A Theory Overview of the Short-Baseline Program

15th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2025)

Madison WI, June 9-13

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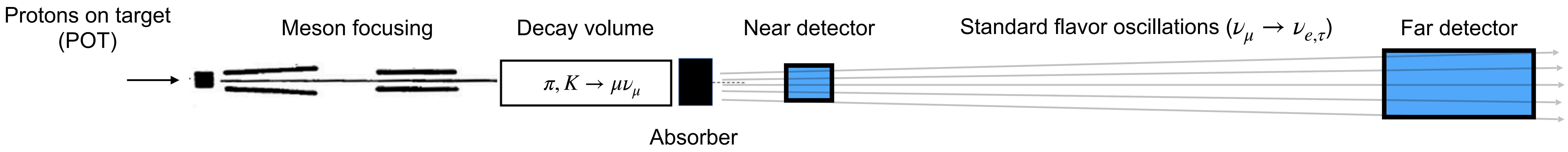
Outline

1) Overview of current sterile neutrino oscillation landscape

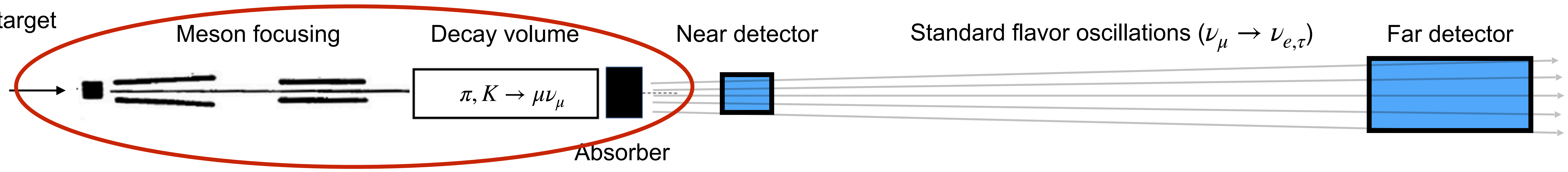
2) Towards stronger and more robust statements about steriles

3) Where dark sector interpretations are going: γ, $\gamma\gamma$, and e^+e^-

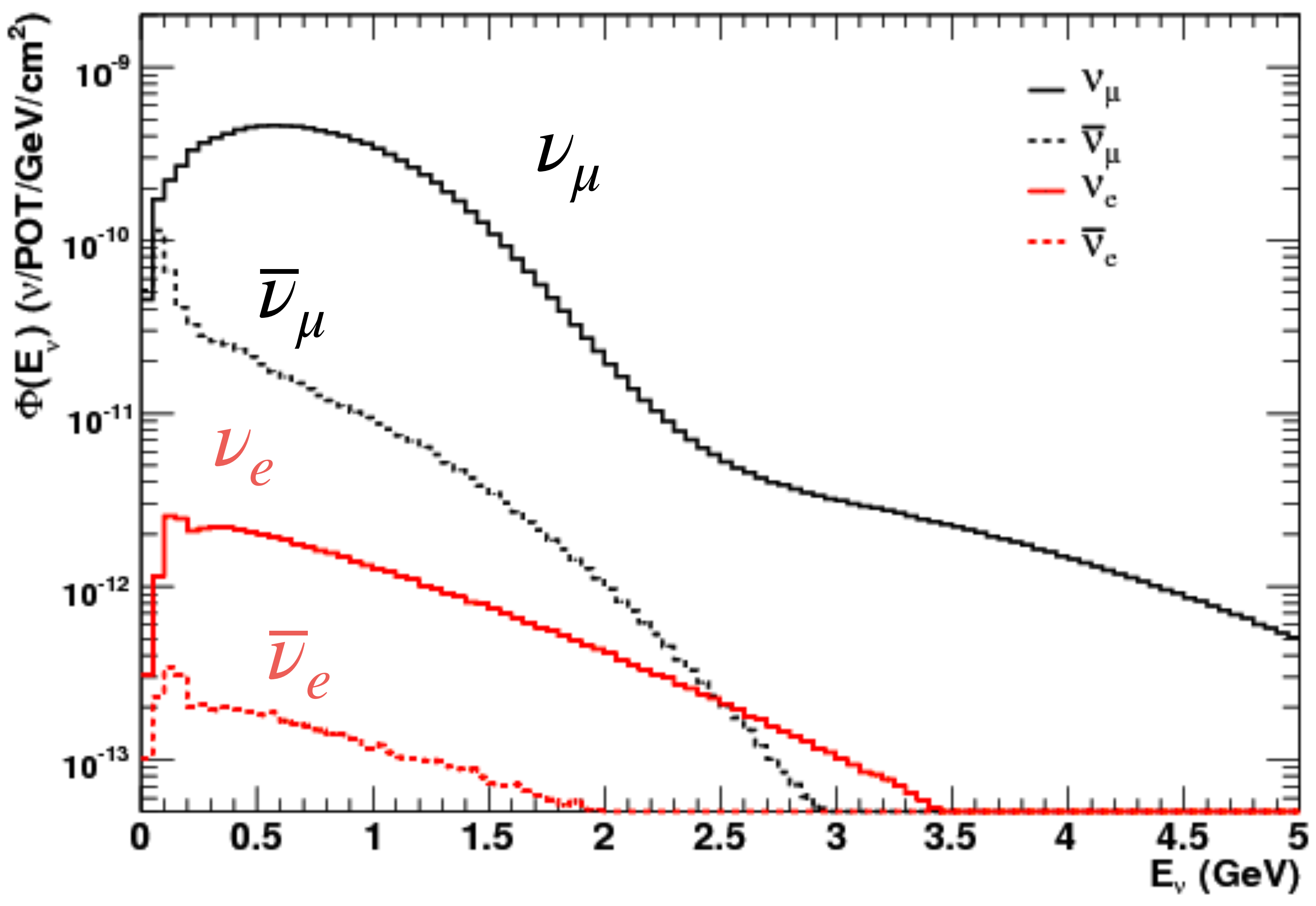
Accelerator Neutrino Experiments



Accelerator Neutrino Experiments



Neutrino fluxes at MiniBooNE



MiniBooNE Collaboration, arXiv:0806.1449

Flavor composition (neutrino mode, focused π^+):

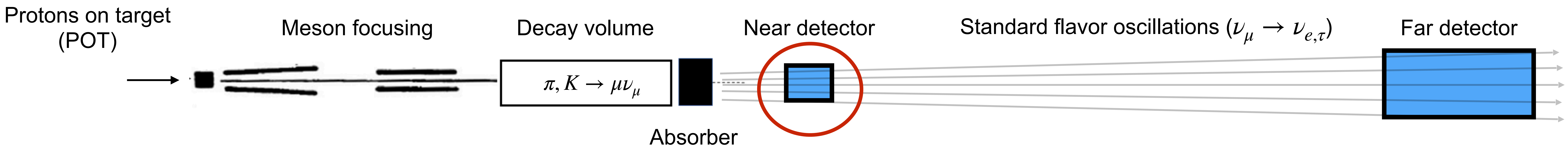
ν_μ: **93.6%**

$\bar{\nu}_\mu$: 5.86%

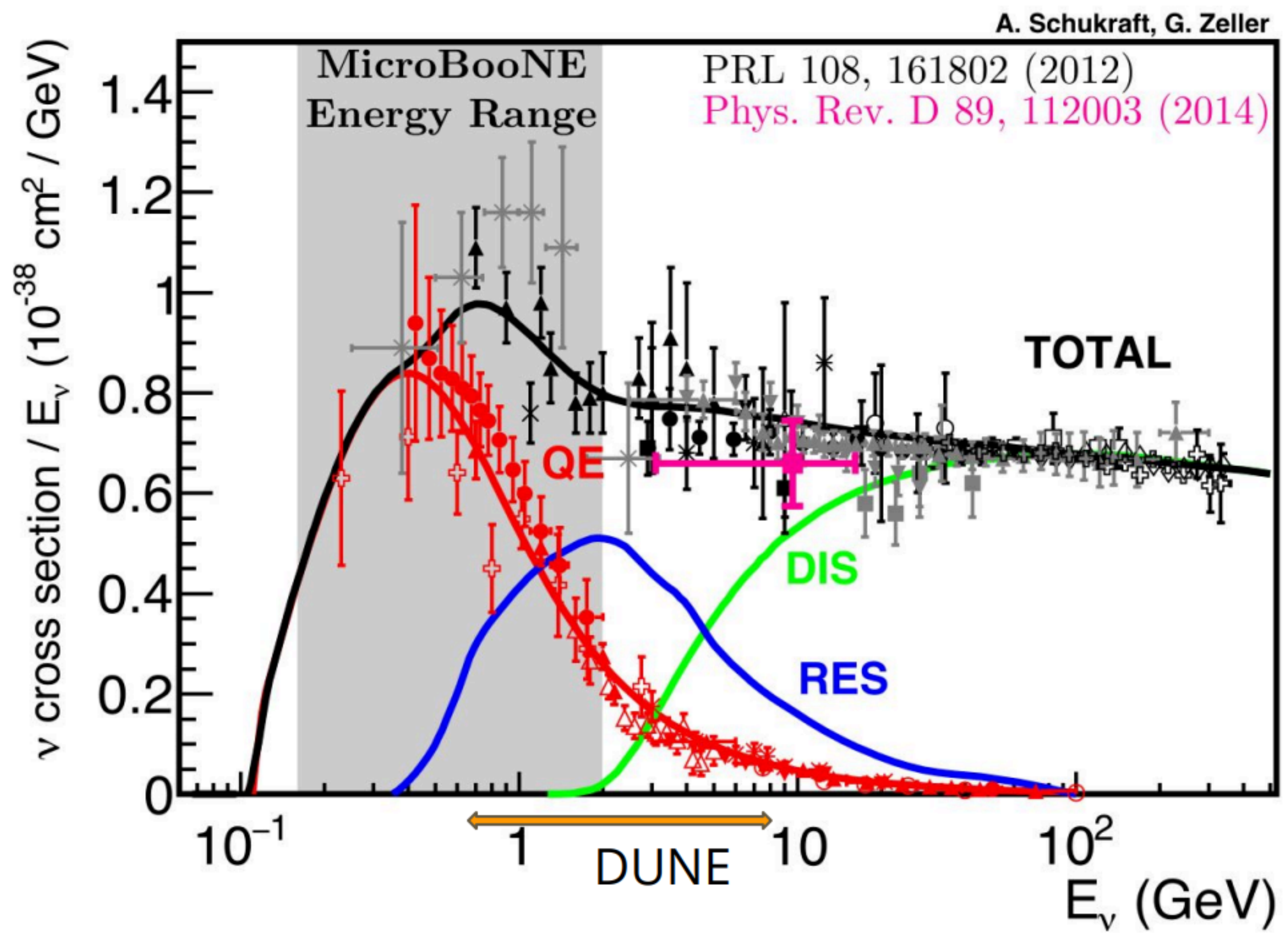
ν_e: **0.52%**

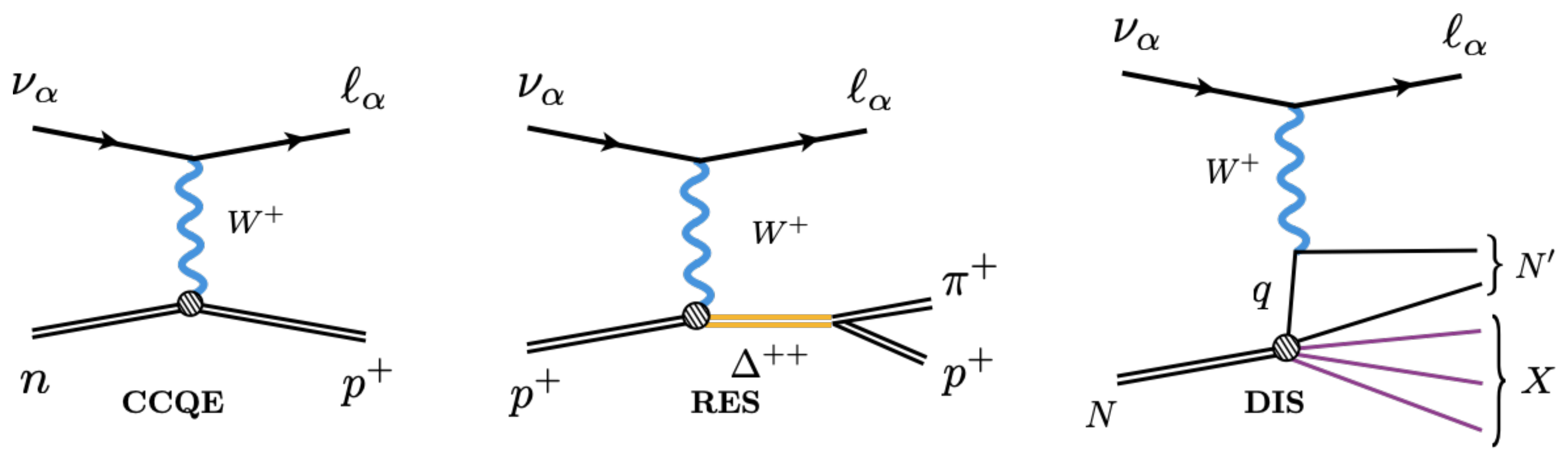
$\bar{\nu}_e$: 0.05%

Accelerator Neutrino Experiments

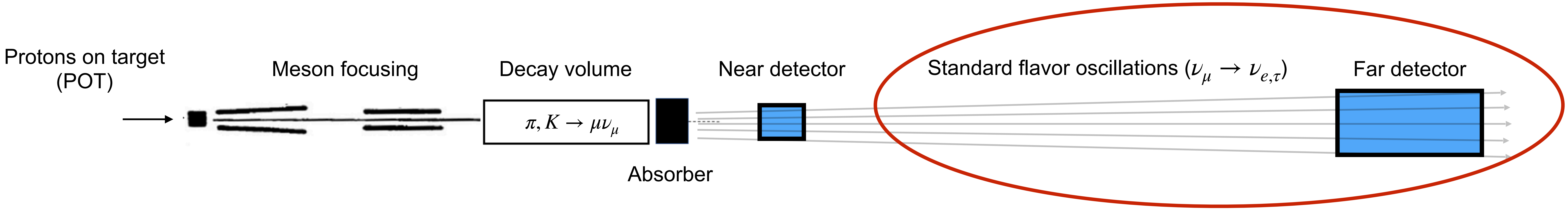


Large sample of neutrino interactions to directly measure (flux × cross sections).



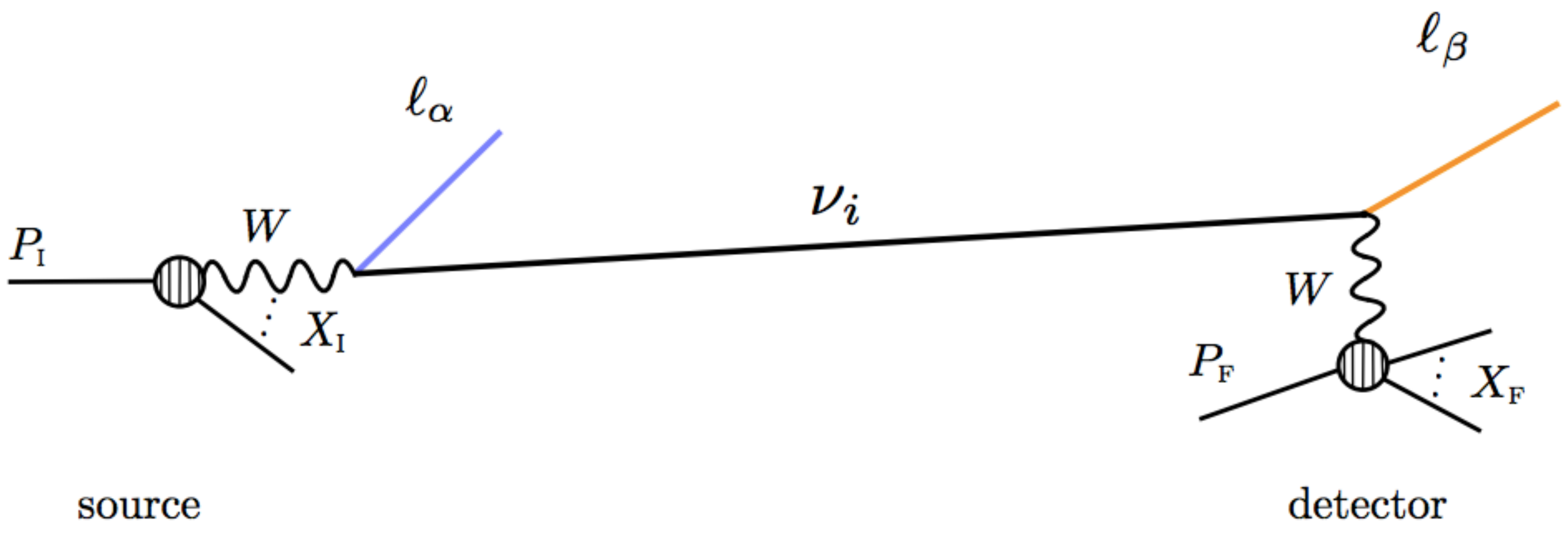


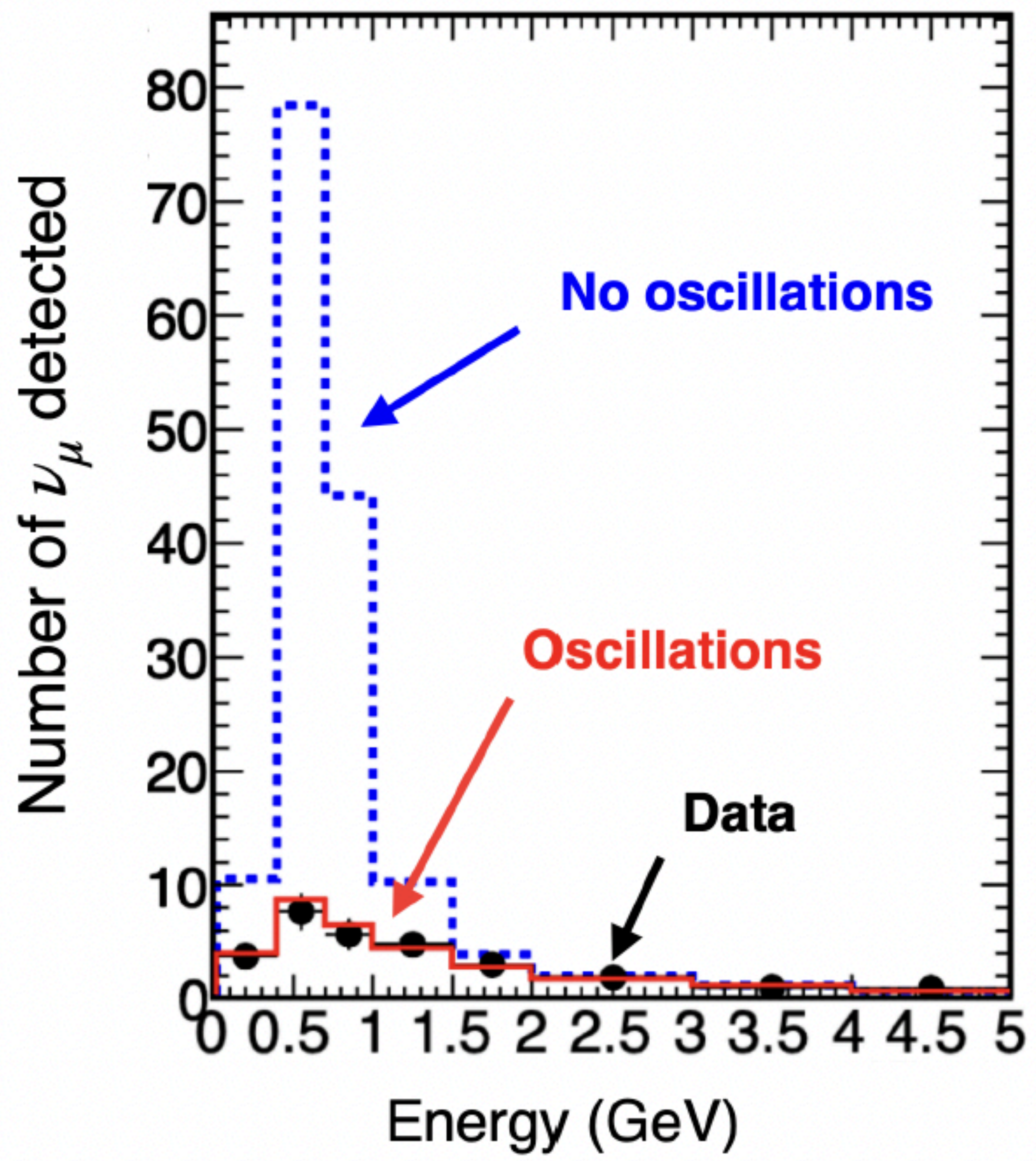
Accelerator Neutrino Experiments



Long-baseline neutrino oscillations at far detector.

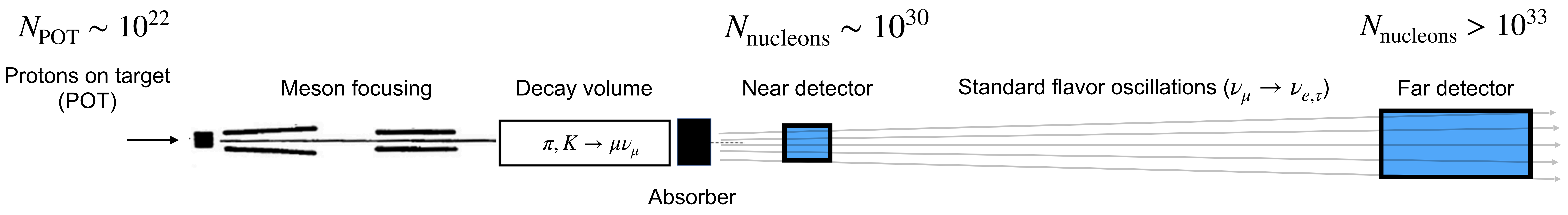
Three-neutrino oscillations are an $O(1)$ effect on the rate.





Adapted from T2K coll., 10.1103/PhysRevD.96.011102

Accelerator Neutrino Experiments



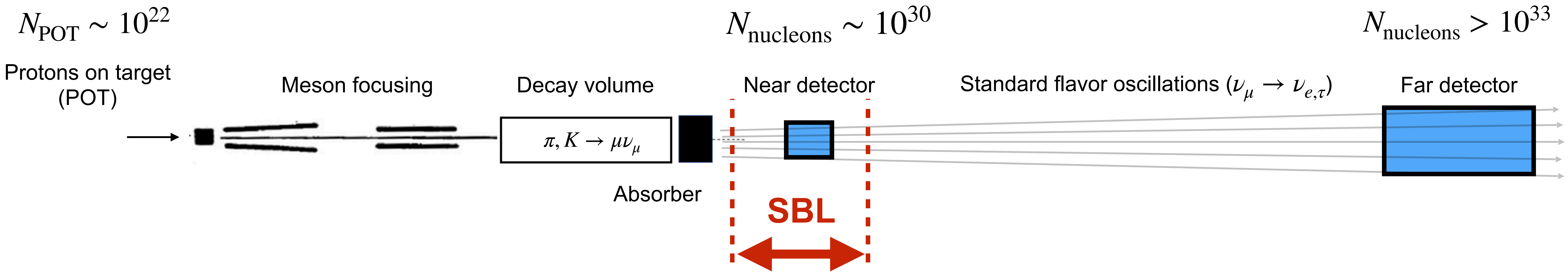
Neutrino scattering events: $N_{\rm events} \sim (N_{\rm POT} N_{\rm nucleons}) \times \left(\frac{\sigma_\nu}{L^2}\right)$

$> 10^{52}$ $< 10^{-48}$

Neutrino experiments are, by construction, sensitive to very rare phenomena.

Really good at searching for weaker-than-Weak effects.

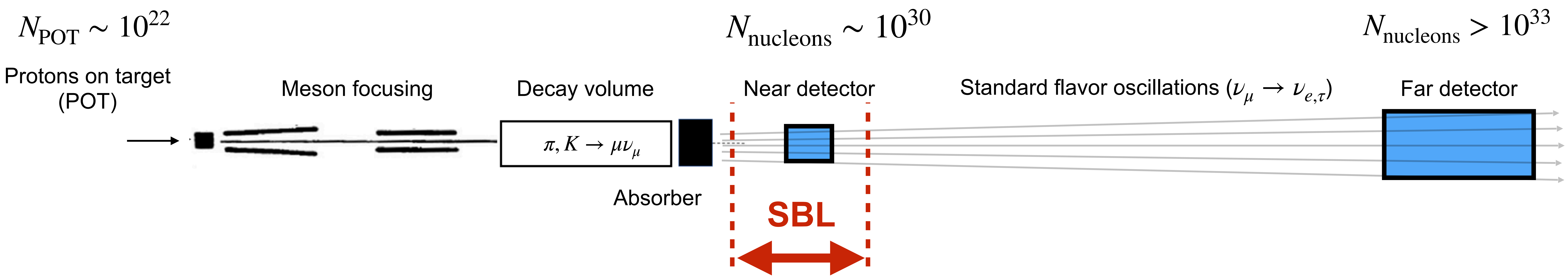
Short-Baseline Neutrino Experiments



Short Baseline (SBL) experiments focus on rare phenomena with large fluxes and *relatively small* (100 t-scale vs 10 kt-scale) detectors

$$\frac{L}{E} \sim \frac{\mathcal{O}(100\ \text{m})}{\mathcal{O}(100\ \text{MeV})}$$

Short-Baseline Neutrino Experiments

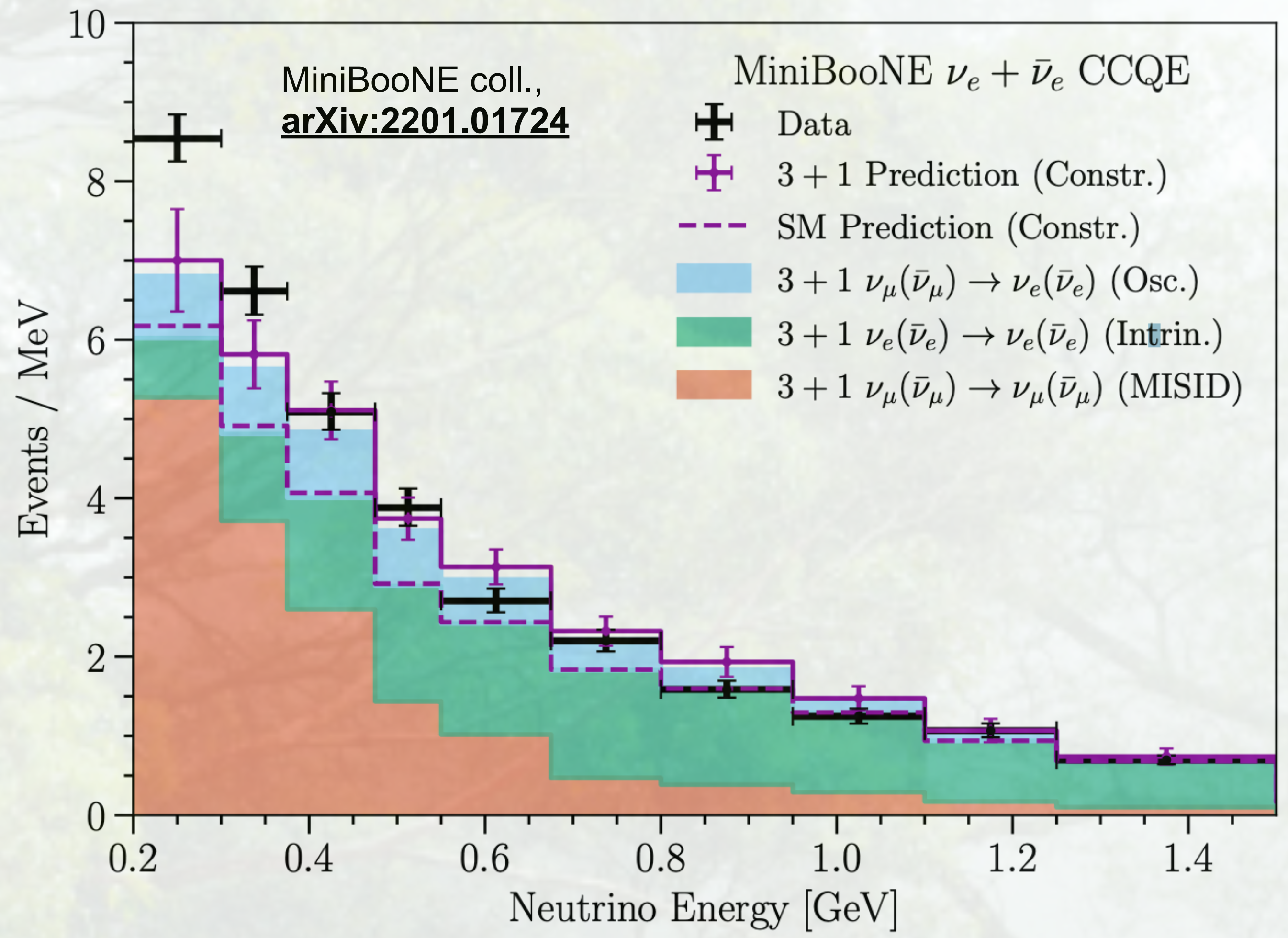


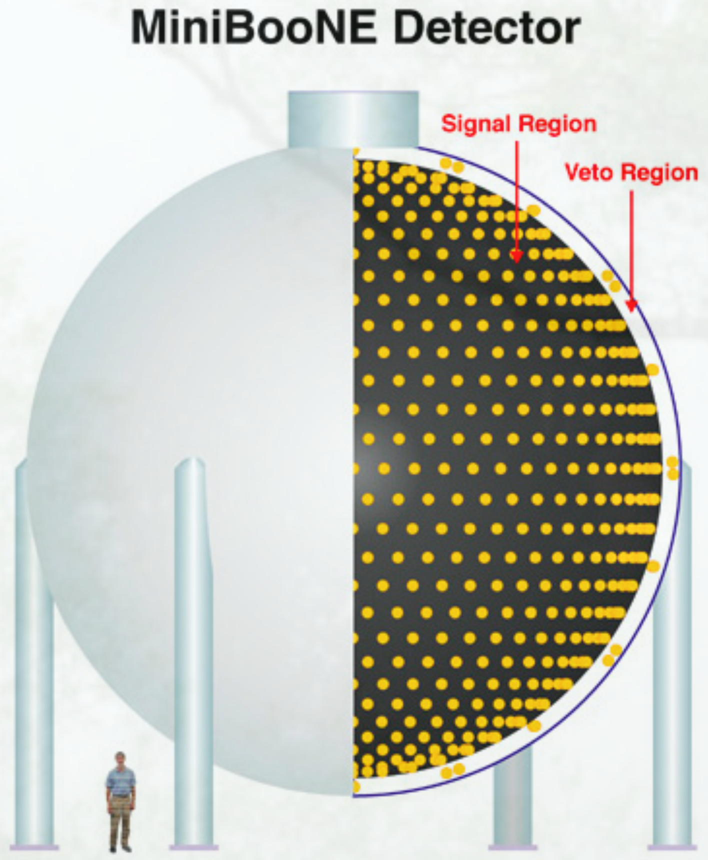
Short Baseline (SBL) experiments focus on rare phenomena with large fluxes and *relatively small* (100 t-scale vs 10 kt-scale) detectors

$$\frac{L}{E} \sim \frac{\mathcal{O}(100\ \text{m})}{\mathcal{O}(100\ \text{MeV})}$$

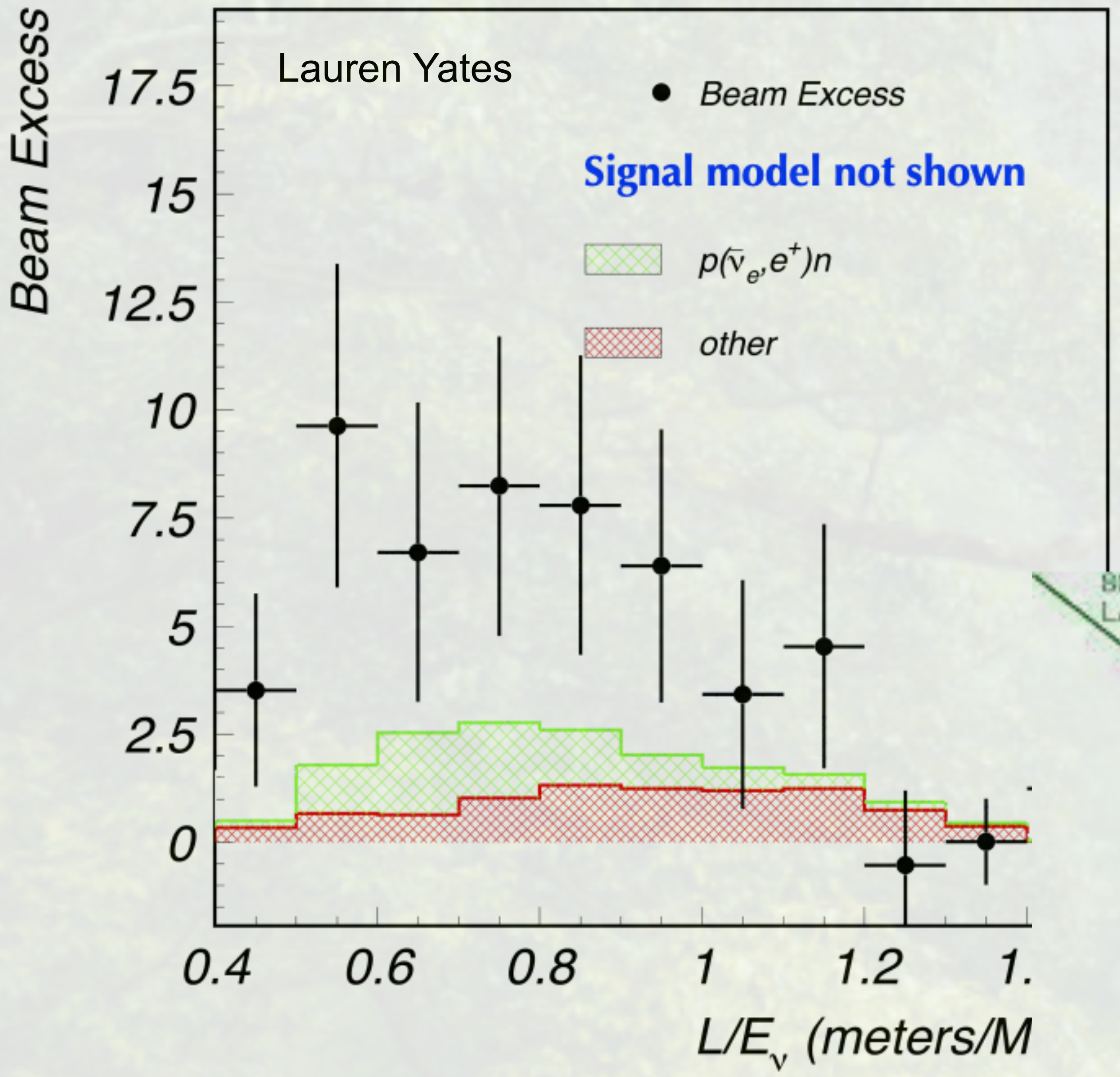
Natural combination of energies and locations, but **historically** this region received extra attention because of various hints for

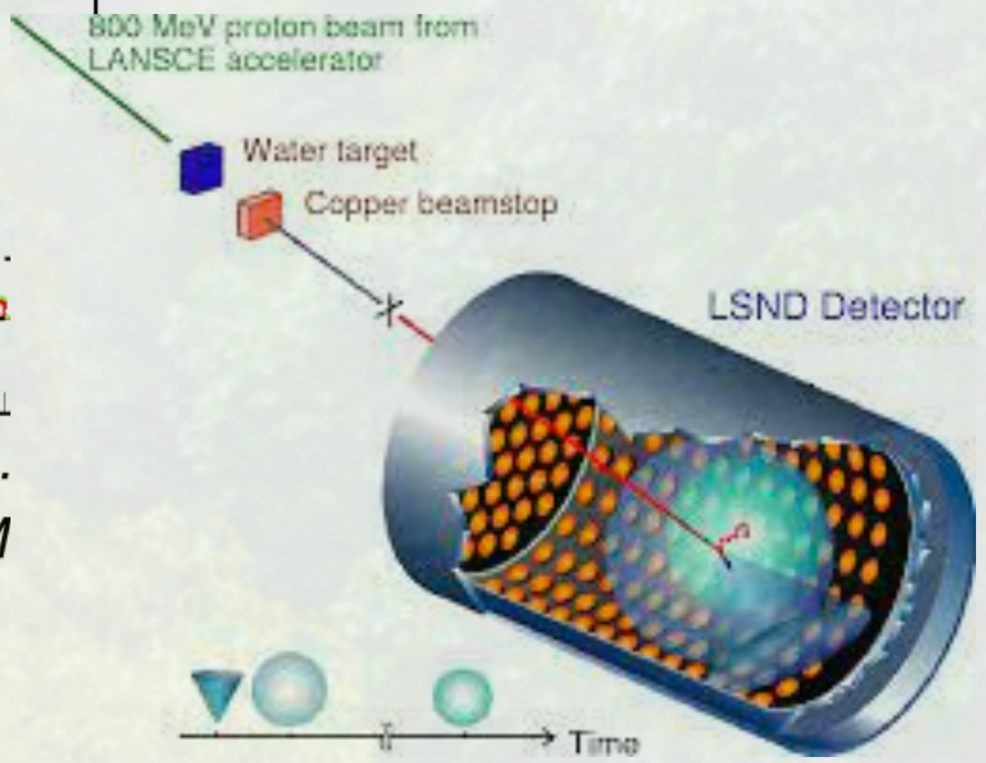
$\overline{\nu}_\mu \to \overline{\nu}_e$ **and** $\nu_\mu \to \nu_e$ **oscillation with** $\Delta m^2_{41} \sim 1\ \text{eV}^2$

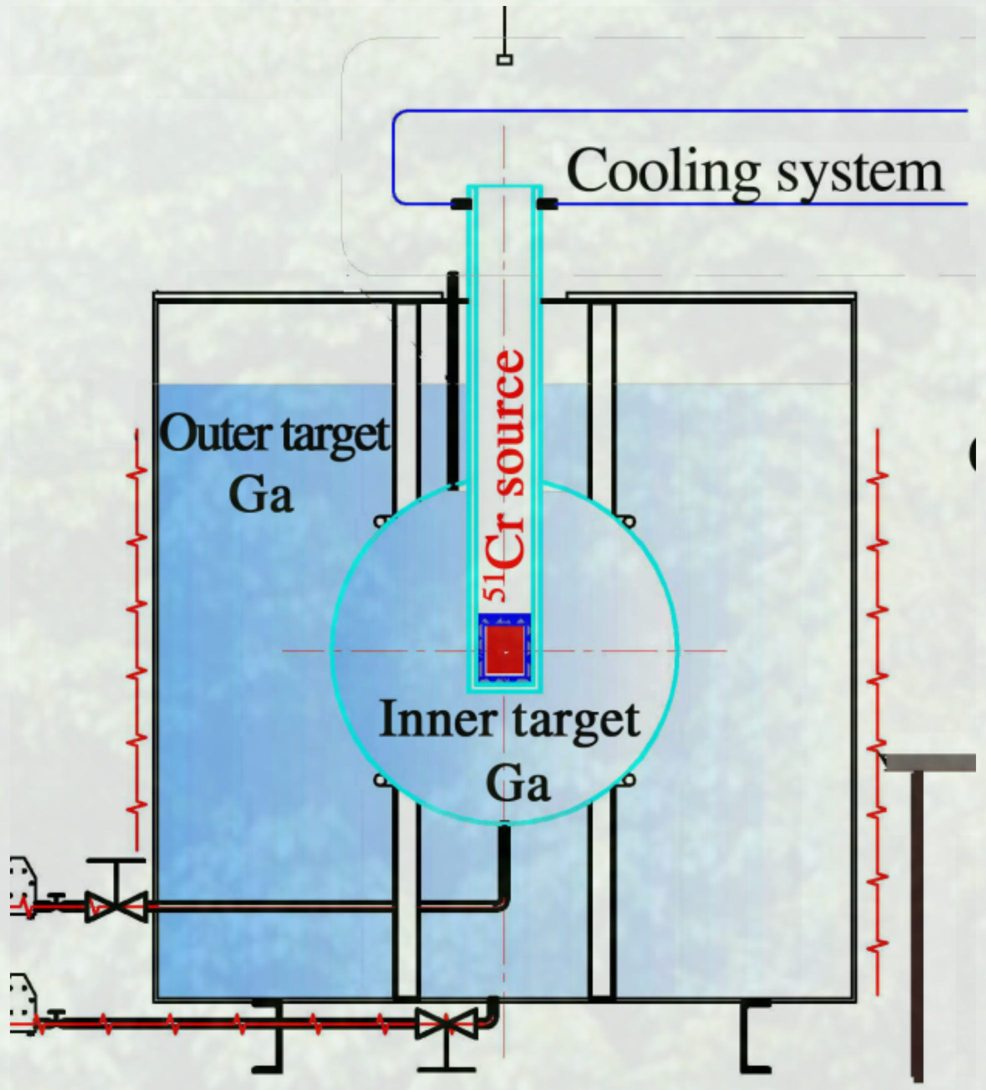




Short-Baseline Puzzle





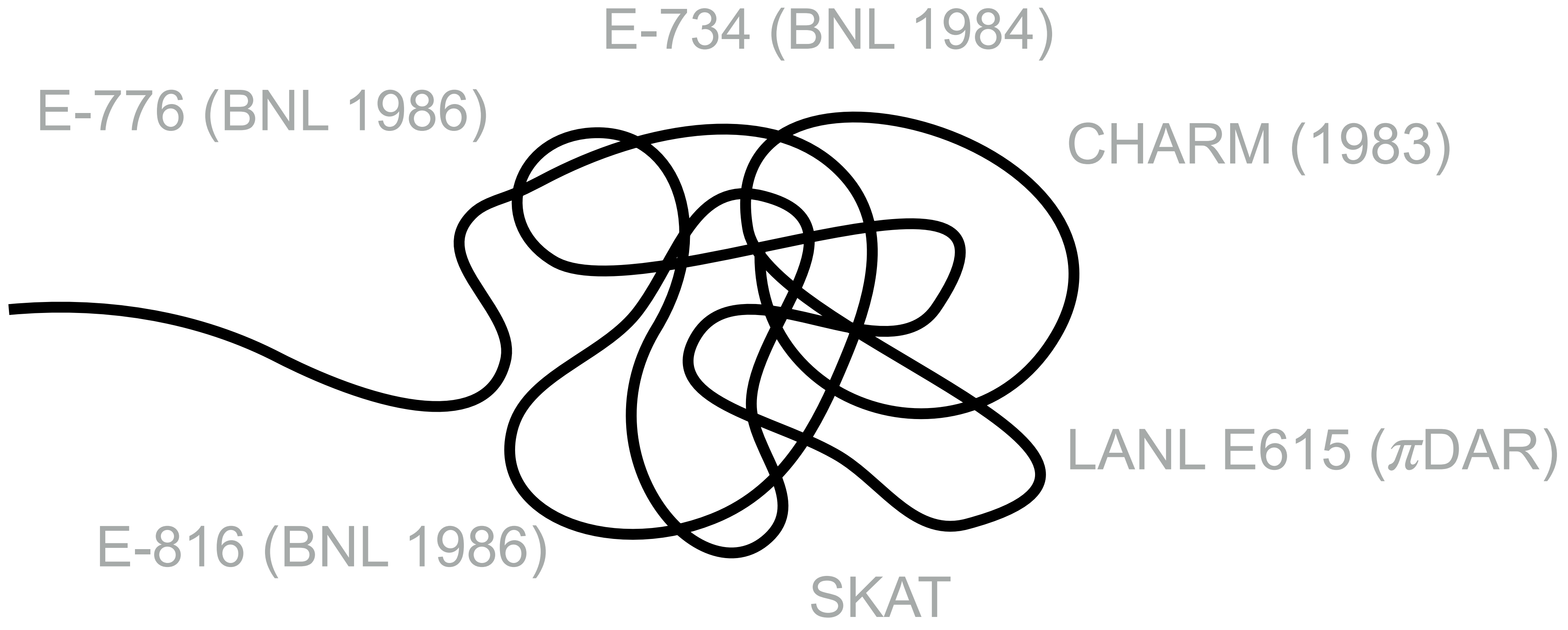


“**Pre-History**” of Short-Baseline Experiments: Oscillations?

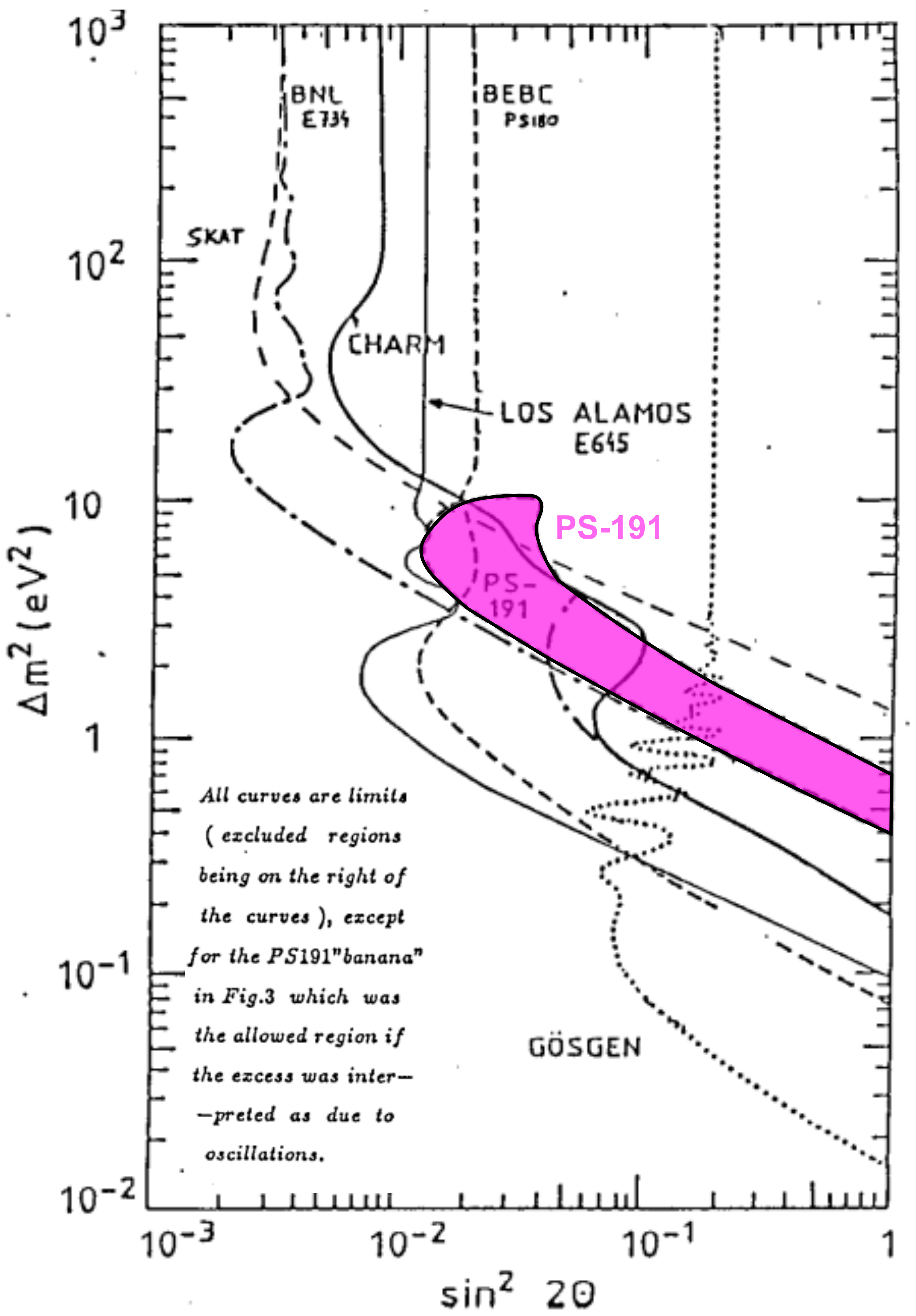
PS-191 (CERN 1984)

Phys.Lett.B 181 (1986) 173-177

23 ± 8 excess of ν_e events (3σ).



Gregorio Bernardi, 1988 ICHEP 88. HEP-88-11



New generation 1993: **LSND** and tantalizing hints for oscillations

πDAR source

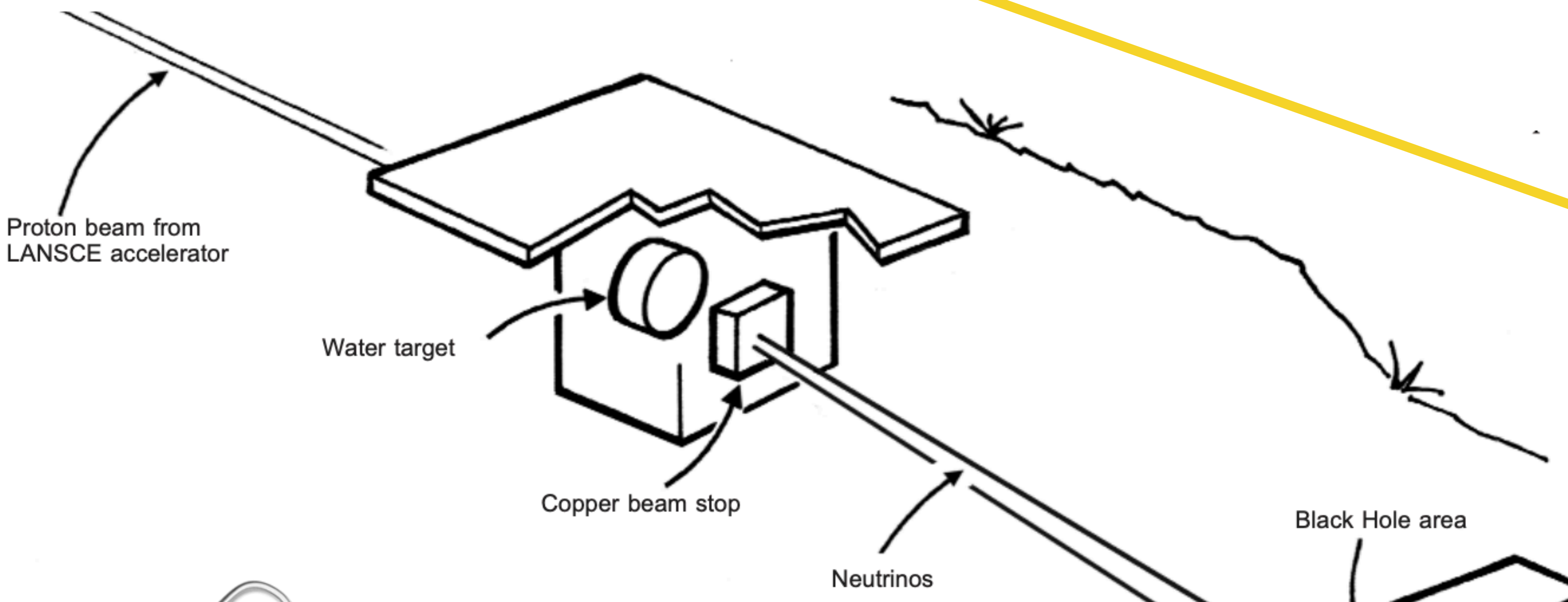
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$

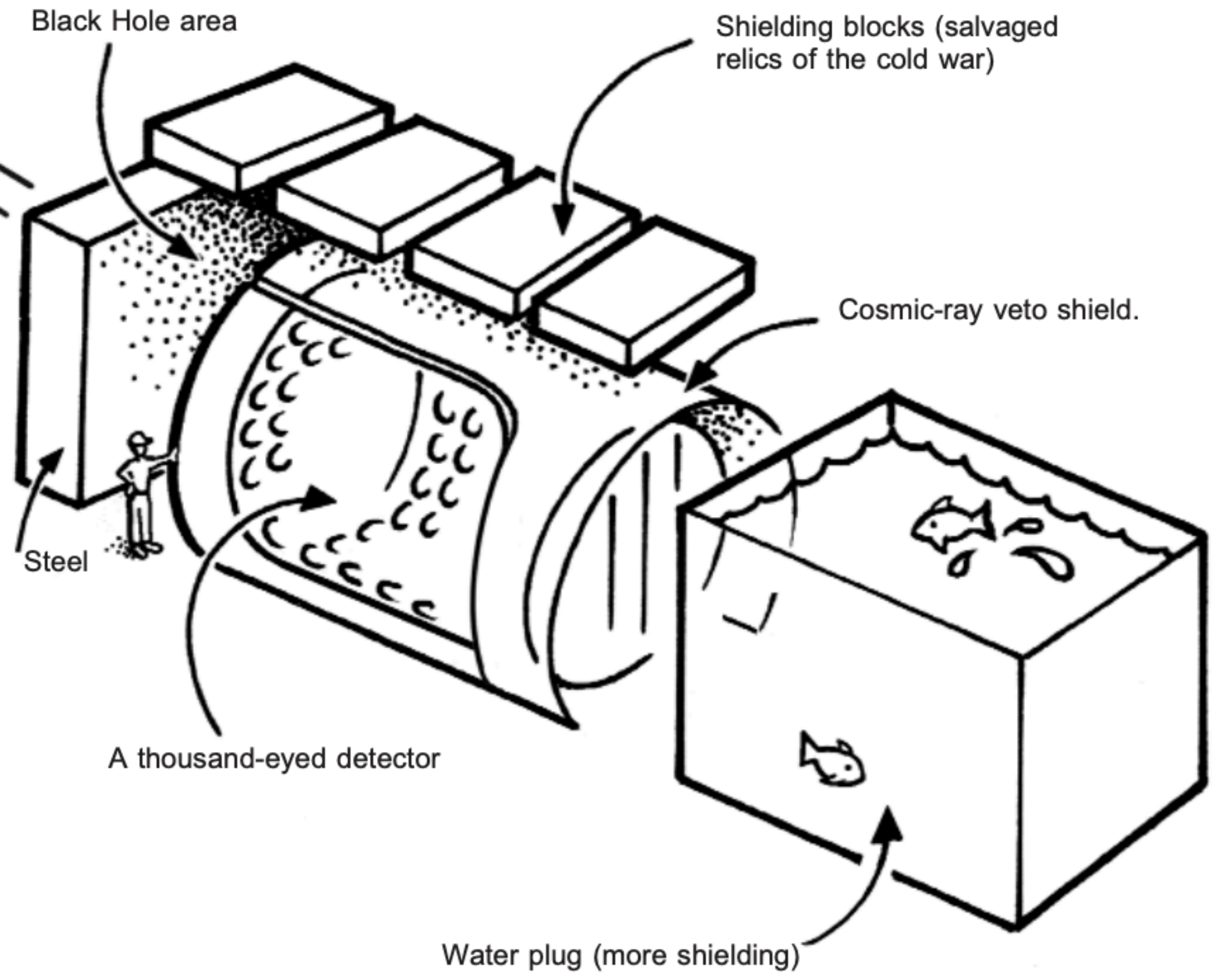
oscillation?

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$$

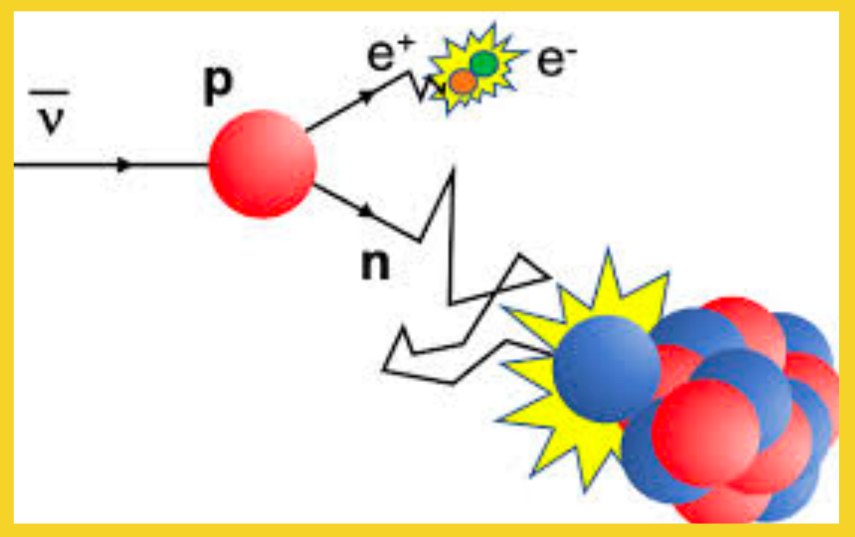
Excess: $87.9 \pm 22.4 \pm 6$ events

3.8σ significance

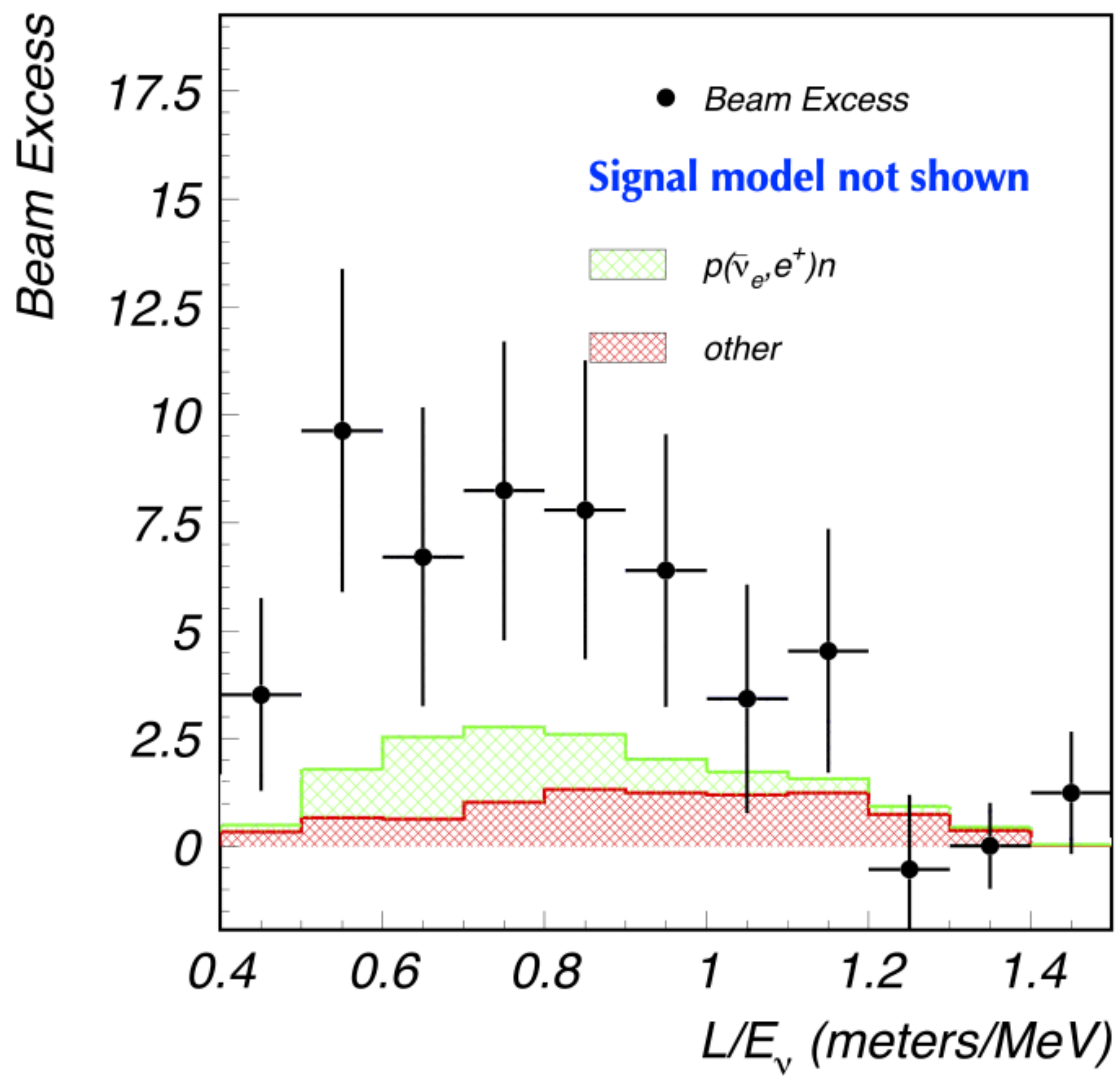




Inverse-Beta-decay detection



Lauren Yates



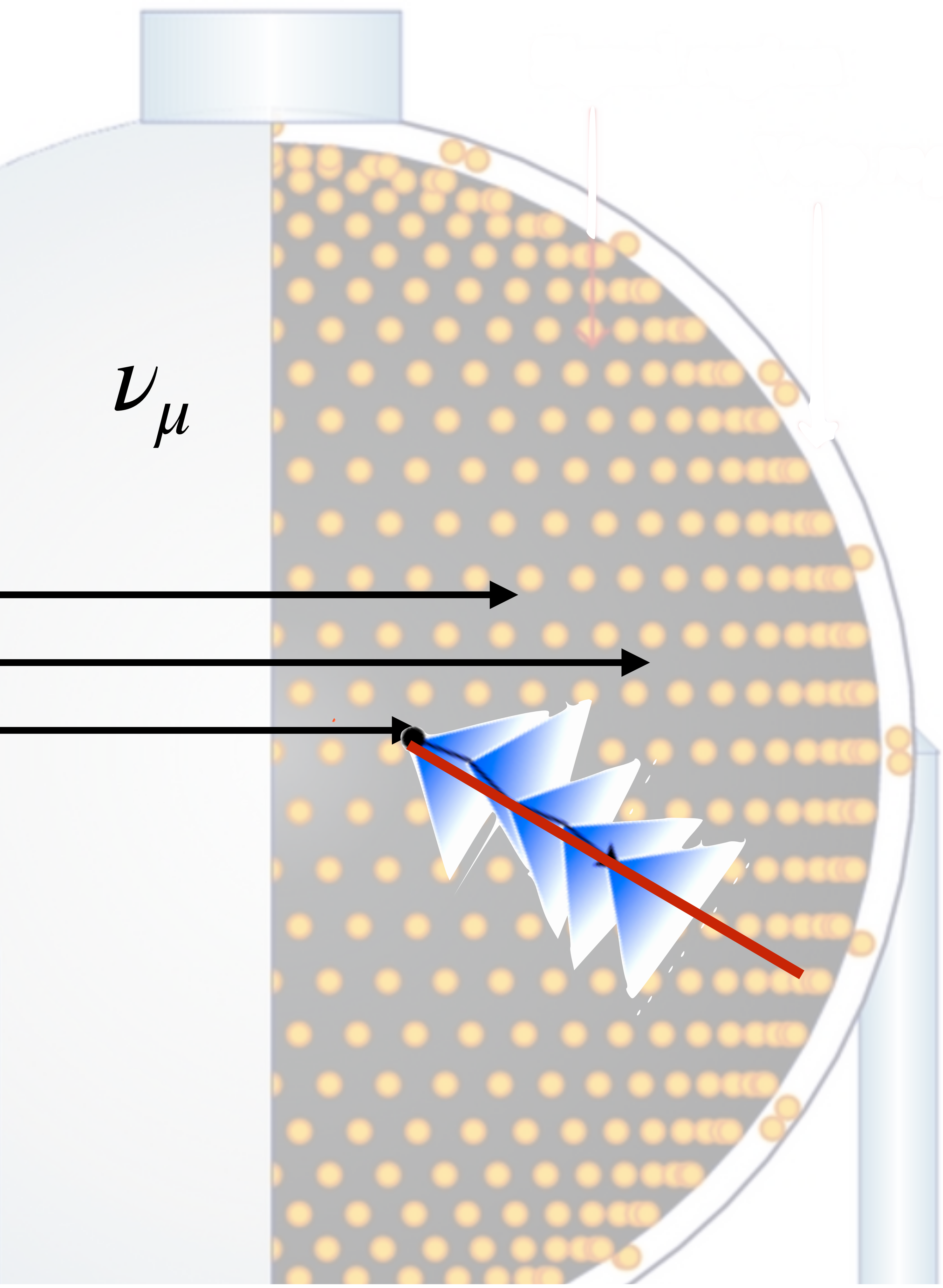
A Thousand Eyes: The story of LSND

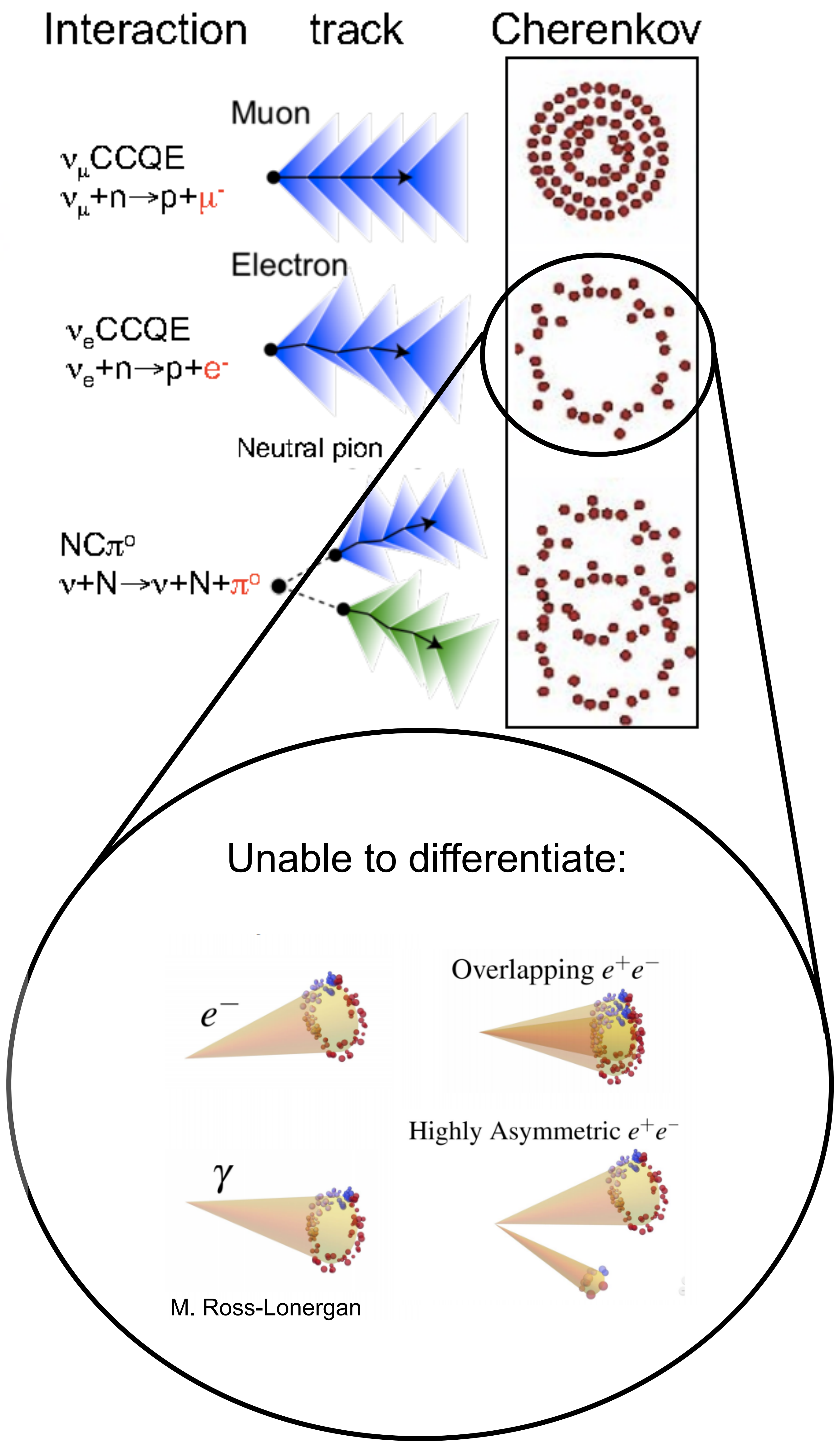
1.8×10^{23} protons (0.8 GeV) on target
30 meters baseline
167 tonnes of Liq. Scintillator

LSND coll. PRD 64 (2001) 112007

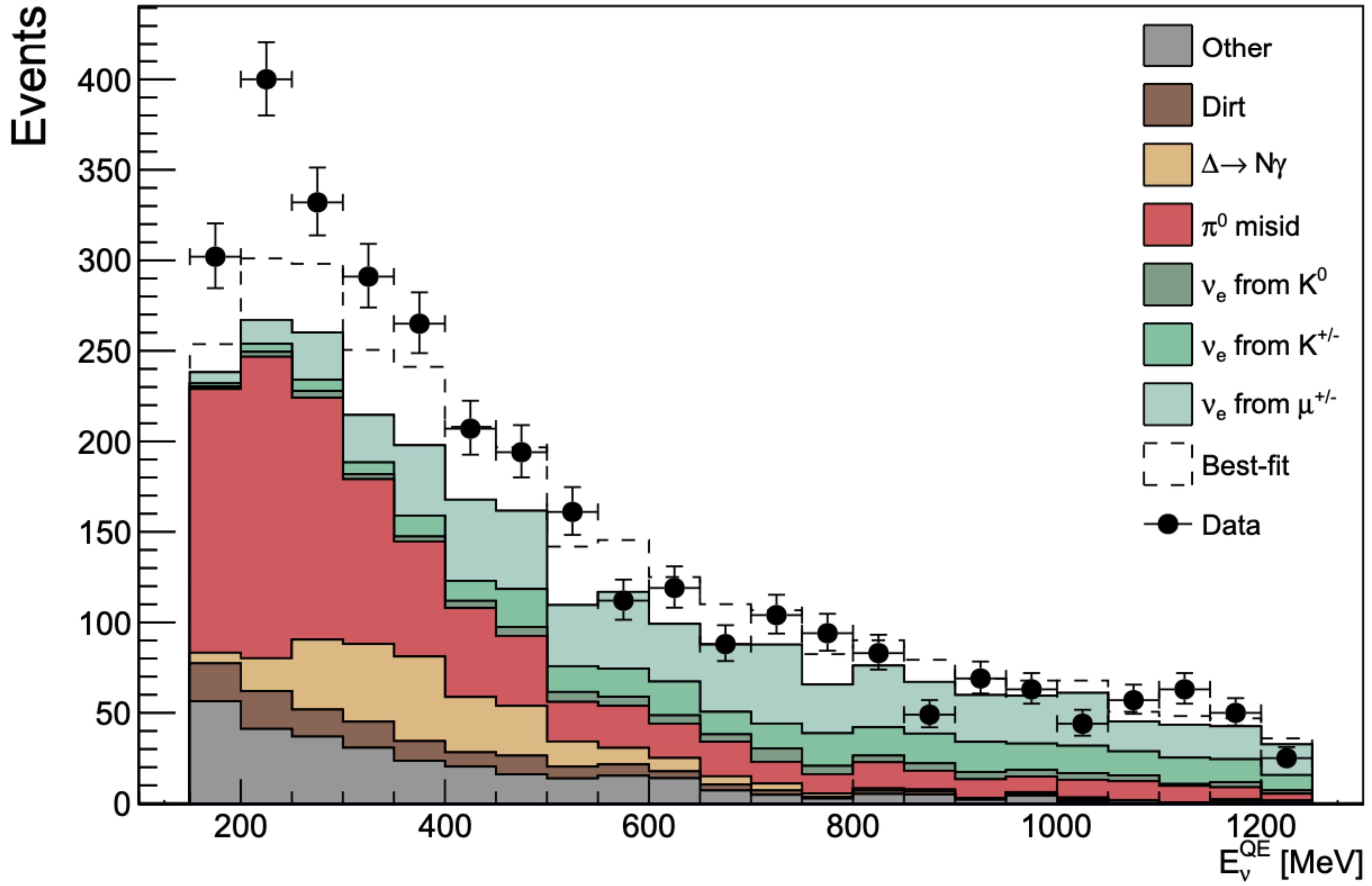
Early 2000's: the low-energy **MiniBooNE** excess

Cherenkov detector





MiniBooNE coll., PRD 103, 052002 (2021)



Reconstructed E_ν^{QE} / MeV

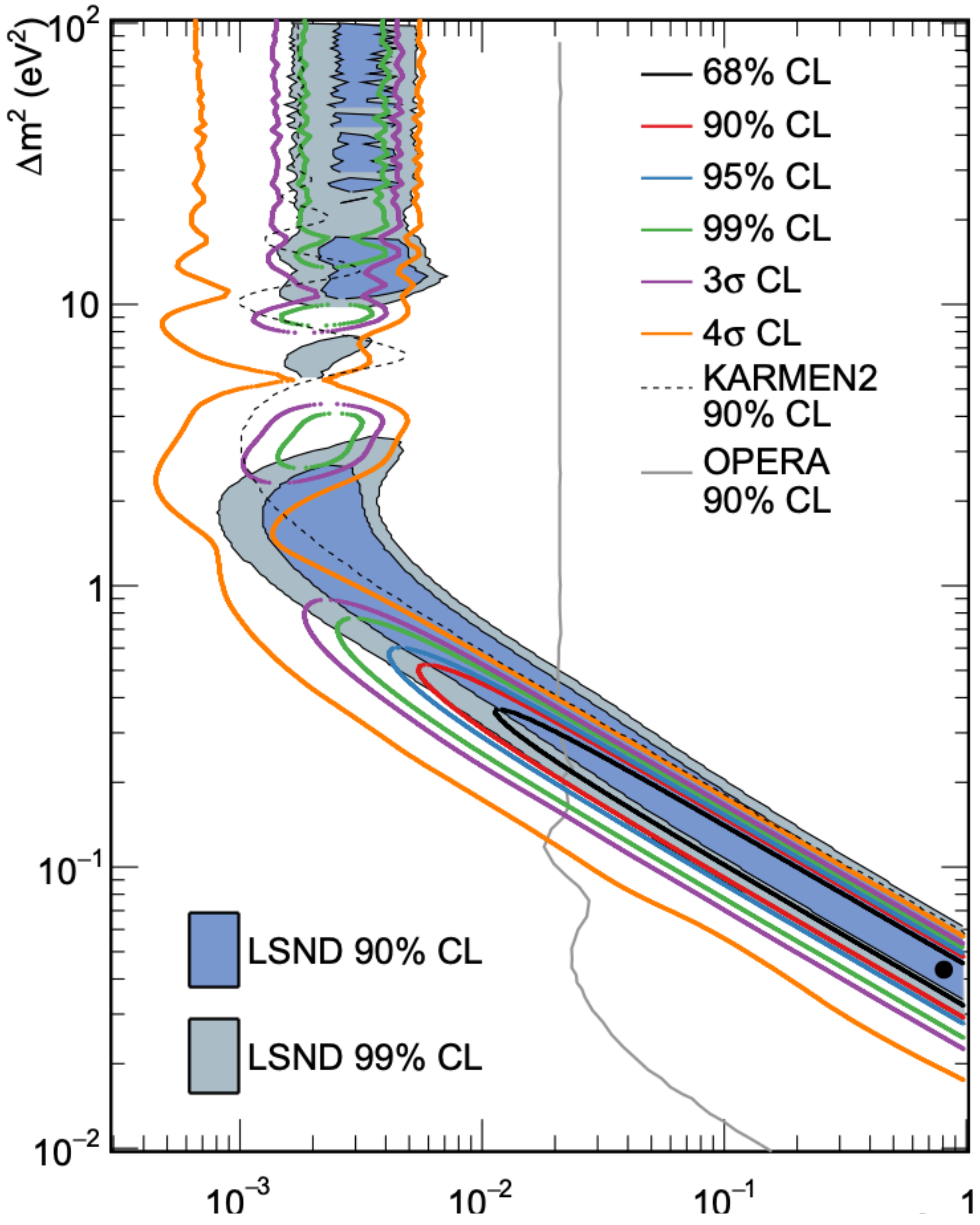
$638 \pm 52(\text{stat.}) \pm 122.2(\text{sys.})$

4.8σ significance

Systematics limited

Is there conclusive evidence for a sterile neutrino?

$\nu_\mu \to \nu_e$ **appearance**



$\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$

Effectively a 2-neutrino oscillation system: $\Delta \equiv \dfrac{\Delta m^2_{41} L}{4E}$

Appearance

$$P_{\nu_\mu\to\nu_e} = \sin^2 2\theta_{e\mu} \sin^2\Delta = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\Delta$$

Implies disappearance:

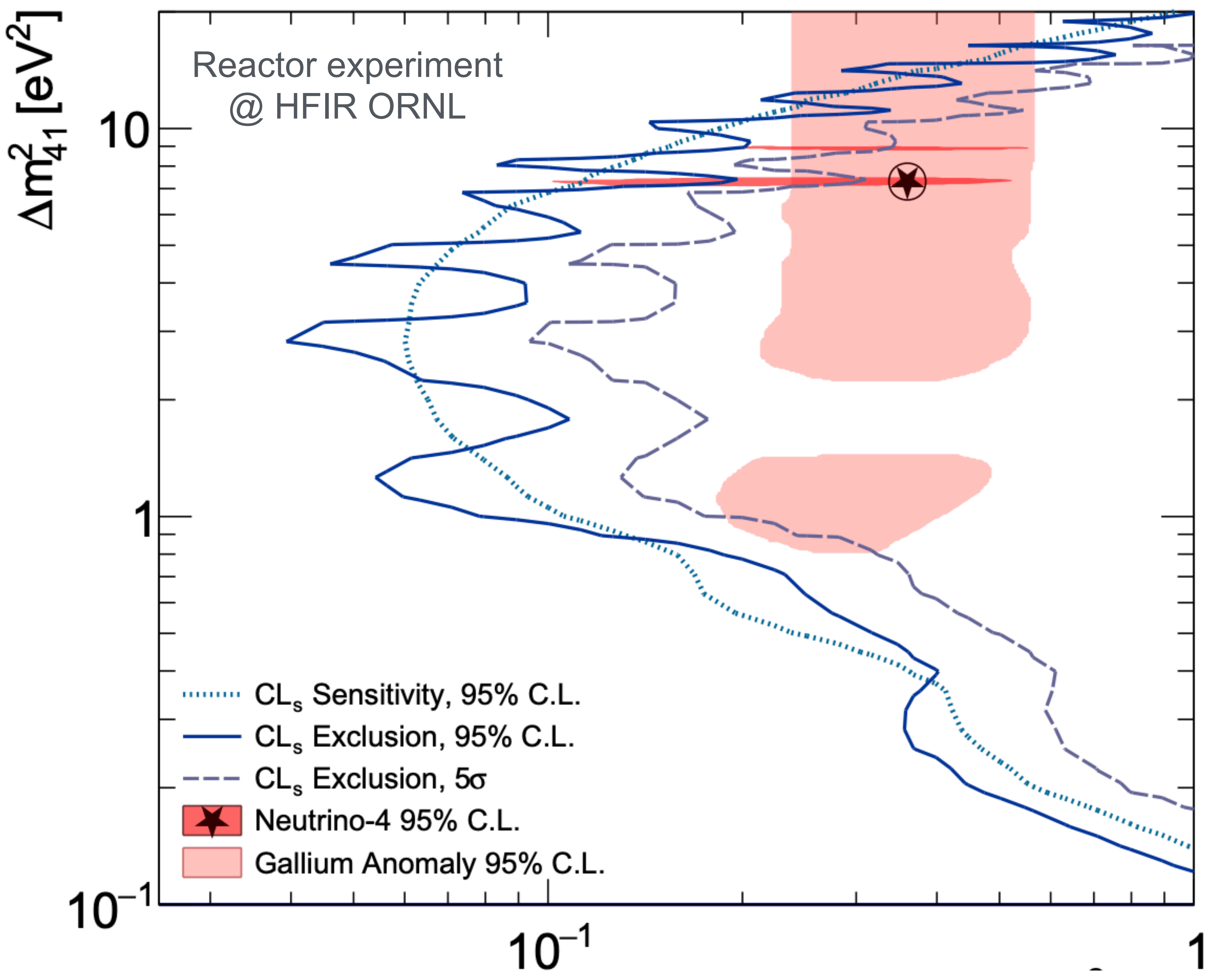
$$P_{\nu_\mu\to\nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2\Delta = 1 - 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)\sin^2\Delta$$

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

Is there conclusive evidence for a sterile neutrino?

ν_e disappearance: No convincing ν_e disappearance is observed (***Gallium anomaly)**

PROSPECT coll. PRL 134 (2025) 15, 151802



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

See also analysis of global reactor data: J. M. Berryman, P. Coloma, P. Huber, T. Schwetz, A. Zhou, JHEP 02 (2022) 055

Is there conclusive evidence for a sterile neutrino?

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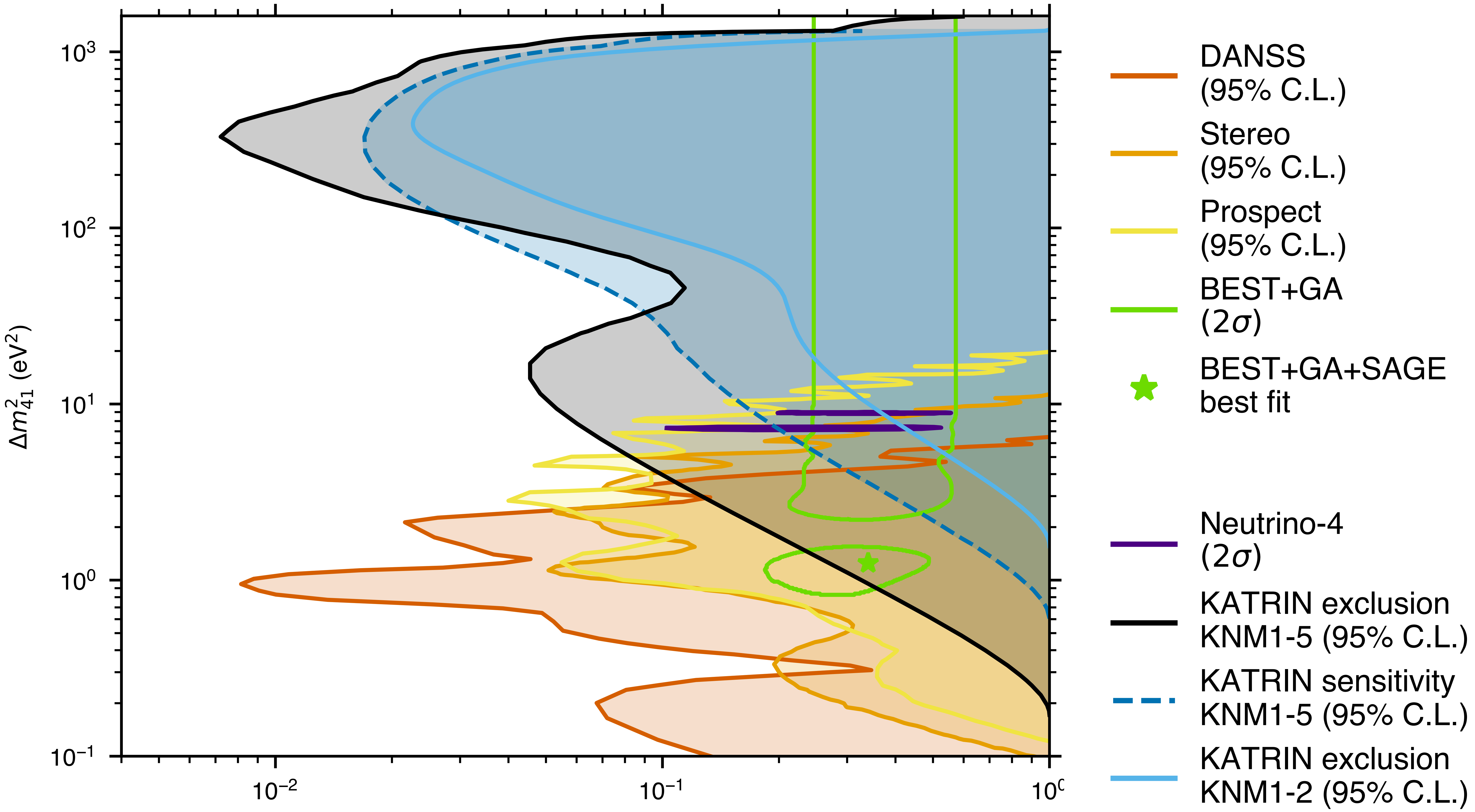
Adapted from KATRIN coll. arXiv:2503.18667



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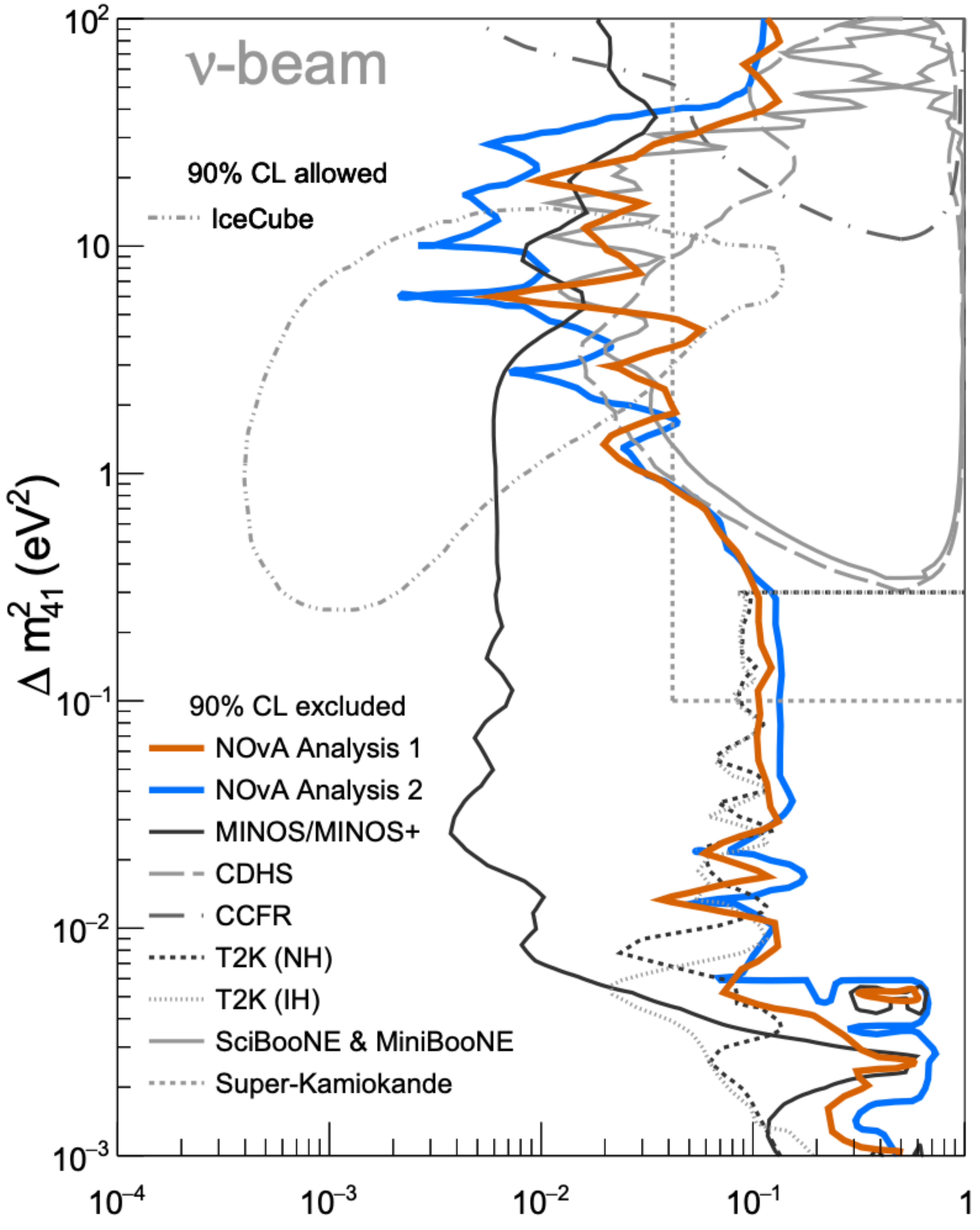
Is there conclusive evidence for a sterile neutrino?

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



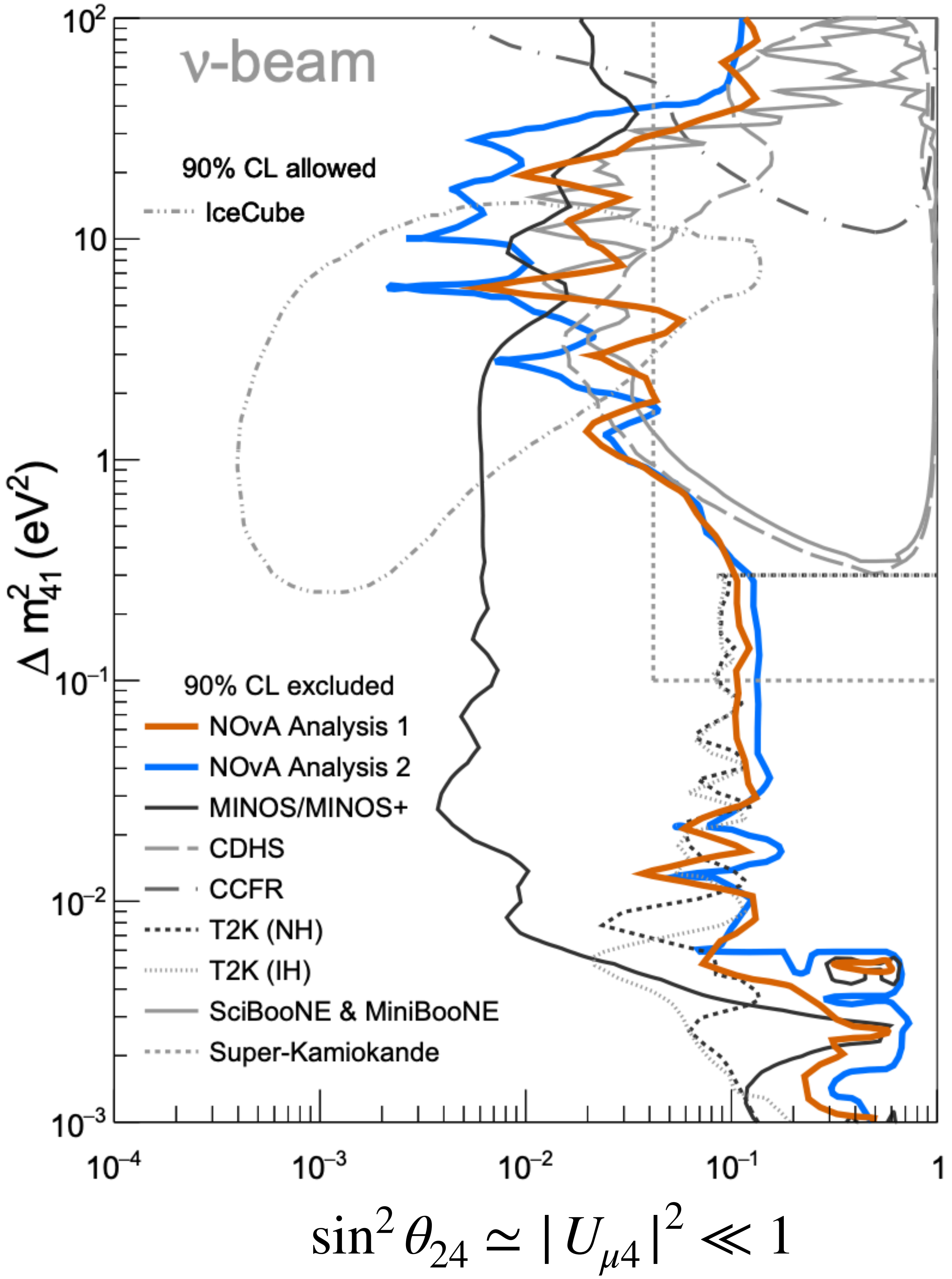
$\sin^2\theta_{24} \simeq |U_{\mu 4}|^2 \ll 1$

ν_μ disappearance

No convincing ν_μ disappearance either.

Is there conclusive evidence for a sterile neutrino?

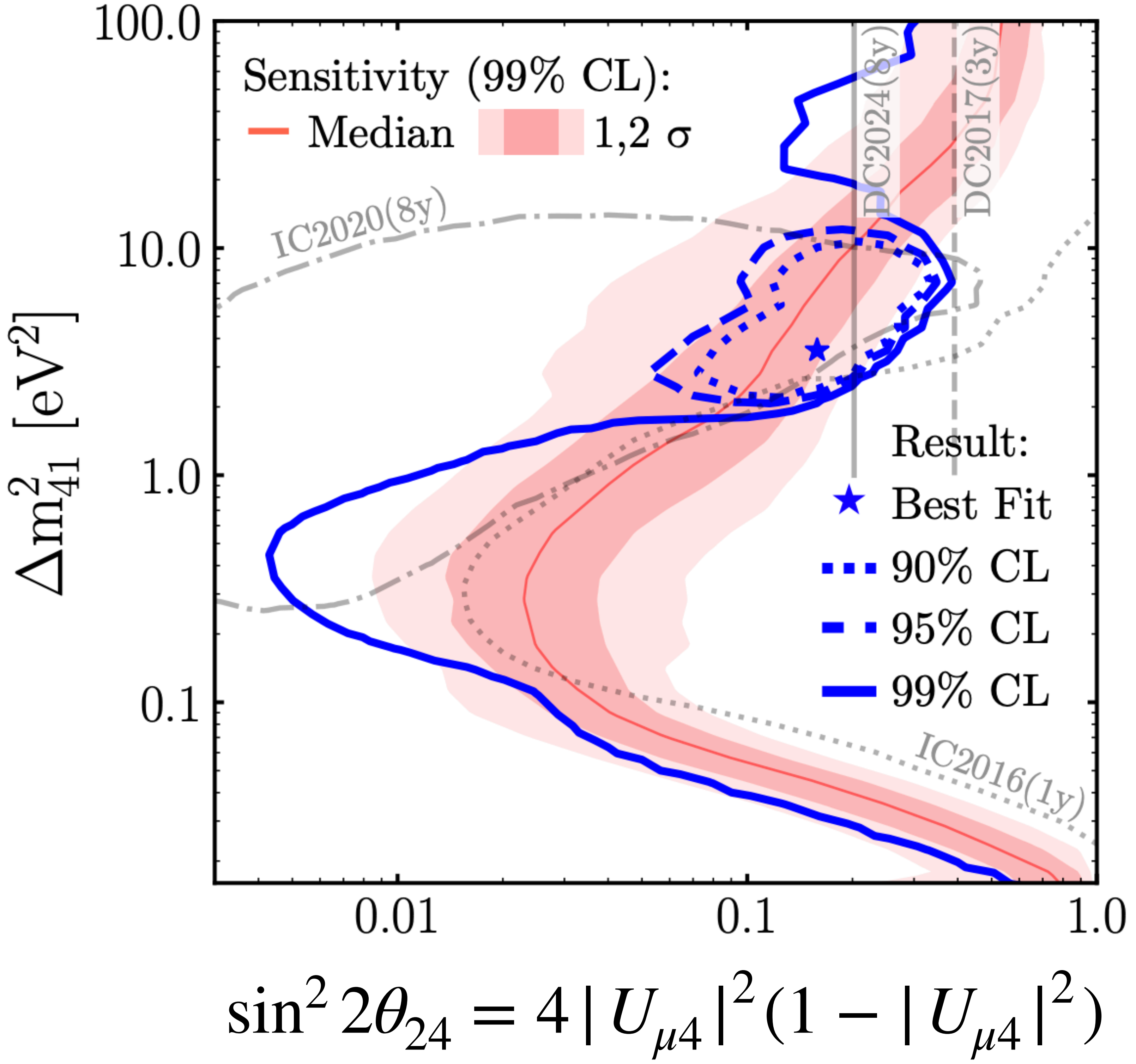
Adapted from
NOvA coll. PRL 134, 081804 (2025)



ν_μ disappearance

No convincing ν_μ disappearance either.

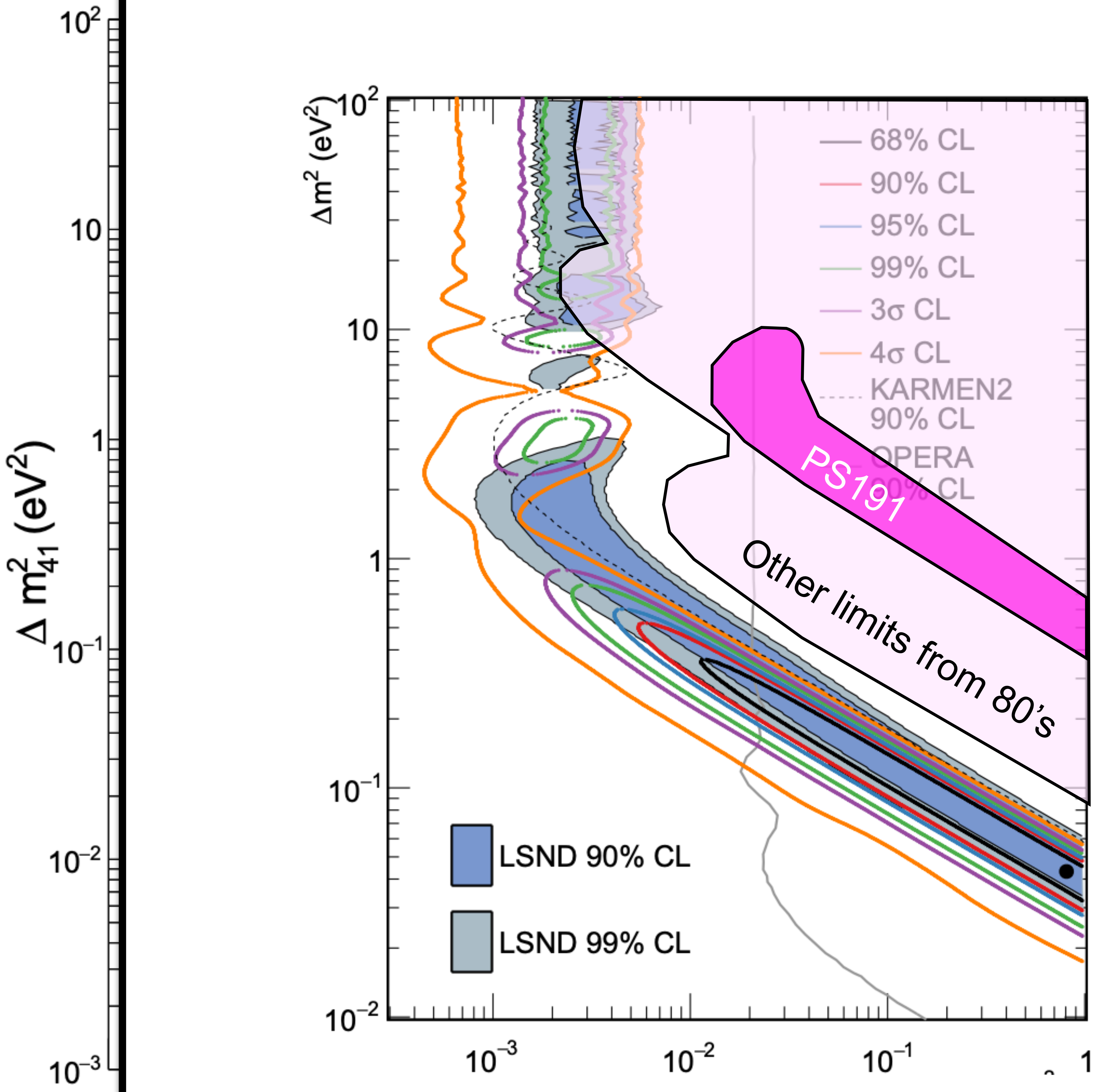
IceCube coll. PRL 133, 201804 (2024)



IceCube sees a small preference for sterile using matter effects.
Mostly in tension with MINOS(+) and NOvA

Is there conclusive evidence for a sterile neutrino?

Adapted from



$$\sin^2 2\theta_{e\mu} = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2$$

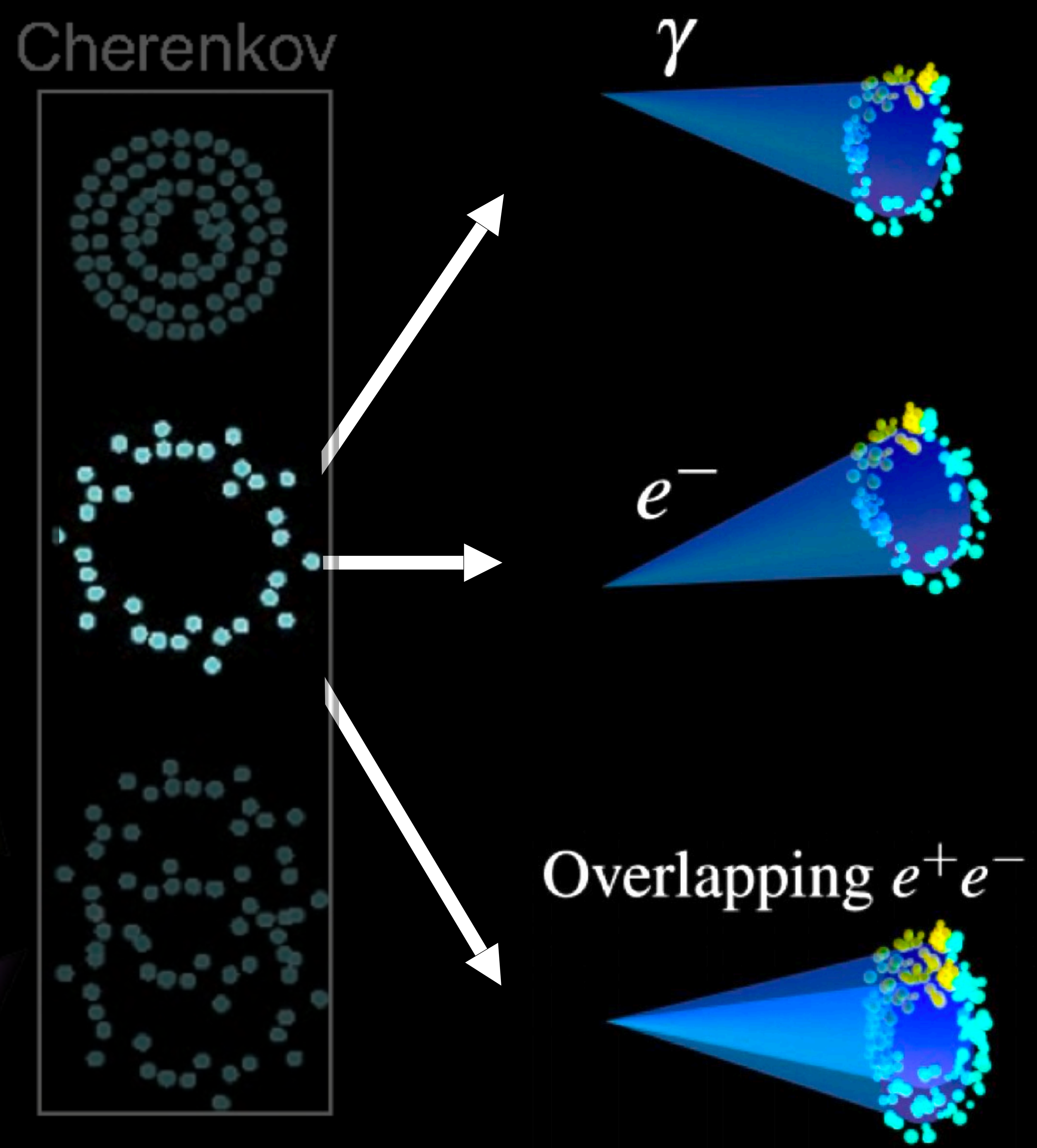
Huge progress.
Moved from $1\,\%$ **to** $0.1\,\%$**.**

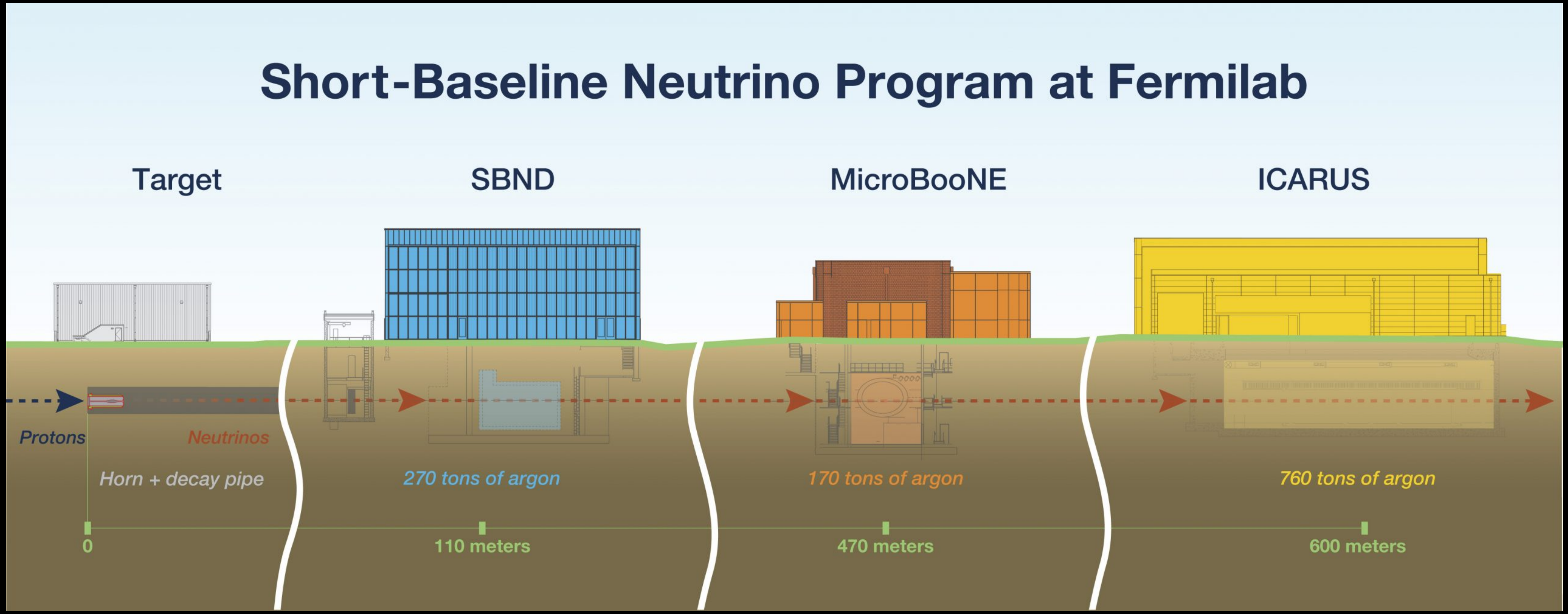
MiniBooNE and LSND stand as the most sensitive appearance experiments to date.

But still no coherent picture.

3+1 oscillations look highly unlikely, but no direct and robust test (yet).

Zooming in on the MiniBooNE low-energy excess (LEE)

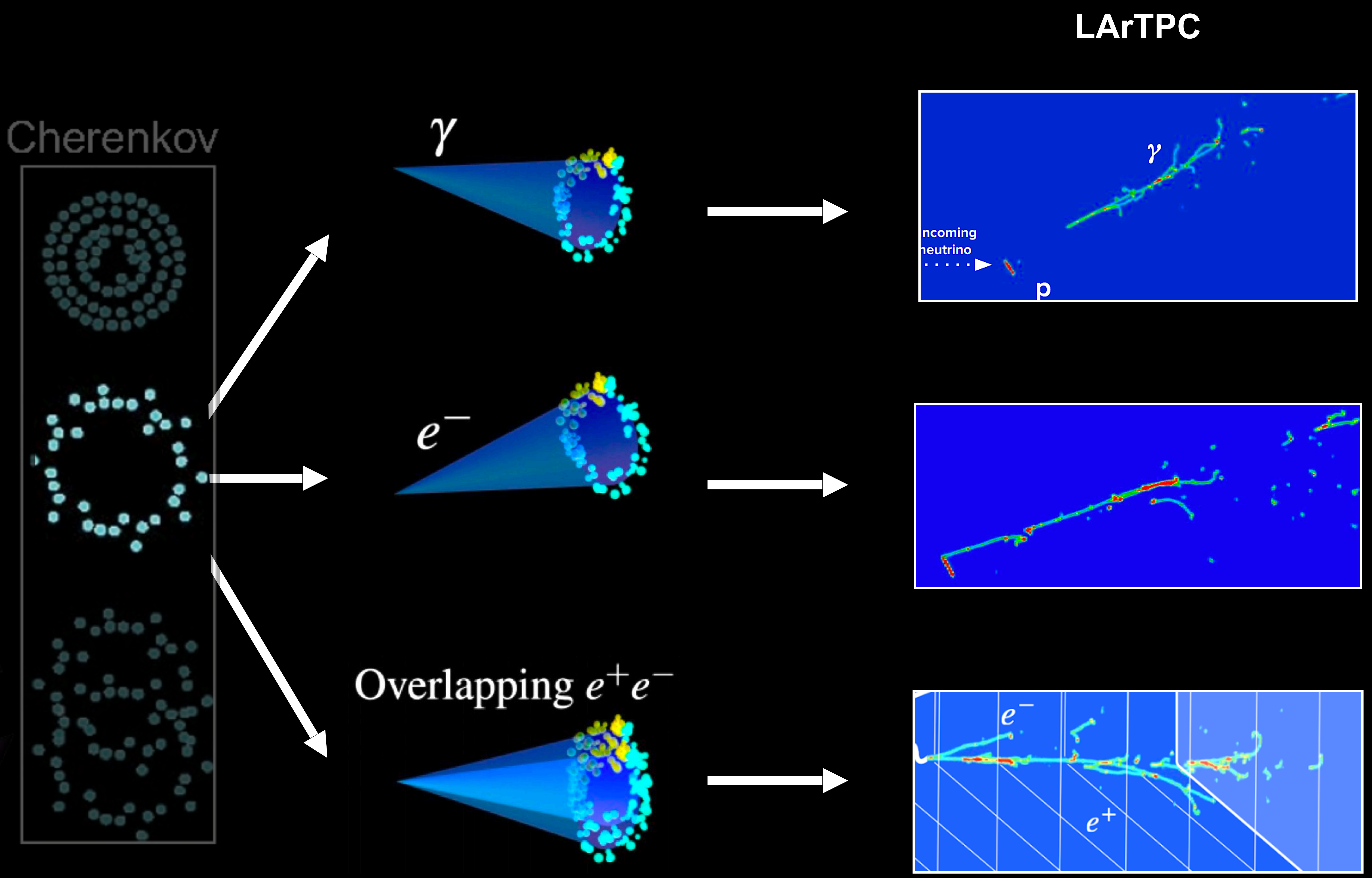




Liquid-Argon Time-Projection-Chamber (LArTPC)

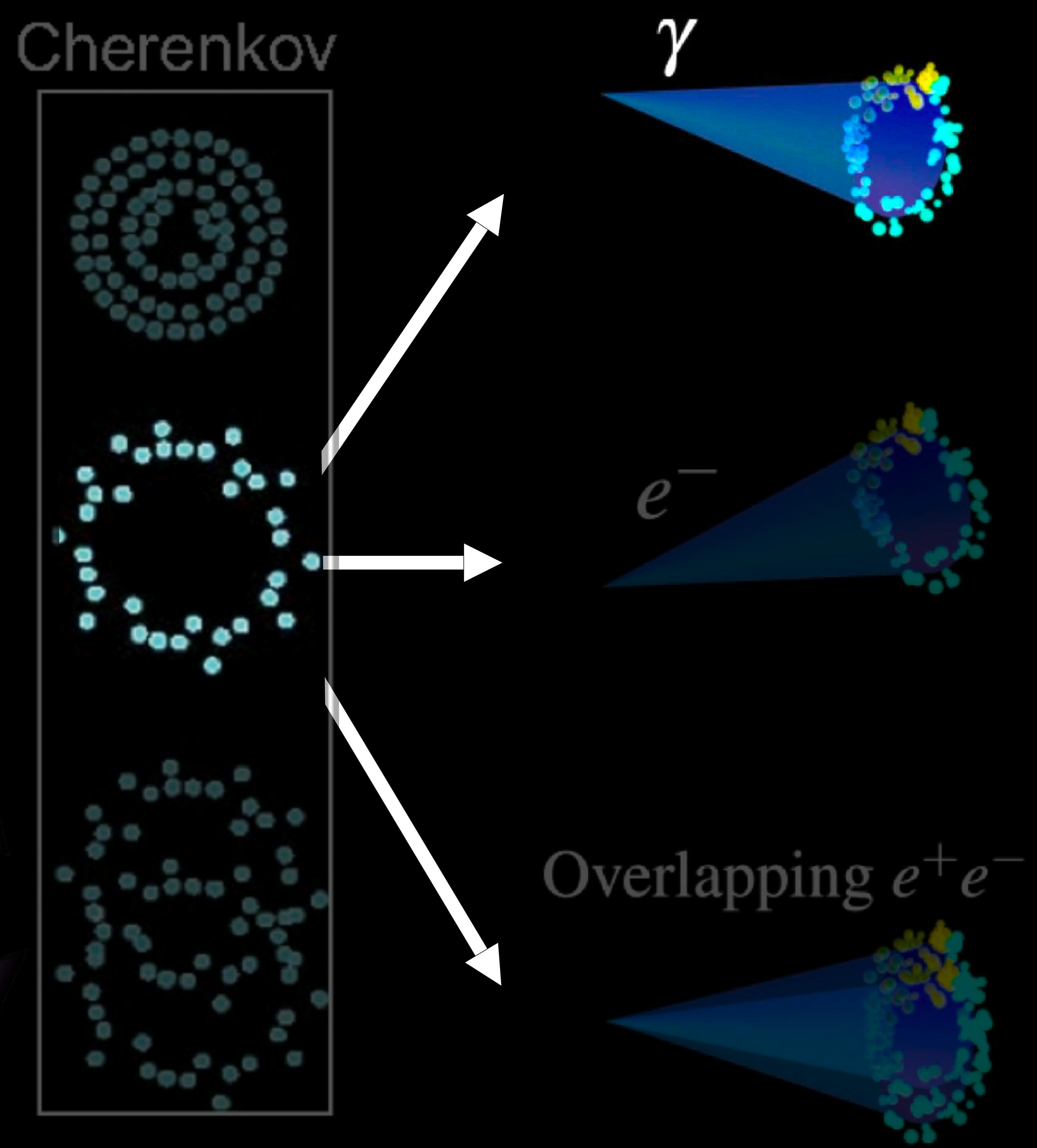
Better particle ID and more capable of disentangling the origin of the excess.

Zooming in on the MiniBooNE low-energy excess (LEE) with MicroBooNE



Disentangling final states

Zooming in on the MiniBooNE low-energy excess (LEE) with MicroBooNE



Second generation of analysis came out early 2025:

Delta radiative: $1\gamma 1p$
arXiv:2502.05750

No excess
94.4% CL exclusion

Coherent: $1\gamma 0p$
arXiv:2502.06091

No excess, but not sensitive to the required value to explain the LEE.

Inclusive: $1\gamma X$
arXiv:2502.06064

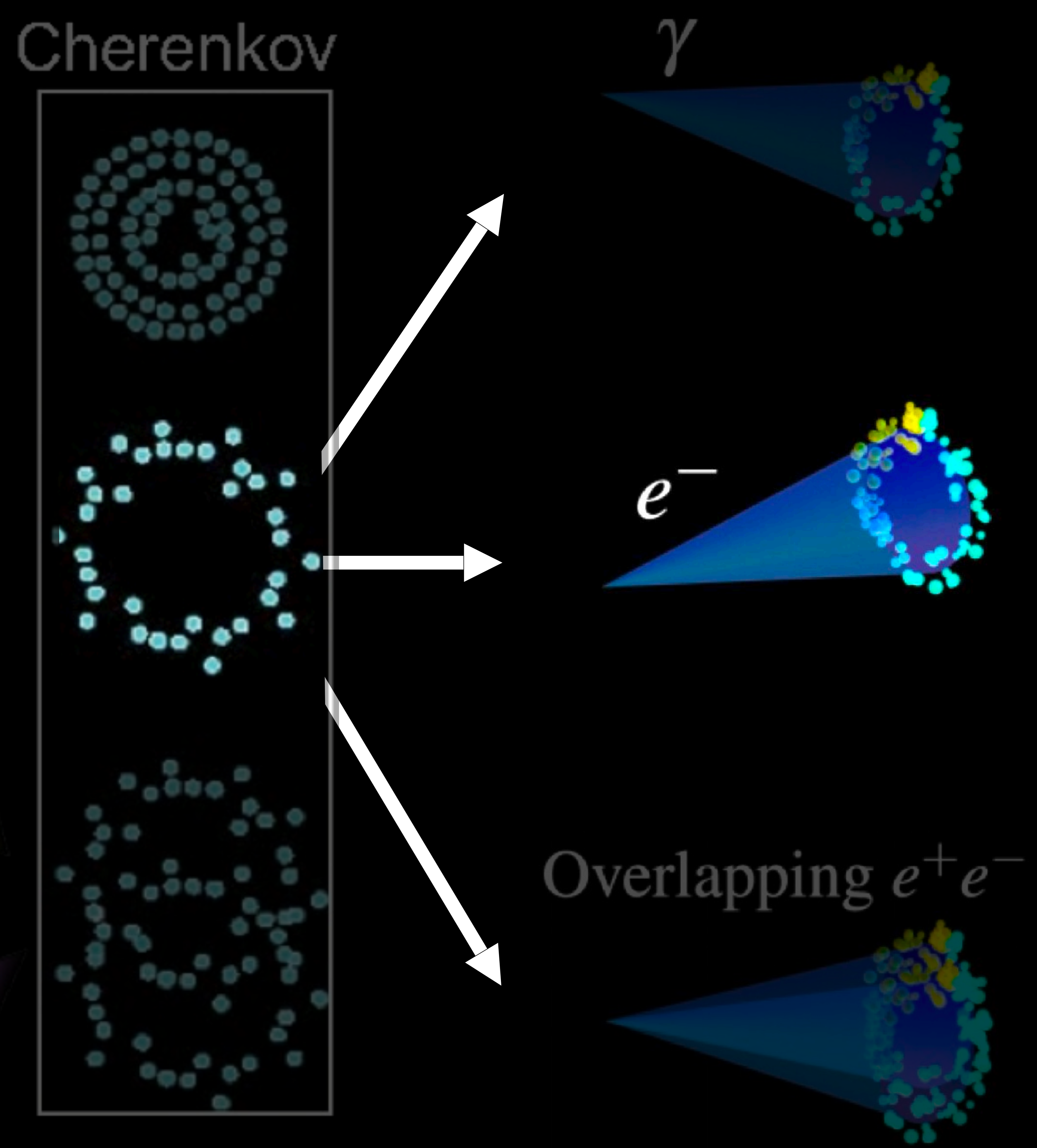
2σ excess in subsample. Could be compatible with LEE.

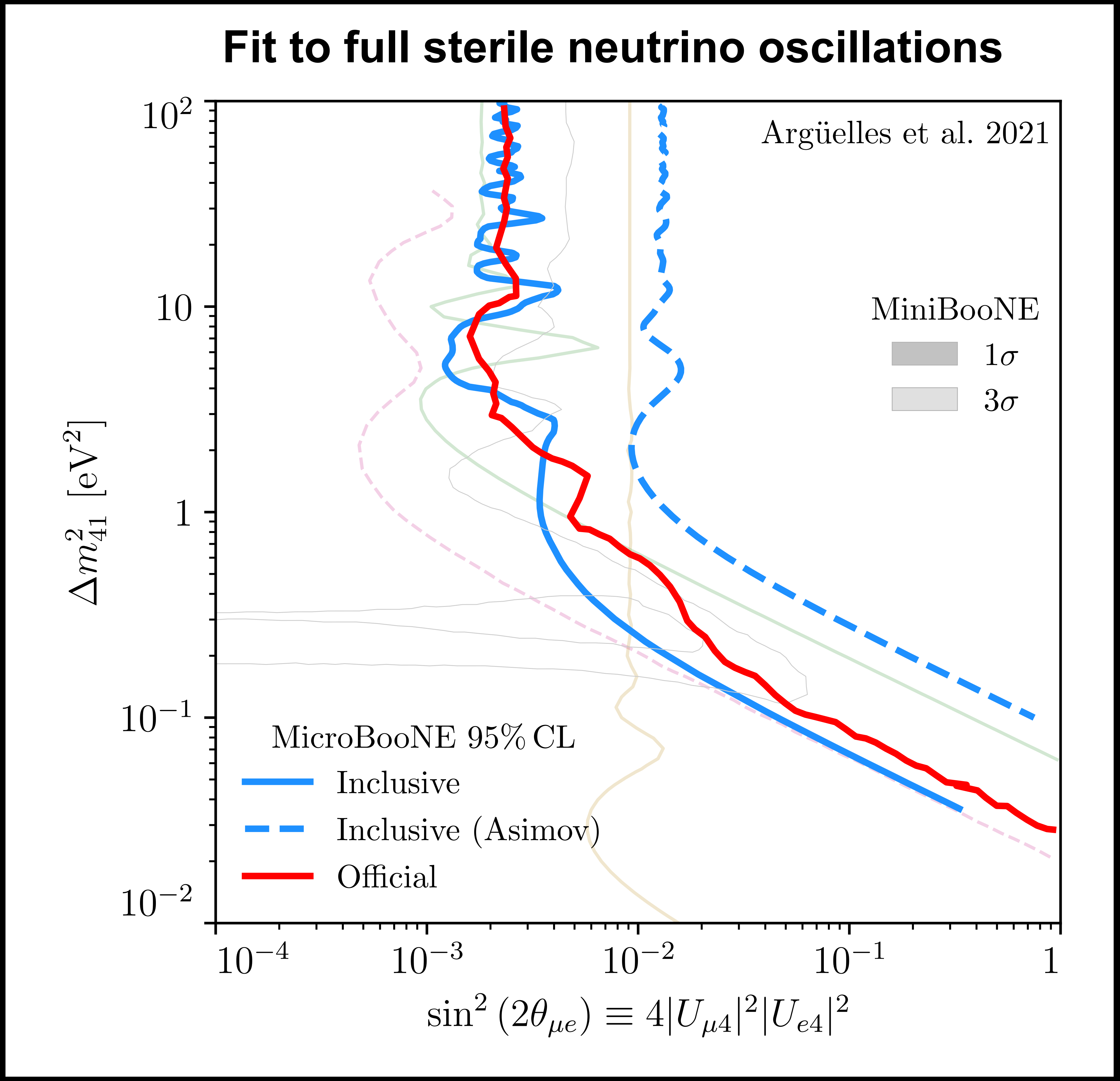
"We then isolate a sub-sample of these events containing no visible protons, and observe 93±22(stat.)±35(syst.) data events above prediction, corresponding to just above 2σ local significance, concentrated at shower energies below 600 MeV."

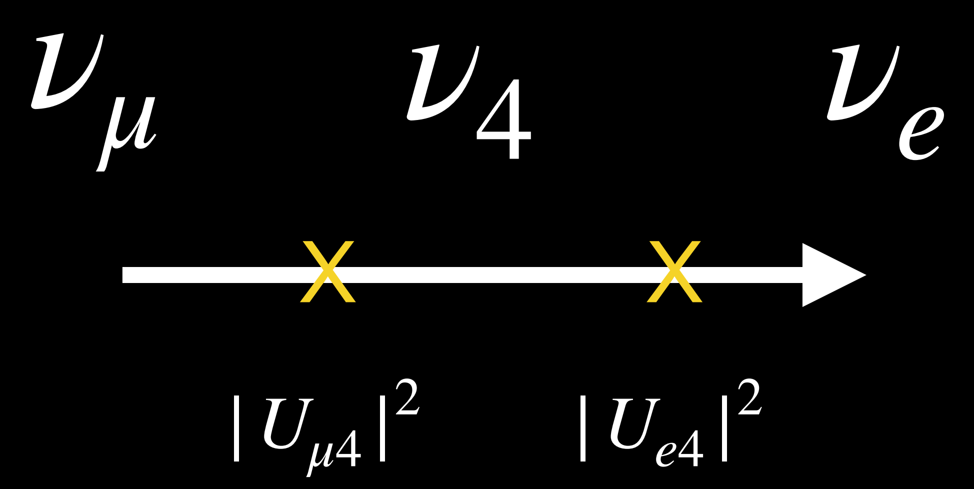
Tantalizing hint for single photon excess?
Keeping a close eye on this.

Zooming in on the MiniBooNE low-energy excess (LEE) with MicroBooNE

The ν_e hypothesis (sterile neutrino oscillations)







C. A. Argüelles, I. Esteban, **MH**, K. J. Kelly, J. Kopp, P. A. N. Machado, I. Martinez-Soler, and Y. F. Perez-Gonzalez

PRL 128, 241802.

MicroBooNE coll.,
PRL. 130 (2023) 1, 011801

eV sterile neutrinos
3+1 oscillations at accelerator experiments

For SBL experiments, 3+1 oscillations are described by 3-parameters:

$$\Delta m^2_{41} \qquad |U_{e4}|^2 \qquad |U_{\mu 4}|^2$$

Limits on results usually **profiled** onto the 2D space of

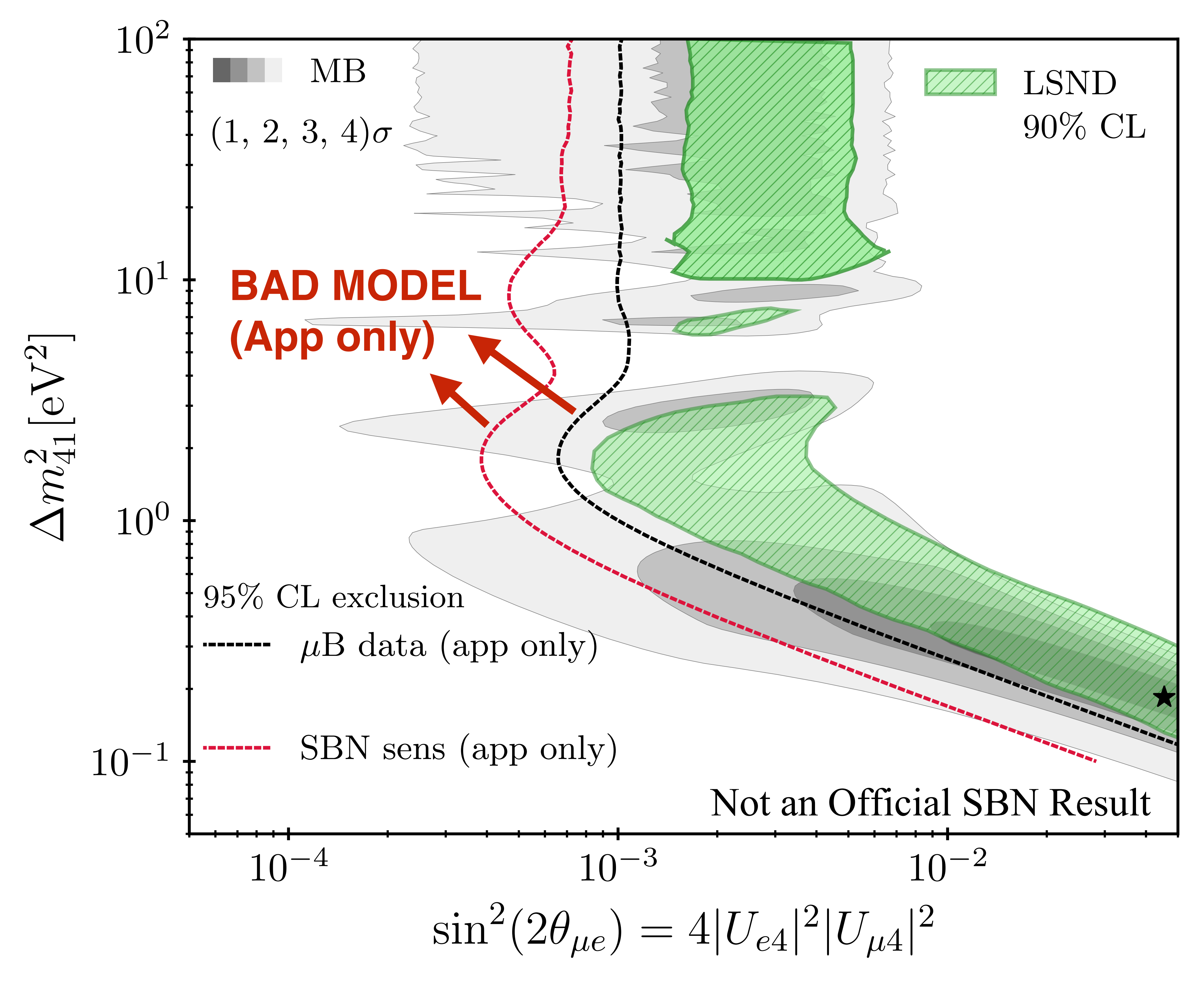
$$\Delta m^2_{41} \text{ vs } \sin^2 2\theta_{e\mu} \equiv 4|U_{e4}|^2 |U_{\mu 4}|^2$$

However, in statistical profiling, **we lose information.**

comparing regions of preference of two experiments *after profiling* can be misleading.

Towards a robust test of sterile neutrinos
Simulating full 3+1 model

O. Benevides Rodrigues, M. Hostert, K. J. Kelly, B. Littlejohn, P. A. N. Machado, I. Safa, **Tao Zhou (Texas A&M)** arXiv:2503.13594



The "usual" plane shown for 3+1 models

At LSND, we do not need to account for disappearance.

At **BNB, disappearance does impact backgrounds.**

Need full 3-parameter, 3+1 model.

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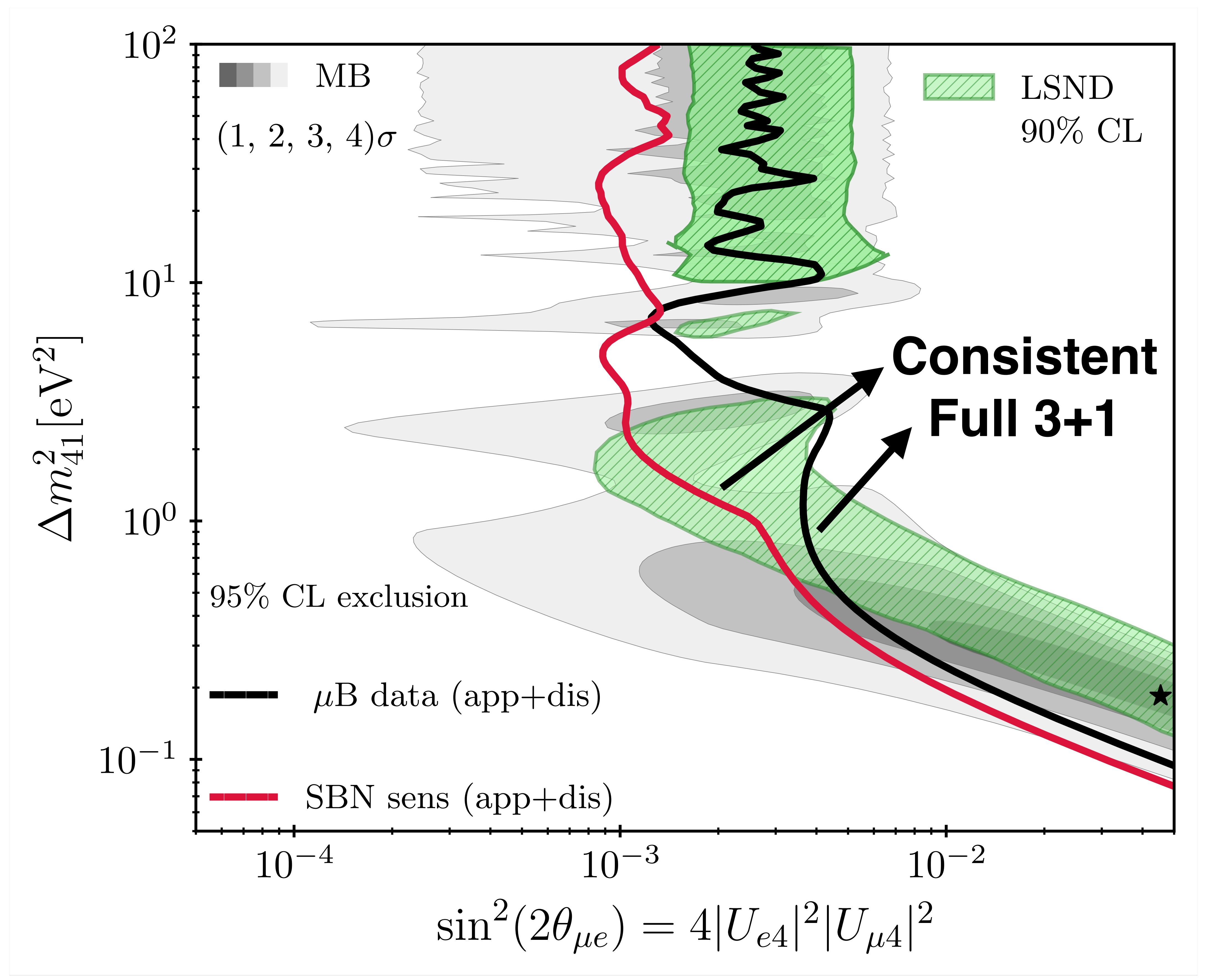

The "usual" plane shown for 3+1 models

In this 2D profiled plane,
the sensitivities look much worse.

↓

Consequence of the degeneracy between
appearance and disappearance.

↓

However, sensitivity loss is artificial and a result of the profiling method.

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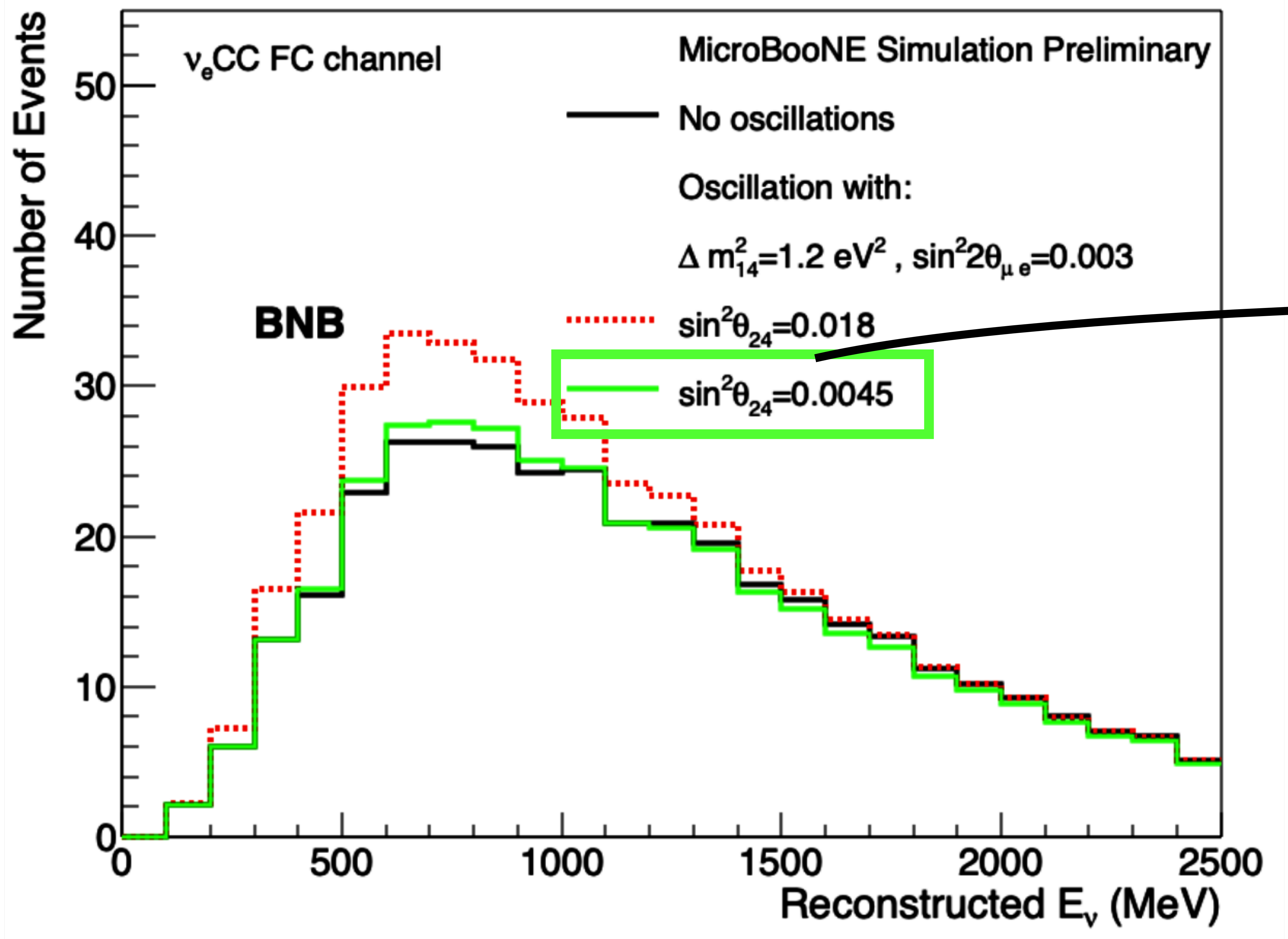
https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1132-PUB.pdf



(a) BNB reconstructed neutrino energy spectrum

Corresponds to a huge amount of ν_e disappearance

$$|U_{e4}|^2 \simeq 0.16 \rightarrow P_{\nu_e \rightarrow \nu_e} \sim 46\,\%$$

In practice, all of the parameter space where the
app vs dis degeneracy matters
is already excluded by other experiments

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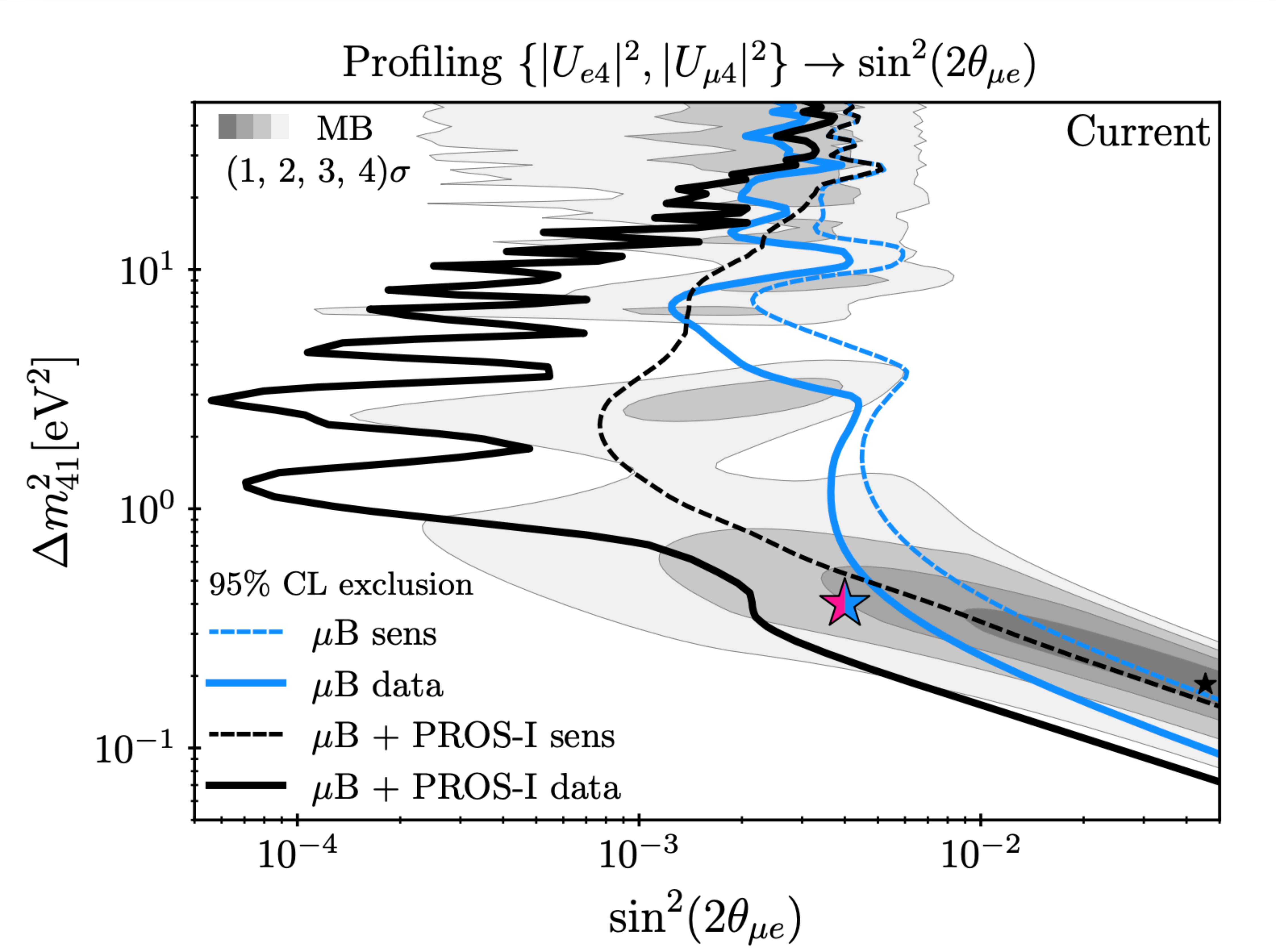

Including external constraint from final PROSPECT results

By forbidding ν_e disappearance, **PROSPECT** removes the degeneracy.

Slight deficit of ν_e at MicroBooNE then pushes constraints to be even stronger

Towards a robust test of sterile neutrinos
Turning to slicing method instead

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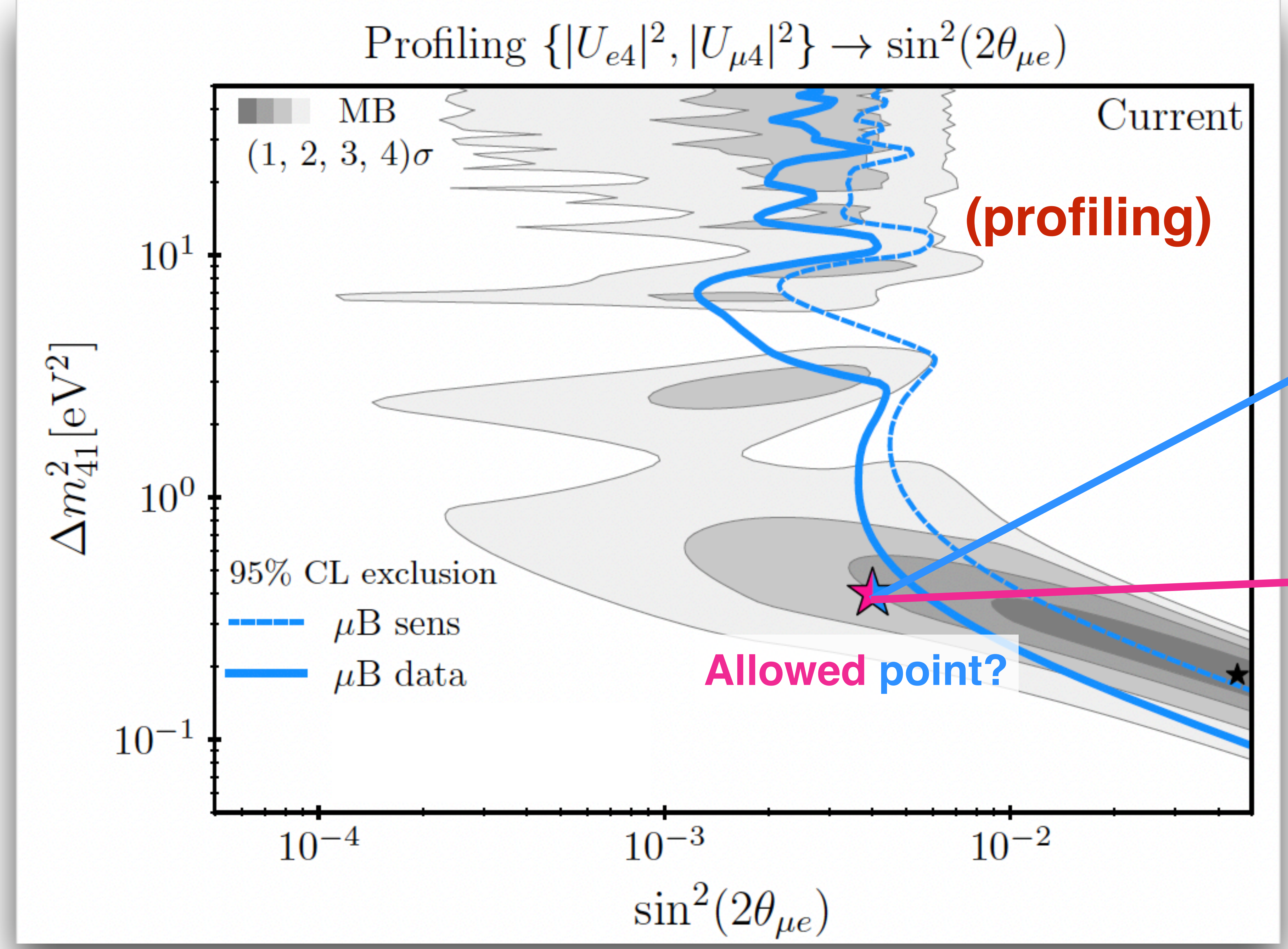
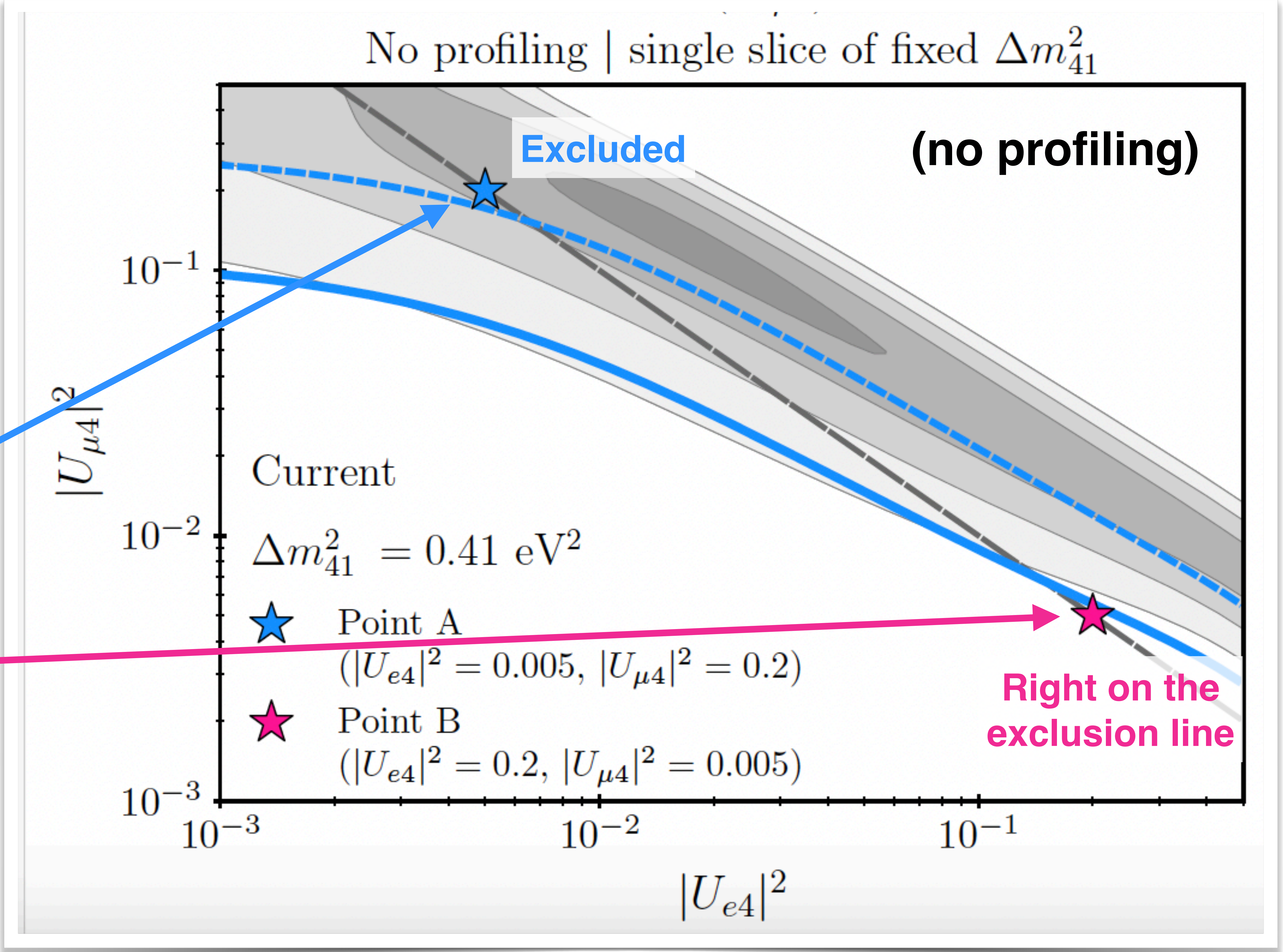


Slice of 3D parameter space



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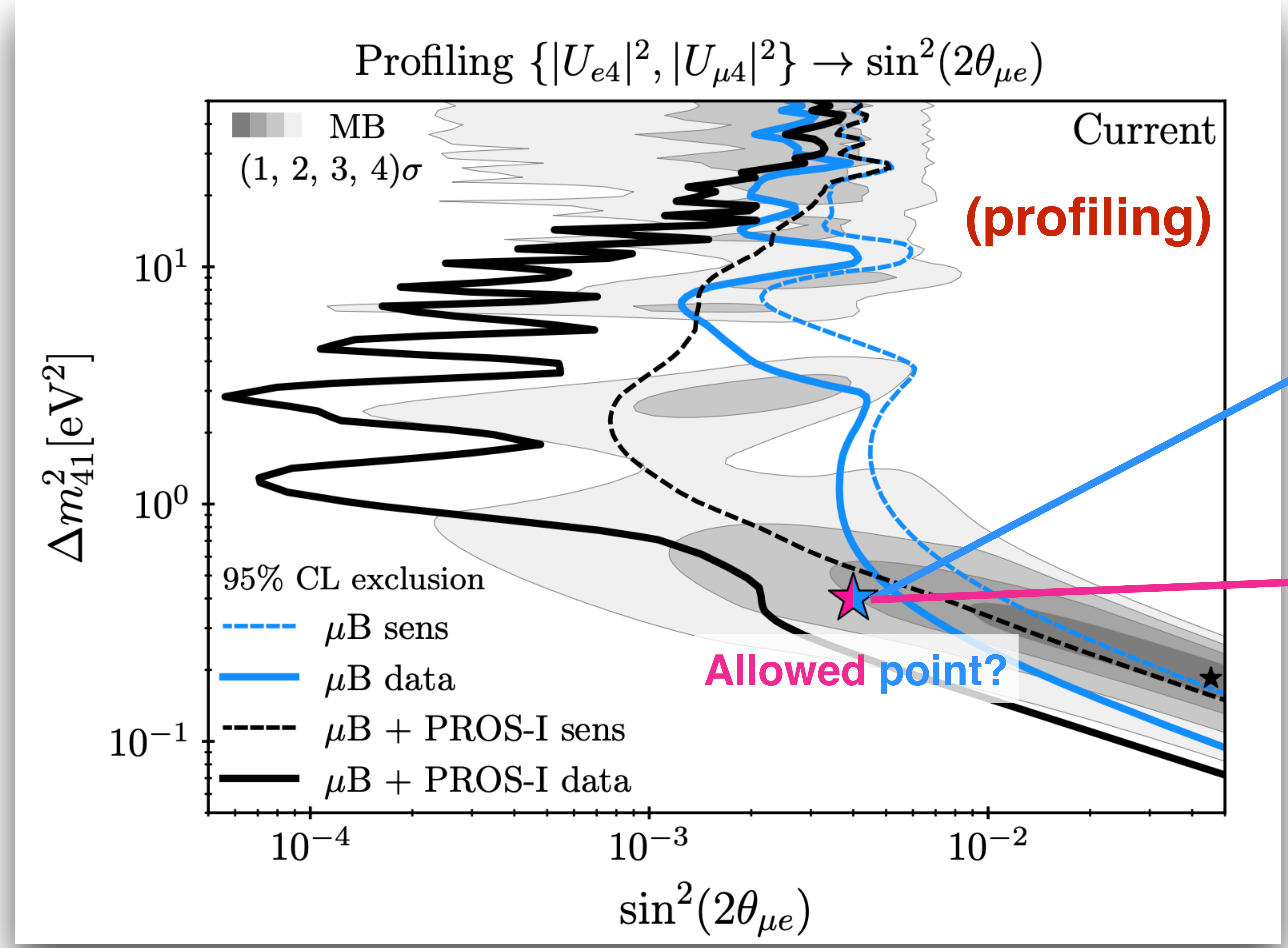
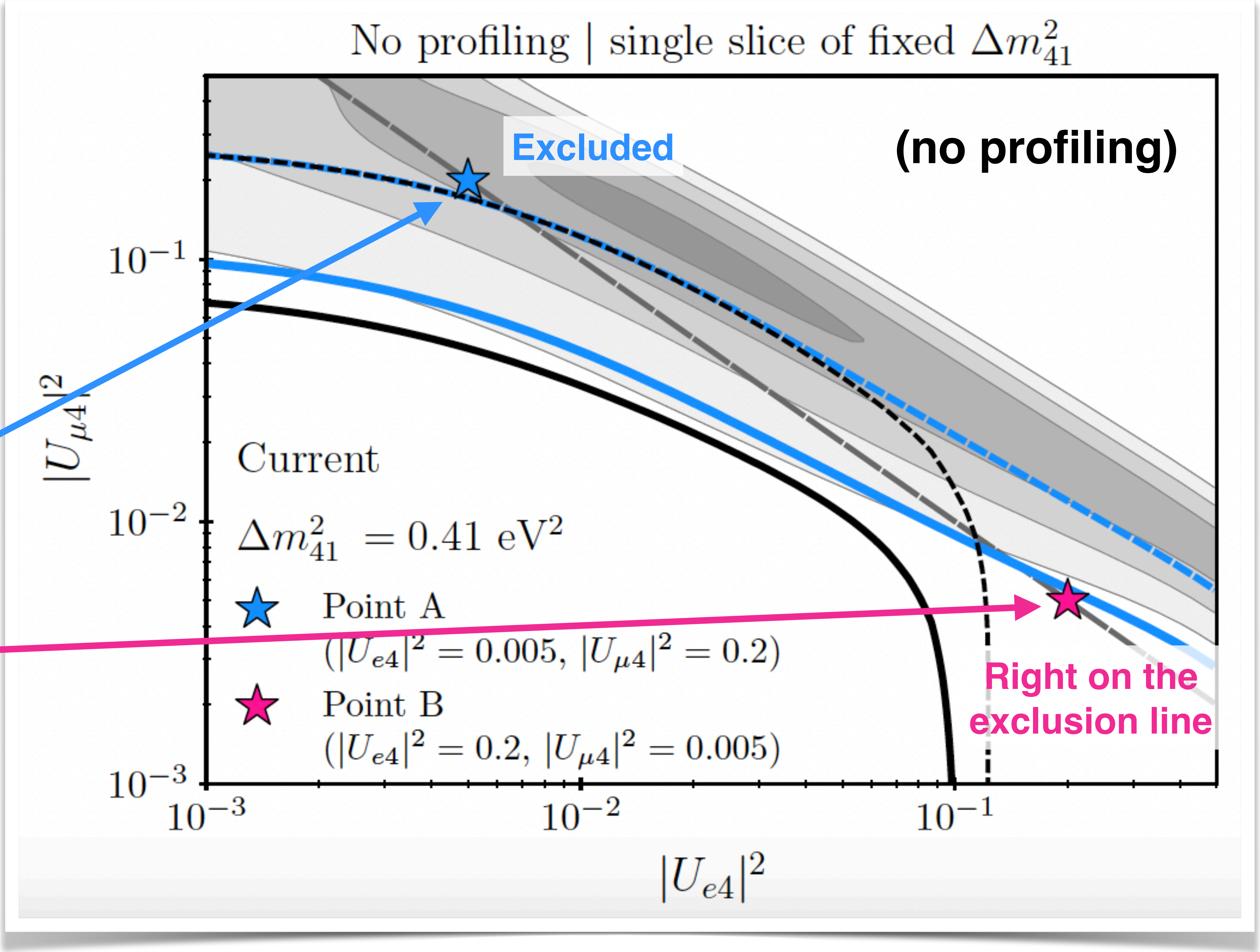
Slice of 3D parameter space + PROSPECT





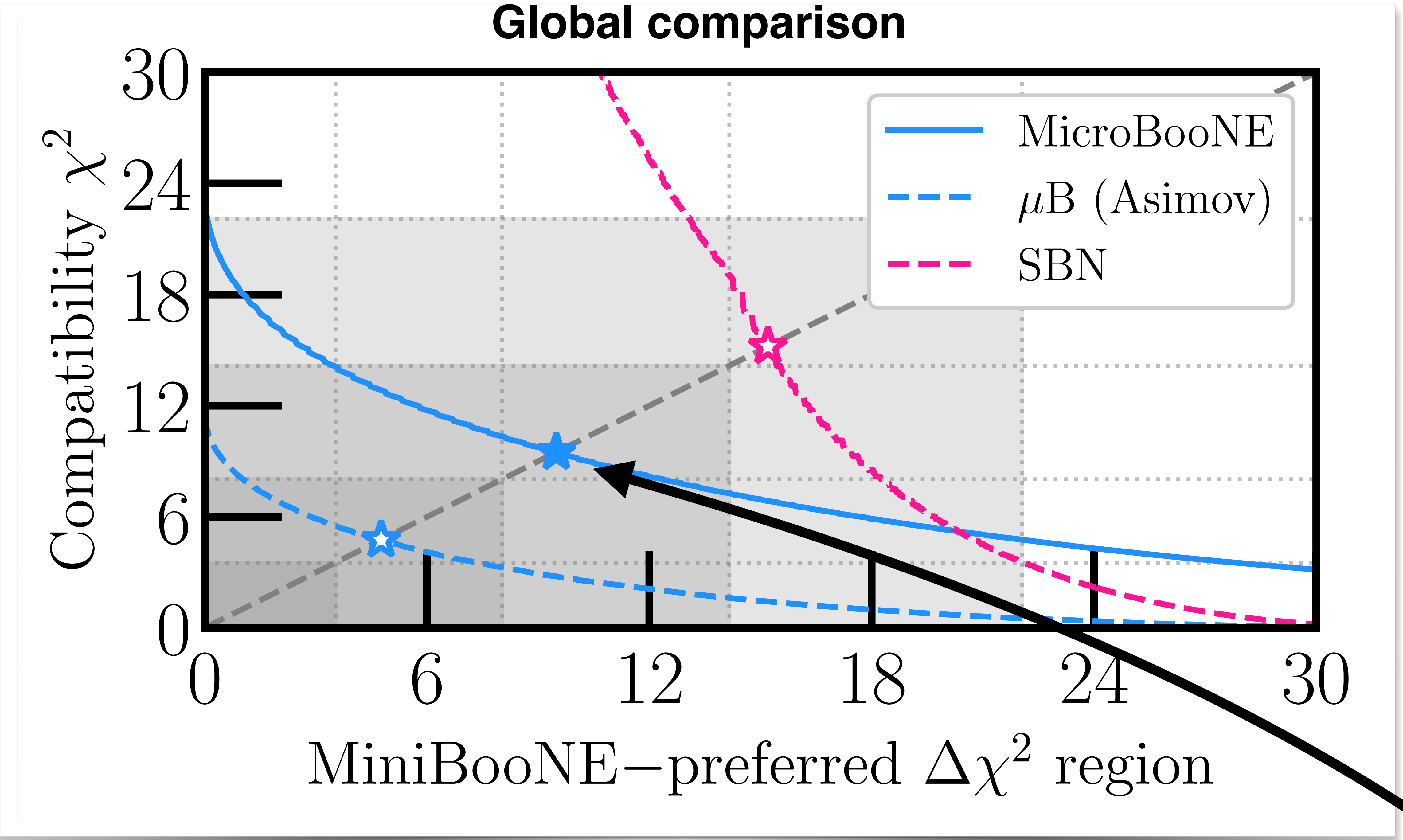
Towards a robust test of sterile neutrinos
Turning to slicing method instead — SBN (future)

O. Benevides Rodrigues, M. Hostert, K. J. Kelly,
B. Littlejohn, P. A. N. Machado, I. Safa,
Tao Zhou (Texas A&M) arXiv:2503.13594

PROSPECT-II is decisive in the profiled plane, but not in the slices.

SBN's 95% sensitivity covers the entire 4σ region of MiniBooNE in this slice.

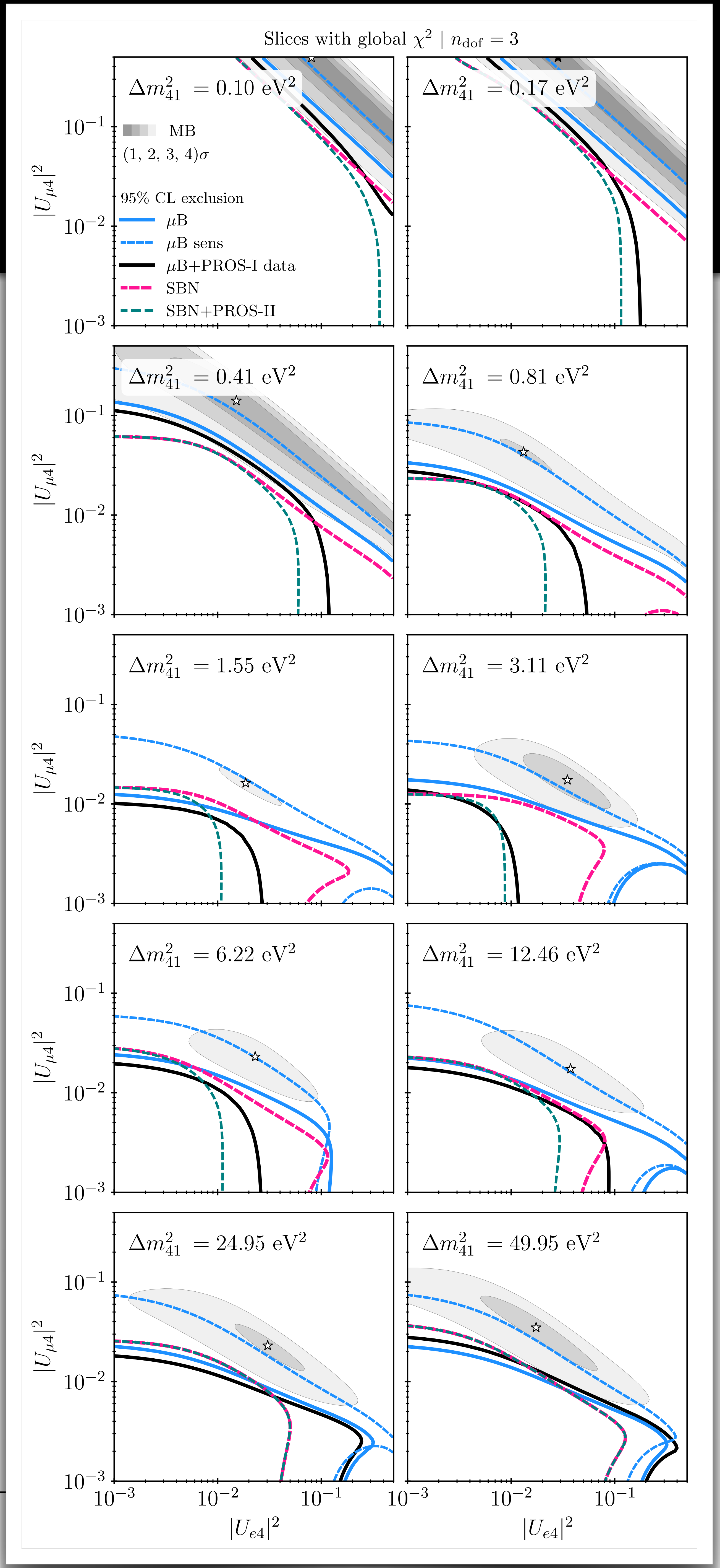
Towards a robust test of sterile neutrinos
A global metric to quantify coverage



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

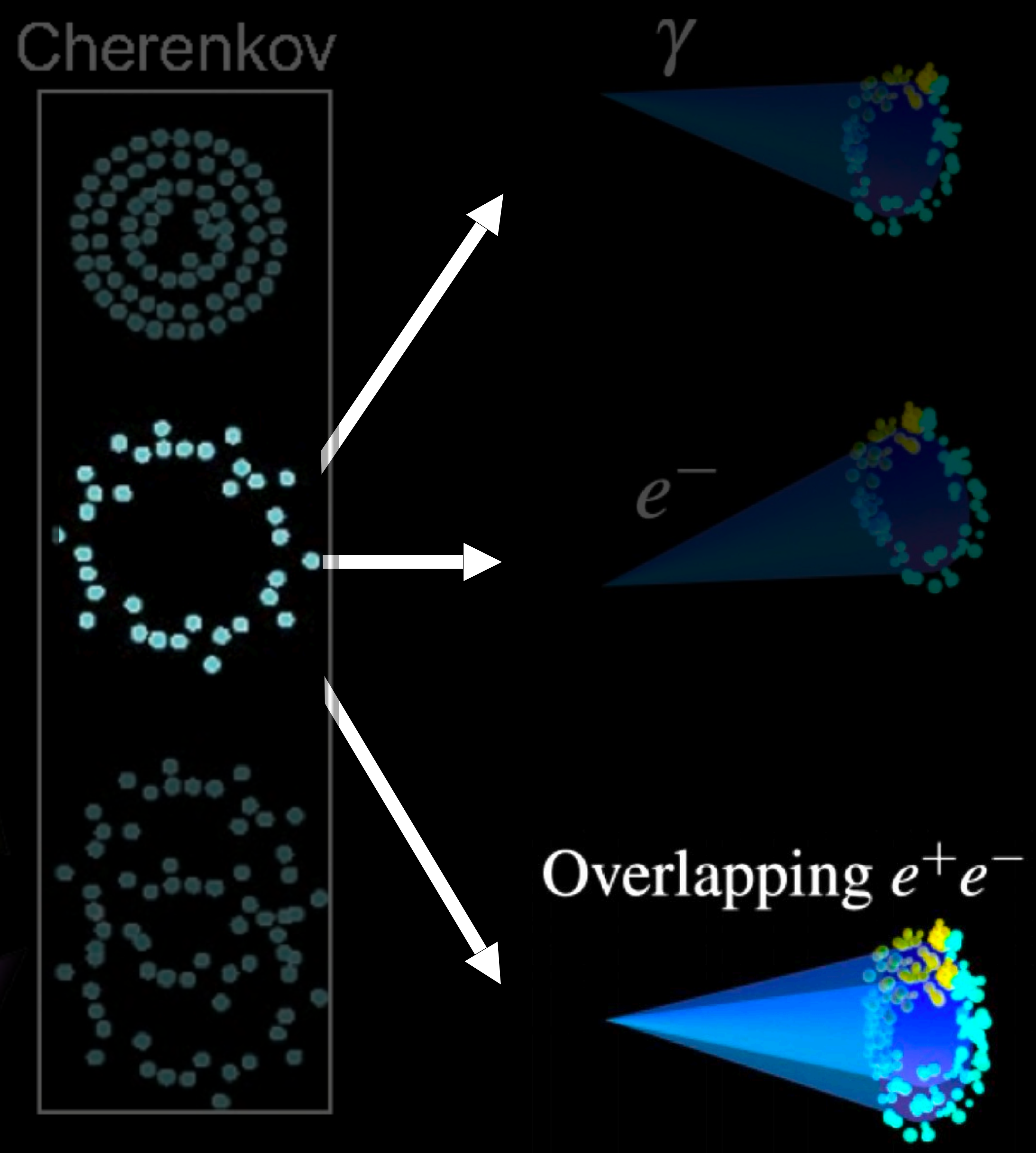
MicroBooNE covers the entire MiniBooNE $\Delta\chi^2 = 9.5$ region at that same value.

With Wilk's, this is equivalent to saying that the entire ~2.3σ MiniBooNE region is excluded by MicroBooNE at ~2.3σ.



Zooming in on the low-energy excess with MicroBooNE

The remaining explanations

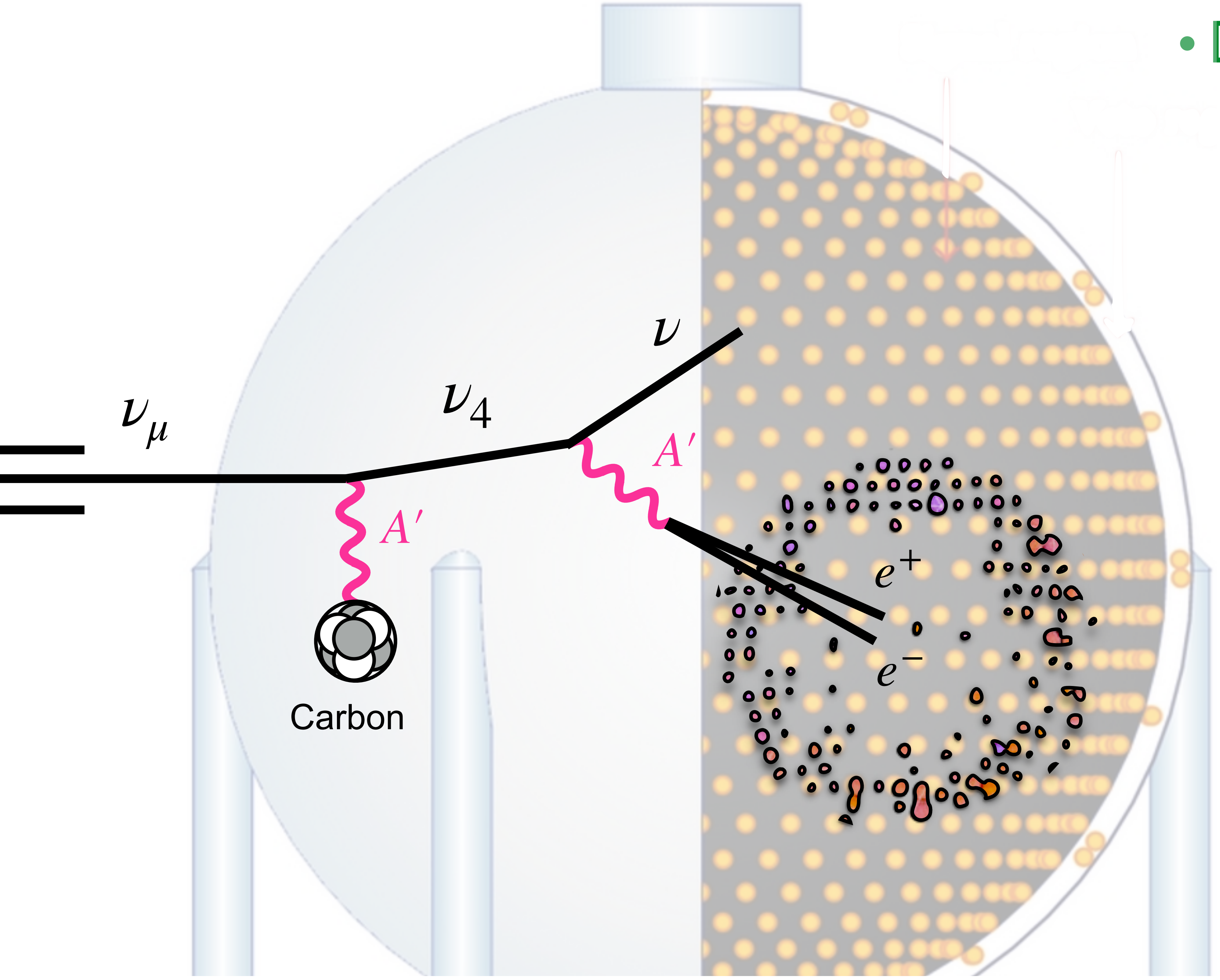


Dark Sectors in the MiniBooNE Low-Energy Excess
Particle production inside the detector

E. Bertuzzo et al, Phys. Rev. Lett. 121, 241801 (2018)
P. Ballett et al, Phys. Rev. D 99, 071701 (2019)

C. Argüelles, **MH**, Y. Tsai, Phys. Rev. Lett. 123, 261801 (2019)
P. Ballett, **MH**, S. Pascoli, Phys. Rev. D 101, 115025 (2020)
A. Abdullahi, **MH**, S. Pascoli, Phys.Lett.B 820 136531 (2021)

MiniBooNE Liquid Scintillator + Cherenkov



Heavy neutrino decays:

- Single photons via transition magnetic moment ($X = \gamma$)
- Di-leptons from dark photons or scalars ($X = e^+e^-$)
- Di-photons from dark scalars ($X = \gamma\gamma$)

On Quanta Magazine:


Is the Great Neutrino Puzzle Pointing to Multiple Missing Particles?

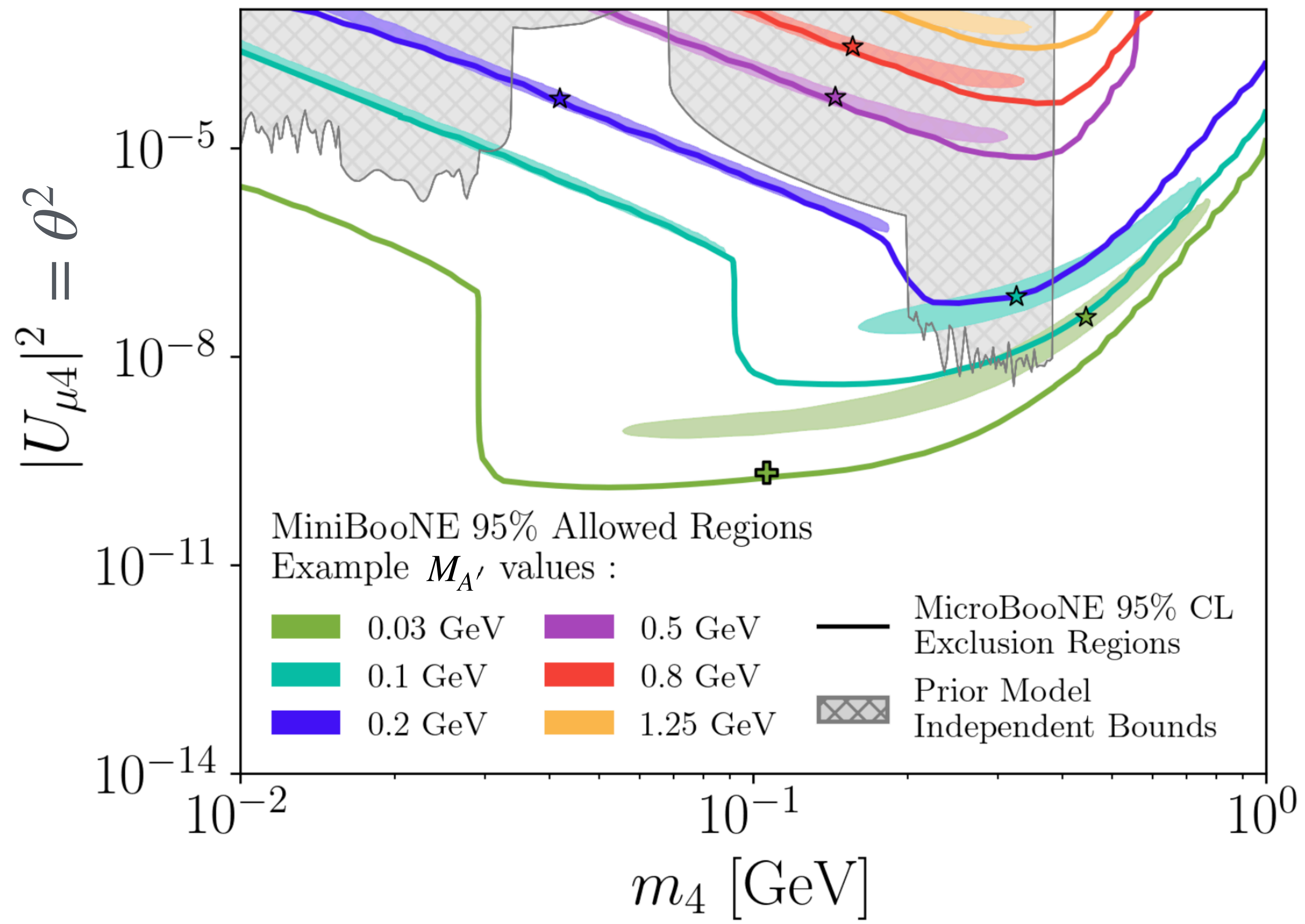
Years of conflicting neutrino measurements have led physicists to propose a "dark sector" of invisible particles — one that could simultaneously explain dark matter, the puzzling expansion of the universe, and other mysteries.

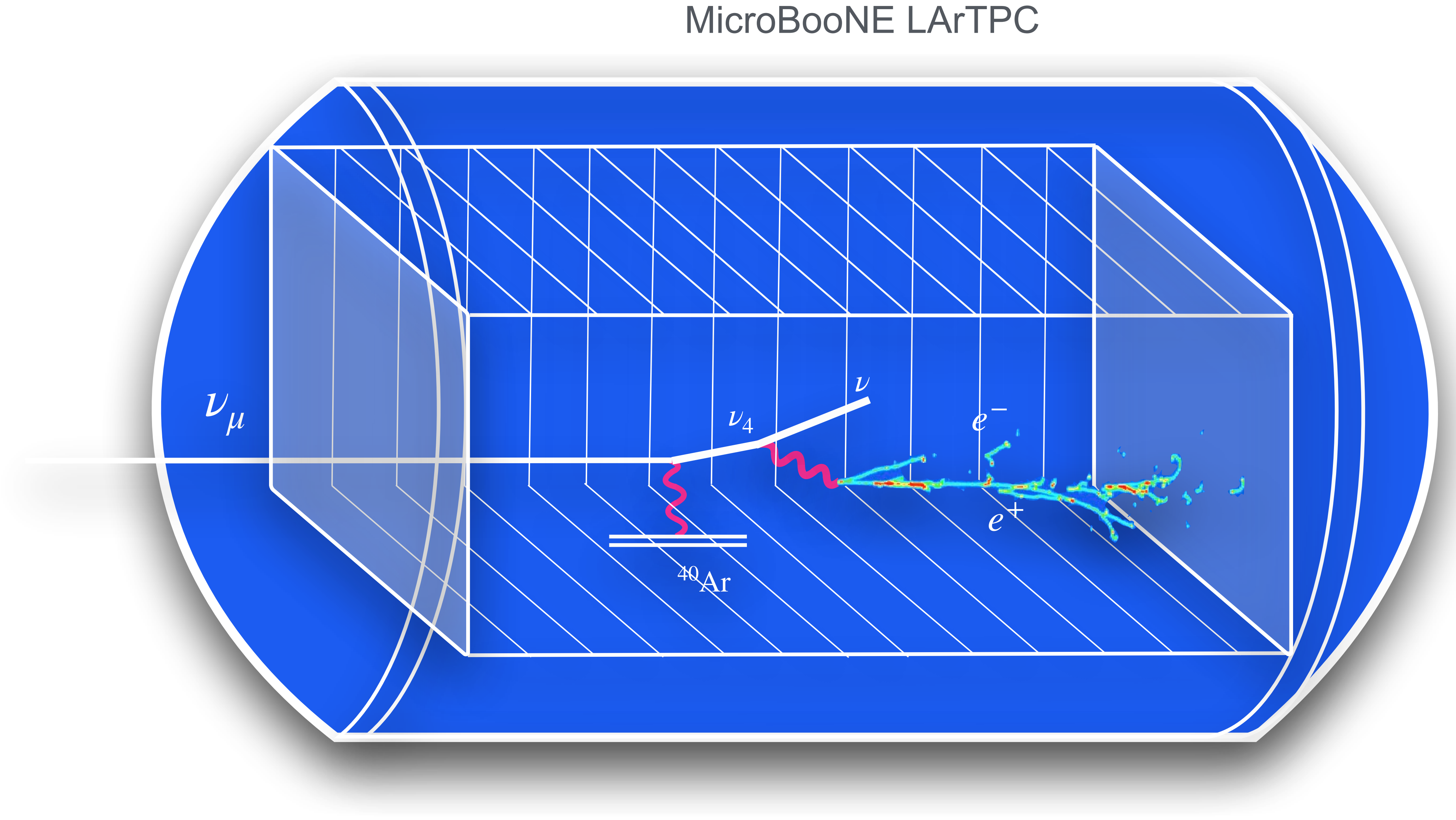
MicroBooNE coll. + MOU with Abdullahi, MH, Massaro, Pascoli, Zink: arxiv.org/abs/2502.10900

First dedicated experimental search for neutrino-induced e^+e^- pairs:

MicroBooNE excludes minimal dark neutrino explanations to the MiniBooNE anomaly

Signal: coherent scattering (no vertex) with subsequent $\nu_4 \to \nu e^+e^-$ decays, targeting one or two showers in LArTPC.





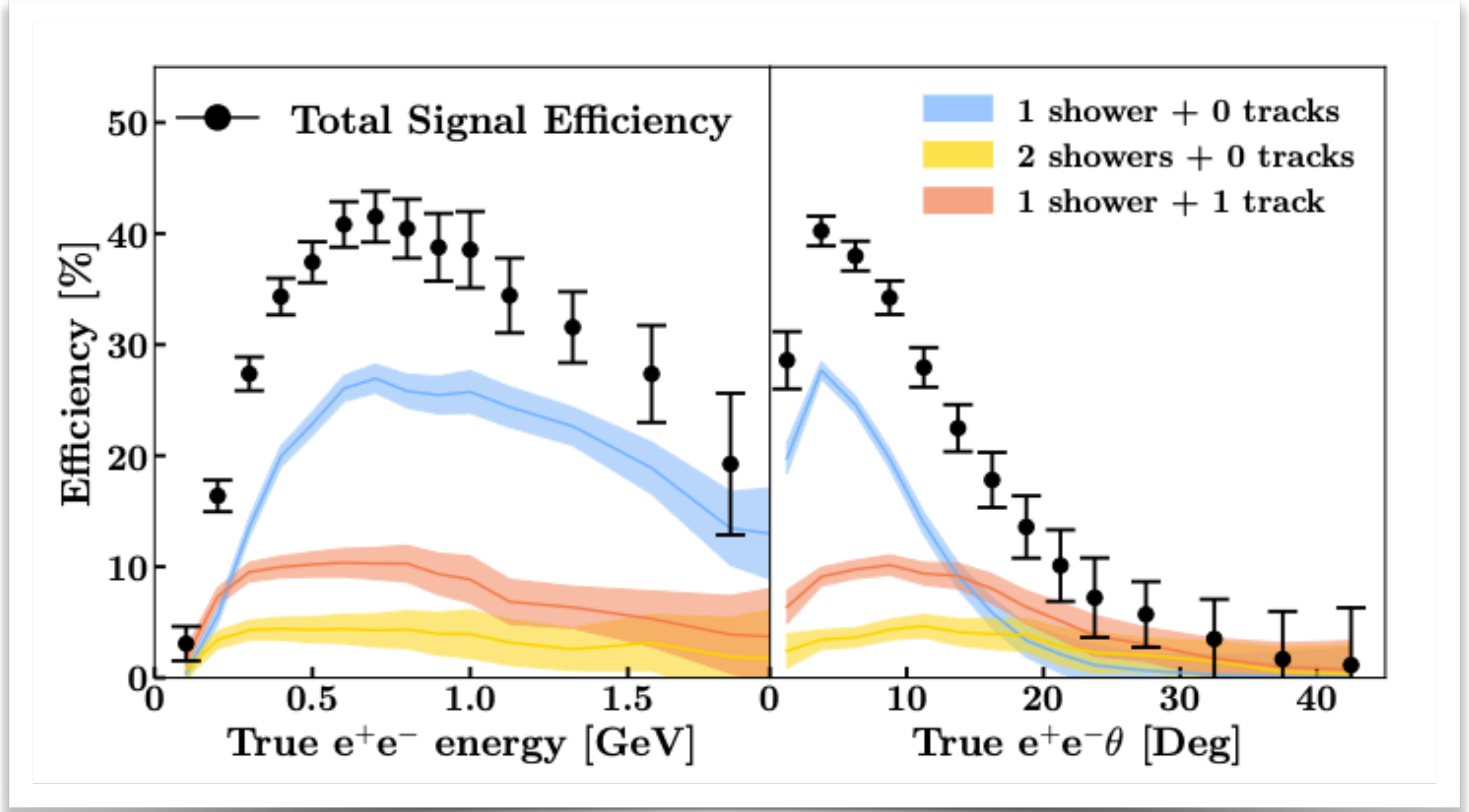
New-physics sources of e^+e^- / $\gamma\gamma$ / γ

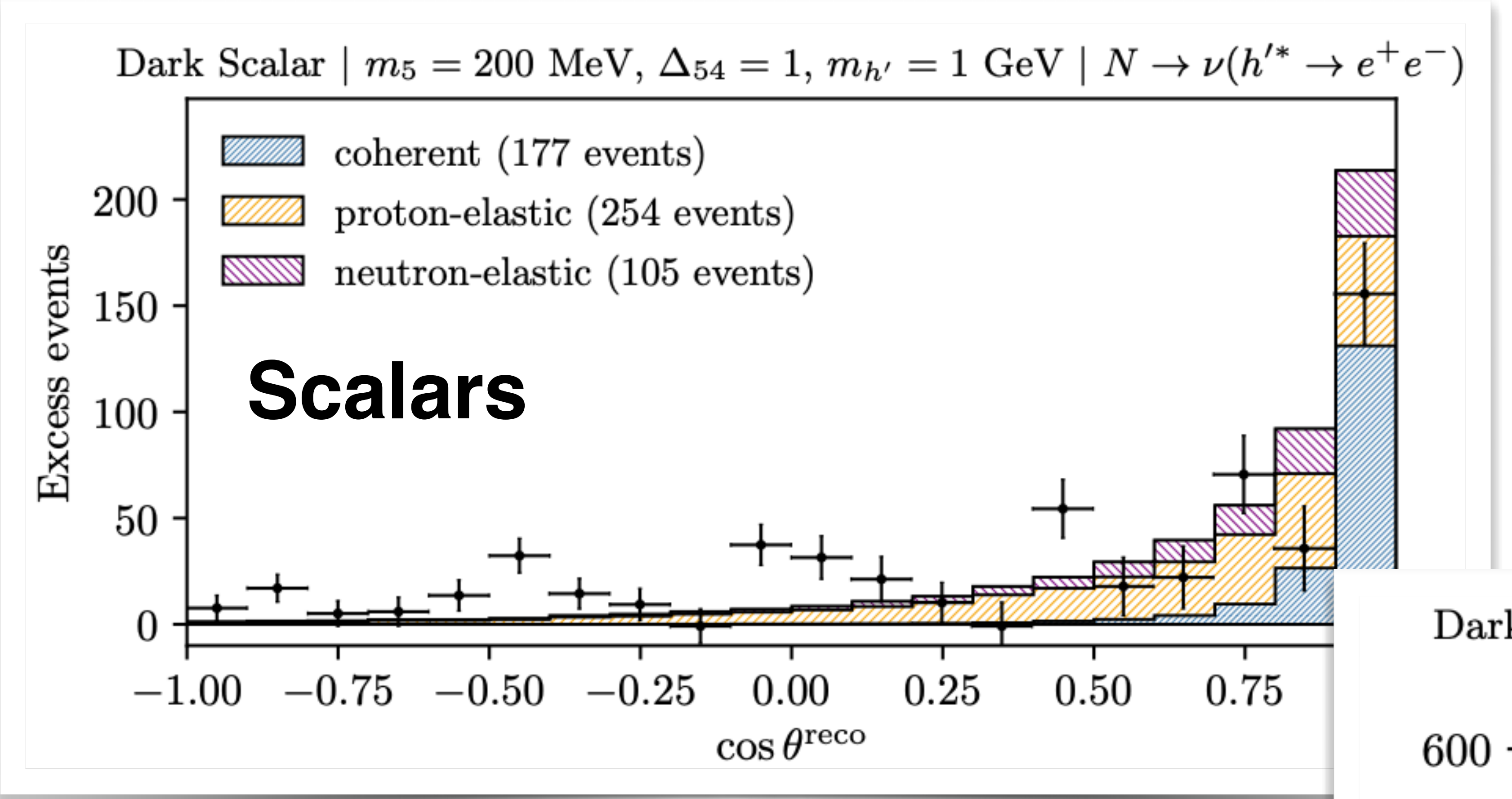
1) **Models with wide angular distributions:** scalars, axion-like-particle (ALP), or dipole portal HNL.

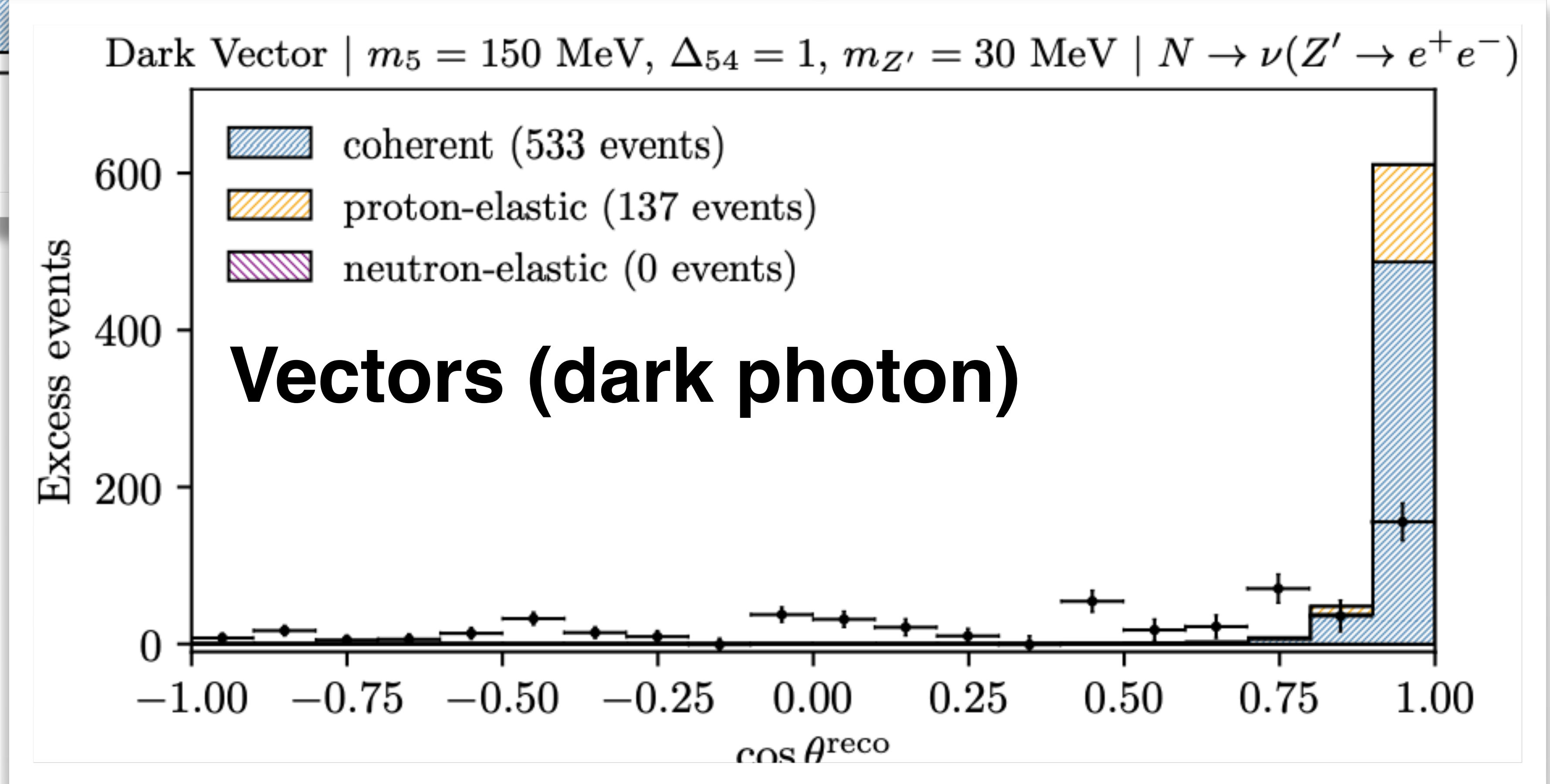
2) **Models with hadronic vertices** (spin-dependent interactions turn off coherent scattering).

3) **More final states**: multiple gammas, such as pion impostors, $N \to \nu\pi^0$ or $a \to \gamma\gamma$.

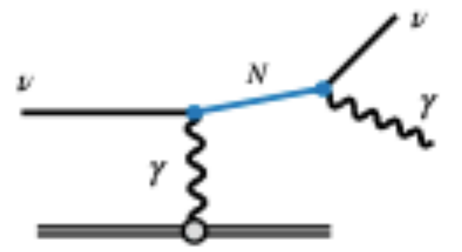
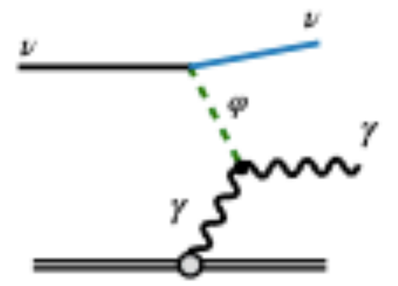
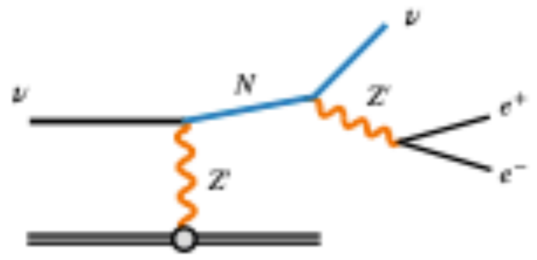
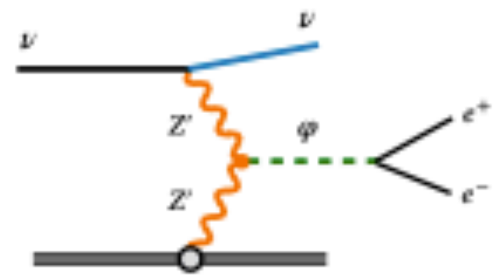
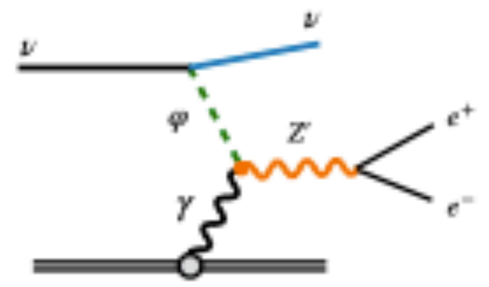
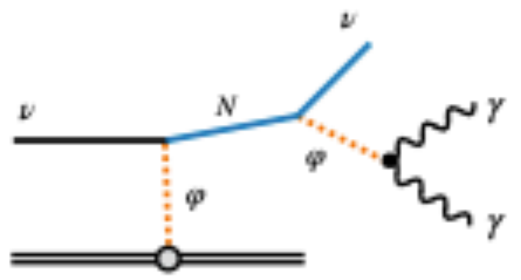
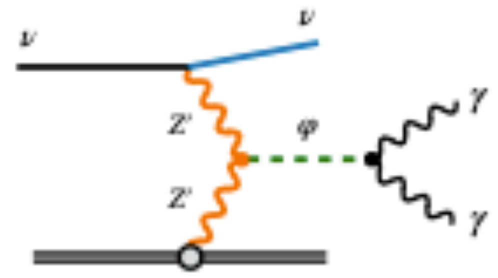
MicroBooNE, arxiv.org/abs/2502.10900







A.M. Abdullahi, J. Hoefken Zink, M. Hostert, D. Massaro, S. Pascoli arXiv:2308.02543

Topology	Model	Diagram	Signal	References
single γ	neutrino upscattering		$N \to \nu\gamma$	[74–84]
	neutrino-induced inverse-Primakoff scattering		$\varphi^* A \to \gamma A$	[84]
e^+e^-	neutrino upscattering		$N \to \nu e^+ e^-$ on-shell N	[36–44] Section IV
	neutrino-induced bremsstrahlung		$Z' \to e^+e^-$ off-shell N	not studied
	neutrino-induced Primakoff scattering		$\varphi \to e^+e^-$	[40]
	neutrino-induced inverse-Primakoff scattering		$Z' \to e^+e^-$	not studied
$\gamma\gamma$	neutrino upscattering		$N \to \nu\gamma\gamma$	[43]
	neutrino-induced Primakoff scattering		$\varphi \to \gamma\gamma$	not studied

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 most of these, but not clear what happens in **scalar mediator** models where the angular distribution is wider.

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, arXiv:2504.08071**

Not constrained
We can call these "**pion impostors**".
Two photons with $m_{\gamma\gamma} \neq m_{\pi^0}$ and different kinematics. **Messes with the sidebands…**

Summary

Thank you for listening!

Matheus Hostert (matheus-hostert@uiowa.edu)

1) **New progress in understanding of short-baseline anomalies:**

New data has excluded several interpretations in SM and beyond, but no resolution just yet.

2) **3+1 oscillations of eV sterile neutrinos continues to be disfavored:**

Demonstrated how current MicroBooNE limits actually already largely cover the entire sterile-interpretation of MiniBooNE at about >2σ.

Collaborations can show results without profiling to make stronger (and consistent) statements.

3) **Put first searches for e^+e^- at MicroBooNE in context:**

Dark neutrino models with dark photon upscattering excluded, but upscattering with large hadronic activity and wide angular distributions not necessarily so. Can be interesting for **inclusive 1γ excess**.

Back-up slides

Some history — SBL neutrino oscillations

Short-baseline oscillations have been discussed for a long time — even before we figured out the resolution to the Solar problem.

PS-191 (1984 at CERN)

Phys.Lett.B 181 (1986) 173-177

A total of 23 ± 8 excess events (3σ).

↓ PS191 detector moved to BNL, behind E734.

E-816 (1986 at BNL)

Nucl.Phys.B 335 (1990) 517-545

Reports a 2σ excess.

$$\frac{\left(\nu_e/\nu_\mu\right)_{\text{obs}}}{\left(\nu_e/\nu_\mu\right)_{\text{pred}}} = 2.2 \pm 0.6$$

Excess attributed to unknown systematics in both experiments.

E-734 (1984 at BNL)

Phys.Rev.D 31 (1985) 2732

PS191 excess not seen at E734.

↓

E-776 (1986 at BNL)

Phys.Rev.Lett. 68 (1992) 274-277
Phys.Rev.Lett. 62 (1989) 2237-2240

Initially reports 2σ excess, but final result shows no excess.

↓

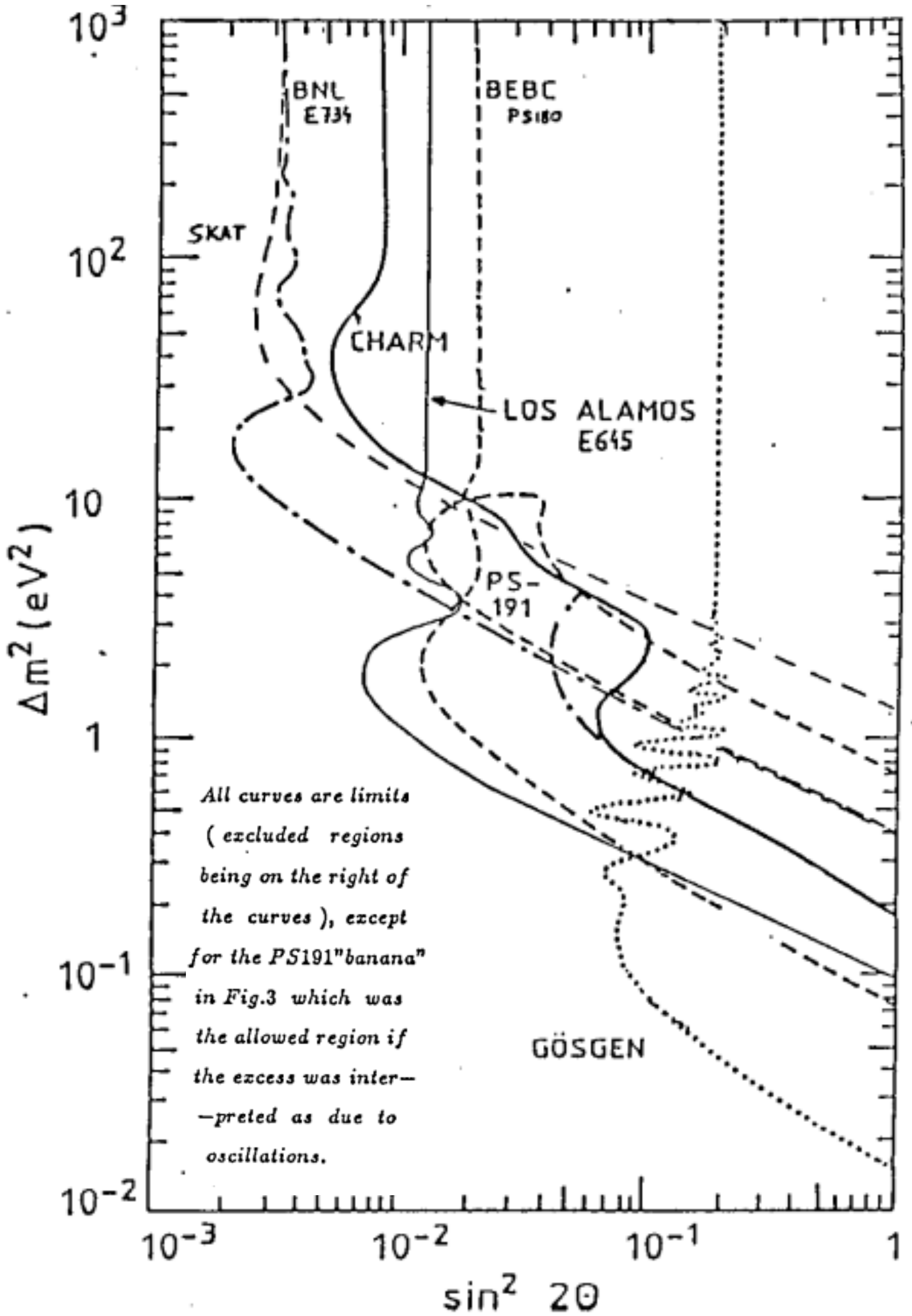
CHARM (1983 PS-beam data, $\langle E_\nu \rangle \sim 1$ GeV)

SKAT ($\langle E_\nu \rangle \sim 8$ GeV)

LANL E615 (πDAR)

Excess was not seen at several other experiments.

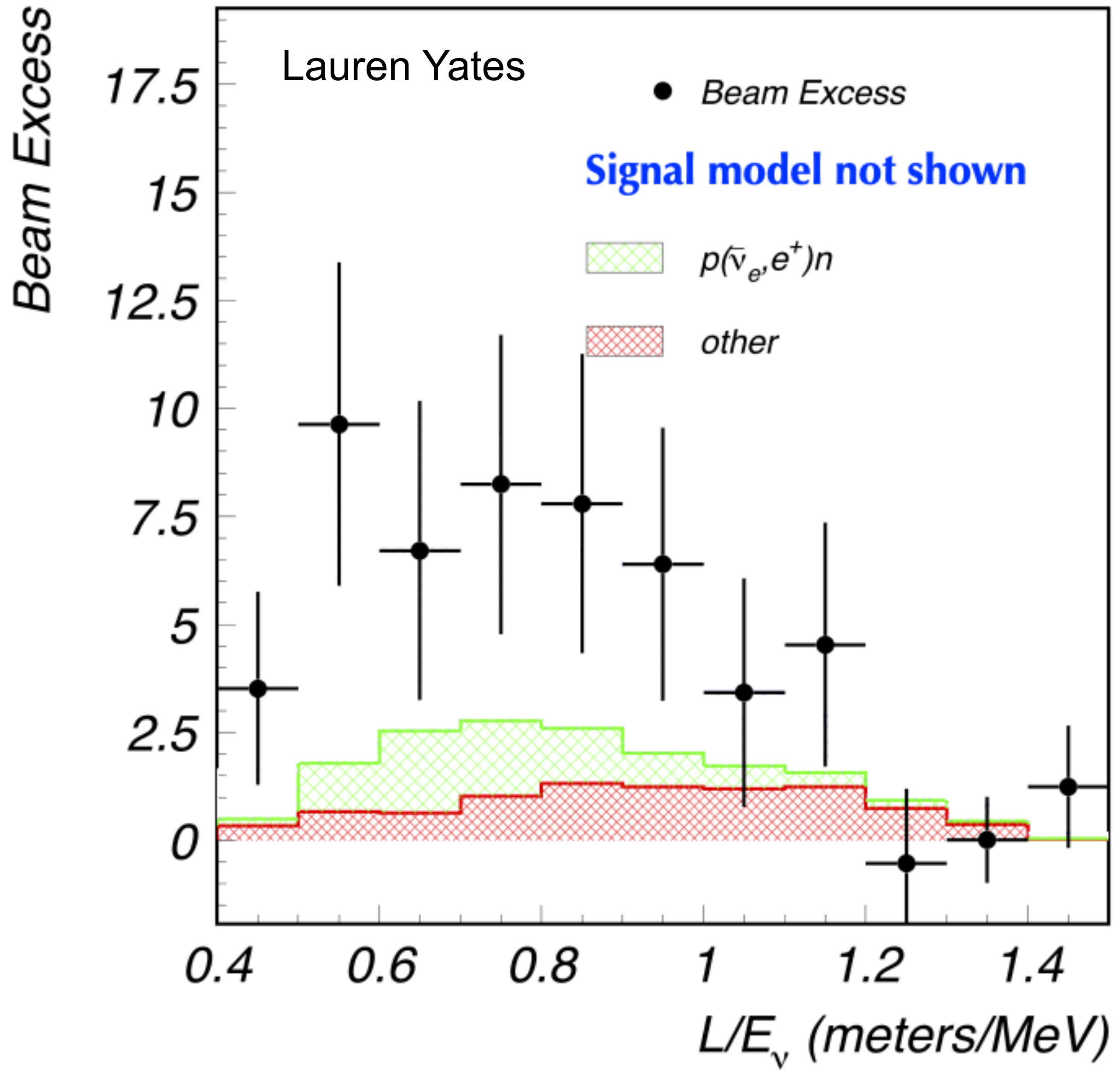
Gregorio Bernardi, 1988 ICHEP 88. HEP-88-11



LSND: 1993 - 1998

Phys.Rev.D 64 (2001) 112007

1) 800 MeV proton beam, 1.8e23 POT.
2) π DAR and DIF:12º nu/p beam angle.
3) π^- contamination: $\bar{\nu}_e/\bar{\nu}_\mu \sim 8 \times 10^{-4}$
4) Baseline of 30 m
5) ~167 tonnes of liquid scintillator
6) 8.3 m long detector.

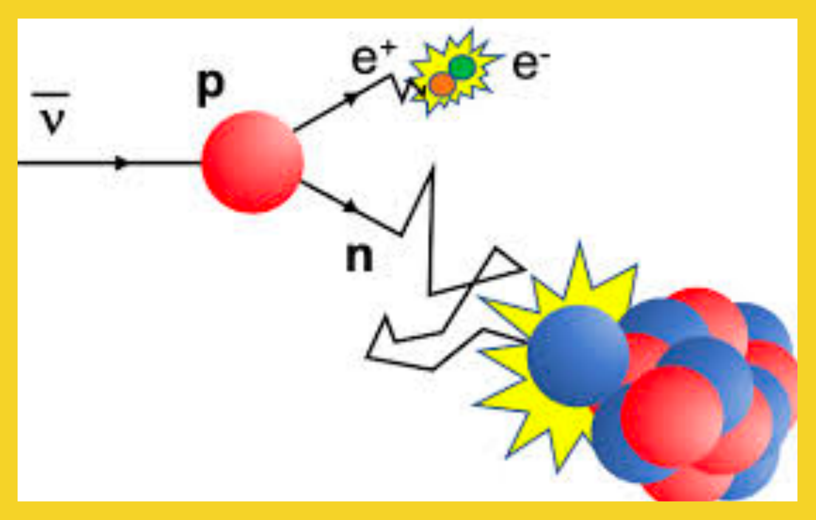


Excess: $87.9 \pm 22.4 \pm 6$ events
3.8σ significance

πDAR source

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

oscillation? $\bar{\nu}_\mu \to \bar{\nu}_e$



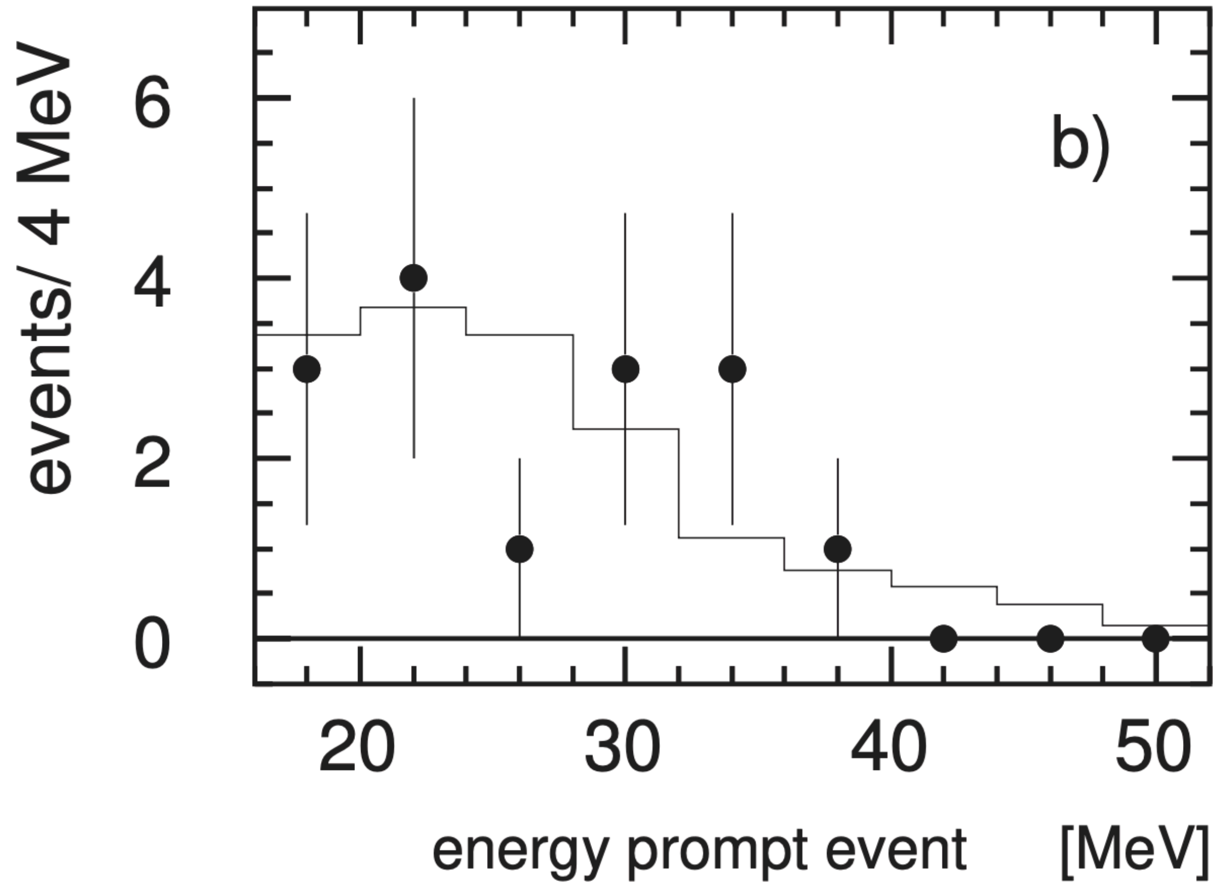
Inverse-Beta-decay detection

More data was needed

KARMEN: 1990 - 2001

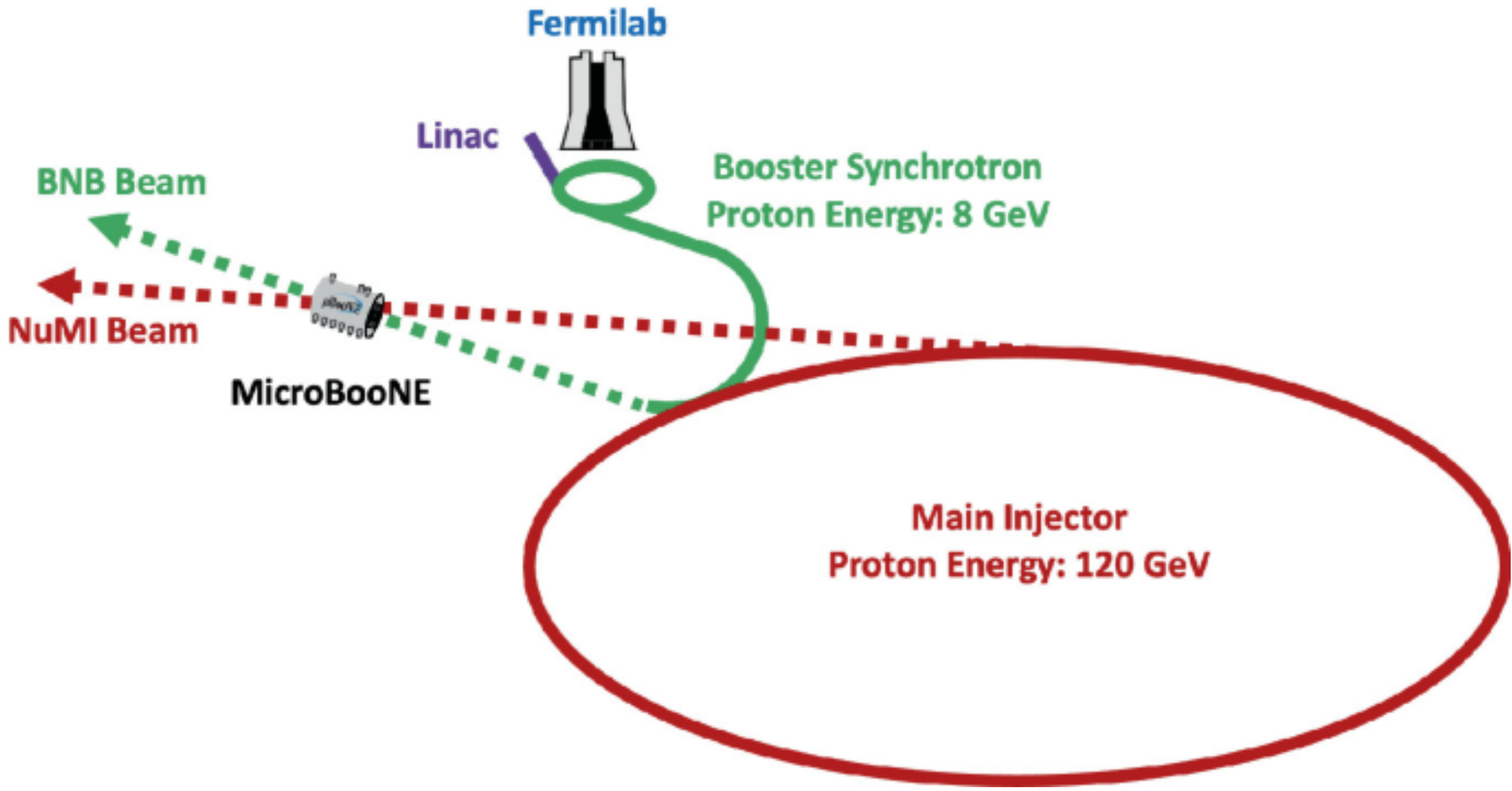
Phys.Rev.D 65 (2002) 112001

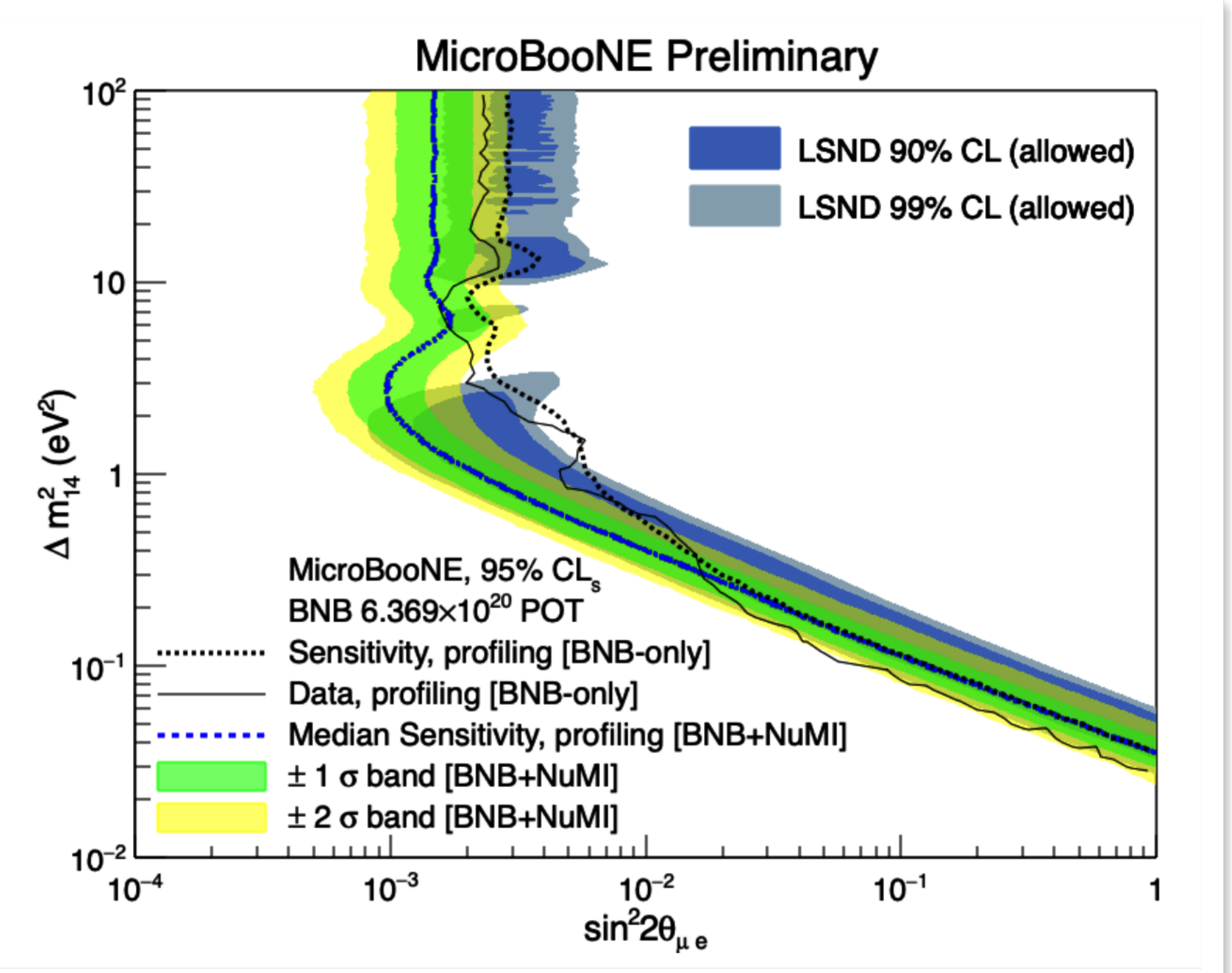
1) 800 MeV proton beam, 6e22 POT.
2) π mostly DAR. Detector 90º from p beam.
3) π^- contamination: $\bar{\nu}_e/\bar{\nu}_\mu = 6.4 \cdot 10^{-4}$
4) Baseline of 17.7 m
5) ~57 tonnes of liquid scintillator
6) 3.5 m long detector.



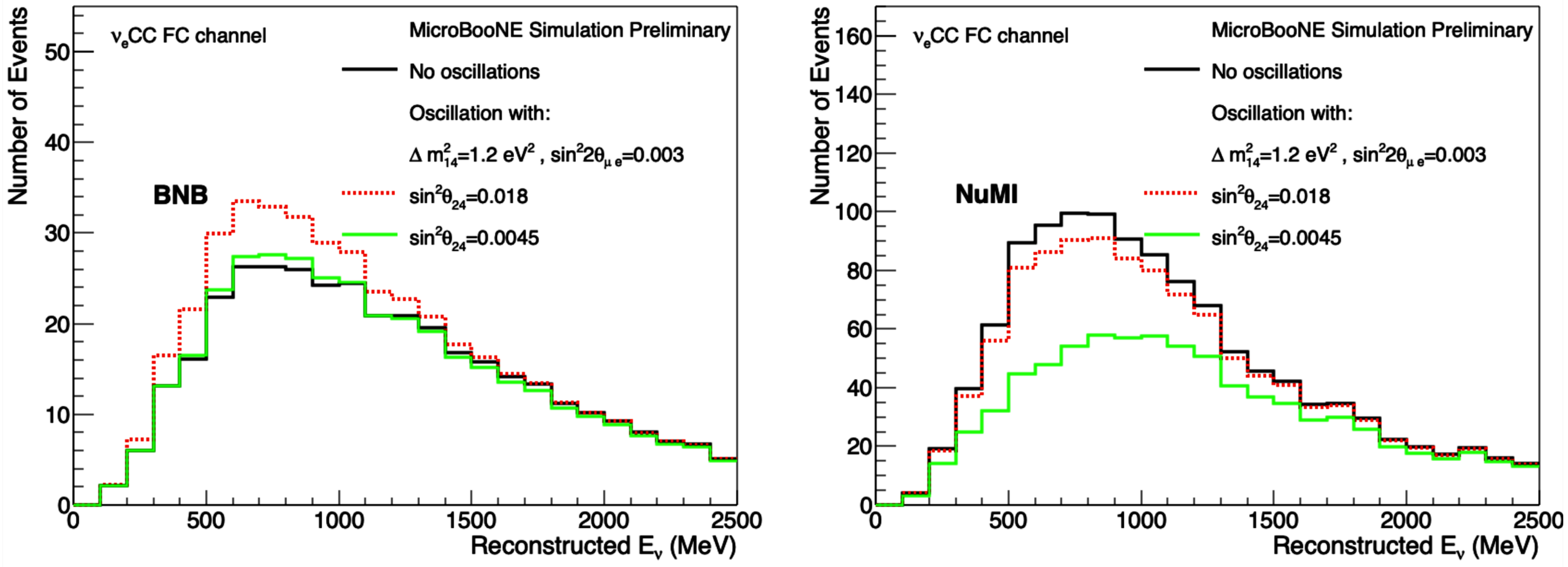
No excess observed,
but could not exclude LSND results.

MicroBooNE strategy has been to eliminate the degeneracy: second beam w/ different flavor composition.





https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1132-PUB.pdf

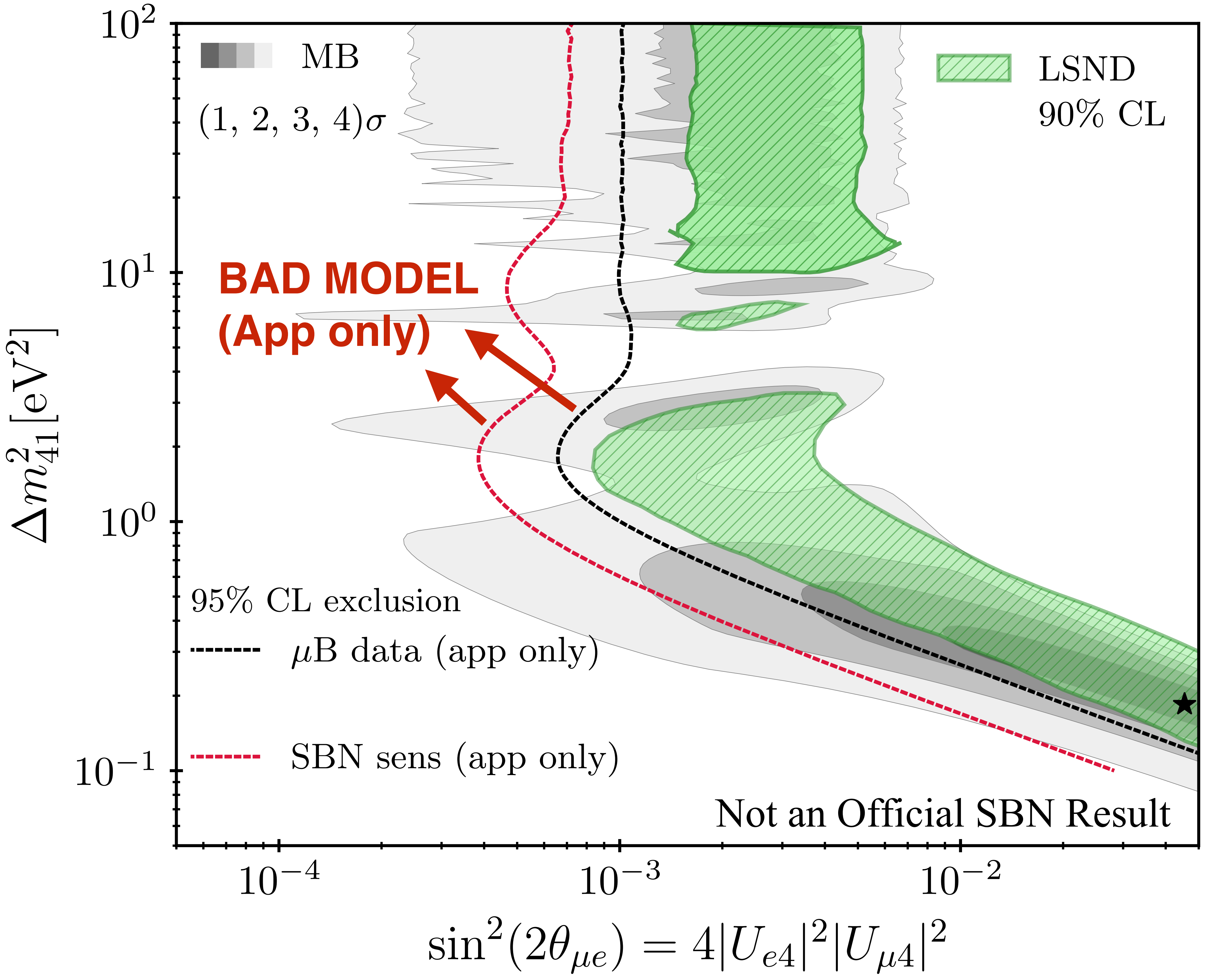


(a) BNB reconstructed neutrino energy spectrum **(b)** NuMI reconstructed neutrino energy

Towards a Robust Exclusion of the Sterile-Neutrino Explanation of Short-Baseline Anomalies

Ohana Benevides Rodrigues, Matheus Hostert, Kevin J. Kelly, Bryce Littlejohn, Pedro A. N. Machado, Ibrahim Safa, Tao Zhou

https://arxiv.org/abs/2503.13594



The "standard" way to look at the parameter space

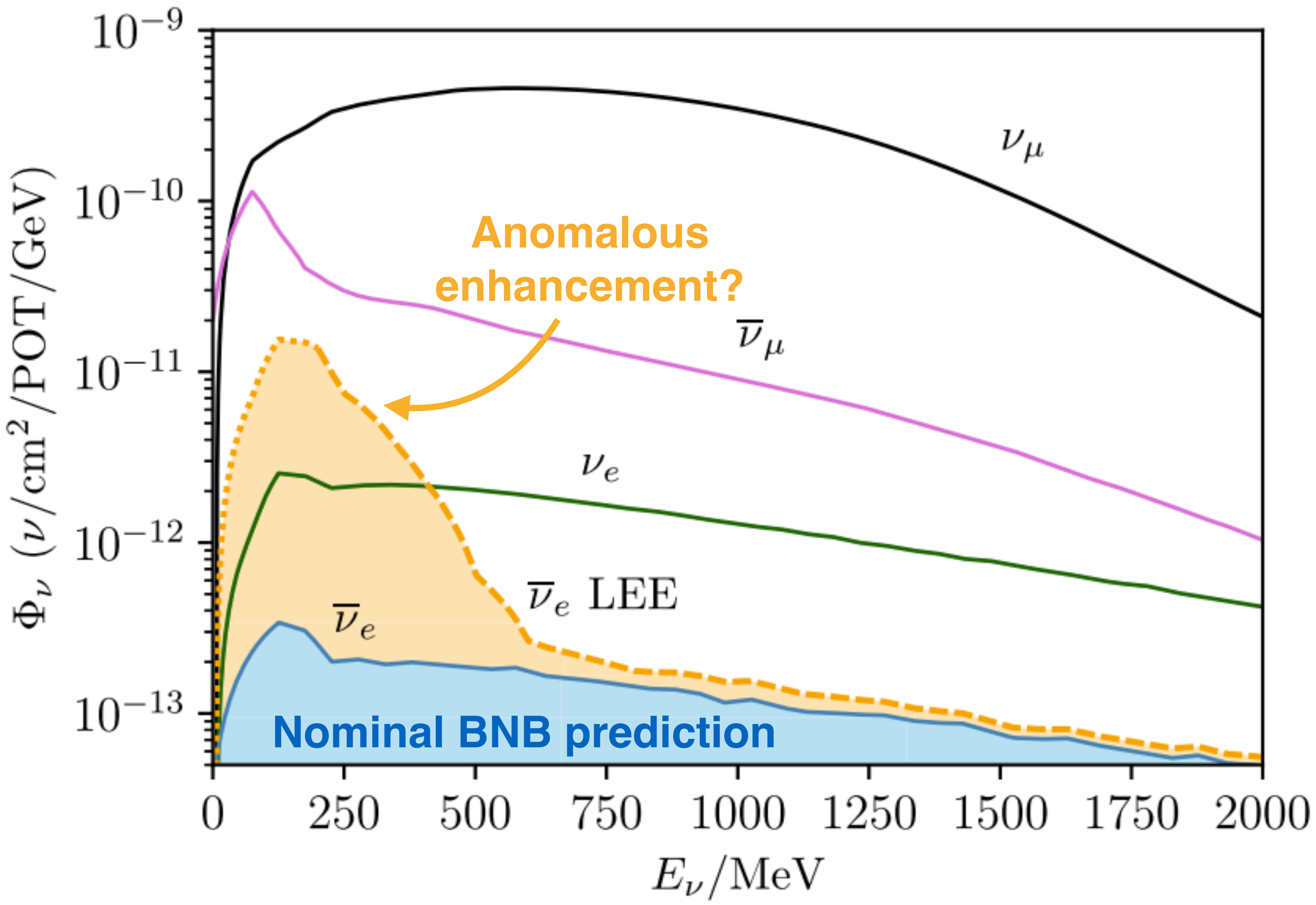
For **LSND**, appearance-only oscillations is a good approximation.

For **BNB**, disappearance impacts sidebands and backgrounds. **Need full 3-parameter, 3+1 model.**

- ★ J. Kopp, P. Machado, M. Maltoni, T. Schwetz (briefly mentioned) arxiv.org/abs/1303.3011
- ★ M/ Dentler, I. Esteban, J. Kopp, P. Machado (pheno fit in the appendix…) arxiv.org/abs/1911.01427
- ★ C. A. Argüelles, I. Esteban, MH, K. J. Kelly, J. Kopp, P. A. N. Machado, I. Martinez-Soler, and Y. F. Perez-Gonzalez **PRL 128, 241802.**
- ★ **MiniBooNE itself only actually used this model in 2022:** arxiv.org/abs/2201.01724
- ★ MicroBooNE coll., **PRL. 130 (2023) 1, 011801**
- ★ **M. Hostert, K. Kelly, T. Zhou: arxiv.org/abs/2406.04401** (This is the pheno fit we use here, see our appendix…)

Constrain the $\overline{\nu}_e$ composition of the BNB flux with LAr.

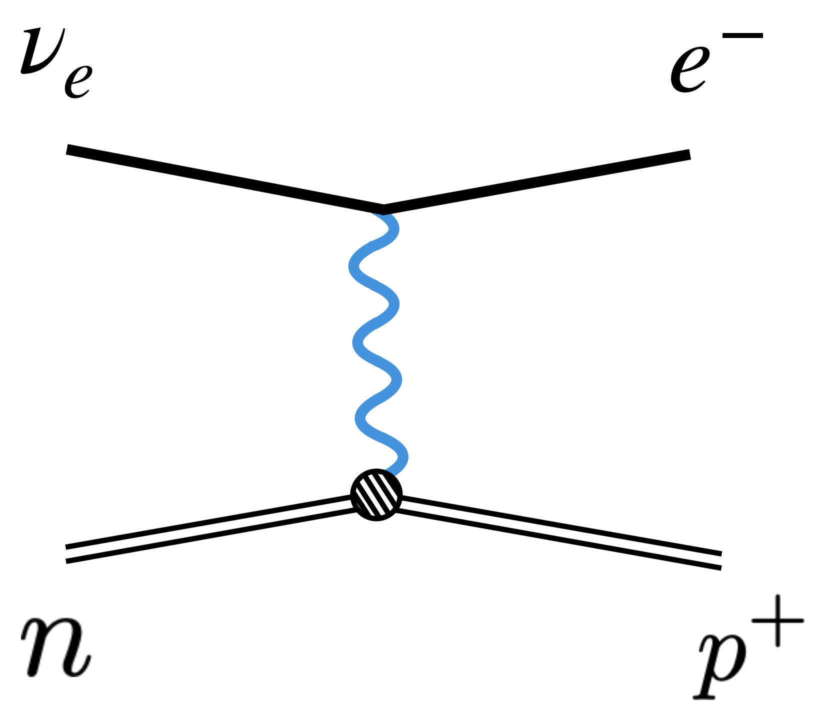
N. Kamp, M. Hostert, C. Argüelles, J. Conrad, M. Shaevitz. PRD107, 092002 (2023)



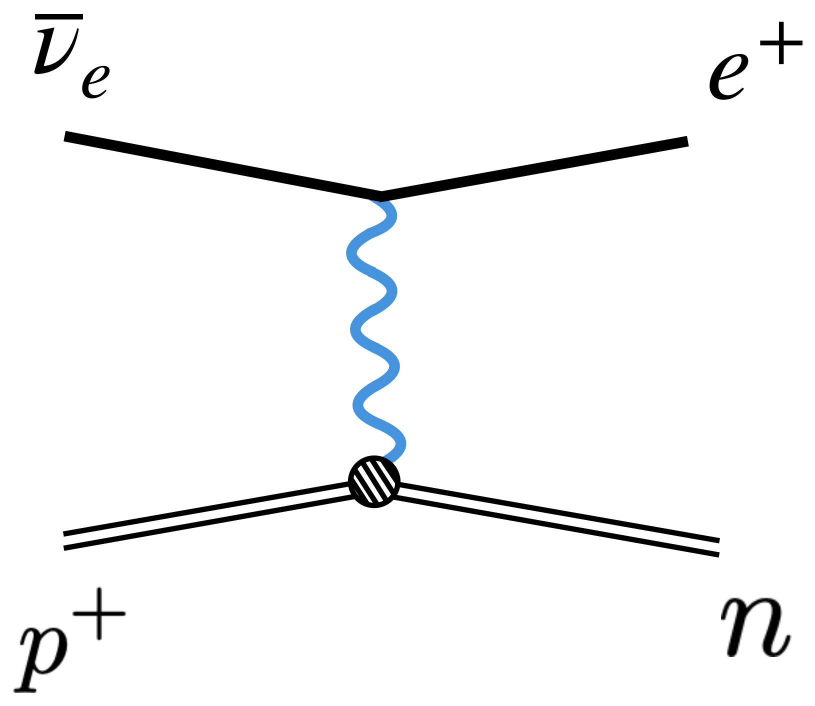
Not easy, but could be a novel search.

No very convincing reason why such a flux would be so high (in SM or BSM), but

have we ever checked that the $\overline{\nu}_e$ ontamination of the beam is as small as we think it is?

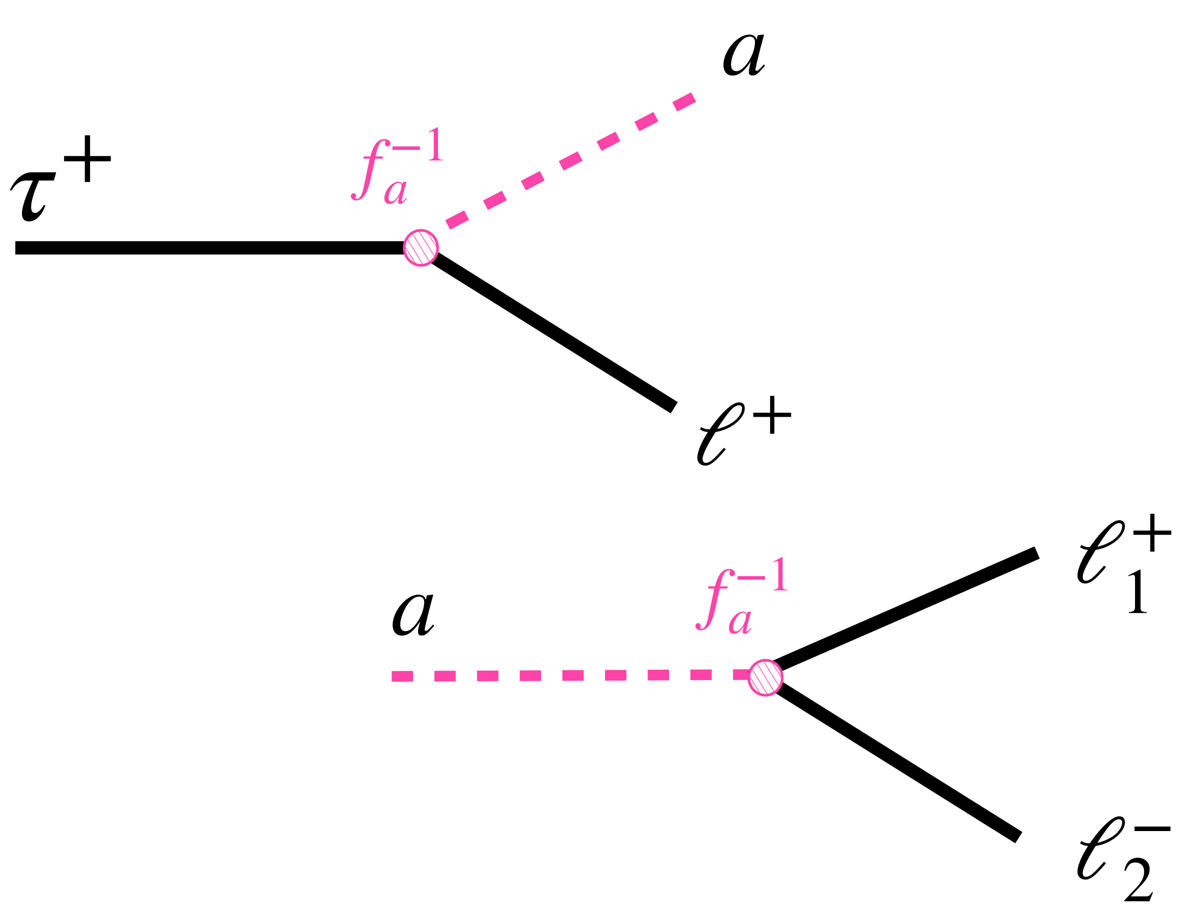


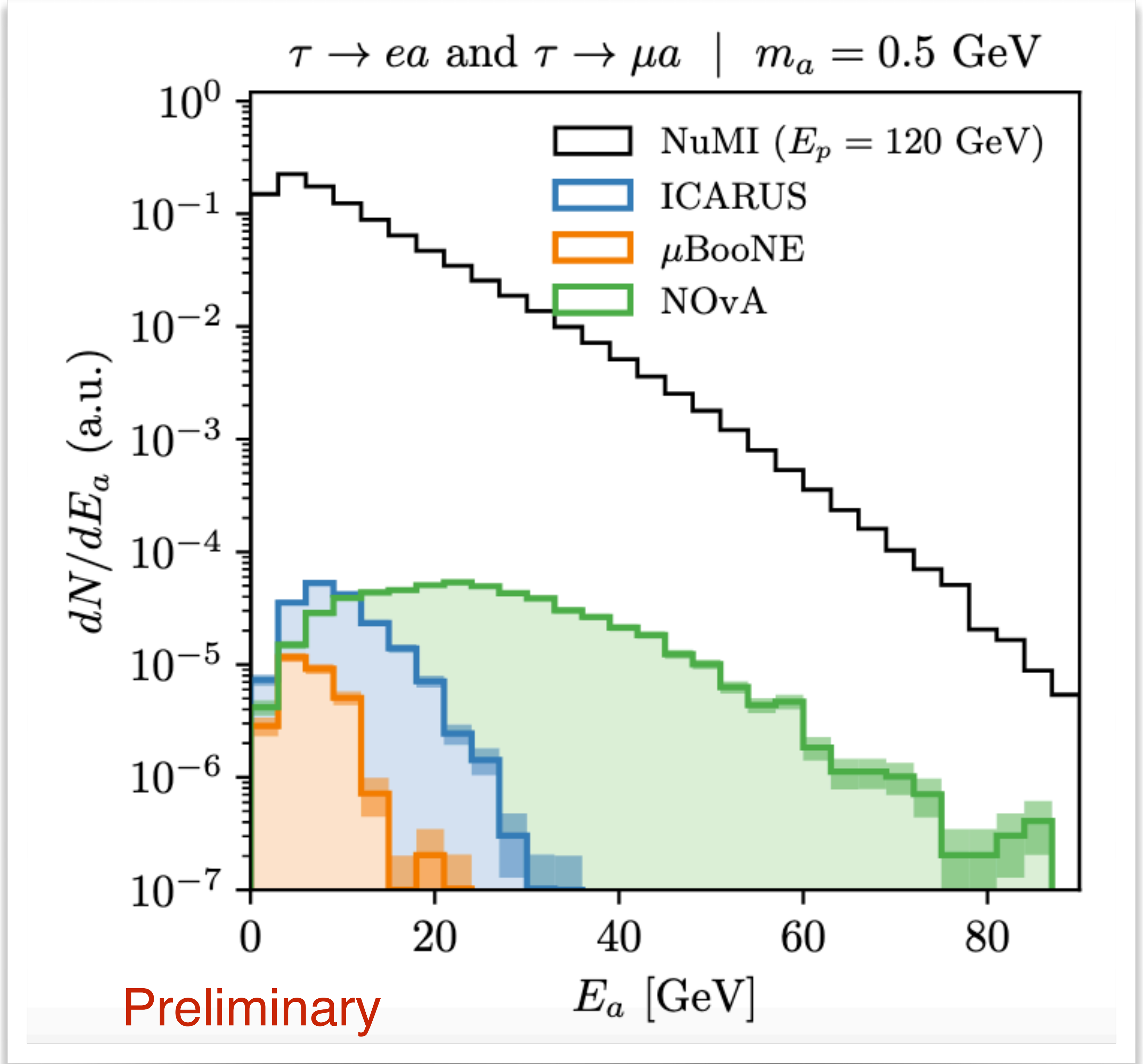
vs



Long-lived particles from NuMI *target* (not absorber)

Y. Ema, P. J. Fox, M. Hostert, T. Menzo, M. Pospelov, A. Ray, J. Zupan, **In preparation**

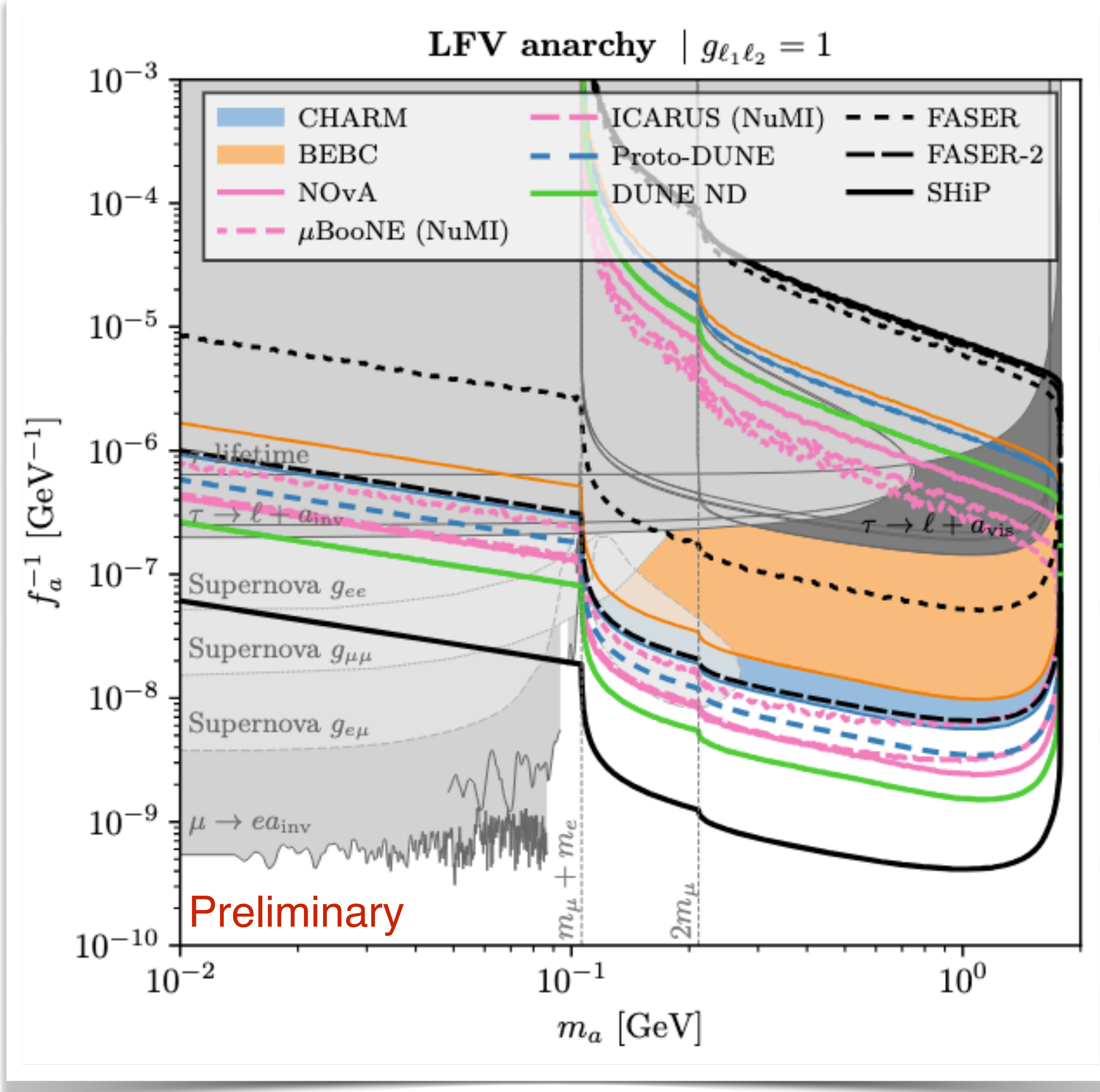




Tau decays at the NuMI target as source of leptophilic axion-like particles.

These are high energy events.
Non-starting $\mu^+\mu^-$ would prob be the best way to enhance the sensitivity.

Comparable sensitivity to (pheno) CHARM curves, but MicroBooNE could do a **first direct experimental search for long-lived flavor-violating ALPs?**



Experiment	p^+ Energy	Exposure	τ/POT	Baseline	Fiducial Volume	Material
MicroBooNE	120 GeV (NuMI)	$2 \cdot 10^{21}$ POT	$5 \cdot 10^{-7}$	685 m (8°)	$2.26 \cdot 2.03 \cdot 9.42$ m^3	LAr

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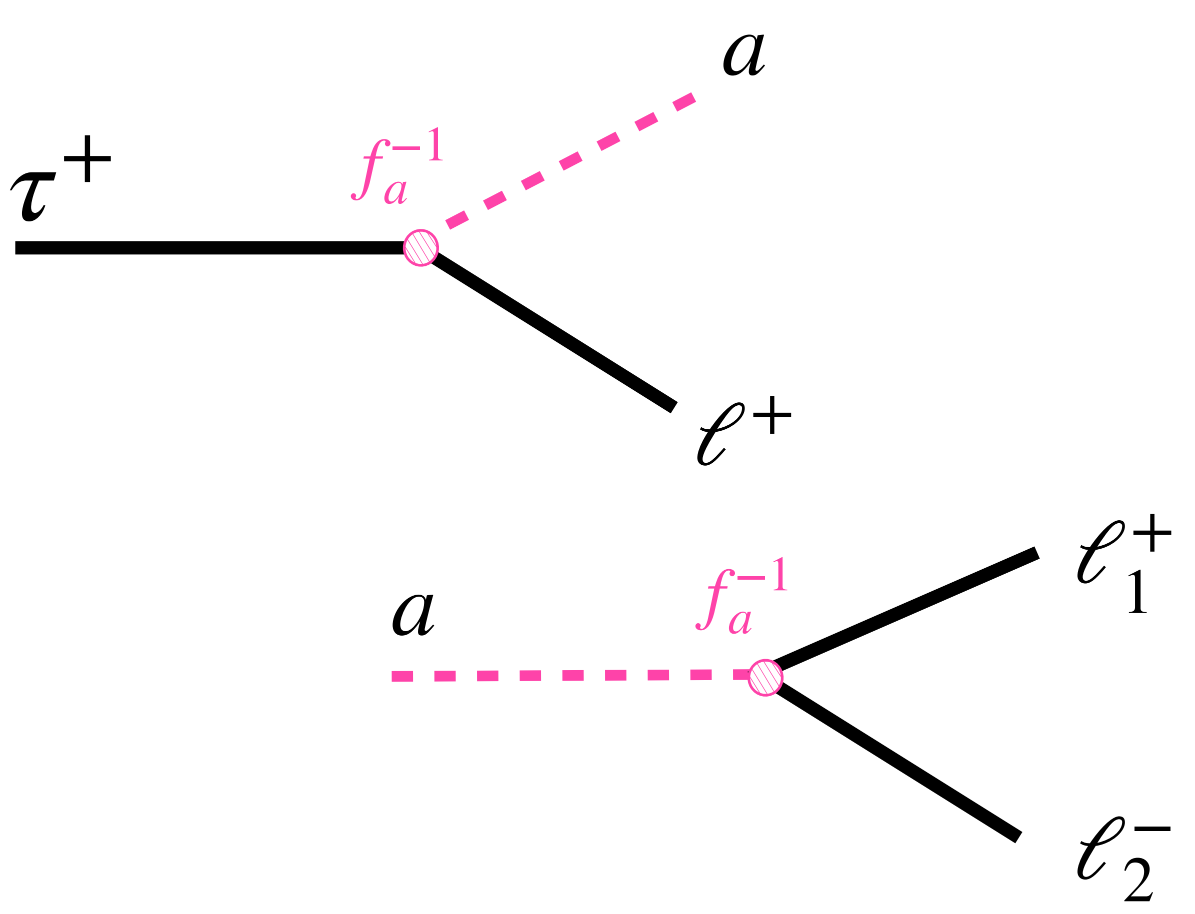

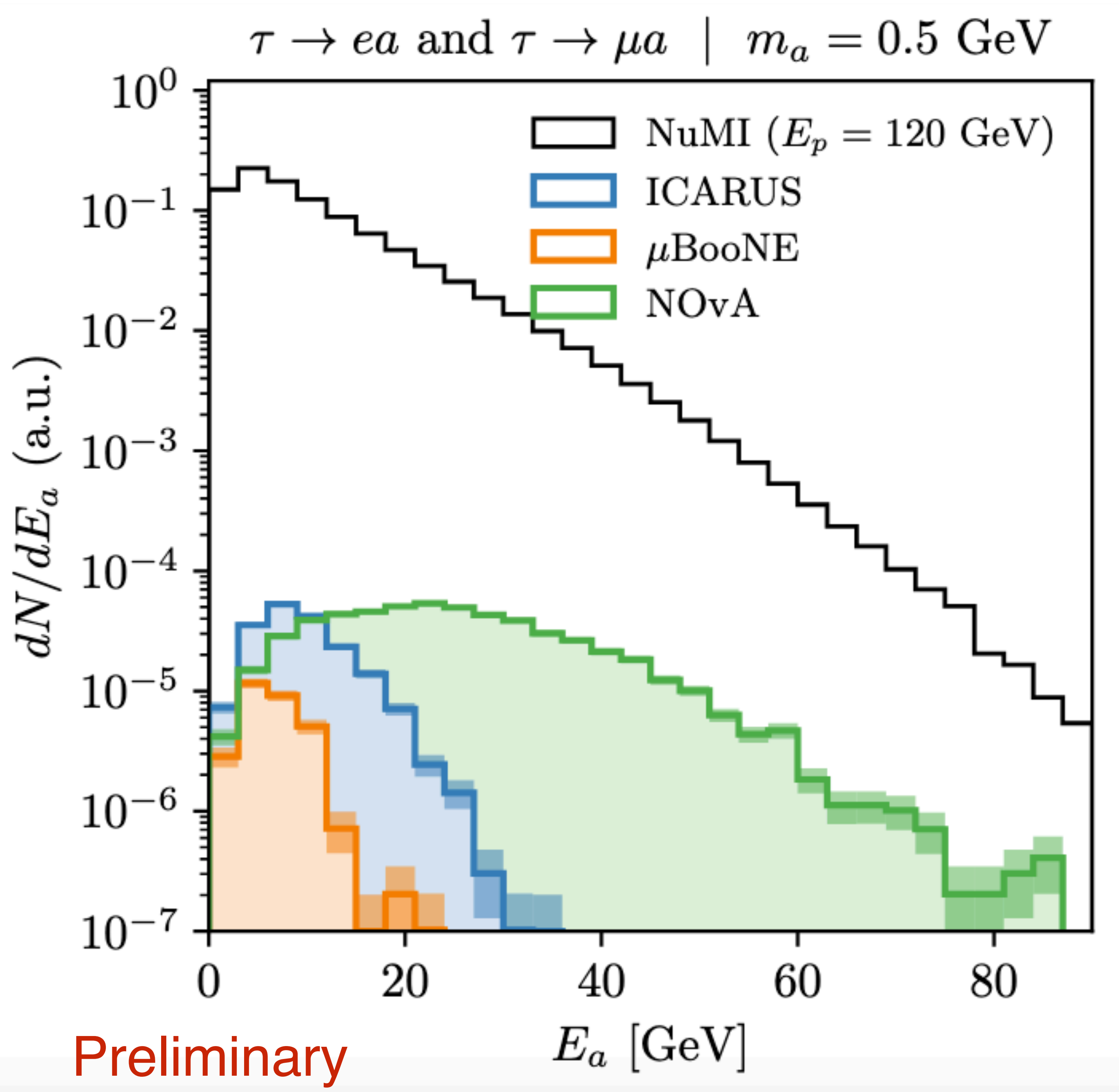

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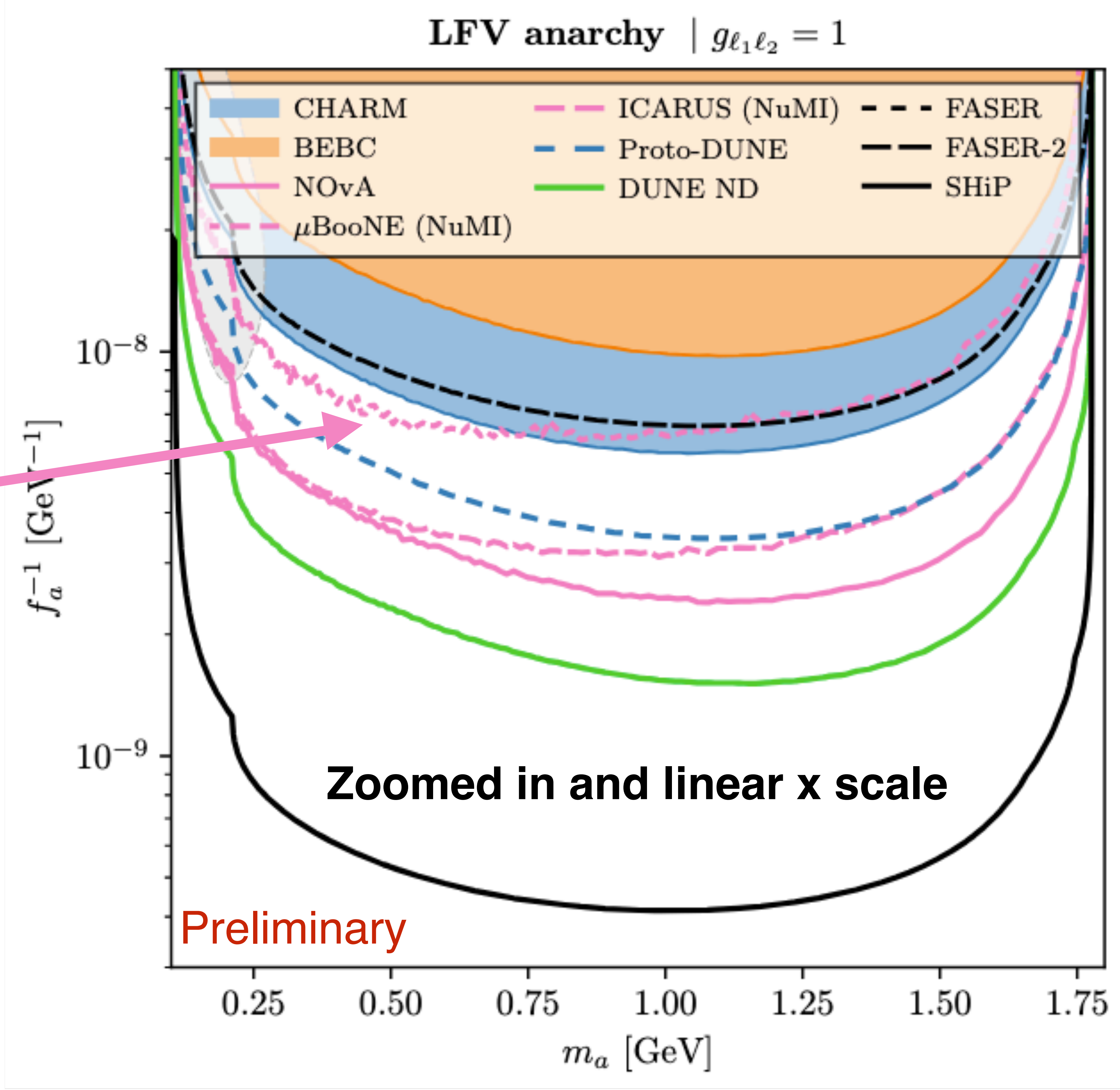

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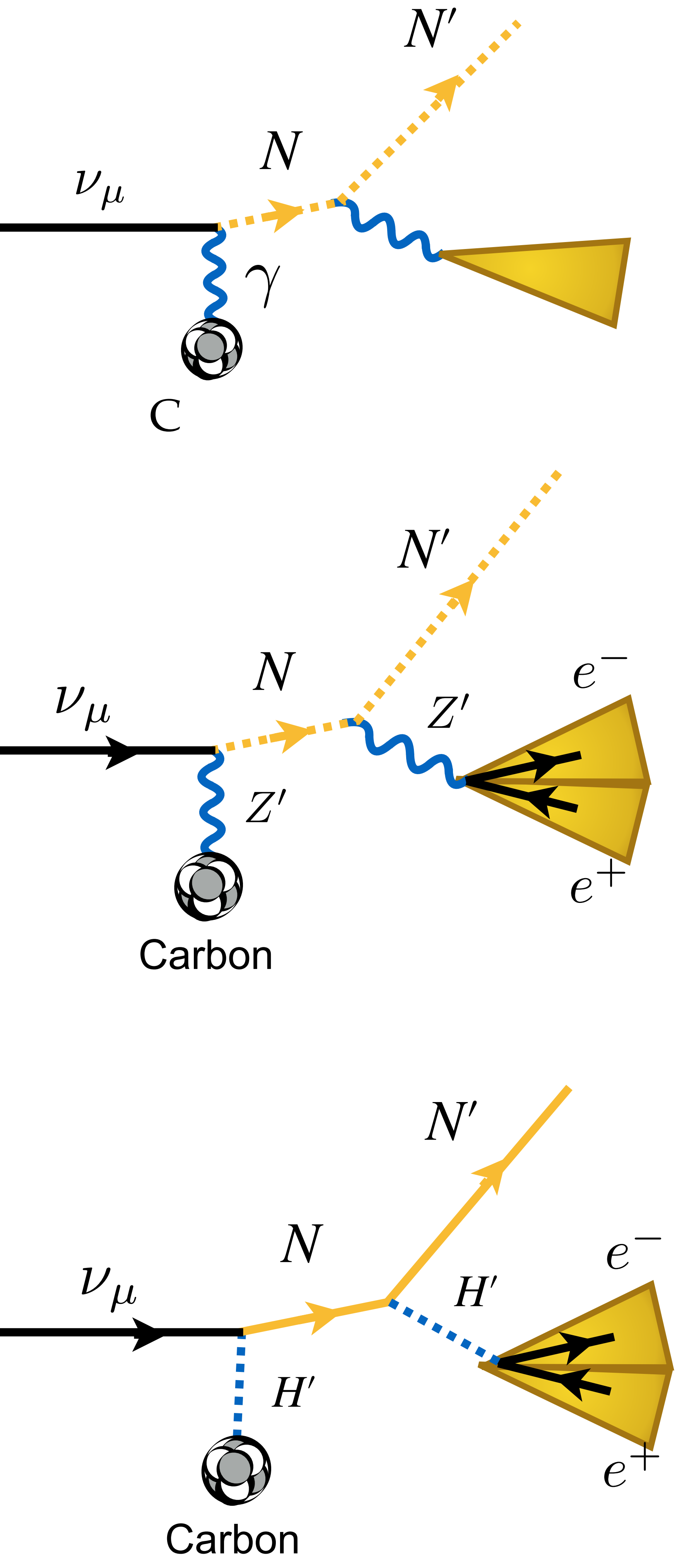
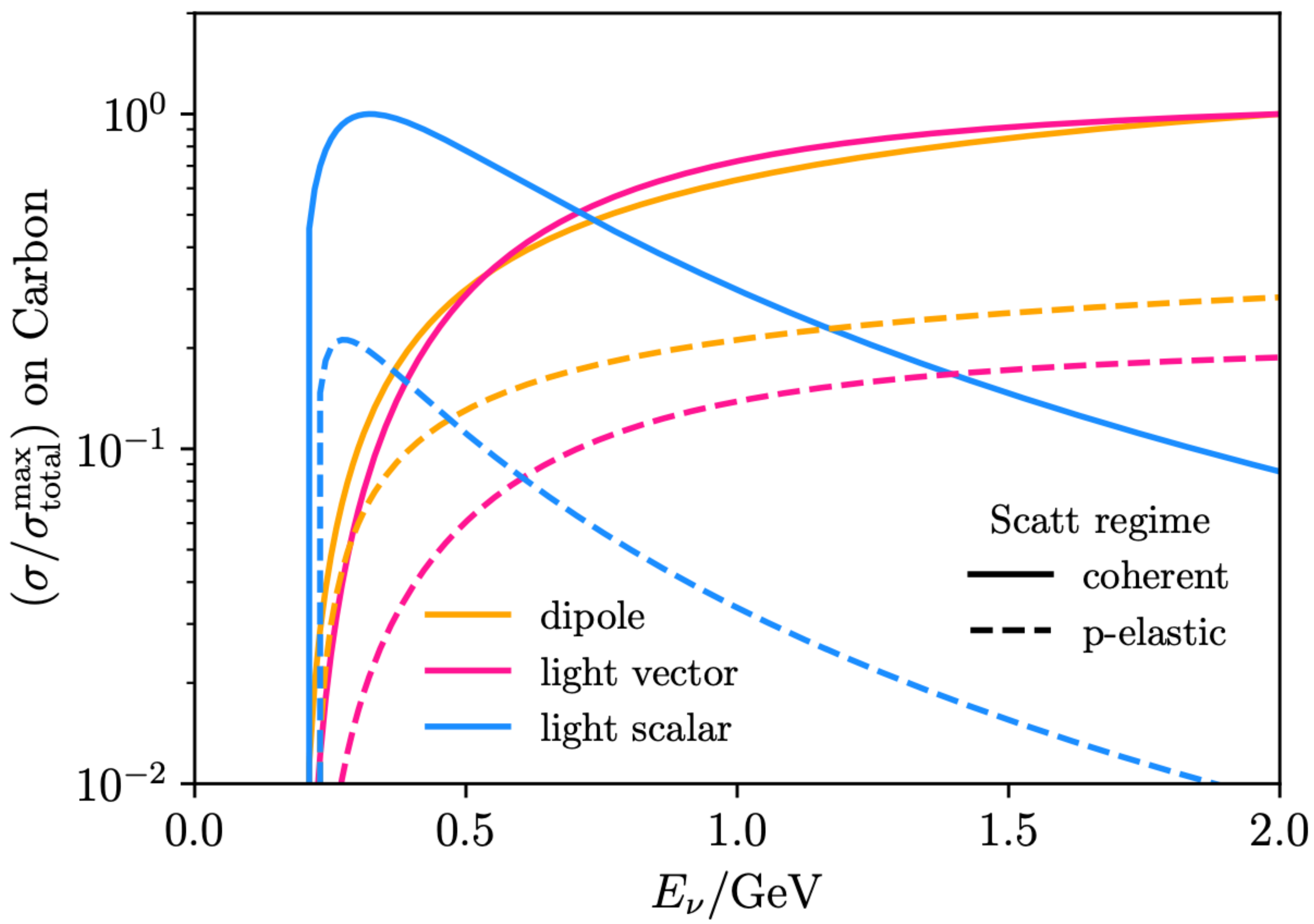
Dark neutrino sectors at MiniBooNE
The nature of the mediator matters



Normalized upscattering cross sections in different models:

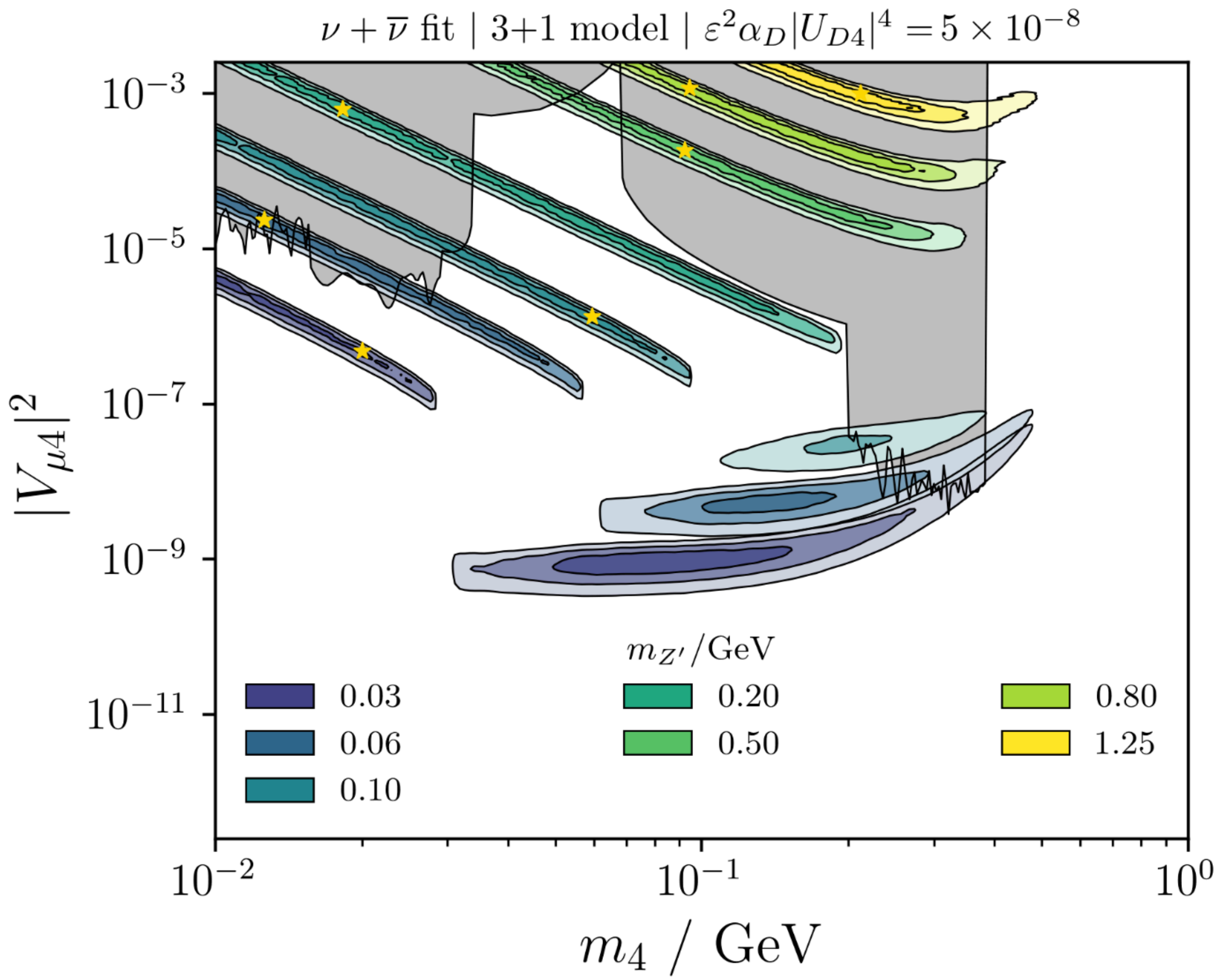


Not all neutrino experiments would see the same physics.

Importance of complementarity.

Dark neutrino sectors at MiniBooNE
A comprehensive fit to dark photon models

A. M. Abdullahi, J. Hoefken Zink, M. Hostert, D. Massaro, S. Pascoli
arXiv:2308.02543



Not a sensitivity plot! Just benchmarking the rate.