JSNS2 Experiment

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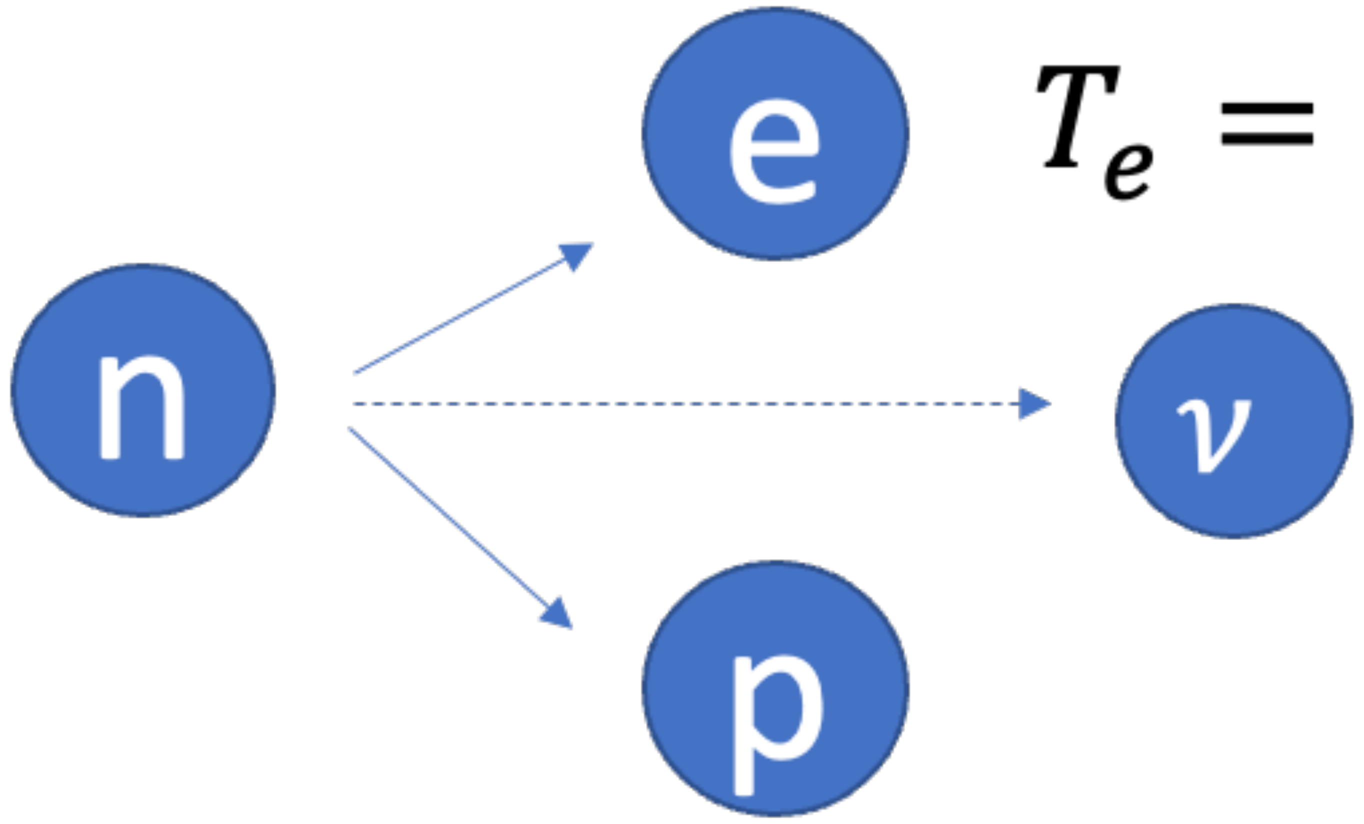
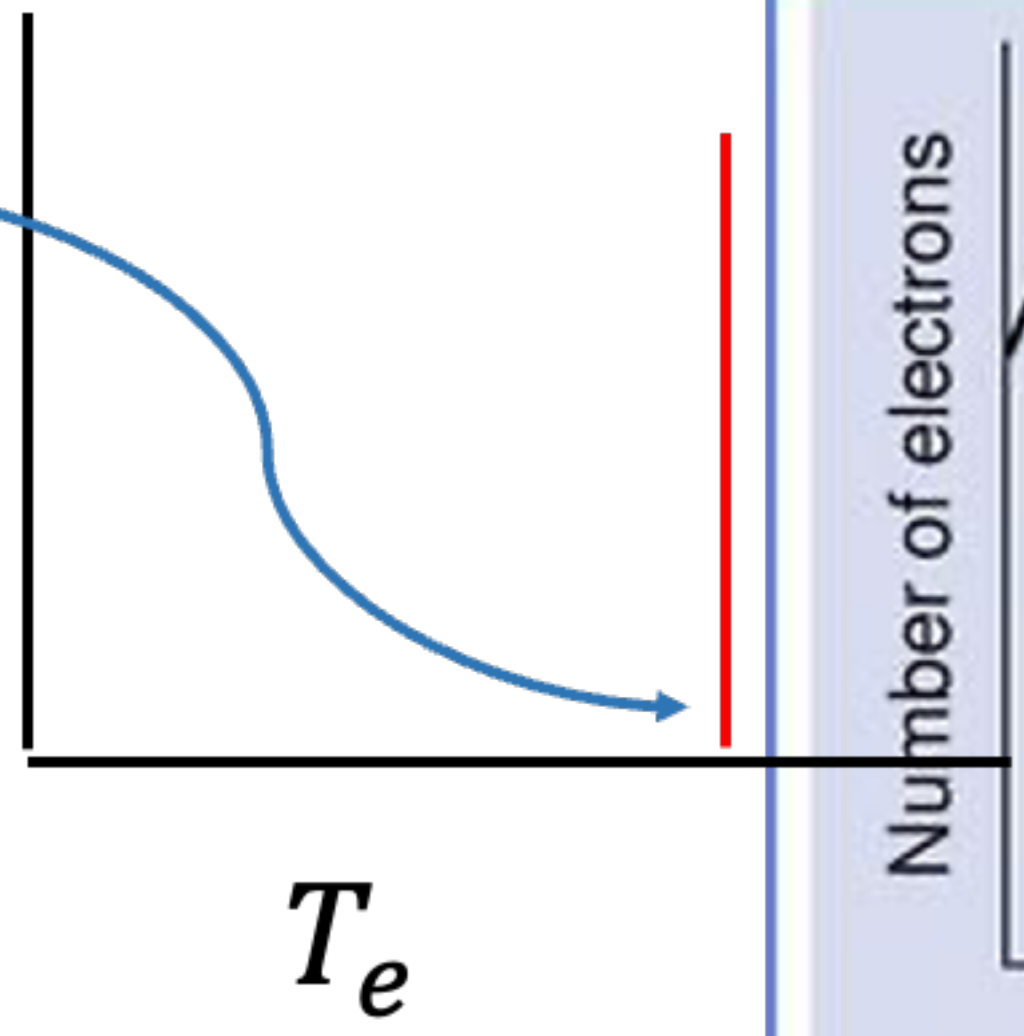
on the behalf of JSNS2 Collaboration

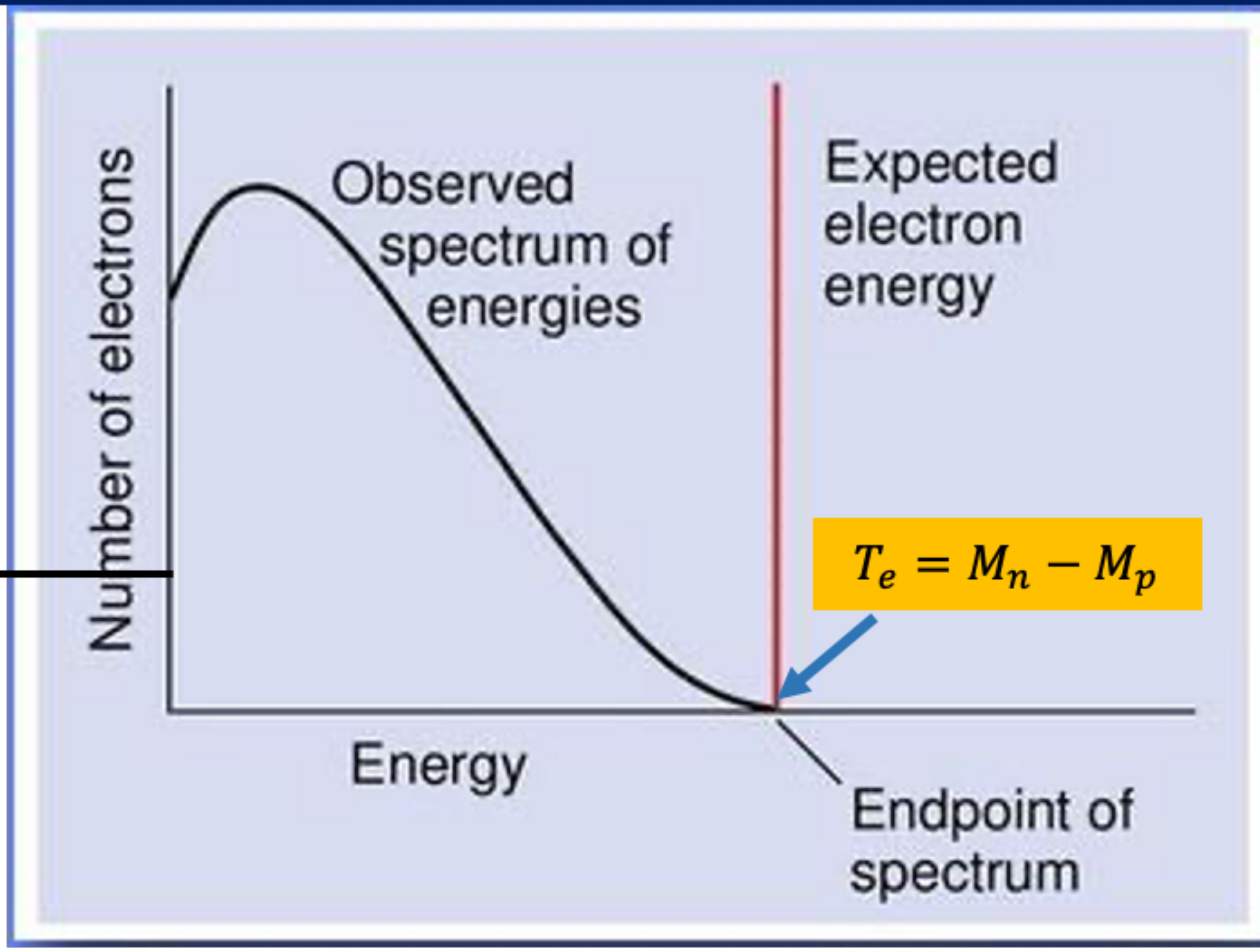
Neutrino Masses and Sterile Neutrino

β-decay and Pauli's Prediction



$$T_e = M_n - M_p$$





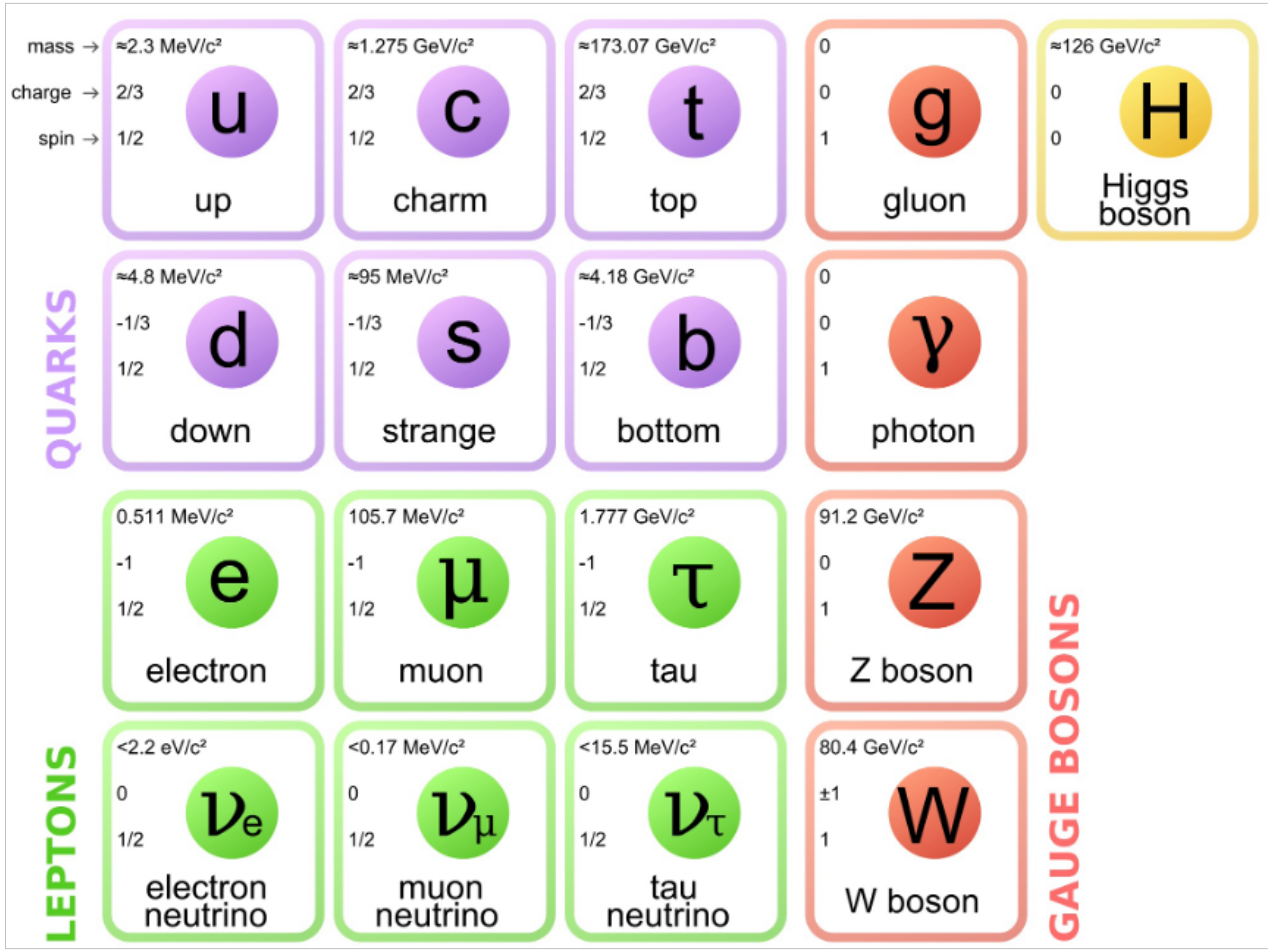
W. Pauli (1900-1958)

A particle has zero mass and rarely interacts with matter.

⇒ neutrino

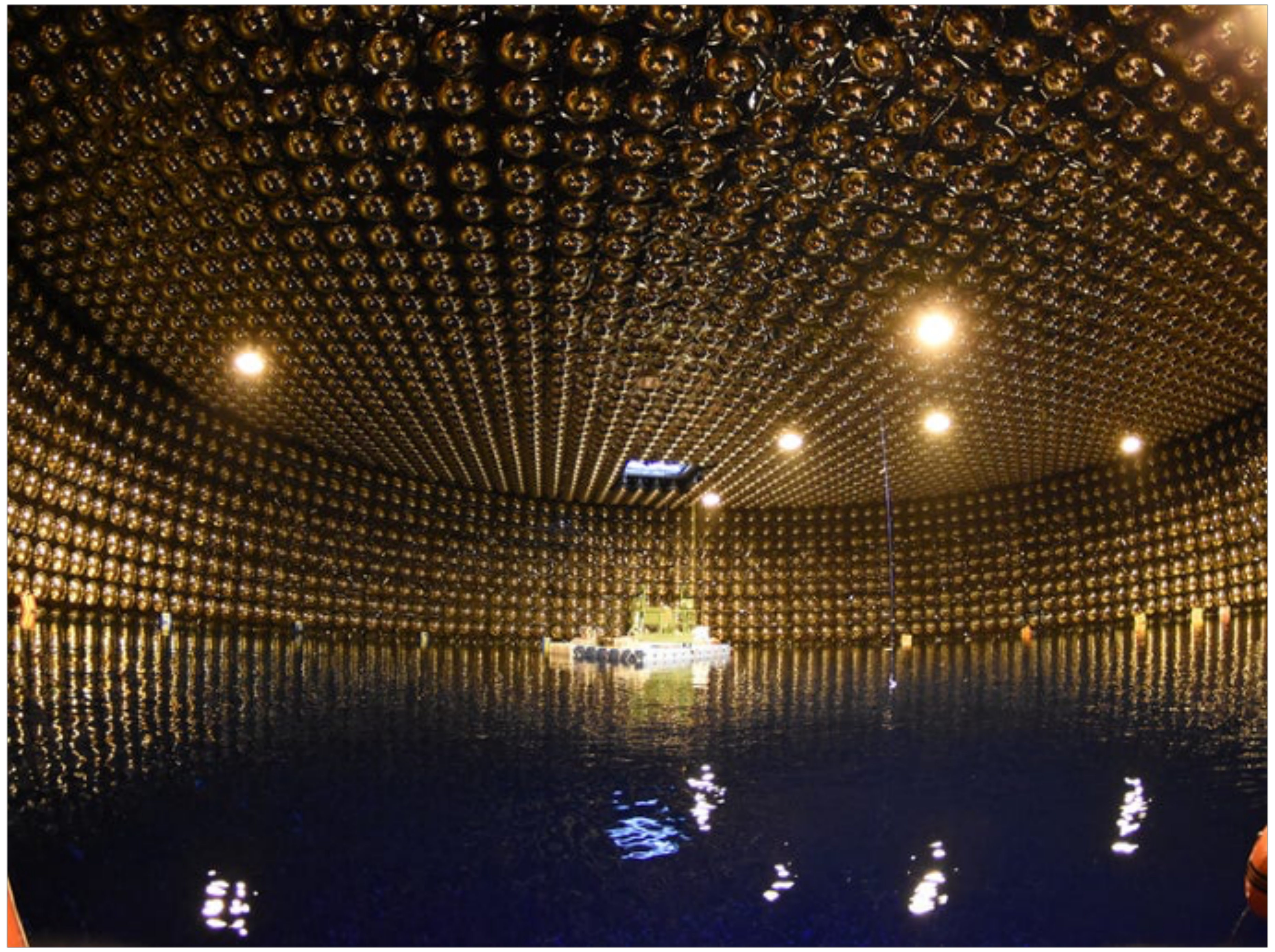
Neutrinos and the Standard Model

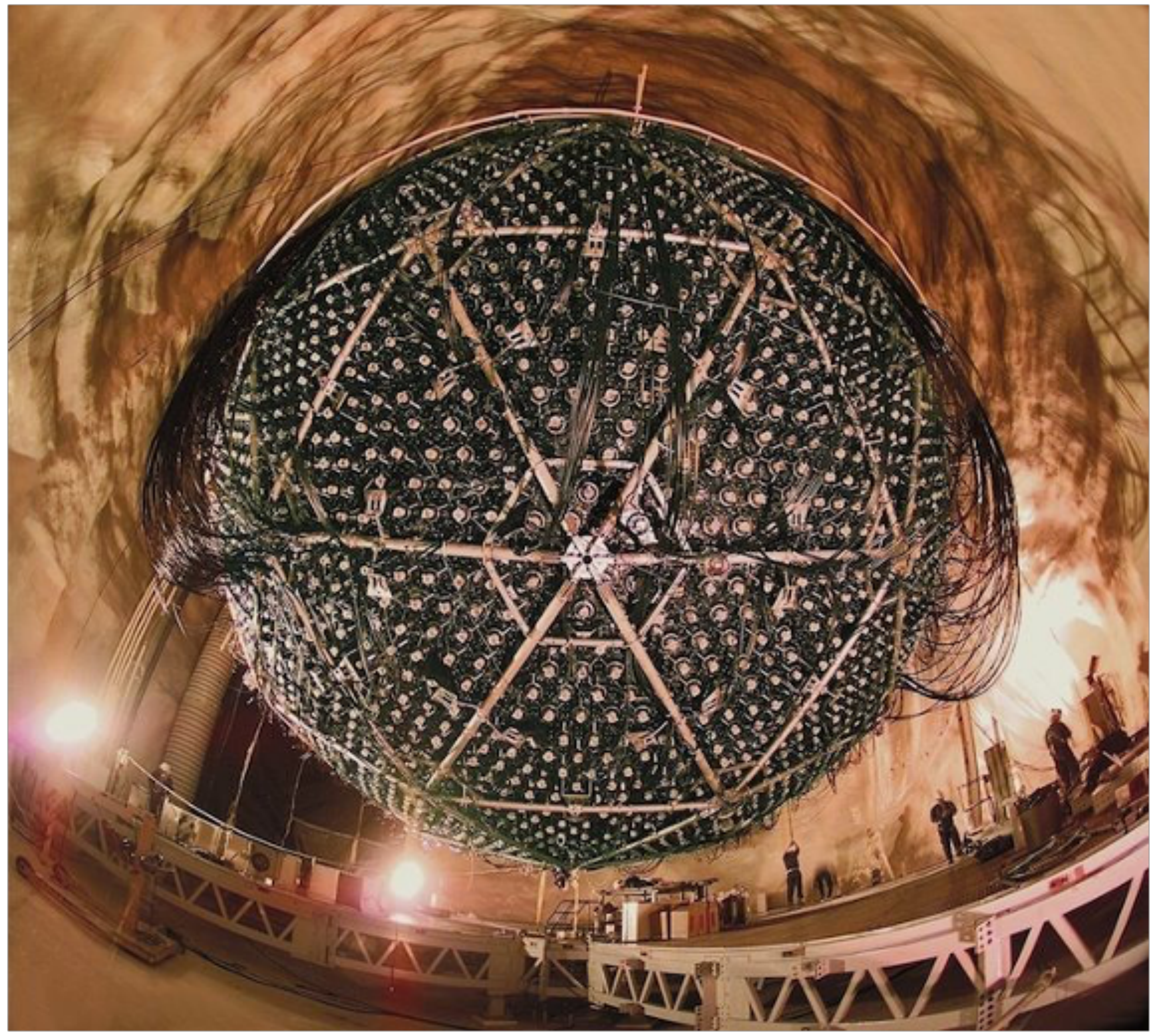
- The standard model requires a large number of input parameters. Because of this, the model itself was a very flexible theory.
- The theoretical basis has been developed based on experimental results in the Standard Model framework.



Neutrino mass ?

- The standard model has so far rarely rejected experimental evidences.
- But Super-K and SNO found evidence of neutrino oscillation in 1998.
  - ⇒ These results provided evidence that neutrinos have mass.
  - ⇒ Neutrinos interact with matter **not only via the weak interaction but also through gravity**.
- However, there is no way to give mass to a neutrino in the model.





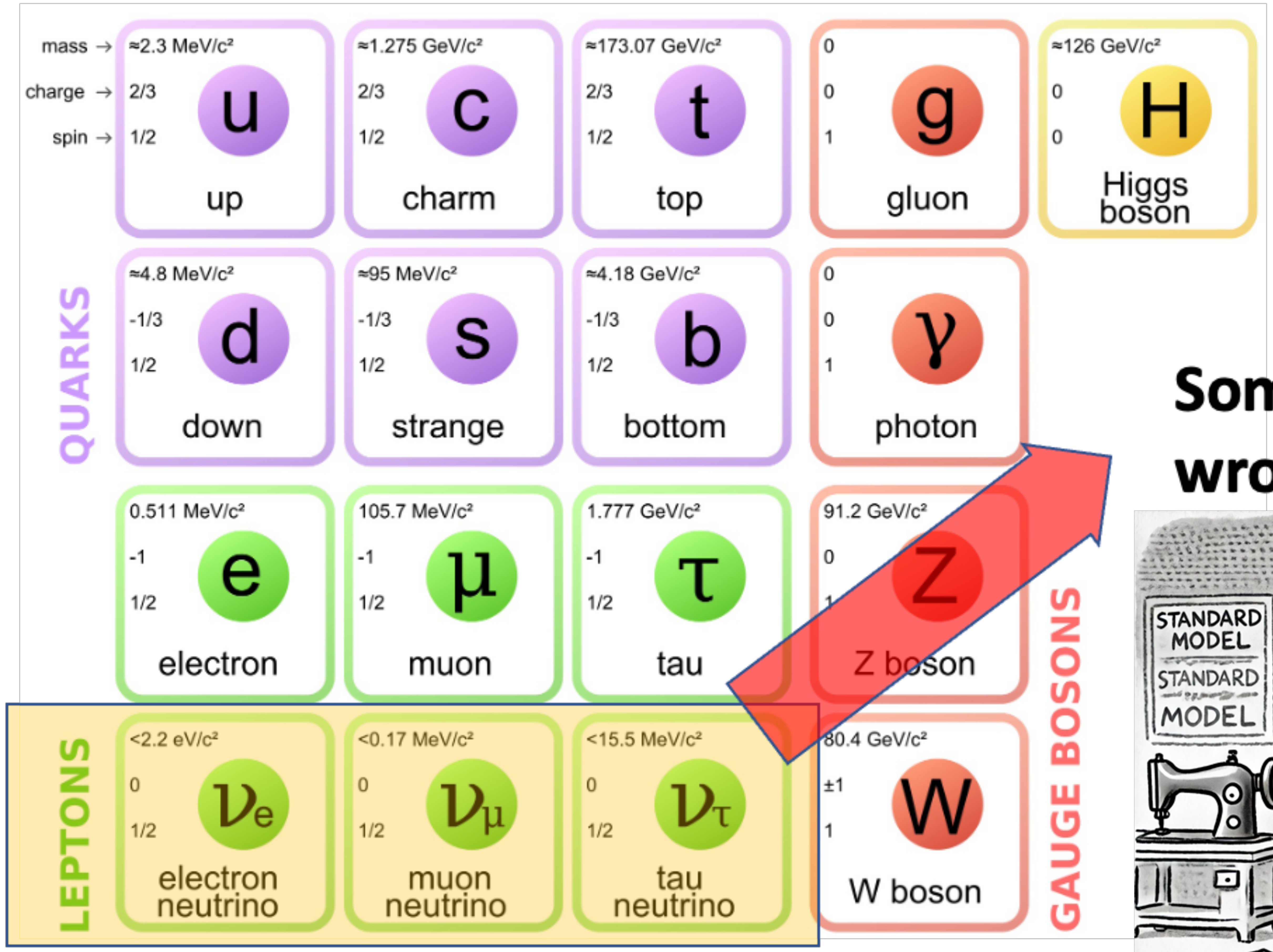
Neutrino oscillation

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

$$\Delta m^2 = m_2^2 - m_1^2$$

In the beginning of the Universe

And God said, “Let there be the Standard Model,” and there was the Standard Model. But, God saw that the Standard Model was not good enough.....



neutrinos

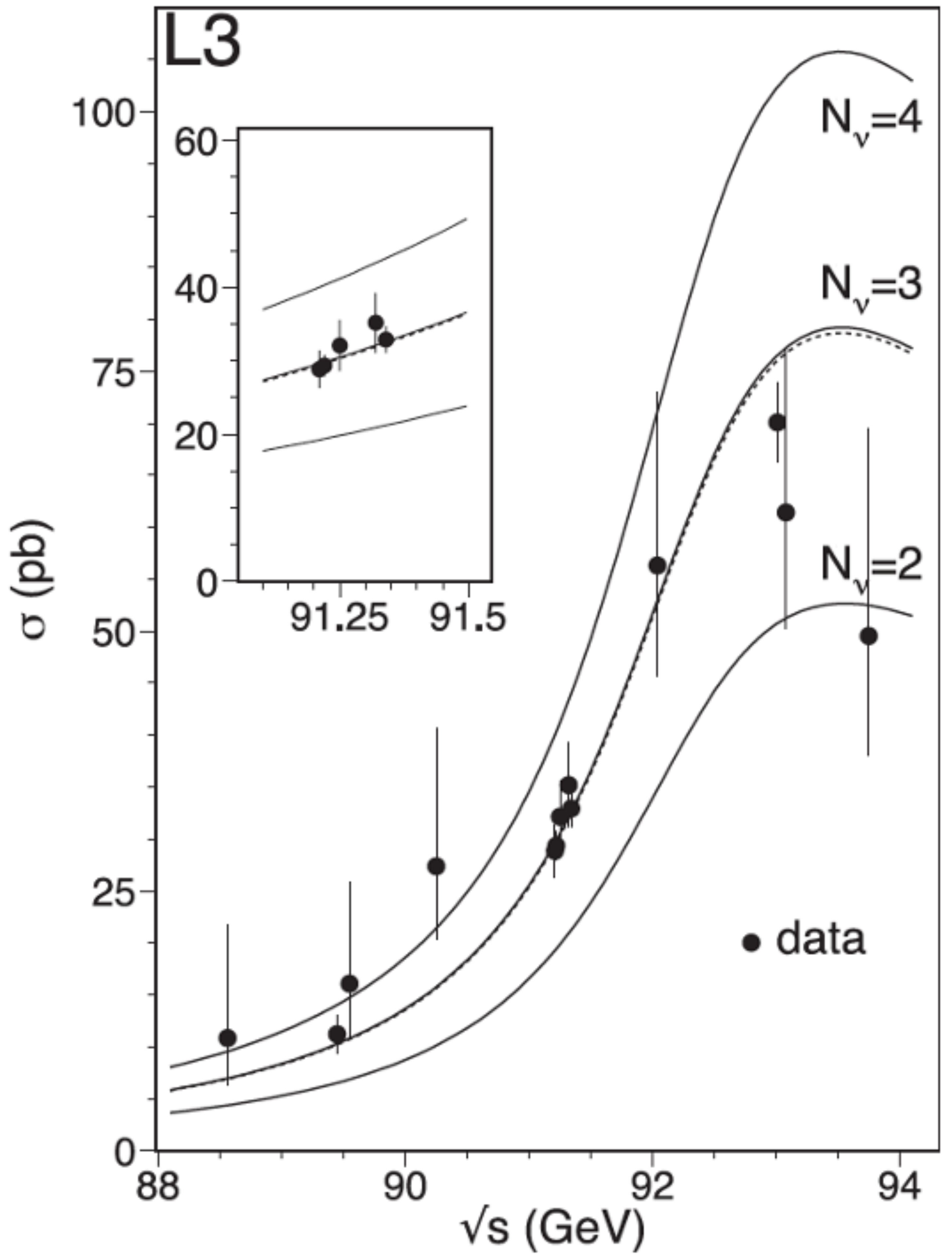
Something seemed slightly wrong in this part.

How many neutrino types in the Universe

- From Z-boson decay, it turns out that there are only three types of neutrinos that have weak interactions.
  - ⇒ Standard Model prediction

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + N_\nu \Gamma_{\nu\nu}$$

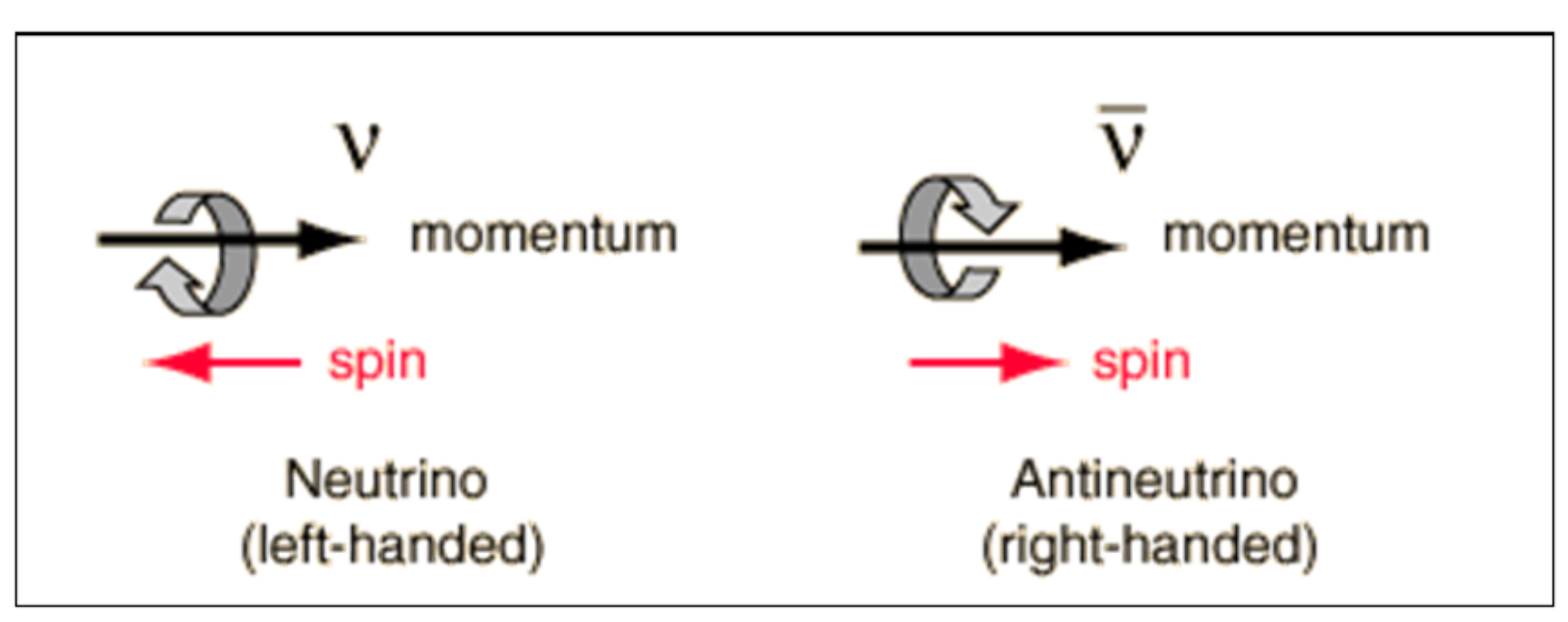
$$N_\nu = 3.00 \pm 0.08.$$



In the Standard Model

- Strong interactions and electromagnetic interactions are independent of the particle's spin.
- However, weak interactions depend on the spin direction of the massless neutrinos.

⇒ Only left-handed neutrino (right-handed antineutrino) affected by weak interaction.



How to explain neutrino mass in the Standard Model

- No mechanism works in the case of neutrino mass.
- Therefore, theoretically, there is a lot of room, and the following assumptions are possible.

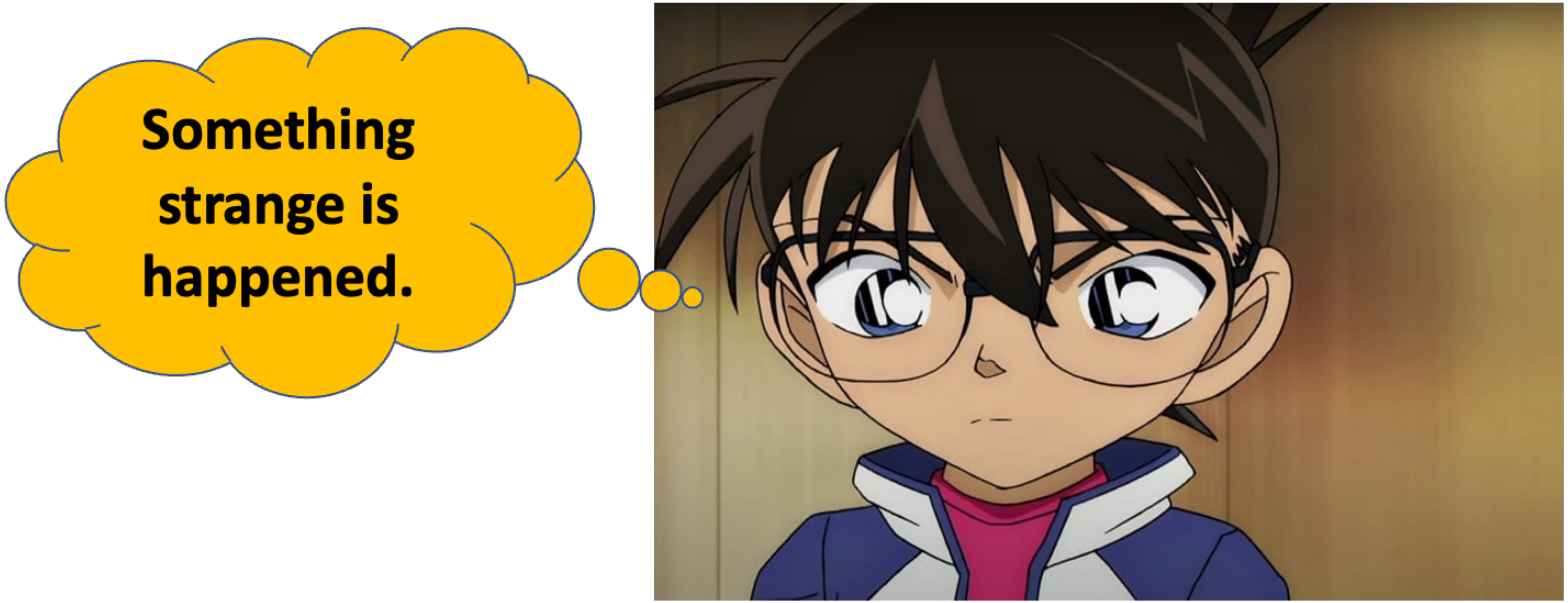
  ⇒ The product of a right-handed neutrino mass and a left-handed neutrino's is a constant : **See-Saw mechanism**

  ⇒ Simple way to introduce a right-handed neutrino

  ☞ $\bar{\nu} = \nu$, so called Majorana neutrino

Now are we happy?

- Now we have a tool giving masses to neutrinos, even we do not know it really works, and three types of neutrinos having weak interaction. So we are happy in the Standard Model?

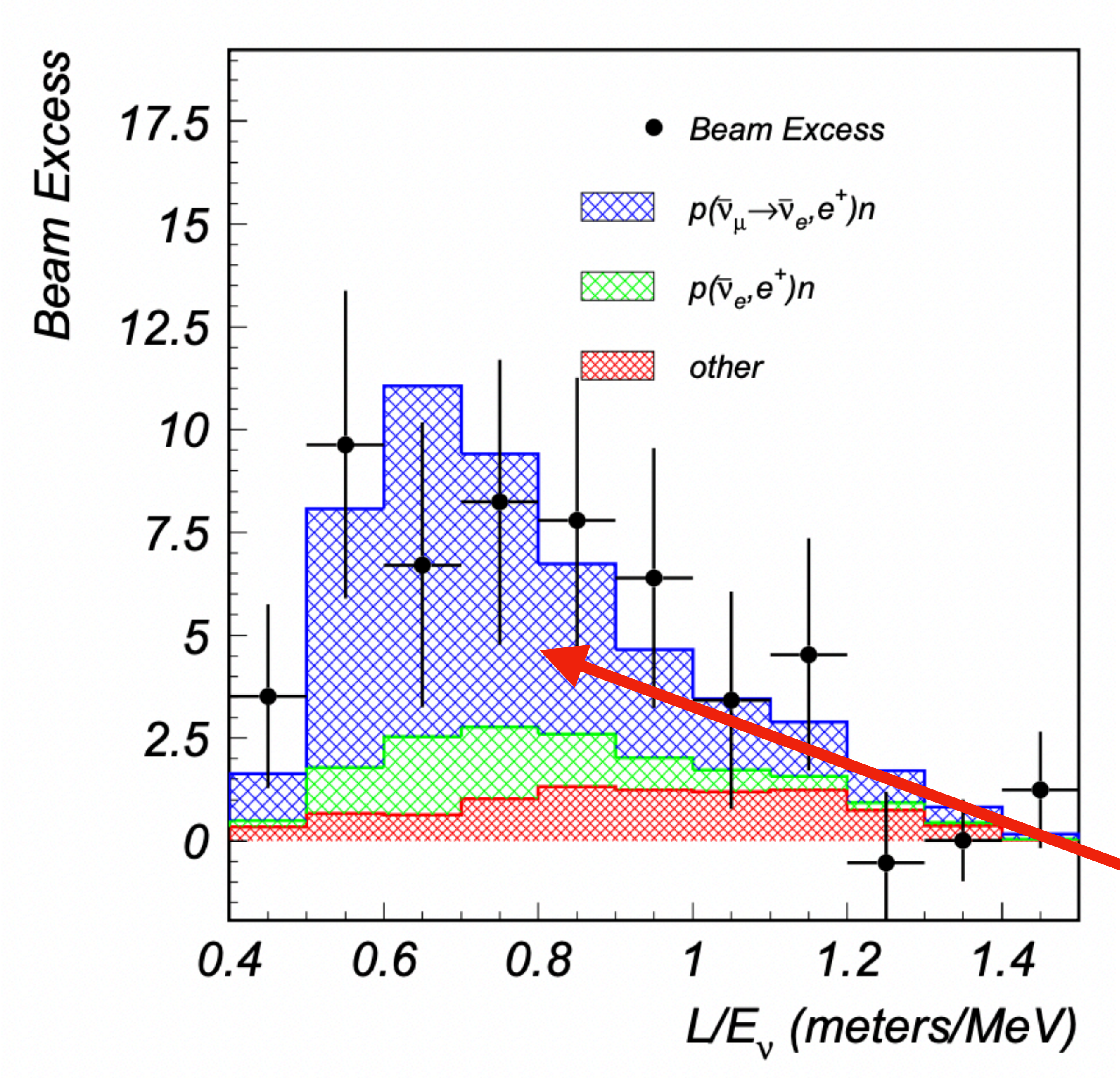


Sterile neutrino?

- **LSND reported an an excess of 87.9±22.4±6.0 anti-electron neutrino events (3.8σ) in 2001.**

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

- **Anomalies, which cannot be explained by three neutrino oscillations for about 20 years is below:**



- 800 MeV proton beam and 30 m baseline
- Neutrinos from muon decay-at-rest
- $\bar{\nu}_e$ appearance signals were detected via Inverse Beta Decay

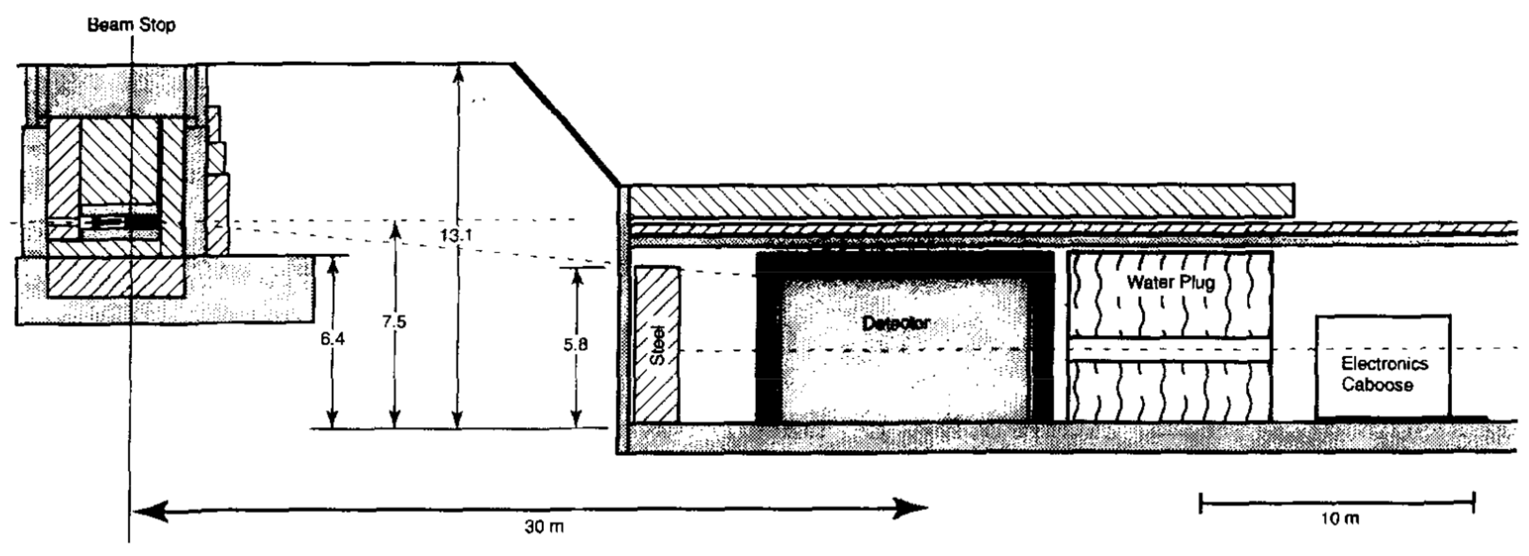


Fig. 1. Detector enclosure and target area configuration, elevation view.

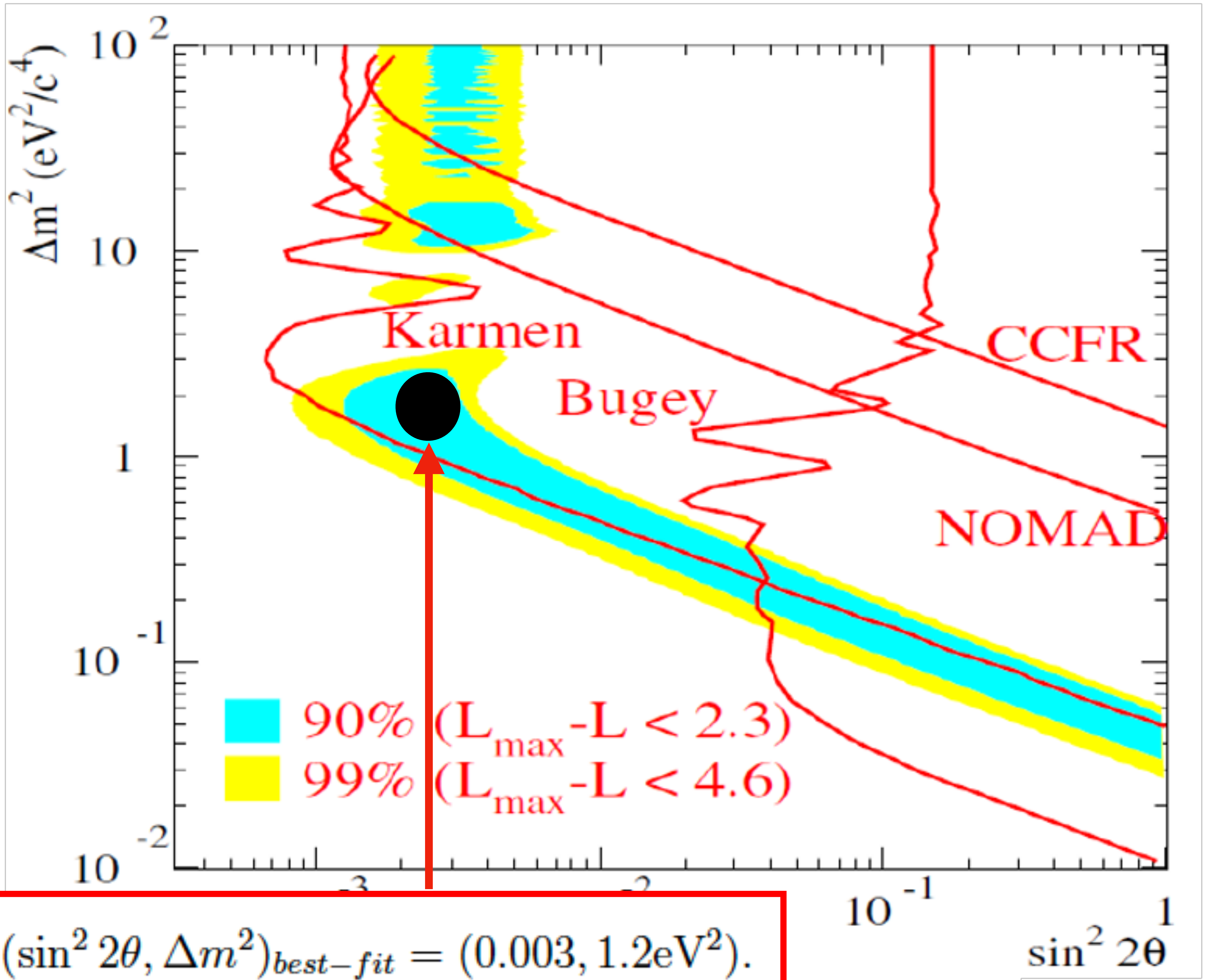
$$(\sin^2 2\theta, \Delta m^2)_{best-fit} = (0.003, 1.2\text{eV}^2).$$

$$\Delta m_{12} = \sim 10^{-5}\text{eV}^2$$

$$\Delta m_{23} = \sim 10^{-3}\text{eV}^2$$

- **Δm^2 ($1.2\ \text{eV}^2$) was significantly larges.**
- **It could not be explained by the three-neutrino standard model framework.** $\Delta m_{12} = \sim 10^{-5}\text{eV}$
  - **Sterile neutrino : from “non-weak interaction”**

But



$(\sin^2 2\theta, \Delta m^2)_{best-fit} = (0.003, 1.2\text{eV}^2)$.

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

(1990-1995, 1997-1999)

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

[PRD 65 (2002) 112001]

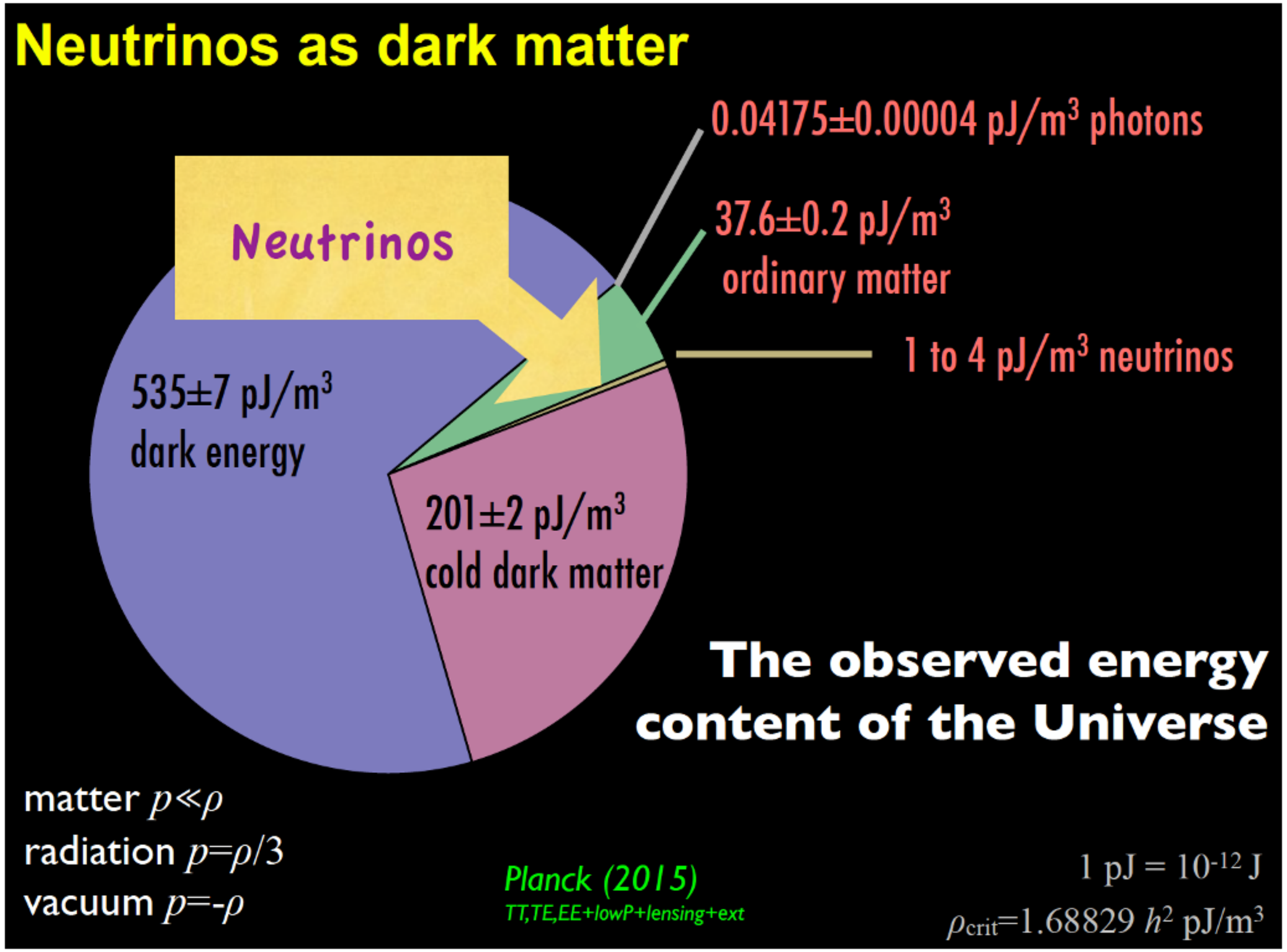
- Which experiment was wrong ?
- What's going on the neutrino sector?
- Many tests had been there after that.

Another type(s) of neutrino?

- We have known there are three types of neutrino.
- But these interact via weak interaction only!!
  - ▻ If neutrino having only mass and independent of weak interaction ?
  - ▻ **Sterile neutrino**
- Some experimental results indicate the possibilty.

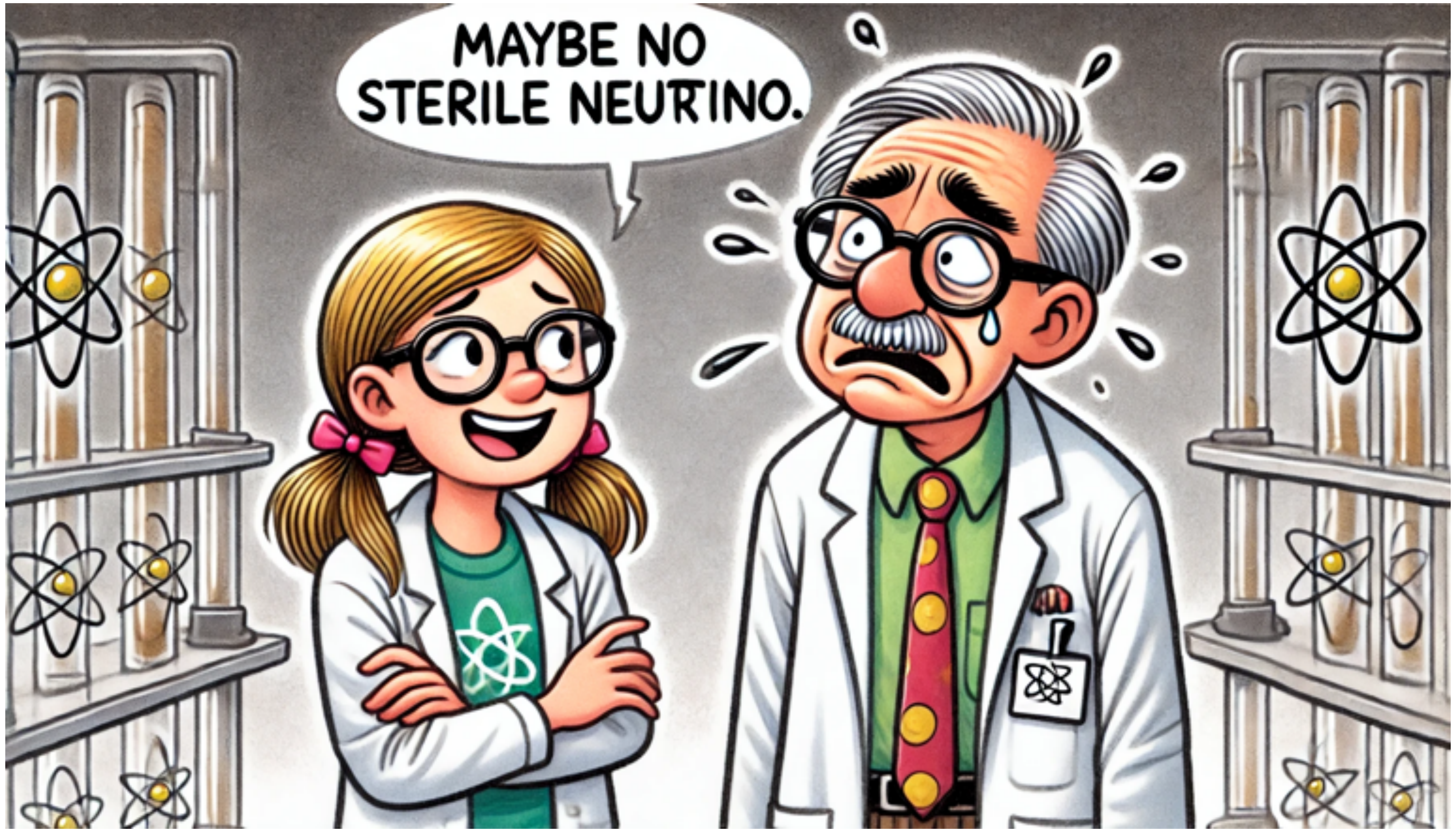
Experiment	ν source	Signal	Significance
LSND	μ Decay-At-Rest	$\overline{\nu_\mu} \to \overline{\nu_e}$	3.8σ
MiniBooNE	π Decay-At-Flight	$\nu_\mu \to \nu_e$	3.4σ
		$\overline{\nu_\mu} \to \overline{\nu_e}$	2.8σ
		combined	3.8σ
Ga/SAGE	e capture	$\nu_\mu \to \nu_x$	2.7σ
Reactors	$\beta -$ decay	$\overline{\nu_\mu} \to \overline{\nu_x}$	3.0σ

Neutrino as Dark Matter



- KATRIN shows the upper bound of standard neutrino mass as $\sum m_\nu < 0.17$ eV.
- Only explains small part of the total mass of the Universe.
- But if sterile neutrino have ~keV mass scale (high mass sterile neutrino), whole dark matter can be explained!!

JSNS^2 / JSNS^2-II Experiment


MAYBE NO STERILE NEUTRINO.

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

Experiments (Neutrino source, signal, significance, energy, baseline)

- **LSND** (μ Decay-At-Rest, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, 3.8 σ, 40 MeV, 30 m, LINAC (600 us), 120 Hz)
- **MiniBooNE** (π Decay-In-Flight, $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, 4.8 σ (combined), 800 MeV, 600 m)
- **BEST** (e capture, $\nu_e \rightarrow \nu_x$, ~4 σ, < 3 MeV, 10 m)
- **Reactors** (Beta decay, $\bar{\nu}_e \rightarrow \bar{\nu}_x$, significance varies, 1-8 MeV, 10 - 100 m)

- **However, other experiments have produced results that contradict the existence of sterile neutrinos.**
- **"Therefore, a completely independent test under the same conditions is necessary."**

JSNS^2 / JSNS^2-II Collaboration

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

Collaboration meeting @ J-PARC (2024/Feb)

JSNS^2 collaboration (61 collaborators)

- 7 Japanese institutions (27 members)
- 10 Korean institutions (25 members)
- 4 US institutions (5 members)
- 1 UK institution (1 member)
- 1 China Institution (3 members)

JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku
Tsukuba

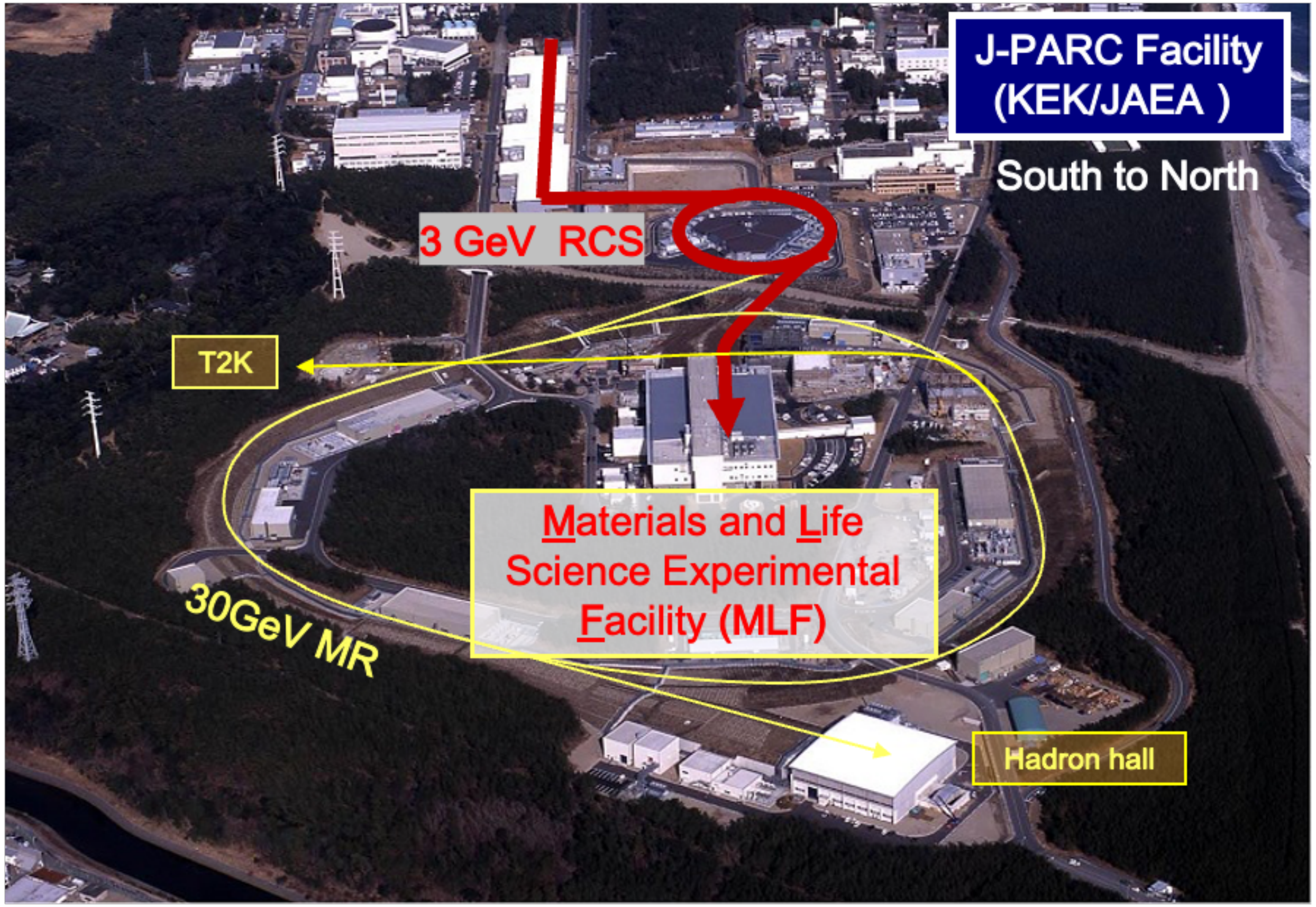
Chonnam National
Jeonbuk National
Dongshin
GIST
Kyungpook
Kyung Hee
Seoyeong
Soongsil
Sungkyunkwan
Seoul National of sci and tech

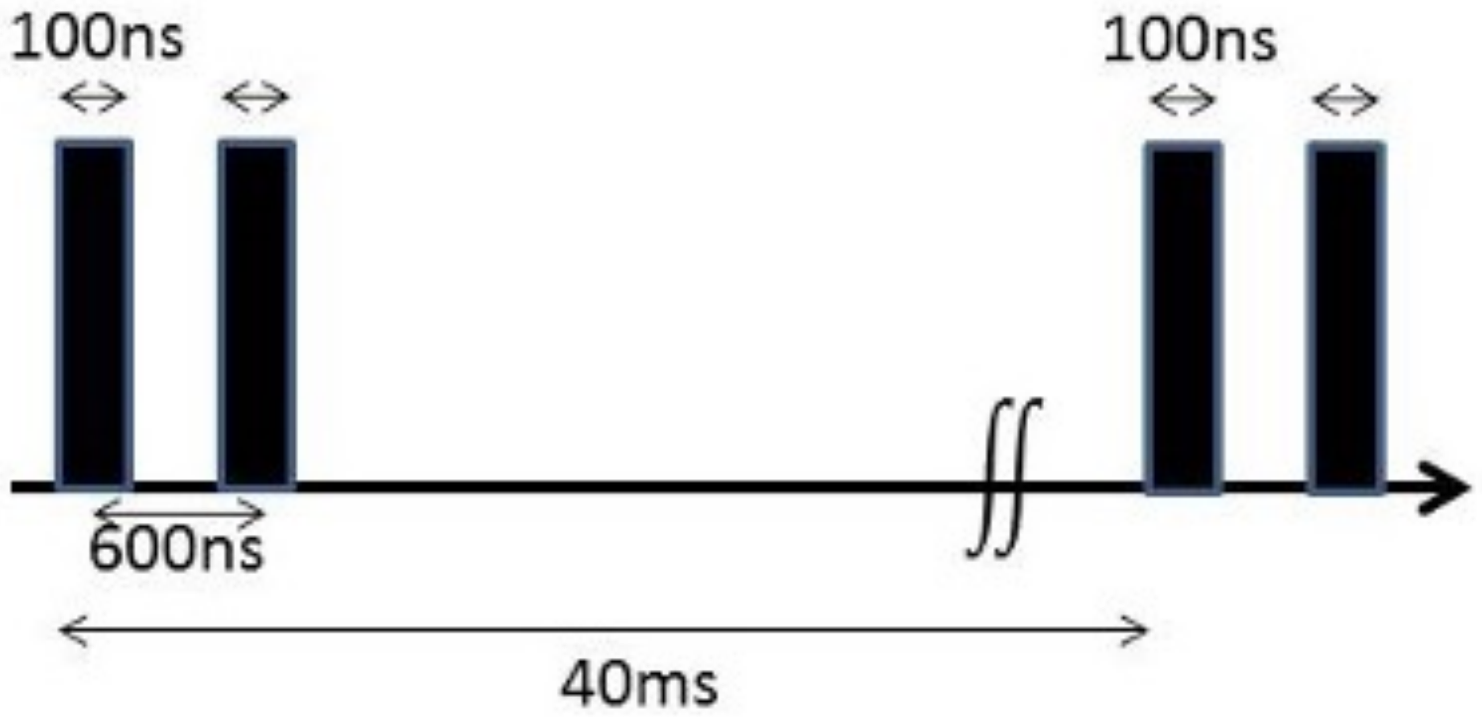
BNL
Florida
Michigan
Utah

Sussex

Sun Yat-sen

J-PARC Facility





Low duty factor beam
(short-pulses + low repetition rate)
Gives an excellent signal to noise ratio

1 MW (design)

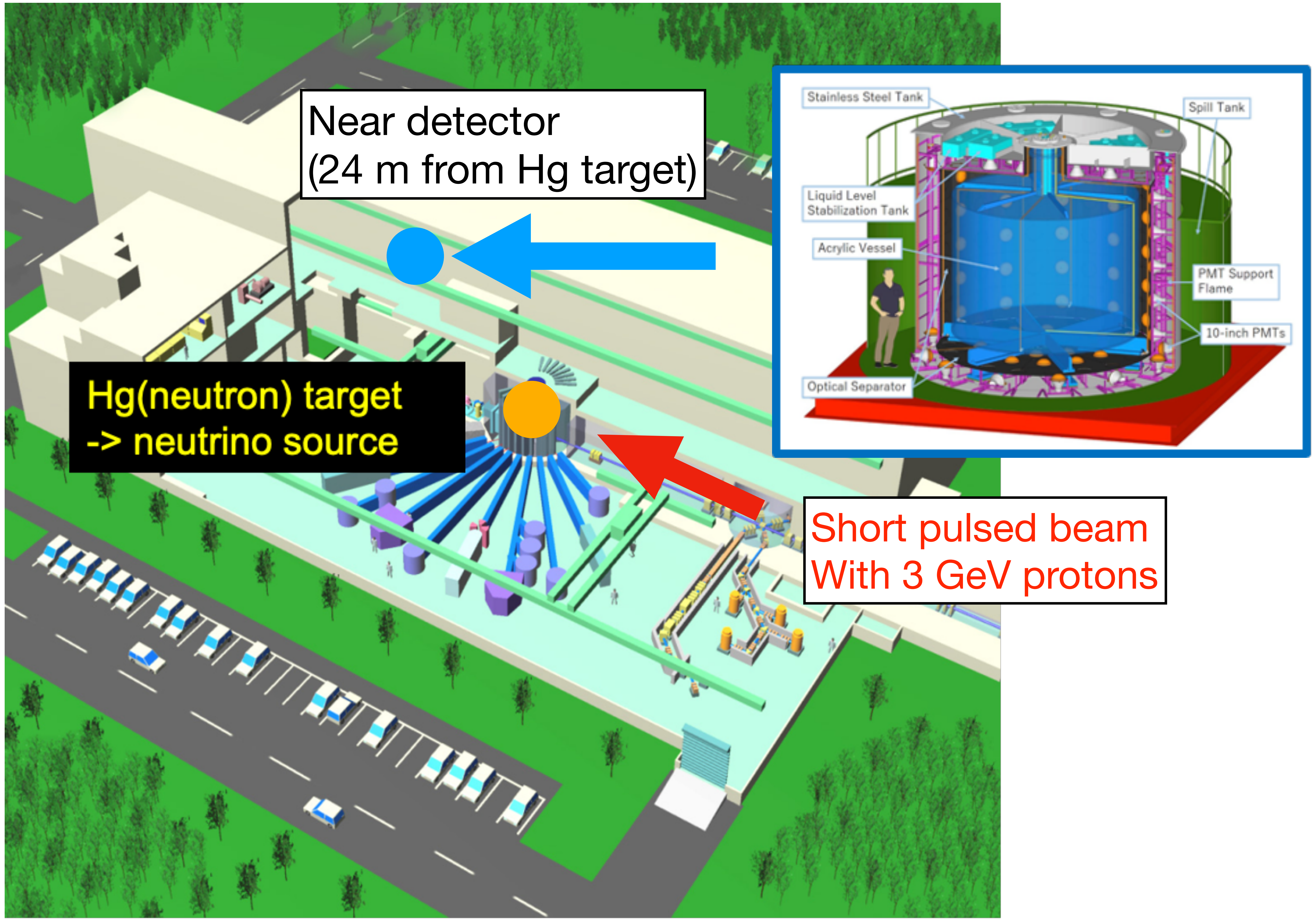
- 0.6-0.7 MW (2021)
- 0.7-0.8 MW (2022)
- 0.84 MW (2023) / 0.65 MW (2023 Dec)
- 0.88-0.95 MW (2024)

Beam power at RCS: 1 MW (2024)

- A part of the beam is passed to the main ring (for T2K or Hadron)

JSNS² detector

(Nucl. Instrum. Methods A 1014 (2021) 165742)



17 tons target, Gd-LS + 10% DIN
31 tons gamma-catcher and veto, LS
120, 10-inch PMTs

Commissioning (2020)

- Calibration
- Beam data with 25 us window
- Eur. Phys. J. C (2022) 82:331

Physics run (2021 - present)

- Eur. Phys. J. C (2024) 84:409
- More papers are under review and available on the arXiv also.

- JSNS^2 uses the **same** neutrino source (μ), target (H), and detection principle (IBD) **as the LSND**
- Even if the excess is not due to the oscillation, JSNS^2 can catch this directly.

Two advantages: **short-pulsed beam (100 ns $\times$ 2, 25 Hz)** and **gadolinium(Gd)-loaded liquid scintillator**

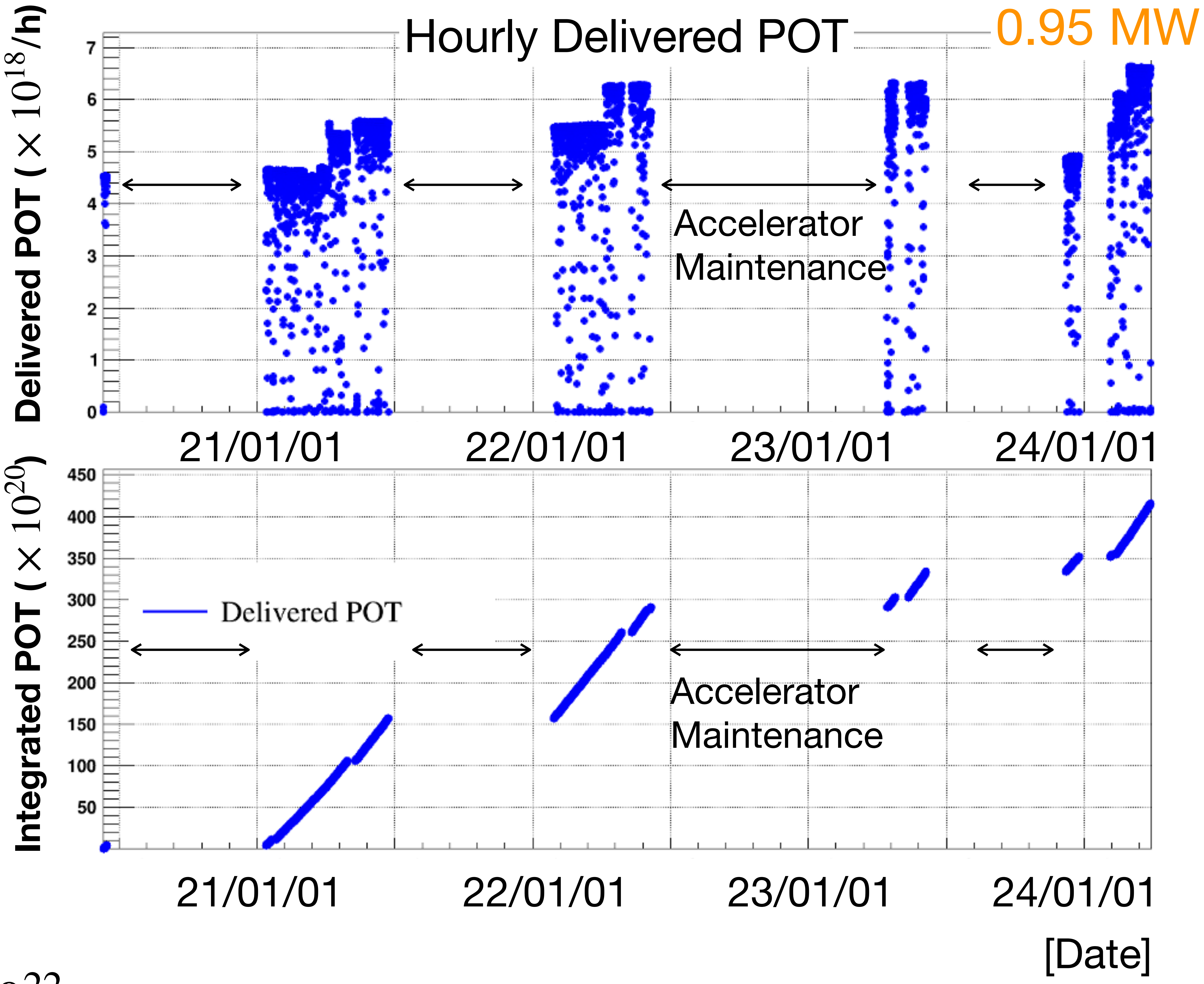
Operation

1st physics run
- 0.6 MW (2021/Jan - Apr/5)
- 0.7 MW (2021/Apr/5 - June/22)

2nd physics run
- 0.7 MW (2022/Jan/28 - Apr/6)
- 0.8 MW (2022/Apr/7 - Jun/6)

3rd physics run
- 0.84 MW (2023/Apr/15 - Jun/2)

4th physics run
- 0.65 MW (2023/Dec/7 - Dec/25)
- 0.88 MW (2024/Feb/6 - Apr/8)
- 0.95 MW (2024/Apr/8 -)



4.09×10^{22} POT has been delivered by end of March

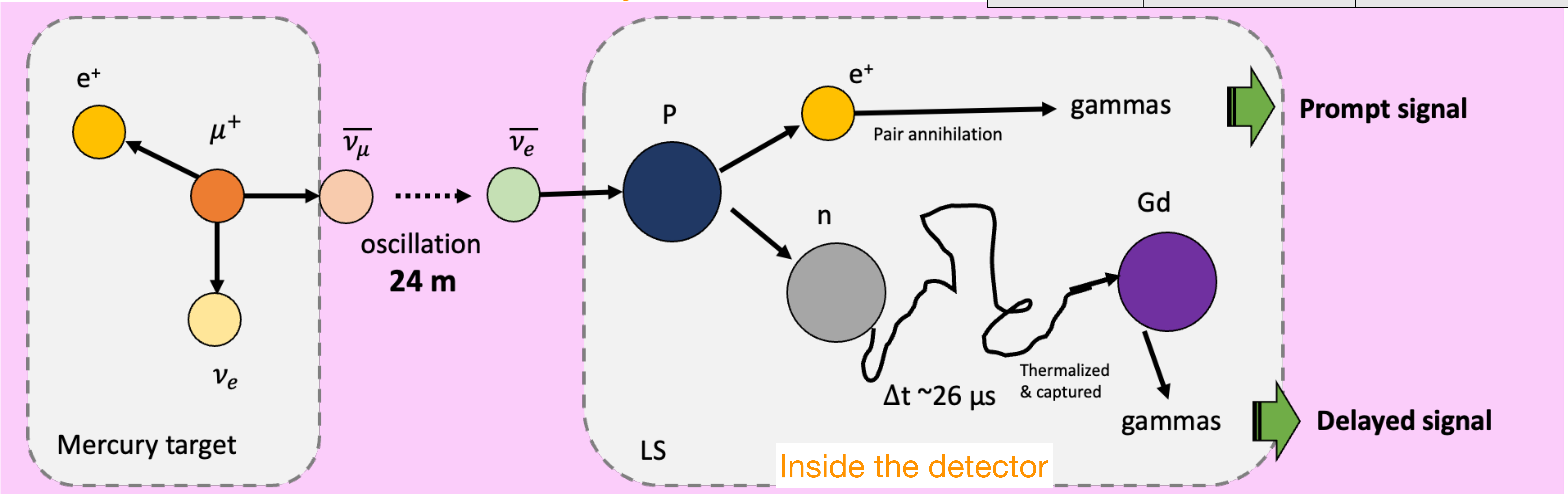
(35.9 % of the approved POT of JSNS^2), **LSND : $\sim 10^{23}$ POT**

Production and detection

If sterile neutrinos exist, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation occurs with 24m

Coincidence of Inverse Beta Decay (IBD)
- The positron annihilation
- Gammas from neutron captured on gadolinium (Gd)

	Timing	Energy
prompt	$1.5 \leq T_p \leq 10$ μs	$20 \leq E \leq 60$ MeV
delayed	$\Delta T_{p\text{-}d} < 100$ μs	$7 \leq E \leq 12$ MeV

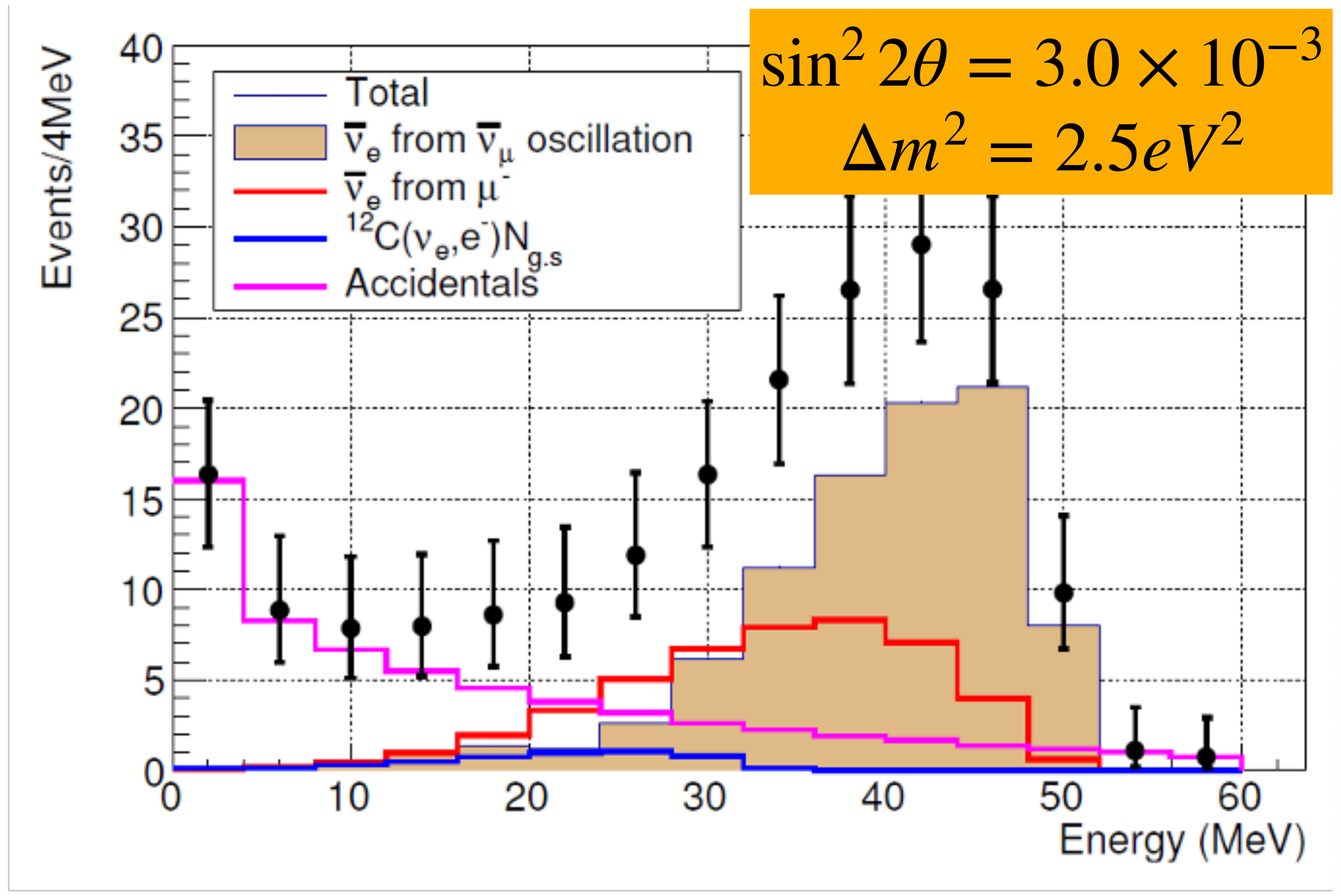


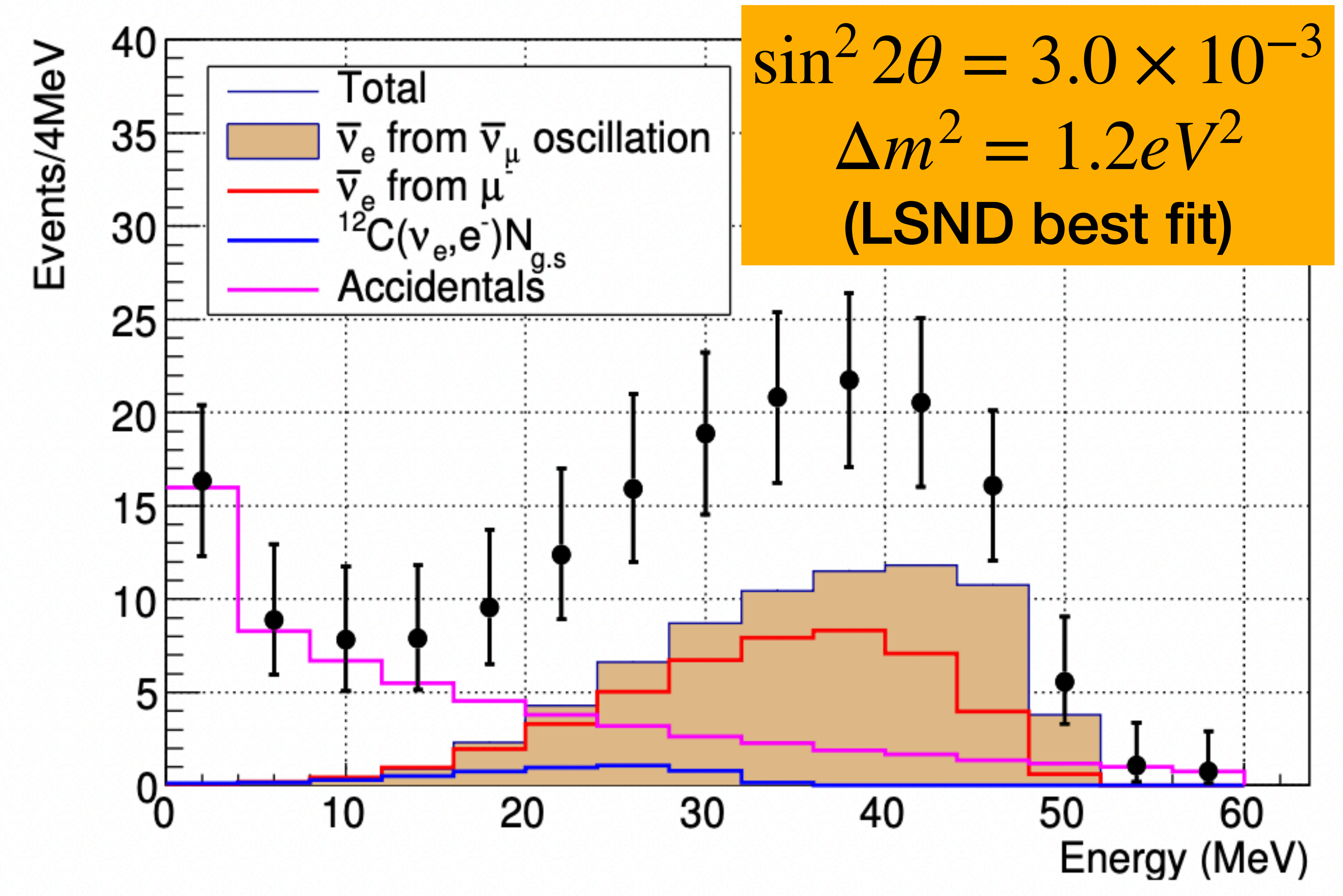
Expected energy spectrum and sensitivity

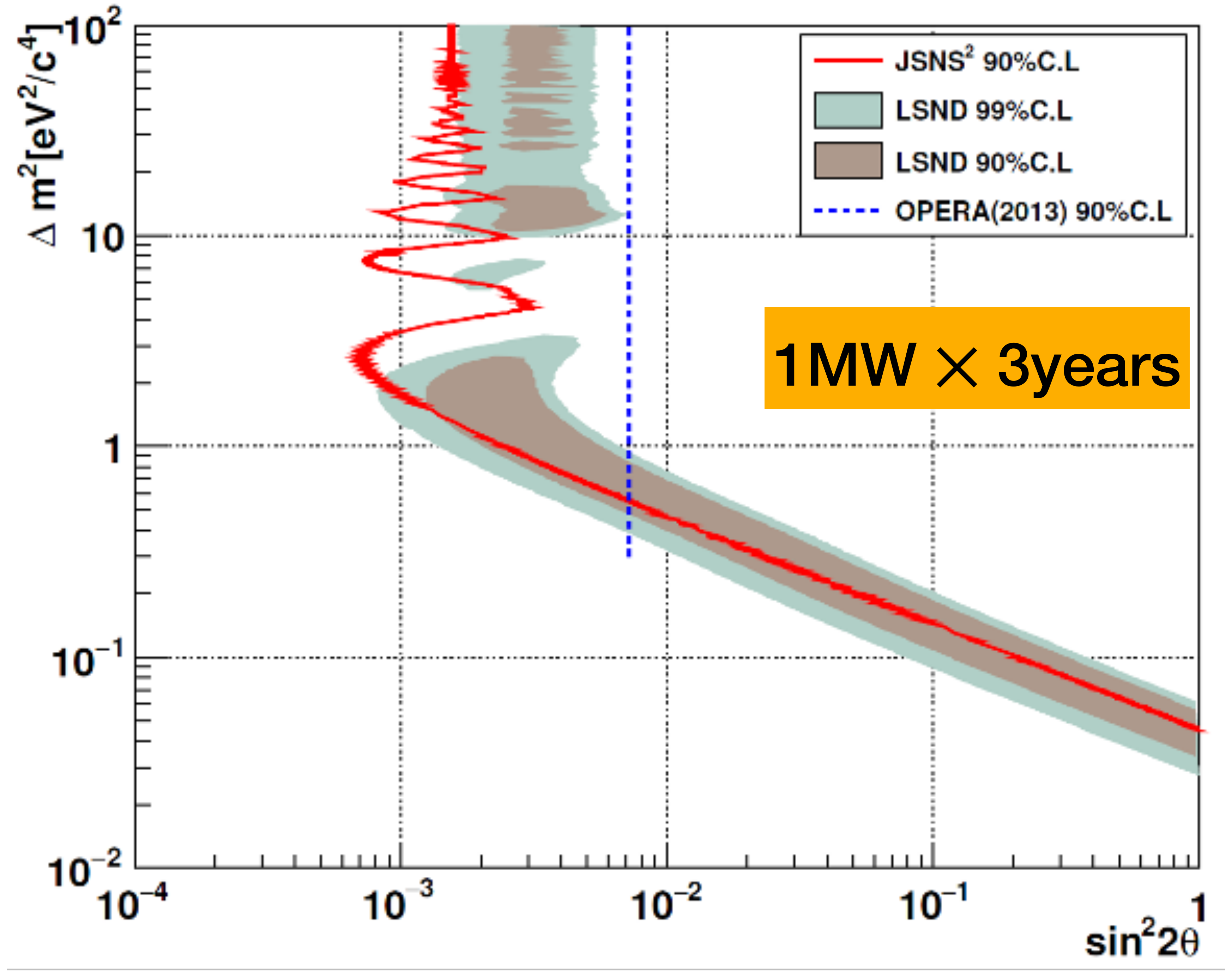
(JSNS² TDR, arXiv:1705.08629)

- $\bar{\nu}_e$ follows decay-at-rest $\bar{\nu}_\mu$ energy distribution
- Prompt single rate (background): ~3.9×10^{-4} per spill
- Delayed single rate (background): ~4.4×10^{-3} per spill
- Spectral fit is sensitive to the difference of energy spectrum

Signal	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 2.5eV^2$ (Best fit values of MLF)	87
	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 1.2eV^2$ (Best fit values of LSND)	62
background	$\bar{\nu}_e$ from μ^-	43
	$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	3
	beam-associated fast n	≤2
	Cosmic-induced fast n	negligible
	Total accidental events	20



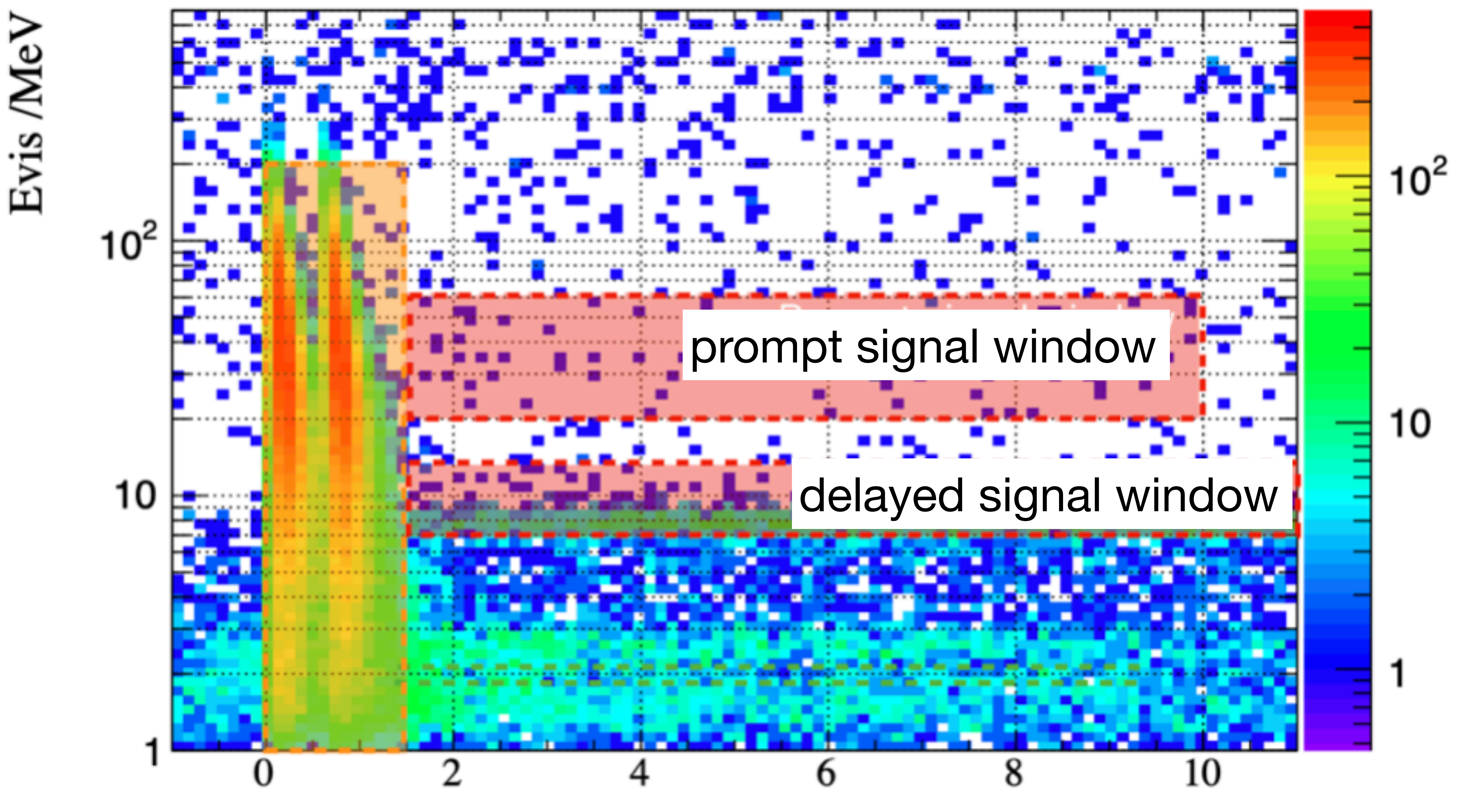


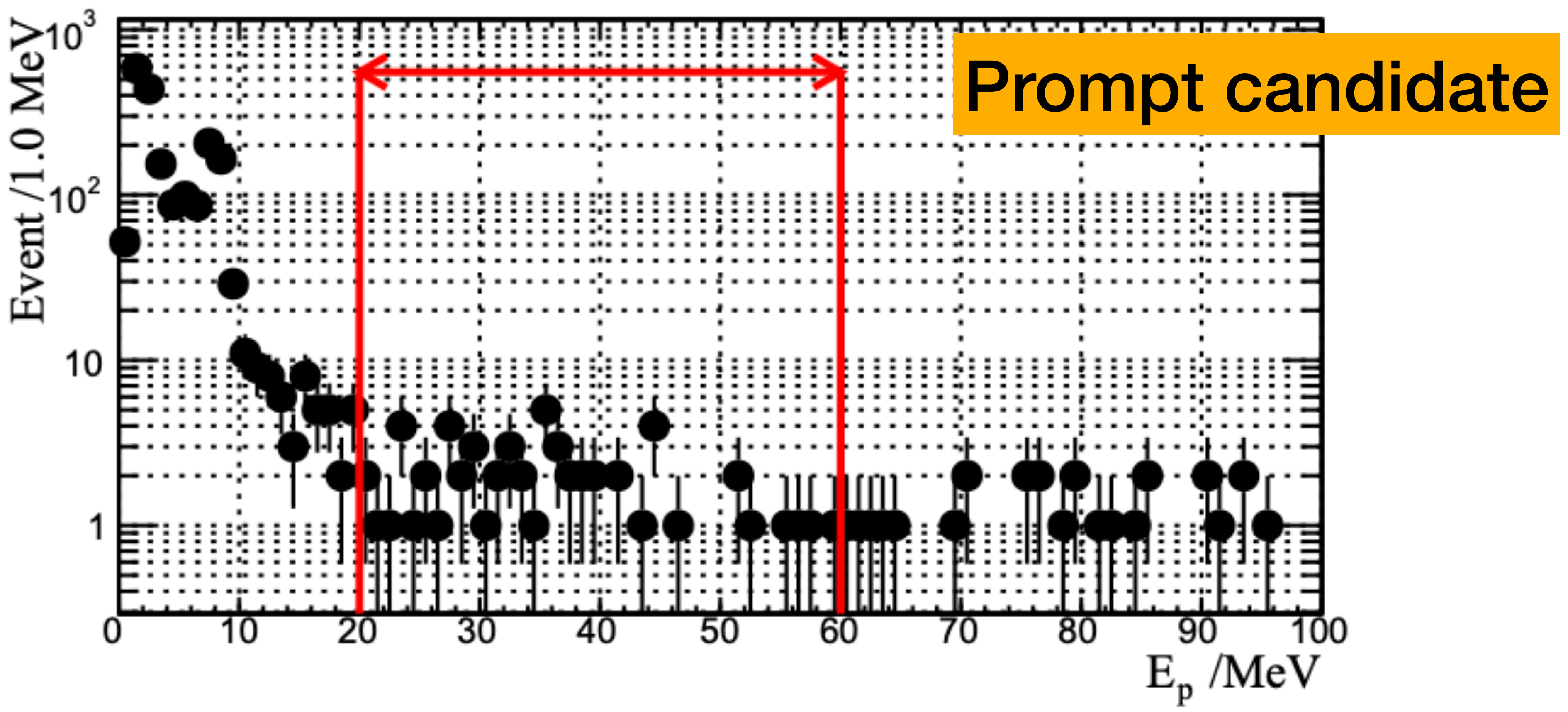


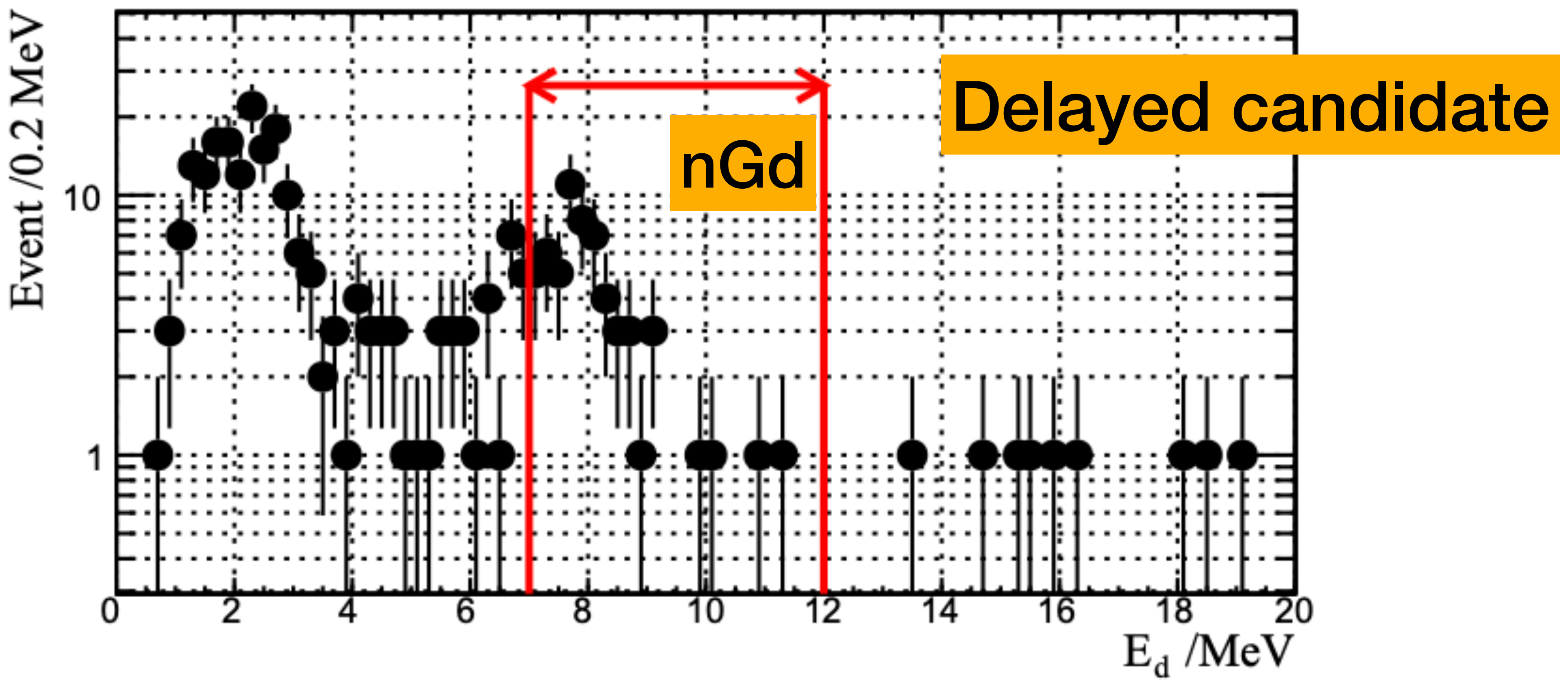
Sterile Neutrino Search

Commissioning run
(Eur. Phys. J. C (2022) 82:331)

- June/5-15, 2020
- Integrated POT: 8.9×10^{20}
- Beam trigger with 25 μs width







Observed correlated event candidates

- 59 ± 8 events / 8 M spills
- **Cosmic-induced fast neutrons** are the dominant background
  - **Correlated background:** 55.9 ± 4.3
  - **Pulse shape discrimination (PSD) would reject them**.
  - Two independent groups are working on it.

Toward the sterile neutrino search

(For the blind analysis)

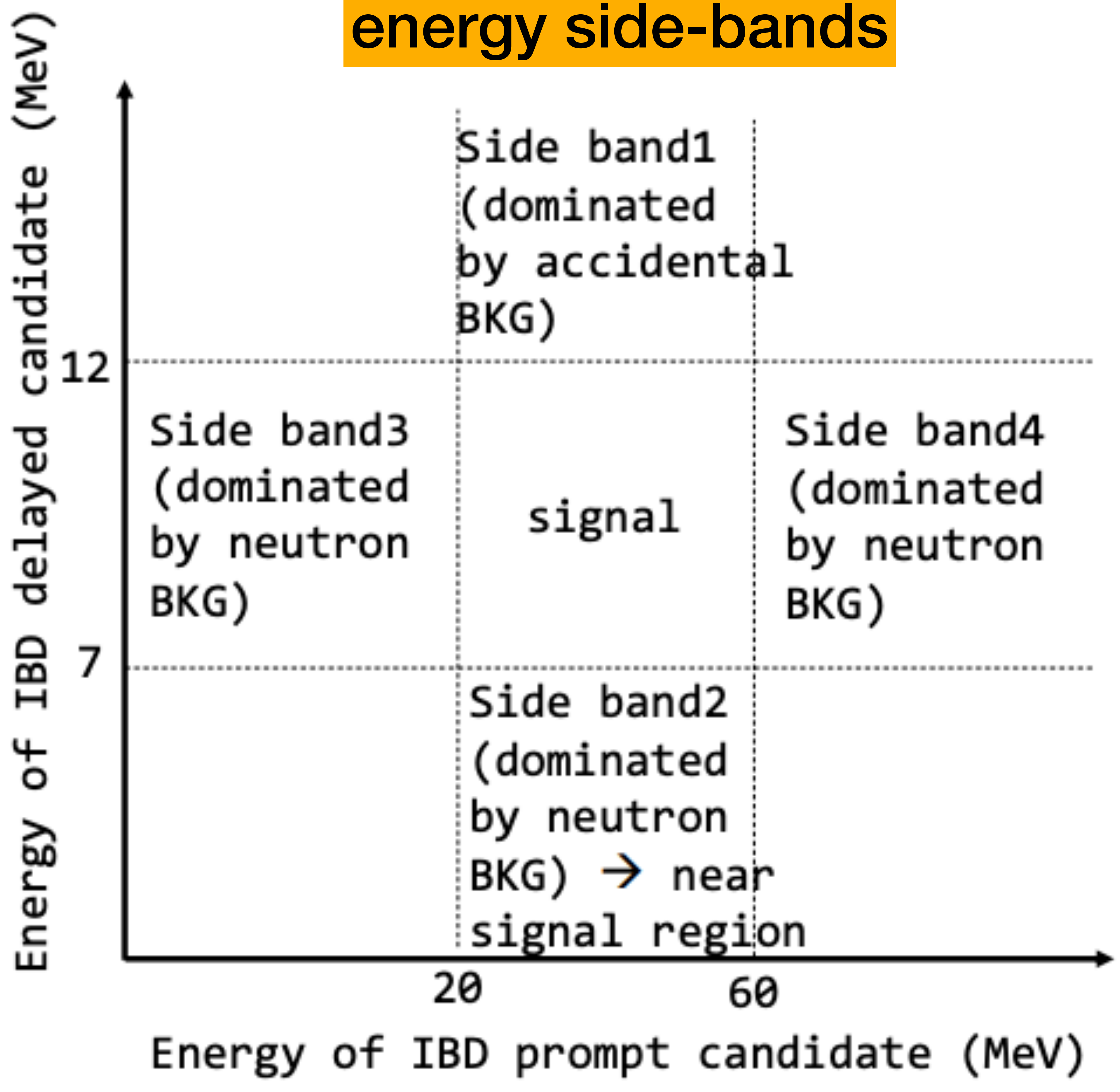
- **Energies define side-bands like a right plot.**

- All side-bands should be understood before Opening the signal region

- The rates in the side-band regions will be Predicted by the control samples driven by data

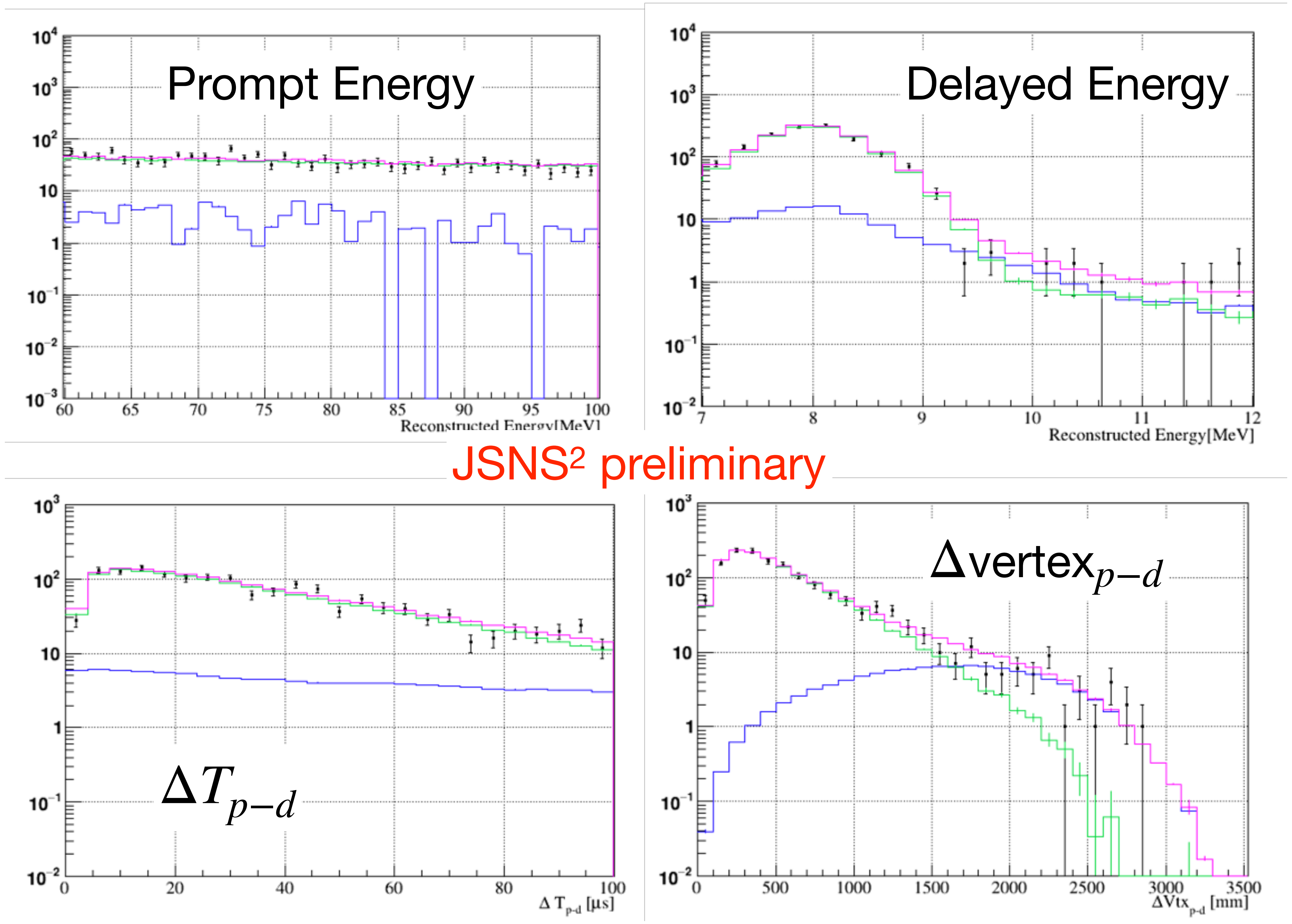
- Now, side-band 4 data are opened
  - Cosmic fast neutrons and accidentals are the main backgrounds in side-band 4

energy side-bands



The first comparison between the observation vs expectation

(Side-band 4, prompt 60-100 MeV)



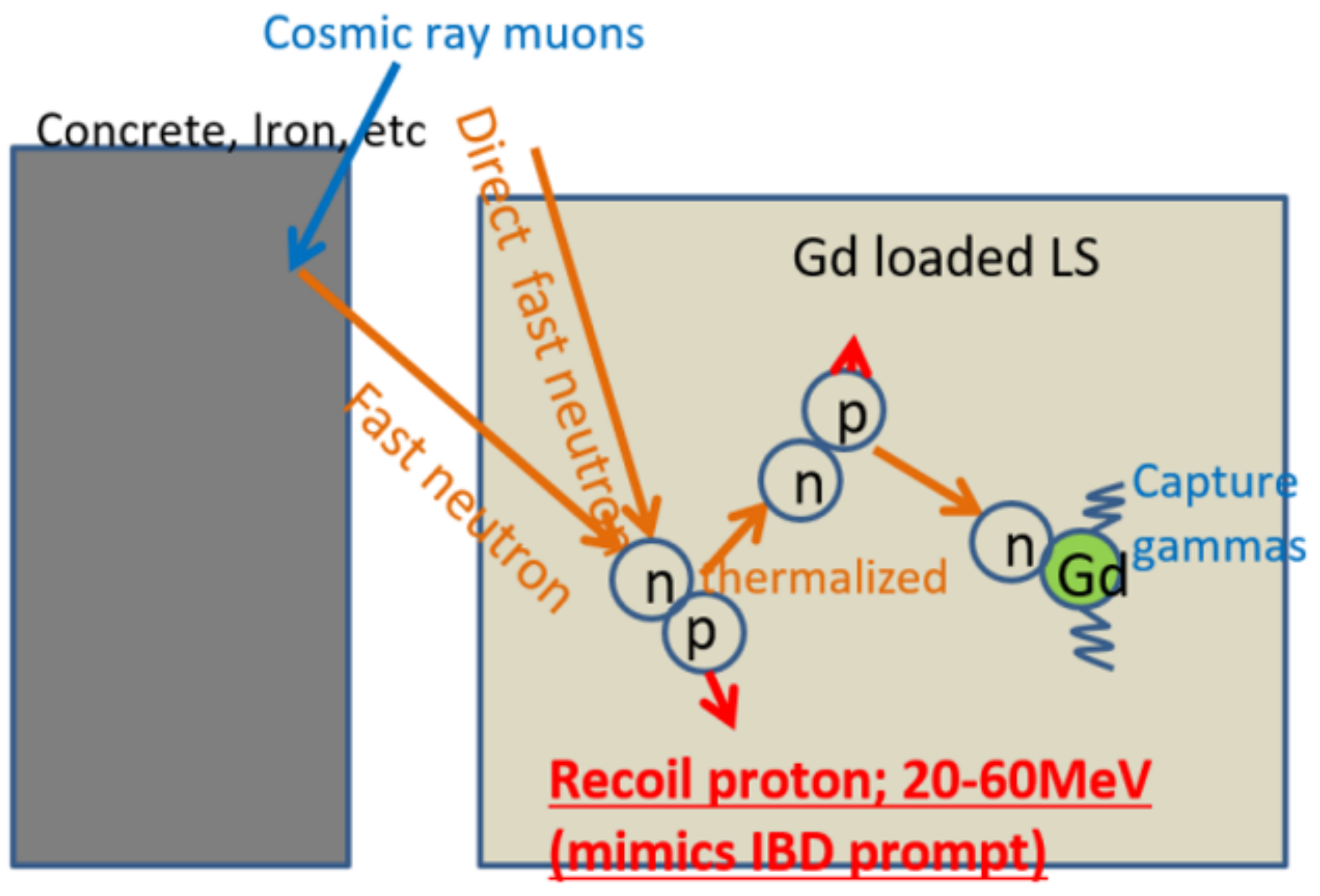
	Observed events	Expected Events
Total	1498 ± 38.7	1528.5 ± 5.9
Neutrons		1421.7 ± 5.7
Accidentals		106.8 ± 1.5

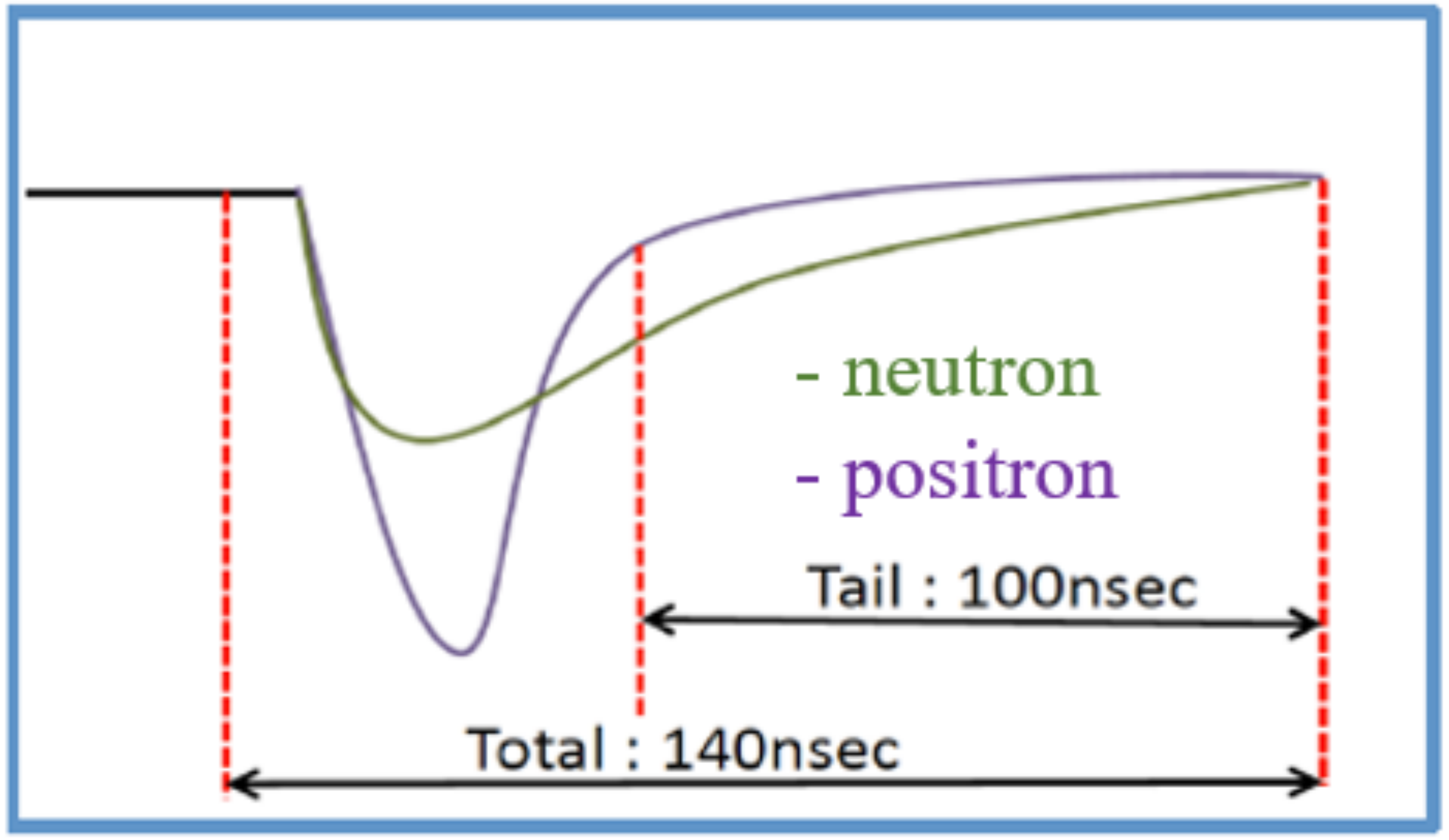
The observed events are compared with the background expectations
(Cosmic fast neutrons + Accidental)

- **They are well-agreed**
- Cosmic fast neutrons background is dominated

Pulse Shape Discrimination (PSD)

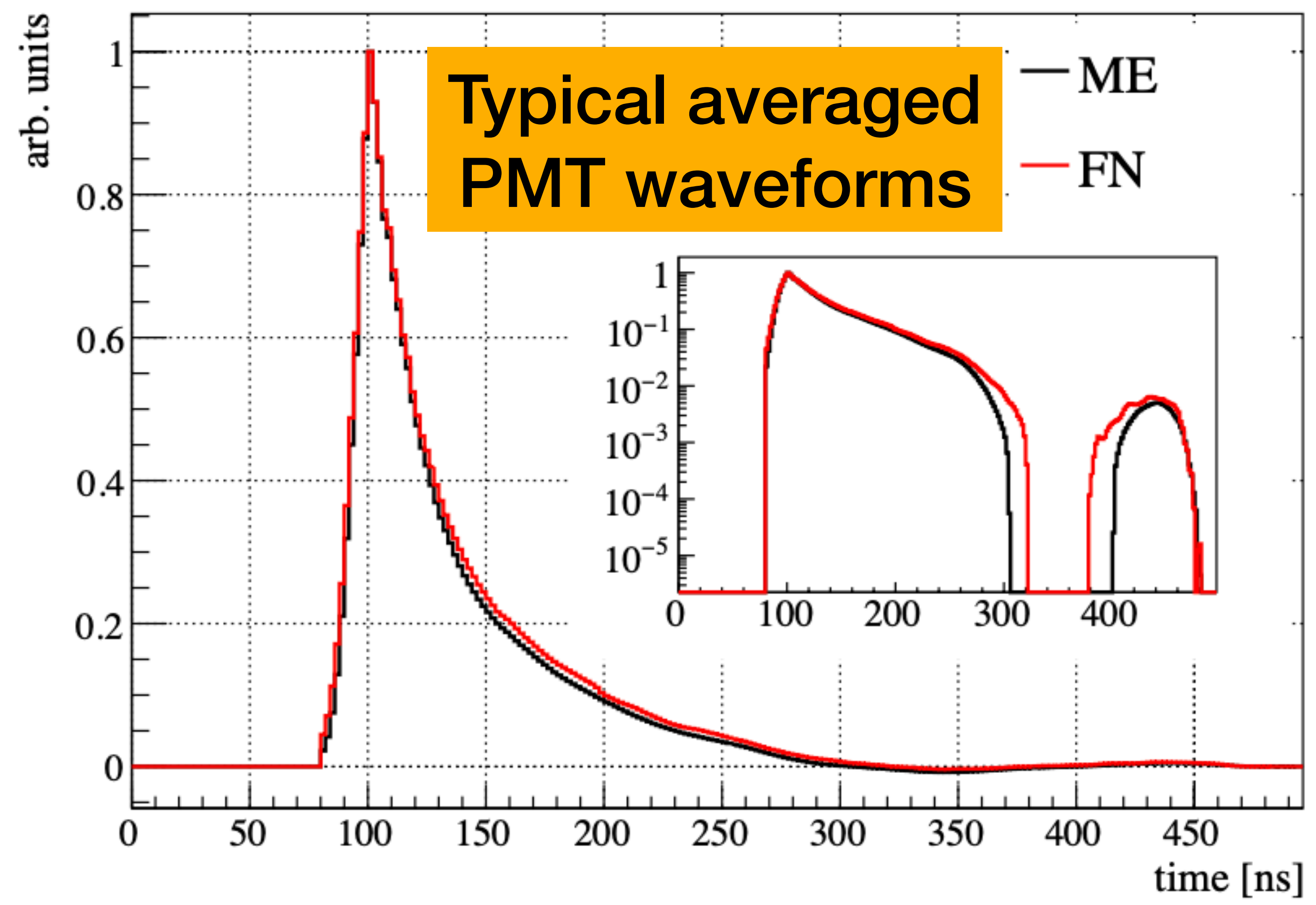
- Fast neutrons can mimic IBD signals from electron anti-neutrino (correlated background)
- PSD can separate the IBD signals and fast neutrons.
- **10% diisopropylnaphthalene (DIN —> EJ-309, 2000L)** has been added to improve the PSD power.
- The goal is to remove 99% of fast neutrons.

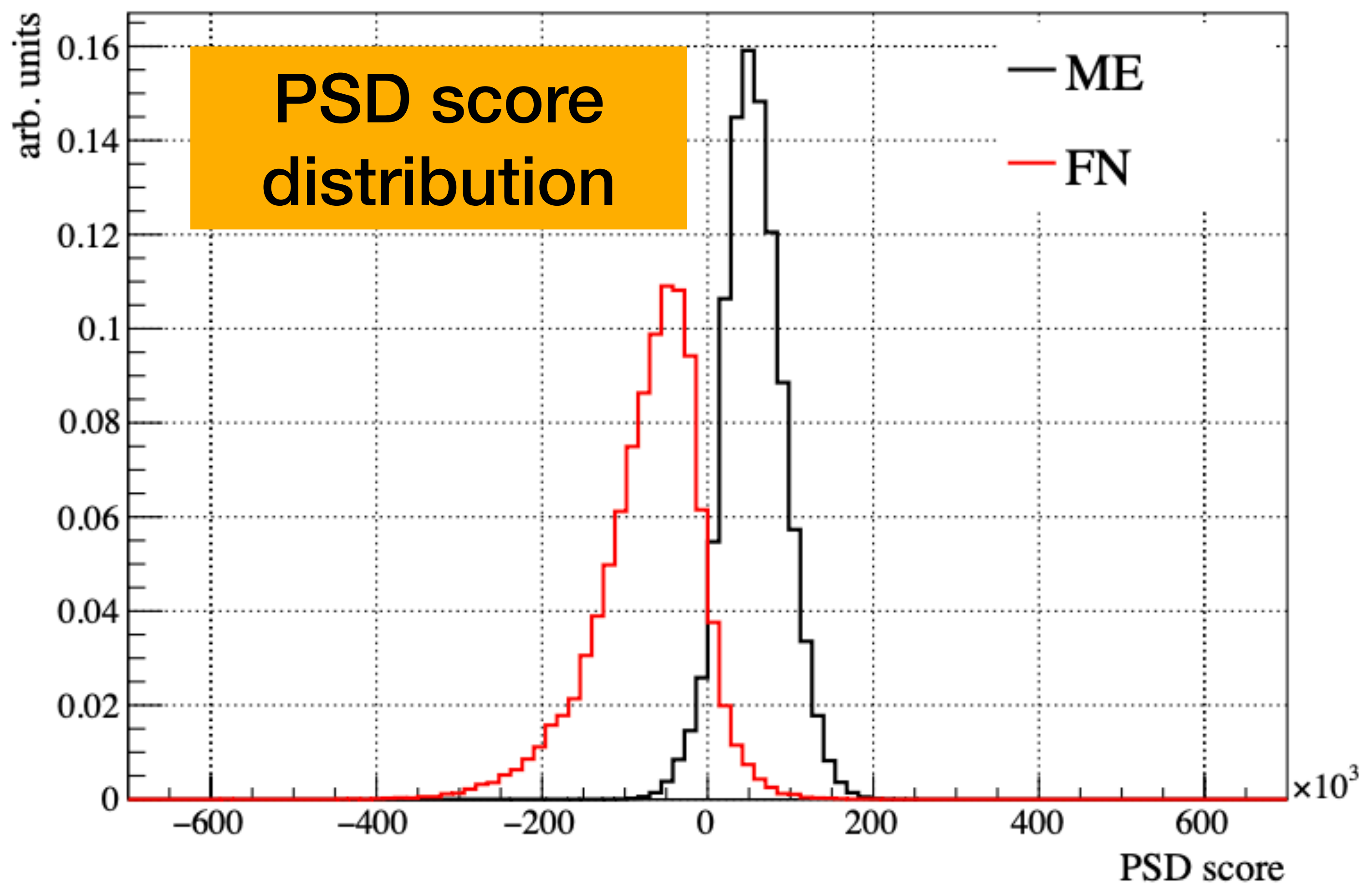


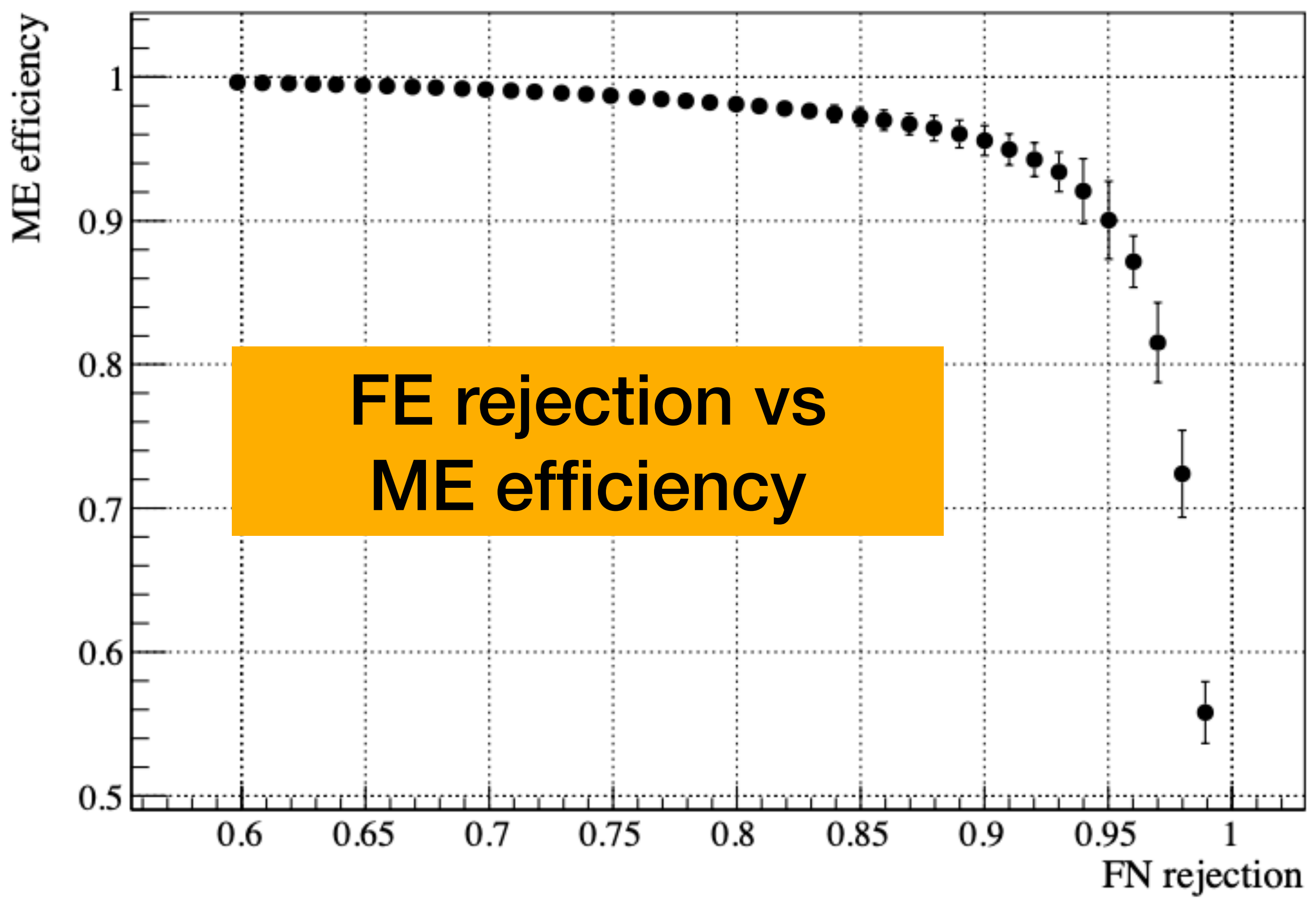


Likelihood method
(arXiv:2404.03679)

- The DAQ of JSNS^2 can measure a waveform every 2ns (500MHz sampling)
- The likelihood judges that each event looks like “a neutron” or “an electron”
- $L = \prod_{PMT}^{i<96} \prod_{bin}^{j<248} [P_{ij}(PH)]$, PH is the peak normalized pulse height of jth bin

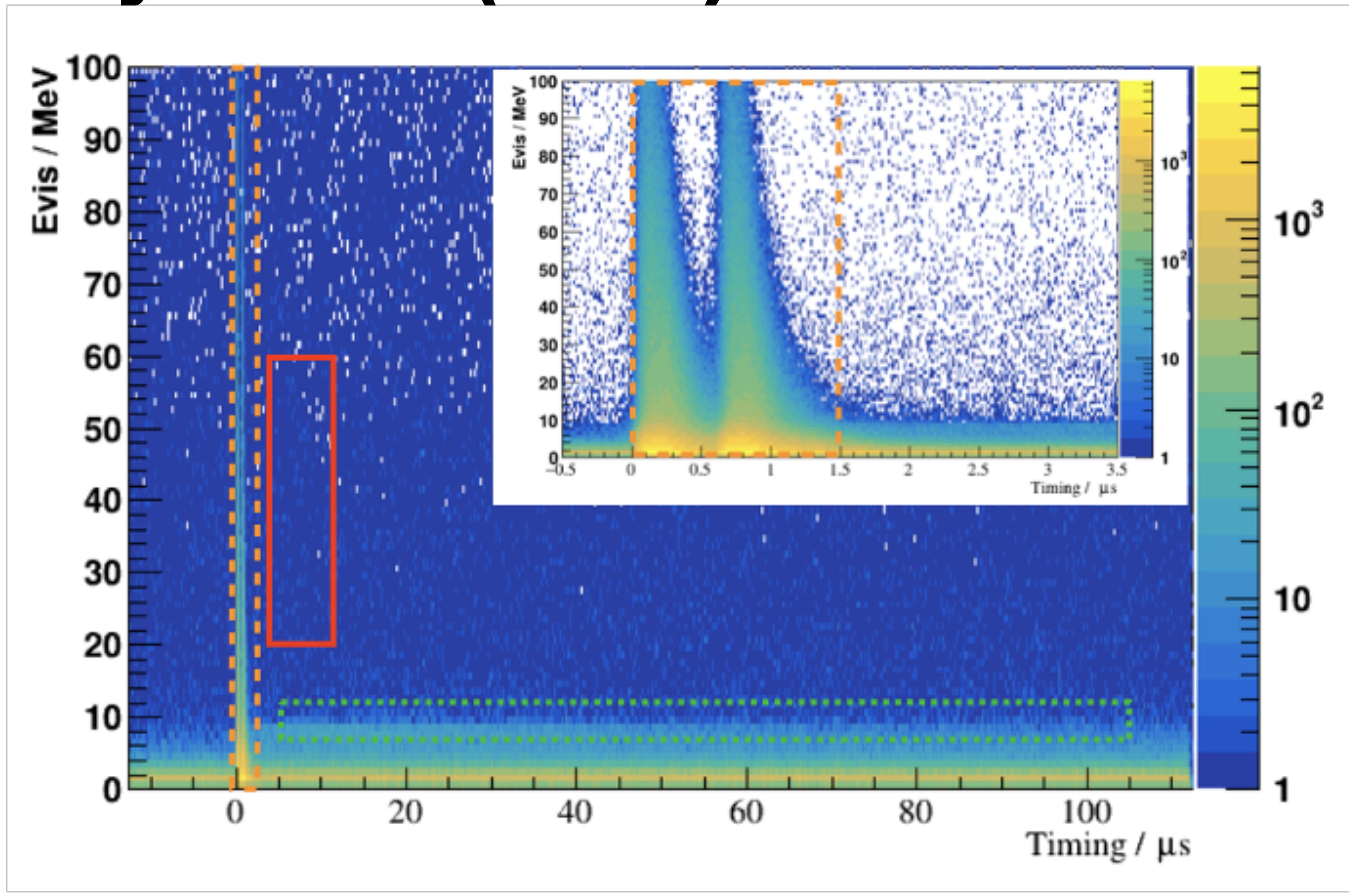




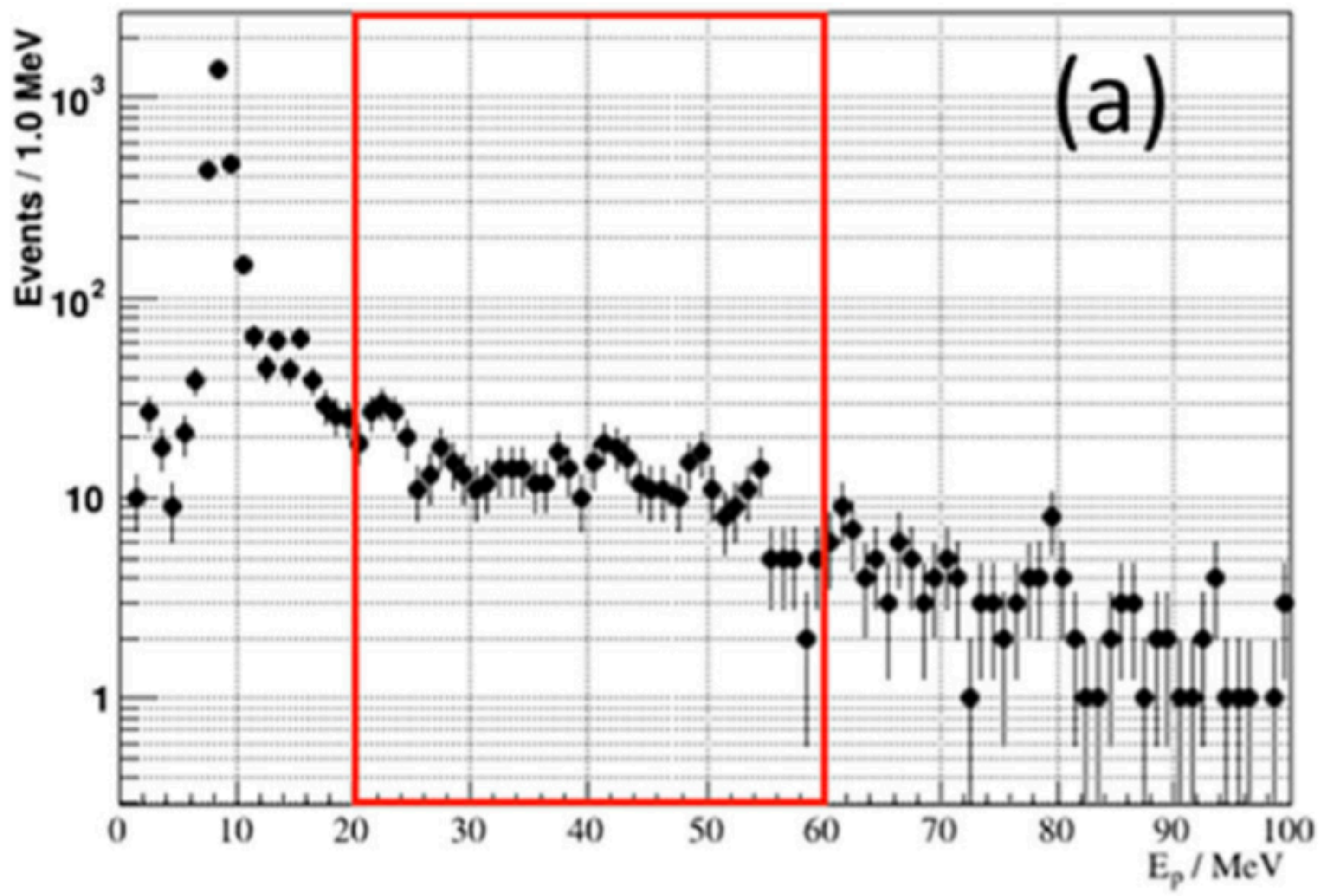


Accidental single rate of IBD prompt and delayed

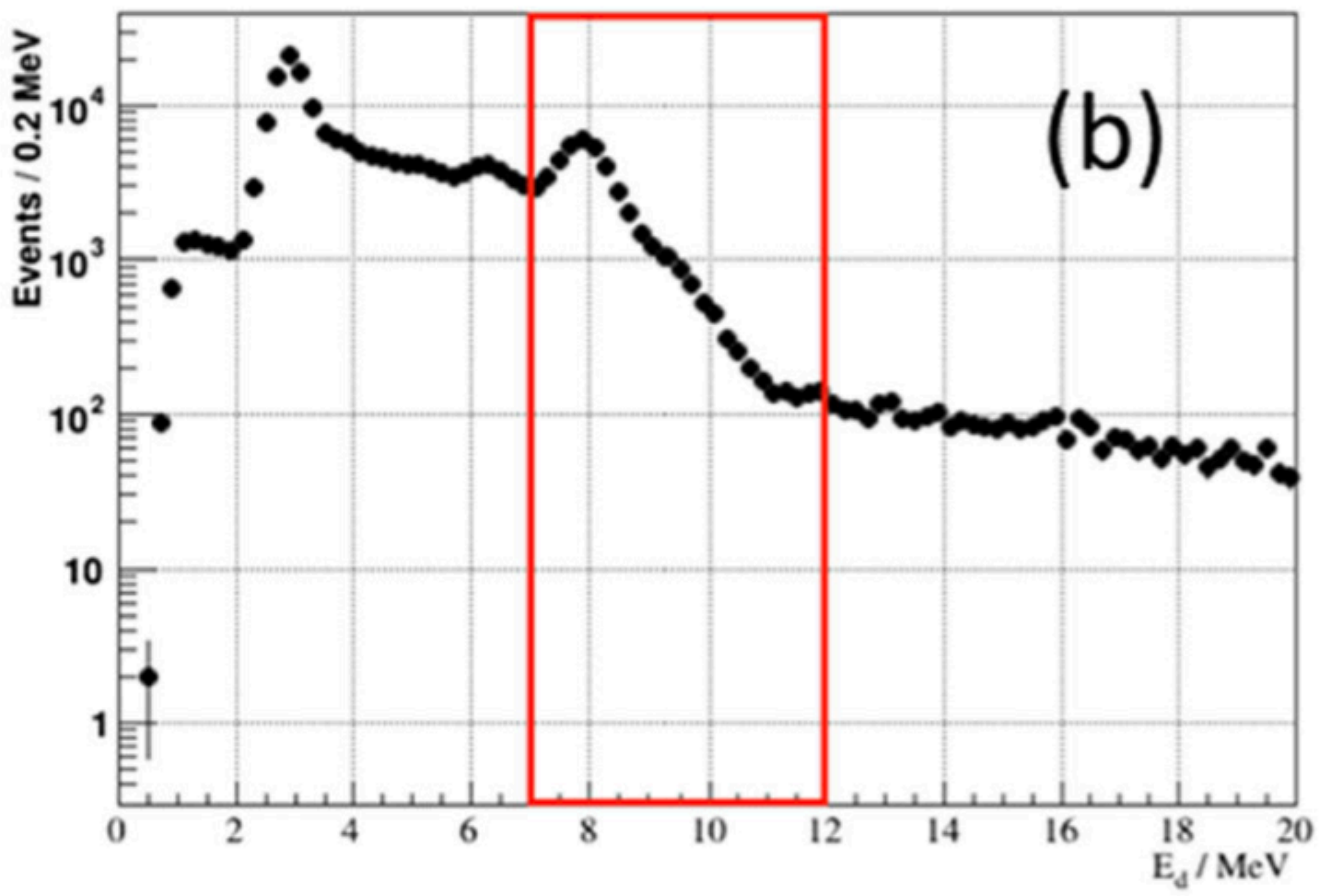
Eur. Phys. J. C (2024) 84:409



IBD prompt candidate



IBD delayed candidate



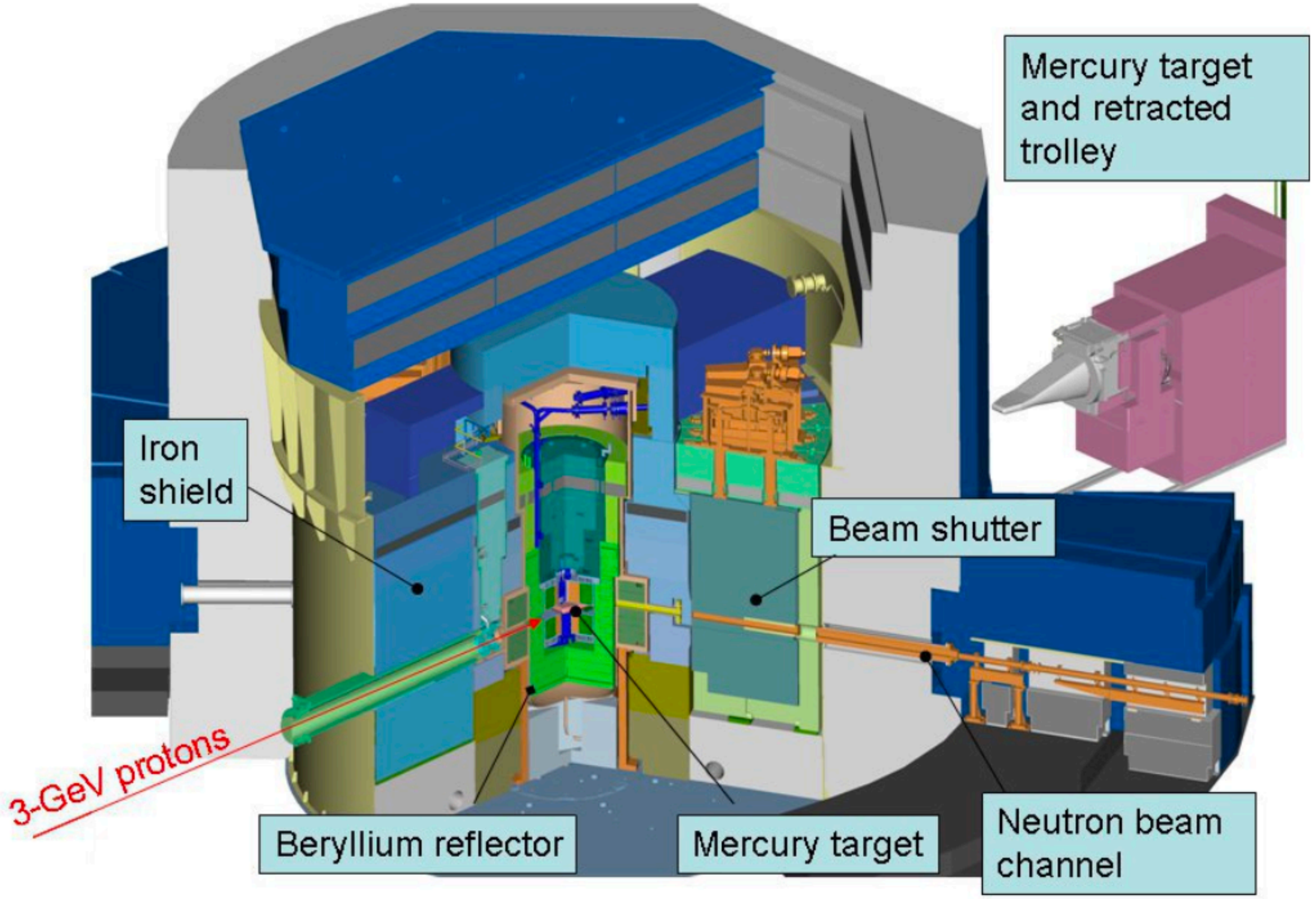
Special calibration run using beam timing with 125 μs time window

Observed (at 0.75 MW of averaged beam power)

- Prompt single rate: $(2.20 \pm 0.09) \times 10^{-4}$/spill
- Delayed single rate: $(1.80 \pm 0.01) \times 10^{-2}$/spill

Better understanding the neutrino beam

(JSNS[2] TDR, arXiv:1705.08629,)



- How to get the absolute $\bar{\nu}_{\mu}$ flux?
- Simulation may give a marginal number.
- μDAR neutrino production by 3 GeV protons
- However, there are Ambiguities in pion production
  - No measurement data of 3 GeV protons to a mercury target is available
  - Uncertainty in pion production from mercury
  - Target geometrical modeling
- Different simulation packages may help
- Or we can estimate from the data

Better understanding the neutrino beam
(JSNS² TDR, arXiv:1705.08629,)

- Simulated μDAR neutrino production by 3 GeV protons
  - Two different packages (FLUKA vs Geant4)
- **μDAR**: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- **CNgs**:
  - $^{12}C + \nu_e \rightarrow e^- + ^{12}N_{g.s.}$ (prompt: electron)
  - $^{12}N_{g.s.} \rightarrow ^{12}C + \nu_e + e^+$ (delayed: positron)
  - Lifetime: ~16 ms
  - Understand the neutrino flux from the data

FLUKA hadron simulation package (central value)

	$\pi^+ \rightarrow \mu^+ \rightarrow \bar{\nu}_\mu$	$\pi^- \rightarrow \mu^- \rightarrow \bar{\nu}_e$
π/p	6.49×10^{-1}	4.02×10^{-1}
μ/p	3.44×10^{-1}	3.20×10^{-3}
ν/p	3.44×10^{-1}	7.66×10^{-4}
ν after $1\mu s$	2.52×10^{-1}	4.43×10^{-4}

Geant4, QGSP-BERT package (cross-check)

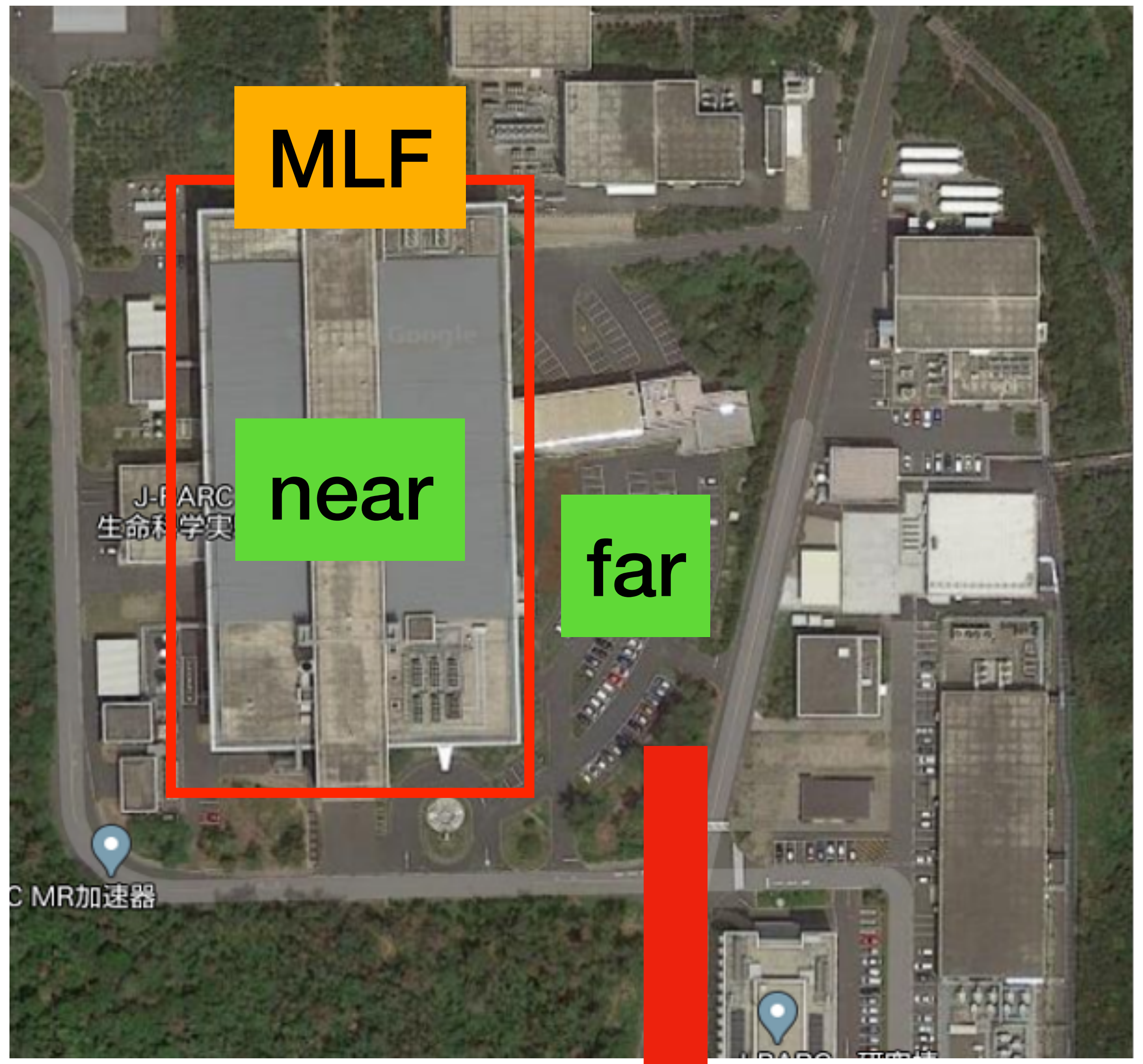
	$\pi^+ \rightarrow \mu^+ \rightarrow \bar{\nu}_\mu$	$\pi^- \rightarrow \mu^- \rightarrow \bar{\nu}_e$
π/p	5.41×10^{-1}	4.90×10^{-1}
μ/p	2.68×10^{-1}	3.90×10^{-3}
ν/p	2.68×10^{-1}	9.34×10^{-4}
ν after $1\mu s$	1.97×10^{-1}	5.41×10^{-4}

JSNS^2-II : The second phase of the JSNS^2

JSNS^2-II
(arXiv:2012.10807)

New far detector

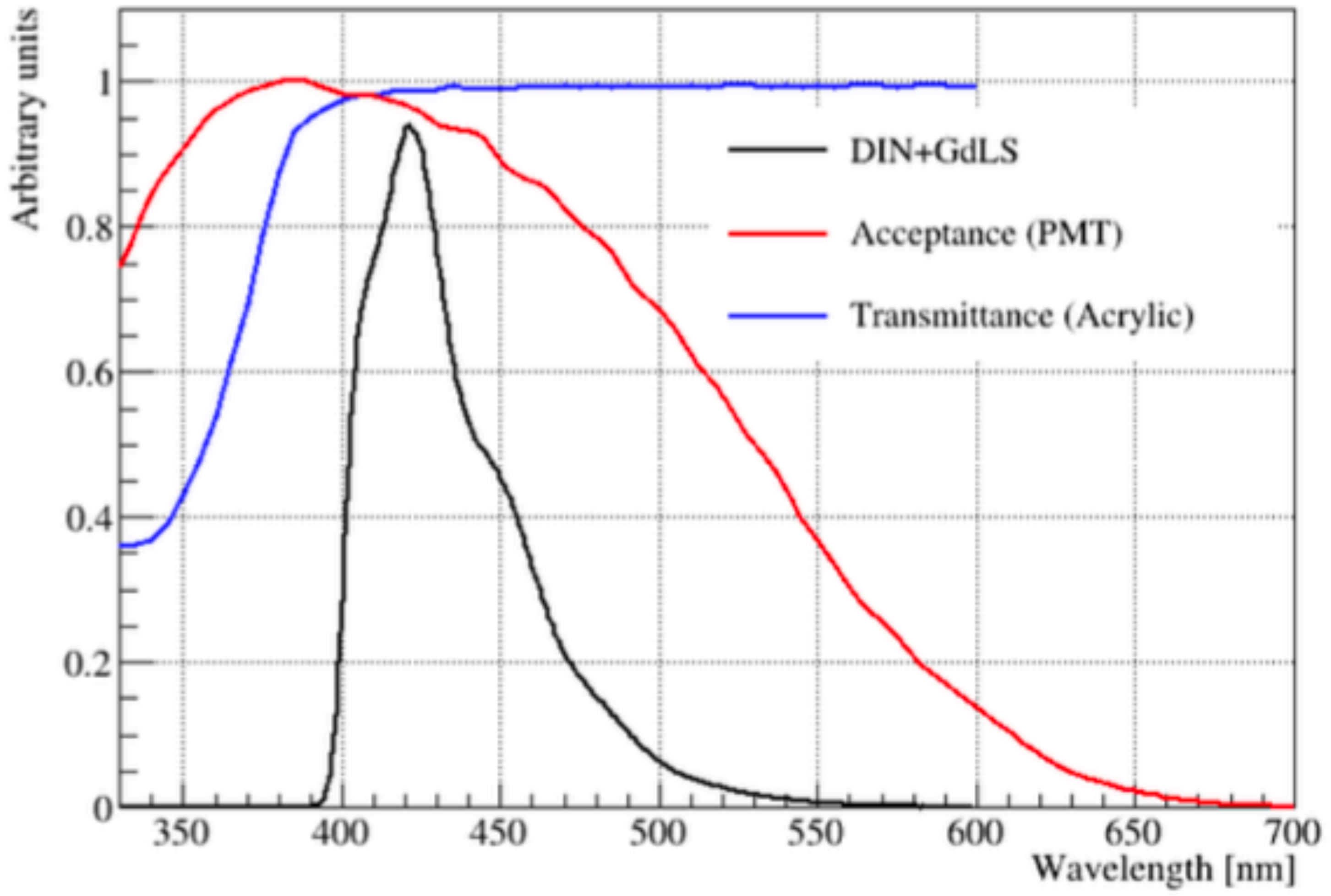
- Fiducial 32 tonnes and 48 m location)
- Two detectors with two different baseline
- A solid conclusion of LSND anomaly
- Improve the sensitivity
- Especially in the low Δm^2 region



New far detector

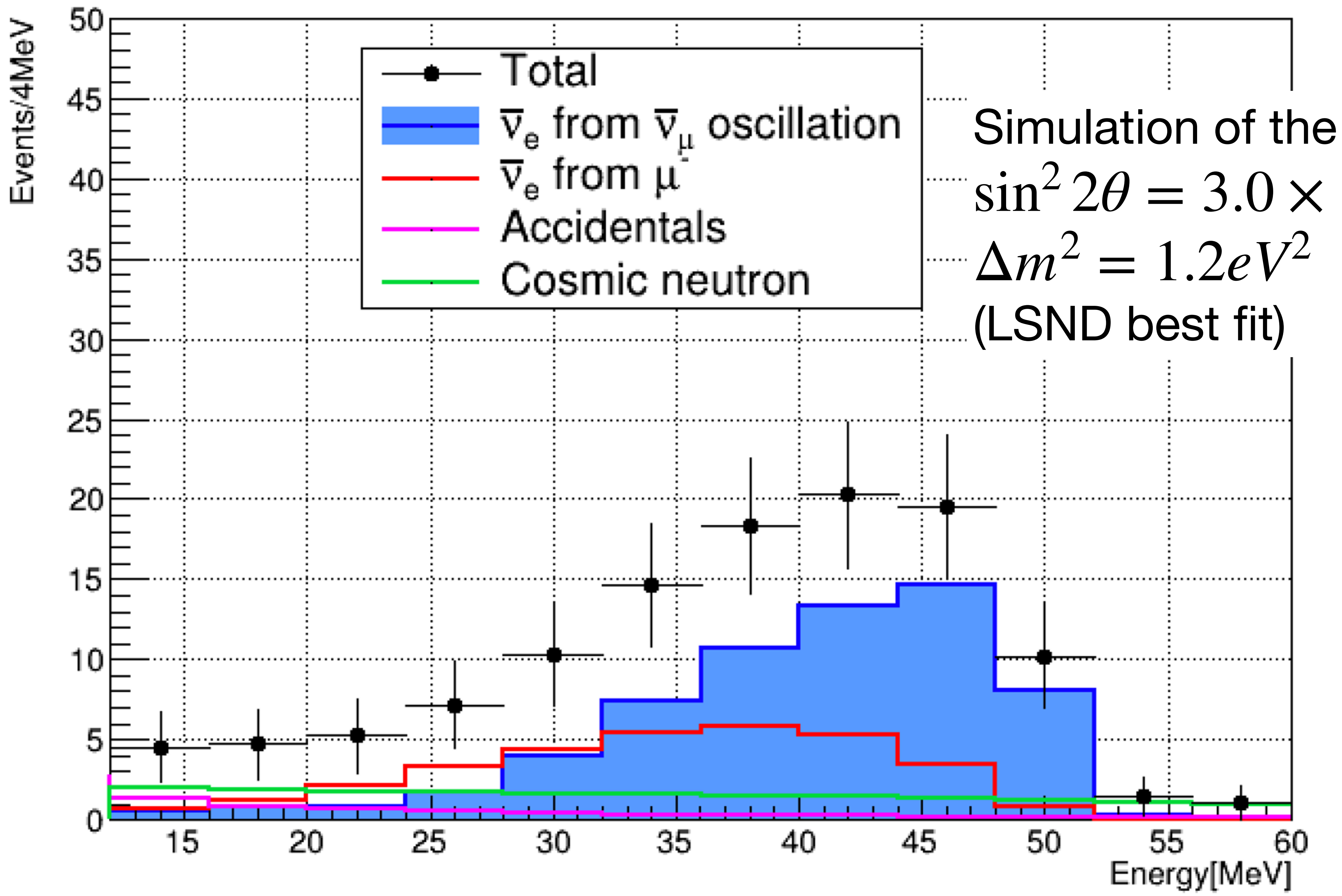
Almost identical to the near detector

- The detector is placed outside of the building
- 37 m^3 Gd-LS for the neutrino target
- 150 m^3 pure LS for the gamma-catcher and veto
- 228, 10-inch PMTs were installed
- The acrylic vessel was made in Taiwan and installed
- GdLS and LS were donated by Daya-Bay in 2021 and are ready to fill
- An LED calibration system and temperature sensors were installed

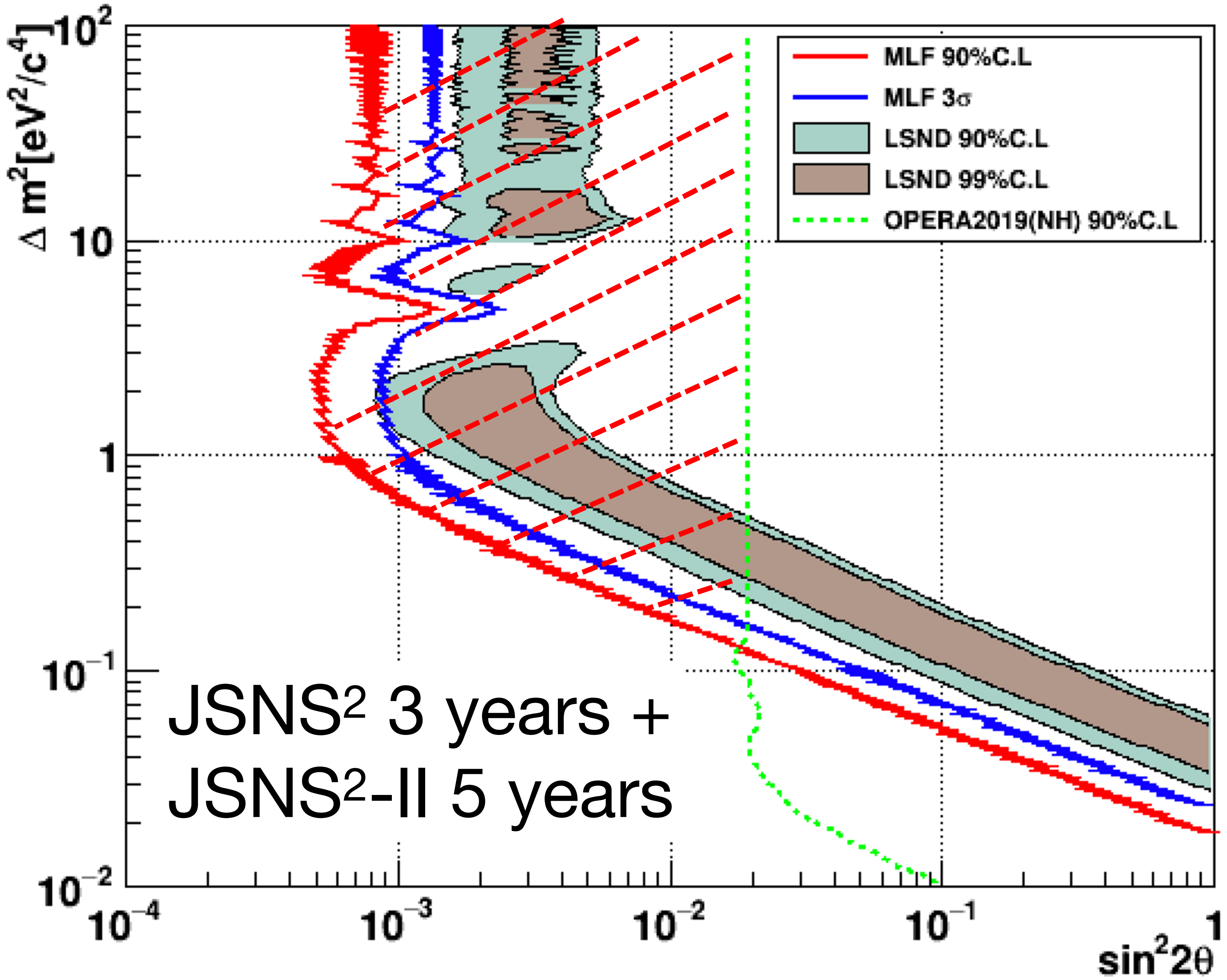


Sensitivity for the JSNS^2-II
(Based on the simulation)

- Each background simulation was done based on the JSNS^2 data
- Covering LSND by 3 sigma



Simulation of the far detector
$\sin^2 2\theta = 3.0 \times 10^{-3}$
$\Delta m^2 = 1.2 eV^2$
(LSND best fit)



Construction schedule of the JSNS^2-II

	2021				2022				2023				2024			
	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12
s.s.tank			bid	Construction												
Acrylic Vessel						bid	Construction		Trans.		Installation					
PMTs									Installation (near)				(Veto)			
		DC dismantle/ shipping (190 PMTs)											30 PMTs			
(Gd)LS	Donation		Storage/keep													
Filling																
Data taking																