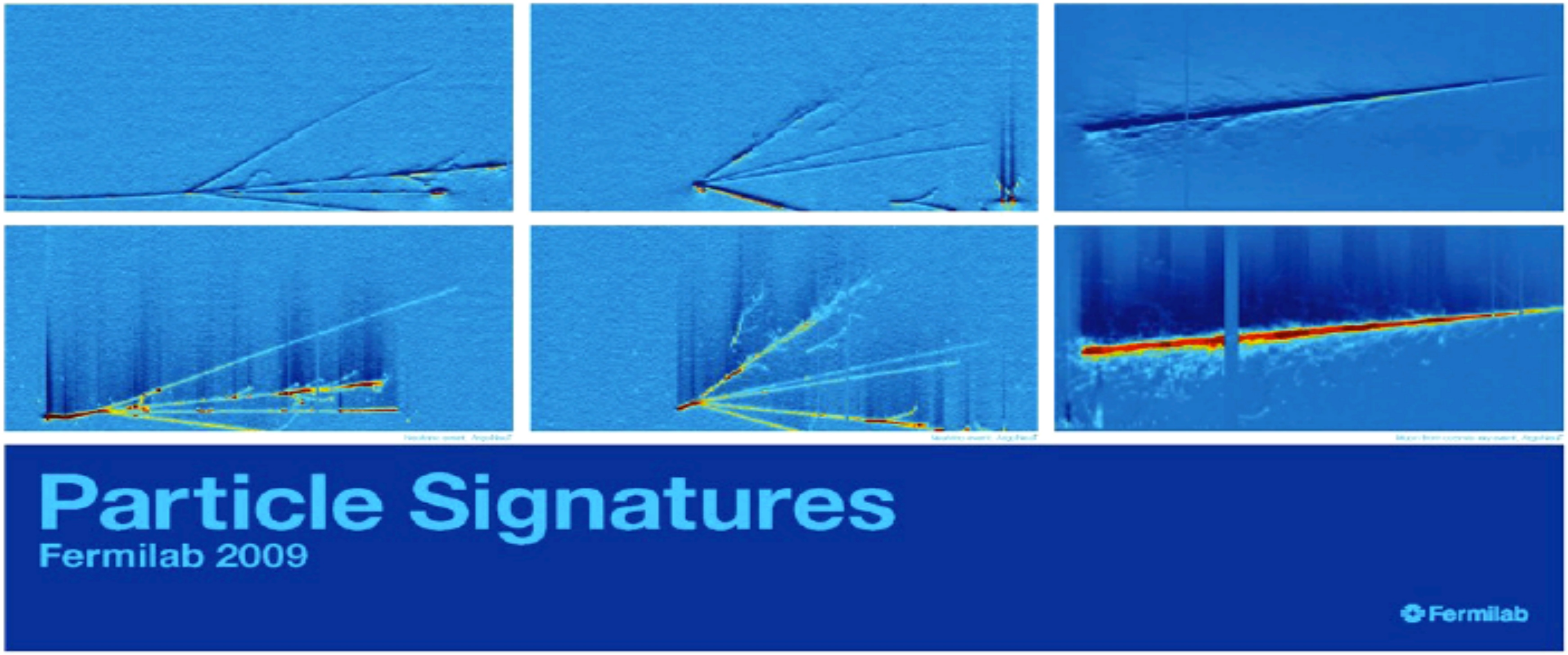


The FNAL LAr neutrino program

Roxanne Guenette
Yale University

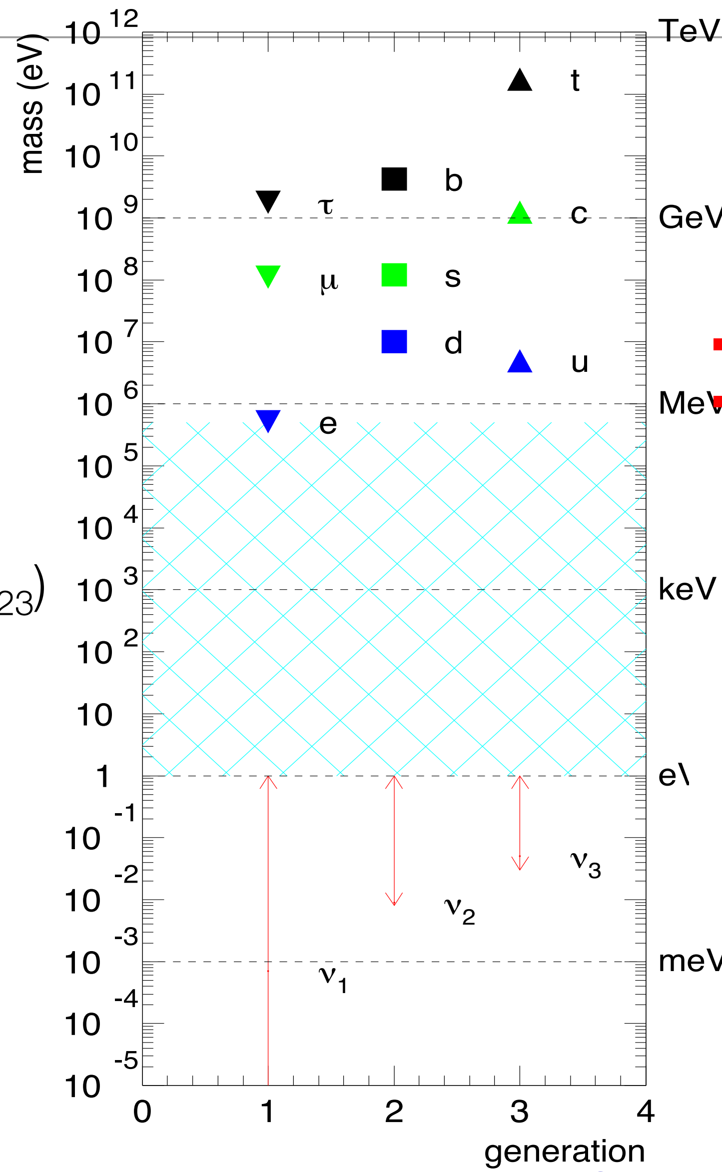
Feb. 24th 2012

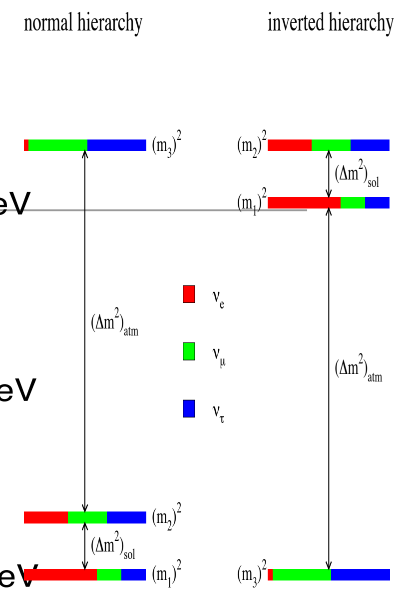
Outline

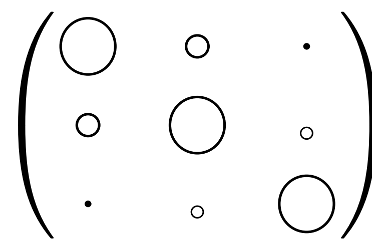
- Overview of neutrino physics “big questions” and LAr neutrino detection technology
- Why neutrino physics is so “IN” right now / The 2011 events!
- LAr detectors at FNAL: ArgoNeuT, MicroBooNE and LBNE
- Conclusions

Remaining questions

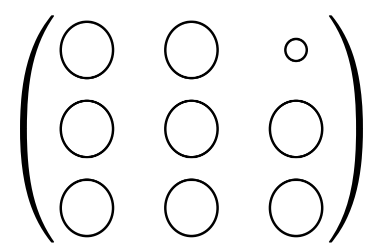
- Mass:
  - ➢ What is the mass?
  - ➢ Why is the mass so small?
  - ➢ What is the mass hierarchy?
- Oscillation parameters:
  - ➢ Is the atmospheric mixing (θ_{23}) maximal?
  - ➢ θ_{13}?
  - ➢ Is there CP violation?
- Are neutrinos Dirac or Majorana?
- Are there sterile neutrinos?







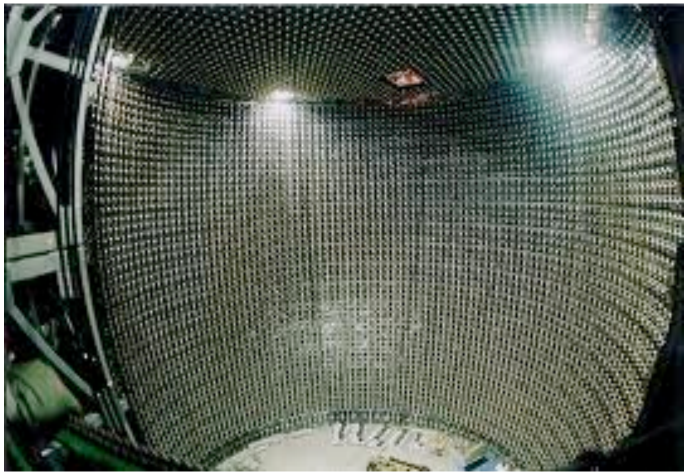
Quark mixing

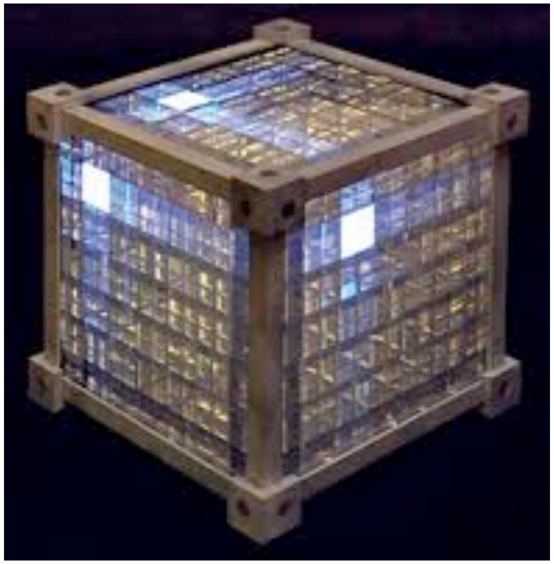


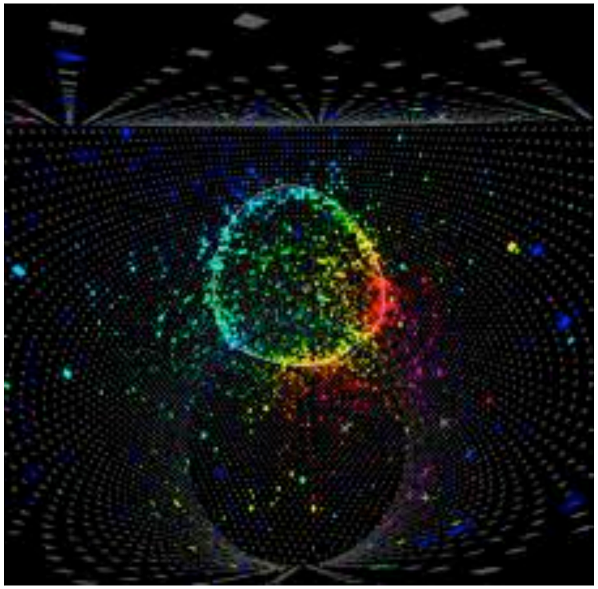
Lepton mixing

De Gouvea A. Proceedings of X Mexican Workshop of Particles and Fields, 2006

NEUTRINO DETECTION



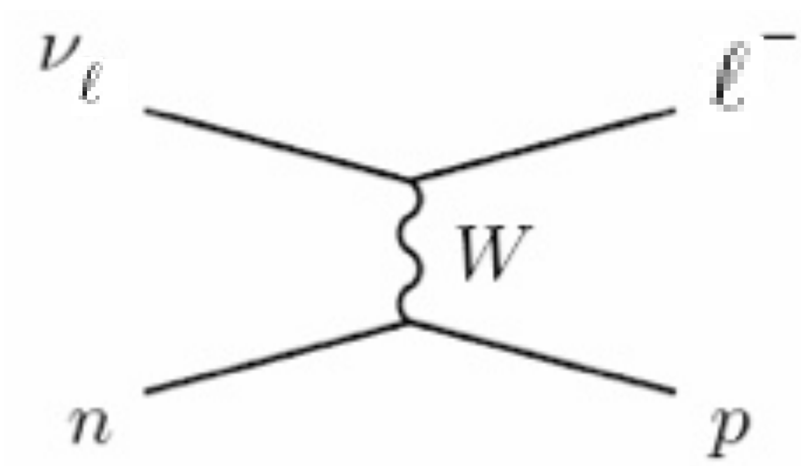




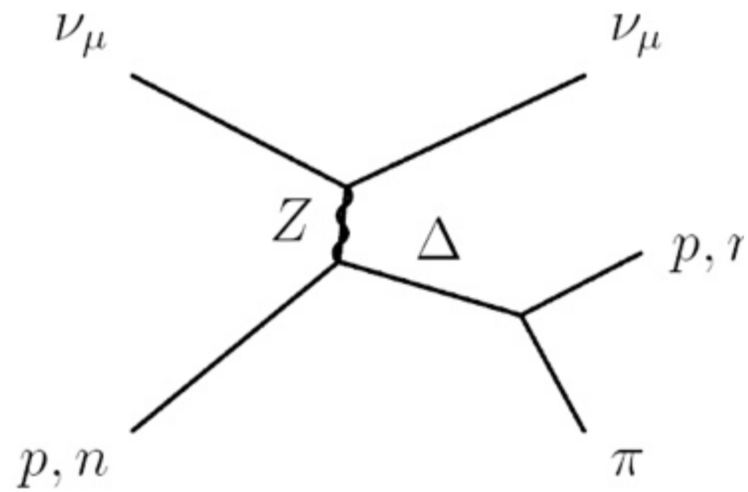
Neutrino Detection

- Neutrinos are not detected directly
- Neutrino interact through “Charged” or “Neutral” current
- Interaction products are detected

Charge Current (CC) Interactions



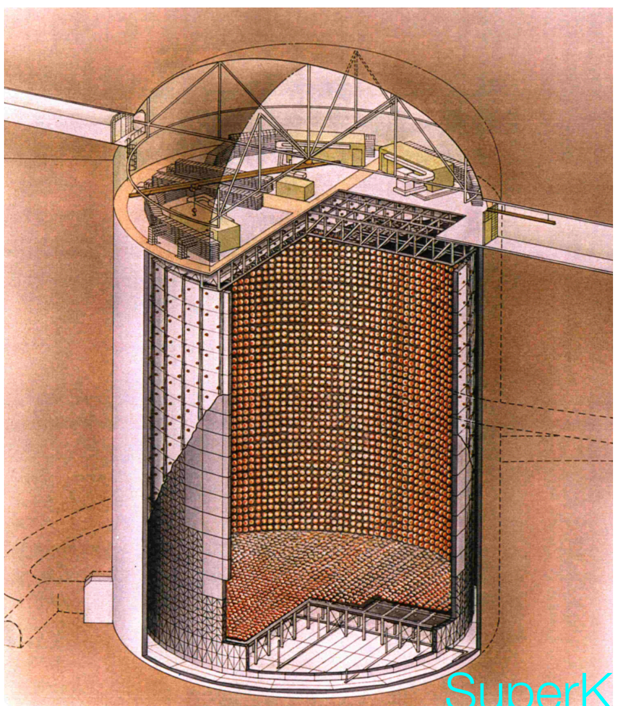
Neutral Current (NC) Interactions



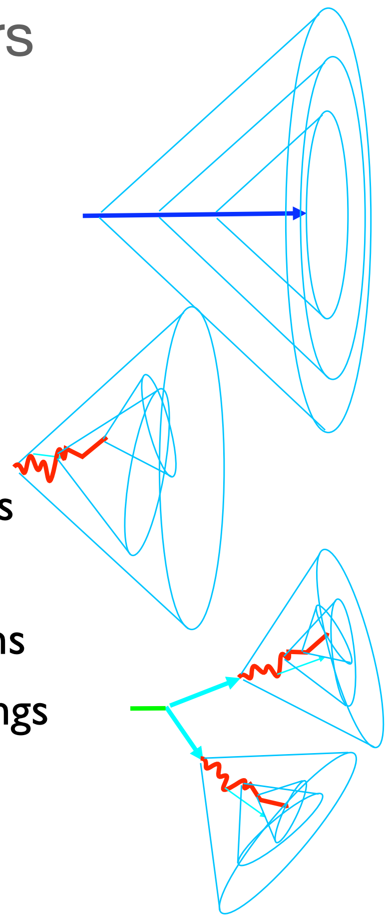
Neutrino Detection

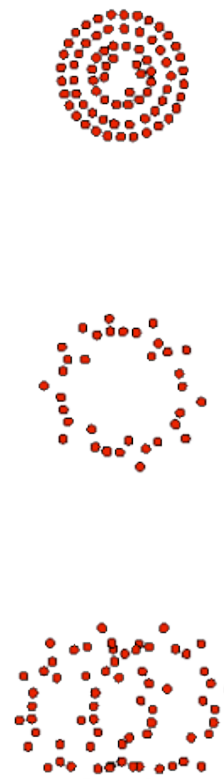
- Traditionally, neutrino detectors used Cherenkov radiation or scintillation light

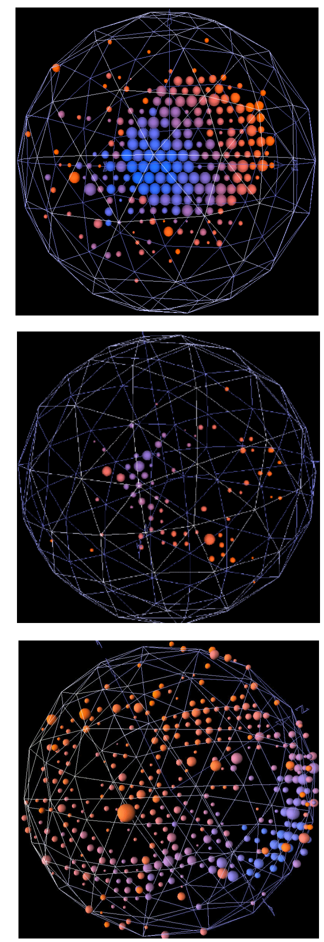
- Ex: Water Cherenkov detectors



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

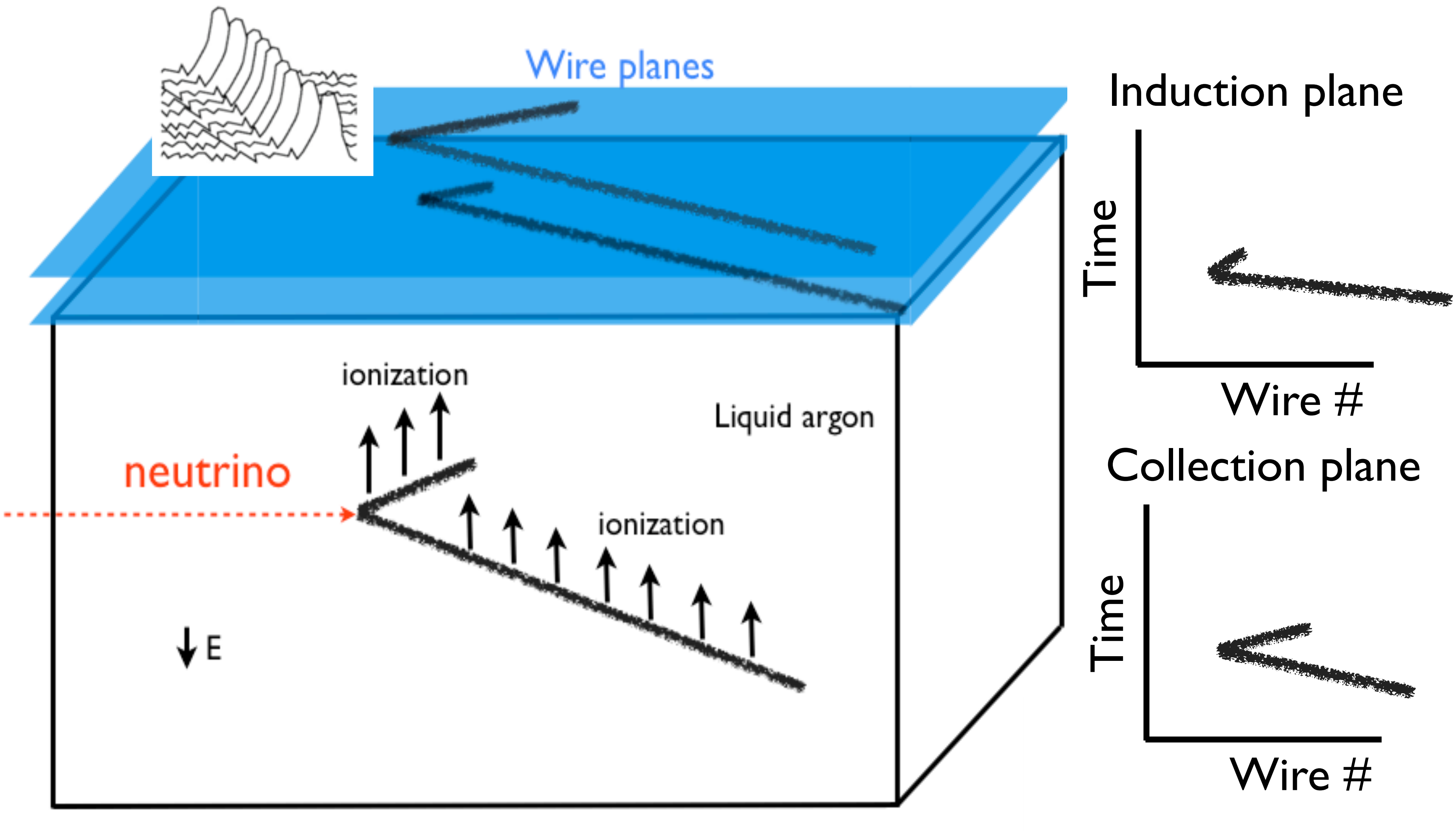






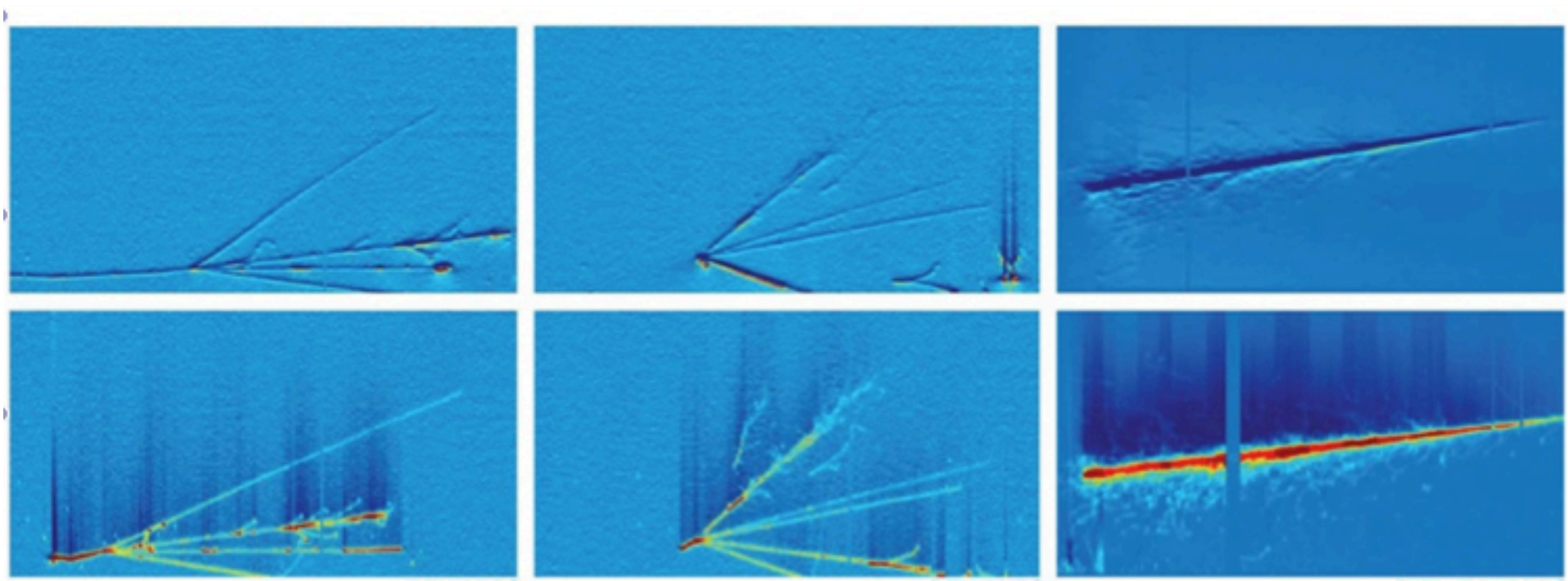
Neutrino Detection: A new technology

Liquid Argon Time Projection Chambers



LAr TPC

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



Very recent discoveries in neutrino physics (2011)

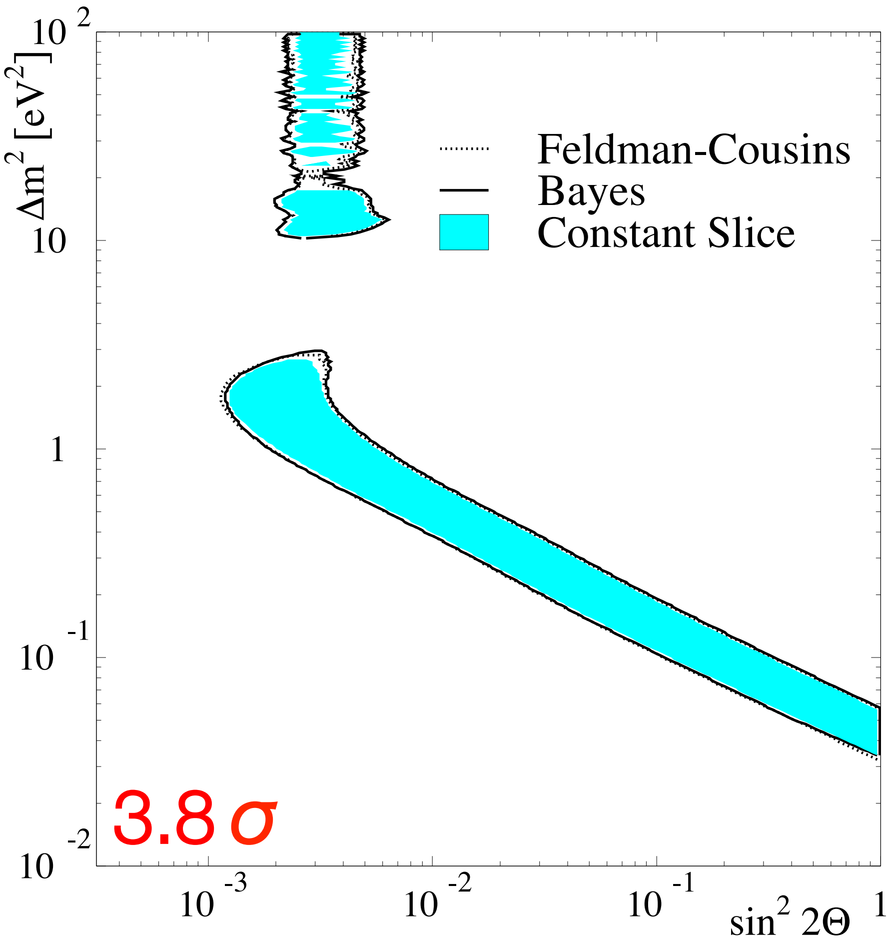
- **The sterile neutrino hypothesis got some back ups**

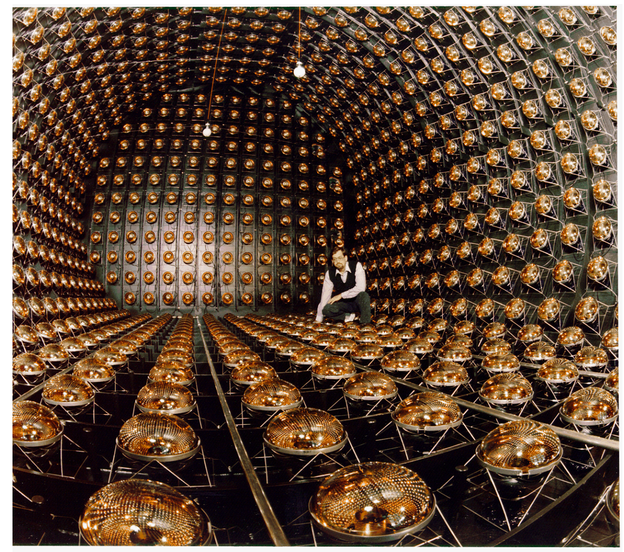
- θ_{13} **seems to be “big”**

- **Neutrinos seem to be quite fast!**

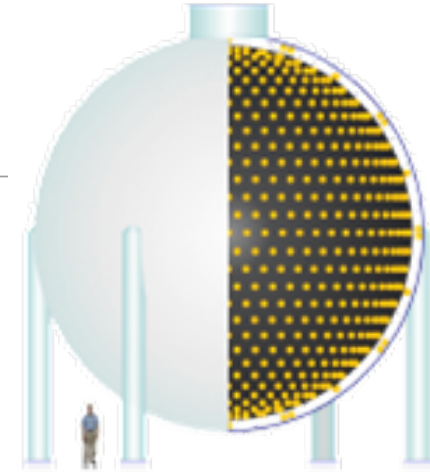
The LSND anomaly

- LSND: short-baseline accelerator, searching for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Would imply $\Delta m^2 \sim 1 eV^2$

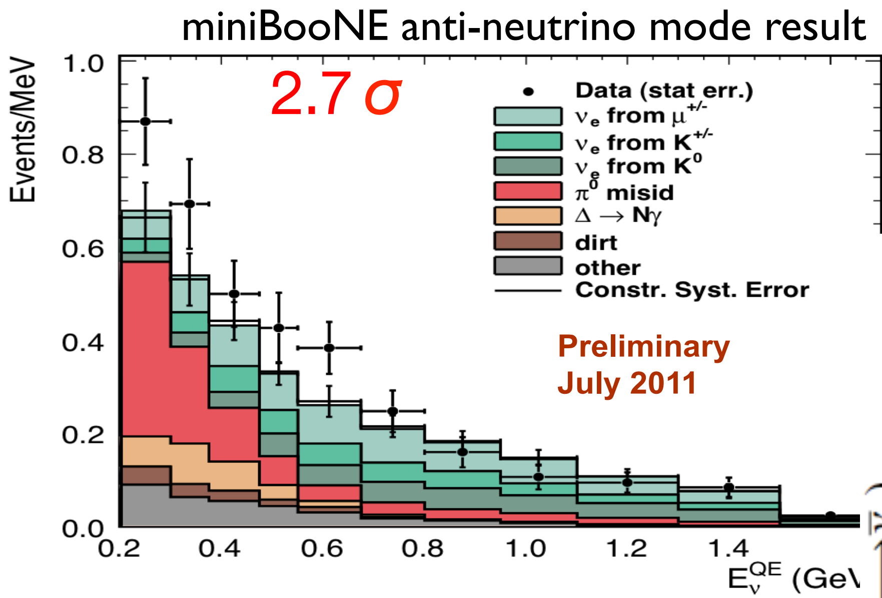




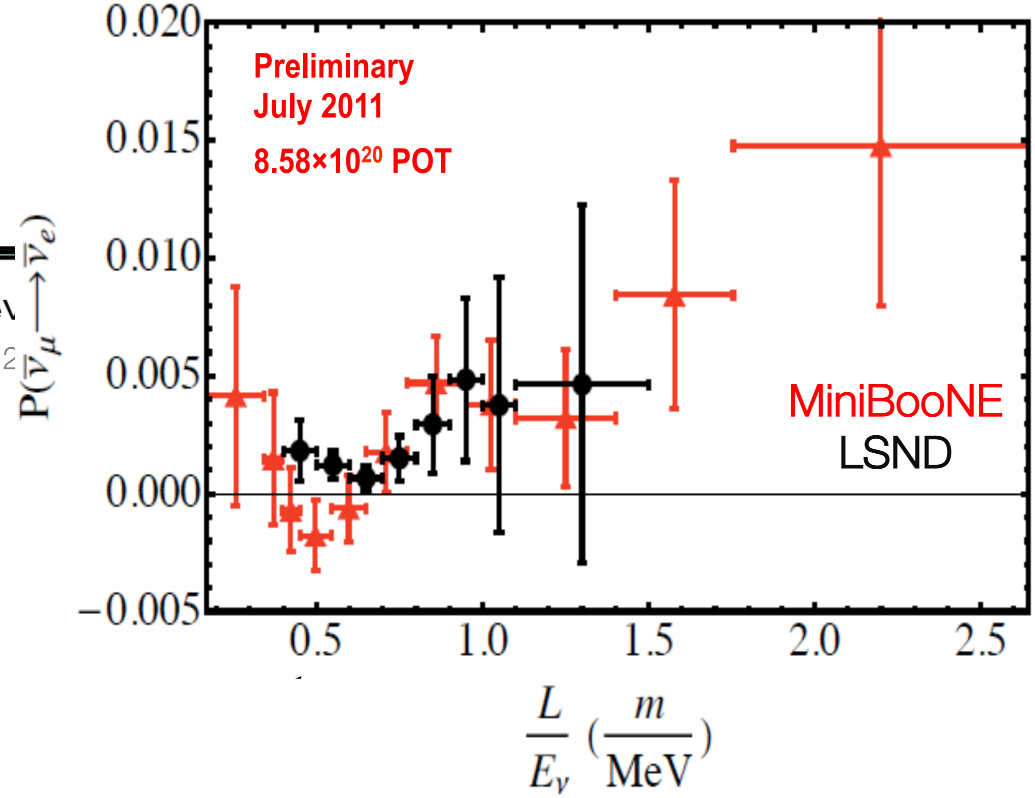
MiniBooNE anti-neutrino results



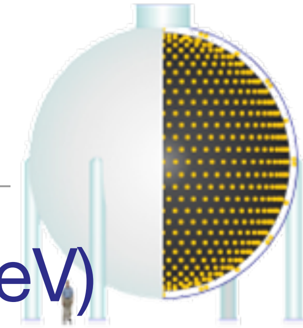
Excess consistent with LSND!



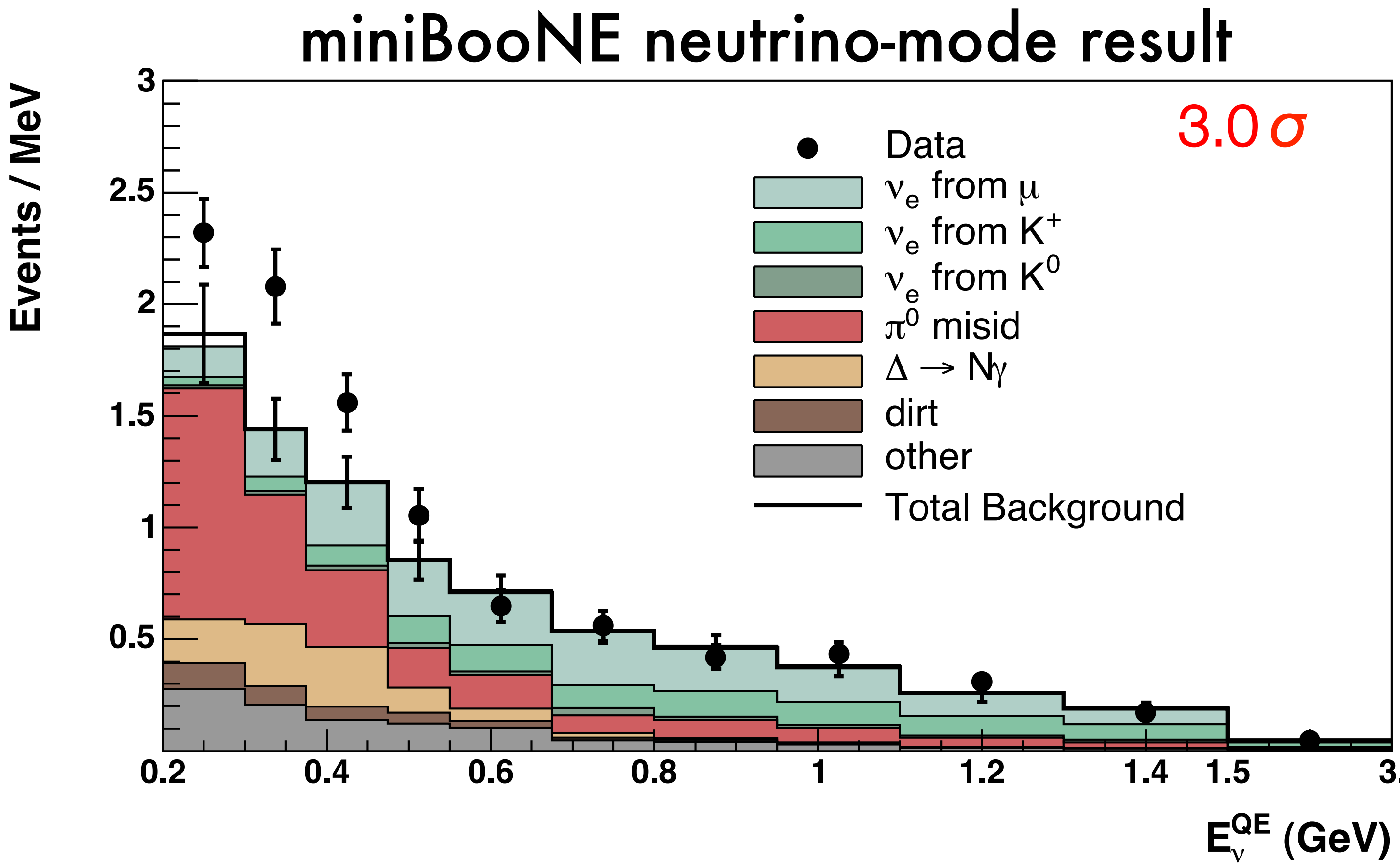
Phys. Rev. Lett. 105, 2



MiniBooNE neutrino results



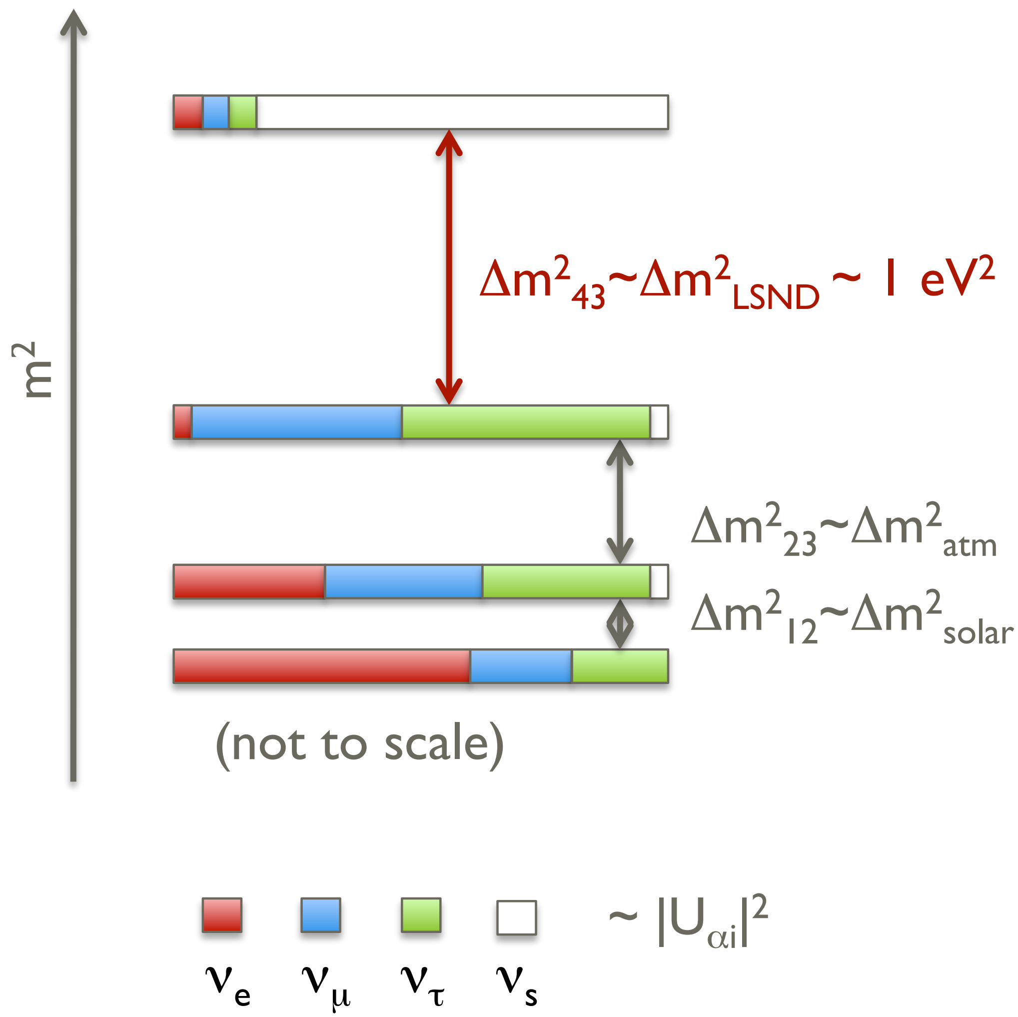
No excess in the LSND region (400MeV-1GeV)



Phys.Rev.Lett.102, 2009

New neutrino?

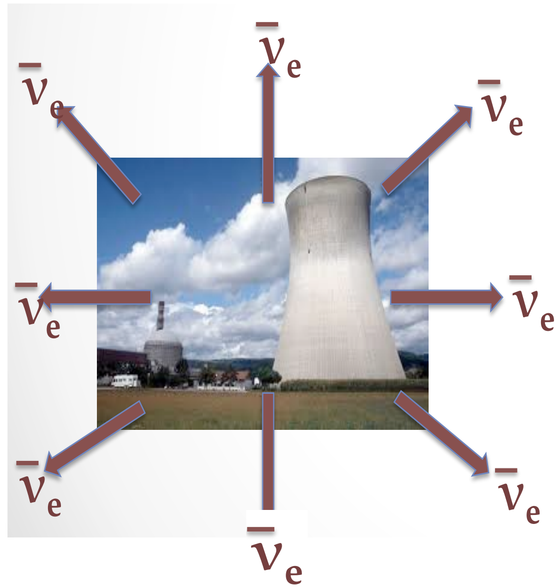
3 active + 1 sterile neutrino states

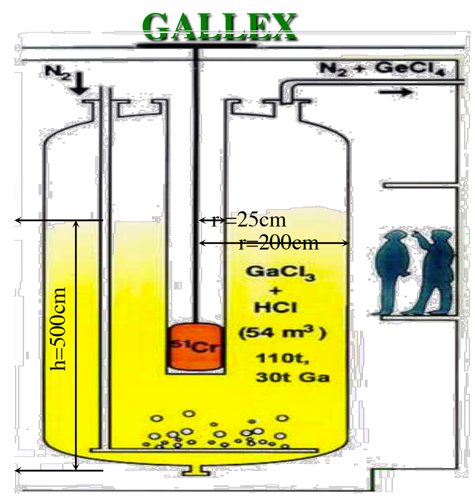


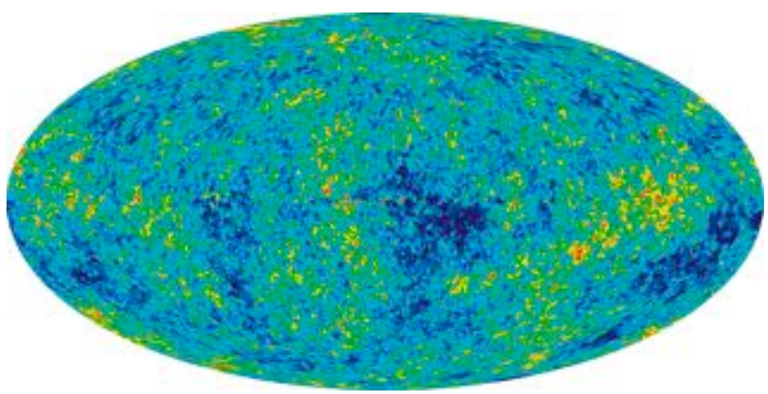
- Need new neutrino (but LEP said only 3!)
- Cannot be active → sterile

Sterile Neutrinos: May not be so crazy after all

- Reactor anomaly
- Gallium anomaly
- Cosmology



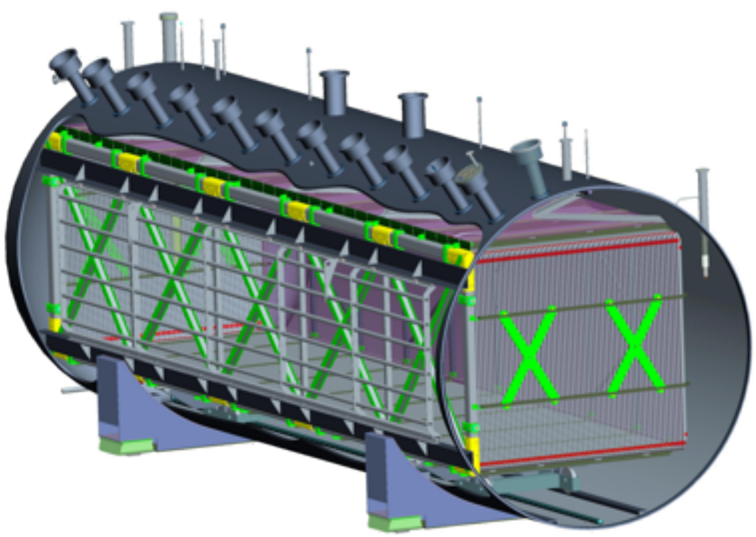




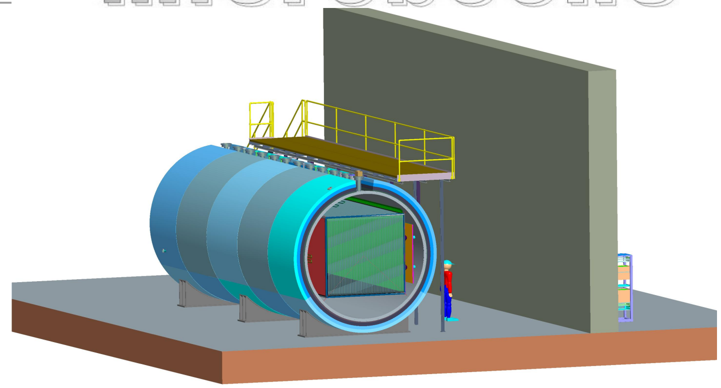
Future of sterile neutrino hypothesis

- MiniBooNE is currently taking more data in anti-neutrino mode
- Planck will tell N_{eff} with precision
- Reactor flux will stay uncertain
- Radioactive source experiments not sensitive enough (who wants MCi in their low radiation detectors!)
- **Short-baseline experiments!**

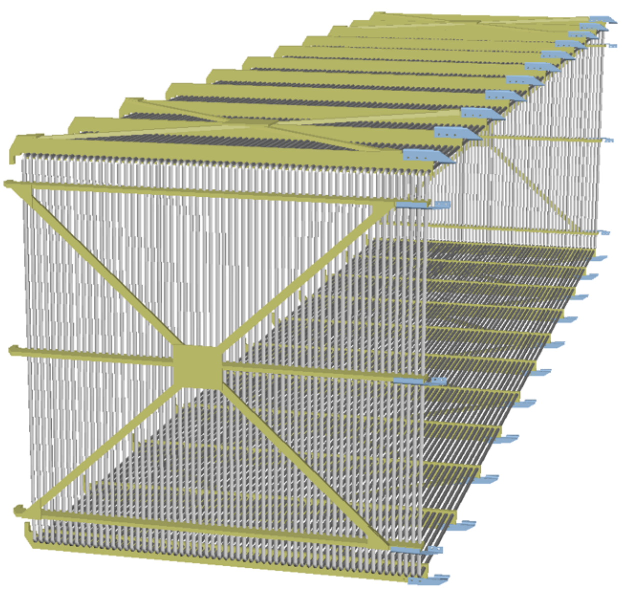
microboone



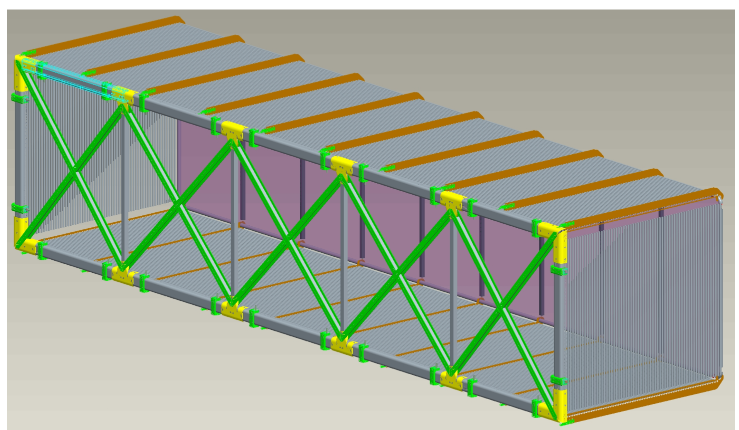
The MicroBooNE detector



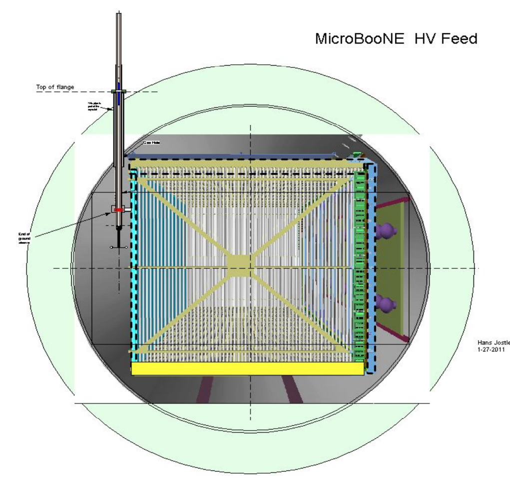
- 170 tons total liquid argon
- 86 tons active volume (60t fiducial)
- TPC dimensions: 2.5m x 2.3m x 10.4m
- 30 PMTs



Field cage

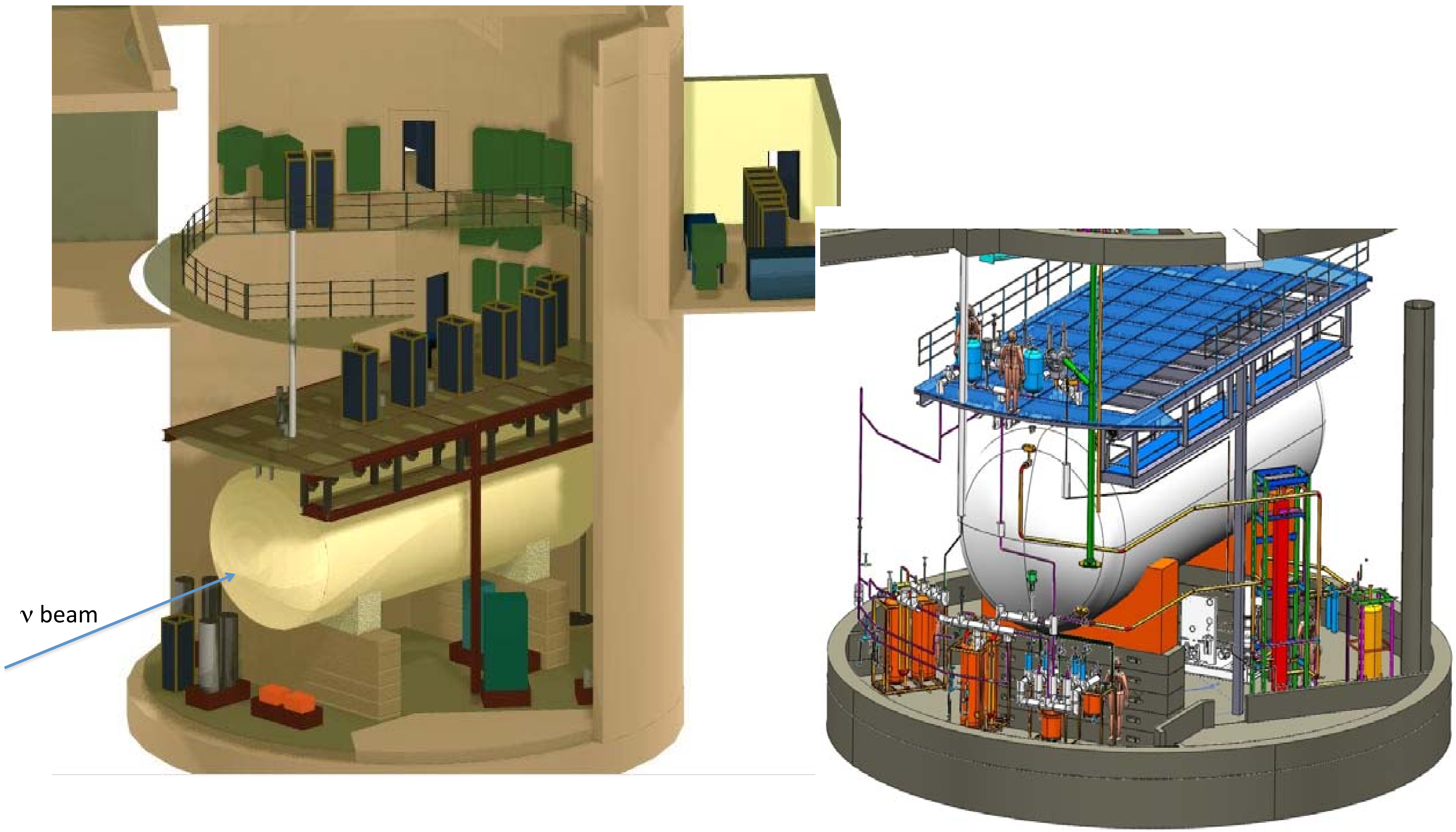


Field cage, anode and cathode planes



Cross section of TPC inside cryostat

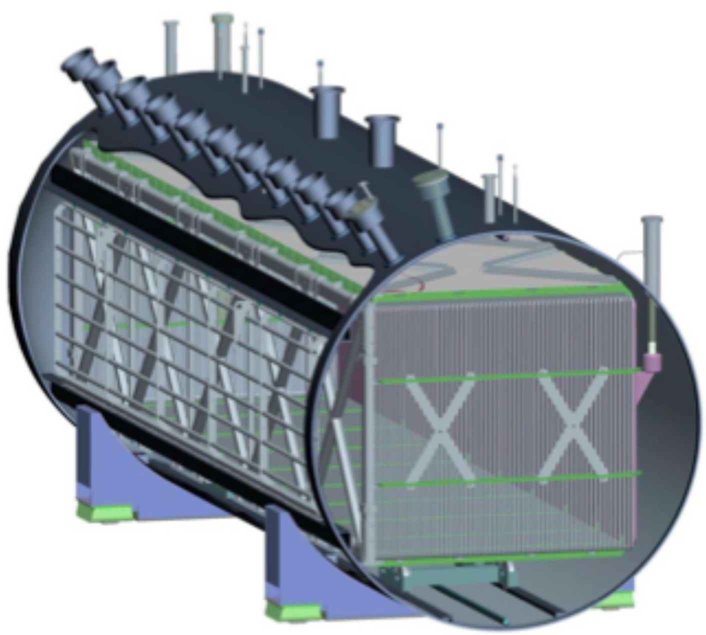
The MicroBooNE detector in-situ



MicroBooNE goals

PHYSICS GOALS

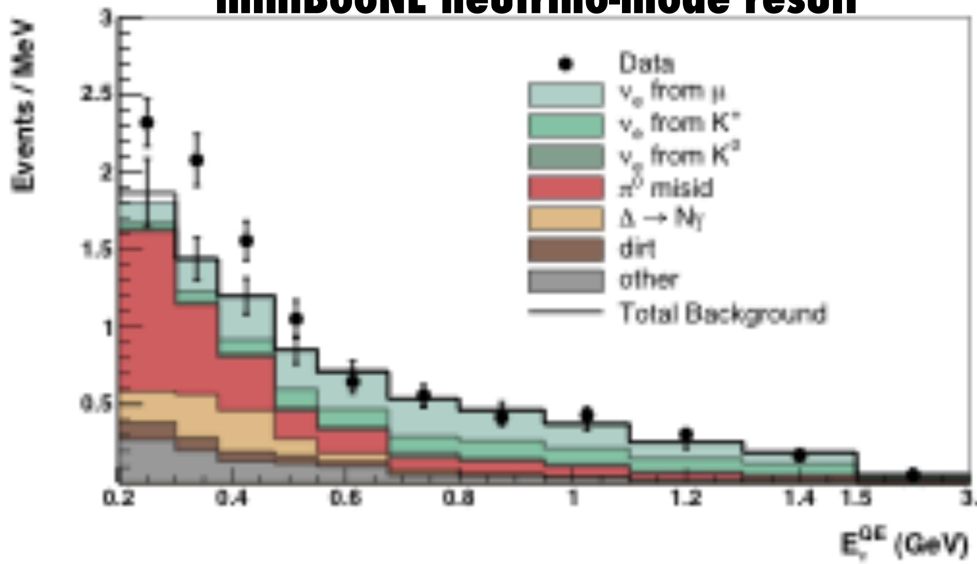
- Address the MiniBooNE low energy excess
- Measure low energy cross sections



MicroBooNE context: The MiniBooNE low-energy excess

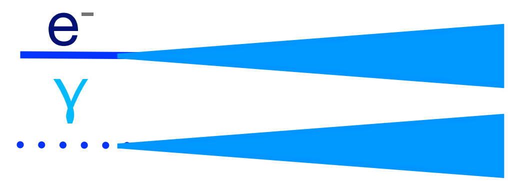
- MiniBooNE experiment observed an excess (3σ) of low-energy (200 MeV - 475 MeV) events in neutrino mode
- The excess events are electron-like: e^-/γ
- Efforts to understand the excess
- MiniBooNE cannot distinguish between electrons and photons
- Need of a new detector (new technology) to address the miniBooNE low-energy excess

miniBooNE neutrino-mode result



Phys.Rev.Lett.102, 2009

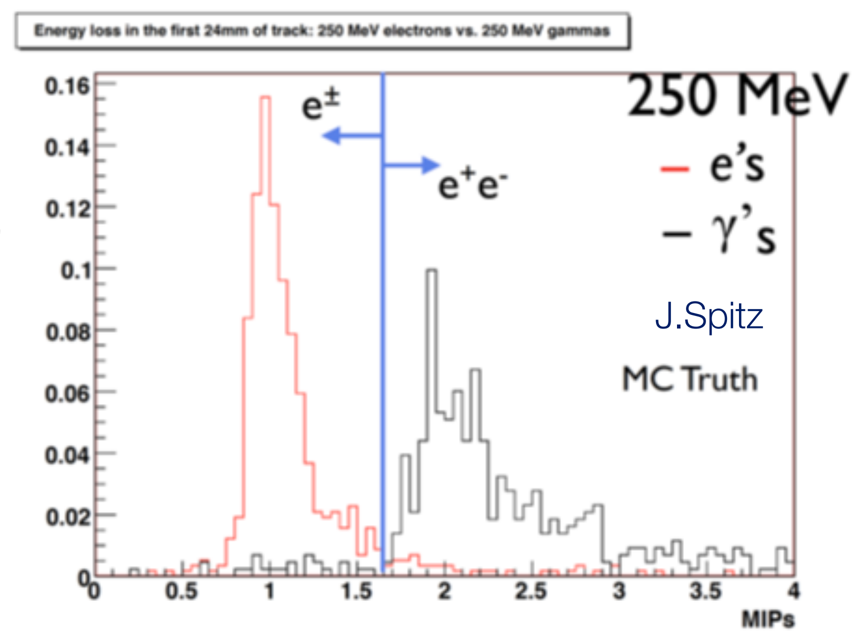
MicroBooNE addressing the miniBooNE excess



- MicroBooNE ability to distinguish between electrons and photons will remove ν_μ induced single photon backgrounds

- MicroBooNE ν_e efficiency ~2x better than MiniBooNE

- MicroBooNE sensitivity at low energies efficiency down to tens of MeV (compared to ~200 MeV for MiniBooNE)



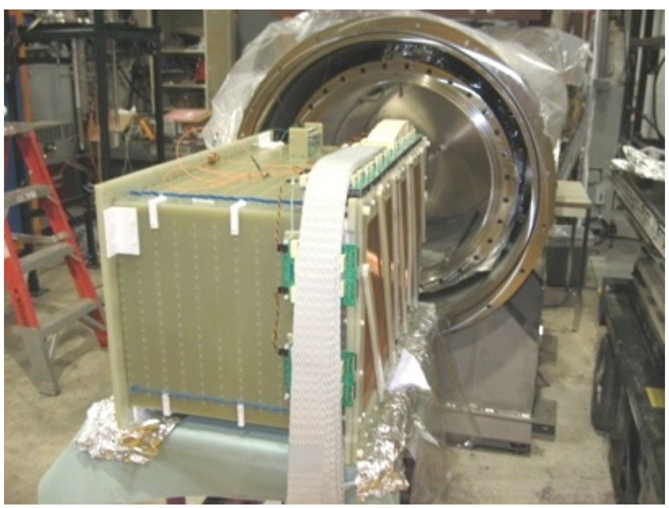
dE/dx for electrons and gammas in first 2.4 cm of track

MicroBooNE is under construction!

- Ground breaking 1 month ago
- TPC fabrication has started
- Wire winding is starting now
- TPC assembly this Summer
- Ready to take data 2013

ArgoNeuT

- Small LArTPC (175l)
- Ran successfully in NuMI beam in 2009-2010
- Demonstrated the principle of LArTPCs
- First physics results!



ν_μ CC-Inclusive Cross Sections

arXiv:1111.0103v1 [hep-ex] 1 Nov 2011

First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon

C. Anderson,[1] M. Antonello,[2] B. Baller,[3] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[6] E. Church,[1] D. Edmunds,[5] A. Ereditato,[7] S. Farooq,[4] B. Fleming,[1] H. Greenlee,[3] R. Guenette,[1] S. Haug,[7] G. Horton-Smith,[4] C. James,[3] E. Klein, K. Lang,[8] P. Laurens,[5] S. Linden,[1] D. McKee,[4] R. Mehdiyev,[8] B. Page,[5] O. Palamara,[2] K. Partyka,[1] A. Patch,[1] G. Rameika,[3] B. Rebel,[3] B. Rossi,[7] M. Soderberg,[3,9] J. Spitz,[1] M. Szelc,[1] M. Weber,[7] T. Yang,[3] and G. Zeller[3]

(The ArgoNeuT Collaboration)

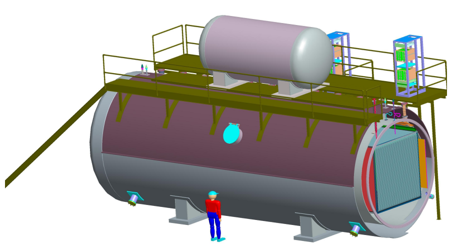
[1]*Yale University, New Haven, CT 06520*
[2]*INFN - Laboratori Nazionali del Gran Sasso, Assergi, Italy*
[3]*Fermi National Accelerator Laboratory, Batavia, IL 60510*
[4]*Kansas State University, Manhattan, KS 66506*
[5]*Michigan State University, East Lansing, MI 48824*
[6]*Universita dell'Aquila e INFN, L'Aquila, Italy*
[7]*University of Bern, Bern, Switzerland*
[8]*The University of Texas at Austin, Austin, TX 78712*
[9]*Syracuse University, Syracuse, NY 13244*

SUBMITTED TO PRL

ArgoNeuT has performed the first ν_μ CC differential cross section measurements for scattering on argon. The results are consistent with the GENIE predictions from $0° < \theta_\mu < 36°$ and $0 < P_\mu < 25$ GeV/c. The results elucidate the behavior of the outgoing muon in ν_μ CC interactions, information useful for tuning neutrino event generators, reducing the systematics associated with a long baseline neutrino oscillation experiment's near-far comparison, and informing the theory of the neutrino-nucleus interaction in general. In addition to importance in understanding neutrino scattering and relevance for neutrino oscillation, these measurements represent a significant step forward for LArTPC technology as they are among the first with such a device.

Beyond microBooNE: Addressing LSND/MiniBooNE excesses

- From 2013, MicroBooNE will take data to fulfill its physics goals
- But in parallel and in future, MicroBooNE could be used to search for MiniBooNE/LSND event excesses
- MicroBooNE II could be combined to a large LAr (larLAr) TPC to have a near/far configuration (different locations possible)



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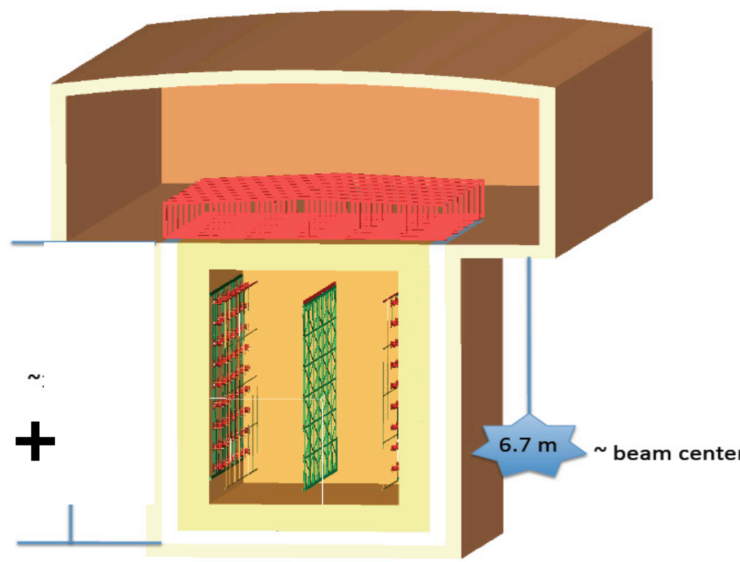
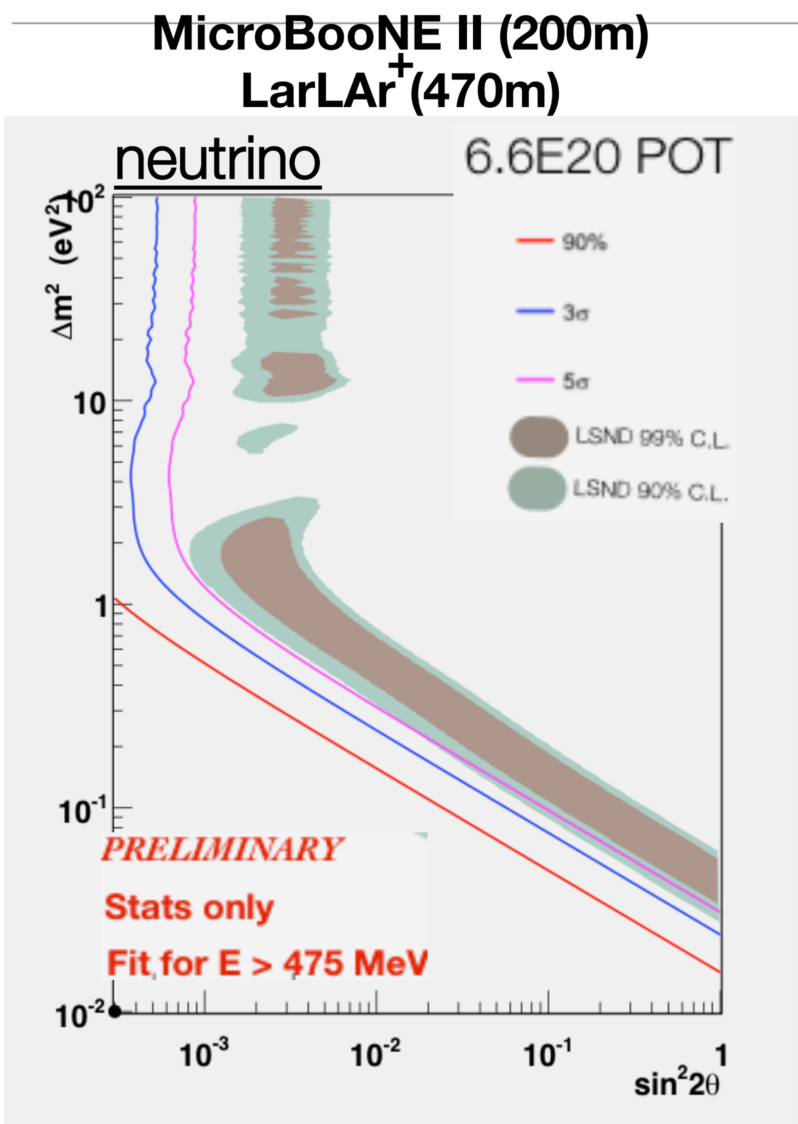
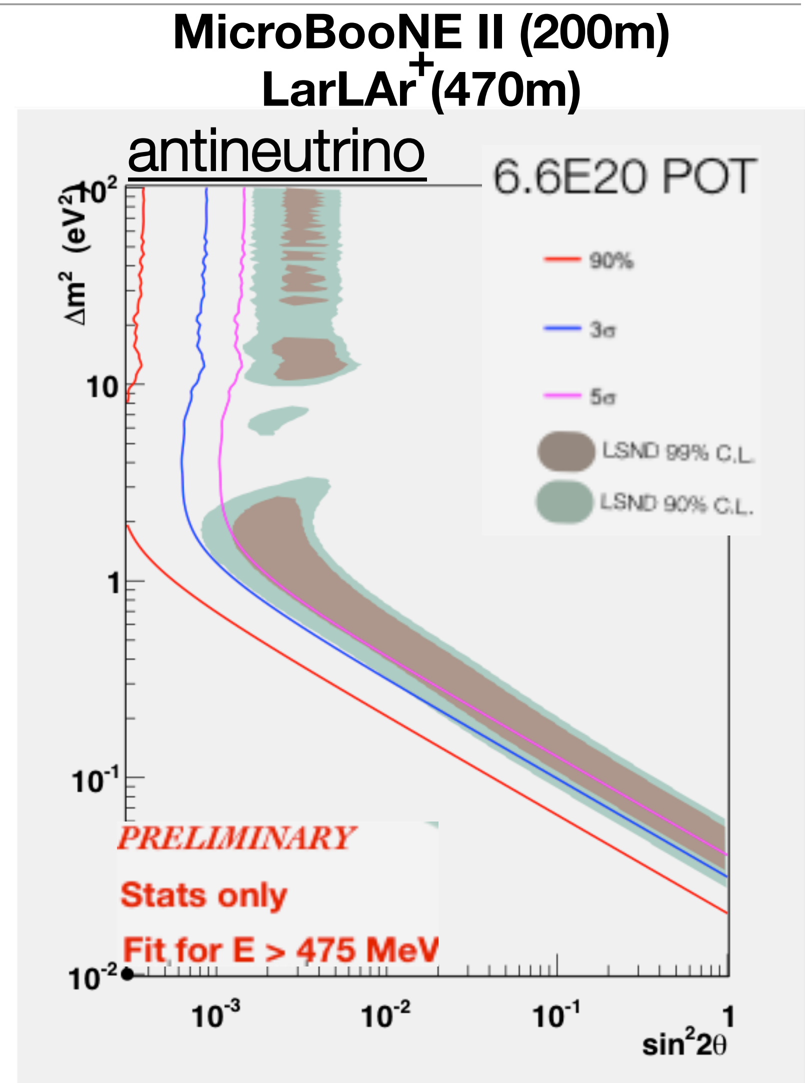


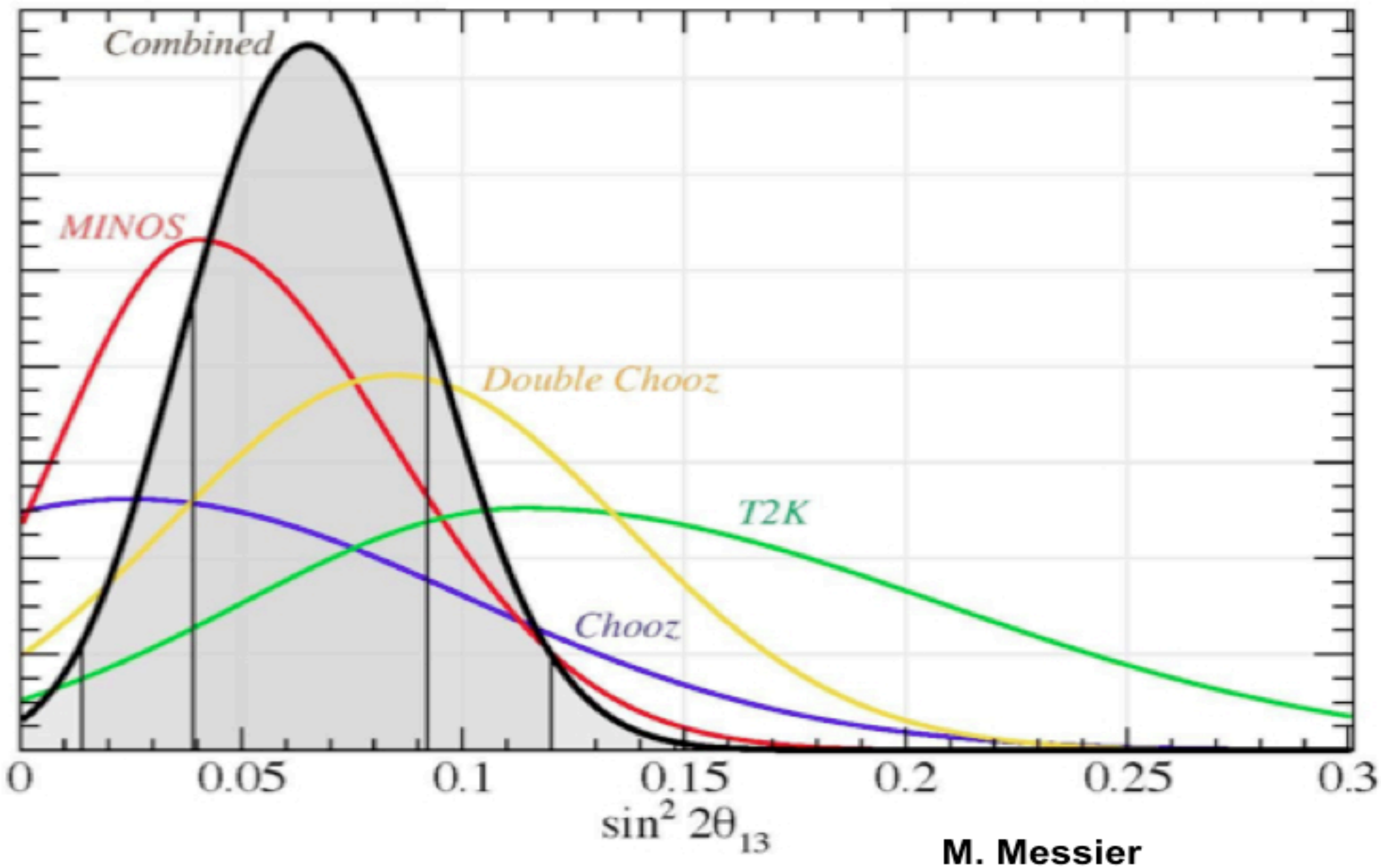
Sensitivities* of MicroBooNEII + LarLAr





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

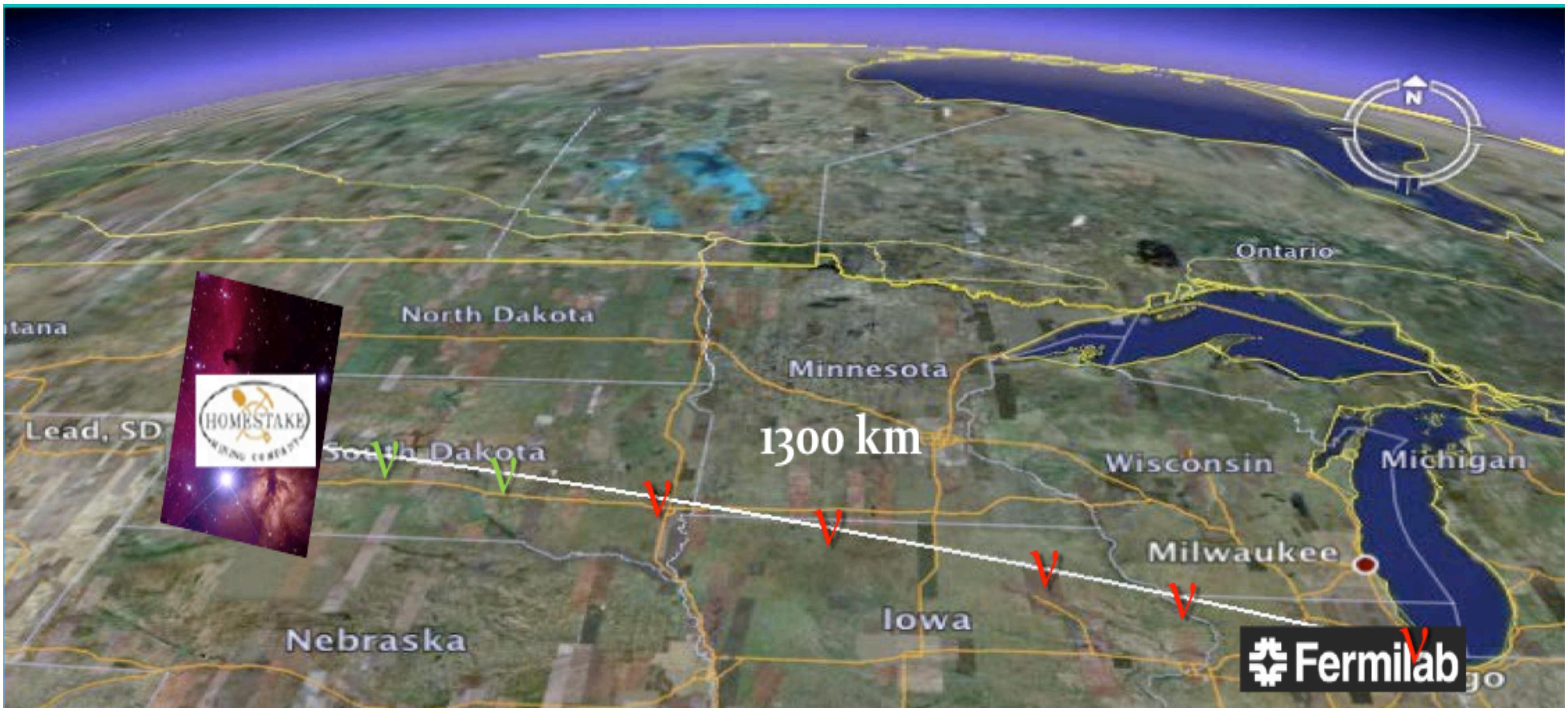
News from θ_{13}



$\theta_{13} = 0$ is now excluded at 3σ !!

Double Chooz on TV!

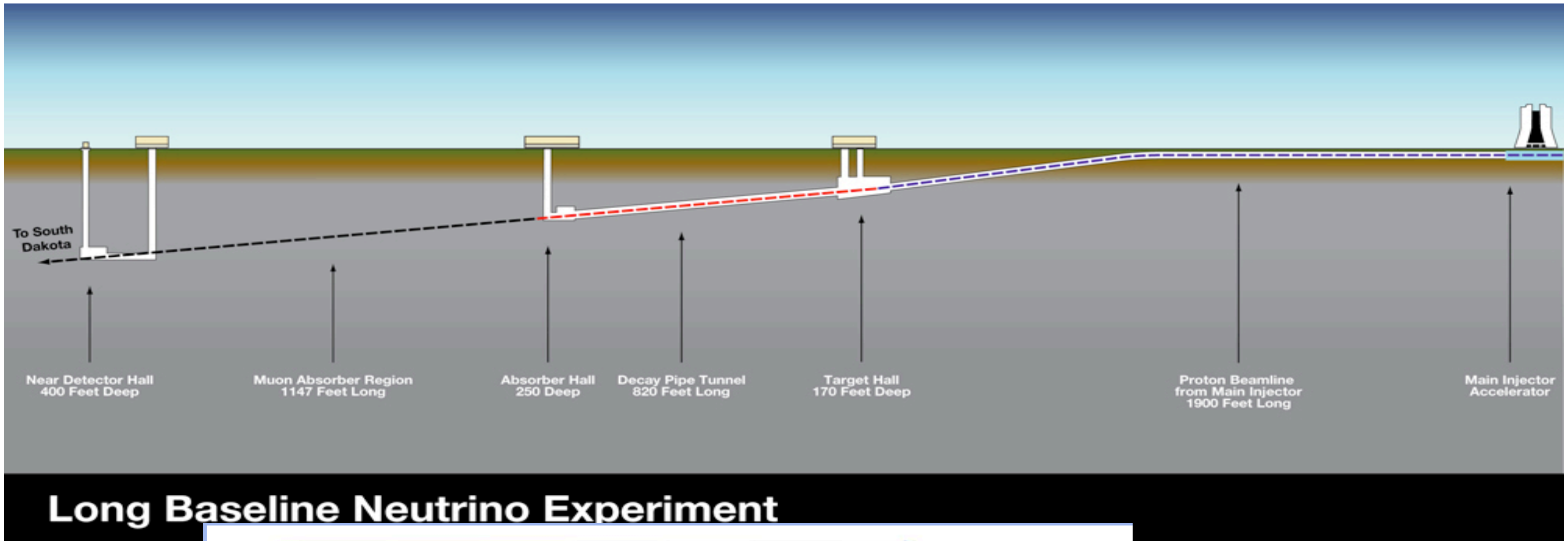
Long-Baseline Neutrino Experiment (LBNE)

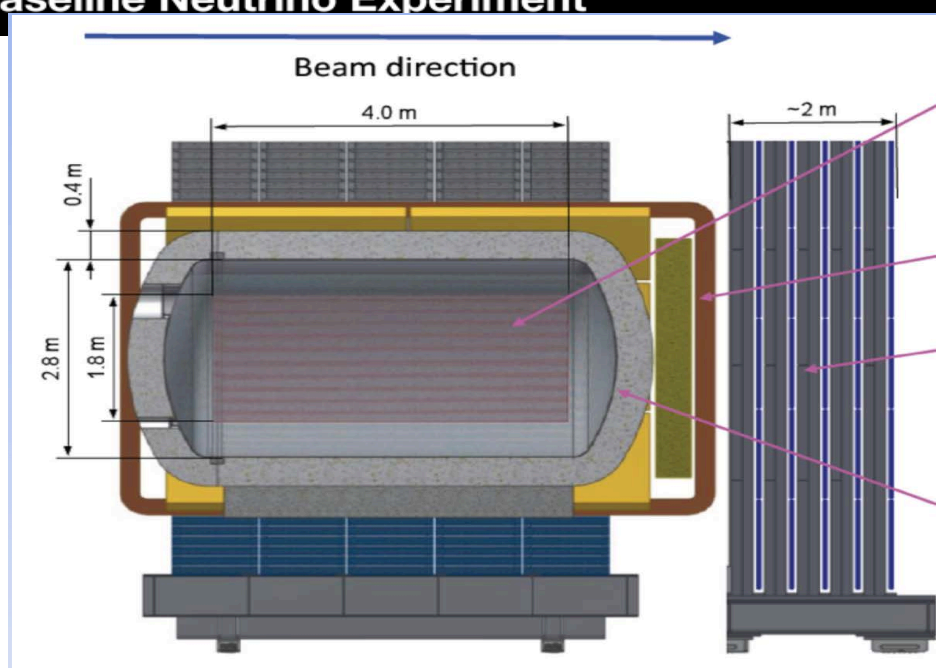


LBNE Science goals

- Primary goal: **Oscillation physics**:
  - ➢ $\nu_\mu \rightarrow \nu_e$: θ_{13} precision measurement, CP violation, mass hierarchy
  - ➢ $\nu_\mu \rightarrow \nu_\mu$: θ_{23} and Δm^2_{31} precision measurement
- Proton decay search
- Supernova burst
- Atmospheric neutrinos

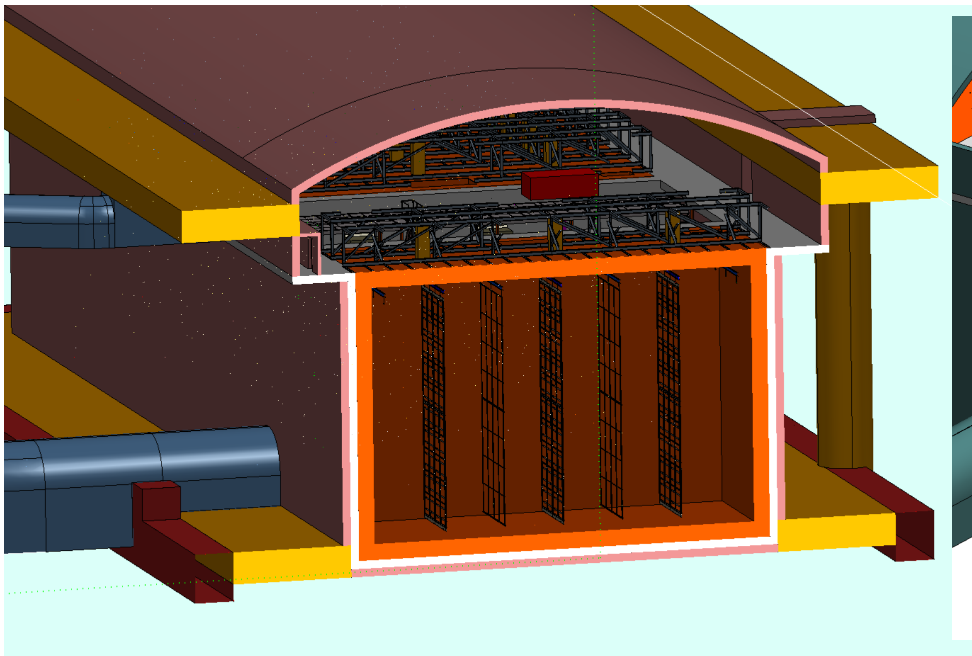
LBNE (Near detector)

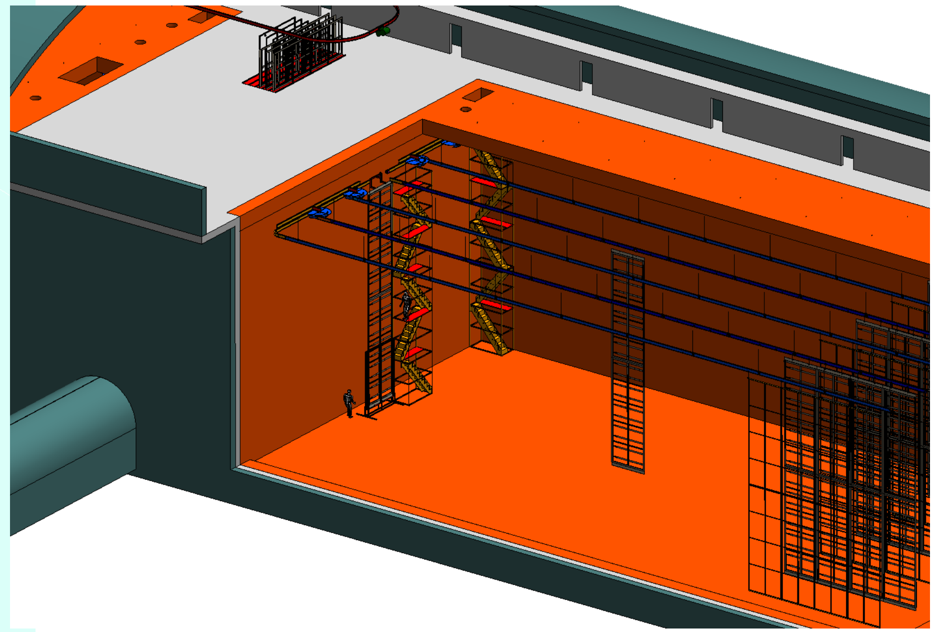


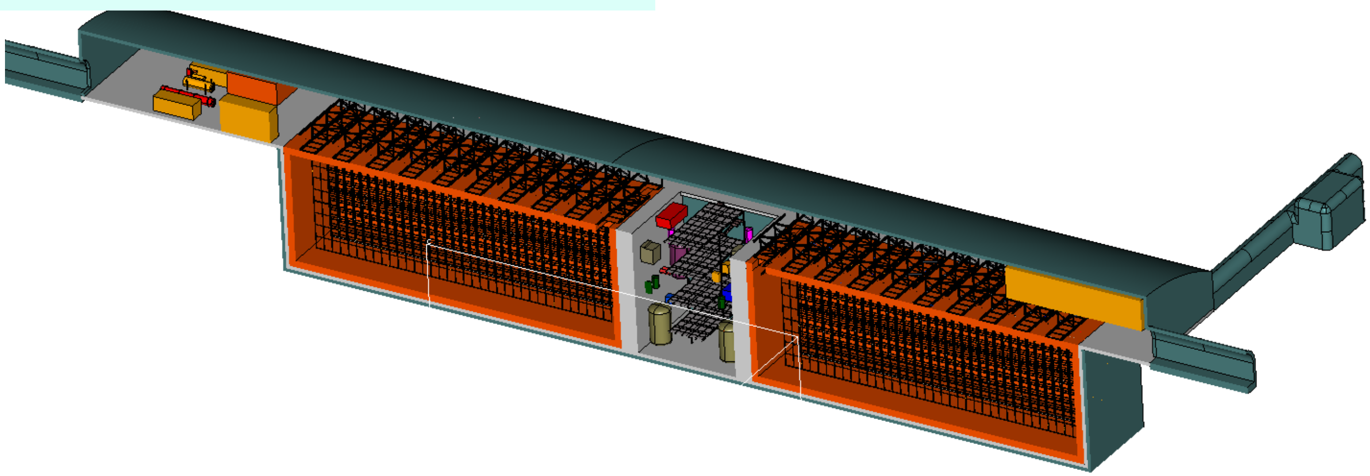


LBNE (Far Detector)

LAr detector (40 kt) at Homestake (1300km)

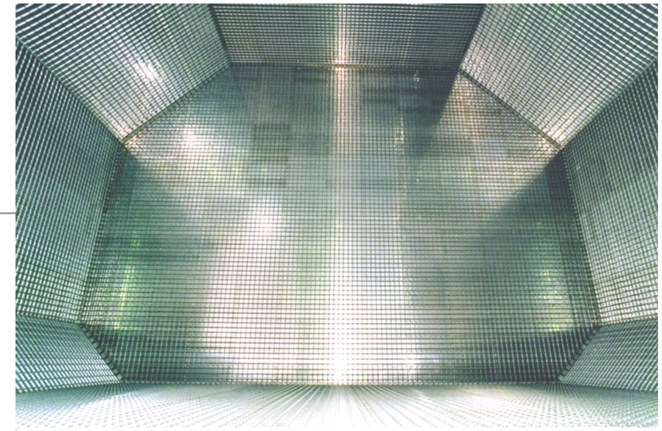


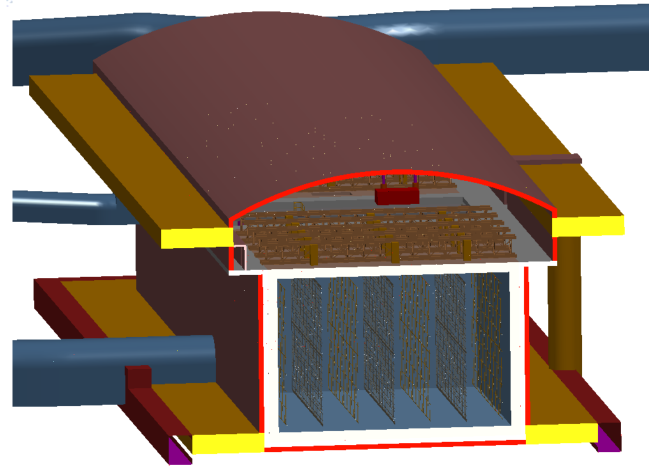


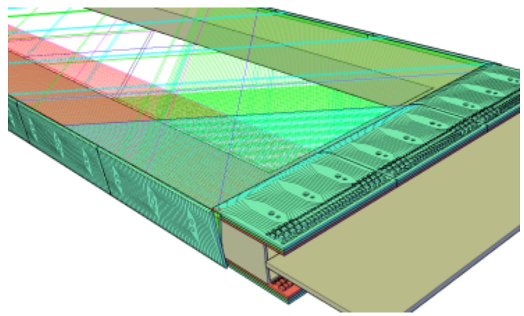


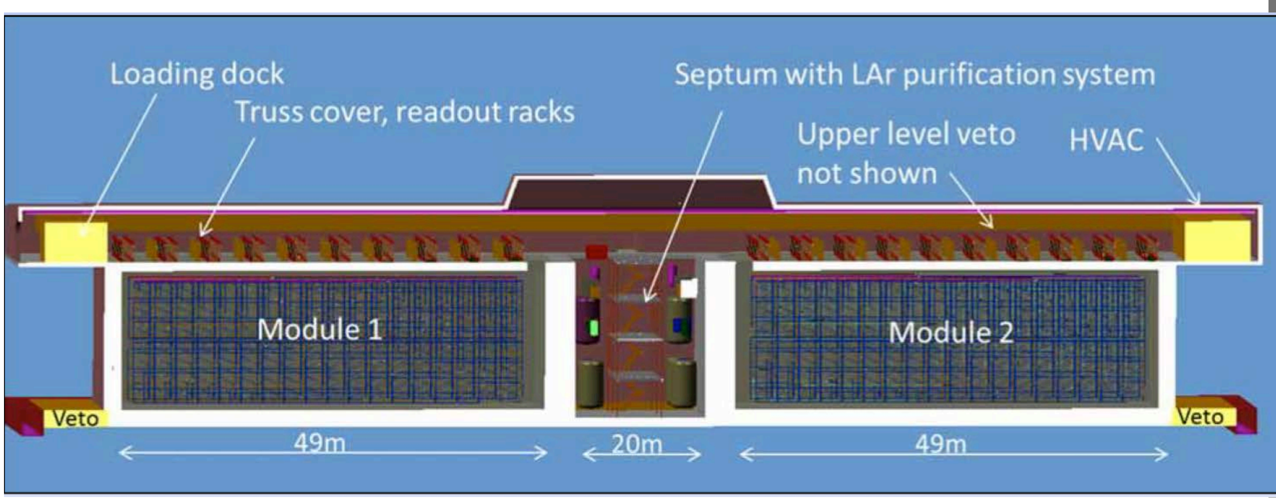
LBNE (Far detector)

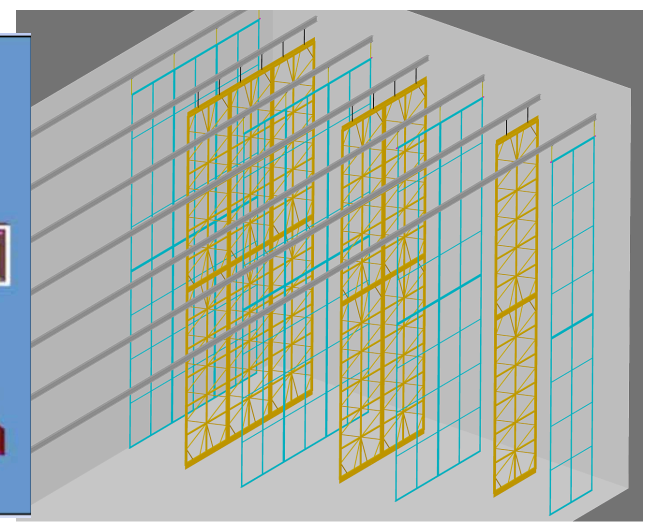
- 2 LAr modules of 20kt
- 3.7m drift
- 224 CPAs and 168 APAs
- 5mm wire spacing





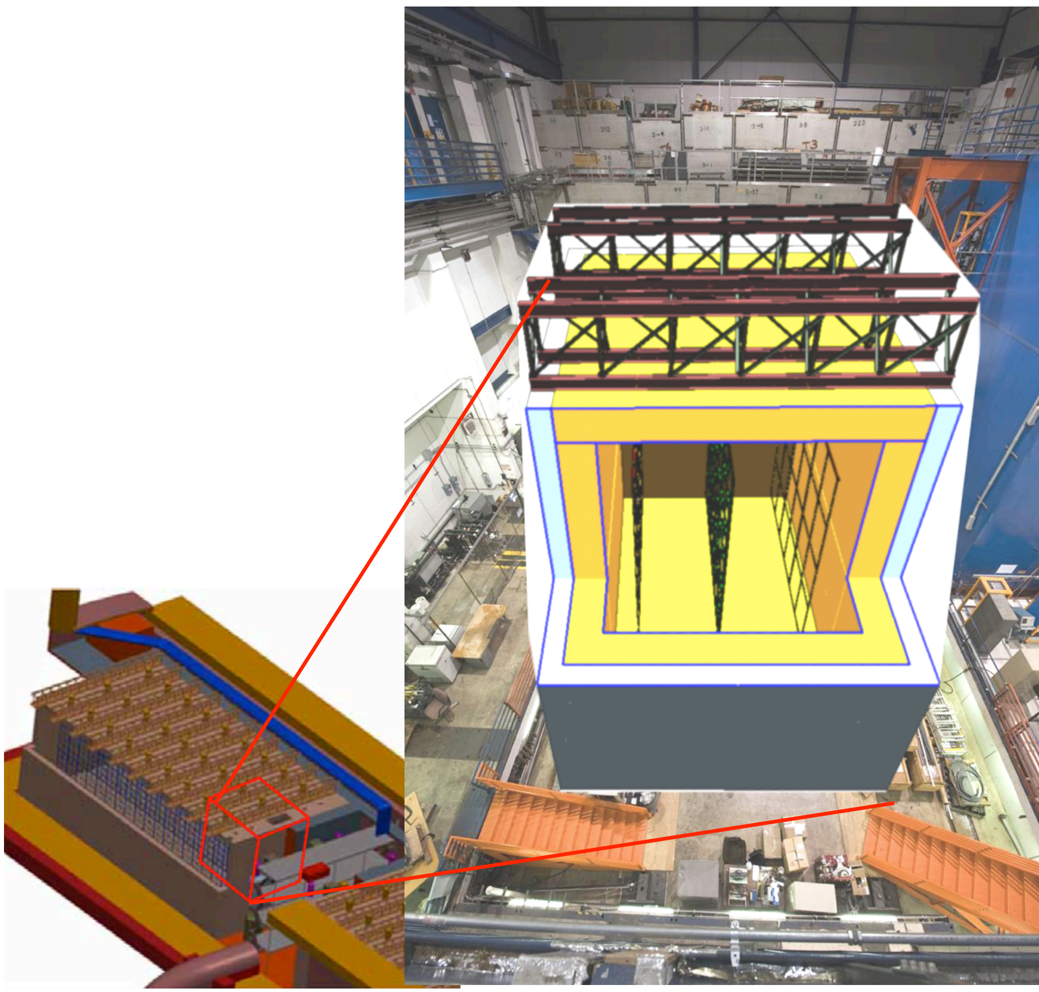






LBNE prototype: LAr1

- kton-scale full engineering prototype

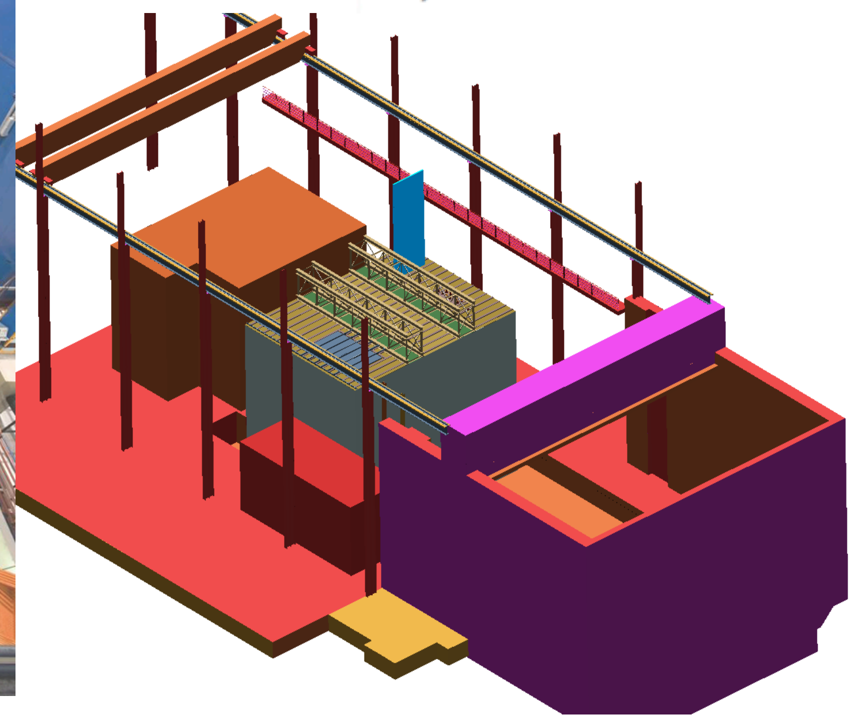


Features

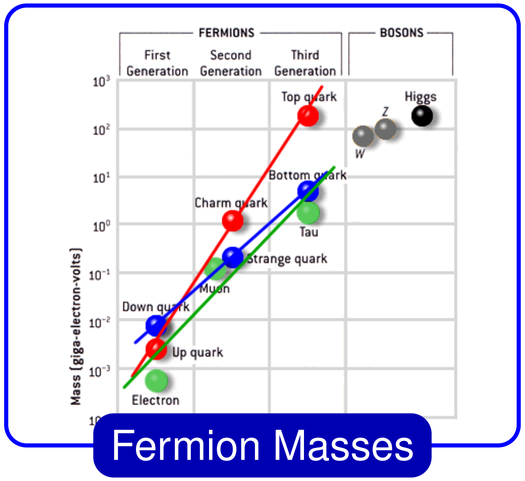
0.8 kton total

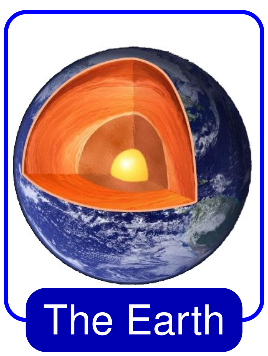
3 APA + 6 CPA

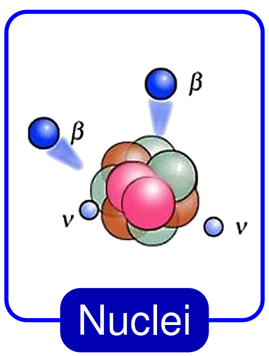
Asymmetric drift

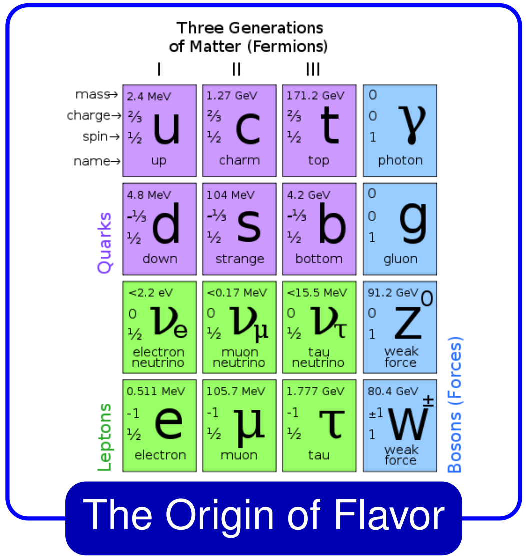


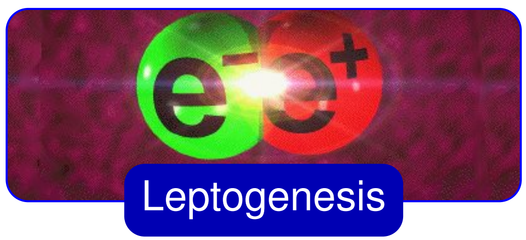
Conclusions

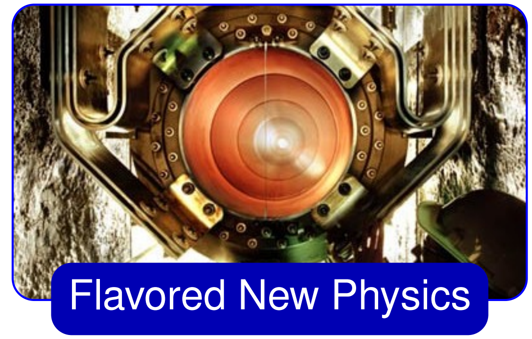


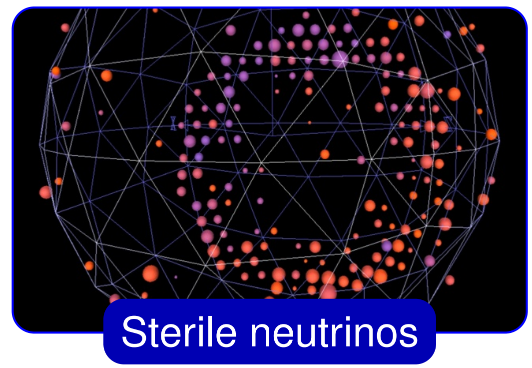




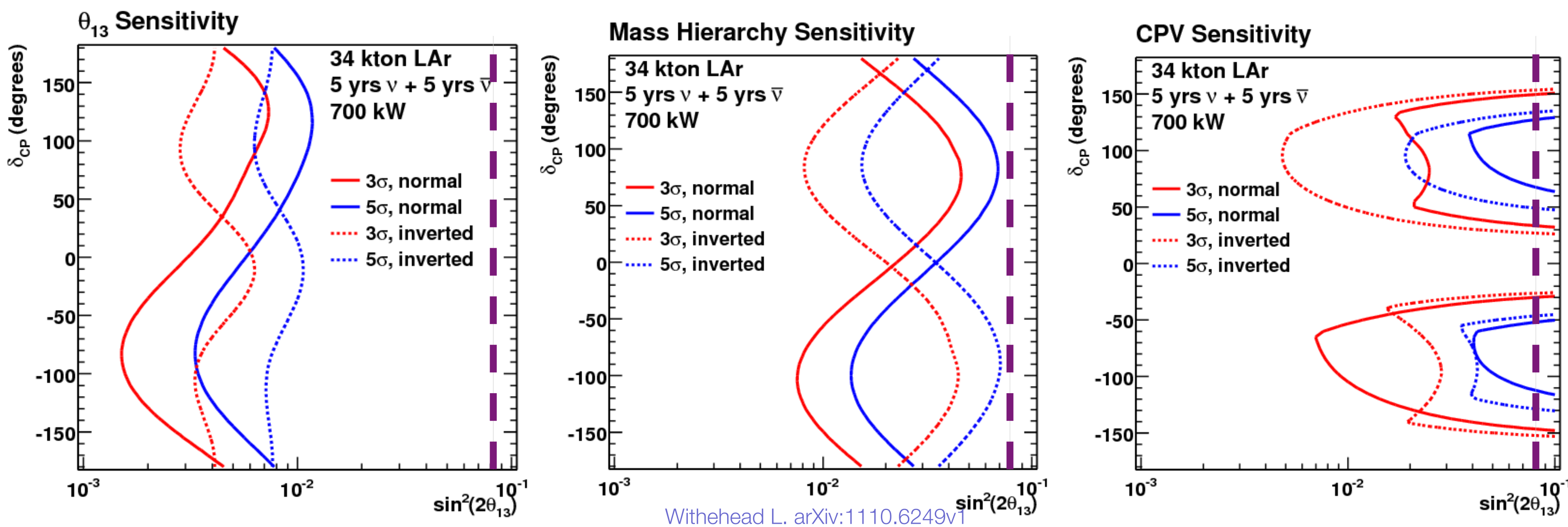






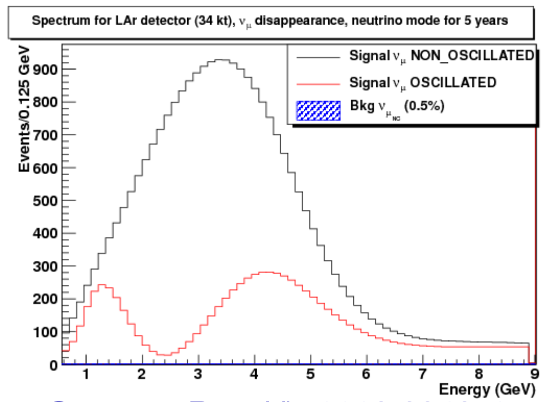


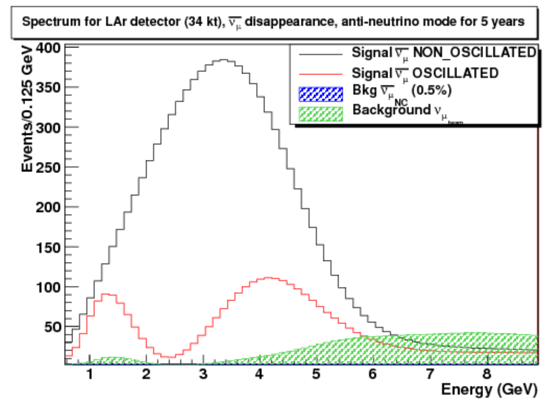
LBNE Sensitivity: θ_{13}, CP violation, mass hierarchy



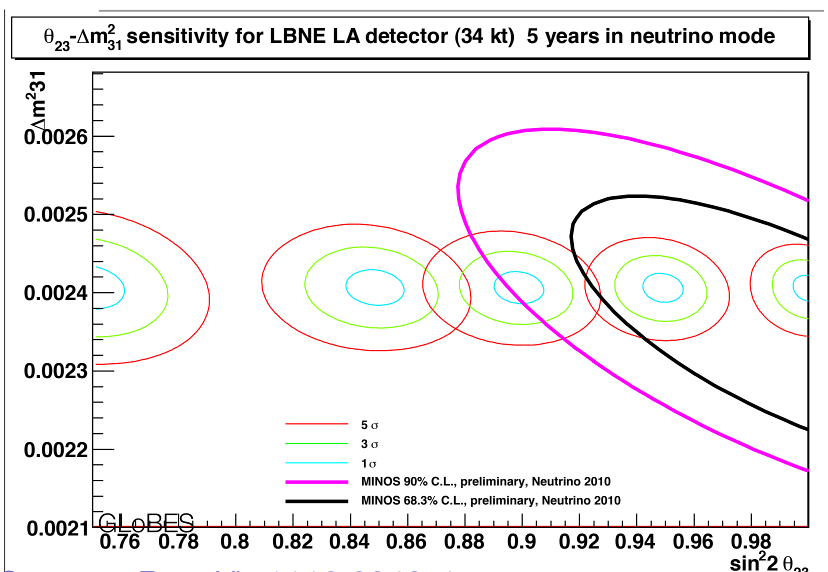
Withehead L. arXiv:1110.6249v1

LBNE Sensitivity: θ_{23} and Δm^2_{31}





Guenette R.. arXiv:1110.6249v1



Guenette R.. arXiv:1110.6249v1

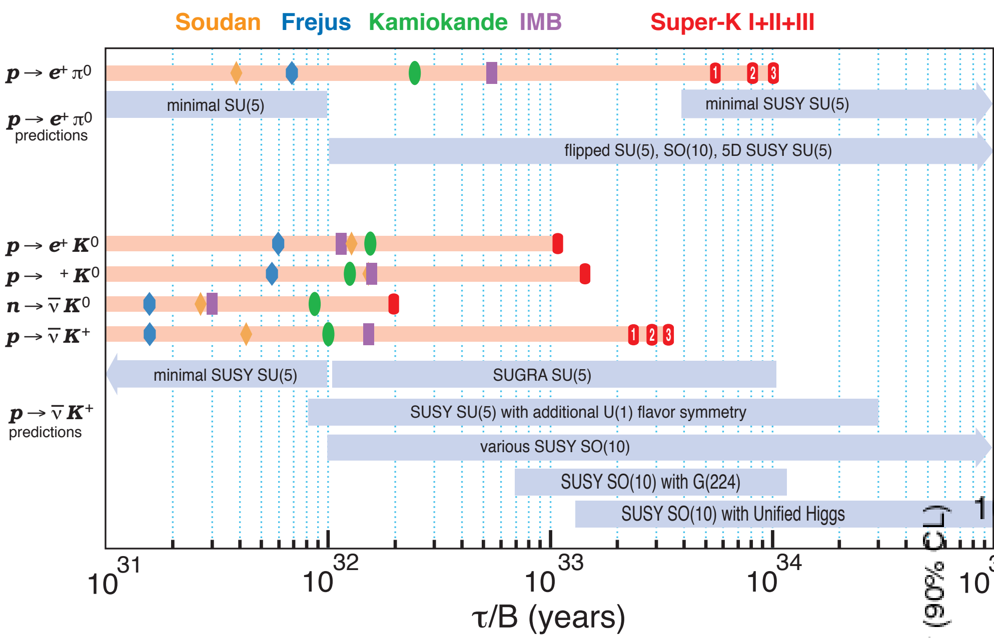
Resolution on both parameters (θ_{23} and Δm^2_{31}) better than 1%

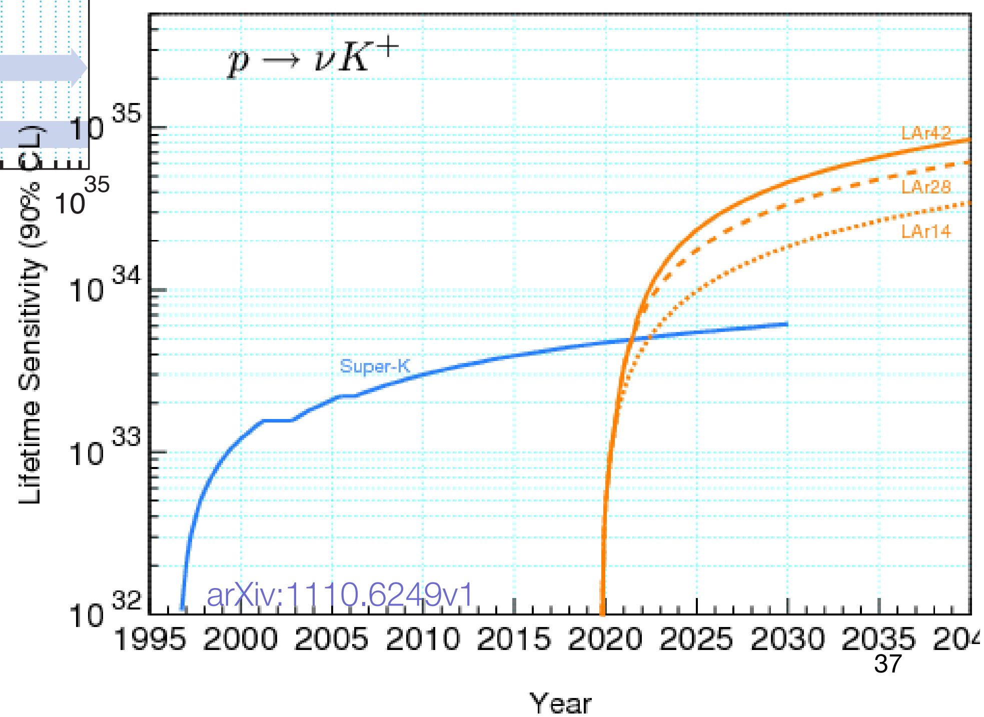
Resolution to distinguish between ν and $\bar{\nu}$ results

This last point would lead to new physics discoveries

LBNE Sensitivity: Proton decay

- New search mode with LAr: $p \rightarrow \nu + K^+$





Sterile Neutrinos: May not be so crazy after all

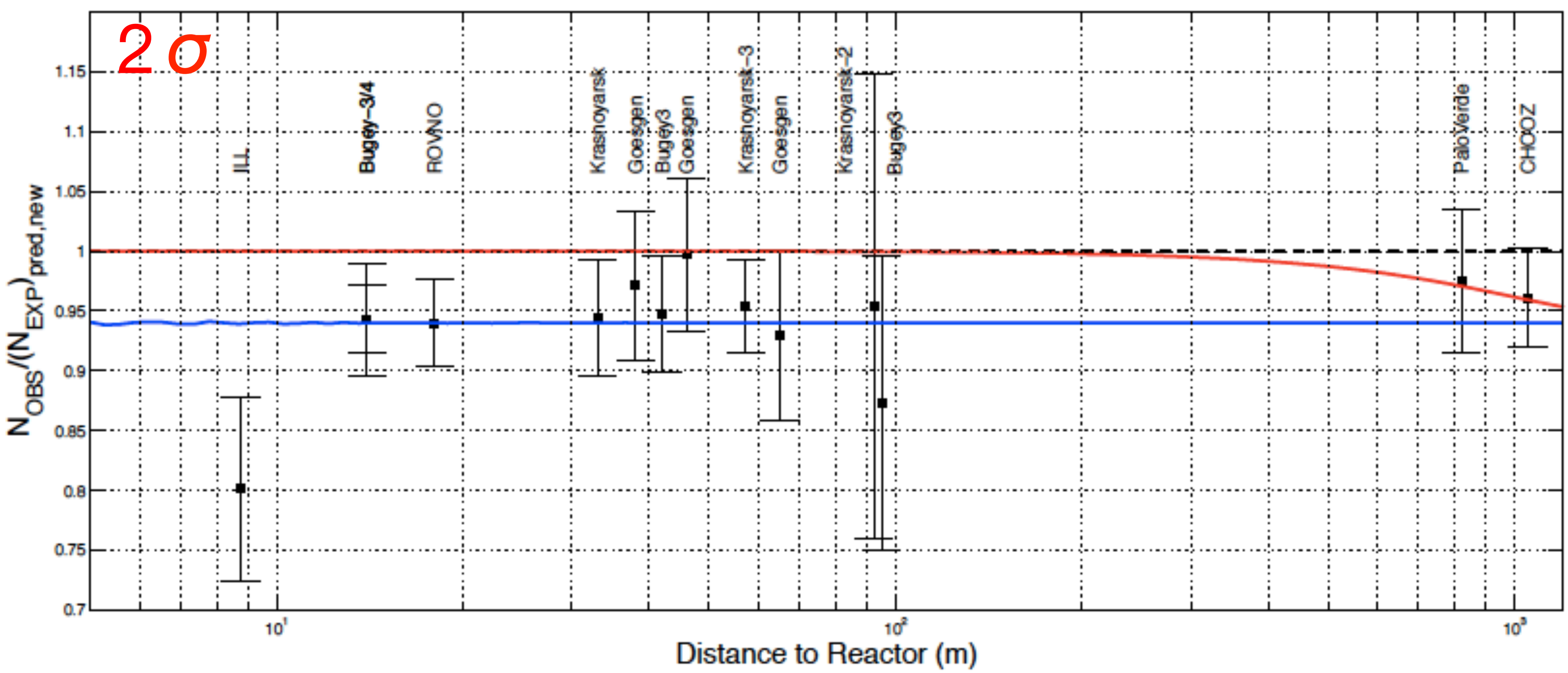
The Reactor anomaly

- Re-calculation of the fission spectrum
- Using > 8000 nuclei, > 10000 β branches
- Re-computed the e$\rightarrow \nu$ spectrum branch by branch
- Applied new corrections (off-equilibrium, neutron lifetime,…)

Sterile Neutrinos: May not be so crazy after all

The reactor anomaly

Old flux underestimated



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

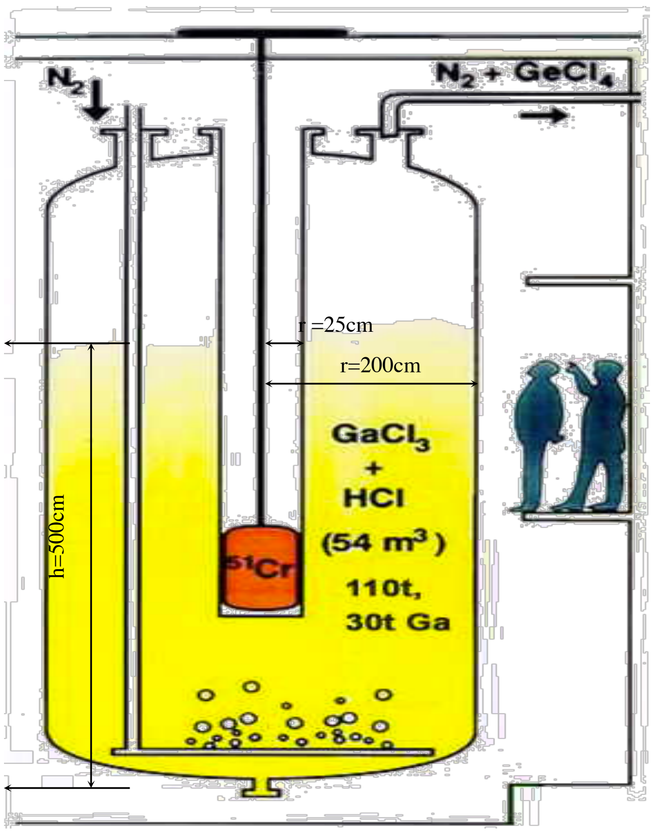
R=0.937+-0.027

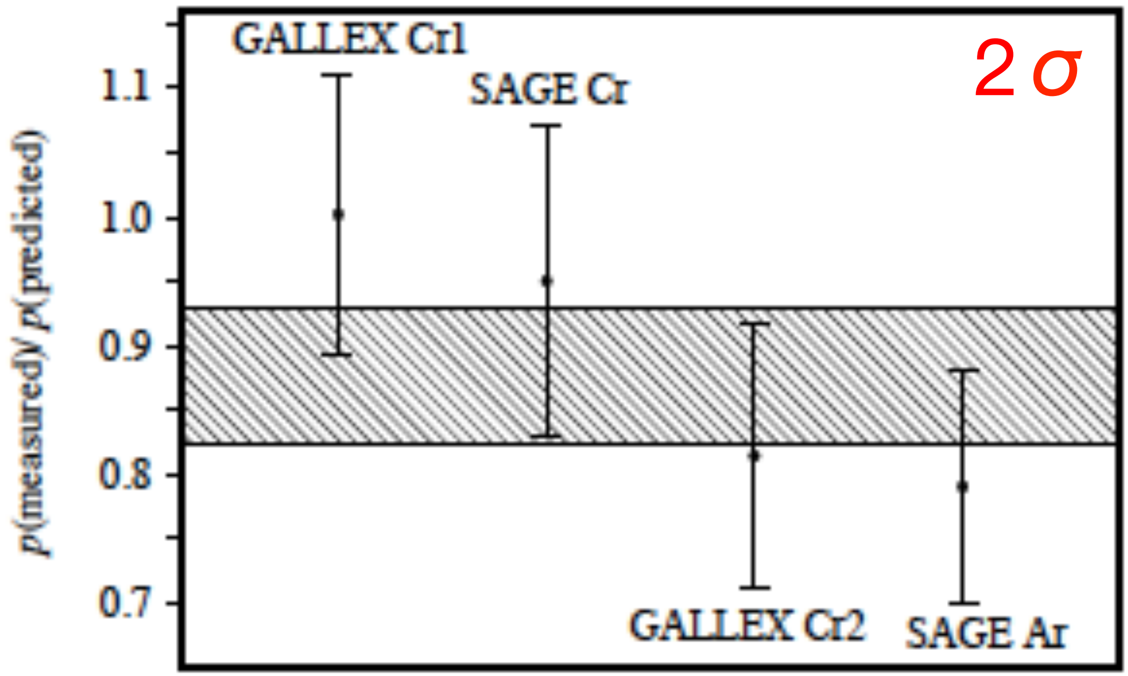
Sterile Neutrinos: May be not so crazy after all

The Gallium anomaly

- Radioactive sources used for calibration (ν_e disappearance)

GALLEX



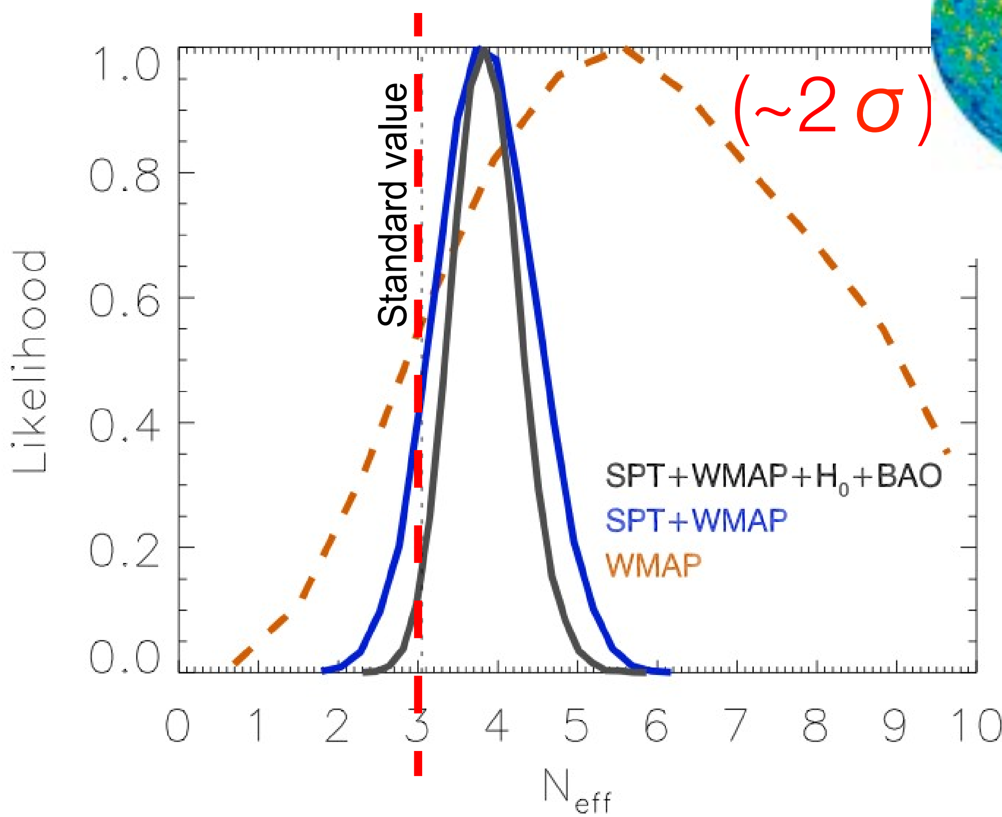


Giunti & Lavender, Phys.Rev.C83:065504,2011

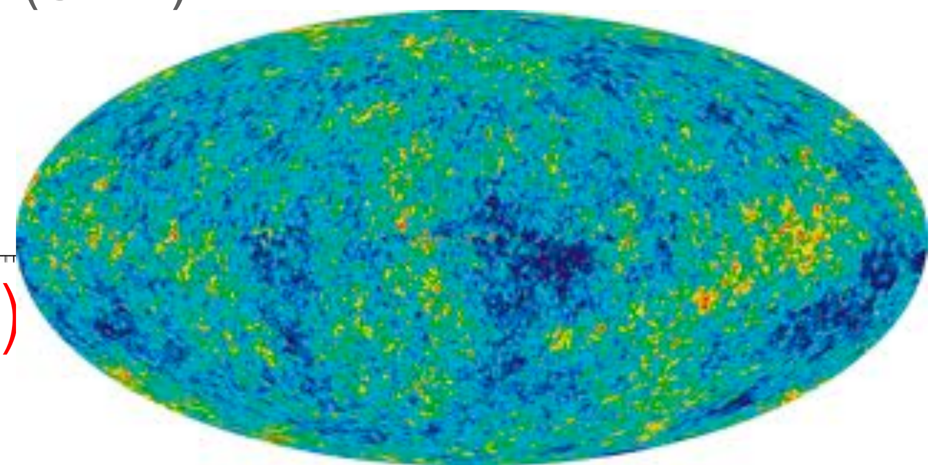
R=0.86+-0.05

Cosmology

- Cosmic Microwave Background (CMB)
- Large-Scale Structures



Keisler et al. [South Pole Telescope] 2011

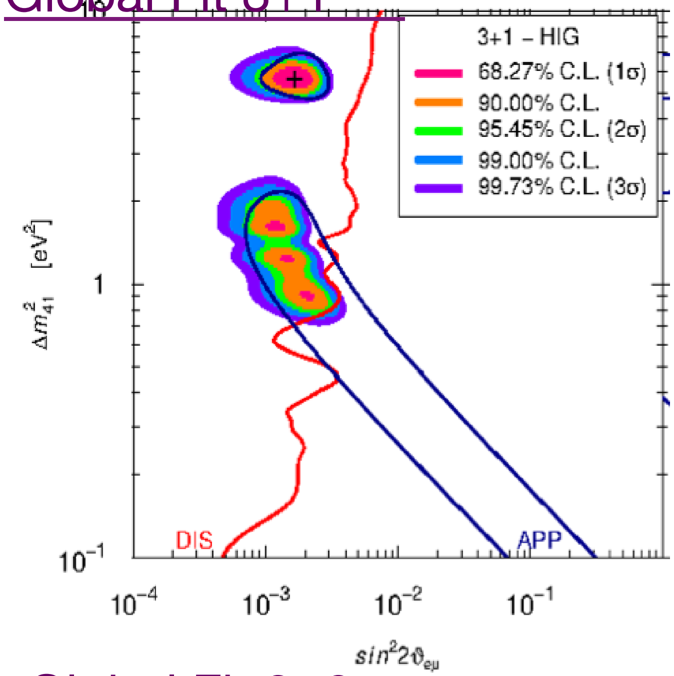


But sterile neutrino mass inferred by cosmology is problematic!

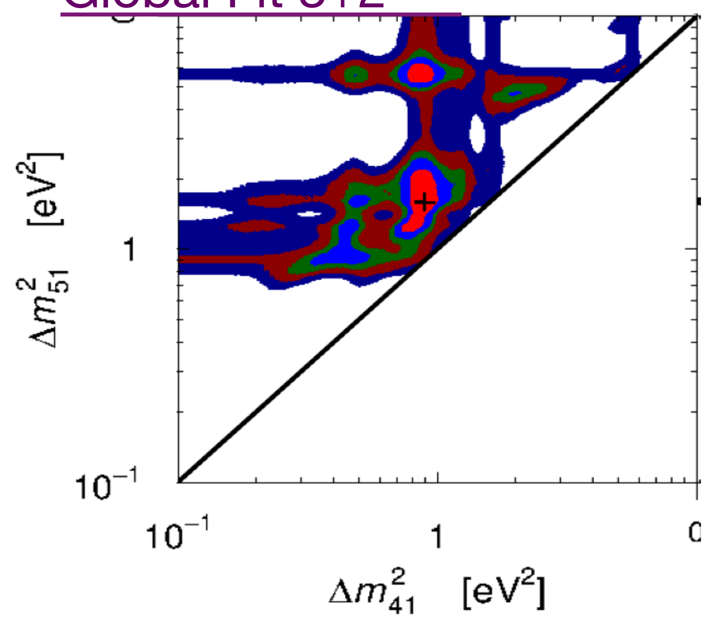
A global picture?

- 3+1 model does not work well
- 3+2 model has some tension
- Probably some experiments are wrong! Which ones?

Global Fit 3+1



Global Fit 3+2



Giunti, Laveder, 1109.4033

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

Neutrino Oscillation

- Neutrinos are the only particles of the SM defined by their flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$

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

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

Neutrino oscillation = neutrino mass!

Neutrino Oscillation

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

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

Atmospheric ν's:
Accelerator (long baseline)

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

Solar ν's:

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

Neutrino Oscillation: Status of the matrix

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

$\sin^2(2\theta_{23}) > 0.91$
(from long baseline (MINOS))

$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$
(from solar (SNO) + reactor (KamLAND))

$\sin^2(2\theta_{13}) < 0.15$ (from reactor experiment)

$\Delta m^2_{13} = (2.35 \pm 0.11) \times 10^{-3}\ \mathrm{eV}^2$
(from long baseline (MINOS))

$\Delta m^2_{12} = (7.59 \pm 0.21) \times 10^{-5}\ \mathrm{eV}^2$
(from solar (SNO) + reactor (KamLAND))