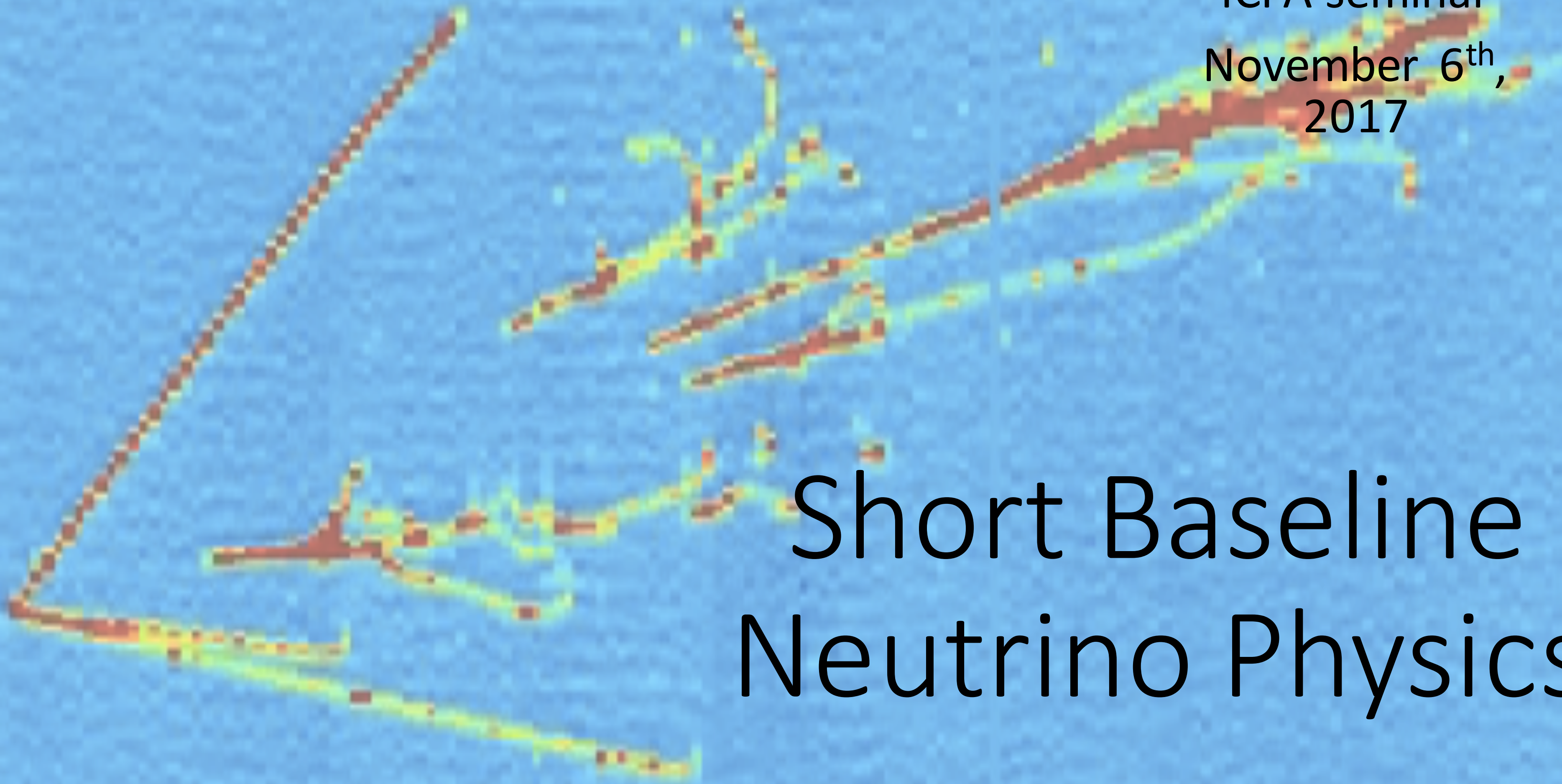
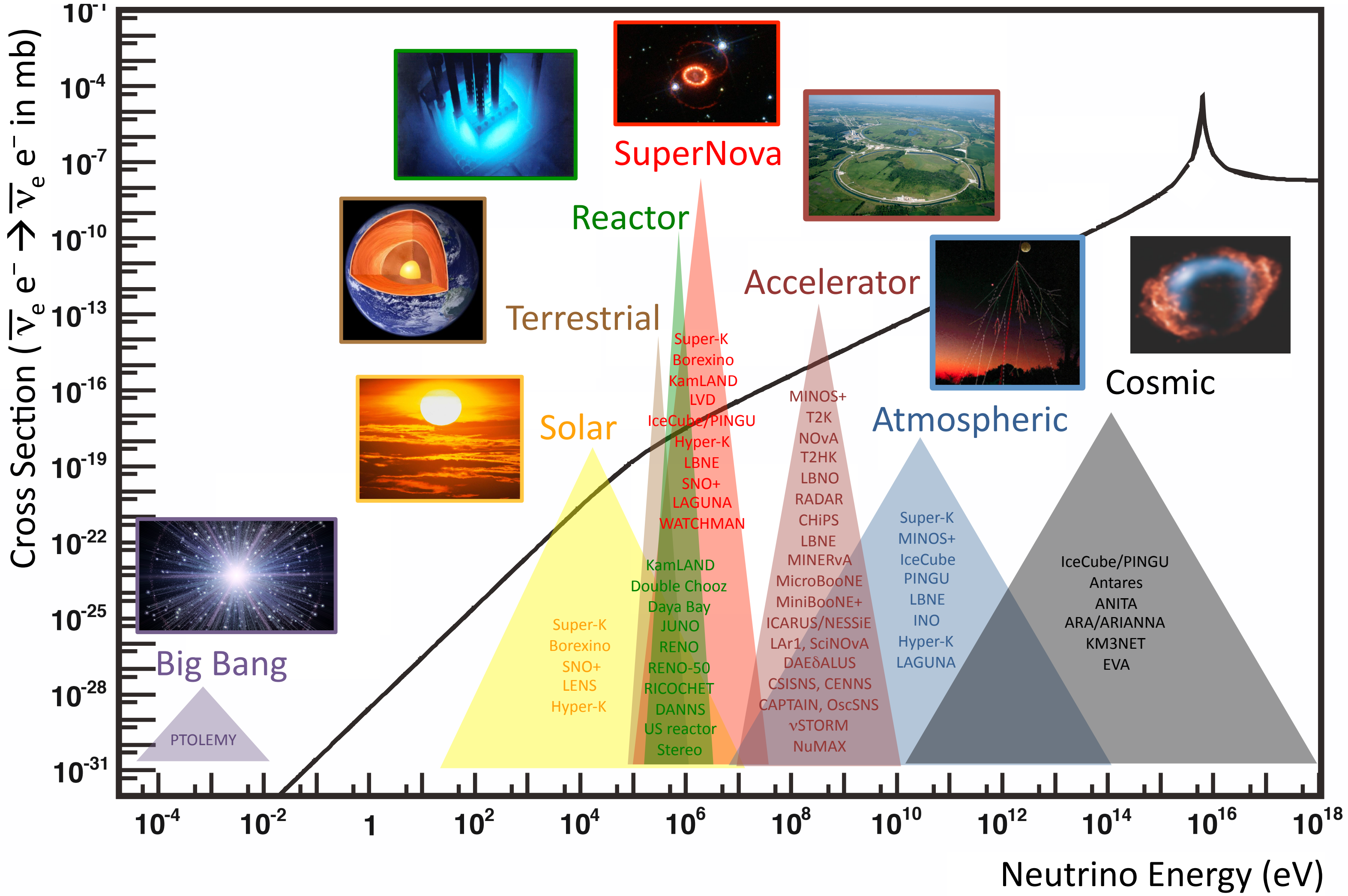


ICFA seminar

November 6th, 2017

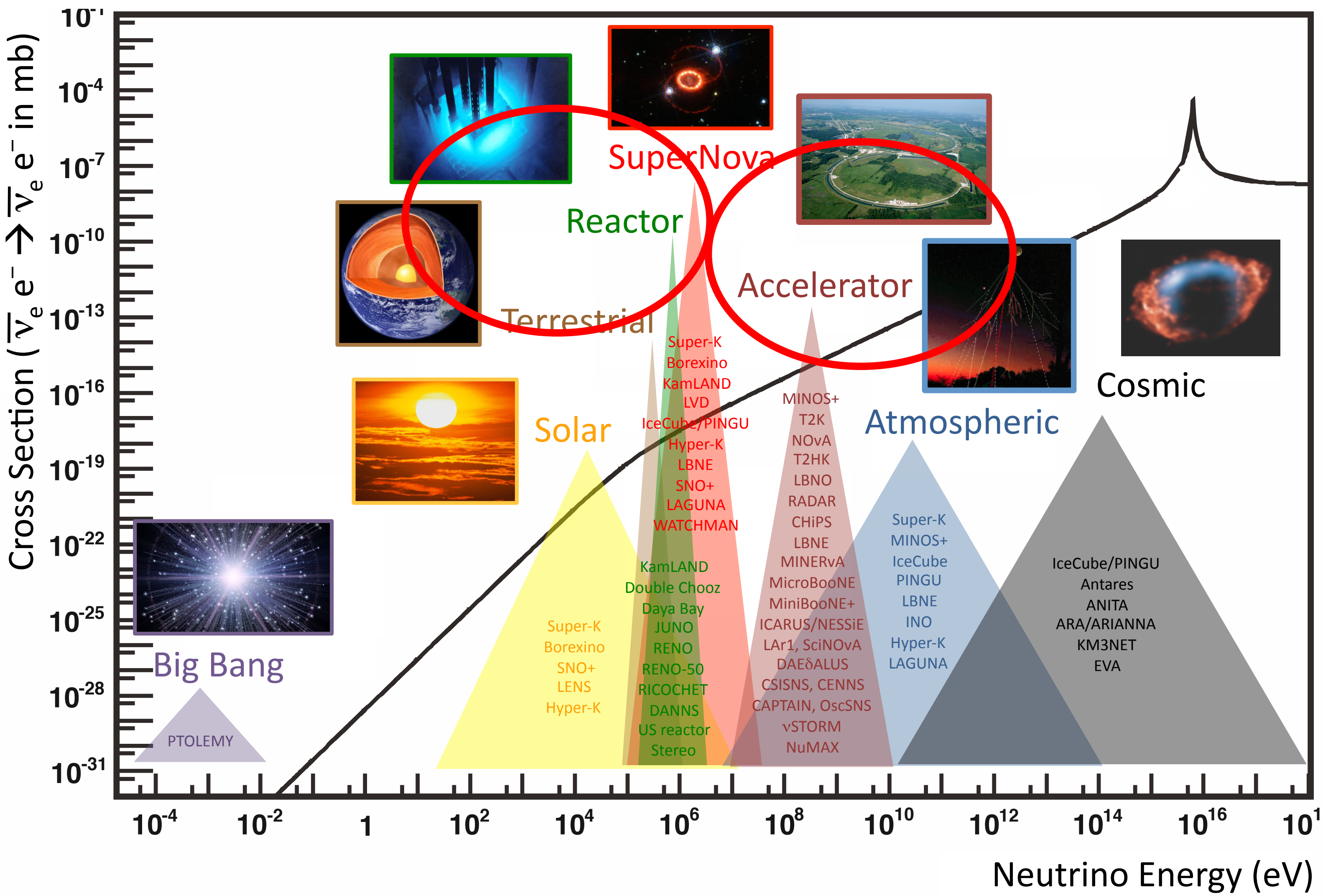
Short Baseline Neutrino Physics

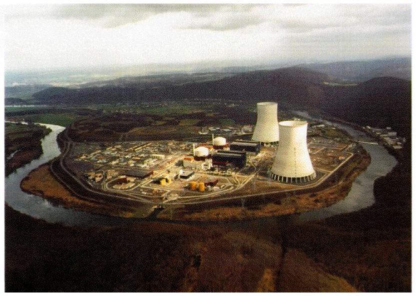
Many Neutrinos and ν experiments over many different energies!
Tell us about neutrinos and about the universe…



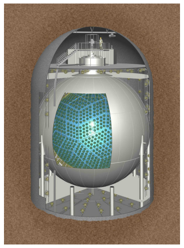
Short Baseline experiments take advantage of terrestrial neutrino sources:

- Reactor neutrinos, Accelerator neutrinos, Radioactive sources





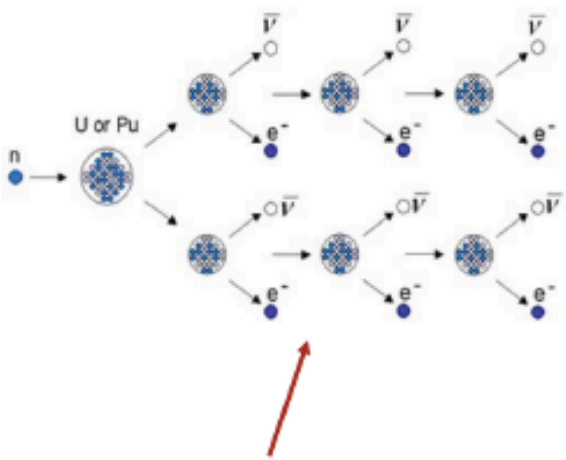
$\bar{\nu}_e$ disappearance?

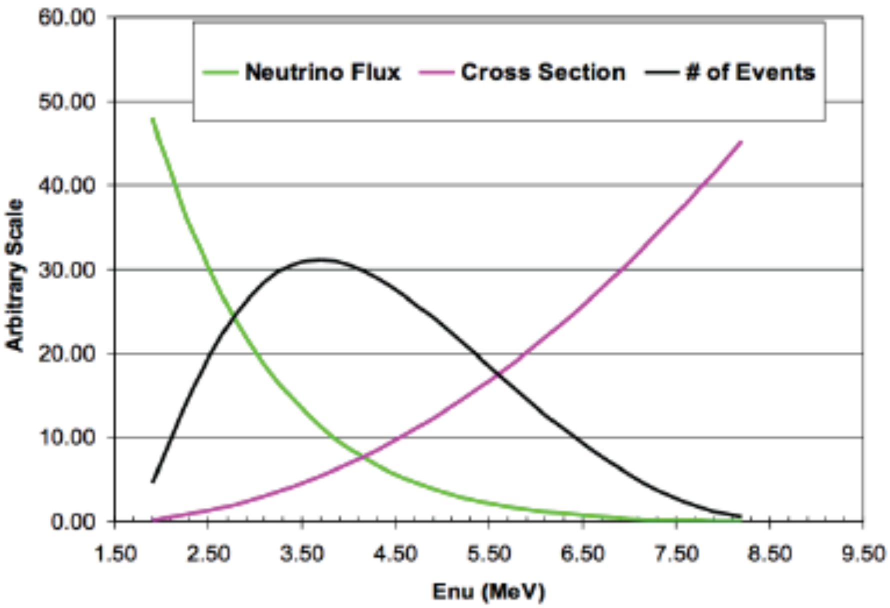


Reactor $\bar{\nu}_e$ production

Detection through inverse β Decay:

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

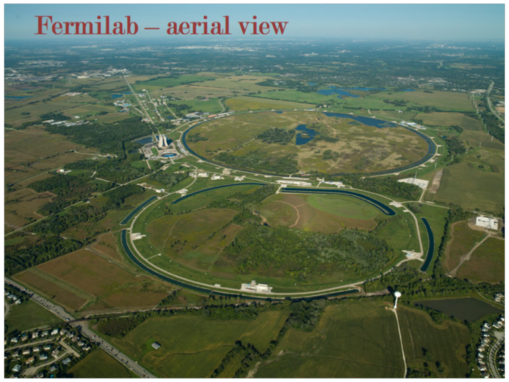


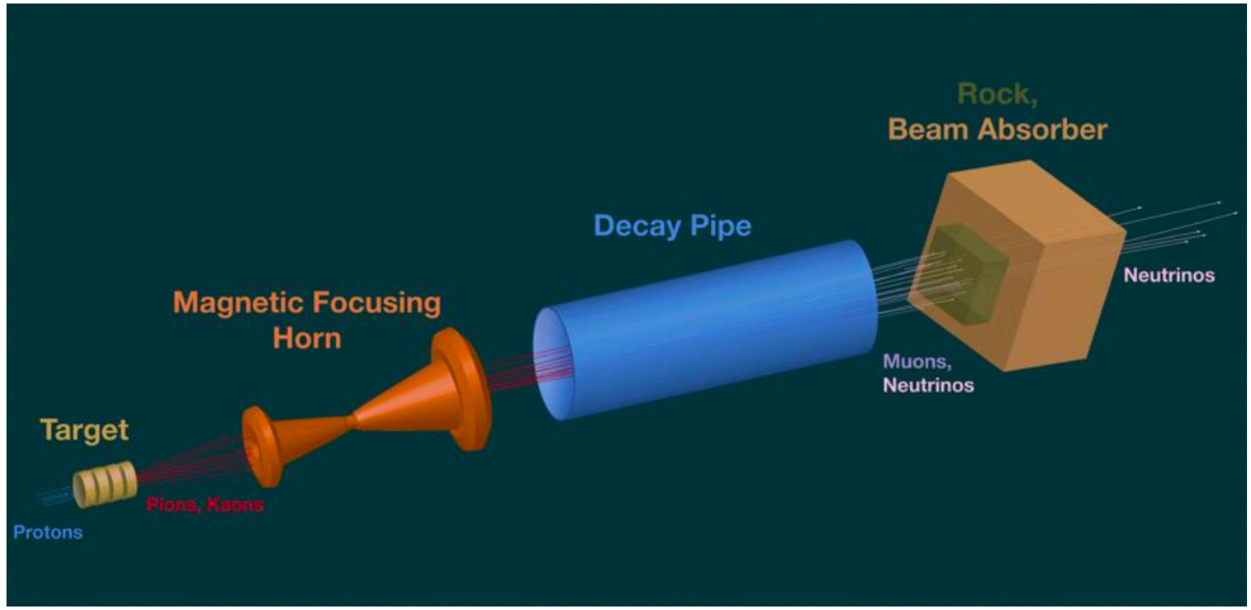


β^- decay of neutron rich fission fragments of U and Pu

$E_{prompt}=E_\nu-0.8$ MeV

Accelerator ν_μ production



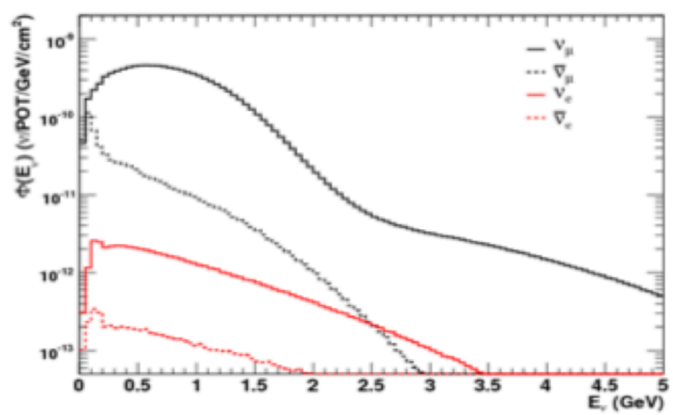


Protons

Produce muon neutrinos much like in the upper atmosphere….

Slam protons into a target to produce showers of particles directed towards a downstream detector, which decay into neutrinos

→ Neutrino beam….

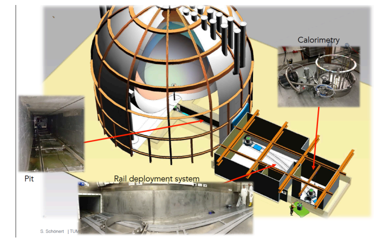


Electron or muon neutrinos produced	Travel over “short” baseline	Detect them in a variety of ways

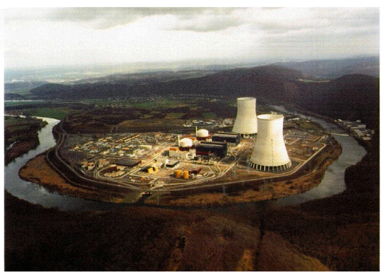
Radioactive Source

Electron and anti-electron neutrinos

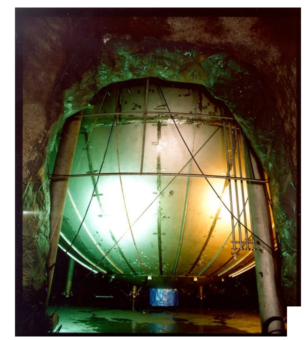
~1m



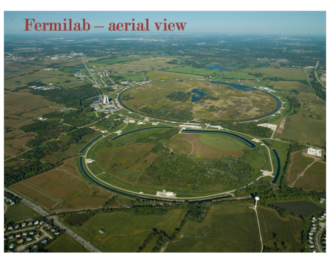
Reactor



Anti-electron neutrinos ~5-50m

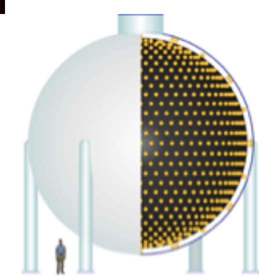


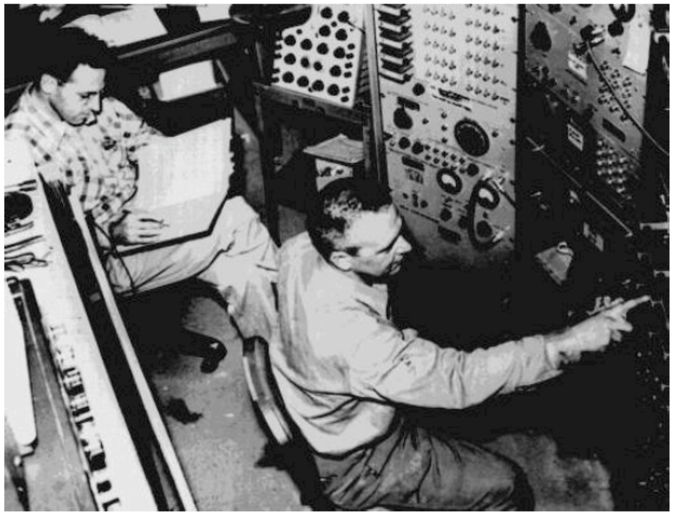
Accelerator



Muon neutrinos

~50-500m





Fred Reines and Clyde Cowan at the Control Center of the Hanford Experiment (1953)

1956: Reines/Cowan observe electron antineutrinos emitted by a nuclear reactor

Fred Reines

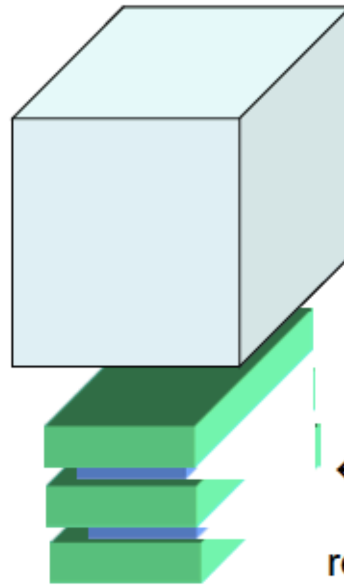
Clyde Cowan, Jr.

Discovery of the neutrino (electron neutrino)

Short baseline reactor experiment…..

```
-------------------------------
   W E S T E R N   U N I O N
-------------------------------

               June 14, 1956

Dear Professor Pauli,

We are happy to inform you
that we have definitely
detected neutrinos. . .

                 Fred Reines
                 Clyde Cowan
```

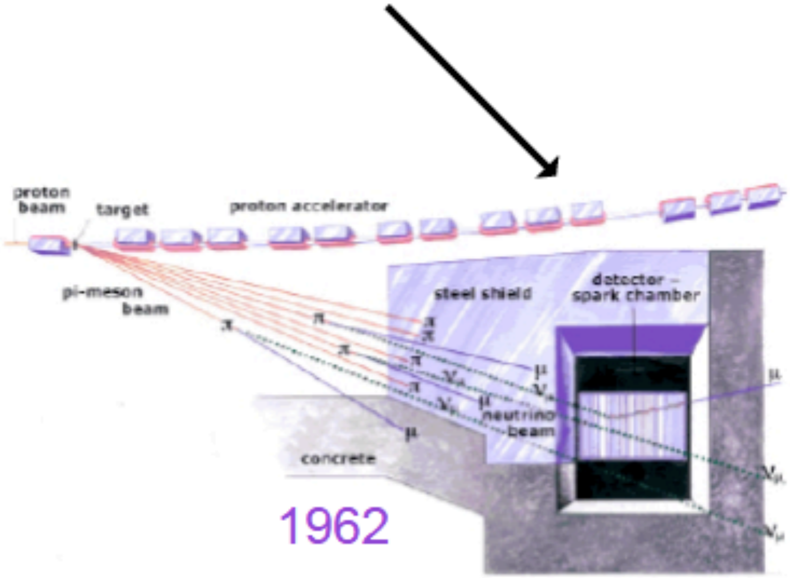
Savannah River nuclear reactor



←installed in basement of reactor building

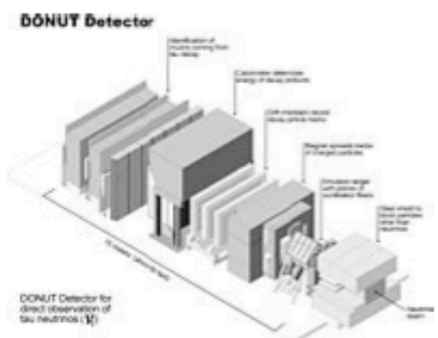
1995 Reines won the Nobel Prize in Physics for his contributions to neutrino physics

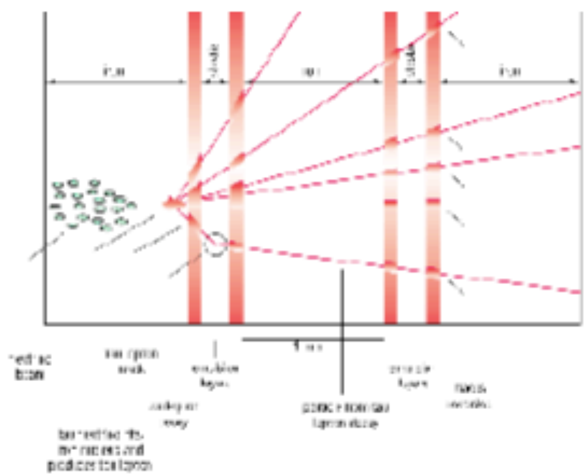
Muon neutrino discovered at BNL



Nobel Prize in 1988

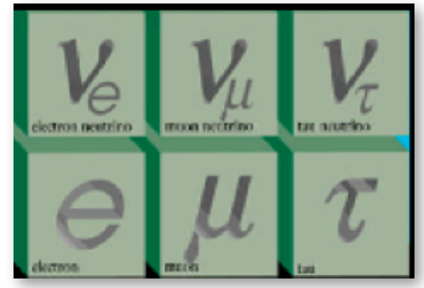
Tau neutrino observed by DONUT at FNAL in 2000





Short baseline accelerator based experiments

Short Baseline Physics



Complete picture?

•Neutrino Cross Section Physics….

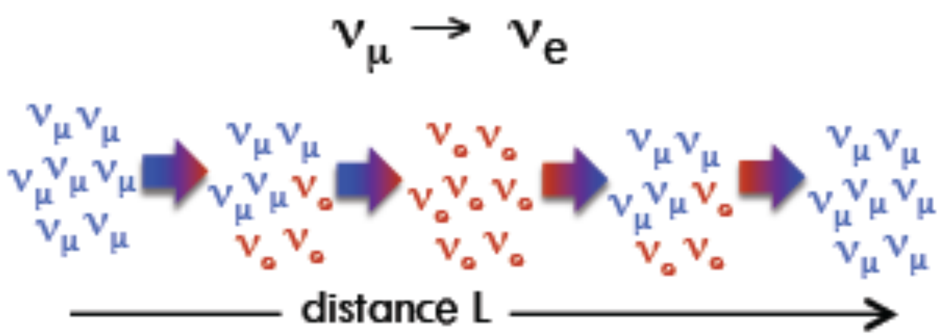
Rich program:

→ nuclear physics of neutrino interactions, critical for LBL osc experiments

•Oscillations over ”short” baselines

Short baseline = ~5-500 meters

Neutrino Source



Detector

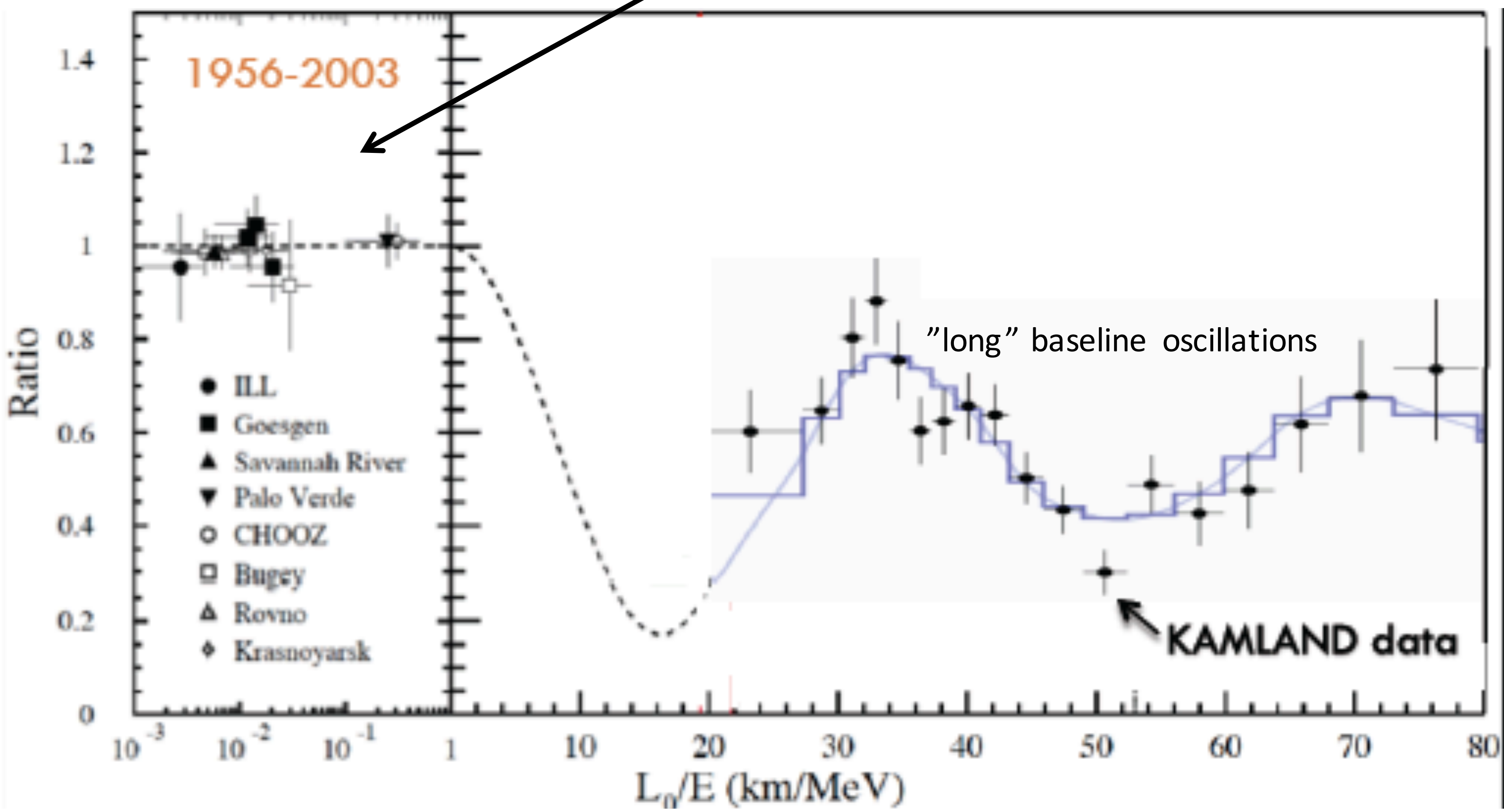
Look for disappearance of neutrinos and/or appearance of new flavors

Neutrino Experimentalists can set up experiments using different neutrinos (flavor and energy) traveling over different baselines to map out the different oscillations

eg:  $\longrightarrow$  or  $\longrightarrow$ 

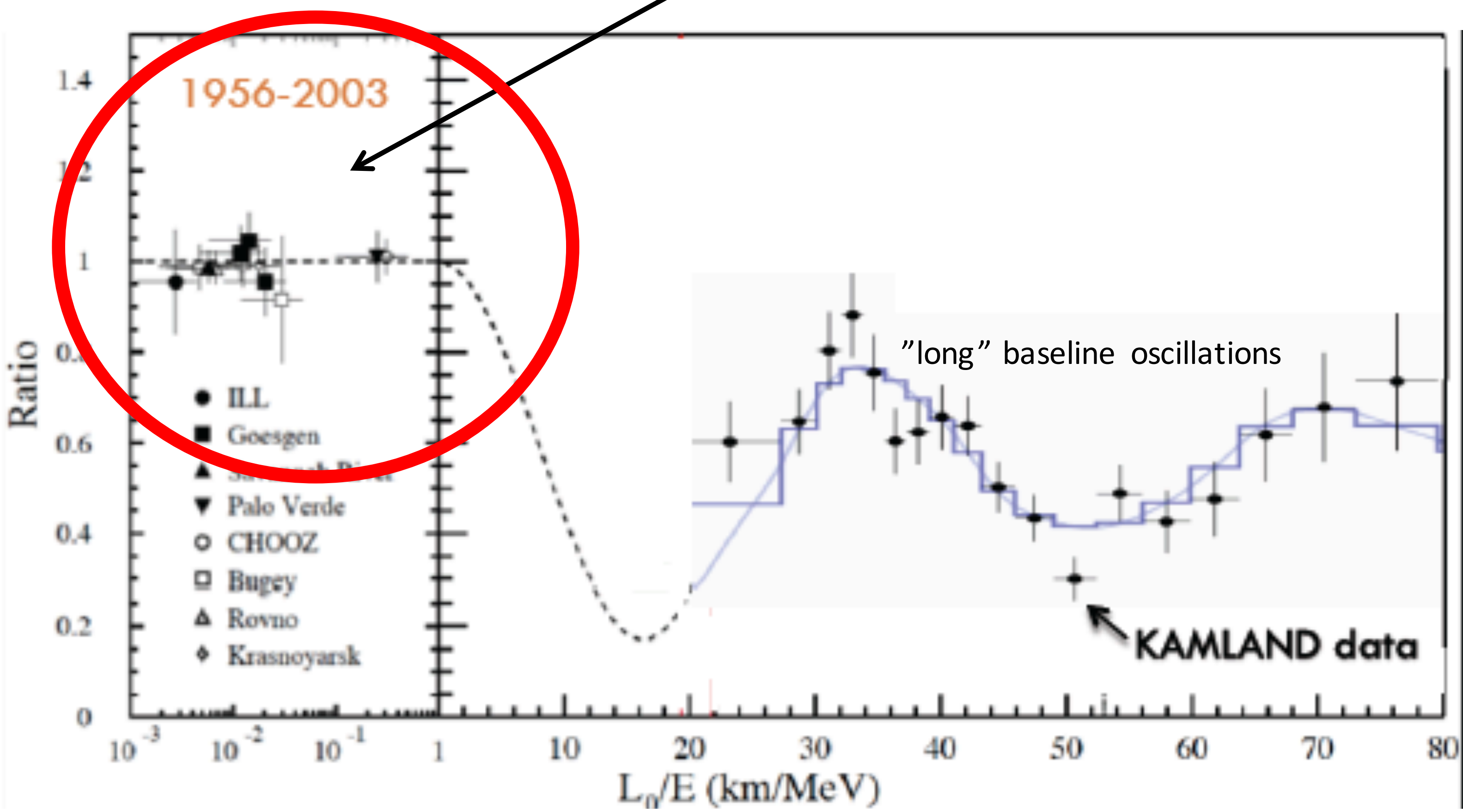
Reactor Measurements…

Experiments at very short baselines for reactors for many years reported some deviation from prediction – not significant



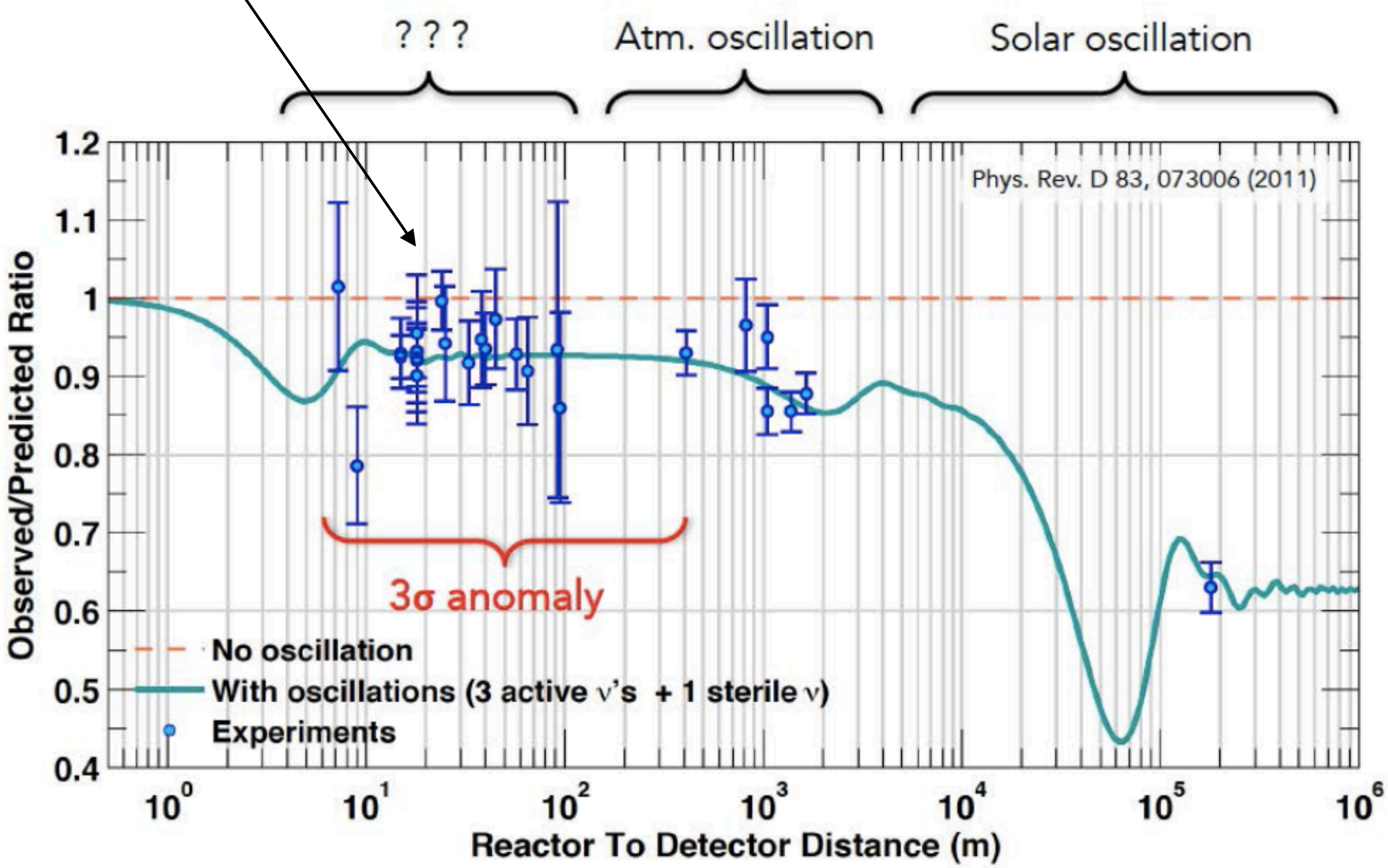
Reactor Measurements…

Experiments at very short baselines for reactors for many years reported some deviation from prediction – not significant



The Reactor Anomaly

At short (???) baselines experiments see fewer neutrinos than expected (red line)



G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D.Lhuillier, M. Cribier, and A. Letourneau, Phys. Rev. D 83, 073006 (2011)

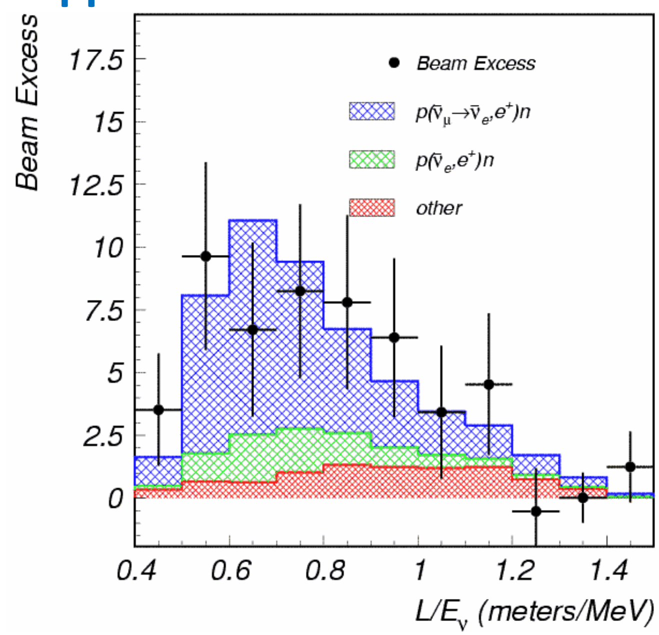
S. Schönert | TUM | Sterile neutrinos

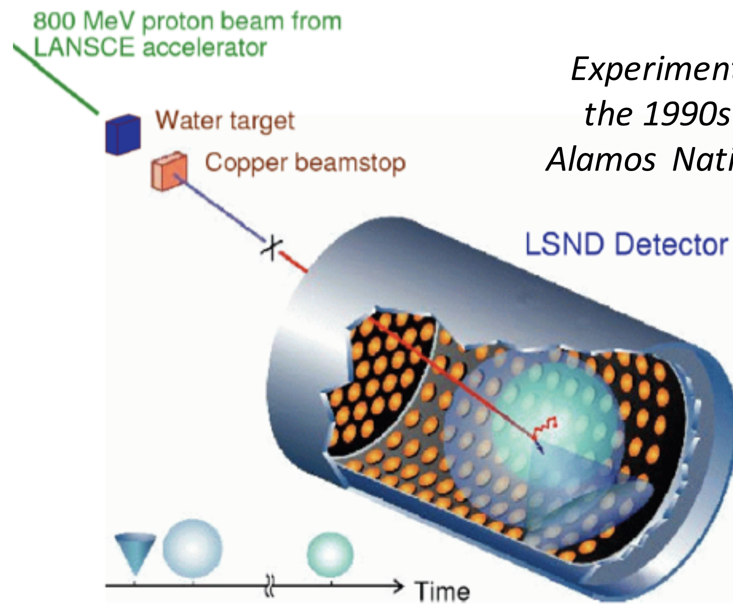
The LSND Anomaly: Accelerator based electron neutrino appearance….

Accelerator Measurements…

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\hookrightarrow ? \; \bar{\nu}_e$$

Electron neutrino appearance observed





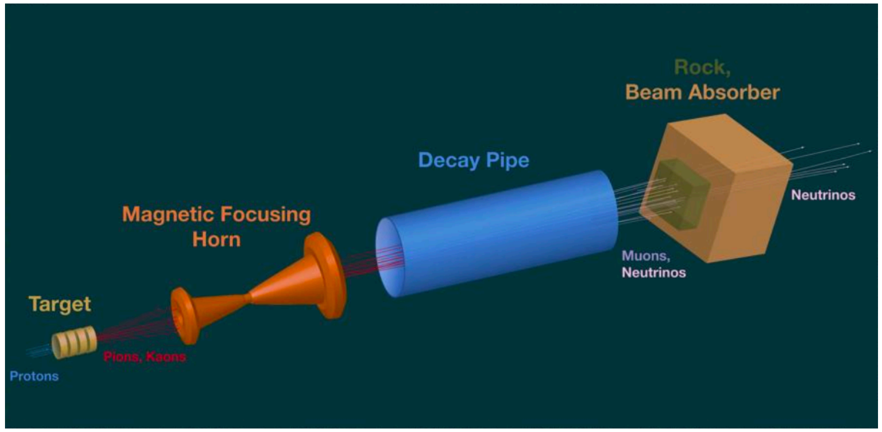
Experiment ran in the 1990s at Los Alamos National Lab

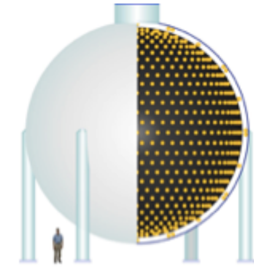
Observed 87.9 ± 22.4 ± 6.0 events
above background
Oscillation Probability: 0.26%

Consistent with a Δm^2 on the order of 1 eV^2
(not consistent with 3 flavor picture)

The MiniBooNE Anomaly

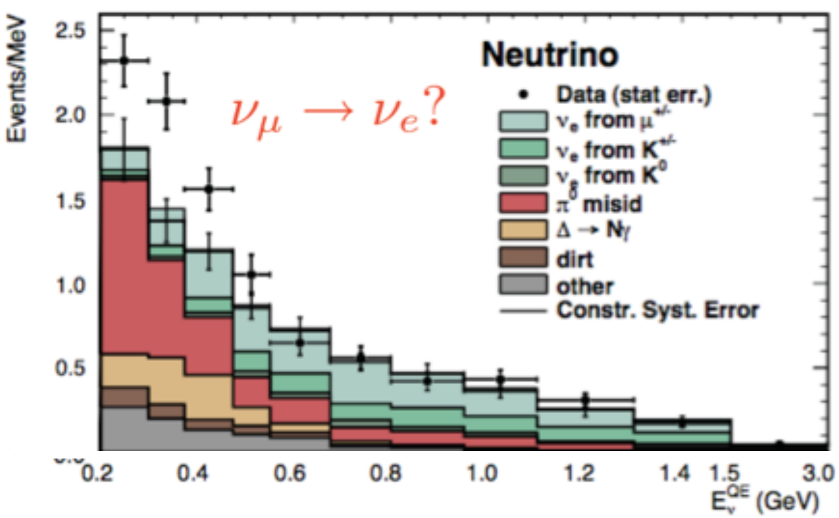
Fermilab Booster





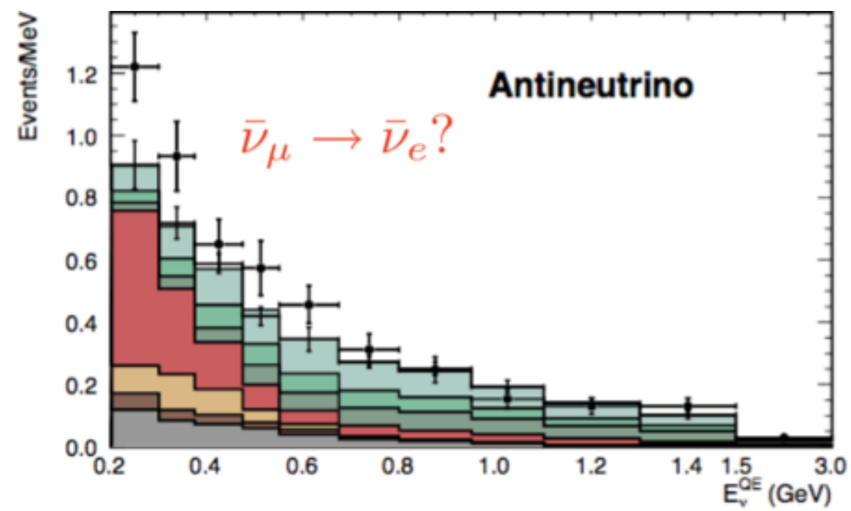
ν_e appearance in a primarily ν_μ beam

Cherenkov imaging detector



3.4σ excess in neutrino mode

$$162.0 \pm 28.1(\text{stat}) \pm 38.7(\text{syst})$$

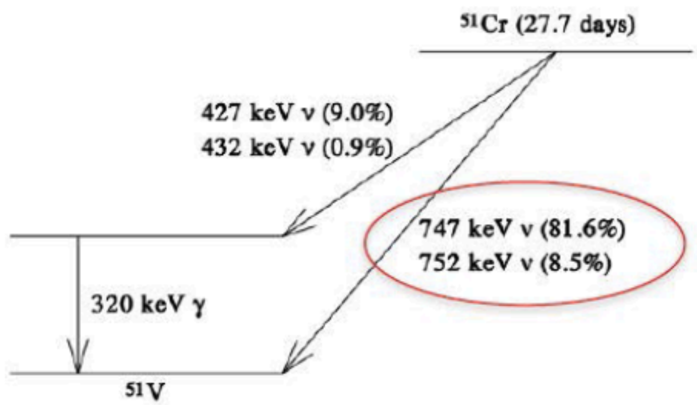


2.8σ excess in antineutrino mode

$$78.4 \pm 20.0(\text{stat}) \pm 20.3(\text{syst})$$

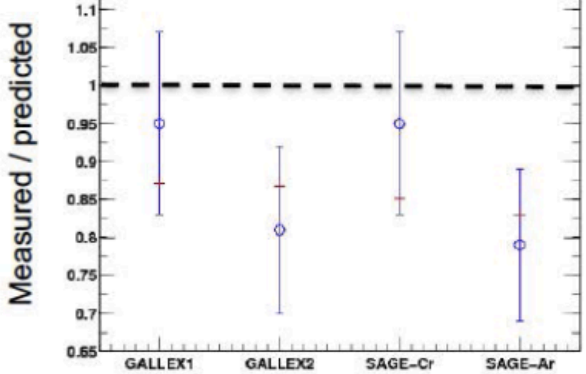
The Gallium Anomaly

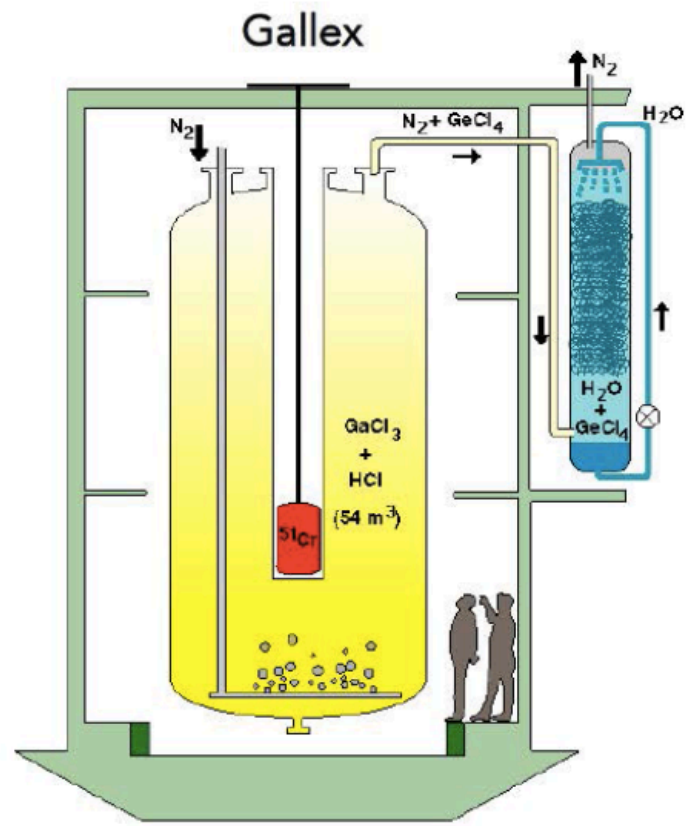
Source measurements…..



3σ anomaly

Electron neutrinos disappearing





Taken individually, each anomaly is not significant enough to be convincing…. But they are all pointing toward the same thing….

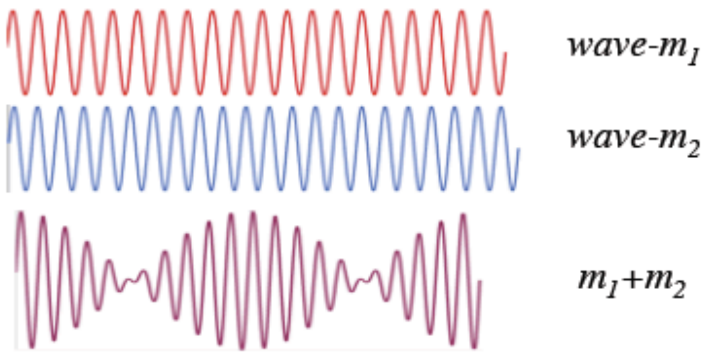
Signals at SBL are at the 2-4σ level
All pointing in the same direction

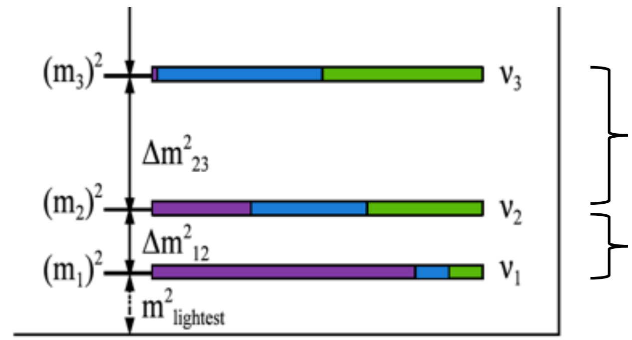
Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

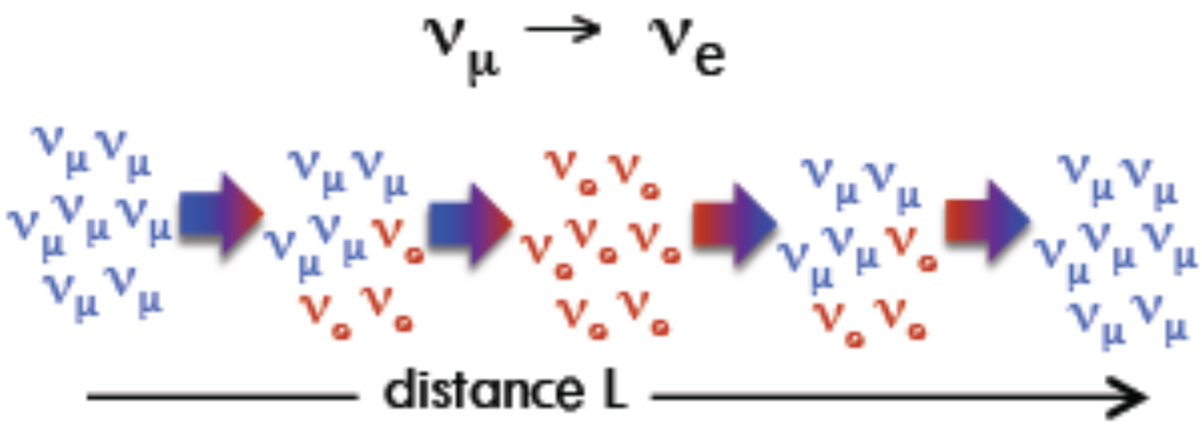
Neutrino Oscillations at short baselines --> to accommodate these, must have a new kind of neutrino in addition to the three standard model neutrinos

For three neutrinos there are two independent mass splittings



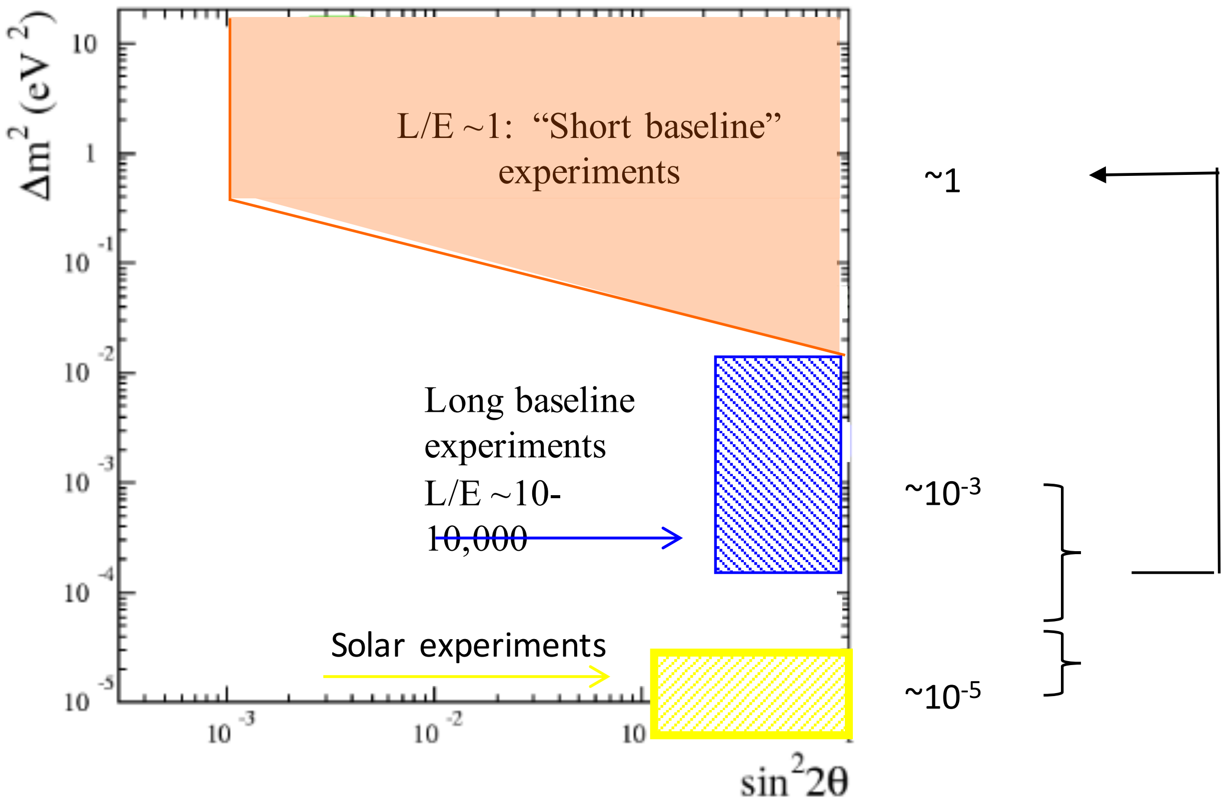


(third is just the sum of the first two)

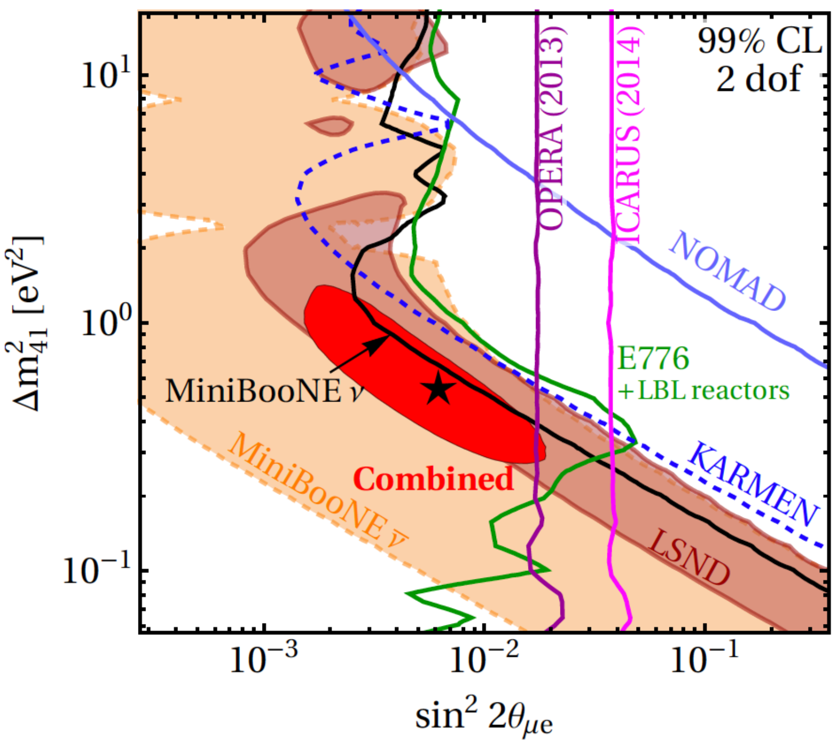


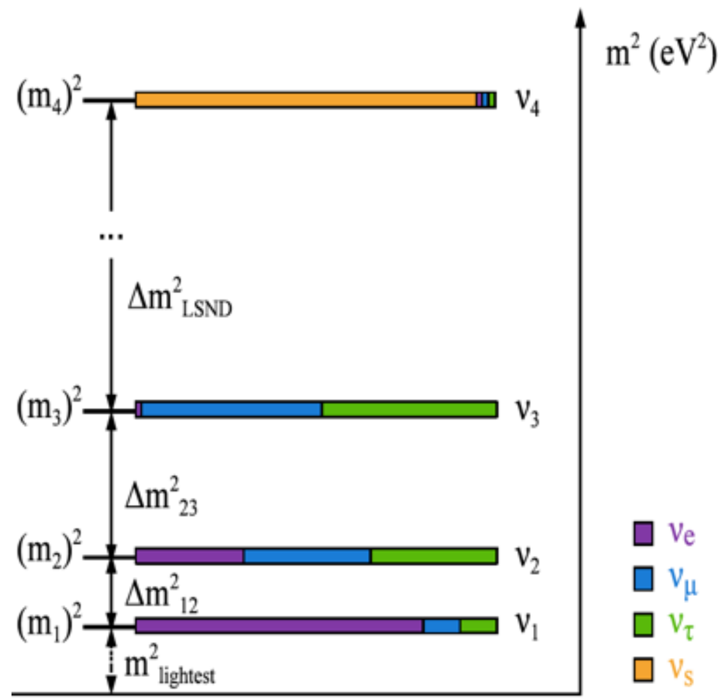
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

Short Baseline Results cannot be explained by three neutrinos responsible for long baseline oscillations

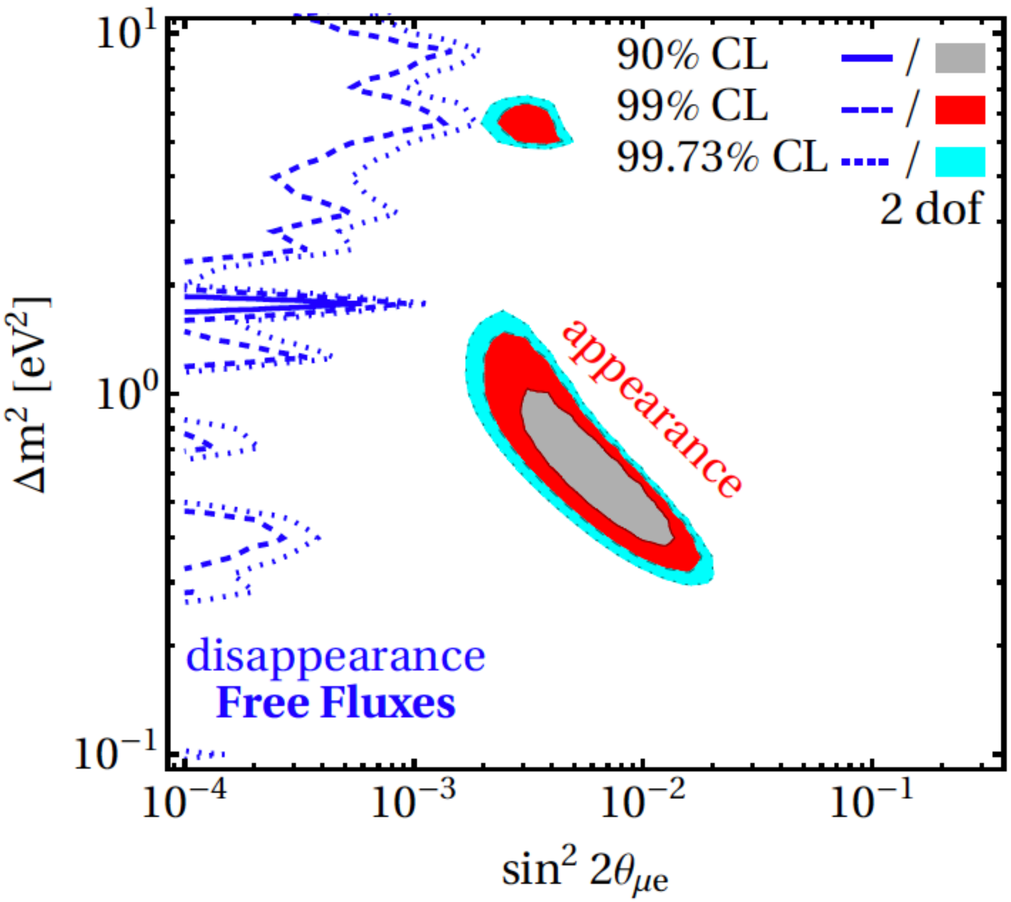


→ A fourth neutrino: The Sterile Neutrino Oscillates with the Standard Model Neutrinos but does not interact like they do (weak interaction)



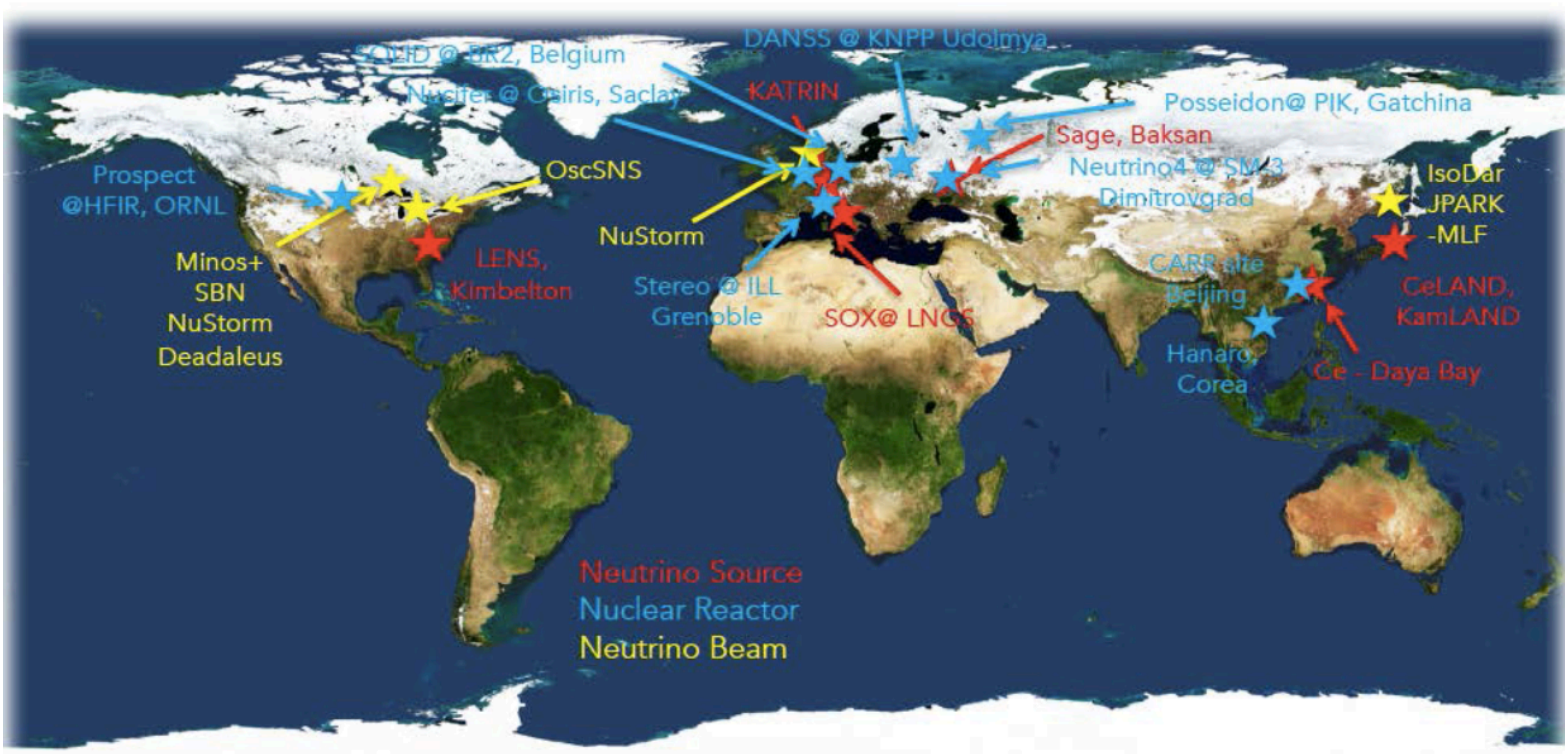


Not as easy as I've made it sound…. Tension between ν_e appearance and ν_μ disappearance results



Dentler, Kopp, Machado, Maltoni, Martinez, TS, preliminary!

Worldwide program to address anomalies



→ Dedicated experiments in planning, under construction, and data taking
Learn from data from Long baseline expertiment and their near detectors….

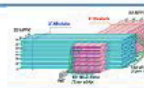
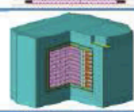
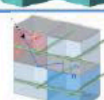
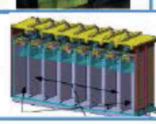
Reactor Measurements…

Short Baseline Reactor Neutrino Physics

→ experiments have different reactor types

→ Different detection techniques

→ First results coming out, still awaiting definitive mmnt

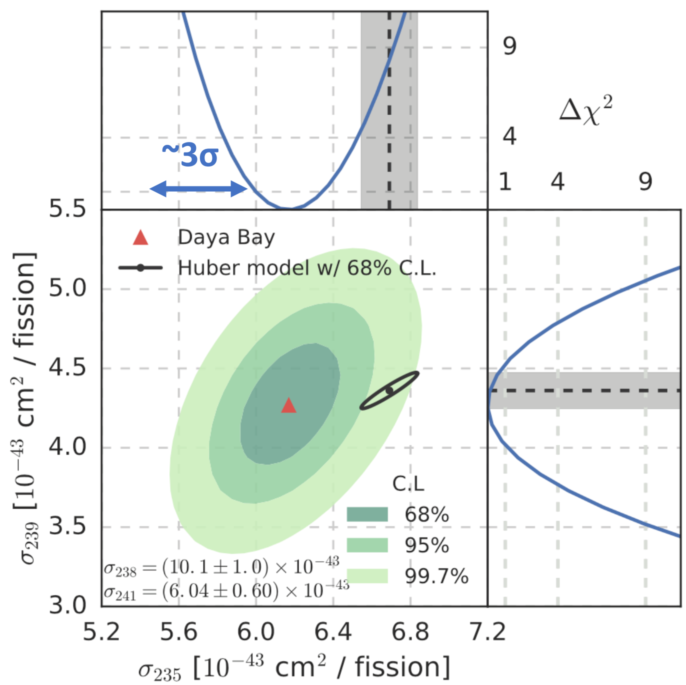
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

N. Bowden AAP 2016

Understanding the reactor flux

Daya Bay Fuel Evolution Analysis

Daya Bay, arXiv:1704.01082v1

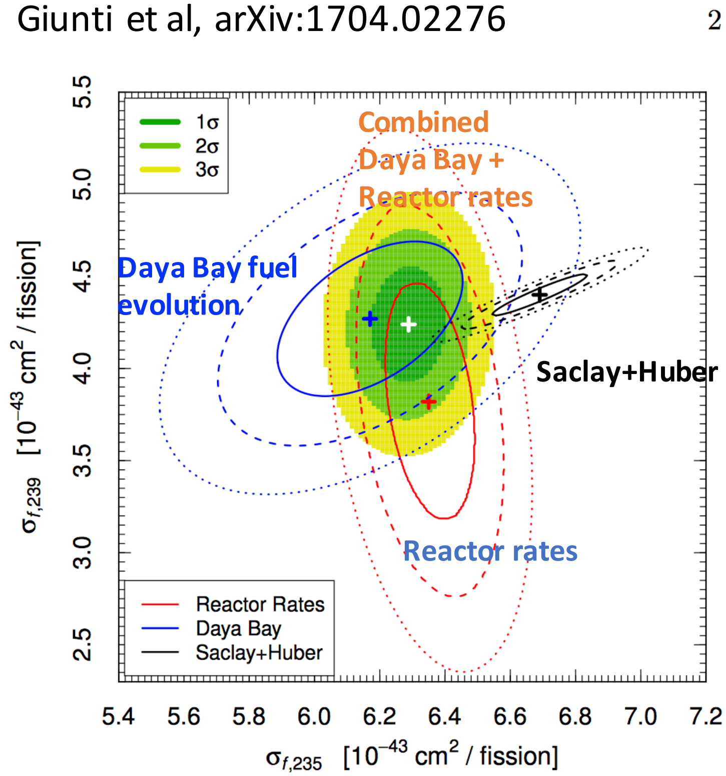


Daya Bay recently reported IBD yields of ^{235}U and ^{239}Pu using evolution of LEU reactors.

Reactor flux model found to be incorrect for ^{235}U.

Improved Determination of Fluxes

Giunti et al, arXiv:1704.02276



IBD yields calculated from reactor rates (of 26 reactor experiments) do not agree with Daya Bay measurement.

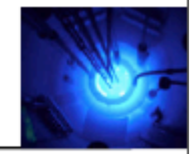
Analysis of Daya Bay with Fuel Burnup

Hayes et al, arXiv:1707.07728

"not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos"

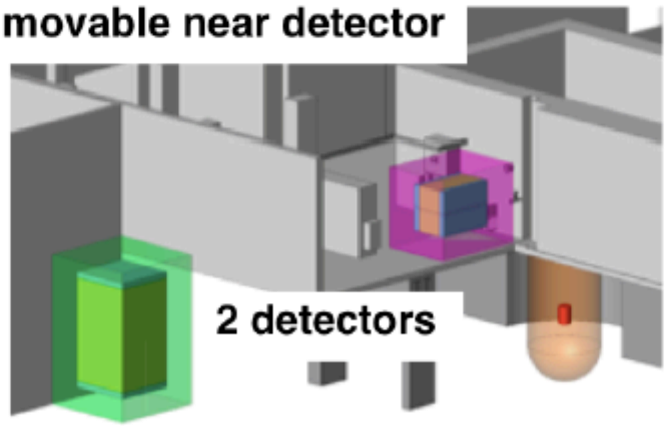
Reactor Measurements…

PROSPECT Physics

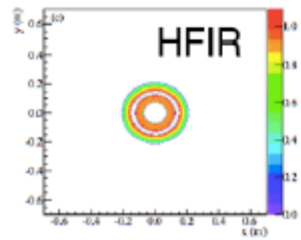


A Precision Oscillation and Spectrum Experiment

movable near detector

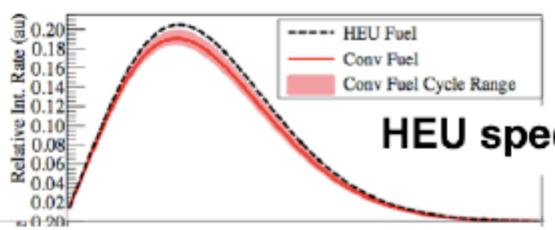


compact reactor core

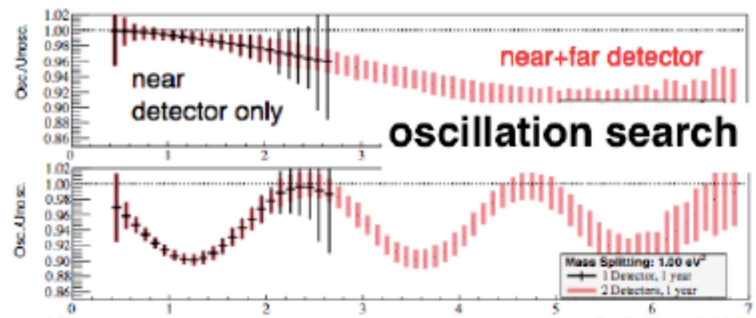


Physics Objectives

1. Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum for physics and safeguards



2. Search for short-baseline oscillation within near detector (+ far detector)

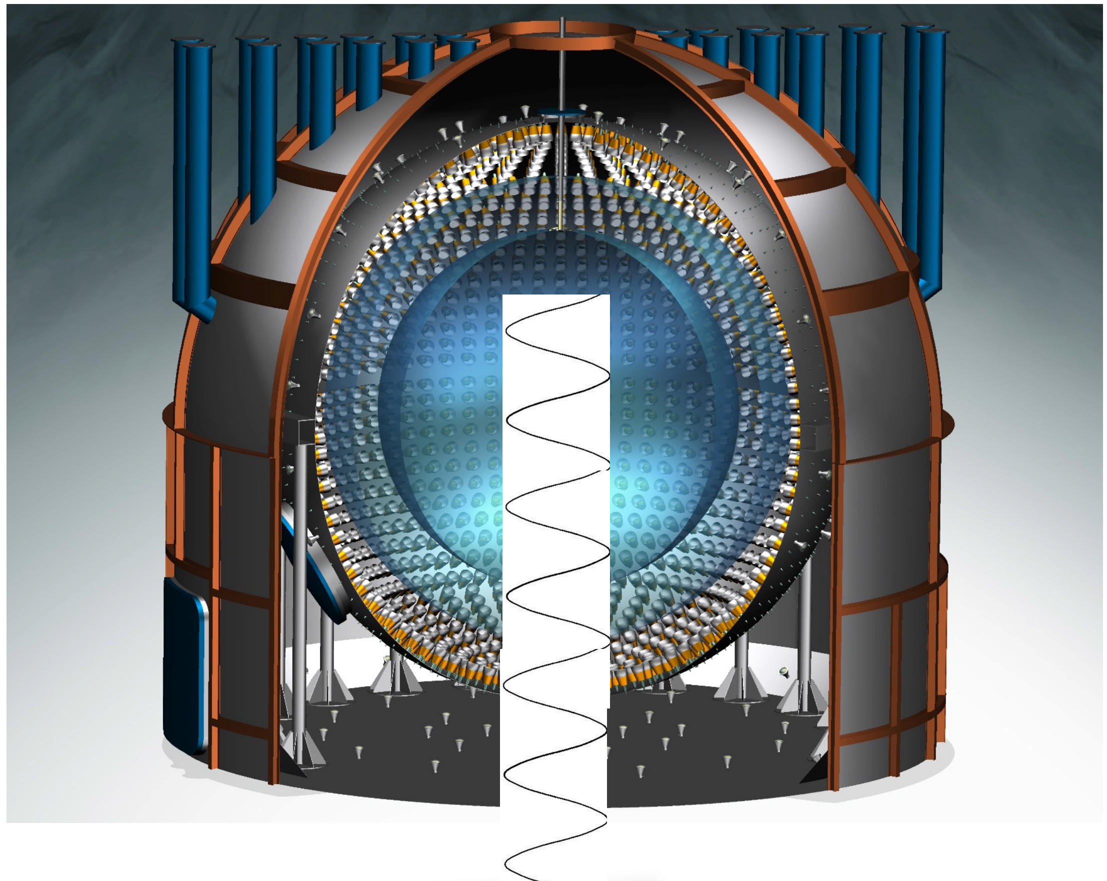


K. Heeger

Source measurements.....

SOX experiment
at Gran Sasso lab

Look for pattern of oscillations inside the Borexino Detector



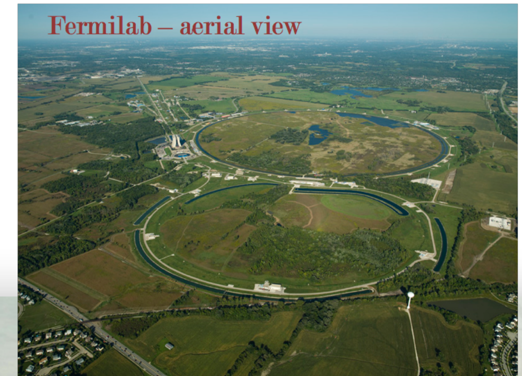
Anti electron neutrino source below the detector

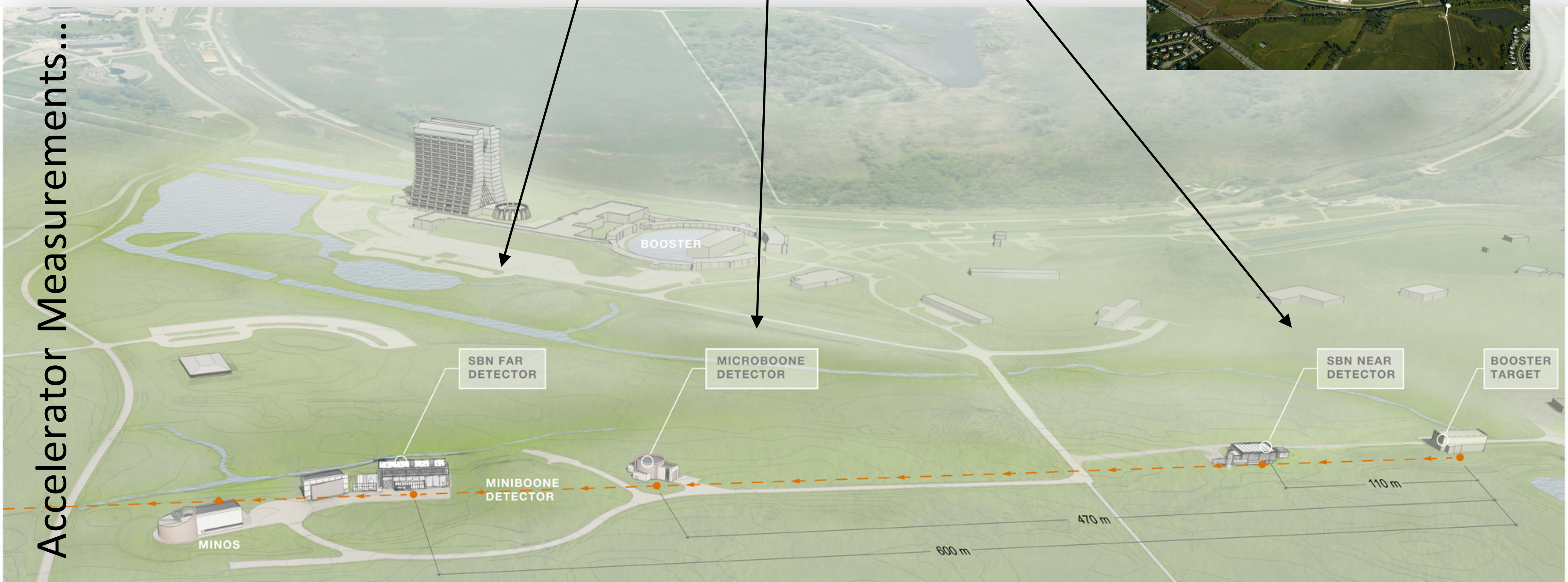
Under Construction
Running 2018/2019

Accelerator Measurements…

Three detector Short Baseline Neutrino (SBN) program underway at Fermilab:

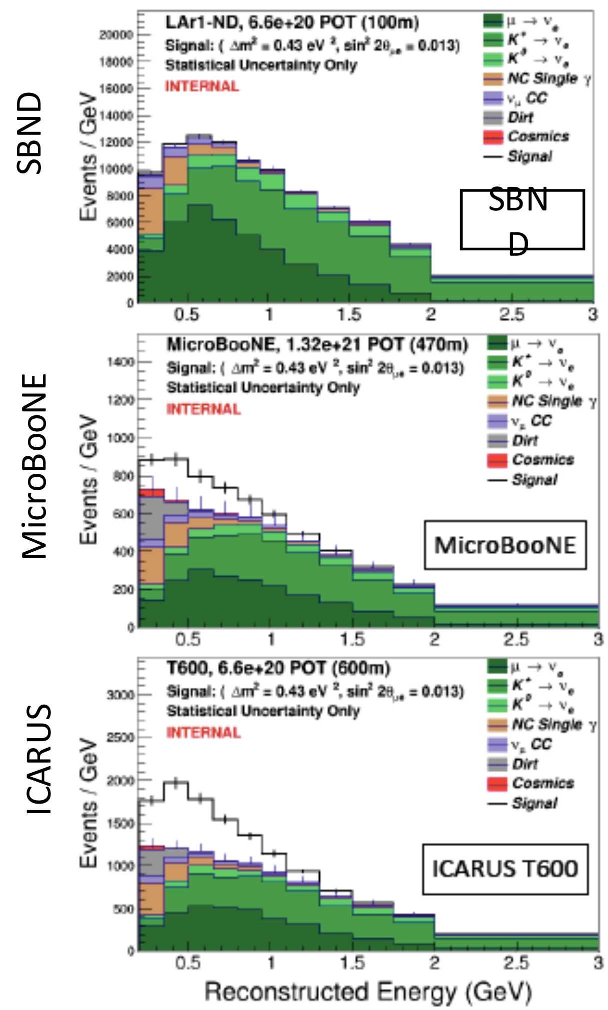
Muon neutrino beam (same as MiniBooNE) sampled at SBND near detector (no oscillations), far detectors: MicroBooNE, ICARUS

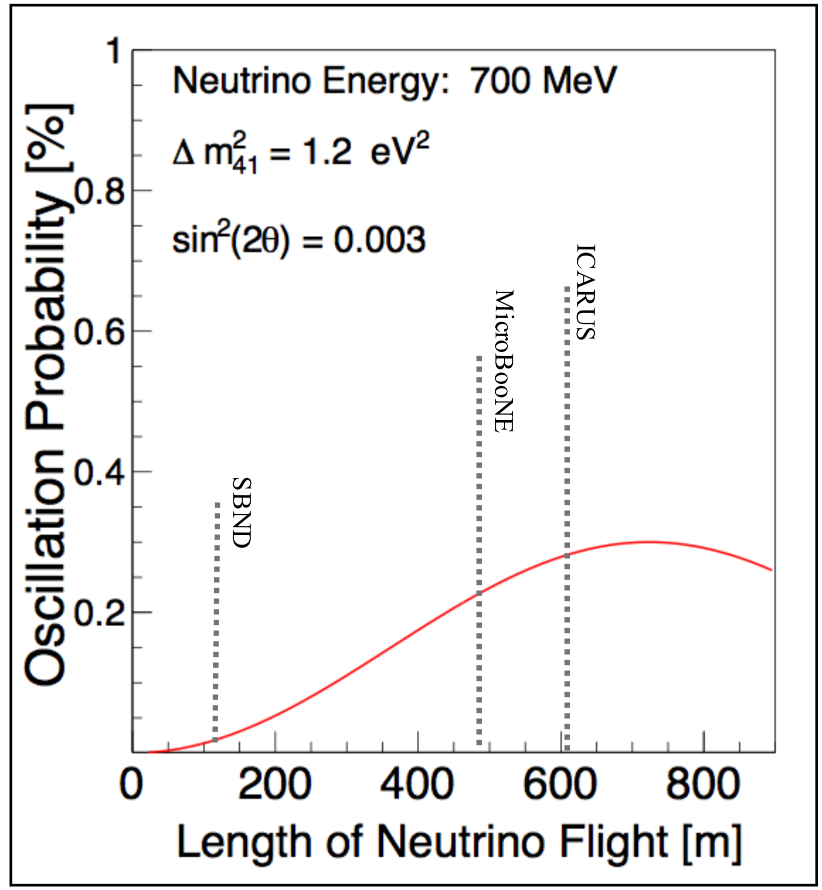




ν_e appearance sensitivity with three detector SBN experiment

Accelerator Measurements…





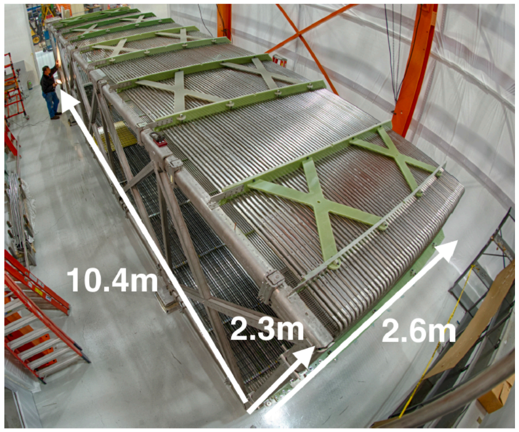
Accelerator Measurements…

MicroBooNE: Phase 1

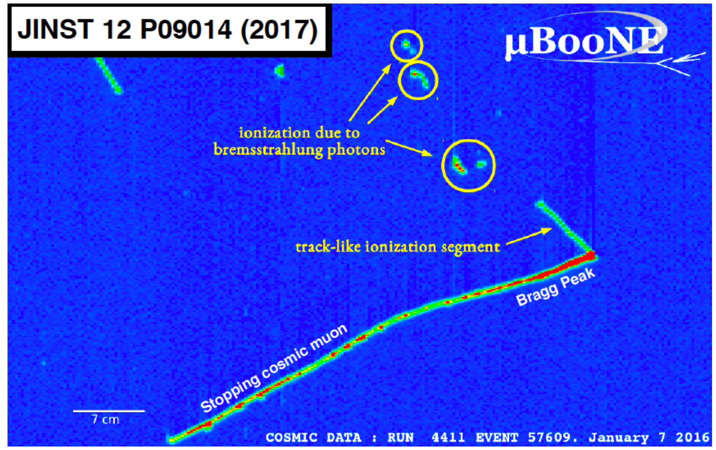
- MicroBooNE → Philosophy: Precision detector technology in same beam as the MiniBooNE experiment to definitively address LSND/MiniBooNE anomaly
  - Running for 2-3 years starting October 2015

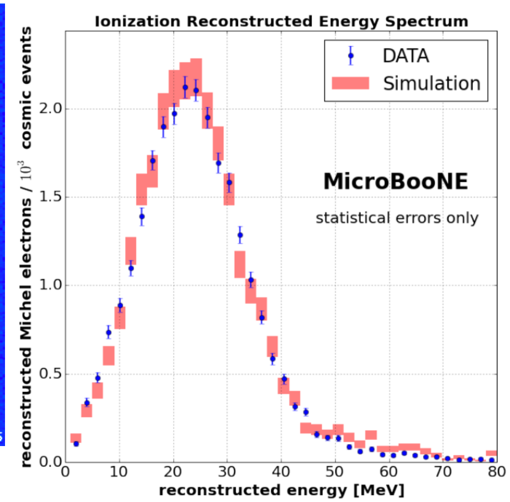
Accelerator Measurements…

89 tonnes of active mass

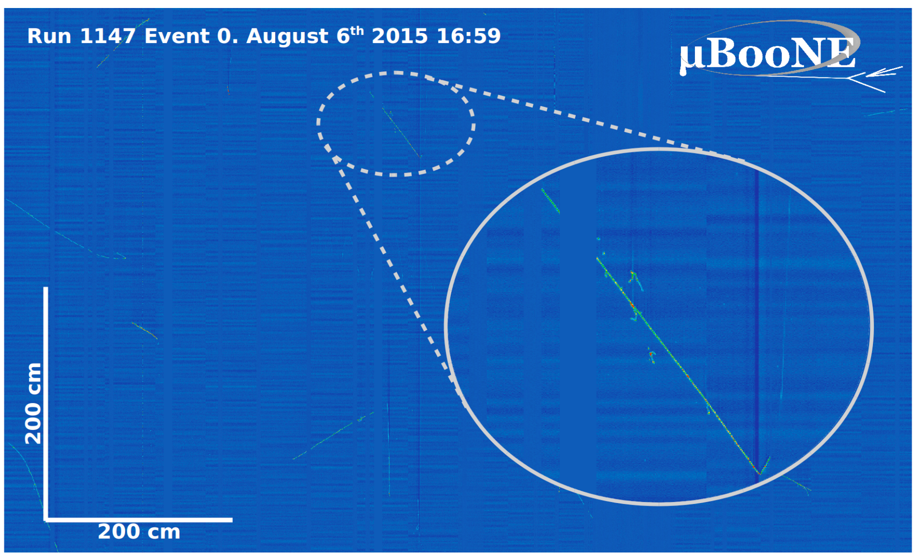


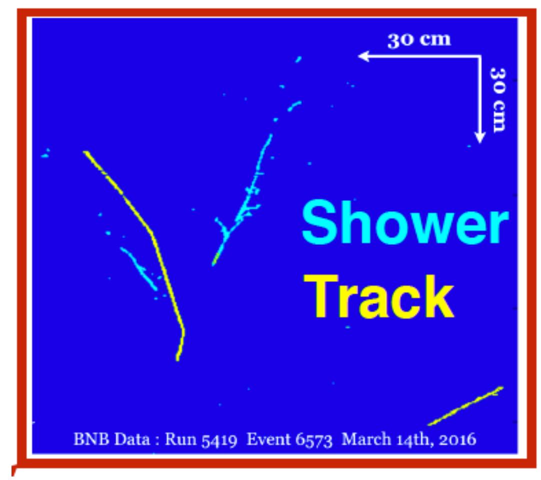
MicroBooNE precision liquid argon TPC detector





First event in 2015



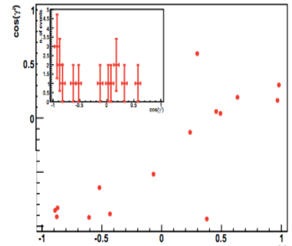
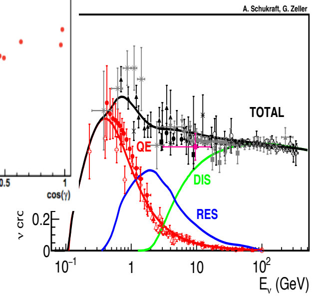


Oscillation Analysis underway….

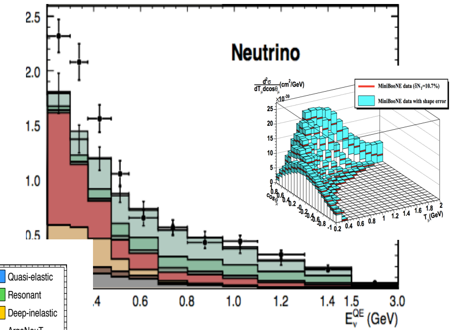
Path to oscillation results

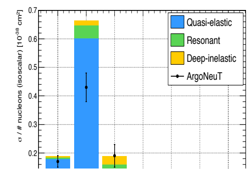
9 papers, 15 public notes

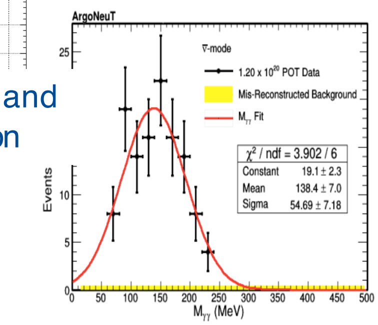
Final year of data taking for 1st oscillation results

Results







Michel Electron Reconstruction Using Cosmic-Ray Data from the MicroBooNE LArTPC; arXiv:1704.02927

Determination of muon momentum in the MicroBooNE LArTPC using an improved model of multiple Coulomb scattering; arXiv:1703.06187

Energy reconstruction and energy scale calibration

Track multiplicities

Momentum reconstruction

Measurement of cosmic-ray reconstruction efficiencies in MicroBooNE using a small external cosmic-ray counter; coming soon

CC muon kinematics

Particle & event ID

Proton ID

3D shower reco

Cosmic removal

Data/MC agreement

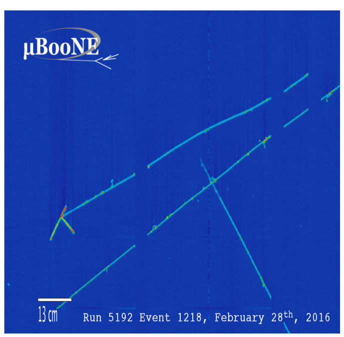
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber; arXiv:1611.05531

Cosmic shielding studies

2D & 3D event reconstruction

The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector; coming soon

Data



Noise filtering & signal processing

Charge extraction

Detector stability studies

Detector response calibration & simulation

Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC; arXiv:1705.07341

Space charge studies

LAr/e propagation properties

Design and Construction of the MicroBooNE Detector; arXiv:1612.05824

[~ since last year's User's meeting]

Anne Schukraft
FNAL User's meeting, 2017

Short Baseline Neutrino Detector (SBND)

Accelerator Measurements...

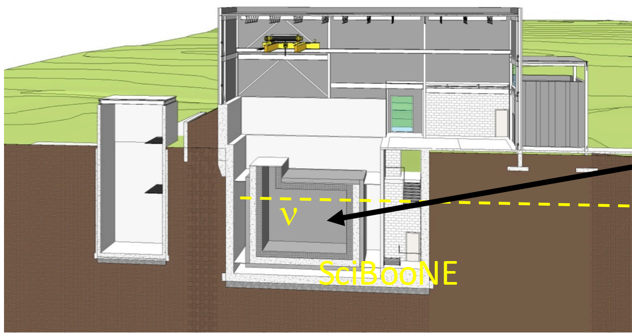
- MicroBooNE → Philosophy: Precision detector technology in same beam as the MiniBooNE experiment to definitively address LSND/MiniBooNE anomaly
  - Running for 2-3 years starting October 2015
- **SBND: Observe if a signal seen in MicroBooNE is baseline dependent – Do we see it 100m from the neutrino production target?**

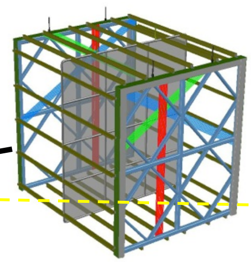
Accelerator Measurements…

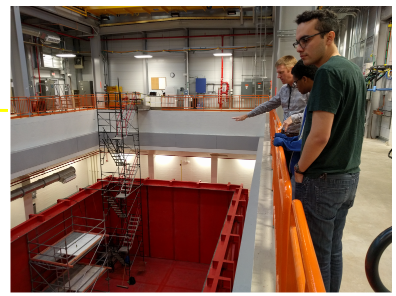
ICARUS

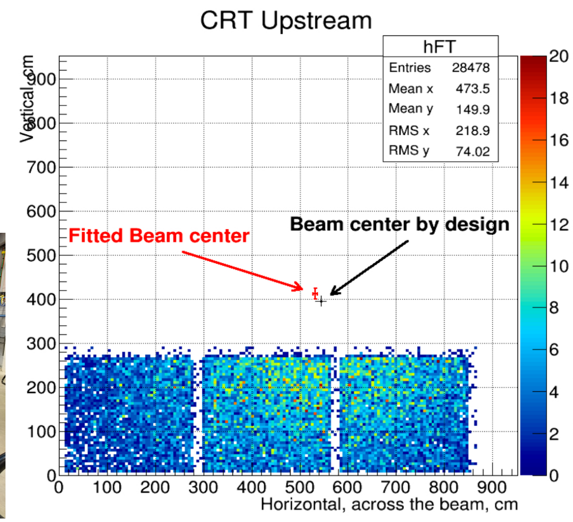
- MicroBooNE → Philosophy: Precision detector technology in same beam as the MiniBooNE experiment to definitively address LSND/MiniBooNE anomaly
  - Running for 2-3 years starting October 2015
- SBND: Observe if a signal seen in MicroBooNE is baseline dependent – Do we see it 100m from the neutrino production target?
- **ICARUS: Look downstream of MicroBooNE with much more mass (~x5) to be sensitive to a broader range of neutrino oscillation parameter space**

Short Baseline Near Detector and ICARUS under construction
Data taking to begin 2019

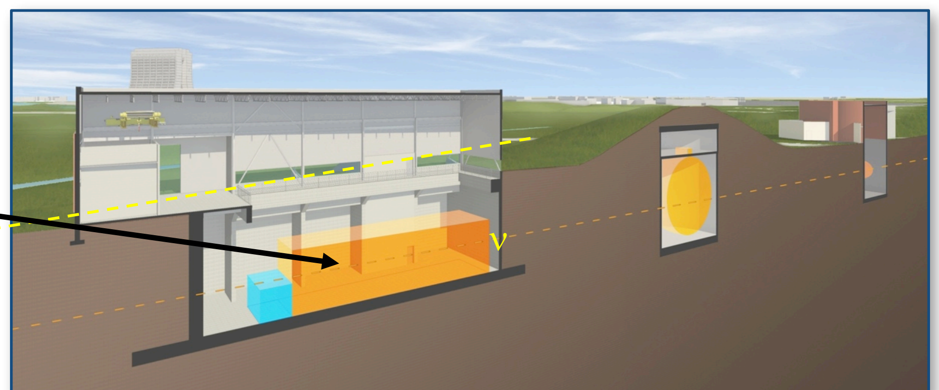








ICARUS



Refurbished at CERN
→ Neutrino Platform

All of these LArTPC experiments develop technology towards DUNE

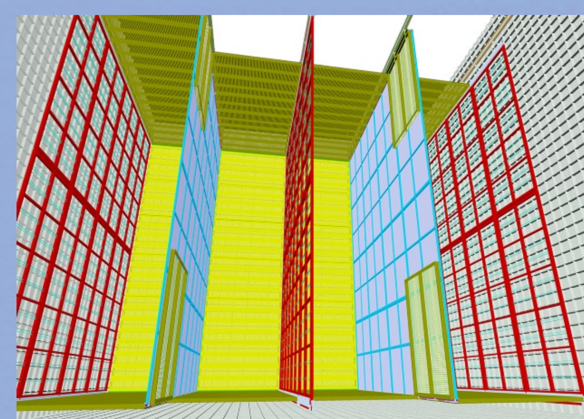
ν Measurements, new physics

Short Baseline
L/E ~1 km/GeV
Hints of sterile neutrinos
New physics?

Long Baseline
L/E ~ 1000km/GeV
Measuring Mass Hierarchy and Looking for CP Violation

$\nu_\mu \rightarrow \nu_e$ appearance experiments
E_ν 1-10 GeV
SBL→ DUNE: Precision detectors:
Liquid Argon TPCs

~100 tons → 40ktons



ICFA seminar

November 6th, 2017

Experimental neutrino physics started with the discovery of the neutrinos at reactors and accelerators

60+ years later we understand much more about neutrinos….

Still a big mystery at short baseline…

Broad program of complimentary precision short baseline experiments to address this

Are we discovering another neutrino?