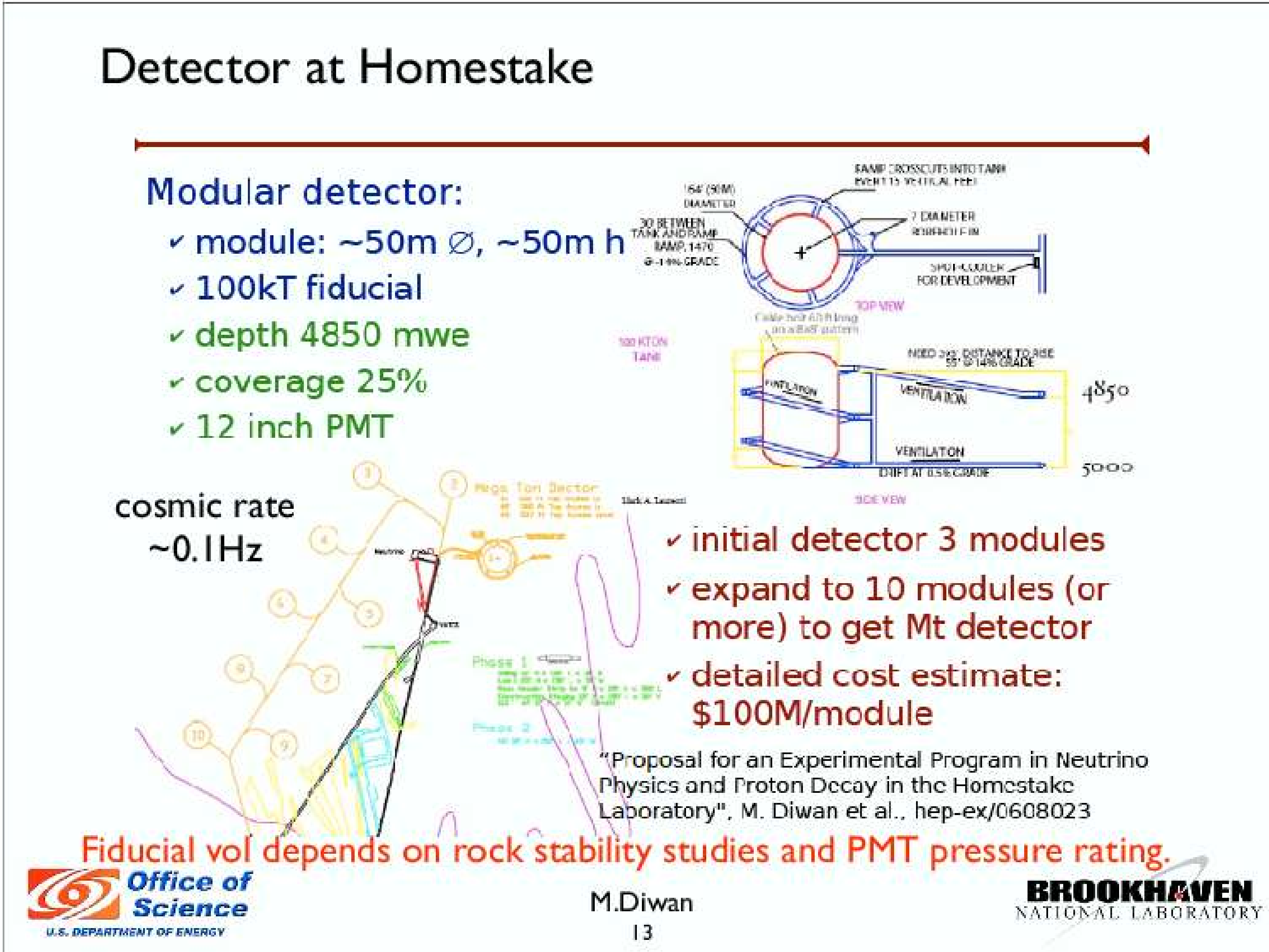
BROOKHAVEN

UNO detector:

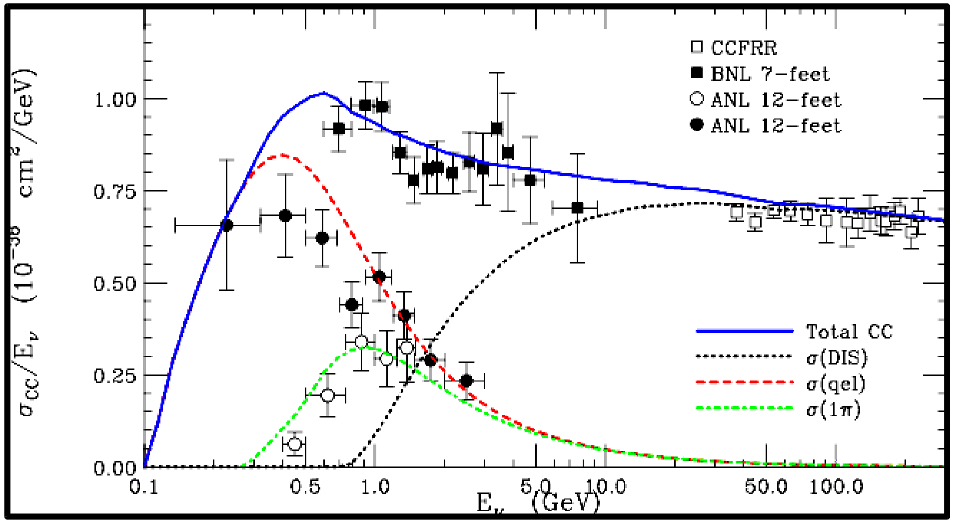
- 1 large cavern
- 3 optically separated modules of 60x60x60 m^3
- total mass 440 kT fiducial
- central module 40% PMT coverage (low E physics)
- outer modules 10% PMT coverage
- optional finer granularity: 20 or 13 inch tubes
- optimal depth 5400mwe (2500 feet)
- construction time: 10 years
- coarse cost estimate scaling Super-K: $500M



Modular option:



For both: need ***intense*** beams, and excellent detectors.....



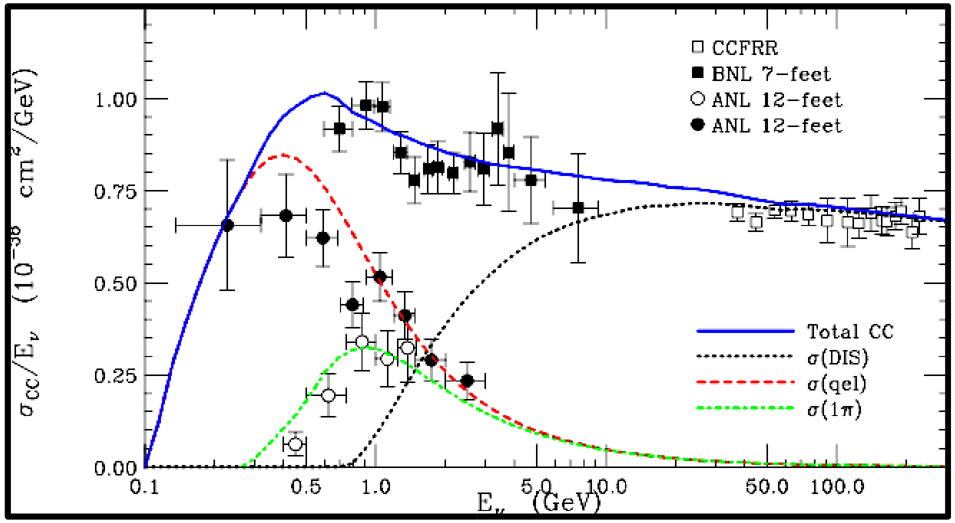
Detector requirements:

- maximize ν_e efficiency
- minimize backgrounds from misIDs
  primarily NC π° interactions

- Water Cerenkov
- Liquid Scintillator
- Liquid Argon TPCs

Scaling up NOνA like detector -> difficult at best…

For both: need ***intense*** beams, and excellent detectors.....



Detector requirements:

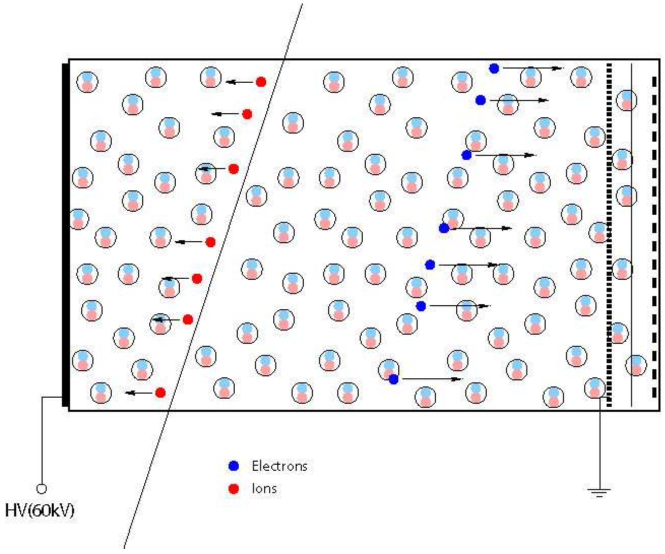
- maximize ν_e efficiency
- minimize backgrounds from misIDs
  primarily NC π° interactions

- Water Cerenkov
- Liquid Scintillator
- Liquid Argon TPCs

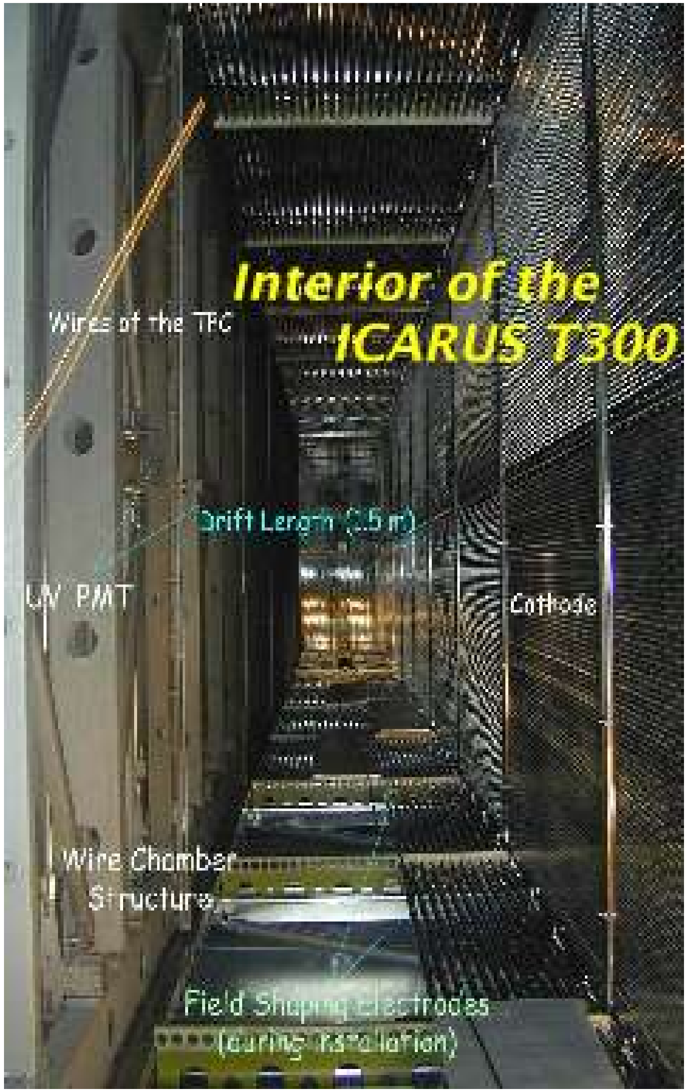
- *great ν_e efficiency : 80-90%*
- *neutral current π° rejection: <0.5%*
- *site detector at or near surface (DUSEL or NuMI program)*
- *have not been built on large scales (largest yet is ICARUS T600 (600 tons)*

Liquid Argon TPCs:

passing charged particles produce
55,000 electrons/cm



Drift ionization electrons over meters of pure liquid argon to collection planes to image track
3-5mm sampling



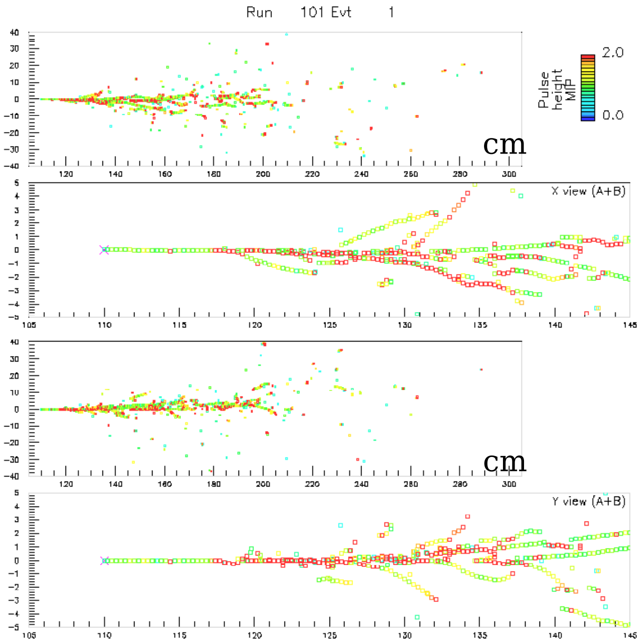
- need very pure Argon
- need good S/N for readout electronics

How does this translate into ν_e efficiency and π° rejection?

Dot indicates hit
color indicates collected charge
green=1 mip, red=2 mips

X plane → zoom in

Y plane → zoom in

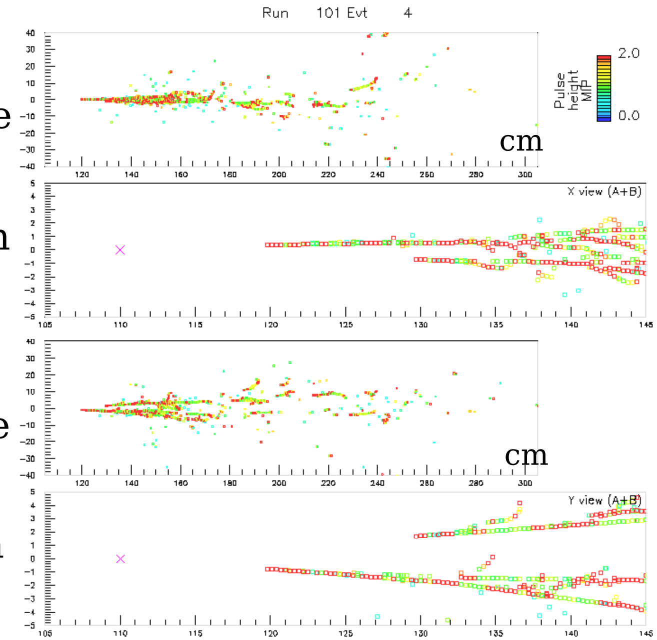


Electrons

Single track (mip scale) starting from a single vertex

X plane → zoom in

Y plane → zoom in



π^0

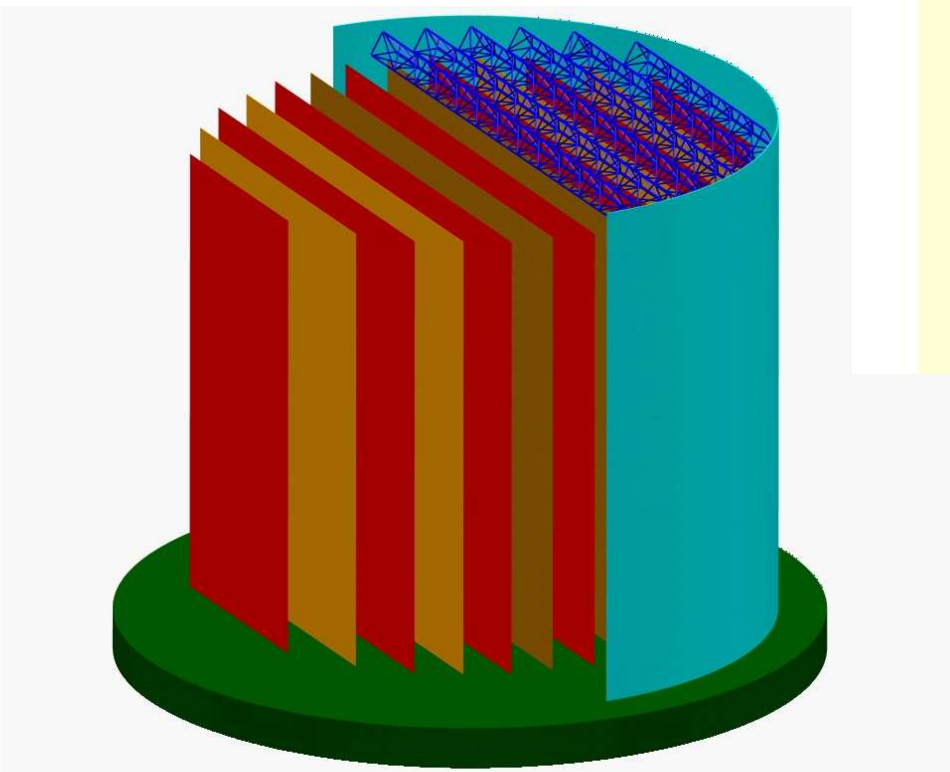
Multiple secondary tracks can be traced back to the same primary vertex

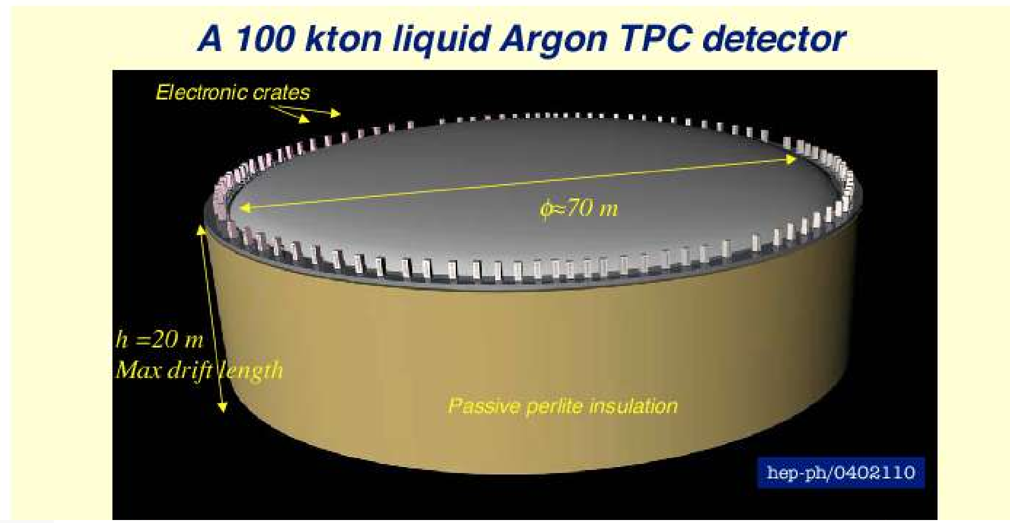
Each track is two electrons – 2 mip scale per hit

Use both topology and dE/dx to identify interactions

Several design ideas in moving beyond the ICARUS T600 to very massive detectors

LArTPC: Modularized drift regions in one large (10-50kton) tank

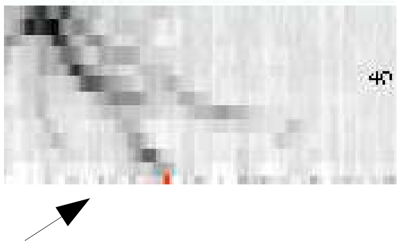




GLACIER: Combination of charge and light collection, single large drift area

LAANDD: modularized evacuated vessels

Great detectors! Challenge: can we build them on large scales?



Active R&D program in US:

- Understand Purity in large vessels
  - New filters tested at FNAL and Yale (first tracks seen in small LArTPC last month!)
  - Materials test stand at FNAL
  - Purity demonstration at FNAL under design
  - Argon purging tests to clean large tanks
- See tracks in NuMI neutrino beam (T962)
- Development of new electronics at MSU
- Problems due to long wires
  - new “Cellular design” from FNAL: ladders of wires to ease installation, avoid wire breakage problems, deal with reconstruction

How do we evaluate the sensitivity of these programs in terms of one “metric”?

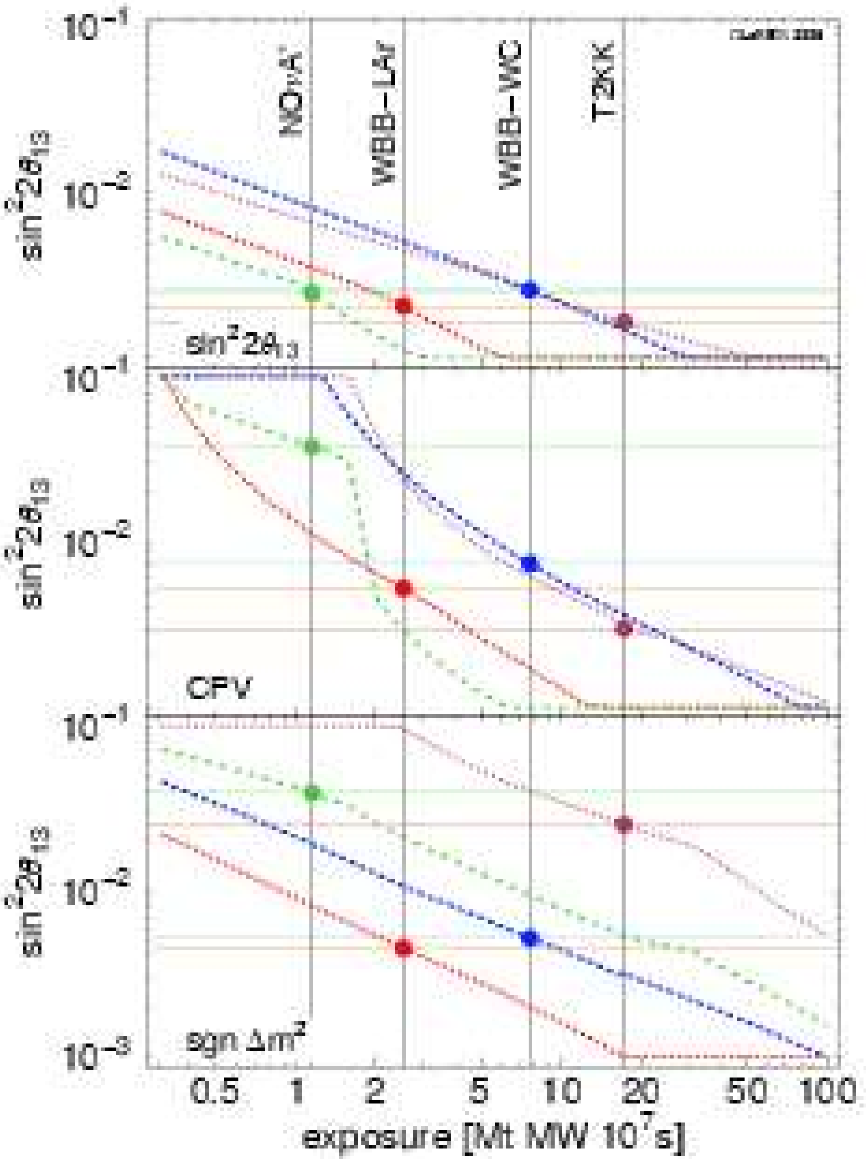
Example: Barger et al.
Exposure = Mt x MW x time

NuMI beam options (NOvA*) are best for θ_{13} and CP Violation for >2MW of beam

WBB is best for mass hierarchy

LAr is ~x4 more sensitive than Water Cerenkov

→ see D. Marfatia's talk Monday afternoon



Barger et al. hep-ph/0610301

“NOvA*” = 100kton LAr detector at 1st osc. max
“WBB” = Wide band beam from FNAL to DUSEL
T2KK = Beam from JPARC to Kamioka and Korea

Conclusions

New results from MiniBooNE with more on the way:

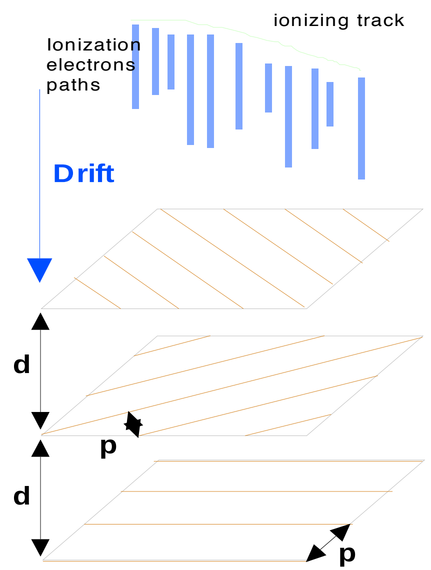
- understanding the low E discrepancy
- working on cross sections

Program to search for $\sin^2 2\theta_{13}$ at reactors and accelerators

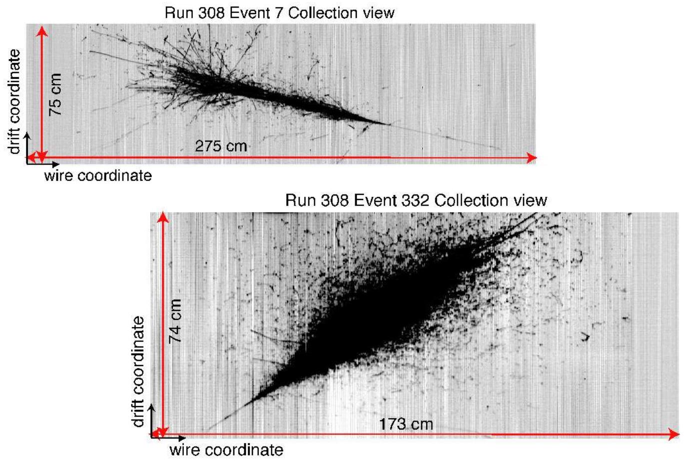
↓

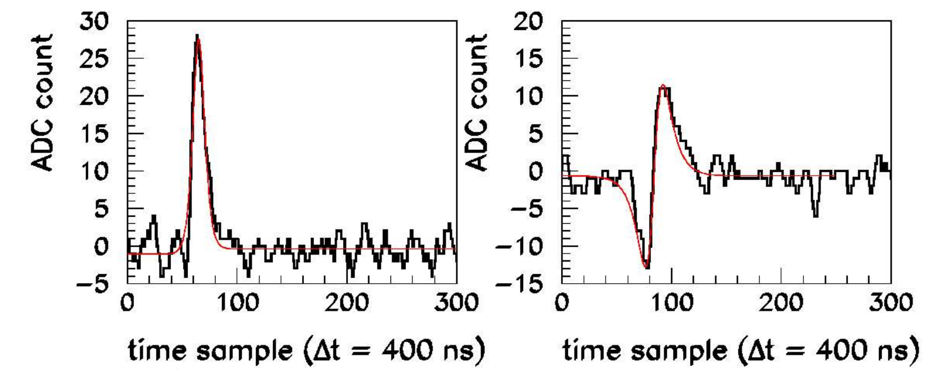
En route to next generation experiments to look for CP Violation in the neutrino sector!

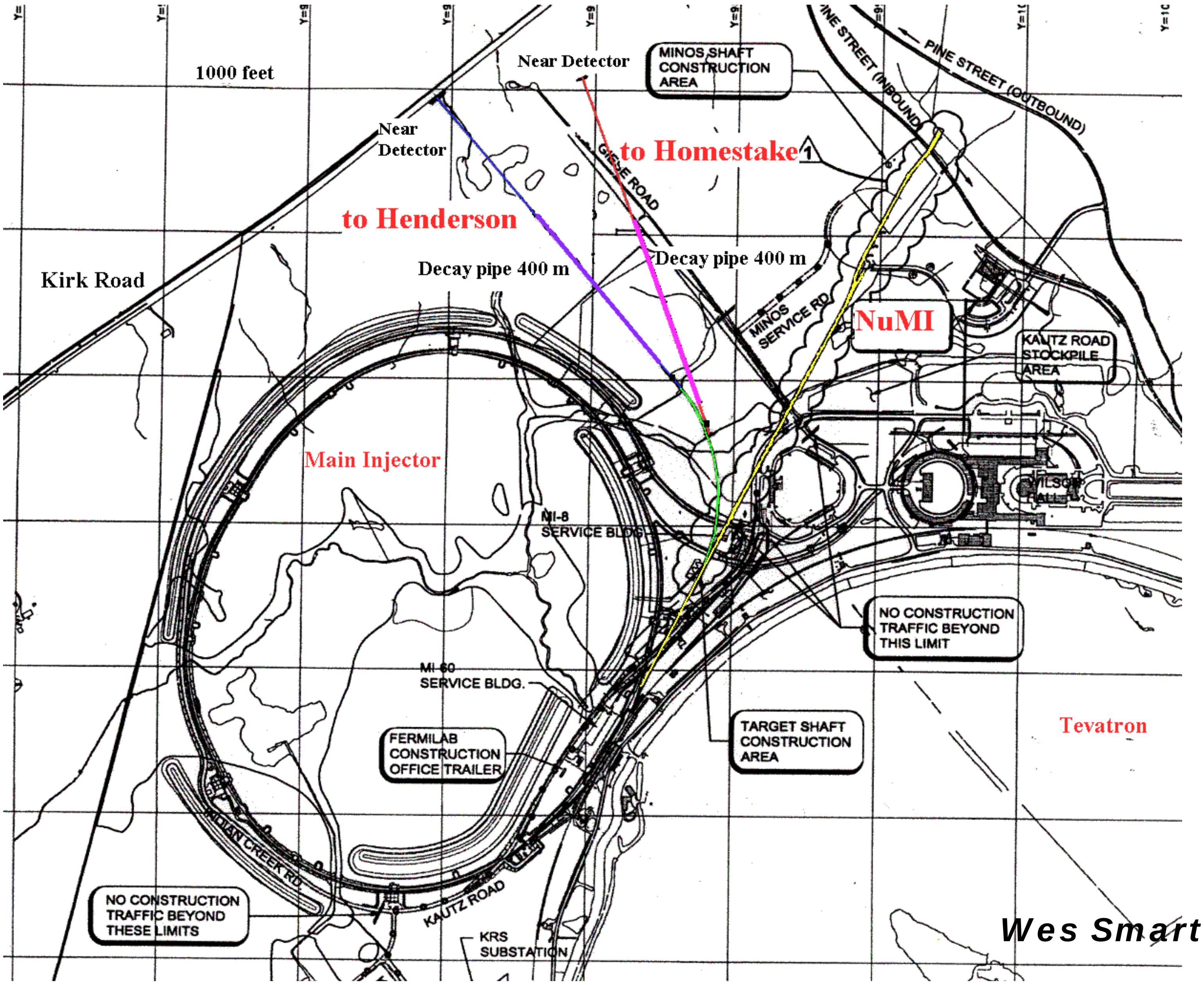
Signals on wire chamber planes



Arrange E fields and wire spacing for total transparency for induction planes. Final plane collects charge

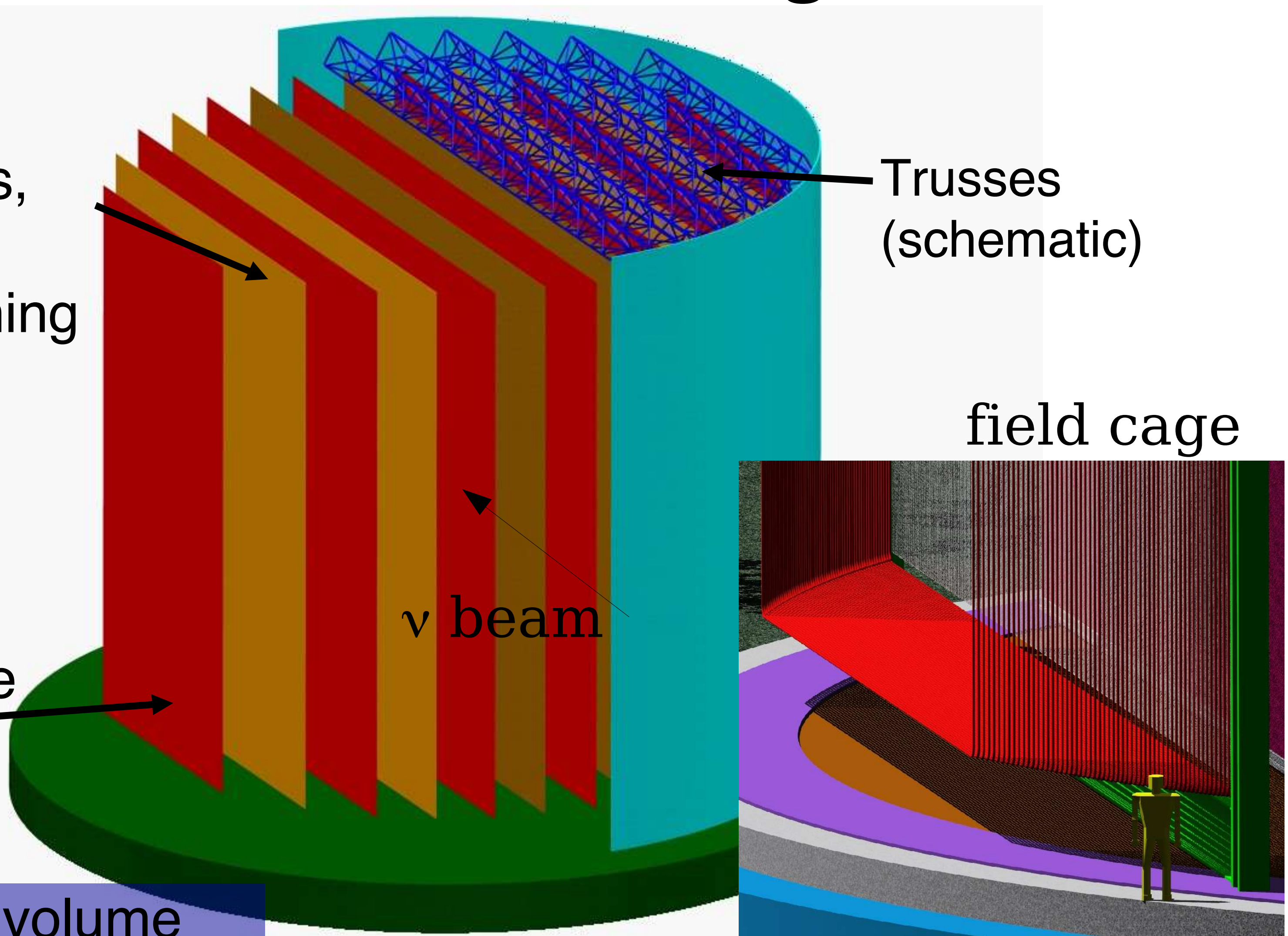






Fermilab beam possibilities: NuMI or new beam to a Deep Underground Science Lab (DUSEL) ie: Henderson or Homestake

LArTPC: Modularized drift regions inside tank



Active volume
Diameter: 40m
Height: 30m

Scalable → 15-50 kTons
4 - 6 wire planes