Global experimental program for sterile neutrino searches

Accelerator-based searches

Joshua Spitz, University of Michigan

KPS 10/27/2017

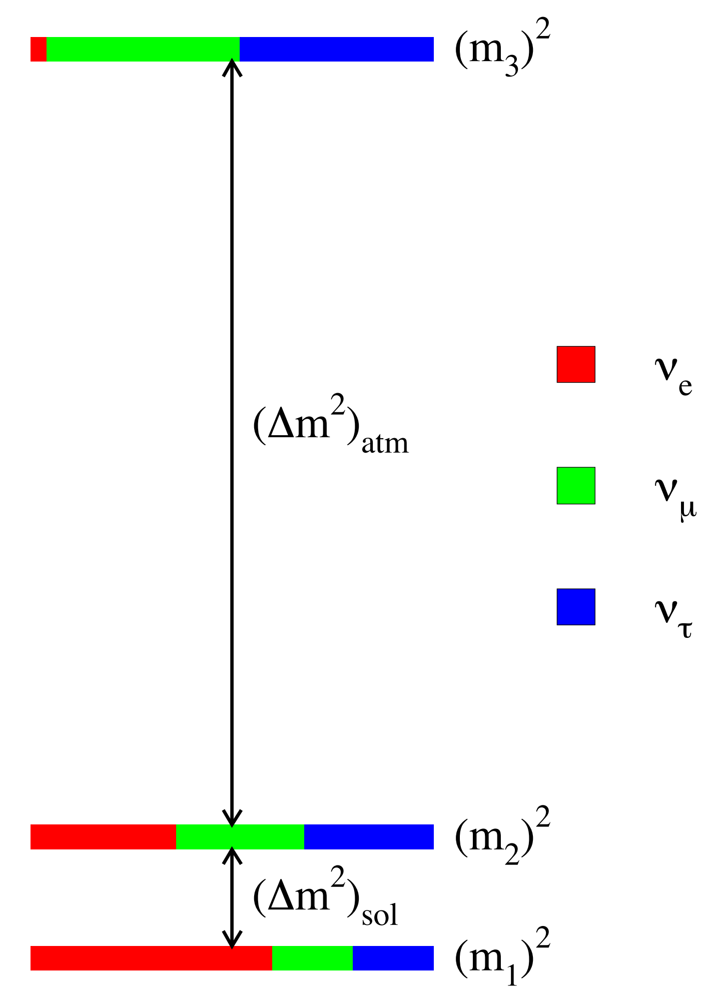
The 3 neutrino oscillation picture

Atmospheric neutrinos
Solar neutrinos
Accelerator neutrinos
Reactor neutrinos

$\Bigg\}$ Well established oscillations

- Almost all of our observed oscillation results fit nicely within the three neutrino picture (two mass splittings and three mixing angles).

- Neutrinos from different sources are oscillating according to the same rulebook!



Neutrino oscillation is a big deal

The time evolution of the neutrino state implies that is has mass!

Big Bang cosmology

Why is the universe made of matter?

Dark matter?

Supernova evolution

How do reactors burn fuel?

How does the sun shine?

How are the neutrino masses ordered?

3, 4, 5, 6 neutrinos?

A hidden sector?

neutrino=antineutrino?

Do neutrinos obey fundamental symmetries?

Heavy element formation

How does the neutrino get its mass?

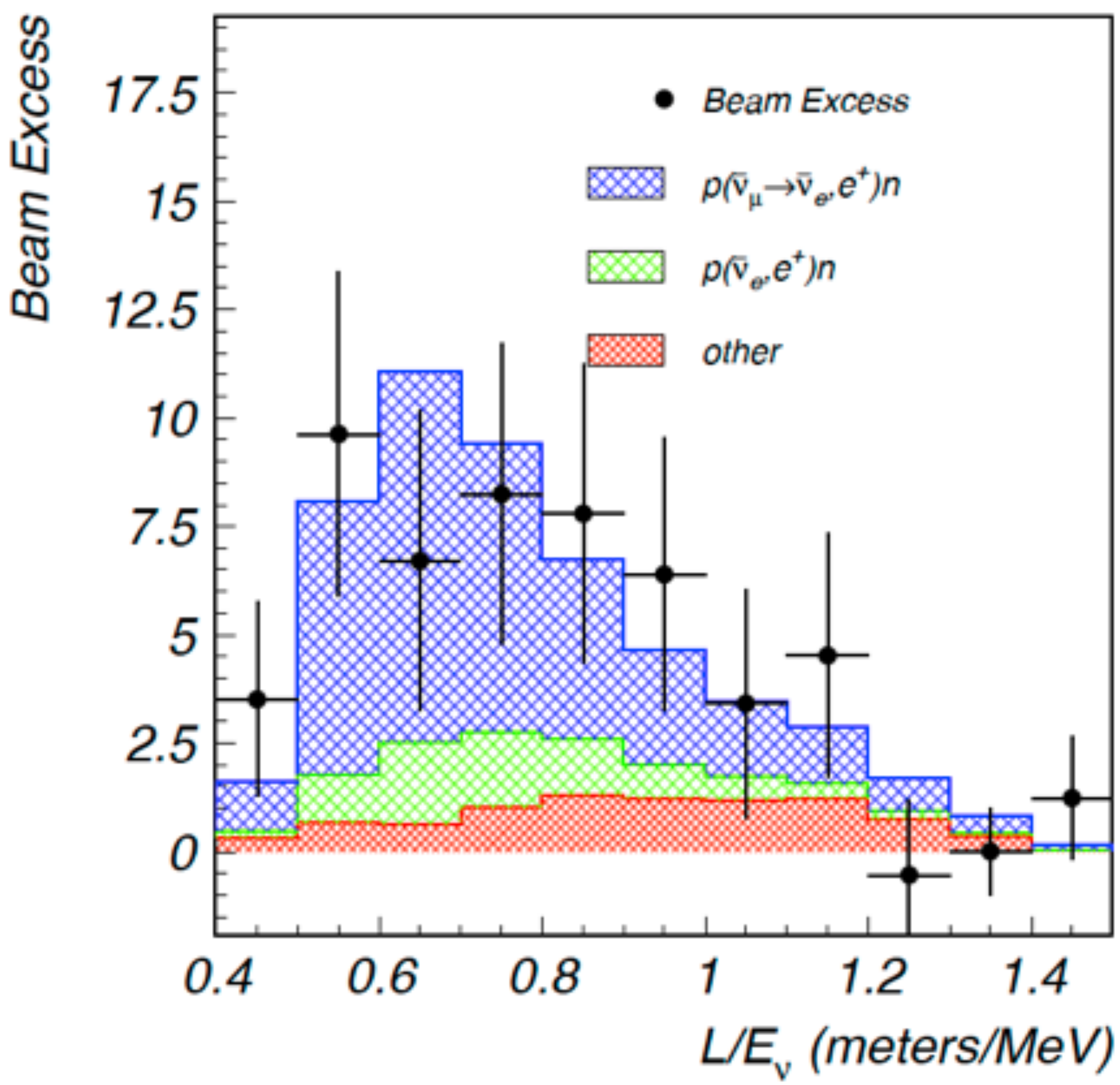
A new neutrino?

The three neutrino oscillation picture works extraordinarily well.

But, there are some anomalies that don't fit.

The Liquid Scintillator Neutrino Detector anomaly

Antineutrinos from an accelerator seem to appear!



- LSND observed $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ at 3.8σ significance with a characteristic oscillation frequency of $\Delta m^2 \sim 1\ \mathrm{eV}^2$.

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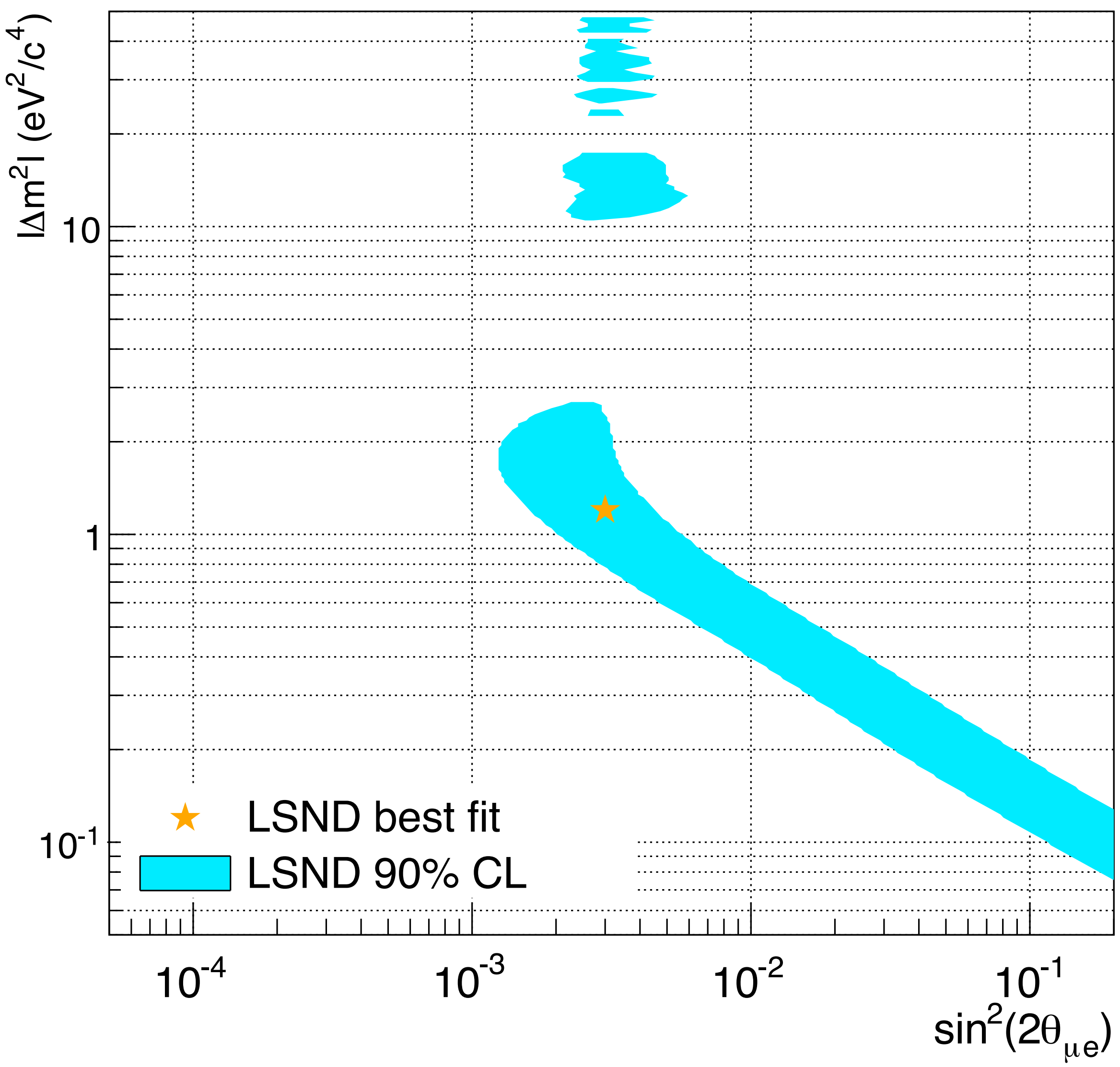
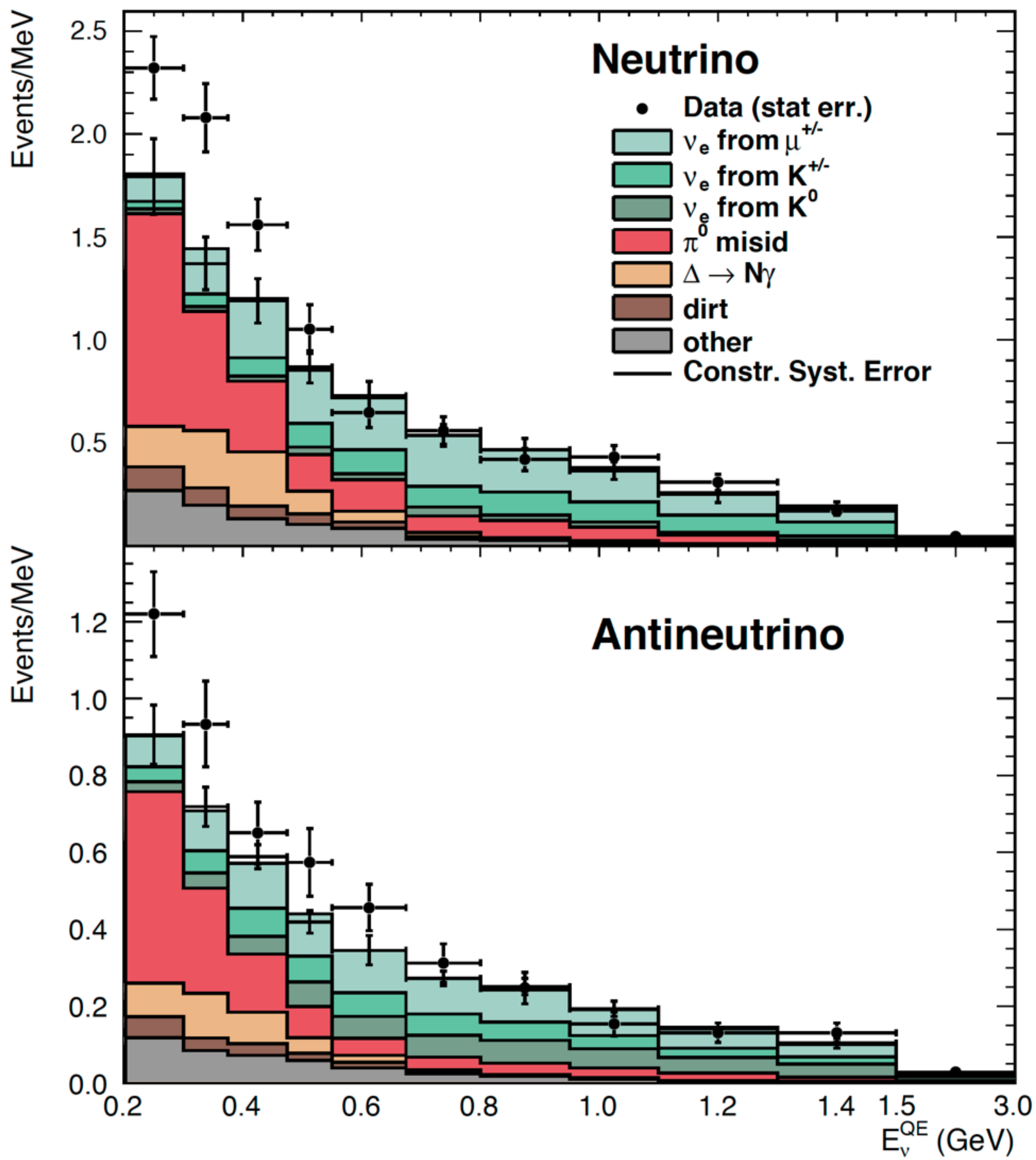


- LSND observed $\overline{\nu}_\mu \to \overline{\nu}_e$ at 3.8σ significance with a characteristic oscillation frequency of $\Delta m^2 \sim 1$ eV^2.
- That's odd. There are two characteristic oscillation frequencies in the three neutrino picture and they are precisely measured.

$$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}})$$

The MiniBooNE anomalies



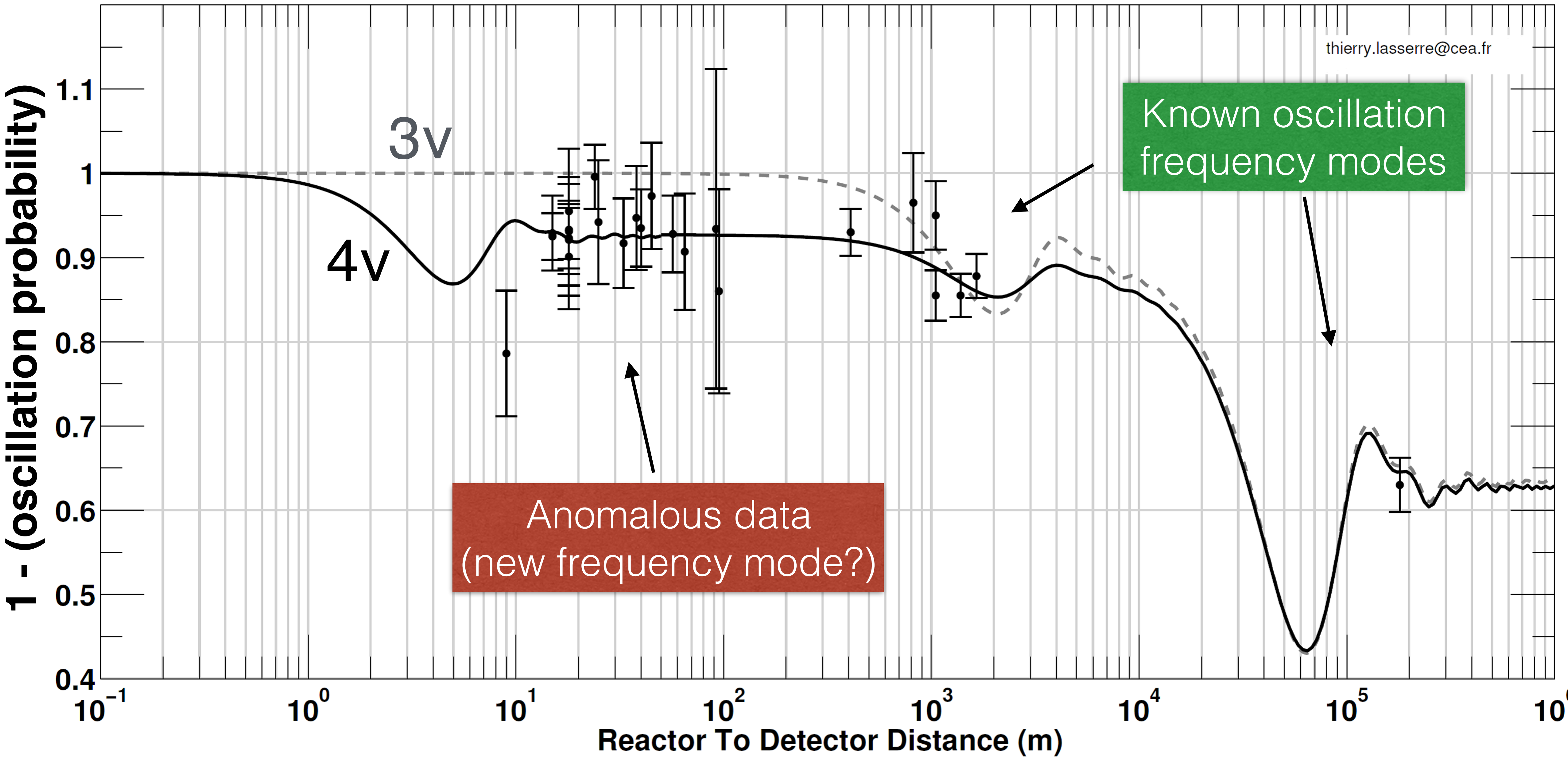
$$\nu_\mu \to \nu_e$$

Neutrinos and antineutrinos from an accelerator seem to appear!

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

A new neutrino?

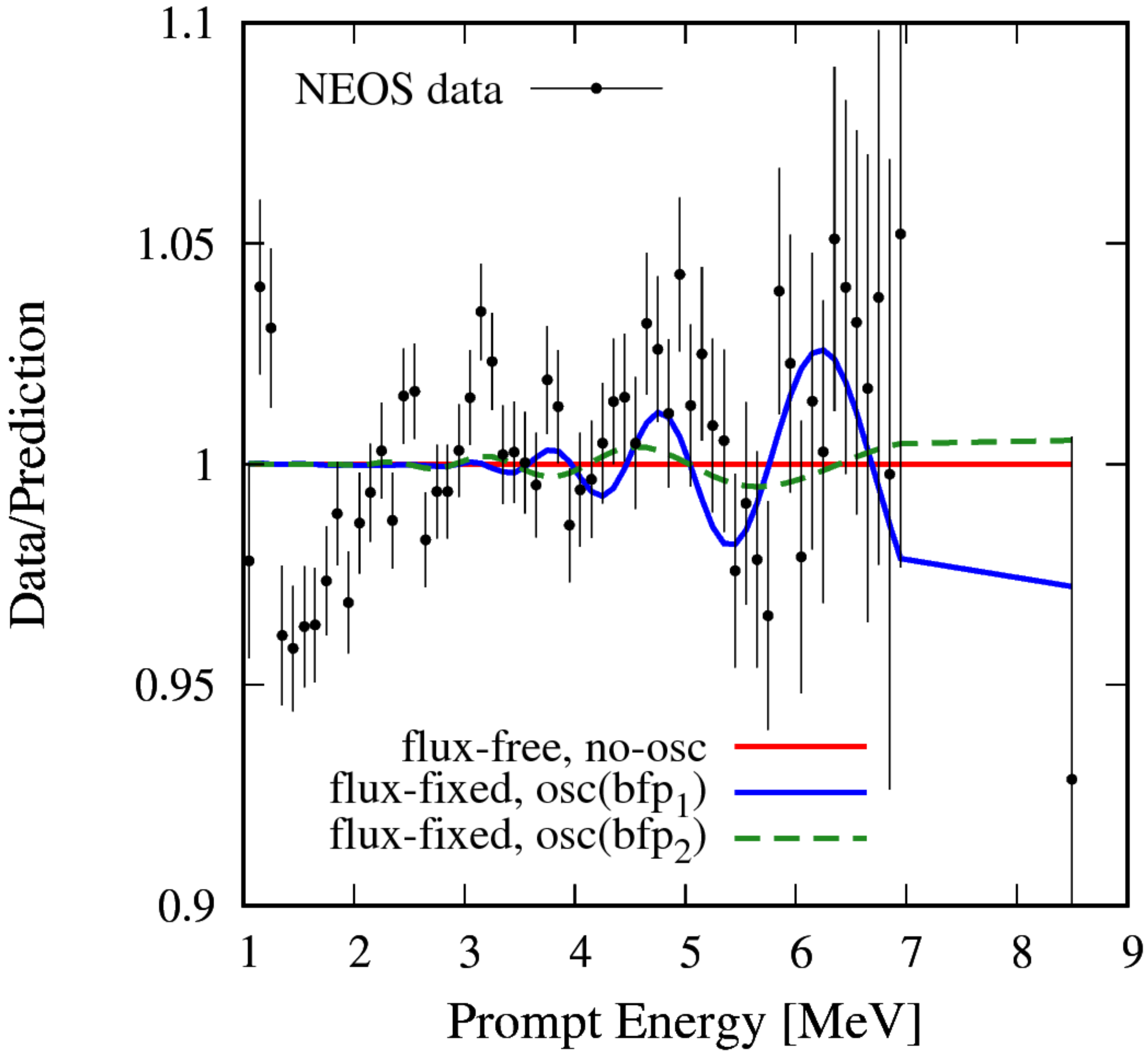
The oscillation modes associated with reactor neutrinos

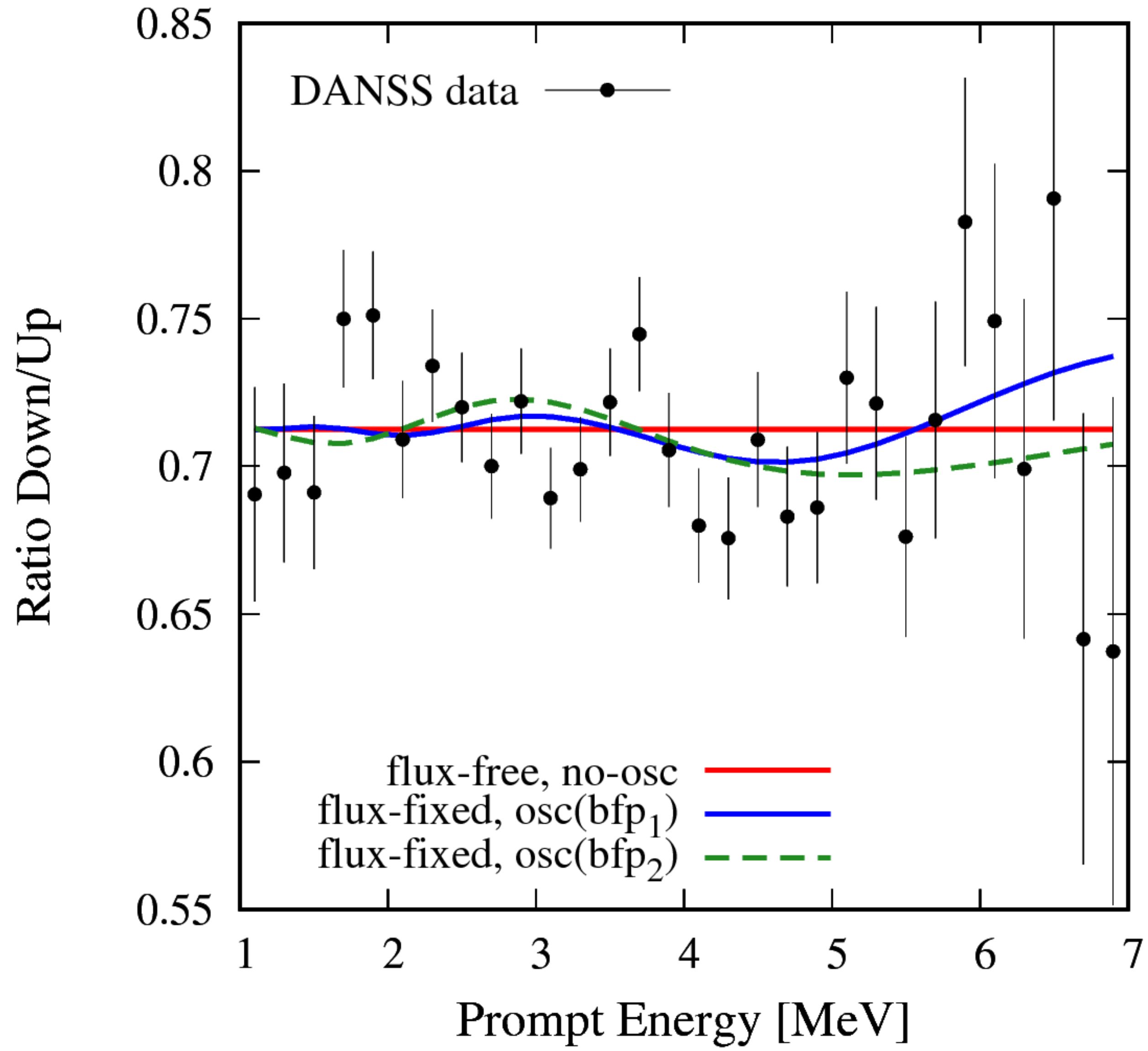


A new neutrino?

Possible first shape indications from reactor neutrino experiments?

best fit global nuebar dis.
best fit reactor data
no oscillations





Dentler, Hernandez-Cabezudo, Kopp, Maltoni, Schwetz; arXiv:1709.04294

Basically, the anomalies seem to indicate that there may be a new characteristic oscillation frequency mode (indicative of a new neutrino state).

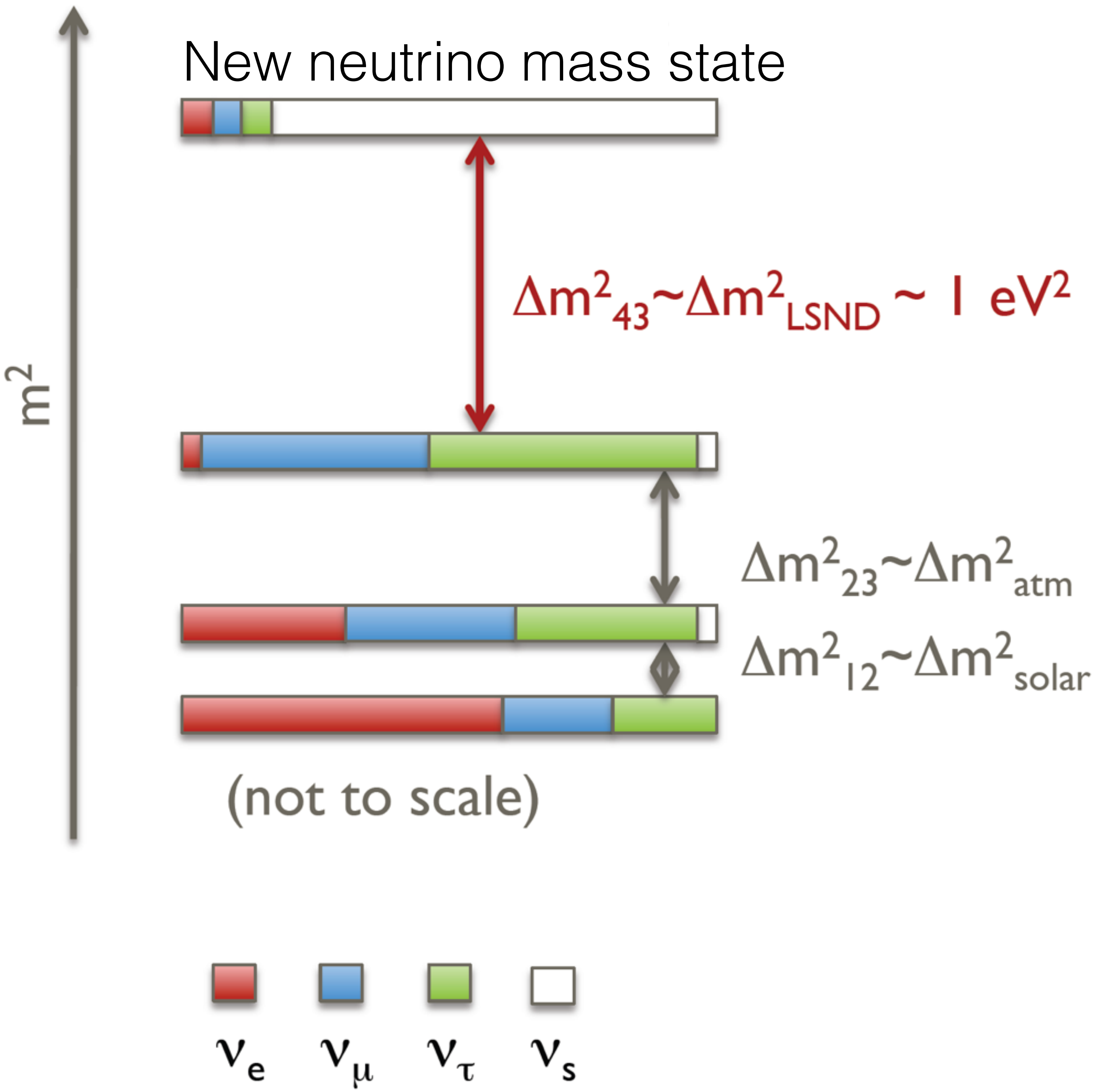
Experiment name	**Type**	**Oscillation channel**	**Significance**
LSND	Low energy accelerator	muon to electron (antineutrino)	3.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (antineutrino)	2.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (neutrino)	3.4σ
Reactors	Beta decay	electron disappearance (antineutrino)	1.4-3.0σ (varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

If it exists, what is this new neutrino?

We know the Z boson decays into three neutrinos.

A new, fourth neutrino would therefore have to be “sterile”.
That is, it doesn’t feel Standard Model interactions.

Where does it fit?



- The observation of neutrino mass implies that there can be sterile, right-handed neutrinos. So, this is not completely unexpected.
- A light sterile neutrino would have profound effects on:
  - Radiation density in the early universe.
  - Supernova evolution.
  - Active neutrino oscillations and particle physics in general.

Present status

A number of experiments hint at a new neutrino mass state.

A number of other experiments don’t seem to see anything.

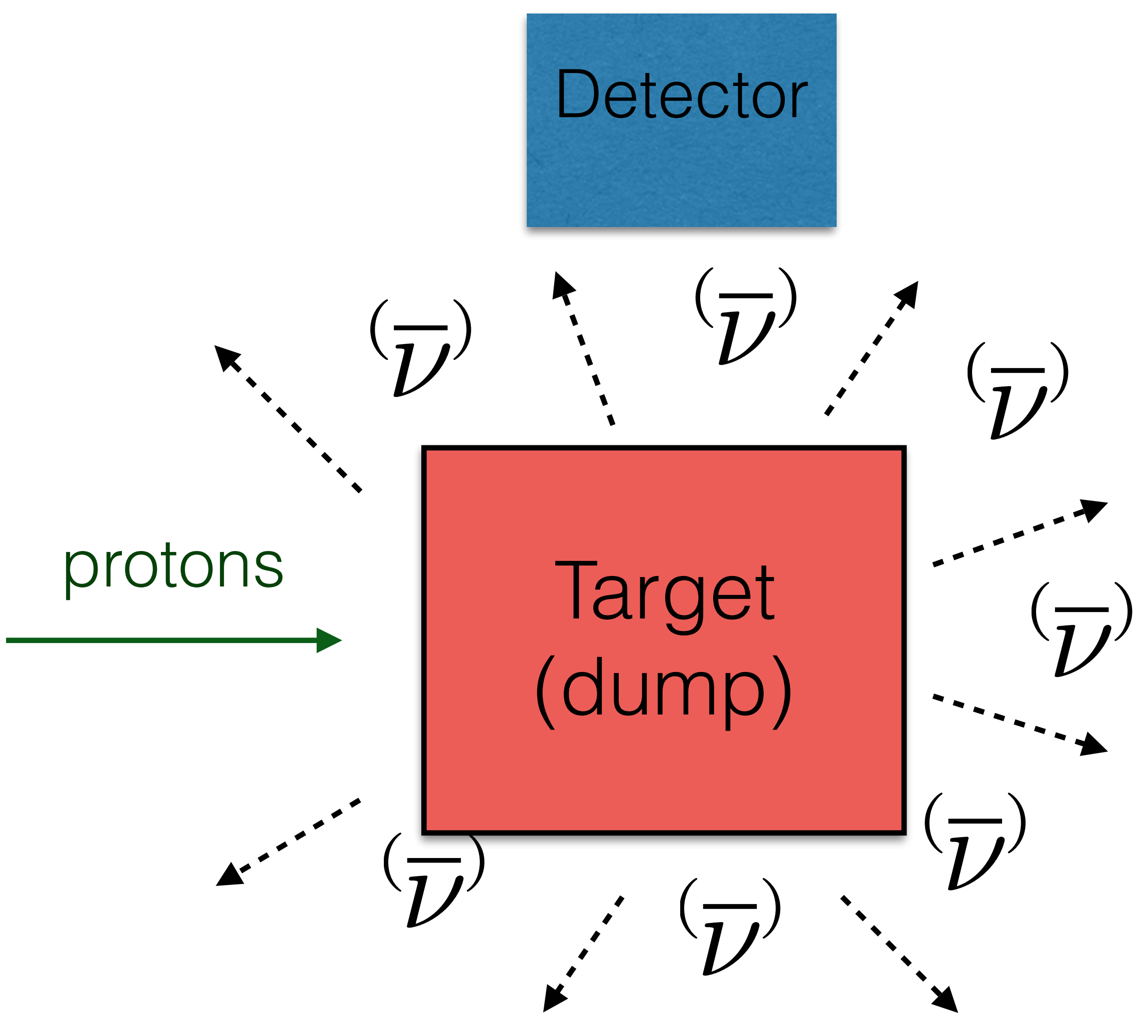
(including new muon disappearance limits from IceCube and MINOS)

A definitive probe of this new neutrino is necessary.

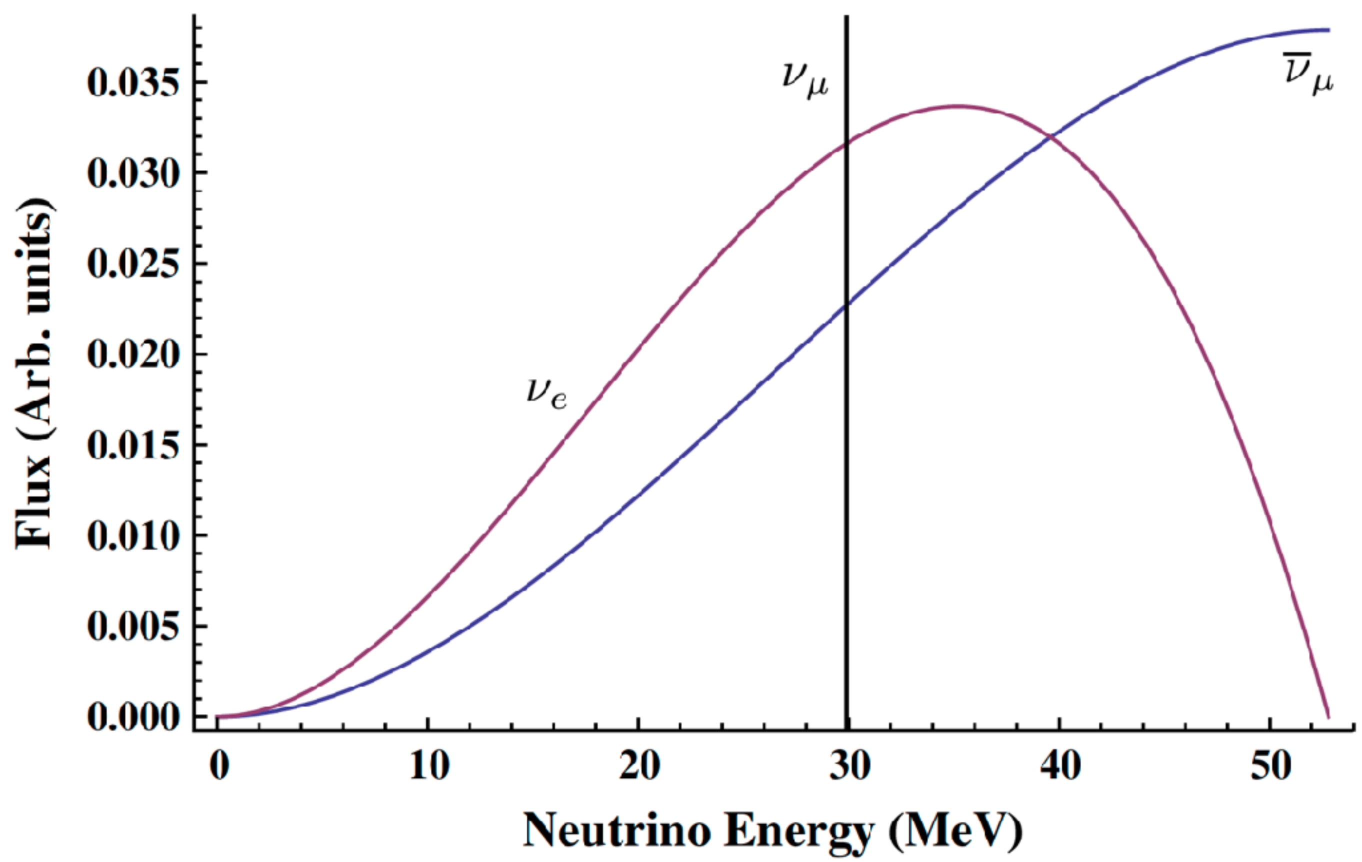
A tour of future accelerator-based probes

- JSNS^2
- SBN at Fermilab
- IsoDAR
- KPIPE
- NuPRISM

Pion and muon decay-at-rest



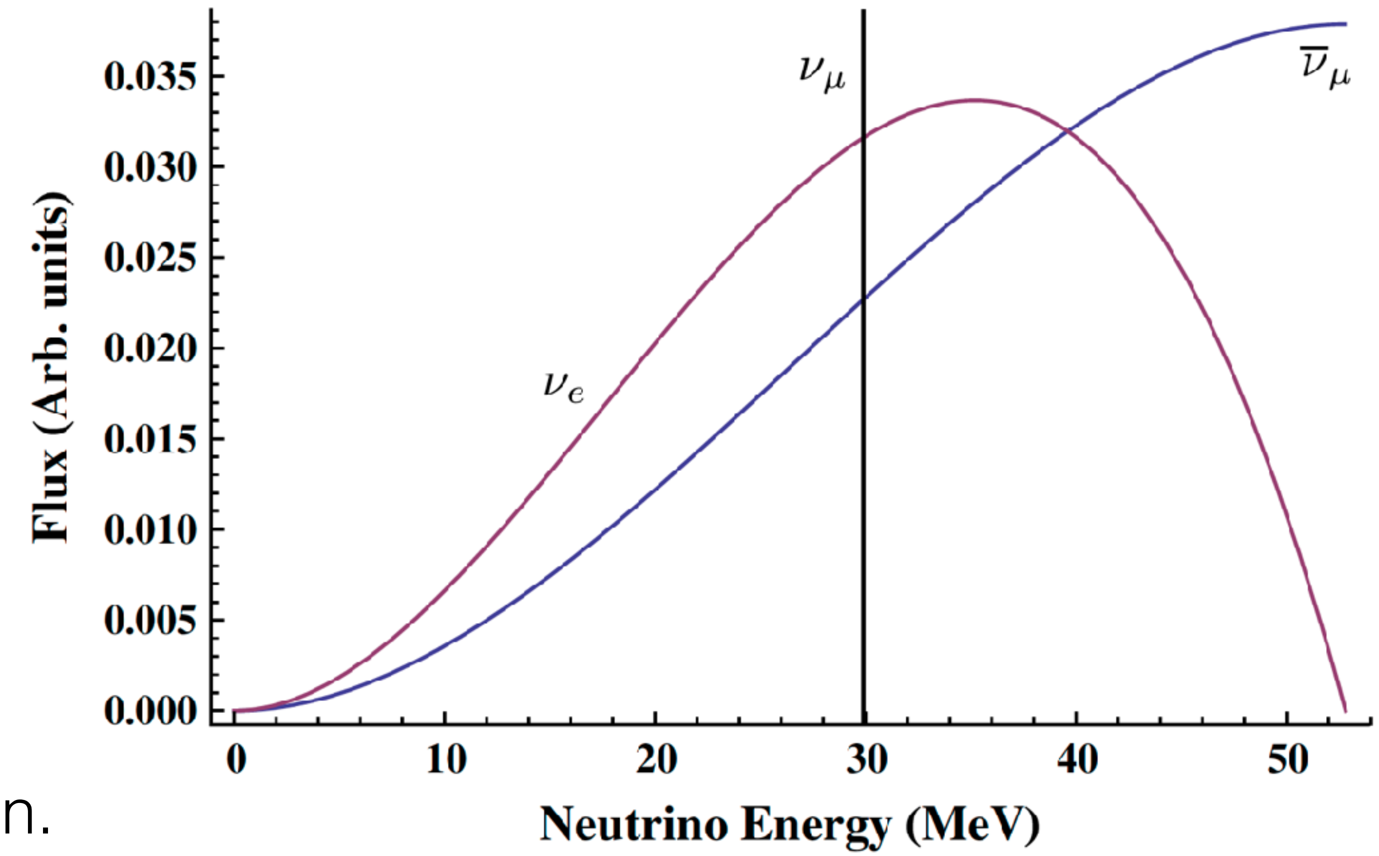
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$



(negative pions/muons are usually captured in dense target material)

Pion and muon decay-at-rest

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$



Why are these neutrinos special?

- Known energy shape!
- IBD xsec (for nuebar app) is well known.
- IBD events (for nuebar app) are easy to reco/ID.
- Background is low.

The JSNS^2 strategy

- **Primary goal: Test LSND in a cost effective and timely way, w/ an existing beam/building.**
  - LSND is THE experiment that drives the high-Δm^2 anomalies. J-PARC's MLF and ORNL's SNS are the best (only) places to *directly* study the LSND anomaly.
- **Other physics:**
  - **Collect a large sample (~50k) of monoenergetic 236 MeV muon neutrinos from KDAR; nuclear probe and xsec measurements.**
    - Highly relevant for current/future long baseline programs and all experiments that rely on a model of the neutrino-nucleus interaction. J-PARC MLF is the best place in the world to do this measurement.
  - **Measure supernova neutrino xsec's.**
- **Perform R&D for future liquid scintillator detectors.**

The JSNS^2 strategy

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    - LSND is THE experiment that drives the high-Δm^2 anomalies. J-PARC's MLF and ORNL's

JSNS^2 status

Obtained Stage 1 (of 2) approval from PAC in 2015;

Secured funding for first 17 ton detector module in 2016;

Submitted TDR to J-PARC PAC (seeking Stage 2 approval) in 2017;

Construction has begun! JSNS^2 expects first data in late-2018.

    - **Measure supernova neutrino xsec's.**
- **Perform R&D for future liquid scintillator detectors.**

JSNS^2 collaboration

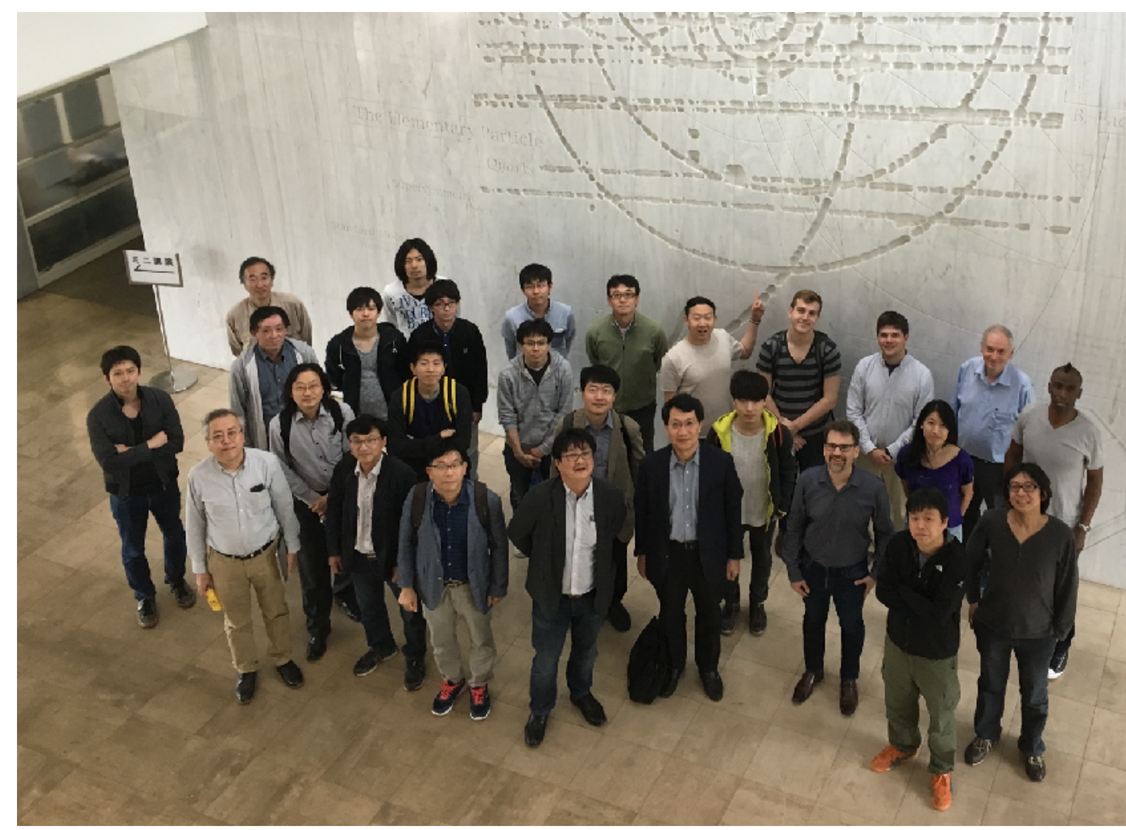
Technical Design Report (TDR): Searching for a Sterile Neutrino at J-PARC MLF (E56, JSNS^2)

S. Ajimura[1], M. K. Cheoun[2], J. H. Choi[3], H. Furuta[4], M. Harada[5], S. Hasegawa[5], Y. Hino[4], T. Hiraiwa[1], E. Iwai[6], S. Iwata[7], J. S. Jang[8], H. I. Jang[9], K. K. Joo[10], J. Jordan[6], S. K. Kang[11], T. Kawasaki[7], Y. Kasugai[5], E. J. Kim[12], J. Y. Kim[10], S. B. Kim[13], W. Kim[14], K. Kuwata[4], E. Kwon[13], I. T. Lim[10], T. Maruyama[*15], T. Matsubara[4], S. Meigo[5], S. Monjushiro[15], D. H. Moon[10], T. Nakano[1], M. Niiyama[16], K. Nishikawa[15], M. Nomachi[1], M. Y. Pac[3], J. S. Park[15], H. Ray[17], C. Rott[18], K. Sakai[5], S. Sakamoto[5], H. Seo[13], S. H. Seo[13], A. Shibata[7], T. Shima[1], J. Spitz[6], I. Stancu[19], F. Suekane[4], Y. Sugaya[1], K. Suzuya[5], M. Taira[15], W. Toki[20], T. Torizawa[7], M. Yeh[21], and I. Yu[18]

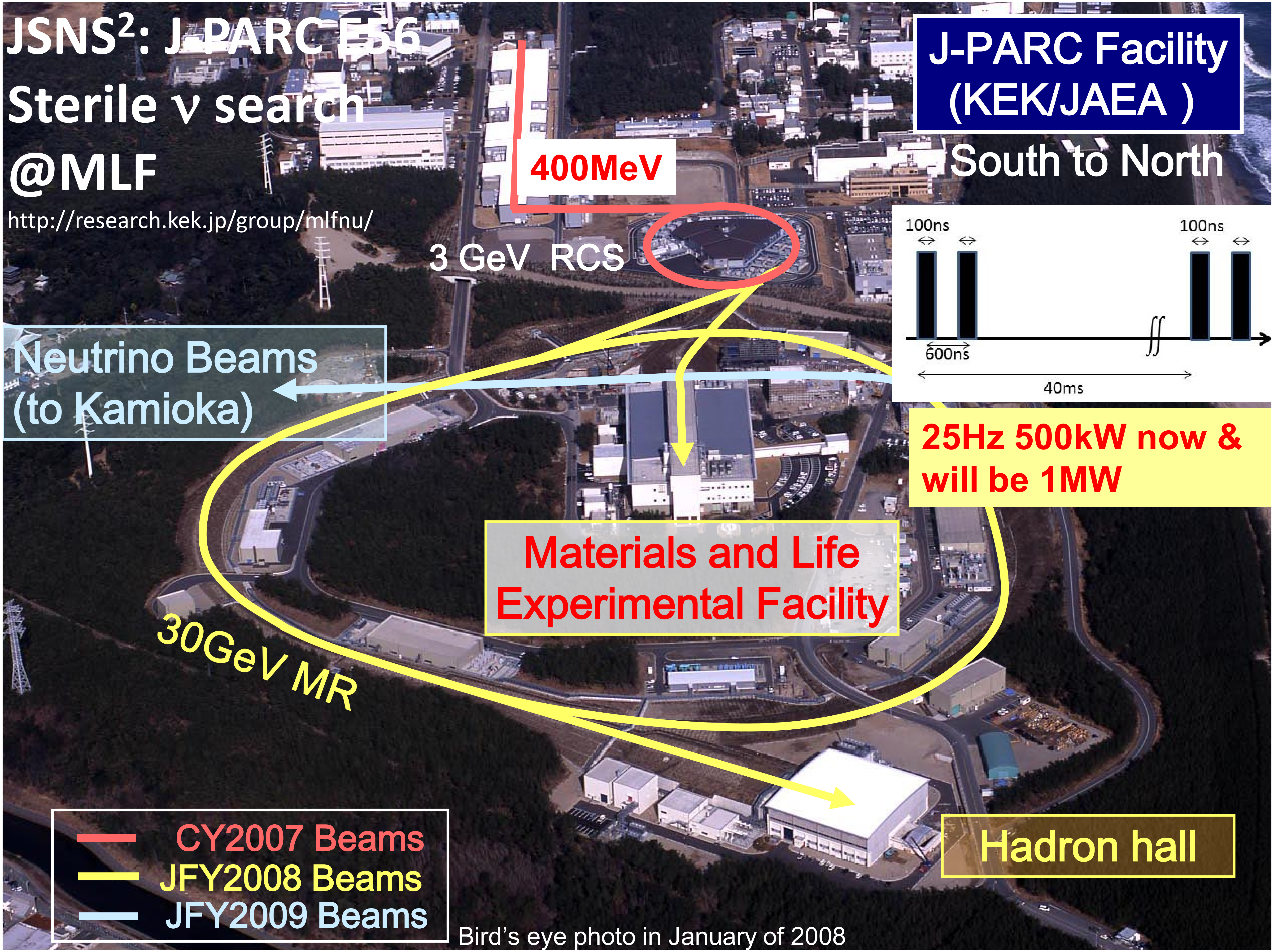
[1] *Research Center for Nuclear Physics, Osaka University, Osaka, JAPAN*
[2] *Department of Physics, Soongsil University, Seoul 06978, KOREA*
[3] *Department of Radiology, Dongshin University, Chonnam 58245, KOREA*
[4] *Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi, JAPAN*
[5] *J-PARC Center, JAEA, Tokai, Ibaraki JAPAN*
[6] *University of Michigan, Ann Arbor, MI, 48109, USA*
[7] *Department of Physics, Kitasato University, Sagamihara 252-0373, Kanagawa, JAPAN*
[8] *Gwangju Institute of Science and Technology, Gwangju, 61005, KOREA*
[9] *Department of Fire Safety, Seoyeong University, Gwangju 61268, KOREA*
[10] *Department of Physics, Chonnam National University, Gwangju, 61186, KOREA*
[11] *School of Liberal Arts, Seoul National University of Science and Technology, Seoul, 139-743, KOREA*
[12] *Division of Science Education, Physics major, Chonbuk National University, Jeonju, 54896, KOREA*
[13] *Department of Physics and Astronomy, Seoul National University, Seoul 08826, KOREA*
[14] *Department of Physics, Kyungpook National University, Daegu 41566, KOREA*
[15] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN*
[16] *Department of Physics, Kyoto University, Kyoto, JAPAN*
[17] *University of Florida, Gainesville, FL, 32611, USA*
[18] *Department of Physics, Sungkyunkwan University, Gyeong Gi-do, KOREA*
[19] *University of Alabama, Tuscaloosa, AL, 35487, USA*
[20] *Colorado State University, Tuscaloosa, AL, 35487, USA*
[21] *Brookhaven National Laboratory, Upton, NY, 11973-5000, USA*

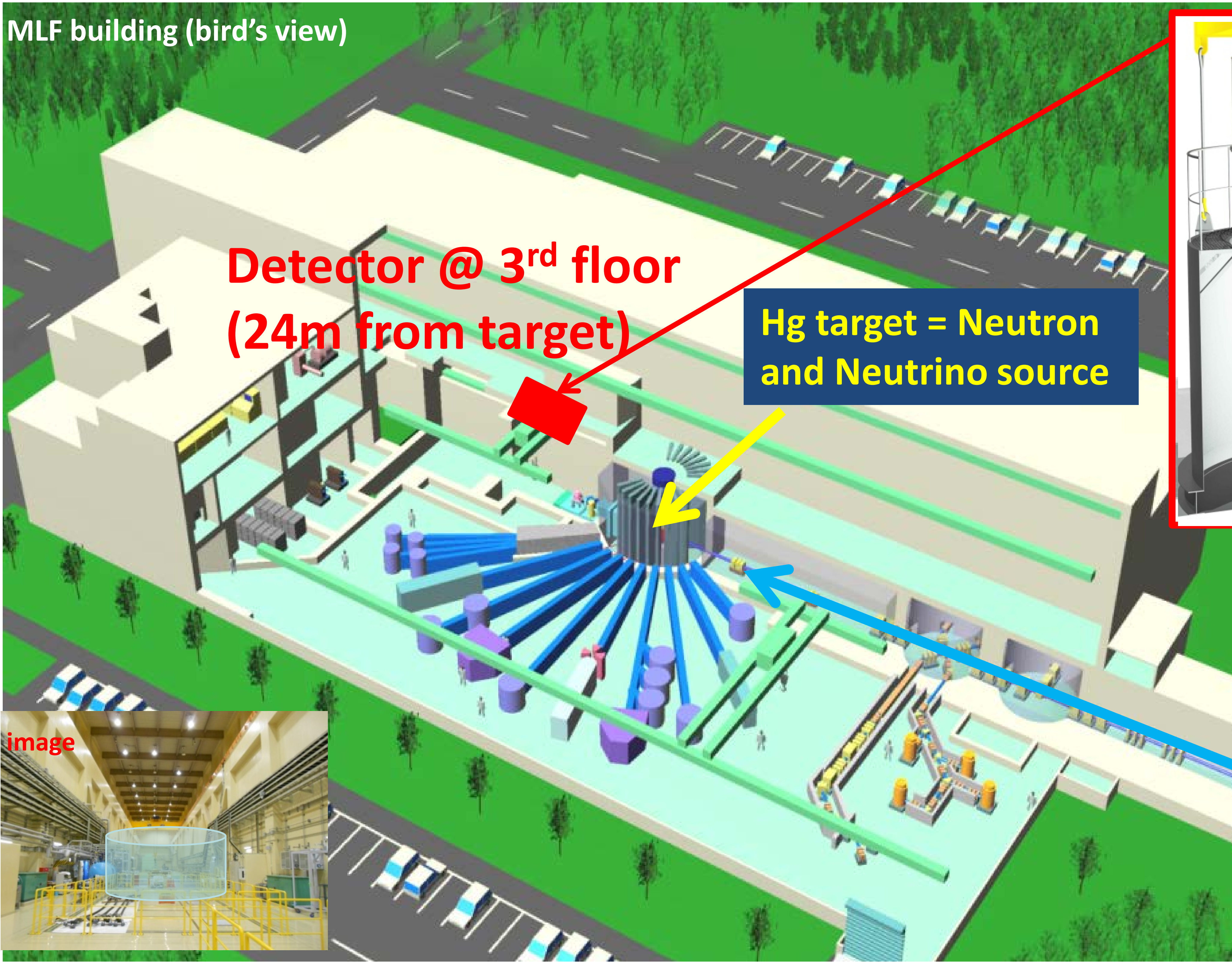
arXiv:1705.08629v1 [physics.ins-det] 24 May 2017

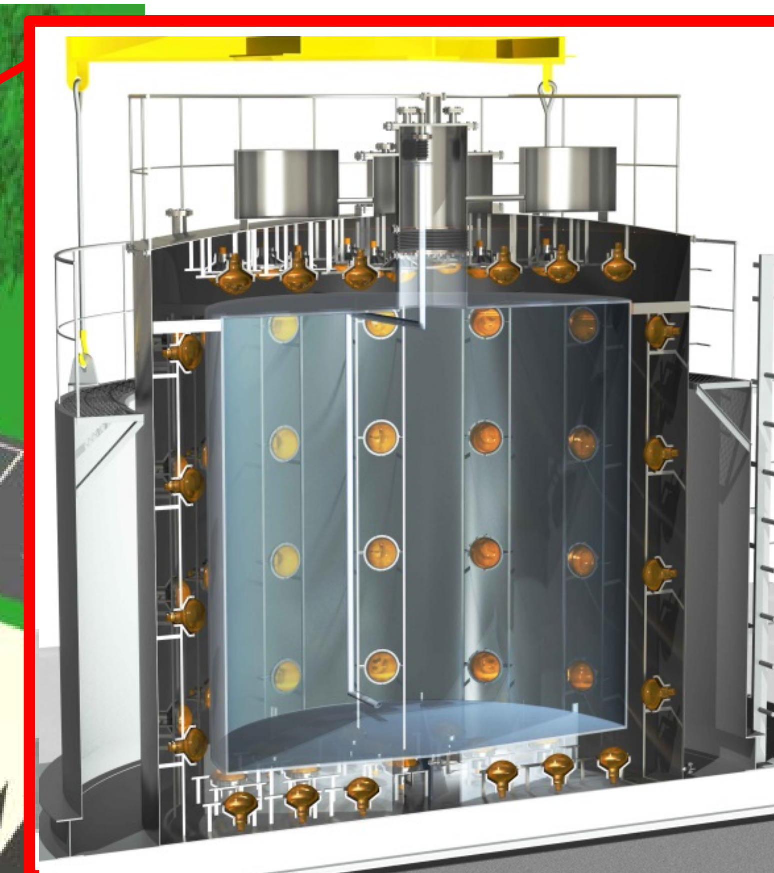
JSNS2 collab. photo, 5/2017 @ KEK



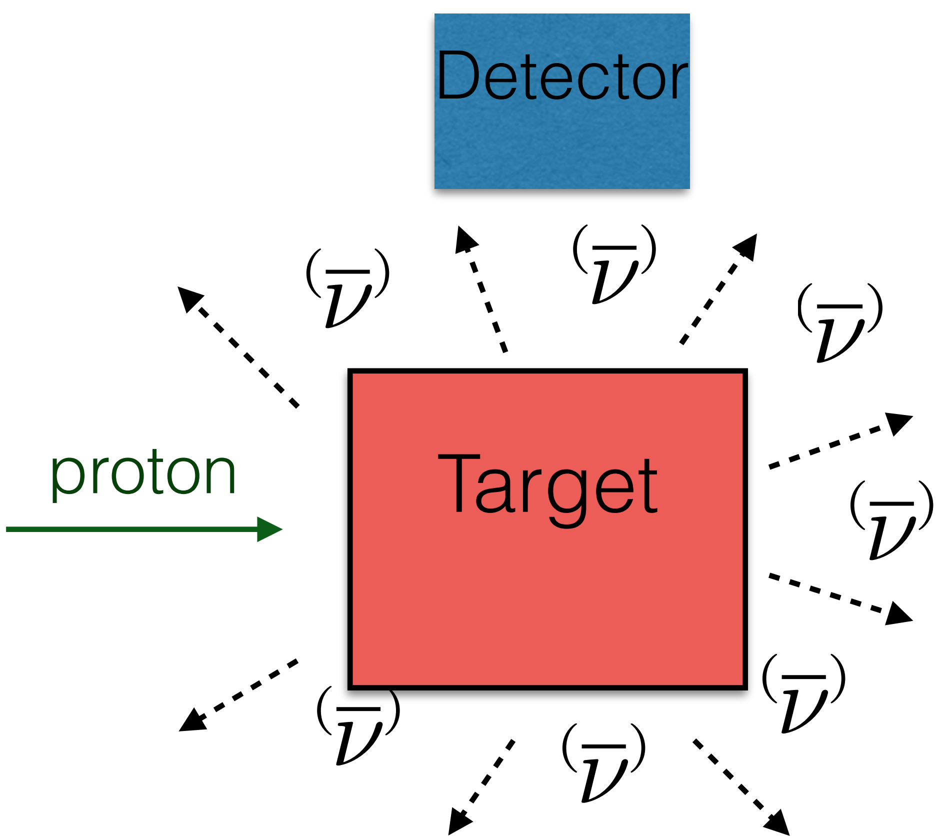
21 institutions, 53 collaborators, Japan/US/Korea


JSNS^2: J-PARC E56
Sterile ν search
@MLF
http://research.kek.jp/group/mlfnu/
J-PARC Facility
(KEK/JAEA)
South to North
400MeV
3 GeV RCS
100ns
100ns
600ns
40ms
Neutrino Beams
(to Kamioka)
25Hz 500kW now &
will be 1MW
Materials and Life
Experimental Facility
30GeV MR
Hadron hall
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008


MLF building (bird's view)
Detector @ 3rd floor
(24m from target)
Hg target = Neutron
and Neutrino source
image
3GeV pulsed proton
beam



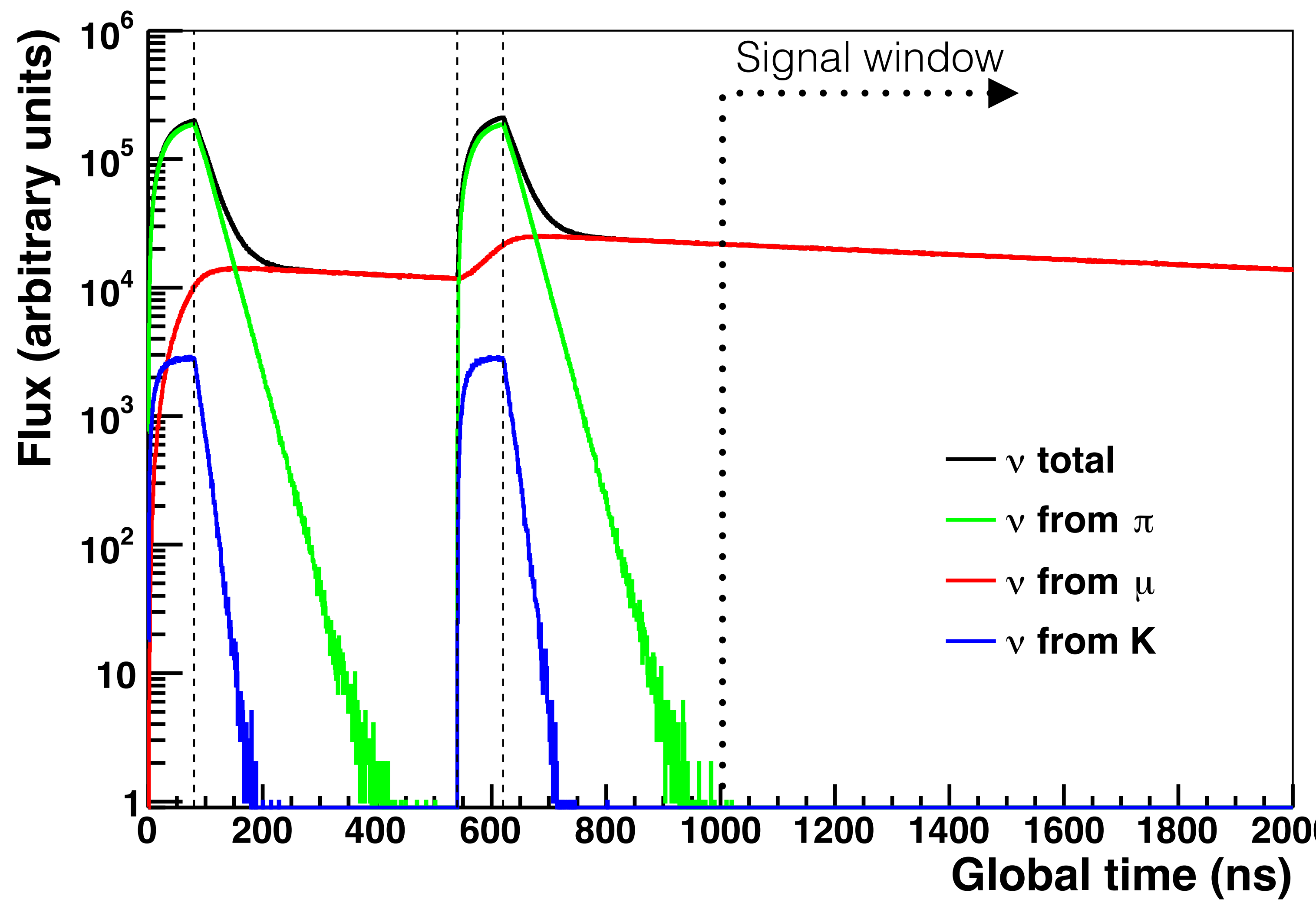
JSNS² beam timing

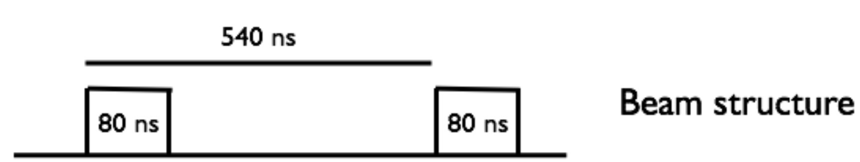


$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

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

$$K^+ \rightarrow \mu^+ \nu_\mu$$

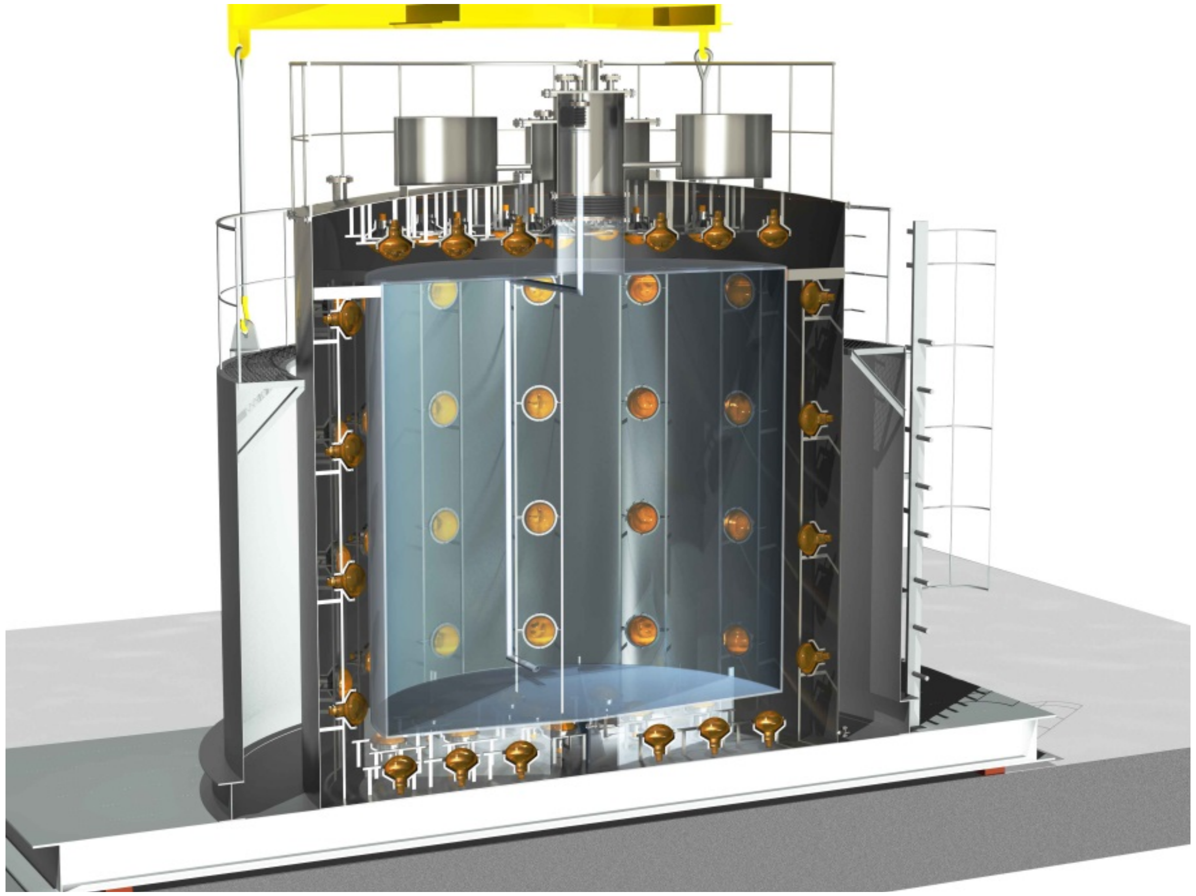




25 Hz

JSNS^2 detection principle

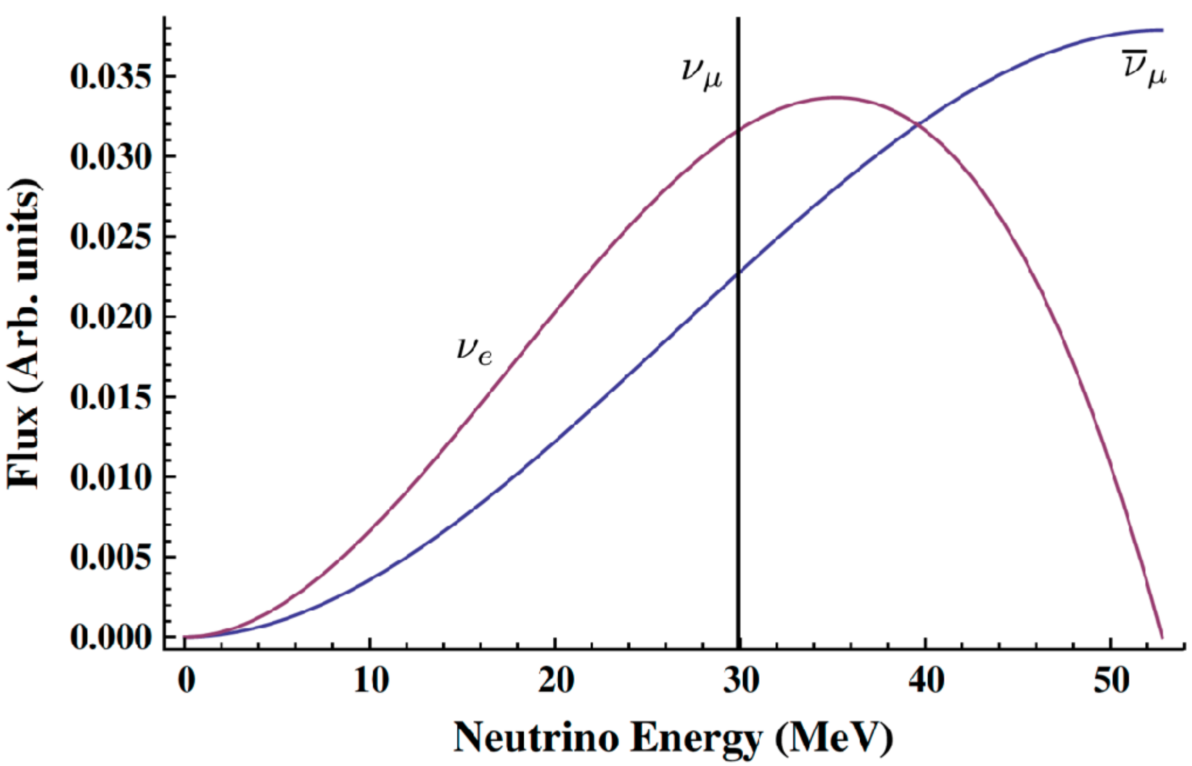
- Target volume is Gd-loaded liquid scintillator
    - Phase 0: 17 tons w/ 193 8'' PMTs
    - Future phase: multi-detector (34 tons)
- Energy resolution ~15%/sqrt[energy in MeV]



$$\overline{\nu}_\mu \to \overline{\nu}_e, \quad \underbrace{\overline{\nu}_e + p \to e^+}_{\text{prompt signal}} + \underbrace{n}_{\text{delayed signal (n-capture)}}$$

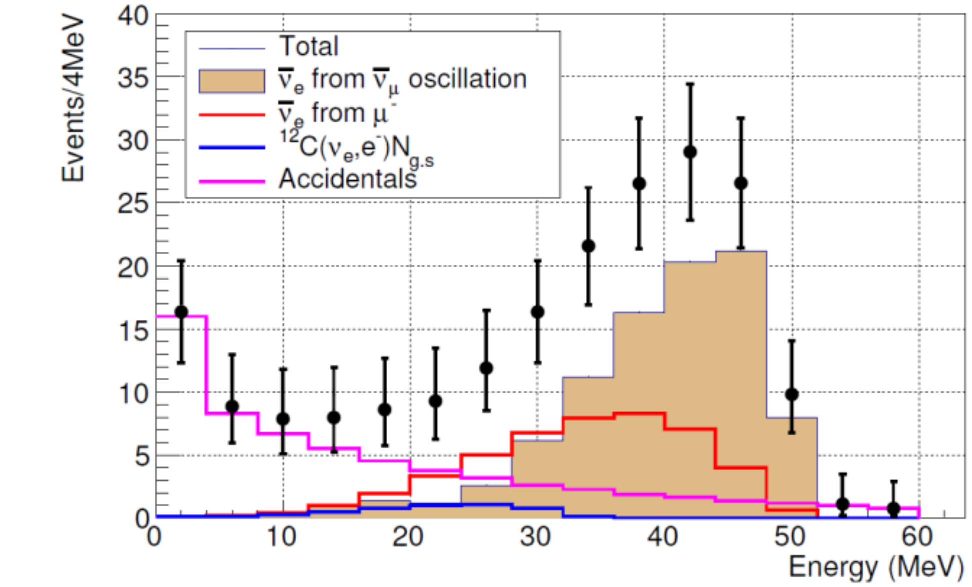
	Time from beam	Energy
Prompt signal	$1<T_p<10\mu s$	20<E<60MeV
Delayed signal	$T_p<T_d<100\mu s$	7<E<12MeV

JSNS² is highly sensitive to *the* smoking gun signature of oscillations: a wiggle in L/E

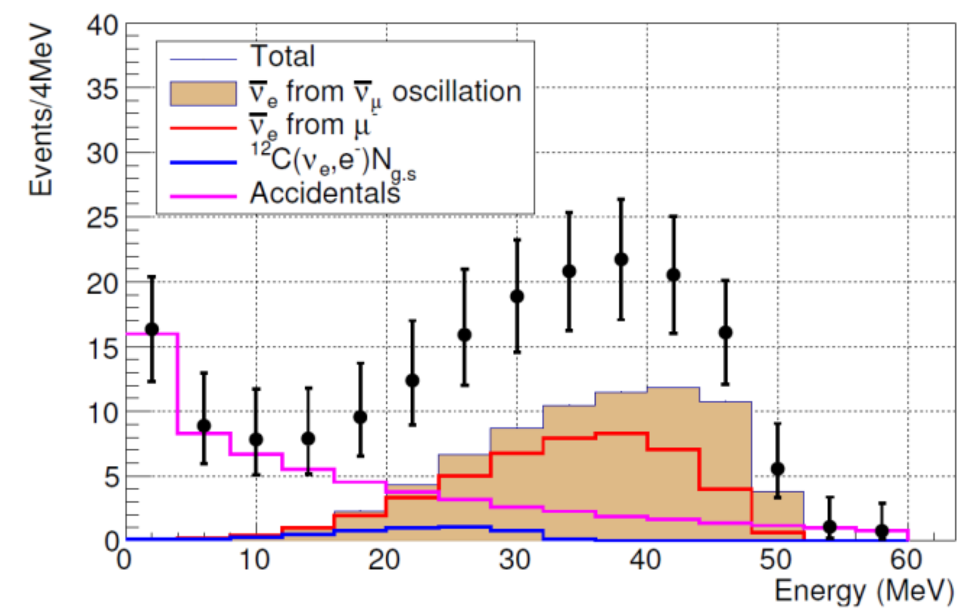


$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$?

Expected spectrum



Case $\Delta m^2 = 2.5\mathrm{eV}^2, \sin^2 2\theta = 0.003$

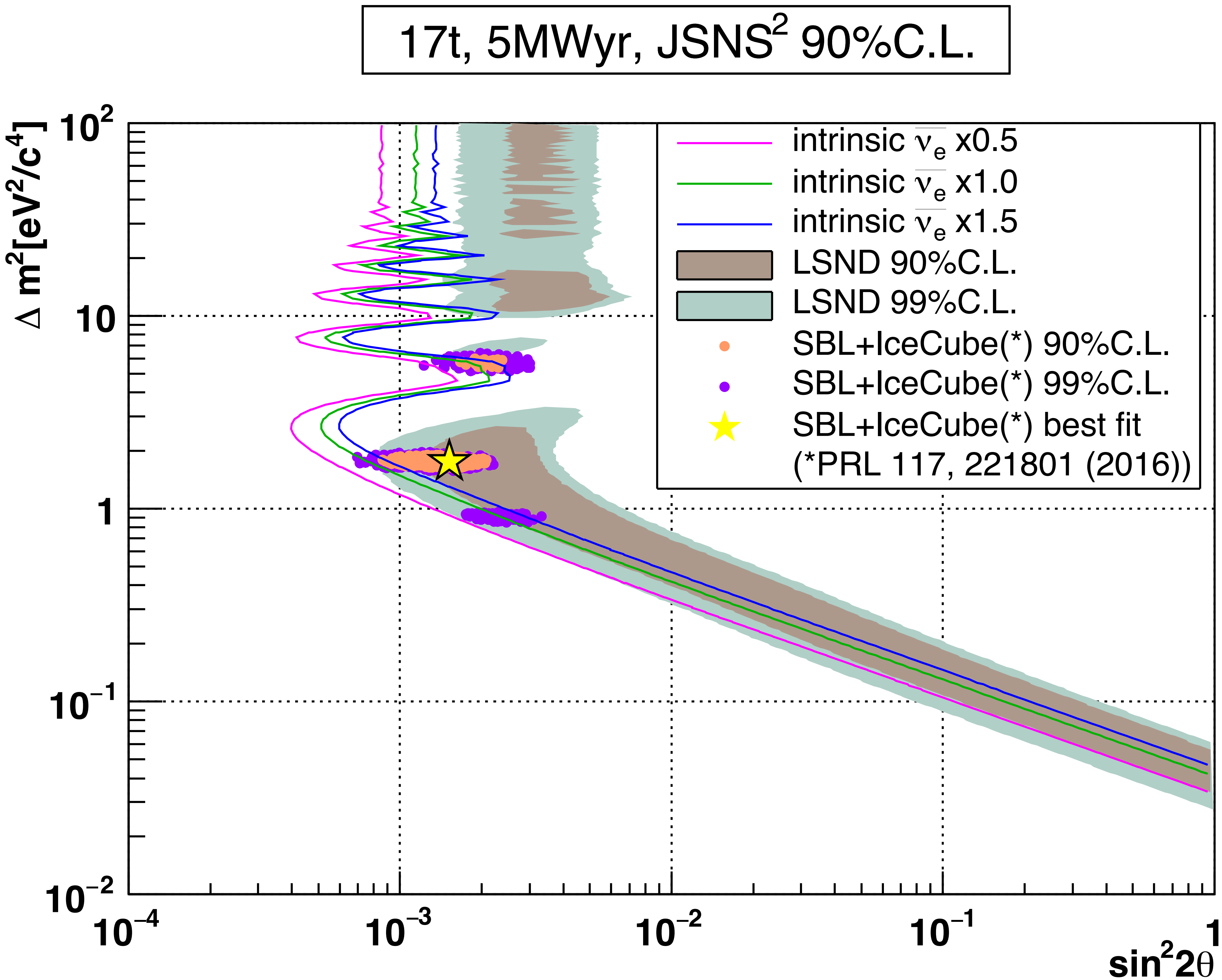


Case $\Delta m^2 = 1.2\mathrm{eV}^2, \sin^2 2\theta = 0.003$

(dominant background: intrinsic nuebar)

(3 years of running)

JSNS² Phase-0 (*now under construction*) expected sensitivity

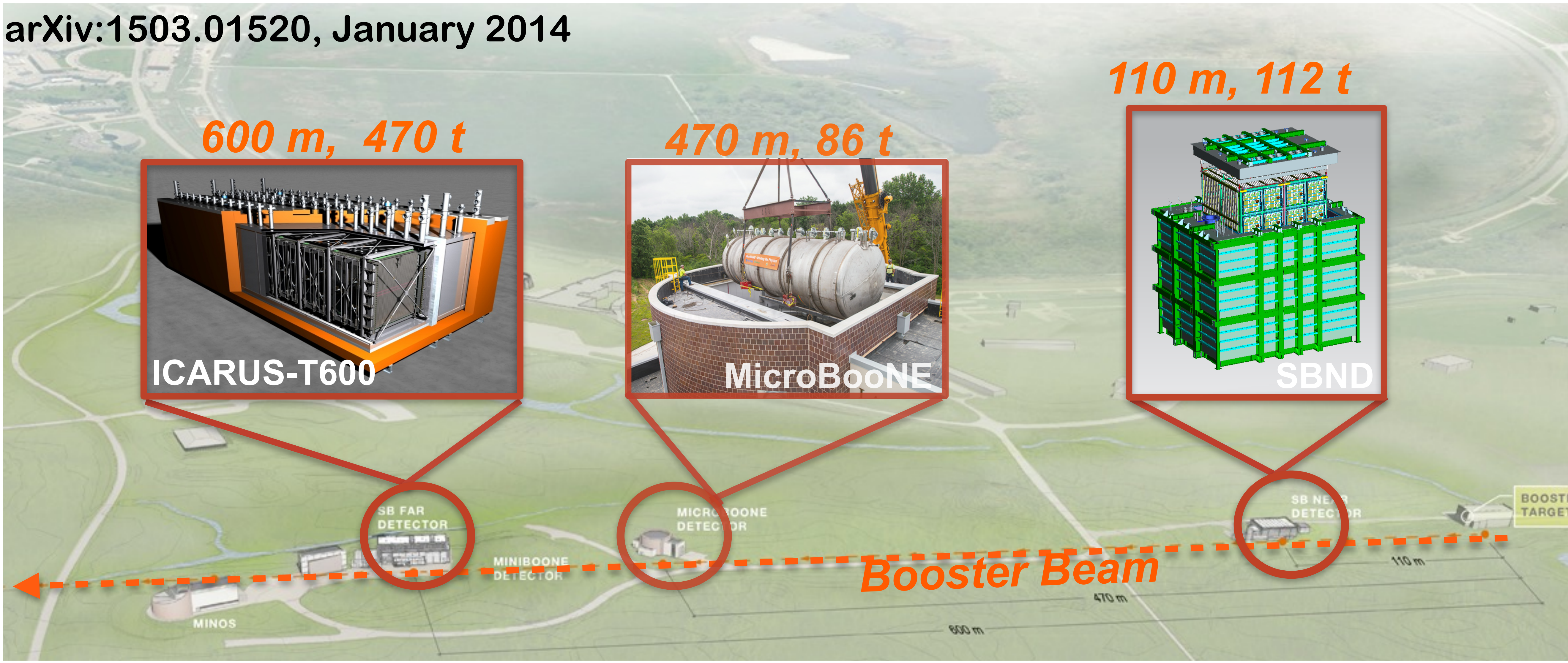


(5 years of running)

Pion decay-in-flight

SBN Program at Fermilab

3 LArTPCs in the Booster Neutrino Beamline

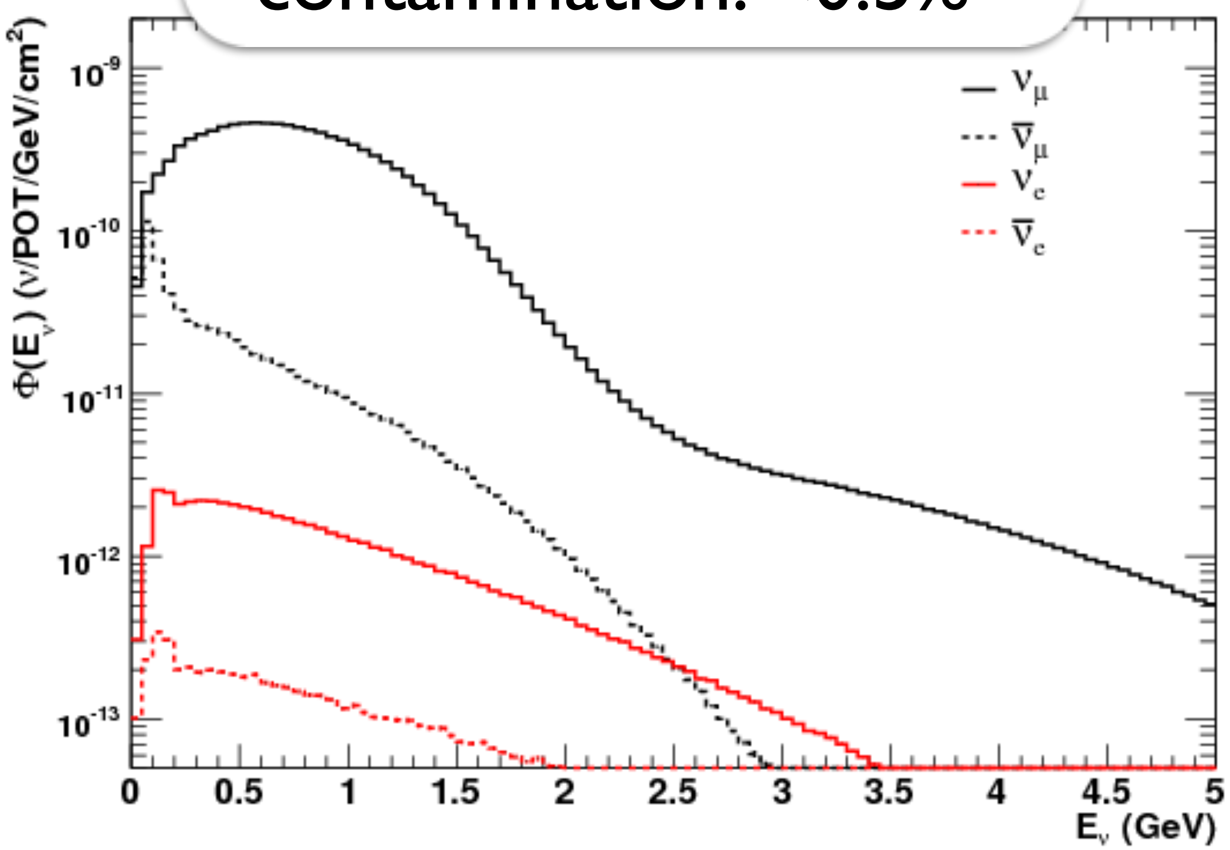


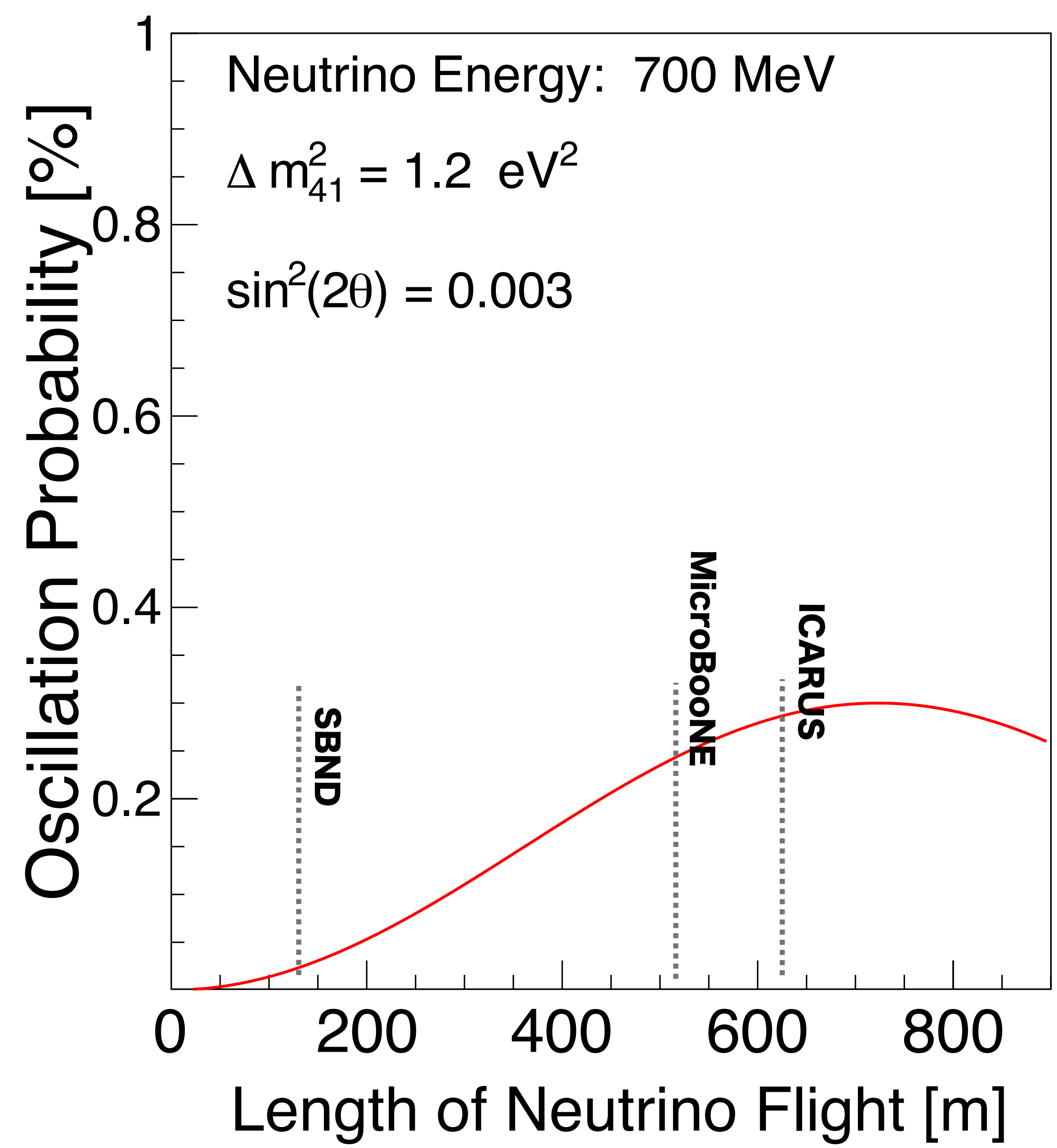
SBND (first data in 2019)
MicroBooNE (first data in late-2015)
ICARUS (first data in 2018)

SBN Program at Fermilab

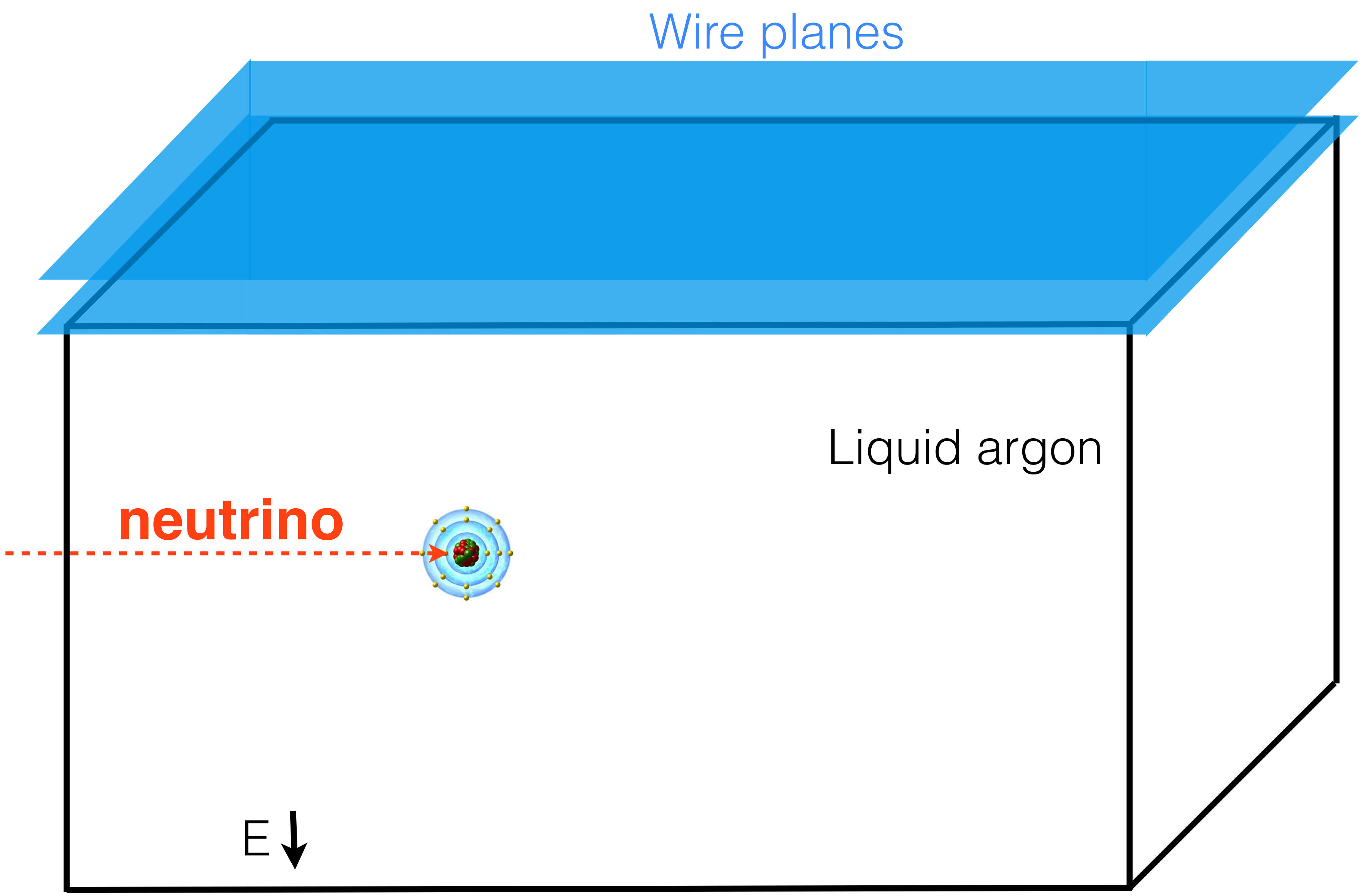
3 LArTPCs in the Booster Neutrino Beamline

Small electron neutrino contamination: <0.5%





Liquid Argon Time Projection Chamber



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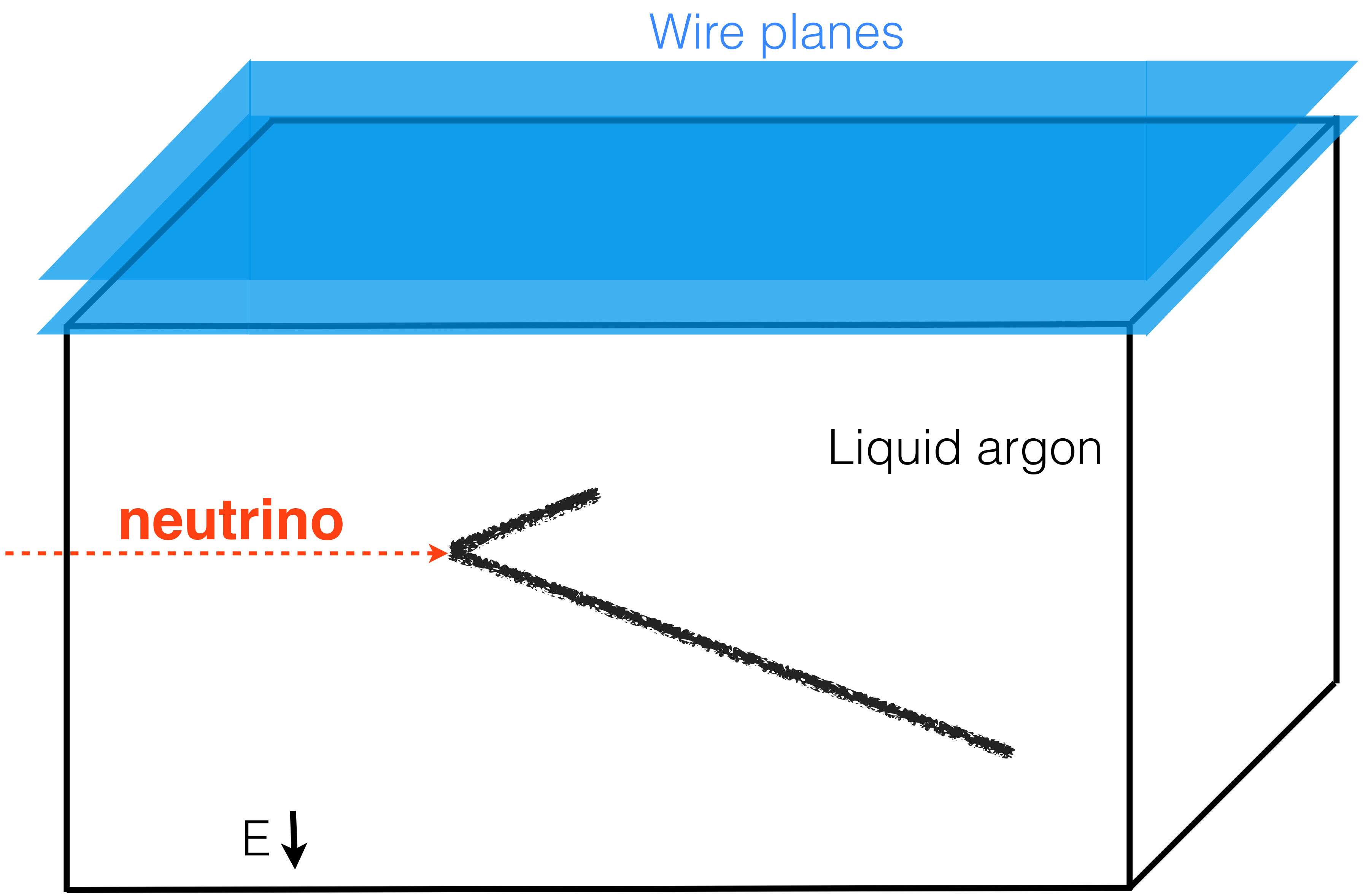
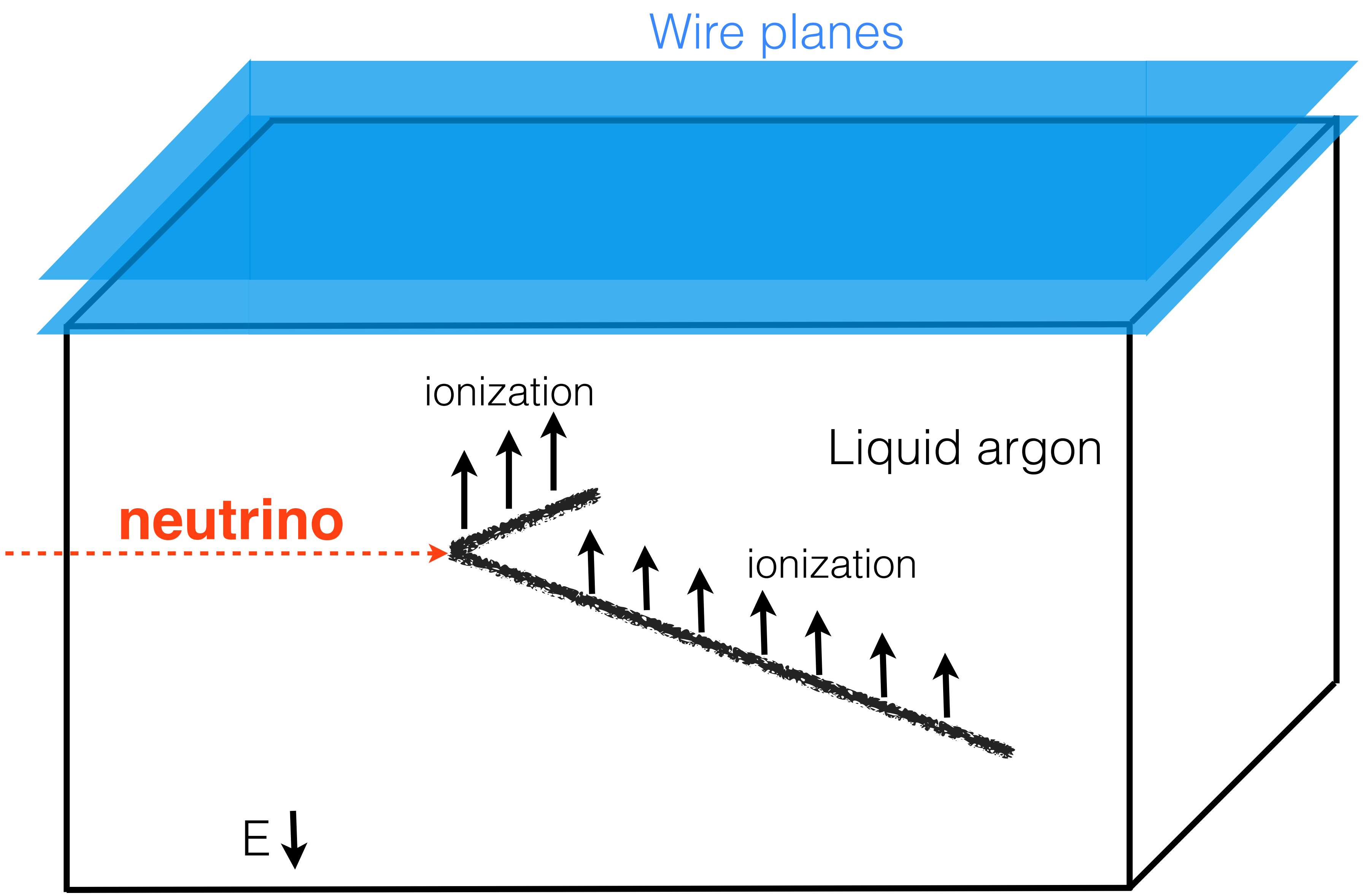


Liquid Argon Time Projection Chamber



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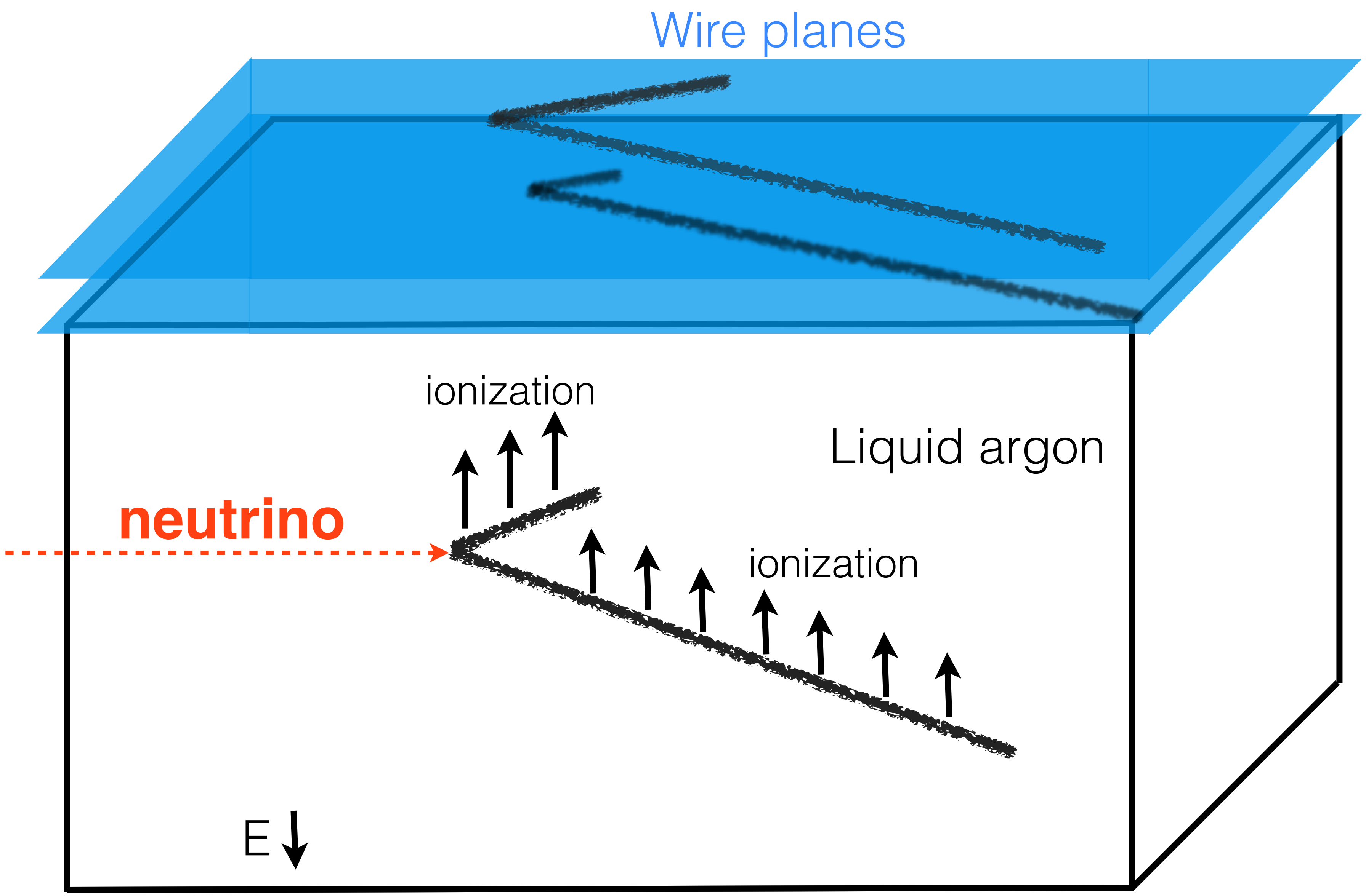
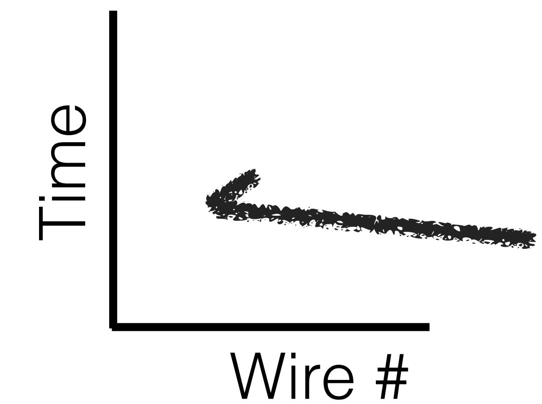
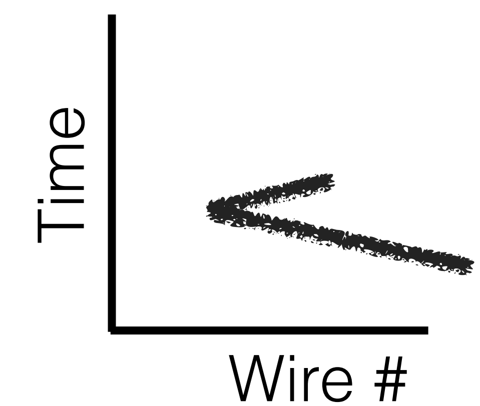
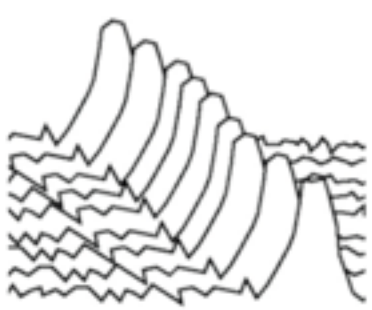


Induction plane



Collection plane

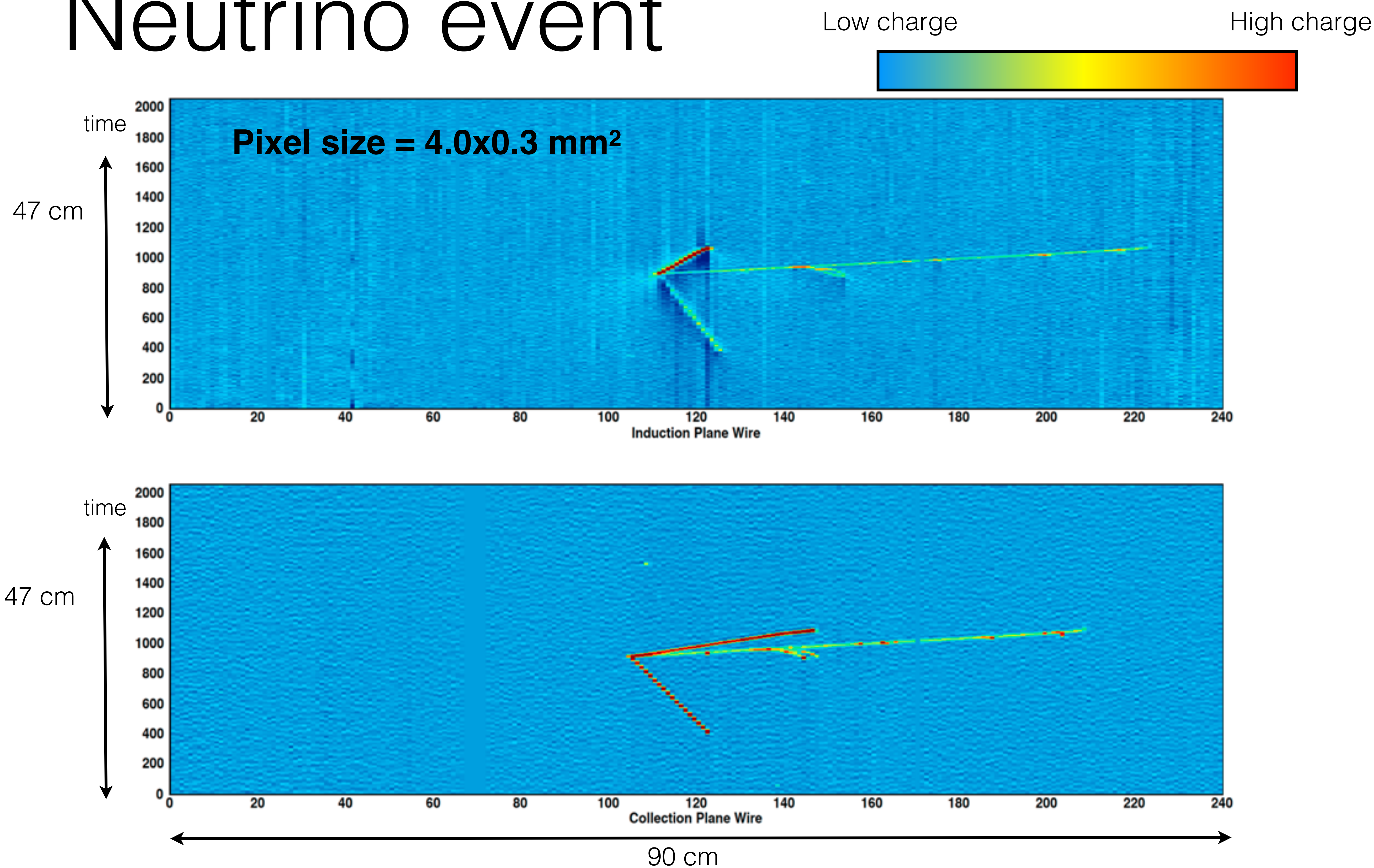




Wire pulses in time give the drift coordinate of the track

induction plane + collection plane + time = 3D image of event

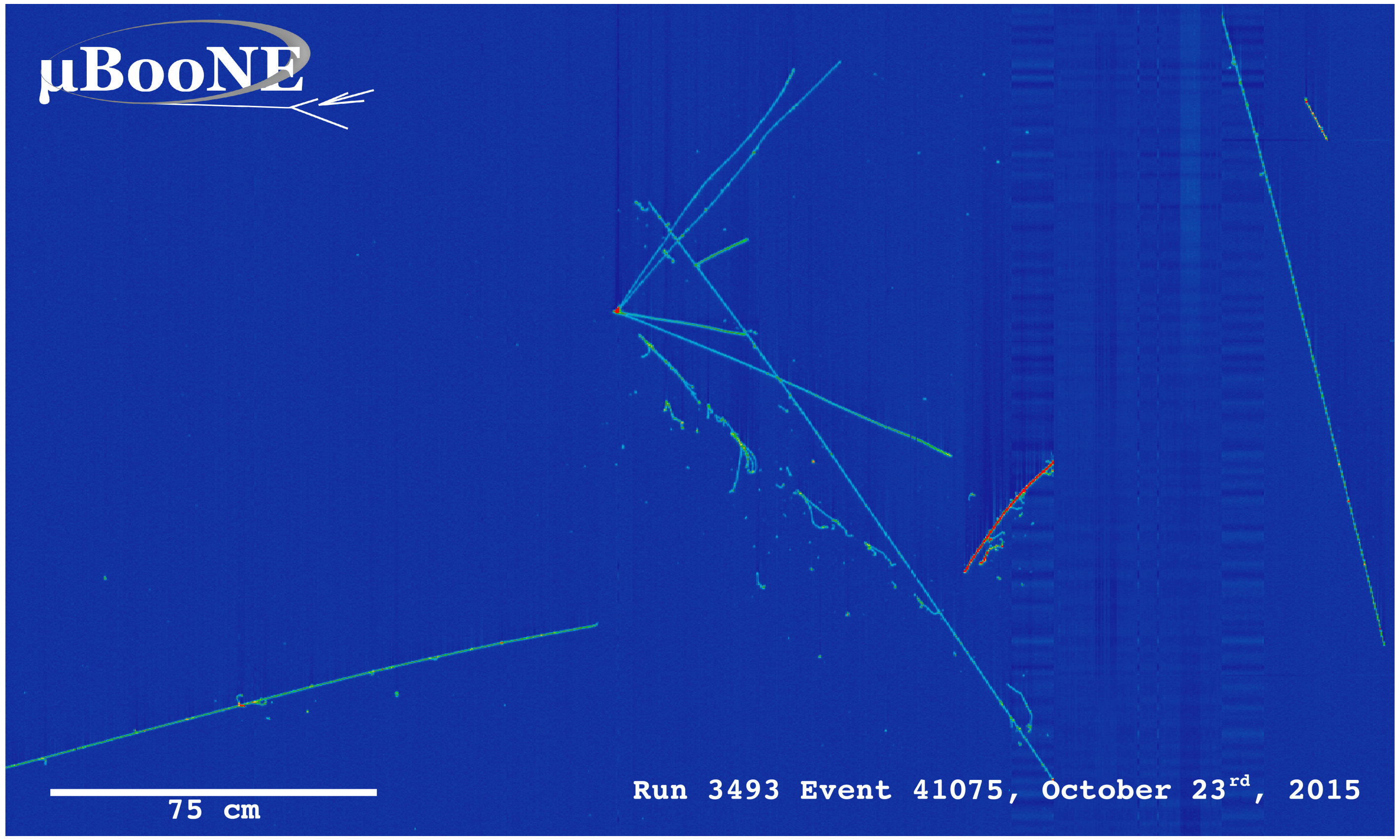
Neutrino event



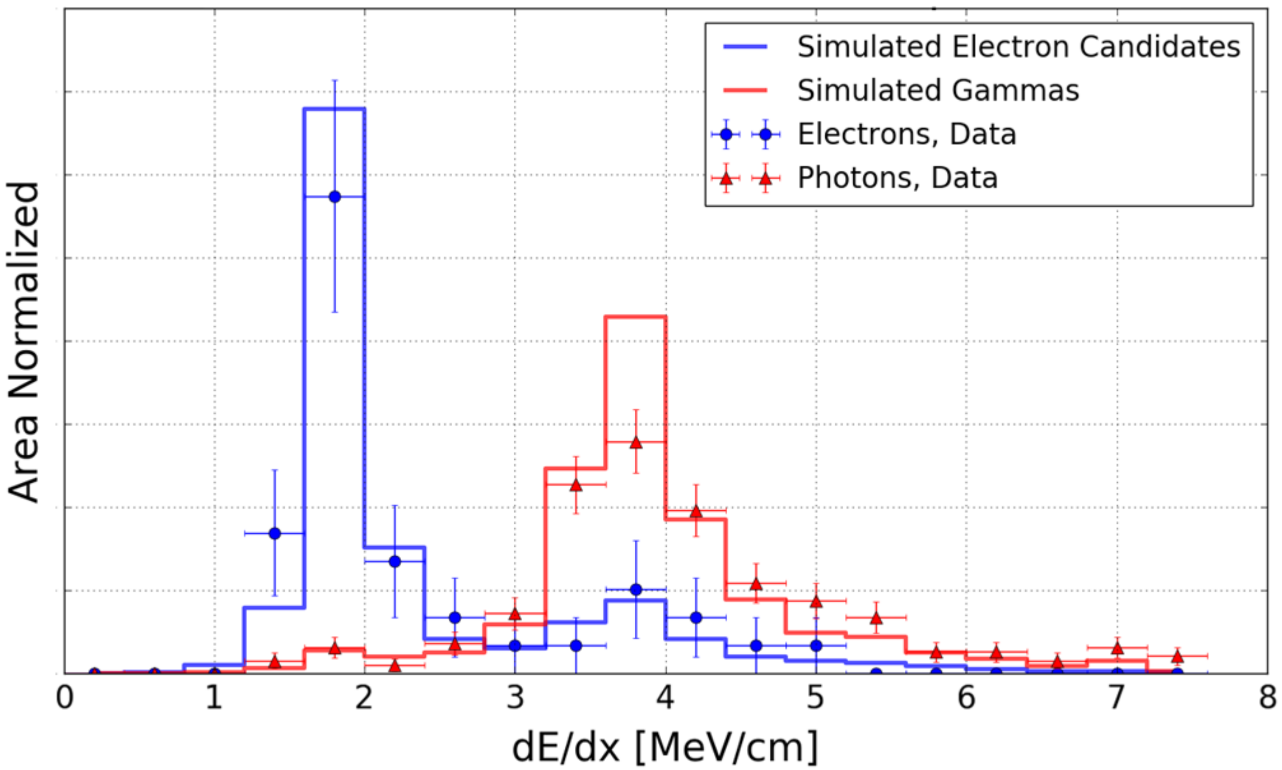
ArgoNeuT experiment at Fermilab

LArTPC technology

Fine-grained imaging of neutrino events

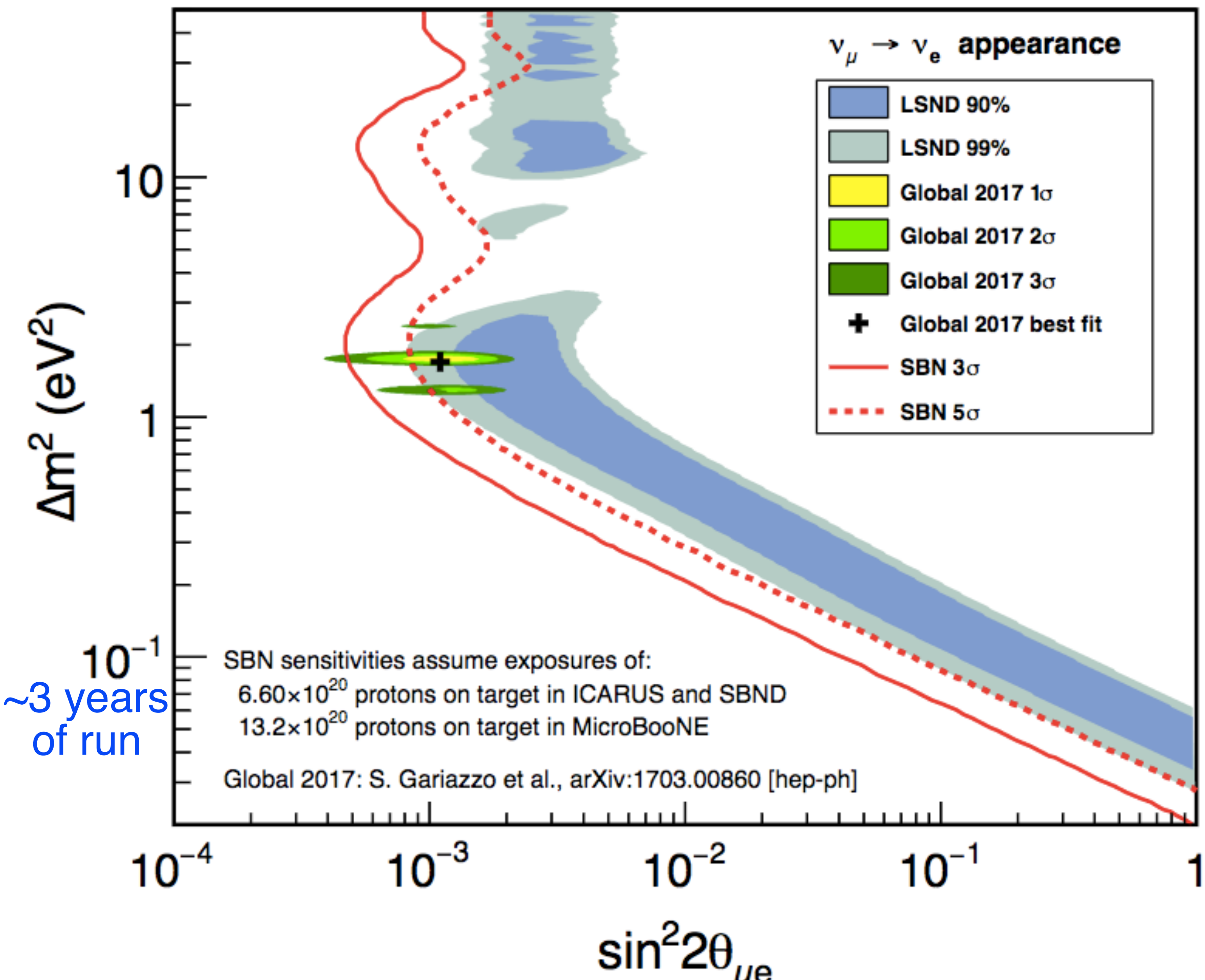


Calorimetric capability to differentiate gammas (background) from electrons (signal)



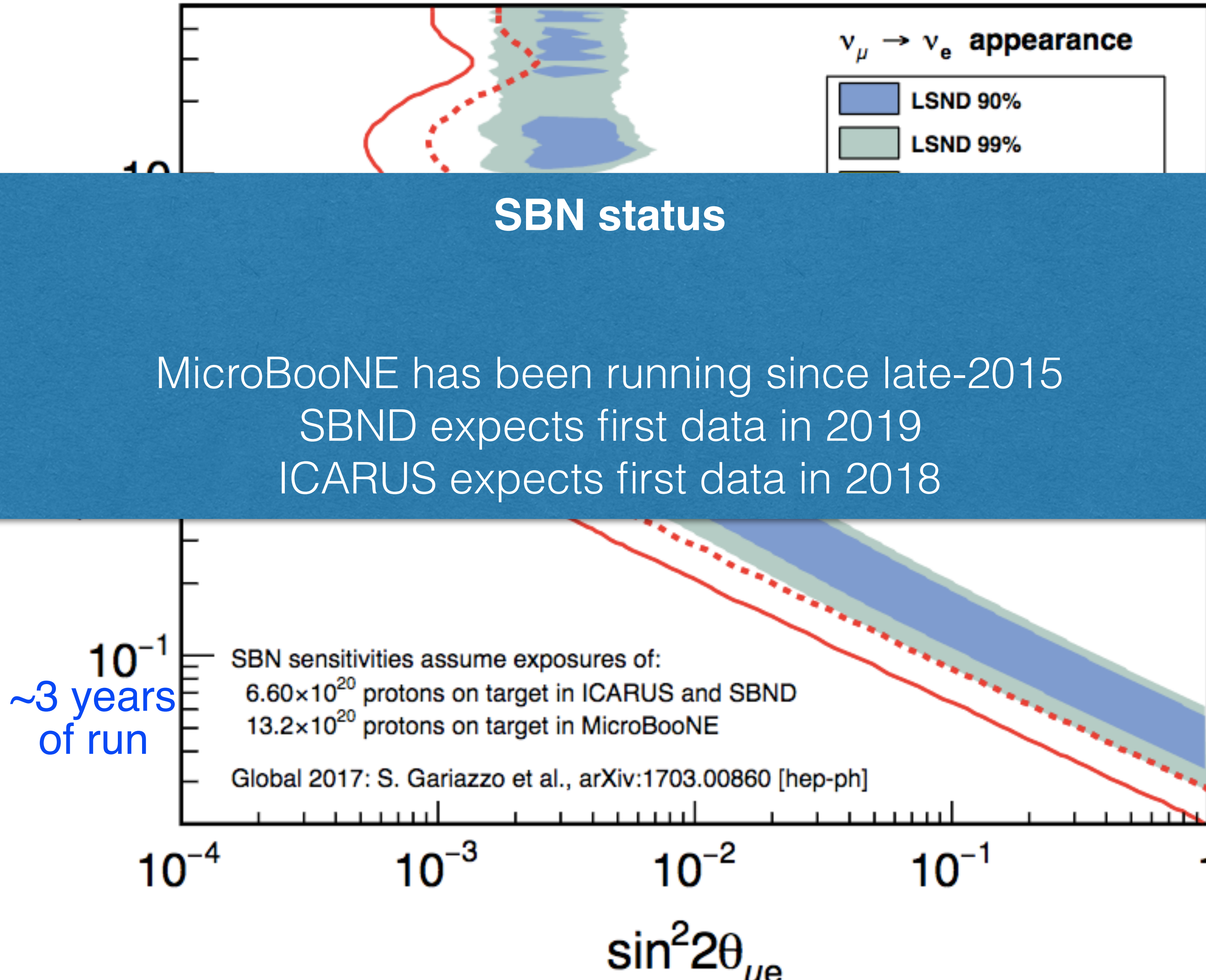
ArgoNeuT;
Phys. Rev. D 95 072005 (2017)

SBN Program at Fermilab



~3 years of run

SBN Program at Fermilab

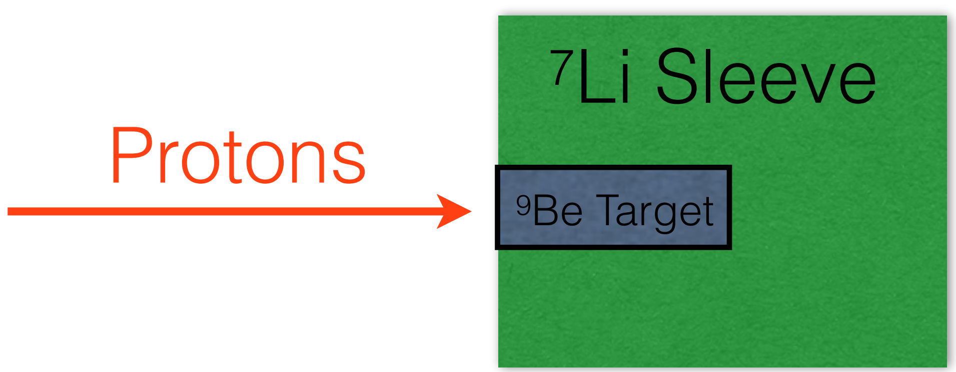


SBN status

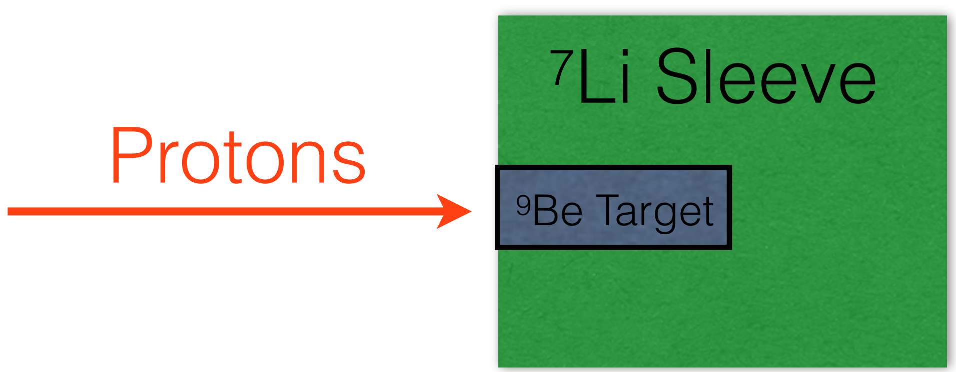
MicroBooNE has been running since late-2015
SBND expects first data in 2019
ICARUS expects first data in 2018

IsoDAR

(doubling as the injector cyclotron design for the DAEδALUS δ_{CP} experiment)



IsoDAR

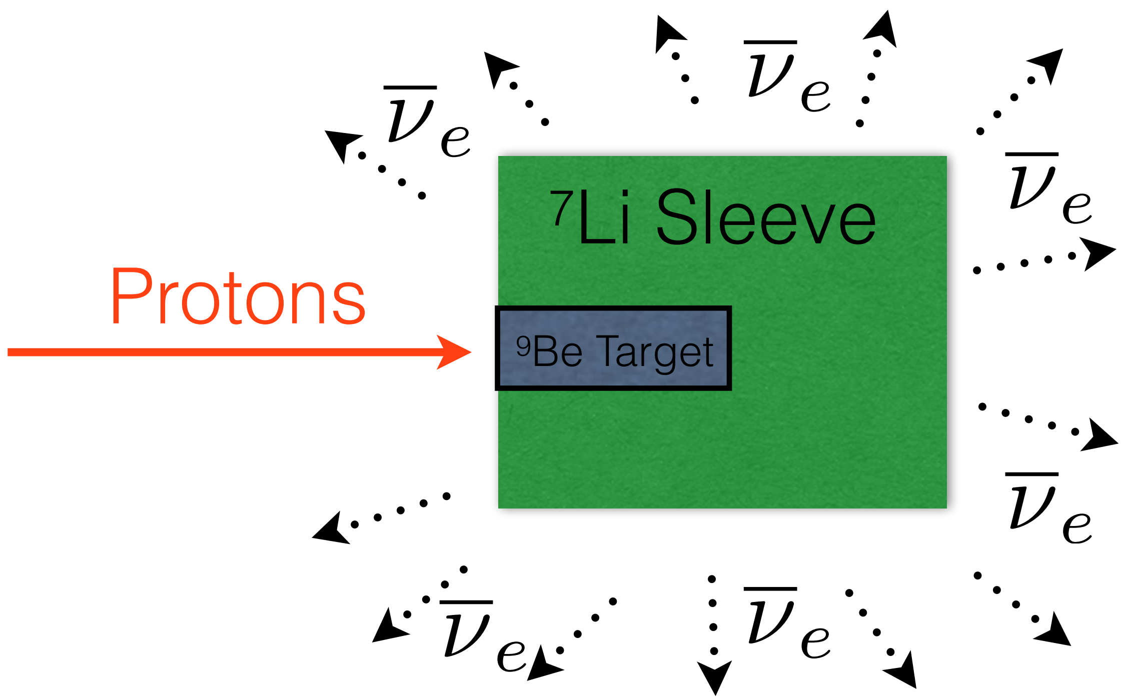


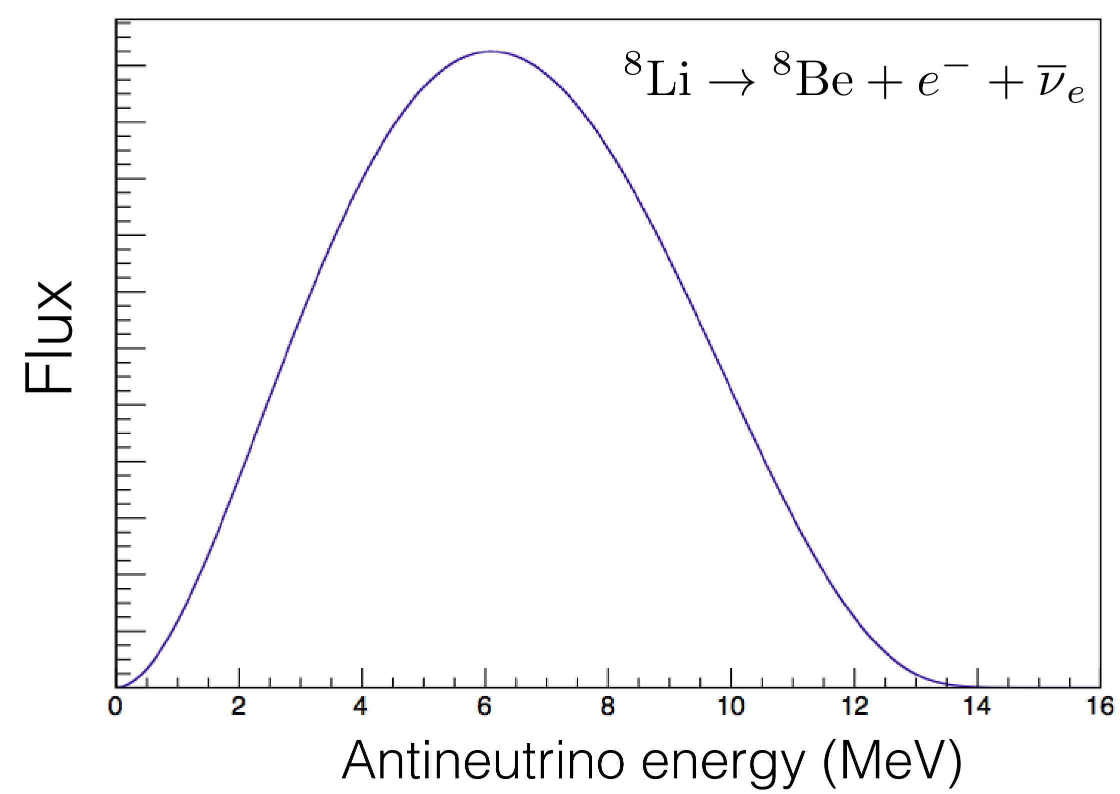
$$p + {}^{9}\mathrm{Be} \rightarrow \boxed{{}^{8}\mathrm{Li}} + 2p$$

$$p + {}^{9}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + n$$

$$n + {}^{7}\mathrm{Li} \rightarrow \boxed{{}^{8}\mathrm{Li}} + \gamma$$

IsoDAR



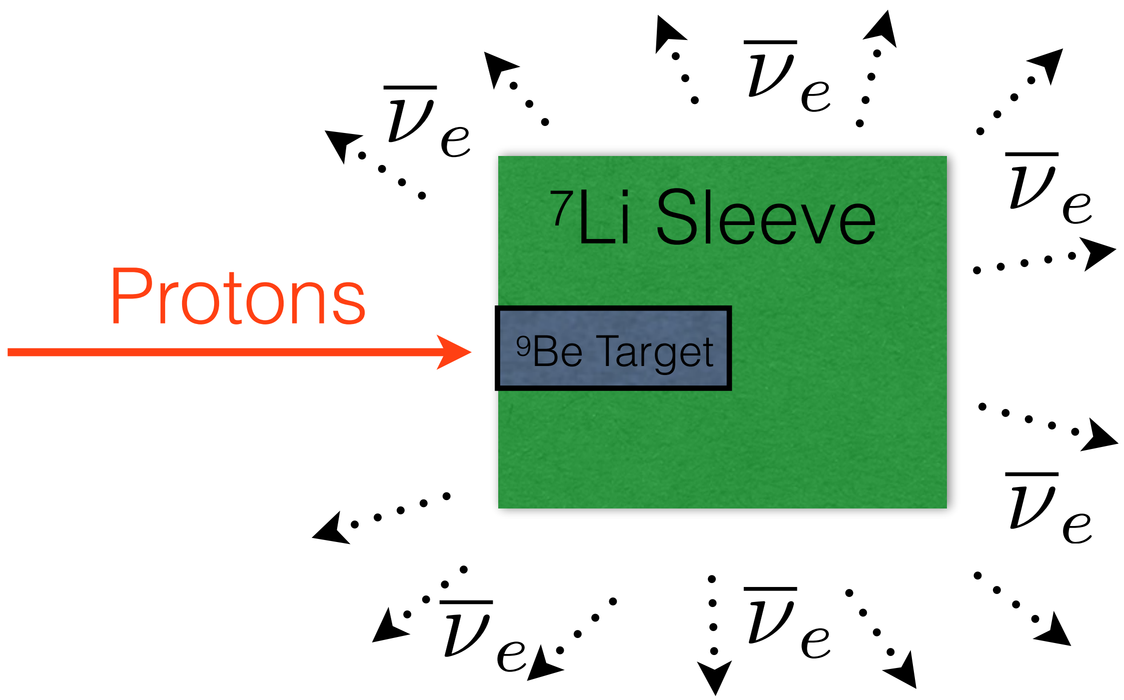


$$p + {}^9\mathrm{Be} \to \boxed{{}^8\mathrm{Li}} + 2p$$

$$p + {}^9\mathrm{Be} \to {}^9\mathrm{B} + n$$
$$n + {}^7\mathrm{Li} \to \boxed{{}^8\mathrm{Li}} + \gamma$$

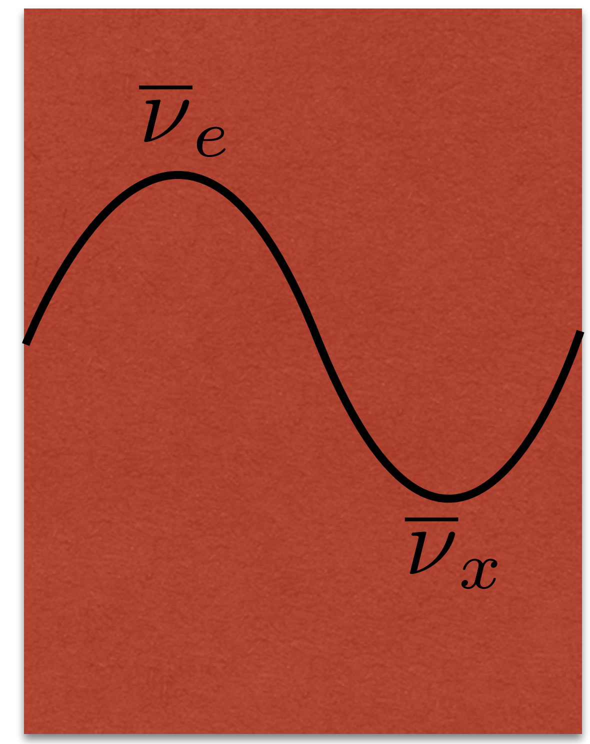
$$^8\mathrm{Li} \to {}^8\mathrm{Be} + e^- + \boxed{\overline{\nu}_e}$$

IsoDAR



$$\overline{\nu}_e \to \overline{\nu}_x \quad ?$$

Detector



$$\overline{\nu}_e p \to e^+ n$$

$$p + {}^9\mathrm{Be} \to \boxed{{}^8\mathrm{Li}} + 2p$$

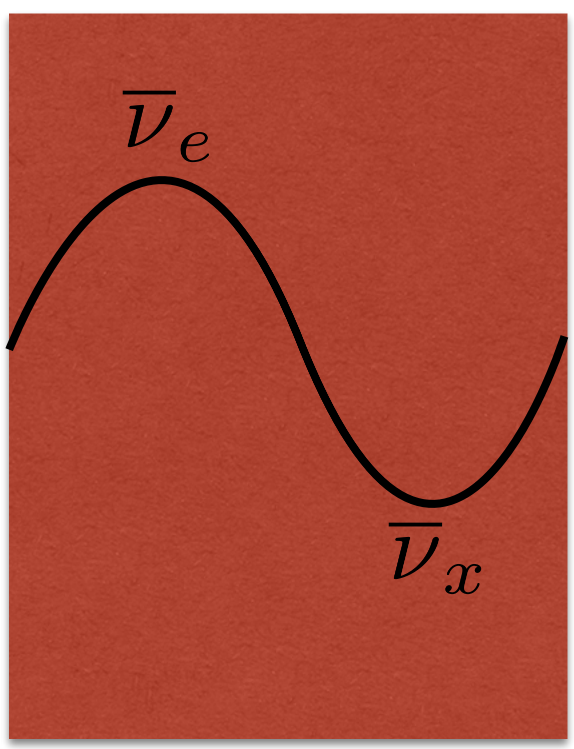
$$p + {}^9\mathrm{Be} \to {}^9\mathrm{B} + n$$
$$n + {}^7\mathrm{Li} \to \boxed{{}^8\mathrm{Li}} + \gamma$$

$$ {}^8\mathrm{Li} \to {}^8\mathrm{Be} + e^- + \boxed{\overline{\nu}_e}$$

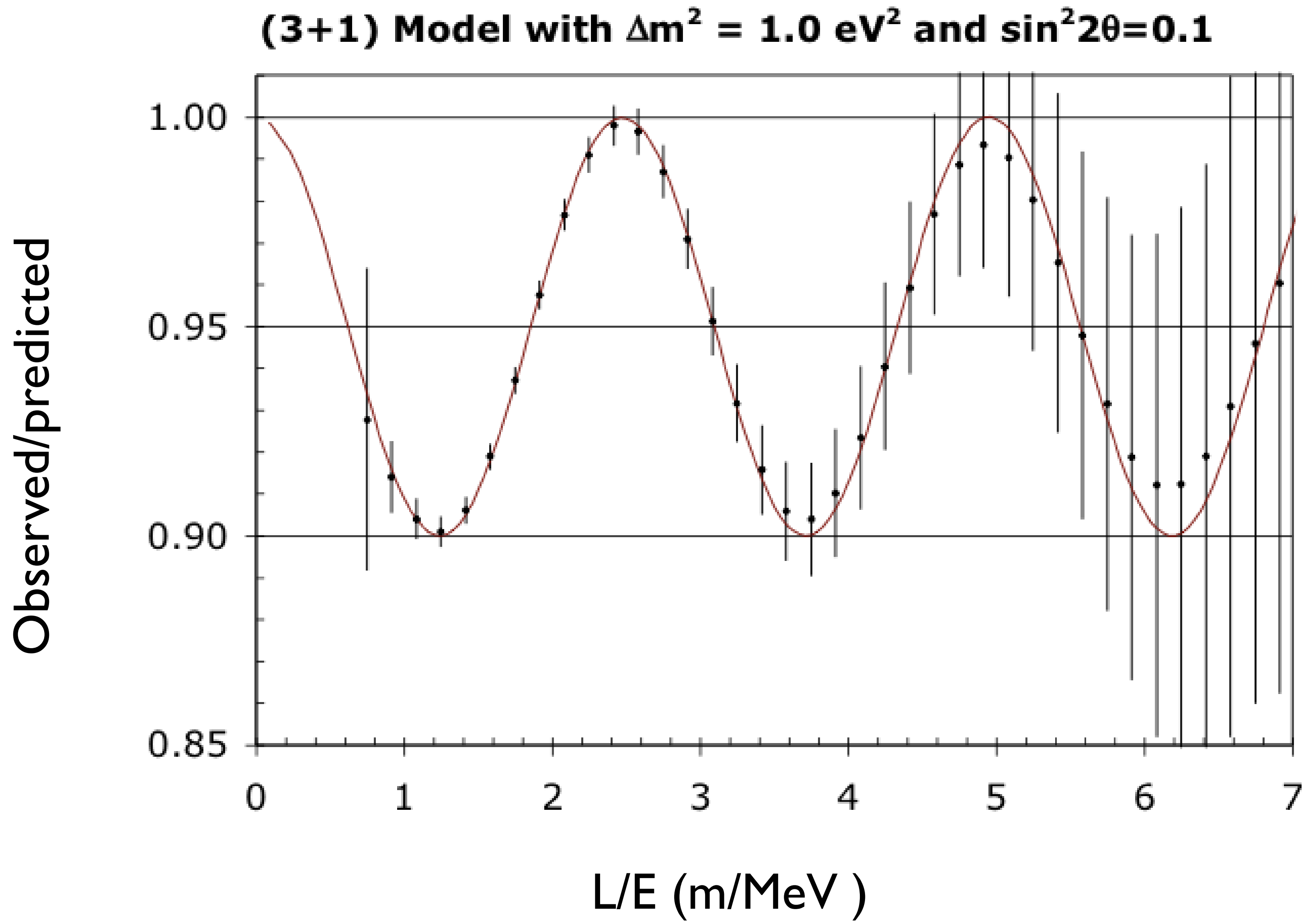
IsoDAR

$$\overline{\nu}_e \rightarrow \overline{\nu}_x \quad ?$$

Detector



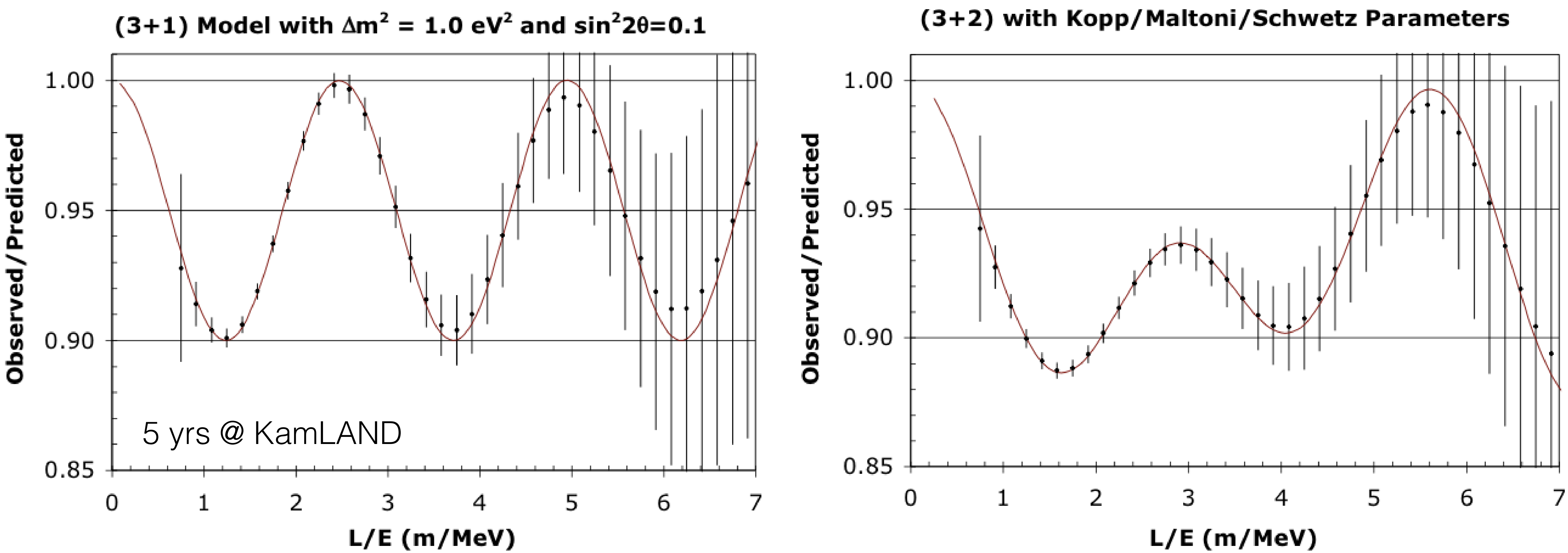
$$\overline{\nu}_e p \rightarrow e^+ n$$



820,000 IBD events in 5 years at KamLAND
(16 m baseline to center of detector)

How many steriles?

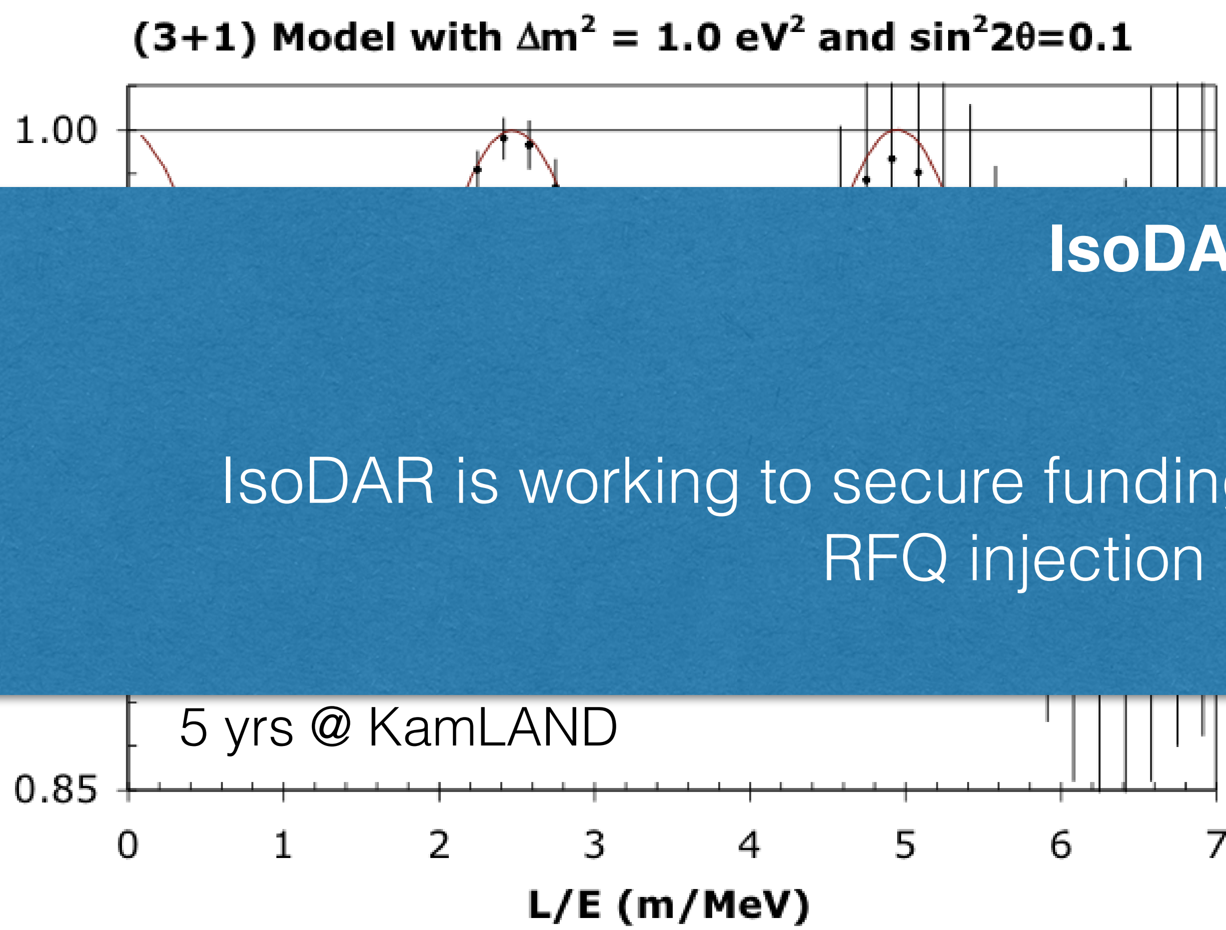
Observed/Predicted event ratio vs L/E, including energy and position smearing

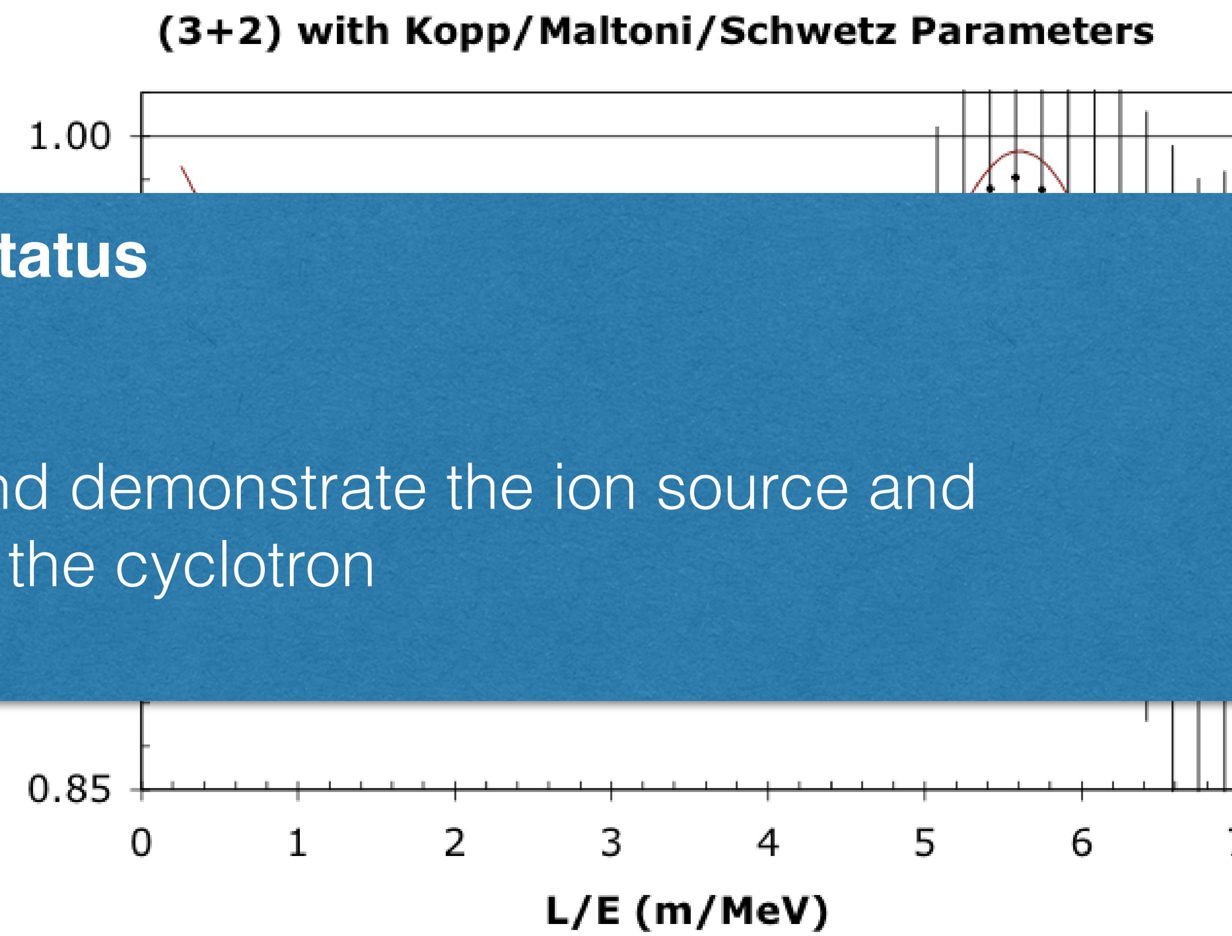


IsoDAR's high statistics and good L/E resolution provide the potential for distinguishing (3+1) and (3+2) oscillation models

How many steriles?

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





IsoDAR status

IsoDAR is working to secure funding and demonstrate the ion source and RFQ injection into the cyclotron

IsoDAR's high statistics and good L/E resolution provide the potential for distinguishing (3+1) and (3+2) oscillation models

What about muon disappearance?

Experiment name	**Type**	**Oscillation channel**	**Significance**
LSND	Low energy accelerator	muon to electron (antineutrino)	3.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (antineutrino)	2.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (neutrino)	3.4σ
Reactors	Beta decay	electron disappearance (antineutrino)	1.4-3.0σ (varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

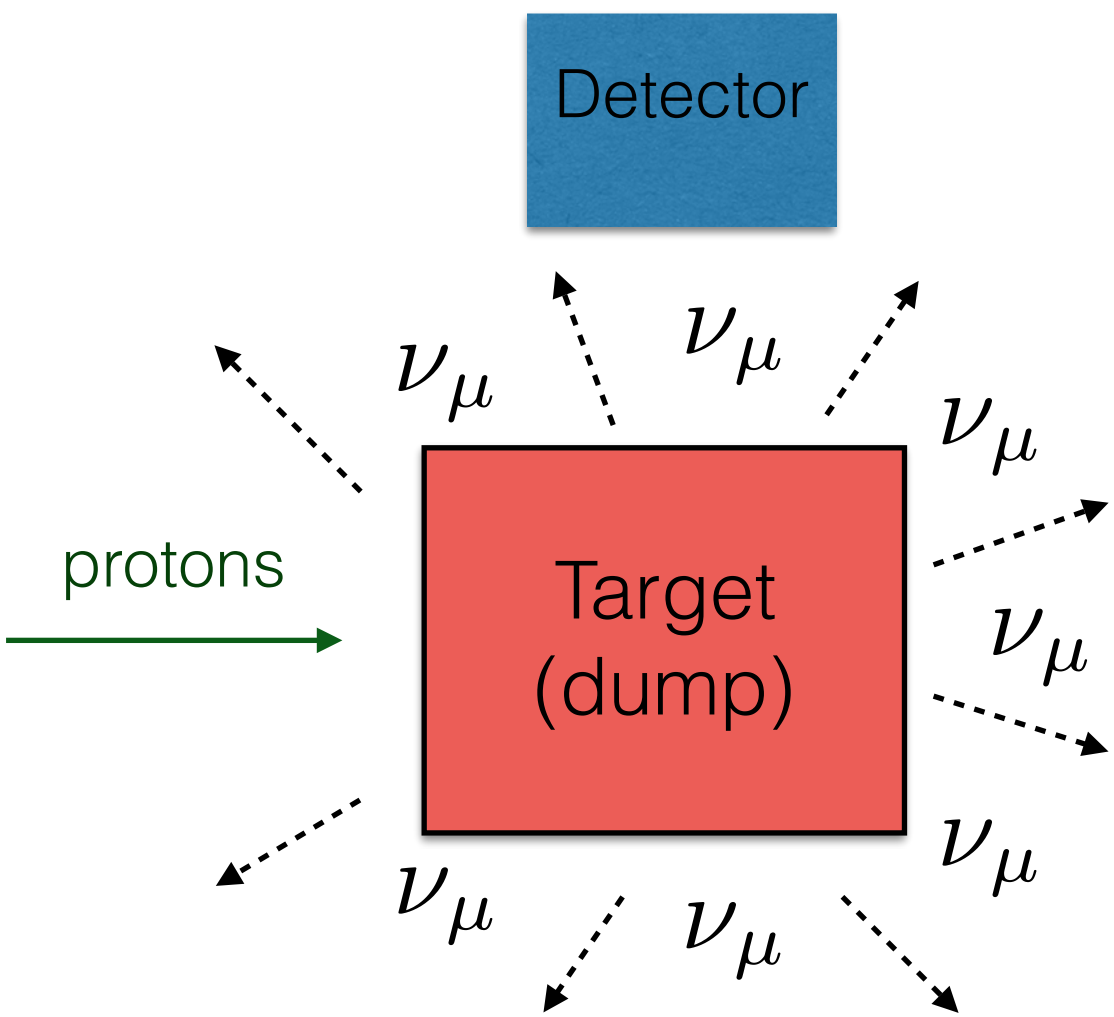
If sterile neutrinos exist, there must be some amount of ν_μ disappearance!

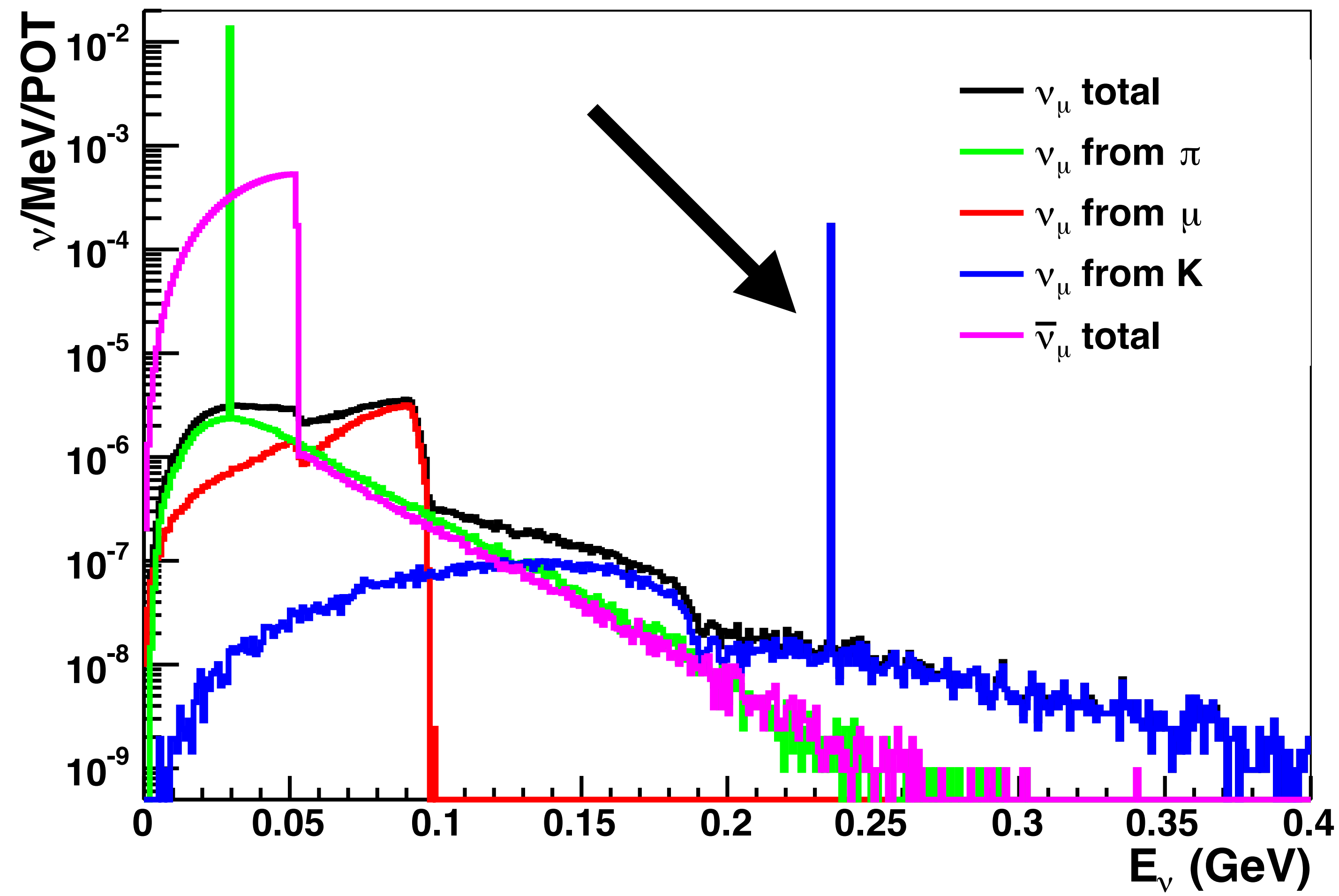
What about muon disappearance?

Experiment name	**Type**	**Oscillation channel**	**Significance**
Accelerator-based experiments (e.g. MicroBooNE, SBN program at Fermilab, JSNS²,…)		muon to electron (antineutrino)	3.8σ
		muon to electron (antineutrino)	2.8σ
		muon to electron (neutrino)	3.4σ
Remeasuring reactor neutrinos up close, high intensity neutrino sources up close (e.g. Prospect, Chandler, NEOS, DANSS, SoLid, SOX, IsoDAR, …)		electron disappearance (antineutrino)	1.4-3.0σ (varies)
		electron disappearance (neutrino)	2.8σ

If sterile neutrinos exist, there must be some amount of ν_μ disappearance!

Kaon decay-at-rest





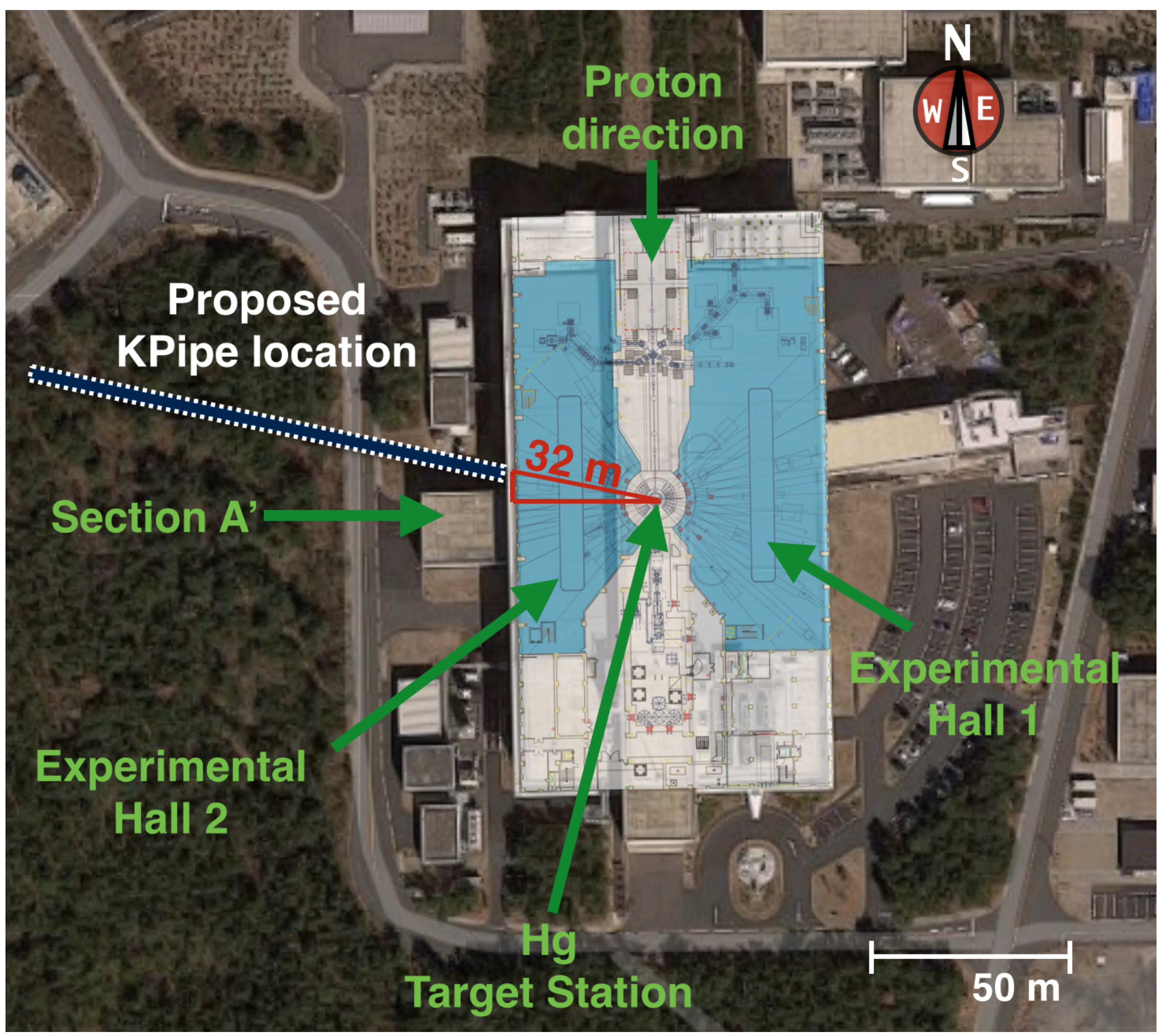
$$K^+ \to \mu^+ \nu_\mu$$

KPIPE

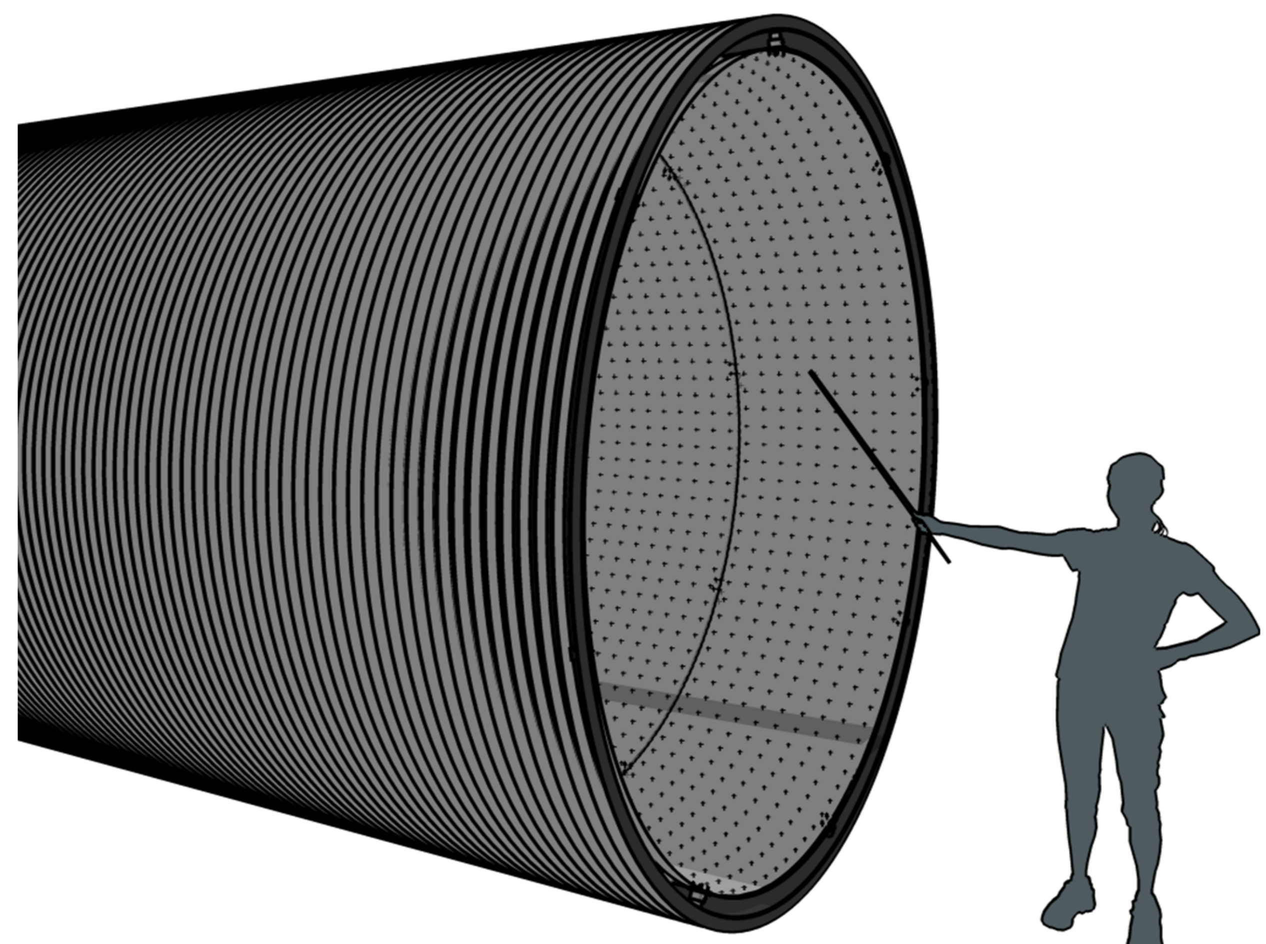
Axani, Collin, Conrad, Shaevitz, Spitz, Wongjirad, Phys. Rev. D 92 092010 (2015)

The idea:

Use a very long liquid scintillator detector to look for ν_μ disappearance (in *L*) using 236 MeV KDAR ν_μ CC events



@ J-PARC MLF

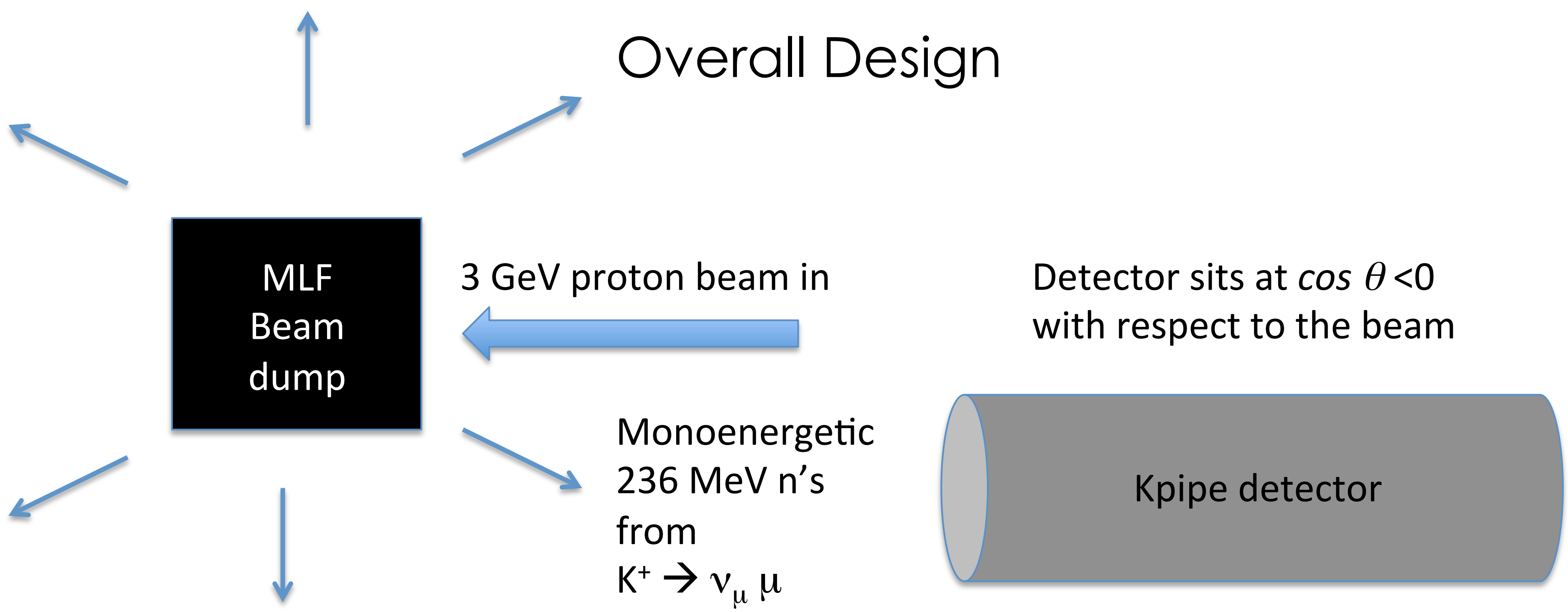


Long LS detector surrounded by SiPMs

KPIPE

Axani, Collin, Conrad, Shaevitz, Spitz, Wongjirad, Phys. Rev. D 92 092010 (2015)

Overall Design

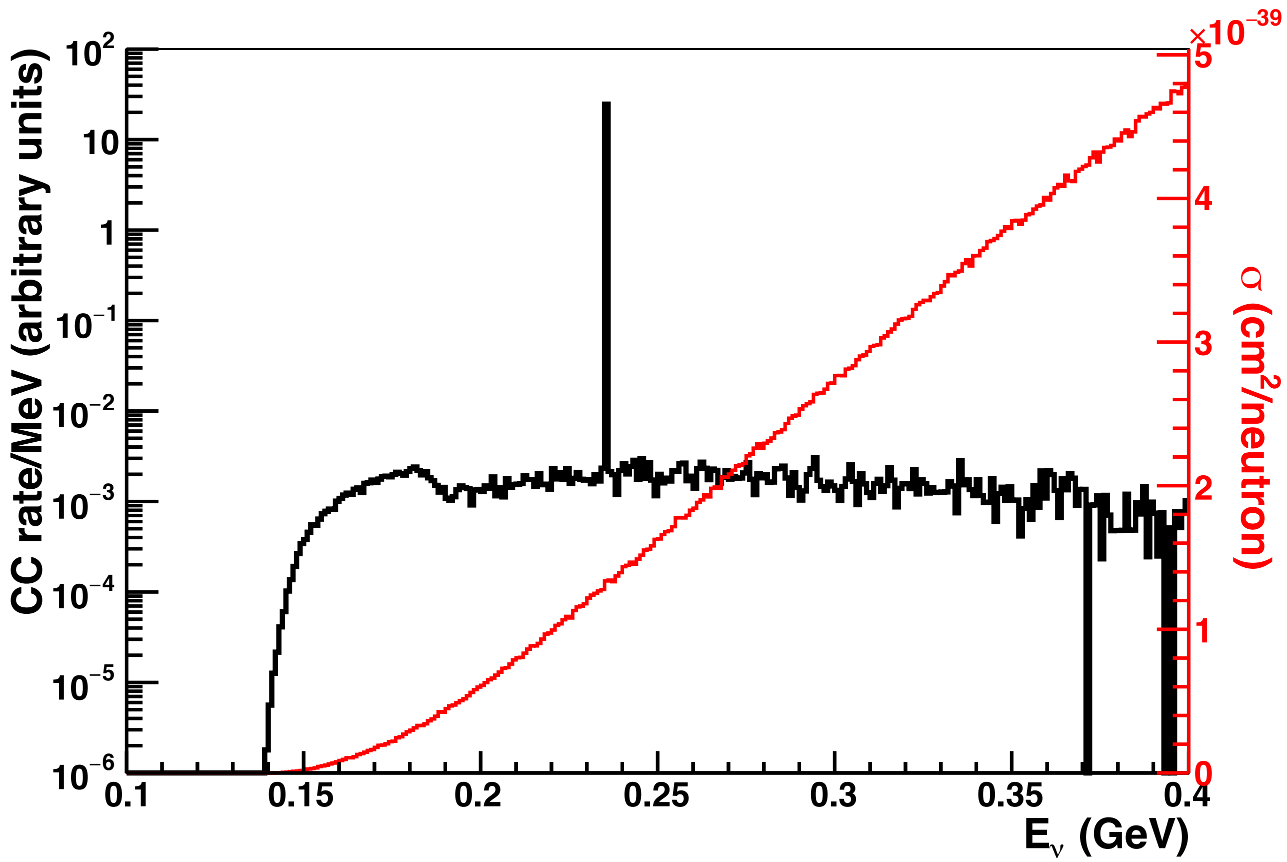


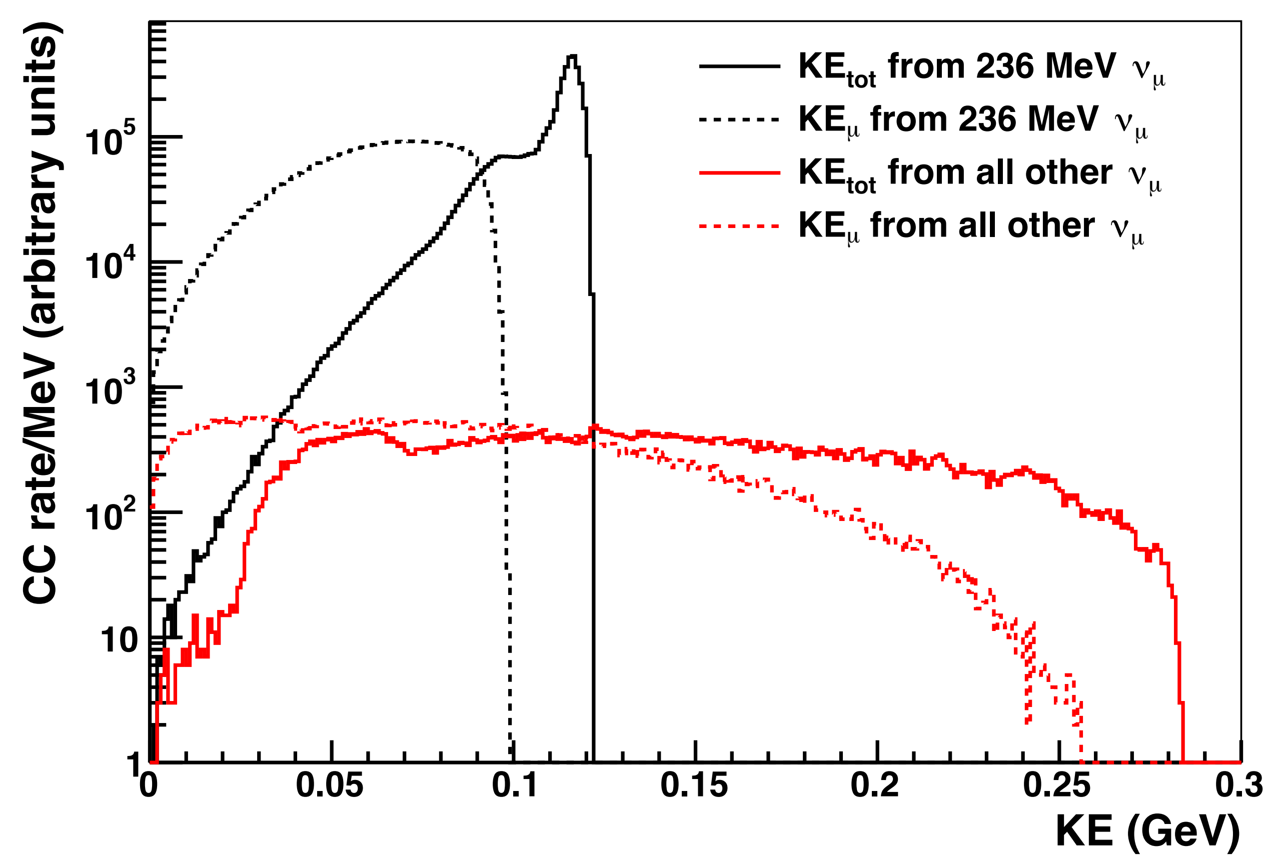
(1) pure, mono-energetic flux of muon neutrinos

(2) long detector to measure the oscillation wave

The beauty of KPIPE

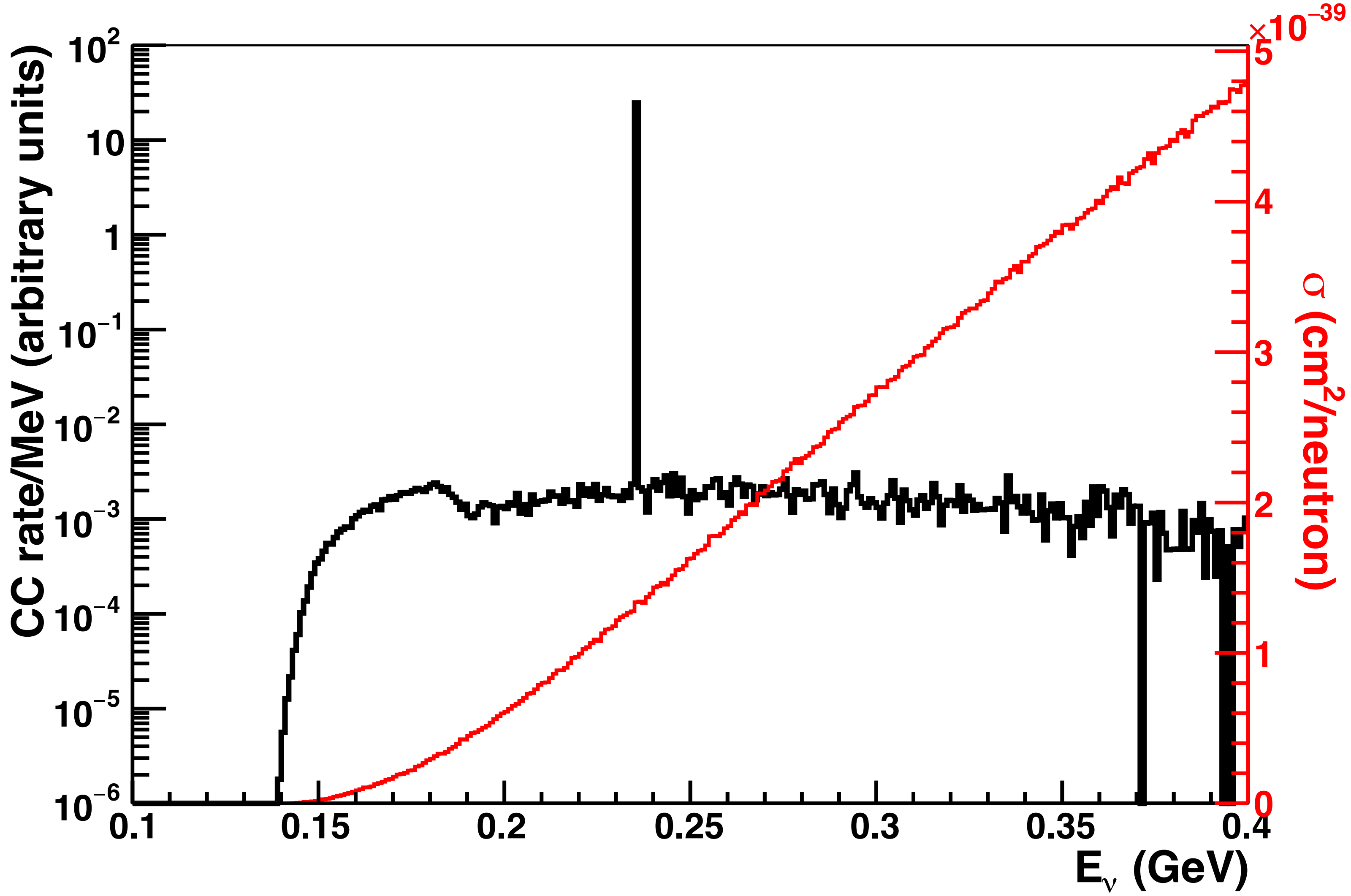
If you detect a numu CC event, you can be 98.5% sure that it was a 236 MeV muon neutrino!





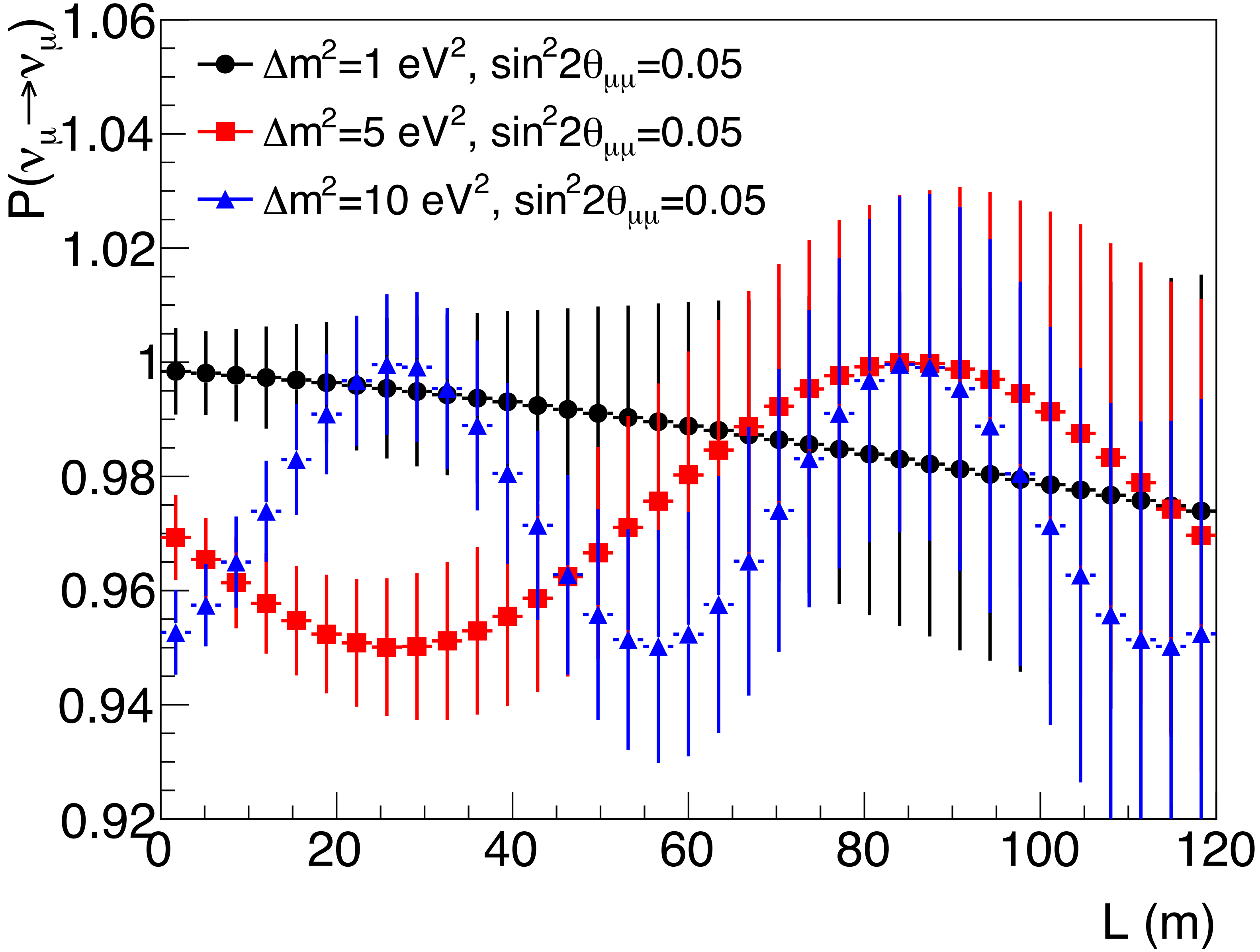
The beauty of KPIPE

Since you know the energy of the neutrino, you don't need to worry about energy resolution. KPIPE calls for 0.4% photocoverage.
Estimated cost of experiment: \$4.5M



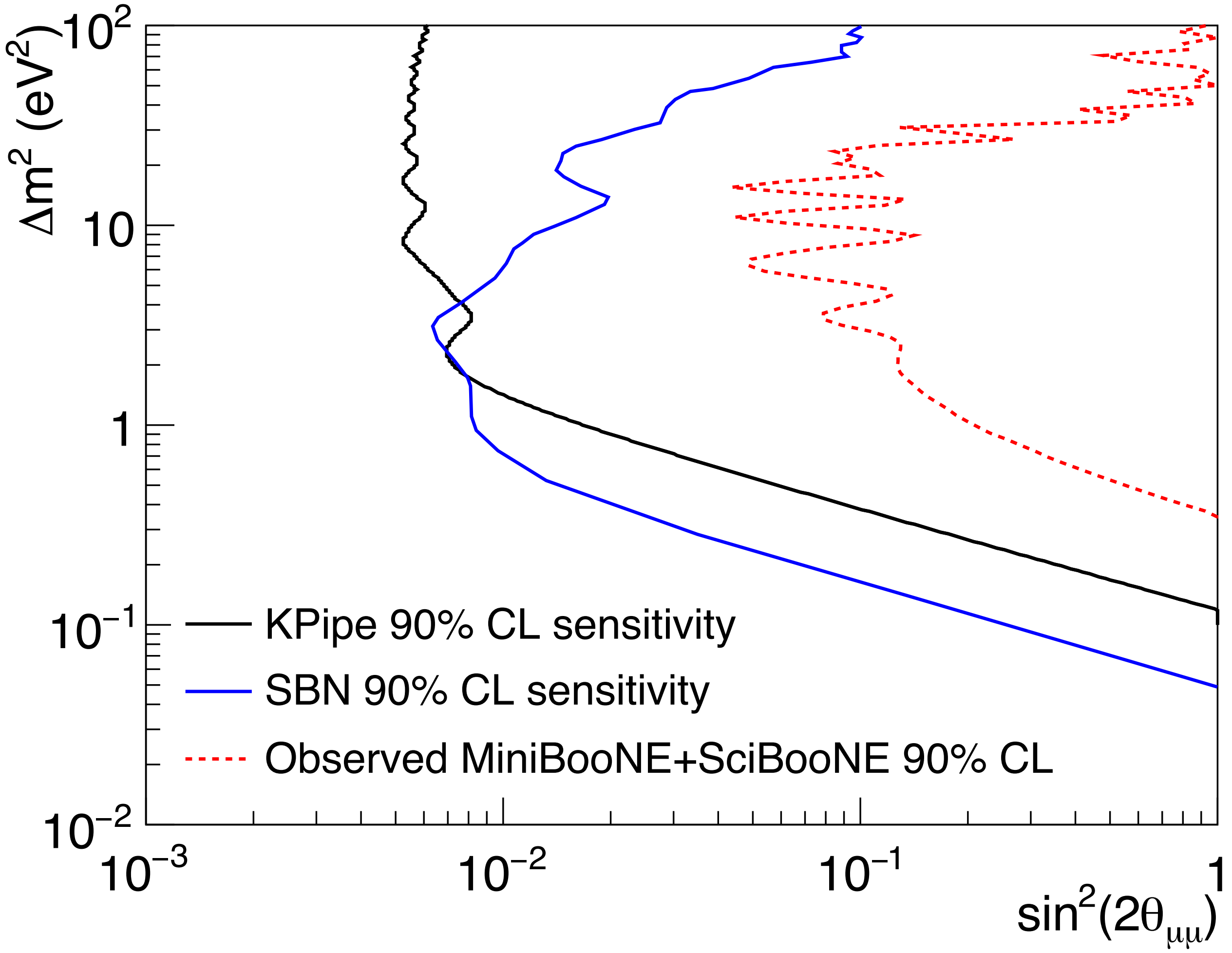
KPIPE cost document: http://hdl.handle.net/1721.1/98388

KPIPE; what would a signal look like?



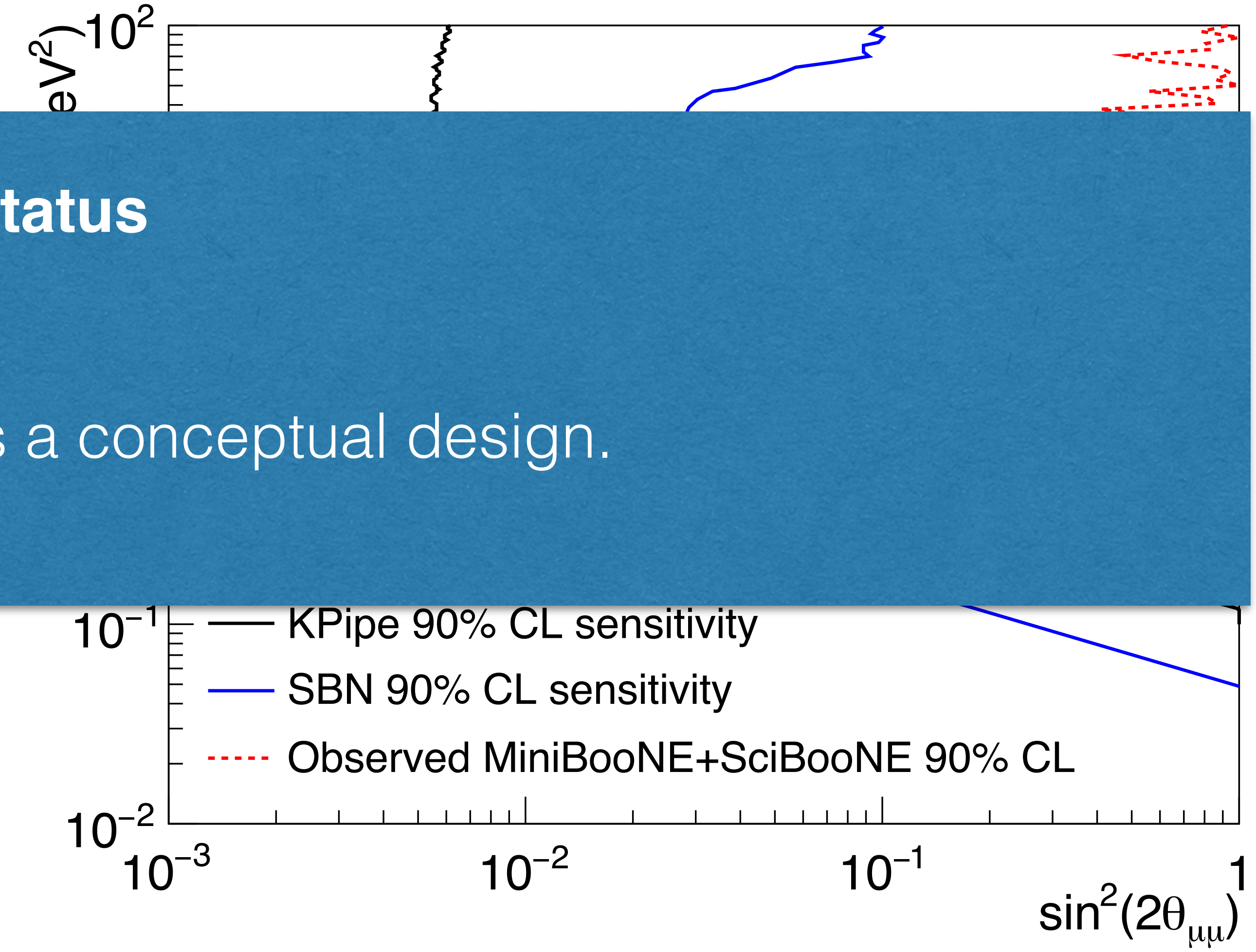
KPIPE sensitivity

- 6 years of running
- Extends limit at high-Δm^2 by an order of magnitude.
- Highly complementary to SBN program.
    - 6 years of MicroBooNE
    - 3 years of T600 and SBND.



KPIPE sensitivity

- 6 years of running



KPIPE status

KPIPE is working towards a conceptual design.

SBN program:

- 6 years of MicroBooNE
- 3 years of T600 and SBND.

	JSNS^2	SBN	IsoDAR	KPIPE	NuPRISM
Detector technology	Liquid scintillator	3 LArTPCs	Liquid scintillator (KamLAND)	Liquid scintillator	Water
Neutrino source	pi/mu/K-DAR	pi-DIF	^{8}Li DAR	K-DAR	pi-DIF
Primary osc. channel	$\overline{\nu}_\mu \to \overline{\nu}_e$	$\nu_\mu \to \nu_e$	$\overline{\nu}_e \to \overline{\nu}_e$	$\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_e$
Energy and baseline	0-53 MeV; 24 m	~700 MeV; 110, 470, 600 m	0-16 MeV; 16 m	236 MeV; 32-152 m	500-1500 MeV; ~1-2 km
Fiducial mass	17 tons in Phase 0	112, 87, 476 tons	KamLAND 897 tons	684 tons	~1000 tons
Additional physics	supernova nu KDAR	xsec, R&D	weak mixing angle	xsec	flux/xsec determination is primary goal
First data	late-2018	2019,2015, 2018	~2021	?	?

Conclusions

- **The discovery of a light sterile neutrino would be a monumental result for particle physics and cosmology.**

- The light sterile neutrino issue needs to be resolved.
- A truly definitive resolution is difficult to achieve and will likely require multiple detectors/experiments.
- We can look forward to multiple experimental searches for a new neutrino in the next ~5 years!

Backup

LSND and JSNS^2 comparison

	LSND	JSNS^2	Advantage of JSNS^2?
Detector mass	167 ton (liquid scintillator)	17 ton in Phase-0 (liquid scintillator)	-
Baseline	30 m	24 m	-
Beam kinetic energy	0.8 GeV	3 GeV	Higher energy enables KDAR measurements
Beam power	0.056 MW	1.0 MW (eventually)	Higher
Beam pulse	600 μs, 120Hz	80 ns (x2), 25 Hz	A factor of 300 less steady state background for IBD
Capture nucleus	H (2.2 MeV)	Gd (~8 MeV)	Higher S:N and a factor of 6 shorter neutron capture time

Theoretical annoyance

- Where do sterile neutrinos come in?
    - Warm dark matter, probe of hidden sector, impacts supernova explosion, may aid in synthesis of heavy elements and explaining pulsar kicks, cosmology. They certainly affect oscillation measurements in the 3 neutrino picture.
- Why are they light? You expect them to be heavy.
    - The need to describe oscillations of the 3 active neutrinos means that at least 3 eigenvalues in the 6x6 mass matrix have to be less that 1 eV. But, there can be 0-3 eigenvalues corresponding to light sterile neutrinos.
- Can we say anything about their properties?
    - We can measure their mass and mixing parameters with the active neutrinos.
- Steriles may be part of a hidden sector. Is there evidence for a hidden sector?
    - A hidden sector is a collection of unobserved fields and their associated particles that does not interact with the SM. The sector may be relevant for dark matter and supersymmetry. We don't know what it is…but we're looking!

Global, non-reactor nuebar searches from Kopp paper

Experiment	Ref.	# Data	Comments	New?
Solar neutrino experiments				
Chlorine	[49]	1	rate	–
GALLEX/GNO	[50]	2	rates	–
SAGE	[51]	1	rate	–
Super-K phases 1–3	[52–54]	119	energy and zenith spectra	–
Super-K phase 4	[55]	46	energy and day/night spectrum	✓
SNO phases I–III	[56–58]	75	energy and day/night spectra	–
Borexino phase I	[59, 60]	39	low-energy and high-energy spectra	–
Borexino phase II	[61]	42	low-energy spectrum	✓
Radioactive source experiments (gallium)				
GALLEX	[50, 62]	2		–
SAGE	[63, 64]	2		–
ν_e **scattering on C-12** ($\nu_e + {}^{12}\mathrm{C} \to \mathbf{e}^- + {}^{12}\mathrm{N}$)				
KARMEN	[65–67]	26		–
LSND	[67, 68]	6		–

Table 4: Experimental data which we combine with the reactor data from table 2 in our global $\nu_e/\bar{\nu}_e$ disappearance analysis. In the last column we indicate updates with respect to ref. [16]. The total number of data points of non-reactor data is 361.

Global, reactor searches from Kopp paper

Experiment	Ref.	# Data	Comments	New?
Bugey-4	[37]	1	rate	–
ILL	[38]	1	rate	–
Gösgen	[39]	3	rates	–
Krasnoyarsk	[34, 40, 41]	4	rates	–
Rovno88	[42]	4	rates	–
Rovno91	[43]	1	rate	–
SRP	[44]	2	rates	–
RENO	[35, 36]	2	rate at near detector + near-far rate ratio	–
Double Chooz	[30]	1	rate at near detector	–
Daya Bay flux	[29]	8	individual fluxes for each isotope (EH1, EH2)	✓
Bugey-3	[45]	35	spectra at 3 dist. with free bin-by-bin norm.	–
NEOS	[21, 26]	60	spectral ratio of NEOS and DayaBay	✓
DANSS	[28]	30	spectral ratio at two distances	✓
Daya Bay spect.	[46]	70	spectral ratios EH3/EH1 and EH2/EH1	✓
KamLAND	[47]	17	spectrum at very long distance	–