An overview of the physics possibilities and the planned searches for sterile neutrinos

Takasumi Maruyama (KEK)

Thank you for the useful discussions and / or slides;
Alejandro Ibarra, David Lhuillier, Barbara Caccianiga,
Joshua Spitz, Bill Louis

Sterile neutrinos

- Sterile neutrinos could give an insight for the questions beyond the standard model;

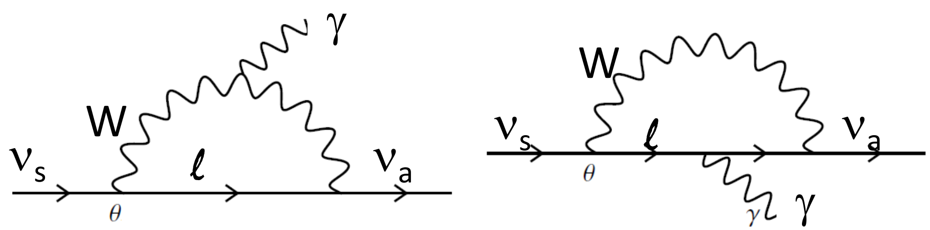
  (E.g.; PLB 631, 151 (2005))

  - No strong, electro-magnetic, weak interactions
  - Observed by only neutrino oscillations
  - Could be ν_R (even see-saw partner) or new particle
  - Beyond PMNS matrix oscillation
  - LSND, MiniBooNE, reactors, Ga experiments indicate the existence.

- Sterile neutrino can be one of the Dark Matter candidate. (see slides later)

Sterile neutrinos as Dark Matter?

- It is guaranteed;
  - Dark Matter = sensitive to gravity
- But, it is possible:
  - Dark Matter ≠ WIMP



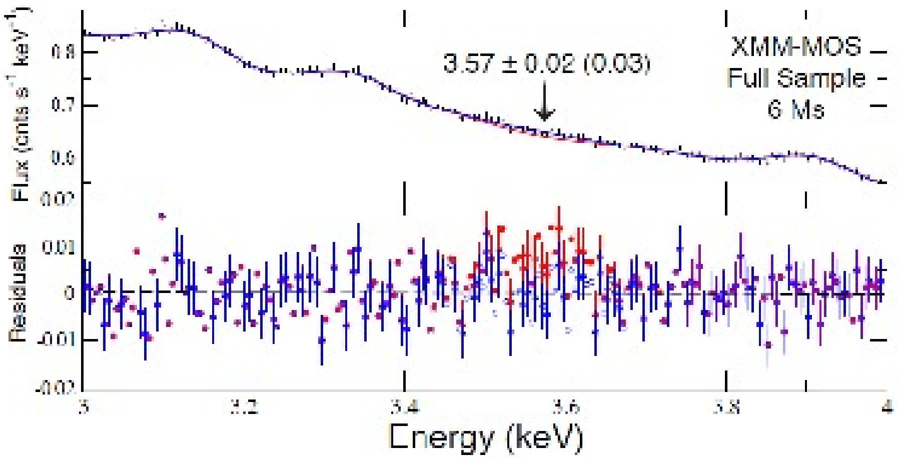
- If Dark Matter = sterile neutrino
  - Gammas from loop diagrams exist.
  - Neutrino oscillation is happened.
  - Mass of Dark Matter is not light sterile neutrino (~1 eV^2) region.
  - However, if one type sterile neutrino exists, other types could exist.

Sterile neutrinos as dark matter

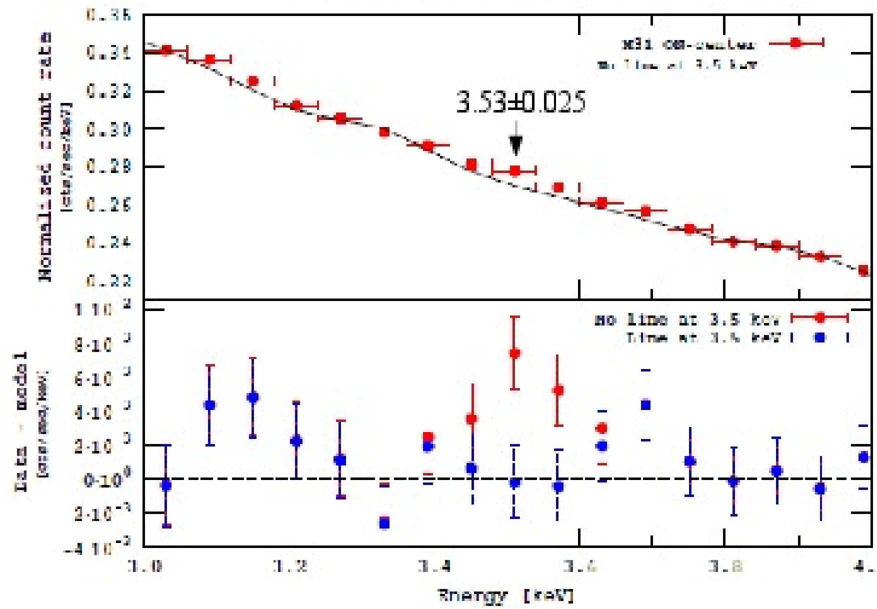
Recent hints for an unidentified X-ray line signal

Alejandro Ibarra's talk at Neutrino2014

Bulbul et al, 1402.2301



Boyarsky al, 1402.4119



- Not observed in the deep "blank sky" dataset. Probably not instrumental.
- Observed in different datasets at different redshifts.
- Atomic origin not demonstrated: candidate atomic lines expected to be much fainter.
- Originated by sterile neutrino decay?

Sterile neutrinos as dark matter

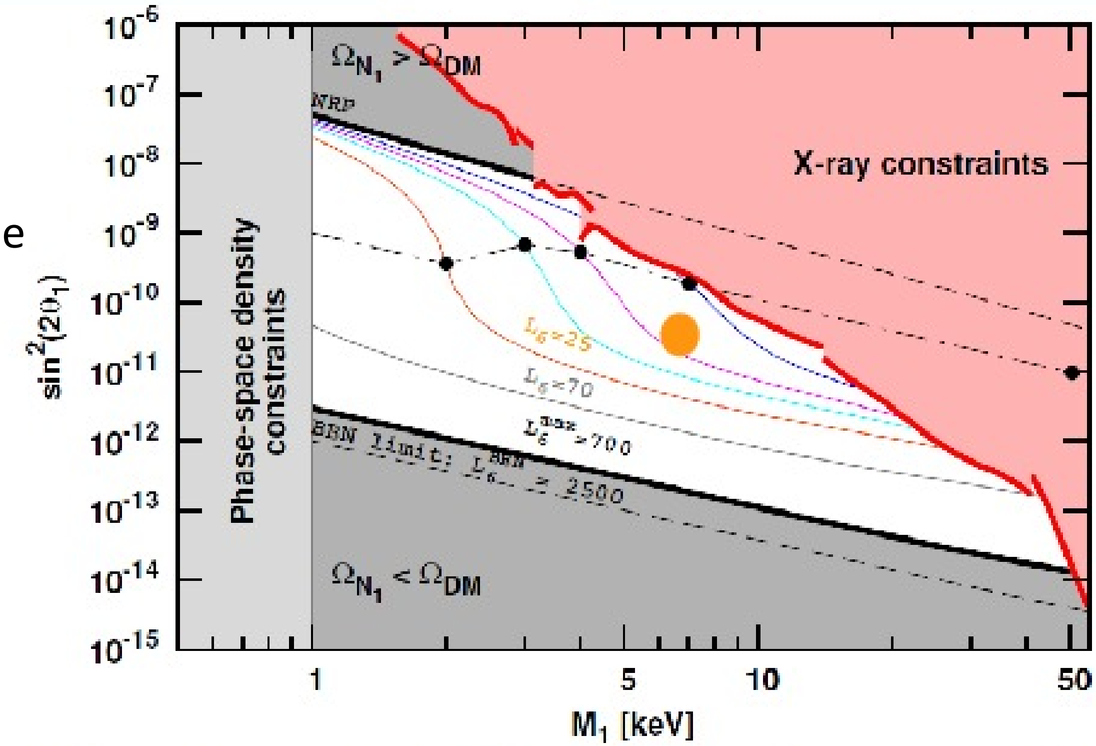
Bulbul et al, 1402.2301

$$m_{\rm DM} = 7.1\,{\rm keV}$$
$$\sin^2 2\theta \approx 7\times 10^{-11}$$

Boyarsky al, 1402.4119

$$m_{\rm DM} = 7.06 \pm 0.05\,{\rm keV}$$
$$\sin^2 2\theta = (2.2 - 20)\times 10^{-11}$$

Note;
Sterile neutrino is "warm" dark matter candidate which satisfies the cosmology well.



Alejandro Ibarra's talk at Neutrino2014

Requires $n_L/s \sim 10^{-5}$ (compared to $n_B/s \sim 10^{-10}$)

The future Astro-H mission will hopefully clarify the nature of this line.

Status of light sterile neutrino (~1eV^2) search

- Anomalies, which cannot be explained by standard neutrino oscillations for 15 years are shown;

Experiments	Neutrino source	signal	significance
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	3.4σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ
		combined	3.8σ
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ

- **Excess or deficit does really exist**?
- The new oscillation between active and inactive (sterile) neutrinos?
  - Note; $\nu_\mu \rightarrow \nu_\mu$ disappearance has no indication.

Neutrino oscillations with $\Delta m^2 \sim 1 eV^2$ region

$$
\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \bullet \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \bullet \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \bullet \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \bullet \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \bullet \end{bmatrix}
$$

Matrix elements, which are considered in 3x3 mixing framework.

$$\sum_{j=1,3} U^*_{ej} U_{\mu j} = -U^*_{e4} U_{\mu 4}$$

Small mixiture with active ν's $U_{e4}, U_{\mu 4} \sim 0.1$ $U_{s4} \sim 1$ $m_4 \sim 1\,eV >> m_{1,2,3}$

$$P_{e\mu} = -4 \sum_{i=1,3} (U^*_{e4} U_{\mu 4} U_{ei} U^*_{\mu i}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 \boxed{|U_{e4}|^2 |U_{\mu 4}|^2} \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

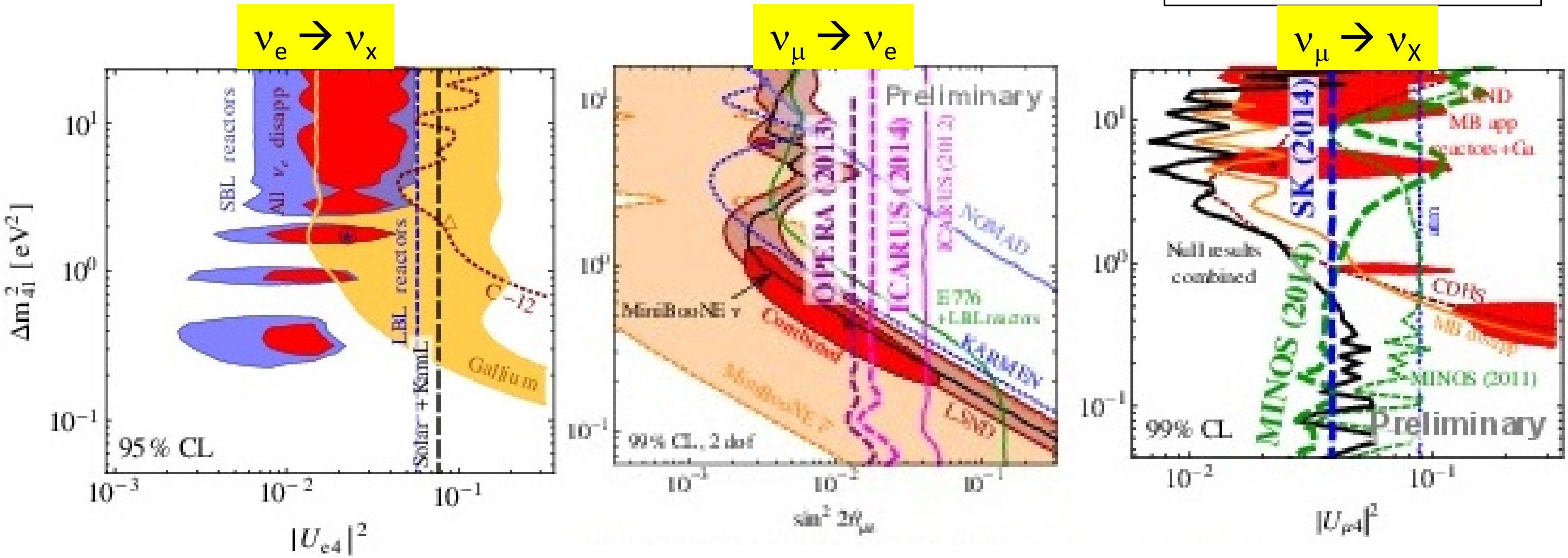
$$P_{es} = -4 \sum_{i=1,3} (U^*_{e4} U_{s4} U_{ei} U^*_{si}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 |U_{e4}|^2 \boxed{|U_{s4}|^2} \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\Theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

(3+1) model

Status as of 2014

J. Kopp's
talk at Neutrino2014



- ICARUS / OPERA experiments have new results in 2014 for appearance channel.
- SK / MINOS have new results in ν_μ disappearance channel.
- Daya-Bay has latest results on ν_e disappearance in this summer

Discrepancy between ν_μ and others?

- Due to issue on theoretical model (3+1) ?
- **Confirming or refuting the anomalies with various E/L is first thing to do for experimentalists.**

Recent status

- Sterile neutrino is **one of the most interesting topics** in neutrino field.
  - A quarter of the presentations in Neutrino 2014 conference mentioned the sterile neutrino.
  - P5 (Particle Panel) endorsed the short baseline neutrino experiments to search for sterile neutrinos.

Presentation and Discussion of P5 Report by S.Ritz (on 22-May-2014)

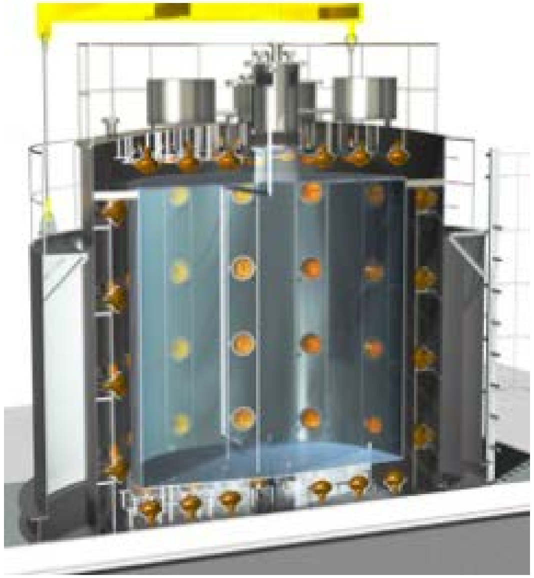
- **Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm.**

New (exciting) experiments

Picking up typical experiments.
Not covering all (sorry!)

Liquid scintillator detector

Many experiments for sterile neutrino search use liquid scintillator.
→ Explaining the detection principle at first

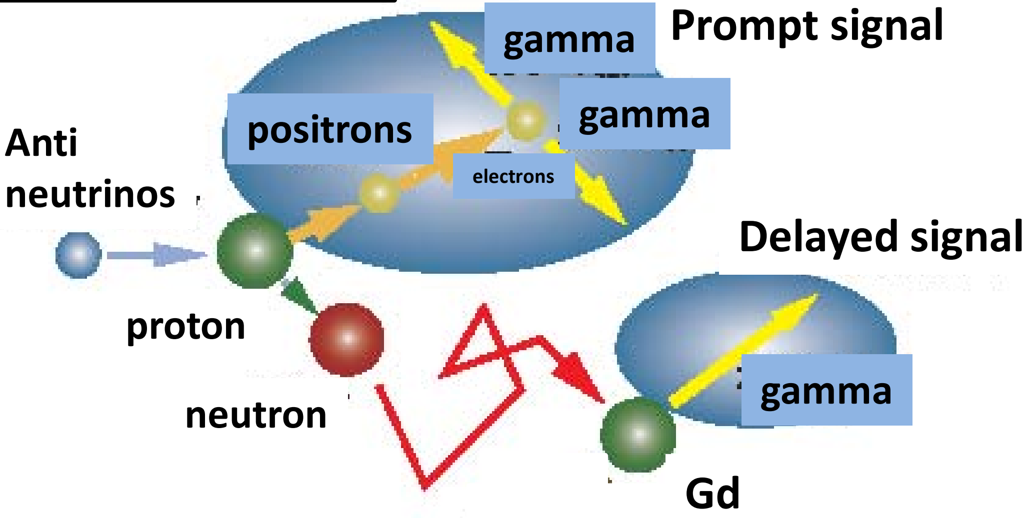


Identify neutrinos with detecting e+ and gammas from n capture on Gd (H).
=>Can reduce accidental BKG (Gd~8MeV γs, capture time ~ several tens μs; Gd case).

Inverse Beta Decay (coincidence)

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

Prompt E_{vis}+0.8MeV ~ Eν ;
- < a few MeV (for beta source)
- 2~ 3MeV (for reactor)
- ~ 40MeV (for muon DAR)



Detection Principle

Severest BKG is fast neutrons from cosmic ray or reactor or acc. Beam.
→ Creating prompt + delayed correlated BKG.

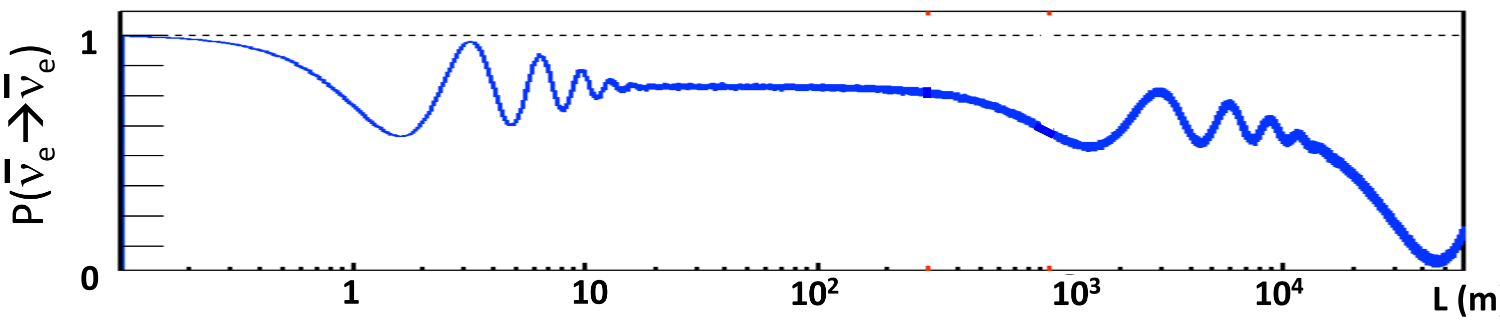
$\overline{\nu}_e \rightarrow \overline{\nu}_e$ disappearance

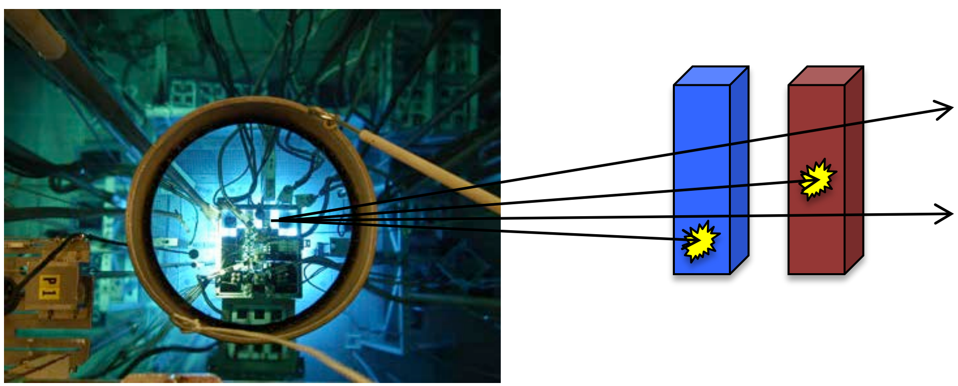
Many talks will be presented later, so I just show the prospects briefly.

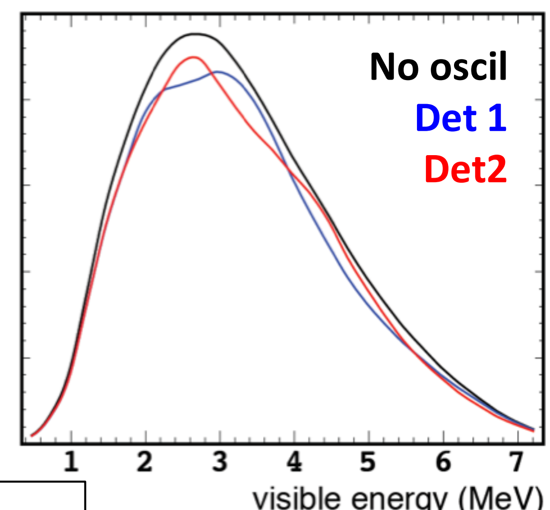
Testing the New Oscillation Hypothesis

Direct test of a new oscillation pattern in E & L

$\Delta m^2 > 0.1$, $\sin^2 2\theta > 0.05$ → L_{osc} = [1-10] m







- **Relative shape distortion in identical detector modules**
- **Complemented by rate info.**

David Lhuillier's talk at Neutrino2014

Candidate detectors

Picking up typical experiments.
Not covering all (sorry!)

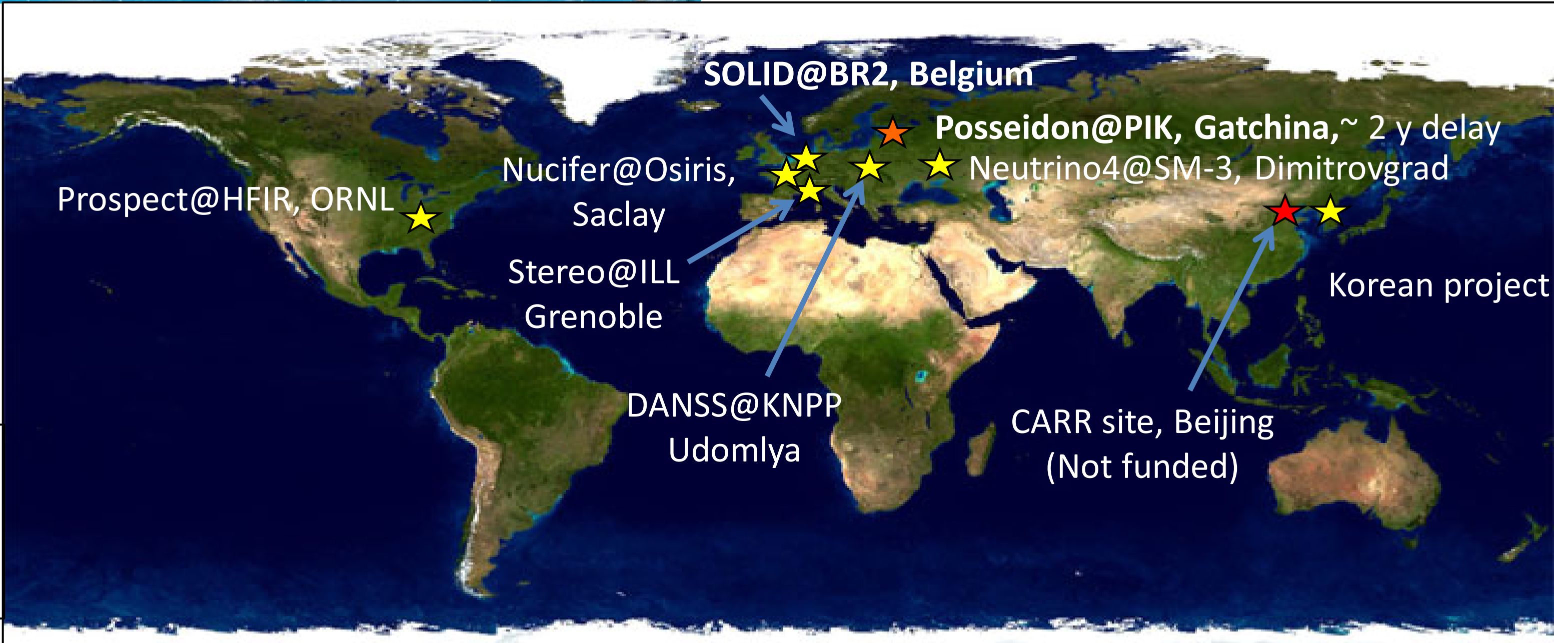
Requirements
- Underground location;
- Large mass, ultra-pure detectors;
- Capability to measure E and L (oscillometry);

Existing large liquid scintillator experiments (Borexino, KamLAND, Daya-Bay)
Future large liquid scintillator experiments (SNO+, LENS, JUNO)
Future experiments based on other techniques (RICOCHET, BEST)

Experiments with radioactive sources

Barbara Caccianiga's talk at Neutrino 2014

Many interesting and exciting results are coming in near future. (2015~)
Many talks will be also coming



Experiments with reactors

David Lhuillier's talk at Neutrino2014

Several papers and ideas

Setup

Technique	Detector	Sources	Reaction	Activity	Reference
Large Liquid scintillator detectors	SOX (Borexino) Will be started 2015	^{51}Cr,	ν+e → ν+e	10MCi	*JHEP08(2013)038,*
		^{144}Ce-^{144}Pr	ν+p → e^{+}+n	100kCi	*Phys. Rev. Lett. 107, 201801 (2011)*
	KamLAND	^{8}Li (ISODAR)	$\bar{\nu}$+p → e^{+}+n	8.2 x 10 ^{14} ν/sec	*arXiV:1205.4419, arXiV:1310.3857*
		^{144}Ce(CeLAND)	$\bar{\nu}$+p → e^{+}+n	100kCi	arXiv:1312.0896
	Daya-Bay	^{144}Ce-^{144}Pr	$\bar{\nu}$+p → e^{+}+n	500kCi	*arXiV:1109.6036*
	LENS	^{51}Cr	ν+^{115}In → ^{115}Sn*+e	10MCi	*Phys.Rev.D75 093006(2007)*
	JUNO	^{8}Li (ISODAR)	$\bar{\nu}$+p → e^{+}+n	8.2 x 10 ^{14} ν/sec	*arXiV:1310.3857*
Radiochemical	BEST	^{51}Cr	ν+^{70}Ga → ^{71}Ge+e	3MCi	arXiV:1204.5379
Bolometers	Richochet	^{37}Ar	ν+N → ν+N	5MCi	Phys. Rev. D85, 013009, (2012)

Barbara Caccianiga's talk at Neutrino 2014

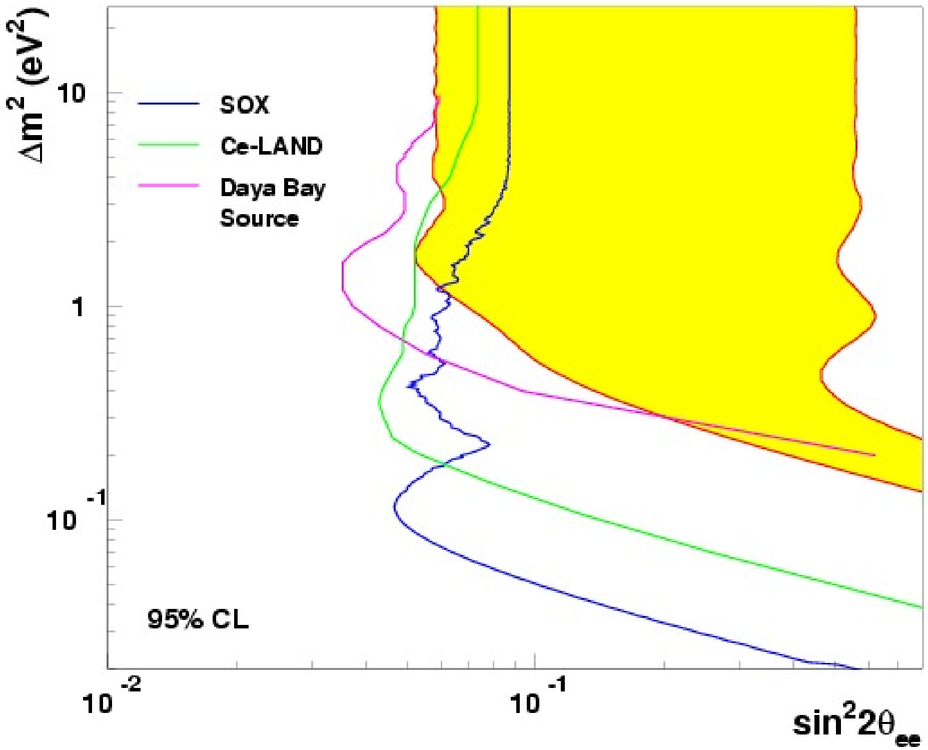
- Need **~MCi** level radio active source
  ^{51}Cr, ^{144}Ce-^{144}Pr, ^{8}Li(+p) are considered.
  Typically Eν < a few MeV
- Need to transport the source to detector

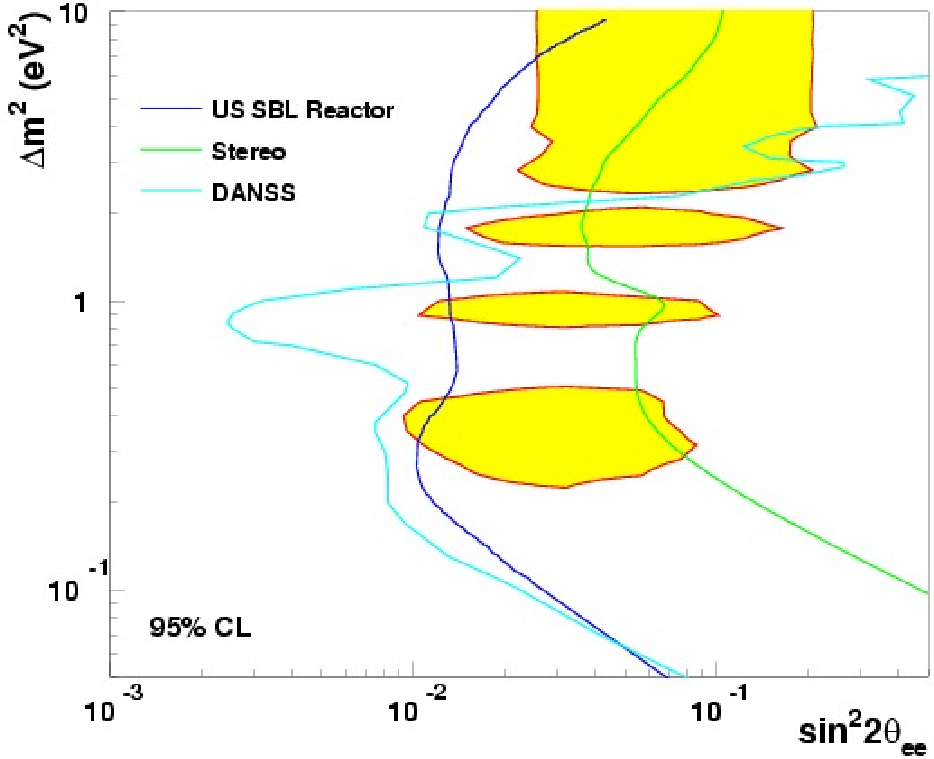
		P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)
On-going	Nucifer (FRA)	70	0.8	7	13
	Poseidon (RU)	100	~ 3	5-8	~ 15
Start in 2015	Stéréo (FRA)	57	1.75	8.8-11.2	18
Start in 2015	Neutrino 4 (RU)	100	1.5	6-12	~ 10
Start in 2015	Hanaro (KO)	30-2800	~ 1	6	few
Final detector In 2015	DANSS (RU)	3000	0.9	9.7-12.2	50
White paper was submitted	Prospect (USA)	85	1 & 10	7-18	few
Aim to operate In 2015	NuLat (USA)	20-1500	~ 1	2.5-8	2-10
Start in 2016	SoLid (UK)	45-80	2.9	6-8	10

- Need PID to reject fast neutrons from reactors. PSD (Pulse Shape Discrimination) helps.
- Need sufficient shield.
- Need to see "Oscillation pattern"

Updated table from David Lhuillier's talk at Neutrino 2014

Sensitivities (arXiv; 1310.4340)





They can achieve the sensitivity with short time scales.
(typically < a few years for 95% C.L.)

$\nu_\mu \rightarrow \nu_e$ appearance

Accelerator based neutrino experiments.

$\nu_\mu \rightarrow \nu_e$ appearance

- LSND / MiniBooNE have significant excess -> to be checked
  - μ Decay-At-Rest source ; J-PARC P56 @MLF (proposed) and OscSNS (white paper was submitted)
    - Better pulsed beam than LSND ($\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$; $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
    - Better liquid scinti. detector than KARMEN / LSND (PID / Gd loaded)
  - LAr + conventional horn focused beam; MicroBooNE, ICARUS,LAr1-ND -> triple LAr@FNAL ($\pi^+ \rightarrow \mu^+ + \nu_\mu$; $\nu_\mu \rightarrow \nu_e$ / reversed horn polarity)
    - Better detector (BKG rejection, e ID, ν energy reconstruction) than MiniBooNE $\rightarrow$ reduced #BKG and systematics on BKG
  - New type of beam + Fe+scintillator detector; nuSTORM
    - Using neutrinos from STORed Muons. ($\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$) ; P5 comments
    - Good sensitivity with golden channel; $\nu_e \rightarrow \nu_\mu$
  - ISODAR ; interesting idea to use Li target for proton.

Conventional beam + LAr

- Clear electron, π^0 and single γ PID can be performed.
- ICARUS + MicroBooNE + LAr1-ND → triple LAr@FNAL now.

ICARUS arXiv:1307.4699 [hep-ex].

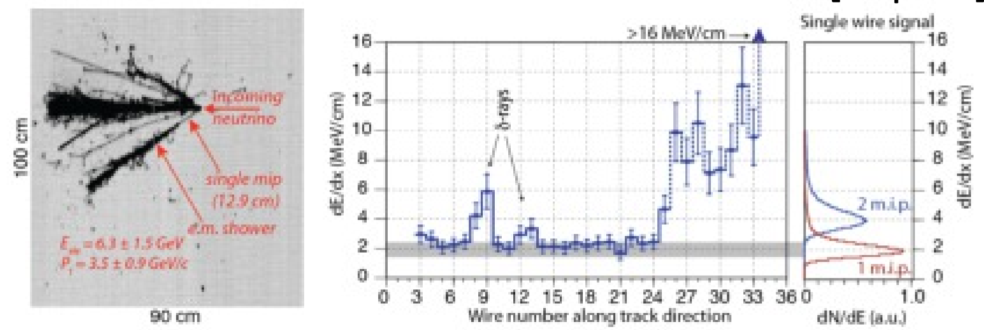
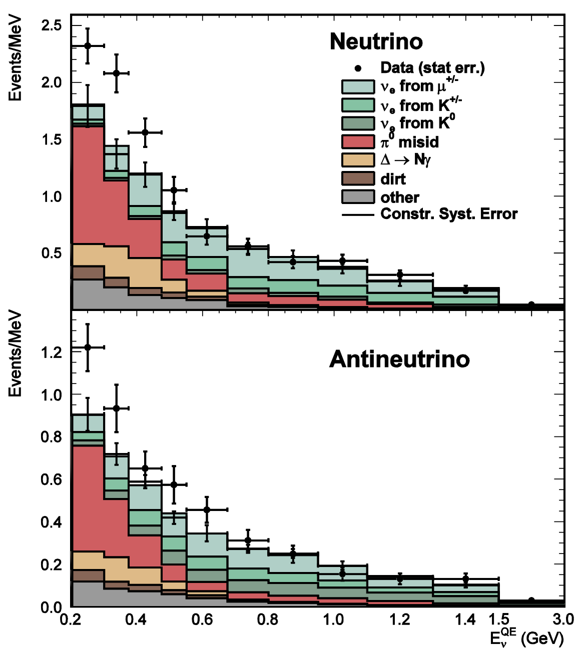


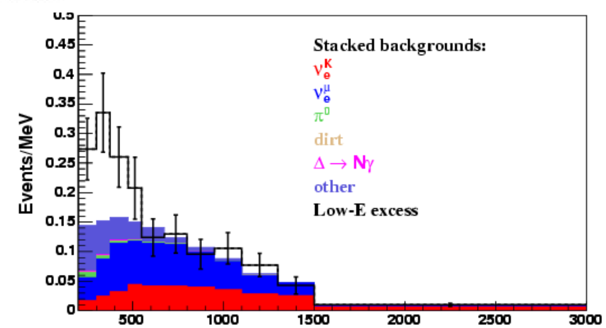
Figure 1. Experimental pictures of the first of the two events with a clear electron signature found in the additional sample of 904 neutrino interactions. The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is shown along the individual wires. The event has a total energy of ~27 GeV and an electron of 6.3 ± 1.5 GeV with a transverse momentum of 3.5 ± 0.9 GeV/c.

MiniBooNE Excess

PRL 110.161801,2013.

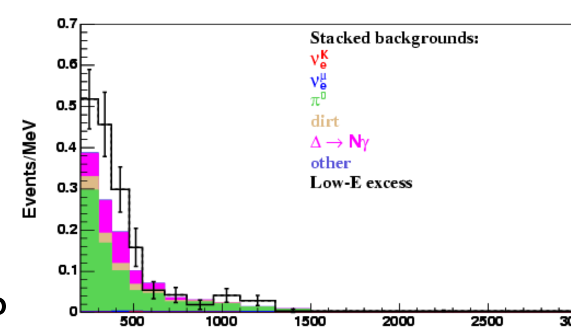


Electron excess (oscillation)?

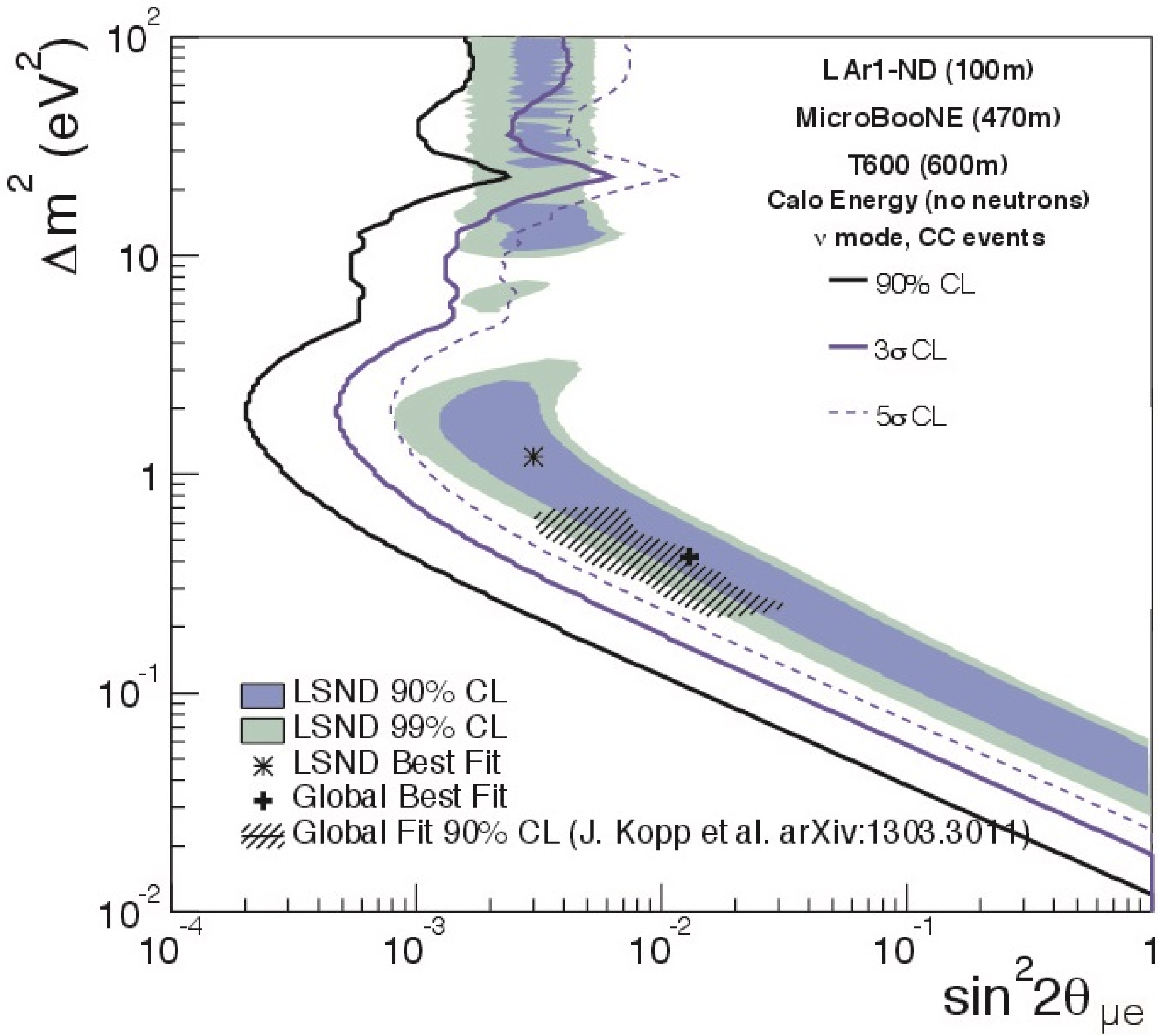


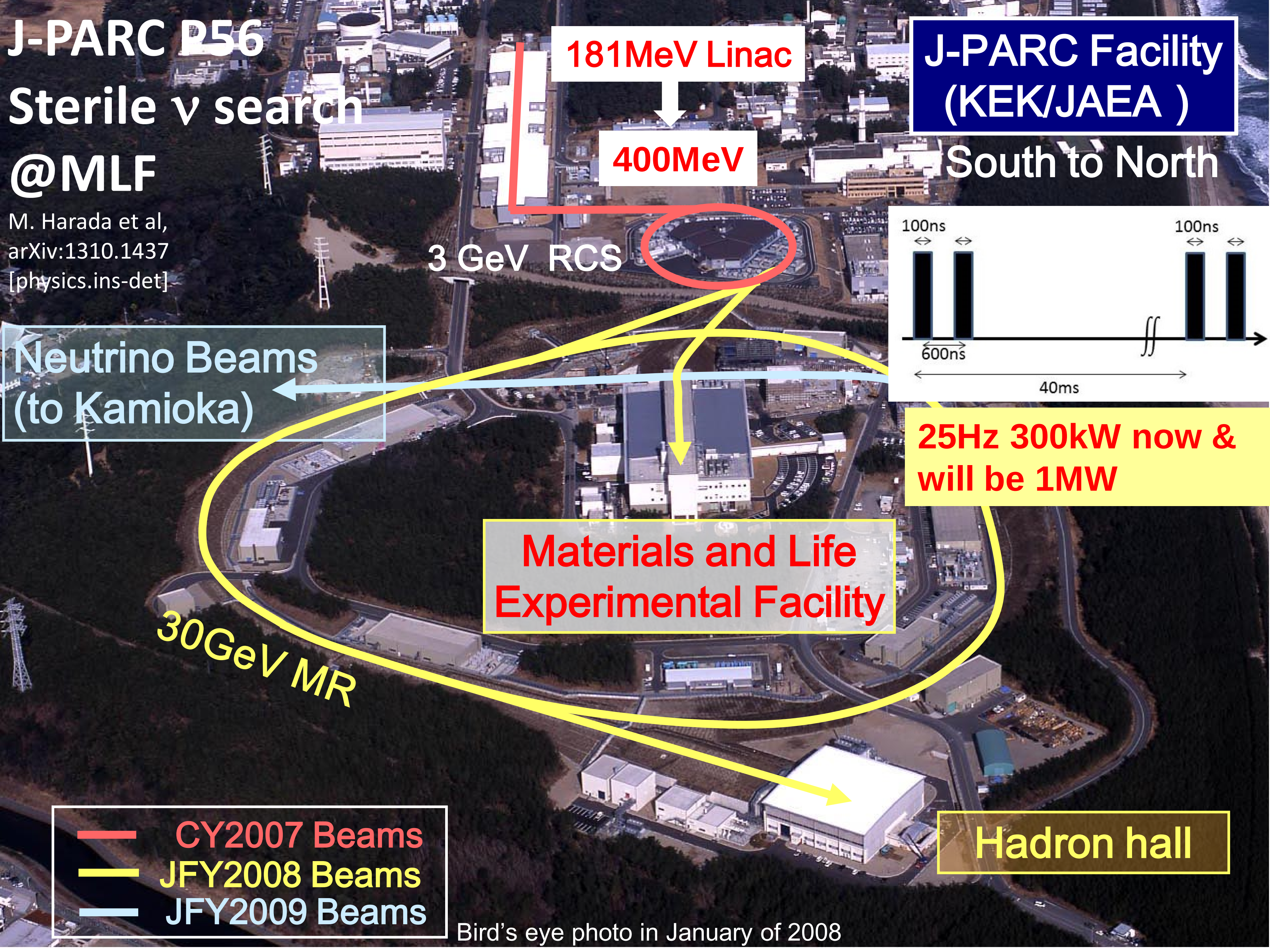
MicroBooNE

or γ excess (uncertainty of ν cross section)?



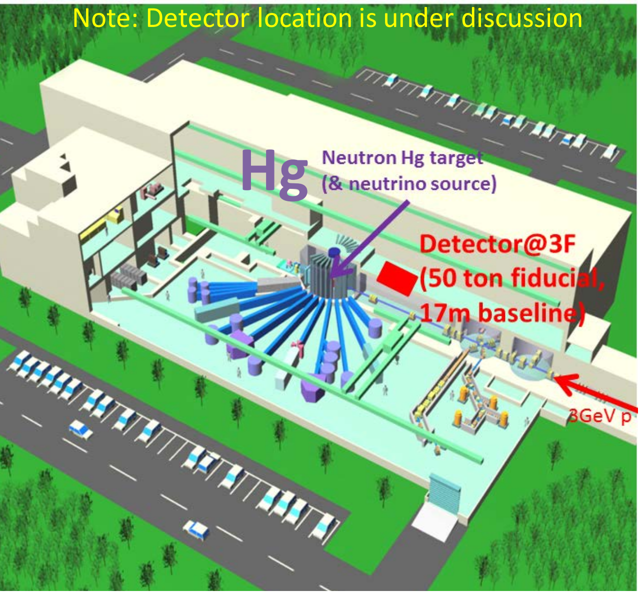
Triple LAr @ FNAL sensitivity



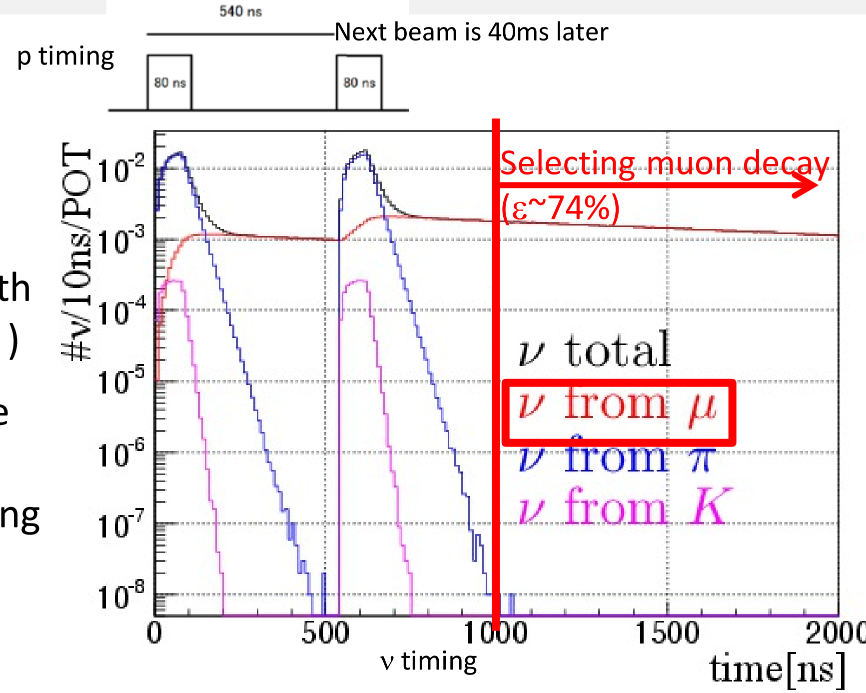

J-PARC P56
Sterile ν search
@MLF
M. Harada et al,
arXiv:1310.1437
[physics.ins-det]
181MeV Linac
400MeV
J-PARC Facility
(KEK/JAEA)
South to North
3 GeV RCS
100ns
100ns
600ns
40ms
Neutrino Beams
(to Kamioka)
25Hz 300kW now &
will be 1MW
Materials and Life
Experimental Facility
30GeV MR
Hadron hall
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

Sterile neutrino search @MLF (proposal in 2013)

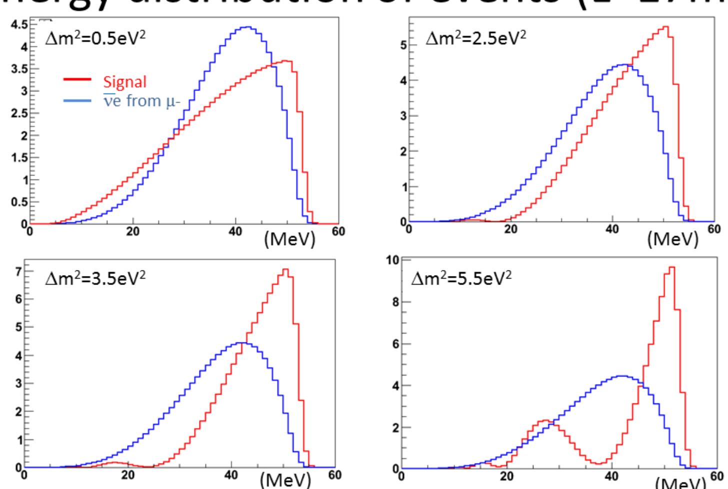
M. Harada *et al*, arXiv:1310.1437 [physics.ins-det]



- J-PARC P56 aims to confirm or refute the neutrino oscillation with sterile neutrino($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- With gating the time we can use ultra-pure neutrinos from stopping μ^+ (top-right)
- Energy distortion → sig vs BKG separation (bottom-left)



Energy distribution of events (L=17m)

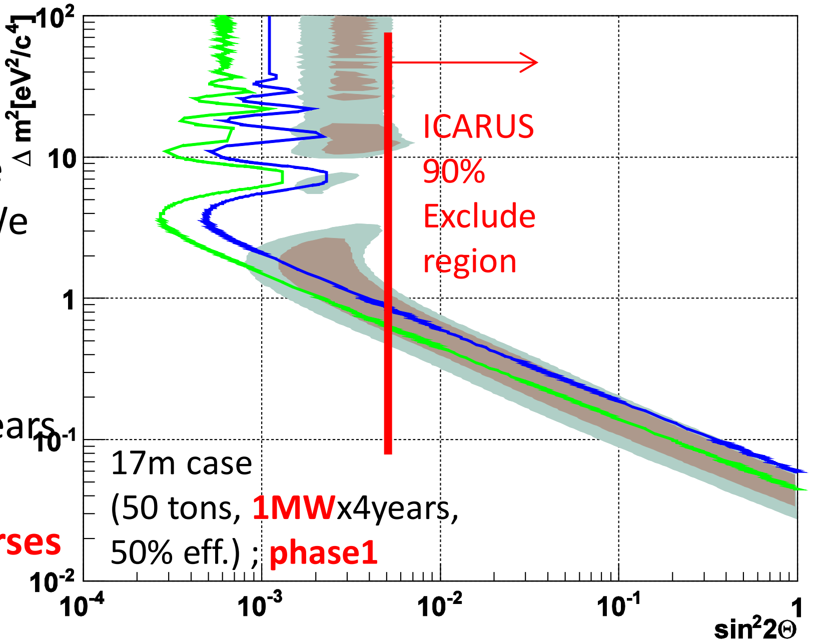


$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \boxed{\Delta m^2} \cdot L}{E_\nu}\right)$$

- Energy is smeared by 15%/sqrt(E) (detector E resolution)

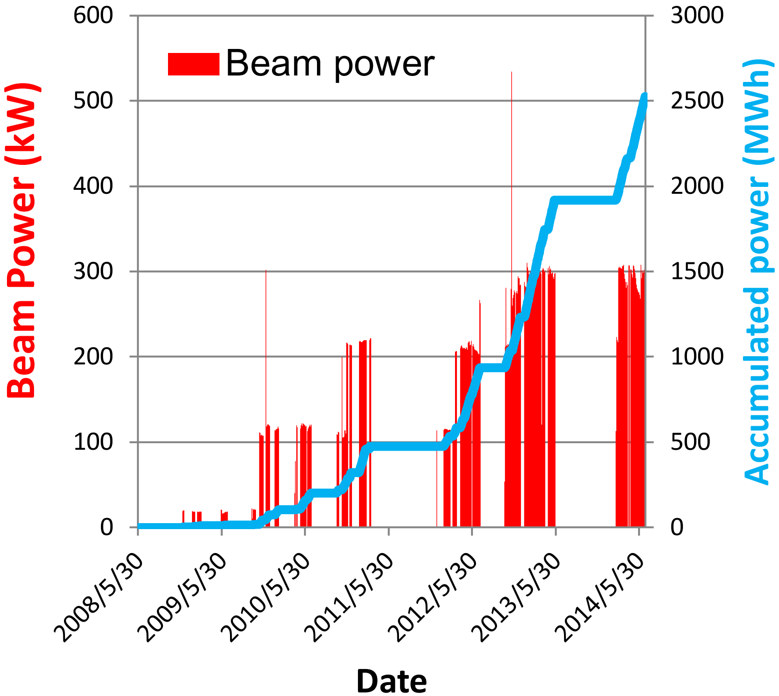
- Sensitivity of P56 (right); blue 5σ, green 3σ. We conclude LSND region (brown (90%CL) & green (99%) within 4 years

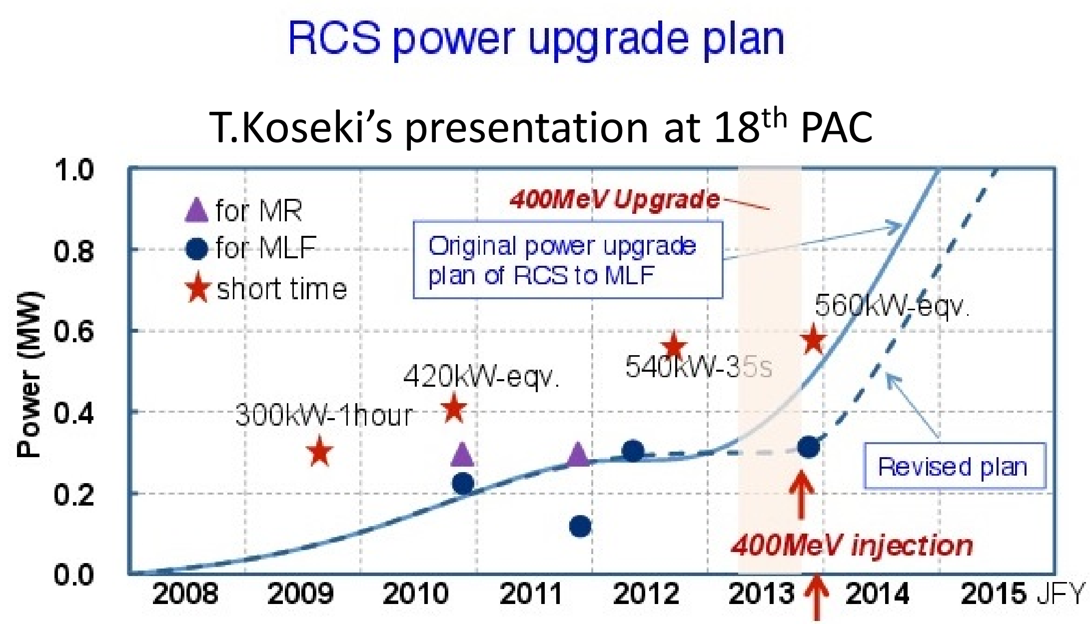
J-PARC PAC endorses scientific merit



Prospects; RCS/MLF beam

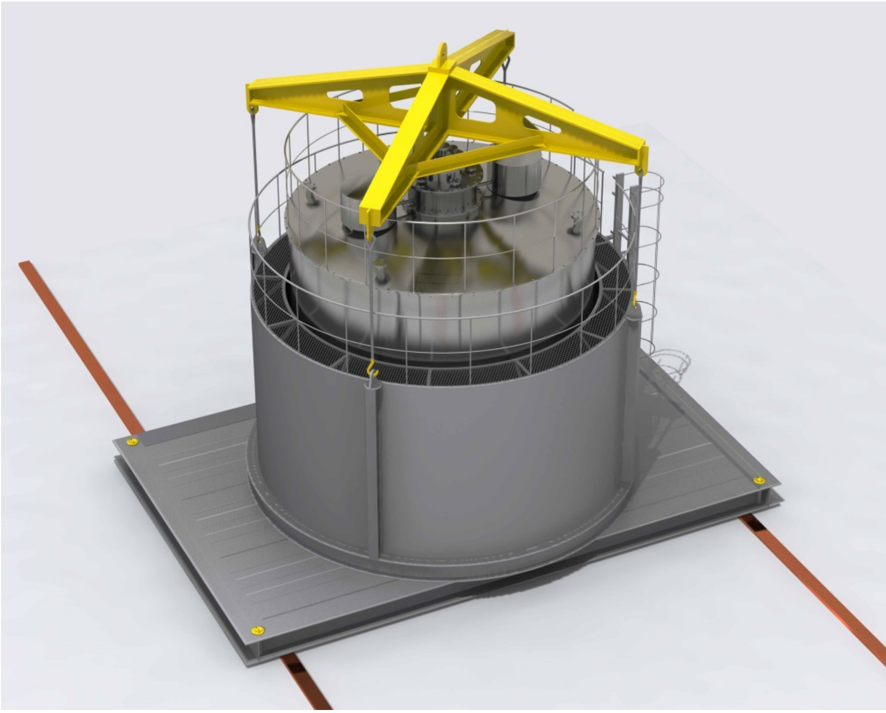
- Linac upgrade (181→400MeV) was done by 2014 Jan successfully.
- Stable beam (300kW) is delivered from Feb-2014 to July-2014. Note this is the first beam after the J-PARC hadron hall accident.
- In 2013, 600kW test was performed successfully (bottom-left). Within 2014 JFY, facility people will try to deliver the stable 600kW beam to MLF.
- Beam power will be increased steadily. On Oct-2014, test will be performed for 1MW beam.





Detector

- Design of the tank is discussed. Strength of tank / endurance for earthquakes are calculated.
- Well established type detector.
- There are Double Chooz / Daya-Bay collaborators in J-PARC P56.

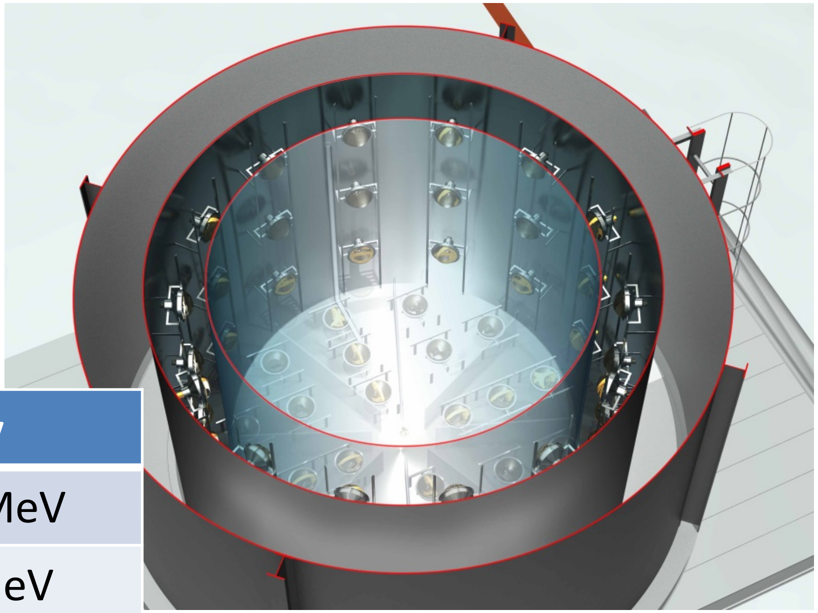


- MLF 3rd floor is the maintenance area for the beam and target related equipment.

→ There is more than one maintenance work(s) / year. Therefore, we have to carry detectors to outside of MLF.

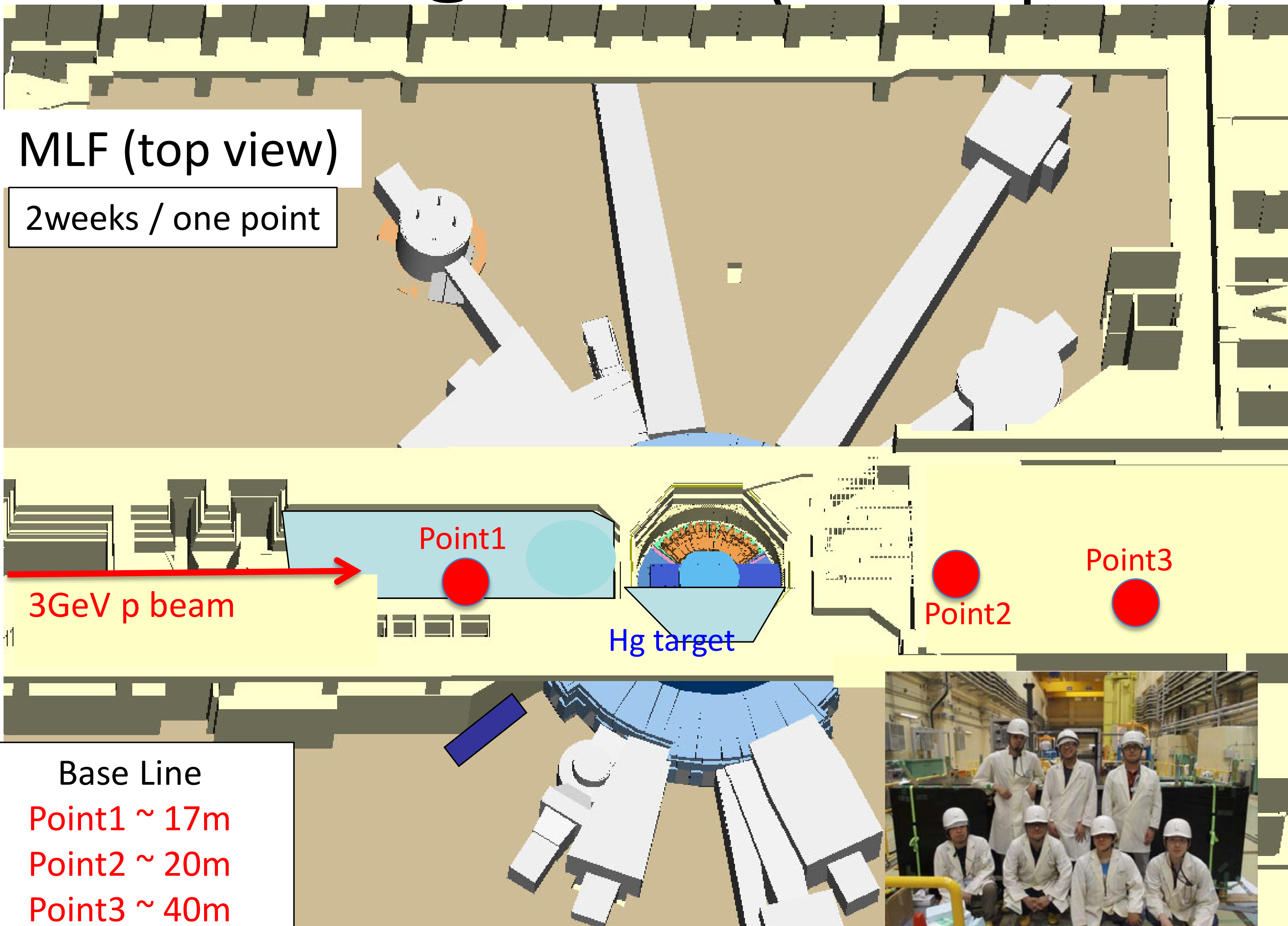
→ Strength during the moving is OK.

- **Interference between our experiment and other maintenance works is being discussed.**
- **Safety will be discussed.**



	Time from beam	Energy
Prompt signal	$1<T_p<10\mu s$	20<E<60MeV
Delayed signal	$T_p<T_d<100\mu s$	6<E<12MeV

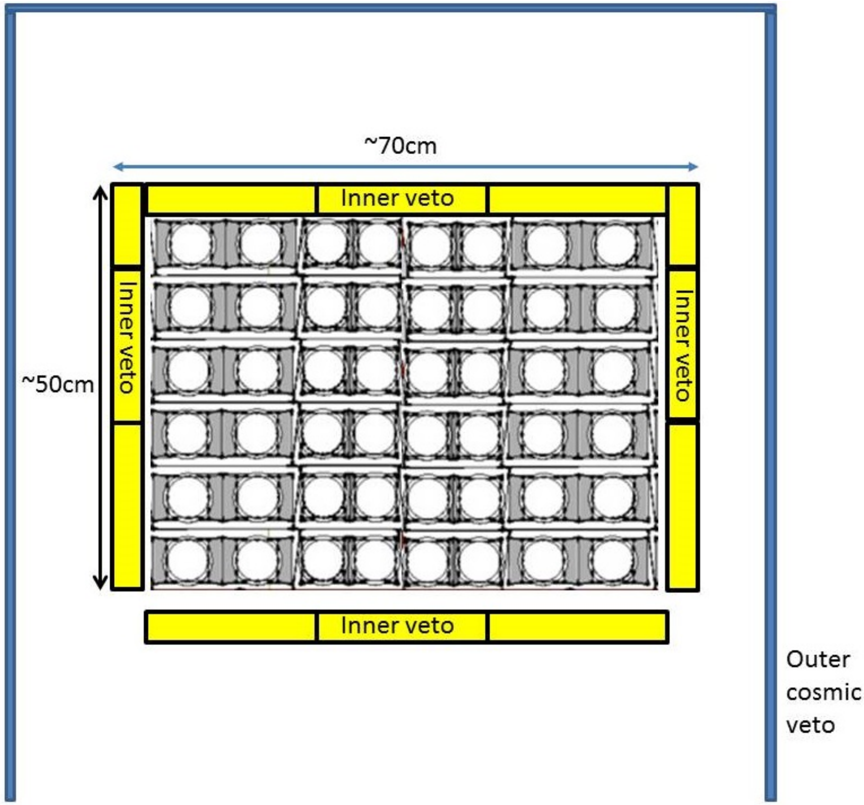
BKG meas. @ MLF 3F (2014 Apr-Jul)

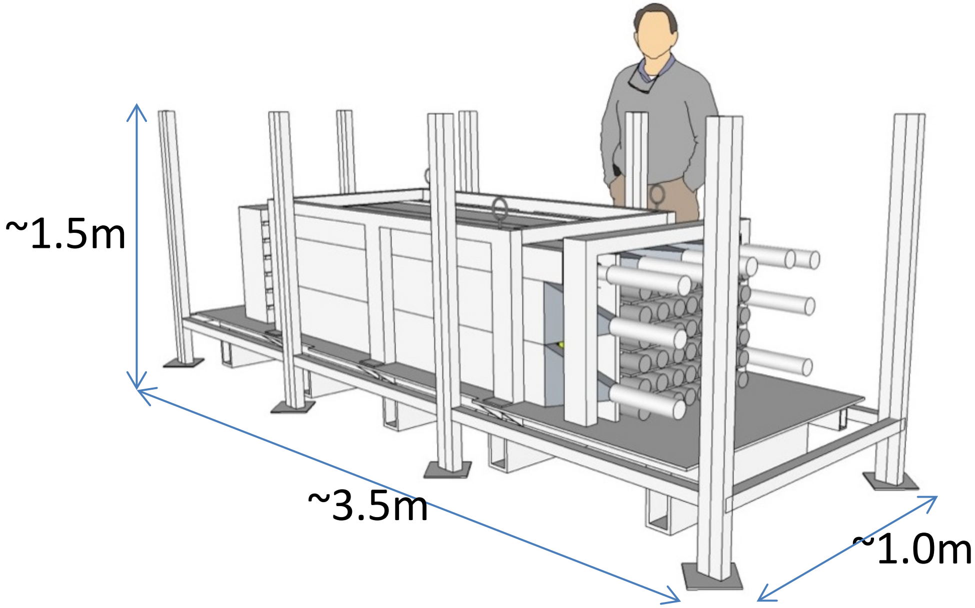


Base Line
Point1 ~ 17m
Point2 ~ 20m
Point3 ~ 40m

Detector

- Concept; minimizing dead spaces (for vertex rec.) and powerful cosmic ray rejection.
- Main scintillators; (borrowed from LEPS2 experiment (RCNP))
  - 24 scintillators in total. **(~500kg)**
  - 4 scintillators / layer and 6 layers
  - 2 Narrower (central part)
  - 2 Wider (in edge sides)
  - Each scintillator has 4 PMTs, and 2 PMTs / one side
- Inner cosmic veto (yellow)
  - 4.3cm thickness scintillators
  - One side readout.
  - Rejection Efficiency >~ 99.5%
- Outer cosmic veto (blue)
  - To surround main part.
  - 1m x 1m or 1m x 2.3m, 1cm (t) scintillators are used.

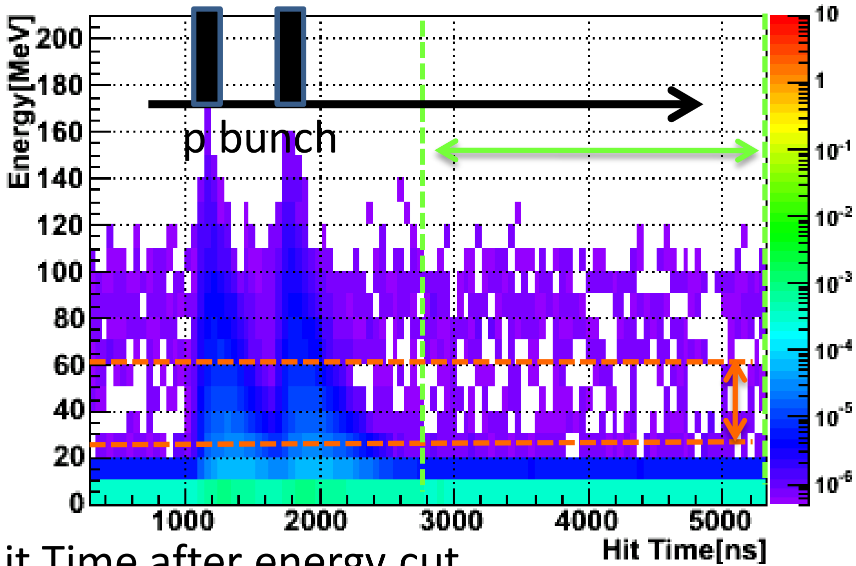




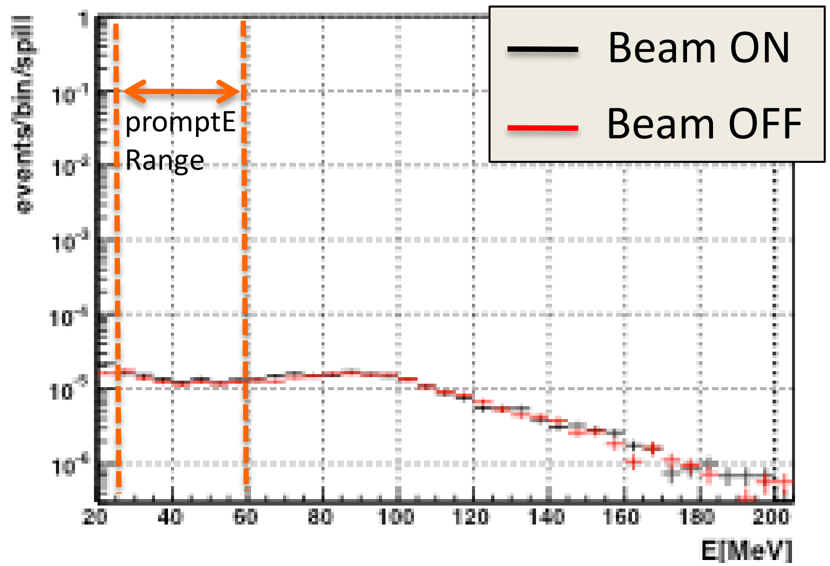
Measurement @ 2^{nd} point (w/o cosmic veto)

Selection; 1.Energy Cut : 25 < E[MeV] < 60 2.Hit Time Cut : 2.8 < Hit Time[μs] < 5.3μs

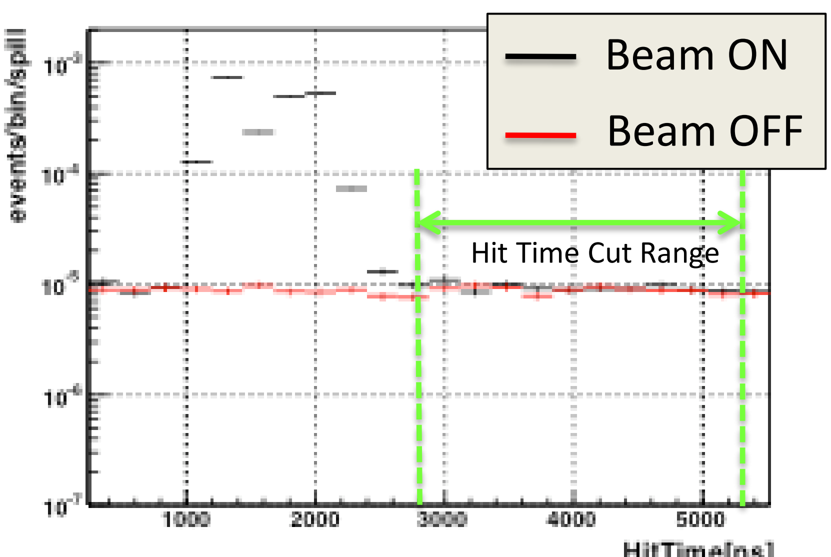
Energy vs Hit Time



Energy after timing cut



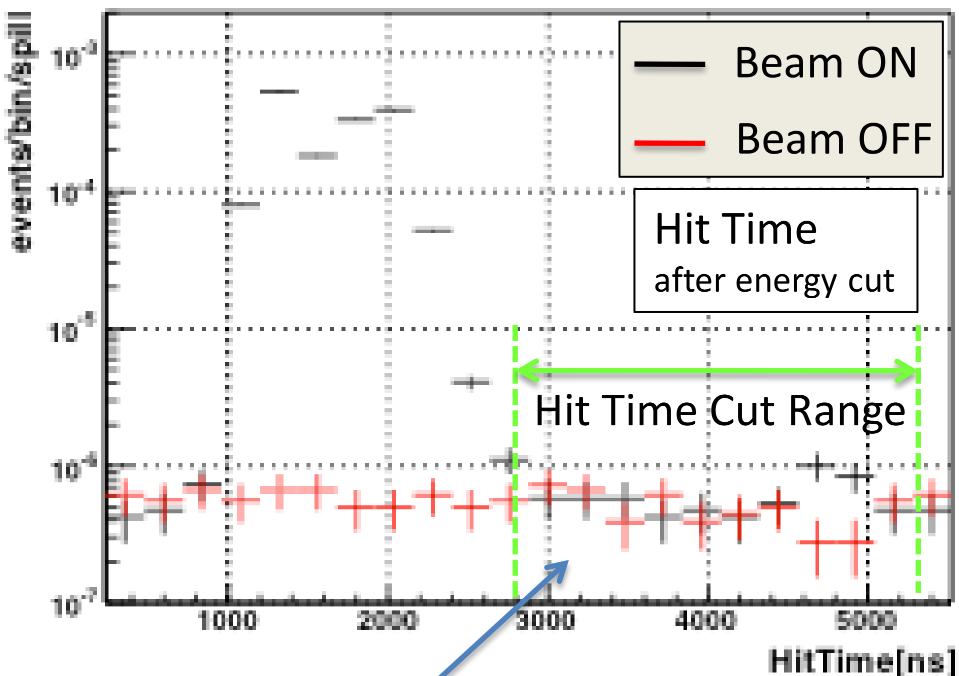
Hit Time after energy cut

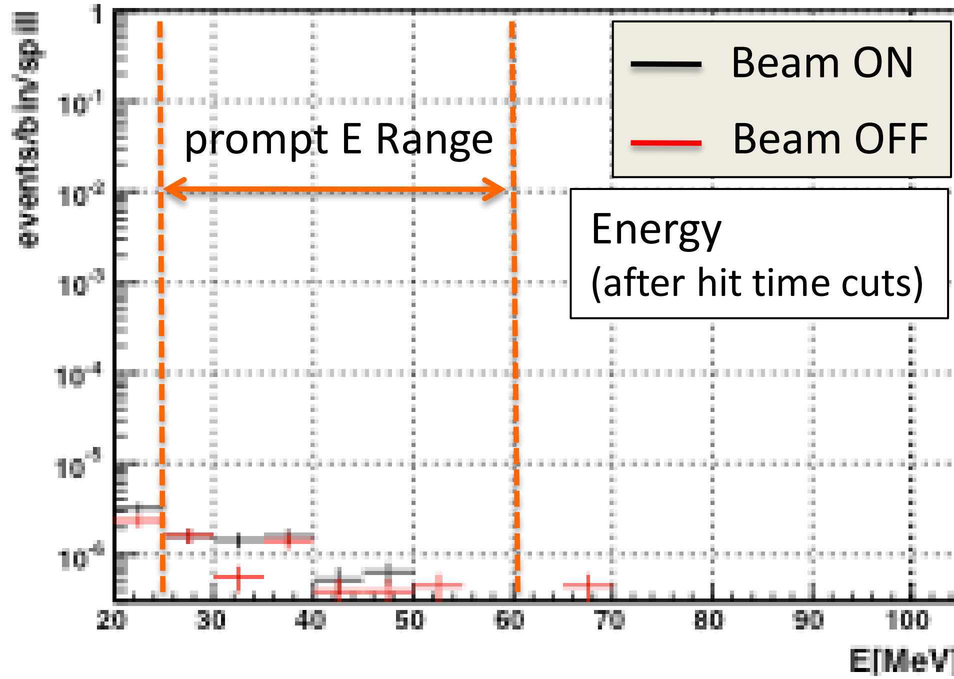


	#spill	#events w/o cosmic veto (events/spill/2.5μs)
ON	19006517	(9.61±0.22)e-5
OFF	17999309	(9.19±0.23)e-5

There is no beam excess

Measurement @ point 2 (w/ veto)





There are no excess for beam events.

HitTime Cut:2.8μs<Hit Time<5.3μs
25<E[MeV]<60

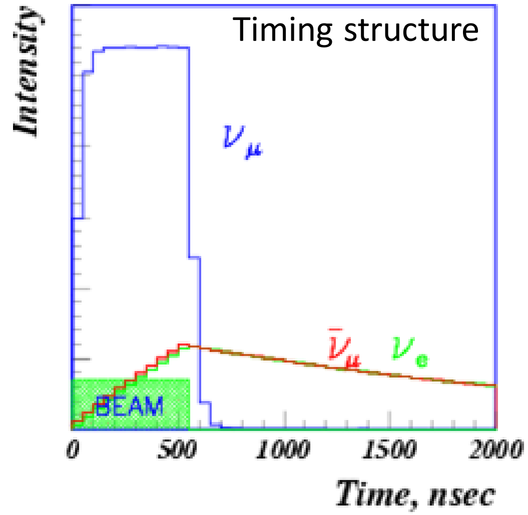
	# of spill	#events after VETO (events/spill/2.5μs)
ON	19006517	(6.10±0.57)e-6
OFF	17999309	(5.06±0.53)e-6
ON-OFF Excess		(0.94±0.78)e-6

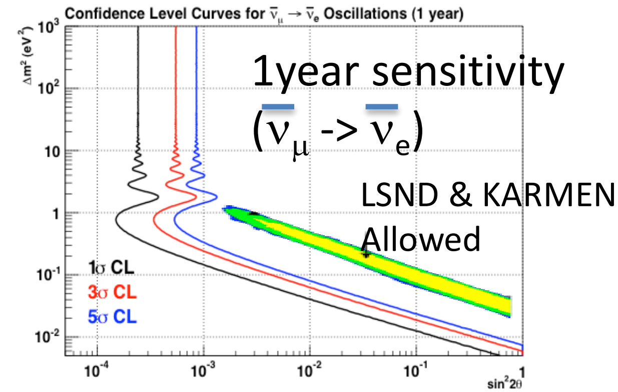
Beam BKG is sufficiently small for the J-PARC P56 experiment.

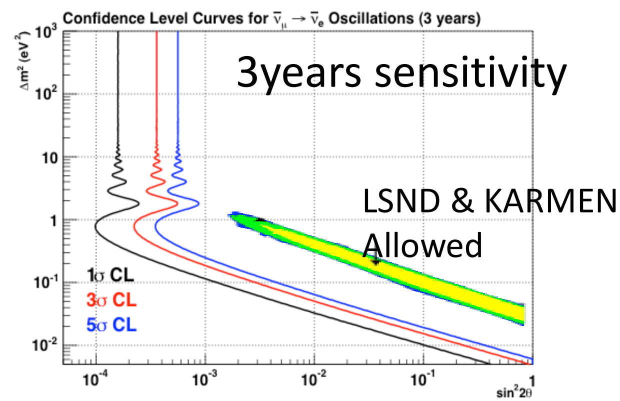
→ upper limit; same level of $\bar{\nu}_e$ from μ^-

OscSNS (arXiv:1307.7097)

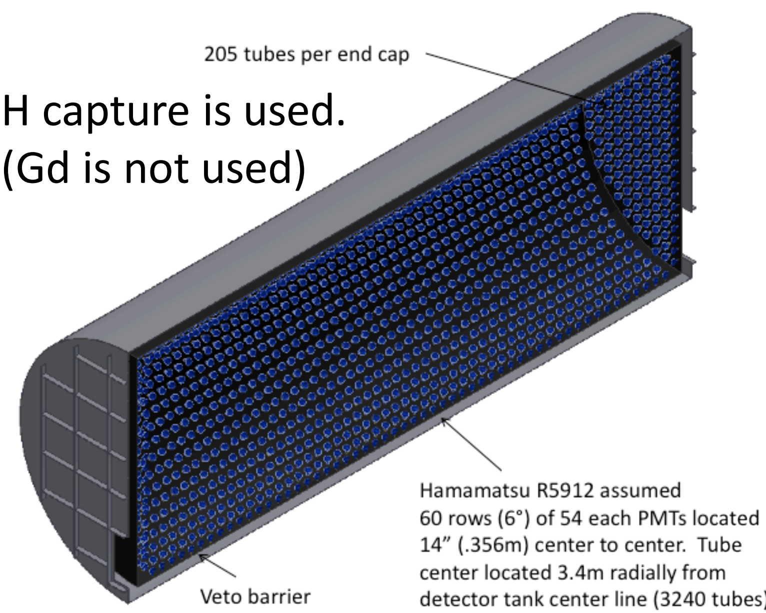
- Use Spallation Neutron Source (SNS) at ORNL
- ~1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos







H capture is used.
(Gd is not used)



Summary / Prospects

- Sterile neutrino is one of most hot topics in neutrino physics.
- Confirming or refuting the anomalies is the first thing to do for experimentalists.
- There are many on-going efforts for this purpose.
  - Using radioactive sources.
  - Using reactors
  - Using accelerators
- Sensitivities of these experiments are good enough for the purpose.

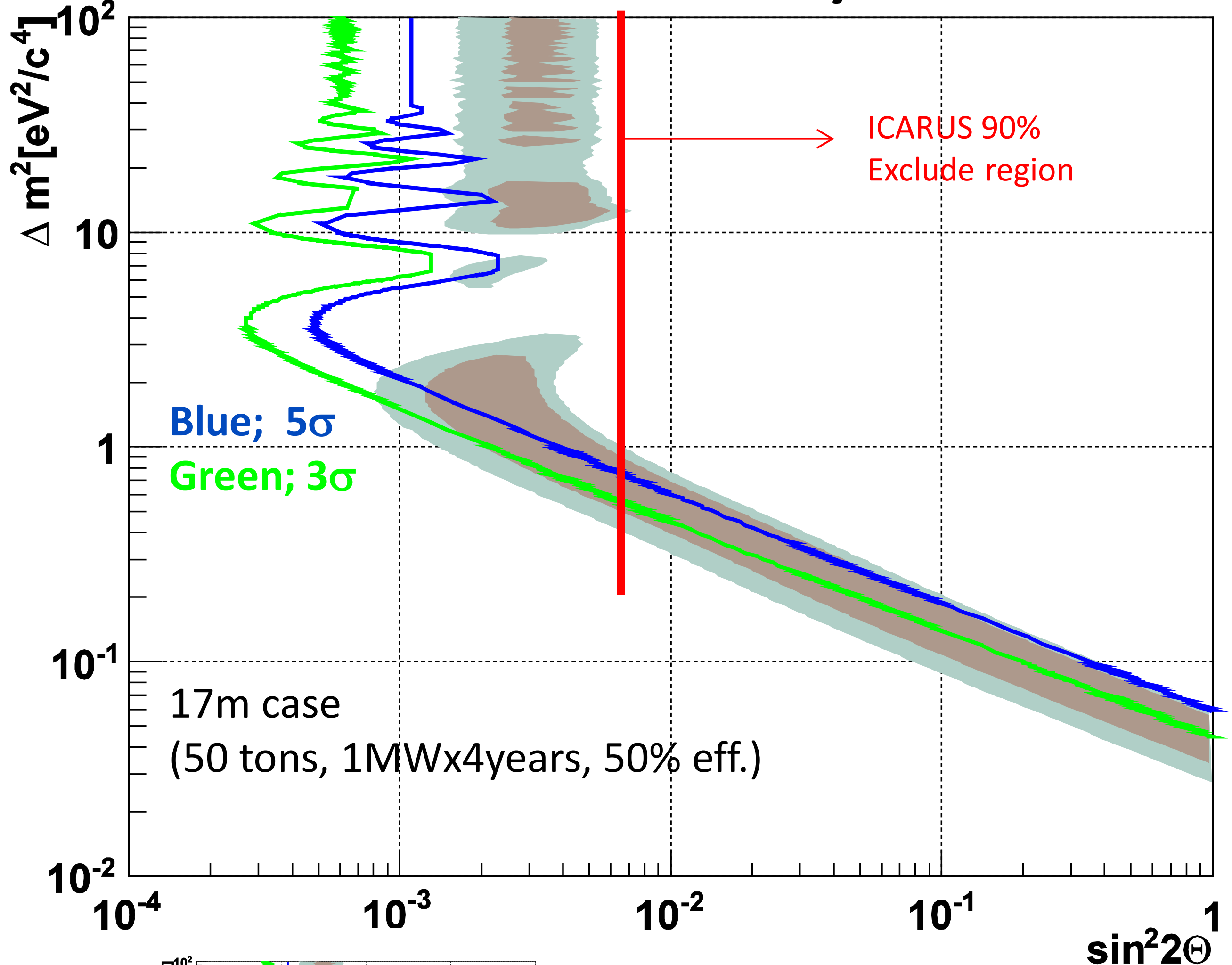
- J-PARC P56 experiment had BKG measurement toward the real experiment in this summer. We have small beam related BKG.

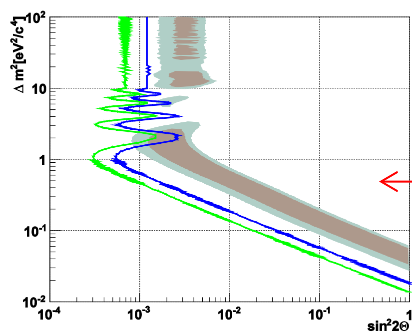
backup

Sensitivity

- Top plot;
  - 1MW x 4 years
  - 4000h / year
  - 50 tons fiducial
  - ~50% detection ε
- a definite conclusion above ~1eV^2 is obtained

- Bottom plot;
  - If no clear result in step1, then we go to step2
  - Example configuration for future step2 is to use 1kt detector with 60 m baseline





PAC report / Motivation

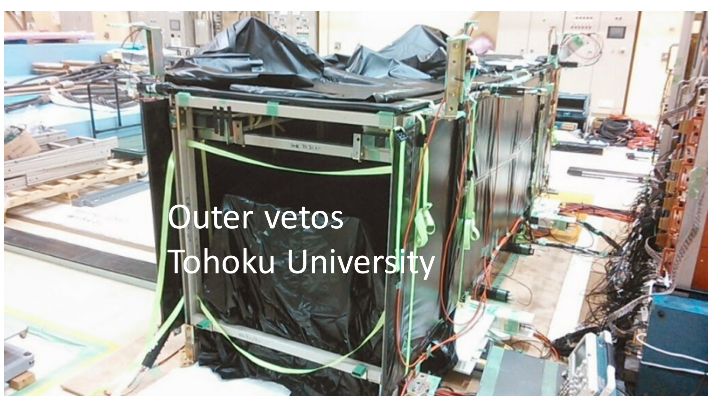
- Bottom table; BKG summary @ previous PAC
- Beam related BKG (red) → much smaller than $\overline{\nu}_e$ from μ^-
- This is from extrapolation from MLF 1st floor meas. with MC → PAC recommends to measure BKG directly at 3rd floor.

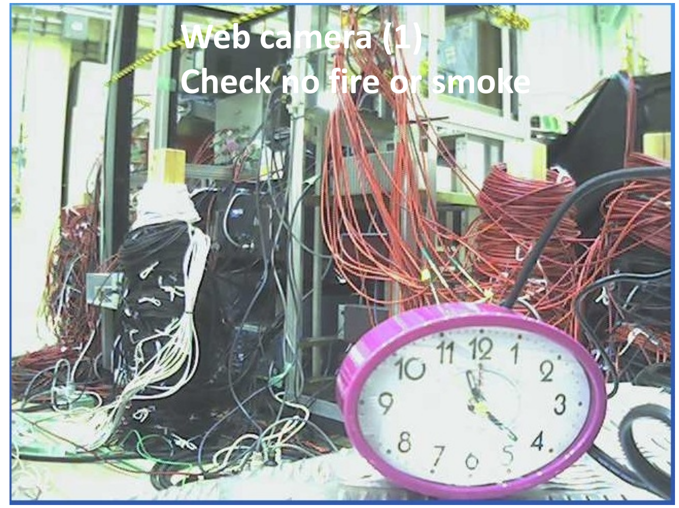
The most critical technical issue is a detailed estimate of the actual background rate at the 3rd floor of the MLF. The PAC recommends a direct measurement of this background with a small-scale prototype detector. If the background levels are as predicted (based on an extrapolation from rates measured at BL13 using a simulation), the experiment would be technically feasible and could receive stage-I approval. http://j-parc.jp/researcher/Hadron/en/pac_1309/PAC17thMinutes_final_draft.pdf

Source	contents	#ev./50tons/4years	comments
background	ν_e from μ-	377	
	$^{12}C(\nu_e,e-)^{12}N_{g.s.}$	38	IBD ε is 0.2%
	Beam fast neutrons	0.3	
	Fast neutrons (cosmic)	42	
	Accidental	37	
signal		881	$\Delta m^2=3.0$, $\sin^2 2\theta=0.003$
		377	$\Delta m^2=1.2$, $\sin^2 2\theta=0.003$

Detector / operation

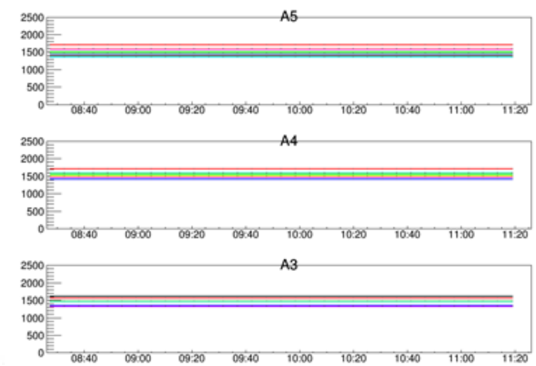
One side
48 PMTs



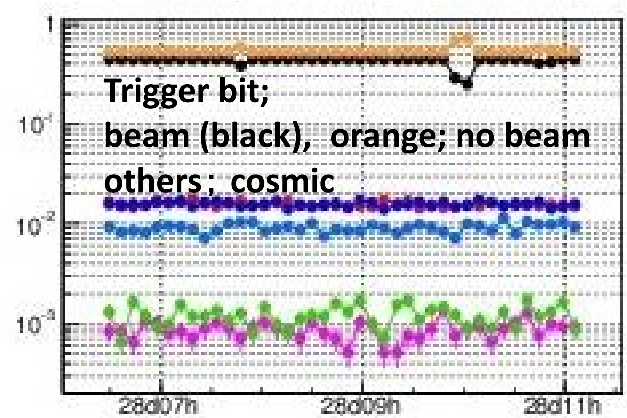


WEBカメラで
火災がないか
24時間体制
で監視。(3か月
間、実験中は
ずっと。)

本実験への
良いデモンスト
レーション



高圧値に異常が
ないか監視



トリガーレート
からDAQが良好
に動いているか
判断。

nuSTORM (neutrinos from STORed Muons)

A low-energy muon storage (P_{μ}=3.8 GeV/c) ring based on existing technology to:

- Address the large Δm^2 neutrino oscillations
- Provide beams for precision ν_e and ν_{μ} cross section measurements
- Provide an accelerator technology test bed (ν-Factory & μ-Collider)
- Provide a neutrino Detector Test Facility
    - Proposal: arXiv:1308.6822
    - Project Definition Report: arXiv:1309.1389

Technologically limited Schedule: 5-7 years

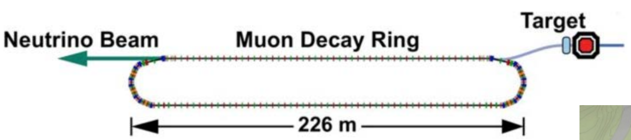
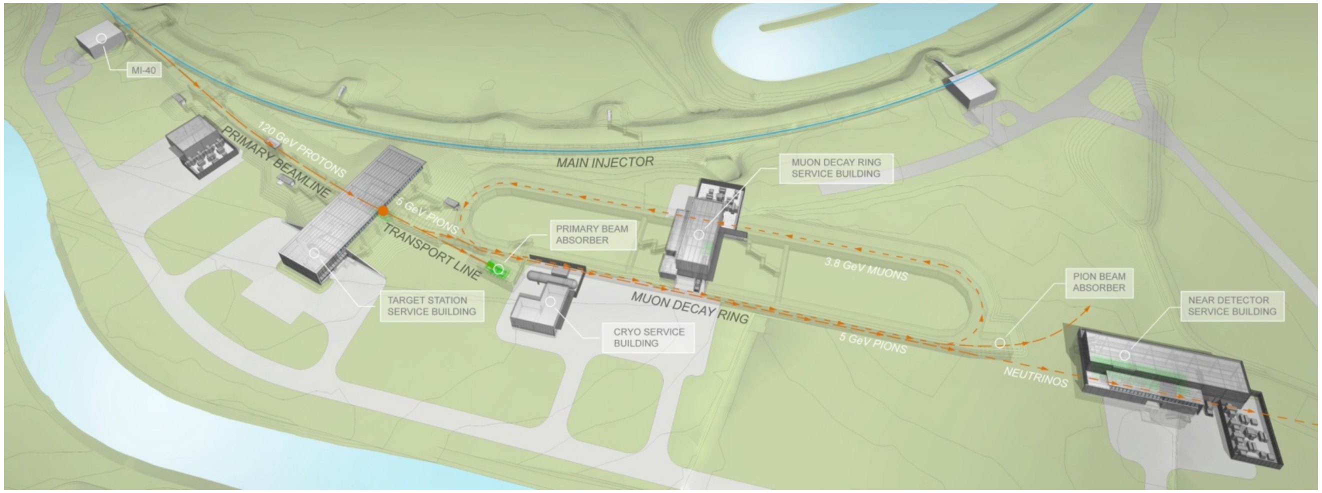


Table 1: Decay ring specifications

Parameter	Specification	Unit
Central momentum P_{μ}	3.8	GeV/c
Momentum acceptance	$\pm$ 10%	
Circumference	480	m
Straight length	185	m
Arc length	50	m
Arc cell	DBA	
Ring Tunes (ν_x, ν_y)	9.72, 7.87	
Number of dipoles	16	
Number of quadrupoles	128	
Number of sextupoles	12	

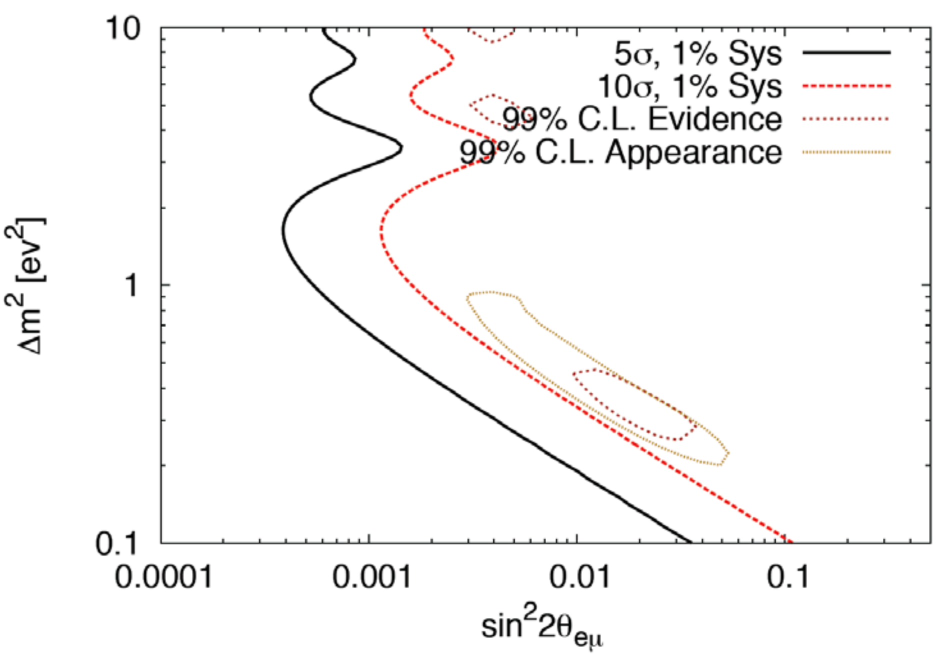
The nuSTORM facility



Sterile ν search sensitivity

- Performance for an exposure of 10^{21} proton on target (120 GeV) from Fermilab Main Injector for sterile neutrino appearance
  - 2×10^{18} useful muon decays
  - Can confirm or rule out LSND/MiniBooNE region at 10σ

Golden mode; $\nu_e \rightarrow \nu_\mu$



5 and 10 σ contours for a Boosted Decision Tree analysis. The 99% confidence level contours from a global fit to all experiments are also shown (from Kopp *et al.* JHEP 1305, 050 (2013).)

Sterile neutrinos as dark matter

Simplest scenario accounting for the dark matter of the Universe

- One new particle, ν_s
- No new symmetries
- Two new parameters: m_{DM}, θ_{as}.

Five things to know about sterile neutrino dark matter

1. Sterile neutrinos can be produced in the early Universe via mixing ν_a - ν_s.

2. Sterile neutrinos should not be overproduced $\Rightarrow$ upper limit on the mixing angle as a function of the DM mass

3. The existence of a lepton asymmetry can resonantly enhance the dark matter production, via the MSW mechanism.

Sterile neutrinos as dark matter

4. Sterile neutrinos are fermions and obey the exclusion principle. It is not possible to have an arbitrarily large ν_s number density.
   The observed DM density in dwarf galaxies implies a lower limit on the DM mass.

5. Sterile neutrinos are not absolutely stable