Sterile Neutrinos II

R.G. Van de Water, P-25, LANL

FNAL Neutrino Summer School
July 9-10, 2007

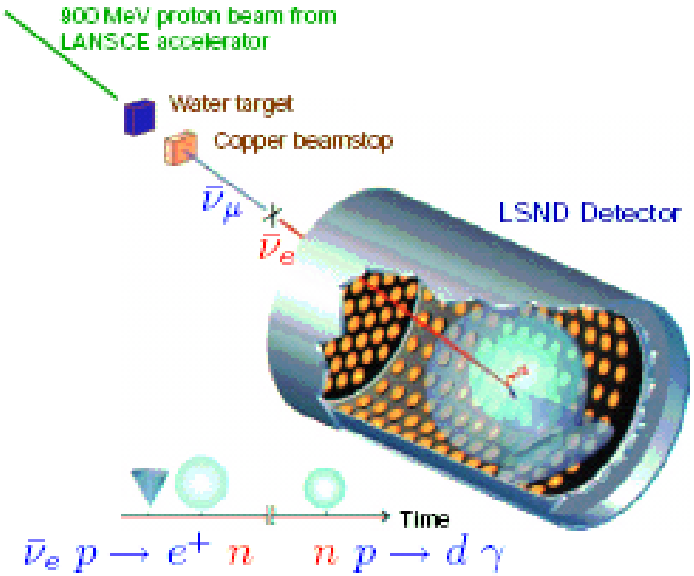
Outline

- Motivation for active-sterile neutrino experiments.
- How to measure active-sterile oscillations.
  - A precision neutrino source.
  - A well understood target.
  - A precision detector.
  - Calibrations and analysis
- Oscillation measurements and sensitivities
- Costs/Conclusion

Evidence for Sterile Neutrinos

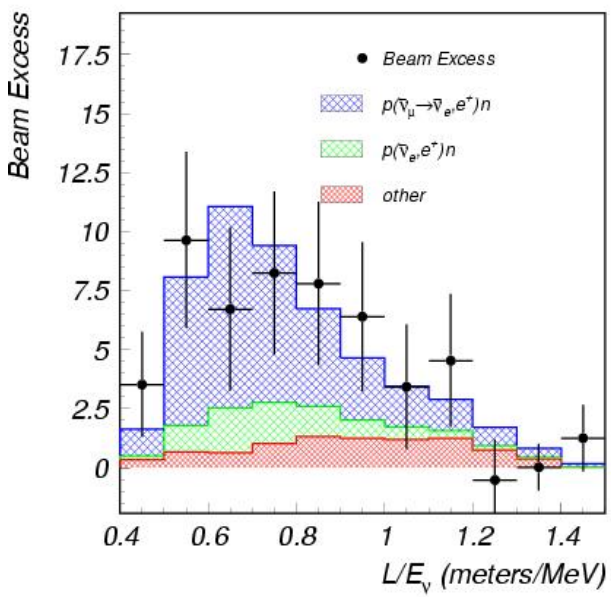
- LSND anomaly indicates best place to look for sterile neutrinos is ~1eV^2 region.
  - Measurement made with antineutrinos.
- Short baseline measurements, including MiniBooNE data.
  - 3+1 models ruled out.
  - 3+2 models with CP okay, tension with disappearance measurements.
- Limits from cosmology/astrophyics, but not as robust as many assumption made.
  - Pulser kicks, R-process, source of dark matter/energy.
- Extra dimensions, hmmmm.....

The LSND Oscillation Signal



- **Beam and detector**
- $\overline{\nu_\mu}$ source from: $\pi^+ \rightarrow \mu^+ \nu_\mu,\ \ \mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$
- E=20-53 MeV, L=25-35 m

  Liquid scintillator detects both Cherenkov and *scintillation light*

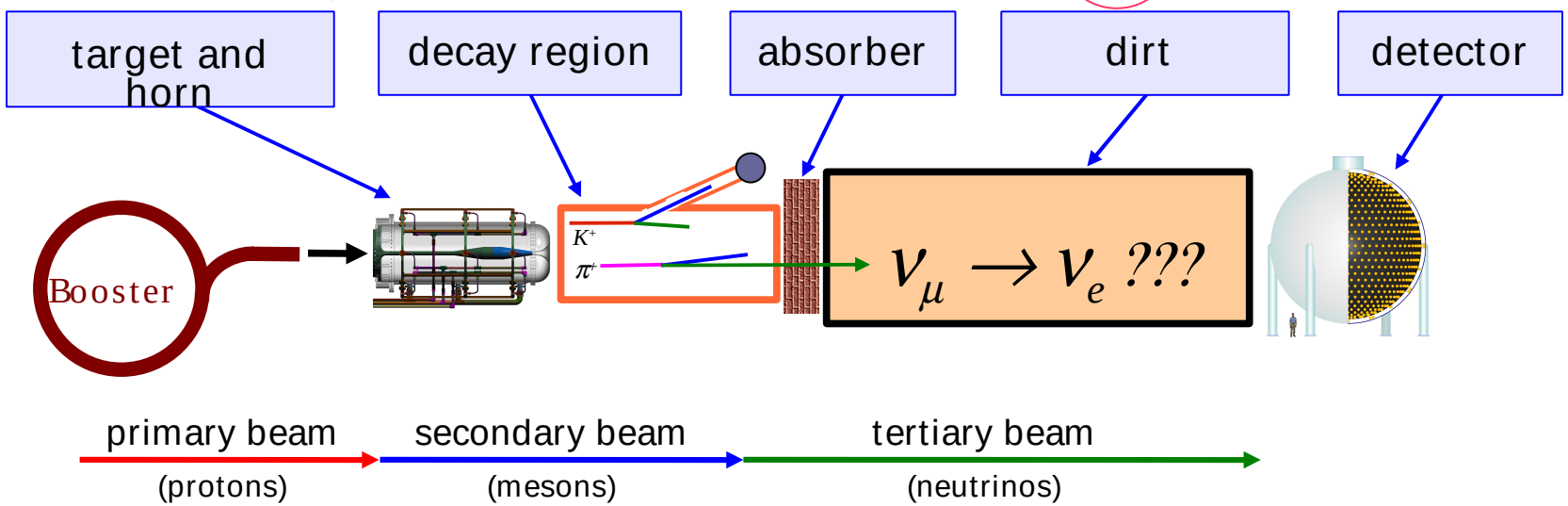


- **Oscillation Search**
- 3.8σ excess of $\overline{\nu_e}$ events in the ~pure $\overline{\nu_\mu}$ beam
- $\langle P(\overline{\nu_\mu} \rightarrow \overline{\nu_e}) \rangle = (0.264 \pm 0.067 \pm 0.045)\ \%$
- L/E distribution of the excess agrees well with oscillations

The MiniBooNE Experimental Design:

While keeping L/E~1 m/MeV, as in LSND, MiniBooNE design changes the backgrounds, energy range, & event signature from the LSND case.

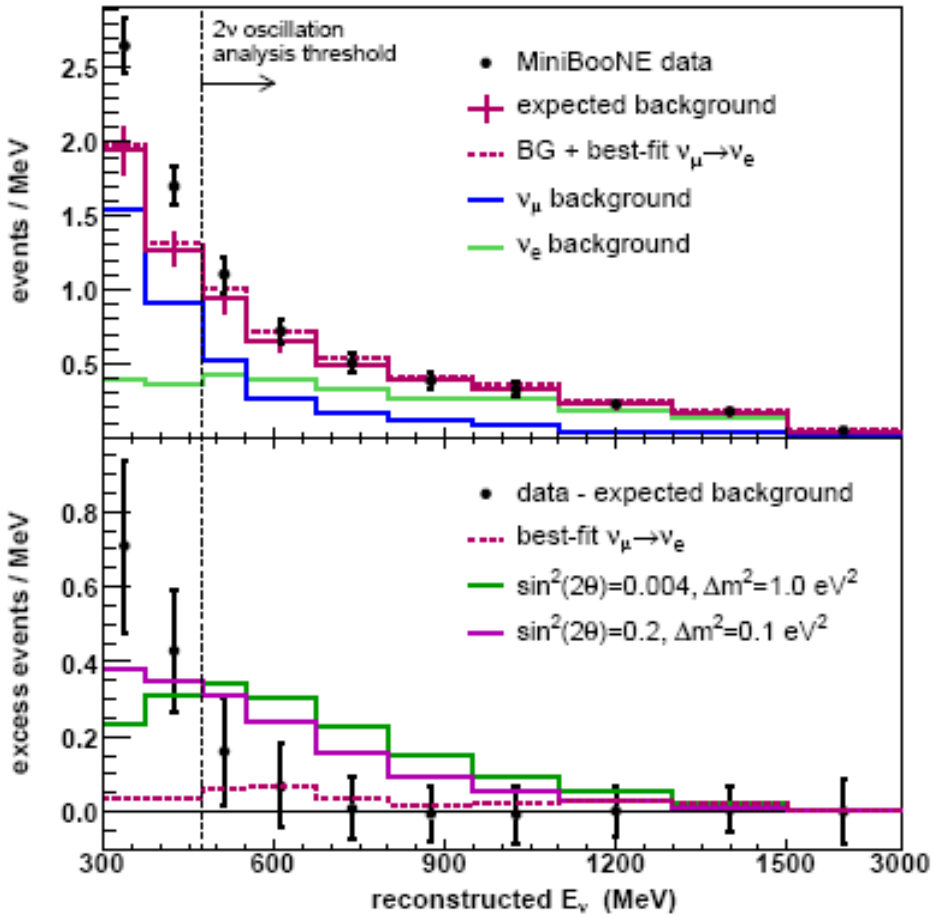
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$



Order of magnitude higher energy (~500 MeV) than LSND (~30 MeV)

Order of magnitude longer baseline (~500 m) then LSND (~30 m)

First Results from MiniBooNE



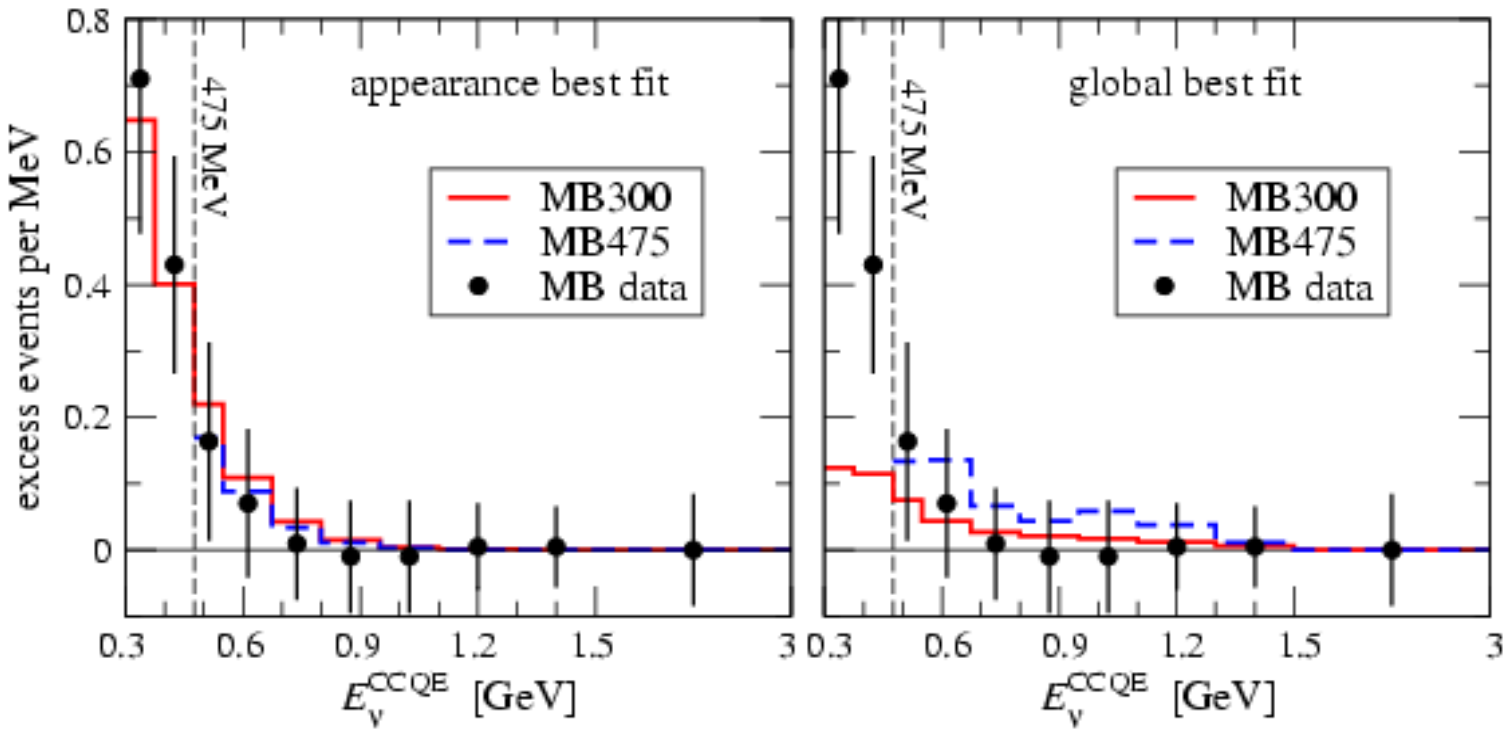
MiniBooNE result **excludes** the LSND 90%CL allowed region **at > 90% CL**…

Counting Expt :
300 MeV < E^{QE} < 475 MeV
Excess over background : 3.7

MiniBooNE measurement made with neutrinos!

Analysis by Maltoni & Schwetz [hep-ph/0705.0107]

3+2 Global Fit Results (with CP)



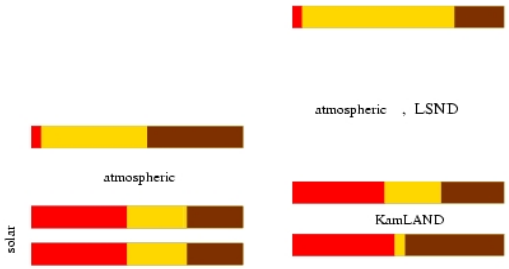
3+2 neutrino models:

- provide a **good fit** to LSND and the recent MB data
- can **account for the low energy** event **excess in MB**

However:

- there is significant **tension between appearance and disappearance data**

Other Beyond the Standard Model Motivations

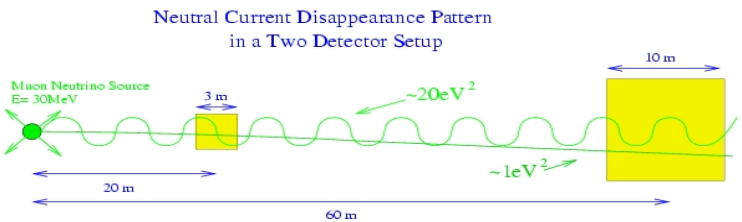


- CPT violation (hep- ph 0212116).
- Mass varying ν, mass depends on medium (hep- ph 0401099).
- Lorentz violation, mass depends on direction (hep- ph 0406255).
- ν_s short cuts in extra dimensions (hep- ph 0504096).

- **Need new high intensity short baseline neutrino experiments!**

Short Baseline Tests of New Physics

- **Sterile neutrinos:**
  - **Measure neutral current rates with two detectors.**

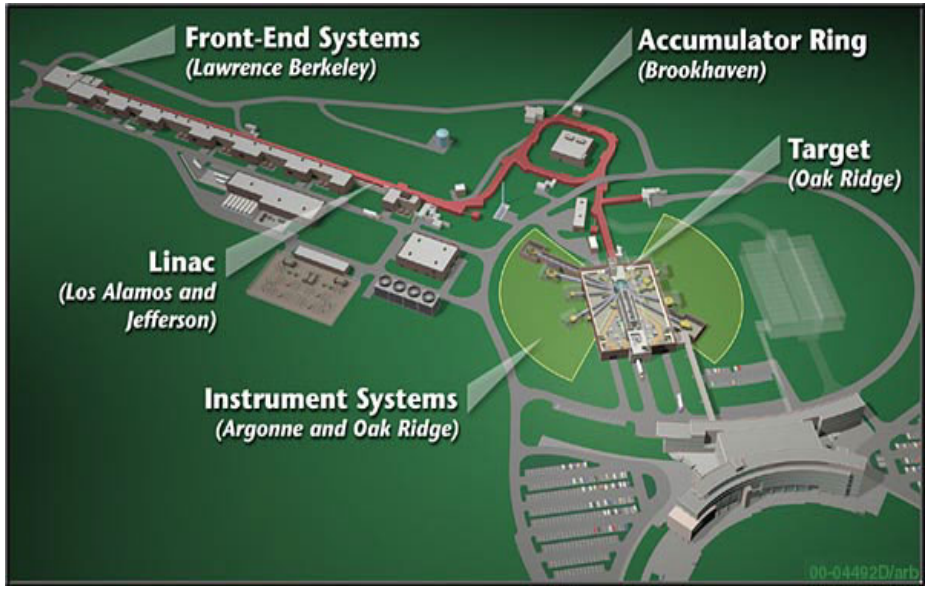


- **CPT violation:**
  - **Run in antineutrino mode, compare $P(\nu_\mu \rightarrow \nu_e)$ to $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.**
- **Mass Varying neutrinos:**
  - **Oscillation probability depends on absence/ presence of matter. Build tunnel to detector to be filled with water/ air.**
- **Lorentz Violation:**
  - **Oscillation probability depends on direction, look for sidereal effects.**

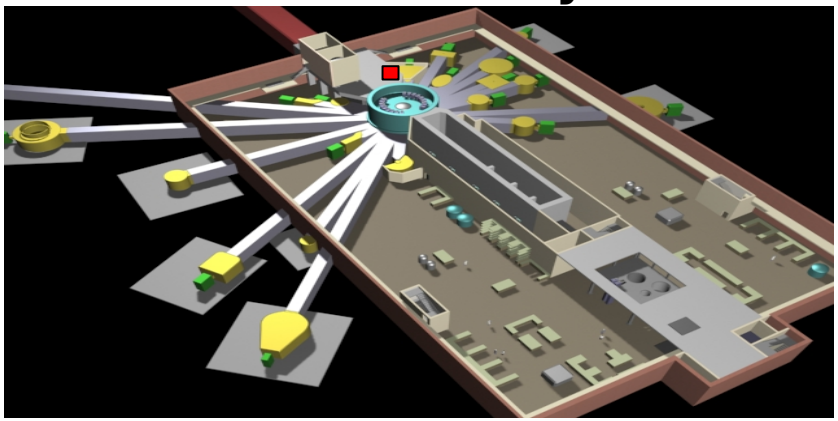
Ingredients needed to measure Active-Sterile Oscillations

- A precision, high intensity neutrino source:
  - Low intrinsic backgrounds.
  - Well determined flux and energy spectrum.
- A neutrino target:
  - Well known neutrino cross sections at the energy of interest.
  - A high rate, easy to identify neutral current interaction.
  - Large mass and high light output (add scintillator).
- A precision neutrino detector:
  - High detection efficiency.
  - Calibration sources.
  - Understood systematic errors.

Stopped Pion/Muon Neutrino Source: The Hardware



- **SNS at ORNL, will be online in 2008 (1.3 GeV, 1.4 MW, 695nsec beam duty factor).**



The SNS will produce about 10^{15} neutrinos per second from the decay of stopped pions

- o at 60 Hz repetition rate
- o pulse width of about 600 ns
- o a flux of about 3×10^6/sec/cm^2 at 50 meters from the SNS target

* The most intense pulsed, intermediate-energy neutrino source in the world!
* The pulse structure
  - o drastically reduces cosmic ray background
  - o allows separation of muon neutrinos from muon anti-neutrinos and electron neutrinos

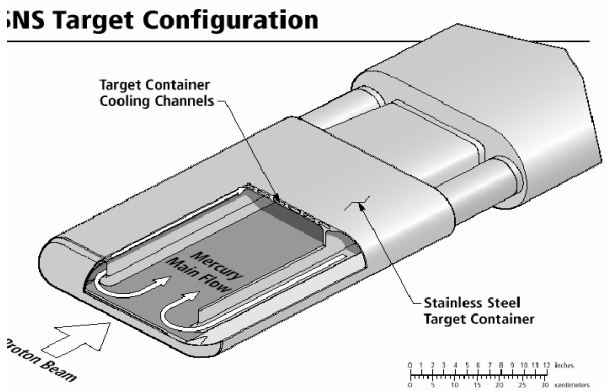
For neutrino physics, the machine is free!!!

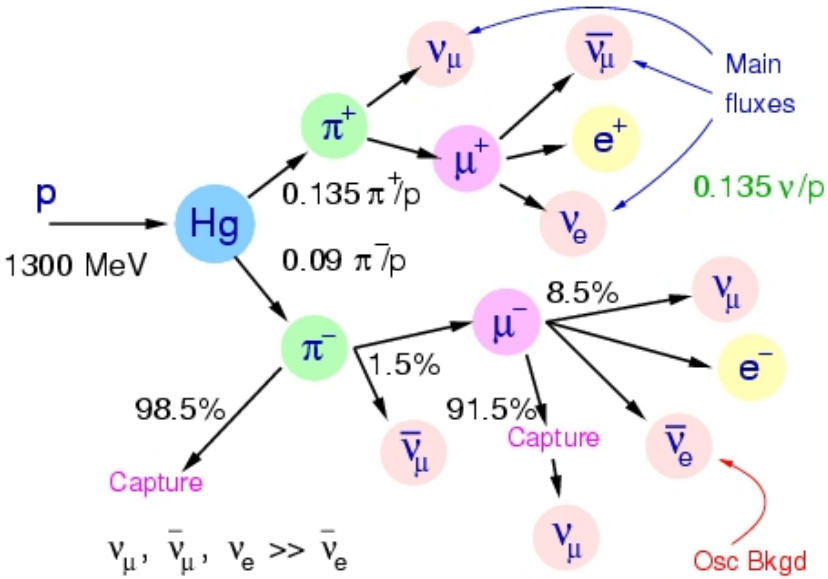
Stopped Pion/Muon Neutrino Source: The Flux

- **Neutrino Production from a Stopped Pion/Muon Source:**

4π neutrino source

Compact liquid mercury target





	FNAL (8 GeV)	FNAL (5 GeV)	SNS
P/yr	4.9×10^{22}	4.9×10^{22}	2.2×10^{23}
DAR $\nu(\nu/P)$	1.5	0.9	0.13
DAR $\nu(\nu/yr)$	7.3×10^{22}	4.4×10^{22}	2.9×10^{22}

nucl-ex/0309014
hep-ex/0408135

From LSND experience, expect flux uncertainties ~5%

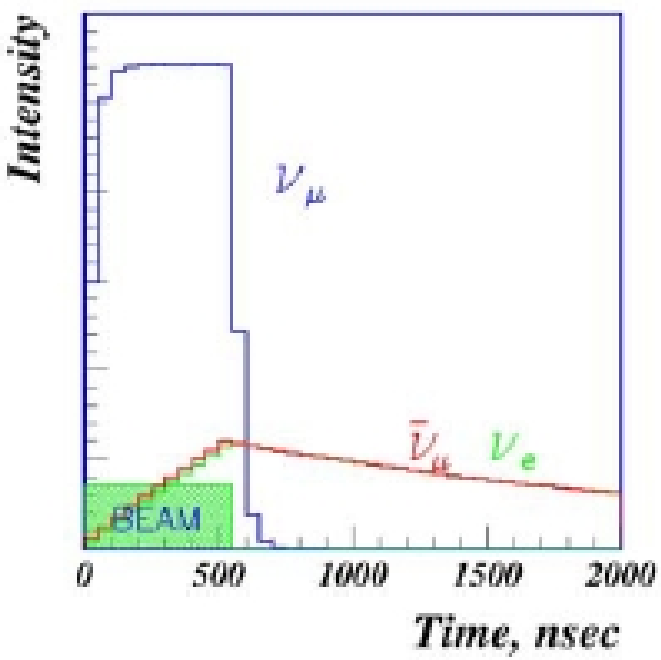
Stopped Pion/Muon Neutrino Source

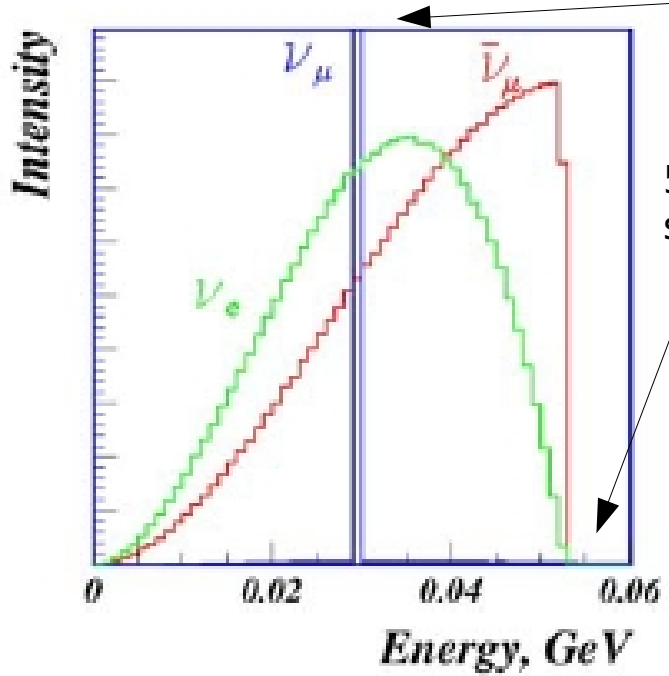
- **Neutrino Flux from a Stopped Pion/Muon Source:**

$$\pi^+ \to \mu^+ \nu_\mu, \quad \tau = 26 nsec$$

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e, \quad \tau = 2.2 \mu sec.$$

event types	$0 \to 0.695\mu$sec	$0.695 \to 5\mu$sec	$> 5\mu$sec
π^+ DAR and $\pi^\pm$ DIF events	96.3%	3.7%	0
μ^+ DAR and oscillation candidates	14.3%	73.6%	12.1%





30 MeV monoenergetic line

53 MeV end point Michel spectrum

Neutrino Reactions from a Stopped Pion/Muon Source in Mineral Oil: The Target

500 ton mineral oil (CH_2) detector 60m from SNS source.

-Cross sections measured to ~5-10%

-CC/NC cross section estimated to be ~3%

Assumed detection efficiency~ 100%

Process	Neutrino Source	Events per Year
$\nu_\mu e$	π^+ DAR	138
$\bar{\nu}_\mu e$	μ^+ DAR	198
$\nu_e e$	μ^+ DAR	1260
Total νe events		1596
$\nu_e\ {}^{12}C \rightarrow e^-\ {}^{12}N_{gs}$	μ^+ DAR	9378
$\nu_e\ {}^{12}C \rightarrow e^-\ {}^{12}N^*$	μ^+ DAR	4294
Total $\nu_e\ {}^{12}C \rightarrow e^- X$ events		13672
$\nu_\mu\ {}^{12}C \rightarrow \nu_\mu\ {}^{12}C^*_{15.11}$	π^+ DAR	3702
$\bar{\nu}_\mu\ {}^{12}C \rightarrow \bar{\nu}_\mu\ {}^{12}C^*_{15.11}$	μ^+ DAR	7504
$\nu_e\ {}^{12}C \rightarrow \nu_e\ {}^{12}C^*_{15.11}$	μ^+ DAR	6186
Total $\nu\ {}^{12}C \rightarrow \nu\ {}^{12}C^*_{15.11}$ events		17392

ES (electron/muon final state)

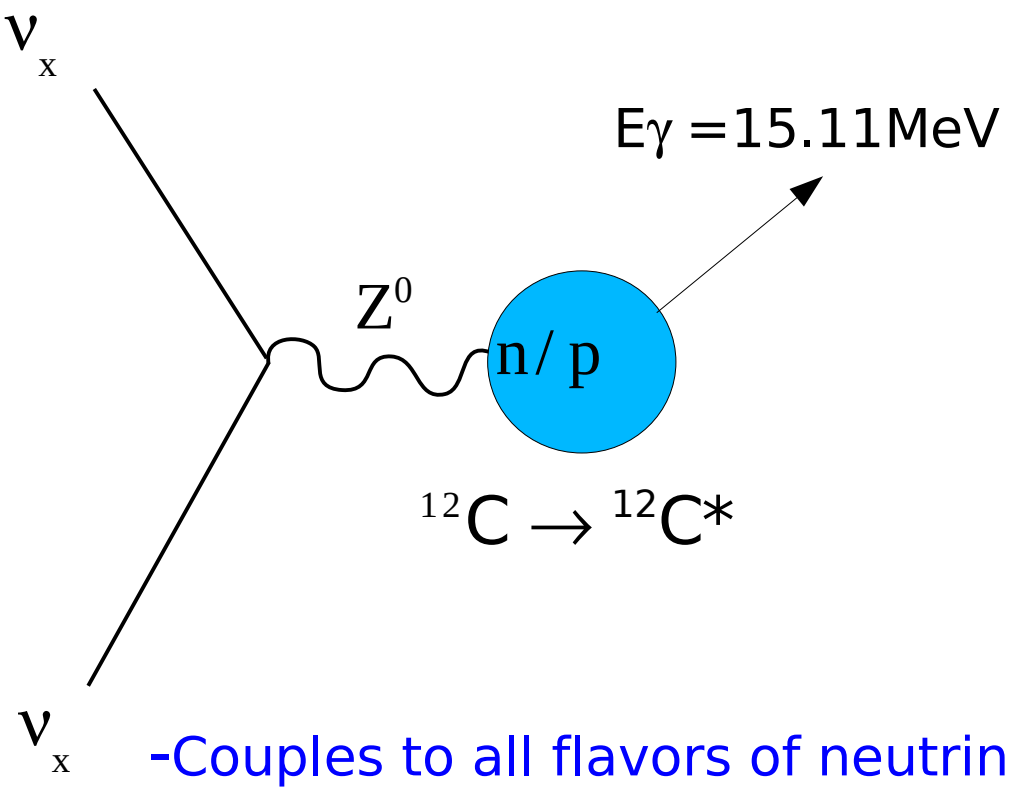
CC (electron final state $E_e = E_\nu$ - 17.33MeV)

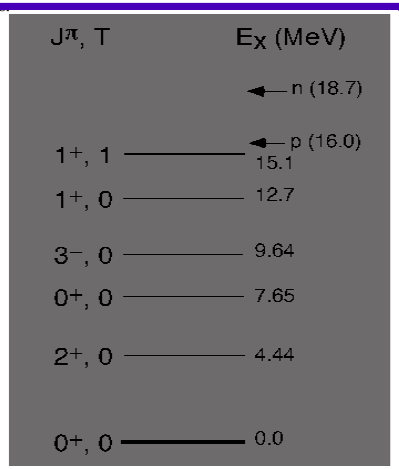
NC (E= 15.11 MeV mono-energetic gamma-ray)

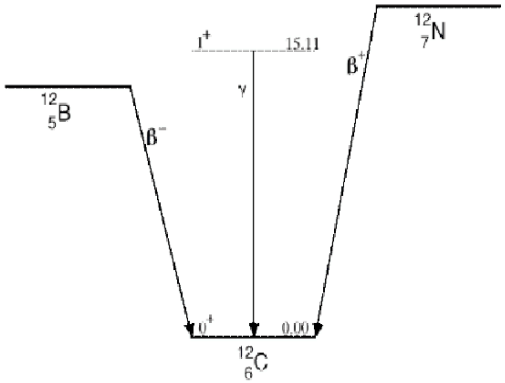
- $\bar{\nu}_e p$ - > n e^+, then np - > dγ (2.2MeV); oscillation channel

Neutral Current Interactions

$\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11MeV)$







-Couples to all flavors of neutrinos and antineutrinos.
-Does not couple to Sterile neutrinos.
-Does not convey energy of initial neutrino.

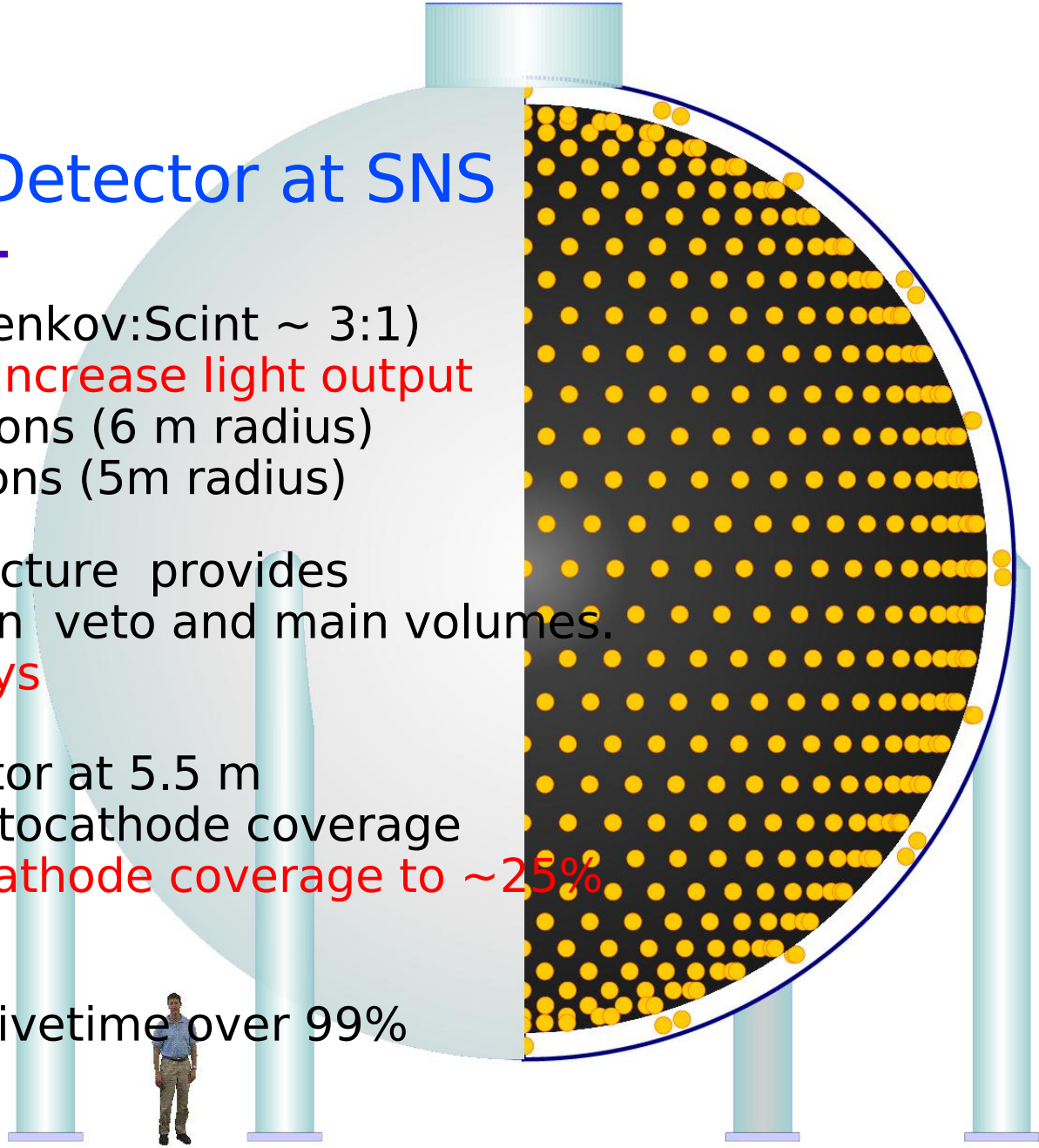
MiniBooNE Style Detector at SNS

- Pure mineral oil (Cherenkov:Scint ~ 3:1)
  → add scintillator to increase light output
  Total volume: 800 tons (6 m radius)
  Fiducial volume: 445 tons (5m radius)

- Phototube support structure provides opaque barrier between veto and main volumes.
  → reject cosmic rays

- 1280 8” PMTs in detector at 5.5 m radius giving 10% photocathode coverage
  → increase photocathode coverage to ~25%
- 240 PMTs in veto.

- High PMT/electronics livetime over 99% for beam.



Light Output Estimates in Mineral Oil

- Relativistic electrons and muons will produce Cerenkov (Θ_{cone}=47.1°) and scintillation light (isotropic). Gamma-rays will mostly Compton scatter (produce electrons).
- Assuming 22% quantum efficiency and 25% photocathode coverage (PE= detected photons= n_{photon}x QE x PC):
- Cerenkov output:
  - Light output in mineral oil ~14 PE/MeV
- Scintillation Light output:
  - Light output in mineral oil ~4.5 PE/MeV.
  - Light output mineral oil + 0.031% Butyl PBD ~15 PE/MeV and 18 nsec time constant.
  - Detector on surface, do not want scintillator concentration too high as it would saturate with cosmic rays, but need to detect 2.2 MeV gamma-rays from neutron capture (~50 PE).
- Cerenkov:Scintillation ratio 1:1.

Light Detectors; the neutrino workhorse

- **8” Hammamatsu 5912 phototube ~$1000/each.**

CHARACTERISTICS (at 25°C)

Parameter		Min.	Typ.	Max.	Unit
Cathode Sensitivity	Luminous (2856K)	—	70	—	μA/lm
	Radiant at 420nm	—	72	—	mA/W
	Blue (CS 5-58 filter)	—	9.0	—	μA/lm-b
	Quantum Efficiency at 390nm	—	22	—	%
Anode Sensitivity [1]	Luminous (2856K)	—	700	—	A/lm
	Radiant at 420nm	—	7.2×10^5	—	A/W
Gain [1]		—	1.0×10^7	—	—
Supply Voltage for Gain of 10^7		—	1500	1800	V
Anode Dark Current (after 30min. storage in darkness) [1]		—	50	700	nA
Dark Count (after dark condition for 15 hours) [1]		—	4	8	kcps
Time Response [1]	Anode Pulse Rise Time	—	3.8	—	ns
	Electron Transit Time	—	55	—	ns
	Transit Time Spread (FWHM) [3]	—	2.4	—	ns
Pre Pulse [4]	4ns to 20ns before Main pulse	—	0.5	2	%
Late Pulse [3]	8ns to 80ns after Main pulse	—	1.5	3	%
After Pulse [3]	100ns to 18μs after Main pulse	—	2	10	%
Single Photoelectron	PHD (Peak to Valley Ratio)	—	2.5	—	—
Pulse Linearity [2]	at ±2% Deviation	—	60	—	mA
	at ±5% Deviation	—	80	—	mA
Magnetic characteristics (at 200mG/20μT)	Sensitivity Degradation	—	10	—	%

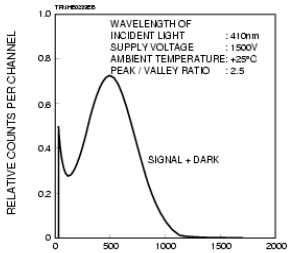


Figure 1: Typical Spectral Response

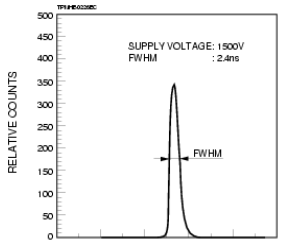
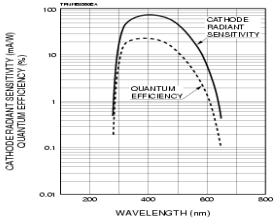
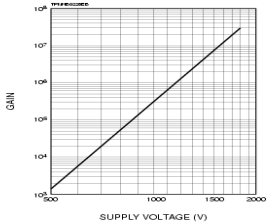


Figure 2: Typical Gain Caracteristic





Important specs:

-Photocathode surface area 520cm^2

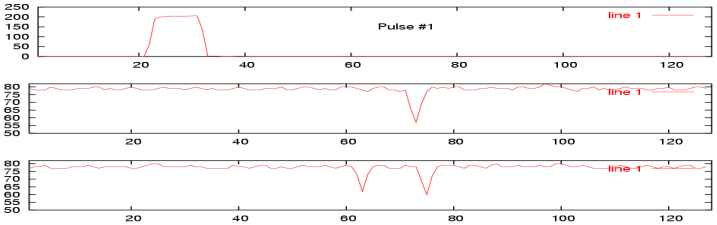
-QM ~21% at 390nm (Bialkali).

-Timing response ~2.4nsec FWHM.

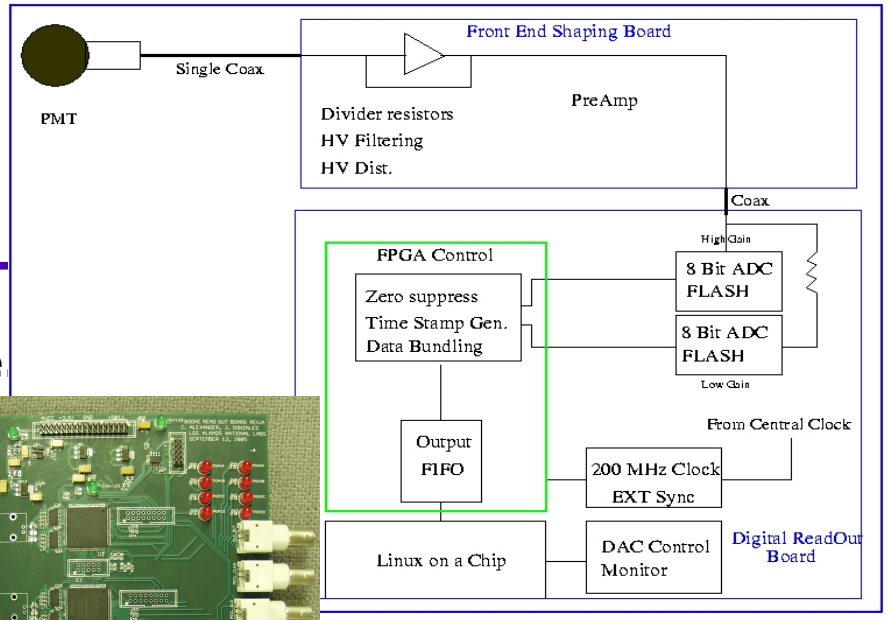
-Charge gain ~10^7 at 1800V.

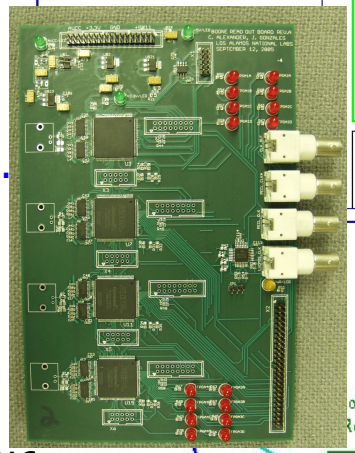
Electronics/DAQ:

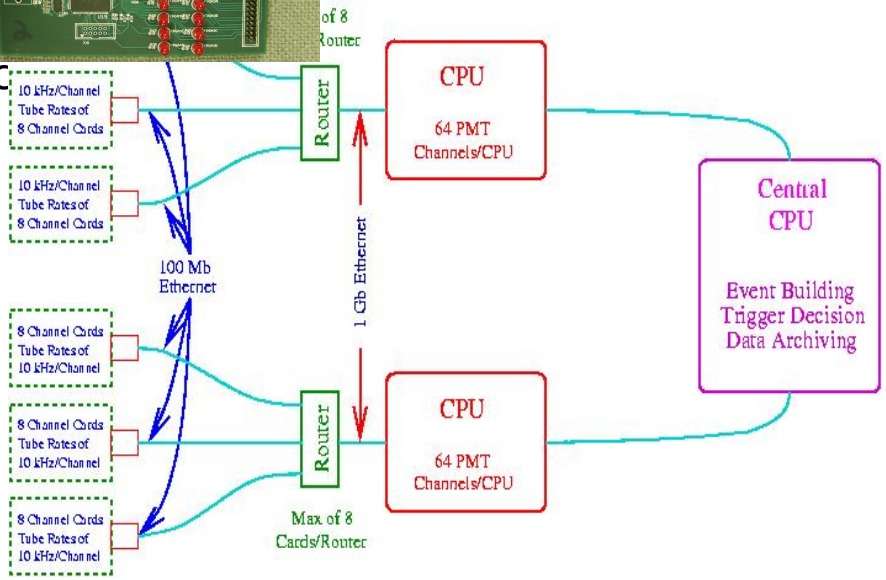
- **New electronics designed for large PMT arrays with much improved performance**
  - 200-400 Mhz FADC's, ~1 nsec time resolution.
  - pulse to pulse time separation ~10 nsec.



  - 5 bit single pe resolution, large Q dynamic range ~500 pe.
  - Front end zero suppression and time stamp/data bundling.
  - All hits readout, software triggering.
  - Front end channel veto/lockout.
  - Low noise, high data rates.
  - ~$200 channel.

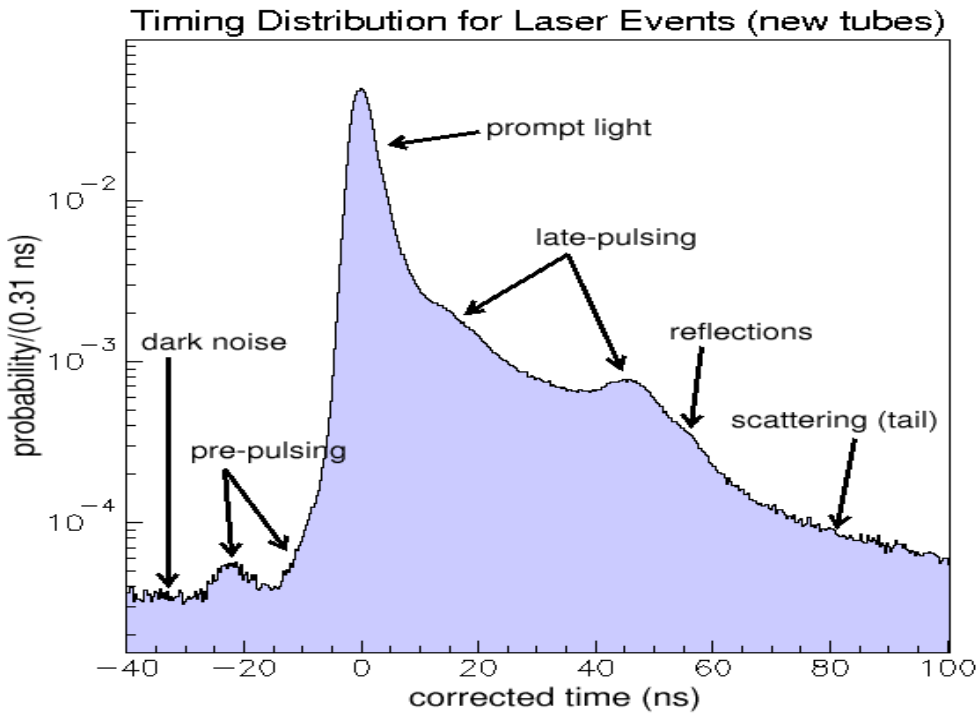




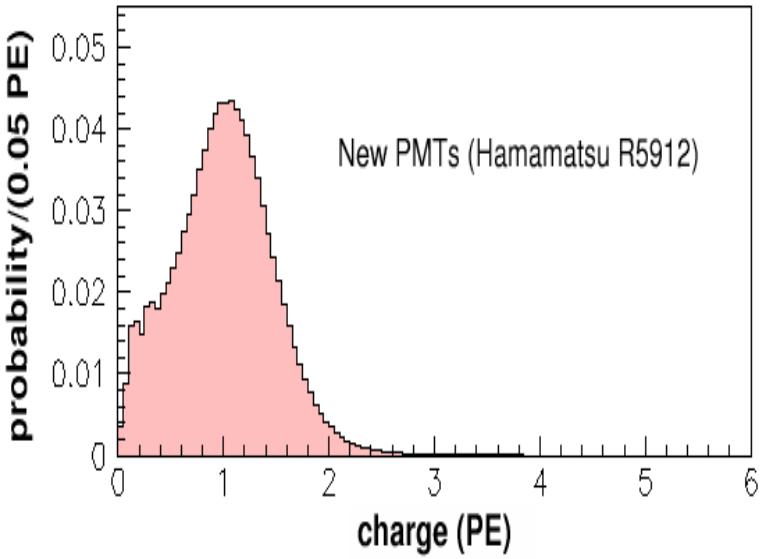


Calibrations

- Laser: light response (optical model) and PMT response



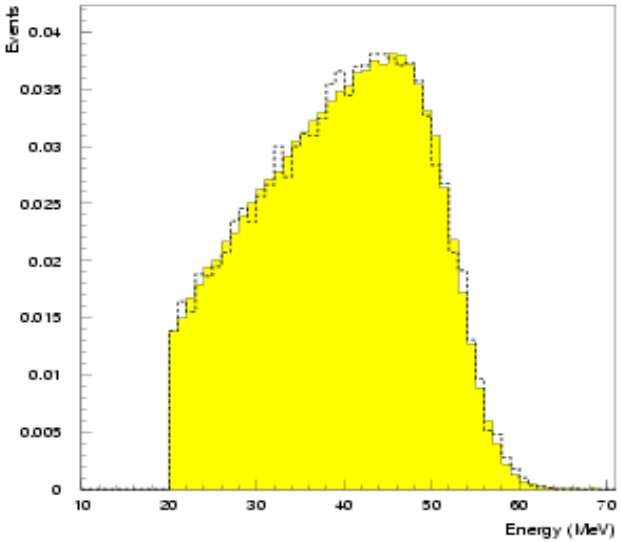
Attenuation length ~20m



Charge and Time response

Calibrations (signal like response)

- Michels electrons from tagged stopped muon: Electron energy calibration from 20-53 MeV).



- ^{16}N gamma-ray source with beta-tag: Gamma-ray energy and response calibration at 6.1 MeV)
- ^{252}Cf neutron source with alpha tagged: Neutron energy and response calibration

Reconstruction

- Use PMT time and charge to reconstruct the position and direction of the Muon/Electron/Gamma-ray.
- Time Model (assuming single PE charge):

$$P(t_i; x_0, y_0, z_0, t_0) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(t_i - t_0 - r_i/c_n)^2}{2\sigma^2}\right],$$

- Add charge model:

$$\mu_i = \frac{\varepsilon_i}{r_i^2}\left[\Phi \exp(-r_i/\lambda_S) f_S(\cos\eta_i) + \rho F(\cos\theta_i, E) \exp(-r_i/\lambda_C) f_C(\cos\eta_i)\right].$$

Scintillation light Cerenkov light

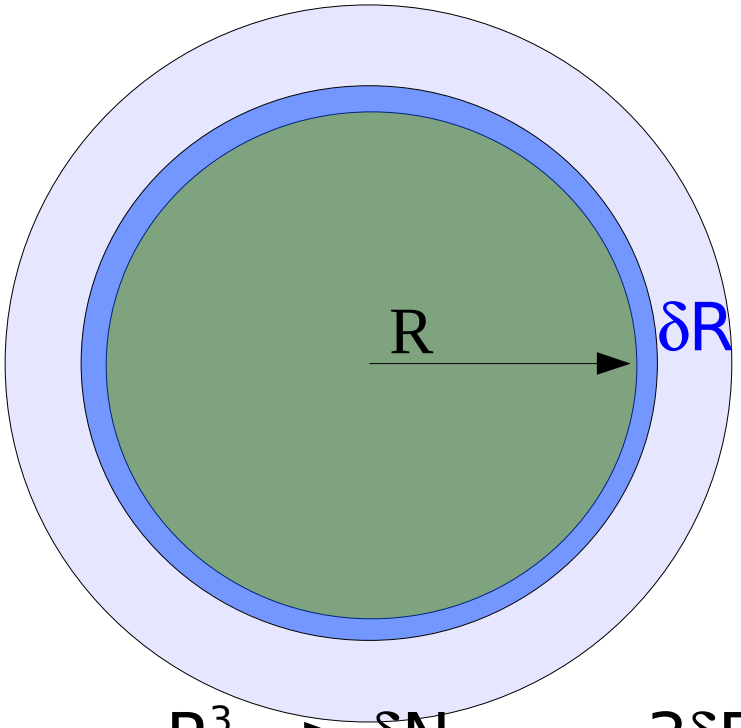
- Maximum likelihood used to determine event x,y,z, and t.
- Spatial resolution ~20 cm, time ~1 nsec.
- Hits with good probability are included in energy estimation.

Reconstruction and Systematic Errors

- Reconstruction efficiency.
  - Dependent on energy and type of particle, ranges from 50% up to 90%.
  - Important to have calibration sources that mimic signal and background processes.
- Fiducial volume errors.
  - Cut at large radius to remove poorly reconstructed events.
  - Defines fiducial volume, reconstruction errors inflated due to volume effect. Sensitive to PMT timing resolution.
- Energy scale errors.
  - Smears energy response of the detector, at threshold can alter number of selected events or decrease significance of a energy peak.
  - More PMT's reduce systematic errors ~1/sqrt(N).

Reconstruction and Systematic Errors

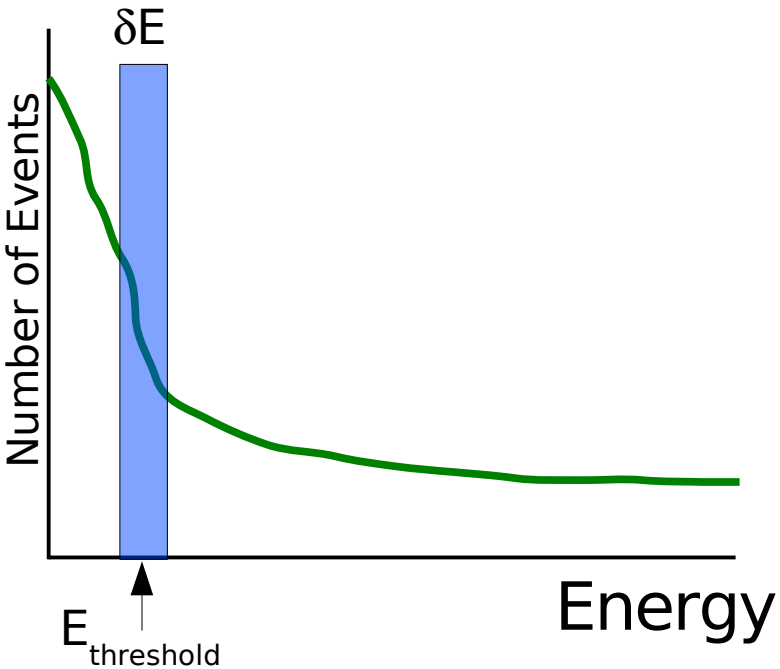
Fiducial Volume Errors



$N_{events} \sim R^3 \Rightarrow \delta N_{events} \sim 3\delta R$

-want good position resolution

Energy Errors



Size of energy error determines how low $E_{threshold}$ can be.

-want good charge resolution

Important low level Inputs to Oscillation Measurements

- Beam
  - Beam quality; losses, on target, timing, etc.
  - Total Protons On Target (POT) counting with toroids.
  - Hg target temperature => POT monitor.
- Neutrino Flux and Interactions (near detector)
  - Measure ES to calibrate/monitor flux.
  - Measure CC, NC and ratios to check models.
- Detector Response
  - Monitor electronics stability, check data quality.
  - Calibration sources to check detector response and model signal/backgrounds.

Physics Measurements at SNS

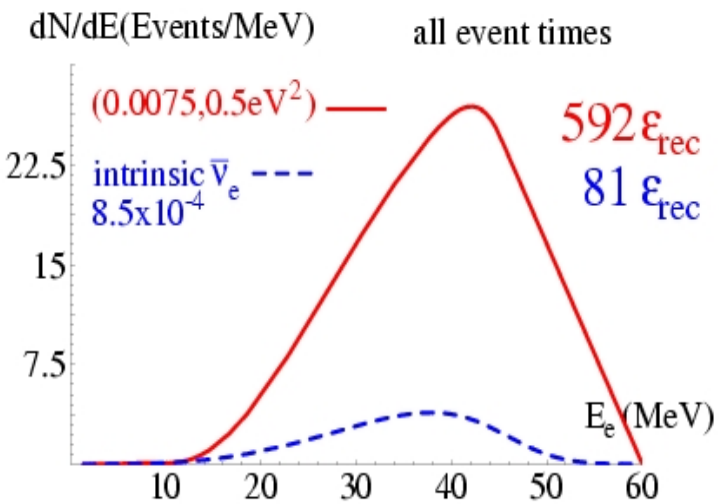
- Check original LSND signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.
- Measure $\nu_\mu \rightarrow \nu_e$ oscillations (new).
- Measure $\nu_\mu\ ^{12}C \rightarrow \nu_\nu\ ^{12}C^*(15.11MeV)$ oscillations as a function of distance (new).
  - Error and background estimates.
  - Sensitivity plots.
- νSNS near detector
  - Cross sections and oscillations.

Test of LSND Stopped Muon $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations

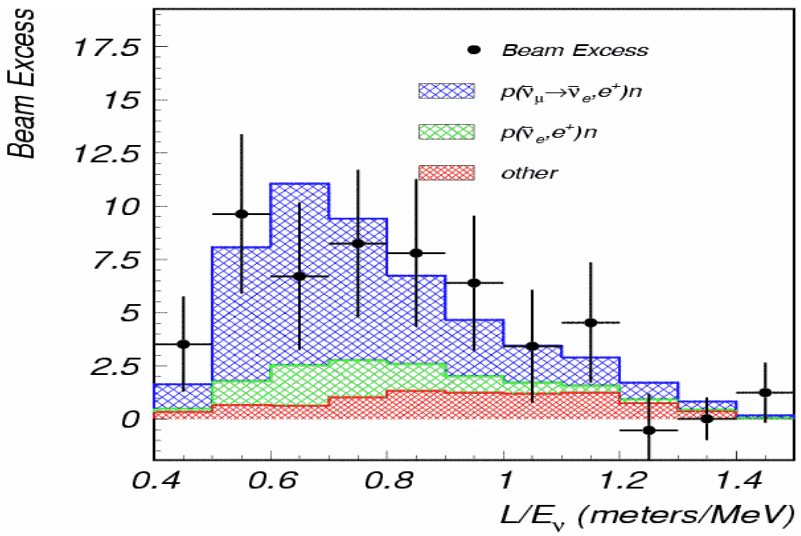
(nucl-ex/0309014)

- Single 250 ton mineral oil detector at 60m from SNS source.
- Oscillation $\bar{\nu}_e$ detected via $\bar{\nu}_e p \rightarrow n\, e^+$, then $np \rightarrow d\gamma$(2.2MeV).
- Backgrounds/yr: 81 intrinsic $\bar{\nu}_e$, ~9 DIF+cosmics.

SNS 1 year



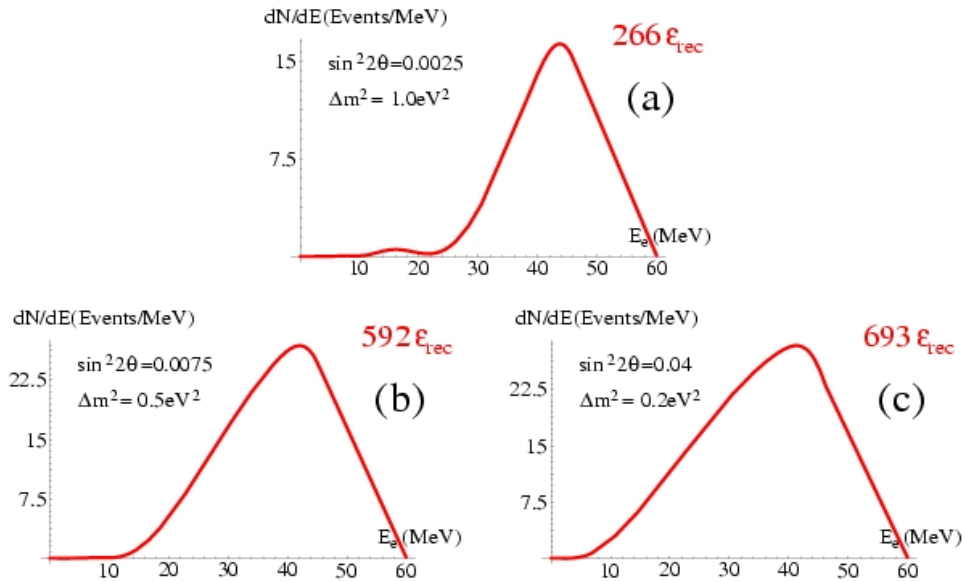
LSND All Data



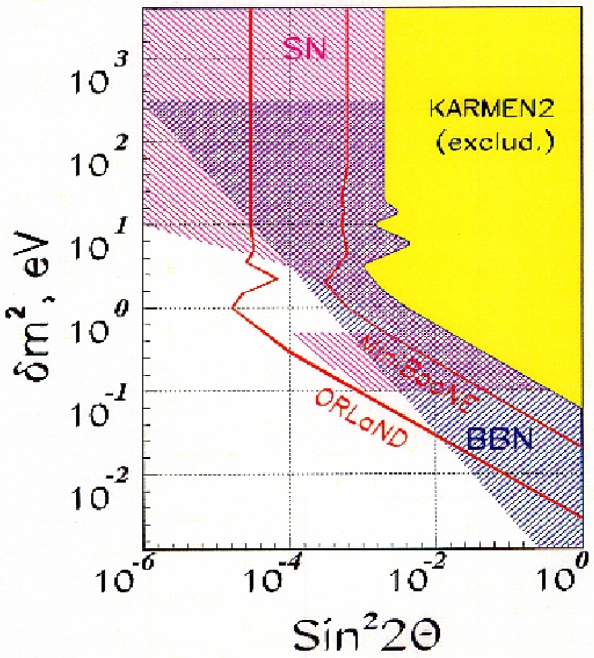
Test of LSND Stopped Muon $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations

(nucl- ex/ 0309014)

- **Spectrum Shape Analysis**

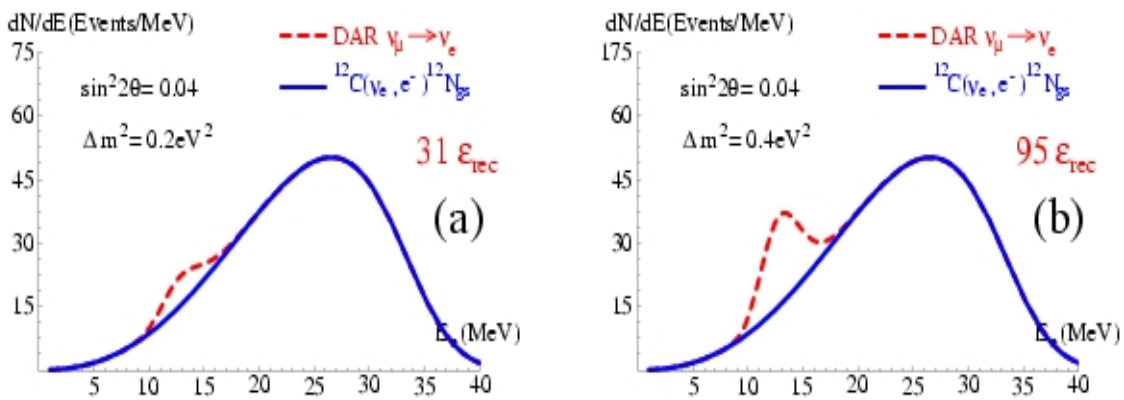


Improved Sensitivity



Measurement of Stopped Pion $\nu_\mu \rightarrow \nu_e$ Oscillations (nucl- ex/ 0309014)

- Single 250 ton mineral oil detector at 60m from SNS source.
- Oscillation ν_e detected via $\nu_e\,{}^{12}C \rightarrow e^-\,{}^{12}N_{gs}$, then ~8 MeV beta (11msec).
- Monoenergetic electron bump at 13 MeV (7% E resolution) on large background from stopped muon DAR ν_e.
- Test CPT by comparing with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ measurement on previous slide.

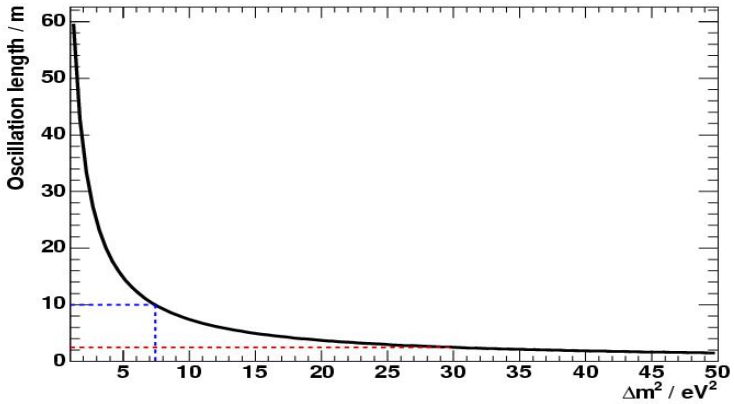


Active-Sterile Neutrino Oscillations with Stopped Pions

hep-ph/0501013

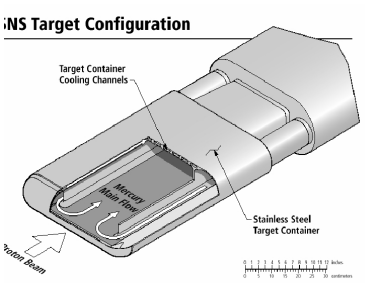
- **If LSND oscillations is $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$, then we expect $P(\nu_\mu \rightarrow \nu_s) > 0.10$**
- **Can detect all neutrinos via NC reaction, $\nu_x\ ^{12}C$ - > $\nu_x\ ^{12}C^*$(15.11MeV).**
- **Since we have monoenergetic ν_μ source, then look for NC rate distortion as a function of L.**

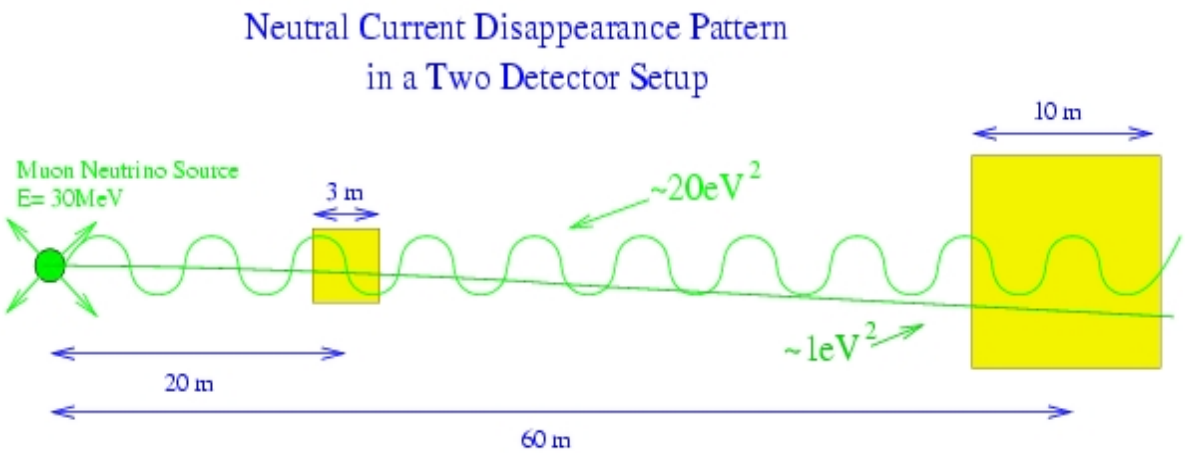
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - sin^2(2\theta)\sin^2(\frac{1.27}{30}\delta m^2 L)$$



Sterile Neutrino Oscillations with $\nu_\mu\ ^{12}C \rightarrow \nu_\nu\ ^{12}C^*(15.11MeV)$

SNS source L=50 cm



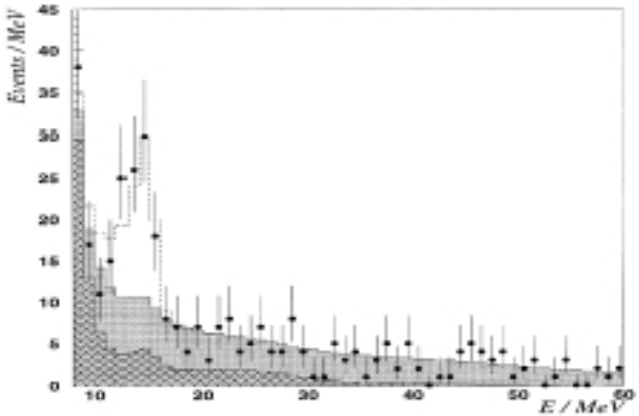


Detector	Source Dist. (m)	FD Size (tons)	FD Length (m)	$\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*$ events/year
SNS Near	18	25	3	2056
SNS Far	60	500	10	3702
FNAL Near	10	116	5	77100
FNAL Far	100	1300	12	8663

We are measuring disappearance of NC interactions as a function of distance. Smoking gun evidence for sterile oscillations!!

Sterile Neutrino Oscillations with $\nu_\mu\ ^{12}C \rightarrow \nu_\nu\ ^{12}C^*(15.11MeV)$

- KARMEN measures $\sigma = (3.2 \pm 0.6) \times 10^{-42}\ cm^2$

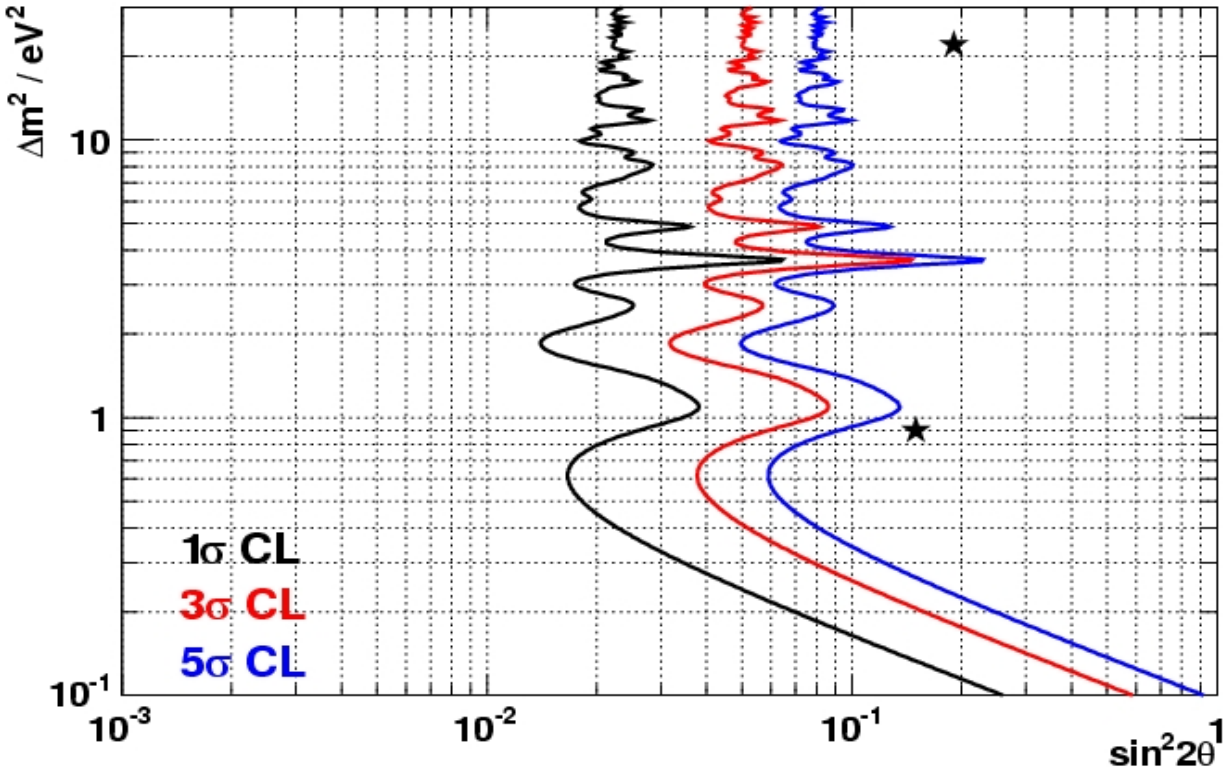


KARMEN gamma $\sigma(E) \sim 2\%$

At SNS design for $\sigma(E) \sim 4$ to 7%

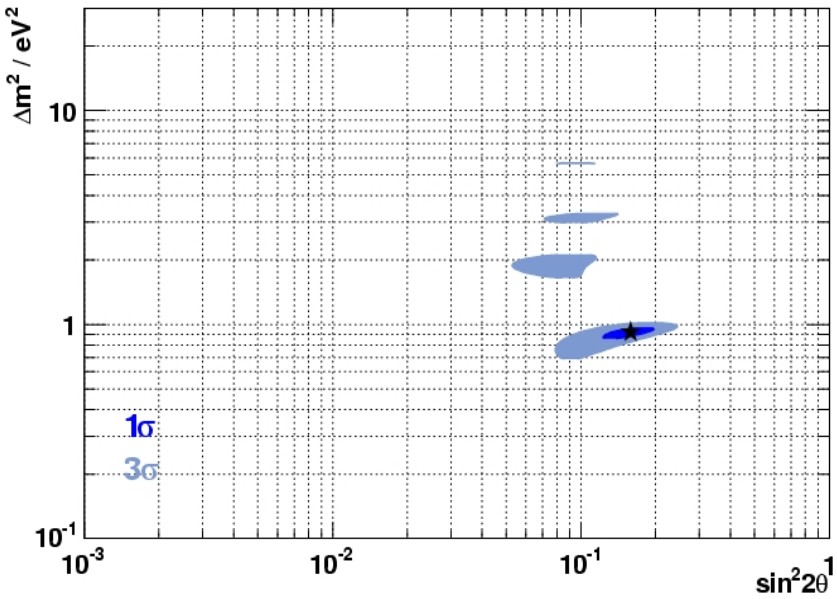
- Expected Backgrounds:
  - → NC $\bar{\nu}_\mu$ and CC ν_e, measured from beam off, ~45%stat.
- L Reconstruction:
  - → 25 cm source size, 60 cm gamma compton scattering.

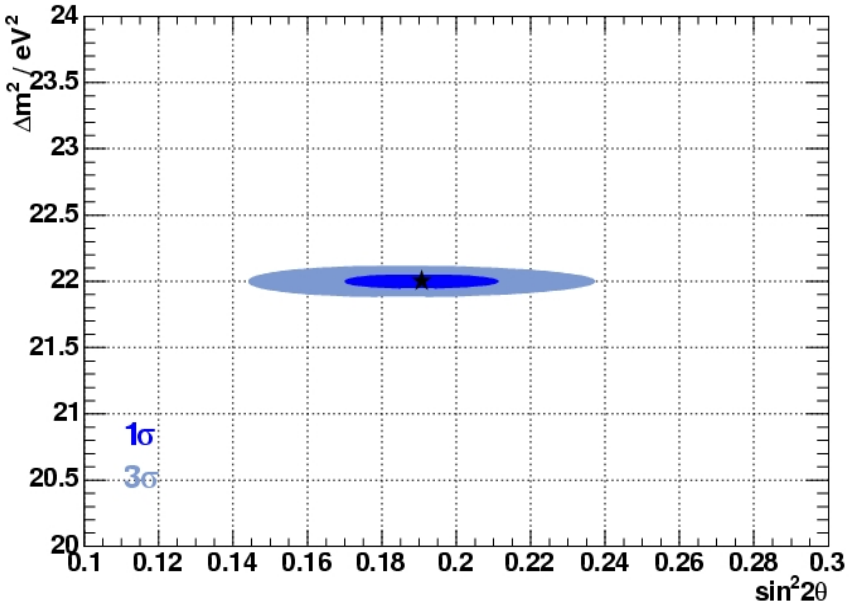
Sterile Neutrino Oscillations Sensitivity with SNS Source and Two Detectors (3 years); 5% flux+xsec systematic error.



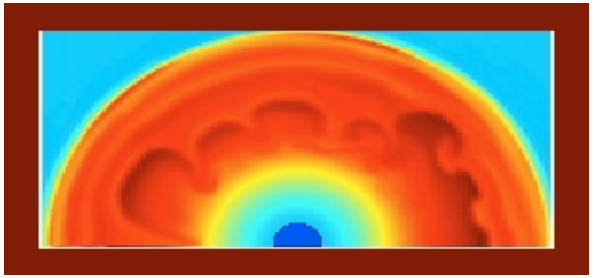
- Assume a physics model; (3+2) oscillations.
- Fold in all systematic errors.

(3+2) Sterile Neutrino Oscillations Measurement with SNS Source and Two Detectors (3 years); 5% flux+xsec systematic error.

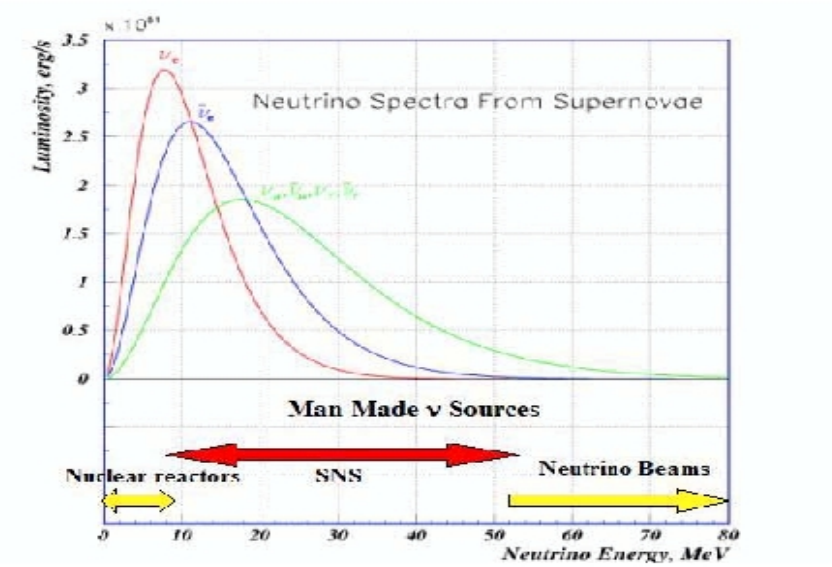


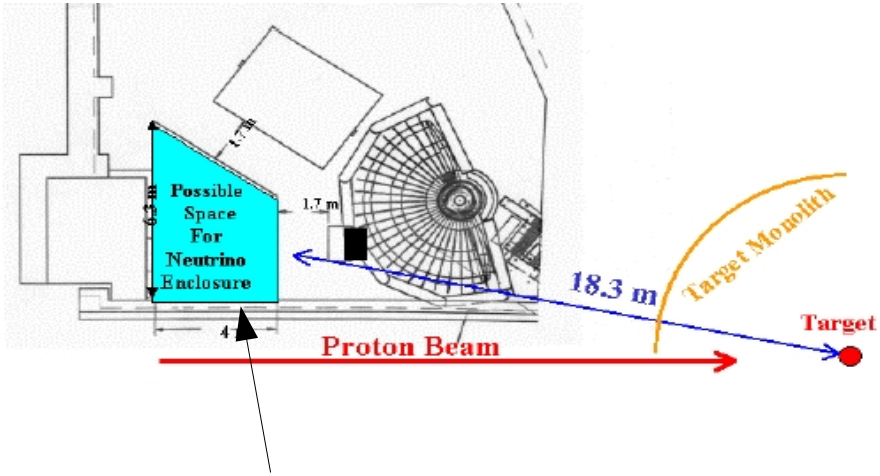


Cross Section Measurements at SNS



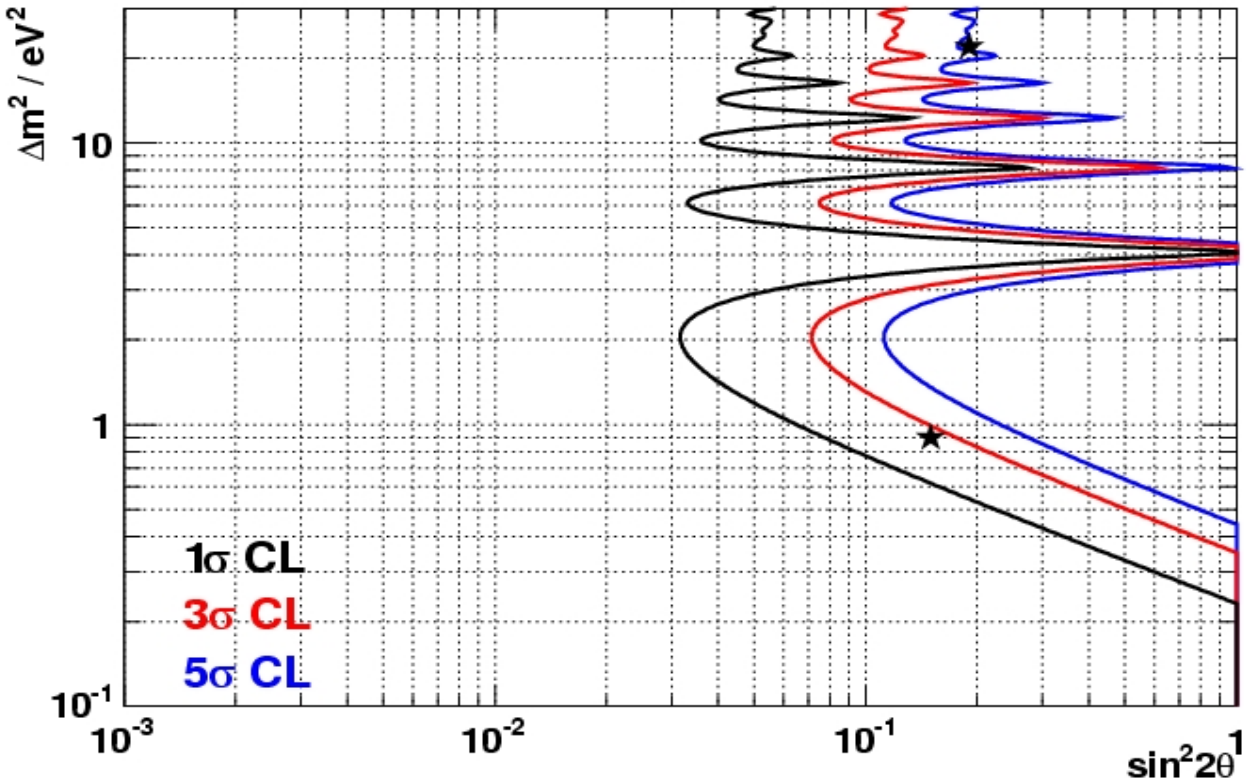
- SNS proposal in the works to measure neutrino nucleus cross sections on Pb, Fe, Al, C, O, D_2O. Strong endorsement from the Aspen APS neutrino meeting.
- Neutrino energies in the supernova type II core collapse region. This is important to studying the astrophysics of supernova, and for supernova neutrino detectors.





- 30 ton liquid scintillator detector

Sterile Neutrino Oscillations Sensitivity with SNS Source and One Near Detector (3 years), 5% flux+xsec systematic error.



OscSNS Cost

- Neutrino source: FREE!
- Near detector: FREE! (νSNS proposal)
- Far detector:

Item	Cost ($K)
Tank and support structure	1200
PMT's	4671
Electronics/DAQ	756
Oil & Scintillator	1636
Calibrations	912
Miscellaneous	180
Engineering & Construction	2347
Total	11702

It is not every day you can propose an experiment with the potential to discover new physics for only ~$10M, a real bargain!!!

Conclusions

- To really test the LSND signal, and make a convincing active-sterile neutrino oscillation measurement requires a neutrino experiment at the SNS.
  - Two LSND/MiniBooNE style detectors at 22m and 60m (see hep-ph/0501013 for details).
- Take advantage of the new (FREE!) high intensity stopped pion/muon source at the SNS.
  - 2014 upgrade to two sources and 3MW!
- We have a white paper written, and will be seeking funding possibilities in the coming year.
- Experiments are hard! But with good planning and careful execution, will succeed and provide exciting physic results!!