MiniBooNE Oscillation Results and Future Prospects

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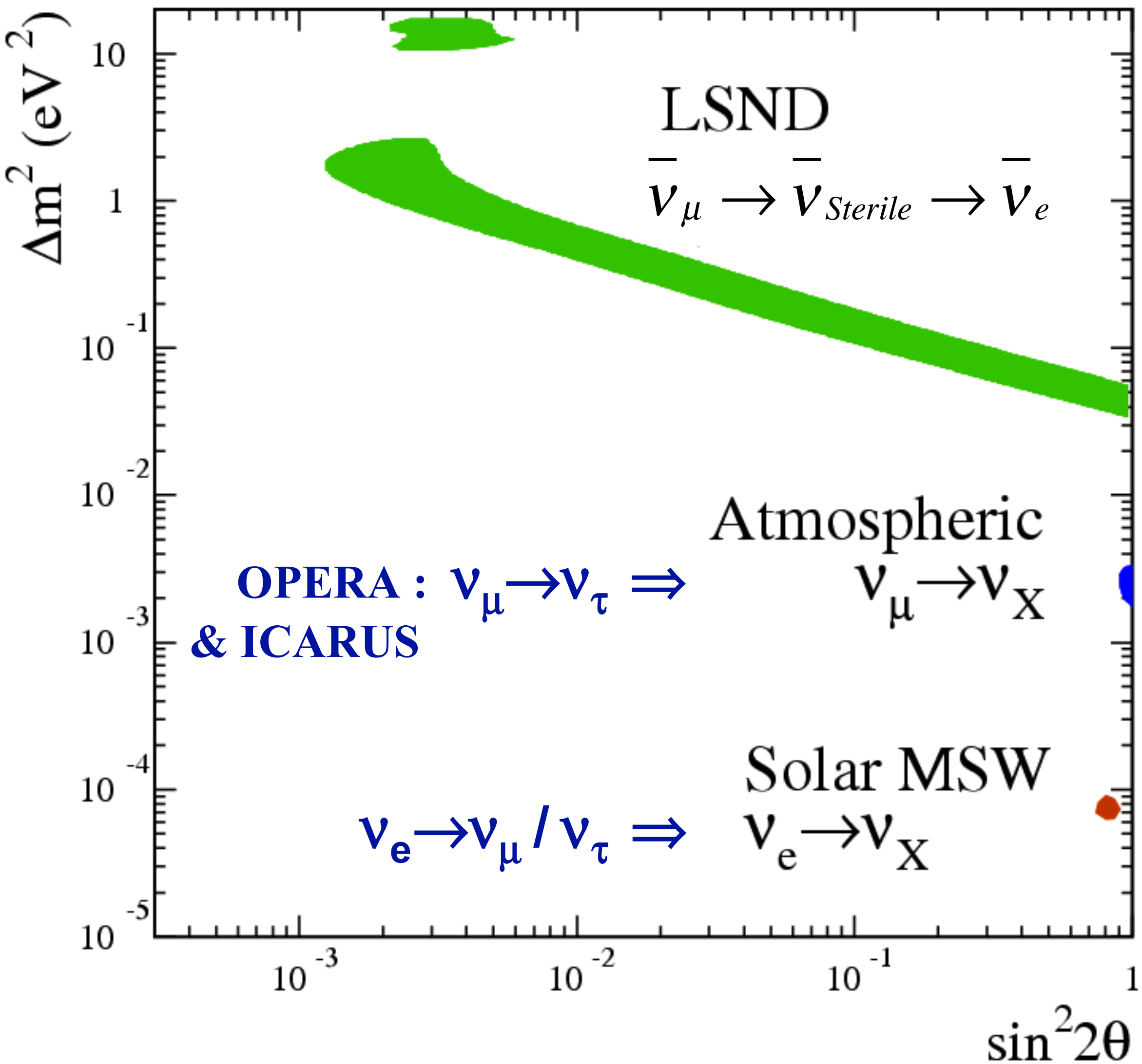
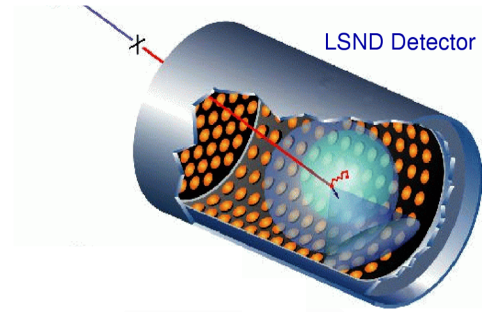
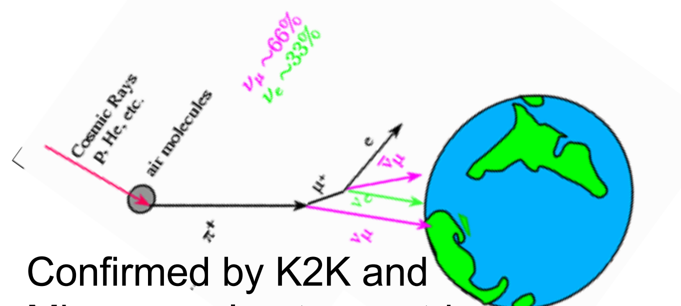
6th International Workshop on Low Energy Neutrino Physics
Seoul National University (Nov. 9 - 12, 2011)

Neutrino Oscillation Summary



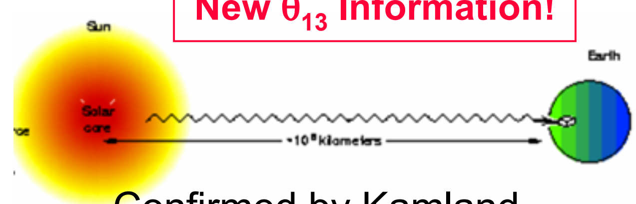


New MiniBooNE $\bar{\nu}_\mu$ consistent



Confirmed by K2K and Minos accelerator neutrino exps

New θ_{13} Information!



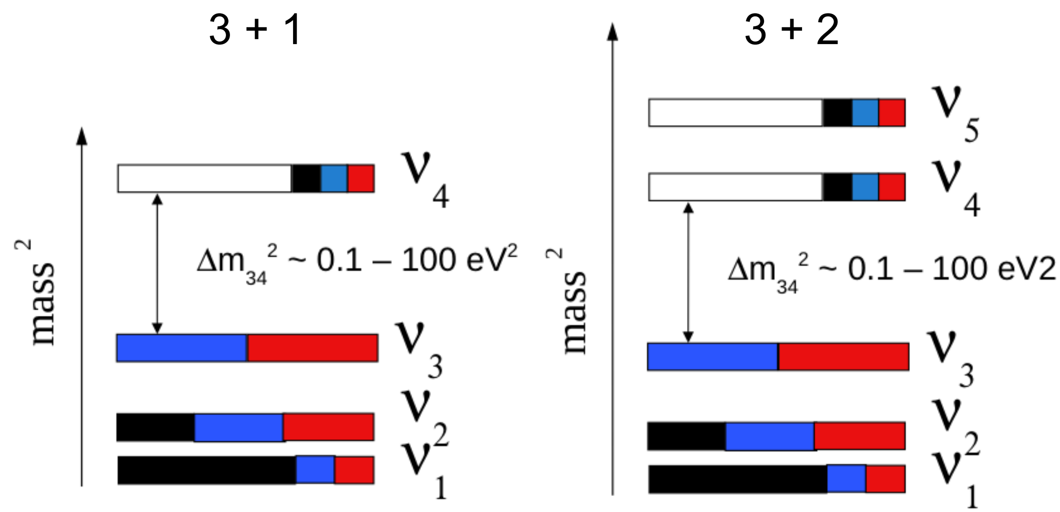
Confirmed by Kamland reactor neutrino exp

Possible Oscillations to Sterile Neutrinos

Sterile neutrinos

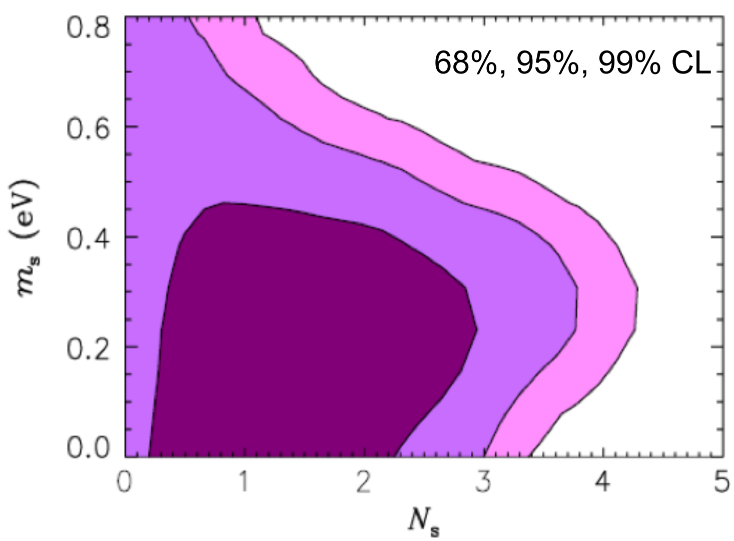
- Partners to the three standard neutrinos
- Have no weak interactions (through the standard W/Z bosons)
- Would be produced and decay through mixing with the standard model neutrinos
- Are postulated in see-saw models to explain small neutrino masses
- Can affect oscillations through mixing

Oscillation Patterns with Sterile Neutrinos



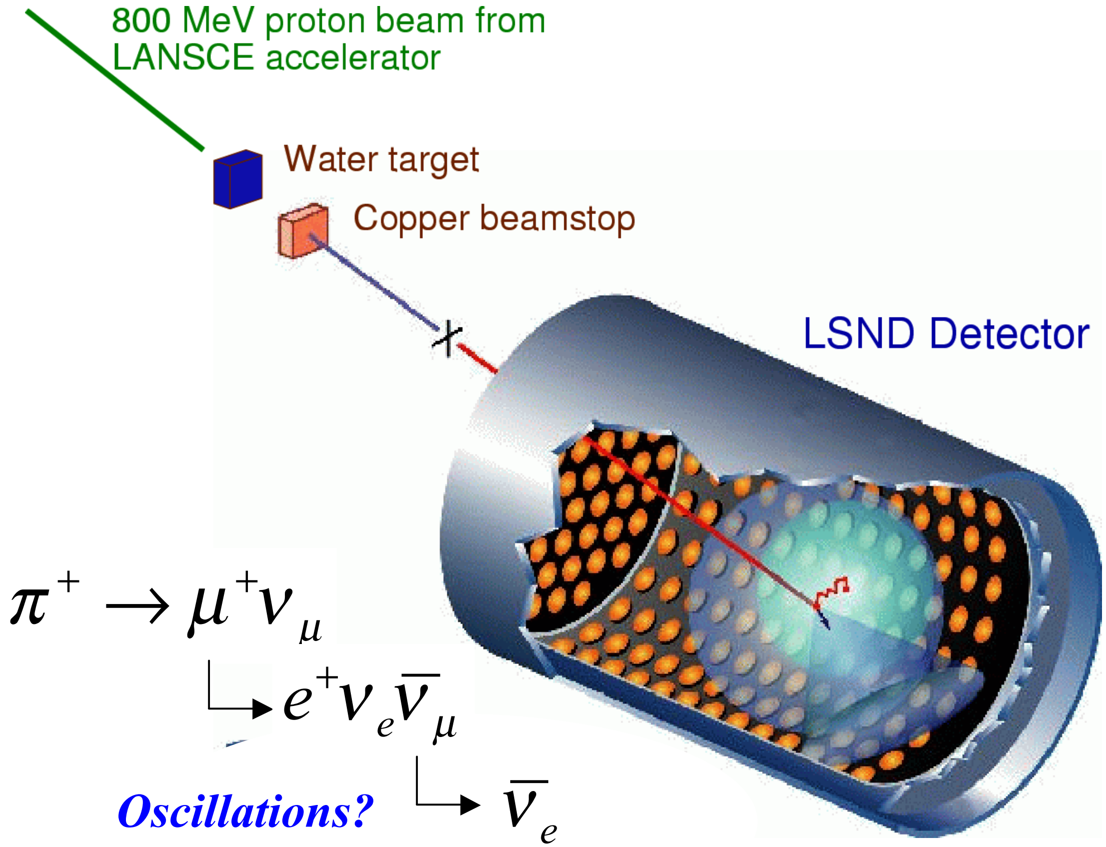
Cosmological Constraints

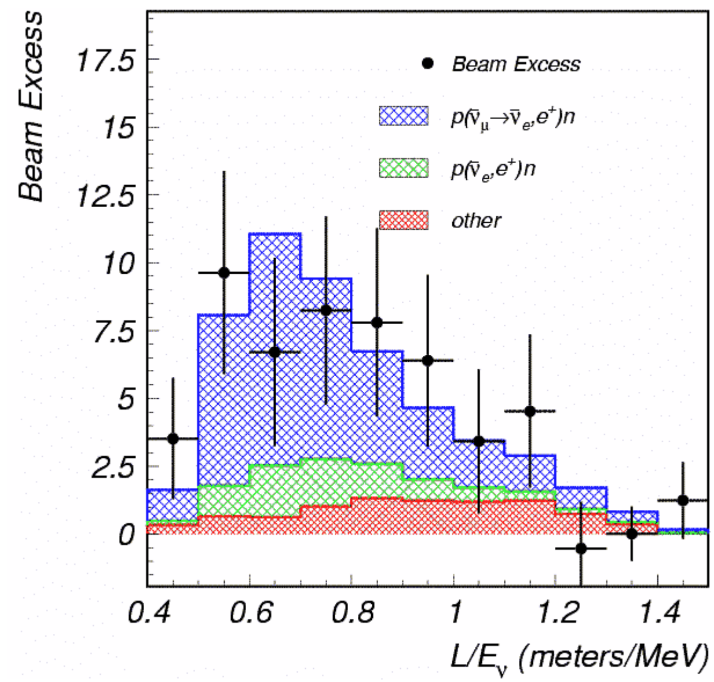
N_S = # of Thermalized Sterile ν States



Phys.Rev.Lett. 105, 181301 (2010)

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





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

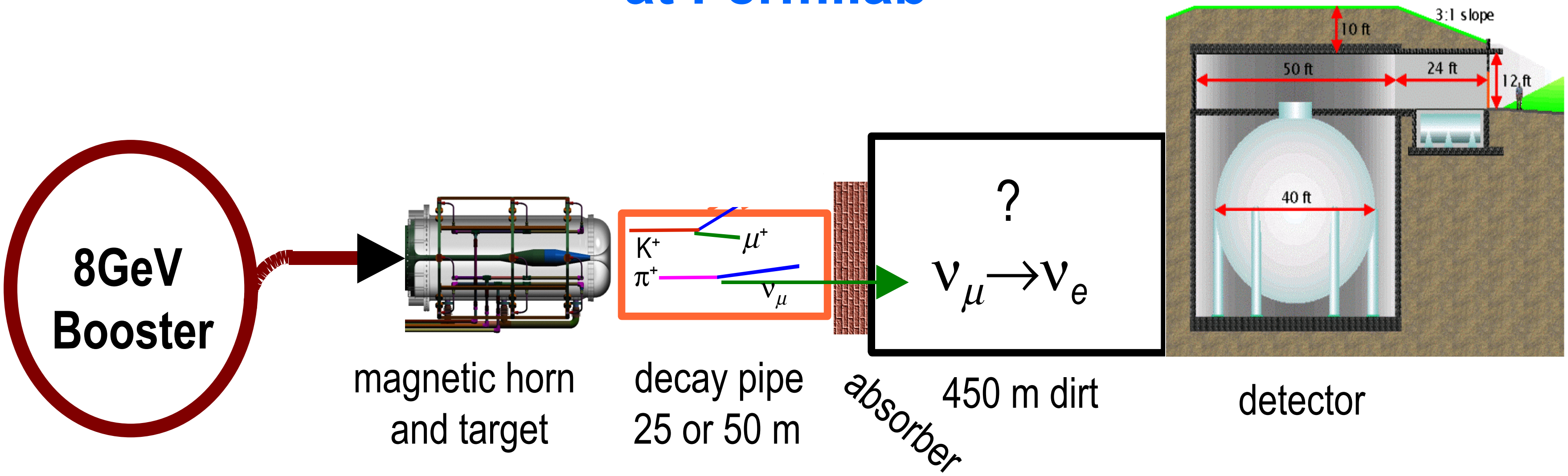
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

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

The MiniBooNE Experiment at Fermilab

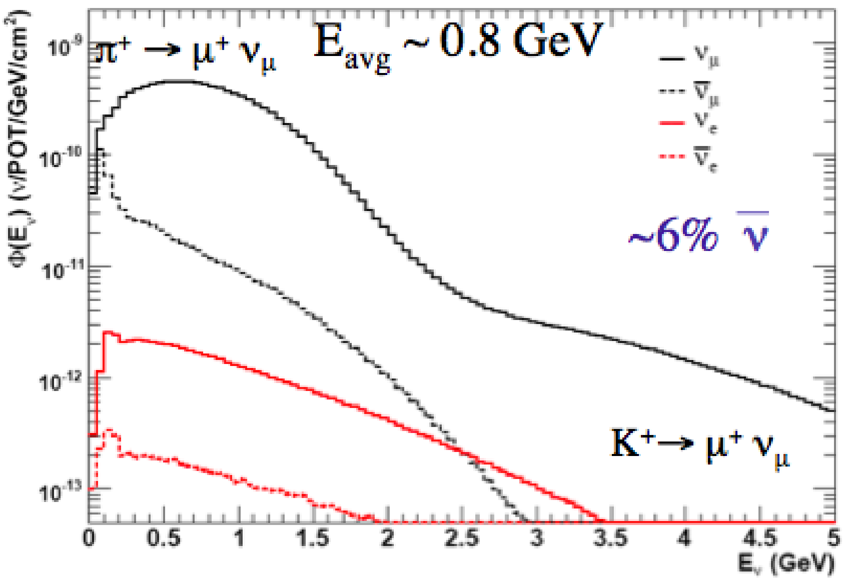


- Goal to confirm or exclude the LSND result - Similar L/E as LSND
  - Different energy, beam and detector systematics
  - Event signatures and backgrounds different from LSND

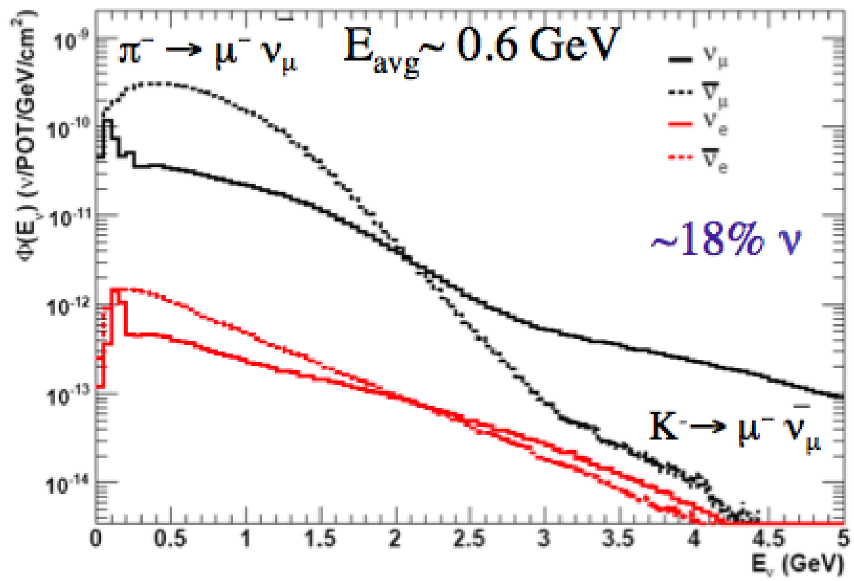
- Since August 2002 have collected data:
  - 6.5×10^{20} POT ν
  - 8.6×10^{20} POT $\bar{\nu}$

Booster Neutrino Beam Flux for MiniBooNE

Neutrino-Mode Flux



Antineutrino-Mode Flux

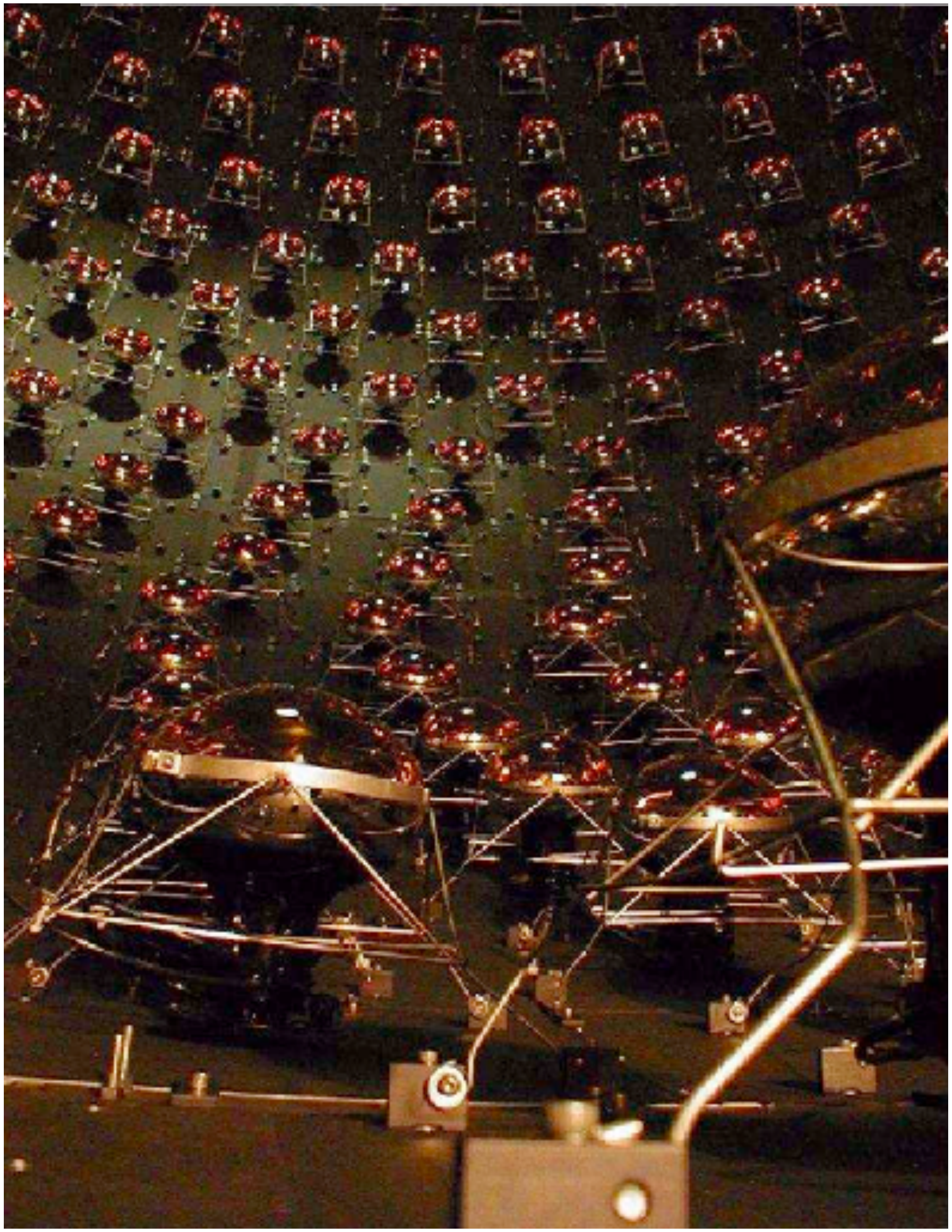


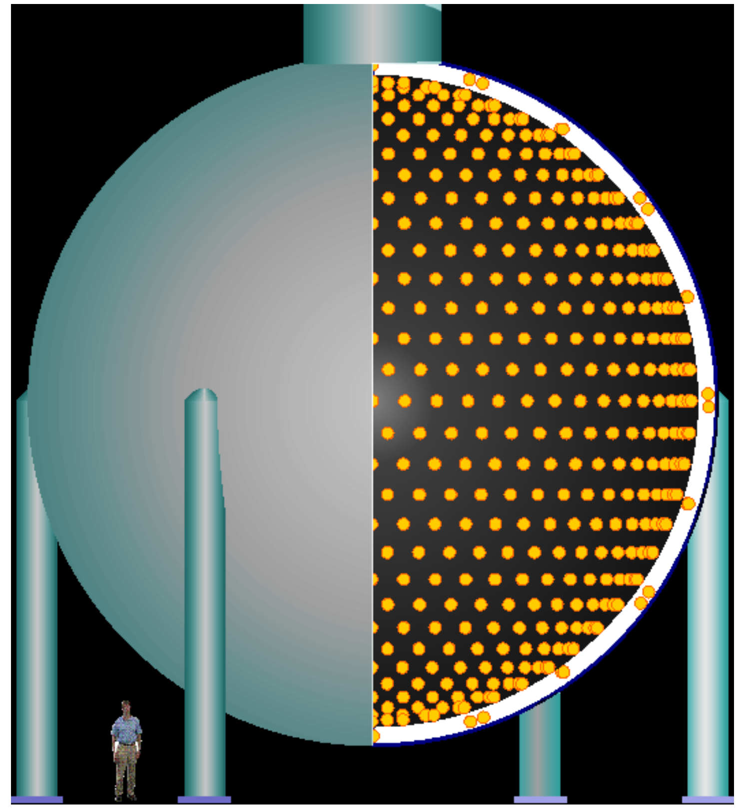
Subsequent decay of the μ^+ (μ^-) produces $\bar{\nu}_e$ (ν_e) intrinsics ~0.5%

neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

MiniBooNE Neutrino Detector

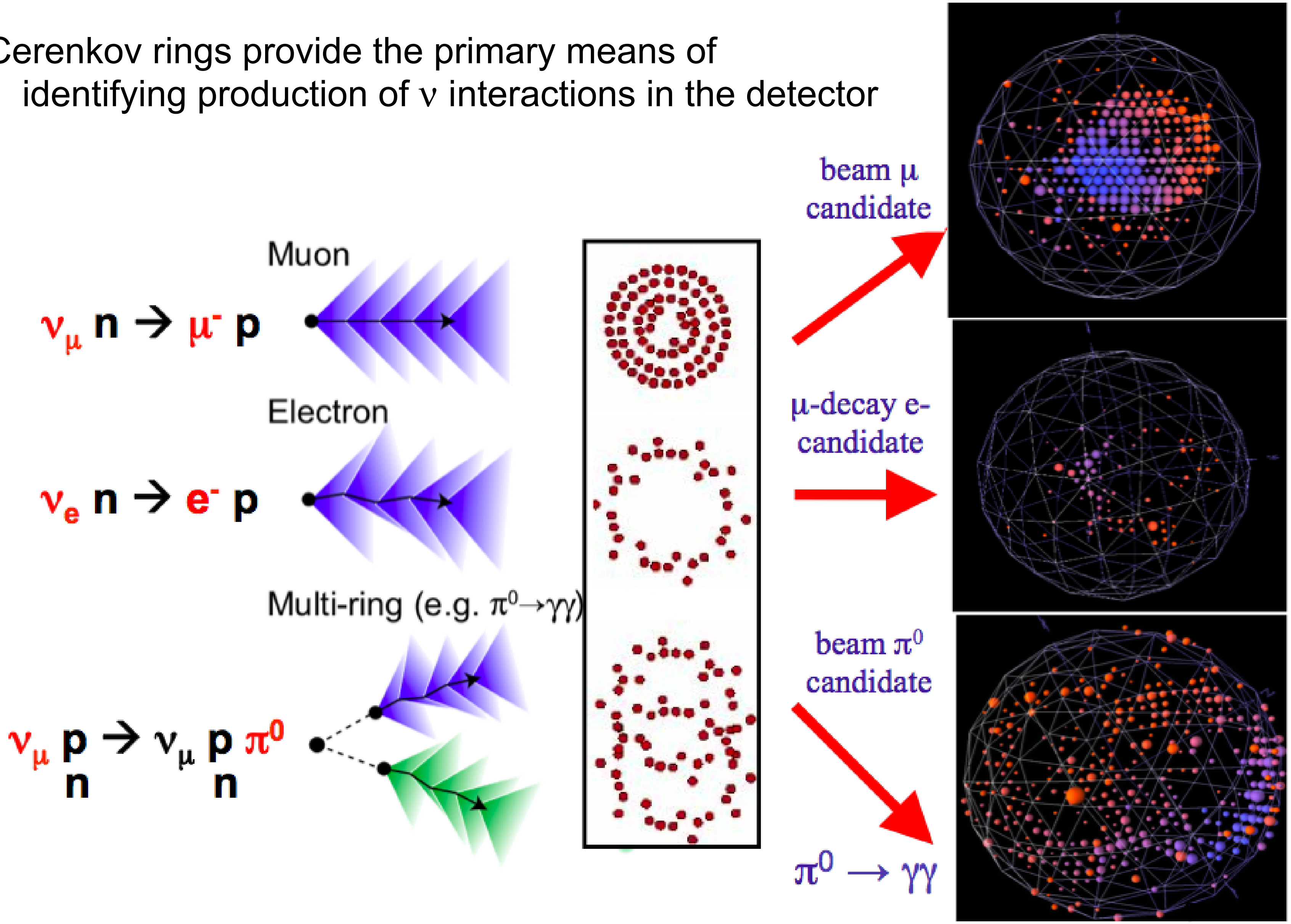




- Pure mineral oil
- 800 tons; 40 ft diameter
- Inner volume: 1280 8” PMTs
- Outer veto volume: 240 PMTs

MiniBooNE Particle Identification

Cerenkov rings provide the primary means of identifying production of ν interactions in the detector

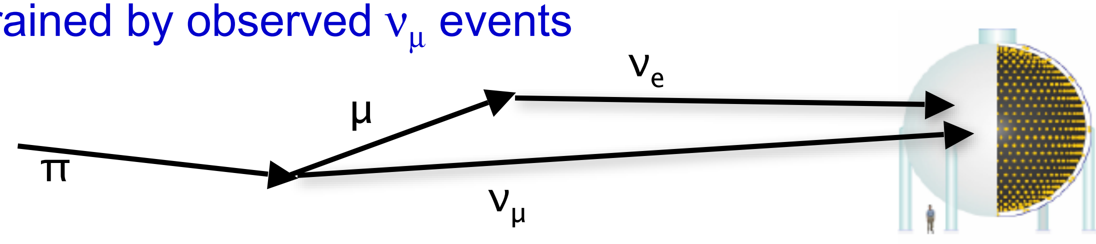


Oscillation Signal and Backgrounds

- MiniBooNE search for ν_e (or $\bar{\nu}_e$) appearance in a pure ν_μ (or $\bar{\nu}_\mu$) beam
  - Signature is interaction with single outgoing electron from $\nu_e + n \rightarrow e^- + p$

- MiniBooNE has very good ν_μ versus ν_e event identification using:
  - Cherenkov ring topology, Scint to Cherenkov light ratio, and μ-decay Michel tag

- All backgrounds constrained by data
  - Intrinsic ν_e in the beam
    - $\Rightarrow$ From K decay - small but constrained by measurements
    - $\Rightarrow$ From μ decay - constrained by observed ν_μ events



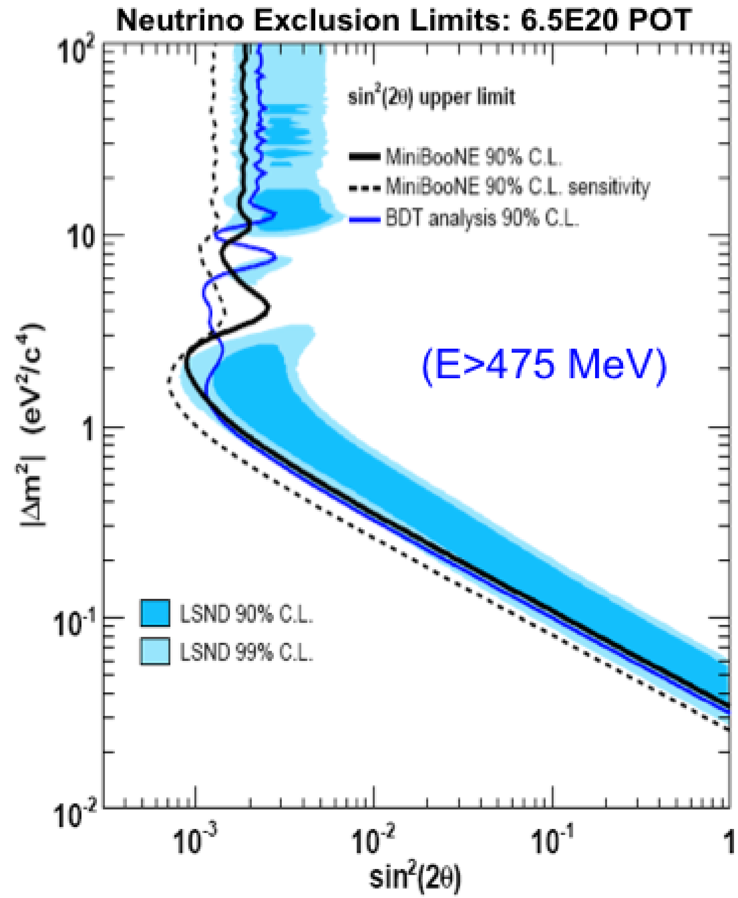
  - Particle misidentification in detector
    - $\Rightarrow$ From NC π^0 production constrained by observed $\pi^0 \rightarrow \gamma\gamma$ events
    - $\Rightarrow$ From single photons from external interactions constrained by observations
  - Measured neutrino contamination in anti-nu mode running ($22 \pm 5\%$)

- Simultaneous fit to ν_e and ν_μ events
  - Reduces flux and ν cross section uncertainties

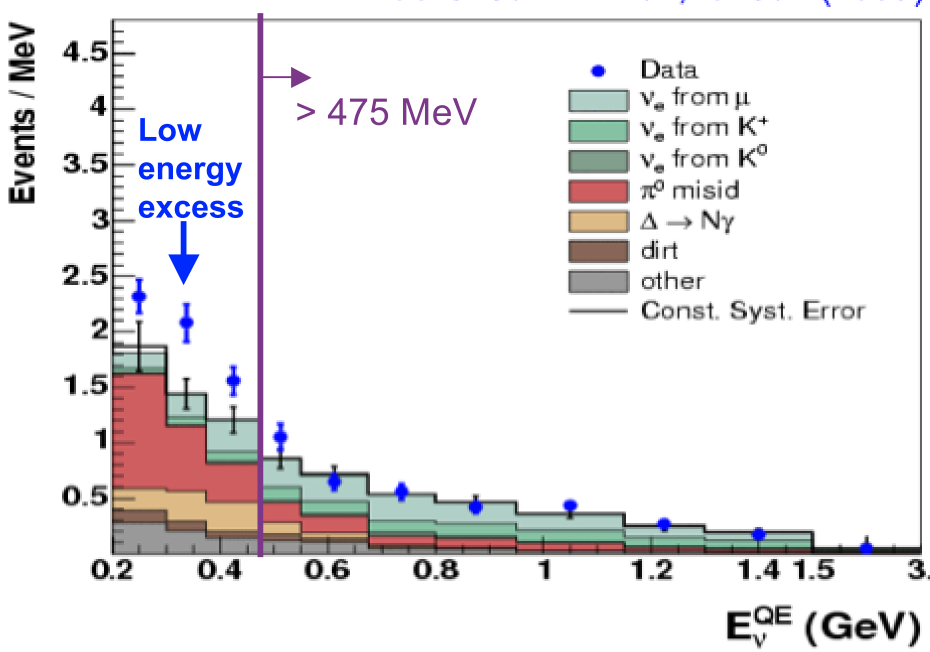
- Systematic error on background $\approx$10% (energy dependent)

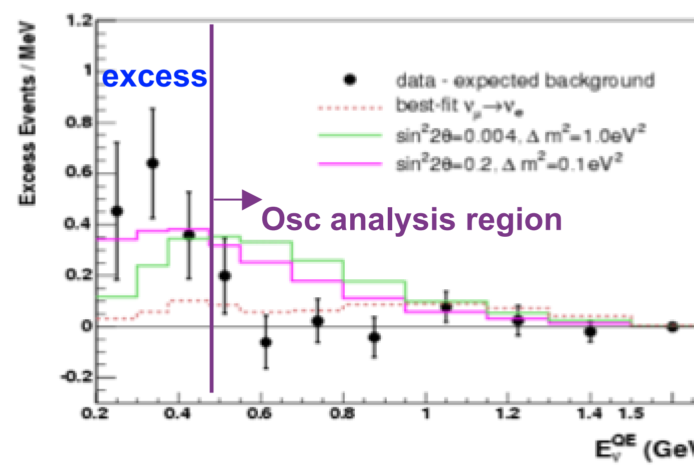
MiniBooNE neutrino-mode results (2009)

- E > 475 MeV data in good agreement with background prediction.
  - A two neutrino fit is inconsistent with LSND at the 90% CL assuming CP conservation.
- E < 475 MeV shows a 3σ excess at low enegy
  - The total excess of 129 ± 43 (stat+syst) is consistent with magnitude of LSND signal



Published PRL 102,101802 (2009)



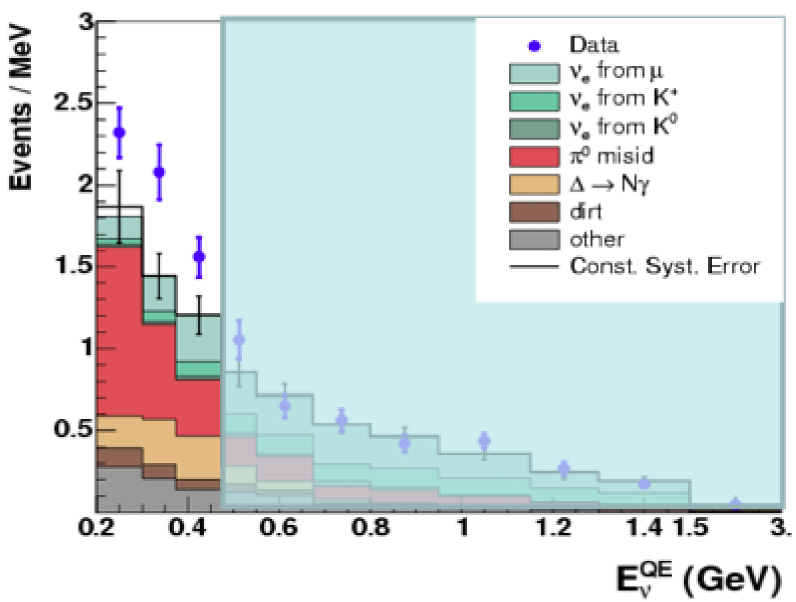


Low-Energy Excess (in Neutrino Mode Data)

Excess of events observed at lower energy:
128.8 ± 20.4 ± 38.3 (3.0σ)

Shape not consistent with simple 2ν oscillations

Magnitude consistent with LSND



Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281

CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.

Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009

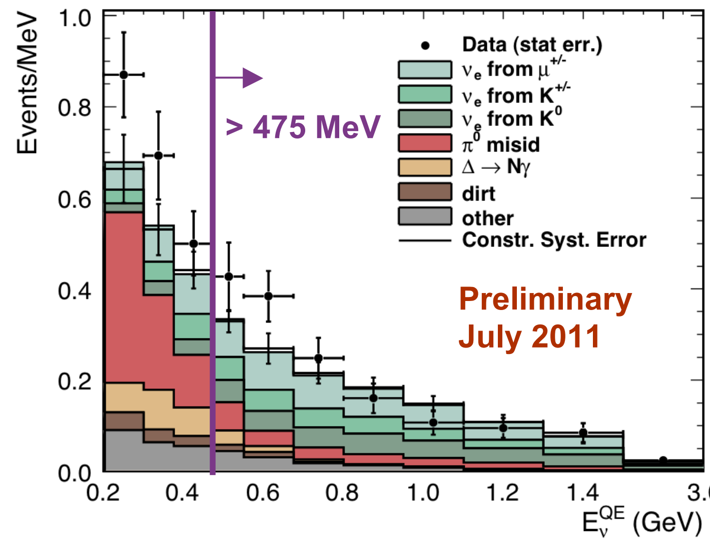
CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

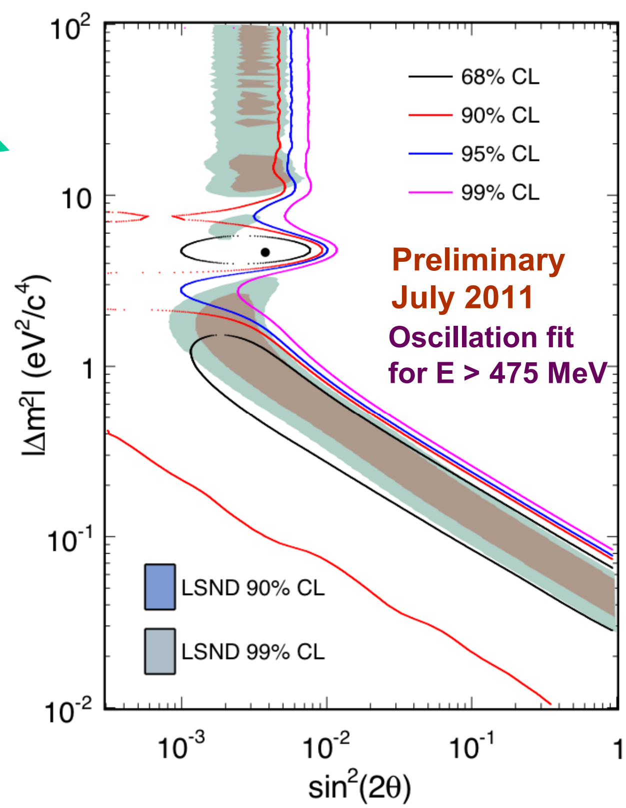
New Gauge Boson with Sterile Neutrinos: Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363

But are there oscillations or a low-energy excess in the MiniBooNE Antineutrino data?

Updated MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Result This Summer (E > 475 MeV)

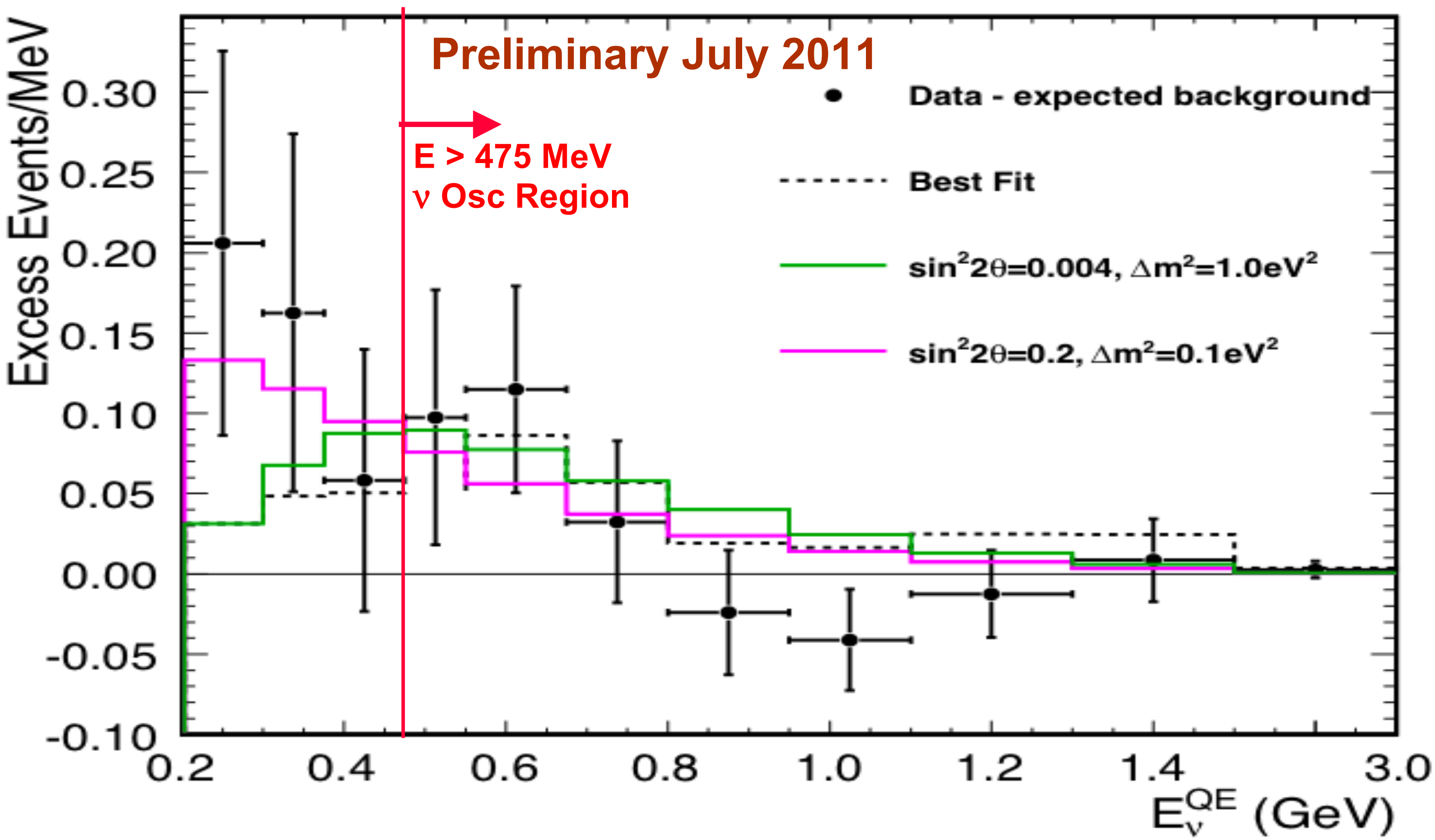
- Updated results in July 2011:
  - 5.66E20 ⇒ 8.58E20 protons-on-target (x1.5)
  - Reduced systematic uncertainties especially backgrounds from beam K^+ decays
- For the original osc energy region above 475 MeV, oscillations favored over background only (null) hypothesis at the 91.1% CL.
- Best fit:
  - $(\sin^2 2\theta, \Delta m^2) = (0.004, 4.6\ \mathrm{eV}^2)$
  - χ^2_{BF} /ndf = 4.3/6 with prob.= 35.5%
    χ^2_{null} /ndf = 9.3/4 with prob.= 14.9%
- Consistent with LSND, though evidence for LSND-type oscillations less strong than published 5.66E20 result
  - Previous result (PRL 105, 181801) :
    - Osc favored over null at 99.4% CL
    - χ^2_{BF} /ndf = 8.0/6 with prob.= 8.7%
      χ^2_{Null} /ndf = 18.5/4 with prob.= 0.5%





Data Excess over Background (in Antineutrino Mode)

Excess = 38.6 +- 18.5 (200-475 MeV)
Excess = 16.3 +- 19.4 (475-1250 MeV)



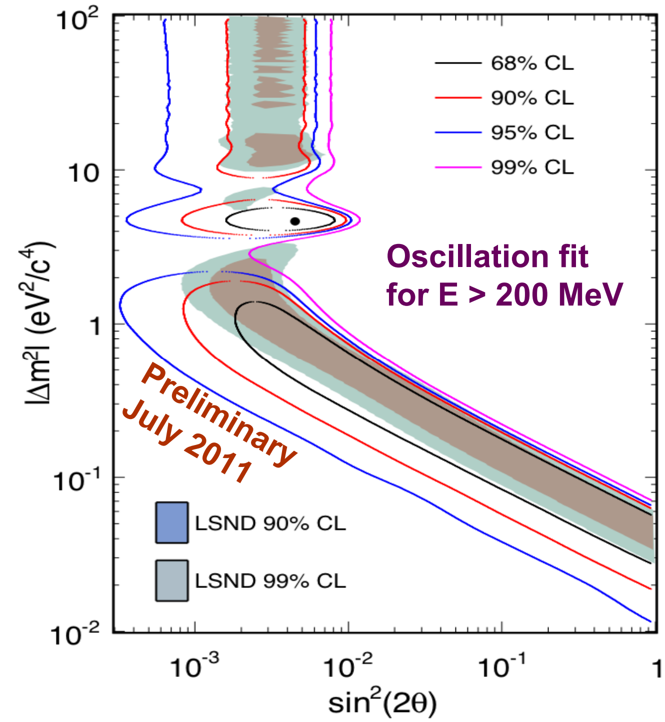
Updated Full Energy Range $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Result

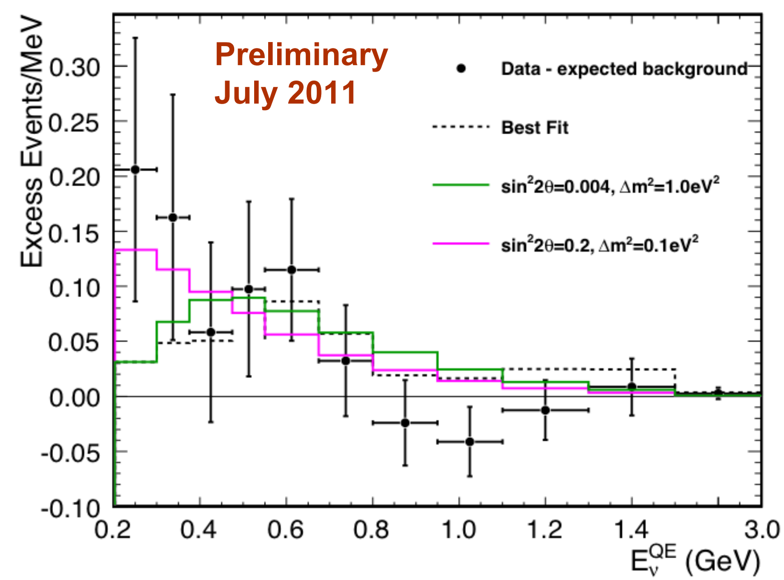
- Using the full energy range for the oscillation fit 200MeV < E_ν < 3000 MeV
  - Oscillations favored over background only (null) hypothesis at the 97.6% CL.
  - This includes low-energy excess from neutrinos in the beam, which gives about 17 events $\Rightarrow$ harder to interpret as pure antineutrino osc.

- Best fit for 200 to 3000 MeV:
  - $(\sin^2 2\theta, \Delta m^2) = (0.004, 4.6\ \text{eV}^2)$
  - χ^2_{BF} /ndf = 4.3/6 with prob.= 50.7%
    χ^2_{null} /ndf = 9.3/4 with prob.= 10.1%

- Low energy excess now more prominent for antineutrino running than previous result
  - For E< 475 MeV, excess = 38.6 $\pm$ 18.5
    (For all energies, excess = 57.7 $\pm$ 28.5)
  - Neutrino and antineutrino results are now more similar.

- MiniBooNE will continue running through spring 2012 (at least) towards the request of 15E20 pot (~x2 from this update)
  - Full data set will probe LSND signal at the 2-3 sigma level

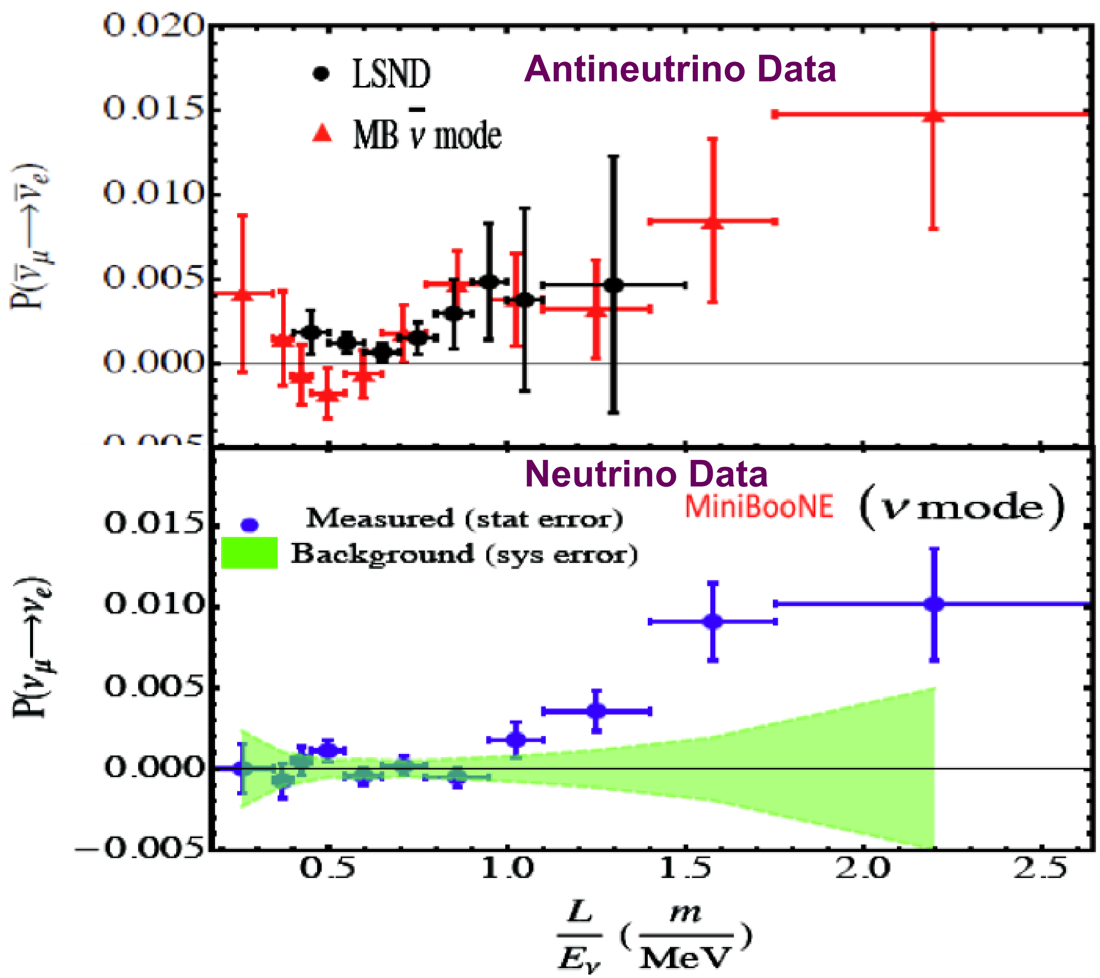




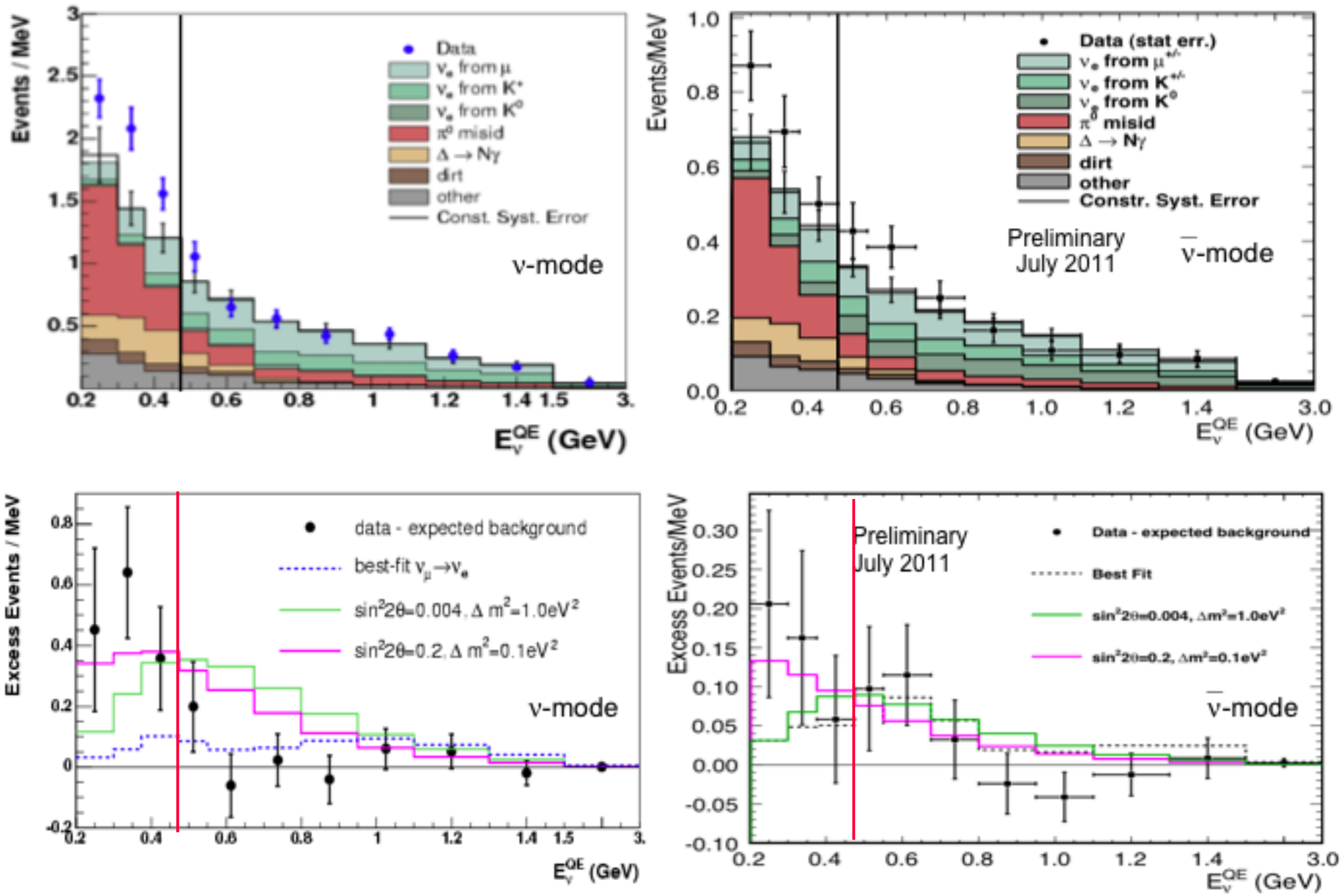
MiniBooNE and LSND L/E Results

$$P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) = \left(\sin^2 2\theta\right) \sin^2\left(1.27 \Delta m^2 L / E\right)$$

- MiniBooNE and LSND are consistent for antineutrino “oscillation” probability versus L/E
- MiniBooNE neutrino low energy excess consistent with hint in antineutrinos



Comparison of ν_e and $\bar{\nu}_e$ Appearance Results

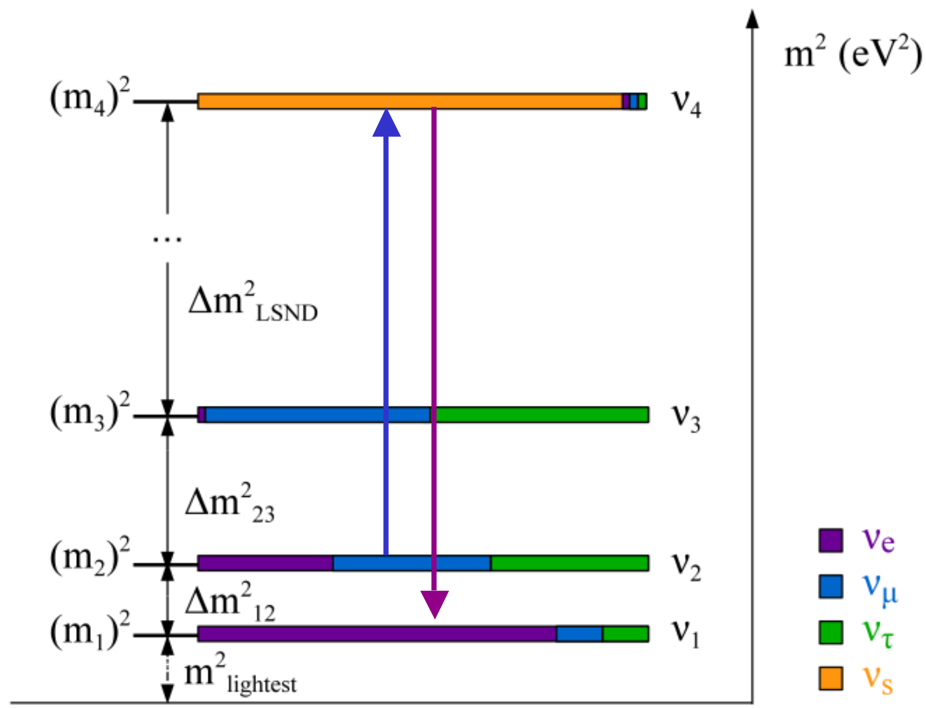


Summary of MiniBooNE Results

- Neutrino Mode:
  - E < 475 MeV:
    - An unexplained 3σ electron/γ-like excess
  - E > 475 MeV:
    - Two neutrino oscillations ruled out at 98% CL
- Antineutrino Mode:
  - E < 475 MeV:
    - Electron/γ-like excess = 38.6 $\pm$ 18.5
  - E > 475 MeV:
    - Excess consistent with an LSND-type two neutrino oscillation over no-oscillations at 91.1% CL
  - E > 200 MeV (full data set):
    - Excess consistent with an LSND-type two neutrino oscillation over no-oscillations at 97.6% CL

Phenomenology of Oscillations with Sterile Neutrinos (3+1 Models)

- In sterile neutrino (3+1) models, high Δm^2 ν_e appearance comes from oscillation through ν_s
  - $\nu_\mu \to \nu_e = (\nu_\mu \to \nu_s) + (\nu_s \to \nu_e)$
- This then requires that there be ν_μ and ν_e disappearance oscillations
  - Limits on disappearance then restrict any (3+1) models
- Strict constraint from CPT invariance
  - Neutrino and antineutrino disappearance required to be the same.



Constraints on Neutrino Disappearance at $\Delta m^2 \sim 1$ eV^2

- Muon neutrino disappearance:
  - Stringent limits from many experiments (i.e. CDHS and CCFR)
  - New SciBooNE/MiniBooNE ν_μ disappearance limit even stronger than previous
  - Less stringent limits for $\bar{\nu}_\mu$ Disappearance from MiniBooNE
  - CPT conservation implies ν_μ and $\bar{\nu}_\mu$ disappearance are the same

- Electron neutrino disappearance:
  - Possible indication of $\bar{\nu}_e$ disappearance
    - Reactor Antineutrino Anomaly

      (G. Mention et al., hep-ex/1101.2755)
  - Possible indication of ν_e Disappearance
    - Gallium Anomaly

      (Giunti and Laveder, 1006.3244v3 [hep-ph])

      $\Rightarrow$ Somewhat restricted by ν_e-Carbon cross section measurements

      (Conrad and Shaevitz, 1106.5552v2 [hep-ex])

Next Steps

Current status:

Difficult to explain the neutrino and antineutrino data even adding sterile neutrinos (3+1) or (3+2) with possible CP violation

- Also, tension between appearance signals and disappearance limits.

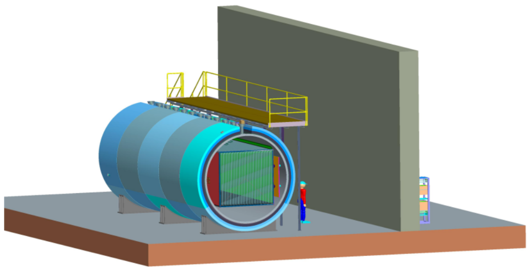
- Search for effects from high Δm^2 sterile neutrinos
  - Address MiniBooNE/LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal
- Address MiniBooNE low-energy ν_e excess
  - Could be oscillations or something else
- Very short baseline ν_e and $\bar{\nu}_e$ disappearance
- Two detector ν_μ, $\bar{\nu}_\mu$ disappearance

Future Plans and Prospects

Approved program:

1. MiniBooNE should reach x1.5 - x2 the current $\bar{\nu}$ data over the next year
   $\Rightarrow$ Address the LSND region at the 2 to 3 σ level

2. New MicroBooNE Exp in front of MiniBooNE (2013)
   Liquid Argon TPC detector which can address the low-energy excess:
   - Reduced background levels
   - Can determine if low-energy excess due to single electron or photon events?



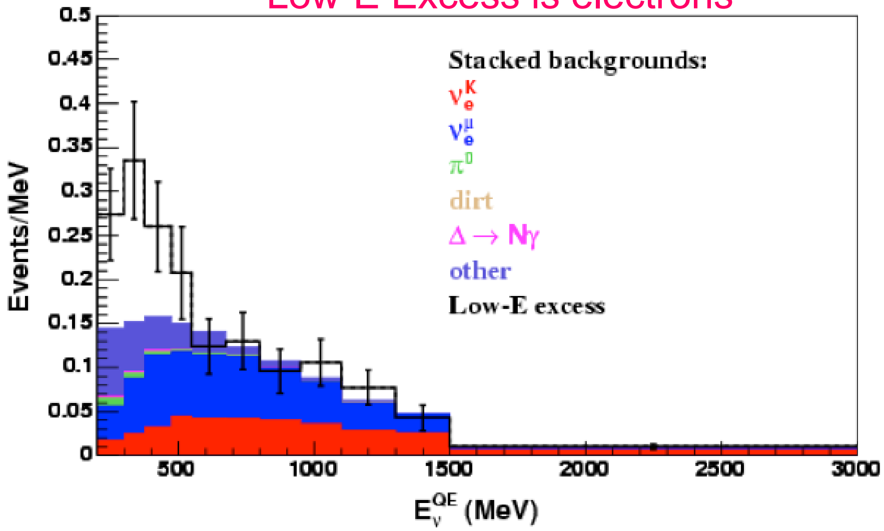
Other ideas:

- New short baseline two detector exp's for appearance and disappearance
  - At Fermilab, add second near detector to MiniBooNE
    $\Rightarrow$ BooNE Proposal
  - CERN PS neutrino beam with Icarus style detectors at 130m/850m
- Very short baseline (VSBL) ν_e disappearance and $\bar{\nu}_e$ appearance exps
  - Use high rate radioactive sources in Borexino (or other) detector
  - Small detector close (<10m) to nuclear reactor
  - Decay-at-rest beam close to a large detector (Water, LAr, Scint)

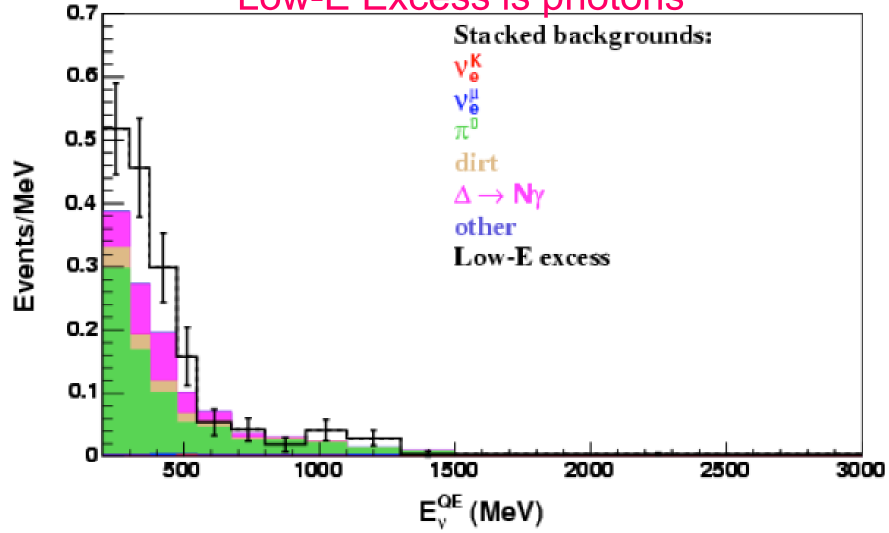
MicroBooNE can resolve Low-E Excess

- MicroBooNE can separate events as to outgoing electrons or photons because photons give twice the ionization at conversion point.
  - Therefore, can determine what the excess is due to
    - Oscillations would give ν_e
    - Photons would indicate a non-oscillation source
- Backgrounds are very different
  - Much better sensitivity for electrons than photons - but either ok

Low-E Excess is electrons



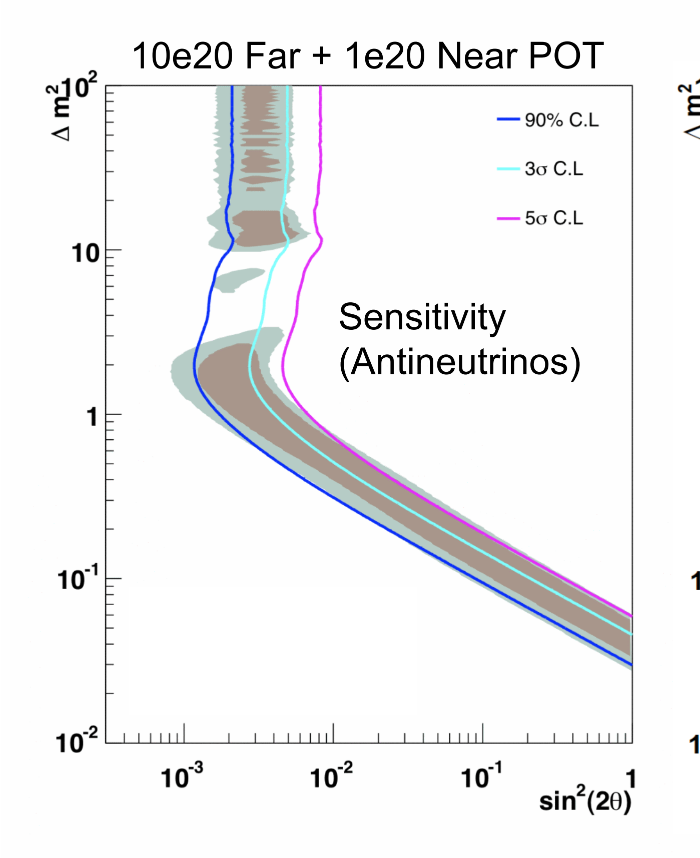
Low-E Excess is photons

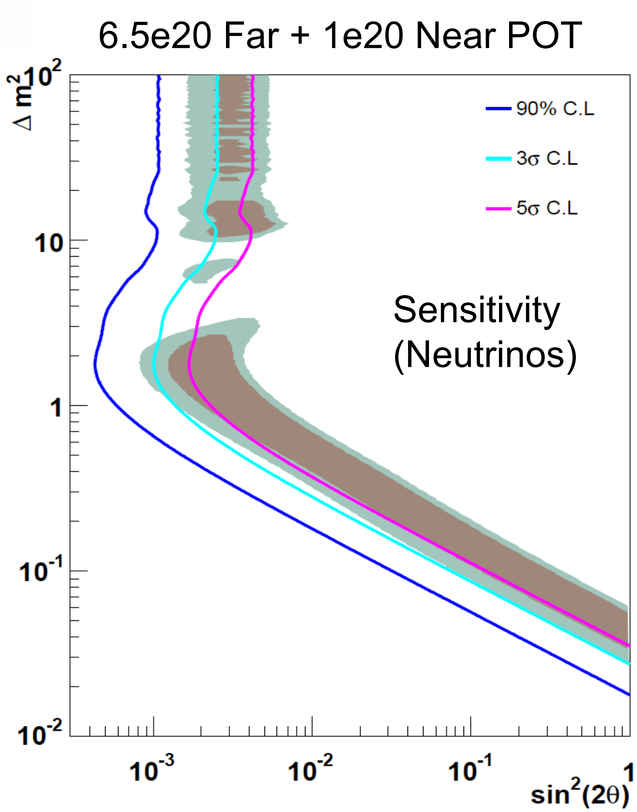


BooNE: Proposed Near Detector at 200m

(LOI arXiv:0910.2698)

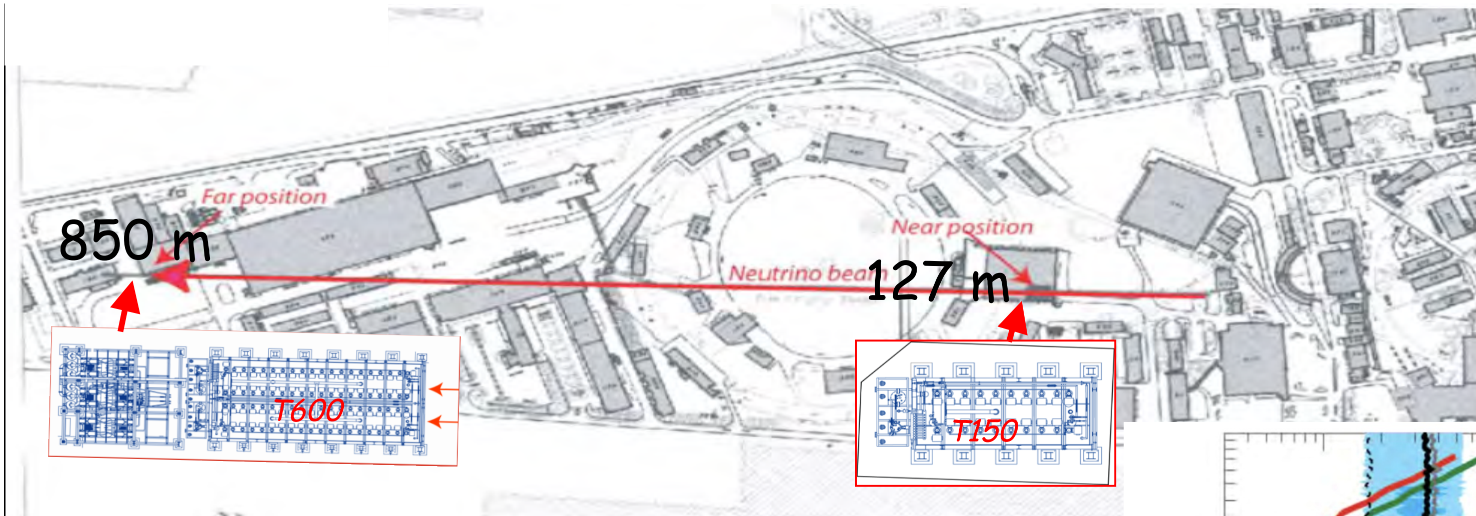
- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and CP violation

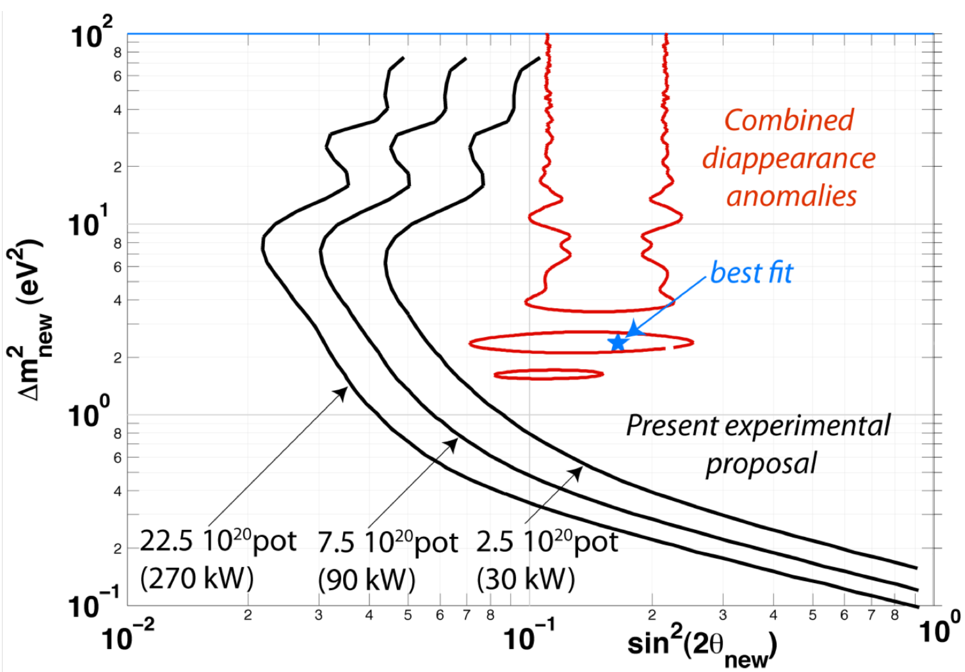


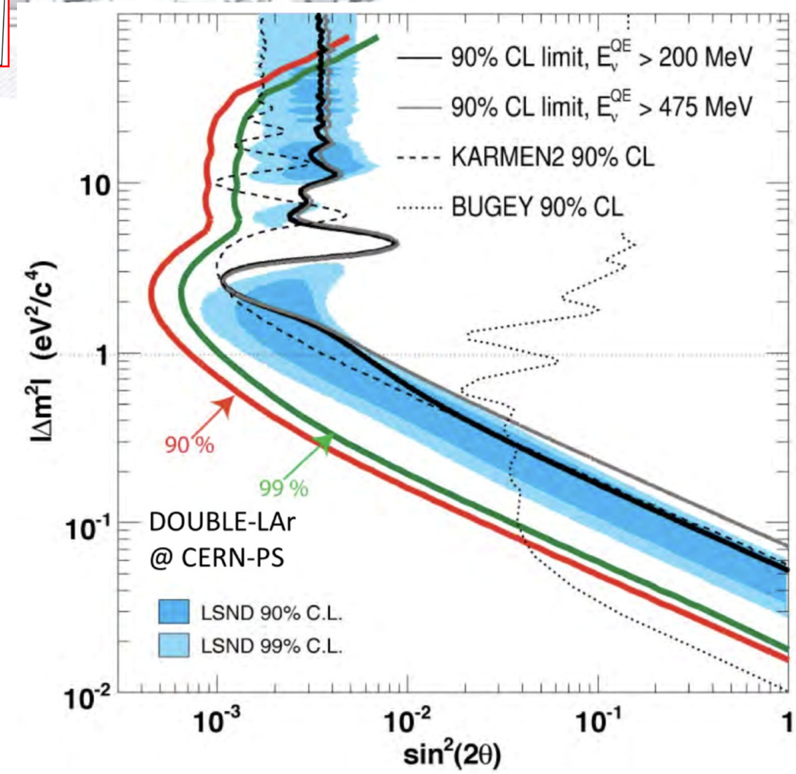


CERN Low Energy (~1GeV) Two Detector Experiment

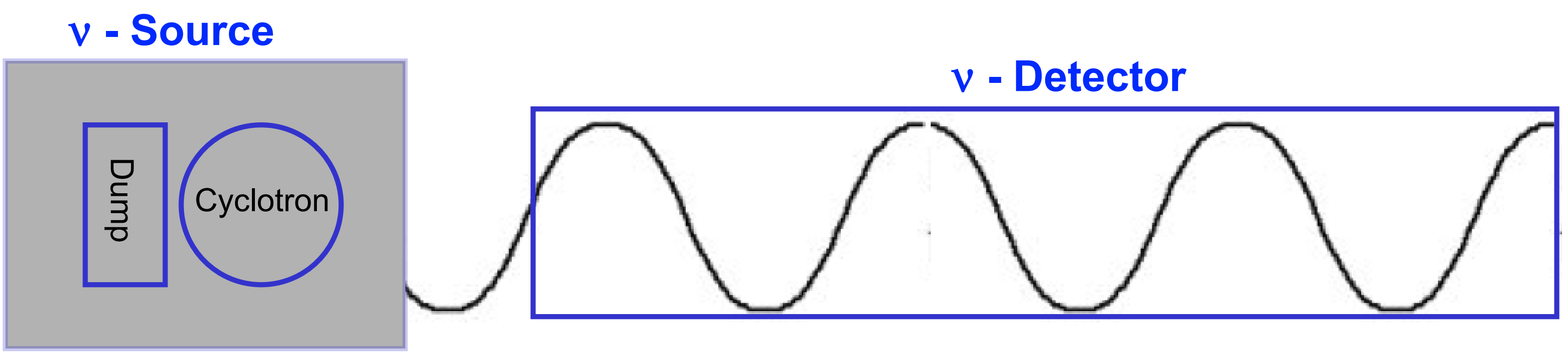
SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION
AT THE CERN PS







Very-short Baseline Oscillation Experiment



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

- Use neutrino source that is almost a point source
  - Small core reactor source
  - Very high activity radioactive source
  - Decay-at-rest beam from proton beam dump

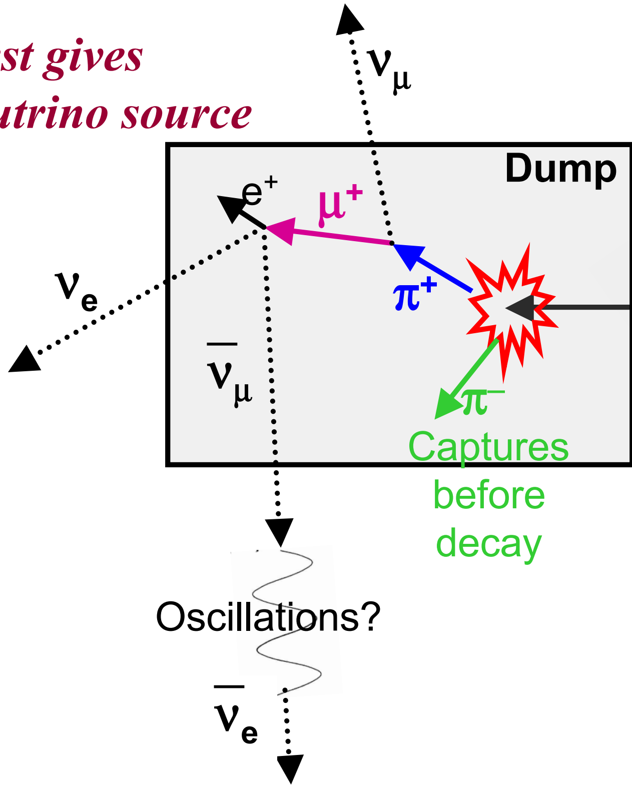
- Look for a change in event rate as a function of energy within a long ν-detector
  - With no oscillations the rate should go as $1/L^2$

- Bin observed events in L/E (corrected for the $1/L^2$) to search for oscillations

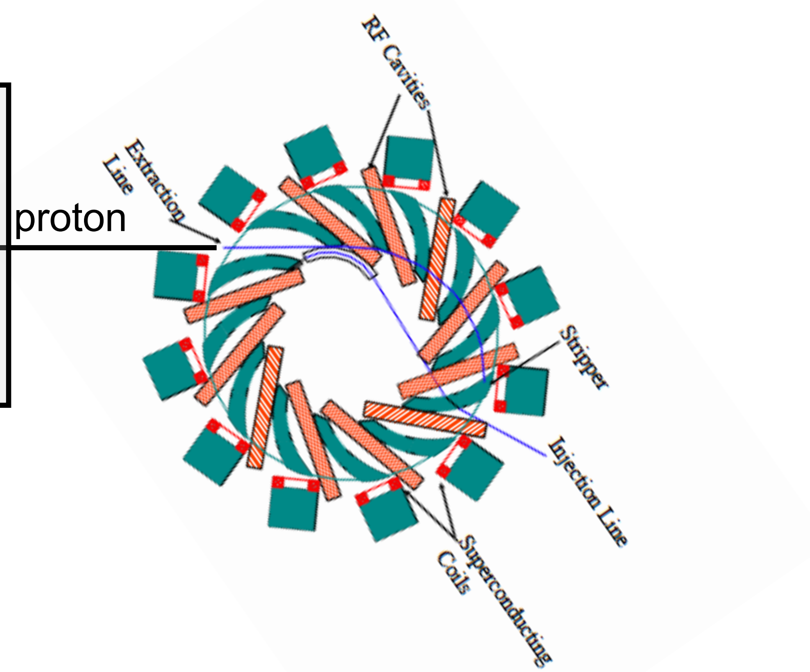
- Backgrounds produce fake events where event distribution is either independent of L or goes like $1/L^2$

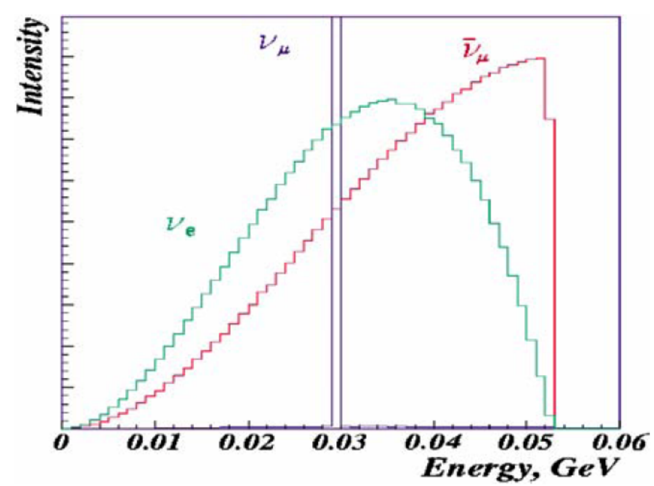
Decay-at-Rest (or Beam Dump) Neutrino Sources

Decay-at-Rest gives isotropic neutrino source



Cyclotron (~800 MeV KE proton)





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

Short-baseline Neutrino Oscillation Waves in Ultra-large Liquid Scintillator Detectors

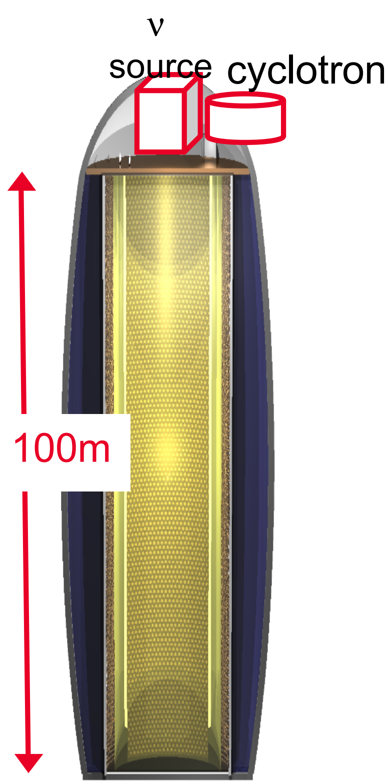
arXiv:1105.4984

Sanjib Kumar Agarwalla[a], J.M. Conrad[b], M.H. Shaevitz[c]

LENA Scintillation Detector

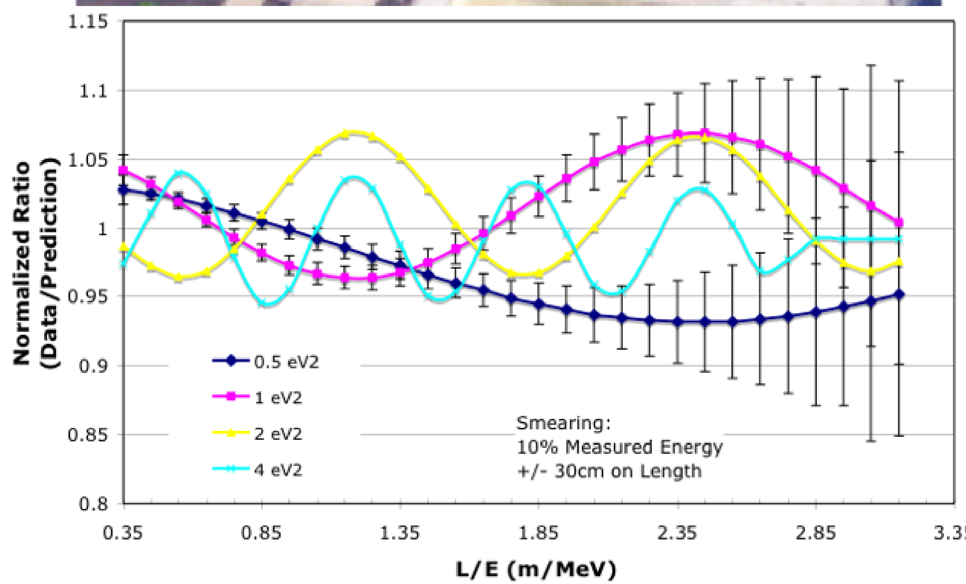
(Part of the European LAGUNA Project)

- 50 kton fiducial mass
- Deep location (4000 mwe) so negligible cosmic muon backgrounds
- Appearance and Disappearance possible



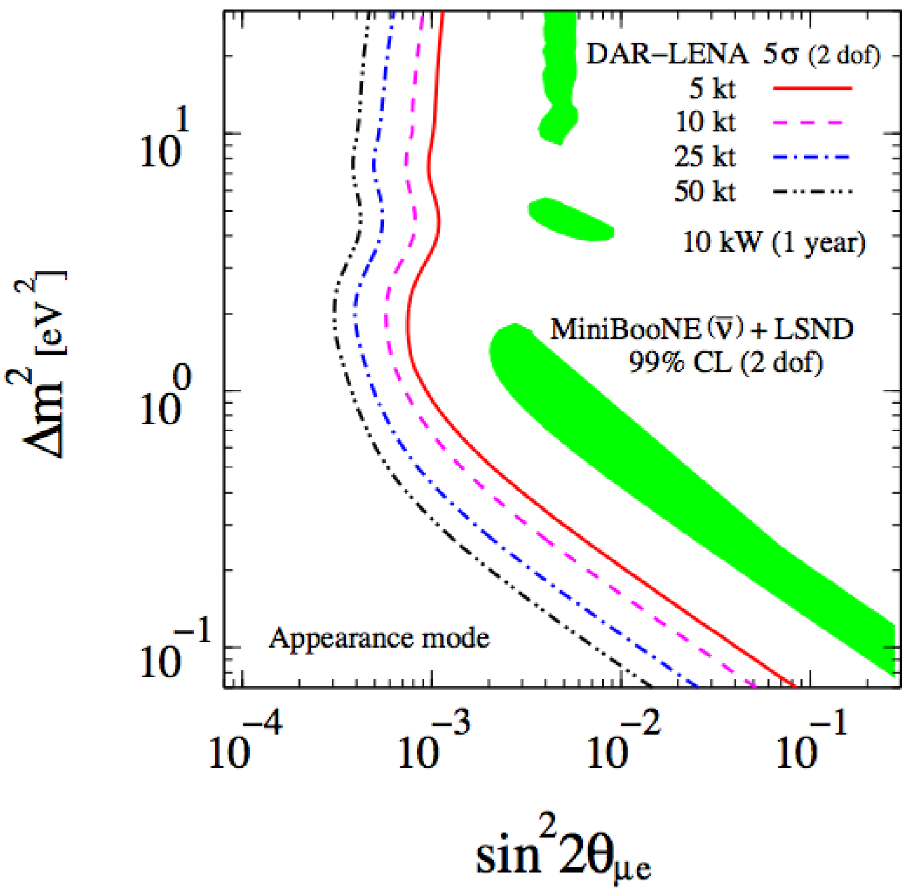
NOvA Scintillation Detector

- 15 kton fiducial mass - 65m long
- On surface so large backgrounds
- Only Disappearance possible

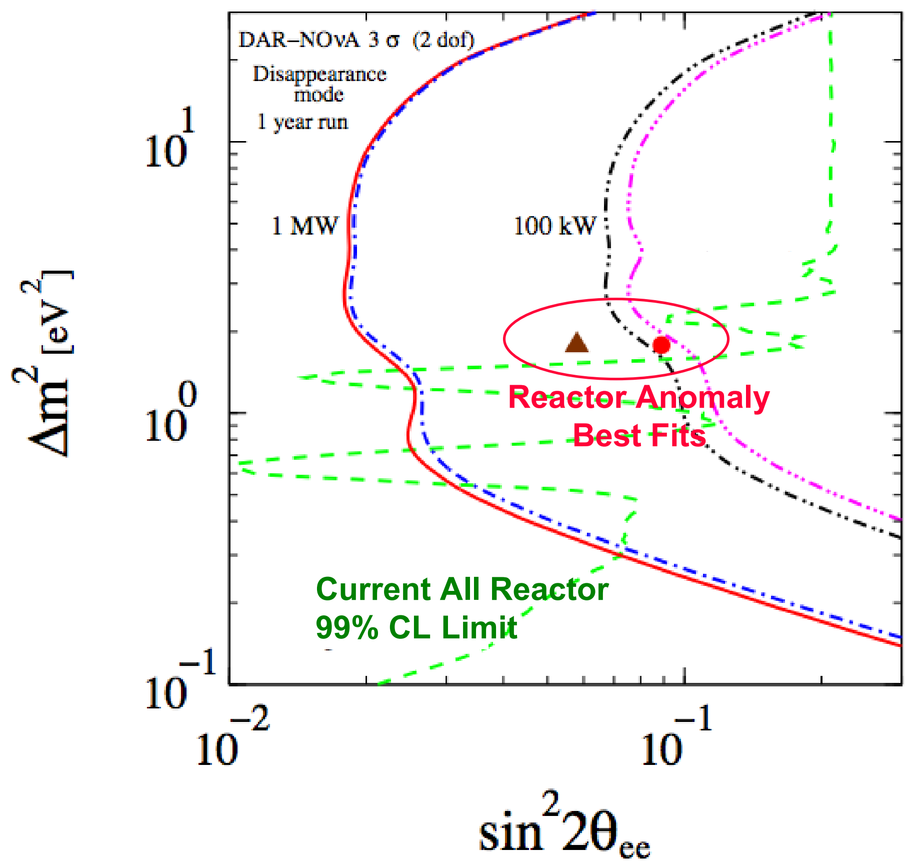


Sensitivity Estimates for Liquid Scint Detectors

LENA style detector $\bar{\nu}_e$ appearance
- Cover LSND at 5σ with 5 kton and 10 kW in 1 year



NOvA ν_e disappearance
- Cover "Reactor Anomaly" at 3σ with 100 to 1000 kW in 1 year



Final Comments

There are a number of results and hints that suggest that there may be oscillations to sterile neutrinos in the $\Delta m^2 \sim 1\ eV^2$ region

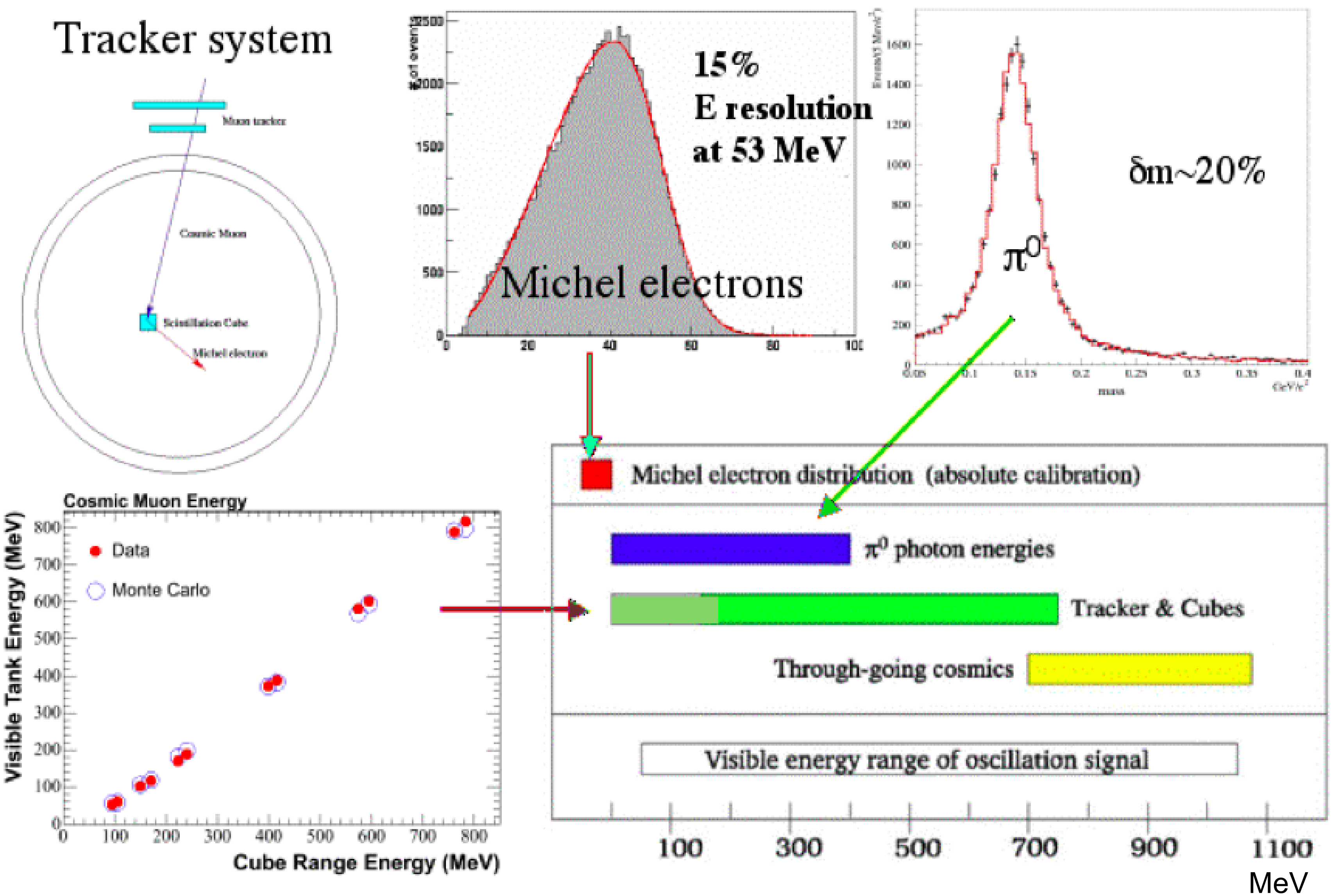
– Of course, neutrinos have provided many surprises in the past
  ⇒ So these results may be due to other types of physics

– Further running and new experiments are being planned to address these results in order to:
  - Provide definitive information on the current signals
  - Probe the oscillation patterns in both appearance and disappearance

⇒ Establishing the existence of sterile neutrinos would be a major result

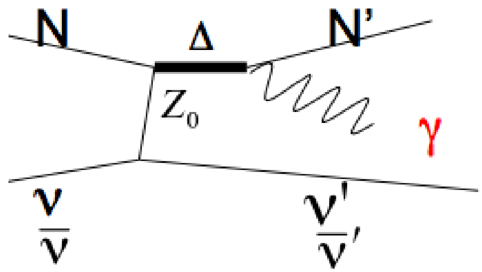
Backup

Energy Calibration



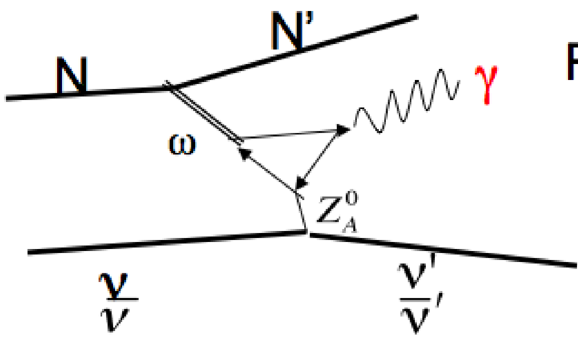
Possible Gamma-Ray Background Sources

Radiative Delta decay is included in the MiniBooNE backgrounds

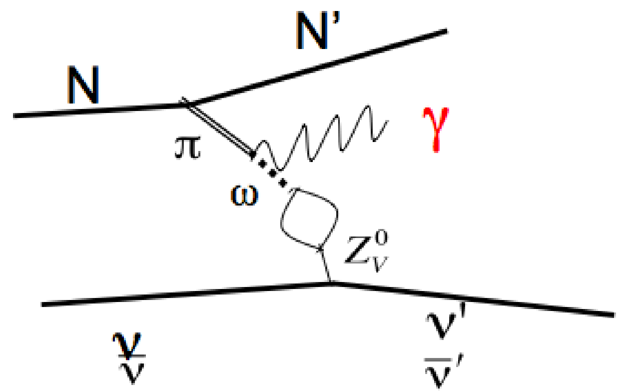


($G^2\alpha/\alpha_S$)

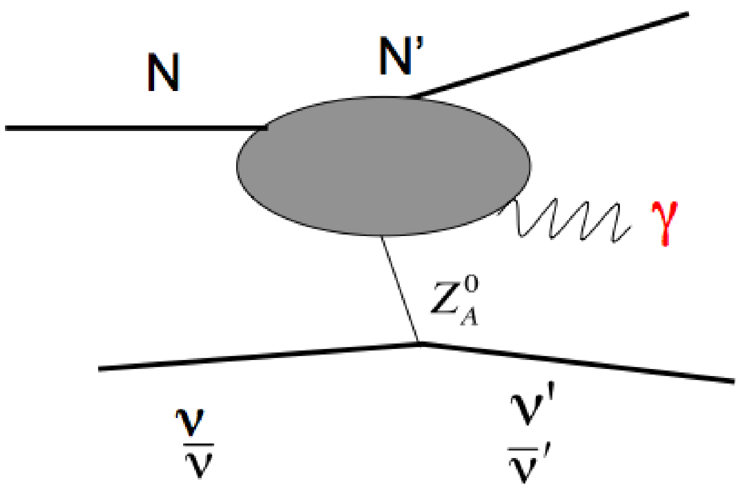
Radiative Delta Decay



Axial Anomaly



Other PCAC



So far no one has found a NC process to account for the $\nu,\bar{\nu}$ difference & the ν low-energy excess. Work is in progress:

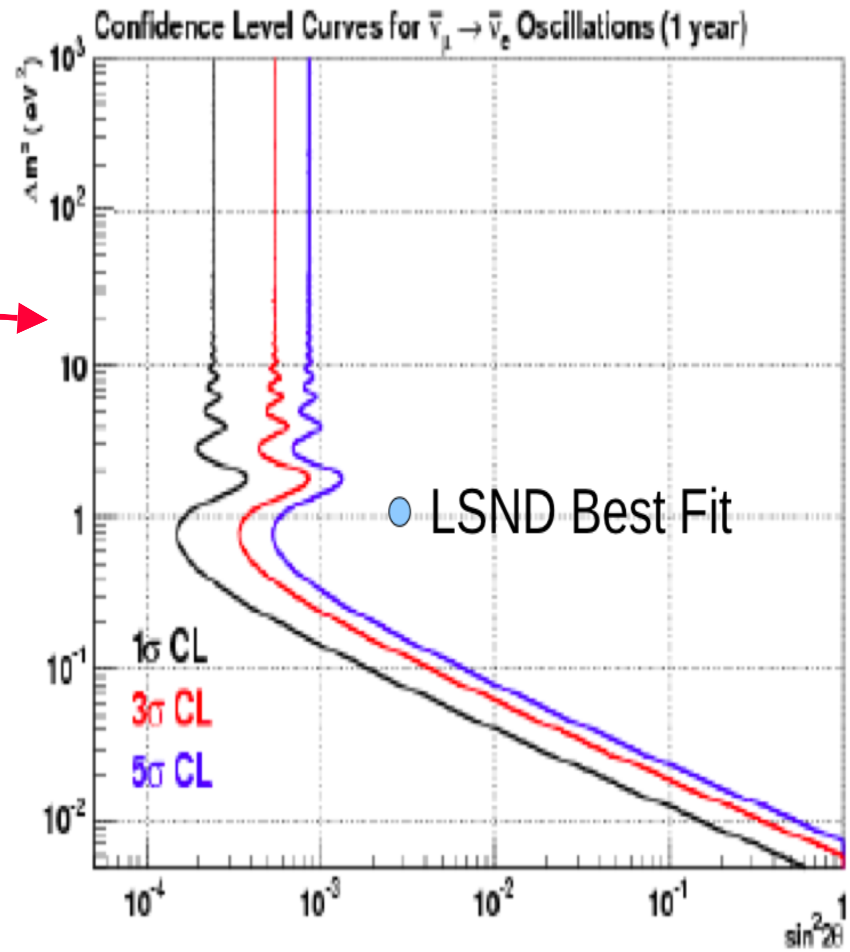
R. Hill, arXiv:0905.0291

Jenkins & Goldman, arXiv:0906.0984

Serot & Zhang, arXiv:1011.5913

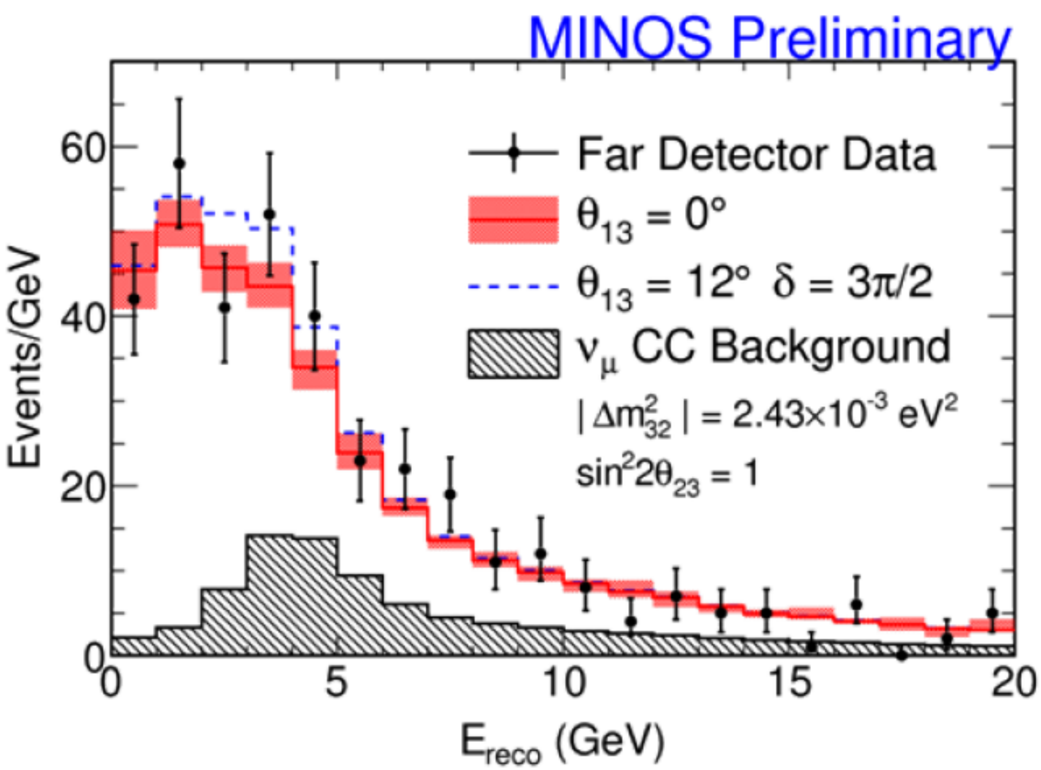
Decay-at-Rest ν Source Already Exists at SNS

- Spallation neutron source at ORNL
- 1 GeV protons on Hg target (1.4 MW)
- Free source of neutrinos
- Unfortunately, no ν detector (OscSNS proposal)



MINOS Search for Oscillations to Sterile Neutrinos

- "Atmospheric region" oscillations from $\nu_\mu \rightarrow \nu_\tau$ but ν_τ energy is below threshold to produce τ leptons $\Rightarrow$ only ν_τ NC interactions
  $\Rightarrow$ NC rate in near and far detector should be the same
- If $\nu_\mu \rightarrow \nu_{sterile}$ then NC rate should be less in far detector

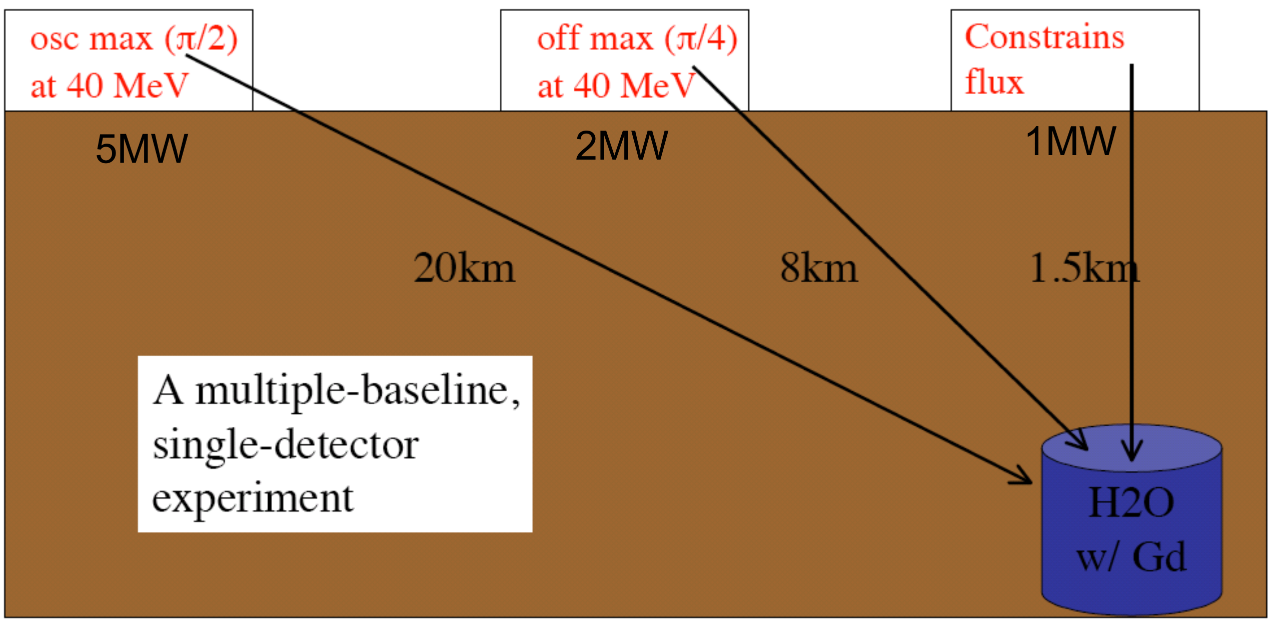


Data are consistent with no NC deficit at FD and thus with no sterile neutrino mixing

Daedalus Experiment

See K. Scholberg talk on Tues. afternoon

- Multiple beam sources using high-power cyclotrons
  - Very few $\bar{\nu}_e$ produced so can do precise $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search
  - For study assume each cyclotron 1 MW at ~0.8 GeV
- Detector is assumed to be 300 kton water Cerenkov detector with gadolinium doping
- Osc signal events are $\bar{\nu}_e + p \rightarrow e^+ + n$ (Inverse-beta decay) which can be well identified by a two part delayed coincidence (Like reactor experiments)
- Excellent CP sensitivity alone or combined with LBNE ν-only running



Sites have sequential duty factors. Timing used to separate event source.

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

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

- Positive indications:
  - LSND/MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal
  - MiniBooNE low-energy excess ($\nu_\mu \rightarrow \nu_e$?)
  - Reactor disappearance anomaly ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)
  - Gallex-Sage reduced calibration source rate (ν_e disappearance?)

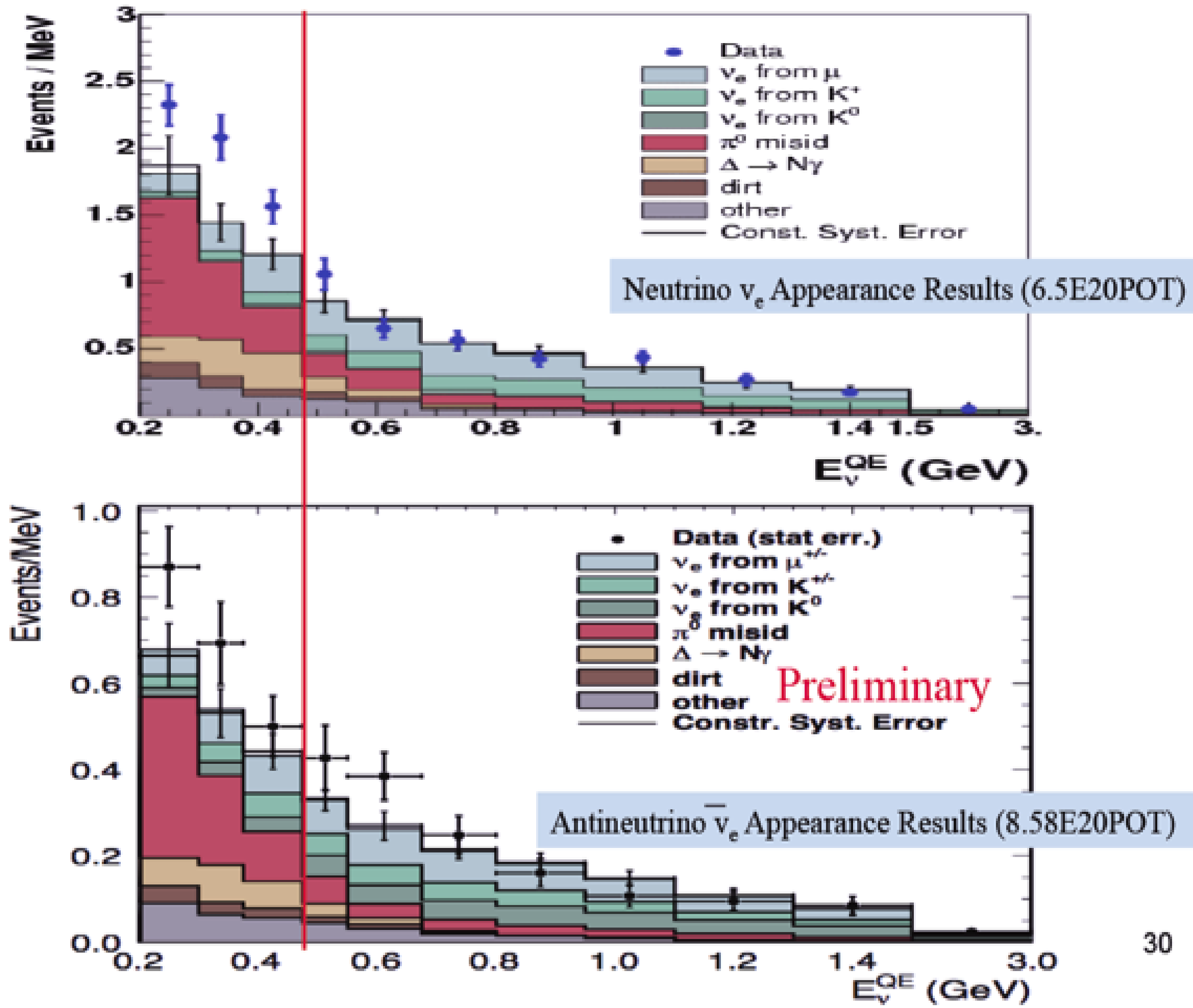
- Negative indications:
  - CDHS and MiniBooNE restrictions on ν_μ disappearance
  - MiniBooNE restrictions on $\bar{\nu}_\mu$ disappearance
  - Karmen restrictions on $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Other negative results

Low Energy Excess Models

- Few standard model explanations and many new physics ideas
- Many models have equal effects in neutrinos and antineutrinos
  - ⇒ These models are "disfavored" by absence of $\bar{\nu}_e$ excess.

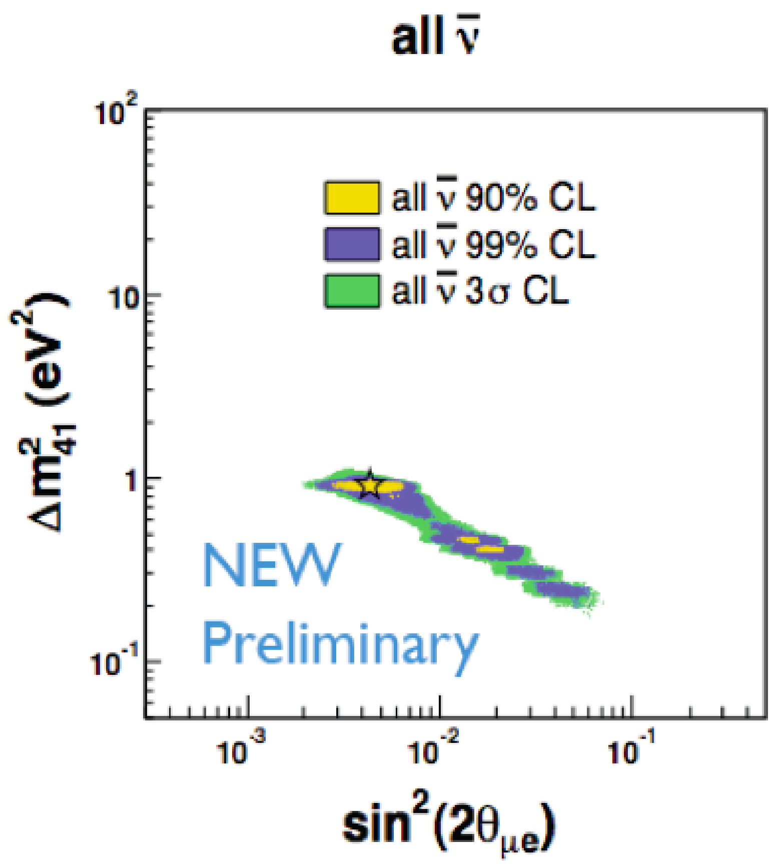
Possible explanation	Status
Anomaly Mediated Neutrino-Photon Interactions: *Harvey, Hill, & Hill, arXiv: arXiv:0905.029*	Disfavored
CP-Violation 3+2 Model: *Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.*	Possible
Lorentz Violation: *Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009*	Possible
CPT Violation 3+1 Model: *Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303*	Possible
VSBL Electron Neutrino Disappearance: *Giunti and Laveder arXiv:0902.1992*	Disfavored
New Gauge Boson with Sterile Neutrinos: *Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363*	Disfavored

Comparison of ν_e and $\bar{\nu}_e$ Appearance Results



$\bar{\nu}$ – Only Data: Good 3+1 Fits with Sterile Neutrinos

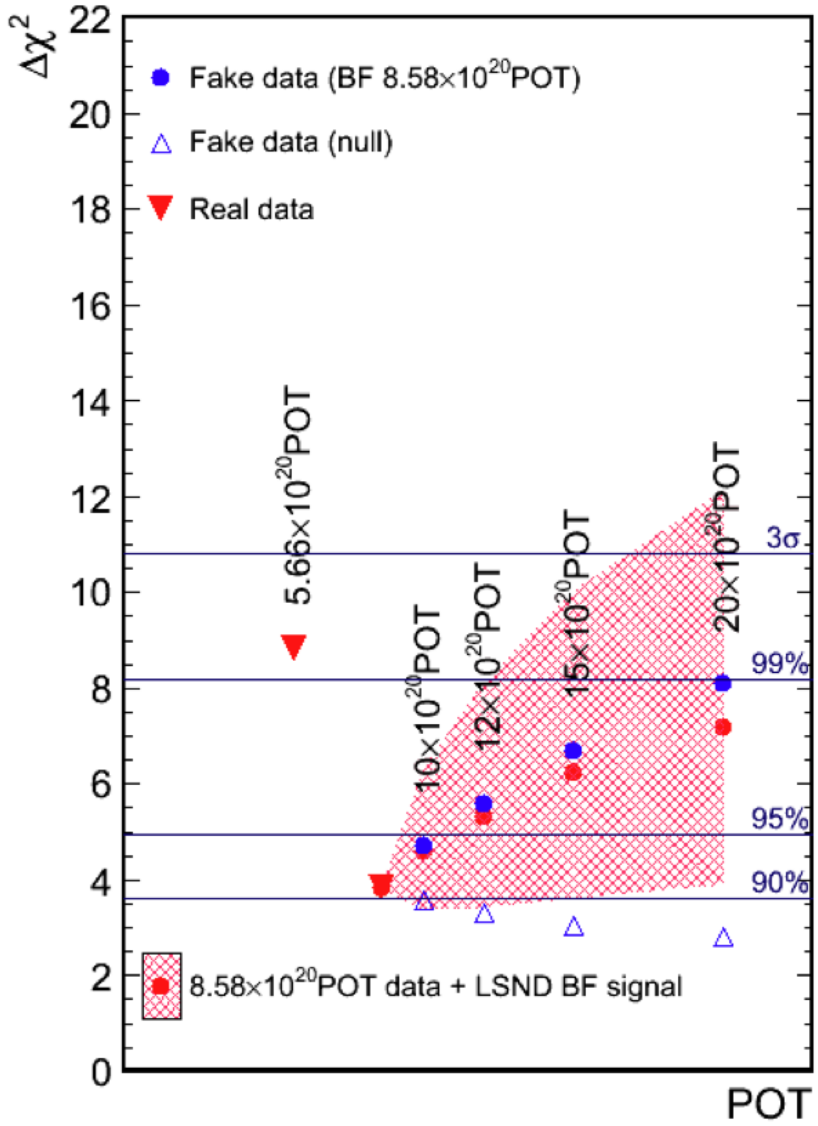
- $\bar{\nu}$ Data from LSND, MiniBooNE, Karmen, Reactor
- Good fits and compatibility for antineutrino - only data.
- MiniBooNE ν_e appearance and CDHS ν_μ disappearance do not fit
  ⇒ Need CP (and maybe CPT) violation ⇒ 3+2 Model



From Georgia Karagiorgi
Columbia University

Future $\bar{\nu}$ OscillationSensitivity Estimates

- MiniBooNE goal is to reach a total of 1.5×10^{21} protons-on-target before next summer.
- Plot shows the potential exclusion of no-osc in antineutrinos assuming the current best fit signal
  - Hashed region shows possible region (68% C.L.) of future results assuming LSND best-fit signal
  - Systematics limit approaches above 2×10^{21} POT
- Also, in the process of doing a combined analysis of ν_e and $\bar{\nu}_e$



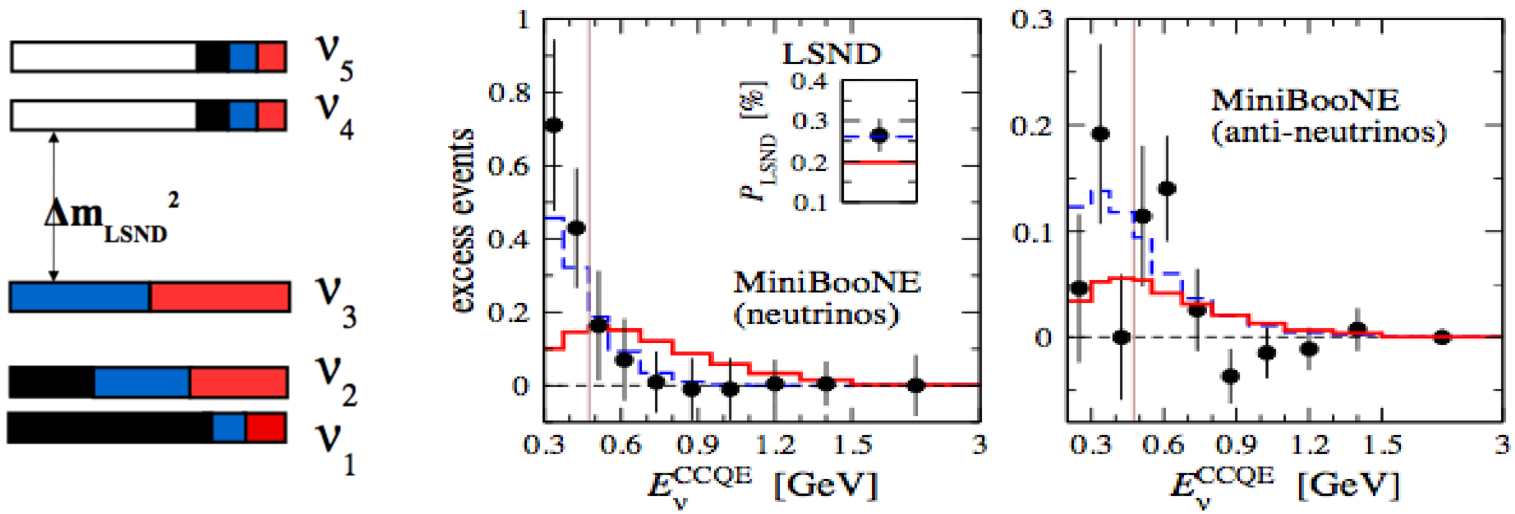
Global 3+2 Fits with Sterile Neutrinos

- In 3+2 fits, CP violation allowed so $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

	Δm_{41}^2	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm_{51}^2	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130

(Kopp et al. - hep-ph:1103.4570)

- But still hard to fit appearance and disappearance simultaneously

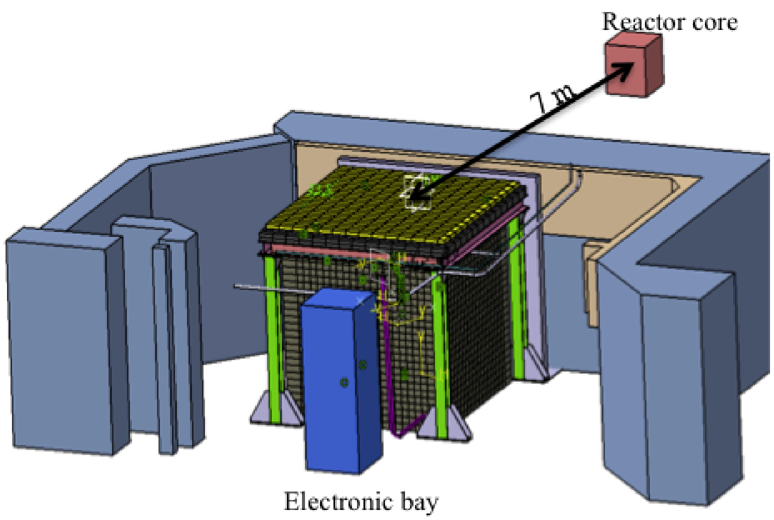


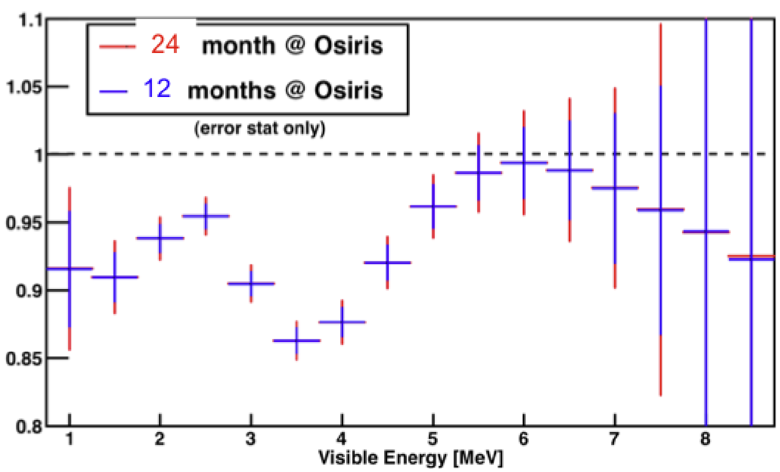
Red: Fit to Disapp + App
Blue: Fit to App Only

- Compatibility between data sets better but still not very good
  - LSND+MB ($\bar{\nu}$) vs Rest = 0.13%
  - Appearance vs Disappearance = 0.53%

Ideas for VSBL Reactor and Radioactive Source Exps

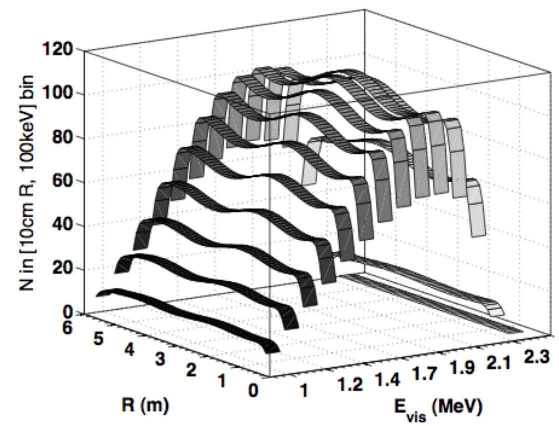
- NUCIFER Proposed Experiment
  - Osiris Research Reactor:
    Core Size: 57x57x60 cm
  - 1.2m x 0.7m detector
    7m distance from core

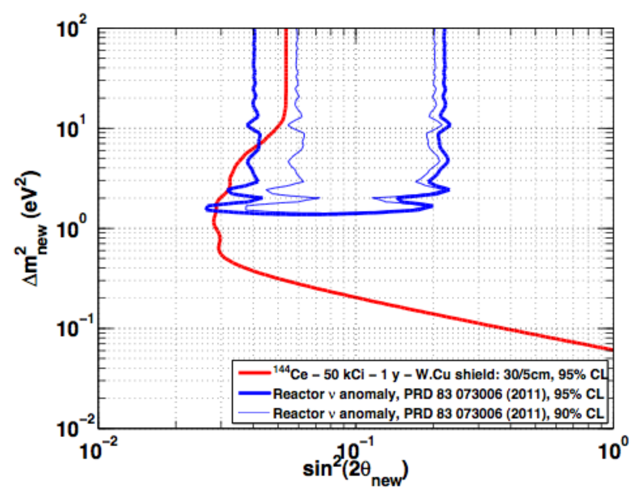




- Radioactive source in Scint Detector
  - 10 kilocurie scale ^{144}Ce or ^{106}Ru antineutrino β-decay source
  - Deployed at the center of liquid scintillator detector (i.e.BOREXINO, KAMLAND…)
    - Detect $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance

arXiv:1107.2335





Very-short Baseline $\bar{\nu}_e$ Appearance and $\bar{\nu}_e/\nu_e$ Disappearance Search Opportunities

- Several indications that there may be oscillations to sterile neutrinos with $\Delta m^2 \approx 1$ eV^2
  - Need definitive check of MiniBooNE/LSND $\bar{\nu}_e$ appearance result
  - Need $\bar{\nu}_e/\nu_e$ disappearance search

- See event rate change within the detector due to oscillations
  - Definitive observation of neutrinos oscillating with L/E
  - Background effects much reduced since don't show oscillation pattern

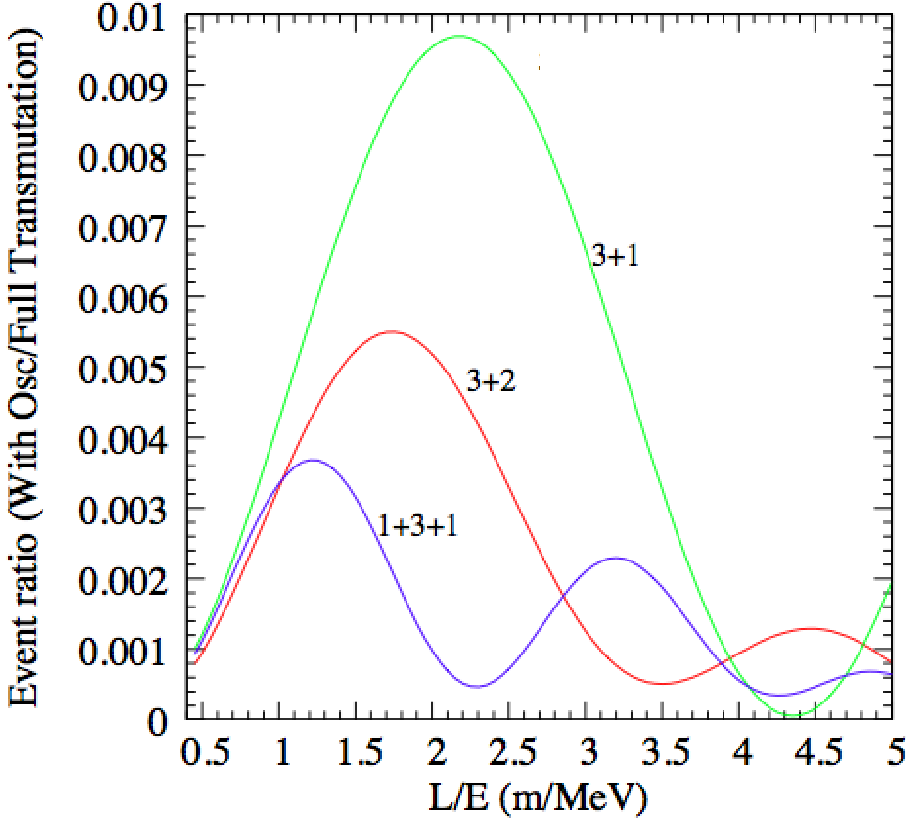
- Need neutrino source with well-known energy distribution and small spatial extent $\Rightarrow$ Several options:
  - Small core reactor source
  - Very high activity radioactive source
  - Decay-at-rest beam from proton beam dump

$\Rightarrow$ *Hard to do this with π-decay accelerator neutrino beam*

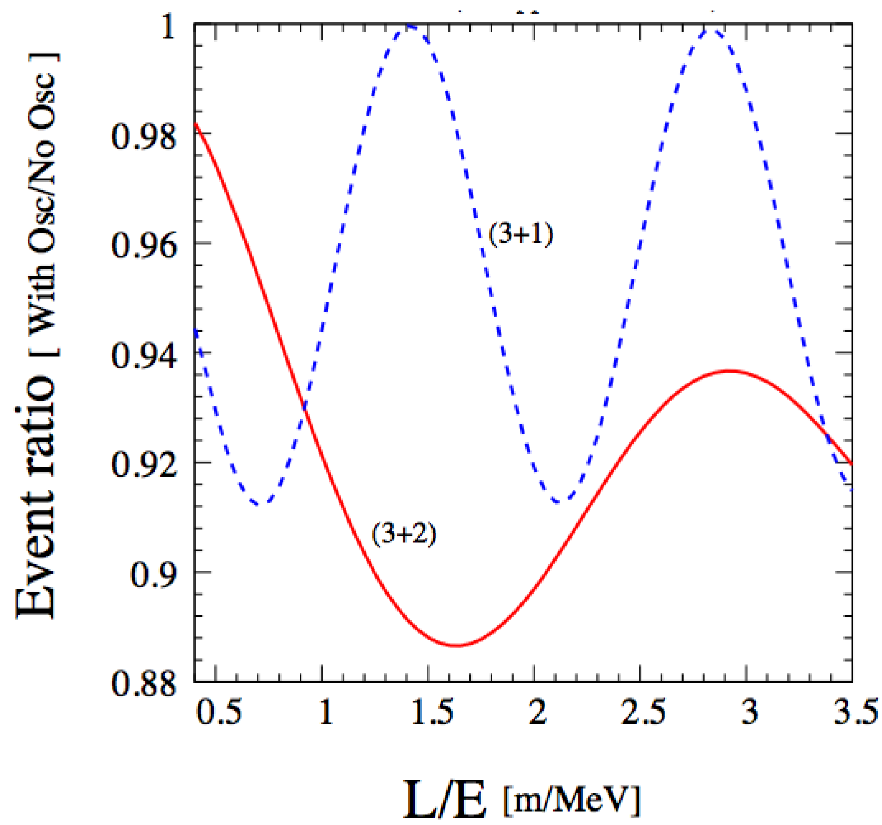
- *Long neutrino source from decay pipe region*
- *Very few $\bar{\nu}_e/\nu_e$ in beam for a disappearance search*

Isolating Sterile Neutrino Models from L/E Waves

$\bar{\nu}_e$ appearance



ν_e disappearance



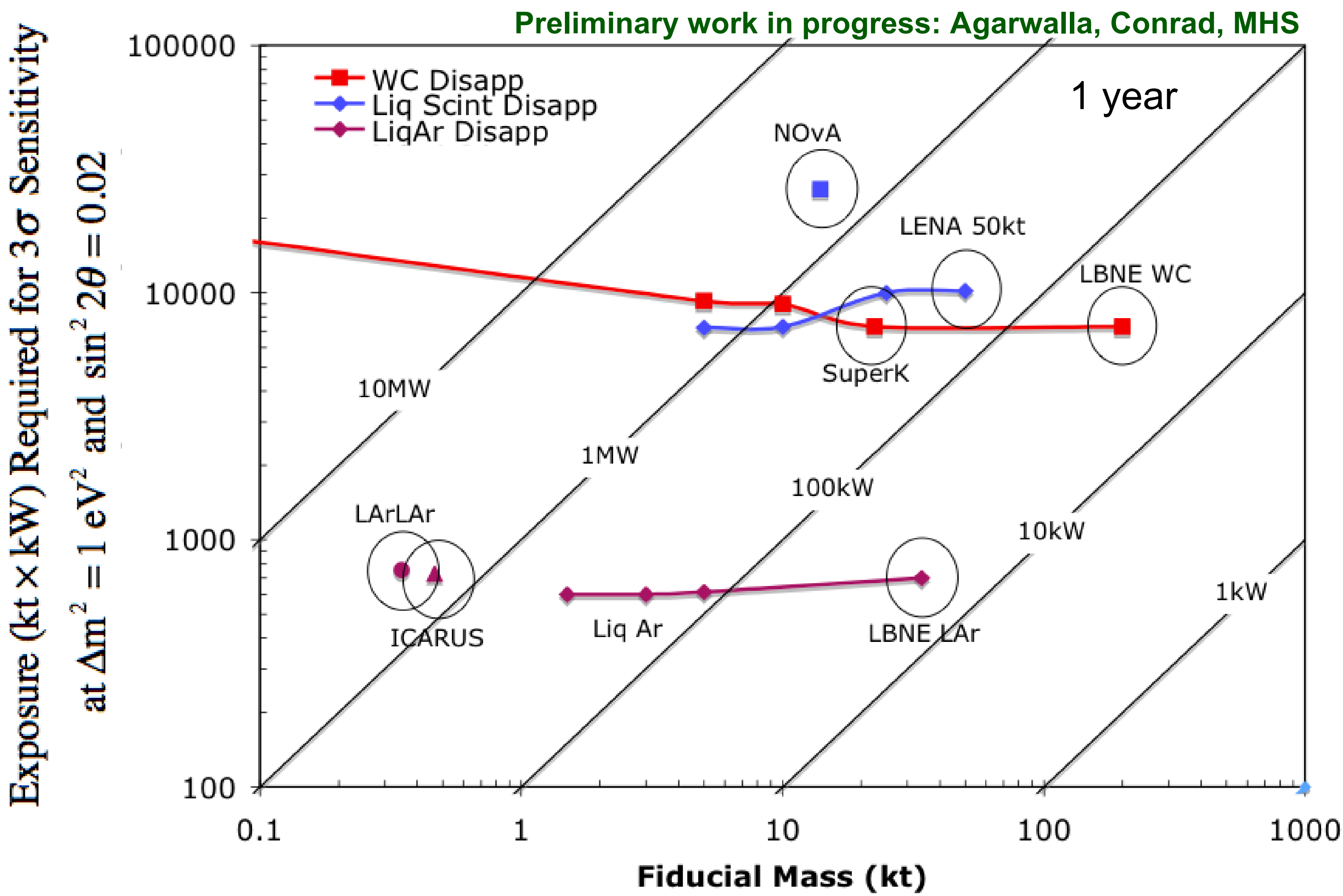
Also Water Cerenkov and Liquid Argon Detectors

- Water Cerenkov Detectors
  - All deep underground so low backgrounds
  - For appearance need to see IBD by tagging neutron
    $\Rightarrow$ Best with Gadolinium doping.
- Examples:
  - Super-K 22 kton , L = 32m
  - LBNE (DUSEL) 200 kton , L = 75m
  - MEMPHYS (LAGUNA) 440 kton , L = 60m
  - Hyper-K 560 kton , L = 250m

- Liquid Argon
  - Backgrounds depend on whether surface or underground
  - Only disappearance since no free protons for IBD interactions
- Examples:
  - ICARUS ~466 ton , L = 38m (surface)
  - LArLAr 335 ton, L = 7m (surface)
  - LBNE LAr (DUSEL) 34 kton , L = 2×65m
  - GLACIER (LAGUNA) 100 kton , L = 60m

VSBL ν_e Disappearance: Source Power and Detector Size for x10 Better Sensitivity Than Current

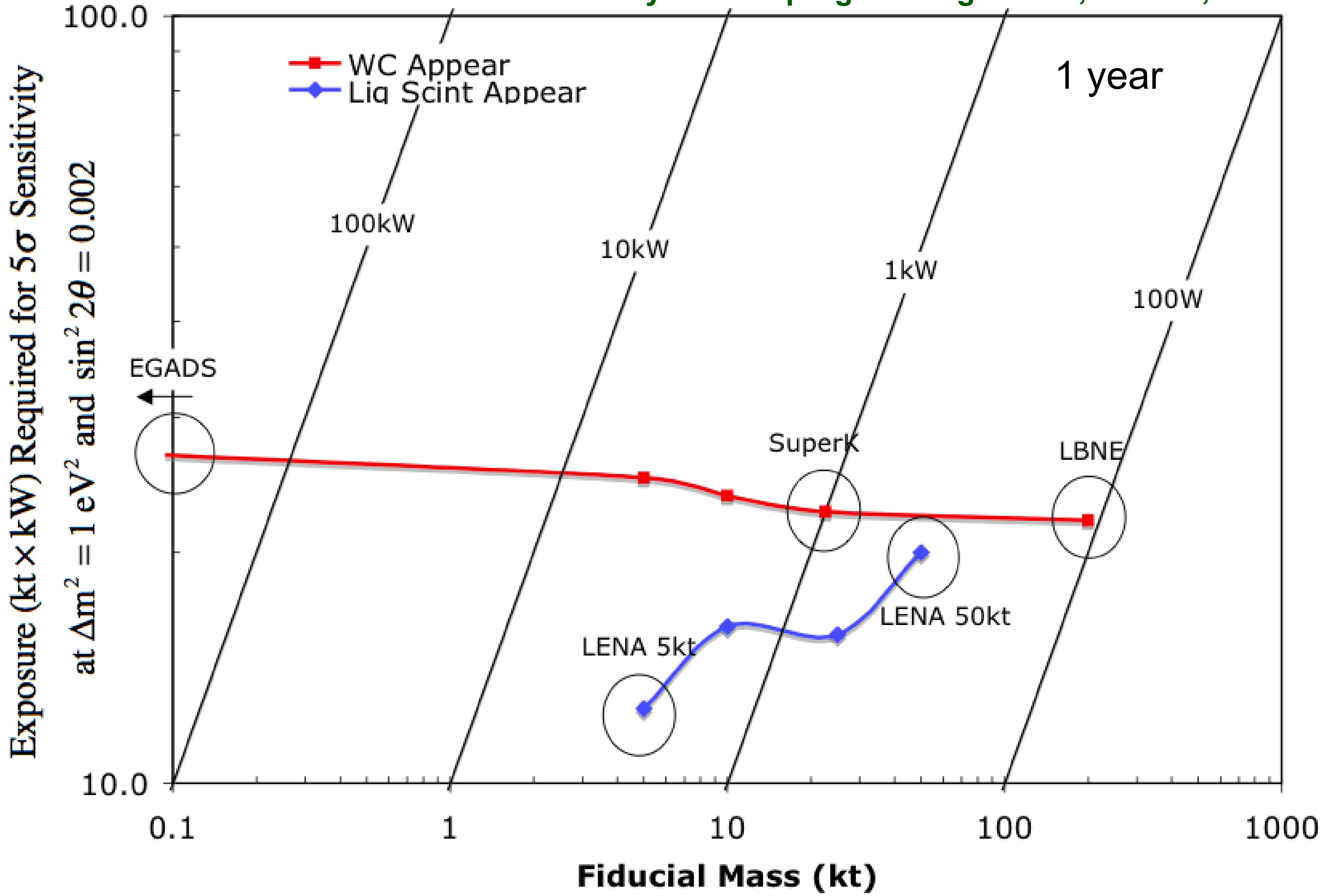
Exposure = Detector Size (kton) × Cyclotron Power (kW)



VSBL $\bar{\nu}_e$ Appearance: Source Power and Detector Size for LSND Coverage at 5σ

Exposure = Detector Size (kton) × Cyclotron Power (kW)

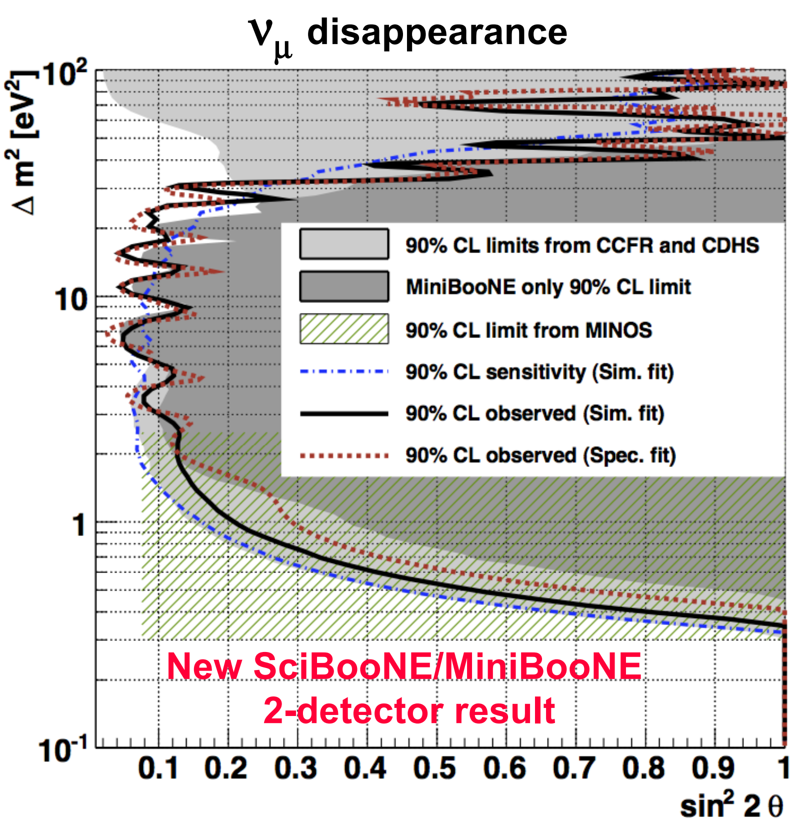
Preliminary work in progress: Agarwalla, Conrad, MHS



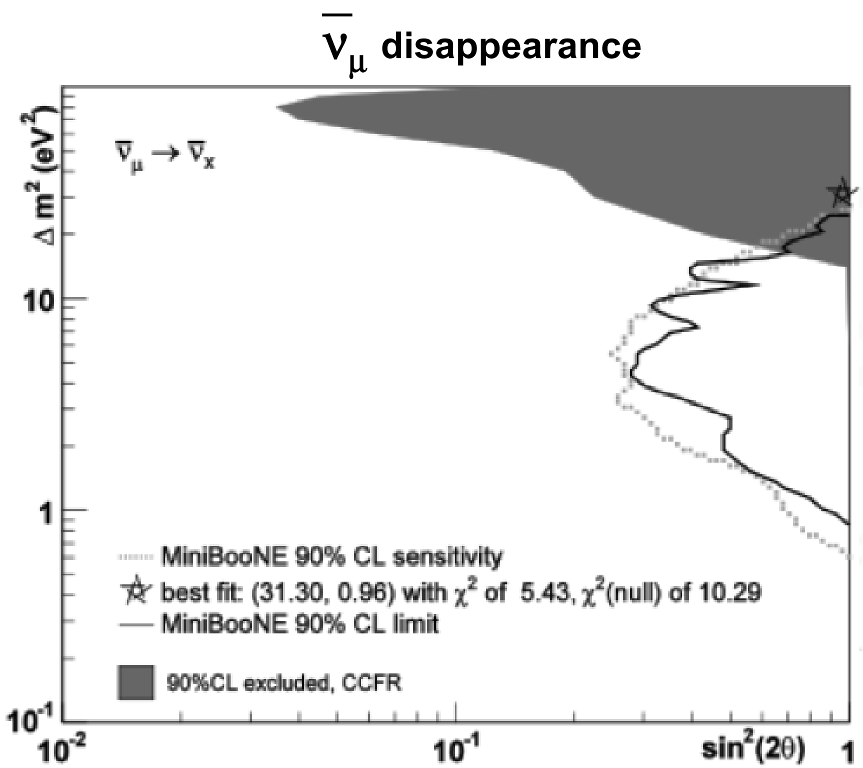
Stringent limits on ν_μ disappearance from experiments

- New SciBooNE/MiniBooNE ν_μ disappearance limit even stronger than previous
- Less stringent limits for $\bar{\nu}_\mu$ Disappearance from MiniBooNE
- CPT conservation implies ν_μ and $\bar{\nu}_\mu$ disappearance are the same

$\Rightarrow$ **Restricts application of 3+1 since ν_μ constrains $\bar{\nu}_\mu$ disappearance.**



Mahn et al. arXiv:1106.5685 [hep-ex], submitted to PRL



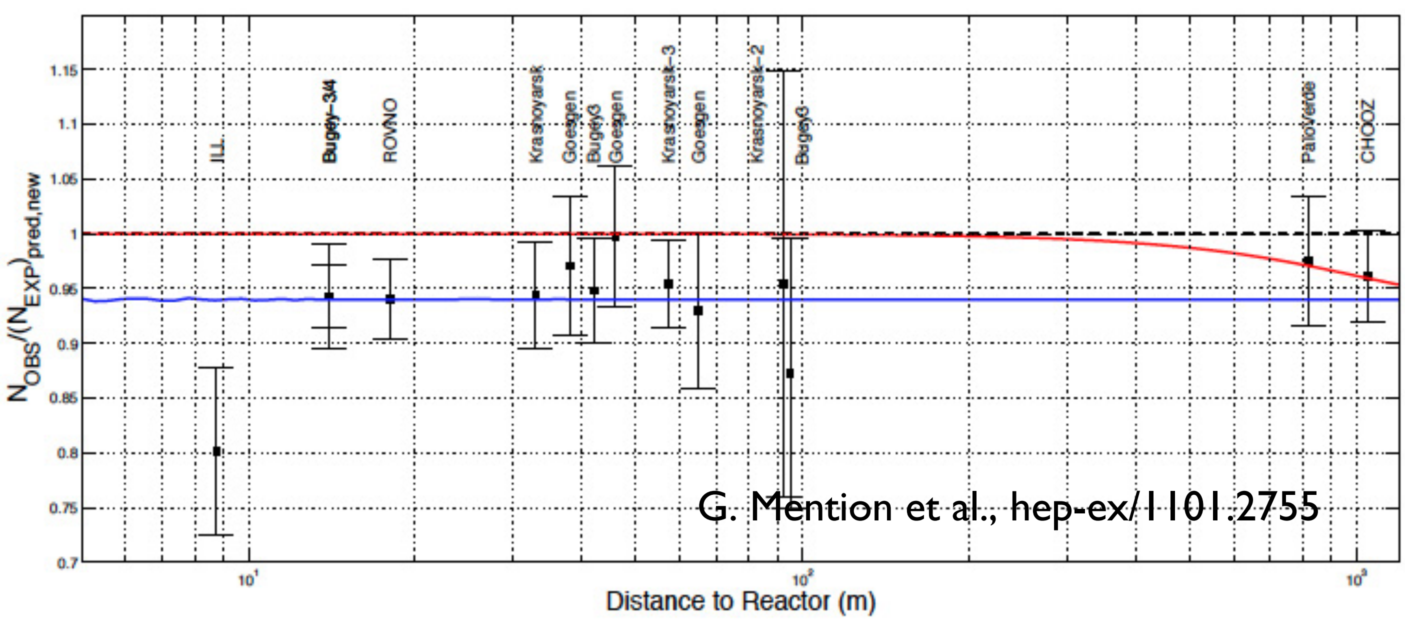
Aguilar-Arevalo et al., Phys. Rev. Lett. 103, 061802 (2009)

Possible Indication of $\bar{\nu}_e$ Disappearance

Reactor Antineutrino Anomaly

Re-analysis of predicted reactor fluxes based on a new approach for the conversion of the measured electron spectra to anti-neutrino spectra.

- Reactor flux prediction increases by 3%.
- Re-analysis of reactor experiments show a deficit of electron anti-neutrinos compared to this prediction – at the 2.14σ level
- Could be oscillations to sterile with $\Delta m^2 \sim 1 eV^2$ and $\sin^2 2\theta \sim 0.1$



Red line: Oscillations assuming 3 neutrino mixing

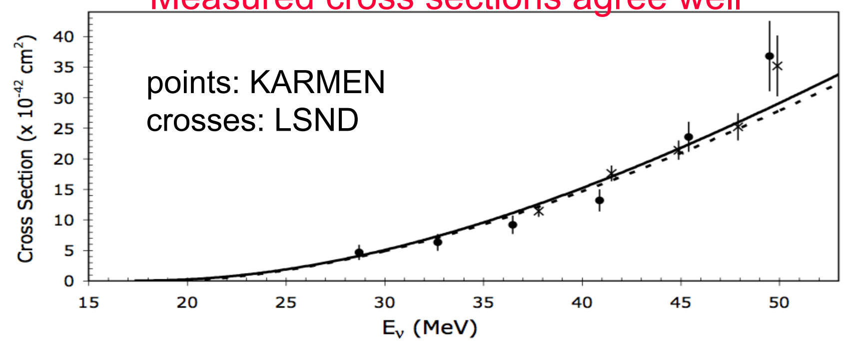
Blue line: Oscillations in a 3 + 1 (sterile neutrino) model

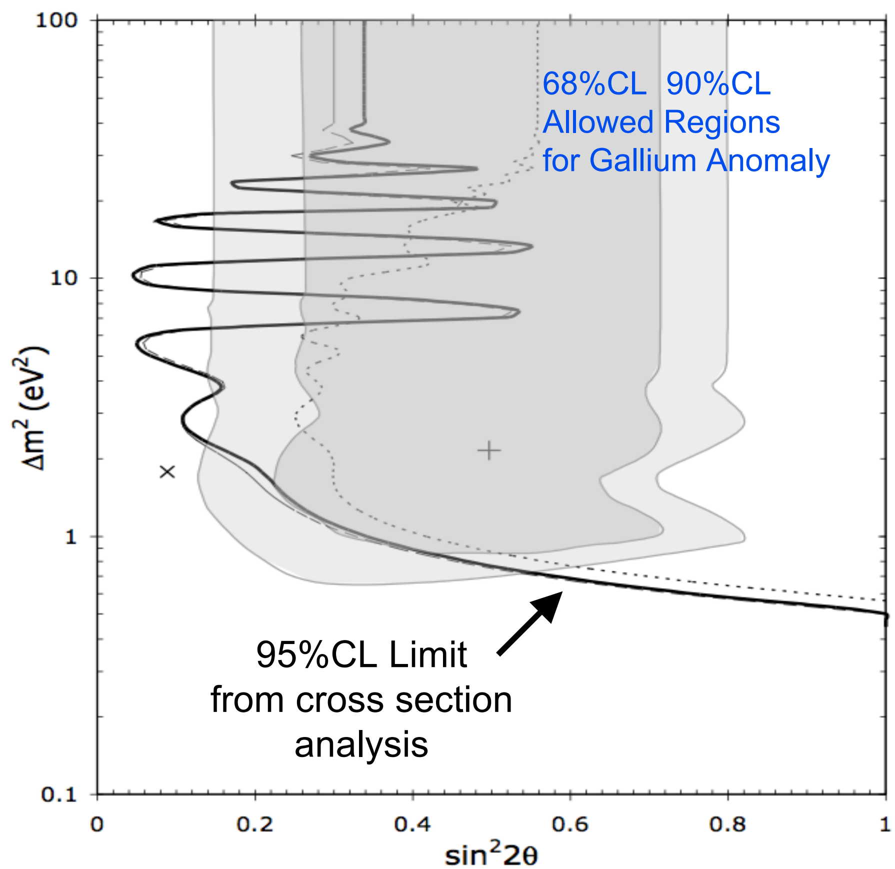
Gallium Anomaly: ν_e Disappearance?

- SAGE and GALLEX gallium 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





Decay-at-Rest VSBL Oscillation Exps using Cyclotron Drivers

- High-power compact cyclotrons could provide a DAR ν-source that could be placed near one of the existing or future large detectors
  - Cyclotron power requirements at the 10 to 100 kW
  - Neutrino source region small ±25 cm
  - Cyclotron source could be as close as 20m to detector
- Detectors:
  - Any large water Cherenkov, liquid argon, or liquid scintillator
- $\nu_e \to \nu_e$ Disappearance
  - Process: Charged current electron neutrino scattering
  - Look for an oscillatory change in ν_e rate with L/E
  - Backgrounds do not have this L/E behavior
- $\bar{\nu}_\mu \to \bar{\nu}_e$ Appearance
  - Process: Inverse Beta Decay (IBD) $\nu_e + p \to e^+ + n$
  - Detector needs to provide free hydrogen targets and be able to detector the capture of the outgoing n

    $\Rightarrow$ Only water or liquid scintillator