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Probing Neutrino Masses and Mixings with Accelerator and Reactor Neutrinos

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Outline

- Introduction to Neutrino Mass and Mixing
- Neutrino Oscillations among ν_e, ν_μ, and ν_τ
  - Physics Opportunities with large θ_{13}
  - Plans and Prospects for Measuring Hierarchy and CP Violation
- Possible Oscillations to Sterile Neutrinos
  - Current Hints and Anomalies
  - Ideas for Future Searches
- Final Comments

Absolute Neutrino Mass Determinations

Tritium β decay	$m_{\nu_e} = \left(\sum_i \lvert U_{ei} \rvert^2 m_i^2 \right)^{1/2}$ → $[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$
Neutrinoless double beta decay	$m_{ee} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$ → $\lvert c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \rvert$
Cosmology	$\sim \sum_i m_i$

Current limit (Mainz):
$m_\nu < 2.2$ eV @ 95% CL
KATRIN Sensitivity:
$m_\nu < 0.2$ eV @ 90% CL

If detect 0ν2β decay
⇒ Neutrinos are Majoranna particles
and information on m_ν at 0.1eV scale

Limits sum of neutrino masses:
$\Sigma m\nu < \sim 0.7\,eV$

To Probe Smaller Masses ⇒ Neutrino Oscillations

The observation of neutrino oscillations where one type of neutrino can change (oscillate) into another type implies:

1. Neutrinos have mass

and

2. Lepton number (electron, muon, tau) is not conserved ($\nu_e \to \nu_\mu$, $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\tau$)

- The phenomena comes about because the mass and flavor states are different as parameterized by a mixing matrix

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

where $\theta =$ mixing angle; $\Delta m^2 = m_b^2 - m_a^2$;

$L =$ travel distance; $E =$ neutrino energy

- 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
  - ***Disappearance Experiment:***
    Look for a change in $\nu_{e/\mu}$ flux as a function of L and E

Oscillations Parameterized by 3x3 Unitary Mixing Matrix

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

$$\begin{pmatrix} Flavor \\ Eigenstate \end{pmatrix} = (Mixing\ Matrix) \begin{pmatrix} Mass \\ Eigenstate \end{pmatrix}$$

Three mass splittings: $\Delta m^2_{12} = m^2_1 - m^2_2$, $\Delta m^2_{23} = m^2_2 - m^2_3$, $\Delta m^2_{31} = m^2_3 - m^2_1$

But only two are independent since only three masses

If $\delta \neq 0$, then have CP violation $\Rightarrow P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

Current Measurements: $\Delta m^2_{12} = 8 \times 10^{-5}\ \text{eV}^2$ (solar) , $\Delta m^2_{13} \approx \Delta m^2_{23} = 2.5 \times 10^{-3}\ \text{eV}^2$ (atmospheric)

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

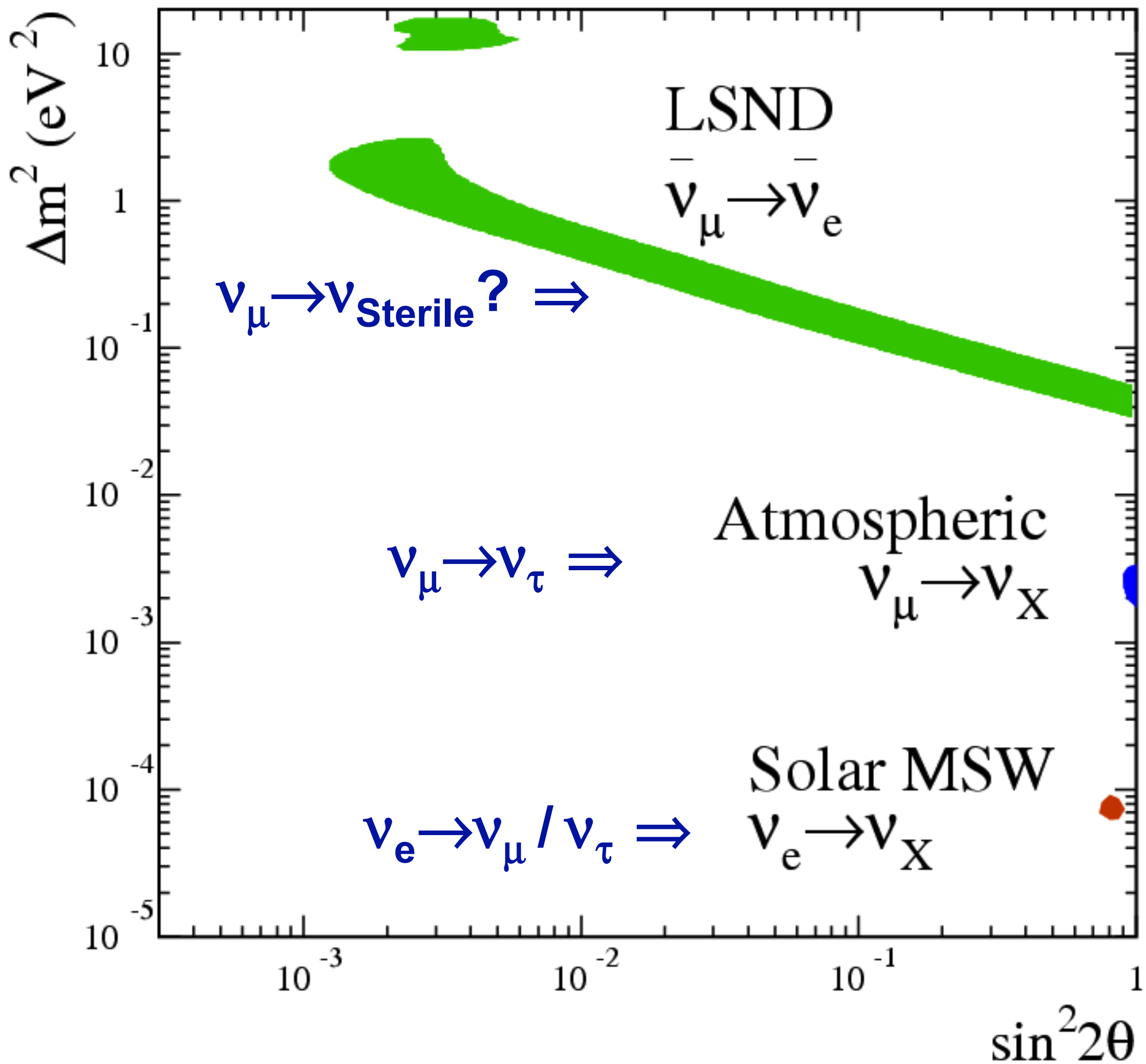
3-mixing angles

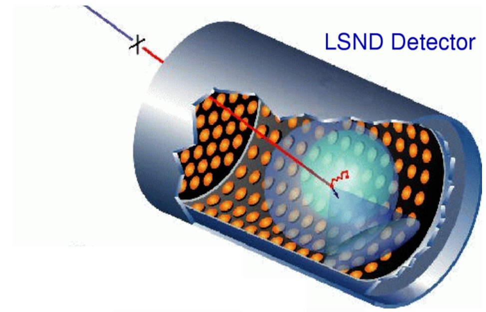
Solar: $\theta_{12} \sim 33°$

$\theta_{13} = 9°$ but $\delta = ??$

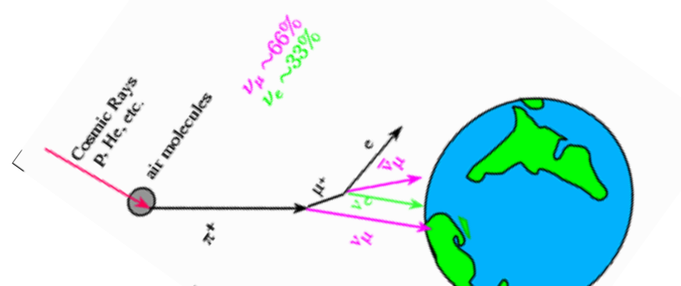
Atmospheric: $\theta_{23} \sim 45°$

Oscillation Summary

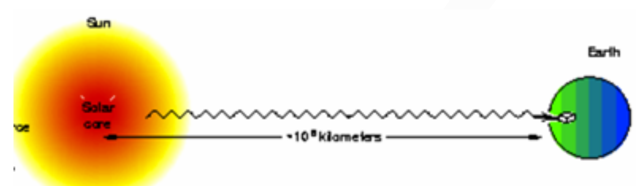




Also, MiniBooNE ν_μ / $\bar{\nu}_\mu$



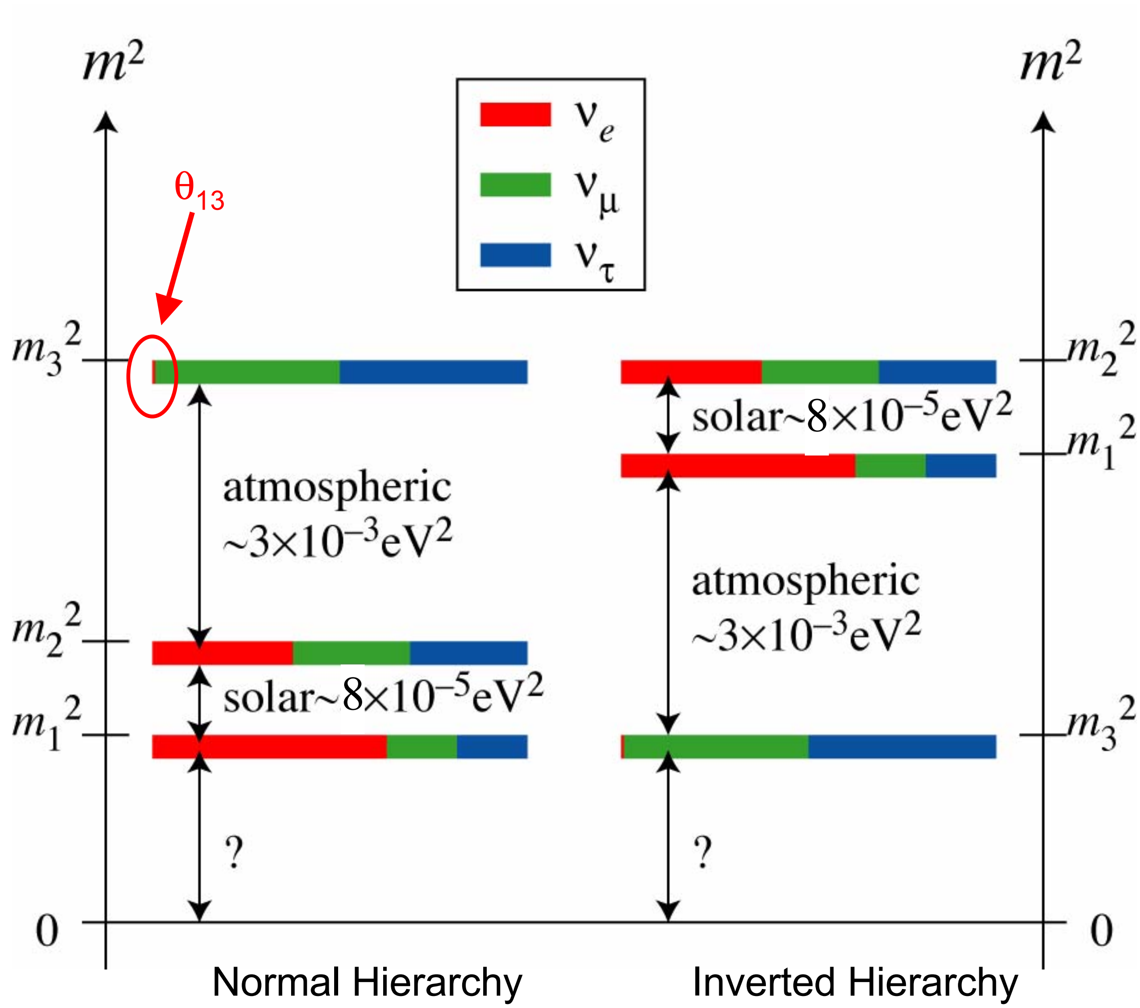
Confirmed by K2K and enhanced by MINOS accelerator exps



Confirmed and enhanced by Kamland reactor neutrino exp

Big Questions in (3x3) Neutrino Mixing

1. What is ν_e component in the ν_3 mass eigenstate? $\Rightarrow$ The size of the "little mixing angle", θ_{13}
   – Now known $\Rightarrow$ θ_{13} = ~9^0
2. What is the mass hierarchy?
   – Is the solar pair the least massive or not?
3. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?
   – If observe CP violation, then gives hints that Leptogenesis models may be used to explain matter-antimatter asymmetry in the universe



Current Neutrino Oscillation Program

Types of Oscillation Experiments

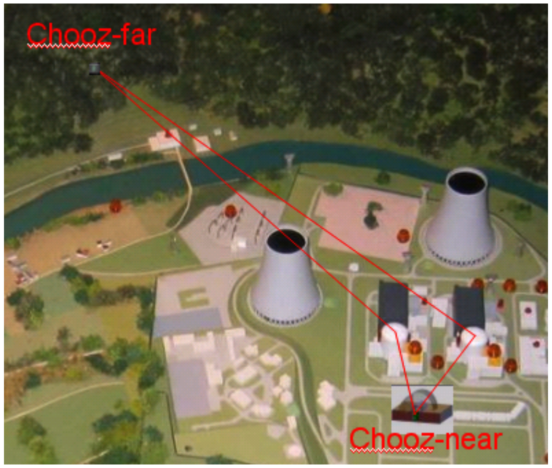
- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV^2
  - Look for appearance of ν_e in a pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

MINOS:
$\langle E_\nu \rangle = 3.0$ GeV
$L = 735$ km
NOνA:
$\langle E_\nu \rangle = 2.3$ GeV
$L = 810$ km

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
$L = 295$ km

- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) at $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV^2
  - Look for a change in $\bar{\nu}_e$ flux as a function of L and E
    - Look for a non- $1/r^2$ behavior of the ν_e rate
    - Use near detector to measure the un-oscillated flux

Double Chooz, RENO, Daya Bay:
$\langle E_\nu \rangle = 3.5$ MeV
$L = \sim 1100$ m



Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent on θ_{13} plus also:

1. CP violation parameter (δ)
2. Mass hierarchy (sign of Δm_{31}^2) "Matter Effects"
3. Size of $\sin^2\theta_{23}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \ (1 - 2S_{13}^2)
\end{aligned}
$$

⇒ ***These extra dependencies are both a "curse" and a "blessing"***

Reactor Disappearance Experiments

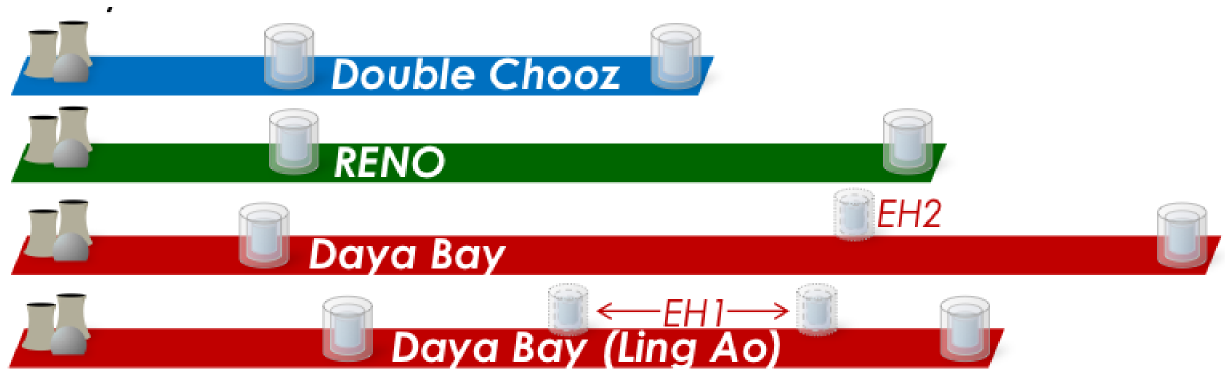
- Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

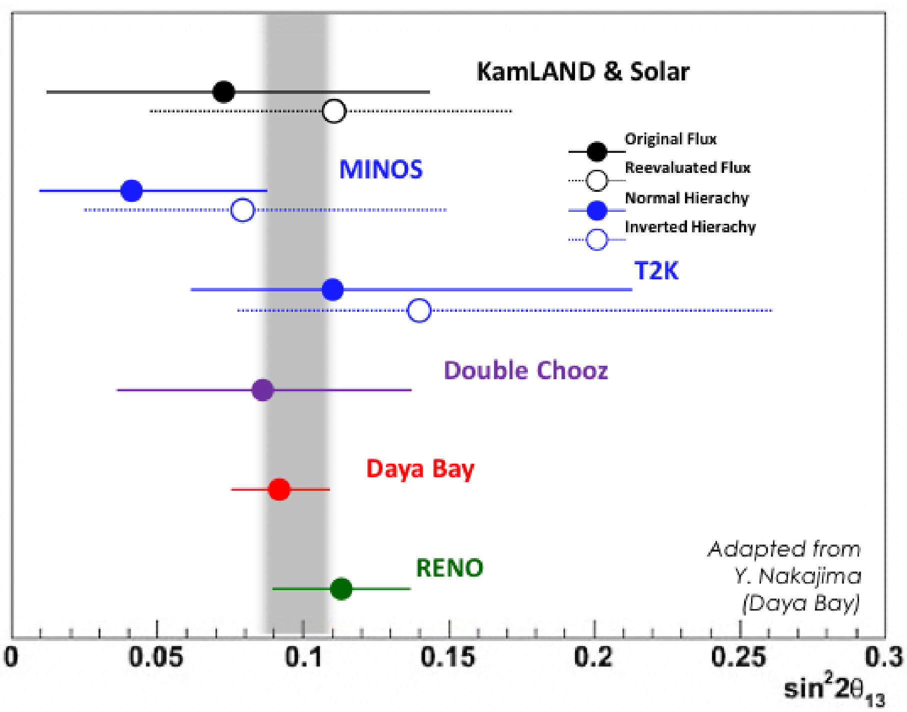
$$
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + \ small\ terms
$$

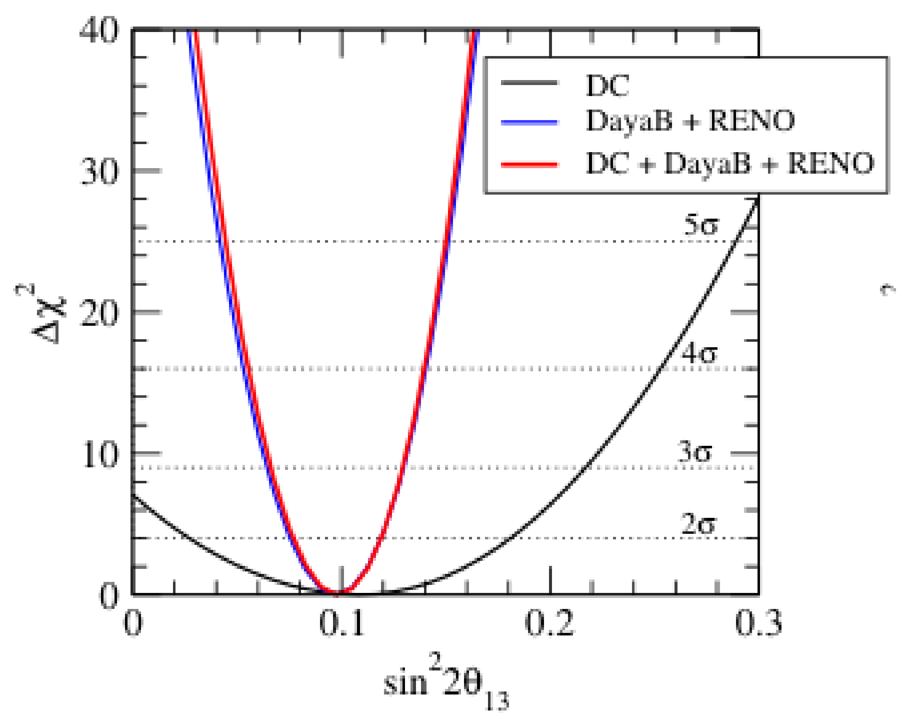
Reactor Neutrino Experiments

Recent Reactor θ_{13} Measurements

In under a year, θ_{13} has gone from unknown to well measured

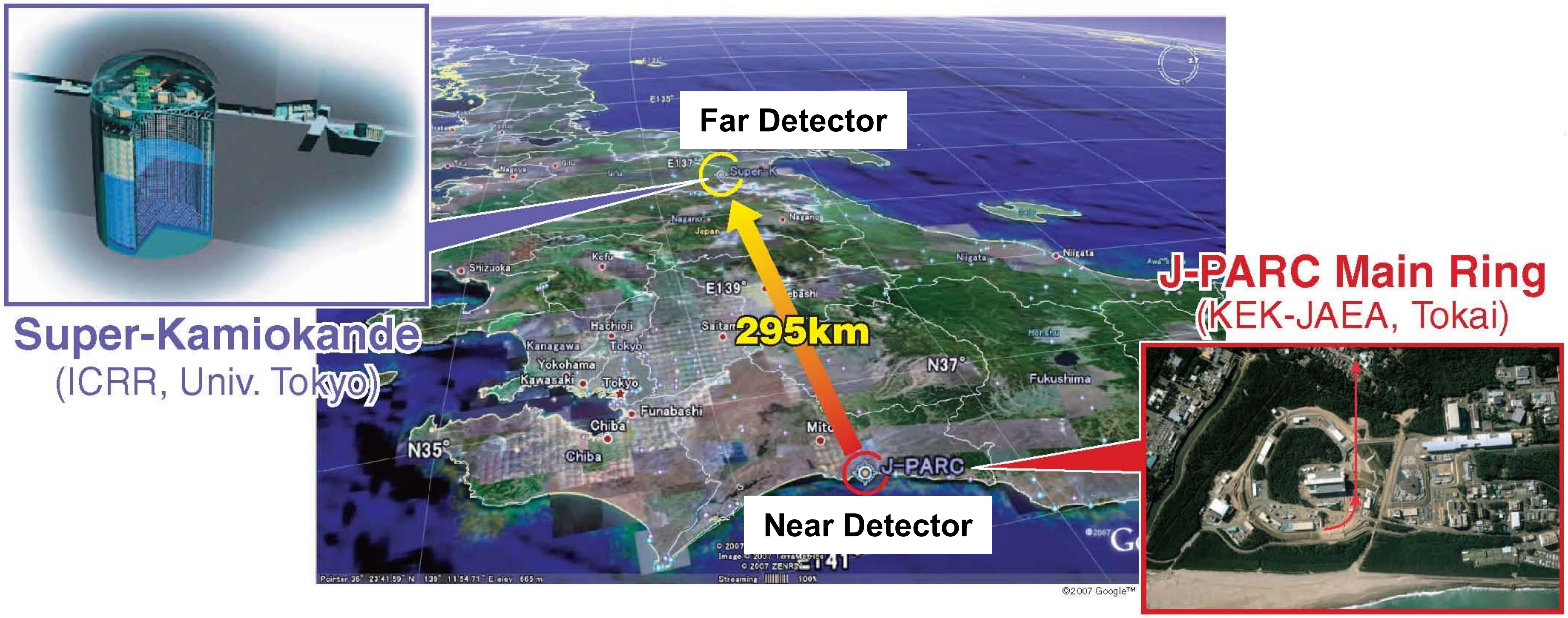






Long-baseline ν_e Appearance Program

T2K $\nu_\mu \rightarrow \nu_e$ Oscillation Experiment



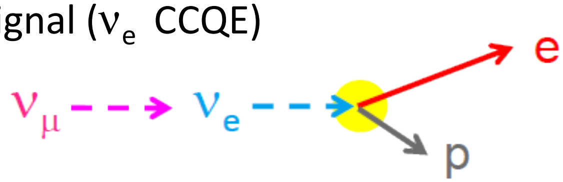
Analysis by May 15th, 2012
2.56×10^{20} POT (Protons On Target)

- RUN-1 (2010): 0.32×10^{20} POT
- RUN-2 (2010-2011): 1.11×10^{20} POT
- RUN-3 (2012): 1.12×10^{20} POT

1st Indication that θ_{13} large in May 2011 !

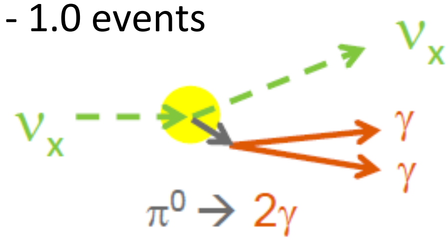
Observe 10 candidate events with 2.7 ± 0.4 event expected background ⇒ 3.2 σ signal

Signal (ν_e CCQE)



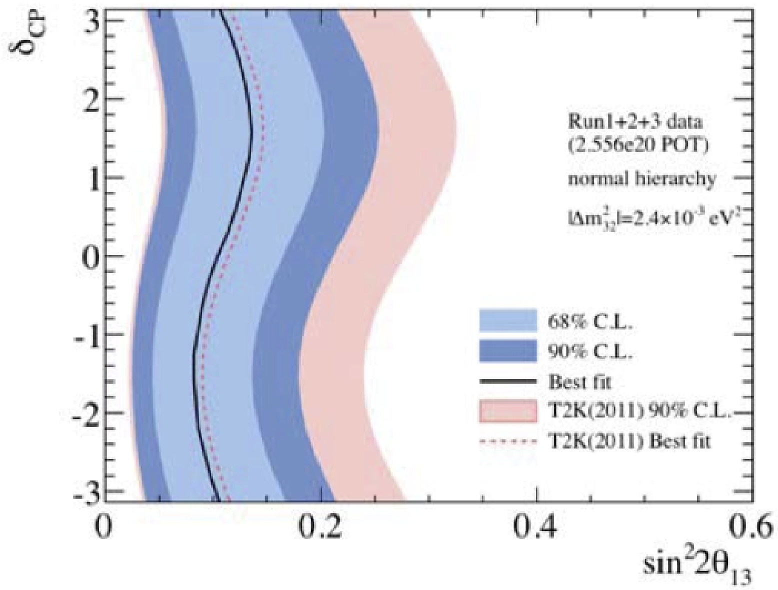
(Also intrinsic ν_e in beam - 1.3 events)

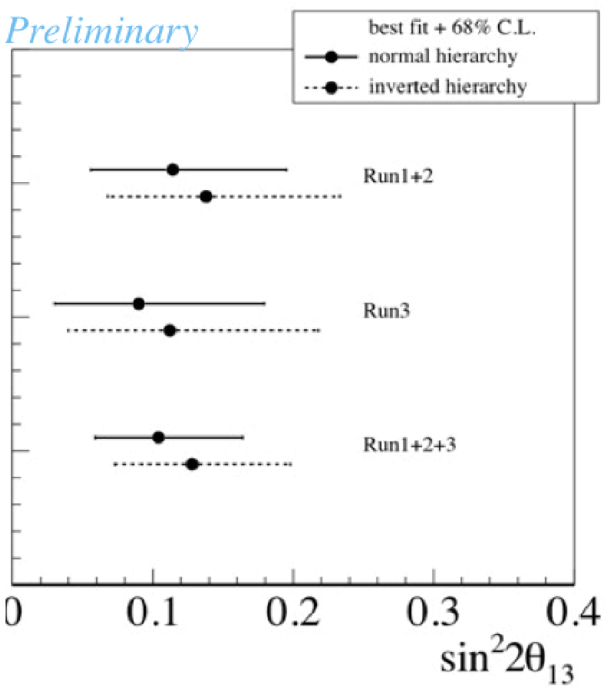
BG (NC π^0) - 1.0 events



Preliminary

New T2K Results for $\sin^2 2\theta_{13}$





Best Fit values for Δm^2_{23}=2.4 x 10^{-3} eV^2, δ_{CP}=0

$\sin^2 2\theta_{13} = 0.104 \pm 0.055$

(normal hierarchy)

$\sin^2 2\theta_{13} = 0.128 \pm 0.065$

(inverted hierarchy)

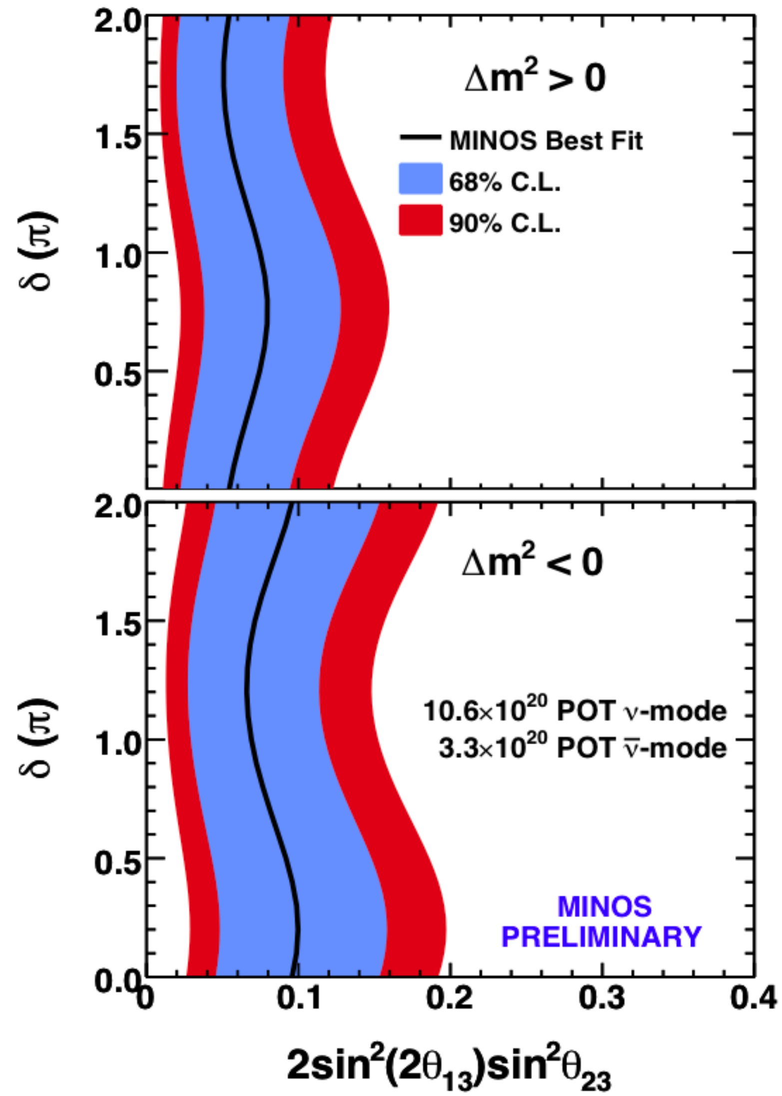
T2K now fully back after earthquake
and proton intensity expected to increase

2.56×10^{20} (2012)
$\rightarrow$ ~8×10^{20} (2013)
$\rightarrow$ ~1.2×10^{21} (2014)
$\rightarrow$ ~1.8×10^{21} (2015)
(x7 increase over 3yrs)

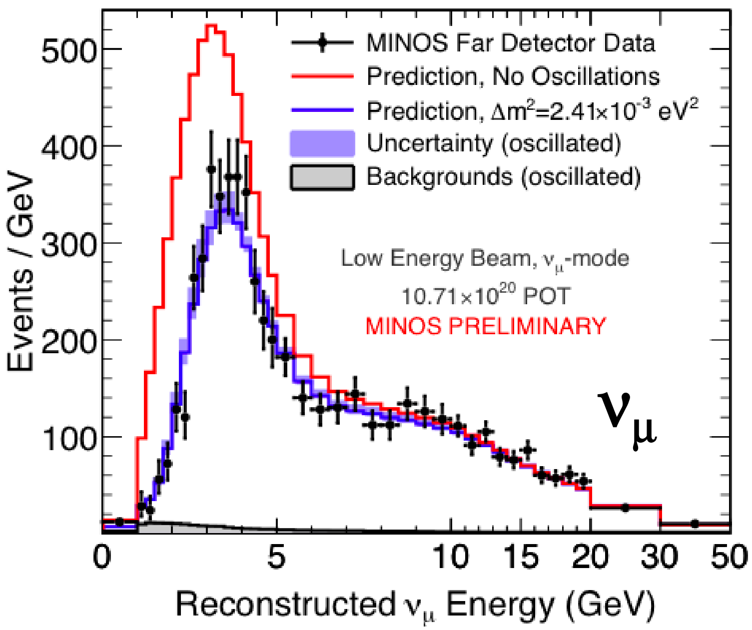
MINOS: $\nu_\mu \rightarrow \nu_e$ Appearance

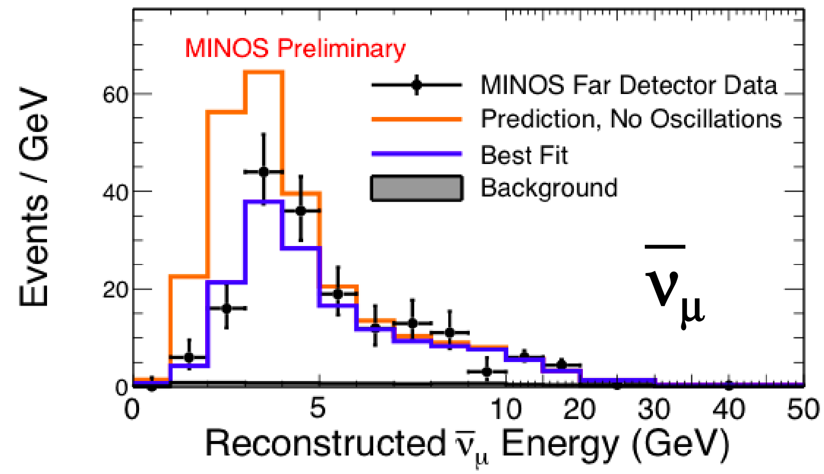
- Neutrino mode
  - Expect: 128.6 events
    (+32.5 signal events @ $\sin^2 2\theta_{13}=0.1$)
  - Observe: 152 events

Disfavour $\theta_{13}=0$ at 96% C.L.



MINOS: ν_μ / $\bar{\nu}_\mu$ Disappearance $\Rightarrow \Delta m^2_{23}$ and $\sin^2 2\theta_{23}$





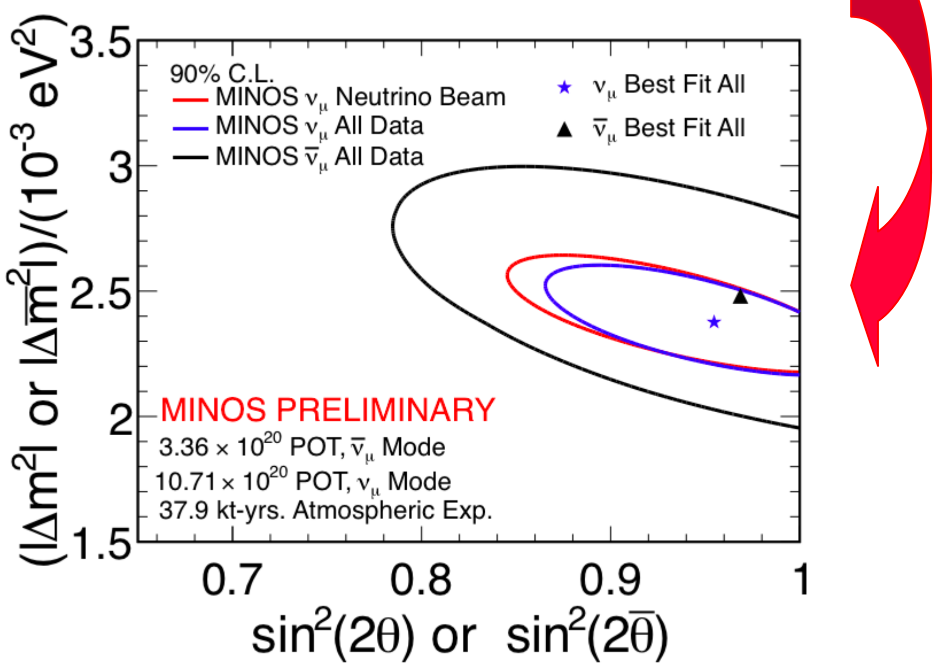
New data has resolved the tension between the neutrino and the old antineutrino results

New MINOS neutrino oscillation parameters:

$$\Delta m^2_{23} = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

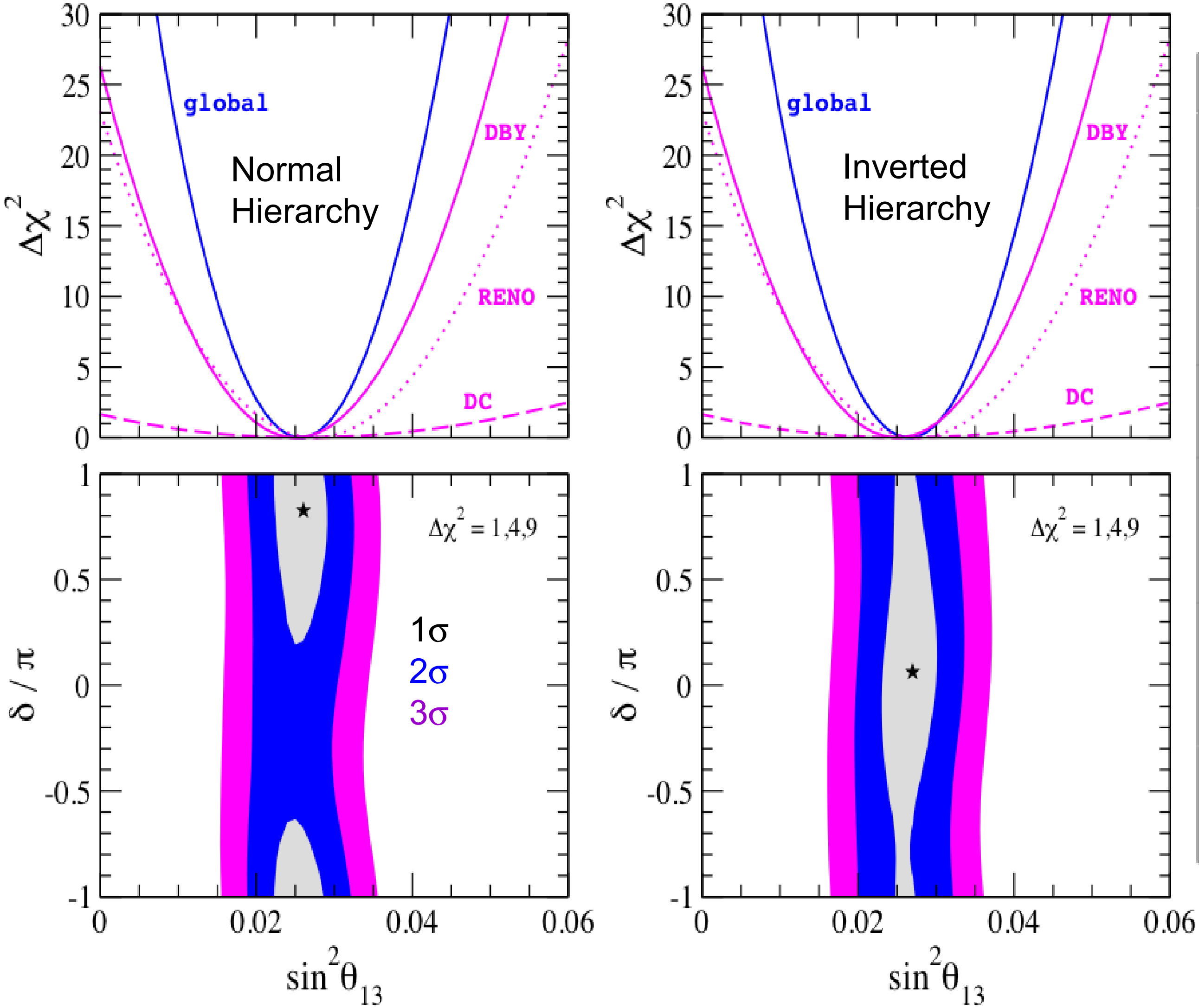
$$\sin^2(2\theta_{23}) = 0.96^{+0.04}_{-0.04}$$

$$\sin^2(2\theta_{23}) > 0.90 \text{ at } 90\% \text{ C.L.}$$



Global Fits to Reactor, T2K, and MINOS

Ferero, Tortola, and Valle arXiv: 1205.4018



parameter	best fit $\pm 1\sigma$
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.62 ± 0.19
Δm^2_{31} $[10^{-3}\text{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$
δ	$\left(0.83^{+0.54}_{-0.64}\right)\pi$ 0.07π [a]

Moving on to Measuring the Mass Hierarchy and CP Violation

Measure CP Violation by Comparing $\nu_\mu \rightarrow \nu_e$ versus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

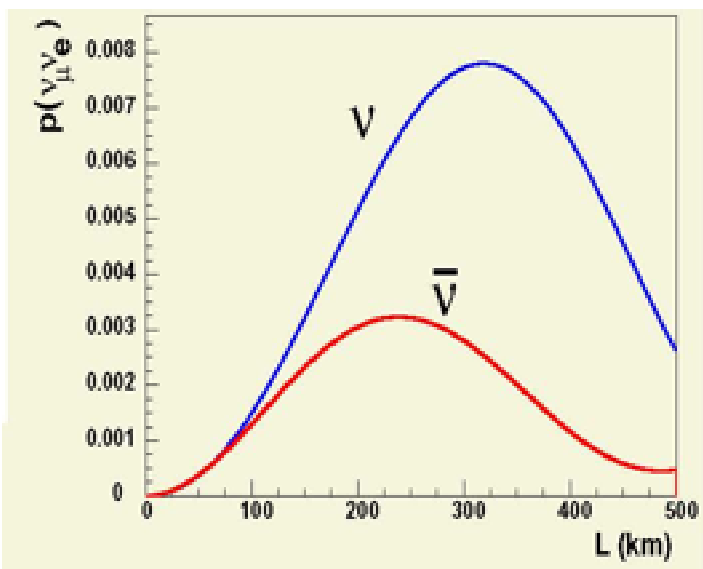
$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \text{ CPeven}$$

$$\pm 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$\pm 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) \qquad \text{matter effect (CP odd)}$$

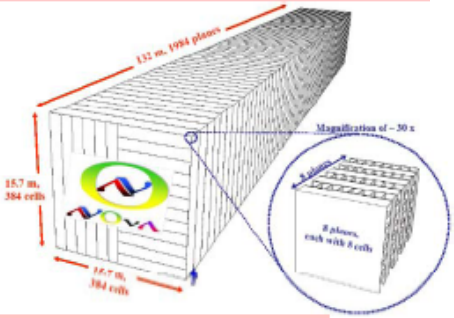


Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \neq 0$$

Present Longbaseline Experiments: T2K and Nova

Improved Beams and Near/Far Detectors
Much Higher Intensity



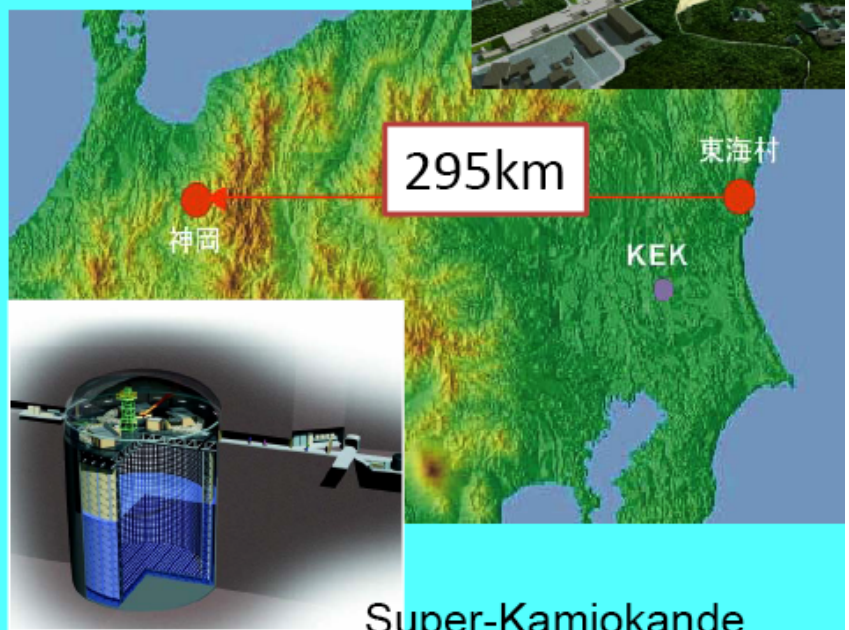
15 kton totally active detector

NOνA (~2013 -)

NuMI beam intensity upgrade to 700 kW

T2K (2009 -)

J-PARC (750kW design)



Super-Kamiokande (22.5 kton fid. vol)

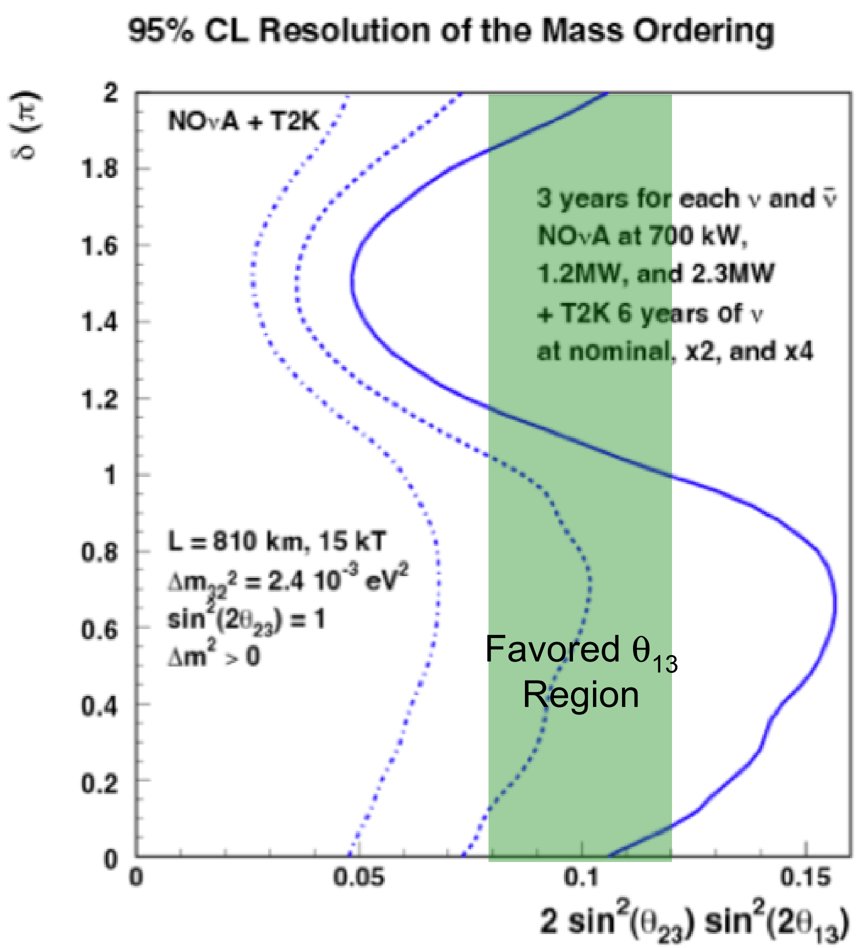
Opportunities with Current Program Data

Combine T2K, NOvA, and Reactor Data

Examples:

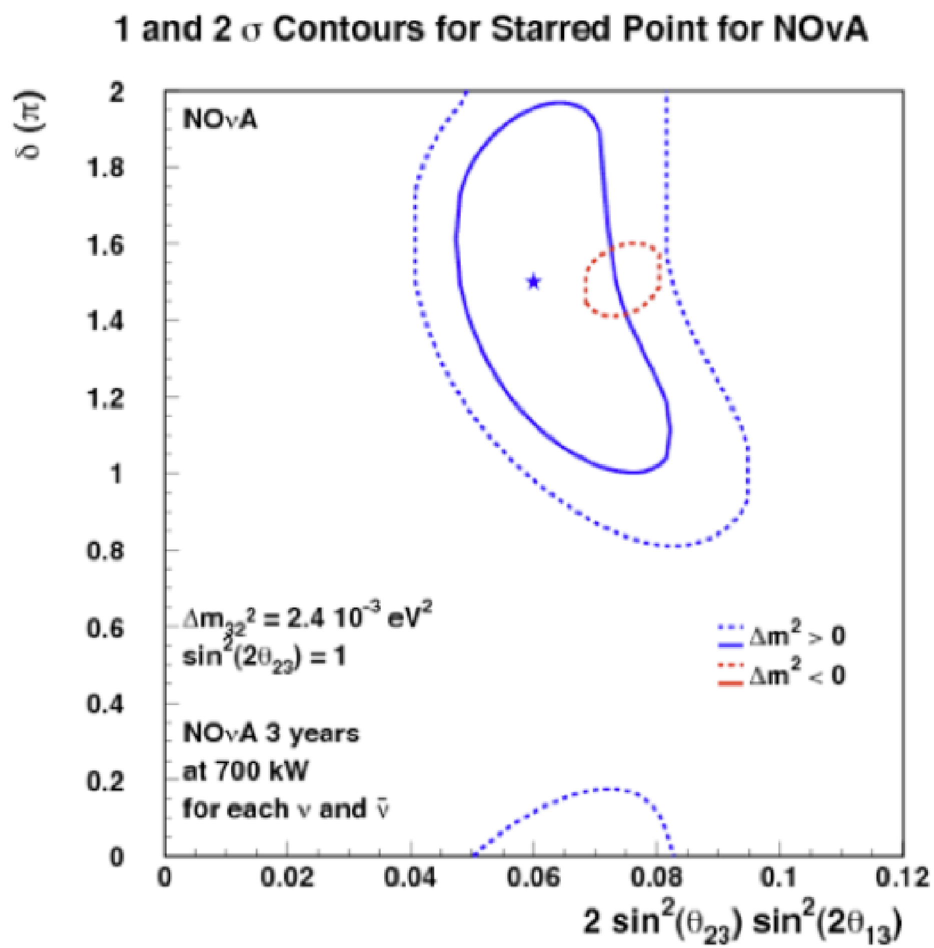
Measuring the mass hierarchy:

Compare NOvA appearance with matter effects to T2K appearance measurement without matter effects



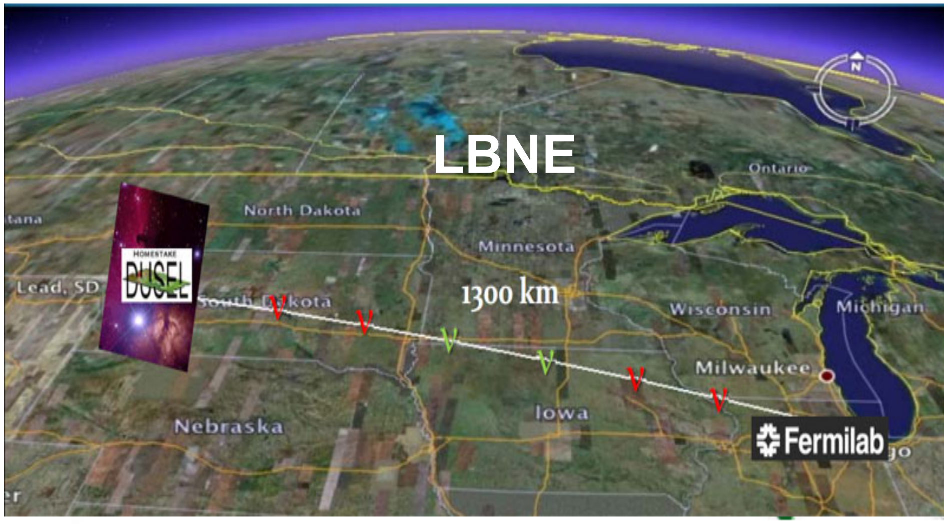
Measuring CP violation:

Compare NOvA neutrino and antineutrino appearance measurements.

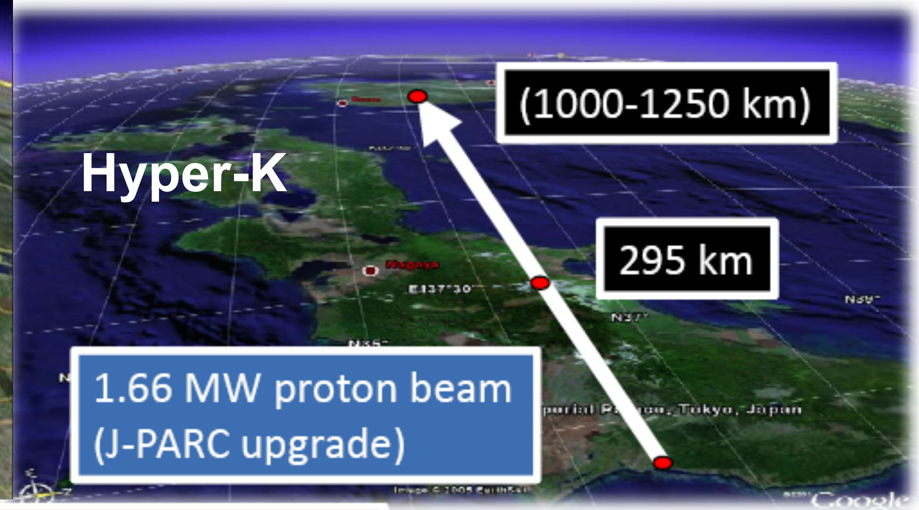


Future Longbaseline Experiments

Homestake Long Baseline Experiment

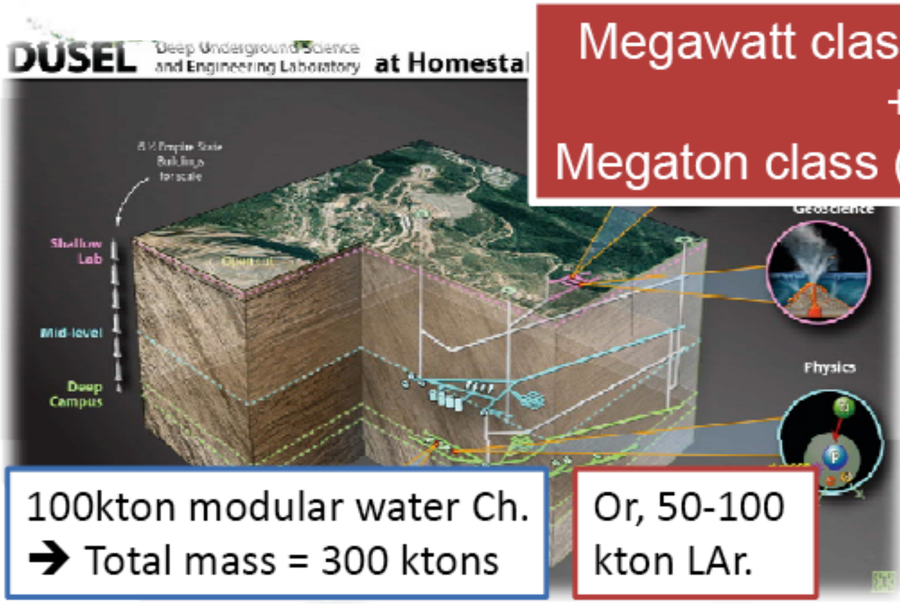


HyperK Long Baseline Experiment



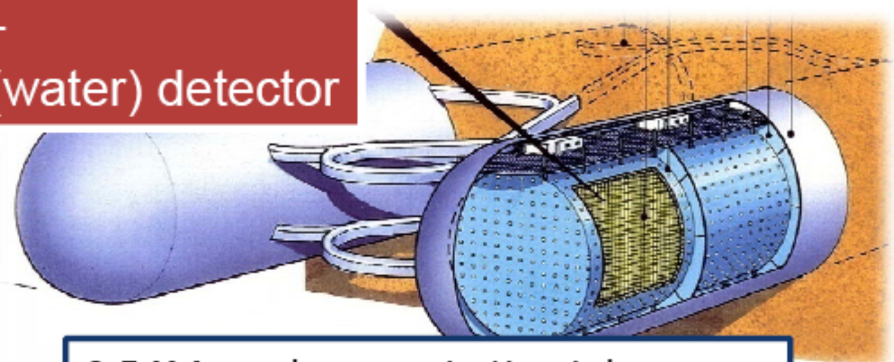
1.66 MW proton beam
(J-PARC upgrade)

Megawatt class super-beam
+
Megaton class (water) detector



100kton modular water Ch.
➔ Total mass = 300 ktons

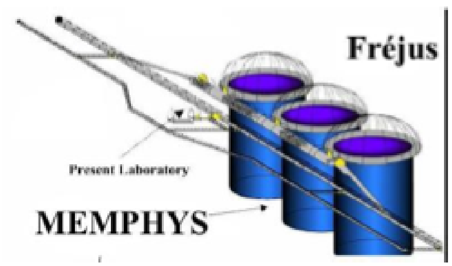
Or, 50-100
kton LAr.



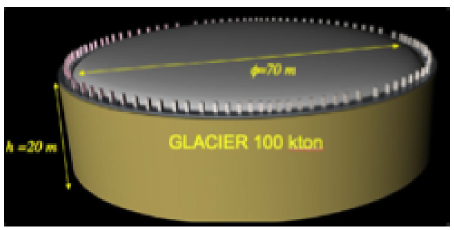
0.54Mton detector in Kamioka, or
0.27 Mton water Cherenkov detector
in Kamioka and Korea.

European Design Study - LAGUNA

(Large Apparatus for Grand Unification and Neutrino Astrophysics)



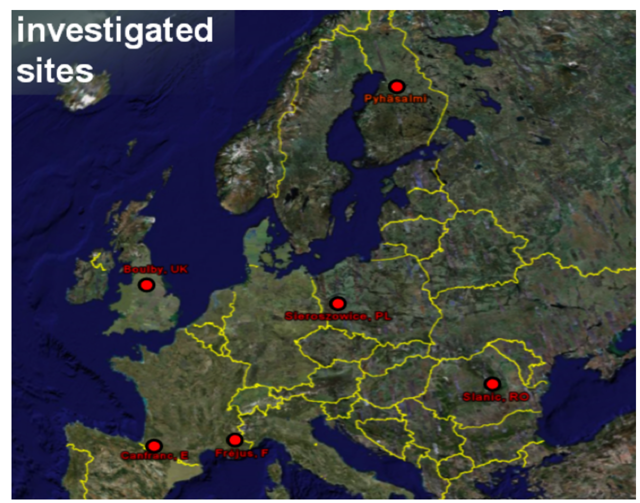
- MEMPHYS - MEgaton Mass PHYSics
  - tanks of 60 m heigth $\times$65 m $\varnothing$
  - $\sim$440 kt water Cherenkov detector



- GLACIER - Giant Liquid Argon Charge Imaging ExpeRiment
  - 20 m heigth $\times$70 m $\varnothing$
  - $\sim$ 100 kt liquid Ar TPC

- LENA - Low Energy Neutrino Astronomy
  - 100 m long $\times$ 30 m $\varnothing$
  - $\sim$ 50 kt liquid scintillator

Possible sites for a program with a neutrino beam from CERN



Saga of the US LBNE Experiment

- US funding agencies decide to pursue a deep underground lab in the old Homestake gold mine in South Dakota (DUSEL)
  - Some politics led to DOE taking on the project
  - LBNE oscillation experiment to be key part of this program

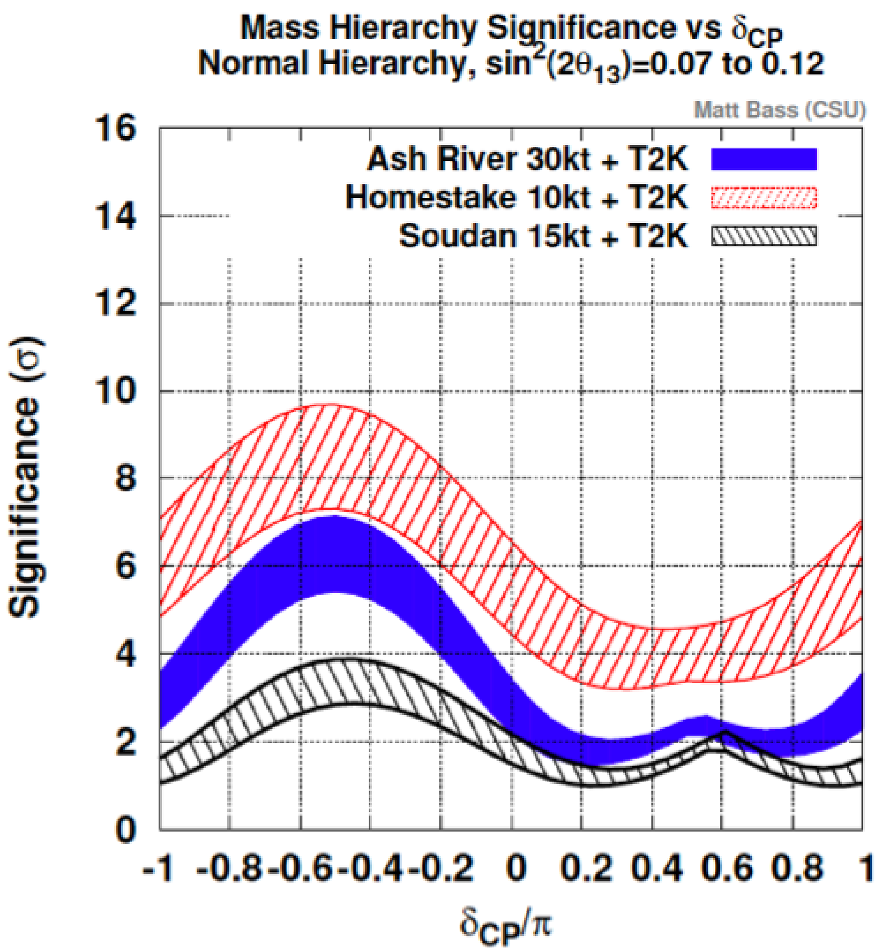
- January 2012: LBNE project management decides to pursue a 34 kton liquid argon (LAr) detector with 700 kW beam from Fermilab to Homestake

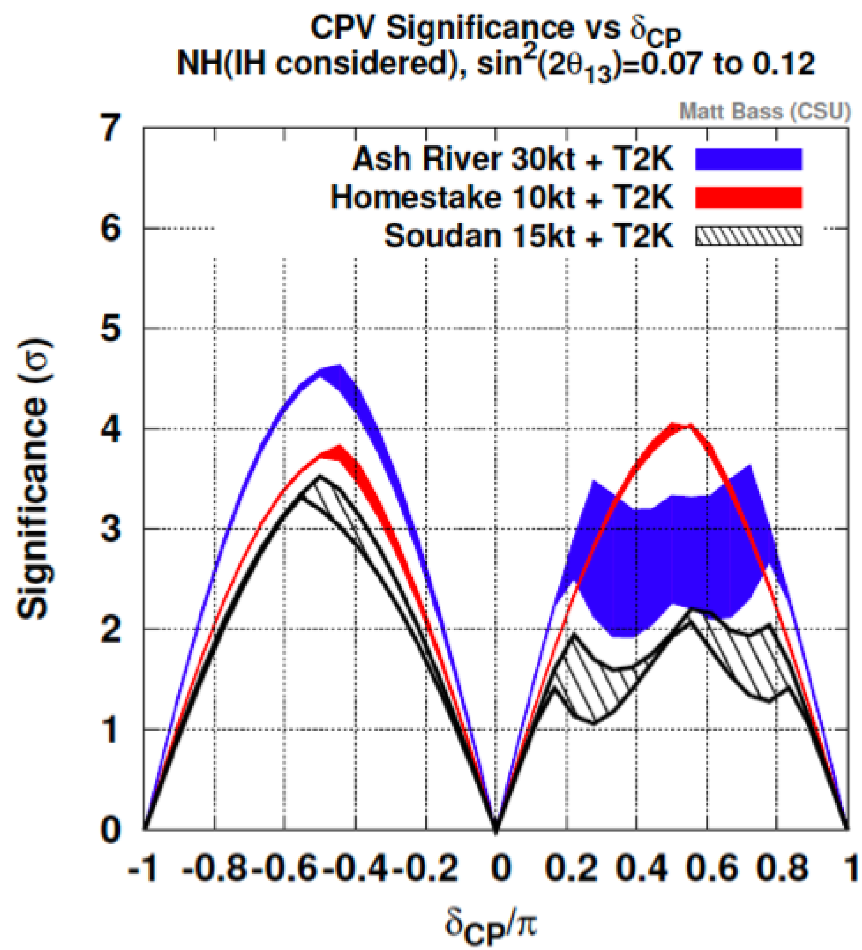
- March 2012: DOE tasks Fermilab to break LBNE into affordable phases that may include new sites but should have physics capabilities at each phase.

- June 2012: Panel set up to decide among three options for Phase I:
  1. 10 kton LAr detector on the surface at Homestake with new Fermilab neutrino beam
  2. 20 kton LAr detector in MINOS underground lab with existing ν beam
  3. 30 kton LAr detector on surface at Nova site with existing ν beam

LBNE Options: Mass Hierarchy and CP Violation Sensitivity

- Homestake option seems to have best overall sensitivity
  - But some worry about running LAr on the surface





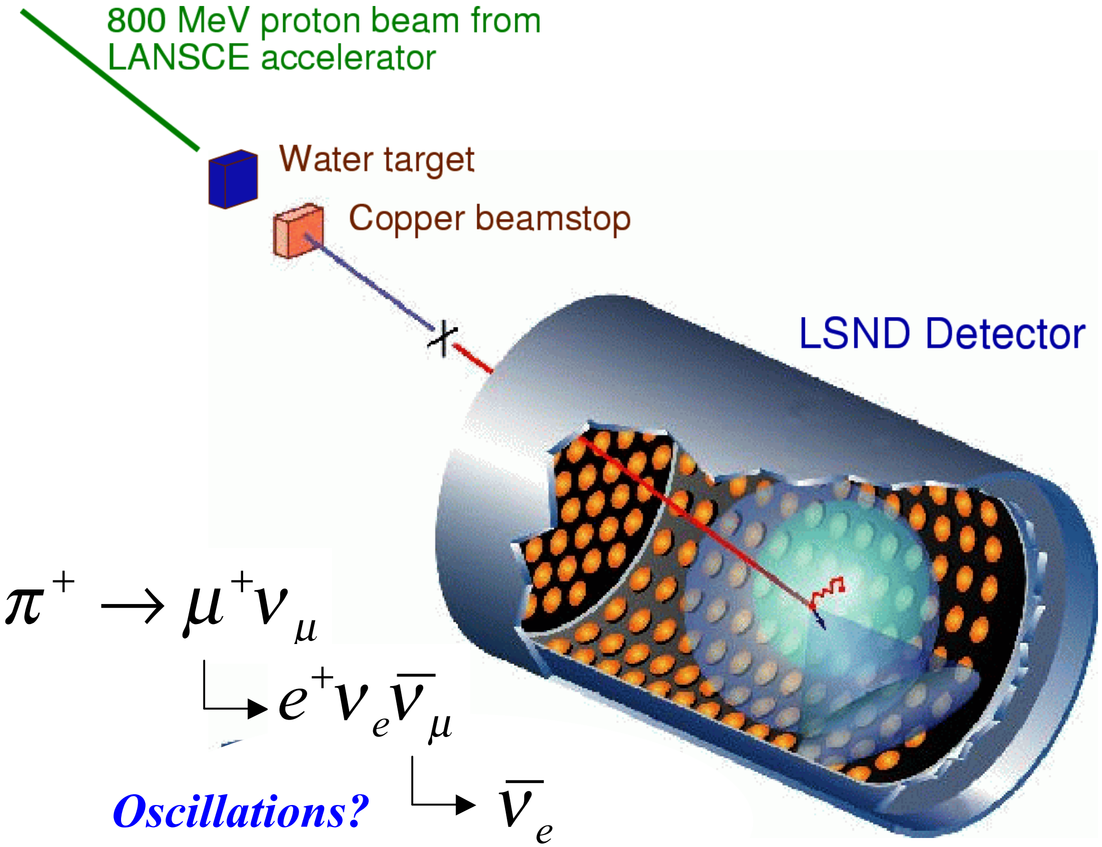
5 years neutrino + 5 years antineutrino

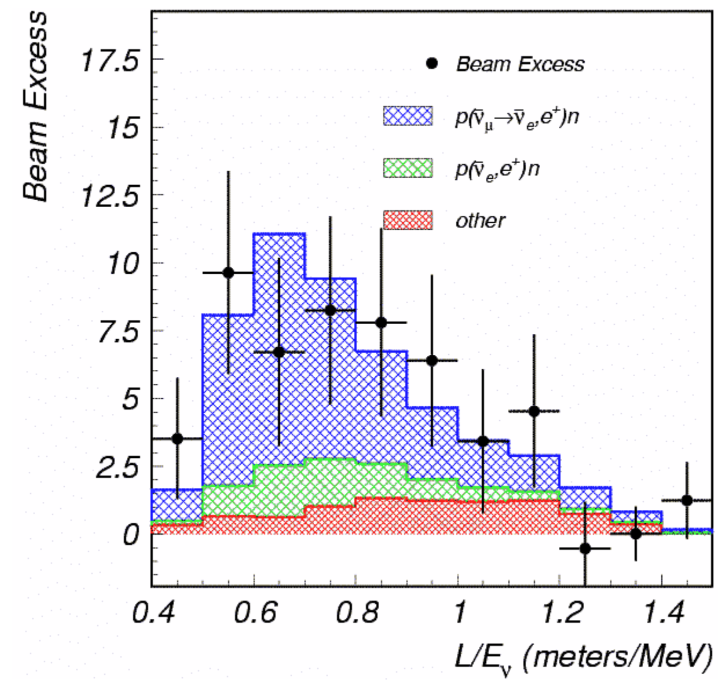
Possible Oscillations to Sterile Neutrinos

Sterile neutrinos

- Have no weak interactions (through the standard W/Z bosons)
- Would be produced and decay through mixing with the standard model neutrinos
- Can affect oscillations through this mixing

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





Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

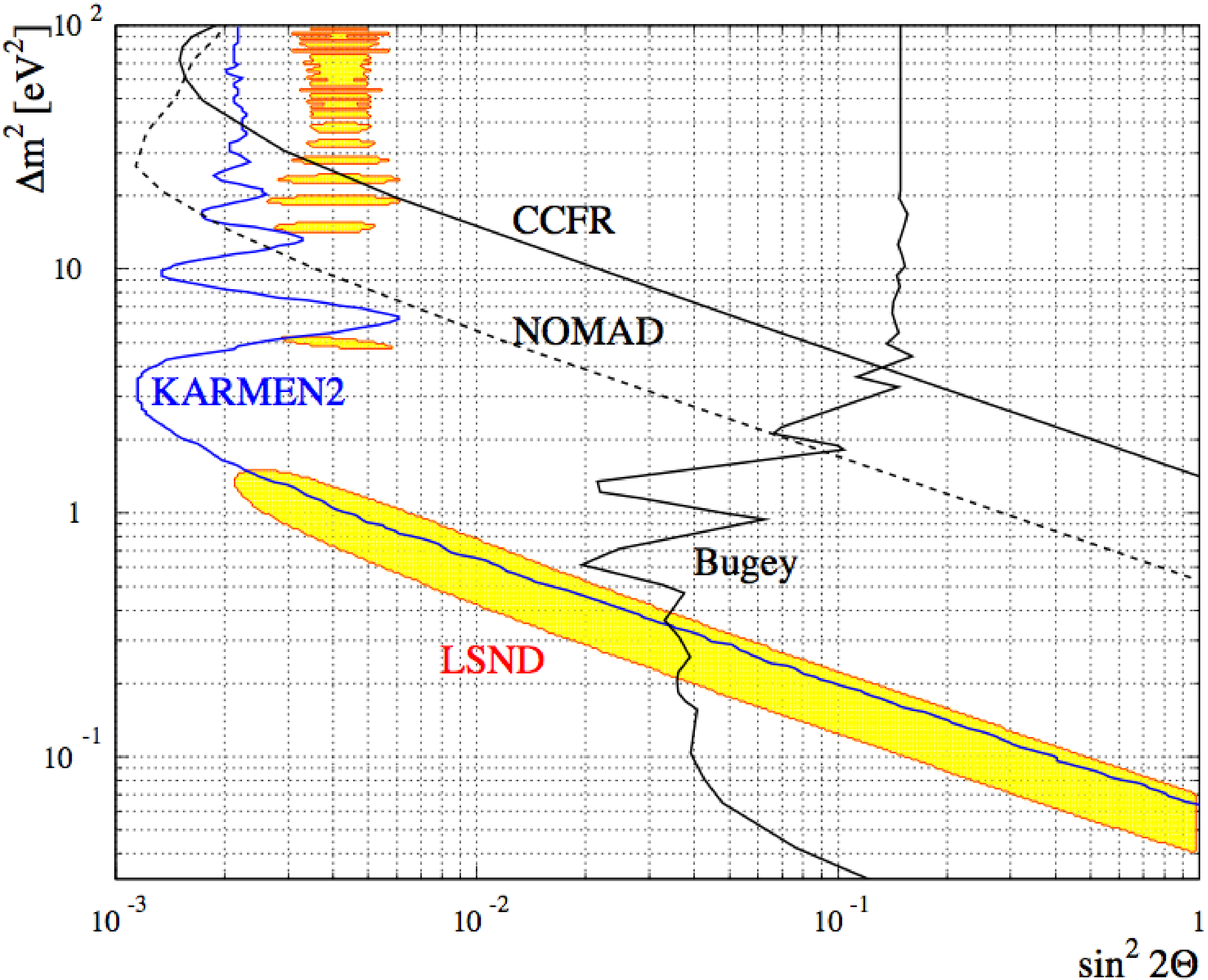
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

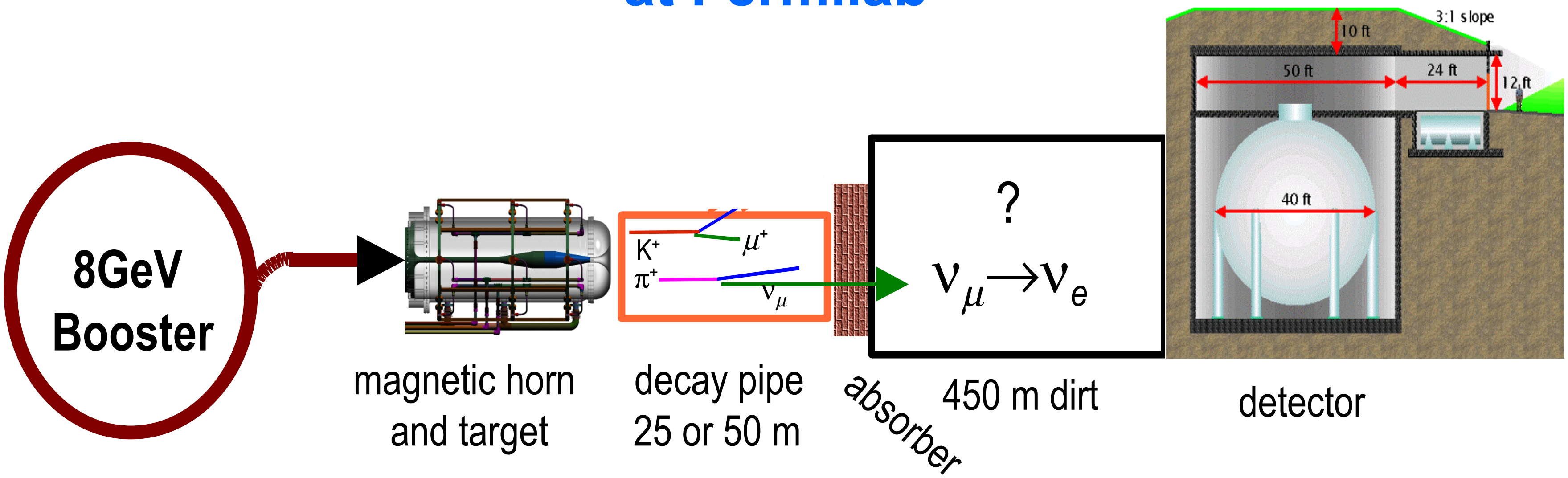
LSND in conjunction with the atmospheric and solar oscillation results needs more than 3 ν's

⇒ Models developed with 1 or 2 sterile ν's

LSND Signal Region

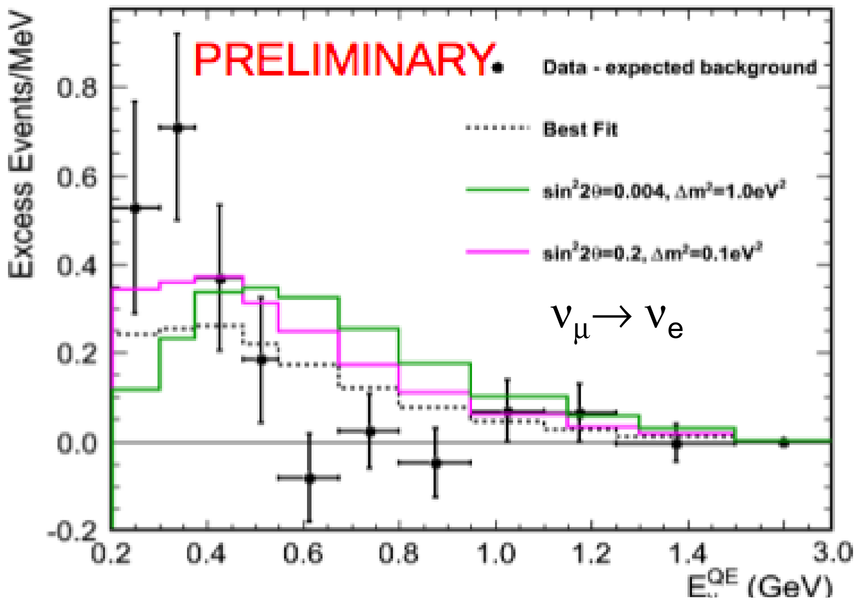


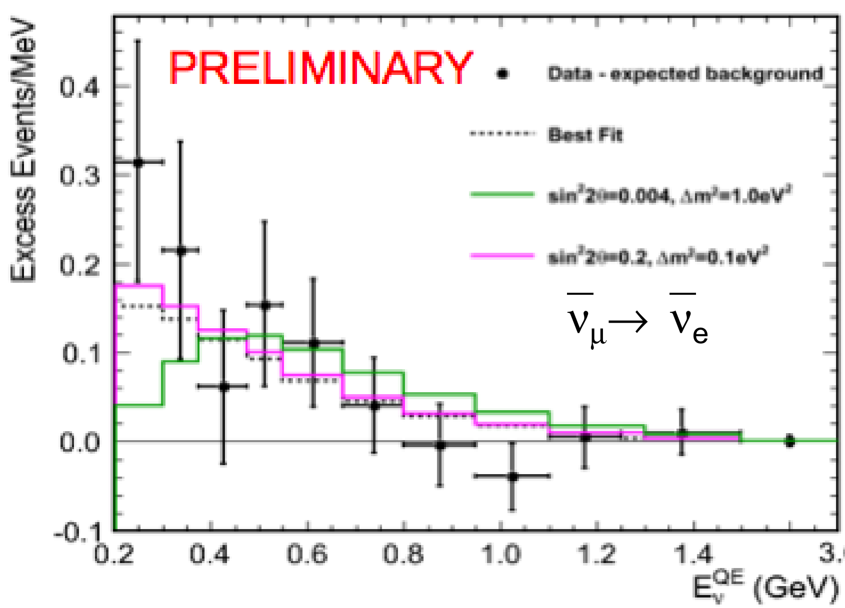
The MiniBooNE Experiment at Fermilab



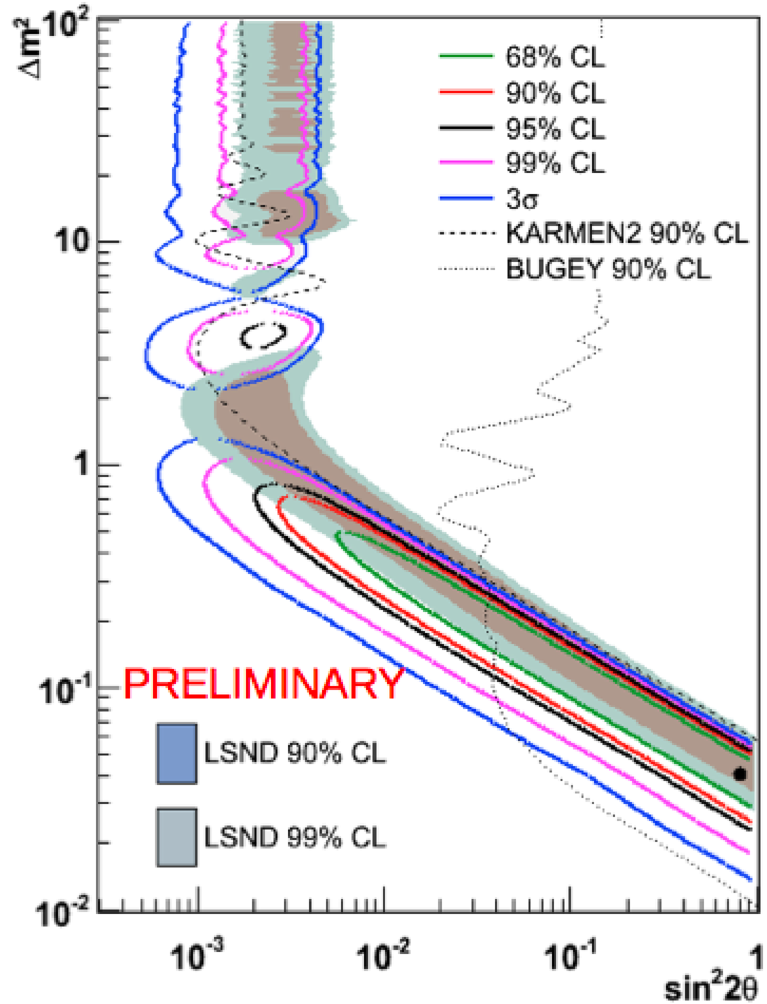
- Goal to confirm or exclude the LSND result - Similar L/E as LSND
  - Different energy, beam and detector systematics
  - Event signatures and backgrounds different from LSND
- Since August 2002 have collected data:
  - 6.7×10^{20} POT ν
  - 11.3×10^{20} POT $\bar{\nu}$

MiniBooNE $\nu_\mu \to \nu_e$ and New $\bar{\nu}_\mu \to \bar{\nu}_e$





- $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ fairly compatible with a common oscillation hypothesis and with the LSND result



Hints for High $\Delta m^2 \sim 1\ eV^2$ Oscillation
$\Rightarrow$ Sterile Neutrinos? or Something Else?

- Positive indications:

	Anomaly	Type	Channel	Significance
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	LSND	DAR	$\bar{\nu}$ CC	3.8 σ
$\nu_\mu \rightarrow \nu_e$	MiniBooNE	SBL accelerator	ν CC	3.0 σ
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	MiniBooNE	SBL accelerator	$\bar{\nu}$ CC	1.7σ
$\nu_e \rightarrow \nu_e$	Gallium/Sage	Source - e capture	ν CC	2.7σ
$\bar{\nu}_e \rightarrow \bar{\nu}_e$	Reactor	Beta-decay	$\bar{\nu}$	3.0σ

New MiniBooNE
Combined $\nu + \bar{\nu}$
Now 3.8 σ

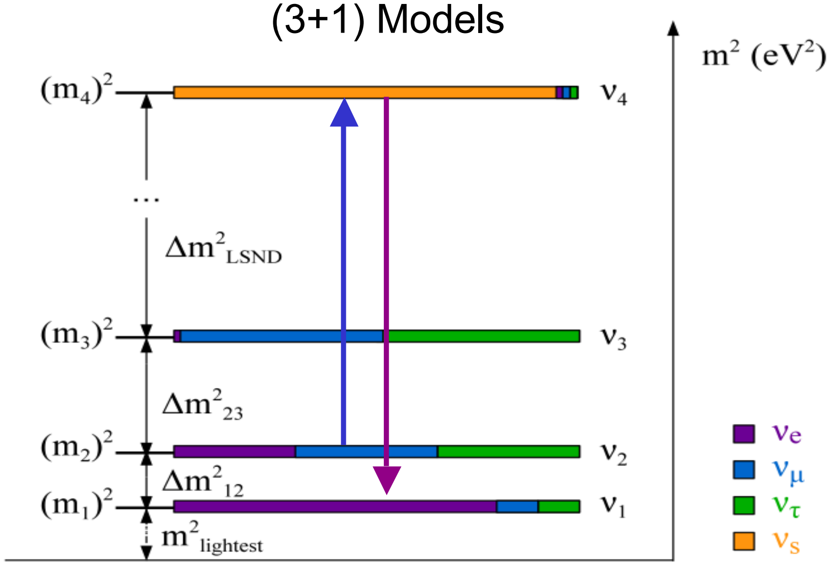
- Negative indications:
  - CDHS and MiniBooNE restrictions on ν_μ disappearance
  - MiniBooNE restrictions on $\bar{\nu}_\mu$ disappearance
  - MINOS restrictions on $\nu_\mu \rightarrow \nu_s$
  - Karmen restrictions on $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Other negative results

New MiniBooNE/SciBooNE
Limits on ν_μ / $\bar{\nu}_\mu$ Disappearance

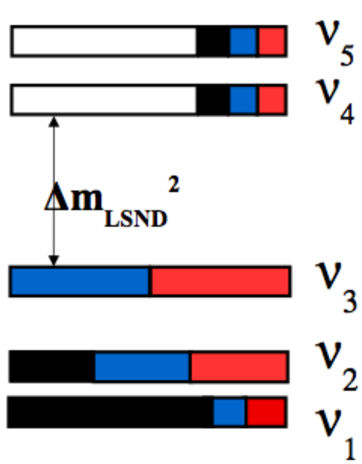
Phenomenology of Oscillations with Sterile Neutrinos

- In sterile neutrino (3+1) models, appearance comes from oscillation through ν_s
  - $\nu_\mu \to \nu_e = (\nu_\mu \to \nu_s) + (\nu_s \to \nu_e)$
- (3+1) models require ν_μ and ν_e disappearance oscillations
  - $\nu_\mu \to \nu_s$ and $\nu_e \to \nu_s$ $\Leftarrow$ **Disappearance**
  - Constraints from disappearance restrict application of (3+1) fits
- Current measurements of appearance and disappearance are not very compatible with (3+1) models $\Rightarrow$ (3+2) models
  - If $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ are different then (3+2) models can have CP violation
  - Still tension between appearance and disappearance

(3+1) Models



(3+2) Models



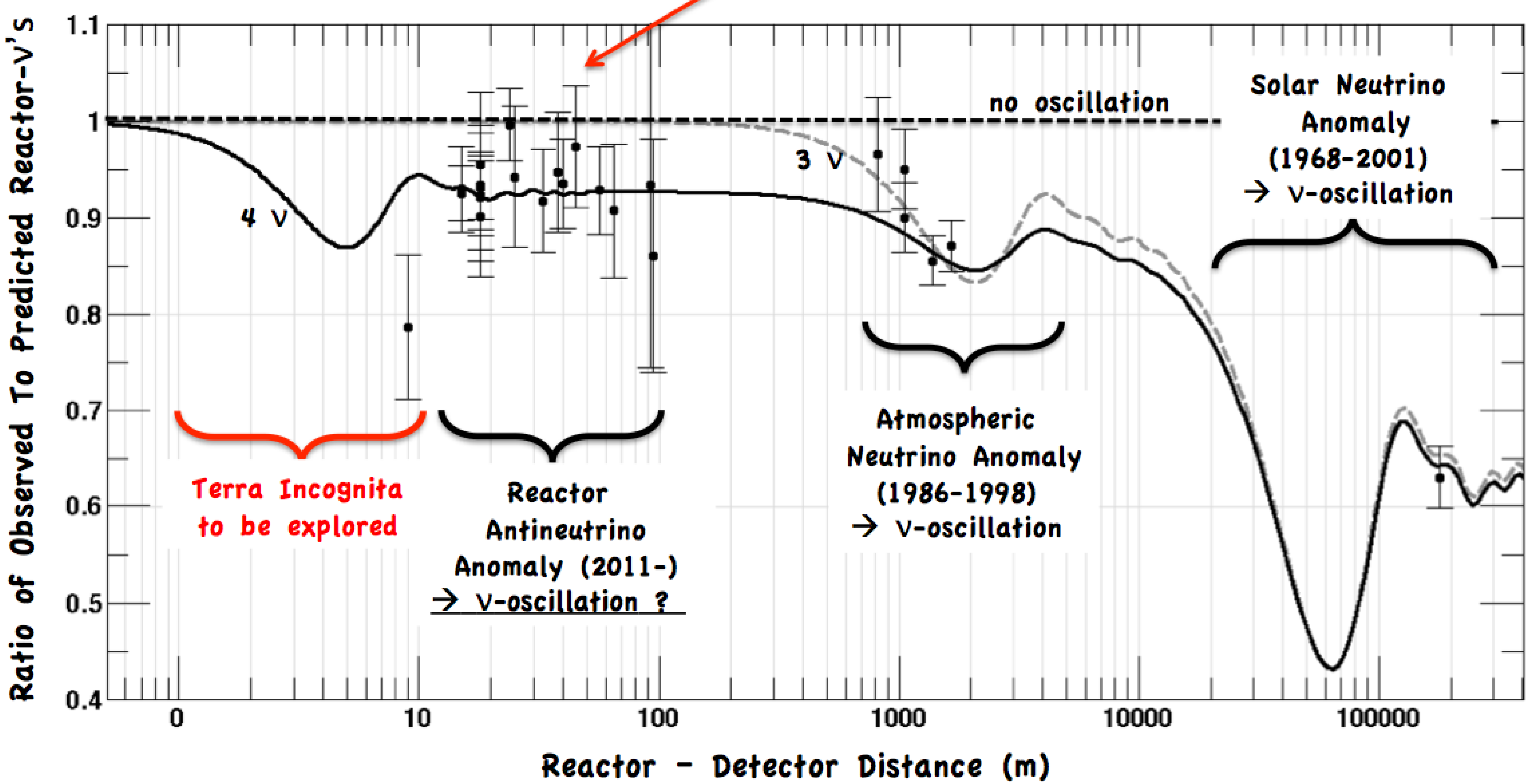
CP violation allowed in 3+2

$\overline{\nu}_e$ Disappearance Observed? ⇒ Reactor Antineutrino Anomaly

- **New Reactor antineutrino Spectra**
  - Net 3% upward shift in energy-averaged fluxes
  - Neutron life time correction & Off-equilibrium effects

- **At least three alternatives:**
  - Wrong prediction of ν-spectra ?
  - Bias in all experiments ?
  - New physics at short baselines: Mixing with 4th ν-state

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

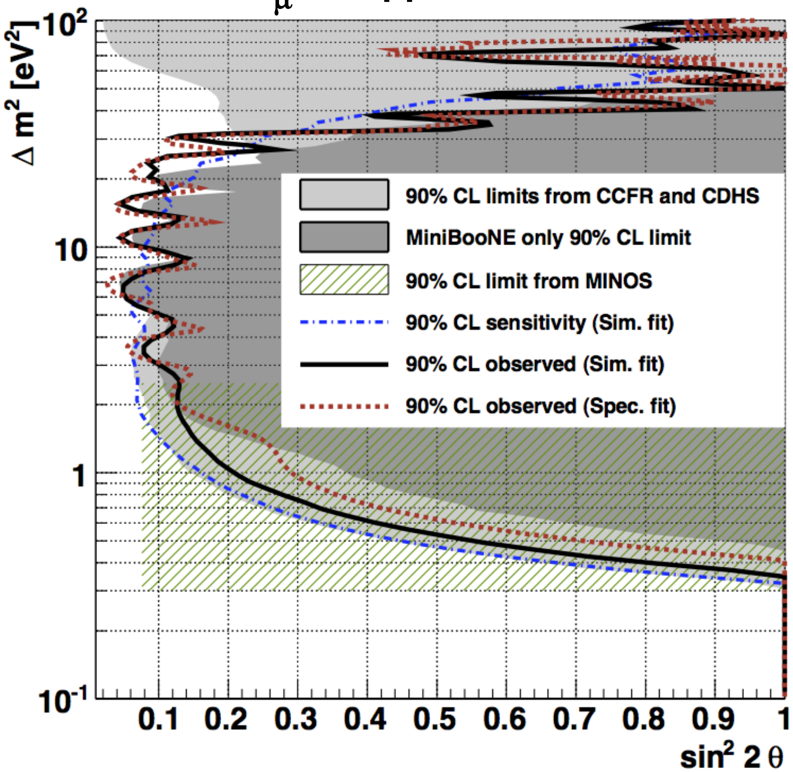


Stringent limits on ν_μ disappearance from experiments

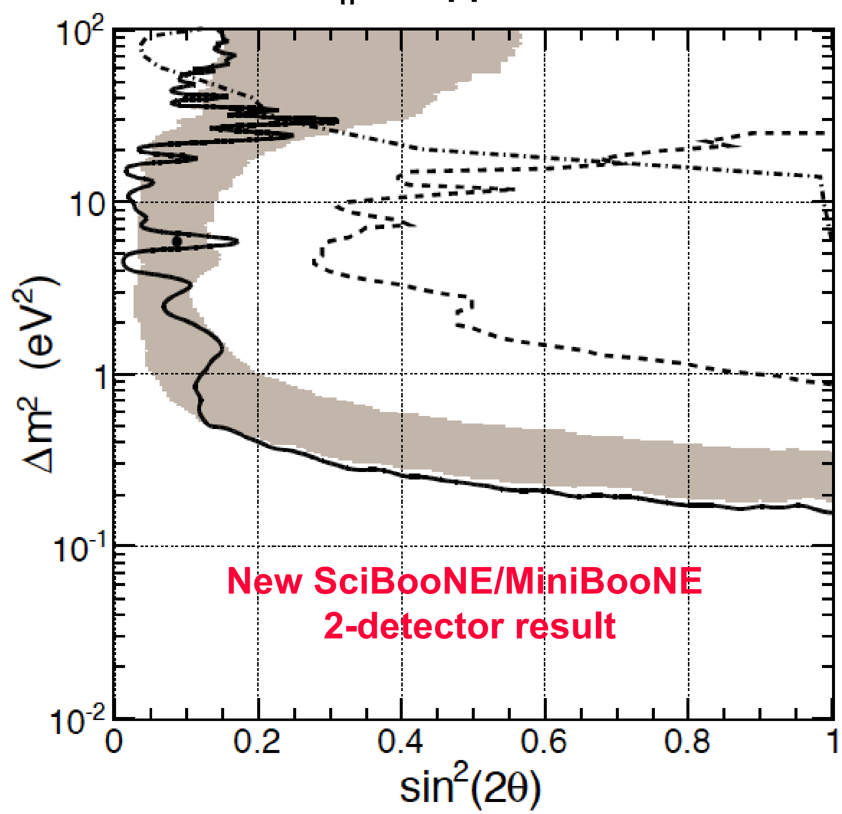
- SciBooNE/MiniBooNE and MINOS ν_μ and $\bar{\nu}_\mu$ disappearance limit

  ⇒ **Restricts application of 3+1 and 3+2 models**

ν_μ disappearance



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



Global Sterile Neutrino Fits to High Δm^2 Hints

- 3+0 Models
  - Solar and Atmospheric Δm^2 already saturates 3 known neutrinos
    $\Rightarrow$ Need to add at least one sterile neutrino

- 3+1 Models:
  - Extra sterile neutrino give high Δm^2
  - Can't explain differences in $\bar{\nu}_e$ vs ν_e appearance rates
  - Can't explain lack of $\bar{\nu}_\mu/\nu_\mu$ disappearance observations

$\nu_e \to \nu_e$ disappearance $\sin^2 2\theta_{ee}$

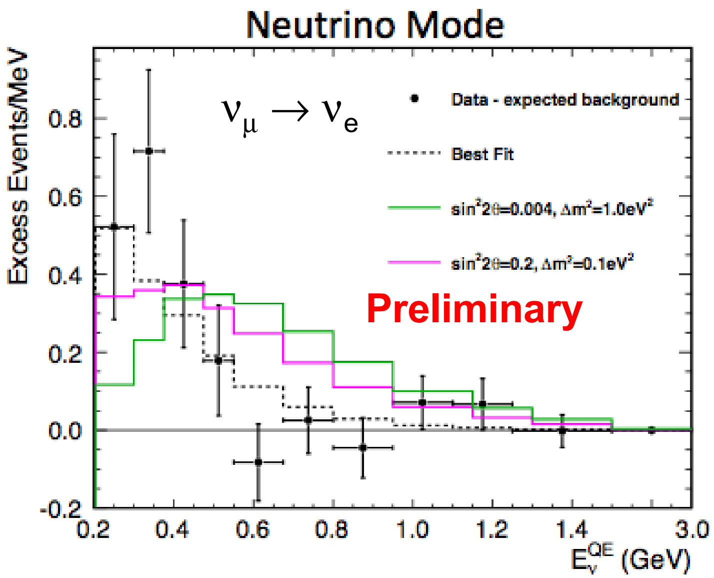
$\nu_\mu \to \nu_\mu$ disappearance $\sin^2 2\theta_{\mu\mu}$

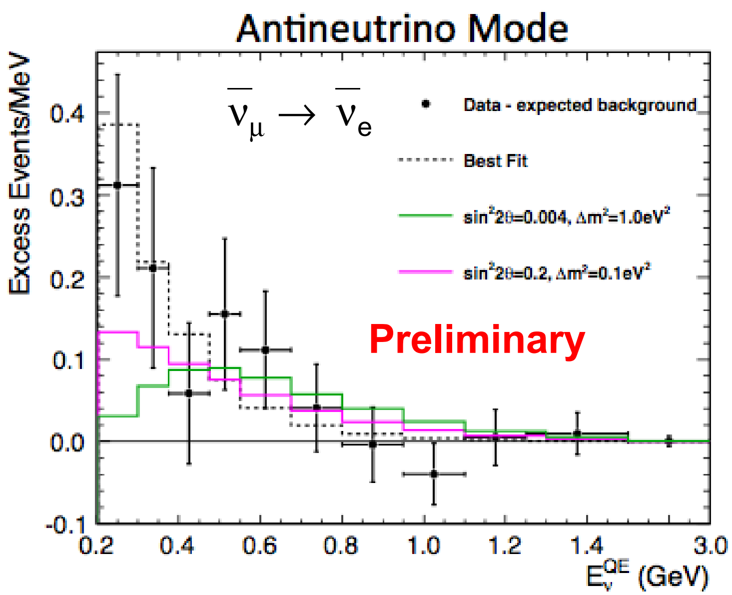
$\nu_\mu \to \nu_e$ appearance $\sin^2 2\theta_{\mu e}$

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

- 3+2 Models:
  - Can explain high Δm^2
  - Can have CP violation that explain differences in $\bar{\nu}_e$ vs ν_e appearance rates
  - Still can't explain lack of $\bar{\nu}_\mu/\nu_\mu$ disappearance observations

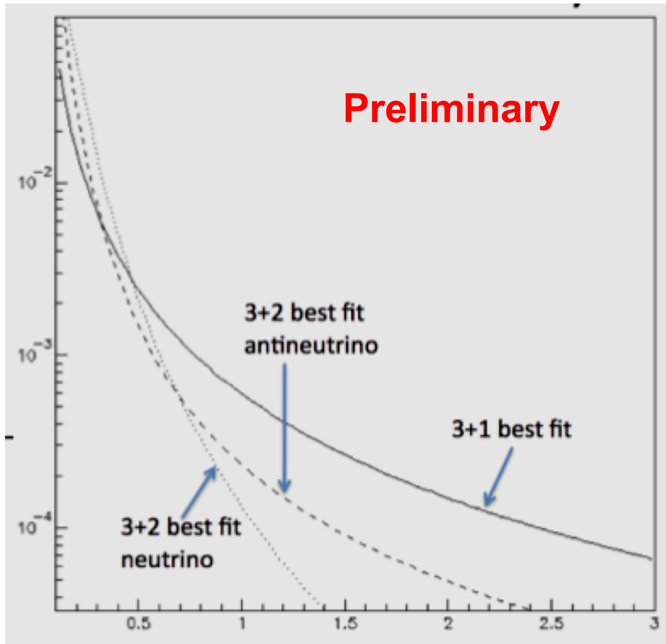
Preliminary (3+2) Fits to New MiniBooNE ν_e / $\bar{\nu}_e$ Appearance

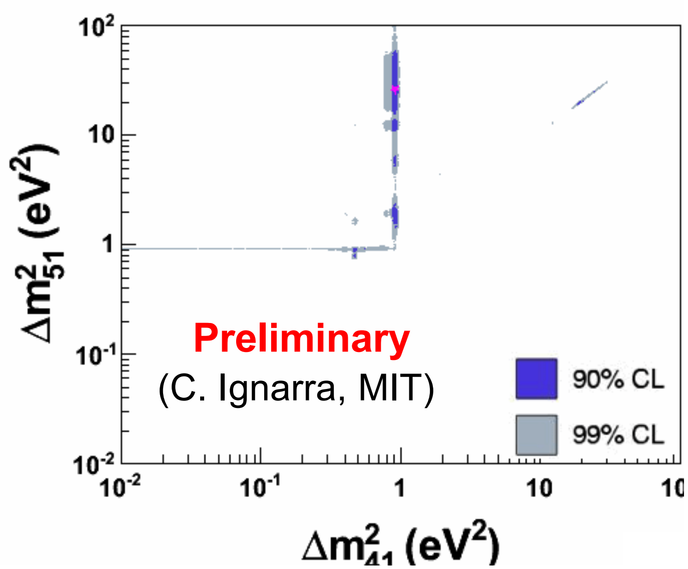




Global 3+2 Fits including new MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Data

- Two high mass scales plus CP violation effects can possibly explain ν_e vs $\bar{\nu}_e$ appearance
- Still some tension with disappearance results.





Many Ideas for Future Experiments

- Establishing the existence of sterile neutrinos would be a major result for particle physics

- Need definitive experiments
  - Significance at the > 5σ level
  - Observation of oscillatory behavior (L and/or E dependence) within a detector or between multiple detectors
  - Oscillation signal clearly separated from backgrounds

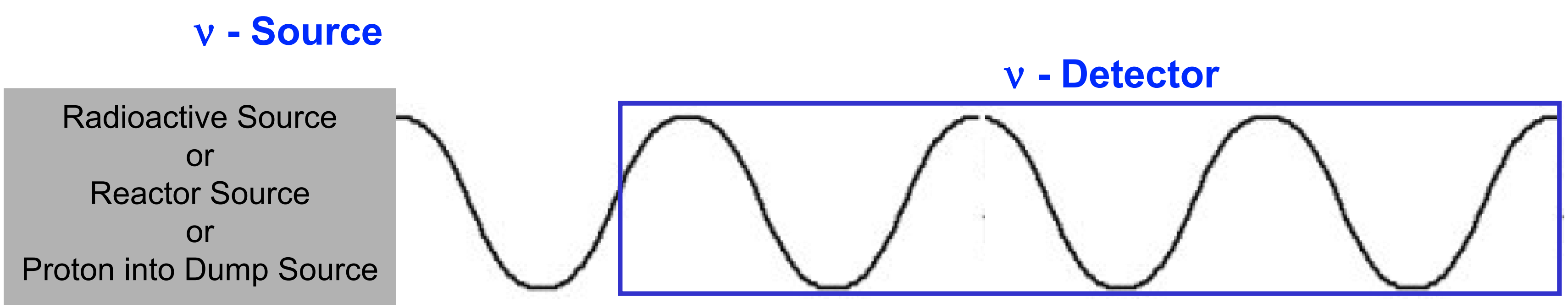
- Need to make both appearance and disappearance oscillation searches for neutrinos and for antineutrinos
  - Needed to prove the consistency with sterile neutrino (3+1) and (3+2) models

- Very active area for the field with many proposals and ideas
  - "Light Sterile Neutrinos: A White Paper" (arXiv:1204.5379) put together by a group of over 170 experimentalists and theorists.
  - Many workshops investigating opportunities and possibilities

Future Experimental Oscillation Proposals

Type of Exp	App/Disapp	Osc Channel	Experiments
Reactor Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	Nucifer, Stereo, SCRAMM, NIST, Neutrino4, DANSS
Radioactive Sources	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$ $(\nu_e \to \nu_e)$	Baksan, LENS, Borexino, SNO+, Richochet, CeLAND, Daya-Bay
Isotope Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest Source	Appearance & Disapp	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Accelerator $\overset{(-)}{\nu}$ using Pion Decay-in-Flight	Appearance & Disapp	$\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-Energy ν-Factory	Appearance & Disapp	$\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	νSTORM at Fermilab

Very-short Baseline Oscillation Experiments



$$1/L^2 \text{ flux rate modulated by } \mathrm{Prob}_{osc} = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L / E\right)$$

- Can observe oscillatory behavior within the detector if neutrino source has small extent .
  - Look for a change in event rate as a function of position and energy within the detector
  - Bin observed events in L/E (corrected for the $1/L^2$) to search for oscillations
- Backgrounds produce fake events that do not show the oscillation L/E behavior and are easily separated from signal

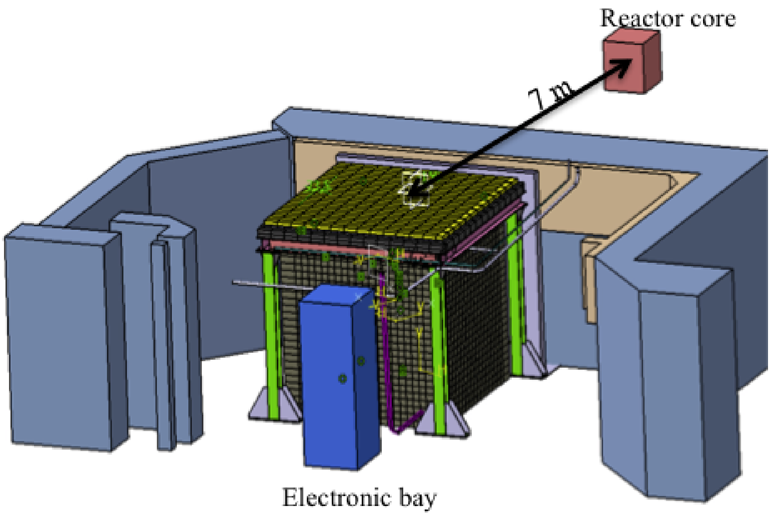
Very-Short Baseline Reactor Experiments
($\bar{\nu}_e$ Disappearance)

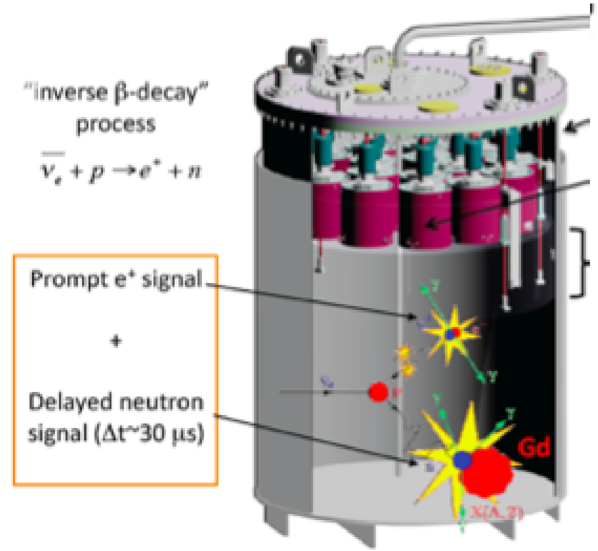
Very-Short Baseline Reactor Experiments

Experiment	Reactor	Baseline	Status
Nucifer (Saclay)	Osiris 70MW	7	Taking Data
Stereo (Genoble)	ILL 50 MW	10	Proposal
SCRAMM (CA)	San-Onofre 3 GW	24	Proposal
NIST (US)	NCNR 20 MW	4-11	Proposal
NEUTRINO4	SM3 100 MW	6-12	Proposal
SCRAMM (Idaho)	ATR 150 MW	12	Proposal
DANSS (Russia)	KNPP 3 GW	14	Fabrication

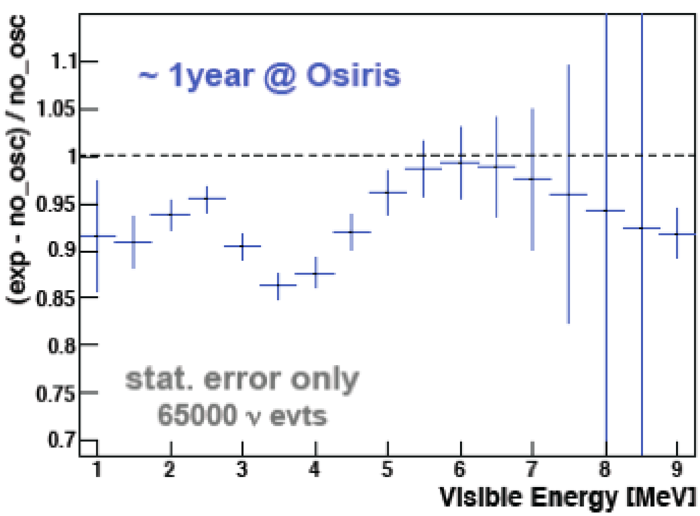
NUCIFER Reactor Experiment

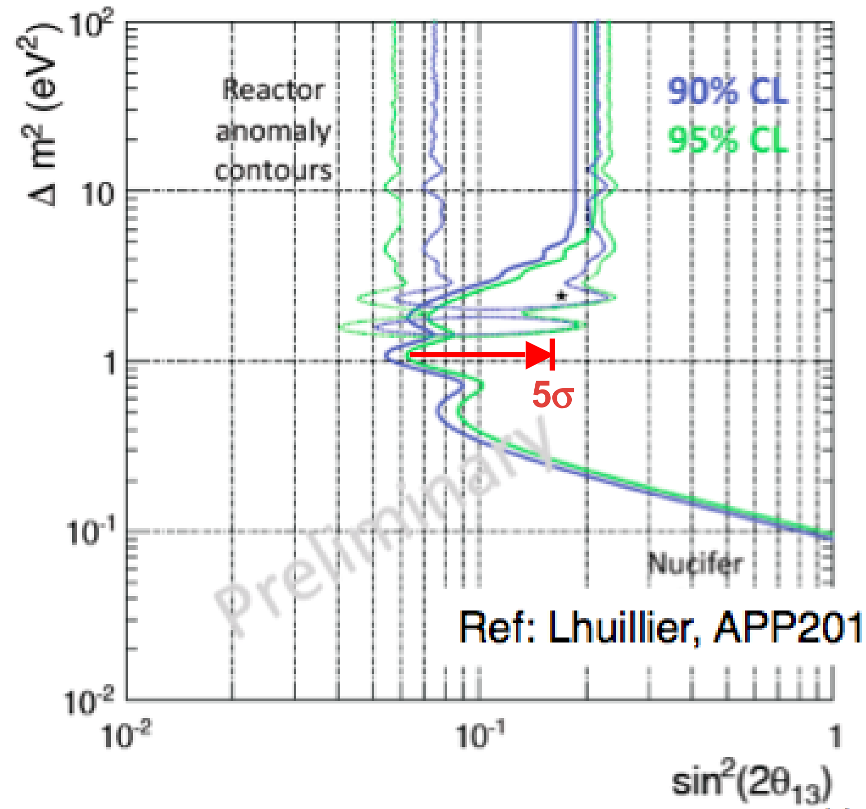
Osiris Research Reactor: Core Size: 57x57x60 cm
1.2m x 0.7m detector , 7m distance from core





Expected E spectrum deformation
with anomaly best fit: $\Delta m^2 = 2.4\ eV^2$ & $\sin^2(2\theta)=0.15$





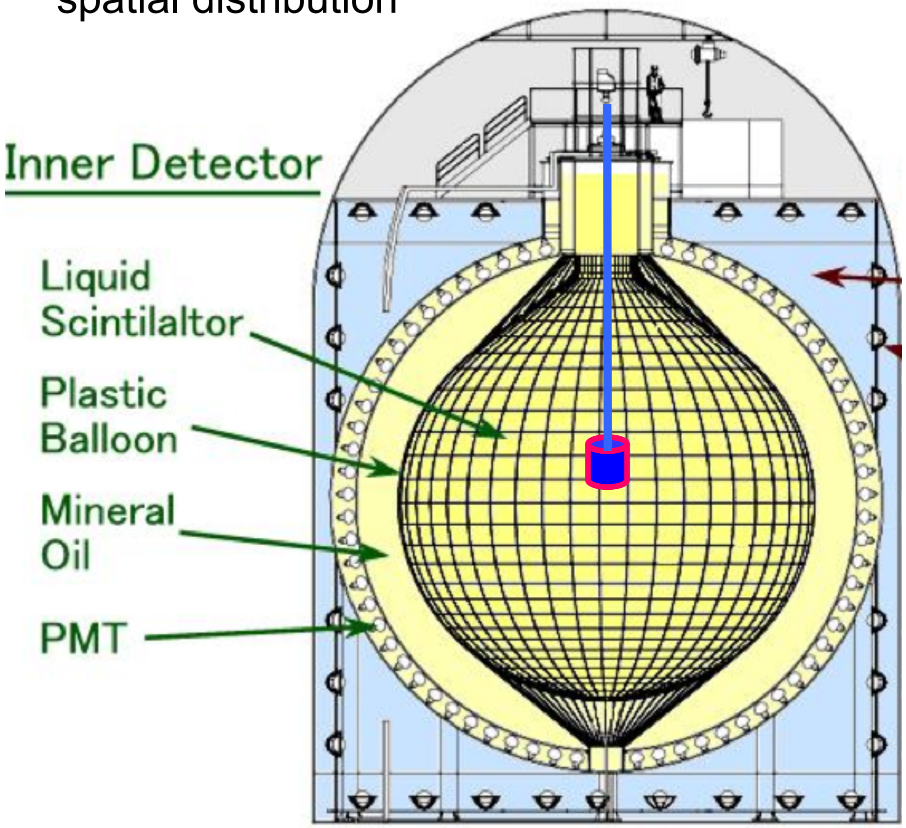
Radioactive β-Decay Source Experiments
(ν_e or $\bar{\nu}_e$ Disappearance)

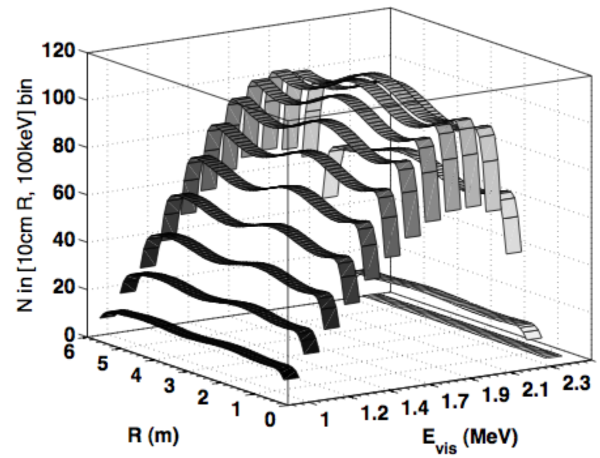
Radioactive β-Decay Source Experiments

Species	Source	Experiment	Status
ν_e	^{51}Cr	Baksan	Proposal
ν_e	^{51}Cr	LENS	Proposal
ν_e	^{51}Cr	Borexino	Proposal
ν_e	^{51}Cr	SNO+	Proposal
ν_e	^{37}Ar	Richochet	Proposal
$\bar{\nu}_e$	^{144}Ce	Ce-LAND	Proposal
$\bar{\nu}_e$	^{144}Ce	Daya-Bay	Proposal

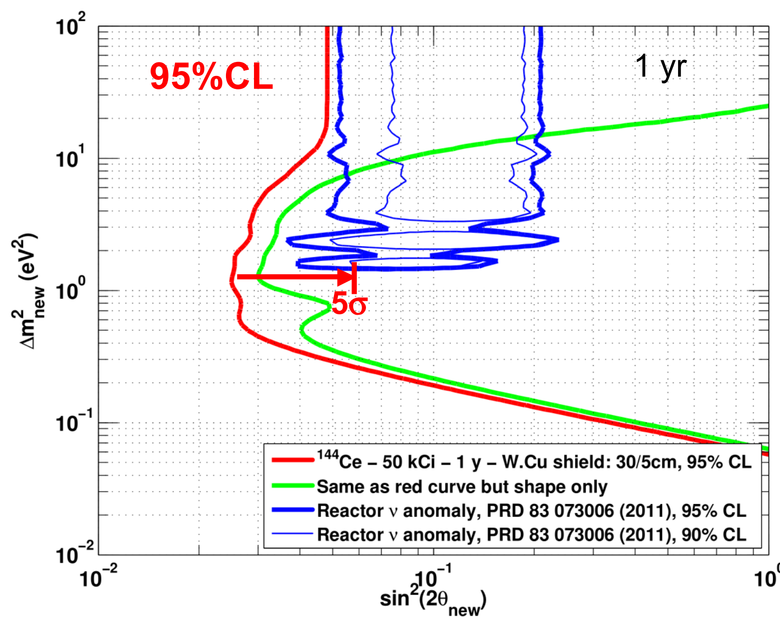
Ce-LAND Exp: Using ^{144}Ce kCi Anti-neutrino Source

- A 50 kCi anti-ν source (10 g of ^{144}Ce) in the middle of a large LS detector
- Inside a thick 35 cm W-Cu shielding → background free
- Energy-dependent oscillating pattern in event spatial distribution





M. Cribier, et al. PRL 107, 201801(2011)

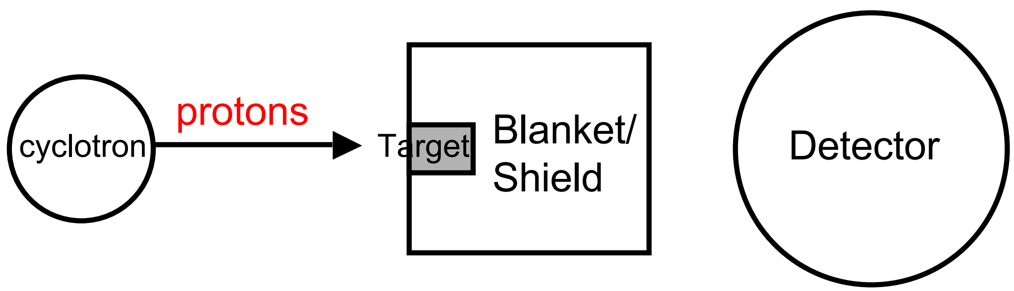


Detectors which could be used for this idea include Kamland, SNO+, or Borexino…

Isotope Decay-at-Rest Neutrino Source
($\bar{\nu}_e$ Disappearance)

IsoDAR $\bar{\nu}_e$ Disappearance Exp
(arXiv:1205.4419)

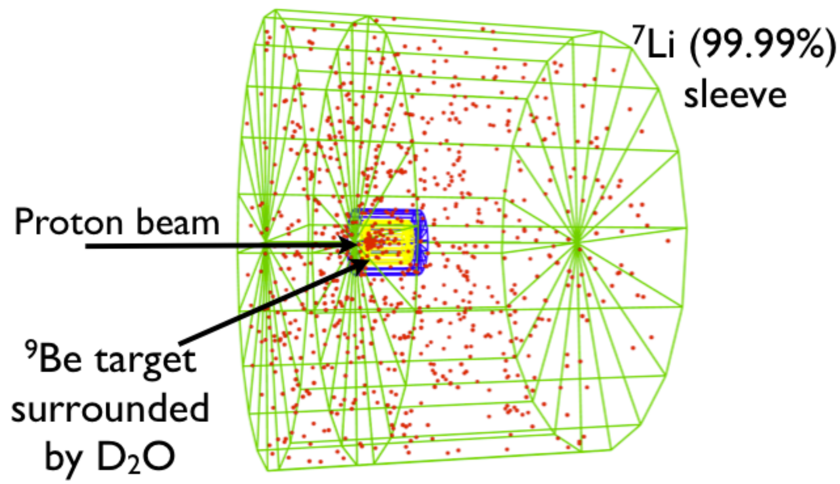
- High intensity $\bar{\nu}_e$ source using β-decay at rest of ^{8}Li isotope ⇒ IsoDAR
- ^{8}Li produced by high intensity (10ma) proton beam from 60 MeV cyclotron ⇒ being developed as prototype injector for DAEδALUS cyclotron system
- Put a cyclotron-isotope source near one of the large (kton size) liquid scintillator/water detectors such as KAMLAND, SNO+, Borexino, Super-K….



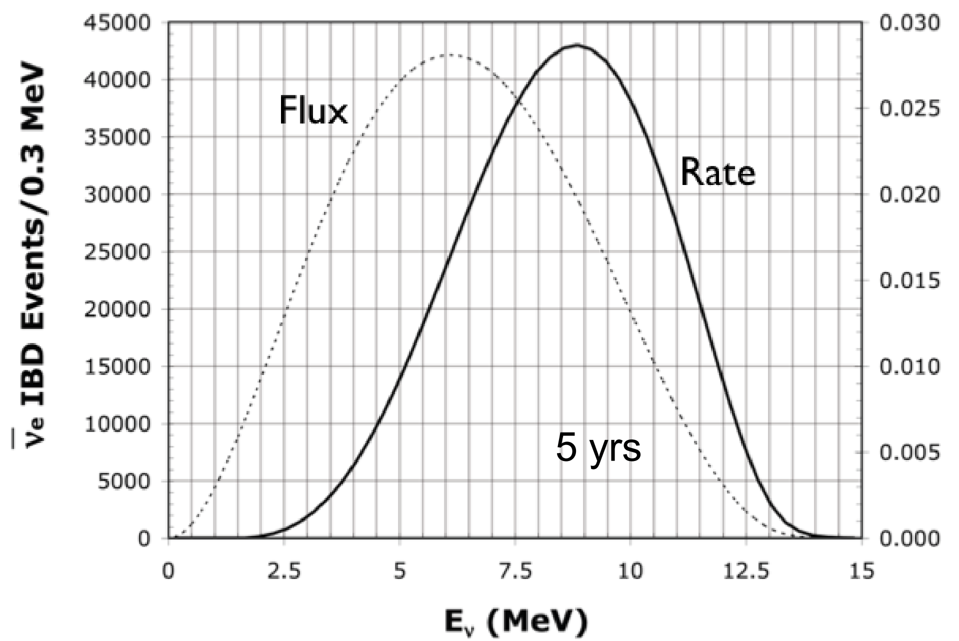
- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector.

IsoDAR Neutrino Source and Events

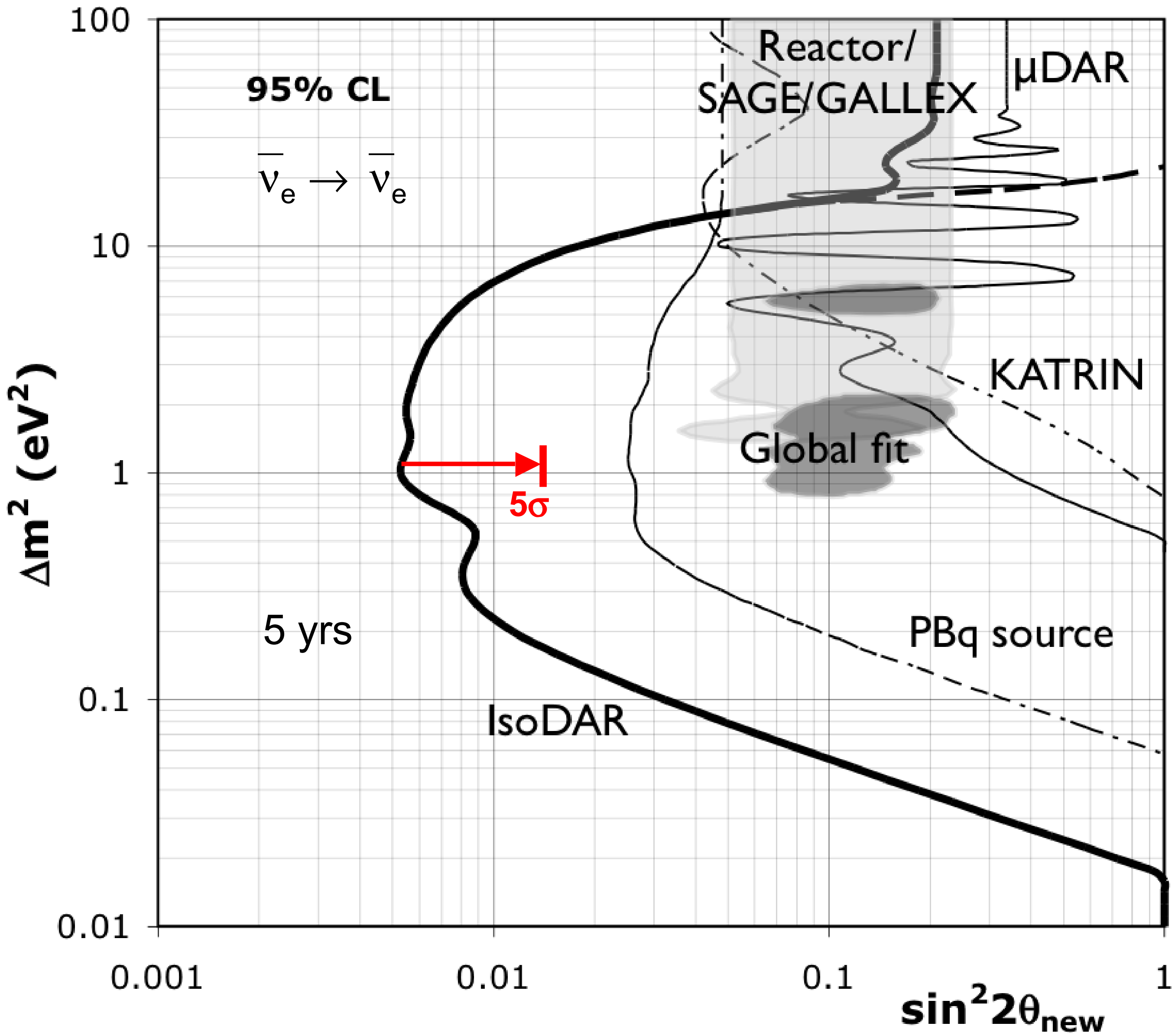
- p (60 MeV) + $^{9}Be \rightarrow {}^{8}Li$ + 2p
  - plus many neutrons since low binding energy
- n + ^{7}Li (shielding) $\rightarrow {}^{8}Li$
- $^{8}Li \rightarrow {}^{8}Be + e^{-} + \bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV
  - 2.6×10^{22} $\bar{\nu}_e$ / yr
- Example detector: Kamland (900 t)
  - Use IBD $\bar{\nu}_e + p \rightarrow e^{+} + n$ process
  - Detector center 16m from source
  - ~160,000 IBD events / yr
  - 60 MeV protons @ 10ma rate
  - Observe changes in the IBD rate as a function of L/E



arXiv:1205.4419

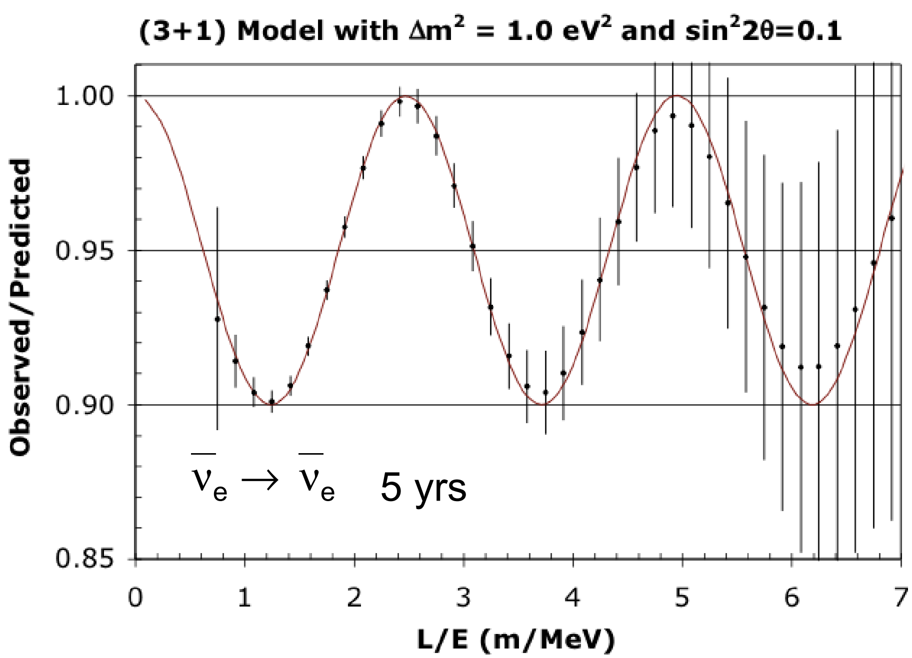


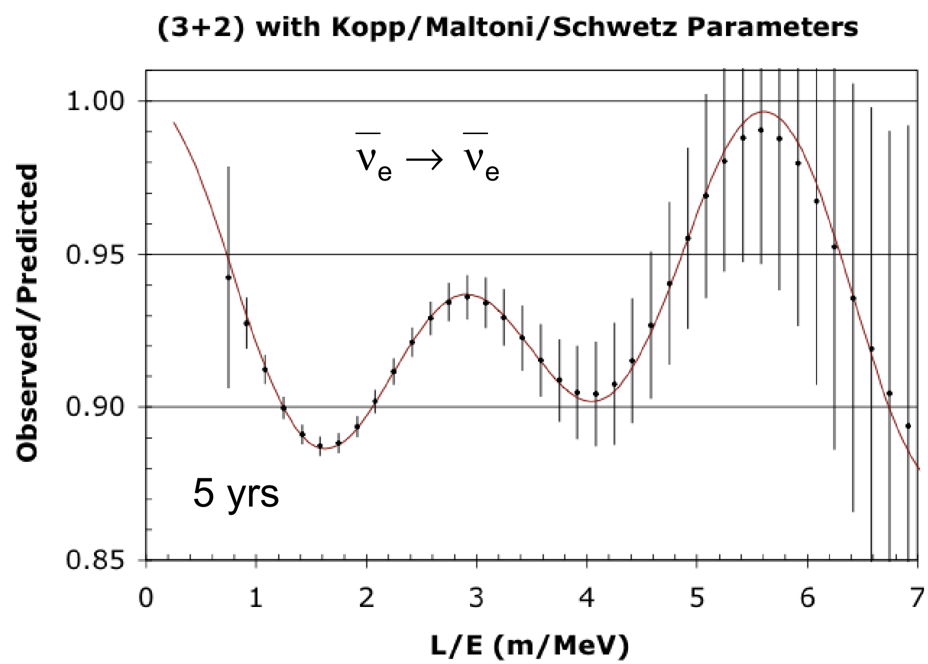
IsoDAR $\overline{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)



Oscillation L/E Waves in IsoDAR

Observed/Predicted event ratio vs L/E including energy and position smearing



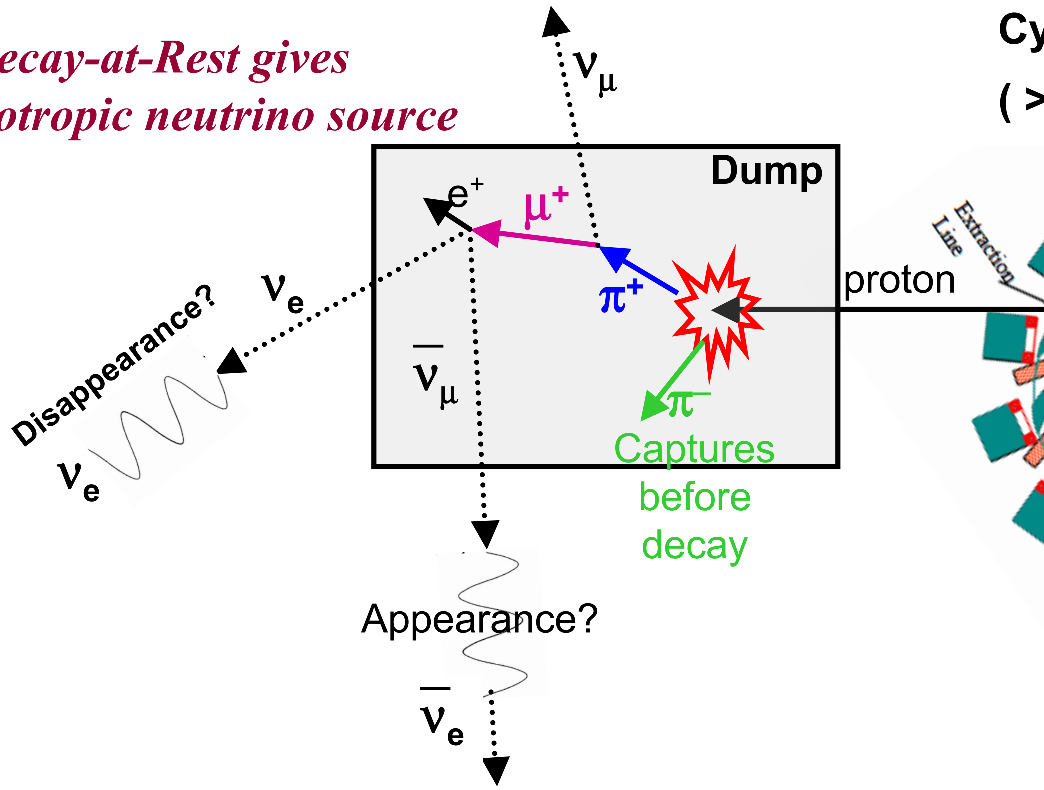


IsoDAR's high statistics and good L/E resolution gives good sensitivity to distinguish (3+1) and (3+2) oscillation models

Pion or Kaon Decay-at-Rest Neutrino Sources

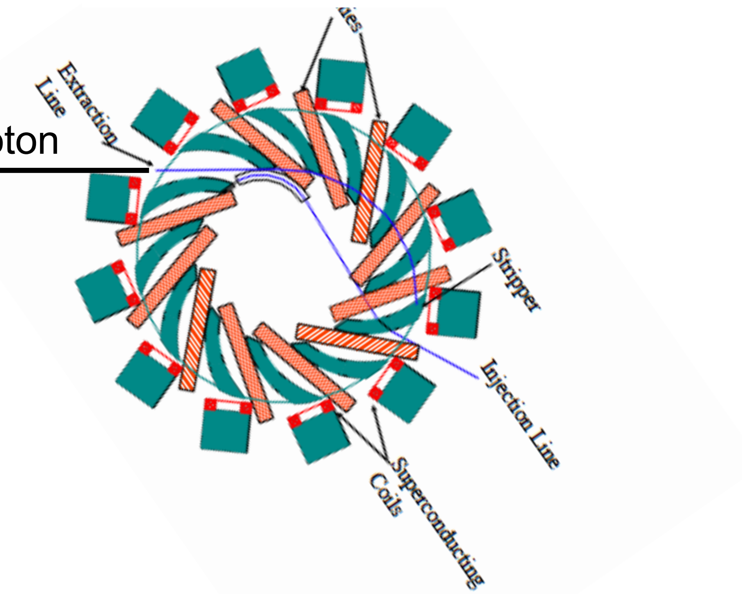
Decay-at-Rest (or Beam Dump) Neutrino Sources

Decay-at-Rest gives isotropic neutrino source

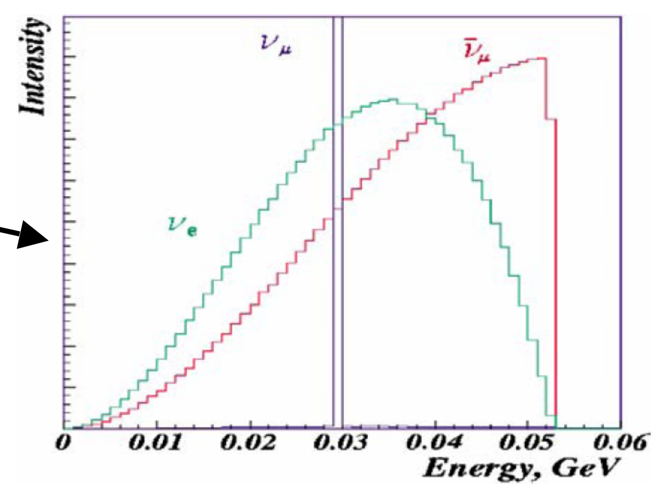


Cyclotron or Other Proton Source

(>800 MeV proton for π production)



Each π^+ decay gives one ν_μ, one ν_e, and one $\bar{\nu}_\mu$ with known energy spectrum



~1 ma of 800 MeV protons (like LSND)

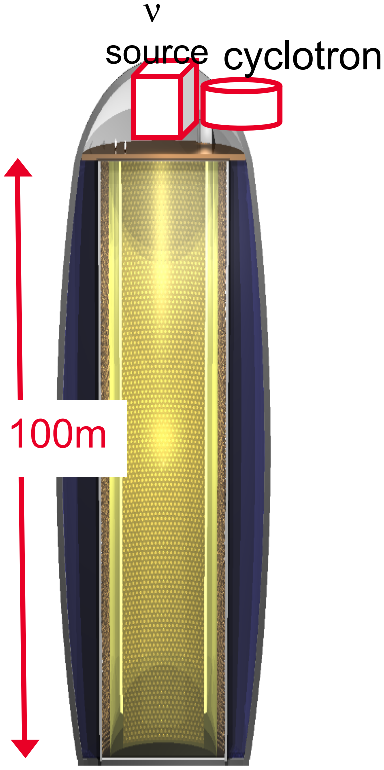
$\Rightarrow$ *0.17 π^+/proton* $\Rightarrow$ *2.3×10^{24} ν / yr*

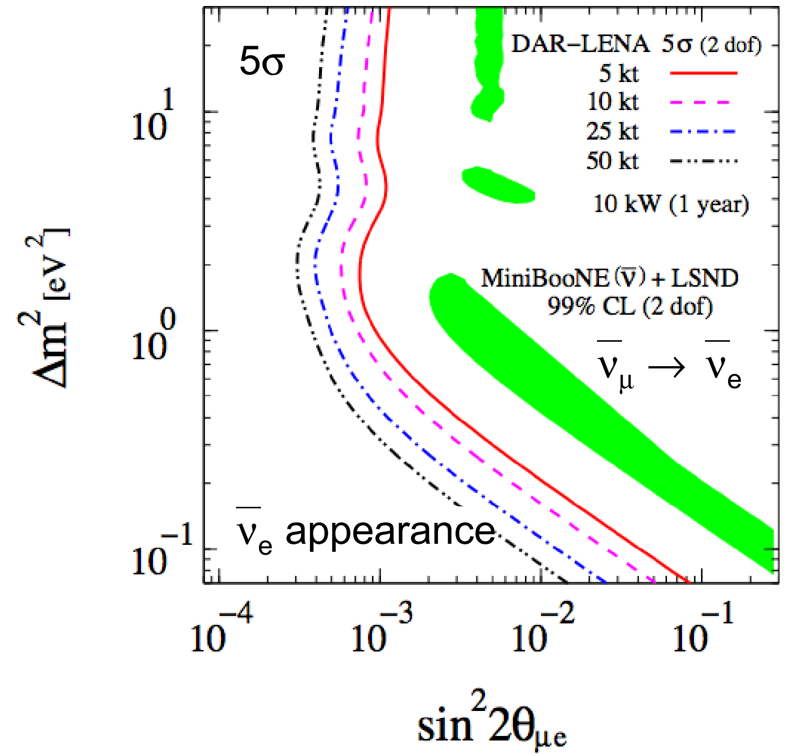
Scintillation Detectors with DAR Neutrino Sources

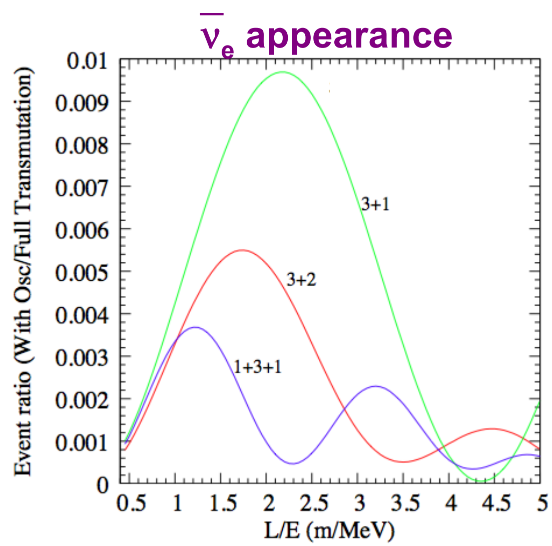
Example: LENA Scintillation Detector

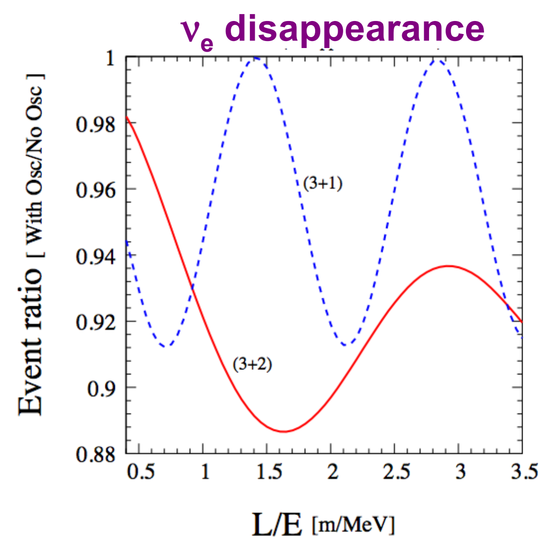
(Part of the European LAGUNA Project)

- For 5σ coverage, only need 10 kW source with 5 kton detector
- Deep location (4000 mwe) so minimal cosmic muon backgrounds
- Appearance and Disappearance possible









Agarwalla, Conrad, and MHS: arXiv:1105.4984 (JHEP 1112 (2011) 085)

OscSNS: DAR Neutrino Source at SNS (ORNL)

arXiv:0810.3175

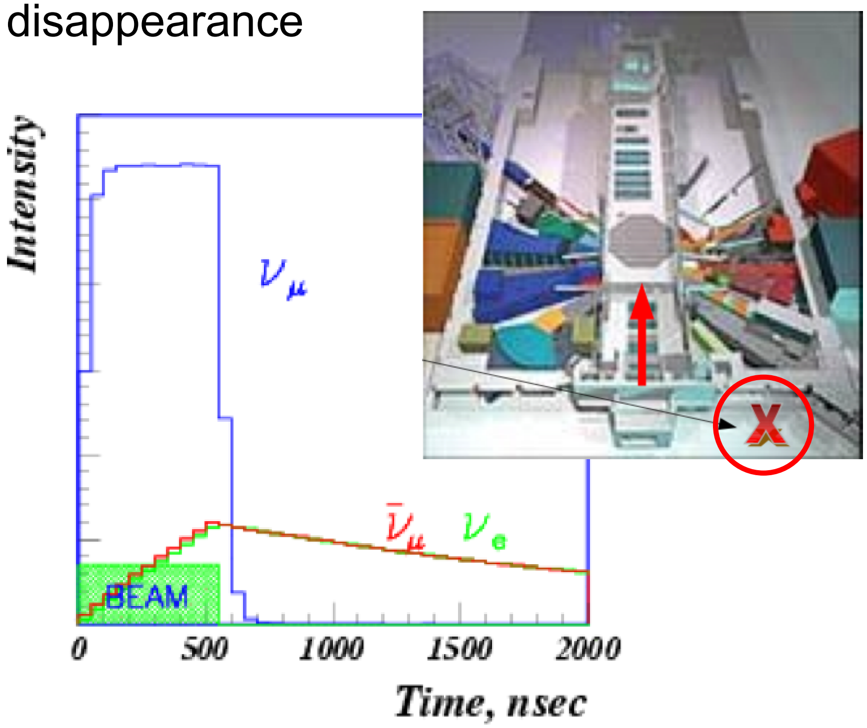
- Spallation neutron source at ORNL
- ~1GeV protons on Hg target (1.4MW)
- 6.2% Duty factor reduces backgrounds
- Time structure 695ns pulses at 20 Hz can separate ν_μ from $\bar{\nu}_\mu$ and ν_e
- 800 ton MiniBooNE style detector 60m from target
- Can do $\bar{\nu}_e$ appearance and other types of disappearance

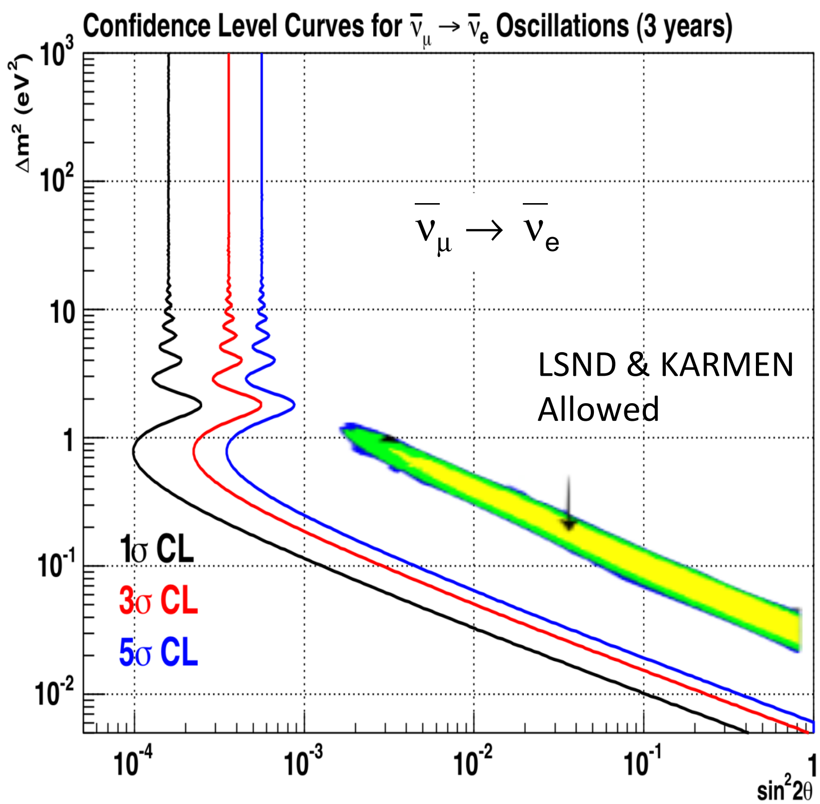
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\nu_e \rightarrow \nu_s$

$\nu_\mu \rightarrow \nu_s$

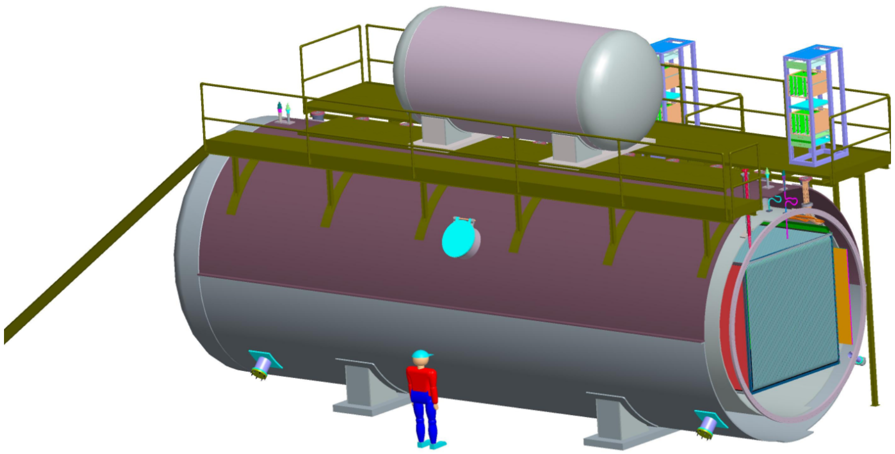
$\bar{\nu}_\mu \rightarrow \bar{\nu}_s$

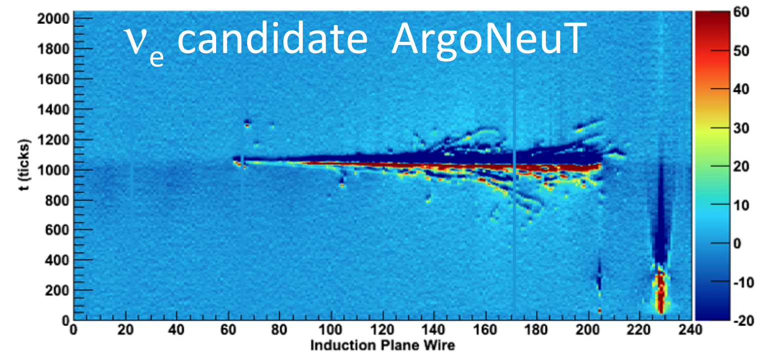




Accelerator ν_μ / $\bar{\nu}_\mu$ Beams using Pion Decay-in-Flight

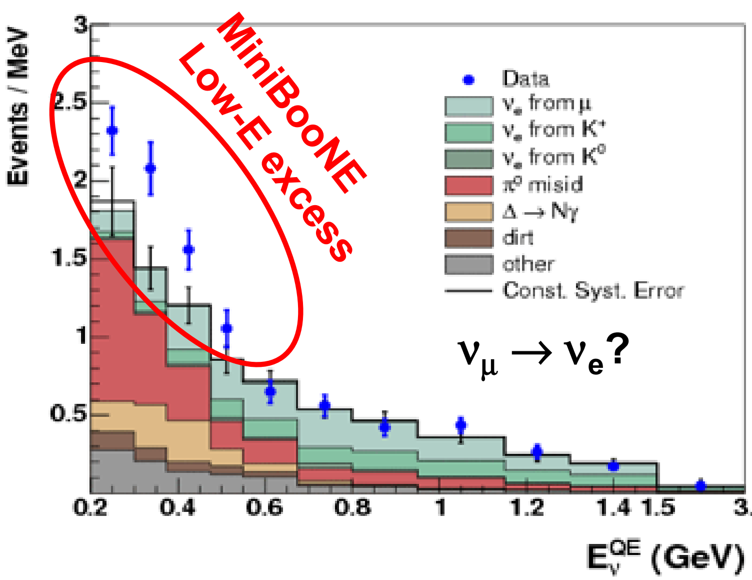
MicroBooNE Experiment (Under Construction) using Fermilab Booster Neutrino Beamline (BNB)



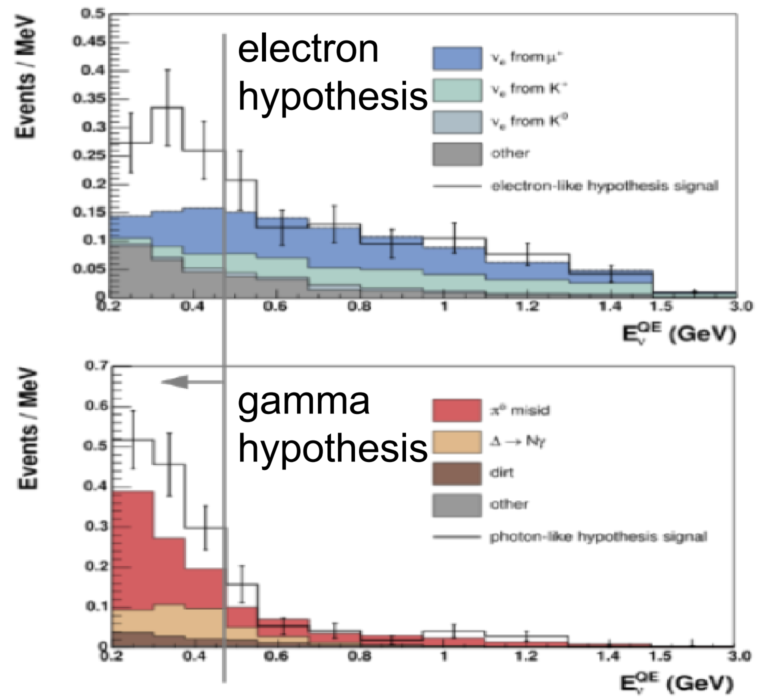


Use topology and dE/dx to differentiate electrons (signal) from gammas (background)

(Indistinguishable in Cerenkov imaging detectors)



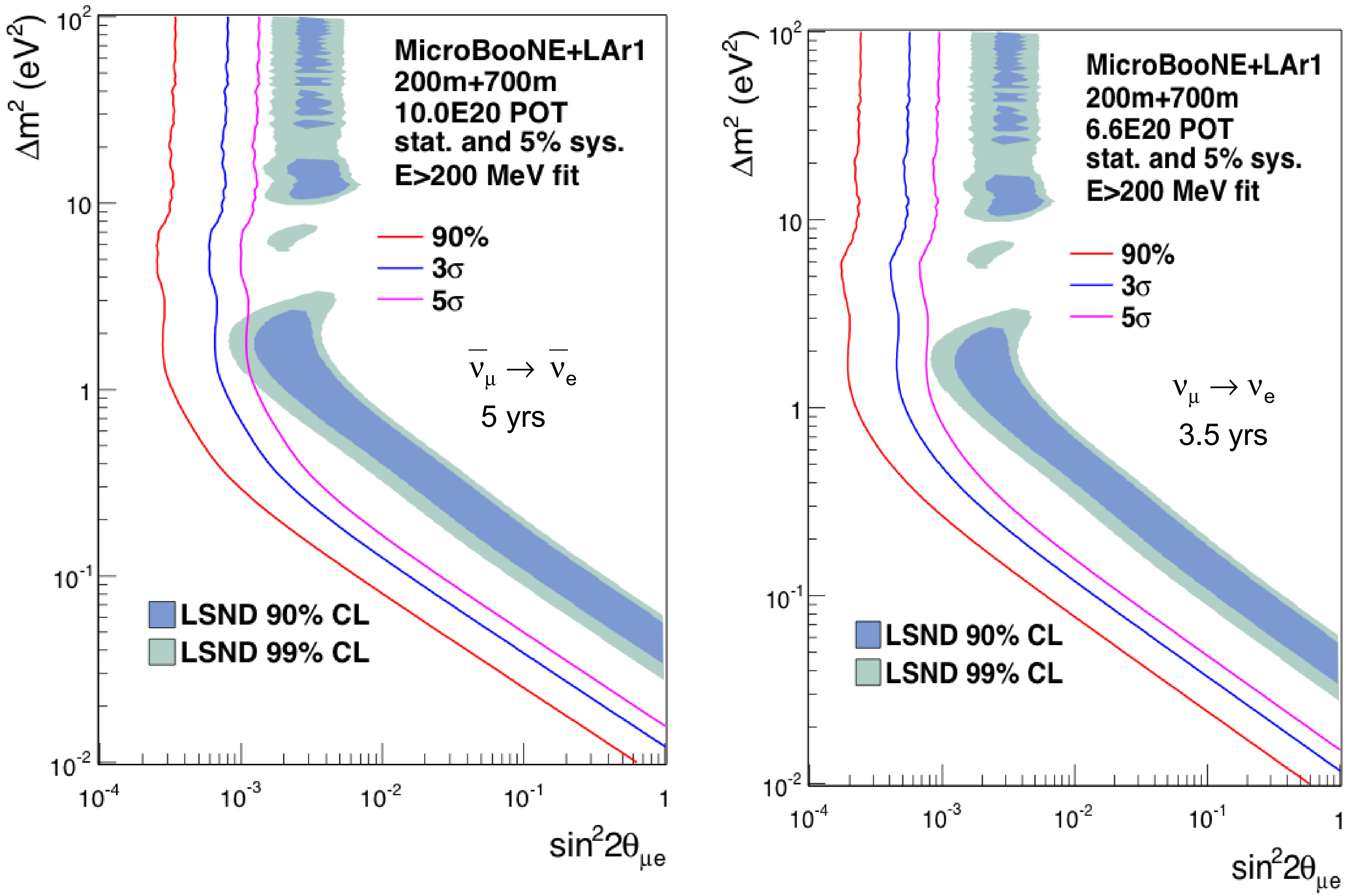
Is it electrons or gammas?



Proposed LAr1kton at Fermilab Booster ν Beamline (BNB)

- To directly address LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal, use multiple detectors in the Fermilab BNB
- Large (1 kton fiducial) LAr detector at 700m plus MicroBooNE at 200m (also maybe MiniBooNE with scintillator at 540 m)
- LAr capabilities significantly reduces gamma and other backgrounds

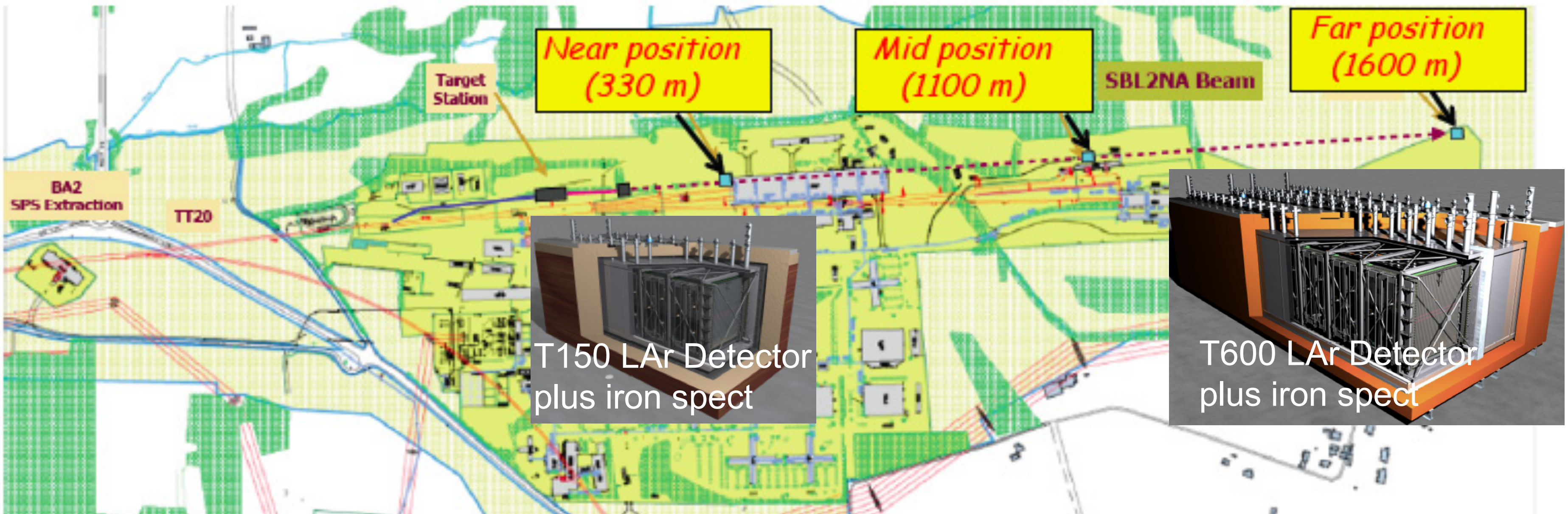
LAr1kton Sensitivity



CERN SPS: Two (or Three) Detector Proposal using Liquid Argon and Iron Spectrometers

- Combined ICARUS and NESSiE Collaborations

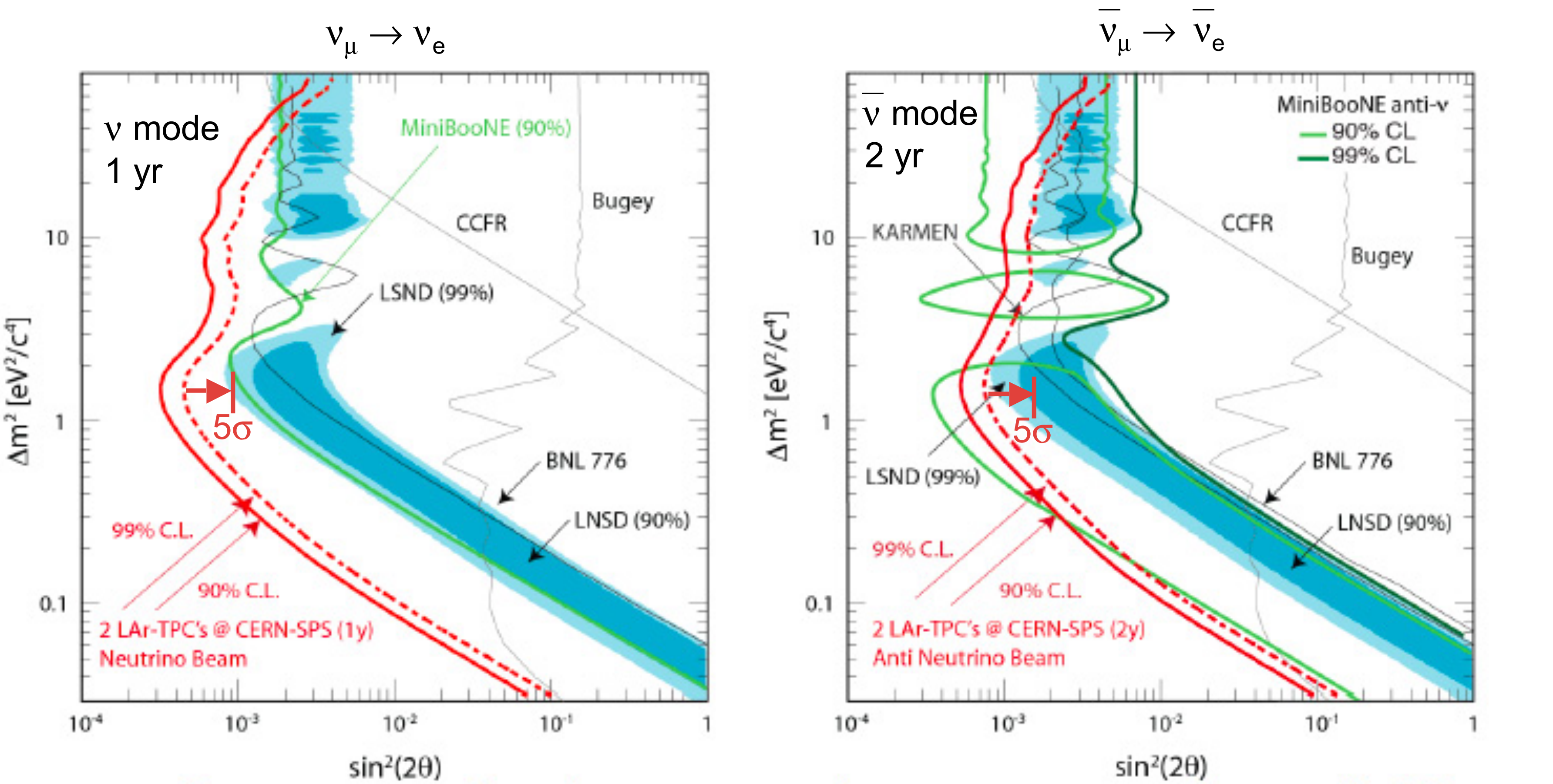
New Neutrino Facility in the CERN North Area



$\langle E_\nu \rangle \approx 2$ GeV

100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe l =100m, ø = 3m; beam dump: 15m of Fe with graphite core, followed by μ stations.

CERN SPS Appearance Sensitivity



Expected sensitivity for the proposed experiment: ν_μ beam (left) and anti-ν_μ (right) for 4.5 10^{19} pot (1 year) and 9.0 10^{19} pot (2 years) respectively. LSND allowed region is fully explored in both cases.

Also, ν_μ and $\bar{\nu}_\mu$ disappearance

Summary and Conclusions

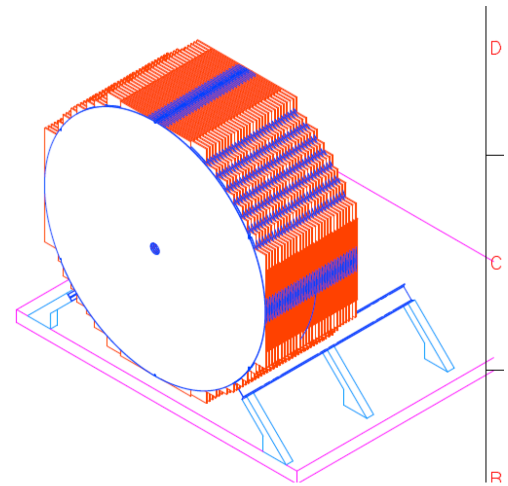
- We are making significant progress is measuring the oscillation parameters
  - θ_{13} angle measured and is fairly large $\Rightarrow \sin^2 2\theta_{13} \sim 0.10 \pm 0.02$
  - Now moving on to measuring:
    - Mass hierarchy
    - CP violation δ
    - plus better $\sin^2\theta_{23}$ and Δm^2_{23}

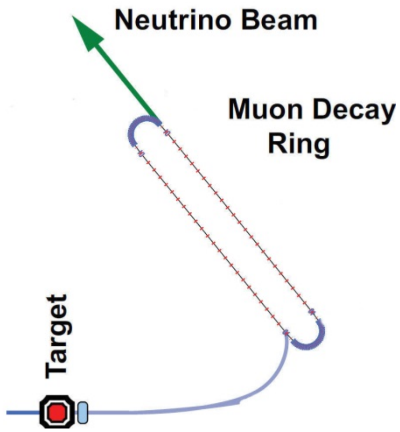
- Establishing the existence of sterile neutrinos would be a major result for particle physics
  - Several hints in the $\Delta m^2 \sim 1$ eV^2 region
    - Some tension with lack of ν_μ disappearance signals
  - Many proposals and ideas for sterile neutrino searches
    - New experiments have better sensitivity (~5σ level) with capabilities to see oscillatory behavior and reduce backgrounds

Backup

Neutrinos from STORed Muons - νSTORM

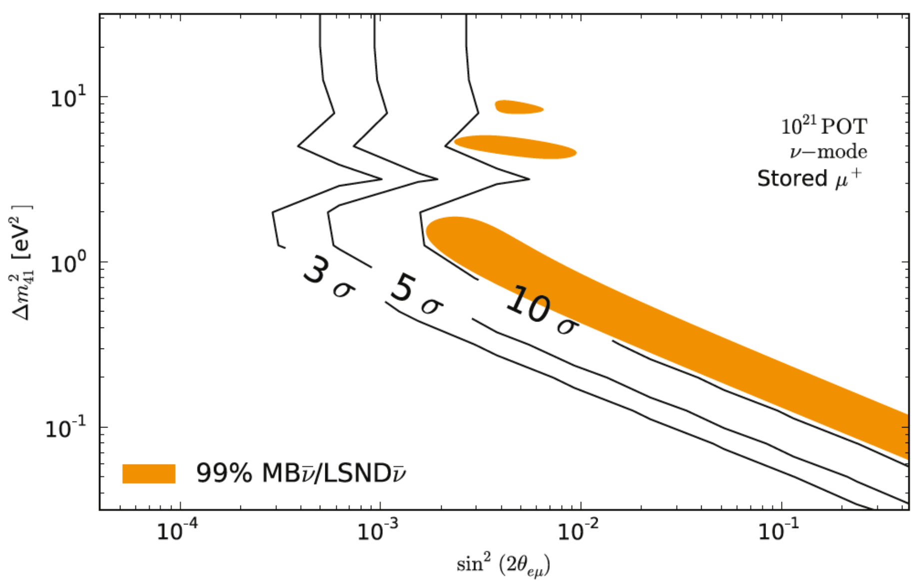
- Simplest implementation of the NF concept
  - 60 GeV protons on solid target (100 kW)
  - Horn capture and π transfer
  - Decay ring
- No new technology is required
  - Little R&D is needed
    ≈"Technology" ready





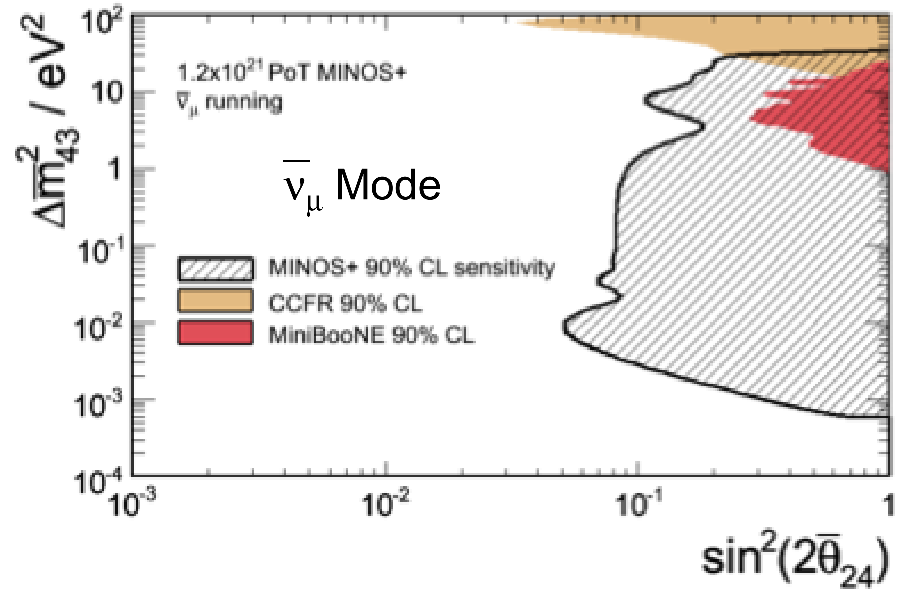
- Performance assumptions:
  - 10^{21} 60 GeV/c POT
- Yields ≈ $2X10^{18}$ useful ν
- ≈2000 m baseline
- 1.3 kT Minos-like detector: SuperB IND
  - Thinner plates
  - 2T B

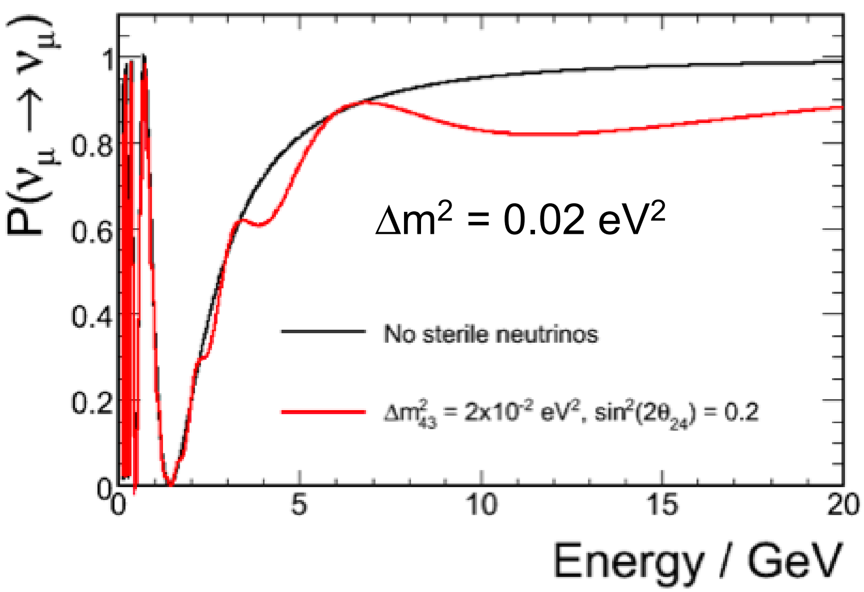
$\nu_e \rightarrow \nu_\mu$: CPT Invariant mode of LSND/MinBooNE

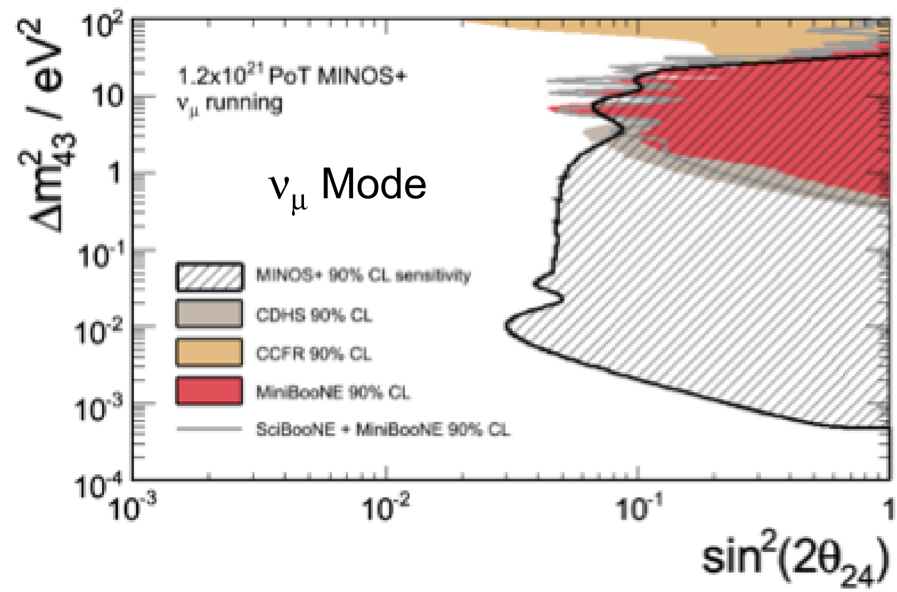


MINOS+ Running (3 yrs) During Nova Era

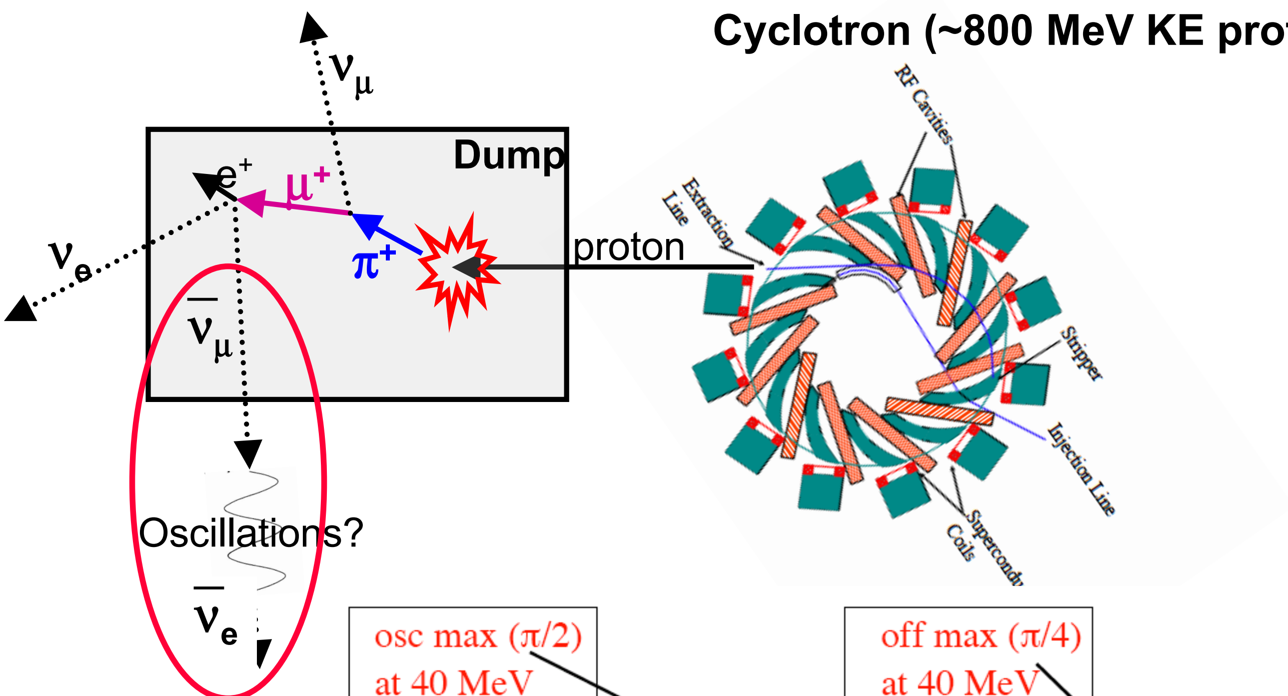
- MINOS+ Sensitivity to sterile neutrinos through neutral current (NC) disappearance between near and far detector
  - If disappearance seen, must be to a sterile neutrino with no NC interactions
- Sensitivity to Δm^2 values to below 0.01 eV^2



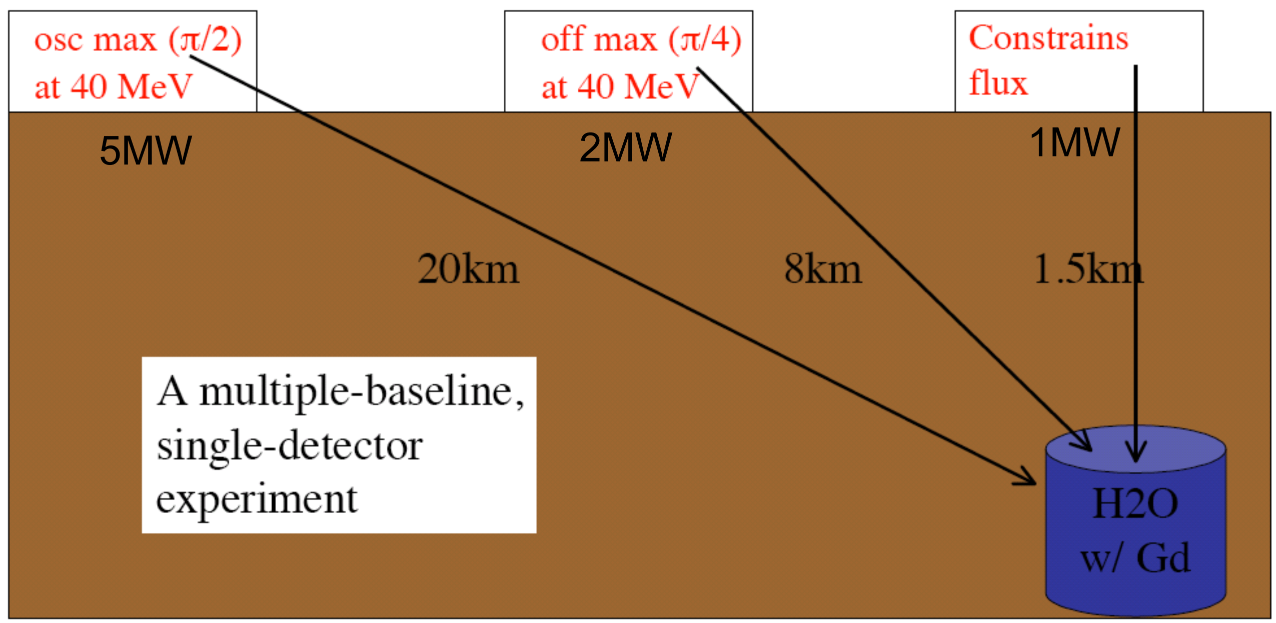




Daedalus Experiment: Antineutrino Source for CP Measurements



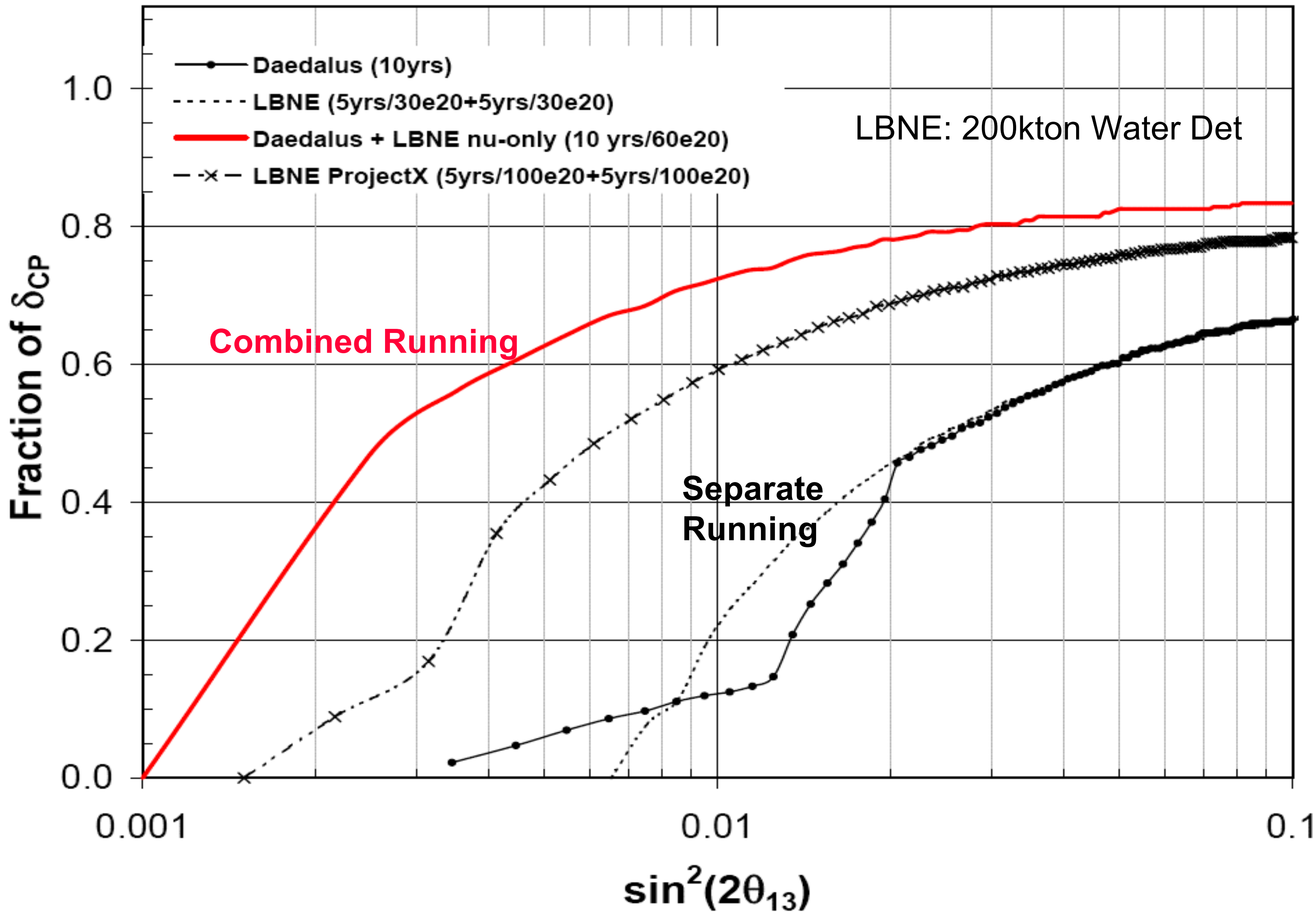
- Combine:
  - High statistics Daedalus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - High statistics Longbaseline $\nu_\mu \rightarrow \nu_e$



(Described in: Conrad/Shaevitz, PRL104,141802 (2010), Alonso et al., arXiv:1006.0260 [physics.ins-det] and 1008.4967 [hep-ex])

Exclusion of δ_{CP}= 0^0 or 180^0 at 3σ

Combined running LBNE plus Daedalus gives best sensitivity

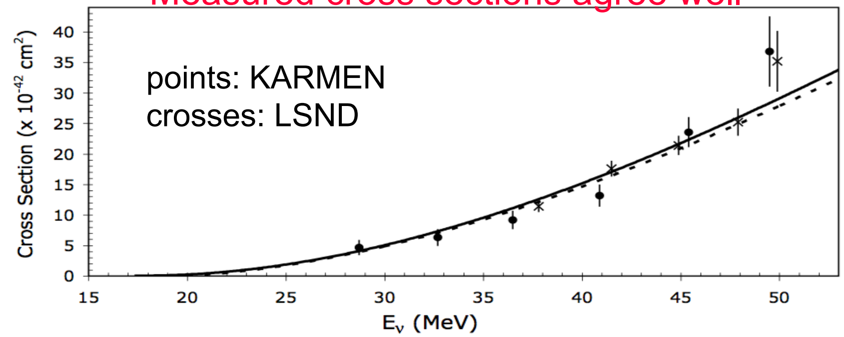


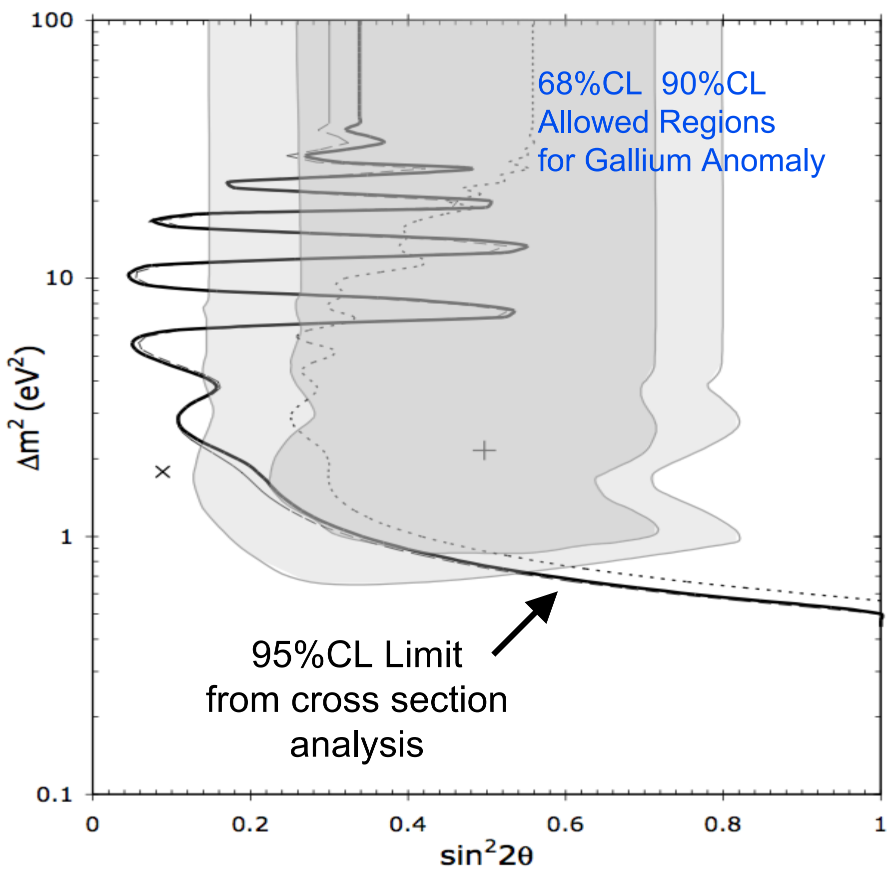
Gallium Anomaly: ν_e Disappearance?

- Gallium SAGE and GALLEX solar neutrino experiments used MCi ^{51}Cr and ^{37}Ar sources to calibrate their detectors
  - A recent analysis claims a significant (3σ) deficit
    (Giunti and Laveder, 1006.3244v3 [hep-ph])
    - Ratio (observation/prediction) = 0.76 ± 0.09
    - An oscillation interpretations gives $\sin^2 2\theta > 0.07, \Delta m^2 > 0.35 eV^2$

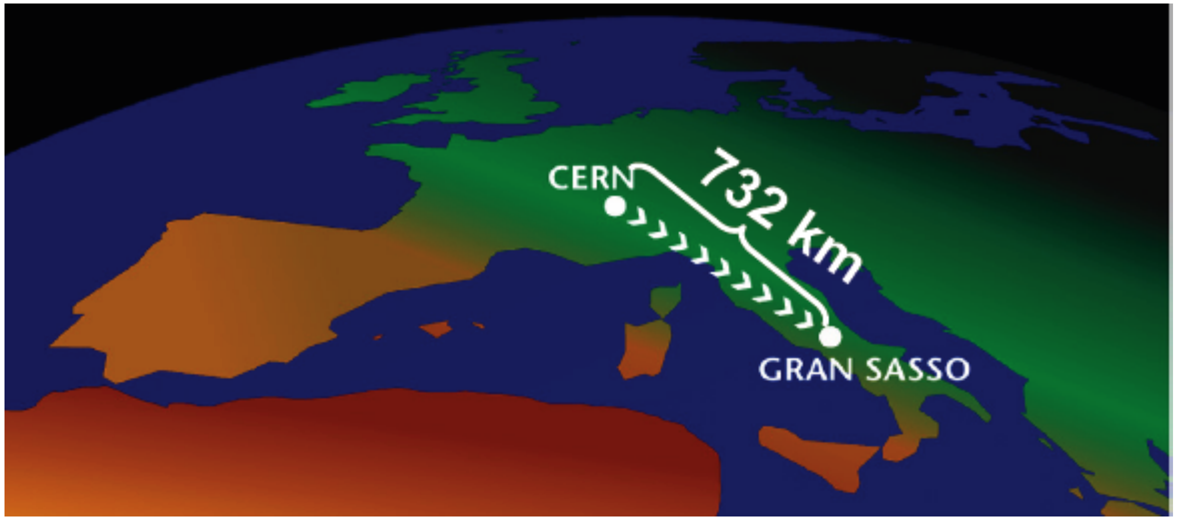
- Such an oscillation would change the measured ν_e-Carbon cross section since assumed flux would be wrong
  - Comparing the LSND and KARMEN measured cross sections restricts possible ν_e disappearance.
    (Conrad and Shaevitz, 1106.5552v2 [hep-ex])
    - Experiments at different distances: LSND (29.8m) and KARMEN (17.7m)

Measured cross sections agree well

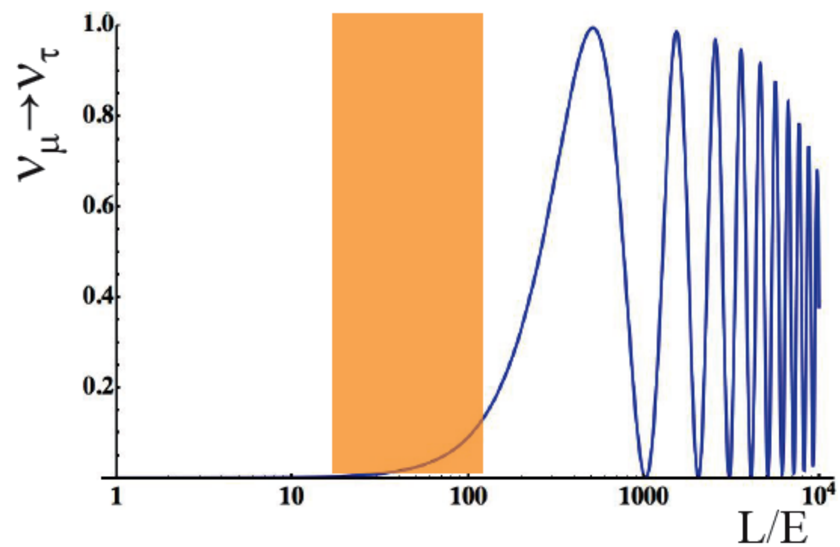




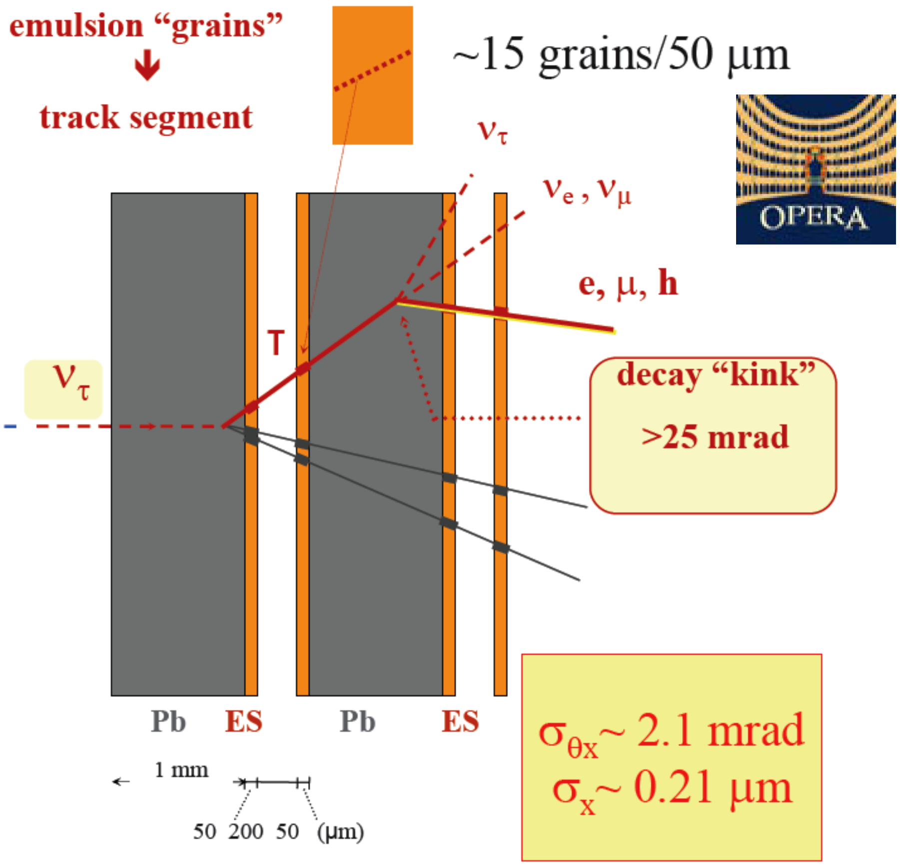
OPERA and ICARUS: ν_τ Appearance Search



- Uses 400 GeV protons to produce neutrino beam $\langle E_\nu \rangle \approx$ 17 GeV
- $\langle E_\nu \rangle$ above threshold to produce τ leptons from ν_τ
- $\langle L/E \rangle \approx 43$ so oscillation probability for Δm^2_{atm} is small



OPERA: Nuclear Emulsion plus Lead



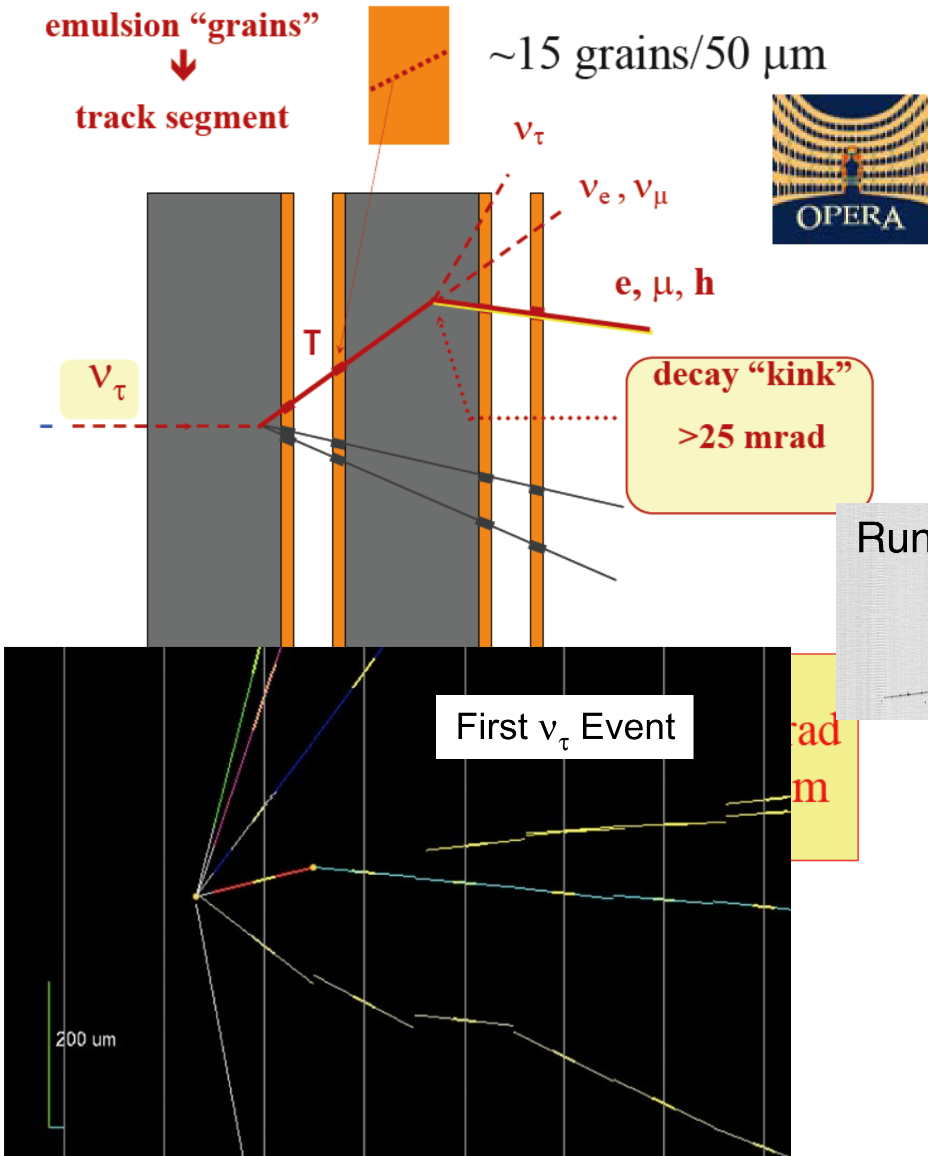
- Scintillator Strips isolate emulsion brick with an event
- Robot then picks out brick to be scanned.
- Currently running since 2007
- Expect about 15 ν_τ events in 5 years

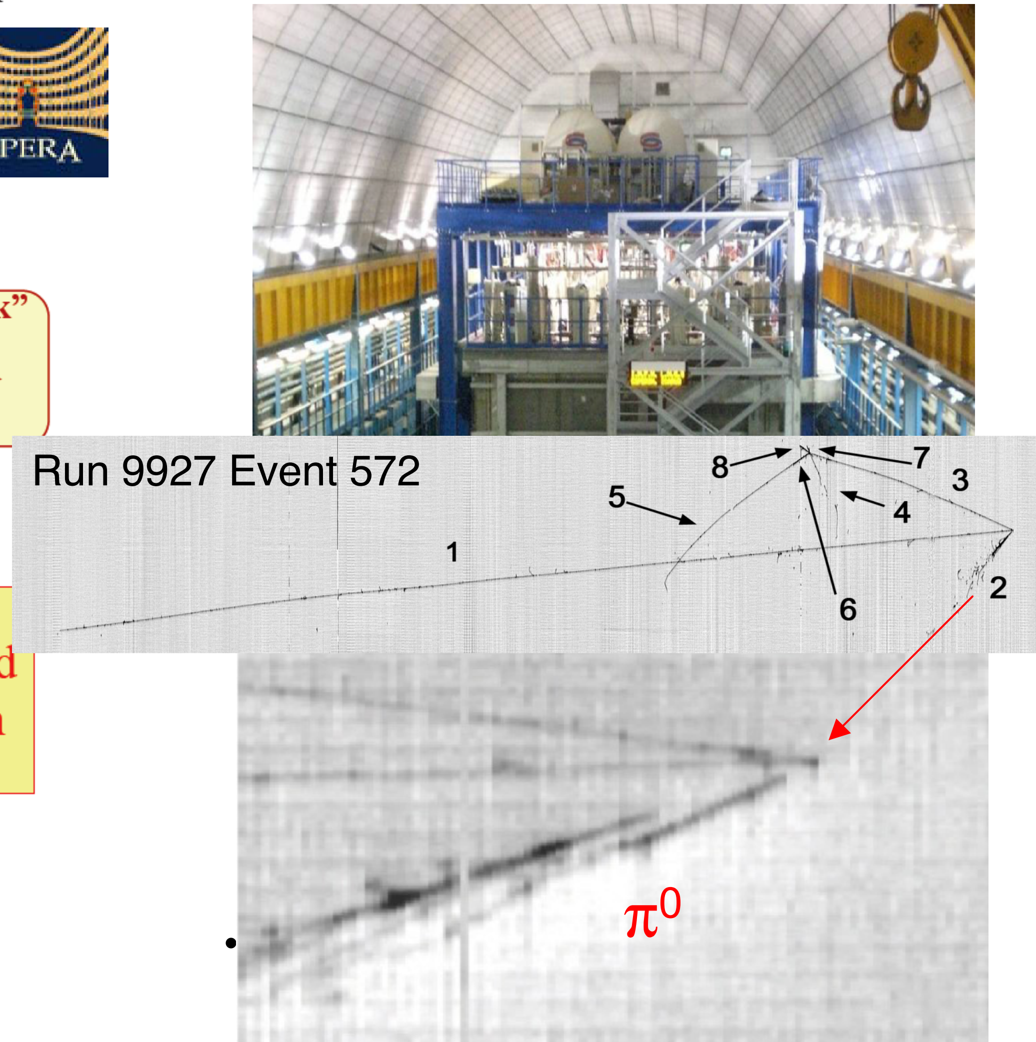
ICARUS: Liquid Argon TPC 600 Tons

- Will use kinematic reconstruction to isolate ν_τ-events.

OPERA: Nuclear Emulsion plus Lead

ICARUS: Liquid Argon TPC 600 Tons





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