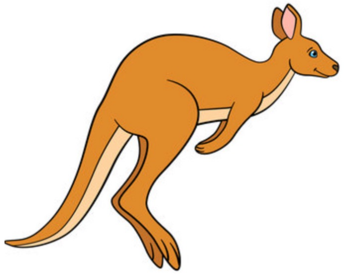
Neutrino Oscillation Experiments: Where are we now?



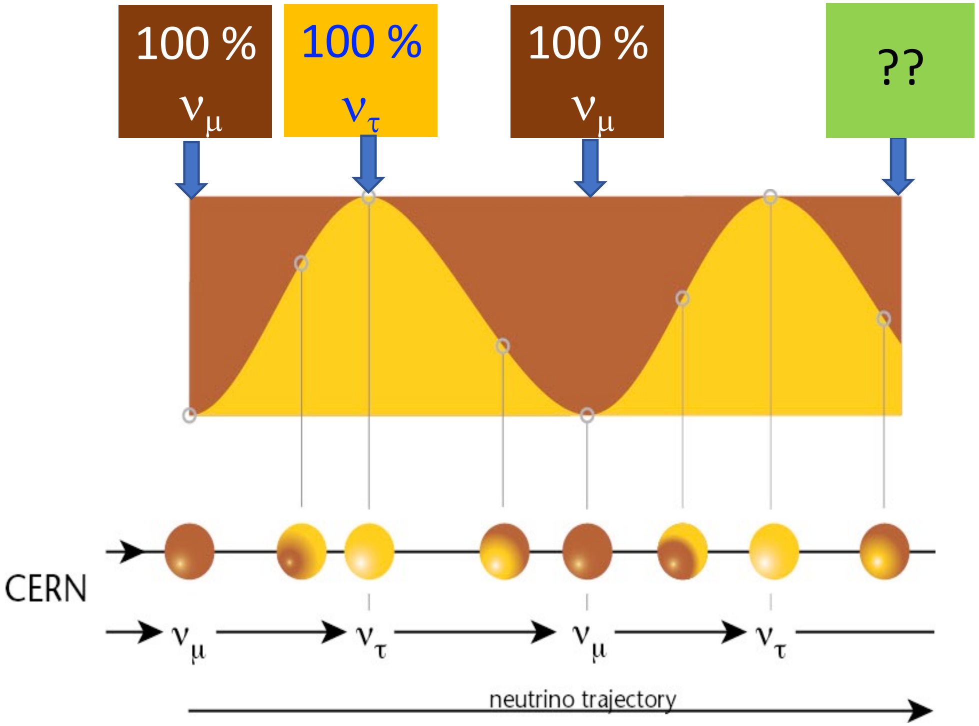
Sunny Seo
IBS

Dec. 7, 2022

Outline

- 3 ν oscillation
- 3 +1 ν oscillation
- keV sterile ν oscillation

Neutrino Oscillation



(1) ν flavor eigenstate
$\neq$ ν mass eigenstate

(2) ν masses are not degenerate.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \boxed{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

PMNS matrix in 1962

$$\boxed{|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle}$$

$\alpha =$ e, μ, τ
$i\ =$ 1, 2, 3

→ results in ν mixing & oscillation

Weak Eigen state

Mass Eigen state

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \boxed{\begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

PMNS matrix

in 1962

- **P**ontecorvo (1957)
- **M**aki
- **N**akagawa
- **S**akata

$$U = \underbrace{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}}_{\text{Atmospheric}} \underbrace{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}}_{\text{“CP” sector}} \underbrace{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Solar}} \underbrace{\begin{bmatrix}e^{-i\alpha_1/2} & 0 & 0\\ 0 & e^{-i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Majorana}}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

δ_{CP} ?

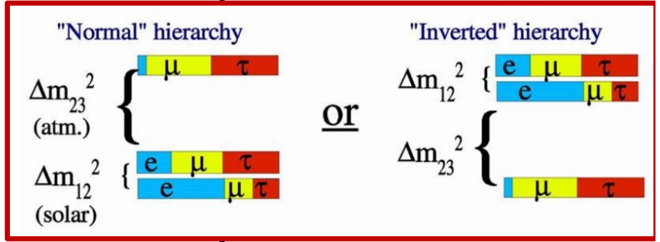
$\theta_{23} \approx 45°$ $\theta_{13} = 9°$ $\theta_{12} \approx 34°$

$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ \text{eV}^2$ $\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ \text{eV}^2$

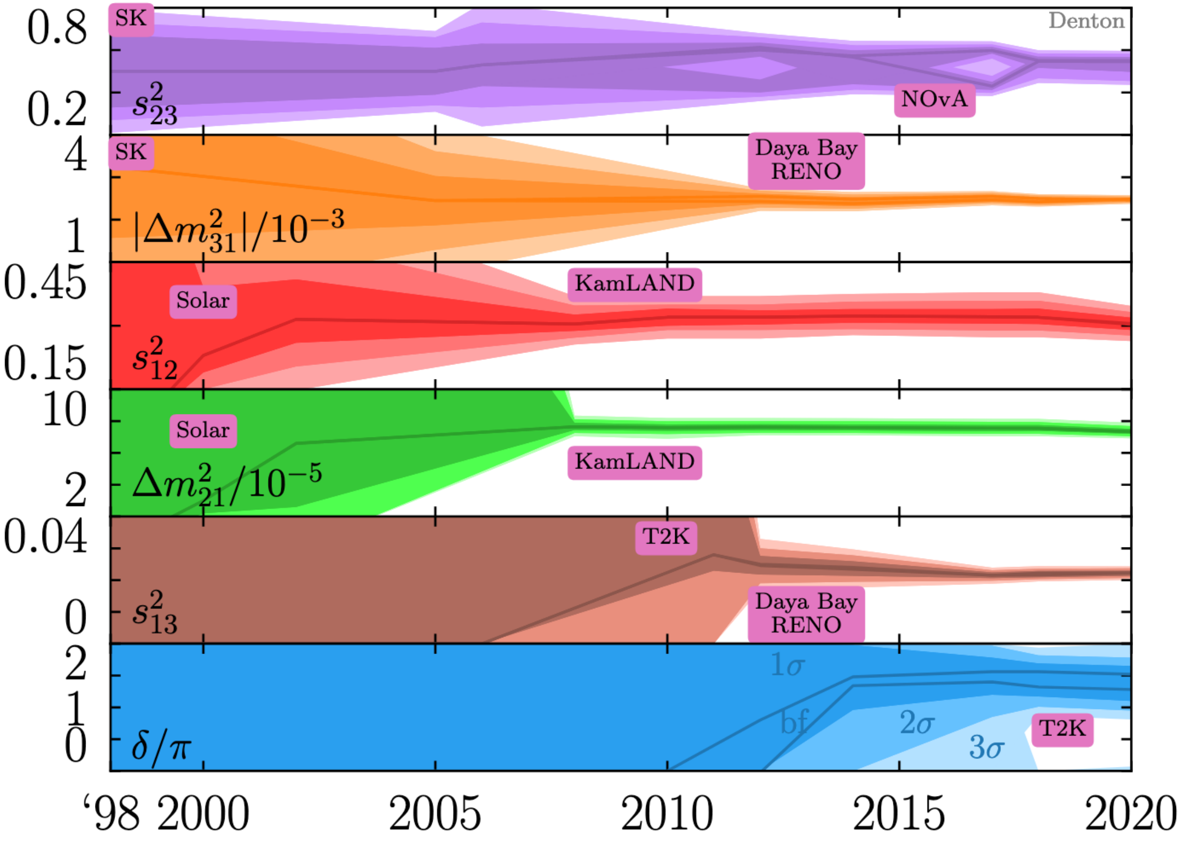
Super-K in 1998 **Daya Bay, RENO in 2012** **SNO in 2001**

Atmos. ν osc. **Reactor ν osc.** **Solar ν conversion**

Mass Ordering (MO)



Current status of neutrino parameters: the era of very precise neutrino physics



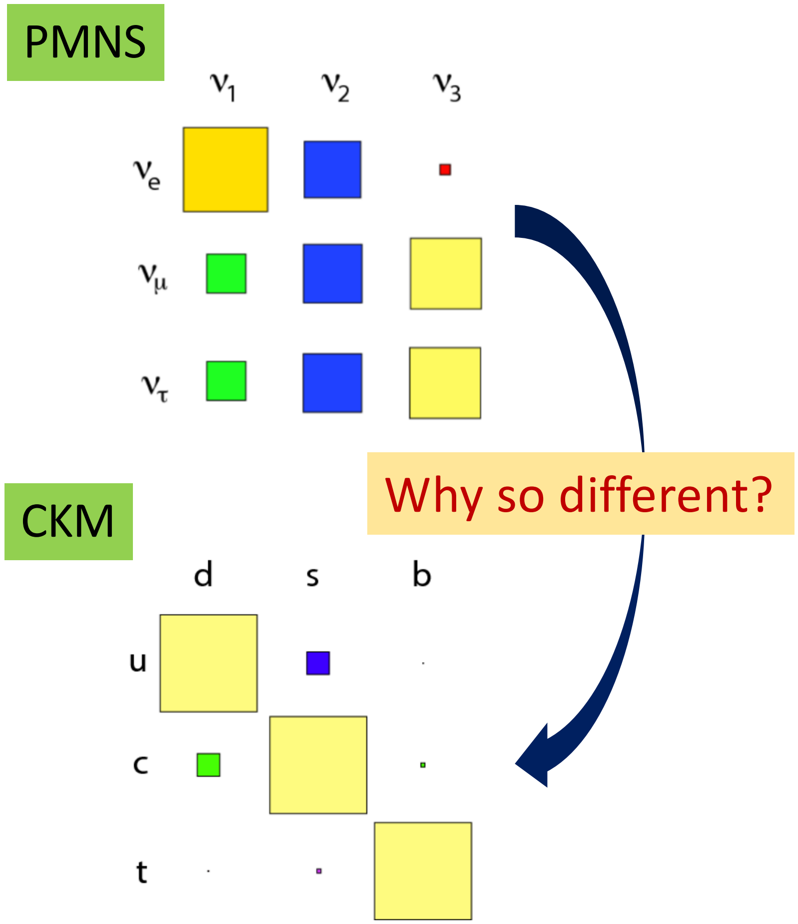
See P. Denton's talk

Neutrino 2022

The past 20 years have seen a remarkable progress in determining neutrino properties!

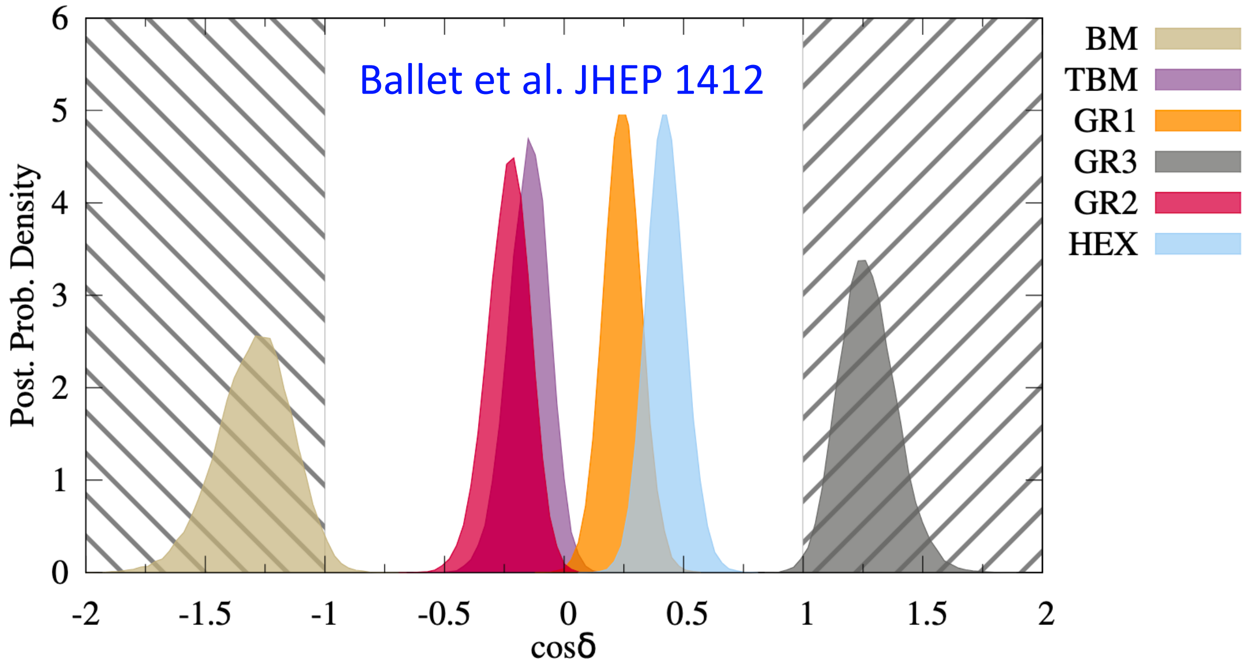
Why Leptonic CPV?

Understanding
the pattern of ν mixing



Why so different?

❑ Which flavor symmetry model?

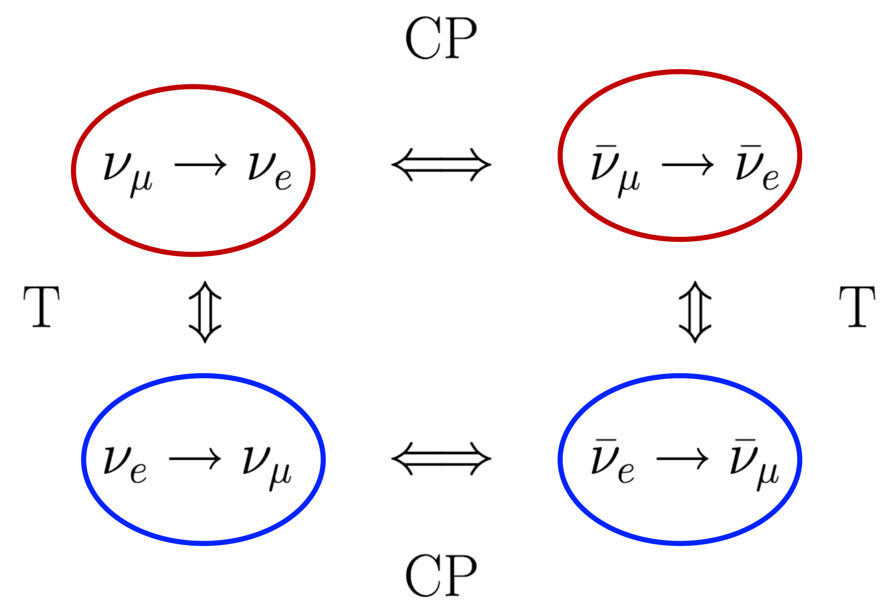


Ballet et al. JHEP 1412

→ δ_{CP} measurement will help identifying flavor symmetry model.

Hint of Leptonic CPV

- There is **hint** of CPV in lepton sector.
  (~ 2sigma @T2K, NOvA)



$$\begin{tikzcd}
\nu_\mu \to \nu_e \arrow[r, Leftrightarrow, "\mathrm{CP}"] \arrow[d, Leftrightarrow, "\mathrm{T}"'] & \bar{\nu}_\mu \to \bar{\nu}_e \arrow[d, Leftrightarrow, "\mathrm{T}"] \\
\nu_e \to \nu_\mu \arrow[r, Leftrightarrow, "\mathrm{CP}"'] & \bar{\nu}_e \to \bar{\nu}_\mu
\end{tikzcd}$$

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

Reactor ν

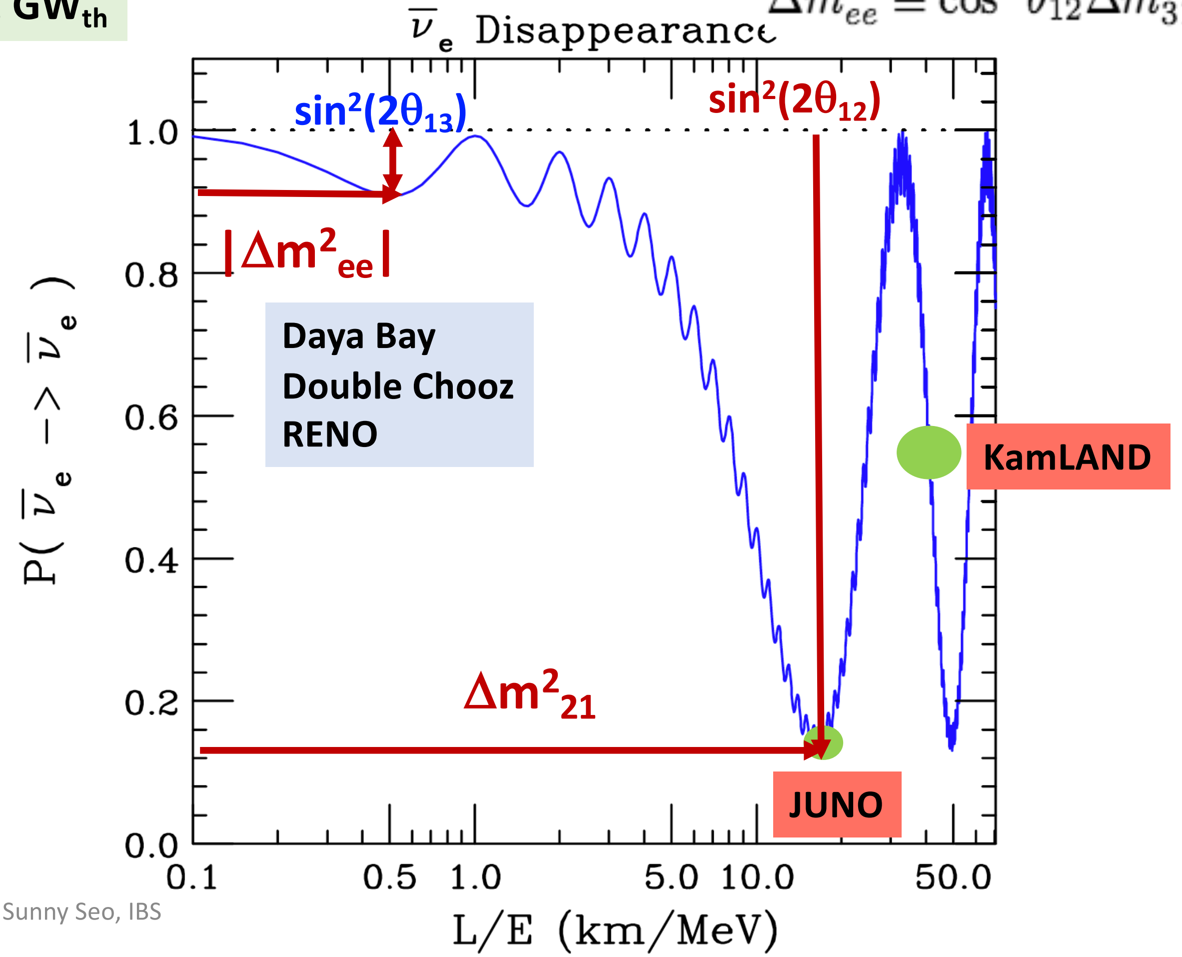
~2x10^{20} $\overline{\nu}_e$
per 1 GW$_{th}$

Short baseline (reactor term) **Medium baseline** (Solar term)

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - \underbrace{\sin^2 2\theta_{13}\sin^2(\Delta m^2_{ee}\frac{L}{4E})}_{\text{Short baseline}} - \underbrace{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta m^2_{21}\frac{L}{4E})}_{\text{Medium baseline}}$$

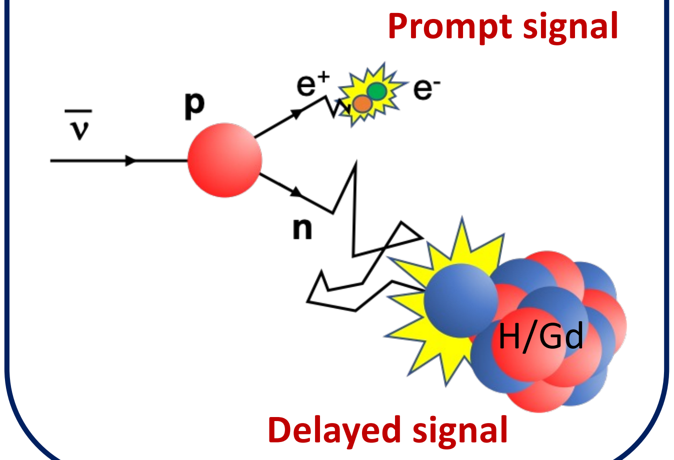
$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Nunokawa, Parke, Funchal
PRD 72, 013009 (2005)



Inverse Beta Decay (IBD)

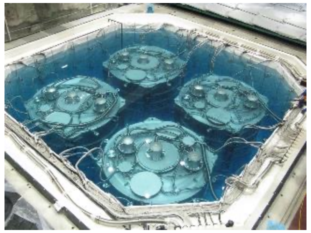
$$p^+ + \overline{\nu}_e \to e^+ + n^0$$



$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13}(\Delta m^2_{ee}\, L/4E)$$

Daya Bay

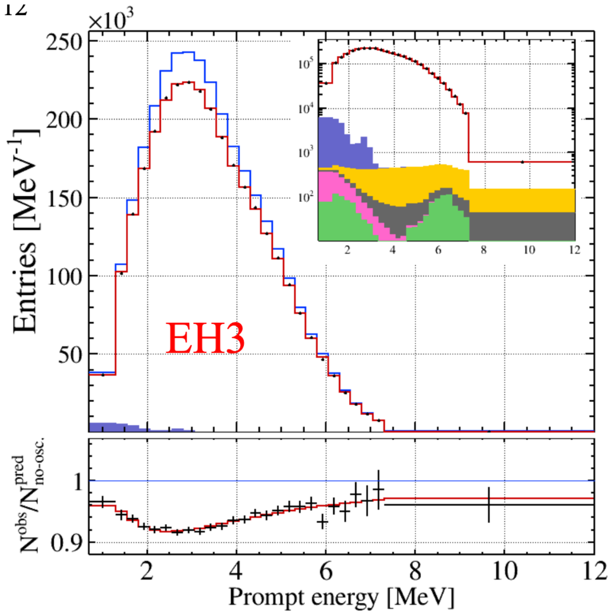
(2011-2020)



17.4 GW_{th}

80 ton GdLS

L: 1650 m



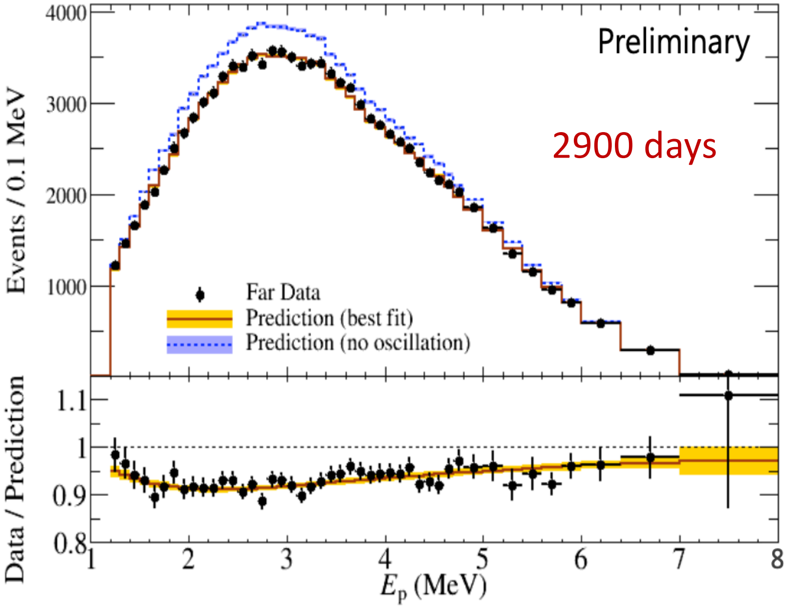
RENO

(2011-2025)

16.8 GW_{th}

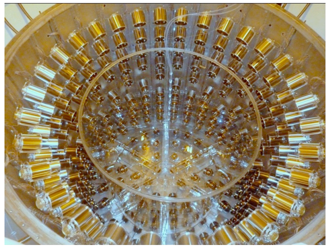
16 ton GdLS

L: 1380 m



DoubleChooz

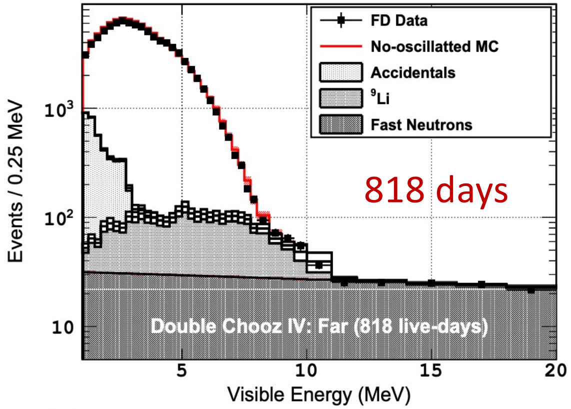
(2011-2018)

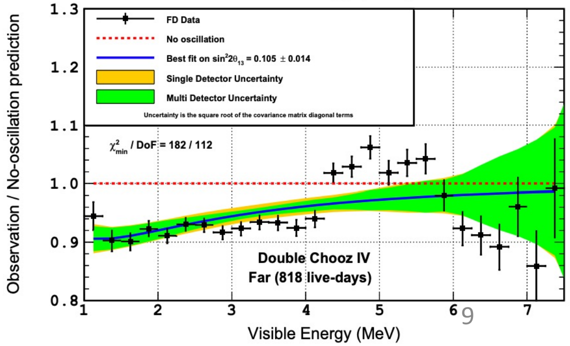


8.5 GW_{th}

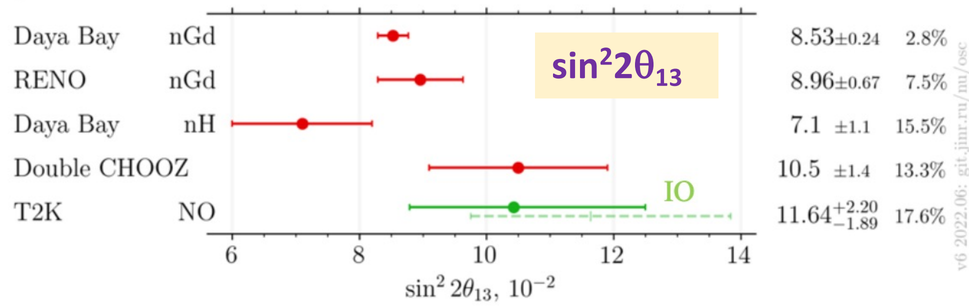
8 ton GdLS

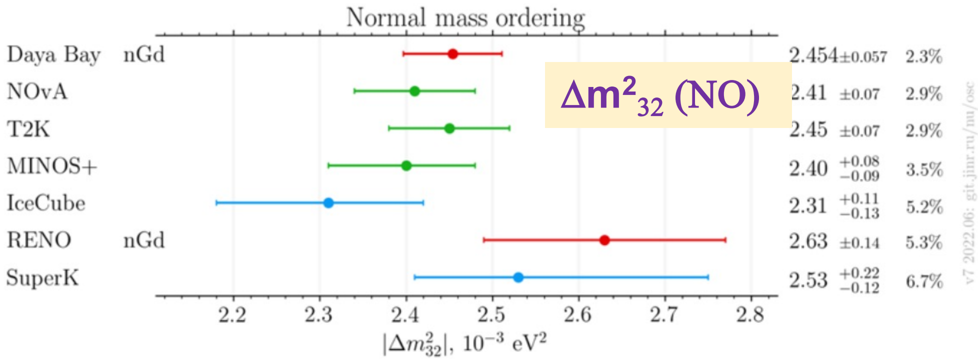
L: 1050 m

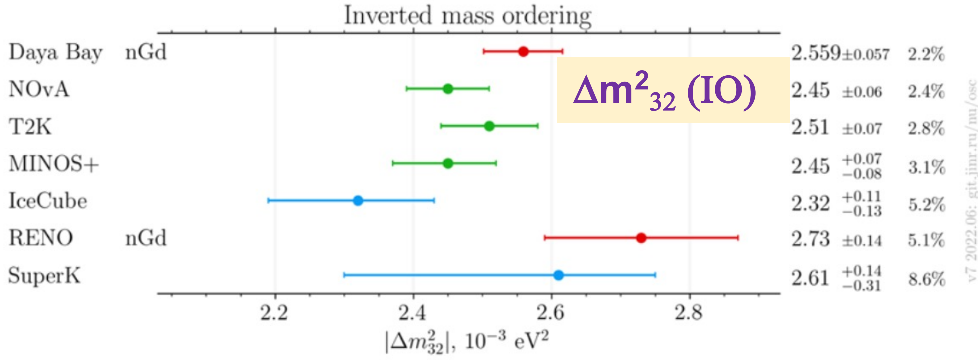




θ_{13} and Δm^2_{31}







Neutrino 2022

2.6% ? (nGd + nH)

- ❑ Daya Bay latest results (n-Gd): days

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$

(2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$

(2.3% preci

Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$

- ❑ RENO latest results (n-Gd): 2900 days

$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(\text{stat.}) \pm 0.0045(\text{sys.})$ (± 7.0 %)

$|\Delta m^2_{ee}| = 2.74 \pm 0.10(\text{stat.}) \pm 0.06(\text{sys.})(\times 10^{-3}\text{eV}^2)$ (± 4.4 %)

- ❑ RENO plans to take data until 2025 (~4400 days)

$\sin^2 2\theta_{13}$: 6.4%, Δm^2_{ee}: 4.1%

- ❑ DUNE can measure $\sin^2 2\theta_{13}$ in $\nu_\mu \rightarrow \nu_e$, w/ a precision of ~5%.

θ_{12} and Δm^2_{21}

	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} eV^2]
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

Before 2020

- Best fit values

KamLAND:

$$\Delta m^2_{21} = 7.50\,^{+0.20}_{-0.20} \times 10^{-5}\ \text{eV}^2,$$

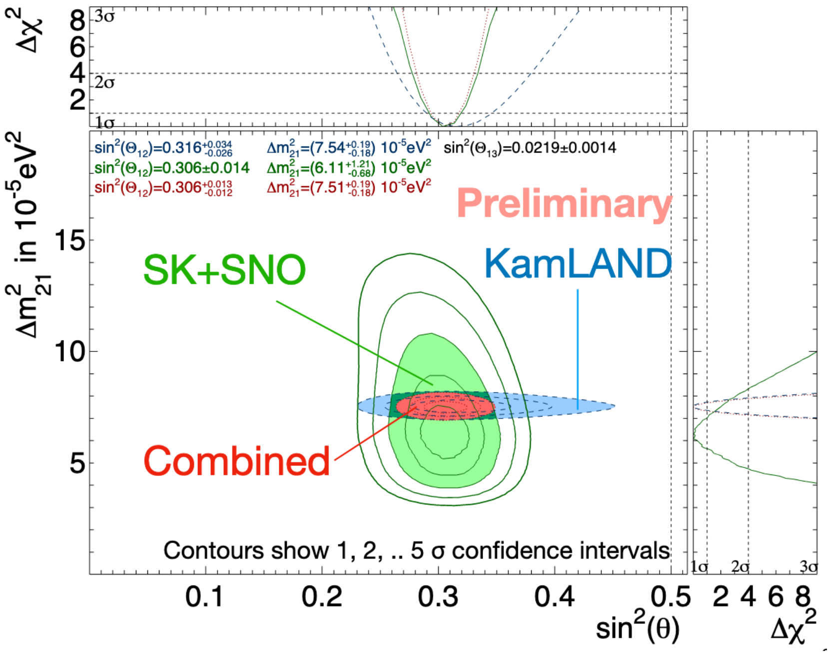
SNO/SK:

$$\Delta m^2_{21} = 5.1\,^{+1.3}_{-1.0} \times 10^{-5}\ \text{eV}^2,$$

~2 σ tension

(SK: 2,055 days data)

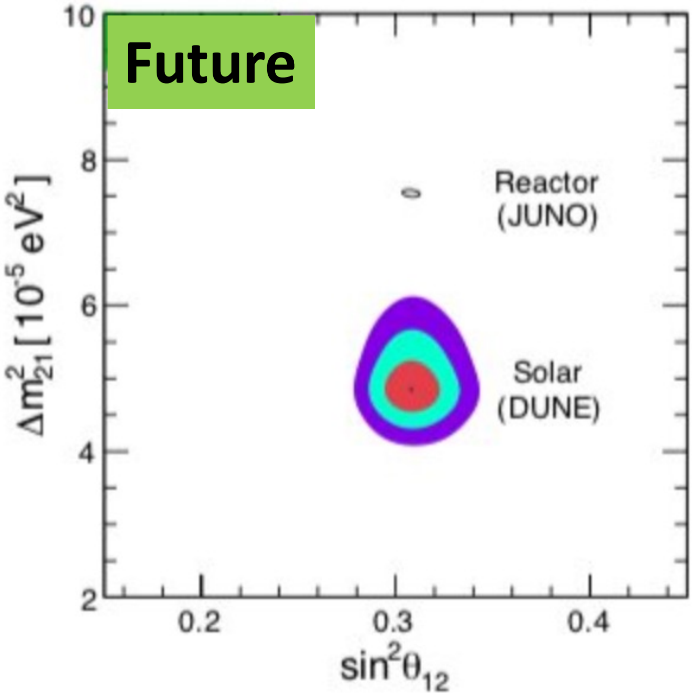
Year 2020



Tension decreased to 1.4 σ.

(SK: 2,970 days data)

Future



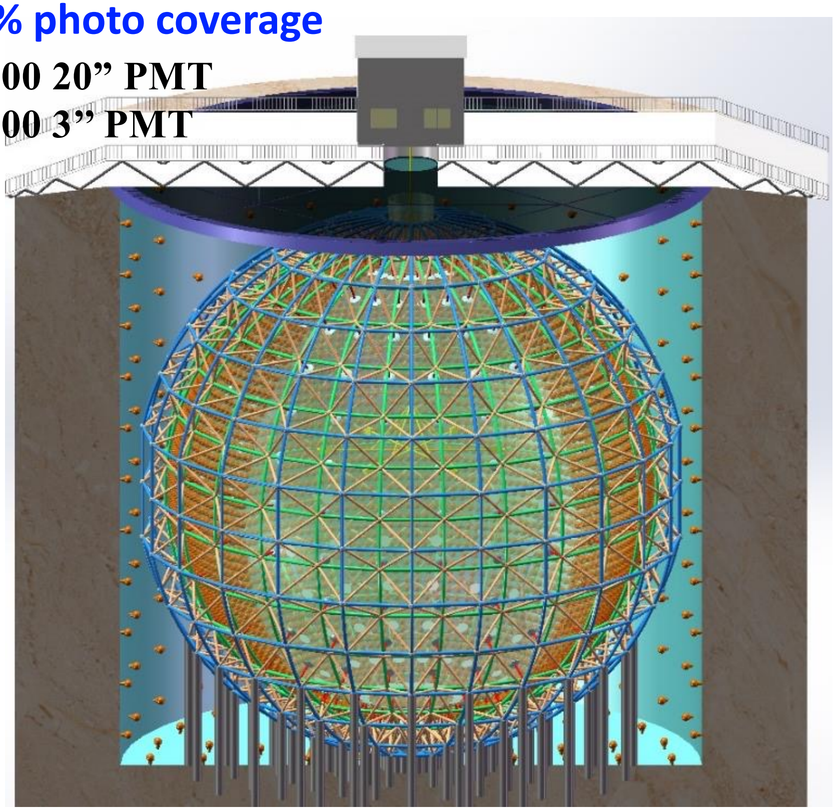
The JUNO Experiment

77 institutions
607 collaborators

Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013, 300 M$, online in ~2024

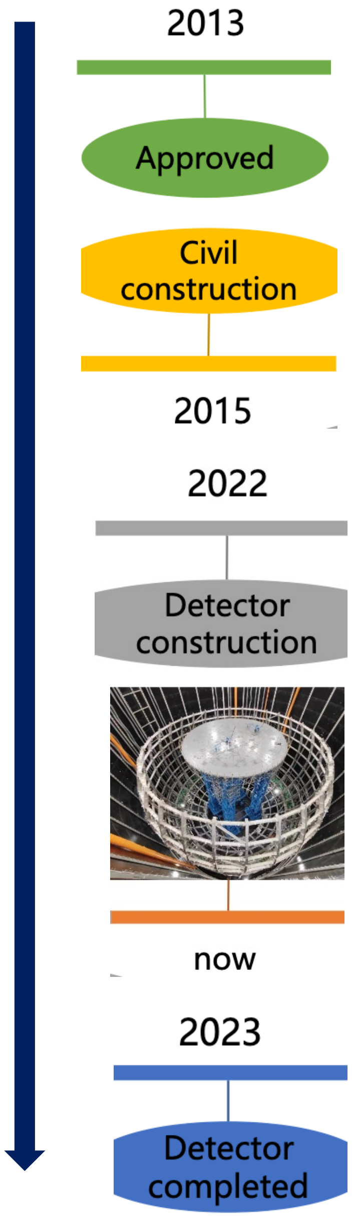
78% photo coverage

18000 20” PMT
25000 3” PMT



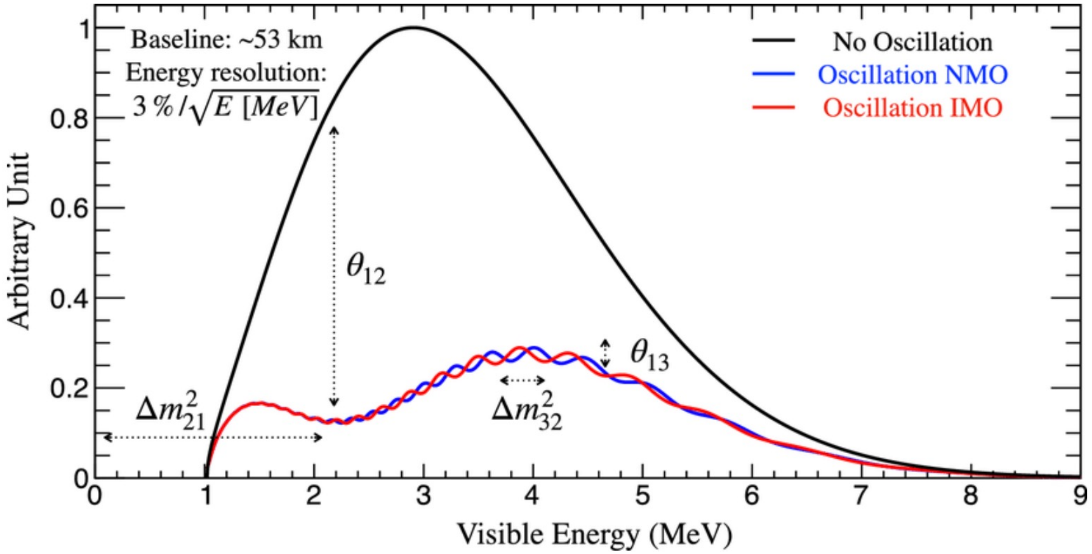
- 20 kton LS detector
- 700 m underground
- 3% energy resolution
- Rich physics possibilities
  - Reactor neutrino
    for Mass ordering and precision measurement of oscillation parameters
  - Supernova neutrino
  - Geo-neutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Proton decay
  - Exotic searches

Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007,2009



2013
Approved
Civil construction
2015
2022
Detector construction
now
2023
Detector completed

Precision Measurements in the (near-)Future



- **MO: ~3 σ (6 yrs data)**

The following papers argue that JUNO can't do 3σ for MO determination.

1309.1638
1508.01392
2107.12410

Only JUNO can do!

	Central Value	PDG2020	100 days	6 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)

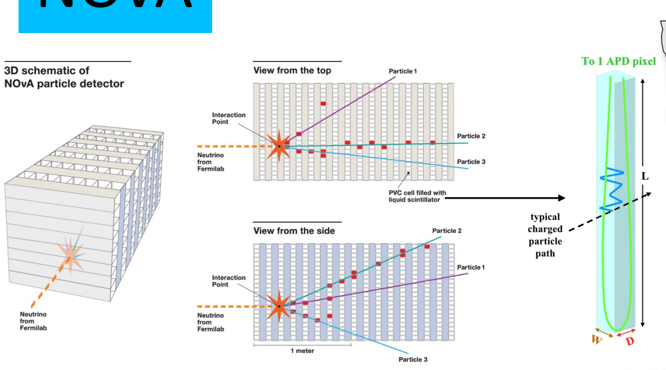
If MO is known

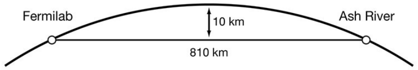
- **Probing the unitarity of U_{PMNS} to 1%, New physics?**

Current & Future Longbaseline ν experiments

- ➢ θ_{23}, Δm^2_{31}, and CPV/MO measurements

NOvA

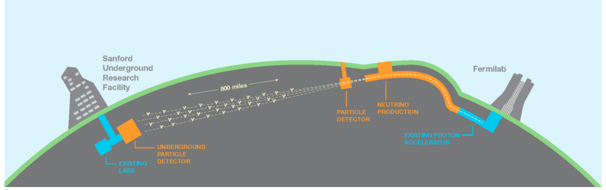




Segmented LS detector, 810 km

DUNE

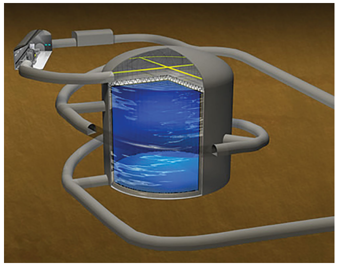
LArTPC, 1300 km



T2K

Water Cherenkov, 295 km

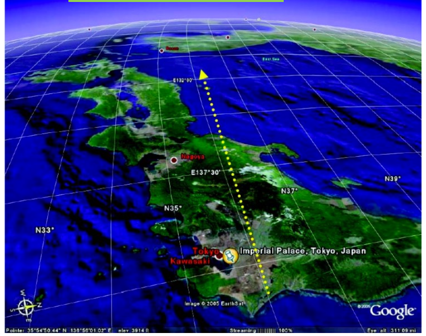
Hyper-K



WC, 295 km

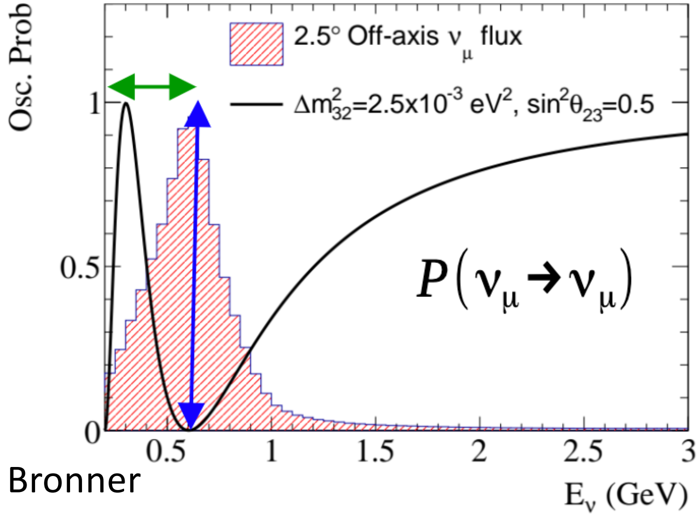
T2HKK

WC, ~1100 km



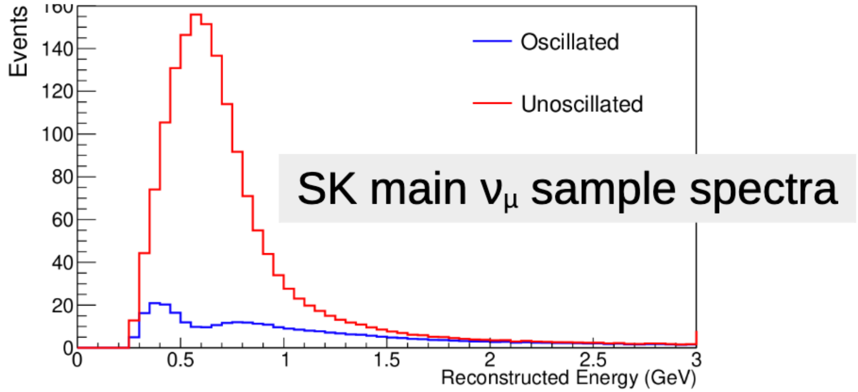
T2K & NOvA ν Oscillation (disappearance) Spectra

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})}\sin^2\left(1.27\frac{\boxed{\Delta m^2}L}{E}\right)$$



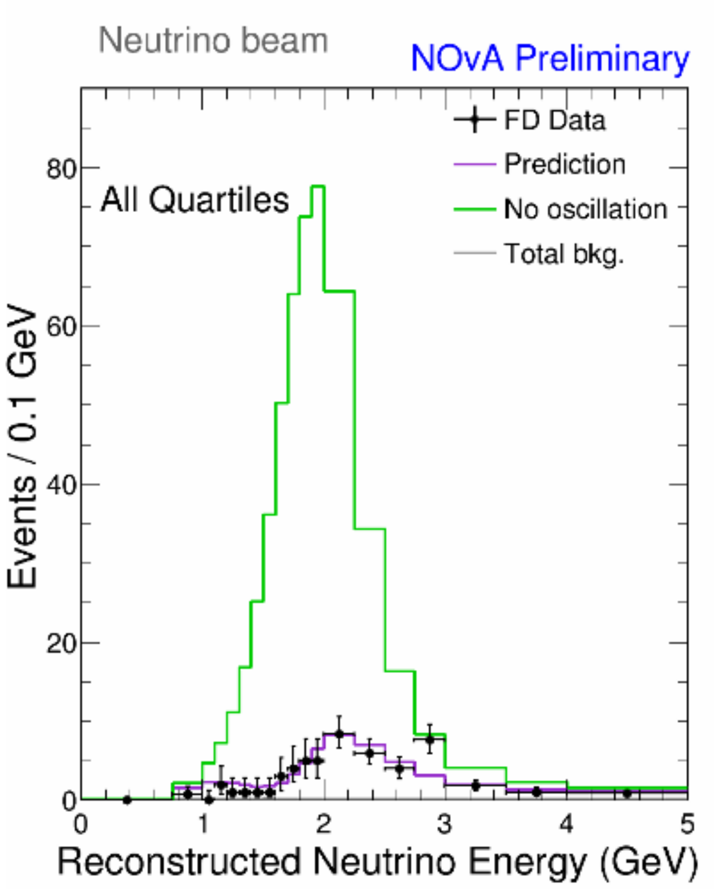
C. Bronner

T2K

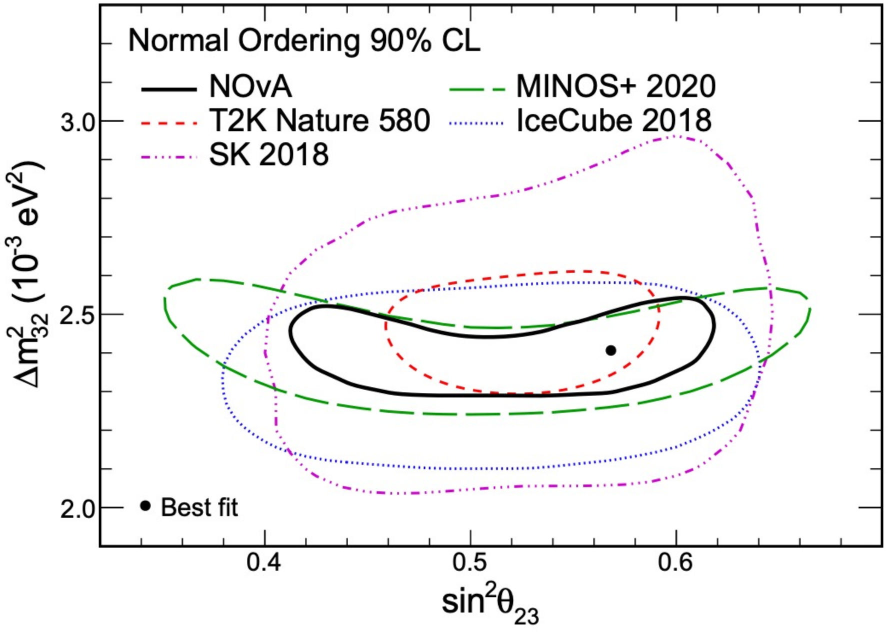


SK main ν_μ sample spectra

NOvA



θ_{23} and $|\Delta m^2_{32}|$



☐ Recent results from T2K and NOvA

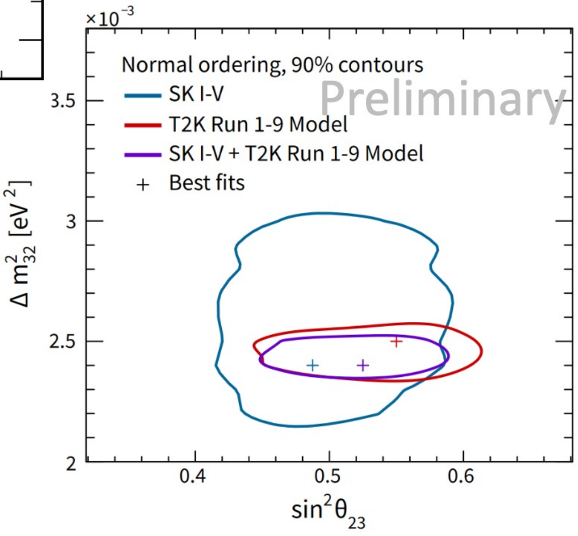
T2K best fit (NO)

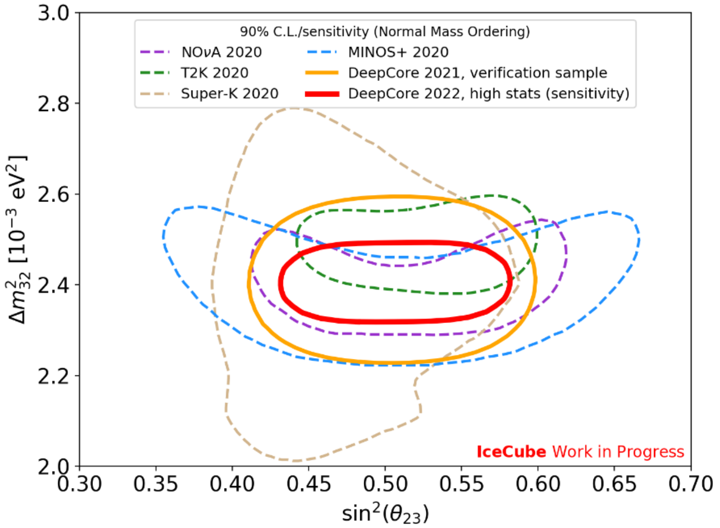
$\sin^2\theta_{23} = 0.532^{+0.030}_{-0.037}$ → +5.6% → -7%

$\Delta m^2_{32} = (2.45 +/- 0.07)X10^{-3}$ → +/- 2.9%

☐ Constraints from SK and IceCube (atm. ν_μ)

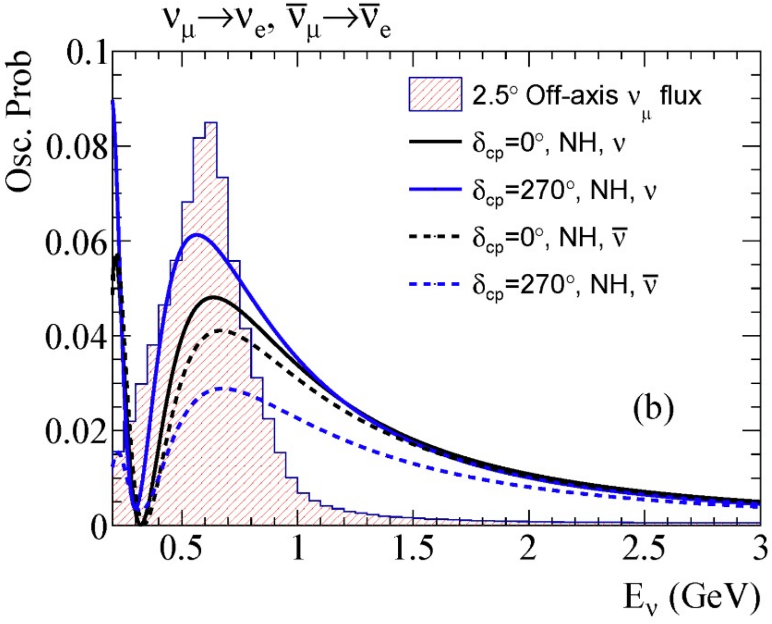
210K ν_μ





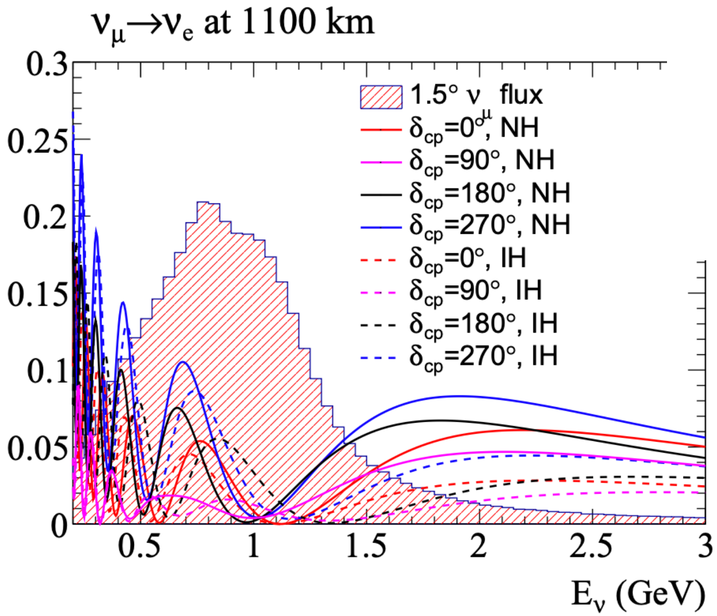
$\nu_\mu \rightarrow \nu_e$ Appearance Channel in LBL

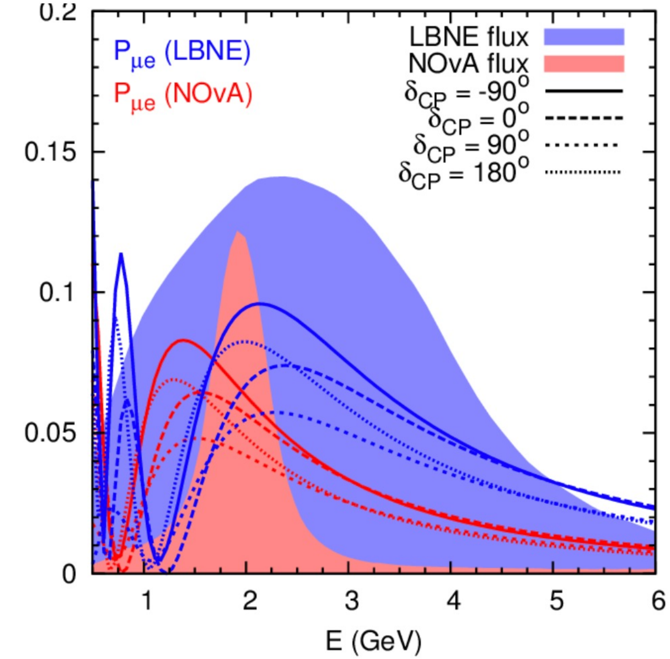
→ Measure CPV, MO



T2K, HK

T2HKK





NOvA, DUNE

2020 3-Flavour Frequentist Result

Best Fit

Normal hierarchy

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$

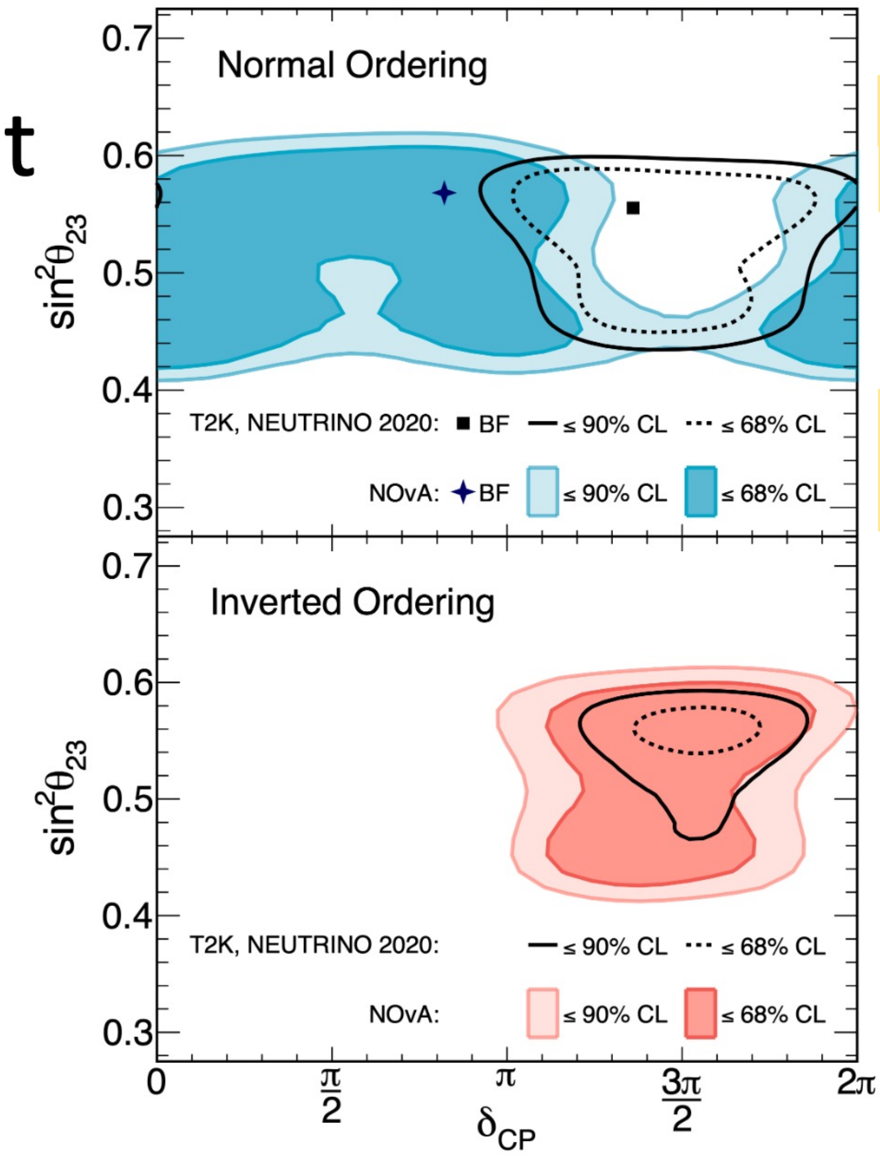
$\sin^2\vartheta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\pi$

Poster 318
Liudmila Kolupaeva
Andrew Sutton

- Significant progress on joint fit with T2K
  - – coming this year

2020 data set: https://arxiv.org/abs/2108.08219



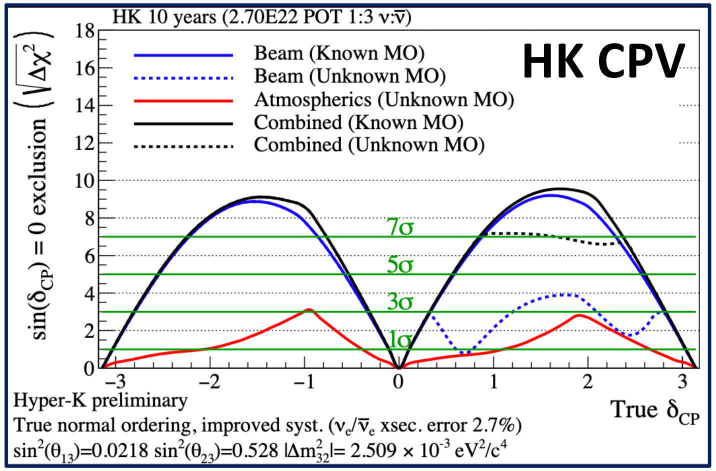
NOvA

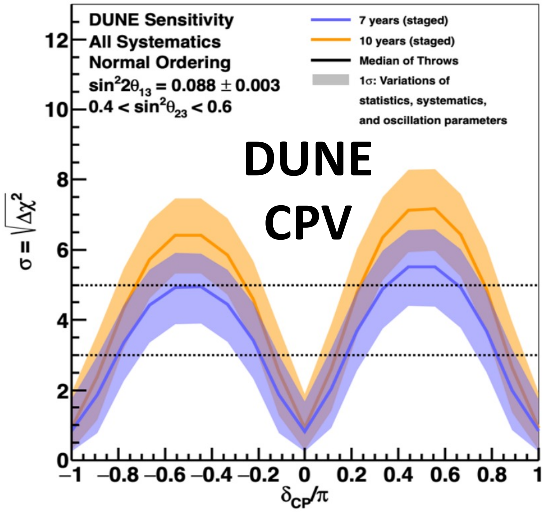
Nu : 13.6×10^{20} POT
Anti-nu : 12.5×10^{20} POT

T2K

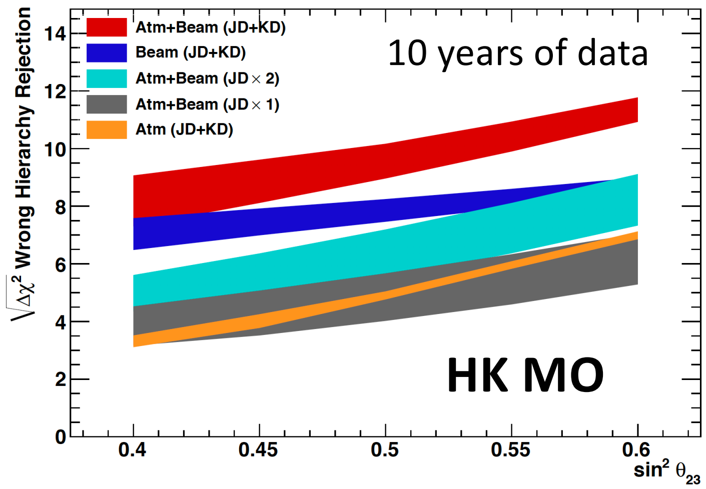
Nu : 19.7×10^{20} POT
Anti-nu : 16.3×10^{20} POT

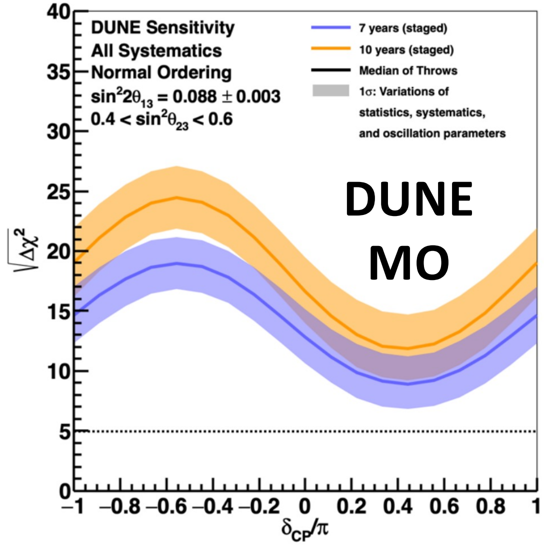
HK vs DUNE: CPV & MO Sensitivities





- ❑ HK 10 years data will exclude $\delta_{CP} = 0$ for 61% of true CP values (5σ).
- ❑ DUNE 10 years data will exclude $\delta_{CP} = 0$ for > 50% of true CP values (5σ).





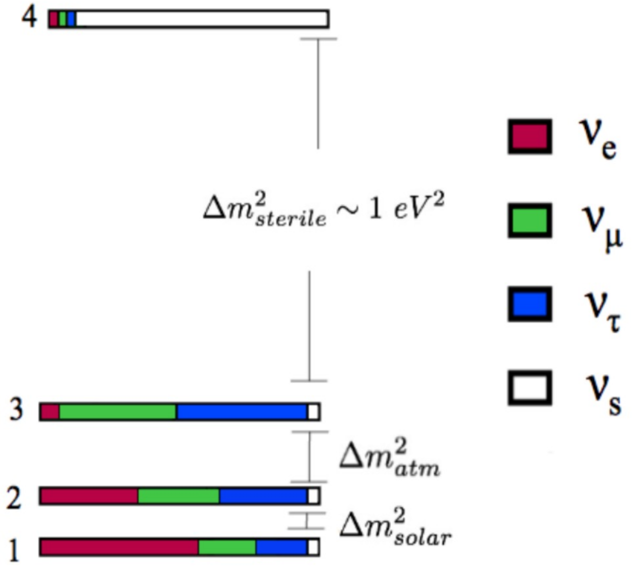
- ❑ HK alone can determine MO between 3σ and 7σ depending on $\sin^2\theta_{23}$ (10 yr data).
- ❑ DUNE can determine MO greater than 7σ for any δ_{CP} values w/ 7 years of data.

3+1 Neutrinos

- Sterile neutrinos are searched only **"via oscillation"** w/ active neutrinos.

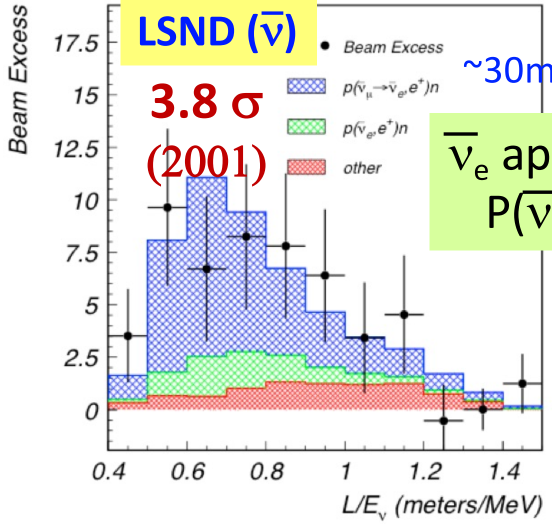
Flavor **U_{3+1}** **Mass**

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



$$U_{3+1} = U(U_{PMNS}, \underbrace{\theta_{14}, \theta_{24}, \theta_{34}}_{\text{3 mixing angles}}, \underbrace{\delta_{14}, \delta_{24}}_{\text{2 CPV phases}}, \Delta m^2_{41})$$

Smoking Guns of Sterile Neutrinos at ~eV?



LSND ($\bar{\nu}$)

3.8 σ

(2001)

~30m/30MeV

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

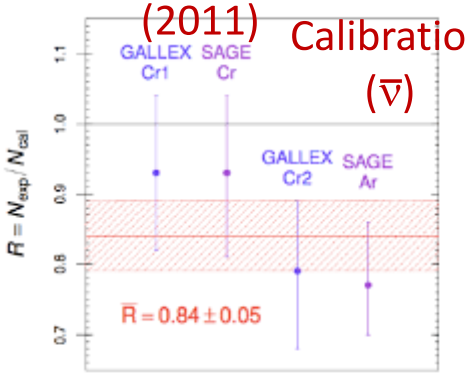
ν_e disappearance
$P(\nu_e \to \nu_e)$

GALLEX/SAGE

3σ

(2011)

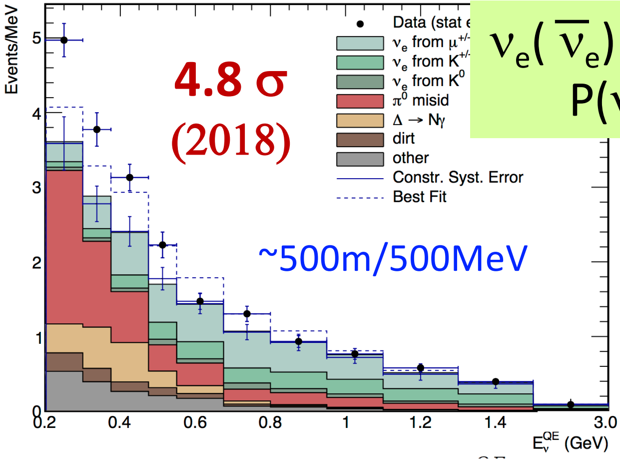
Source Calibration ($\bar{\nu}$)



Phys. Rev. C83, 065504 (2011)

3σ~4σ
evidences

MiniBooNE (ν, $\bar{\nu}$)



4.8 σ

(2018)

~500m/500MeV

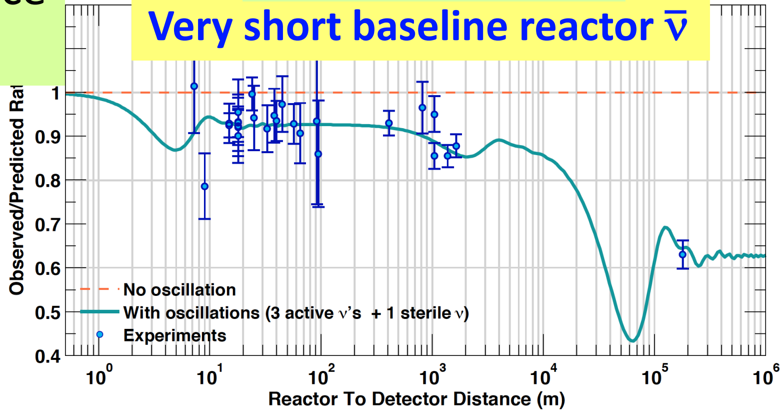
$\nu_e(\bar{\nu}_e)$ appearance
$P(\nu_\mu \to \nu_e)$

$\bar{\nu}_e$ disappearance
$P(\bar{\nu}_e \to \bar{\nu}_e)$

3σ

(2011)

Very short baseline reactor $\bar{\nu}$

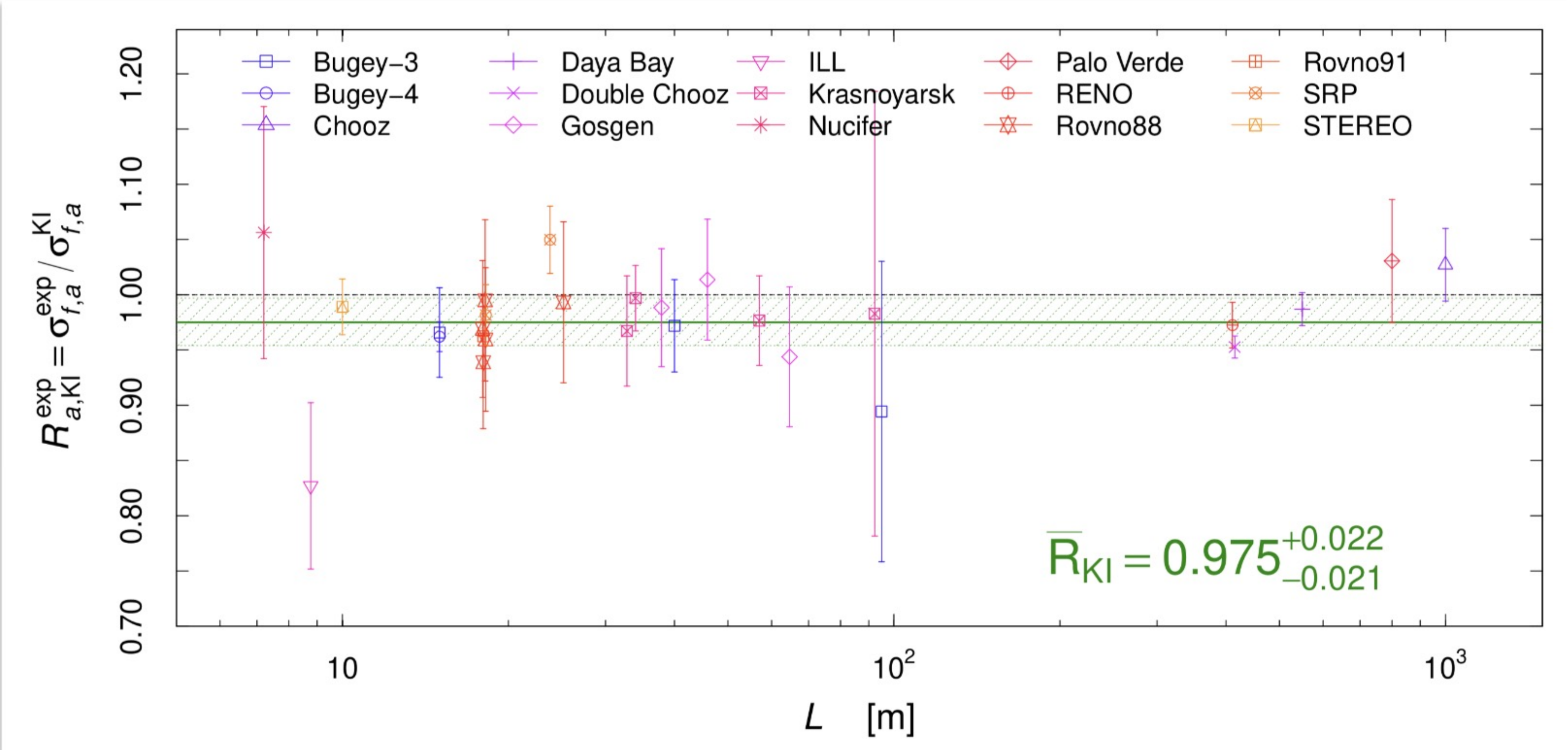


reactor ν

With updated input data to flux calculation

(new β spectra from ^{235}U fission)

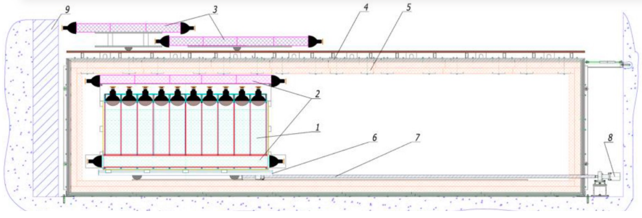
Kopeikin Skorokhvatov Titov arXiv:2103.01684
Berryman Huber arXiv:2005.01756
Giunti Li Ternes Xin arXiv:2110.06820



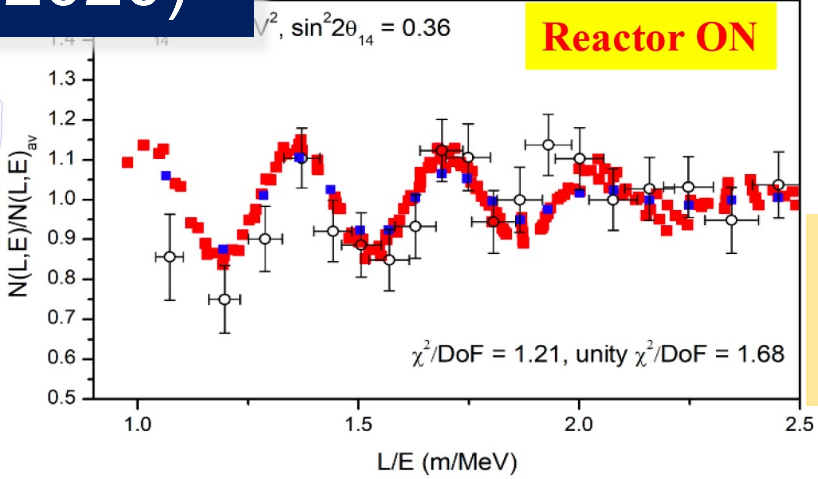
J. Kopp
@Nu2022

→ Reactor ν flux anomaly disappears !

Neutrino-4 (2016-2020)



- Reactor: 100 MW_{th}
- Segmented GdLS (1.8 ton)
- Baseline: 6 -12 m



❑ **Best fit**: **~140 K IBDs**

- $\Delta m_{41}^2 = 7.30 \pm 1.17\ eV^2$
- $\sin^2(2\theta_{14}) = 0.36 \pm 0.12_{stat}$ (2.9 σ)

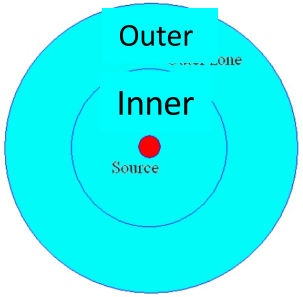
BEST (2019)

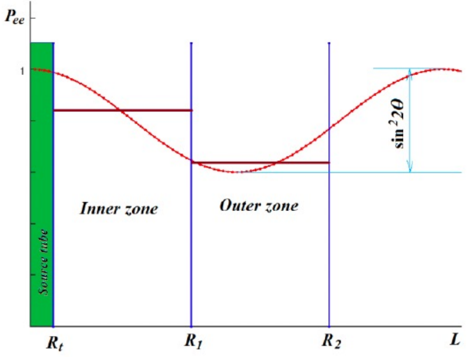
^{51}Cr of 3 MCi ($\Delta W/W < 0.5\%$)
(r = 10.5 cm)
neutrino flux measurment:
$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$

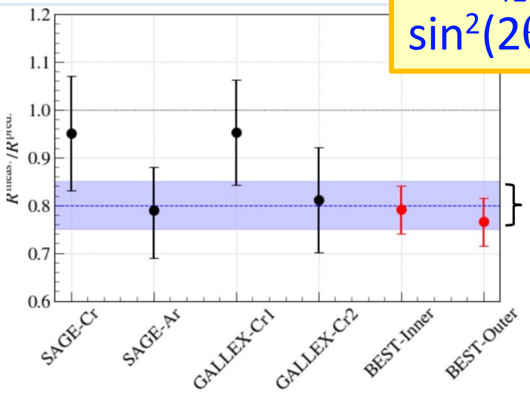
$R_{out}/R_{in} = 0.97 \pm 0.07$

BEST best fit:

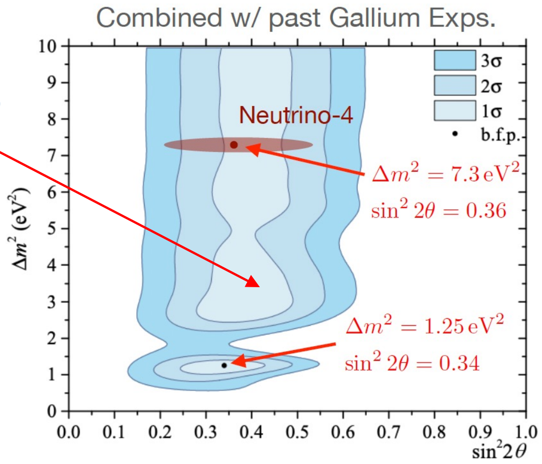
$\Delta m^2_{41} = 3.3\ eV^2$,
$\sin^2(2\theta_{14}) = 0.42$



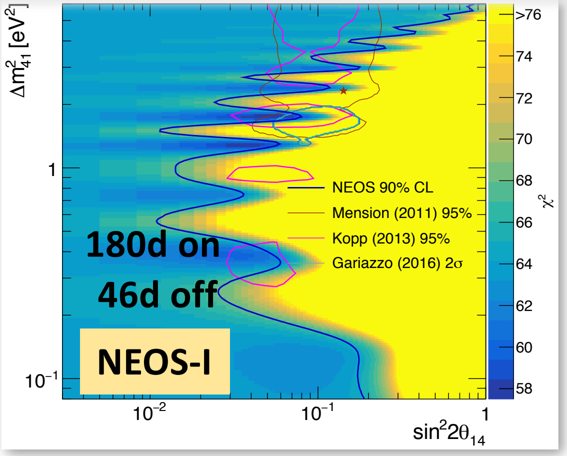




Combined result:
$R_0 = 0.80 \pm 0.05$



Current VSBL Reactor (3+1) ν Limits



180d on

46d off

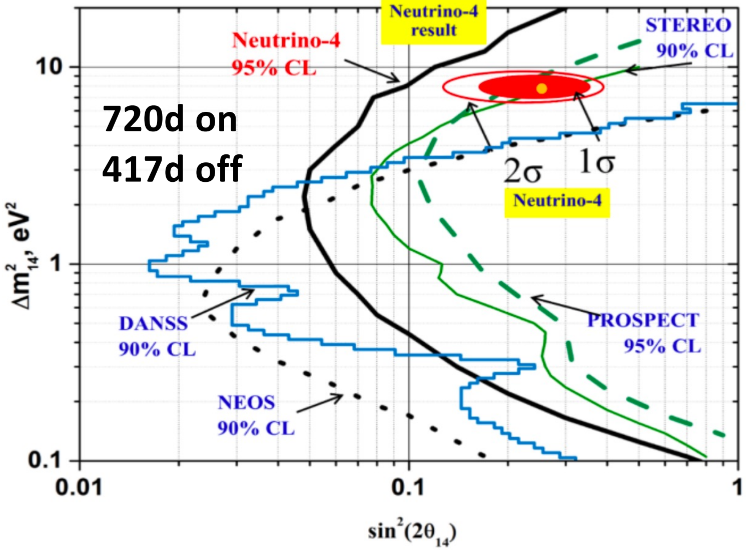
NEOS-I

PRL 118, 042502 (2017)

VSBL = Very Short Base Line

Neutrino-4

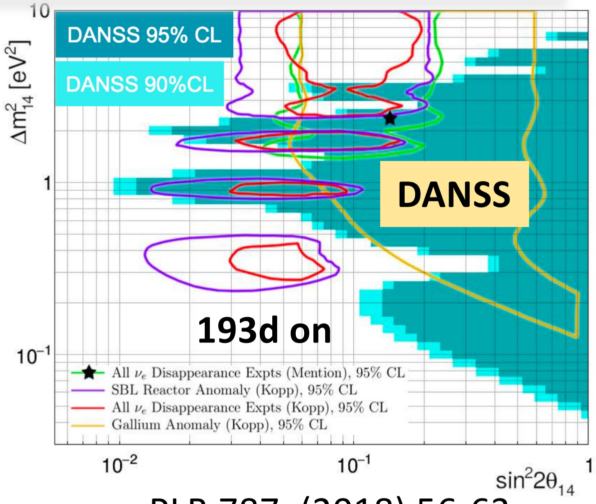
2005.05301



720d on

417d off

Neutrino-4 result is partially excluded by STEREO and PROSPECT.

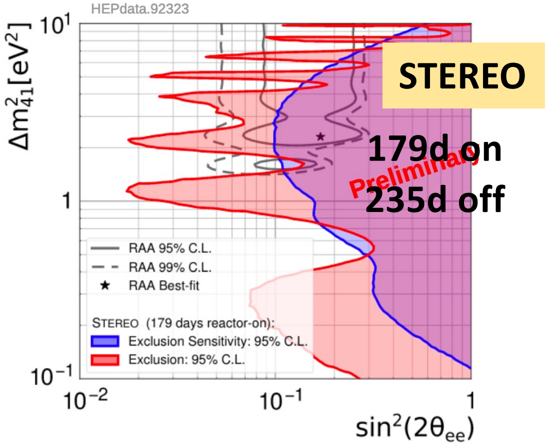


DANSS

193d on

PLB 787, (2018) 56-63

arXiv:1912.06582

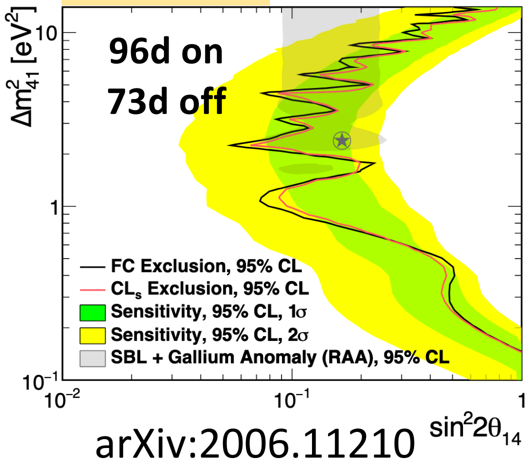


STEREO

179d on

235d off

PROSPECT



96d on

73d off

arXiv:2006.11210

VSBL Near Future Plans

☐ DANSS-II

-- Data-taking until spring 2022

-- Finish upgrade of detector in 2022

E resolution goal: 13% @1MeV

☐ PROSPECT-II

-- will upgrade detector

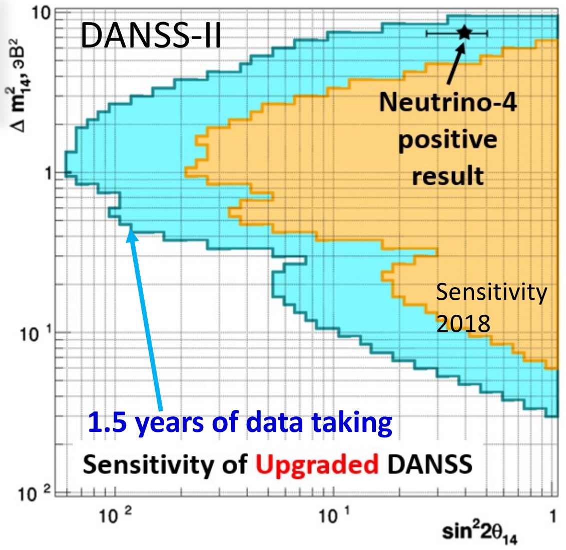
- PMTs outside LS target
- Better isolation & control of LS
- Increase target size

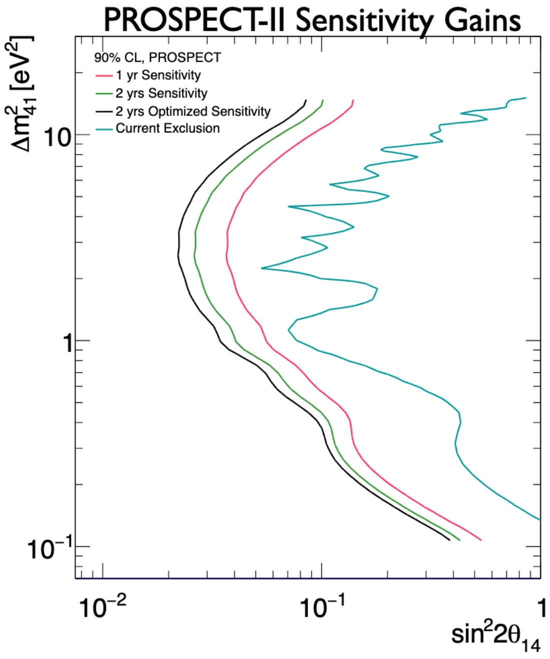
-- Data-taking: 2023 (?)

☐ Neutrino-4

-- will upgrade current detector

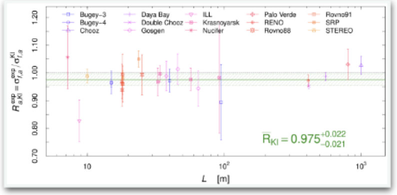
-- Restart of data-taking: end of 2022





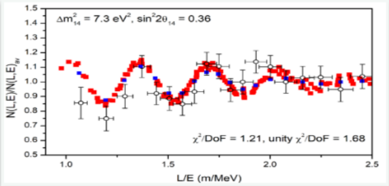
Short-Baseline Anomalies: Current Status

J. Kopp
@Nu2022



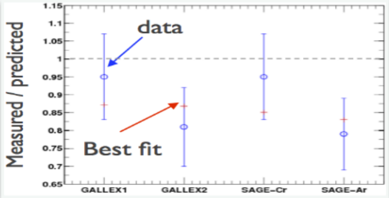
reactor flux anomaly
resolved with new input data
to flux calculation

✓



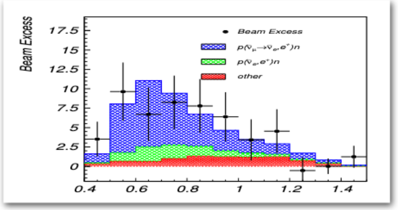
reactor spectra
is there really an anomaly?

?



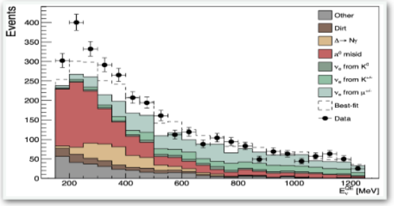
gallium anomaly
unresolved, recently reinforced

?



LSND
unresolved

?



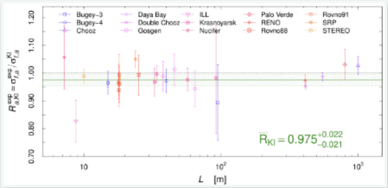
MiniBooNE
unresolved

?

Still
unresolved

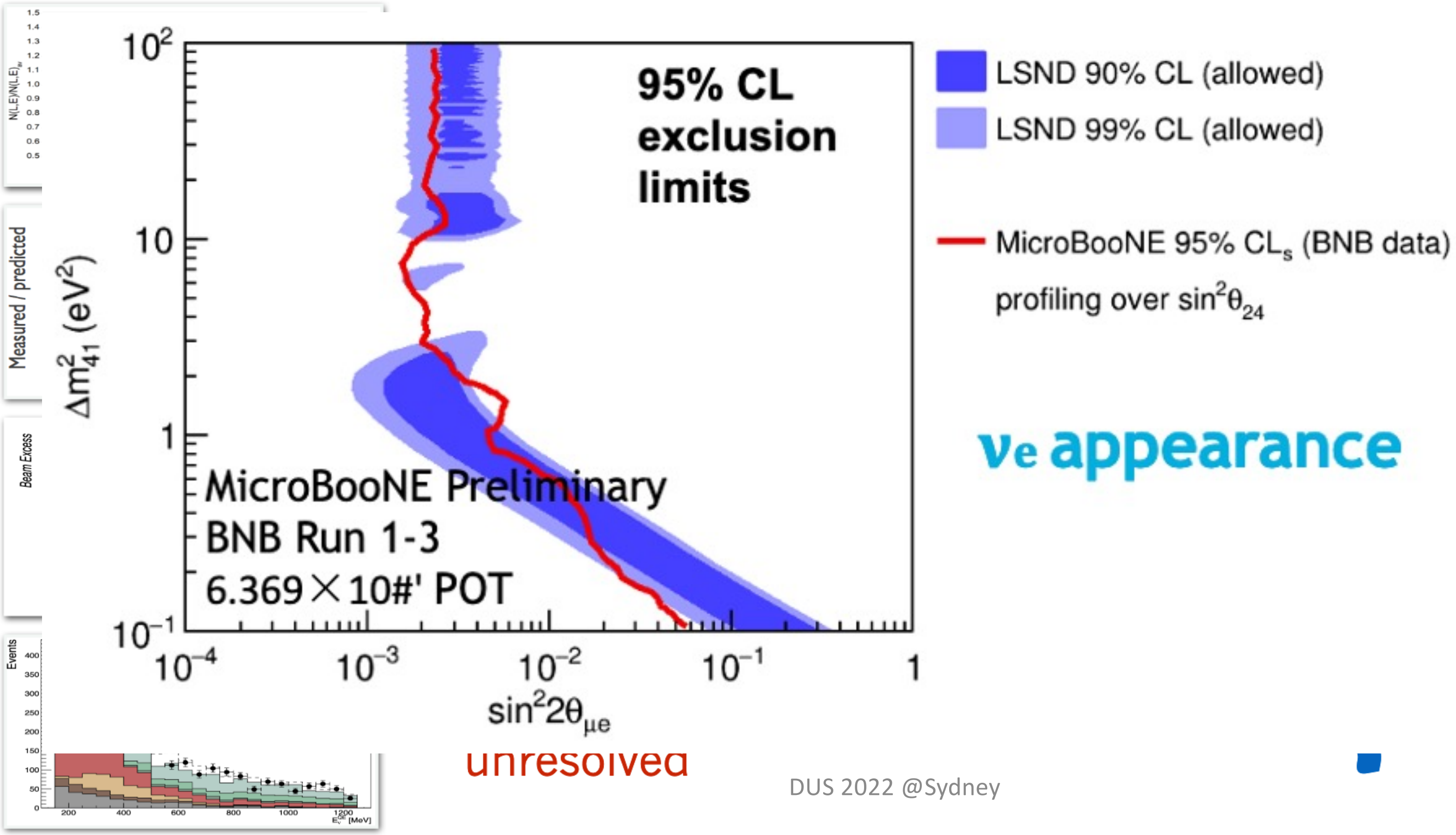
Short-Baseline Anomalies: Current Status

J. Kopp
@Nu2022



reactor flux anomaly
resolved with new input data
to flux calculation

✓



ν_e appearance

Still
unresolved

unresolved

JSNS^2 @J-PARC

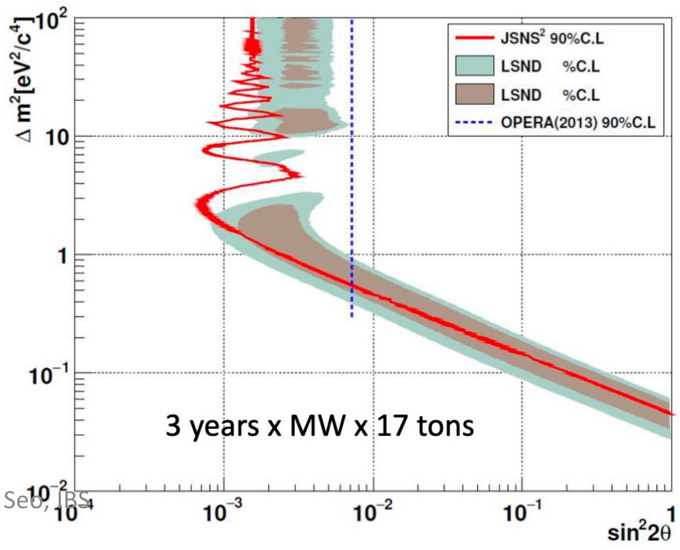
→ Direct tests for LSND

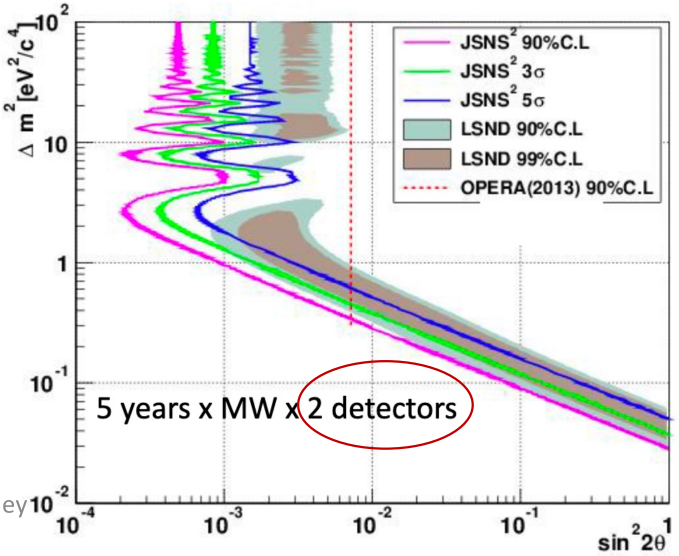
Experiment	ν-source	Energy E_ν	Distance L	Signal
LSND [1]	π DAR	40 MeV	30 m	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
MiniBooNE [2]	π DIF	800 MeV	600 m	$\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
FNAL SB program [7]	π DIF	800 MeV	110 m / 470 m / 600 m	$\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
JSNS^2 [6]	π DAR	40 MeV	24 m	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- 17 ton GdLS target (cf. LSND = 167 ton LS)
- Better E resolution than LSND (2.4 % vs 7% at 45 MeV)

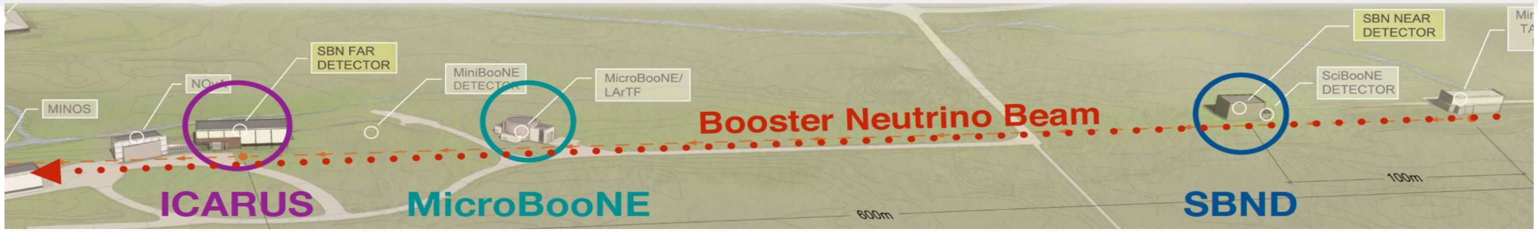
JSNS^2-II

Data taking:
End of 2023





Short Baseline Neutrino (SBN) Status @Fermilab



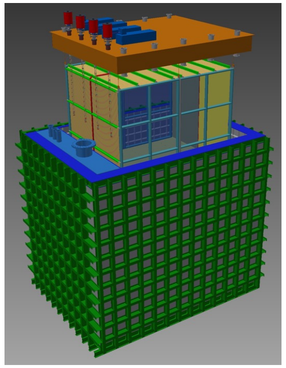
Anne Schukraft @Nu2022

SBND

(110 m, 112 ton)

- Detector construction underway
- Detector installation: end of 2022
- Detector commissioning: 2023

← **Systematic Constraint (~% level)**



ICARUS

(600 m, 476 ton)

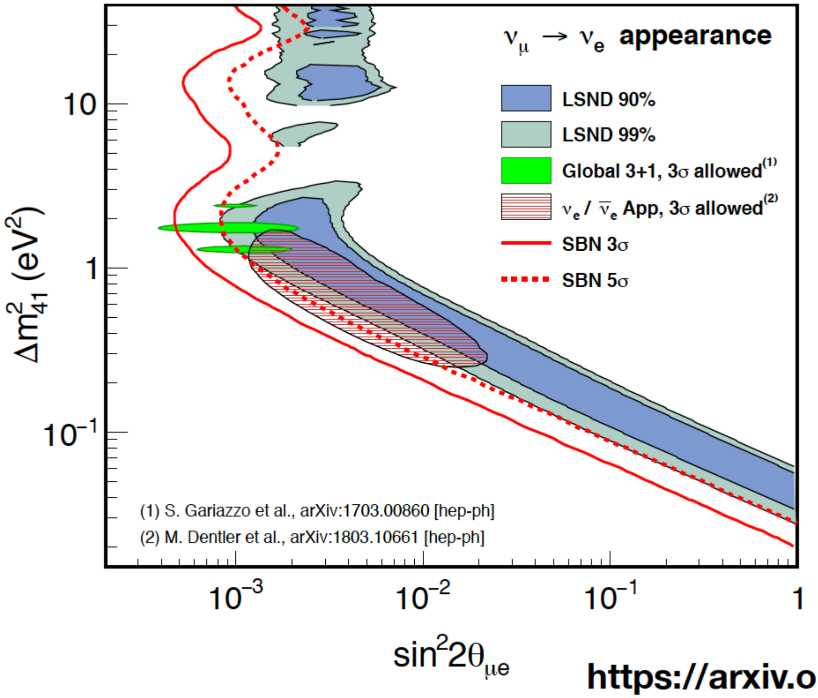
- Detector installation: July ‘18 – ’19
- Detector commissioning: 2020
- 1st Physics data: June 2021
- Calibration campaign in process
- Preparing to start its physics run

SBN@Fermilab Sensitivities

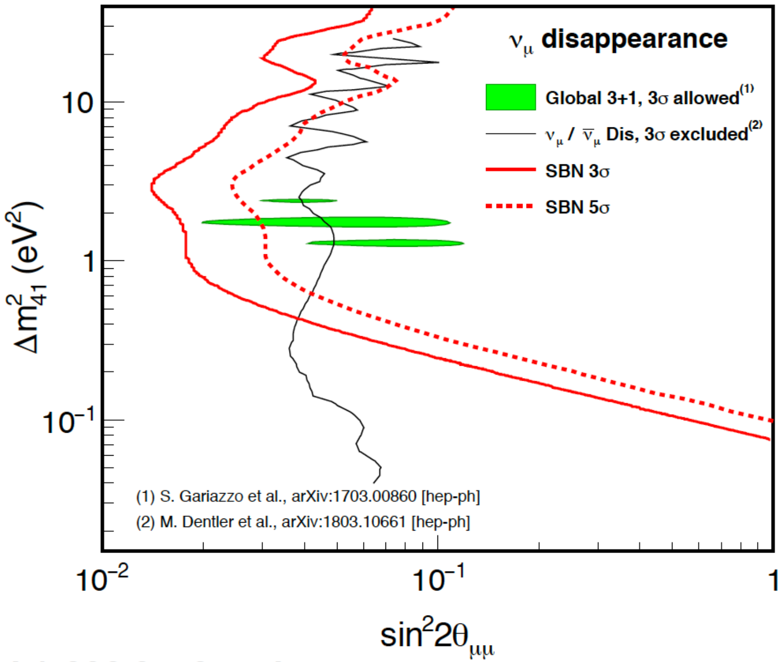
- Reach of full program
  - SBND/ICARUS (6.6e20 POT ~ 3 years)
  - MicroBooNE (13.2e20 POT ~ 6 years)

Appearance and disappearance tested in one program

ν_e appearance



ν_μ disappearance



https://arxiv.org/pdf/1903.04608.pdf

20

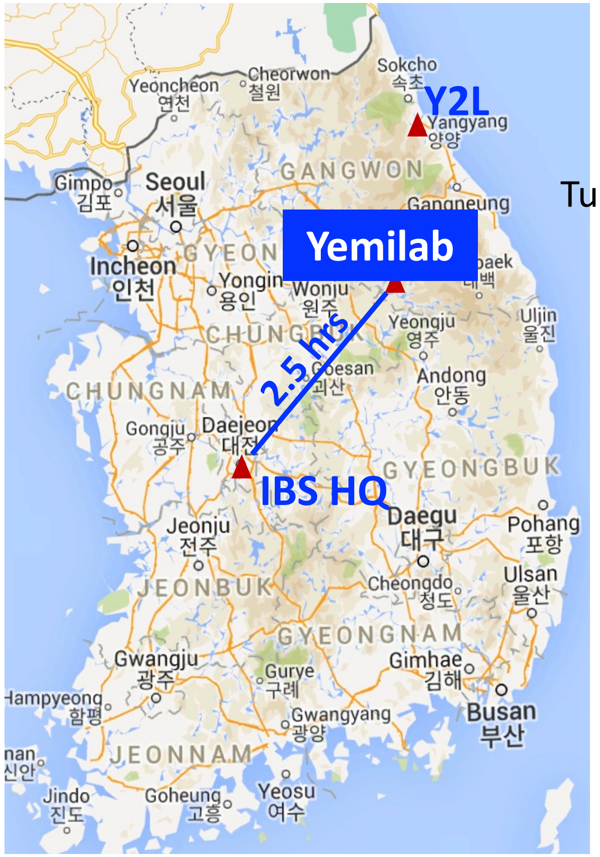
LSC @Yemilab, Korea

❑ **Yemilab: new underground lab in Korea (~1 km overburden)**

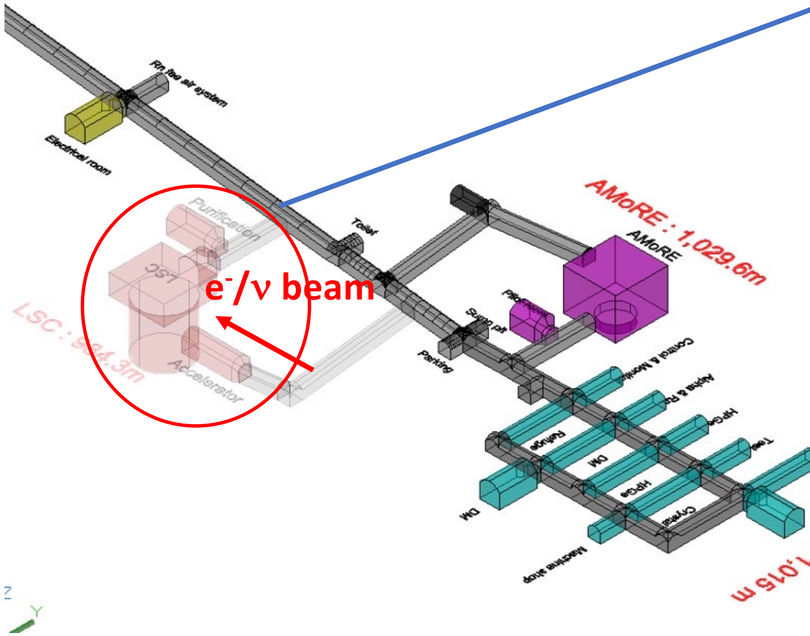
LSC = Liquid Scintillation Counter

LSC Pit: 20 m (D) x 20 m (H)

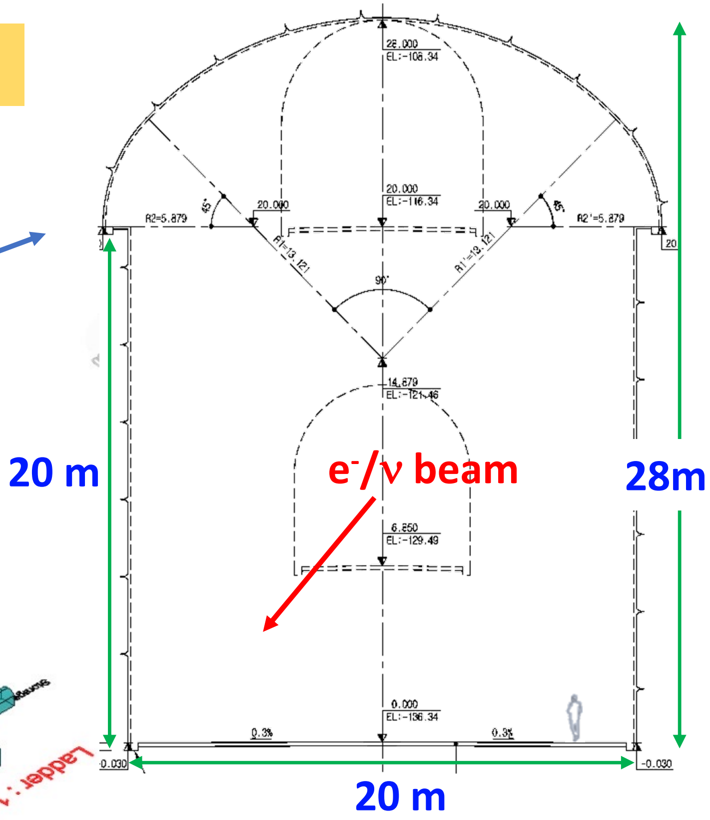
LSC Hall construction:
June 2021 – Feb. 2022



Tunnel entrance



LSC Hall



The 1st Yemilab Workshop

Oct.15-18, 2022

Oct 15 – 18, 2022
High-1 Resort, Grand Hotel Convention Tower 5th floor
Asia/Seoul timezone

https://indico.ibs.re.kr/event/531/

This is a Hybrid Workshop. Registered participatns will get ZOOM connection info.

✉ sunny.seo@ibs.re.kr

Welcome to the 1st Yemilab Workshop!

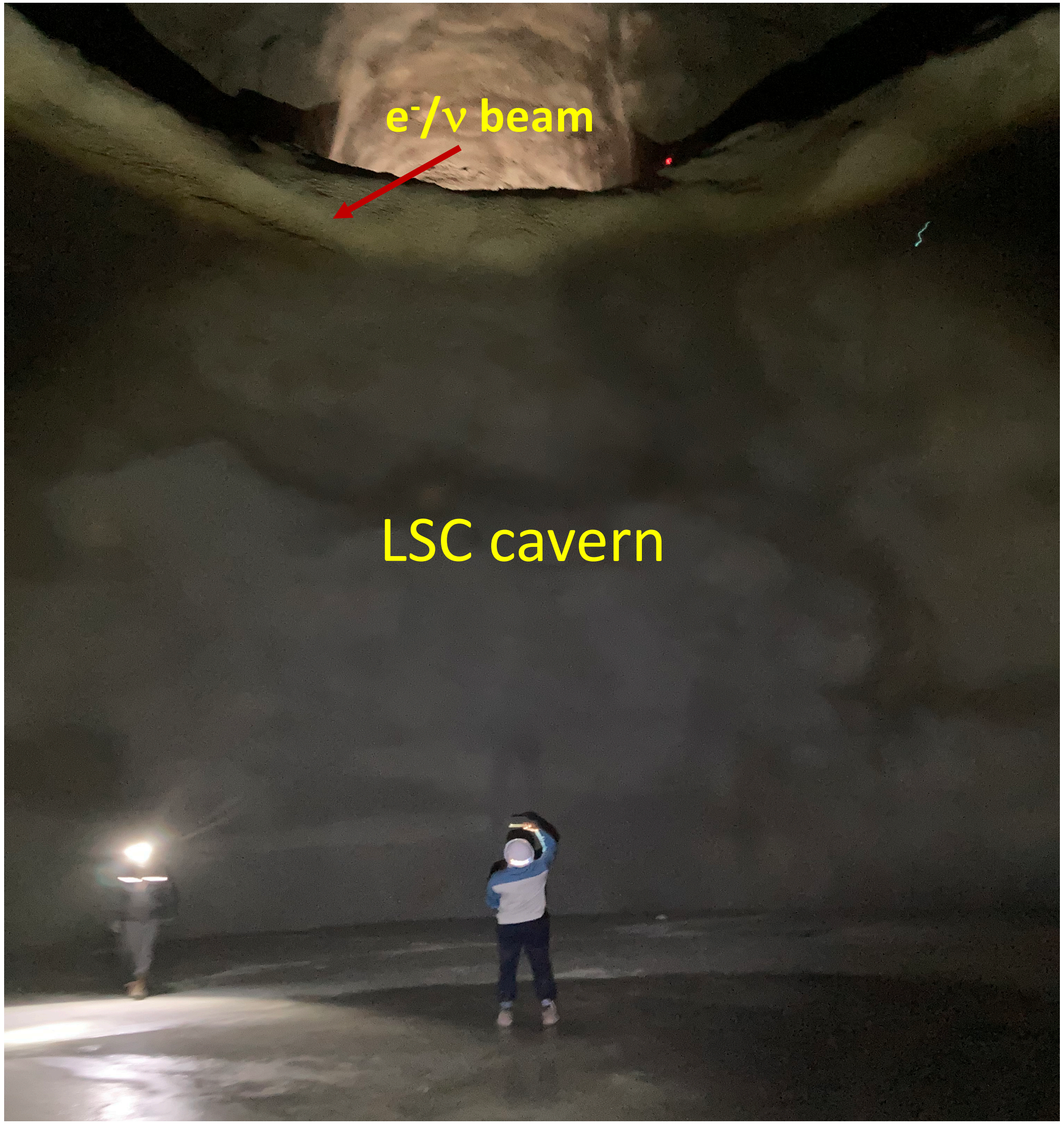
Yemilab is the first deep underground lab dedicated to science in Korea and its construction was successfully finished recently. To celebrate the kick-off of the Yemilab, we are organizing this workshop and cordially invite world experts in underground physics. New ideas, technologies, or perspectives will be shared in this workshop.

Anyone who is curious or excited about Yemilab is very welcome to join us!

No registration fee.

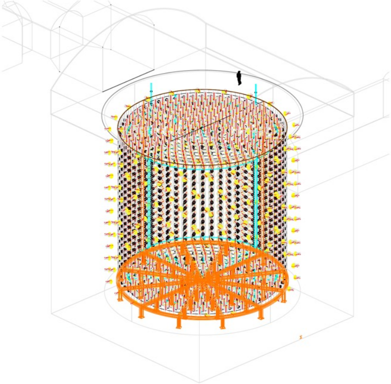
Free meals for all in-person participants who register **by Oct. 6 (Th)**.

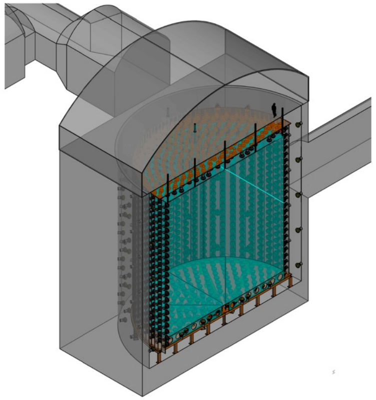
- 10/15 (Sat): Arrival, Registration, Reception
- 10/16 (Sun): Yemilab Tour
- 10/17(M)-18(Tu): Physics Workshop, Banquet

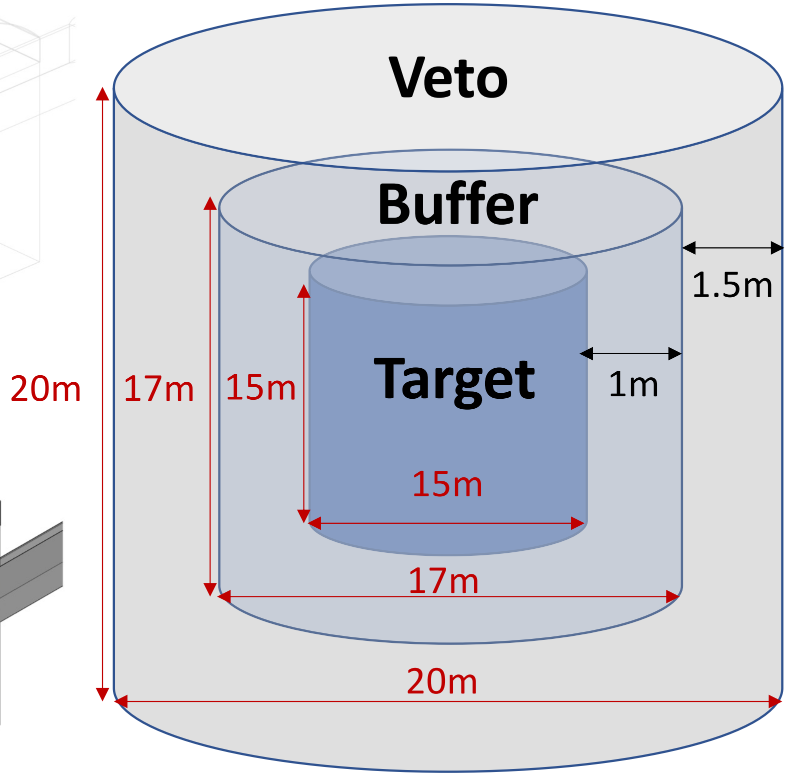



Oct. 5, 2022

Candidate Detector Design



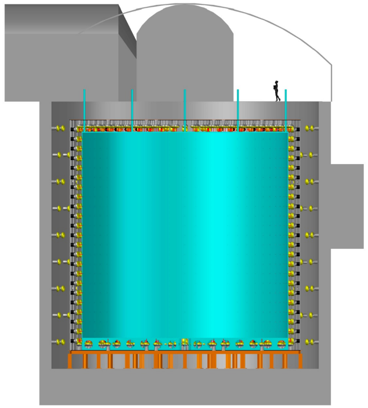




Target: **2.26 kton LS**

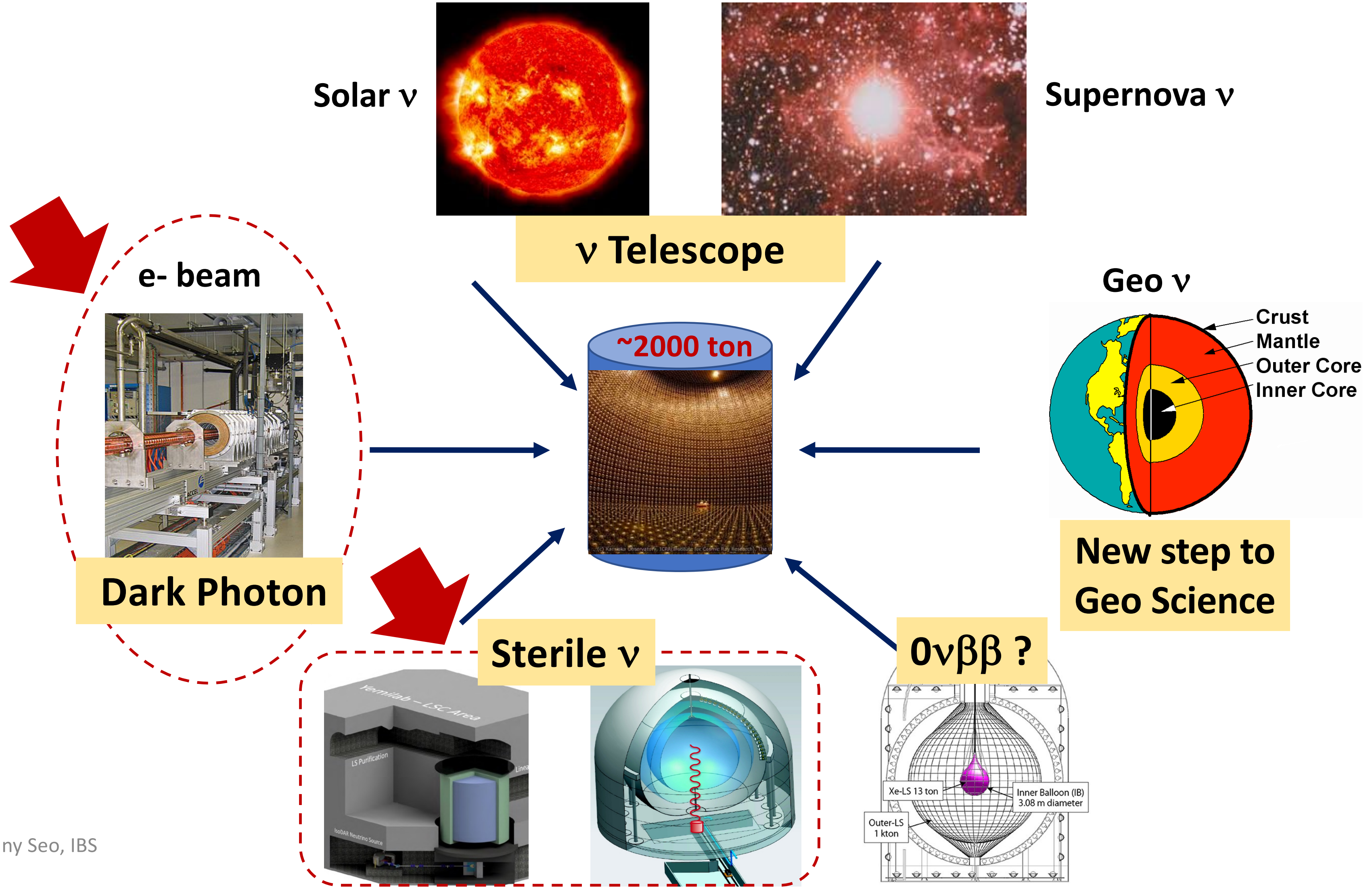
Buffer: 1.14 kton mineral oil

Veto: 2.41 kton water



1200(1800,2400) x 20 inch PMTs = 20% (30, 40)% coverage

Broad Physics Program



Solar ν

Supernova ν

ν Telescope

e- beam

Dark Photon

~2000 ton

Geo ν

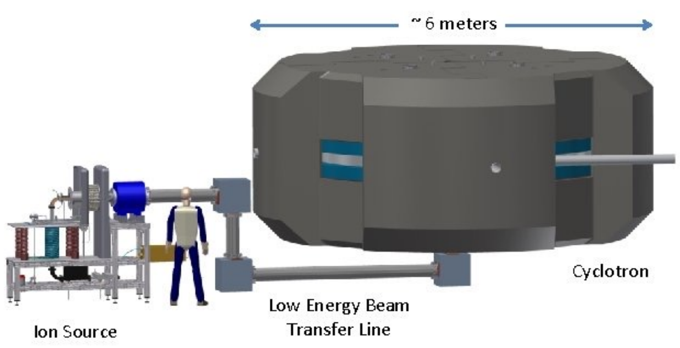
New step to Geo Science

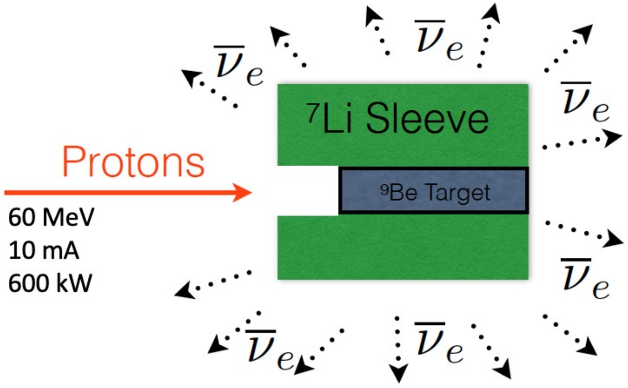
Sterile ν

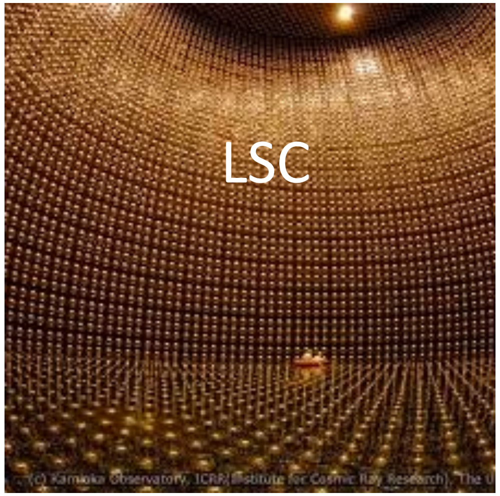
0νββ ?

❑ Sterile ν search w/ IsoDAR@Yemilab

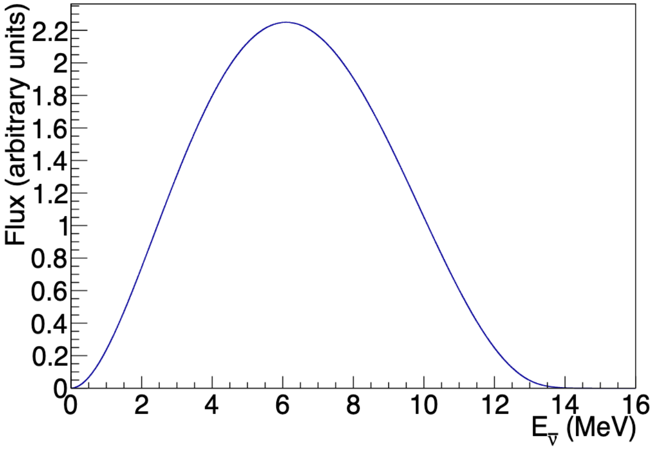
The IsoDAR Cyclotron and Ion Source







IsoDAR $\overline{\nu}$ spectrum



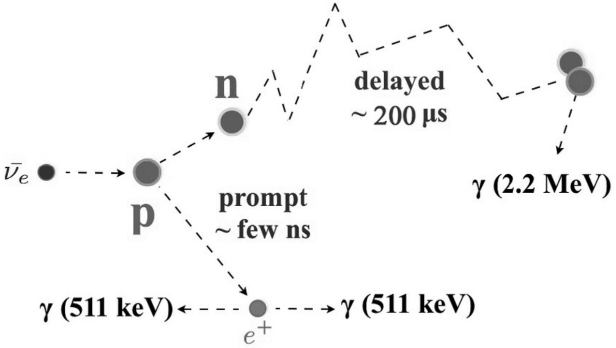
(1) $p + {}^9\text{Be} \rightarrow {}^8\text{Li} + 2p$

(2) $p + {}^9\text{Be} \rightarrow {}^9\text{B} + n$
$n + {}^7\text{Li} \rightarrow {}^8\text{Li} + \gamma$

$\boxed{{}^8\text{Li} \rightarrow {}^8\text{Be} + e^- + \overline{\nu}_e}$

IBD interaction

$$\boxed{p^+ + \overline{\nu}_e \rightarrow e^+ + n^0}$$

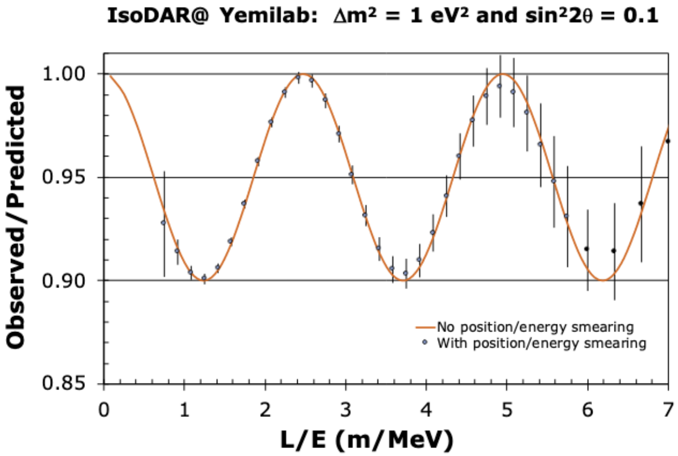


Sterile ν Search w/ IsoDAR@Yemilab

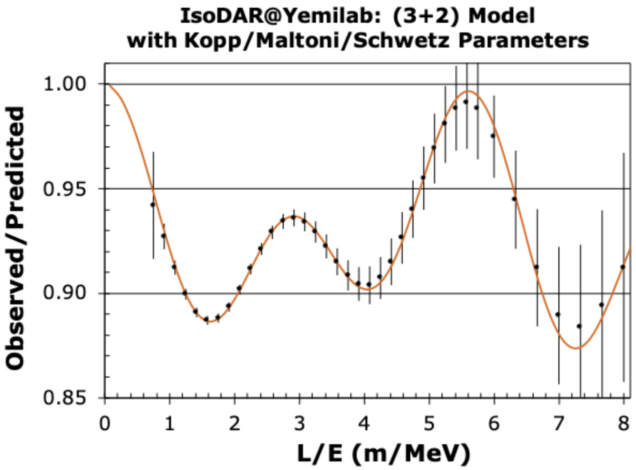
Possible Models & Signatures

arXiv:2111.09480
PRD 105 (2022) 5, 052009

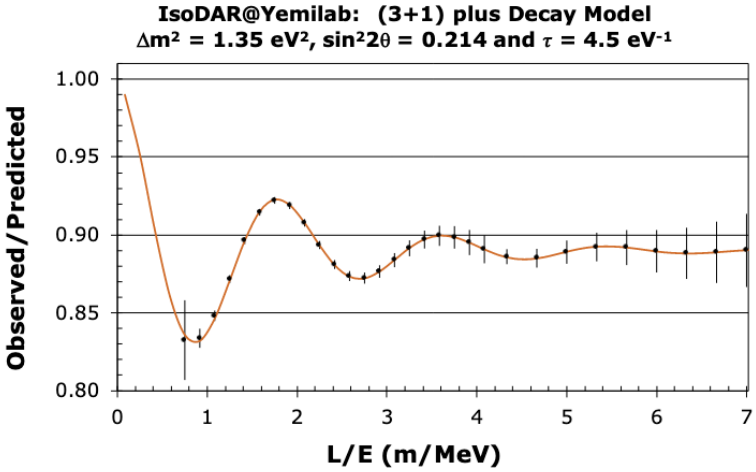
(3+1) ν


IsoDAR@ Yemilab: Δm^2 = 1 eV² and $\sin^2 2\theta$ = 0.1

(3+2) ν


IsoDAR@Yemilab: (3+2) Model
with Kopp/Maltoni/Schwetz Parameters

(3+1) ν + ν_s decay


IsoDAR@Yemilab: (3+1) plus Decay Model
Δm^2 = 1.35 eV², $\sin^2 2\theta$ = 0.214 and τ = 4.5 eV⁻¹

→ IsoDAR@Yemilab can well distinguish different new physics models.

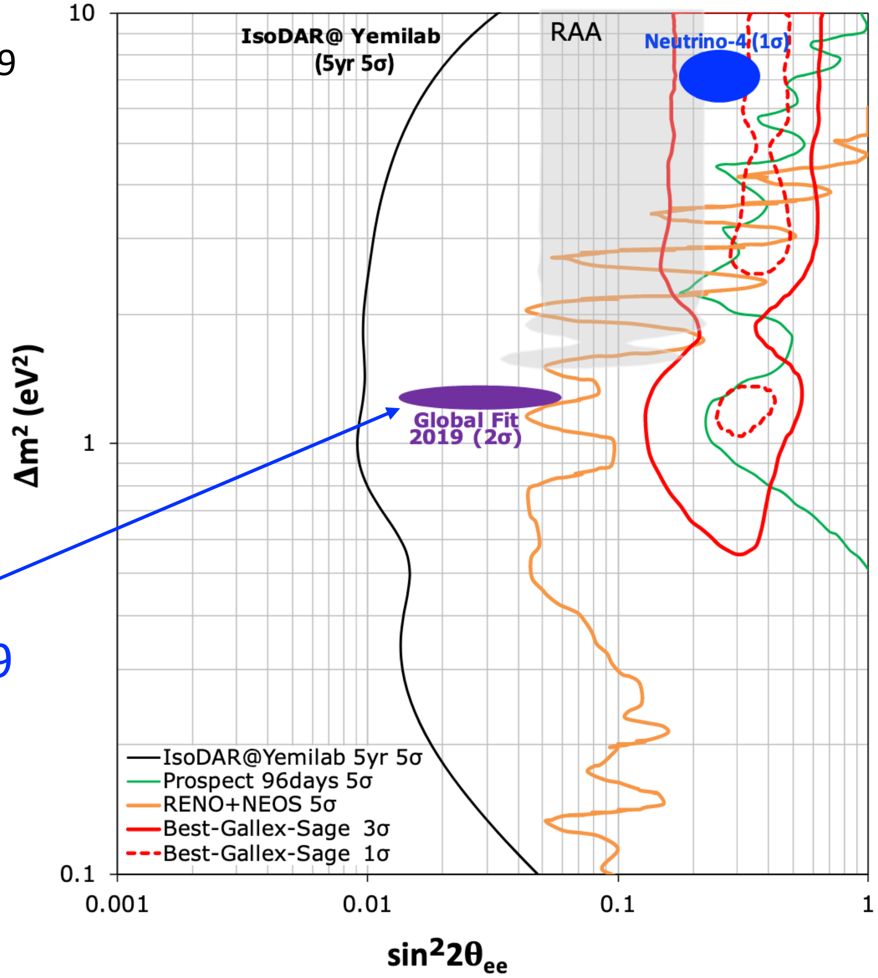
- The (3+1)+decay model significantly reduces the tension between appearance and disappearance experiments, improving the global-data goodness-of-fit.

1910.13456

Sterile neutrino search Sensitivity

IsoDAR @Yemilab $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$

arXiv:2111.09480
PRD 105 (2022) 5, 052009



Global Fit 2019

- World-leading result
- Definite conclusion on (3+1) ν or not

Advantage:
Unlike reactor/accelerator ν, IsoDAR has very well defined ν flux and shape.

keV Sterile ν

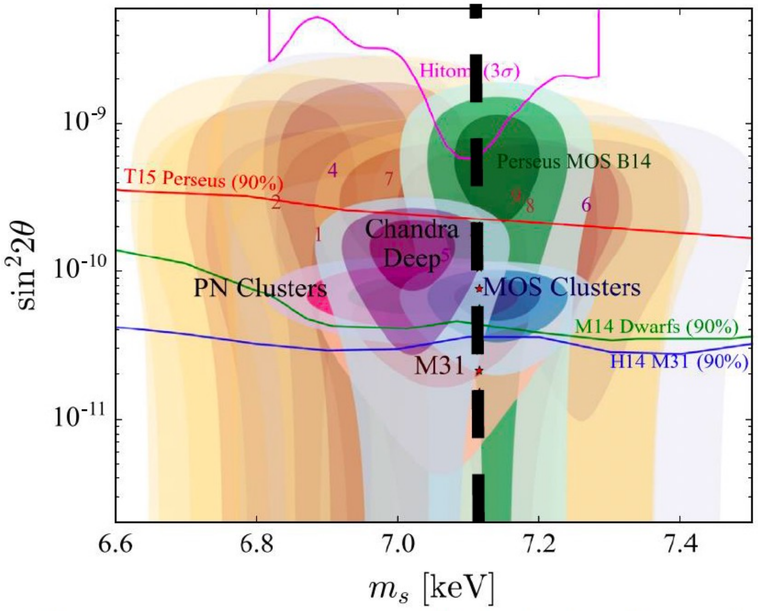
keV sterile ν → good candidate of warm DM

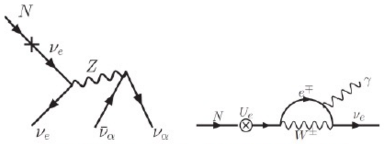
If purely keV sterile ν DM → $m_\nu > 0.4$ keV

"Light" keV Searches (1 – 10 keV) – Hints?

Kyle Leach
@Nu2022

- Few keV mass neutrinos are strong WDM candidates
- Deep-field X-ray measurements of galactic clusters *hint* at a 3.5 keV line





R. Adhikari et al., JCAP **25** (2017)

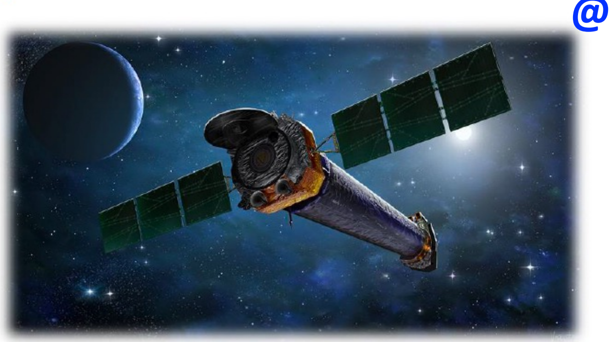


Image Courtesy: Chandra/NASA

7.1 keV neutrino?

N. Cappellutiet al., Astrophys. J **854**, 179 (2018)
F.A. Aharonian et al., Astrophys. J **837**, L15 (2017)
A. Boyarsky et al., Phys. Rev. Lett. **113**, 251301 (2014)

Or something else?

Dessert *et al.*, Science **367**, 1465–1467 (2020)

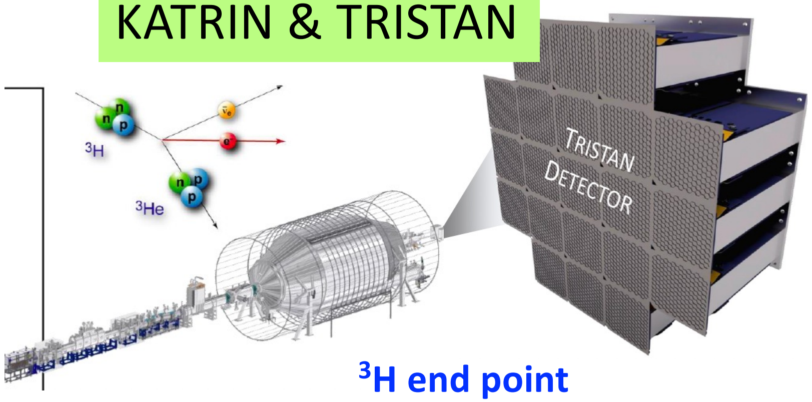
Image Courtesy: HITOMI/NASA

These measurements provide intriguing hints of new physics, BUT we need model independent measurements across a wide mass range for definitive searches….

Here is where the power of beta decay plays a major role!

keV Sterile ν Search Experiments

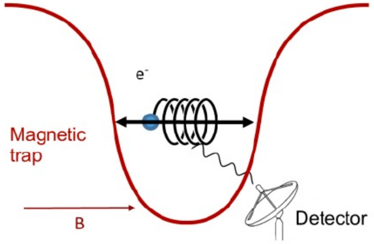
KATRIN & TRISTAN



^{3}H end point

PROJECT-8

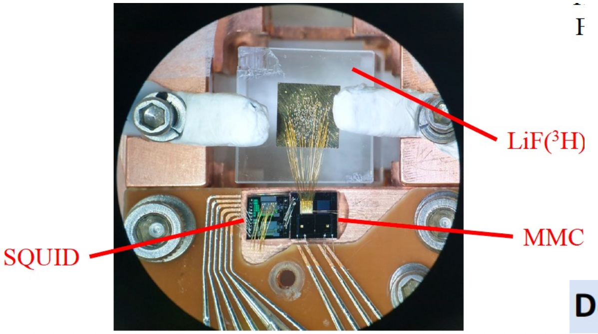
^{3}H end point

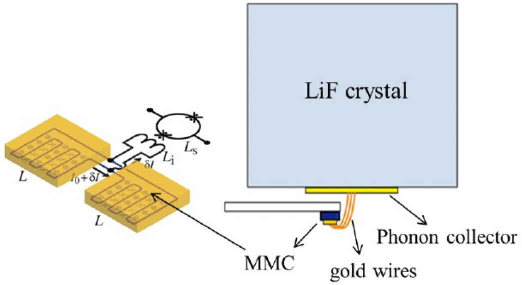


CUP Tritium Exp.

^{3}H end point

LiF + MMC

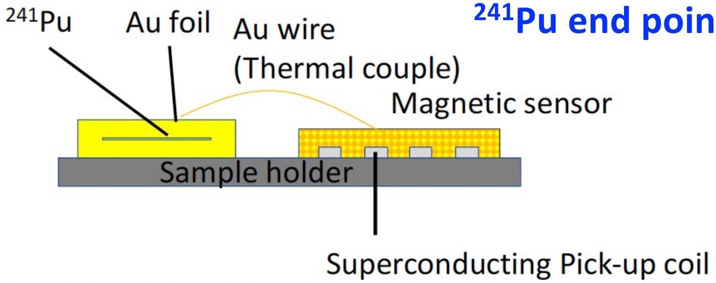




MAGNETO-ν

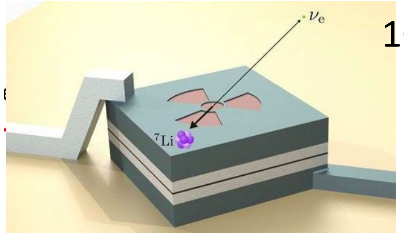
Detector: Magnetic Quantum Sensors with Gold foils

^{241}Pu end point

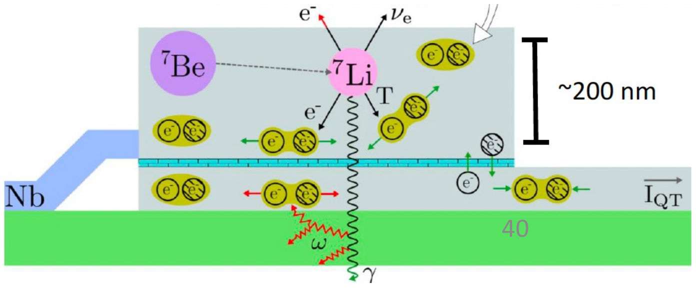


BeEST

EC decay of ^{7}Be



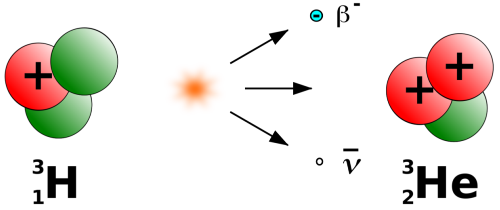
10~100 keV



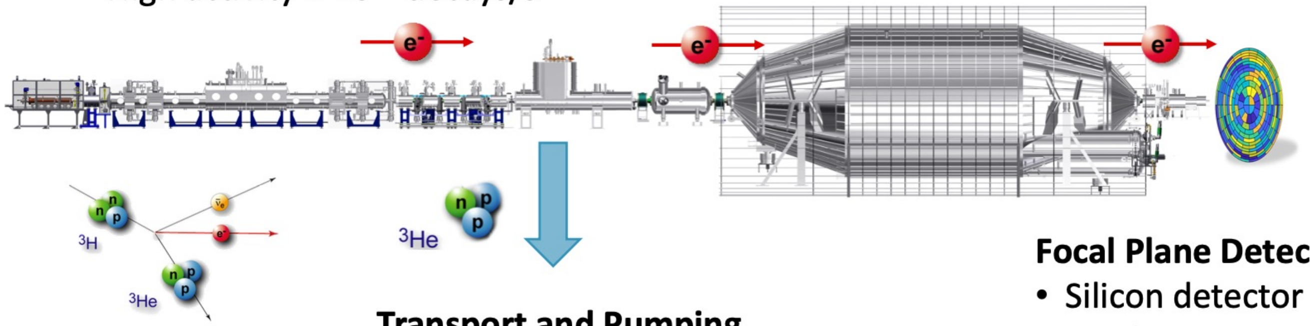
KATRIN

Tritium β Decay

$\tau_{1/2}$ (^{3}H) = 12.3 yrs



Q-value (E_0): 18.57 keV



Tritium Source

- 95% gaseous T_2
- High activity $2 \cdot 10^{10}$ decays/s

Spectrometer

- MAC-E filter → High pass filter
- Energy resolution 2.7 eV

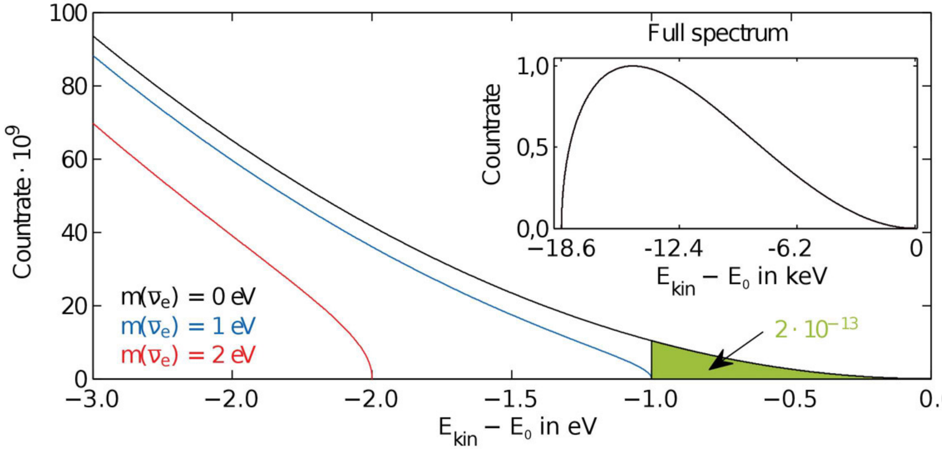
Transport and Pumping

- Transport of electrons
- Rejection of tritium ions

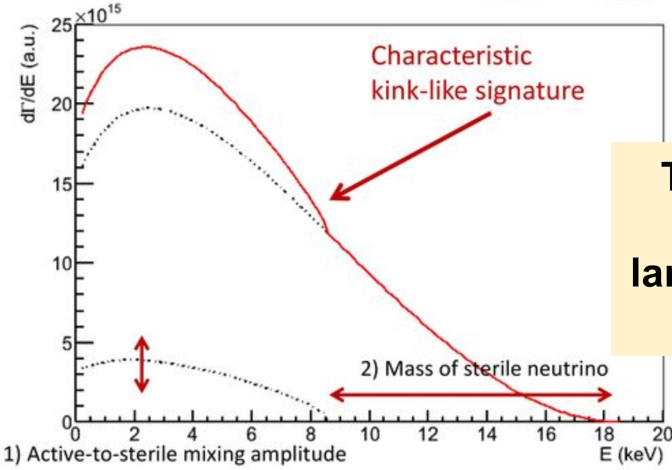
Focal Plane Detector

- Silicon detector
- 117/148 pixels used
- Counts electrons

If $m_\nu = 0$, then β^- end point is 18.57 keV.



$$\frac{dN}{dE} = \cos^2\theta \frac{dN}{dE}(m_{\nu,active}) + \sin^2(\theta)^{1)} \frac{dN}{dE}(m_{\nu,s})^{2)}$$



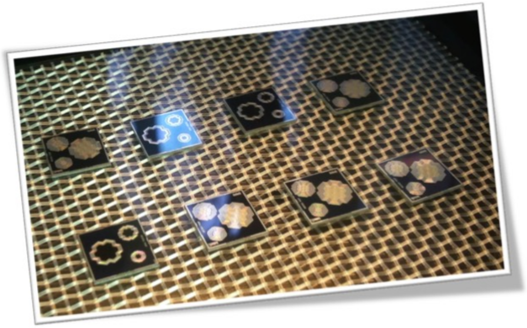
The count rate will be orders of magnitude larger than in the normal KATRIN operation

TRISTAN

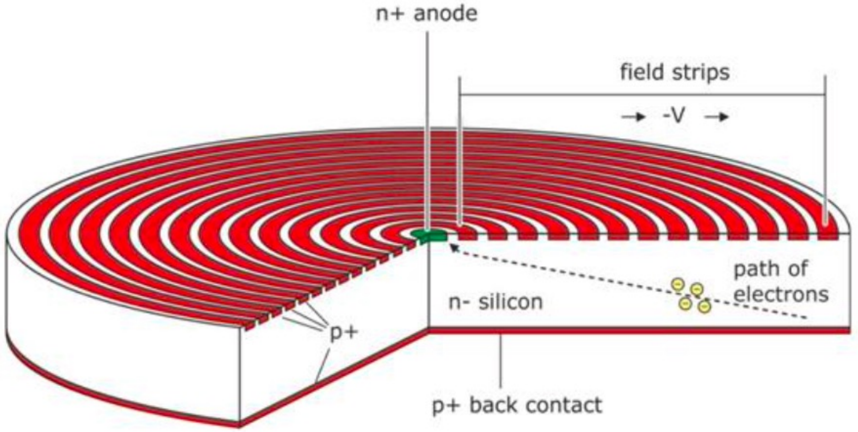
- To handle high statistics: >100 MHz
- To measure entire spectrum w/ extremly small systematic uncertainty
- Good energy resolution (300 eV @200 keV)
- Low threshold: 1 keV

☐ Phase-0: using existing KATRIN
☐ Phase-1: new detector system

Prototype

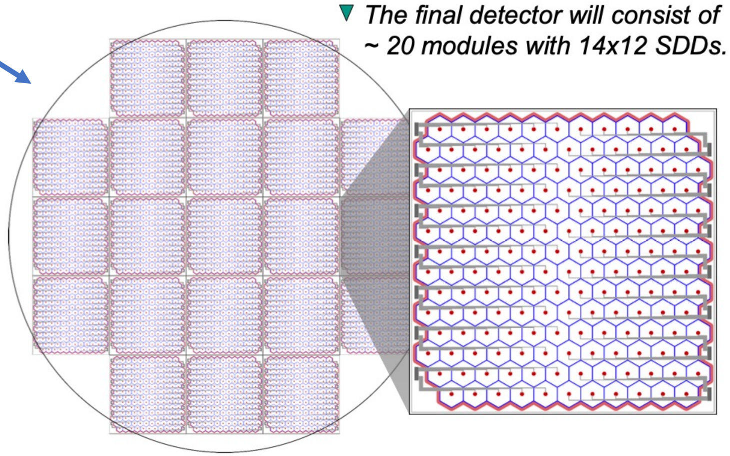


Silicon Drift Detector



Final detector

Install in 2023



The final detector will consist of ~ 20 modules with 14x12 SDDs.

keV Sterile ν Searches: Conclusion & Outlook

Kyle Leach
@Nu2022

- Nuclear decay provides a powerful, model-independent probe in the keV – MeV mass range

- Significant progress in measurements over the past 3 years – enabled by quantum sensing

- Experiments poised to increase sensitivity by 5+ orders of magnitude in the next decade

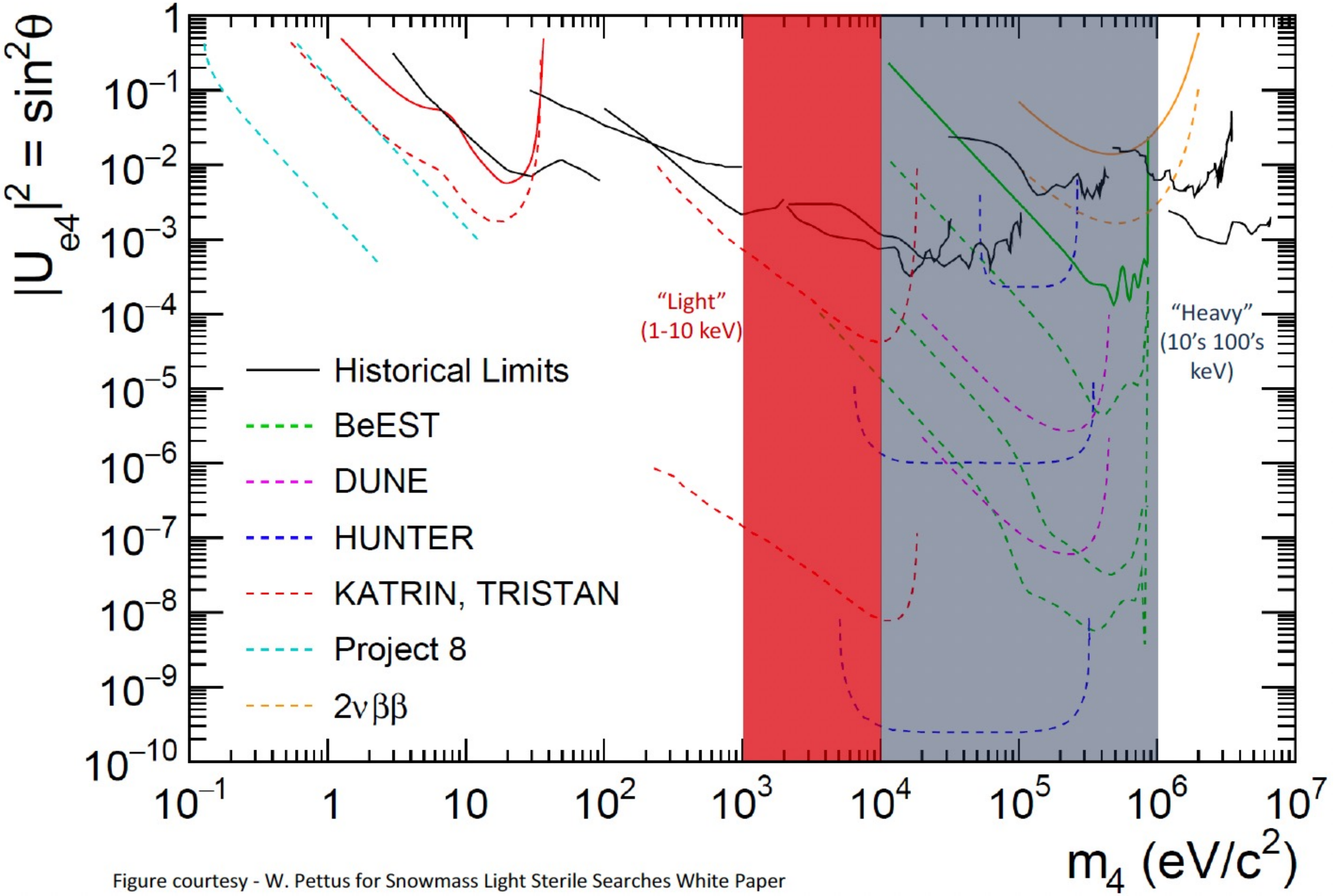


Figure courtesy - W. Pettus for Snowmass Light Sterile Searches White Paper

Takeaway Message

- ☐ ν oscillation physics has been very successful in the past and present.

- ☐ Precise measurements of oscillation parameters are needed.

  JUNO: $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ → < 1 % level (6 yrs data)

- ☐ DUNE and Hyper-K will measure CPV and ν mass ordering w/in 15 yr.

- ☐ Sterile ν (~eV scale) scenario will be checked by (near-)future exp.

- ☐ keV sterile neutrino is still one of candiates of DM.

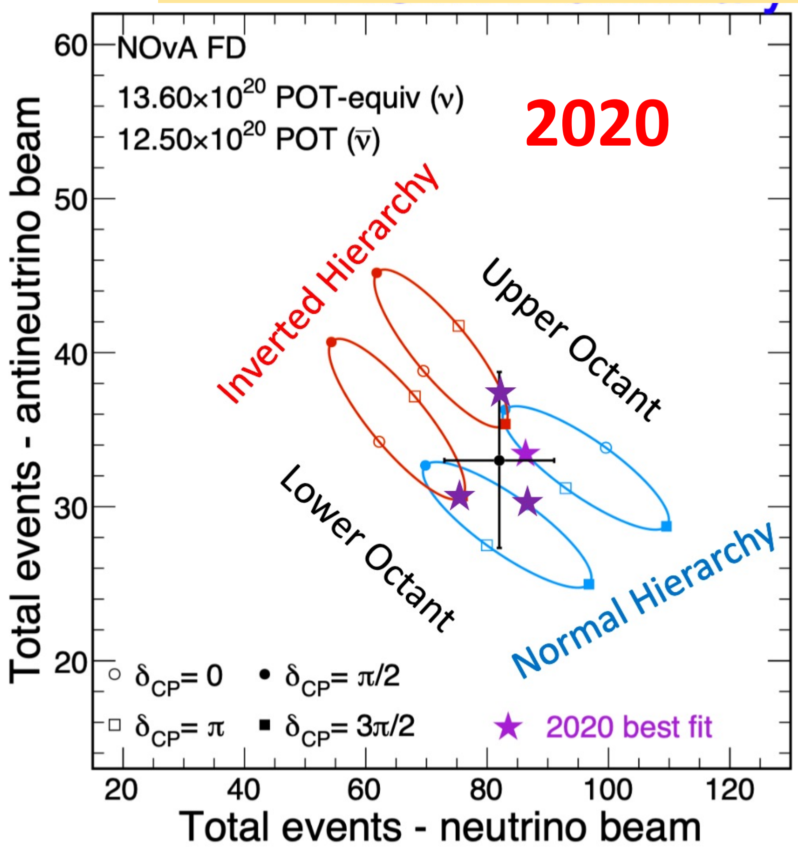
  → Direct searches are pursued by many current/future lab experiments.

Backup Slides

Recent Results on CP, MO

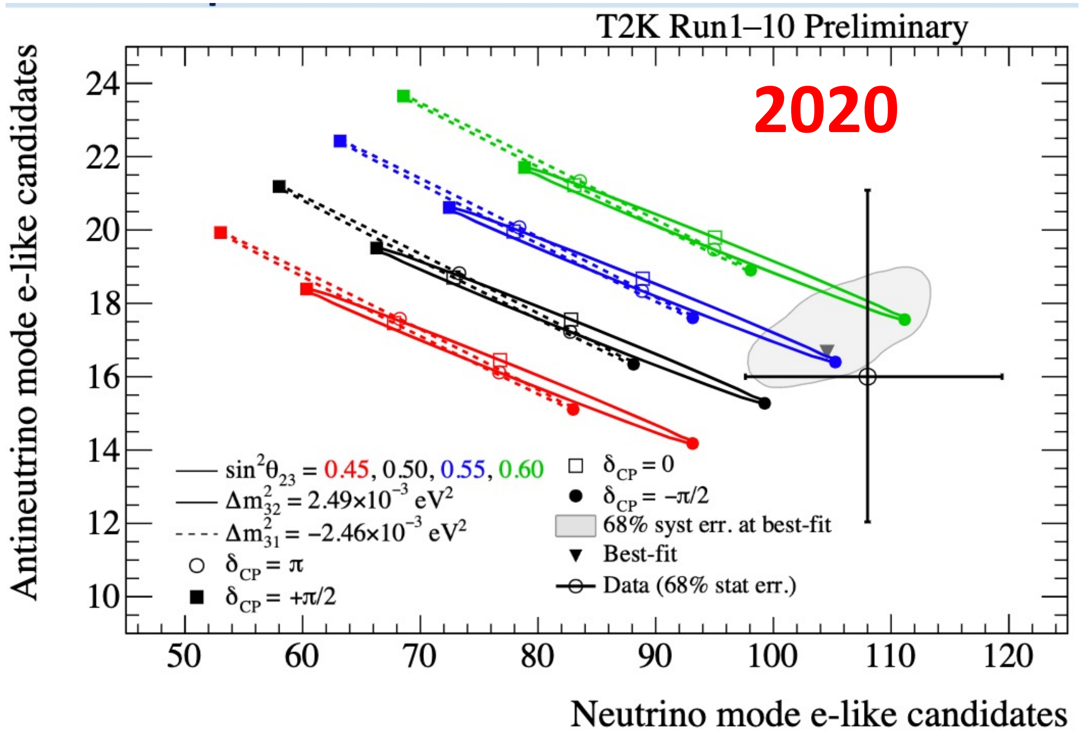
NOvA

Neutrinos: 13.6 x 10^{20} POT
Anti-nu : 12.5 x 10^{20} POT



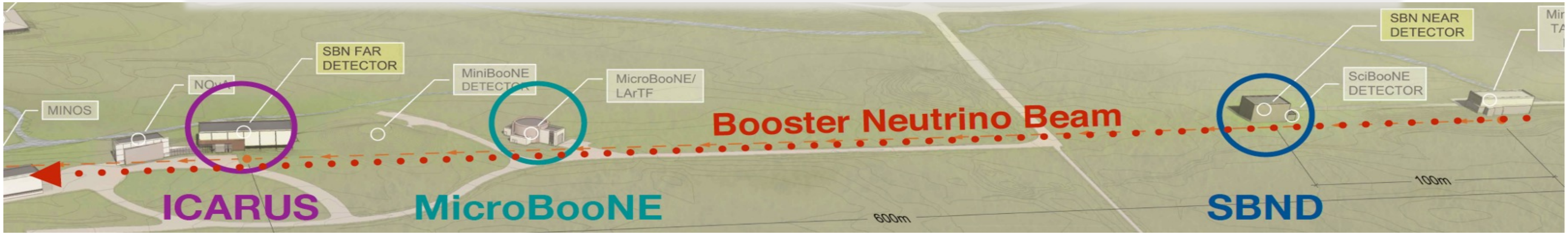
T2K

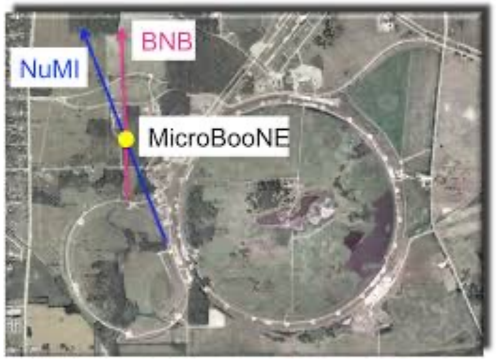
Neutrinos: 19.7 x 10^{20} POT
Anti-nu : 16.3 x 10^{20} POT

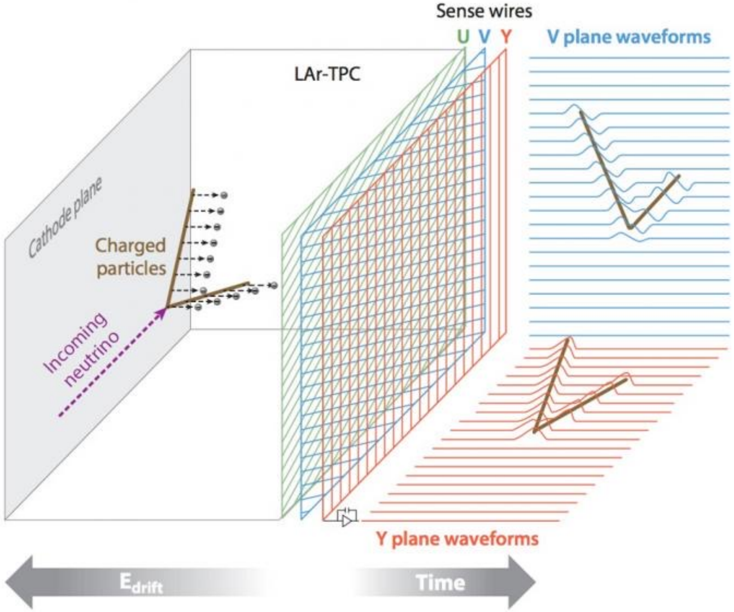


Statistical error dominant !

MicroBooNE







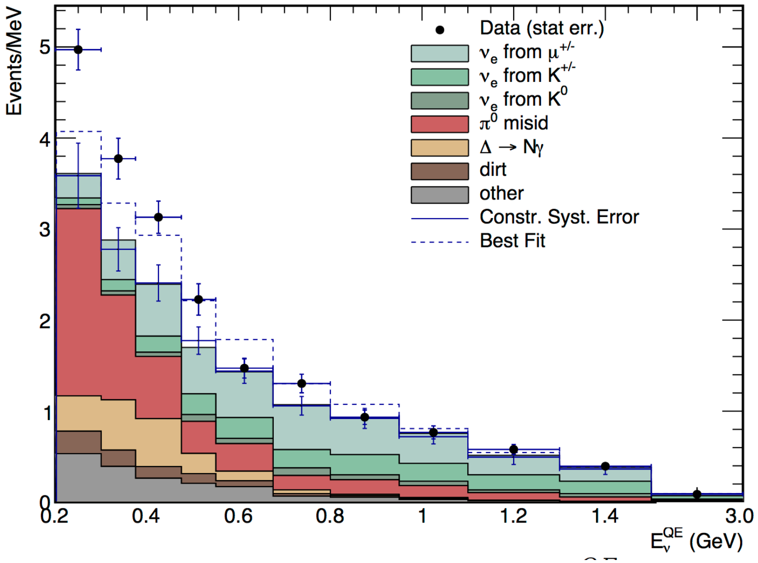
LArTPC

- LAr: 150 ton (80 ton active)
- TPC: 3 wire planes
  (2.5 x 2.3 x 10.4 m^3)
  total 8256 wires

- ➢ Data taking: 2015 – 2019?
- ➢ Total **~1.32 x 10^{21} POT**

➢ MicroBooNE can distinguish e$^-$ and γ.

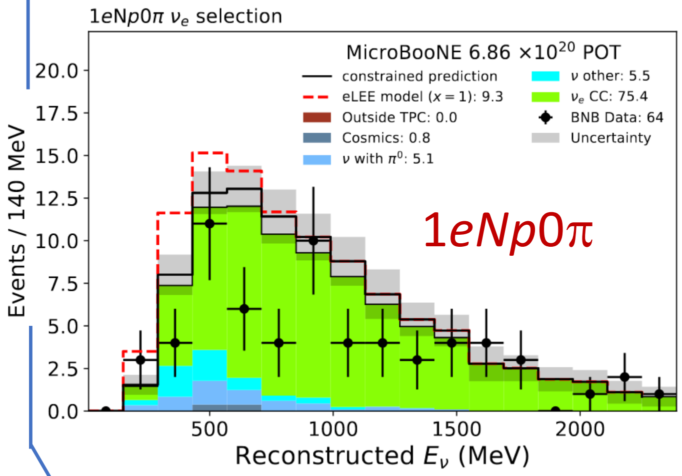
MiniBooNE

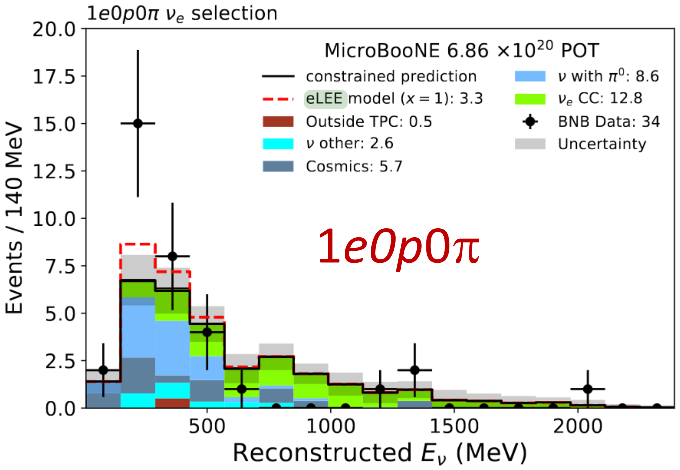


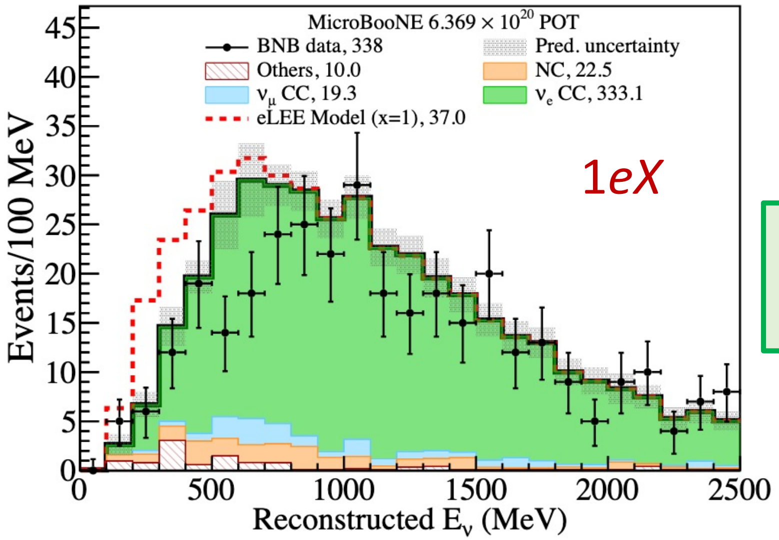
- ➢ Data taking: 2002 - 2019
- ➢ Total **~3 x 10^{21} POT** (1.66 : 1 in $\nu : \bar{\nu}$)

MicroBooNE

arXiv:2110.14054





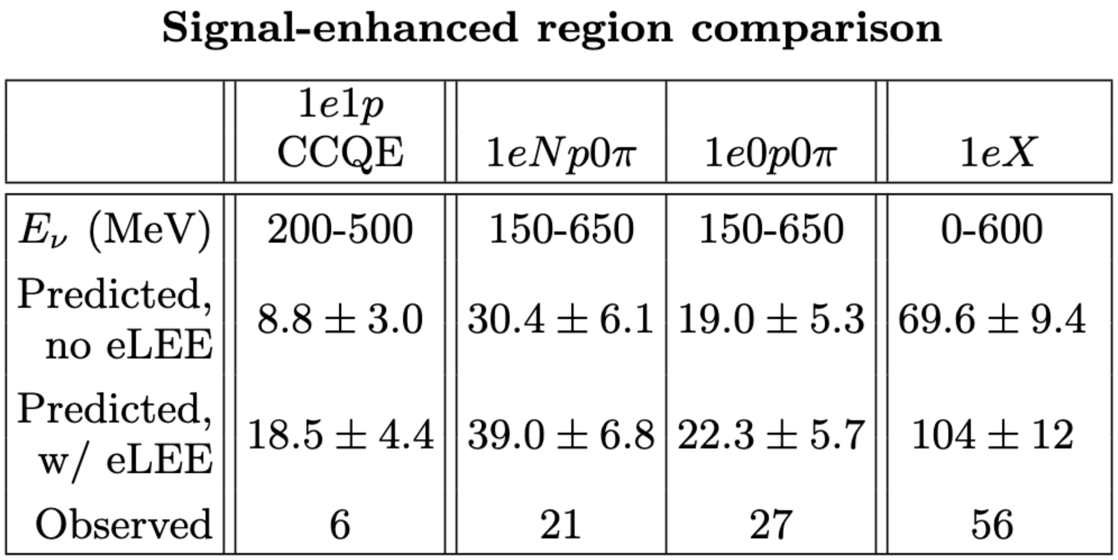


6.86 x 10^{20} POT
ν data

(50 % data)

MicroBooNE

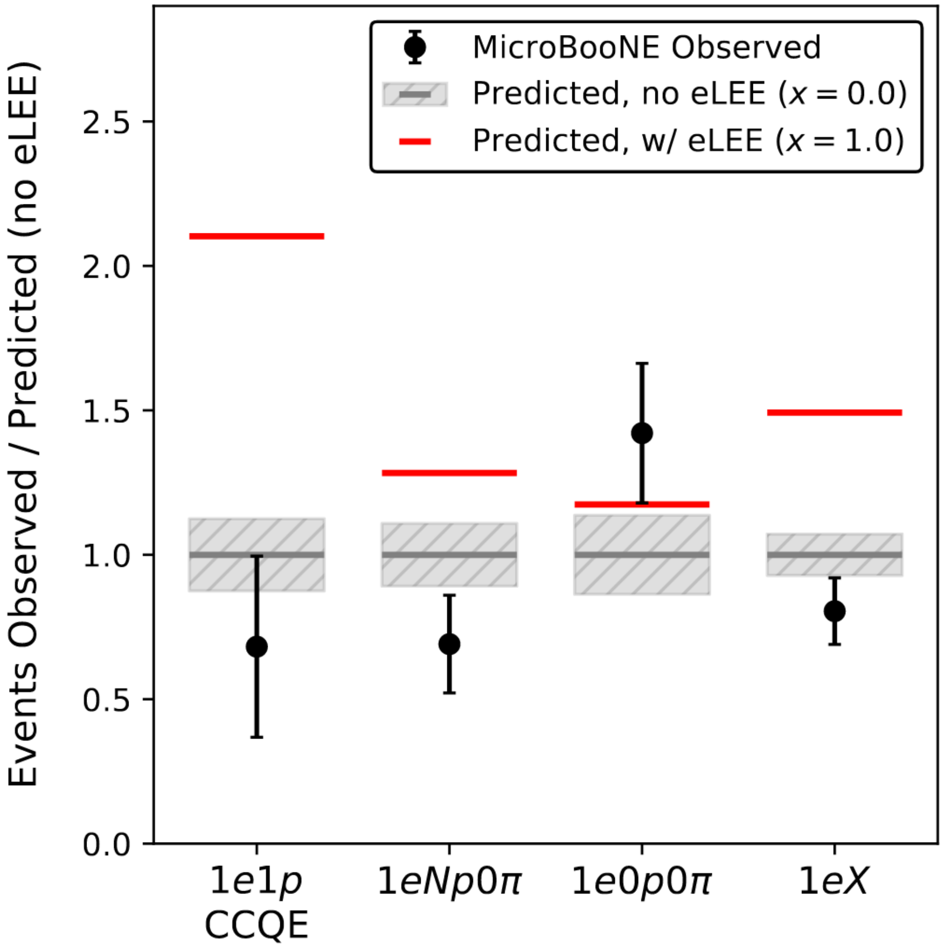
arXiv:2110.14054



Signal-enhanced region comparison

	1e1p CCQE	1eNp0π	1e0p0π	1eX
E_ν (MeV)	200-500	150-650	150-650	0-600
Predicted, no eLEE	8.8 ± 3.0	30.4 ± 6.1	19.0 ± 5.3	69.6 ± 9.4
Predicted, w/ eLEE	18.5 ± 4.4	39.0 ± 6.8	22.3 ± 5.7	104 ± 12
Observed	6	21	27	56

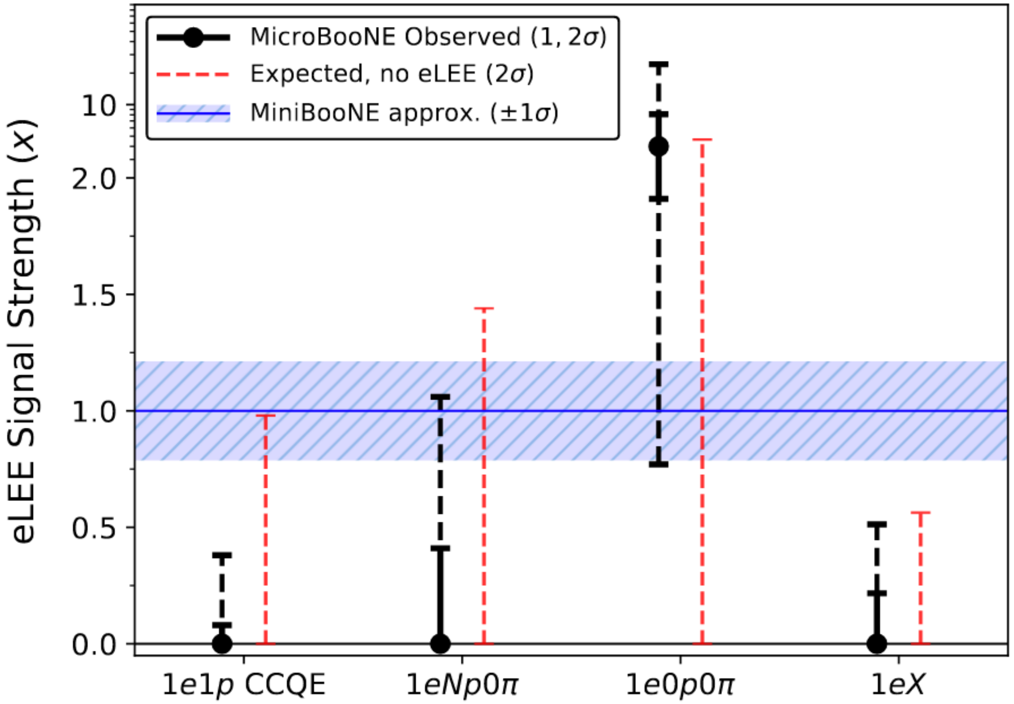
eLEE : e Low Energy Excess



- ❑ The expected event rate is dominated by intrinsic ν_e CC events originating from the **beamline**, rather than background events involving photons.

MicroBooNE

arXiv:2110.14054



- MicroBooNE rejects the hypothesis that ν_e CC interactions are fully responsible for that excess at > 97% CL for both exclusive (1e1p CCQE, 1eN p0π) and inclusive (1eX) event classes.

- Additionally, MicroBooNE disfavors generic ν_e interactions as the primary contributor to the excess, with a 1σ (2σ) upper limit on the inclusive ν_e CC contribution to the excess of 22% (51%).

- While the MiniBooNE excess remains unexplained, MicroBooNE sensitive measurements are so far inconsistent with a ν_e interpretation of the excess.

“Sterile Neutrino Searches with MicroBooNE: Electron Neutrino Disappearance”

arXiv:2111.05793

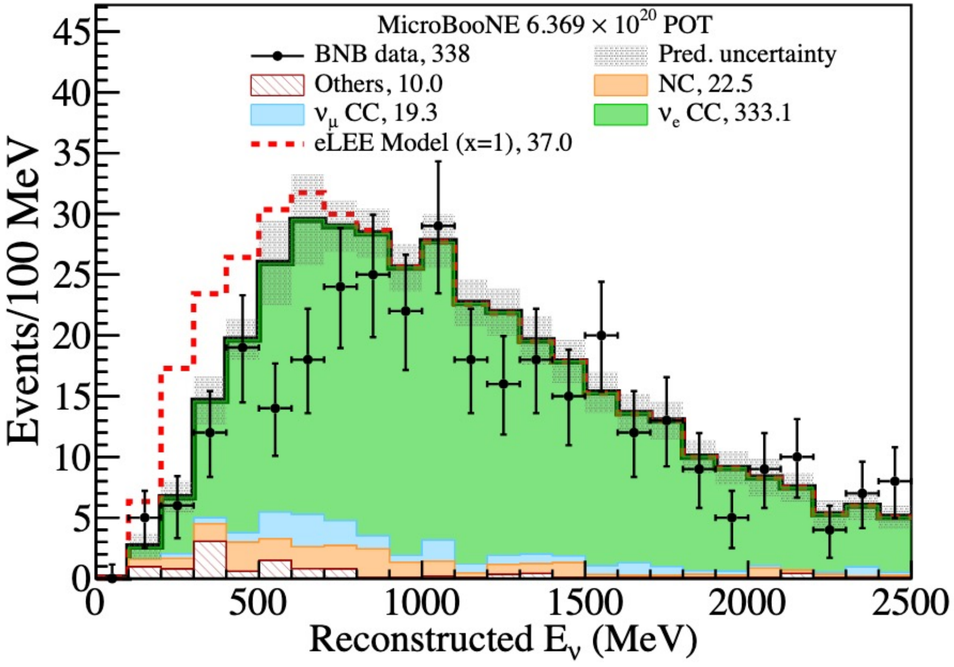
☐ Note the deficit was observed in 1*eX* channel.

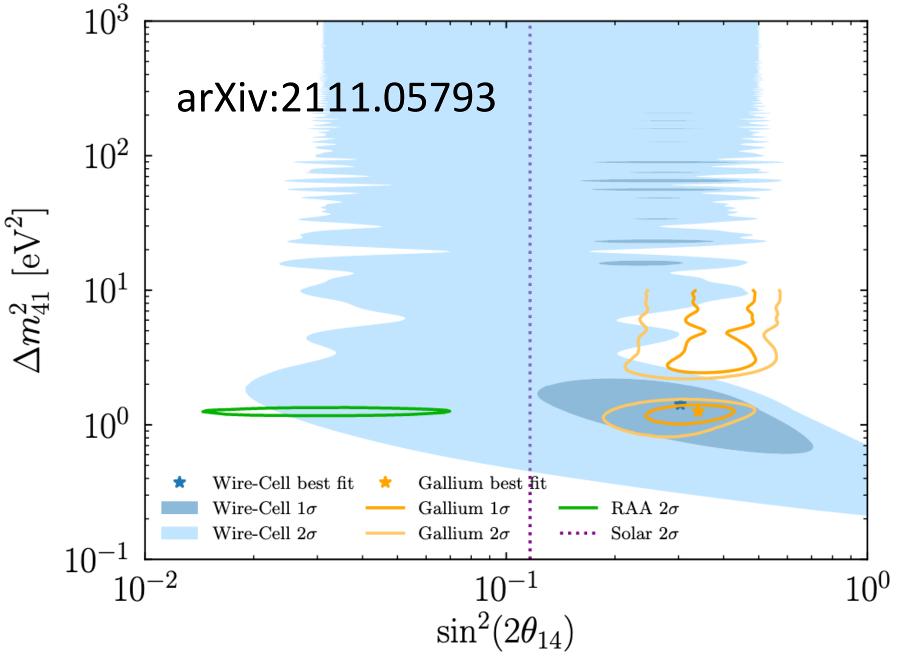
→ **ν_e disappearnce ?**

→ $\sin^2(2\theta_{14}) = 0.30$, $\Delta m_{41}^2 = 1.42$ eV^2 at 2.2σ

(* The other partially independent channels have compatible hints.)

1*eX* channel





→ **Or unmodelled inefficiencies cause the deficit ?**

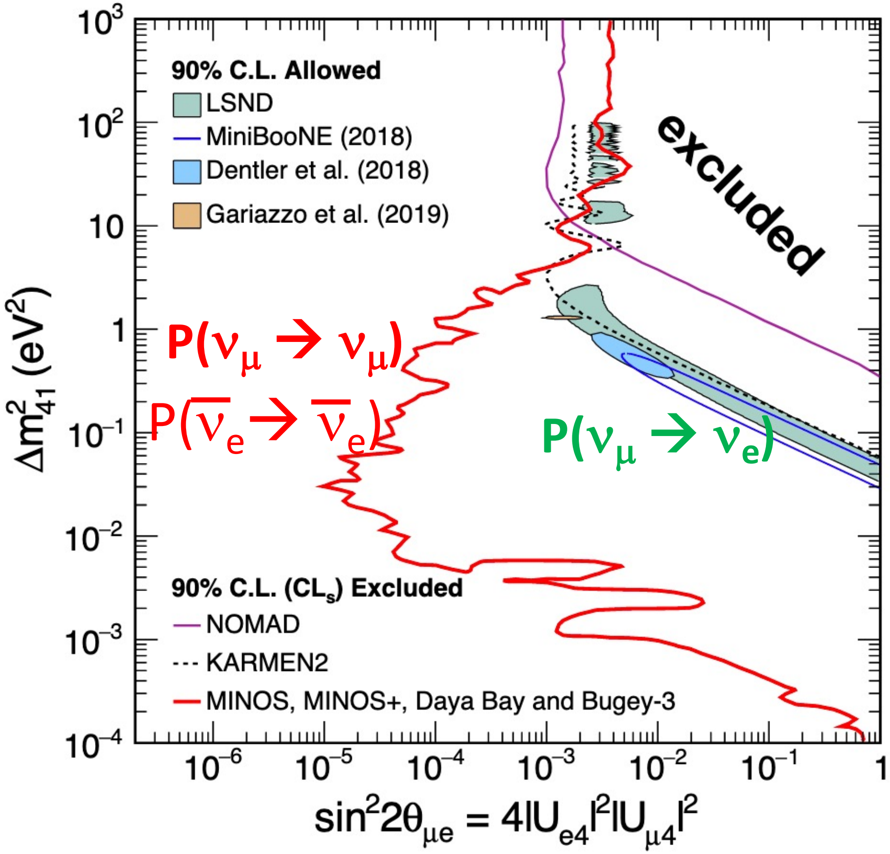
- Disagreement between MiniBooNE & MicroBooNE
- The tension between appearance and disappearance in the global fits
- The possible unmodeled source of photon-like signals in MiniBooNE

→ Need a more complex sterile ν model ?

(if new physics is indeed the source of the anomalous results)

➢ IsoDAR@Yemilab can test more complex sterile ν model.

PRL 125, 071801 (2020)



- Some disagreements between MiniBooNE & MicroBooNE
- The tension between appearance and disappearance channels

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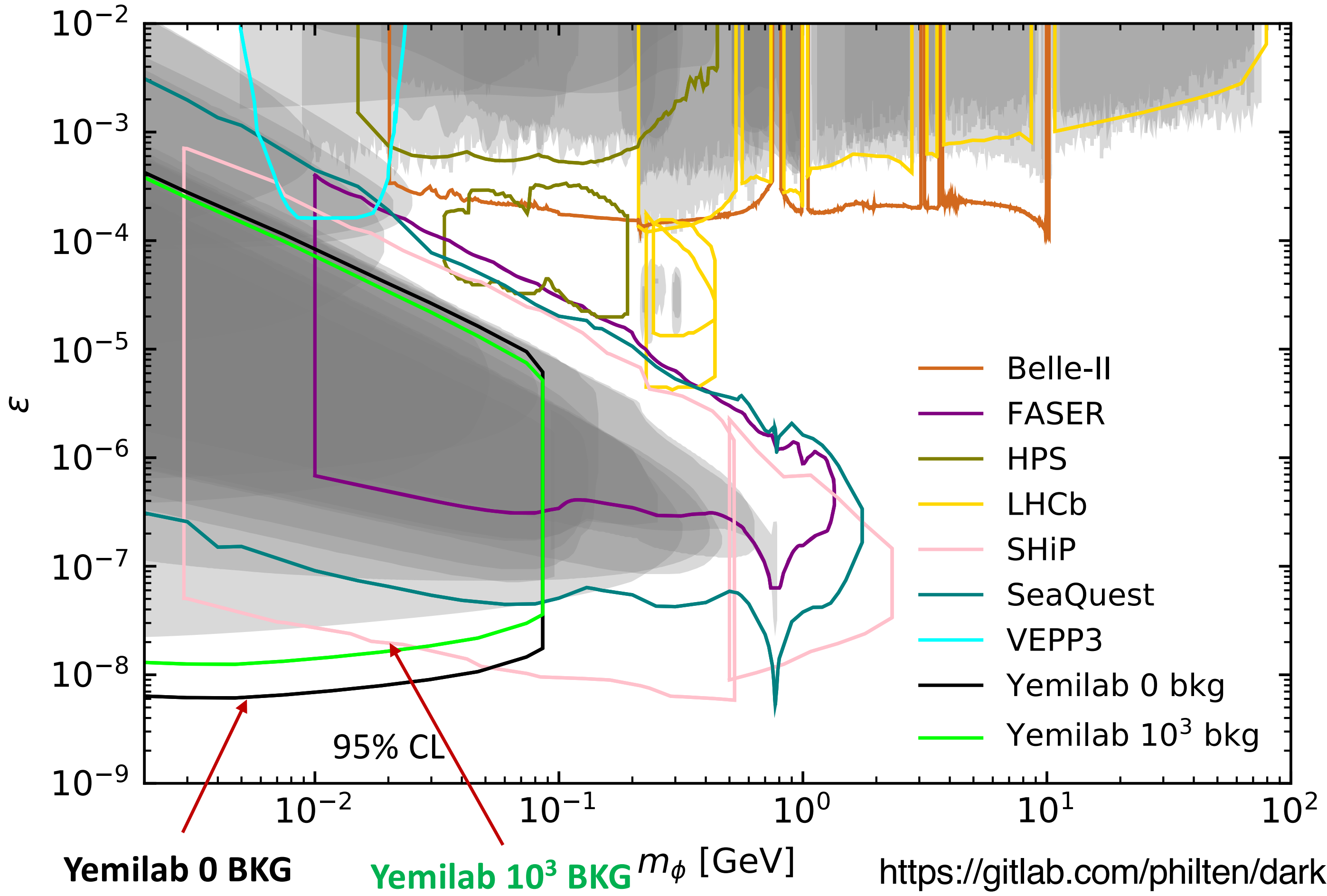
Current Limits & Future Projections

S.H. Seo & Y.D. Kim
JHEP04(2021)135



Yemilab 0 BKG

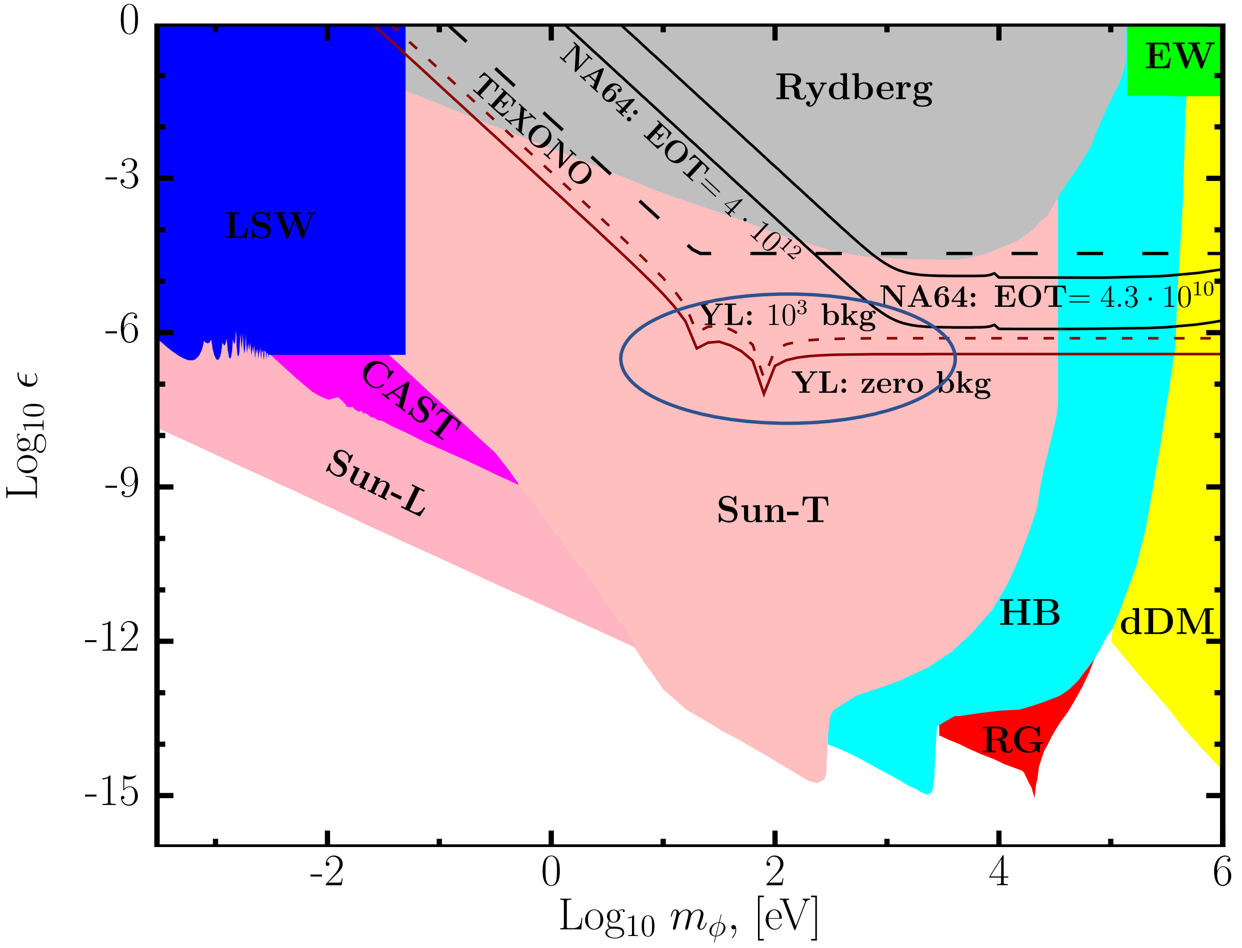
Yemilab 10^3 BKG

https://gitlab.com/philten/darkcast

Best “direct” DP search sensitivity in $M_\phi < 30$ MeV (10^3 BKG)

γ → A' Oscillation Sensitivity

S.H. Seo & Y.D. Kim
JHEP04(2021)135



$m_\phi < 1$ MeV

Best “direct” DP search sensitivity at sub-MeV region

Current & Future Longbaseline ν experiments

	T2K	**NOvA**	**DUNE**	**Hyper-K**	**T2HKK/KNO**
Beam	J-PARC	NuMi	NuMi	J-PARC	J-PARC
Beam power	**515 kW (in 2020)**	**700 kW**	**1.2 → 2.4 MW**	**1.3 MW**	**1.3 MW**
ν energy	< 2 GeV		< 8 GeV	< 2 GeV	< 2 GeV
Baselines	**280m/295km**	**1km/810km**	**1300 km**	**280m/295km**	**280m/1100km**
Off-axis angle	**2.5°**	**0.8°**	**on-axis**	**2.5°**	**1~3°**
Near Det.	ND280 (on-axis)		DUNE-Prism (on-/off-axis)	ND280 (on-axis)	ND280 (on-axis)
		0.3 kt			
Far Det.	Water Cherenkov	segmented sciintillator	LAr-TPC	Water Cherenkov	Water Cherenkov
	SK (50 kt)	14 kt	**4 x 17 kt**	**260 kt**	260 kt

operating

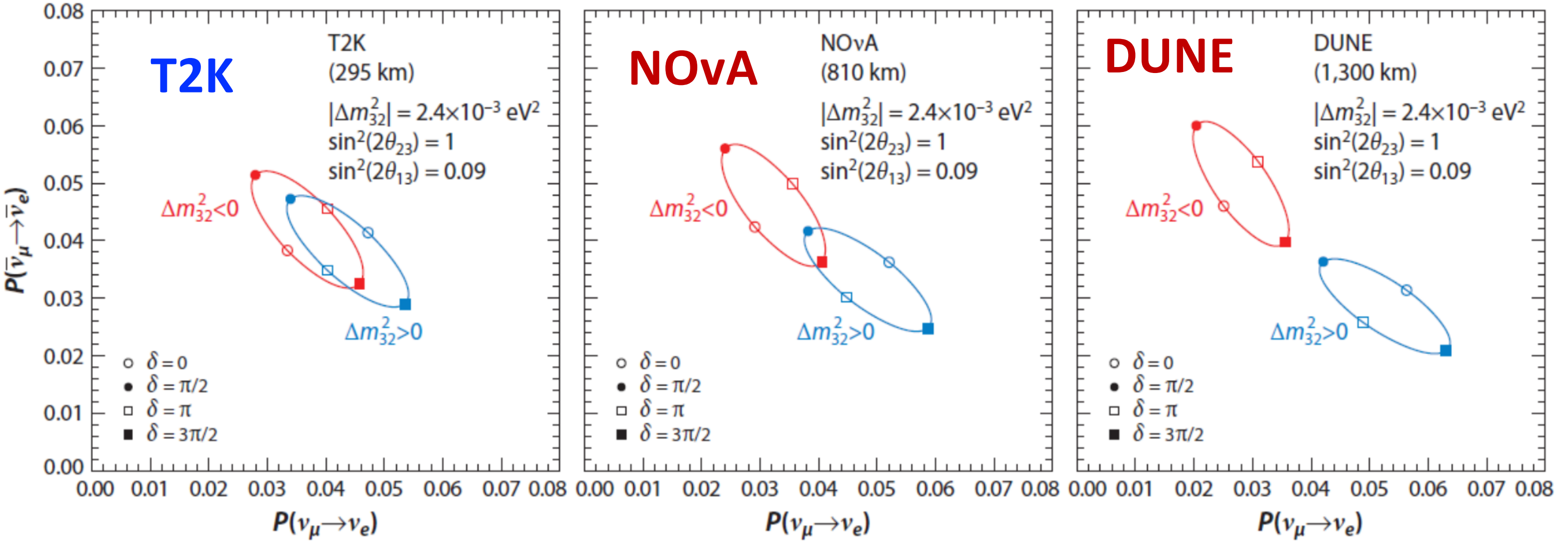
Construction phase

IWC detector for HK
(off-axis)

Leptonic CPV & MO in < 2040

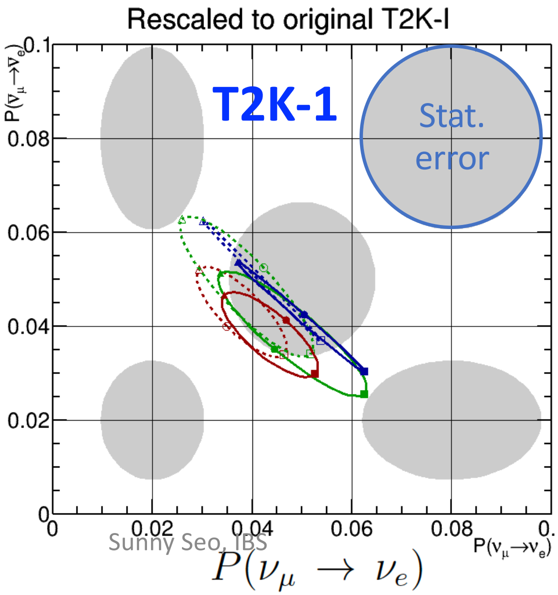
	HK: JD Beam ν	HK: JD + KD Beam ν	HK: JD + KD Beam+ atm. ν	DUNE Beam ν
Baseline	295 km	295 km + ~ 1100 km	295 km + ~ 1100 km	1300 km
Detector Fiducial Vol.	190 kton water	2 x 190 kton water	2 x 190 kton water	40 kton LAr
POT (run time, ν:$\bar{\nu}$)	2.7 x 10^{22} (10 yrs, 1:3)	2.7 x 10^{22} (10 yrs, 1:3)	2.7 x 10^{22} (10 yrs, 1:3)	556/ kt.MW.yr (10 yrs, 1:1)
δ_{CP} = $\pi/2$, $3\pi/2$ (known N.O.)	~ 8 σ	> 8 σ	> 8 σ	[7 σ, 8 σ]
δ_{CP} precision @ δ_{CP} = **$\pi/2$, $3\pi/2$**	22°	13~14°	~11°	~9°
δ_{CP} coverage (known NO)	~76 % at 3 σ	> 76 % at 3 σ	> 76 % at 3 σ	65 % at 3 σ
MO (true: NO)	> 1 σ for all δ_{CP}	> 6 σ for all δ_{CP}	> 7.5 σ for all δ_{CP}	> 8 σ for all δ_{CP}

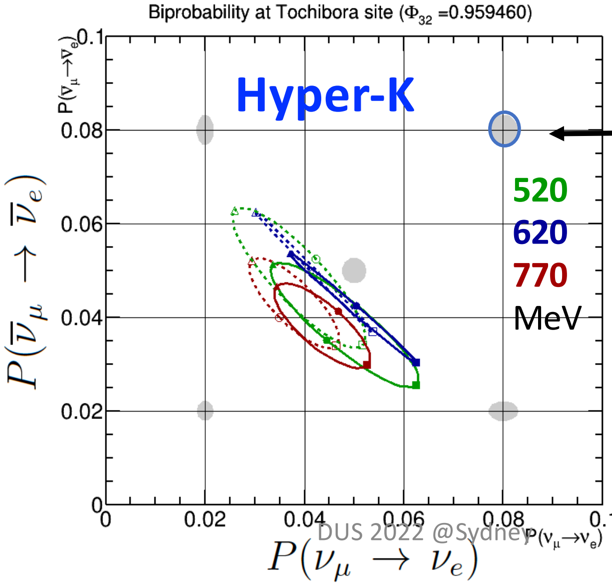
NH: enhance ν, suppress anti-ν IH: enhance anti-ν, suppress ν



More mater effects at DUNE

→ Better separation between NO & IO





Hyper-K improves statistics

Blue: Energy of peak QE rate
Red: median of high-energy tail
Green: “ “ low-energy “