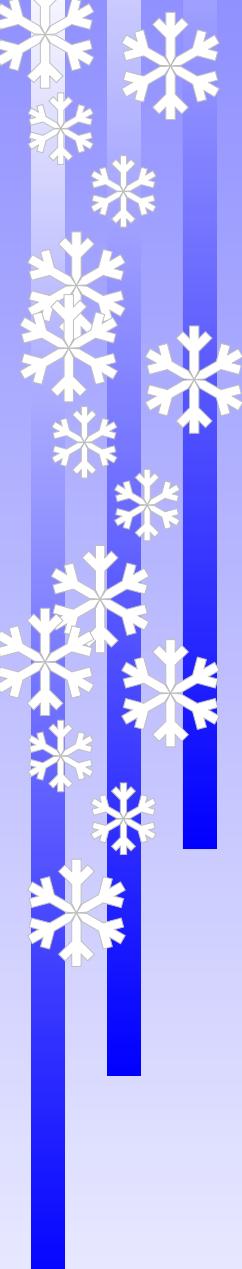


## Very Short Baseline Neutrino Oscillation Experiments using Cyclotron Decay-at-Rest Sources

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IFIC/CSIC, University of Valencia, Spain



# Short-baseline $\nu$ oscillation

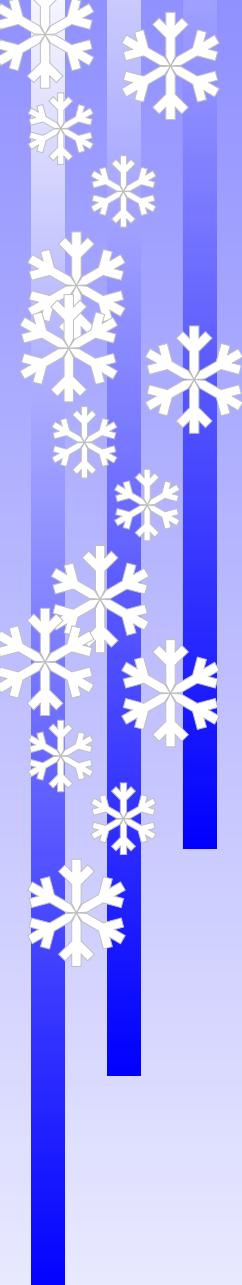
- Recent results from short-baseline neutrino experiments hint towards high  $\Delta m^2 \sim 0.1\text{--}10 \text{ eV}^2$  oscillation
- Are they pointing towards Sterile  $\nu$ s or something else?
- Short-baseline means :  $L/E \sim 1$  (m/MeV or km/GeV)

**LSND :  $L = 30 \text{ m}$ ,  $\langle E_{\nu_\mu} \rangle = 40 \text{ MeV}$**

- $3.8\sigma$  excess of  $\bar{\nu}_e$  events in a beam of  $\bar{\nu}_\mu$

**MiniBooNE :  $L = 541 \text{ m}$ ,  $\langle E_{\nu_\mu, \bar{\nu}_\mu} \rangle = 700 \text{ MeV}$**

- A  $2.8\sigma$  excess of  $\bar{\nu}_e$  events in the anti-neutrino mode above 475 MeV, consistent with LSND



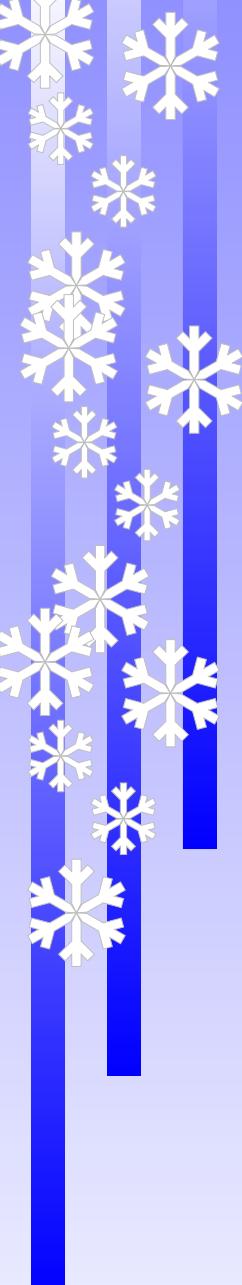
# SBL $\nu$ oscillation continued..

- No oscillation in the  $\nu$ -mode for energies above 475 MeV
- An unexplained  $3\sigma$  excess of  $\nu_e$  events in the  $\nu$ -mode of MiniBooNE below 475 MeV
- No hint of steriles in MiniBooNE  $\nu_\mu/\bar{\nu}_\mu$  disappearance

## Recent Reactor Anomaly

- Reanalysis of reactor fluxes in Mueller *et al.*, (arXiv:1101.2663) shows 2.5% upward shift in flux
- Overall reduction in predicted flux compared to existing data can be interpreted as oscillations at baselines of order 10–100 m (arXiv:1101.2755)

Gallex-Sage reduced calibration source rate also suggesting possible  $\nu_e$  disappearance



# What do we need?

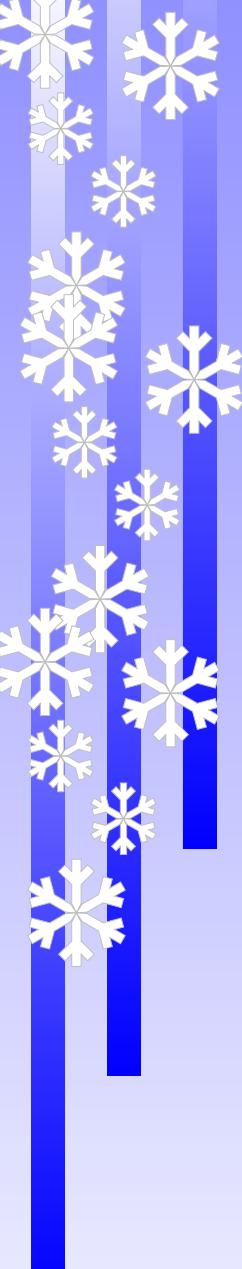
- ➊ We have both positive and negative hints for sterile high  $\Delta m^2$  oscillation. Nothing is conclusive !!
- ➋ We need powerful new experiments to have appearance and disappearance searches at high significance involving both neutrinos and anti-neutrinos

Combine powerful new multi-kiloton liquid scintillator, argon or water detectors with a modest power decay-at-rest neutrino source at short-baseline

Observe the  $L/E$  dependence of the oscillation wave across the length scales of these detectors

SKA, Patrick Huber, arXiv:1007.3228

SKA, J.M. Conrad, M.H. Shaevitz, arXiv:1105.4984



# Stopped Pion Source

- 800 MeV protons from cyclotrons interact in a low-A target (C, H<sub>2</sub>O) producing  $\pi^+$  and, at a low level,  $\pi^-$

$$p + X \rightarrow \pi^\pm + X'$$

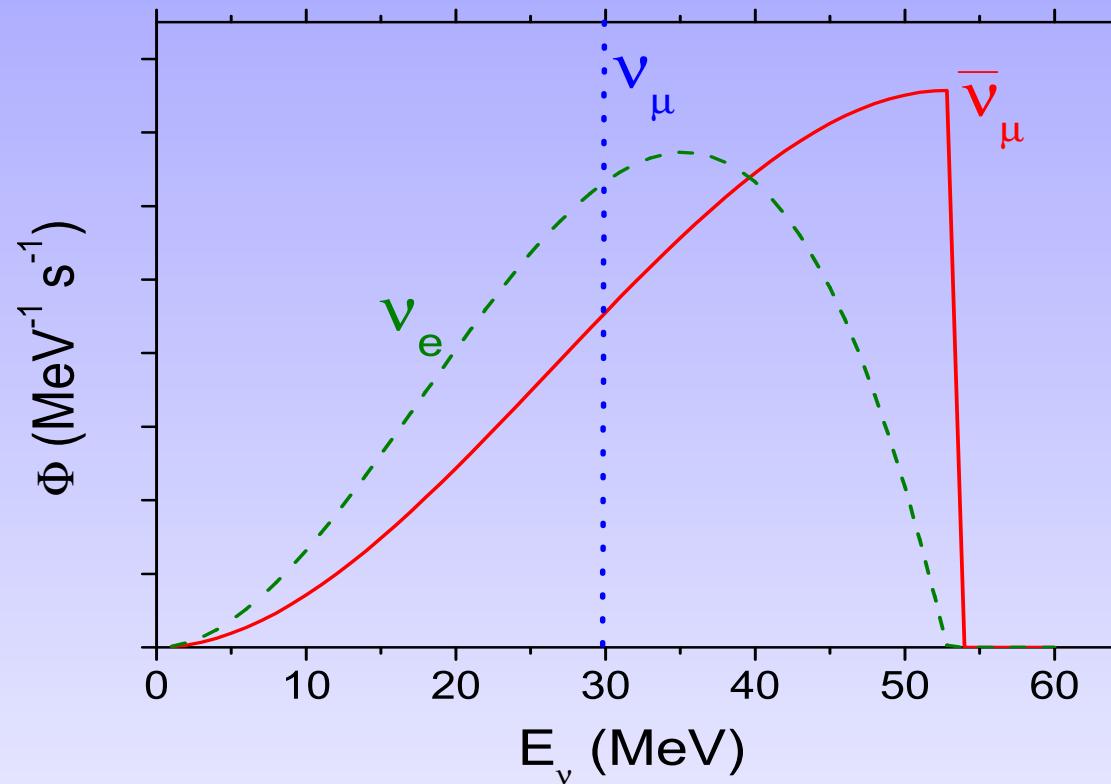
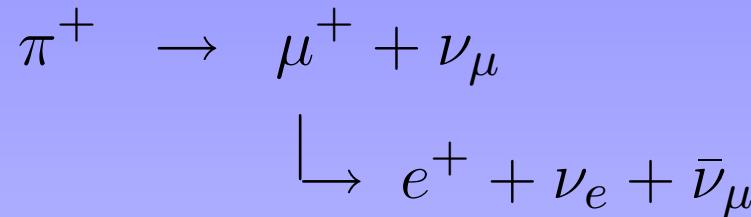
- Low-A target is embedded in a high-A, dense material where pions are brought to rest
- $\pi^-$  & daughter  $\mu^-$  captured before DIF, minimizing  $\bar{\nu}_e$
- $\pi^+$  decay produces mono-energetic 29.8 MeV  $\nu_\mu$  &  $\mu^+$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- $\mu^+$  decays at rest, providing Michel spectrum

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

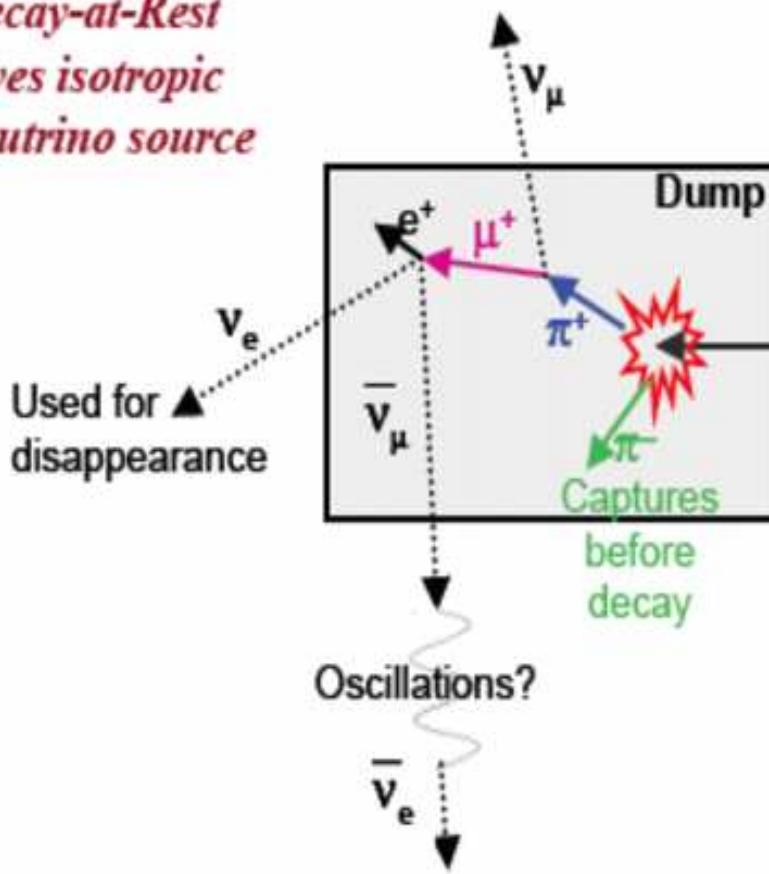
# Decay At Rest (DAR) Source



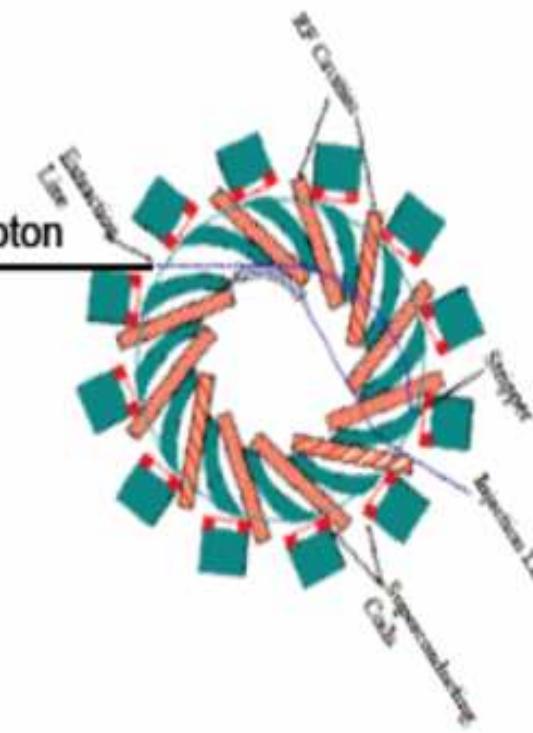
Provides an equal, high-intensity, isotropic, DAR  $\nu_\mu$ ,  $\nu_e$  and  $\bar{\nu}_\mu$  beam with tiny  $\bar{\nu}_e$  contamination ( $4 \times 10^{-4}$ )

# Cyclotron : Proton Source

*Decay-at-Rest  
gives isotropic  
neutrino source*



**Cyclotron (~800 MeV KE proton)**



Mike Shaevitz, SBNW11, Fermilab

Cyclotrons : ideal low-cost source for low energy protons

Bunch spacing  $\sim$  few tens of ns, continuous source

Average beam power, 10 - 100 kW, prototypes for DAE $\delta$ ALUS

# Neutrino Source Details

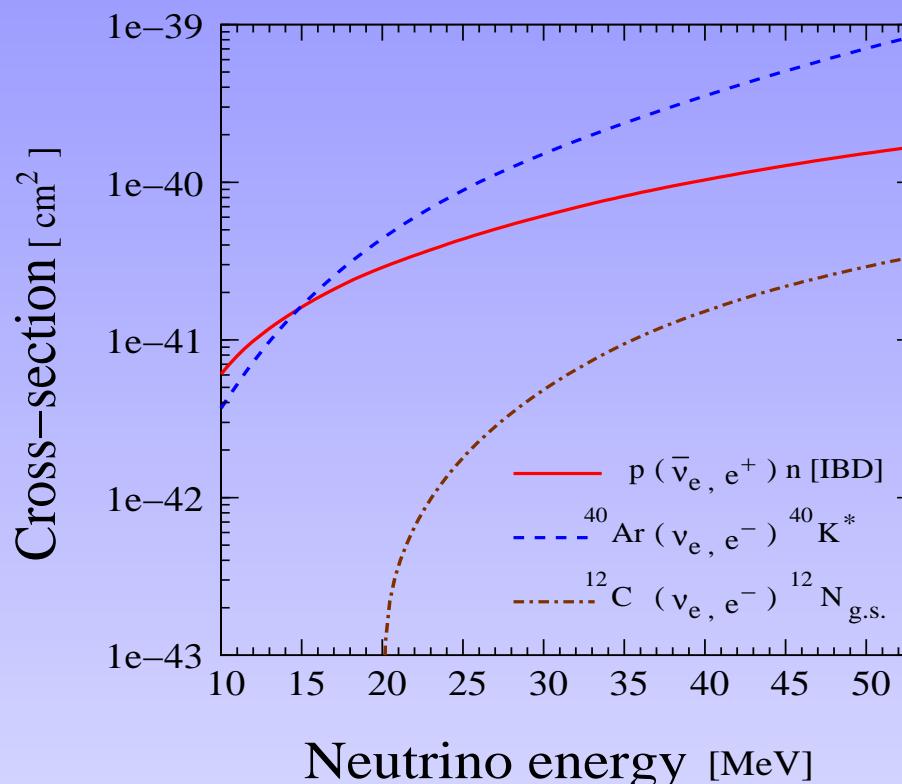
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$4 \times 10^{21}$  per year, per flavor ( $\nu_\mu$ ,  $\bar{\nu}_\mu$  and  $\nu_e$ ),  
 $1.6 \times 10^{18}$  per year of  $\bar{\nu}_e$  ( $4 \times 10^{-4}$  compared to other flavors);  
Delivered as 100 kW average power, with 200 kW instantaneous power,  
(50% duty factor allowing equal beam-on and beam-off data sets);  
800 MeV protons on target;  
 $\pm 25$  cm smearing (assumed flat) on neutrino production point;  
20 m distance from average production point to face of detector fiducial region.

---

- p/ $\pi$  ratio uncertain : conservative 10% correlated normalization error on all flavors
- 20% normalization error on the  $\pi^-$  DIF background
- No uncertainty in the shape of the energy spectrum

# DAR beam interactions



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



Free protons : Liquid scintillator oil, H<sub>2</sub>O

Low kinematic threshold : 1.81 MeV

Coincidence tag between prompt positron  
and the delayed neutron capture by a proton



$\nu_e \rightarrow \nu_e$  Disappearance

$\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}_{\text{g.s.}}$ . Threshold 17.33 MeV, well measured,  $\sim 5$  to 10% uncertainty  
prompt  $e^-$ , followed within a 60 ms window by  $e^+$  from  $\beta$ -decay of the  $^{12}\text{N}_{\text{g.s.}}$ , mean  $\tau = 15.9$  ms

$\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$  Threshold 4.24 to 5.89 MeV depending on which  $^{40}\text{K}^*$

It has the highest cross-section in the energy range of interest, excellent for Disappearance studies

# 3+1 SBL oscillations

Add one sterile  $\nu$  with three active ones at the eV scale

SBL approximation :  $\Delta m_{21}^2 \approx \Delta m_{31}^2 \approx 0$  and  $x_{ij} \equiv \Delta m_{ij}^2 L / 4E$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 x_{41} \equiv \sin^2 2\theta_{\mu e} \sin^2 x_{41}$$

Example Fit :  $\Delta m_{41}^2 = 0.57$  eV $^2$  and  $\sin^2 2\theta_{\mu e} = 0.0097$  using LSND, MB- $\bar{\nu}$ , KARMEN (Karagiorgi *et al.*, arXiv:0906.1997)

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

Example Fit :  $\Delta m_{41}^2 = 1.78$  eV $^2$  and  $\sin^2 2\theta_{ee} = 0.089$  using all reactor data with new fluxes (J. Kopp *et al.*, arXiv:1103.4570)

No CPV : can't reconcile  $\bar{\nu}$  (LSND, MB) and  $\nu$  (MB) data

# 3+2 SBL oscillations

Add two sterile neutrinos with three active ones at the eV scale

SBL approximation :  $\Delta m_{21}^2 \approx \Delta m_{31}^2 \approx 0$  and  $x_{ij} \equiv \Delta m_{ij}^2 L / 4E$

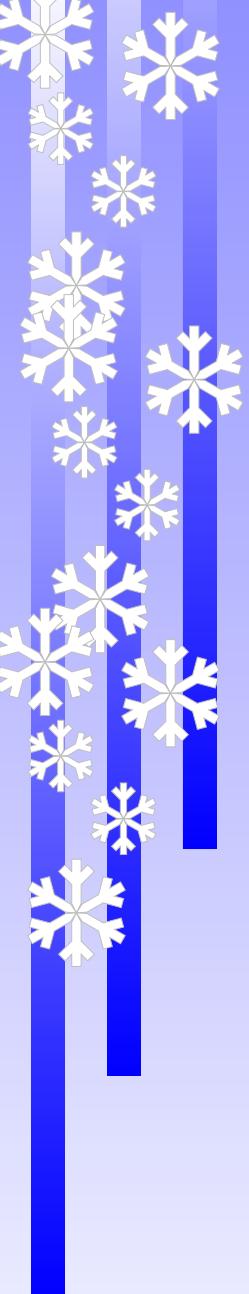
$$\begin{aligned} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) &= 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 x_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 x_{51} \\ &\quad + 8|U_{e4}U_{\mu 4}U_{e5}U_{\mu 5}| \sin x_{41} \sin x_{51} \cos(x_{54} + \delta) \end{aligned}$$

$\delta \equiv \arg(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)$  is the *CP*-phase

$$\begin{aligned} P(\nu_e \rightarrow \nu_e) &= 1 - 4(1 - |U_{e4}|^2 - |U_{e5}|^2)(|U_{e4}|^2 \sin^2 x_{41} + |U_{e5}|^2 \sin^2 x_{51}) \\ &\quad - 4|U_{e4}|^2|U_{e5}|^2 \sin^2 x_{54} \end{aligned}$$

	$\Delta m_{41}^2$	$ U_{e4} $	$ U_{\mu 4} $	$\Delta m_{51}^2$	$ U_{e5} $	$ U_{\mu 5} $	$\delta/\pi$
A : arXiv:1103.4570	0.47	0.128	0.165	0.87	0.138	0.148	1.64
B : arXiv:0906.1997	0.39	0.40	0.20	1.10	0.21	0.14	1.1

Global best-fit points for (3+2) model. Mass splittings are shown in eV<sup>2</sup>



## LENA Scintillation Detector

50 kt Fiducial (Unsegmented)

100 m tall by 30 m diameter

Source-to-detector-face = 20 m

Low detection threshold

Excellent Vertex and Energy Resolution

Clear coincidence signal for  $\bar{\nu}_e$  IBD events

Deep underground location (4000 mwe)

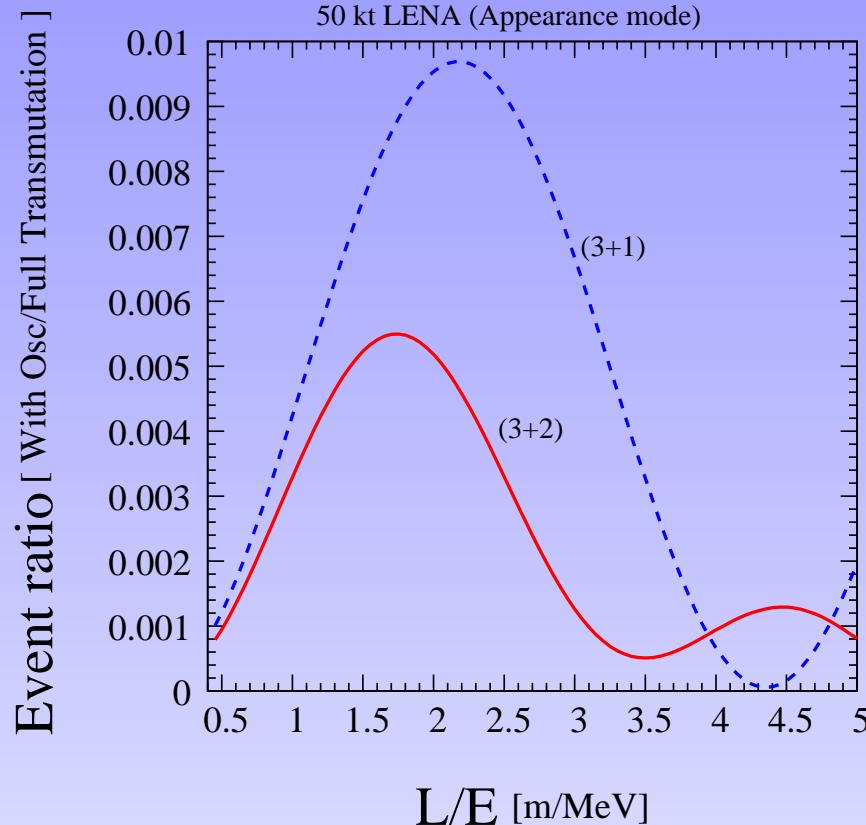
Negligible cosmic muon backgrounds

Neutrino Energy threshold

For appearance :  $E_\nu > 20$  MeV

For disappearance :  $E_\nu > 33$  MeV

# Appearance wave in LENA



Bin and fit IBD data with reconstructed  $L/E$

(3+1) fit : Karagiorgi *et al.*, arXiv:0906.1997

$$\Delta m_{41}^2 = 0.57 \text{ eV}^2 \text{ & } \sin^2 2\theta_{\mu e} = 0.0097$$

(3+2) fit : J. Kopp *et al.*, arXiv:1103.4570

Accessible L range : 20–120 m

DAR energy range : 20–52.8 MeV

**SKA, J.M. Conrad, M.H. Shaevitz, arXiv:1105.4984**

Oscillation wave is dramatic in the long LENA detector and can provide a powerful handle to discriminate between (3+1) and (3+2) schemes

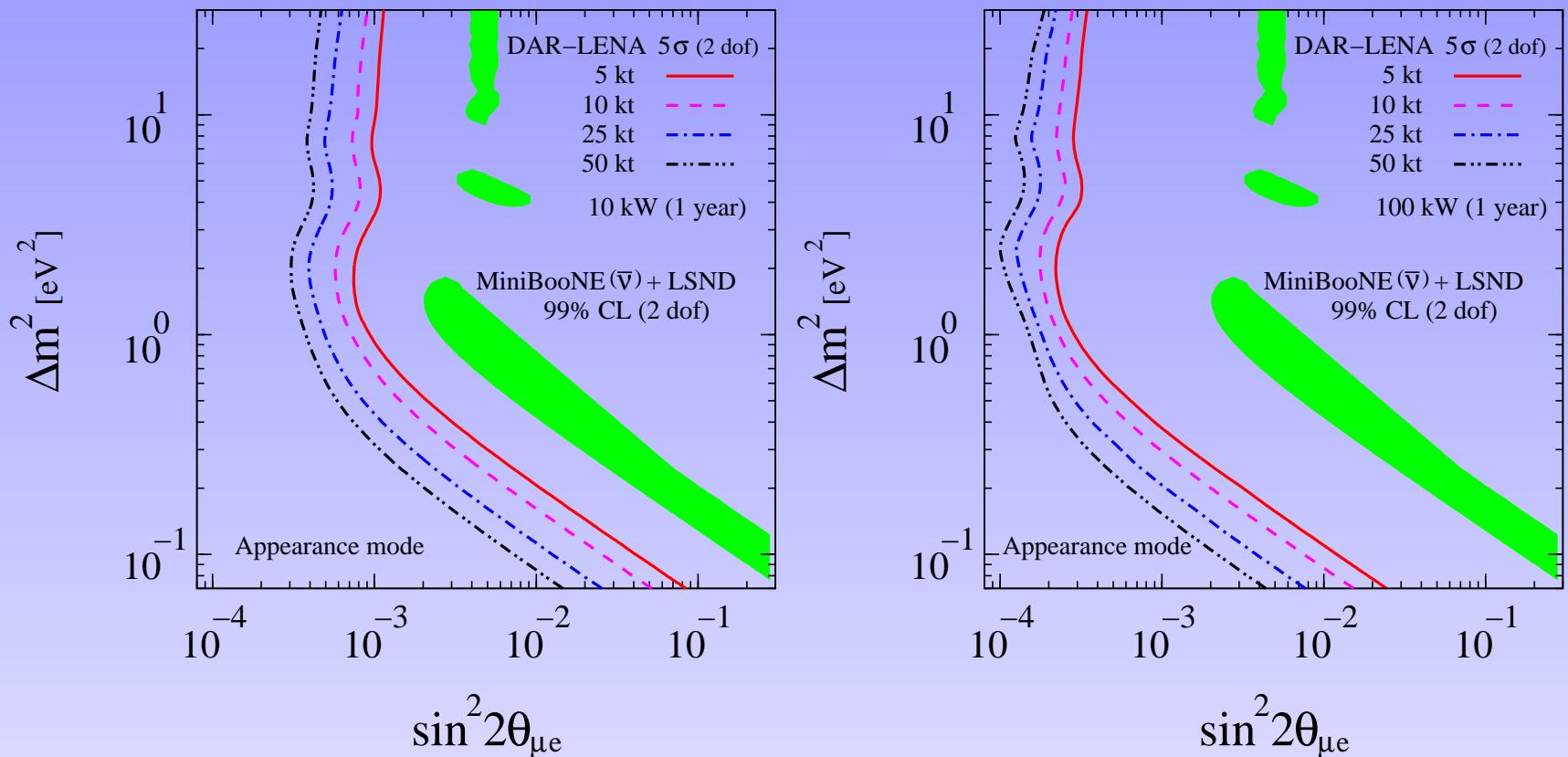
# Appearance Event Rates

	$\Delta m_{41}^2$	$ U_{e4} $	$ U_{\mu 4} $	$\Delta m_{51}^2$	$ U_{e5} $	$ U_{\mu 5} $	$\delta/\pi$
A : arXiv:1103.4570	0.47	0.128	0.165	0.87	0.138	0.148	1.64
B : arXiv:0906.1997	0.39	0.40	0.20	1.10	0.21	0.14	1.1

Fiducial Mass	Radius	Length	Signal (A : 1103.4570)	Signal (B : 0906.1997)	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

- Signal and beam background events in 5 to 50 kt LENA
- Total  $4 \times 10^{21} \bar{\nu}_\mu$  (100 kW source), efficiency 90%
- The intrinsic  $\bar{\nu}_e$  beam contamination is  $4 \times 10^{-4}$

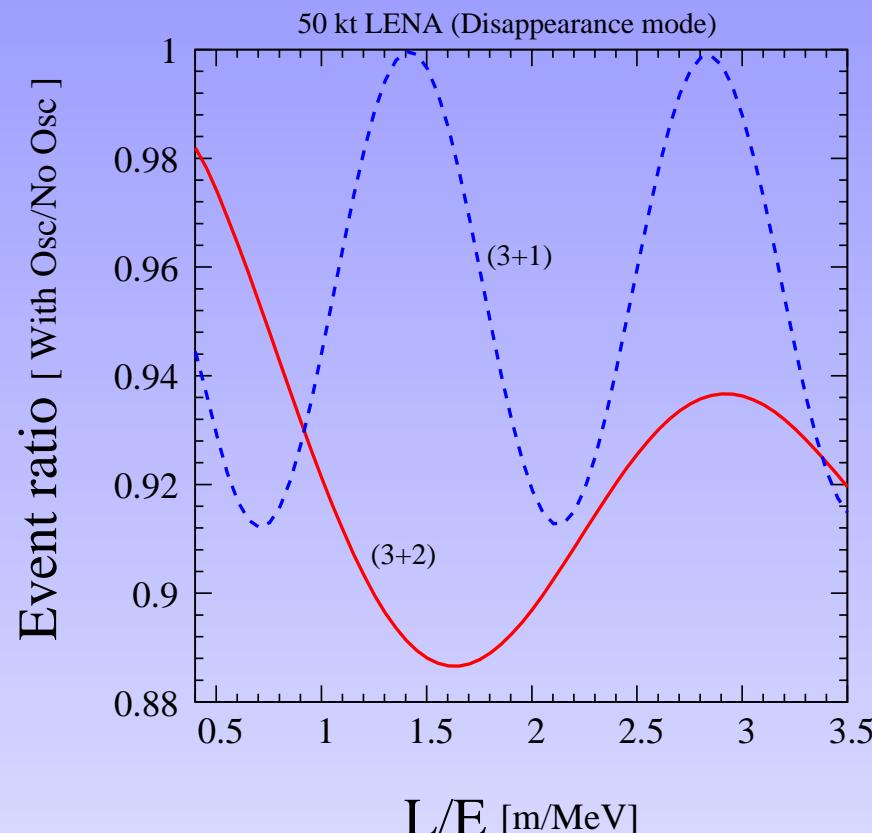
# DAR-LENA $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Sensitivity



SKA, J.M. Conrad, M.H. Shaevitz, arXiv:1105.4984

5 kt LENA combined with a small 10 kW DAR source can test the LSND/MiniBooNE anti-neutrino signal at 5 $\sigma$  CL in 3+1 model in 1 yr

# Disappearance wave in LENA



Bin and fit  $\nu_e$  scattering data with  $L/E$

(3+1) fit : J. Kopp *et al.*, arXiv:1103.4570

$\Delta m_{41}^2 = 1.78 \text{ eV}^2$  and  $\sin^2 2\theta_{ee} = 0.089$

(3+2) fit : J. Kopp *et al.*, arXiv:1103.4570

Accessible L range : 20–120 m

DAR energy range : 33–52.8 MeV

**SKA, J.M. Conrad, M.H. Shaevitz, arXiv:1105.4984**

Different shape for (3+1) and (3+2) waves.  
Comparison between the amplitudes of the wave  
in various  $L/E$  bins cancels flux uncertainties

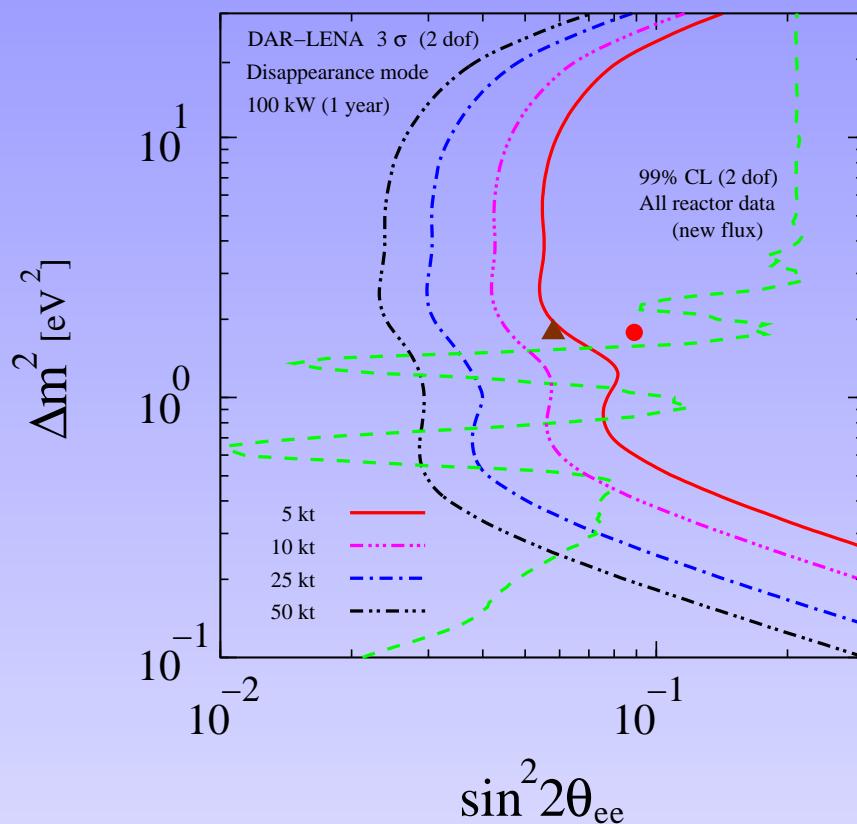
# Disappearance Event Rates

	$\Delta m_{41}^2$	$ U_{e4} $	$ U_{\mu 4} $	$\Delta m_{51}^2$	$ U_{e5} $	$ U_{\mu 5} $	$\delta/\pi$
A : arXiv:1103.4570	0.47	0.128	0.165	0.87	0.138	0.148	1.64
B : arXiv:0906.1997	0.39	0.40	0.20	1.10	0.21	0.14	1.1

Fiducial Mass	Radius	Length	Evts w/ Osc (A : 1103.4570)	Evts w/ Osc (B : 0906.1997)	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

- CC  $\nu_e$  scattering events on  $^{12}\text{C}$  in 5 to 50 kt LENA
- Total  $4 \times 10^{21} \nu_e$  (100 kW source), efficiency 80%
- $E_\nu$  threshold of 33 MeV and resolution  $10\%/\sqrt{E_e/\text{MeV}}$

# DAR-LENA $\nu_e \rightarrow \nu_e$ Sensitivity

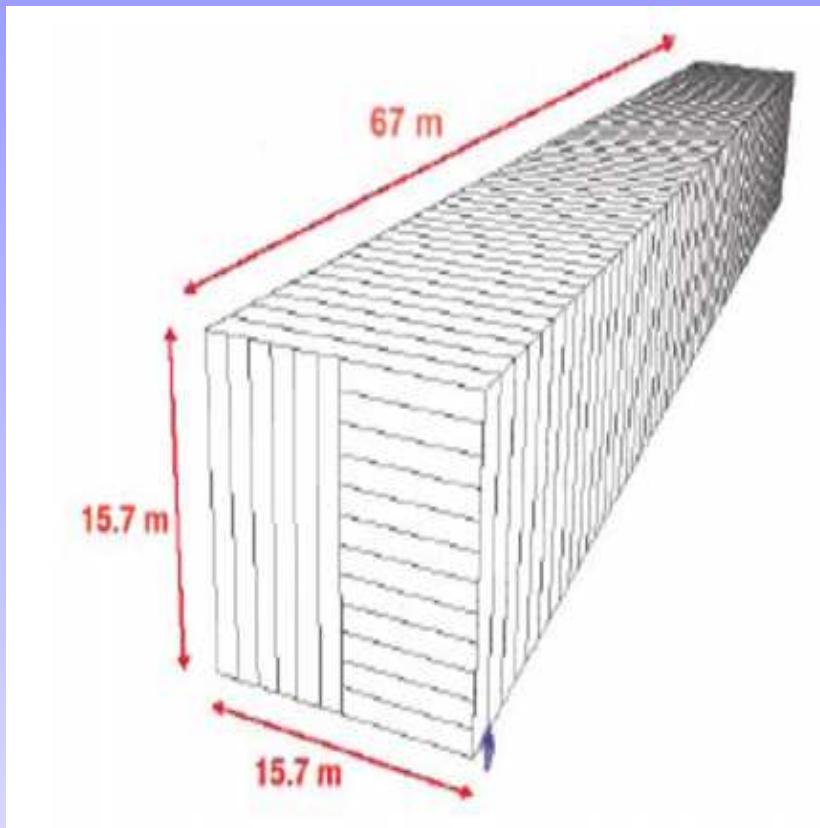


100 kW source ( $4 \times 10^{21} \nu_e$ ), 5 - 50 kt fiducial  
 (3+1) model with simple 2- $\nu$  approximation  
 Triangle & Bullet : (3+1) best-fit values for all reactor data with old & new fluxes  
 Dashed green curve : 99% CL (2 dof) limit from reactor data with new reactor fluxes

**SKA, J.M. Conrad, M.H. Shaevitz, arXiv:1105.4984**

10 kt LENA with a flux of  $4 \times 10^{21} \nu_e$  can provide stringent test of the recent reactor anomaly at 3  $\sigma$  CL (2 dof)

# NO $\nu$ A : Coming Soon



## Segmented Scintillator Detector

Detector mass 14 kt

CH<sub>2</sub> Scintillator Target, 30% PVC

Dimensions : 15.7 m × 15.7 m × 67 m

NO $\nu$ A not made for low energy signal

It can only perform  $\nu_e$  disappearance

Cannot see the 2.2 MeV  $\gamma$  from n capture

Very little shielding – 3 m of Earth

Largest background :  $10^{10}$  Michel electrons/year produced by stopped cosmic muon decay

Michel electron events identified and vetoed by tracking the parent muon

For this study, we consider 10,000 to 50,000 un-vetoed Michel background events

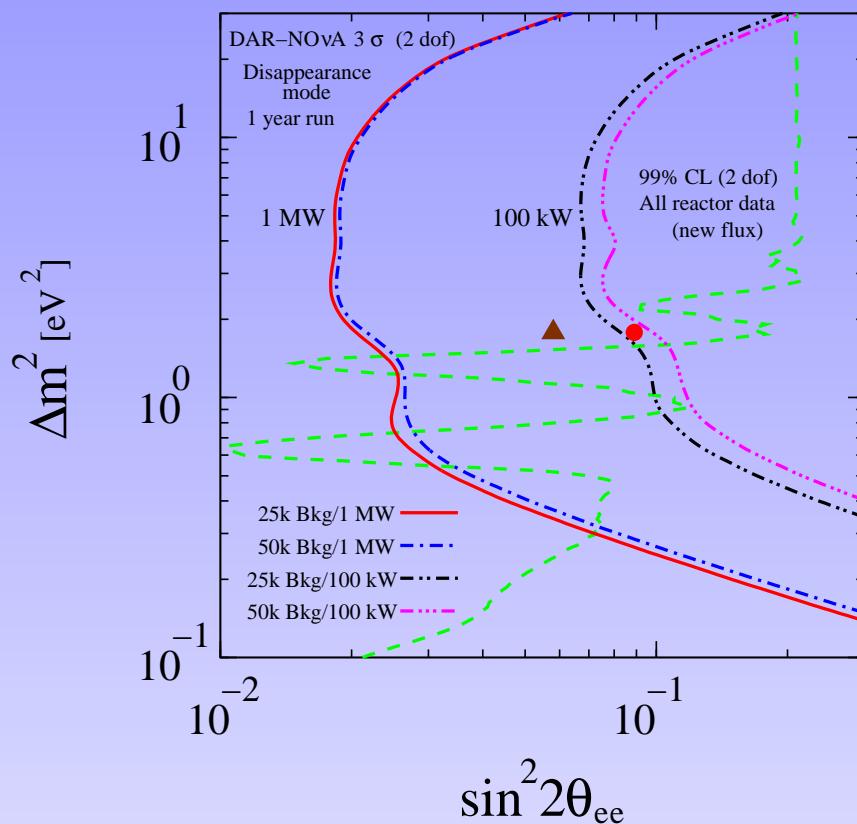
# NO $\nu$ A Event Rates

	$\Delta m_{41}^2$	$ U_{e4} $	$ U_{\mu 4} $	$\Delta m_{51}^2$	$ U_{e5} $	$ U_{\mu 5} $	$\delta/\pi$
A : arXiv:1103.4570	0.47	0.128	0.165	0.87	0.138	0.148	1.64
B : arXiv:0906.1997	0.39	0.40	0.20	1.10	0.21	0.14	1.1

Fiducial Mass	Length	Breadth	Height	Evts w/ Osc 1103.4570	Evts w/ Osc 0906.1997	Evts, No Osc
14 kt	67 m	15.7 m	15.7 m	32388	27407	34415

- CC  $\nu_e$  scattering events on  $^{12}\text{C}$  in 14 kt NO $\nu$ A far detector
- Total  $4 \times 10^{21} \nu_e$  (100 kW source), efficiency 50%
- $\nu$  energy threshold of 38 MeV and resolution  
 $100\%/\sqrt{\text{E}_e/\text{MeV}}$

# DAR-NO $\nu$ A $\nu_e \rightarrow \nu_e$ Sensitivity



100 kW & 1 MW average source power

25k & 50k effective Michel  $e^-$  Backgrounds

(3+1) model with simple 2- $\nu$  approximation

Triangle & Bullet : (3+1) best-fit values for all reactor data with old & new fluxes

Dashed green curve : 99% CL (2 dof) limit from reactor data with new reactor fluxes

**SKA, J.M. Conrad, M.H. Shaevitz, arXiv:1105.4984**

100 kW machine is marginal in covering the test points and a higher-power, full DAEδALUS type machine, is needed

# Future Liquid Argon Detector

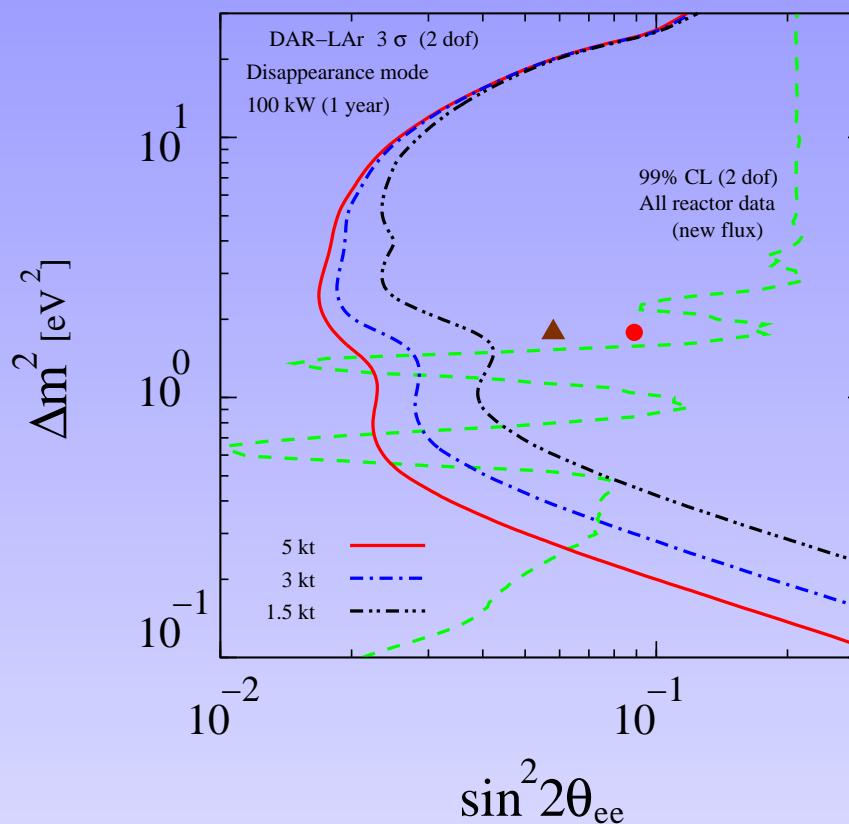
Possible detector for  $\nu_e$  disappearance search with DAR beam

	$\Delta m_{41}^2$	$ U_{e4} $	$ U_{\mu 4} $	$\Delta m_{51}^2$	$ U_{e5} $	$ U_{\mu 5} $	$\delta/\pi$
A : arXiv:1103.4570	0.47	0.128	0.165	0.87	0.138	0.148	1.64
B : arXiv:0906.1997	0.39	0.40	0.20	1.10	0.21	0.14	1.1

Fiducial Mass	Length	Breadth	Height	Evts w/ Osc 1103.4570	Evts w/ Osc 0906.1997	Evts, No Osc
5 kt	50 m	10 m	7 m	345601	288061	368812
3 kt	30 m	10 m	7 m	292671	250392	309799
1.5 kt	15 m	10 m	7 m	211445	186585	221281

- CC  $\nu_e$  scattering events on  $^{40}\text{Ar}$  in 1.5 to 5 kt LAr detector
- Total  $4 \times 10^{21} \nu_e$  (100 kW source), efficiency 90%
- $\nu$  energy threshold of 20 MeV and resolution  $11\%/\sqrt{E_e} + 2.5\%$

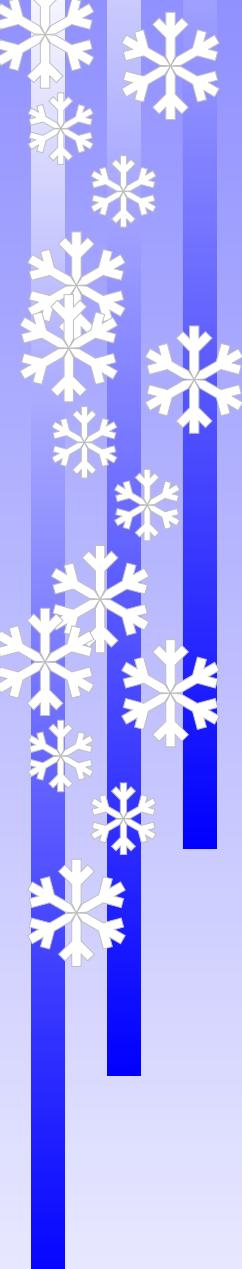
# DAR-LAr $\nu_e \rightarrow \nu_e$ Sensitivity



100 kW average source power  
 Negligible background from cosmic muons  
 (under 4000 mwe of shielding)  
 (3+1) model with simple 2- $\nu$  approximation  
 Triangle & Bullet : (3+1) best-fit values for all reactor data with old & new fluxes  
 Dashed green curve : 99% CL (2 dof) limit from reactor data with new reactor fluxes

**SKA, J.M. Conrad, M.H. Shaevitz, work in progress**

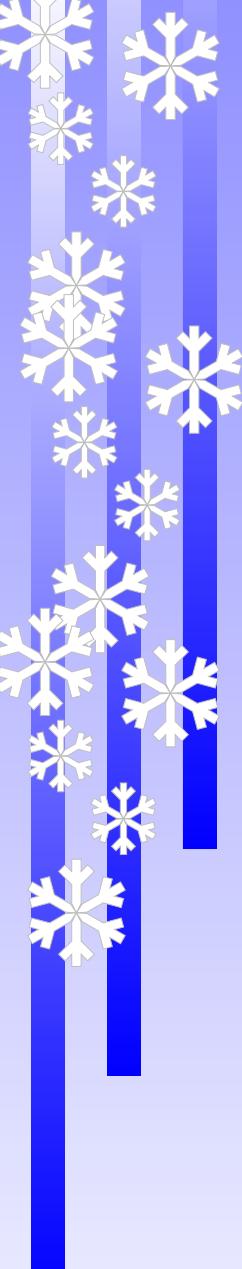
1.5 kt LAr detector and 100 kW source is enough to test the reactor anomaly at high significance



# Surface LAr detector

Can we use DAR beam with ICARUS or LarLAr?

- Use photo detectors to determine the  $t_0$  for the  $\nu_e$  events
- Determining  $t_0$  is compromised if a muon comes through within  $5 \mu\text{s}$  before the event
- Assume 20 kHz muon rate through the detector. One puts a 99.9% scintillator veto on top of the detector and vetos any events with a muon within  $5 \mu\text{s}$  of the event. This produces a deadtime of  $20,000\text{Hz} \times 5 \mu\text{s} = 10\%$
- 0.1% of the through-going muons will not be vetoed at a rate of 20 Hz. The random coincidence of these with a real  $\nu_e$  event within  $5 \mu\text{s}$  will be  $10^{-4}$  fraction of the real events which is negligible
- Use LAr detector itself to veto muons with light detectors



# Conclusions

Large neutrino detectors using liquid scintillator and liquid argon will come on-line within the next decade

These detectors combined with high intensity 10–100 kW cyclotron DAR neutrino sources would have unprecedented sensitivity to sterile  $\nu$  oscillations in the high  $\Delta m^2 \sim 0.5\text{--}10 \text{ eV}^2$  region

These experiments are an important option as a next major step to search for sterile neutrino oscillations

*Thank you*