Detection of Coherent Elastic Reactor Neutrino Scattering & Search for Sterile Neutrino

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Overview

Development of a Bolometric Detector "LOCOND"
For Coherent Reactor Neutrino Elastic Scattering (CEvNS)

- Use a low-radioactivity & phonon sensitive CsI(Na) or HPGe crystals for sufficient CEvNS
- Use a cryogenic sensor such as STJ or TES to have an energy threshold as low as ~10 eV

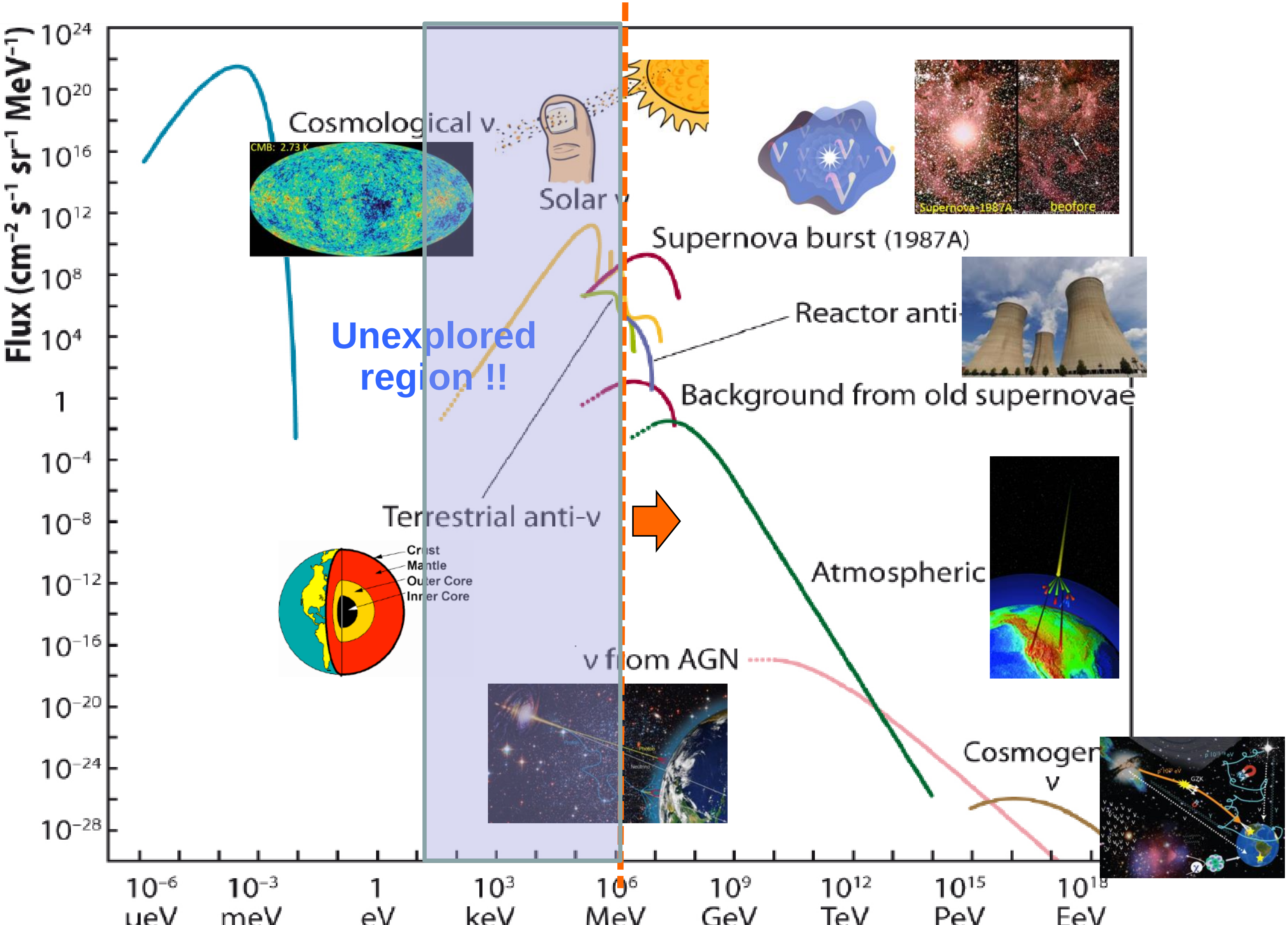
Detection of reactor antineutrino below 1.8 MeV via CEvNS

Open a new field of detecting extremely low-energy neutrinos that have never been observed

- Searches for neutrino magnetic moment and sterile neutrino
- Reactor monitoring for nuclear non-proliferation
- Compact neutrino telescope for core-collapse supernova

* *LOCOND: LOw temperature COherent Neutrino Detector*

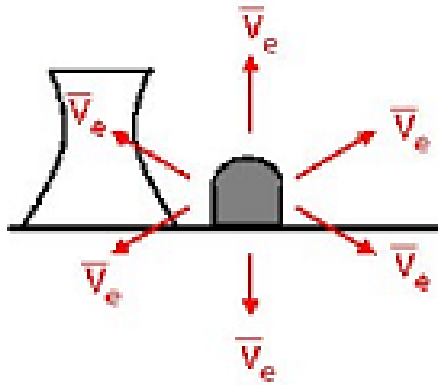
Neutrino Sources and Reactor Neutrino



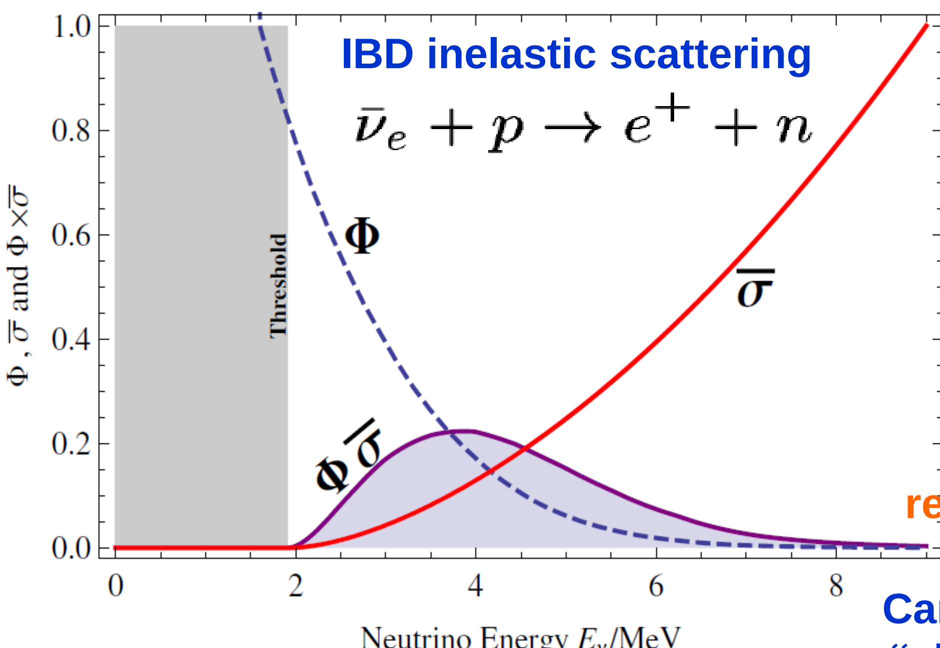
* Taken from Katz & Spiering (2012)

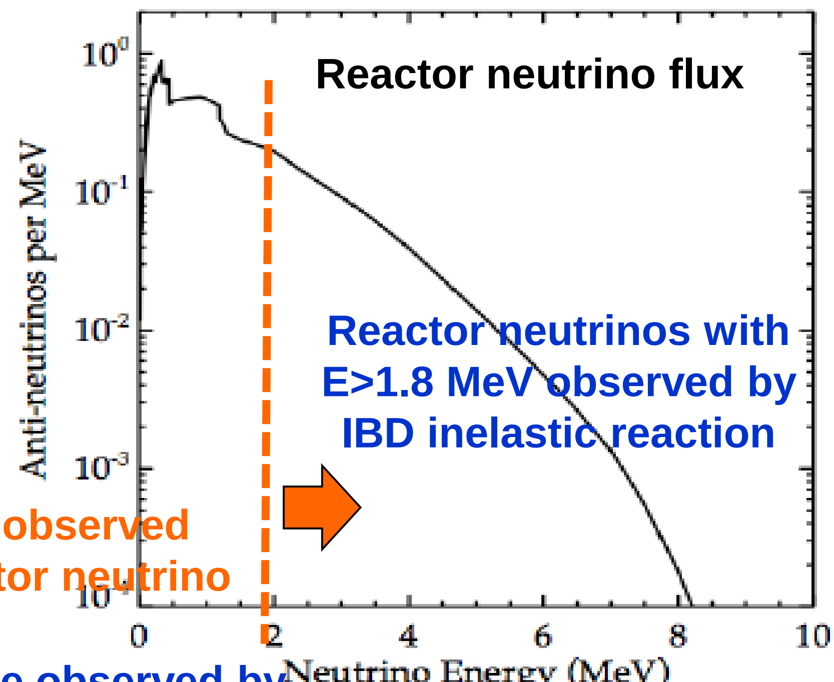
Unobserved Low-Energy Reactor Neutrino

Reactor : copious source of electron antineutrinos



3 GW_{th} reactor
$\rightarrow$ ~$6\text{x}10^{20}$ $\bar{\nu}_e$/sec





Unobserved
reactor neutrino

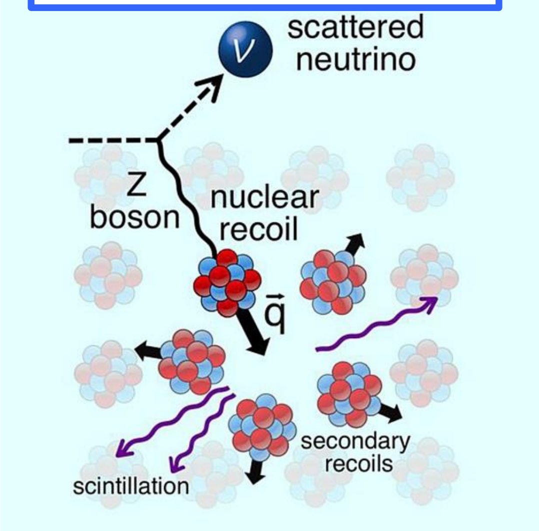
Can be observed by
"elastic" scattering

Enhancement of Low-Energy Neutrino Cross Section

Coherent Elastic Neutrino-Nucleon Scattering **(CEvNS)**

Extremely difficult to detect low energy (E_ν) neutrinos
→ lower cross section (~ E_ν^2)
→ need a large detector and a high flux of neutrinos!

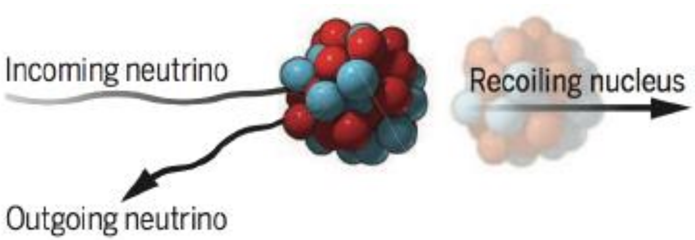
$\nu + N \rightarrow \nu + N$



Z-exchange of a neutrino with nucleus :
→ Coherent up to E_ν ~ 50 MeV
(coherent length ~ 1/ E_ν)
→ Nucleus recoils as a whole

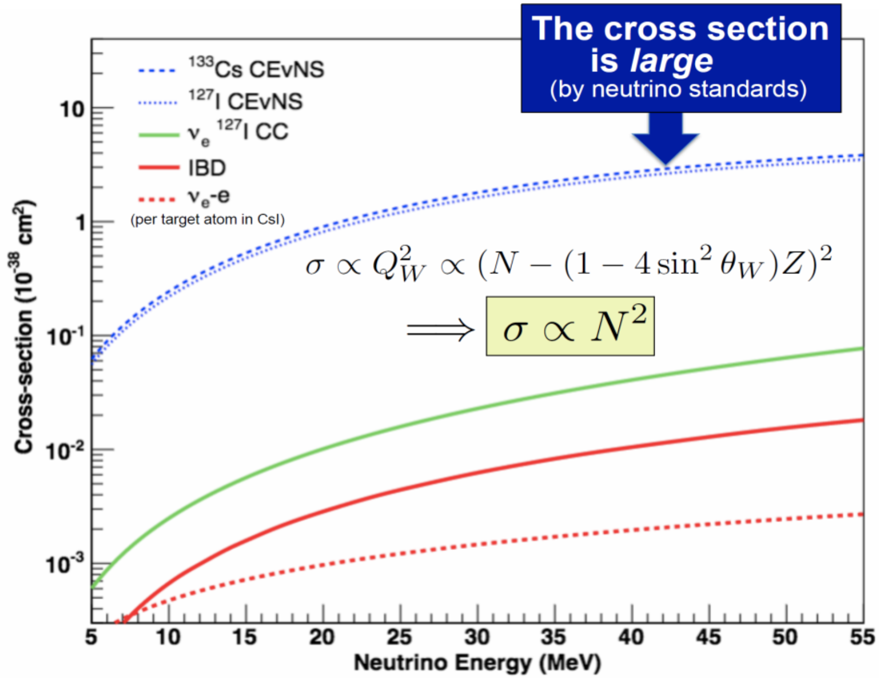
$$\left(\frac{d\sigma}{dT}\right)^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N \underbrace{\left[Z(1-4\sin^2\theta_W) - N\right]}_{\sim N}{}^2 \left[1 - \frac{m_N T_N}{2E_\nu^2}\right] \quad \sim N^2$$

N≈40 → N^2=1600 → detector mass 10 t → a few kg



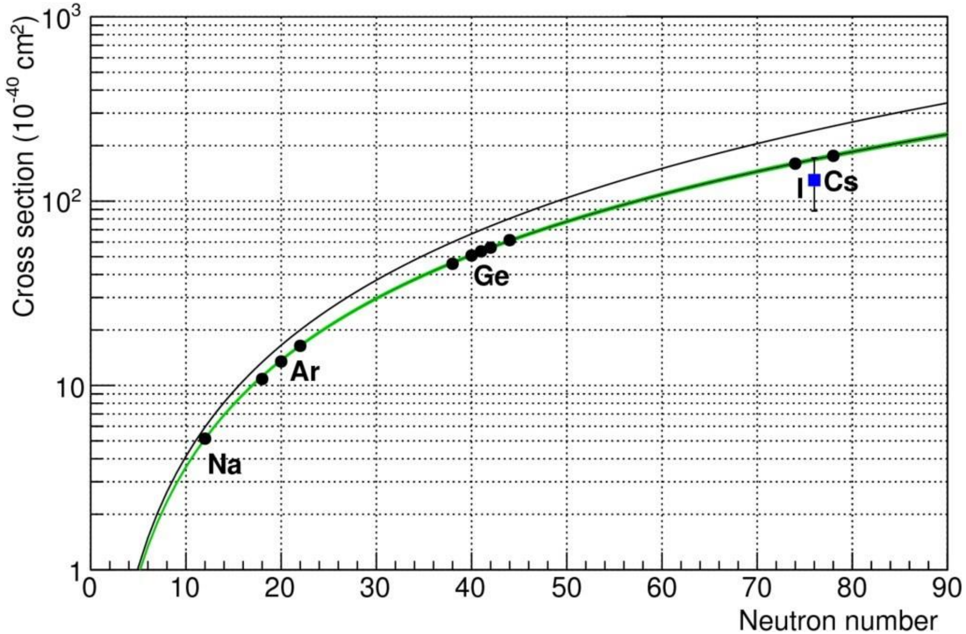
Enhanced (~100 times) neutrino cross section at low energy (D.Z. Freedman, 1974)

Enhanced Neutrino Cross Section via CEvNS



A neutrino becomes coherent up to ~50 MeV.

CsI and Ge crystals can provide sufficient CEvNS cross sections.



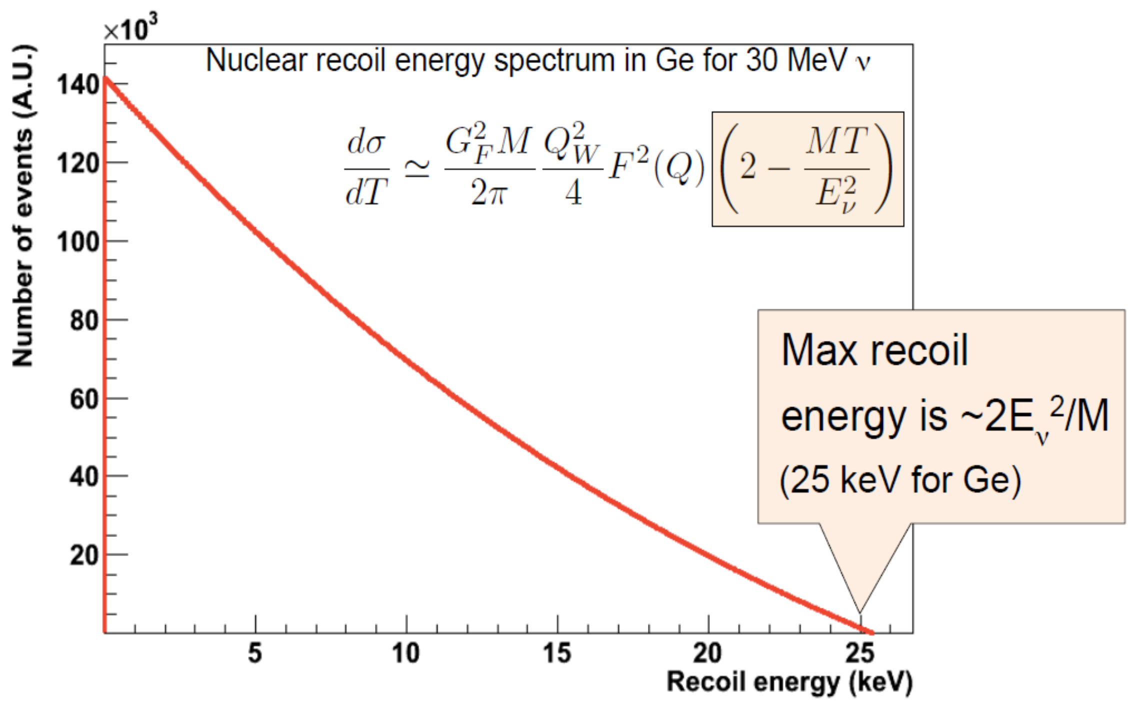
Challenge: Tiny Nuclear Recoil Energy

- **Extremely low recoil energy (~ keV) for a heavy, neutron-rich nucleus**

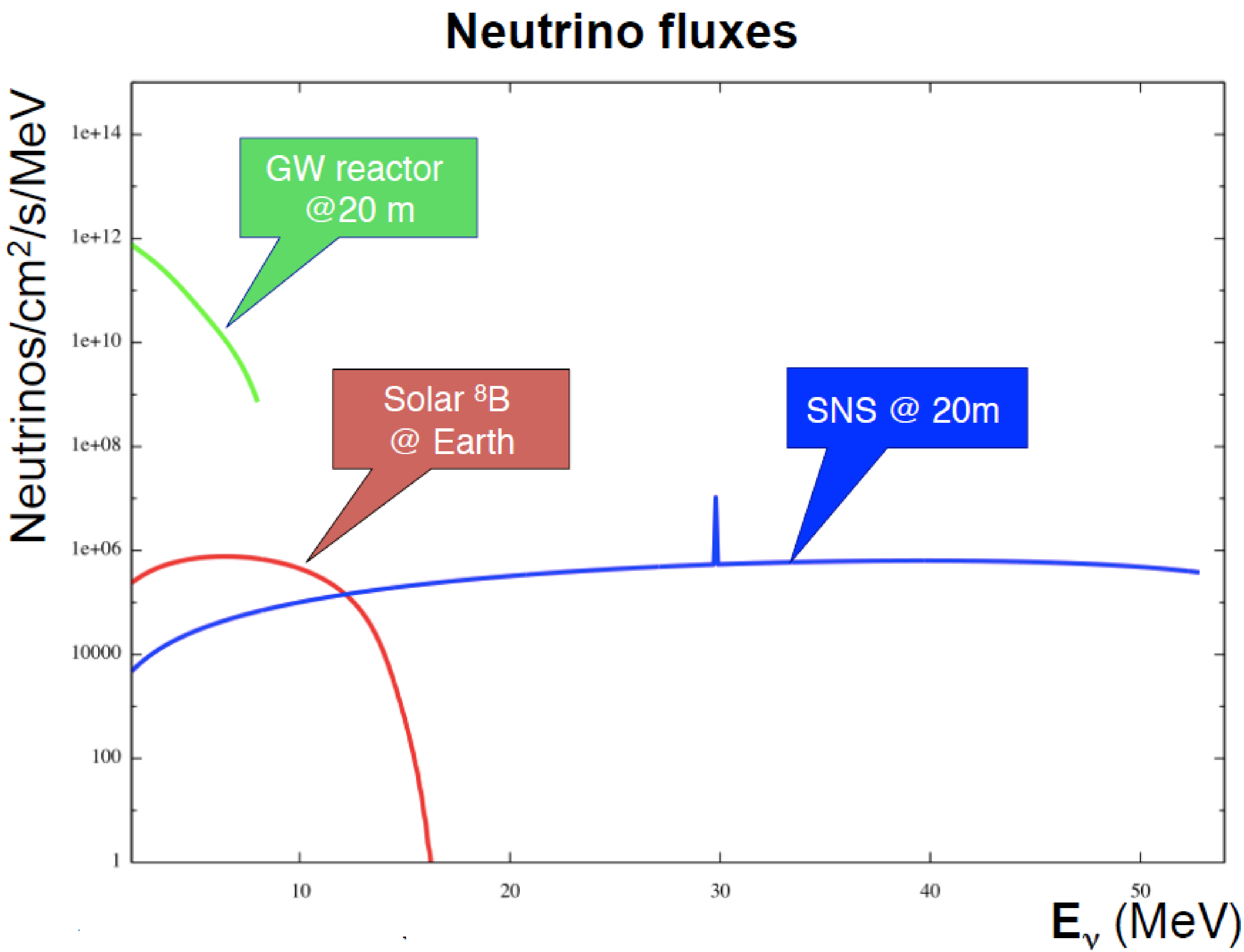
$$T_{max} \approx \frac{2E_\nu^2}{m_n(N+Z)}$$

E_ν = 10 MeV → $T_{max} \approx$ 3 keV (in Ge)
50 MeV → 75 keV
1 MeV → 30 eV

Nuclear recoil energy spectrum in Ge for 30 MeV neutrino

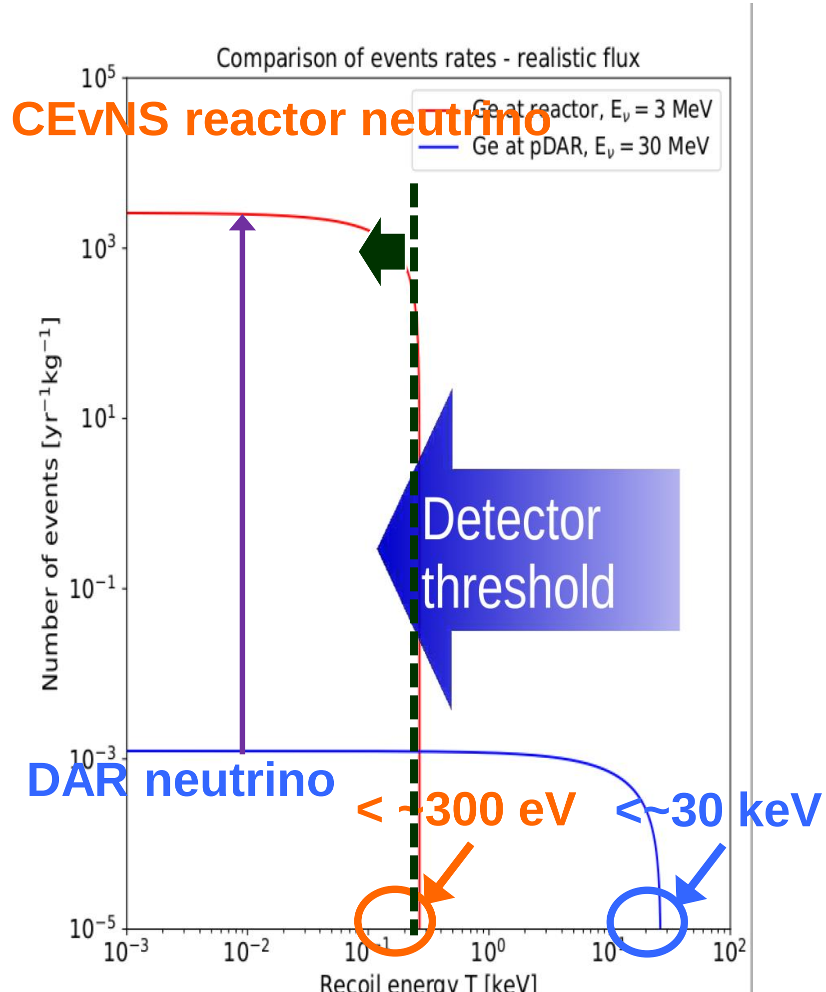


Neutrino Sources for CEvNS Detection



Expected Reactor Antineutrino CEvNS

- Quite low nuclear recoil energy in Ge: <2~3 keV
- Even more enhanced CEvNS cross section
- Intense neutrino flux near reactor core



- Reactor antineutrinos (in Ge)
  [E_ν = 0 - 8 MeV]
  E_ν = 8 MeV → $T_{max} \approx$ 2 keV
  3 MeV → 270 eV
  1 MeV → 30 eV

- DAR neutrinos (in Ge)
  [E_ν = 0 - 50 MeV]
  E_ν = 50 MeV → $T_{max} \approx$ 75 keV
  30 MeV → 27 keV

Observation of Coherent Elastic Neutrino Scattering

356,
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First COHERENT result July 2017

- 15 month of live-time accumulated with CsI[Na]
- 6.7 σ significance for excess in events, with 1 σ consistency with the SM prediction

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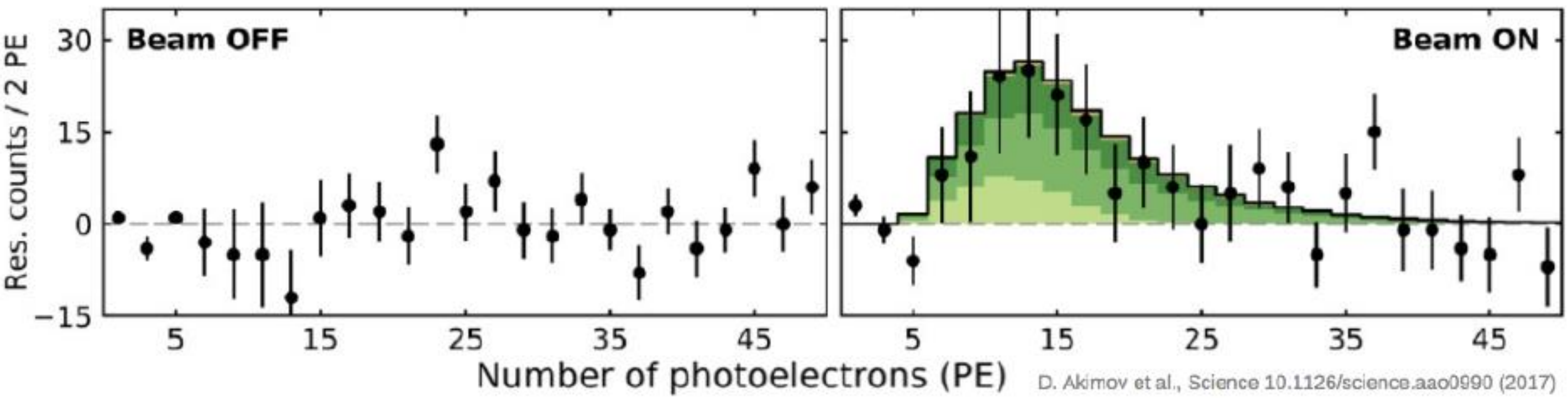
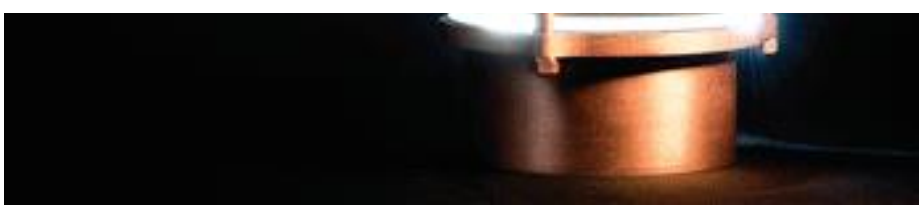
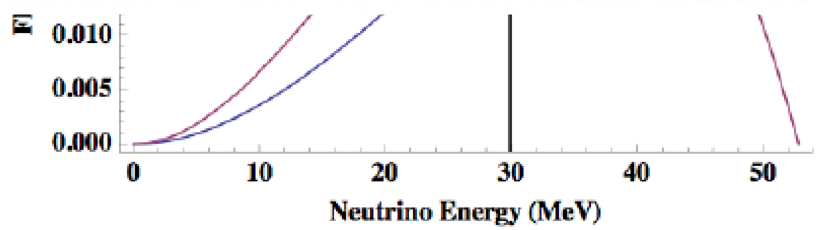
e LAr detector
lating crystal
detector



D. Akimov et al., Science 10.1126/science.aao0990 (2017)





Worldwide Efforts on Reactor Neutrino CEvNS

Experiment	Technology	Threshold (eV)	Mass (kg)	Location	Status
CONNIE	Si CCD	~40	0.1	Brazil	1 g under development
CONUS	HPGe	300	4	Germany	*Data taken for no signal observed*
MIνER	Ge/Si cryogenic	~100	10	USA	Under development
Nu-Cleus	Cryogenic $CaWO_4$, Al2O3 calorimeter array	~20	0.01~0.1	Europe	1 g under development
νGEN	Ge PPC	350	1.6	Russia	Under preparation
RED-100	LXe dual phase	1000	~100	Russia	Under preparation
RICOCHET	Ge, Zn bolometers	100	1	France	Under development
TEXONO	p-PC Ge	~10	0.5~1.0	Taiwan	Under development
LOCOND	**HPGe or CsI(Na) with TES cryogenic sensor**	**~10**	**20~30**	**Korea**	**Under proposal**

* *LOCOND: LOw temperature COherent Neutrino Detector*

Significance of Reactor Neutrino CEvNS Detection

Establish a new field of detecting unexplored energy region of neutrinos

- Explore a new region of neutrino magnetic moment
- Efficient search for existence of sterile neutrino by neutral current
- Practical and peaceful application such as reactor monitoring for nuclear non-proliferation
- Development of a compact neutrino telescope sensitive to detection of an intense neutrino burst from a nearby core-collapse supernova
- Precise measurement of nuclear form factors $F(Q^2)$
- Neutrino’s non-standard interaction (NSI) search
- CEvNS solar neutrino detection as a neutrino floor of direct dark-matter searches
- Precise measurement of $\sin^2\theta_W$ at low energies

Motivation for Mobile Reactor Neutrino Detector

The reactor neutrino community and IAEA are eager to develop a compact and mobile antineutrino detector that can be used for peaceful and practical purposes.

Core Idea: Development of LOCOND Detector

Requirements for Low temperature Coherent Neutrino Detector :

- Mobile CEvNS reactor antineutrino detector
- Low energy threshold for nuclear recoil energy
  (should be < 2 keV (270 eV) to detect CEvNS with E < 8 (3) MeV &
  < 50 eV to observe neutrinos with E < 1.8 MeV)
- Sufficient neutrino target mass
- High-purity and low-radioactivity neutrino target
- Efficient neutron shielding and veto component

⇩

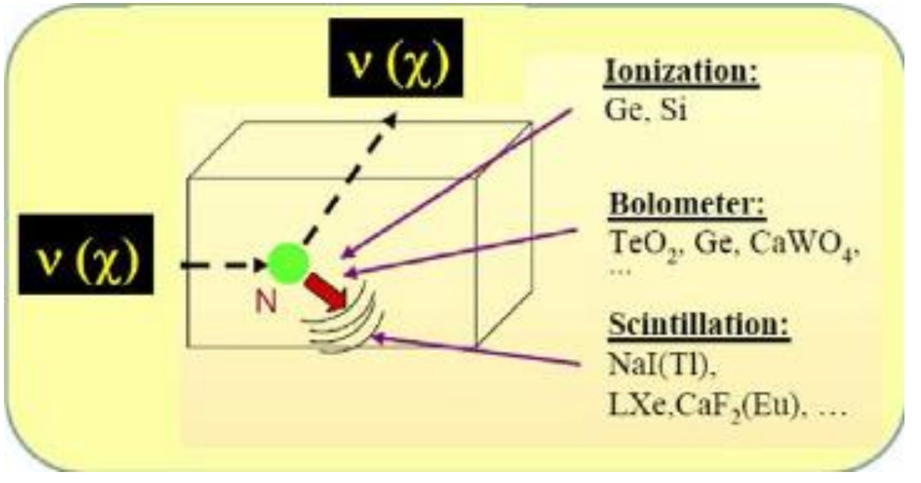
- Use *20~30 kg of scintillating CsI(Na) or ionizing radiation PPC Ge crystals* as a phonon (lattice vibration) excitation detector.

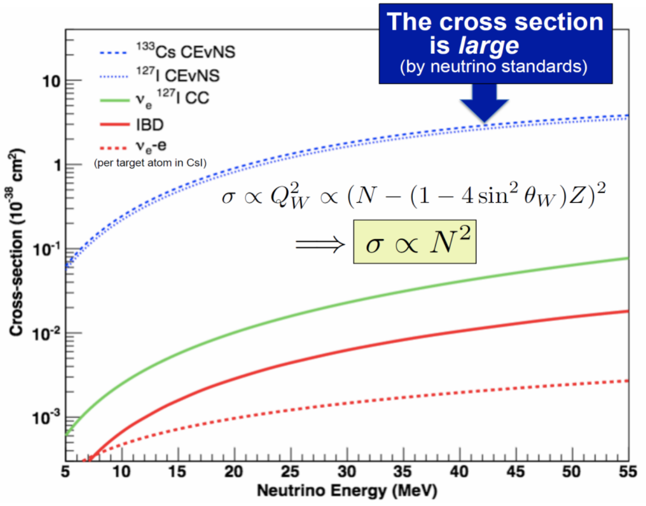
- Use *a cryogenic sensor for phonon detection*.

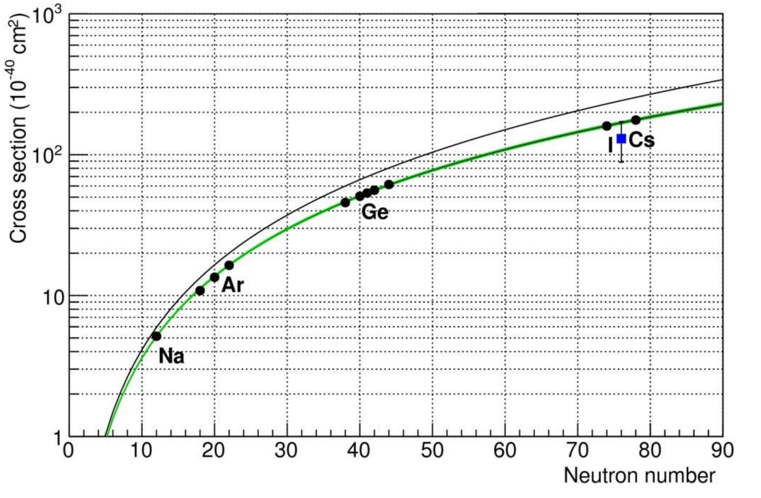
- Detect both phonons and photons (or e-h pairs) coming from the recoil energy in the crystal in order to obtain the energy threshold at 10 eV.

High Performance Crystal as Neutrino Target

- Use a **scintillating CsI(Na)** or **ionizing PPC Ge** crystal that contains *a heavy, neutron-rich nucleus* providing *sufficient CEvNS cross section* and reasonable recoil energy (<2 keV).



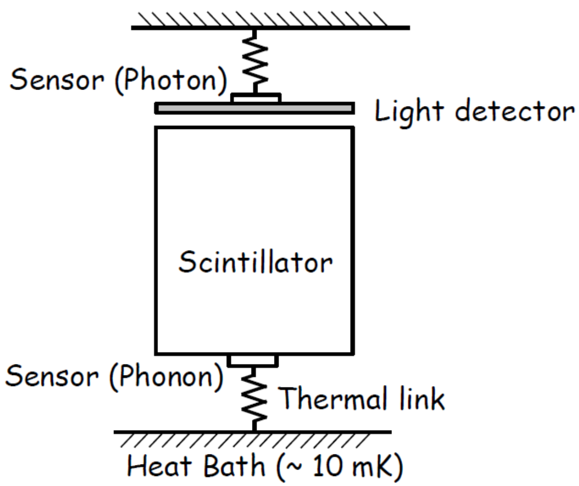




Detection of Phonon and Photon/Ionization

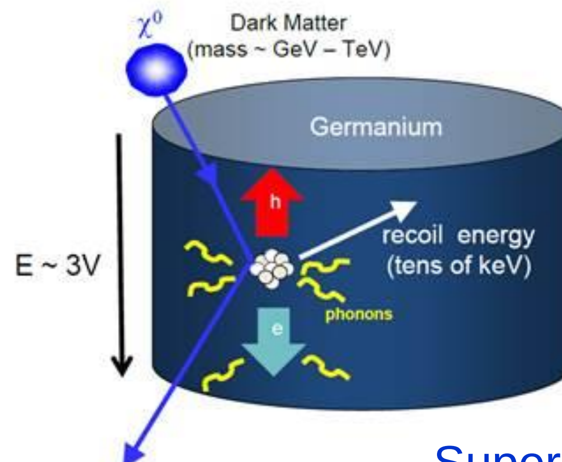
- *A simultaneous measurement of both heat and scintillation* enables *significant reduction of backgrounds and particle identification (β/γ and α)* in order to achieve a nuclear recoil energy threshold as low as 10 eV.

Phonon & Photon Cryogenic Detector



CRESST-II

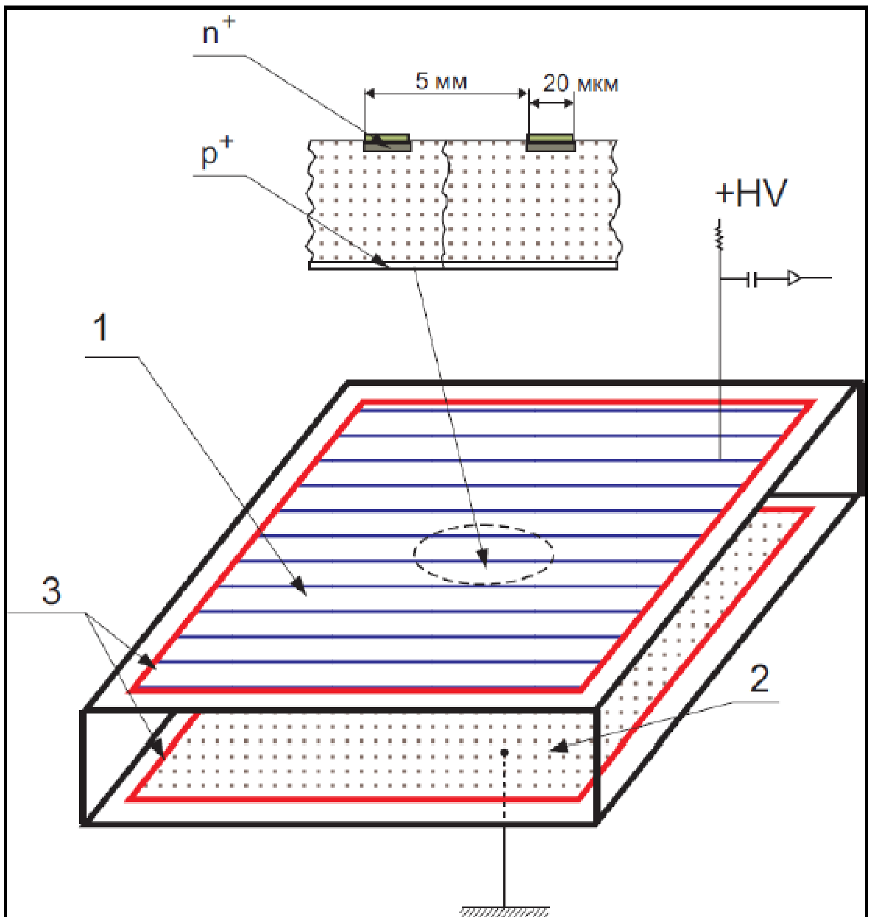
Phonon & Ionization Cryogenic Detector



SuperCDMS

R&D for Ge Ionization Amplification

Development of Ge planar strip detector



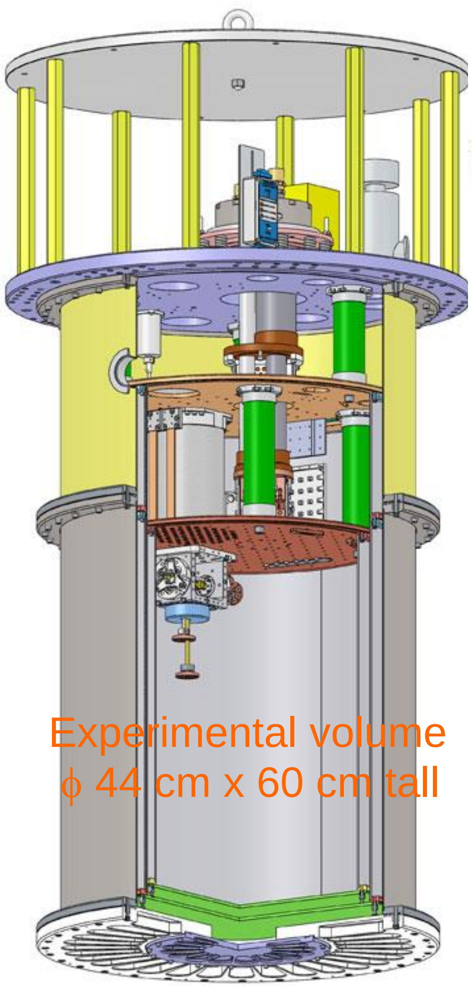
Participation in
international collaborative efforts

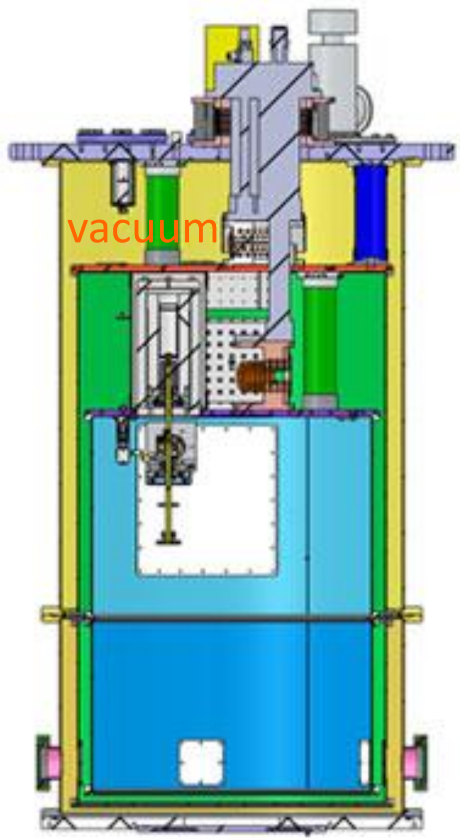
GEMADARC
Germanium Materials and Detectors
Advancement Research Consortium

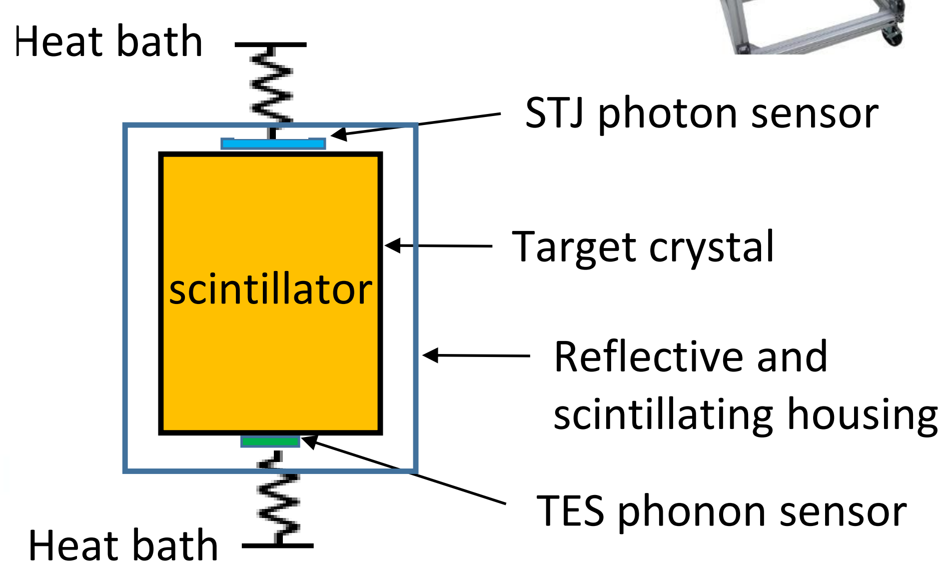
- Charge amplification by electric field of 10^5 V/m
- Obtain recoil energy threshold as low as 10 eV with liquid nitrogen cooling

Cryogenic Bolometric Detector

- *A thermal signal from nuclear recoil energy* is observed by a cryogenic phonon sensor (STJ or TES) and used to determine the energy deposited.





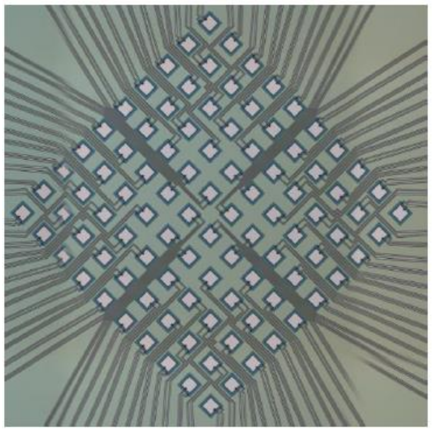


Section view of 104 Olympus ADR cryostat showing pulse-tube head, adiabatic demagnetization refrigerator (ϕ 55 cm x 110 cm)

Multi-pixel STJ Array Detector

National Institute of Advanced Industrial Science and Technology (AIST)

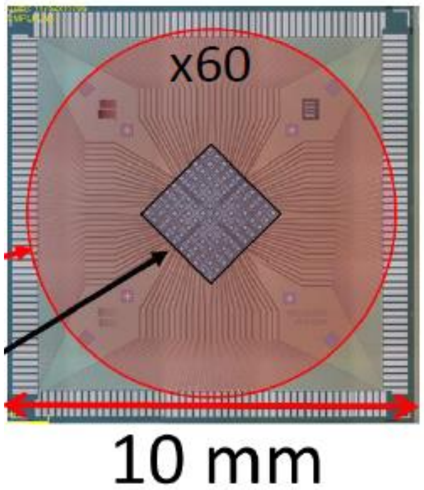
The STJs were fabricated in the clean room for analog-digital superconductivity (CRAVITY) at AIST.



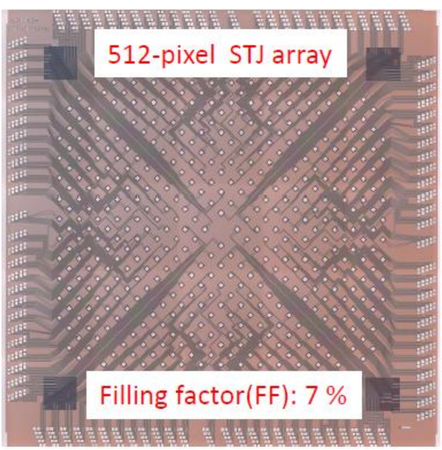
Developed 100-pixel STJ array

- Detection area : 1 mm^2
- Mean energy resolution :
  6.7 eV@400 eV
- Max. counting rate :
  100 kcps

100-pixel STJ array



Development of 1000 pixels STJ array

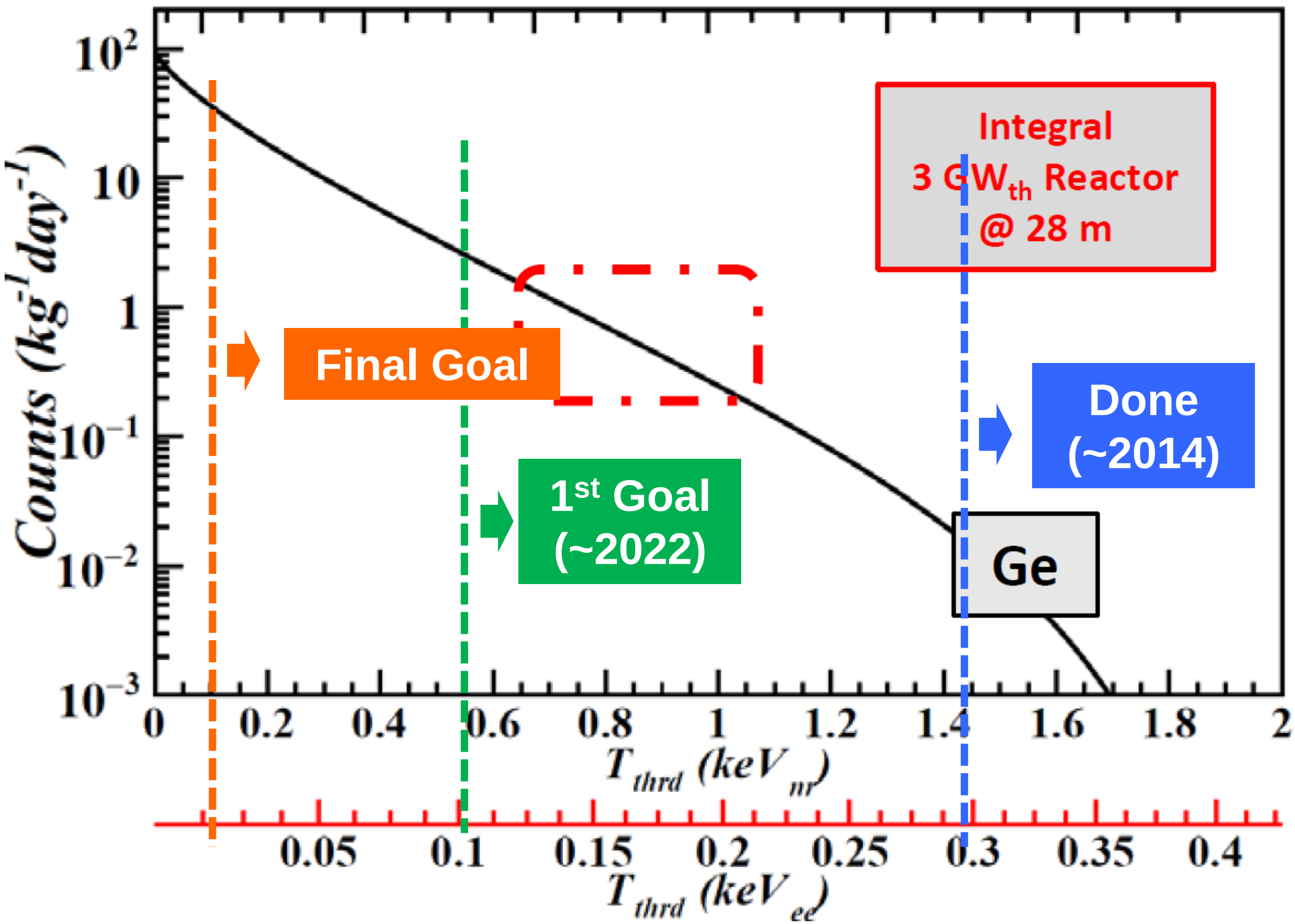


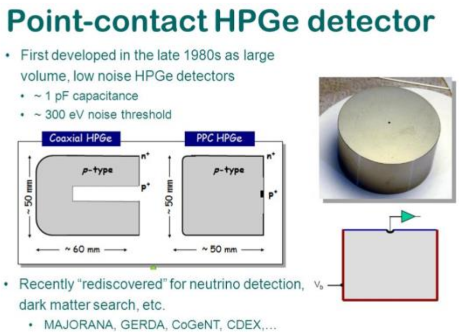
We have developed 1024-pixel STJ array spectrometer and evaluated the performances.

- Operation yield: ~ 95 %
- Mean energy resolution: 12.6 eV

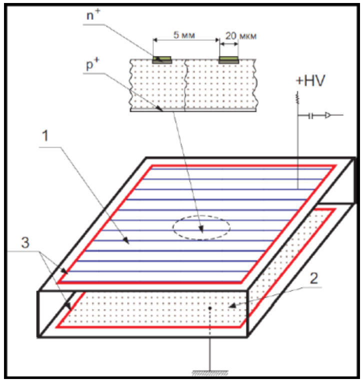
Expected Nuclear Recoil Energy Threshold

- Efforts on lowering the recoil energy threshold to a few tens of eV.





Ge-ionization development



- Light yield of CsI(Na) at cryogenic temperature ~8K : x5 enhancement from 54/keV

Efficient Neutron Shielding and Active Veto

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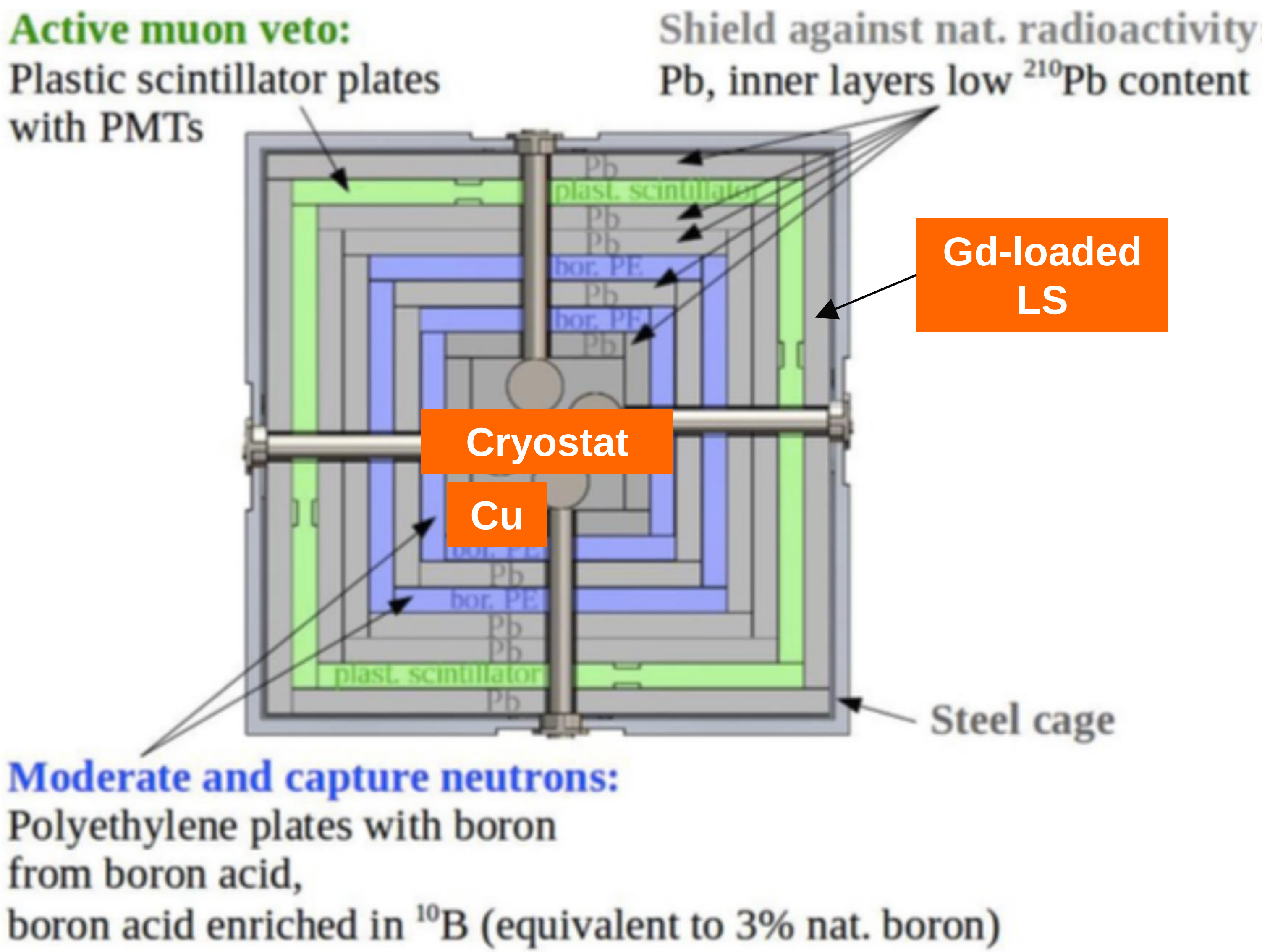


* Borrowed from CONUS

Research Programs and Schedule

Development of CEvNS reactor Antineutrino Detector

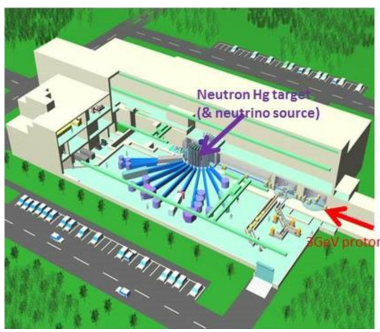
CEvNS observation of reactor neutrino at nuclear power plant

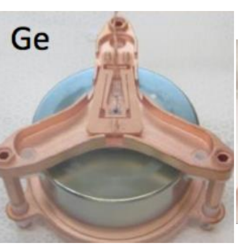
(2025)

CEvNS detection of HANARO research reactor neutrino with LOCOND

(2023-2024)

(2021)





CEvNS detection using DAR neutrino beam at J-PARC MLF

(2022)

1 kg LOCOND prototype

Sterile Neutrino Search at JSNS^2

JSNS^2

J-PARC Sterile Neutrino Search
at J-PARC Spallation Neutron Source

Sterile Neutrino

Sterile neutrino : insight for the questions beyond the SM (e.g. PLB 631, 151 (2005))

- No strong, EM and weak interactions
- Introduced to explain both results of LSND and LEP
- Maybe recognized by neutrino oscillations
- Could be right-handed neutrino or new particle
- Beyond the PMNS standard oscillation
- Indicated by LSND, MiniBooNE, reactor anomaly, and Ga experiment

Sterile neutrino can be also one of the Dark Matter candidate?

Hints for Sterile Neutrino ($\Delta m^2 \sim 1\ eV^2$)

- Anomalies that cannot be explained by standard neutrino oscillations for ~20 years

Experiments	Neutrino source	signal	significance	E(MeV),L(m)
LSND	μ Decay-At-Rest	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	3.8σ	40,30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	4.5σ	800,600
		$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	2.8σ	
		combined	4.8σ	
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ	<3,10
Reactors	Beta decay	$\overline{\nu}_e \rightarrow \overline{\nu}_x$	3.0σ	3,10-100

→ Excess or deficit does really exist?

→ A new oscillation between active and inactive (sterile) neutrinos?

→ However, no indication for $\nu_\mu \rightarrow \nu_\mu$ and negative results from recent reactor measurements using energy spectra

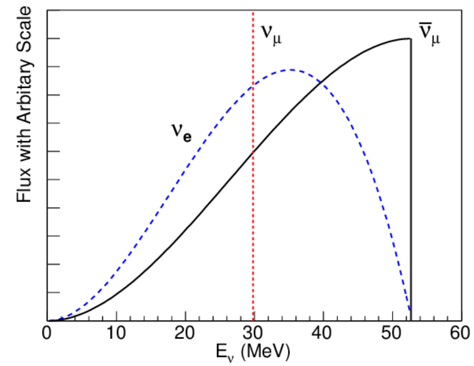
Please also see M.Dentler et al JHEP 08, 010 (2018) for recent reviews

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

1998 at LANL

($\bar{\nu}_e$ appearance)

$$\pi^+(\text{stop}) \rightarrow \mu^+ + \nu_\mu \quad \text{DAR}$$
$$\hookrightarrow \mu^+(\text{stop}) \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

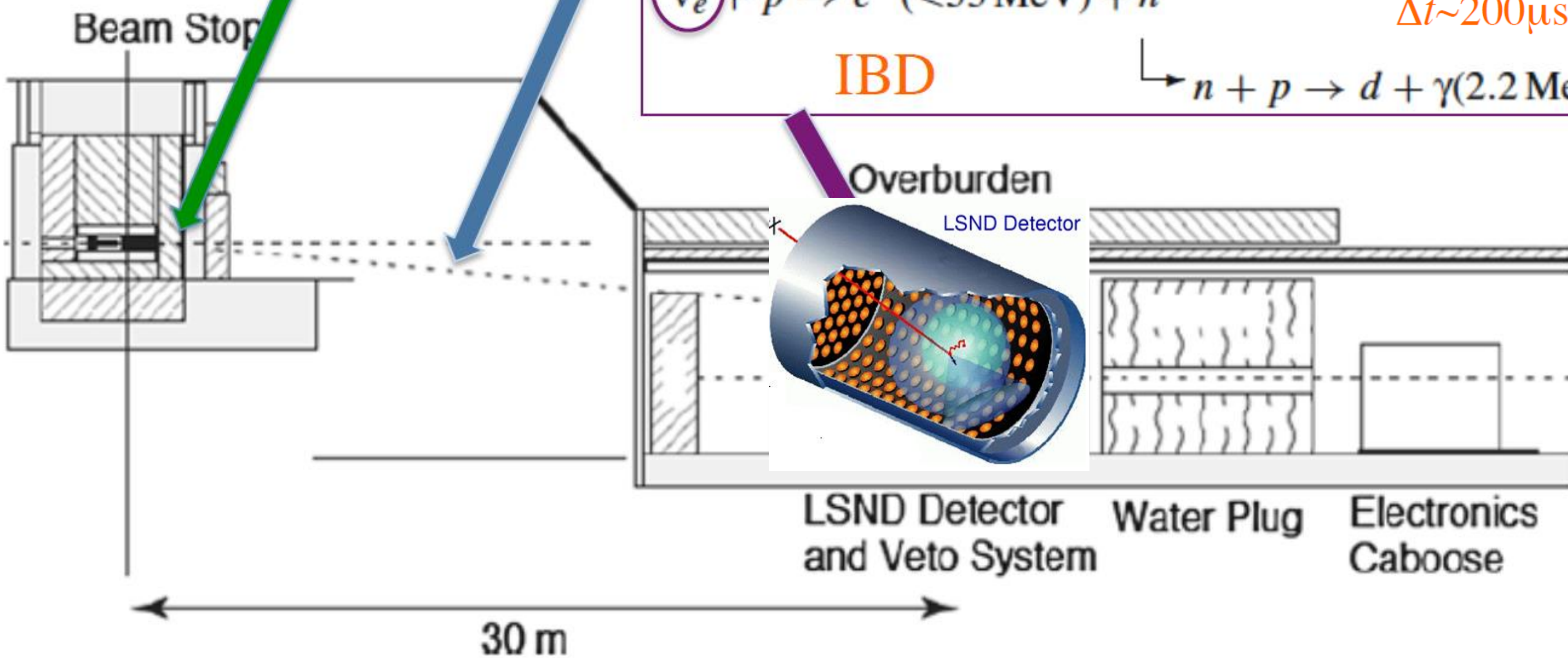


800MeV p

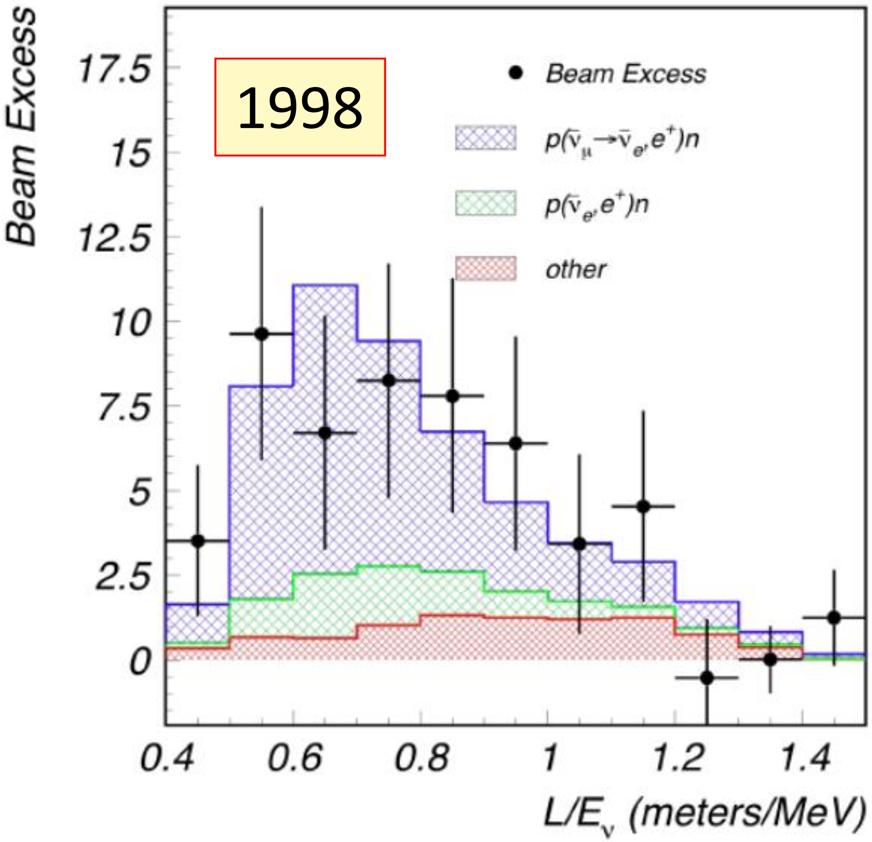
Liquid Scintillator

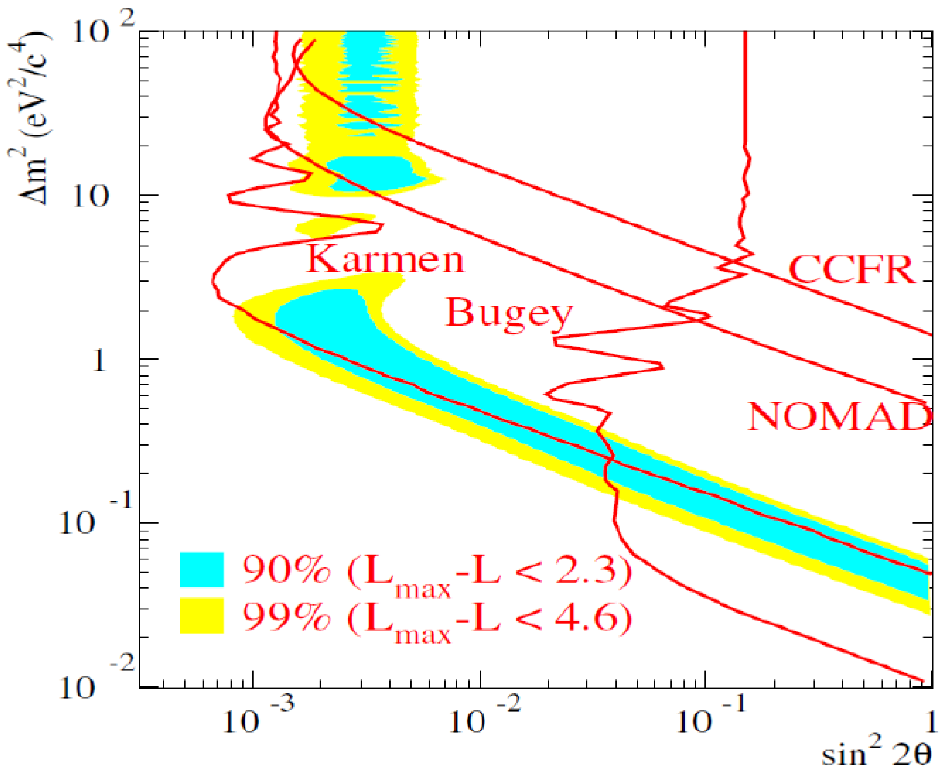
Delayed Coincidence $\Delta t \sim 200\mu s$

$$\bar{\nu}_e + p \rightarrow e^+(<53\,\text{MeV}) + n \quad \text{IBD}$$
$$\hookrightarrow n + p \rightarrow d + \gamma(2.2\,\text{MeV}).$$



LSND Results and Allowed Region





$$\Delta m^2_{\mathrm{SBL}} \gtrsim 0.1\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}}$$

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.

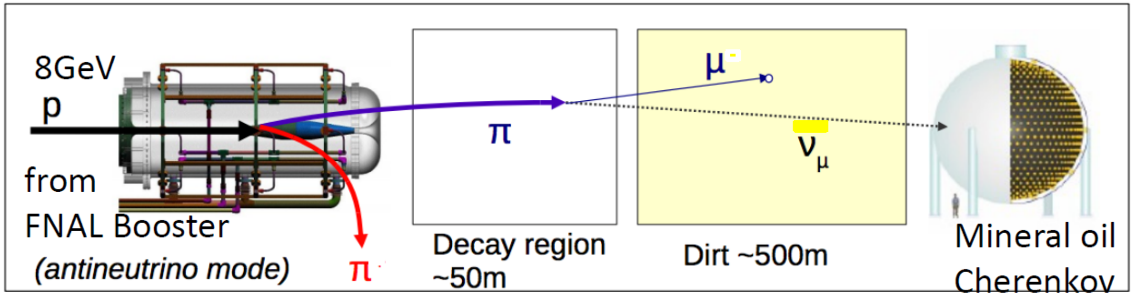
$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$

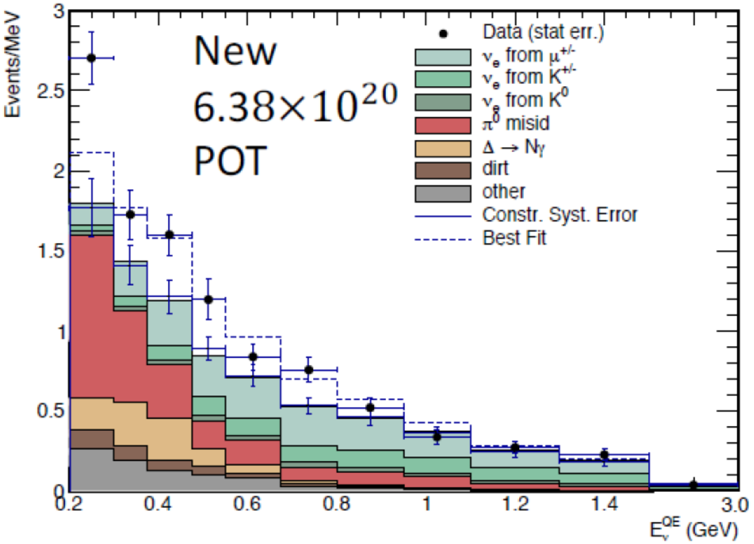
(1990-1995, 1997-1999)

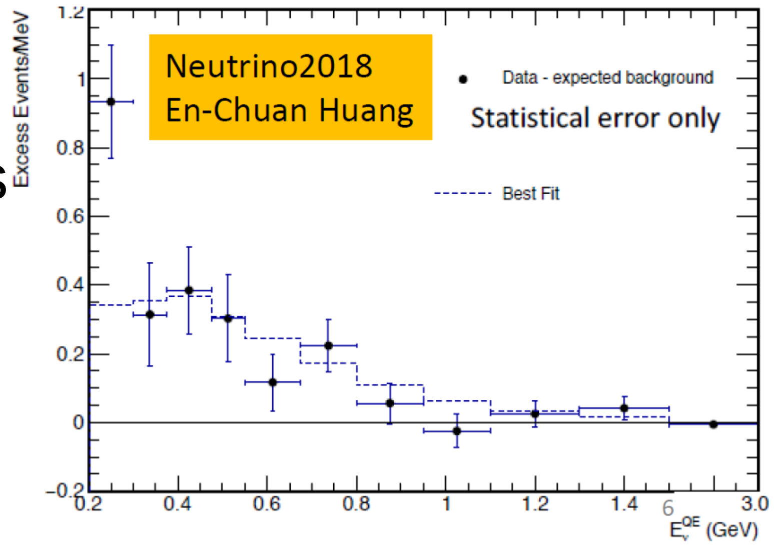
But signal not seen by KARMEN at $L \simeq 18\,\mathrm{m}$ with the same method

[PRD 65 (2002) 112001]

MiniBooNE Latest Results







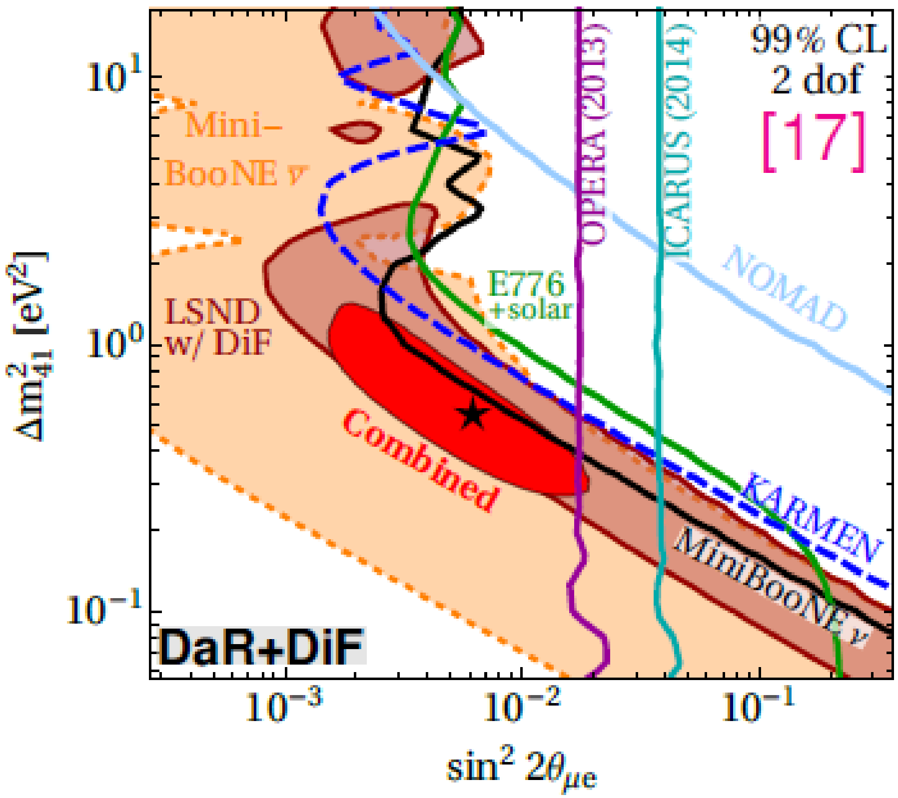
- Significant excess of low energy events : 4.5 σ
- The excess is claimed due to the same oscillation observed by the LSND.
- Concerns on systematic uncertainties of neutrino interactions and background understanding
- MicroBooNE can check the excess due to the gamma rays or electron antineutrinos

Sterile Neutrino Oscillation

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

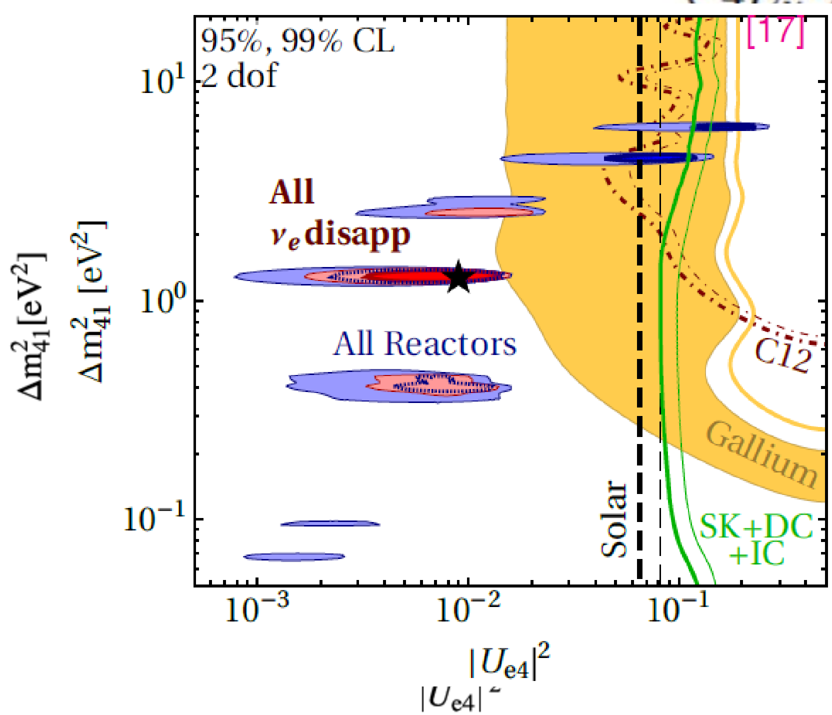
$$|U_{s4}|^2 \sim 0.9, \quad |U_{e4}|^2 \sim 0.1, \quad |U_{\mu4}|^2 \sim 0.01$$
$$m_4 > 1eV$$

ν_e Appearance



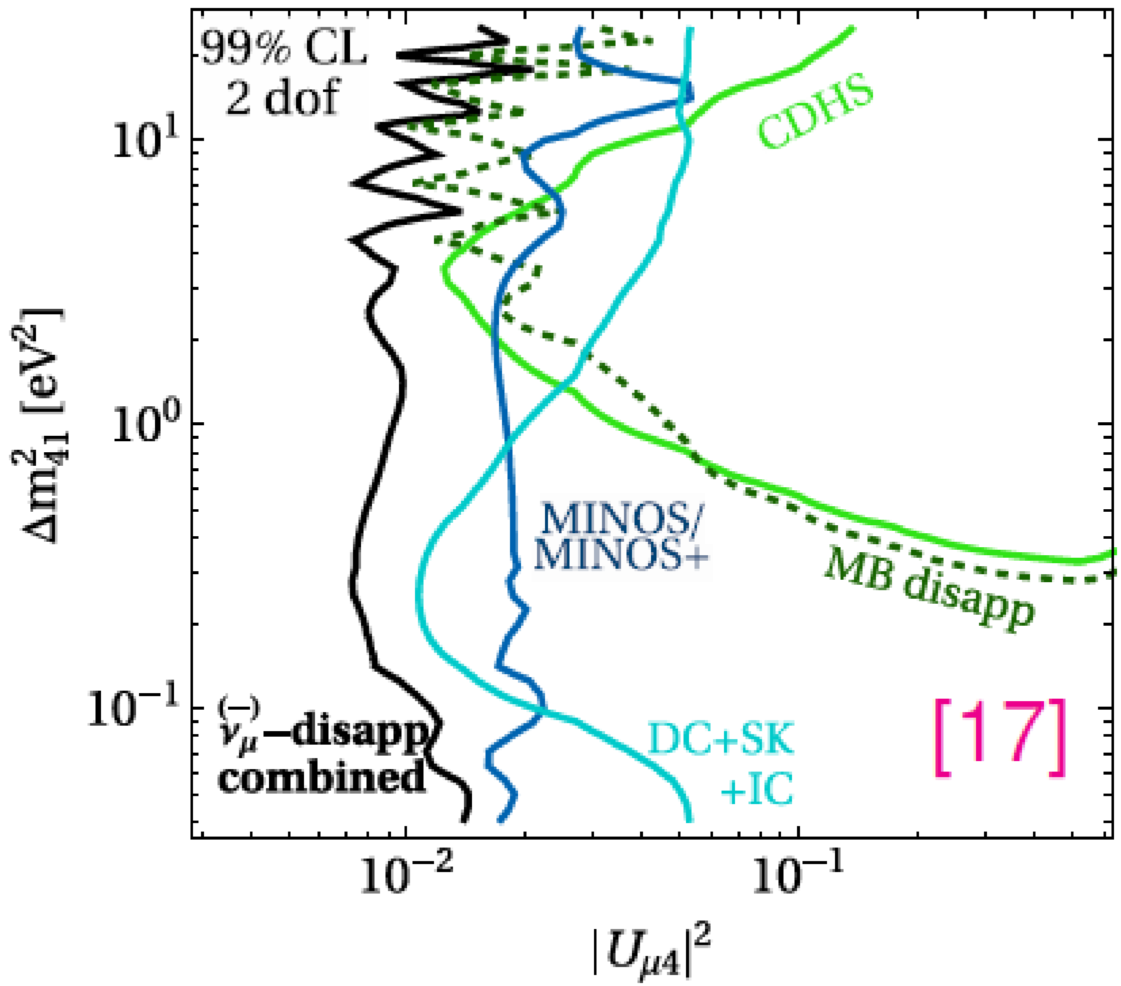
ν_e Disappearance

$$P_{\nu_e\to\nu_e} \sim 1 - 4|U_{s4}|^2|U_{e4}|^2 \sin^2\left(\frac{m_4^2 L}{4E_{\nu}}\right)$$



Sterile Neutrino Oscillation

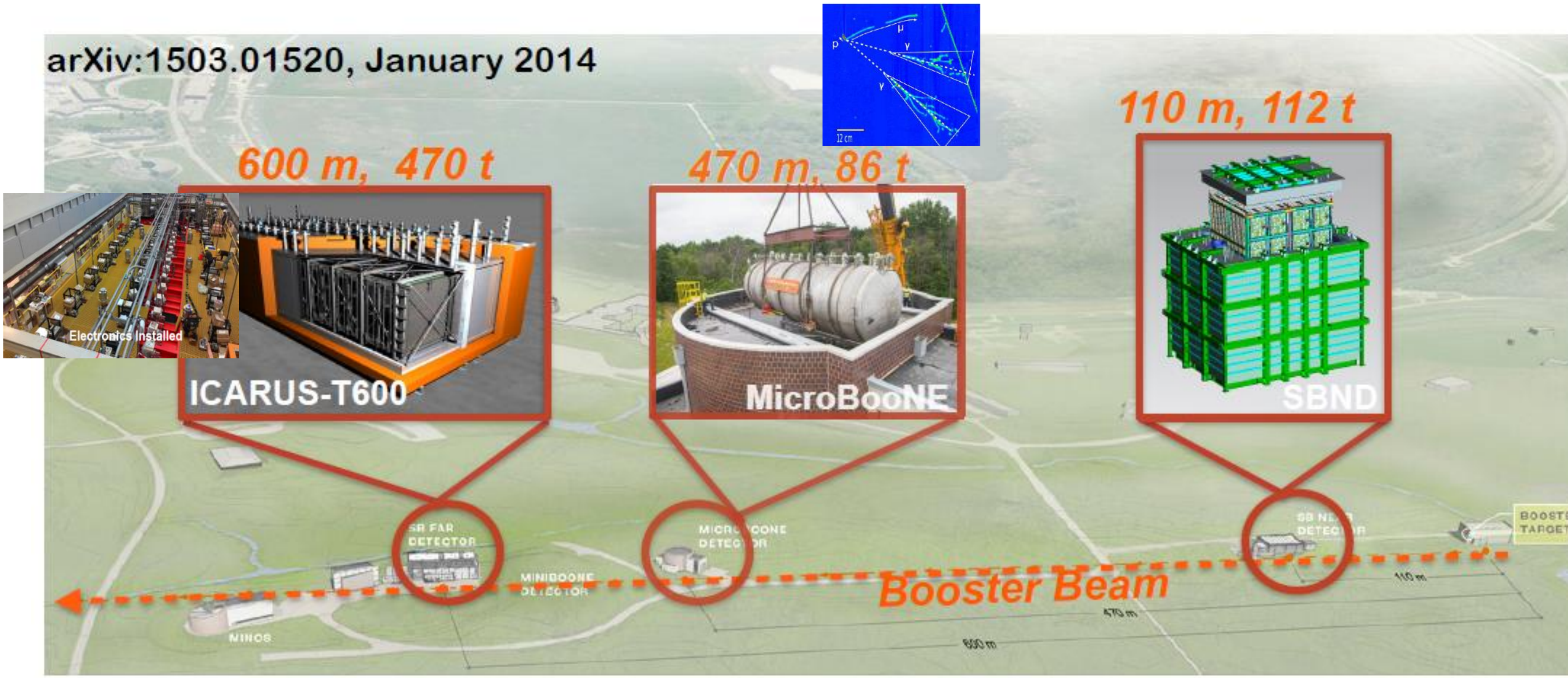
Null results of ν_μ disappearance



[17] Dentler, Hernández-Cabezudo, Kopp, Machado, MM, Martinez-Soler, Schwetz, arXiv:1803.10661.

SBN Program at Fermilab

3 LArTPCs in the Booster Neutrino Beamline

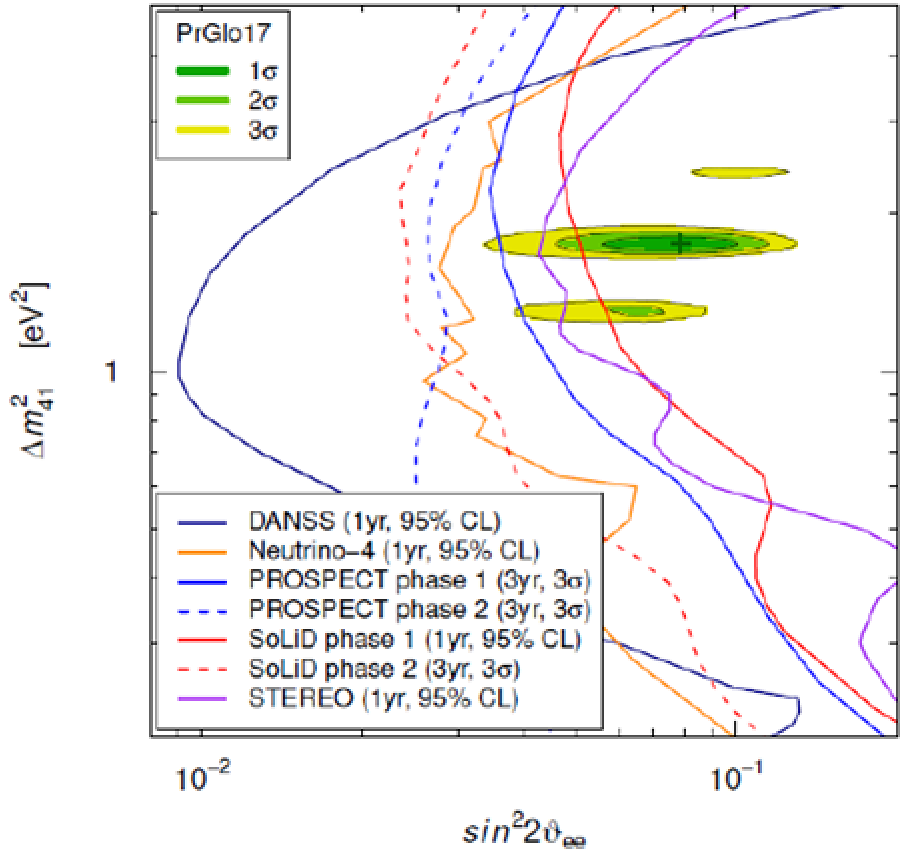


Direct test for MiniBooNE Anomaly.

SBND (first data in ~~2019~~) 2021
MicroBooNE (first data in late-2015)
ICARUS (first data in ~~2018~~) 2020

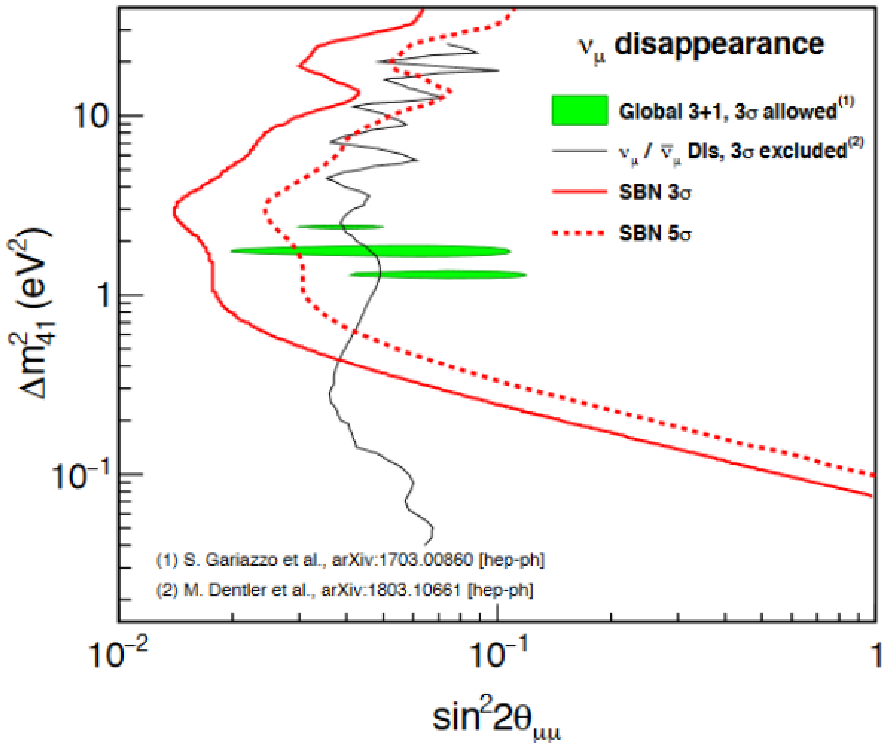
Future Sterile Neutrino Search

$\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e$ **(Reactor disappearance)**



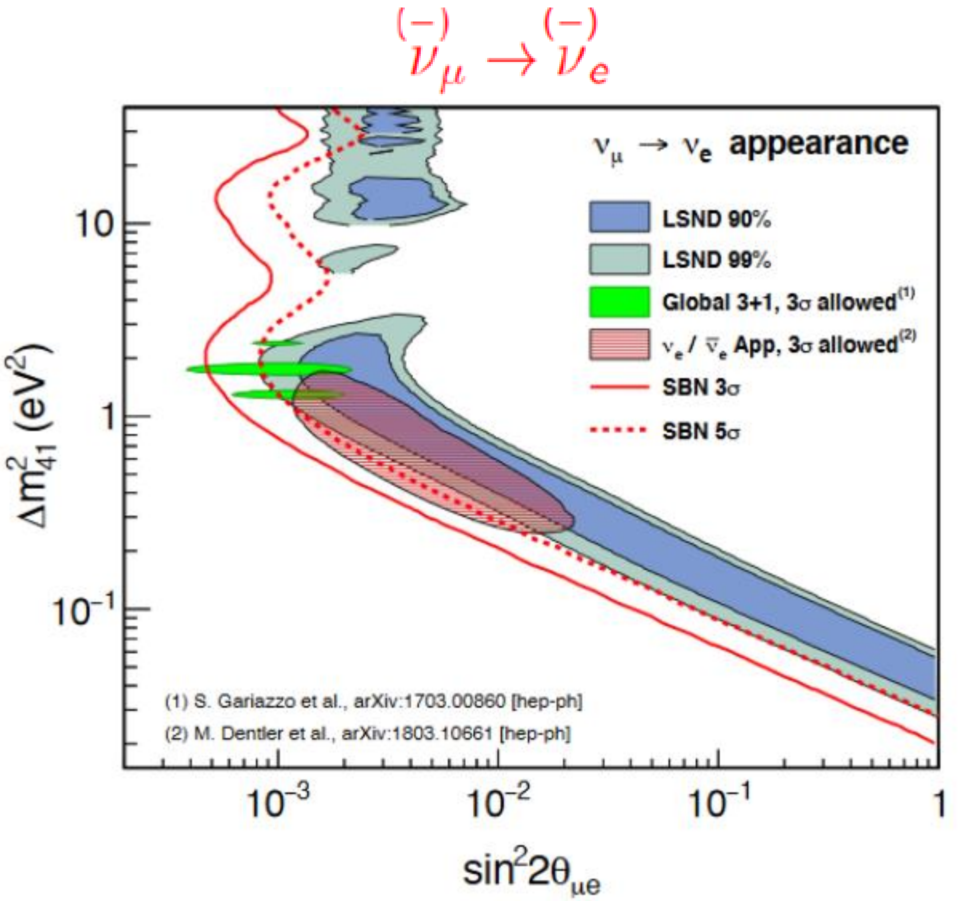
Yufeng Li

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$ **3 yrs**

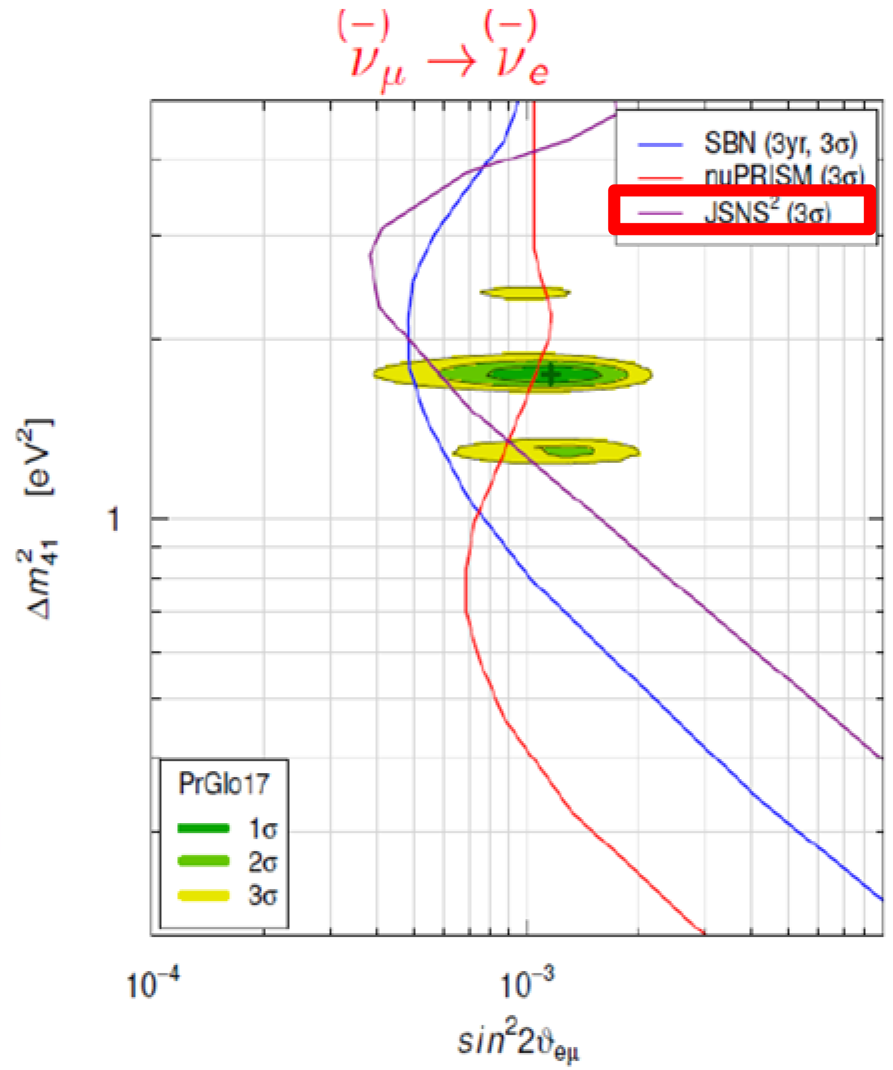


J.Spitz's talk in NuFact2019

Future Sterile Neutrino Search



J.Spitz's talk in NuFact2019



Yufeng Li

JSNS^2 Experiment

(*J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source*)

J-PARC Sterile Neutrino Search
at J-PARC Spallation Neutron Source

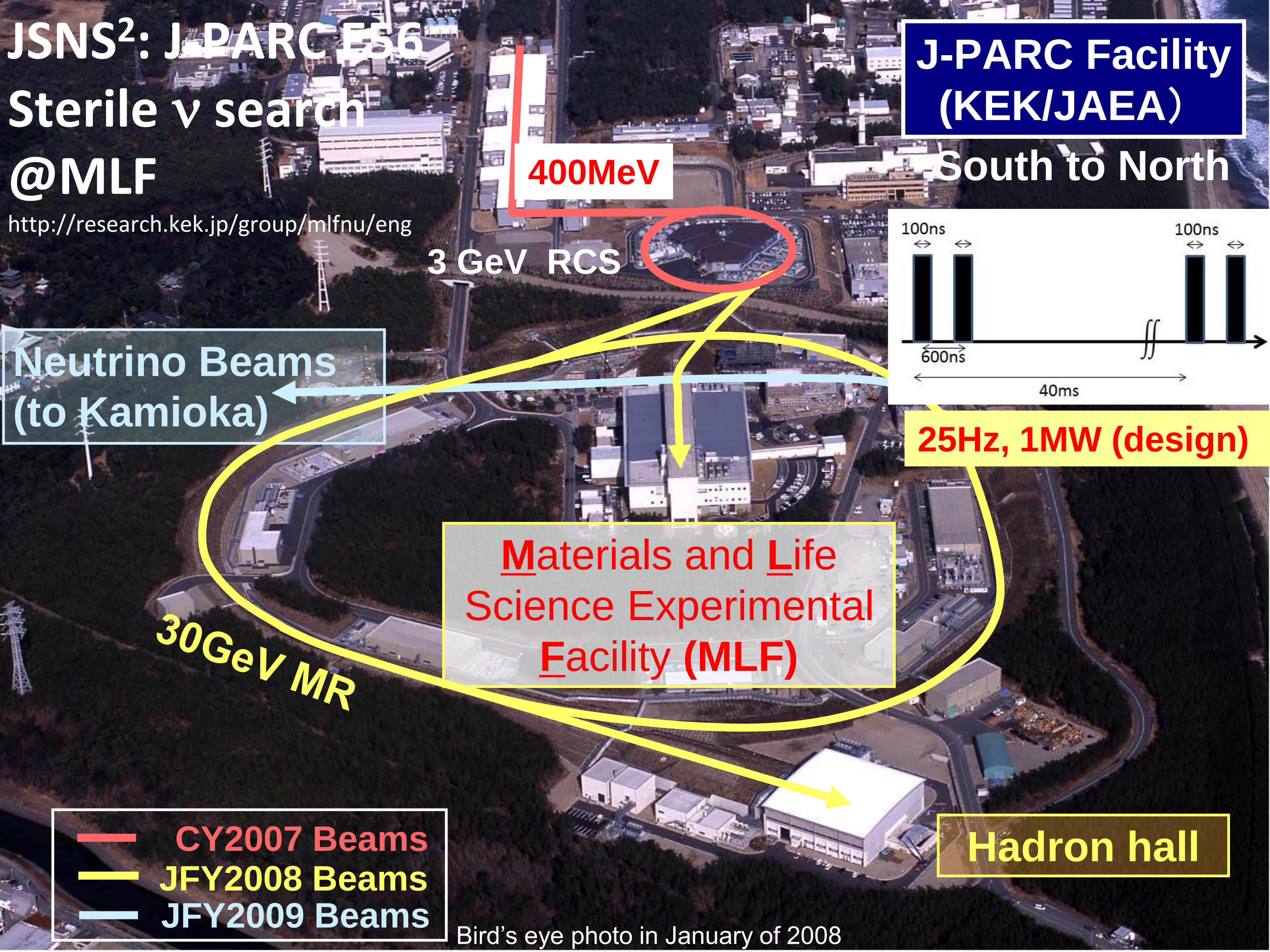

JSNS^2 Collaboration
JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku
Soongsil
Dongshin
GIST
Seoyeong
Chonnam
Seoul
Chonbuk
Kyungpook
Sungkyunkwan
Seoul Sci Tech
Alabama
BNL
Florida
Michigan
Sussex

Improved Search at JSNS^2

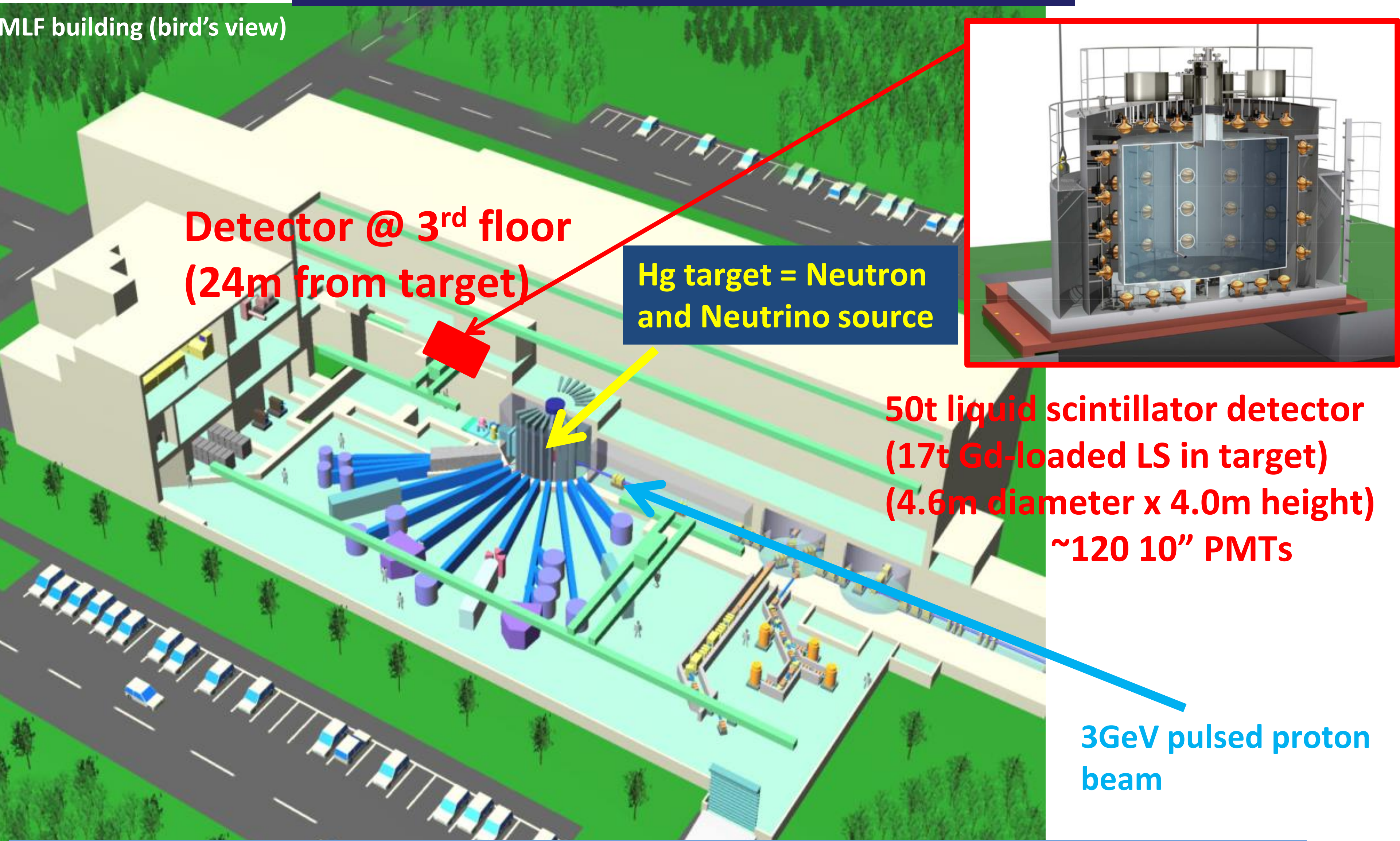
- **Direct test of the LSND with better sensitivity**
  - Muon antineutrino beam from muon Decay At Rest (DAR)

- ***Narrow (~9 μs) pulsed (every 40 ms) neutrino beam*** **at J-PARC MLF : (vs. continuous beam used by LSND)**
  - Pure muon decay at rest
  - Narrow timing window for cosmic ray rejection
  - No decay-in-flight source
  - No beam induced fast neutrons
  - The neutrino energy spectrum is perfectly known
  - The neutrino beam already available

- **Improved detector :**
  - *Gd doped LS*
  → significant reduction of backgrounds by a tighter (~1/6) time coincidence and a higher (2.2 → 8 MeV) delayed energy + well-known cross section of IBD


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

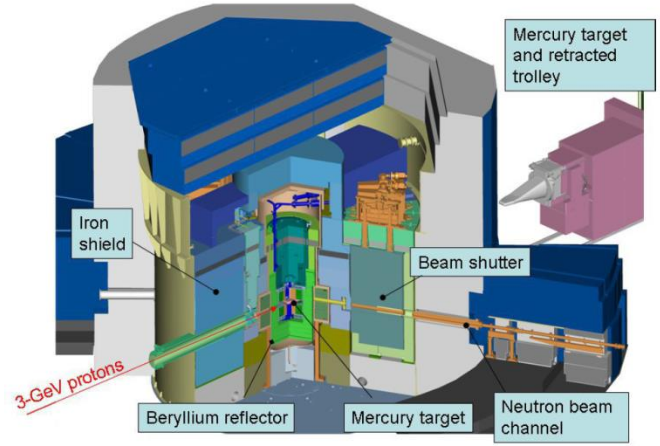
JSNS^2 at J-PARC MLF

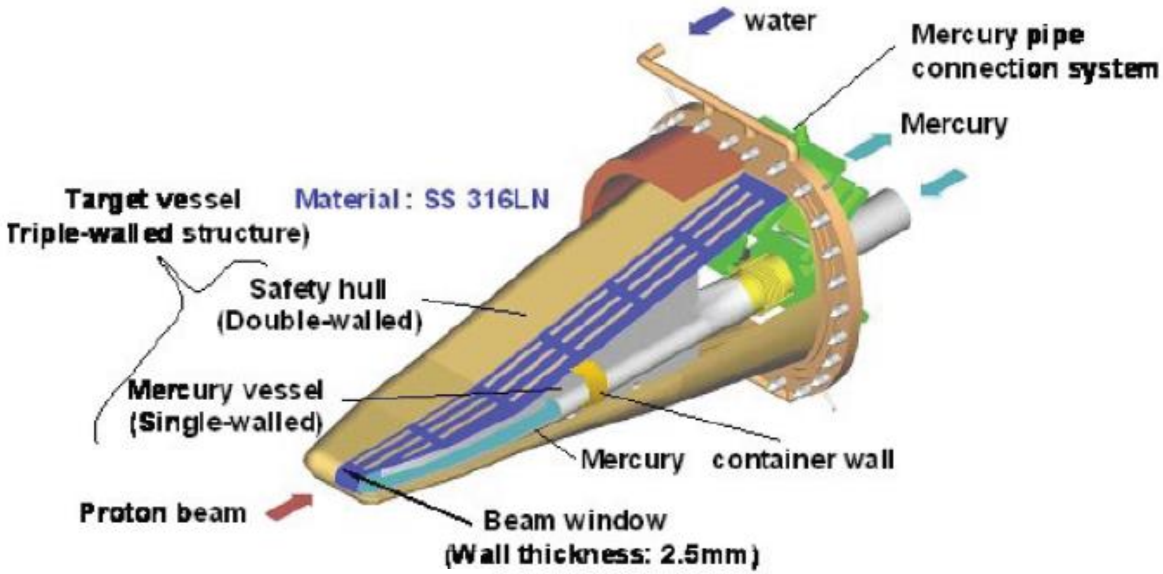


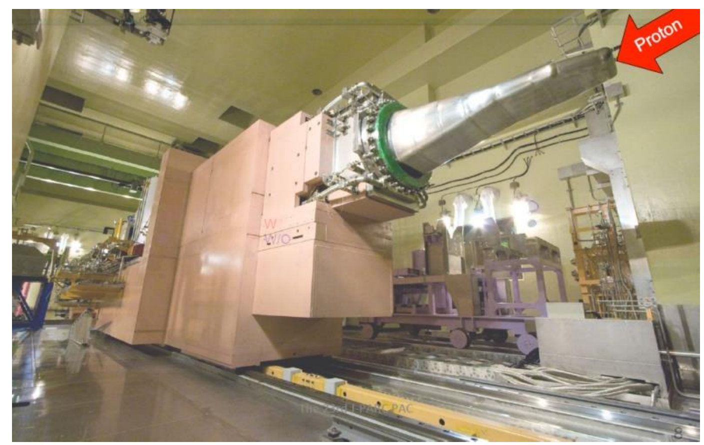
Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

Neutrino Source: Mercury Target at MLF

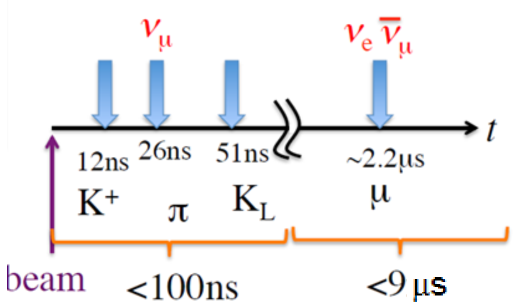
- **World-class high intensity neutron source driven by high power proton beam**
  - beam energy: 3 GeV
  - design beam power: 1 MW







Timing of the ν production



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

$$\pi^{\pm}(stop) \to \mu^{+} + \nu_{\mu}$$

$$\bar{\nu}_e / \bar{\nu}_\mu \sim 1.7 \times 10^{-3}$$

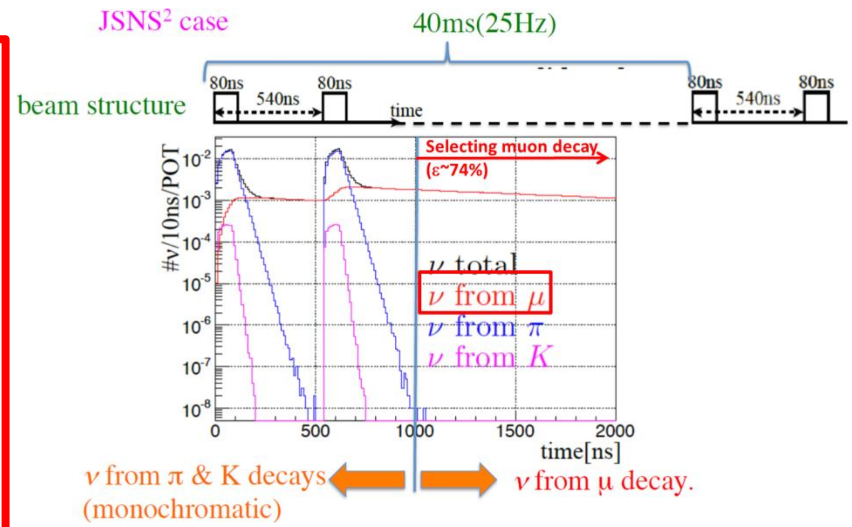
$$\mu^{+}(stop) \to e^{+} + \nu_e + \bar{\nu}_\mu$$

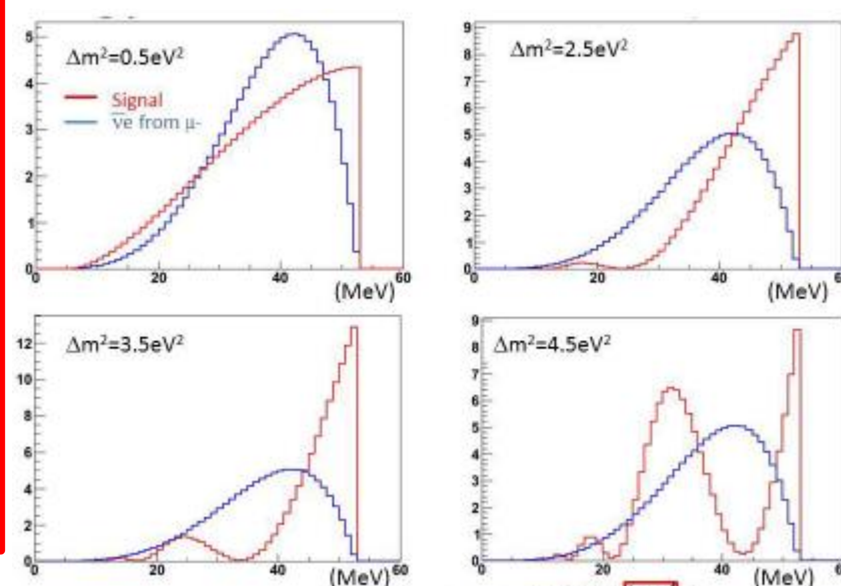
Timing and Energy of Neutrino Beam

- **Timing**: Ultra-pure ν from μ^+ Decay-at-Rest by a pulsed neutrino beam
  - ➢ Removal of ν from π and K with beam timing
  - ➢ Removal of beam fast neutrons w/ time
  - ➢ Reduction of cosmic BKG by 9μs time window.

➢ **Energy**: Good for signal BKG separation
  - ➢ Well-known spectrum of ν from μ
  - ➢ Easy energy reconstruction of IBD. (Eν ~ Evis + 0.8MeV)
  - ➢ Highly suppressed ν from μ-

$$\overline{\nu}_e / \overline{\nu}_\mu \sim 1.7 \times 10^{-3}$$





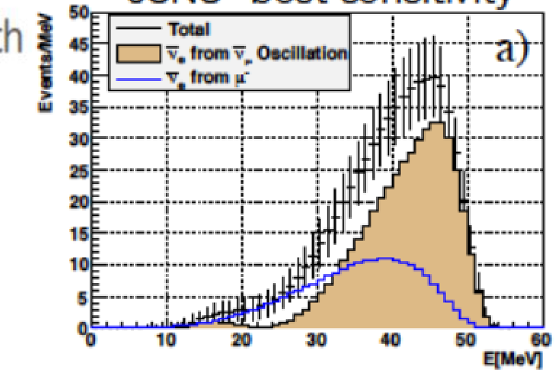
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\cdot \boxed{\Delta m^2}\cdot L}{E_\nu}\right)$$

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

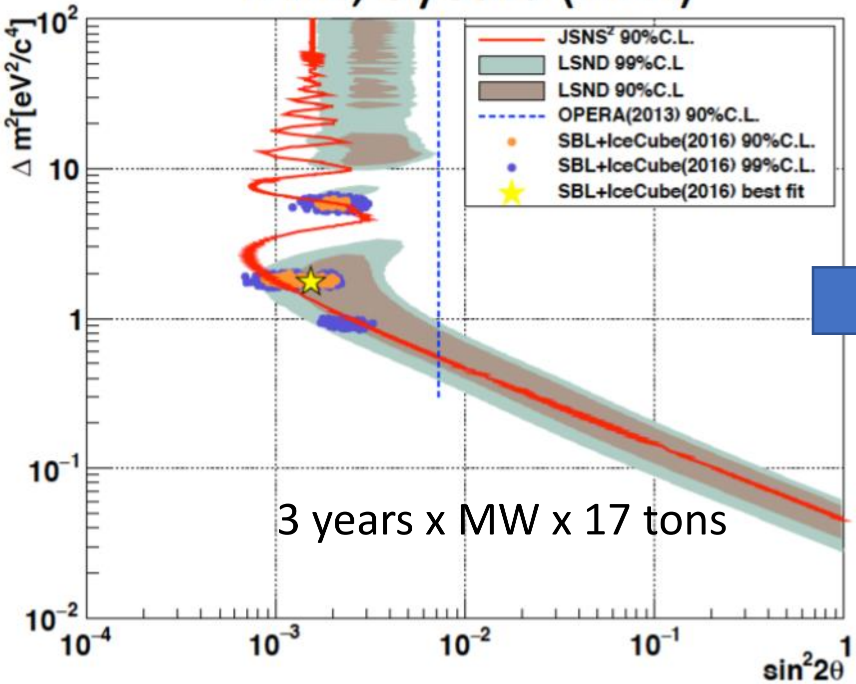
Signal Extraction & Sensitivity

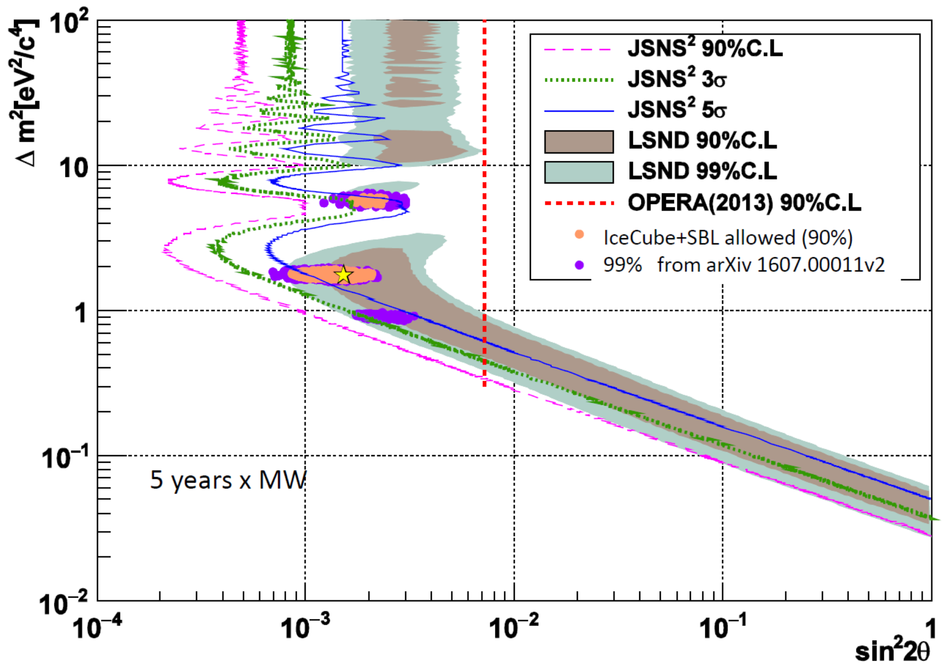
- Signal events can be distinguished from the dominant background (from another neutrino process) by using the difference of energy distributions
- Most of the parameter region indicated by LSND exp. can be explored with more than 5σ significance in 5 years with 1MW beam power

JSNS² best sensitivity

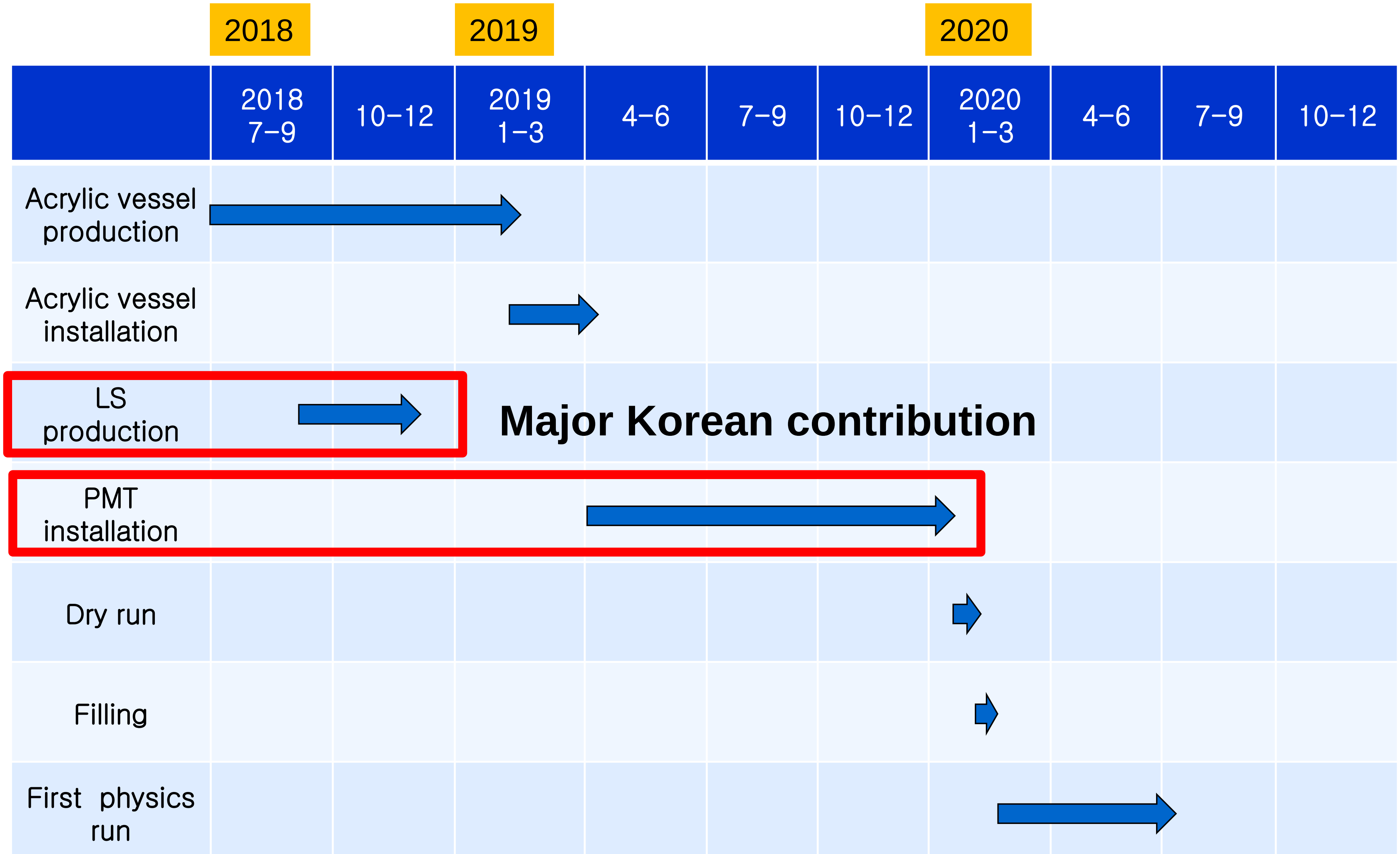


24m, 3years (TDR)

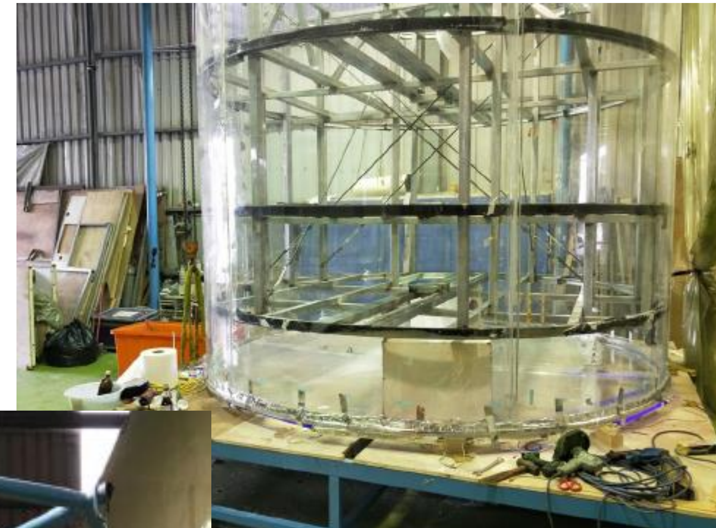




Schedule for Detector Construction



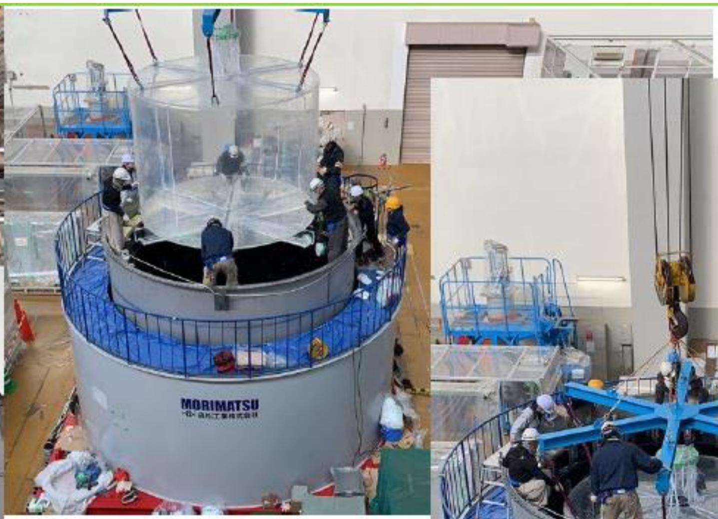
Construction of Acrylic Vessel



Relocated SUS Tank (Mar. 14, 2018)

There were no big issues.

SUS Tank and Acrylic Vessel at J-PARC



- The stainless steel tank and the acrylic vessel are ready to perform the experiment.
- On 2019-Feb, we already had rehearsal of the installation of the acrylic vessel. → succeeded.
- They are waiting for completion of PMT installation.

PMT Installation

PMT support structure

Reflection sheet

- 105 PMTs from RENO, Korea
  23 PMTs from DC, Japan
- 33 PMTs installed and ~40 will be installed till Oct. 2019.
- 50 more PMTs will arrive before Dec. 2019.

PMT installation

PMT

Current status

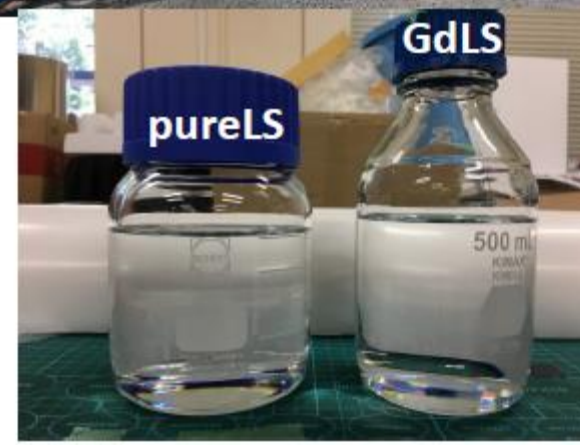
Liquid Scintillator by Ko

35 tons of LS was produced at RENO site and delivered t

Date (2018)	J
Sep. 12 - 18	R
Sep. 28	IS
Oct. 1 - 22	L

21 batches in t
- 4 peoples pe
- 2 of ISO tank

LS and GdLS storage in Japan



-- Daya-Bay experiment kindly donated 20 tons of GdLS.

-- arrived at Japan on 2019-Aug-1.

-- Now both GdLS and LS are stored at Kawasaki in Japan.

-- quality is OK.

Summary

• Confirming or refuting existence of "sterile neutrino oscillation" results has been one of the hottest topics in the neutrino physics in the last two decades.

• The $JSNS^2$ experiment will begin data taking in early 2020 and provide an ultimate test of the LSND anomaly without any ambiguity.

• If sterile neutrino oscillation is indeed found, it will be a big discovery of a dark matter candidate.

• The Korean group has been actively participating in the detector construction including delivering 36 tons of liquid scintillator and ~100 10-inch PMTs. We expect to play an important role in obtaining results.

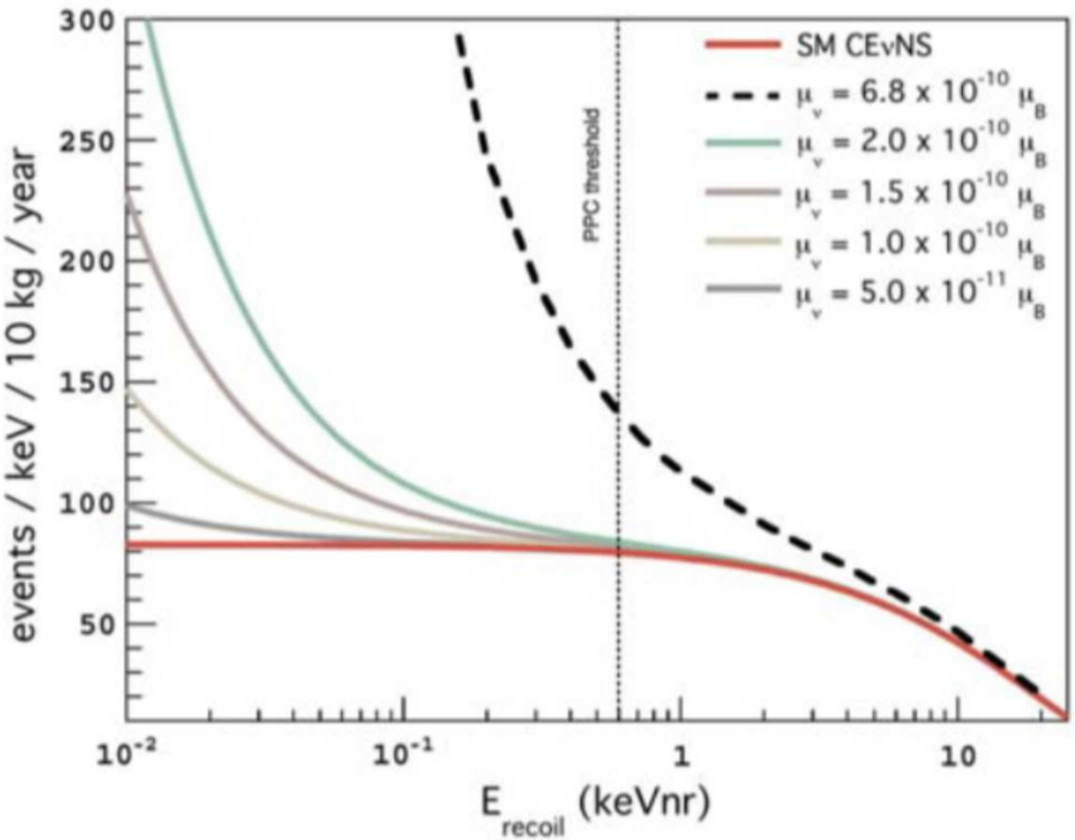
Thanks for your attention!

Backup Slides

Efficient Search for Neutrino Electromagnetic Property

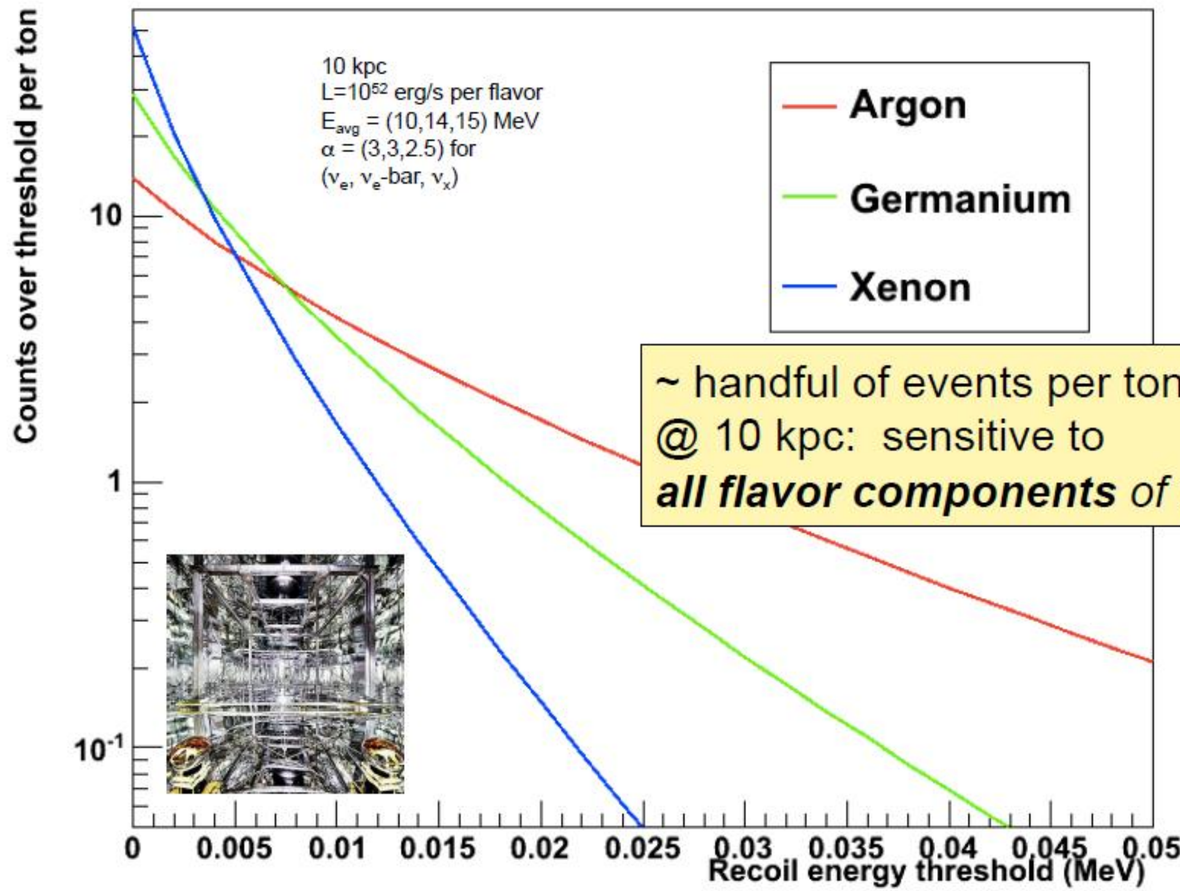
- Change of CEvNS cross section at low energies due to neutrino magnetic moment

$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-T/E_\nu}{T}+\frac{T}{4E_\nu^2}\right)$$

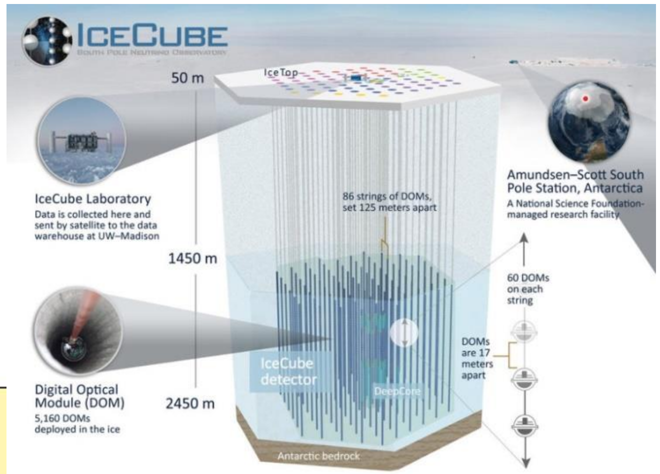


Compact Neutrino Telescope

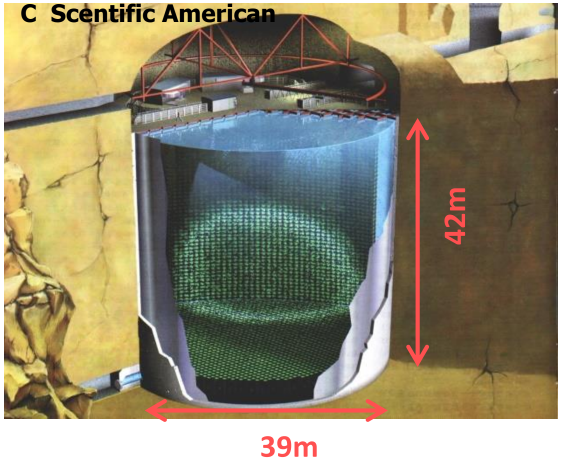
- Development of CEvNS telescope to detect an intense neutrino burst from Supernova



~ handful of events per tonne
@ 10 kpc: sensitive to
***all flavor components** of the flux*



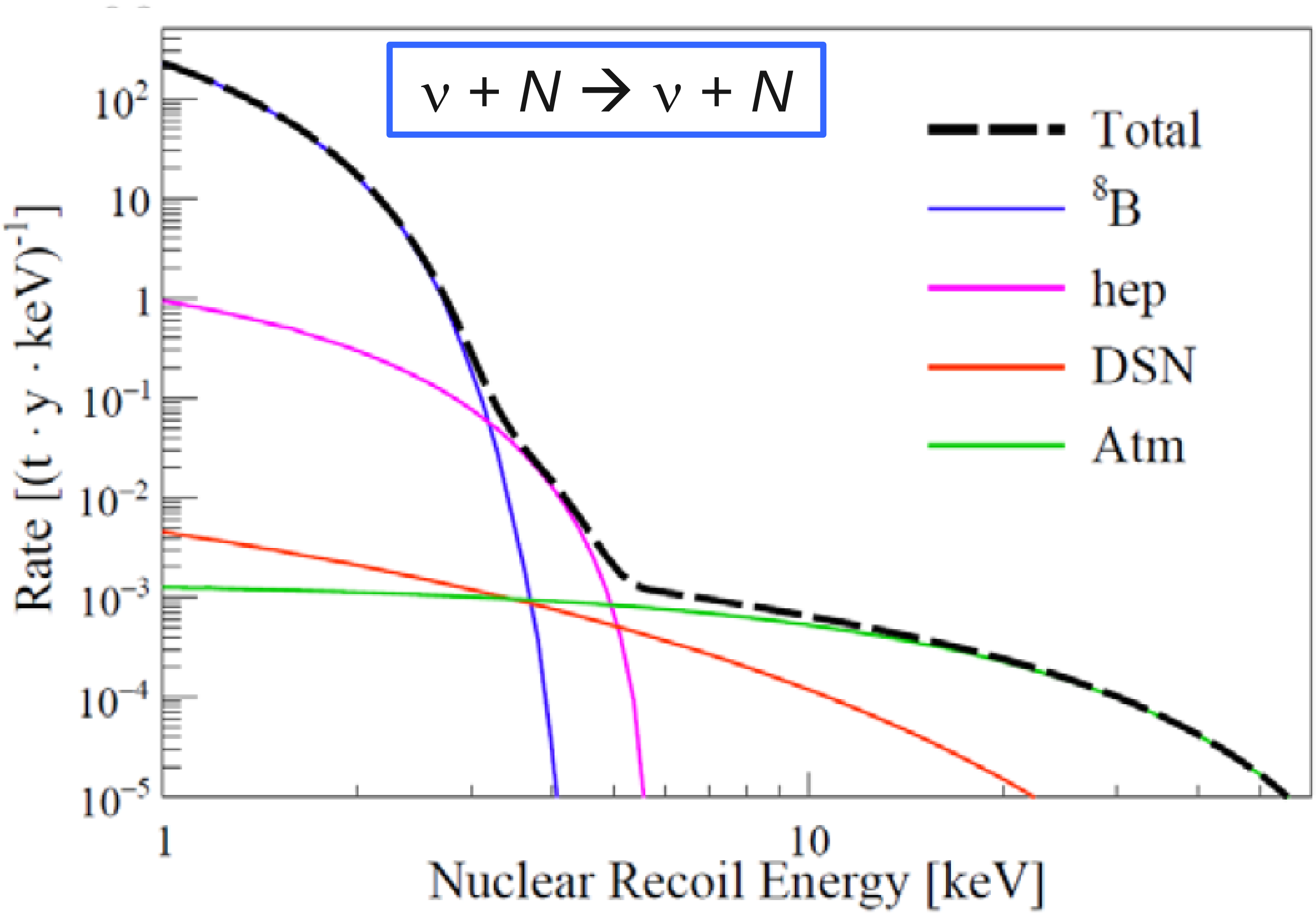
IceCUBE
25M ton water



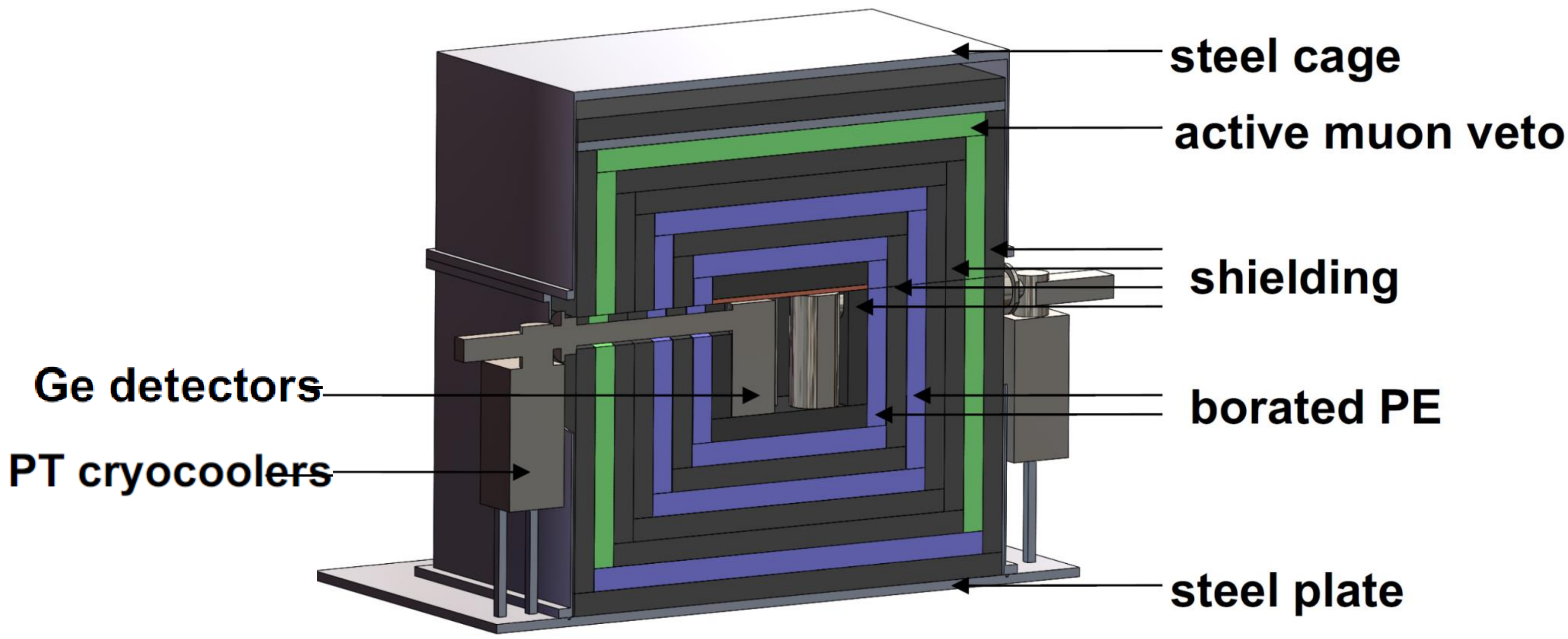
Super-Kamiokande
50k ton water

CEvNS Solar Neutrino Detection

- Solar neutrino detection with a compact detector due to enhanced CEvNS cross section

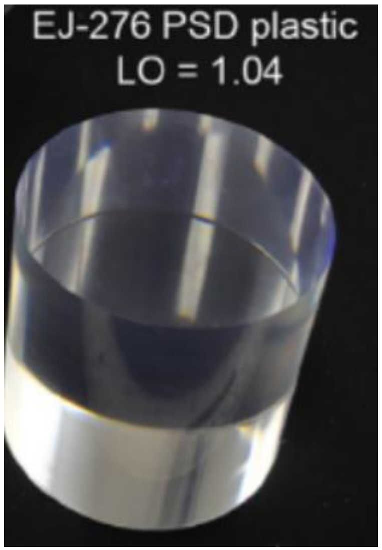


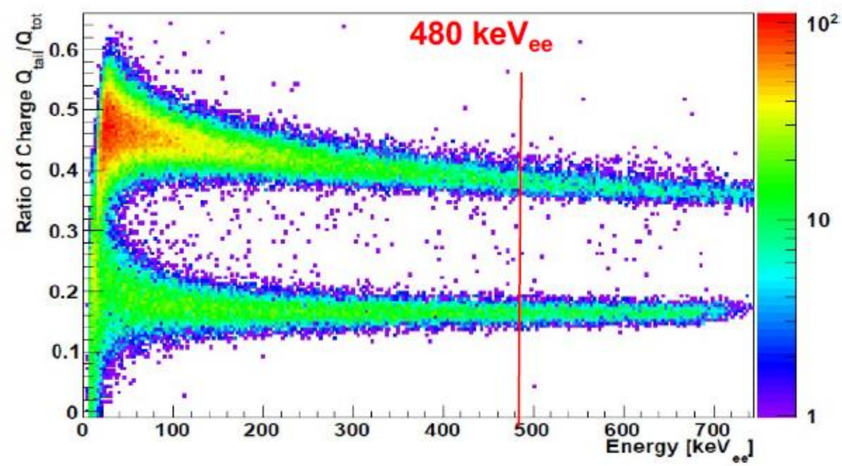
CONUS Detector



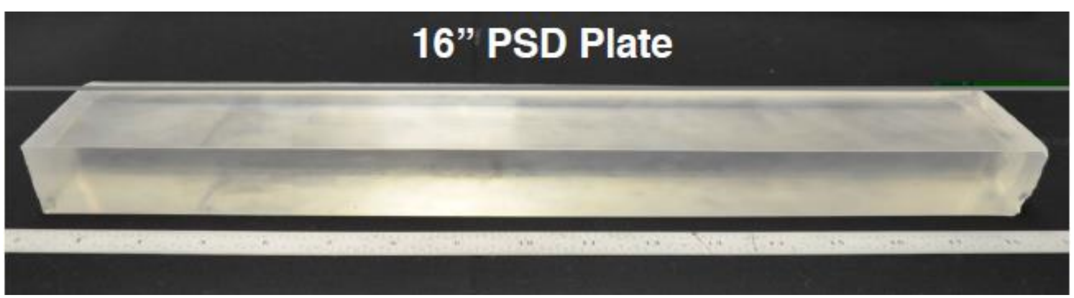
Plastic Scintillator for PSD

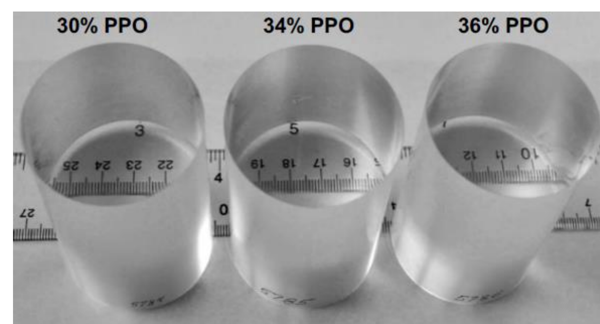
Development of plastic scintillator providing pulse shape discrimination (PSD) between neutron and gamma by Eljen & LLNL





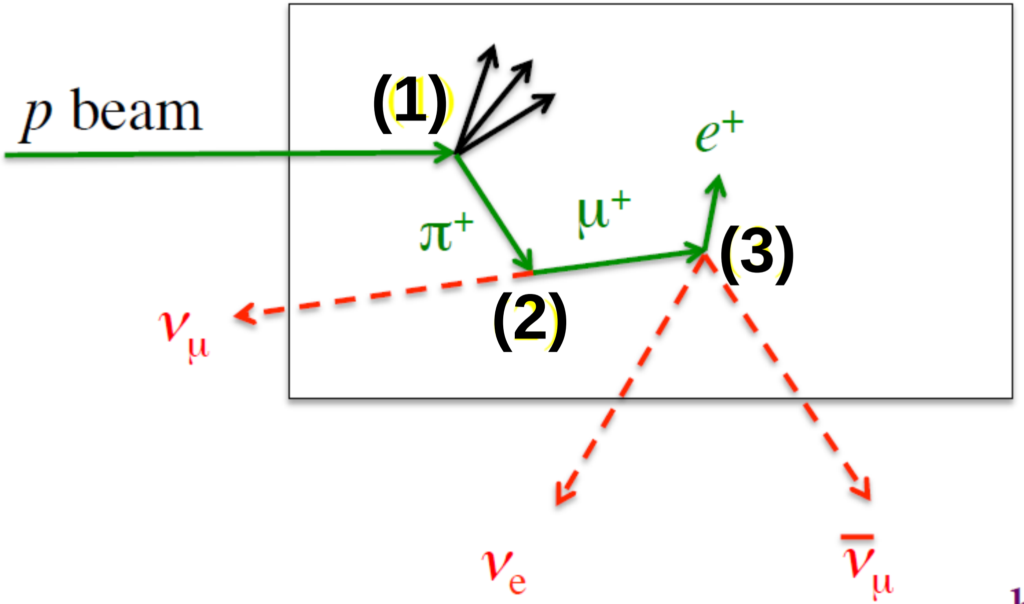
Upgraded plastic scintillator showing PSD performance similar to scintillator EJ-309



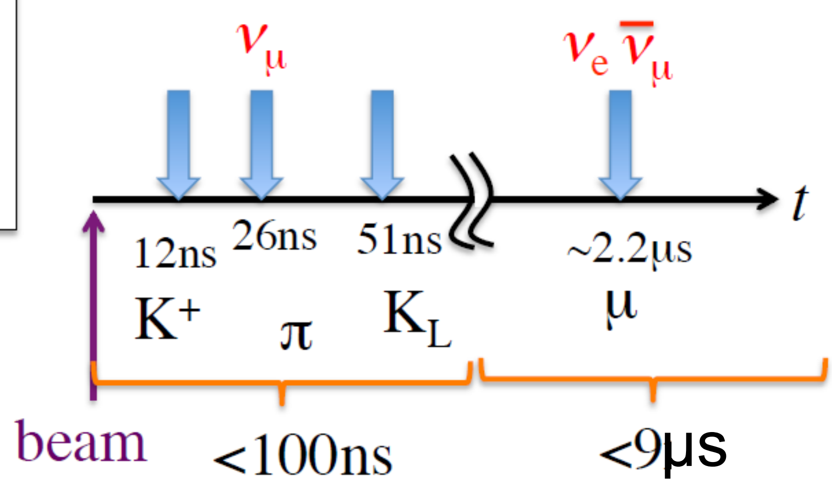


Neutrinos from Muon Decay At Rest (DAR)

(1) High energy (~GeV) protons hit a dense target material and produce π^+.
(2) π^+ stops in the material and decays producing ν_μ and μ^+.
(3) μ^+ stops in the material and decays producing ν_e and $\bar{\nu}_\mu$.
(4) ν's from π^- and μ^- are highly suppressed. $\bar{\nu}_e/\bar{\nu}_\mu \sim 1.7\times10^{-3}$

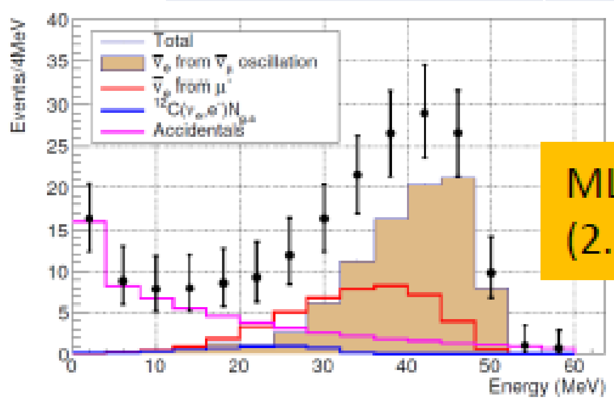


Timing of the ν production



Expected Signal and Background

Source	contents	#ev.(17tons x 3years)	Reference : SR2014 (50tons x 5 years)	comments
background	$\overline{\nu}_e$ from μ-	43	237	Dominant BKG
	$^{12}C(\nu_e,e-)^{12}N_{g.s.}$	3	16	
	Beam fast neutrons	Consistent with 0 < 2 (90%CL UL)	<13	Based on real data
	Fast neutrons (cosmic)	~0	37	
	Accidental	20	32	Based on real data
signal		87	480	Δm^2=2.5, $\sin^2 2\theta$=0.003
		62	342	Δm^2=1.2, $\sin^2 2\theta$=0.003



MLF best Δm^2 (2.5eV^2)