Exploring AI/ML-based Real-time Anomaly Detection in DUNE for Supernova Burst Neutrinos

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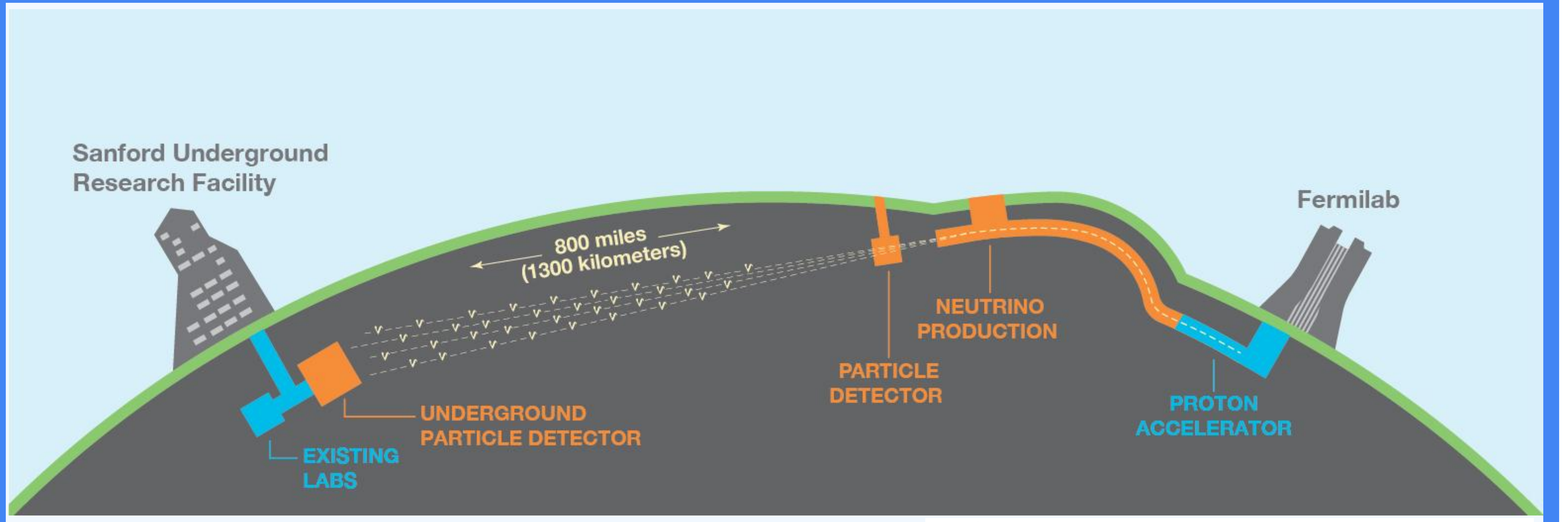
DEEP UNDERGROUND NEUTRINO EXPERIMENT

1. The DUNE experiment[1]

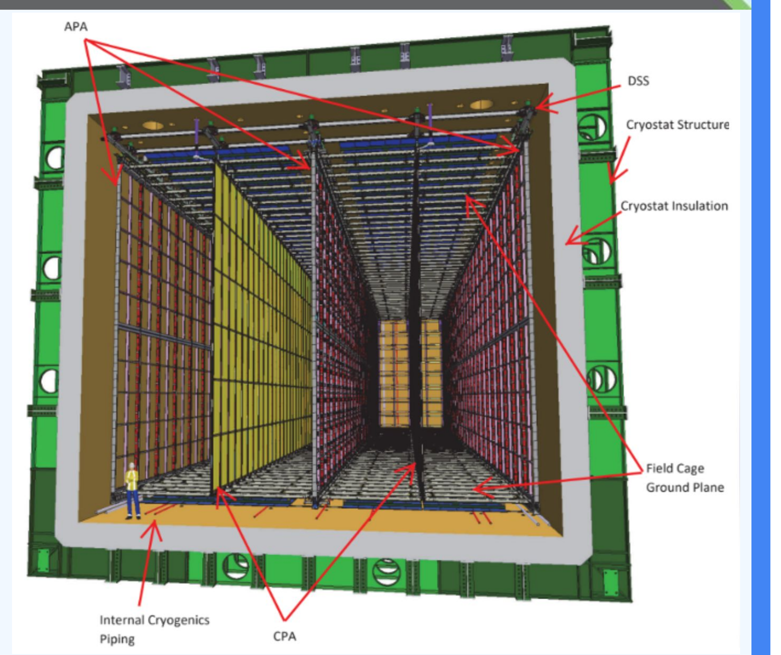


DUNE physics goals:

- Neutrino oscillation physics
- **Supernova burst neutrinos (SNB)**
- Search for rare processes & BSM physics

Dune far detector (FD)[2]:

- **~1300 km baseline**
- **1478 m underground** in Lead, SD
- Liquid argon time projection chamber (**LArTPC**): high-resolution **imaging** detector
- **10 kt LAr** fiducial volume per module
- 500 V/cm E field
- Phase I: 1 horizontal drift (**HD**) & 1 vertical drift module, 1.2 MW beam
- Phase II: 2 more modules, ~2 MW beam



FD-HD

- 100 Cathode Plane Assembly (CPAs)
- 150 Anode Plane Assembly (APAs)

1 APA = 1 collection plane each side (480 ch./side) + 2 induction planes (800 ch./plane)

2. Definition, Motivation, Method

"Anomaly" Definition:

- **Supernova Burst Neutrinos**
  → rare signals: 1~3 per century for galactic Supernova burst (nominally there is huge radiological background in low energy below 100 MeV)
- **Beyond Standard Model (BSM) Physics**
  → rare signatures from exotic particles. (nominal: SM particles)
- **Detector Glitch**

Motivation:

- **Supernova Burst Neutrinos**
  To provide improved trigger and/or filter for online SNB pointing for multi-messenger astronomy
- **BSM Physics**
  To provide dedicated BSM trigger and/or filter to accelerate discovery
- **Detector Glitch**
  To provide dedicated data stream for detector monitoring

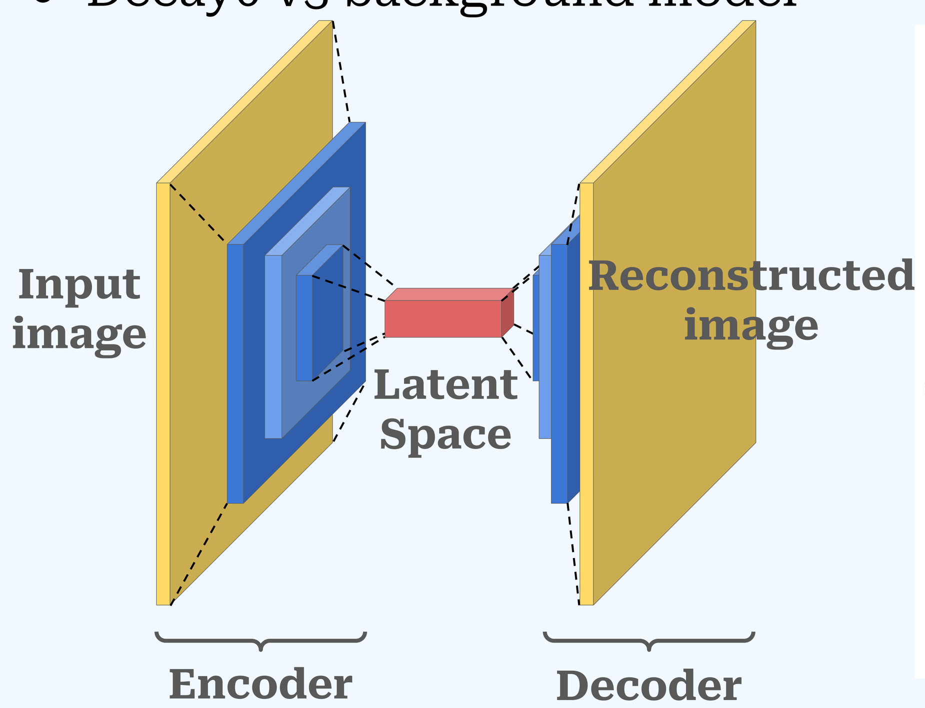
Method:

- **Unsupervised ML** → to reduce explicit bias in event selection
  Base ML architecture: **CNN-based autoencoder**
- **Raw waveform** → for ML to learn rich features of waveform
- **Real-time** → to increase **S/B ratio** in trigger and/or filter level

3. Autoencoder Training Pipeline

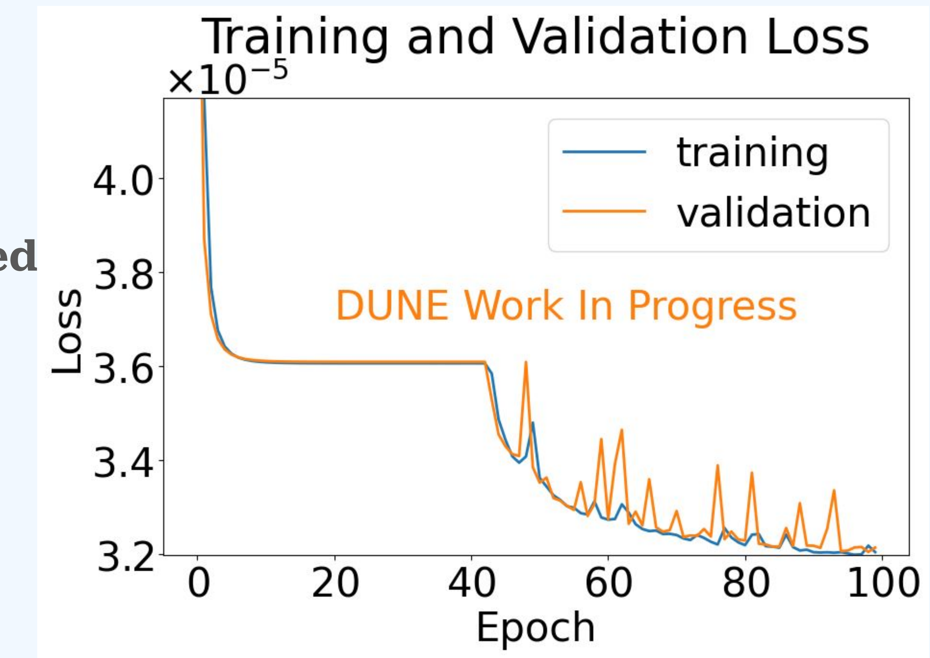
Input Data:

- 480 channels x 200 time ticks **Raw ADC waveforms in TPC** (collection plane only)
- DUNE far detector, horizontal drift, central drift volume
- ~10k 480x200 window radiological bkg. samples
- Decay0 v3 background model

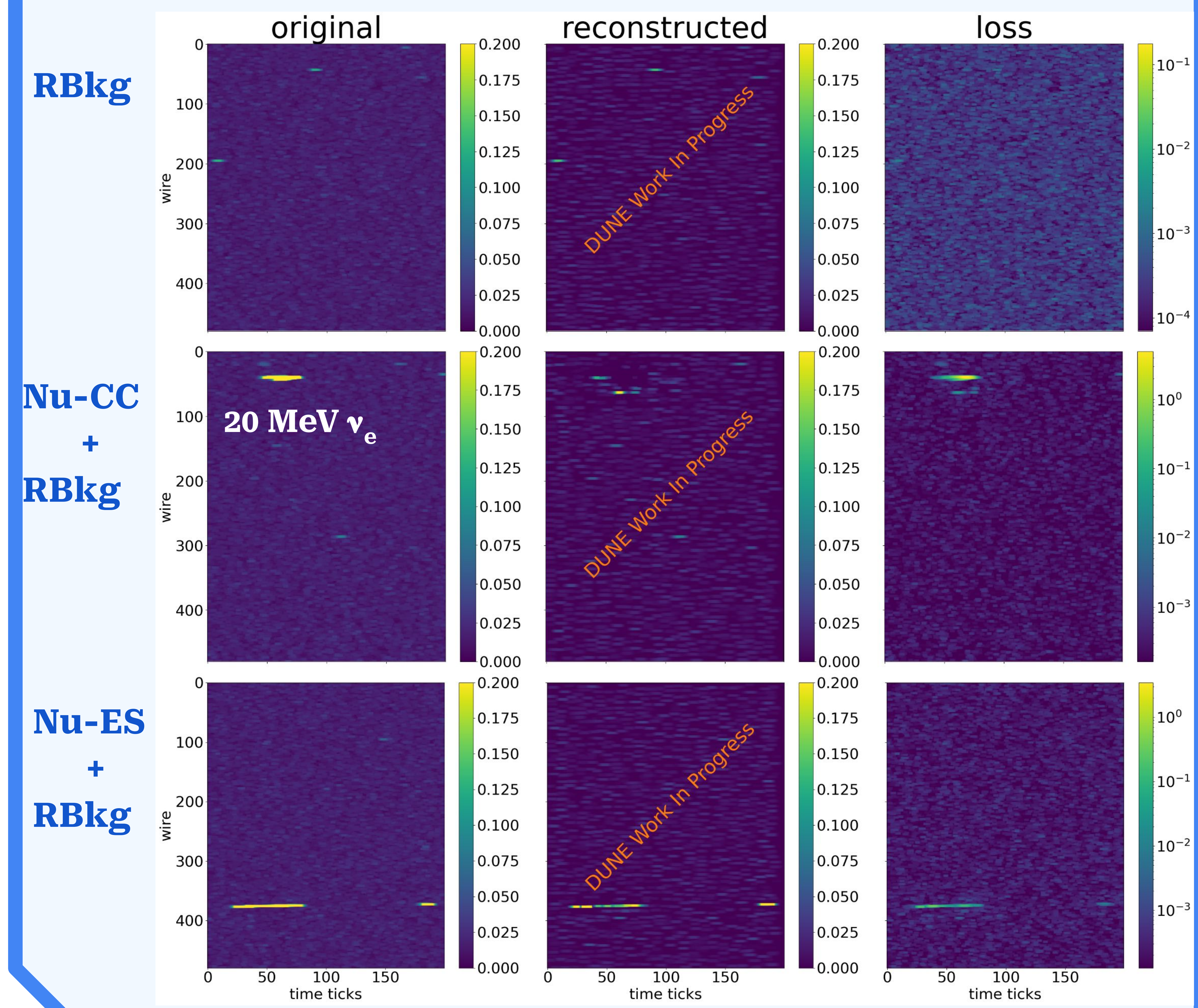


Training:

- 20 GB on Nvidia A100
- CNN-based autoencoder model
- 100 epochs, batch size 16, learning rate: 10^{-3}, weighted MSE loss
- **96k parameters**
- Encoder/Decoder: 4x (1 Conv Layer + 1 ResBlock + 1 Max Pool)



4. Autoencoder Example Events



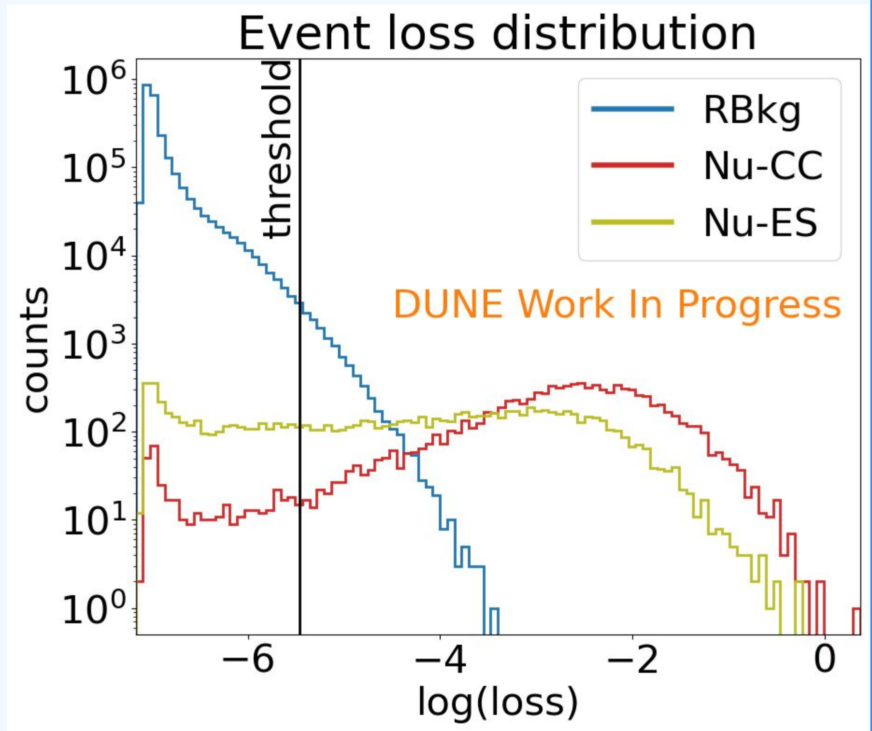
5. Autoencoder Performance

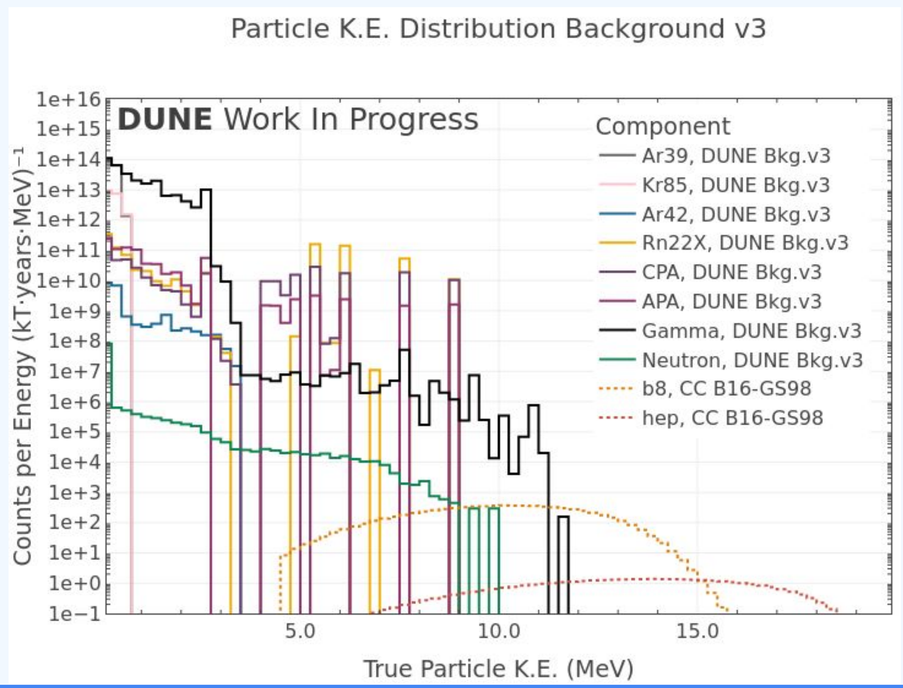
Evaluation Data:

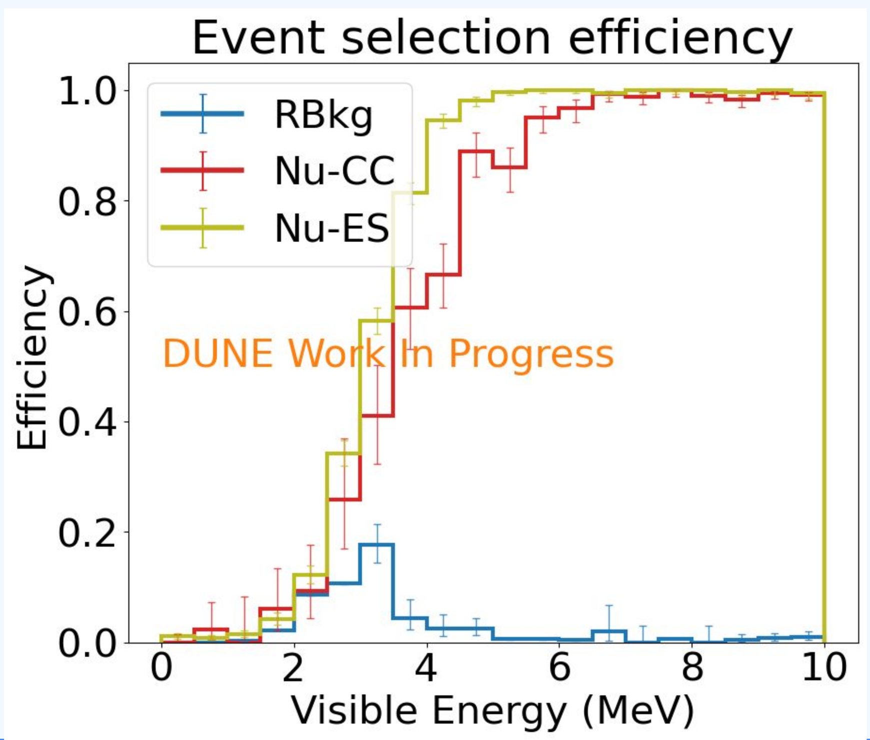
- 10k Nu-CC and 10k Nu-ES events: **spectral distribution** (Livermore SNB model), with added radiological background (RBkg).
- ~2M 480x200 window RBkg. samples
- Little statistics for > 3 MeV Gamma and Neutron backgrounds (work in progress to increase statistics)

Evaluation:

- Mean-log squared error (50 largest values only)
- Threshold: **0.5% rbkg** total passing rate (arbitrary choice for now)







6. Conclusions & Next Steps

Conclusion:

- Current ML pipeline **removes 99.5% of all RBkg**, while keeping ~100% of Nu-ES/CC events above ~5 MeV both, and efficiently removes **radon events** above 3 MeV
- Simple autoencoder approach already yields promising results, but still needs improvements in both model and statistics to allow RBkg passing up to ~10^-5% (~1 Hz) level

Next steps:

- Explore more sophisticated models, e.g. using Manifold Projection–Diffusion Recovery (MPDR)[3]

References:

1. Abi et al., *The DUNE Far Detector Interim Design Report Volume 1: Physics, Technology and Strategies*, arXiv:1807.10334, 2018
2. Abi et al., *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV: Far Detector Single-phase Technology*, arXiv:2002.03010, 2020
3. Lachner et al., *Deep-learning-based low-energy trigger algorithms for the Hyper-Kamiokande experiment*, arXiv:2605.31391, 2026

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