

Sterile Neutrinos Theory Overview



IOWA

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UC Irvine

The three-neutrino oscillation picture is becoming sharper.

The origin of neutrino masses, however, remains as blurry as ever.

Why is this exciting:

Extrapolating the logic of the Higgs mechanism to neutrinos leads us to a very strange particle: **right-handed** or “**sterile**” or **singlet** neutrino ν_R

Does not play by Standard Model rules: ~~$SU(3) \times SU(2) \times U(1)$~~





For example: ν_R admits a Majorana mass m_R .
Possibly unrelated to the **electroweak scale** $\langle h \rangle$.

$$\begin{pmatrix} \vec{\nu}_L & \vec{\nu}_R \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix} \begin{pmatrix} \vec{\nu}_L \\ \vec{\nu}_R \end{pmatrix} \quad \begin{matrix} (3 \times 3) & (3 \times ?) & (? \times ?) & (? \times 3) \\ M_\nu \sim M_D M_R^{-1} M_D^T \end{matrix} \quad U = \left(\begin{array}{c|c} U'_{\text{PMNS}} & U_{\alpha I} \\ \hline U_{si} & U_{sI} \end{array} \right)$$

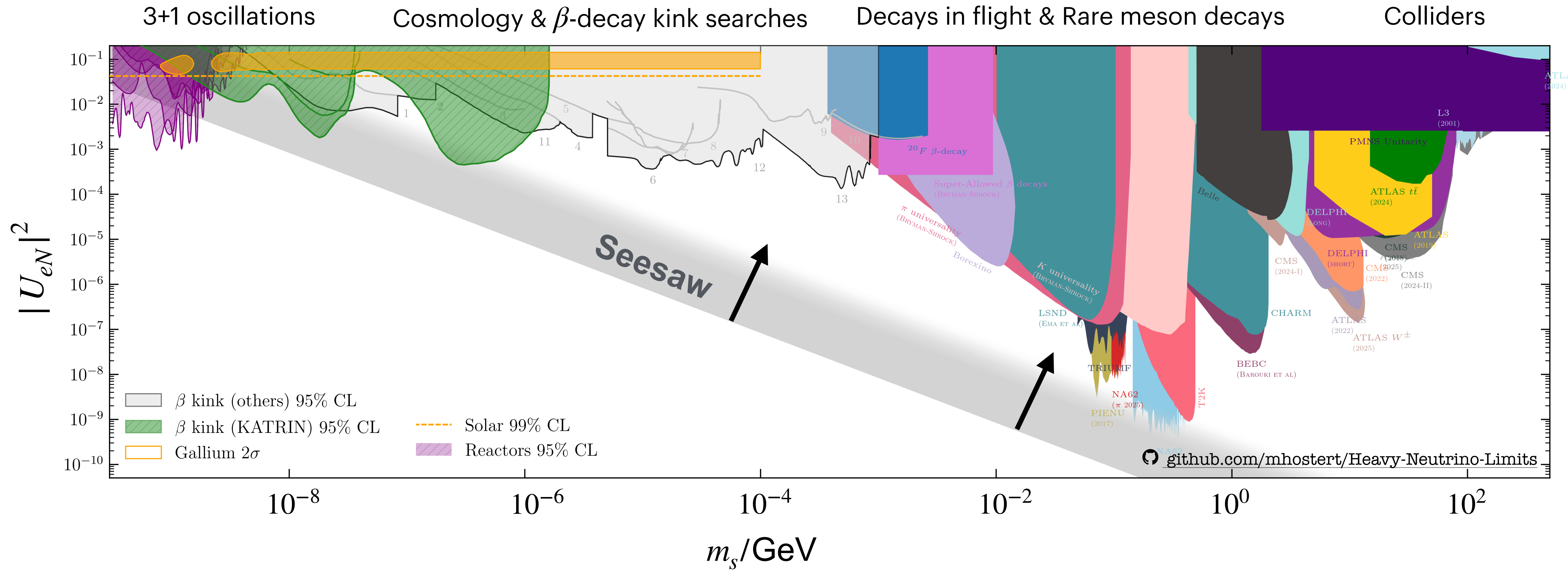
We know nothing about neutral lepton **mass and mixing matrix** U .

Size of Majorana masses? New symmetries? Dynamics?

See talk by [Ks Babu](#), [M. Schmidt](#) & [B. Dev](#)

Sterile neutrinos may very well be light particles

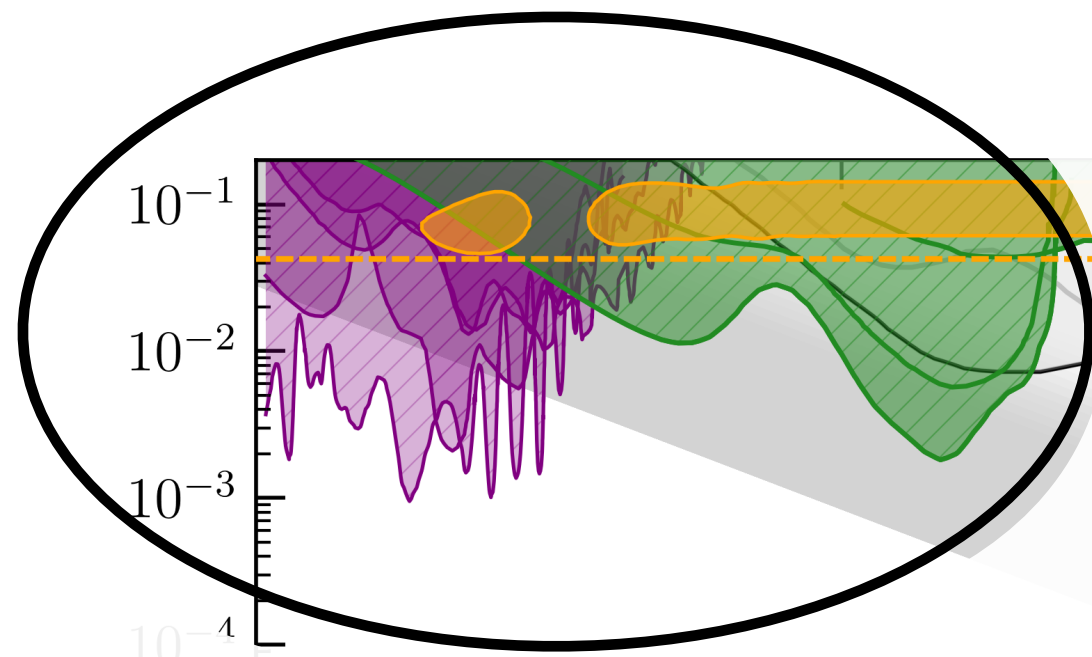
Can be within reach of experiments



See talks by [K. Kelly](#) & [R. Zukanovich Funchal](#)

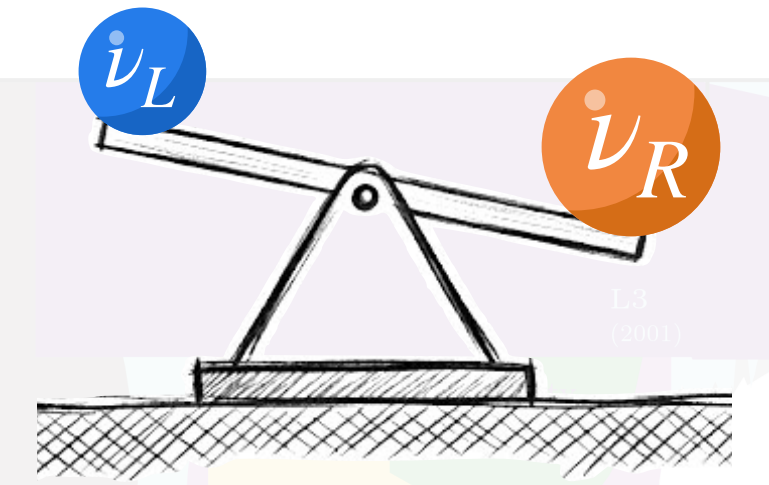
eV Sterile Neutrinos

3+1 oscillations



A small lever arm “seesaw”:

$$m_\nu \sim \frac{m_D^2}{m_s}, \quad m_s \sim \mathcal{O}(1 \text{ eV}) \implies \theta^2 \sim \frac{m_\nu}{m_s} \sim \mathcal{O}(10^{-2})$$



It makes sense that light steriles come with large mixing angles.
 Could also just be a seesaw'ed state that happens to be mostly sterile.

In any case, eV steriles **not a prediction** of the seesaw, but can be **accommodated** within it.

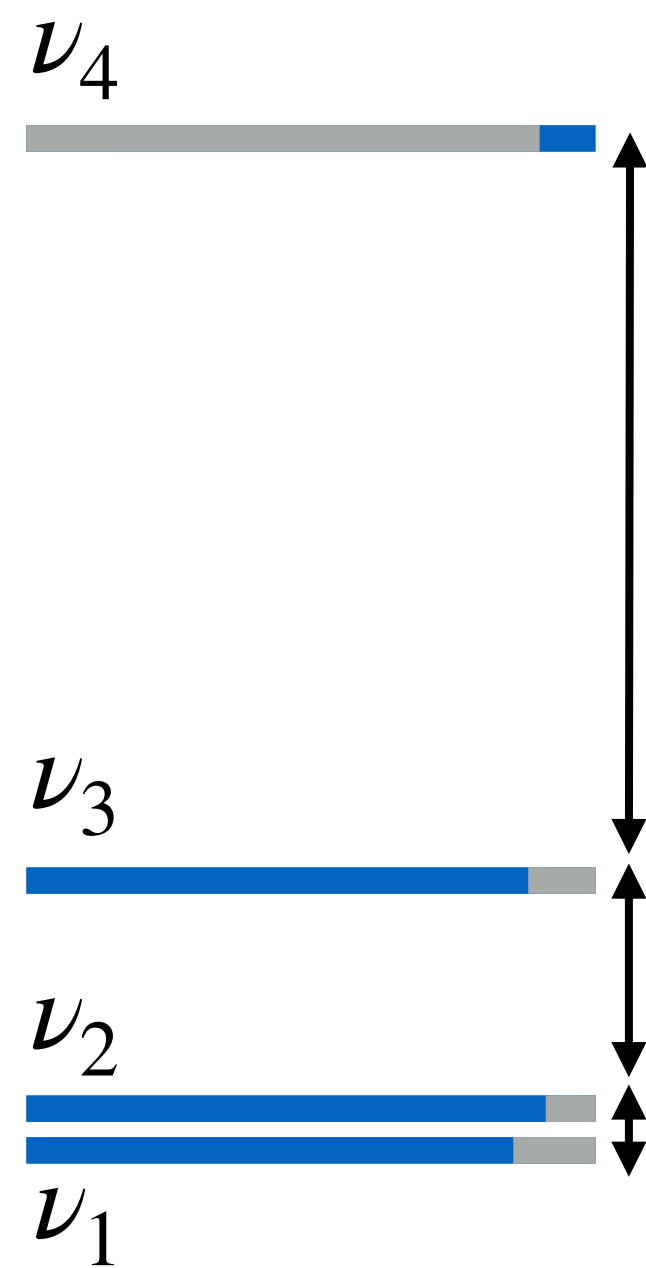
What does the data say?

See, e.g., A. de Gouvêa, [PRD 72 \(2005\) 033005](#), A. de Gouvêa, J. Jenkins, and N. Vasudevan, [PRD 75, 013003](#)

Extended seesaws: H. Zhang, [PLB 714 \(2012\) 262-266](#), J. Barry, W. Rodejohann, H. Zhang, [JHEP 07 \(2011\) 091](#)

3 (active) + 1 (sterile) neutrino oscillations

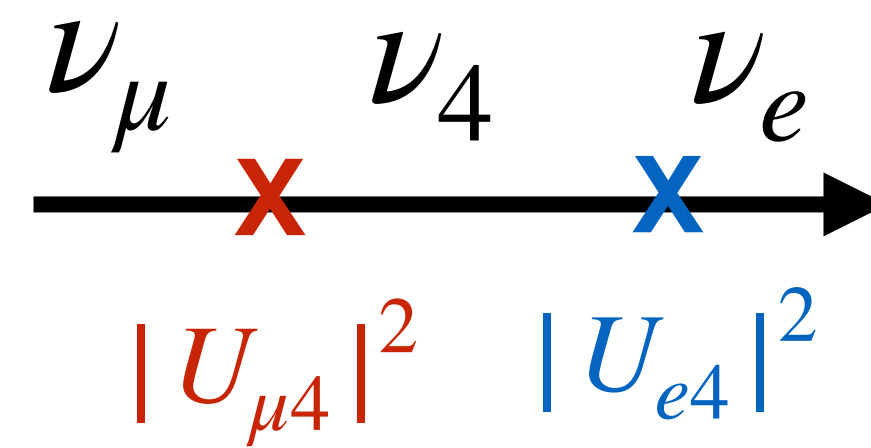
Effectively a 2ν oscillation system with L/E of **km/GeV** or **meters/MeV**



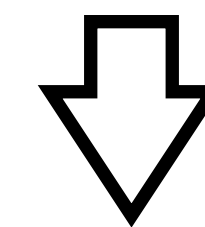
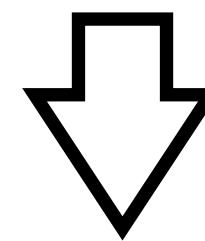
$$\Delta m_{43}^2 \simeq \Delta m_{41}^2$$

$$\Delta m_{32}^2$$

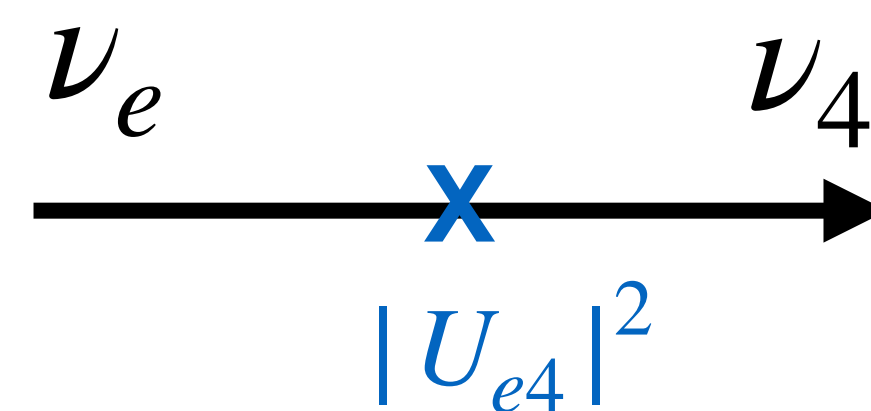
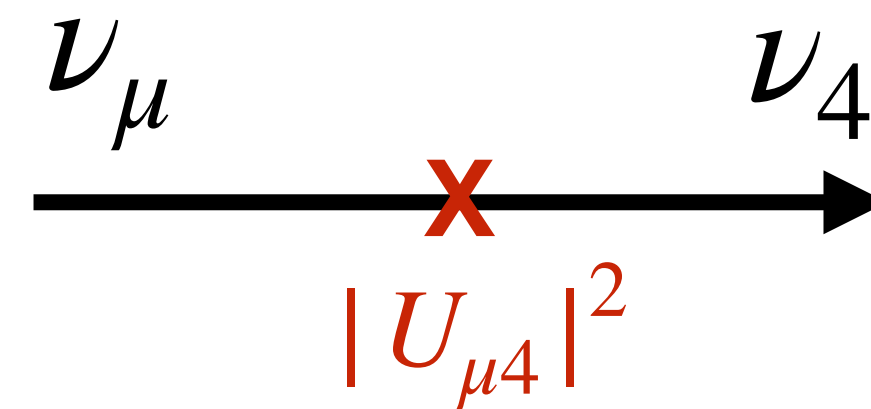
$$\Delta m_{21}^2$$



Appearance



Implies



Disappearance

Appearance Experiments

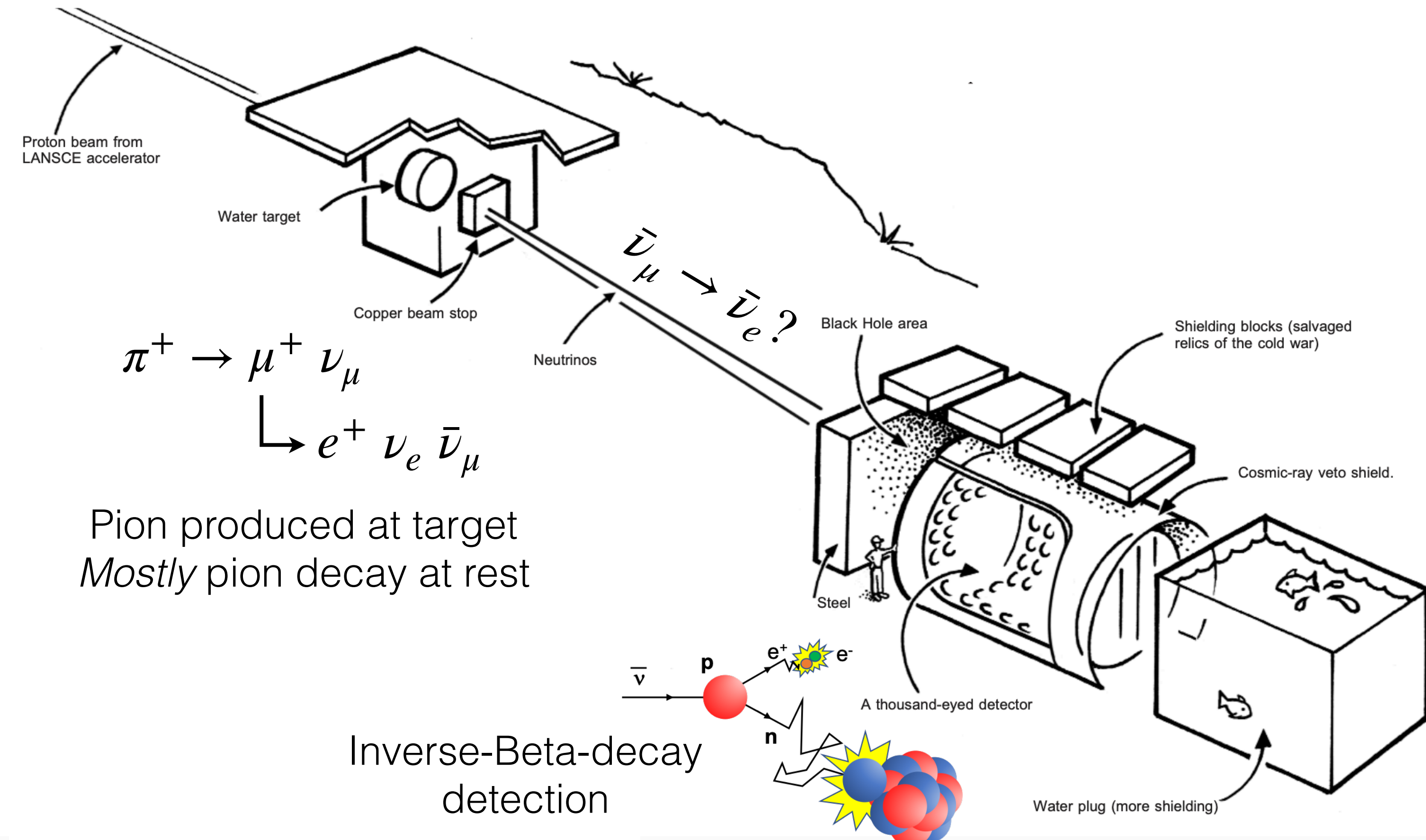
Anomalies in $\nu_{\mu} \rightarrow \nu_e$ and $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$

1990s: LSND and the excess of IBD events

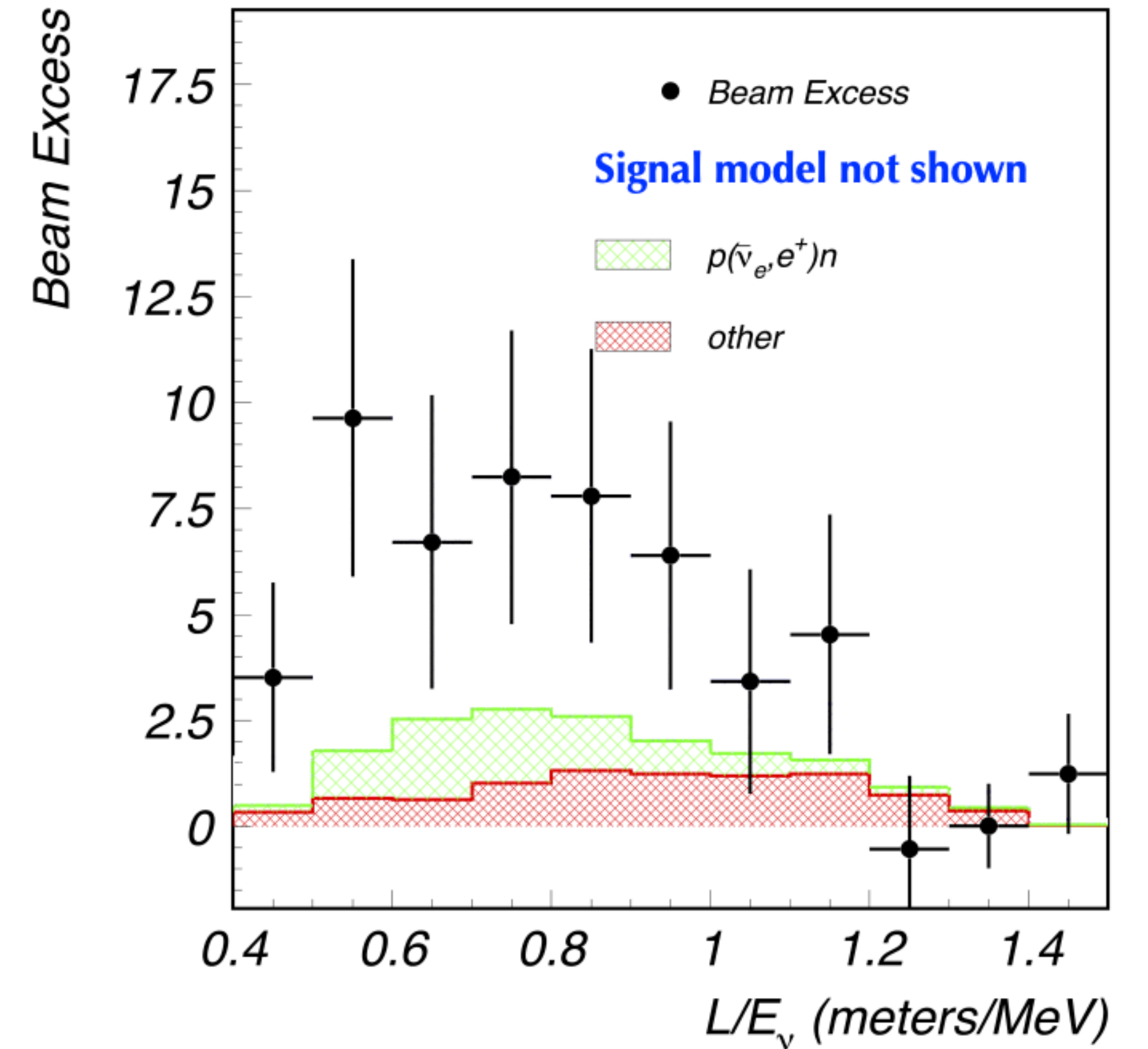
Los Alamos 800 MeV protons, 1.8×10^{23} POT \sim 0.3 moles

$L = 30$ meters to \sim 167 tonnes of Liquid Scintillator

A Thousand Eyes: The story of LSND



Lauren Yates, adapted from PRD 64 (2001) 112007



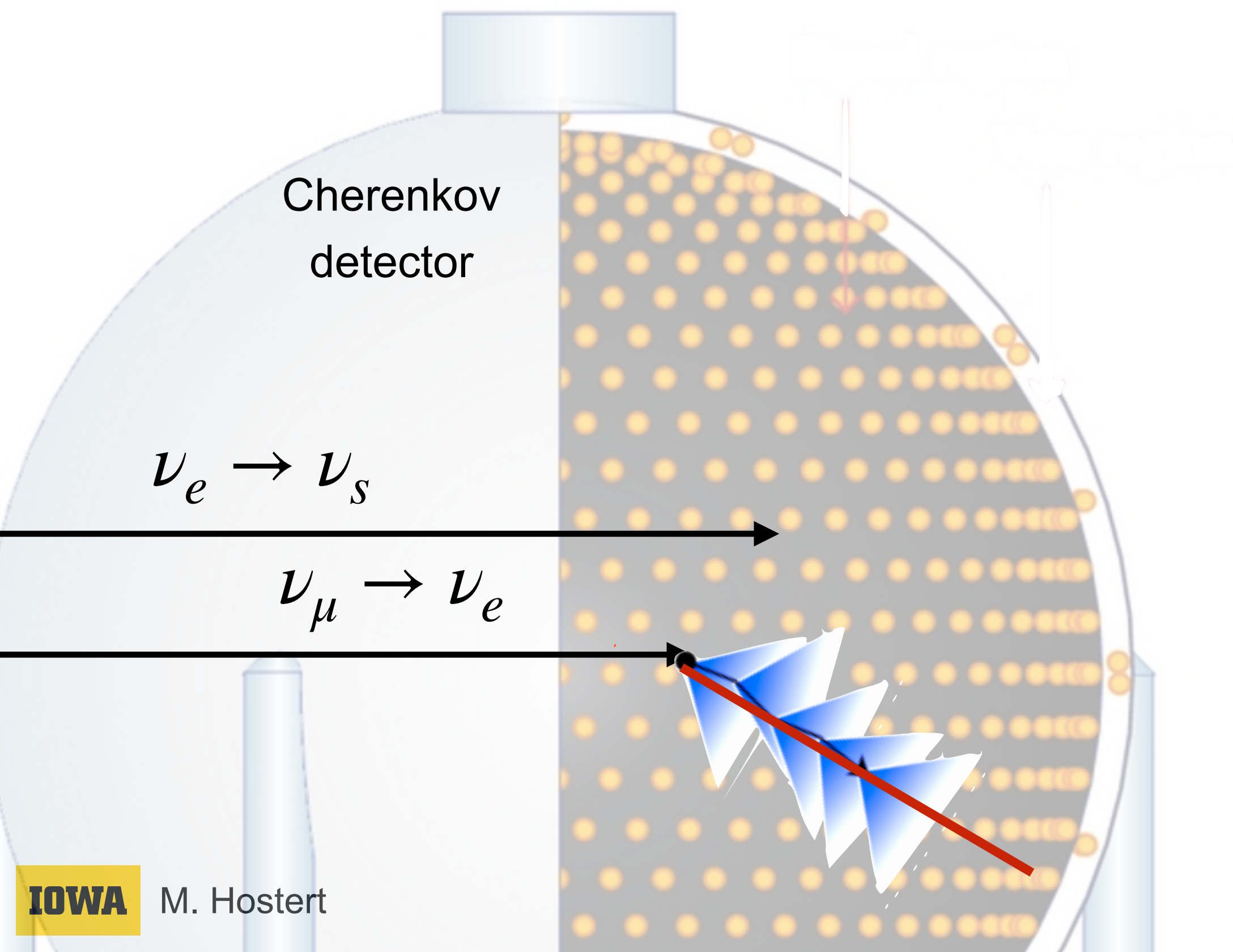
Excess: $87.9 \pm 22.4 \pm 6$ events

3.8σ significance

2000s: MiniBooNE and the ν_e -like Low-Energy Excess

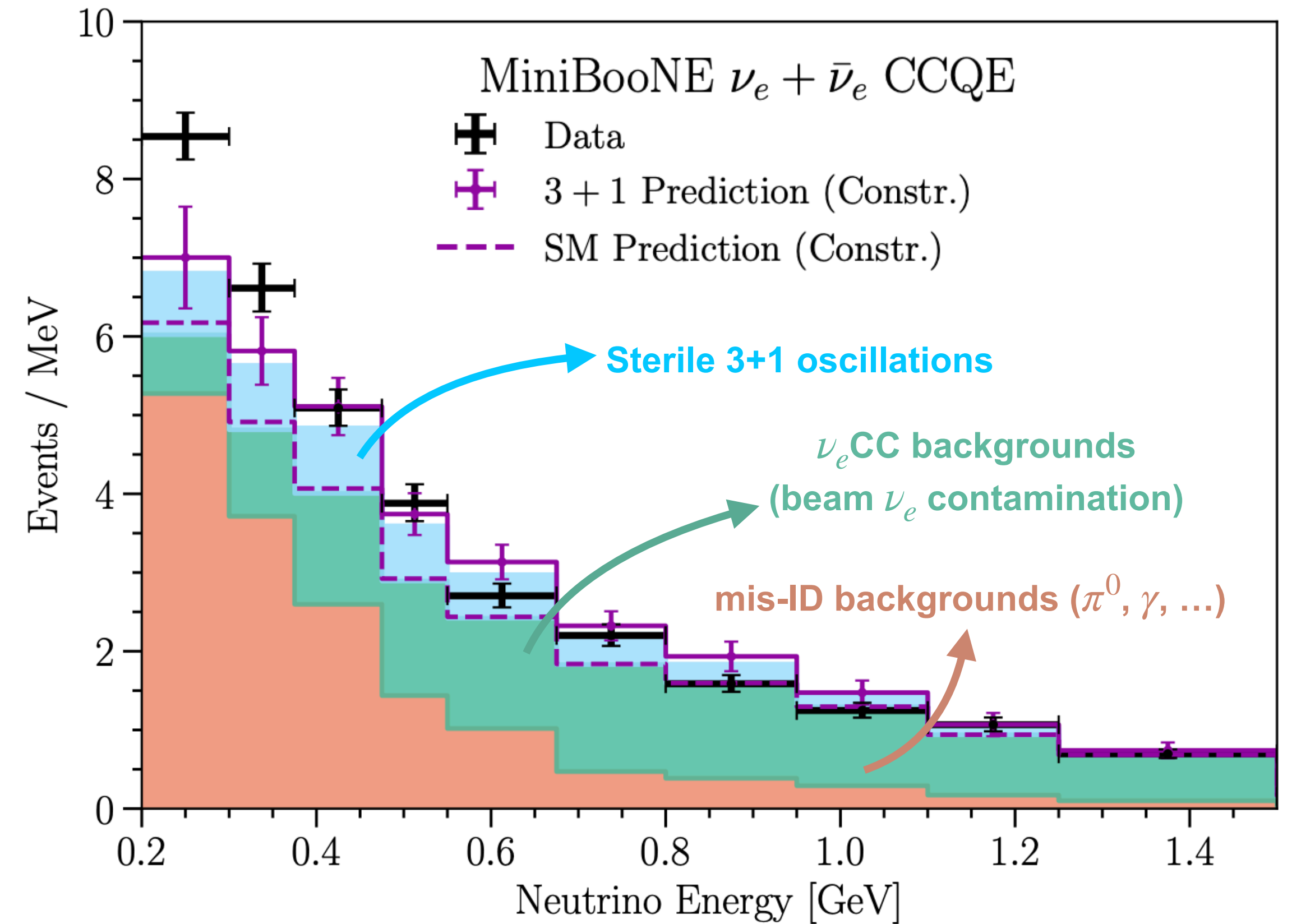
Booster Neutrino Beam 8 GeV p^+
 π and K decay in flight

- 18.75×10^{20} POT neutrino mode
- 11.27×10^{20} POT antineutrino mode



MiniBooNE coll., [PRD 103, 052002 \(2021\)](#)

Adapted from MiniBooNE coll., [PRL129 \(2022\) 20, 201801](#)



$$638 \pm 52(\text{stat.}) \pm 122.2(\text{sys.})$$

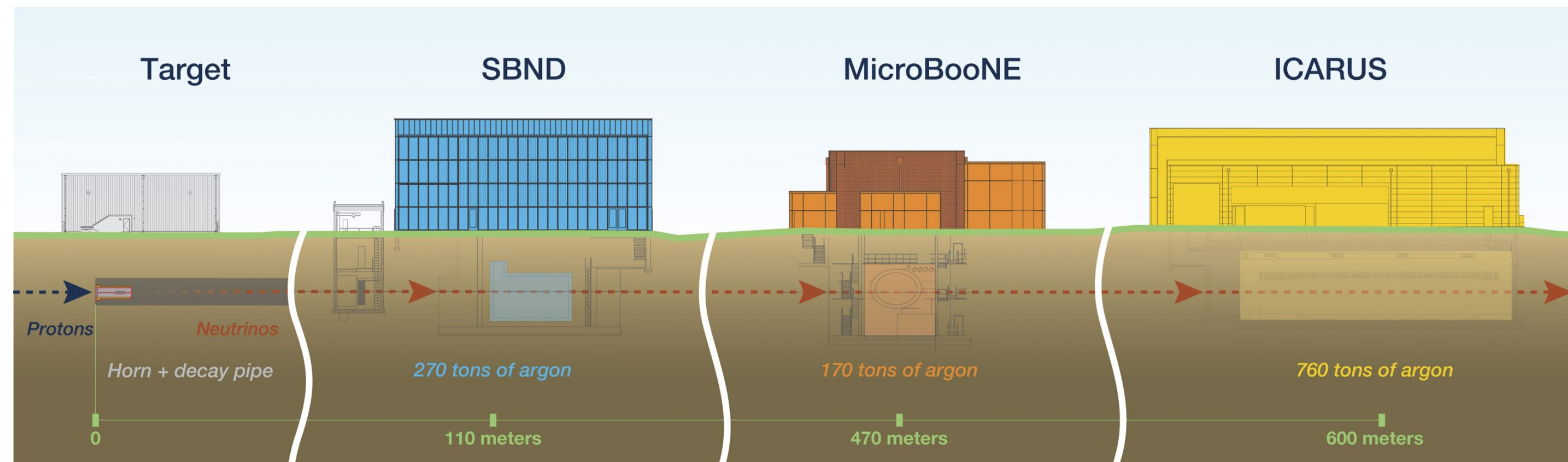
4.6 σ preference of **full 3+1 oscillations**

over background-only hypothesis.

Current “direct” tests of the appearance signals (this session)

MicroBooNE and SBND Program

Use both **BNB on-axis** (same as MiniBooNE) and **NuMI off-axis** at Fermilab



LArTPC can help resolve MiniBooNE low-energy excess into

$$\gamma / \gamma\gamma / e^{\pm} / e^{+}e^{-}$$

J. Hyun (**MicroBooNE**) & M. Mooney (**ICARUS**) & L. Wan (**SBND**)

JSNS²-I and JSNS²-II

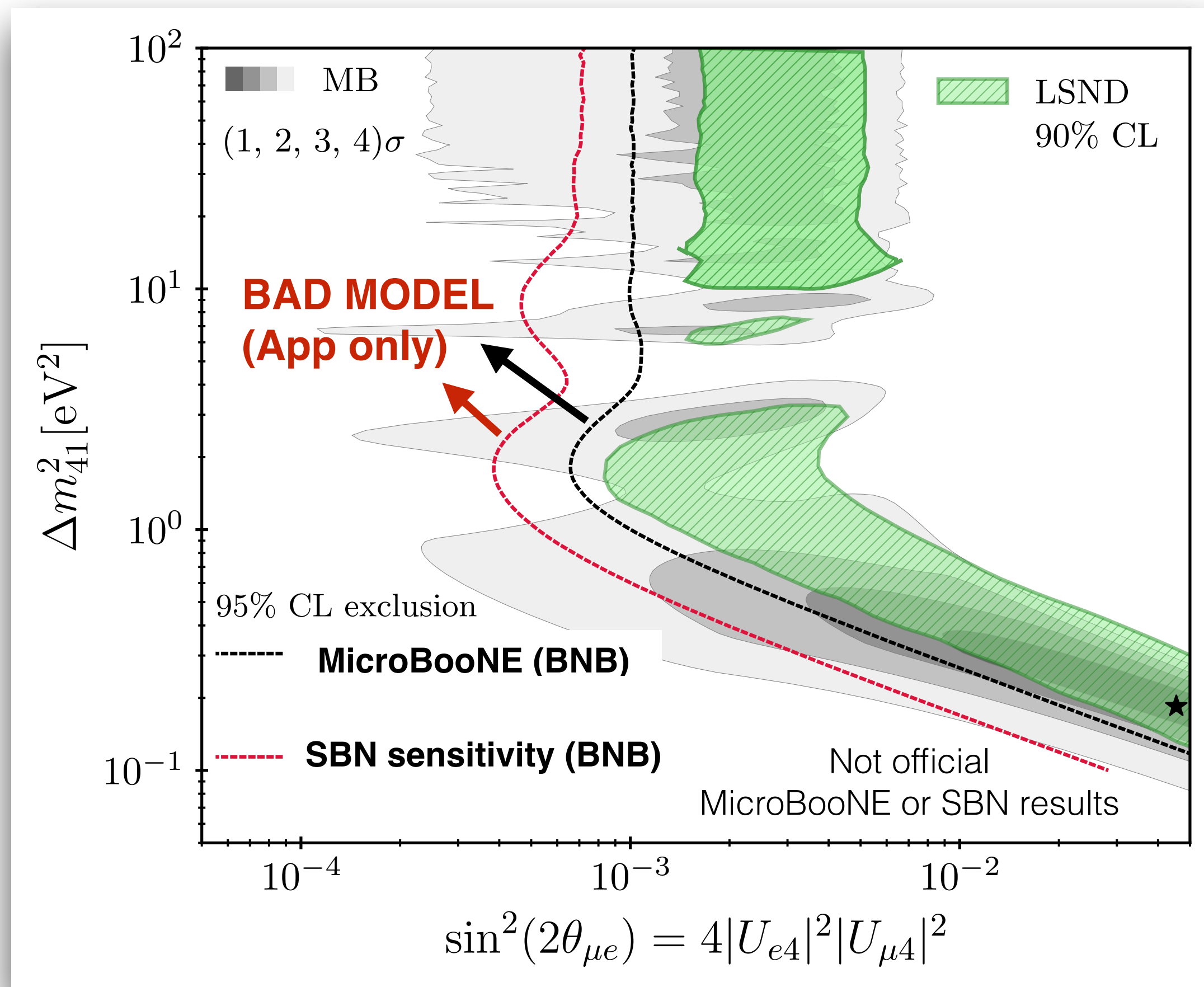
LSND test with IBD events at JSNS (J-PARC)



D. Lee (**JSNS²**)

Pitfalls of profiling and Appearance vs Disappearance degeneracy

O. Benevides Rodrigues, MH, K. J. Kelly,
B. Littlejohn, P. A. N. Machado, I. Safa, T. Zhou [PRL 135, 081801](#)

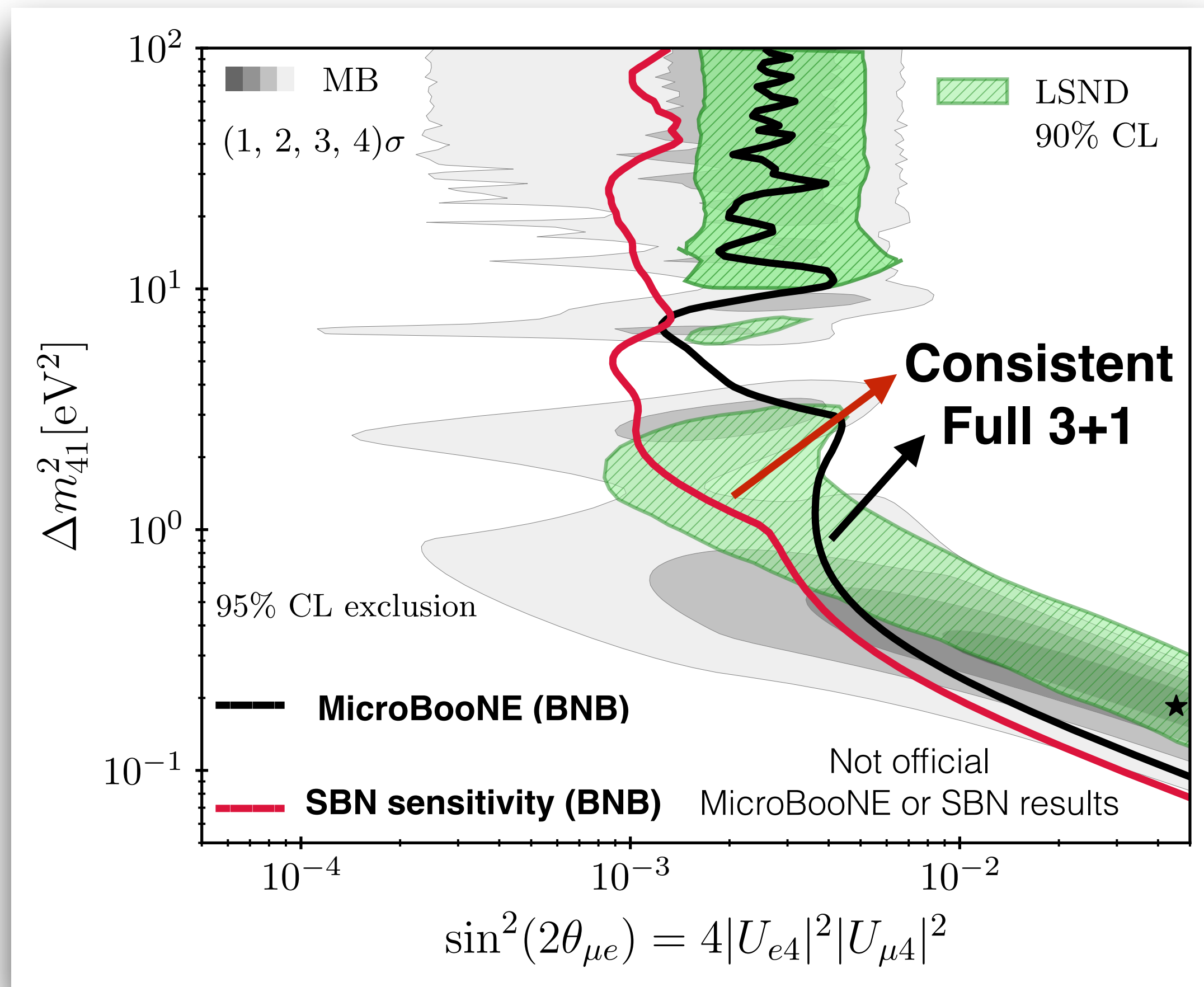


For historical reasons, many analyses were done using an “**appearance only**” model.

This is okay for LSND.

Pitfalls of profiling and Appearance vs Disappearance degeneracy

O. Benevides Rodrigues, MH, K. J. Kelly,
B. Littlejohn, P. A. N. Machado, I. Safa, T. Zhou [PRL 135, 081801](#)



For historical reasons, many analyses were done using an “**appearance only**” model.

This is okay for LSND.

For MiniBooNE, MicroBooNE, and SBN, this **fails: backgrounds can oscillate** and counteract effect of $\nu_{\mu} \rightarrow \nu_e$ appearance.

Results shown in a **2D (profiled!) plane** look much less exciting...

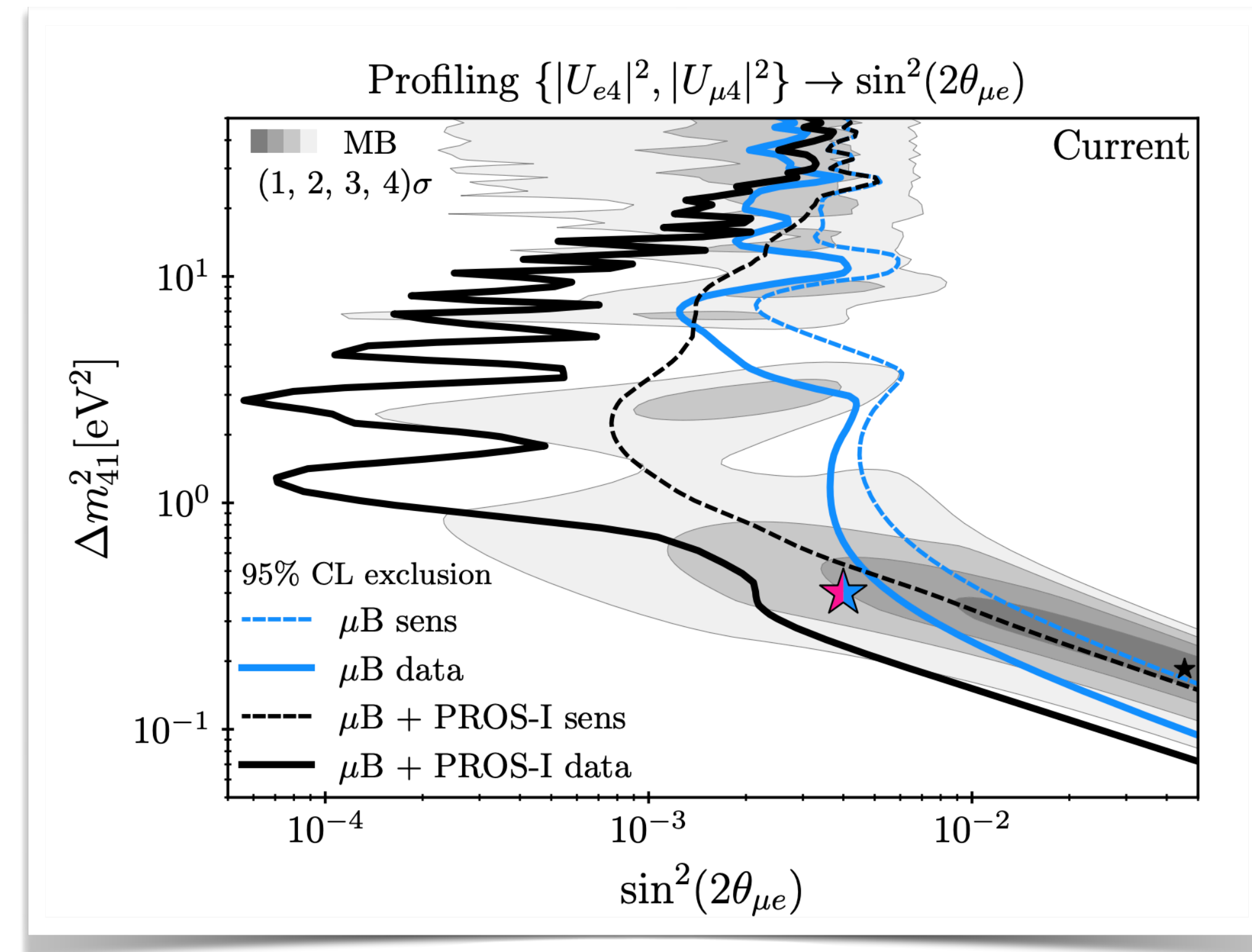
Three solutions to what “appears” to be a problem

- 1) Use more than one source, with **complementary flavor composition** (different ν_e “contamination”)

BNB + NuMI data helps break the degeneracy

MicroBooNE coll. [Nature 648, 64-69 \(2025\)](#)
- 2) Use **external constraints on ν_e disappearance** (Using PROSPECT data. Could also consider KATRIN.)
- 3) Do not compare independently-profiled regions. Assess coverage in 3D space.

O. Benevides Rodrigues, *MH*, K. J. Kelly, B. Littlejohn, P. A. N. Machado, I. Safa, T. Zhou [PRL 135, 081801](#)



The 2.3σ **MicroBooNE** exclusion already covers the 2.3σ **MiniBooNE** allowed region.

The $> 5\sigma$ **SBN** sensitivity covers the entire 2σ **MiniBooNE** region.

Disappearance Experiments

Lessons from the ν_e and ν_μ sectors

ν_e disappearance \rightarrow deficit

Sterile neutrino interpretation requires unrealistically large mixing angles

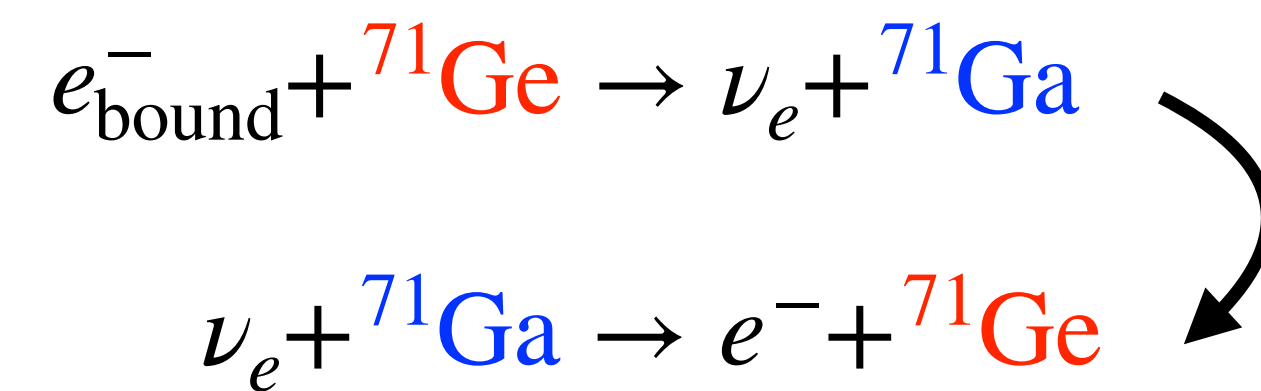
$\gtrsim 3\sigma$ tension with solar measurements

M. C. Gonzalez-Garcia, M. Maltoni, J. Paulo Pinheiro
 PLB 862 (2025) 139297

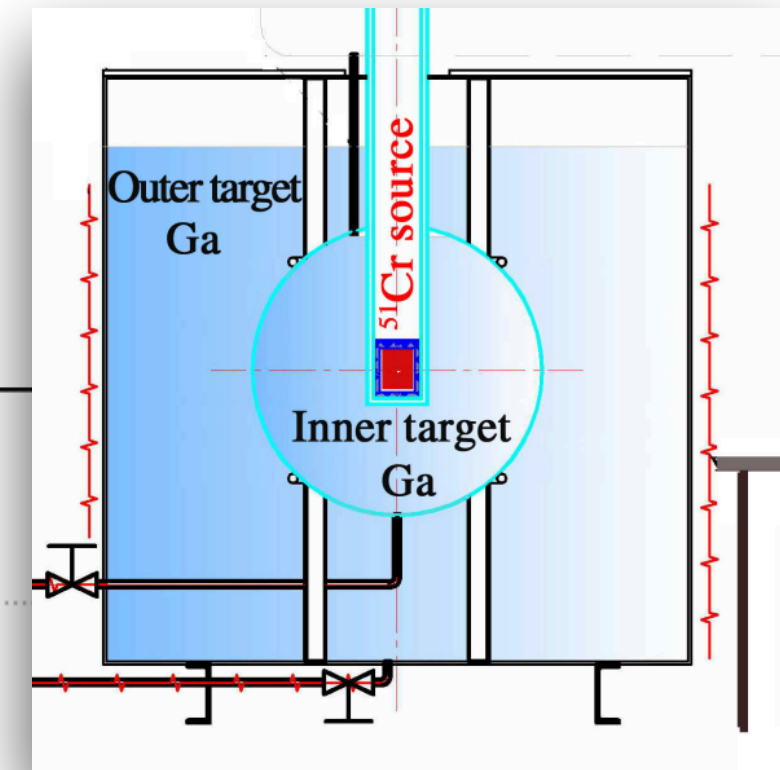
Recently:

Detailed balance method called into question.

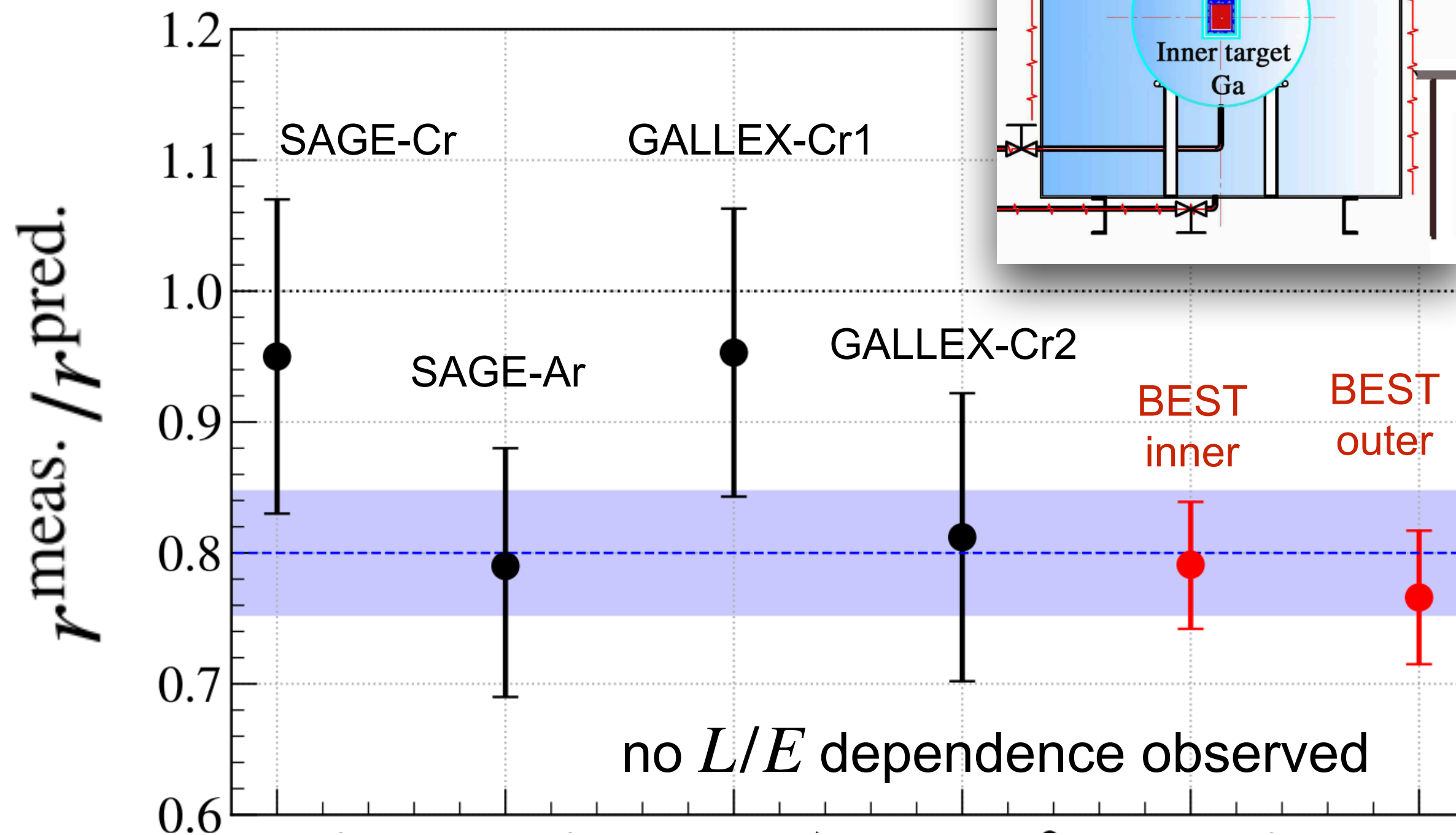
M. Cadeddu, N. Cargioli, F. Dordei, L. Ferro, C. Giunti, and M. Pitzalis, [arXiv:2512.20560](https://arxiv.org/abs/2512.20560)



Find that assumption of leptonic & nuclear wave function factorization can bias ν_e capture cross section.



Adapted BEST coll.
 PRC 105 (2022) 6, 065502

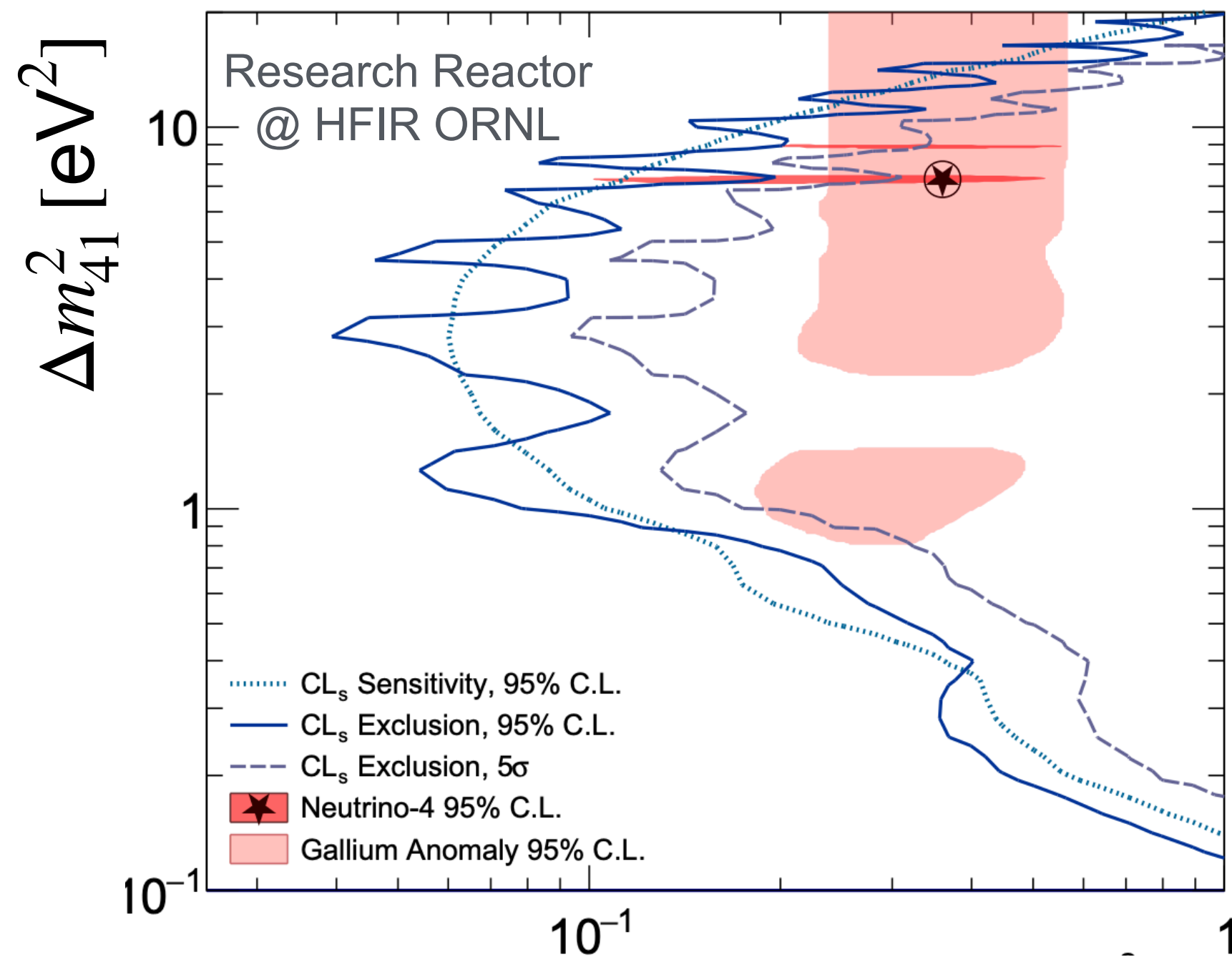


Gallium anomaly
 Close to 5σ when combined

Null results at reactors ($\bar{\nu}_e$)

Talk by [C. Zhang](#) earlier today

PROSPECT coll. [PRL 134 \(2025\) 15, 151802](#)



$$\sin^2 2\theta_{ee} = 4 |U_{e4}|^2 (1 - |U_{e4}|^2)$$

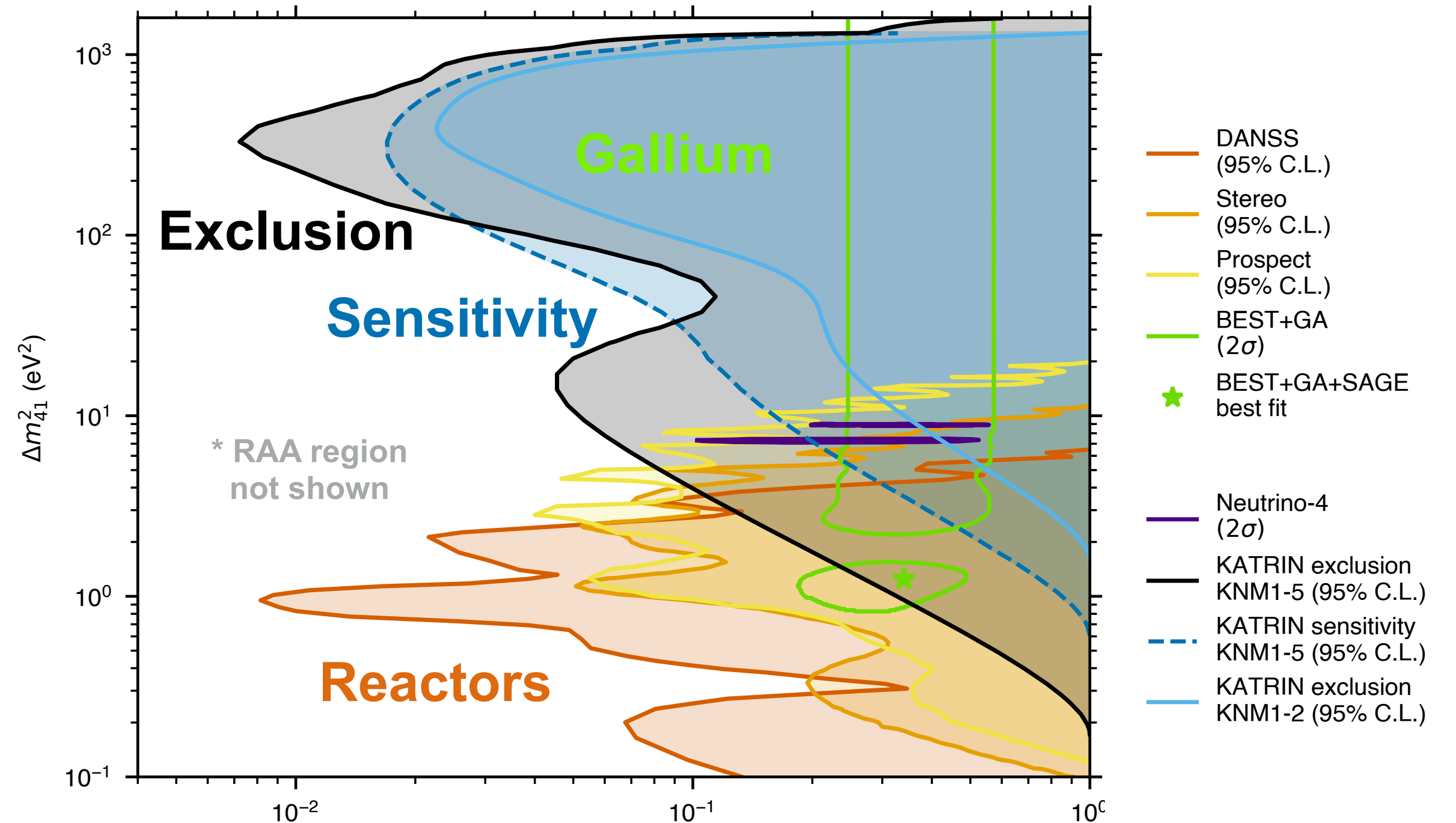
Consistent with DANNS, STEREO, NEOS, DayaBay, and others.

See also global analysis

J. M. Berryman, P. Coloma, P. Huber, T. Schwetz, A. Zhou,
[JHEP 02 \(2022\) 055](#)

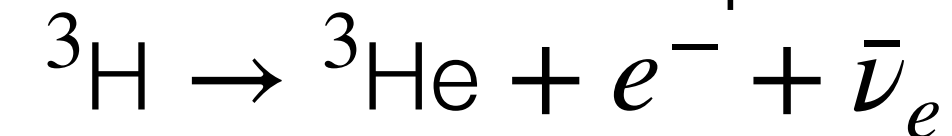
Null results at KATRIN

Adapted from KATRIN coll. [Nature 648 \(2025\) 8092, 70-75](#)



$$\sin^2 2\theta_{ee} = 4 |U_{e4}|^2 (1 - |U_{e4}|^2)$$

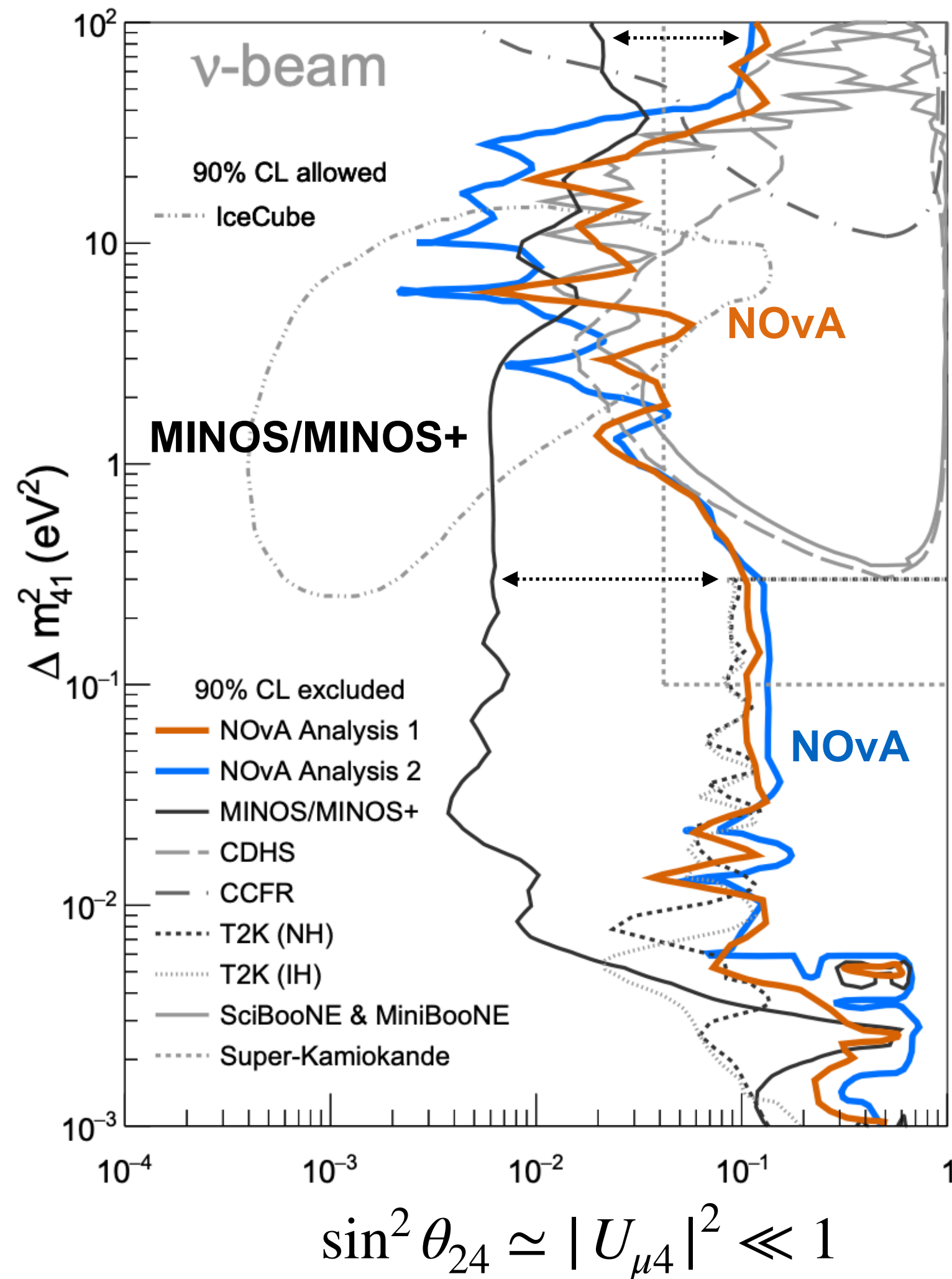
Kink search on beta spectrum of



Sensitive to **kinematics**, not oscillation.

ν_μ disappearance

Adapted from
NOvA coll. PRL 134, 081804 (2025)



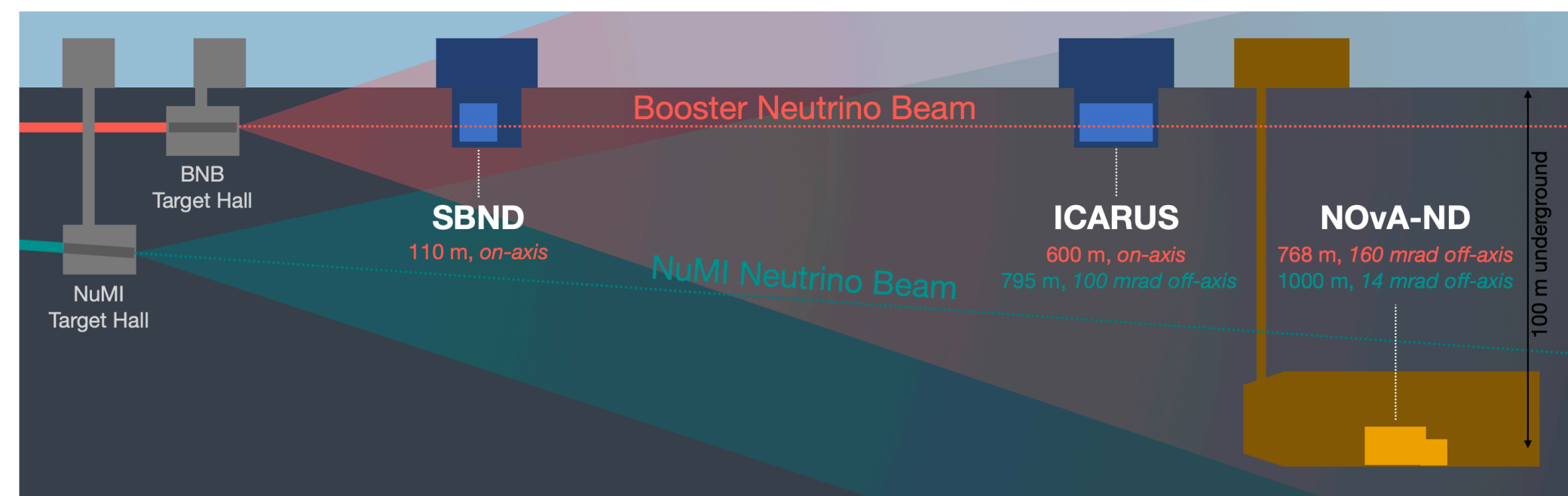
Two detector fit for CC and NC events.

Near detector: short-baseline (sterile oscillation)
Far detector: long-baseline (standard oscillation)

No ν_μ disappearance observed.

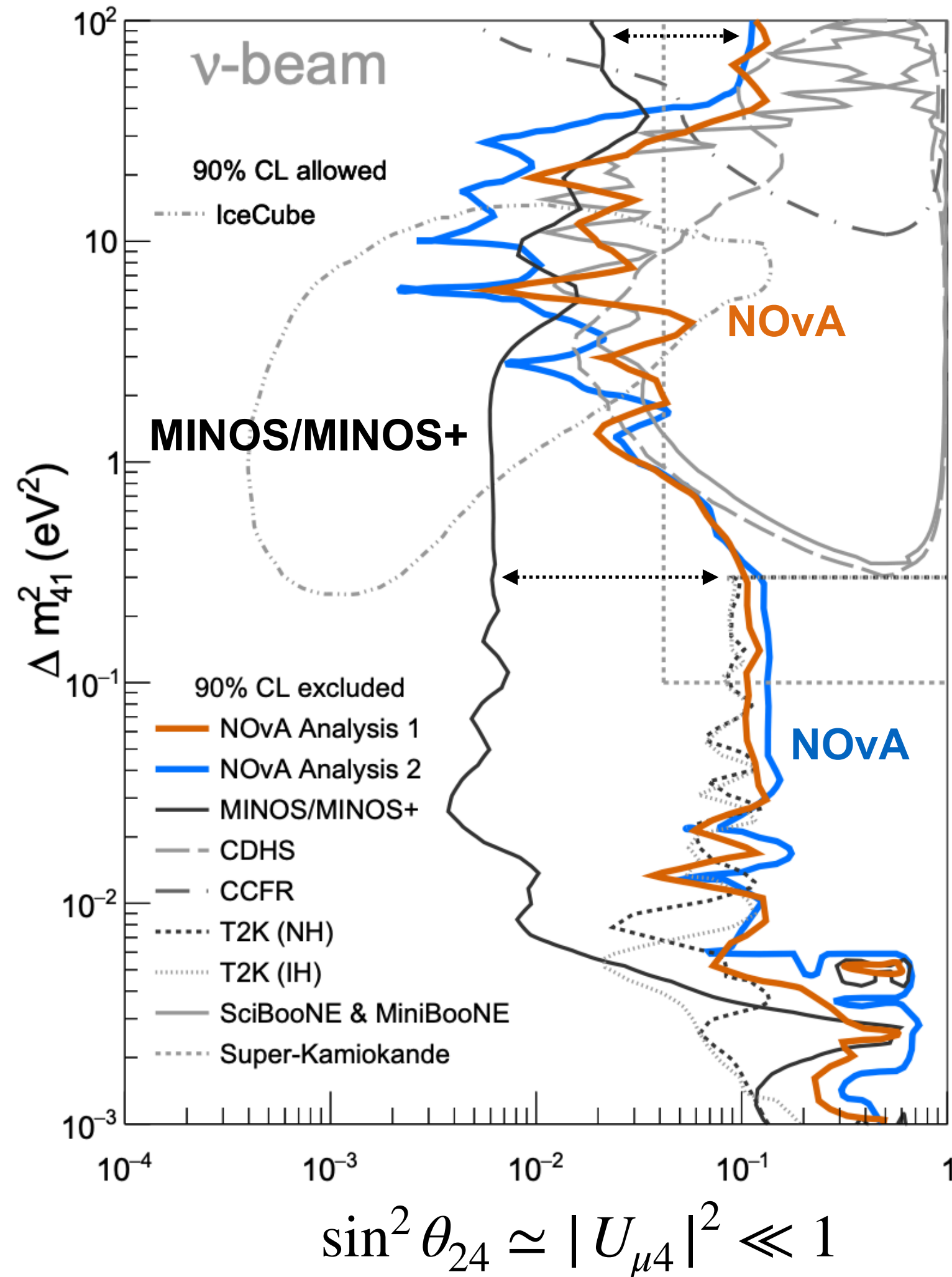
Interesting ideas to use
BNB for **NOvA** near detector

A. Lister (NOvA coll., NuPhys 2026)



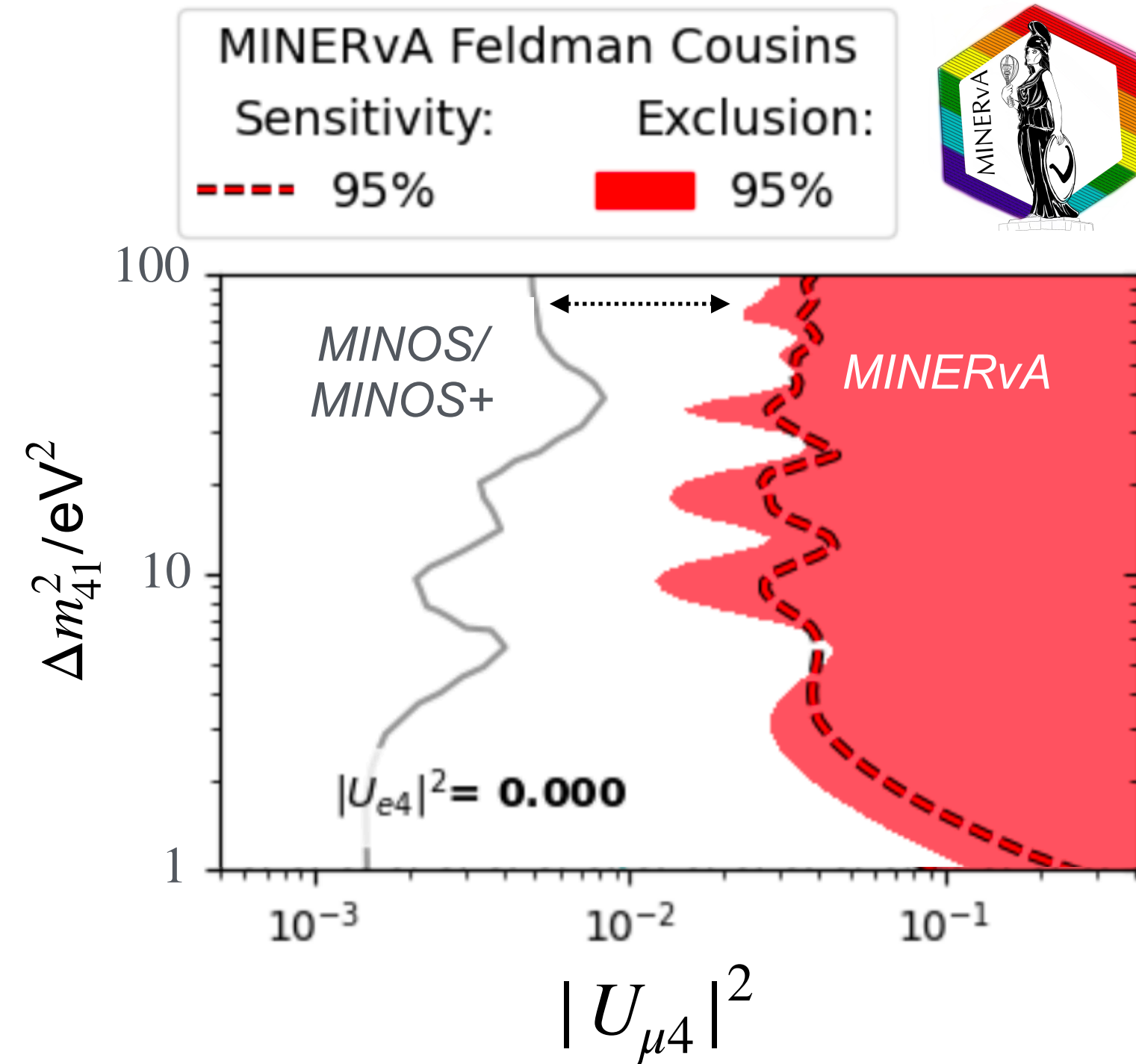
ν_μ disappearance

Adapted from
NOvA coll. PRL 134, 081804 (2025)



MINERvA

Adapted from Ryan Howell,
Fermilab W&C Seminar, Sept 5th, 2025

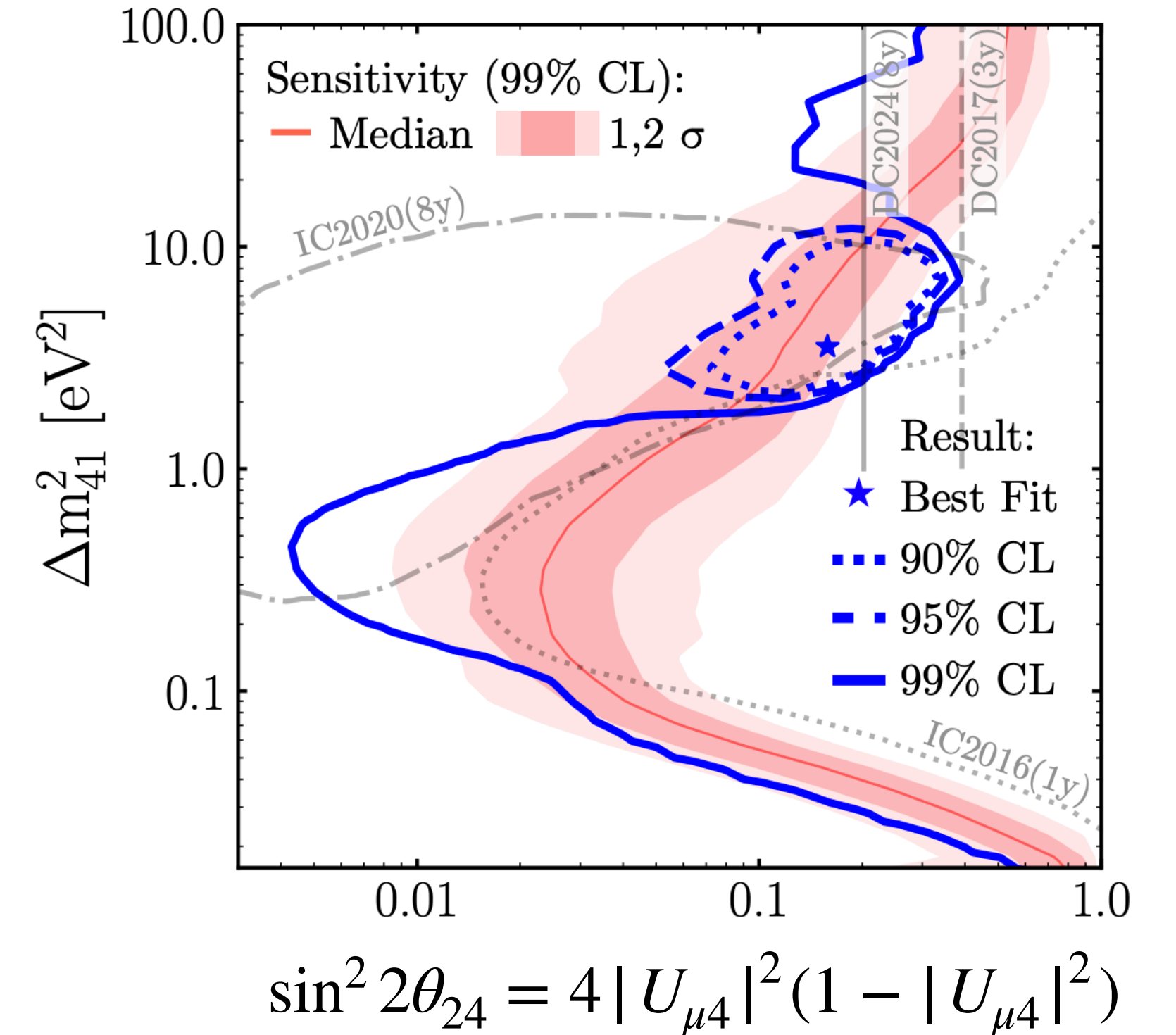


Multi-channel fit with NuMI data

*Let's take a closer look
at MINERvA's results

IceCube

IceCube coll. PRL 133, 201804 (2024)



Resonant oscillations for $\bar{\nu}_\mu \rightarrow \bar{\nu}_s$
inside the Earth at $E_\nu \sim \mathcal{O}(\text{few})$ TeV.

MINERvA's single-detector sterile neutrino search

Or... “Why you should not do a sterile neutrino search with a single detector” — Kevin McFarland

Multi-channel measurement with a single detector.
All samples in principle sensitive to 3+1 oscillations.

Adapted from Ryan Howell,
Fermilab W&C Seminar, Sept 5th, 2025

- | | |
|---|--|
| (1) $\nu + e \rightarrow \nu + e$ events | } Helps with flux calibration |
| (2) $\nu_\mu + e \rightarrow \nu_e + \mu^-$ events | |
| (3) CC $\nu_\mu + \bar{\nu}_\mu$ events (low E_{had}) | } Ratio (3)/(4) reduces impact of interaction model uncertainties. |
| (4) CC $\nu_e + \bar{\nu}_e$ events (low E_{had}) | |

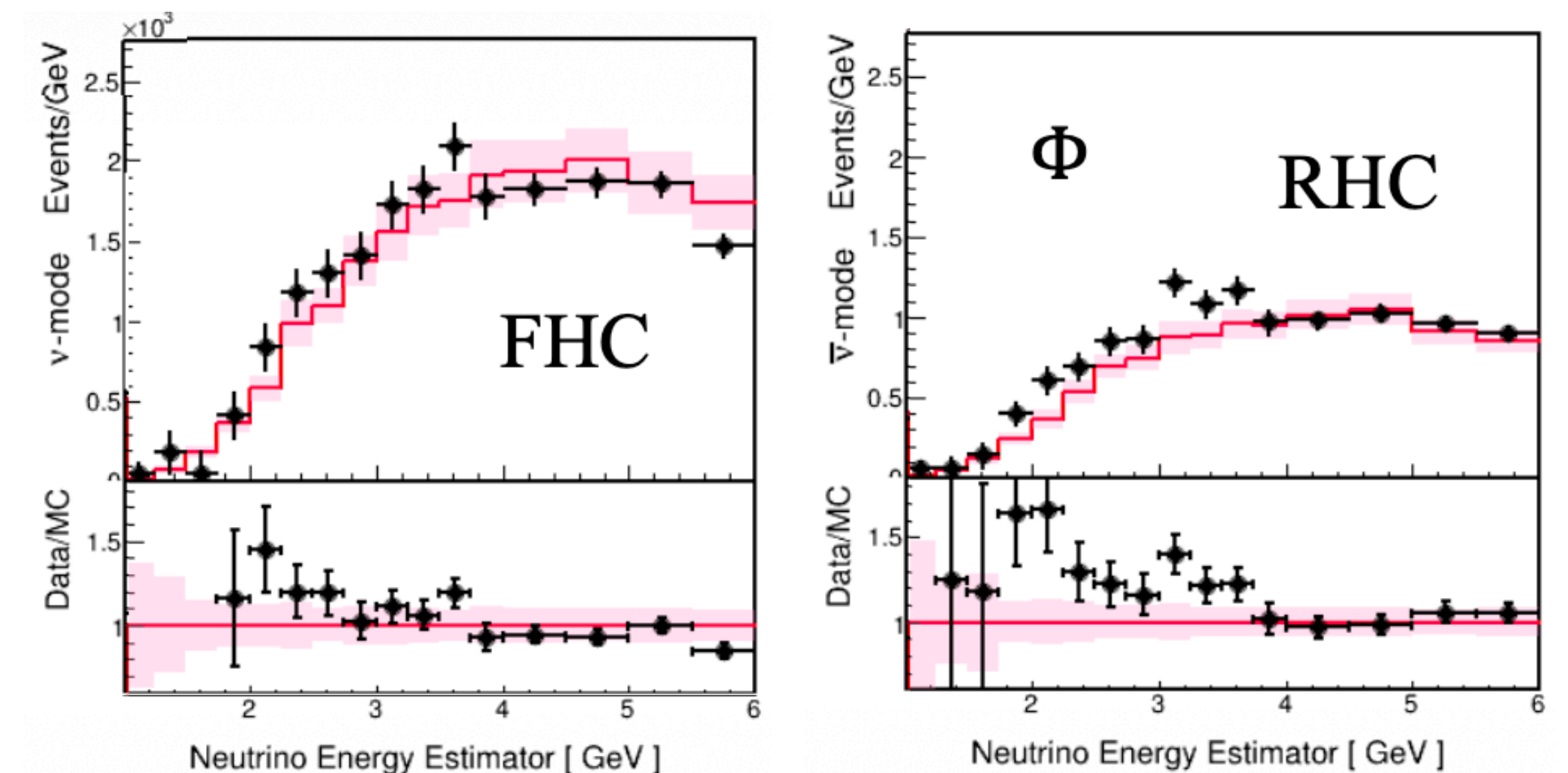
Substantial **excess of low-energy ν_e -like events.**

Likely electrons, not photons, due to dE/dX.

BUT! Not compatible with 3+1 oscillations.

Limits shown in slices of 3D space:

$$|U_{e4}|^2, |U_{\mu4}|^2, \Delta m_{41}^2$$



Flux pulls are large. Even after (1) + (2) constraints.

Likely pointing to missing ingredients in flux model.

Are sterile neutrinos the solution?

Seems unlikely that 3+1 is the right solution

We have seen important progress from “direct” tests,
but this result has been known for a long time.

Global fits have long shown **tension**
between **appearance** and **disappearance**

No room for an eV sterile with large
mixing **in standard cosmology**

M. Maltoni, T. Schwetz, J. W. F. Valle
[PLB 518 \(2001\) 252-260](#)

S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M.
Zavanin, [J.Phys.G 43 \(2016\) 033001](#)

M. Dentler, A. Hernández-Cabezudo, J.
Kopp, P. A. N. Machado, M. Maltoni, I.
Martinez-Soler, T. Schwetz
[JHEP 08 \(2018\) 010](#)

A. Diaz, C.A. Argüelles, G.H. Collin, J.M. Conrad,
M.H. Shaevitz, [Phys.Rept. 884 \(2020\) 1-59](#)

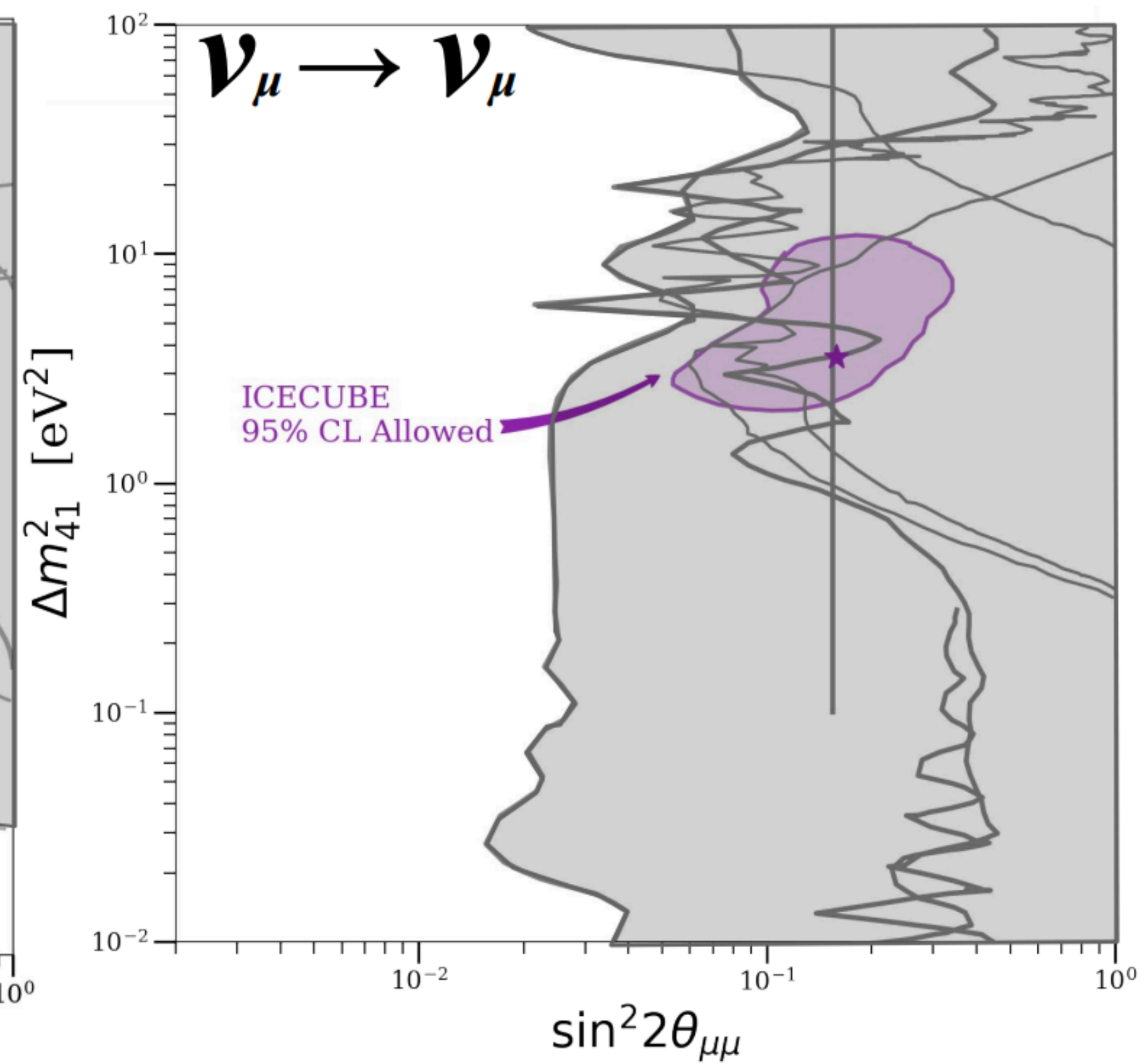
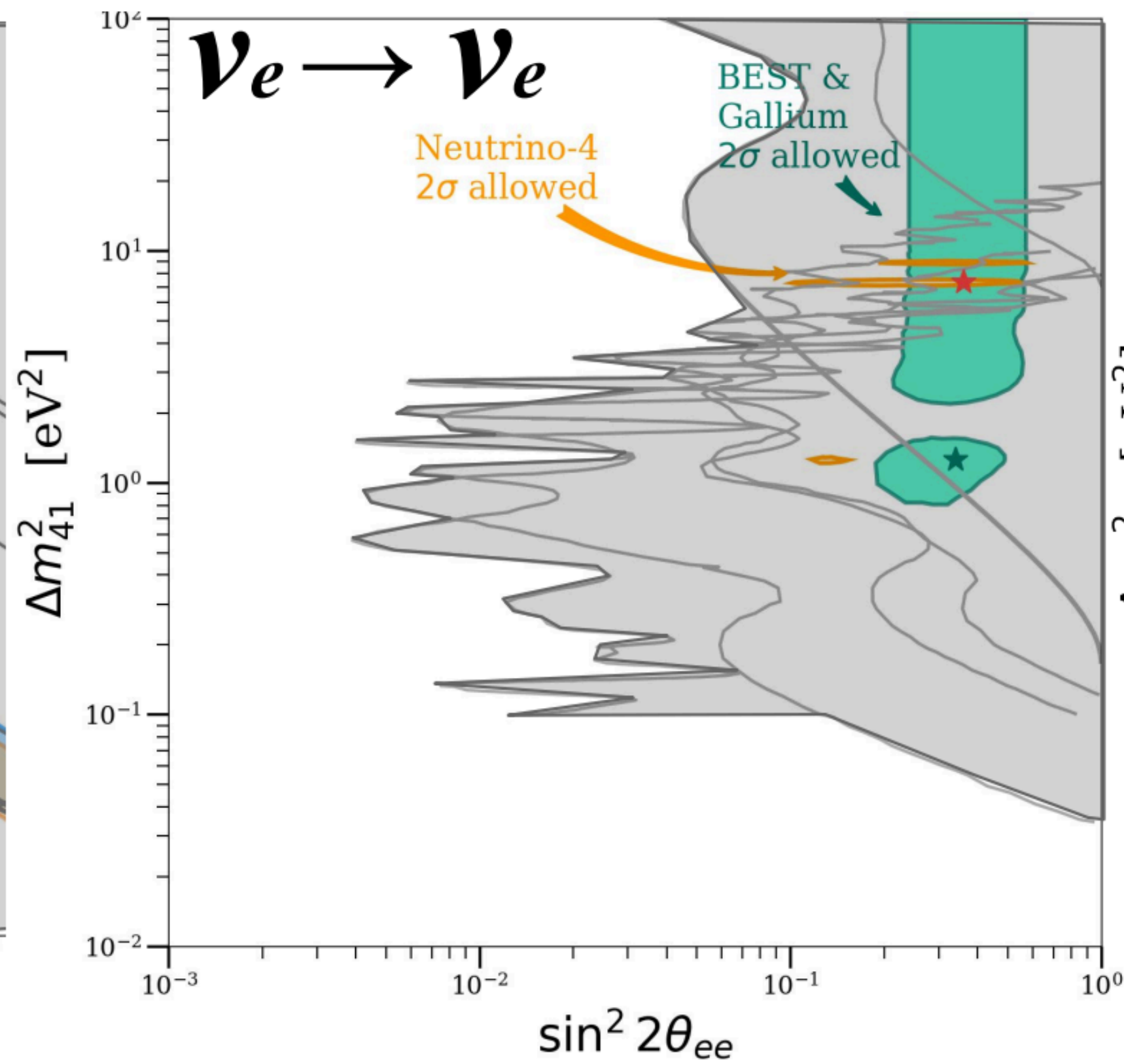
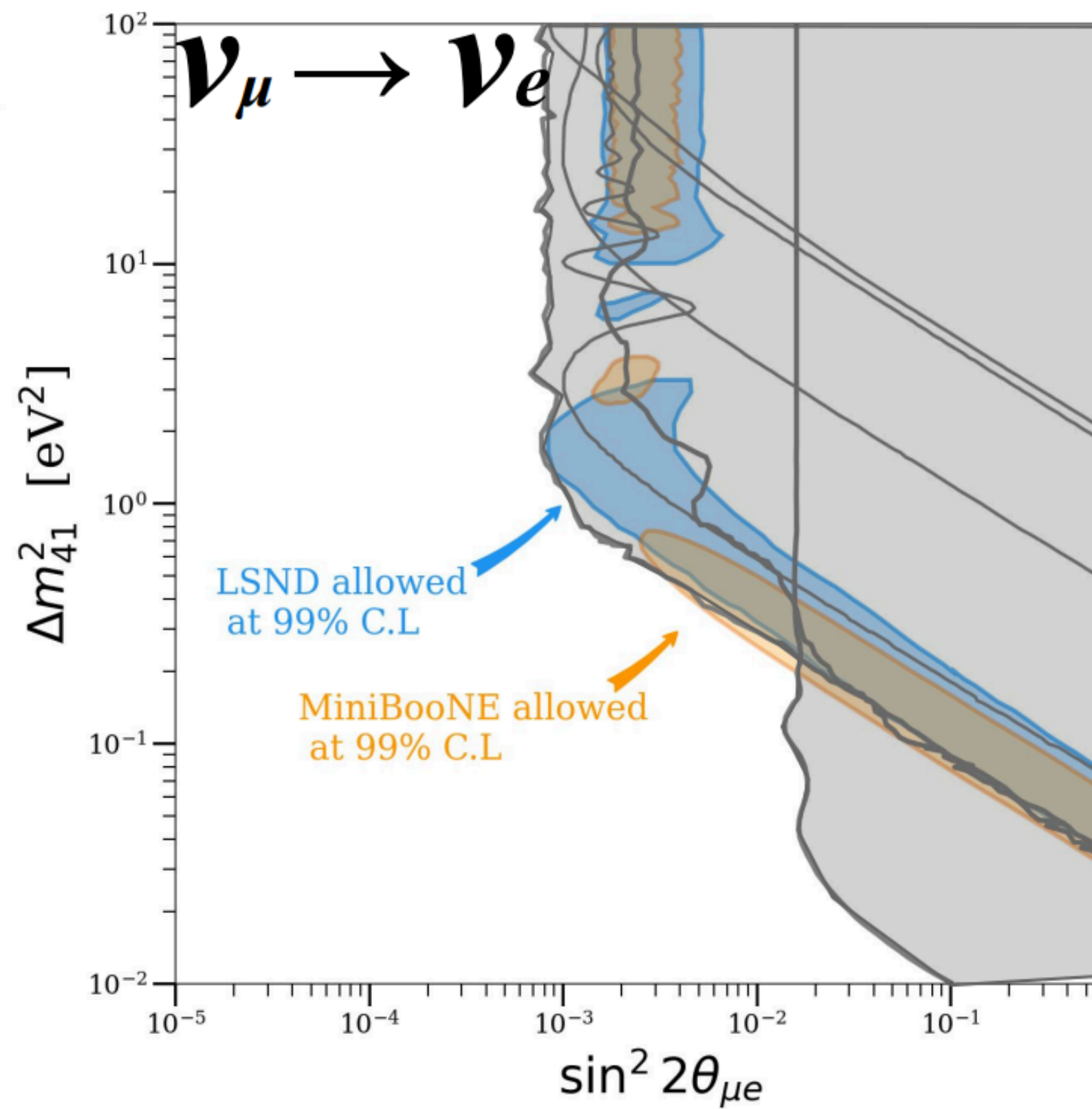
J. P. Woodward, J. Villarreal, J. M. Hardin,
A. Schneider, J. M. Conrad, [arXiv:2603.15322](#)

Among many other refs:

S. Hagstotz, P. F. de Salas, S. Gariazzo, M. Gerbino,
M. Lattanzi, S. Vagnozzi, K. Freese, S. Pastor [PRD](#)
[104 no. 12, \(2021\) 123524](#)

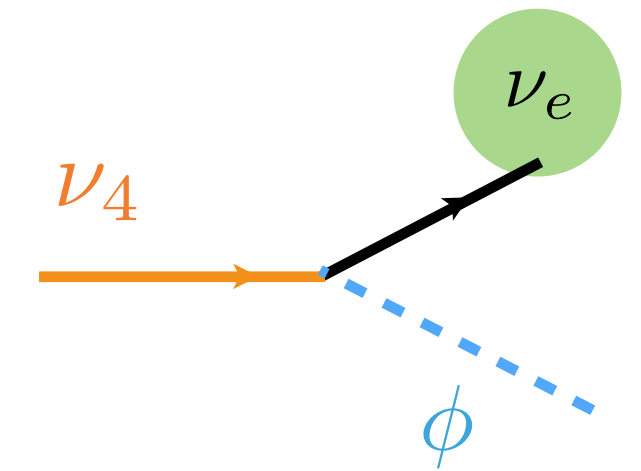
As of June 22, 2026, 4:16 pm US Pacific Time

Mark Ross-Lonergan, [NuPhys 2026](#)



Singlet nature of ν_R provides a blank canvas to be creative

- **3 + 2 models** (more sterile states) \rightarrow Conclusions largely unchanged. **However**, CP violation now possible. MicroBooNE NuMI sample rich in $\bar{\nu}_\mu$ & $\bar{\nu}_e$. May be worth a refreshed look.
- **3 + 1 with unstable sterile:** visible decay mechanism can decouple APP from DIS.
- **Couplings to Dark Particles:** scattering and decay signatures, plethora of dark sector models.



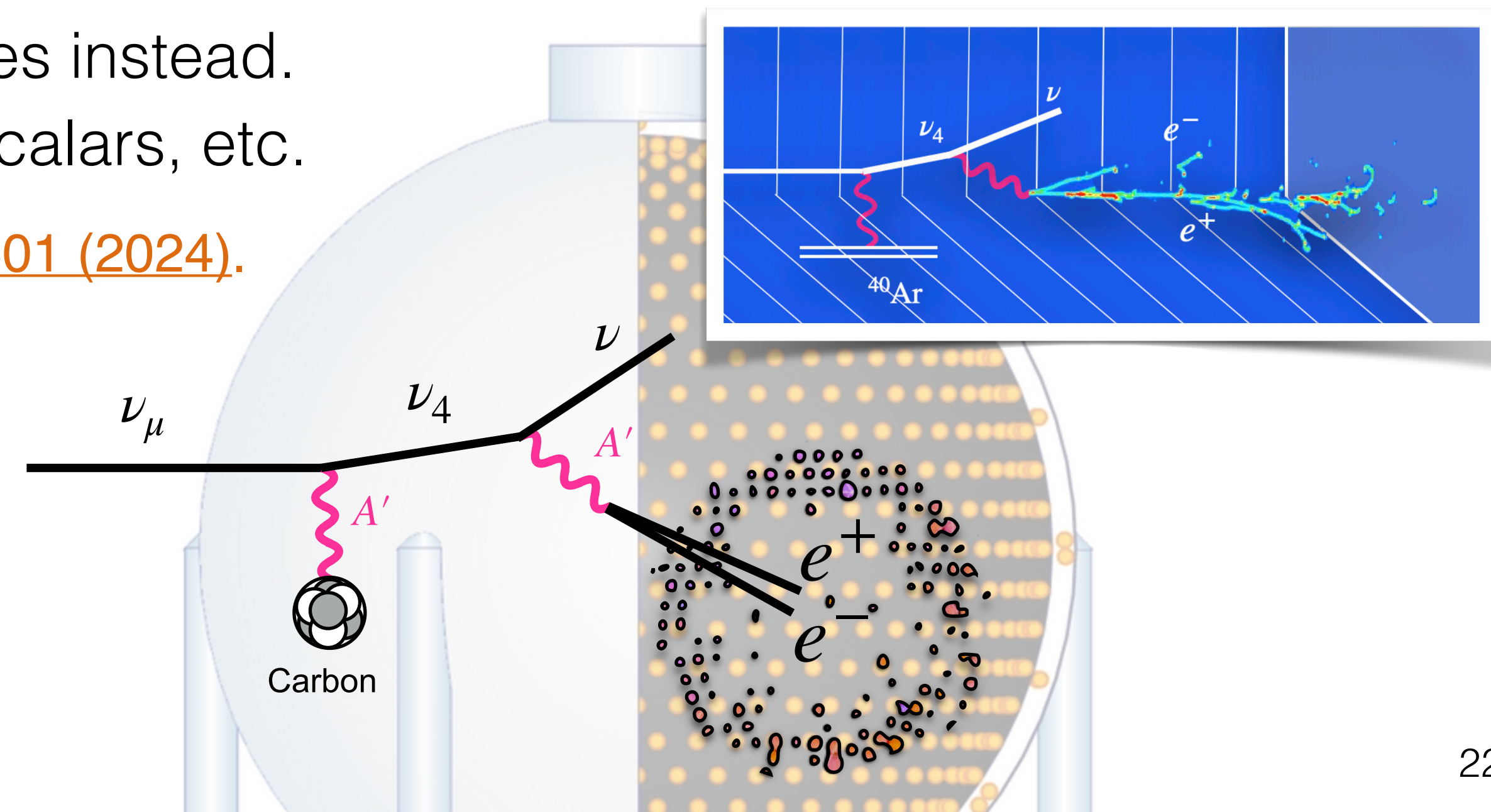
Can explain MiniBooNE with γ , $\gamma\gamma$, or e^+e^- final states instead. E.g., transition magnetic moments, dark neutrinos, scalars, etc.

[Snowmass White Paper: J. Phys. G: Nucl. Part. Phys. 51 120501 \(2024\).](#)

Dark neutrino search by MicroBooNE

Excludes some e^+e^- hypotheses of the excess

MicroBooNE coll. & A. Abdullahi, MH, D. Massaro, S. Pascoli, J. Zink, PRL 136 (2026) 12, 121804



A scenic view of a beach with palm trees and buildings in the background. The image shows a wide, sandy beach with gentle waves lapping at the shore. In the distance, a hillside is covered with numerous buildings, likely a residential or resort area. The sky is clear and blue, and the overall atmosphere is bright and sunny. The text is overlaid on the center of the image.

New Tools and Methods

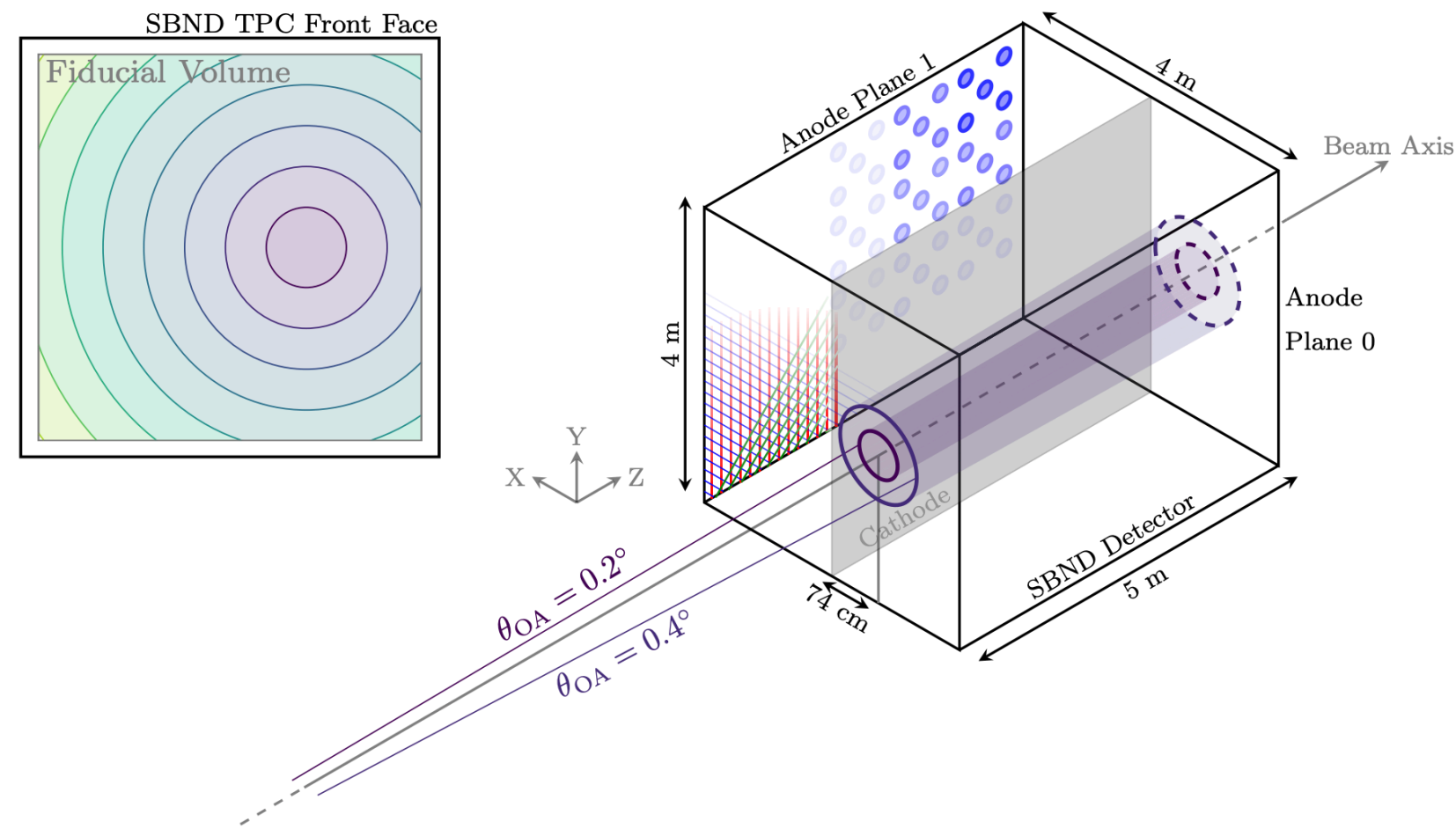
Toward more robust and sensitive sterile neutrino searches

Exploring the PRISM concept for sterile neutrinos



DUNE ND CDR

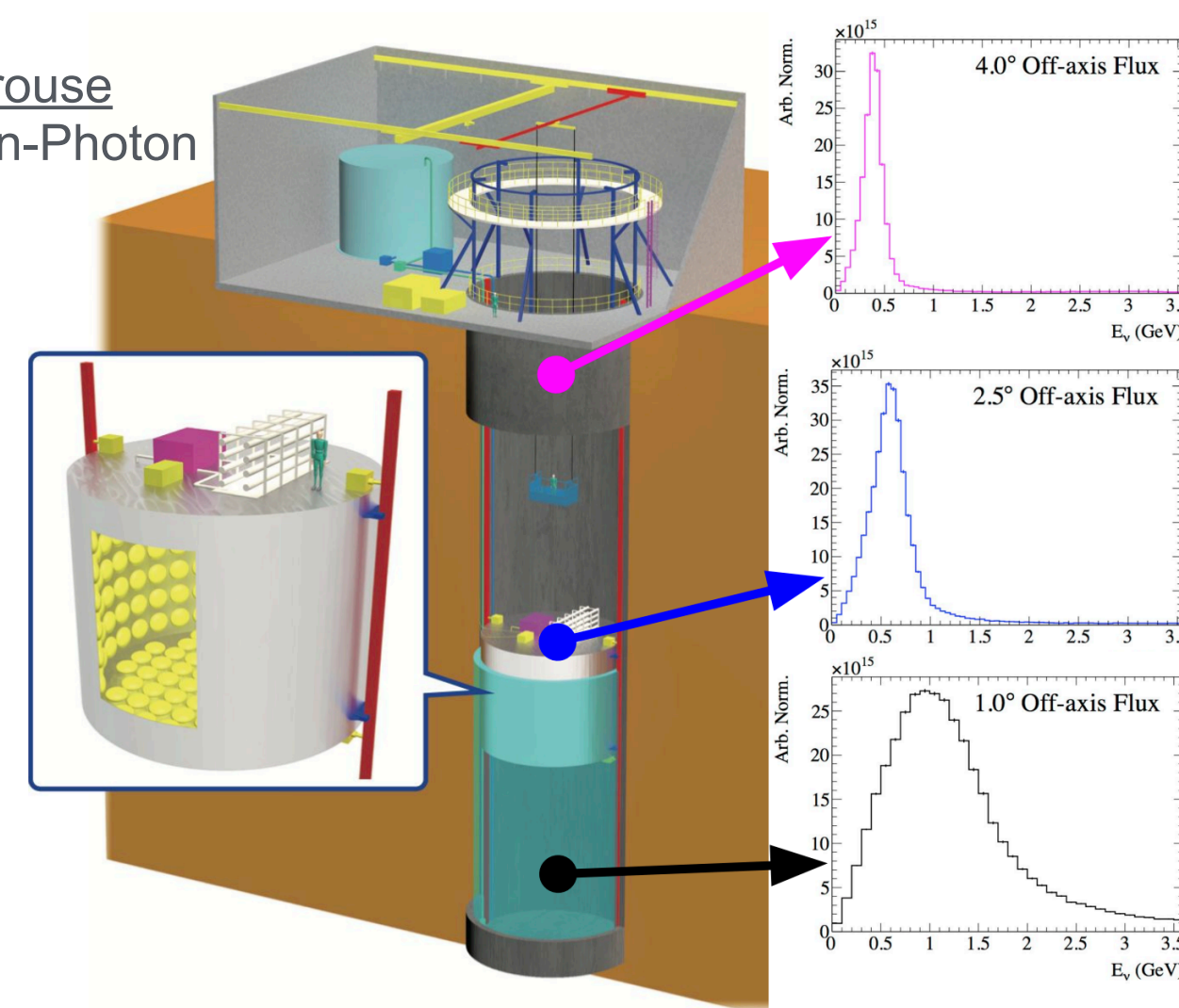
SBND-PRISM Angular spread of the beam



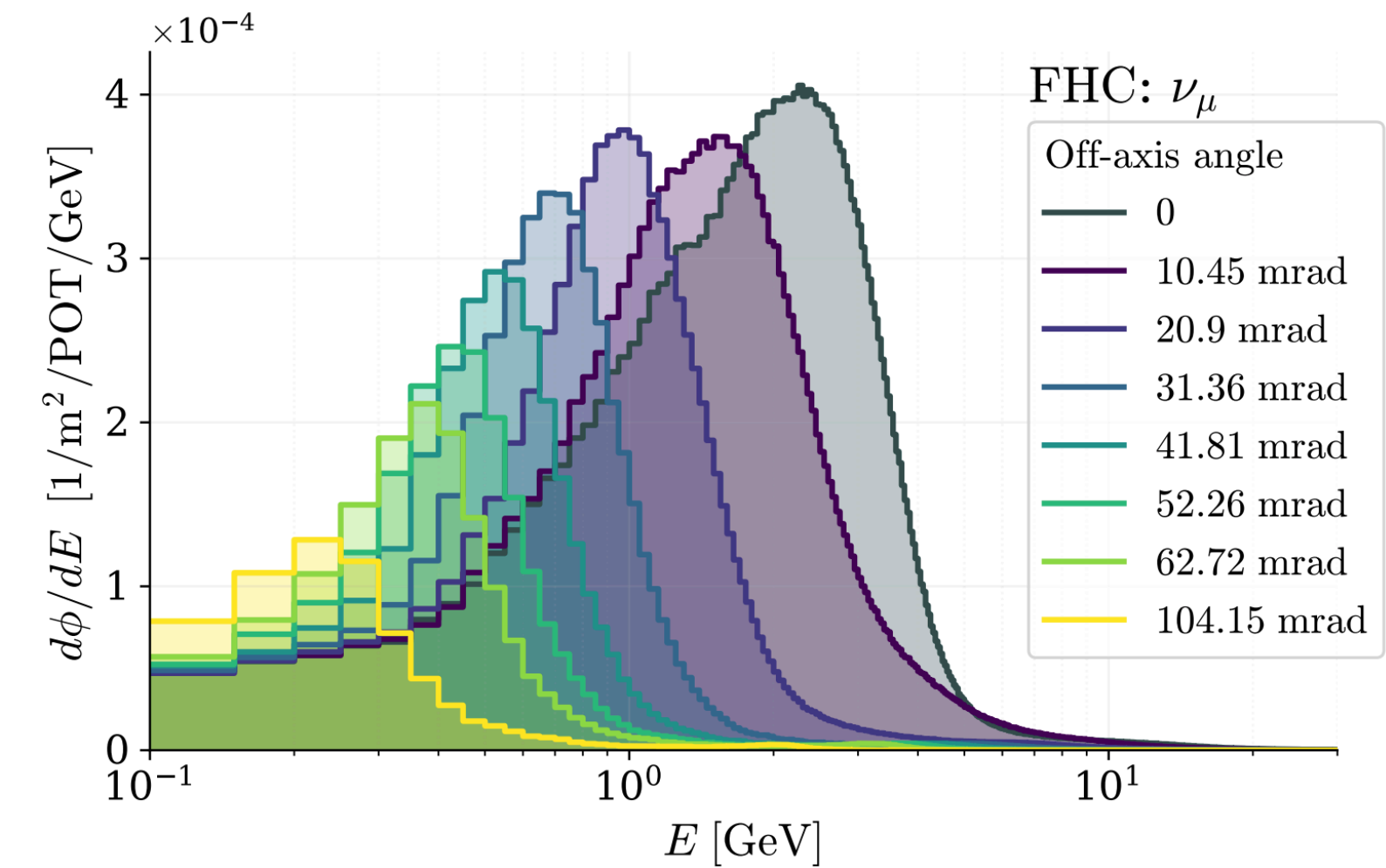
The SBND Collaboration
PRD 113, 072007 (2026)

Hyper-K IWCD Intermediate Water Cherenkov Detector

N. Prouse
@ Lepton-Photon



nuPRISM Letter of Intent → IWCD



J. Hernández-García, J. López-Pavón,
S. Urrea, [2604.20951](#)

Helps mitigate the limitation of systematic uncertainties on **flux**, cross section, and $E_\nu^{\text{true}} \rightarrow E_\nu^{\text{reco}}$

Tagged beams: measure L and E_ν for each event, ν SCOPE.

A. Blanchet, C. Jesús-Valls, A. Chatterjee, S. Dolan,
P. Granger, L. Munteanu. [2606.14263](#)

Muon beams for neutrinos, e.g., ν STORM.

J. Franklin, R. Kamath, D. Pasari, Y. F. Perez-Gonzalez, J. Turner,
M. Athina Vogiatzi, [JHEP 02 \(2026\) 127](#)

Bringing Neutrino Sources Underground

Low cosmic rates + high intensity + large detectors \implies Rare event searches

- **IsoDAR** at **Yemilab**, Korea, could realize this.

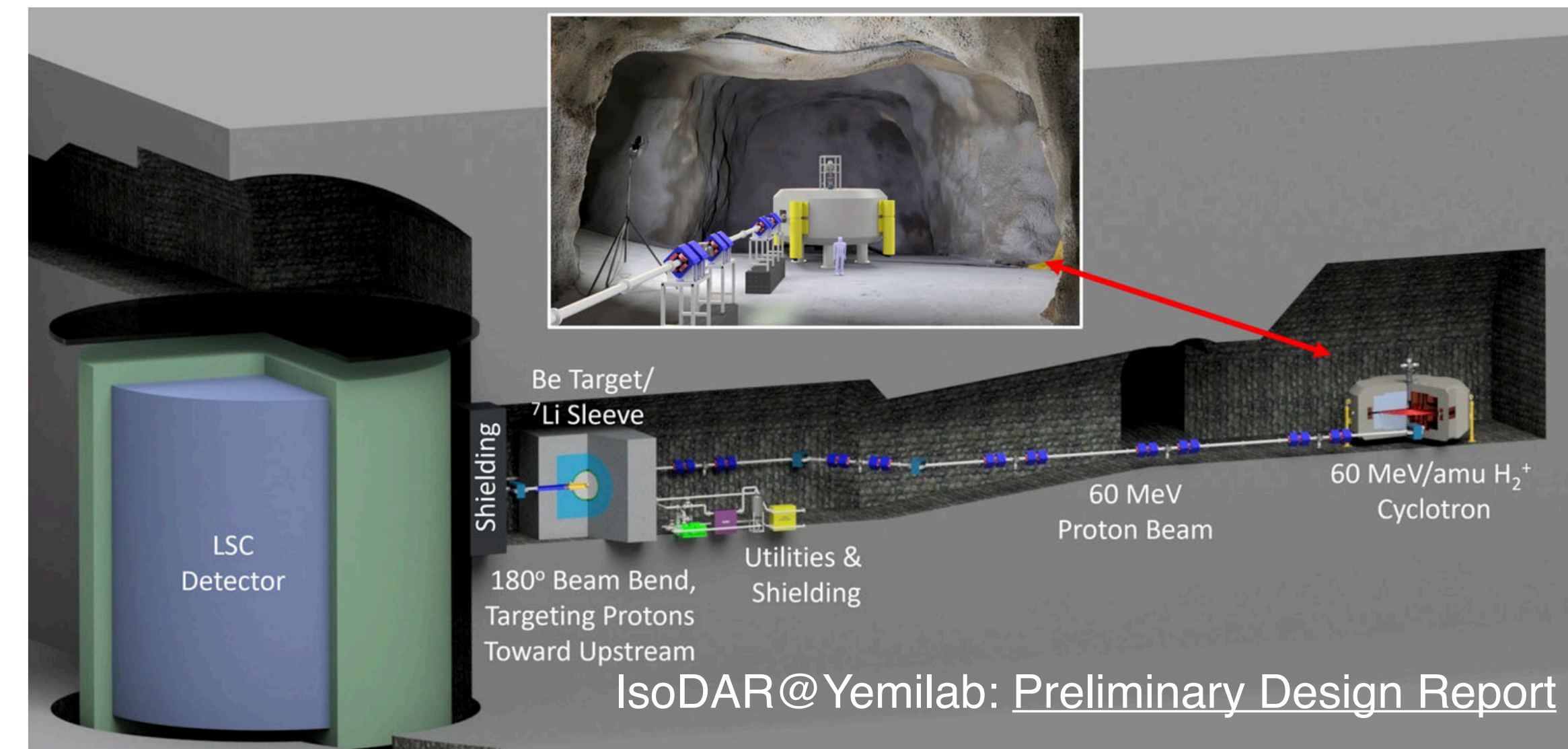
Cavern built for cyclotron and ν **EYE** detector.

Sensitivity jump to $\lesssim \mathcal{O}(1\%) \bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance.

ν EYE CDR

Millions of IBD, thousands of $\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$ events

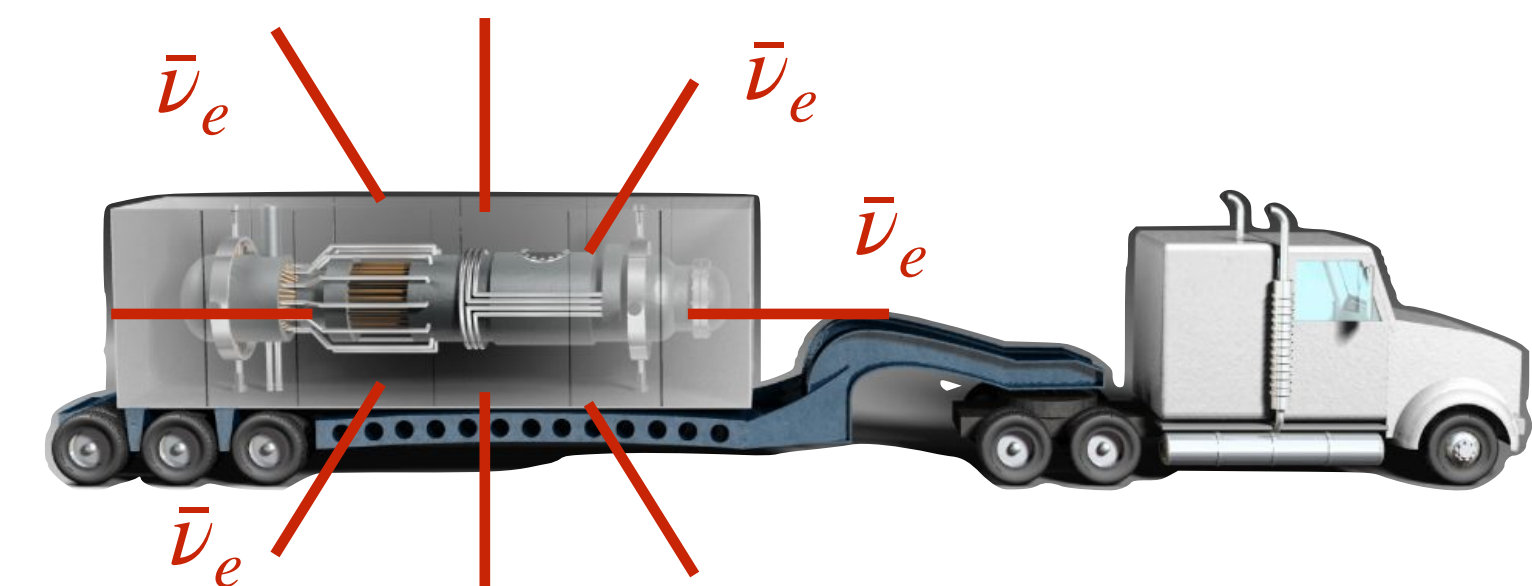
~ 15 MeV $E_{\bar{\nu}_e}$ endpoint energy.



- **Micro-reactor technology actively pursued in the US and China**

Mobile reactors with $\mathcal{O}(1 - 10)$ MW_{th} **may** soon be a reality.

Potentially interesting direction for the future of projects like **JUNO**.



To conclude, this talk is really about 2 topics:

Historically strongly intertwined, but current landscape shows these are likely unrelated.

Short-baseline anomalies

eV sterile neutrinos

Null results can only rule out explanations, not data.

Anomalies remain even if sterile neutrino interpretation under severe strain.

Theoretical possibilities not exhausted, both within and beyond the Standard Model.

Sterile neutrino searches will likely continue: familiar experimental lamppost

Every measurement in a given experiment can be impacted by 3+1 oscillations.

If anything, stress test of flux, cross section, and detector models.

Discovery not guaranteed, but would sure provide much needed clues on key fundamental questions in particle physics.

Outstanding Issues & Wishlist

- How do we move forward with Gallium anomaly *theoretically* and *experimentally*?
- What other lessons about LSND can we learn from JSNS² aside from oscillation search?
- Perform 3D comparisons between MiniBoone, MicroBooNE, and SBN. Profiling undersells sensitivity/coverage.
- Use external constraints on ν_e DIS from reactors / KATRIN in MicroBooNE + SBN + KATRIN.
- Consider wrong-sign neutrino hypothesis of the MiniBooNE excess ($\bar{\nu}_e$ in FHC mode). May be targeted directly with LArTPCs, even if cross sections are lower than in CH₂.
- MicroBooNE and ICARUS see ν_μ **excess** / ν_e **deficit**: $< 2\sigma$ effect and covered by large errors. Would it be as scrutinized if it were ν_μ **deficit** / ν_e **excess** instead?

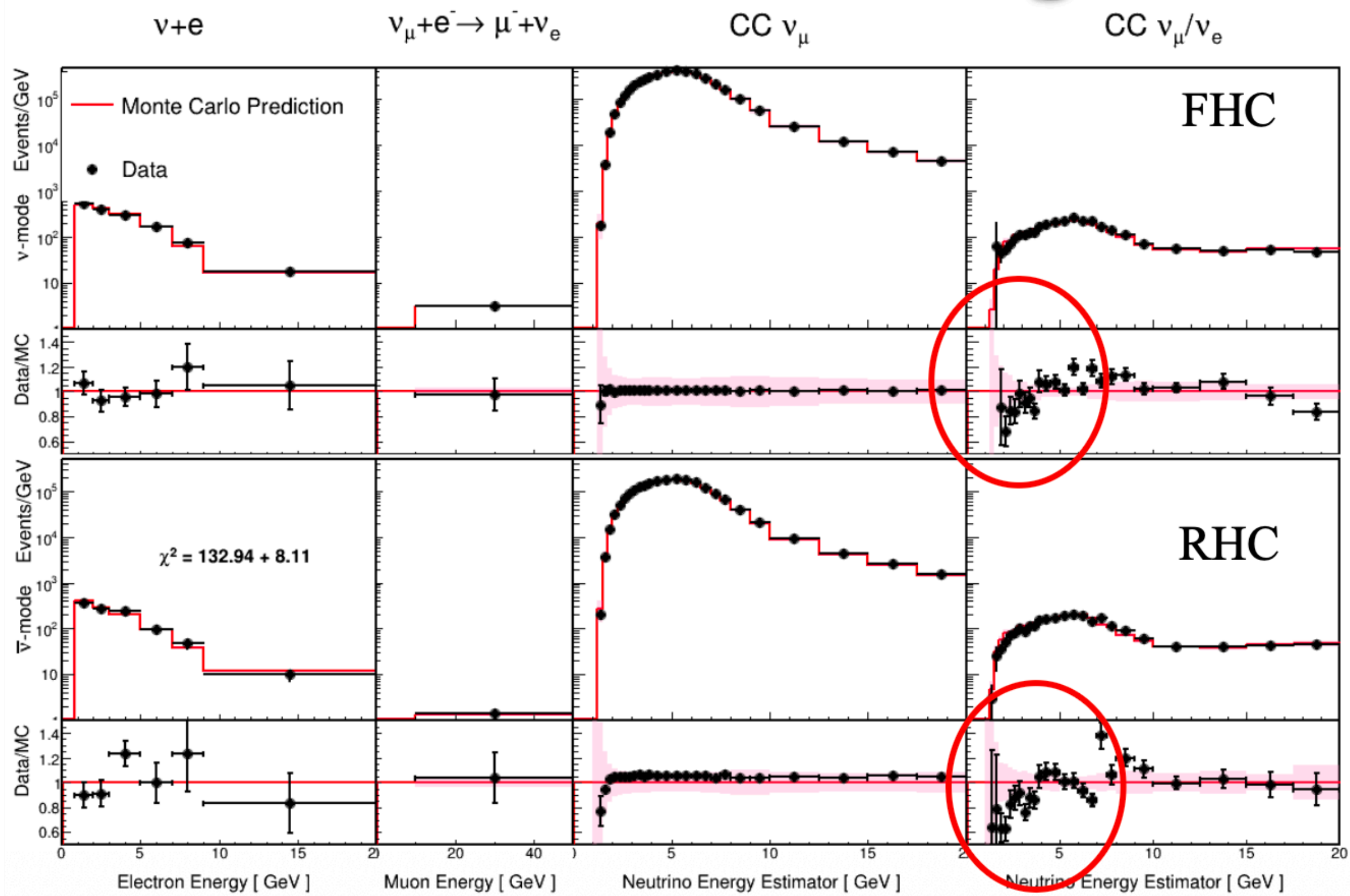
A panoramic view of a tropical beach. The foreground shows a sandy beach with a large area of white pebbles. Two tall palm trees stand prominently on the right. The ocean is a vibrant blue, with gentle waves lapping at the shore. In the background, a coastal town is built on a hillside under a clear blue sky with light clouds. The text "Bonus Slides" is centered in white, bold font.

Bonus Slides

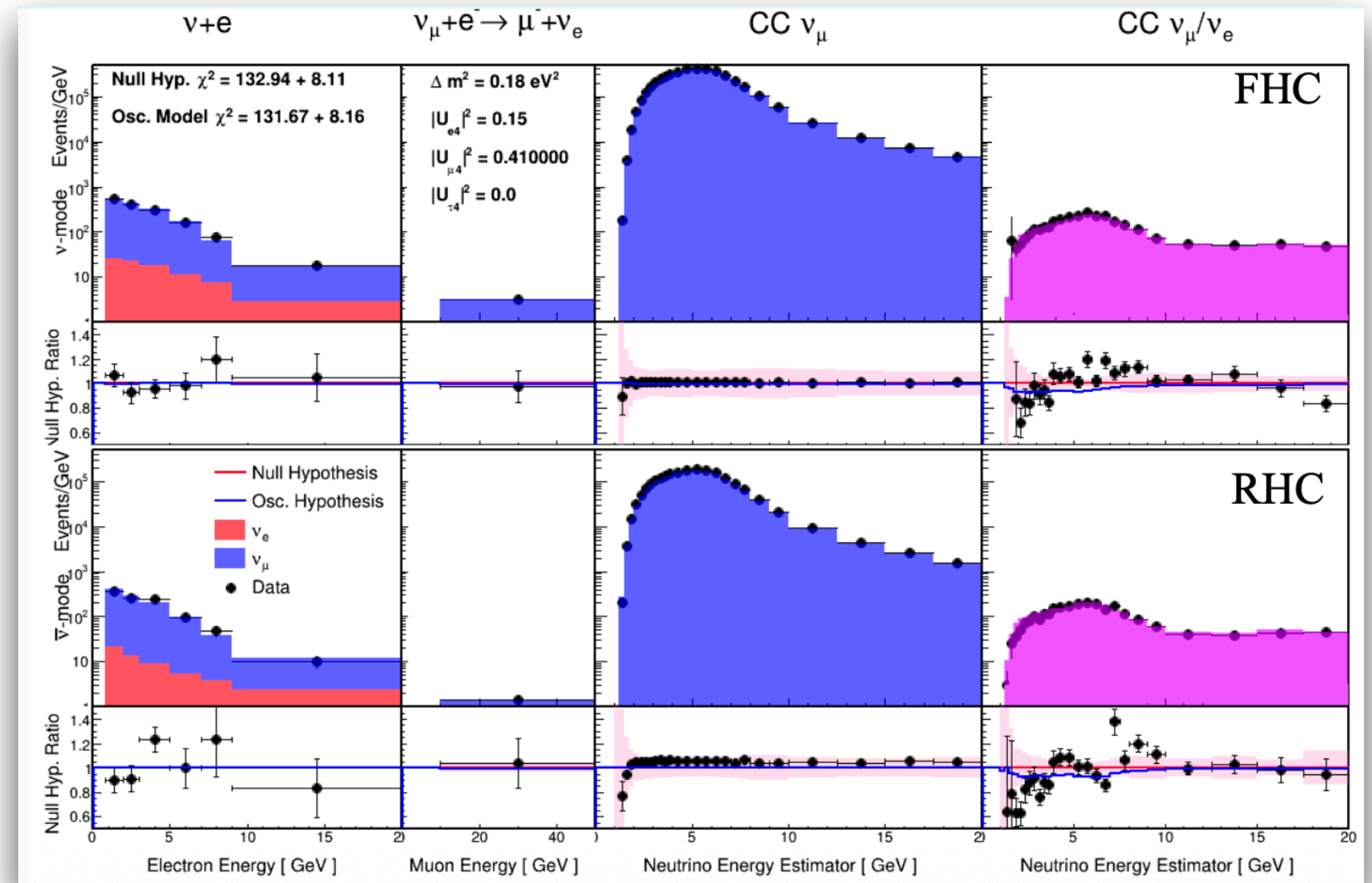
MINERVA's single-detector sterile neutrino search

Adapted from Ryan Howell,
Fermilab W&C Seminar, Sept 5th, 2025

After Flux Profiling



Oscillation best-fit



ν_μ disappearance through the Earth

MSW resonant oscillations for $\bar{\nu}_\mu \rightarrow \bar{\nu}_s$ inside the Earth at $E_\nu \sim \mathcal{O}(\text{few})$ TeV. Parametric enhancement if crossing the core. Non-resonant oscillations for ν_μ .

Q.Y. Liu, A.Yu. Smirnov, [NPB 524 \(1998\) 505-523](#)

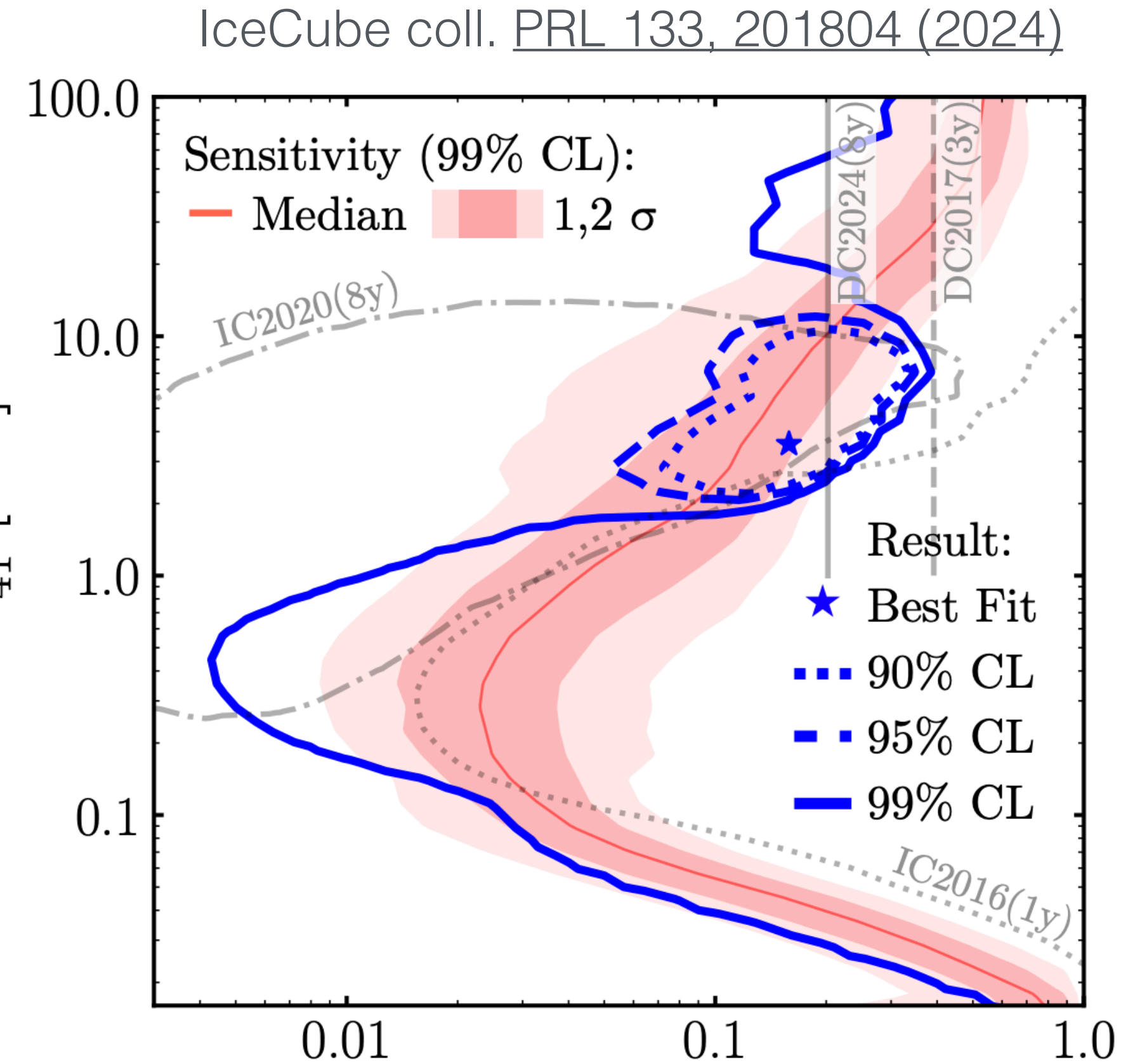
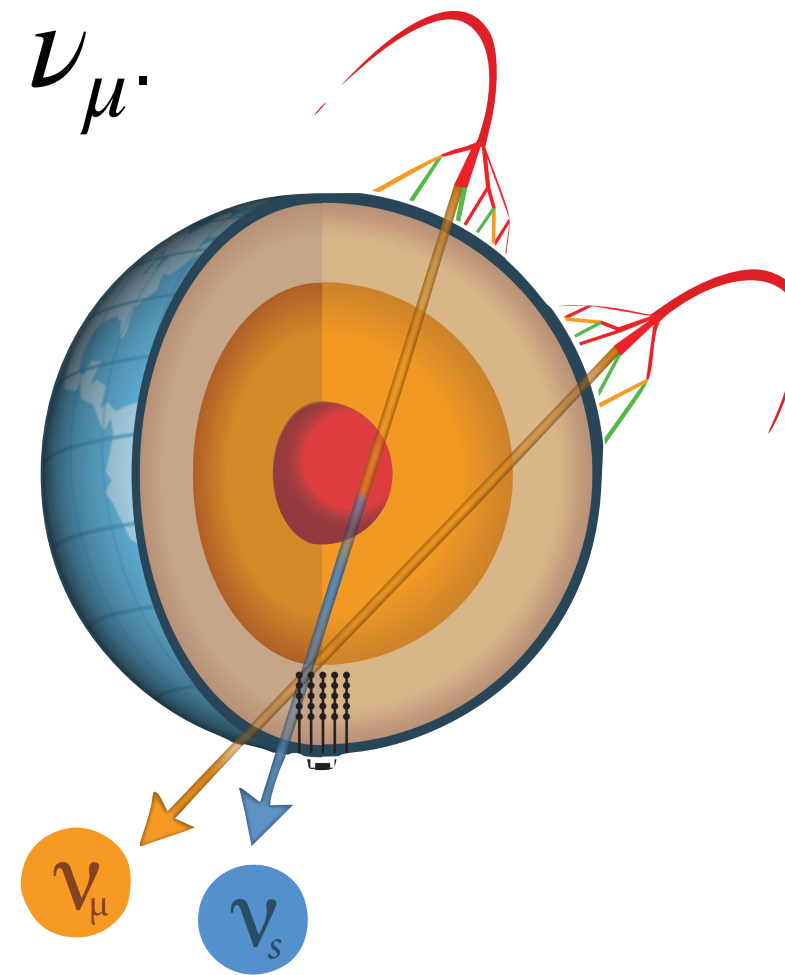
H. Nunokawa, O. L. G. Peres, and R. Zukanovich-Funchal, [PLB 562 \(2003\) 279-290](#)

IceCube: closed 95% CL contours.
p-value of no oscillation hypothesis 3.1%

Analysis is systematics dominated, but better detector (ice) models and IC Upgrade will likely help.

Resonance is too high-energy for **KM3NeT/ORCA**, but it can also set complementary limits on eV steriles.

KM3NeT coll. [JHEP 02 \(2026\) 080](#)

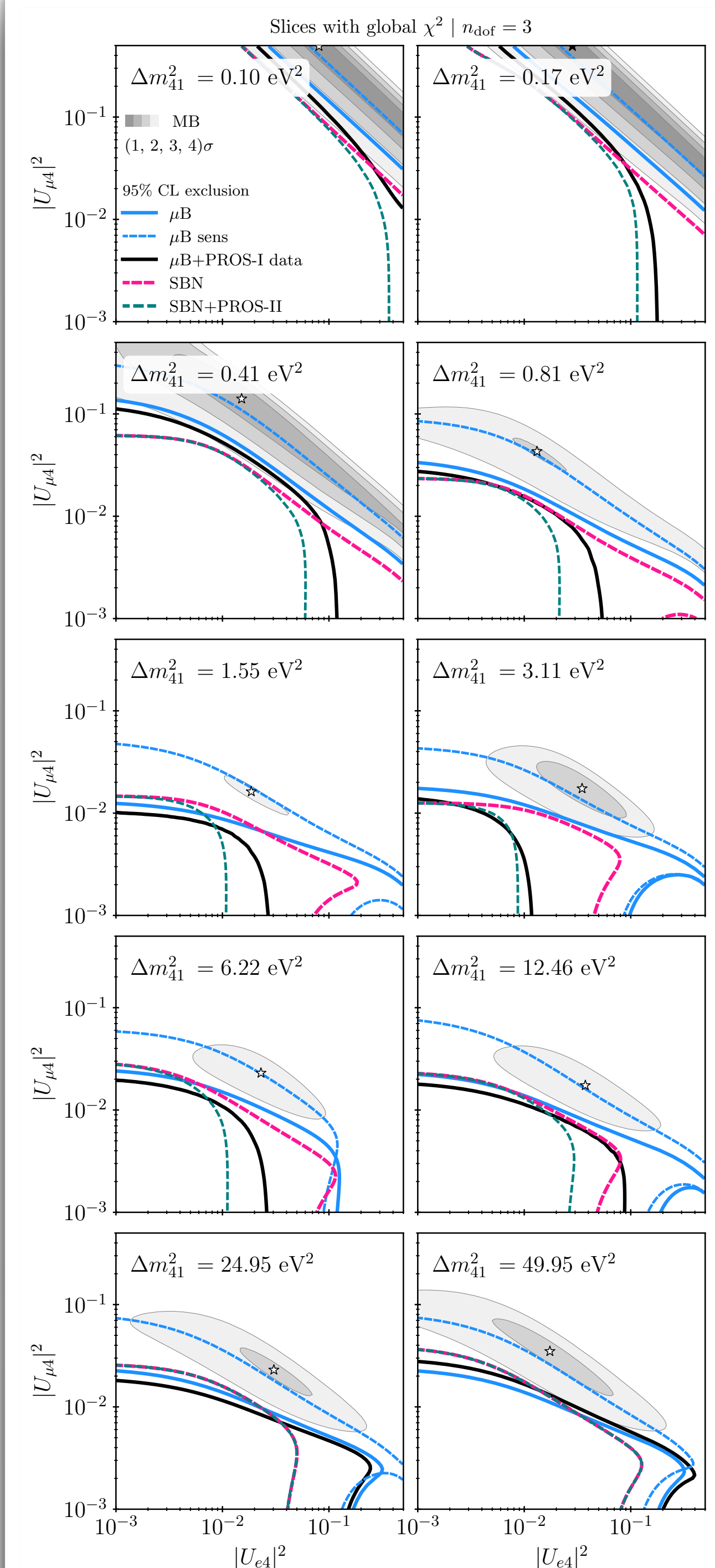
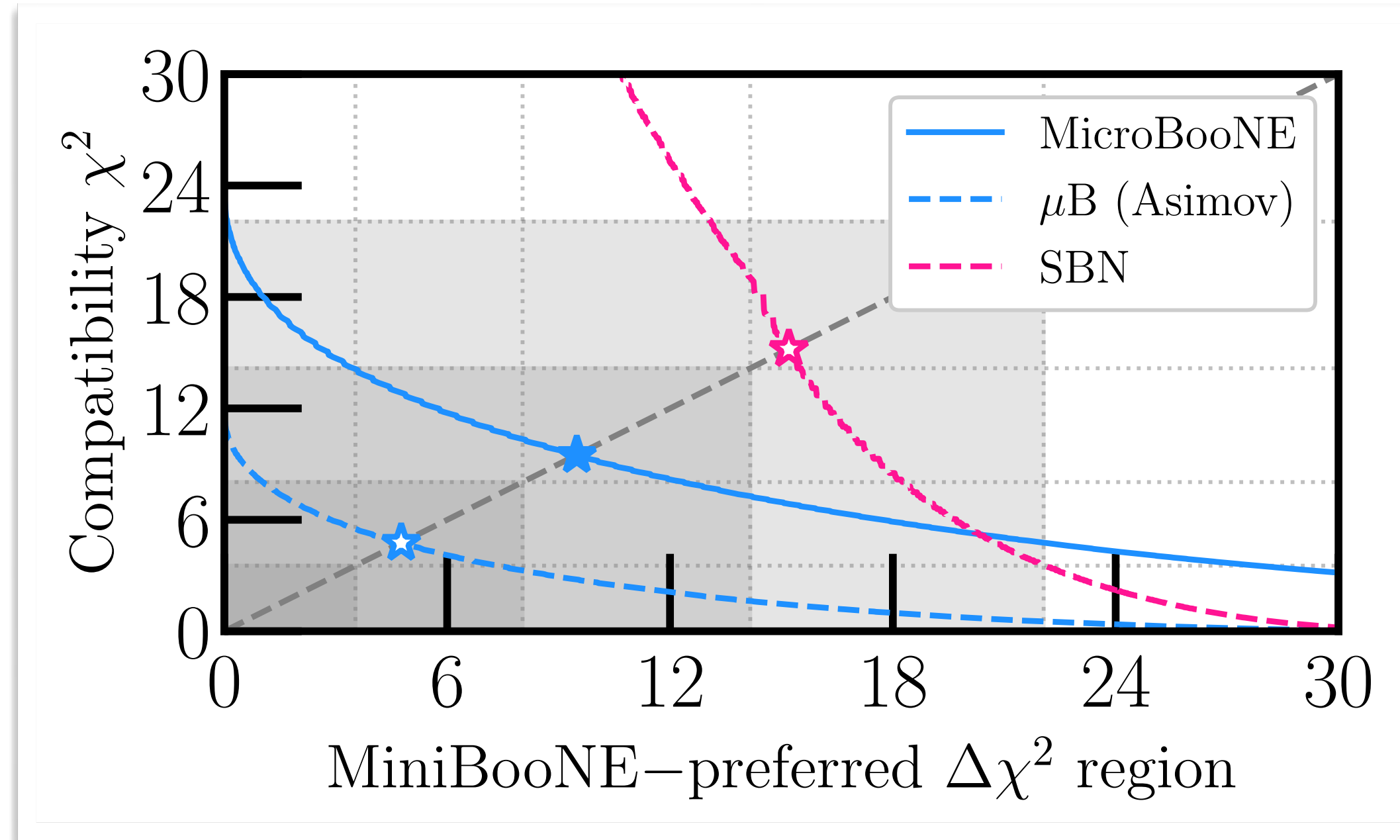


$$\sin^2 2\theta_{24} = 4 |U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$$

Towards a robust test of sterile neutrinos

A global metric to quantify coverage

2D slices of 3D space →



Compatibility χ^2 : The MicroBooNE/SBN significance for which there is complete coverage of the $\Delta\chi^2$ preferred-region of MiniBooNE.

MicroBooNE covers the entire MiniBooNE $\Delta\chi^2 = 9.5$ region at that same value.

With Wilk's, this is equivalent to saying that the entire $\sim 2.3\sigma$ MiniBooNE region is excluded by MicroBooNE at $\sim 2.3\sigma$.

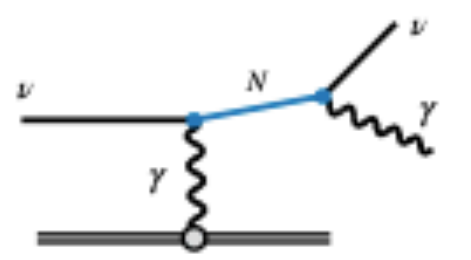

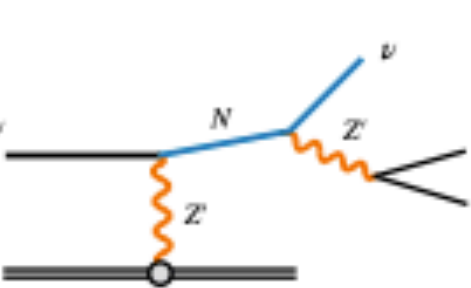
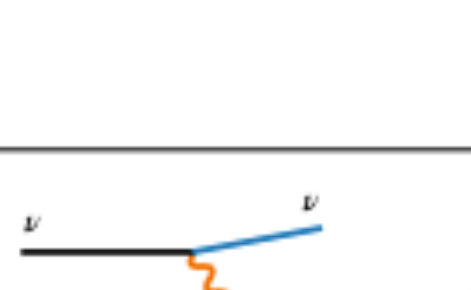
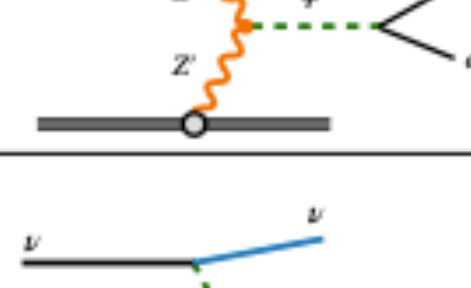
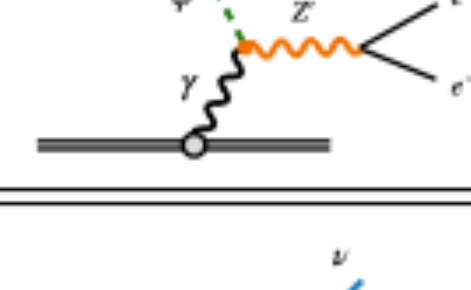
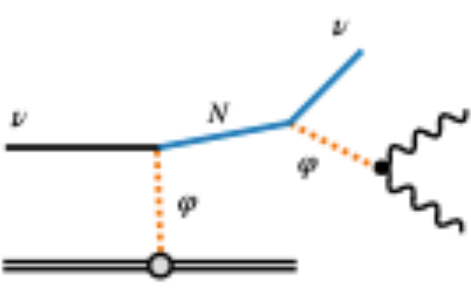
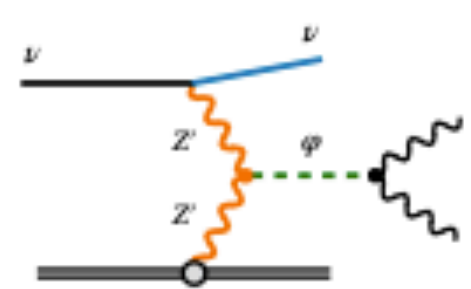
SBL anomaly interpretations

Model landscape evolved significantly over the years.

But not all alternative explanations connect all SBL anomalies.



Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma \gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✓	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

single γ		$N \rightarrow \nu\gamma$
		$\varphi^* A \rightarrow \gamma A$
e^+e^-		$N \rightarrow \nu e^+ e^-$ on-shell N
		$Z' \rightarrow e^+ e^-$ off-shell N
		$\varphi \rightarrow e^+ e^-$
		$Z' \rightarrow e^+ e^-$
$\gamma\gamma$		$N \rightarrow \nu\gamma\gamma$
		$\varphi \rightarrow \gamma\gamma$

Model landscape evolved significantly over the years.

Constrained (indirectly)

Not directly searched for, but indirectly targeted by MicroBooNE single photon analyses. Can they explain the excess?

Direct searches would be very interesting.

Constrained (directly)

MicroBooNE's e^+e^- excludes many models. Inconclusive for **non-vector mediator** models. No coherence, different kinematics.

Constrained (indirectly)

Anomaly-mediated photon production and similar diagrams. Challenging model-building.

See recent study: B. Dutta, A. Karthikeyan, D. Kim, A. Thompson, R. G. Van de Water, *PRD* 113 (2026) 1, 015029

Not constrained

“**Pion impostors**”. Two photons with $m_{\gamma\gamma} \neq m_{\pi^0}$ and different kinematics. **Messes with the sidebands...**