JSNS^2: J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source (E56)

Status and Prospects of the JSNS^2 Experiment

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KPS Fall Meeting 2019

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Outline

1. Motivation
2. Sterile neutrino searches
3. J-PARC MLF Facility
4. The JSNS^2 Experiment
5. Current Status
6. Outlook and Conclusions

<u>Please also visit the following posters:</u>

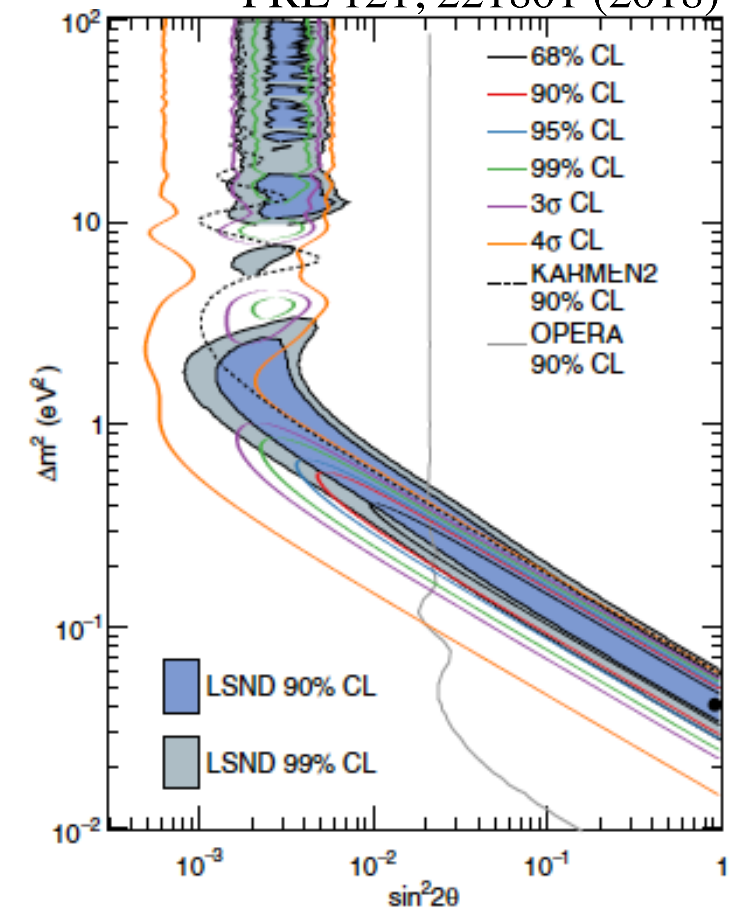
- *PMT Pre-calibration in JSNS^2* (Daeun Jung, SKKU)
- *Energy spectrum of anti-electron neutrinos from mu- decay in the JSNS^2 experiment* (Sanghoon Jeon, SKKU)
- *IBD event study at the JSNS^2 experiment* (Hyoungku Jeon, SKKU)

Motivation / Sterile Neutrino Searches

Neutrino Anomalies

Experiments	Neutrino source	Signal	Significance	E(MeV), L(m)
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8σ	40,30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \to \nu_e$	4.5σ	800,600
		$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8σ	
		combined	4.7σ	
Ga (calibration)	e capture	$\nu_e \to \nu_x$	2.7σ	<3,10
Reactors	Beta decay	$\bar{\nu}_e \to \bar{\nu}_x$	3.0σ	3,10-100

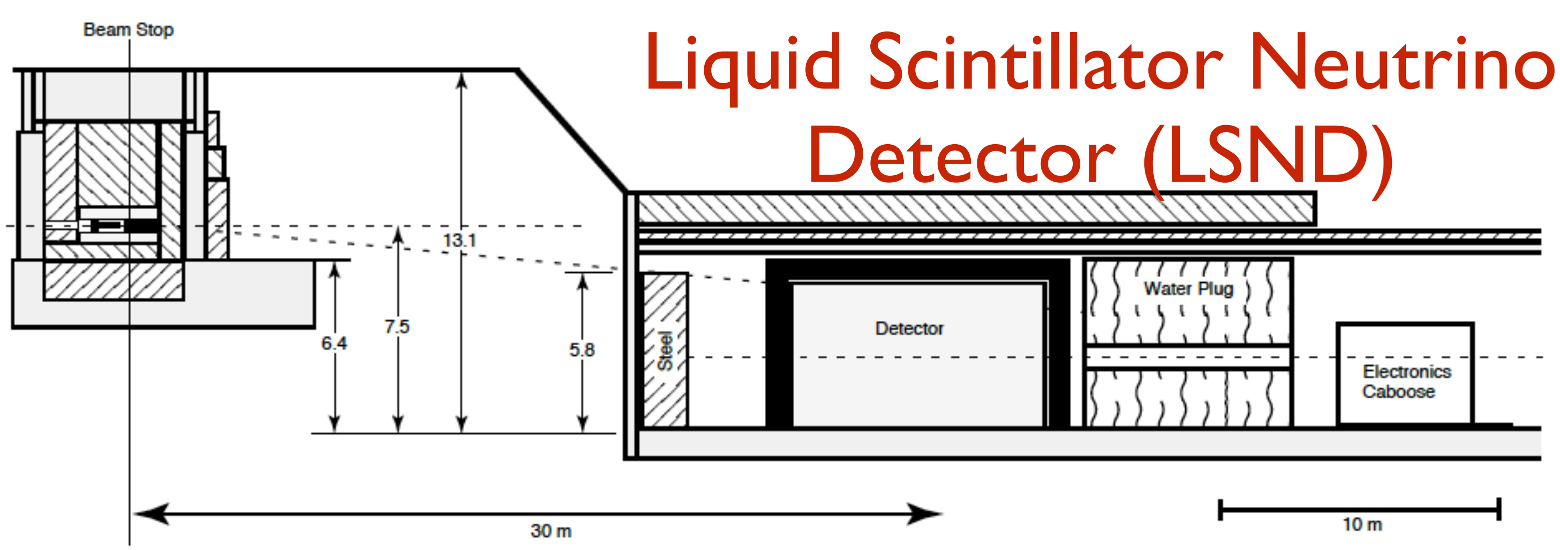
PRL 121, 221801 (2018)



Indication of a sterile neutrino ($\Delta m^2 \sim 1 eV^2$) ?

Updated MiniBooNE + LSND Result 6.0σ
PRL 121, 221801 (2018)
arXiv:1805.12028

Liquid Scintillator Neutrino Detector (LSND)



Nucl.Instrum.Meth.A388:149-172,1997

LSND reported an excess of 87.9±22.4 ±6.0 anti-electron neutrino events (3.8σ) in 1998

Extension of neutrino ν mixing matrix

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_s\rangle \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* & U_{e4}^* & \cdots \\ U_{\mu1}^* & U_{\mu2}^* & U_{\mu3}^* & U_{\mu4}^* & \cdots \\ U_{\tau1}^* & U_{\tau2}^* & U_{\tau3}^* & U_{\tau4}^* & \cdots \\ U_{s1}^* & U_{s2}^* & U_{s3}^* & U_{s4}^* & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \vdots \end{pmatrix}$$

The neutrino mixing matrix can be extended to introduce sterile neutrinos.
The theoretical framework predicts variations in the standard neutrino oscillation probabilities

For $3(\nu_\alpha)+1(\nu_s)$ & $m_4 >> m_{1\sim3}$ case,

$$P_{\nu_e\to\nu_e} \sim 1 - 4(1-|U_{e4}|^2)|U_{e4}|^2 \sin^2\left[\frac{m_4 L}{4E_\nu}\right]$$

ν_e disappearance

$$P_{\nu_\mu\to\nu_e} \sim 4|U_{\mu4}|^2|U_{e4}|^2 \sin^2\left[\frac{m_4 L}{4E_\nu}\right]$$

$\nu_\mu \rightarrow \nu_e$ appearance

$$P_{\nu_\mu\to\nu_\mu} \sim 1 - 4(1-|U_{\mu4}|^2)|U_{\mu4}|^2 \sin^2\left[\frac{m_4 L}{4E_\nu}\right]$$

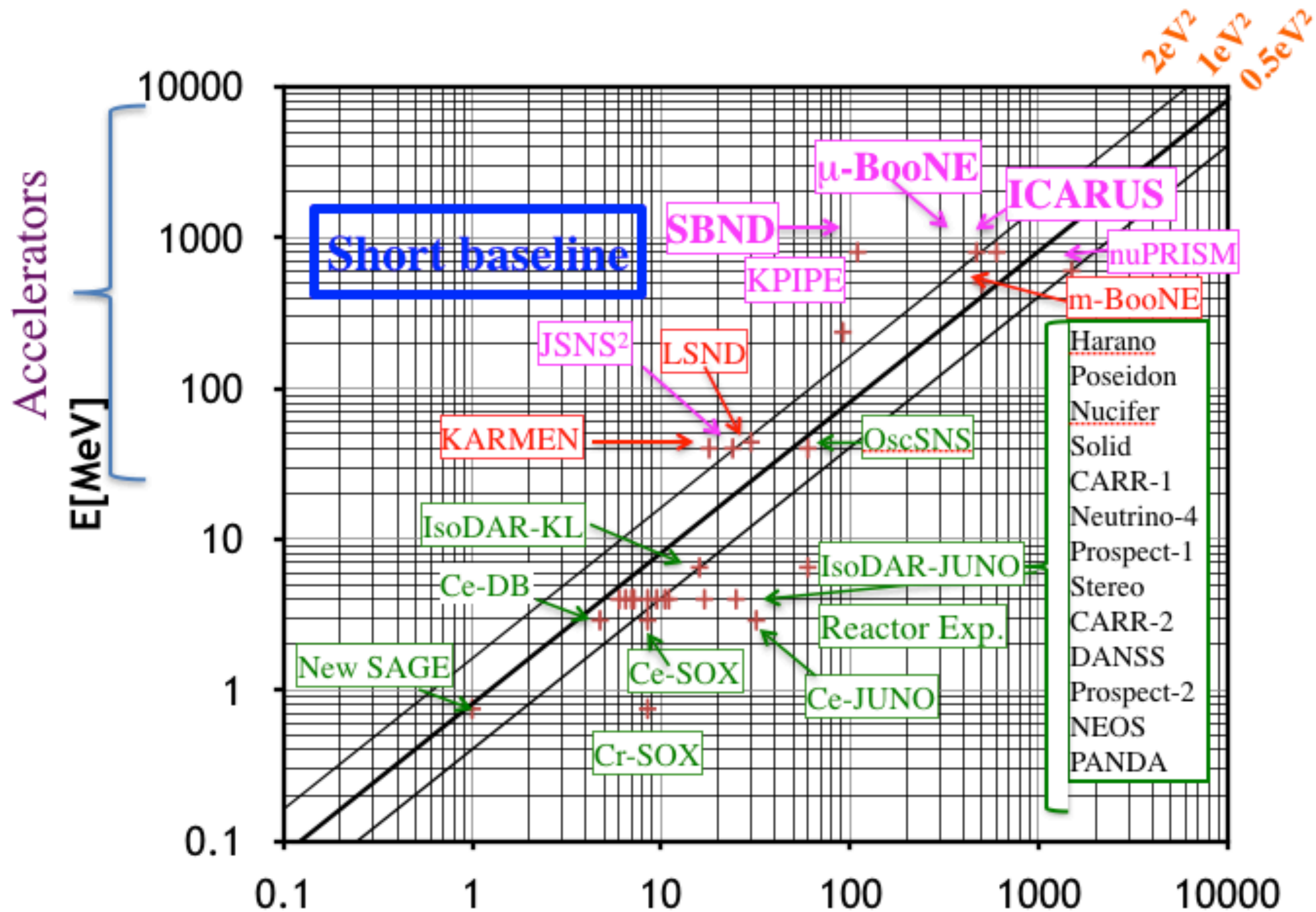
ν_μ disappearance

Accelerator Experiments can measure

➔ ν_s might be detectable via neutrino ν oscillations effects

Importance of JSNS²

- Intense international efforts to search for sterile neutrinos
  - Reactor neutrino experiments
  - Neutrino Telescopes - Atmospheric Neutrino Measurements
  - Short baseline neutrino experiments



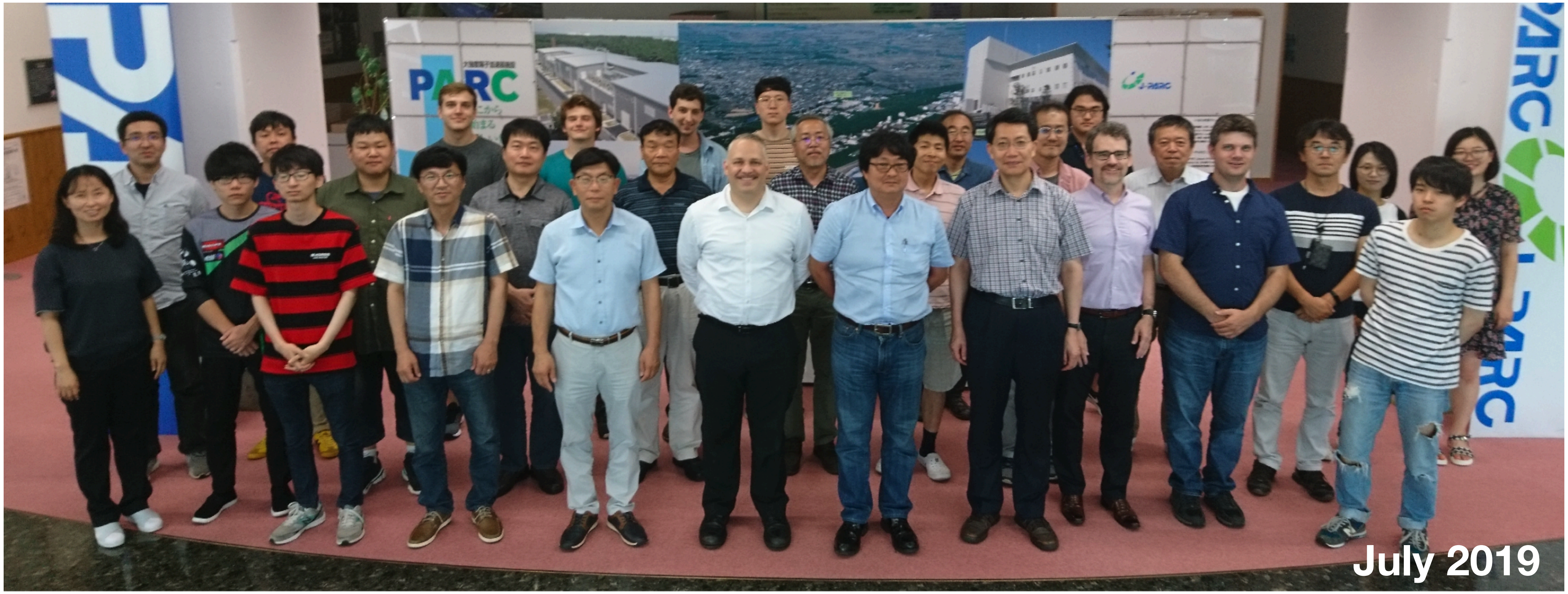
Disappearance

$$P_{\nu_e \to \nu_e} \sim 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2\left[\frac{m_4 L}{4E_\nu}\right]$$

Global data cannot be explained by addition of sterile neutrinos

The J-PARC Facility and the JSNS^2 Experiment

JSNS^2 Collaboration



- ~50 collaborators from 4 countries

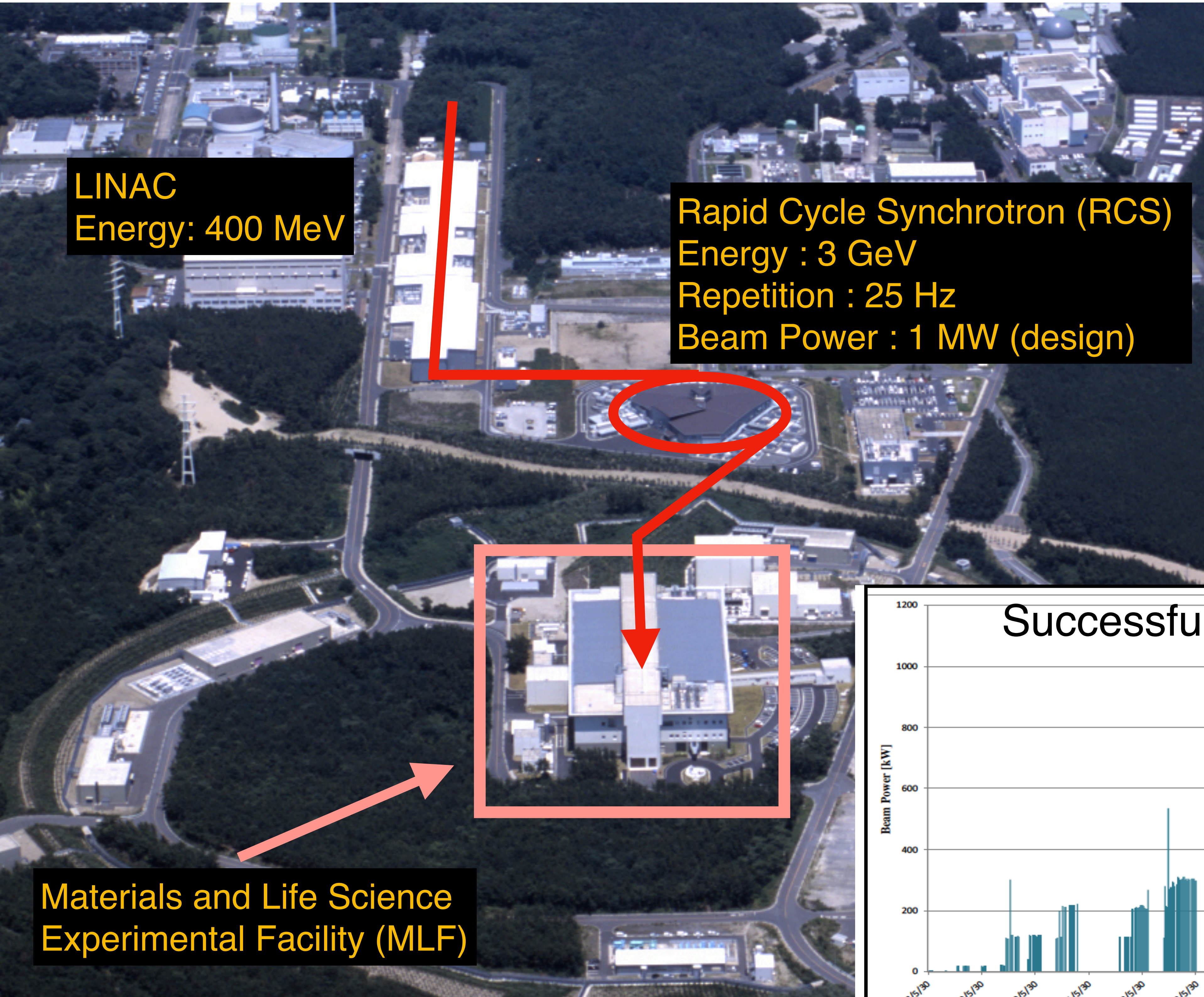
U.S.

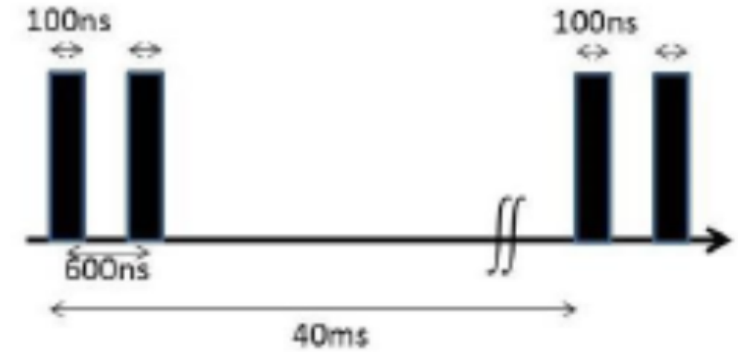
Japan

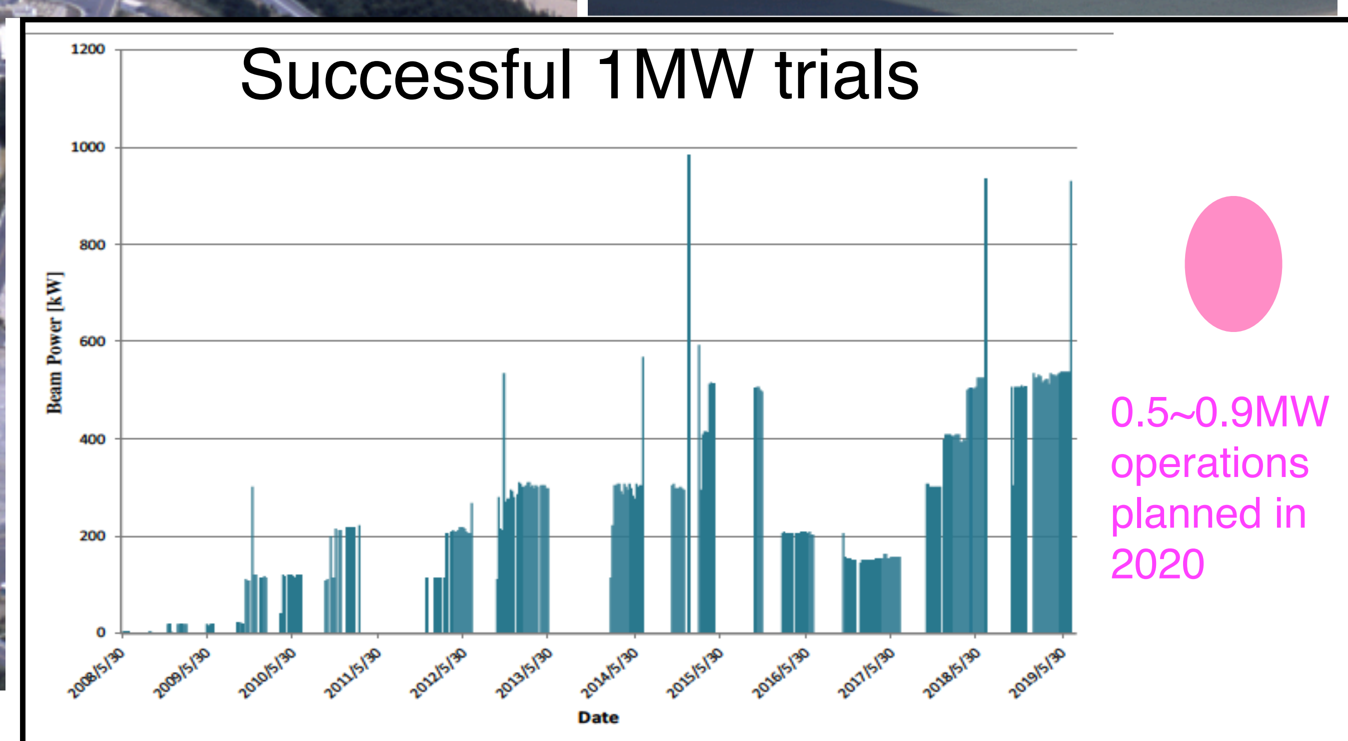
Korea

UK

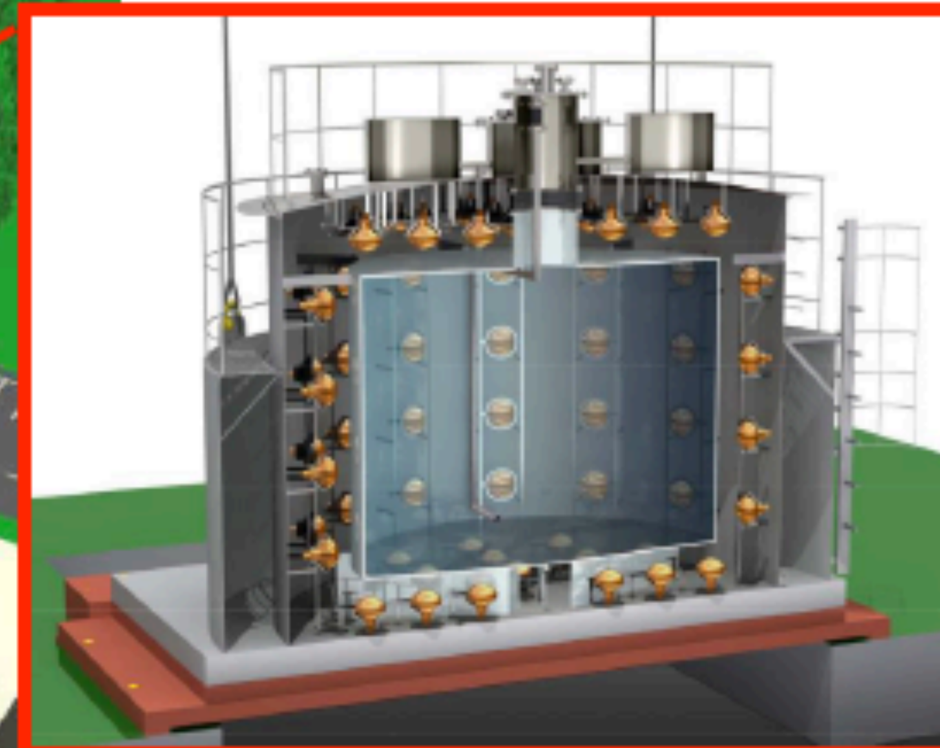
J-PARC Facility (KEK/JAEA)







Detector location at J-PARC MLF



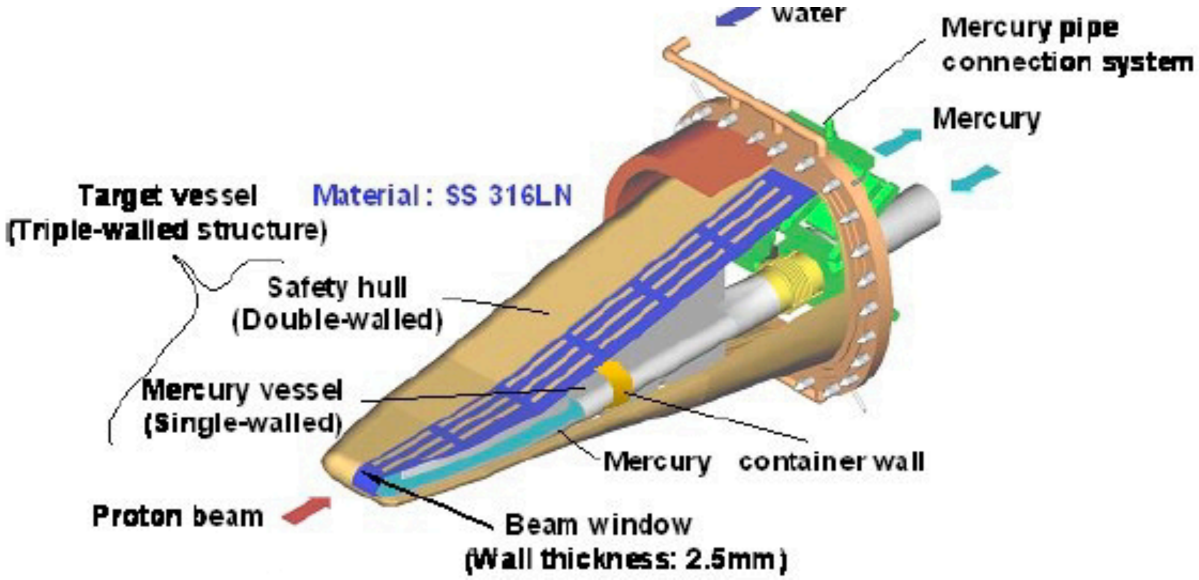
50t of Liquid scintillator
(including 17t Gd loaded)
(4.6m diameter x
4.0m height)

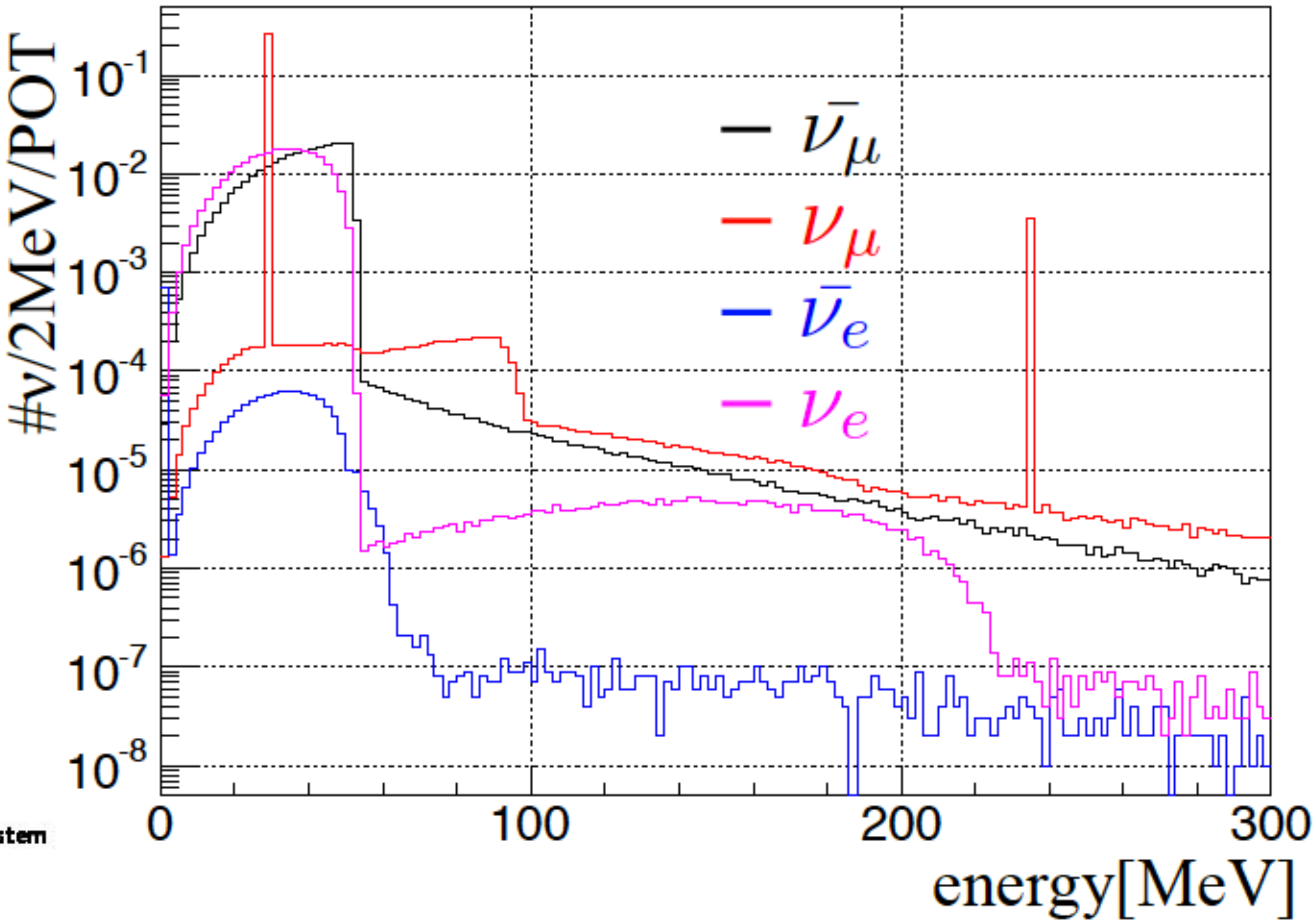
3GeV proton beam
(design power 1MW)

Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

Decay at Rest Neutrino Source (Hg target)

- Precisely known neutrino spectrum
- High intensity neutrino flux





Spectrum for each neutrino flavor precisely known and with specific time structure

Jnique for Material and Life Science Experimental Facility at J-PARC

Production / Detection

$p+\mathrm{Hg} \to \pi^+ + X$

$\pi^+(stop) \to \mu^+ + \nu_\mu$

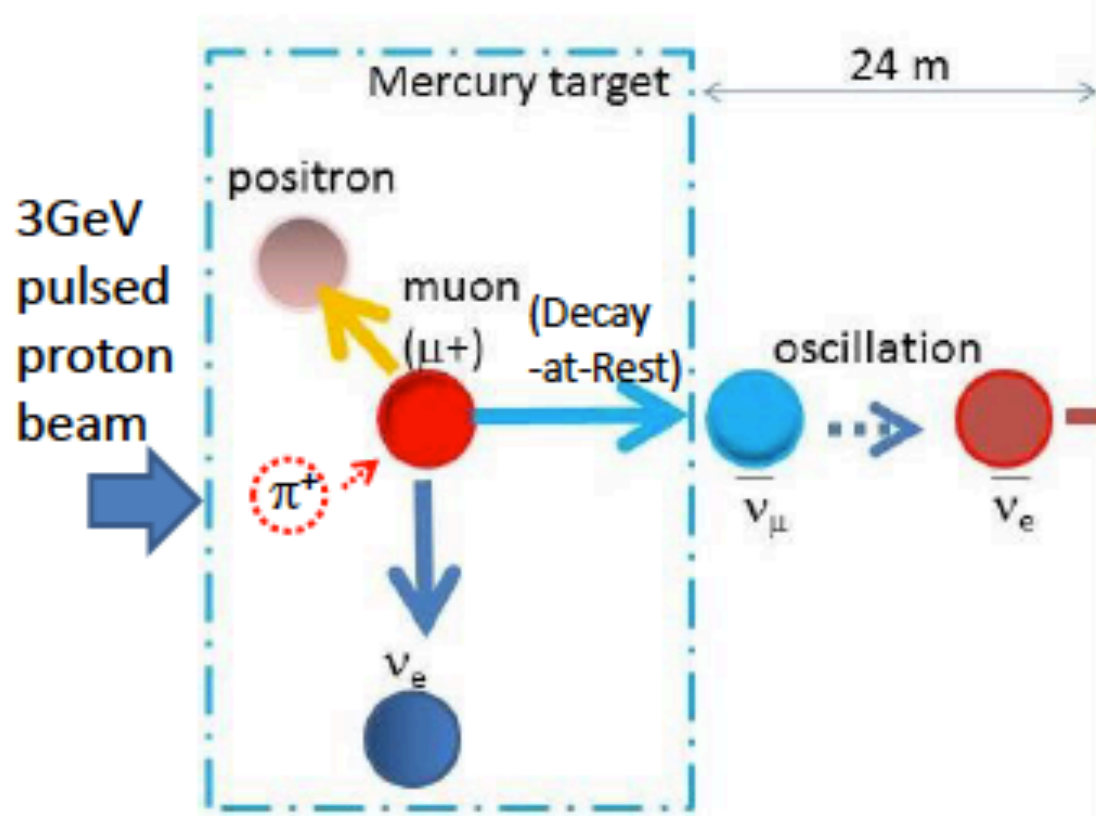
$\mu^+(stop) \to e^+ + \nu_e + \bar{\nu}_\mu \xrightarrow[\text{24m}]{\text{Oscillation}} \bar{\nu}_e$

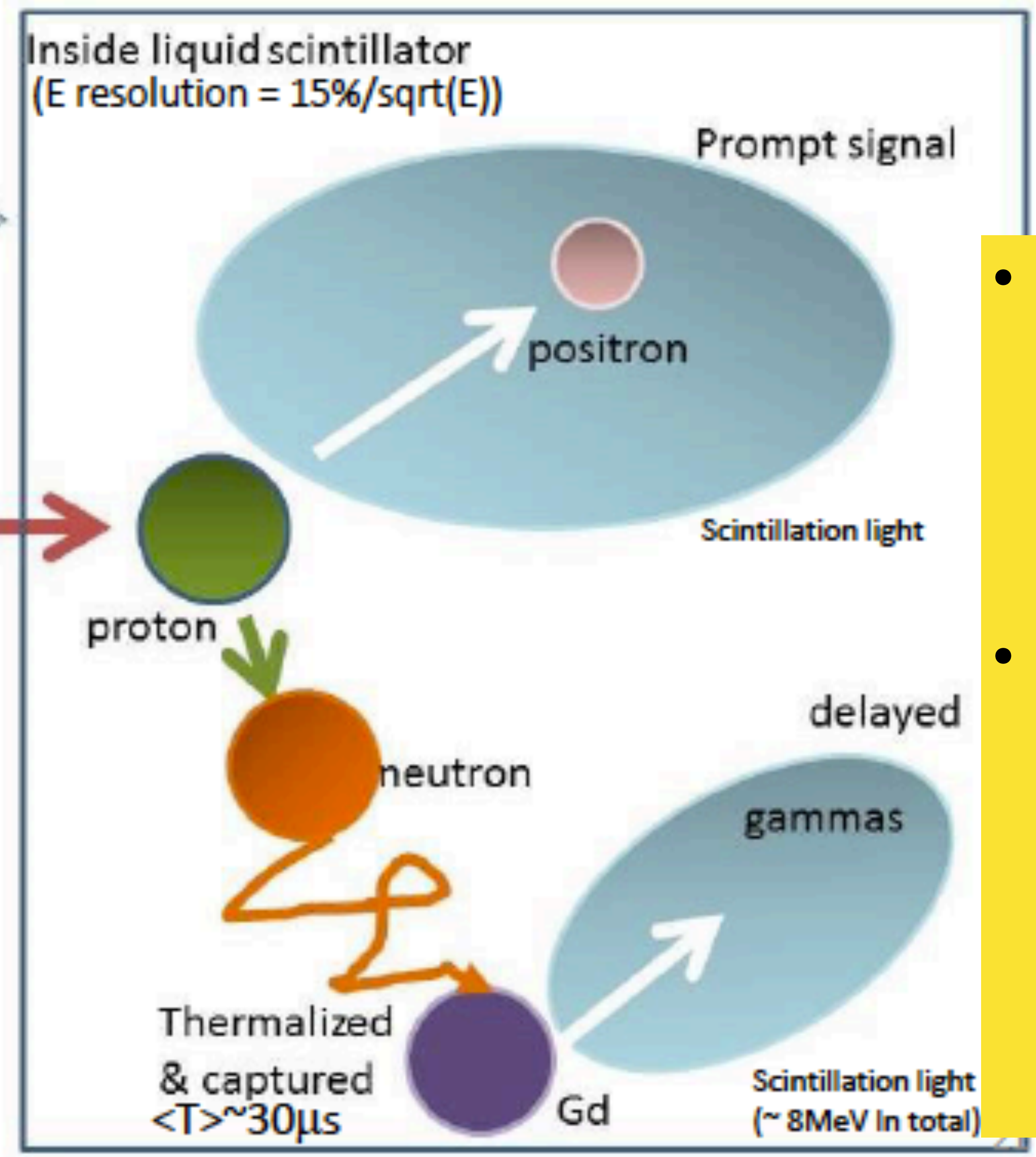
Look for this neutrino

$E_\nu = 0 \sim 53\,\mathrm{MeV}$

- **Large number of parent μ+ in Hg target → production of ν_μ**
- **Search for $\nu_\mu \to \nu_e$ oscillations at a 24m baseline length**

- Oscillated $\bar{\nu}_e$ is detected by Inverse Beta Decay (IBD): $\bar{\nu}_e + p \to e^+ + n$ w/ well established detector technique



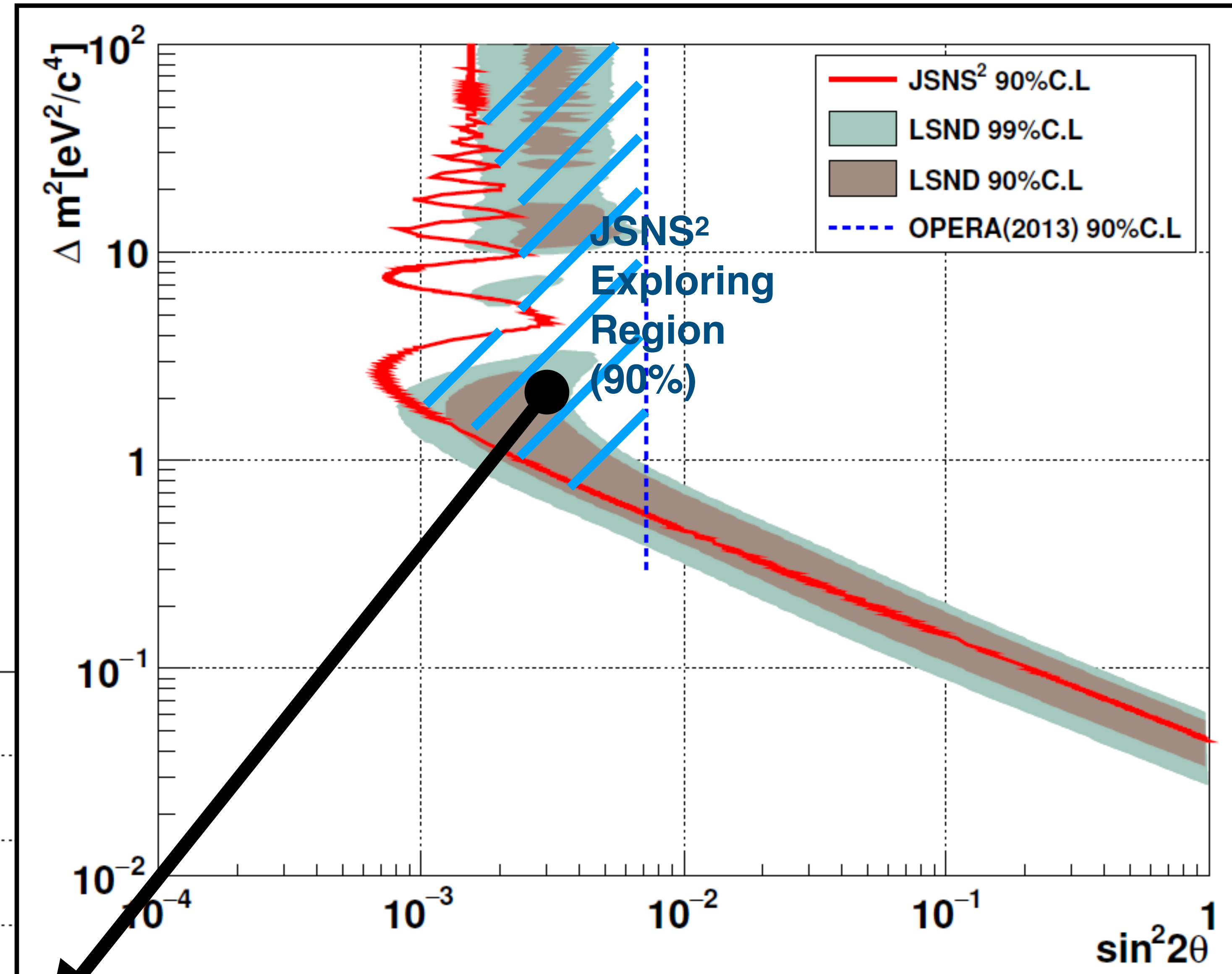


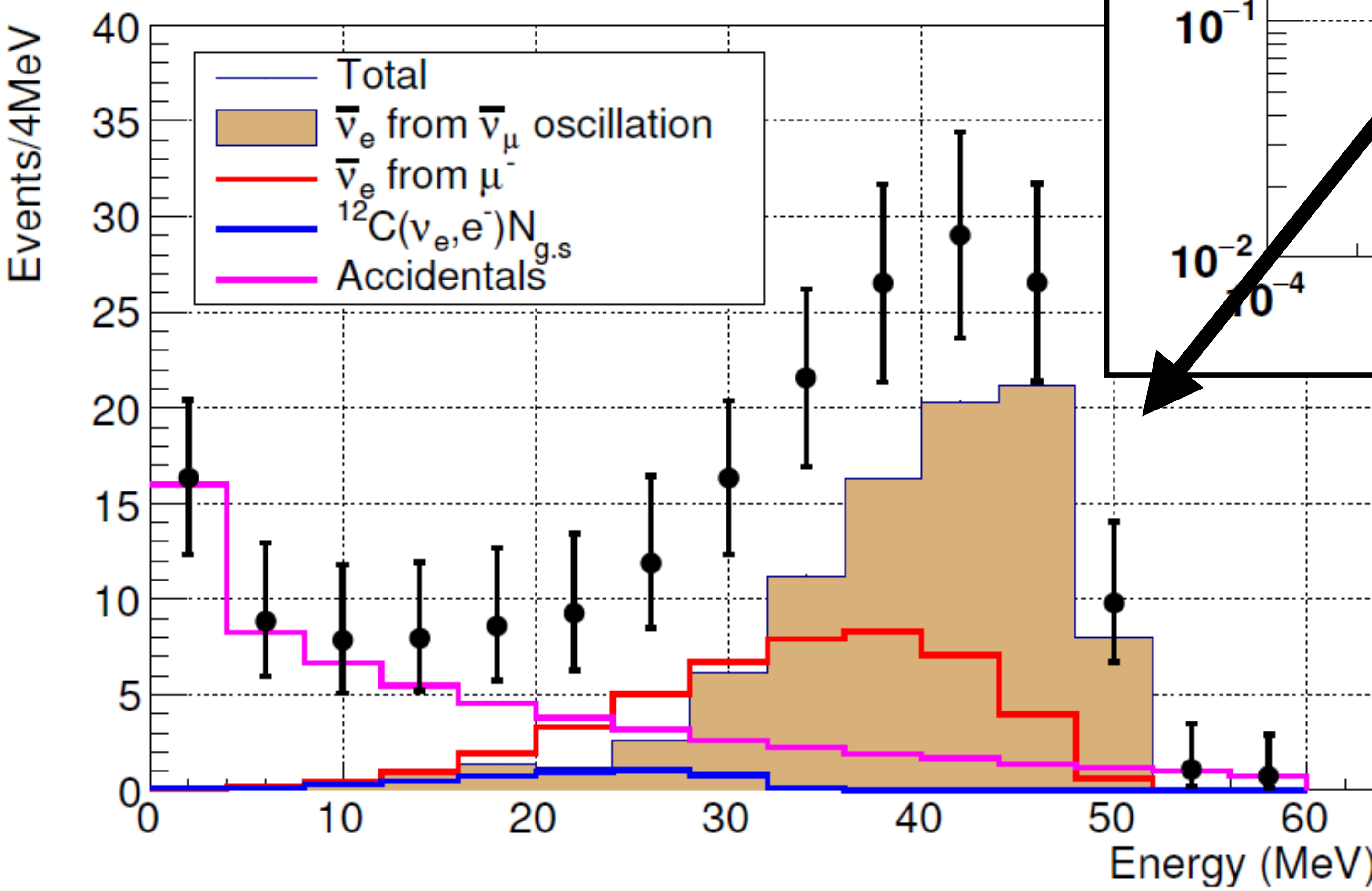
IBD criteria	Timing	Energy
Prompt	$1<T_p<10\mu s$	20<E<60MeV
Delayed	$T_p<T_d<100\mu s$	7<E<12MeV

- **Process similar to LSND**
  - **Direct and ultimate test for LSND**
- **Much better beam characteristics and Gd loaded LS**
  - **Significantly improved S/N**
  - **Reduced systematics**

Science Objectives

Sensitivity with 3 years physics run





Efforts underway to obtain funding for a second detector

Science at JSNS^2

- **Discovery potential !**
  - **Sterile neutrino search**
    - Discovery or resolve long standing anomaly
  - Beyond the Standard Model Searches
- **Guaranteed science**
  - Cross section measurements with neutrinos with a few 10 MeV from muon decay at rest and with monochromatic 236MeV from kaon decay at rest (KDAR).
    - important for
      - Supernova explosion
      - Nuclear reaction cross sections
      - Dark Matter Searches

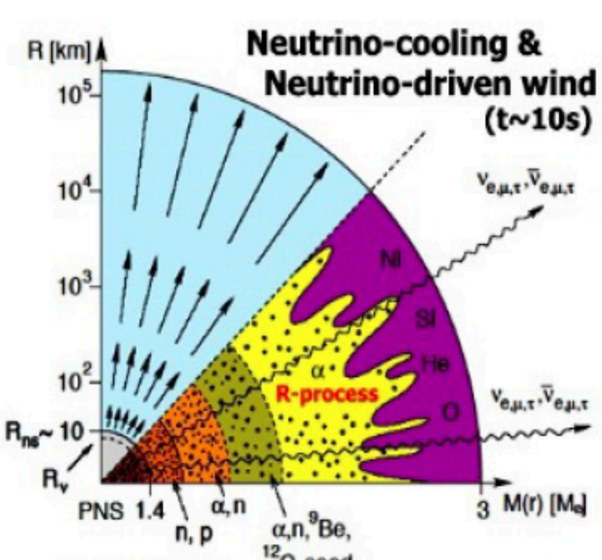
A. Aguilar et al. (LSND Collaboration) Phys. Rev. D 64, 112007 (2001)

Example: Pseudo-Dirac Dark Matter - J. Jordan et al. 1806.05185

Core collapsing supernova explosions (Type-II SNe).

$$^{12}\mathrm{C}(\nu_e,\mathrm{e}^-)^{12}\mathrm{N}$$

Example:
C. Rott, J. Siegal-Gaskins, J.F. Beacom, Phys.Rev. D88 (2013) 055005



Janka (2004)

ν-A interactions are important in
- core-cooling by ν-emission
- ν-heating on shock wave
- ν-process of nucleosynthesis
- efficiency of neutrino detectors

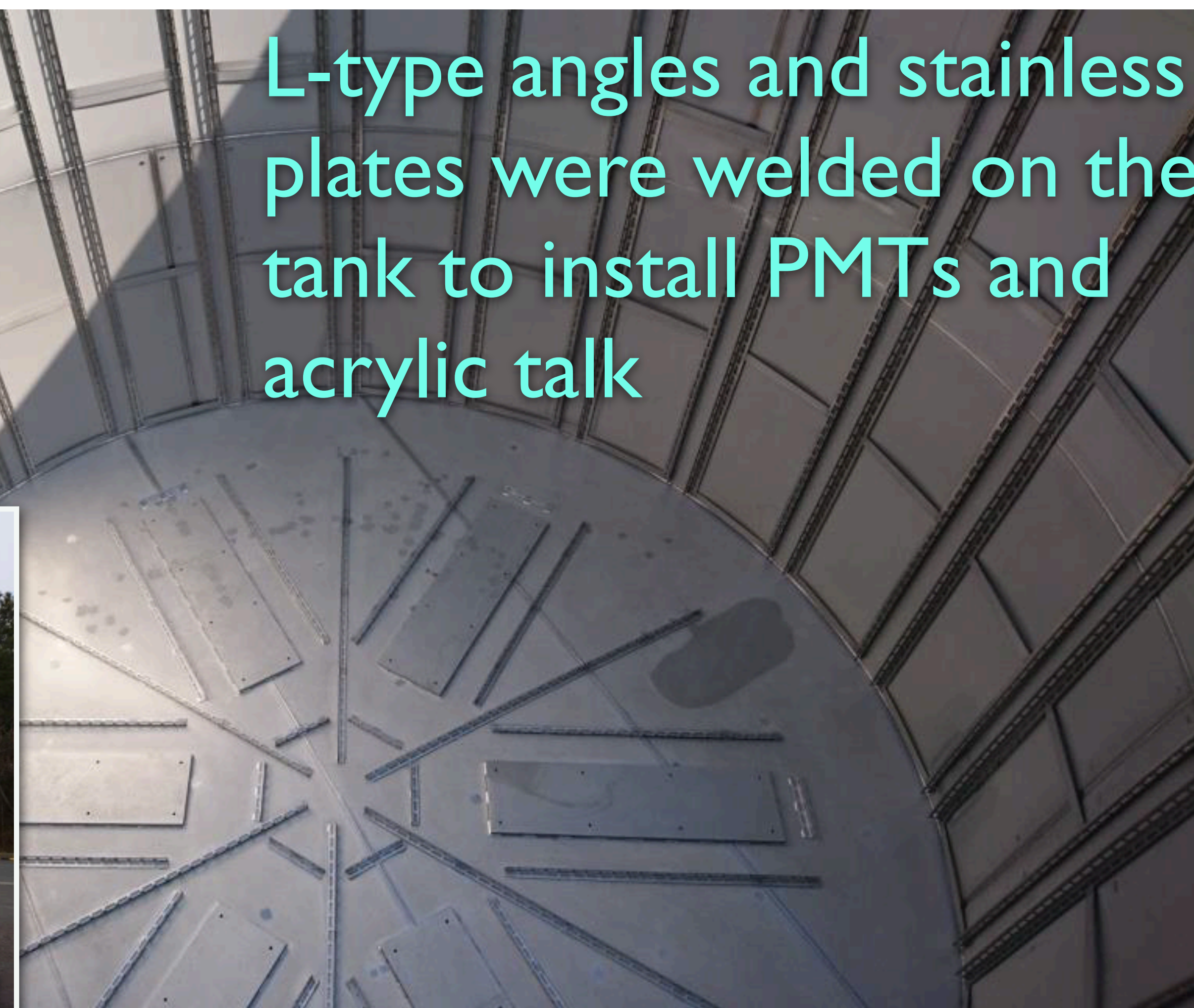
Reaction rates are to be known with accuracy better than ~10%!

Experiment	$\sigma(^{12}\mathrm{C}(\nu_e,e^-)^{12}\mathrm{N}_{g.s.})$ (10^{-42} cm^2)
KARMEN (PLB332, 251 (1994))	9.1±0.5±0.8 (10.4%)
LSND (PRC64, 065501 (2001))	8.9±0.3±0.9 (10.7%)
JSNS^2 (arXiv:1601.01046)	(~3%(stat.) expected in 5yrs)

JSNS^2 Experimental Status

Stainless Steel Tank Construction

- Stainless steel tank construction at J-PARC (Dec 2017 - Jan 2018)
- Welding and water leak test completed in Feb 2018

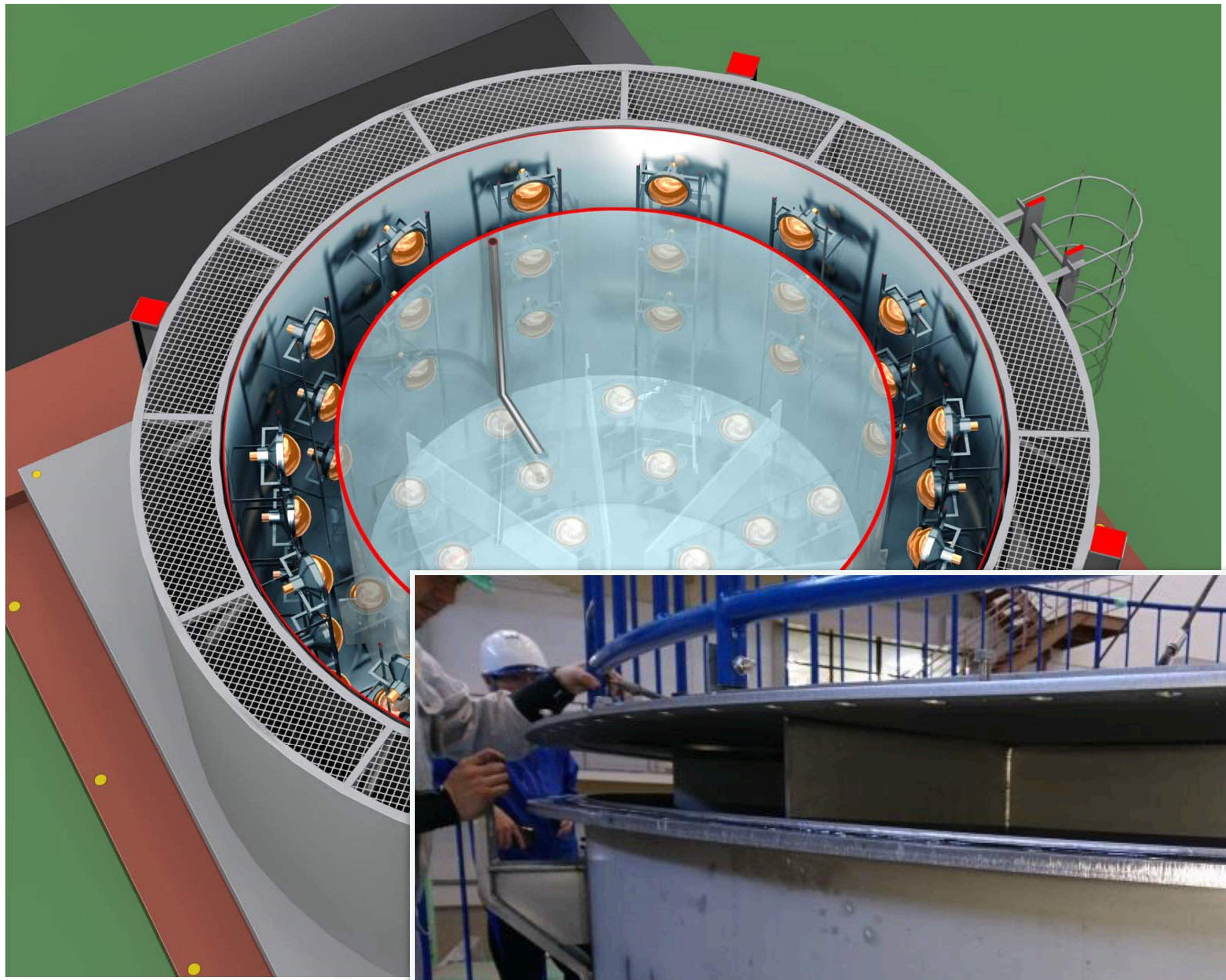


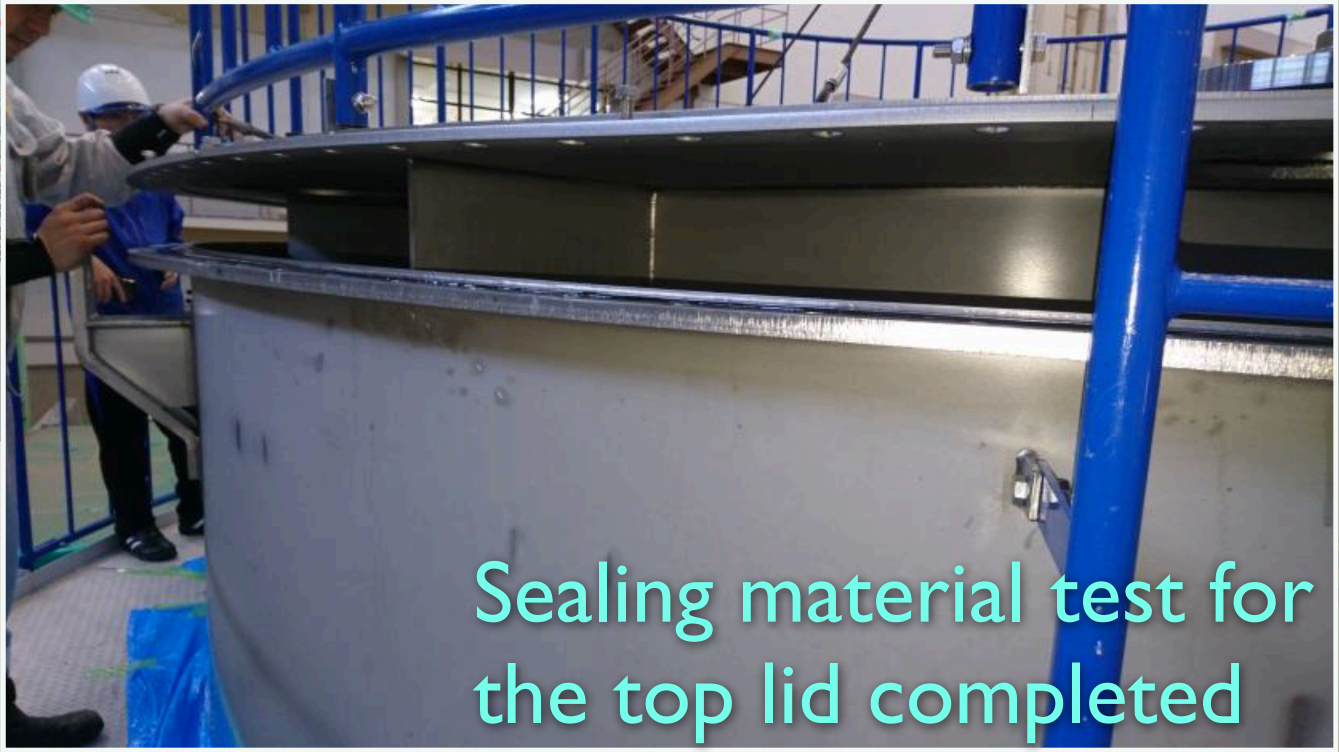
Transport of the tank to the assembly building

Tank was moved about 2.2km

Installation Work

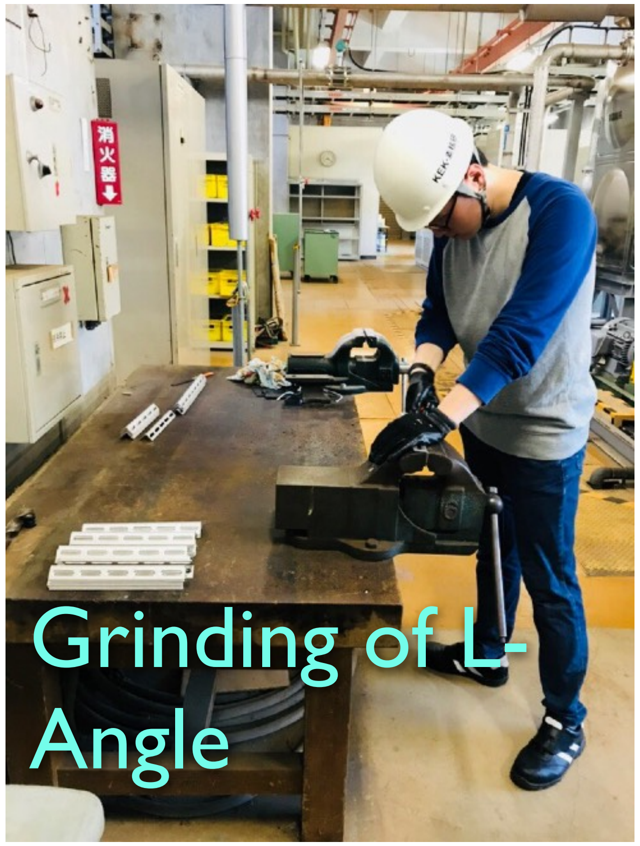
- Installation work has been on-going since March 2018





Sealing material test for the top lid completed

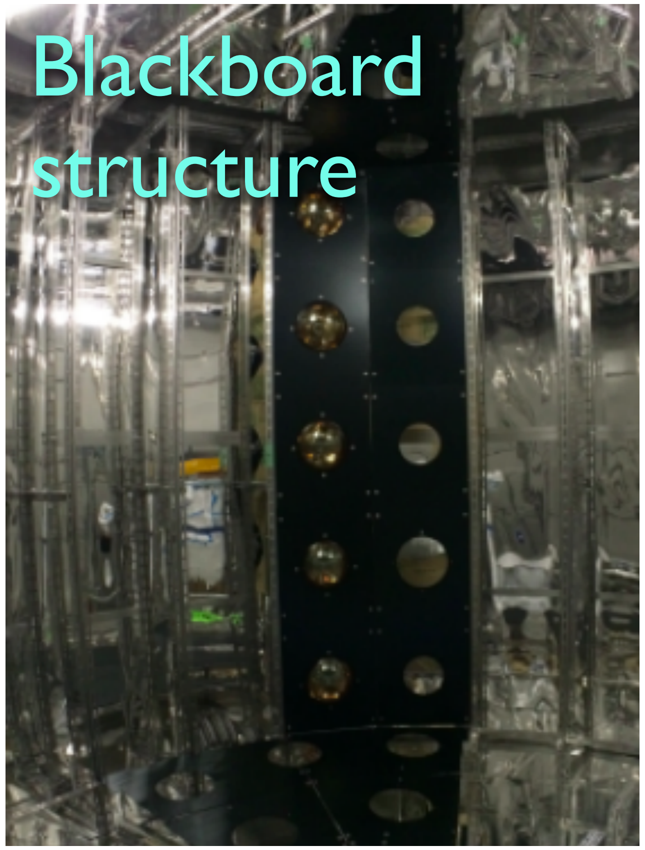
July 24, 2018

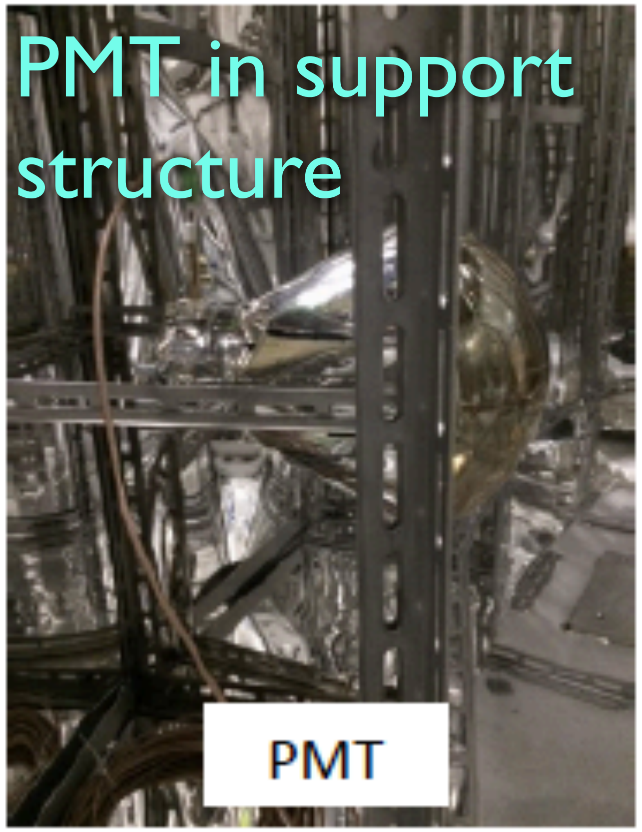


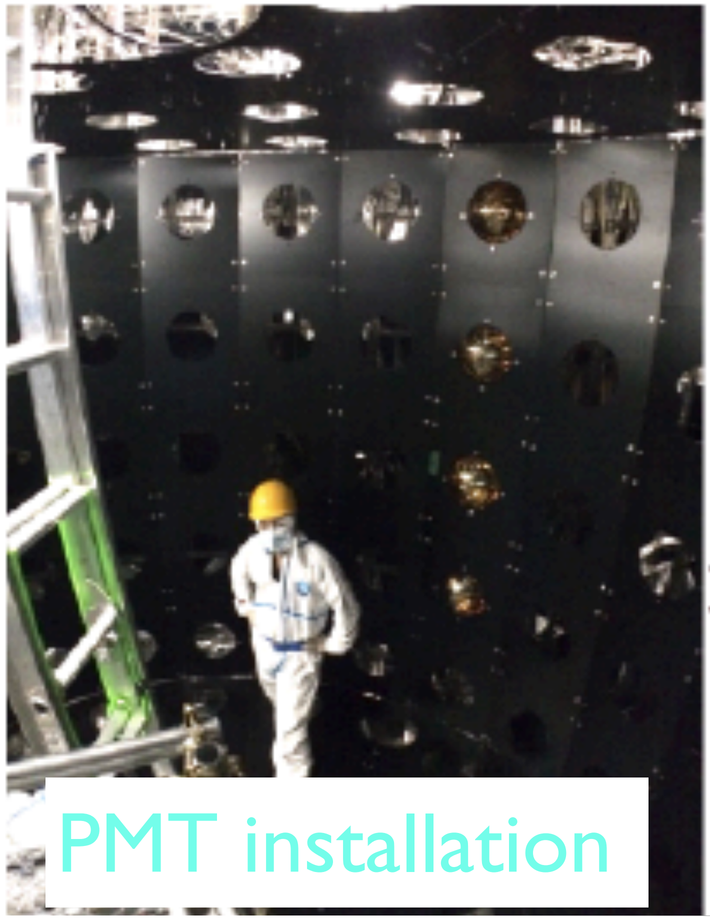
Inner tank work
Spring/Summer 2018

Installation work inside of the Stainless steel tank

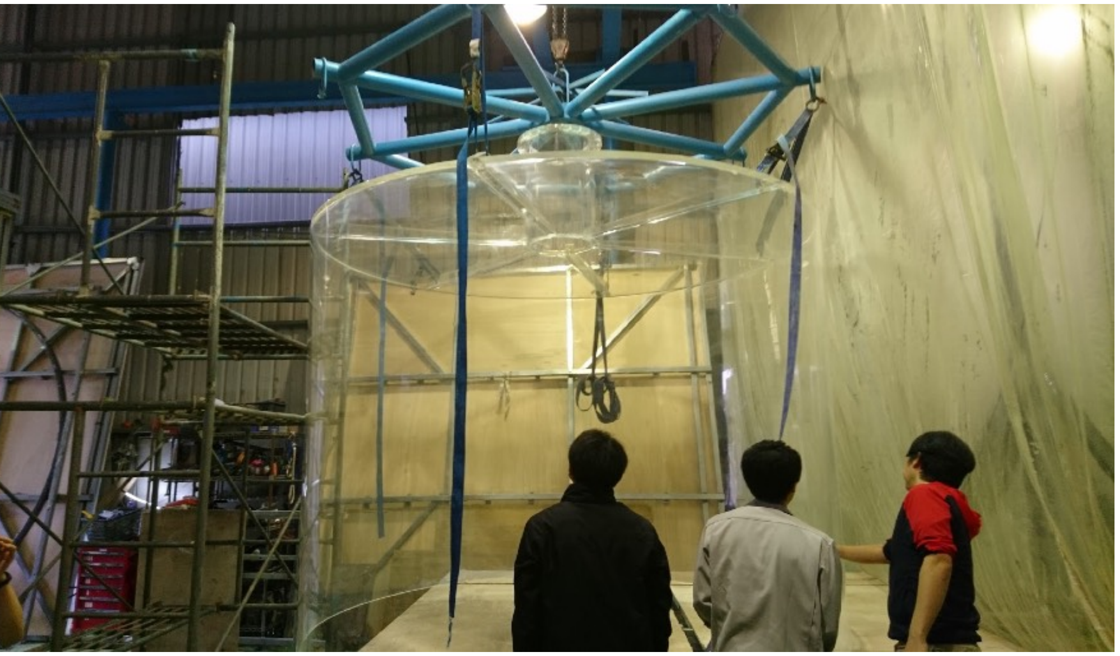
- Cleaning with pure water and ethanol
- Ultra-sonic cleaning of components and ethanol
- Completed installation of PMT support structure
- Installation of optical separators
- PMT installations

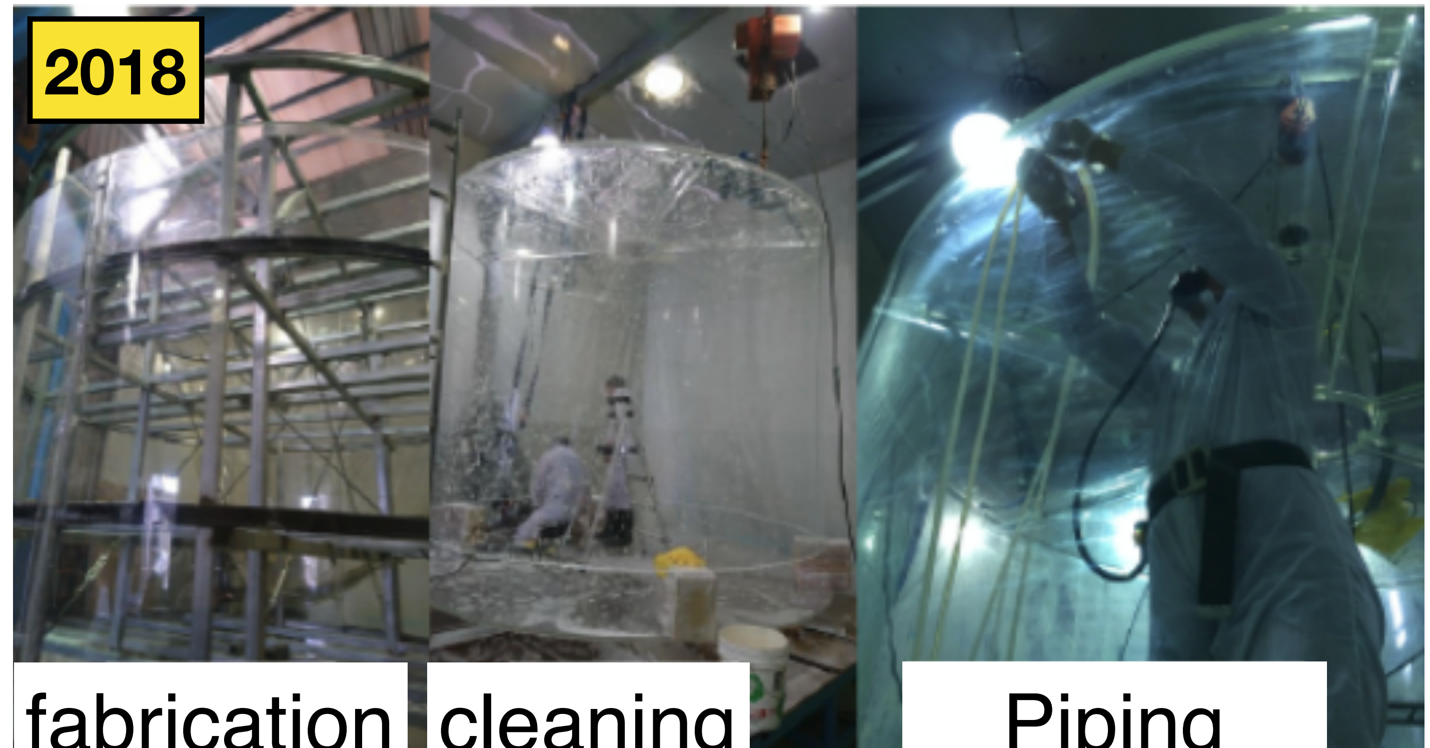




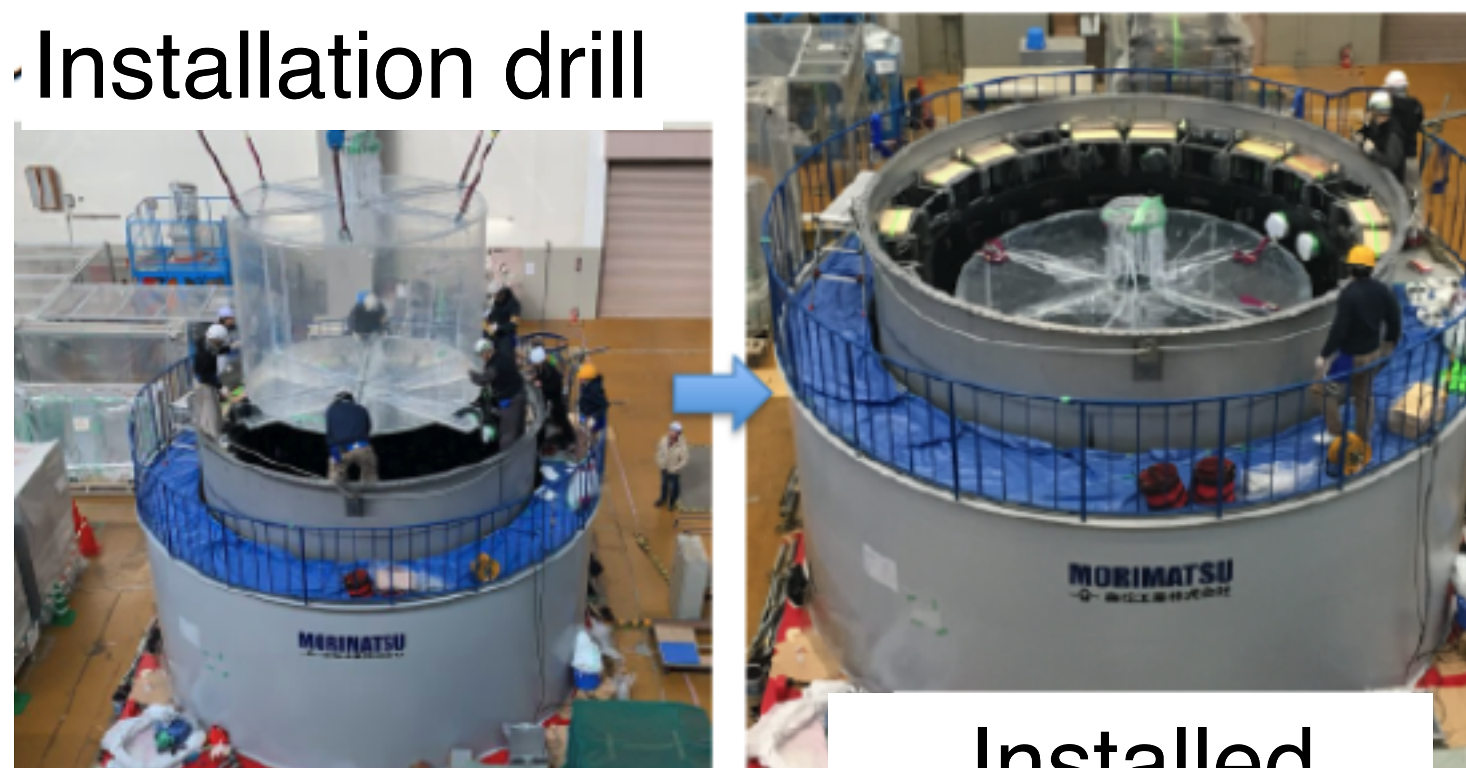


Acrylic tank ready





Installation drill

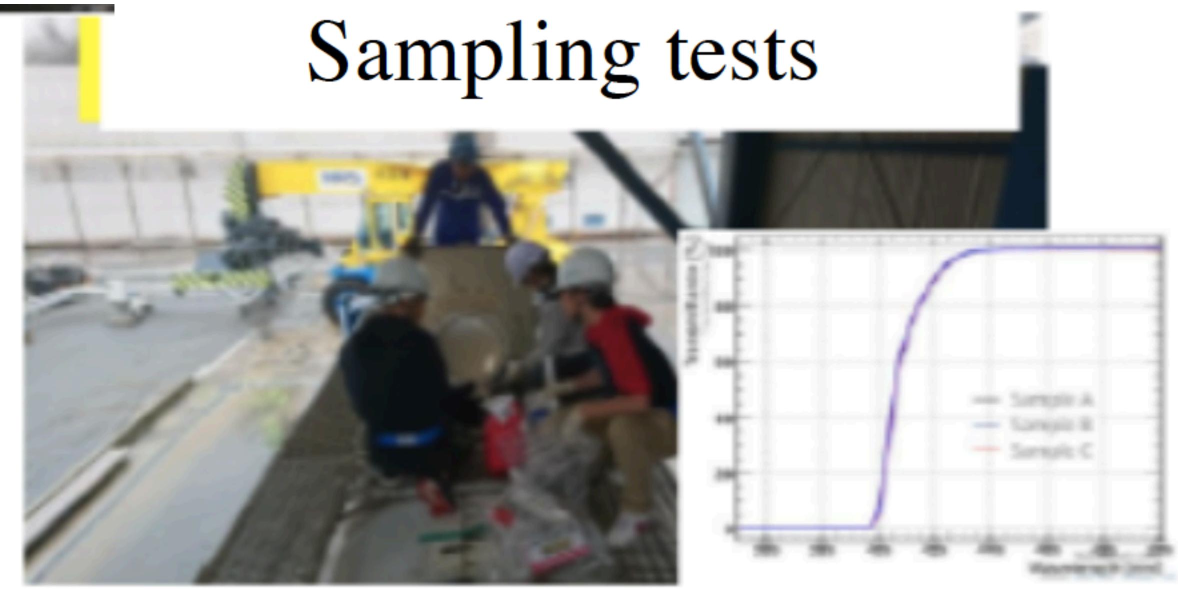


Liquid Scintillator

LS was produced during Fall 2018 in Korea and was delivered to Japan
Quantity: 21 batches in total (37000 L)
Storage: 2 ISO tanks
Man-power: 4 peoples per day (6x 1/2 weeks shift)

Schedule	Activities
Sep. 12-18, 2018	Refurbishment and cleaning
Sep. 28, 2018	ISO tank arrived at RENO site
Oct. 1 - 22, 2018	LS production (6 shift periods)
	Shipping of ISO tanks to Japan

LS from Korea (unloaded)

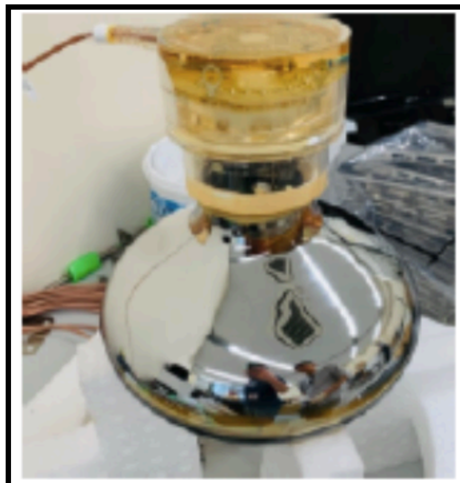


Gd loaded LS
(donated from Daya-Bay)
[We thanks the DB group👍]

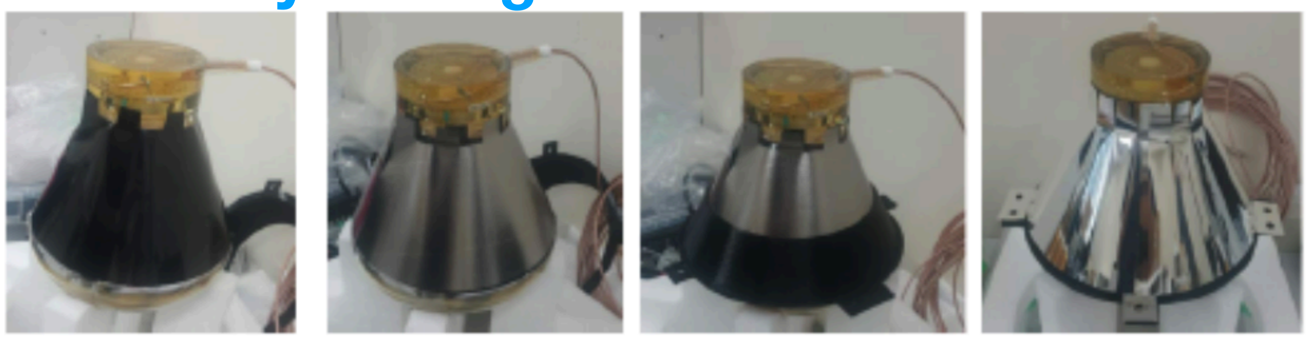
June 2019	Empty ISO-tank was sent to China
June/July 2019	ISO-tank filled with Gd-LS by Daya-Bay team members
July 2019	ISO-tank left Huanpu
Aug 2019	the Gd-LS has arrived in Japan. Now at our storage yard (Kawasaki)

PMTs / calibration /electronics

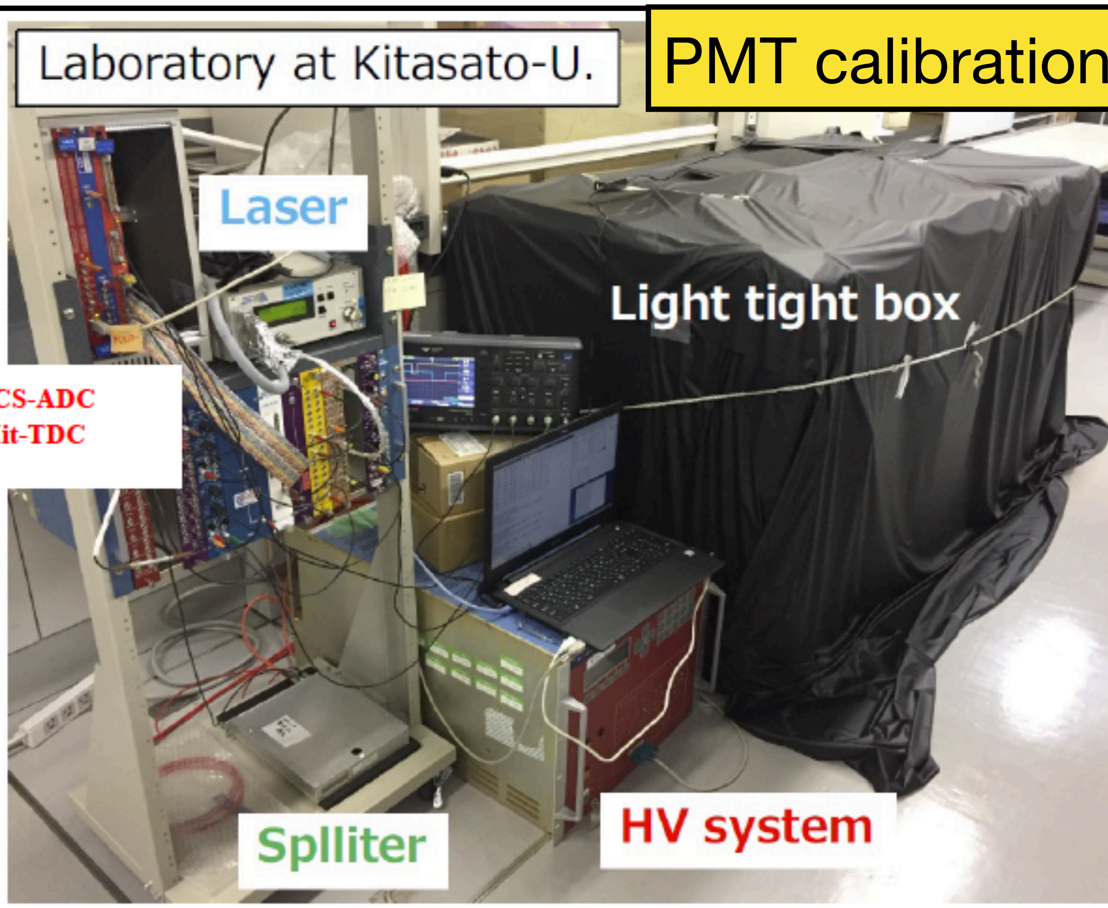
JSNS² uses 10" PMTs from RENO & Double CHOOZ spares + newly purchased PMTs



Assembly of magnetic shield

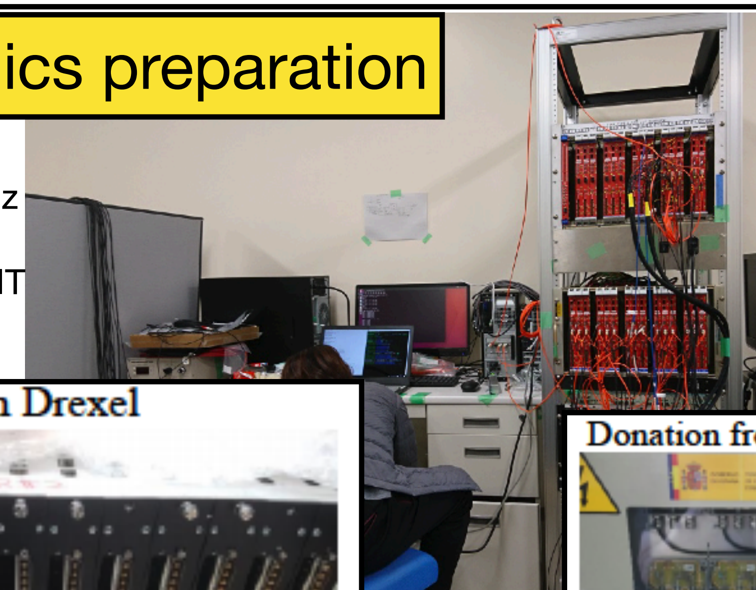


PMT calibration



Electronics preparation

Success to take data 8bit 500MHz FADCs
Donation from TIT



Donation from Drexel

< Amplification modules with analog sum >

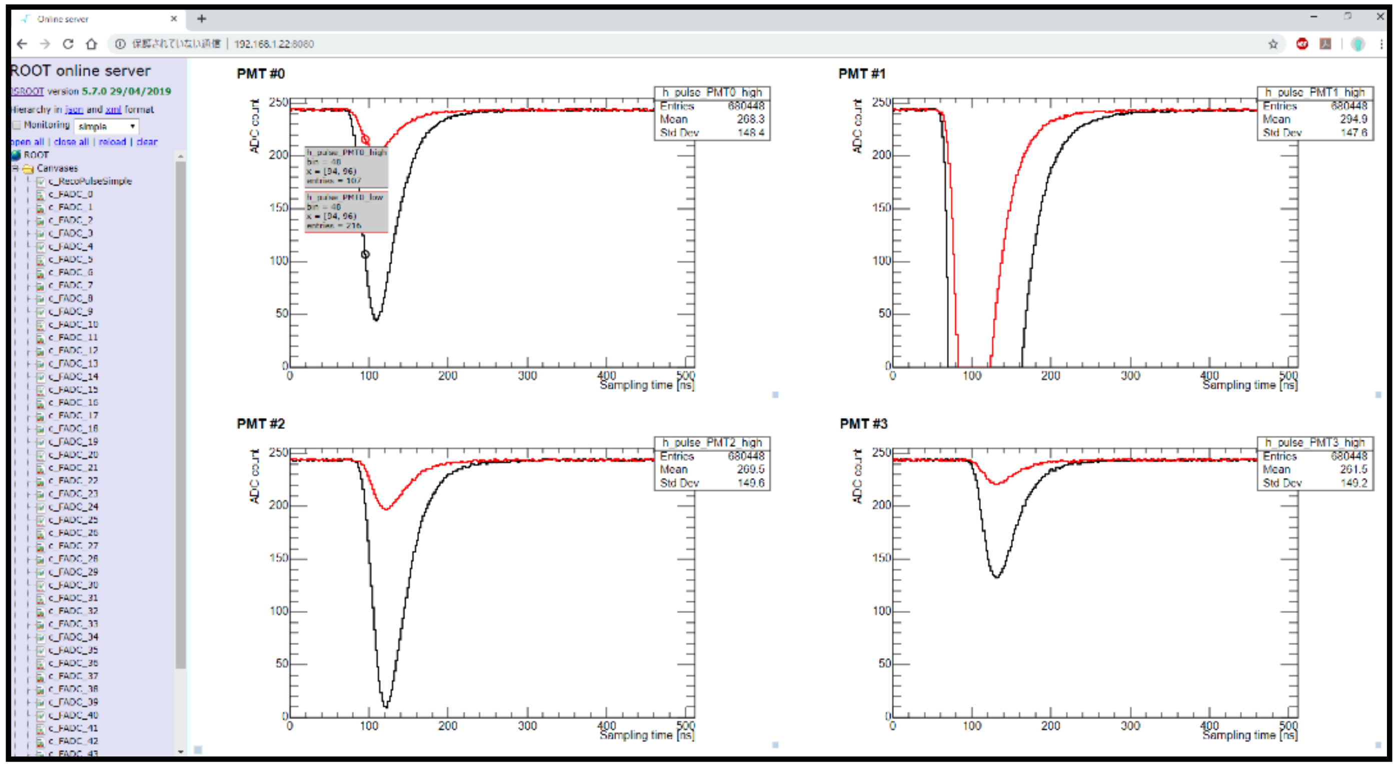
Donation from CIEMAT

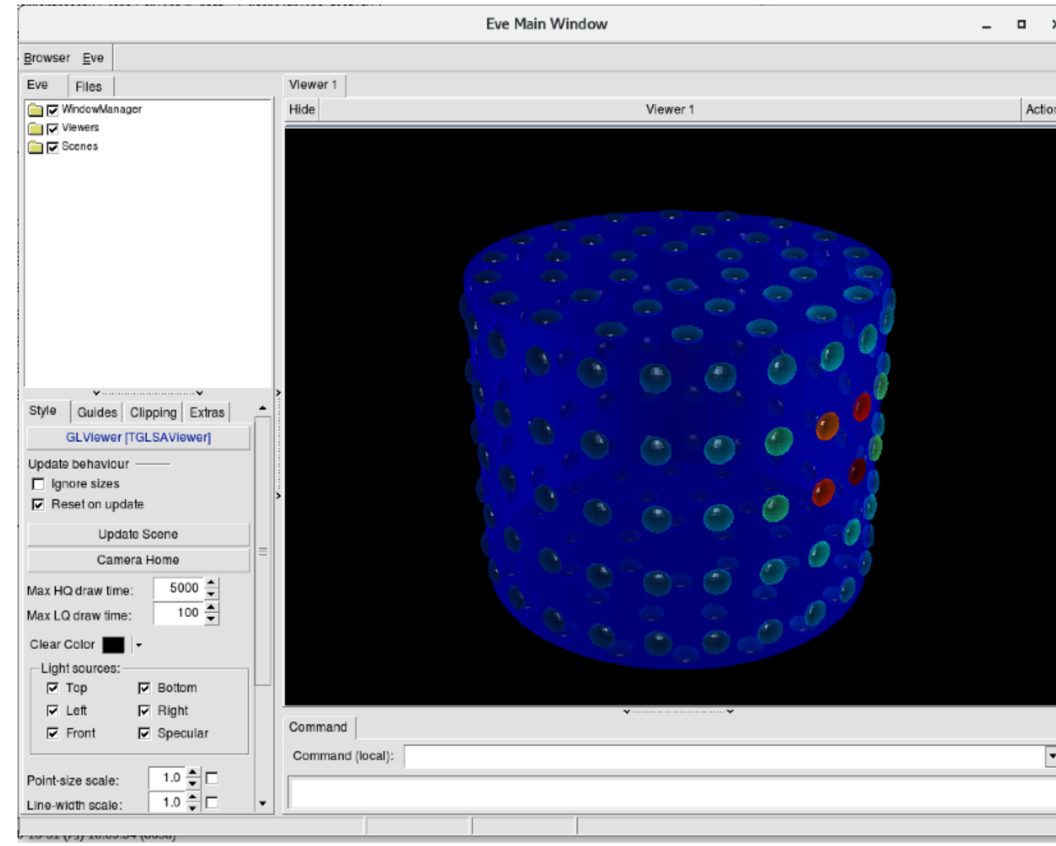
196 ch of signal/HV separator

➡PMTs mostly in hand and securing more

➡Upgrade with Michigan JSNS2 (500MHz, 14bit electronics)

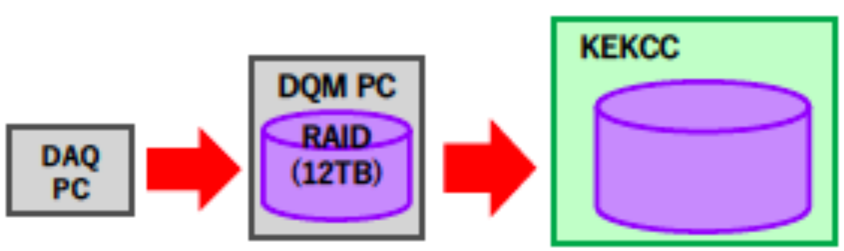
Online Data Quality Monitor /display

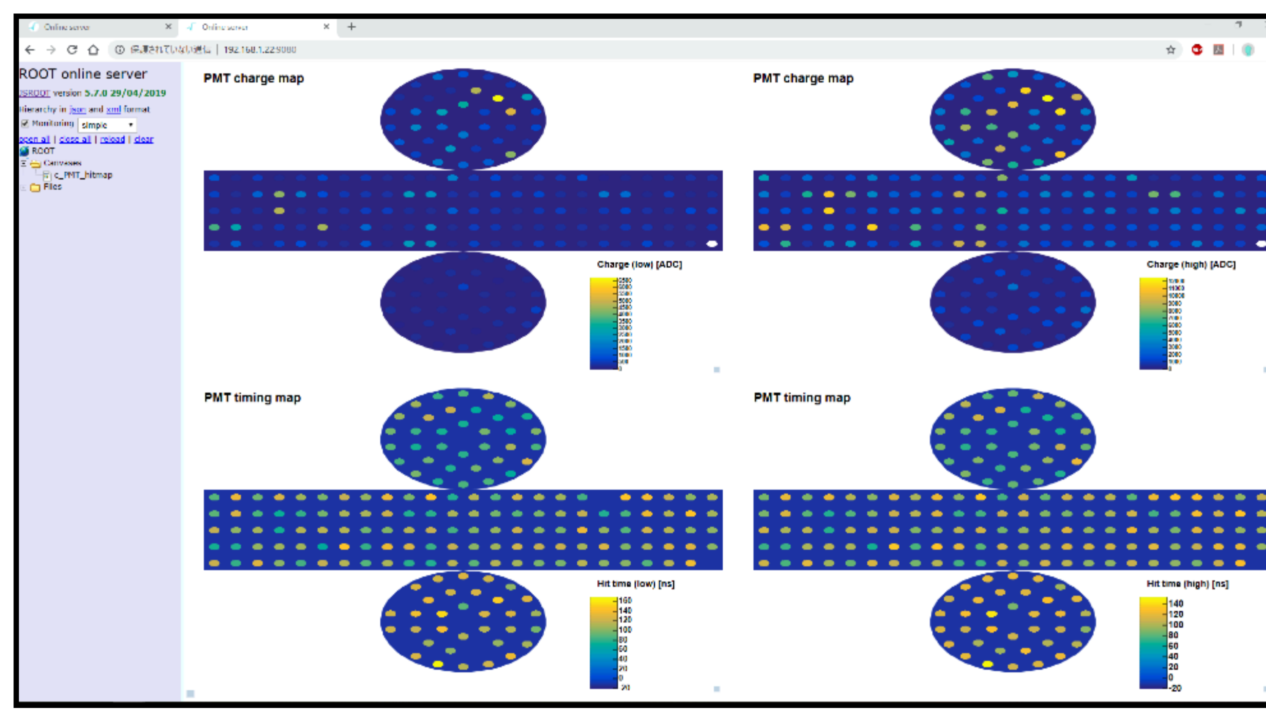




Online DQM framework is ready

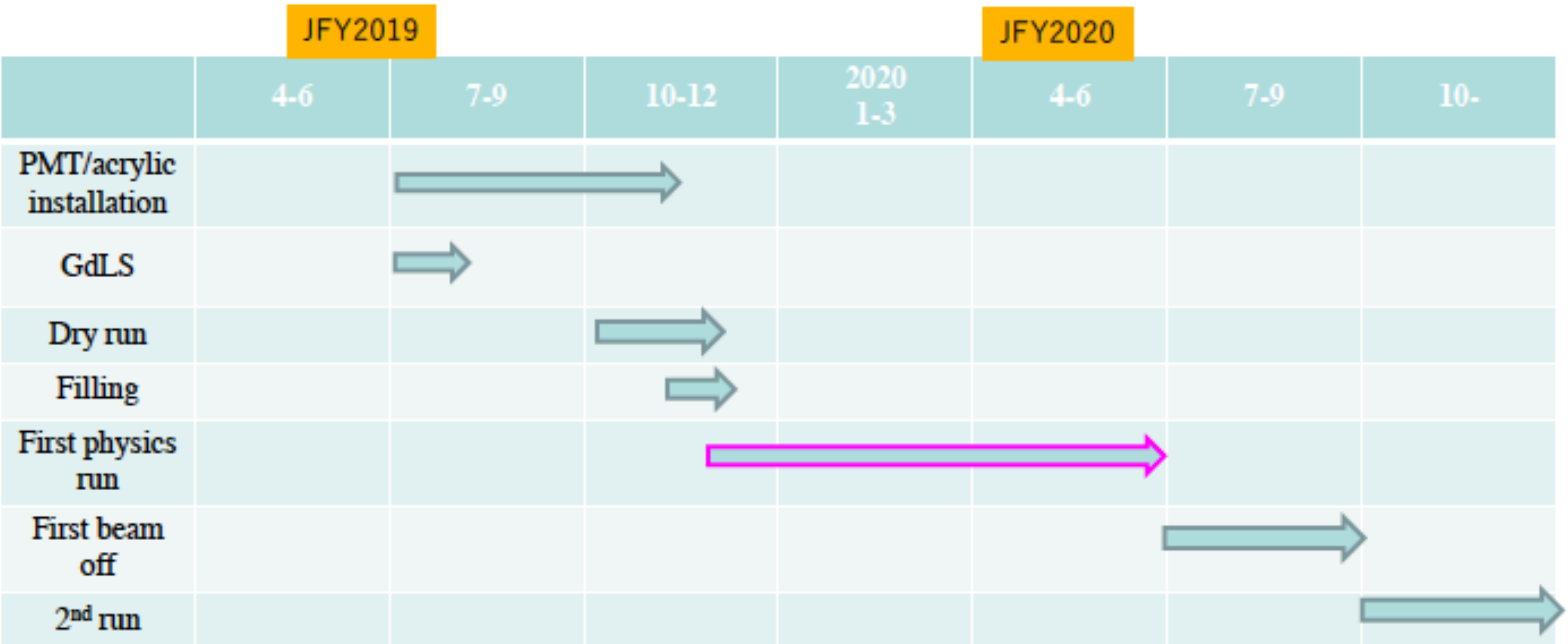
- Analyzes online FADC data into Hit map / Waveform /3D display
- Stores data files in 12 TB disk
- Copies to KEKCC (not connected)





Almost ready

Overall schedule

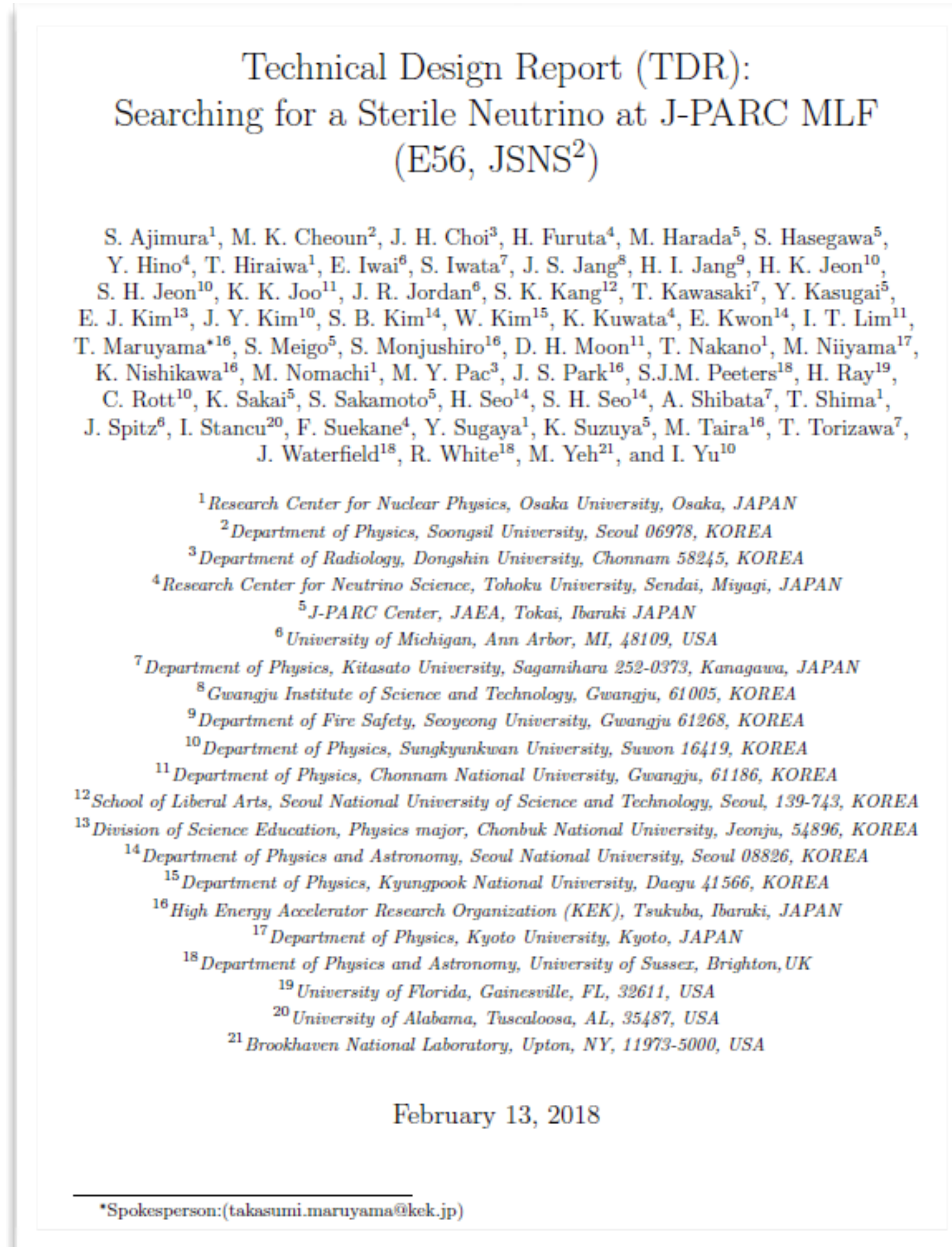


Eager to start the experiment in early 2020

Conclusions

Conclusions

- The neutrino sector has proven numerous times to hold surprises
  - Global neutrino data is inconclusive on the existence of sterile neutrinos
  - During the past two decades, sterile neutrino searches wear driven by the LSND anomaly and results obtained in the follow up experiments
- The JSNS² experiment is a direct and ultimate test of the long standing LSND anomaly
  - The same neutrino source, target material and almost identical baseline length will be used
- Detector preparations nearly completed
- J-PARC beam power approaching design value
- JSNS² will start in early 2020 to search for sterile neutrinos
- Rich physics program associated with JSNS² besides the sterile neutrino search



Technical Design Report (TDR):
Searching for a Sterile Neutrino at J-PARC MLF
(E56, JSNS²)

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], H. K. Jeon[10], S. H. Jeon[10], K. K. Joo[11], J. R. Jordan[6], S. K. Kang[12], T. Kawasaki[7], Y. Kasugai[5], E. J. Kim[13], J. Y. Kim[10], S. B. Kim[14], W. Kim[15], K. Kuwata[4], E. Kwon[14], I. T. Lim[11], T. Maruyama*[16], S. Meigo[5], S. Monjushiro[16], D. H. Moon[11], T. Nakano[1], M. Niiyama[17], K. Nishikawa[16], M. Nomachi[1], M. Y. Pac[3], J. S. Park[16], S.J.M. Peeters[18], H. Ray[19], C. Rott[10], K. Sakai[5], S. Sakamoto[5], H. Seo[14], S. H. Seo[14], A. Shibata[7], T. Shima[1], J. Spitz[6], I. Stancu[20], F. Suekane[4], Y. Sugaya[1], K. Suzuya[5], M. Taira[16], T. Torizawa[7], J. Waterfield[18], R. White[18], M. Yeh[21], and I. Yu[10]

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February 13, 2018

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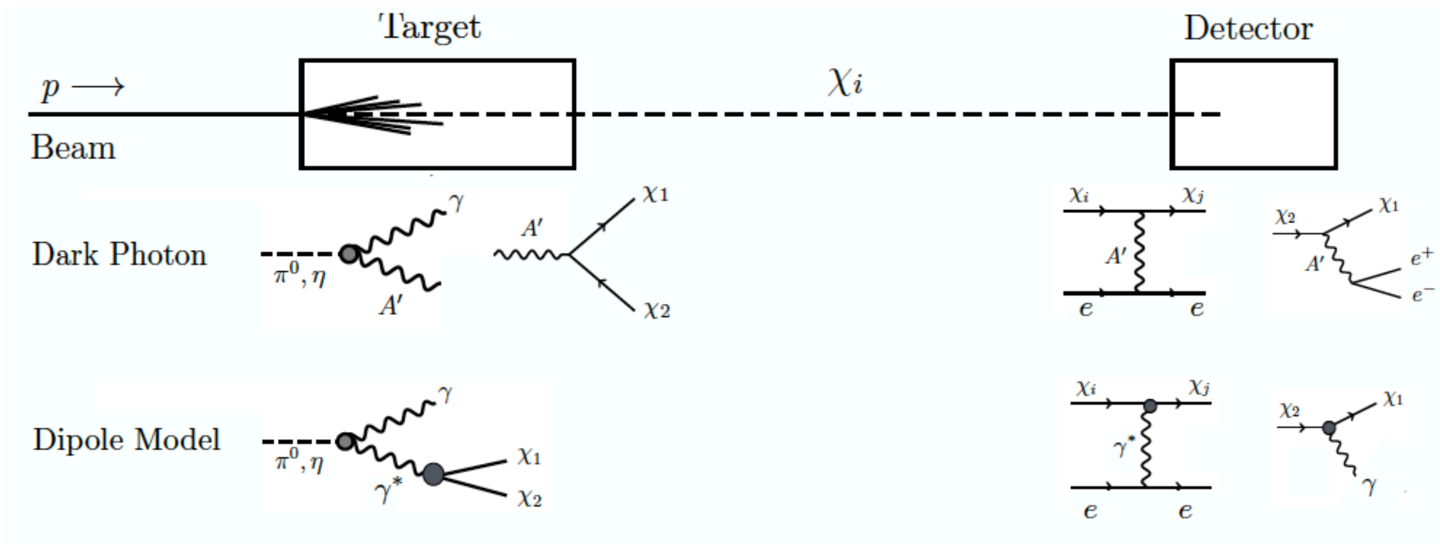
For details please see the JSNS² TDR: arXiv:1705.08629

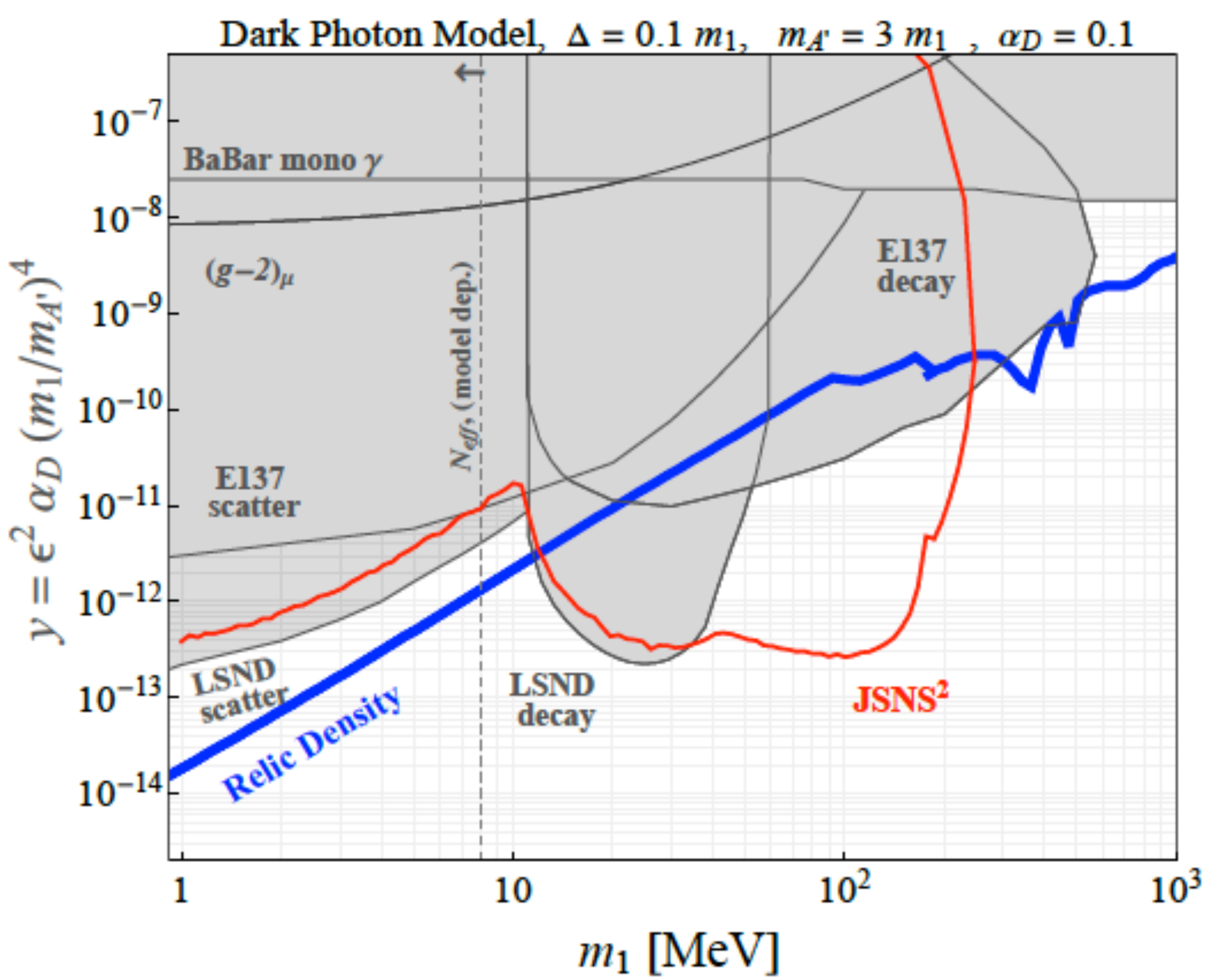
Backup

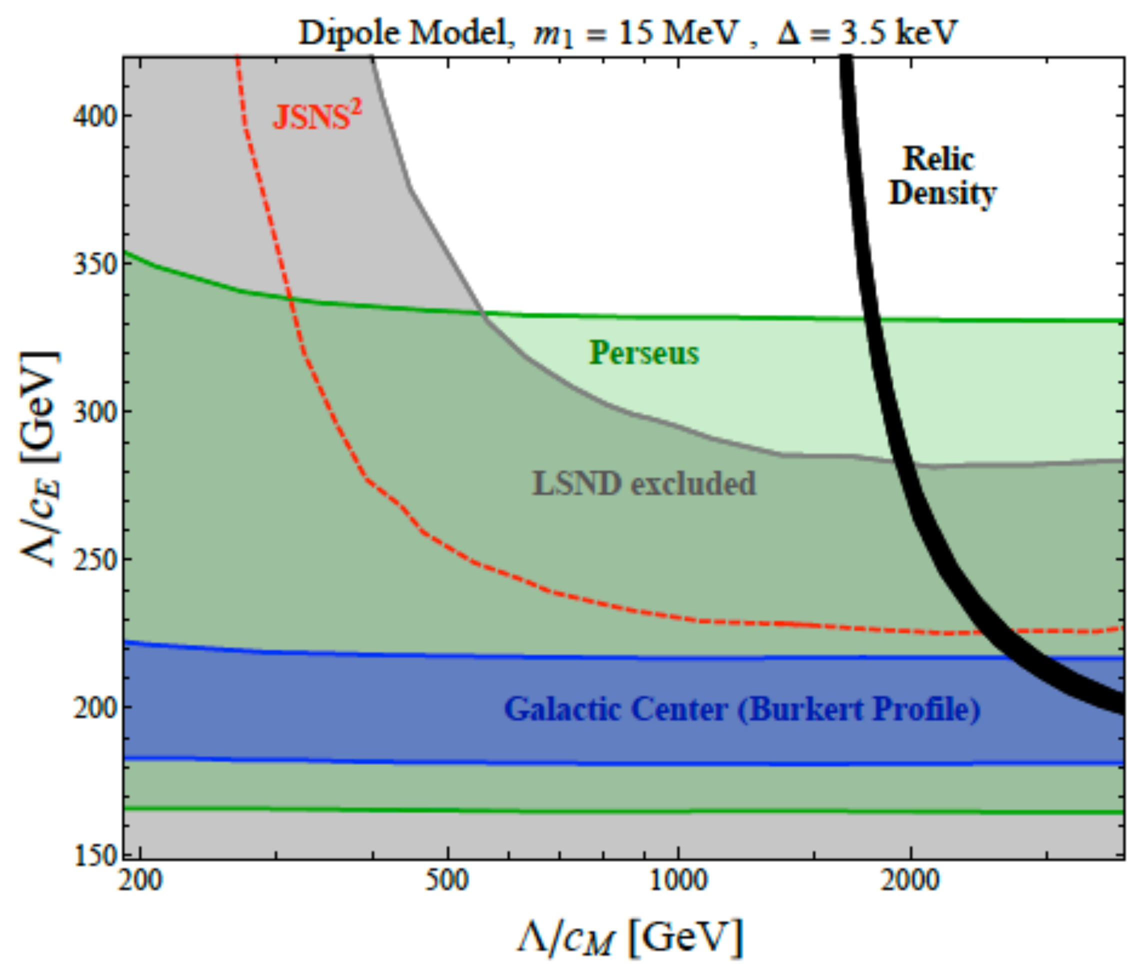
Phys. Rev. D 98, 075020 (2018)

Pseudo-Dirac Dark Matter



- Dark photon models can be tested with JSNS²
- LSND and future JSNS² measurements can severely constrain/test the viable parameter space dipole dark matter which could explain the 3.5 keV excess





Dark Photon Models

J. Alexander et al. (2016) arXiv:1608.08632 [hep-ph].
M. Battaglieri et al., (2017), arXiv:1707.04591 [hep-ph]

Dipole Models:

F. D'Eramo, K. Hambleton, S. Profumo, and T. Stefaniak, Phys. Rev. D93, 103011 (2016), arXiv:1603.04859

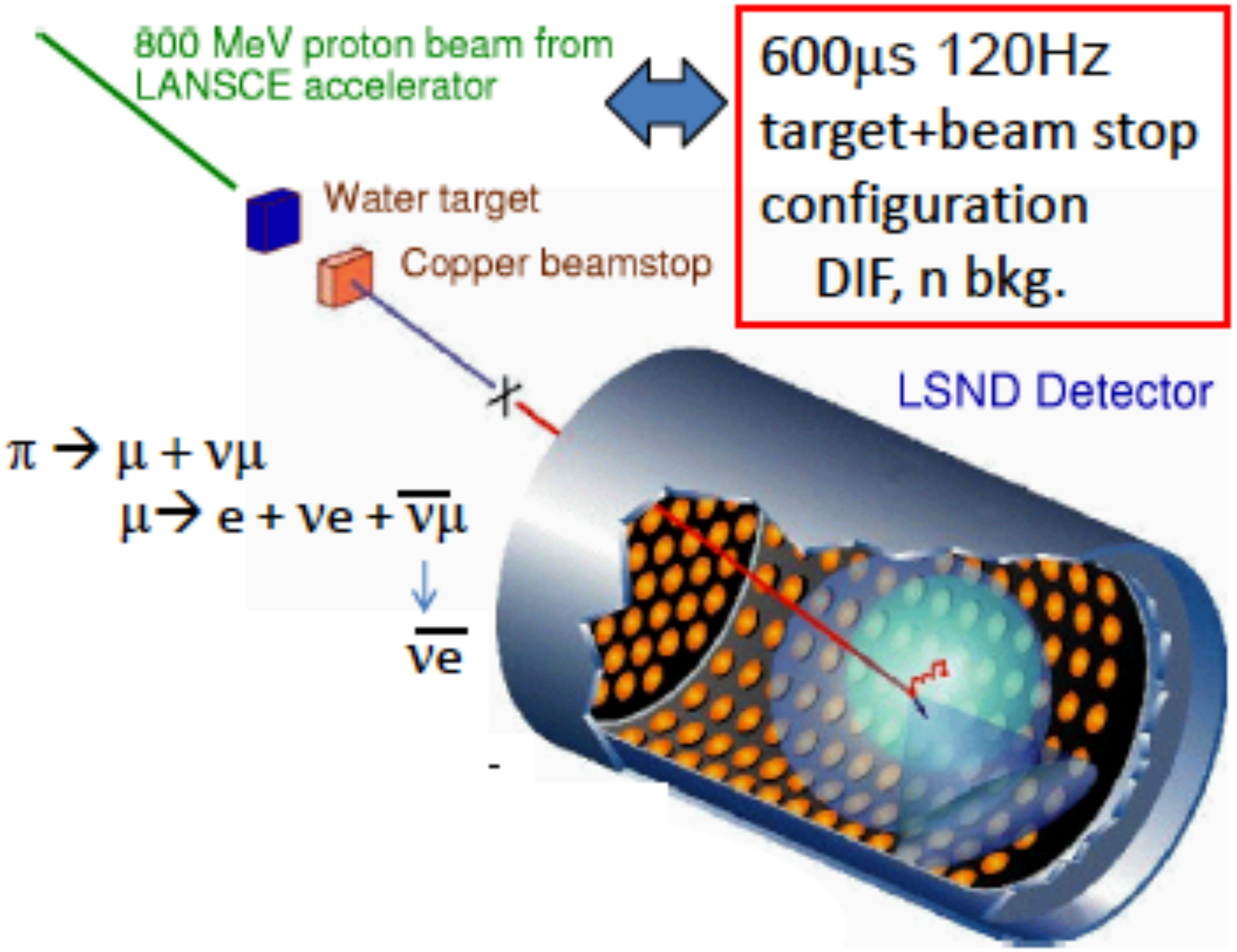
LSND

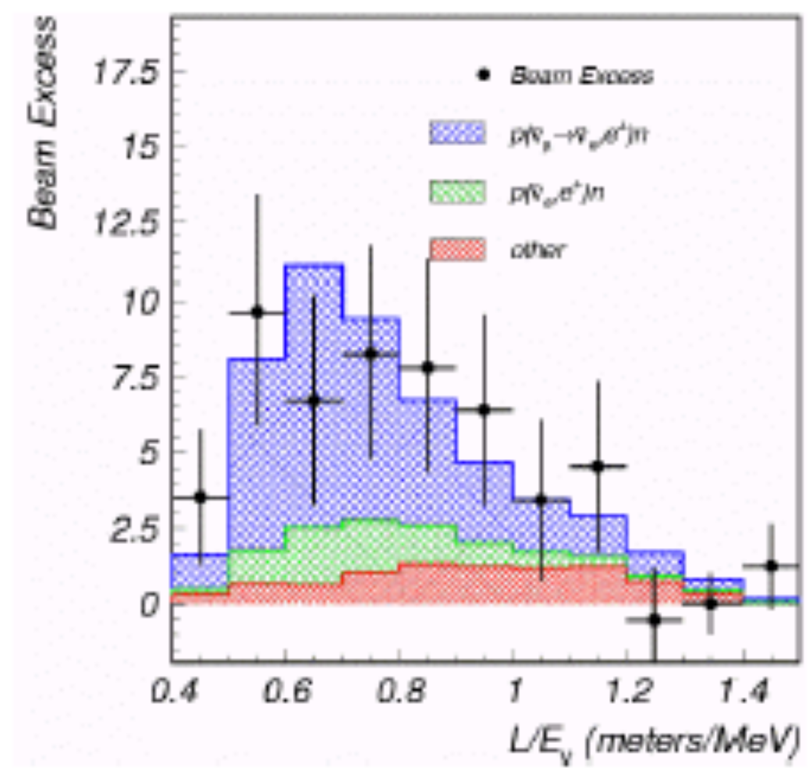
Appearance

LSND $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ Signal

1998 at LANL

600μs 120Hz
target+beam stop
configuration
DIF, n bkg.





Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of
(0.264 ± 0.067 ± 0.045)%.

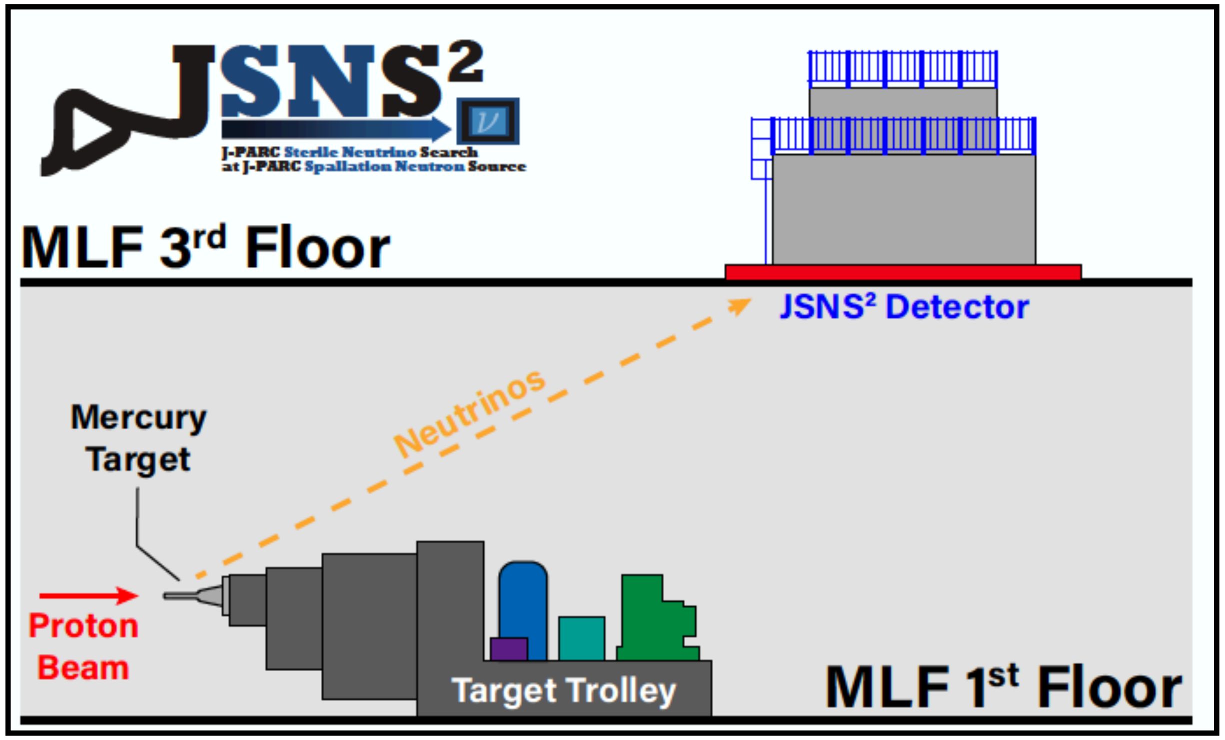
3.8 σ evidence for oscillation.

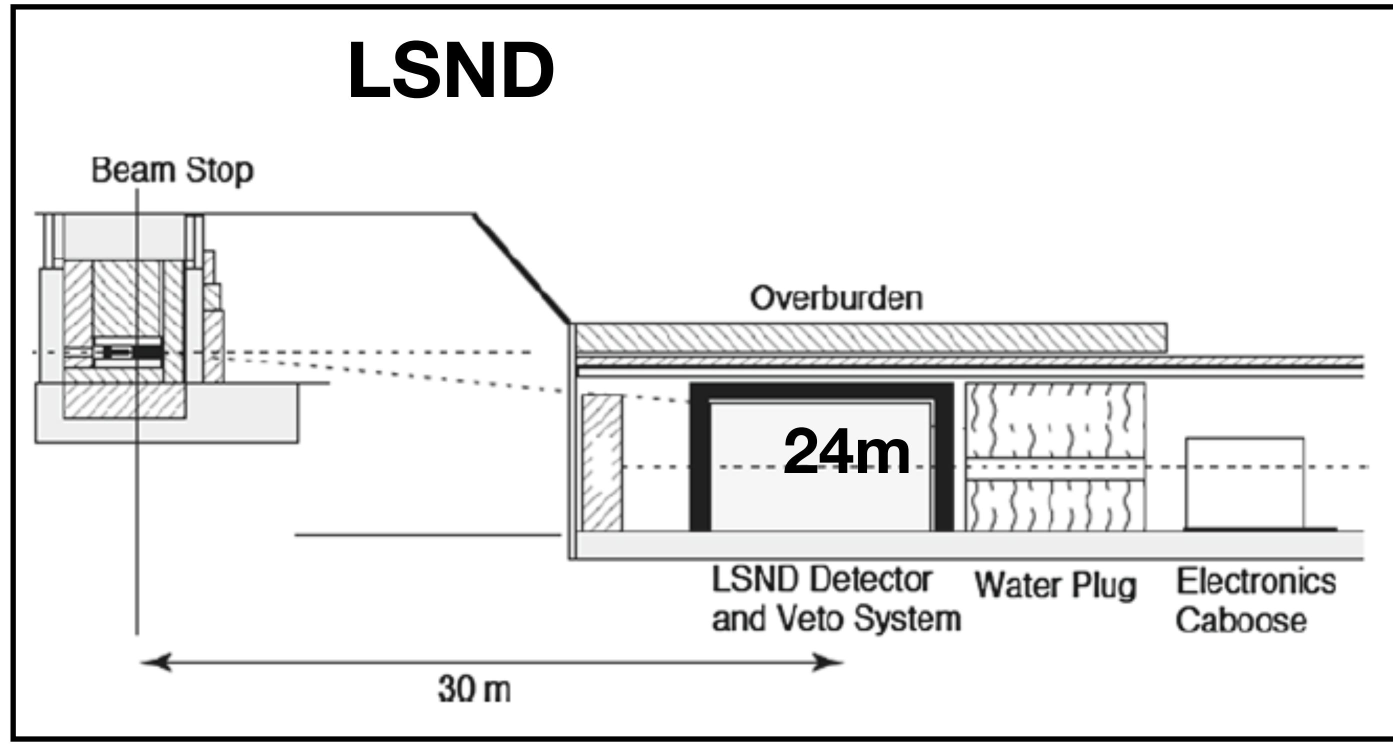
π^-, μ^- absorbed before decay into ν's
there should not be $\overline{\nu e}$ at the level of $7\text{x}10^{-4}$

Signal : $\overline{\nu e}$ p→e⁺n np→d γ(2.2MeV)

Takasumi Maruyama @ DBD2018

JSNS² / LSND comparison





- Same neutrino signal (muon decay at rest)
- Same detection mechanism (Inverse beta decay (IDB))
- Similar baseline (24m vs 30m)
- Low beam backgrounds (detector location / short pulses)
- Much better S/N (pulsed beam, neutron tagging via Gd, PSD)
- Better energy resolution. (Scintillator vs Ch.-level light)
- High statistics

JSNS2 / LSND comparison

	JSNS²(1st phase)	LSND
Target Mass.	17t	167t
Baseline	24m	30m
Beam energy	3GeV	0.8GeV
Beam power	1MW	--
Beam Duty Factor	1/8,800	1/14
Stopping μ^-/μ^+	1.7×10^{-3}	6.5×10^{-4}
Delayed signal	8MeV, $\Delta t \sim 30\mu s$	2.2MeV, $\Delta t \sim 200\mu s$
Liquid Scintillator	Gd Loaded	Cherenkov + Low LO Scinti.
Cosmic fast n rejection	Pulse Shape Discri.	Cherenkov
$\bar{\nu}_e$ signal events	29/year $(\sin^2 2\theta = 0.003)$	15/year
$\Delta E/E$	3%@35MeV	7%@45MeV