# Putting the Short-Baseline Anomalies to the Test

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4th Neutrino Workshop
Univ. Chicago, May 18-19, 2012

U.S. DEPARTMENT OF ENERGY

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# INTRODUCTION

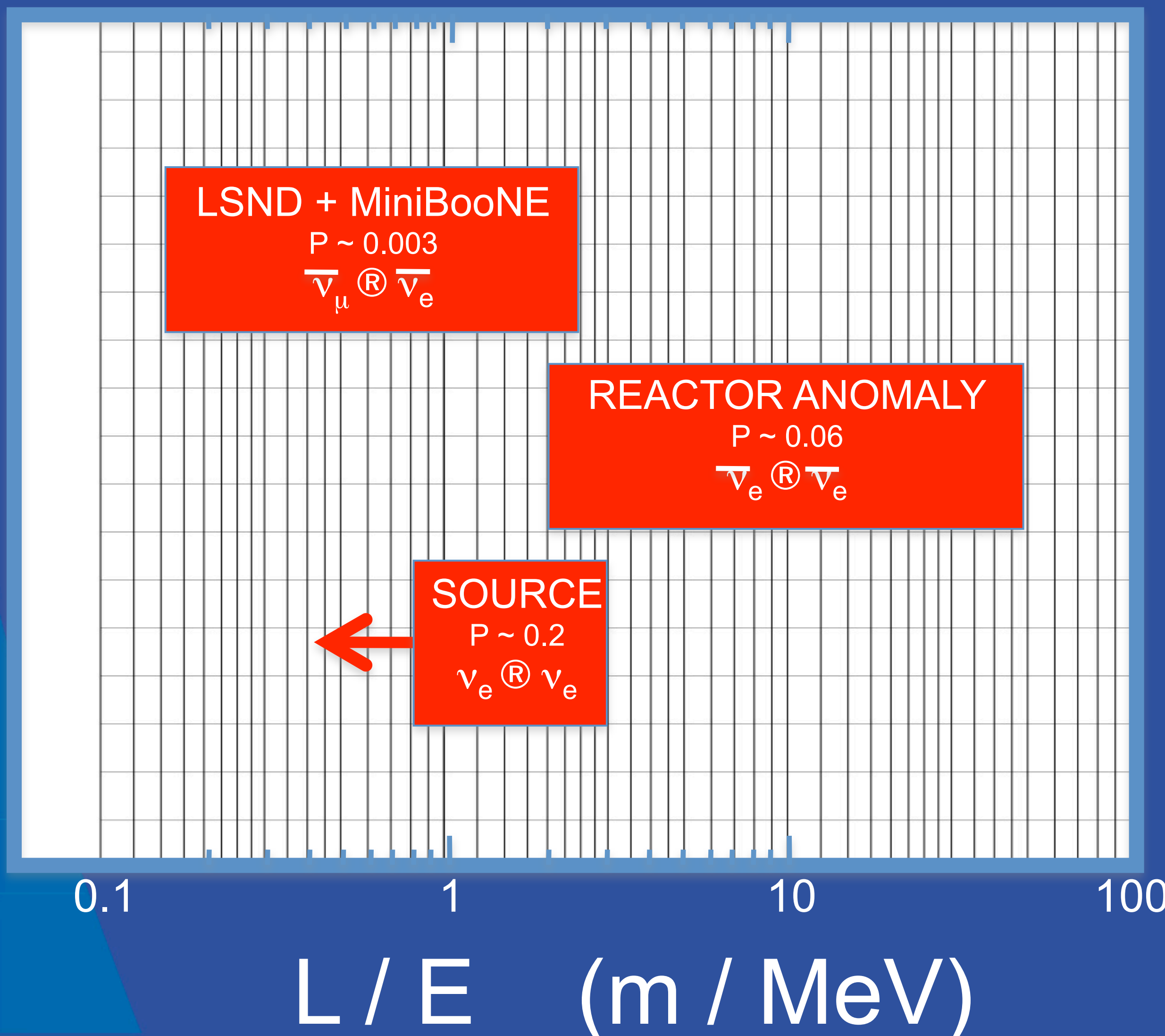
- There are some indications that three-flavor mixing might not be the whole story. These indications come from:
  - Reactor anti-neutrino measurements at short distances
  - Radioactive source measurements
  - Accelerator-based neutrino & anti-neutrino measurements (LSND & MiniBooNE)

- In addition, cosmological measurements provide hints that there may be more than 3 neutrino states.

- The tensions with 3-flavor mixing are at the level of $2\sigma$ – $4\sigma$. None of them are definitive. Some or all of them may be due to statistical fluctuations and/or systematic effects.

- However, taken together, the experimental evidence for the presence or absence of neutrino flavor transitions on a timescale characterized by L/E ~ 1 m/MeV is confusing, and needs experimental clarification.

# L/E COVERAGE







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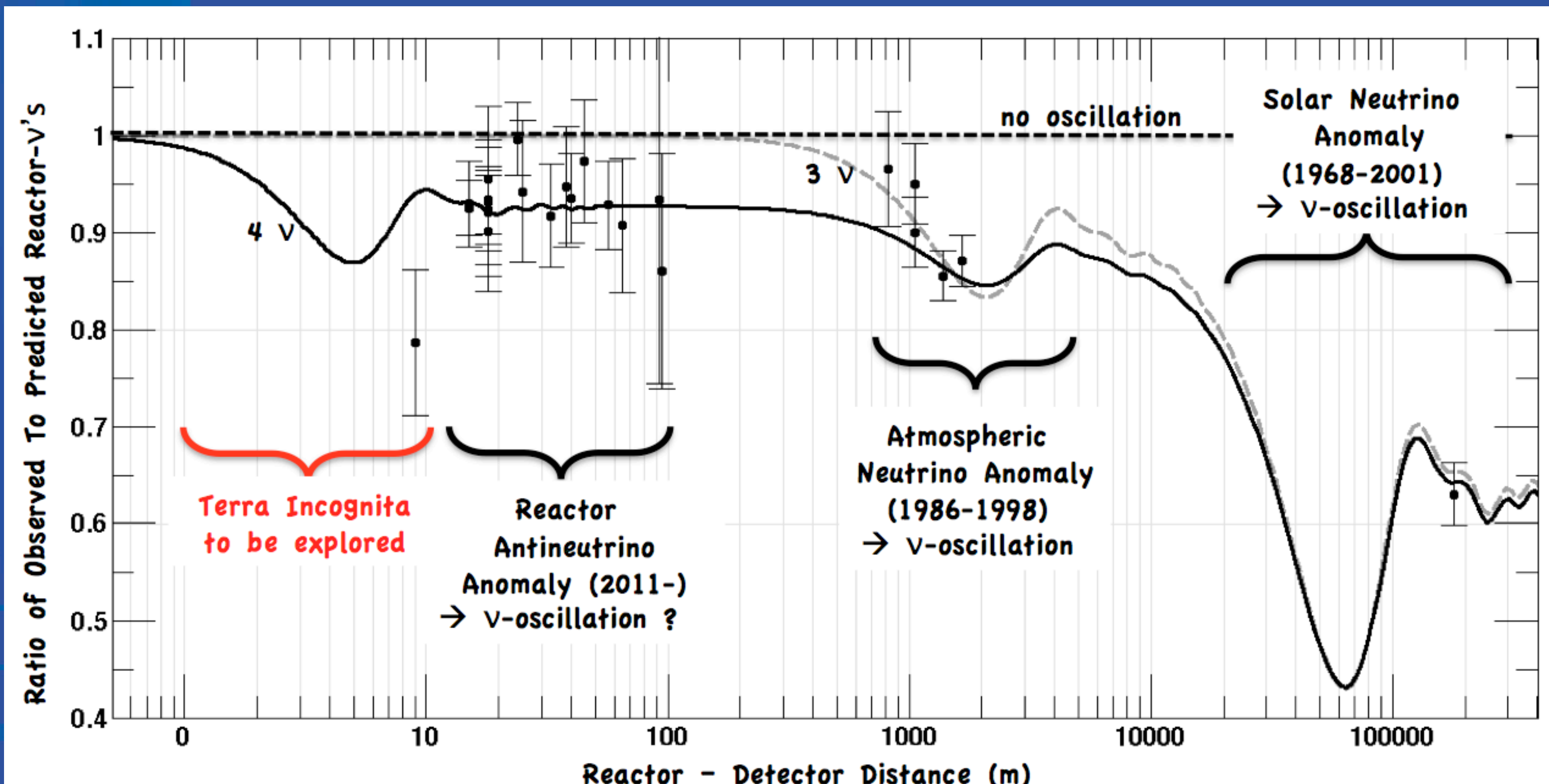
# REACTOR BASELINES

We would like reactor experiments to probe shorter baselines





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# REACTOR INITIATIVES

- To obtain convincing results, experiments are being proposed that:
  - Use research reactors with a simpler fuel mix to reduce uncertainties on the flux calculation.
  - Measure the spectrum as well as the rate.
  - Use small-core reactors to minimize baseline-smearing (of the distorted spectrum).
  - Use more than one baseline to search for L/E differences & minimize impact of flux uncertainties.
  - Get as close as possible with the “near” detector

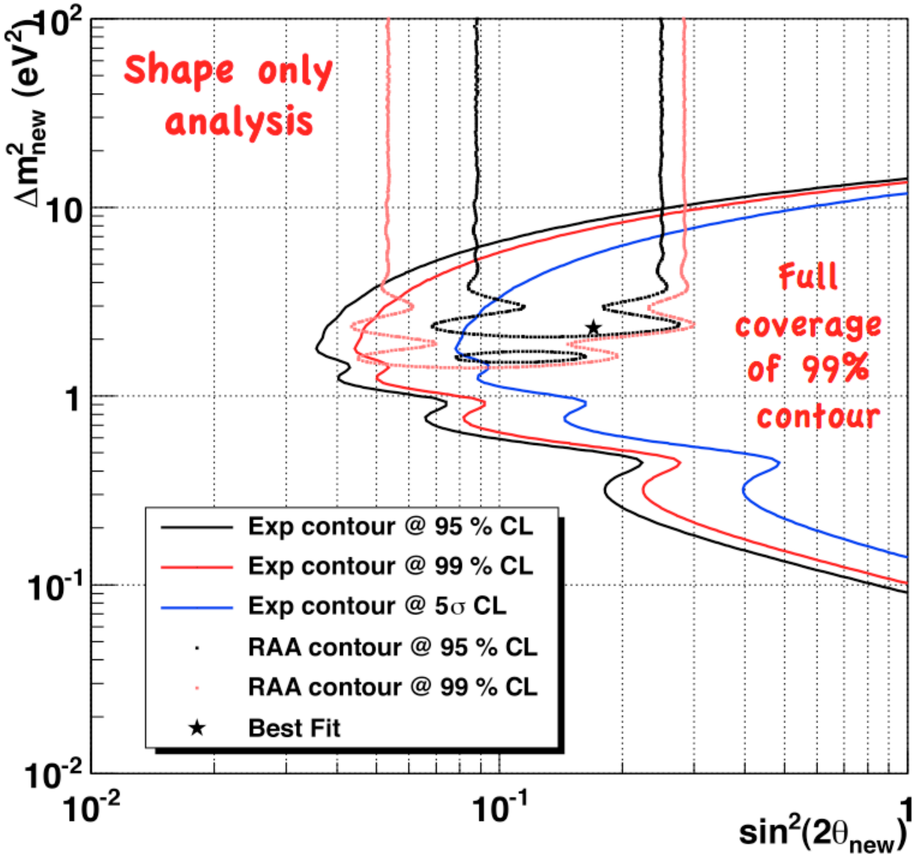
# REACTOR INITIATIVE LIST

| Proposal | Reactor | Fuel (#fissions) | Core Size (m) | <L> (m) | Depth (mwe) | Status | Comment |
|---|---|---|---|---|---|---|---|
| Nucifer Saclay | Osiris 70 MW | $^{235}U$ ON-OFF cycle | <1 | 7 | 5 | Data Taking | Non proliferation 1 $m^3$ Gd-LS Mostly Rate + Shape? |
| Stereo Genoble | ILL 50 MW | $^{235}U$ ON-OFF cycle | <1 | 10 | 10 | Proposal | 2 $m^3$ Gd-LS Rate + Mostly shape |
| SCRAMM (Ca) | San-Onofre 3 GW PWR | $^{235,238}U$ $^{239,241}Pu$ | 3x3.8 | 24 | 30 | Proposal | 2 $m^3$ Gd-LS Mostly Rate + Shape |
| SCRAMM (Idaho) | ATR 150 MW | $^{235}U$ ON-OFF cycle | <1 | 12 | 15 | Proposal | 2 $m^3$ Gd-LS Rate + Mostly shape |
| DANSS (Russia) | KNPP 3 GW PWR | $^{235,238}U$ $^{239,241}Pu$ | few | 14 | 70 | Being Built | Segmented detector 1 $m^3$ Rate + Shape? |
| NIST (US) | NCNR 20 MW | $^{235}U$ ON-OFF cycle | ≈1 | 4-11 | 0 | Proposal | Rate + Mostly shape |

T. Lasserre, European Strategy for ν Osc. Physics, CERN

# REACTOR PROPOSAL EXAMPLE

## Stereo, ILL (courtesy D. Lhuillier)




- 300 days, 50 W, $L_0$ = 8 m
- S/B = 1.5
- Threshold $E_{vis}$>2 MeV
- Neutron cut = 6 MeV
- 5 baseline bins of 40 cm
- Complete det. Response (Geant4)
- 2% E scale + error budget of predicted spectra
- ~ 700 $\bar{\nu}$/d

→Do NOT rely on Reactor Flux Prediction

→Cover the reactor antineutrino anomaly parameter space

# SOURCE INITIATIVES

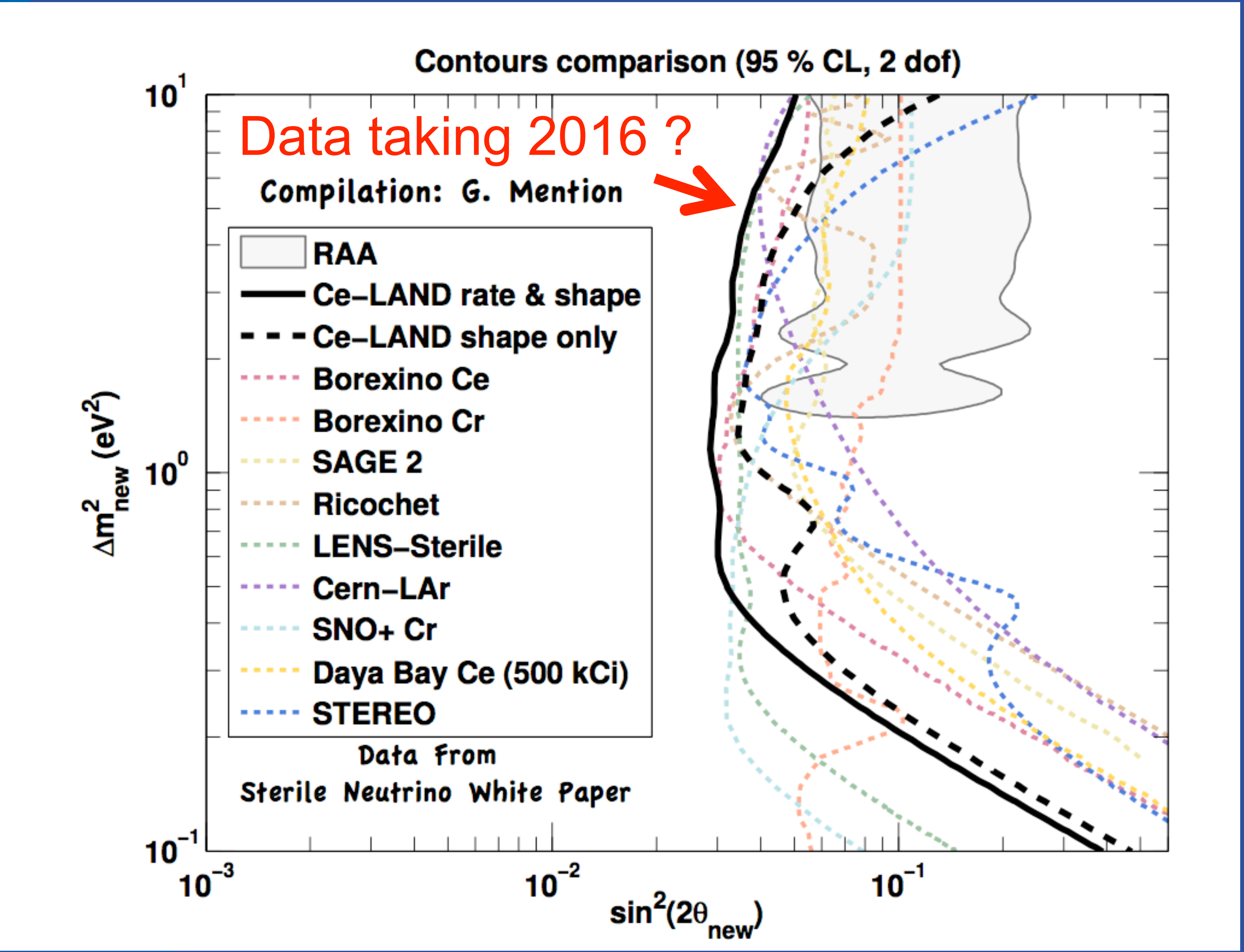
- To be convincing, would like to see a modulation of the event rate with L within the detector. This means the source must be either within the detector, or just outside the detector.
- Must produce an intense source of the right type. Since detectors for these experiments already exist, the challenges and timescales associated with source production play an important role in determining what experiment can be done & when.

# SOURCE EXPERIMENT INITIATIVES

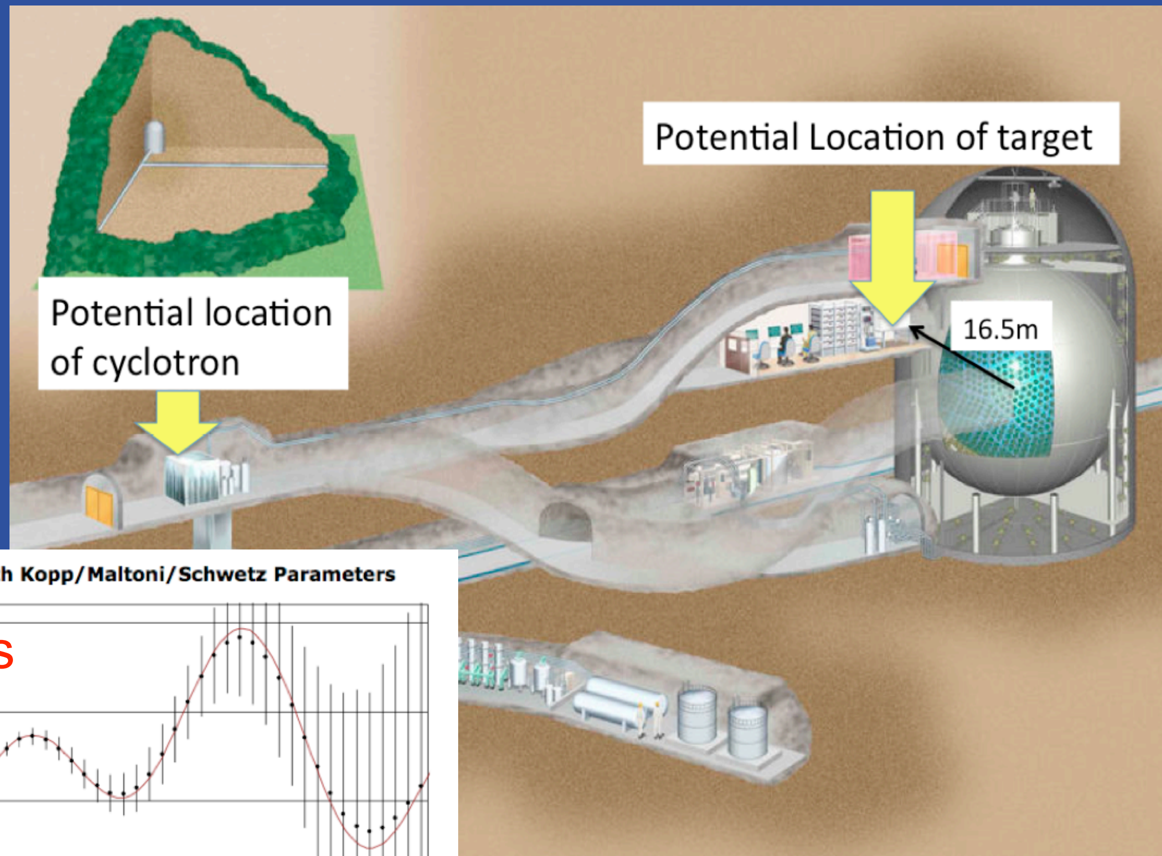
| Type | channel | Background | Source | Production | Activity (Mci) | | Proposal |
|---|---|---|---|---|---|---|---|
| $\nu_e$ | $\nu_e e \rightarrow \nu_e e$<br>Compton edge<br>5% $E_{res}$<br>15cm $R_{res}$ | radioactivity (managable)<br>Solar $\nu$ (irreducible)<br>$\nu$-Source (out ok but in ?) | $^{51}Cr$<br>0.75 MeV<br>$t_{1/2}$=26d | $n_{th}$ irradiation in Reactor | in | >3 | Baksan LENS |
| | | | | | out | 5-10 | Borexino SNO+ |
| | | | $^{37}Ar$<br>0.8 MeV<br>$t_{1/2}$=35d | $n_{fast}$ irradiation in Reactor (breeder) | in | >1 | - |
| | | | | | out | 5 | Ricochet (NC) |
| $\bar{\nu}_e$ | $\bar{\nu}_e p \rightarrow e^+ n$<br>$E_{th}$=1.8 MeV<br>$(e^+,n)$ Coincidence<br>5% $E_{res}$<br>15cm $R_{res}$ | reactor $\nu$ & $\nu$-Source<br>→<br>Background free! | $^{144}Ce$<br>E<3MeV<br>$t_{1/2}$=285d | spent nuclear fuel reprocessing | in | 0.005-0.05 | CeLAND Borexino |
| | | | | | out | 0.5 | Daya-Bay |
| | | | $^{90}Sr$<br>$^{106}Rh$ | | - | - | - |
| | | | $^{42}Ar$ | ? | - | - | - |

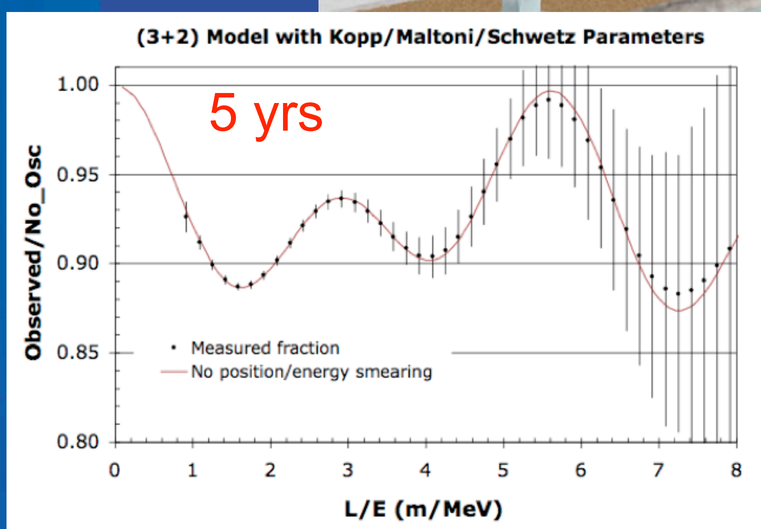
T. Lasserre, European Strategy for ν Osc. Physics, CERN

# SOURCE EXPERIMENT SENSITIVES



# In Situ SOURCE IDEA: IsoDAR




Shaevitz et al

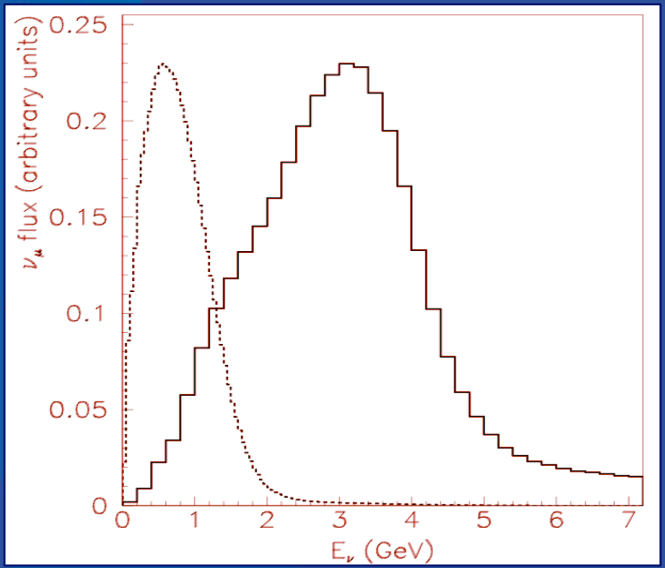
# ACCELERATOR-BASED INITIATIVES

- There is an active ongoing short-baseline program at Fermilab … so let's start with that.
  - Near term program
  - Beyond the near-term

- There are short-baseline "proposals" for other potential host labs:
  - CERN
  - ORNL (OscSNS) … see W. Louis talk
  - Cyclotron at a deep underground lab

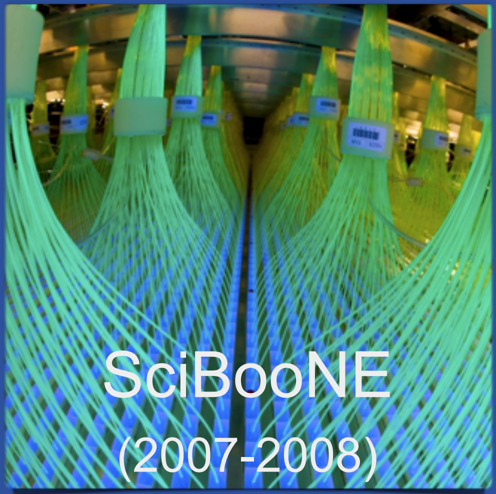
# TWO NEUTRINO BEAMS AT FNAL

- **NuMI** (Neutrinos at the Main Injector)
  - 120 GeV protons from MI
  - 90 cm graphite target
  - 675 m decay region
- **BNB** (Booster Neutrino Beam)
  - 8 GeV protons from Booster
  - 71 cm beryllium target
  - 50 m decay region



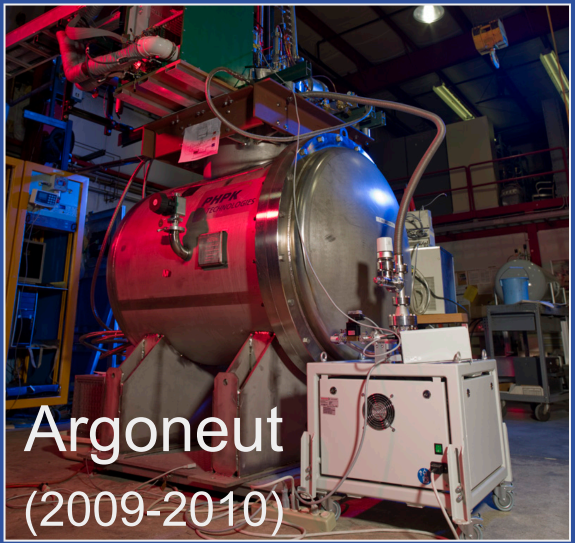

# RECENT FNAL SBL EXPERIMENTS

Booster Beam Experiments (+ NuMI Off-Axis)

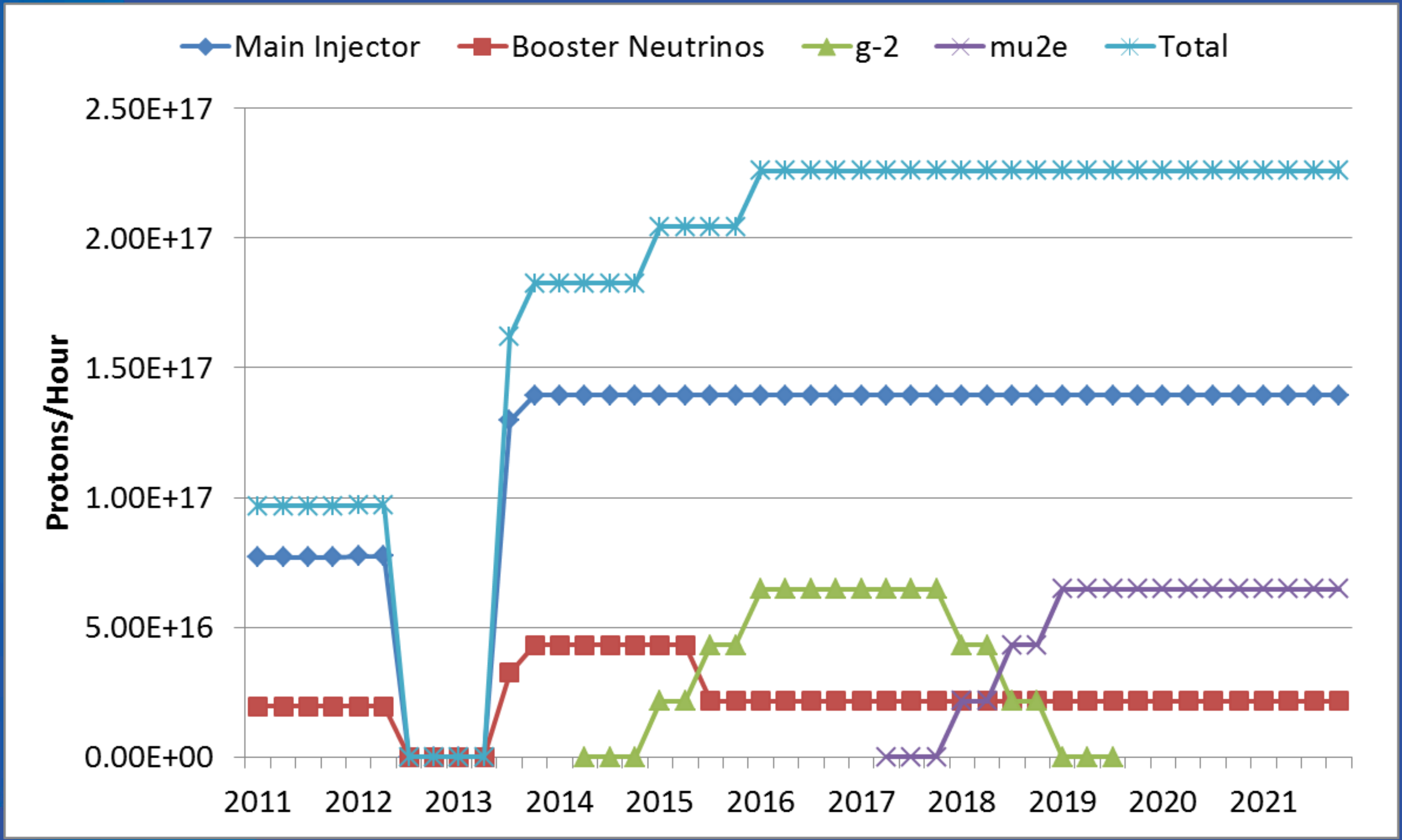




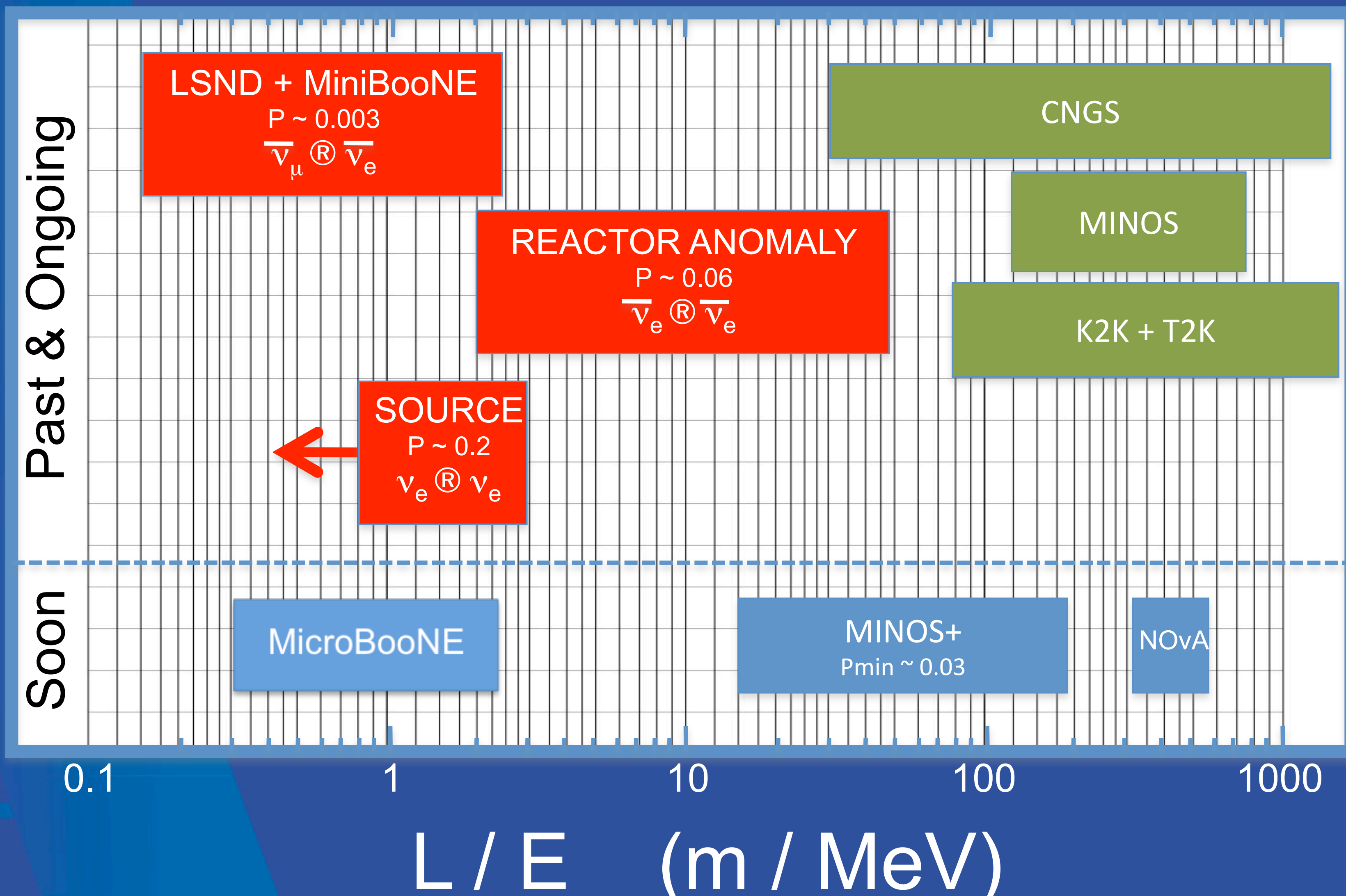
NuMI Beam Experiments




# PROTON BUDGET: NEAR FUTURE

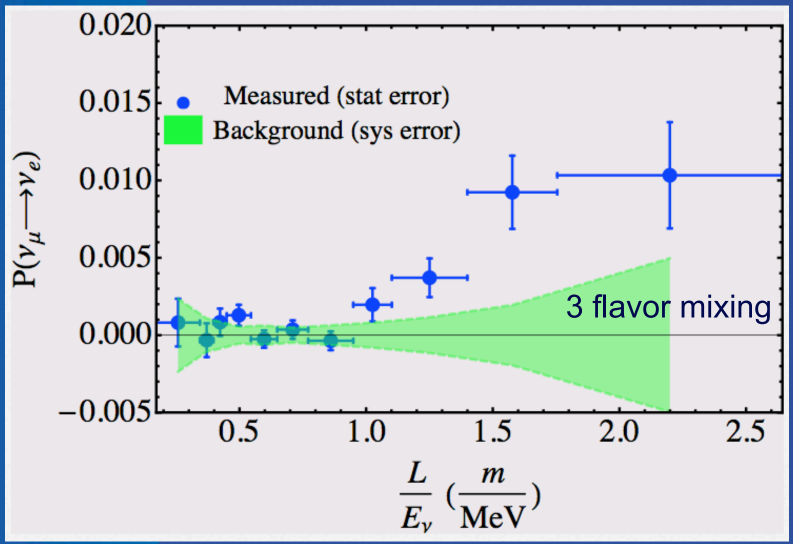


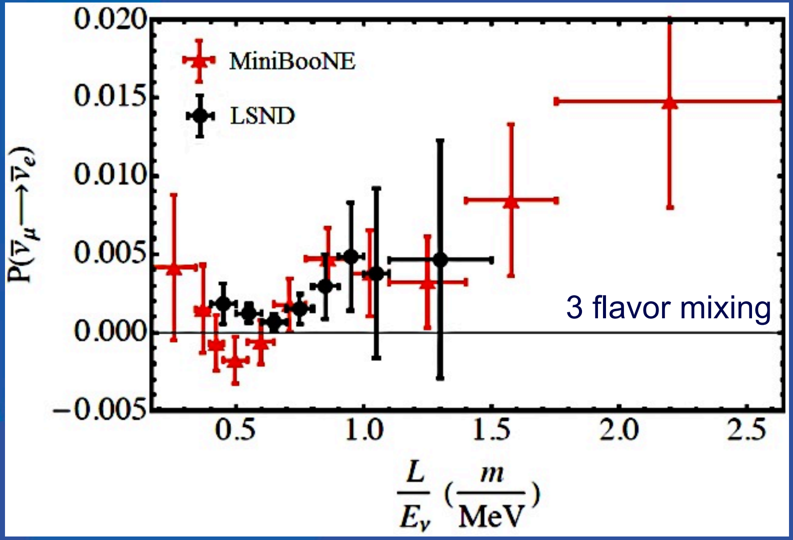
# L/E COVERAGE



Past & Ongoing
Soon
LSND + MiniBooNE
P ~ 0.003
$\bar{\nu}_\mu$ ® $\bar{\nu}_e$
REACTOR ANOMALY
P ~ 0.06
$\bar{\nu}_e$ ® $\bar{\nu}_e$
SOURCE
P ~ 0.2
$\nu_e$ ® $\nu_e$
CNGS
MINOS
K2K + T2K
MicroBooNE
MINOS+
Pmin ~ 0.03
NOvA
0.1
1
10
100
1000
L / E (m / MeV)

# THE LSND + MINIBOONE CHALLENGE




An ~3$\sigma$ excess of $\nu_\mu$ ® $\nu_e$ events above background seen by MiniBooNE at low neutrino energies (E < 0.5 GeV) . At higher energies data consistent with background.

A >3$\sigma$ excess of $\bar{\nu}_\mu$ ® $\bar{\nu}_e$ events above background seen by LSND + MiniBooNE, corresponding to a transition probability O(0.003).

Are these “signals” statistical fluctuations ? Are the “electrons” really photons ?

# MicroBooNE

- Short baseline experiment to explore the origin of the low energy excess reported by MiniBooNE, measure neutrino cross-sections, & develop liquid argon time projection (LArTPC) technology for future facilities.
- Will use a 170 ton LArTPC in the Booster Neutrino Beam (E=0.7 GeV) at a distance of L=0.5 km. It also sees the NuMI beam at a wide off-axis angle.
- European participation: Bern, Gran Sasso, L'Aquila

Data taking expected to start in 2014.

2-3 years run will yield $6 \times 10^{20}$ POT and $10^5$ neutrino events

**TABLE 2.** Summary of event rates in MicroBooNE's 60 ton volume by the neutrino mode BNB (6E20 POT), 468 m from the target.

| production mode | formula | #evt ($\times 10^3$) |
|---|---|---|
| CC quasi-elastic | $\nu_\mu + n \to \mu^- + p$ | 66 |
| NC elastic | $\nu_\mu + N \to \nu_\mu + N$ | 21 |
| CC resonance $\pi^+$ | $\nu_\mu + N \to \mu^- + N + \pi^+$ | 28 |
| CC resonance $\pi^\circ$ | $\nu_\mu + n \to \mu^- + p + \pi^\circ$ | 7 |
| NC resonance $\pi^\circ$ | $\nu_\mu + N \to \nu_\mu + N + \pi^\circ$ | 8 |
| NC resonance $\pi^\pm$ | $\nu_\mu + N \to \nu_\mu + N' + \pi^\pm$ | 3 |
| CC DIS | $\nu_\mu + N \to \mu^- + X, W > 2$ GeV | 1 |
| NC DIS | $\nu_\mu + N \to \nu_\mu + X, W > 2$ GeV | 0.5 |
| CC coherent $\pi^\circ$ | $\nu_\mu + A \to \mu^- + A + \pi^+$ | 3 |
| NC coherent $\pi^\pm$ | $\nu_\mu + A \to \nu_\mu + A + \pi^\circ$ | 2 |
| CC Kaon production | $\nu_\mu + N \to \mu^- + K + X$ | ~0.1 |
| NC Kaon production | $\nu_\mu + N \to \nu_\mu + K + X$ | <0.1 |
| others | | 4 |
| total | | 143 |



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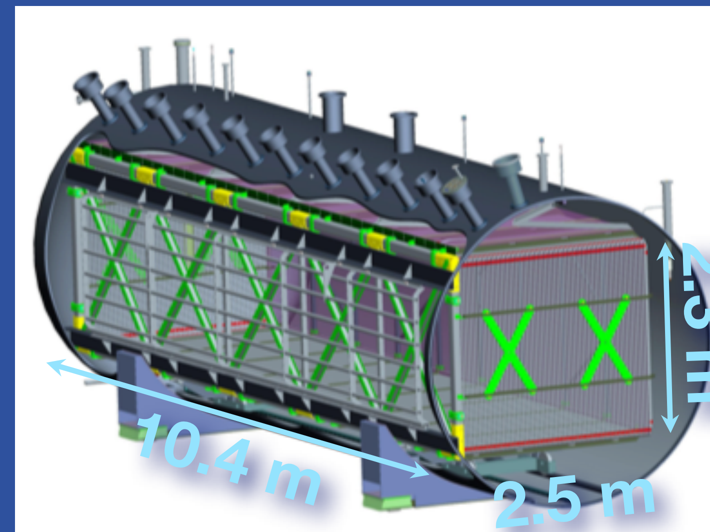
# MicroBooNE

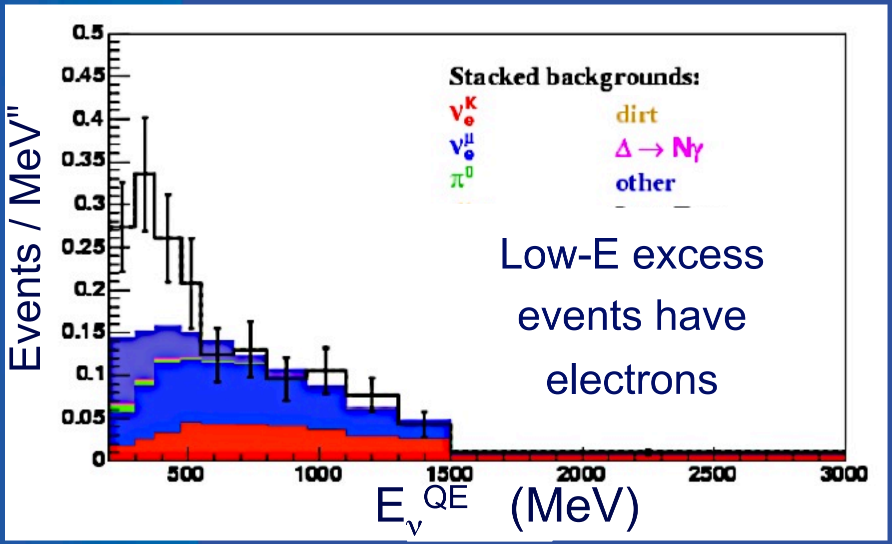


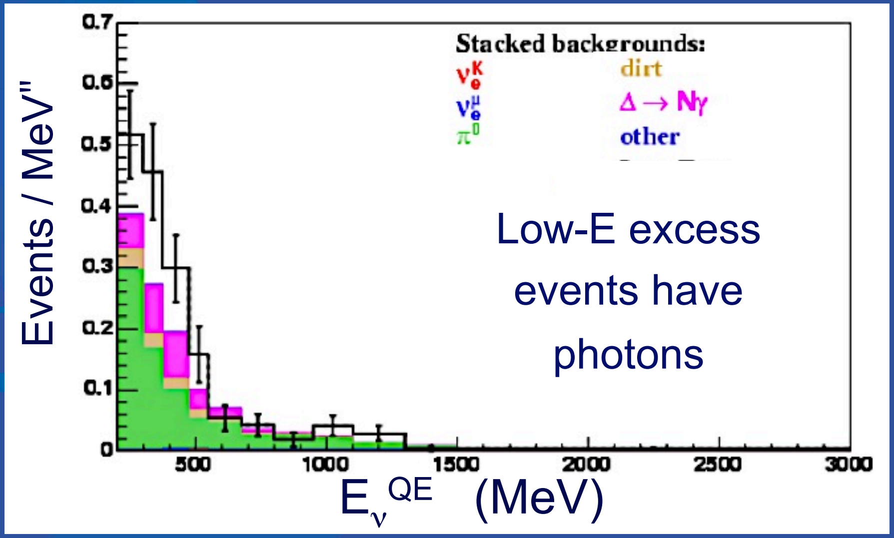
3D tracks with 3 mm resolution. Wires spaced with 3 mm pitch measure y-z coordinates. Drift time gives x. The 8256 wires arranged in planes at -60$^o$, 0$^o$, +60$^o$ wrt vertical.

170 tons total liquid argon / 86 tons instrumented / 60 tons fiducial

Field cage establishes 500 V/cm & drift velocity of 1.6 mm / µsec.

# MicroBooNE



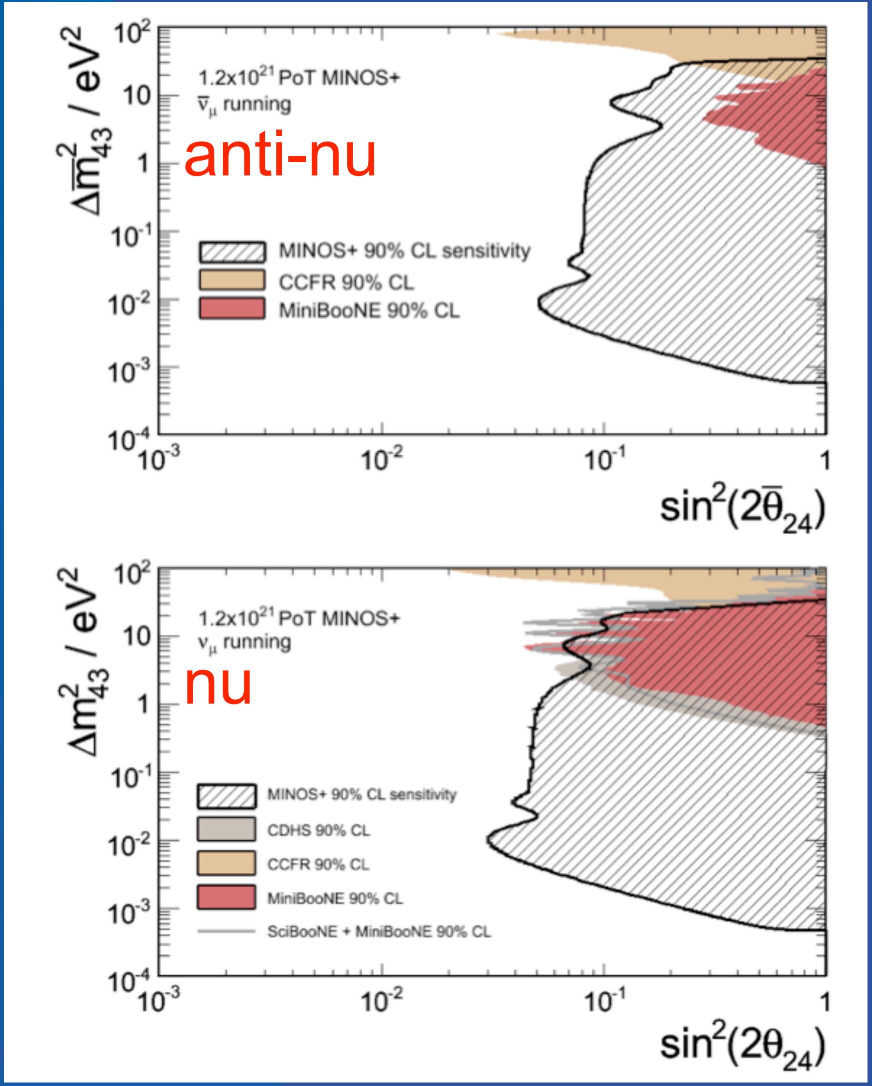




$6 \times 10^{20}$ pot in neutrino mode (2-3 year run, starting 2014)

If the MiniBooNE low energy excess is due to electrons, MicroBooNE expects a $5\sigma$ signal

If the MiniBooNE low energy excess is due to photons, MicroBooNE expects a $4\sigma$ excess

# MINOS+

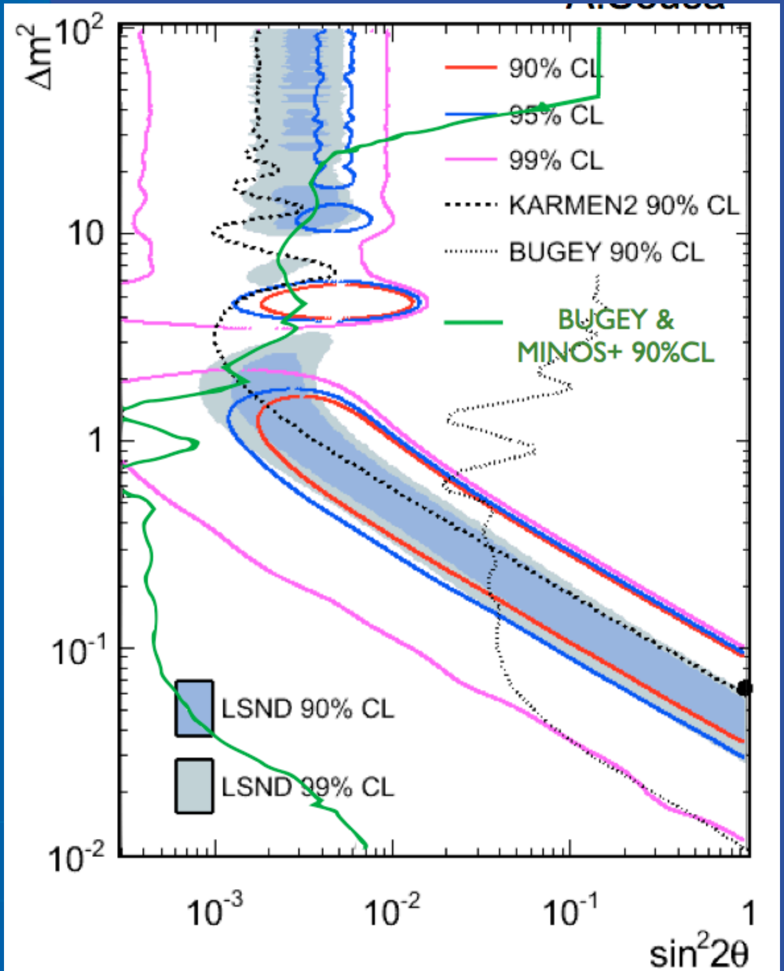



Continuation of MINOS running in the NOvA era

Starts April 2013, and will run for 3 years

Search for $\nu_\mu$ and anti-$\nu_\mu$ disappearance

# MINOS+




$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$

Within the 3+1 framework, can combine $\nu_\mu$ disappearance results with anti-$\nu_e$ disappearance to say something about $\nu_\mu \rightarrow \nu_e$

# WHAT IS THE SHORT-BASELINE PROGRAM AT FNAL BEYOND MINERvA & MicroBooNE ?

# FOCUS GROUP

Short-Baseline Neutrino Focus Group was convened by the Fermilab Directorate end of CY11 with the following charge:

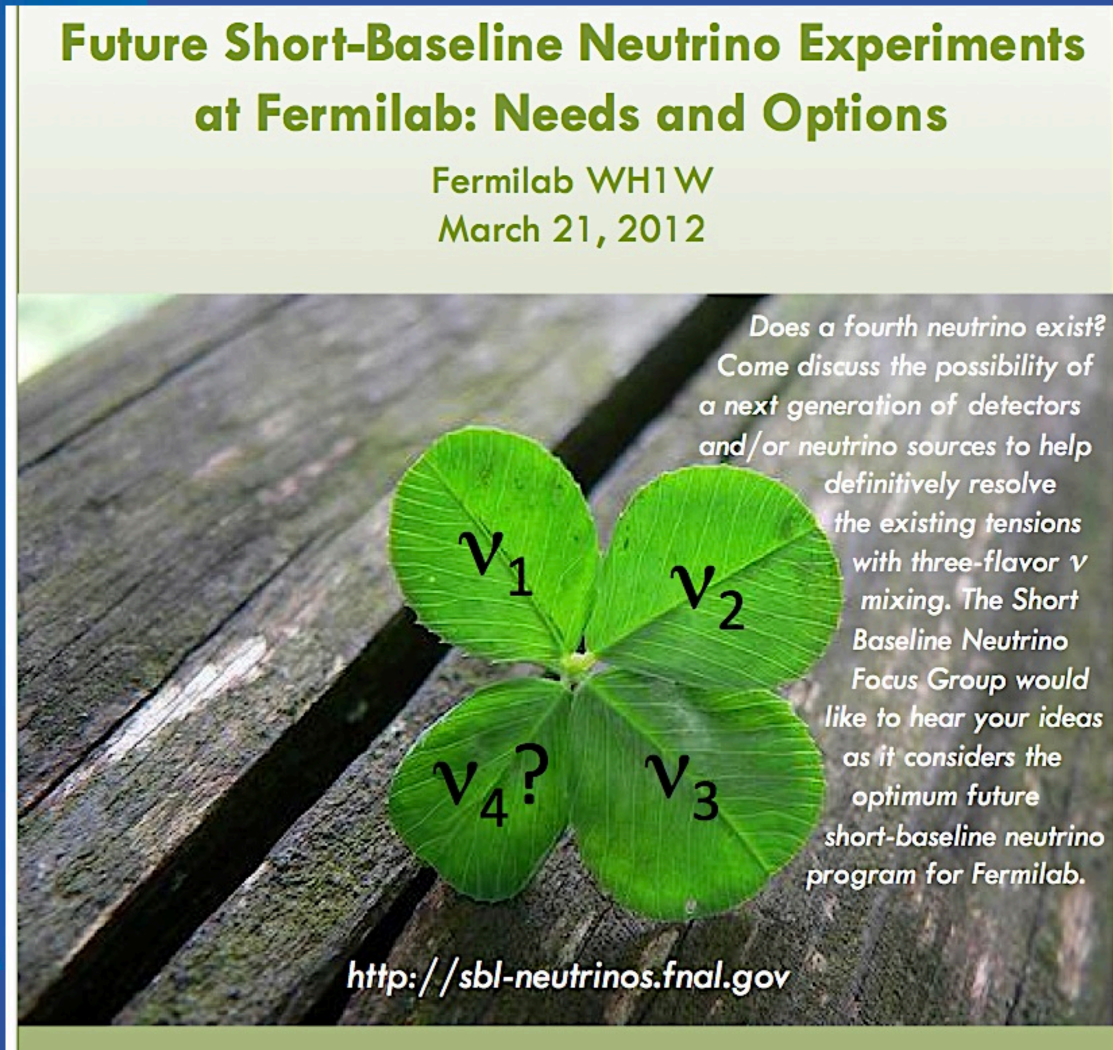
Several neutrino oscillation experiments have produced results that exhibit, at the level of a couple of standard deviations, a tension with the simple three-flavor mixing framework. These tensions might be purely statistical in origin, or might arise from one or more unidentified systematic effects, or from new physics. Together with the laboratory and the community, we would like to ask you to consider new generation detectors and/or new types of neutrino sources that would lead to a definitive resolution of the existing anomalies. With this in mind:

1. Evaluate to what extent the ongoing and planned neutrino experiments will be able to resolve the origin of each of the couple of sigma tensions with three-flavor mixing. Identify any additional measurements that might be needed, and options for making these measurements.

2. Compare with competing facilities the future capabilities at Fermilab for supporting a short baseline neutrino program to definitively resolve the present anomalies, and suggest what the optimal short baseline neutrino program might be beyond the presently approved and running experiments.

➔First meeting of the Focus Group was Jan 9, 2012.

# COMMUNITY MEETING




112 Participants

19 Talks

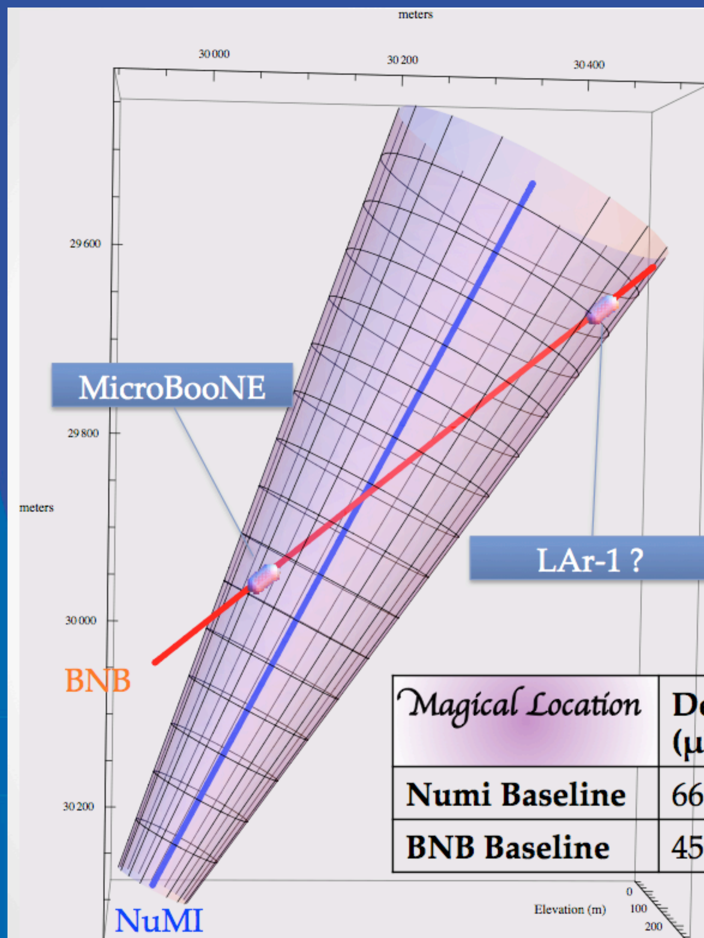
Depending on how you count, 10-20 different experiments concepts presented/discussed

# IDEAS FROM THE COMMUNITY FOR FUTURE SHORT-BASELINE EXPERIMENTS

| | |
|---|---|
| **RADIOACTIVE SOURCES** | |
| ELASTIC SCATTERING | Borexino (nu and anti-nu), SNO+Cr |
| CHARGED CURRENT | LENS, Baksan, Ce-LAND, Borexino, Daya Bay |
| COHERENT SCATTERING | RICOCHET using bolometers |
| **REACTORS** | |
| SMALL CORE | SCRAAM (Bugey, SONGS, ATR), Stereo |
| COHERENT SCATTERING | RICOCHET using bolometers |
| **ATMOSPHERIC NEUTRINOS** | |
| Fe CALORIMETER | ICAL, INO |
| OTHER | LAr Detector, IceCube |
| **ACCELERATORS: DECAY AT REST** | |
| LSND-LIKE | OscSNS (ORNL or FNAL), LSND Reloaded (Super-K + cyclotron) |
| COHERENT SCATTERING | RICOCHET using bolometers |
| **ACCELERATORS: DECAY IN FLIGHT** | |
| PION-DECAY | BooNE, MicroBooNE+LAr (LArLAr), NOvA short-baseline, SciNOvA |
| MUON DECAY | Muon decay ring (VLENF), Entry-level Neutrino Factory, Full NF |
| Nu-tau APPEARANCE | With L/E ~ 1 m/MeV |
| **OTHER MEASUREMENTS** | |
| HADRON PRODUCTION | MIPP-Upgrade, NA61/Shine |

# EXAMPLE IDEA - 1

Two detectors at “magic” locations using 2 beams with same off-axis angle (hence neutrino spectrum) for off-axis beam.




## Two Detectors & Two Neutrino Beams

Locate a far detector for $\mu$ BooNE such that it is:

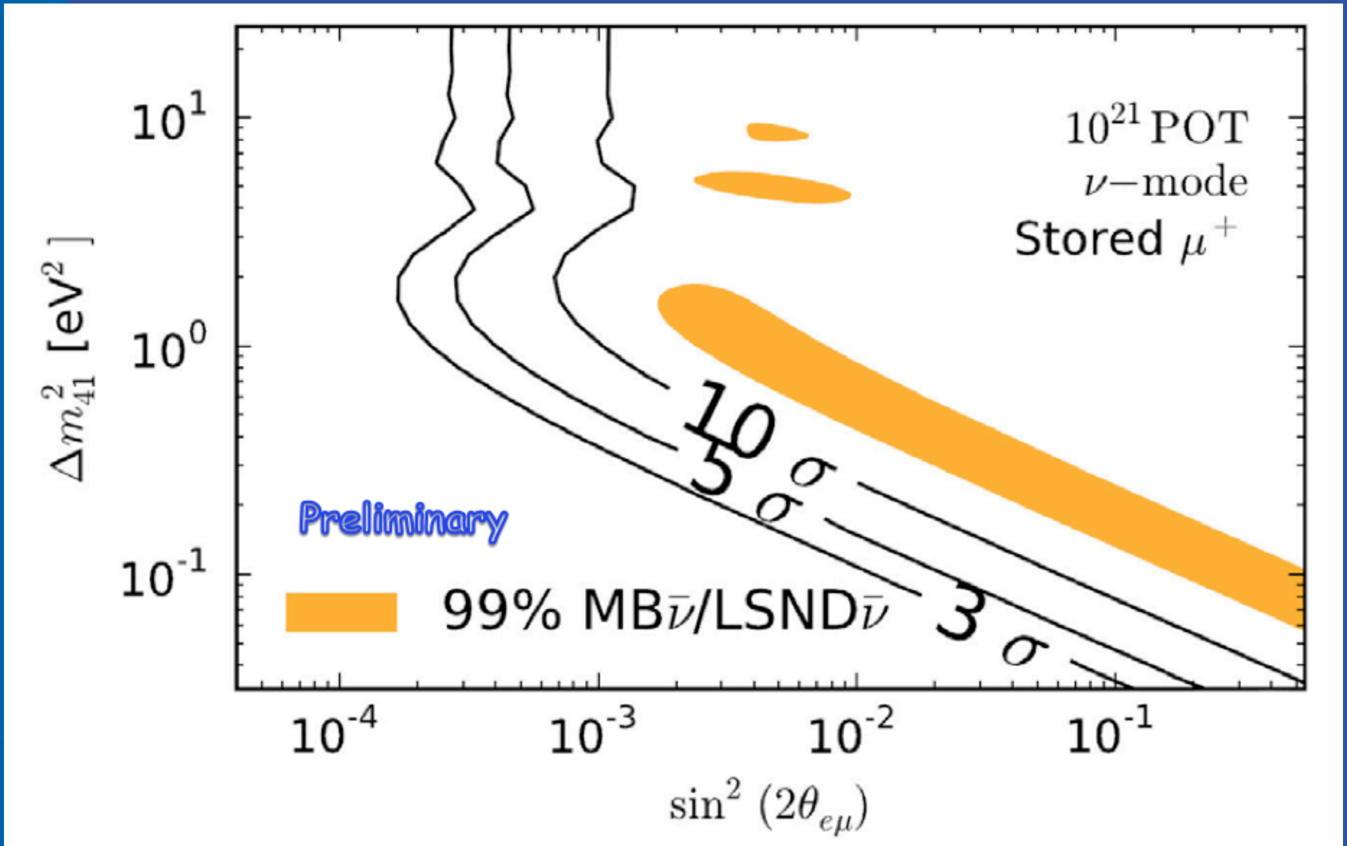
- on-axis for the BNB
- at the same off-axis angle

| *Magical Location* | Detector 1 (μBooNE) | Detector 2 (LAr-1) |
| --- | --- | --- |
| **Numi Baseline** | 667 m | 1110 m |
| **BNB Baseline** | 450 | 925 |

Geoff Mills

# EXAMPLE IDEA - 2

Simple muon storage ring to generate anti-$\nu_e$ beam




Alan Bross

# EXAMPLE IDEA - 3

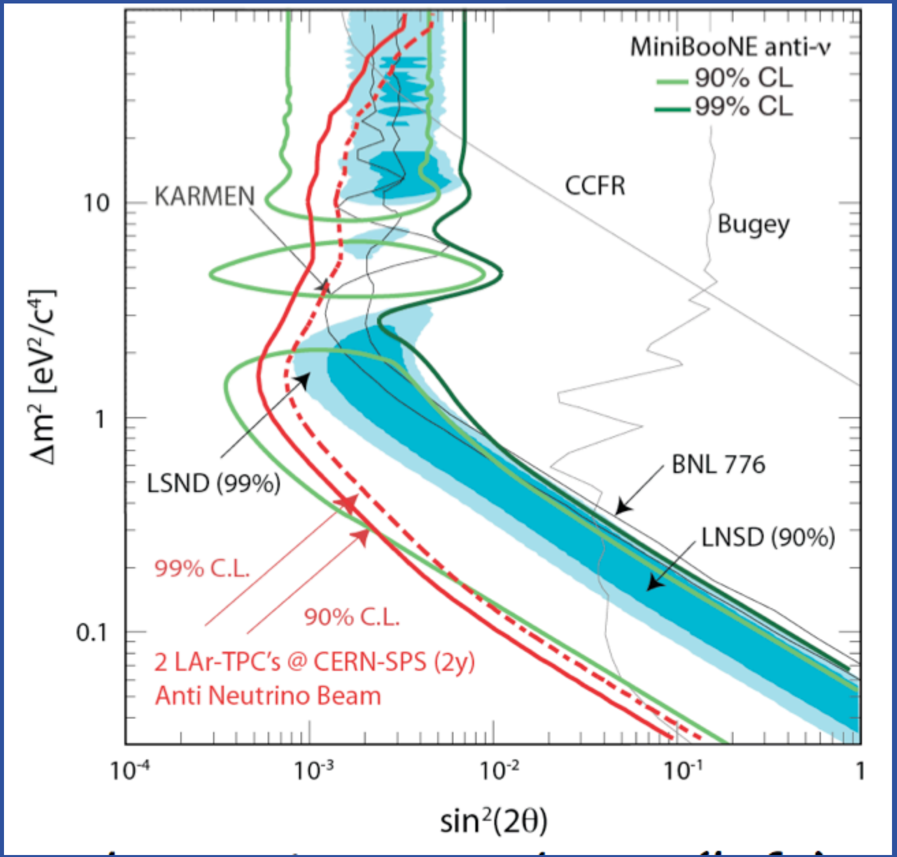
ICARUS + NESSIE at CERN (C. Rubbia et al.)

-Existing T600 module + new T150 module + external magnetic spectrometer

-Needs new beamline at CERN: 100 GeV primary beam from SPS, 100m long decay region

-Experiment in North Area

2 years running





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# SUMMARY

- We don't know if the anomalies are all statistical and/or systematic in origin, or if they indicate an emerging discovery. To definitively resolve this, we will need an experimental campaign of reactor-, source-, and accelerator-based experiments.
- This campaign is still emerging. Some experiments are already going ahead (Nucifer, DANSS, MicroBooNE, MINOS+ … ), many others are being proposed.
- For the accelerator-based part of the campaign in the U.S., there is a Short-Baseline Neutrino Focus Group looking at the possibilities with the Fermilab neutrino beams ➔ report to the June PAC meeting.
- If we are seeing an emerging discovery, we can anticipate exciting results, probably in the later part of the decade, followed by an extensive experimental program to sort out the phenomenology and measure the associated parameters.

# BACKUP SLIDES

# EVOLUTION OF FACILITIES

| Program: | Stage-0: Proton Improvement Plan | Stage-1: 1 GeV CW Linac driving Booster & Muon Campus | Stage-2: Upgrade to 3 GeV CW Linac (MI>70 GeV) | Stage-3: Project X RDR (MI>60GeV) | Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW |
|---|---|---|---|---|---|
| MI neutrinos | 470-700 kW** | 515-1200 kW** | 1200 kW | 2300 kW | 2300-4000 kW |
| 8 GeV Neutrinos | 15 kW + 0-50 kW** | 0-40 kW* + 0-90 kW** | 0-40 kW* | 85 kW | 3000 kW |
| 8 GeV Muon program e.g, (g-2), Mu2e-1 | 20 kW | 0-20 kW* | 0-20 kW* | 85 kW | 1000 kW |
| 1-3 GeV Muon program | ----- | 80 kW | 1000 kW | 1000 kW | 1000 kW |
| Kaon Program | 0-30 kW** (<30% df from MI) | 0-75 kW** (<45% df from MI) | 1100 kW | 1100 kW | 1100 kW |
| Nuclear edm ISOL program | none | 300 kW | 300 kW | 300 kW | 300 kW |
| Ultra-cold neutron program | none | 300 kW | 300 kW | 300 kW | 300 kW |
| Nuclear technology applications | none | 300 kW | 300 kW | 300 kW | 300 kW |
| # Programs: | 4 | 8 | 8 | 8 | 8 |
| Total* power (mean): | 660 kW | 2020 kW | 4210 kW | 5490 kW | 11300kW |

Steve Holmes, March 21st, 2012 meeting