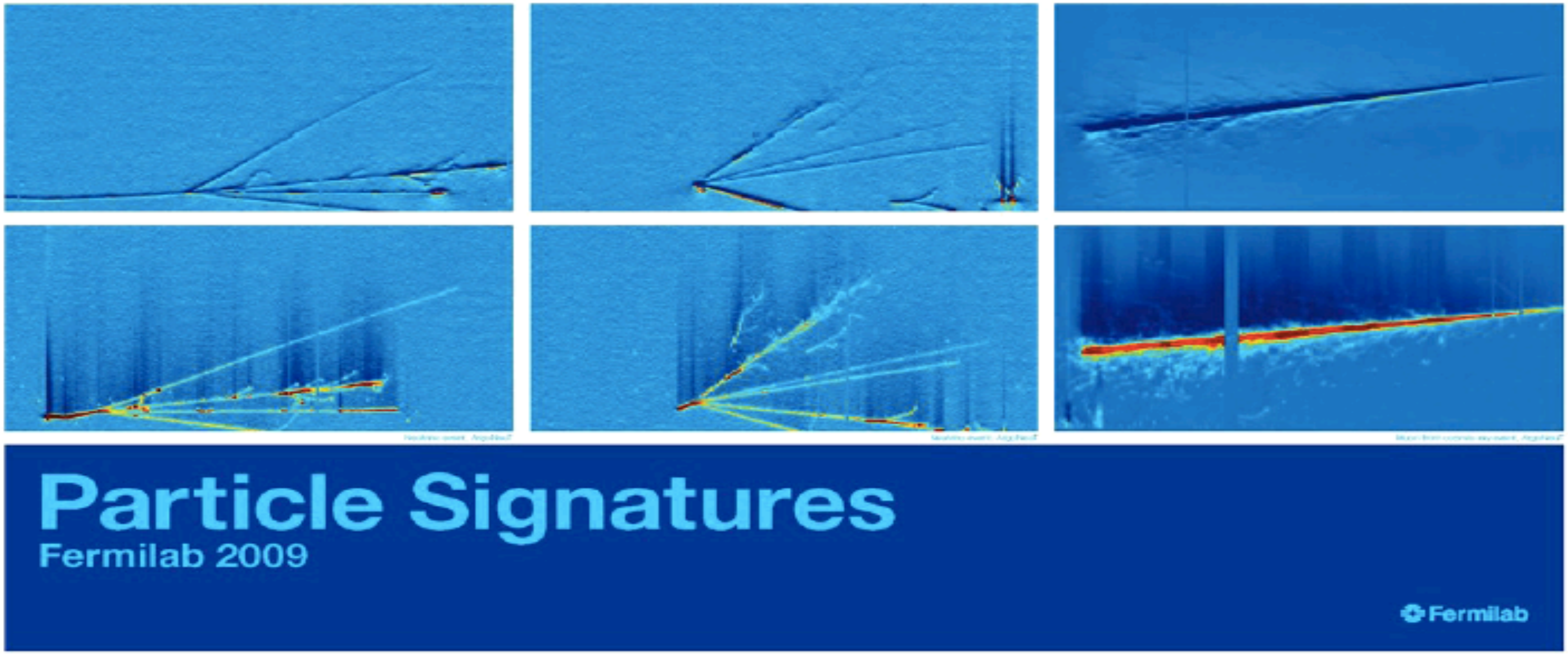


Searching for sterile neutrinos with LAr detectors

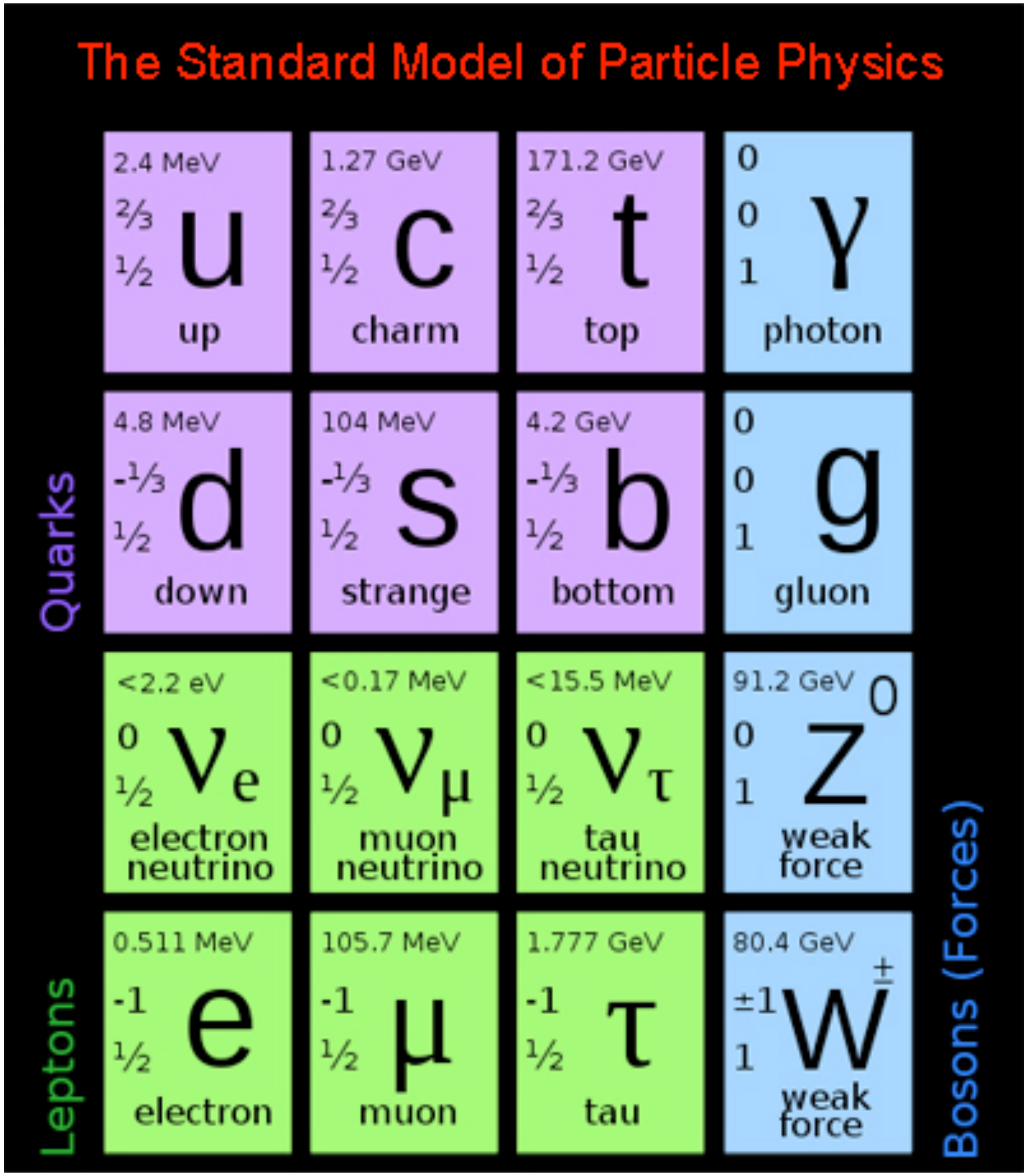
Roxanne Guenette
University of Oxford

25 February 2015

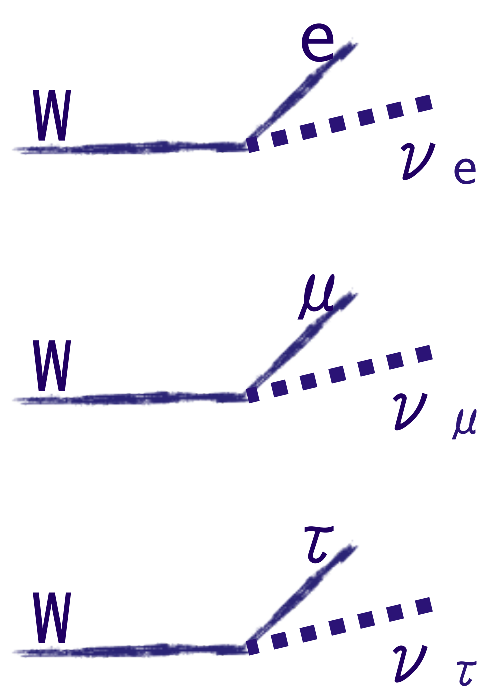
Outline

- Reminder on neutrinos and on oscillation physics
- LAr detectors for neutrino experiments
- Sterile Neutrinos: The Chronological Story…
- MicroBooNE
- The Short-Baseline Neutrino Programme at FNAL
- Conclusions

Neutrinos and Standard Model



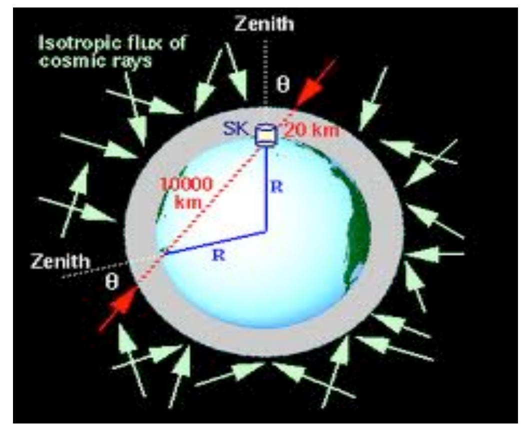
- Three flavors
- Weak Interaction Only
- Zero-mass



Neutrino oscillation: Experimental point of view

- Evidence from solar neutrino experiments

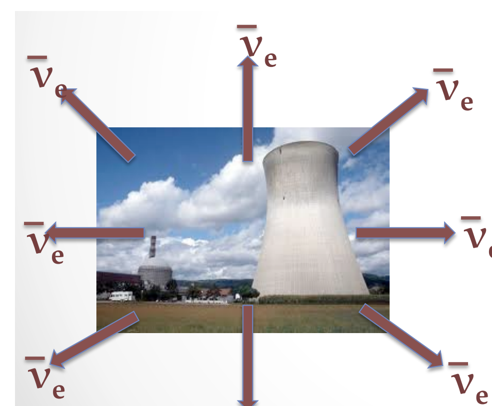
- Discovery of neutrino oscillation at SuperKamiokande (1998) with atmospheric neutrinos



- Confirmed by reactor experiments (KamLand)

- Confirmed by accelerator experiments

- **Now indisputable that neutrino oscillate!**



Neutrino oscillation: Theoretical point of view

- ν are the only particles of the SM defined by their flavor eigenstates (ν_e,ν_μ,ν_τ)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino oscillation: Theoretical point of view

- ν are the only particles of the SM defined by their flavor eigenstates (ν_e,ν_μ,ν_τ)

2 neutrino case

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p_i}\cdot\vec{x})}|\nu_i(0)\rangle$$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = sin^2 2\theta sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

Neutrino oscillation: Theoretical point of view

- ν are the only particles of the SM defined by their flavor eigenstates (ν_e,ν_μ,ν_τ)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = sin^2 2\theta sin^2 \left(1.27 \frac{\Delta m^2(eV^2) L(km)}{E(GeV)} \right)$$

➡ **Neutrino oscillation = neutrino masses!**

A bit more on neutrino oscillation

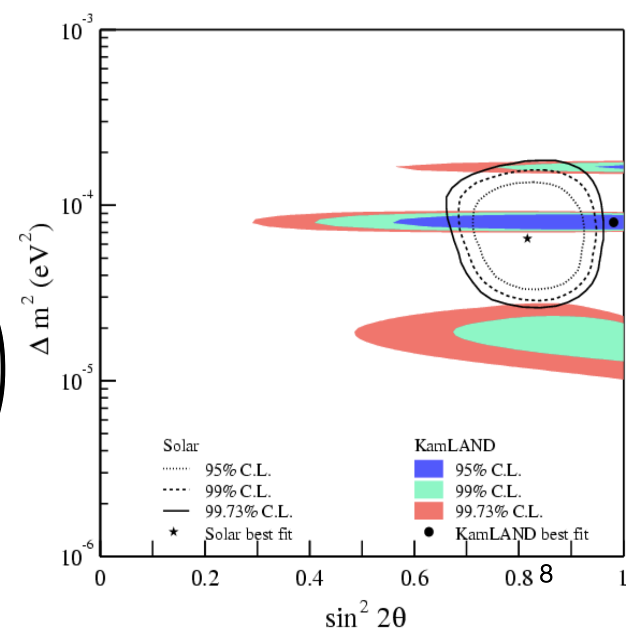
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \quad \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}} \quad \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

Atmospheric ν's:
Accelerator (long baseline)

Short baseline reactor ν's:
Accelerator (long baseline)

Solar ν's:



$$P_{\nu_\alpha \to \nu_\beta}(L,E) = sin^2 2\theta sin^2 \left(1.27 \frac{\Delta m^2 (eV^2) L(km)}{E(GeV)} \right)$$

A bit more on neutrino oscillation

- Study appearance channels

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = sin^2 2\theta sin^2 \left(1.27 \frac{\Delta m^2 (eV^2) L(km)}{E(GeV)}\right)$$

- Or study disappearance channels

$$P_{\nu_\alpha \to \nu_\alpha}(L, E) = 1 - sin^2 2\theta sin^2 \left(1.27 \frac{\Delta m^2 (eV^2) L(km)}{E(GeV)}\right)$$

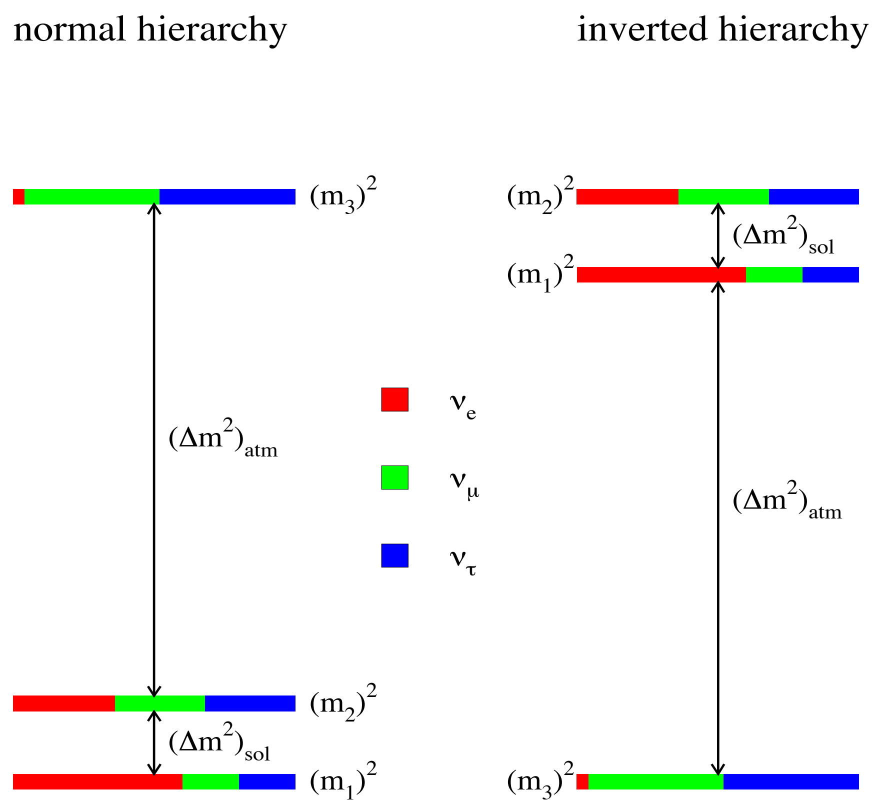
Neutrinos, the global picture

- 3 neutrinos

- Mass differences squared well known

Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	$2.43^{+0.06}_{-0.10}$ $(2.42^{+0.07}_{-0.11})$
$\sin^2\theta_{12}$	$0.307^{+0.018}_{-0.016}$
$\sin^2\theta_{23}$	$0.386^{+0.024}_{-0.021}$ $(0.392^{+0.039}_{-0.022})$
$\sin^2\theta_{13}$ [173]	0.0241 ± 0.0025 $(0.0244^{+0.0023}_{-0.0025})$

- What is the mass hierarchy?



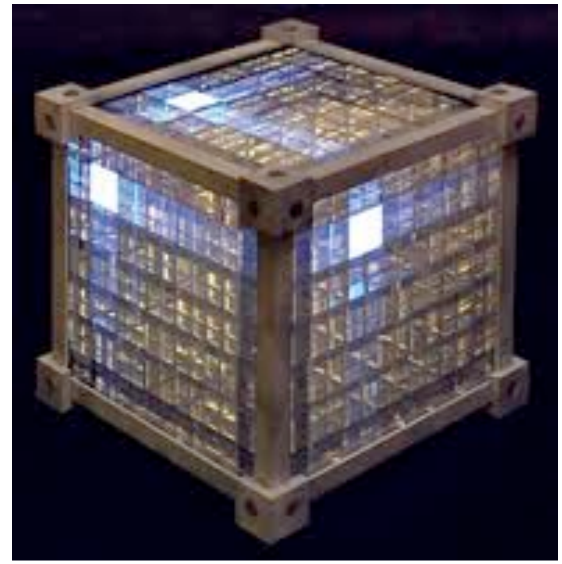
- Absolute mass:
  $0 < \Sigma m < 0.44$ (~2) eV

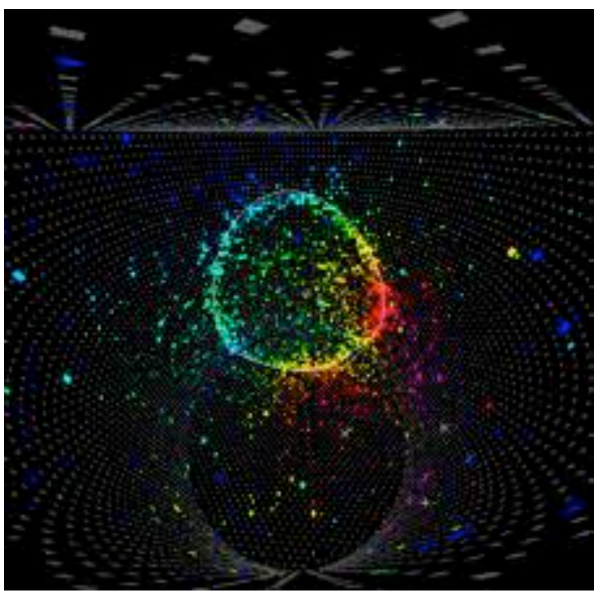
- Is there CP violation?
  (ν and $\bar{\nu}$ different?)

- What is δ_{CP}?

- Are there really 3 neutrinos??

NEUTRINO DETECTION

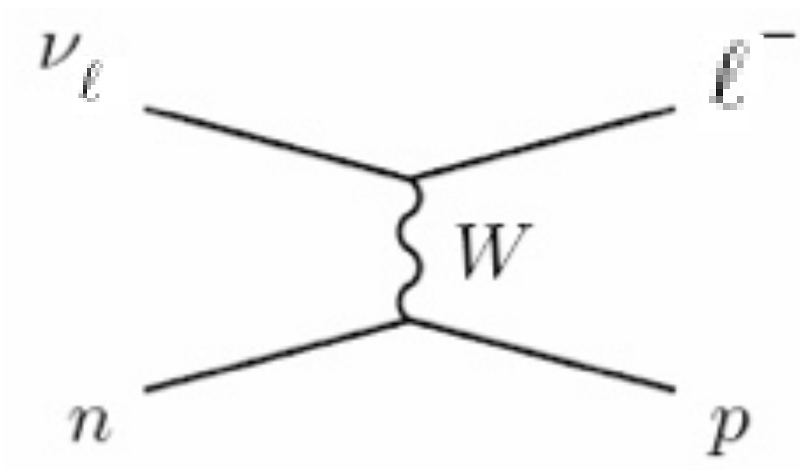




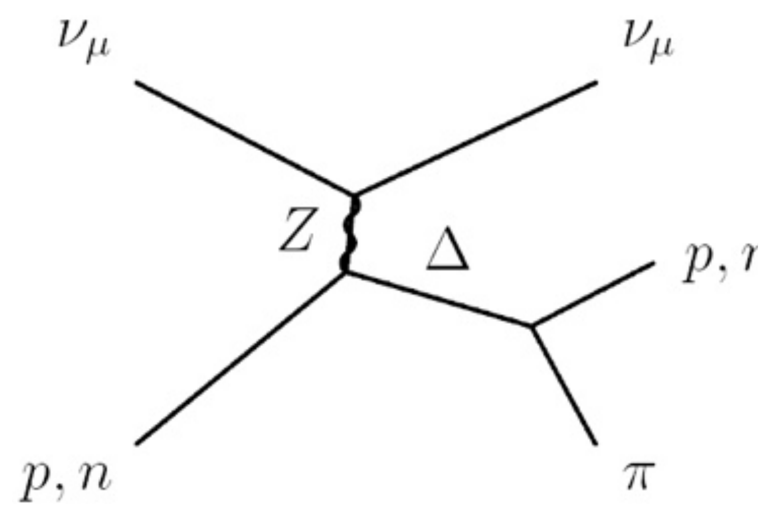
Neutrino detection

- Neutrinos are not detected directly
- Neutrinos interact through “Charged” and “Neutral” currents
- Interaction products are detected

Charge Current (CC) Interactions



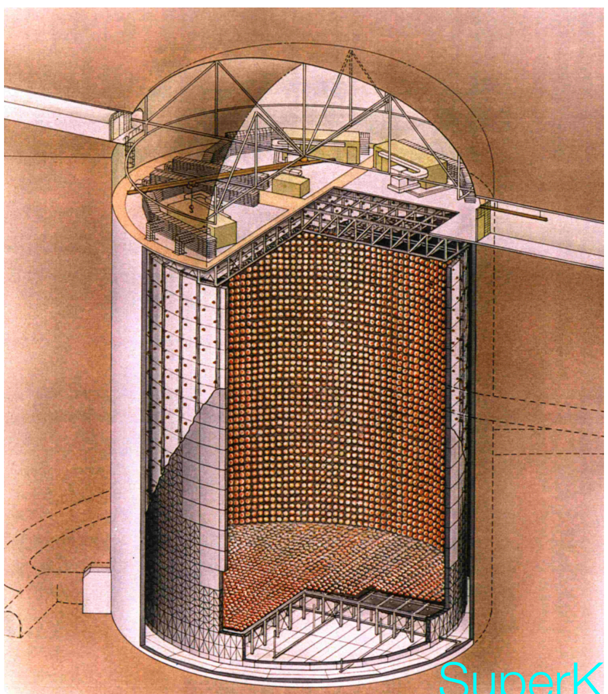
Neutral Current (NC) Interactions



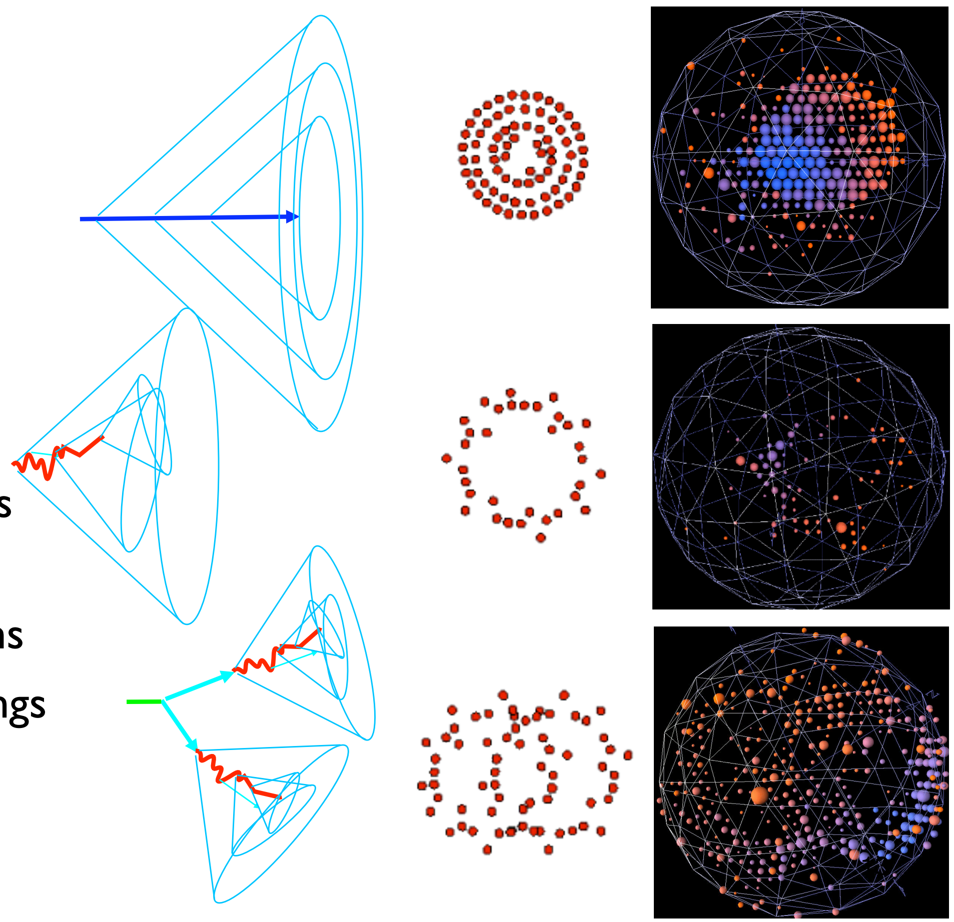
Neutrino detection

- Traditionally, neutrino detectors used Cherenkov radiation or scintillation light

- Ex: Water Cherenkov detectors

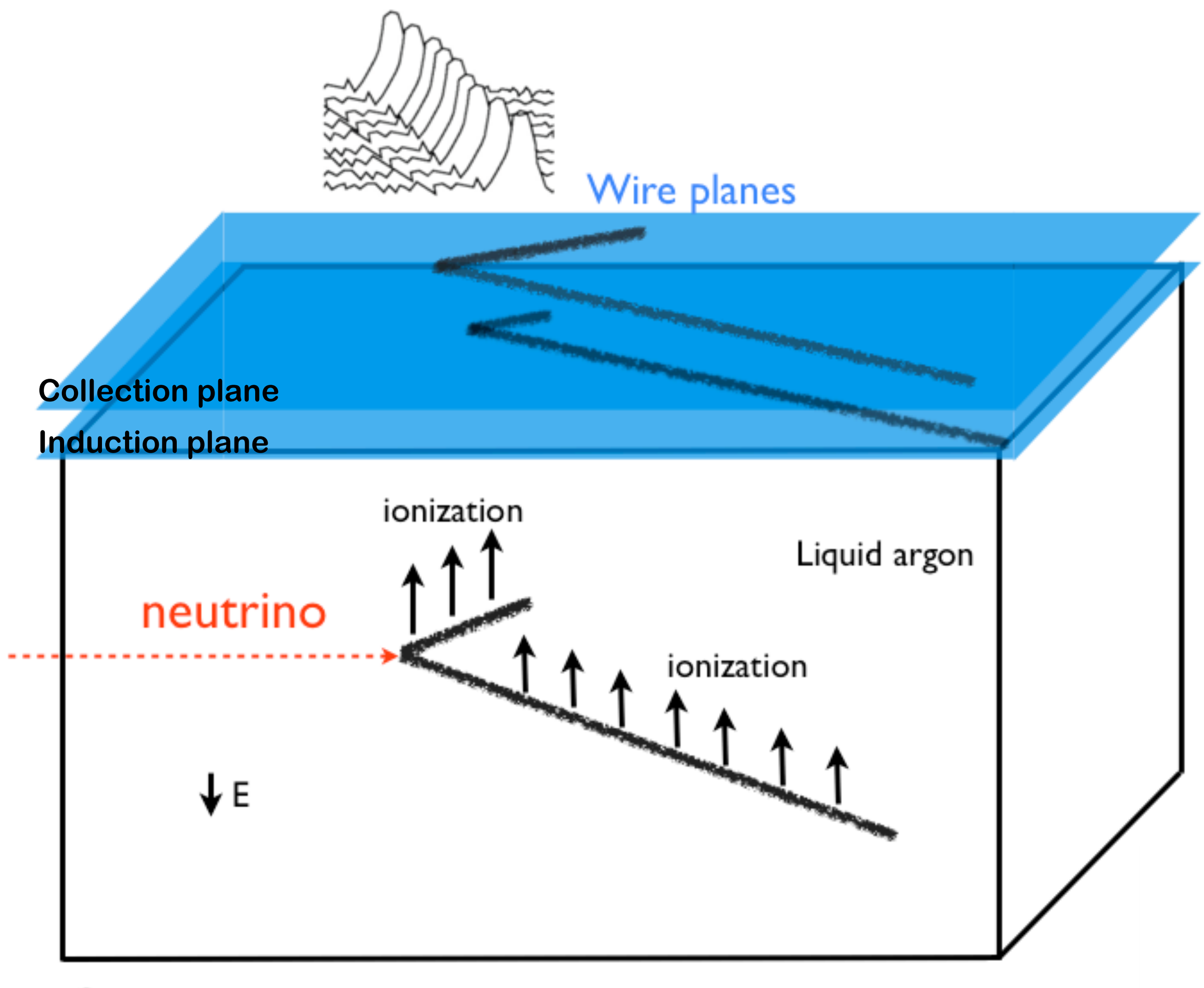


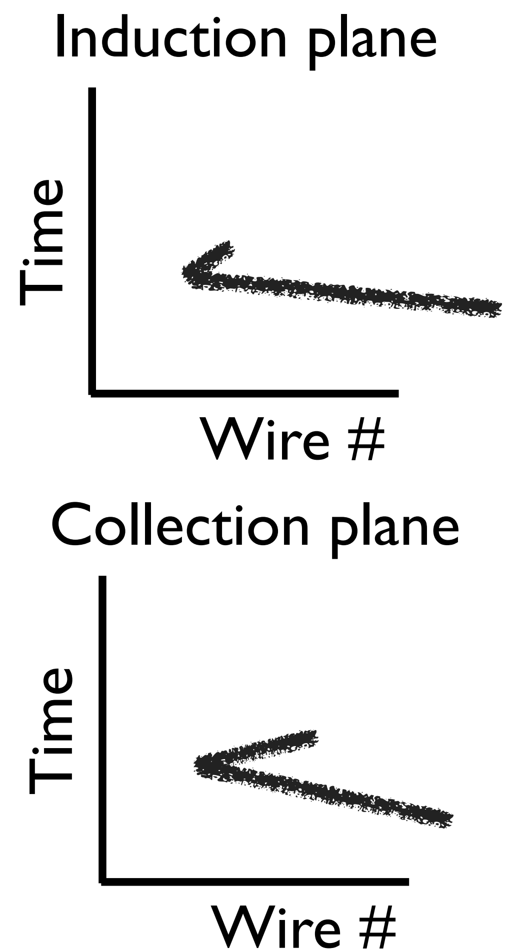
- Muons
  - full rings
- Electrons
  - fuzzy rings
- Neutral pions
  - double rings



New technology for neutrino detection

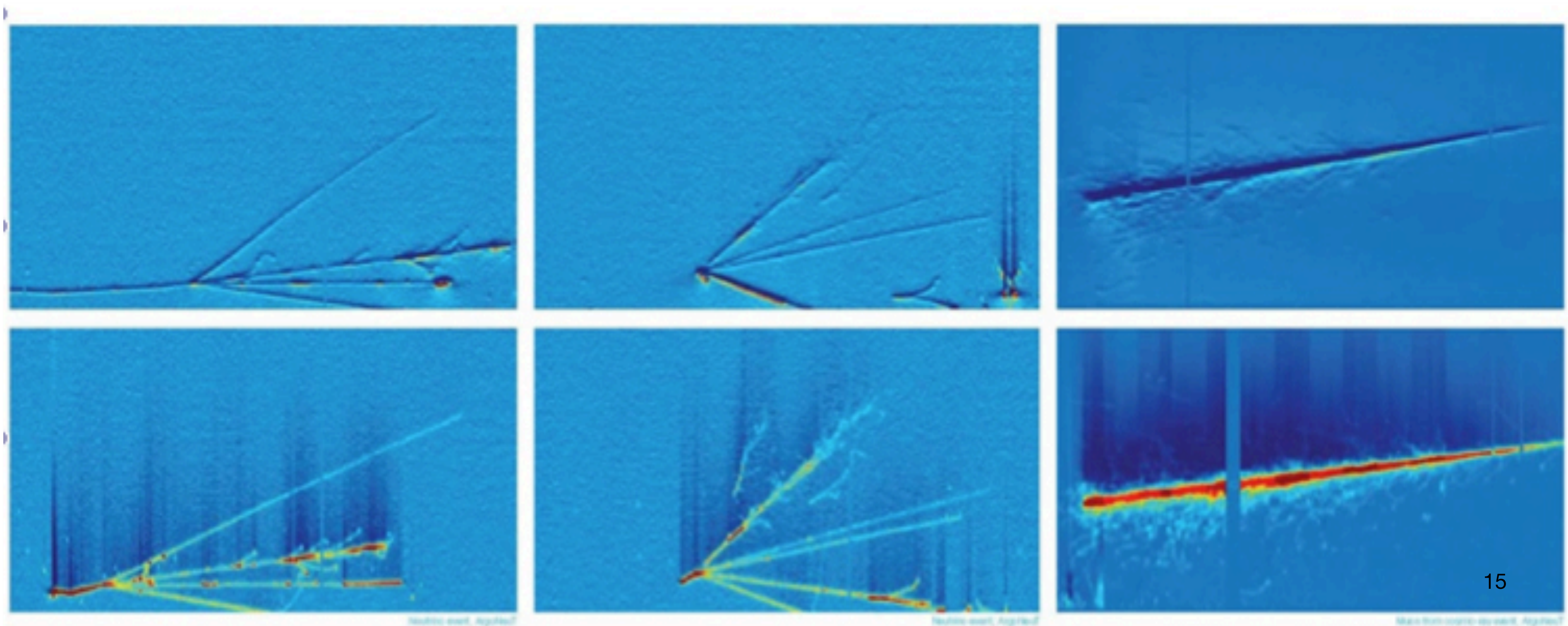
Liquid Argon Time Projection Chamber





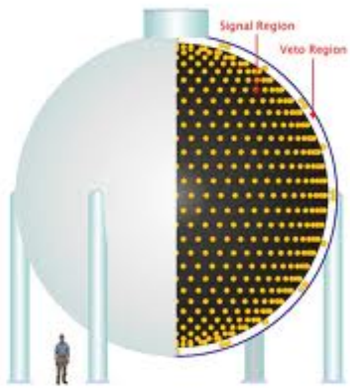
LAr TPCs

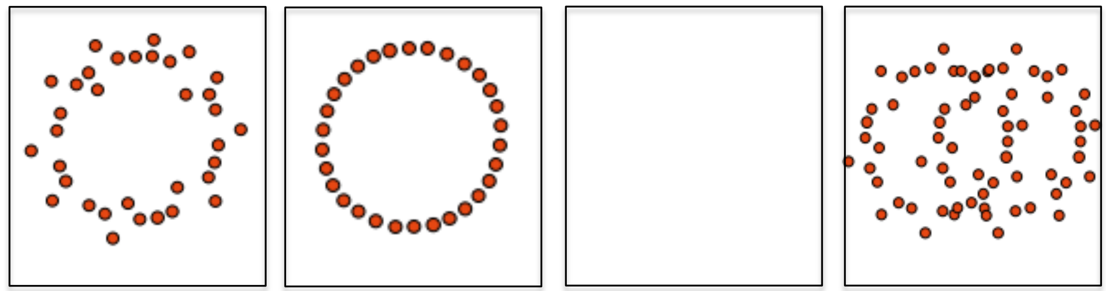
- ✓ 3D imaging
- ✓ High neutrino detection efficiency
- ✓ Excellent background rejection
- ✓ Good calorimetric reconstruction



LAr TPCs

MiniBooNE

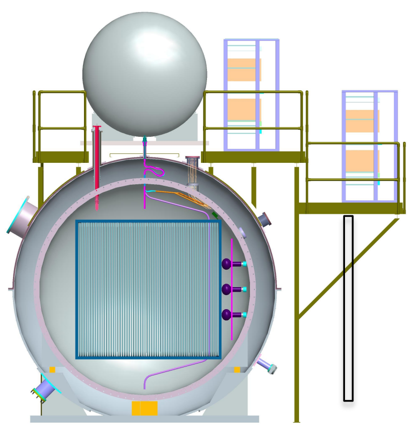


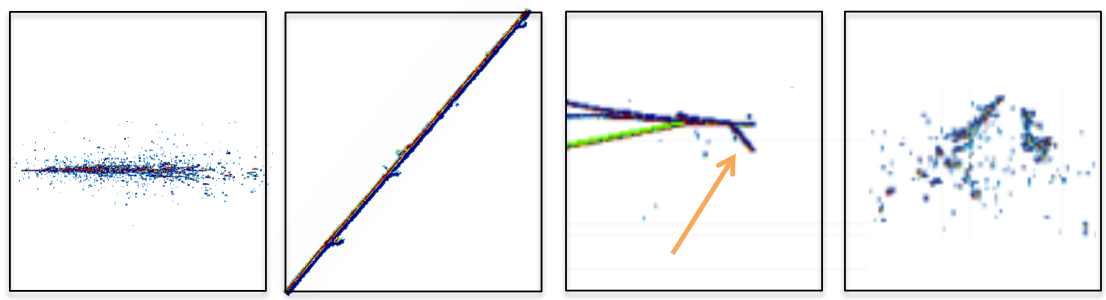


Electron, Photon | Muon | Proton | $\pi^0 \rightarrow \gamma + \gamma$

(Cherenkov Detector)

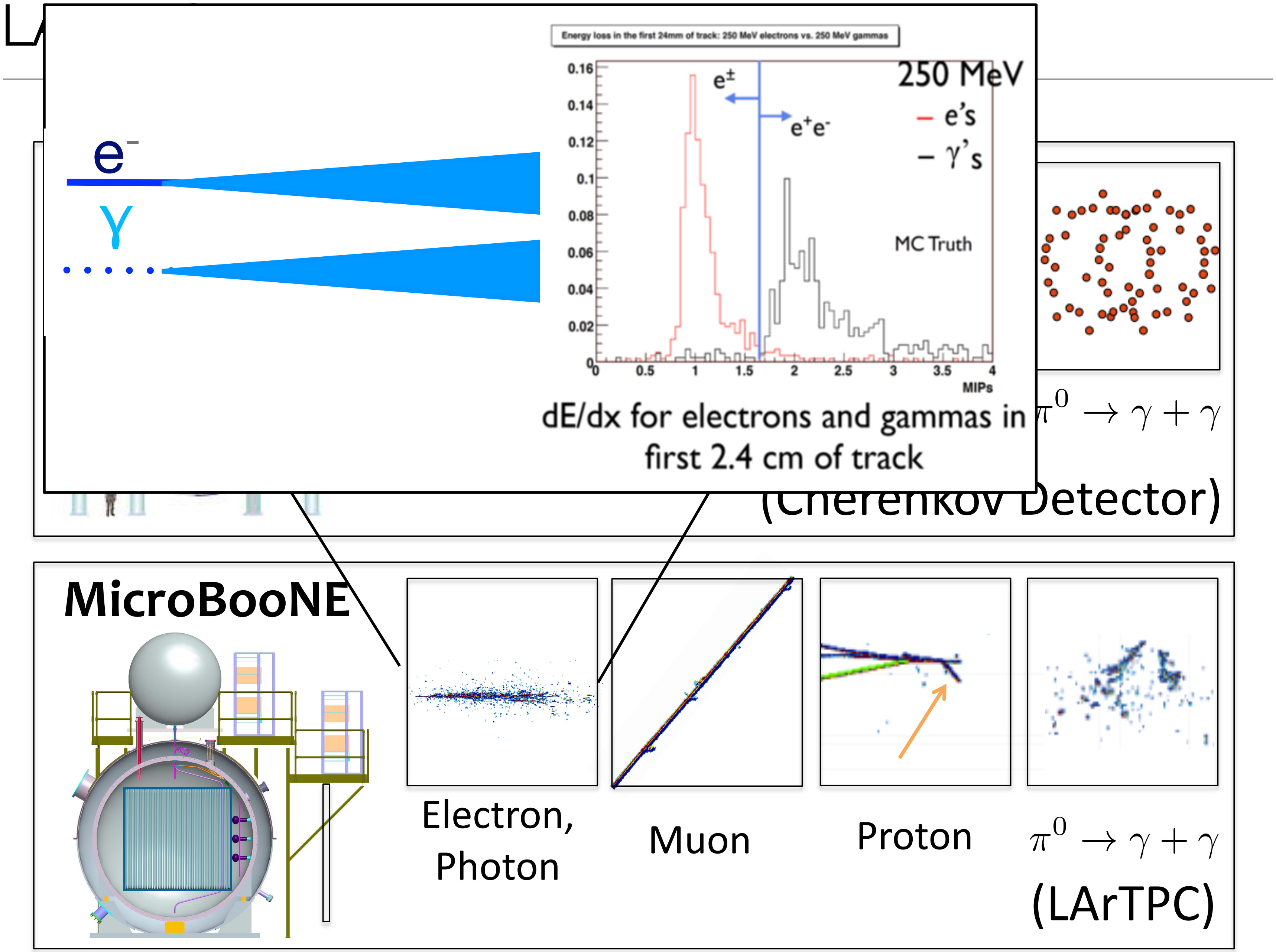
MicroBooNE





Electron, Photon | Muon | Proton | $\pi^0 \rightarrow \gamma + \gamma$

(LArTPC)


e⁻
γ
Energy loss in the first 24mm of track: 250 MeV electrons vs. 250 MeV gammas
250 MeV
e's
γ's
e±
e+e-
MC Truth
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3
3.5
4
MIPs
dE/dx for electrons and gammas in first 2.4 cm of track
$\pi^0 \rightarrow \gamma + \gamma$
(Cherenkov Detector)
MicroBooNE
Electron, Photon
Muon
Proton
$\pi^0 \rightarrow \gamma + \gamma$
(LArTPC)

Why Ar?

- Ionization electrons can be drifted over long distances (no electron attachment)
- Scintillation light used for detection (Ar is transparent to it's own scintillation)
- Very good dielectric properties allow high voltages in detector

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

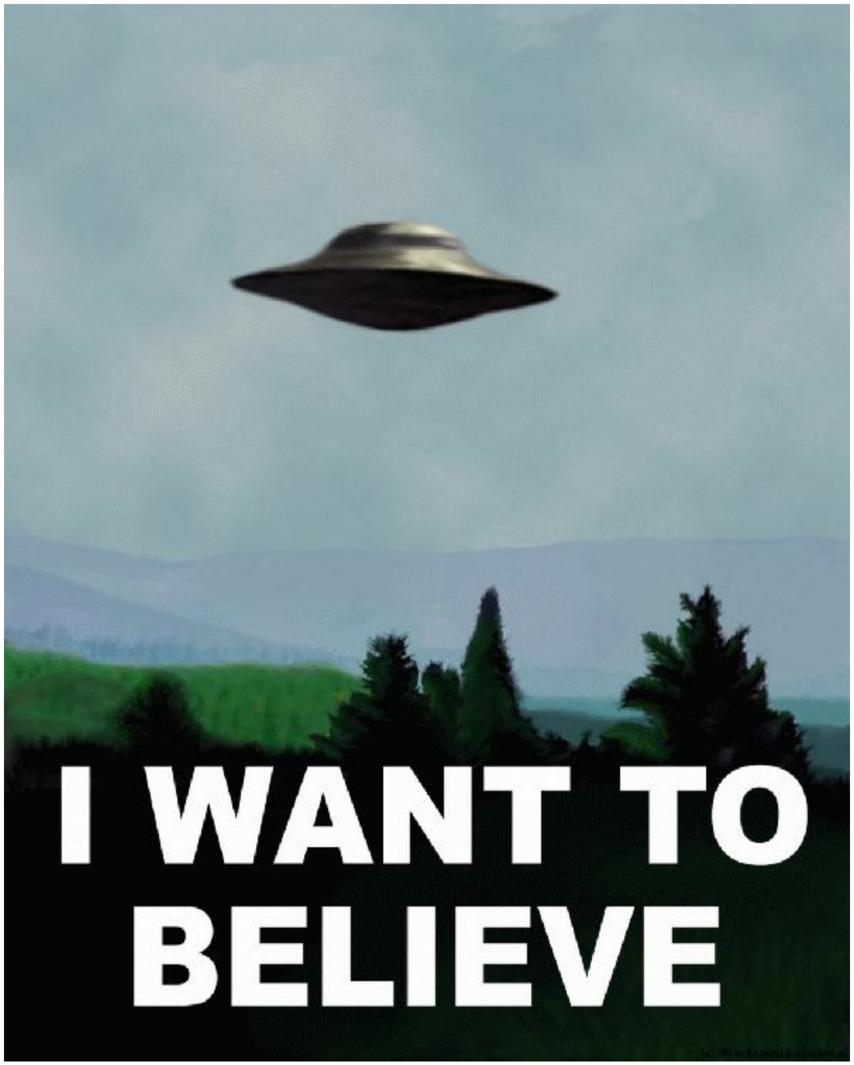
'Mitch Soderberg

Why Ar?

- Today what matters is:

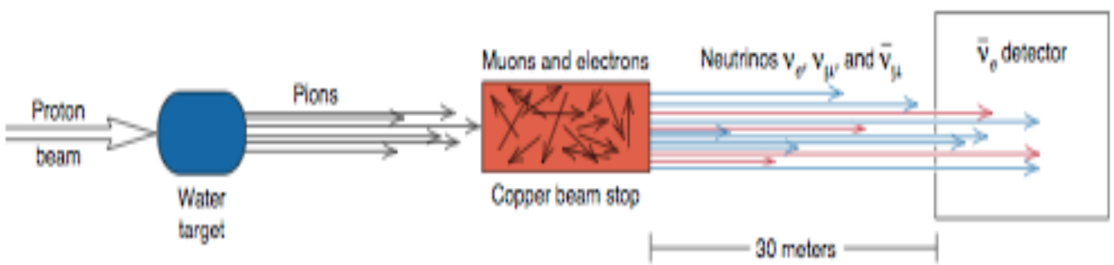
	He	Ne	Ar	Kr	Xe	Water
Price	~10$/l	~100$/l	< 1$/l	~300$/l	~3000 $/l	Depends on the country

Sterile Neutrino

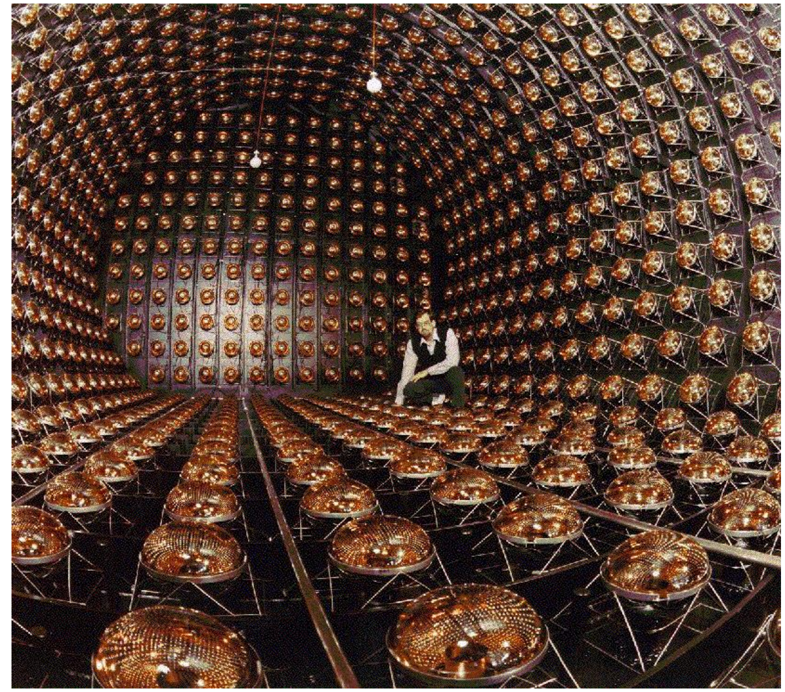


The LSND experiment

- LSND: short-baseline experiment
- Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Signal: $\bar{\nu}_e + p \rightarrow e^+ + n$; $np \rightarrow d\gamma$



E_ν ~ 60 MeV



Location: 30m (L/E→ ~1)

Cylindrical tank

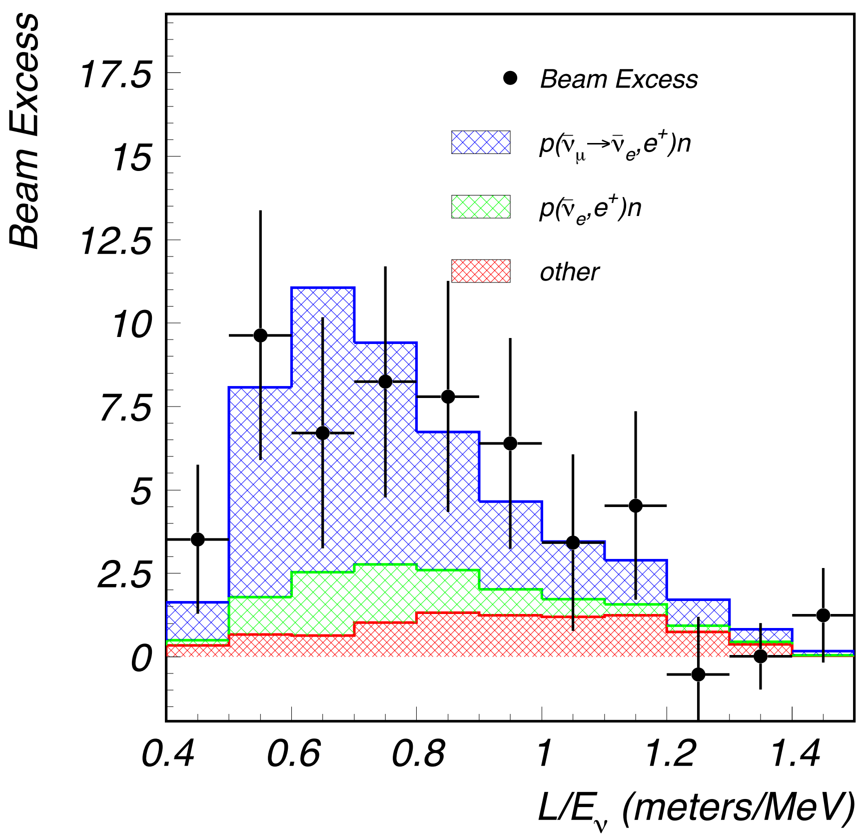
(167t mineral oil with b-PBD)

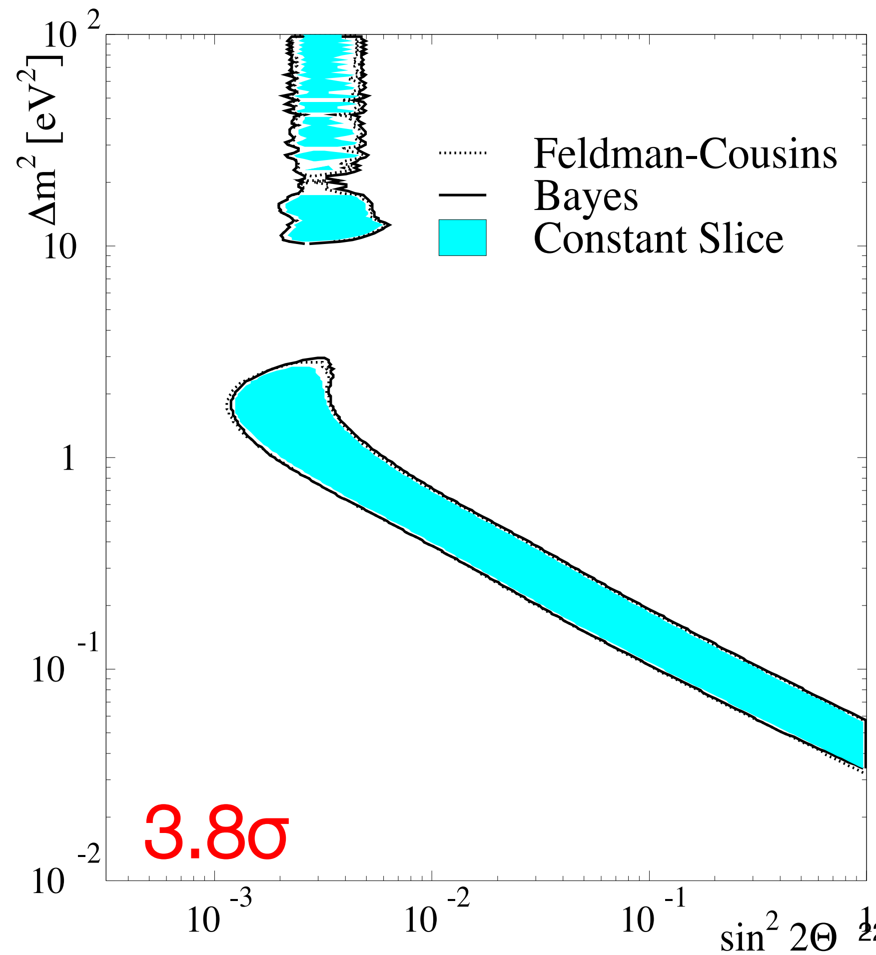
L:8.3m x R:5.7

1220 8” PMTs (25% coverage)

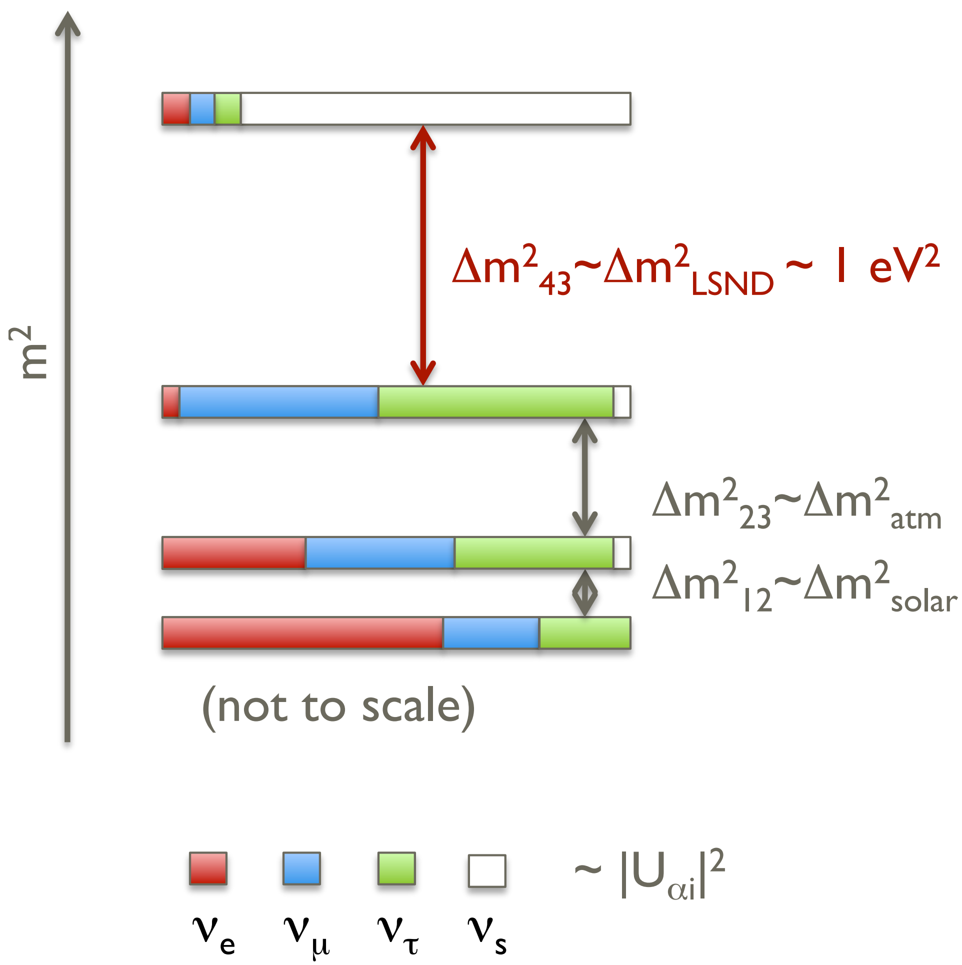
The LSND anomaly

- Observed an excess of $\bar{\nu}_e$
- Would imply $\Delta m^2 \sim 1 eV^2$



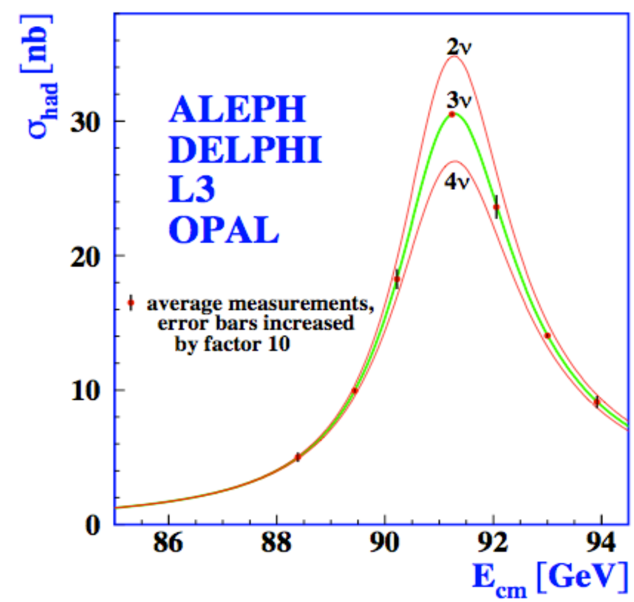


New neutrino?



Need additional neutrino (but LEP showed that there are only 3!)

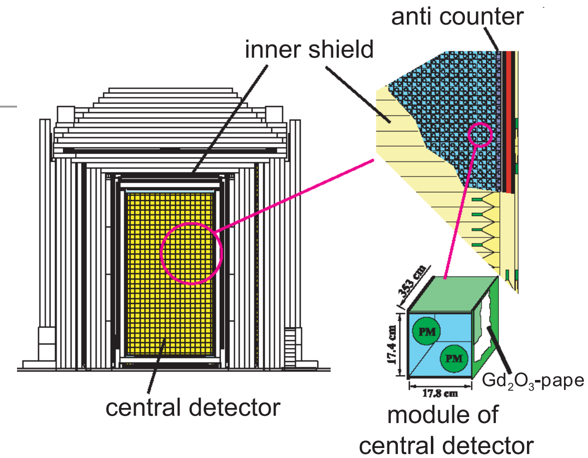
$e^+e^- \rightarrow Z \rightarrow \nu\,\bar{\nu}$ (at Z resonance)

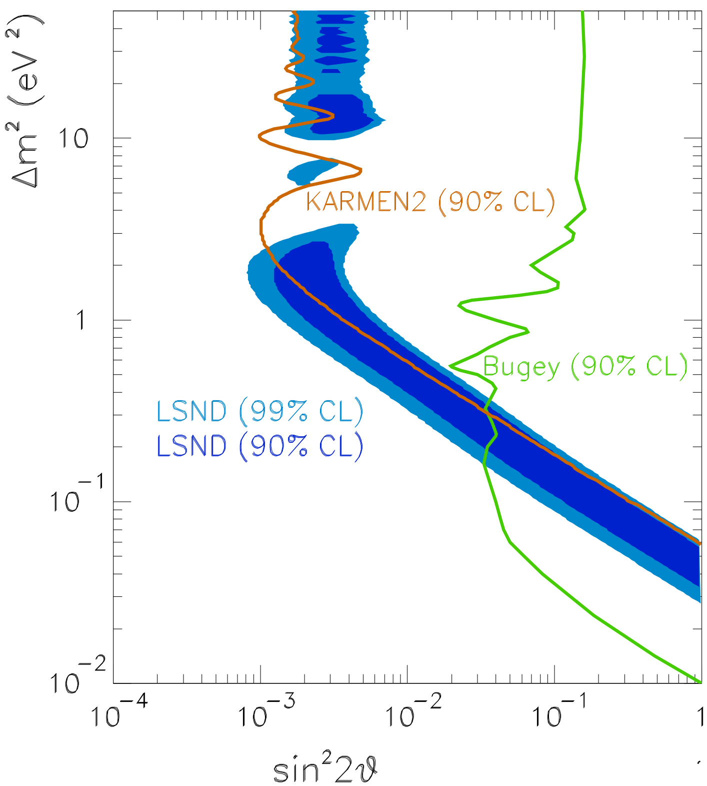


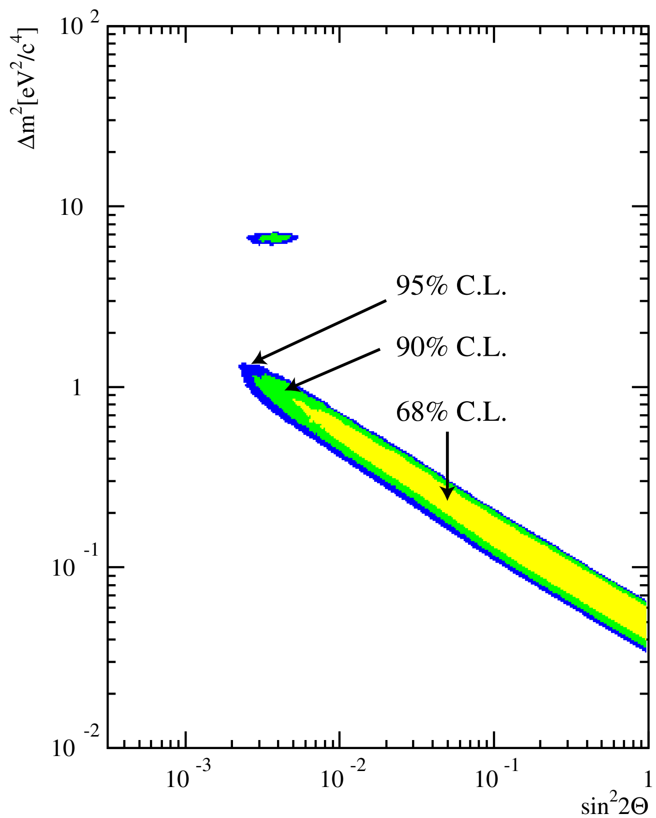
Non-active neutrino
→ **sterile**

KARMEN

- Similar beam as LSND but off-axis
- But a distance of 17.7 m (different L/E)
- NULL result!



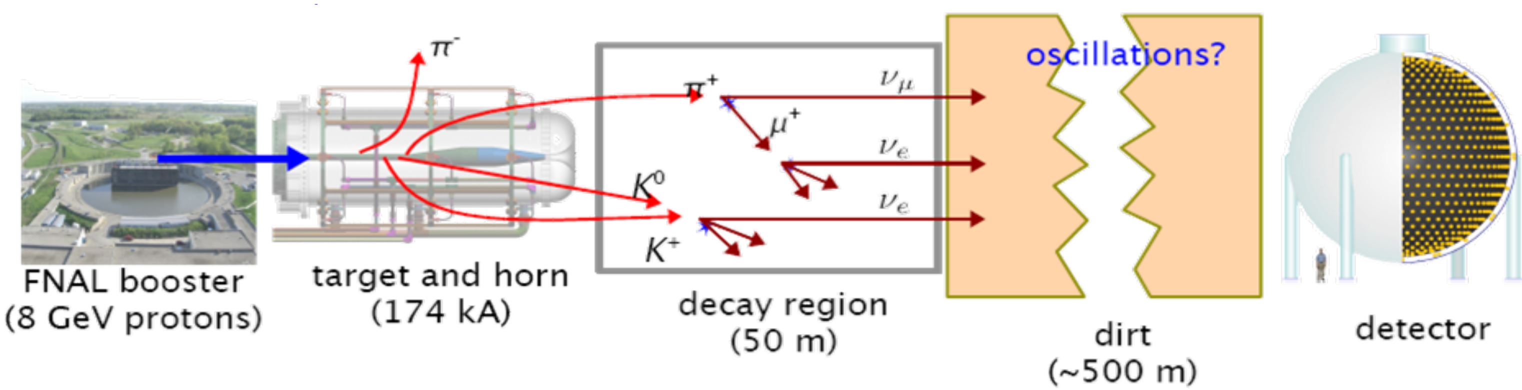




Combined LSND and KARMEN

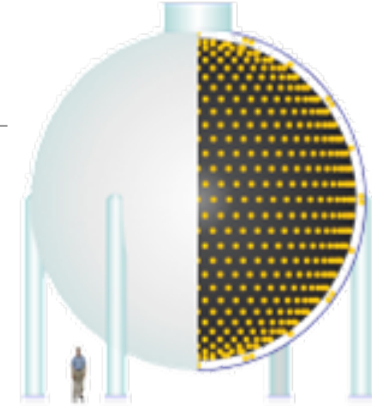
The MiniBooNE experiment

- Goal: test LSND
- 800t of mineral oil (~4.5 times LSND)
- Location: 541m (L/E → ~1)

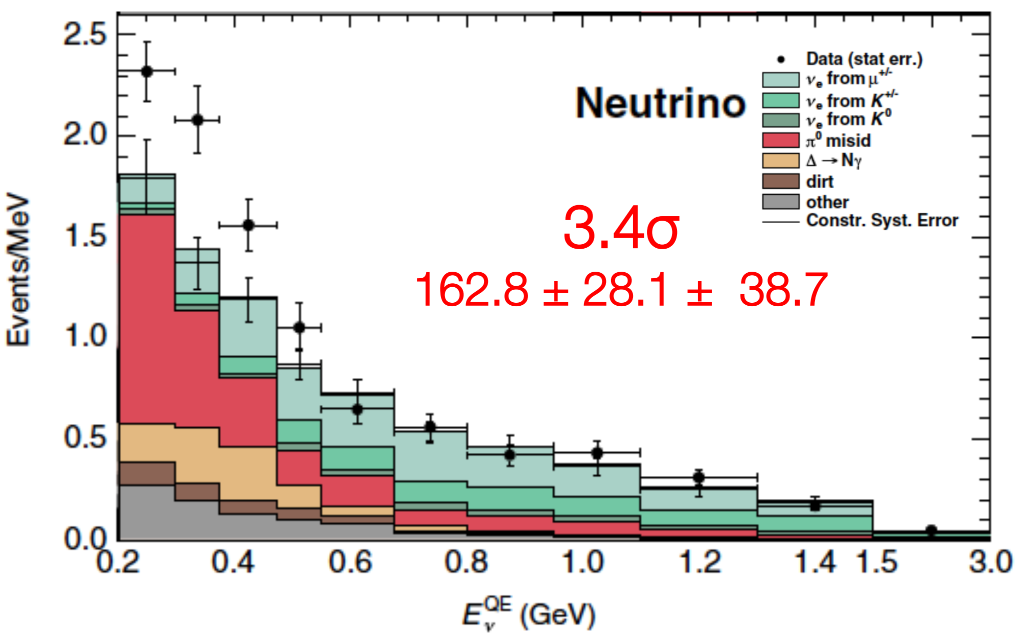


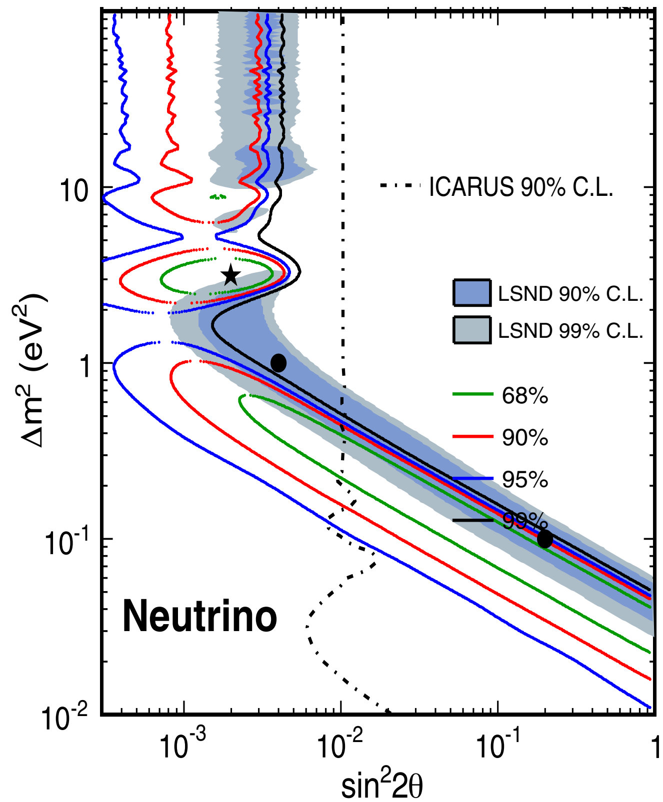
E_ν ~ 600 MeV

The MiniBooNE anomaly (neutrinos)



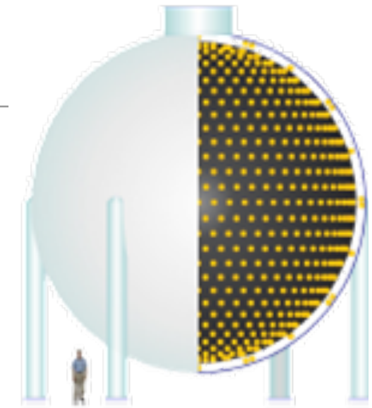
Excess at different energies than LSND!





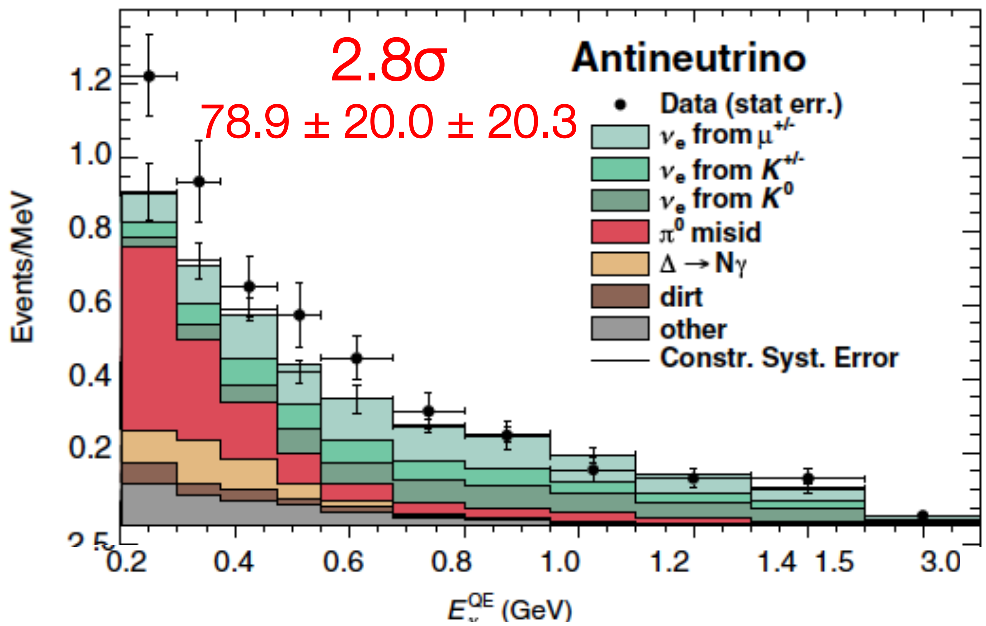
Phys. Rev. Lett. 110, 2013

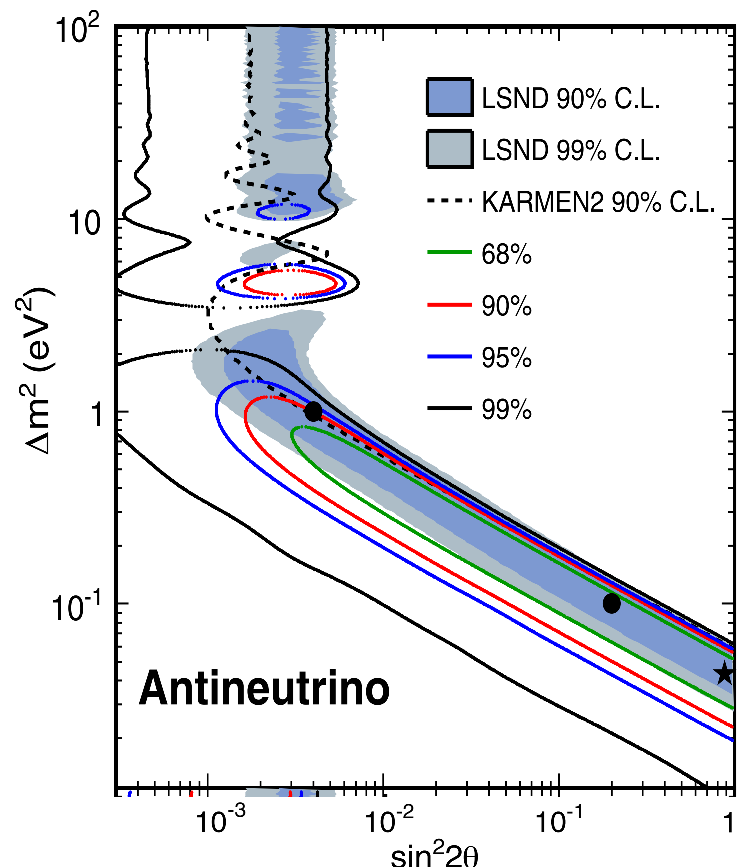
The MiniBooNE anomaly (antineutrinos)



Excess consistent with LSND!

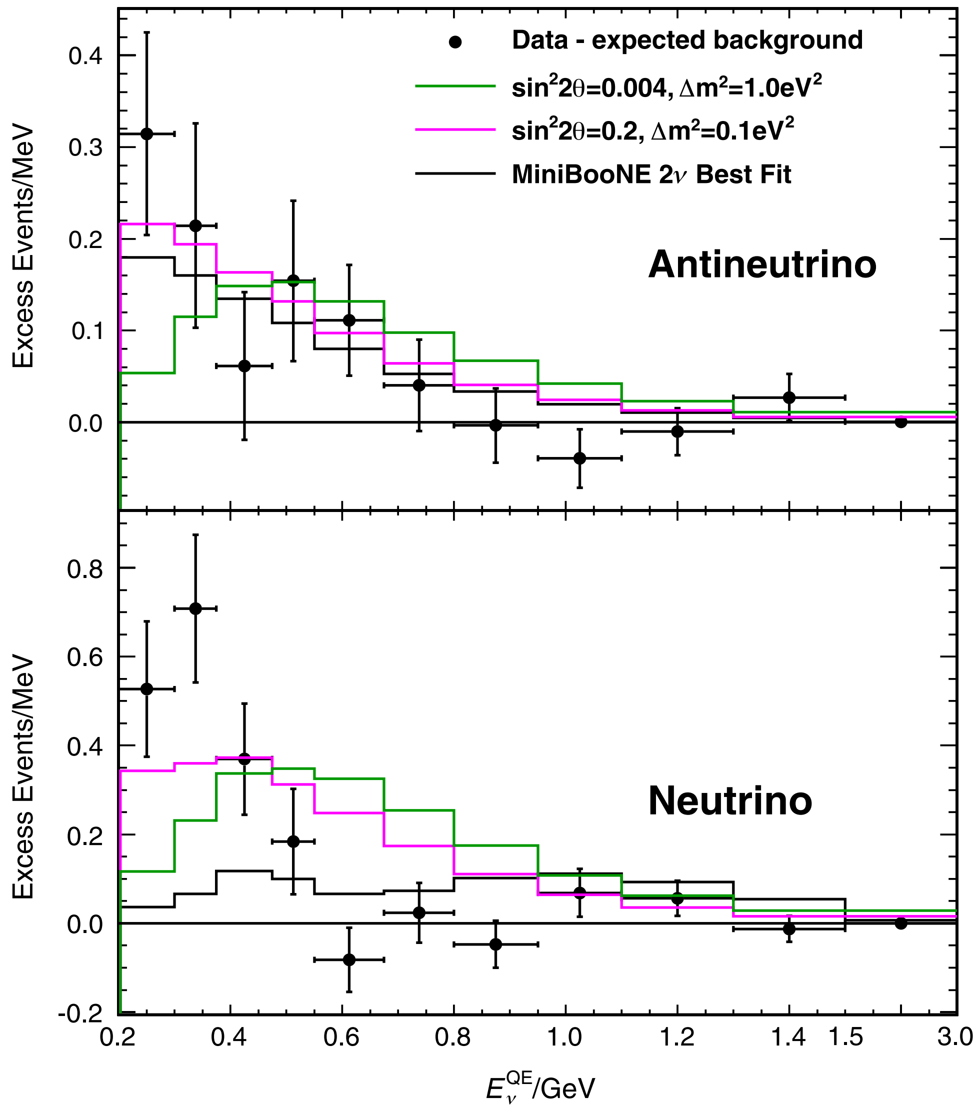
miniBooNE anti-neutrino mode result





Phys. Rev. Lett. 110, 2013

The MiniBooNE anomaly



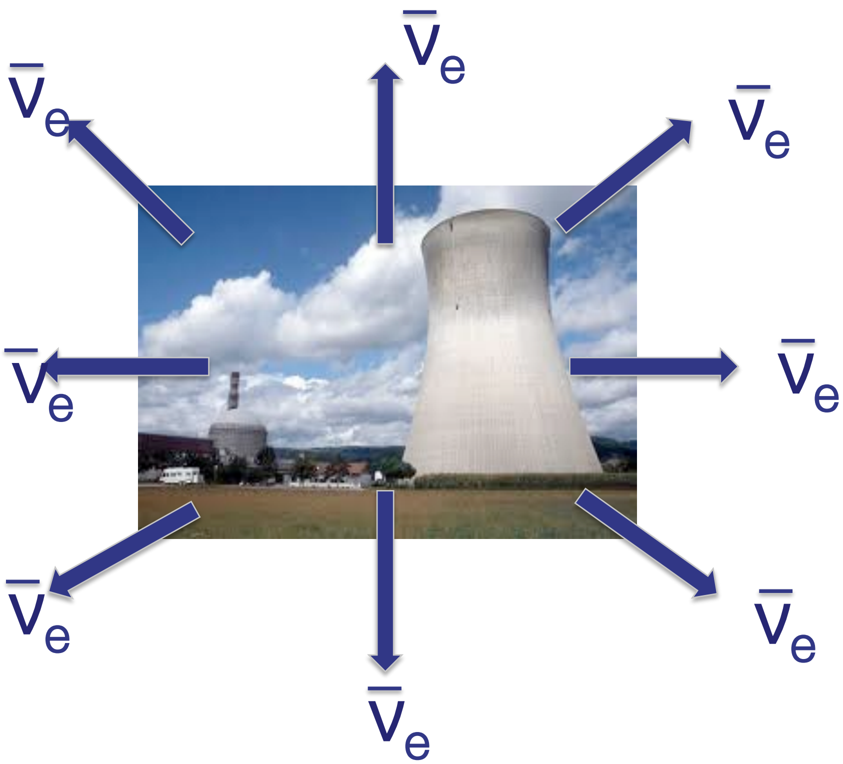
Phys. Rev. Lett. 110, 2013

Antineutrino results consistent with oscillation in 0.01-1 eV^2 range

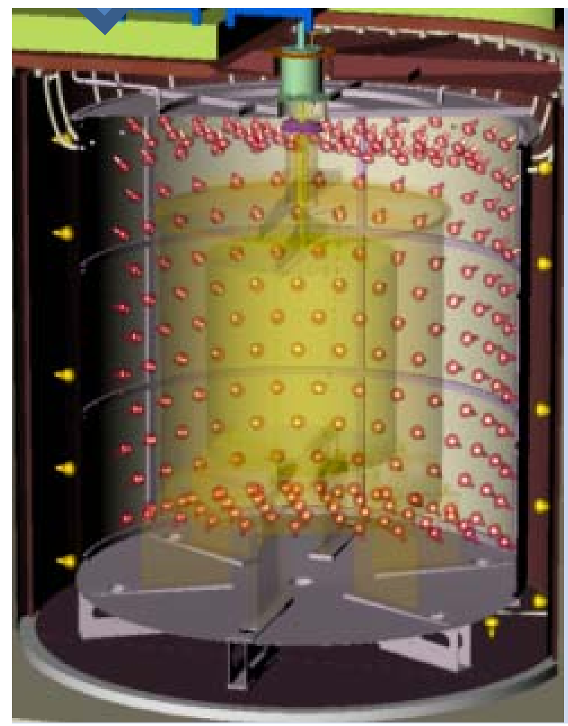
Neutrino results only marginally consistent

Reactor experiments

- Powerful anti-neutrino source ($E_\nu \sim$ 1-10 MeV)
- Detectors at distances ~10-1000 m



$$\bar{\nu} + p \longrightarrow \beta^{+} + n$$



Reactor experiments

- Very hard to calculate the reactor flux precisely!
- Most important systematics in single detector

$$N_\nu \text{expected} = (P_{th}) \times (E/\text{fission})^{-1} \times (N\nu/\text{fission}) \times (\Delta\Omega) \times (\sigma) \times (N_{protons}) \times (Eff.)$$

Thermal Power $\sigma < 1\%$

Energy released per fission $\sigma < 0.3\%$

$$dN/dE = \Sigma_n Y_n(Z,A,t)\, \Sigma_i b_{n,i}(E_0^i)\, P(E_\nu, E_0^i, Z)$$

$Y_n(Z,A,t)$: Known with sufficient accuracy

$b_{n,i}(E_0^i)$: β decay branching ratio:
Some known precisely
Some totally and partially unknown

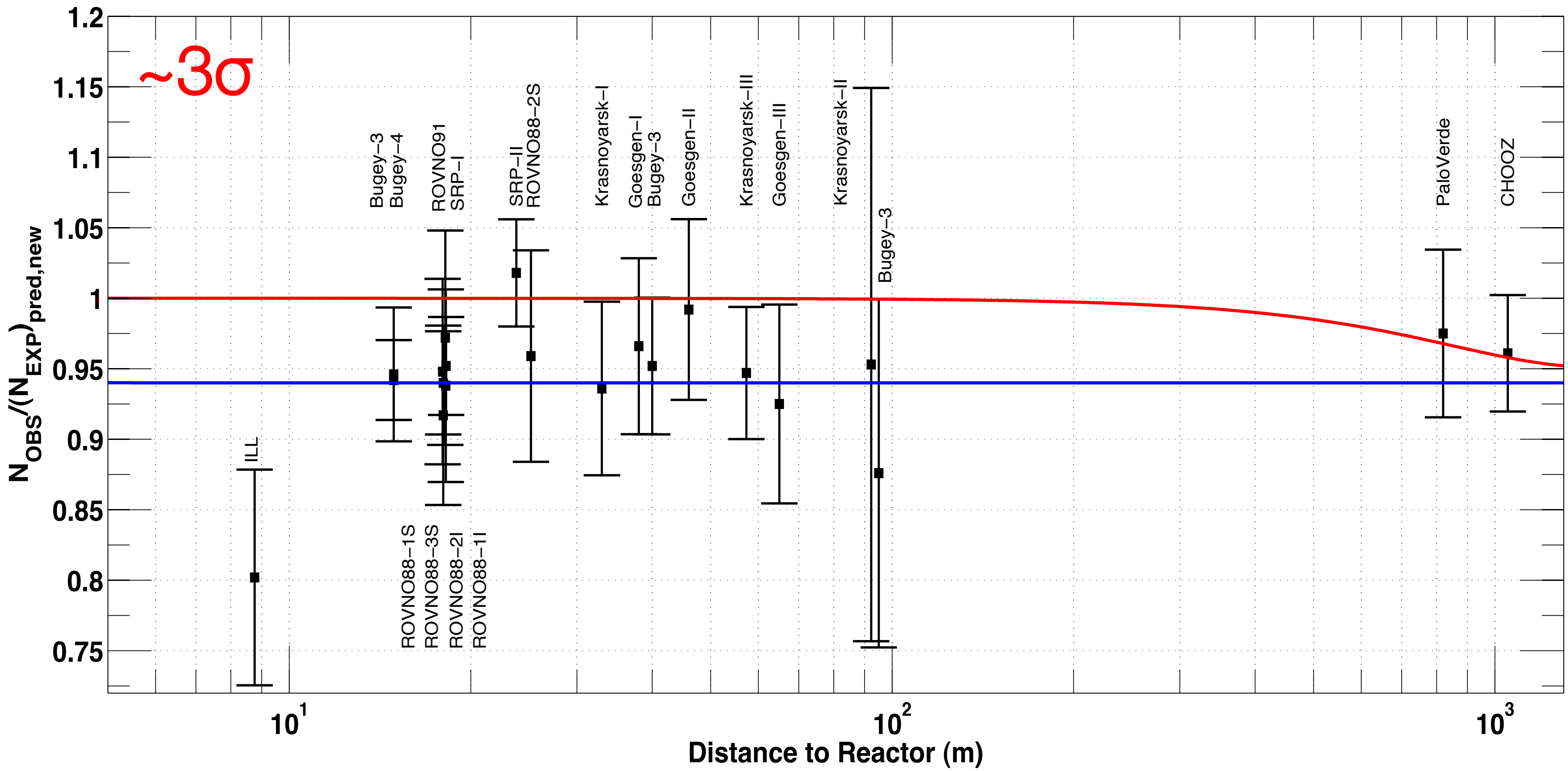
$P(E_\nu, E_0^i, Z)$: Only allowed decay shape known
Needs corrections $(P(E_n, E_0^i, Z)\ (1 + d_{qed} + d_{WM} + d_C))$
Forbidden decays not treated

Reactor anomaly

- Re-calculation of the fission spectrum
- Using > 8000 nuclei, > 10000 β-branches
- Re-calculation of e→$\bar{\nu}$ spectrum branch by branch
- New corrections (off-equilibrium, neutron lifetime,…)

Reactor anomaly

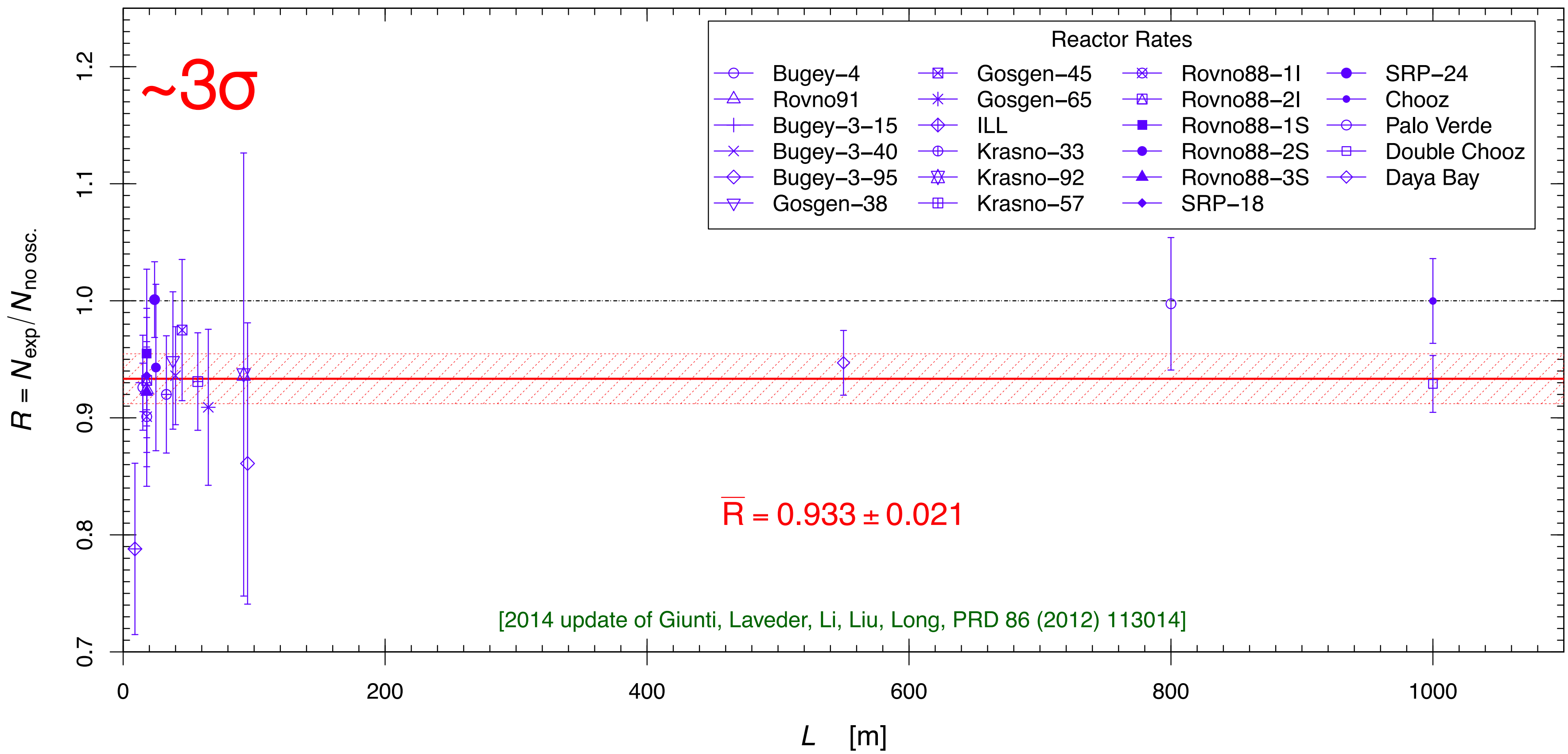
Old flux underestimated!



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

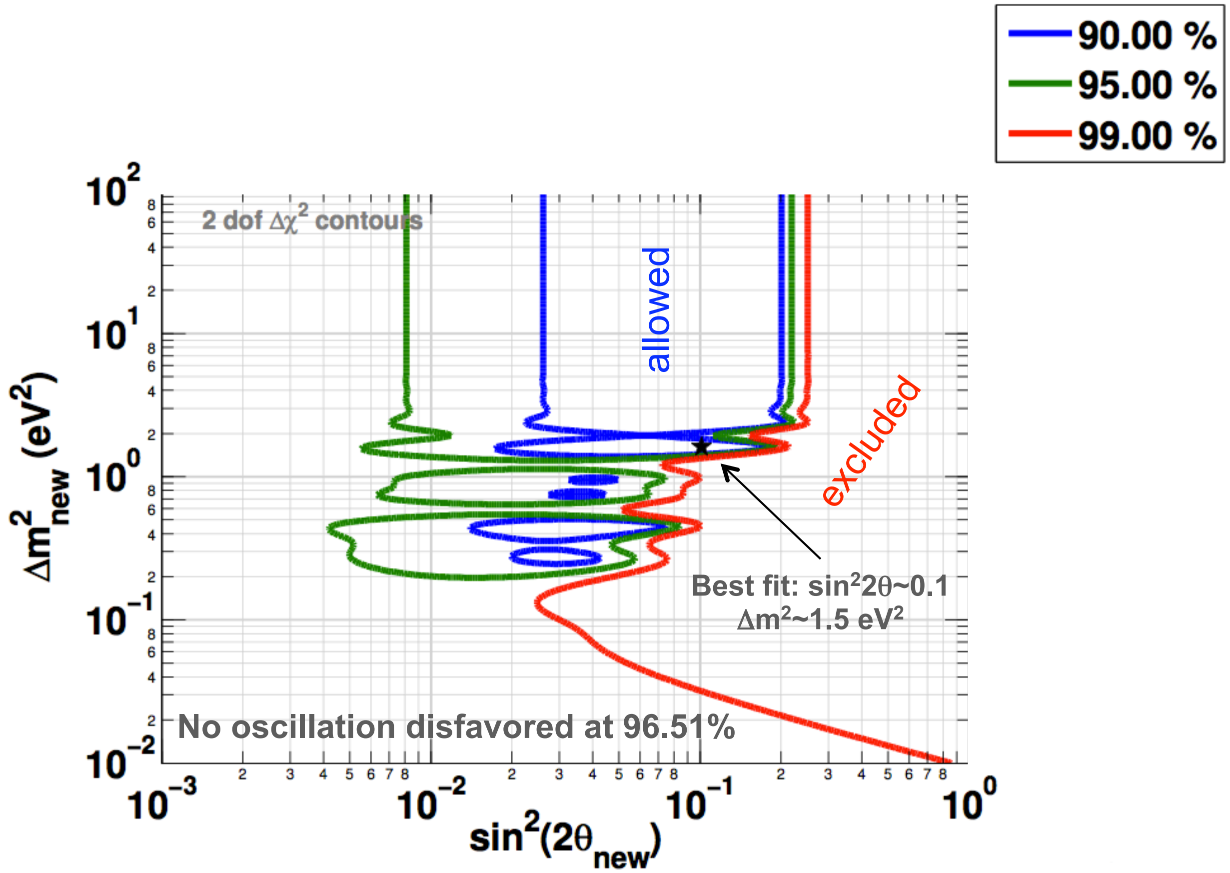
Reactor anomaly

Going down…



Reactor anomaly vs neutrino oscillation

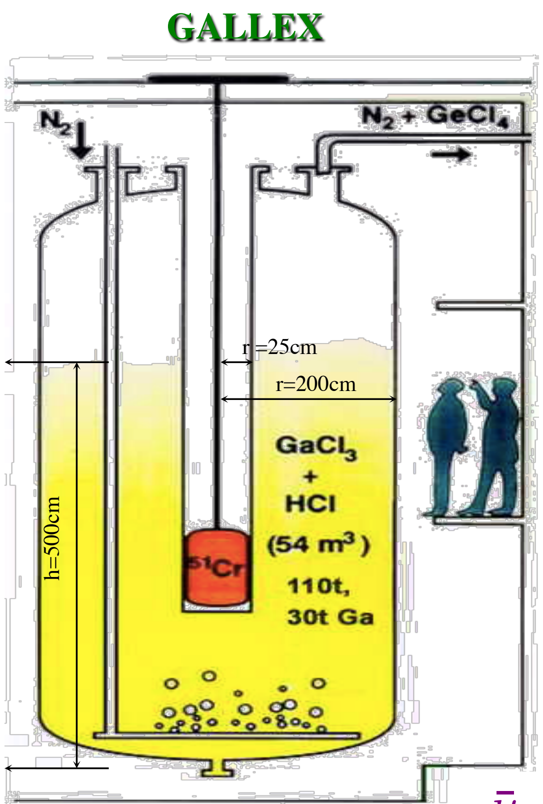
$\overline{\nu}_e$ disappearance

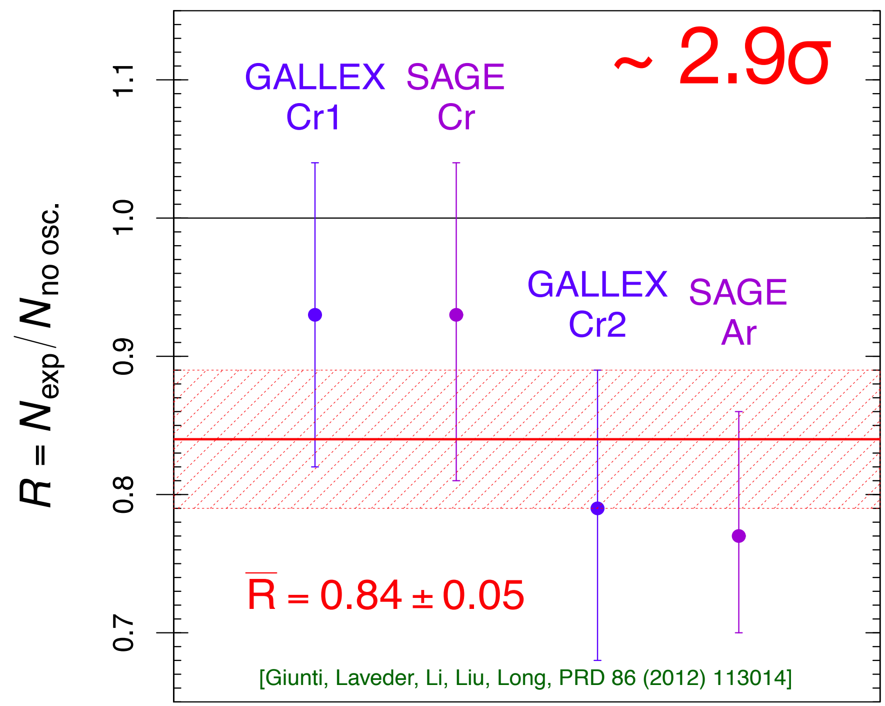


Sterile Neutrino White Paper, arXiv:1204.5379, 2012

Gallium anomaly

- Radioactive sources for calibration (ν_e disappearance)





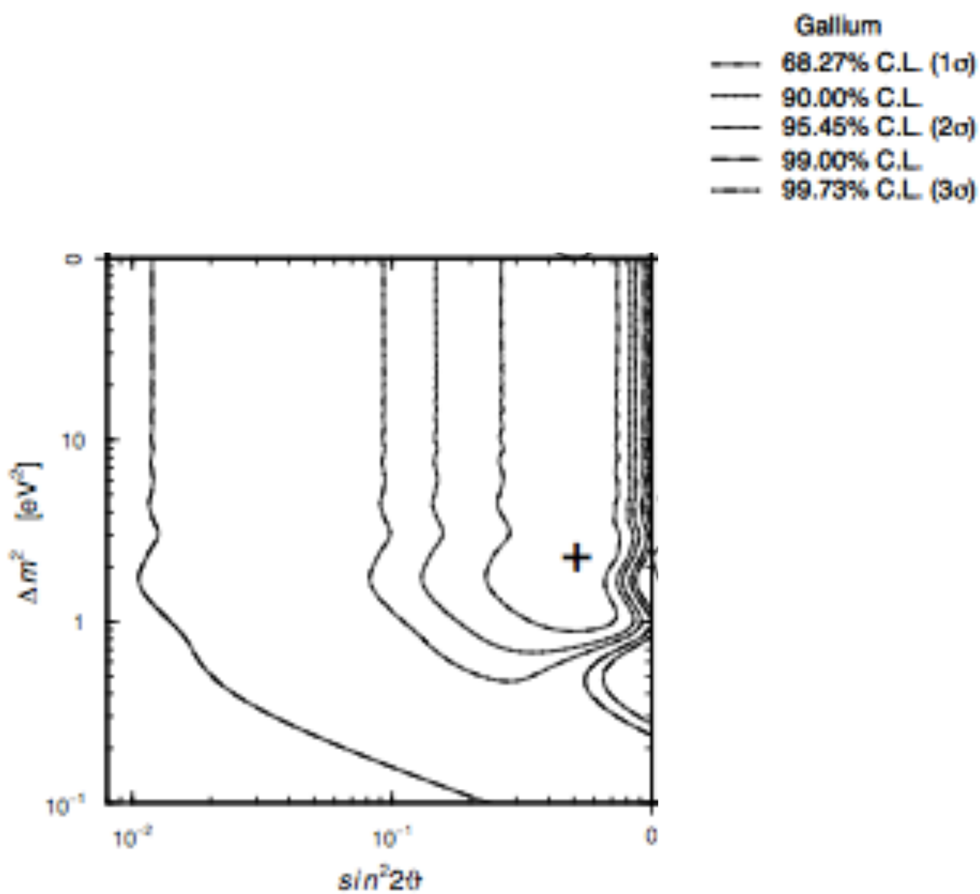
$\bar{\nu}_e \to \bar{\nu}_e$ $\quad E \sim 0.7\,\text{MeV}$

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$

$\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

Gallium anomaly vs neutrino oscillation

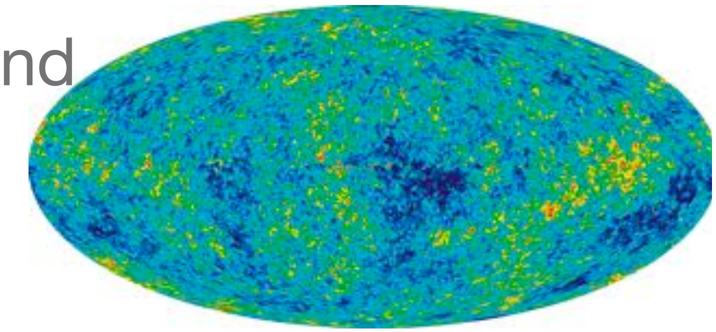
- ν_e disappearance



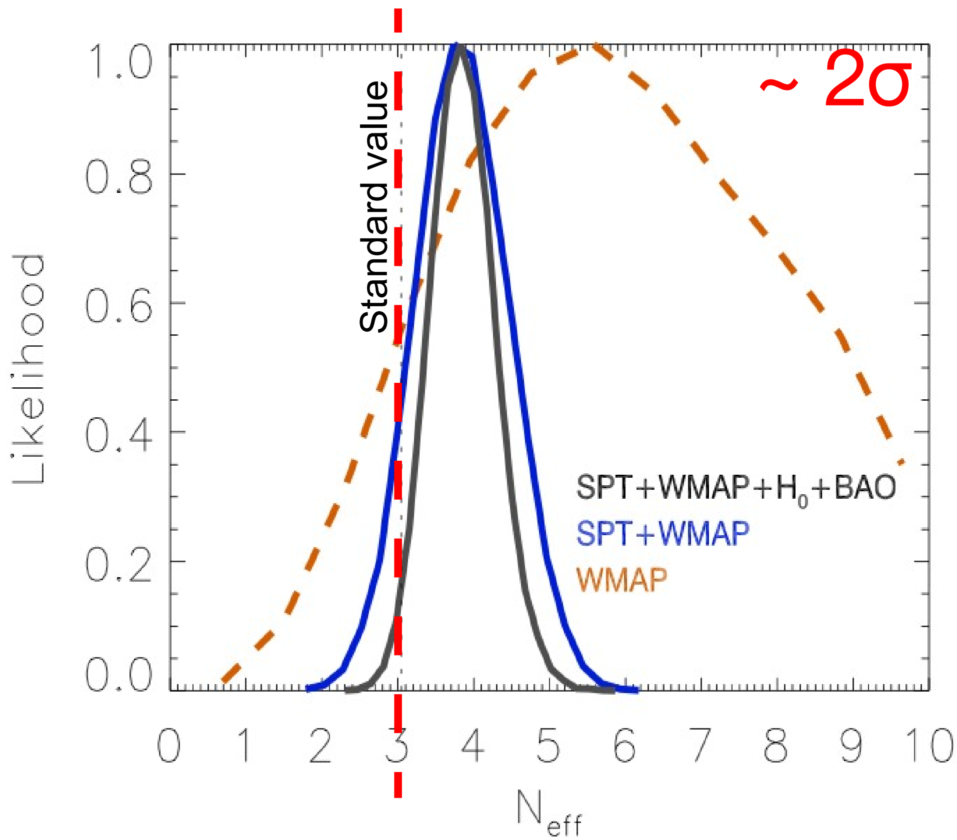
Giunti & Lavender, Phys.Rev.C 83,2011

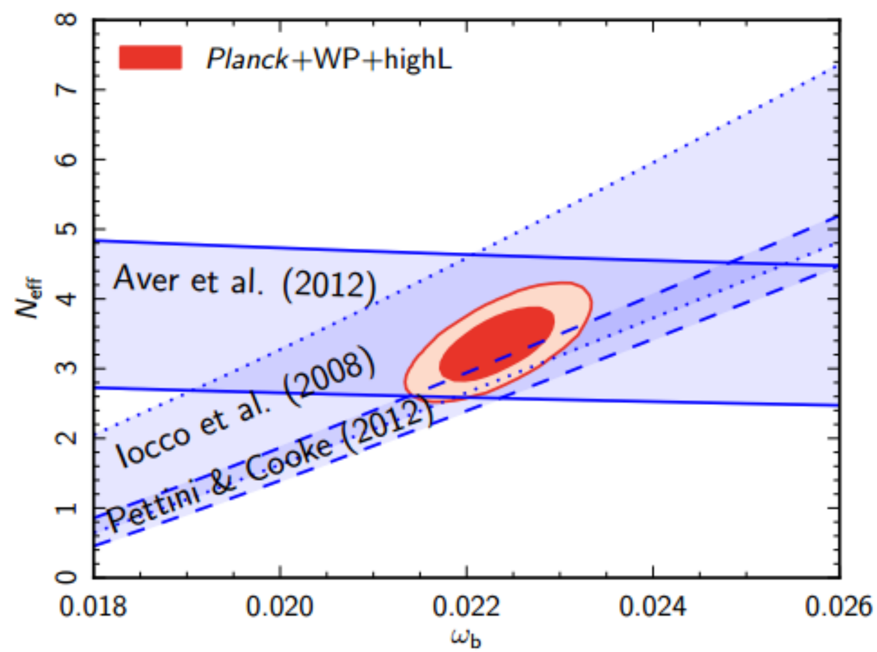
Cosmology

- Cosmological Microwave Background



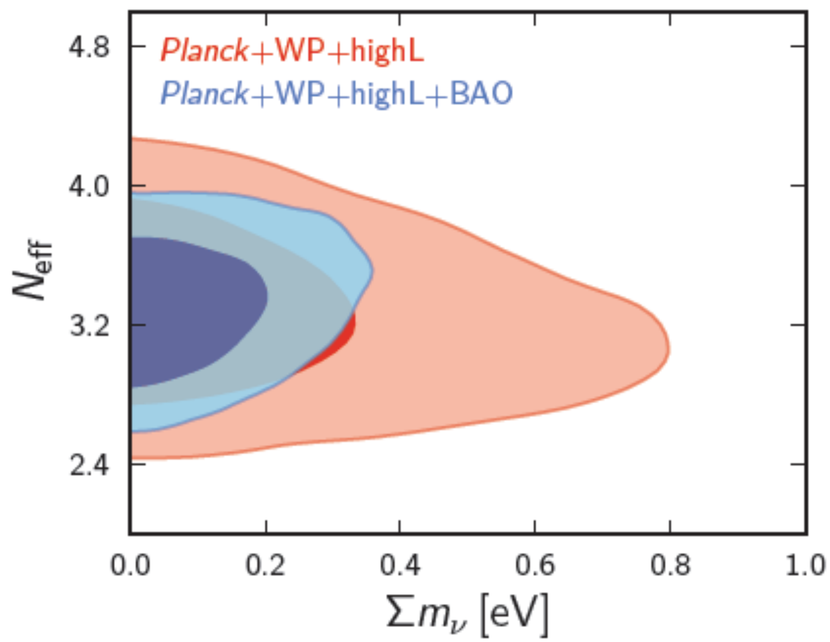
- Large Scale Structures





Keisler et al. [South Pole Telescope] 2011

Cosmology: Not so simple…



A global picture ?

Let's take ALL the results we have:

becomes 4x4

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Appearance:
  - ➢ $\nu_\mu \rightarrow \nu_e$: MiniBooNE Low-Energy Excess
  - ➢ $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$: LSND and MiniBooNE, and Karmen, NOMAD

appearance

$$P_{\mu e} = \sin^2 2\theta_{\rm app} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm app} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

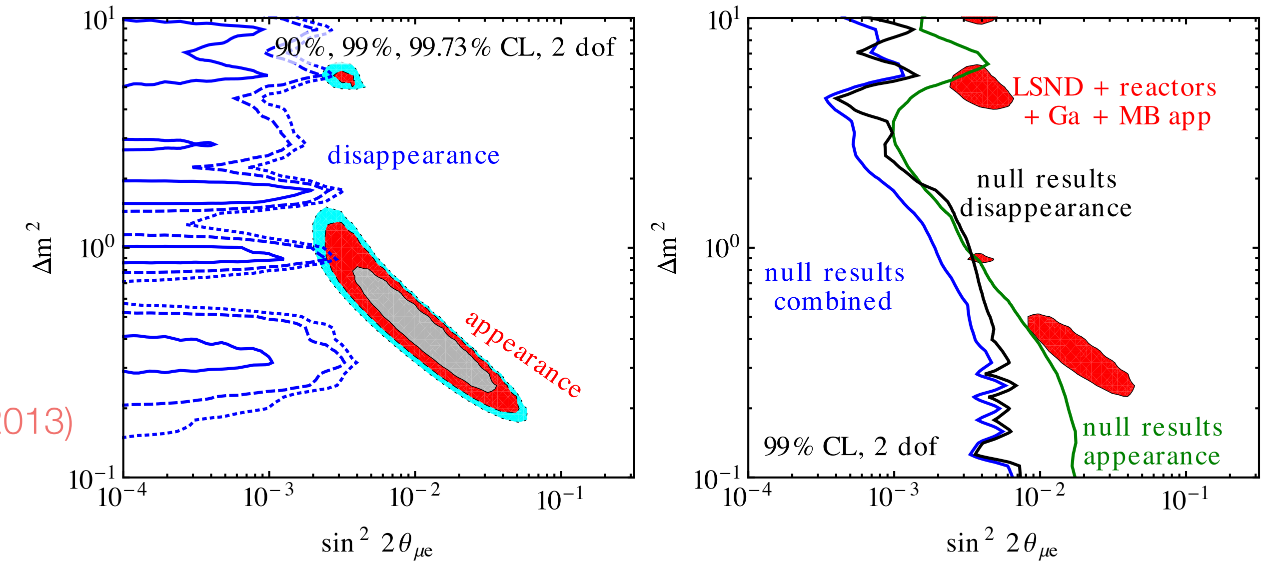
- Disappearance:
  - ➢ $\overline{\nu}_e$: Reactors (Bugey-3,4, Goessgen, Krasnoyarsk, Rovno, ILL, Palo Verde, Chooz)
  - ➢ ν_μ: CDHS, MiniBooNE, atmospheric, MINOS NC
  - ➢ ν_e : Radioactive sources

disappearance

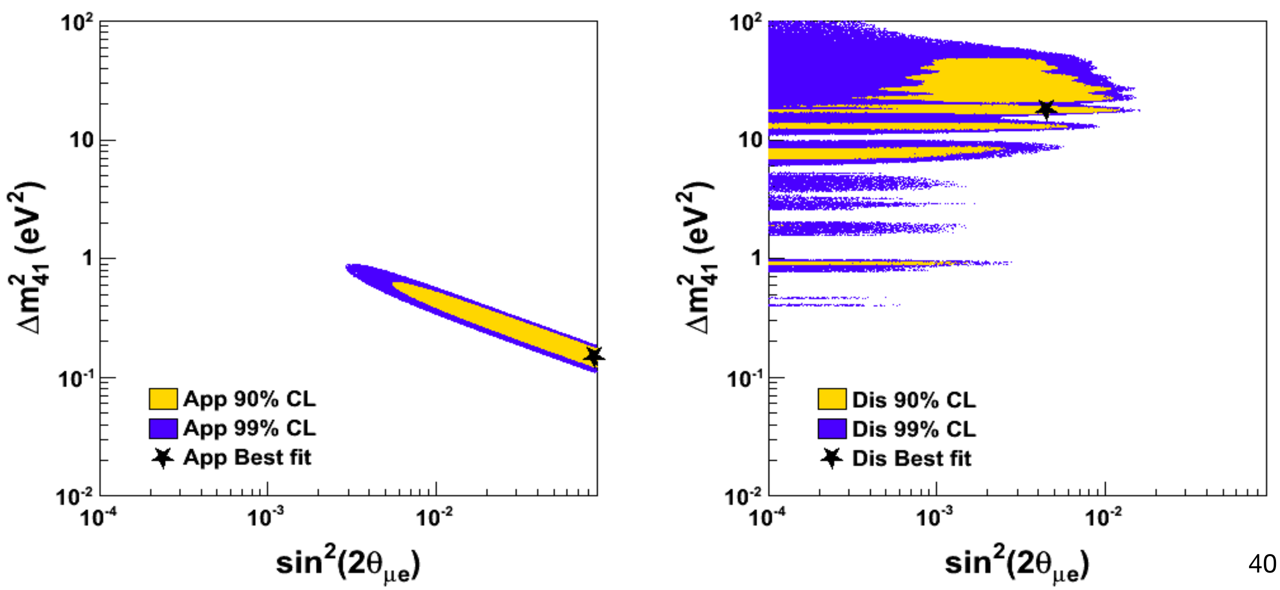
$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\rm dis} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm dis} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

A global picture ?

3+1 global fit



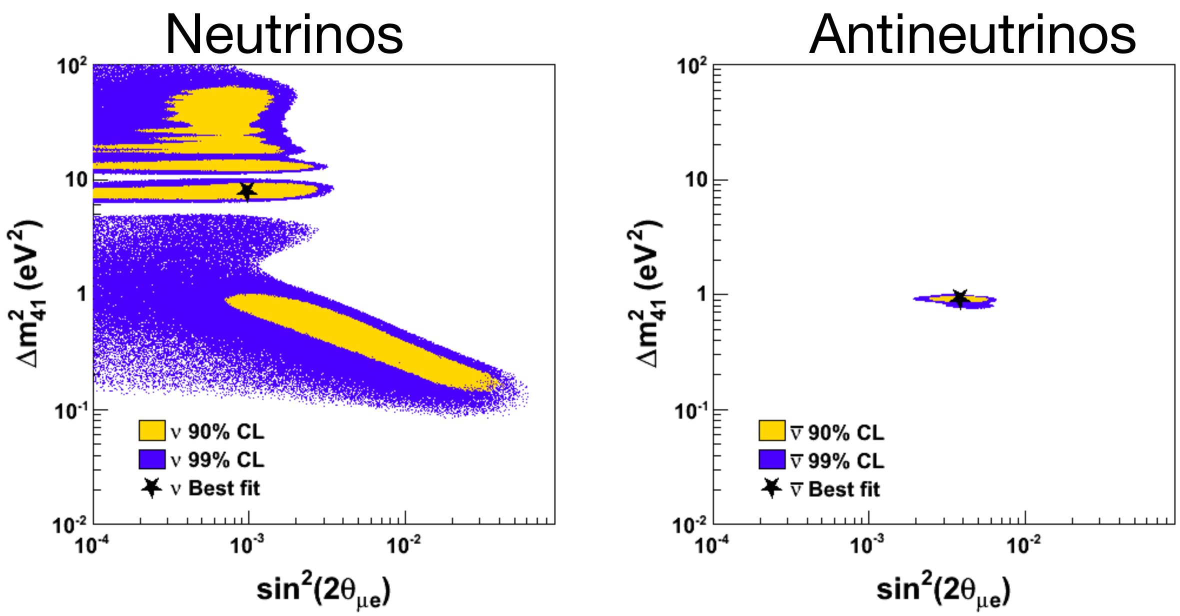
J.Kopp et al., JHEP 1305 (2013)



J.M. Conrad et al., Adv.High Energy Phys. 2013 (2013)

A global picture ?

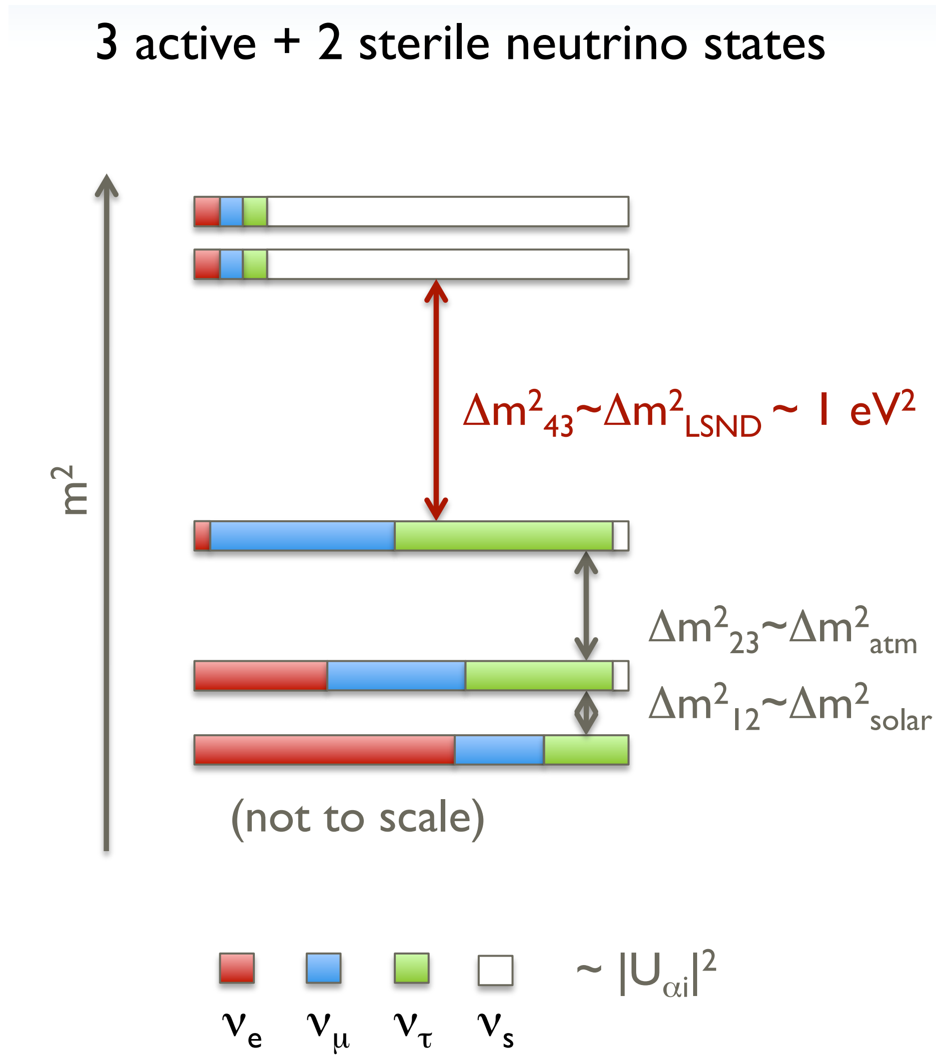
3+1 global fit



J.M. Conrad et al., Adv.High Energy Phys. 2013 (2013)

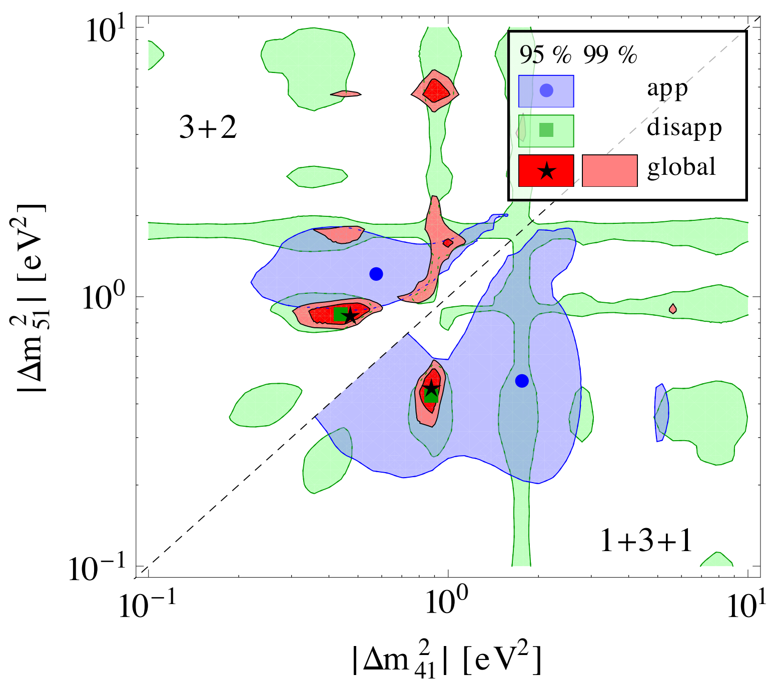
A global picture ?

Let's add a second sterile neutrino!

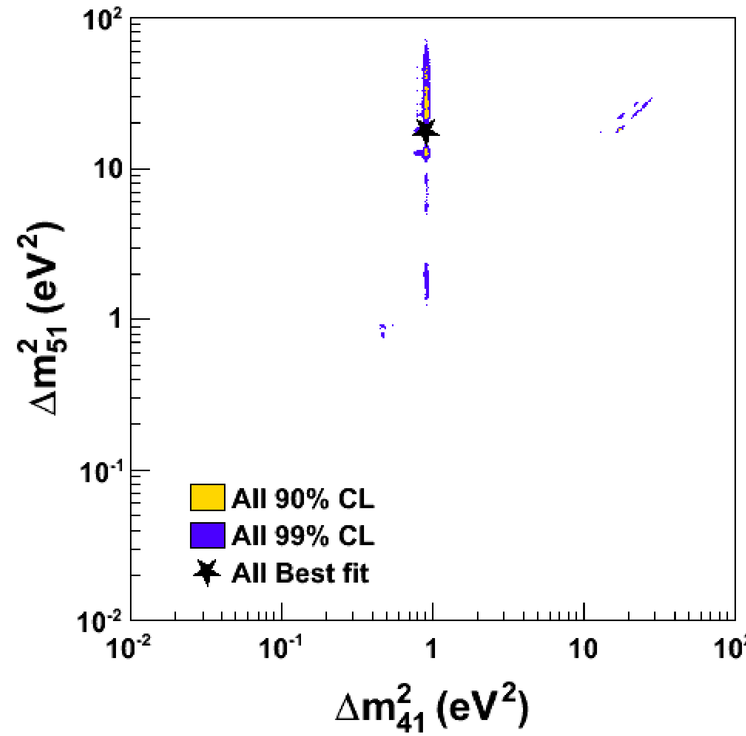


A global picture ?

3+2 global fit

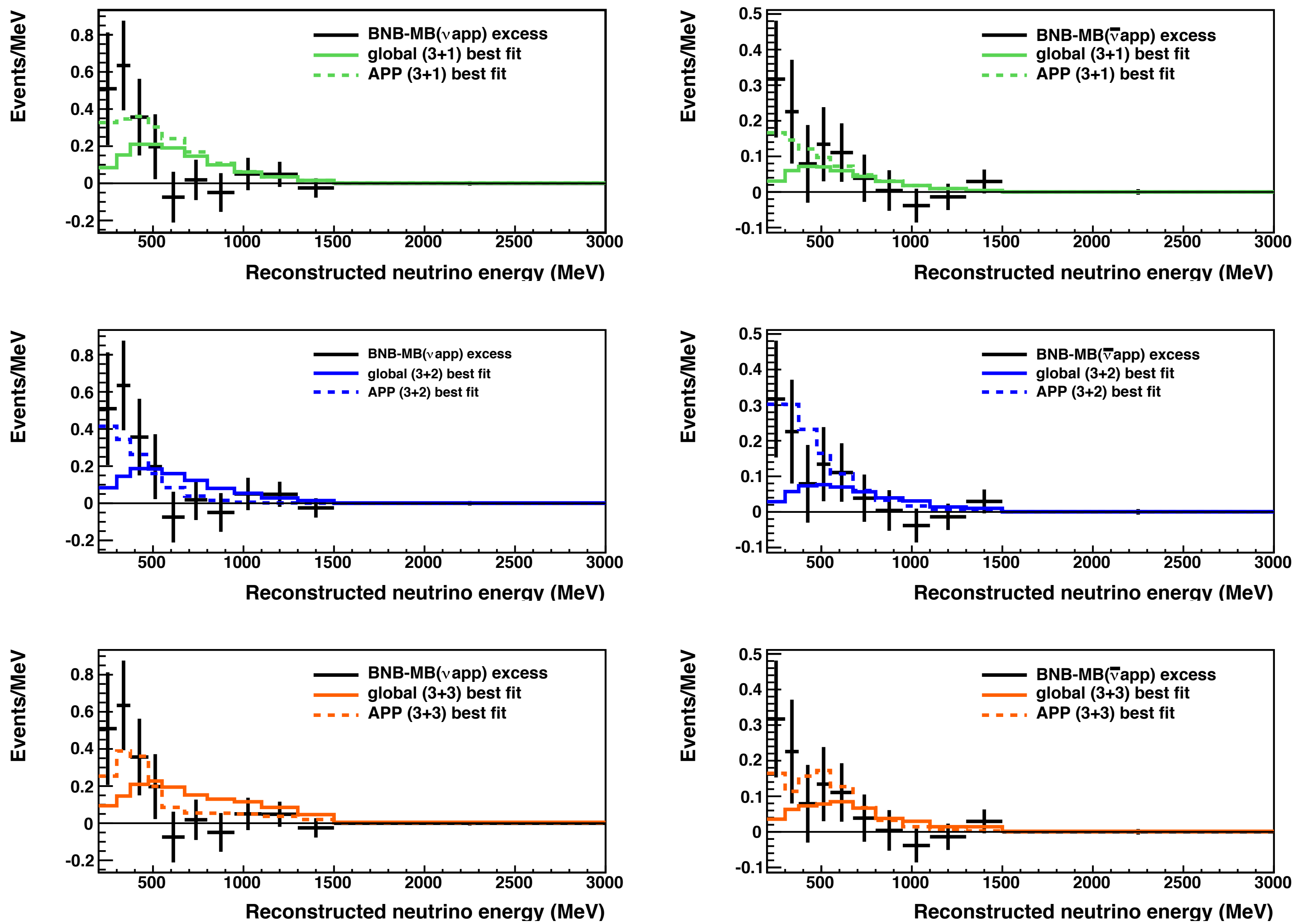


J.Kopp et al., JHEP 1305 (2013)



J.M. Conrad et al., Adv.High Energy Phys. 2013 (2013)

A global picture ?



J.M. Conrad et al., Adv.High Energy Phys. 2013 (2013)

A global picture ?

- 3+1 picture doesn't work well
- 3+2 also has tension
- 3+3 ???
- May be some experiments are wrong! Which ones?

A global picture ? The theorist approach

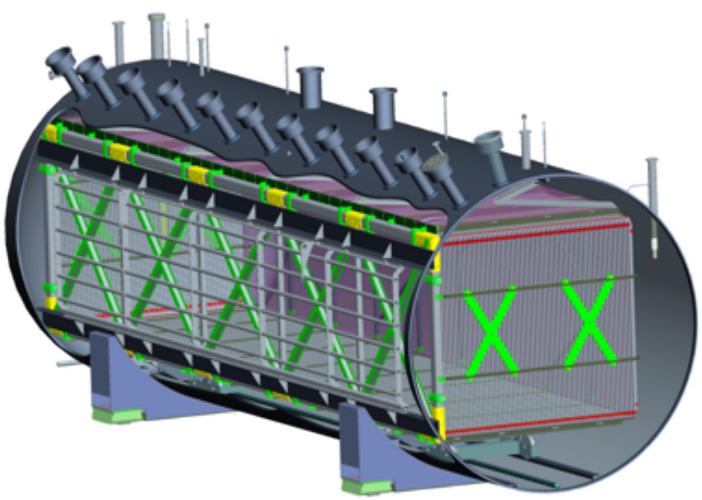
- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 10
- 2 decaying sterile neutrinos with CPV
- energy dependent quantum decoherence Farzan, TS, Smirnov 07
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10

most of these proposals involve sterile neutrinos

Future of sterile neutrino hypothesis

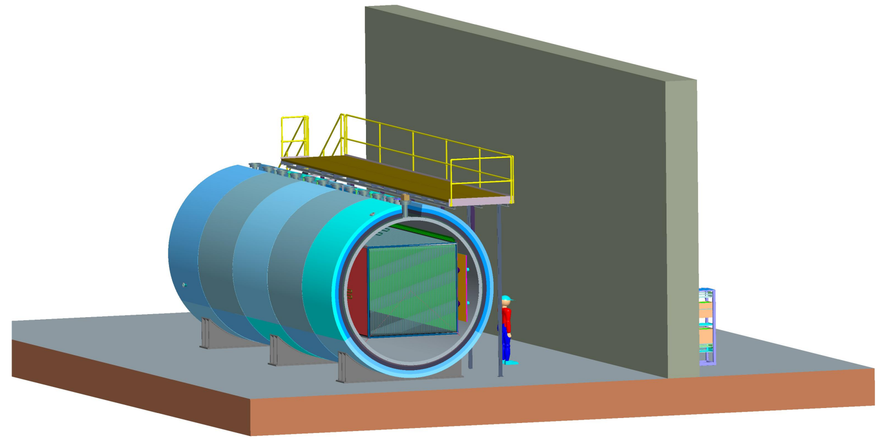
- MiniBooNE is done
- Planck did not answer the question definitely
- Reactor flux will stay uncertain
- Radioactive source experiments not sensitive enough (who wants MCi in their low radiation detectors!)
- **Short-baseline experiments!**

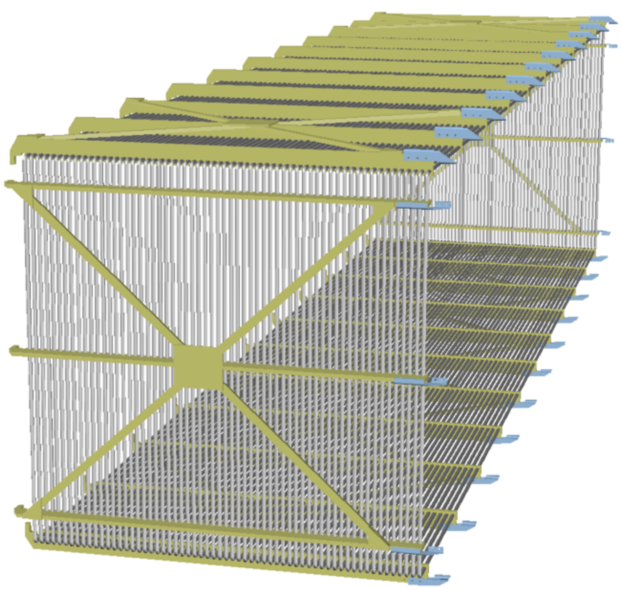
MICROBOONE



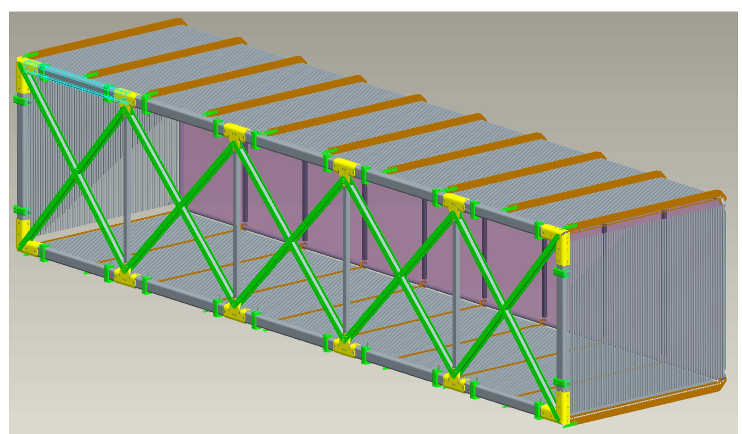
The MicroBooNE detector

- 170 tons total liquid argon
- 86 tons active volume (60t fiducial)
- TPC dimensions: 2.5m x 2.3m x 10.4m
- 32 PMTs

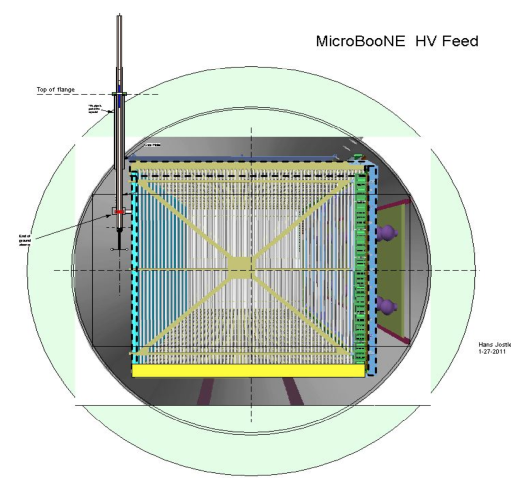




Field cage



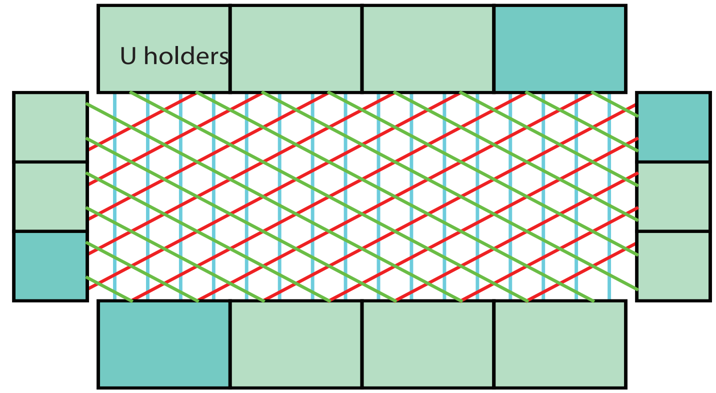
Field cage, anode and cathode planes

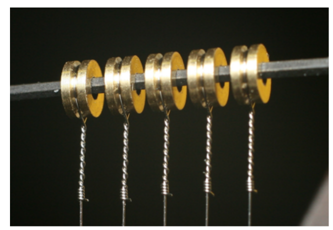


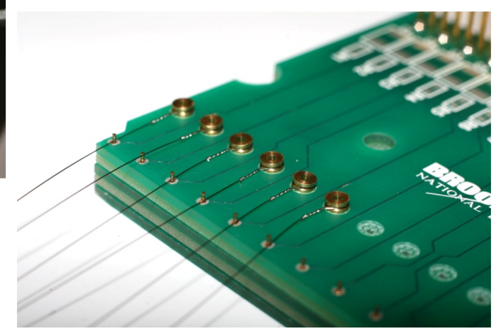
Cross section of TPC inside cryostat

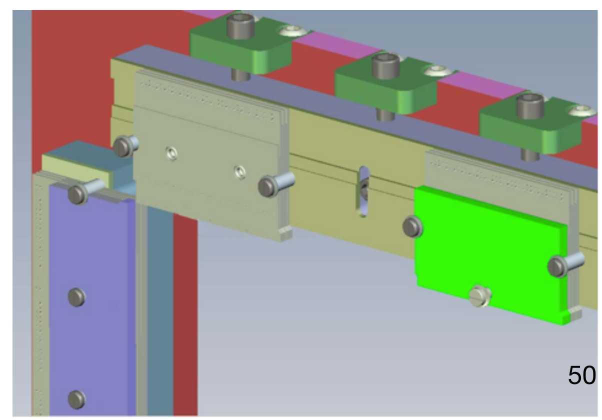
The MicroBooNE detector

- 3 wire planes (U,V,Y)
  - •Y (3456 wires): vertical
  - •U (2400 wires): +60°
  - •V (2400 wires): -60°
- 3mm wire pitch
- Wires are in stainless steel coated with copper and gold flash: high breakload and low resistance
- Wire attachment via ferrule fixed on wire carrier boards
- Fully automated wire winding machine



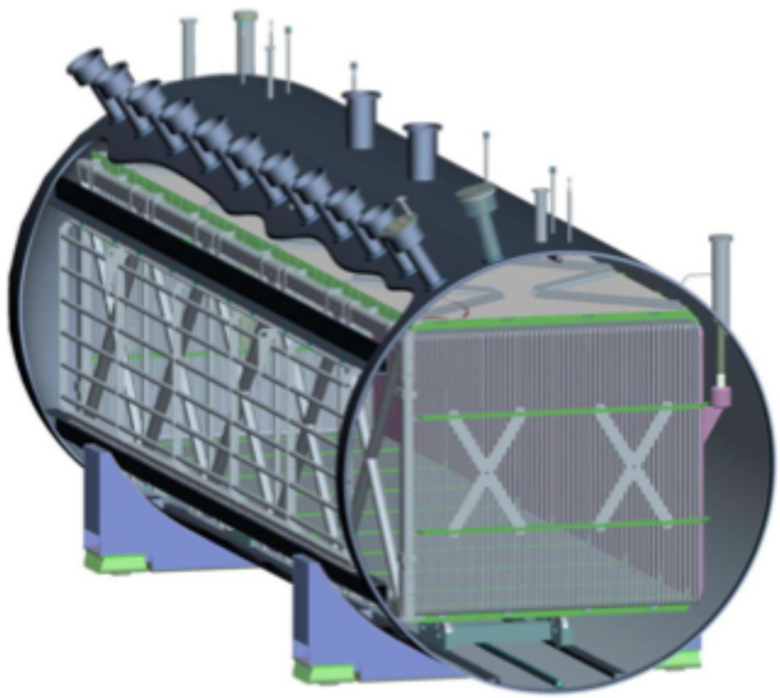






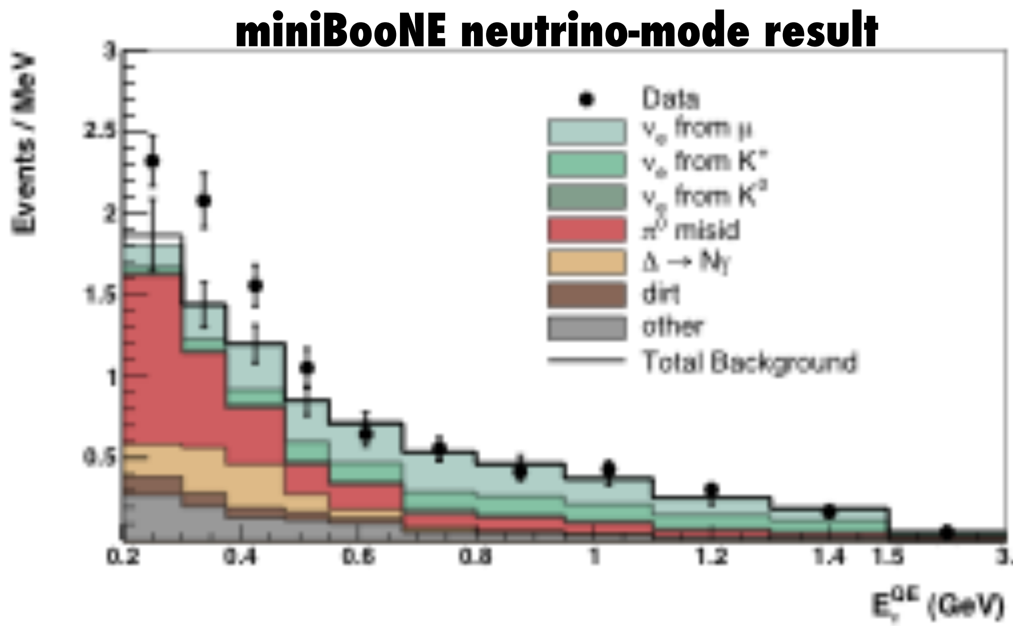
The science of MicroBooNE

- Study the MiniBooNE neutrino low energy excess
- Measure low energy cross-sections



MicroBooNE and the low energy excess

- MiniBooNE experiment observed an excess (3σ) at low energies (200 MeV - 475 MeV) in neutrino mode
- The excess events are electron-like: e^-/γ
- MiniBooNE cannot distinguish between electrons and photons
- Need a new detection technology:
  → **MicroBooNE**

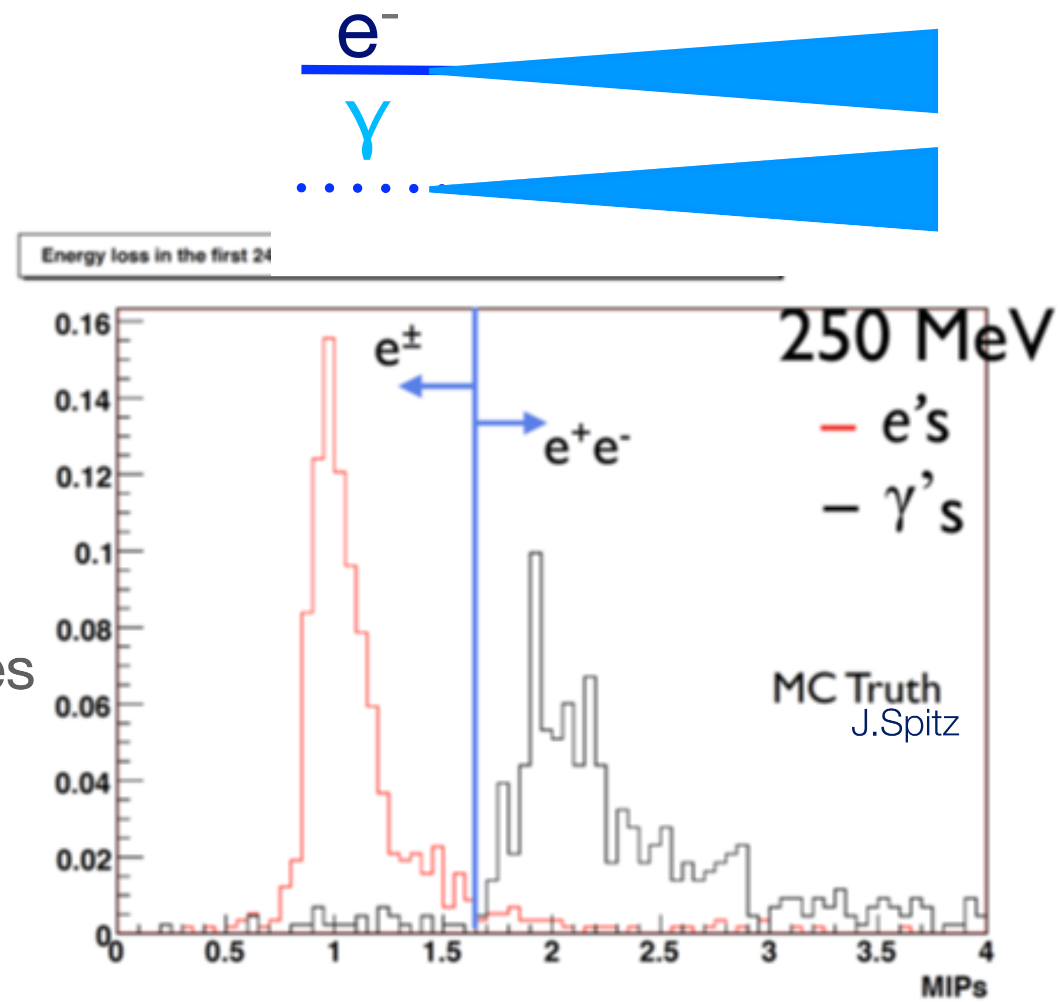


Phys.Rev.Lett.102, 2009

MicroBooNE and the low-energy excess

MicroBooNE:

- Distinction between e/γ
- ν_e efficiency ~2x better
- Sensitivity at lower energies

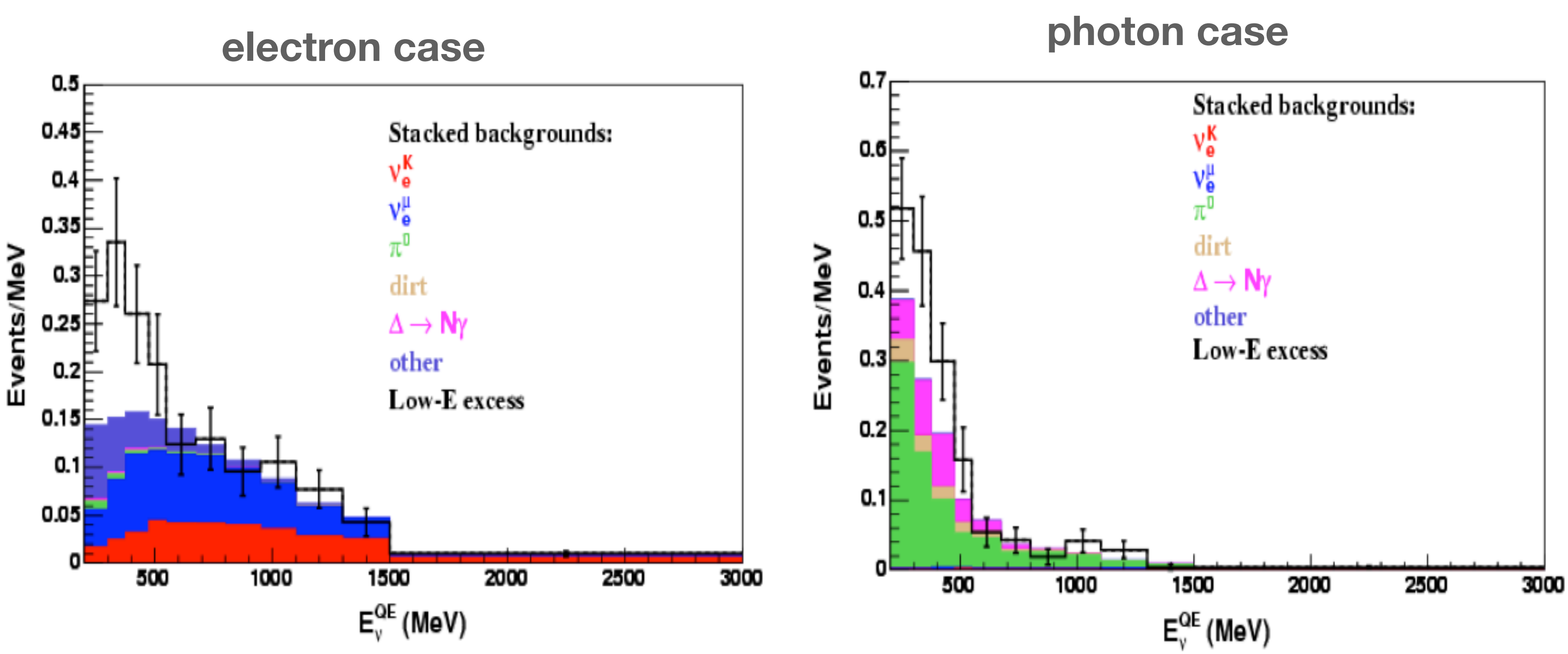


dE/dx for electrons and gammas in first 2.4 cm of track

MicroBooNE addressing the MiniBooNE excess

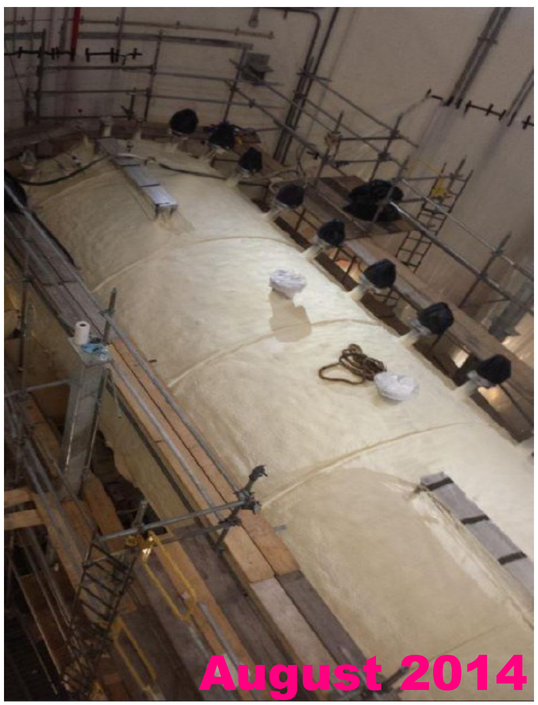
(6.6x10^{20} POT neutrino mode)

For microBooNE, as a counting experiment: 5σ sensitivity if excess is ν_es,
4σ sensitivity if excess is γs



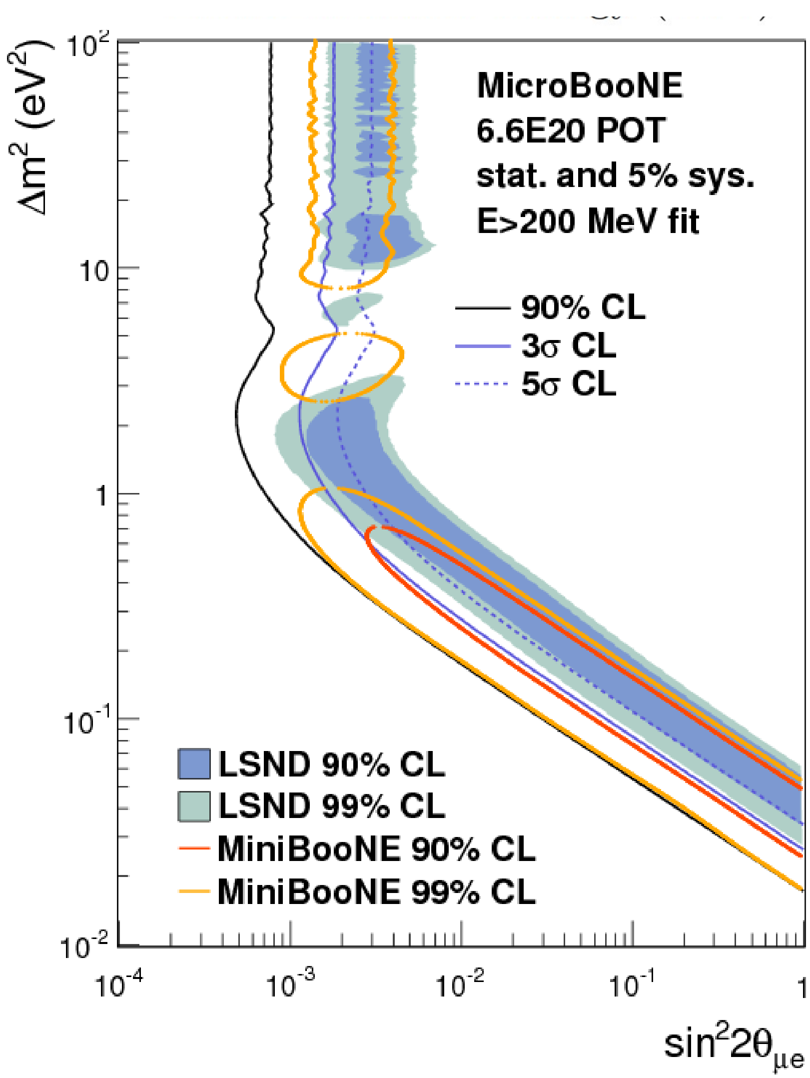
MicroBooNE has been built!

MicroBooNE status



Data taking will start early soon!

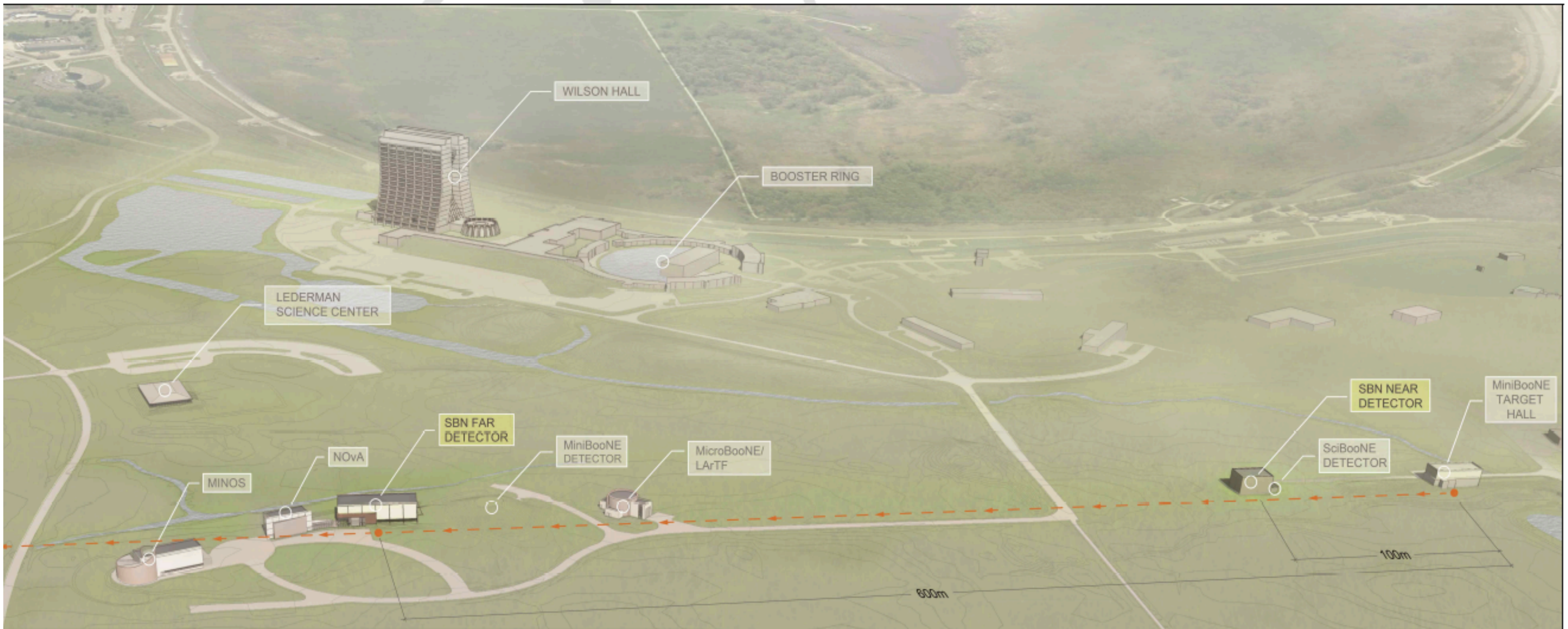
MicroBooNE sensitivity to sterile neutrinos

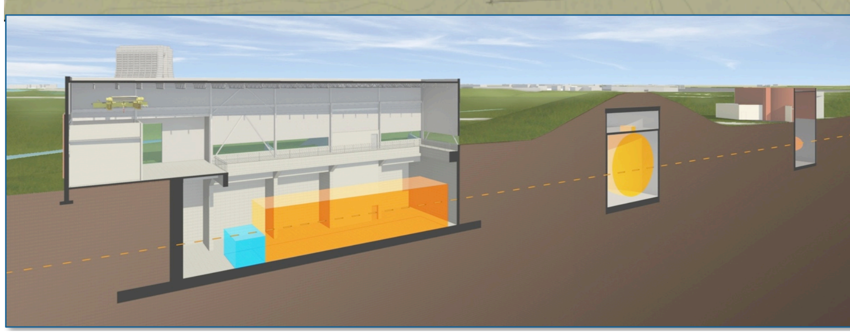


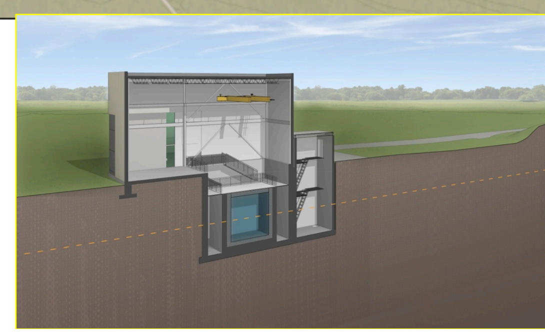
LAr1-ND Proposal (http://www.fnal.gov/directorate/program_planning/Jan2014PACPublic/LAr1ND_Proposal.pdf)

Beyond MicroBooNE: Addressing LSND/MiniBooNE excesses

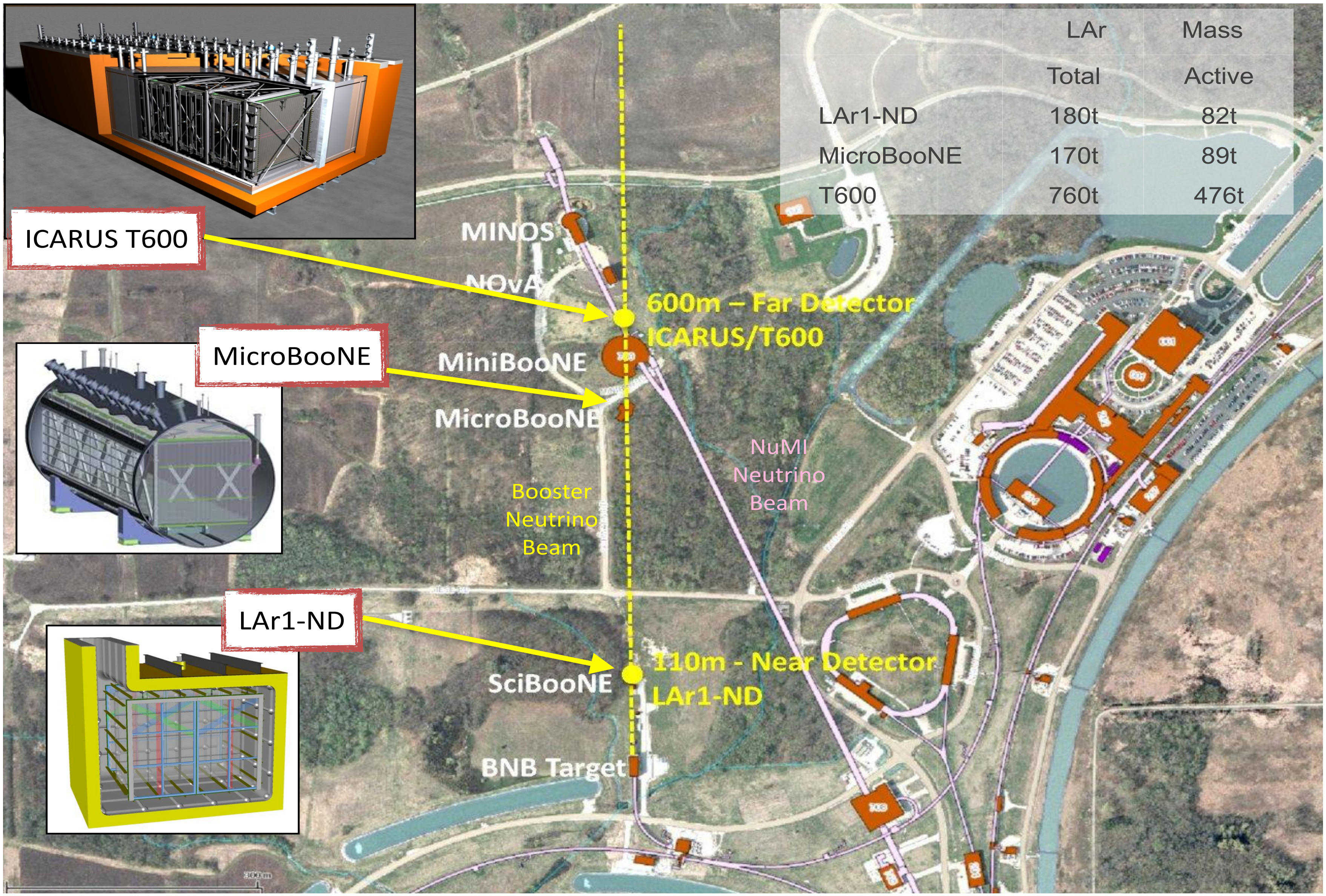
THE SBN PROPOSAL







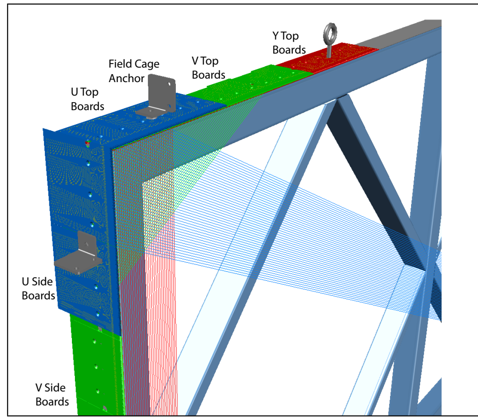
The SBN proposal

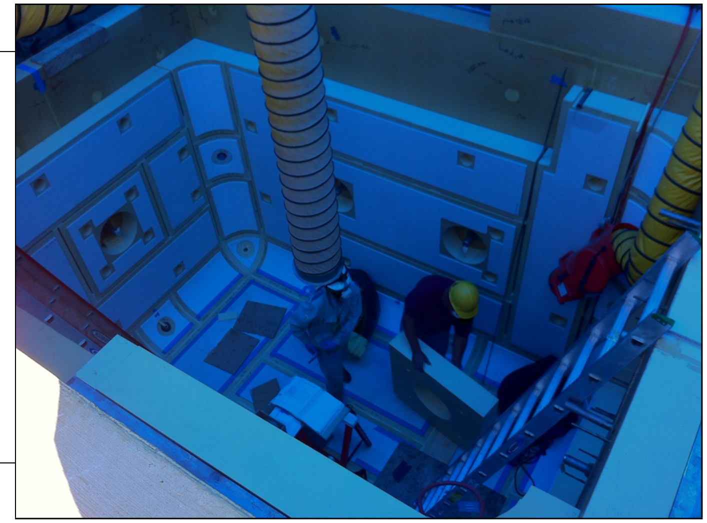


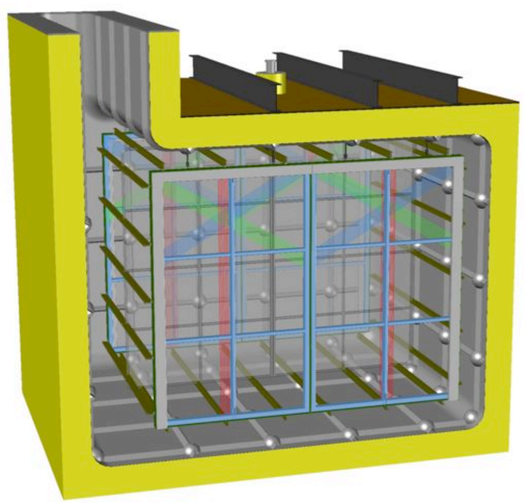
	LAr Total	Mass Active
LAr1-ND	180t	82t
MicroBooNE	170t	89t
T600	760t	476t

The LAr1-ND

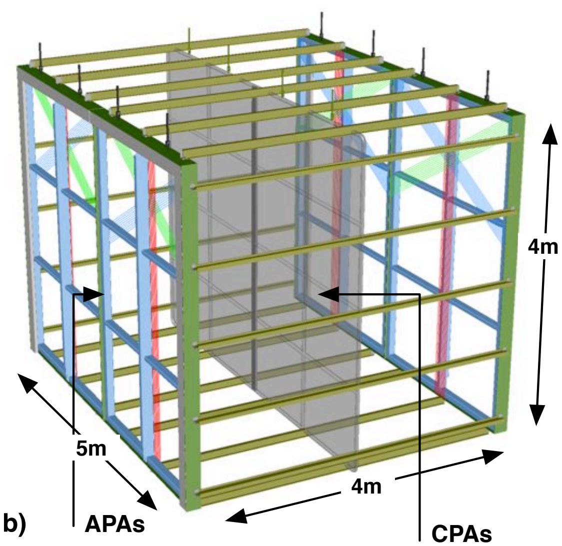
- 180t LAr detector (82t fiducial)
- Membrane Cryostat
- 2 Anode Plane Assemblies + 1 Cathode Plane





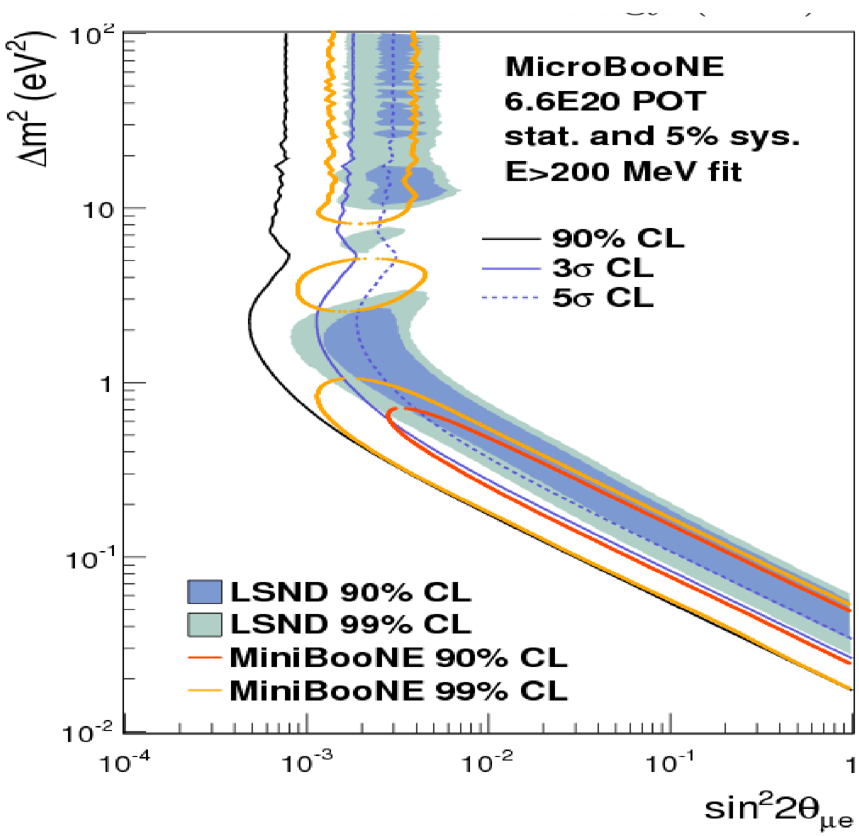


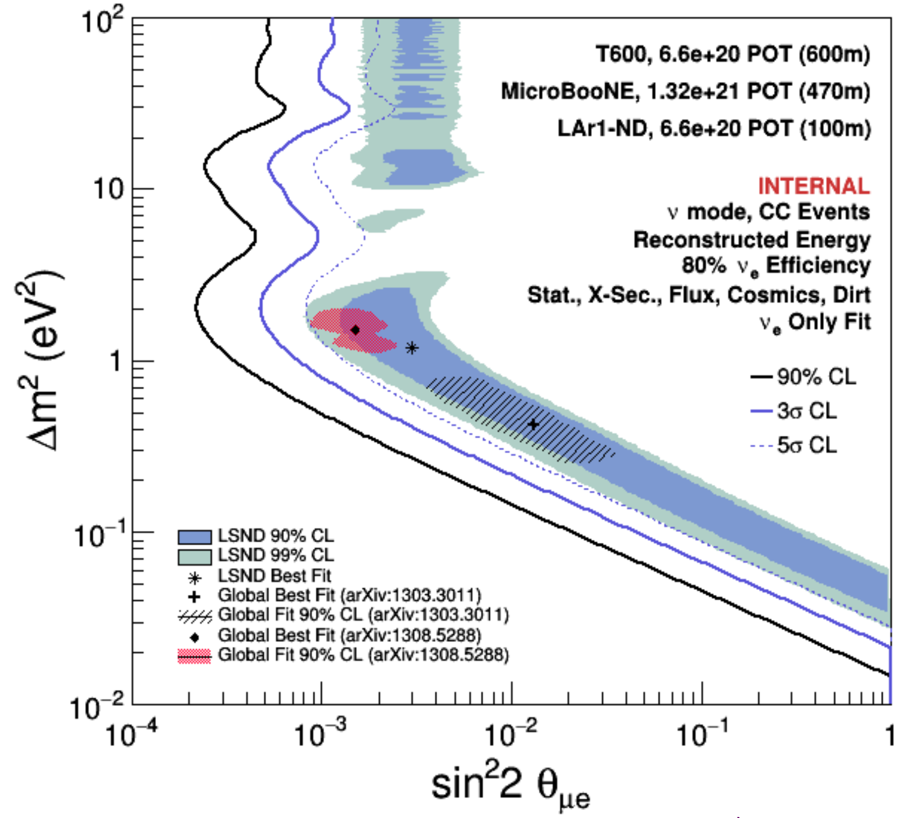
a)



b)

Sensitivities* in **neutrino** mode for LAr-ND





SBN Proposal (http://www.fnal.gov/directorate/program_planning/Jan2015PACPublic/SBN_Proposal.pdf)

* The studies here only consider a simple 2-neutrino model

SBN proposal status

- Proposal was submitted in January 2015
- Very positive response

"The Committee recommends Stage 1 approval for the SBN program, which incorporates LAr1ND and ICARUS with MicroBooNE towards a coherent SBN program. We recommend that the Laboratory provide the necessary engineering and technical resources to allow the program to move forward expeditiously, and to understand the scope of the Booster Neutrino Beamline modifications and improvements."

http://www.fnal.gov/directorate/program_planning/Jan2015Public/PAC-2015Jan_final.pdf

Other suggestions??

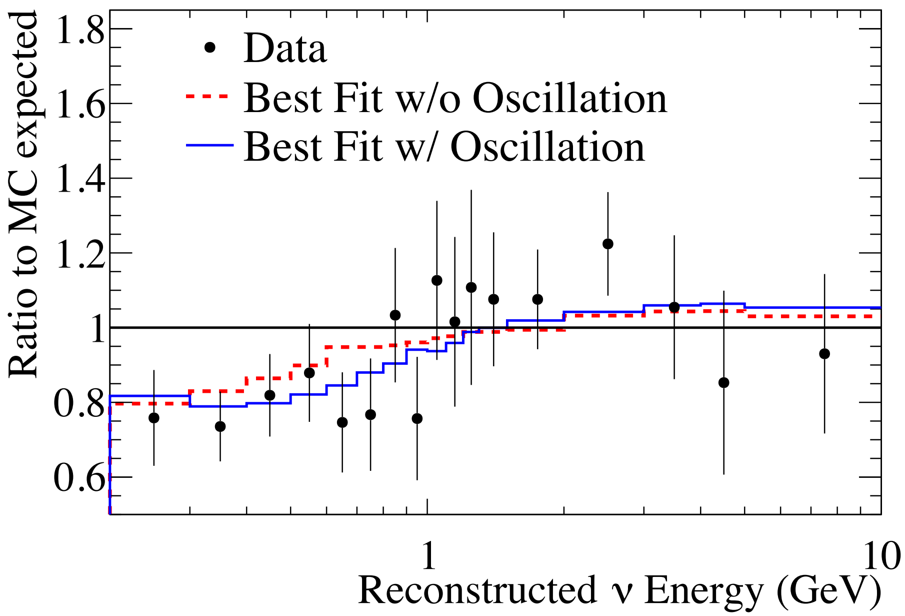
A. Future Experiments

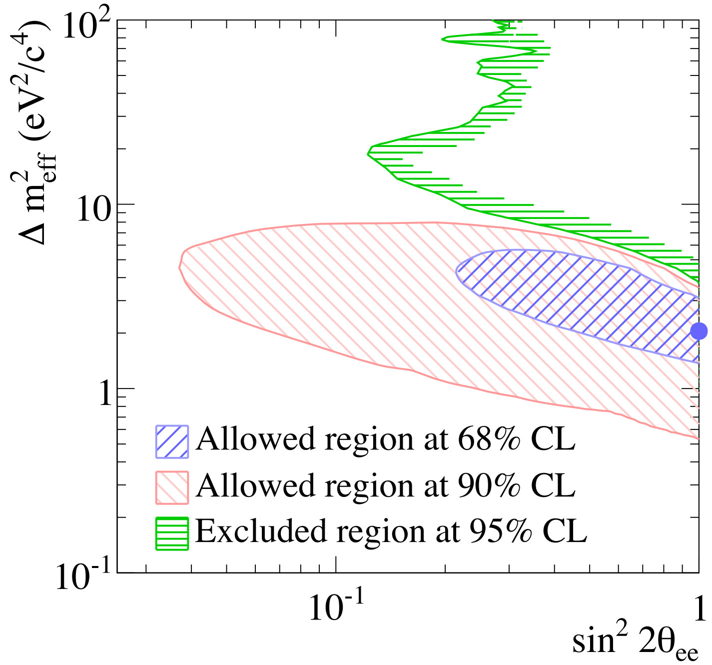
1. LENS-Sterile
2. RICOCHET: Coherent Scattering and Oscillometry Measurements with Low-temperature Bolometers
3. Very Short Baseline $\nu_e \rightarrow \nu_x$ Oscillation Search with a Dual Metallic Ga Target at Baksan and a ^{51}Cr Neutrino Source
4. Proposed search of sterile neutrinos with the Borexino detector using neutrino and antineutrino sources
5. Ce-LAND: A proposed search for a fourth neutrino with a PBq antineutrino source
6. Search for Sterile Neutrinos with a Radioactive Source at Daya Bay
7. SNO+Cr
8. Reactors with a small core
9. SCRAAM: A reactor experiment to rapidly probe the Reactor Antineutrino Anomaly
10. Nucifer: a Small Detector for Short-Distance Reactor Electron Antineutrino Studies
11. Stereo Experiment
12. A Very Short-Baseline Study of Reactor Antineutrinos at the National Institute of Standards and Technology Center for Neutron Research
13. OscSNS: A Precision Neutrino Oscillation Experiment at the SNS
14. LSND Reloaded
15. Kaon Decay-at-Rest for a Sterile Neutrino Search
16. The MINOS+ Project
17. The BooNE Proposal
18. Search for anomalies with muon spectrometers and large LArTPC imaging detectors at CERN
19. Liquid Argon Time Projection Chambers
20. Very-Low Energy Neutrino Factory (VLENF)
21. Searching for Sterile Neutrinos with Low Energy Beta-Beams
22. Probing active-sterile oscillations with the atmospheric neutrino signal in large iron/liquid argon detectors

Sterile Neutrino White Paper, arXiv:1204.5379, 2012

New Results! T2K ν_e Disappearance

$\nu_e \to \nu_e$ $L \simeq 280\,\text{m}$ $E \sim 500\,\text{MeV}$



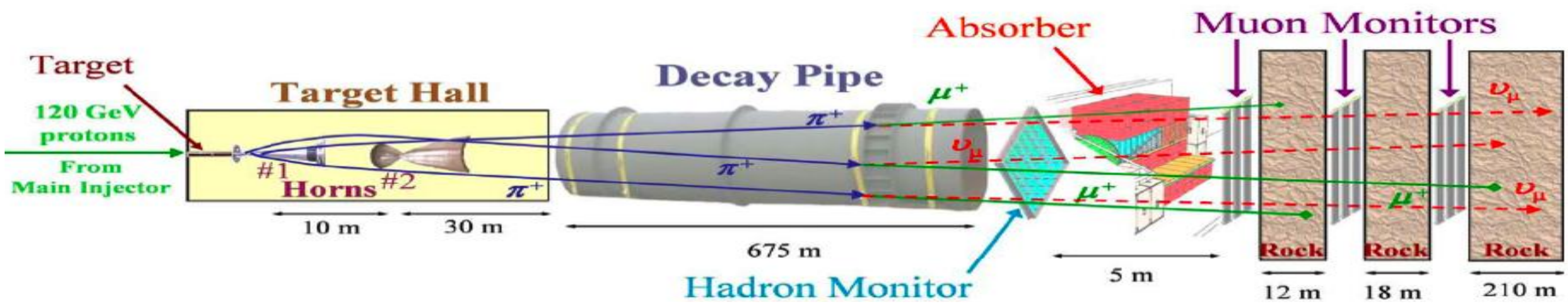


$\sim 1.4\sigma$ deviation

Conclusions

- Sterile neutrinos are back in fashion
- Need **DEFINITIVE** tests
- MicroBooNE is near commissioning and will answer the MiniBooNE low energy excess
- Definitive measurements could be done with SBN
- LAr1-ND and SBN will improve search considerably: proposal submitted to PAC January 2015 (Very positive response!)
- Stay tuned!

Neutrino Production

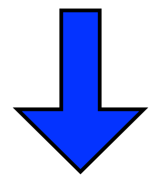


MicroBooNE: measuring cross sections

Expected event rates for 6.6 x 10^{20} POT on the BNB neutrino target

production mode	# events
CC QE ($\nu_\mu n \to \mu^- p$)	60,161
NC elastic ($\nu_\mu N \to \nu_\mu N$)	19,409
CC resonant π^+ ($\nu_\mu N \to \mu^- N \pi^+$)	25,149
CC resonant π^0 ($\nu_\mu n \to \mu^- p \pi^0$)	6,994
NC resonant π^0 ($\nu_\mu N \to \nu_\mu N \pi^0$)	7,388
NC resonant $\pi^\pm$ ($\nu_\mu N \to \nu_\mu N' \pi^\pm$)	4,796
CC DIS ($\nu_\mu N \to \mu^- X$, $W > 2$ GeV)	1,229
NC DIS ($\nu_\mu N \to \nu_\mu X$, $W > 2$ GeV)	456
NC coherent π^0 ($\nu_\mu A \to \nu_\mu A \pi^0$)	1,694
CC coherent π^+ ($\nu_\mu A \to \mu^- A \pi^+$)	2,626
NC kaon ($\nu_\mu N \to \nu_\mu K X$)	39
CC kaon ($\nu_\mu N \to \mu^- K X$)	117
other ν_μ	3,678
total ν_μ CC	98,849
total ν_μ NC+CC	133,580
ν_e QE	326
ν_e CC	657

- Low energy cross-section measurements
- Coherent vs resonant pion production
- K production: cross section and proton decay studies
- ν_e cross sections

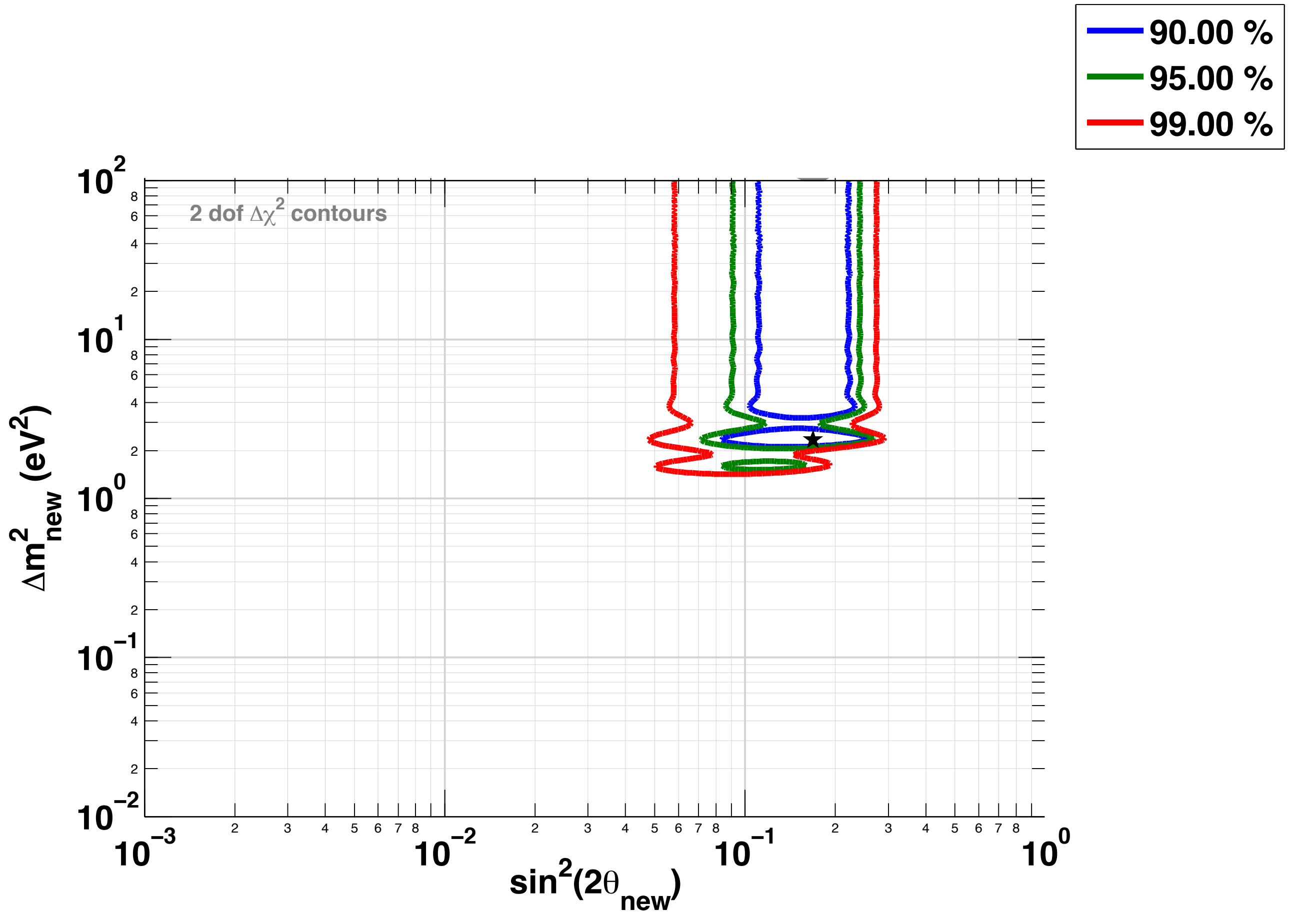


✦Good statistics for rare channels

✦Low energy threshold

✦Resolution of activity at the vertex to observe nuclear effects

Reactor + Gallium anomalies



Sterile Neutrino White Paper, arXiv:1204.5379, 2012

Sensitivity to disappearance for SBN