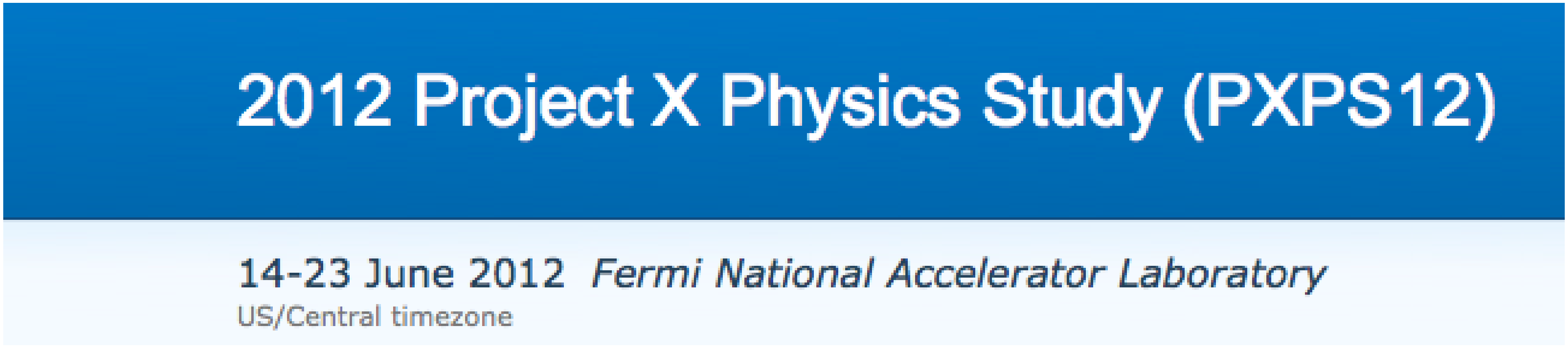


2012 Project X Physics Study (PXPS12)

14-23 June 2012 *Fermi National Accelerator Laboratory*
US/Central timezone

Review of future short baseline accelerator experiments

M. Shaevitz - Columbia University

Hints for High $\Delta m^2 \sim 1\ \text{eV}^2$ Oscillation
⇒ Sterile Neutrinos? or Something Else?

- Positive indications:

	Anomaly	Type	Channel	Significance
$\bar{\nu}_\mu \to \bar{\nu}_e$	LSND	DAR	$\bar{\nu}$ CC	3.8 σ
$\nu_\mu \to \nu_e$	MiniBooNE	SBL accelerator	ν CC	3.0 σ
$\bar{\nu}_\mu \to \bar{\nu}_e$	MiniBooNE	SBL accelerator	$\bar{\nu}$ CC	1.7σ
$\nu_e \to \nu_e$	Gallium/Sage	Source - e capture	ν CC	2.7σ
$\bar{\nu}_e \to \bar{\nu}_e$	Reactor	Beta-decay	$\bar{\nu}$	3.0σ

New MiniBooNE

Combined $\nu + \bar{\nu}$

Now 3.8 σ

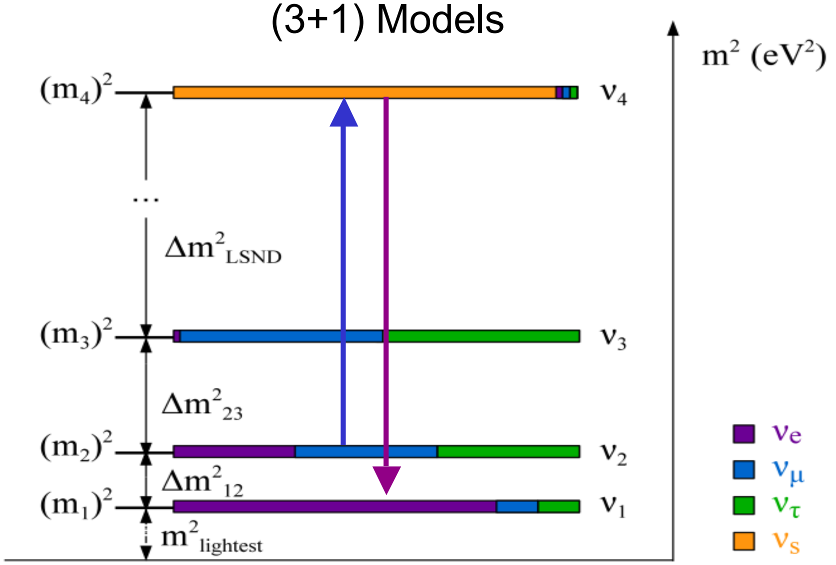
- Negative indications:
  - CDHS and MiniBooNE restrictions on ν_μ disappearance
  - MiniBooNE restrictions on $\bar{\nu}_\mu$ disappearance
  - MINOS restrictions on $\nu_\mu \to \nu_s$
  - Karmen restrictions on $\bar{\nu}_\mu \to \bar{\nu}_e$
  - Other negative results

New MiniBooNE/SciBooNE
Limits on ν_μ / $\bar{\nu}_\mu$ Disappearance

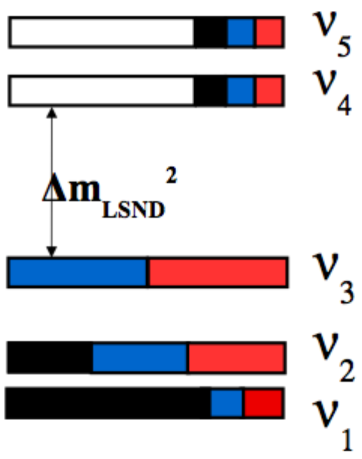
Phenomenology of Oscillations with Sterile Neutrinos

- In sterile neutrino (3+1) models, appearance comes from oscillation through ν_s
  - $\nu_\mu \rightarrow \nu_e = (\nu_\mu \rightarrow \nu_s) + (\nu_s \rightarrow \nu_e)$
- (3+1) models require ν_μ and ν_e disappearance oscillations
  - $\nu_\mu \rightarrow \nu_s$ and $\nu_e \rightarrow \nu_s$
  - Constraints from disappearance restrict application of (3+1) fits
- Current measurements of appearance and disappearance are not very compatible with (3+1) models ⇒ (3+2) models
  - If $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ are different then (3+2) models can have CP violation
  - Still tension between appearance and disappearance

(3+1) Models

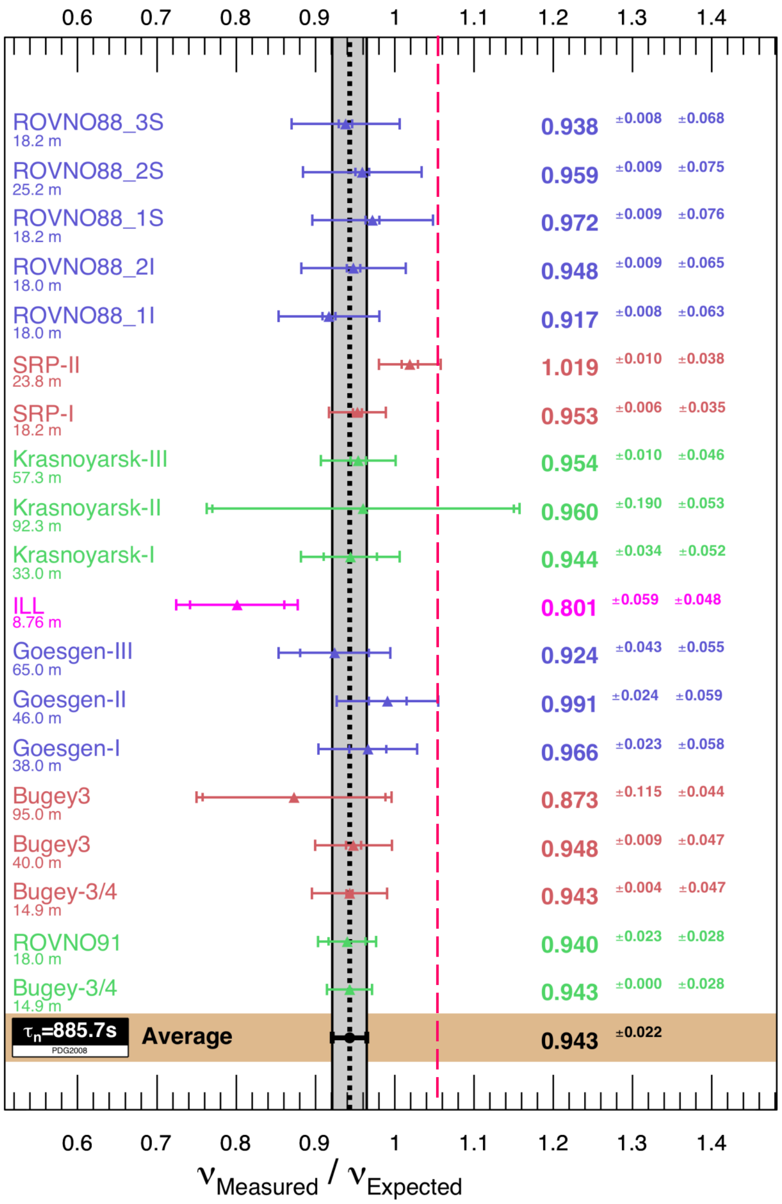


(3+2) Models



CP violation allowed in 3+2

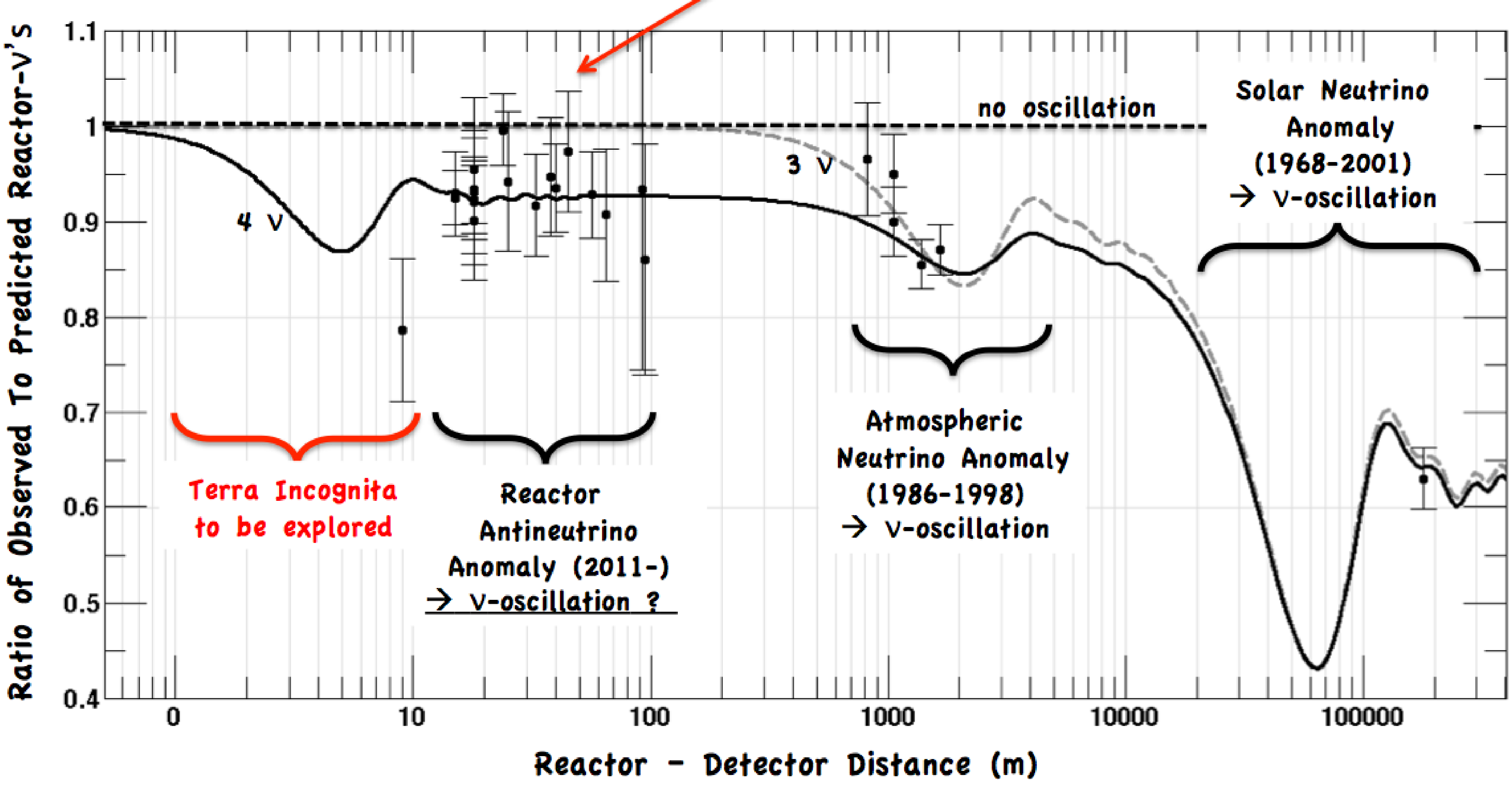
Reactor Antineutrino Anomaly



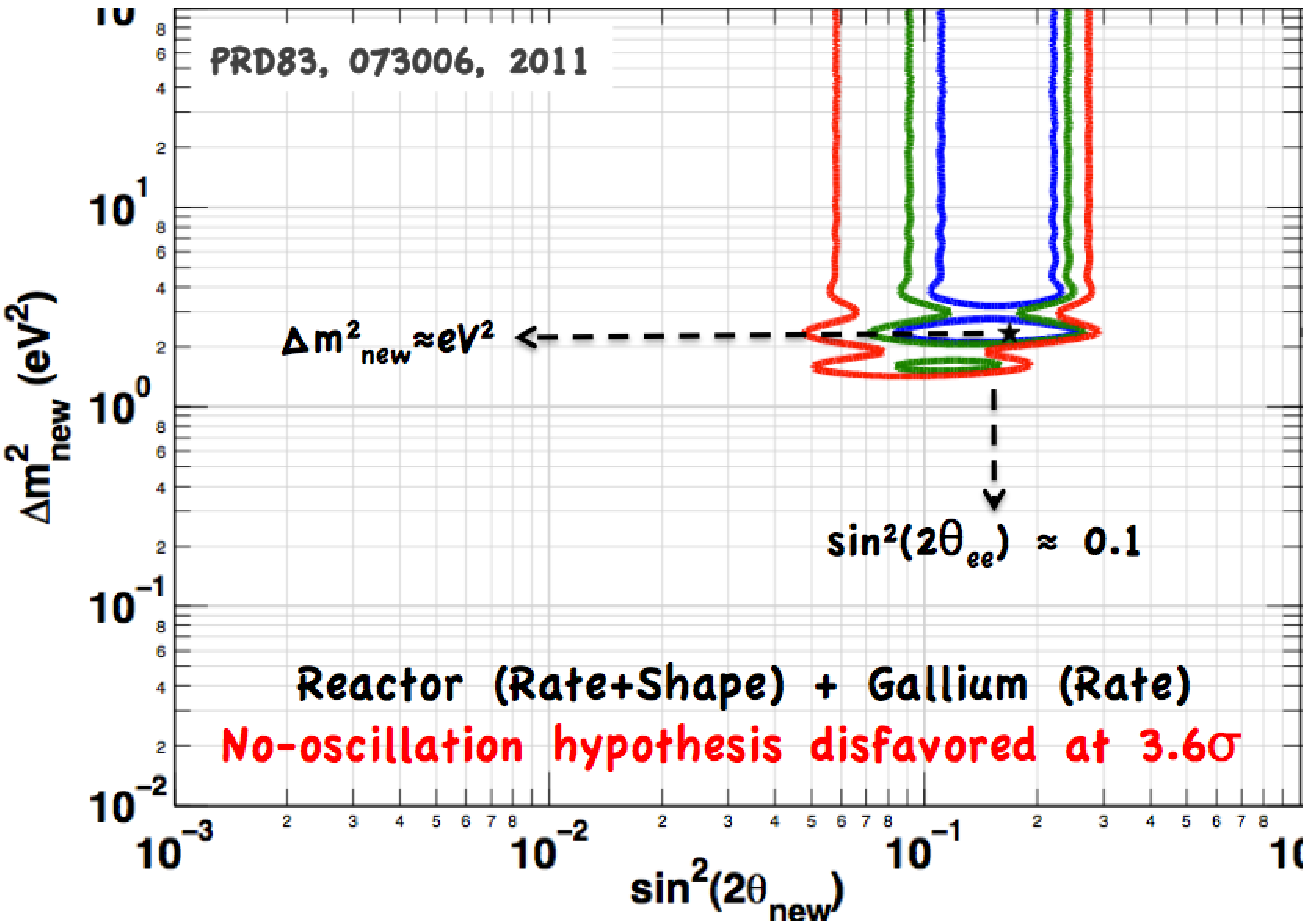
- **New Reactor antineutrino Spectra**
  - Net 3% upward shift in energy-averaged fluxes
  - Phys. Rev. C83, 054615, 2011
- **Recent re-analysis of 19 reactor neutrino results**
  - Neutron life time correction & Off-equilibrium effects
  - Phys. Rev. D83, 073006, 2011
  - **Obs/Pred = 0.927±0.023 (3 σ)**
- **At least three alternatives:**
  - Wrong prediction of ν-spectra ?
  - Bias in all experiments ?
  - New physics at short baselines:
    Mixing with 4th ν-state

Reactor Antineutrino Anomaly

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



Combined Gallium and Reactor Allowed Region (3+1)



PRD83, 073006, 2011

$\Delta m^2_{new} \approx eV^2$

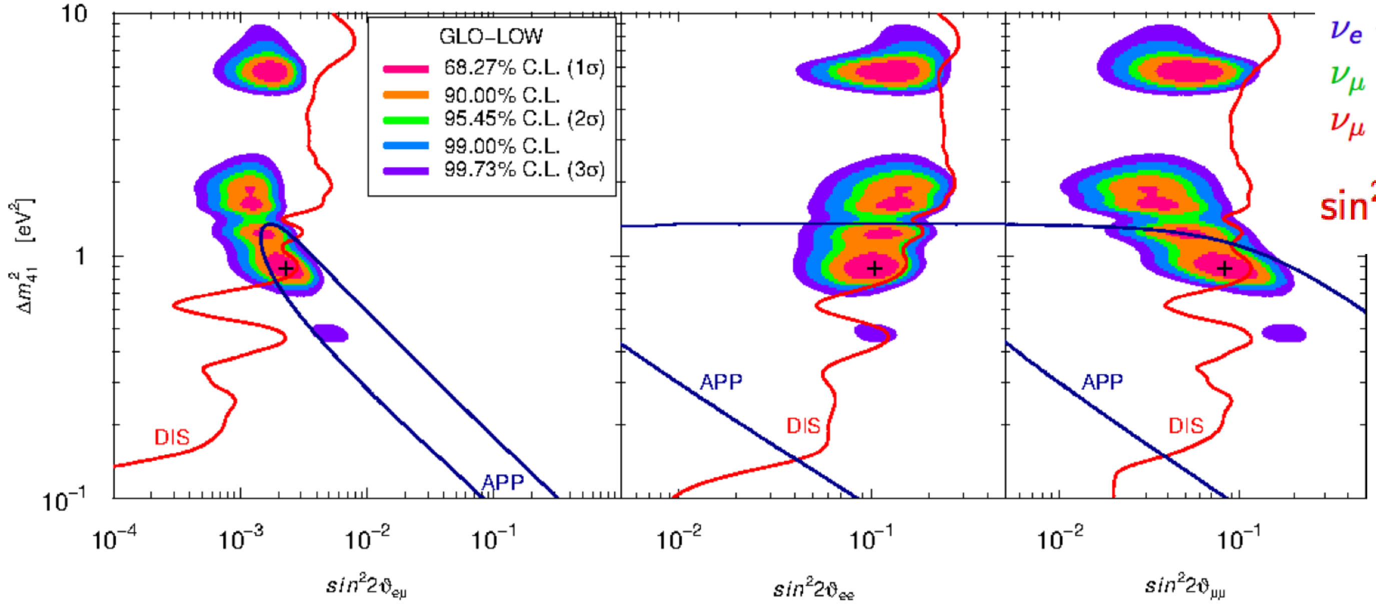
$\sin^2(2\theta_{ee}) \approx 0.1$

Reactor (Rate+Shape) + Gallium (Rate)

No-oscillation hypothesis disfavored at 3.6σ

Global Fits to Appearance and Disappearance Results

- In 3+1 models, hard to reconcile $\bar{\nu}_e/\nu_e$ appearance/disappearance with $\bar{\nu}_\mu/\nu_\mu$ disappearance
  - Compatibility among data sets for 3+1 fits less than 1%



$\nu_e \to \nu_e$ disappearance $\sin^2 2\theta_{ee}$

$\nu_\mu \to \nu_\mu$ disappearance $\sin^2 2\theta_{\mu\mu}$

$\nu_\mu \to \nu_e$ appearance $\sin^2 2\theta_{\mu e}$

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

Giunti, Laveder
arXiv:1111.1069

- 3+2 models better since there can be CP violating interference

appearance:

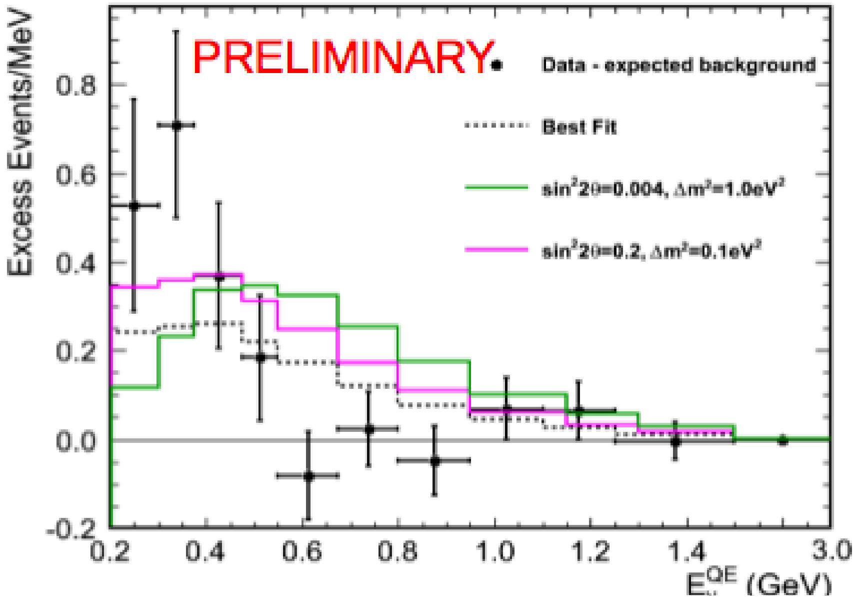
$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\phi_{41} + 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2\phi_{51} \\ &+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta) \end{aligned}$$

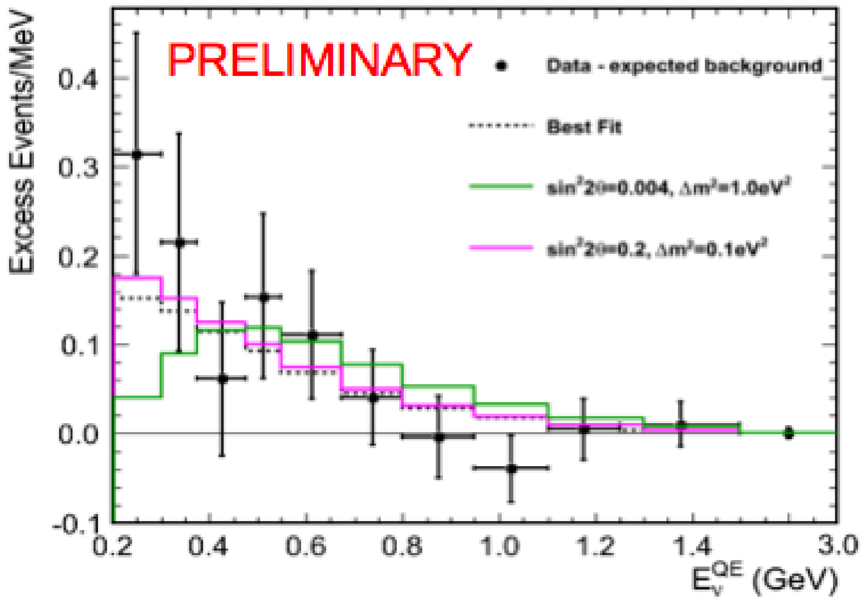
disappearance:

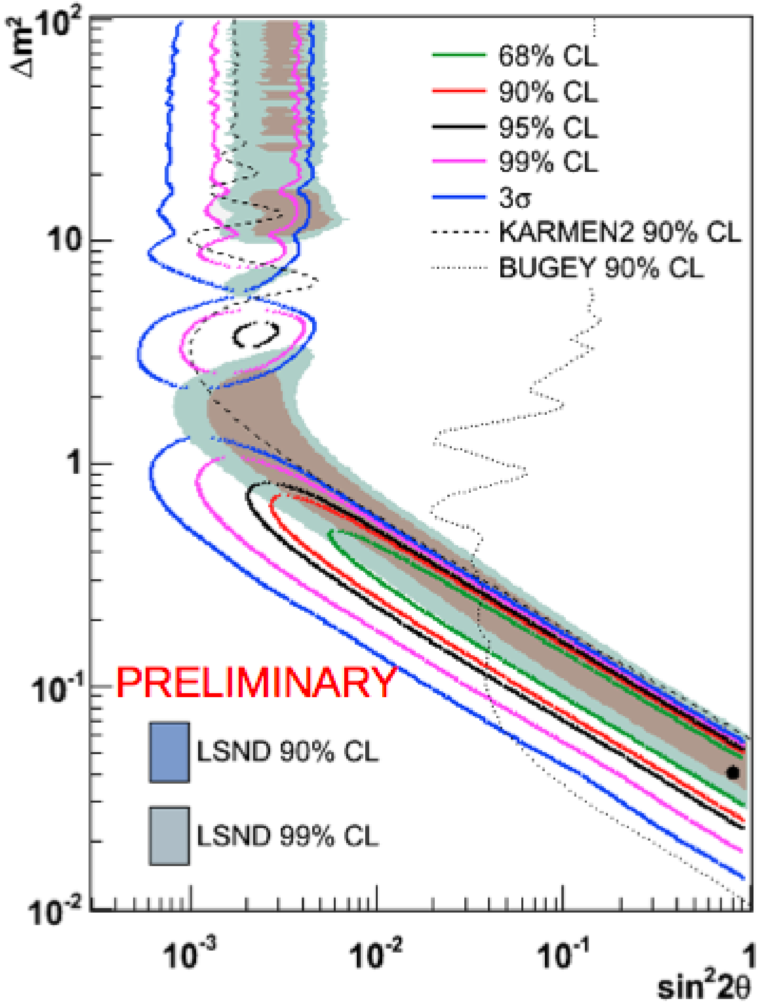
$$P_{\nu_\alpha \to \nu_\alpha} \approx 1 - 4 \sum_{i=4,5} |U_{\alpha i}|^2 \sin^2\phi_{i1} - 4\,|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2\phi_{54}$$

New MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$

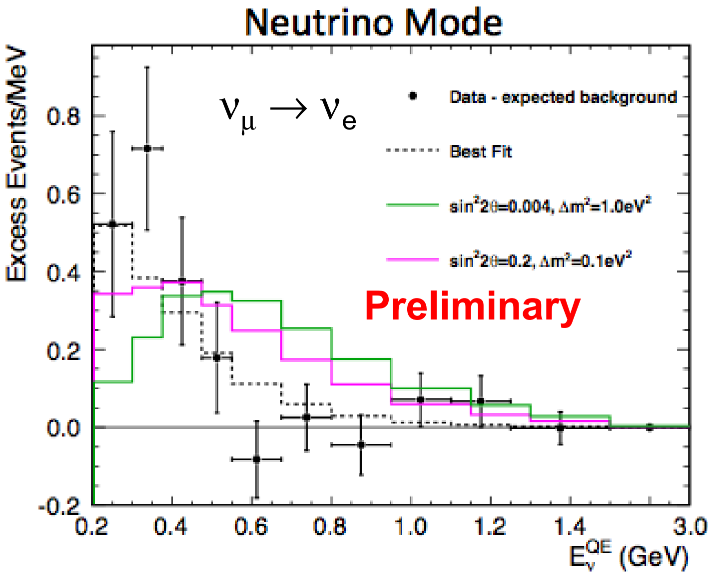
- $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ becoming more compatible with a common oscillation hypothesis and with the LSND result

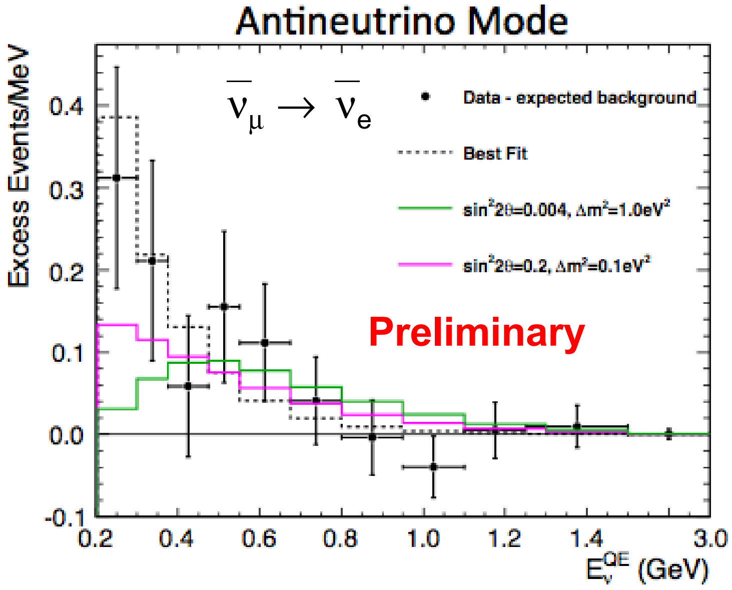






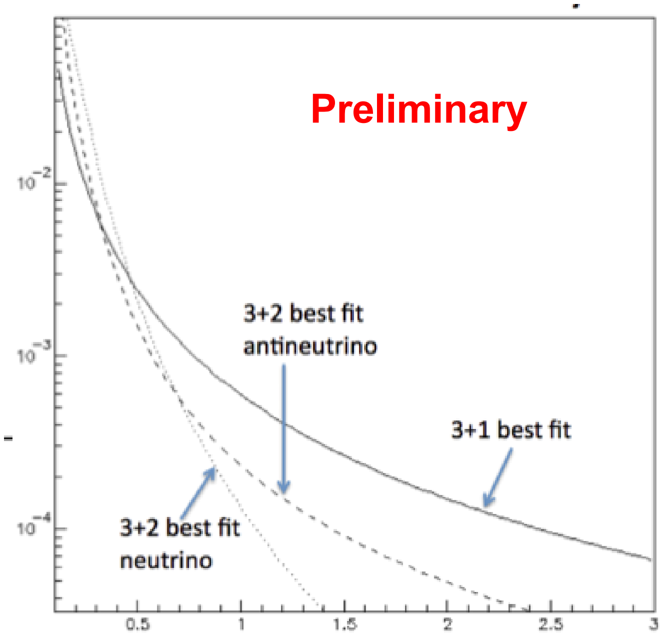
Preliminary (3+2) Fits to New MiniBooNE ν_e / $\bar{\nu}_e$ Appearance

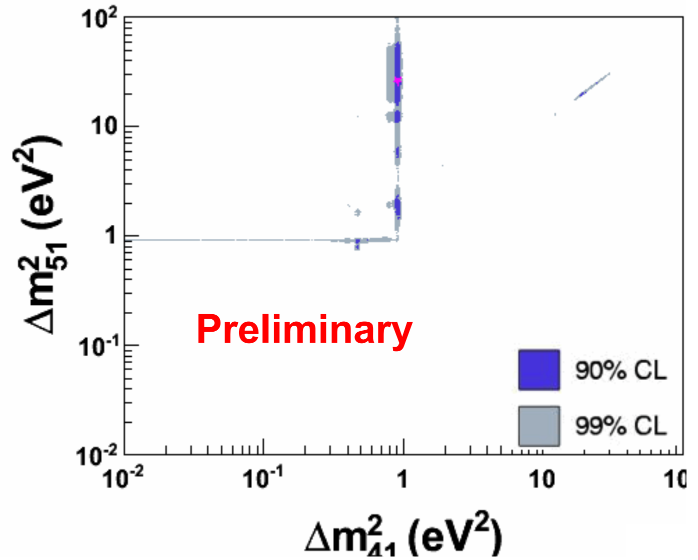




Global 3+2 Fits including new MiniBooNE $\bar\nu_\mu \to \bar\nu_e$ Data - C. Ignarra (MIT)

- Two high mass scales plus CP violation effects can possibly explain ν_e vs $\bar\nu_e$ appearance
- Still some tension with disappearance results.





Many Ideas for Future Experiments

- Establishing the existence of sterile neutrinos would be a major result for particle physics

- Need definitive experiments
  - Significance at the > 5σ level
  - Observation of oscillatory behavior (L and/or E dependence) within a detector or between multiple detectors
  - Oscillation signal clearly separated from backgrounds

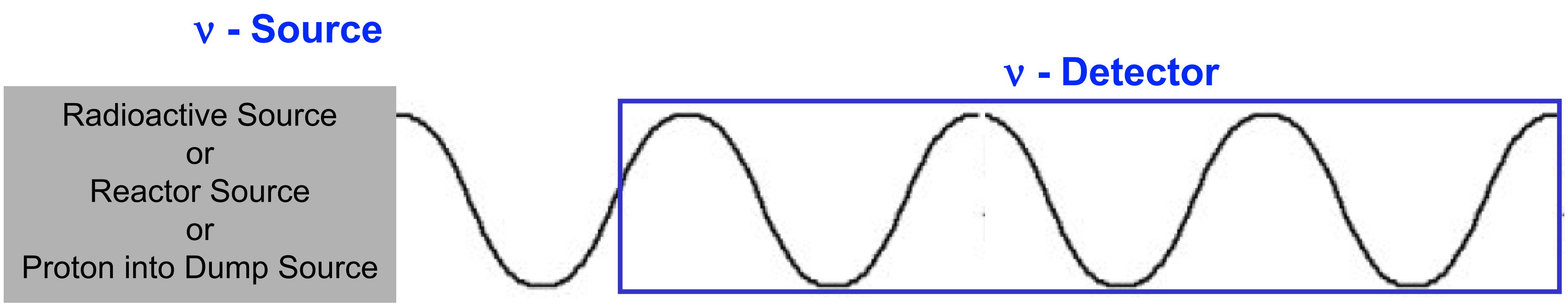
- Need to make both appearance and disappearance oscillation searches for neutrinos and for antineutrinos
  - Needed to prove the consistency with sterile neutrino (3+1) and (3+2) models

- Very active area for the field with many proposals and ideas
  - "Light Sterile Neutrinos: A White Paper" (arXiv:1204.5379) put together by a group of over 170 experimentalists and theorists.
  - Many workshops investigating opportunities and possibilities

Future Experimental Oscillation Proposals

Type of Exp	App/Disapp	Osc Channel	Experiments
Reactor Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	Nucifer, Stereo, SCRAMM, NIST, Neutrino4, DANSS
Radioactive Sources	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$ $(\nu_e \to \nu_e)$	Baksan, LENS, Borexino, SNO+, Richochet, CeLAND, Daya-Bay
Isotope Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest Source	Appearance & Disapp	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Accelerator $\overset{(-)}{\nu}$ using Pion Decay-in-Flight	Appearance & Disapp	$\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-Energy ν-Factory	Appearance & Disapp	$\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	νSTORM at Fermilab

Very-short Baseline Oscillation Experiments



ν - Source

Radioactive Source
or
Reactor Source
or
Proton into Dump Source

ν - Detector

$$1/L^2 \text{ flux rate modulated by } \mathrm{Prob}_{osc} = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L / E\right)$$

- Can observe oscillatory behavior within the detector if neutrino source has small extent .
  - Look for a change in event rate as a function of position and energy within the detector
  - Bin observed events in L/E (corrected for the $1/L^2$) to search for oscillations
- Backgrounds produce fake events that do not show the oscillation L/E behavior and are easily separated from signal

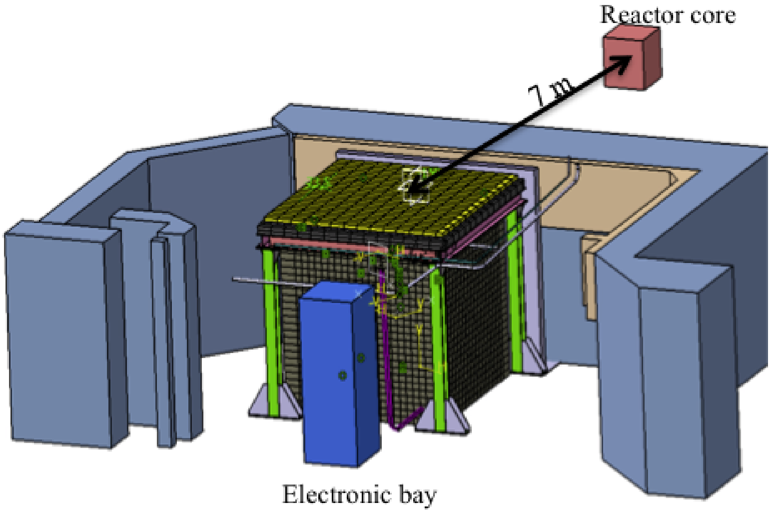
Very-Short Baseline Reactor Experiments
($\bar{\nu}_e$ Disappearance)

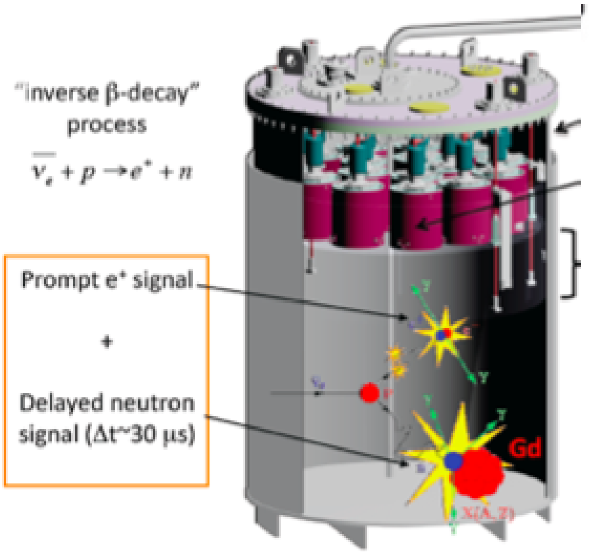
Very-Short Baseline Reactor Experiments

Experiment	Reactor	Baseline	Status
Nucifer (Saclay)	Osiris 70MW	7	Taking Data
Stereo (Genoble)	ILL 50 MW	10	Proposal
SCRAMM (CA)	San-Onofre 3 GW	24	Proposal
NIST (US)	NCNR 20 MW	4-11	Proposal
NEUTRINO4	SM3 100 MW	6-12	Proposal
SCRAMM (Idaho)	ATR 150 MW	12	Proposal
DANSS (Russia)	KNPP 3 GW	14	Fabrication

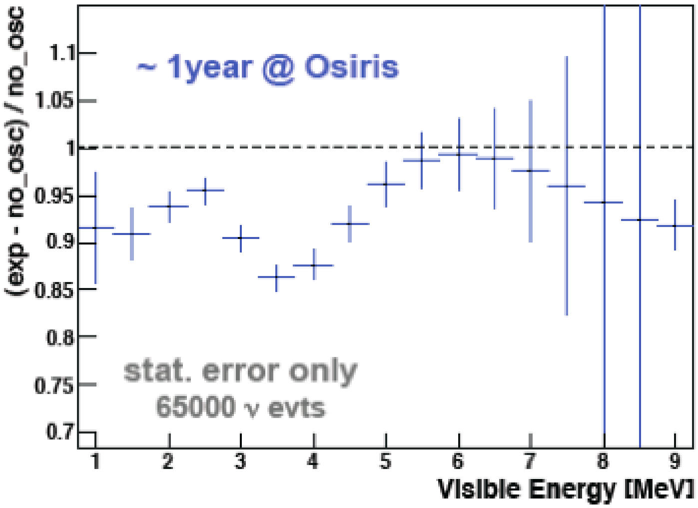
NUCIFER Reactor Experiment

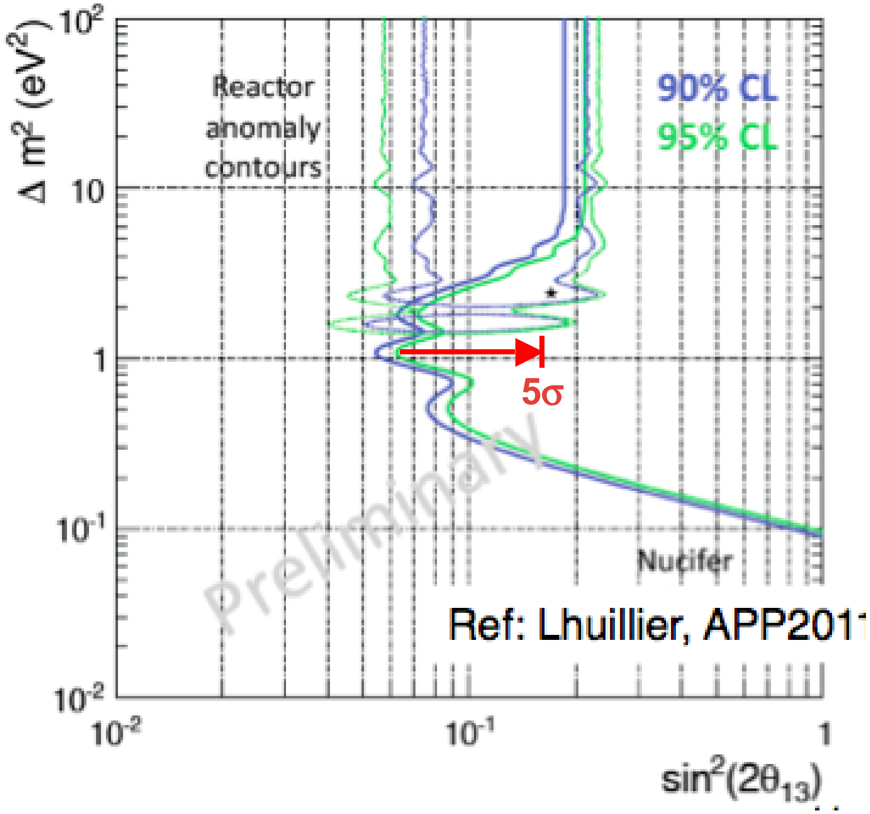
Osiris Research Reactor: Core Size: 57x57x60 cm
1.2m x 0.7m detector , 7m distance from core





Expected E spectrum deformation
with anomaly best fit: $\Delta m^2 = 2.4\ eV^2$ & $\sin^2(2\theta)=0.15$





Ref: Lhuillier, APP201

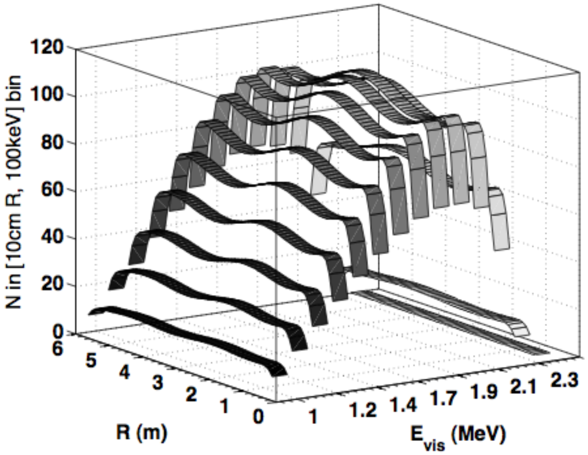
Radioactive β-Decay Source Experiments
(ν_e or $\bar{\nu}_e$ Disappearance)

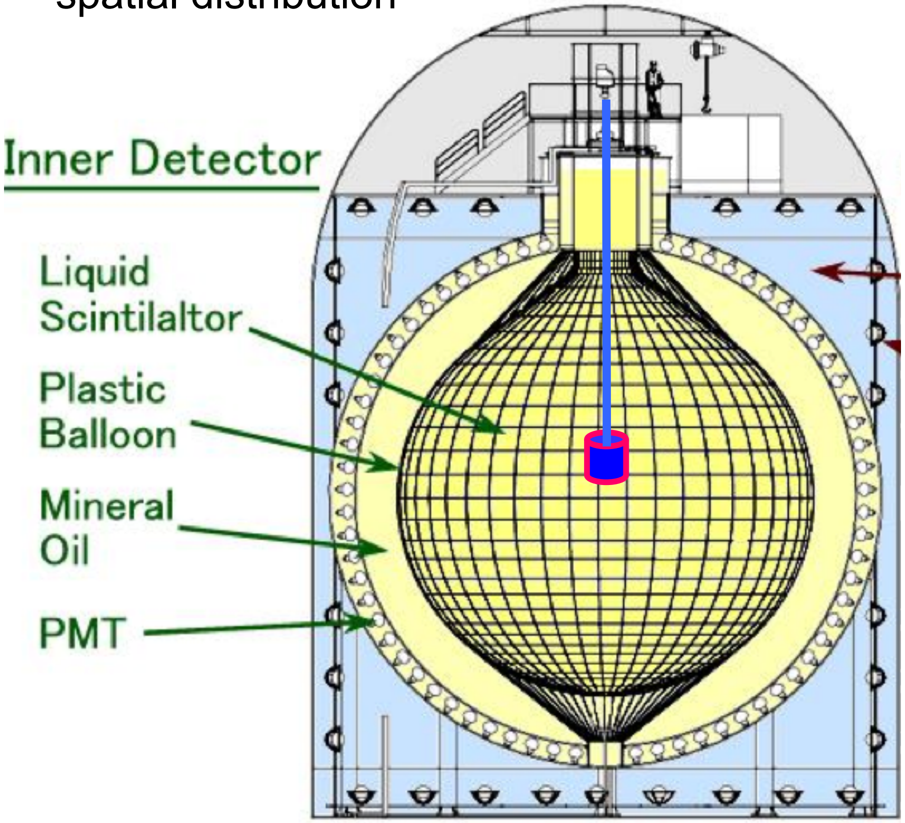
Radioactive β-Decay Source Experiments

Species	Source	Experiment	Status
ν_e	^{51}Cr	Baksan	Proposal
ν_e	^{51}Cr	LENS	Proposal
ν_e	^{51}Cr	Borexino	Proposal
ν_e	^{51}Cr	SNO+	Proposal
ν_e	^{37}Ar	Richochet	Proposal
$\overline{\nu}_e$	^{144}Ce	Ce-LAND	Proposal
$\overline{\nu}_e$	^{144}Ce	Daya-Bay	Proposal

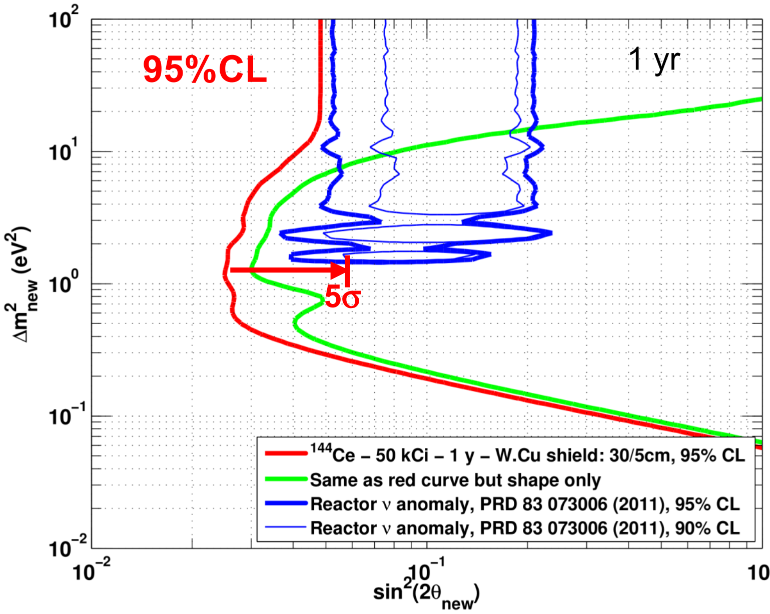
Ce-LAND Exp: Using ^{144}Ce kCi Anti-neutrino Source

- A 50 kCi anti-ν source (10 g of ^{144}Ce) in the middle of a large LS detector
- Inside a thick 35 cm W-Cu shielding → background free
- Energy-dependent oscillating pattern in event spatial distribution





M. Cribier, et al. PRL 107, 201801(2011)

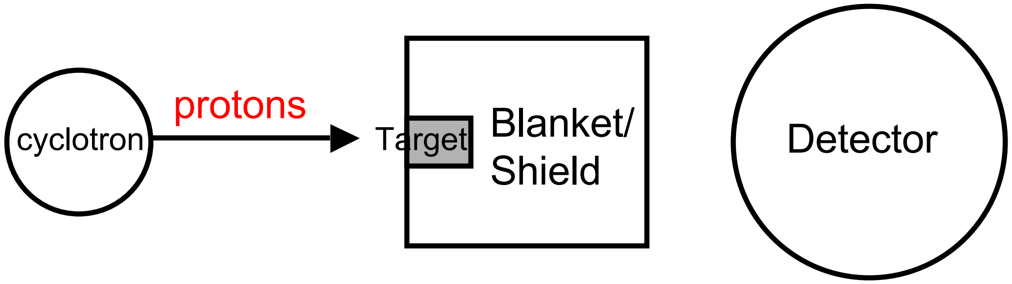


Detectors which could be used for this idea include Kamland, SNO+, or Borexino…

Isotope Decay-at-Rest Neutrino Source
($\bar{\nu}_e$ Disappearance)

IsoDAR $\bar{\nu}_e$ Disappearance Exp (arXiv:1205.4419)

- High intensity $\bar{\nu}_e$ source using β-decay at rest of ^{8}Li isotope ⇒ IsoDAR
- ^{8}Li produced by high intensity (10ma) proton beam from 60 MeV cyclotron ⇒ being developed as prototype injector for DAEδALUS cyclotron system
- Put a cyclotron-isotope source near one of the large (kton size) liquid scintillator/water detectors such as KAMLAND, SNO+, Borexino, Super-K….



- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector.

IsoDAR 60 MeV Proton Cyclotron (Under Development)

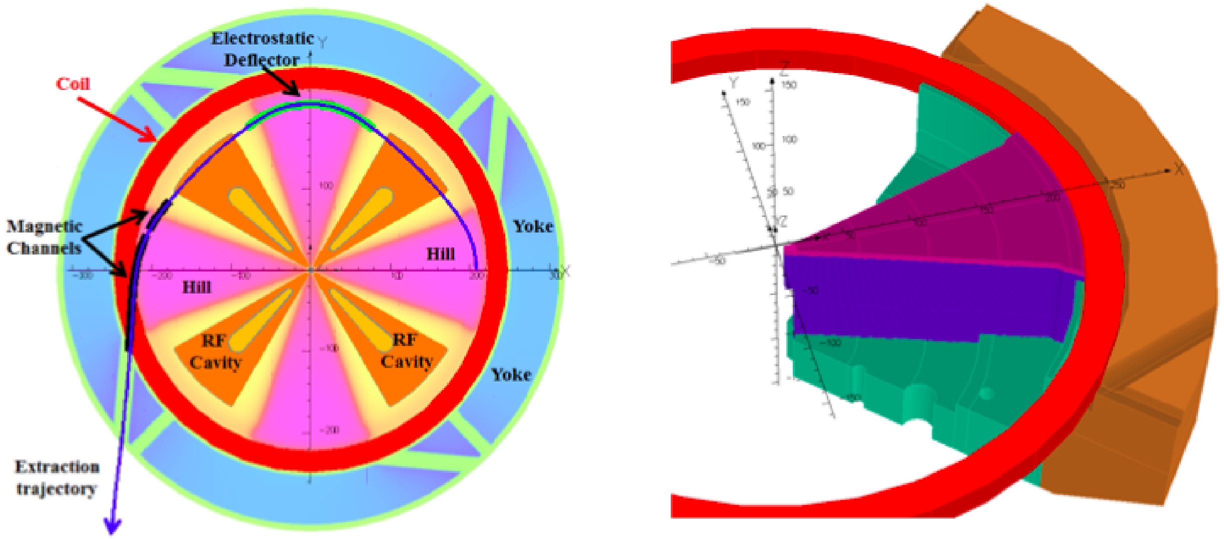


Figure 3: *Left: Layout of the injector cyclotron. Pastel colors indicate magnetic field map (pink is highest). The hill/valley structure is apparent. Extraction trajectory for* H_2^+ *is shown. Right: Illustration of the Opera3D finite element magnetic model showing one quarter of the cyclotron with the pole, the return yoke and the coil.*

Table 1: *Parameters of the DAEδALUS injector cyclotron*

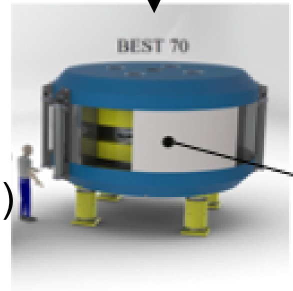
E_{max}	60 MeV/amu	E_{inj}	35 keV/amu
R_{ext}	1.99 m	R_{inj}	55 mm
$< B >$ @ R_{ext}	1.16 T	$< B >$ @ R_{inj}	0.97 T
Sectors	4	Hill width	28 - 40 deg
Valley gap	1800 mm	Pole gap	100 mm
Outer Diameter	6.2 m	Full height	2.7 m
Cavities	4	Cavity type	$\lambda/2$, double gap

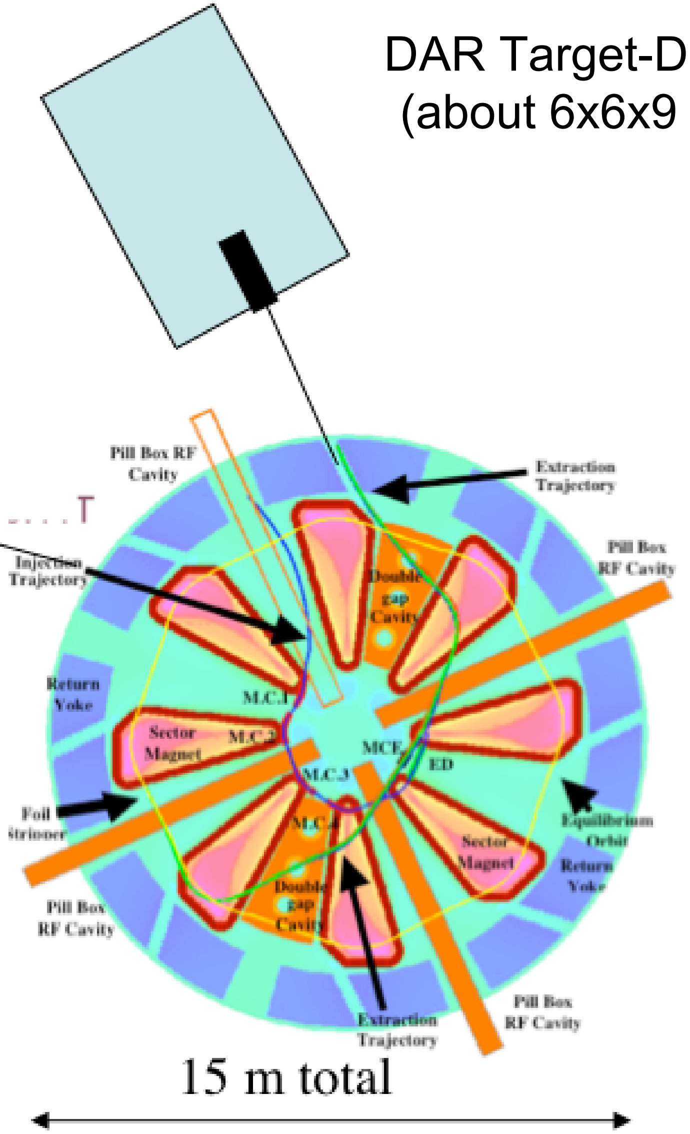
DAEδDALUS 800 MeV Cyclotron System (Under Development)

H_2^+ Ion Source

IsoDAR Cyclotron

Injector Cyclotron (Resistive Isochronous)



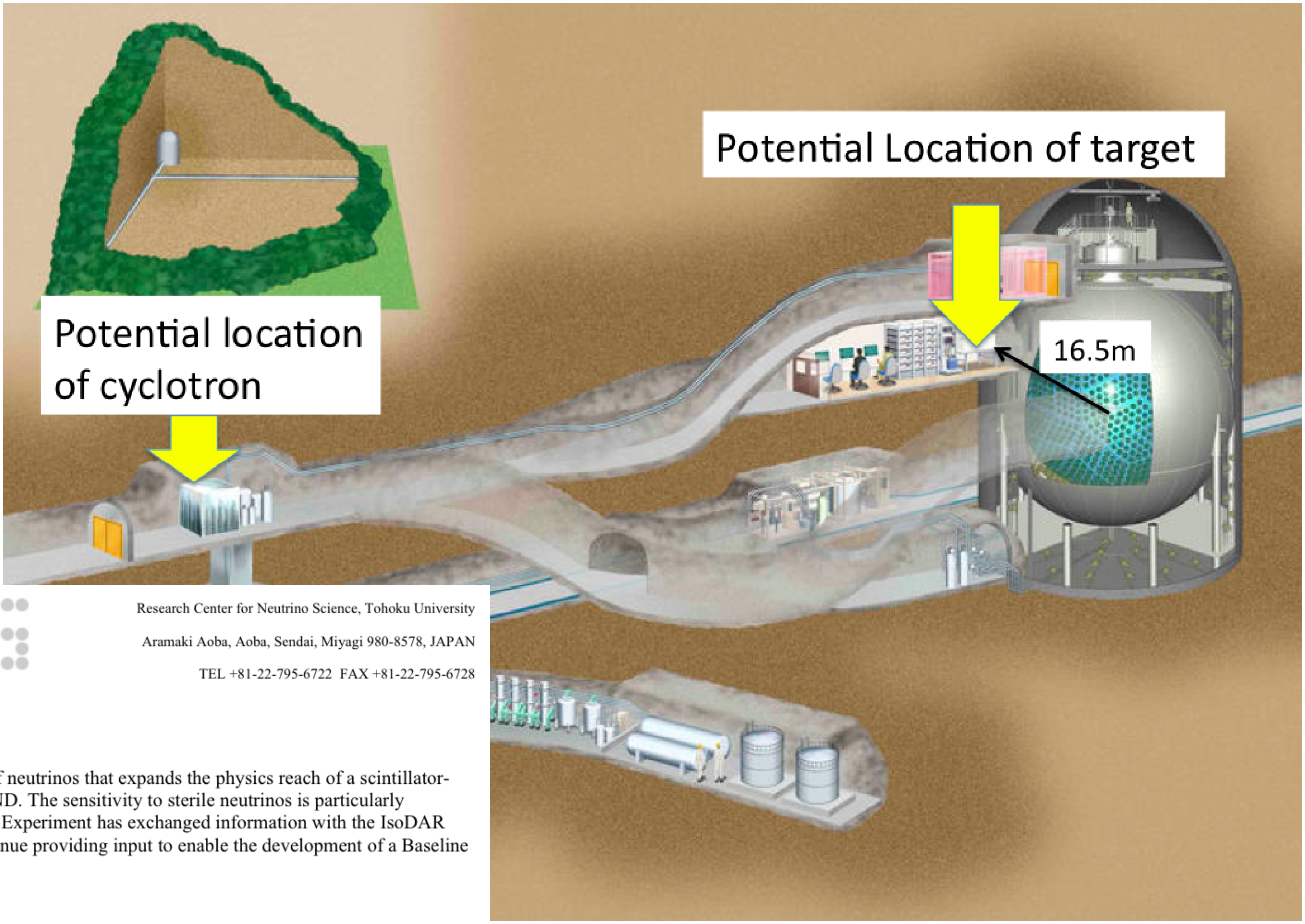


DAR Target-Dump (about 6x6x9 m^3)

Ring Cyclotron (Superconducting)

“Isochronous cyclotron” where mag. field changes with radius, but RF does not change with time. This can accelerate many bunches at once.

IsoDAR at Kamland



RCNS

Research Center for Neutrino Science, Tohoku University
Aramaki Aoba, Aoba, Sendai, Miyagi 980-8578, JAPAN
TEL +81-22-795-6722 FAX +81-22-795-6728

Letter of Collaboration

IsoDAR provides a source of neutrinos that expands the physics reach of a scintillator-based detector like KamLAND. The sensitivity to sterile neutrinos is particularly motivating. The KamLAND Experiment has exchanged information with the IsoDAR group already, and will continue providing input to enable the development of a Baseline Design Report.

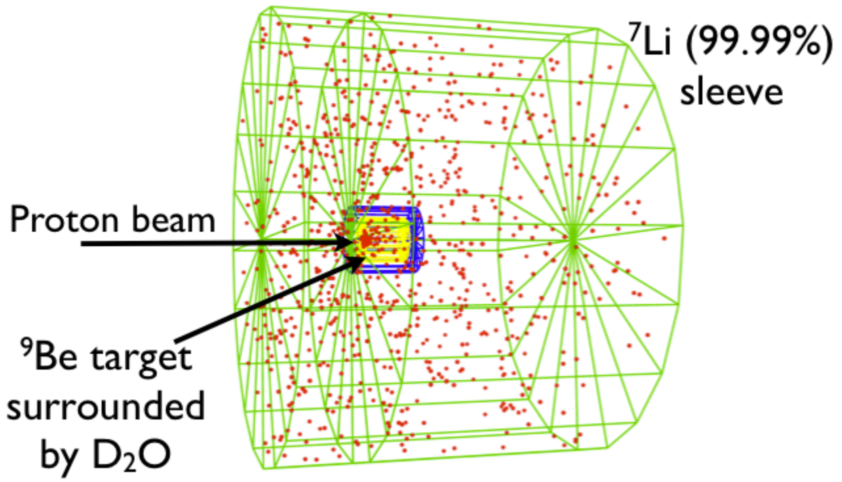
Sincerely,

Kunio Inoue

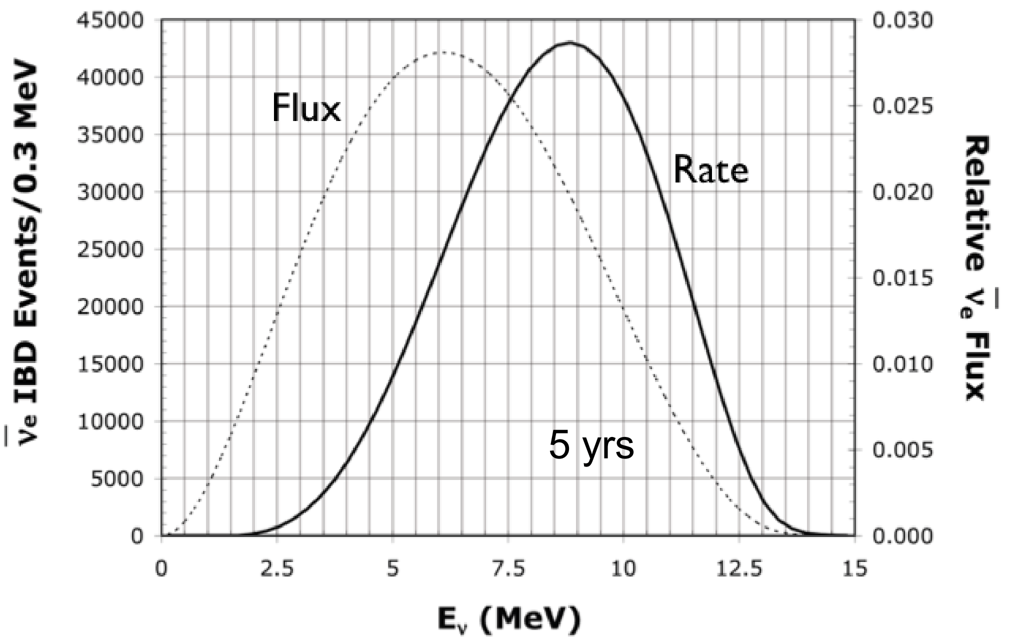
Kunio Inoue
Research Center for Neutrino Science,
Tohoku University

IsoDAR Neutrino Source and Events

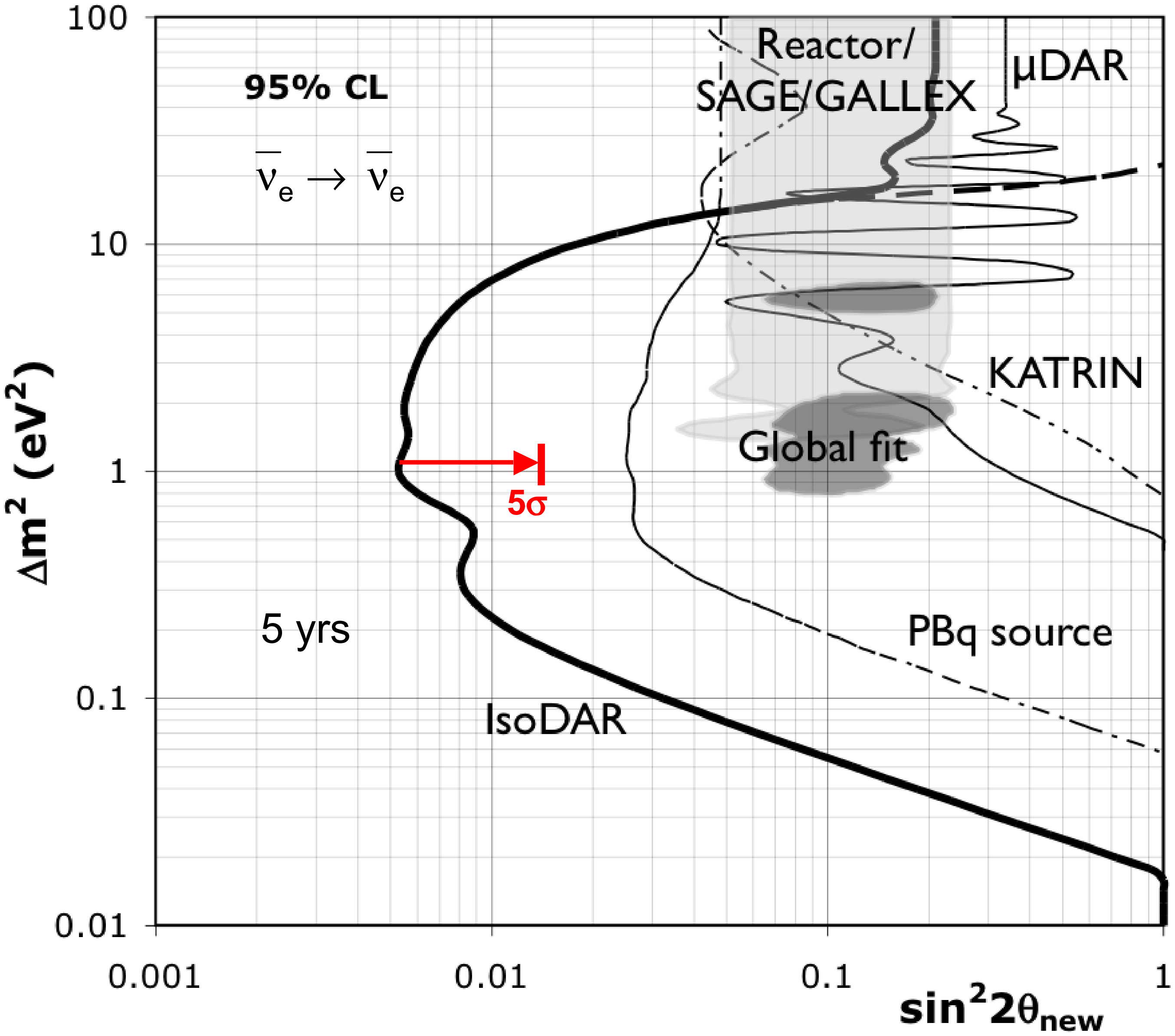
- p (60 MeV) + ^{9}Be → ^{8}Li + 2p
  - plus many neutrons since low binding energy
- n + ^{7}Li (shielding) → ^{8}Li
- ^{8}Li → ^{8}Be + e^{-} + $\bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV
  - 2.6×10^{22} $\bar{\nu}_e$ / yr
- Example detector: Kamland (900 t)
  - Use IBD $\bar{\nu}_e + p \rightarrow e^{+} + n$ process
  - Detector center 16m from source
  - ~160,000 IBD events / yr
  - 60 MeV protons @ 10ma rate
  - Observe changes in the IBD rate as a function of L/E



arXiv:1205.4419

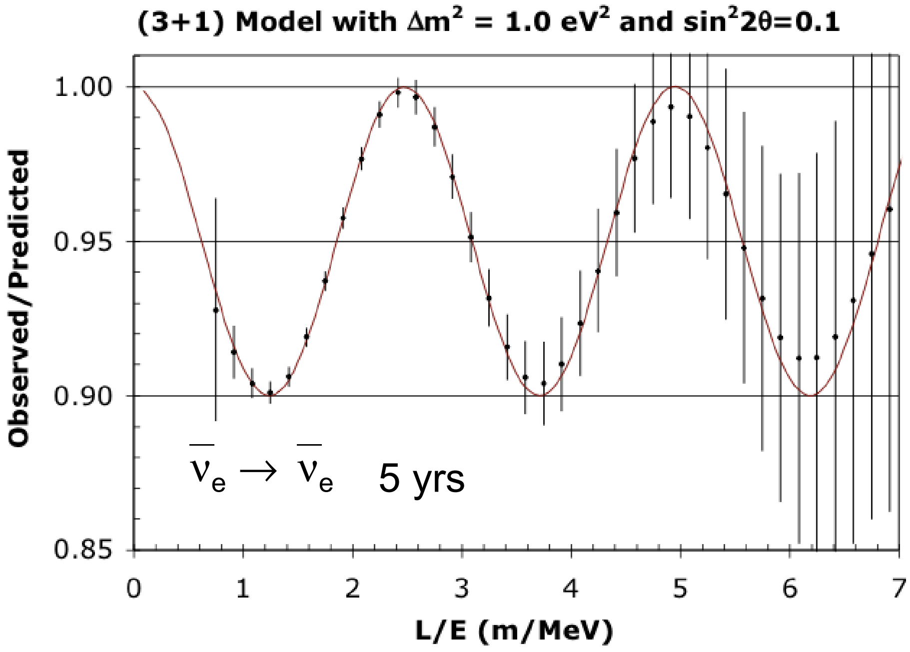


IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)

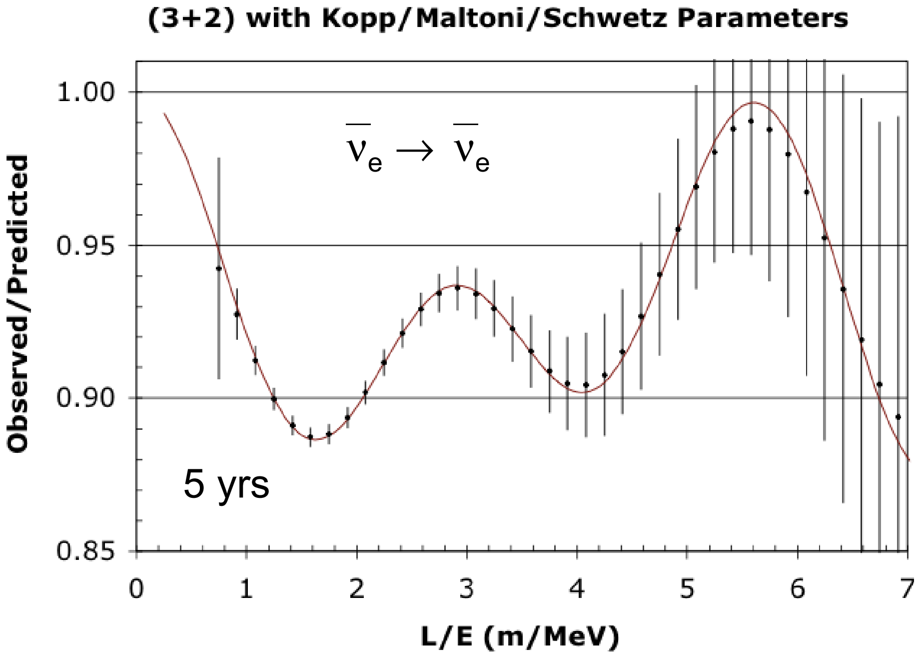


Oscillation L/E Waves in IsoDAR

Observed/Predicted event ratio vs L/E including energy and position smearing



(3+1) Model with Δm^2 = 1.0 eV^2 and $\sin^2 2\theta$=0.1



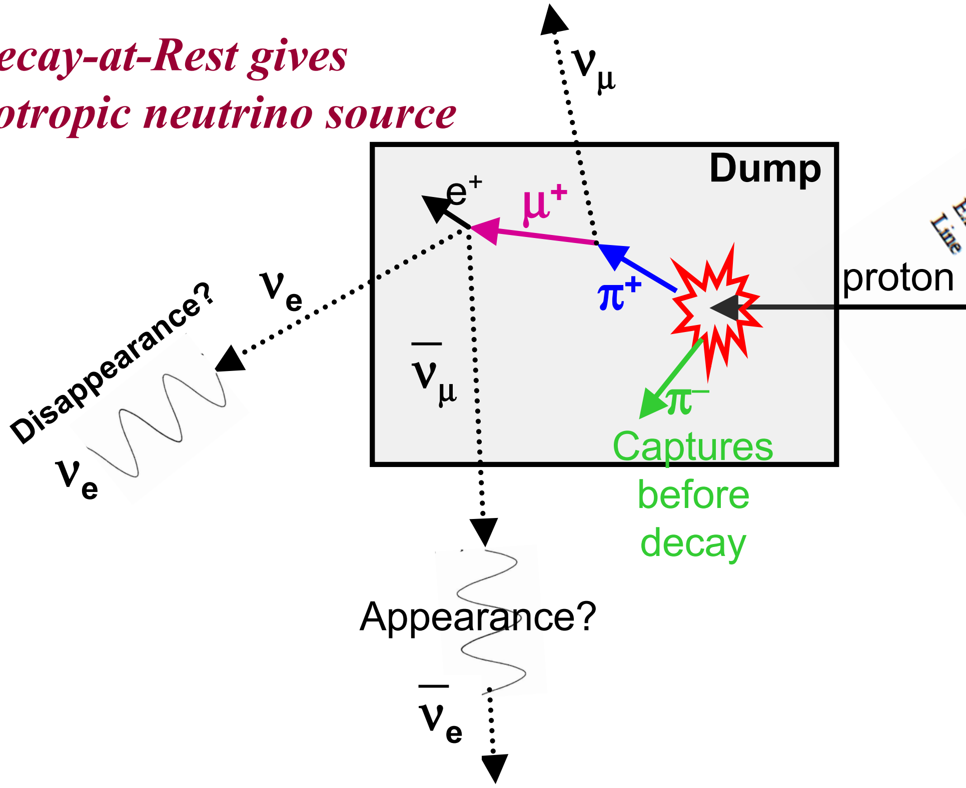
(3+2) with Kopp/Maltoni/Schwetz Parameters

IsoDAR's high statistics and good L/E resolution gives good sensitivity to distinguish (3+1) and (3+2) oscillation models

Pion or Kaon Decay-at-Rest Neutrino Sources

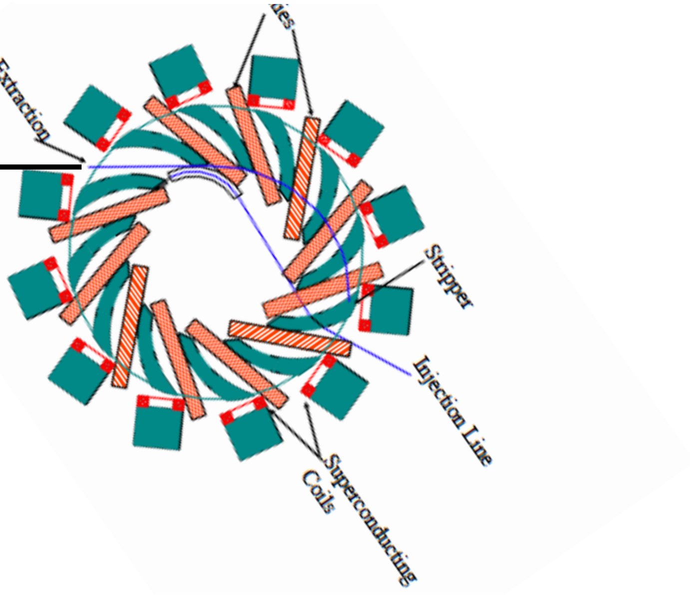
Decay-at-Rest (or Beam Dump) Neutrino Sources

Decay-at-Rest gives isotropic neutrino source

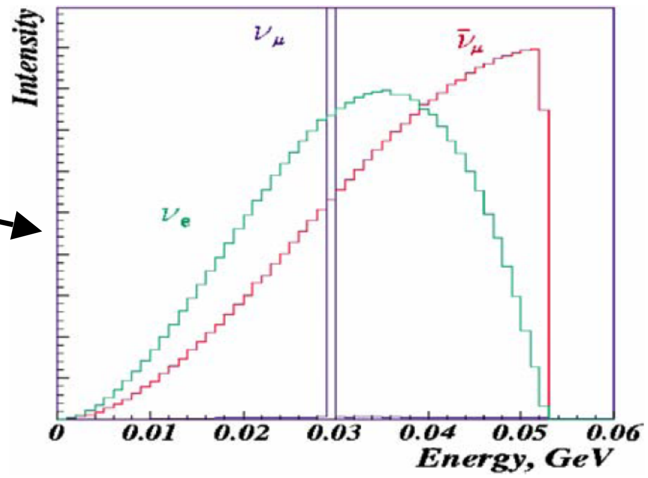


Cyclotron or Other Proton Source

(>800 MeV proton for π production)



Each π^+ decay gives one ν_μ, one ν_e, and one $\bar{\nu}_\mu$ with known energy spectrum



~1 ma of 800 MeV protons (like LSND)

$\Rightarrow$ *0.17* π^+*/proton* $\Rightarrow$ $2.3 \times 10^{24}\ \nu\,/\,yr$

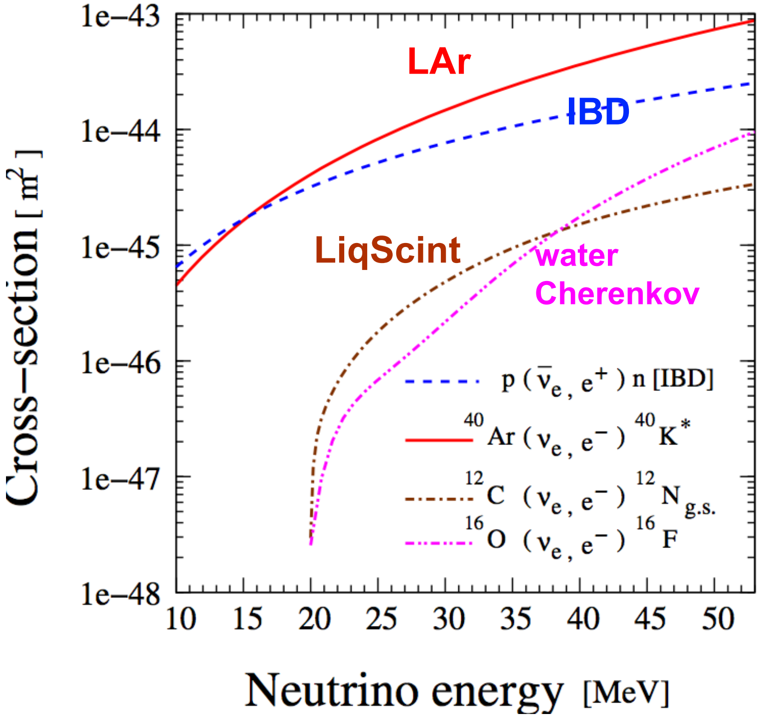
Short Baseline Osc Exps using DAR Sources

- Good oscillation sensitivity for DAR ν / $\bar{\nu}$ -source placed near large detector
  - Neutrino source has small extent (± 25 cm) and can be close (~20m) to detector
  - Energy range 20 to 50 MeV
  - Possible to observe L/E oscillations within the detector

- Detectors: Cherenkov (water or oil), liquid argon, or liquid scintillator

- $\nu_e \rightarrow \nu_e$ Disappearance
  - Process: Charged current scattering ($\nu_e + N \rightarrow e^- + N'$)
  - Look for an oscillations in ν_e rate with L/E
  - Backgrounds do not have this L/E behavior

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance
  - Process: Inverse Beta Decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Look for oscillation wave in L/E
  - Detector needs to free hydrogen targets and be able to capture the outgoing n
    ⇒ Only water or liquid scintillator (with Gd better)

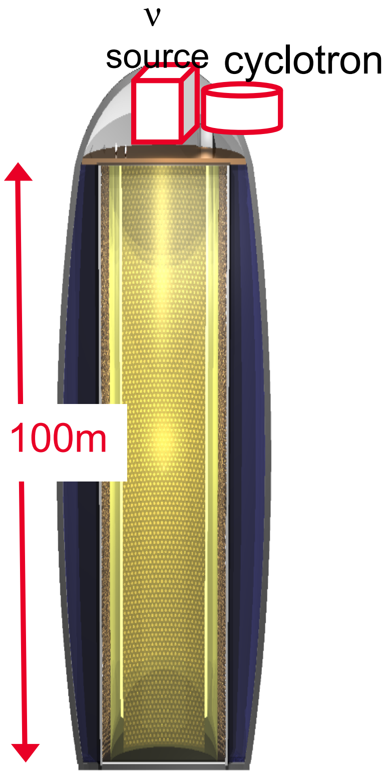


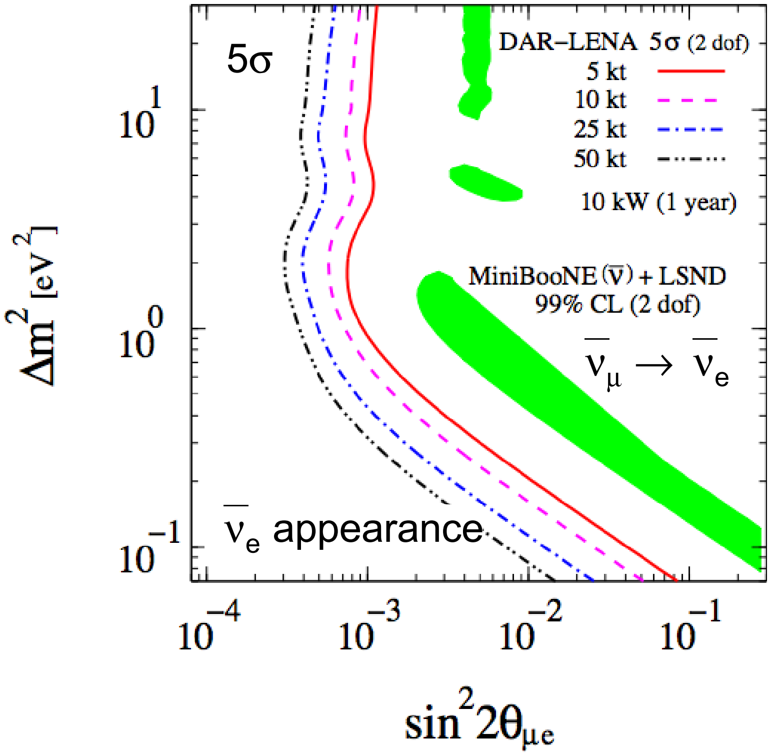
Scintillation Detectors with DAR Neutrino Sources

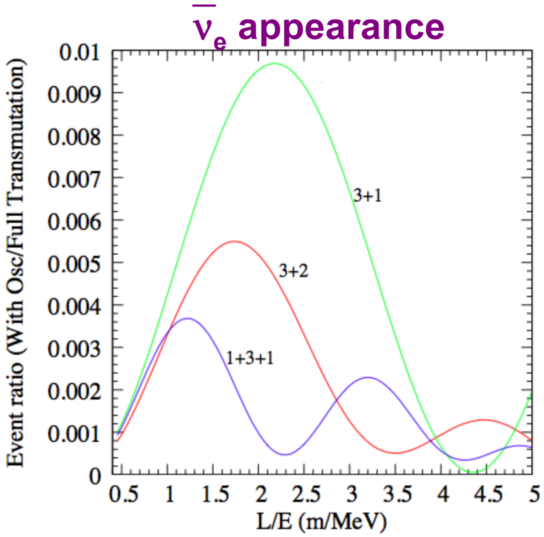
Example: LENA Scintillation Detector

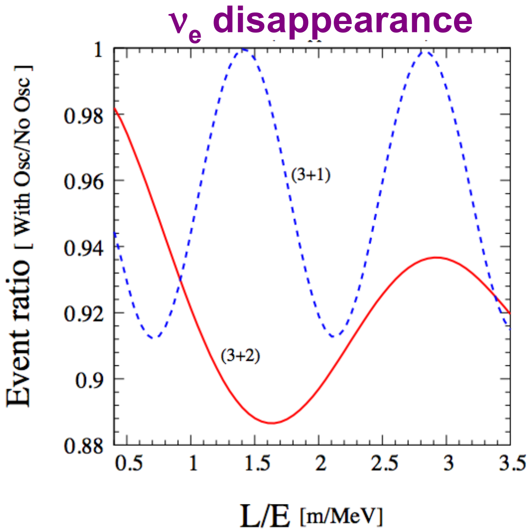
(Part of the European LAGUNA Project)

- For 5σ coverage, only need 10 kW source with 5 kton detector
- Deep location (4000 mwe) so minimal cosmic muon backgrounds
- Appearance and Disappearance possible









Agarwalla, Conrad, and MHS:
arXiv:1105.4984 (JHEP 1112 (2011) 085)

OscSNS: DAR Neutrino Source at SNS (ORNL)

arXiv:0810.3175

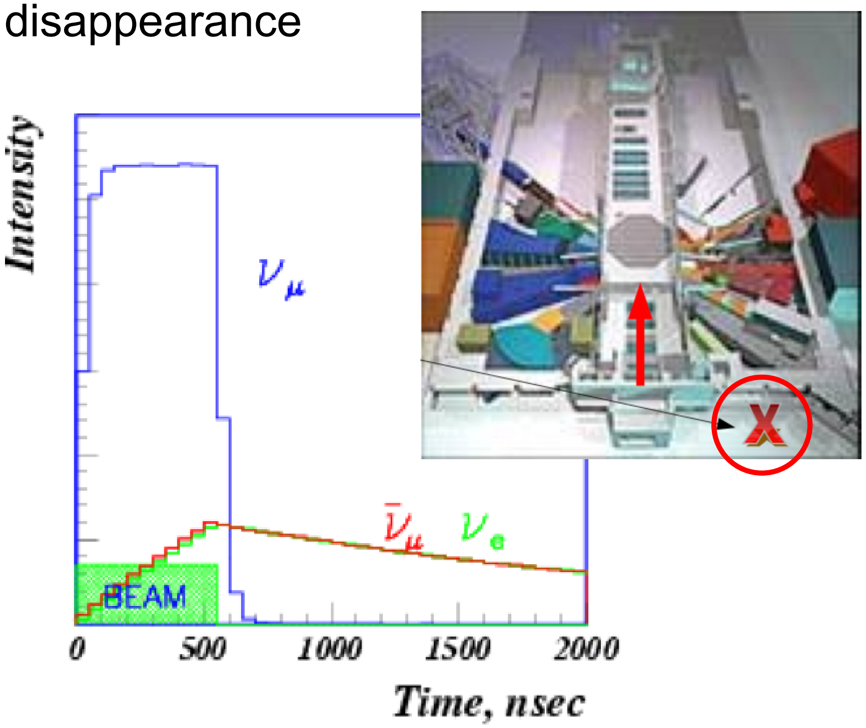
- Spallation neutron source at ORNL
- ~1GeV protons on Hg target (1.4MW)
- 6.2% Duty factor reduces backgrounds
- Time structure 695ns pulses at 20 Hz can separate ν_μ from $\bar{\nu}_\mu$ and ν_e
- 800 ton MiniBooNE style detector 60m from target
- Can do $\bar{\nu}_e$ appearance and other types of disappearance

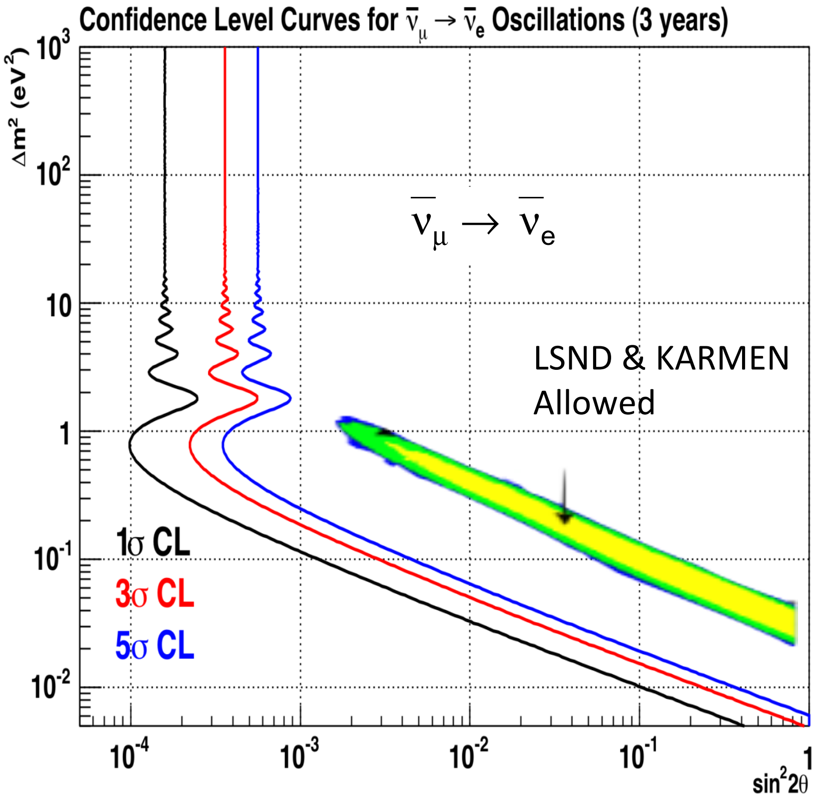
$\bar{\nu}_\mu \to \bar{\nu}_e$

$\nu_e \to \nu_s$

$\nu_\mu \to \nu_s$

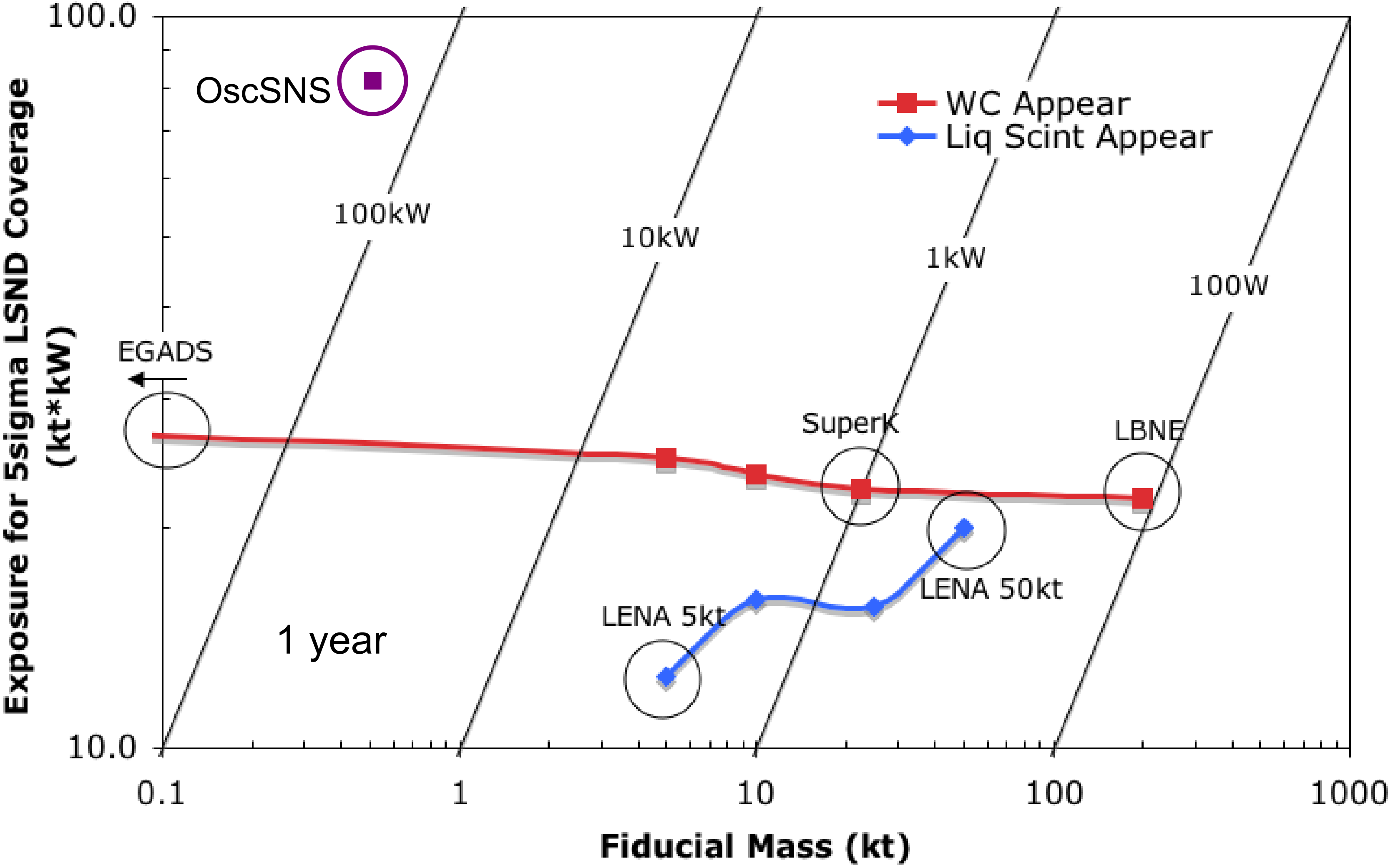
$\bar{\nu}_\mu \to \bar{\nu}_s$





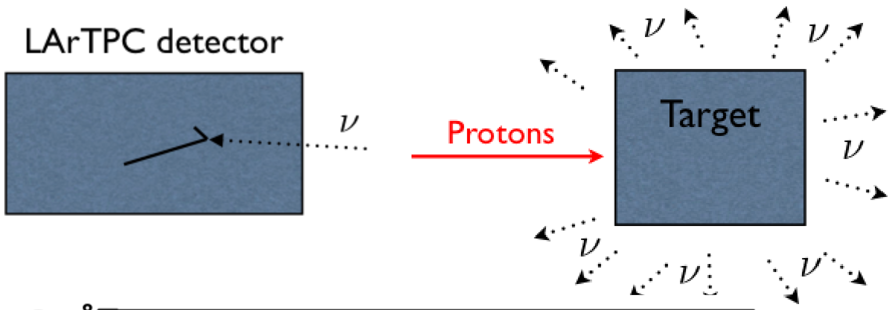
VSBL $\bar{\nu}_e$ Appearance: Source Power and Detector Size for LSND Coverage at 5σ

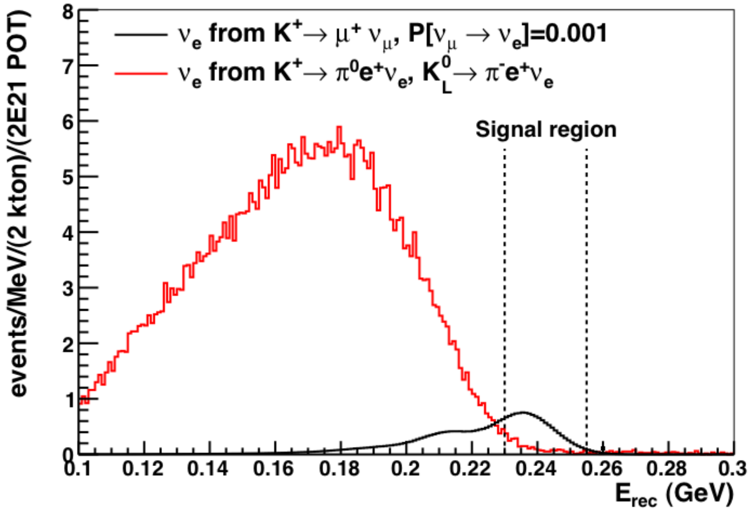
Exposure = Detector Size (kton) × Cyclotron Power (kW)
(5σ LSND Coverage in 1 year)

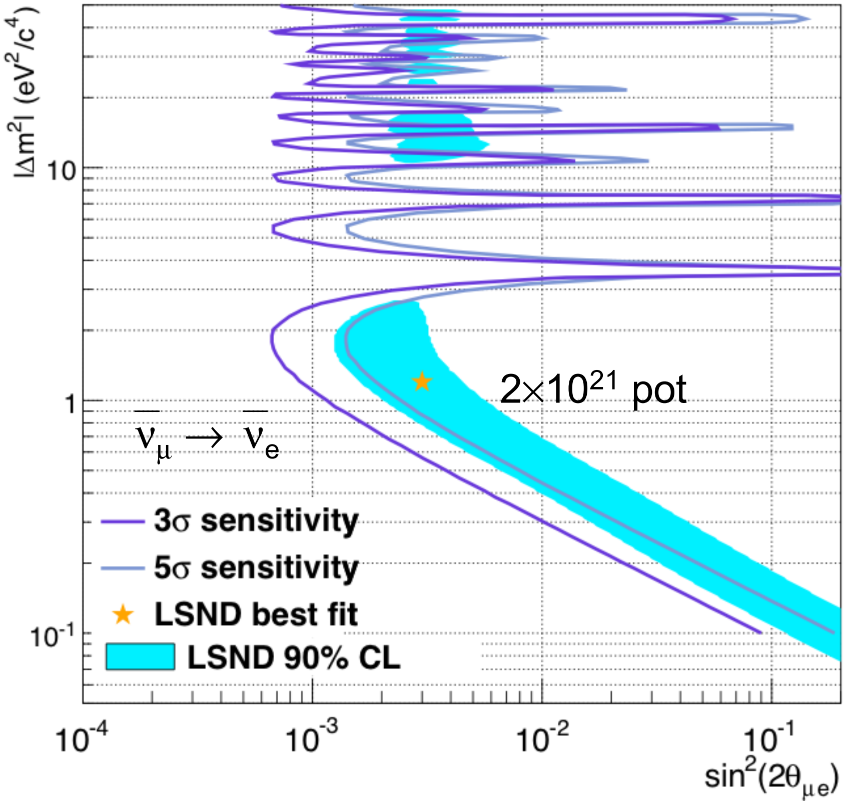


Kaon Decay-at-Rest Experiment

- >10 GeV high-intensity, proton beam into target-dump to produce kaons that stop and decay at rest.
  - Gives a monoenergetic muon neutrinos (235 MeV) from $K \rightarrow \mu + \nu_\mu$
- 2 kton LAr detector placed at 160m in backwards direction.
- Look for $\nu_\mu \rightarrow \nu_e$ oscillations by identifying ν_e events at high energy





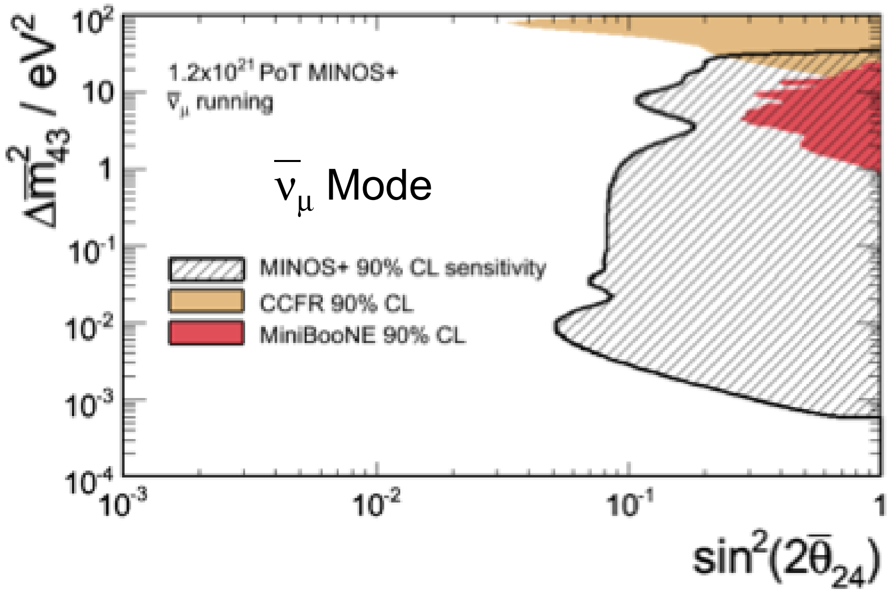


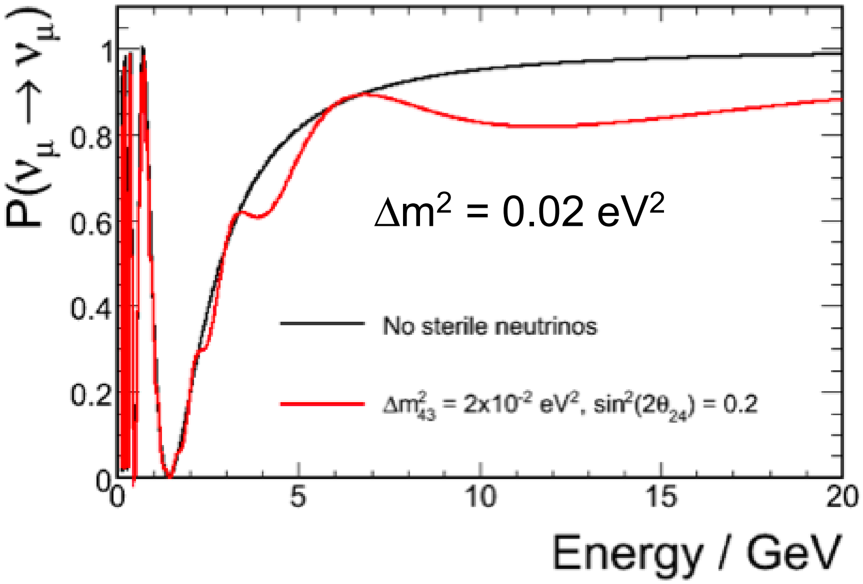
(KDAR: J. Spitz, arXiv:1203.6050)

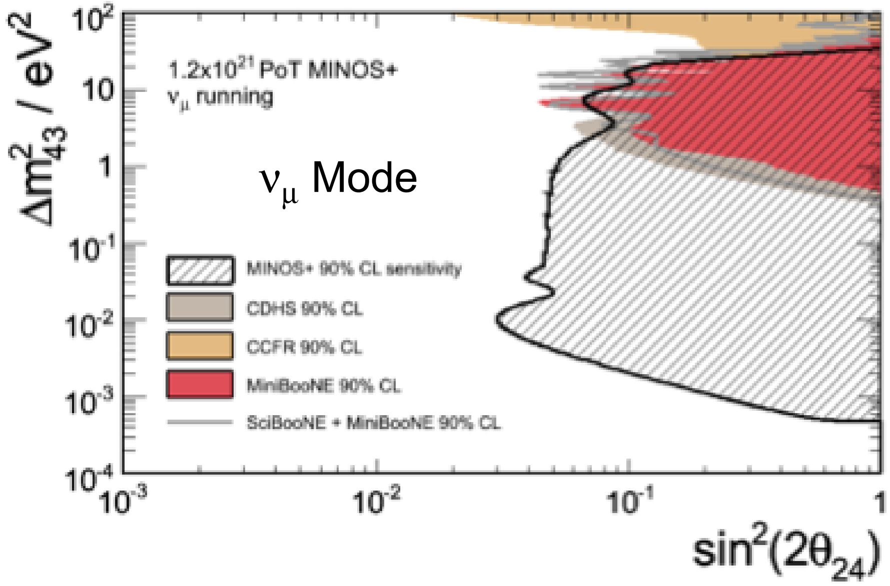
Accelerator ν_μ / $\bar{\nu}_\mu$ Beams using Pion Decay-in-Flight

MINOS+ Running (3 yrs) During Nova Era

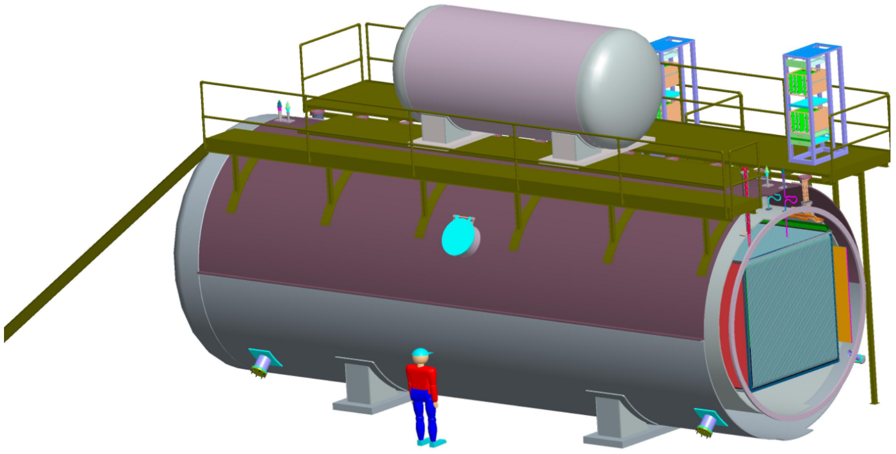
- MINOS+ Sensitivity to sterile neutrinos through neutral current (NC) disappearance
  between near and far detector
  - If disappearance seen, must be to a sterile neutrino with no NC interactions
- Sensitivity to Δm^2 values to below 0.01 eV^2



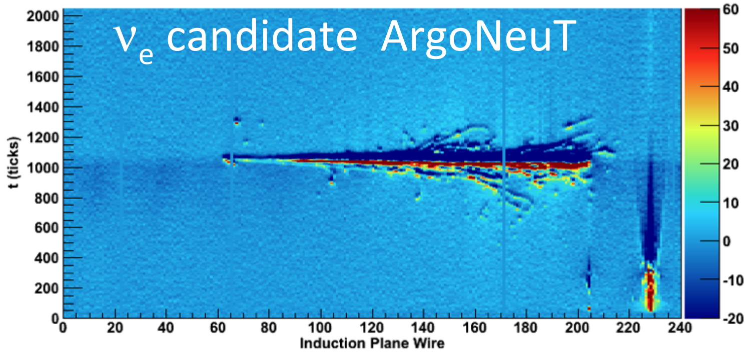




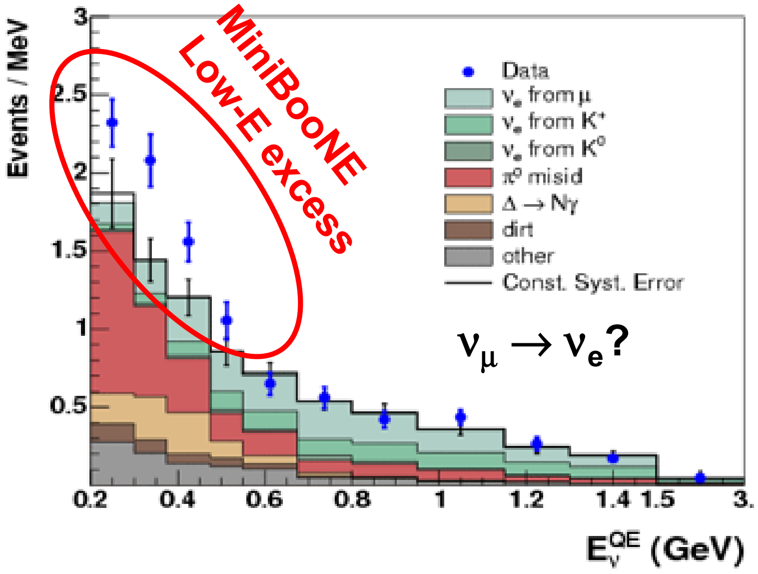
MicroBooNE Experiment (Under Construction) using Fermilab Booster Neutrino Beamline (BNB)



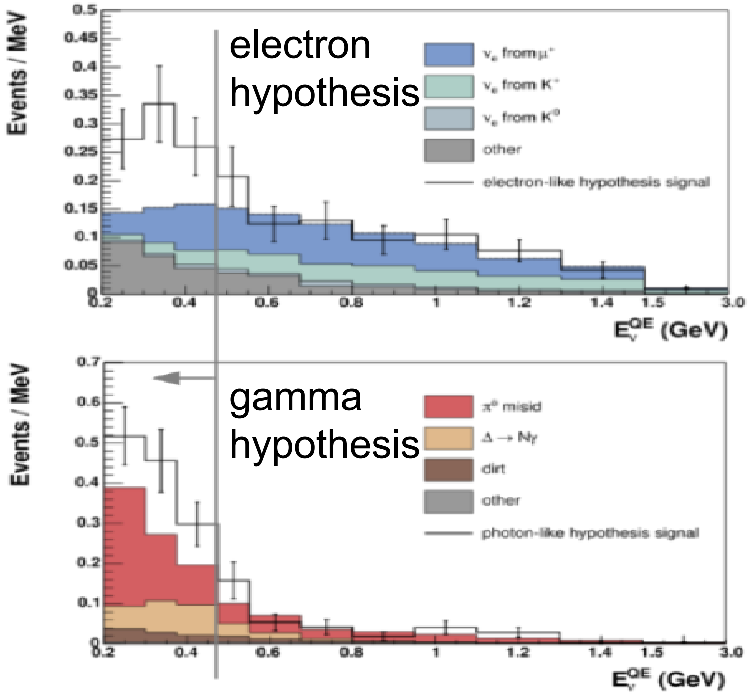
See poster #167 G. Karagiorgi



Use topology and dE/dx to differentiate electrons (signal) from gammas (background)
(Indistinguishable in Cerenkov imaging detectors)



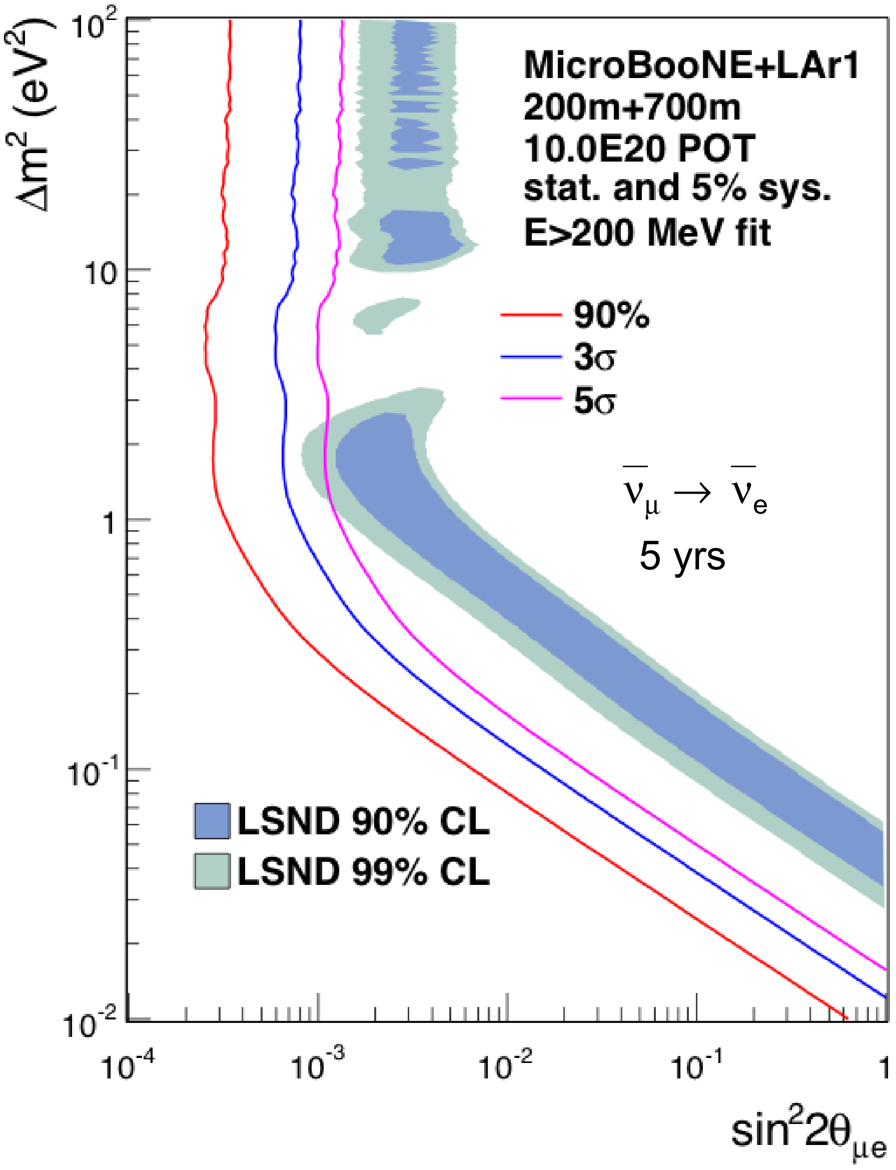
Is it electrons or gammas?

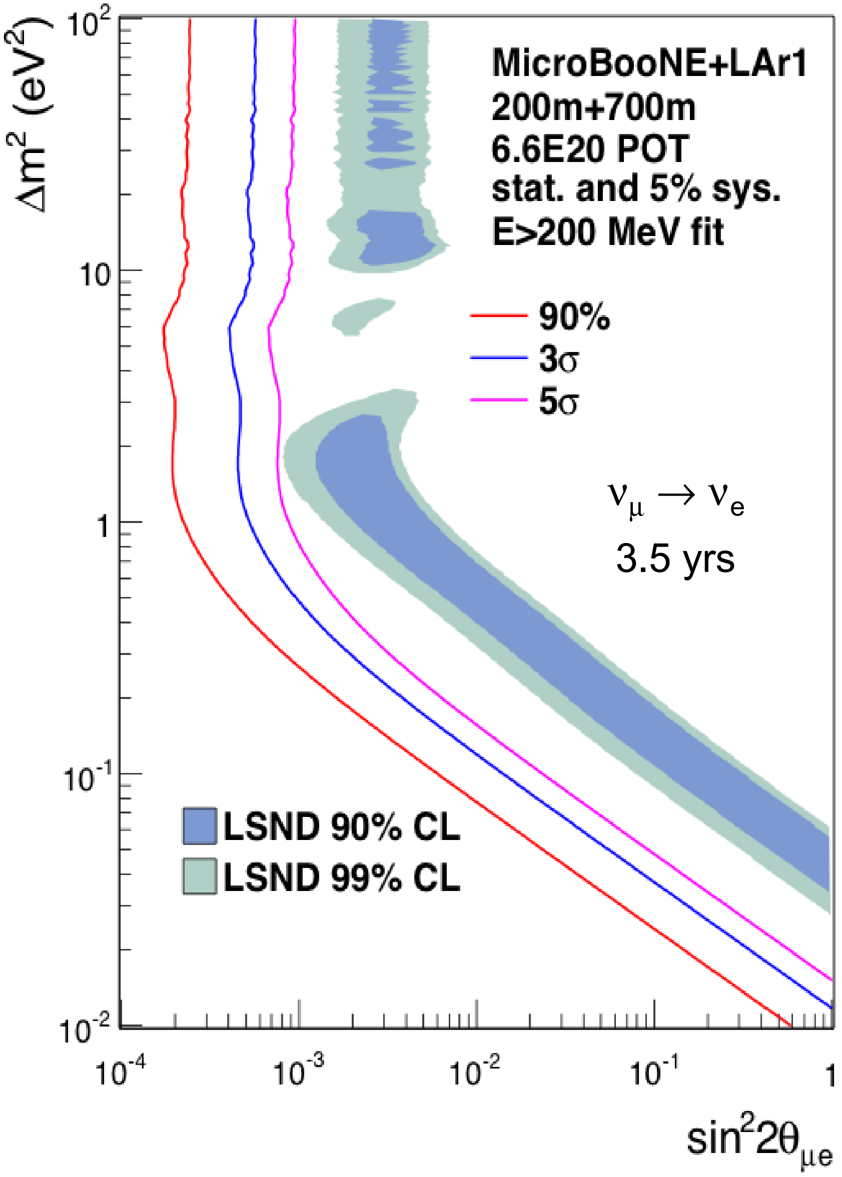


LAr1kton at Fermilab Booster ν Beamline (BNB)

- To directly address LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal, use multiple detectors in the Fermilab BNB
- Large (1 kton fiducial) LAr detector at 700m plus MicroBooNE at 200m (also maybe MiniBooNE with scintillator at 540 m)
- LAr capabilities significantly reduces gamma and other backgrounds

LAr1kton Sensitivity

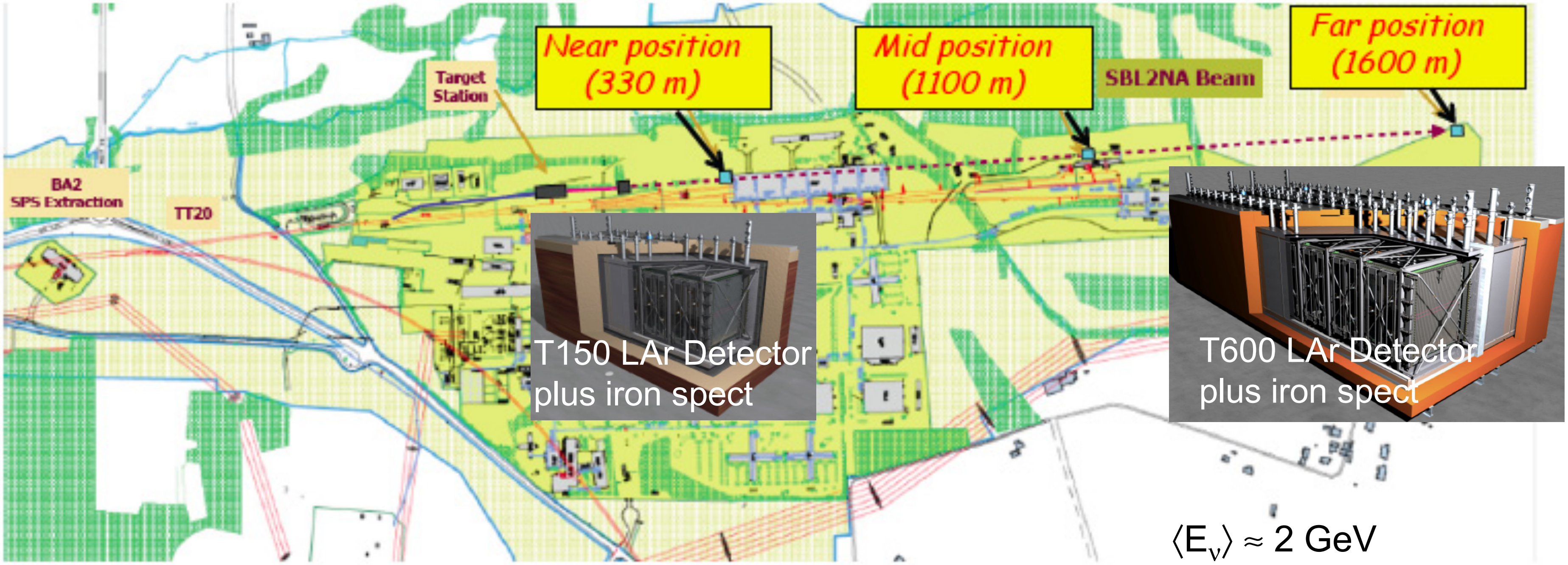




CERN SPS: Two (or Three) Detector Proposal using Liquid Argon and Iron Spectrometers

- Combined ICARUS and NESSiE Collaborations

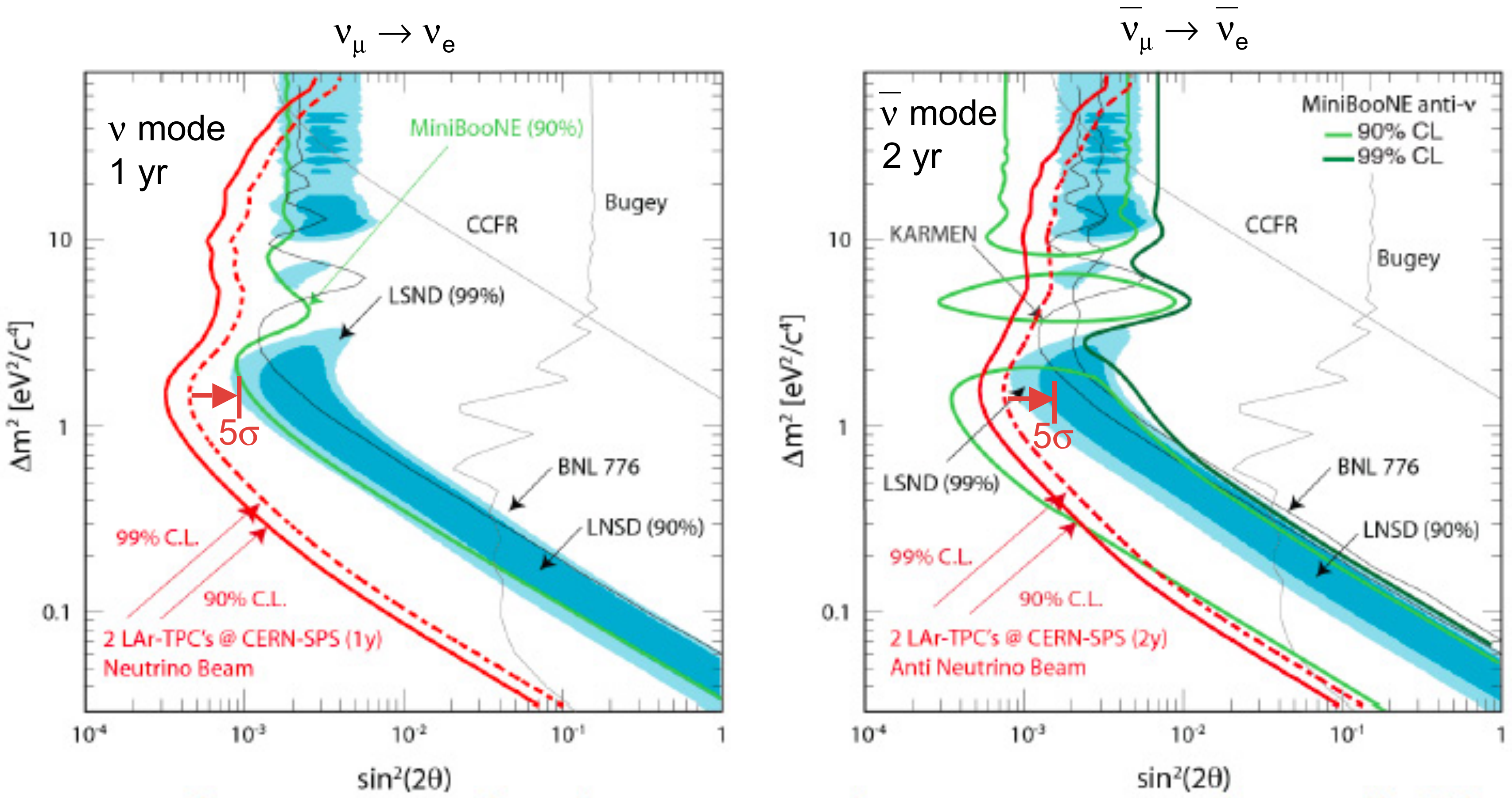
New Neutrino Facility in the CERN North Area



$\langle E_\nu \rangle \approx 2$ GeV

100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe l =100m, ø = 3m; beam dump: 15m of Fe with graphite core, followed by μ stations.

CERN SPS Appearance Sensitivity



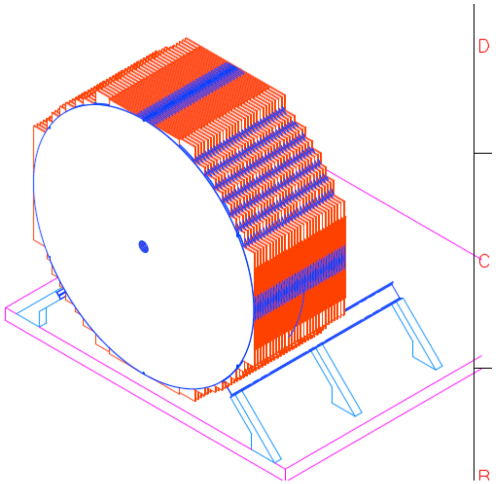
Expected sensitivity for the proposed experiment: ν_μ beam (left) and anti-ν_μ (right) for 4.5 10^{19} pot (1 year) and 9.0 10^{19} pot (2 years) respectively. LSND allowed region is fully explored in both cases.

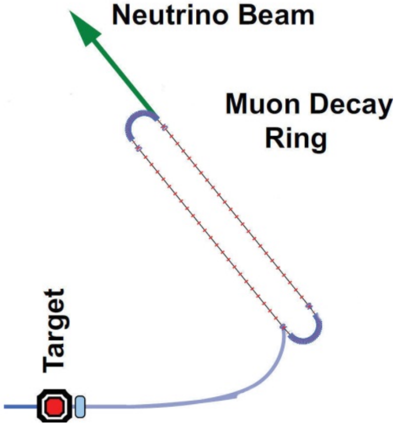
Also, ν_μ and $\bar{\nu}_\mu$ disappearance

Very Low Energy Neutrino Factory ν / $\bar{\nu}$ Source

Neutrinos from STORed Muons - νSTORM

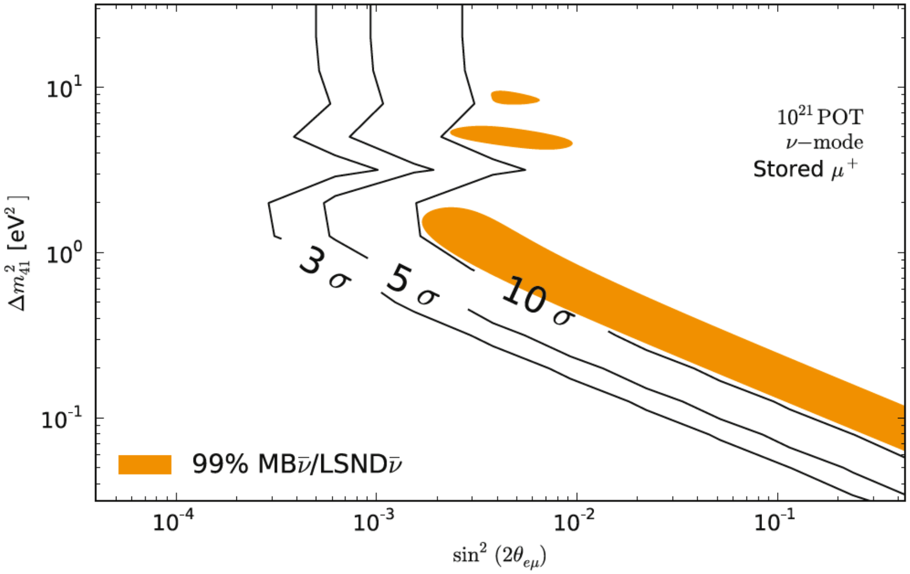
- Simplest implementation of the NF concept
  - 60 GeV protons on solid target (100 kW)
  - Horn capture and π transfer
  - Decay ring
- No new technology is required
  - Little R&D is needed
    ≈"Technology" ready





- Performance assumptions:
  - 10^{21} 60 GeV/c POT
- Yields ≈ $2X10^{18}$ useful ν
- ≈2000 m baseline
- 1.3 kT Minos-like detector: SuperB IND
  - Thinner plates
  - 2T B

$\nu_e \rightarrow \nu_\mu$: CPT Invariant mode of LSND/MiniBooNE



Summary and Conclusions

- Establishing the existence of sterile neutrinos would be a major result for particle physics

- Many proposals and ideas for sterile neutrino searches in the $\Delta m^2 \sim 1$ eV^2 region
  - New experiments have better sensitivity (~5σ level) with capabilities to see oscillatory behavior and reduce backgrounds

- Many different techniques, neutrino sources, and proposals

Type of Exp	App/Disapp	Osc Channel	Experiments
Reactor Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	Nucifer, Stereo, SCRAMM, NIST, Neutrino4, DANSS
Radioactive Sources	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$ $(\nu_e \to \nu_e)$	Baksan, LENS, Borexino, SNO+, Richochet, CeLAND, Daya-Bay
Isotope Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest Source	Appearance & Disapp	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Accelerator ν / $\bar{\nu}$ using Pion Decay-in-Flight	Appearance & Disapp	$\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-Energy ν-Factory	Appearance & Disapp	$\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	νSTORM at Fermilab

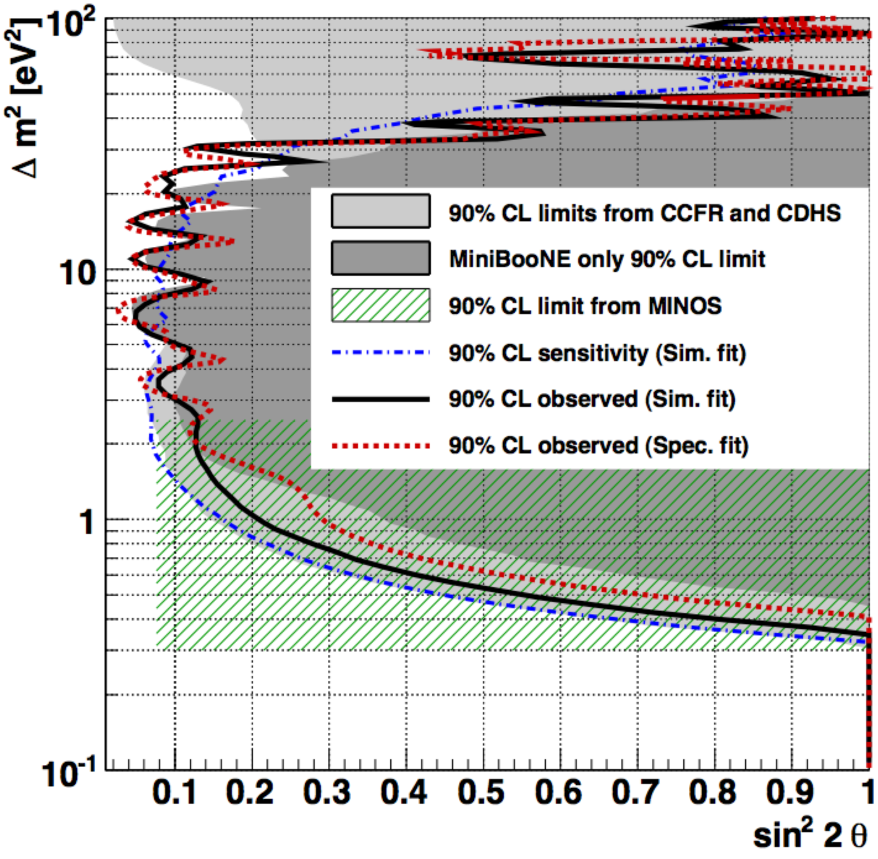
Very Short Baseline Exps and Project-X

- See talk by Heather Ray
- Some comments and questions:
  - Need large detectors (>1 kton) with capability to detect IBD events
    - Best to see oscillations within the detector
    - Need PMT coverage to be able to see neutron capture on hydrogen
  - Neutrino sources
    - Isotope source using 60 to 100 MeV with 200 kW to 600 kW
    - DAR sources using 800 MeV proton beams of 10 kW to 100 kW
  - Can one use timing to overcome backgrounds rather that going deep underground?
    - Isotope source - Probably not.
      - ^{8}Li halflife 840 msec
    - DAR Source - May be possible
      - Neutron capture takes 190 μsec on hydrogen
      - But need big enough detector to see oscillatory behavior

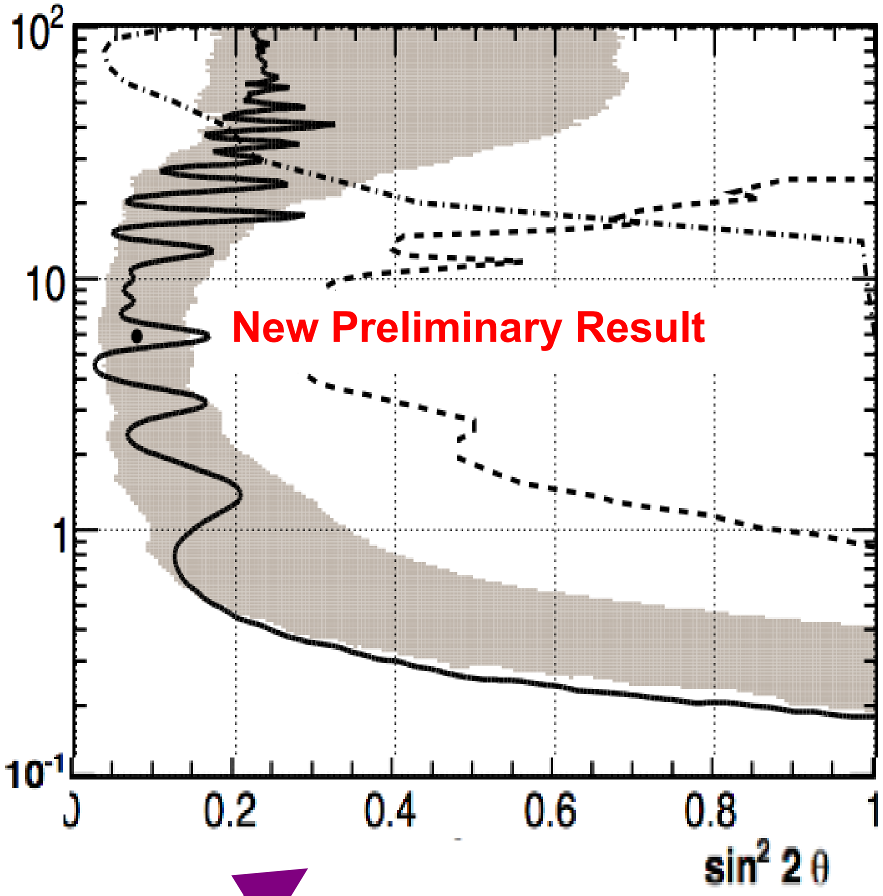
Backup

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

ν_μ Disappearance



$\bar{\nu}_\mu$ Disappearance

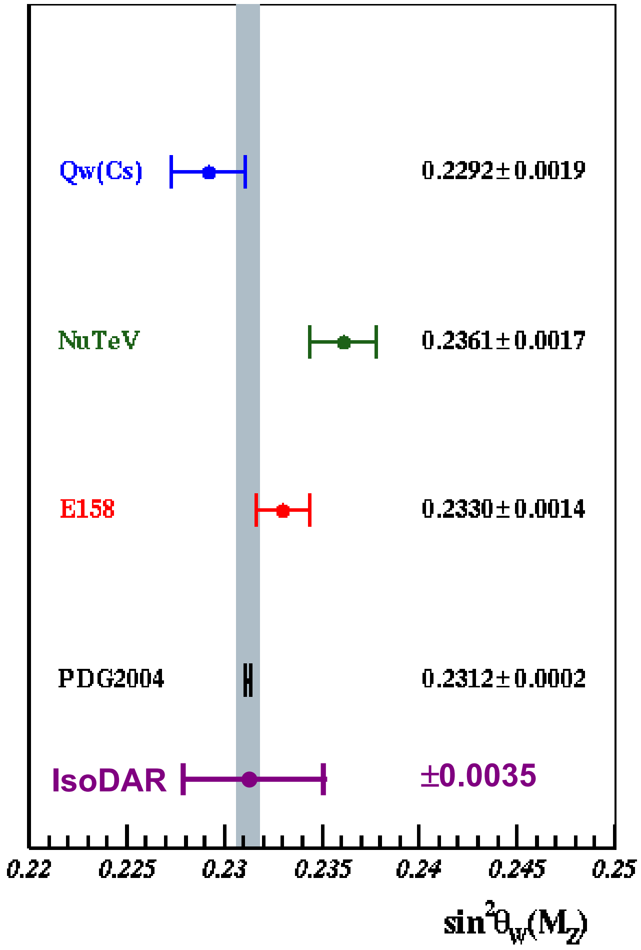


New Preliminary Result

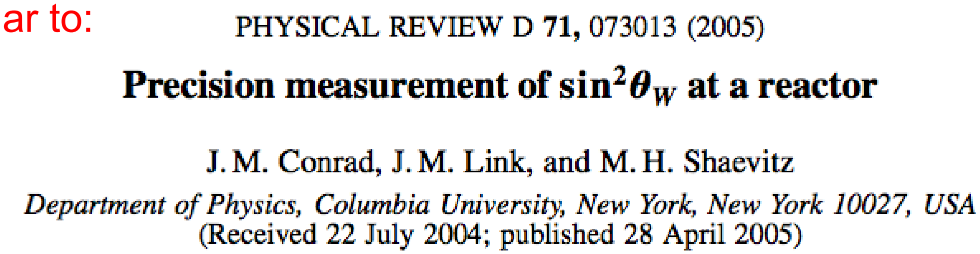
= by CPT Invariance

IsoDAR $\sin^2\theta_W$ Measurement

- Weak mixing (Weinberg) angle θ_W
  - Measured very precisely by LEP experiments
  - NuTeV neutrino-quark scattering measurement ~3σ high (NuTeV anomaly)
- Measure in IsoDAR using $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$
  - If IsoDAR also sees discrepancy then this could be new physics associated with neutrinos
  - If IsoDAR does not see a discrepancy then NuTeV Anomaly something to do with quark distributions or other quark physics.



Similar to:


PHYSICAL REVIEW D **71,** 073013 (2005)

Precision measurement of $\sin^2\theta_W$ at a reactor

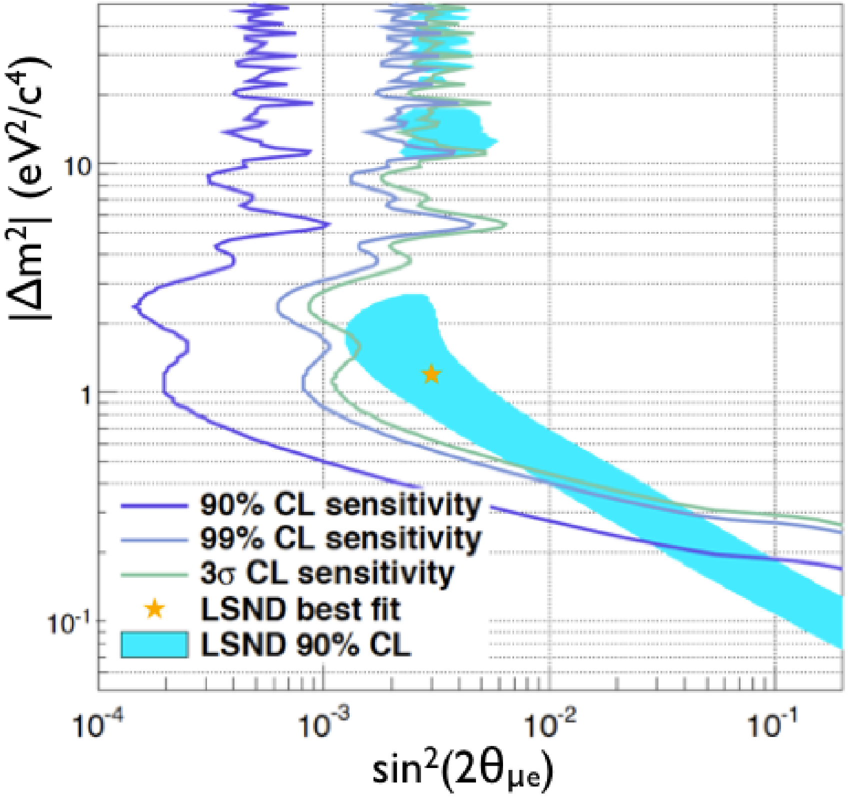
J. M. Conrad, J. M. Link, and M. H. Shaevitz

Department of Physics, Columbia University, New York, New York 10027, USA

(Received 22 July 2004; published 28 April 2005)

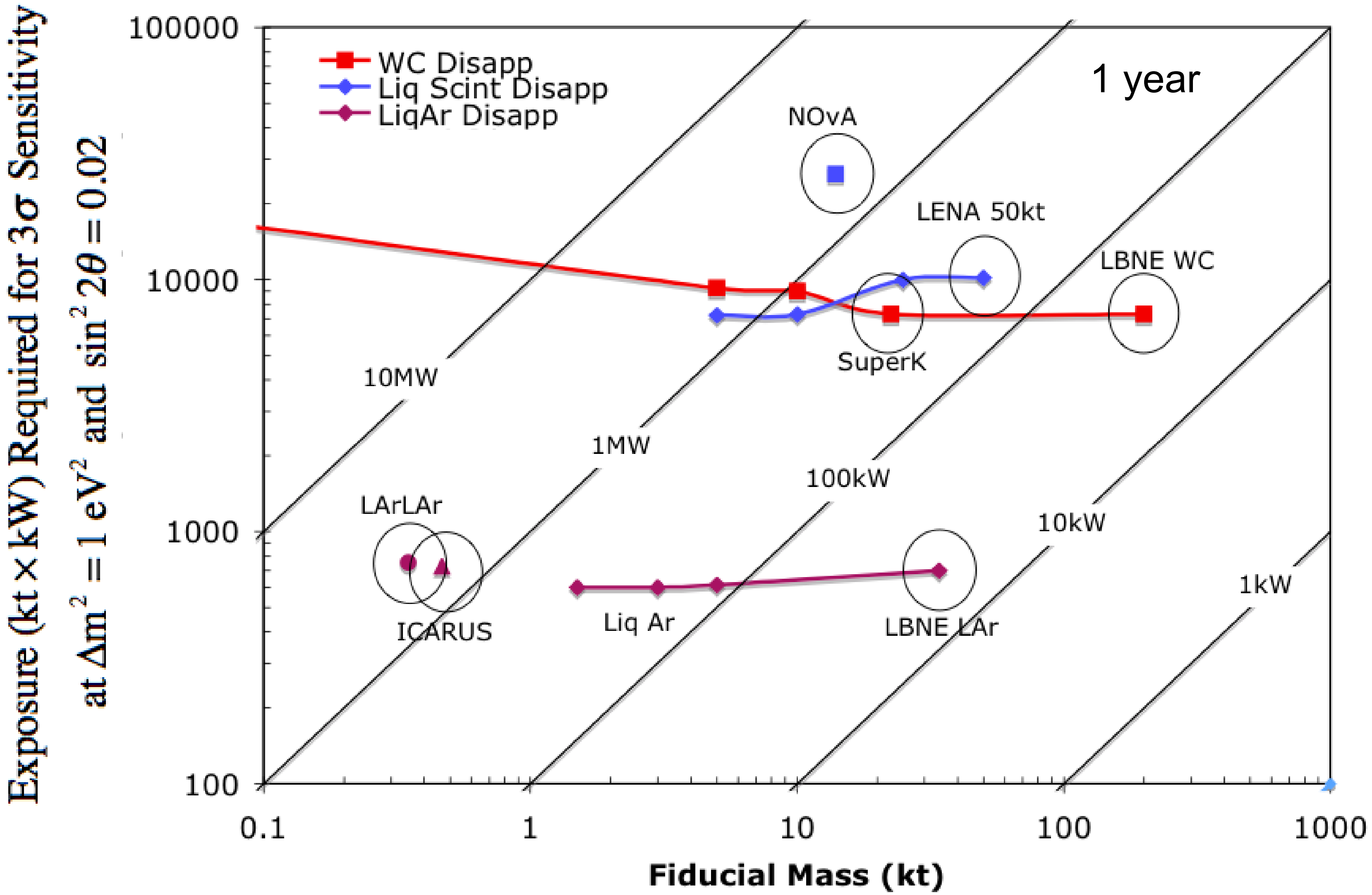
Using Coherent ν-Nucleon Scattering with DAR Source

- Coherent process sensitive to all active neutrinos so any disappearance would indicate osc to sterile neutrinos
- High cross section but very low recoil energy (few to tens of keV)
  - Need to use high sensitivity detectors: LAr (LNe),CDMS,COUPP
- CLEAR proposal: 450kg LAr 46m from dump at SNS (arXiv:0910.1989)
- DAEδALUS DAR source: 100kg Ge detector at 10m (>2000 evnts/yr)



VSBL ν_e Disappearance: Source Power and Detector Size for x10 Better Sensitivity Than Current

Exposure = Detector Size (kton) × Cyclotron Power (kW)



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

3+1 Model:

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

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

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:

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

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

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: $\Delta m^2_{12} \approx \Delta m^2_{13} \approx 0$)