The Nevis Neutrino Program

Leslie Camilleri

Nevis, January 24th 2013

Who are we?

Mike Shaevitz
Bill Willis (deceased 2012)
LC

Post Docs:
Georgia Karagiorgi
Camillo Mariani → Virginia Tech.
Kazuhiro Terao ← MIT Spring 2013

Graduate Students:
Matt Toups. Graduated → MIT.
Arthur Franke. Graduated → Financial World
Gary Cheng
Rachel Carr
David Kaleko
David Caratelli

Undergraduates:
Kathleen Tatem
Jennett Dickinson

Strong support from

Computing
William Seligman

Electronics Team
Bill Sippach
Cheng-Yi Chi
Nancy Bishop

Mechanical Technician
David Thomas

Plan of talk

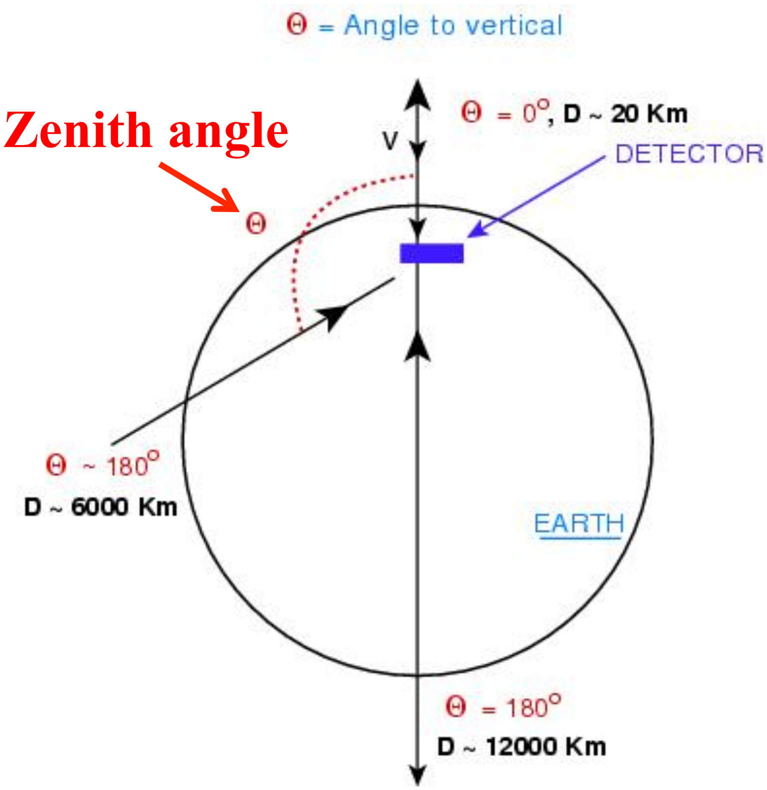
- Historical Introduction
- Brief theory of Neutrino oscillations
- The present state of knowledge
- What still needs understanding?
- How will Nevis experiments contribute?
  - Double Chooz
  - MicroBooNE
  - MiniBooNE
  - SciBooNE
  - LAr1
  - IsoDAR
  - (LBNE)

Puzzle I: Atmospheric Neutrinos: ν_e and ν_μ

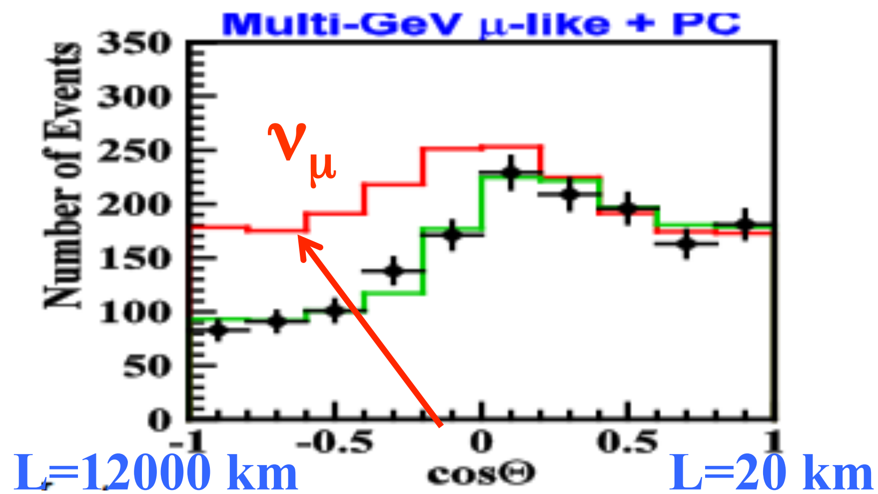
Produced by π and K decays in upper atmosphere

- They decay ---> $\mu + \nu_\mu$.
- Then the muons decay to $e + \nu_e + \nu_\mu$

Expect $N_{\nu\mu}/N_{\nu\varepsilon} \sim$ **2**
Instead measured ~ 1

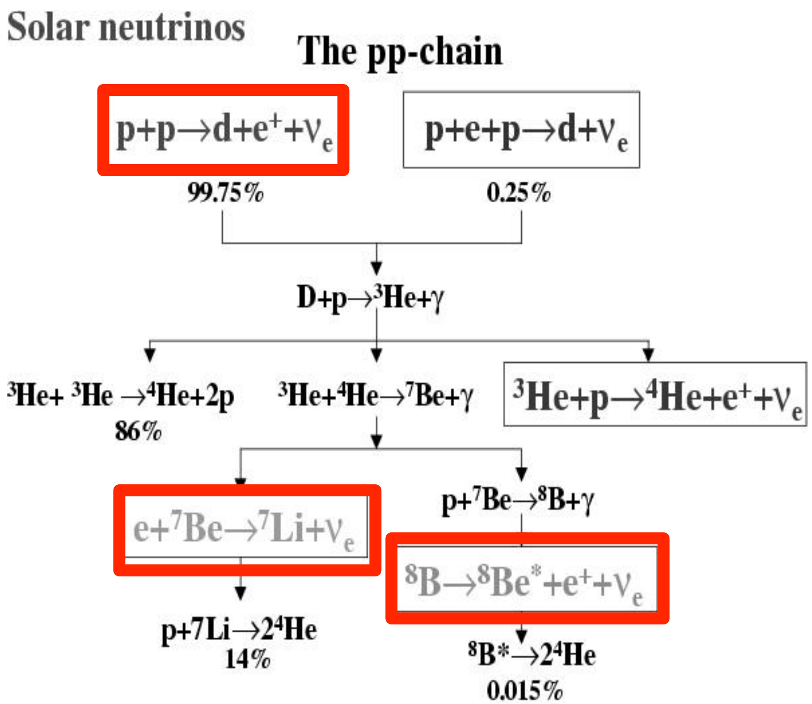


Zenith angle → BASELINE = L

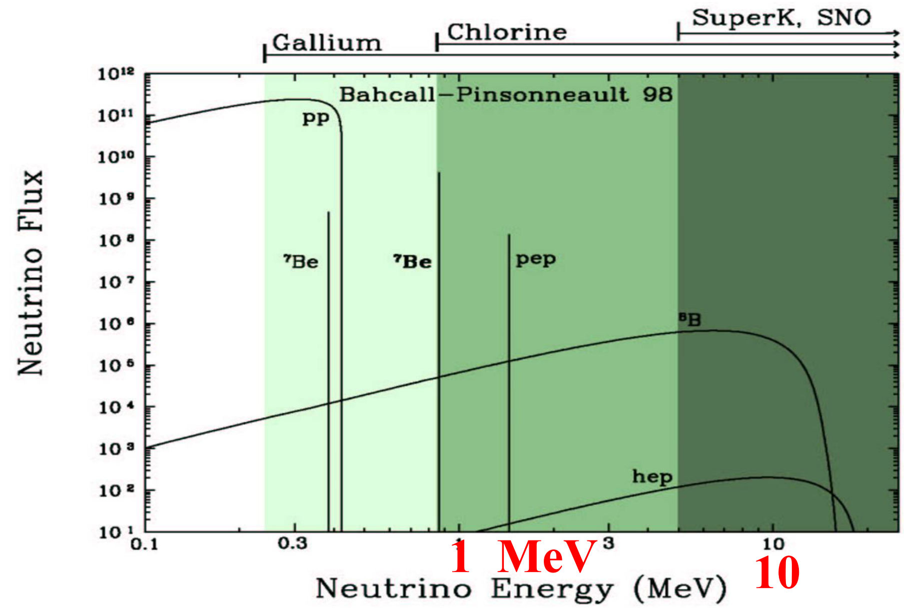


ν_μ disappear

ν_e do NOT

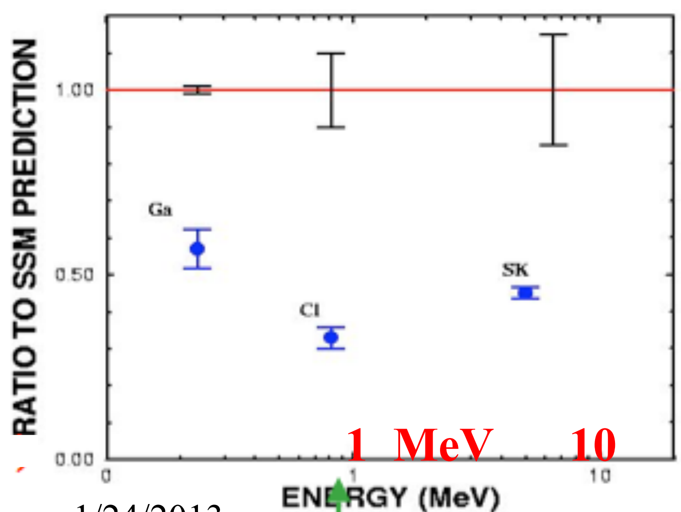


Puzzle II: Solar ν's



All experiments sensitive only, or mostly, to ν_e

Radiochemical and Real Time → suppression



Then **SNO**: Use Heavy water D_2O.
Only 2 .2 MeV needed to break up D

- Neutral Current (NC) reactions on nucleons

$\nu_x + n \rightarrow n + \nu_x$

Sensitive to flux from ALL flavours, $\phi(\nu_e, \nu_\mu, \nu_\tau)$

$\phi_{NC} = 5.14^{+0.21}_{-0.20}$ x 10^6 cm^{-2}. s^{-1} ← **All there**

$\phi_{SSM} = 5.69 \pm 0.91$ x 10^6 cm^{-2}. s^{-1}

Just changed flavour

Neutrinos: Flavour and Mass states

- 3 ν FLAVOURS: ν_e, ν_μ, ν_τ
- They "change" from one to another : $\nu_e \rightarrow \nu_\mu$: ⟹ Oscillations.
- **WHY ?**
- Because they are, each, a sum of 3 different MASS states: ν_1, ν_2, ν_3.

$$|\nu_f> = \sum_k U^*_{fk} |\nu_k>$$

$$\textbf{With } U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}$$

When you produce a ν_μ, it has the **EXACT** mix of ν_1, ν_2, ν_3 to **BE** a ν_μ.

What happens when they start to propagate?

At time t = 0 we produce a beam of a given flavour ν_α → correct m_k mix.

Then at time t = t

$$|\nu_\alpha(\mathbf{t})> = \mathbf{e}^{\mathbf{ip.r}} \sum_{\mathbf{k=1}}^{\mathbf{3}} \mathbf{U}^{*}_{\alpha\mathbf{k}} \; \mathbf{e}^{-\mathbf{iE_k\,t}} \; |\nu_{\mathbf{k}}>$$

$E^2=p^2+m^2$

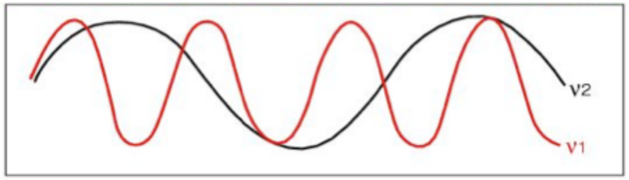
$$= \mathbf{e}^{\mathbf{ip.r}} \sum_{\mathbf{k=1}}^{\mathbf{3}} \mathbf{U}^{*}_{\alpha\mathbf{k}} \; \mathbf{e}^{-\mathbf{i}\sqrt{(\mathbf{p^2+m_k{}^2})}\mathbf{t}} \; |\nu_{\mathbf{k}}>$$

The different $|\nu_k>$ will evolve differently with time

because of the different m_k's in the exponent

$|\nu_k>$ mix will change with time.

No longer a pure ν_α.



NOTE: To have oscillations, the m's must be non-zero and different.

Oscillation probability

U is usually represented as a product of three rotation matrices

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Solar

- Oscillations should involve all 3 mass states always.
- Matrix involves 3 angles and a phase, δ_{CP}.

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\ (1 - 2S_{13}^2)\right)$$
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$
$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E}\ \frac{aL}{4E}\ (1 - 2S_{13}^2)$$

To measure δ_{CP}
All 3 angles
must be ≠0

Term changes sign
for $\bar{\nu}$

Oscillation probability

- For most oscillations phenomena we need deal with only 2 states at a time.
- **U** then simplifies to a **SINGLE** rotation matrix with one parameter: **θ**.

θ Will be different depending on which pair of states we are dealing with

$$P_{\alpha\beta}(t) = \sin^2 2\theta \sin^2 \left[1.27 \frac{L(m)}{E_\nu(MeV)} \Delta m^2 (eV^2)\right], \Delta m^2 = m_i^2 - m_j^2$$

To maximize oscillations: → $\pi/2$

Observe large oscillations at small **L** means Δm^2 is large

Note:

- Cannot determine the SIGN of Δm^2 through oscillations in vacuum
- Cannot determine the ABSOLUTE mass scale: only mass differences

Present knowledge

Two angles have been measured:

"Solar" angle $\theta_{12} = (33.96 \pm 0.99)^o$

"Atmospheric" angle $\theta_{23} = (46.14 \pm 3.46)^o$

In 2011 the angle $\boldsymbol{\theta_{13}}$, had only a limit set by a reactor experiment CHOOZ: $< 11^o$

With 3 neutrino's we have 2 independent mass differences. They have been measured

$\Delta m_{12}^2 = (7.59 \pm 0.19) \text{x } 10^{-5}\ eV^2$ Solar mass difference

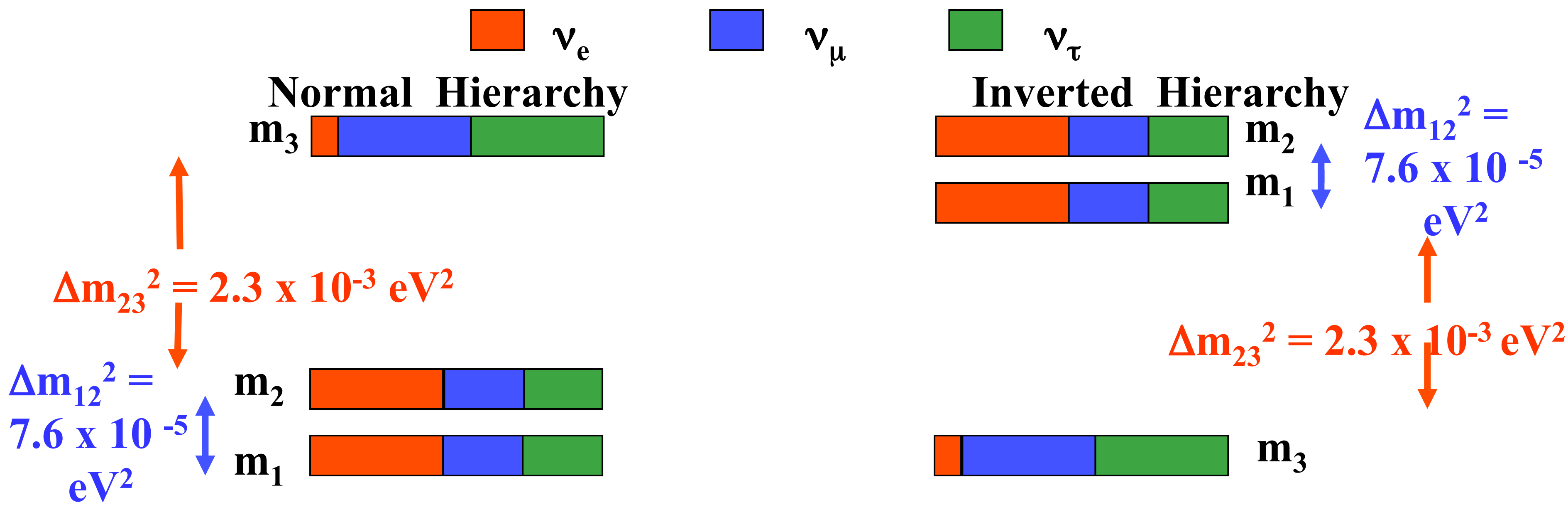
$\Delta m_{23}^2 = (2.32 \pm 0.12) \text{ x } 10^{-3}\ eV^2$ Atmospheric mass difference

Three remaining questions

I. Sign of Δm^2_{23}

Question 1: What is the mass hierarchy? $m_3 > m_1, m_2$ or $m_3 < m_1, m_2$

[The sign of Δm_{12} is determined by matter effects in the sun affecting solar ν's]



Must send ν's through matter: presence of e's in matter and no (μ's and τ's) Introduces an extra term in their propagation and linear terms in Δm^2.

Significant matter effect requires ν's travelling ~ 1000km through the Earth.

Mass hierarchy

To make [1.27 Δm^2 L/E] $= \pi/2$ with $\Delta m_{23}^2 = 2.3 \times 10^{-3}$ eV^2 and L ~ 1000km

⇓

E ~ 1000 MeV

⇓

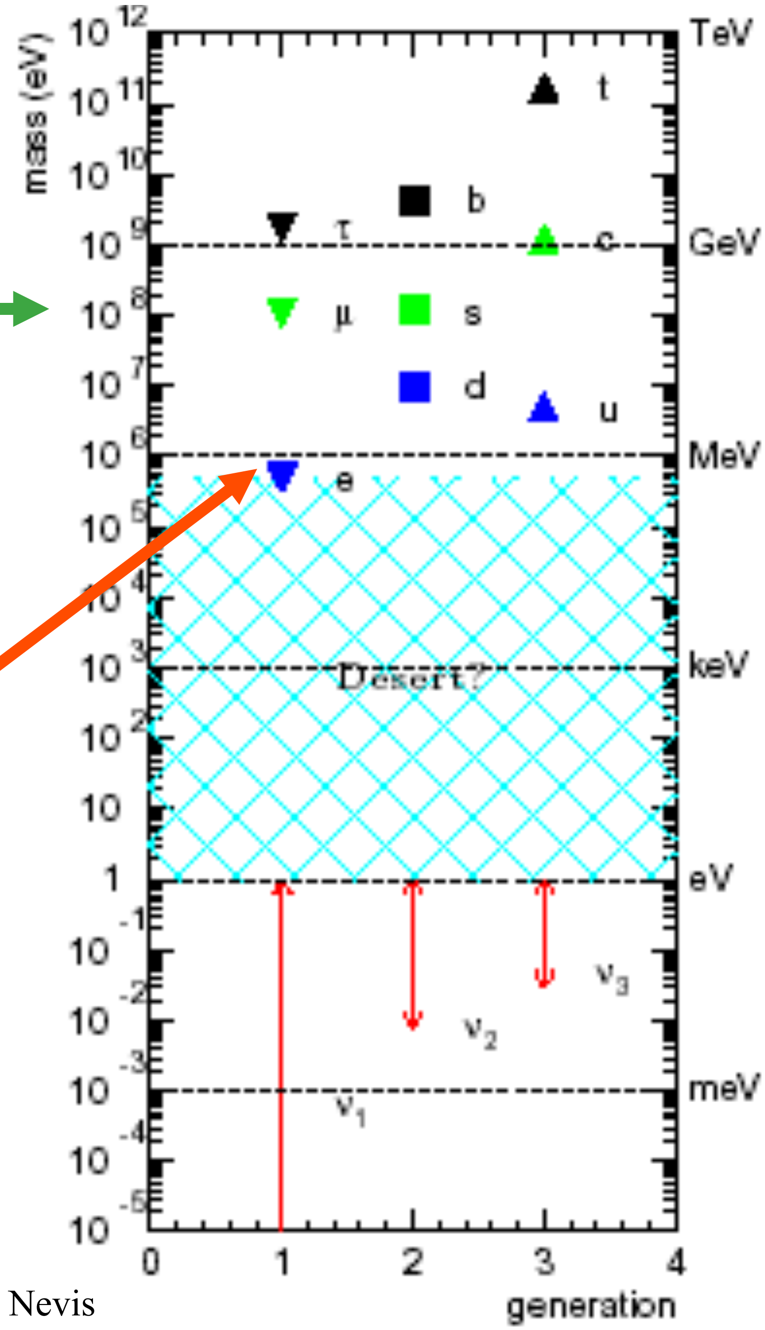
Accelerator ν beam

Fermilab to Homestake (SD)

Long Base Line Neutrino Experiment(LBNE)

- Large International Collaboration
- Tens of kilotons of Liquid Argon
- Granted DOE CD1 approval.

Other particles



Why are neutrino masses so small????

6 orders of magnitude smaller than the next heaviest particle: the electron

II. CP Violation

Question 2: Is $\delta_{CP} \neq 0$?

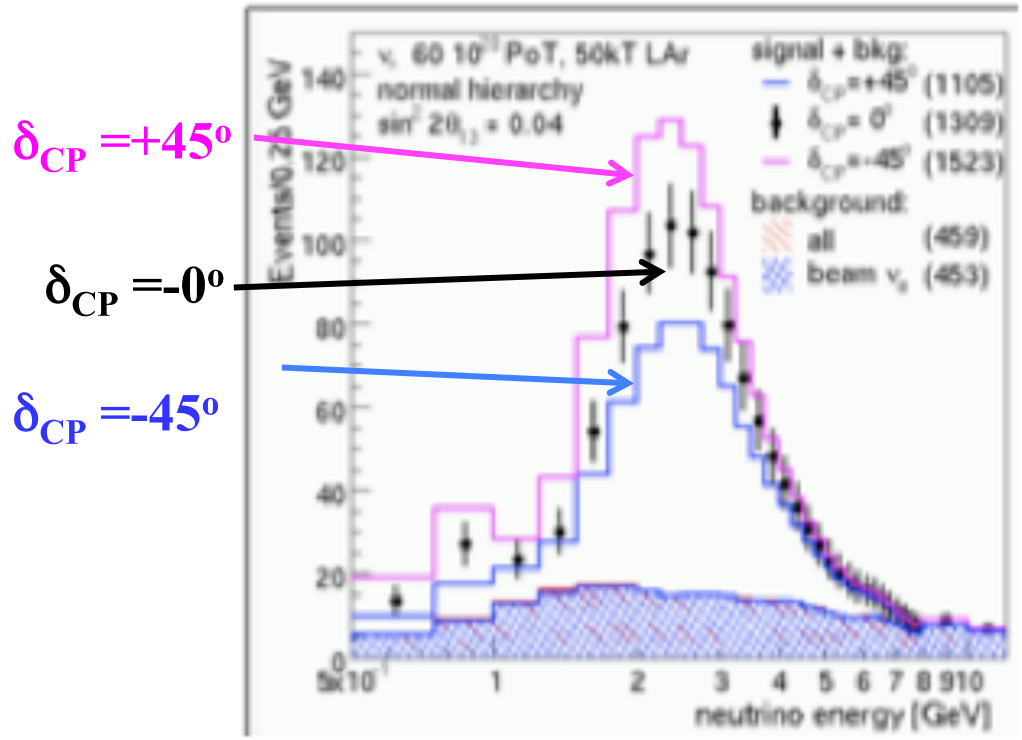
$\nu_\mu \rightarrow \nu_e$ (ν_e appearance)

Two ways to determine this:

If the phase δ_{CP} is $\neq$ **0**

⬇

- $\nu_\mu \rightarrow \nu_e$ osc. $\neq \overline{\nu}_\mu \rightarrow \overline{\nu}_e$ osc
- Strength of oscillations depends on δ_{CP}

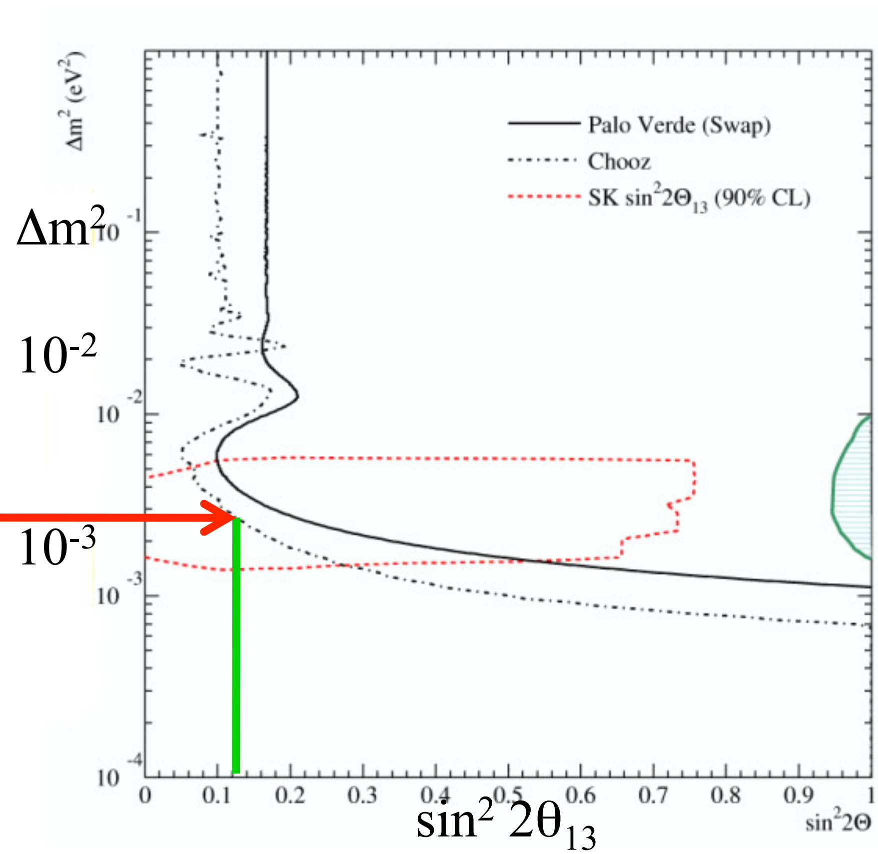


50 kton of Liquid Argon

III. The value of the third angle θ_{13}.

Question 3: What is θ_{13}? $\neq 0$?

Best limit set by CHOOZ:
Reactor antineutrino disappearance.



For $\Delta m^2 = 2.32 \times 10^{-3}\ eV^2$

$\sin^2 2\,\theta_{13} < 0.12$

Measure θ_{13}: First Nevis contribution. Double Chooz

The Fly in the Ointment....

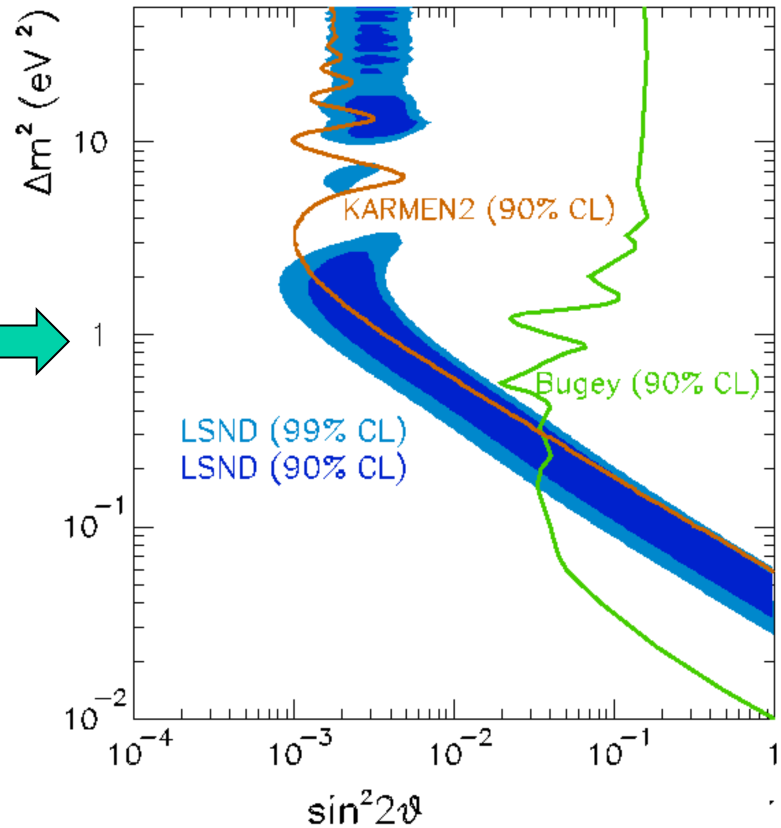
LSND

LSND observed a (~3.8σ) excess of $\bar{\nu}_e$ events in a pure $\bar{\nu}_\mu$ beam

If due to oscillations:
L/E → High $\Delta m^2 \sim 1\ eV^2$
Implies a FOURTH neutrino

But Z^o width allows ONLY 3 low mass ν's
Can only be a new

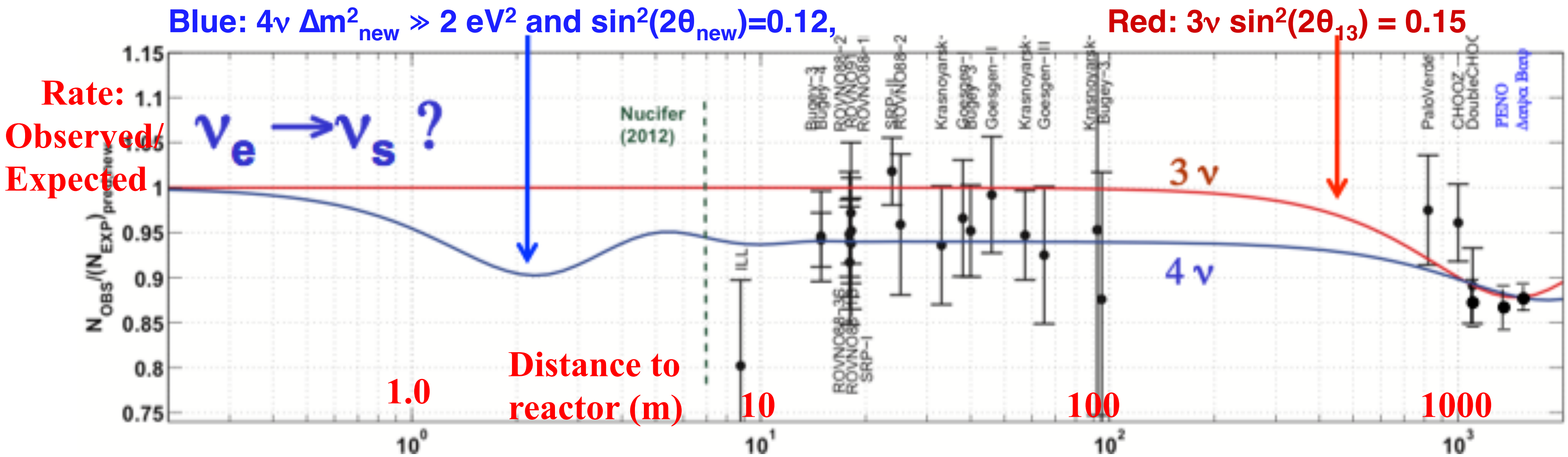
LOW MASS STERILE ν



Second Nevis contribution: Check LSND. MiniBooNE.
Third Nevis contribution: Check LSND. MicroBooNE.

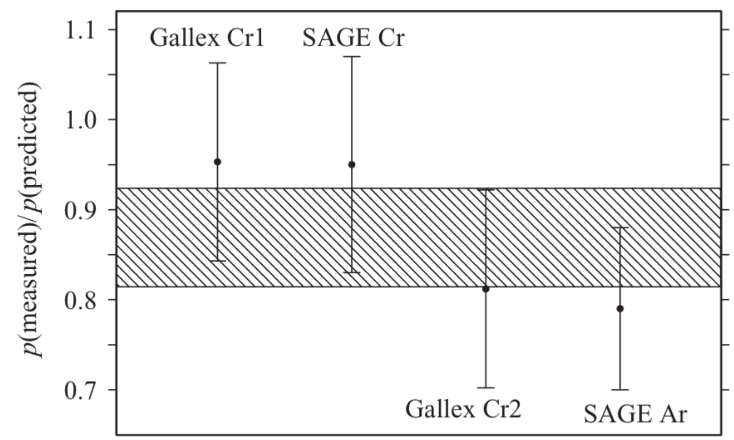
More flies….

Reactor Anomaly: Short baseline reactor experiments observe a deficit of $\bar{\nu}_e$



Source Anomaly: Sources of ν_e used to calibrate solar neutrino detectors (SAGE and Gallex) also observe a deficit.

Small **L** implies high $\Delta m^2 \sim 1$ eV^2
A FOURTH ν with higher mass ?



Fourth Nevis contribution.
Proposed: LAr1, IsoDAR.

Double Chooz

Measure θ_{13} by studying oscillations of reactor antineutrinos ($\bar{\nu}_e$'s)

Neutrino identification → Charged Current interactions → e, μ, τ.
Reactor antineutrinos not energetic enough to produce μ,τ.
Cannot search for oscillations through APPEARANCE of $\bar{\nu}_\mu$, $\bar{\nu}_\tau$.

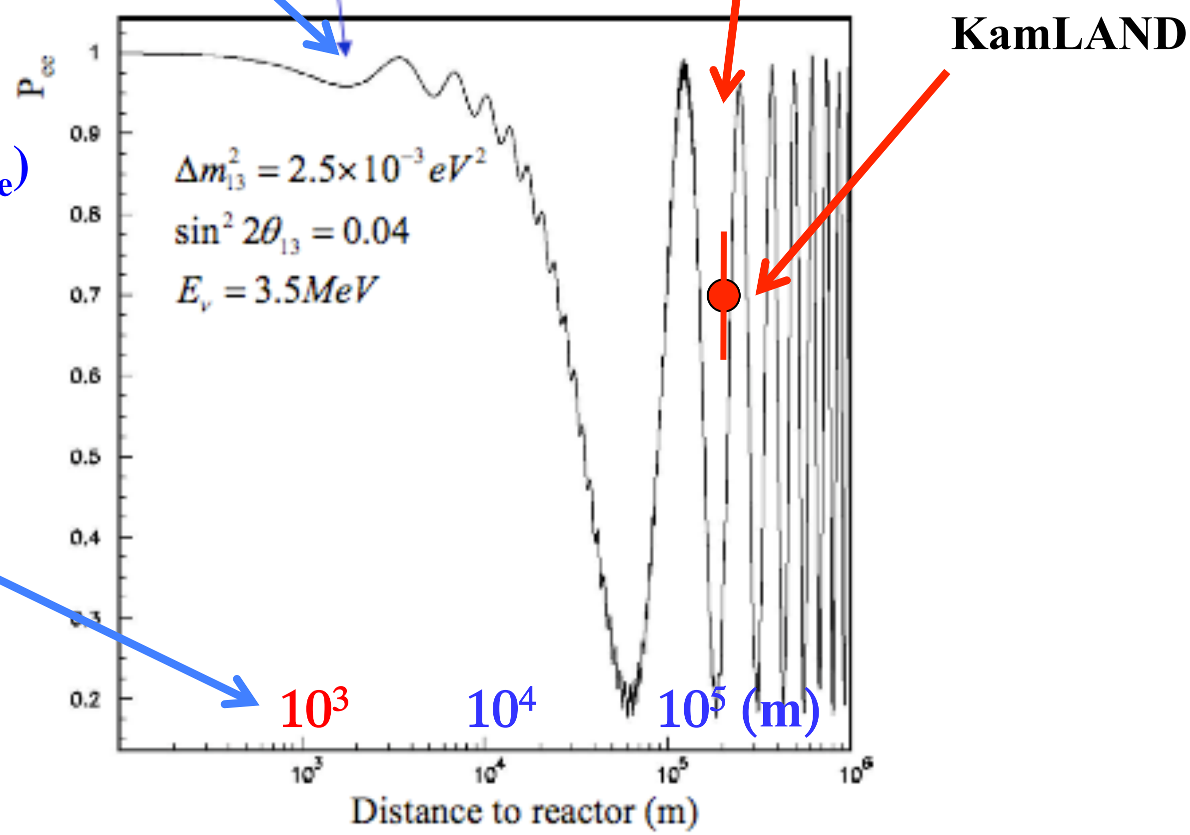
DISAPPEARANCE of $\bar{\nu}_e$' s ONLY

Sensitivity to θ_{13}

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m_{13}^2 L/4E) - \sin^2 2\theta_{12} \sin^2(\Delta m_{12}^2 L/4E)$

$\Delta m_{12}^2 << \Delta m_{13}^2$

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$



Place detector at a distance ~1000m
→ θ_{12} term negligible

Technique used by CHOOZ and Palo Verde to set a limit on θ_{13}.

Detection Technique: Scintillator target.

Detection through inverse β decay:

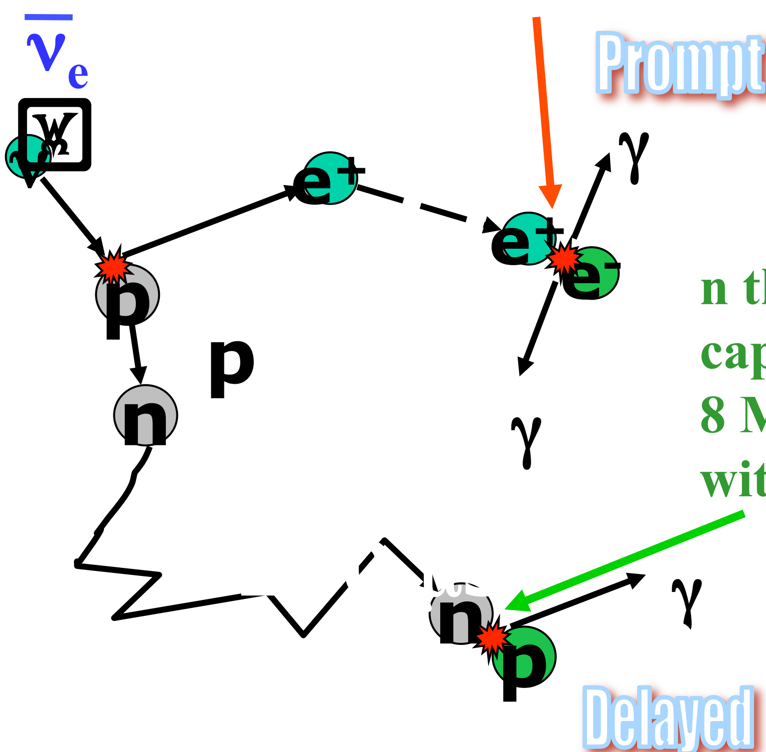
$\bar{\nu}_e + p = e^+ + n$

On free protons only: Hydrogen

e^+ annihilates with e^- of liquid: → 2 photons (0.7 – 12.2 MeV)

Detector : Liquid scintillator loaded with gadolinium:

Large cross section for neutron capture → photons



n thermalizes and is then captured by Gadolinium : 8 MeV of photons emitted within 10's of μsec. (6 – 12 MeV)

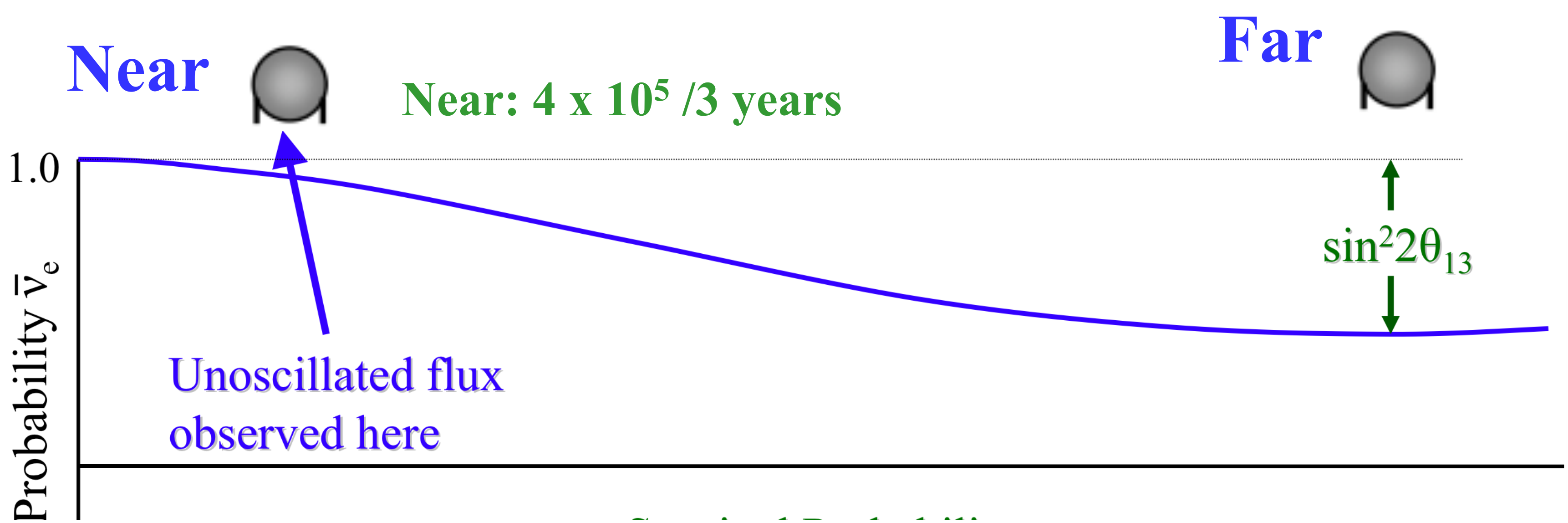
Delayed Coincidence of 2 signals (2-100μs) Reduces background

How do we improve on CHOOZ?

- Statistics: 2.8% → 0.4%.
  - Larger detector ($5.55 m^3$ → $10.3\ m^3$) x 2
  - More stable scintillator → Longer running time. (3 months → 3 years) x 12

    2700 events → Far: 65 000events/3years

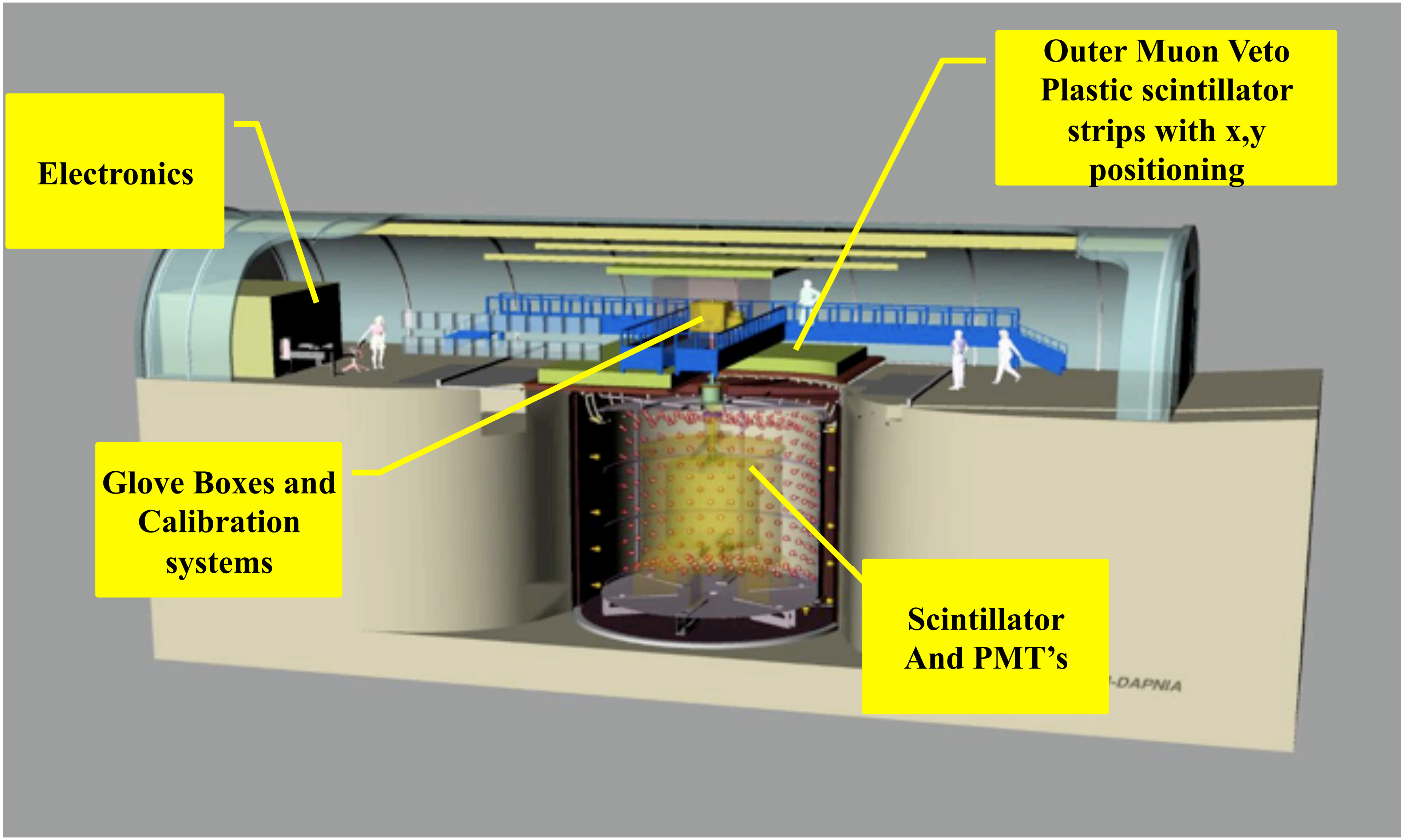
- Systematics: 2.7% → 0.6%.
  - Reduce **flux uncertainty** by measuring it in a Near detector



Two detectors

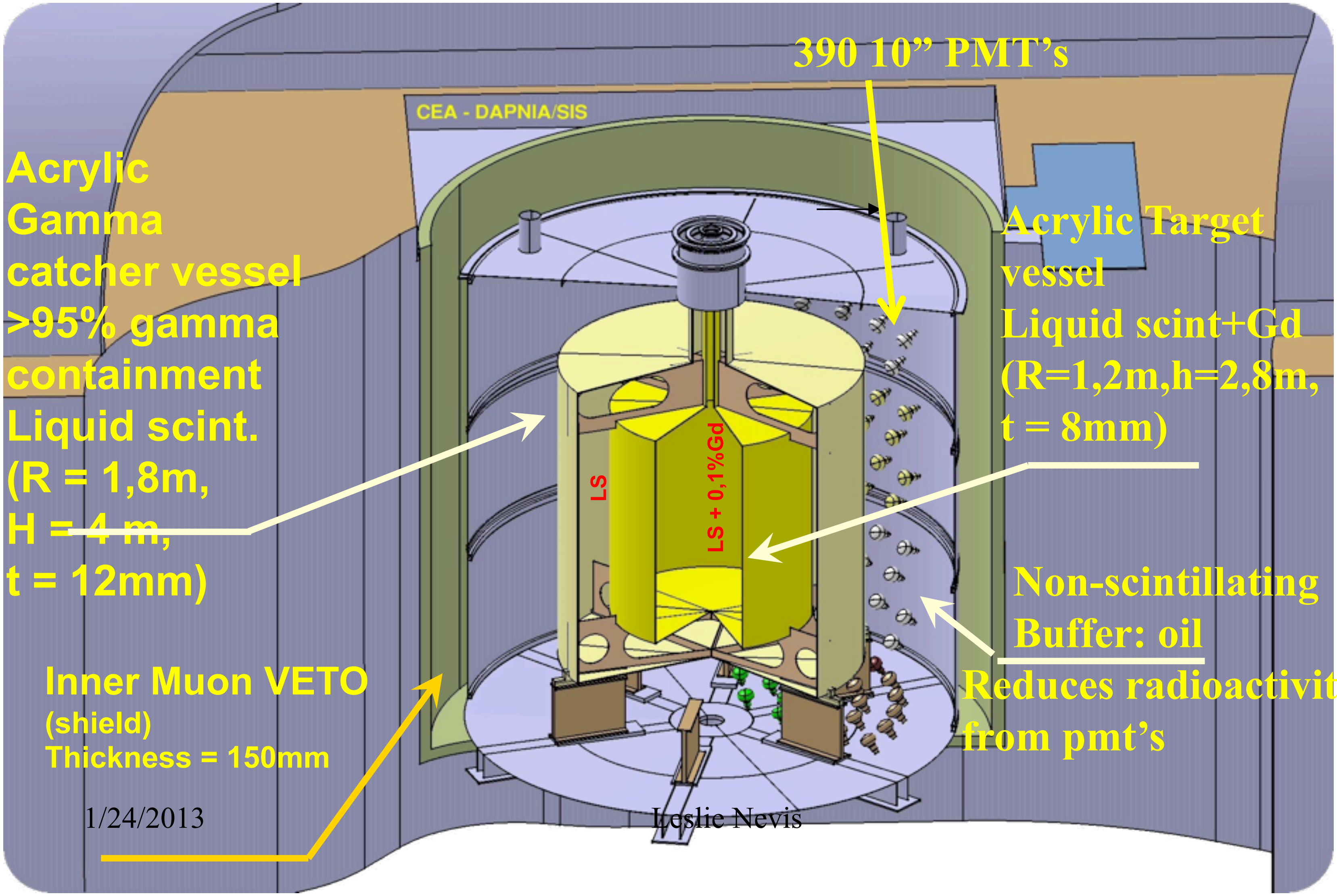

PASSAGE
PIÉTONS

The Lab

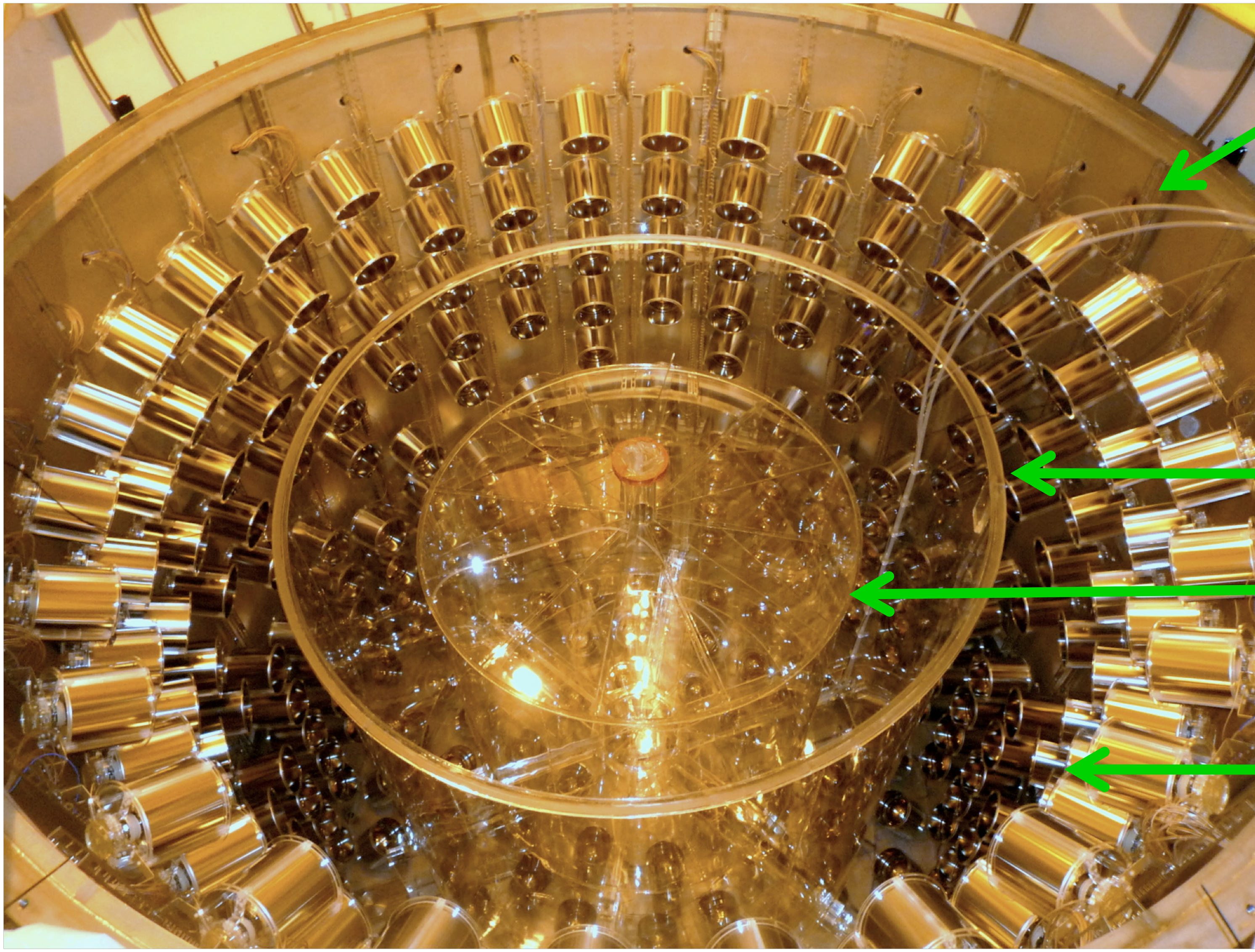

Electronics
Outer Muon Veto
Plastic scintillator
strips with x,y
positioning
Glove Boxes and
Calibration
systems
Scintillator
And PMT's

Double Chooz detector

Inner detector, gamma catcher, mineral oil buffer , inner μ veto , outer veto (scintillator strips)



DC Target



Calibration source Guide Tube

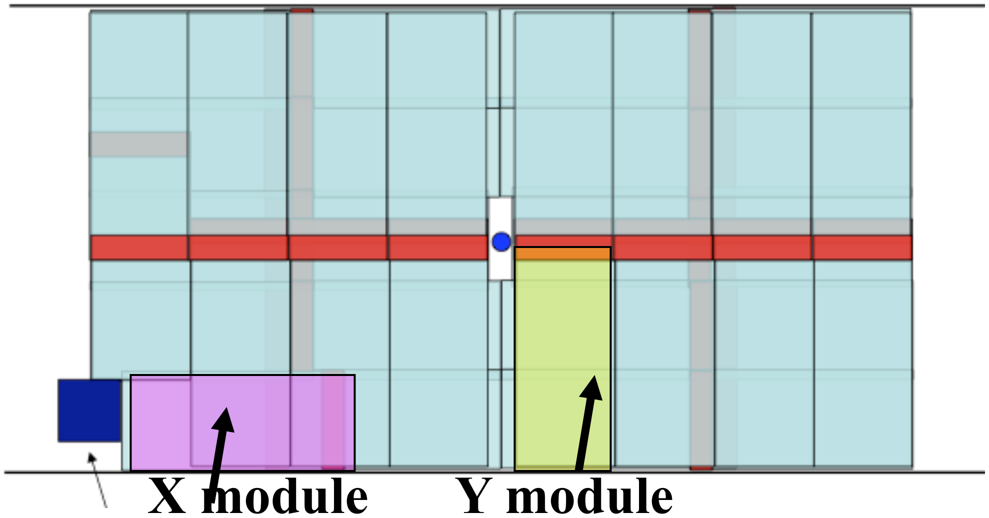
Gamma Catcher

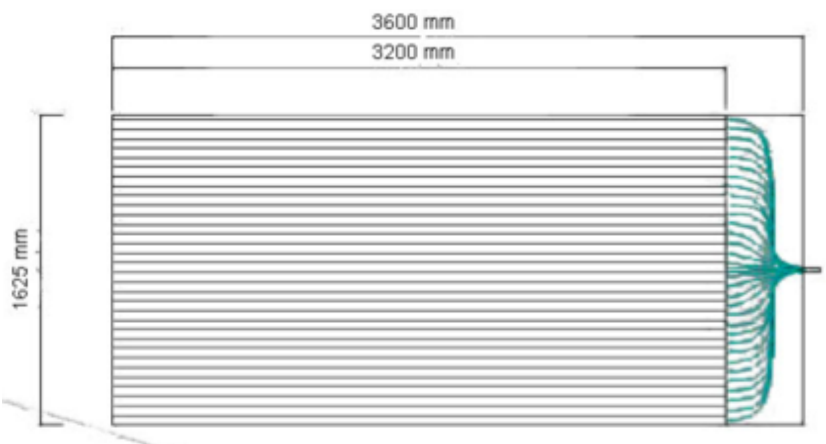
Target

Buffer and PMT's

The Outer Veto

Made of modules each comprising 64 scintillator strips.
A layer of modules with strips in the X direction.
A second layer with strips in Y direction.





Read by Hamamatsu H8804 64 channel
Multi-anode pmt's.

PMT's and their electronics readout:
Nevis hardware contribution
(Camillo Mariani → Rachel Carr)

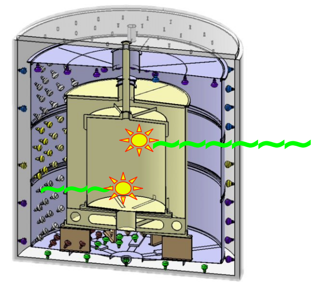
Background

Signal: (Prompt e+-like energy) x (Delayed n-like energy)

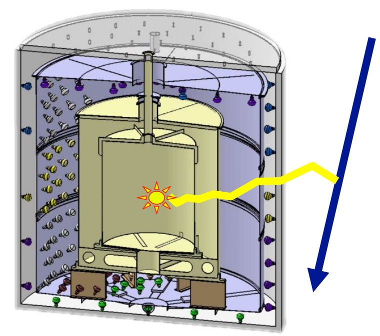
Three types:

➢ Uncorrelated

- Two radioactivity induced pulses (pmt's or surrounding rock) in random delayed coincidence: → e+ like and n-like signals

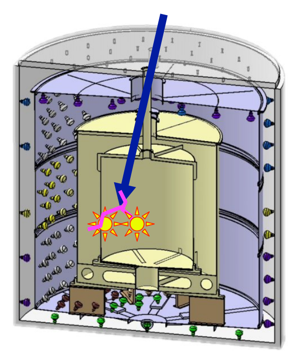


- A cosmic μ interacts in the surrounding rock producing a Fast neutron:
  - Giving a recoil proton → e+ like signal
  - Slowing down and getting captured → n signal

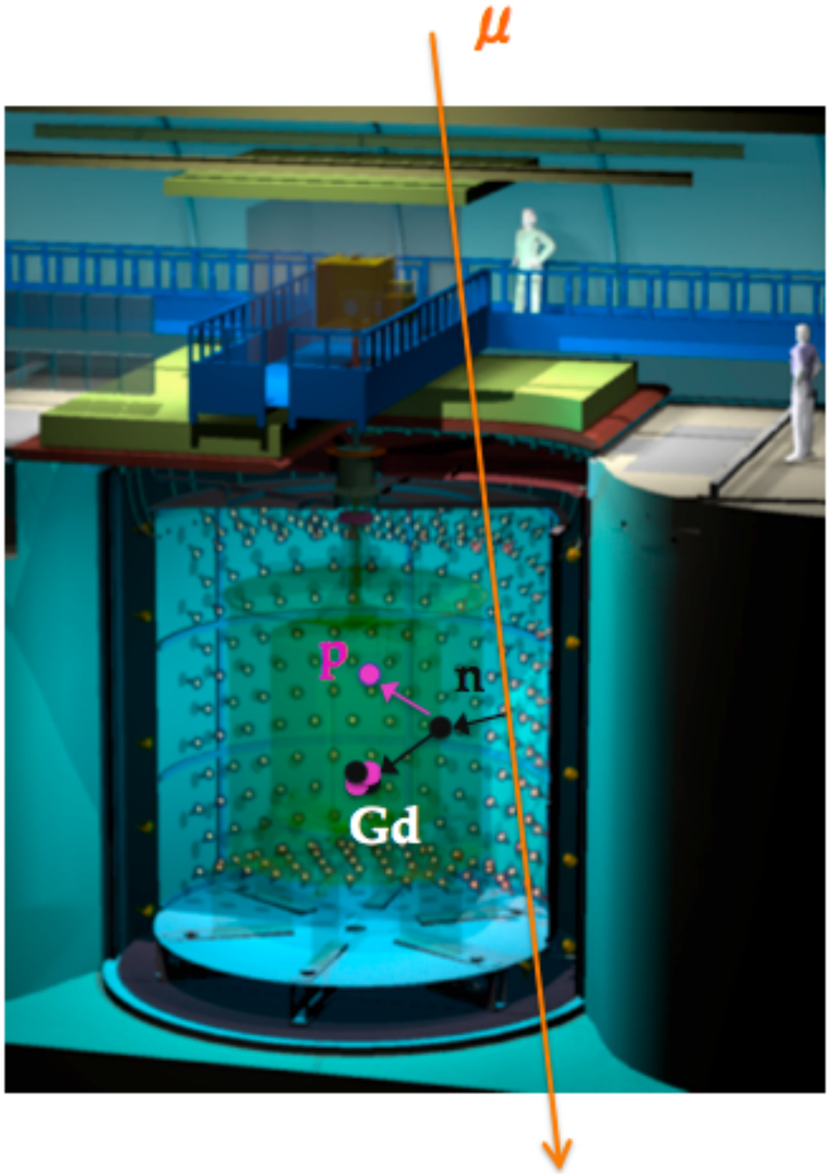


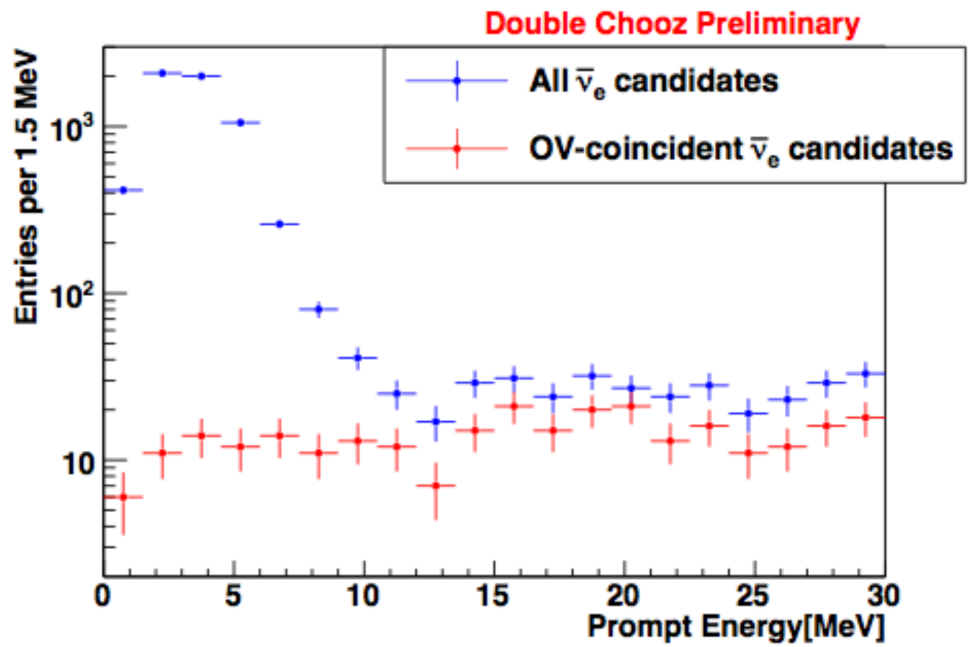
- A cosmic μ interacts in the target producing ^{9}Li or ^{8}He
  - Which then β-decays resulting in → e+ like signal and n signal

  Too long a half life (>100msec) to veto on μ passage.



Outer veto contribution (Nevis)

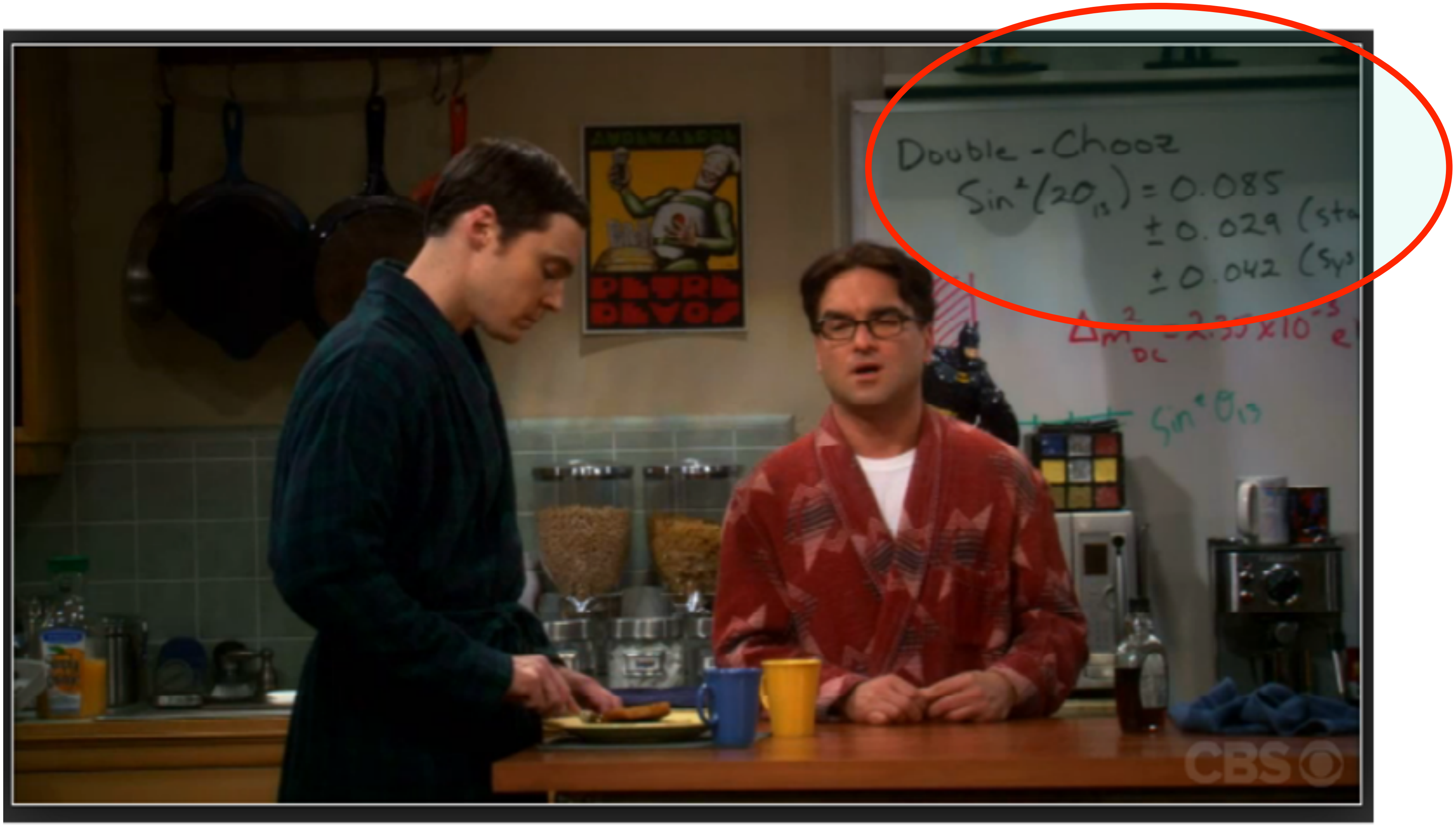




28% of Fast neutron and Stopping Muon Background rejected by OV.

Results

First published in Big Bang Theory !

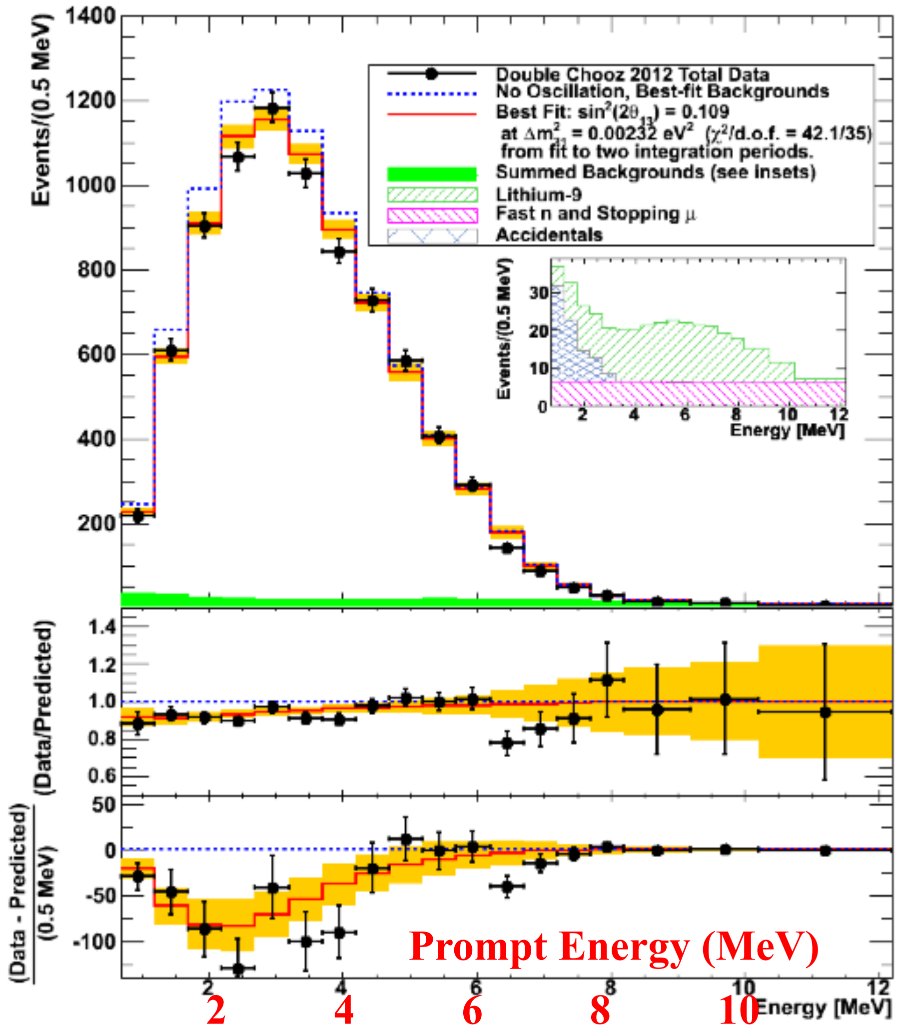


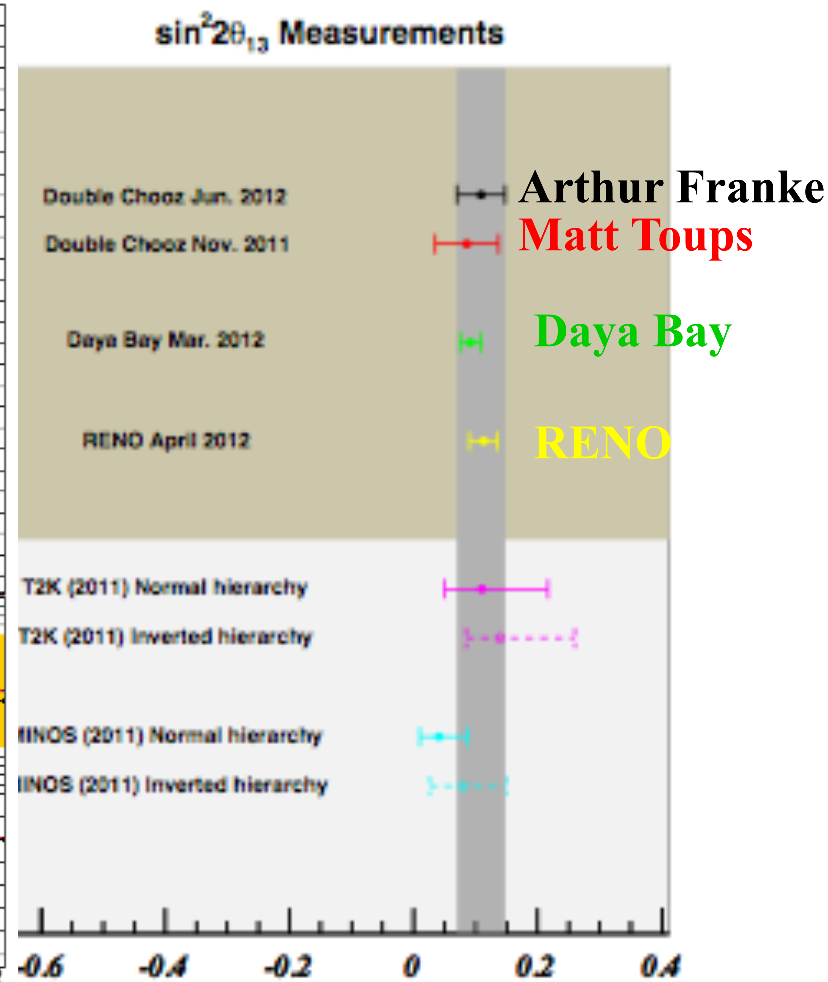
Results

Fit Rate + energy distribution SHAPE: 18 prompt energy bins

Observed/
Predicted

Observed-
Predicted





PRL **108**, 131801 (2012)
PRD **86**, 052008 (2012)

$\sin^2 2\theta_{13} = 0.109 \pm 0.030 \text{ (stat)} \pm 0.025 \text{ (syst)}$

Double Chooz Unique Contributions. I.

- RENO and Daya Bay now have more precise results than us on θ_{13} .
  Near detectors, more mass, more flux.
- They use ONLY the total event **RATE** to determine θ_{13}.

- But…. Double Chooz has:

Energy distribution shape as well as event rate

- **Used the event RATE + SHAPE of the energy distribution to determine θ_{13}**
  - Allows the background to be constrained using event distribution at high energy where little signal is expected.
  - Allows to confirm that the shape is consistent with the Δm_{31}^2 found by MINOS.

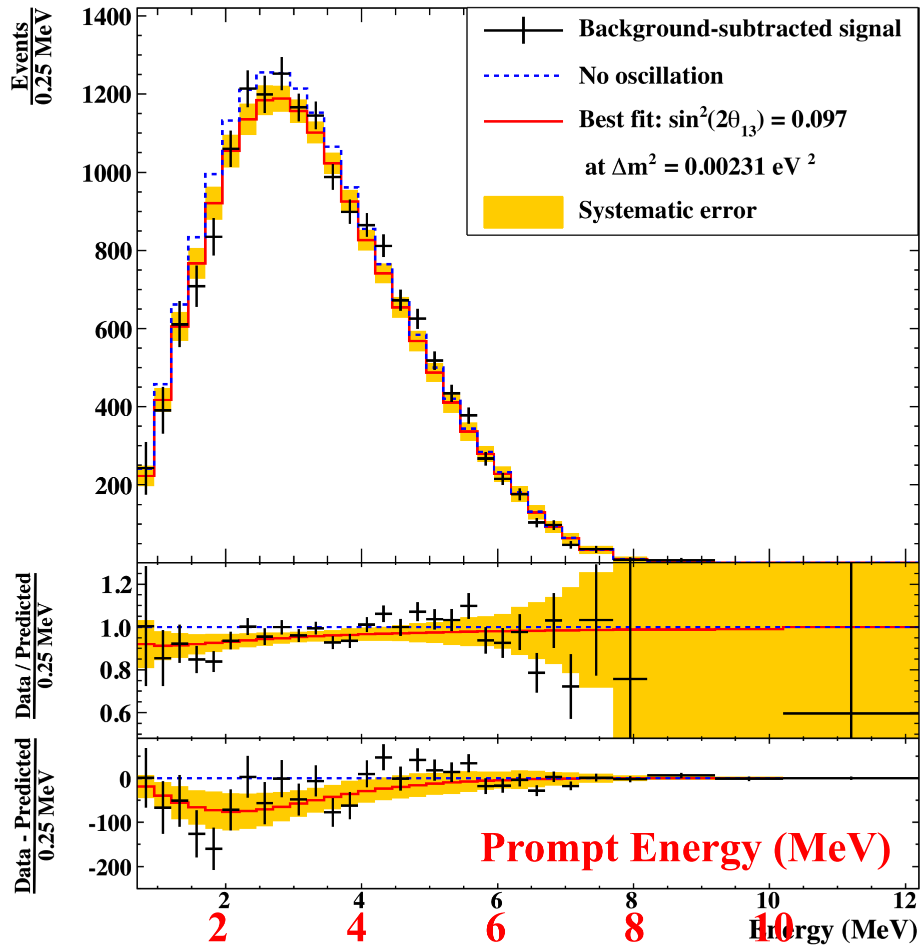
Double Chooz Unique Contributions. II.
Measured θ_{13} using the Gamma Catcher Hydrogen as well.

n capture on hydrogen: photon of 2.2 MeV → Delayed energy range: 1.5 to 3 MeV

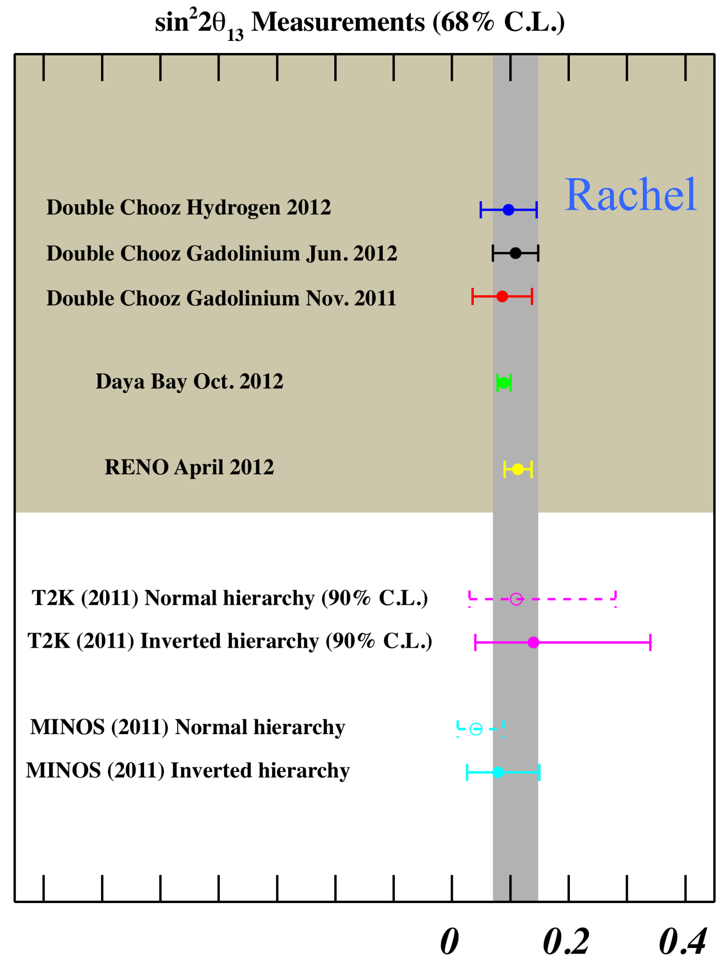
Promp

Observed/ Predicted

Observed- Predicted



Prompt Energy (MeV)



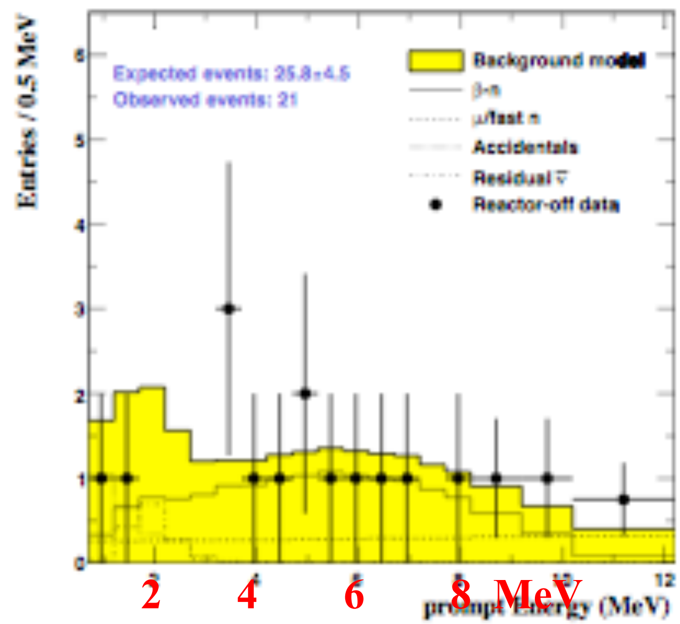
Rachel

$\sin^2 2\theta_{13} = 0.097 \pm 0.034(stat) \pm 0.034(syst)$

Submitted to PRL.

Double Chooz Specific Contributions. III.
Collected data with ALL (2) reactors OFF

Allows a direct measure of the background.
RENO and Daya Bay use TOO MANY reactors for this to happen ever.
Measured an event rate consistent with estimated background over 8 days.

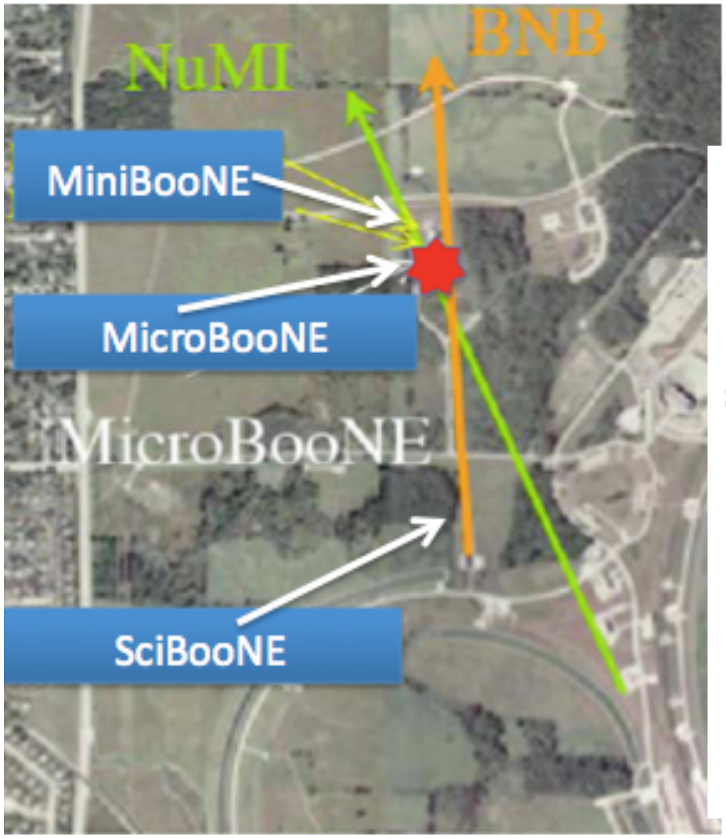


2 4 6 8 MeV
Prompt energy

Expected: 25.8 ± 4.5 events
Observed: 21

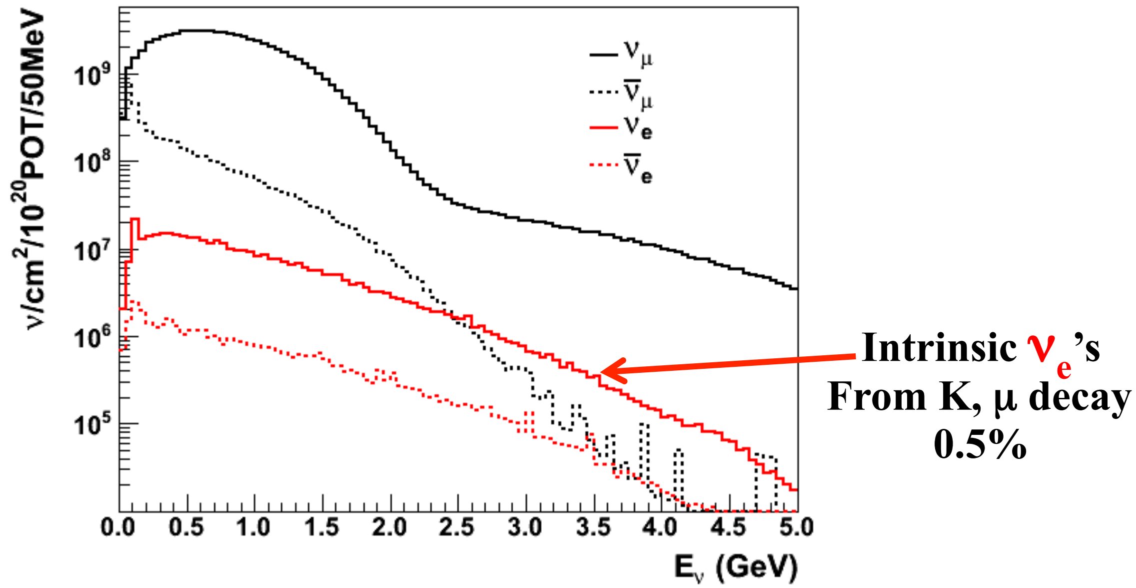
PRD **87**, 011102(R) (2013)

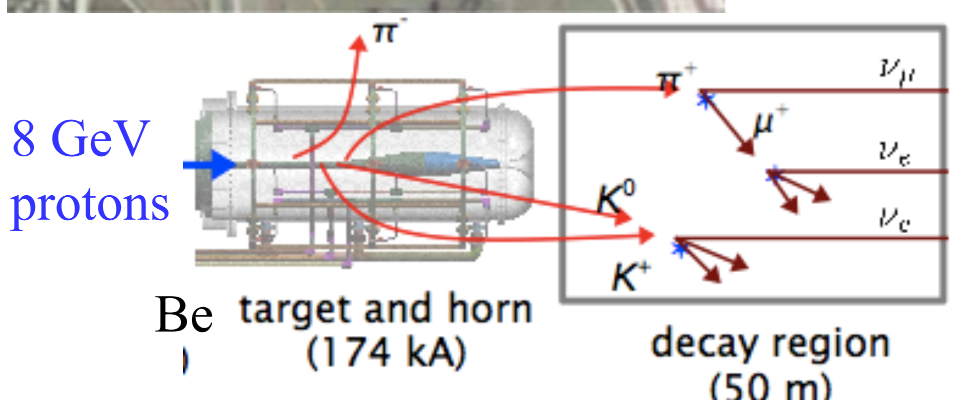
The BooNE Experiments: Sterile ν's ?

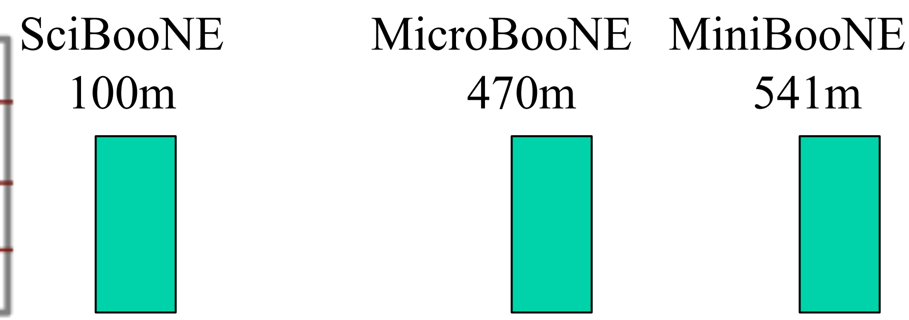


ν_μ ($\bar{\nu}_\mu$) beam. Look for Appearance of ν_e's($\bar{\nu}_e$'s)

Similar L/E as LSND 30m/40MeV ~ 541m/**600MeV**



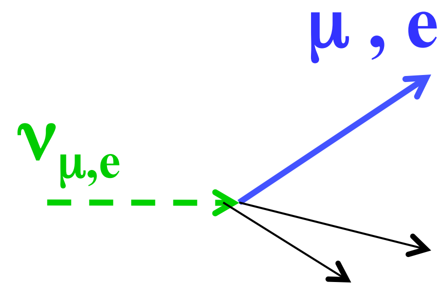


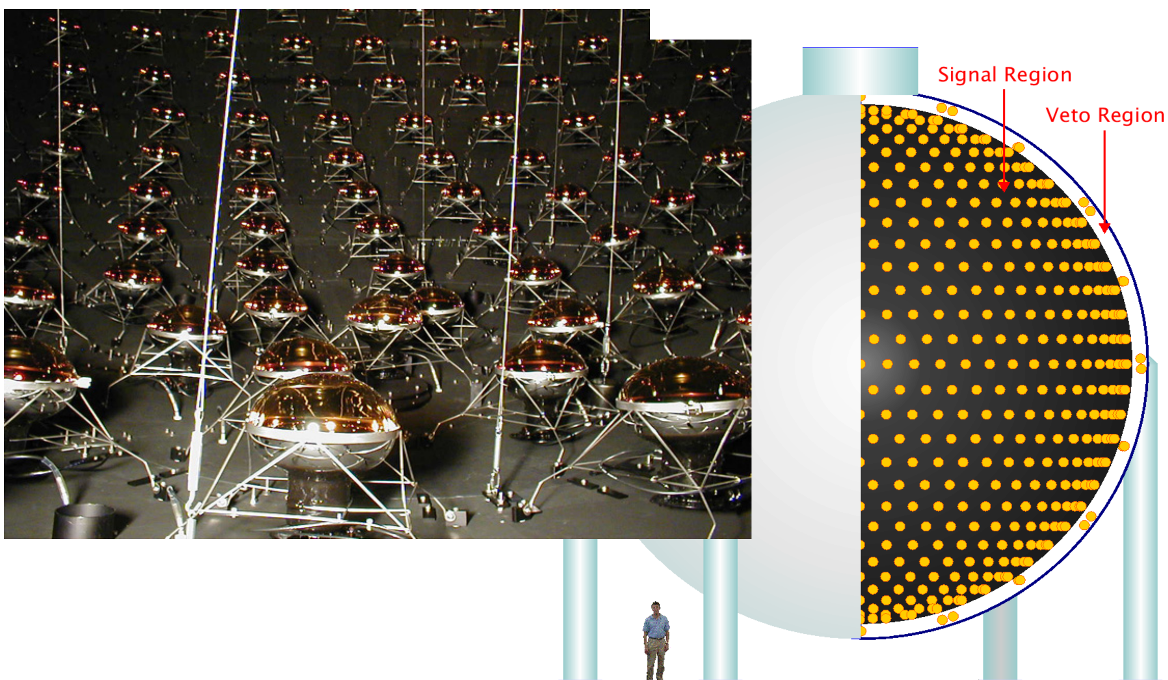


MiniBooNE: Check LSND

- 12m diameter tank
- Filled with 900 tons of pure mineral oil
- Optically isolated inner region with 1280 PMTs on the sphere inner wall.
- Detector Requirements:
  - Separate ν_μ (→ μ)events from ν_e (→ e) events
  - using Cerenkov Ring Technique

Charged Current Interaction



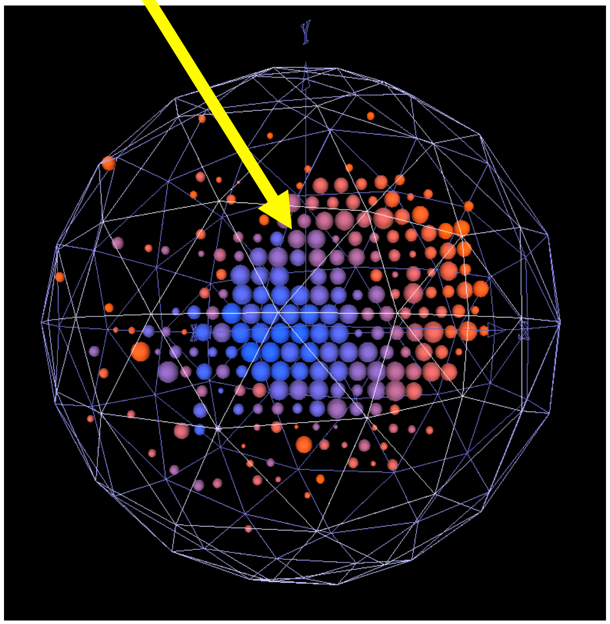


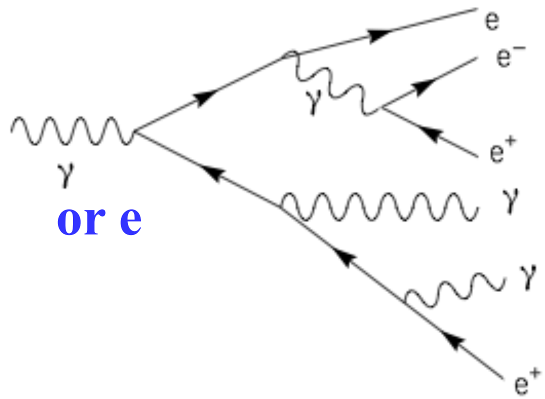
Detector Publication: NIM A599, 28 (2009)

μ/e identification

ν_μ X → μ + …

μ: Long track
- Reaches pmt array
- emitting Cerenkov light
- Filled –in ring: **disk**



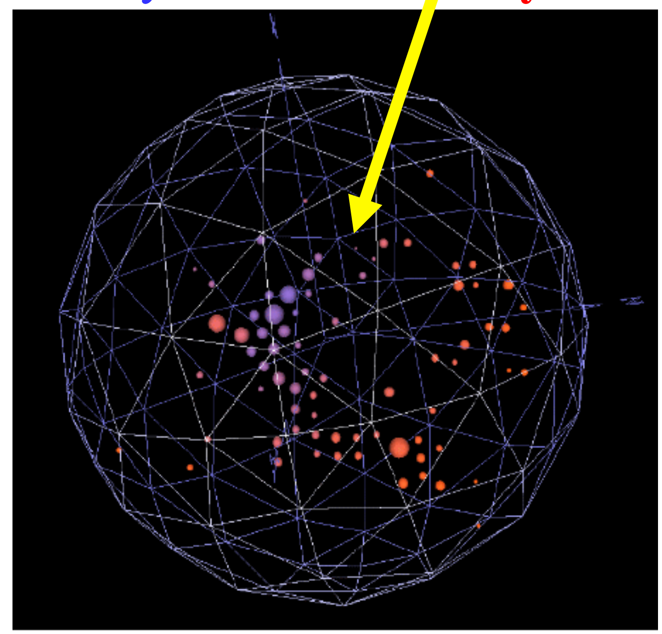


or e

γ will look the same as an electron

ν_e X → e + …

e: Showers→ several e-, e+
- Each one short track
- Will not reach pmt array
- Rings are not filled-in
- Many of them→ **Fuzzy.**

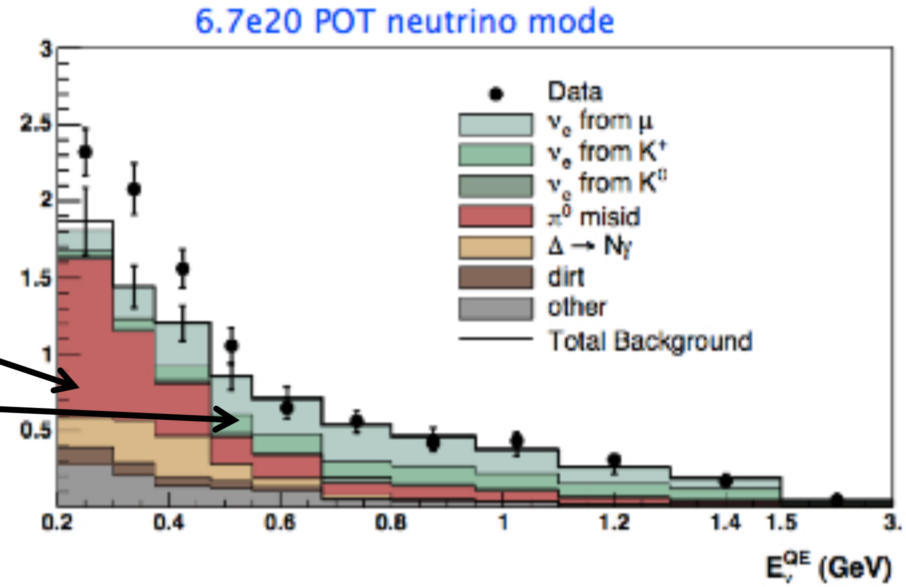


Can distinguish μ's from electrons and therefore ν_μ from ν_e
But NOT very good at distinguishing an electron from a converting γ to e+e-

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ Appearance Searches in LSND Region

e^- e^+

- Method: Search for an excess of "ν_e" events over expectation
  $\Rightarrow$ **Knowing expectation is key**
  - γ from π^0 --> $\gamma\gamma$ in a NC interaction
    Miss one γ
  - **e** from CC ν_e's intrinsically in beam:



Expect LSND "effect" to extend to 0.8 GeV

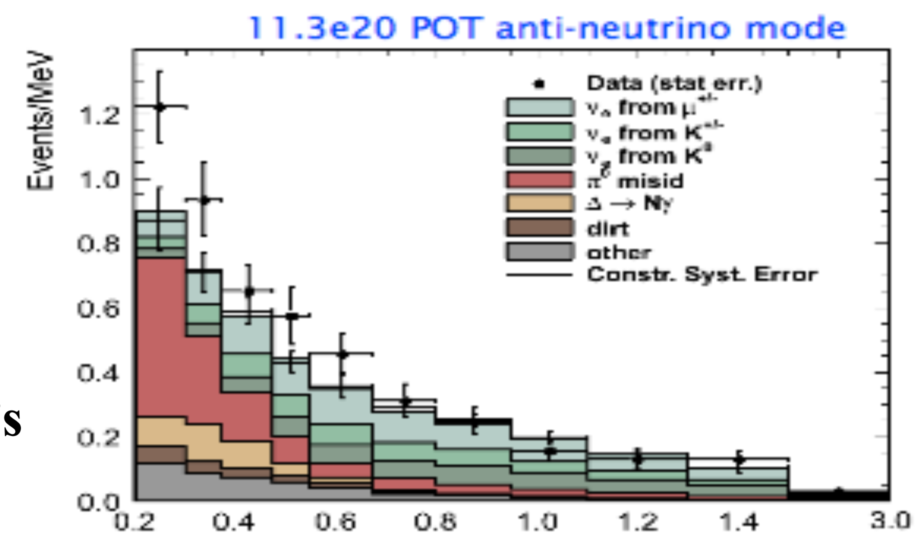
It does in $\bar{\nu}_\mu \to \bar{\nu}_e$

But no strong evidence for excess in $\nu_\mu \to \nu_e$

But an Excess at lower energy!

What is it due to? Electrons or Photons?

Oscillations **Unexpected γ's**



Third Nevis contribution: MicroBooNE

SciBooNE and MiniBooNE

Constraining $\bar{\nu}_\mu$ disappearance. Gary Cheng

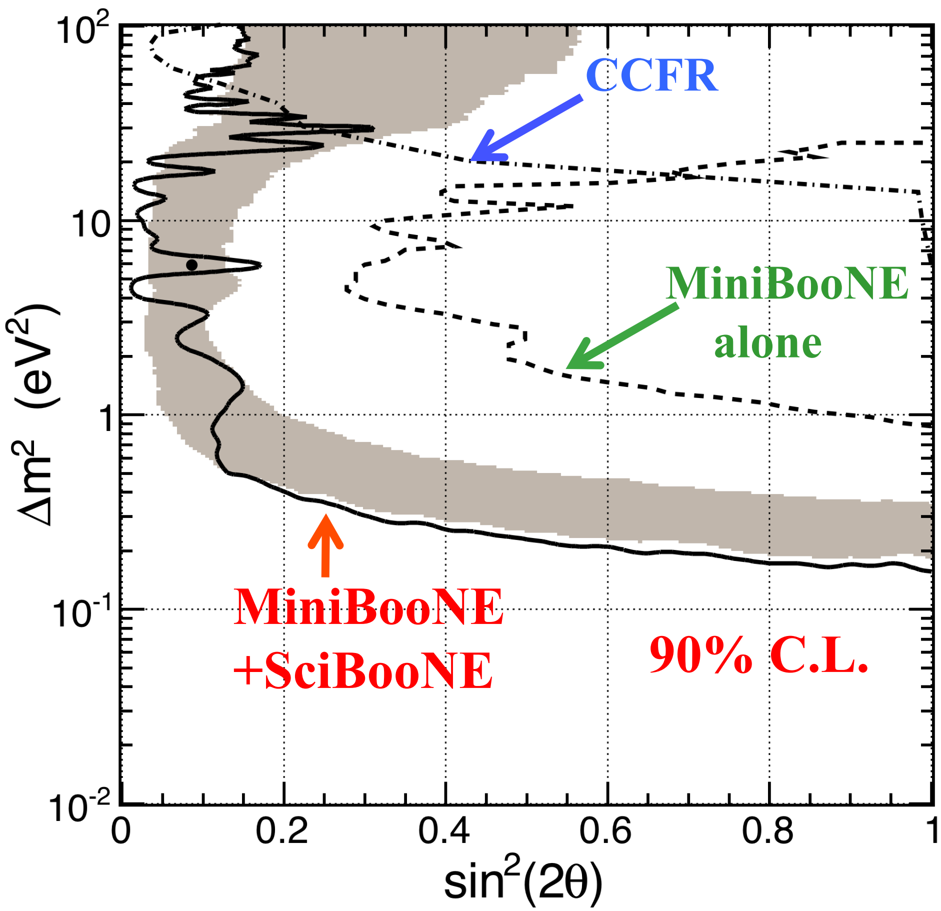
If energy spectrum distortion is due to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation via a sterile $\bar{\nu}_s$

Then two-step process:

$\bar{\nu}_\mu \rightarrow \bar{\nu}_s$

Followed by

$\bar{\nu}_s \rightarrow \bar{\nu}_e$



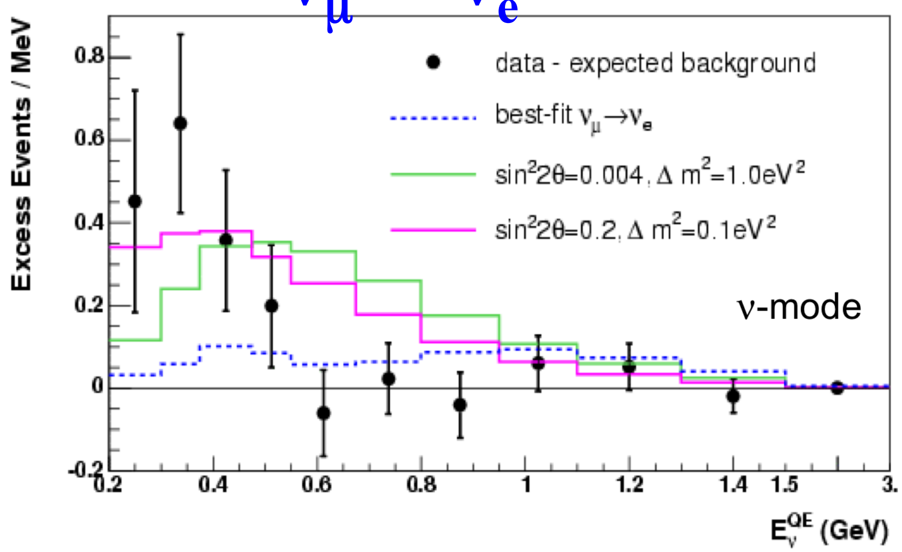
But then must have Significant $\bar{\nu}_\mu$ disappearance

Using SciBooNE (100m) and MiniBooNE (470m) compare $\bar{\nu}_\mu$ fluxes through muon events. Disappearance **NOT** seen.

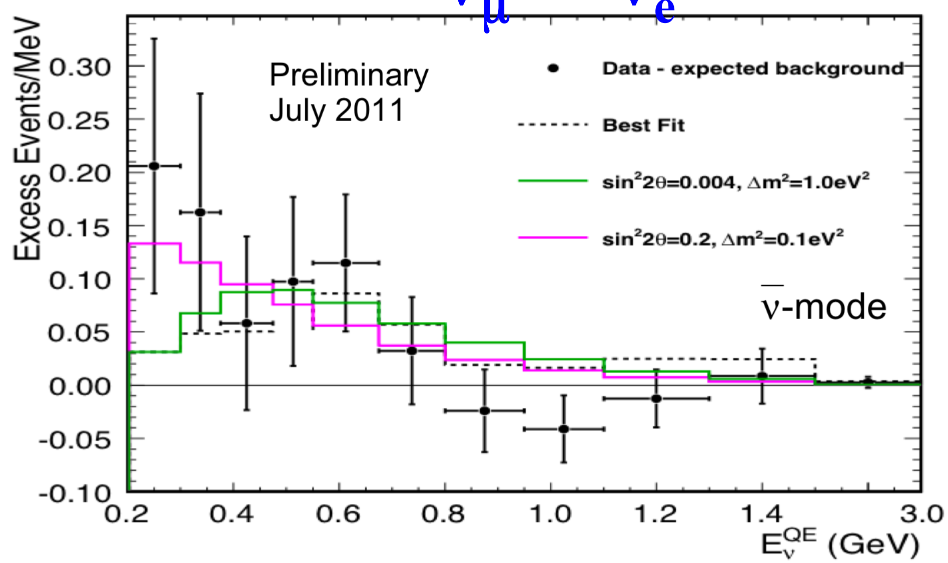
Big improvement
In Exclusion region
Constrains the mixing angle
And mass of a sterile neutrino

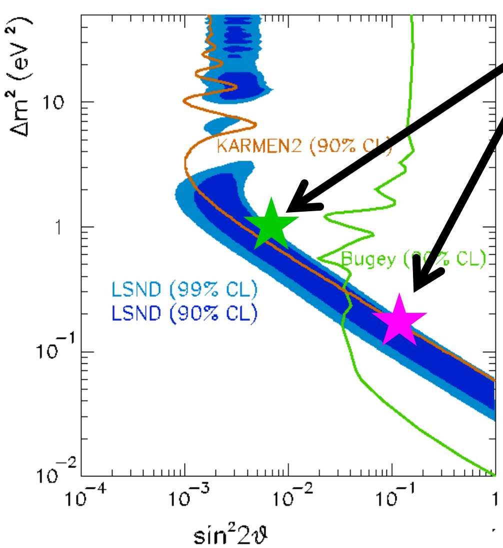
MiniBooNE compatibility with LSND

$\nu_\mu \rightarrow \nu_e$



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





2 test points

- In $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Good compatibility.
- But NOT in $\nu_\mu \rightarrow \nu_e$. No signal above 0.5 GeV.
- Why not?
- More complicated neutrino schemes: 2 or 3 sterile ?

Is excess really electrons? Or could it be photons?

→ MicroBooNE.

MicroBooNE

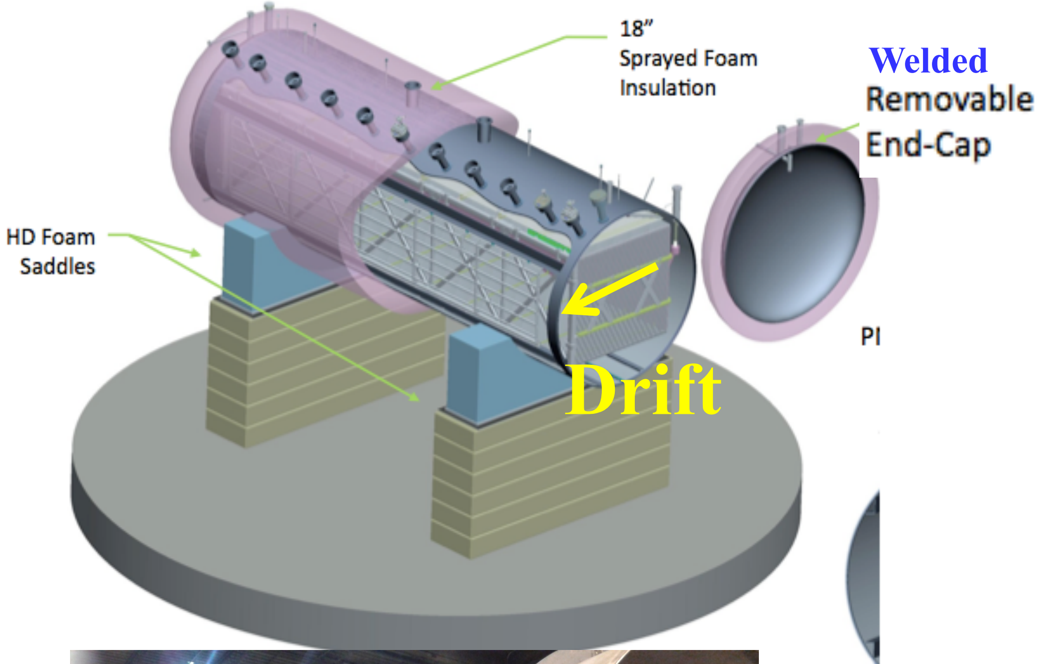
- Similar L/E as LSND
- 30m/40MeV ~ 471m/600MeV
- → Same oscillation Prob → ν_e

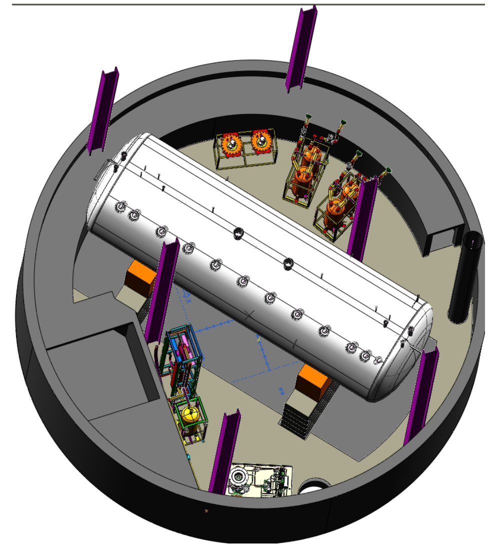
- Same beam and L/E as MiniBooNE
- → Low energy Excess

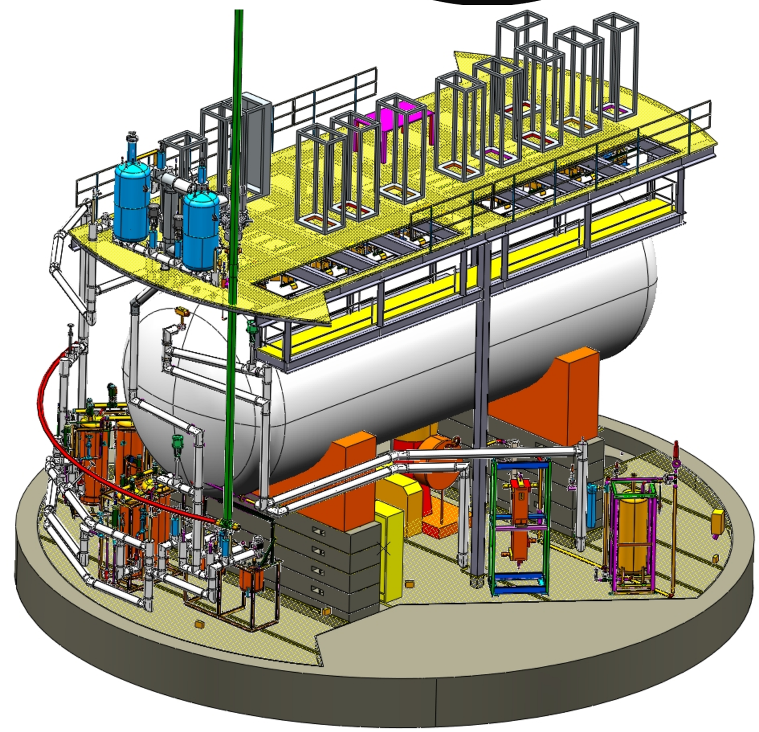
- **Different systematics**
  - Event signatures
  - Backgrounds

Time Projection Chamber (TPC):
Immersed in 100 tons of LAr
(60 tons FV)
in insulated cryostat
30 PMT's

Detector description

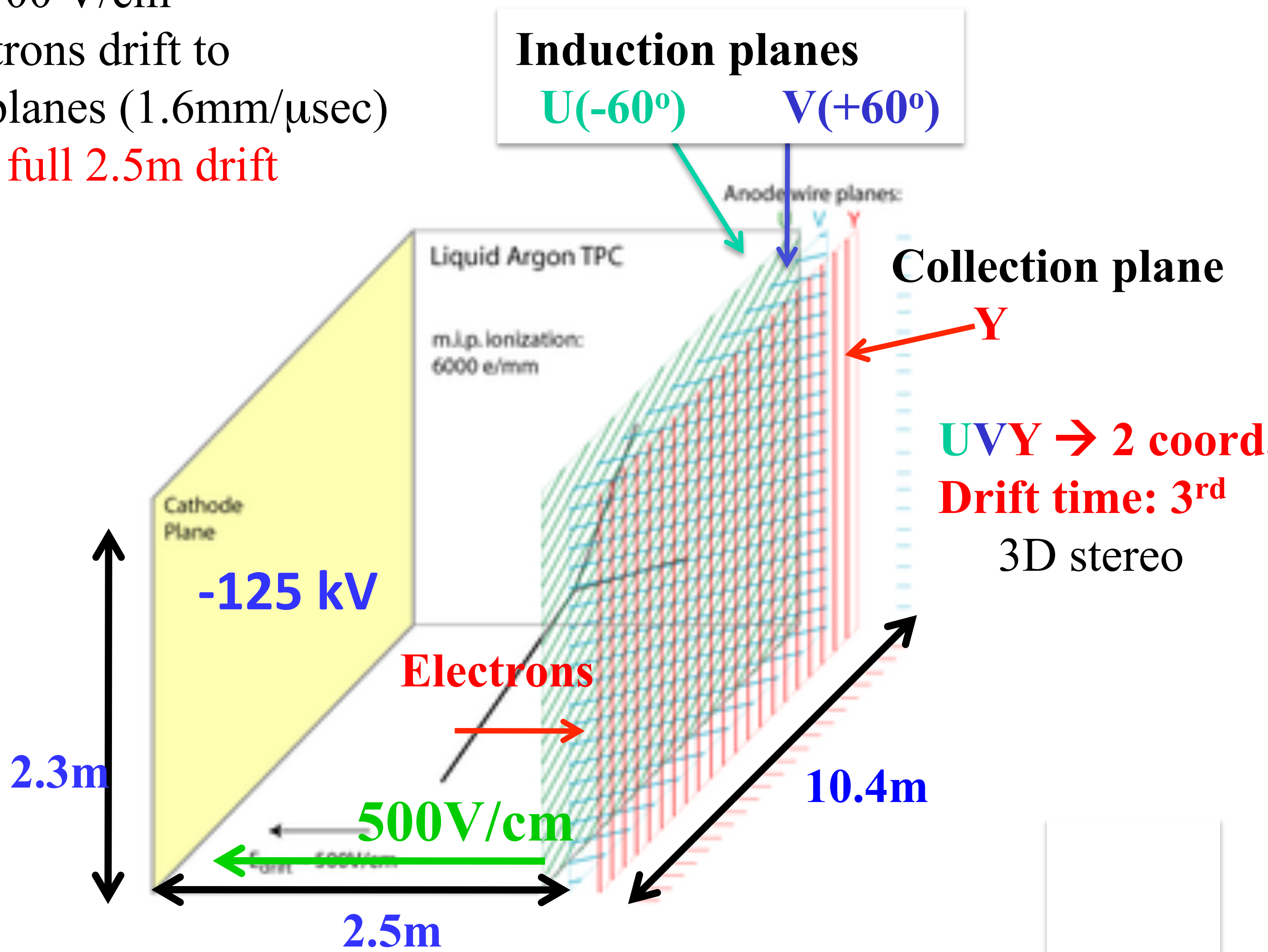




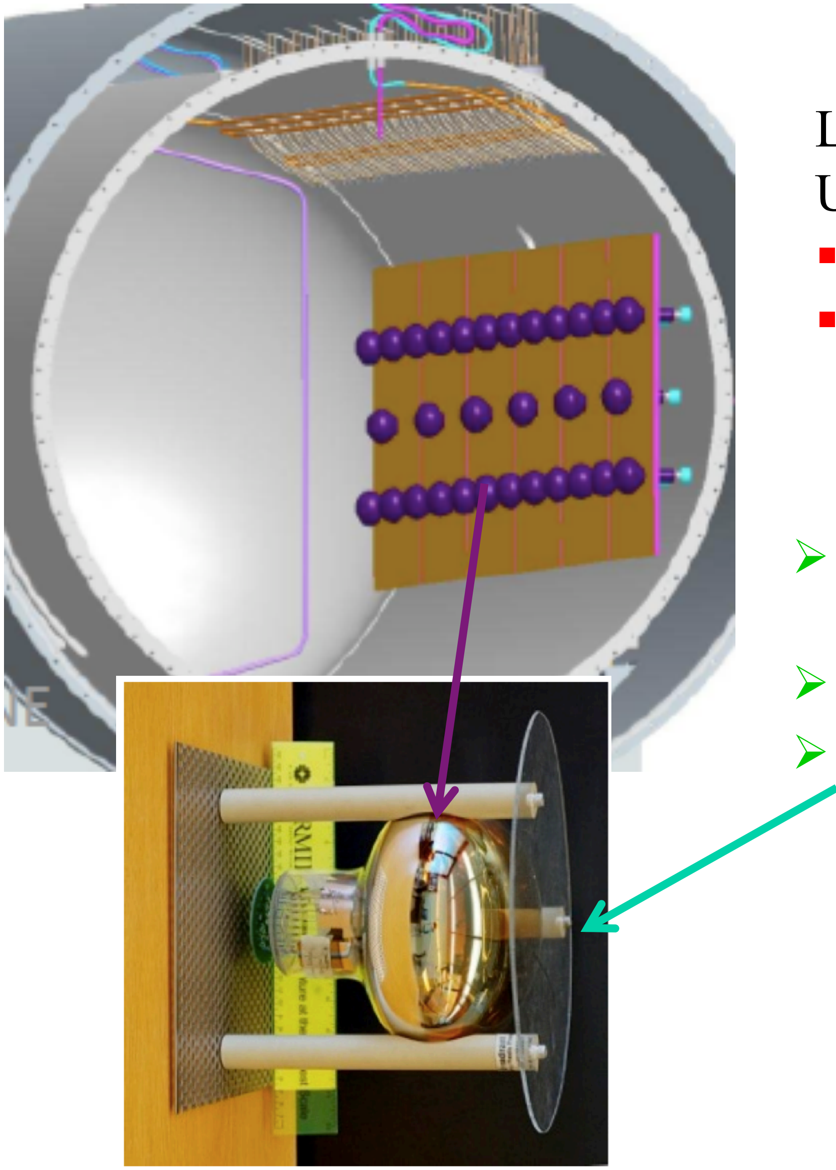


MicroBooNE TPC

- Electric field: 500 V/cm
- Ionization electrons drift to
  3 recording planes (1.6mm/µsec)
  1.6 msec full 2.5m drift



MicroBooNE Photodetectors



LAr scintillates in the UV at 128nm:
Use it

- To determine time of event
- To trigger on events in time with beam

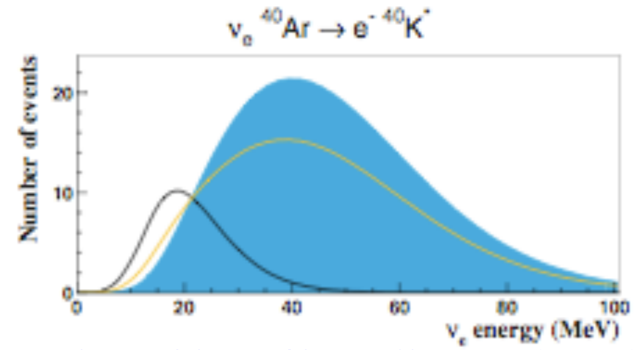
- 30 Hamamatsu R5912-02 14 stage 8 inch pmt's.
- Located behind collection plane
- Plate coated with Tetraphenyl-butadiene (TPB) to shift UV light to visible in front of each pmt.

Other Physics Motivations

- Measure Quasi-elastic and particle production cross sections on Argon nucleus, with High Statistics, High spatial resolution
- Observe SuperNova neutrino interactions

For a Galactic SN expect 10-20 absorption events

$\nu_e\ {}^{40}Ar \rightarrow e^-\ {}^{40}K^*$



I. Gil-Botella and A. Rubbia JCAP 10(2003)009

Technical R&D

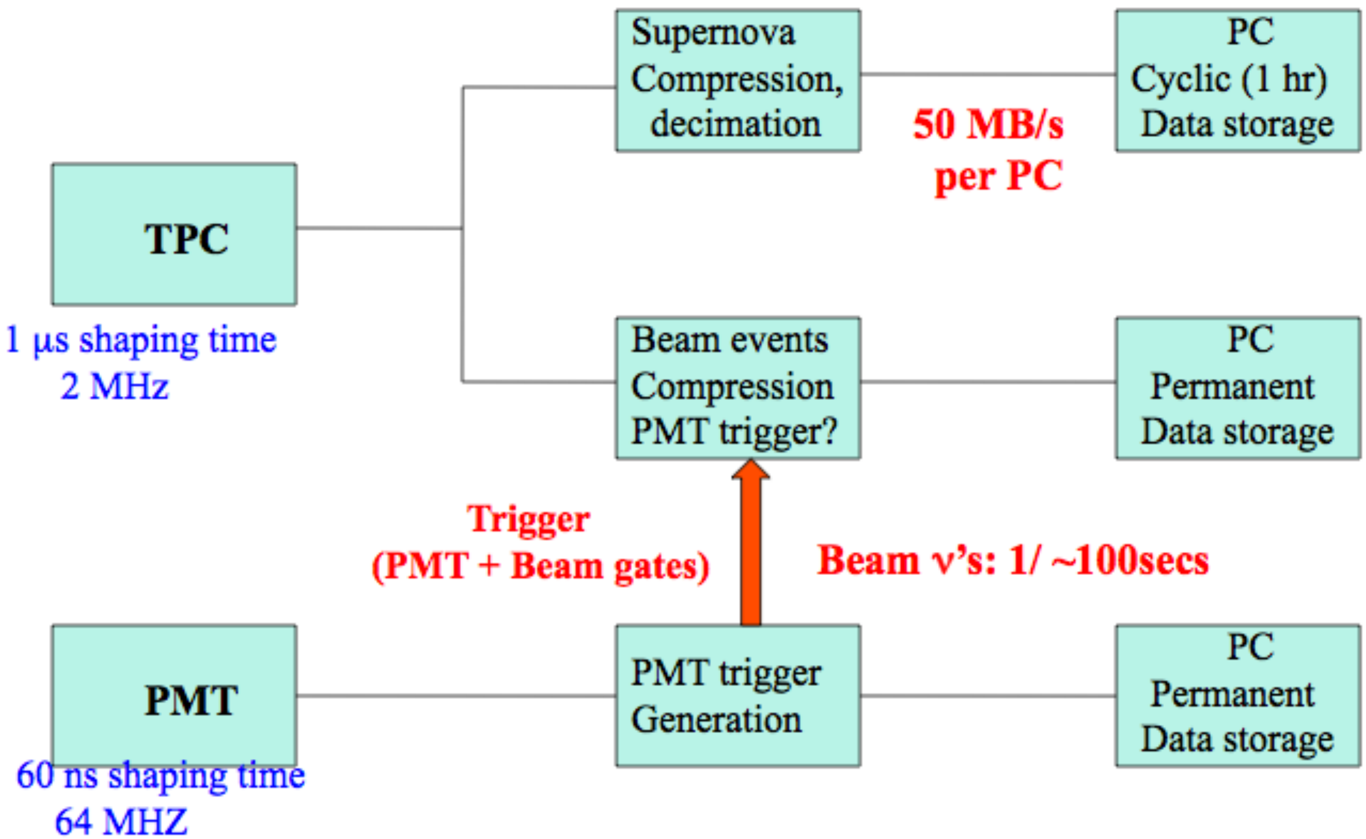
- Argon fill without first evacuation. (Evacuation capability exists)
- Long Drift spaces (2.5m up from 1.5m).
- Cold Front end electronics (up to and including shaper) in Liquid Argon

Continuous readout for SN: TPC data read by 9 PC's each covering ~ 1.1 m along the beam

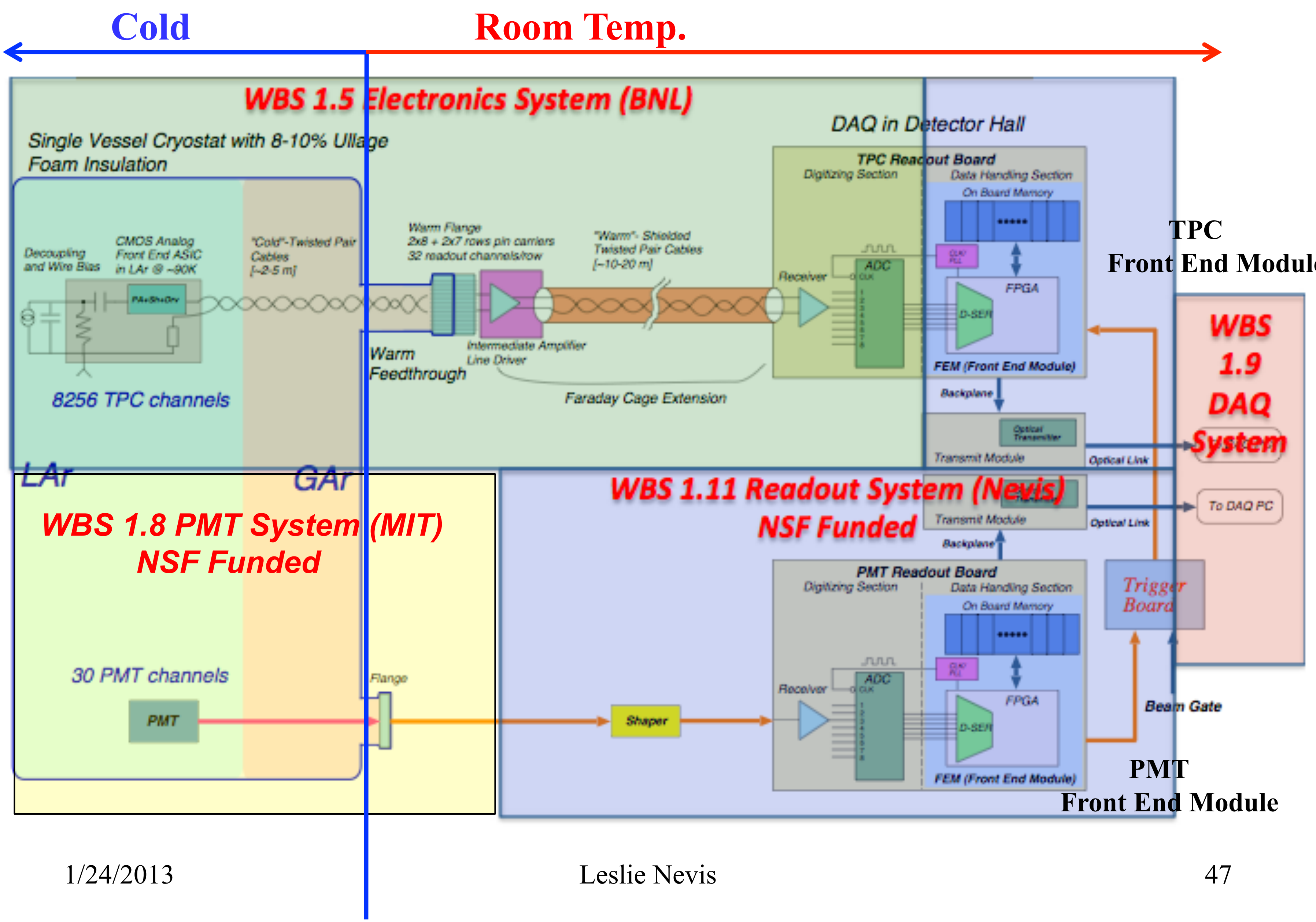
- Beam ν: Trigger on Beam Gate + PMT signal

- SuperNova ν: Continuously store the last hour of data in cyclic buffer.

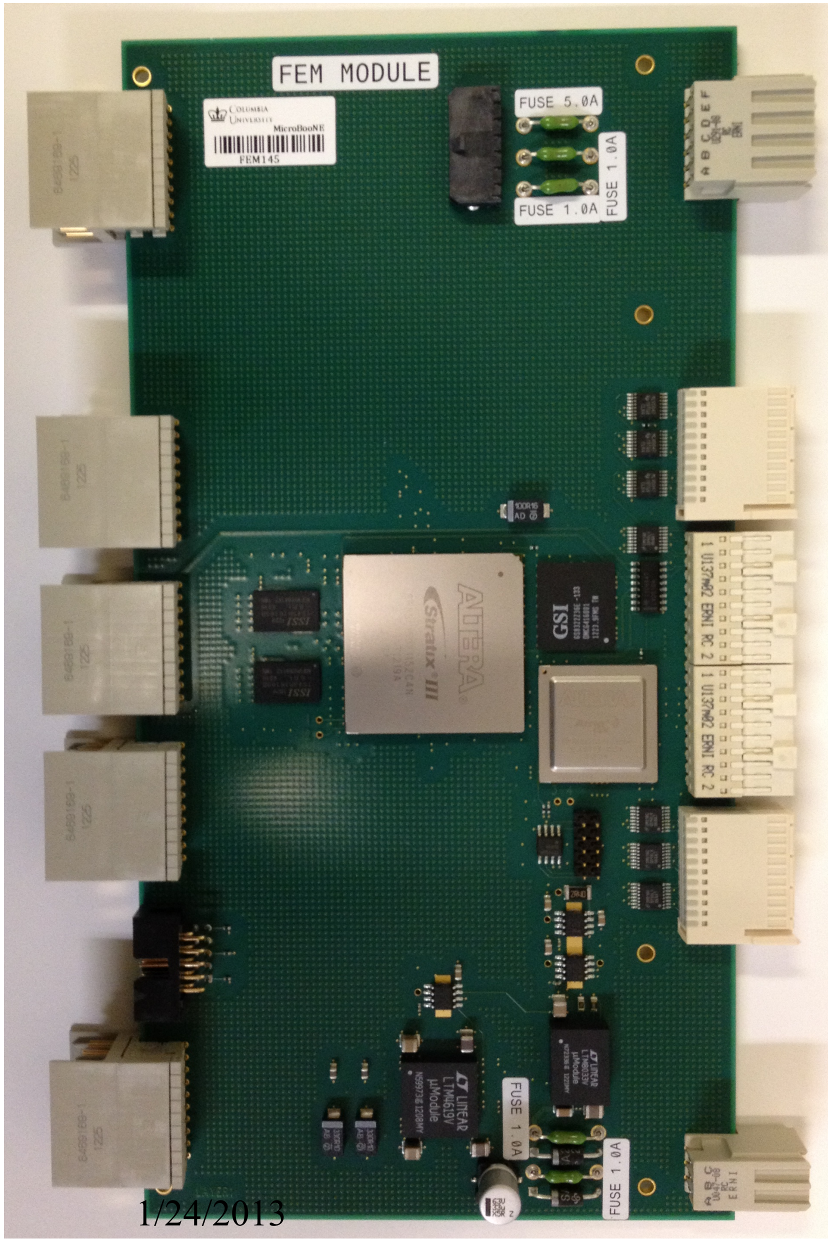
Permanent storage of relevant time span if SuperNova alert from SNEWS network

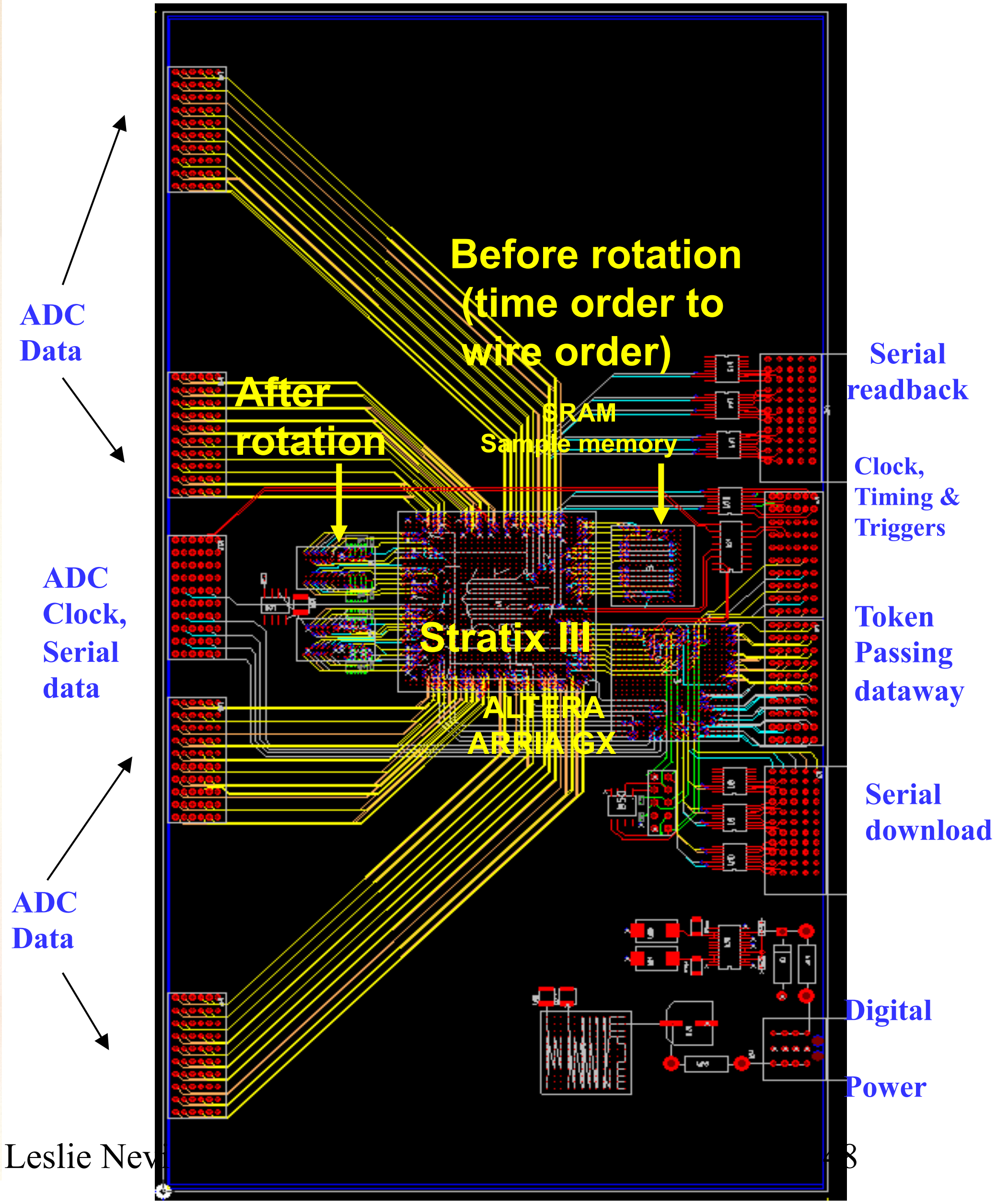


MicroBooNE Electronics

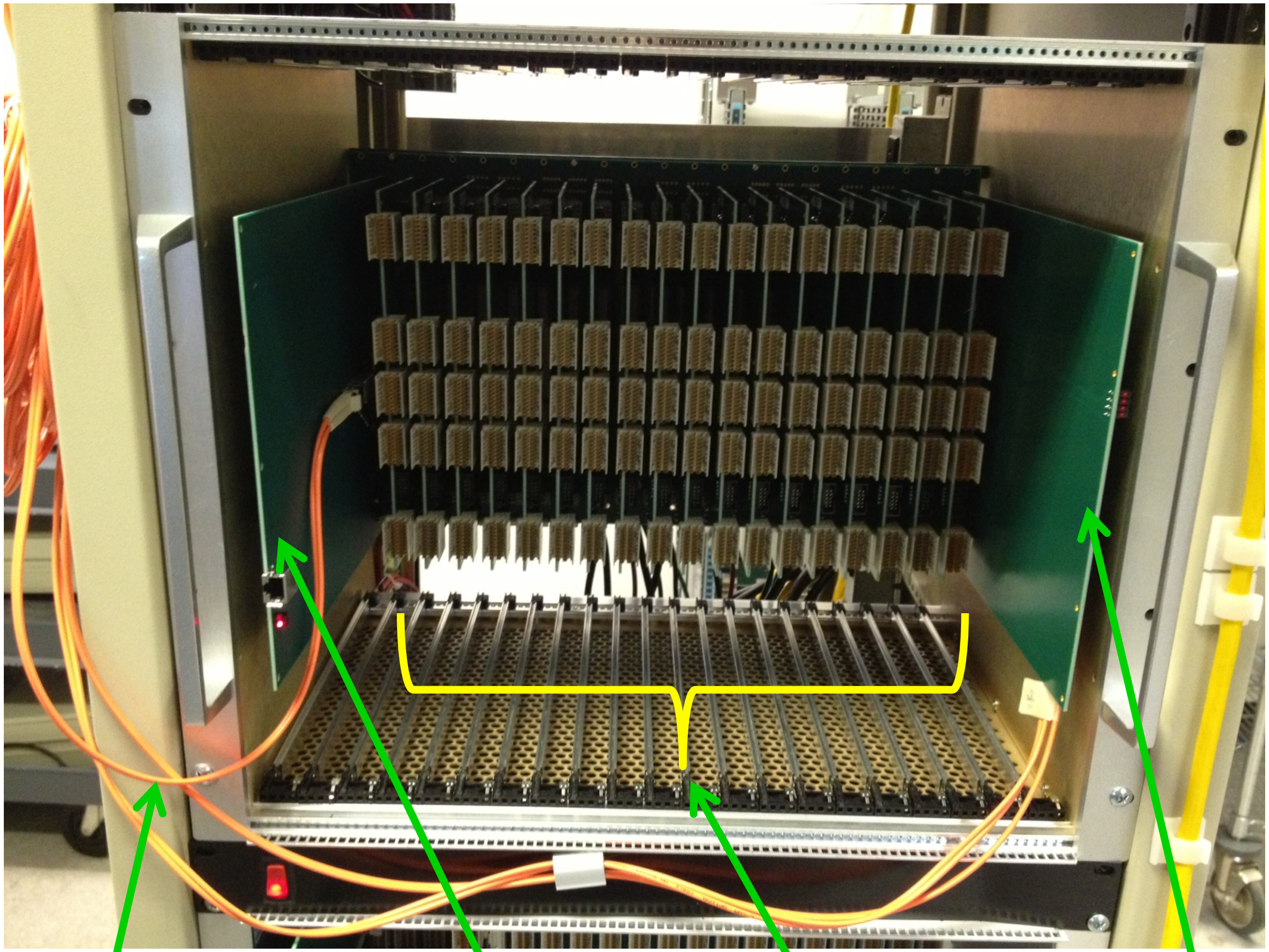


FEM Layout


FEM MODULE
FUSE 5.0A
FUSE 1.0A
FUSE 1.0A
FUSE 1.0A
FUSE 1.0A
ALTERA
Stratix III
GSI


ADC Data
ADC Clock, Serial data
ADC Data
Before rotation (time order to wire order)
After rotation
SRAM
Sample memory
Stratix III
ALTERA ARRIA GX
Serial readback
Clock, Timing & Triggers
Token Passing dataway
Serial download
Digital
Power

Nevis boards



- Crate backplane
- Front End Module (TPC and PMT)
- Crate Controller
- Transmit module
- Trigger module
- PMT shaper
- PMT ADC
- PCIe (PC communication)

Optical links to PC

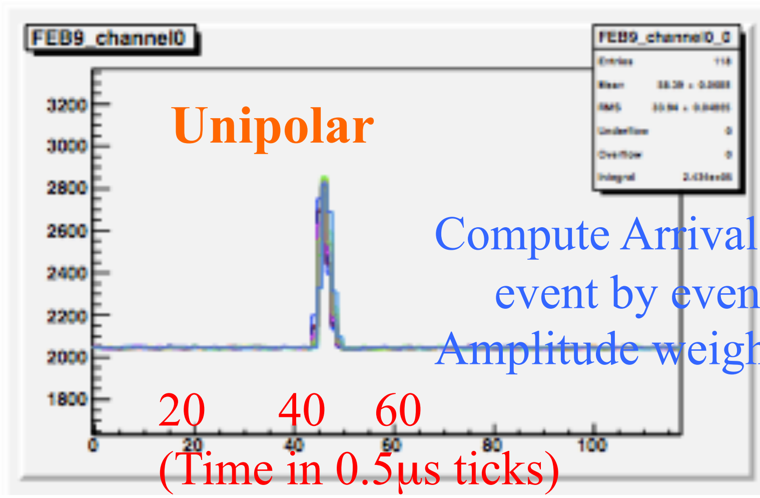
Crate Controller

18 FEM's

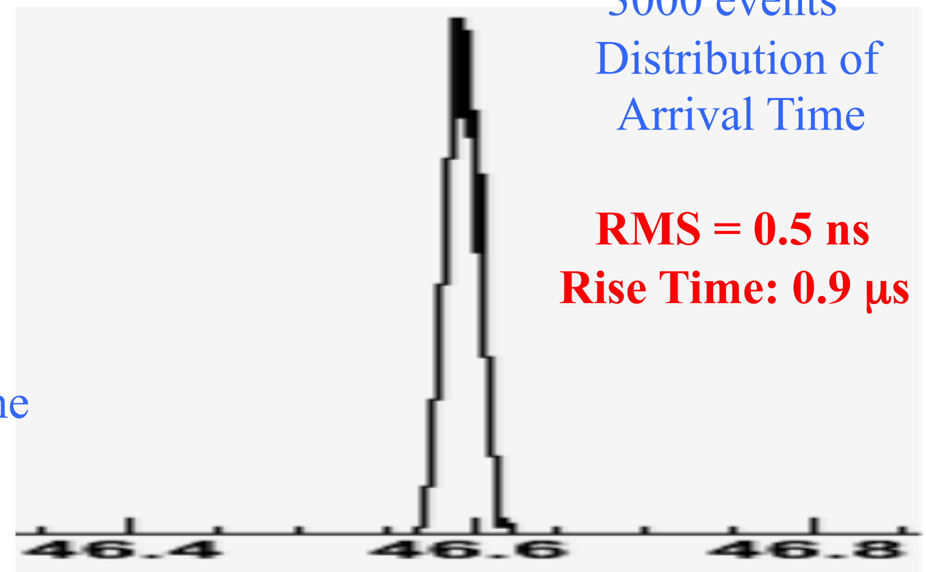
XMIT Transmit Module

Trigger and Readout Tests

TPC CALIBRATION pulses readout through TPC readout chain
Triggered by External calibration pulse.



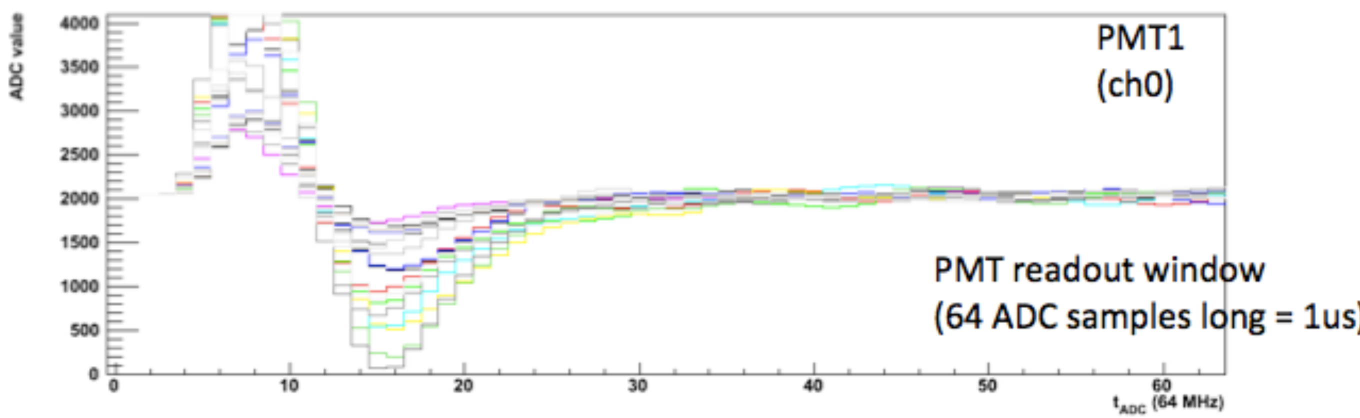
Compute Arrival time
event by event :
Amplitude weighted time



3000 events
Distribution of
Arrival Time

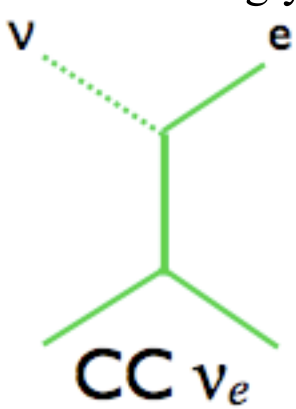
RMS = 0.5 ns
Rise Time: 0.9 μs

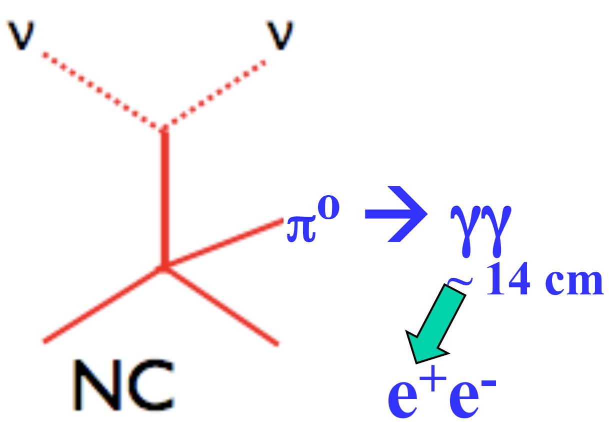
Readout of cosmic rays **PMT** pulses through whole PMT readout chain
Triggered by PMT Trigger algorithm in PMT readout board.

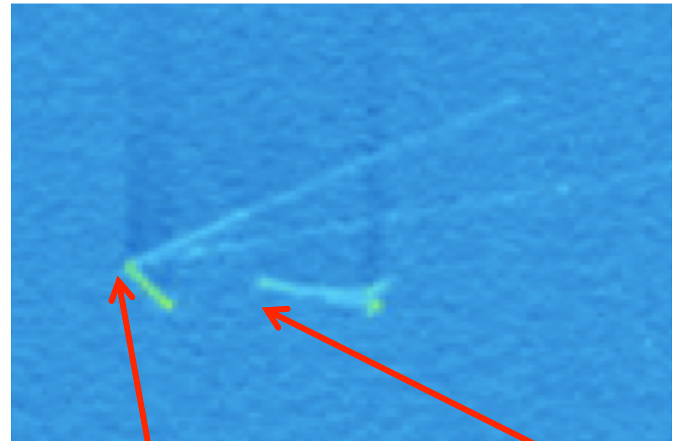


Distinguishing Electrons from Photons.

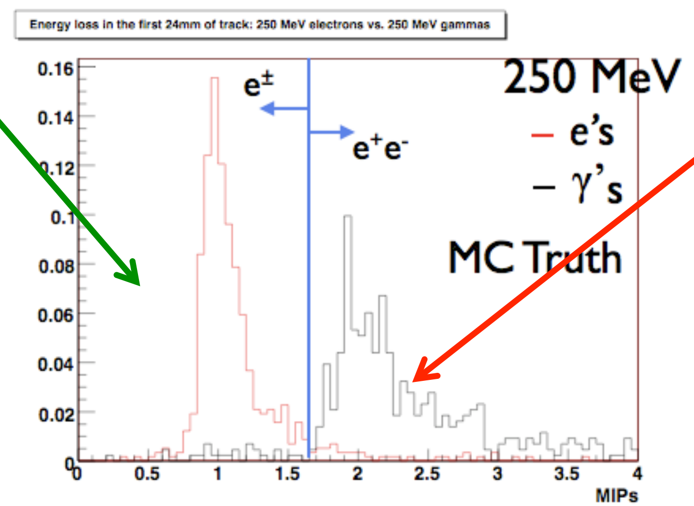
Electron : Connected to
primary vertex
And singly ionizing track







Photon: Gap between primary vertex and conversion point
and doubly ionizing track

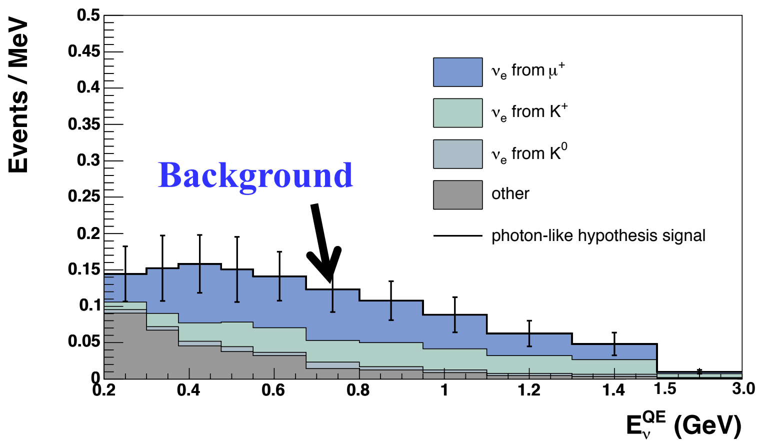


dE/dx for electrons and gammas in
first 2.4 cm of track

If Excess due to Electrons.

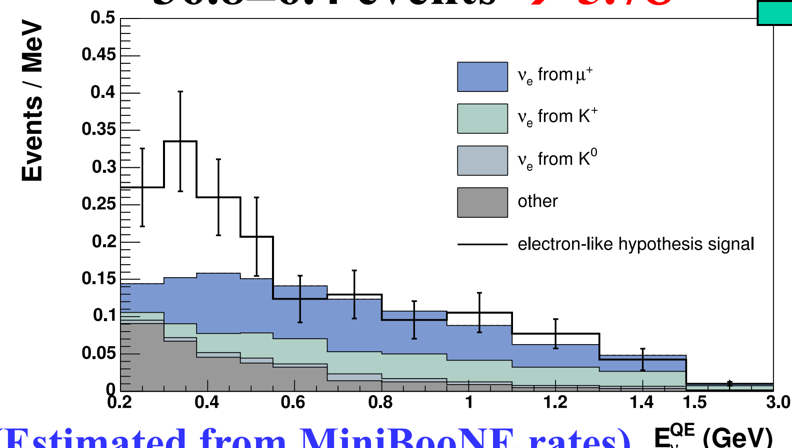
Cuts to Select Electrons, Reject γ's

Excess NOT due to electrons



Excess IS due to electrons

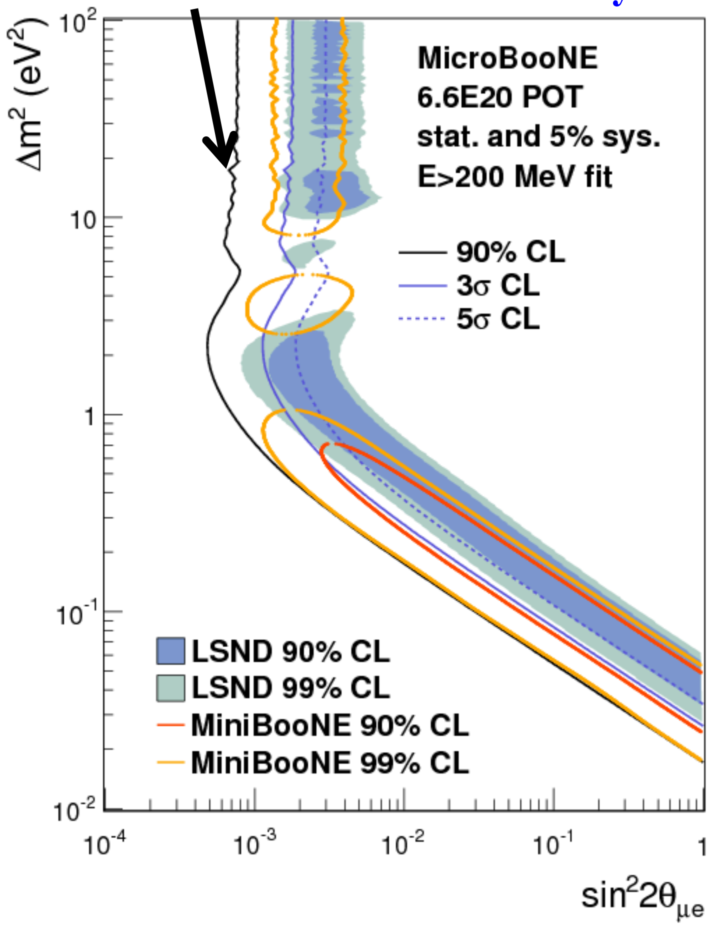
36.8±6.4 events → 5.7σ



(Estimated from MiniBooNE rates)

◆If there is any electron excess
In the context of $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ oscillations
(3+1 oscillations)

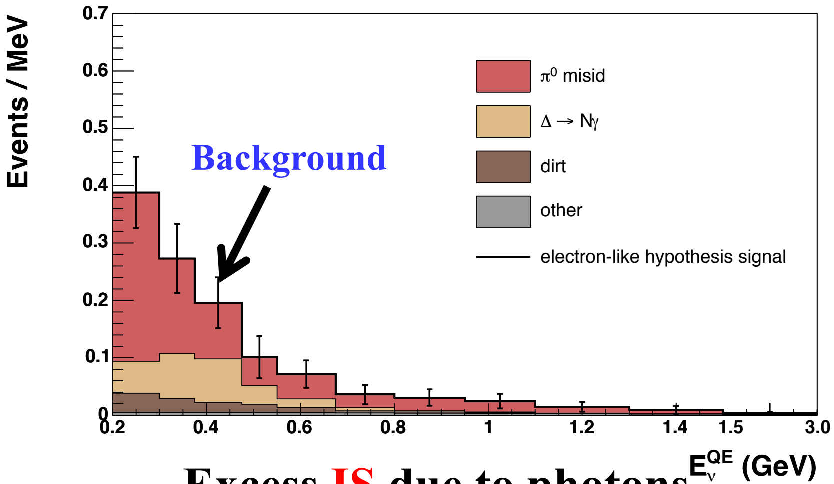
MicroBooNE 90% CL Sensitivity



If Excess due to Photons.

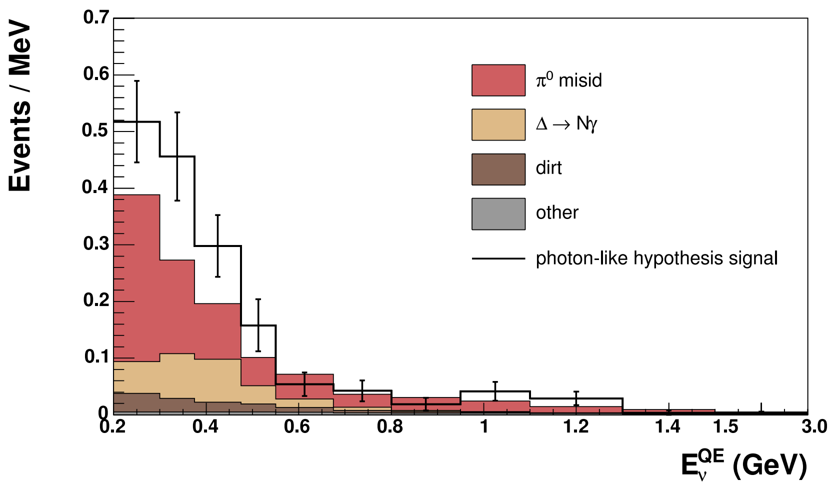
Cuts to Select Photons, Reject e's

Excess is NOT due to photons



Excess IS due to photons

36.8±8.9 events → 4.1σ



(Estimated from MiniBooNE rates)

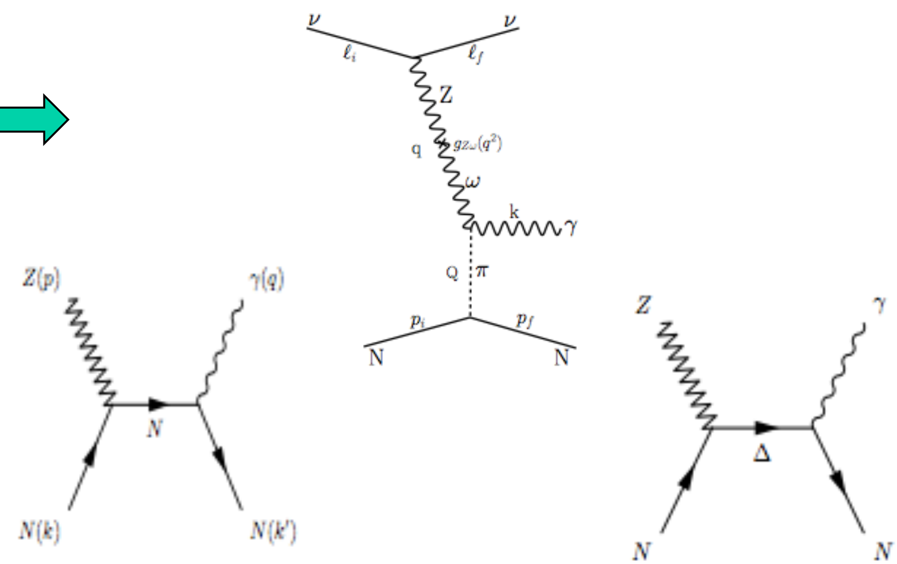
- **Background: γ or π^0**

OR

- **Radiative ν interaction**

Examples:

- **R. Hill arXiv: 0905.0291**
- **Jenkins et al arXiv:0906.0984**
- **Serot et al arXiv: 1011.5913**



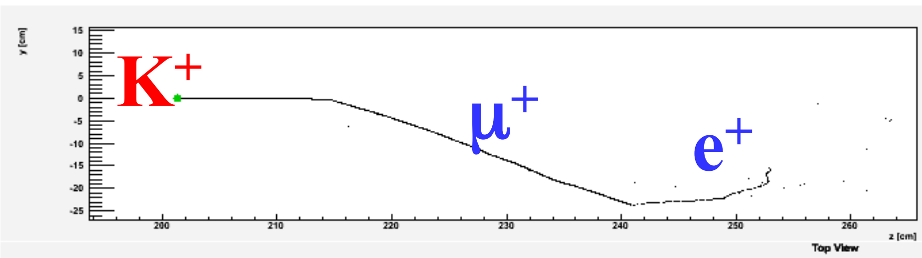
“Physics” R&D Motivations

MicroBooNE is a test-bench for a future large LAr (40ktons) detector (LBNE) that will study Neutrino oscillations.

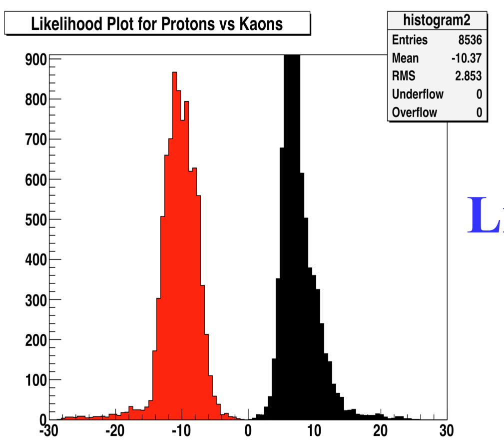
LAr is also good to study Proton decay in particular **$p \rightarrow K^+ \overline{\nu}_\mu$**

(K+ below Cerenkov threshold in water detectors)

We can study the backgrounds in MicroBooNE

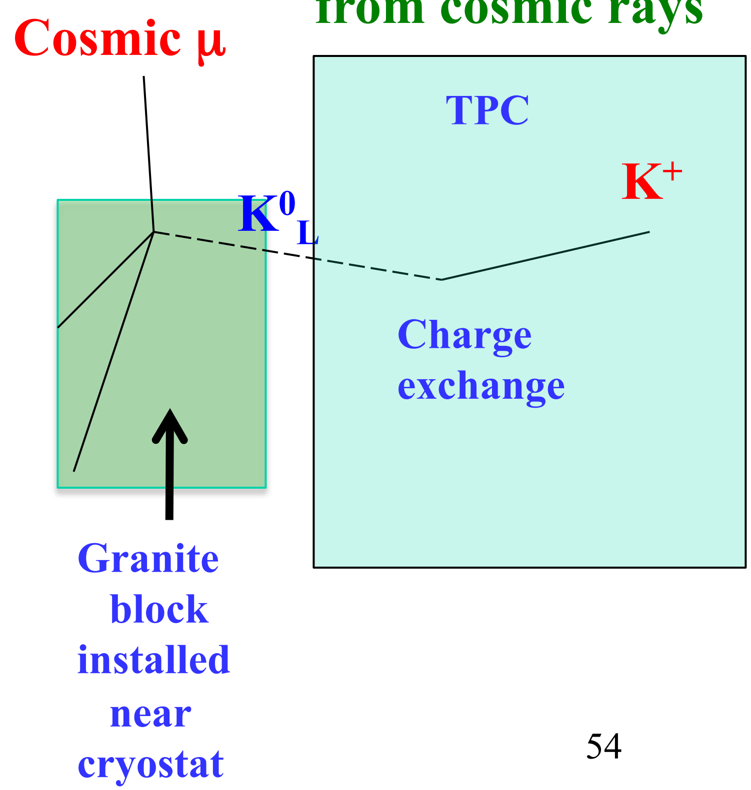


Separating 339 MeV/c K^+ from protons.



Likelihood: 4 dE/dx measurements along track

2. Measure background from cosmic rays



The Nevis Road to Sterile Neutrinos

Fits to all relevant data sets → Constraint on Sterile ν (s)

and

Propose Future Searches for Sterile Neutrinos

Fits to all relevant data sets → Constraint on Sterile ν (s)

Mike, Georgia et al…arXiv:1207.4765 hep-ex :
Fits to ~ 10 different appearance,disappearance, ν and $\bar{\nu}$'s data sets

3 + 1 fits: 1 mass splitting

- Poor compatibility between **ν** and **$\bar{\nu}$** data sets
- Poor compatibility between **appearance** and **disappearance**

3 + 2 fits: 2 mass splittings and introduces a CP violating phase: ν appearance ≠ $\bar{\nu}$ appearance

- Better compatibility between ν and $\bar{\nu}$.
- Bad compatibilty between **appearance** and **disappearance**

Reason:

Mass splittings **0.31 and 1.0 eV^2** for appearance and 0.96 and 18 eV^2 for disappearance.

3 + 3 fits: 3 mass splittings: **0.90, 16.0 and 5.0 eV^2.**

- Good compatibilty between ν and $\bar{\nu}$.
- Appearance and disappearance still incompatible.

Reason:

Mostly due to MiniBooNE ν and $\bar{\nu}$ appearance data.

- **MiniBooNE needs to be checked: → MicroBooNE**
- **If Sterile exist, $\Delta m^2 \sim$ 1-20 eV^2 is a good range to investigate: IsoDAR and LAr1**

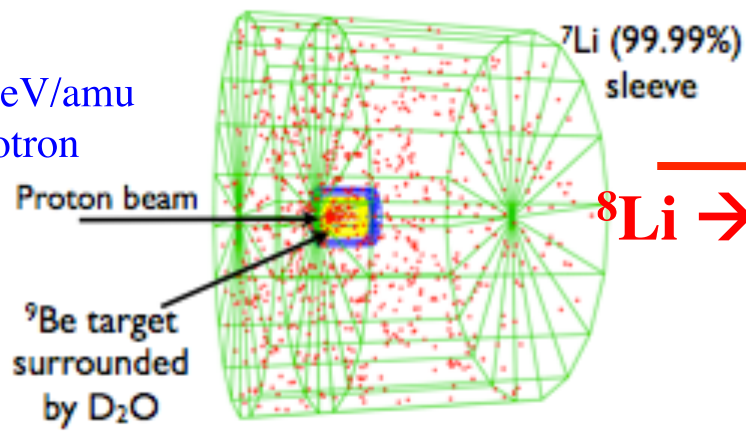
IsoDAR

^{8}Li at rest → ^{8}Be + e^{-} + $\bar{\nu}_e$

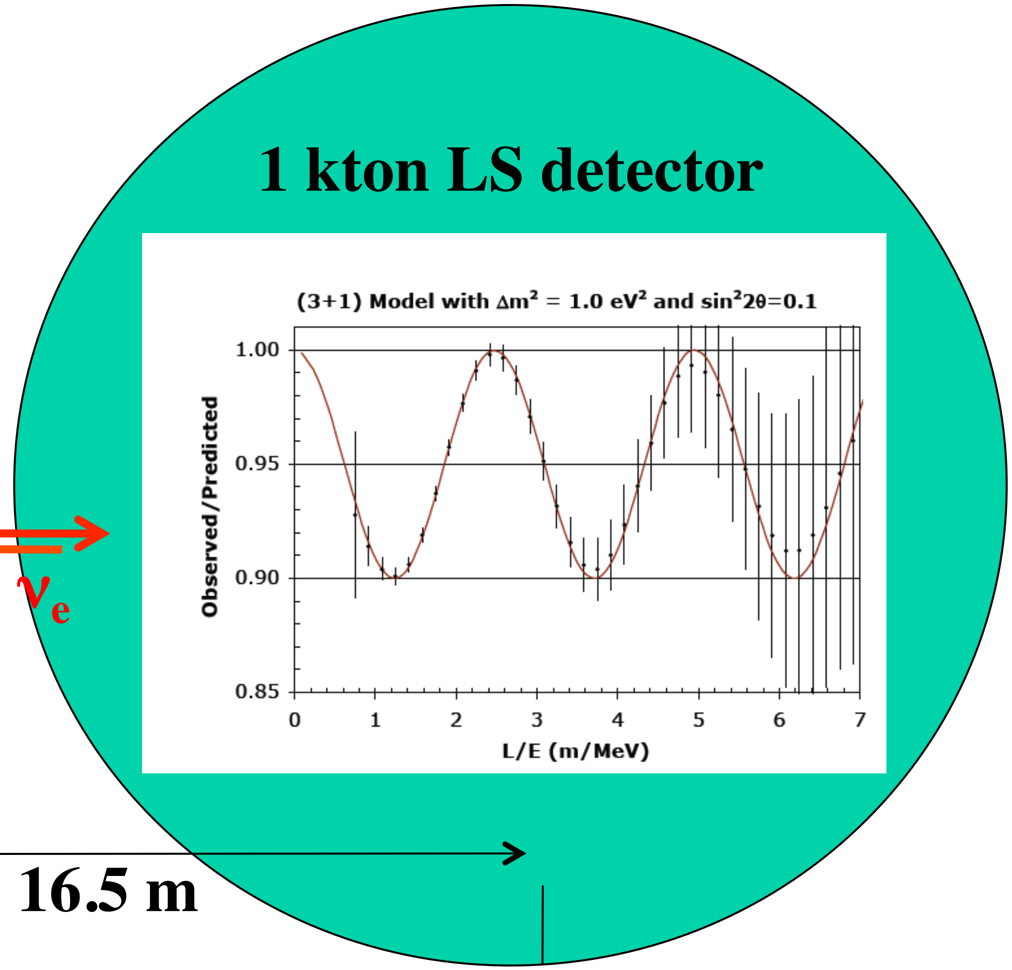
Detect $\bar{\nu}_e$ in a liquid scintillator detector : Very short baseline.

- **Be Target + p → neutrons**
- **D_2O → Thermalizes neutrons**
- **^{7}Li sleeve → n + ^{7}Li → ^{8}Li**
- ^{8}Li → ^{8}Be + e^{-} + $\bar{\nu}_e$ **neutrons**

60 MeV/amu Cyclotron



^{8}Li → $\bar{\nu}_e$

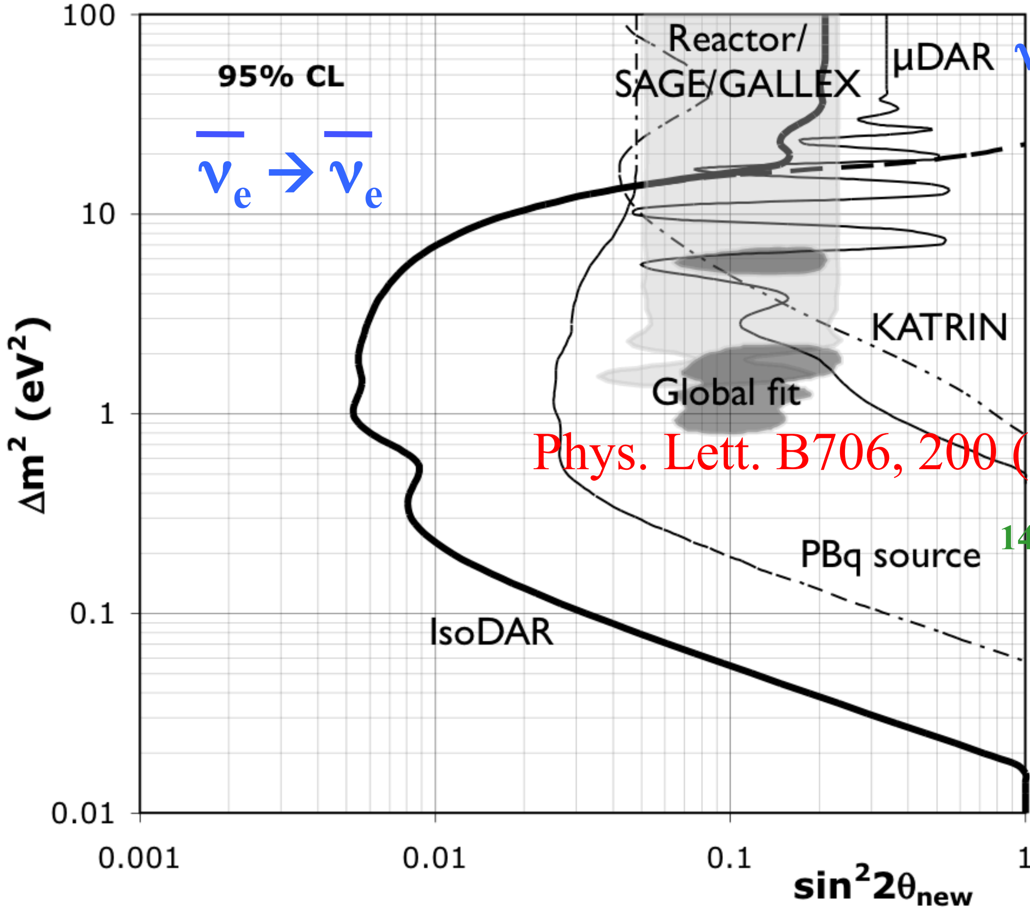


16.5 m

Needs development
→ High intensity

Scintillator detector, large enough to observe oscillations as a function of L/E

IsoDAR Sensitivity.



$\bar{\nu}_e \rightarrow \bar{\nu}_e$

$\nu_e + {}^{12}C \rightarrow {}^{12}N_{gs} + e^-$

Phys. Lett. B706, 200 (2011)

^{144}Ce or ^{106}Ru (50 kCi)

IsoDAR covers the 0.1-15 eV^2 region predicted by models justifying the anomalies in terms of sterile neutrinos.

LAr1.

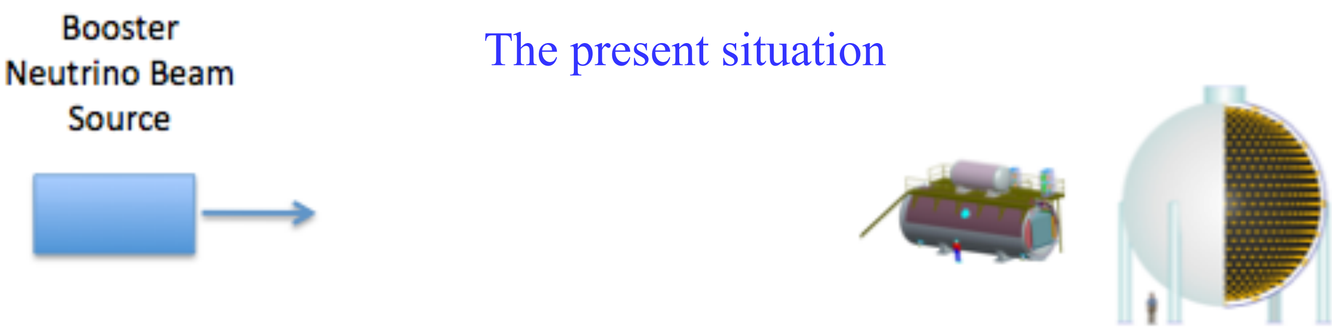
- **LAr1:** Two liquid argon detectors in the Fermilab Booster Neutrino Beam

  To reduce systematics from intrinsic ν_e content uncertainties

  Compare the ν_e flux

  - in the NEAR detector BEFORE the ν_μ have time to oscillate to ν_e
  - to the one in the FAR detector AFTER possible oscillations.

The present situation

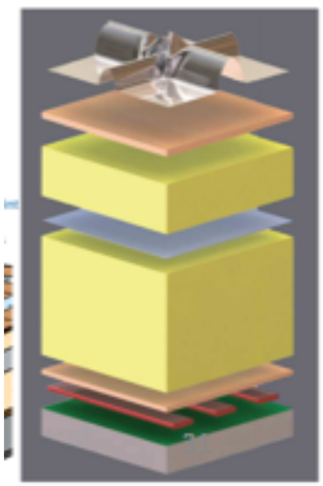


The proposal

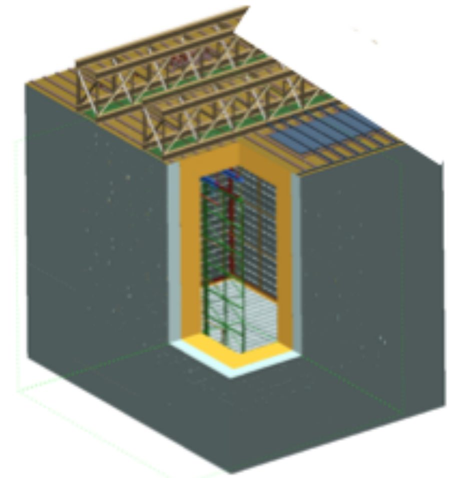
Move MicroBooNE closer to 200m. Build a new LAr detector at 700m.

LAr1 Design (based on LBNE) and Sensitivity.

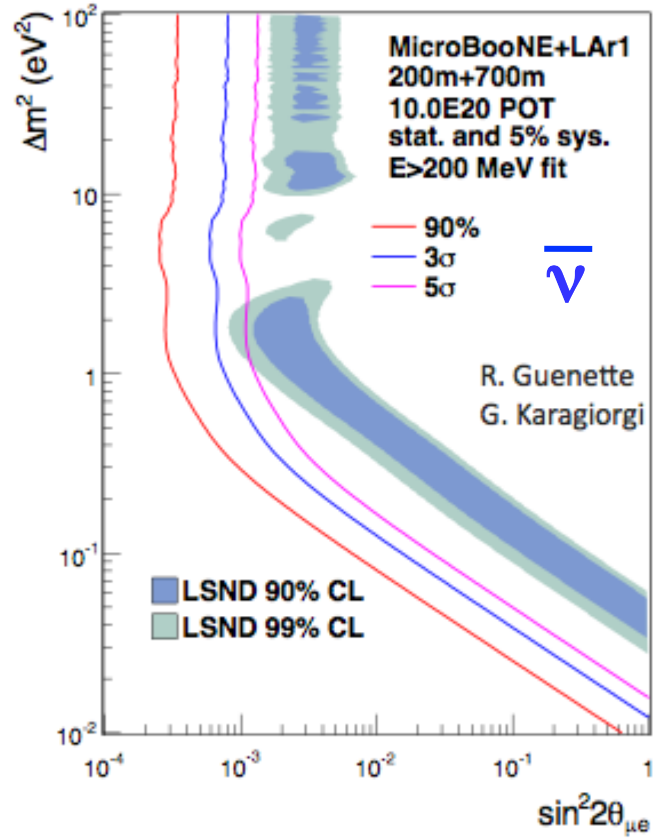
Membrane cryostat made of several layers of insulation.



Supported by external cavern walls.



1 kton of LAr



Running $\bar{\nu}$'s LAr1 covers the LSND favoured region in a 3+1 scenario

LAr1 would also point Nevis towards LBNE → CP violation and mass hierarchy

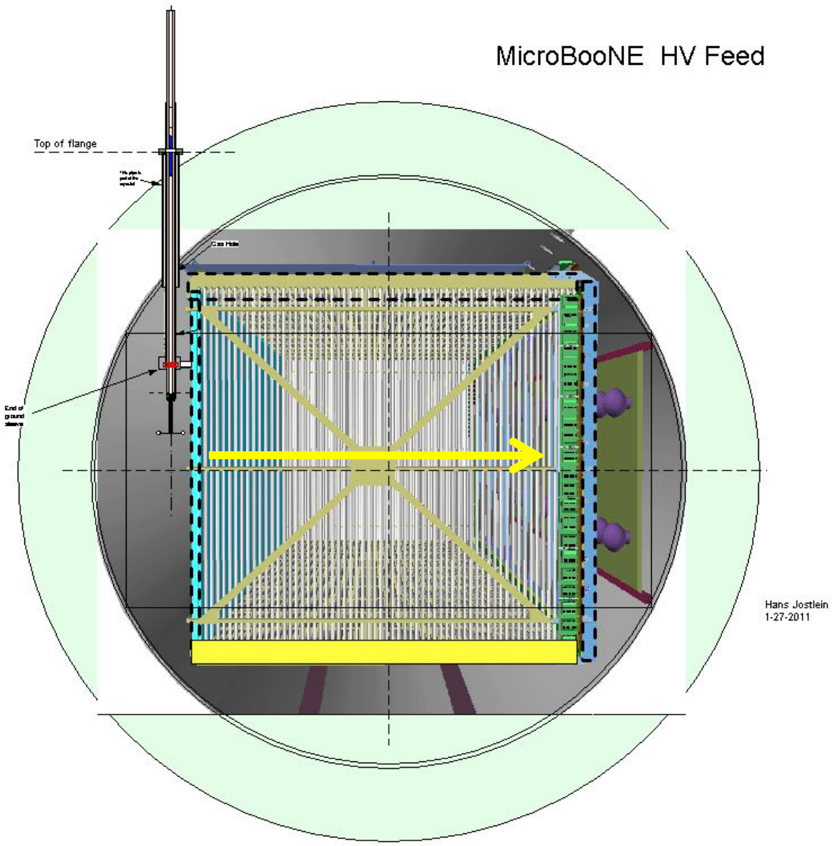
Conclusion

Neutrino Oscillation Physics is very topical.

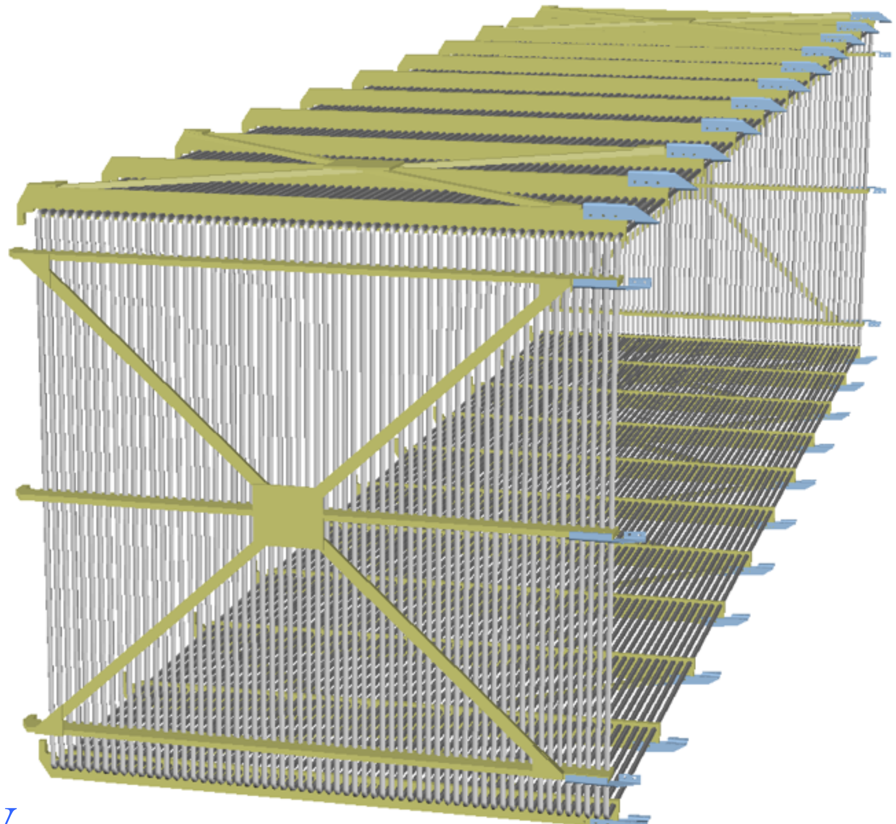
Nevis is participating in many of the experiments addressing crucial issues in the field.

Back Up

Field cage



Field cage
Succession of electrodes with increasing potential
→ Uniform drift electric field



0 V

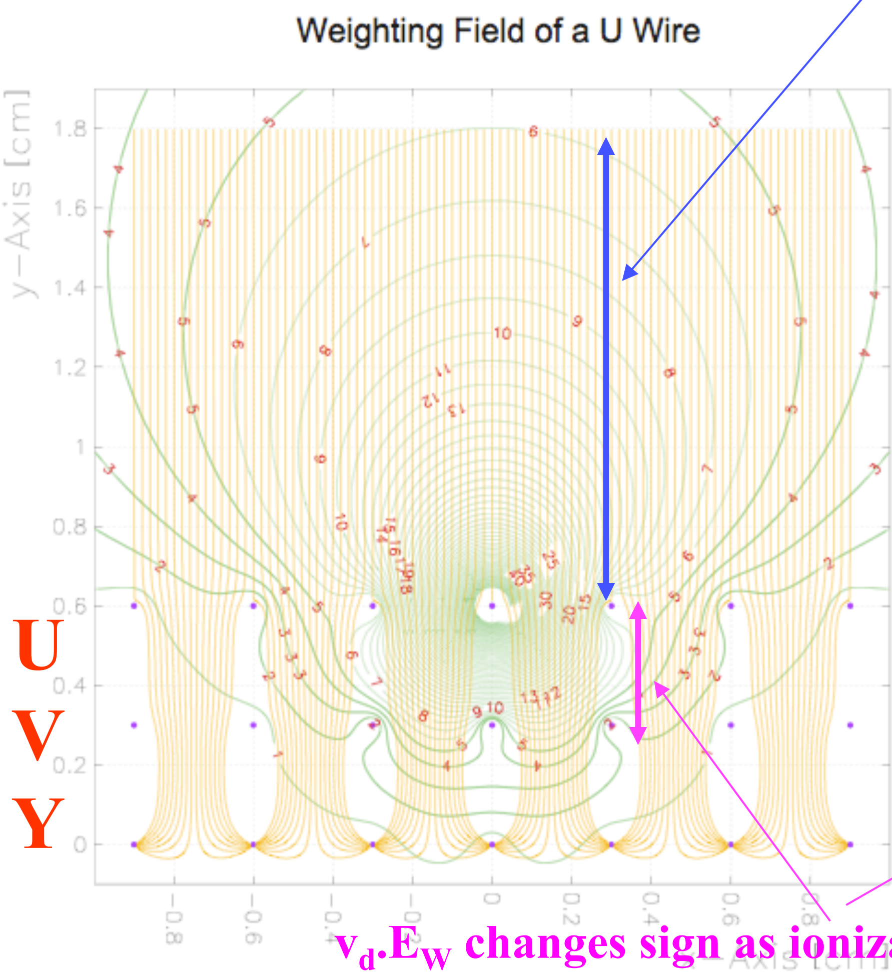
+125 kV

Data Volume per event

- Full drift time: ~ at 1.63mm/μsec = **1.6 msec.**
- To include any events happening close in time digitize for a total of **4.8 msec**.
- We digitize at 2 MHz → every 0.5 μsec.
- We have 8256 wires
- Data volume per "event": $8256 \times (2 \times 10^{6}) \times (4.8 \times 10^{-3}) = 7.9 \times 10^{7}$ words
- 2 Bytes/word → 15.8×10^{7} Bytes = 158 Mbytes.

Pulse shapes

Long negative pulse seen on U until charge drifts passed U:



$v_d.E_W$ changes sign as ionization drifts passed U: pulse changes sign
Continues positive until charge collected at Y

Photodetector electronics specifications

- Minimum energy deposition to be sensitive to: 5 MeV.
- 6000 photons/MeV x 5 = 30 000 photons.
- With a pmt coverage of 0.8% and a quantum efficiency of 8% → 19 pe/5MeV

  pe = photoelectron
- With a pmt gain of 5 x 10^6 → 15.2 pC/5MeV.
- Spread over 30 pmt's → Must be sensitive to a **SINGLE PE**.
- Positioning the single pe in channel 20 of a 12 bit (4096) ADC , the dynamic range will be **1 to 200 pe's**. (200 pe's is equivalent to **2.2 mips** traversing the whole TPC).
- Event Time resolution: **2ns**, to match the Booster rf structure (2ns every 18ns).

“Technical” R&D Motivations

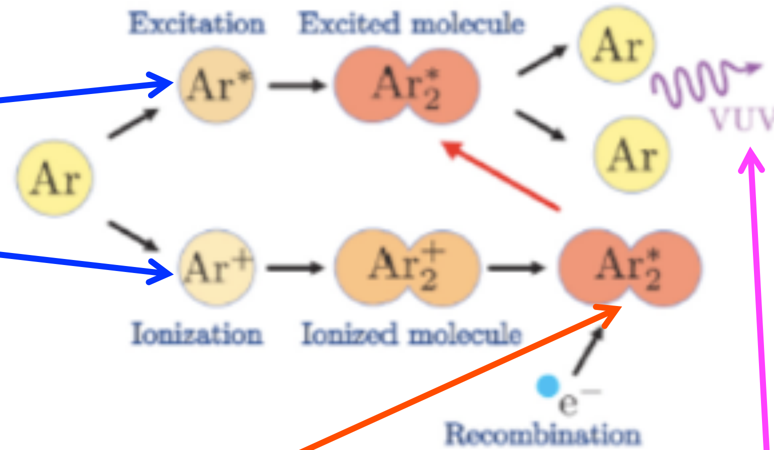
- Preamps within cryostat: cold.
  - Short wires to preamps and temperature reduce noise.
- Purity: will drift ~ 2.5m:
  - Must master purity to avoid electron recombination.
- Supernovae: Need continuous data recording techniques.
- Handling cosmic rays on or near the surface.

Scintillation light in Liquid Argon

Particle passage results in

- **Excitation**
- **Or Ionization**

Of Liquid Argon



Result: an **excimer**

(bound state of two LAr atoms

one of which is in an excited state).

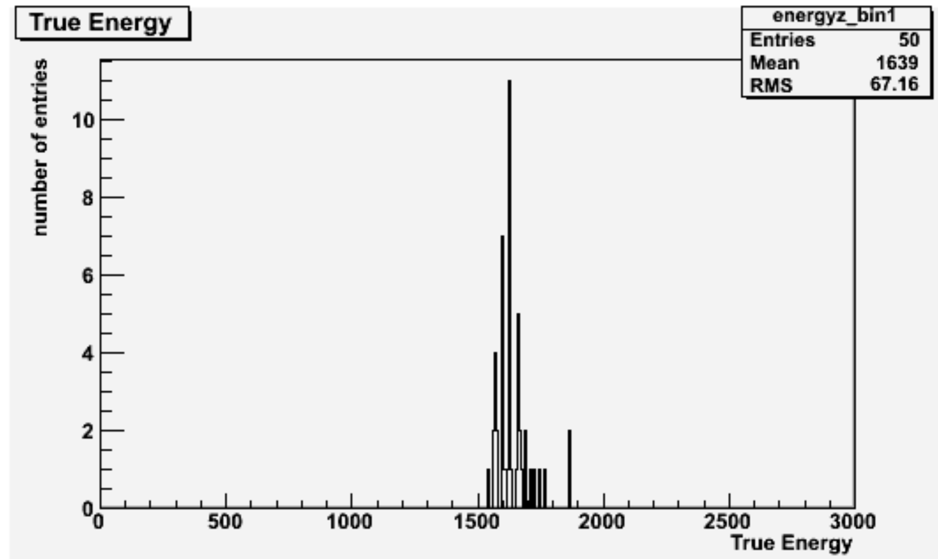
The excimer de-excites via the emission of an ultra violet photon: 128nm.
The excimer can be in two excited states.
This causes its decay to the dissociated ground state to have two components:

A fast **(6ns)** component 23% of the time
A slow **(1 μs)** component **77%** of the time.

Look at the particles resulting from the annihilation

True Energy
Sum their energy:
Mean 1639 MeV/c^2

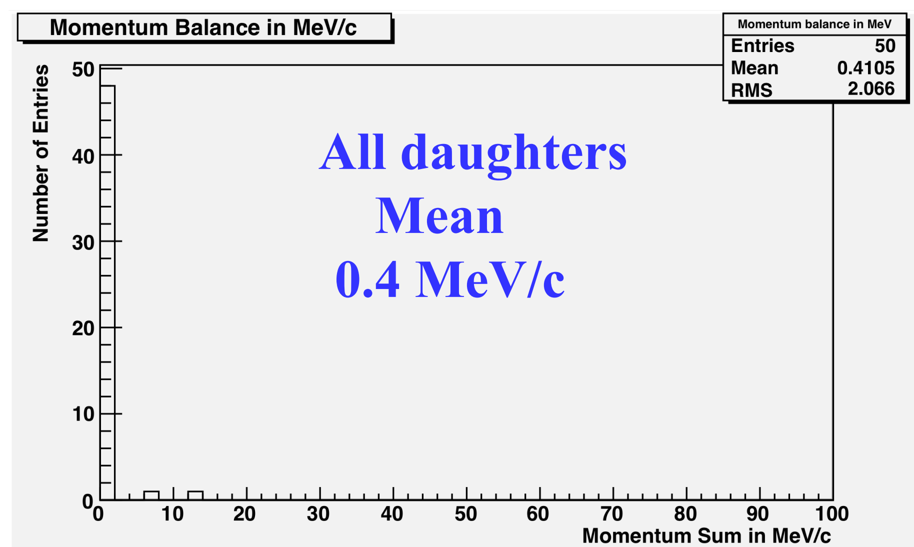
Note that the sum does not add up to 2 x nucleon mass:
2 x 938.3 MeV/c^2 = 1876.6 MeV/c^2
Will have to check why?



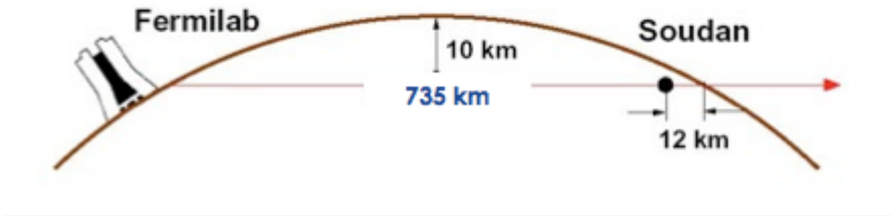
Total Momentum
Vector sum of their momenta
0.4 MeV/c

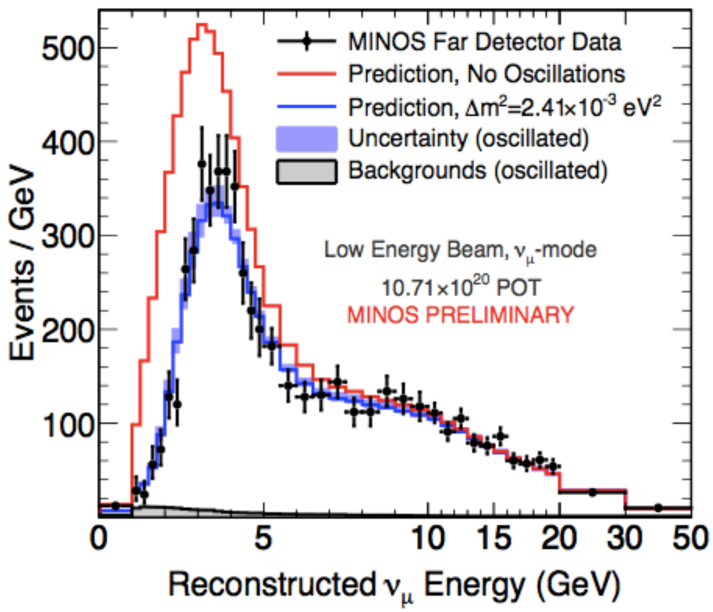
Should be zero.

But will any particle elude Detection?

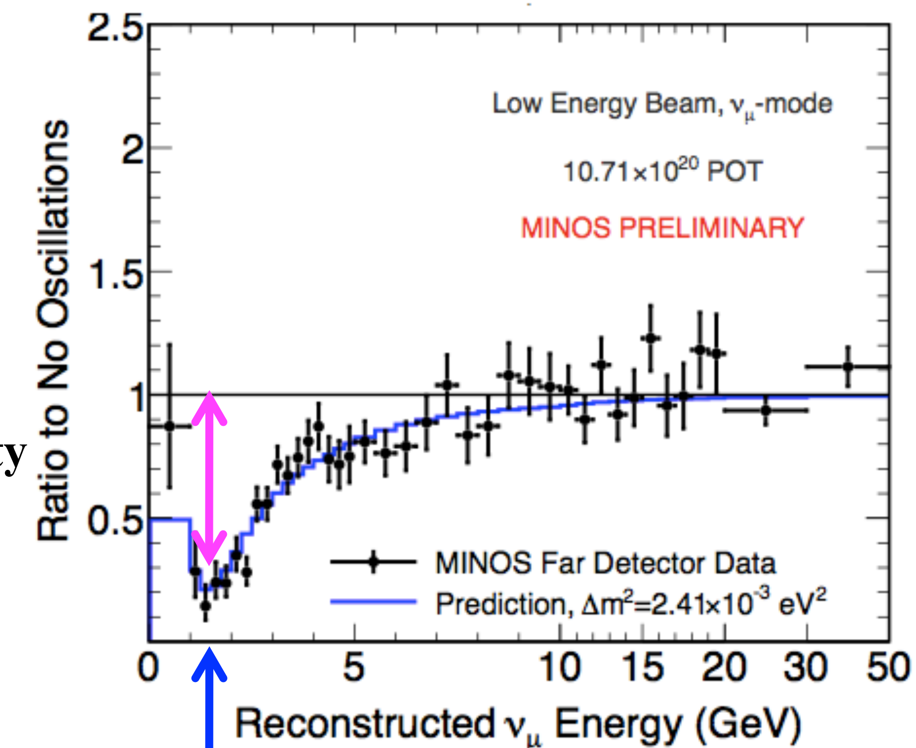


Example of an Oscillation: MINOS $\nu_\mu \rightarrow \nu_e$





Ratio ~ Probability



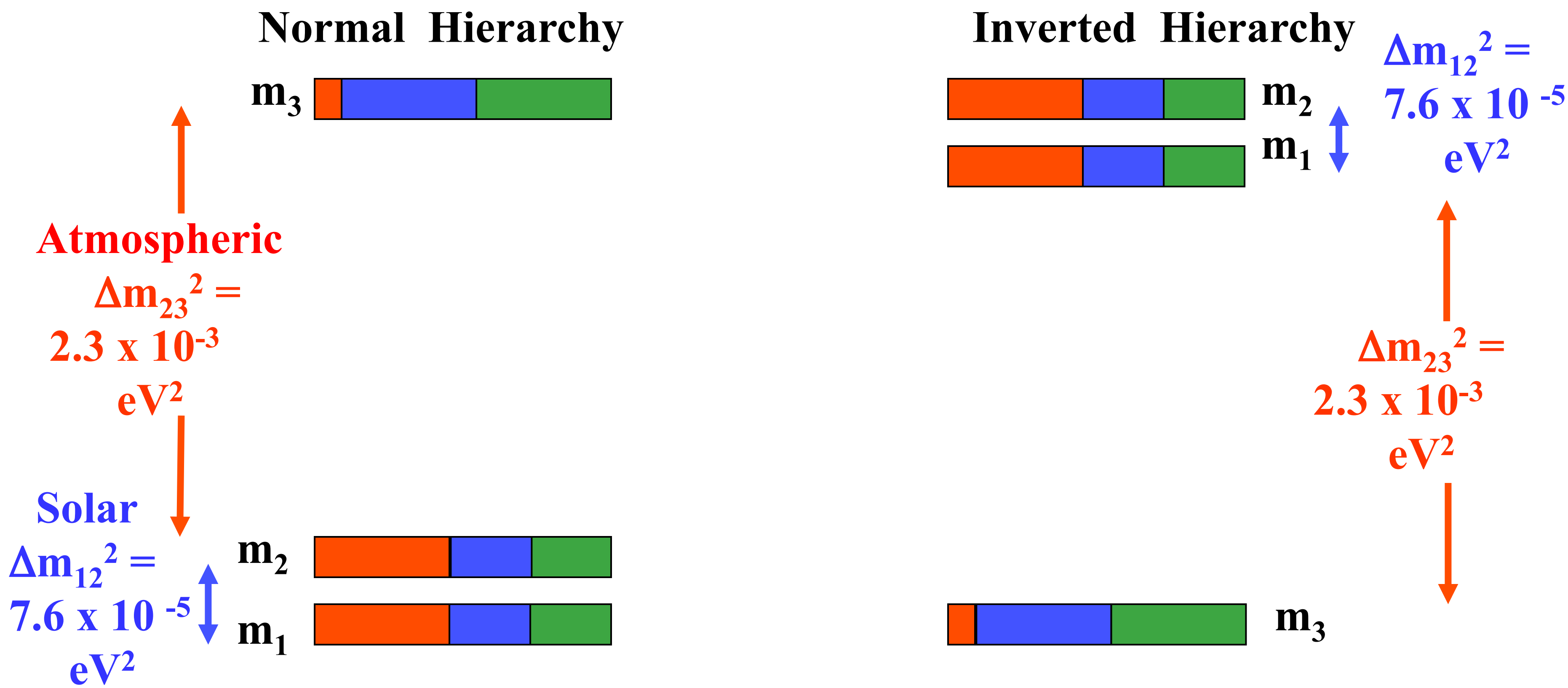
$$P_{\alpha\beta}(t) = \sin^2 2\theta \, \sin^2 \left[1.27 \frac{L(m)}{E(MeV)} \Delta m^2 (eV^2)\right], \quad \Delta m^2 = m_i^2 - m_j^2$$

Strength of oscillation

Determines energy of Maximum oscillation
$\sin^2 \pi/2 \rightarrow E=(1.27L\Delta m^2)/(\pi/2)$

Mass Differences
Sign of Δm^2_{23}

ν_ε ν_μ ν_τ

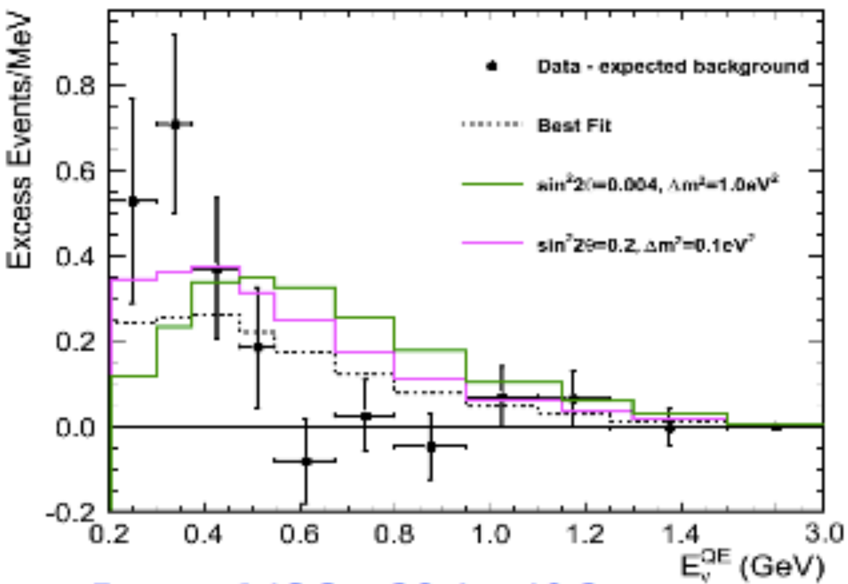


Oscillations only tell us about DIFFERENCES in masses

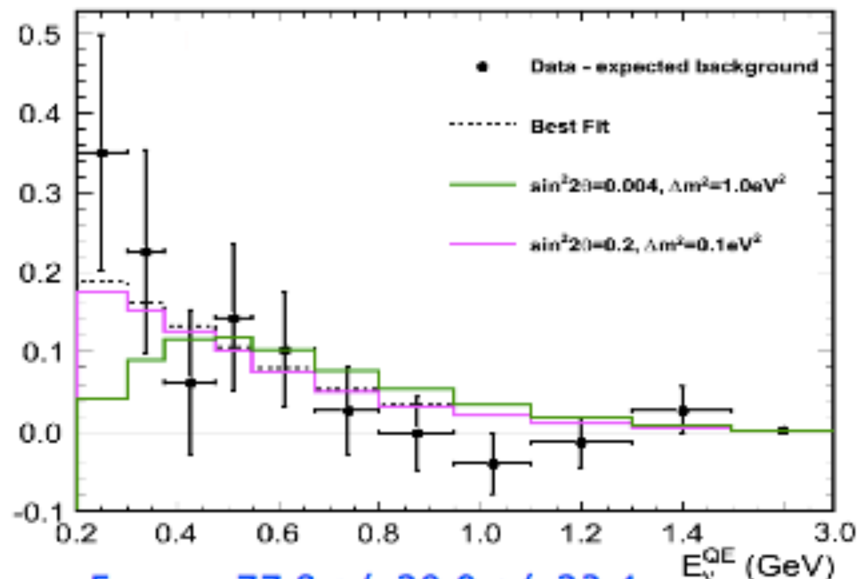
NOT the ABSOLUTE mass scale

$\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Excesses in Low Energy Region

Subtract known background



Excess: 146.3 ± 28.4 ± 40.2



Excess: 77.8 +/- 20.0 +/- 23.4

What is the excess due to ?

- $\nu_\mu \rightarrow \nu_e$ then $\nu_e + n \rightarrow e + p$?
- $\nu_\mu + C \rightarrow \nu_\mu + X + \gamma$?
- $\nu_\mu\, C \rightarrow \nu_\mu\, X\, \pi^0$ then $\pi^0 \rightarrow \gamma\gamma$?

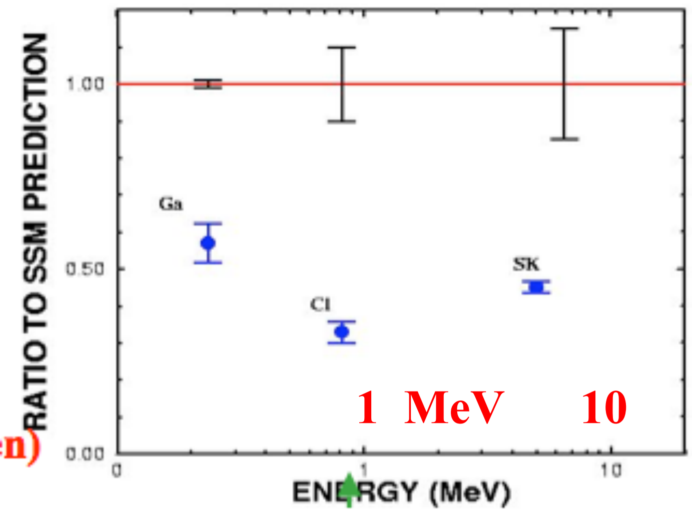
First step:

- Is the excess due to electrons?
- Or photons ?

MicroBooNE

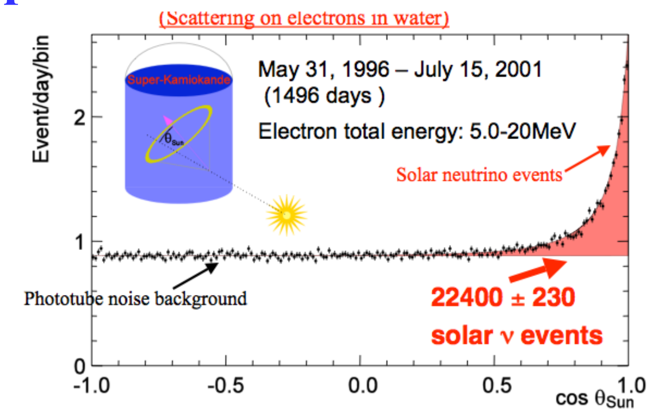
Puzzle II: Solar Neutrinos: ν_e .

Both Radiochemical and Real Time showed a suppression



$\nu + e \rightarrow \nu + e$

They really come from the sun !



$$\Phi_{CC} = 1.68^{+0.06}_{-0.06}(stat.)^{+0.08}_{-0.09}(sys.)\times 10^6 cm^{-2}s^{-1}$$ ← ν_e only

$$\Phi_{ES} = 2.35^{+0.22}_{-0.22}(stat.)^{+0.15}_{-0.15}(sys.)\times 10^6 cm^{-2}s^{-1}$$ ← ν_e mostly

$$\Phi_{NC} = 4.94^{+0.21}_{-0.21}(stat.)^{+0.38}_{-0.34}(sys.)\times 10^6 cm^{-2}s^{-1}$$ ← ν_e, ν_μ, ν_τ

$$\Phi_{BP04} = 5.82 \pm 1.34\times 10^6 cm^{-2}s^{-1}$$

Using ALL neu

Solar Model problems or Neutrino Physics ?
All experiments sensitive only, or mostly, to ν_e.

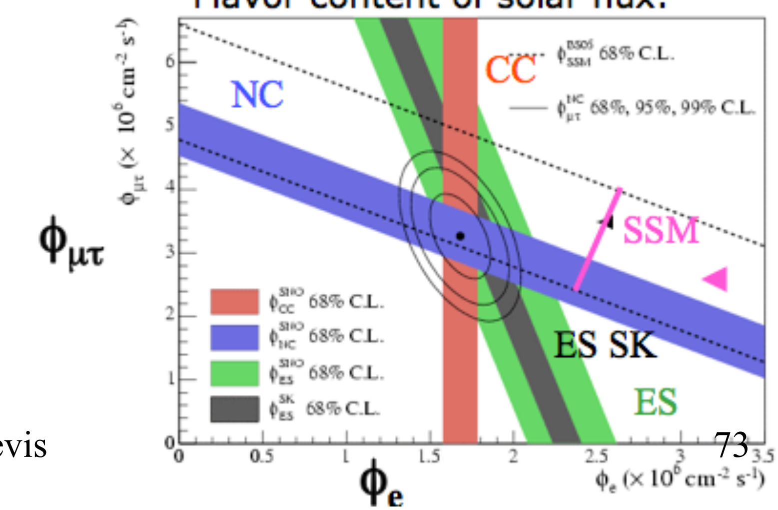
Then SNO: Use Heavy water D_2O.
Only 2 .2 MeV needed to break up D → Possible

- Neutral Current (NC) reactions on nucleons

$\nu_x + n \rightarrow n + \nu_x$

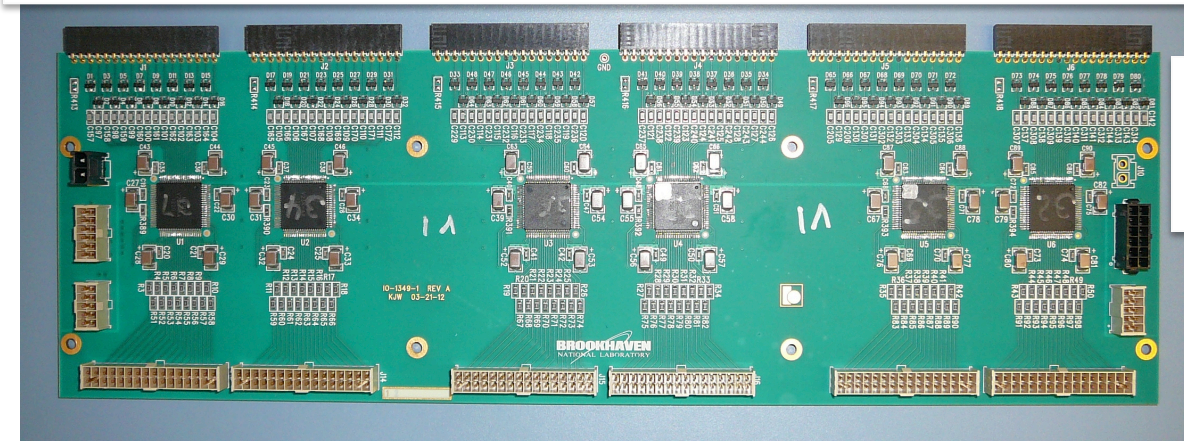
Sensitive to flux from ALL flavours, $\phi(\nu_e, \nu_\mu, \nu_\tau)$

Flavor content of solar flux.



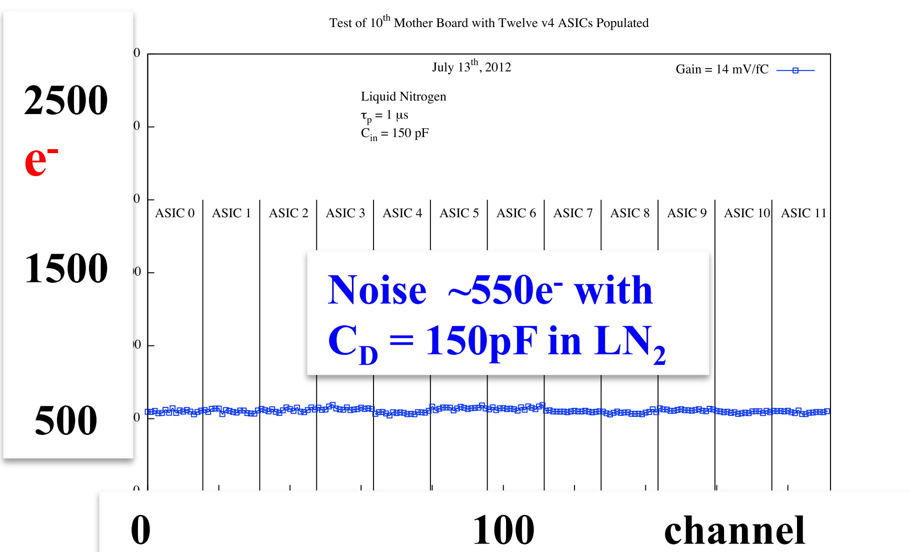
Cold Electronics : CMOS Analog Front End ASIC (BNL)

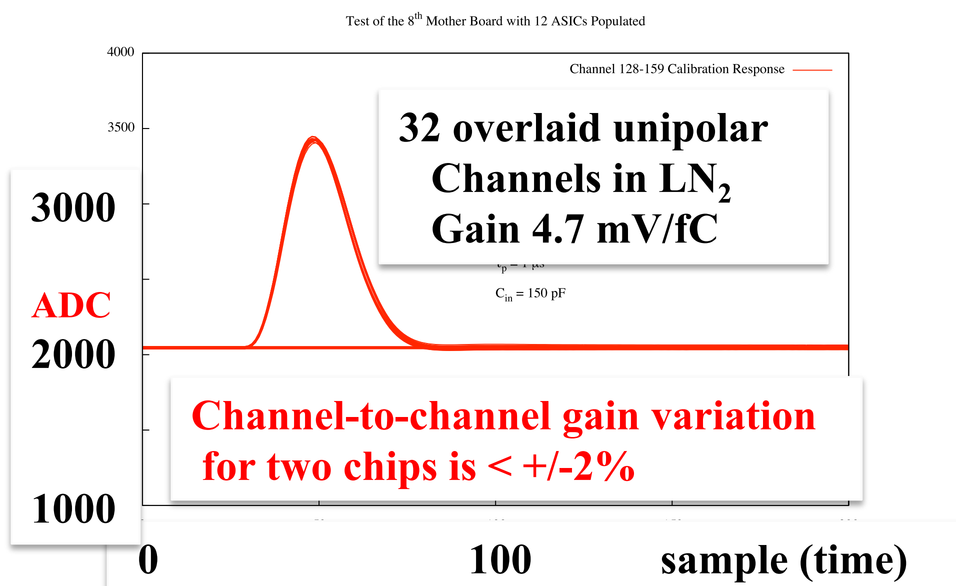
16 channel/chip charge amplifier: Adjustable Gain 4.7, 6.8, 14.0, 25.0 mV/fC
Adjustable peaking time 0.5,1,2,3 μs, 5.5 mW/channel



Prototype Vertical
Cold Mother Board
with prototype ASICs

Crosstalk < 0.3%

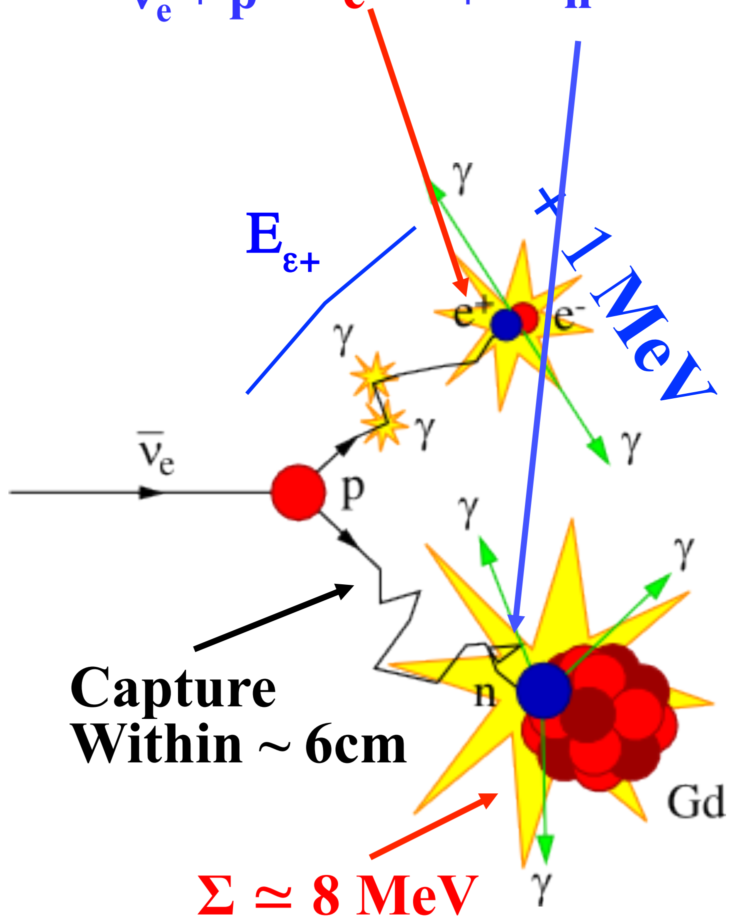




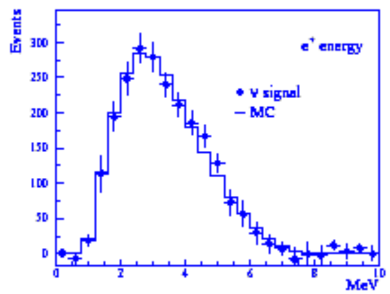
Detection Technique: Scintillator target.

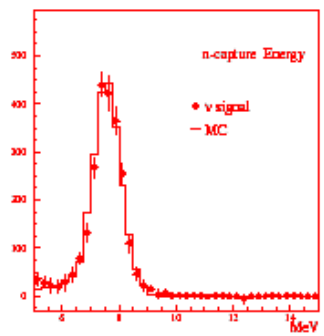
Measure through inverse β decay:

$\nu_e + p = e^+ + n$



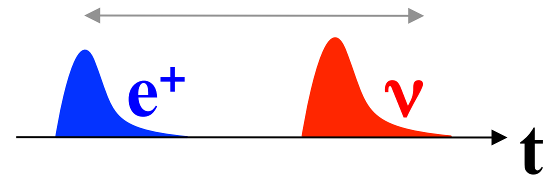
(1) 0,7 < E_{prompt} < 12.2 MeV

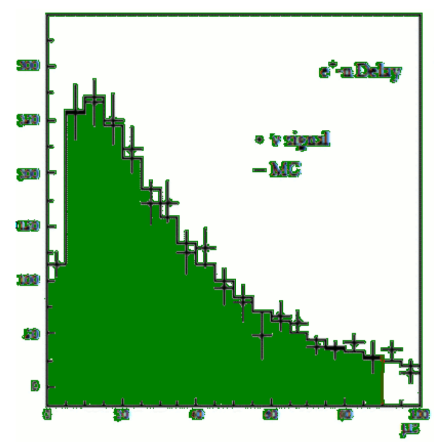




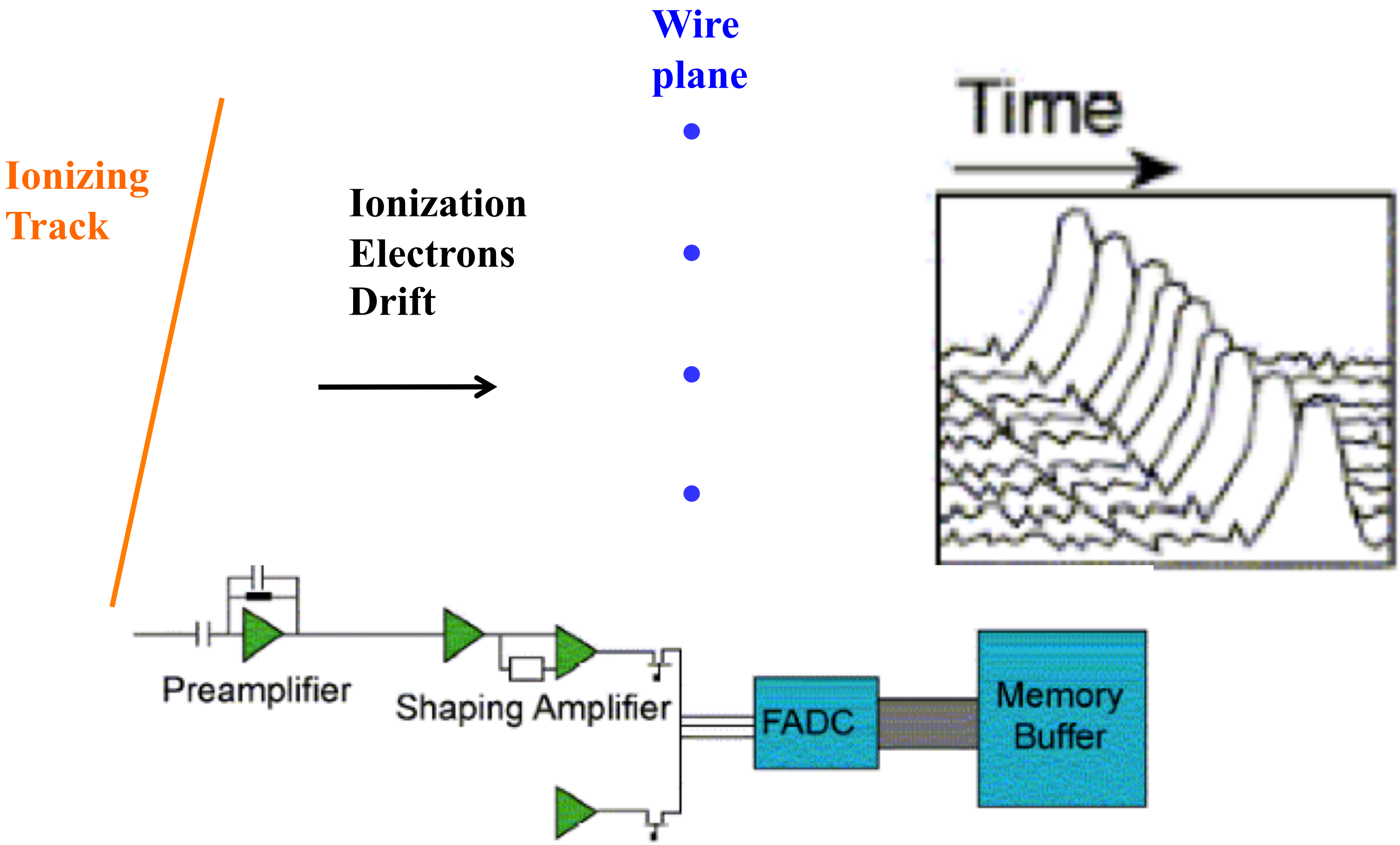
(2) 6 < $E_{delayed}$ < 12 MeV

(3) 2 μs < Δt < 100 μs





Pulse shape and Electronics



FADC: Fast Analog to Digital Converter: measures and digitizes pulse height on a wire Every 0.5 µsec (2MHZ)

Oscillation Fit Strategy (Arthur Franke→ Rachel Carr)

- MC Events & Data flow handled in parallel
- Apply correction for MC/Data differences
- Covariance matrix or pull terms approach

- 2 Integration Periods:
  - both reactor with power > 90%
  - one reactor or both with power < 20%

- Final result decided based on sensitivity studies

- Binning established using sensitivity studies 18 energy bins per period

Definition of χ^2 estimator

$$\chi^2 = \sum_{i,j}\left(N_i - \left(N_i^{\text{exp}} + \sum_{\text{BG}} N_i^{\text{BG}}\left(1+p^{\text{BG}}\right)\right)\right) \times \left(M_{i,j}^{\text{stat}} + M_{i,j}^{\text{reac.}} + M_{i,j}^{\text{eff.}} + \sum_{BG} M_{i,j}^{\text{BG}}\right) \times \left(N_j - \left(N_j^{\text{exp}} + \sum_{\text{BG}} N_j^{\text{BG}}\left(1+p^{\text{BG}}\right)\right)\right) + \sum_{\text{BG}}\left(\frac{p^{\text{BG}}}{\sigma^{\text{BG}}}\right)^2 + \left(\frac{p^{\text{Escale}}}{\sigma^{\text{Escale}}}\right)^2 + \left(\frac{p^{\Delta m^2}}{\sigma^{\Delta m^2}}\right)^2$$

- i, j : label of energy bin: 1 to 18 for IP-0 and 19 to 36 for IP-1
- N_i : observed number of in i-th bin
- N_i^{exp} : expected weighted by oscillation
- $M_{i,j}$: covariance matrix
- p: pull terms and σ: systematic uncertainties

Used Blind Analysis (reactor prediction not known better than 10% until the selection cuts were frozen).

Event rates

- Booster Neutrino Beam: The booster runs at a maximum of **15Hz**.

  So the electronics must be able to run at that rate.
- Although the beam neutrino event rate is much lower: **1/600 secs.**
- **To avoid recording unnecessary "empty spill data" the photodetectors will provide a trigger for neutrino beam events.**
- **Will be recorded WITHOUT loss of information: Compression only.**

- Supernova events are spread over ~ 20 secs and are low energy.

  Impossible to recognize amidst radioactivity and cosmic rays background.

  Must rely on "external alert" from the supernova alert watch: ~ 1 hour.

→ **The last hour of supernova data must be always available in case…**

Will be Compressed AND zero suppressed.

Physics Motivation II: Measurement of Cross sections

Argon nucleus, High Statistics, High spatial resolution

Expected event rates for 6.6 x 10^{20} POT

production mode	# events
CC QE ($\nu_\mu n \rightarrow \mu^- p$)	60,161
NC elastic ($\nu_\mu N \rightarrow \nu_\mu N$)	19,409
CC resonant π^+ ($\nu_\mu N \rightarrow \mu^- N \pi^+$)	25,149
CC resonant π^0 ($\nu_\mu n \rightarrow \mu^- p \pi^0$)	6,994
NC resonant π^0 ($\nu_\mu N \rightarrow \nu_\mu N \pi^0$)	7,388
NC resonant $\pi^\pm$ ($\nu_\mu N \rightarrow \nu_\mu N' \pi^\pm$)	4,796
CC DIS ($\nu_\mu N \rightarrow \mu^- X$, $W > 2$ GeV)	1,229
NC DIS ($\nu_\mu N \rightarrow \nu_\mu X$, $W > 2$ GeV)	456
NC coherent π^0 ($\nu_\mu A \rightarrow \nu_\mu A \pi^0$)	1,694
CC coherent π^+ ($\nu_\mu A \rightarrow \mu^- A \pi^+$)	2,626
NC kaon ($\nu_\mu N \rightarrow \nu_\mu K X$)	39
CC kaon ($\nu_\mu N \rightarrow \mu^- K X$)	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

Suite of low energy cross section measurements

- Measurement of **Δs** through NC elastic scattering at very low Q^2
- **Pion production**: Coherent vs. resonant
- **K production**: cross sections and proton decay studies
- **Electron neutrino** cross sections

Physics Motivation III: SuperNovae neutrino's

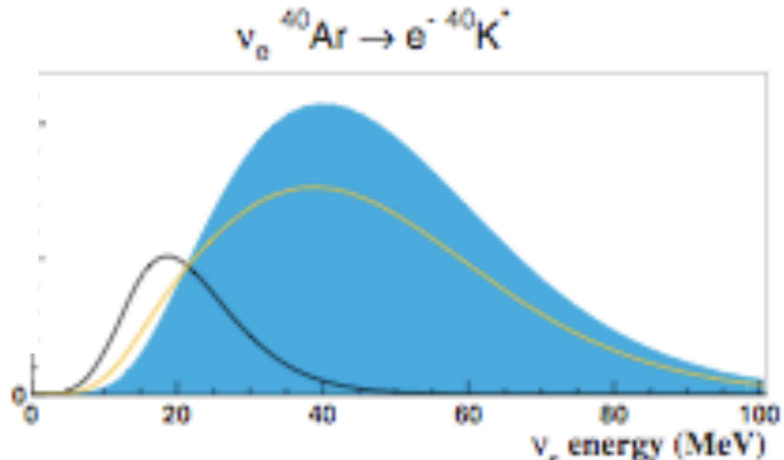
About 29 neutrino events observed for SN1987a

Between 10 and 20 Absorption events

$\nu_e\ {}^{40}Ar \rightarrow e^- \ {}^{40}K^*$

expected for a galactic supernova

Electron Energy: **tens of MeV**



0 20 40 60 80 E_ν (MeV)

0 20 40 60 80 E_e

I. Gil-Botella and A. Rubbia JCAP 10(2003)009

Questions 1 and 2.

- $\Delta = \Delta m^2_{31} L/4E$
- qualitative understanding $\Rightarrow$ expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31}$; $V = \sqrt{2} G_F n_e$

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
& \pm \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
& + \cos\delta_{CP}\,\alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
& + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

CP violation: Difference between ν and $\bar{\nu}$ Oscillations

Mass hierarchy accessible through Matter effects.

II. CP Violation

Question 2: Is $\delta_{CP} \neq 0$?

Oscillation formula: $\Delta m_{31}{}^2 = 2.3 \times 10^{-3}$ eV^2. Requires L ~ 10^3 km for E ~ 1 GeV.

Questions 1 and 2 require Long Baseline experiments

Fits to all relevant data sets → Constraint on Sterile ν (s)

Mike, Georgia et al…arXiv:1207.4765 hep-ex

- LSND, KARMEN $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance
- LSND, KARMEN $\nu_e + {}^{12}C \rightarrow {}^{12}N_{gs} + e^-$
- MiniBooNE $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance
- MiniBooNE ν_μ , $\bar{\nu}_\mu$ disappearance
- NOMAD $\nu_\mu \rightarrow \nu_e$ Appearance

- CCFR, CDHS ν_μ disappearance
- Reactor $\bar{\nu}_e$ disappearance
- SAGE, GALLEX MCi sources: ν_e disappearance
- MINOS ν_μ disappearance
- Atmospheric ν's disappearance

CP violation:

ν appearance $\neq \bar{\nu}$ appearance

CPT conservation:

ν disappearance $= \bar{\nu}$ disappearance

Oscillation Fit Strategy (Arthur Franke→ Rachel Carr)

- MC Events & Data flow handled in parallel
- Apply correction for MC/Data differences
- Covariance matrix or pull terms approach

- 2 Integration Periods:
  - both reactor with power > 90%
  - one reactor or both with power < 20%

- Final result decided based on sensitivity studies

- Binning established using sensitivity studies 18 energy bins per period

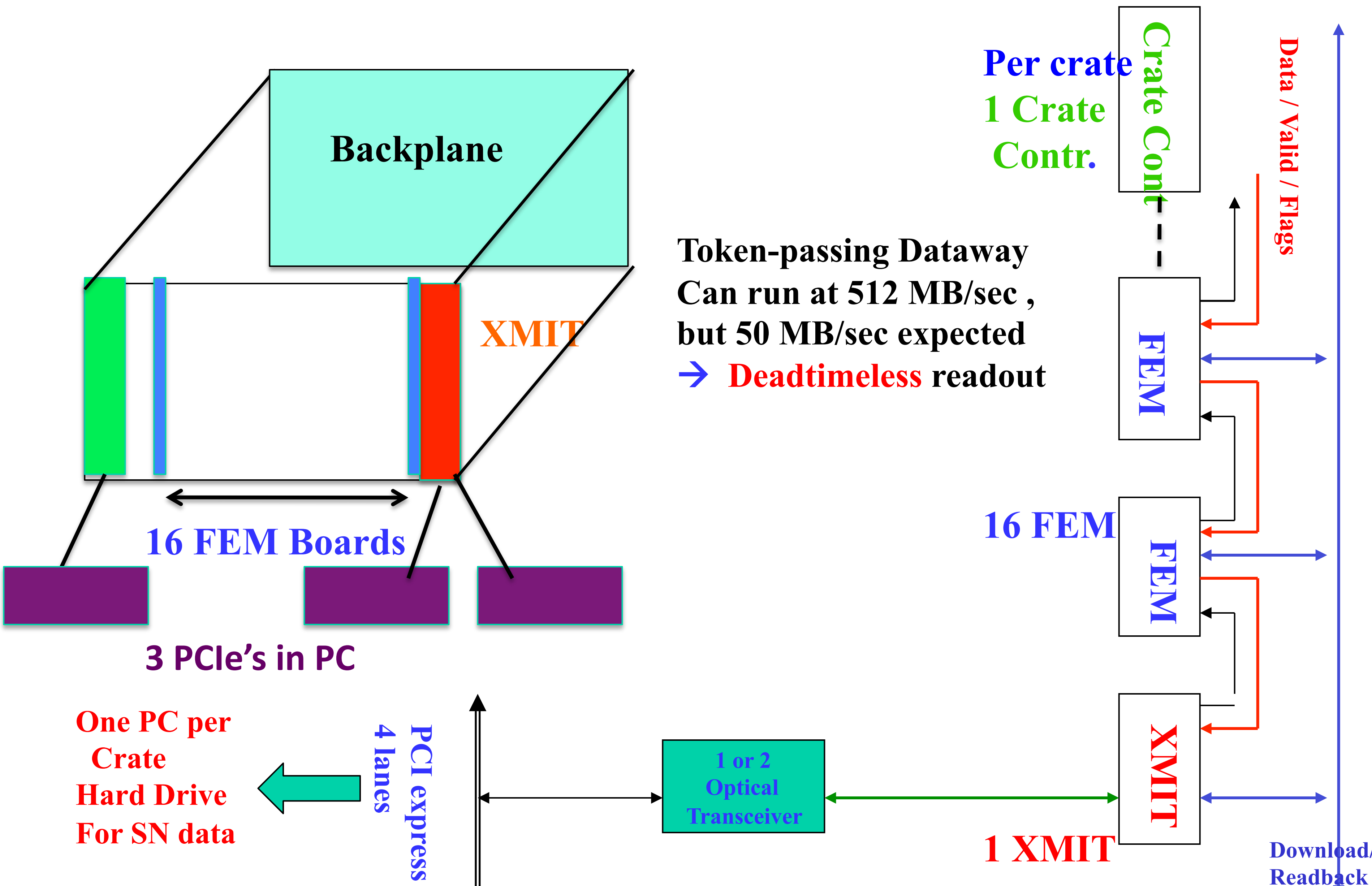
Definition of χ^2 estimator

$$\chi^2 = \sum_{i,j}\left(N_i - \left(N_i^{\exp} + \sum_{BG} N_i^{BG}\left(1+p^{BG}\right)\right)\right) \times \left(M_{i,j}^{\text{stat}} + M_{i,j}^{\text{reac.}} + M_{i,j}^{\text{eff.}} + \sum_{BG} M_{i,j}^{BG}\right) \times \left(N_j - \left(N_j^{\exp} + \sum_{BG} N_j^{BG}\left(1+p^{BG}\right)\right)\right) + \sum_{BG}\left(\frac{p^{BG}}{\sigma^{BG}}\right)^2 + \left(\frac{p^{\text{Escale}}}{\sigma^{\text{Escale}}}\right)^2 + \left(\frac{p^{\Delta m^2}}{\sigma^{\Delta m^2}}\right)^2$$

- i, j : label of energy bin: 1 to 18 for IP-0 and 19 to 36 for IP-1
- N_i : observed number of in i-th bin
- $N_i^{\exp}$: expected weighted by oscillation
- $M_{i,j}$: covariance matrix
- p: pull terms and σ: systematic uncertainties

Used Blind Analysis (reactor prediction not known better than 10% until the selection cuts were frozen).

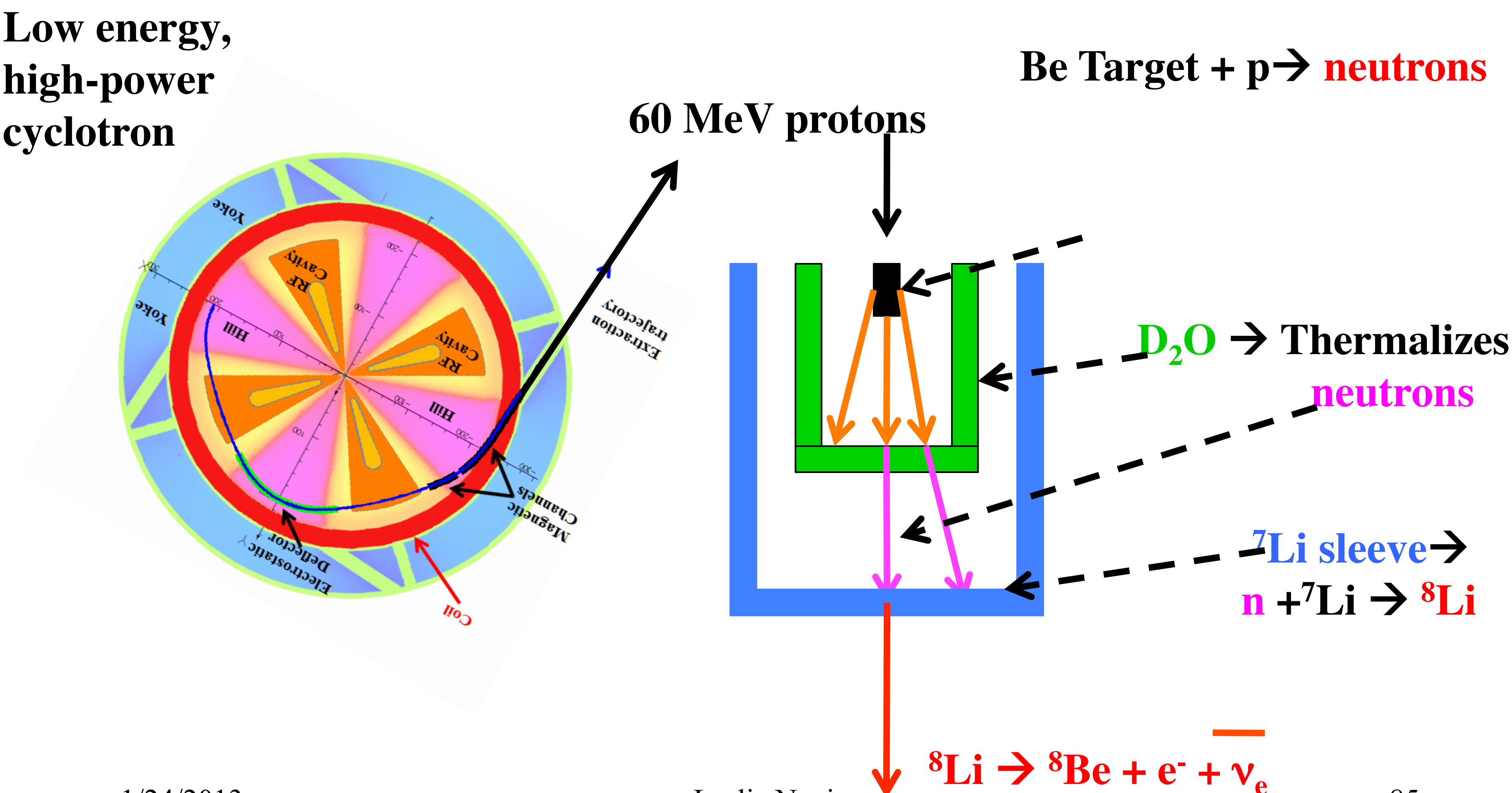
Digitization components: 9 TPC + 1 PMT crates



IsoDAR

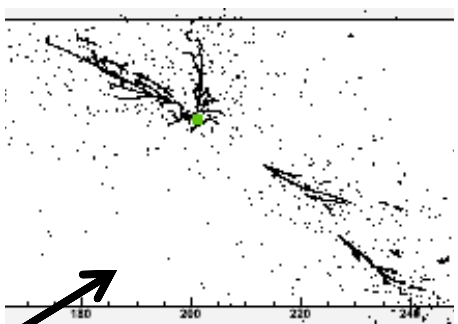
PRL **109**, 141802 (2012)

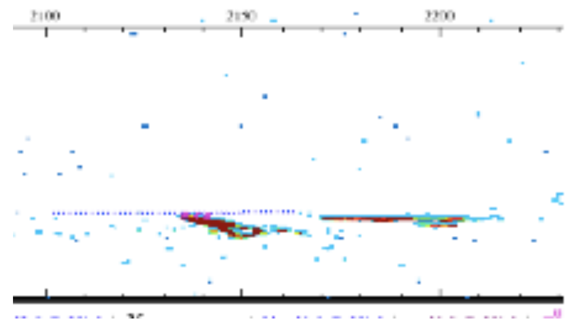
- **IsoDAR:** Radioactive beam of $^{8}Li \rightarrow {}^{8}Be + e^{-} + \bar{\nu}_e$
  Detect $\bar{\nu}_e$ in a liquid scintillator detector :Very short baseline.



R&D V: Background to Proton Decay: $n\bar{n}$ oscillations → annihilation

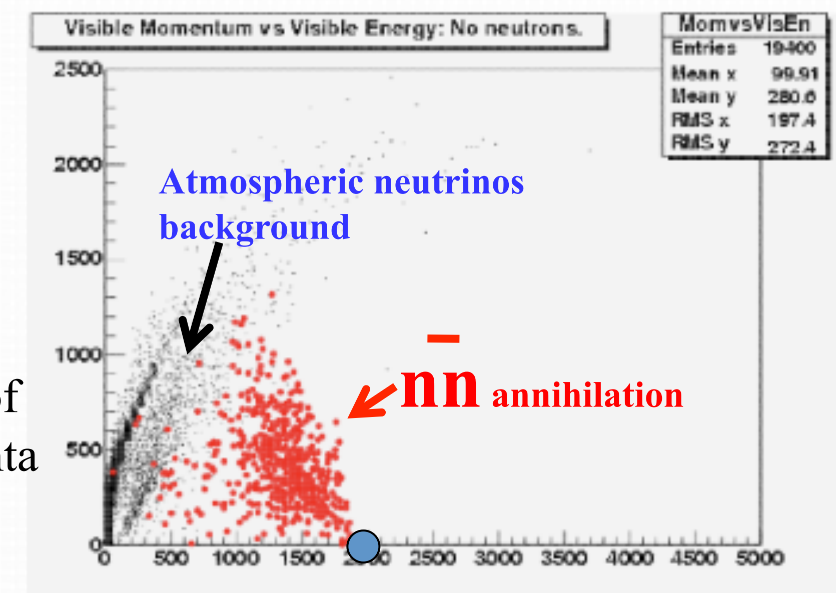
Oscillation of neutron to antineutron followed by annihilation of antineutron with an Argon nucleus nucleon.





Annihilation

- Spherical
- Zero NET momentum
- Total energy = 2 M_n



Sum of Momenta

Sum of Energies

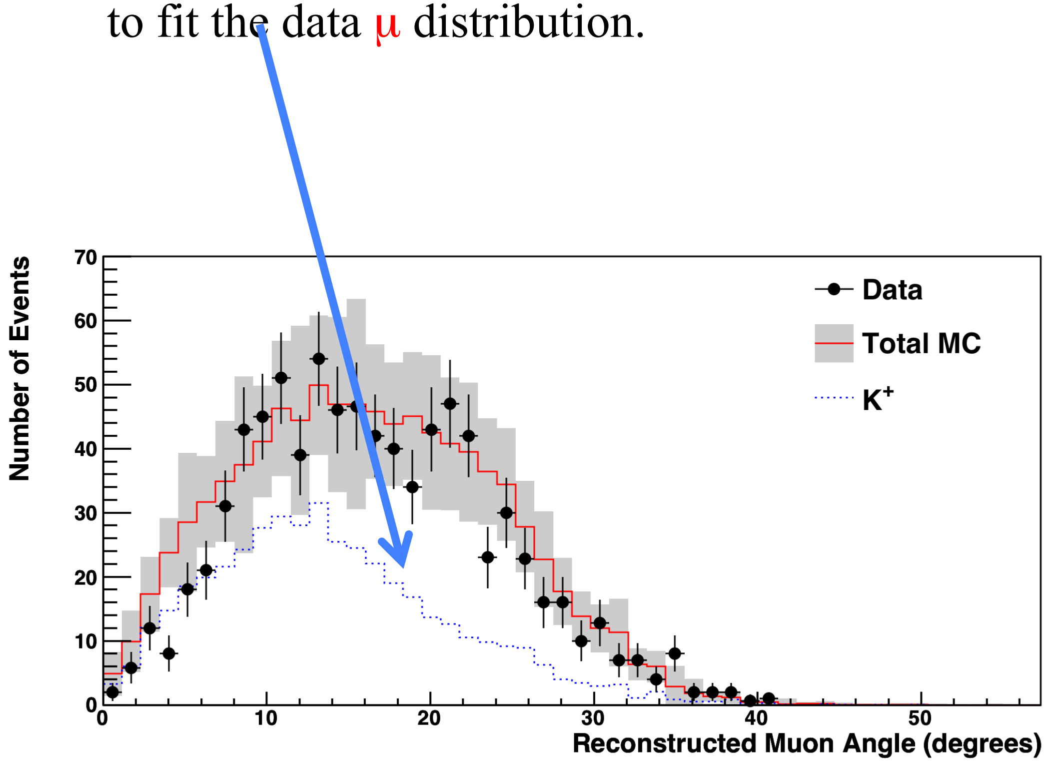
Atmos. ν (Main background)

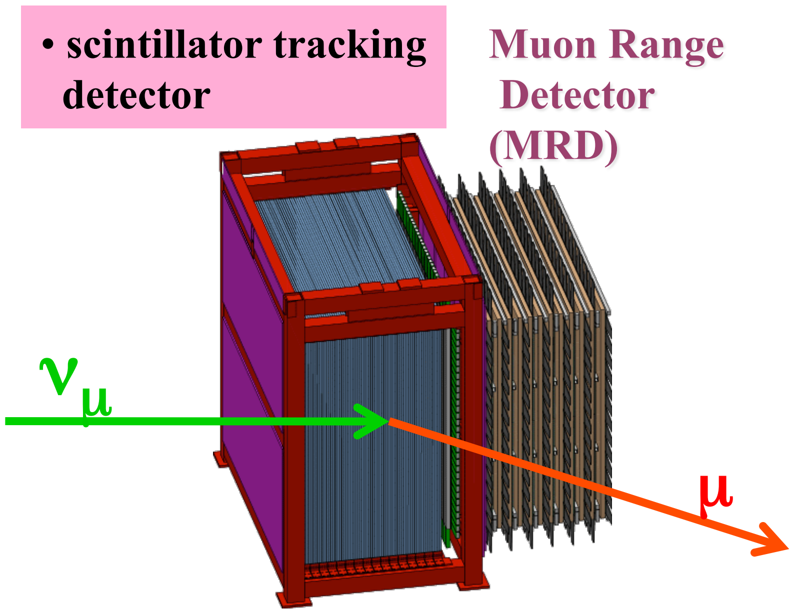
- Linear
- Non-zero momentum
- No constraint on energy

Simulation using Truth to Measure cosmic background in MicroBooNE.

SciBooNE: Constraining the ν_e background from beam K^+
Gary Cheng

- Detect ν_μ from π+ and K+ through their CC interactions (→μ in) SciBooNE.
- ν_μ from K+ have higher energy.
- Look at muons with p > 1 GeV/c.
- Adjust K+ contribution in the beam simulation to fit the data μ distribution.





Reduced the uncertainty On the intrinsic ν_e from K+ From 40% to 14%.