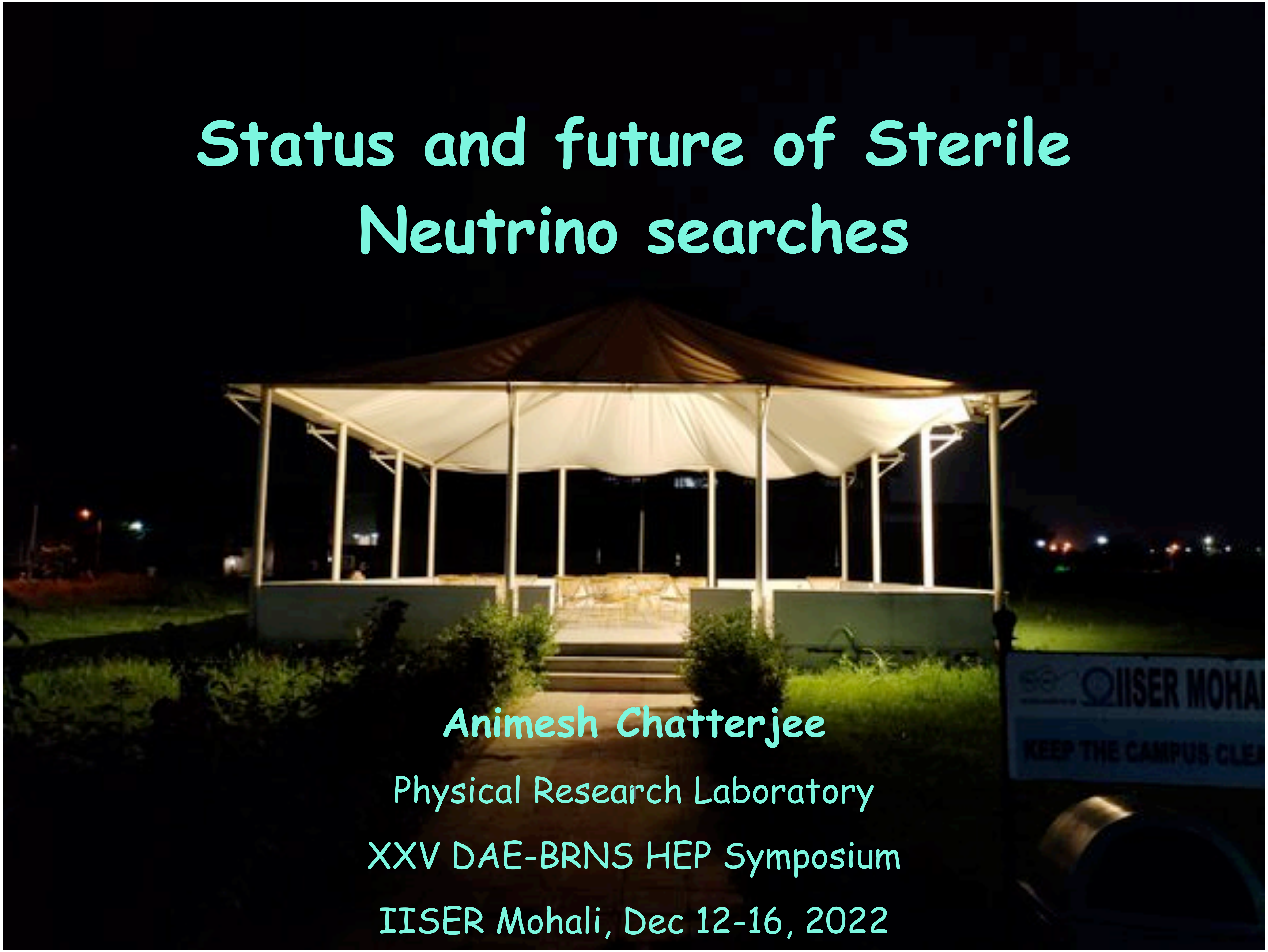
Status and future of Sterile Neutrino searches



Animesh Chatterjee

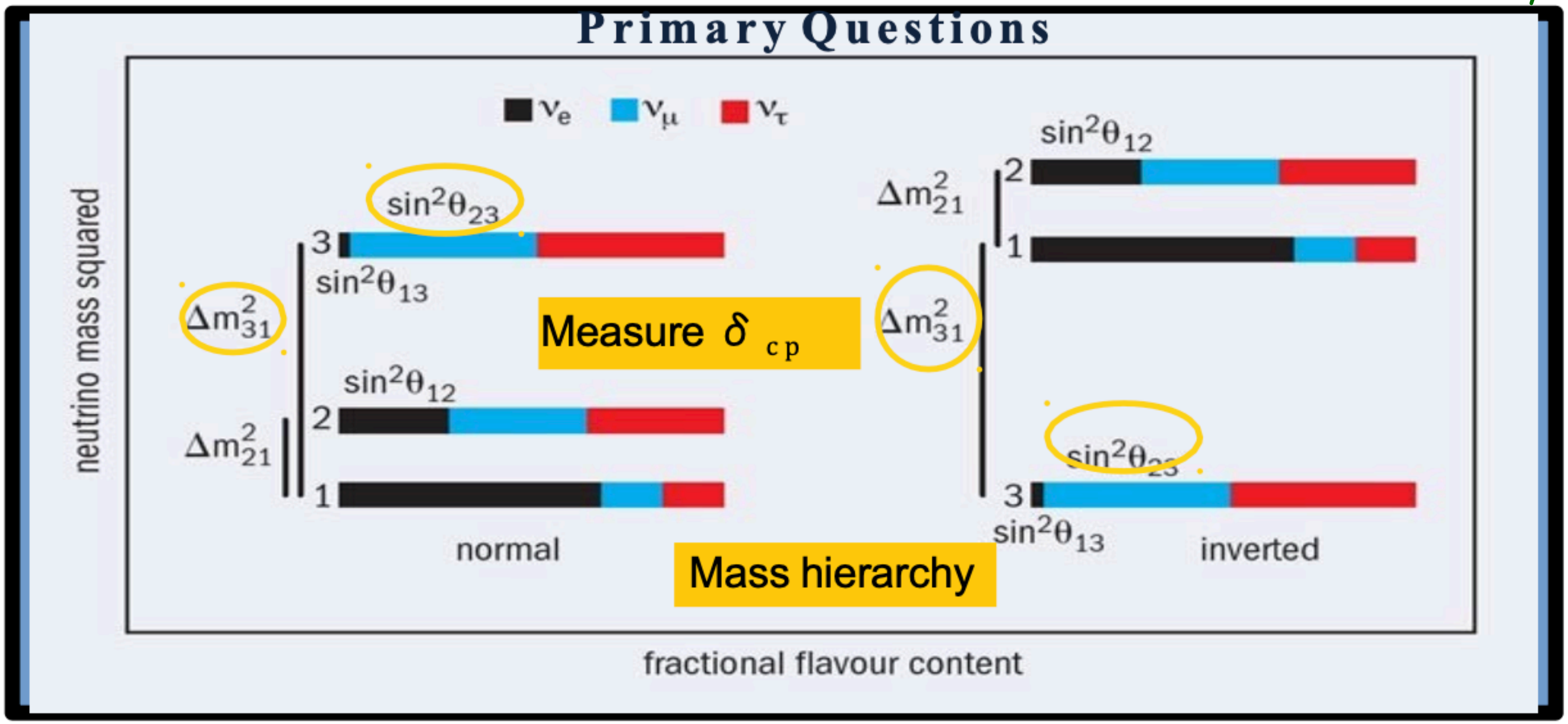
Physical Research Laboratory

XXV DAE-BRNS HEP Symposium

IISER Mohali, Dec 12-16, 2022

What we know so far about Neutrino Oscillations ?

Detailed talk by Rahul, Poonam



Neutrino mixing matrix :

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

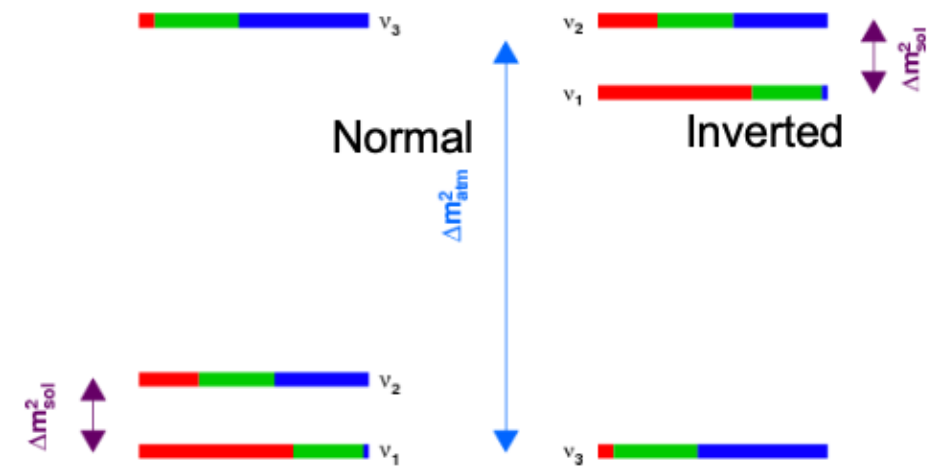
$|U_{e3}|$ (recent discovery)

Several decades of a rich program of experimental neutrino measurements have provided the resolution to decades-long experimental anomalies associated with solar and atmospheric neutrino measurement

Neutrino Oscillations : Primary questions ?

☑ ***ν mass hierarchy:***

> ★ *Are the states ν_1 & ν_2 heavier or lighter than ν_3 ?*



CP Violation:

> ★ $\delta_{CP} \neq (0,\pi)$?, *Neutrino and anti-neutrino asymmetry*

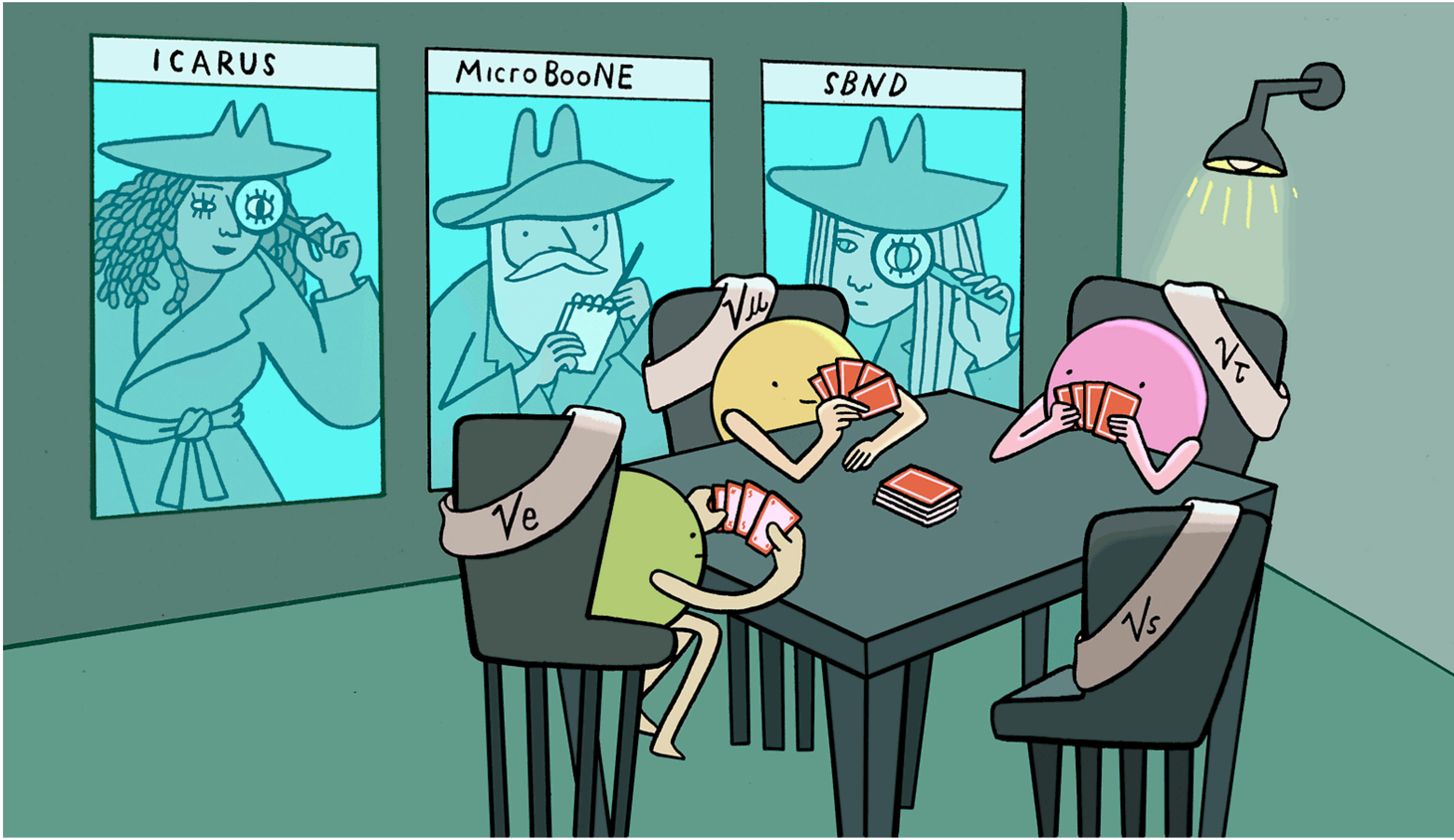
Octant of θ_{23}

> ★ $\sin^2\theta_{23} \neq 0.5$? *Non maximal mixing? If so, which way?*

Precision oscillation measurements !

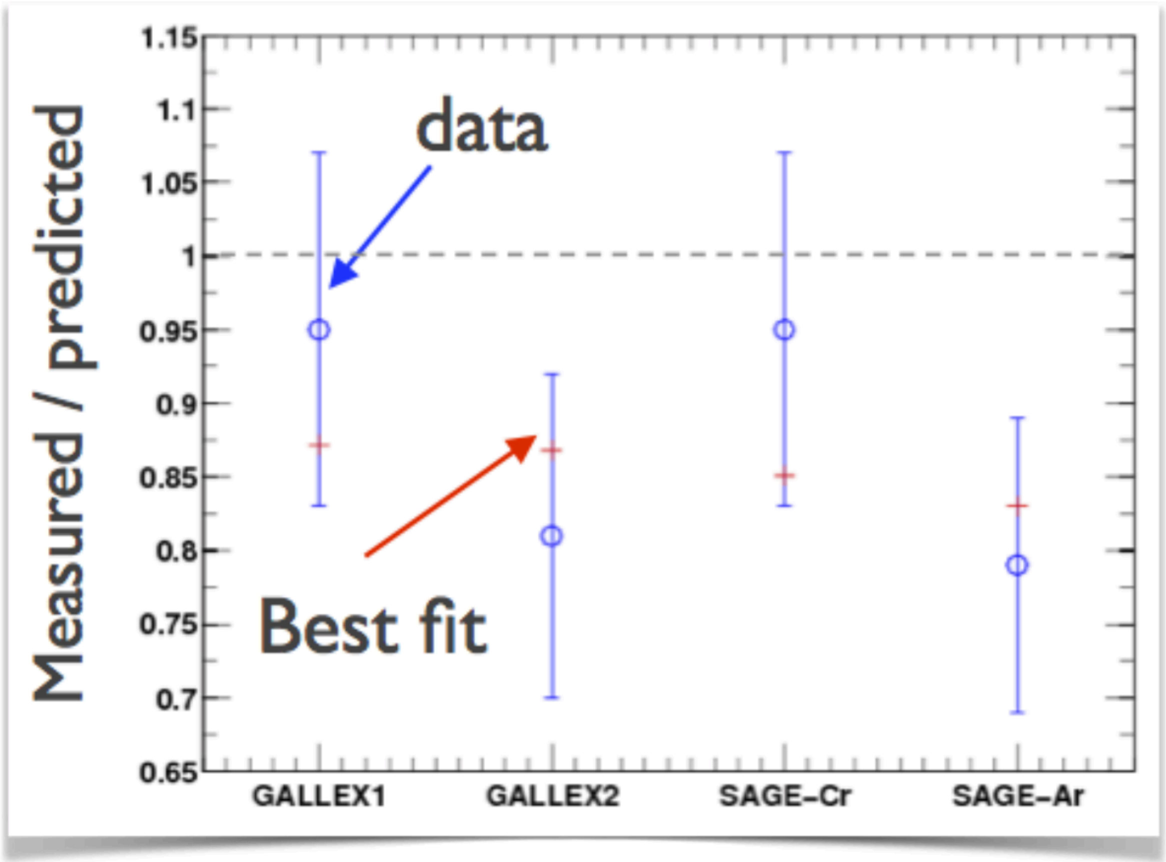
BUT experimental neutrino anomalies have been observed that still remain unresolved, and have served as primary drivers in the development of the next generation experiments.

Short Baseline Anomaly

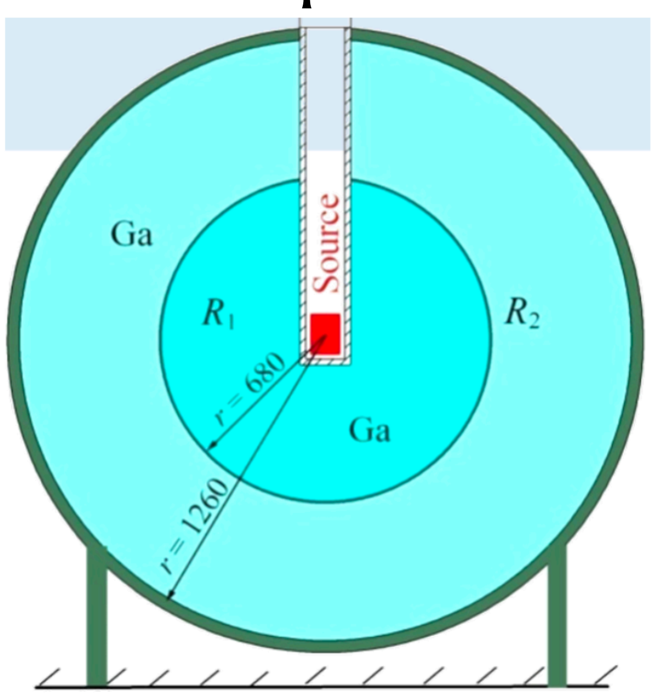


Anomaly #1 : the Gallium Anomaly

- The SAGE and GALLEX experiments designed to confirm neutrino oscillation from SUN
- Neutrino detection via
- $^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^-$
- The ratio of observed over expected ~ 0.86 ± 0.05 (~ 3σ deficit)
- ν_e disappearance into sterile state?
- Recently confirmed by BEST experiment (~4σ) BEST arXiv:2109.11482 , Barinov Gorbunov arXiv:2109.14654
- They found the ratio to be ~0.8, consistent with the SAGE and GALLEX



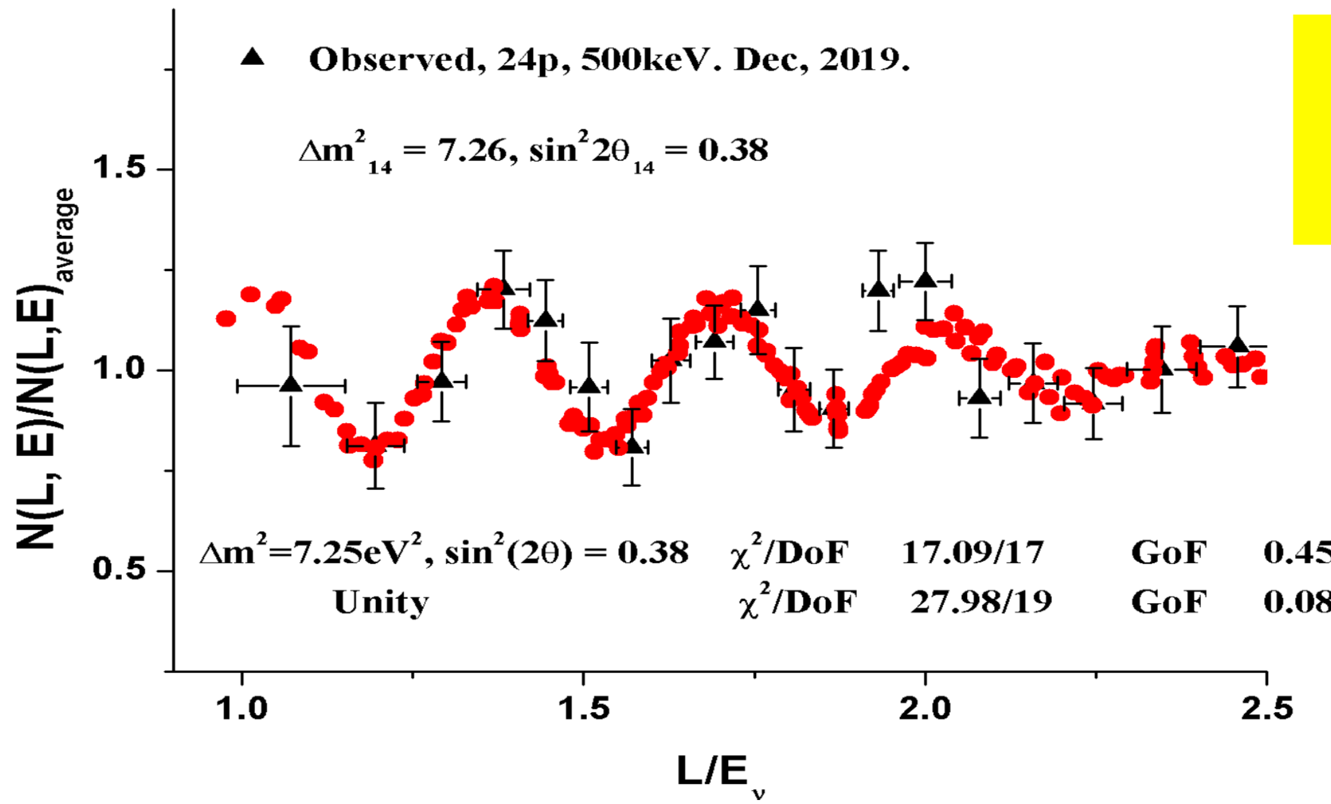
Best Experiment



Anomaly #2 : the Neutrino 4 experiment

- 100 MW thermal power SM-3 reactor
- Anti-neutrino detector (liquid scintillator) located at a distance of 5m from the reactor
- Measurement performed with the reactor ON/OFF condition, which provides antineutrino spectrum.

All data 2016 -2019 + background 20119



The period of oscillation for neutrino energy 4 MeV is 1.4 m

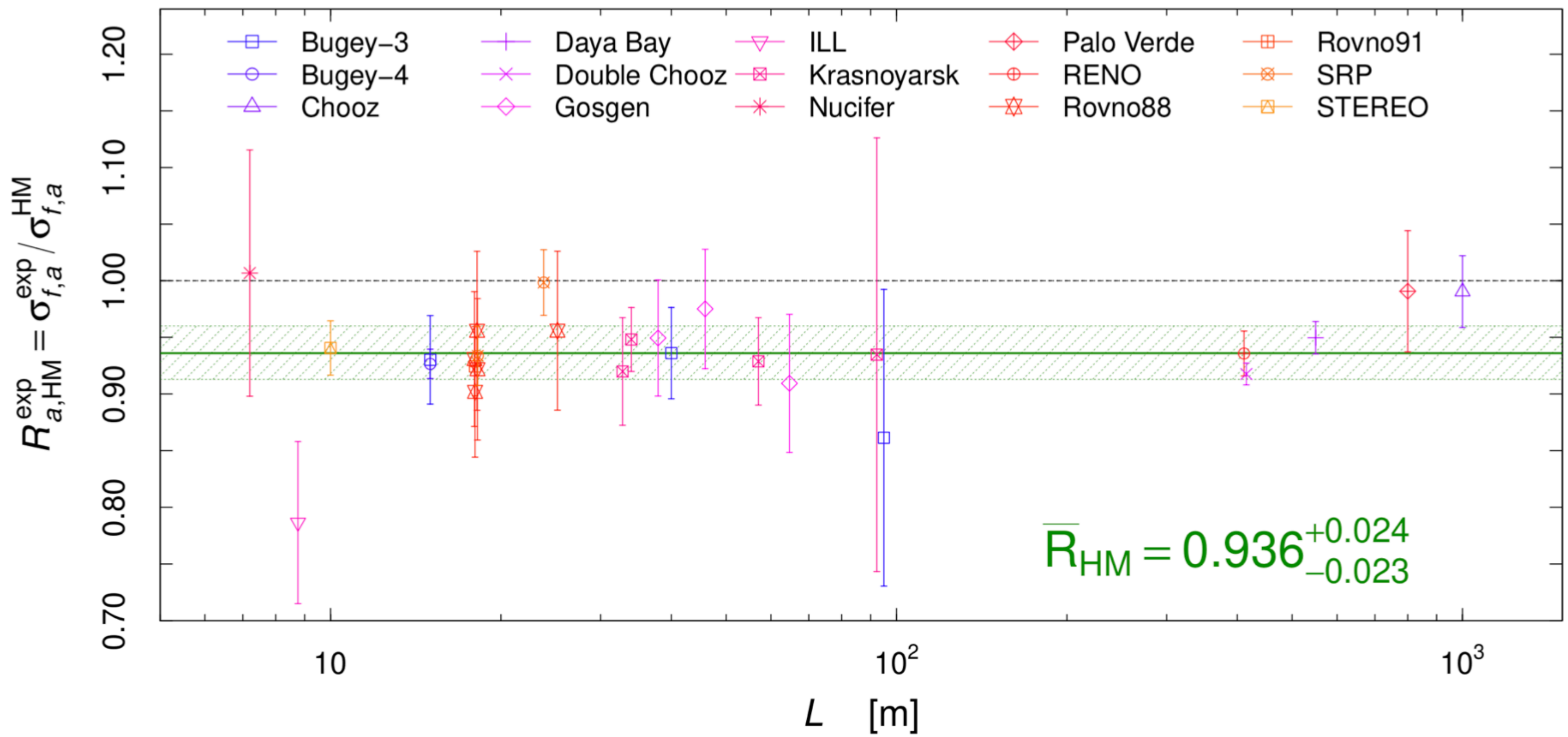
A.P.Serebrov, et al.
JETP Letters, Volume 109, Issue 4, pp 213–221.
arxiv:1809.10561

* No contradiction with Gallium Anomaly, the combined result of the Neutrino-4 and gallium anomaly gives

$$\sin^2 2\theta_{14} \approx 0.35 \pm 0.07\ (5.0\sigma)$$

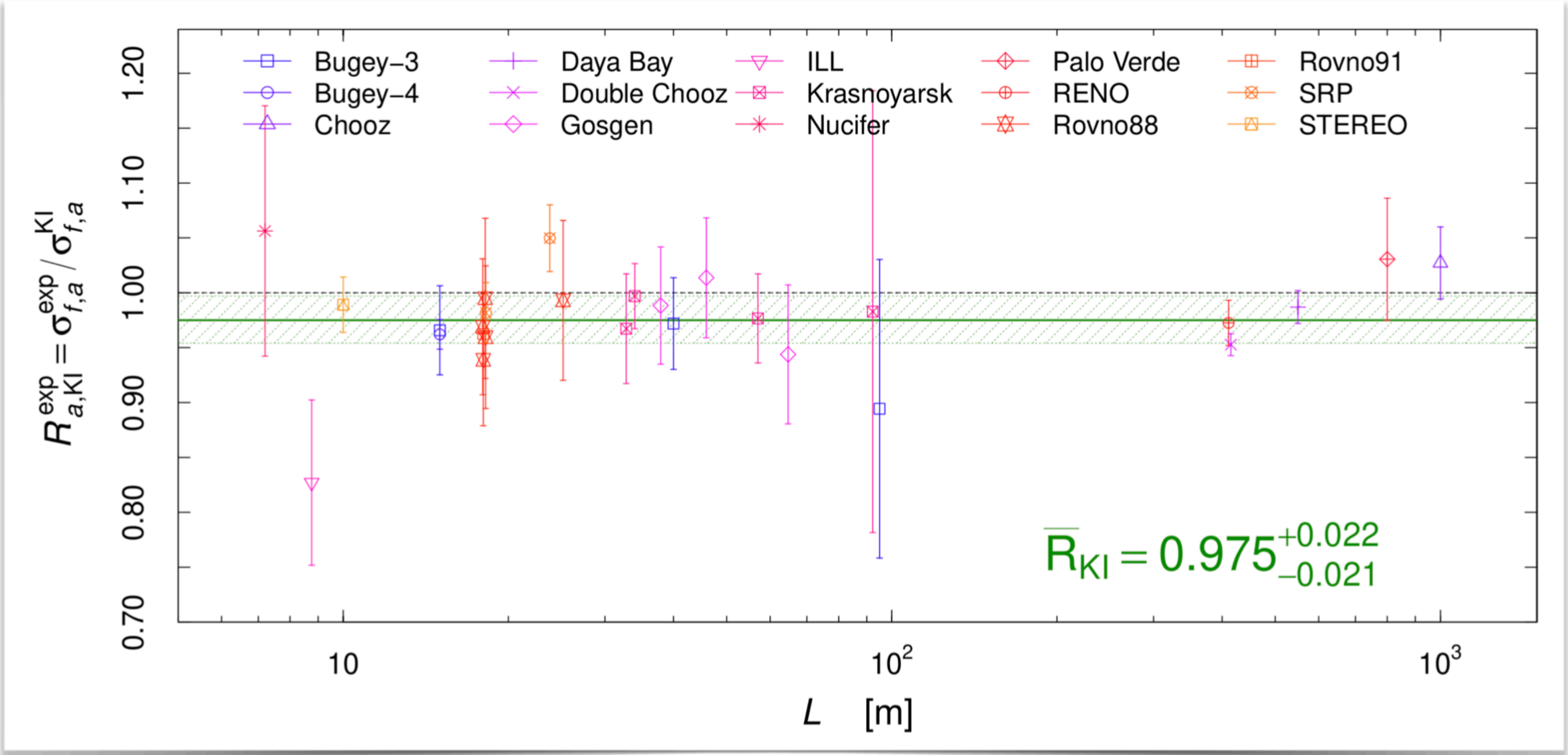
Anomaly #3 : Reactor Neutrino Fluxes

Mueller *et al.* 1101.2663, Huber 1106.0687, Giunti *et al.* 2110.06820



- $\bar{\nu}_e$ flux from nuclear reactors ~ 3.5% (~ 3σ) below prediction
- Oscillation of $\bar{\nu}_e$ into sterile neutrino $\bar{\nu}_s$? (L/E too small for standard oscillations)

Anomaly #3 : Reactor Neutrino Fluxes

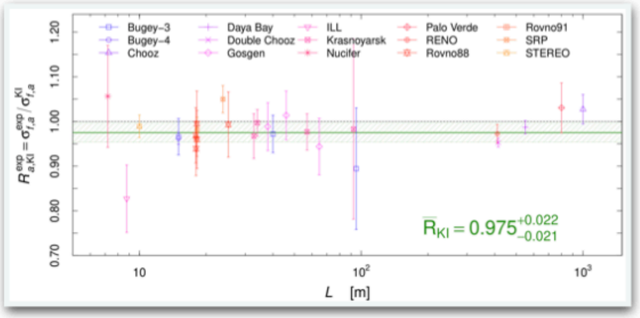


Kopeikin Skorokhvatov Titov arXiv:2103.01684, Berryman Huber arXiv:2005.01756, Giunti Li Ternes Xin arXiv:2110.06820

☑ With updated input data to flux calculation (new β spectra from ^{235}U fission)

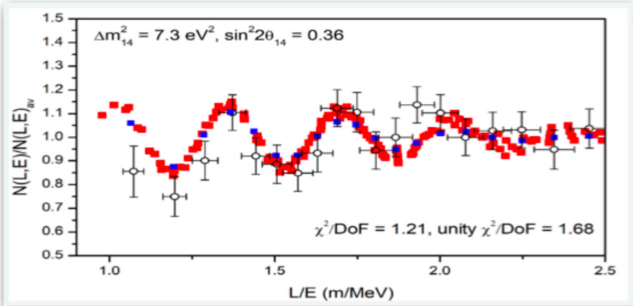
reactor flux anomaly, resolved with new input data to flux calculation

Short-Baseline Anomaly



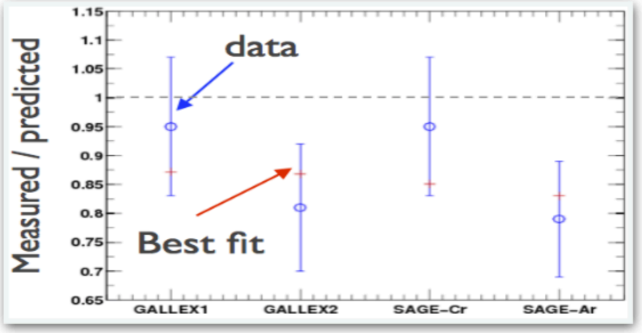
reactor flux anomaly
resolved with new input data
to flux calculation

✓



reactor spectra
is there really an anomaly?

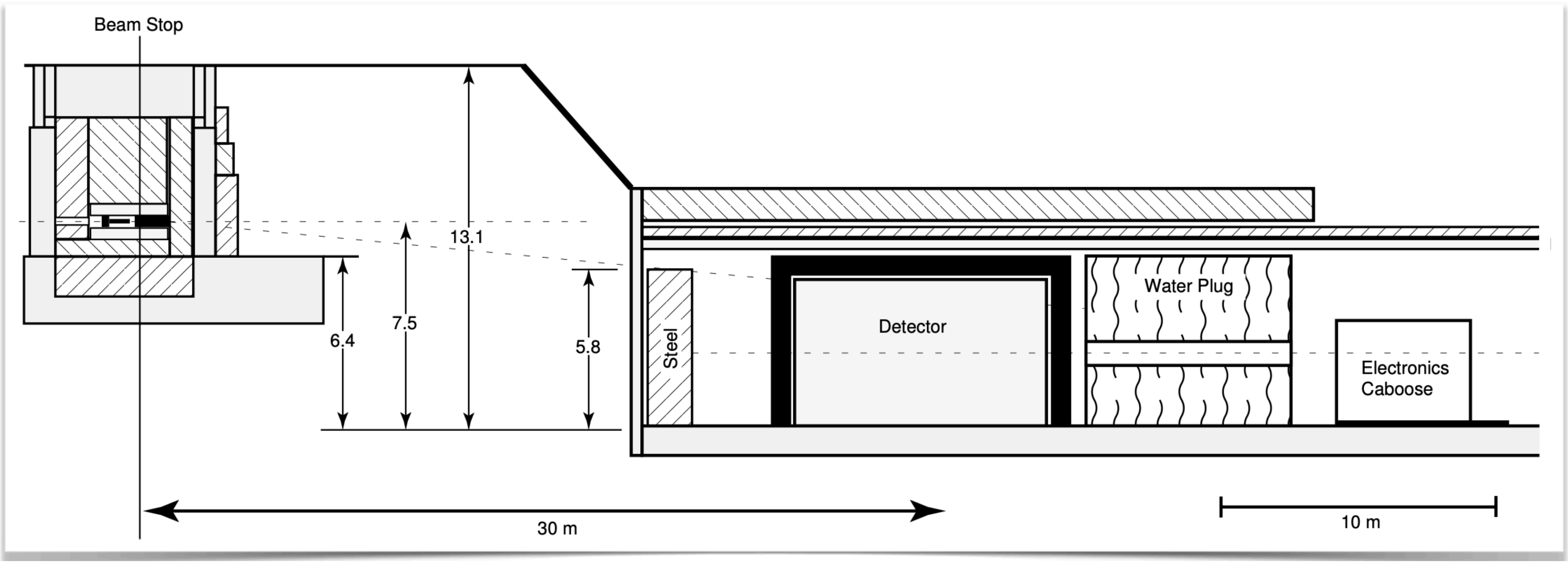
?



gallium anomaly
unresolved, recently reinforced

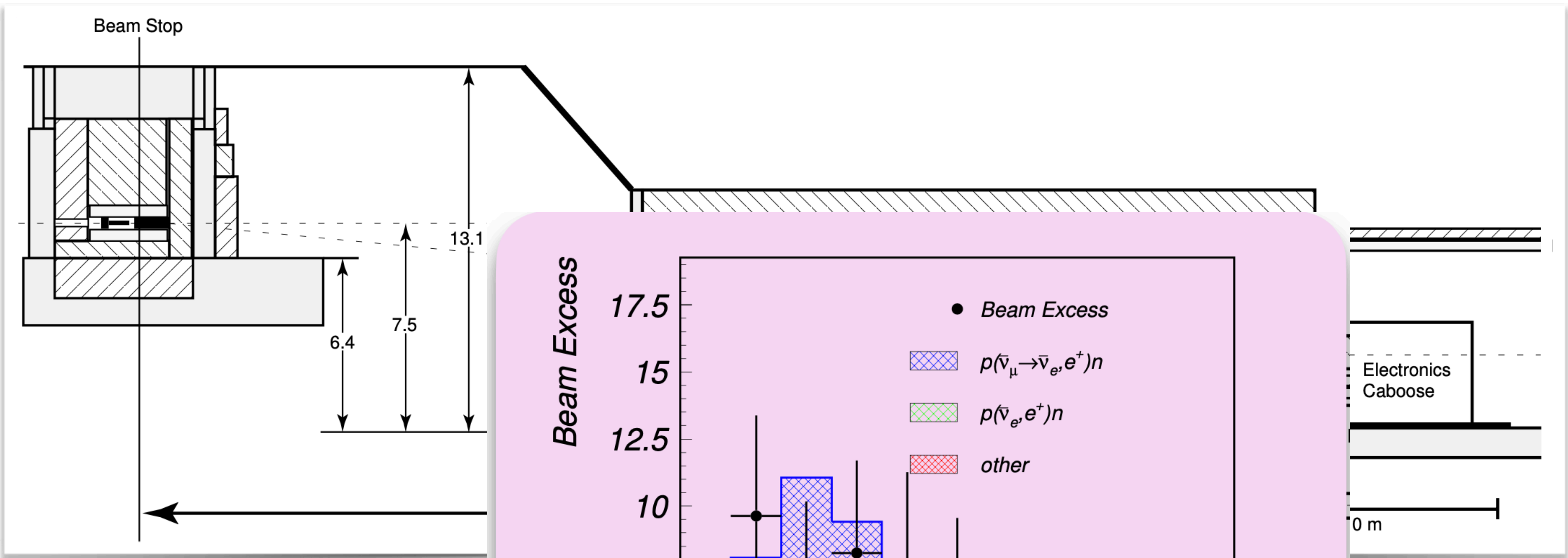
?

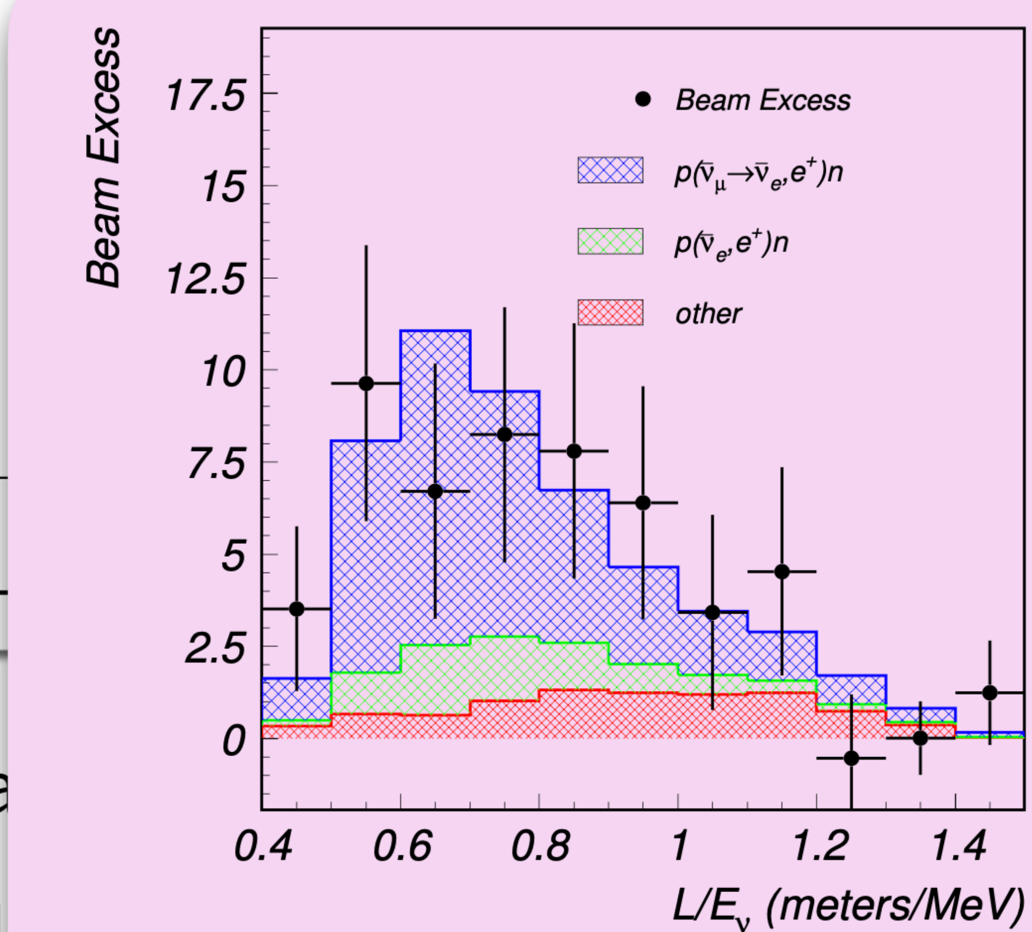
Anomaly #4 : LSND



- $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam(~3σ)
- Source—detector distance ("baseline") ~ 30 m
- $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations

Anomaly #4 : LSND

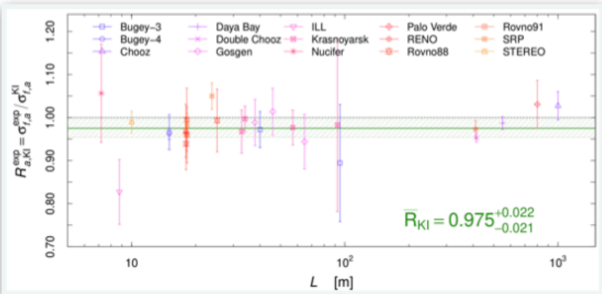




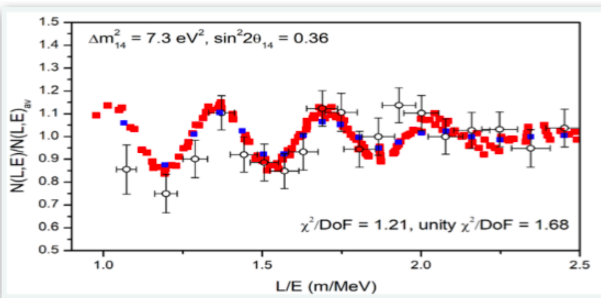
LSND Collaboration, hep-ex/0104049

- ☑ $\bar{\nu}_e$ appearance in
- ☑ Source—detect
- ☑ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations?

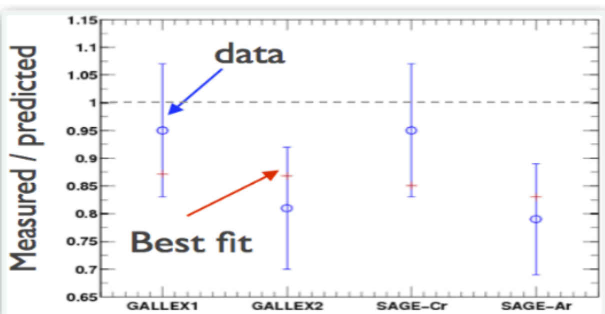
Short Baseline Anomaly



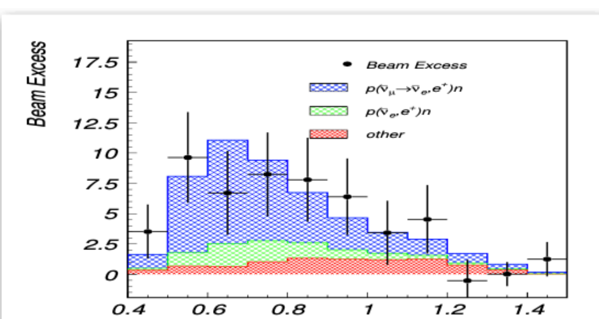
reactor flux anomaly
resolved with new input data
to flux calculation



reactor spectra
is there really an anomaly?

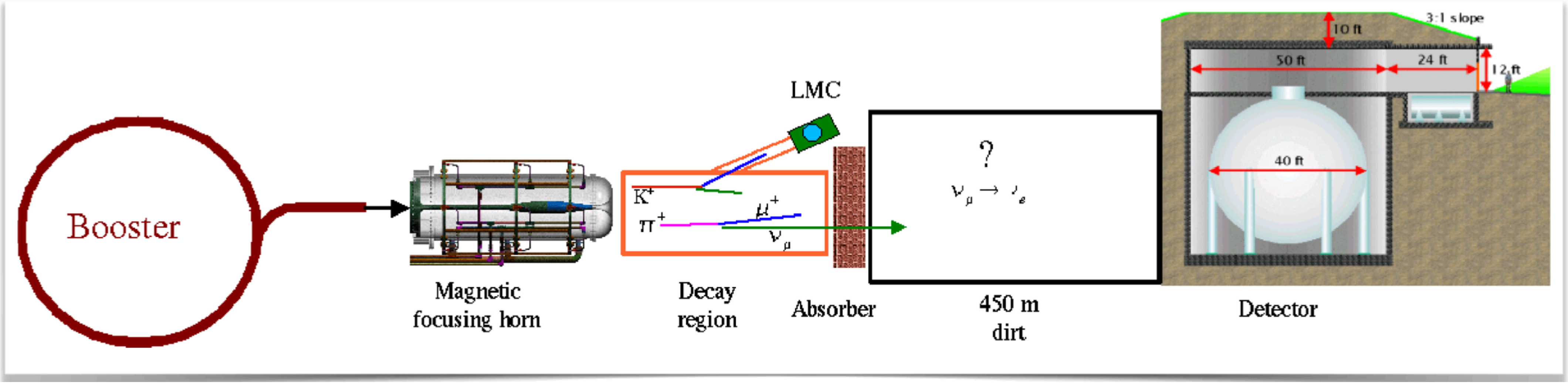


gallium anomaly
unresolved, recently reinforced



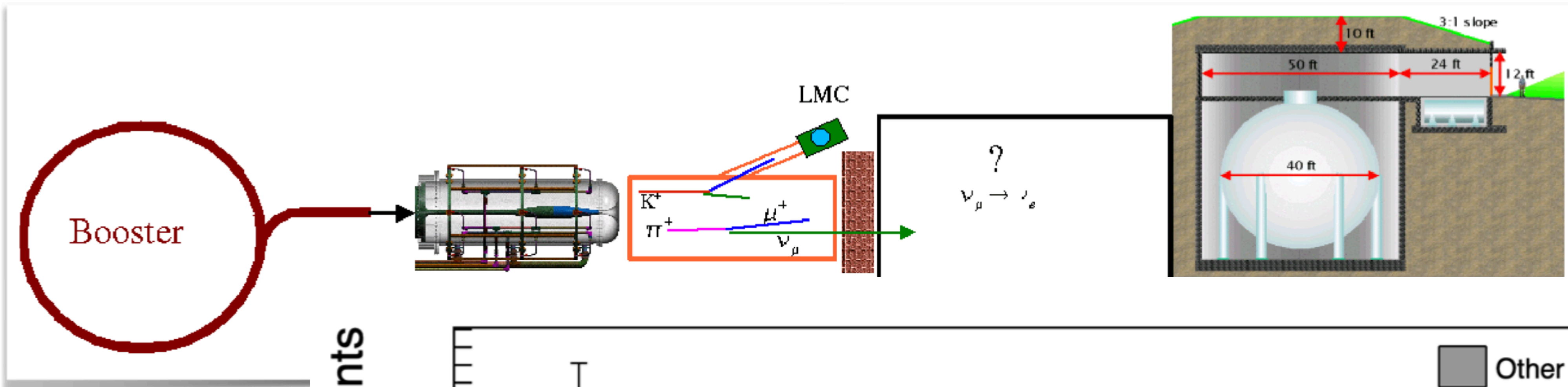
LSND
unresolved

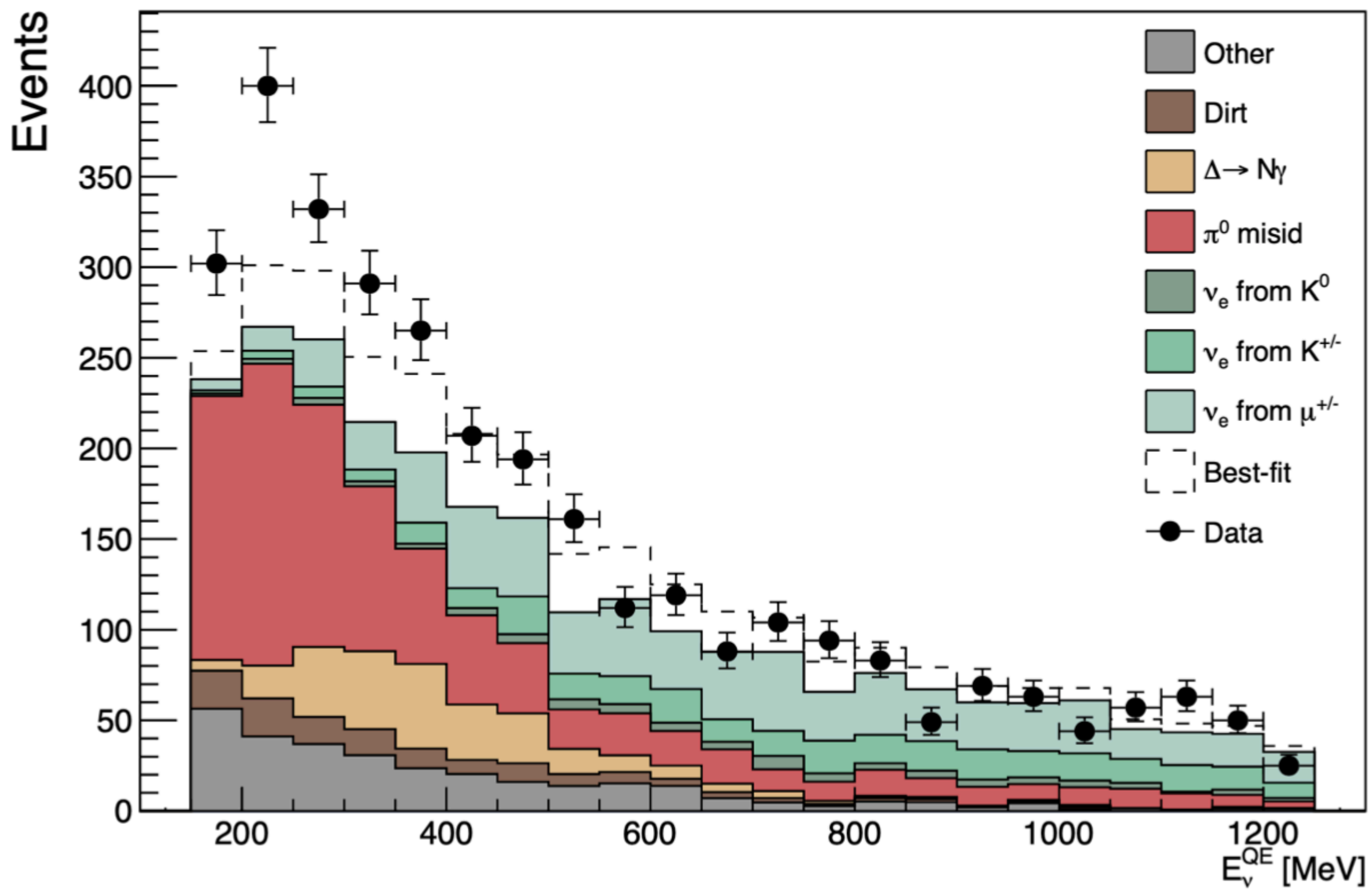
Anomaly #5: MiniBooNE



- ☑ Unexplained low-E excess (4.8σ)
- ☑ Consistent with LSND
- ☑ L/E too small for std. oscillations (wrong Δm^2)

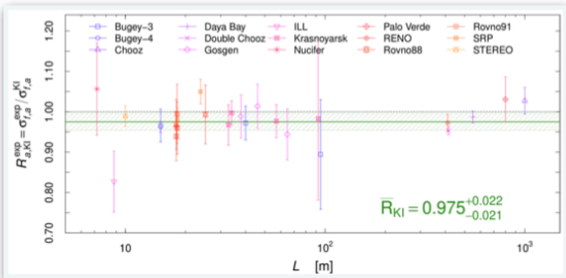
Anomaly #5: MiniBooNE





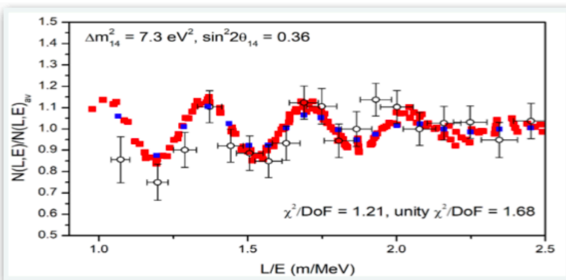
- ☑ Unexplai
- ☑ Consist
- ☑ L/E too (wrong Δ

Short Baseline Anomaly



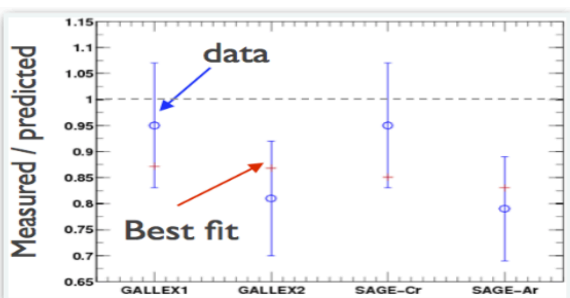
reactor flux anomaly
resolved with new input data
to flux calculation

✓



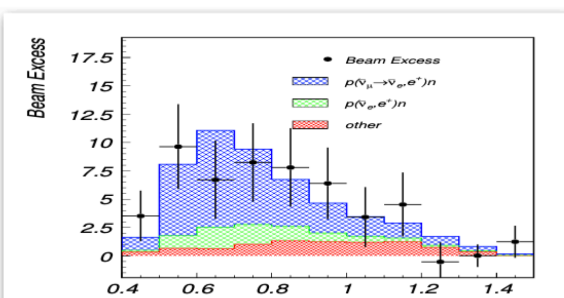
reactor spectra
is there really an anomaly?

?



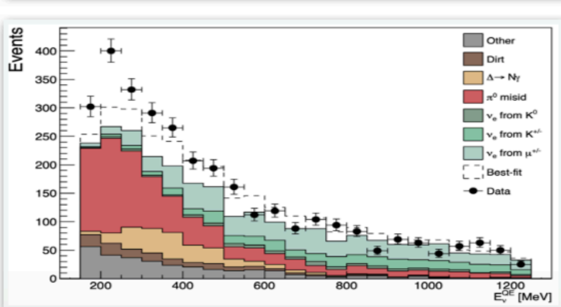
gallium anomaly
unresolved, recently reinforced

?



LSND
unresolved

?



MiniBooNE
unresolved

?

Is there a common explanation for all the anomalies ?

- ☑ Flavor conversion : Inclusion of a new light sterile neutrino

- ☑ Inclusion of dark sectors: Dark matter particles, dark neutrinos, Long lived Heavy Neutrinos etc.

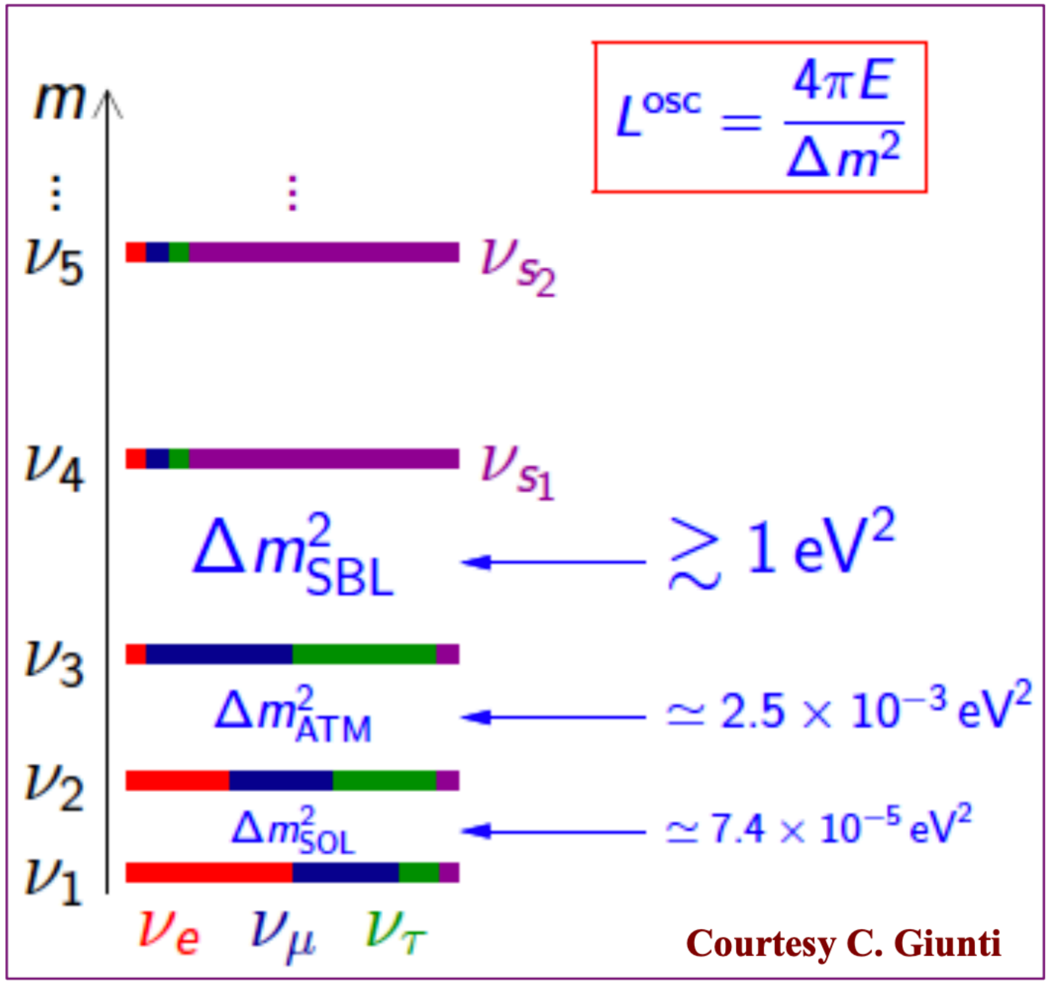
- ☑ Conventional explanation : Single photon production, reactor flux modeling etc.

And many more theoretical models ...

Anomalies hint towards a eV-Scale Sterile neutrino

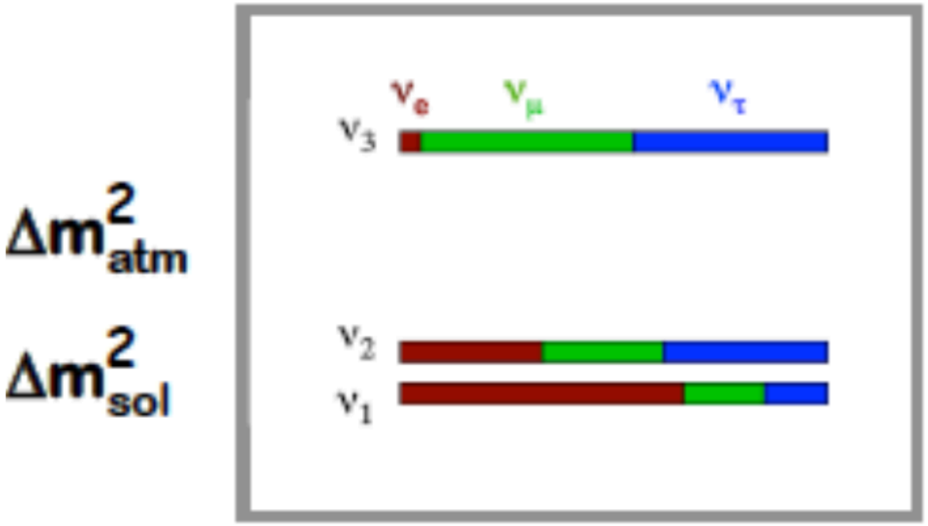
Require additional neutrinos with masses at eV scale

- ν_S : Sterile States (no weak interactions)
- singlets of SU(2) × U(1) gauge group
- Can affect oscillations through mixing
- The right-handed neutrinos are, by definition, sterile.
- To generate neutrino masses, we need to couple the (active) left-handed neutrinos to right-handed neutrinos.
- Hence, sterile neutrino has a great motivation both from theory and experiments

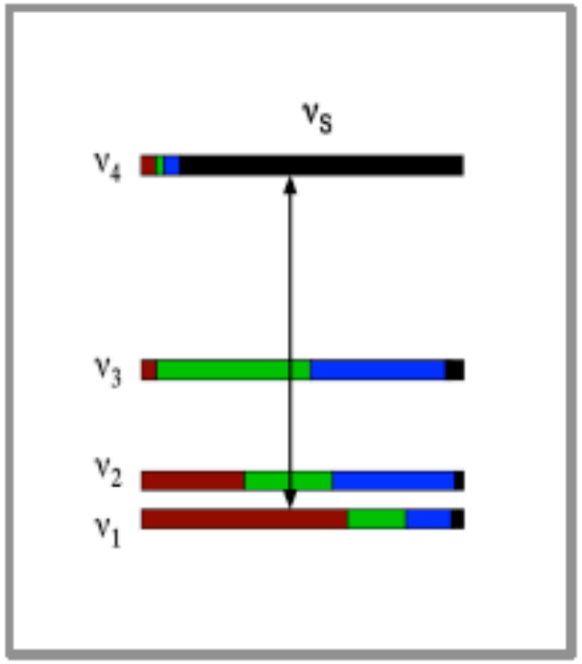


3+1 Sterile-Active Neutrino Oscillations

3ν scheme



3+1 scheme



$\Delta m^2_{41} \sim 1\ \mathrm{eV}^2$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

Small perturbation of 3ν mixing

$|U_{e4}|^2 << 1, |U_{\mu4}|^2 << 1, |U_{\tau4}|^2 << 1, |U_{s4}|^2 \approx 1$

3+1 Short Baseline Oscillation

Appearance ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- Amplitude of ν_e disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- Amplitude of ν_μ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \simeq 4|U_{\mu 4}|^2$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

See reviews by C. Giunti

Current Status and future of the Sterile neutrino Experiments

- Short-Baseline means : L/E ~ 1 (m/MeV or km/GeV)
- It covers a wide range of experiments
- Reactor based ν experiments (L/E ~ m/MeV)
- Accelerator produced ν experiments (L/E ~ 1 km/GeV)
- Atmospheric Neutrinos in IceCube (L/E ~ 1000km/TeV)

Reactor based ν experiments : Status and future

Key aspect : **distance to reactor** (L) $\Delta m^2_{41} \simeq 2 - 10\ \text{eV}^2 \times \left(\frac{10\ m}{L}\right)$

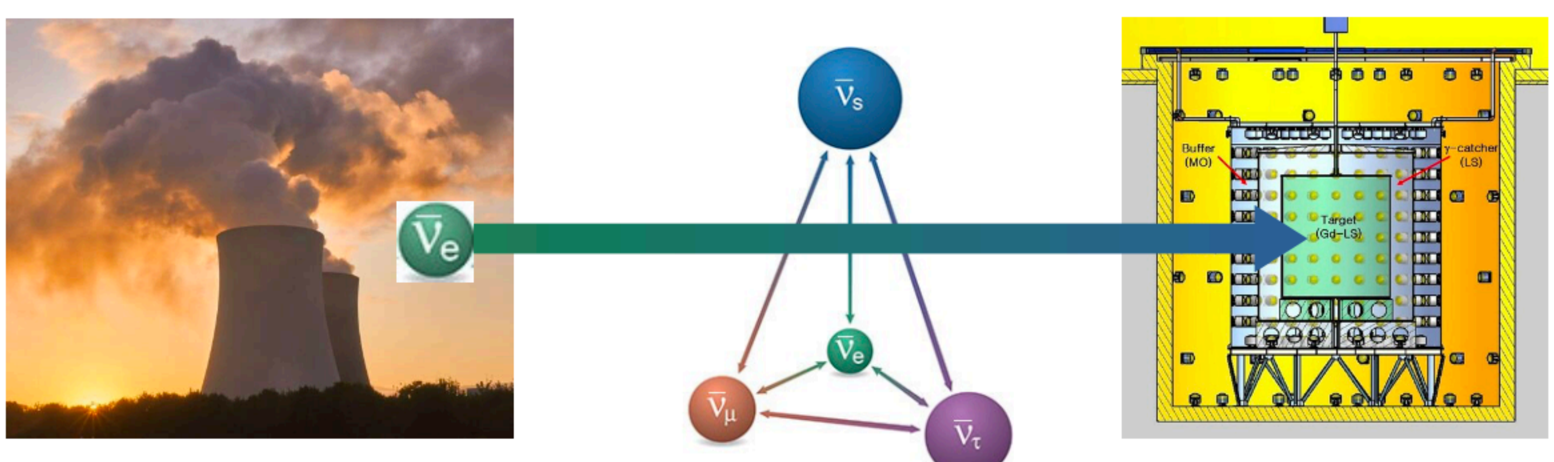
Very short baseline (VSBL)
- L ~ O(10 m)
- access to large Δm²
- restricted space available, high background environnement

← **Complementary Δm² coverage** →

Short baseline (SBL)
- L ~ O(1 km)
- restricted to smaller Δm²
- larger detectors possible
- no reactor background

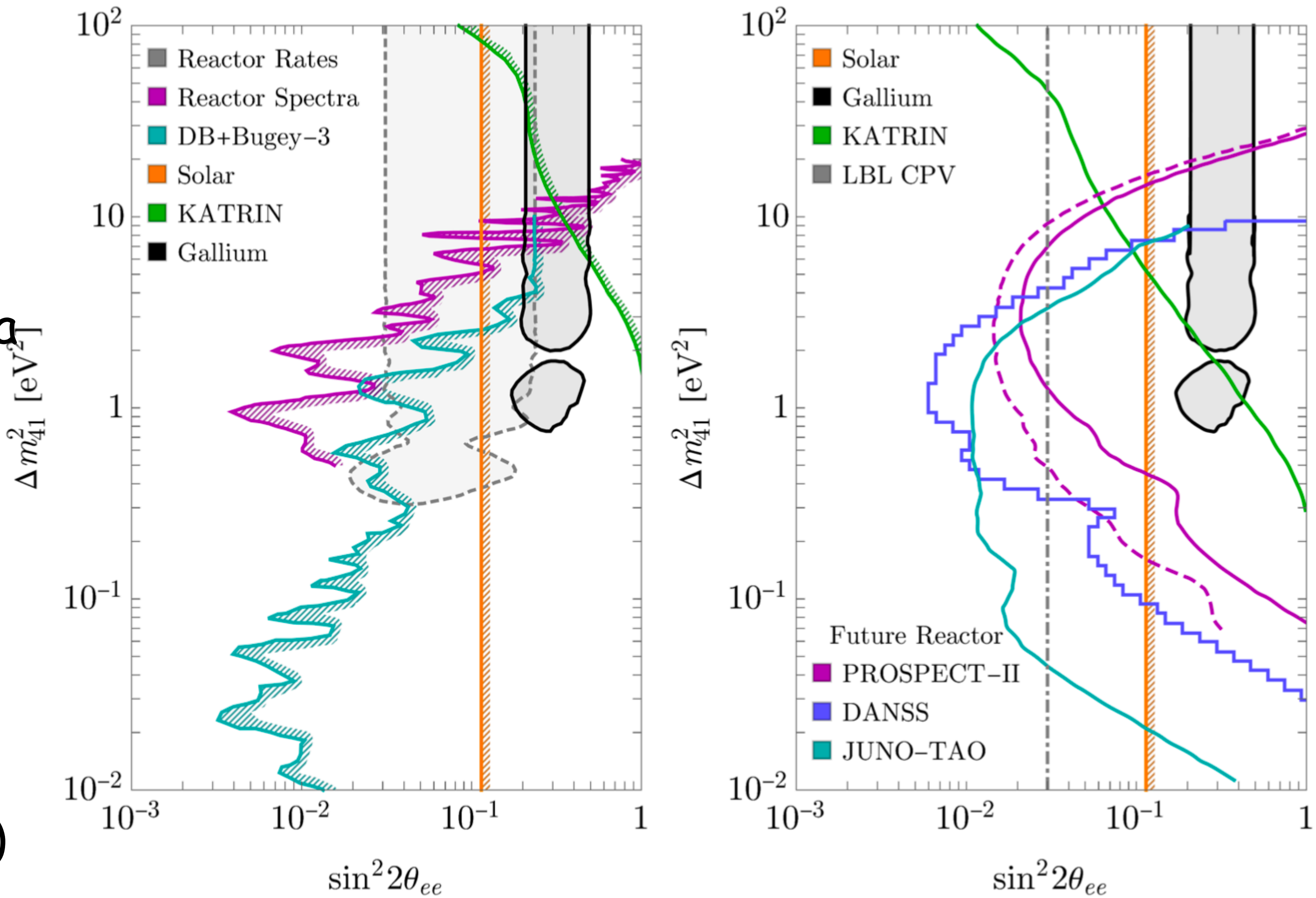
Research reactors (HEU)
- lower power, lower stat
- compact core (Ø ≈ 0.5m)
- *pure ^{235}U (irrelevant)*

Commercial reactors (LEU)
- high power, high stat
- extended core (Ø ≈ few m)
- *mixed isotopes (irrelevant)*



Reactor based ν experiments : Status and future

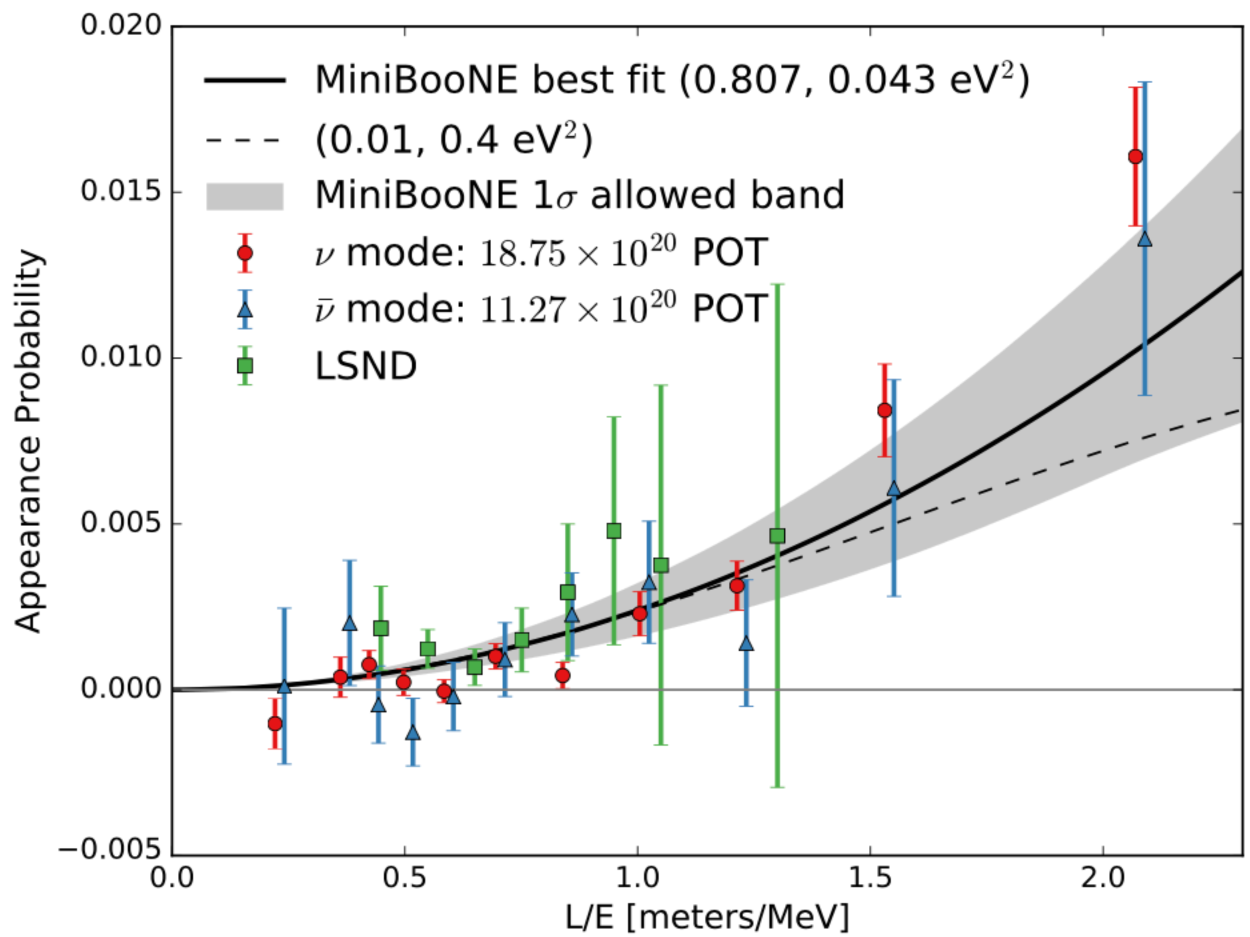
- Complementary constraints from different reactor experiments (SBL + VSBL) allow to probe a large range of Δm^2
- KATRIN + Reactor constraints already cover most of Gallium Anomaly parameters
- Reactor Anomaly strength ($\leftrightarrow \sin 2\theta_{ee}$) still depends on flux modeling: not fully solved yet

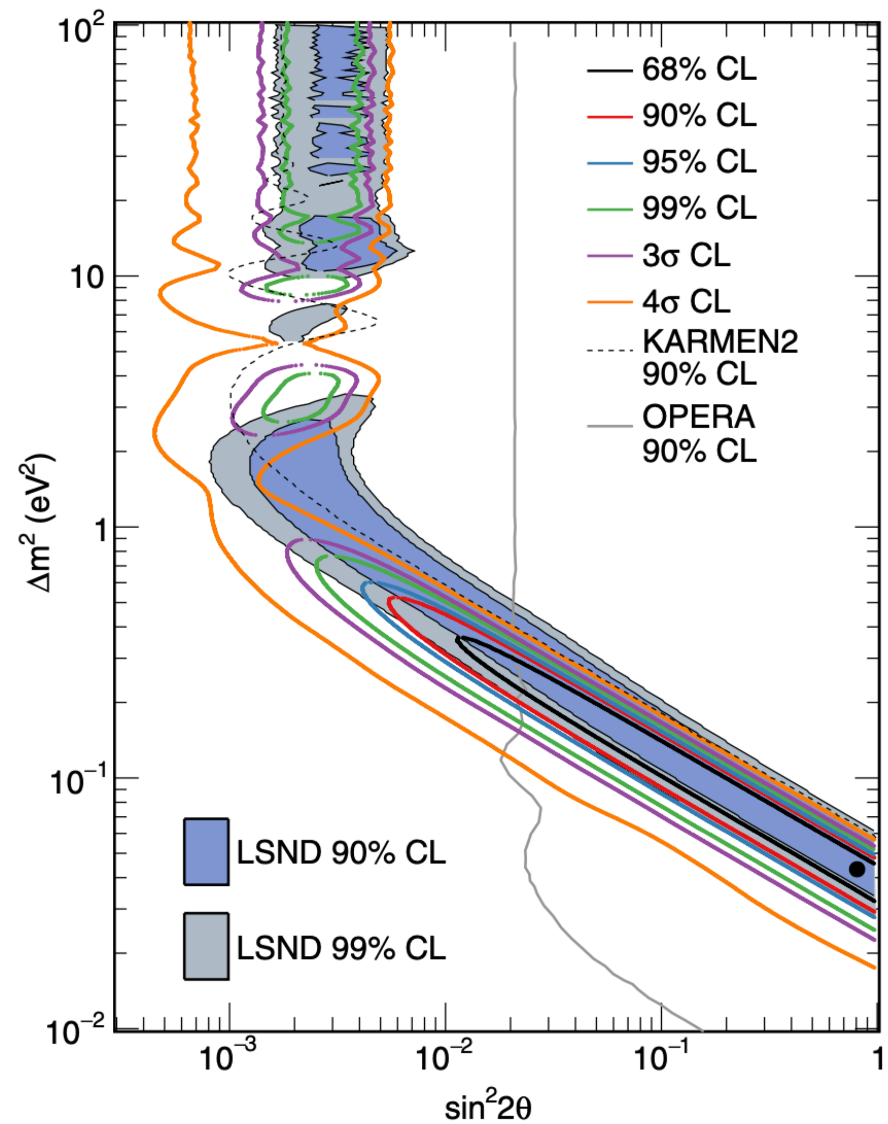


Snowmass 2021 white paper 2203.07214

Positive observations (BEST, Neutrino-4, RENO-NEOS) **in (strong) tension** with other experiments, to be confirmed in the next few years

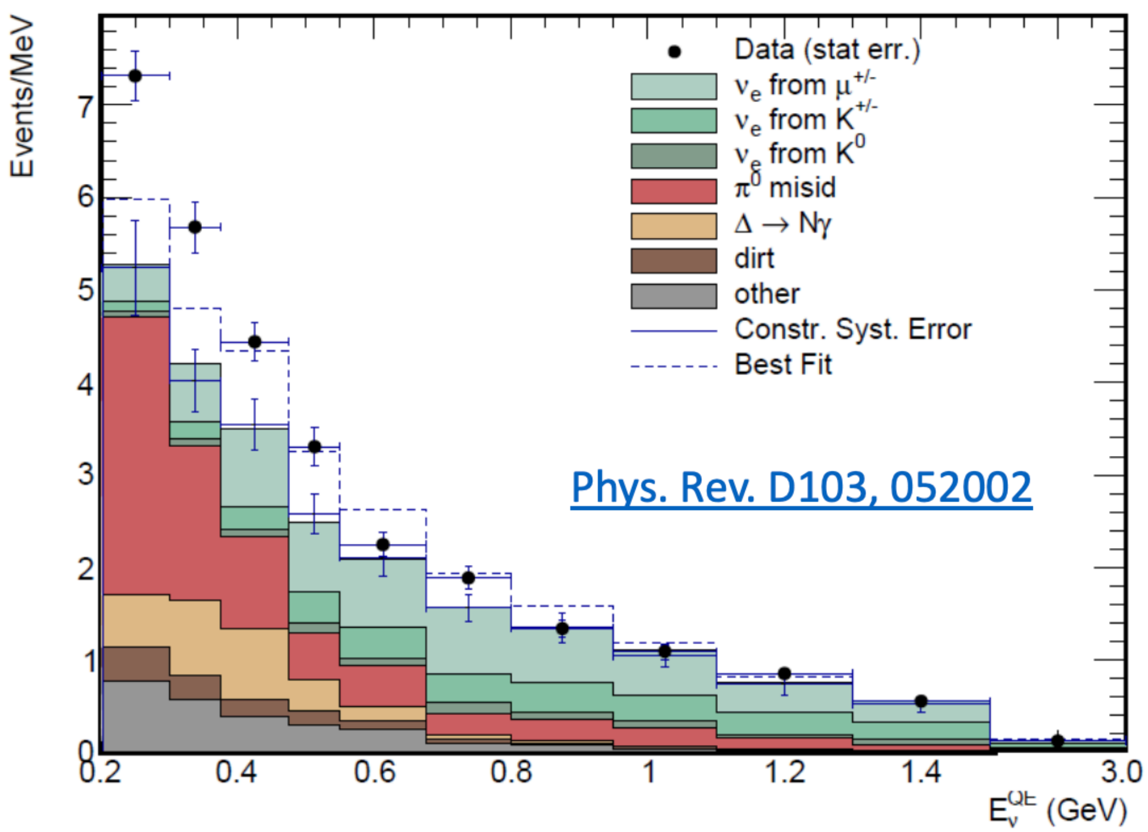
Accelerator based ν experiments : LSND & MiniBooNE





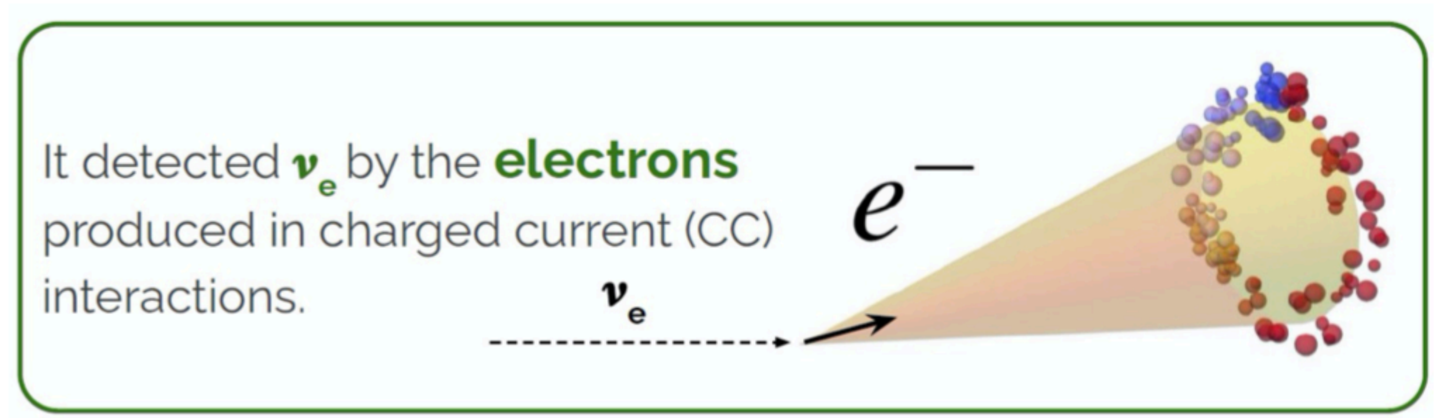
- The MiniBooNE experiment observes a total excess of 638.0 +/ 52.1 (stat) +/132.8 (syst)
- The overall significance of the excess, 4.8σ, is limited by systematic uncertainties, assumed to be Gaussian, as the statistical significance of the excess is 12.2σ.

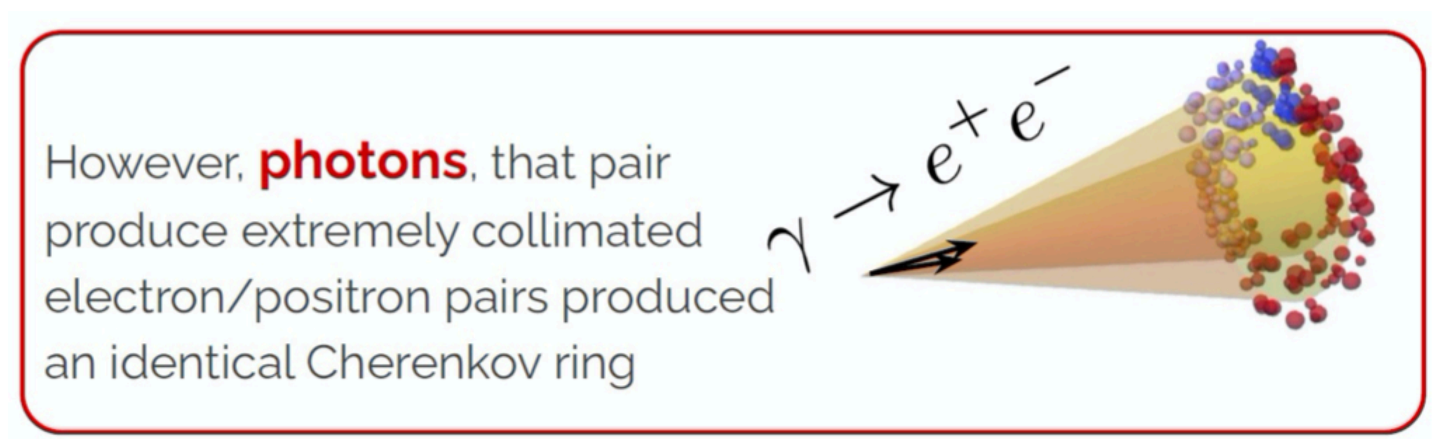
MiniBooNE Anomaly



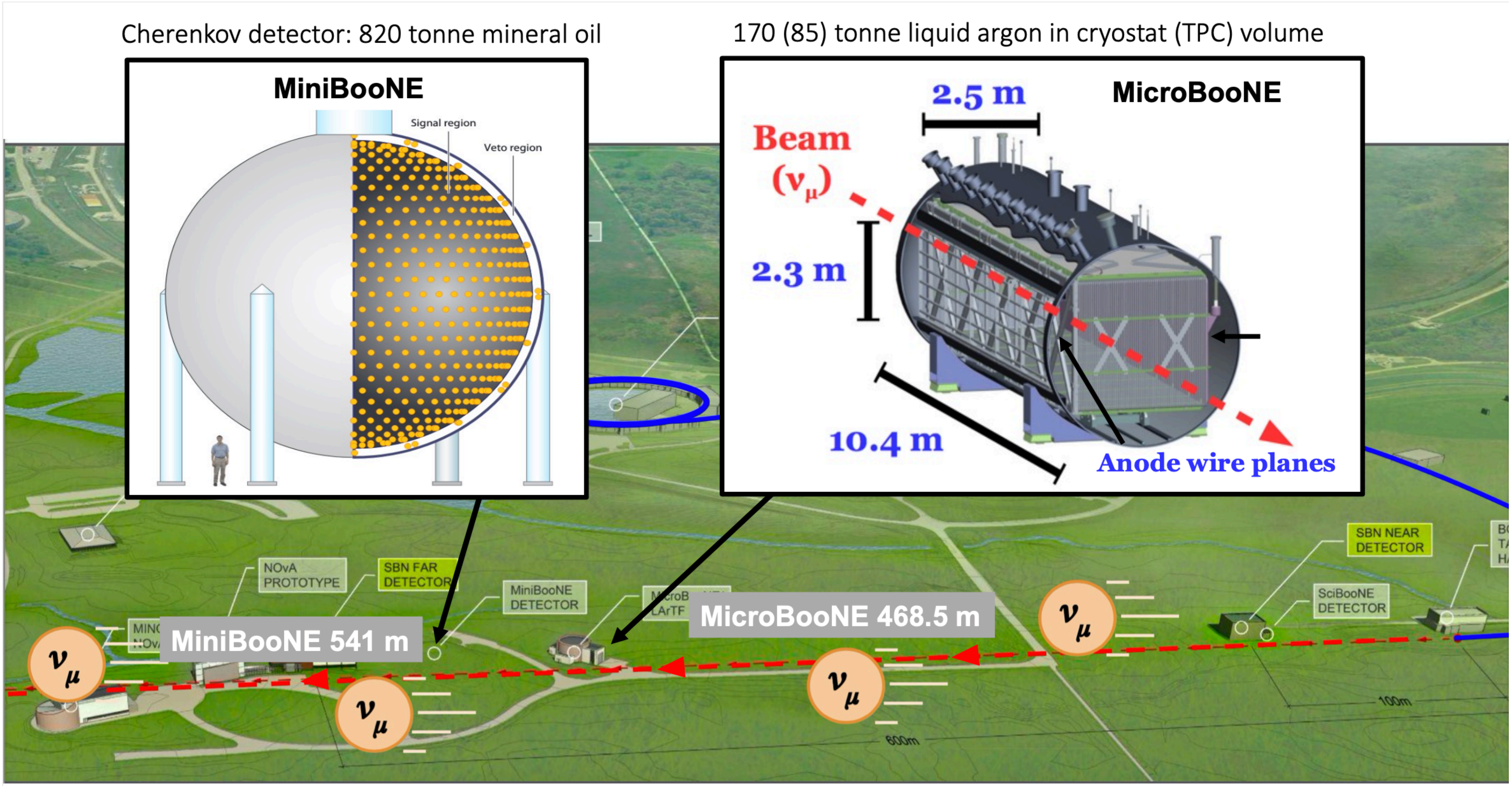
MiniBooNE (2002-2019) observed a low-energy excess (LEE) of electromagnetic events with 4.8σ significance

- ☑ MiniBooNE Cherenkov detector unable to distinguish photons and electrons, and unable to detect hadronic final- state particles below Cherenkov threshold.





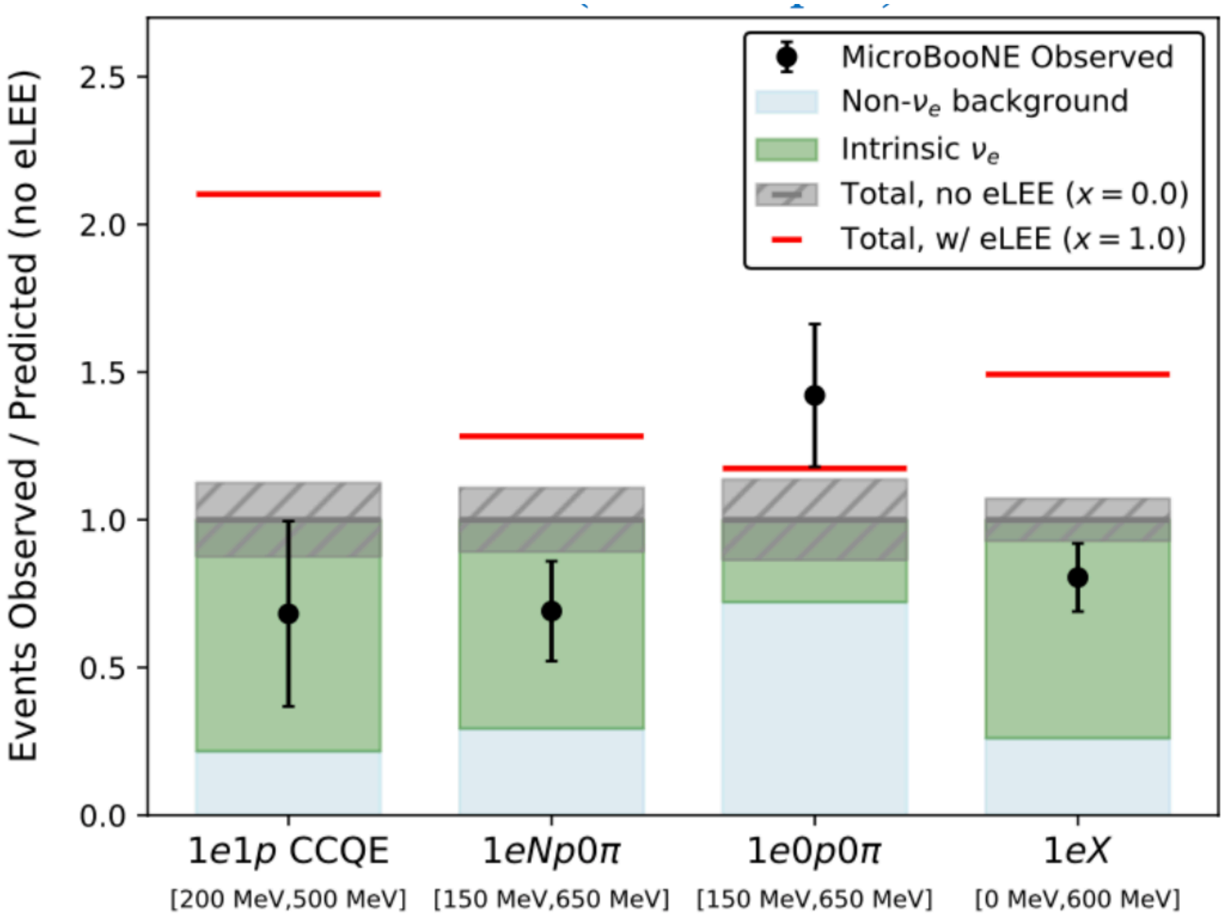
MicroBooNE



MicroBooNE experiment is designed to understand the MiniBooNE LEE region (same L/E) with LArTPC detector

Examination of MiniBooNE LEE

- Electron-like excess (ν_e excess)
  - Mismodeled/ unknown process?
  - Oscillation-driven excess ?



- Photon-like excess
  - Mismodeled/unknown process producing photons, e.g. NC Δ resonance radiative decay?

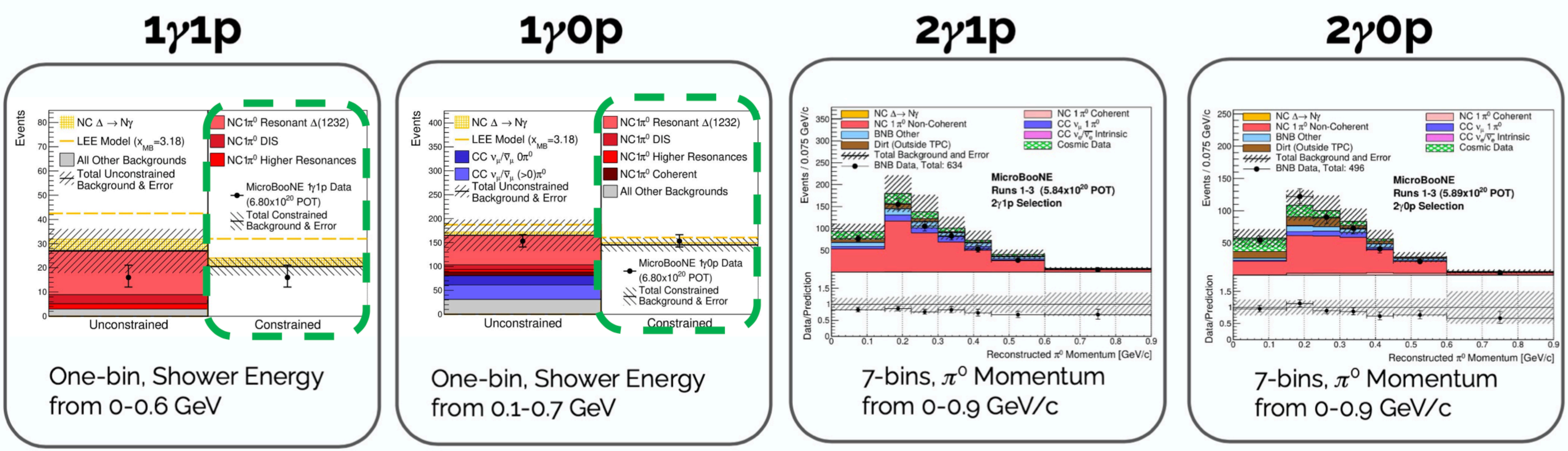
- Observed ν_e candidate rates are statistically consistent with the predicted background rates in the LEE region
- The MicroBooNE eLEE result disfavors the MiniBooNE anomaly originating from a pure ν_e excess
- The MicroBooNE eLEE results can be re- interpreted under a sterile neutrino oscillation hypothesis: a combination of short-baseline ν_e appearance and ν_e disappearance

Examination of MiniBooNE LEE

- This LEE search proceeds with a simultaneous side-by-side fit of four topologically distinct samples

Two **NC Δ→Nγ** rich **single-photon** selections ➕ Two high-statistics **NC π^0 rich** **two-photon** selections

[Phys. Rev. Lett. **128**, 111801]



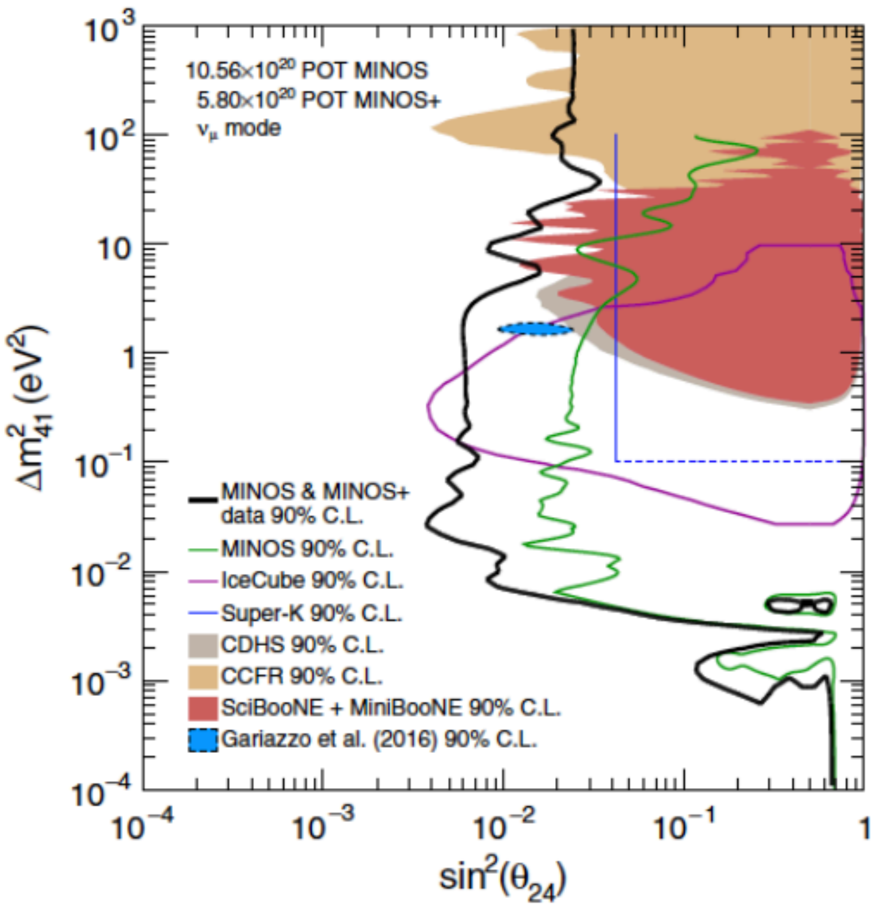
- No evidence for an enhanced rate of single photons from NC Δ → Nγ decay above nominal expectation
- This result disfavors the most suspect single-photon background as a sole source of the MiniBooNE excess

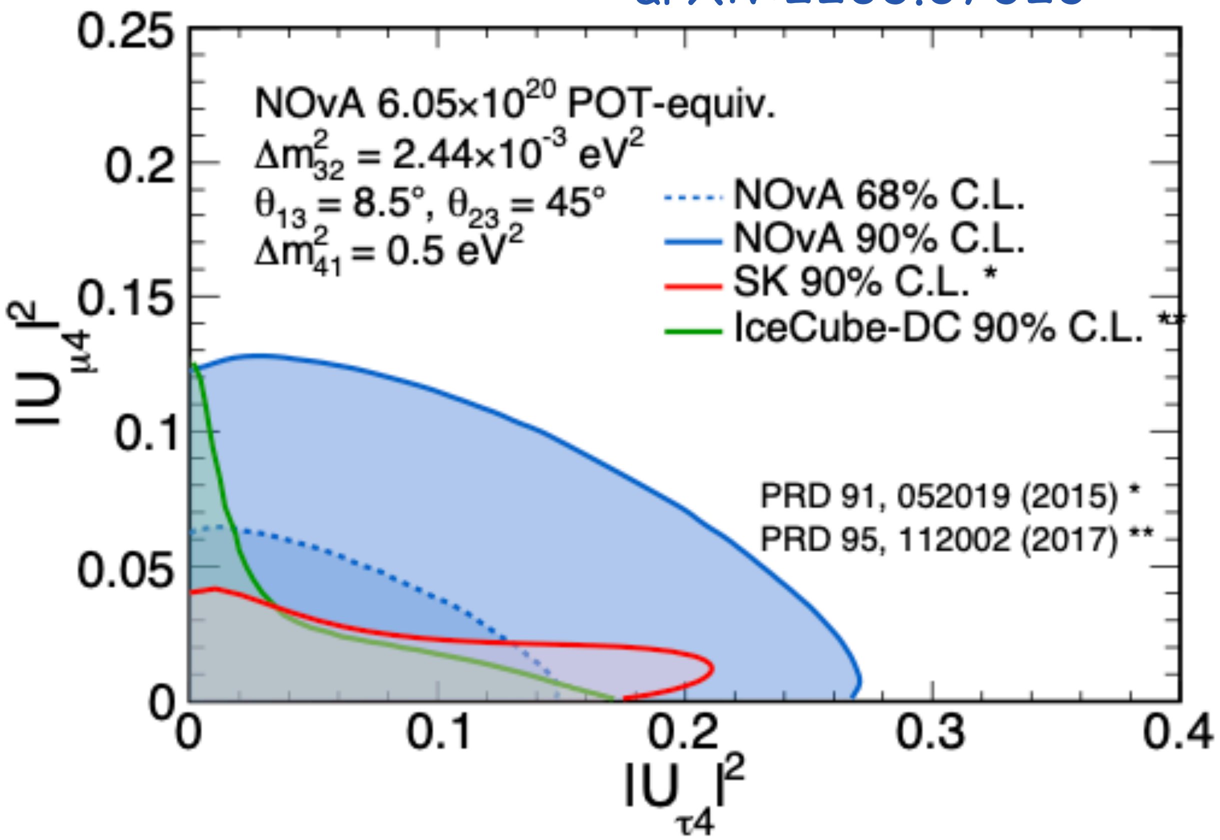
MINOS & NOvA

- The Main Injector Neutrino Oscillation Search (MINOS) experiment was a long-baseline neutrino oscillation experiment using the NuMI neutrino beam and two detectors placed within a 735 km baseline

- A combined analysis of the MINOS neutrino data and MINOS+ neutrino data using a two-detector fitting technique placed stringent limits on sterile driven muon neutrino disappearance within a 3+1 model

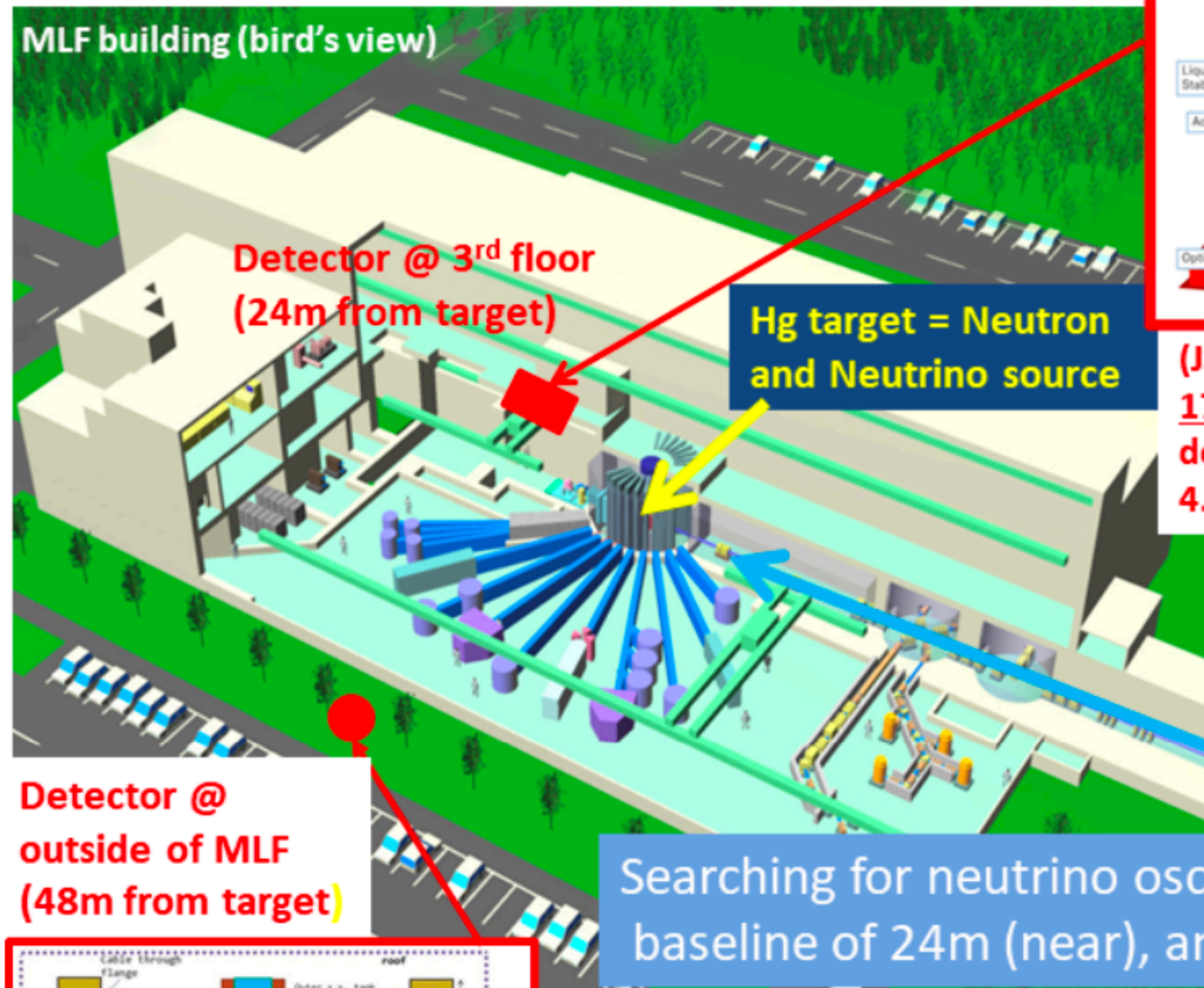
arXiv:2203.07323

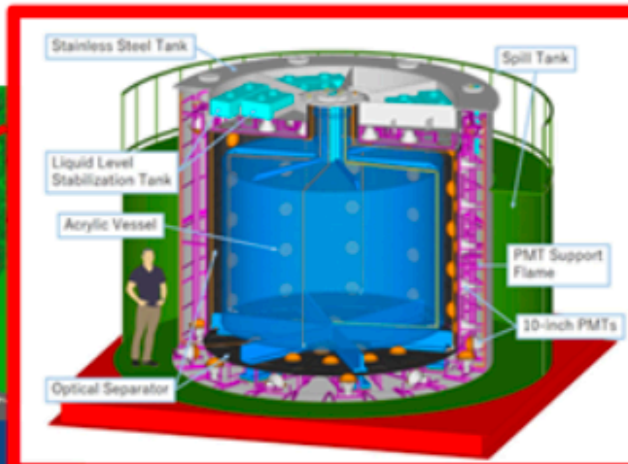




- The NuMI Off-Axis ν_e Appearance (NOvA) experiment performed sterile neutrino search at the FD and compared with SK, and IceCube

JSNS2 and JSNS2-II



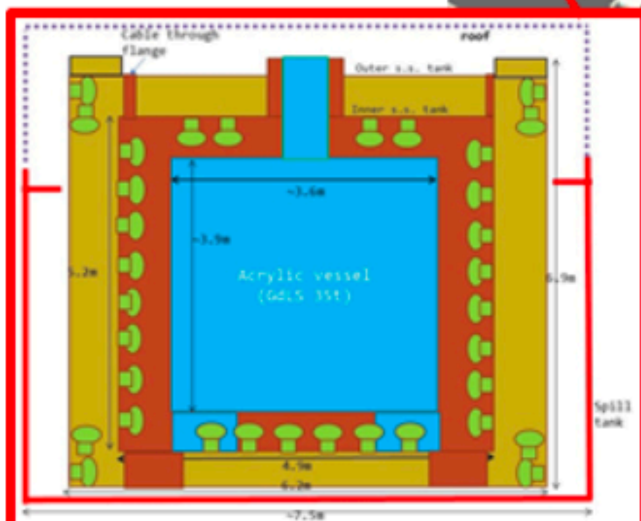


(JSNS^2, JSNS^2-II near detector)
17t GdLS fiducial (target)
detector (4.6m dia. x
4.0m height, 120 10" PMTs)

3GeV pulsed
proton beam

Detector @
outside of MLF
(48m from target)

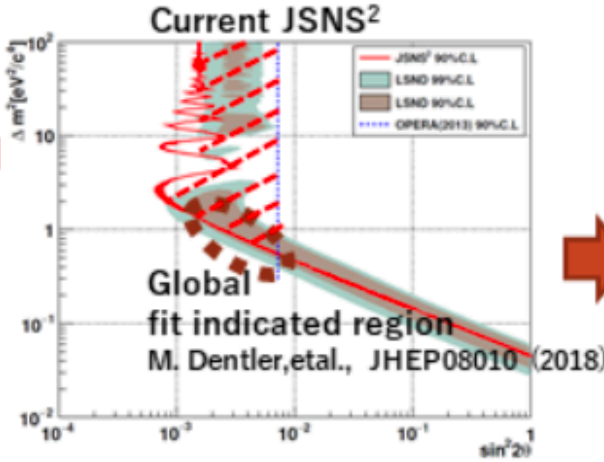
Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m (near), and 48m (far)



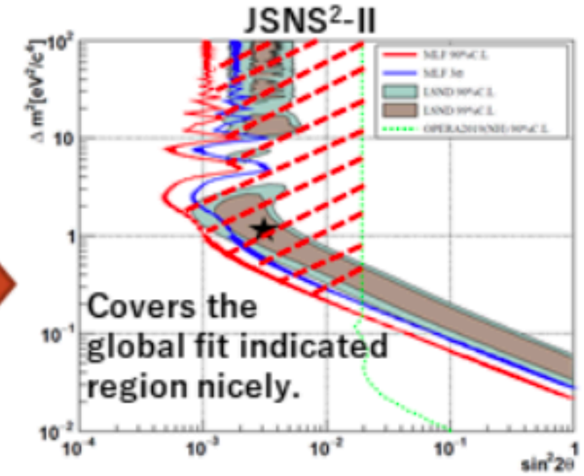
(JSNS^2-II:
far detector)
32t GdLS fiducial

(6.2m dia. x
6.9m (h)
~220 10" PMTs)

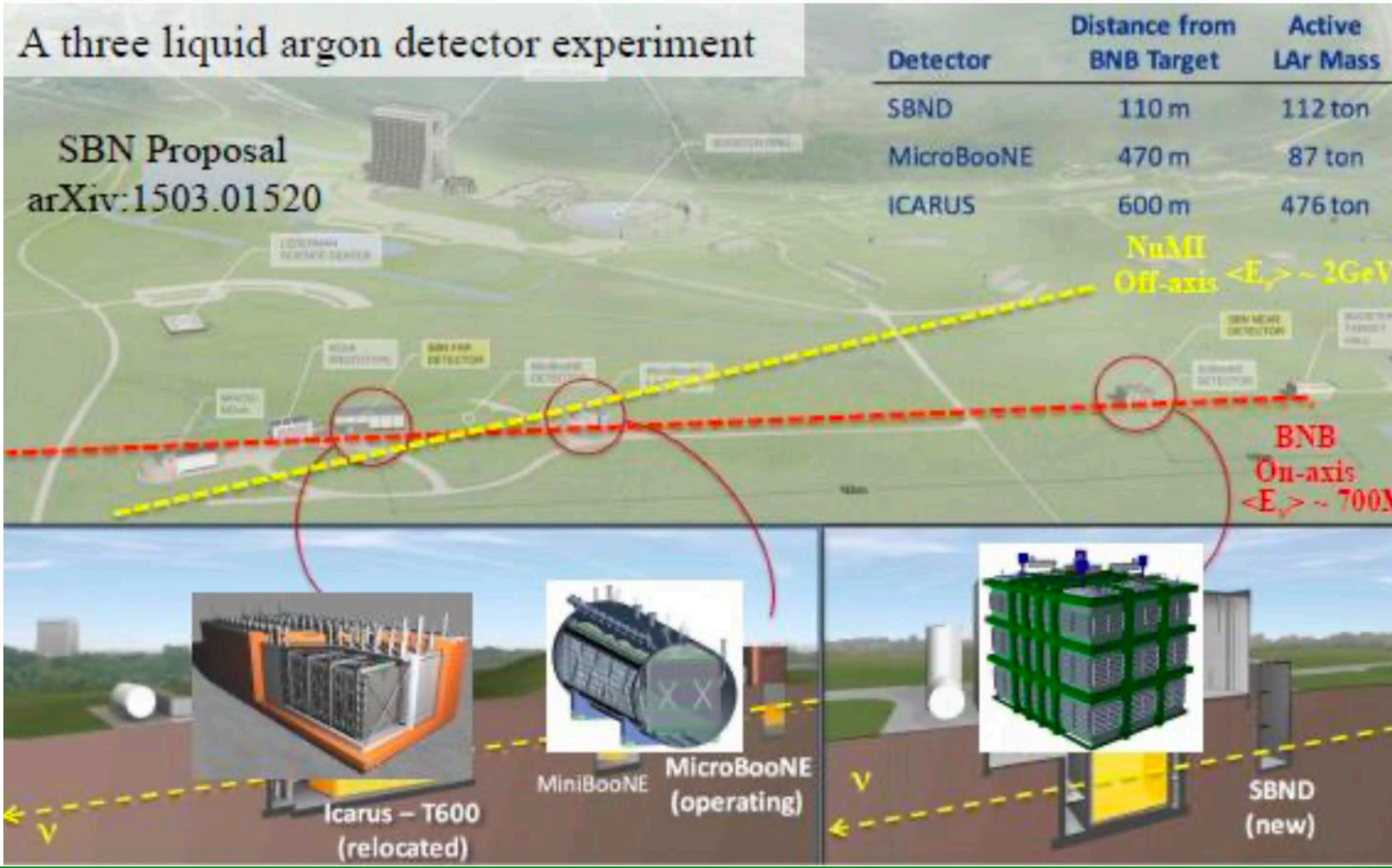
Current JSNS^2



JSNS^2-II



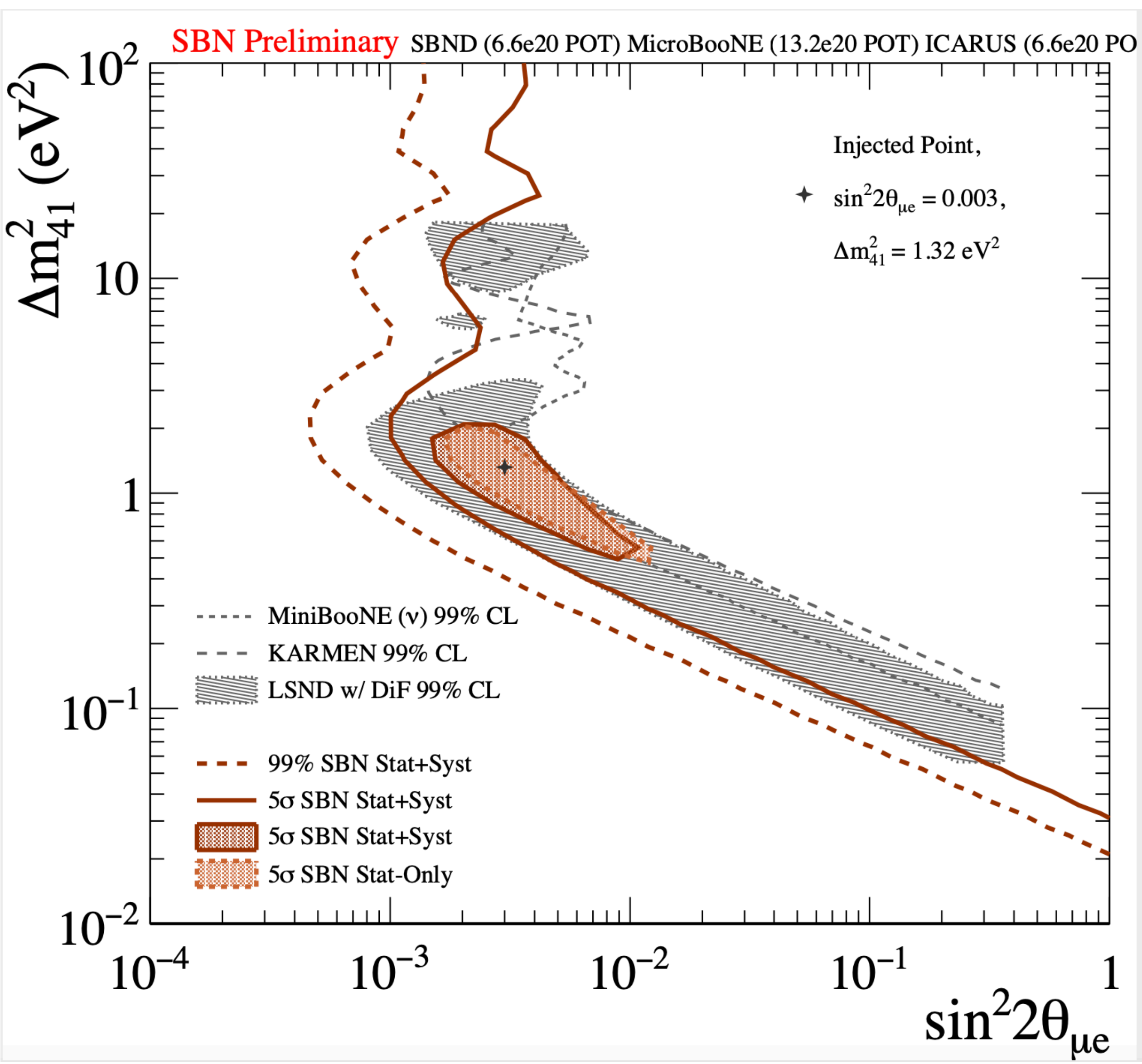
Future : Short Baseline Neutrino Program (SBN)



☑ The SBN Program is composed of three LArTPC detectors with the goal of definitively addressing the hints of eV-scale sterile neutrinos

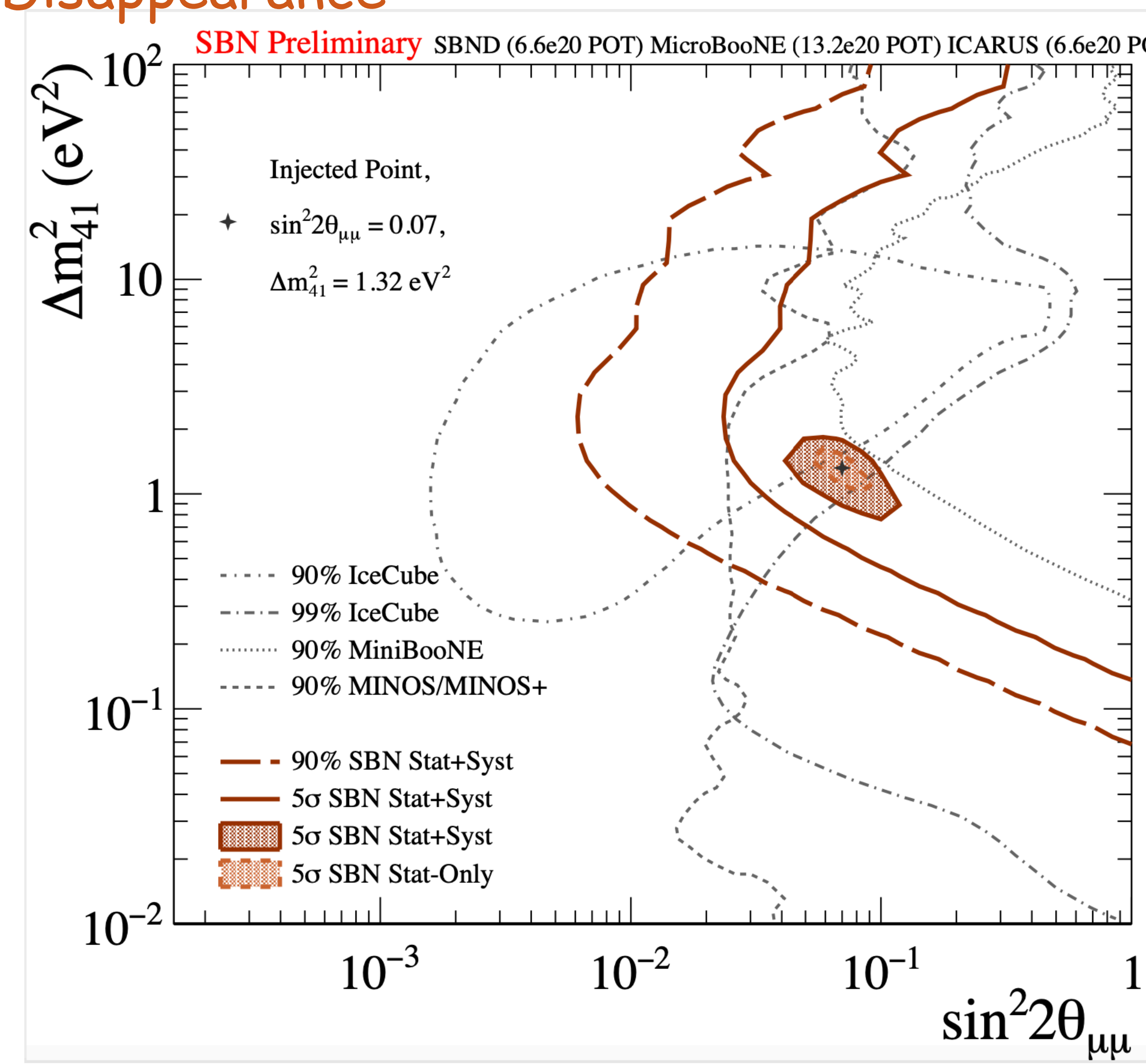
Future : SBN

Appearance



Disappearance

Detailed talk by Biswaranjan Behera

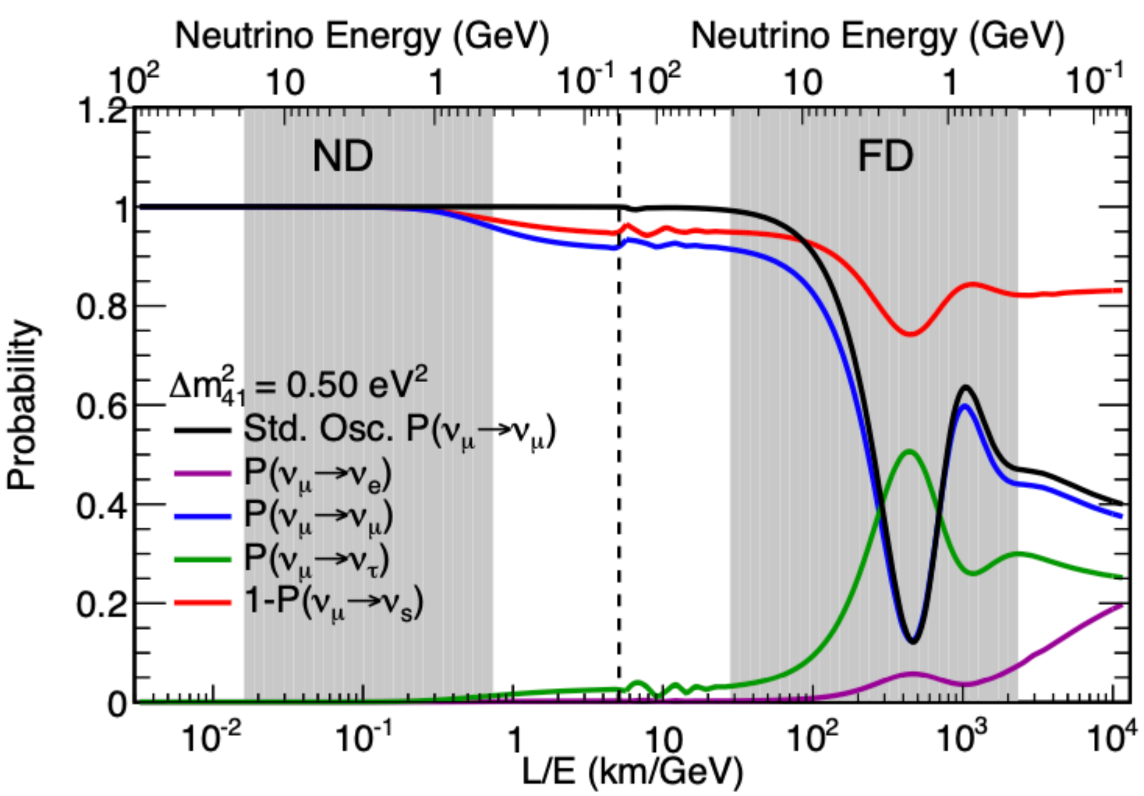


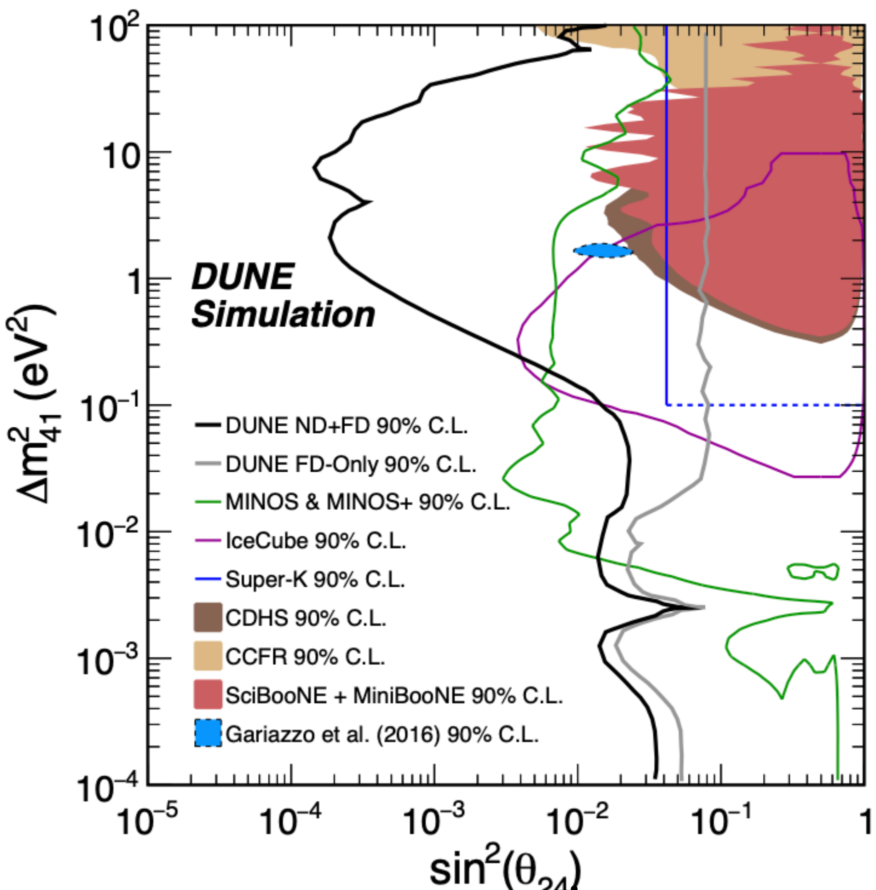
- ☑ The LSND 99% C.L. will be covered at 5 σ C.L. with just 3 years of data
- ☑ Observations of ν_μ disappearance and ν_e appearance signal will confirm any excess due to sterile neutrino or not
- ☑ ICRUS experiment at SBN started taking data recently, stay tuned.

Future : DUNE

- The Deep Underground Neutrino Experiment (DUNE) i s a leading edge, international experiment for neutrino science and proton decay
- Due to the high-power proton beam, the Near detector, and the massive Far detector, DUNE provides enormous opportunities to probe sterile neutrinos.

arXiv:2008.12769

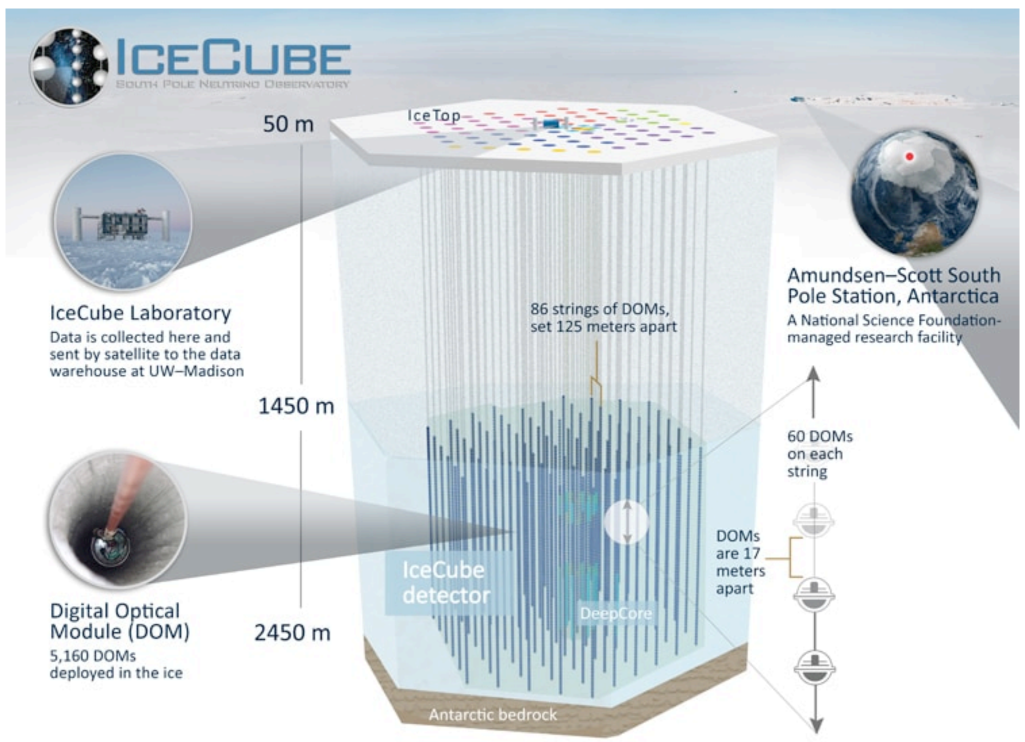




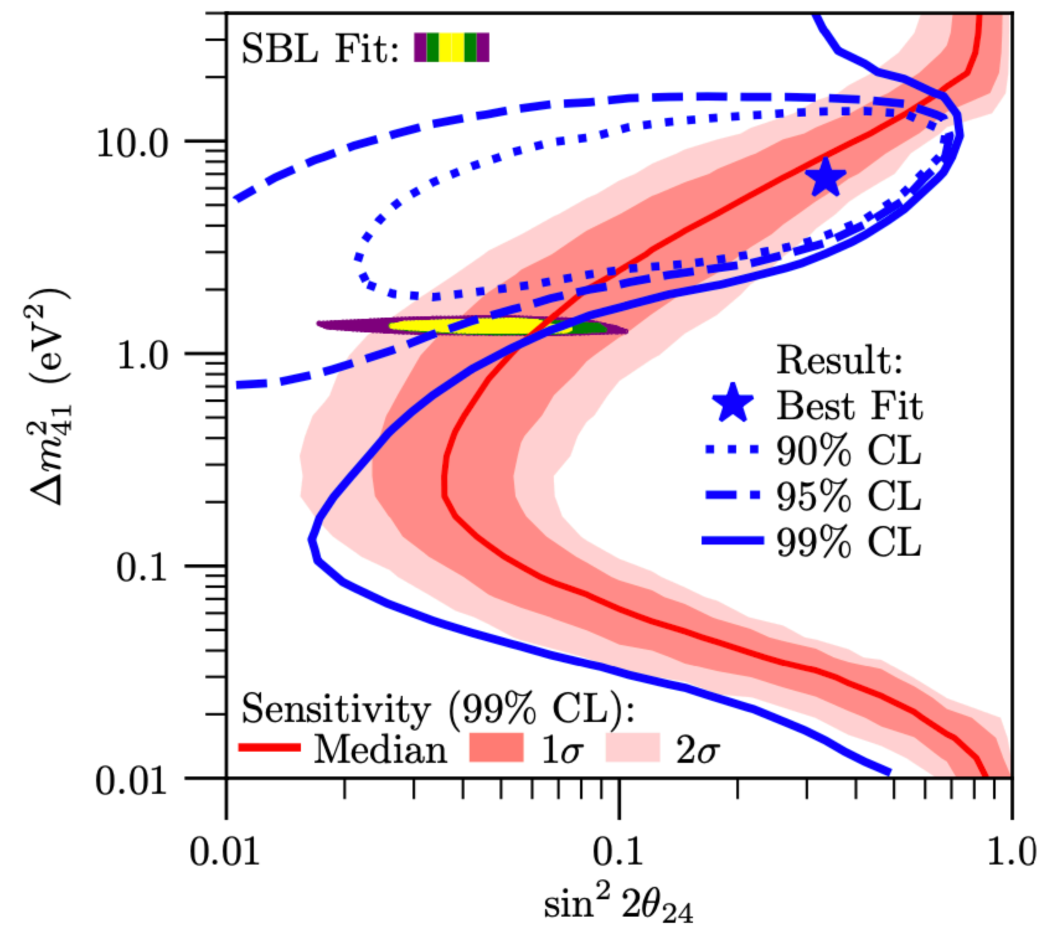
- The θ_{24} mixing angle, the ν_μ CC and NC disappearance samples are analyzed jointly
- Other LBL experiments looking at the sterile searches are ESSnuSB, HK

Atmospheric Neutrinos in ICECUBE

- IceCube is a cubic- kilometer neutrino detector buried 1.5km–2.5km beneath the surface of the Antarctic glacier at the South Pole
- IceCube has made powerful sterile neutrino searches in both high (≳ 400 GeV) and low (≲ 60 GeV) energy ranges



- Phys.Rev.Lett. 129 (2022) 15, 15



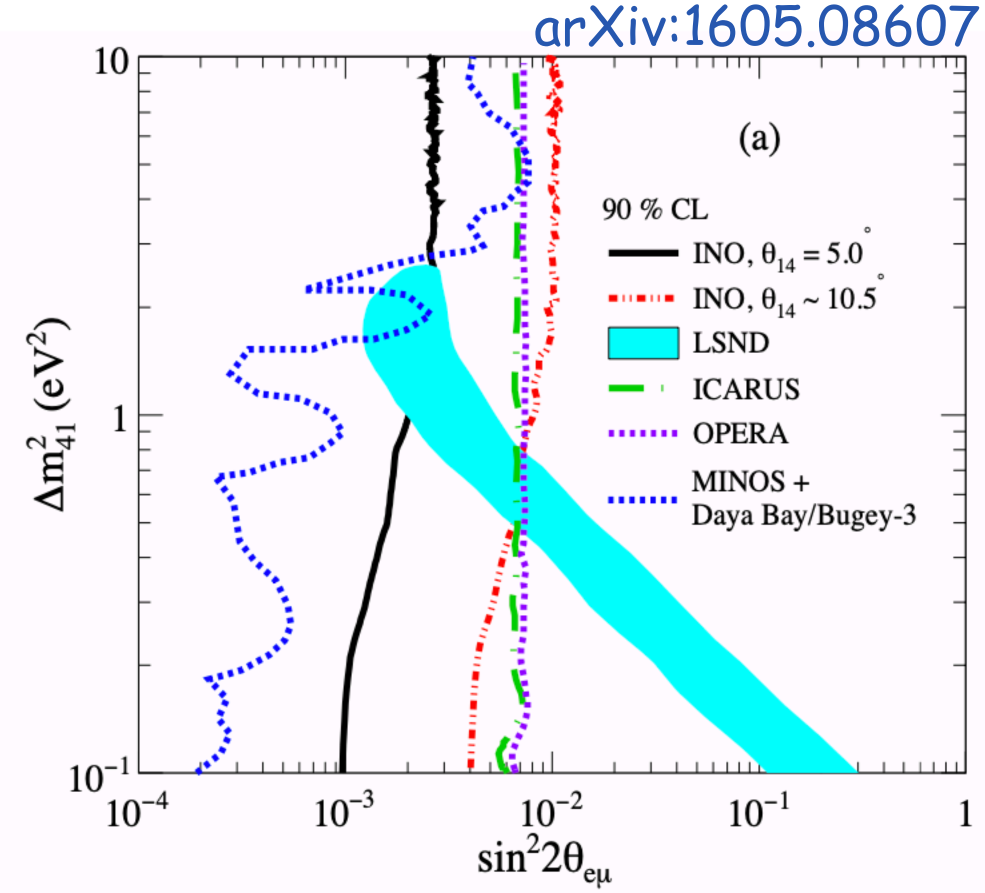
- This result is one of the world's most sensitive in the ν_μ disappearance channel at eV²-scale mass splittings
- The expected sensitivity of the combined high energy ν_μ disappearance and cascade appearance signatures

Atmospheric Future

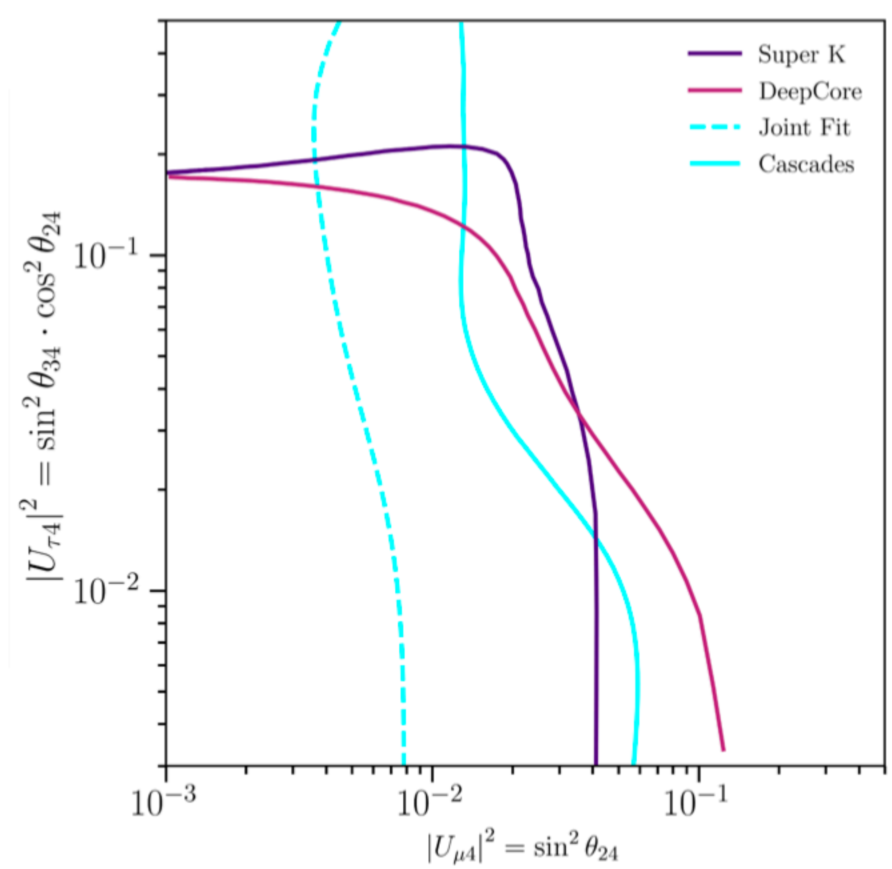
- The proposed 51kton Iron CALorimeter detector (ICAL) will be placed underground at the India-Based Neutrino Observatory

- The sensitivity of ICAL to active-sterile neutrino mixing has been performed and expected bounds on the sterile mixing angles are obtained

arXiv:1605.08607



arXiv:2203.07323



- Other proposed atmospheric neutrino experiments looking for the sterile searches are THEIA, KM3NeT and ORCA, ARCA

-

Sterile Neutrinos in Cosmology

- 1 eV-mass light sterile neutrino motivated by the short baseline anomalies is in strong tension with cosmological measurements primarily because of the non-detection of a non-standard Neff ~ 4

- $$N_{\rm eff} = 3.11^{+0.37}_{-0.36} \quad (95\%\ \rm CL)$$ $$\sum m_\nu < 0.16\ \rm eV$$

measure for the energy density in relativistic particles

sum of neutrino masses affects structure formation, sterile neutrino compatible with anomalies would imply $\Sigma\, m_\nu \sim 1$ eV

- Given the large number of unknowns in cosmology, e.g., the nature of dark energy, inflation, etc., and with different extended models can explain the short-baseline neutrino anomalies with light sterile neutrino hypothesis

Impact of Sterile neutrino in Neutrino Oscillations

- ☑ **What will be the impact of light eV-scale sterile neutrino in currently running and upcoming neutrino oscillation experiments ?**
- ☑ How to resolve the degeneracy in the neutrino oscillations in the presence of sterile neutrinos ?

A lot of studies have been performed in this regard,

try to provide few examples … not able to present all the studies performed..

Impact on CPV

$$A^{CP}_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

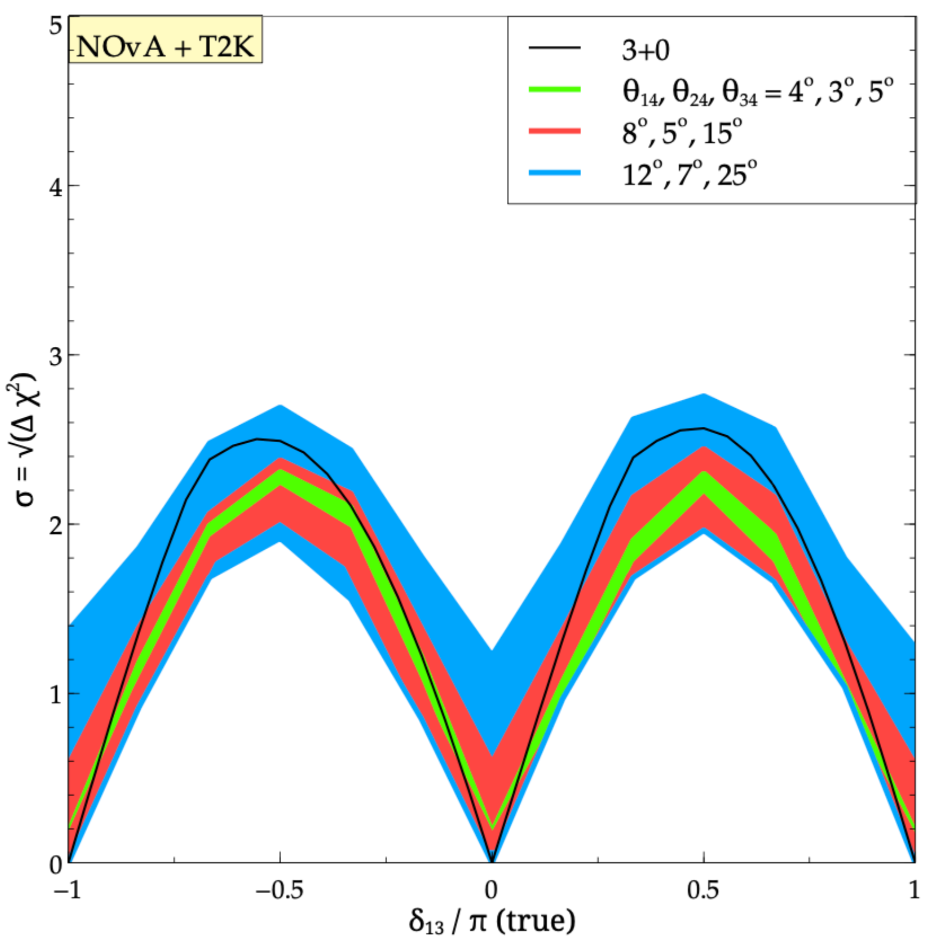
$$A^{CP}_{\alpha\beta} = -16 J^{12}_{\alpha\beta} \sin\Delta_{21} \underbrace{\sin\Delta_{13} \sin\Delta_{32}}$$

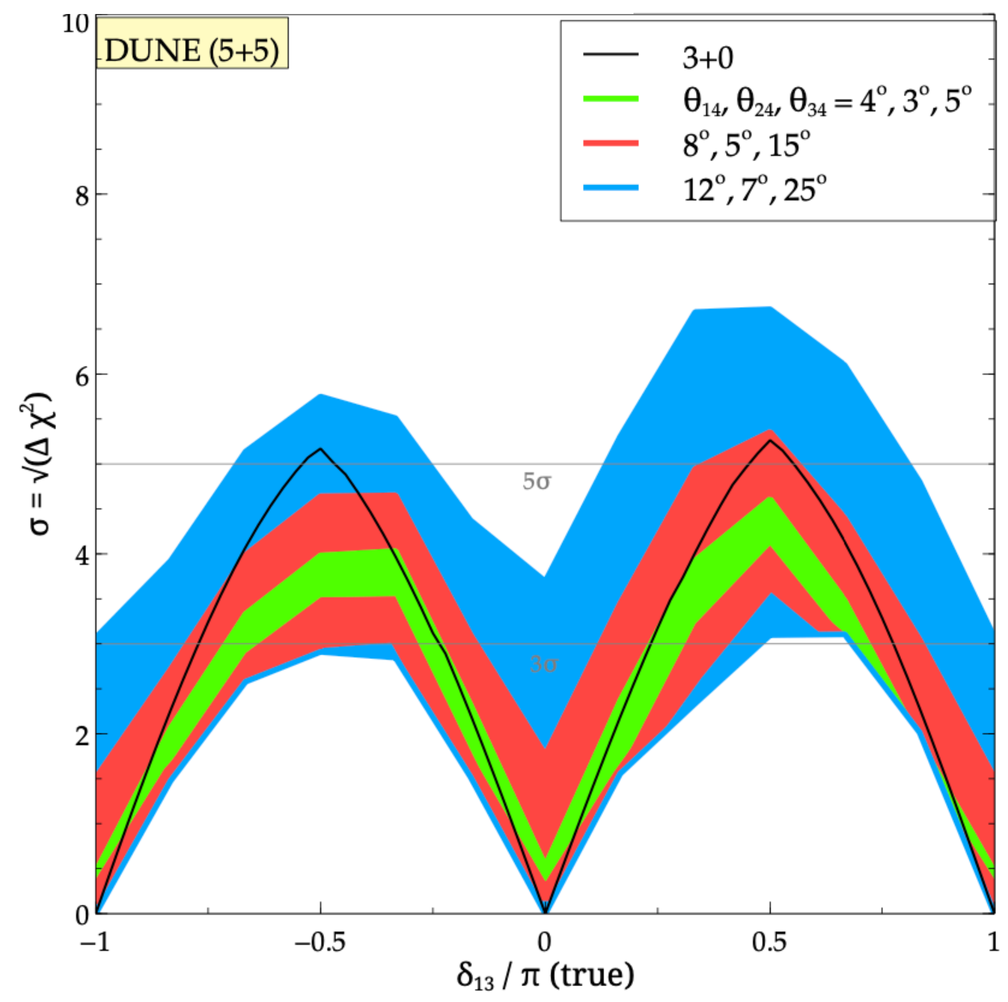
if $\Delta \equiv \Delta_{13} \simeq \Delta_{23} \gg 1$ → $\langle \sin^2 \Delta \rangle = 1/2$

osc. averaged out by finite E resol.

It can be: $A^{CP}_{\alpha\beta} \neq 0$ (if sin δ = ∅)

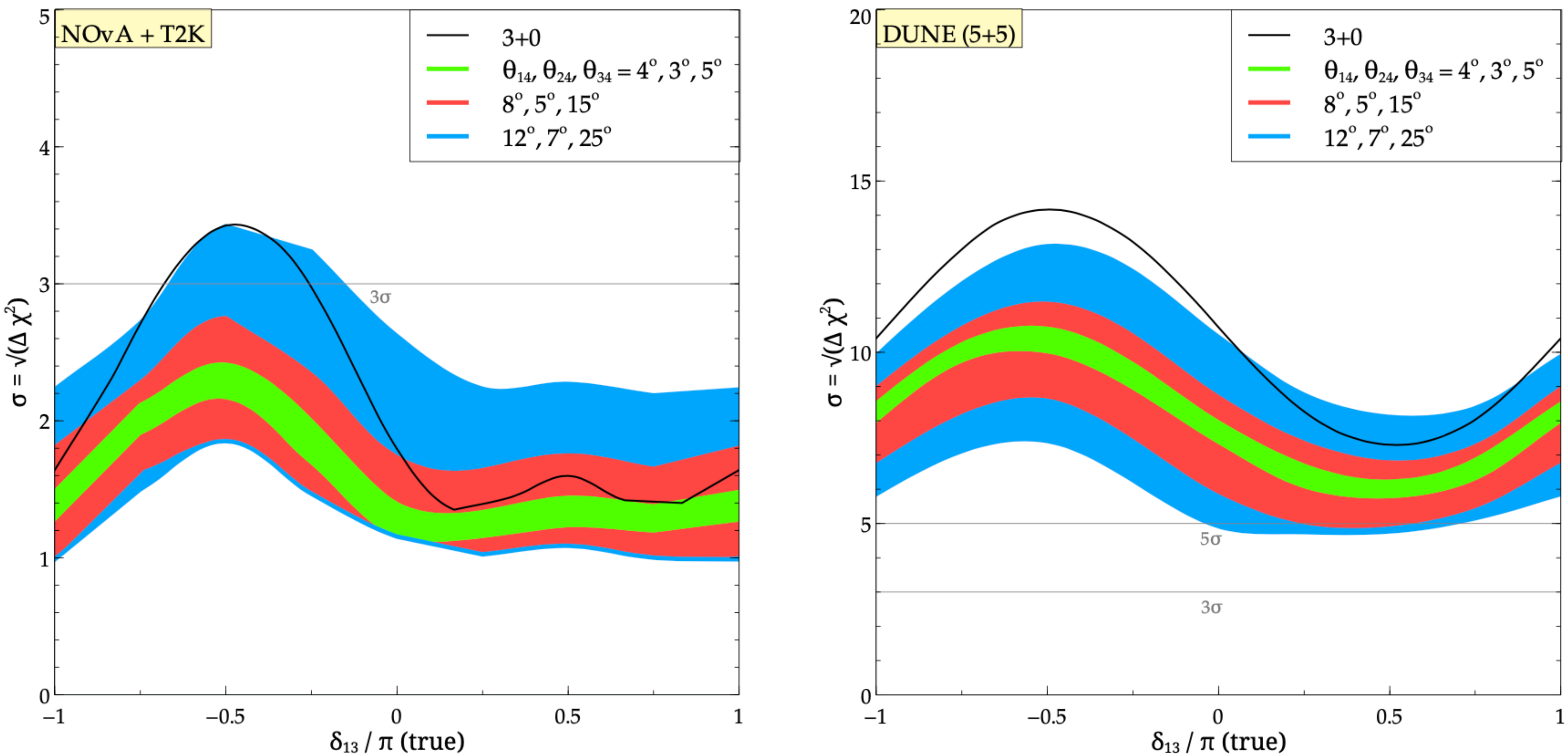
Dutta, Gandhi et al. arXiv: 1607.02152





Impact on MH

Dutta, Gandhi et al. arXiv: 1607.02152



☑ Significant effect of sterile mixing and phases, reduction of sensitivity is mostly due to marginalization over large parameter space.

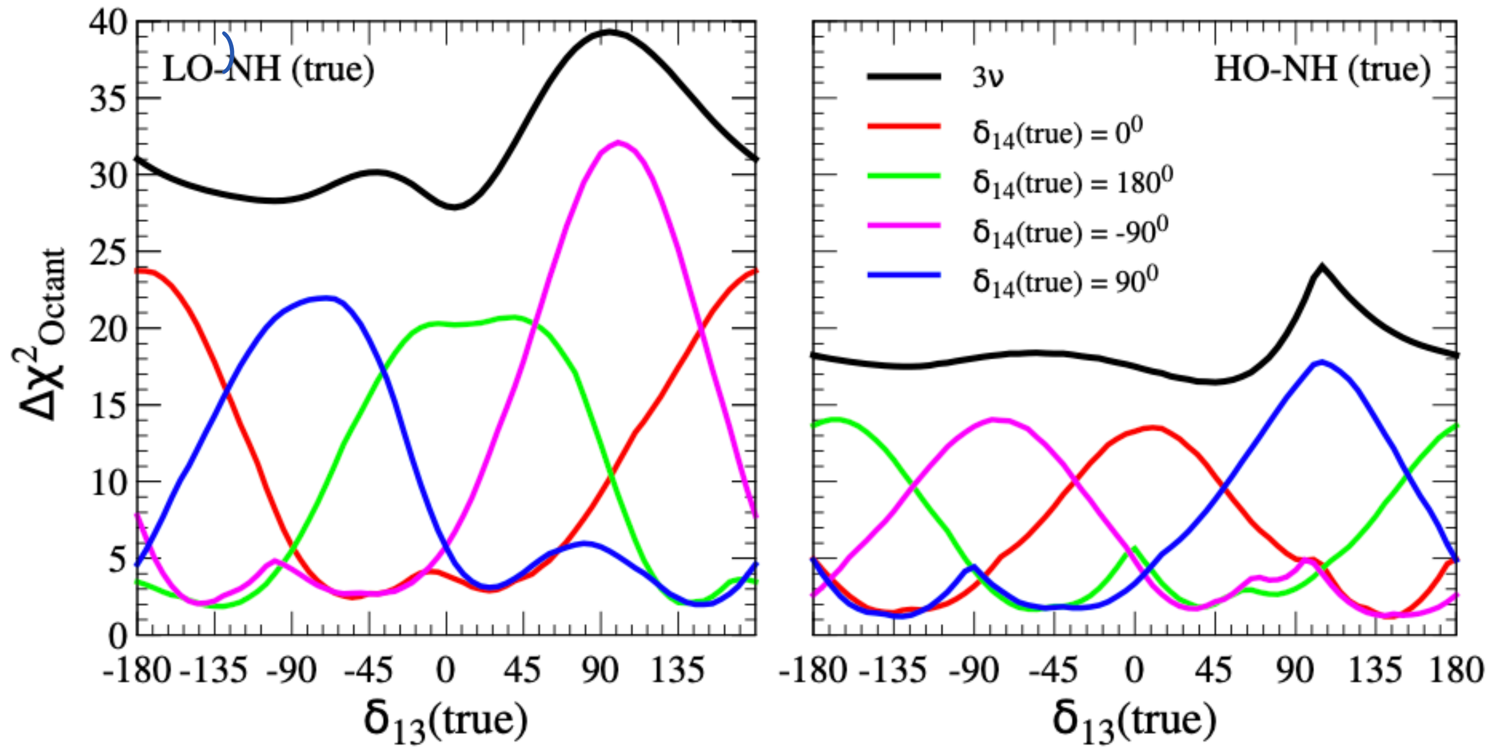
Other studies performed to understand MH , here are few of them :

Agarwalla, Chatterjee, et al. (arXiv:1603.03759), Berryman et al.(arXiv:1507.03986), Chattopadhyay, Devi et al. (arXiv: 2211.03473) and many more .....

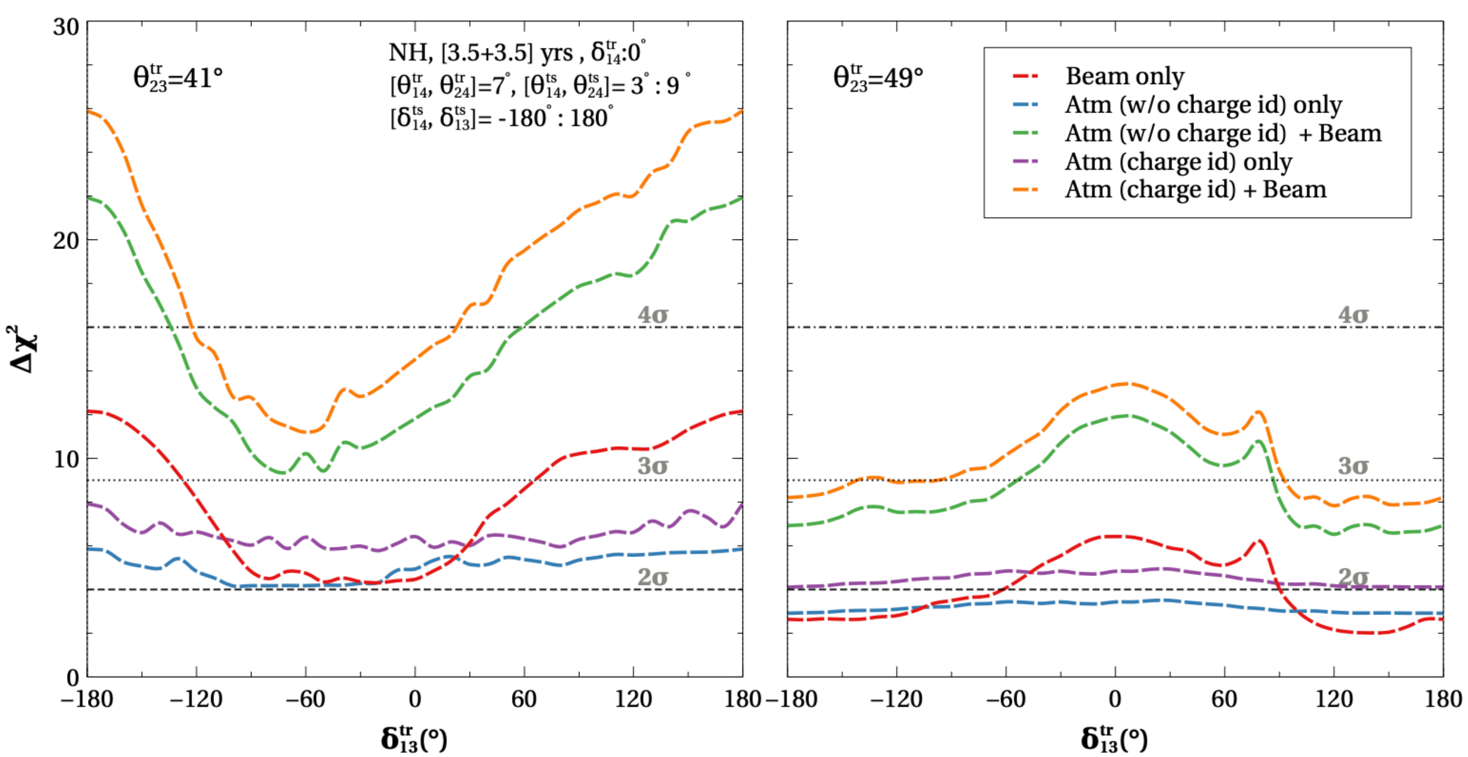
Octant of θ_{23}

- ☑ 3+1 scheme there exist unfavorable combinations of δ_{13} (true) and δ_{14} (true) for which the octant sensitivity falls below the 2σ level

Agarwalla, Chatterjee, et al. (Phys.Rev.Lett. 118 (2017) 3, 031804)



Chatterjee, Goswami, Pan (arXiv: 2212.02949)



- ☑ This study shows 3σ sensitivity can be achieved for the octant if beam and atmospheric data combined in DUNE

Detailed talk by Suprio Pan

Snowmass White paper on light Sterile neutrino

White Paper on Light Sterile Neutrino Searches and Related Phenomenology

NF02 Contributed Paper to Snowmass 2021

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Outlook

- The simplest theoretical interpretation of the outstanding short-baseline anomalies in neutrino physics, namely, the light sterile neutrino within the context of a 3+1 model
- Despite significant progress in the form of new experimental measurements and theoretical development, the short-baseline experimental neutrino anomalies remain unresolved
- MicroBooNE first searches for low-energy excess found no evidence of excessive events as seen by MiniBooNE, but not ruled out sterile hypothesis
- Different experimental efforts (accelerator-based short/long-baseline, reactor- based short-baseline, atmospheric neutrinos, and radioactive source) will provide solution of the anomalies

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Thank you