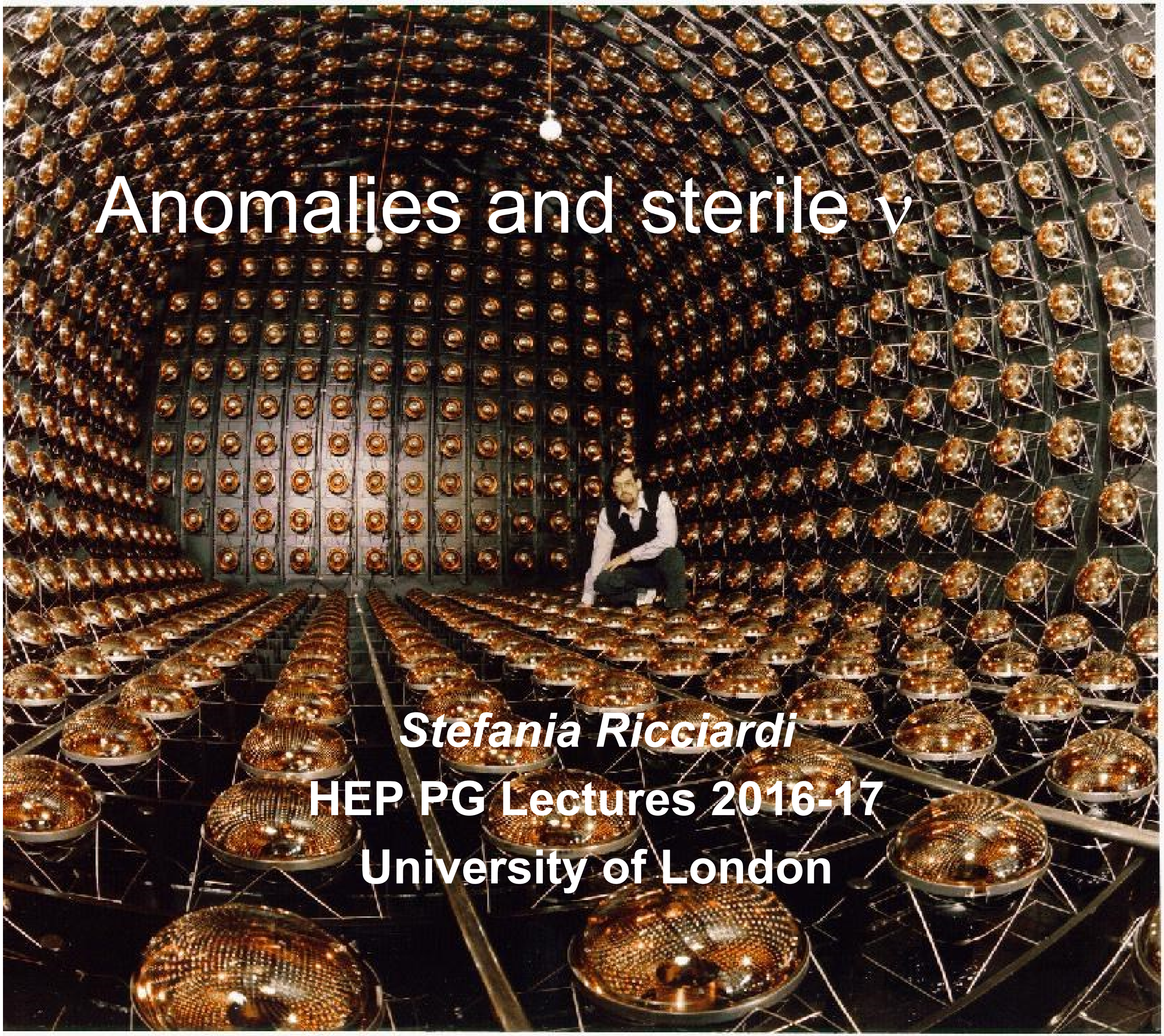


Anomalies and sterile ν

Stefania Ricciardi
HEP PG Lectures 2016-17
University of London

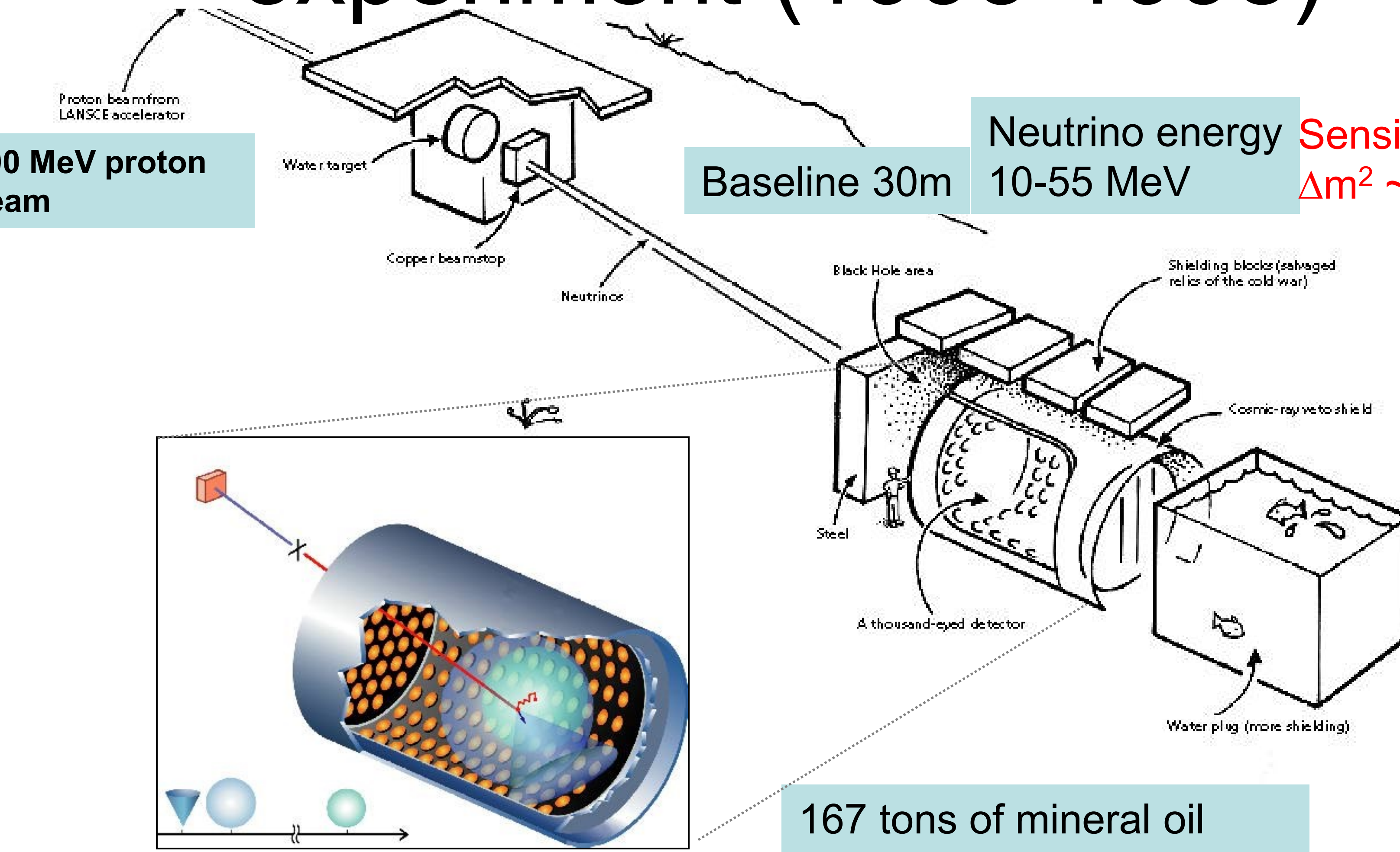
The LSND appearance experiment (1993-1998)

800 MeV proton beam

Baseline 30m

Neutrino energy 10-55 MeV

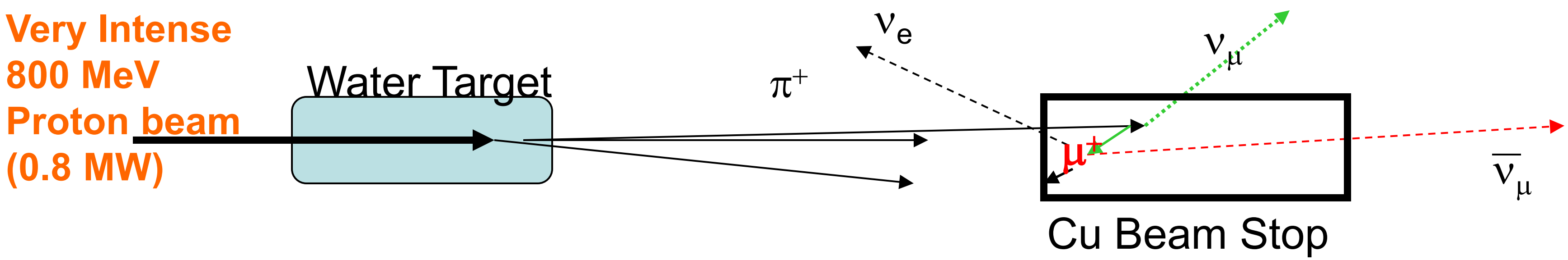
Sensitive to $\Delta m^2 \sim E/L \sim 1\ eV^2$



167 tons of mineral oil (cherenkov directional light + scintillator isotropic light)

Decay At Rest (DAR) ν beam

The main analysis of LSND uses anti-ν_μ from decay at rest of positive muons stopping in the Cu beam stop



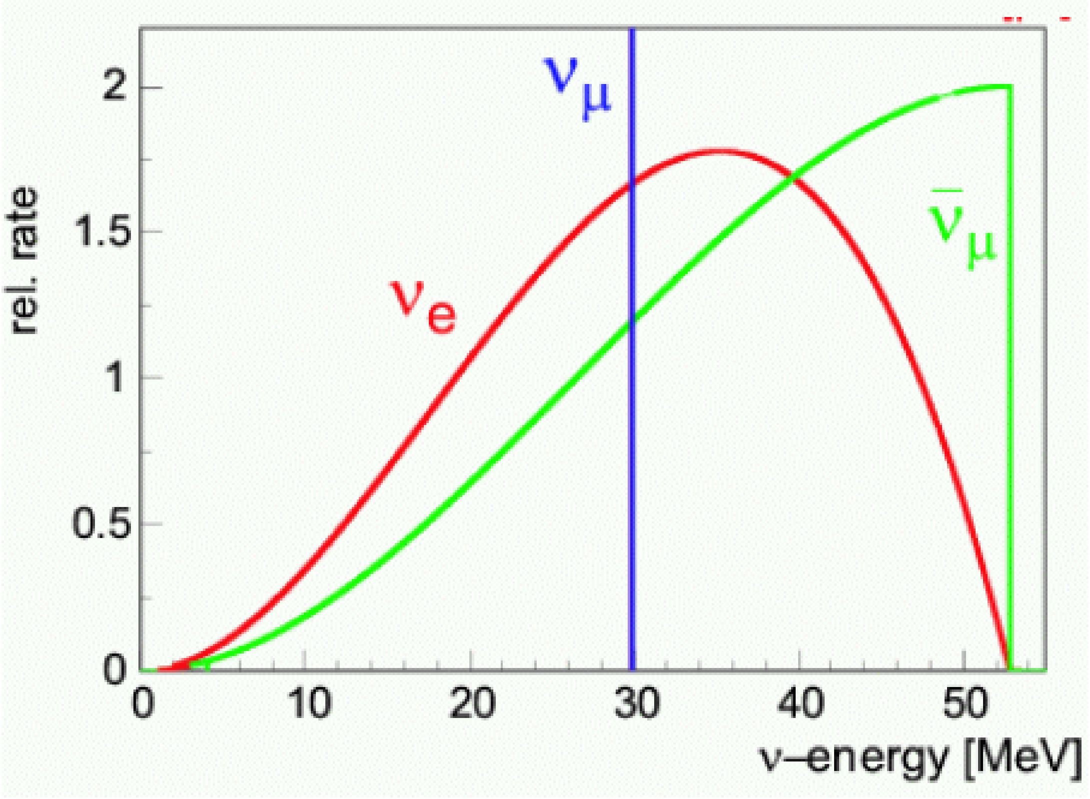
- p + target $\rightarrow$ lots of pions (mainly positive, leading charge)
- Some π^+ stop in the beam-stop and then decay

  $\pi^+ \rightarrow \mu^+ \nu_\mu$
- μ^+ stops in the beam-stop and then decays

  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

Not an efficient way of making a neutrino beam.
However, 3 kinds of neutrinos can fly in the (close) detector (and "no" anti-ν_e).
Good for anti-ν_μ to anti-ν_e appearance search!

DAR beam energy spectrum



Extremely well defined flux shape:
monochromatic line from pion 2-body decay
+ 2 neutrinos from well known muon decay
But low energies limit choice of interactions and cross-section

LSND Oscillation Signature

Decay at Rest (DAR)
$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Max Eν energy 53 MeV

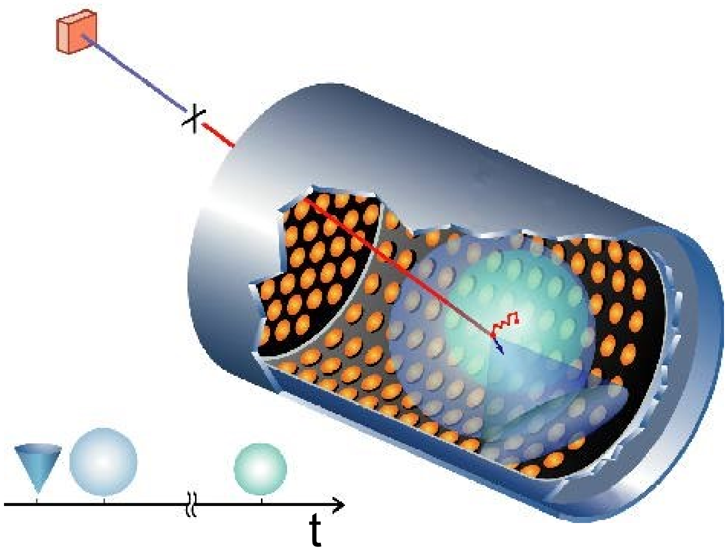
Prompt Cerenkov + scintillation signal

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

$\downarrow$ ***186 μs later***

$n + p \rightarrow d + \gamma$

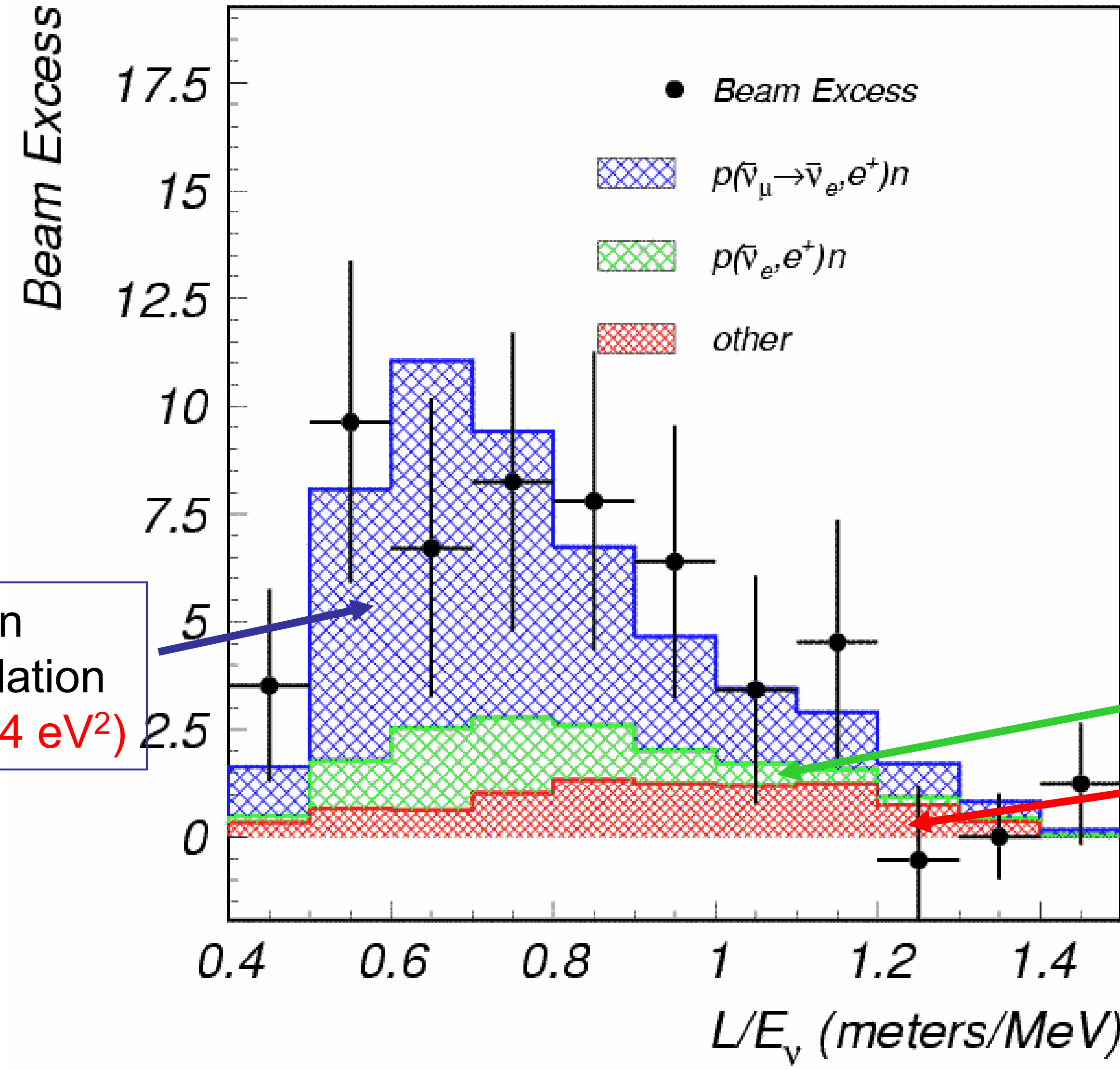
2.2 MeV scintillation signal



Reconstruct e^+ and γ with appropriate space and time-delayed coincidence

The LSND evidence (DAR)

http://journals.aps.org/prd/pdf/10.1103/PhysRevD.64.112007



Data points:
Excess after
Beam-off
Background
Subtraction

Final result:
87.9 ± 22.4 ± 6.0
Events
over background
4σ evidence of
oscillation

Expectation
From oscillation
($\Delta m^2 = 0.24\ eV^2$)

Size of
The beam
Related
backgrounds

Backgrounds

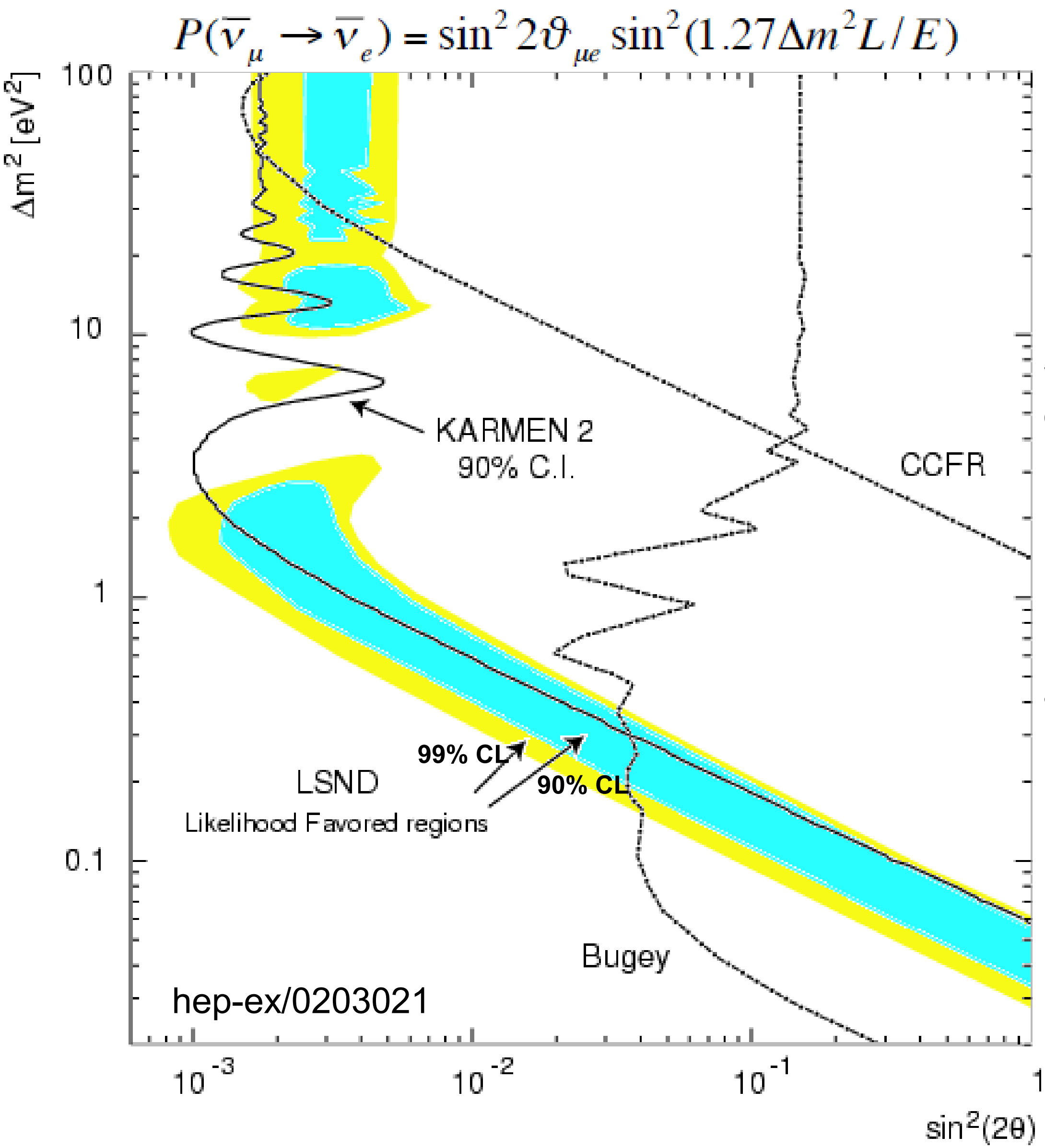
Example of backgrounds:

1) Anti-ν_e from beam contamination: $\pi^- \to \mu^- \overline{\nu_\mu}$ followed by $\mu^- \to e^- \overline{\nu_e} \nu_\mu$
   π^+/π^- ~7,and π^- and μ^- are captured before decay
   anti-ν_e :Total reduction factor 1/1000
   (estimated 20 $\pm$ 4 events)

2) $\overline{\nu_\mu} + p \to \mu^+ + n$
   when over CC threshold and muon is mid-identified as electron
   (estimated 10 $\pm$ 5 events)

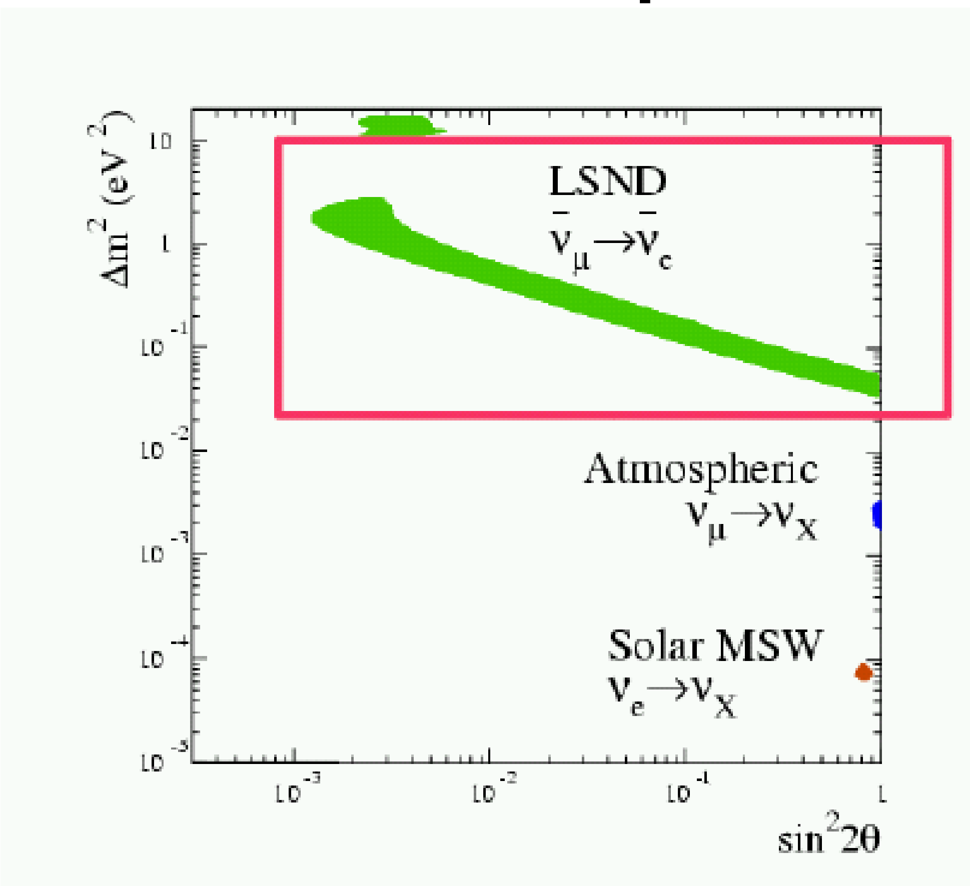
3) accidental coincidence of neutrons with e-like interaction from ν_e interaction. Well under control: neutrons can be captured producing 1γ, but also knock onto nucleus and produce multiple gammas$\Rightarrow$ Excess of neutrons would produce an excess of multiple γ events. Such excess NOT observed.

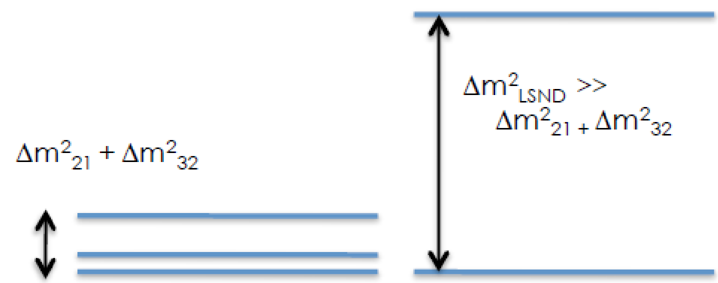
LSND/KARMEN Final Result



Karmen
similar short-baseline experiment
in the UK!
Smaller data sample
Excludes at 90% CL a large region allowed by LSND but NOT ALL!

Can LSND result fit in the global oscillation picture?



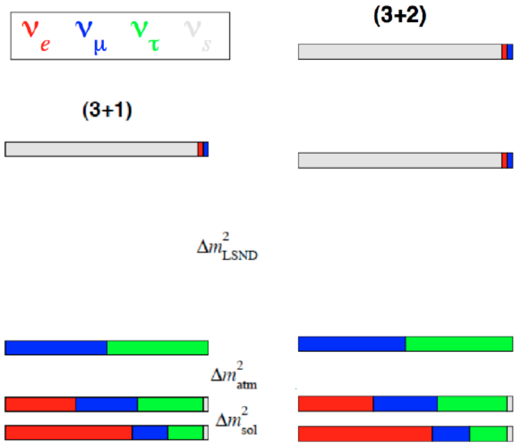


3 different Δm^2 !!
Cannot fit with 3 families
$\Rightarrow$ It must be New Physics

More neutrino species?

Δm^2_{sol} (~7 x10^{-5} eV^2) << Δm^2_{atm} (~2 x10^{-3} eV^2)<< Δm^2_{LSND} (~eV^2)
imply at least 4 neutrinos

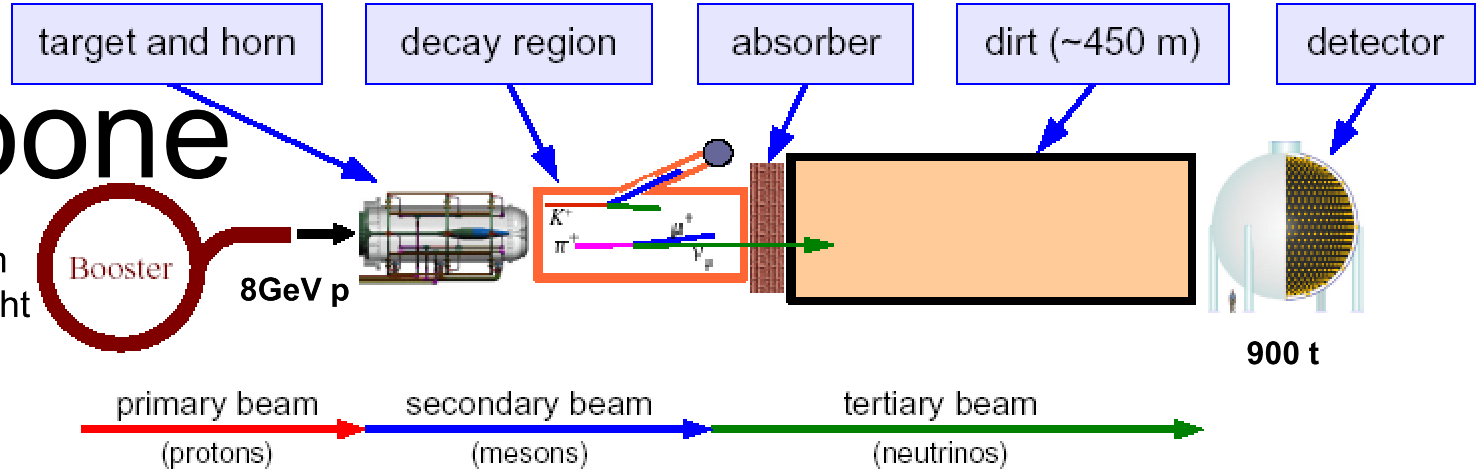
Given LEP results (only 3 active neutrino generations)
the additional neutrino must be sterile (no weak interactions)
Global fits to all oscillation data now prefer models with multiple sterile neutrinos

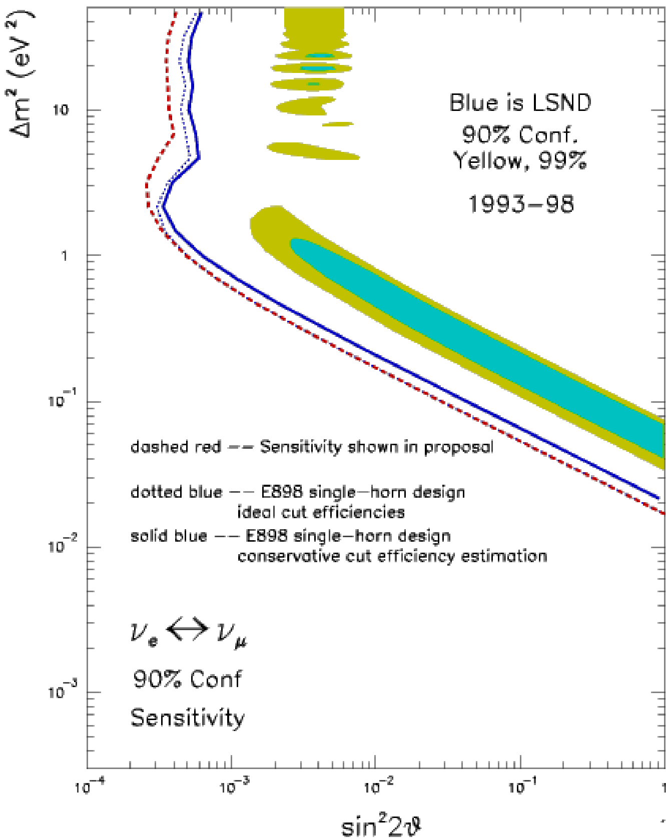


Nice recent review at graduate student level: J. Conrad and M.Shaevitz, "Sterile neutrinos: an introduction to experiments" arXiv:1609.07803

MiniBoone

Conventional beam
From Decay in Flight
(DIF)





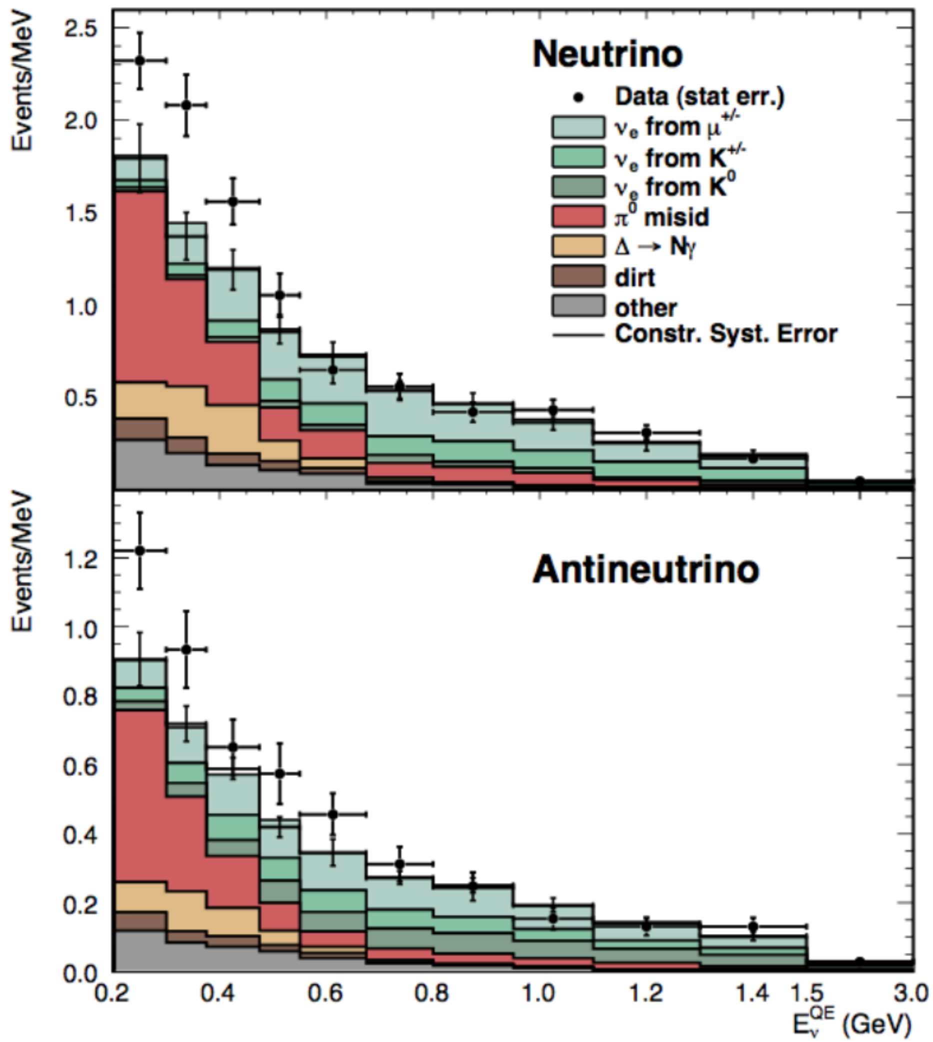
Purpose:
Test the LSND signal with:
- ν_μ beam (to start)
- x10 larger data sample
- different systematics
    - -E x10 resulting in different background and event signatures
- L x10 to achieve similar E/L than LSND

MiniBoone ***expected*** final sensitivity
(started Aug 2002)
LSND can be excluded at ~5σ or thousands of events observed in excess if signal is real!

10 years of suspence…

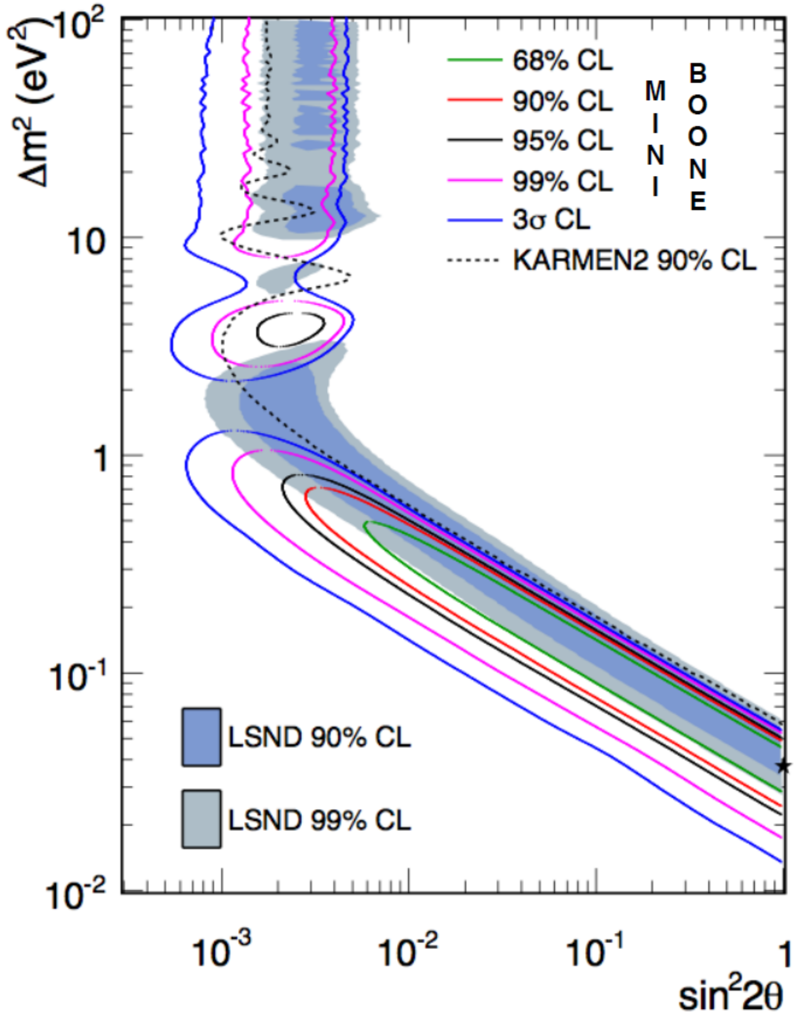
What’s your bet?

MiniBoone results [arXiv:1207.4809]



Total excess
(neutrinos+antineutrinos):
240 +/- 63 events

Allowed Δm^2-$\sin^2 2\theta$ regions



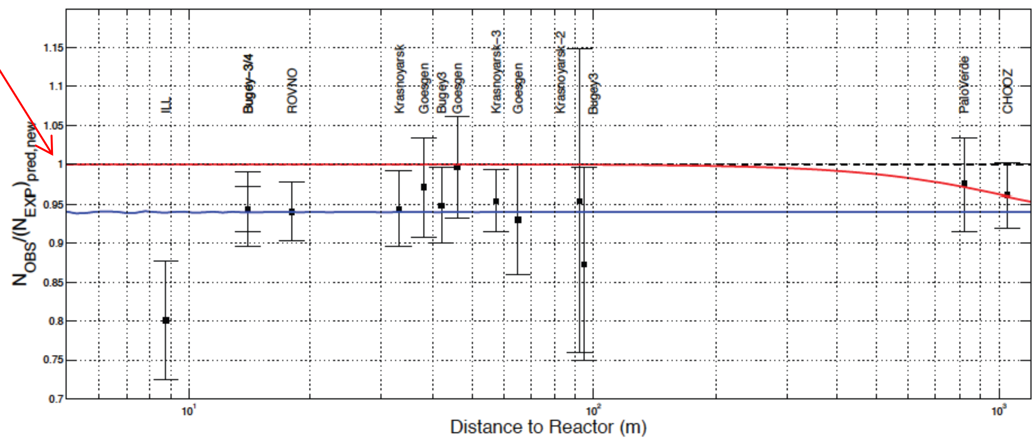
Including MiniBoone neutrino+antineutrino data with $E\nu$>200MeV

LSND and MiniBoone Allowed regions In a 2-neutrino framework

A new anomaly:
Reactor neutrino anomaly

- to predict the $\bar{\nu}_e$ flux from nuclear reactors one has to convert the measured e^- spectra from ^{235}U, ^{239}Pu, ^{241}Pu into neutrino spectra
  Schreckenbach et al., 82, 85, 89
- recent improved calculation Mueller et al., 1101.2663 yields
  $\sim$ 3% higher fluxes

Mention et al., 1101.2755



Red: Oscillations
for 3-neutrinos mixing

Blue: Oscillations
for 3+1 (sterile) neutrinos mixing

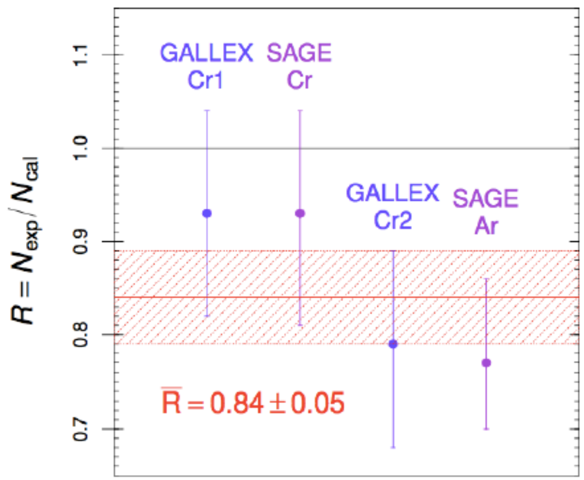
Significance of observed rate reduction depends on systematics/theoretical uncertainties

Another anomaly:
Gallium anomaly

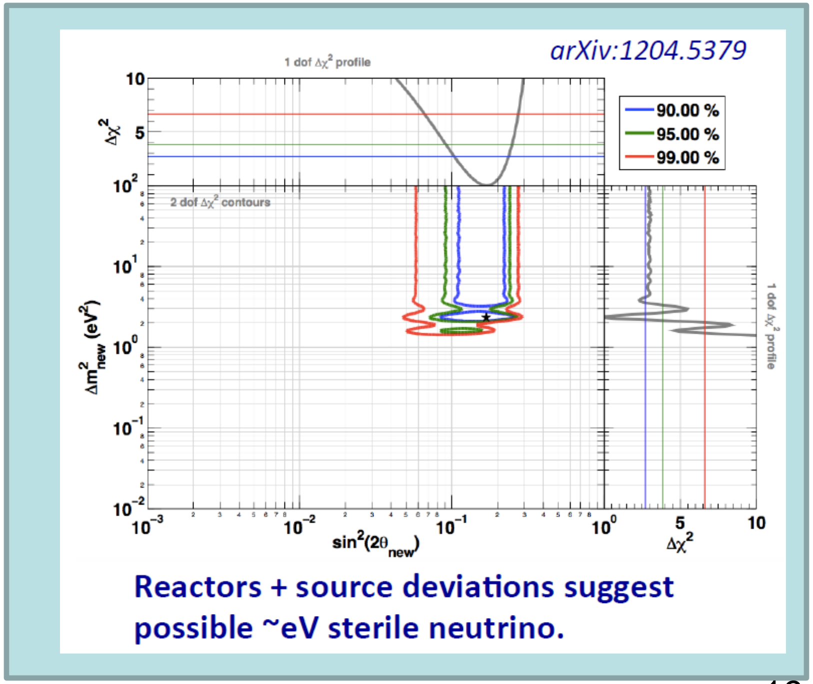
SAGE and Gallex, the two gallium solar neutrino experiments used MCi sources of ^{51}Cr and ^{37}Ar to calibrate their detectors

3σ deficit:

- Ratio (observed/prediction) = 0.85 ± 0.05



Phys. Rev. C83, 065504 (2011)



ν_e *disappearance?*

Active-sterile neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \cdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \cdots \end{pmatrix}$$

Appearance

$$P(\nu_\mu \to \nu_e) = 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

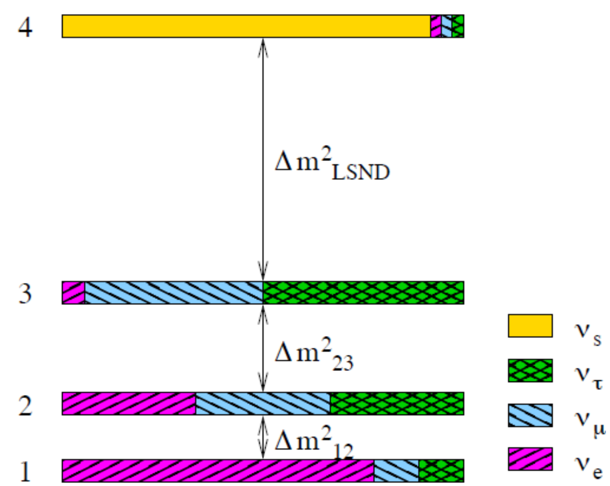
Disappearance

$$P(\nu_\mu \to \nu_\mu) = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

$$P(\nu_e \to \nu_e) = 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)\sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

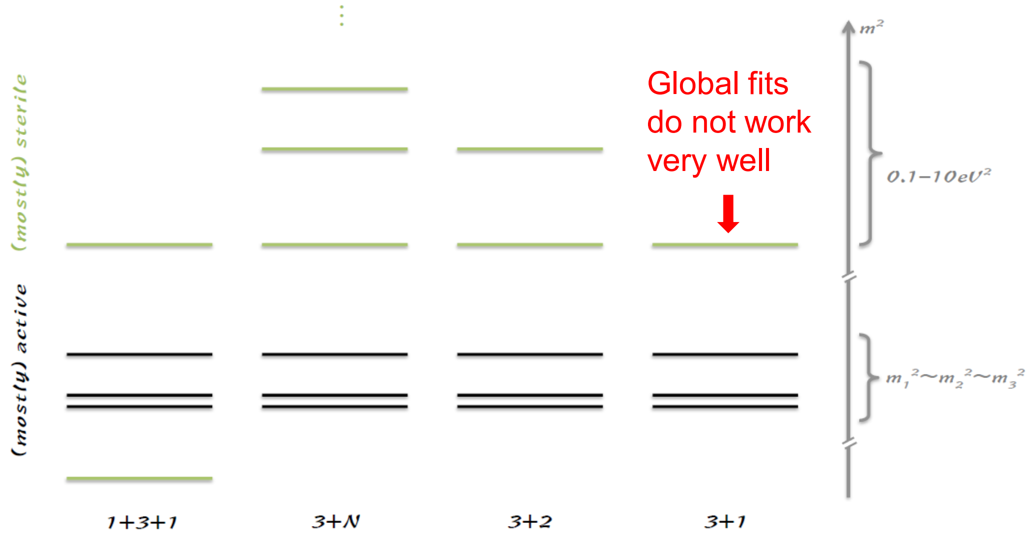
Close relationships between appearance and disappearance channels

3+1 sterile neutrino scheme



No oscillation signal for ν_μ disappearance observed so far:
Tensions between appearance experiment and disappearance experiments under 3+1

If more than 1 sterile neutrinos



- For a 3 +2 spectrum, the oscillation probabilities are more complicated. However if the extra neutrino mass-eigenstates are mostly sterile, still disappearence and appearance probabilities are related

$$[1 - P(\overline{\nu_\mu} \to \overline{\nu_\mu})][1 - P(\overline{\nu_e} \to \overline{\nu_e})] > P(\overline{\nu_\mu} \to \overline{\nu_e})$$

- For a 3 +3 spectrum, the oscillation probabilities are even more complicated. However, it improves the global fits to short-baseline terrestrial data

Still significant tension in global fits to disappearance and appearance data (mainly contributed by MiniBoone low E excess in neutrino mode)

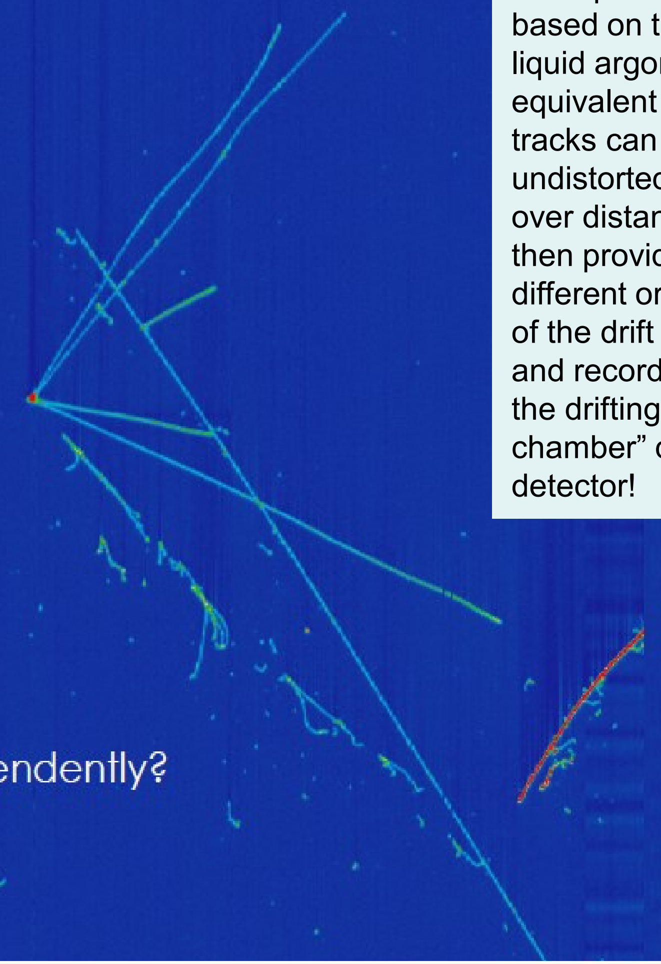
Proposed future experiments

Channels and processes to explore via complementary experiments

Flavor Transition	CPT Conjugate
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_{\not e}$	$\bar{\nu}_e \rightarrow \bar{\nu}_{\not e}$
$\nu_\mu \rightarrow \nu_{\not\mu}$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_{\not\mu}$

A comprehensive and recent reference:
K. Abazajian et al, “Light sterile neutrinos: a white paper”, arXiv:1204.5379

µBooNE



The operational principle of LAr TPC is based on the fact that in highly purified liquid argon (less than 0.1 *ppb* O_2 equivalent contamination) ionization tracks can be transported practically undistorted by a uniform electric field over distances of meters. Imaging is then provided by wire planes with different orientations placed at the end of the drift path, continuously sensing and recording the signals induced by the drifting electrons. "Bubble chamber" quality images, with real time detector!

A liquid argon TPC detector.
Data taking has begun!

Will definitively be able to address the
MiniBooNE Low Energy Excess Anomaly:

Can the excess be confirmed independently?

If it is confirmed, is it
electron-like or photon-like?

If the excess is in single **electrons** events
MicroBooNE could be seeing ν_e appearance (sterile neutrino oscillations, NSI, extra dimensions) or be in position to measure some other new production mechanism (?)

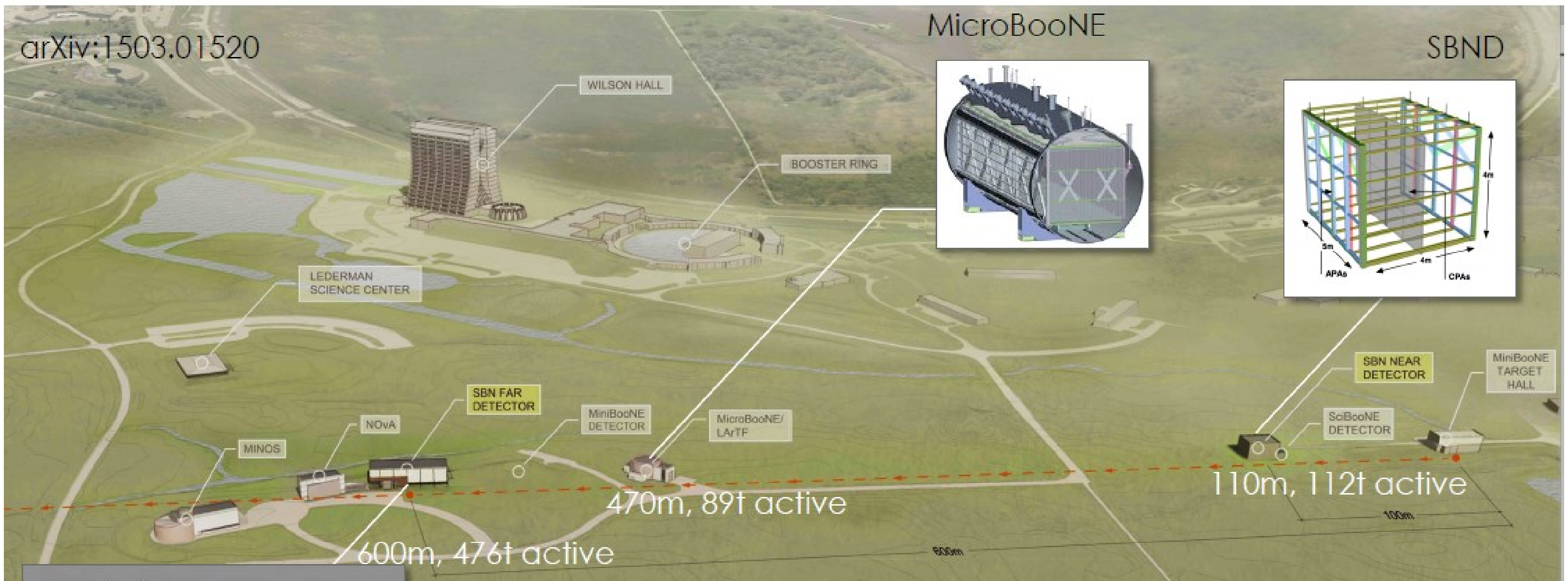
75 cm

Run 3493 Event 41075, October 23rd, 2015

Future SBN program at Fermilab

(Beyond MicroBooNE:) Short Baseline Neutrino program at Fermilab

A **second** & **third** LArTPC placed in the BNB at Fermilab, in line with MicroBooNE

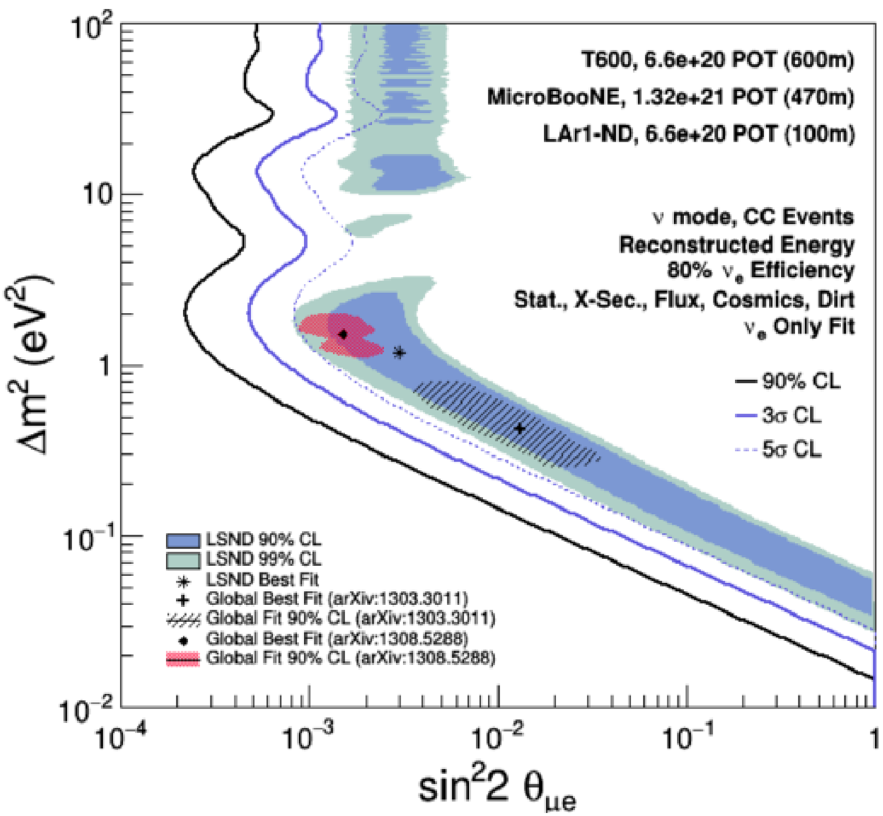


Refurbished ICARUS T600 detector

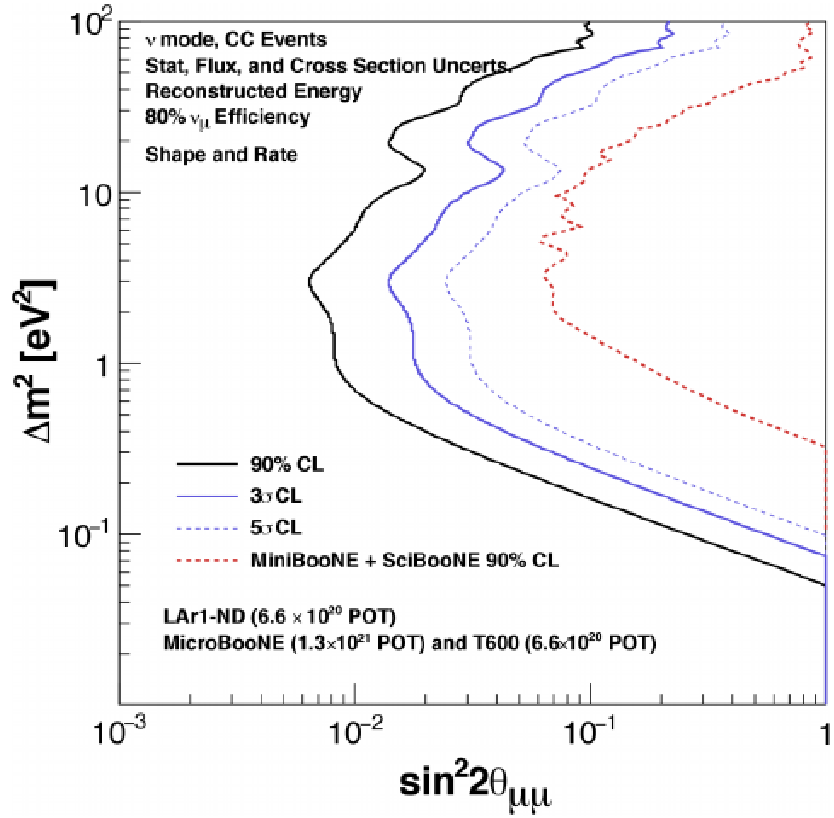
- Near/mid/far comparison for short-baseline oscillation search
- **Definitive search for sterile neutrino oscillations**

Projected SBN sensitivities

Appearance

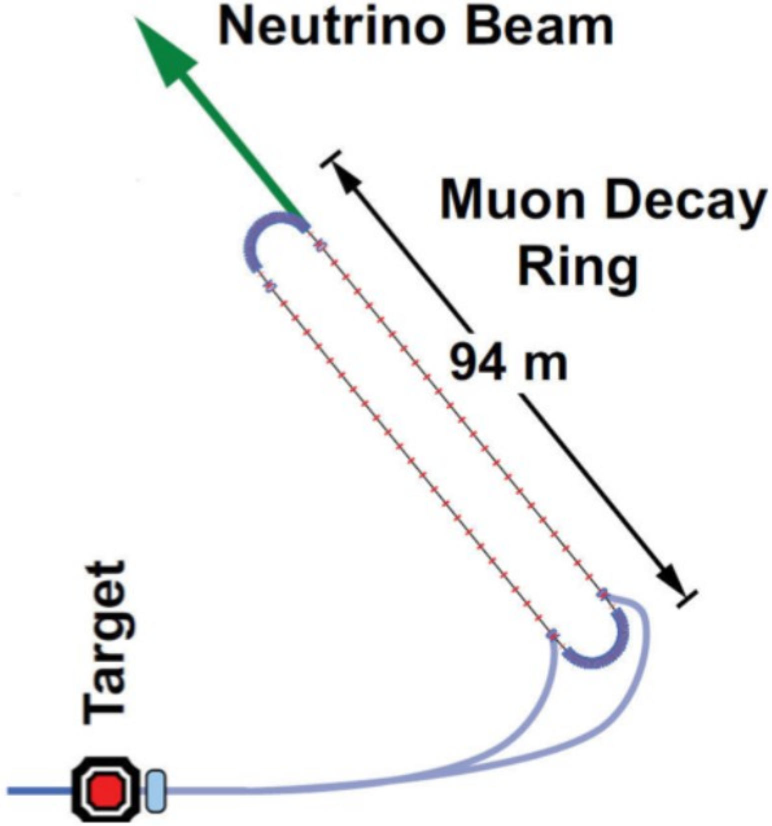


Disappearance



A different proposal: νStorm

The first stage of a very low energy Neutrino Factory



$E_\mu \sim 4$ **GeV**

If store μ^+, can study—

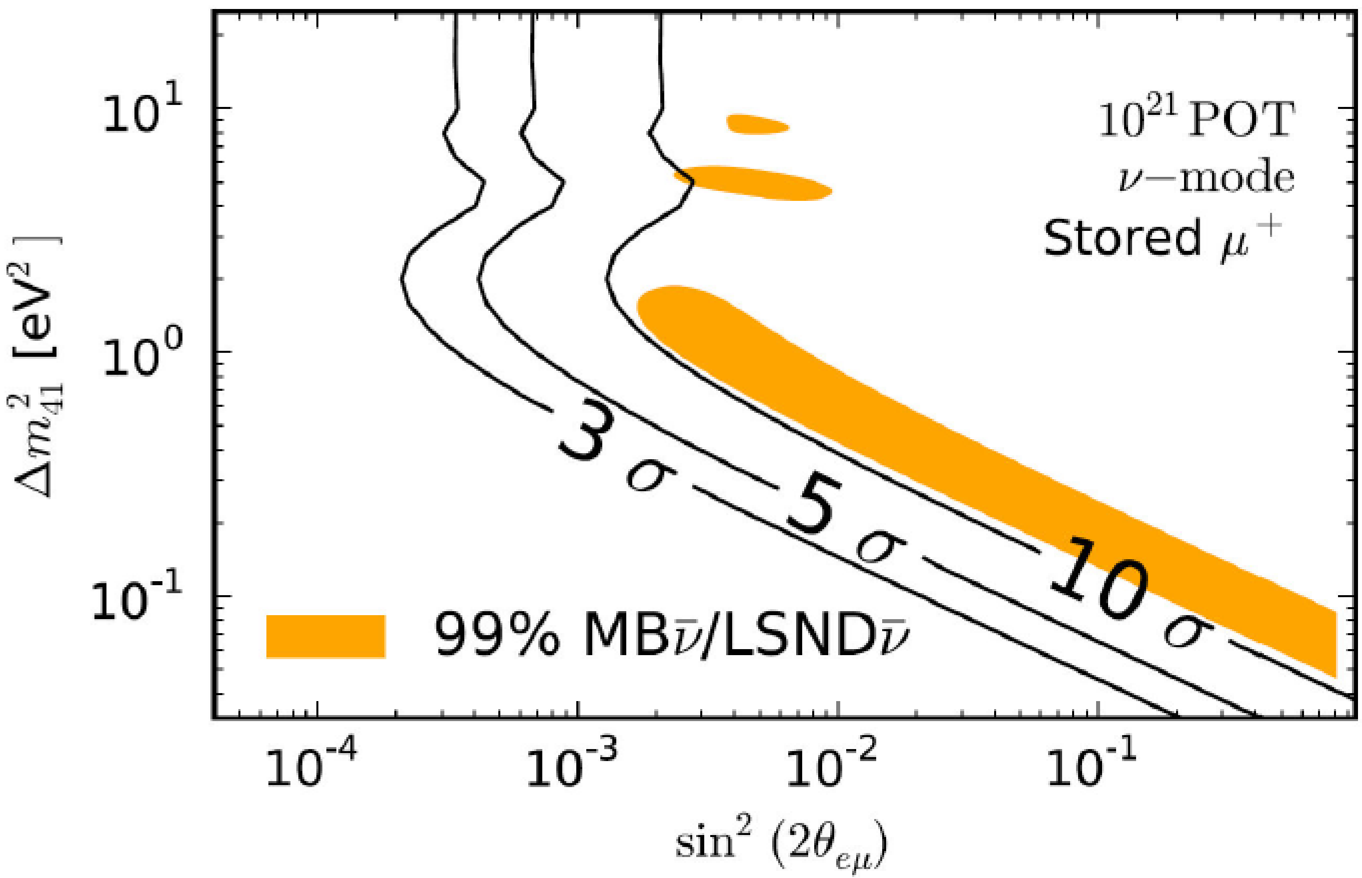
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

followed by —

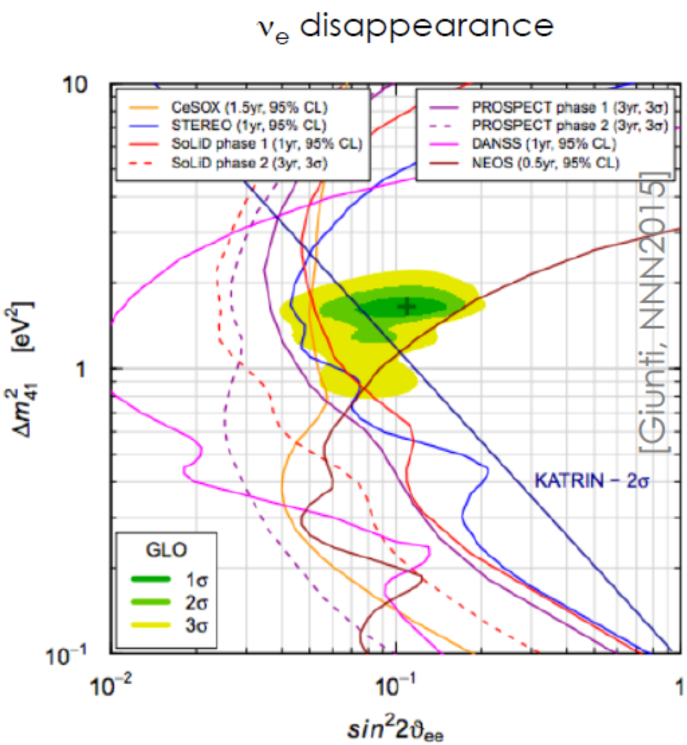
$$\nu_e \to \nu_\mu \; .$$

LSND reported $\bar{\nu}_\mu \to \bar{\nu}_e$. $P(\nu_e \to \nu_\mu) \underset{\text{CPT}}{=} P(\bar{\nu}_\mu \to \bar{\nu}_e)$

νStorm
$\nu_e \rightarrow \nu_\mu$ sensitivity



Future disappearance experiments with ν_e radioactive sources or at reactors



CeSOX (BOREXINO, Italy)
144Ce – 100 kCi [Vivier@TAUP2015]
rate: 1% normalization uncertainty
8.5 m from detector center

KATRIN (Germany)
Tritium β decay [Mertens@TAUP2015]

STEREO (France)
L ≃ 8-12m [Sanchez@EPSHEP2015]

SoLid (Belgium)
L ≃ 5-8m [Yermia@TAUP2015]

PROSPECT (USA)
L ≃ 7-12m [Heeger@TAUP2015]

DANSS (Russia)
L ≃ 10-12m [arXiv:1412.0817]

NEOS (Korea)
L ≃ 25m [Oh@WIN2015]

Field in rapid evolution – Main challenges:

- Radioactive sources are short-lived
  - ➢ Time-limited high-intensity runs
- Reactor experiments very near to source
  - ➢ Background

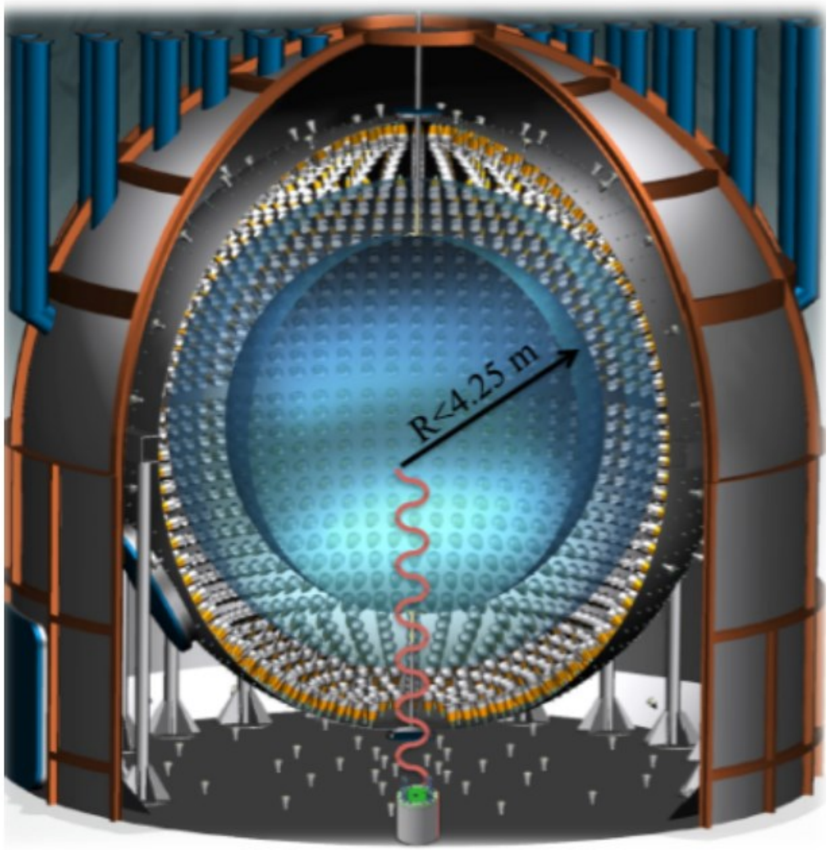
Radioactive source experiments

Source Experiments:
Use intense radioactive sources as neutrino emitters.
^{144}Ce: antineutrinos
^{51}Cr: neutrinos

SOX:
Use Borexino detector @ Gran Sasso

Look for sterile oscillation pattern across detector volume.

~4 PBq ^{144}Ce source currently being manufactured in Russia.
Aiming for measurement in ~2016.



Phys. Rev. D91, 072005 (2015)

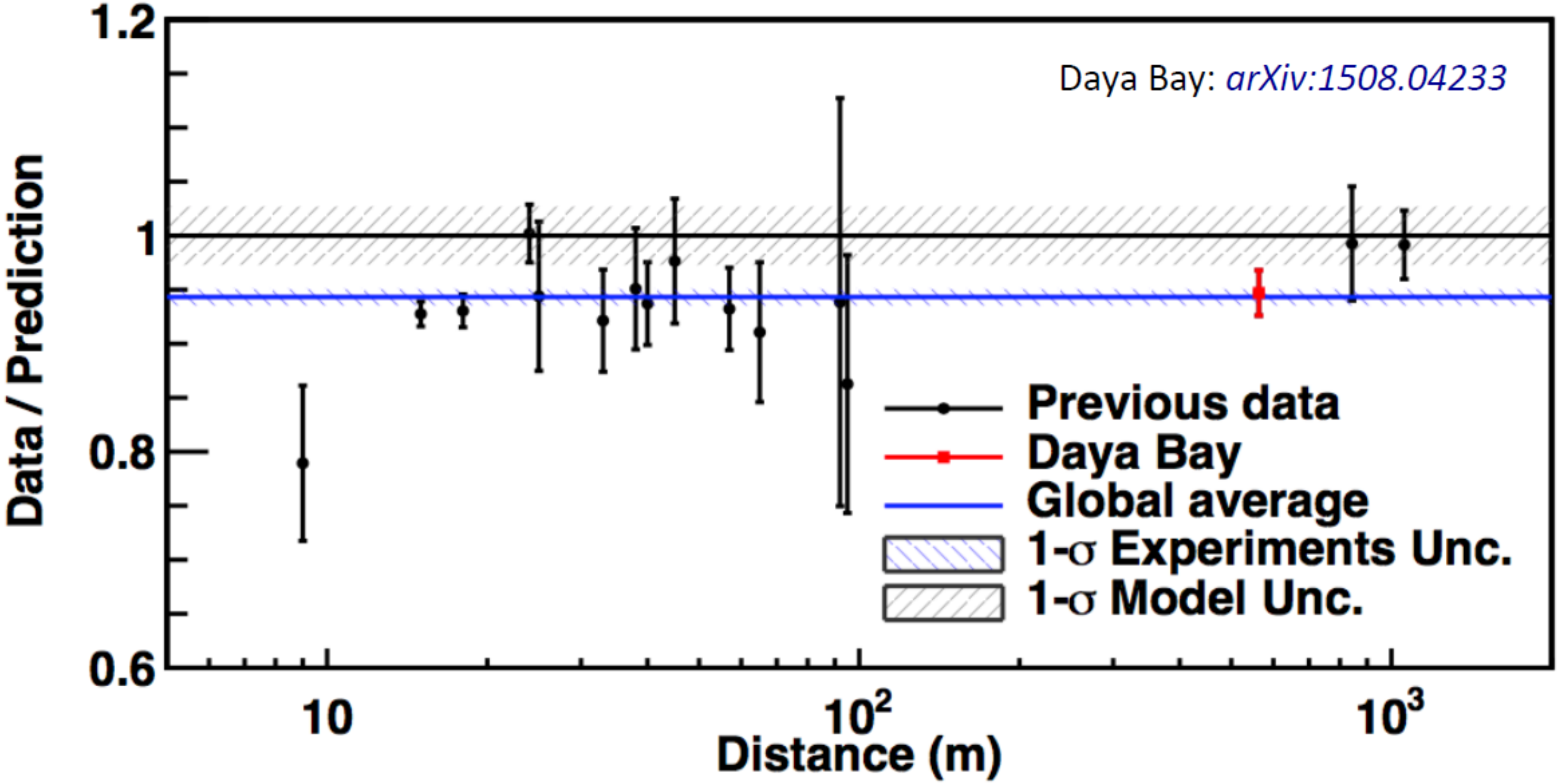
Conclusion

- The bulk of data on neutrino oscillations is fitted perfectly within the three-flavour framework (SNO, superK, MINOS, T2K, ..)
  - Strong evidence of oscillatory behaviour of the survival probability as a function of neutrino energy (Kamland data)
- There are intriguing hints for sterile neutrinos at the eV scale but no consistent picture has emerged so far
  - LSND/MiniBoone results
  - Reactor neutrino anomaly (predicted reactor neutrino flux 6% higher than observed)
  - Gallium experiments calibration anomaly
- Extensive experimental programme to investigate the observed anomalies:
  - Direct searches for oscillation to sterile neutrinos at accelerator/reactor & with neutrino sources
  - Improved measurements and models for reactor anti-nue emission (NOT DISCUSSED)

ADDITIONAL MATERIAL

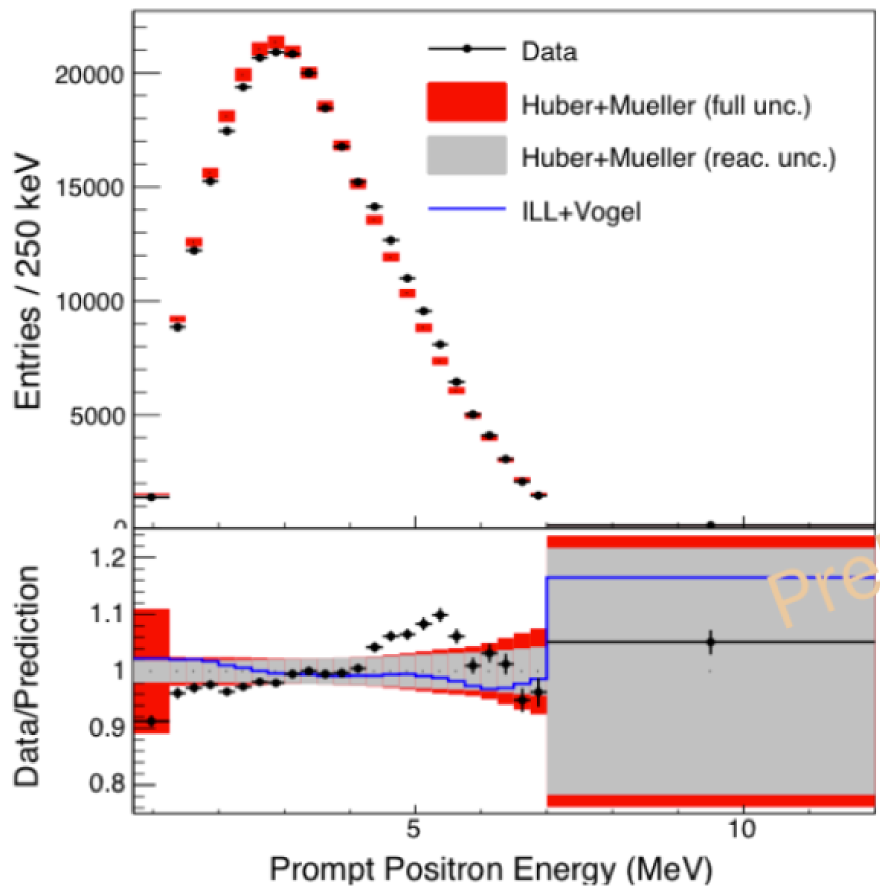
Reactor Flux anomaly

Latest measurements confirms 6% discrepancy with β^- conversion.



The Dark side: Discrepancies in antinue spectrum observed at reactors

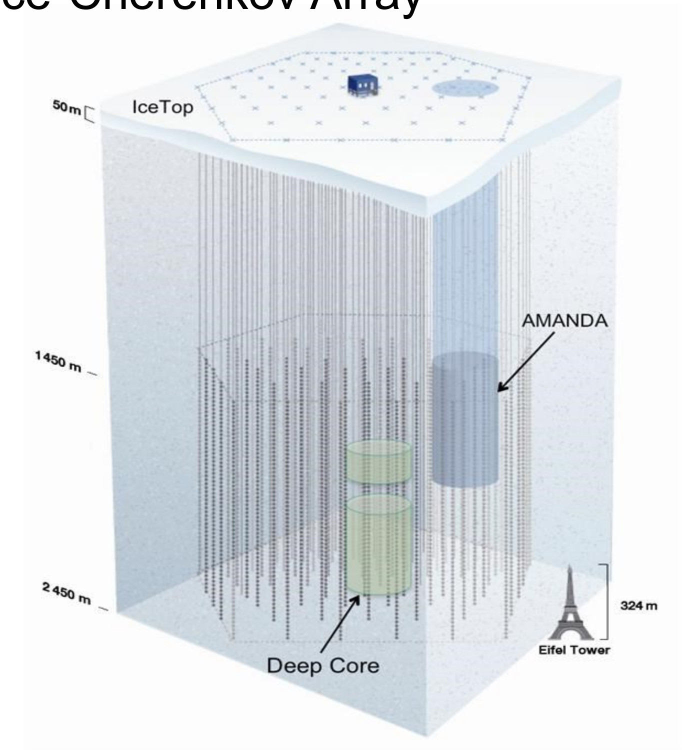
2014: Observed energy spectra disagree with existing models.



RENO: *Neutrino 2014*
Double Chooz: *Neutrino 2014*
Daya Bay: *ICHEP 2014*

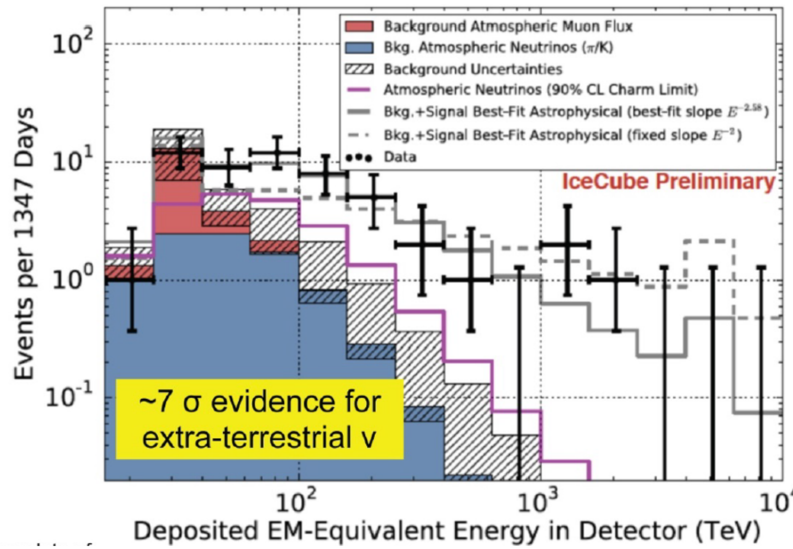
Megaton-scale
Ice-Cherenkov Array

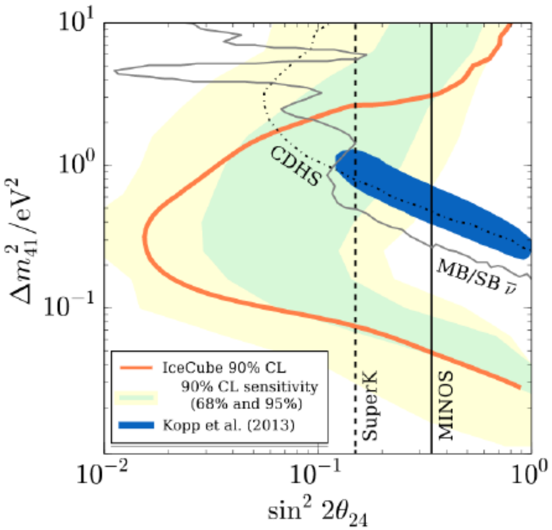
ICECube



First detection of diffuse astrophysical neutrino flux

54 events observed with 20±6 expected from atmosphere





ICECube sterile neutrino searches:
No ν_μ disappearance signal, L/E~1m/MeV (similar to LSND)

- High-energy neutrinos 0.4-20 TeV
- Path-length related to angle of up-going ν through Earth
- Matter-magnified signature enhances sensitivity to 3+1 models consistent with short-baseline anomalies
    - Analogous to solar MSW: extra-potential in effective Hamiltonian due to active neutrino components propagation affected by matter density, while sterile is not