Very Short Baseline Neutrino Oscillation Experiments using Cyclotron Decay-at-Rest Sources

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Hints for High $\Delta m^2 \sim 1\ eV^2$ Oscillation $\Rightarrow$ Sterile Neutrinos? or Something Else?

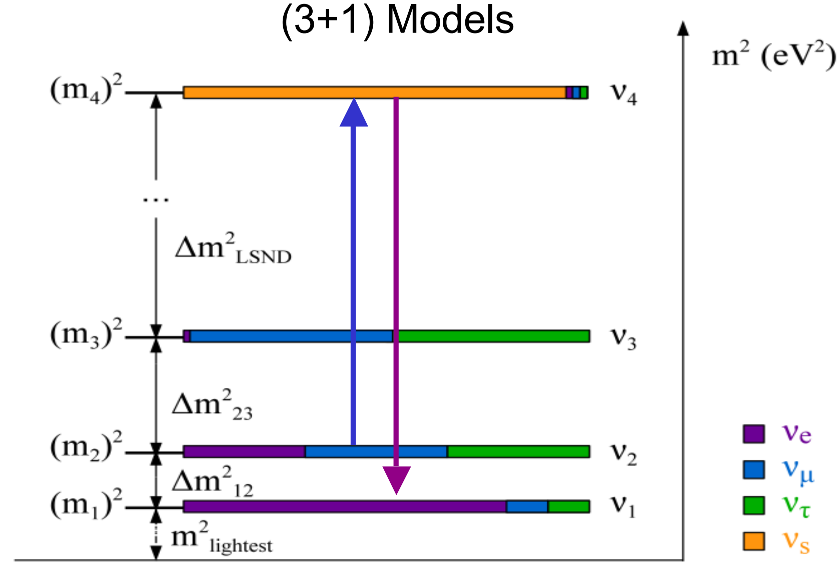
- Positive indications:
  - LSND/MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal
  - MiniBooNE low-energy excess ($\nu_\mu \rightarrow \nu_e$?)
  - Reactor disappearance anomaly ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)
  - Gallex-Sage reduced calibration source rate (ν_e disappearance?)

- Negative indications:
  - CDHS and MiniBooNE restrictions on ν_μ disappearance
  - MiniBooNE restrictions on $\bar{\nu}_\mu$ disappearance
  - Karmen restrictions on $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Other negative results

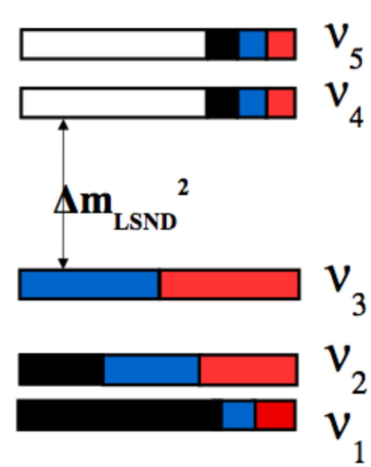
Phenomenology of Oscillations with Sterile Neutrinos

- In sterile neutrino (3+1) models, high Δm^2 ν_e appearance comes from oscillation through ν_s
  - $\nu_\mu \to \nu_e = (\nu_\mu \to \nu_s) + (\nu_s \to \nu_e)$
- This then requires that there be ν_μ and ν_e disappearance oscillations
  - In the past, constraints on disappearance have restricted any (3+1) models but reactor anomaly has maybe relaxed this costraint
- Information on appearance and disappearance confusing
  - Differences needed between ν versus $\bar{\nu}$ disappearance needed
    - But CPT invariance demands neutrino and antineutrino disappearance to be the same.
  - Also differences between $\nu_\mu \to \nu_e$ and $\bar{\nu}_e \to \bar{\nu}_e$
    - Need to bring in (3+2) models

(3+1) Models



(3+2) Models



Example (3+1) and (3+2) Model Fits

3+1 Model:

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 x_{41} = \sin^2 2\theta_{\mu e} \sin^2 x_{41}$$

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2 x_{41} = 1 - \sin^2 2\theta_{ee} \sin^2 x_{41}$$

Example Fit: $\Delta m^2_{41} = 0.92\, eV^2$ $\sin^2 2\theta_{\mu e} = 0.0025$ $\sin^2 2\theta_{\mu\mu} = 0.13$ $\sin^2 2\theta_{ee} = 0.073$

G. Karagiorgi, Z. Djurcic, J. Conrad, M. Shaevitz, and M. Sorel, Phys.Rev. D80, 073001 (2009), 0906.1997

$$x_{ij} \equiv \Delta m^2_{ij} L/4E$$

3+2 Model:

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 x_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 x_{51} + 8|U_{e4}U_{\mu 4}U_{e5}U_{\mu 5}| \sin x_{41} \sin x_{51} \cos(x_{54} \pm \delta)$$

± : ν vs $\bar{\nu}$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2 x_{54}]$$

Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π
0.47	0.128	0.165	0.87	0.138	0.148	1.64

J. Kopp, M. Maltoni, and T. Schwetz (2011), 1103.4570.

(Short baseline approximation where highest mass state dominates: $\Delta m^2_{12} \approx \Delta m^2_{13} \approx 0$)

Next Experimental Steps

If we are seeing oscillations through sterile neutrinos, then one needs to make both appearance and disappearance oscillation searches for neutrinos and antineutrinos

- This information can prove the consistency with (3+1) and (3+2) models

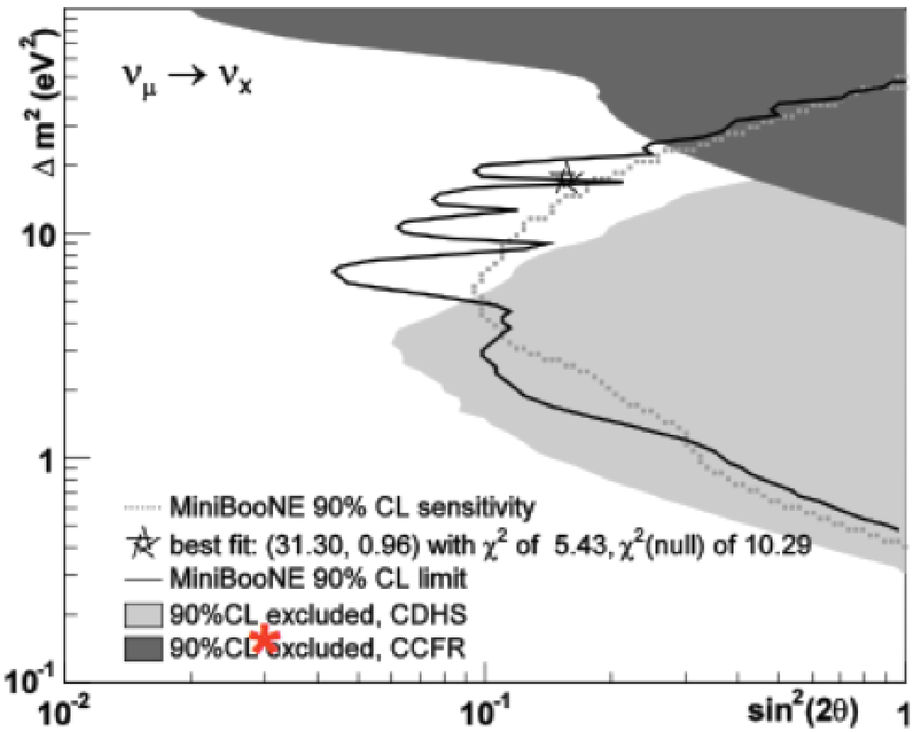
1. Address MiniBooNE/LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal
2. Address MiniBooNE low-energy ν_e excess
3. Very short baseline ν_e and $\bar{\nu}_e$ disappearance
4. Two detector ν_μ and $\bar{\nu}_\mu$ disappearance

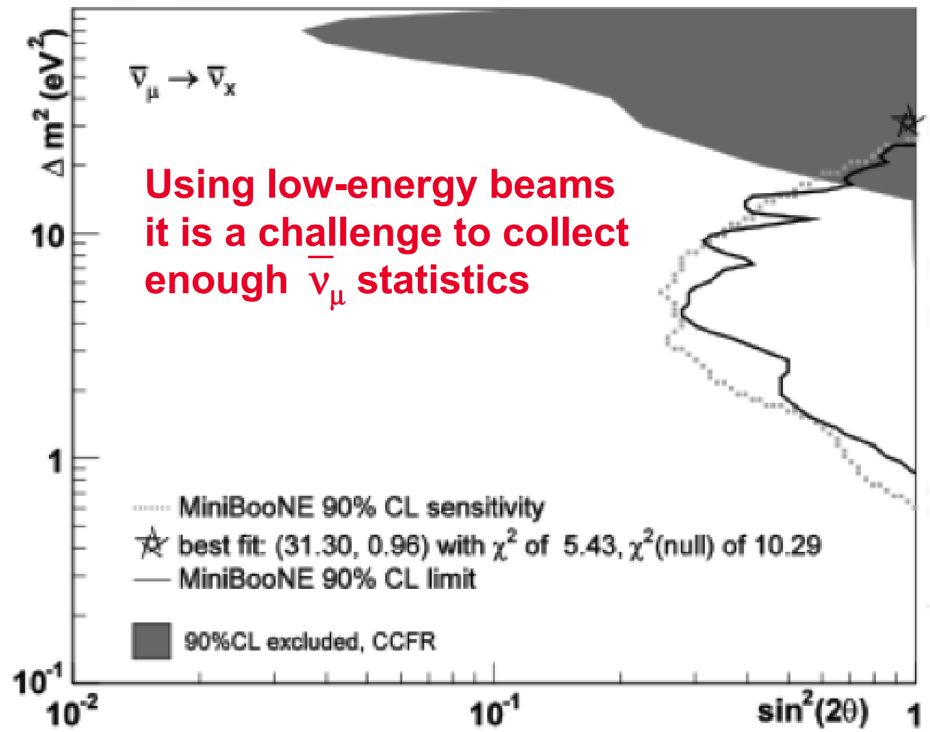
(Items 3 and 4:) CPT Invariance implies that ν and $\bar{\nu}$ disappearance are the same

Do we need to look for both ν and $\bar{\nu}$ disappearance?

MiniBooNE, CDHS, CCFR ν_μ and $\bar{\nu}_\mu$ Disappearance Limits

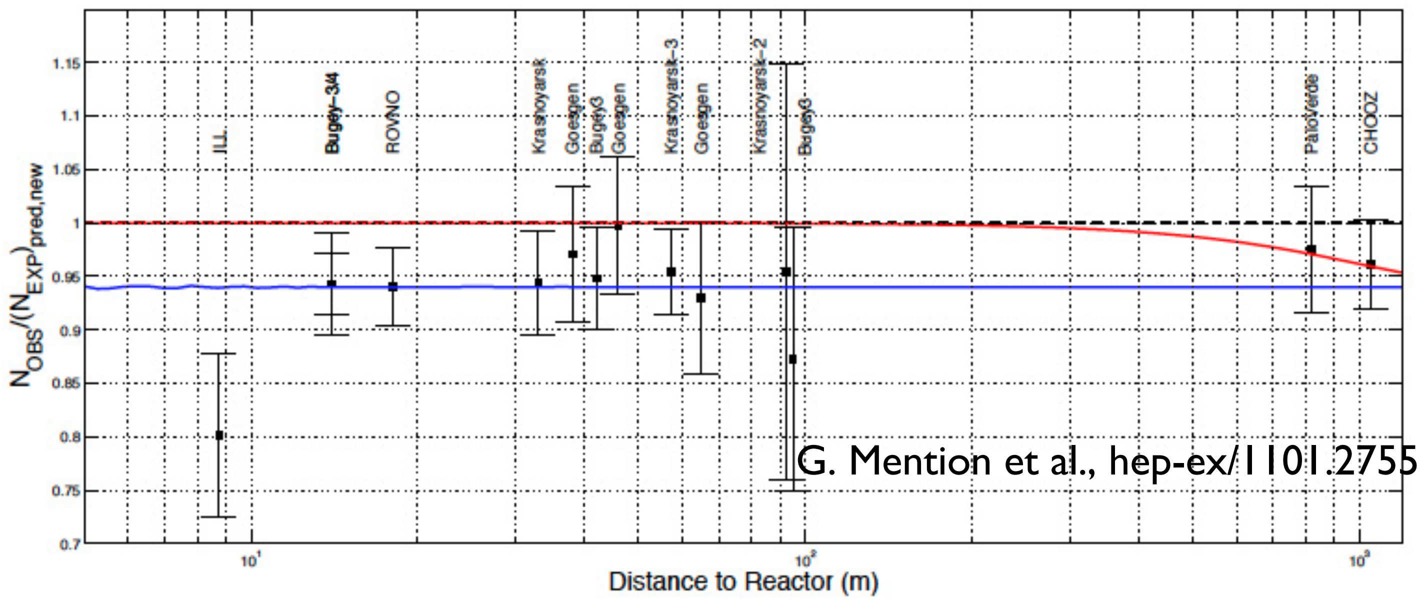
- Stringent limits on ν_μ disappearance from previous experiments
- Less stringent limits for $\bar{\nu}_\mu$ disappearance
  - Antineutrino rate low





Reactor Antineutrino Anomaly - $\bar{\nu}_e$ Disappearance

- Could be oscillations to sterile neutrino with $\Delta m^2 \sim 1 eV^2$ and $\sin^2 2\theta \sim 0.1$



Red line: Oscillations assuming 3 neutrino mixing

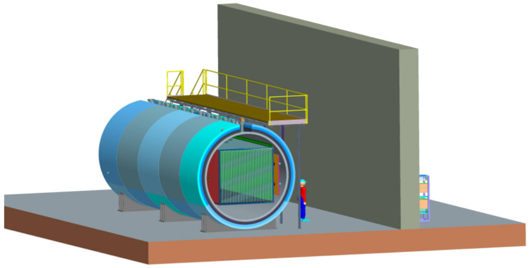
Blue line: Oscillations in a 3 + 1 (sterile neutrino) model

- Hard to design a follow-up experiment to prove there is $\bar{\nu}_e$ disappearance
  - Current program of two detector reactor measurements will see same disappearance in near and far detectors.
  - Need to place near detector very close to be sensitive to $\Delta m^2 \sim 1 eV^2$ oscillations using a ~3 MeV reactor source.
    - Does source and detector size wash out oscillations ?

Present Plans and Ideas

Approved program:

1. Increase by x2-x3 the MiniBooNE $\bar{\nu}$ data over the next year
   ⇒ Reach 3 to 4 σ?



2. New MicroBooNE Exp in front of MiniBooNE (2013)
   Liquid Argon TPC detector which can address the low-energy excess:
   - Reduced background levels
   - Can determine if low-energy excess due to single electron or photon events?

Other ideas:

- New one or two detector experiments for appearance and disappearance
  - At Fermilab using using new detectors in MiniBooNE beamline
  - CERN PS neutrino beam with Icarus style detectors at 130m/850m
  - Decay-at-rest beam close to large scintillator (or water) detector (LENA)
- Very short baseline ν_e disappearance
  - Use high rate radioactive sources in Borexino detector
  - Small detector close (<10m) to nuclear reactor
  - Decay-at-rest beam close to a large detector (Nova, LENA, LAr_1kton)

Possible Methods for a ν_e Disappearance Search

- Can search for ν_e disappearance is several ways
  - Look for a deficit in the number of ν_e events with respect to prediction.
    - Need to know absolute normalization of ν_e flux
    - Difficult since ν_e flux in a typical ν_μ beam is a small background
    - Large backgrounds to isolating ν_e events in most detectors

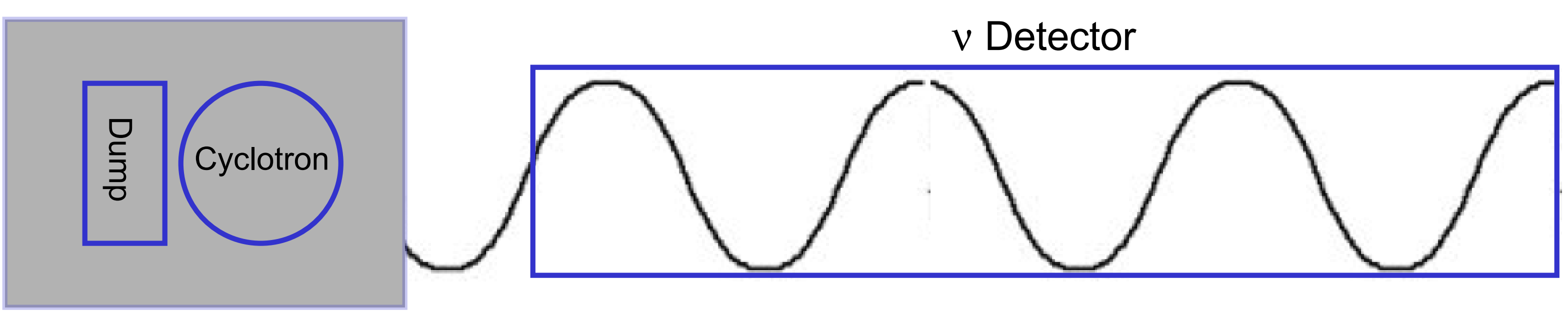
    $\Rightarrow$ No precise ν_e disappearance measurements yet

  - Look for a change in rate for ν_e events versus L/E
    - In a conventional beam, poor knowledge of L and E
      - Uncertainties in ν_e energy distribution from hard to model background processes
      - Uncertainties in ν_e production point due to long decay pipes
    - Decay-at-rest beam does not have these uncertainties
      - Extremely well know energy spectrum (muon decay-at-rest spectrum)
      - Production point uncertainty <30cm from interaction length in dump

$\Rightarrow$ ***Cyclotron decay-at-rest beams is a good choice for a ν_e disappearance measurement***

Very-short Baseline ν_e Disappearance Experiment

- Use cyclotron decay-at-rest source (almost a point source)
- Look for a change in event rate as a function of energy within a long ν-detector
  - With no oscillations the rate should go as $1/L^2$
- Bin observed events in L/E (corrected for the $1/L^2$) to search for oscillations



Decay-at-rest Beam Can Also be Good for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Search

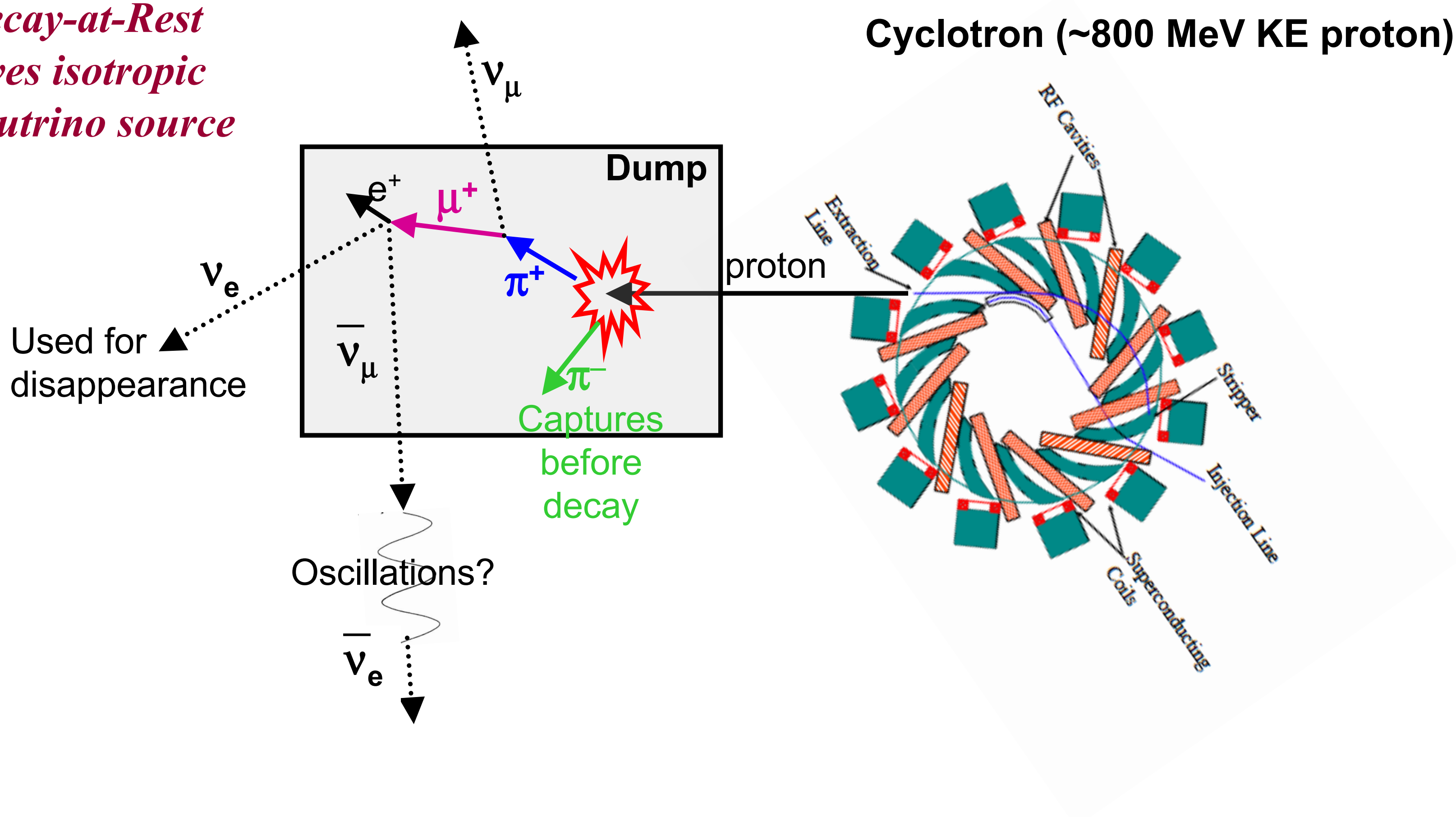
- With cyclotron source close to detector, rate is very high
  - Much of the physics I will show can be done with lower power than DAEdALUS, so these machines can be prototypes for DAEdALUS

- Use inverse beta-decay (IBD) to isolate the $\bar{\nu}_e$ signal

- Need to use delayed coincidence between outgoing positron and neutron capture to reduce background from ν_e CC scatters
  - Detector needs to be able to see neutron capture so need:
    - free hydrogen (scintillator or water)
    - (or dope detector with Gadolinium.)

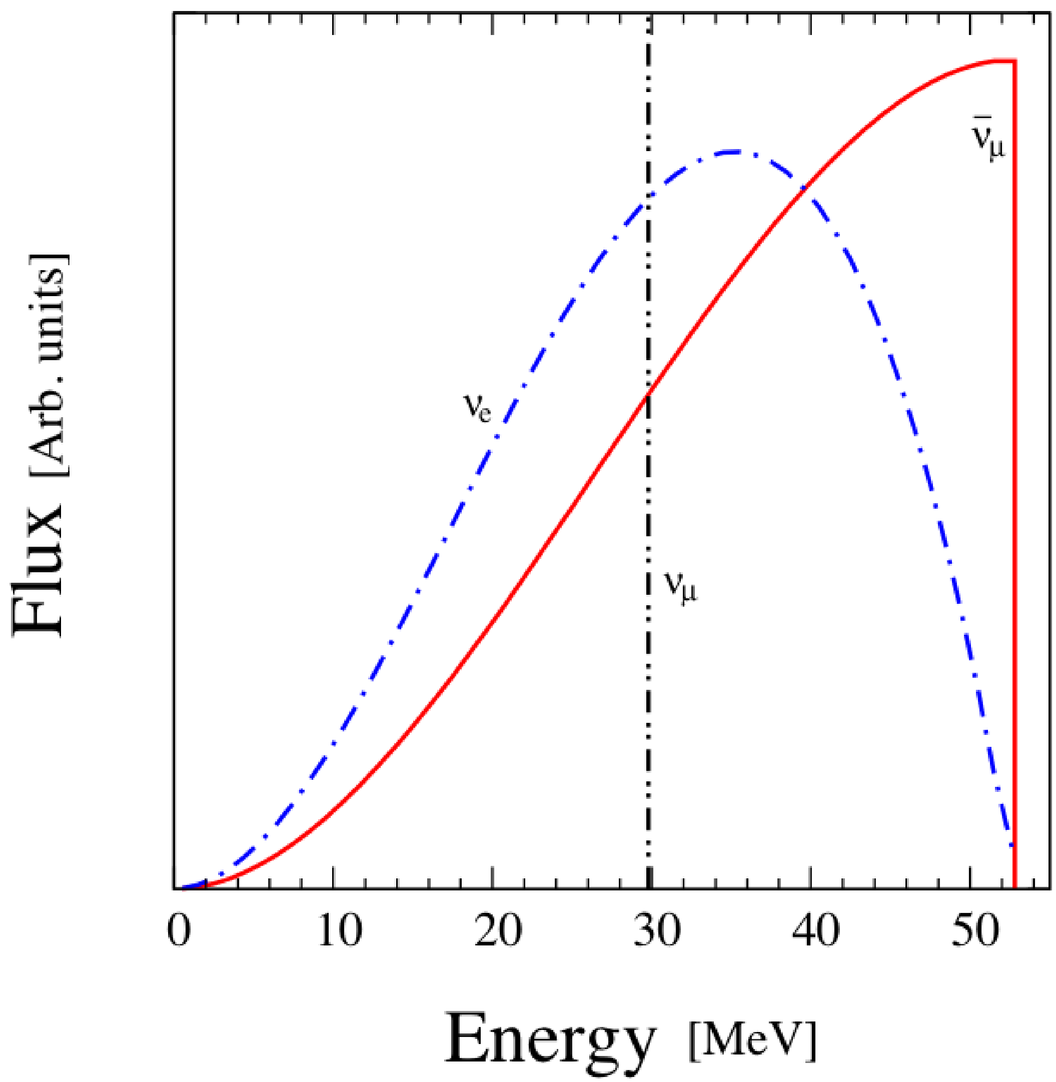
Decay-at-Rest (or Beam Dump) Neutrino Source

Decay-at-Rest gives isotropic neutrino source



Each π^+ decay gives one ν_μ, one ν_e, and one $\bar{\nu}_\mu$ so measuring any of these will set the neutrino flux normalization.

Energy Spectrum for π Decay-at-Rest Beam
(No uncertainty in energy spectrum)



EURONU-WP6-11-32
IFIC/11-22

Short-baseline Neutrino Oscillation Waves in Ultra-large Liquid Scintillator Detectors

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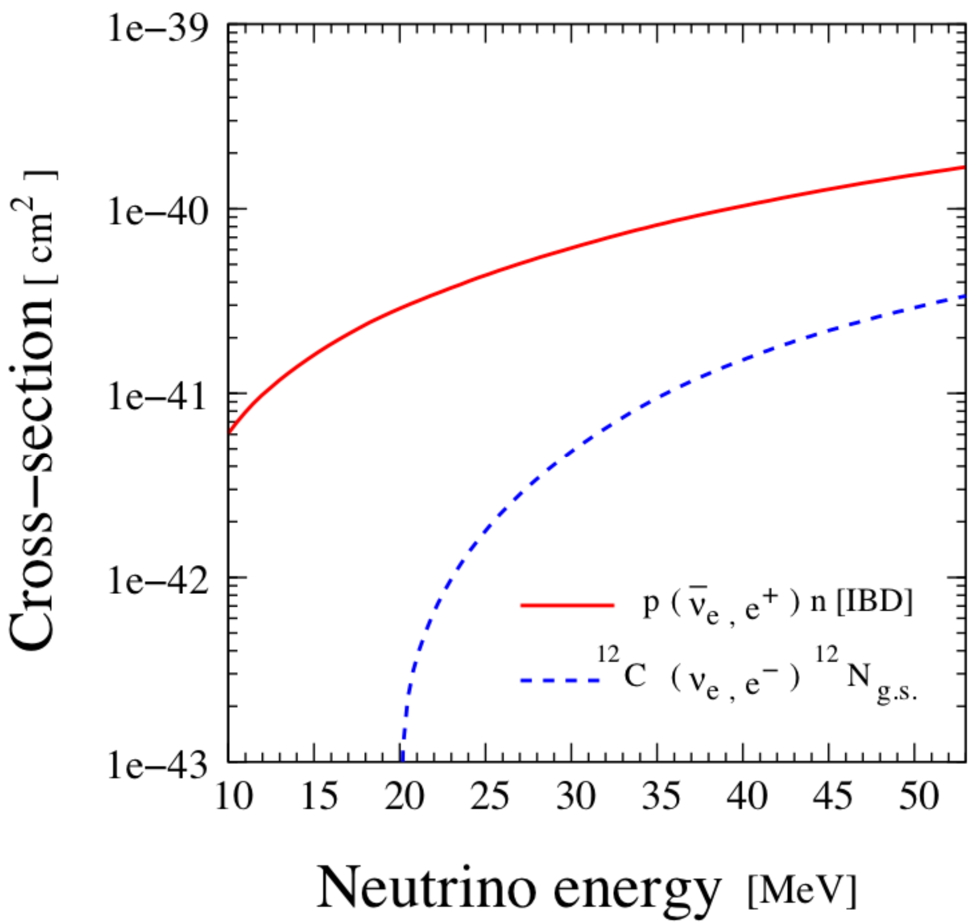
For these studies assume:

- **100 kW** cyclotron DAR source over 1-2 years ⇒ 4.0e21 ν_e and 4.0e21 $\bar{\nu}_\mu$
- Intrinsic $\bar{\nu}_e$ background from π^- assumed to be at the 4×10^{-4} level

Also, would run 50% beam-on and 50% beam-off to measure backgrounds

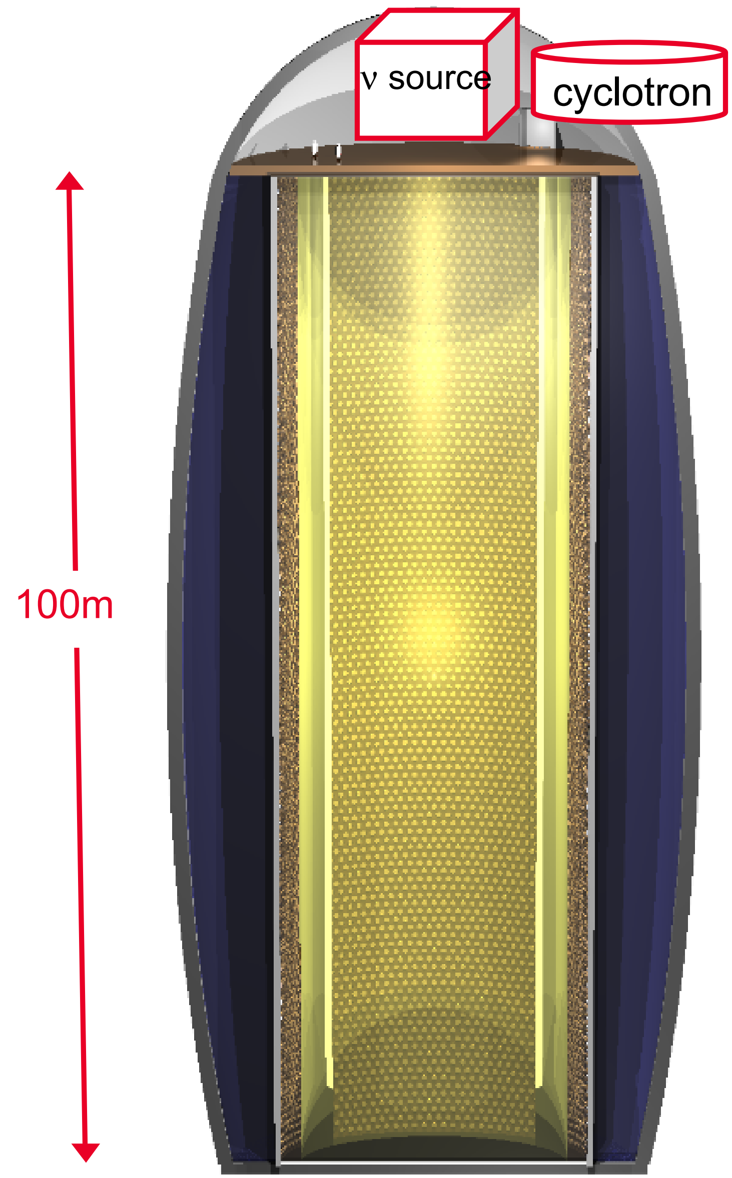
Processes and Cross Sections for Osc Study



- $\nu_e \rightarrow \nu_e$ Disappearance
  - Process:
    $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N_{gs}$
  - Look for an oscillatory change in ν_e rate with L/E
  - Threshold = 17.3 MeV
    - $E_{vis} = E_\nu$ - 17.3 MeV
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance
  - Process:
    $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Detector needs to provide free hydrogen targets and be able to detector the capture of the outgoing n
  - Threshold = 1.8 MeV
    - $E_{vis} = E_\nu$ - 0.8 MeV

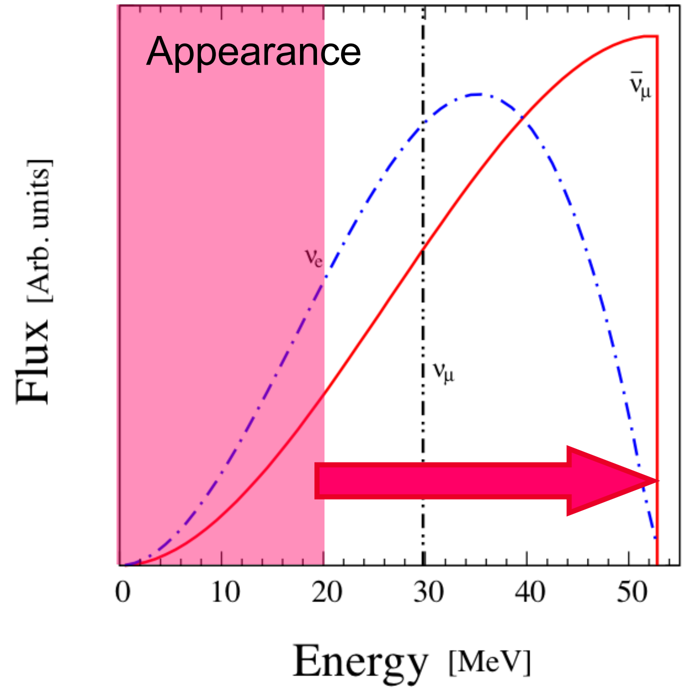
LENA Scintillation Detector
(Part of the European LAGUNA Project)

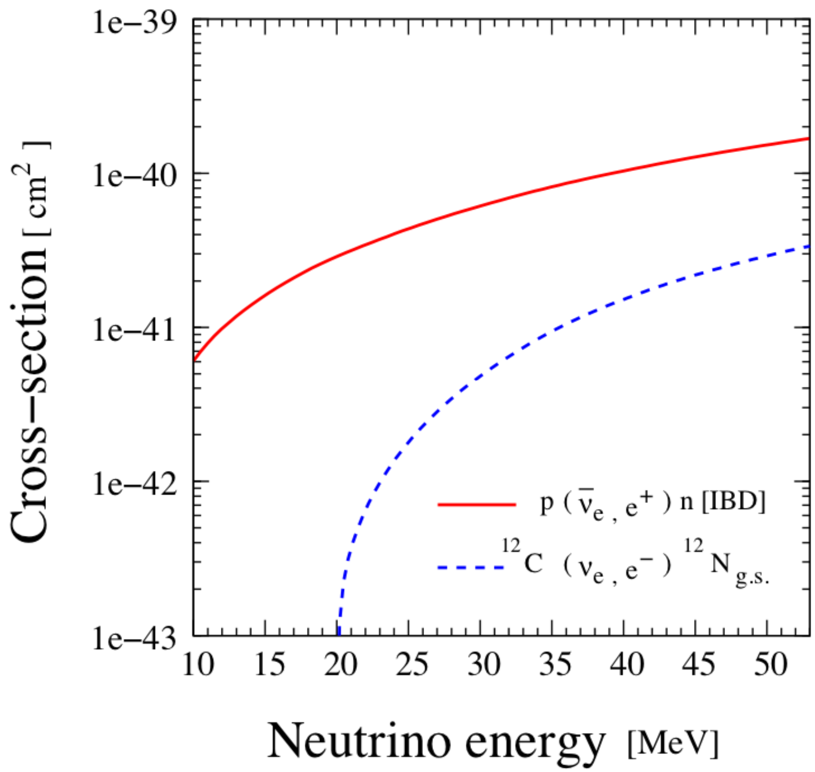
- 50 kton fiducial mass
- 100 m tall by 30 m diameter
- Low detection threshold down to 200 keV
- Energy resolution 10% / √E(MeV)
- Clear coincidence signal for $\bar{\nu}_e$ IBD events ($\bar{\nu}_e + p \to e^+ + n$)
- Deep location (4000 mwe) so negligible cosmic muon backgrounds
- Energy cuts:
  - Appearance: E_ν > 20 MeV
  - Disappearance: E_ν > 33 MeV

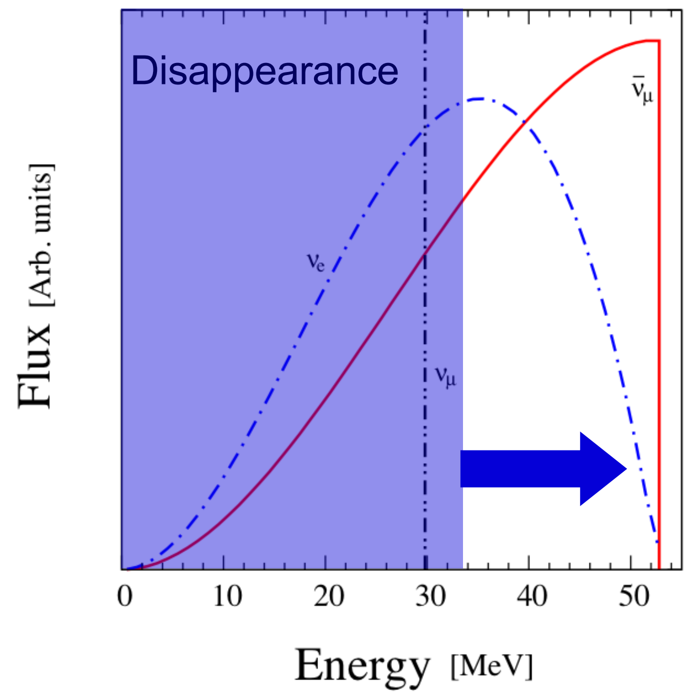


Visible Energy Reduced by Q-value

- Visible energy cut E_{vis}> ~20 MeV
  - Reduce backgrounds
  - Good trigger and measurement eff
- Implies effective E_ν cut
  - Appearance ⇒ E_ν > 20 MeV
  - Disappearance ⇒ E_ν > 33 or 37 MeV

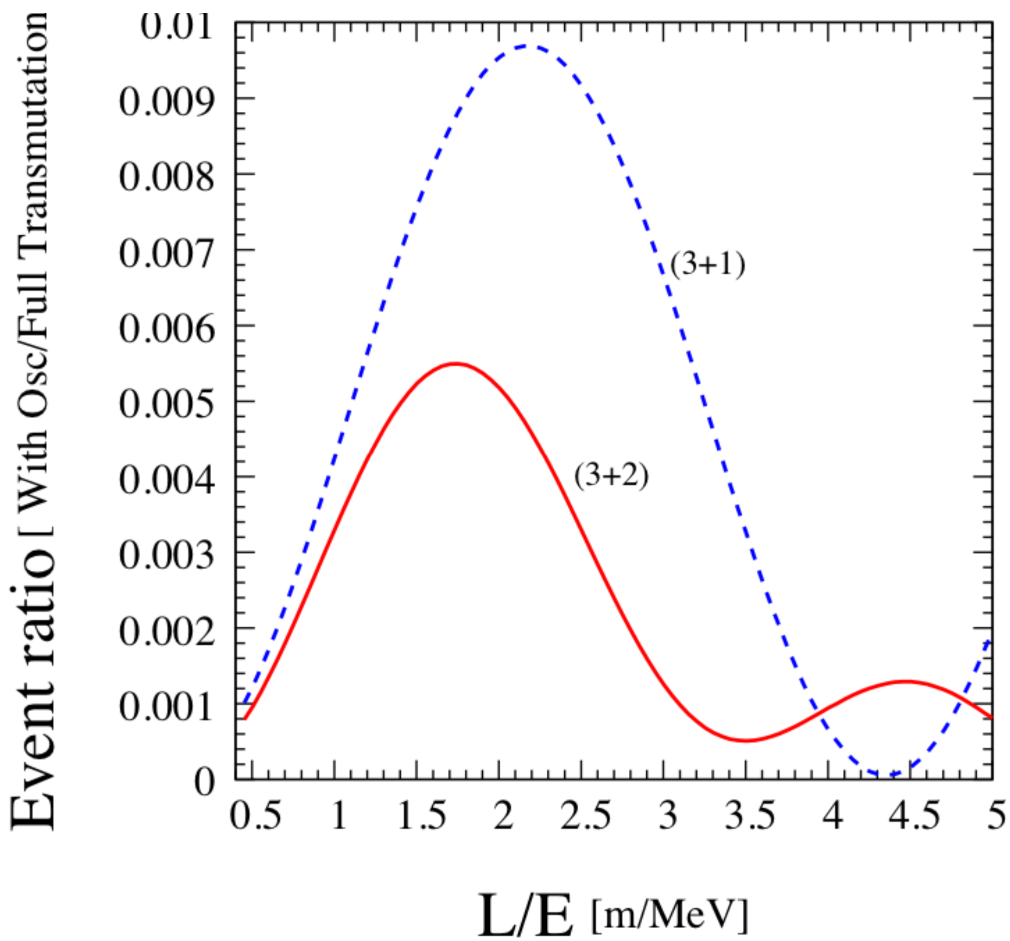






Appearance Mode Analysis

- Bin and fit $\bar{\nu}_e + p \rightarrow e^+ + n$ data as a function of L/E
  - Include normalization uncertainty of 10% mainly due to neutrino flux
  - Include intrinsic $\bar{\nu}_e$ background (4e-4 level) with 20% uncertainty



(3+1) *Fit*
Karagiorgi et al.
$\Delta m^2_{41} = 0.57$
$\sin^2 2\theta_{\mu e} = 0.0097$

(3 + 2) *Fit* Kopp, Maltoni, Schwetz (2011), 1103.4570.

(3+2) Model $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Sensitivity: LENA with DAR Source

- Consider LENA type detectors with various total fiducial mass
- Compare to Kopp et al. (Ref. A) and Karagiorgi et al. (Ref. B) (3+2) best fits

Event Rates

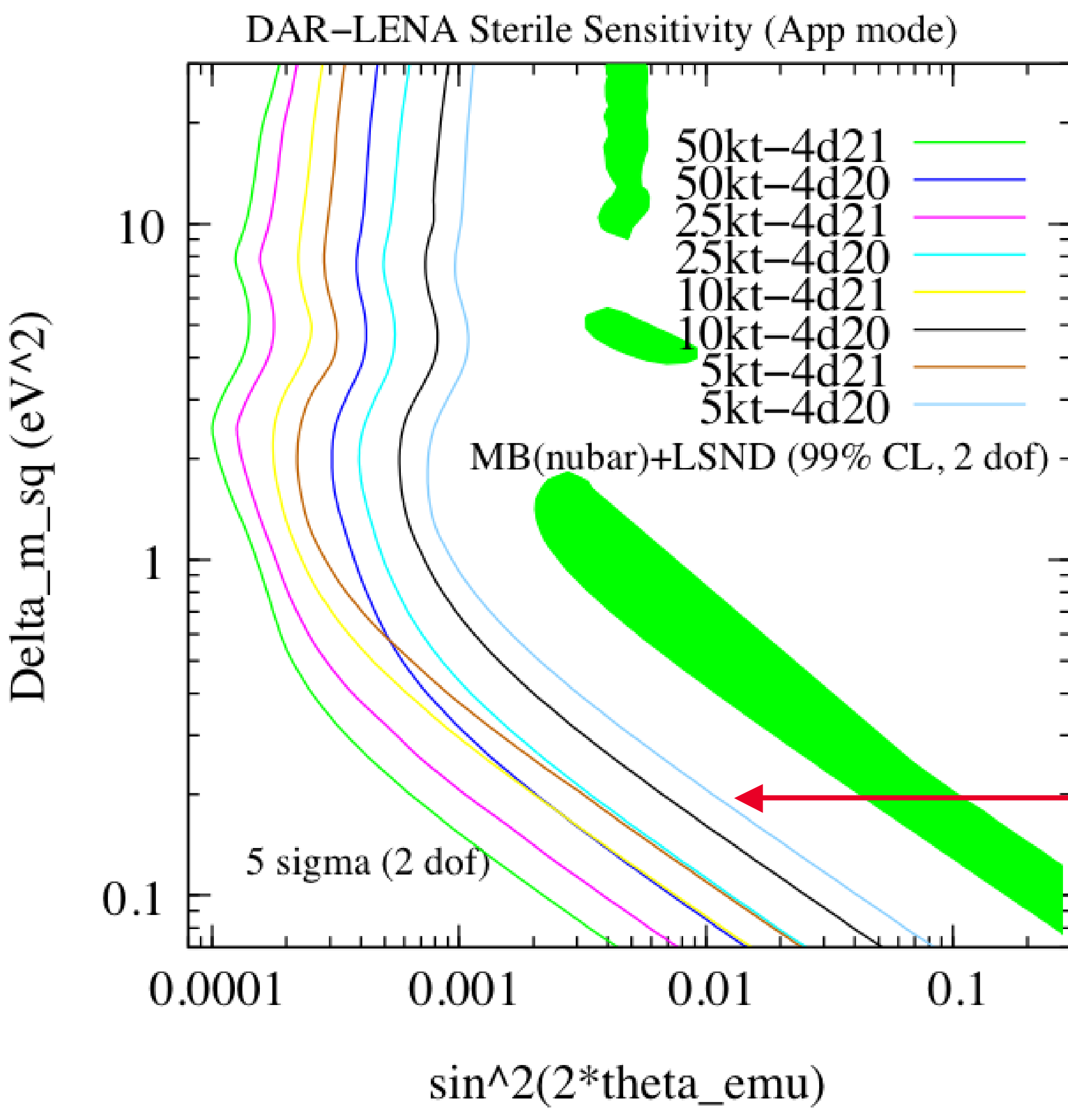
100 kW cyclotron with 4e21 $\bar{\nu}_\mu$'s

Fiducial Mass	Radius	Height	Signal (A : Ref. [25])	Signal (B : Ref. [24])	Intrinsic $\bar{\nu}_e$ Background
50 kt	13.58 m	100 m	12985	32646	1450
25 kt	10.78 m	79.37 m	7787	18356	875
10 kt	7.94 m	58.48 m	3753	7964	443
5 kt	6.3 m	46.42 m	2080	4044	261

Total Neutrino Flux needed to exclude (3+2) Best Fits at 5σ for Ref. A and Ref. B

Fiducial Mass	Flux (A : Ref. [25])	Flux (B : Ref. [24])
50 kt	0.912×10^{19}	0.302×10^{19}
25 kt	1.535×10^{19}	0.539×10^{19}
10 kt	3.235×10^{19}	1.27×10^{19}
5 kt	5.935×10^{19}	2.6×10^{19}

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Sensitivity (3+1) at 5σ LENA with DAR Source



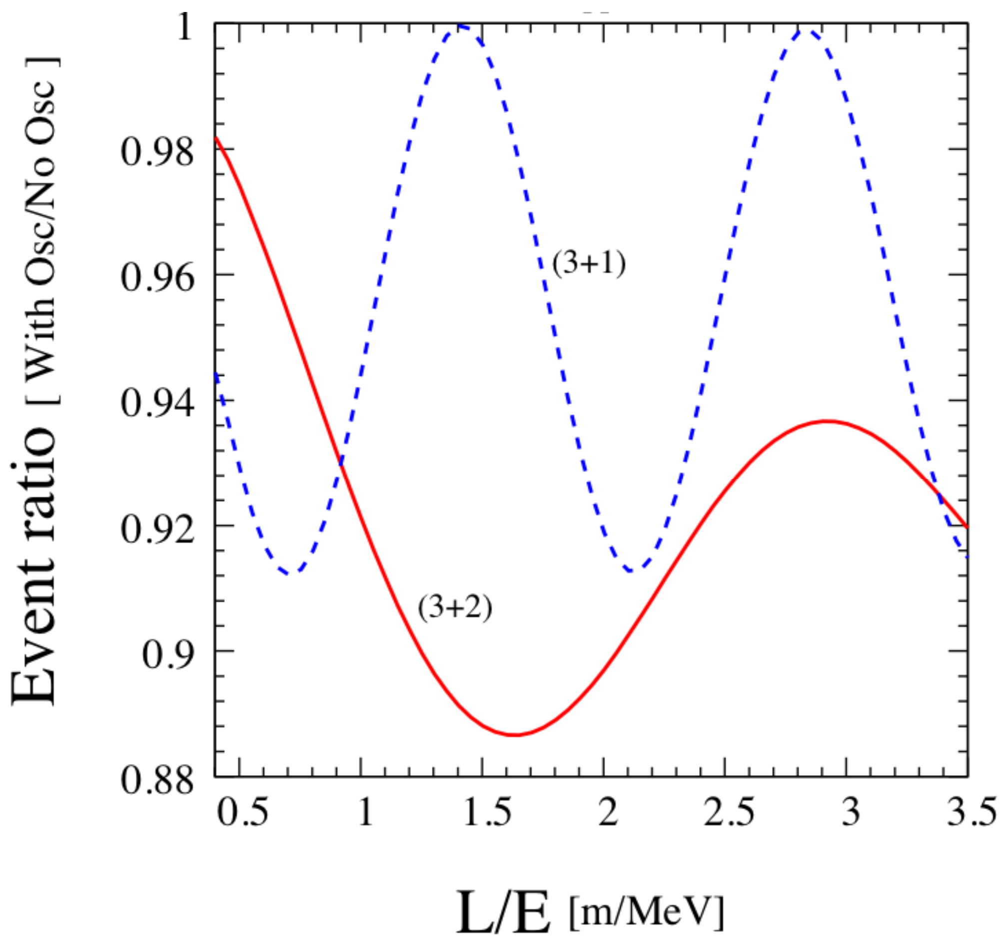
3+1 Type Model with simple two-neutrino

Results for:
100 kW, 4e21 nu's
10 kW, 4e20 nu's
and with various fiducial masses

A 5 kton scintillator detector combined with a small 10 kW source can test the MiniBooNE/LSND signal at 5 s !

Disappearance Mode Analysis

- Bin and fit $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N_{gs}$ data as a function of L/E
  - Include normalization uncertainty of 15% due to neutrino flux and xsec uncertainties
  - Negligible background from cosmic muons since beam ν_e CC event rate is very high and detector is under 4000 mwe of shielding.



(3+1) and (3+2) Examples from Kopp, Maltoni, Schwetz, (2011) 1103.4570

(3+2) Model $\nu_e \rightarrow \nu_e$ Disappearance Sensitivity: LENA with DAR Source

- Again consider LENA type detectors with various total fiducial mass
- Compare to Kopp et al. (Ref. A) and Karagiorgi et al. (Ref. B) (3+2) best fits

Event Rates

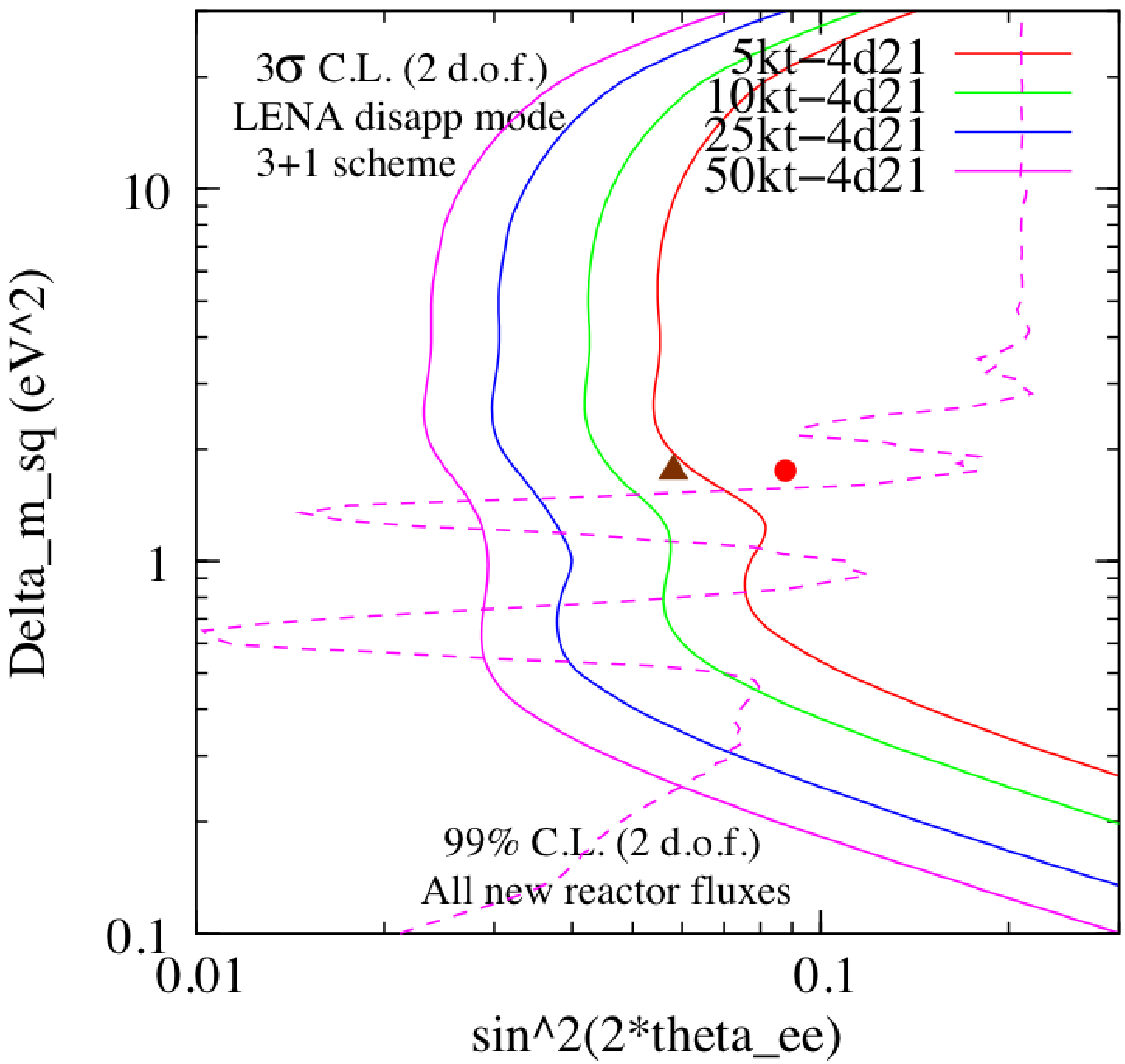
100 kW cyclotron with 4e21 ν_e's

Fiducial Mass	Radius	Length	Evts w/ Osc (A : Ref. [25])	Evts w/ Osc (B : Ref. [24])	Evts, No Osc
50 kt	13.58 m	100 m	170191	139119	181672
25 kt	10.78 m	79.37 m	102726	85271	109590
10 kt	7.94 m	58.48 m	52105	43940	55439
5 kt	6.3 m	46.42 m	30874	26321	32735

Total Neutrino Flux needed to exclude (3+2) Best Fits at 3σ for Ref. A and Ref. B

Fiducial Mass	Flux (A : Ref. [25])	Flux (B : Ref. [24])
50 kt	3.39×10^{20}	0.093×10^{20}
25 kt	5.55×10^{20}	0.214×10^{20}
10 kt	11.25×10^{20}	0.569×10^{20}
5 kt	22.1×10^{20}	1.202×10^{20}

ν_e Disappearance (3+1): LENA with DAR Source



3+1 Type Model with simple two-neutrino approximation

Results for:
100 kW, 4e21 nu's and with various fiducial masses

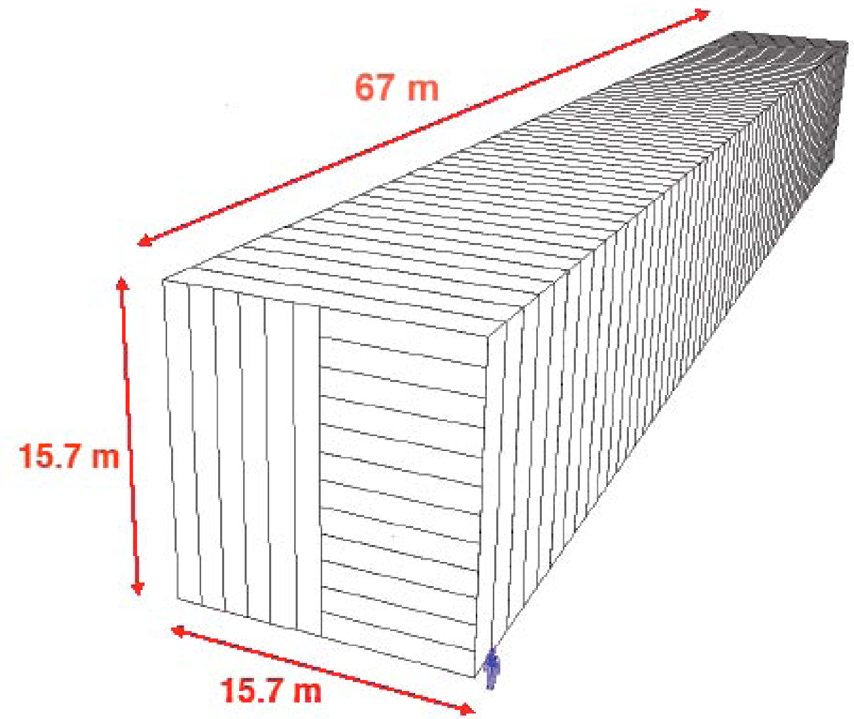
Triangle and the bullet (3+1) best-fit values for all reactor data with old and new fluxes.

But we will have a new very large scintillator detector soon

$\Rightarrow$ The Nova Experiment

Nova Experiment

- Detector mass 14 kton
  - CH_2 Scintillator Target - 30% PVC
- 15.7m x 15.7m x 67m long
- Nova not made to detect low enegy signal
  - Plan to use beam gate to reduce cosmic bkgnd
- Nova can only probably do ν_e disappearance
  - Cannot detect the 2.2 MeV gamma from neutron capture on hydrogen
- Energy resolution 15% / $\sqrt{E(MeV)}$
- Very little shielding - 3m of earth
- Signal is 3,400 (20kW) to 34,000 evt/yr (100kW)
- Cosmic-ray background from stopping muon producing Michel electron decays
  - 10^{10} stopping muons need to be vetoed down to 10,000 event per year
  - For studies, consider backgrounds from 10,000 to 50,000



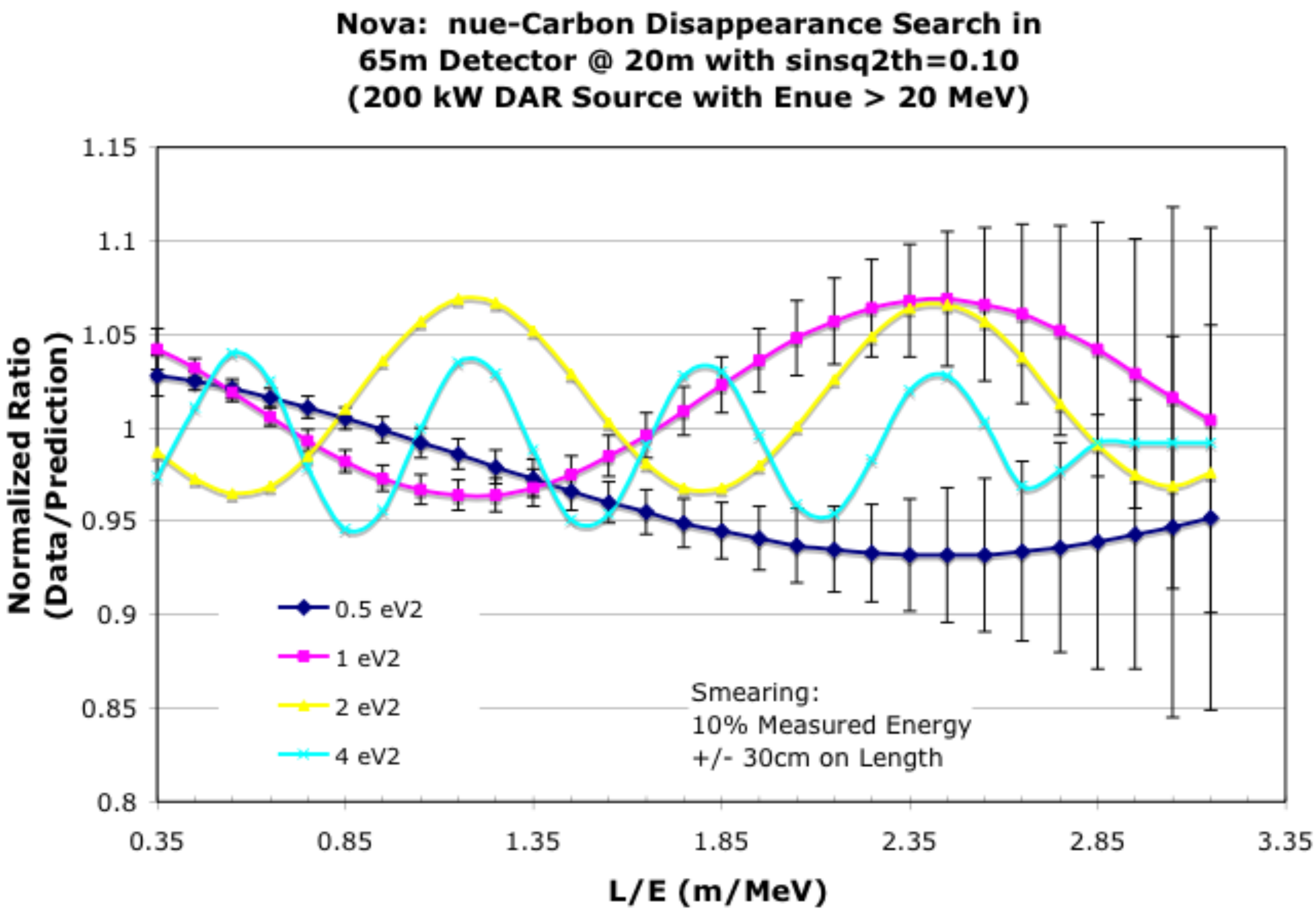
Nova Experiment

Far detector site, September 12, 2010

Possible Cyclotron Location: Nova Experiment

Nova: Rate Ratio vs L/E

1 year of data



(3+2) Model $\nu_e \rightarrow \nu_e$ Disappearance Sensitivity: Nova with DAR Source

- Results for Nova assuming various background rates
- Compare to Kopp et al. (Ref. A) and Karagiorgi et al. (Ref. B) (3+2) best fits

Event Rates

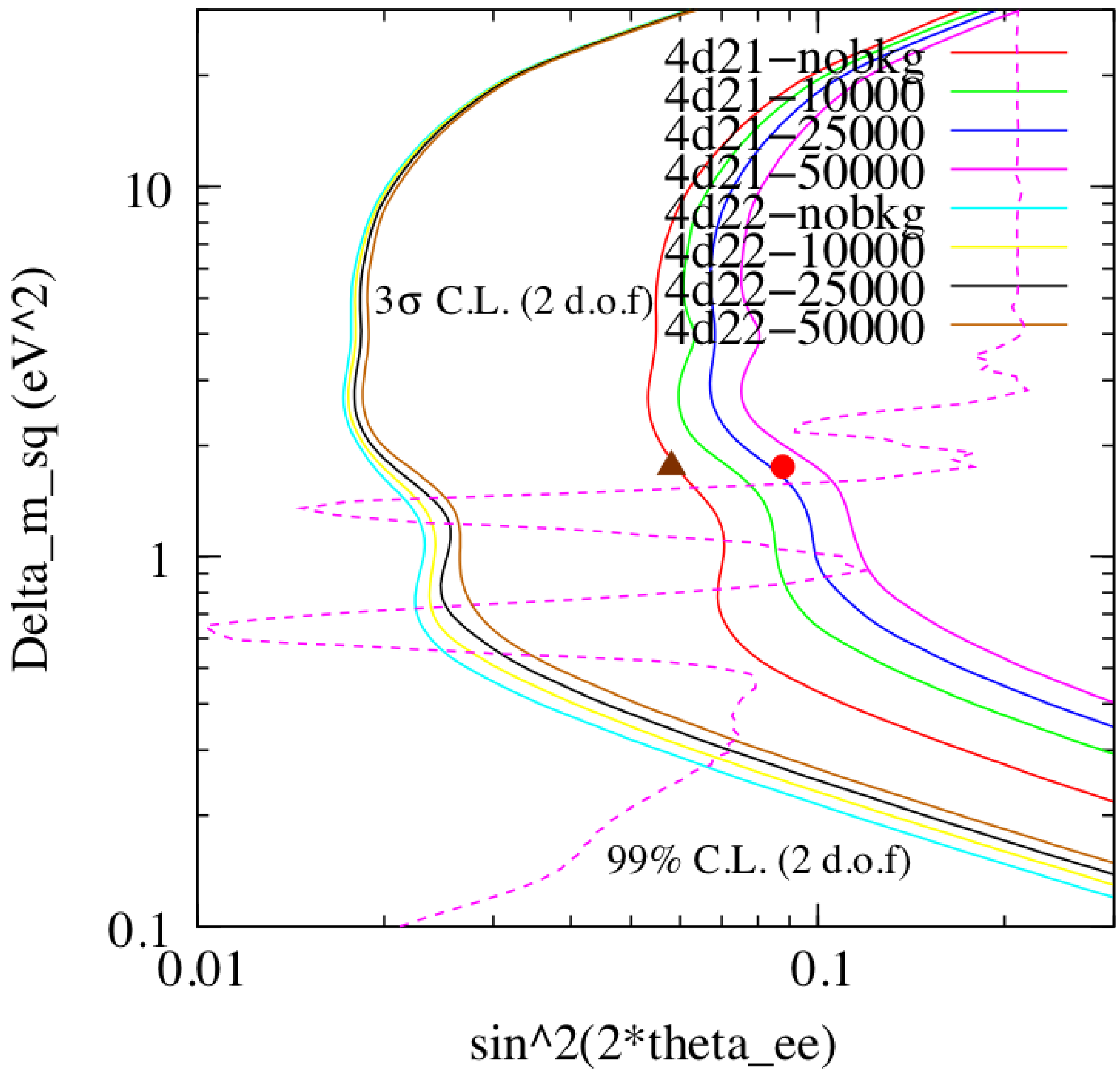
100 kW cyclotron with 4e21 ν_e's

Fiducial Mass	Length	Breadth	Height	Evts w/ Osc (A : Ref. [25])	Evts w/ Osc (B : Ref. [24])	Evts, No Osc
14 kt	67 m	15.7 m	15.7 m	32388	27407	34415

Total Neutrino Flux needed to exclude (3+2) Best Fits at 3σ for Ref. A and Ref. B

Total Background	Flux (A : Ref. [25])	Flux (B : Ref. [24])
50000	5.9×10^{21}	1.325×10^{21}
25000	4.615×10^{21}	0.963×10^{21}
10000	3.408×10^{21}	0.636×10^{21}
0	1.742×10^{21}	0.0945×10^{21}

ν_e Disappearance (3+1): Nova with DAR Source



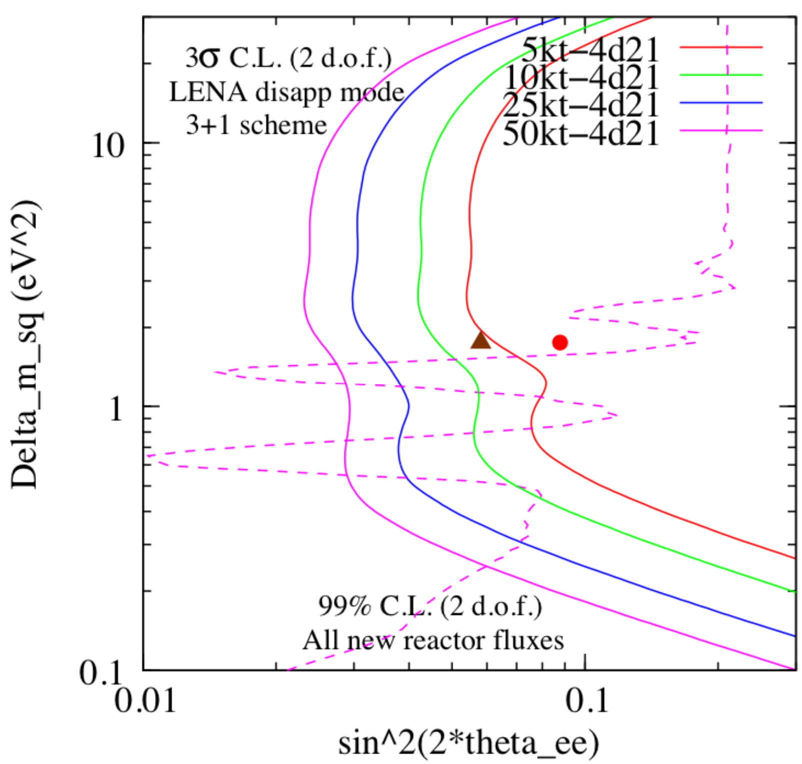
3+1 Type Model with simple two-neutrino approximation

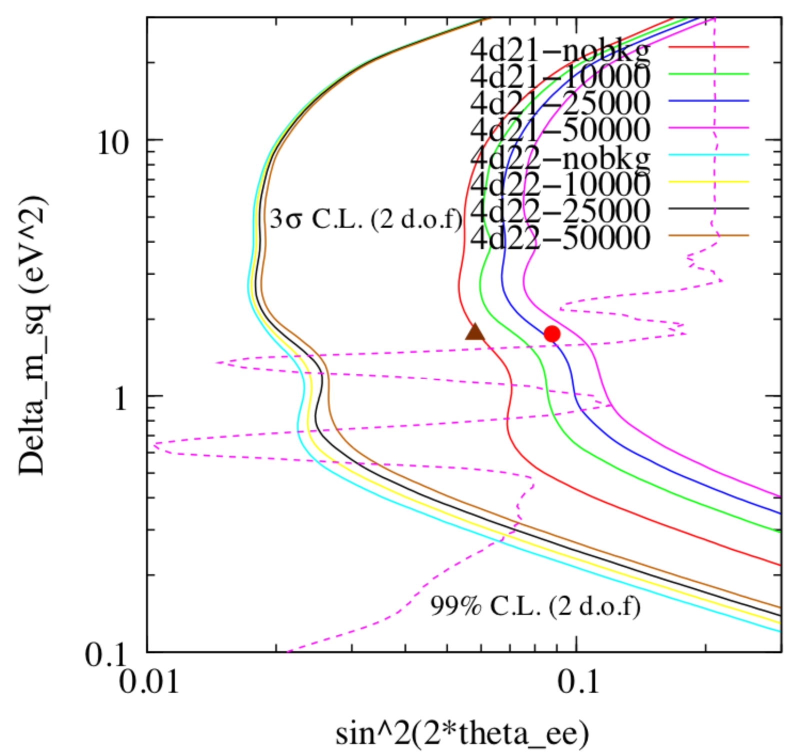
Results for:
100 kW, 4e21 nu's
(1 MW, 4e22 nu's)
and with various background rates

Triangle and the bullet (3+1) best-fit values for all reactor data with old and new fluxes.

Comparison: Nova vs LENA

Detector Characteristics	NOνA Far Detector	LENA
Shape	Rectangular	Cylindrical
Fiducial Mass	14 kt	(5 – 50) kt
Overburden	3 m earth-equivalent	1450 m of rock/4060 m.w.e. @ Pyhäsalmi
Solvent	CH_2	LAB ($C_{18}H_{30}$)
Threshold	38 MeV (Dis)	20 MeV (App) 33 MeV (Dis)
Detection Efficiency	50% (Dis)	90% (App) 80% (Dis)





Large (1 - 2 kton) Liquid Argon Detector
Also a Possible DAR Detector
for a ν_e Disappearance Search

(Some Preliminary Studies)

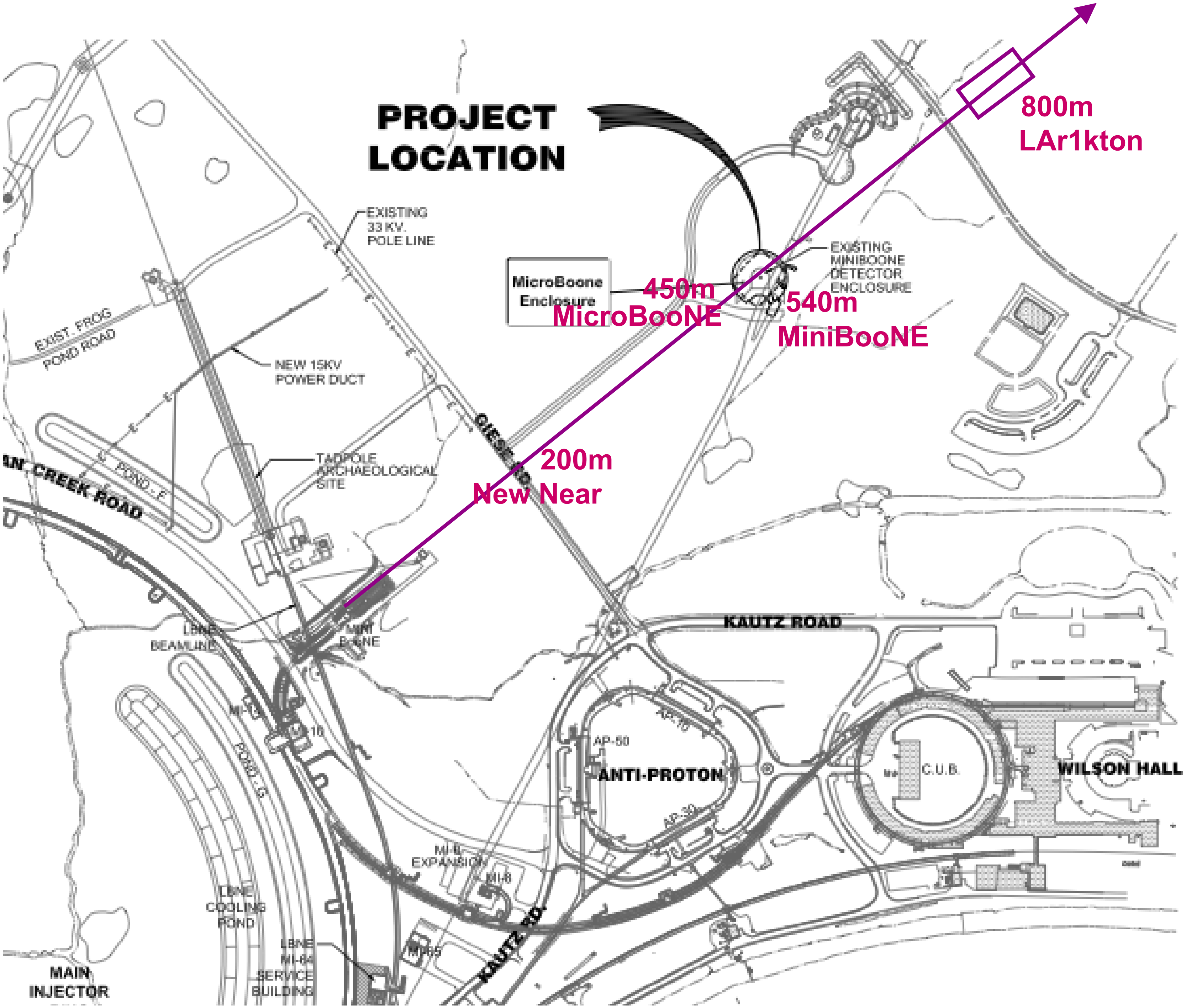
New LAr Detector on the Booster Neutrino Beamline LAr1kton

- Add a large LAr detector in the MiniBooNE Booster Neutrino Beam
  - Address MiniBooNE/LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance appearance signal with better statistics (efficiency) and less background

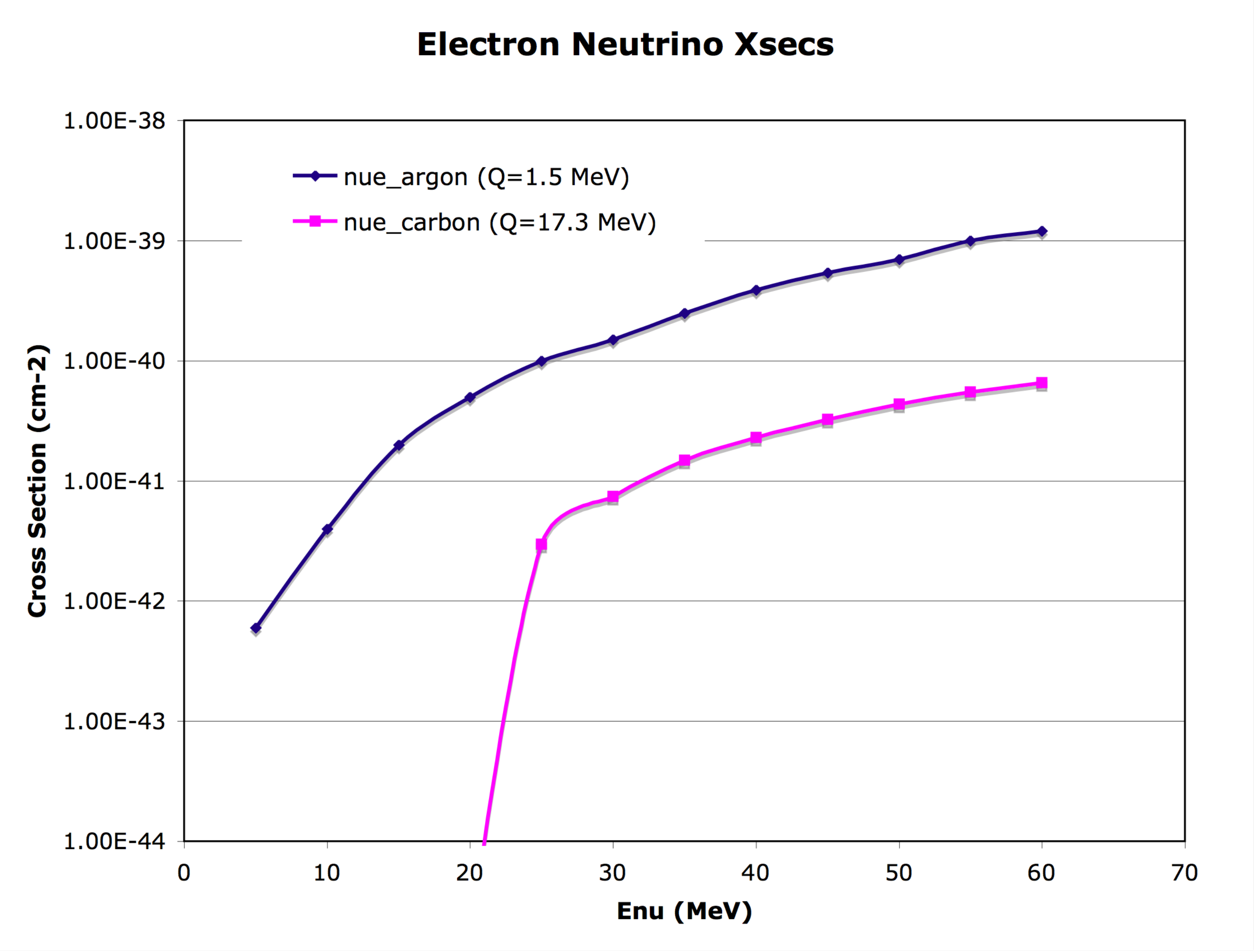
- Address MiniBooNE low-energy ν_e excess
  - MicroBooNE will show if this excess is electrons or photon
  - LAr1kton could explore oscillation parameters with high statistics and different L

- Two detector ν_μ and $\bar{\nu}_\mu$ disappearance
  - New near detector or move MicroBooNE to near location
  - Also, may use 540m to 800m comparison

- Very short baseline ν_e disappearance with cyclotron DAR beam

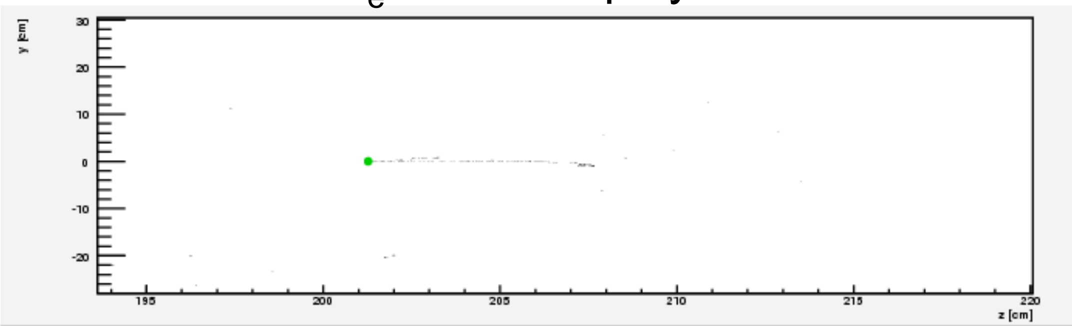

PROJECT
LOCATION
800m
LAr1kton
EXISTING
33 KV.
POLE LINE
MicroBoone
Enclosure
450m
MicroBooNE
EXISTING
MINIBOONE
DETECTOR
ENCLOSURE
540m
MiniBooNE
EXIST. FROG
POND ROAD
NEW 15KV
POWER DUCT
GIESE RD.
200m
New Near
TADPOLE
ARCHAEOLOGICAL
SITE
CREEK ROAD
POND - E
LBNE
BEAMLINE
MINI
BOONE
KAUTZ ROAD
AP-50
AP-10
ANTI-PROTON
AP-30
C.U.B.
WILSON HALL
POND - G
MI-8
EXPANSION
LBNE
COOLING
POND
LBNE
MI-64
SERVICE
BUILDING
KAUTZ RD.
MAIN
INJECTOR

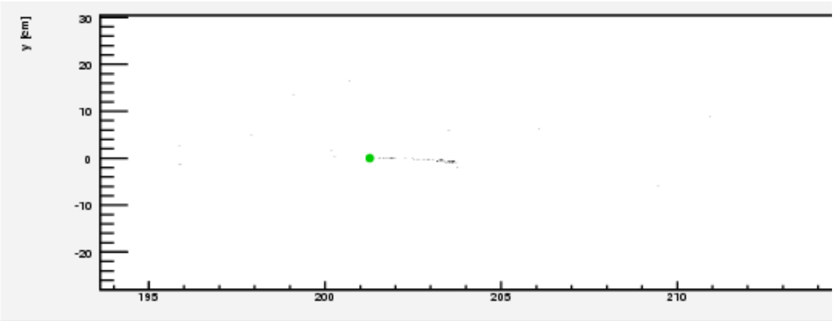
Xsec much larger for Argon than Scintillator (Carbon)

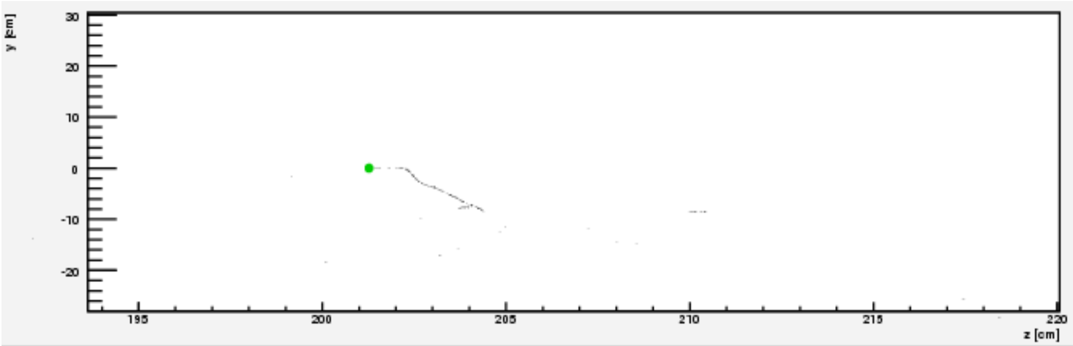


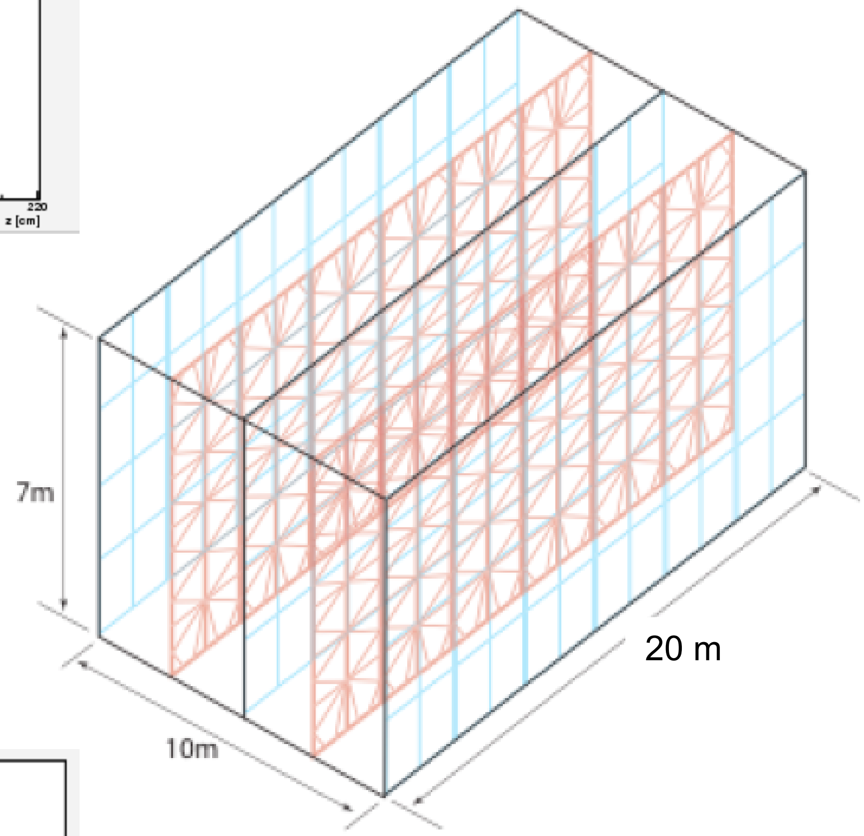
1 kton Liq. Argon Detector (10m x 7m x 20m)

30 MeV ν_e Event Displays

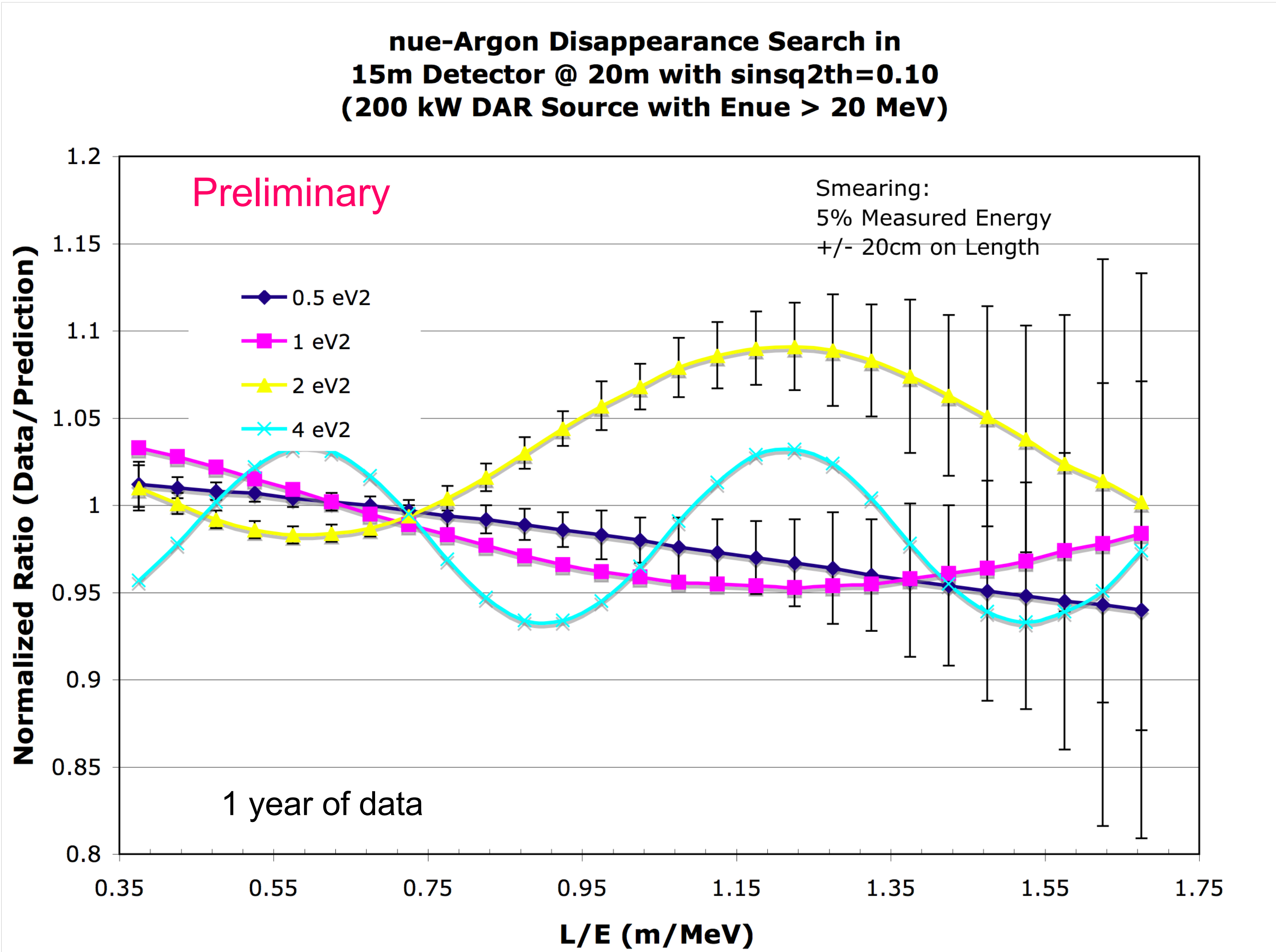


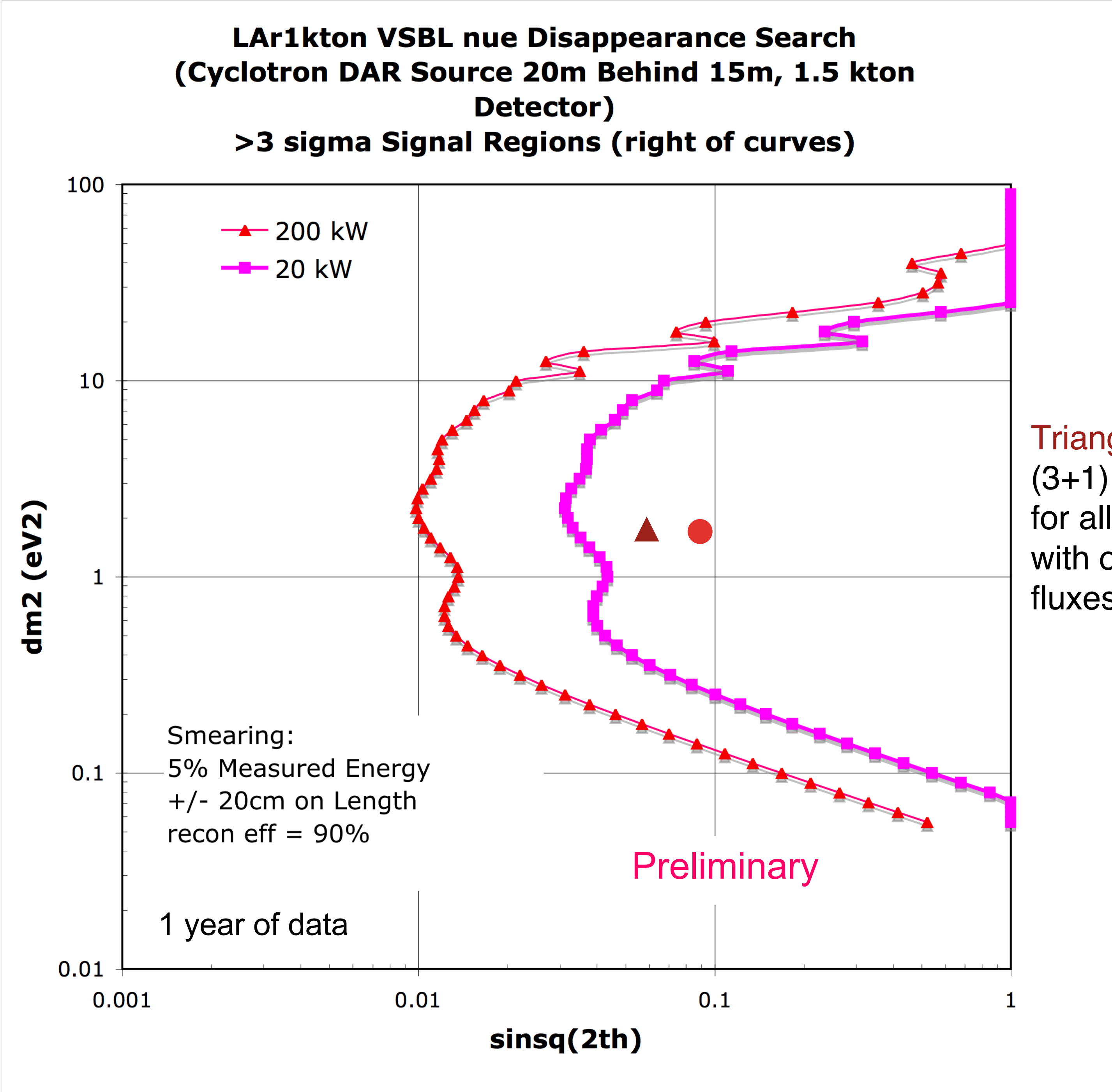






LAr1kton: Rate Ratio vs L/E





Triangle and the bullet (3+1) best-fit values for all reactor data with old and new fluxes.

Conclusions

- If sterile neutrino hints hold up, need to quantify neutrino oscillations in all channels:
  - ν_e and $\bar{\nu}_e$ appearance
  - ν_μ and $\bar{\nu}_\mu$ disappearance
  - ν_e and $\bar{\nu}_e$ disappearance

- Cyclotron decay-at-beam can provide a unique neutrino source to use in searches for very short baseline oscillations associated with:
  - ν_e appearance
  - ν_e disappearance

  Using large scintillator or liquid argon detectors.

Backups

Detector Characteristics	NOνA Far Detector	LENA
Shape	Rectangular	Cylindrical
Fiducial Mass	14 kt	(5 – 50) kt
Overburden	3 m earth-equivalent	1450 m of rock/4060 m.w.e. @ Pyhäsalmi
Solvent	CH_2	LAB ($C_{18}H_{30}$)
Threshold	38 MeV (Dis)	20 MeV (App) 33 MeV (Dis)
Detection Efficiency	50% (Dis)	90% (App) 80% (Dis)
Energy Resolution, σ(E) in units of MeV	$15\%\sqrt{E}$	$10\%\sqrt{E}$ [58]
Signal error (syst.)	20% (Dis)	10% (App) 15% (Dis)
Background error (syst.)	5% [Non-beam] (Dis)	20% [Intrinsic $\bar{\nu}_e$, 4×10^{-4}] (App) –