Short-Baseline Neutrinos

W. C. Louis, LANL, SSI2015, August 17-18, 2015

- Neutrino Properties
- What is Short-Baseline?
- Neutrino Detectors
- Evidence for Short-Baseline Neutrino Oscillations
- 3+N Sterile Neutrino Models
- Neutrino Cross Sections
- Future Short-Baseline Neutrino Oscillation Experiments
  - Accelerators: SBN, DUNE
  - Spallation Sources & Cyclotrons: OscSNS, JSNS^2, IsoDAR
  - Reactors: PROSPECT, Chandler/SOLID
  - Radioactive Sources: SOX
  - IceCube

THE STANDARD MODEL OF
PARTICLES AND FORCES

IS THIS **ALL THAT EXISTS**?

Salient Features of Neutrinos

- Neutrinos are neutral, spin ½, point-like particles with small, non-zero masses (< ~1 eV)
- Neutrinos interact very weakly with matter
- Neutrinos & photons dominate the universe in terms of number of particles
- Neutrinos undergo oscillations

How Do Particles Interact?

I. Protons Interact By:

- Strong Force
- Electromagnetic Force
- Weak Force
- Gravitational Force

II. Electrons Interact By:

- Electromagnetic Force
- Weak Force
- Gravitational Force

III. Neutrinos Interact By:

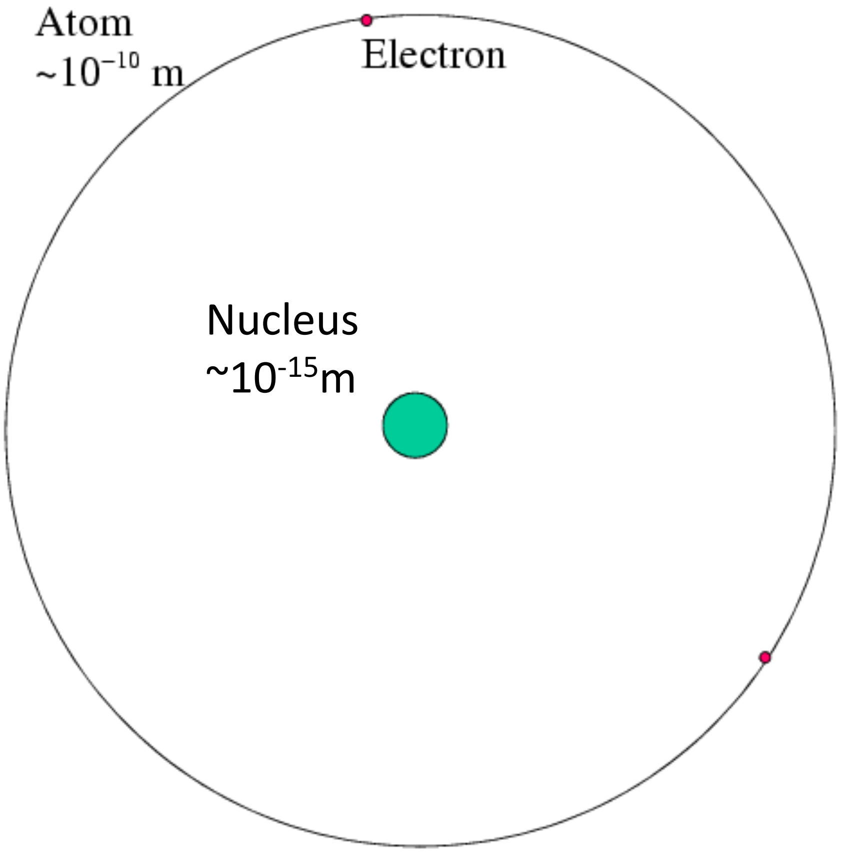
- Weak Force
- Gravitational Force

IV. Sterile Neutrinos Interact By:

- Gravitational Force only? Other New Force?

Atomic & Nuclear Sizes

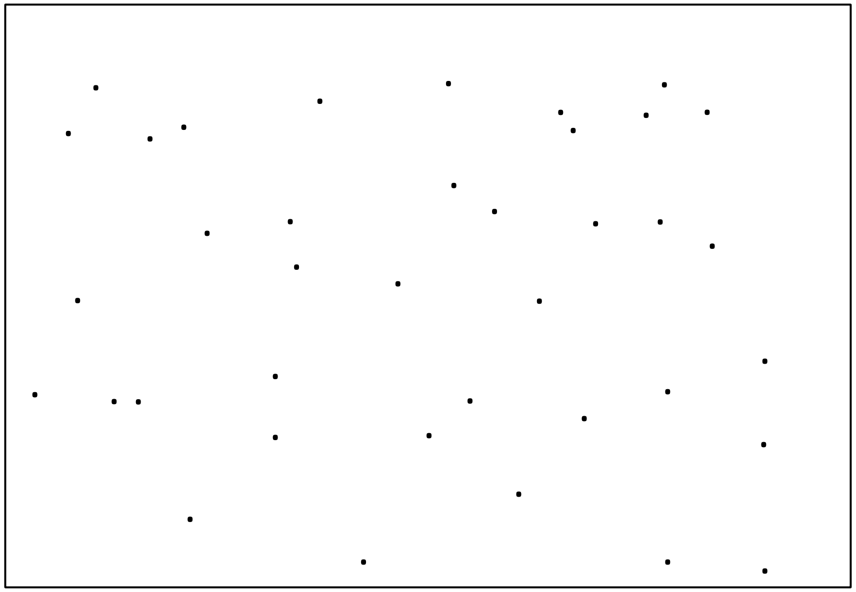
(Matter is mostly “empty space”)



If the nucleus were the size of an orange, the atom would be the size of the Santa Fe Ski area!

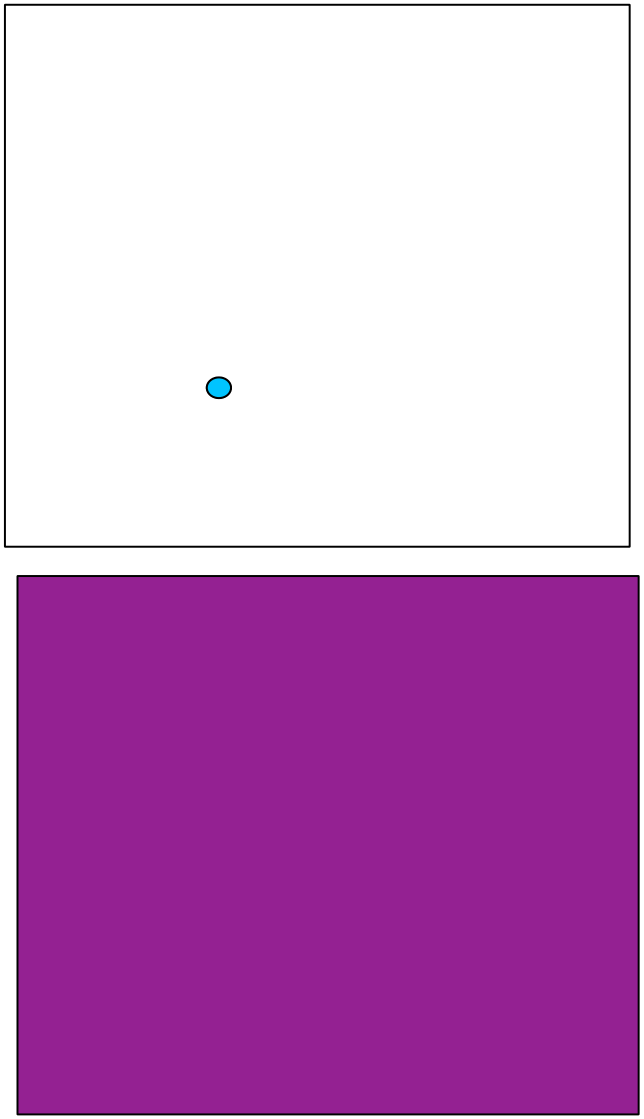
Neutrinos "See" Mostly Empty Space

Castle seen by a person.



Castle “seen” by a neutrino.

Neutrinos & Photons Dominate the Universe!



● Proton

<1 proton/m^3

● Neutrinos

~300,000,000
neutrinos/m^3

Neutrinos Masses Are Important!

There are approximately a billion times more neutrinos and photons in the universe than protons!

Neutrinos and photons dominate the universe.

If neutrinos have a mass ~ 4×10^{-33}g (~2 eV), then neutrinos would contribute as much mass to the universe as all protons & neutrons!

Neutrinos affect cosmology.

How do you measure such a tiny mass from such a particle?

Neutrino Oscillations!

Neutrino Oscillations occur because neutrinos are a superposition of mass eigenstates!

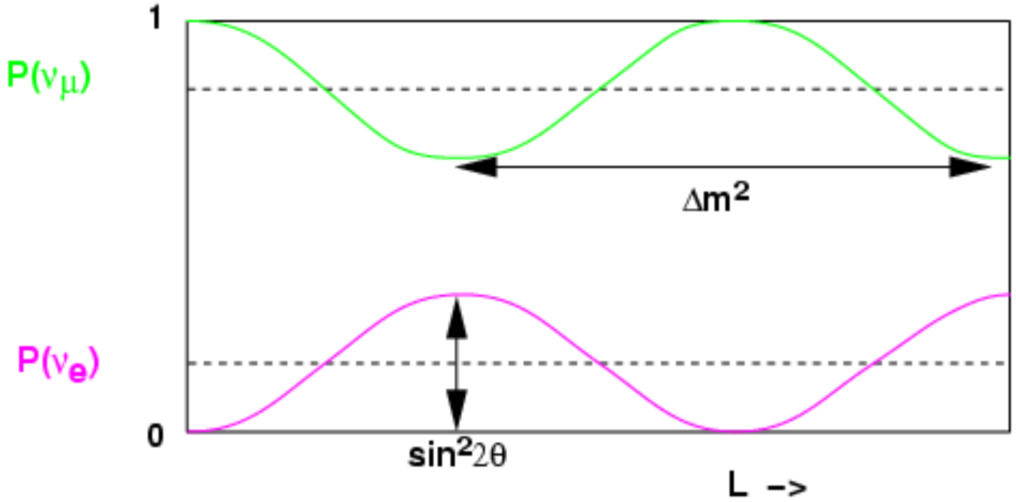
Neutrino Oscillations are a beautiful example of quantum mechanics.

Neutrino Oscillations

Weak Eigenstates **Eigenstates of Propagation**

$\nu_\mu = \cos\Theta\,\nu_1 + \sin\Theta\,\nu_2$

$\nu_e = -\sin\Theta\,\nu_1 + \cos\Theta\,\nu_2$



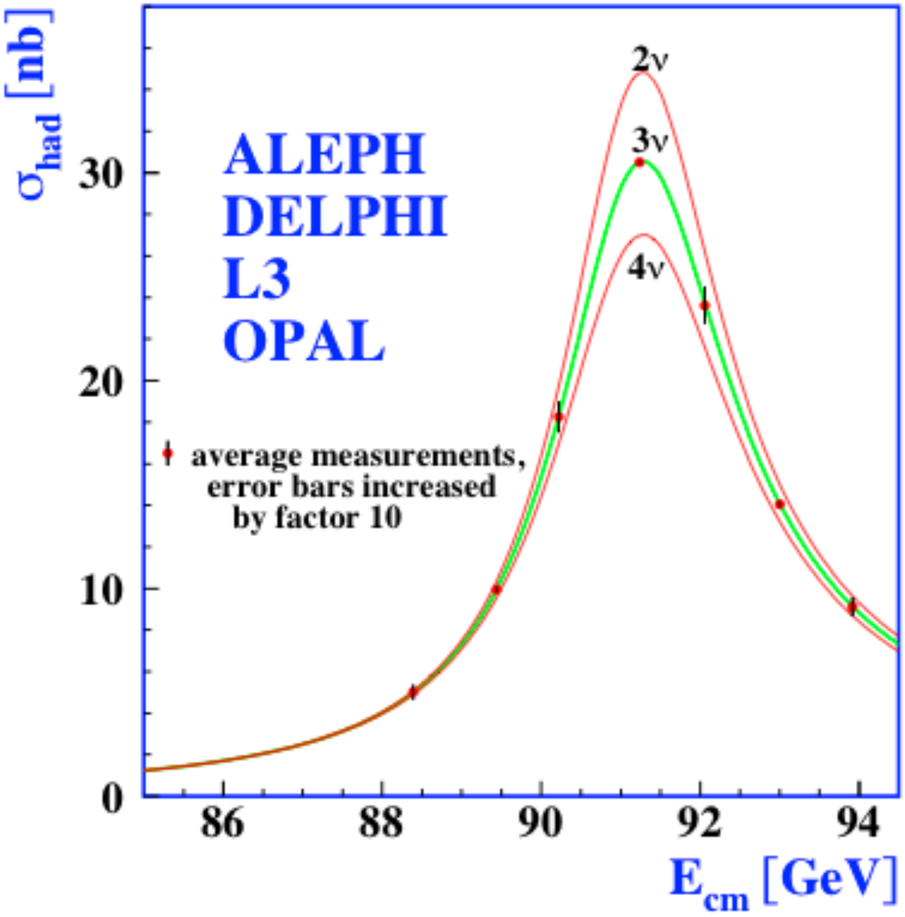
$$P_{\nu_\mu \to \nu_e} = \sin^2(2\Theta)\ \sin^2(1.27\,\Delta m^2\, L/E_\nu)$$

$\Delta m^2 = m_2^2 - m_1^2$ in eV^2, L in meters, E_ν in MeV

Neutrino Oscillations Are Due to the Superposition of Mass Eigenstates

If μ^+ is precisely measured in $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay => One would know the mass eigenstate & No Oscillations!

Experiments at SLAC & CERN: 3 Active Neutrinos!



arXiv:hep-ex/0509008v3

The SLAC & CERN experiments have Measured the number of light, active neutrinos to be 3. Therefore, any additional neutrinos would need to be **Sterile** to the Weak Interaction.

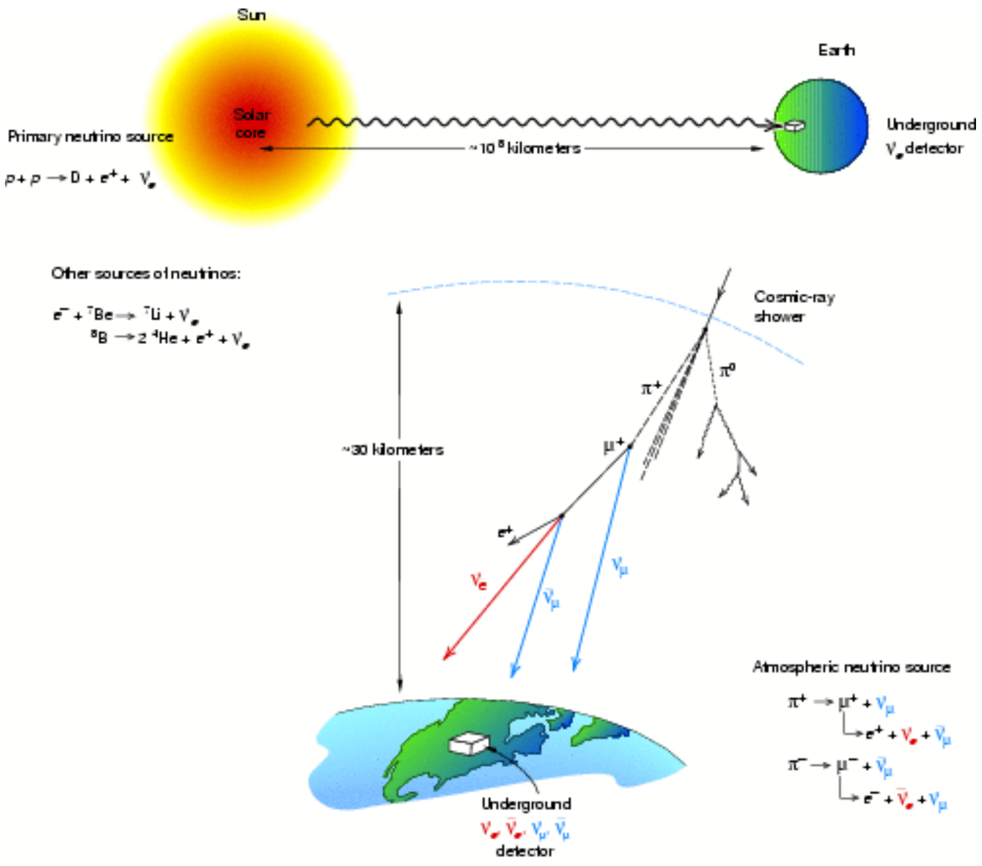
Sterile neutrinos would interact by Gravity but not by the Strong, Electromagnetic, or Weak Interactions.

Neutrino oscillations can occur regardless of whether the neutrinos are active or sterile.

Neutrino Oscillations Allow Searches for T, CP, & CPT Violation in the Lepton Sector

$\nu_\alpha -> \nu_\beta \neq \nu_\beta -> \nu_\alpha$	T Violation
$\nu_\alpha -> \nu_\beta \neq \bar{\nu}_\alpha -> \bar{\nu}_\beta$	CP Violation
$\nu_\alpha -> \nu_\beta \neq \bar{\nu}_\beta -> \bar{\nu}_\alpha$	CPT Violation

Evidence/Observation of ν Oscillations

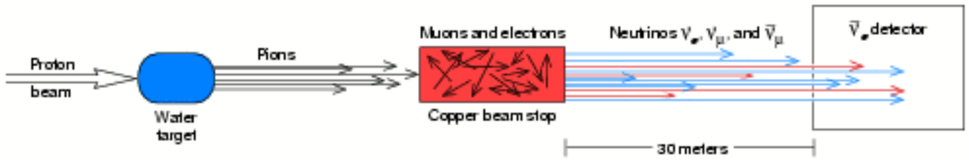


SuperK, SNO, KamLAND, BOREXINO

$\Delta m^2 \sim 0.00007\ \text{eV}^2$

SuperK, K2K, MINOS, OPERA, T2K, Double Chooz, Daya Bay, RENO, NOvA

$\Delta m^2 \sim 0.002\ \text{eV}^2$



LSND, MiniBooNE, Reactor ν, Gallium Anomaly

$\Delta m^2 \sim 1\ \text{eV}^2$

What Is Short Baseline?

Short-Baseline Neutrino Oscillations:

$\Delta m^2 \sim 1\ \mathrm{eV}^2$ or $L/E \sim 1\ \mathrm{m/MeV}$

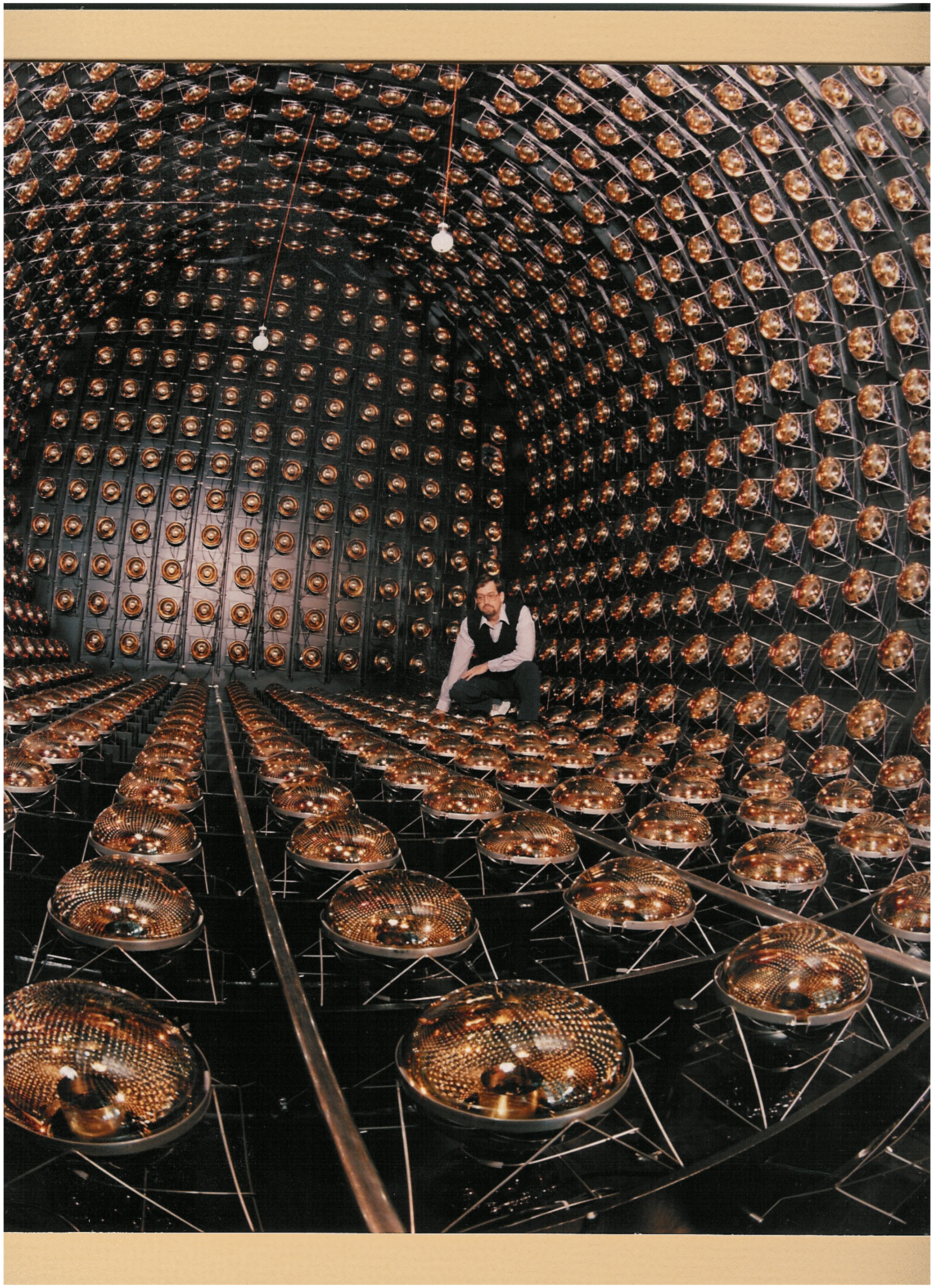
“Short” refers to L/E and not to L!

Short Baseline Neutrino Detectors

Neutrino Detectors need large mass (and a low cost/ton)!

There are only a few detector designs that are used for short-baseline neutrino experiments:

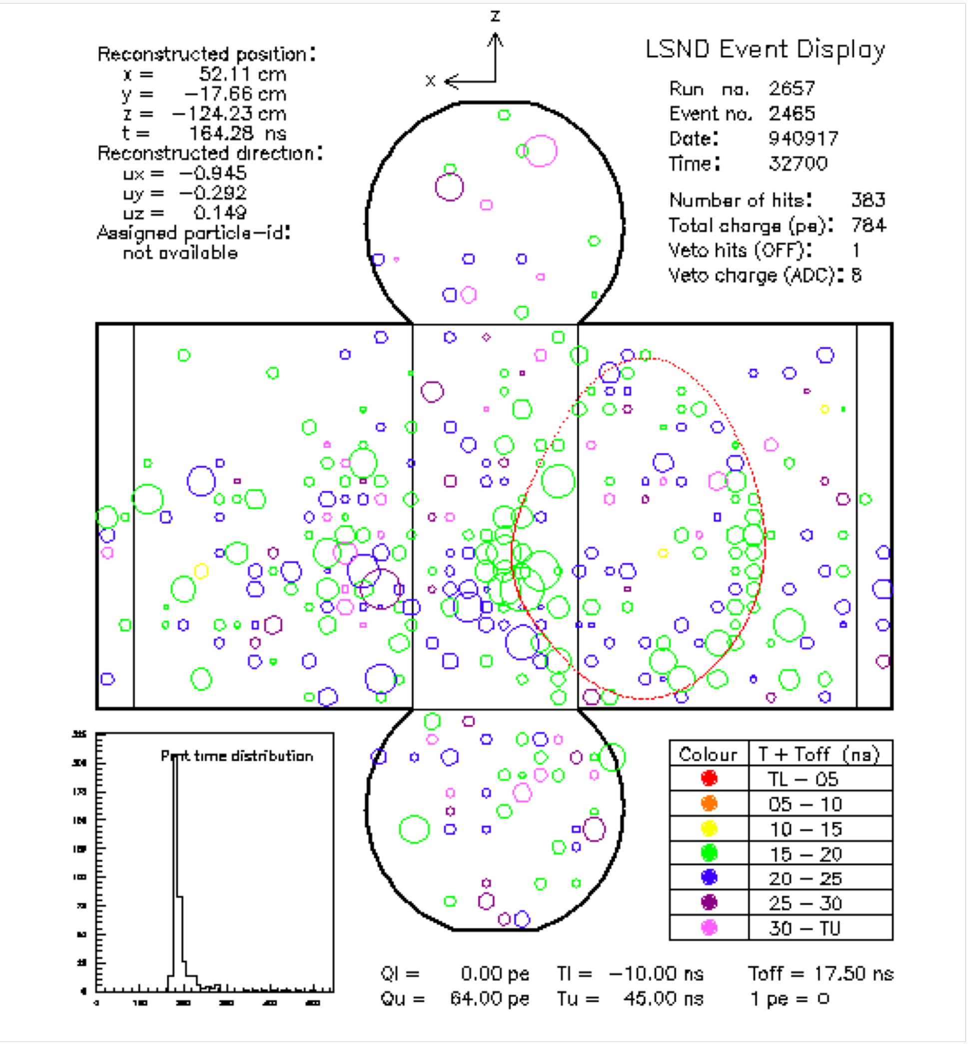
- Liquid Cherenkov/Scintillation Detectors (Crude Resolution; Fast, ns timing)
- Segmented Scintillator Detectors (Liquid or Plastic Scintillators; Moderate Resolution; Fast, ns timing)
- Liquid Argon TPC Detectors (Excellent resolution; Can distinguish electron/gamma tracks; Slow, ms timing, but has fast, ns scintillation light)



LSND Liquid Cherenkov/Scintillation Detector

Events are reconstructed from the charge/time of each hit PMT

Typical Michel Electron Event Display



Reconstructed position:
x = 52.11 cm
y = −17.66 cm
z = −124.23 cm
t = 164.28 ns
Reconstructed direction:
ux = −0.945
uy = −0.292
uz = 0.149
Assigned particle−id:
not available

LSND Event Display

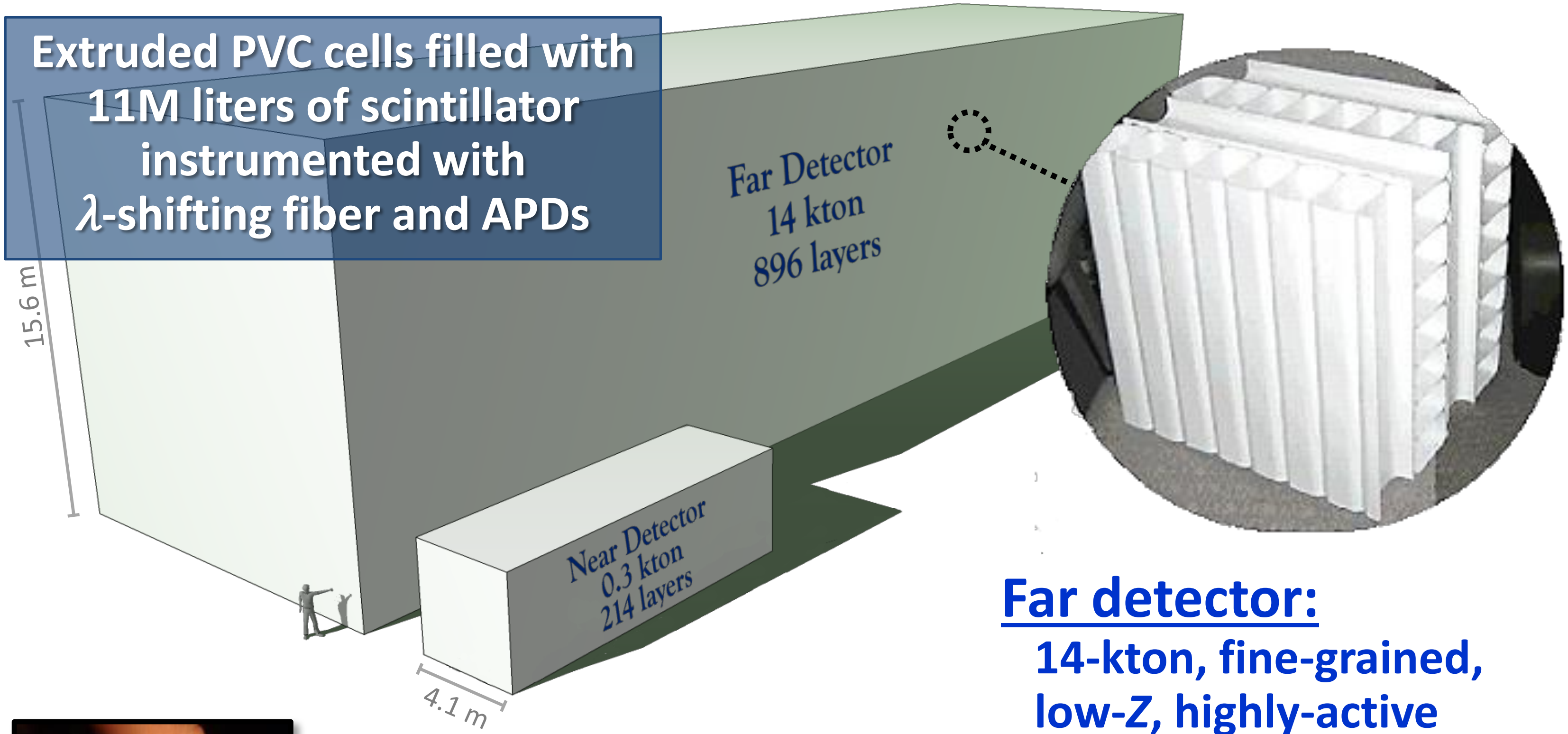
Run no. 2657
Event no. 2465
Date: 940917
Time: 32700

Number of hits: 383
Total charge (pe): 784
Veto hits (OFF): 1
Veto charge (ADC): 8

Colour	T + Toff (ns)
●	TL − 05
●	05 − 10
●	10 − 15
●	15 − 20
●	20 − 25
●	25 − 30
●	30 − TU

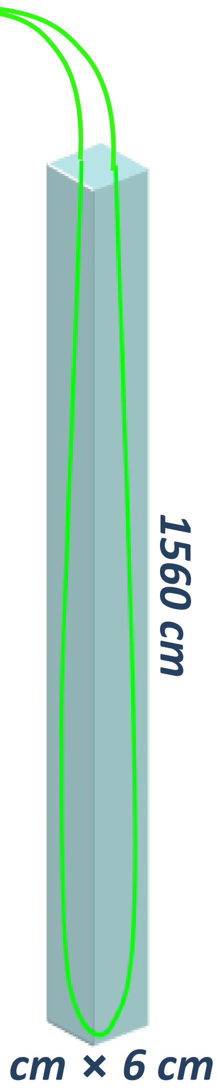
Ql = 0.00 pe
Qu = 64.00 pe
Tl = −10.00 ns
Tu = 45.00 ns
Toff = 17.50 ns
1 pe = o

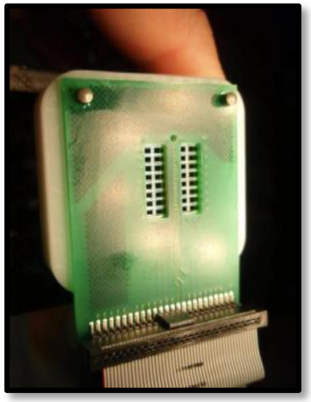
NOνA detectors



Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs

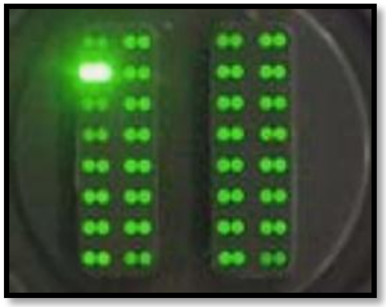
A NOνA cell





32-pixel APD

Fiber pairs from 32 cells



Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter

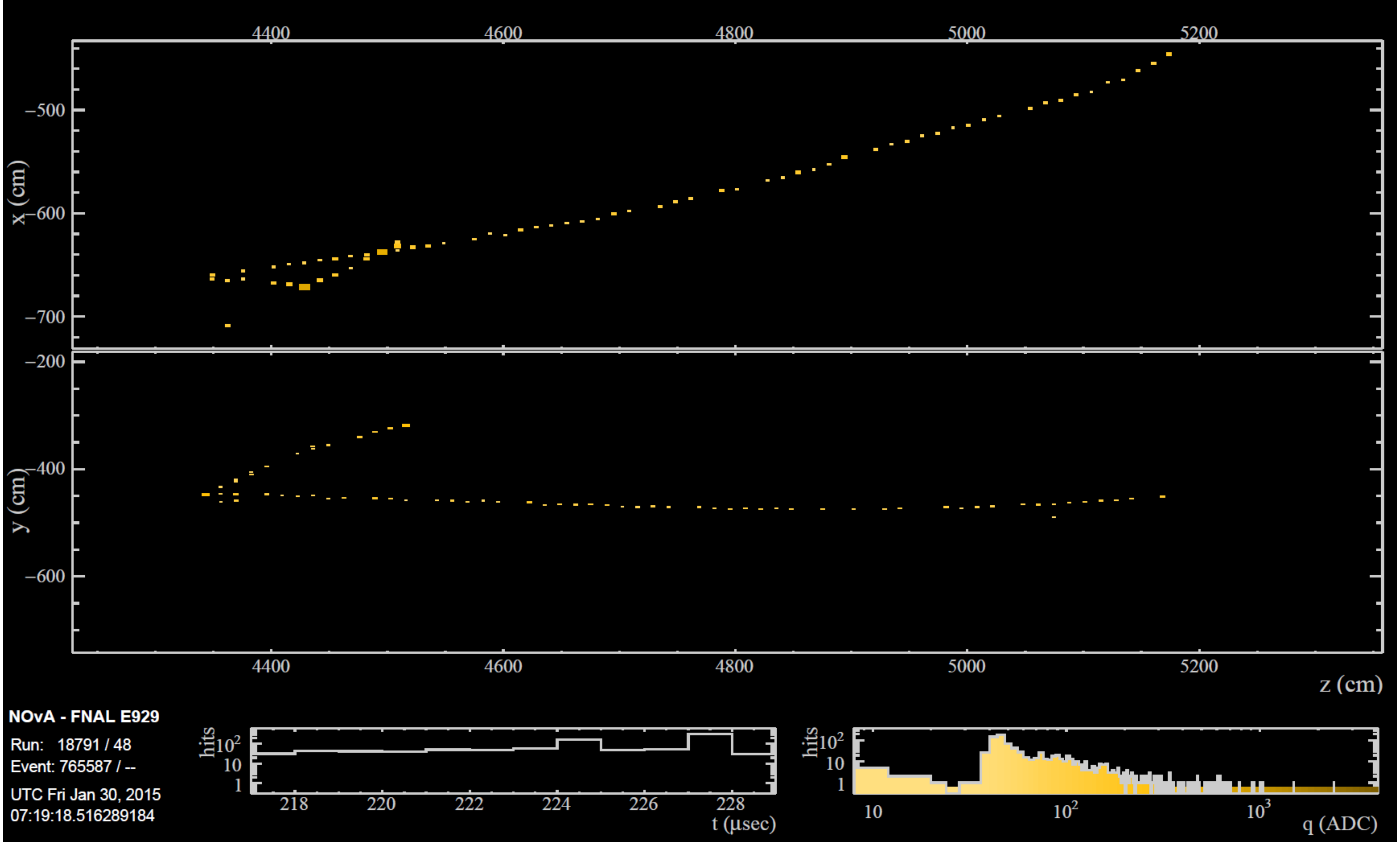
→ *344,000 channels*

Near detector:

0.3-kton version of the same

→ *20,000 channels*

Far Detector selected ν_μ CC candidate

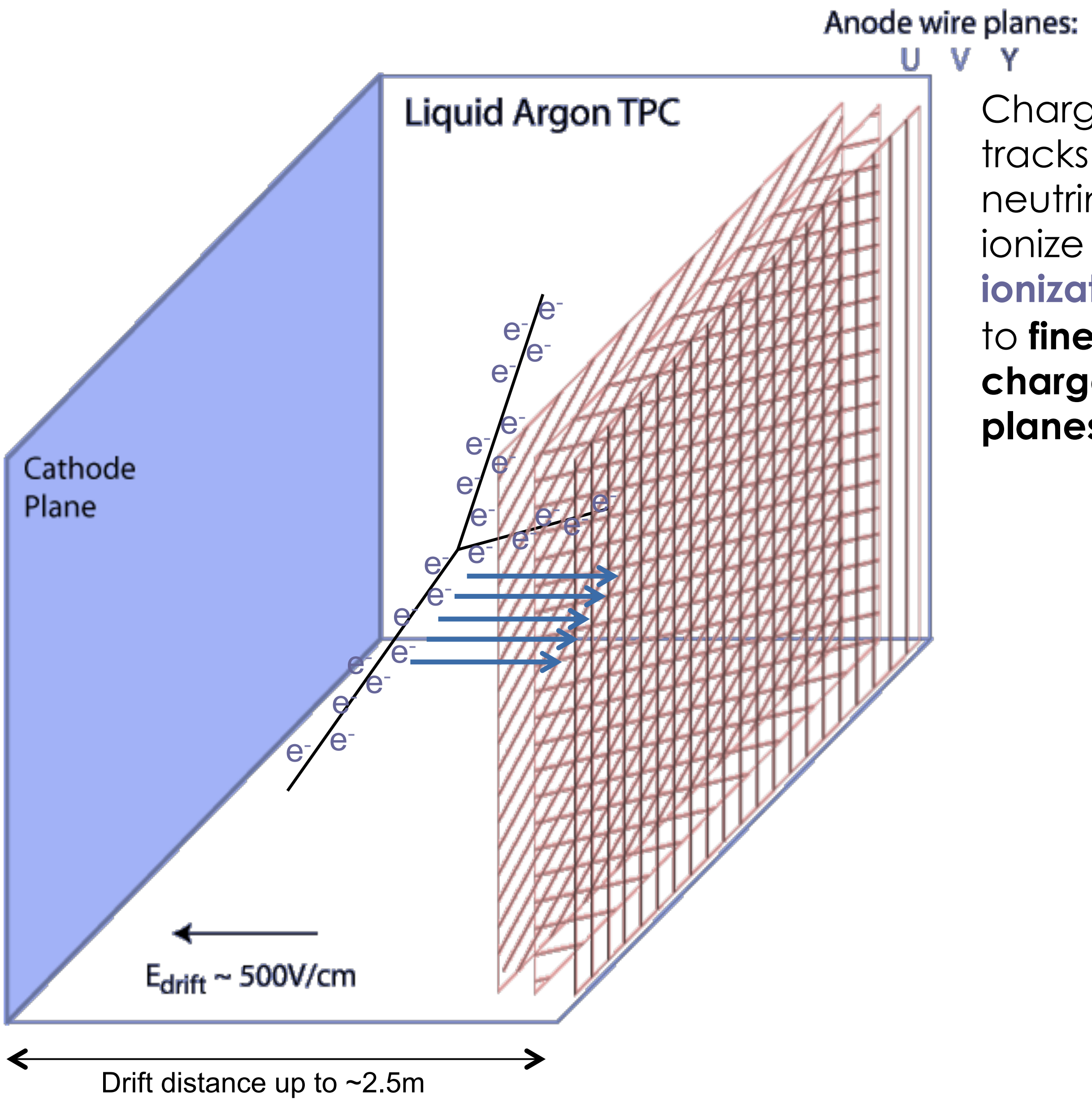


NOvA - FNAL E929

Run: 18791 / 48
Event: 765587 / --

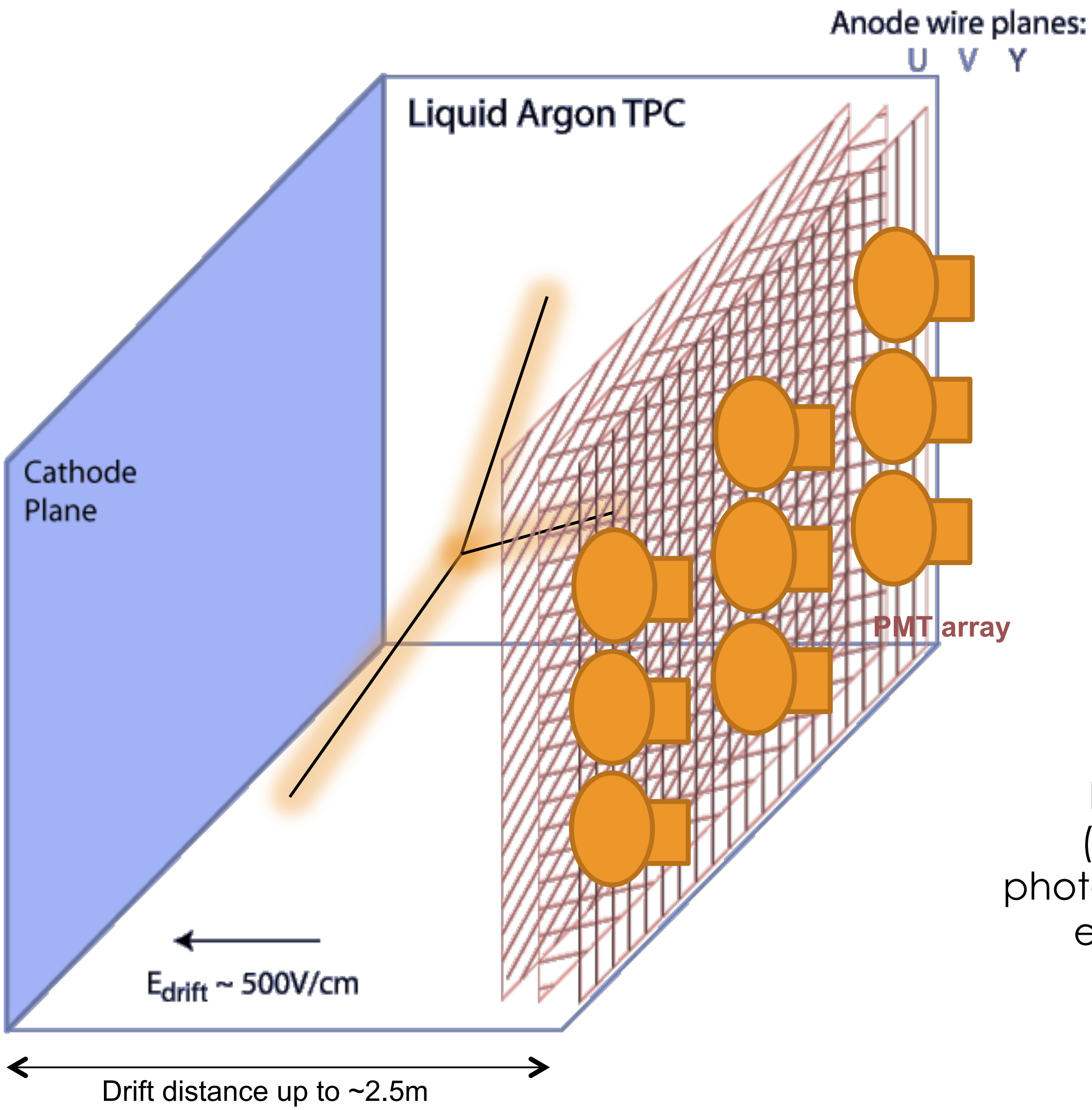
UTC Fri Jan 30, 2015
07:19:18.516289184

LArTPC working principle



Charged particle tracks produced in neutrino interactions ionize argon atoms; **ionization charge** drifts to **finely segmented charge collection planes** over ~1-few ms.

LArTPC working principle

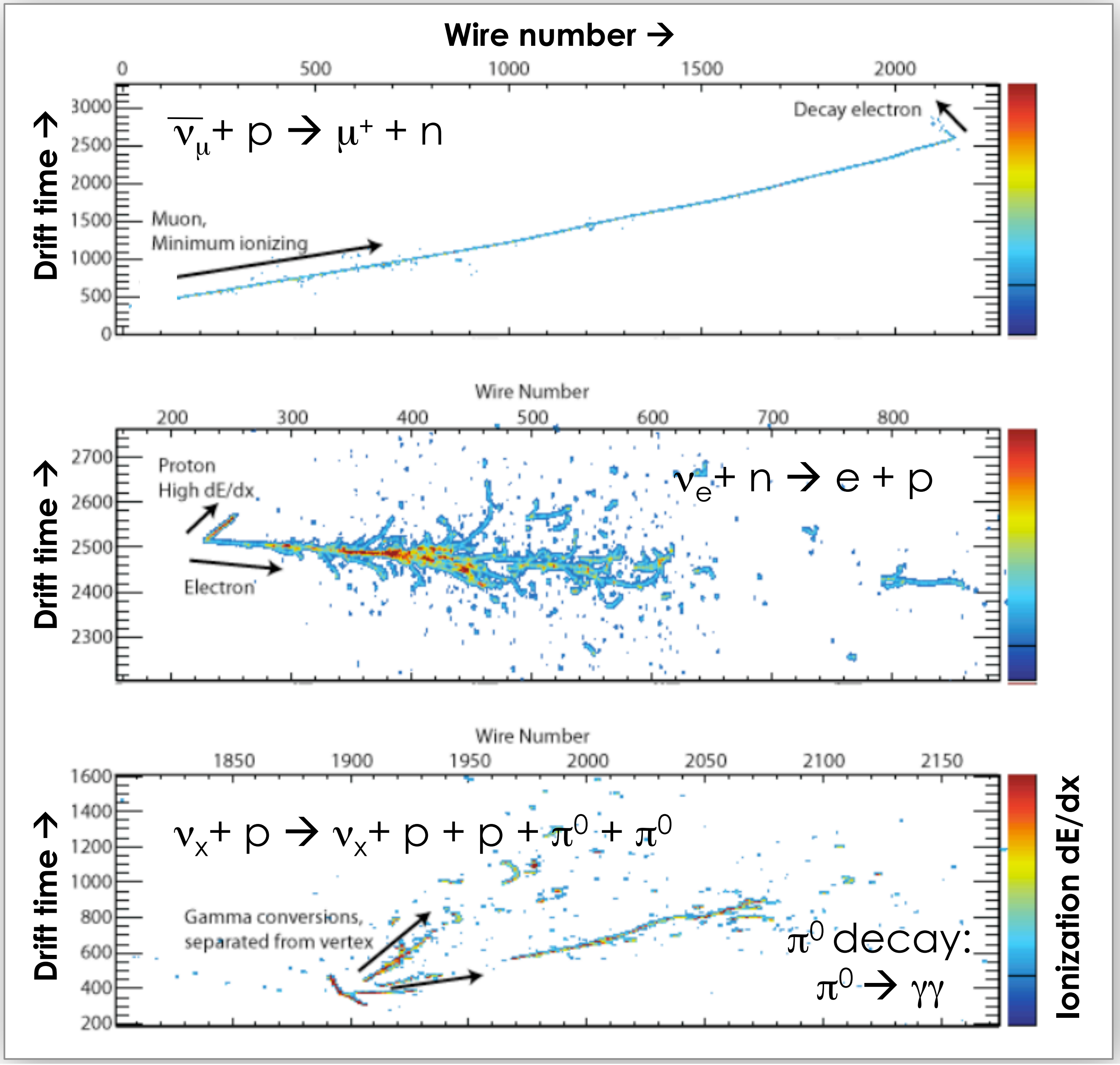


Prompt **scintillation light** (~few ns) is detected by photo-sensitive detectors for event t_0, drift coordinate determination, and triggering

LArTPC exquisite event topology

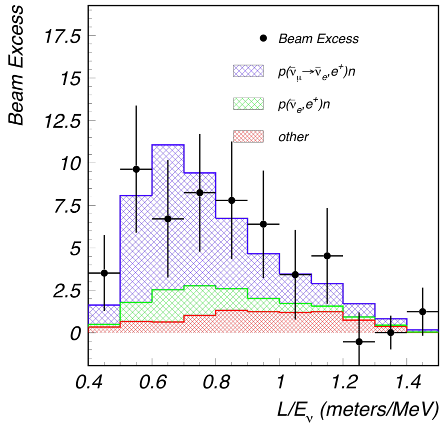
Bubble chamber-quality data, with calorimetric information (ionization dE/dx)

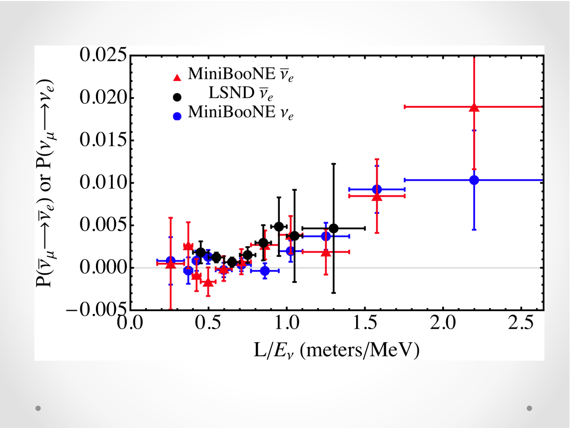
High event selection efficiency and excellent background rejection!

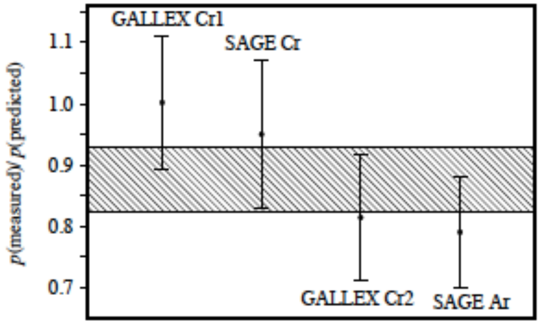


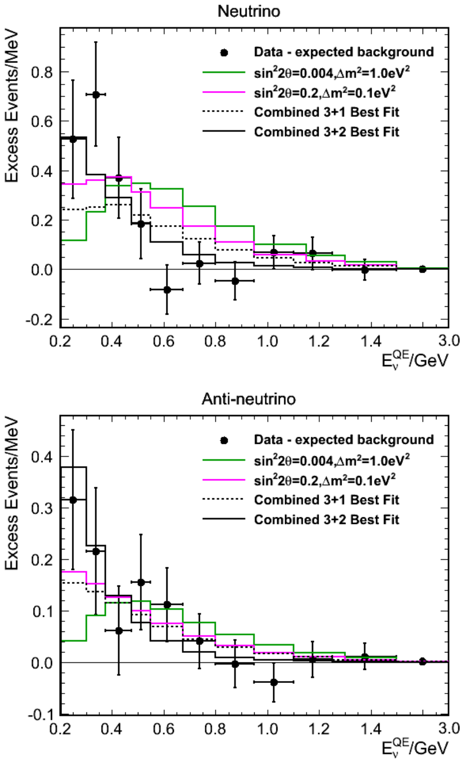
Example simulated neutrino events (E_ν ~ 0.5-1 GeV)

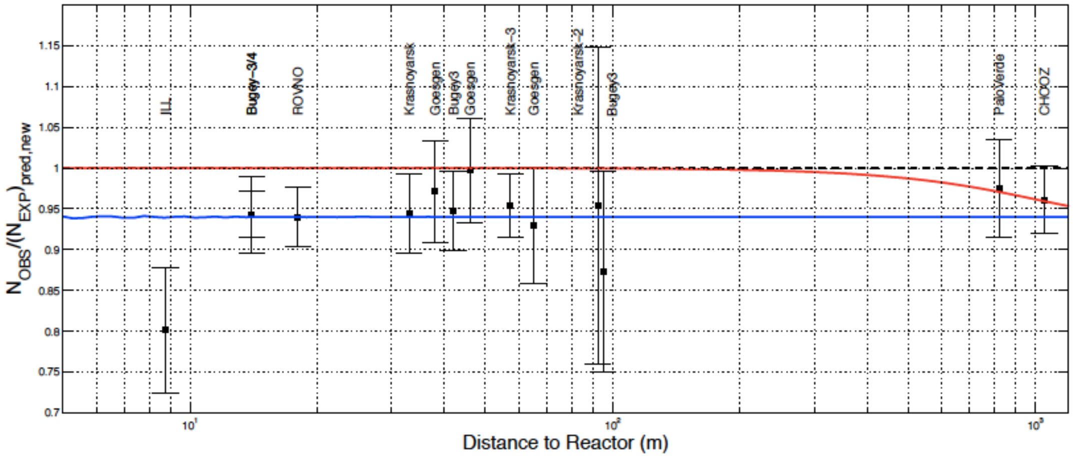
Short-Baseline Neutrino Anomalies







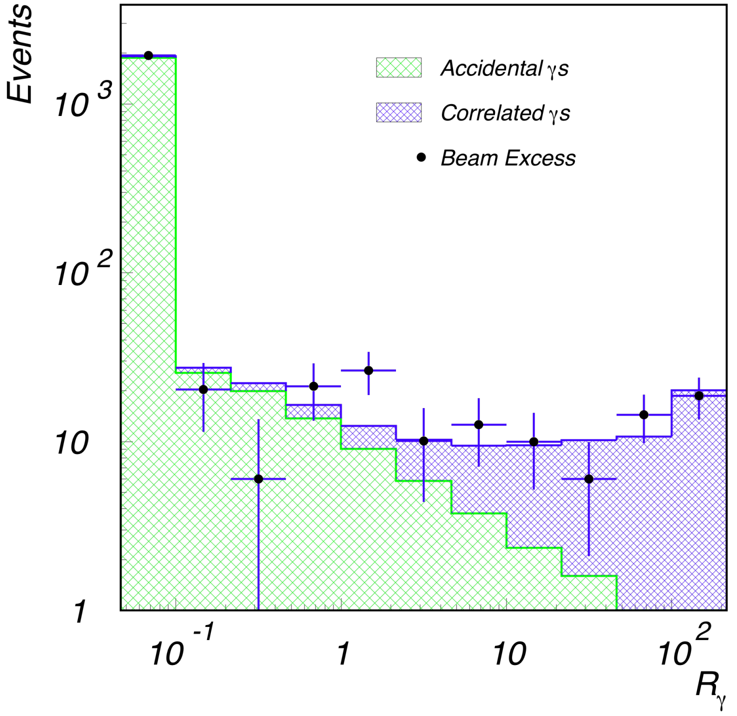


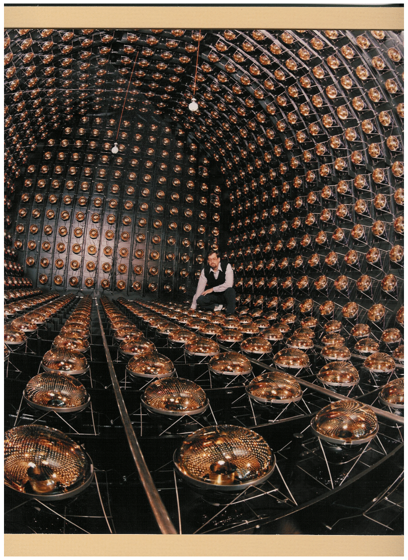


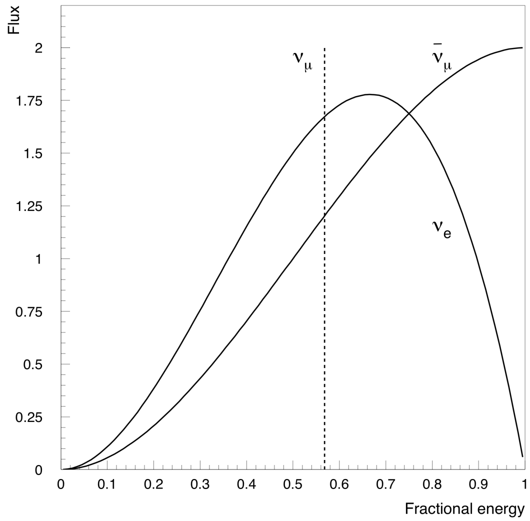
LSND Event Excess

A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)

Correlated γ = 117.9+-22.4 events
Excess = 87.9+-22.4+-6.0 events





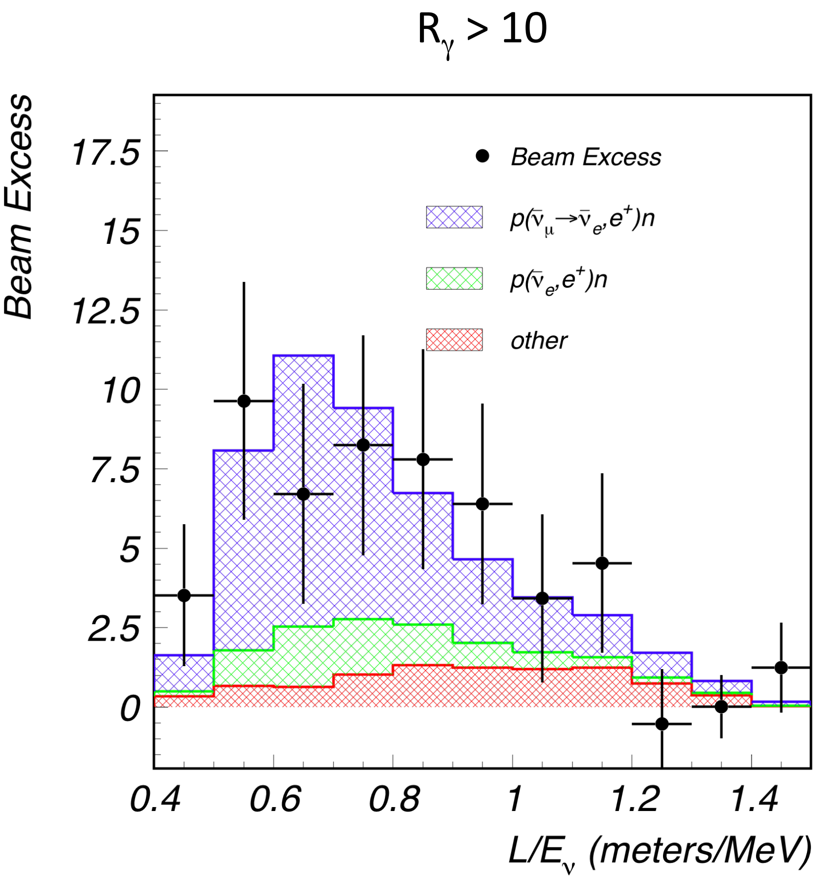


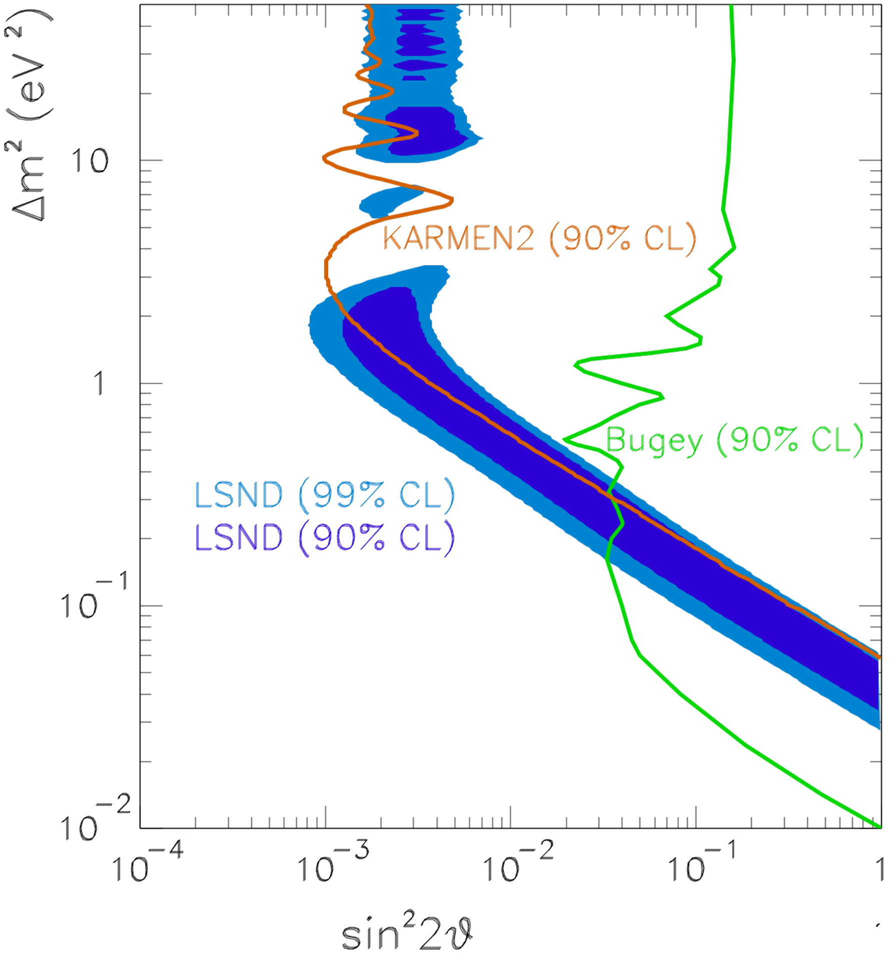
$\bar{\nu}_e$ p -> e^+ n, n p -> d γ(2.2 MeV)

LSND collected 28,896 C on target and observed a 3.8 σ excess of events consistent with $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillations, corresponding to P_{osc} = (0.264+-0.067+-0.045)%

LSND Event Excesses

A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)

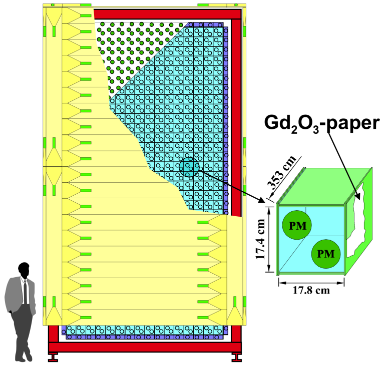




Joint LSND/KARMEN Analysis

E. D. Church, K. Eitel, G. B. Mills, and M. Steidl, Phys. Rev. D66, 013001, (2002)

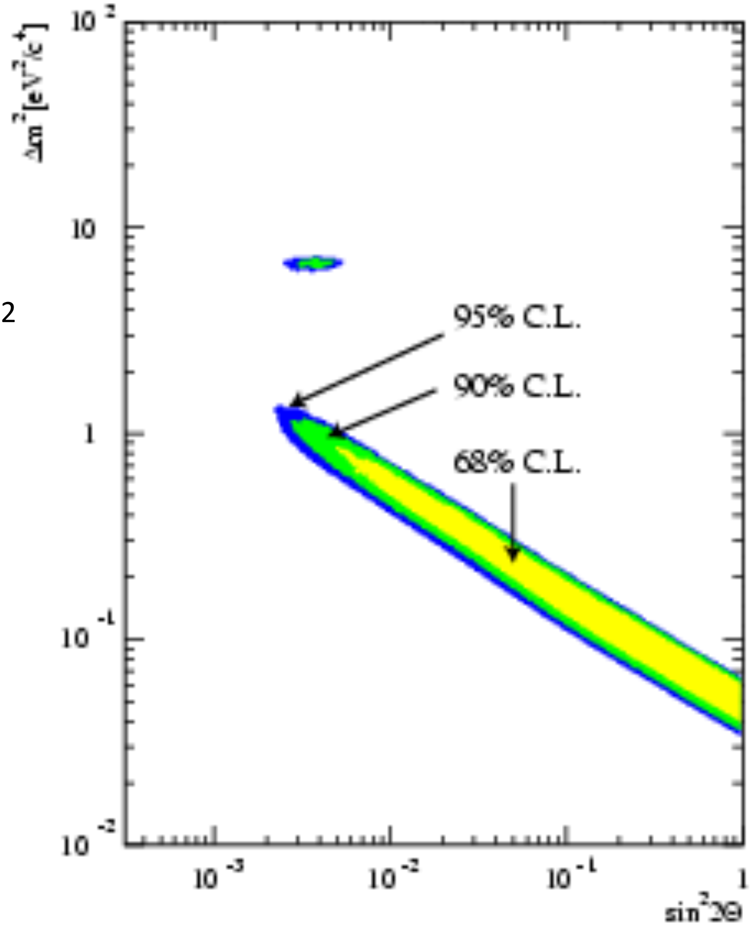
KARMEN detector

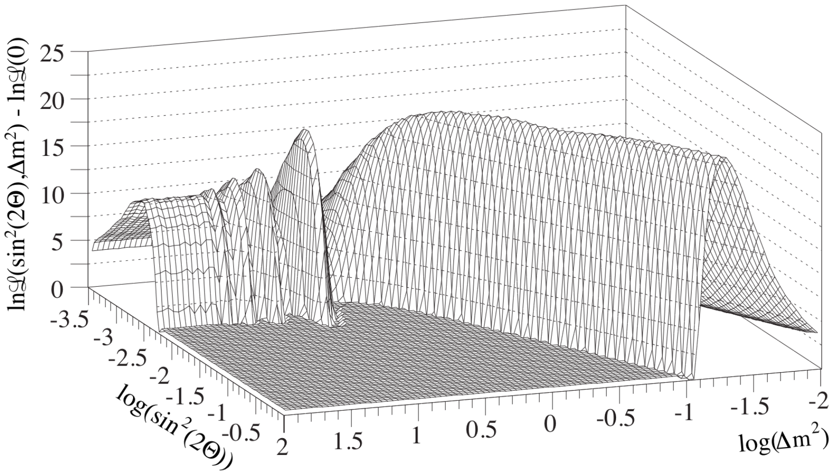


96% active volume of ^{12}C and p

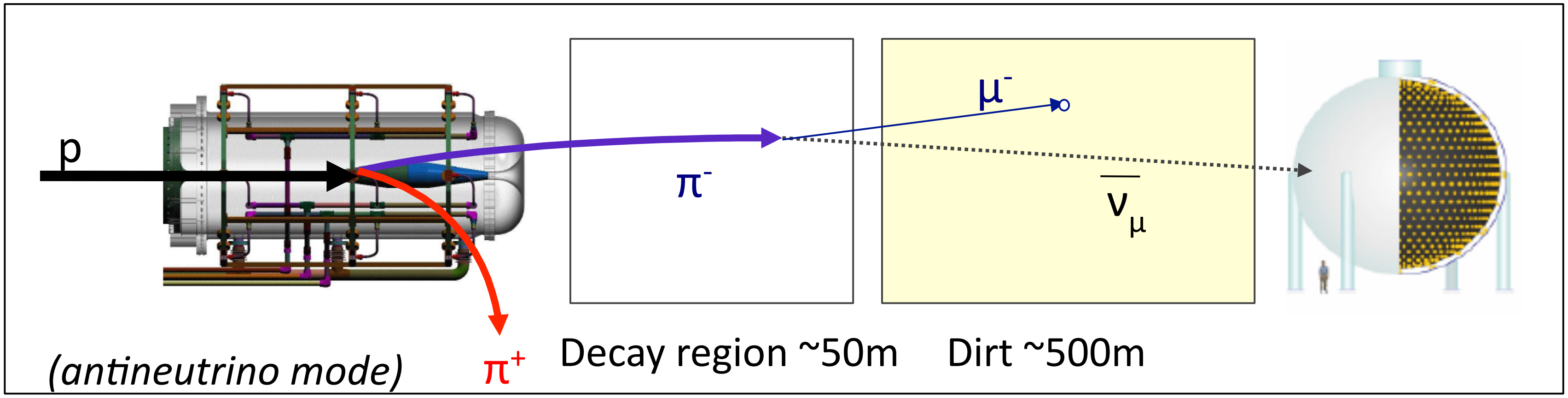
$E \quad \frac{11.5\%}{\sqrt{E[\mathrm{MeV}]}} \qquad t_{ISIS} \quad 2ns$

KARMEN observed no event excess; however, a joint analysis of KARMEN (17.7m) & LSND (30m) reveals a favored region of $\Delta m^2 < 1$ eV^2



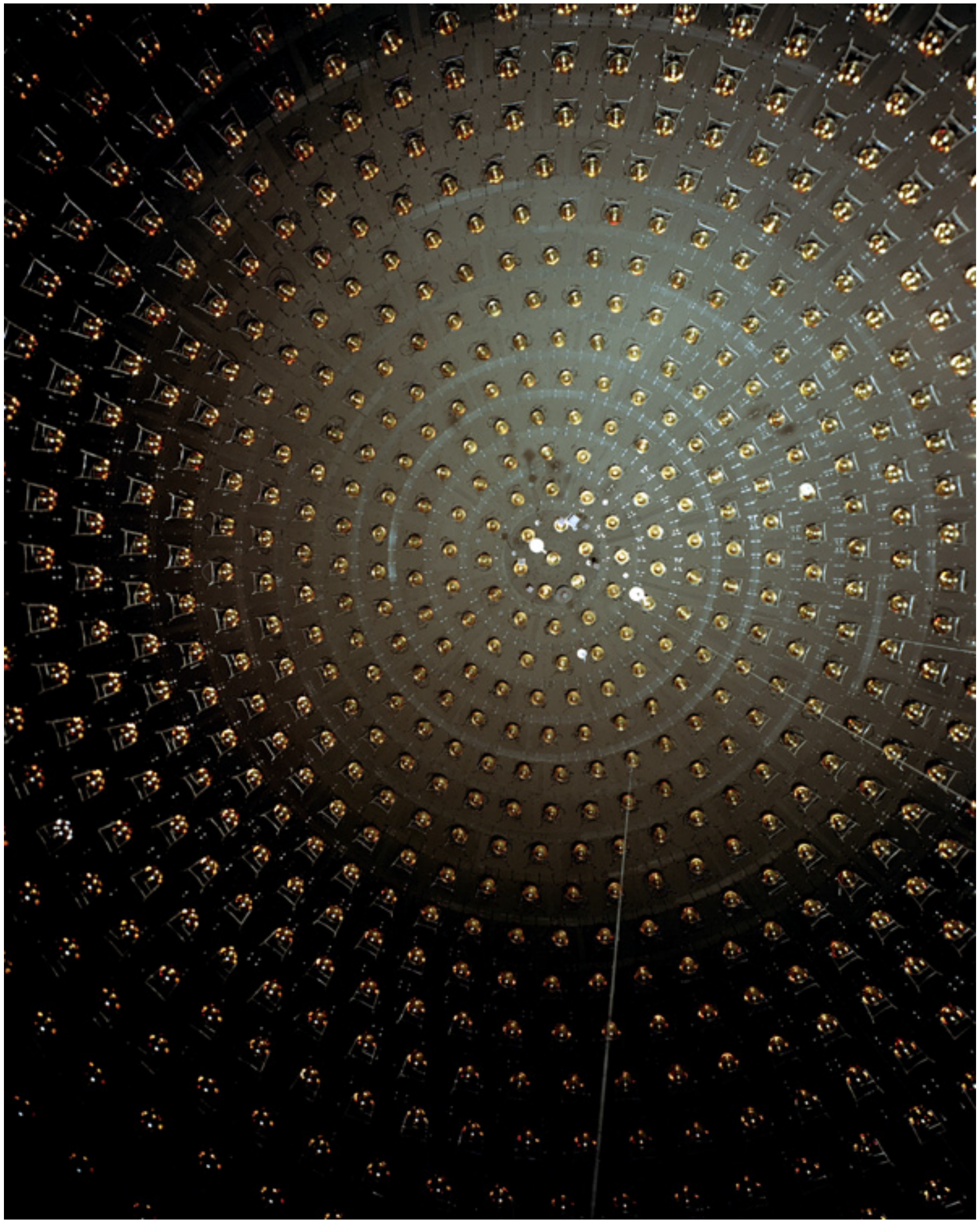


MiniBooNE Experiment



- Similar L/E as LSND for $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ & ν_μ -> ν_e oscillations
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

MiniBooNE Detector Tank



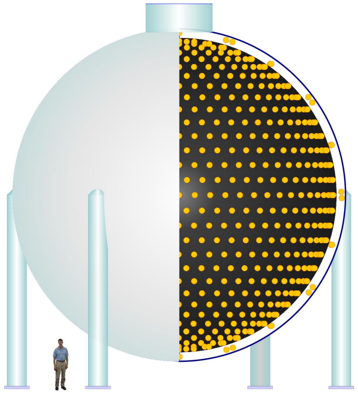
800 tons of mineral oil with ~0.031 g/l of b-PBD

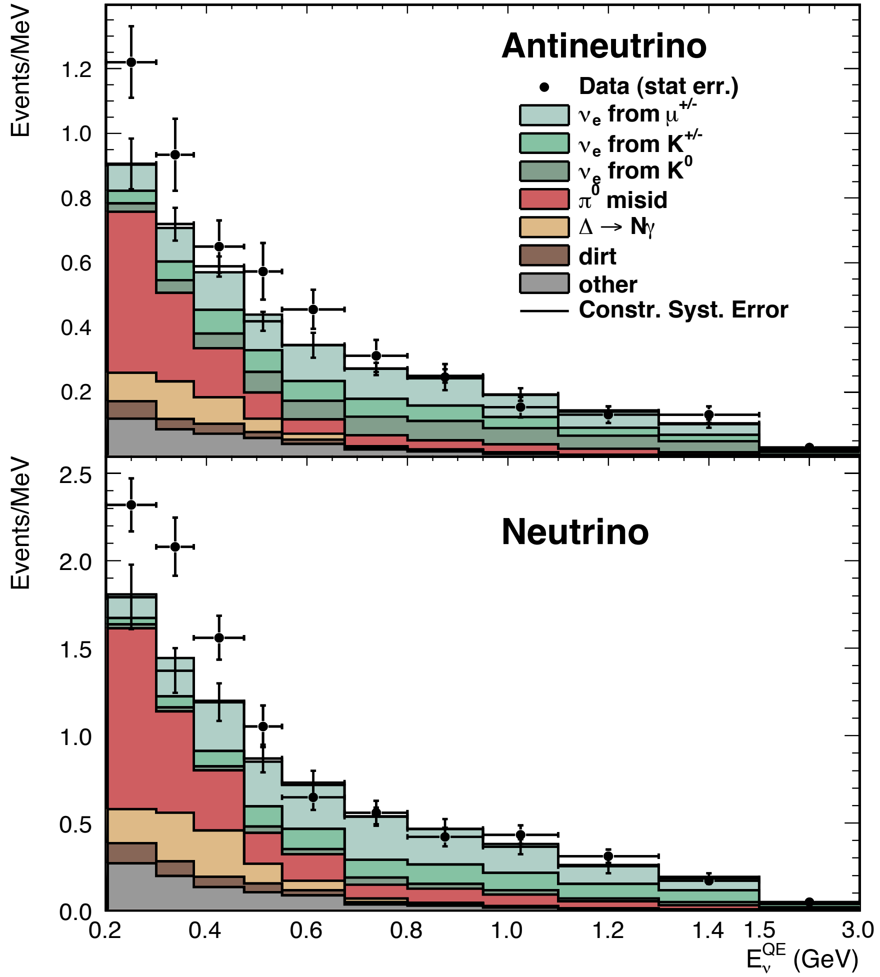
10%-25% Photocathode coverage with 8” Hamamatsu Phototubes: R1408, R5912

Charge Resolution:
1.4 PE, 0.5 PE
Time Resolution:
1.7 ns, 1.1ns

MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)





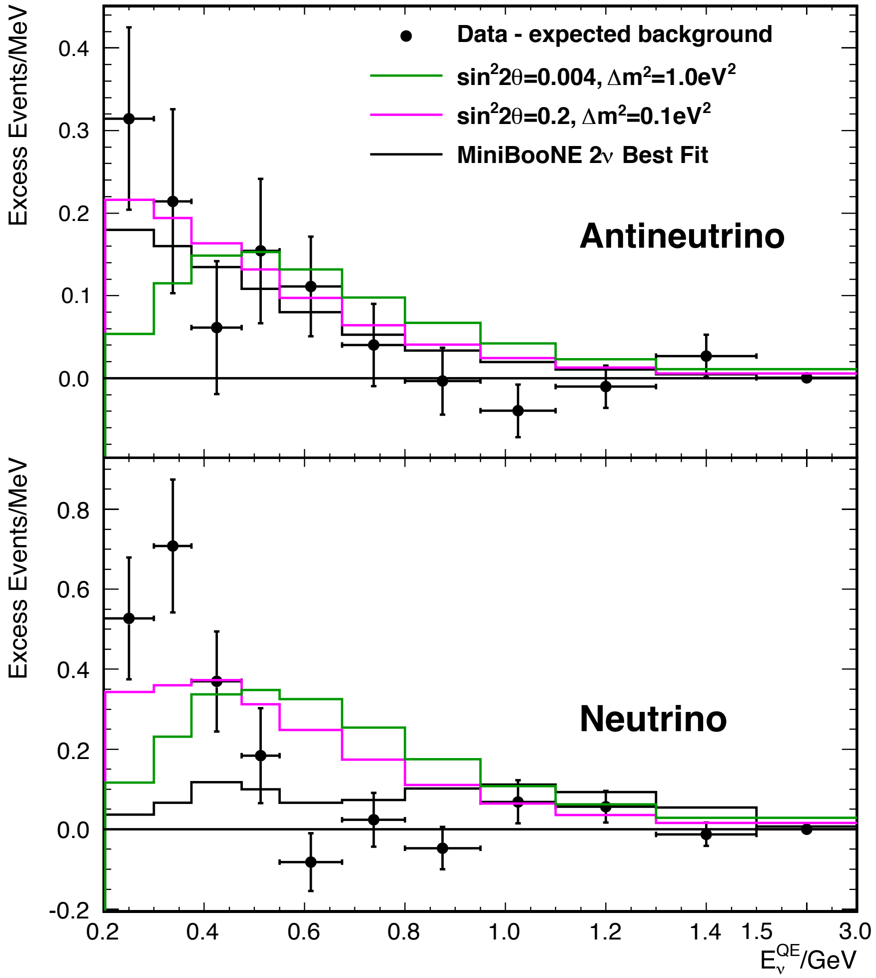
11.27×10^{20} POT

6.46×10^{20} POT

MiniBooNE observes an excess of events consistent with $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations

MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)



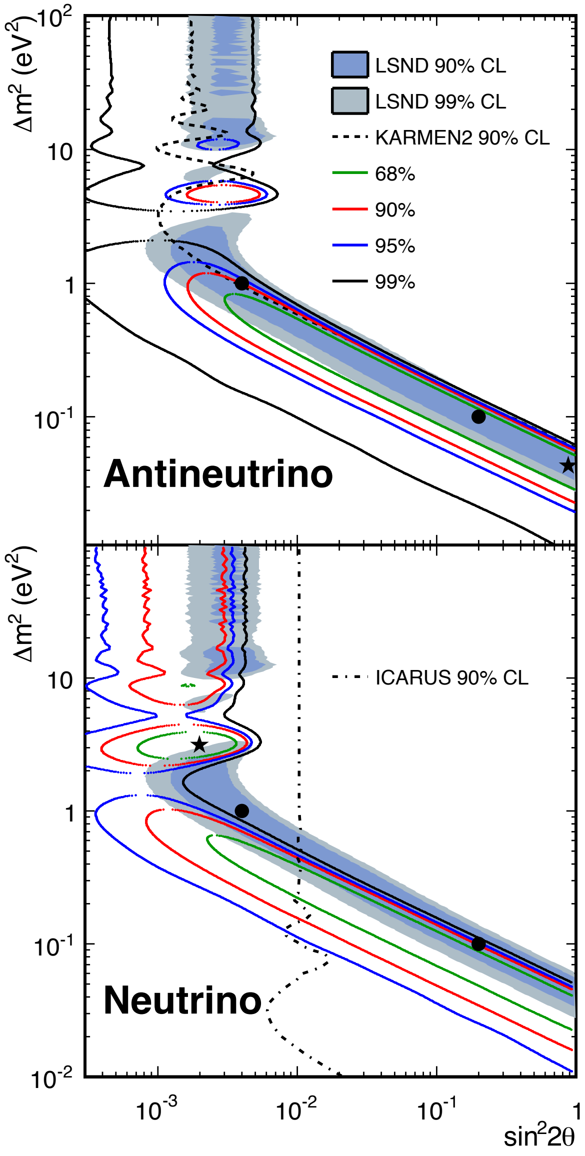
Antineutrino Event Excess from 200-1250 MeV = 78.4+-20.0+-20.3 (2.8σ)

Neutrino Event Excess from 200-1250 MeV = 162.0+-28.1+-38.7 (3.4σ)

Combined Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)

MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)



Antineutrino

$P_{bf} = 66\%$, $P_{null} = 5.4\%$

P_{null} relative to $P_{bf} = 0.5\%$

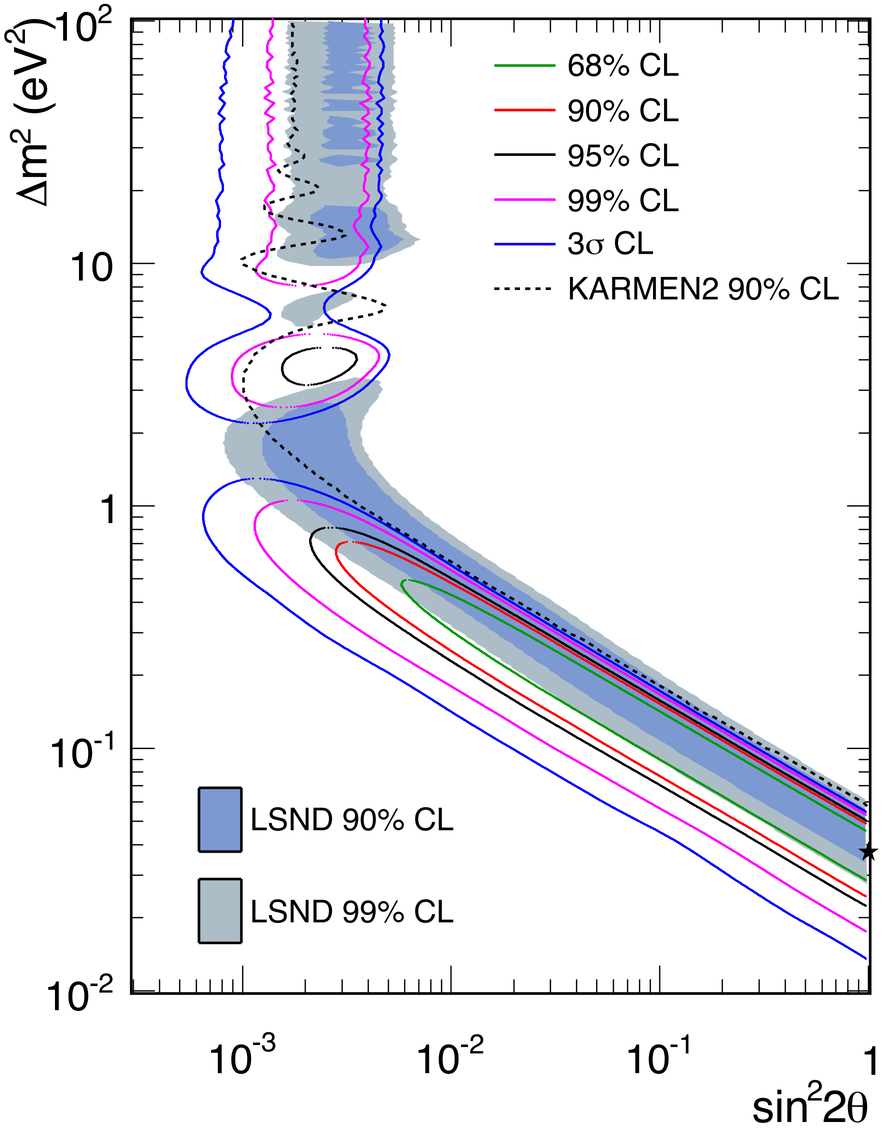
Neutrino

$P_{bf} = 6.1\%$, $P_{null} = 0.5\%$

P_{null} relative to $P_{bf} = 2.0\%$

Caveats Associated with MiniBooNE Combined Neutrino + Antineutrino 2ν Fit

arXiv:1207.4809



P_{bf} = 6.7%, P_{null} = 0.1%

P_{null} relative to P_{bf} = 0.03%

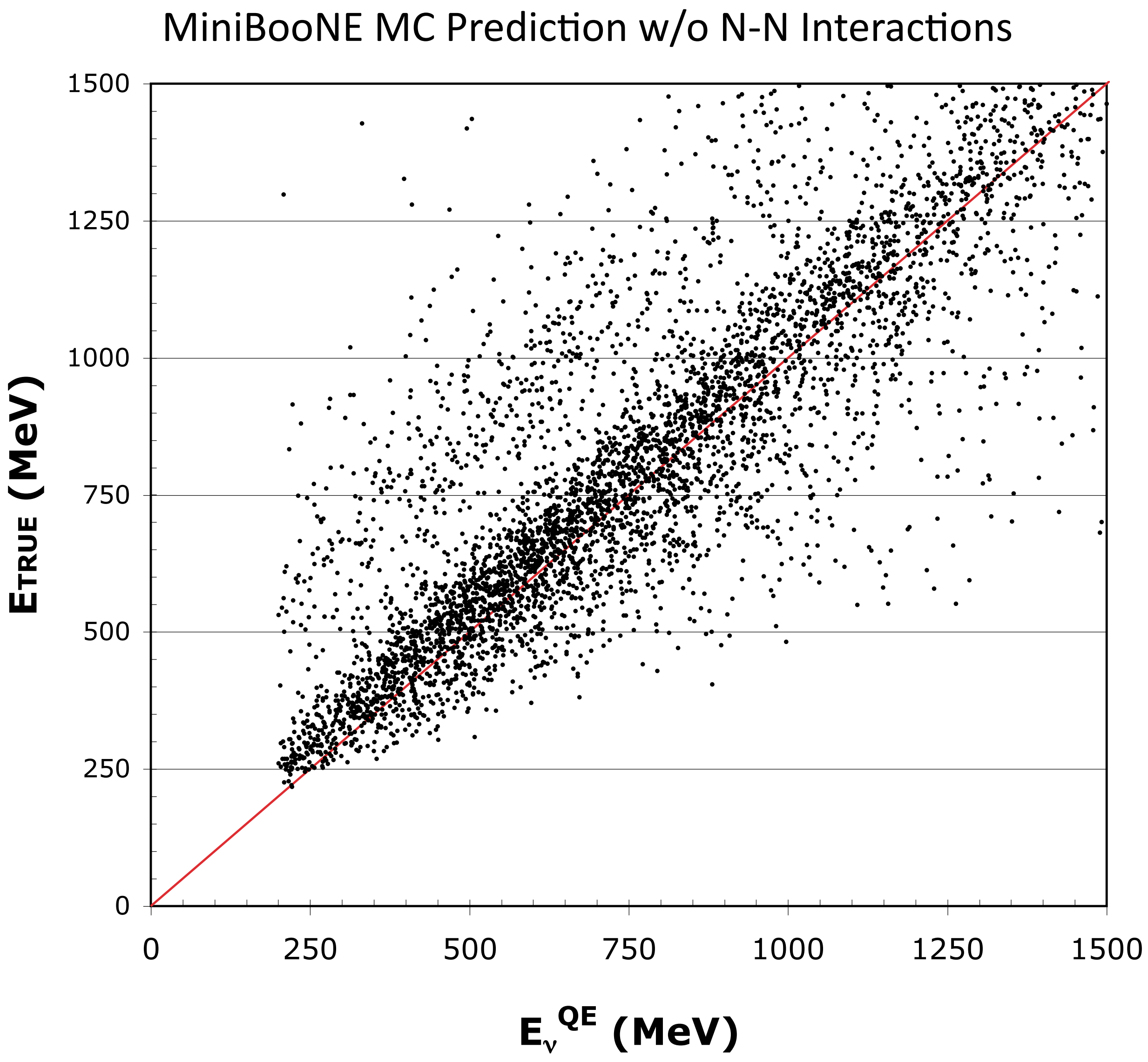
Caveats:

ν energy distortions can affect the oscillation fits:

- 2-body N-N interactions
- ν_e & ν_μ disappearance
- 3+N models with $\cancel{C}$P

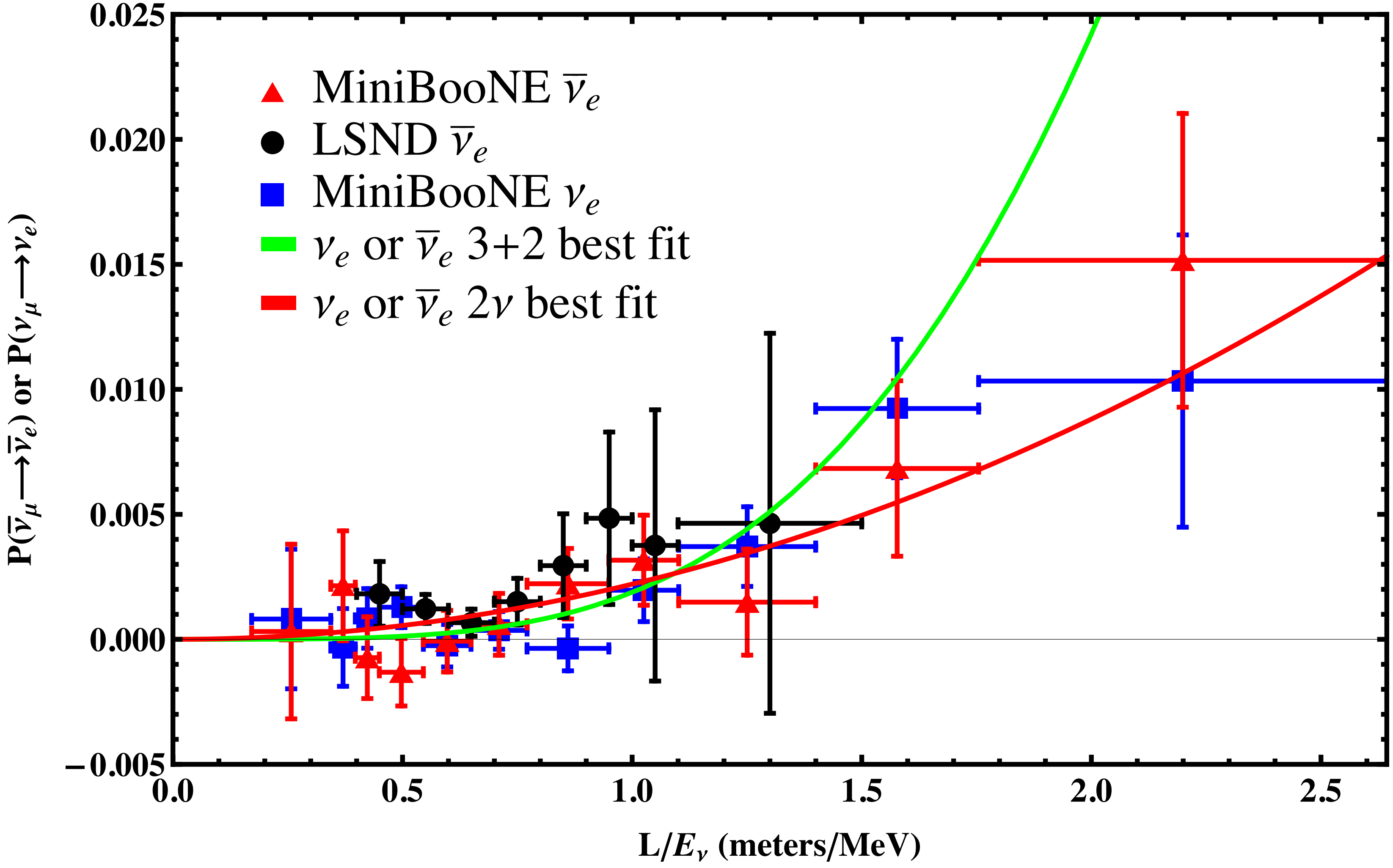
$\langle E_{true} \rangle > \langle E_{recon} \rangle$

(This Causes the Oscillation Probability to be Overestimated)



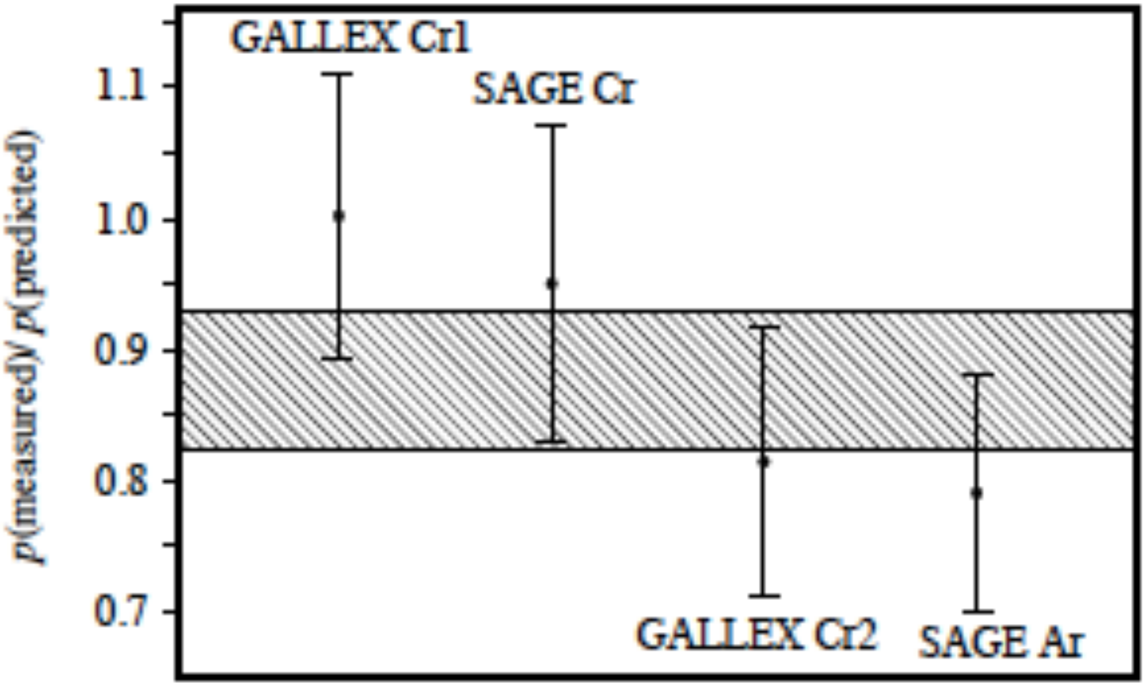
MiniBooNE L/E Distributions

arXiv:1207.4809



Gallium Anomaly

SAGE, Phys. Rev. C 73 (2006) 045805



R=0.86+-0.05

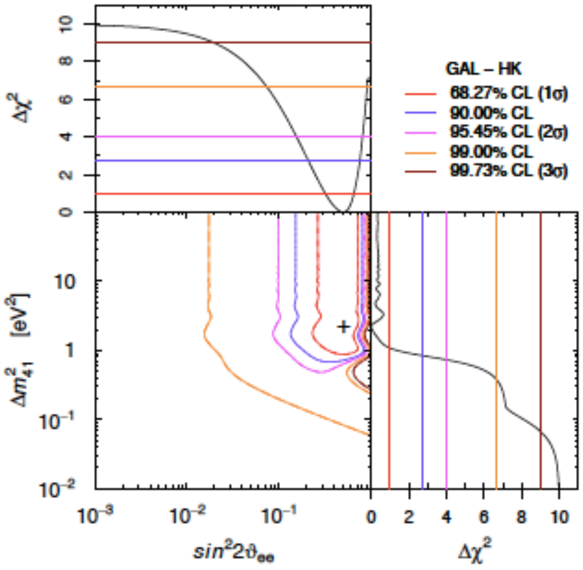
GALLEX & SAGE observe fewer events than expected from their calibration measurements, consistent with ν_e disappearance to sterile neutrinos

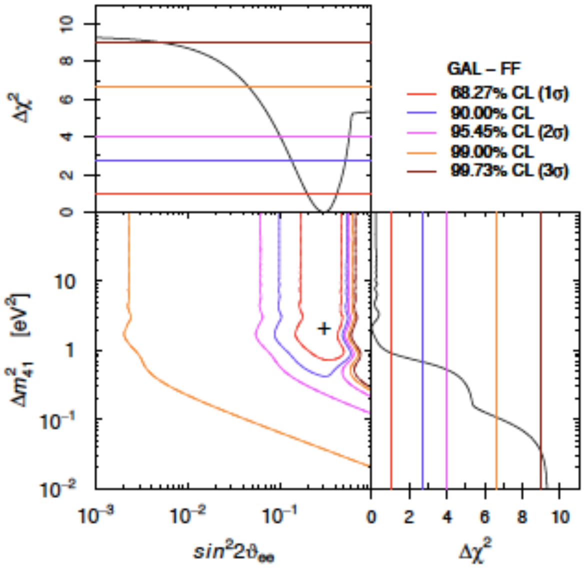
Gallium Anomaly

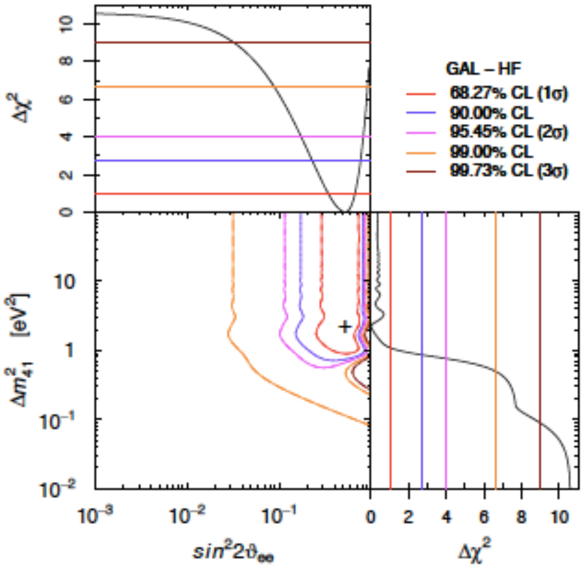
Giunti et al.; arXiv:1210.5715

TABLE II. Ratios of measured and expected ^{71}Ge event rates in the four radioactive source experiments. G1 and G2 denote the two GALLEX experiments with ^{51}Cr sources [30–32], S1 denotes the SAGE experiment with a ^{51}Cr source, and S2 denotes the SAGE experiment with a ^{37}Ar source [33–36]. AVE denotes the weighted average.

	G1	G2	S1	S2	AVE
R_{B}	$0.95^{+0.11}_{-0.11}$	$0.81^{+0.10}_{-0.11}$	$0.95^{+0.12}_{-0.12}$	$0.79^{+0.08}_{-0.08}$	$0.86^{+0.05}_{-0.05}$
R_{HK}	$0.85^{+0.12}_{-0.12}$	$0.71^{+0.11}_{-0.11}$	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.09}_{-0.09}$	$0.77^{+0.08}_{-0.08}$
R_{FF}	$0.93^{+0.11}_{-0.11}$	$0.79^{+0.10}_{-0.11}$	$0.93^{+0.11}_{-0.12}$	$0.77^{+0.09}_{-0.07}$	$0.84^{+0.05}_{-0.05}$
R_{HF}	$0.83^{+0.13}_{-0.11}$	$0.71^{+0.11}_{-0.11}$	$0.83^{+0.13}_{-0.12}$	$0.69^{+0.10}_{-0.09}$	$0.75^{+0.09}_{-0.07}$

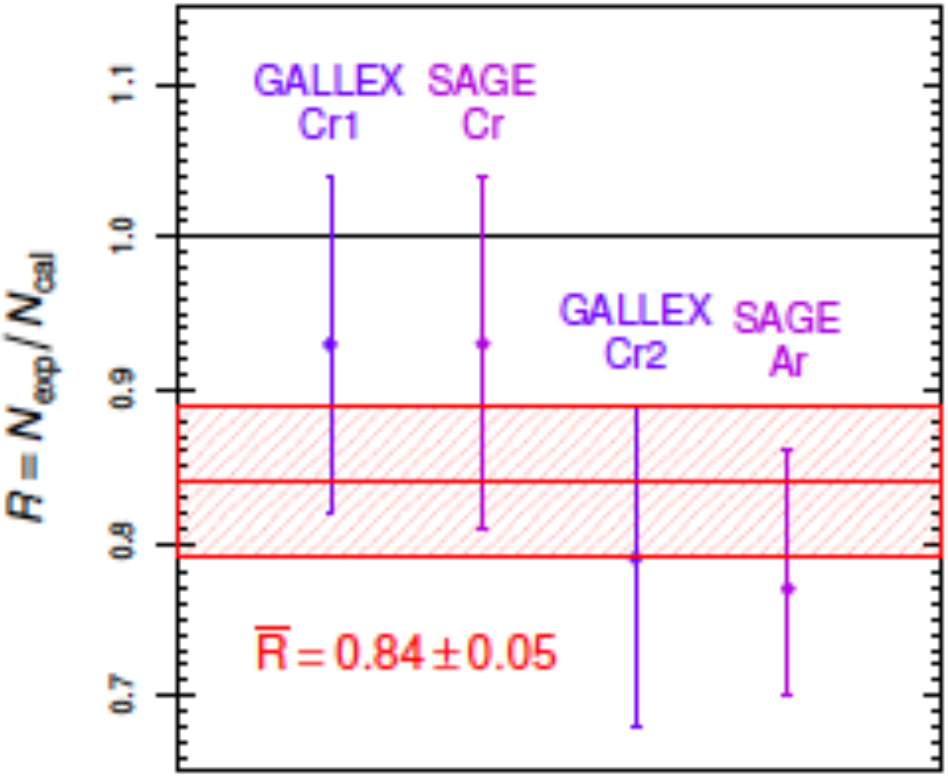






Gallium Anomaly

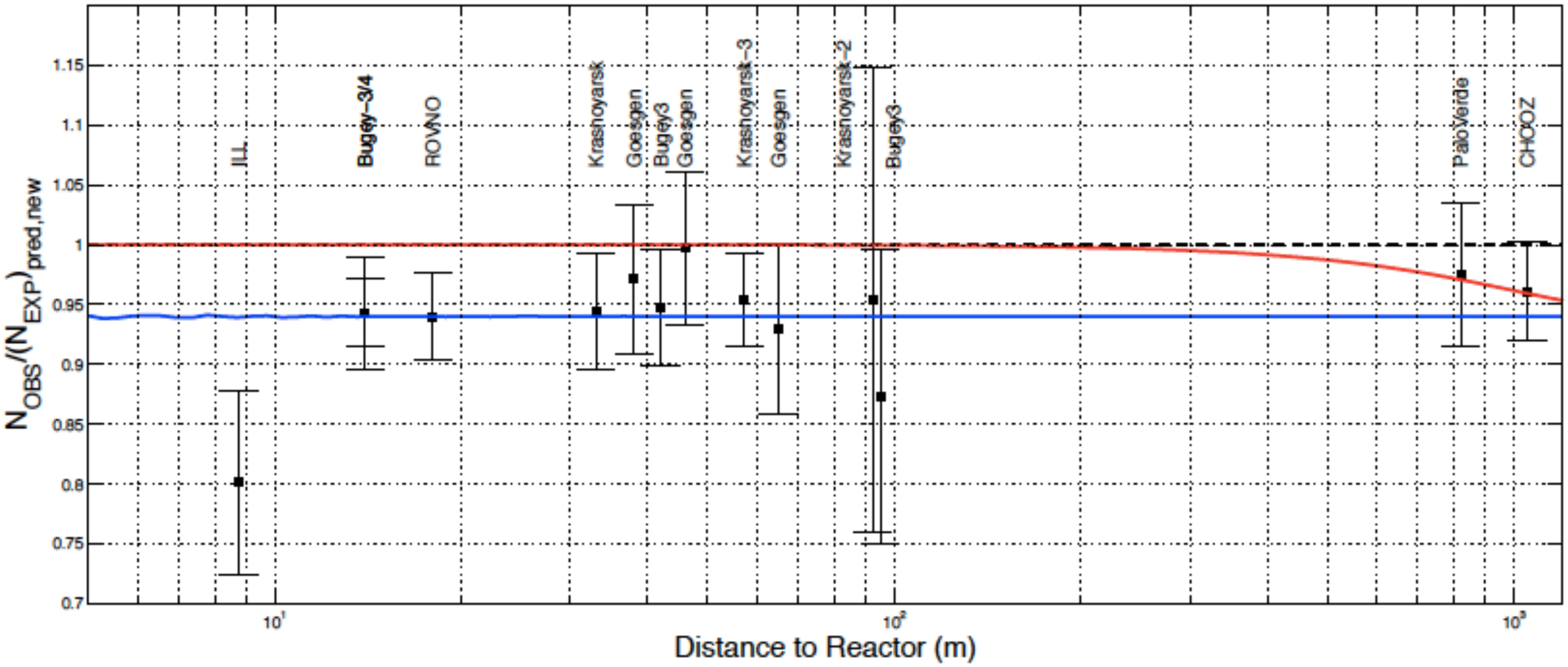
S. Gariazzo, C. Giunti, M. Laveder, Y. F. Li, & E. M. Zavanin, arXiv:1507.08204



GALLEX & SAGE observe fewer events than expected from their calibration measurements, consistent with ν_e disappearance to sterile neutrinos

Reactor Neutrino Anomaly

G. Mention et al., Phys.Rev.D83:073006,2011

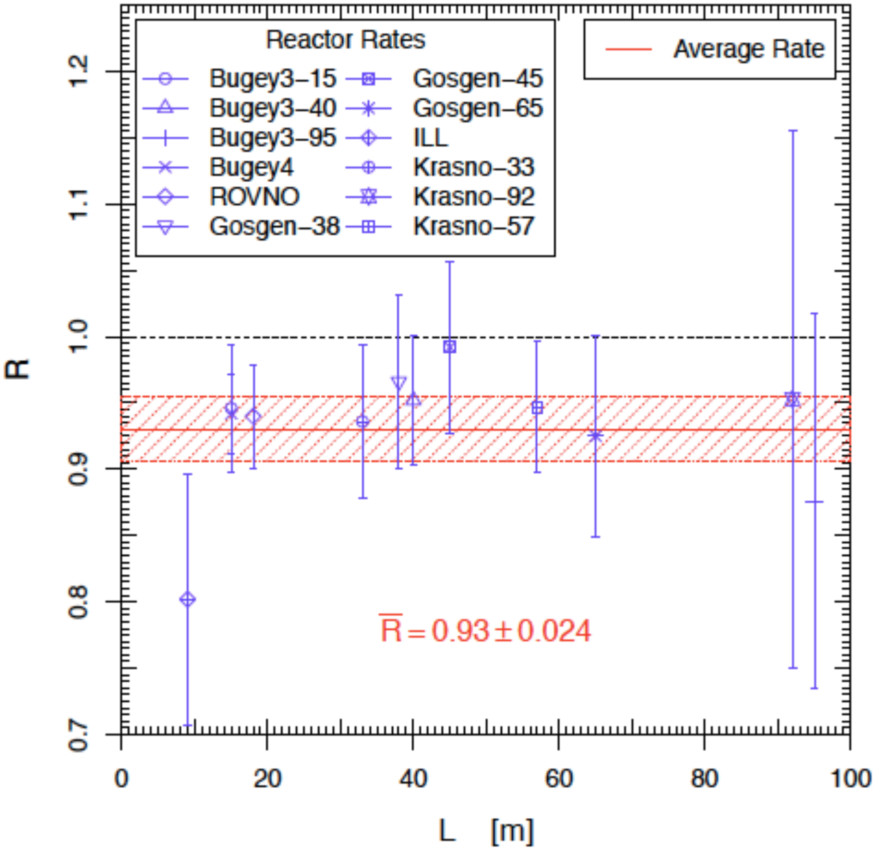


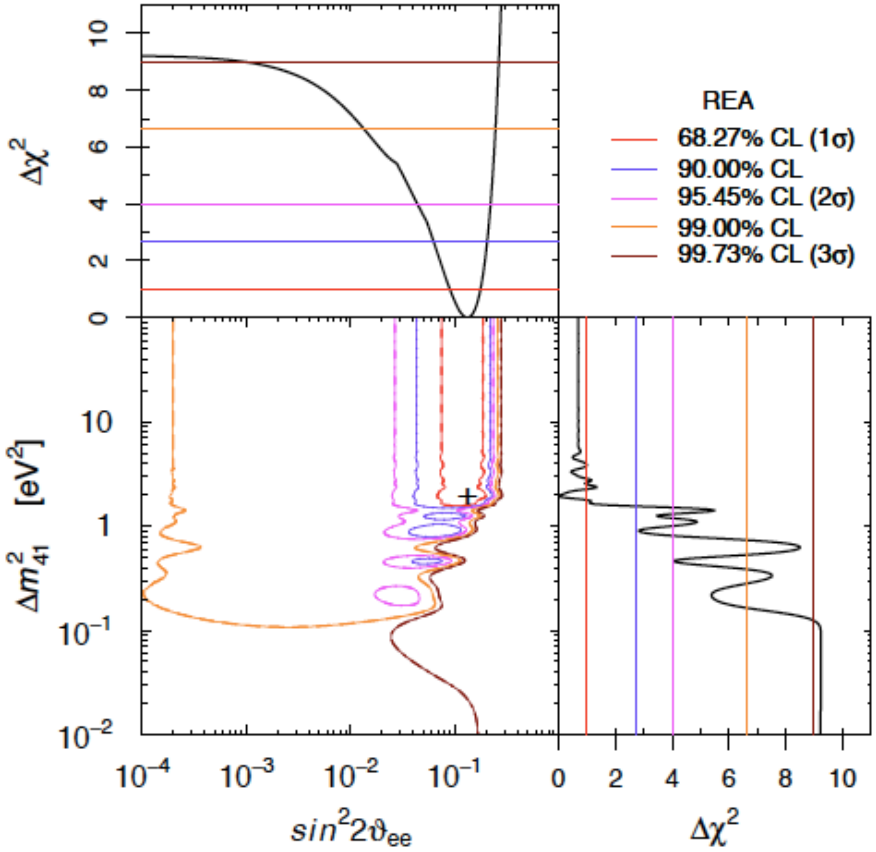
R=0.937+-0.027

Reactor Neutrino experiments observe fewer events than expected, consistent with $\bar{\nu}_e$ disappearance to sterile neutrinos. However, what is systematic uncertainty in neutrino flux?

Reactor Neutrino Anomaly

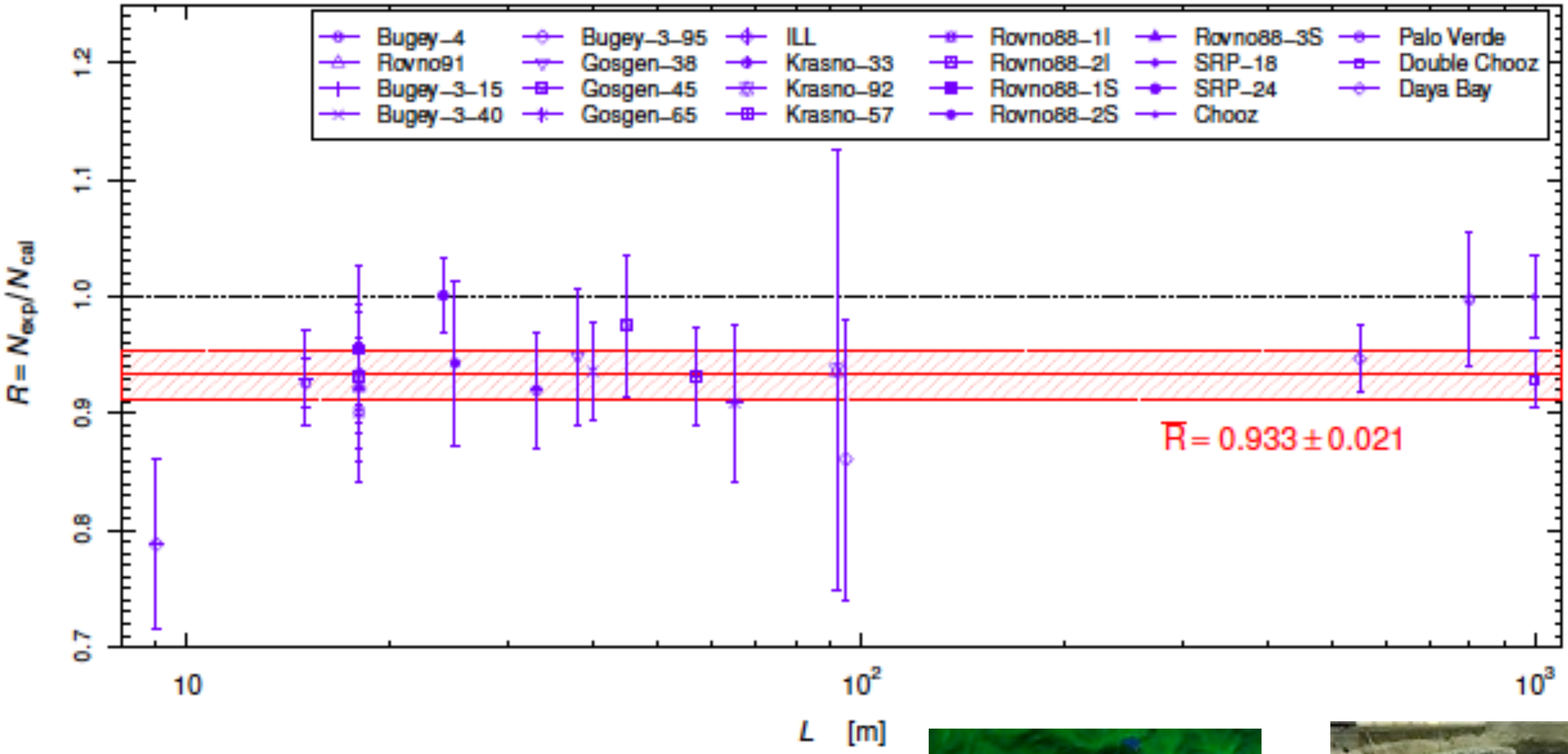
Giunti et al.; arXiv:1210.5715





Reactor Neutrino Anomaly

S. Gariazzo, C. Giunti, M. Laveder, Y. F. Li, & E. M. Zavanin, arXiv:1507.08204



Reactor Neutrino experiments observe fewer events than expected, consistent with $\bar{\nu}_e$ disappearance to sterile neutrinos. However, what is systematic uncertainty in neutrino flux?

Daya Bay Experiment

T2K Long-Baseline Experiment

Super-Kamiokande
(ICRR, Univ. Tokyo)

Neutrino Facility
at J-PARC
(KEK-JAEA, Tokai)

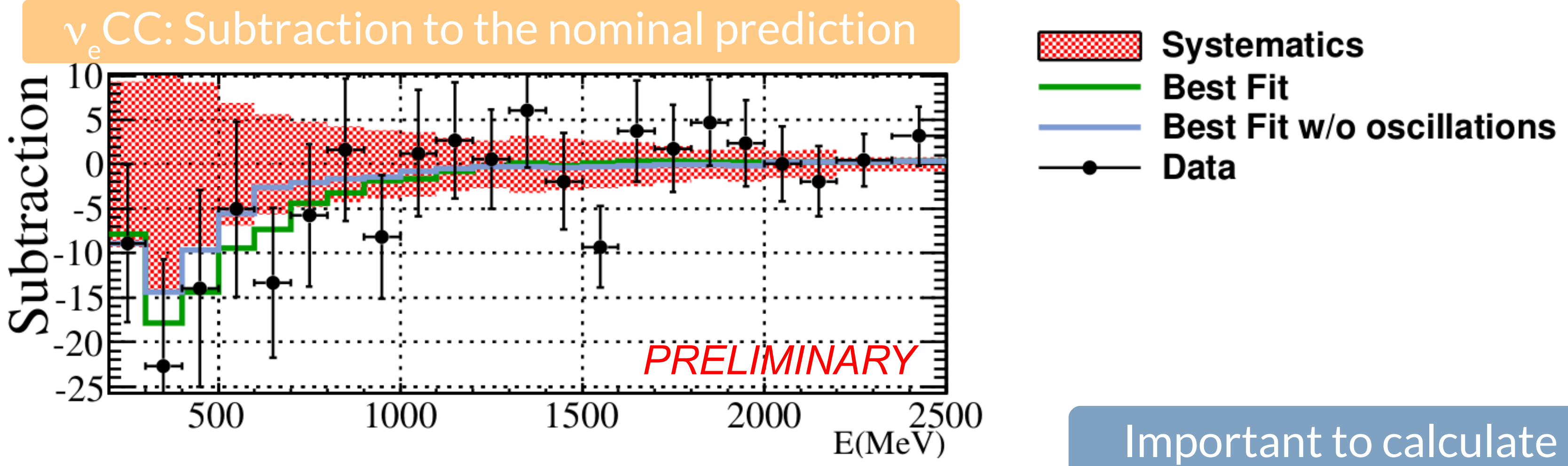
Binned log-likelihood fit

T2K **arXiv:1410.8811**

Binned log-likelihood ratio analysis

$$\chi^2 = \chi^2_{\upsilon_e} + \chi^2_{\gamma} + \mathit{penalty\ term}(\vec{f})$$

Nuisance parameters to model the systematics



ν_eCC: Subtraction to the nominal prediction

Best fit parameters

$$\Delta m^2_{41bf} = 2.14\,\mathrm{eV}^2$$

$$\sin^2(2\theta_{ee})_{bf} = 1.00$$

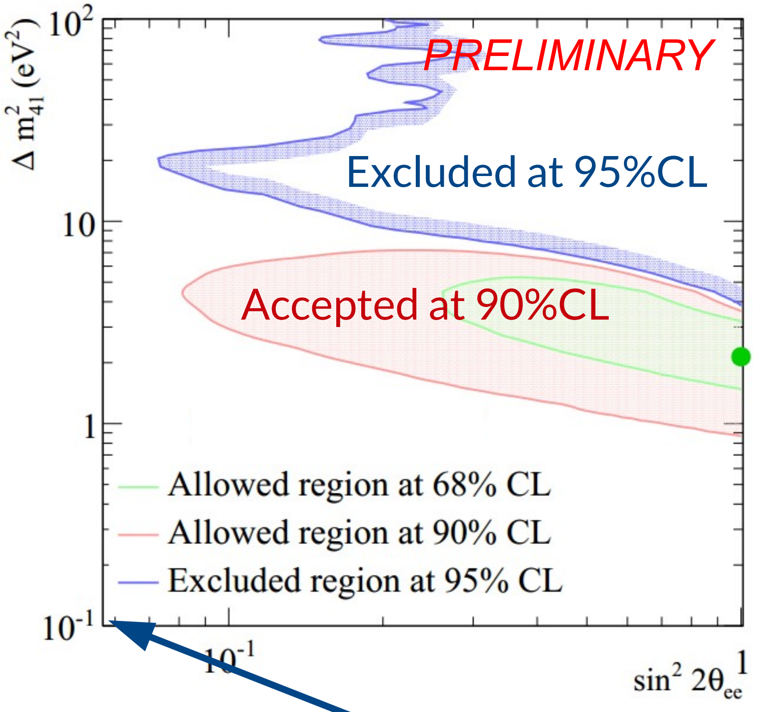
Important to calculate the significance

Confidence intervals

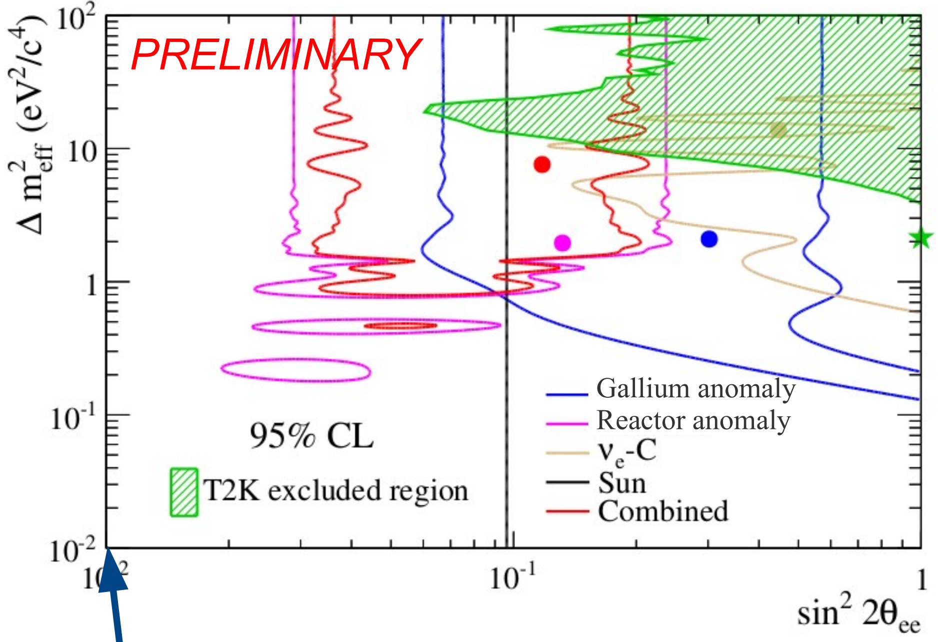
T2K **arXiv:1410.8811**

Used the ***Feldman & Cousins*** *method to extract the confidence contours*

ND280 results



Excluded by ND280

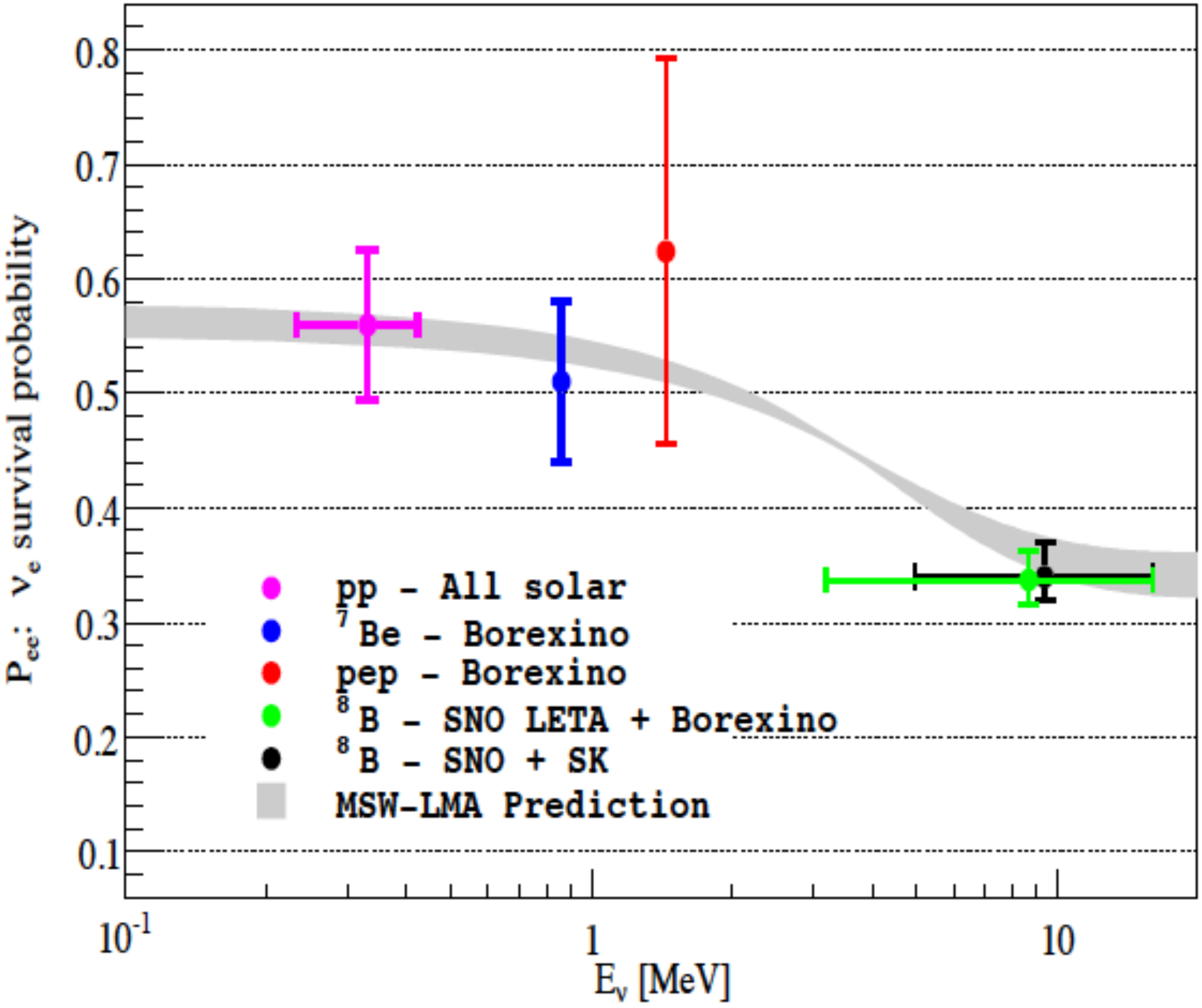


Null hypothesis
excluded at ~94%CL

Solar Measurements

(Errors still too large to give competitive limits)

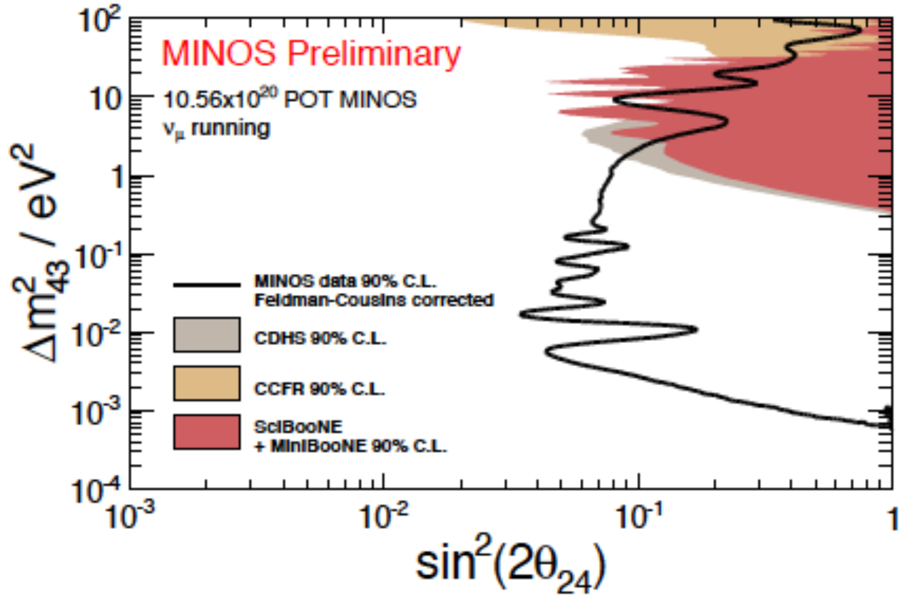
arXiv:1410.0779

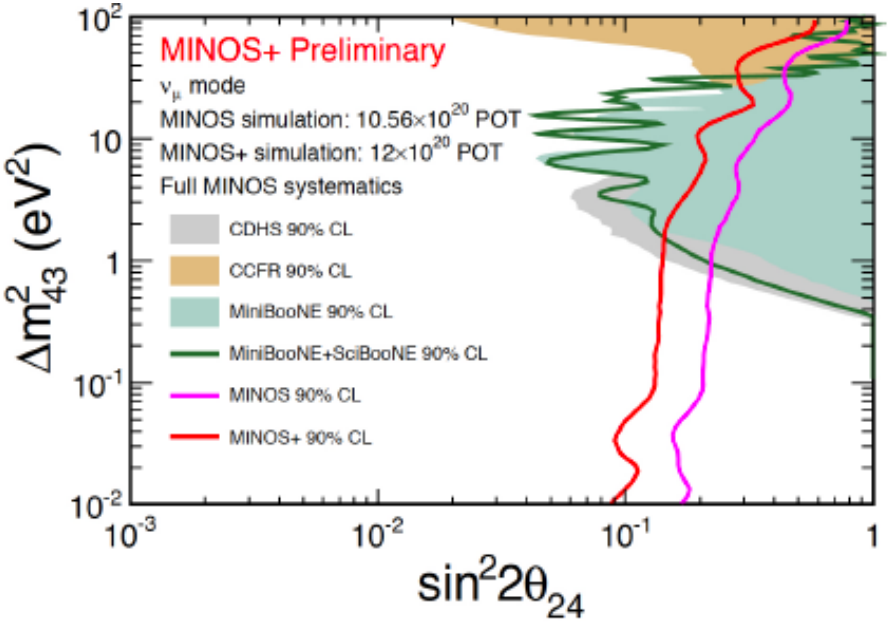


MINOS ν_μ Disappearance Limit

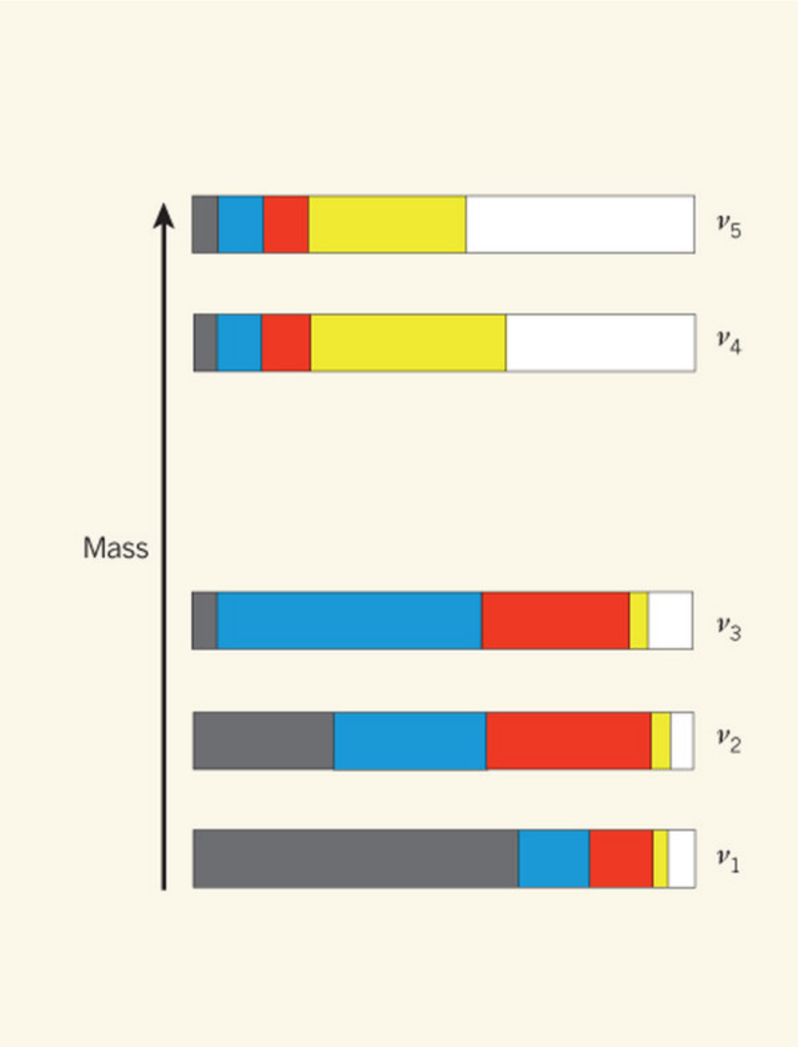
Alexandre Sousa, arXiv:1502.07715

No evidence for ν_μ disappearance has been observed. However, no experiment has yet had sufficient sensitivity.





3+N Sterile Neutrino Models



- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \neq \nu_\mu \rightarrow \nu_e$

Note: There are also other, more exotic possibilities

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j \left|U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha j}\, U_{\beta j}\right| \sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As #ν increases, the formalism gets rapidly more complicated!

#ν	$\#\Delta m_{ij}^2$	$\#\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
4	3	6	3
5	4	10	6
6	5	15	10

Therefore, there needs to be ≥ 3 neutrino mixing for CP Violation!

3+N Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, $P(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{4} P(\nu_\mu \rightarrow \nu_x) P(\nu_e \rightarrow \nu_x)$

Assuming that the 3 light neutrinos are mostly active
and the N heavy neutrinos are mostly sterile.

For 3+1 Models:
arXiv:1207.4765

$$P(\nu_\alpha \to \nu_\beta) \simeq 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \ ,$$

$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - 4(1 - |U_{\alpha 4}|^2)|U_{\alpha 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \ .$$

3+N Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, P(ν_μ −> ν_e) ~ ¼ P(ν_μ −> ν_x) P(ν_e −> ν_x)

Assuming that the 3 light neutrinos are mostly active
and the N heavy neutrinos are mostly sterile.

For 3+2 Models:
arXiv:1207.4765

$$\begin{aligned}
P(\nu_\alpha \to \nu_\beta) \simeq & -4|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} \sin^2(1.27\Delta m^2_{54} L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| + |U_{\alpha 5}||U_{\beta 5}| \cos\phi_{54})|U_{\alpha 4}||U_{\beta 4}| \sin^2(1.27\Delta m^2_{41} L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} + |U_{\alpha 5}||U_{\beta 5}|)|U_{\alpha 5}||U_{\beta 5}| \sin^2(1.27\Delta m^2_{51} L/E) \\
& +2|U_{\beta 5}||U_{\alpha 5}||U_{\beta 4}||U_{\alpha 4}| \sin\phi_{54} \sin(2.53\Delta m^2_{54} L/E) \\
& +2(|U_{\alpha 5}||U_{\beta 5}| \sin\phi_{54})|U_{\alpha 4}||U_{\beta 4}| \sin(2.53\Delta m^2_{41} L/E) \\
& +2(-|U_{\alpha 4}||U_{\beta 4}| \sin\phi_{54})|U_{\alpha 5}||U_{\beta 5}| \sin(2.53\Delta m^2_{51} L/E) \ ,
\end{aligned}$$

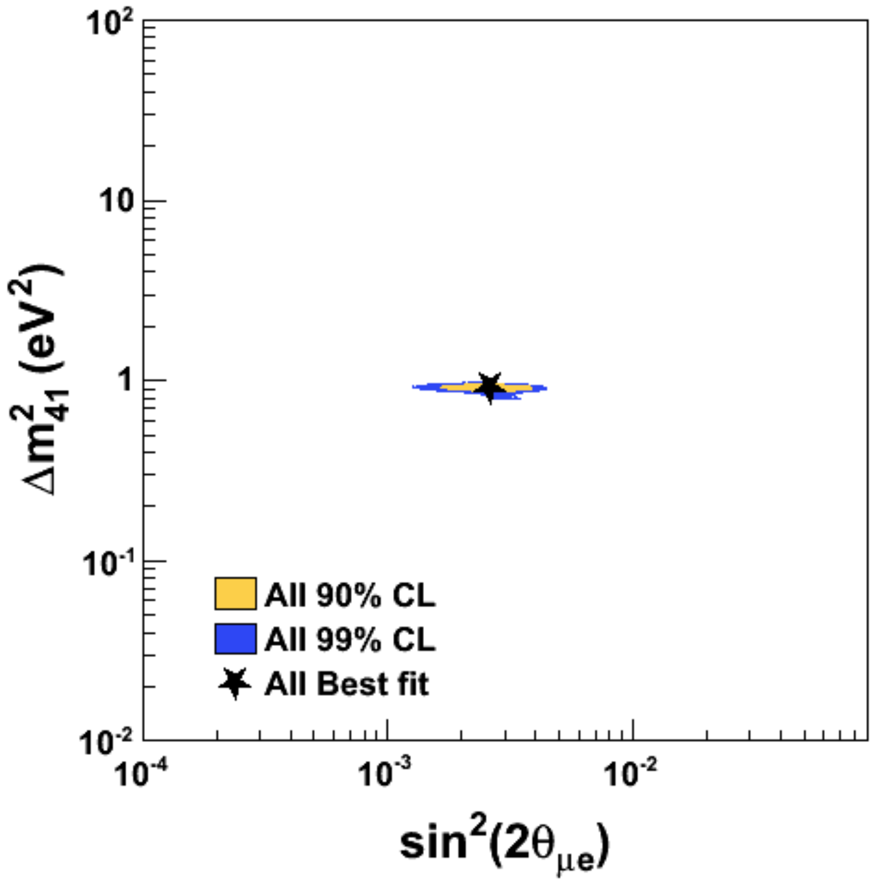
ϕ_{54} is the CP
Phase angle

$$\begin{aligned}
P(\nu_\alpha \to \nu_\alpha) \simeq & \, 1 - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2(1.27\Delta m^2_{54} L/E) \\
& -4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \\
& +|U_{\alpha 5}|^2 \sin^2(1.27\Delta m^2_{51} L/E)) \ .
\end{aligned}$$

Global 3+N Fits to World Data

J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, & J. Spitz, arXiv:1207.4765

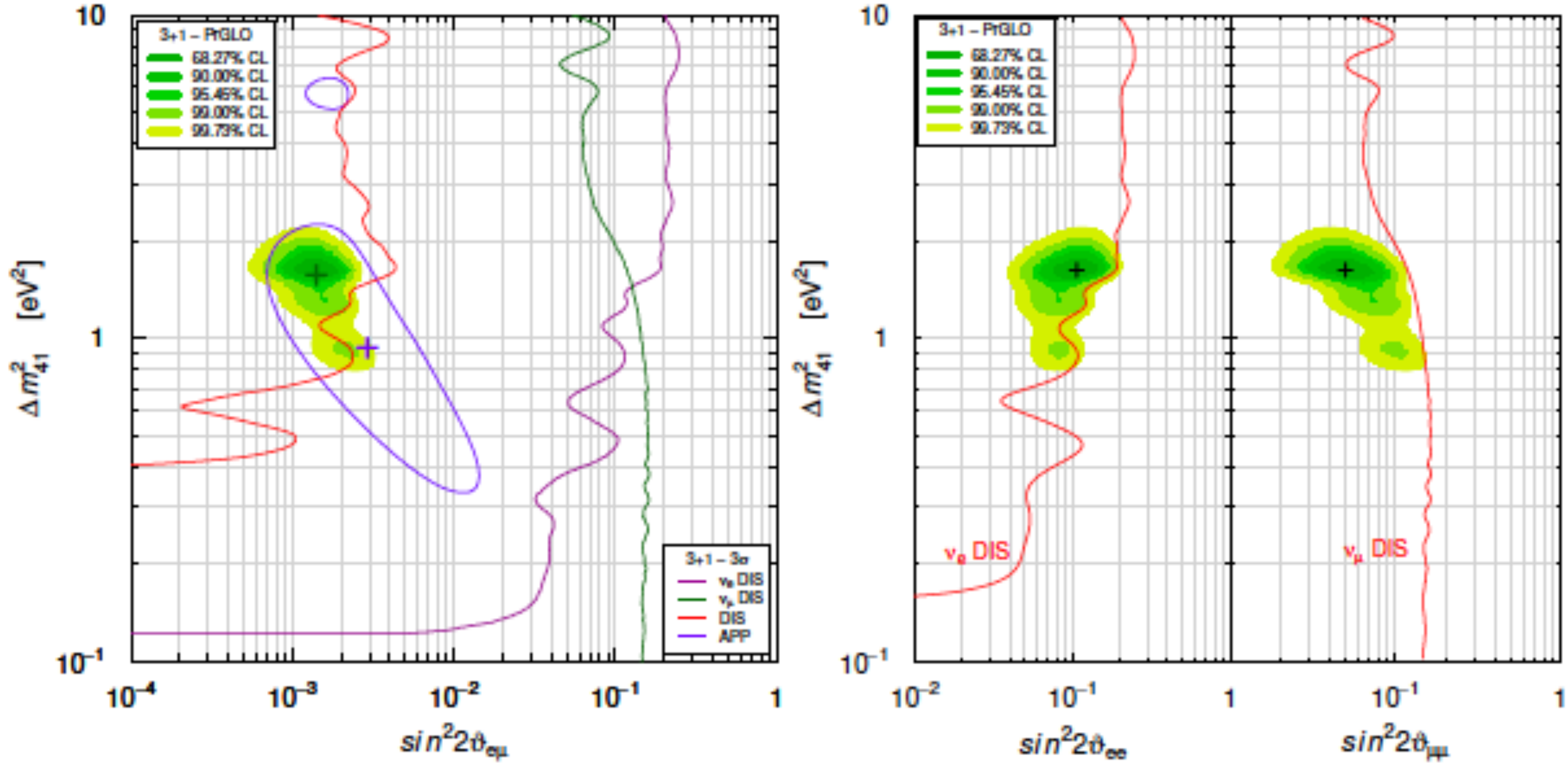
3+1 (P=55%)



Global 3+N Fits to World Data

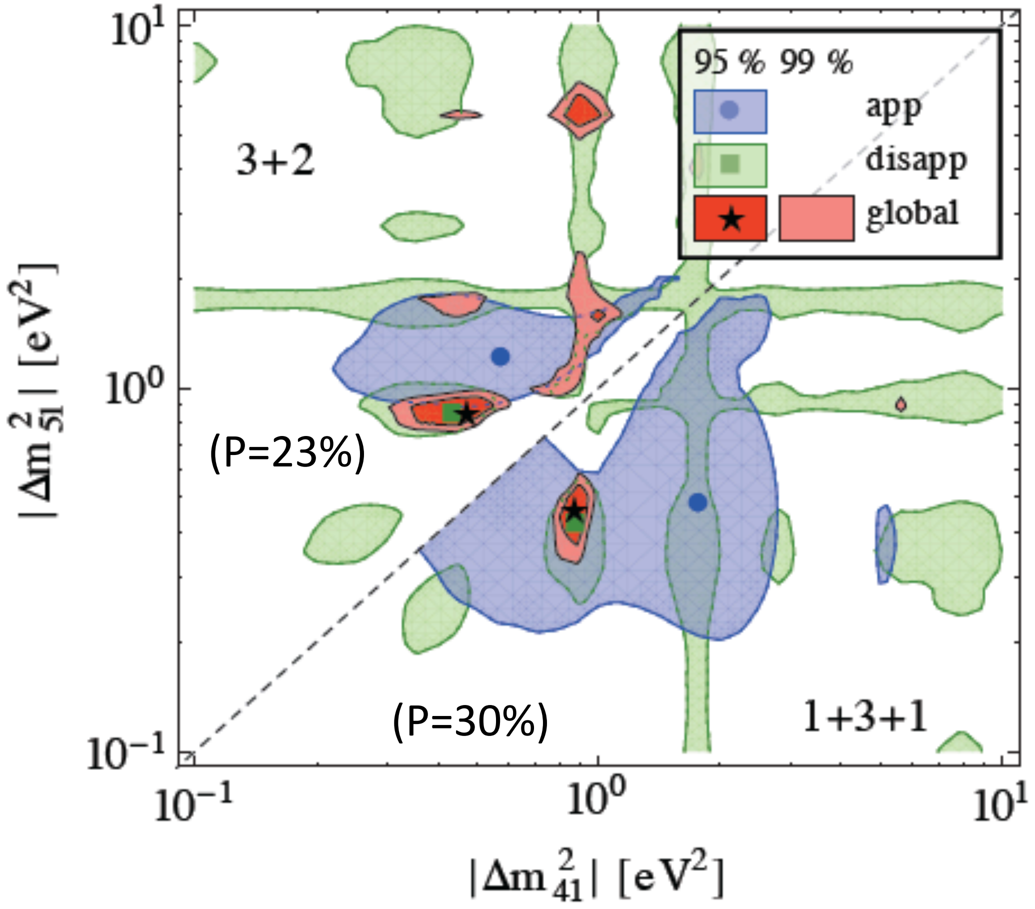
S. Gariazzo, C. Giunti, M. Laveder, Y. F. Li, & E. M. Zavanin, arXiv:1507.08204

3+1 (P=26%)



Global 3+2 & 1+3+1 Fits

Kopp, Machado, Maltoni, & Schwetz, arXiv:1303.3011

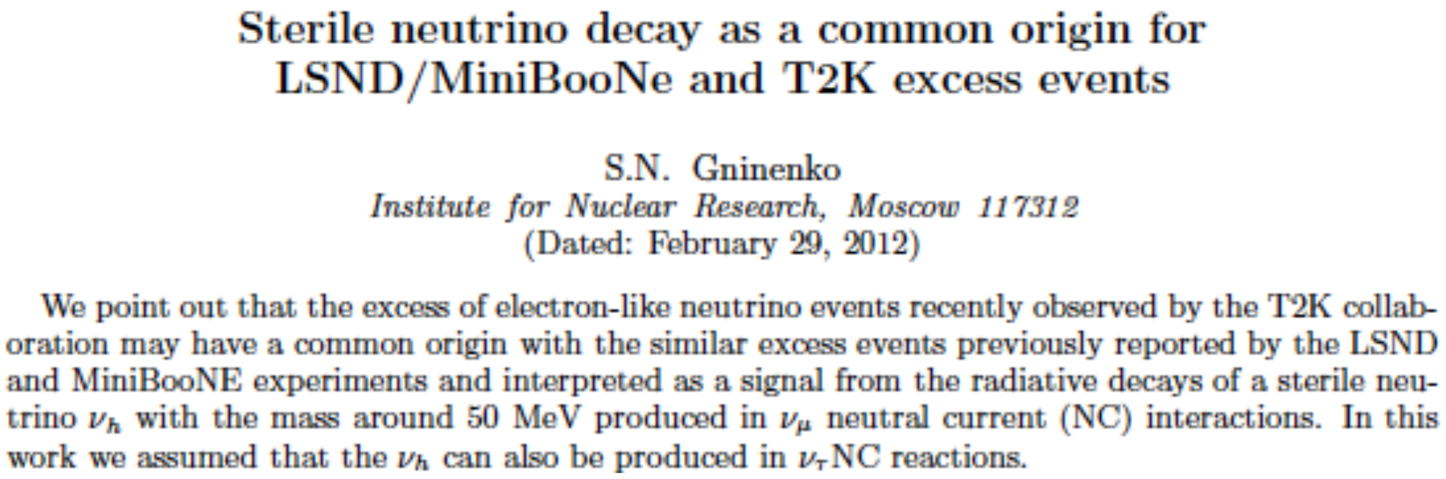


Note that there are problems associated with the Parameter Goodness of Fit (arXiv:1408.7075).

More Exotic SBL Possibilities

- Sterile Neutrino Decay
- Light WIMP Production (Light WIMPs can behave like neutrinos)
- Sterile Neutrino Self Interactions & New Vector Bosons

- Lorentz Violation & CPT Violation
- Extra Dimensions (active neutrinos are stuck on the brane, while sterile neutrinos can propagate in the bulk)
- Mass-Varying Neutrinos
- Neutrino Decoherence
- etc.

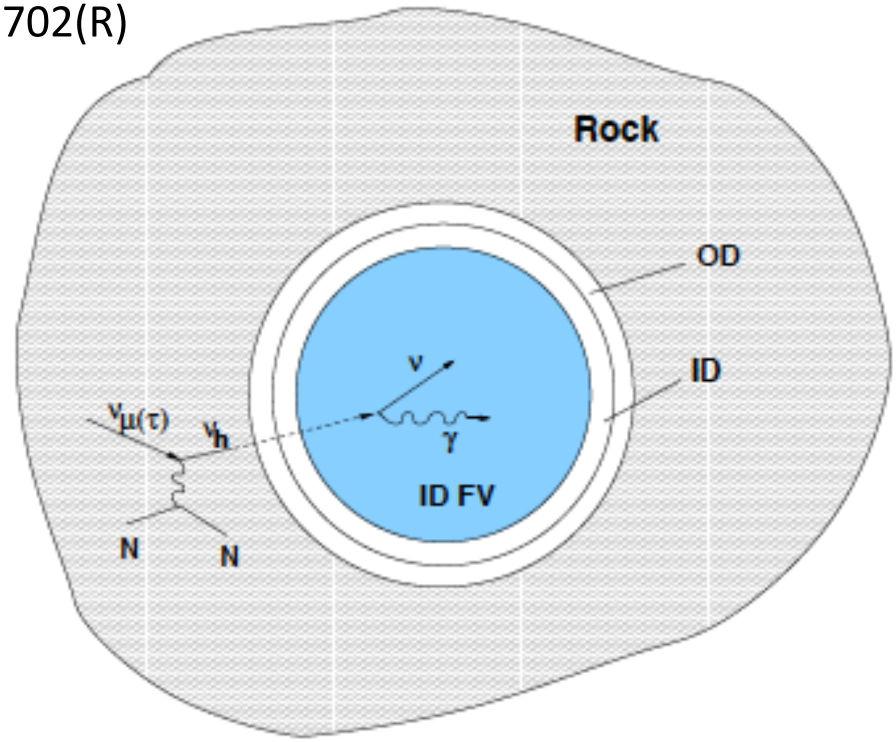


Sterile neutrino decay as a common origin for LSND/MiniBooNe and T2K excess events

S.N. Gninenko
Institute for Nuclear Research, Moscow 117312
(Dated: February 29, 2012)

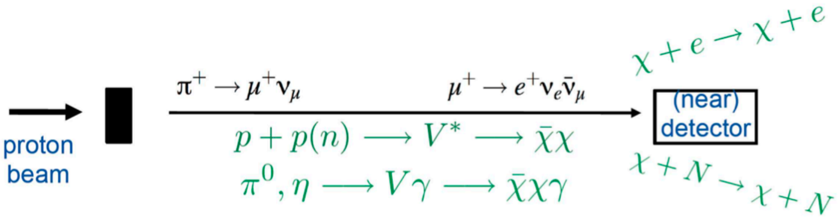
We point out that the excess of electron-like neutrino events recently observed by the T2K collaboration may have a common origin with the similar excess events previously reported by the LSND and MiniBooNE experiments and interpreted as a signal from the radiative decays of a sterile neutrino ν_h with the mass around 50 MeV produced in ν_μ neutral current (NC) interactions. In this work we assumed that the ν_h can also be produced in ν_τNC reactions.

Phys. Rev. D85 (2012) 051702(R)
arXiv:1107.0279



Hidden/Secluded Sector Searches:

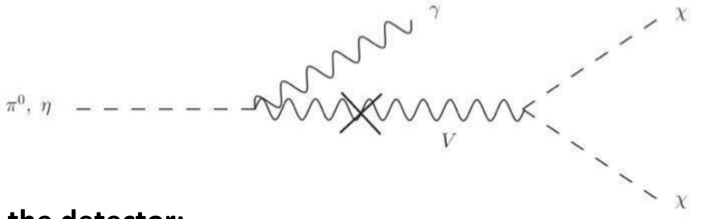
Test U(1) Dark Sector Models which are motivated by sub-GeV Dark Matter and the muon g-2 anomaly.



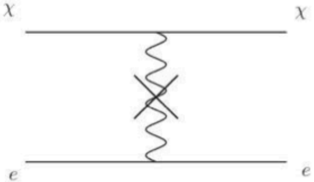
$p + p(n) \longrightarrow V^* \longrightarrow \bar{\chi}\chi$

$\pi^0, \eta \longrightarrow V\gamma \longrightarrow \bar{\chi}\chi\gamma$

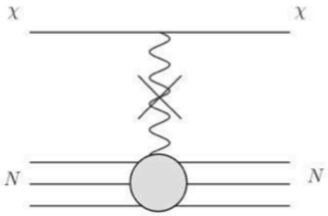
In the target/absorber:



In the detector:

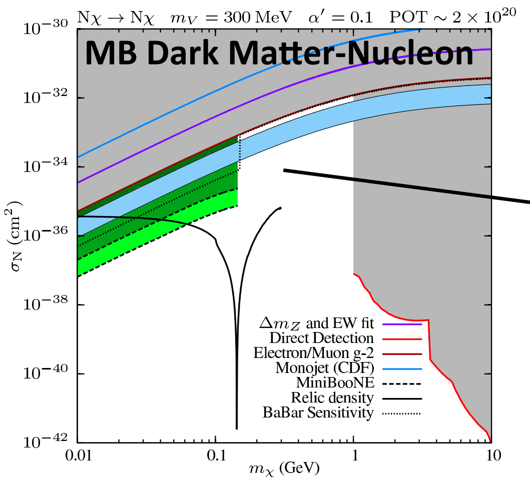


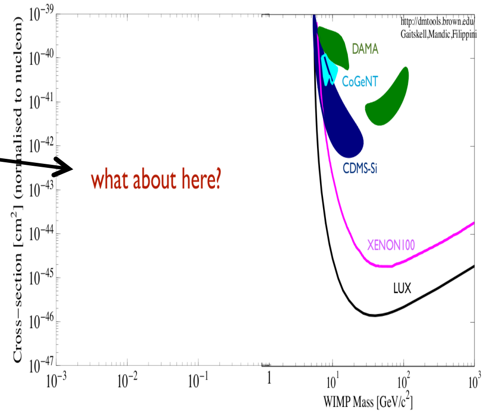
Electron Elastic scattering



Nucleon Elastic scattering

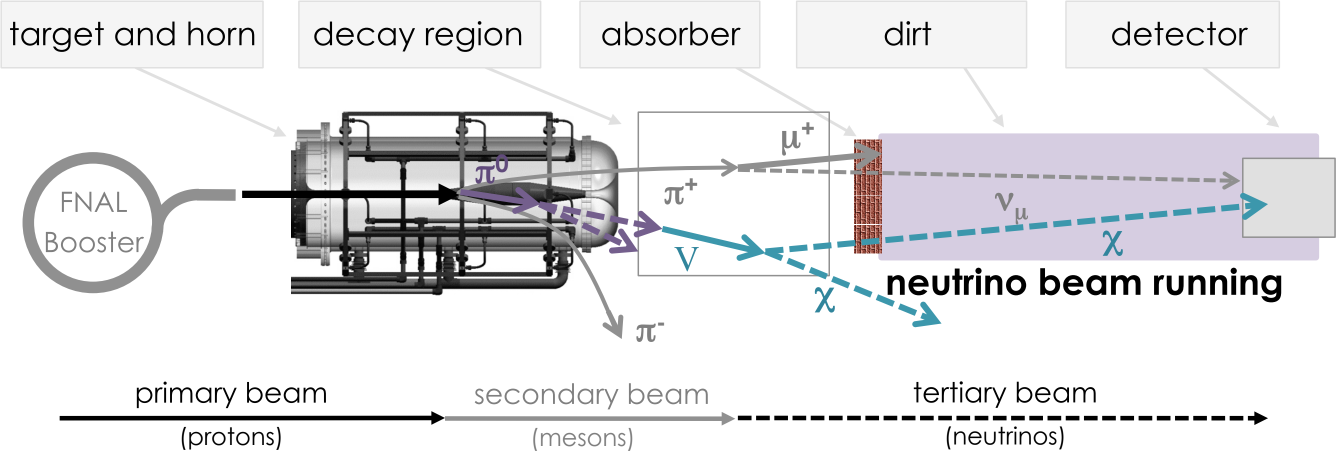
- Dark sector mediator **(V)** couples to photons from beam π^0 decay.
- Dark Matter **(χ)** scatters off detector nucleons or electrons.

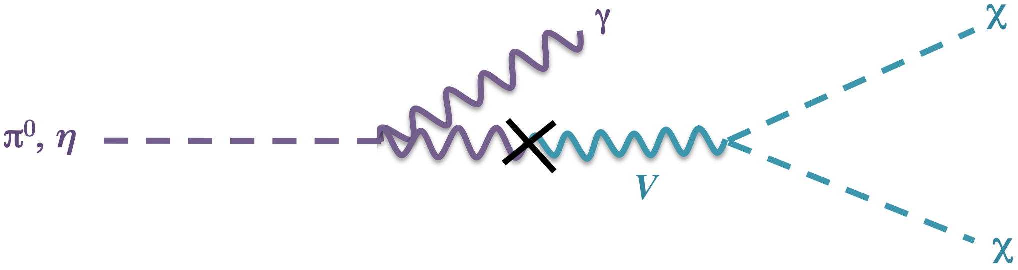




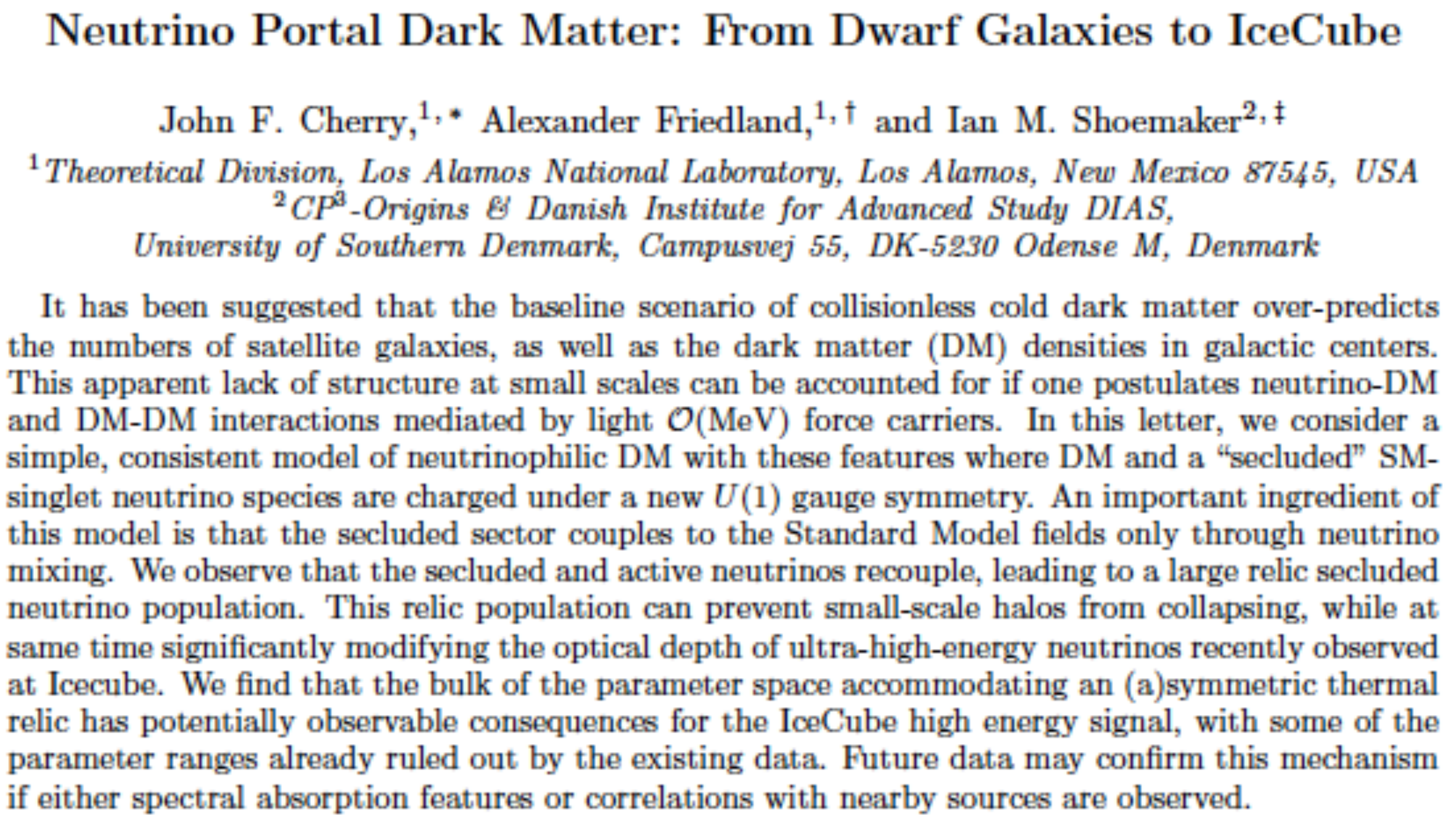
- ❖ Overlaps muon g-2 region and relic density curve (solid line).
- ❖ Beam-dump run significantly (x50) reduces neutrino backgrounds.
- ❖ SBN-LAr will have have good signal sensitivity, but need improved low energy background rejection with PDS.

Light dark matter production in BNB and detection in MiniBooNE





Signature in MiniBooNE is an enhanced NC/CC event rate. Results from MiniBooNE Beam-Dump run later this year.

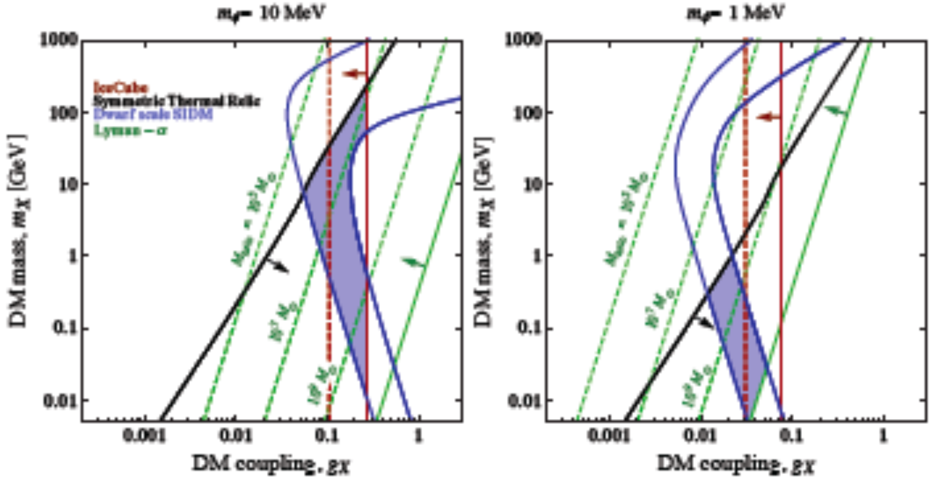


Neutrino Portal Dark Matter: From Dwarf Galaxies to IceCube

John F. Cherry,[1,*] Alexander Friedland,[1,†] and Ian M. Shoemaker[2,‡]
[1]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*CP^3-Origins & Danish Institute for Advanced Study DIAS,*
University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark

It has been suggested that the baseline scenario of collisionless cold dark matter over-predicts the numbers of satellite galaxies, as well as the dark matter (DM) densities in galactic centers. This apparent lack of structure at small scales can be accounted for if one postulates neutrino-DM and DM-DM interactions mediated by light $\mathcal{O}$(MeV) force carriers. In this letter, we consider a simple, consistent model of neutrinophilic DM with these features where DM and a "secluded" SM-singlet neutrino species are charged under a new $U(1)$ gauge symmetry. An important ingredient of this model is that the secluded sector couples to the Standard Model fields only through neutrino mixing. We observe that the secluded and active neutrinos recouple, leading to a large relic secluded neutrino population. This relic population can prevent small-scale halos from collapsing, while at same time significantly modifying the optical depth of ultra-high-energy neutrinos recently observed at Icecube. We find that the bulk of the parameter space accommodating an (a)symmetric thermal relic has potentially observable consequences for the IceCube high energy signal, with some of the parameter ranges already ruled out by the existing data. Future data may confirm this mechanism if either spectral absorption features or correlations with nearby sources are observed.

Sterile neutrino couples to new gauge boson and dark matter and couples to SM fields only through neutrino mixing.

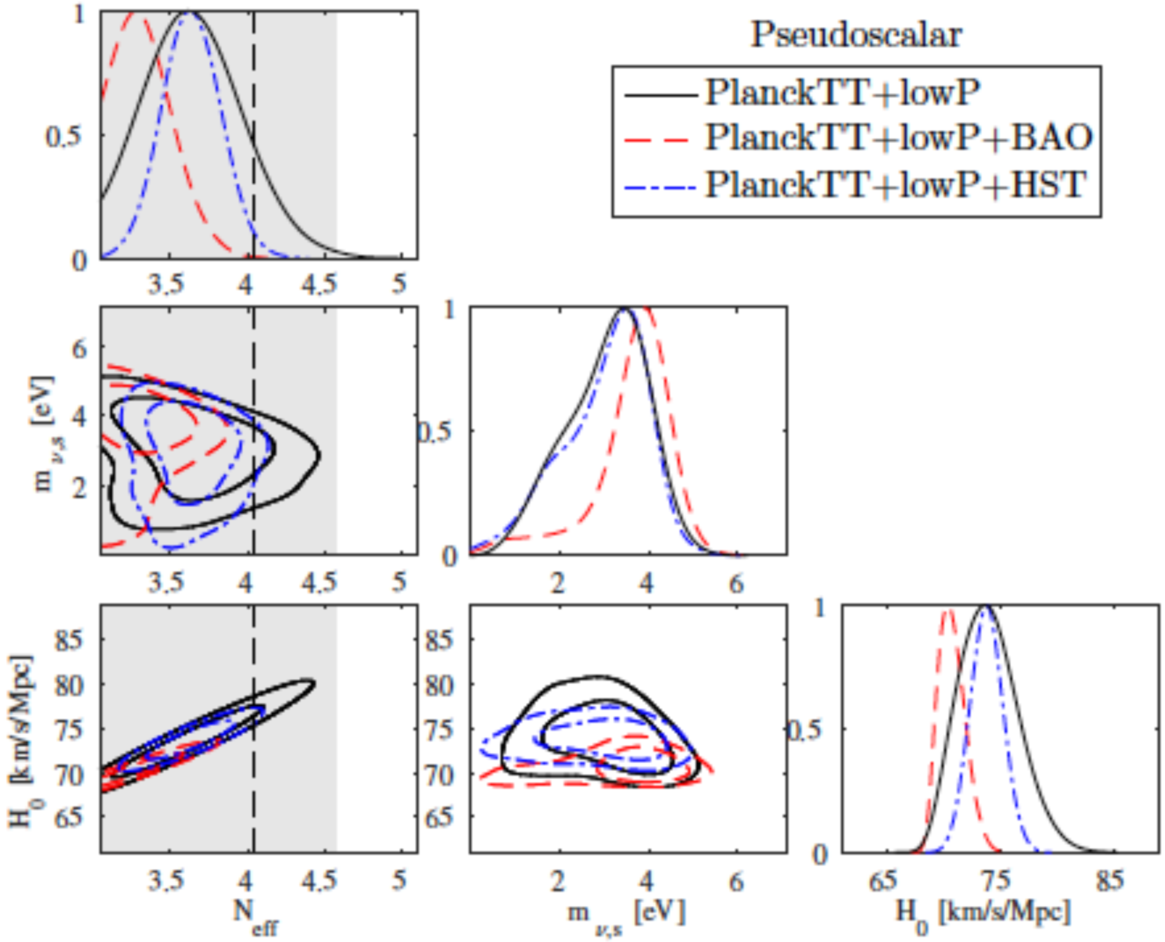


arXiv:1411.1071

Active-sterile neutrino oscillations are the **Portal** connecting the SM to the Dark Sector.

Cosmology Fits with New Pseudoscalar Interaction

Archidiacono, Hannestad, Hansen, & Tram, arXiv:1508.02504



Neutrino Cross Sections & Neutrino Energy Reconstruction for Accelerator Neutrino Experiments

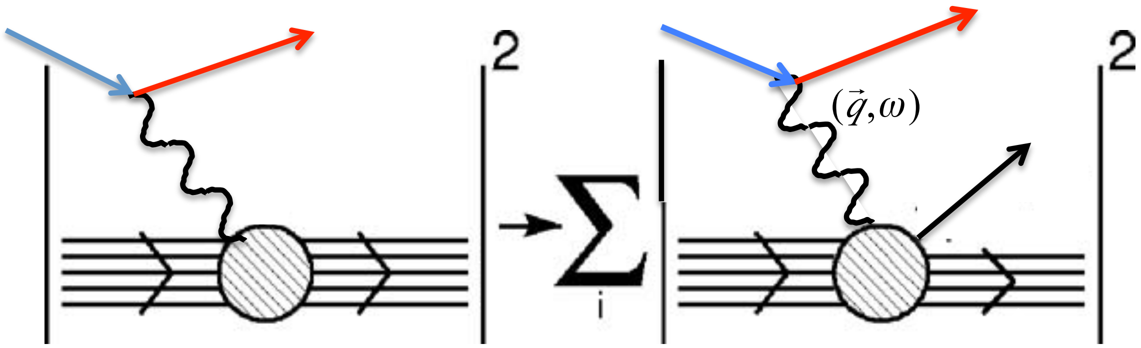
2-body N-N interactions can greatly affect the neutrino cross sections and neutrino energy reconstruction!

Circa 2009 AD

Inclusive Quasi Elastic Scattering

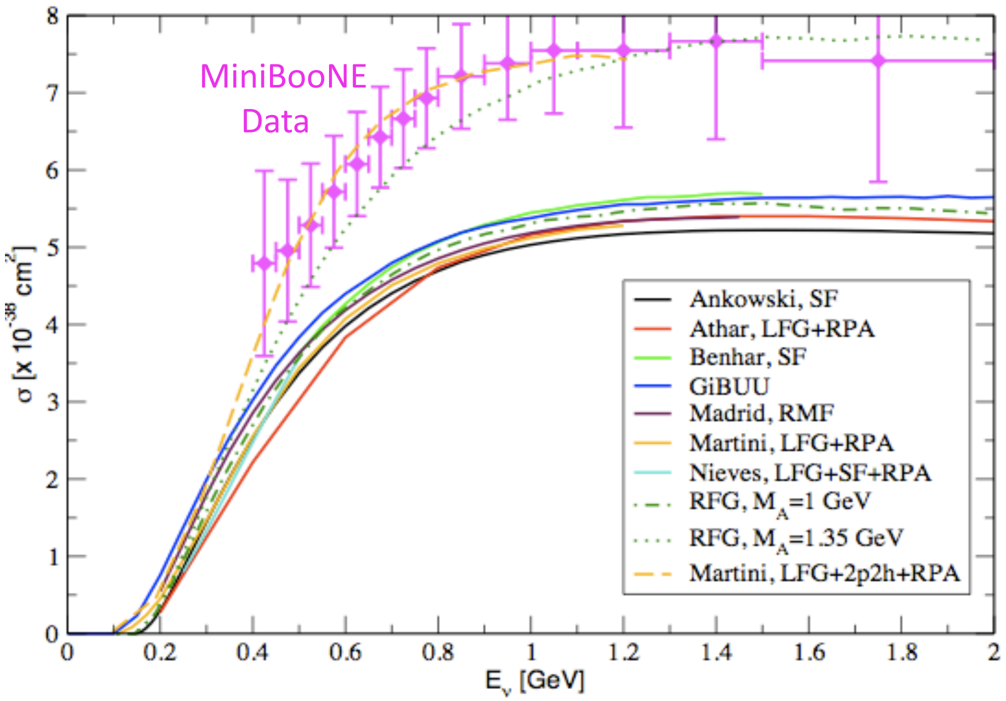
Model

Impulse approximation –Fermi Gas



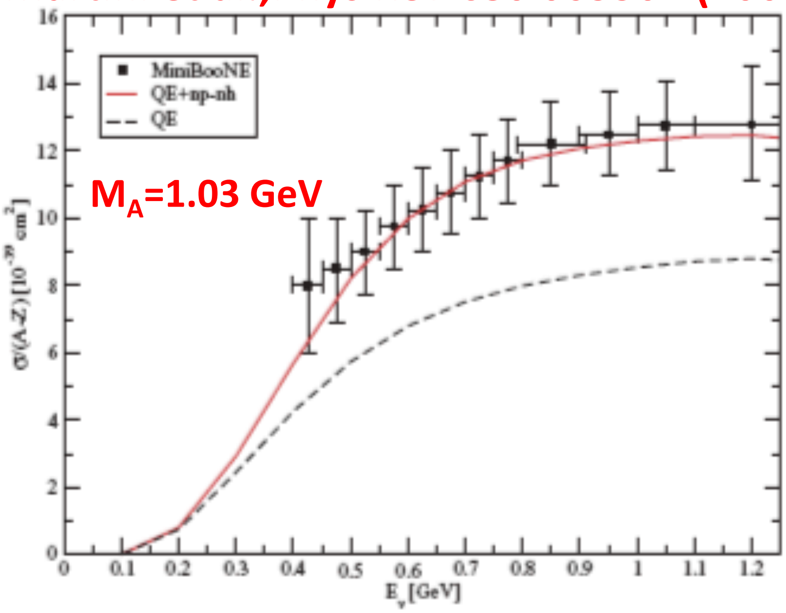
Produced

$\sigma(\nu_\mu + {}^{12}C \rightarrow \mu^- + X(\cancel{\pi}))$

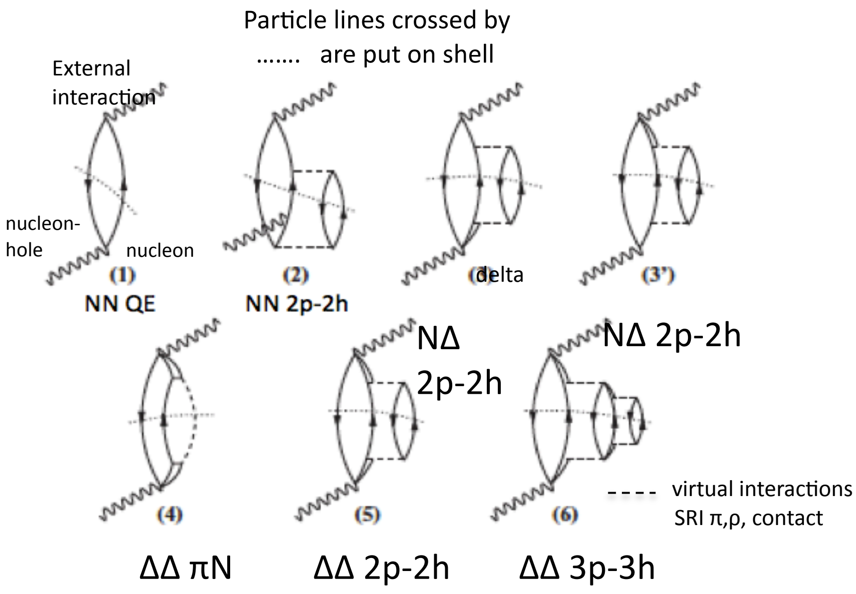


Including N-N interactions via RPA produced

M. Martini et al.,Phys Rev C80 065501 (2009)



The starting point is a Fermi gas with interactions treated diagrammatically



But introduces uncertainty into $E_\nu = E_\mu + \omega$

In Mean Field:

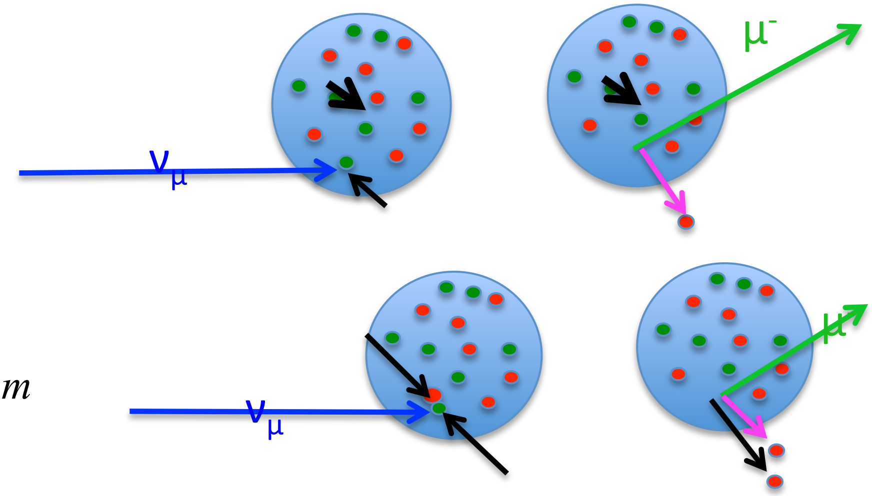
$$\omega_1 = \left(\sqrt{(\vec{q}+\vec{p})^2 + m^2} - m\right) + \frac{p^2}{2(A-1)m} + S_1$$

In 2 body Correlation assuming $p_{CM}=0$:

$$\omega_2 = \left(\sqrt{(\vec{q}+\vec{p})^2 + m^2} + \sqrt{p^2 + m^2} - 2m\right) + S_2$$

Correlated partner

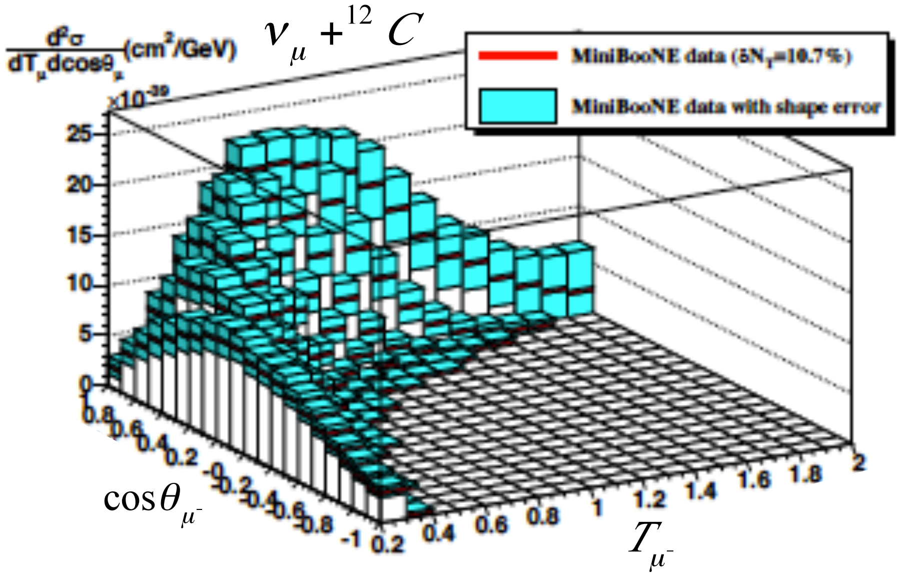
ω *can be much larger than inferred from mean field assumption !!*



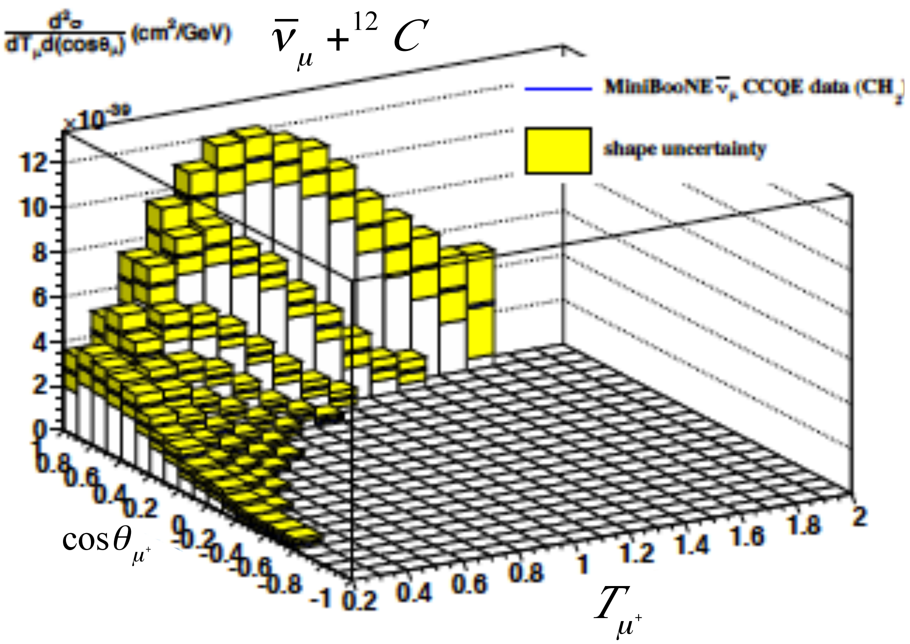
MiniBooNE model independent CCQE data

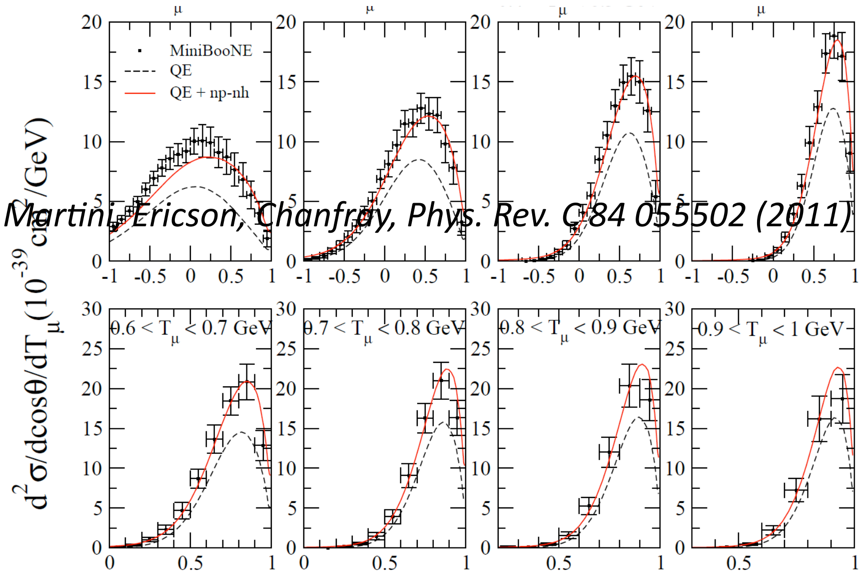
Get away from assumptions about assignment of $E_{\nu(\bar{\nu})}$

Phys. Rev. D81, 092005 (2010)

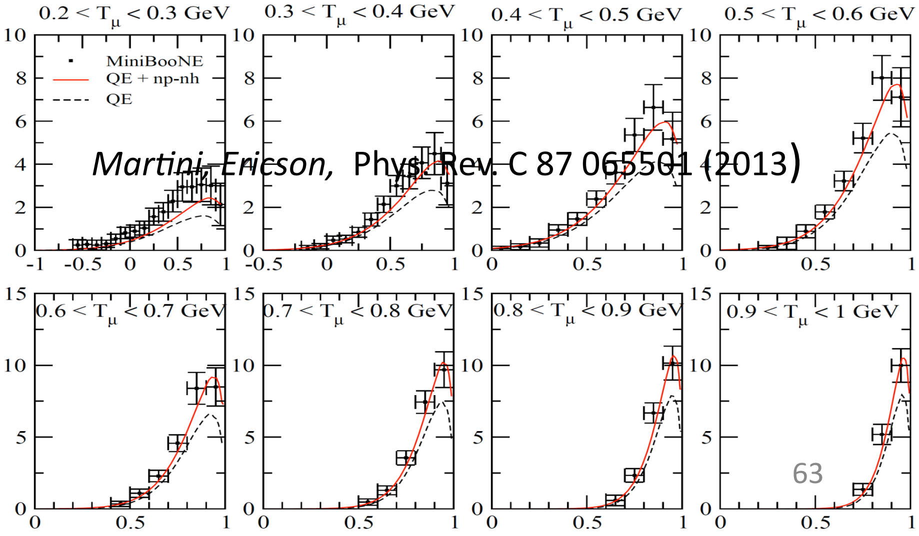


Phys. Rev. D88, 032001 (2013)





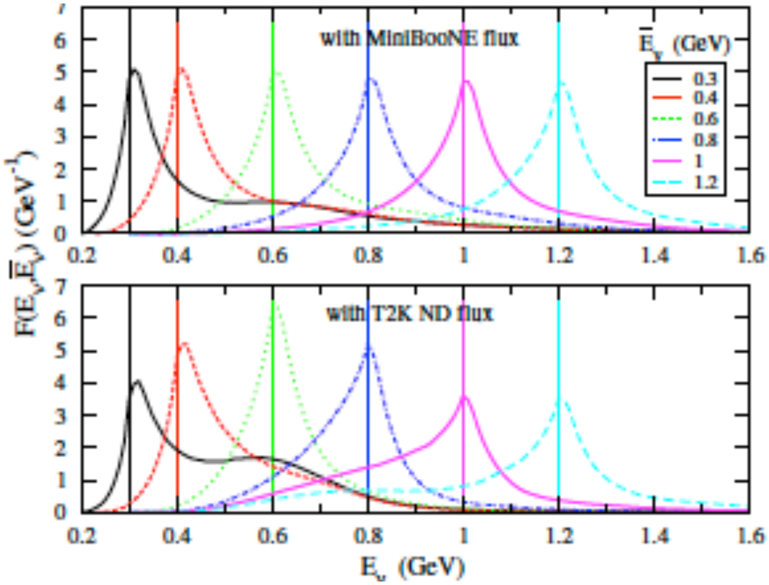
Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)

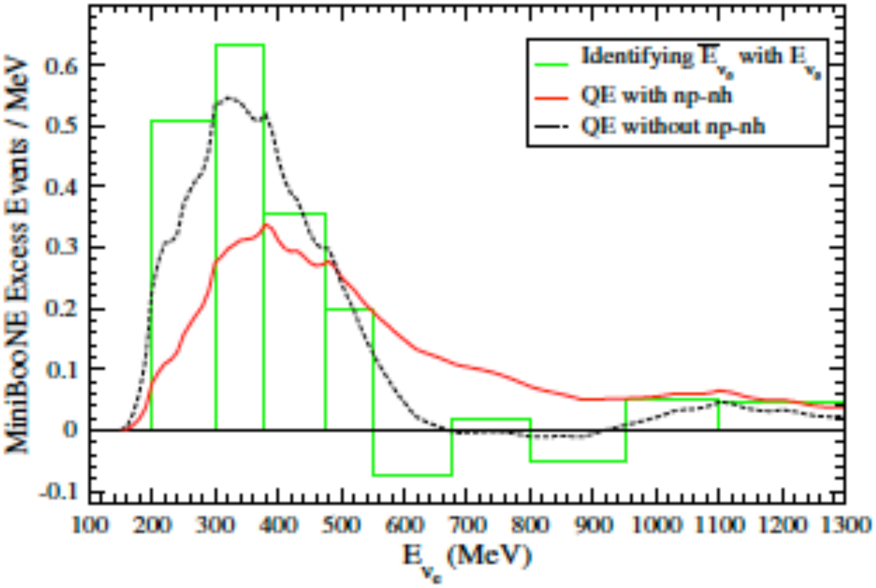


Martini, Ericson, Phys. Rev. C 87 065501 (2013)

Example of incorrect neutrino energy assignment

Martini et al Phys Rev D85 093012 (2012)





Comments on RPA formalism: not usually applied to short range correlation, mostly used for characterizing the excitation of low lying long range correlations.

Uncertainties:
Why is their transverse axial response the same as transverse vector?
How are CVC and PCAC respected?
Start with a Fermi Gas ground state. All hadronic states are plane waves.

More robust basis sought → GFMC: Phys Rev C65 024002,(2002), nucl-th 1412.3081

Future Short-Baseline ν Experiments

- There is a diverse set of experiments, spanning vastly different energy Scales (from ~1 MeV to ~10 TeV), that have been proposed to test the 3+N models & resolve the present anomalies:

- Accelerator ν Experiments: MicroBooNE+SBND+ICARUS, MINOS+, NuStorm , DUNE, OscSNS at ORNL, J-PARC E56, IsoDAR, nuPRISM

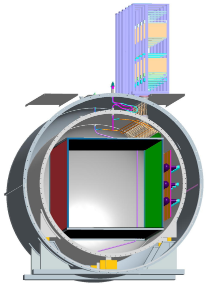
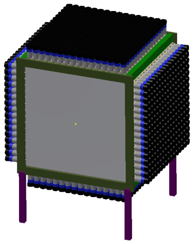
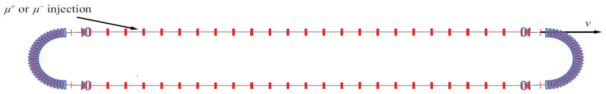


Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

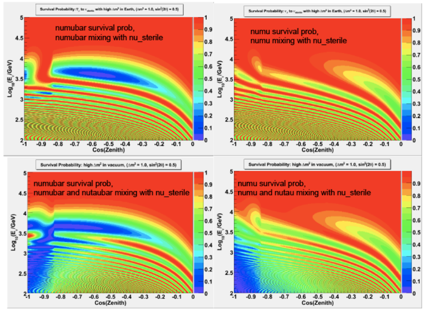
- Reactor ν Experiments: Chandler/SOLID, PROSPECT

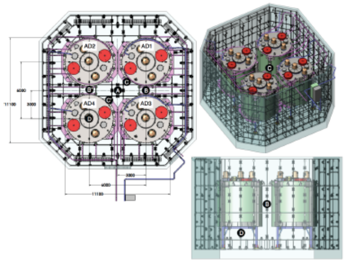




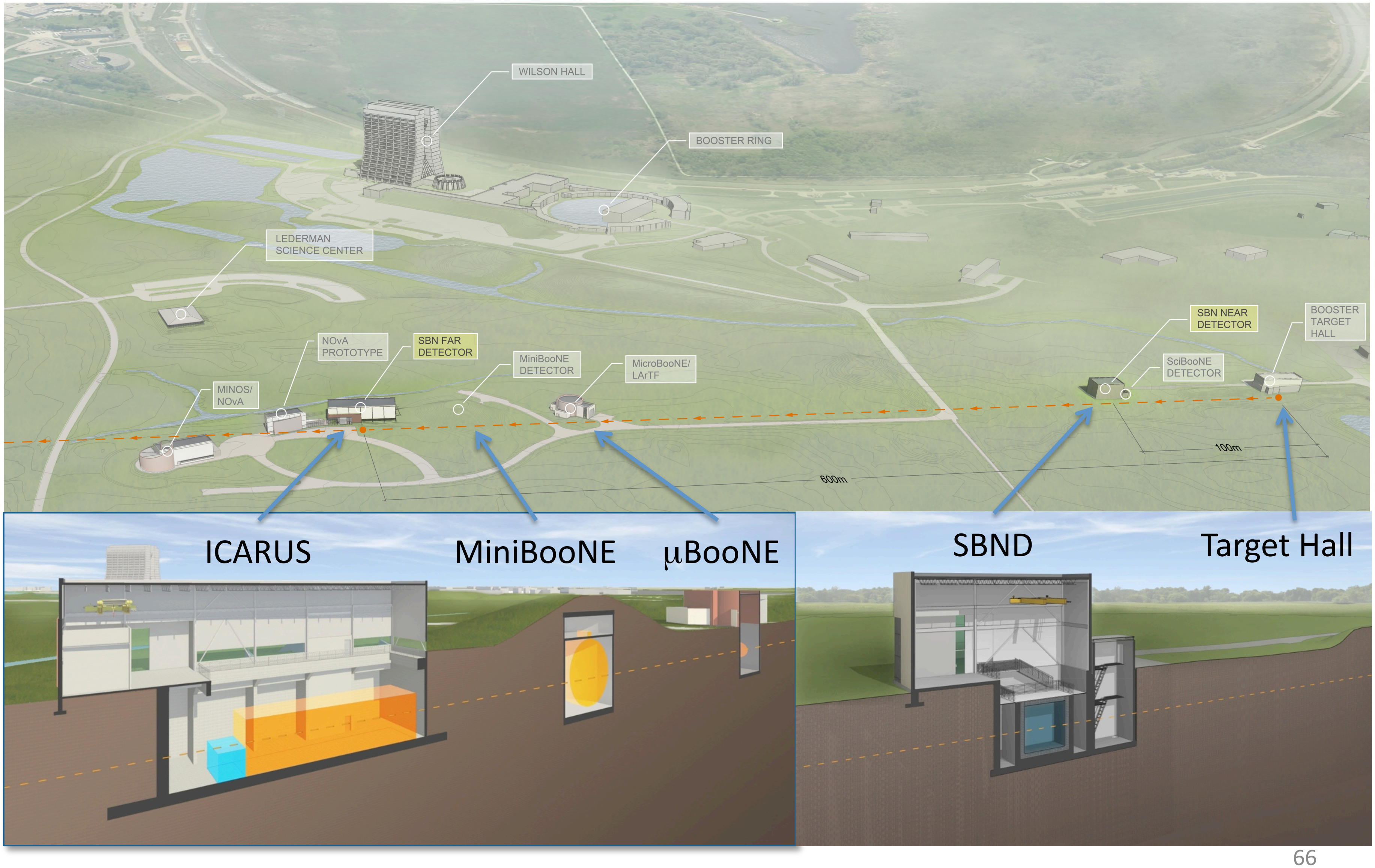
- Radioactive Source ν Experiments: BOREXINO-SOX, KamLAND, Daya Bay, Baksan, LENS

- Atmospheric ν Experiments: IceCube

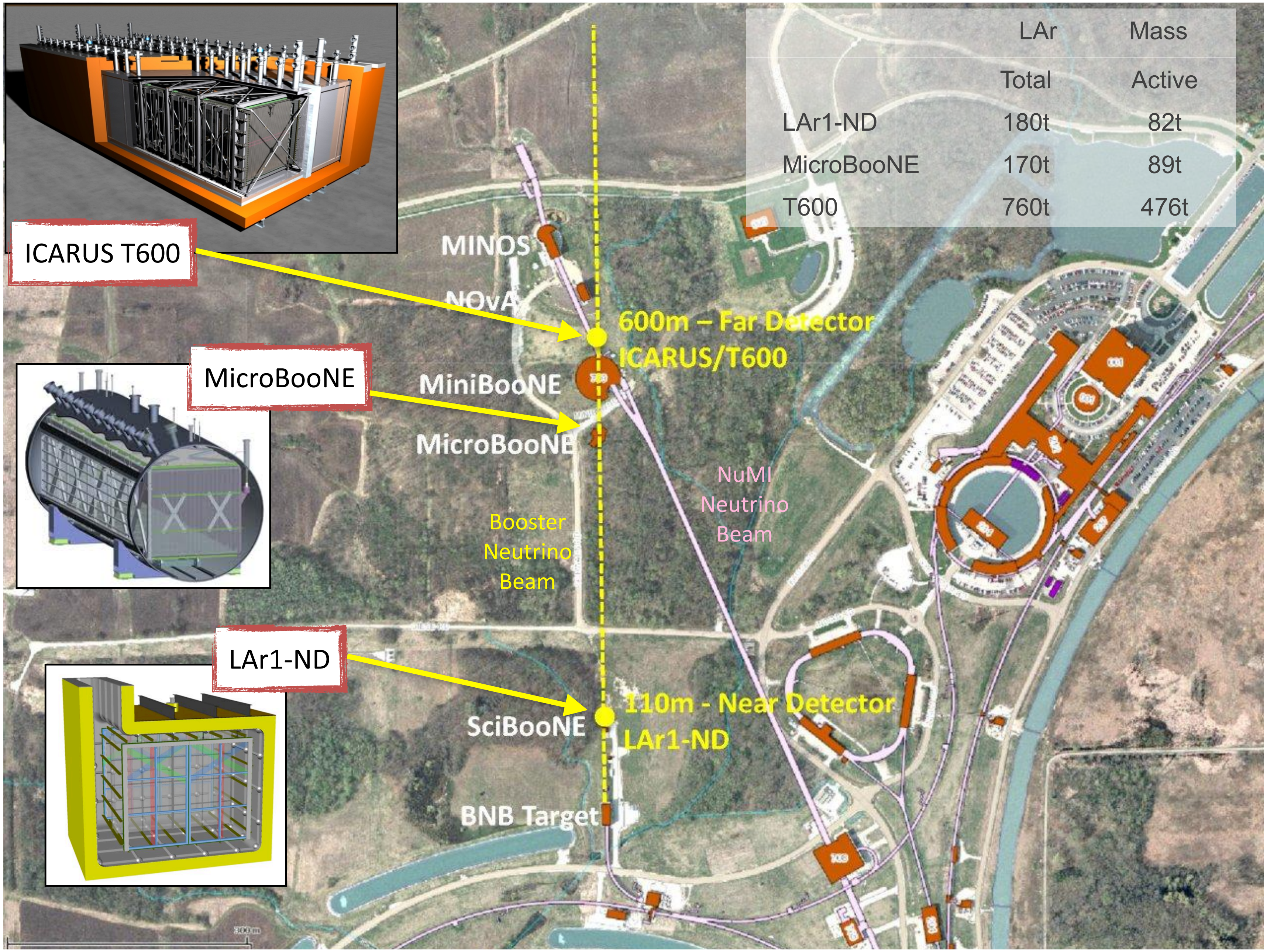




SBN: A Multi-LAr TPC Short-Baseline Program at FNAL



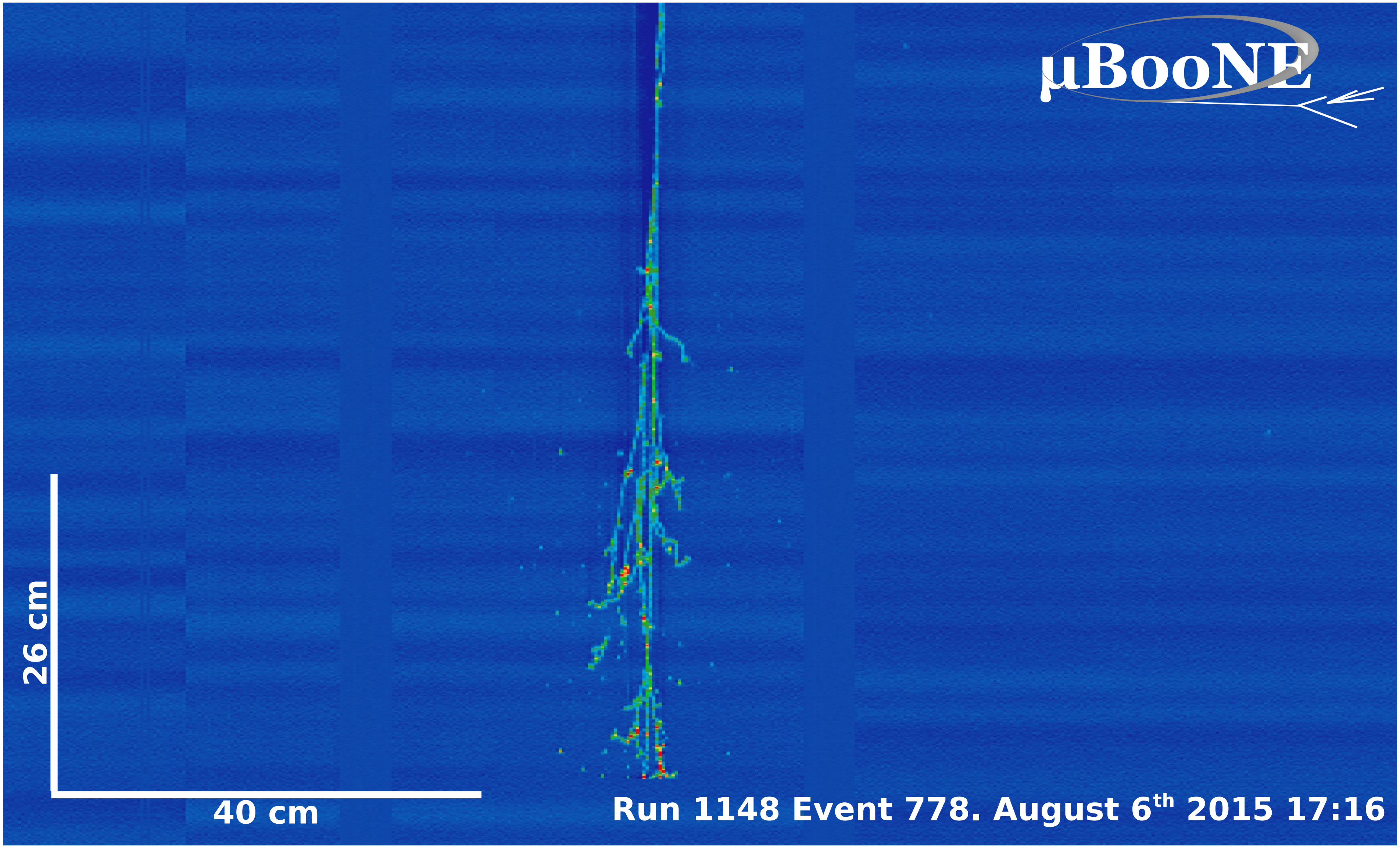
SBN: A Multi-LAr TPC Short-Baseline Program at FNAL



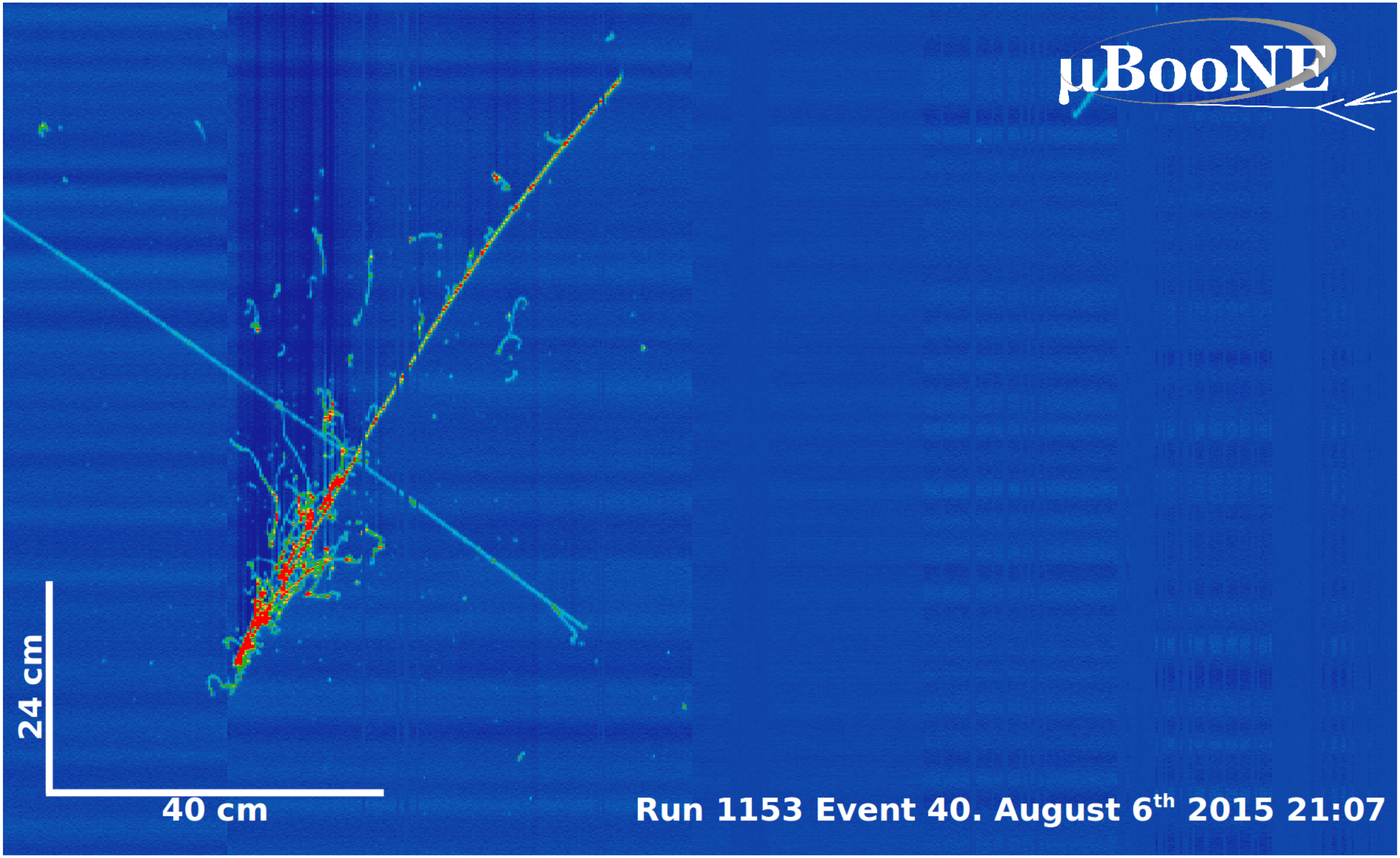
	LAr	Mass
	Total	Active
LAr1-ND	180t	82t
MicroBooNE	170t	89t
T600	760t	476t

MicroBooNE Liquid Argon TPC

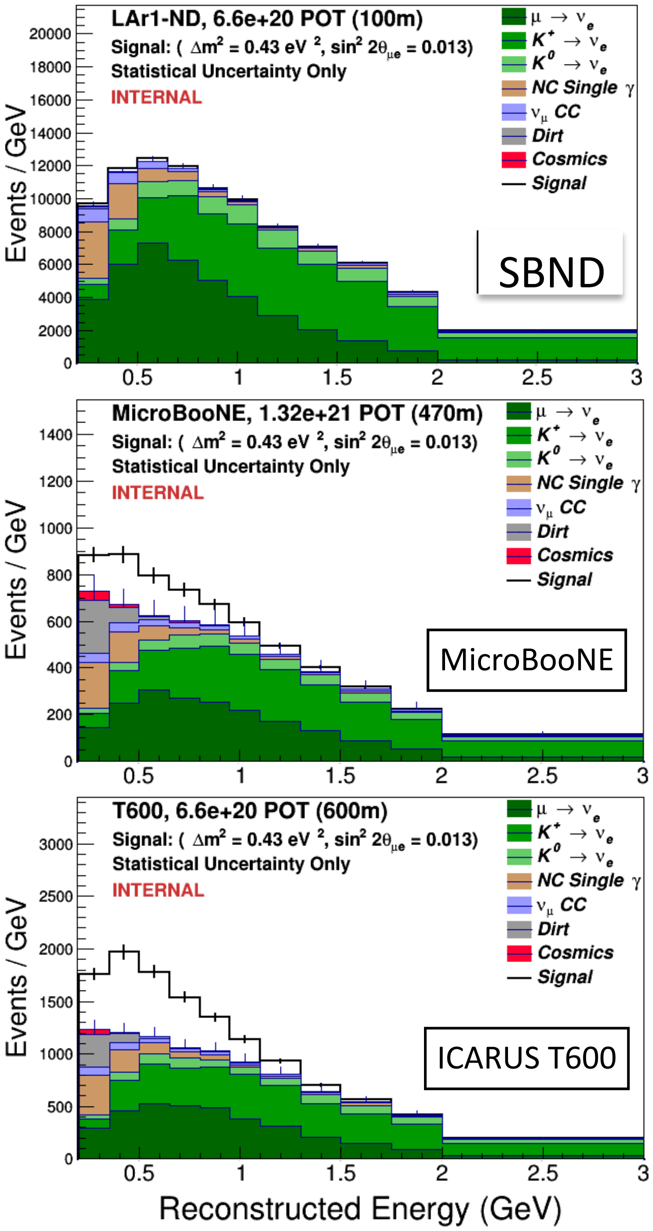
MicroBooNE Now Observing Cosmic Ray Events

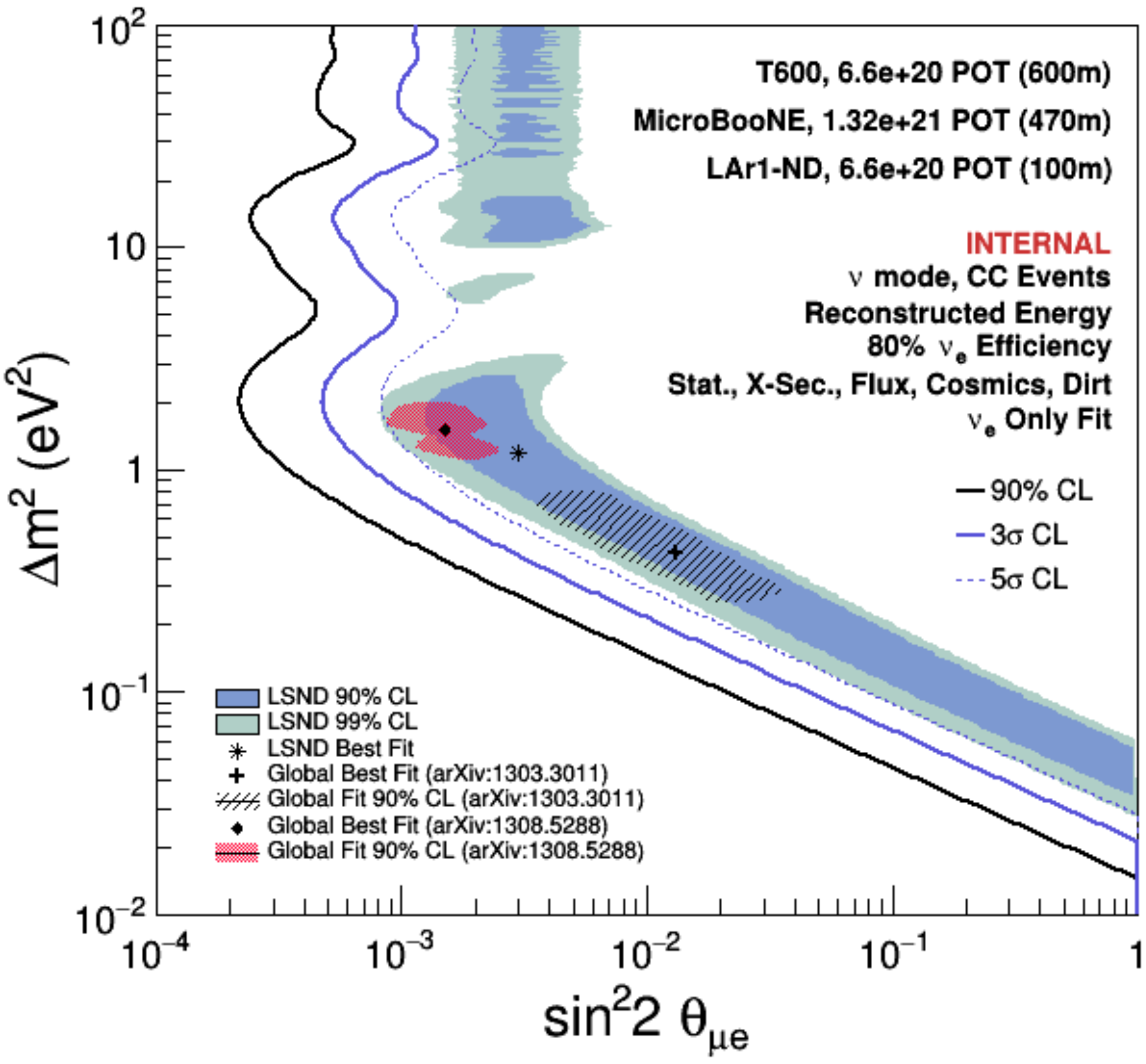


MicroBooNE Now Observing Cosmic Ray Events

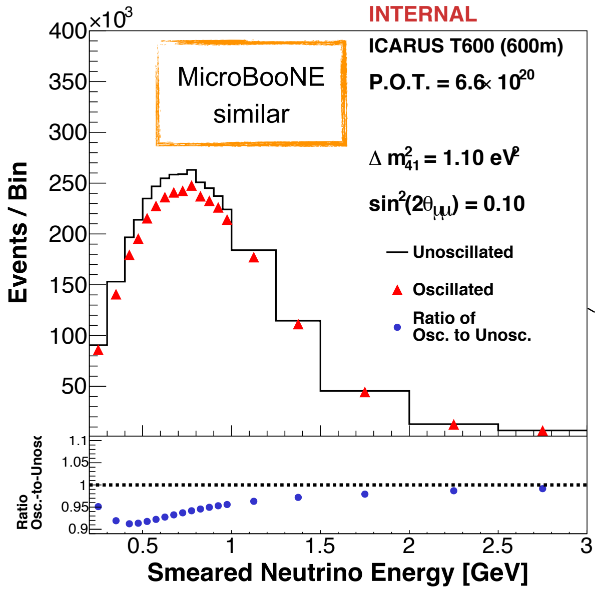


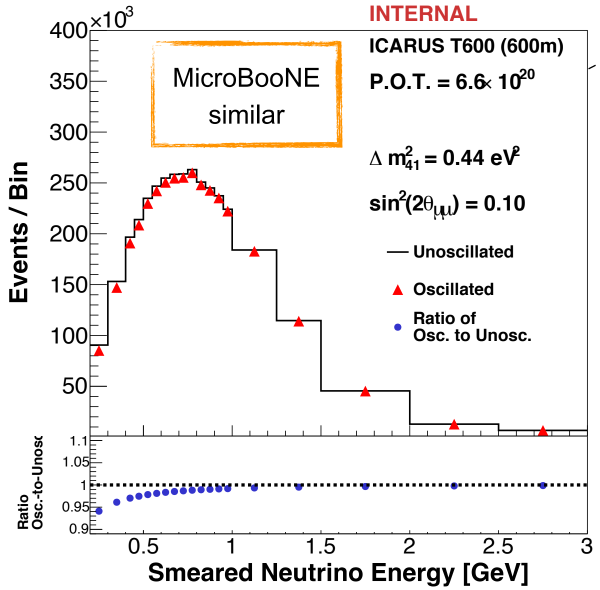
ν_e Appearance Sensitivity

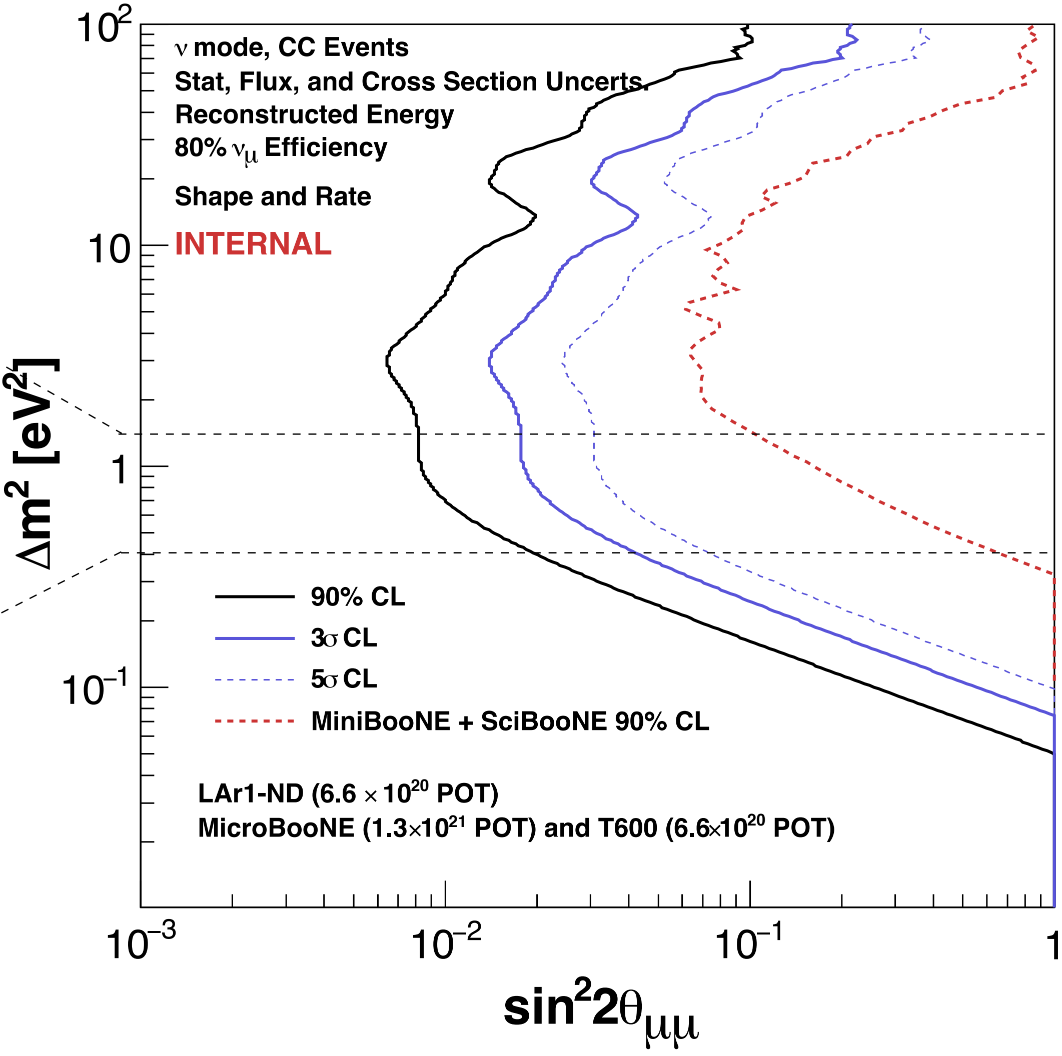




ν_μ Disappearance Sensitivity



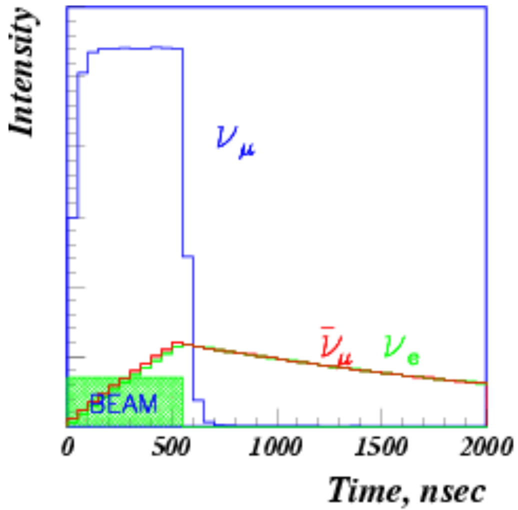


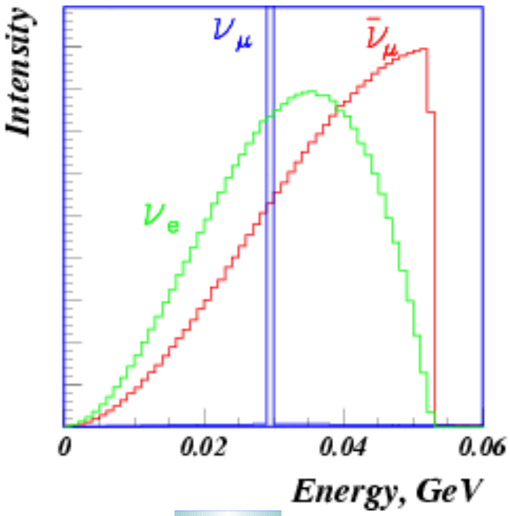


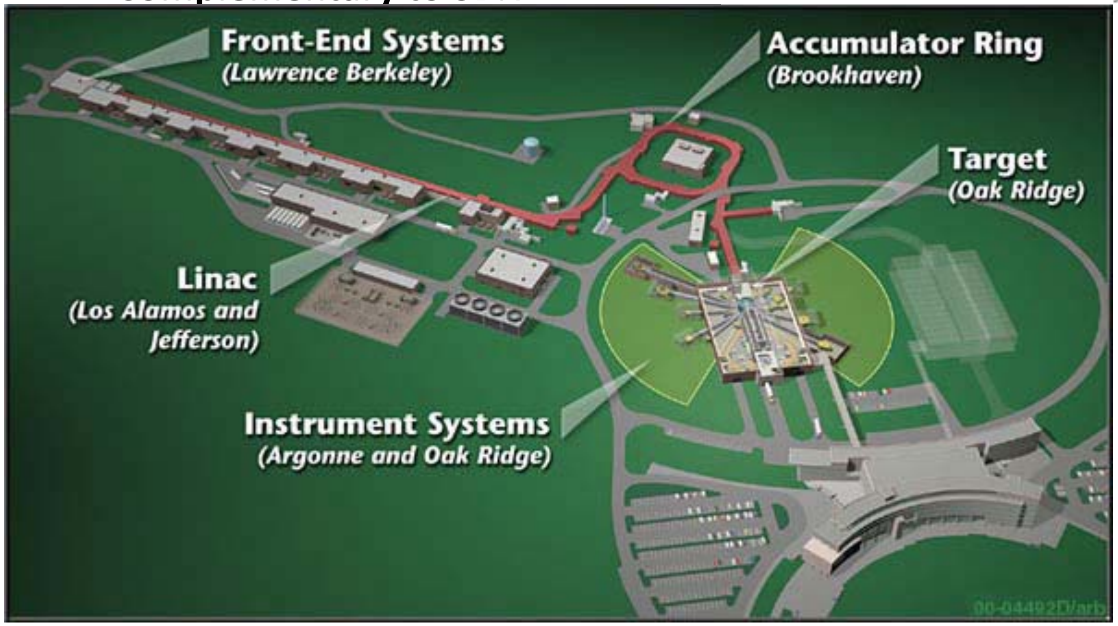
Sensitivity includes full flux and cross section systematics, but not detector systematics at this time.

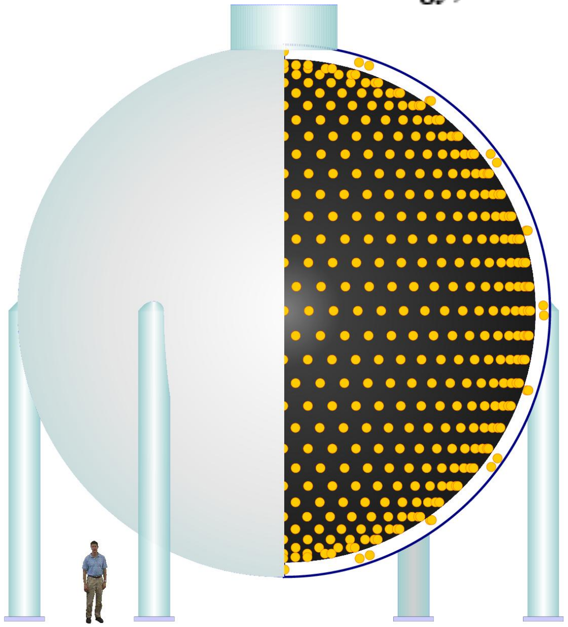
OscSNS

- Spallation neutron source at ORNL
- ~1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos
- **Complementary to SBN**

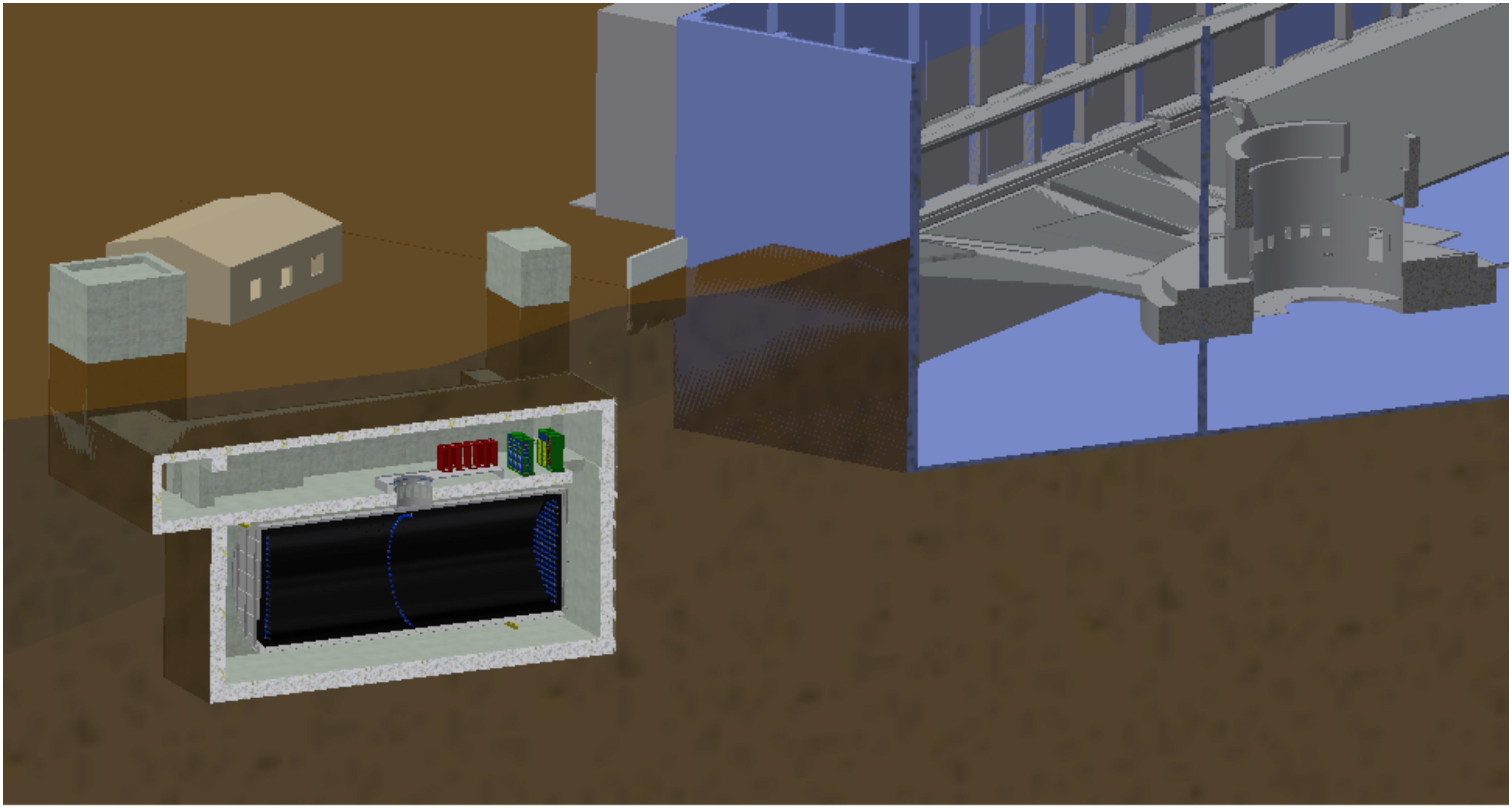








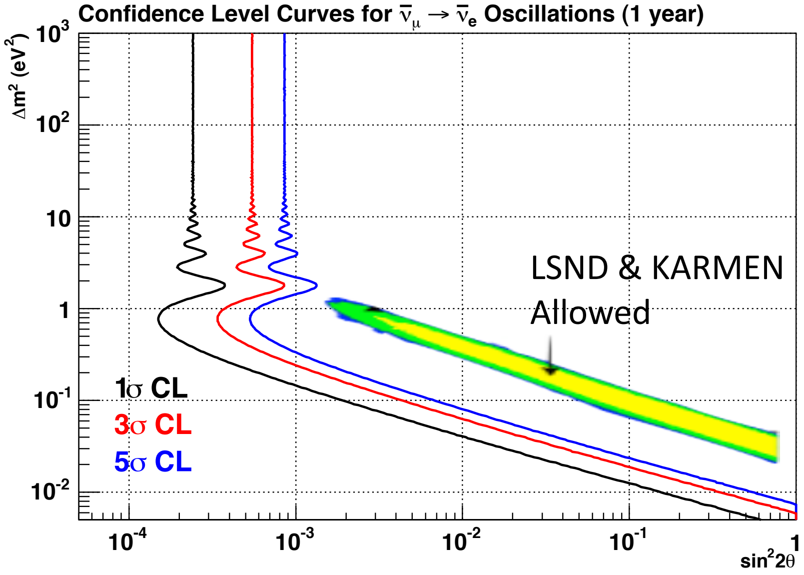
Spallation Neutron Source at ORNL

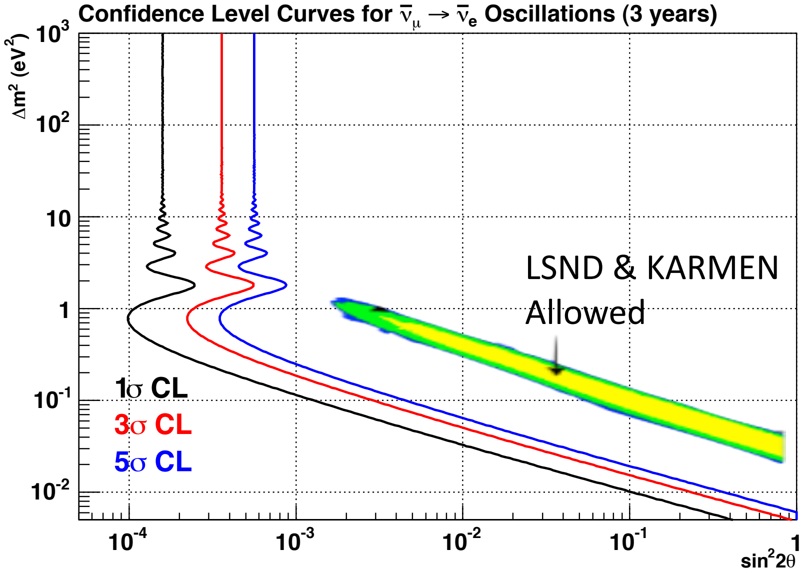


$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ Appearance

- $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ appearance sensitivity for 2 & 6 years of running:

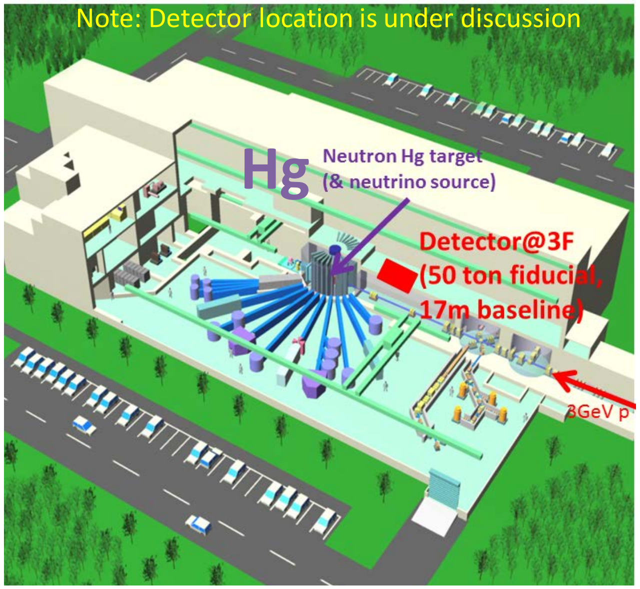
$\bar{\nu}_e$ p -> e^+ n; n p -> d γ (2.2 MeV)



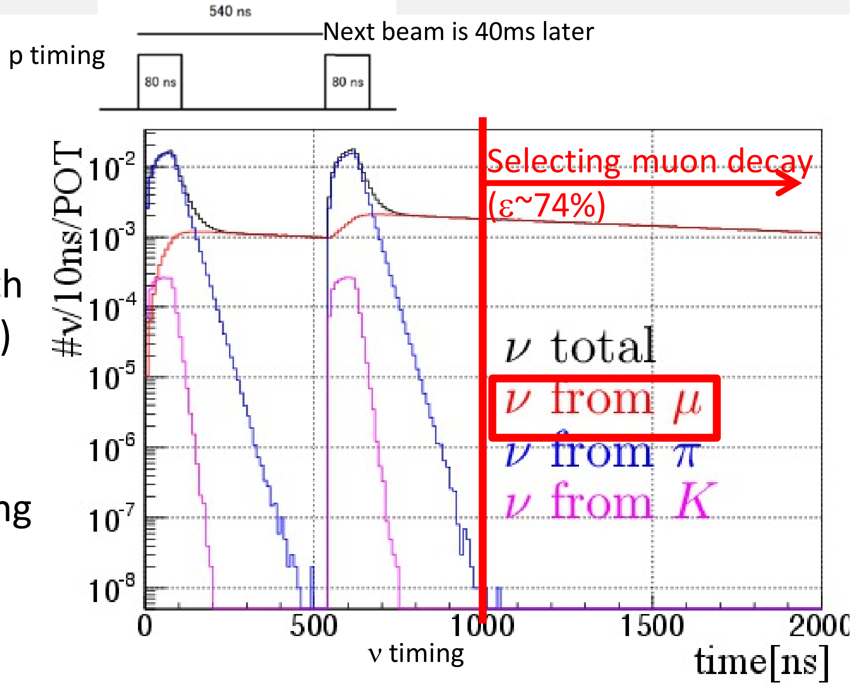


Sterile neutrino search @MLF (proposal in 2013)

M. Harada *et al*, arXiv:1310.1437 [physics.ins-det]

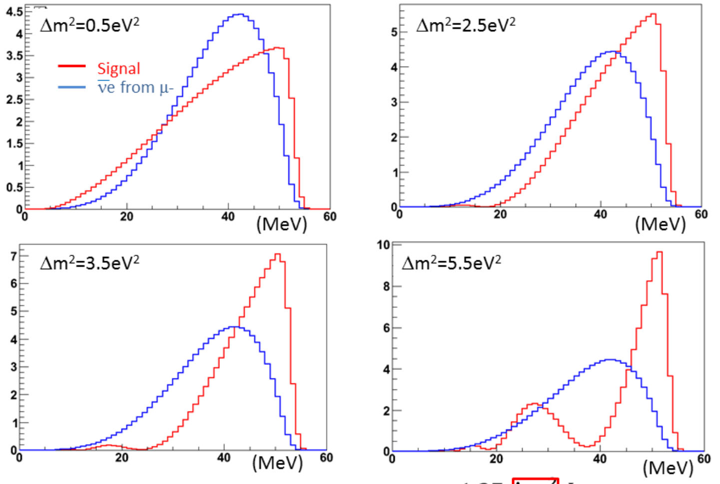

Note: Detector location is under discussion

- J-PARC P56 aims to confirm or refute the neutrino oscillation with sterile neutrino($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- With gating the time we can use ultra-pure neutrinos from stopping μ^+ (top-right)
- Energy distortion → sig vs BKG separation (bottom-left)



Selecting muon decay (ε~74%)

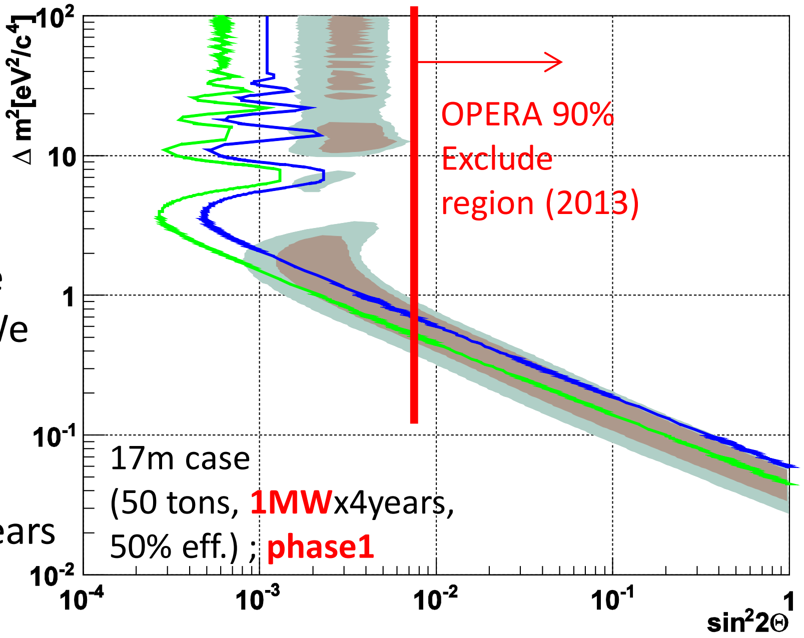
Energy distribution of events (L=17m)



$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \boxed{\Delta m^2} \cdot L}{E_\nu}\right)$$

- Energy is smeared by 15%/sqrt(E) (detector E resolution)

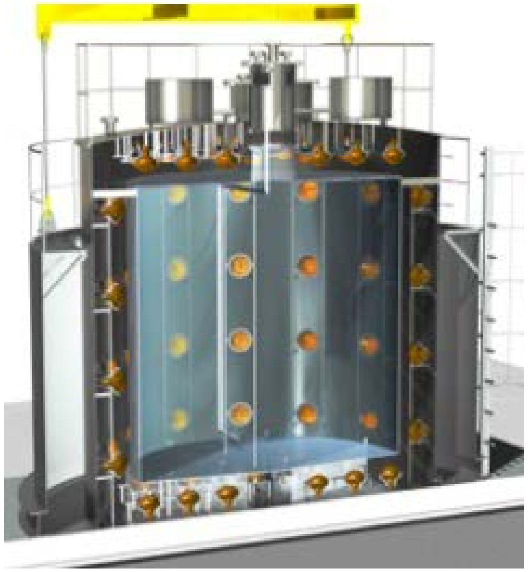
- Sensitivity of P56 (right); blue 5σ, green 3σ. We conclude LSND region (brown (90%CL) & green (99%) within 4 years



OPERA 90% Exclude region (2013)

17m case
(50 tons, **1MW**x4years,
50% eff.) ; **phase1**

Detector and Detection Principle (reminder)



Detector

Target volume => **Gd-loaded LS**
(25tons x 2 detector ~ total 50tons)

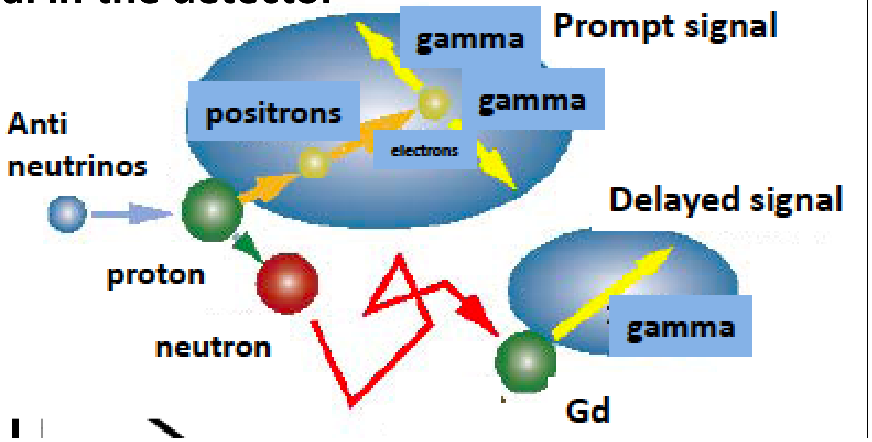
150 10" PMTs/detector
E resolution ~ 15%/√MeV

Delayed Coincidence (IBD)

$$\boxed{\overline{\nu}_\mu \underset{\text{oscillation}}{=>} \quad \overline{\nu}_e + p \rightarrow e^+ + n}$$

Identify ν with detecting
e^+ and γs from n capture on Gd.
=>Can reduce accidental BKG
(Gd~8MeV γs, capture time ~ several tens μs).

IBD Signal in the detector

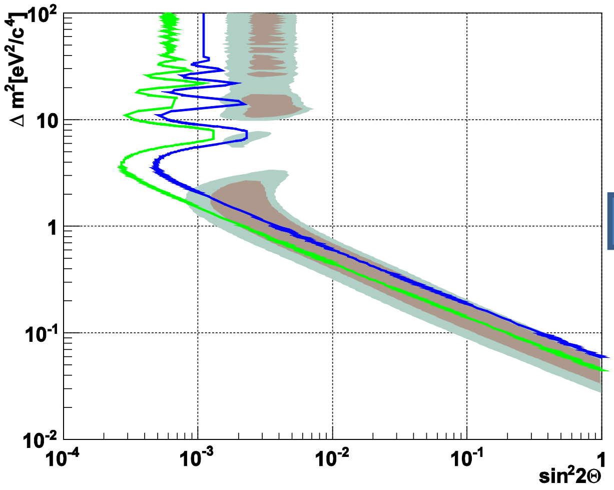


Selection criteria for IBD

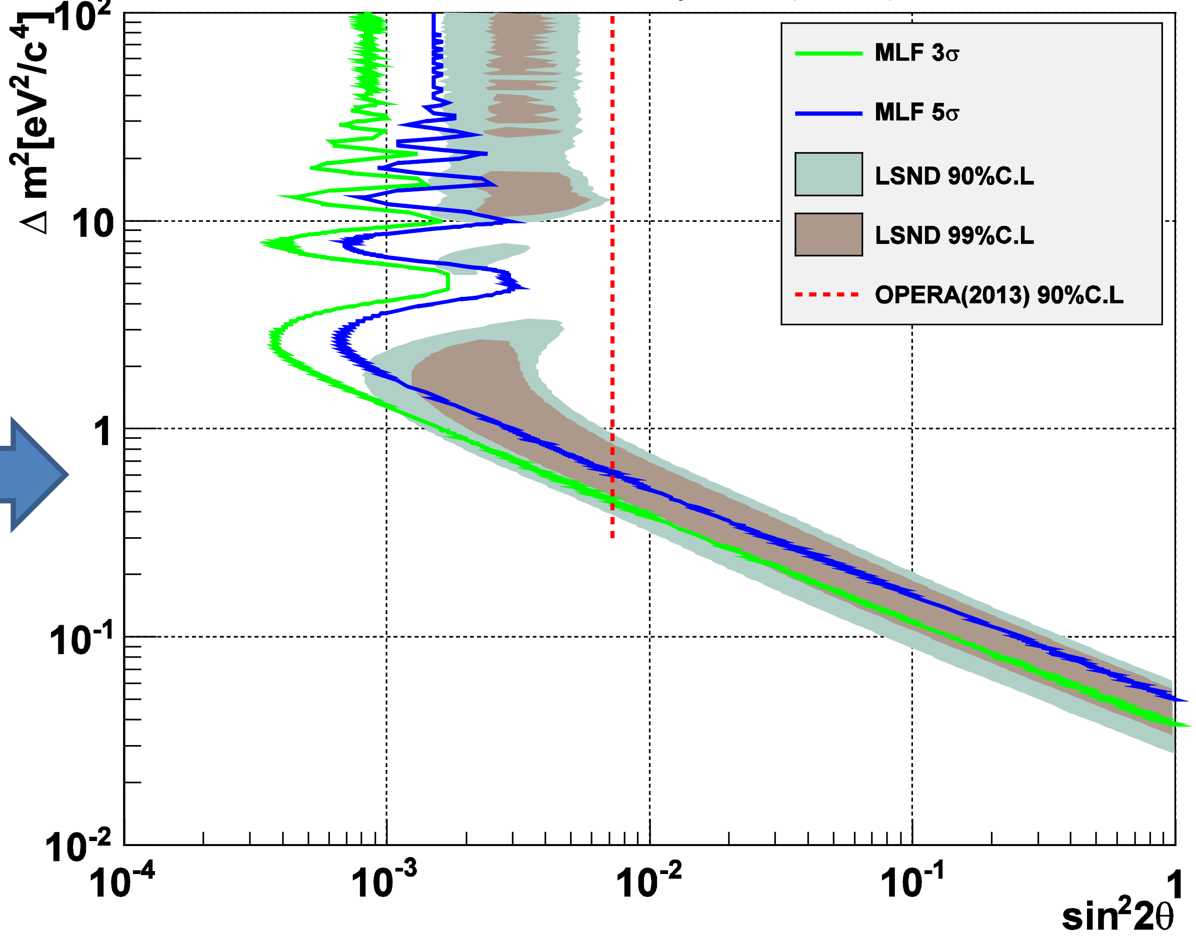
	Time from beam	Energy
Prompt signal	1<T<10μs	20<E<60MeV
Delayed signal	T<100μs	6<E<12MeV

Sensitivity

MW × 4years @ 17m
(proposal)



MW × 5years (24m)



- To manage BKG; baseline 17m → 24m. #signal events are decreased.
- But, low Δm^2 can be explored easily.
- Operation time is 5 years to compensate the baseline changing.
- LSND allowed region -> 5σ with $\Delta m^2 > 2.0\text{eV}^2$. Almost all regions can be discussed with 3σ

IsoDAR

Phys. Rev. D 89, 057301 (2014)

IsoDAR involves the construction of a cyclotron next to an underground detector (e.g. KamLAND or JUNO). 60 MeV protons interact on a Be target, surrounded by ^{7}Li. Neutrons capturing on ^{7}Li produce ^{8}Li, which beta decays, producing $\overline{\nu}_e$ with <E> ~ 6.5 MeV. The $\overline{\nu}_e$ are detected by the $\overline{\nu}_e$ p -> e^+ n reaction.

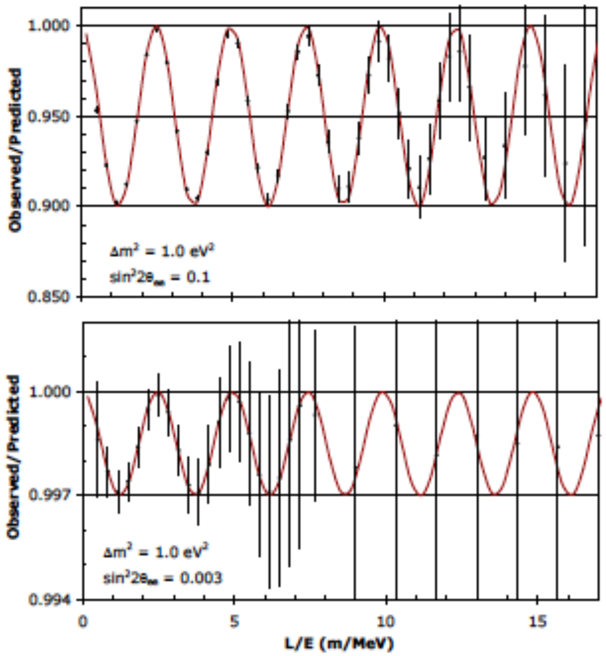


FIG. 3: The L/E dependence of the oscillation signature after five years of IsoDAR@JUNO running for $\Delta m^2 = 1.0$ eV^2 and $\sin^2 2\theta = 0.1$ (top) –a solution within the Global Fit allowed region– and $\sin^2 2\theta = 0.003$ (bottom) –a solution within the Global $\bar{\nu}_e$ Appearance allowed region. The black points are the simulated data and the solid curve is the oscillation probability with no smearing in the reconstruction of position and energy.

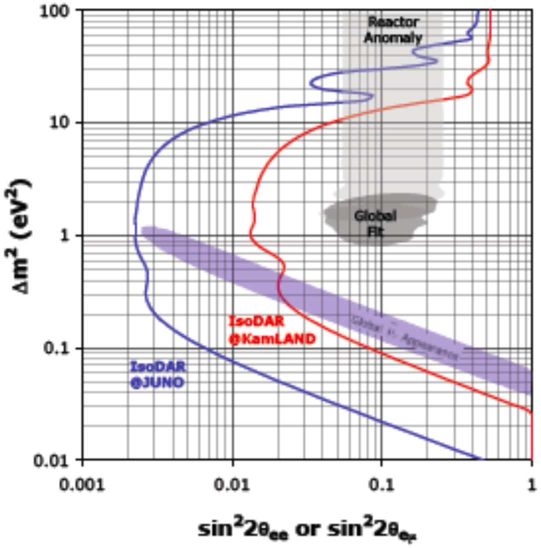
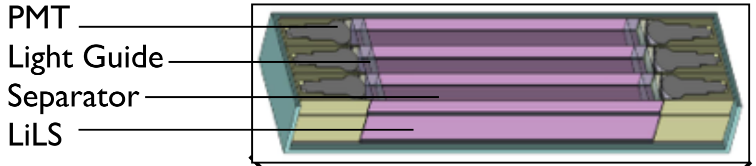


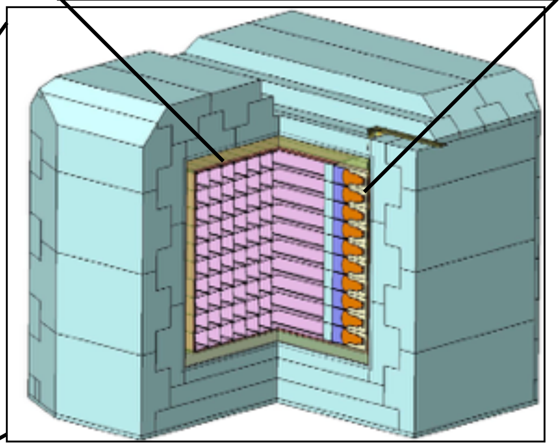
FIG. 1: Allowed regions and sensitivities for various experiments. The red and blue solid curves indicate Δm^2 vs. $\sin^2 2\theta_{ee}$ boundaries where the null oscillation hypothesis can be excluded at 5σ with IsoDAR@KamLAND and IsoDAR@JUNO experiments respectively for five-year data runs. Also, shown by the light (dark) gray areas are the 99% allowed regions for the Reactor Anomaly[5] (Global Oscillation Fit[7]). Finally, the purple region corresponds to the Δm^2 vs. $\sin^2 2\theta_{e\mu}$ allowed region at 99% CL from a combined fit to all $\bar{\nu}_e$ appearance data[1].

PROSPECT Experimental Layout

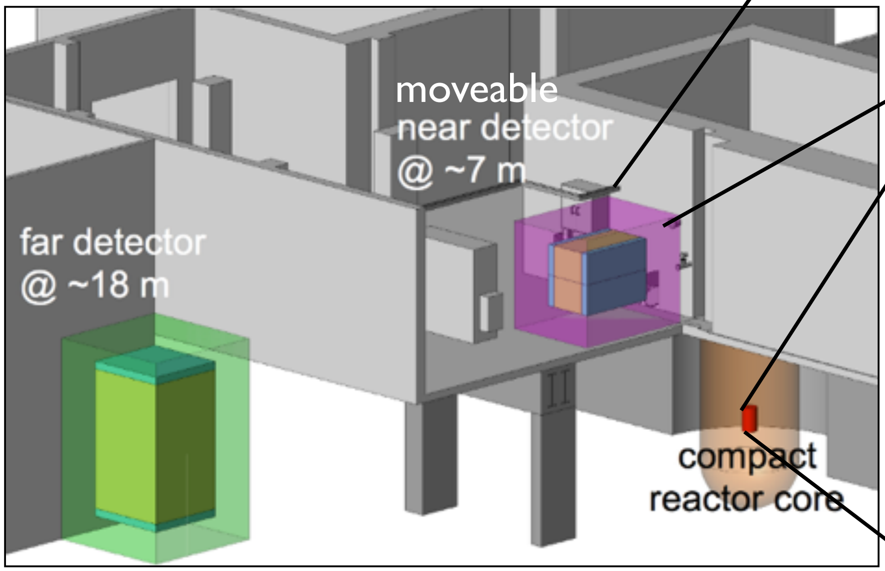
- High Flux Isotope Reactor: ORNL
- Extensive passive shielding
- Segmented liquid scintillator target region: ~3 tons for near detector (Phase I)
- Moveable: 7-11 m baselines

Sub-cell conceptual design

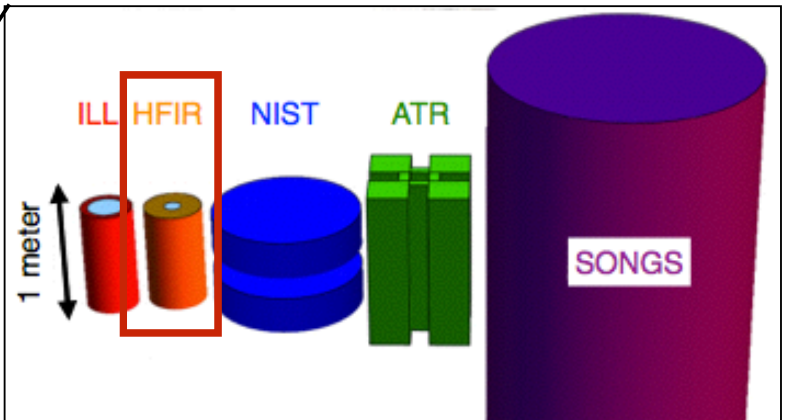




Near detector conceptual design



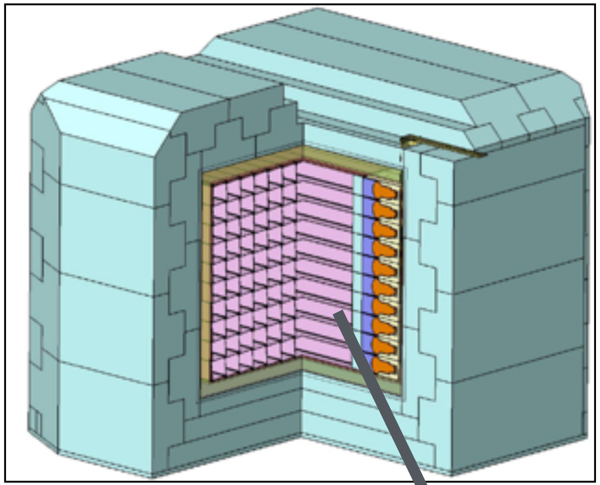
Two-detector PROSPECT deployment at HFIR

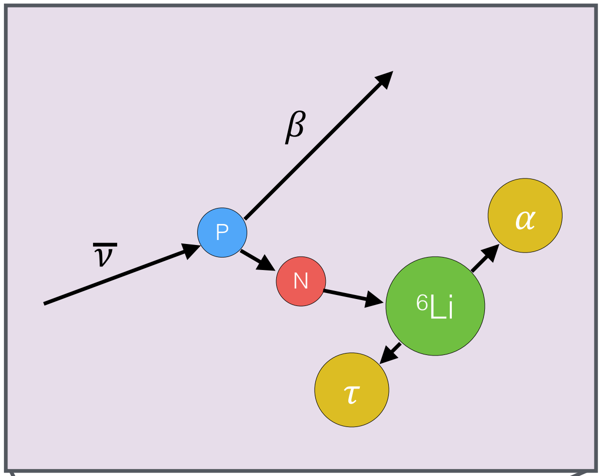


HFIR core shape and relative size comparison

IBD Detection in Target

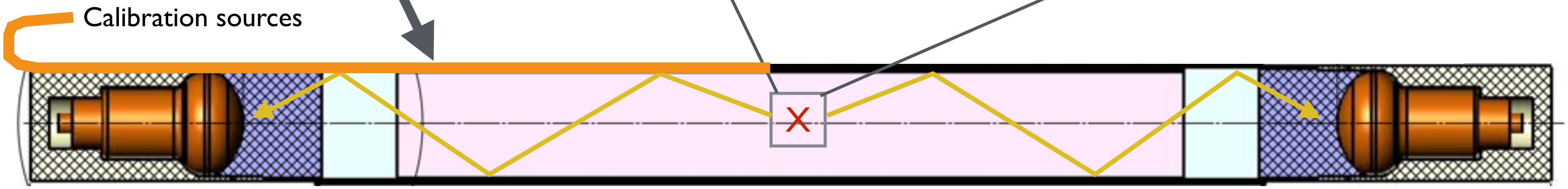
- Inverse beta interactions in Li-loaded PSD liquid scintillator
- 10 x 14 optically decoupled cells: ~15cm x 15cm x 100cm each
- Specularly reflecting cell walls quickly guide light to PMTs
- System can meet position/energy resolution requirements





Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

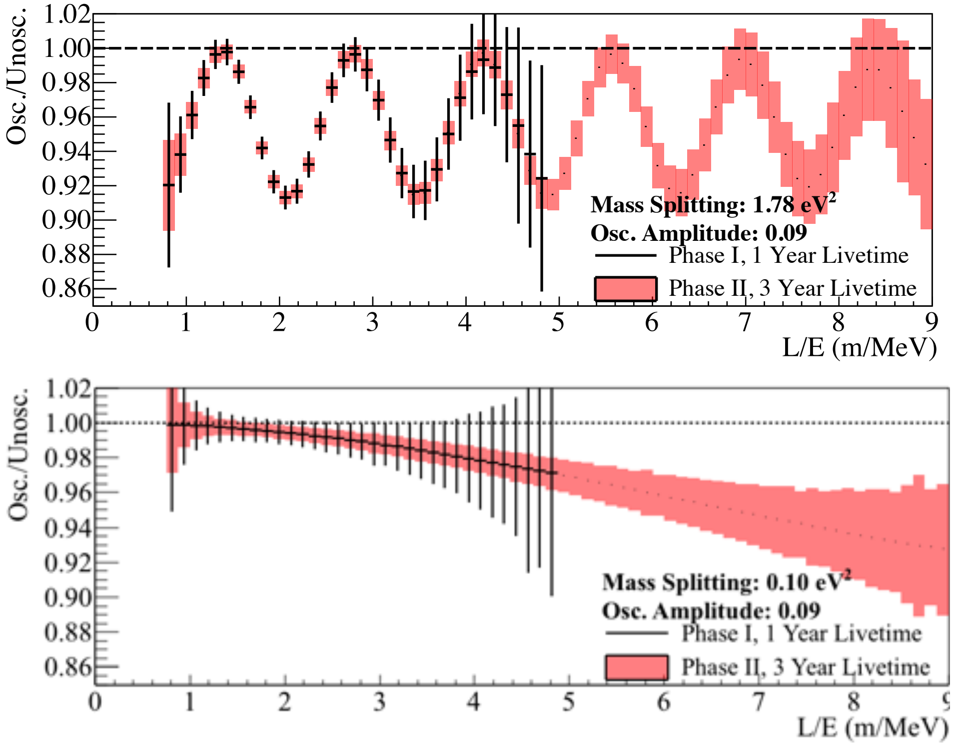
Delay signal: ~0.5 MeV signal from neutron capture on ^{6}Li

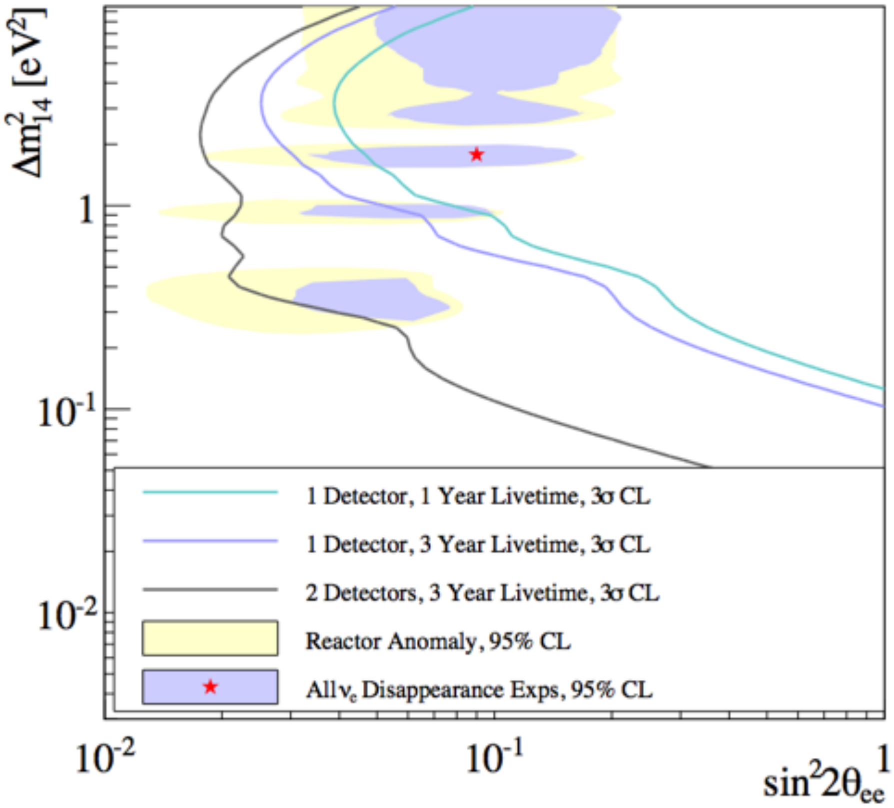


PROSPECT Physics: Oscillations

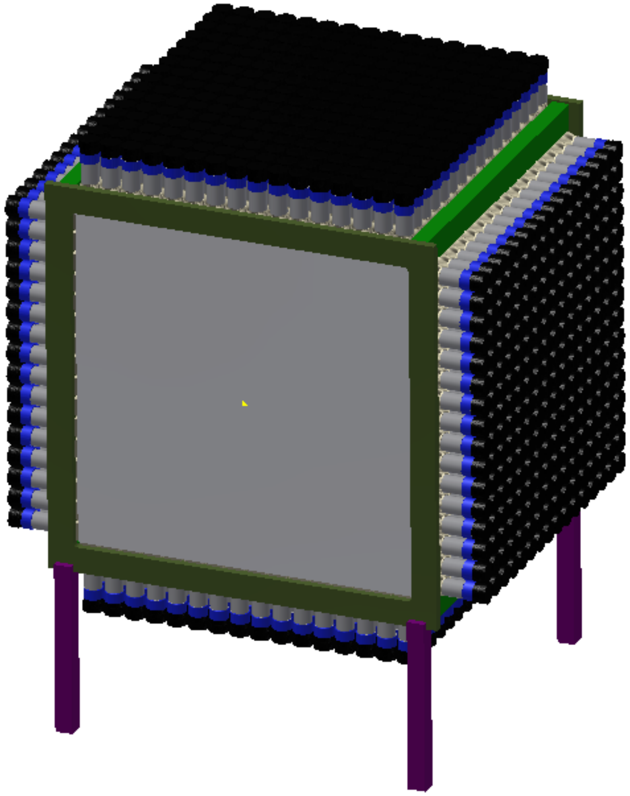
- Excellent oscillation discovery potential at PROSPECT
    - If new sterile neutrino is where global fits suggest, it’s very likely we’ll see it!
    - No reliance on absolute spectral shape or normalization: pure relative measurement
    - Good coverage with a single detector and one/three calendar years of data-taking

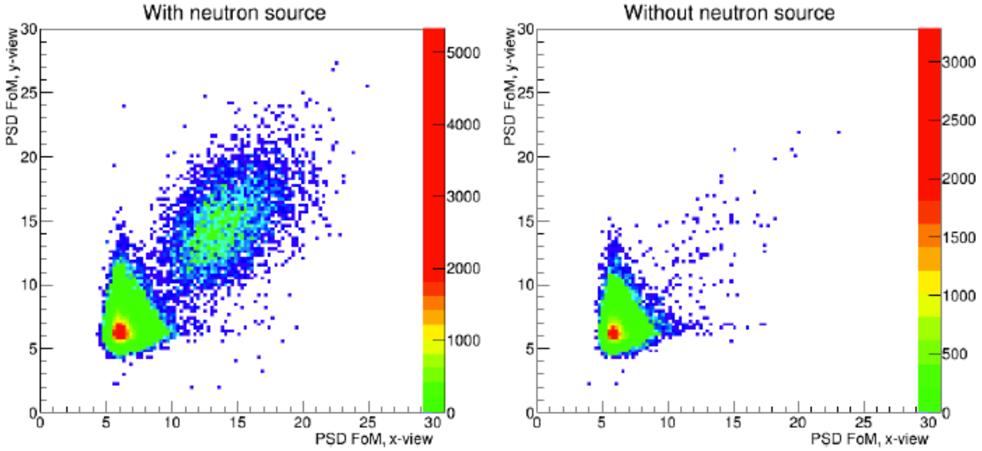
Simulated PROSPECT data, binned in L/E; Stat err. only

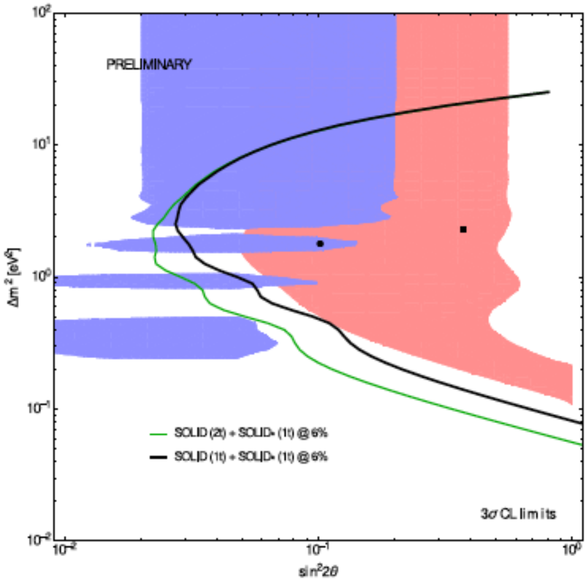




Chandler/SOLID Reactor Neutrino Experiment



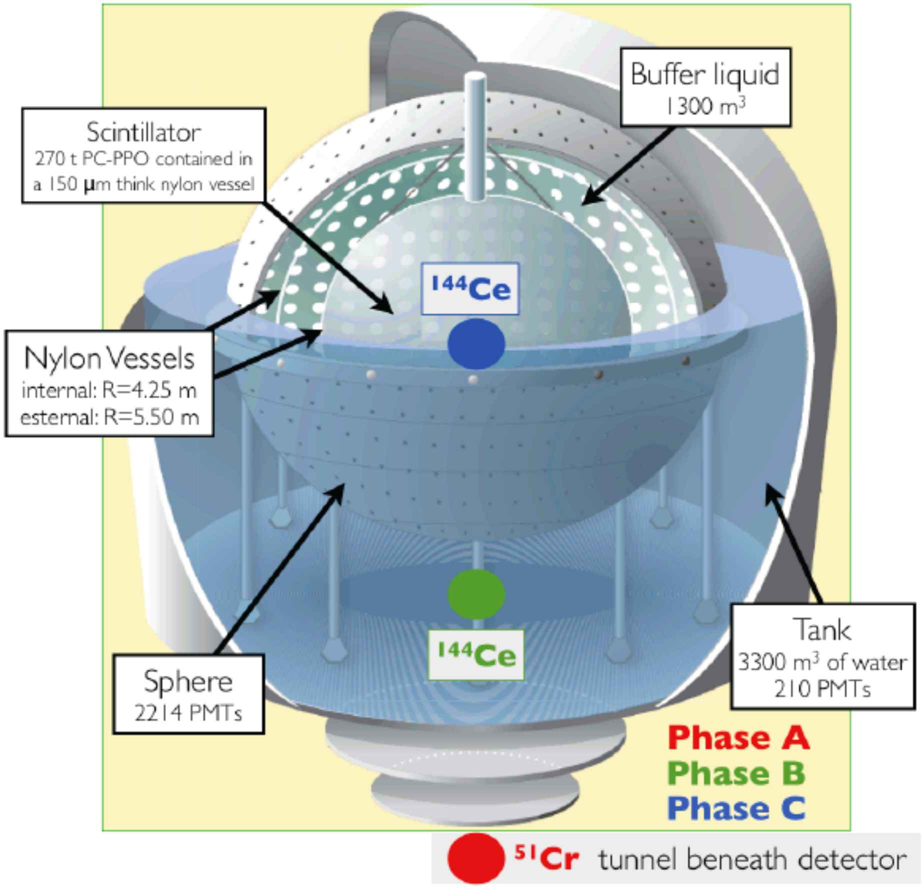


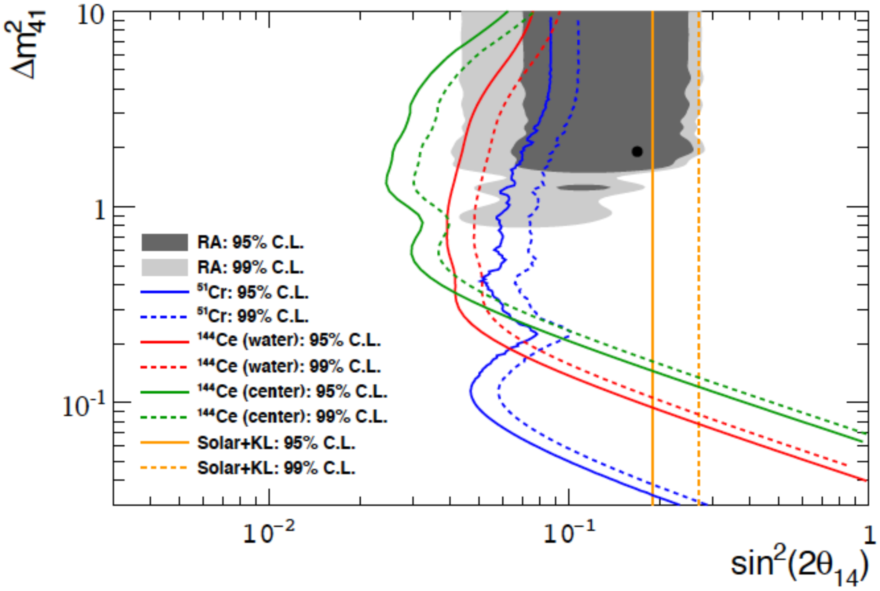


Chandler consists of a 16x16x16 array of scintillator cubes (6.2x6.2x6.2 cm^3) with sheets of ^{6}LiF and ZnS phosphor mixture for neutron identification.

SOX Radioactive Source Experiment

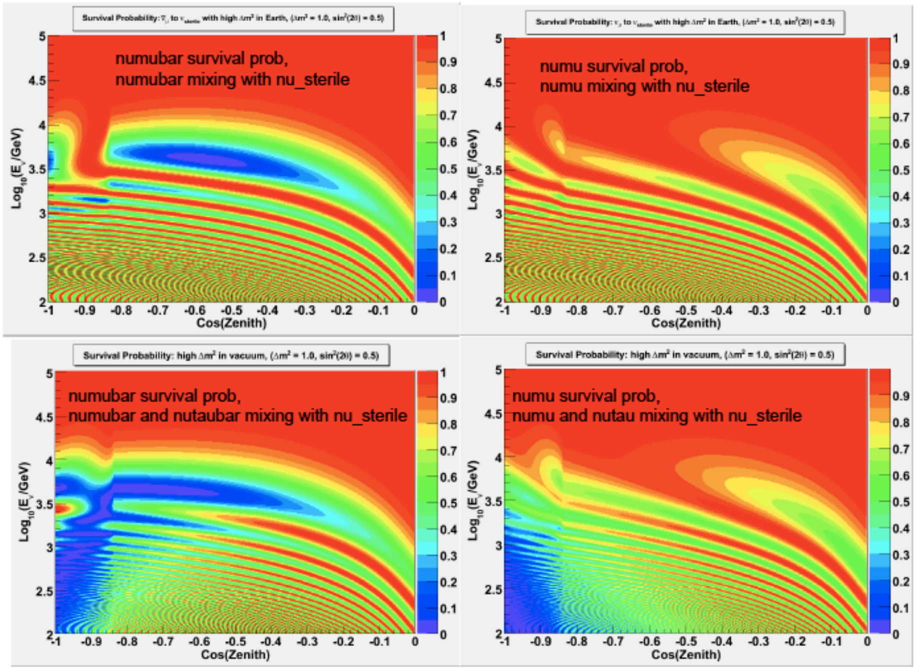
arXiv:1410.0779

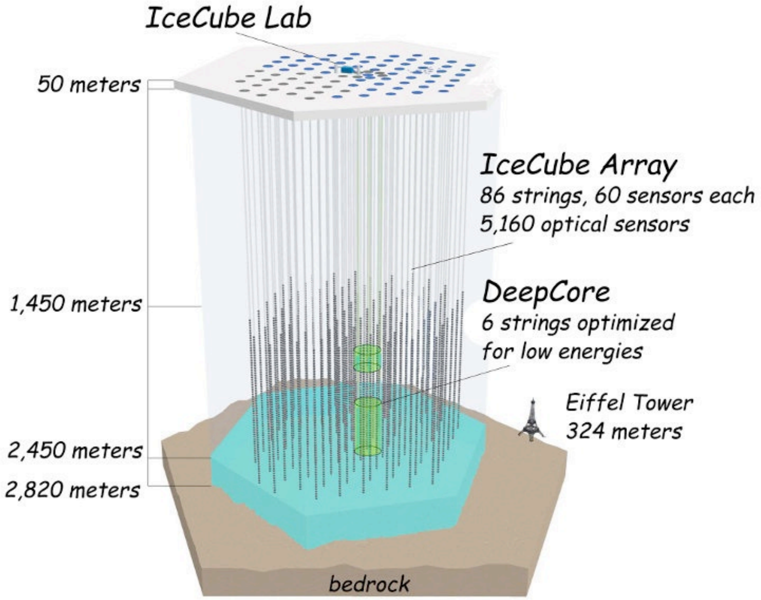




SOX will search for $\bar{\nu}_e$ (^{144}Ce) and ν_e (^{51}Cr) disappearance by placing intense radioactive sources (200-400 PBq) near or inside the BOREXINO detector.

IceCube Experiment at the South Pole

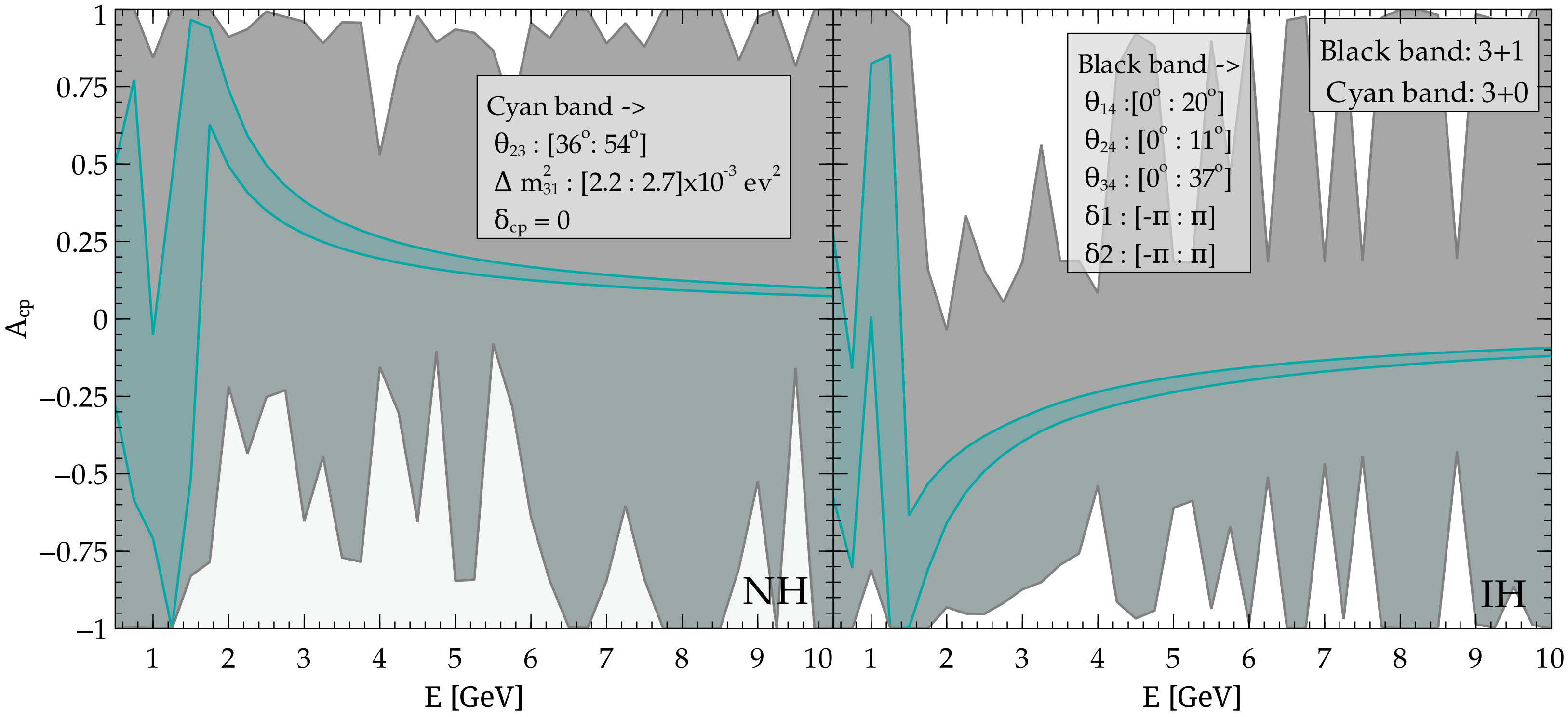




IceCube is searching for ν_μ disappearance with atmospheric neutrinos. Sterile neutrinos will cause “matter-enhanced” oscillations.

DUNE Long-Baseline ν Experiment

DUNE Expectation from Boris Kayser



3+0 with no ~~CP~~ (as in 1st plot), and 3+1 with ~~CP~~.

In 3+1 ~~CP~~ has a ***huge*** *effect.*

Effect of 3+1 Sterile ν Model on Long-Baseline Expts.

*** Best fit to T2K data**

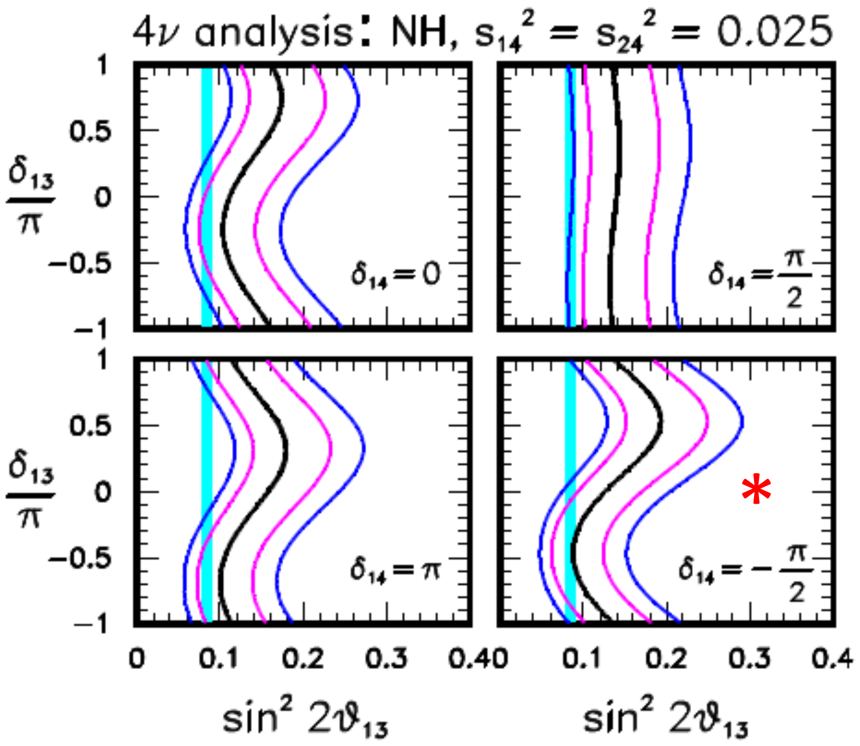


FIG. 3: Regions allowed by T2K for four values of CP-phase δ_{14}. Normal hierarchy is assumed. The mixing angle θ_{23} is marginalized away. The vertical band represents the region allowed by reactor experiments. Confidence levels as in Fig. 2.

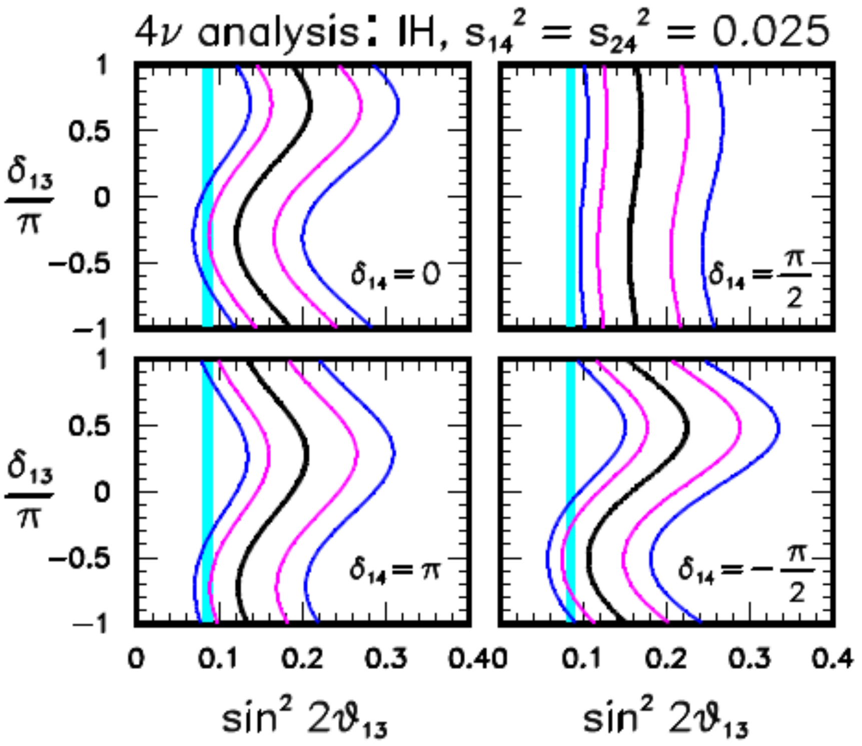
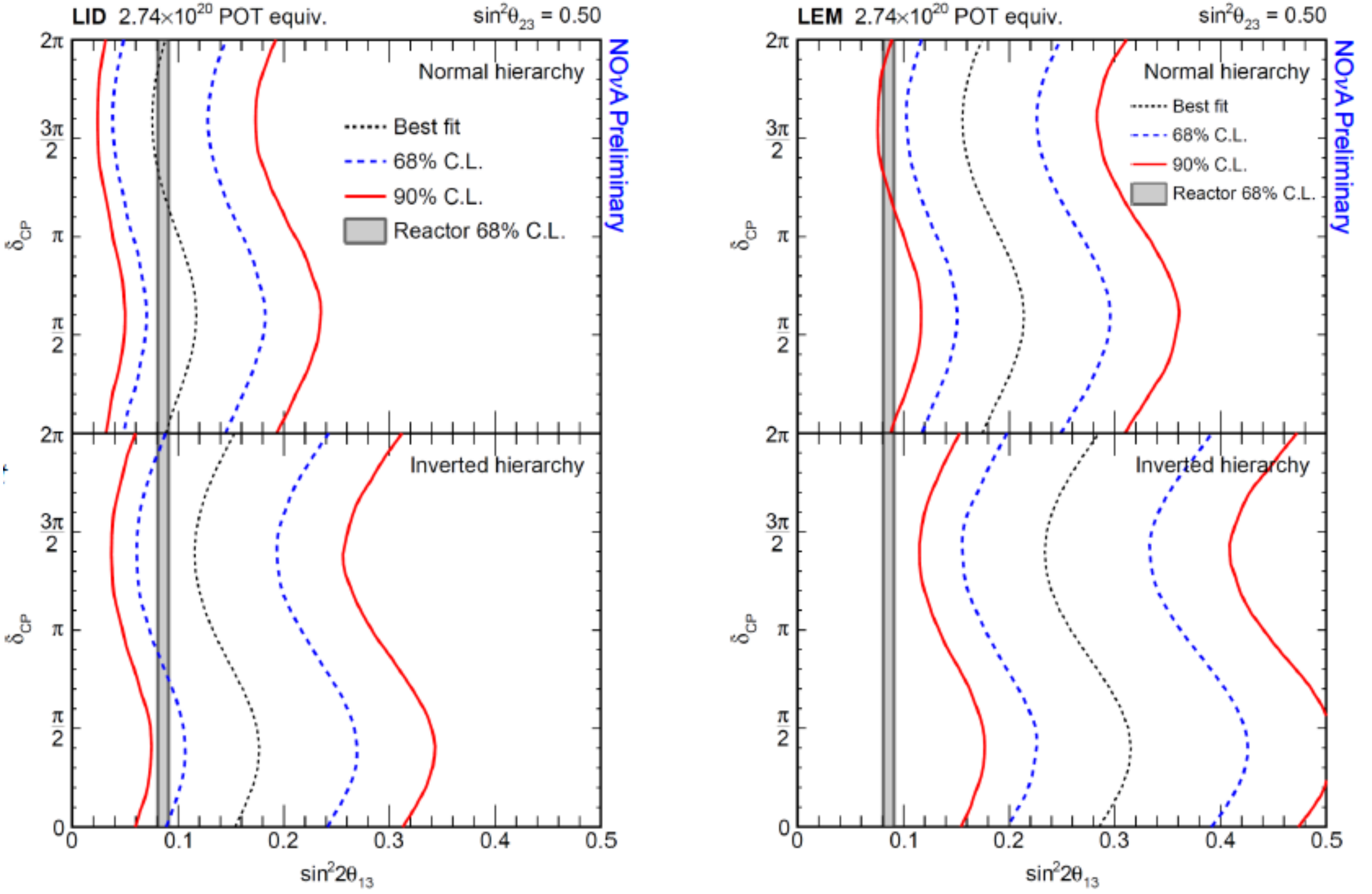


FIG. 4: Regions allowed by T2K for four values of CP-phase δ_{14}. Inverted hierarchy is assumed. The vertical band represents the region allowed by reactor experiments. The mixing angle θ_{23} is marginalized away. Confidence levels as in Fig. 2.

Klop & Palazzo, arXiv:1412.7524

Effect of 3+1 Sterile ν Model on Long-Baseline Expts.



NOvA Preliminary Results

Conclusion

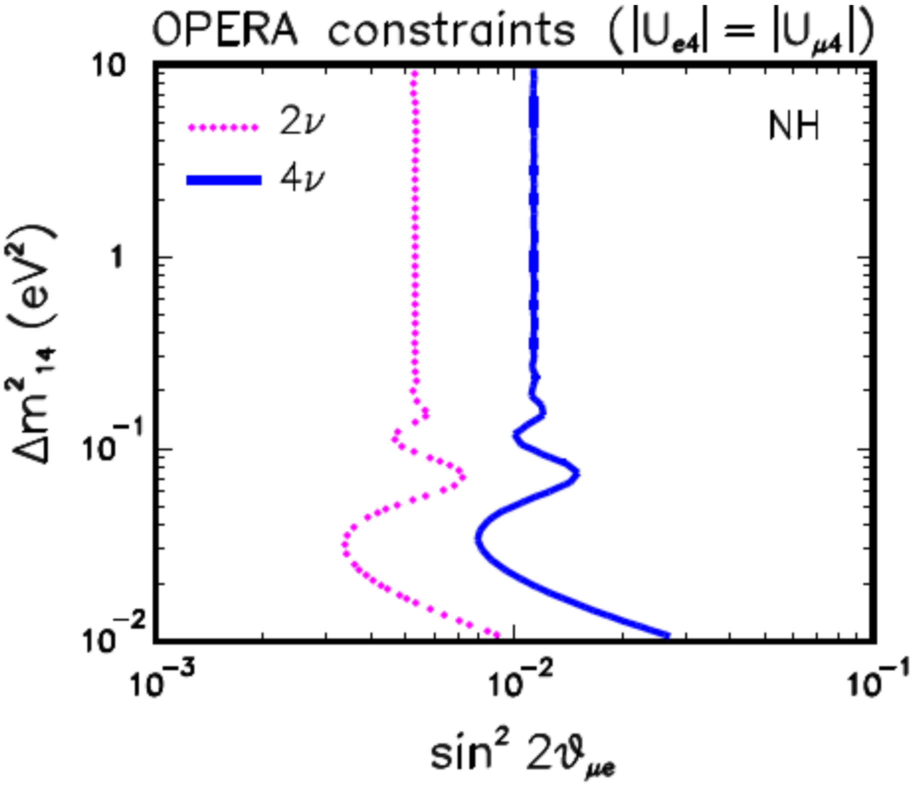
- The results from LSND & MiniBooNE and the other anomalies in short baseline ν experiments cannot be explained by the 3 ν paradigm and suggest the existence of sterile ν.
- Sterile ν would contribute to the dark matter of the universe and would have a big impact on particle physics, nuclear physics, astrophysics and cosmology.
- The world neutrino & antineutrino data can be fit fairly well to a 3+N oscillation model, although there is some tension at present between appearance and disappearance experiments.
- Future experiments (e.g. SBN at Fermilab) have the golden opportunity of proving whether short-baseline oscillations and light, sterile neutrinos exist!

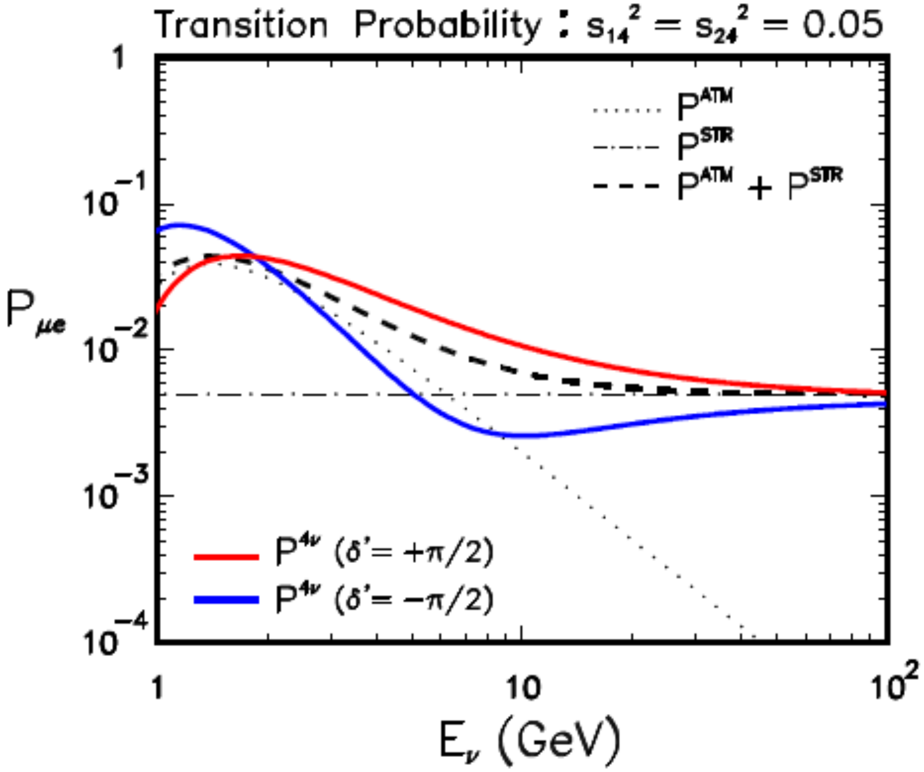
Backup

MiniBooNE Detector Tank

Limits from OPERA & ICARUS

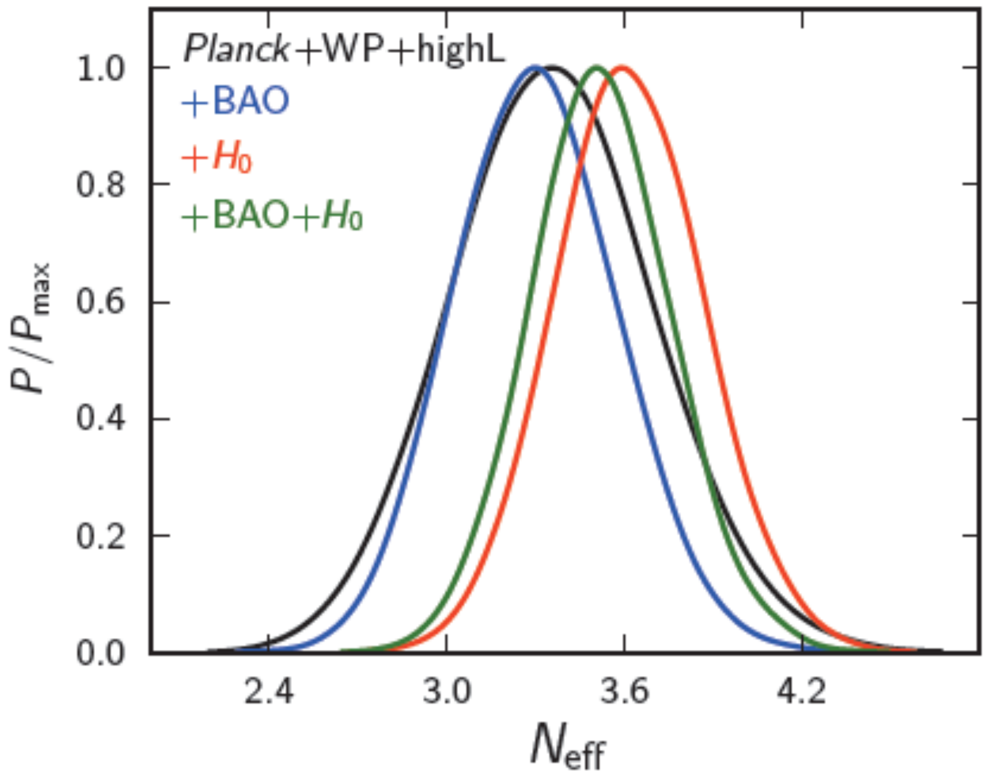
Antonio Pallazzo, arXiv:1503.03966



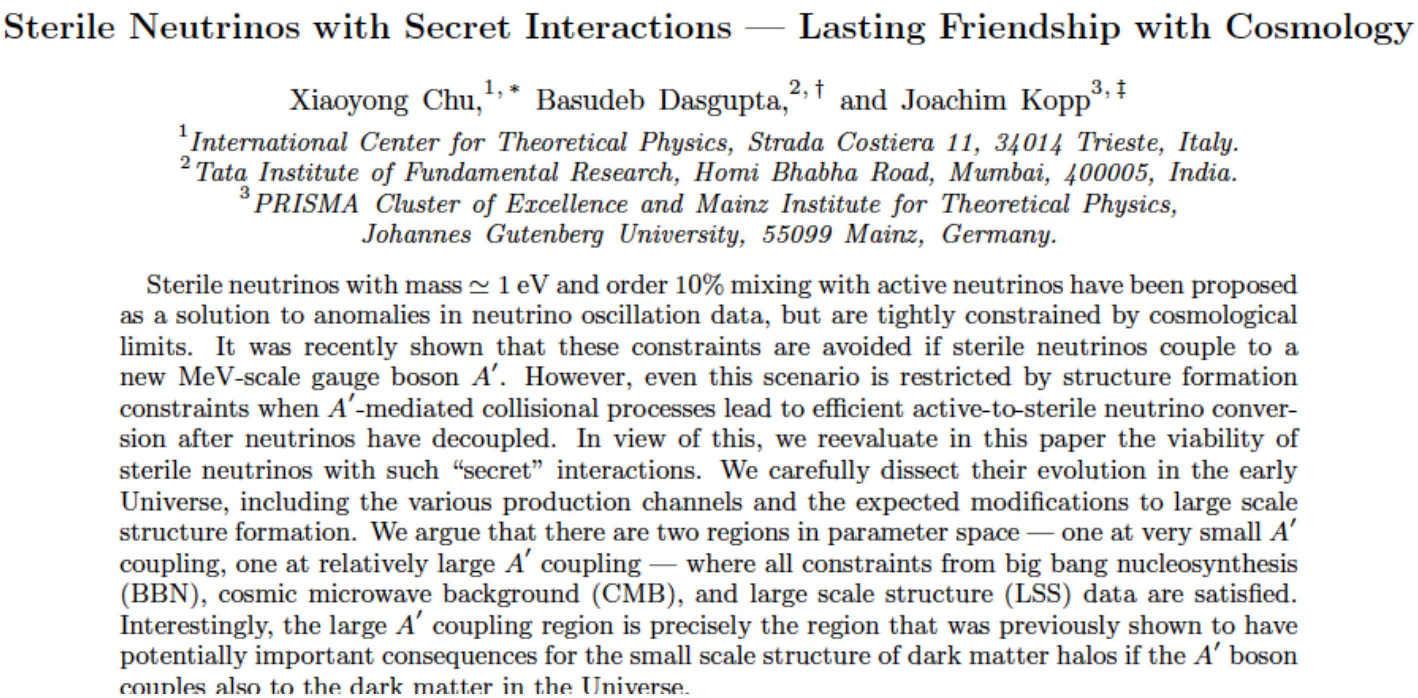


SPT & Planck Results

arXiv:1212.6267 & arXiv:1303.5076 & arXiv:1304.5981



Neff = 3.36+-0.34	CMB(Planck+ACT)
3.30+-0.27	CMB(Planck+ACT)+BAO
3.62+-0.25	CMB(Planck+ACT)+H_0
3.52+-0.24	CMB(Planck+ACT)+BAO+H_0
3.71+-0.35	CMB(SPT)+BAO+H_0
3.62+-0.24	CMB(Planck+SPT+ACT)+BAO+H_0



Sterile Neutrinos with Secret Interactions — Lasting Friendship with Cosmology

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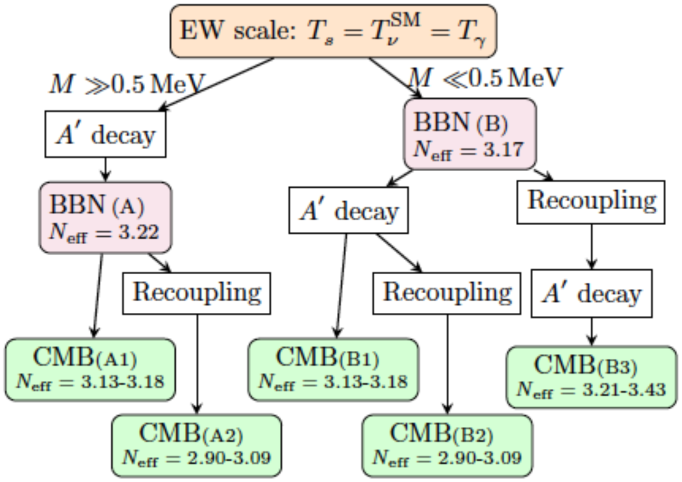
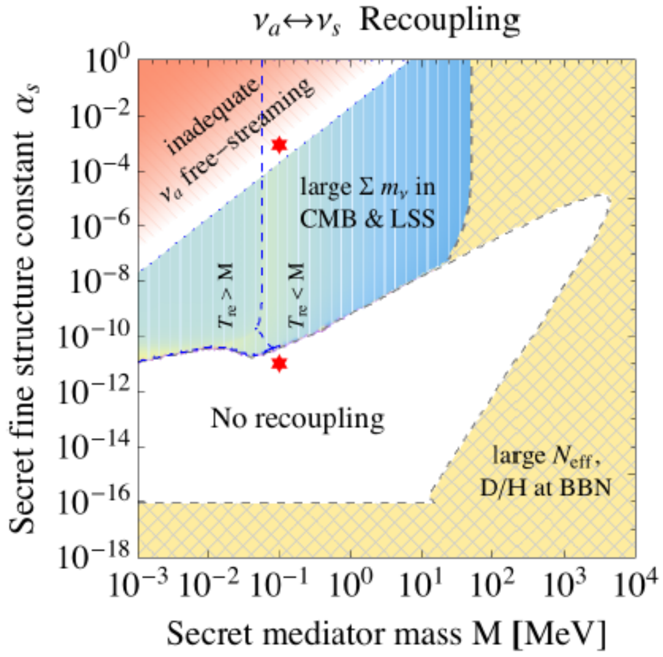
Sterile neutrinos with mass $\simeq 1$ eV and order 10% mixing with active neutrinos have been proposed as a solution to anomalies in neutrino oscillation data, but are tightly constrained by cosmological limits. It was recently shown that these constraints are avoided if sterile neutrinos couple to a new MeV-scale gauge boson A'. However, even this scenario is restricted by structure formation constraints when A'-mediated collisional processes lead to efficient active-to-sterile neutrino conversion after neutrinos have decoupled. In view of this, we reevaluate in this paper the viability of sterile neutrinos with such "secret" interactions. We carefully dissect their evolution in the early Universe, including the various production channels and the expected modifications to large scale structure formation. We argue that there are two regions in parameter space — one at very small A' coupling, one at relatively large A' coupling — where all constraints from big bang nucleosynthesis (BBN), cosmic microwave background (CMB), and large scale structure (LSS) data are satisfied. Interestingly, the large A' coupling region is precisely the region that was previously shown to have potentially important consequences for the small scale structure of dark matter halos if the A' boson couples also to the dark matter in the Universe.

arXiv:1505.02795

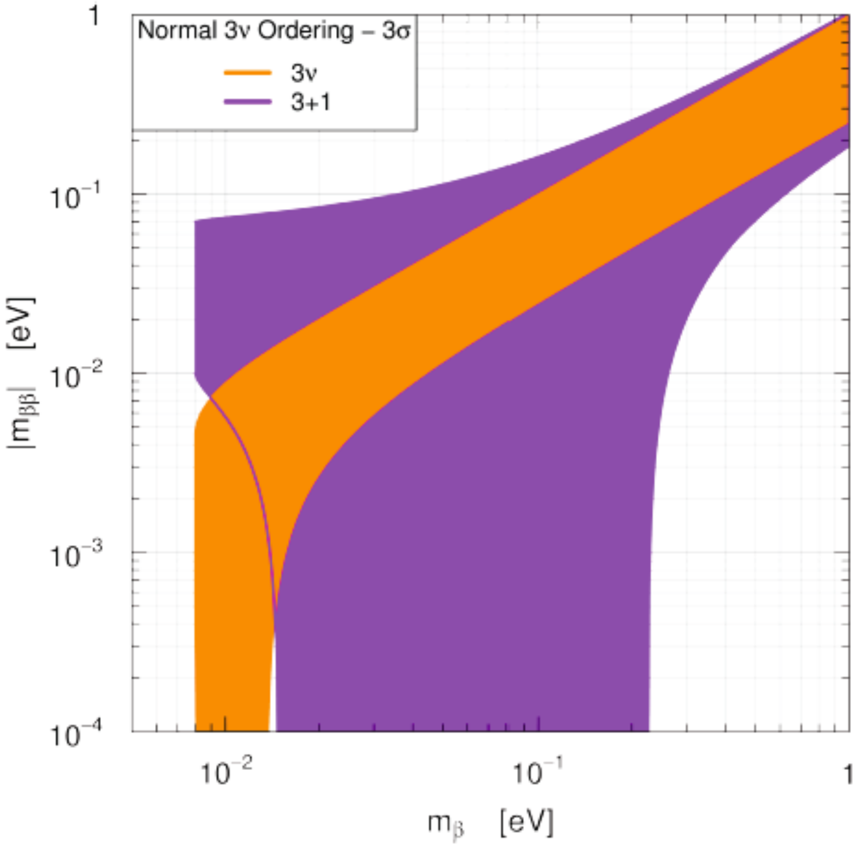


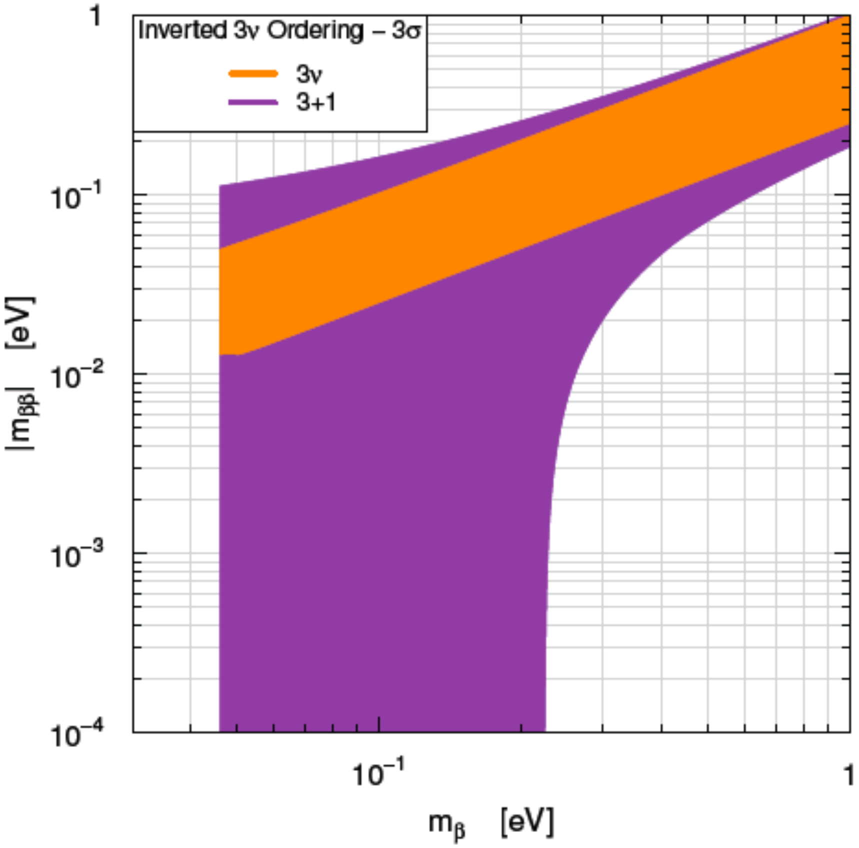
N_{eff} is consistent with Planck Measurements (N_{eff} = 3.15+-0.23)



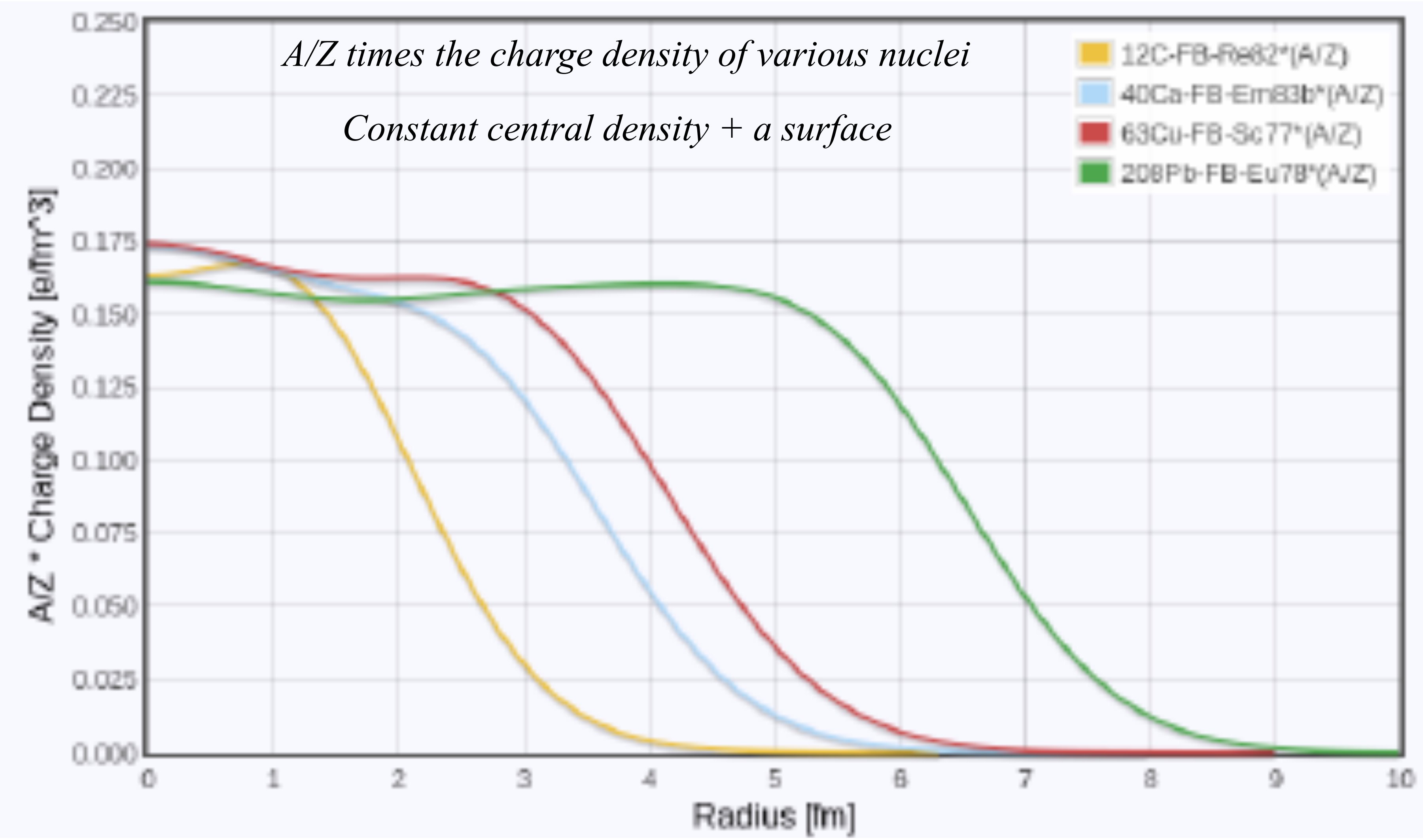
Double β Decay & Tritium β Decay in 3+1 Model

arXiv:1505.00978





Nuclear Universality



A/Z times the charge density of various nuclei

Constant central density + a surface

Effect of 3+1 Sterile ν Model on Long-Baseline Expts.

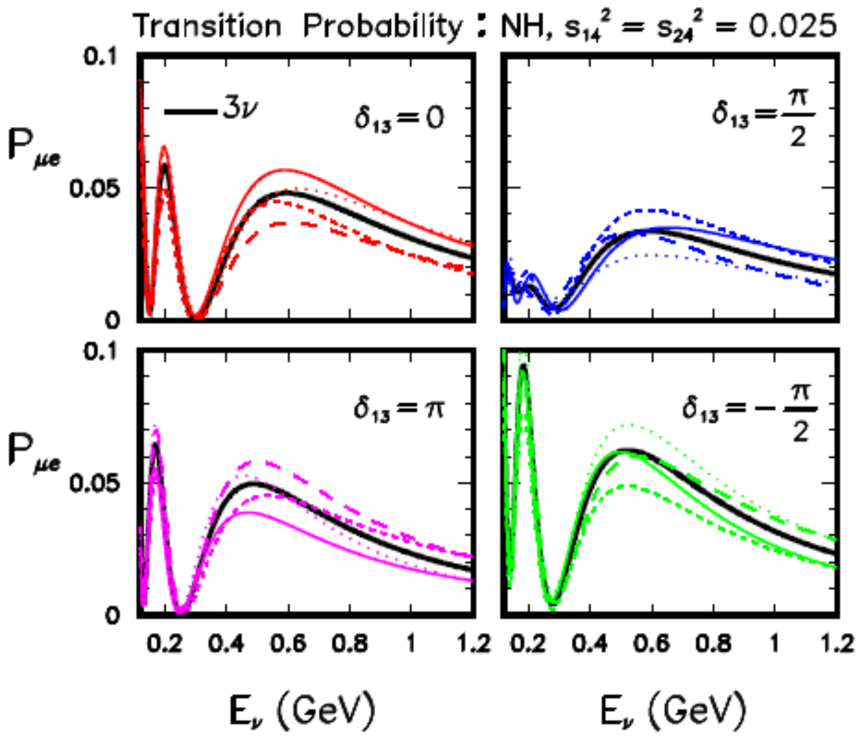
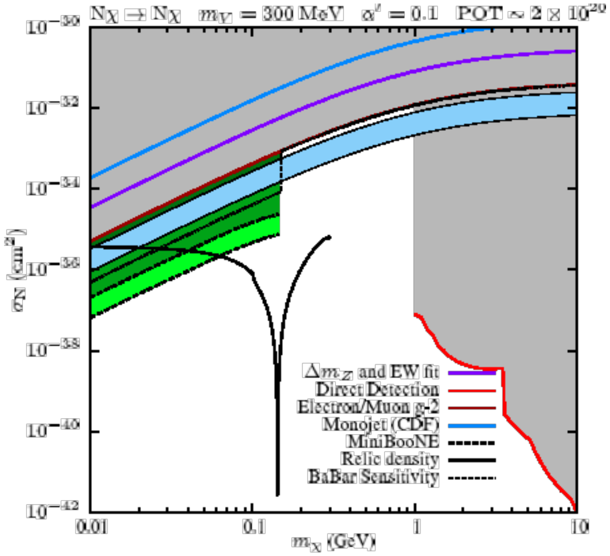


FIG. 7: Probability of $\nu_\mu \to \nu_e$ transition in the 3+1 scheme. The four panels correspond to four different values of the standard CP-phase δ_{13}. In each panel, the black thick solid line represents the 3-flavor case ($\theta_{14} = \theta_{24} = 0$), while the colored lines represent the 4-flavor case (with $s_{14}^2 = s_{24}^2 = 0.025$) for the following four different values of the non-standard CP-phase: $\delta_{14} = 0$ (solid), $\delta_{14} = \pi$ (long-dashed), $\delta_{14} = \pi/2$ (short-dashed), $\delta_{14} = -\pi/2$ (dotted).

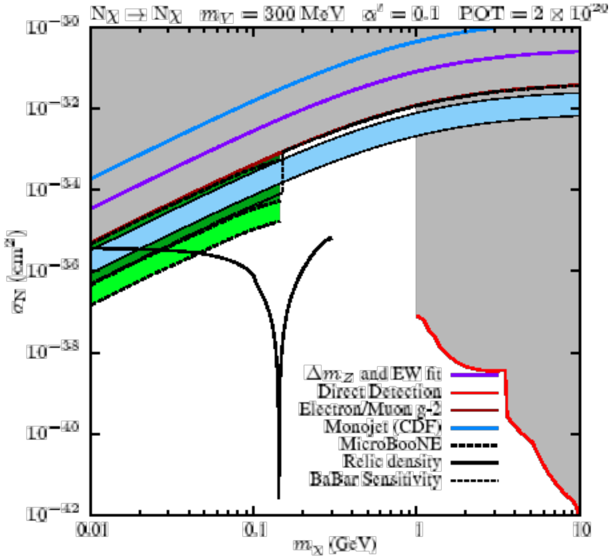
Klop & Palazzo, arXiv:1412.7524

Signal Sensitivities for DM-NUCLEON Scattering (2E20 POT) Cross Section vs. Dark Matter Mass

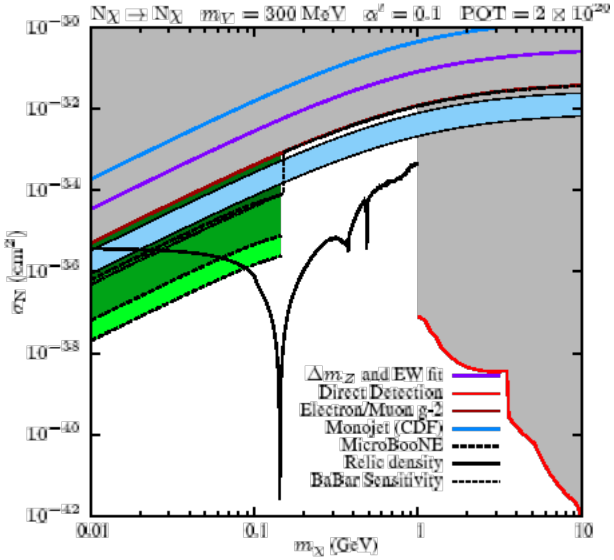
MiniBooNE-CH_2



MicroBooNE-LAr



SBND



- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.
- **SBND does an order of magnitude better!**