Exploring Sterile Neutrinos and the Dark Sector with MicroBooNE

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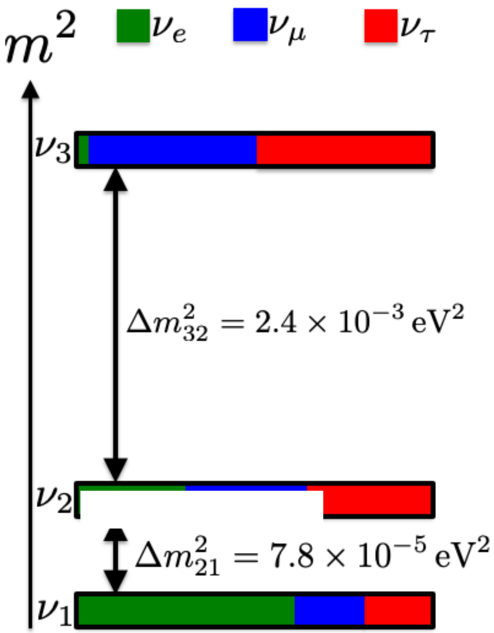
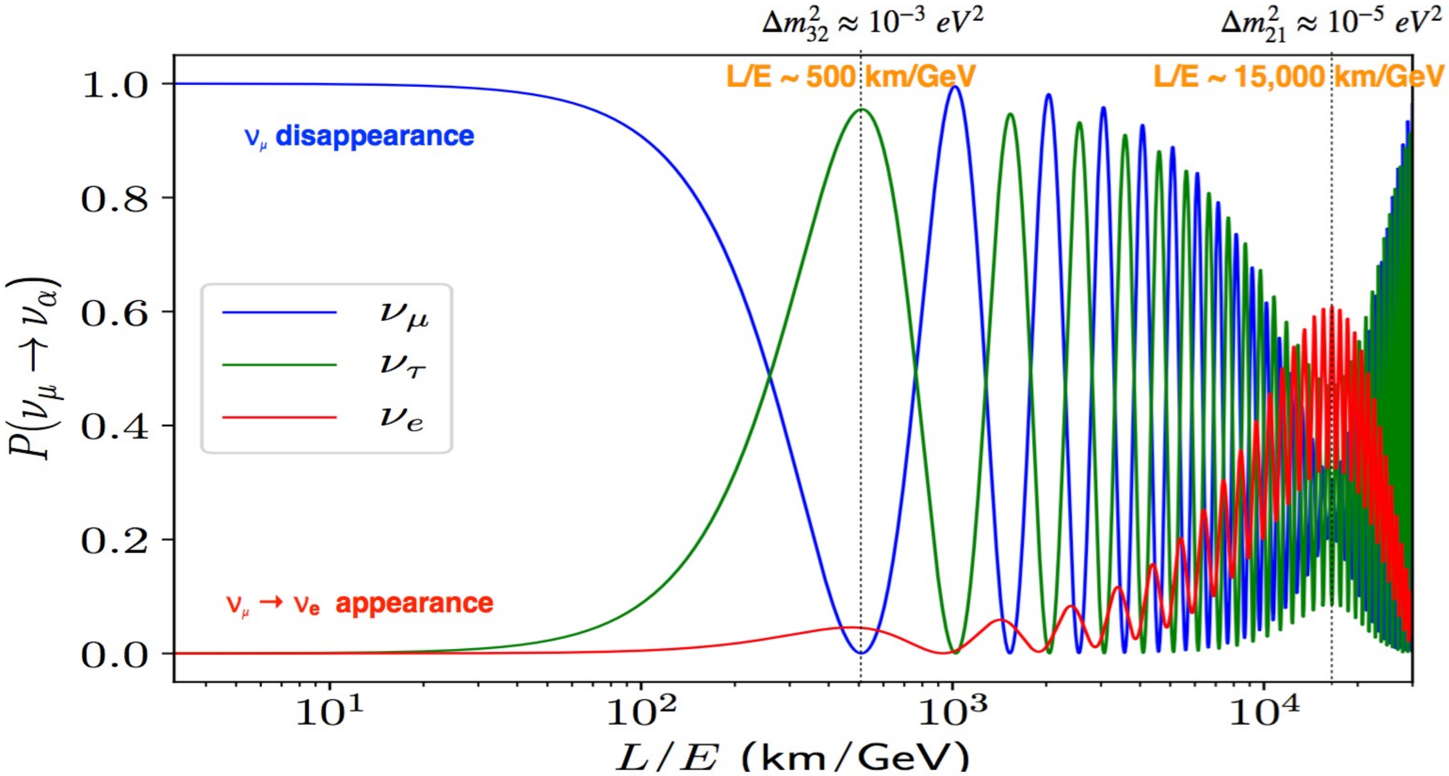
PASCOS, Sheffield
24 June 2026

Neutrino Oscillations with three flavours





Baseline/Neutrino energy

Oscillation frequency given by:

$$\frac{\Delta m^2 L}{4E}$$

Typical neutrino beam energy is 1-3 GeV

Fixing baseline, energy, and frequency

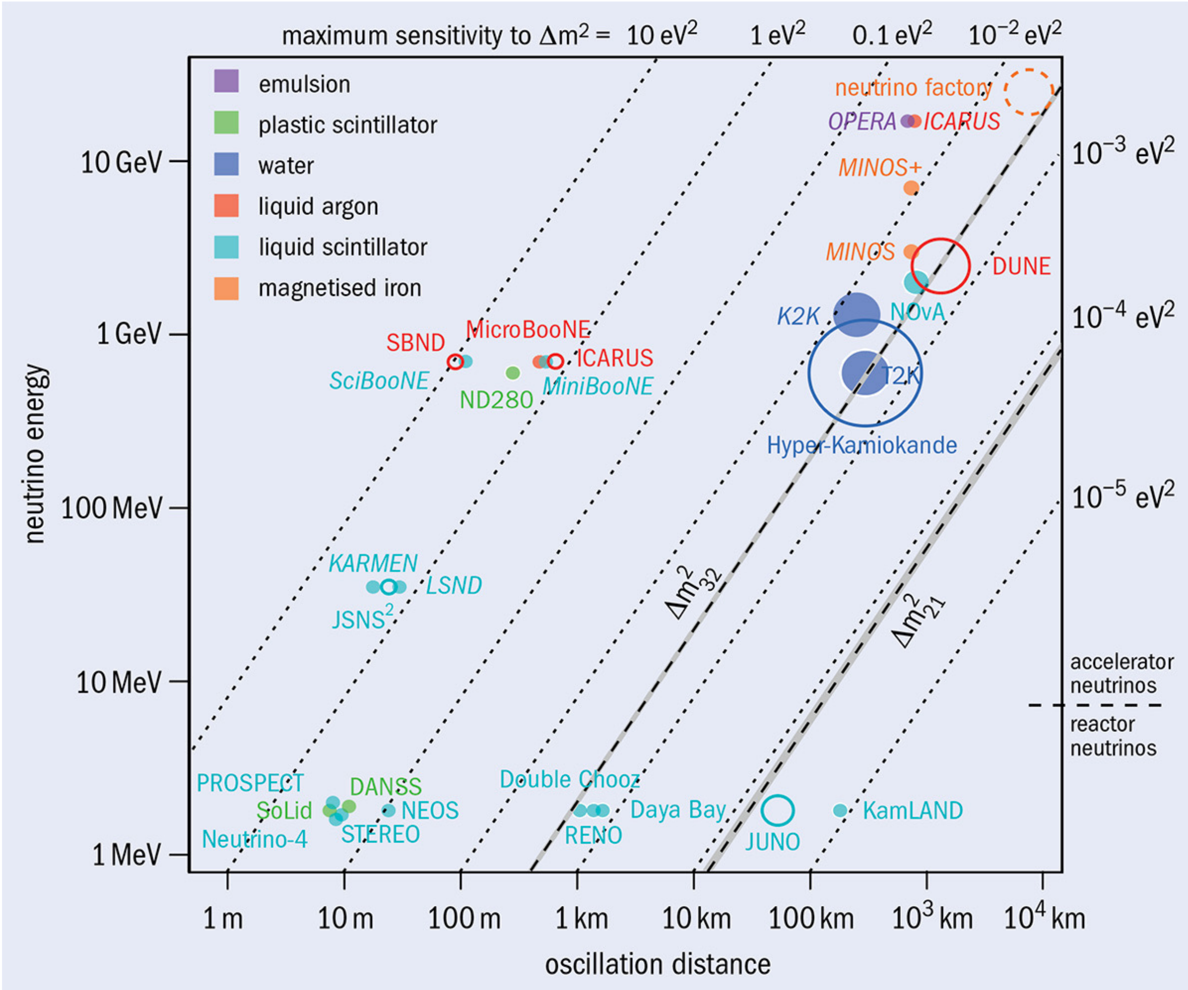
M. Rayner, CERN courier

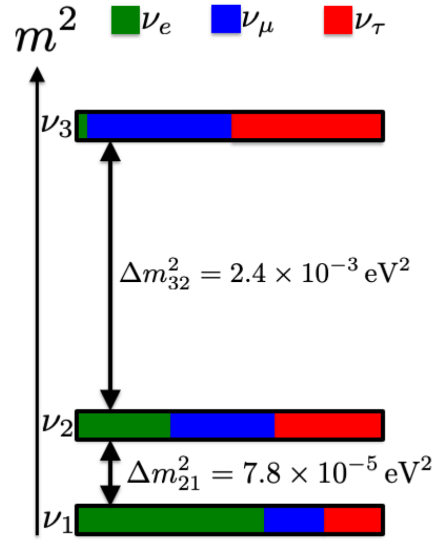
$$\frac{\Delta m^2 L}{4E}$$

Energy

Accelerator neutrinos

Reactor neutrinos





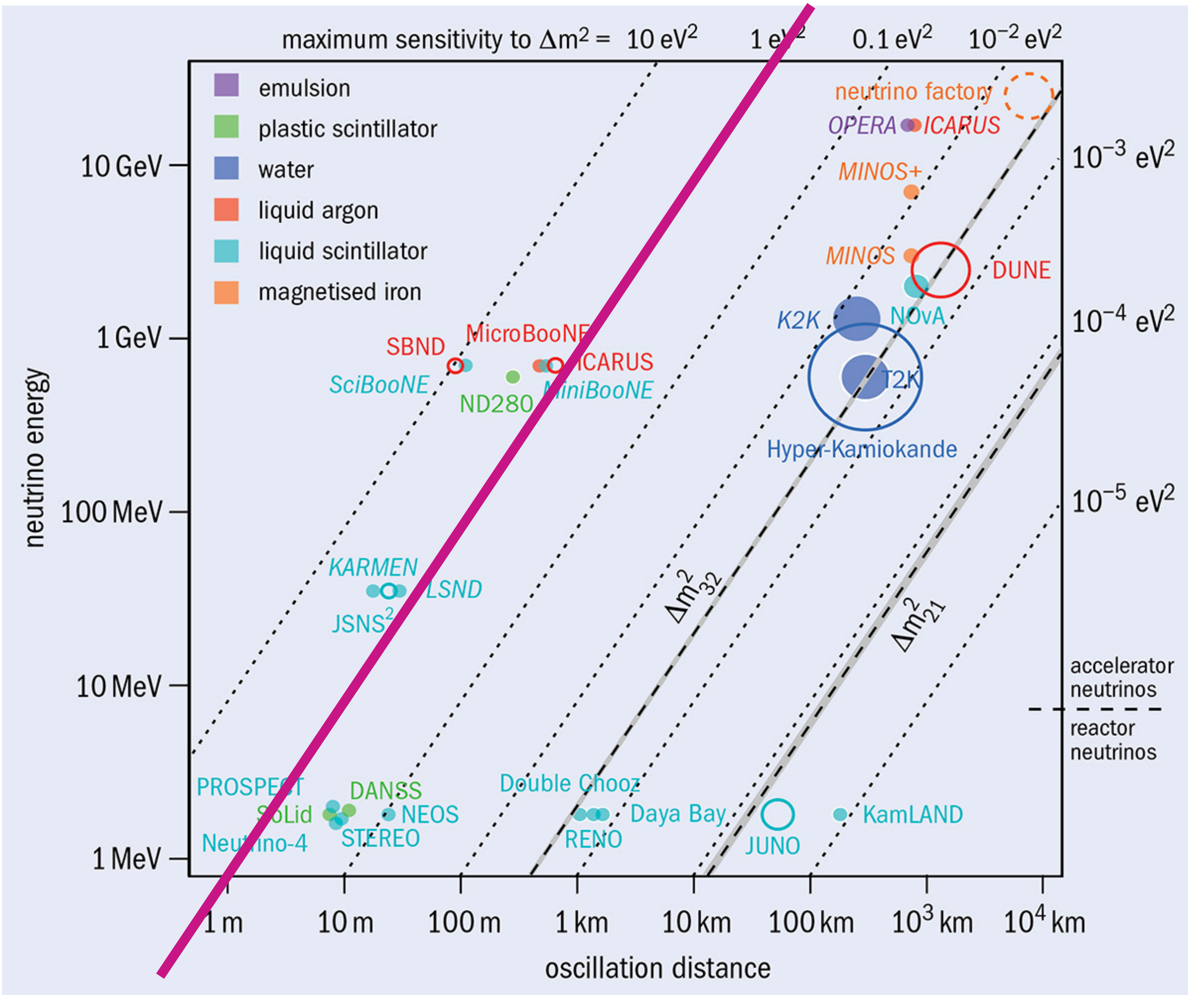
Distance

Fixing baseline, energy, and frequency

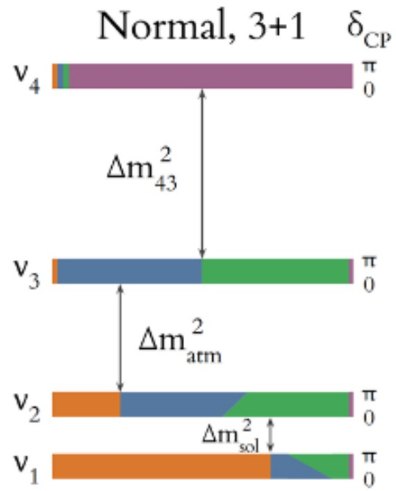
Energy

Accelerator neutrinos

Reactor neutrinos



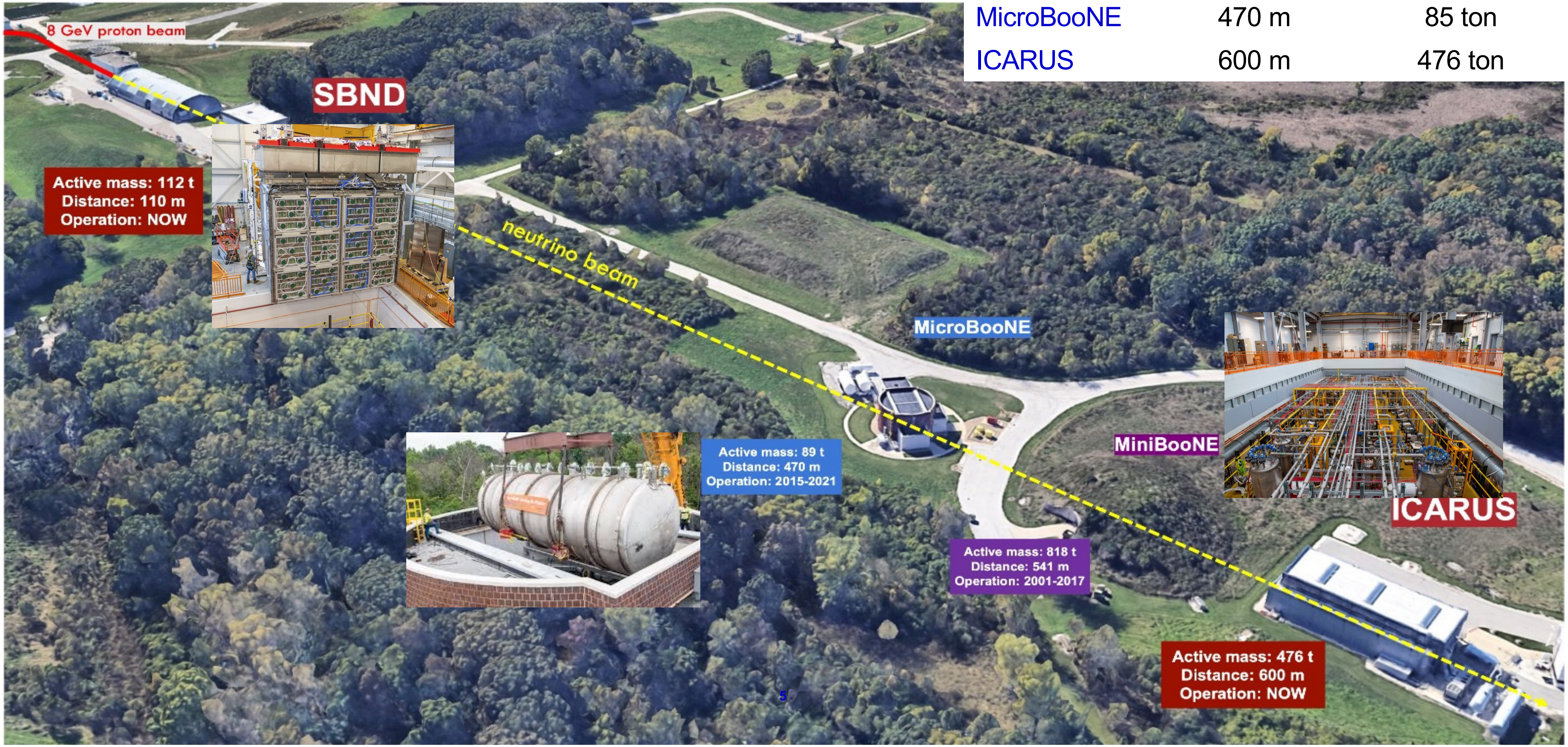
$$\frac{\Delta m^2 L}{4E}$$



Distance

Fermilab short-baseline programme

Detector	Distance from Target	Instrumented LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	85 ton
ICARUS	600 m	476 ton



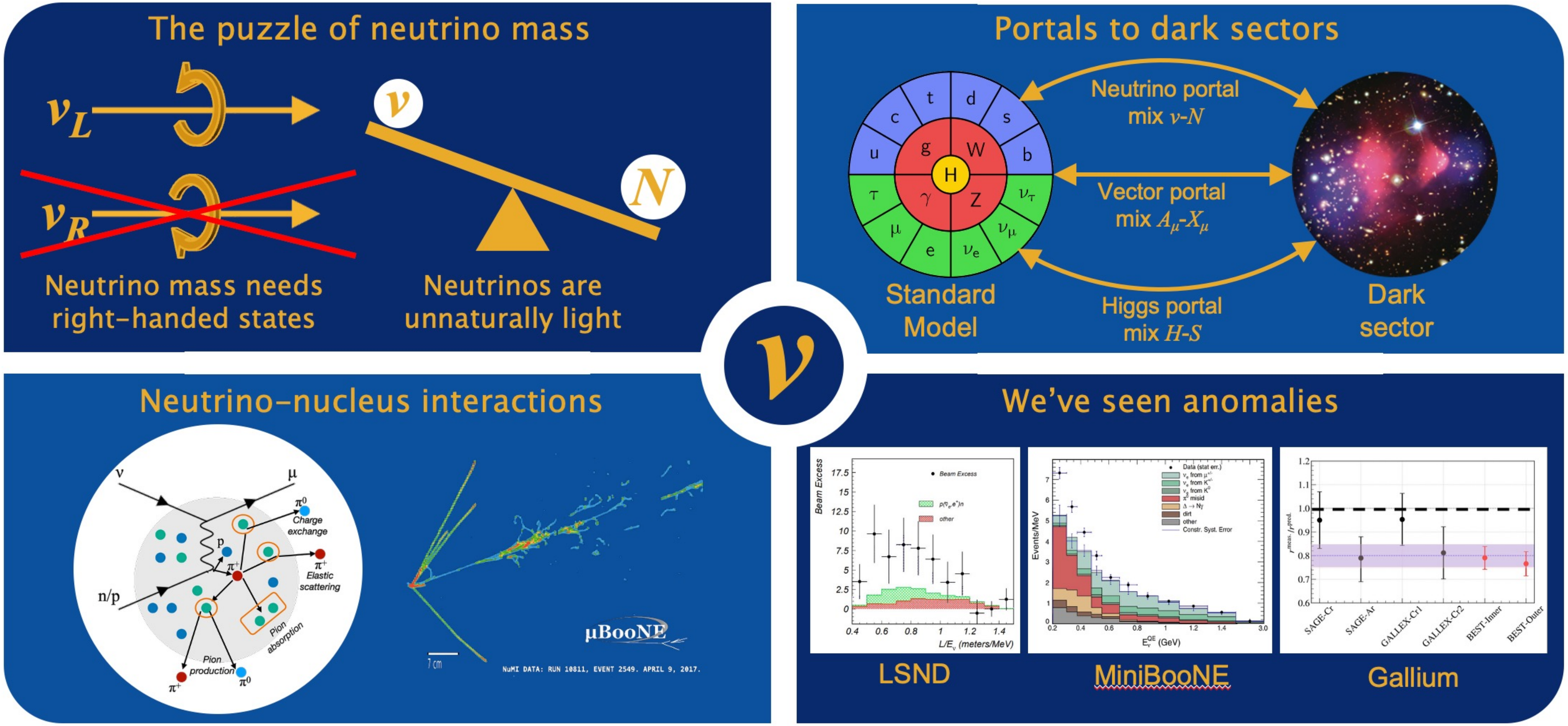
MicroBooNE - primus inter pares

- MicroBooNE was the first in the US Short-Baseline Neutrino Programme: took data 2015-2021

- Harnessed the **full power of Liquid Argon Time Projection Chamber (LArTPC) detector technology** to perform new precision measurements
  - World's first high-statistics precision cross-section measurements on argon
  - Detailed initial investigations into MiniBooNE anomaly
  - Further searches for new physics

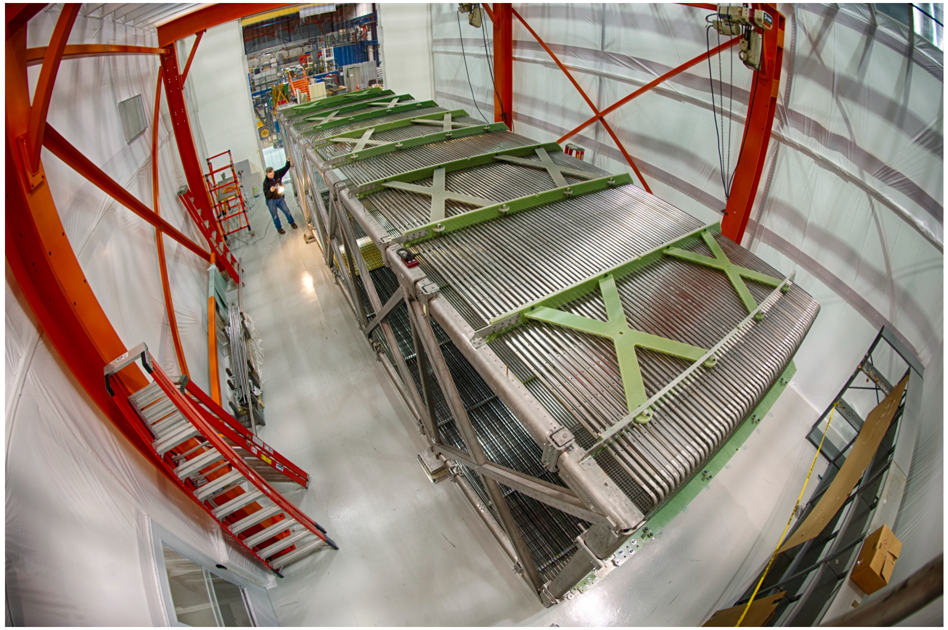
- MicroBooNE has also **laid the groundwork for further LArTPC detector programmes**: SBND, ICARUS (more investigation of the MiniBooNE anomaly) and the future multi-kt neutrino experiment DUNE

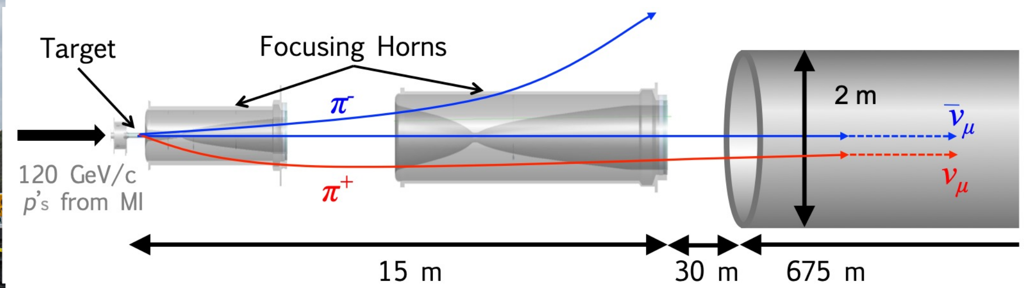
Neutrinos at short baselines – resolving mysteries



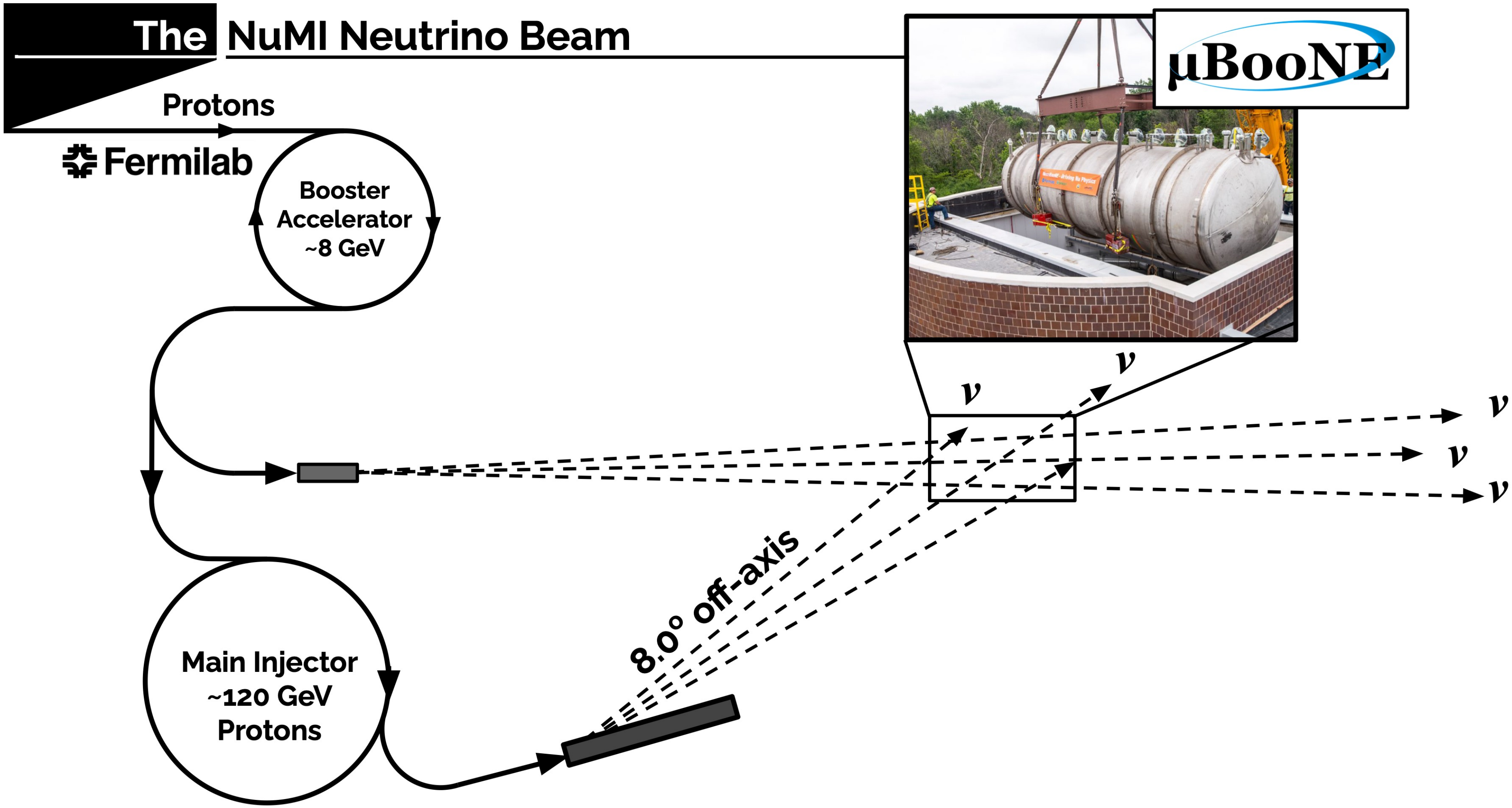
The MicroBooNE Detector

- Active mass: 85 tonnes of liquid argon
- Active volume: 2.6 x 2.3 x 10.4 m^3





MicroBooNE exposed to two neutrino beams



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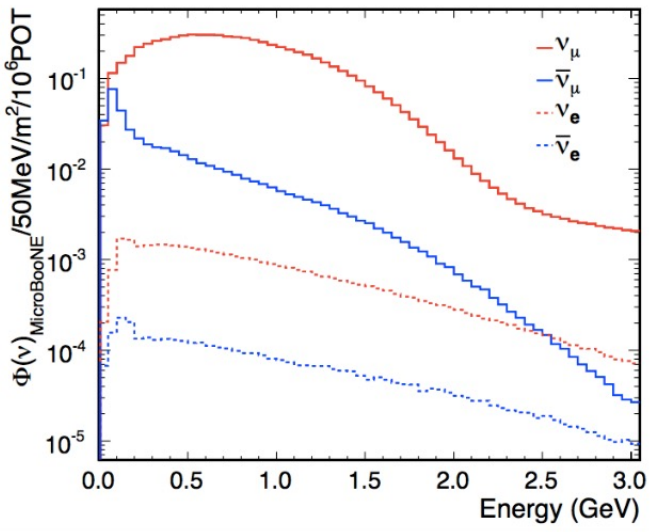
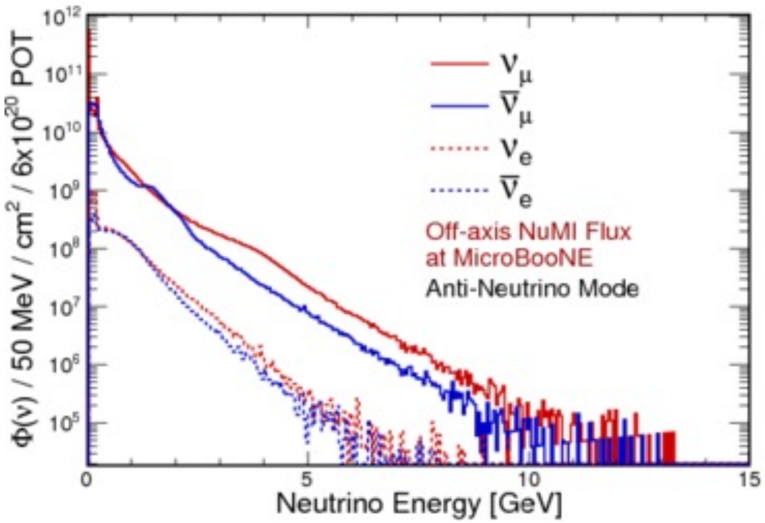
MicroBooNE exposed to two neutrino beams

BNB flux prediction at MicroBooNE



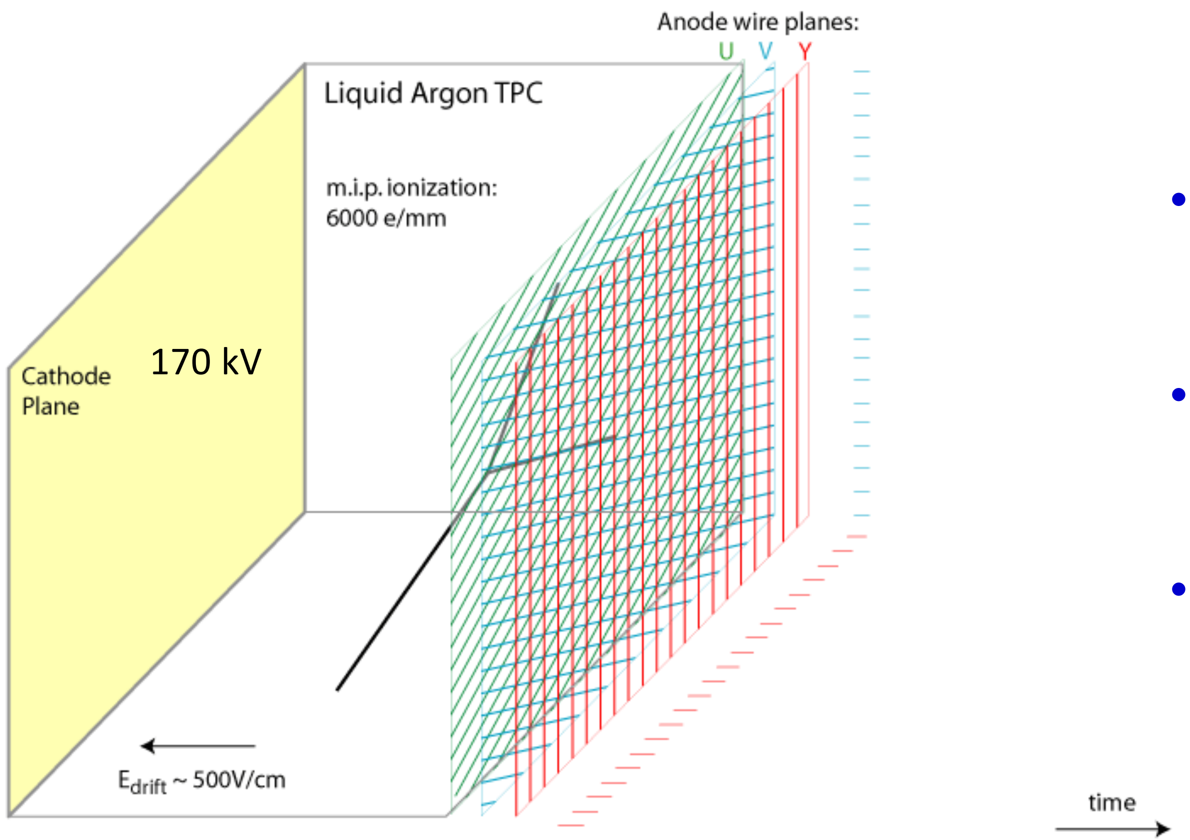
- 8 GeV protons
- Mean neutrino energy: 0.8 GeV
- ~470 m from MicroBooNE
- On-axis

NuMI flux prediction at MicroBooNE



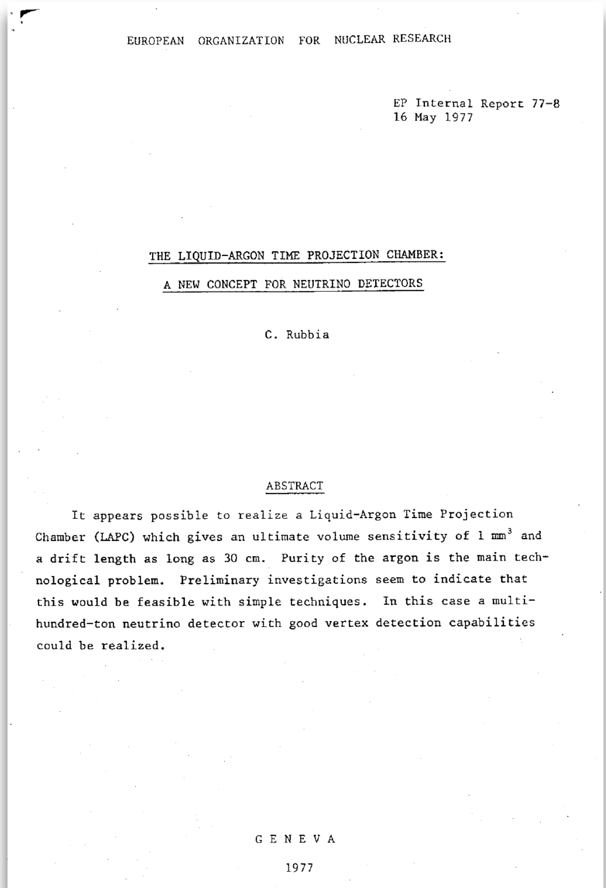
- 120 GeV protons
- Mean neutrino energy: 1.5 GeV
- ~680 m from MicroBooNE
- ~8º off-axis from MicroBooNE
- Absorber ~100 m from MicroBooNE

Liquid-argon Time Projection Chambers



- Fully-active tracking calorimeter
- 32 PMTs collect light from flash at time of interaction
- 3 planes of wires (vertical, +60°, -60°) with 3 mm spacing

Some history



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

GENEVA

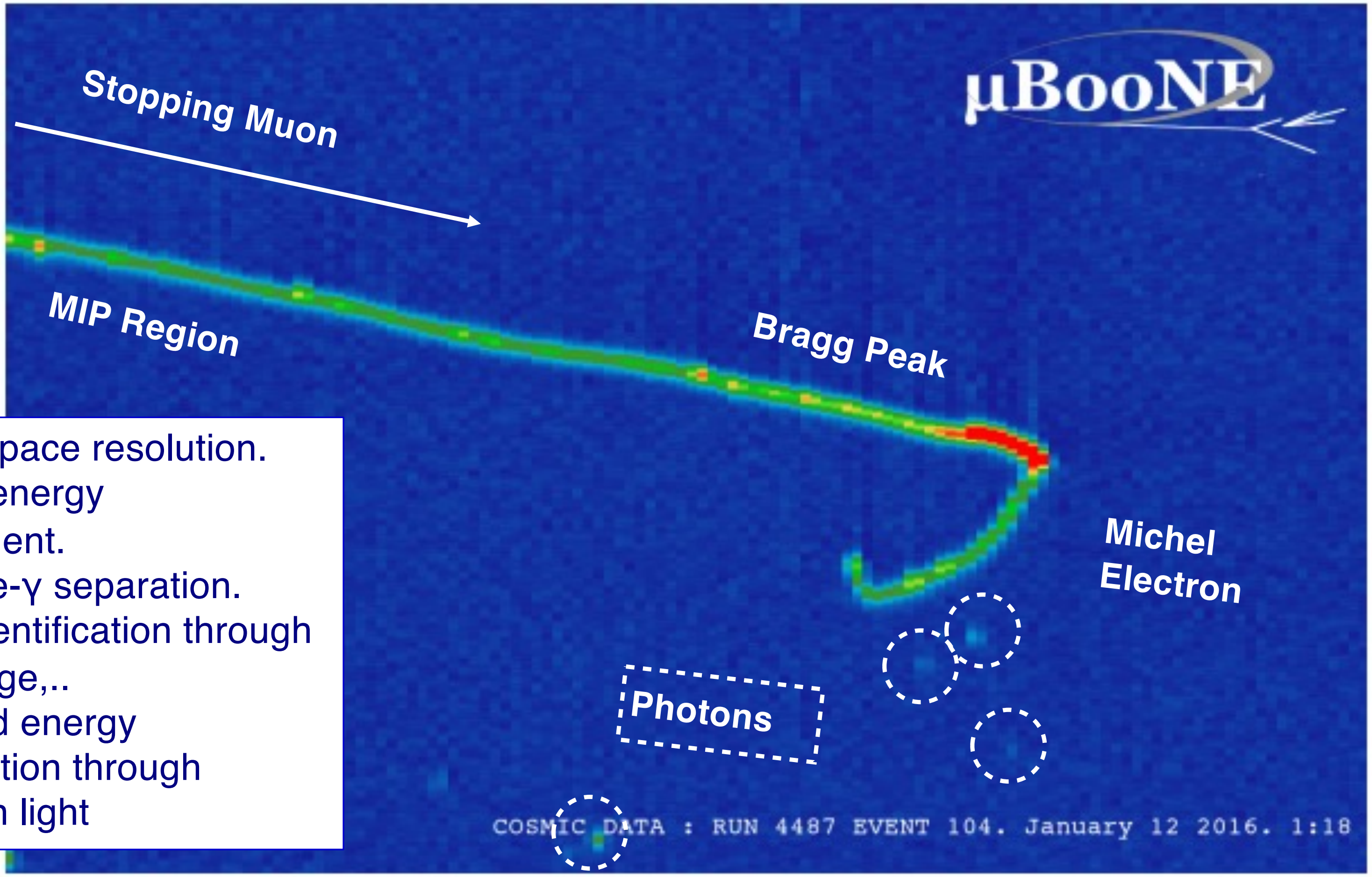
1977

- "Briefly, the idea consists of drifting the whole electron image of an event occurring in the noble liquid towards a collecting multi-electrode array which is capable of reconstructing the three-dimensional image (x,y,z) of the event from the (x,y) information and the drift time (t)".
- "the purity of the Argon is the main technological problem. … electron lifetimes corresponding to residual oxygen impurity content of about 4 x 10^{-2} ppm" are reachable. However, this limits "the electron mean free path to about 30 cm. Clearly, oxygen-free argon is the central problem for the LAr TPC".

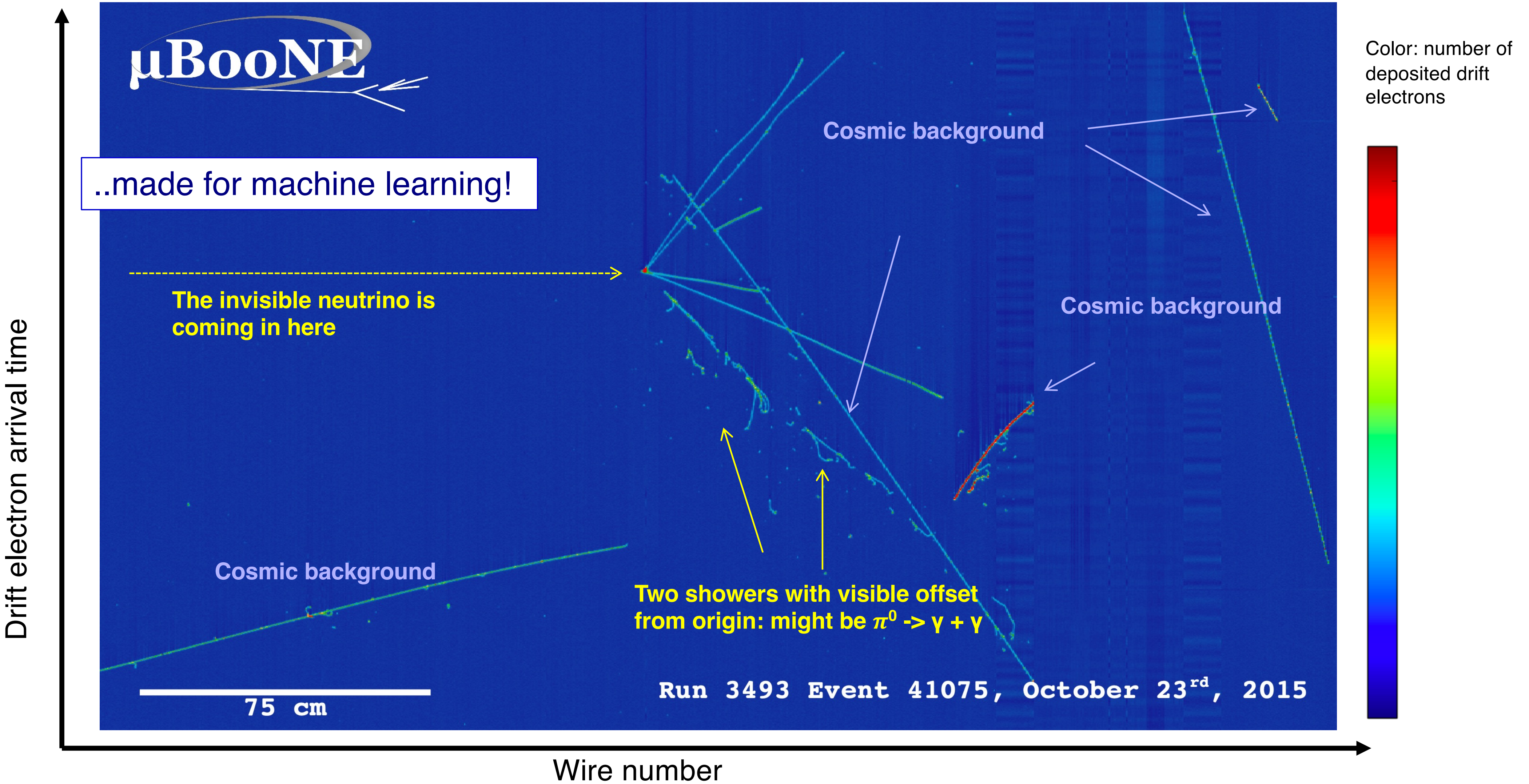
LArTPC technology pioneered by ICARUS T600 (Gran Sasso)

Drift lengths in DUNE of up to 12 m.

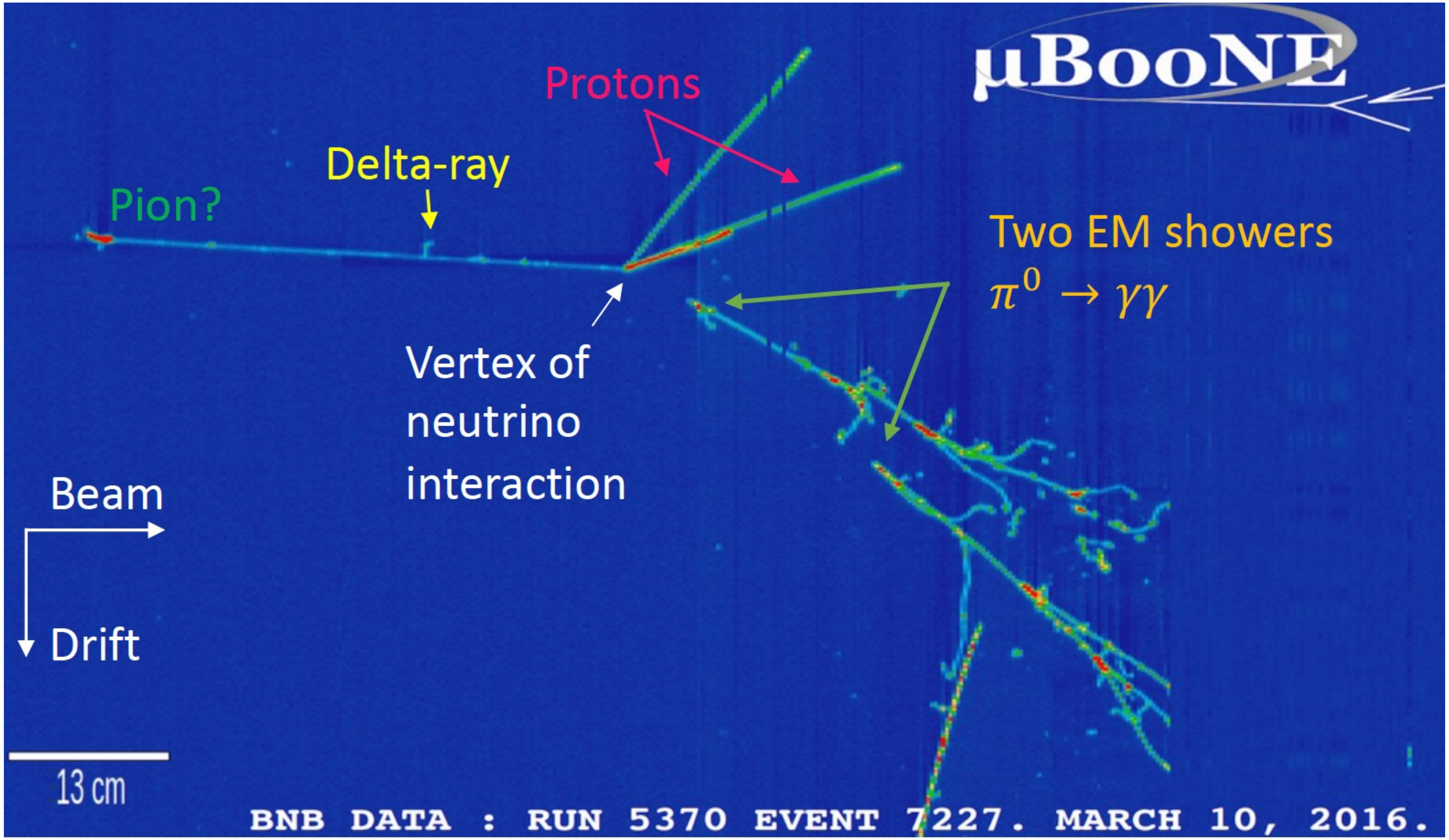
A liquid-argon “Bubble Chamber”



- Few mm space resolution.
- Excellent energy measurement.
- Excellent e-γ separation.
- Particle identification through dE/dx, range,..
- Timing and energy reconstruction through scintillation light



μBooNE
..made for machine learning!
The invisible neutrino is coming in here
Cosmic background
Cosmic background
Cosmic background
Two showers with visible offset from origin: might be $\pi^0 \rightarrow \gamma + \gamma$
75 cm
Run 3493 Event 41075, October 23rd, 2015
Drift electron arrival time
Wire number
Color: number of deposited drift electrons

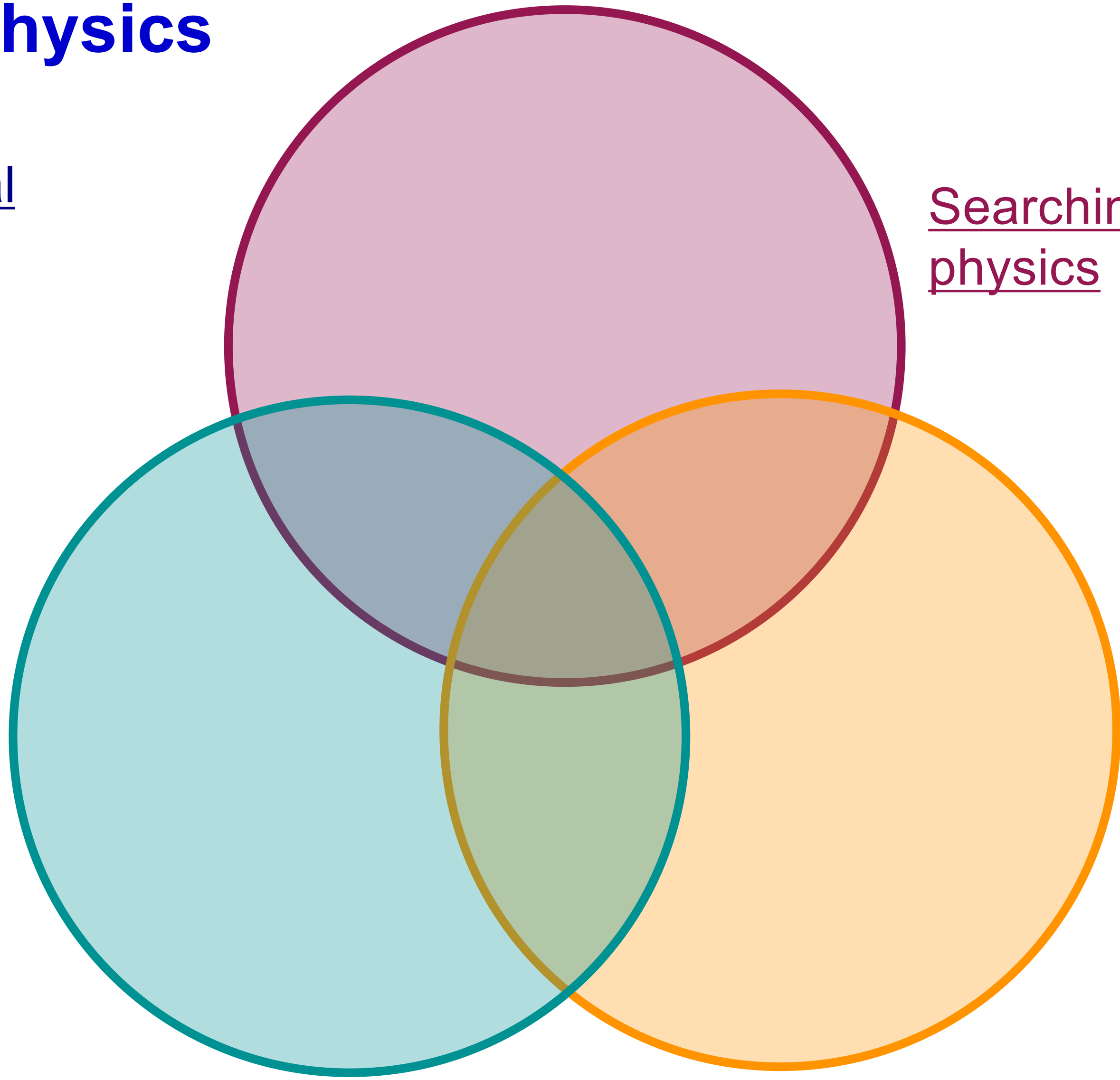


Need state-of-the-art algorithms (e.g., CNNs etc) to reconstruct these events

MicroBooNE Physics

More than 83 journal publications

Searching for new physics

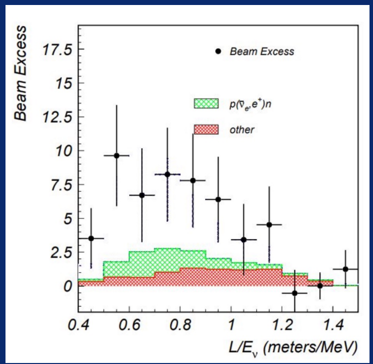


Understanding v-Ar interactions

Understanding LArTPCs and developing techniques

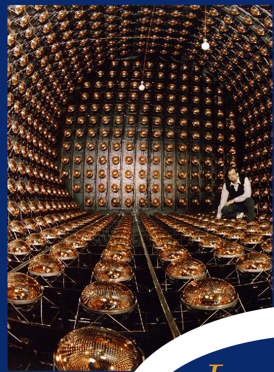
Searching for new physis: the anomalies

LSND

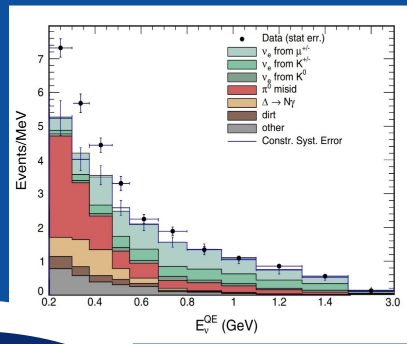


3.8σ $\bar{\nu}_e$–like excess in $\bar{\nu}_\mu$ source from μ decay at rest

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



MiniBooNE

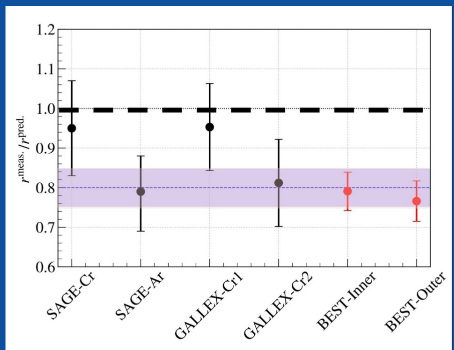


4.8σ excess of electromagnetic activity in a ν_μ beam

$\nu_\mu \to \nu_e$, $\nu_\mu \to \gamma$, $\nu_\mu \to e^+e^-$

$$\frac{L}{E} \sim \mathcal{O}(1\,\mathrm{eV}^2)$$

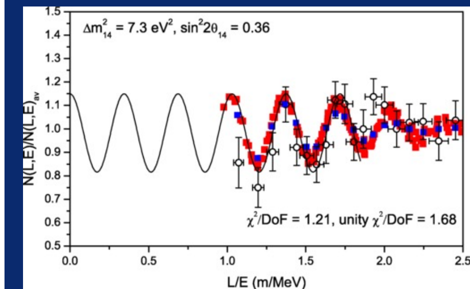
Gallium



4.0σ deficit of ν_e from radioactive sources across three experiments

$\nu_e \to \nu_e$

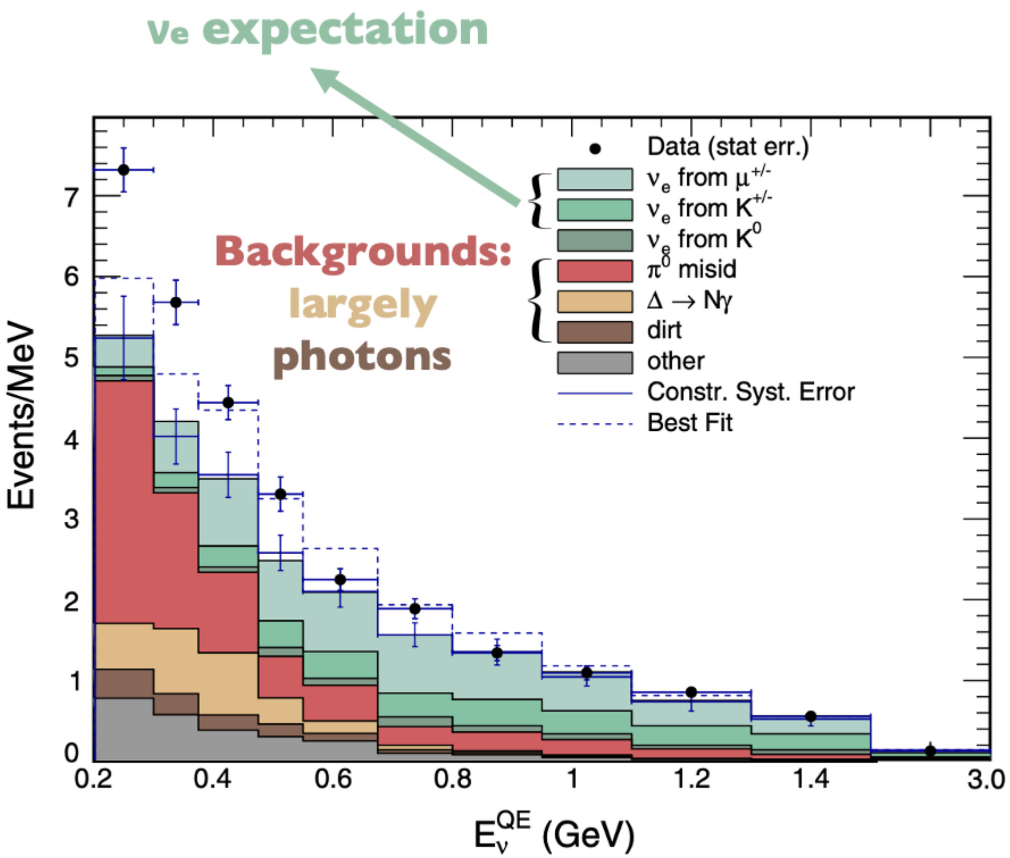
Reactor neutrinos



Neutrino–4 reports an oscillatory signal

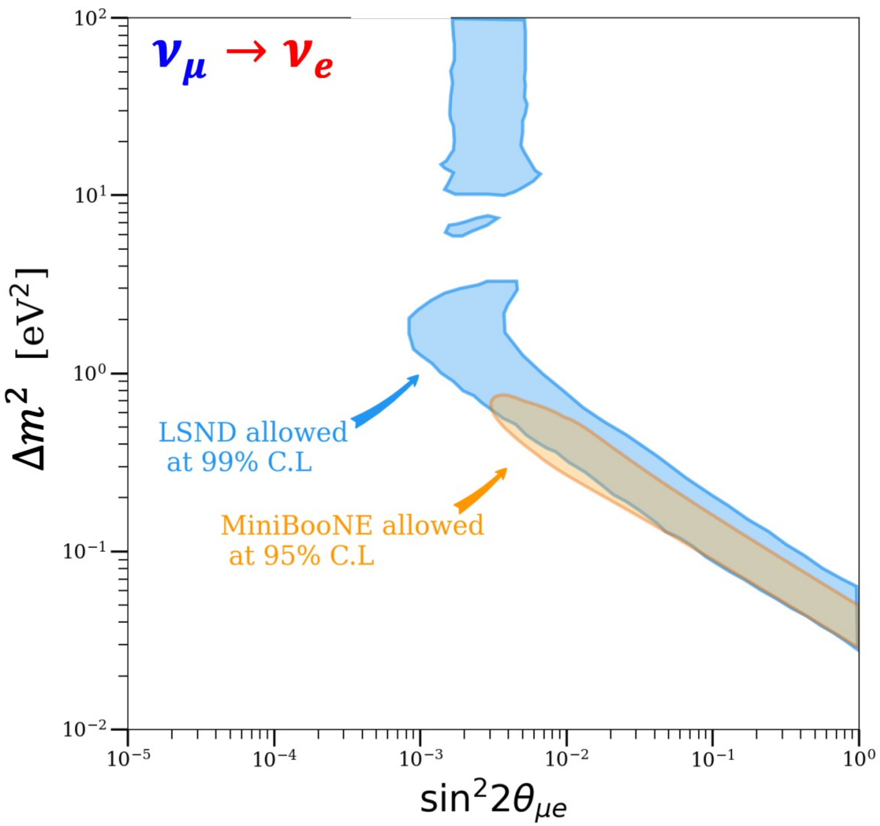
$\nu_e \to \nu_e$

The MiniBooNE Low Energy Excess



- 4.8σ excess of measured νe and $\bar{\nu}_e$ over prediction, focused at low energy
- Consistent with prior results from the LSND experiment: combined significance of 6.1σ
- Source of excess not known:
  - could be νe, or something else?
  - photons look identical to electrons in MiniBooNE detector

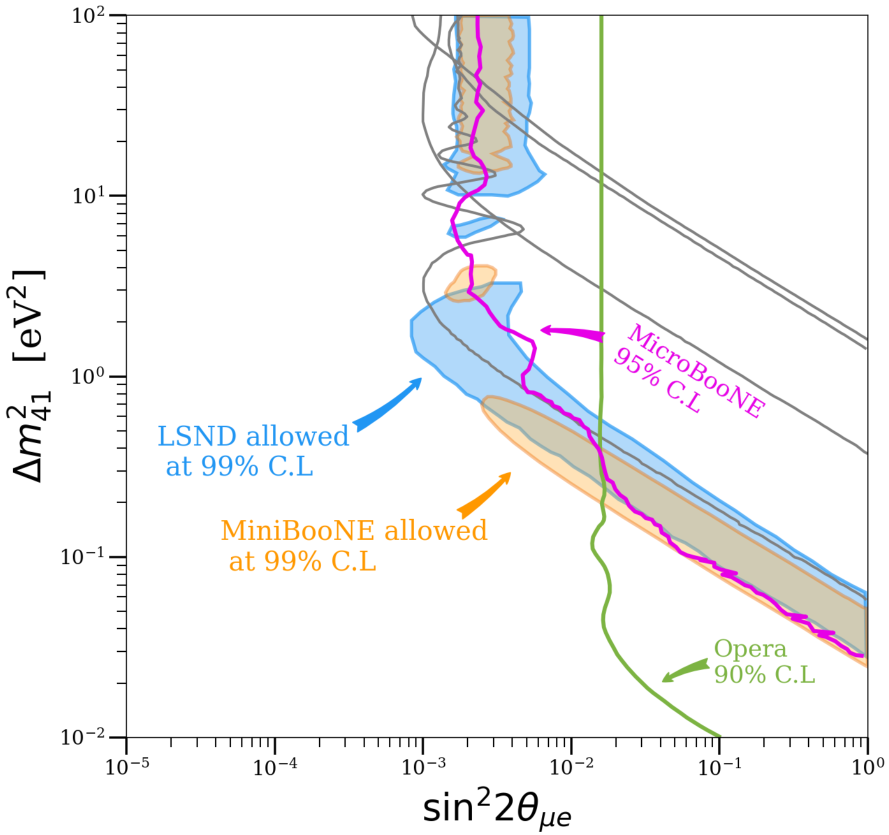
The MiniBooNE Low Energy Excess



- If interpreted as ν_e appearance through a two-flavour neutrino oscillation, best fit $\Delta m^2 = 0.04$ eV^2
- Not consistent with any known neutrino flavour → new "sterile" neutrino?

Phys. Rev. D 103, 052002

Electron Neutrino Appearance



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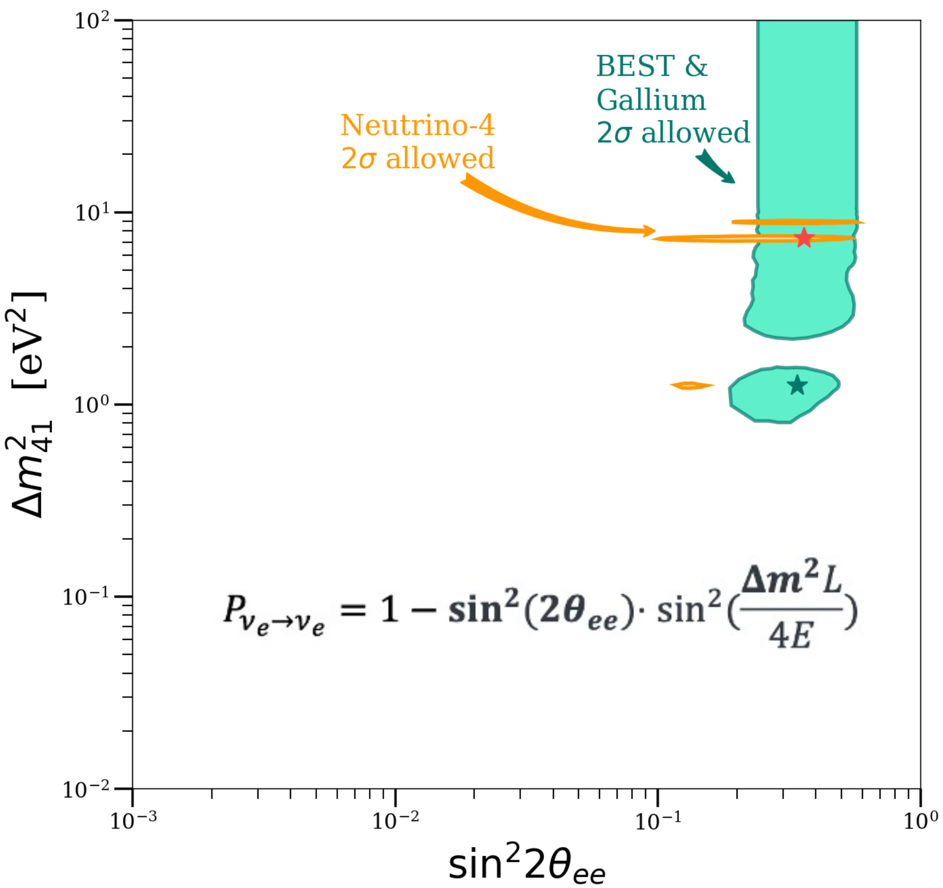
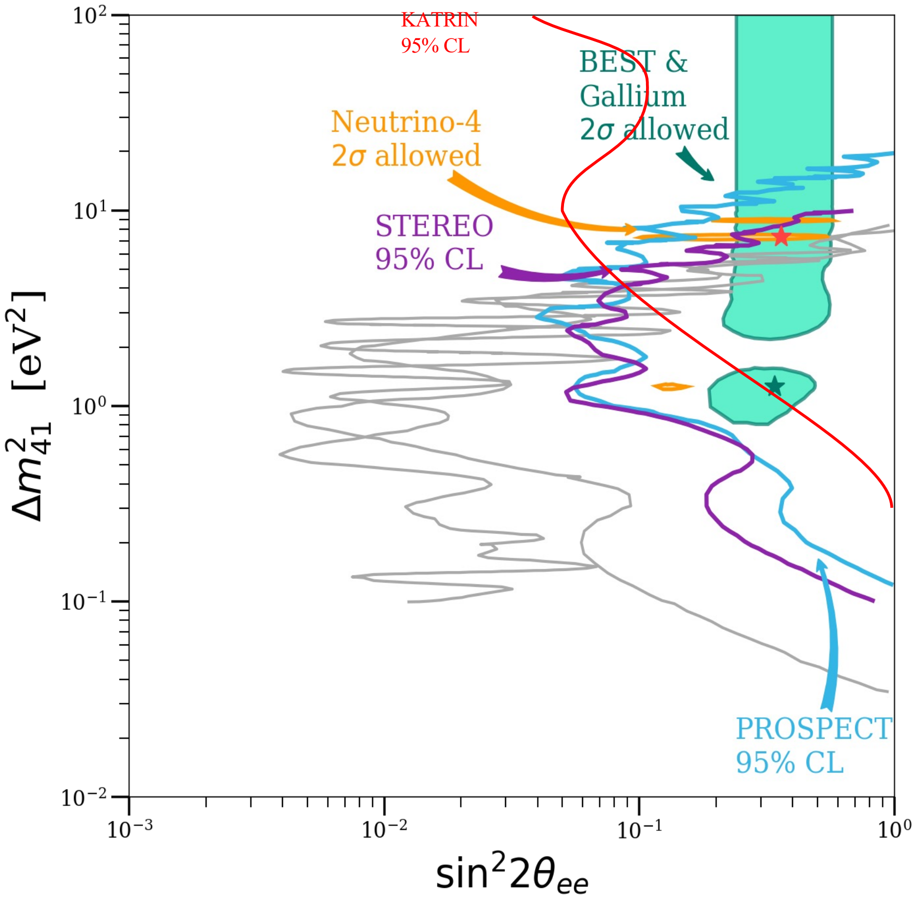
Electron Neutrino Disappearance - Sterile Neutrinos?



- Other anomalous results from gallium experiments and Neutrino-4 could be explained by ν_e appearance at Δm^2~1-10 eV.
- Also not consistent with any known neutrino flavour but some overlap with mass indicated by MiniBooNE/LSND experiments
- Need a full test of sterile neutrino hypothesis → MicroBooNE!

Electron Neutrino Disappearance - Sterile Neutrinos?



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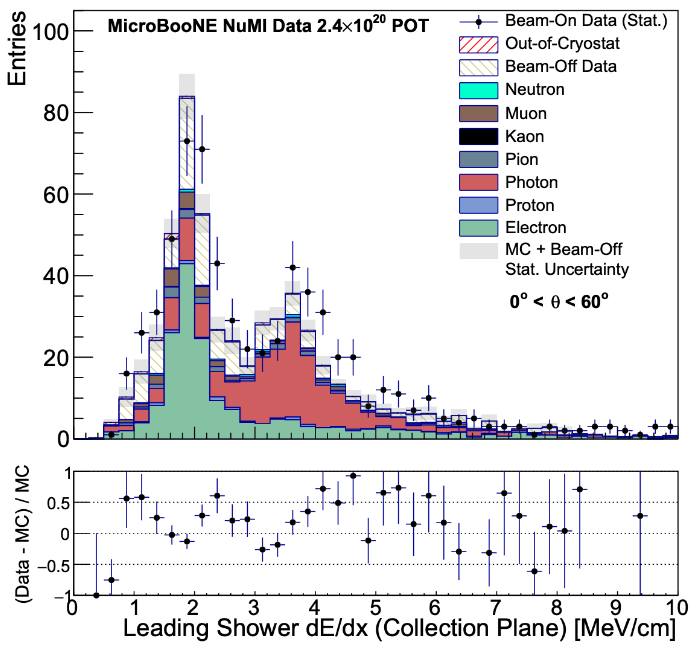
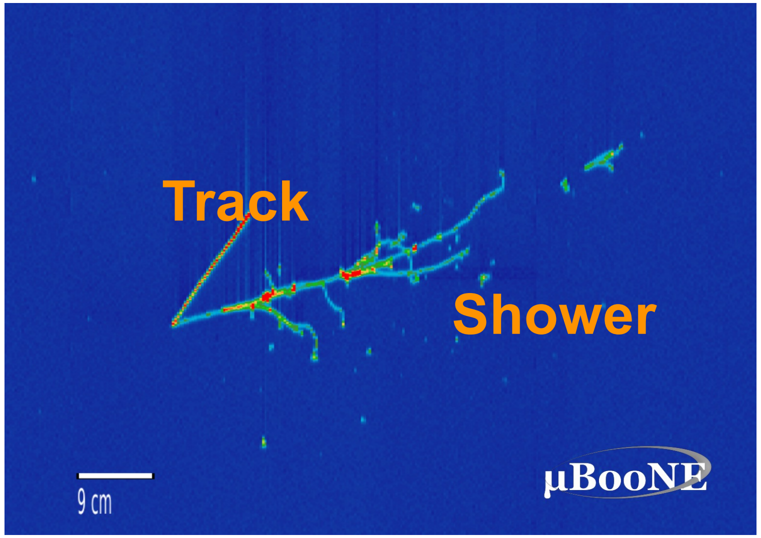
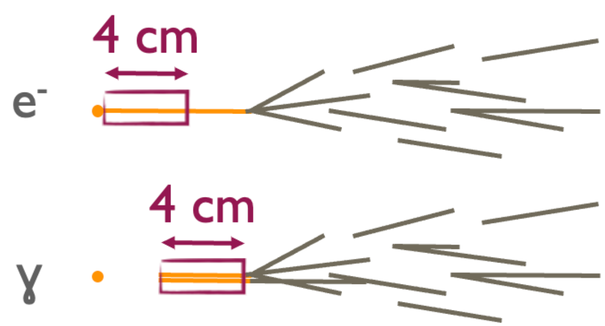
Electron/Photon discrimination

- MiniBooNE background largely photons.
- Electron/photon discrimination using dE/dx at start of shower and start point strong point of LArTPCs.



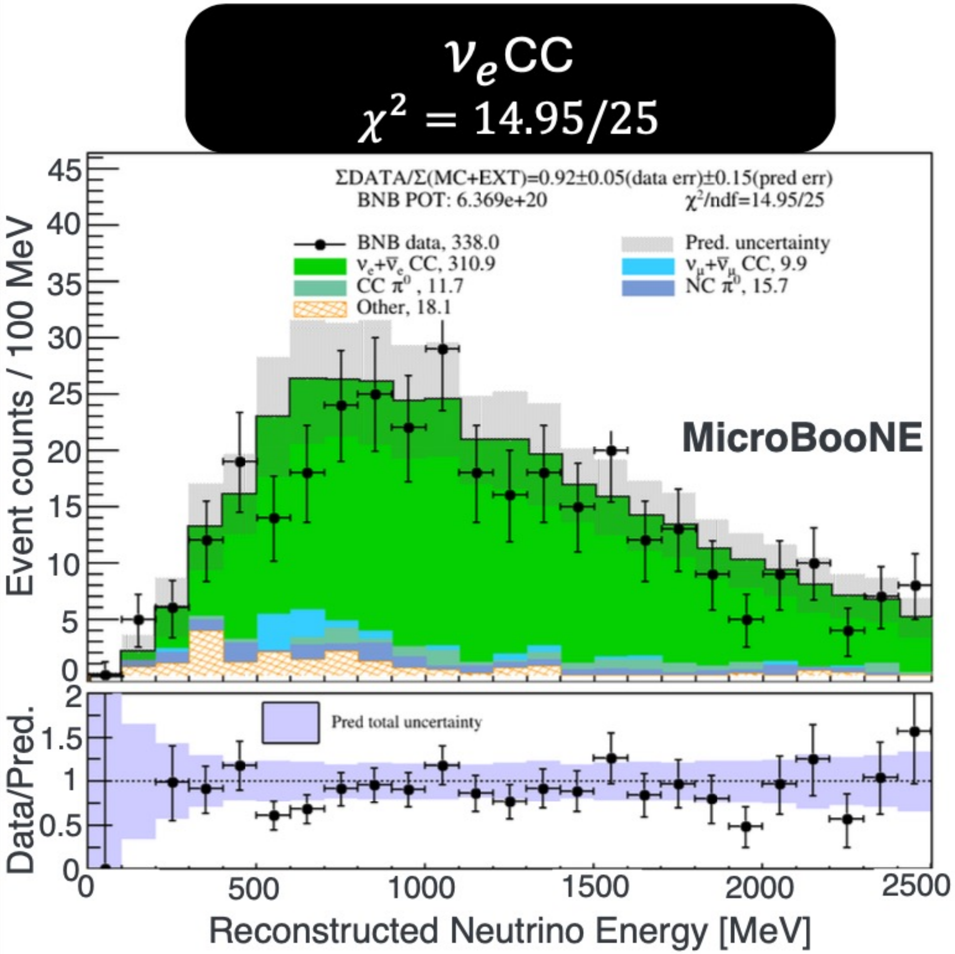


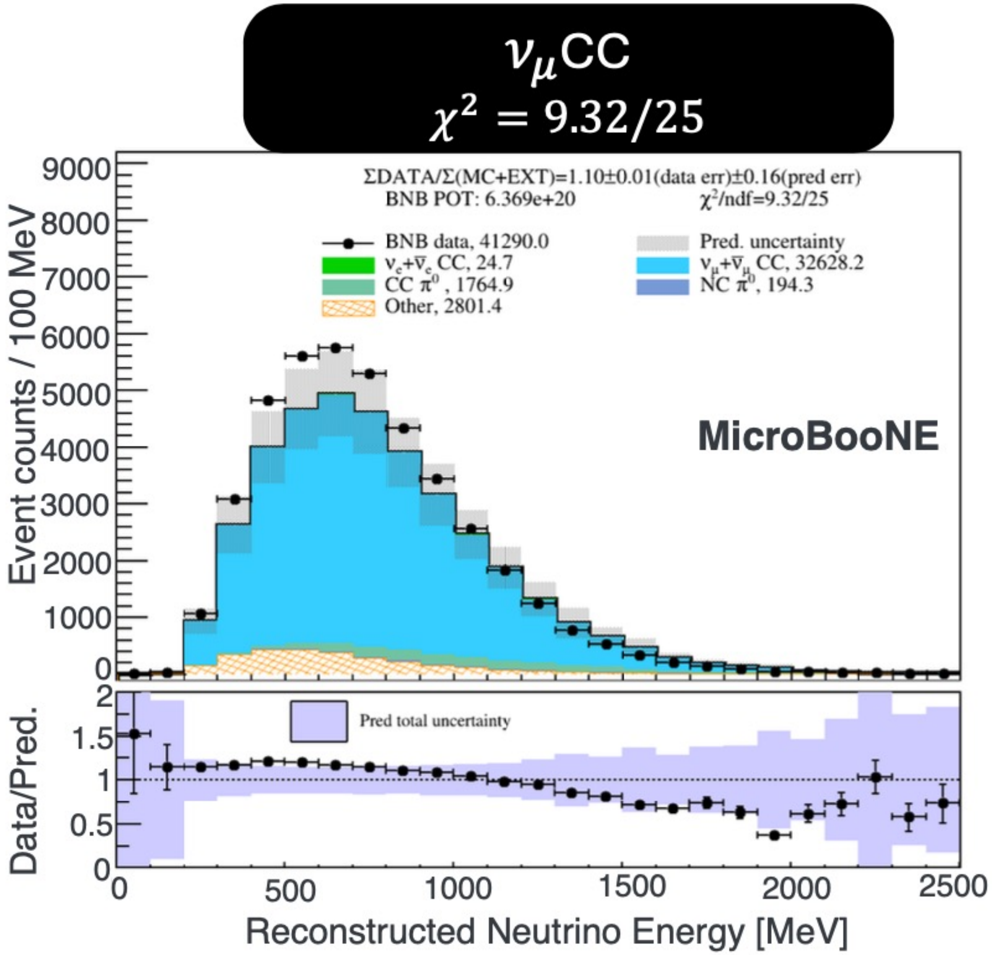


Phys. Rev. D 104, 052002 (2021)

Very pure data selection (BNB)

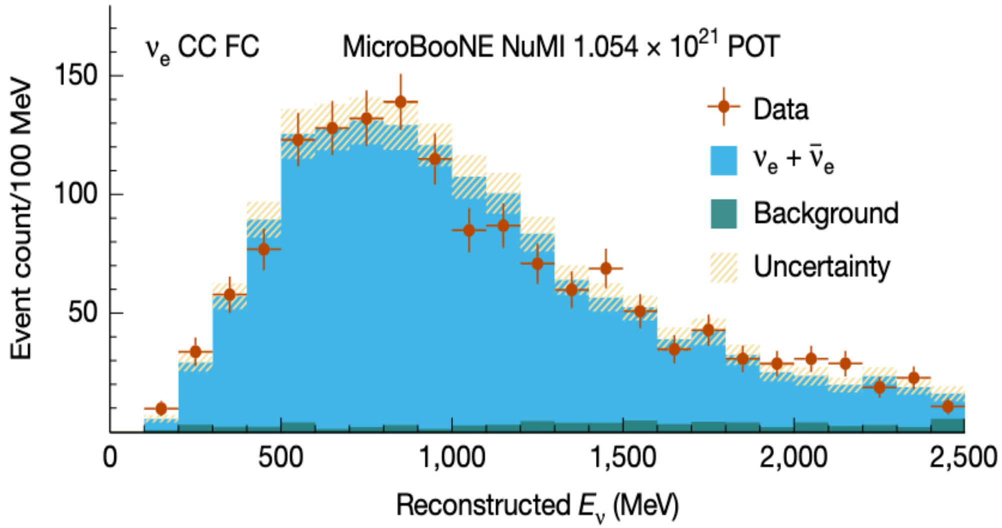
Nature 648, 64-69 (2025)



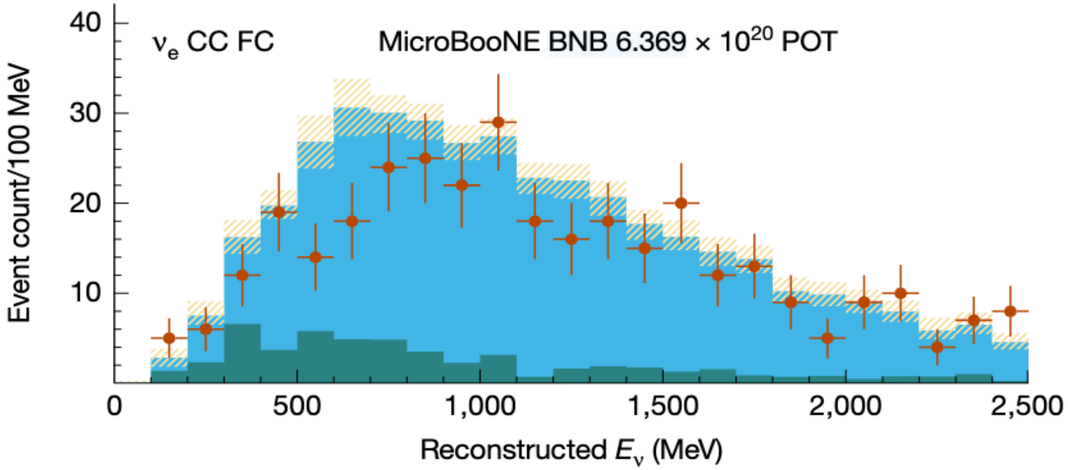


3+1 Sterile Neutrino Search (ν_e appearance)

- After constraining the uncertainties using the muon neutrinos, we can look for an excess in the electron neutrinos, We look for an excess in the ν_e spectrum.
- No excess observed over the expected background, both in BNB and NuMI.

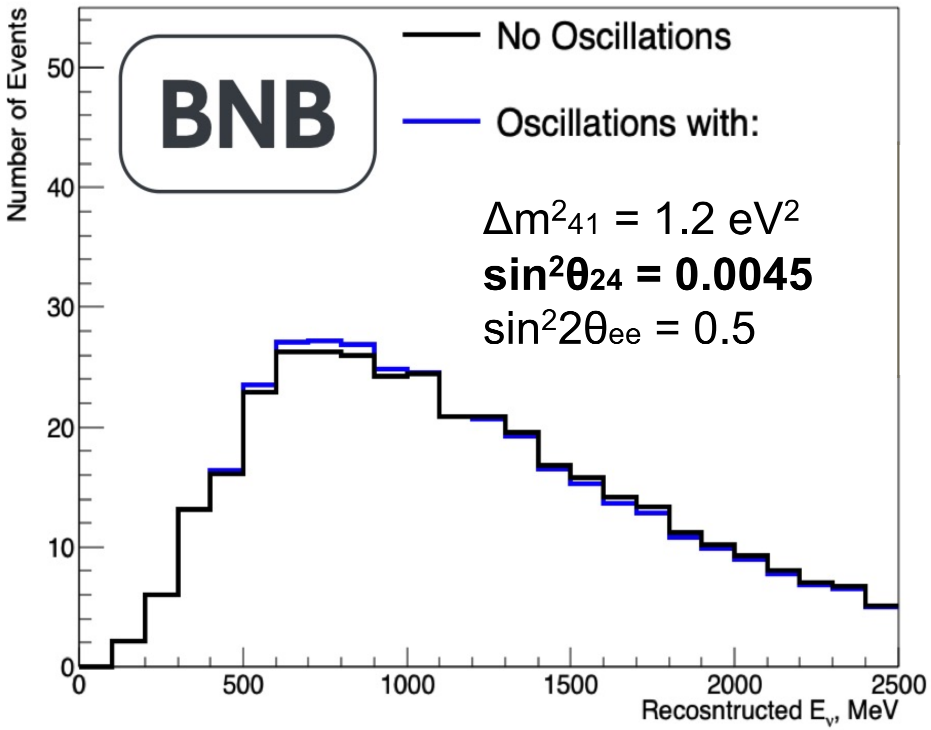


NuMI CC ν_e



BNB CC ν_e

Oscillation Parameter Degeneracy



ν_e disappearance $\quad$ ν_e appearance

$$N_{\nu_e} = N_{\text{intrinsic }\nu_e} P_{\nu_e \to \nu_e} + N_{\text{intrinsic }\nu_\mu} P_{\nu_\mu \to \nu_e}$$

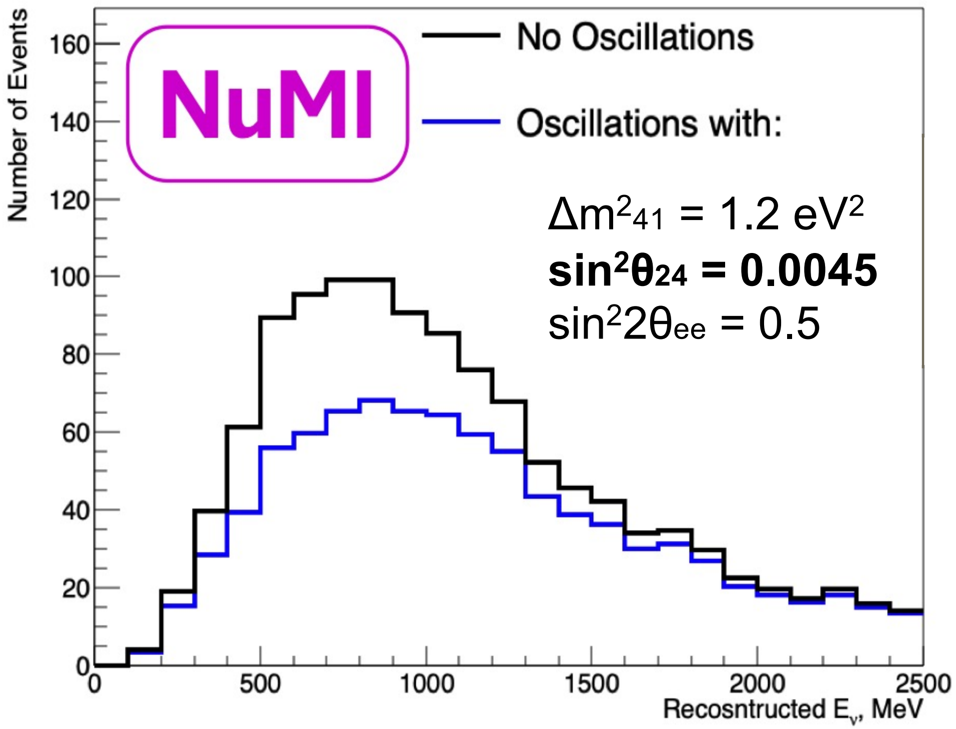
$$= N_{\text{intrinsic }\nu_e}[1 + (R_{\nu_\mu/\nu_e} \sin^2\theta_{24} - 1)\sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}]$$

Cancellation if $\sin^2\theta_{24} = R_{\nu e/\nu\mu}$

$R_{\nu e/\nu\mu} \cong 0.005$ in BNB
$R_{\nu e/\nu\mu} \cong 0.04$ in NuMI

where $R_{\nu e/\nu\mu}$ is the ratio of ν_e to ν_μ in each beam.

Oscillation Parameter Degeneracy



ν_e disappearance ν_e appearance

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} P_{\nu_\mu \to \nu_e}$$

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Cancellation if $\sin^2\theta_{24} = R_{\nu e/\nu\mu}$

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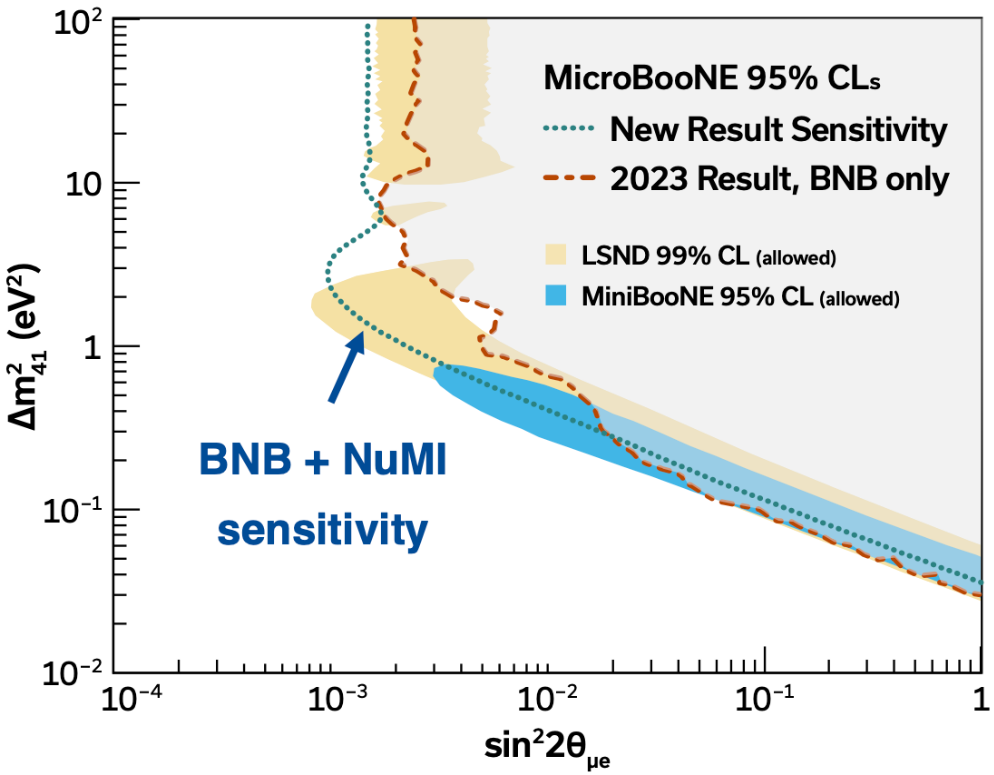
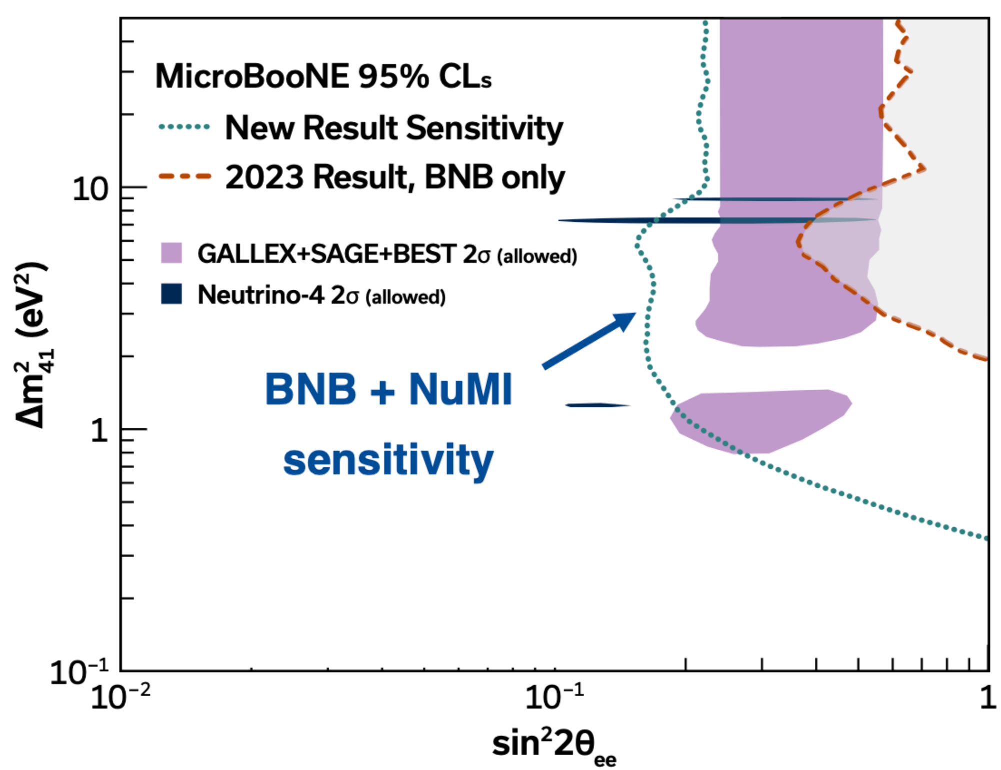
Two-beam sensitivity (BNB+NUMI)





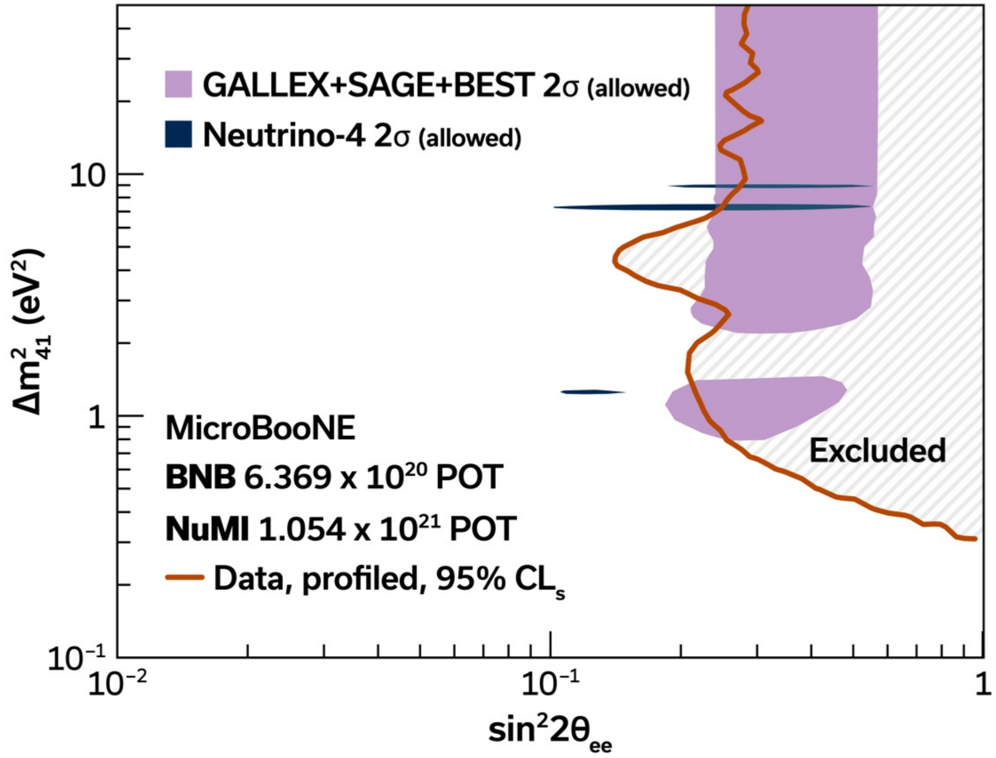
- New result (Nature 648 (2025)) uses three years of BNB and NuMI data
- Combining the two datasets unlocks their full power to test the 3+1 model

Two-beam results (ν_e disappearance)

No significant evidence for ν_e appearance or disappearance in data → set exclusion limits

Disappearance limits
MicroBooNE data at 95% CL:

- Slightly weaker than sensitivity due to mild deficit in BNB ν_e (not seen in NuMI), see previous slide
- Excludes most of the Gallium allowed region
- Excludes part of the Neutrino-4 allowed region

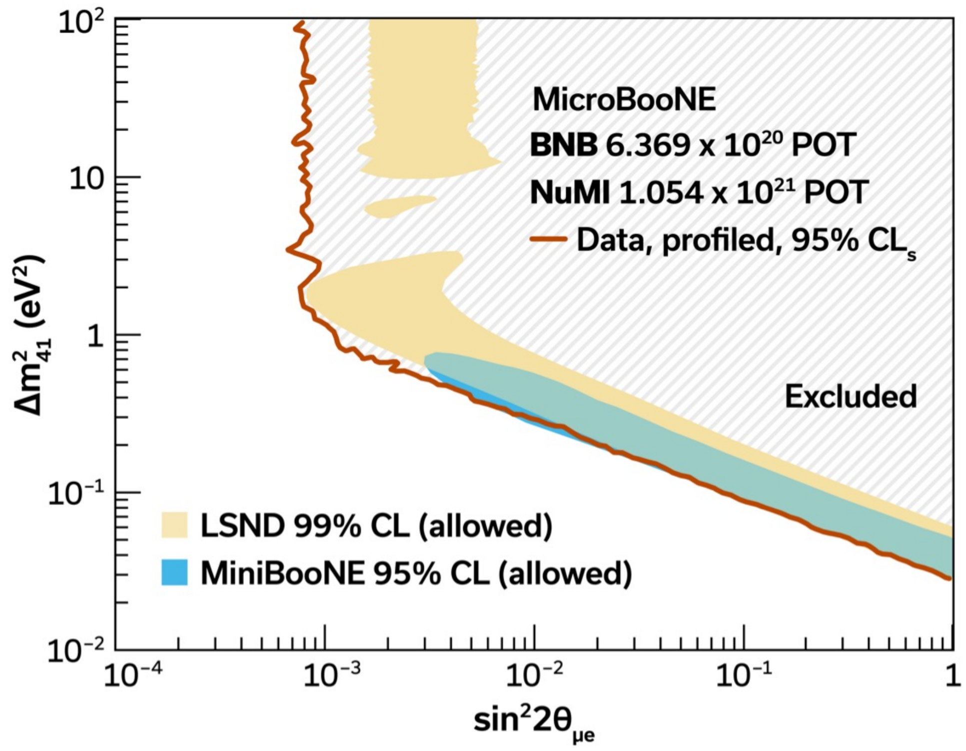


Two-beam results (ν_e appearance)

No significant evidence for ν_e appearance or disappearance in data → set exclusion limits

Appearance limits
MicroBooNE data at 95% CL:

- Slightly stronger than sensitivity due to mild deficit in BNB ν_e (not seen in NuMI)
- Excludes LSND 99% allowed region
- Excludes vast majority of MiniBooNE 95% allowed region

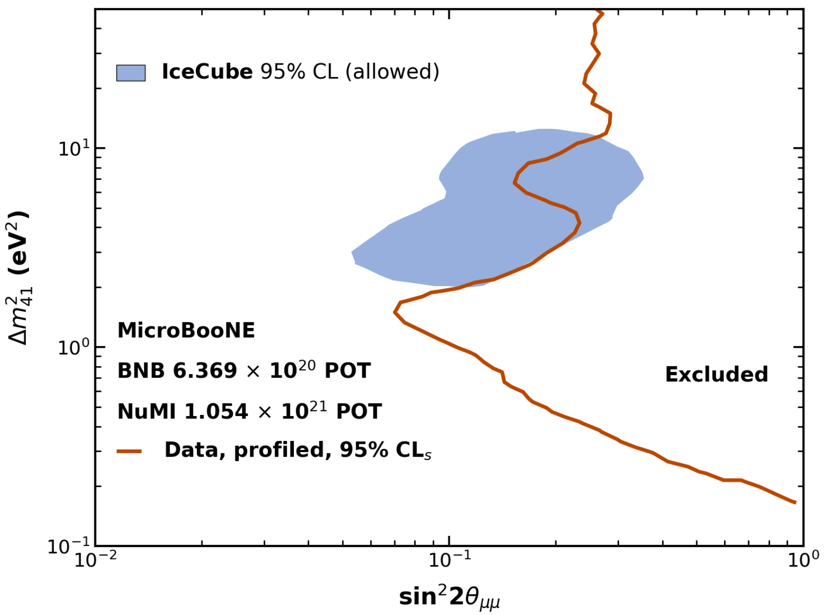


(can be translated into Neff, see Eur. Phys. J. C (2020) 80:758)

Two-beam results (ν_μ disappearance) – new at Neutrino 2026!

- Data exclusion is weaker than median sensitivity in high Δm^2 region, and slightly stronger in low Δm^2 region.

- MicroBooNE excludes part of the IceCube allowed region at 95% CL – similar sensitivity.



Implications of this result

- The simple 3+1 sterile neutrino model strongly disfavoured.
- However, MiniBooNE excess is still there at 4.8 sigma, still a lot of interest in these anomalies
- A big focus now on MicroBooNE: investigating non-oscillation explanations (e.g,. excess photon production).

nature

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Article | Open access | Published: 03 December 2025

Search for light sterile neutrinos with two neutrino beams at MicroBooNE

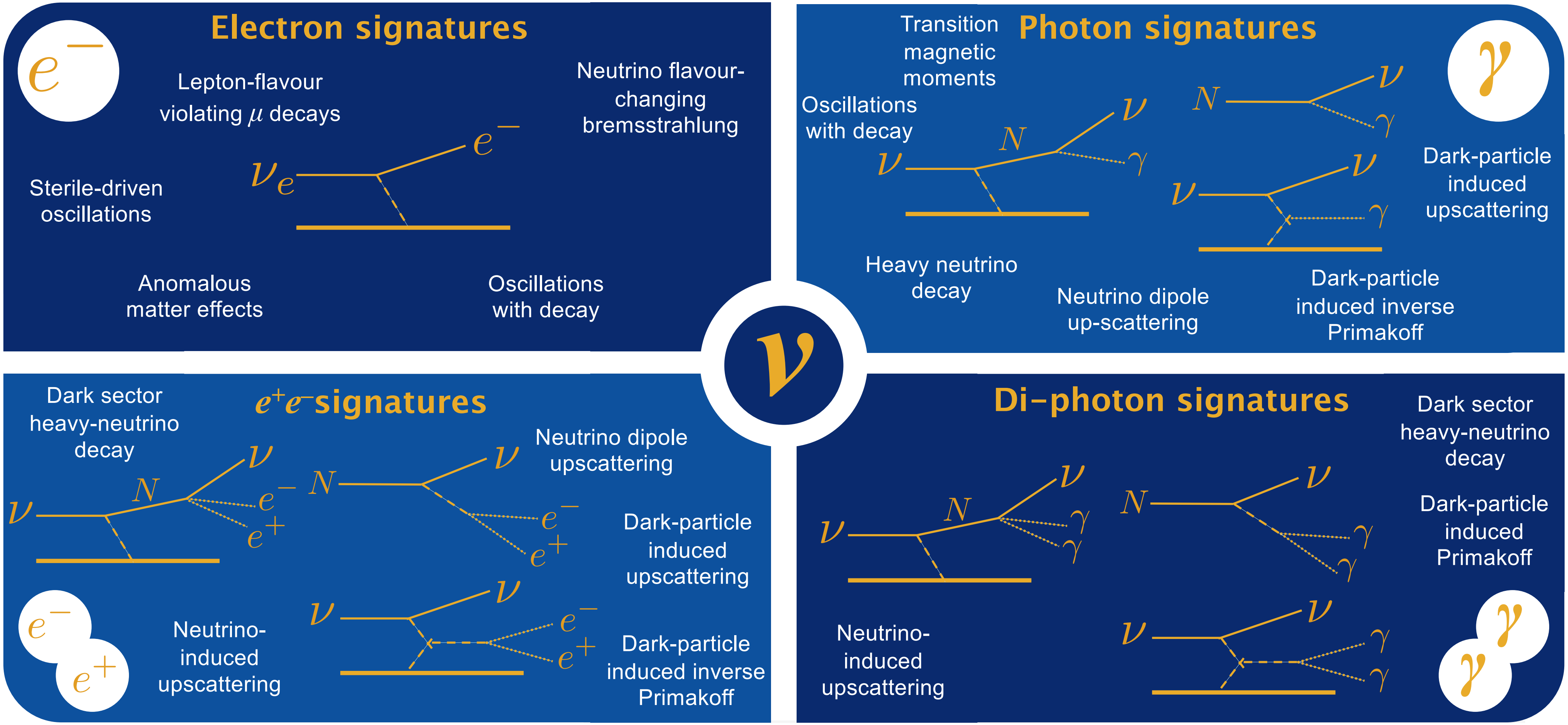
The MicroBooNE Collaboration

Nature **648**, 64–69 (2025) | Cite this article

Abstract

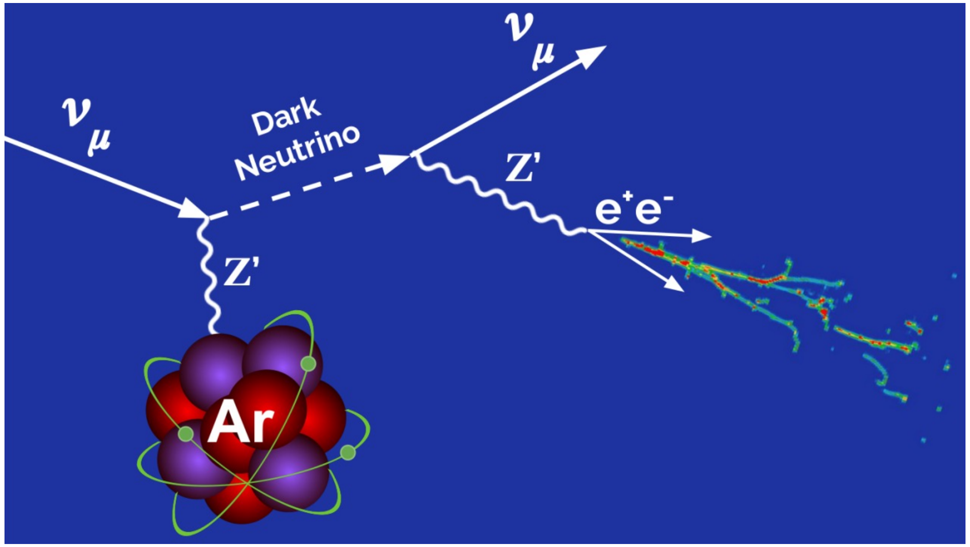
The existence of three distinct neutrino flavours, ν_e, ν_μ and ν_τ, is a central tenet of the Standard Model of particle physics[1,2]. Quantum-mechanical interference can allow a neutrino of one initial flavour to be detected sometime later as a different flavour, a process called neutrino oscillation. Several anomalous observations inconsistent with this three-flavour picture have motivated the hypothesis that an additional neutrino state exists, which does not interact directly with matter, termed as 'sterile' neutrino, ν_s (refs. [3,4,5,6,7,8,9]). This includes anomalous observations from the Liquid Scintillator Neutrino Detector (LSND)[3] experiment and Mini-Booster Neutrino Experiment (MiniBooNE)[4,5], consistent with $\nu_\mu \rightarrow \nu_e$ transitions at a distance inconsistent with the three-neutrino picture. Here we use data obtained from the MicroBooNE liquid-argon time projection chamber[10] in two accelerator neutrino beams to exclude the single light sterile neutrino interpretation of the LSND and MiniBooNE anomalies at the 95% confidence level (CL). Moreover, we rule out a notable portion of the parameter space that could explain the gallium anomaly[6,7,8]. This is one of the first measurements to use two accelerator neutrino beams to break a degeneracy between ν_e appearance and disappearance, which would otherwise weaken the sensitivity to the sterile neutrino hypothesis. We find no evidence for either $\nu_\mu \rightarrow \nu_e$ flavour transitions or ν_e disappearance that would indicate non-standard flavour oscillations. Our results indicate that previous anomalous observations consistent with $\nu_\mu \rightarrow \nu_e$ transitions cannot be explained by introducing a single sterile neutrino state.

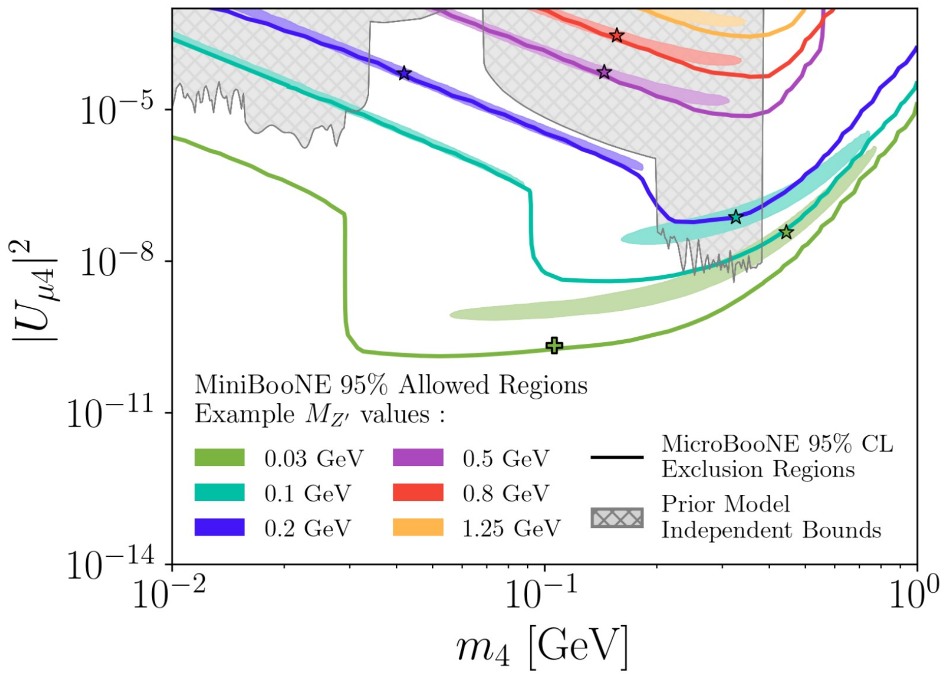
New physics landscape and characteristic signatures



Dark neutrinos and dark photons

A dark neutrino mediator produces a dark photon (Z') that decays into an electron-positron pair – looks like a single shower.

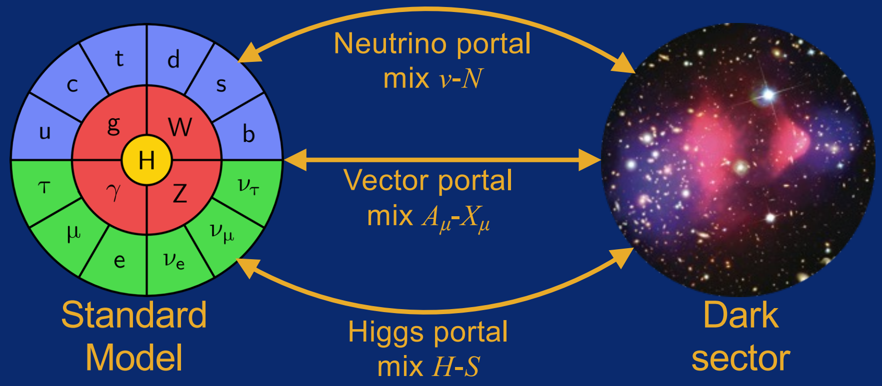




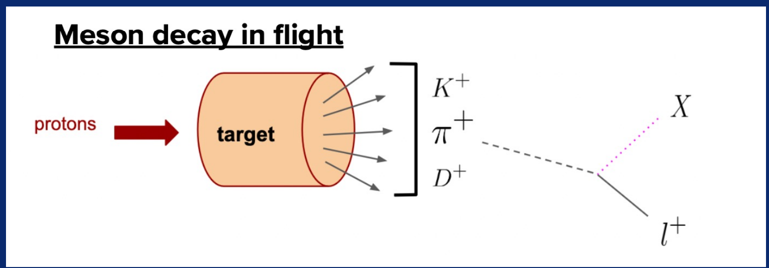
(a) Single dark neutrino scenario, $\varepsilon = 8 \times 10^{-4}$.

MiniBooNE LEE as this dark neutrino model excluded at ≥ 95% CLs for several Z' masses.

Portals to dark sectors

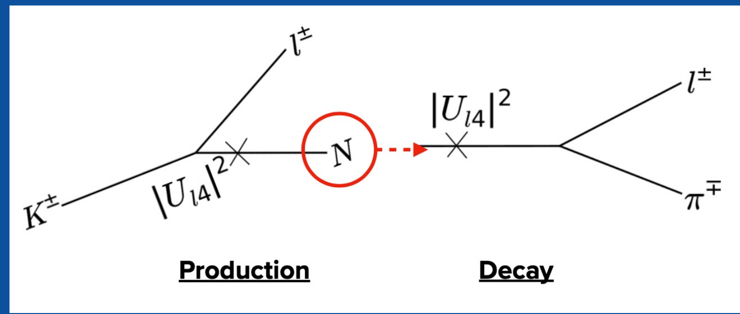


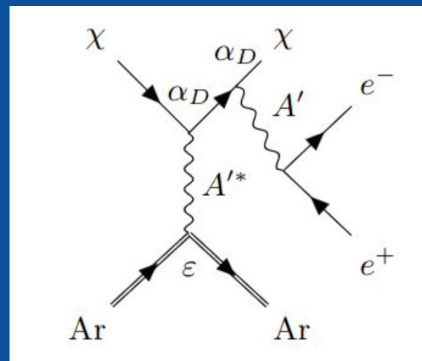
Large flux of charged & neutral mesons from high intensity proton beams



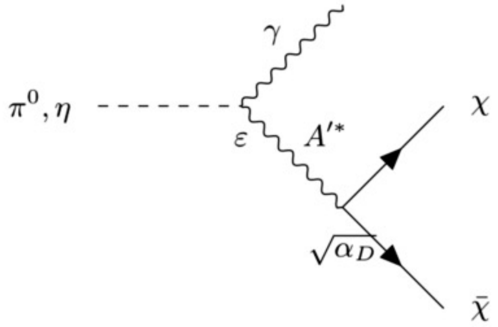
New particles produced from meson decays

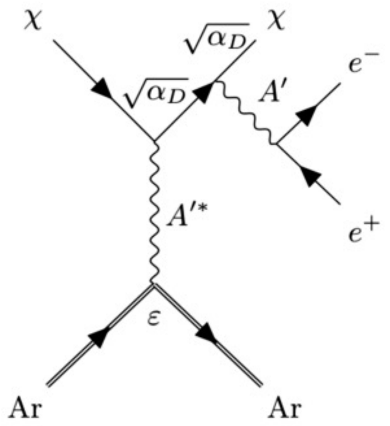
New particles interact or decay in detector



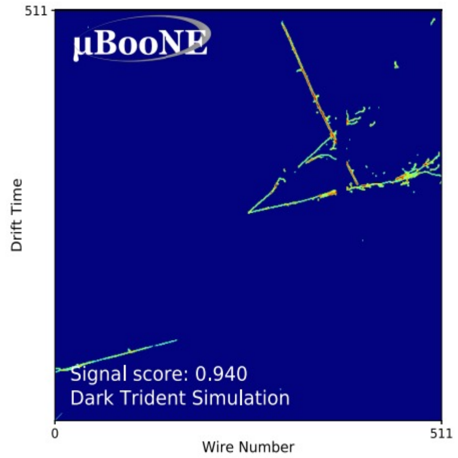


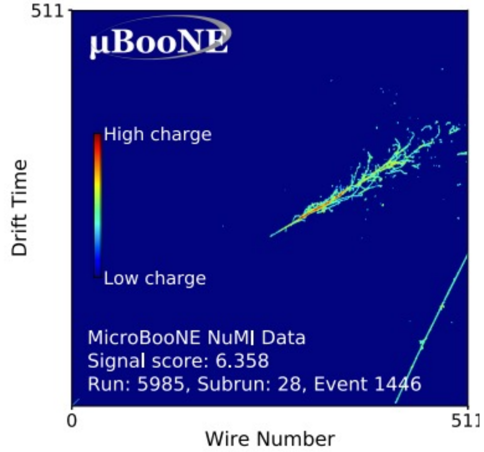
Dark Tridents



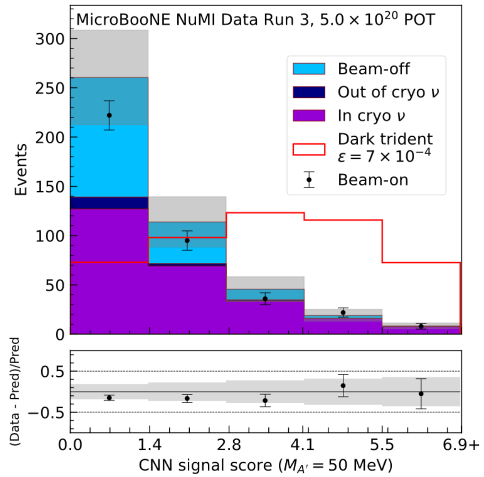


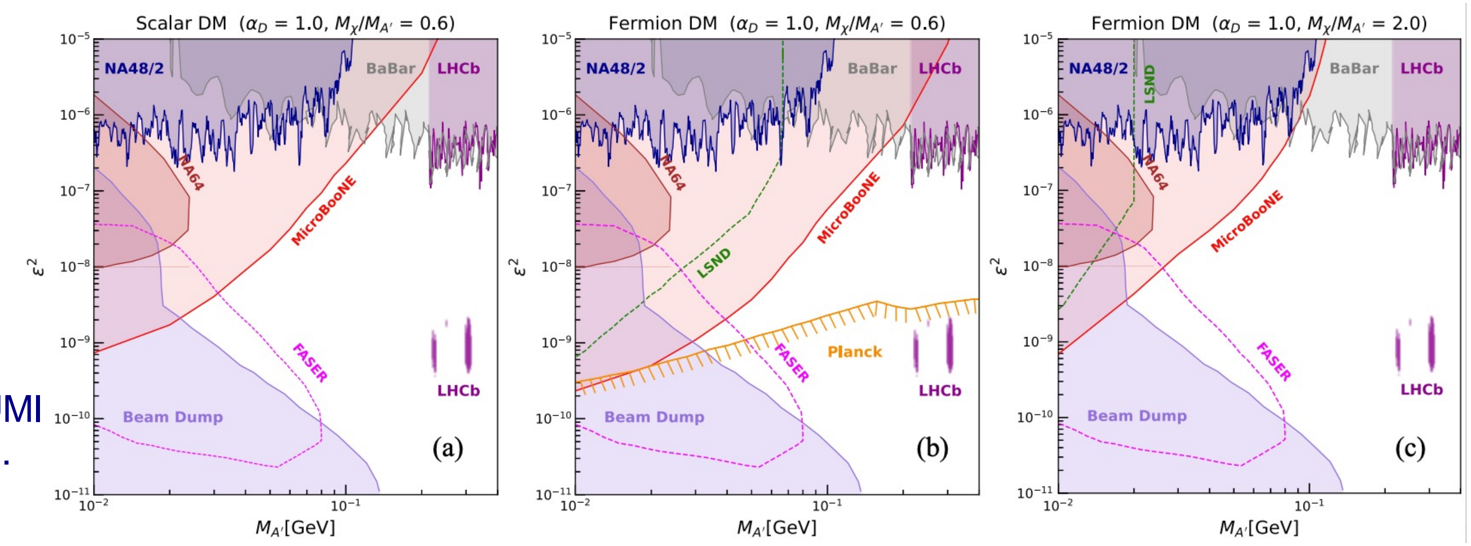
Dark matter particle produced in NUMI π0 beam interacts in MicroBooNE.





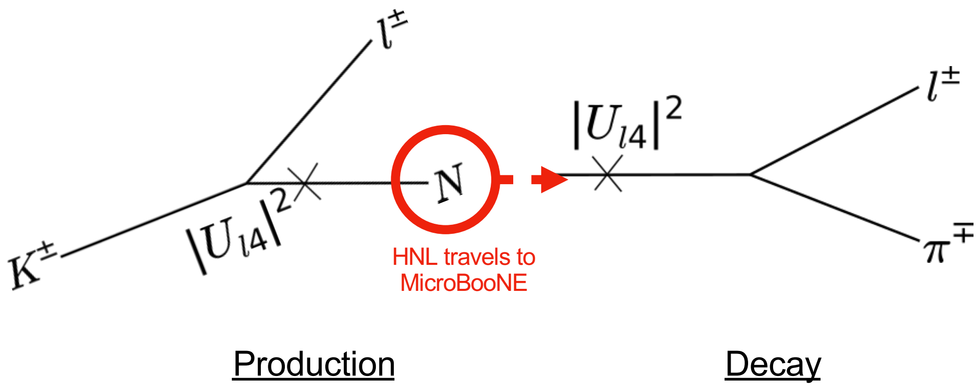
CNN Score

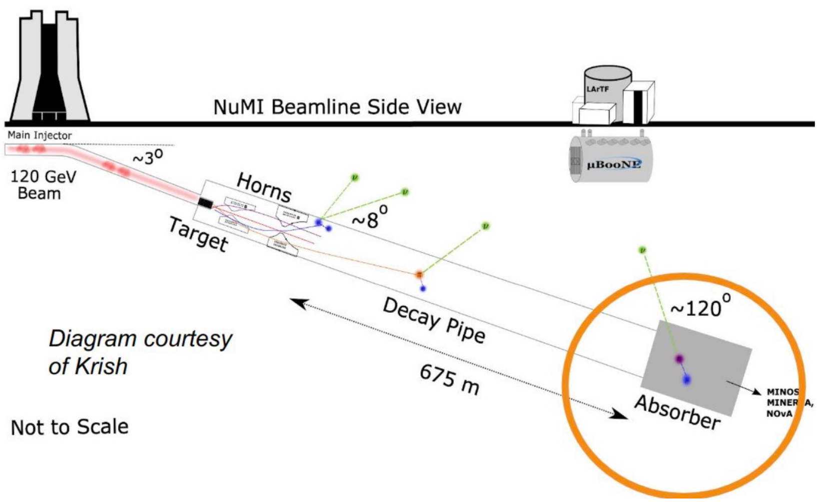


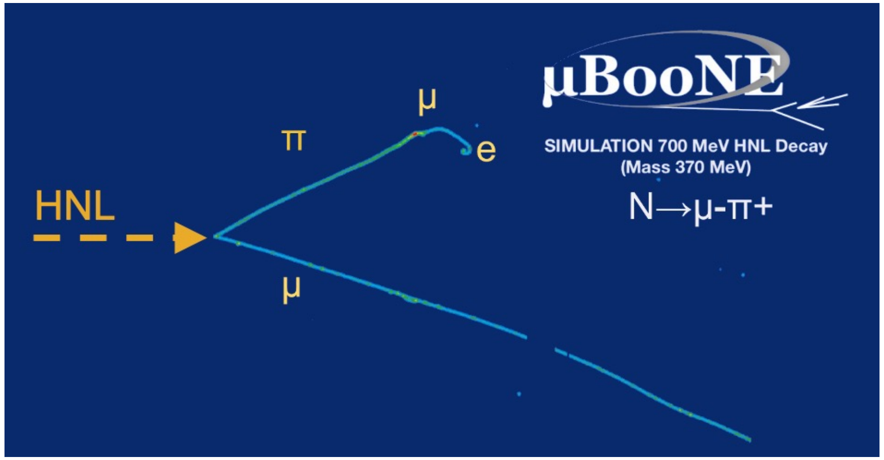


Heavy Neutral Leptons

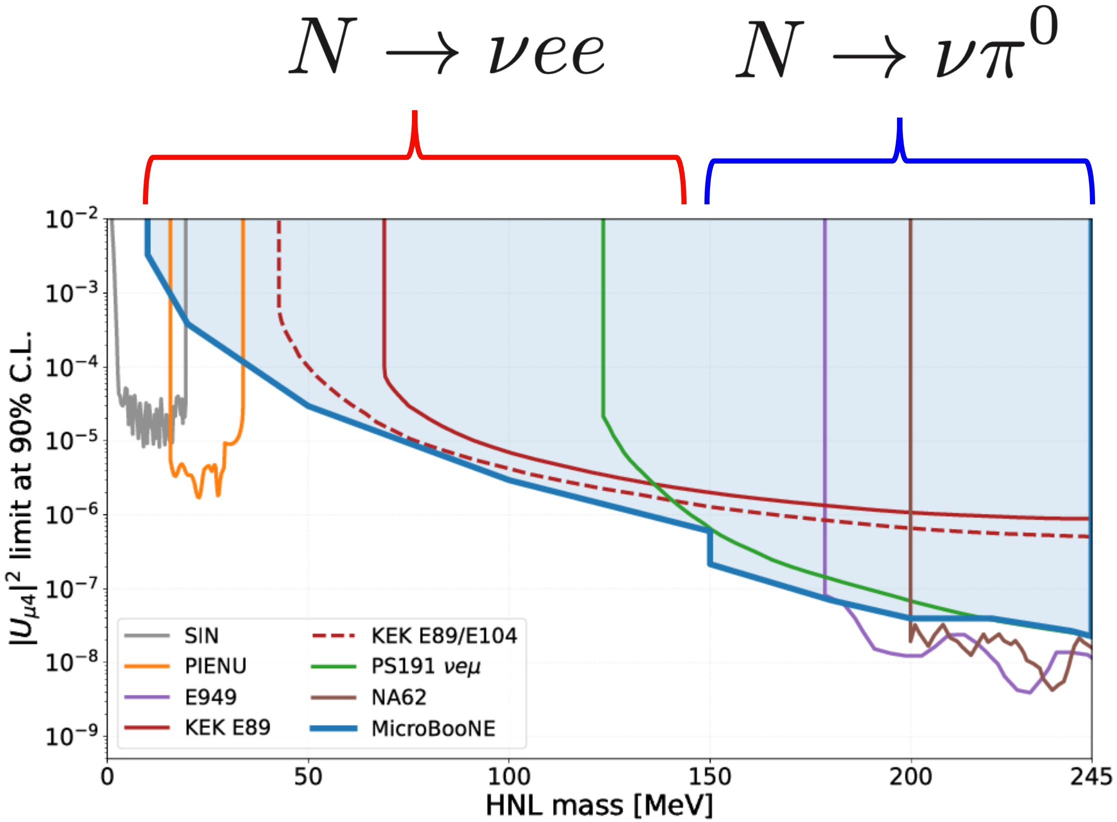
- One new right-handed singlet that mixes with active neutrinos via extended PMNS matrix
- HNLs can be produced in place of neutrinos when kinematically allowed:
  - Rate proportional to $|U_{l4}|^2$.
  - Assume only one non-zero $|U_{l4}|^2$.







Heavy Neutral Leptons



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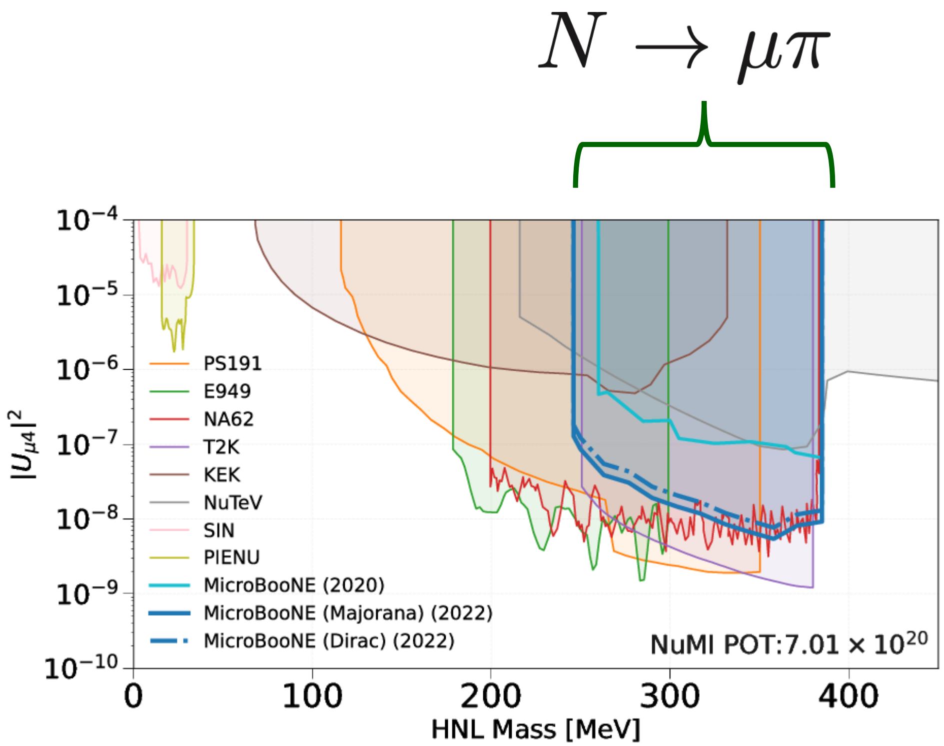

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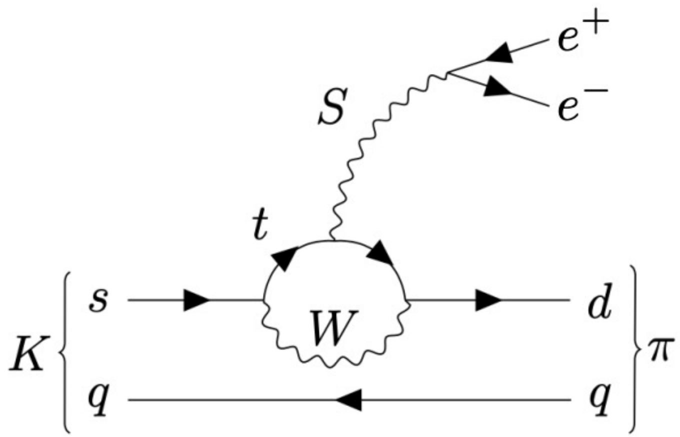
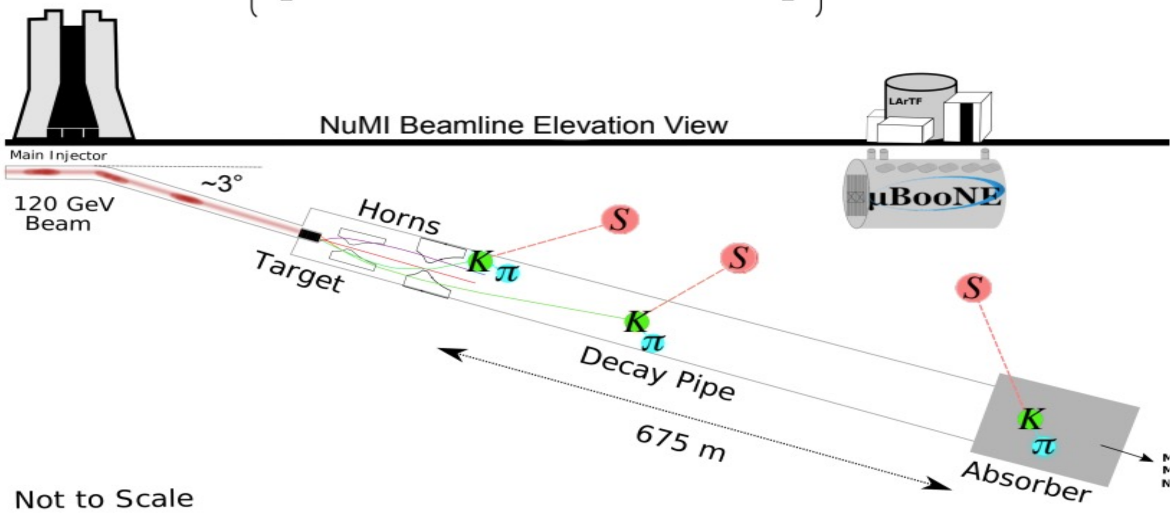
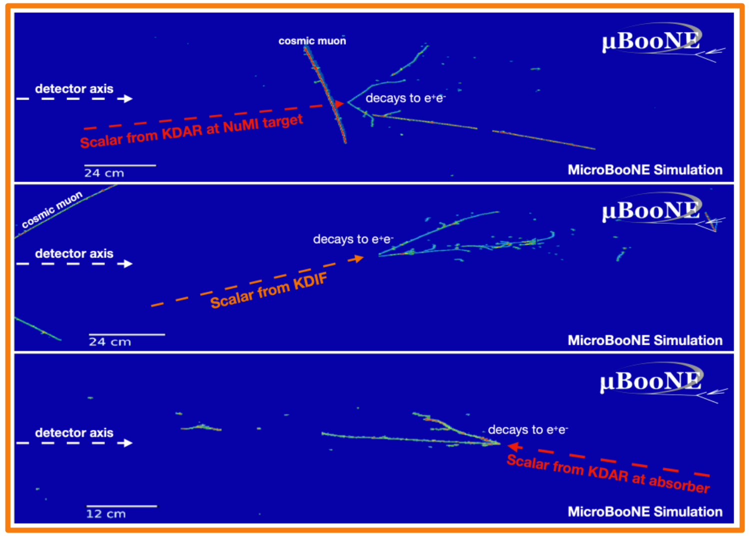
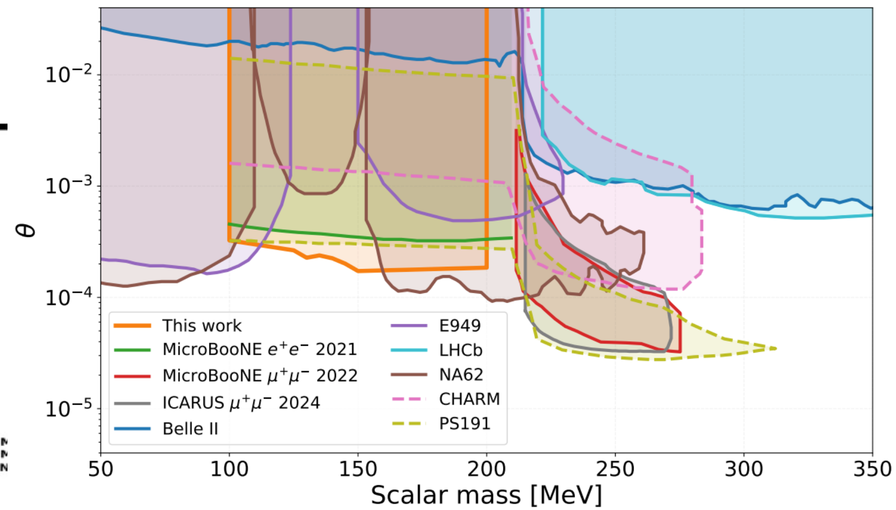
Higgs Portal Scalars



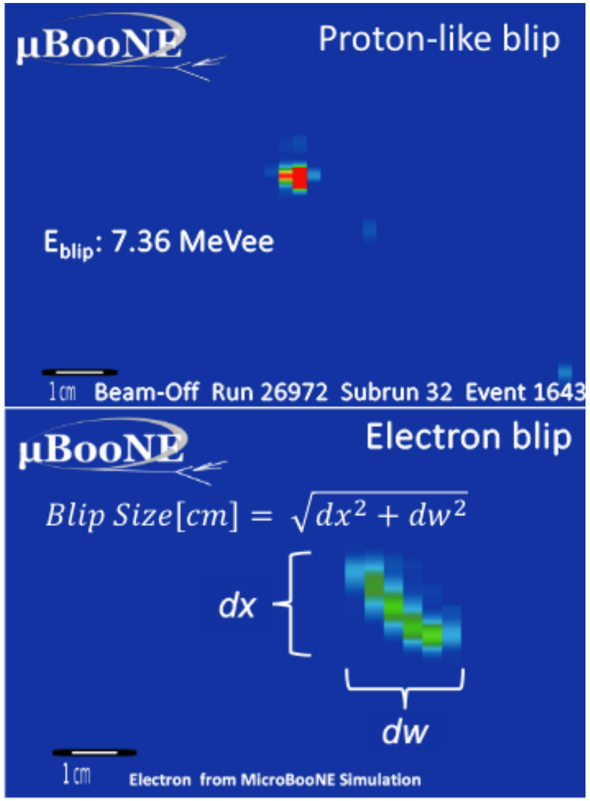


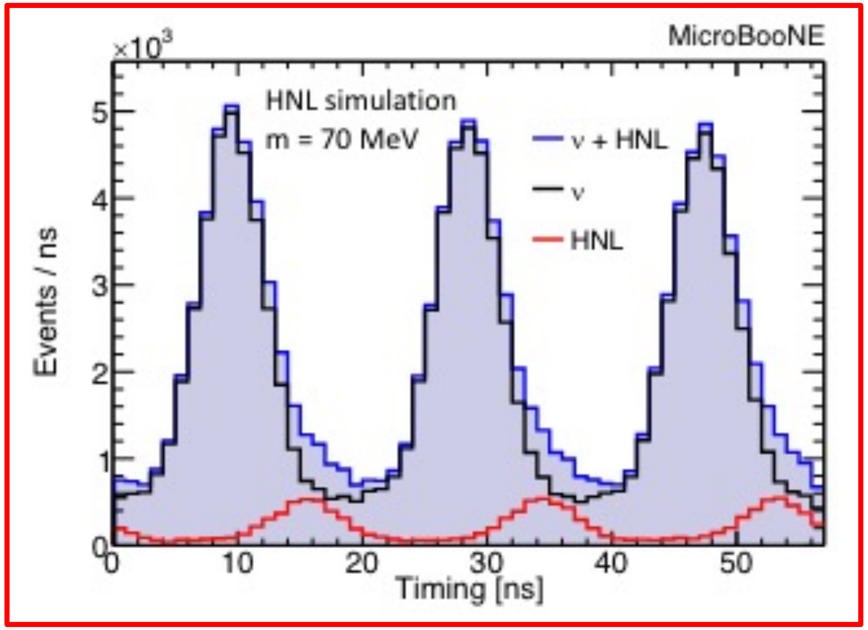




Ongoing Developments

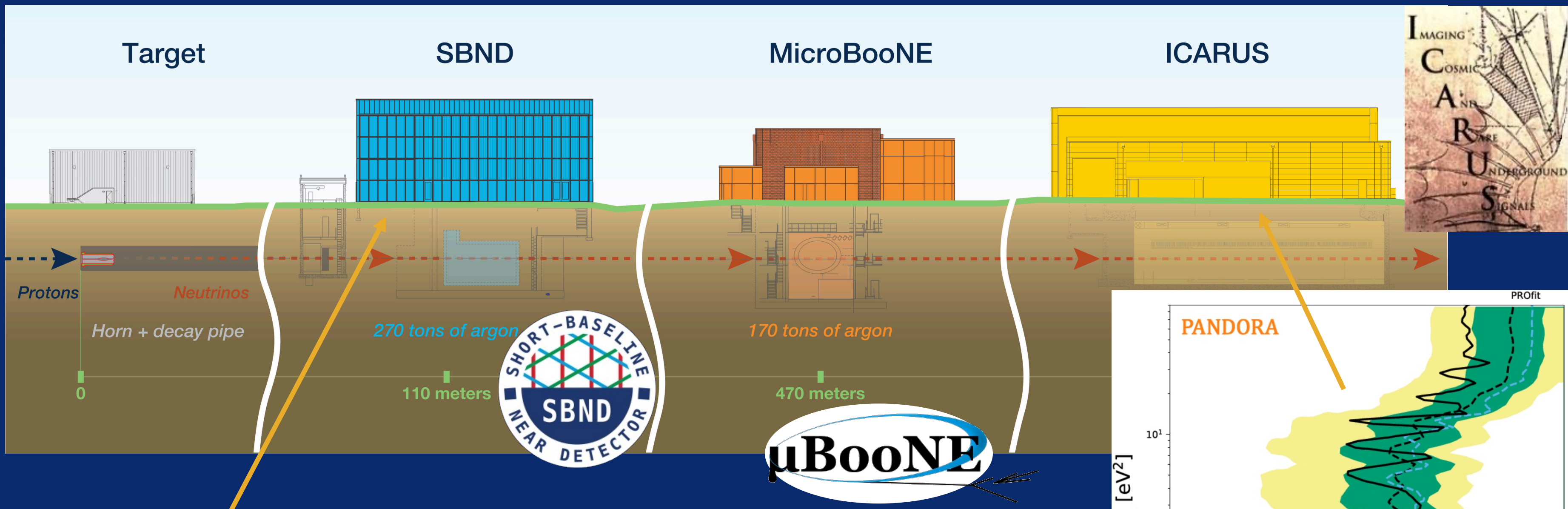
Reconstruction of MeV-scale blips can be used to search for low-energy signatures.





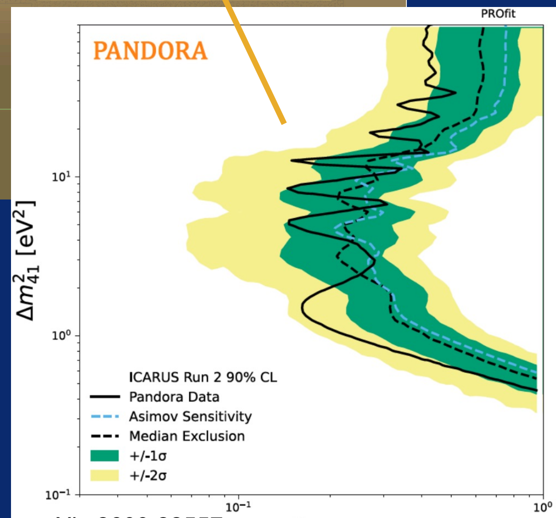
- Beam structure can be used to mitigate backgrounds from cosmics - reconstruction with ns precision.
- Example: HNL will travel slower and reach the detector later.

The Fermilab Short-Baseline Programme



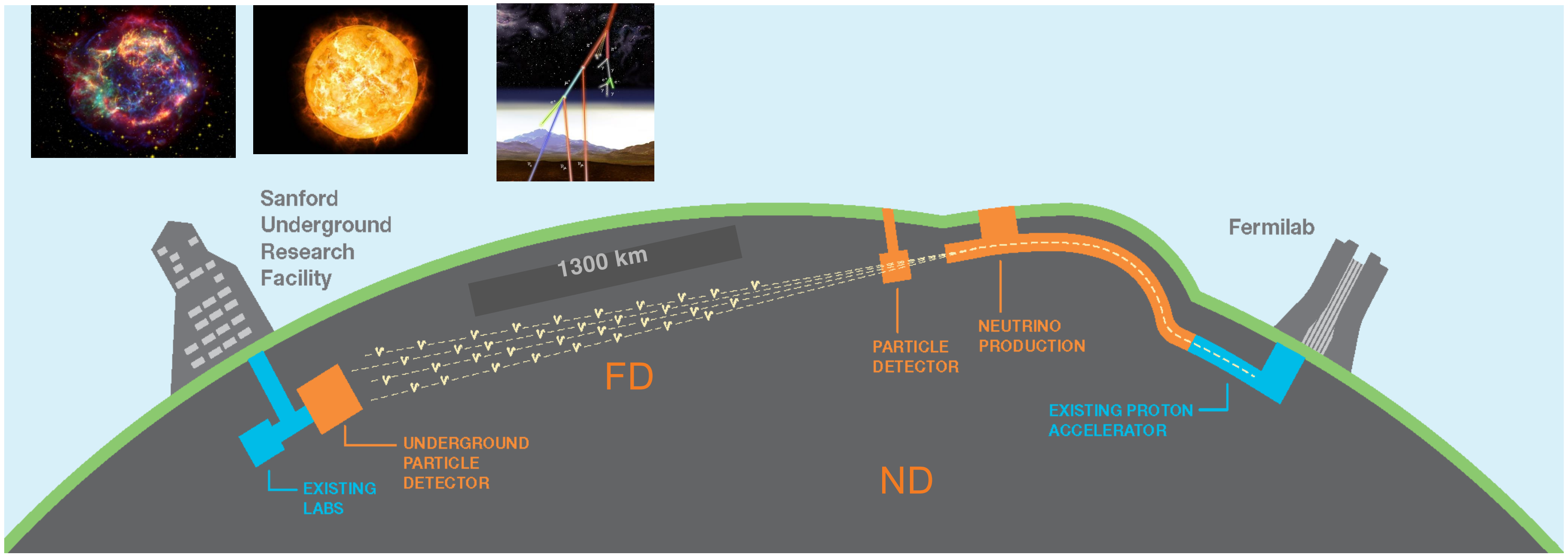
- 2,000,000 ν_μ CC interactions per year
- 15,000 ν_e CC interactions per year

New limits on sterile-driven ν_μ disappearance



arXiv:2603.22557

DUNE as next-generation long-baseline neutrino experiment



Four key ingredients:

1. The high-power, wide-band **muon neutrino beam.**
2. The **Far Detector** with a long baseline of about 1300 km leading to matter effects.
3. The **liquid-argon technology** providing flavour and topology reconstruction as a function of energy (L/E).
4. A movable, highly capable **Near Detector**.

DUNE BSM Physics

DUNE sensitive to new physics in three-flavour oscillations: sterile neutrino mixing, CPT violation, Non-Standard Interactions (NSI)…

- DUNE covers a very broad range of L/E at both the Near Detector and Far Detector
- High statistics in ν & $\bar{\nu}$ measurements $\rightarrow$ search for CPT violation
- DUNE has unique sensitivity to NSI matter effects due to long baseline

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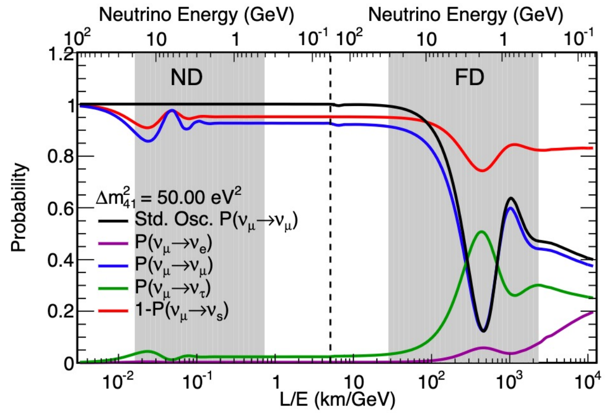
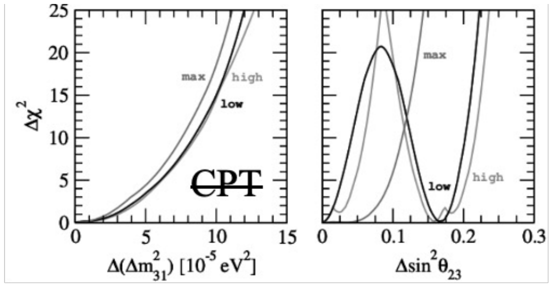
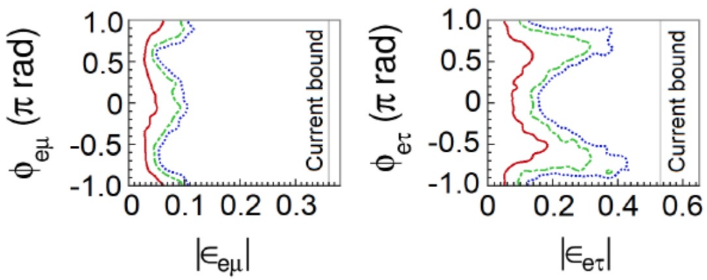
Sterile Neutrinos



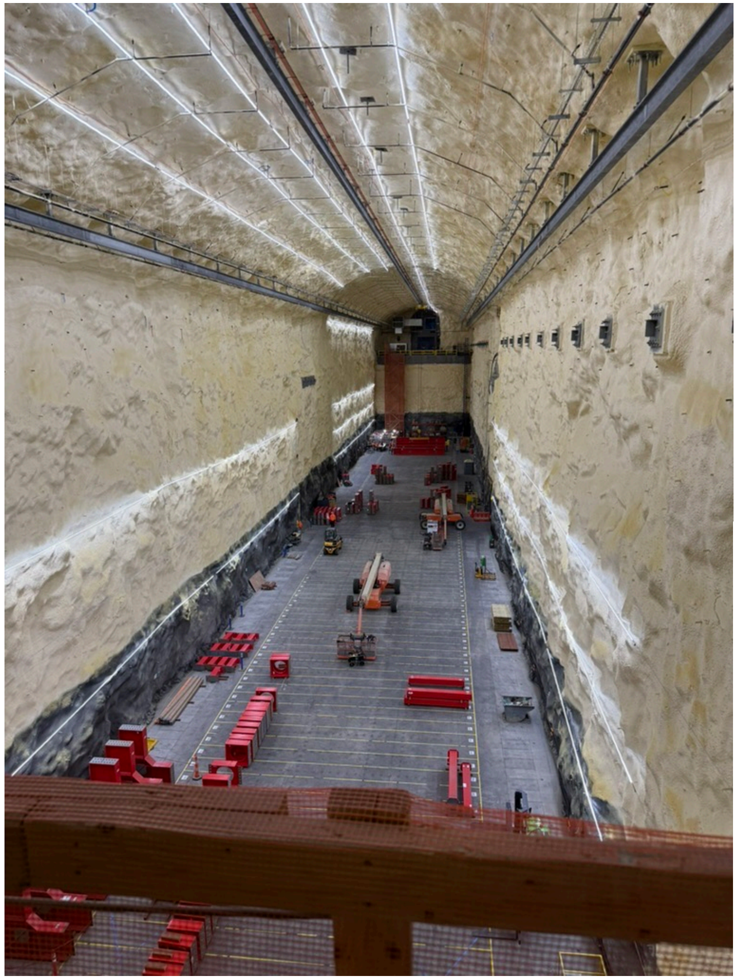
Charge-Parity-Time Violation



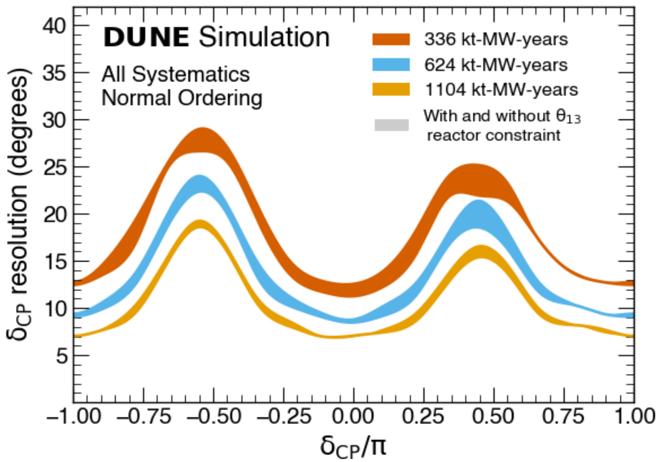
Non-Standard Interactions

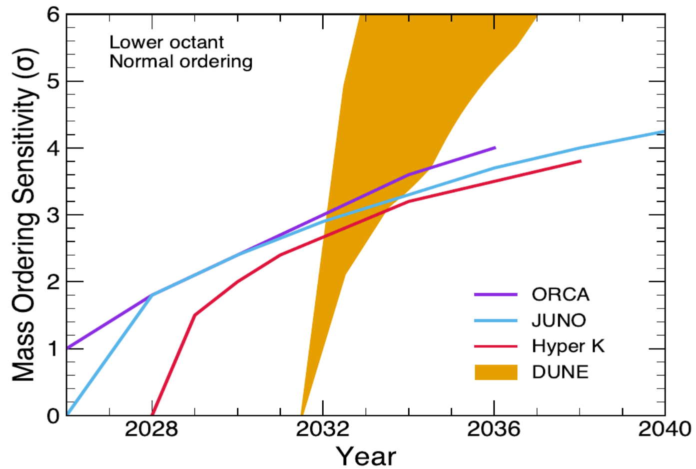


DUNE science programme



- A broad and exciting science programme (three-flavour paradigm, MO, CPV, atmospheric, solar, supernova neutrinos, proton decay, BSM physics) - first physics results this decade.
- Fully exploit power of liquid-argon technology as demonstrated by MicroBooNE.





Summary

- Detailed search for “lowest-level” 3+1 explanation of the MiniBooNE anomaly shows no evidence for oscillations and excludes LSND and (almost all the) MiniBooNE allowed regions in ν_e appearance phase space. Further investigations into other explanations underway.

- MicroBooNE is providing world-leading constraints for several dark-sector models (e.g., HNLs, dark photons, Higgs portal scalars).

- MicroBooNE is also laying the groundwork for future LArTPC detector programmes: SBND, ICARUS (further investigation of the MiniBooNE anomaly) and the next-generation neutrino experiment DUNE.