First demonstration for a LArTPC-based search for intranuclear neutron-antineutron transitions and annihilation in ^{40}Ar using the MicroBooNE detector

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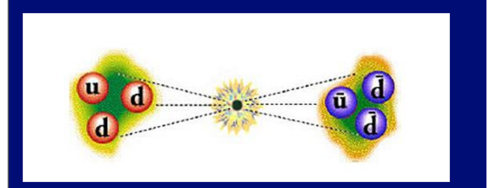
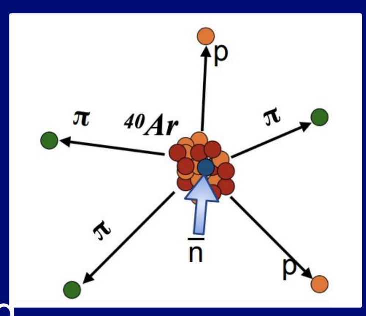
Neutron Antineutron Transitions ($n \rightarrow \bar{n}$)

- A baryon number violating process → necessary to constrain theories of baryogenesis.
- Intranuclear $n \rightarrow \bar{n}$ (within a nucleus) is suppressed due to nuclear potential.
- Transition of $n \rightarrow \bar{n}$ is followed by n annihilation with nearby nucleon leading to final state particles (mostly pions) giving rise to semi-spherical topology.





A schematic showing $n \rightarrow \bar{n}$ transition followed by annihilation

$$\tau_m = R\tau^2_{n-\bar{n}}.$$

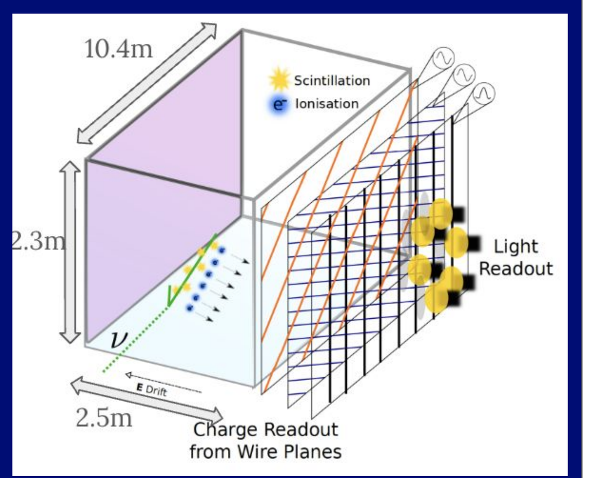
Bound neutron lifetime; Suppression factor; Free neutron lifetime

Experimental Searches

- This process is not discovered yet.
- Current best limits-
  - SuperK[1]- ^{16}O-bound neutron transition time 3.6×10^{32} years with 90% CL.
- **First-ever $n \rightarrow \bar{n}$ search demonstration within ^{40}Ar nucleus using MicroBooNE detector[3] → Important proof-of-principle for DUNE.**

MicroBooNE Detector

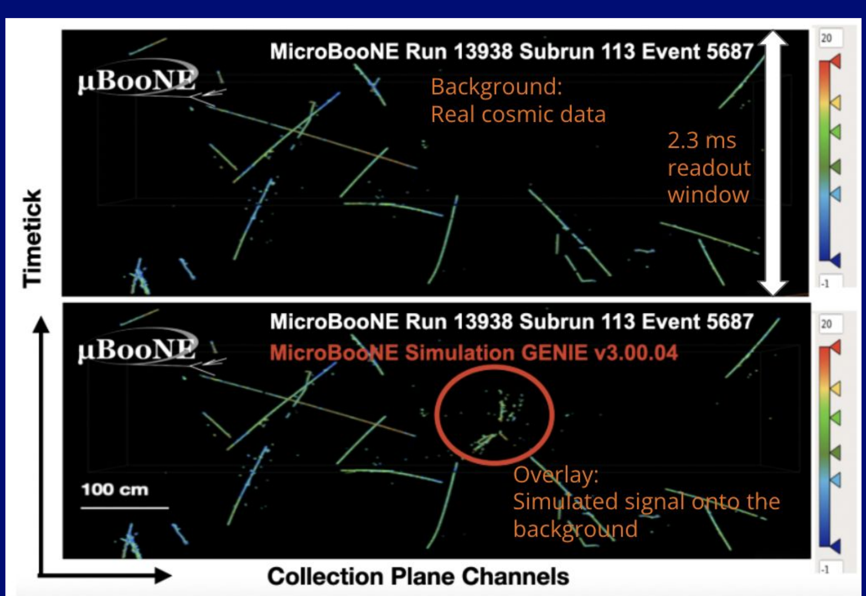
- MicroBooNE used 85 tonne active mass liquid argon time projection chamber (LArTPC) detector.
- Detection mechanism-
  - Ionization charge by three anode wire planes → mm level spatial resolution.
  - Scintillation light by photomultiplier tubes → ns level timing resolution.
- Data collection from 2015-2021-
  - Neutrino beam data
  - **Off-beam data (no neutrino interactions) → used in this analysis**



A schematic showing the MicroBooNE LArTPC

$n \rightarrow n$ Search Strategy in the MicroBooNE Detector

Reconstructed clusters over 2.3 ms exposure intervals → Image-based selection using machine-learning (ML) and deep-learning (DL) techniques → Limit on lifetime of $n \rightarrow \bar{n}$ process with 90% CL



- Each interaction (2.3 ms of readout) consists of multiple reconstructed clusters
  - Cluster is a 3D spacepoint carrying information on wire position, time and ionization charge.

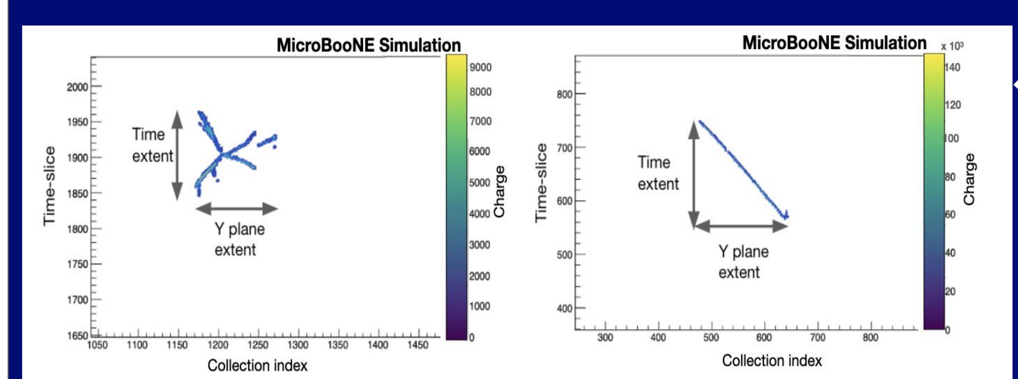
- **Background:** Real off-beam data is used as background.
  - This data is used to evaluate background interaction rate.
  - Predominantly cosmic ray muons and their induced electromagnetic and hadronic showers.

- **Signal:** Signal interactions are simulated using GENIE event generator.
  - MicroBooNE's default nuclear model configuration hA-LFG.
  - Signal interactions are subsequently processed through GEANT4 and detector geometry,

GENIE (hA-Local Fermi Gas) Simulates $n \rightarrow \bar{n}$ interactions → GEANT4 Accounts for hadron-Ar reinteractions → Detector simulation

- **Overlay:** Signal interactions are overlaid on real cosmic background to generate overlay samples.
  - Used to evaluate signal selection efficiency.
  - Assumed negligible signal in the off-beam data (consistent with the SuperK's best limit.

Topological-driven Selection

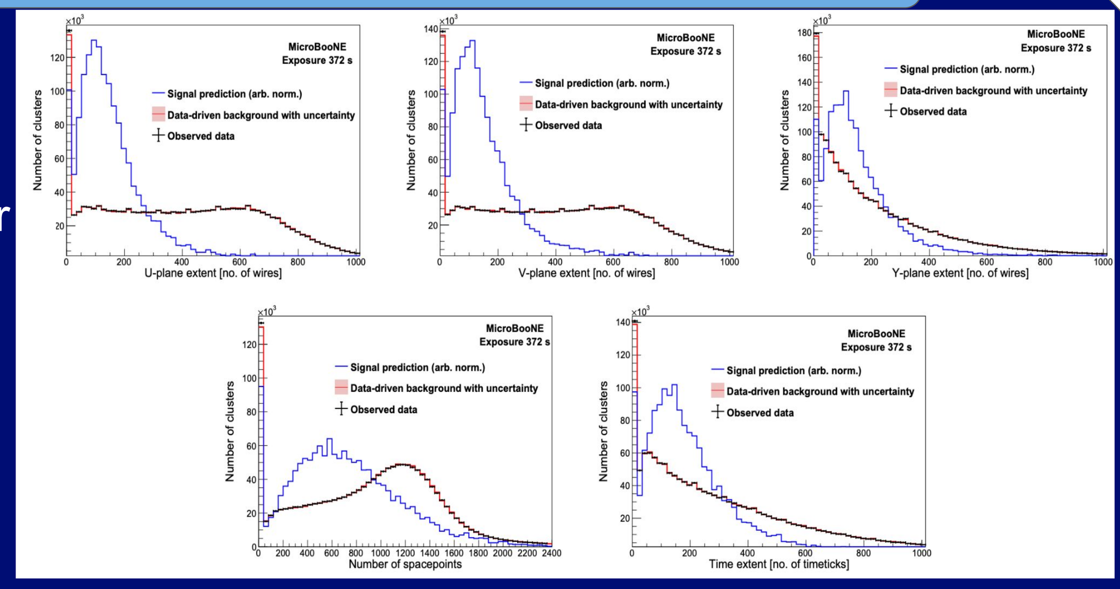


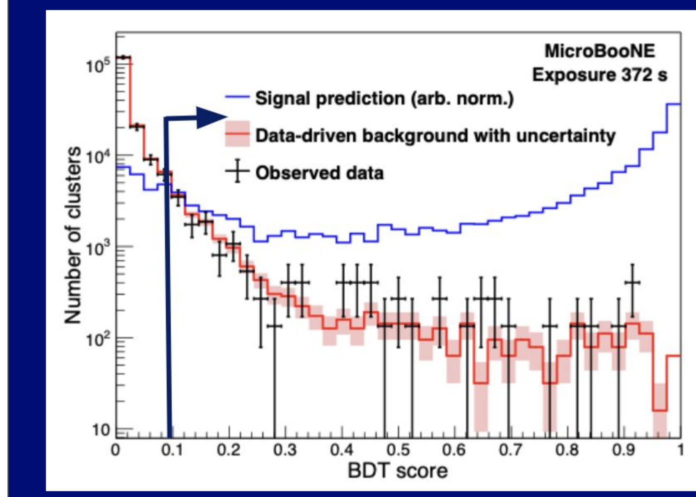
Signal topology **Cosmic ray background topology**

- Topological features are used to train machine learning and deep learning algorithms-
  - Localized and semi-spherical star-like topology for signal.
  - Extended track-like topology for typical cosmic ray background.

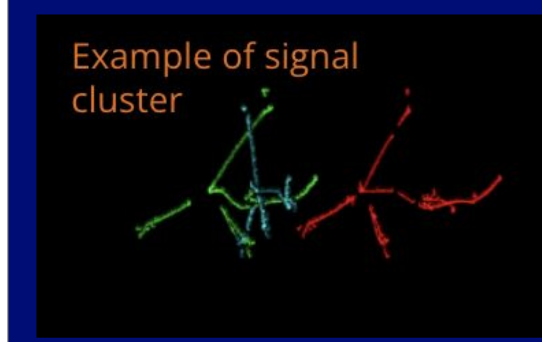
Image-based Selection

- Topological features are quantified using an extent in space and time, and number spacepoints in a cluster.

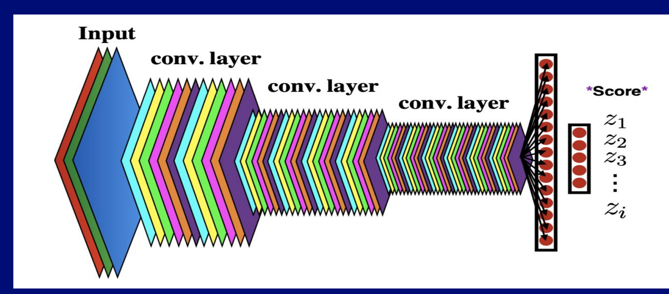




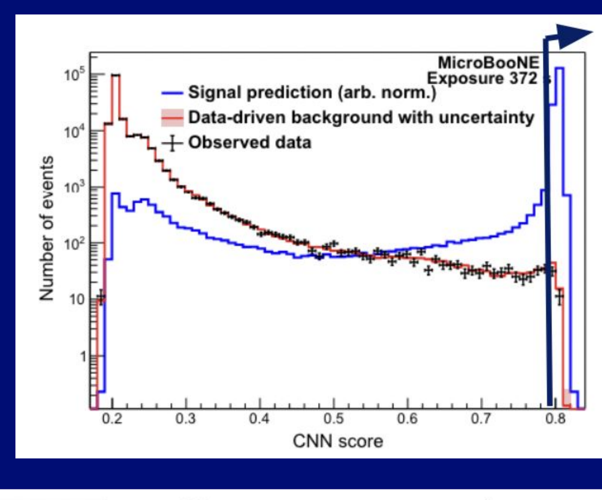
- **Boosted Decision Tree (BDT)** is trained using above five topological variables to reject cosmic ray background.
- Remaining clusters are used to train a **sparse Convolution Neural Network (sCNN)[4]**.
  - Trained using a million of events



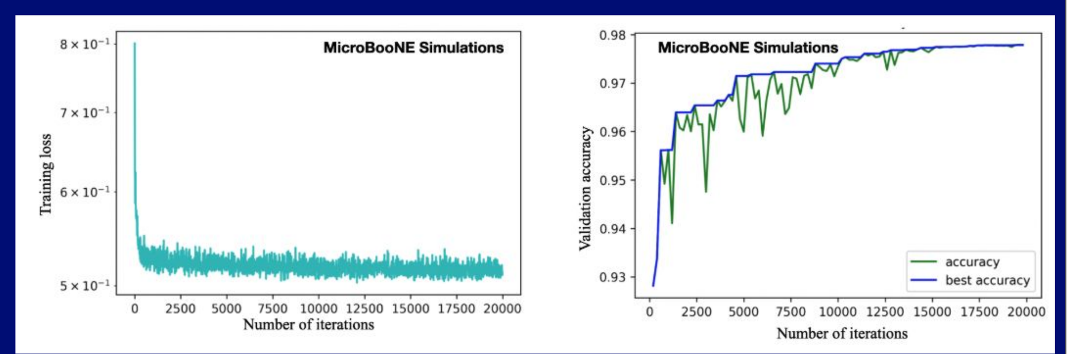
An example of sparsified input image

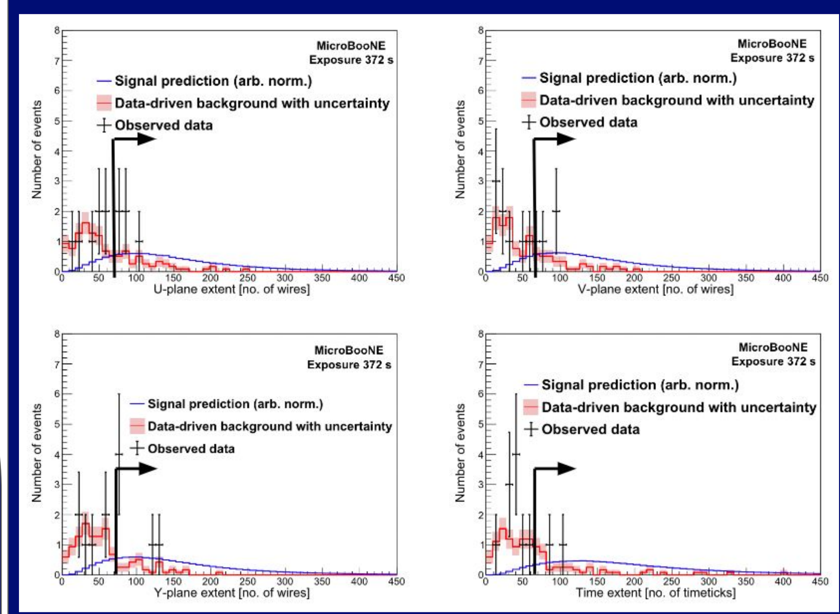


A sCNN using VGG16 network architecture



Network is optimized by minimizing training loss and maximizing validation accuracy.





The expected background corresponding to 372 s of exposure (used for reporting results) is 3.20 ± 1.79 (stat.) ± 0.57 (syst.)

Image-based selection is followed by topological extent cuts to further reject the background.

Cut-flow Table

Using 3720s of exposure	Signal	Background
No selection	1,633,525	1,618,827
Image-based selection	1,202,281	142
Topological cuts	1,147,57	32
Signal selection efficiency	70.2%	
Background efficiency		0.0020%

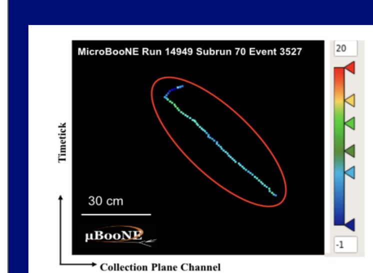
Uncertainties on Signal and Background

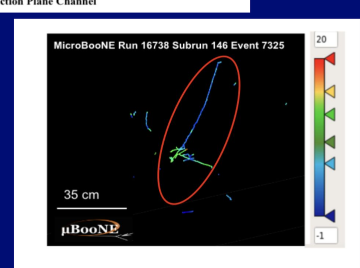
Systematic uncertainties on signal selection efficiency	
GENIE (diff. Nuclear models)	4.85%
Detector (charge & light response)	6.72%
GEANT4 (hadron-Ar reinteractions)	2.32%
Total systematic uncertainty on signal	8.61%

Background uncertainty comes from statistical uncertainty on number of final selected background interactions in 3720 s of data → 17.68%.

Results

- Using 372 s of exposure, a demonstrative lower limit is reported which is lower than the current best limits due to low exposure, small-sized detector and high background but **substantial improvement in signal selection efficiency.**





	Exposure	Signal selection efficiency	Observed interactions (events)	Expected background	90% CL limit (years)
MicroBooNE ^{40}Ar	372s	**70.2%**	2	3.2	**1.1×10^{26}**
SuperK ^{16}O	6050 days	**4.1%**	11	9.3	**3.6×10^{32}**

- **Demonstrates LArTPC's capability (using real data) in searching for this process in next-generation large sized detector with high signal selection efficiency and improved sensitivity → Proof-of-principle for DUNE**

References

1. Phys. Rev. D 103 (2021) 012008.
2. Phys. Rev. Lett. 52 (1984) 720.
3. arXiv:2308.03924 [hep-ex].
4. Phys. Rev. D 103 (2021) 05212, arXiv:1711.10275, arXiv:1706.01307.

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