ML for anomaly detection and background discrimination in LZ

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U.S. DEPARTMENT OF ENERGY
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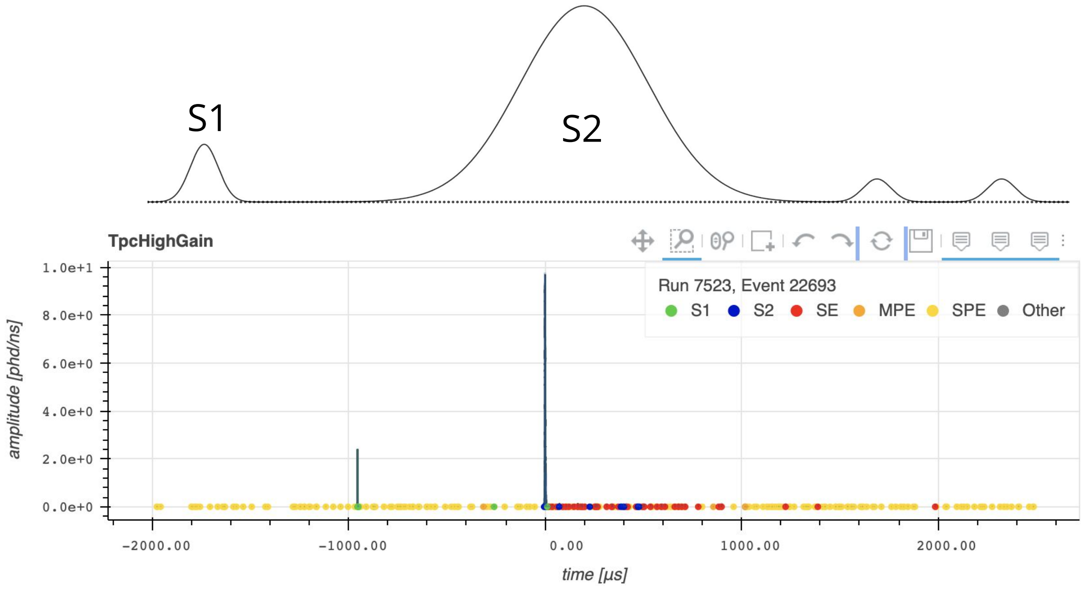
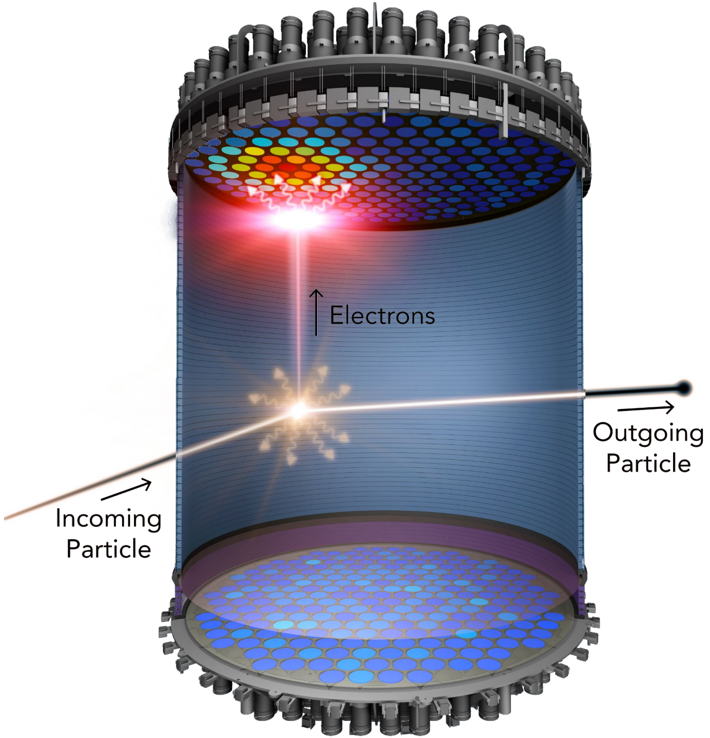
SLAC NATIONAL ACCELERATOR LABORATORY

The LZ Detector



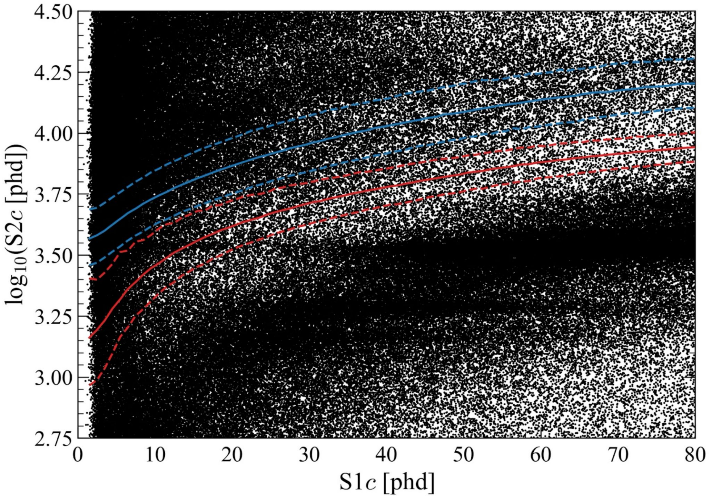


Dual Phase TPC Detector

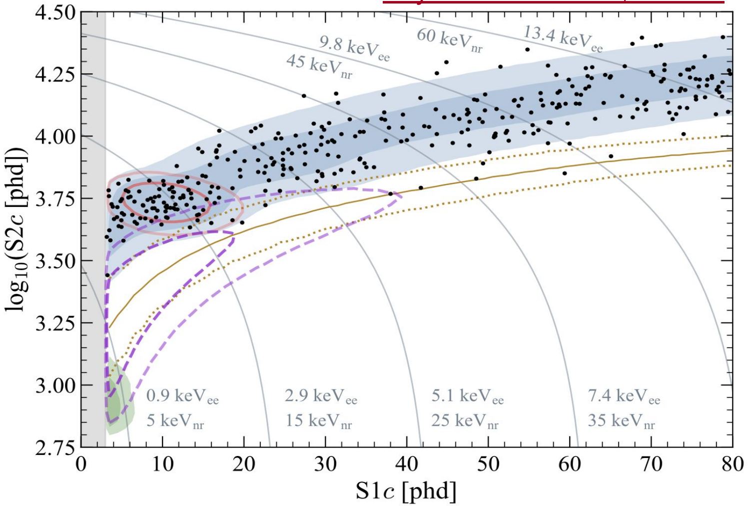
- Primary scintillation (light) → S1
- Secondary scintillation (from charge) → S2
- Radial position from top PMT array S2 pattern
- Z position determined from the drift time

Event Selection

looking for needle in a haystack



SR1 results - Phys. Rev. Lett. **131**, 041002



- Single Scatter Event Selection
- Temporal Uniformity Cuts (analysis hold-off)
- Spatial Uniformity Cut
- Accidental coincidence of S1 and S2 pulses
- Skin and OD veto cuts

Using ML to find anomalous data and discriminate backgrounds

SLAC

1. **Anomaly finding with Dimensional Reduction**
    - Map *N dimensional* (~30 features) data to *2D representation*
    - **Why? –** Outliers in multidimensional feature spaces are difficult to detect visually.
    - **Goal –** quickly identify and study (*not cut*) outlier events → *tune the data reconstruction software, investigate anomalous populations*
    - **UMAP**: Uniform Manifold Approximation and Projection & **tSNE**: T-distributed Stochastic Neighbor Embedding → nonlinear dimensionality reduction method: tend to preserve *local* structure as well as *global* structure
2. **Anomalous S2 waveforms with autoencoders**
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    - **Goal –** identify anomalous S2 pulses, has the potential of resolving overlapping multiple scatters! work in progress
3. **Discrimination of multiple scatter single ionisation (MSSI) background**
    - A boosted decision tree model was successfully used in LZ EFT studies to reduce a problematic background

Multidimensional Data

Hybrid data containing both pulse level and event level information

- **Event level Features**
  - Total area of all pulses in an event
  - Total area of different types of pulses in an event: single electrons (SE), single photo electrons (SPE)...
- **S1 Pulse Features:**
  - S1 pulse length and pulse area
  - S1 pulse shape features
- **S2 Pulses Features:**
  - S2 pulse length and pulse area
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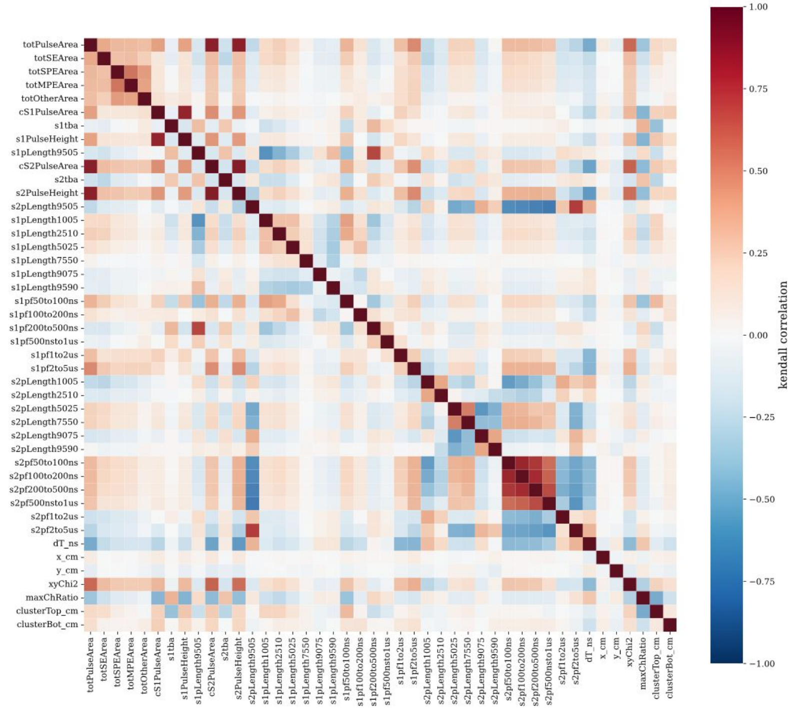
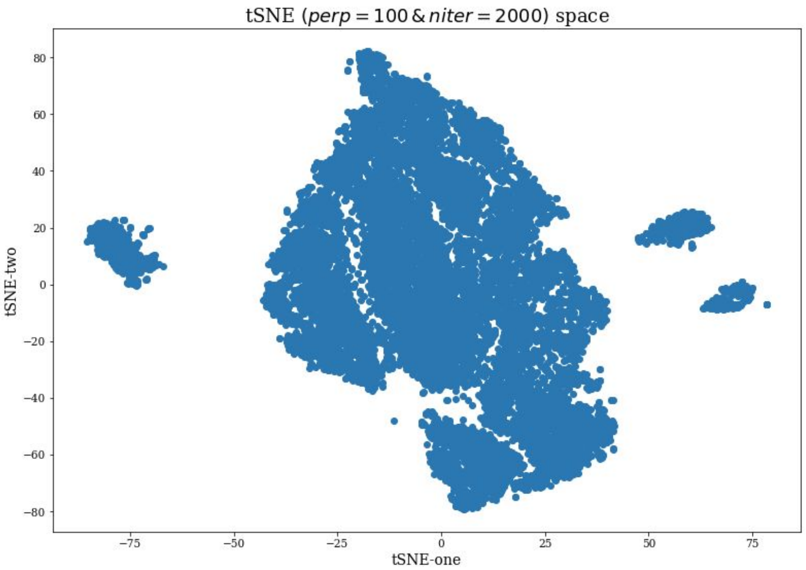
- **Other Features:**
  - S1 and S2 top bottom asymmetry (TBA)
  - Drift Time
  - XY information
  - S1 top array and bottom array cluster size
  - …

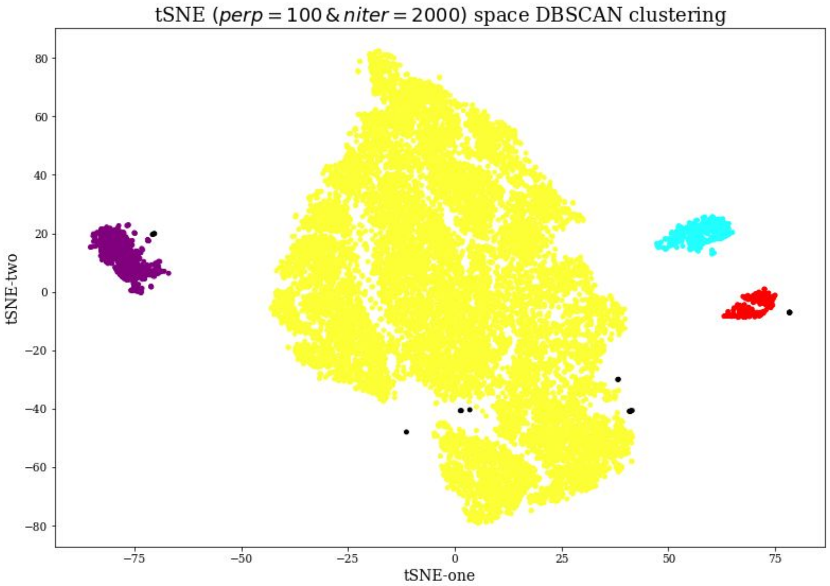


- Features are preprocessed to reduce cross correlation

Clustering in tSNE Space of Simulated Data

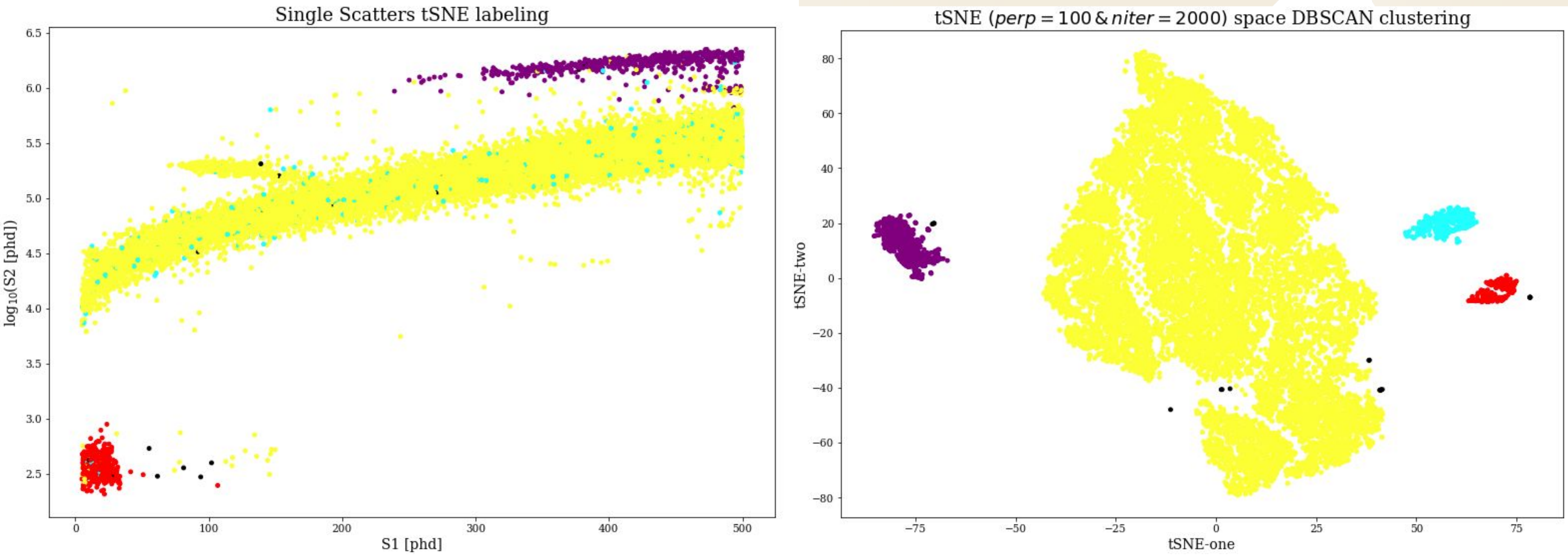


DBSCAN



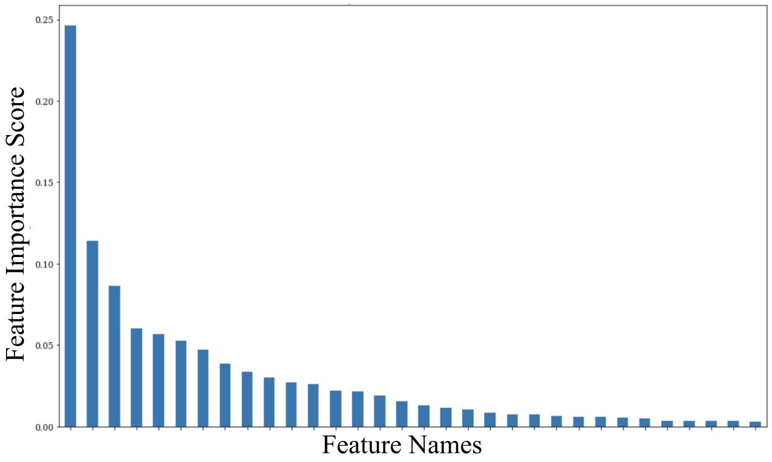
- Density based clusterization in tSNE space
- Black events classified as noise → null cluster

Clustering in tSNE Space of Simulated Data

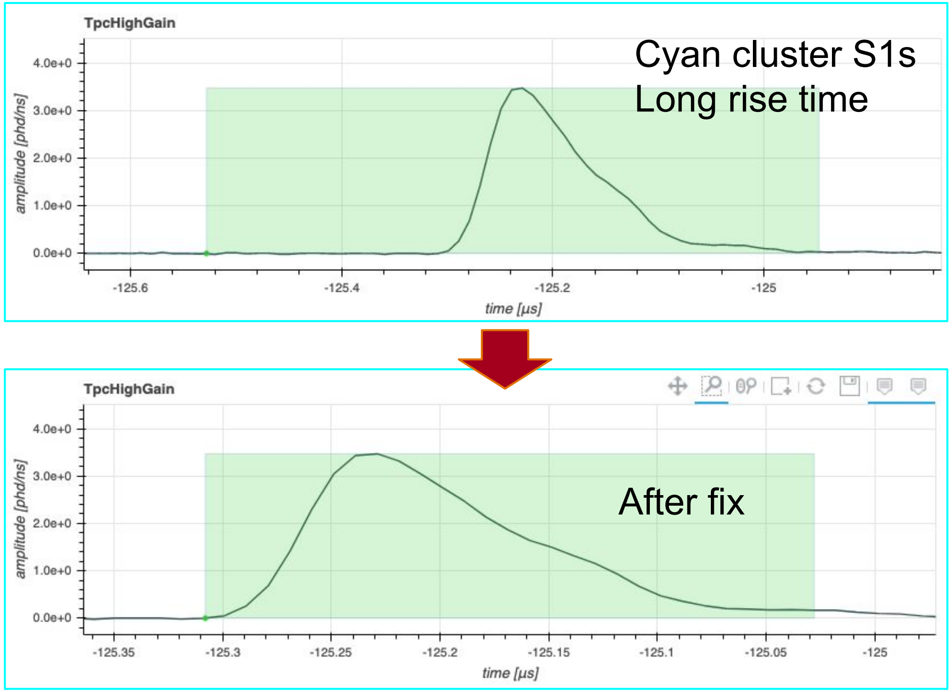


- Red population → Instrumental background
- Purple population → Simulation bug
- Cyan population → Reconstruction bug
- Yellow population → dominant cluster

Feature Importances of Clusters

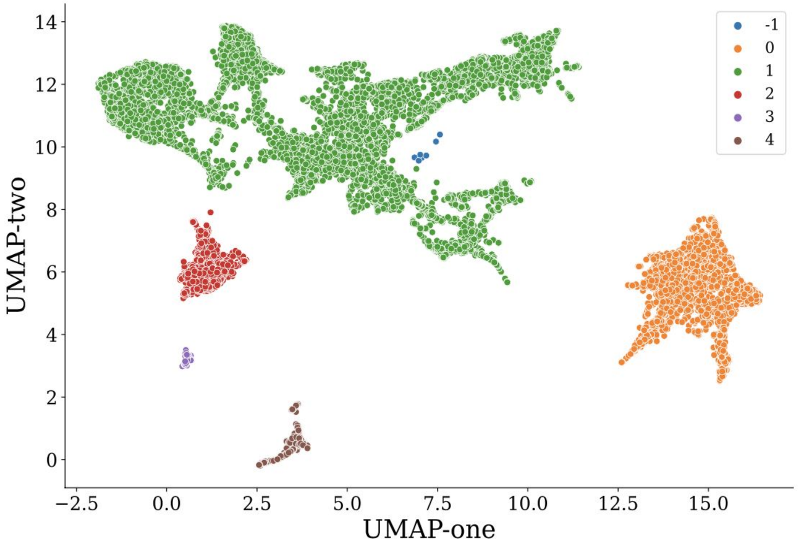


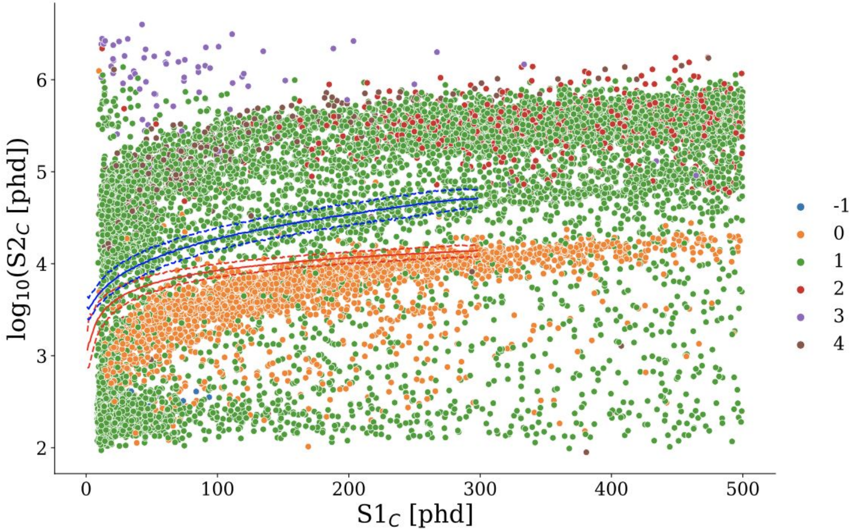
- Identify feature importances of clusters using RandomForestClassifier
  - What makes a cluster different?
  - Which parameter space is effective to make cuts?
- Improved our data reconstruction process



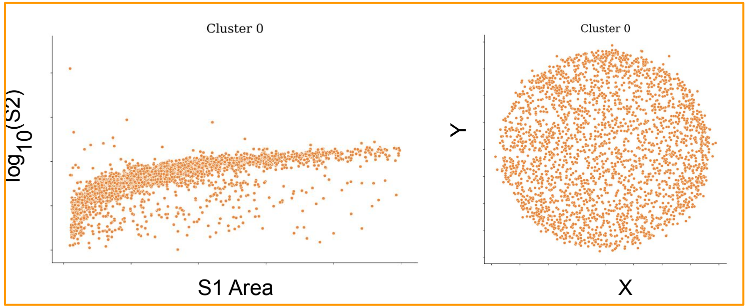
Early successes

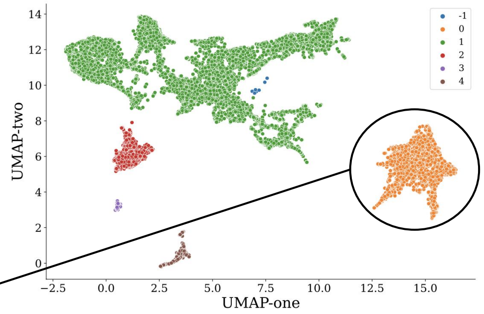
Application on First Science (SR1) Data



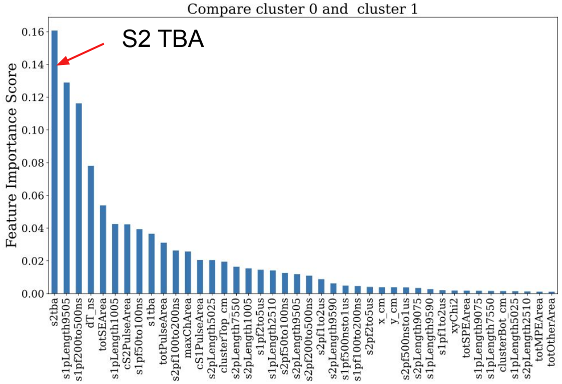


Over-Anode Gas Events





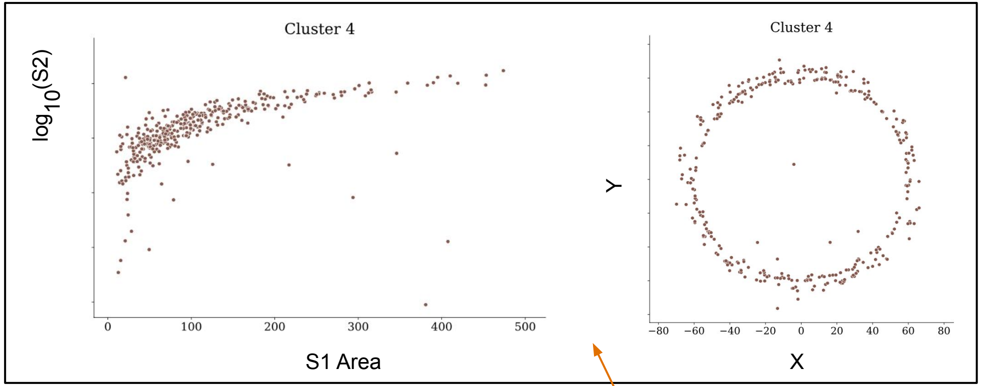
Comparing orange to dominant green population



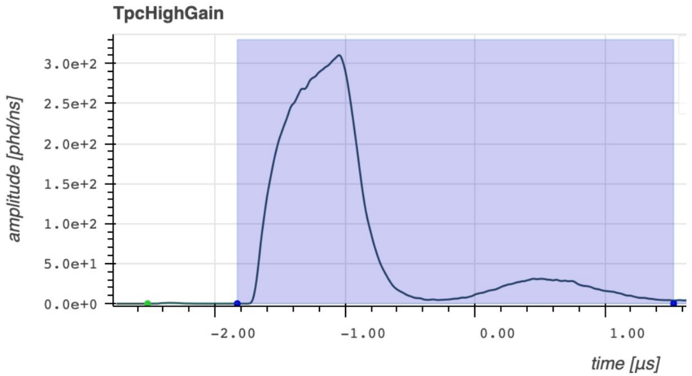
Cluster 0 (orange) found to be gas events originating above the anode → *detector effect*

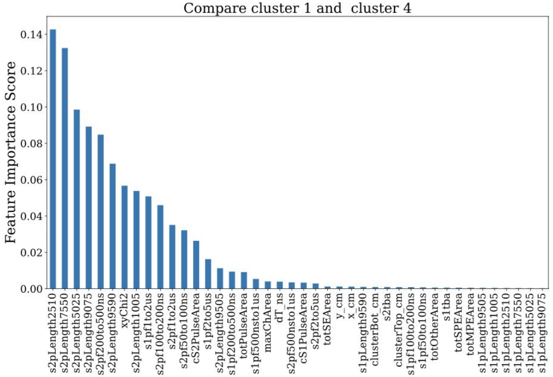
- *<u>Feature importances tool</u> allows identification of relevant RQ where this population can be further investigated*
- Found to have large S2 TBA → helped to develop conventional cuts to discriminate this background

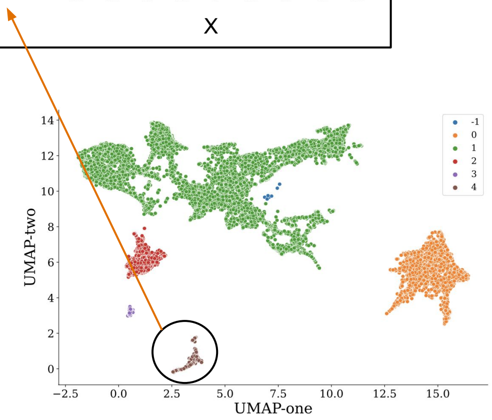
Gate Photoionization Events



- Photoionization of the wire electrodes from S2 light
- Originates near the walls in extraction region
- *Detector effect*







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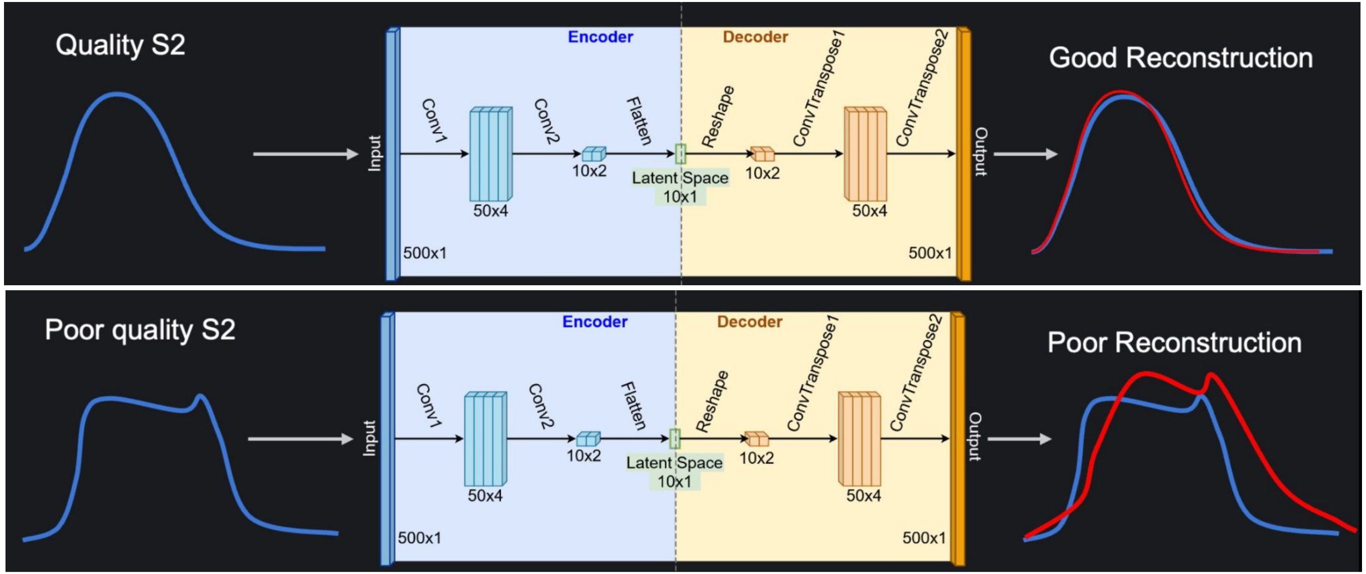
S2 Waveform Anomalies with Autoencoders

Work by Tyler Anderson

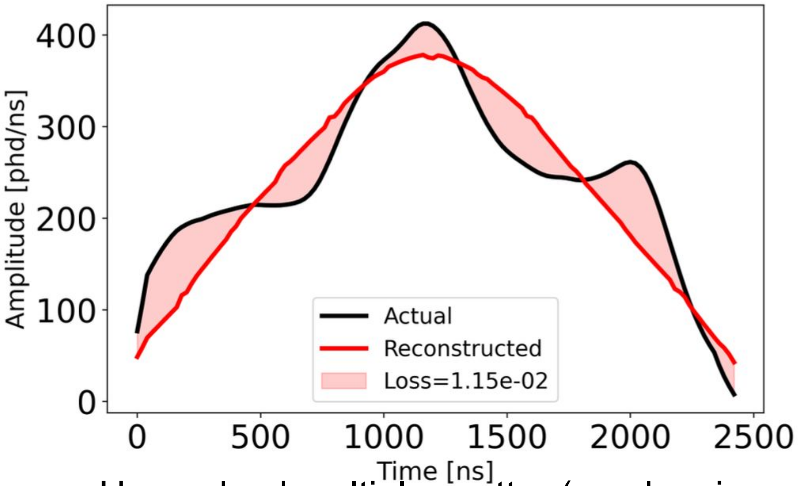
- Using signal waveforms allows to capture abnormal features washed out during reconstruction
- S2 waveforms encode a lot of relevant information due to electron cloud movement in drift region

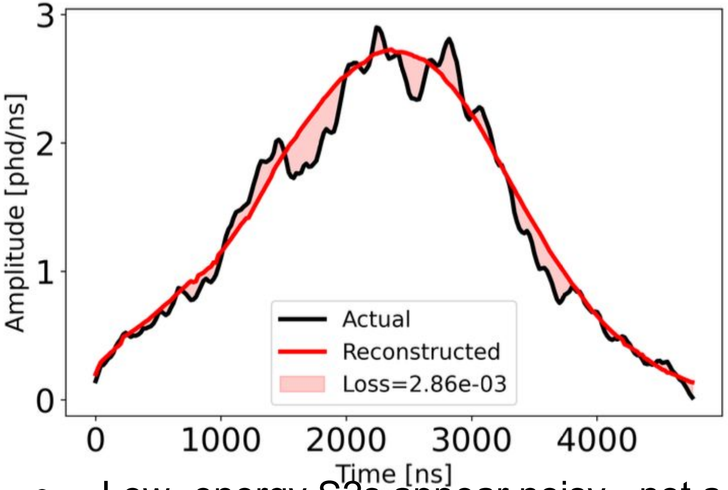


- A neutral network: trained to recreate their inputs
  - Encoder: compress the input to lower dimensional latent space
  - Decoder: convert from latent space back into original input
  - Reconstruction error can be a proxy for how different an input looks from training set.

Anomalous S2s found by the Autoencoder

Work by Tyler Anderson





- Unresolved multiple scatter (overlapping multiple S2s)
- potential background for DM searches as it would be classified as single scatter

- Low- energy S2s appear noisy - not a problem!

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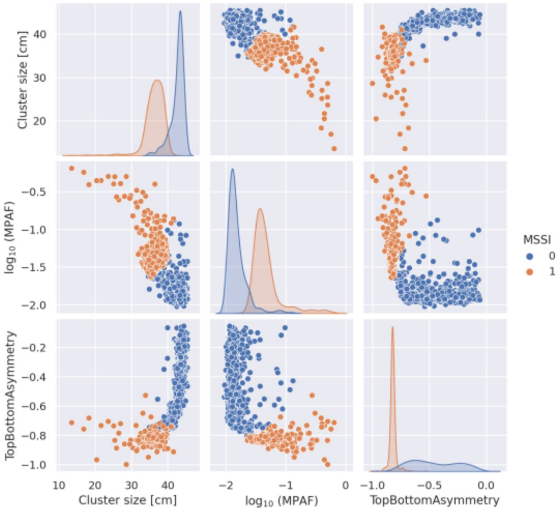
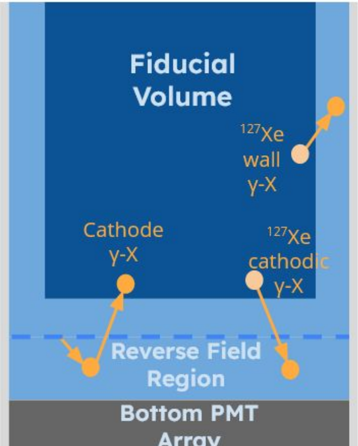
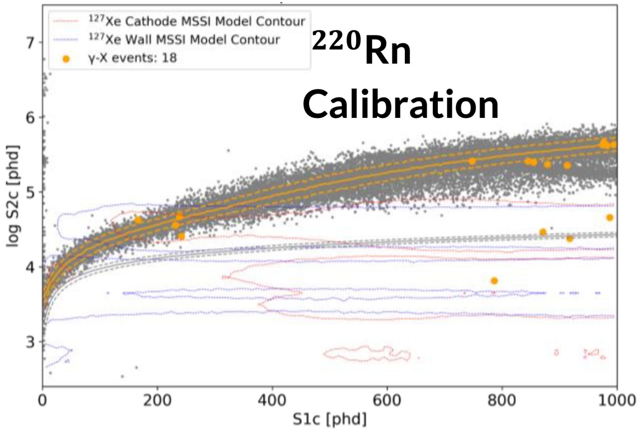
Multiple Scatter Single Ionisation: γ-X Events

Work by Chamindu Amarasinghe et.al

- **γ-X Events**: Multiple S1-contributing scatters, one S2-contributing scatter
  - WIMP-like ER Pathologies that can mimic DM signal
- **Boosted Decision Tree** trained on simulated data and tested on calibration and side band datasets
  - reduced quantities used in classification: *S1 cluster size, Max Peak Area Fraction, Top Bottom Asymmetry, S1 Area, log(S2 Area), Radius, Drift Time*







$\downarrow$ P, $\rightarrow$ T	SS	γ-X
SS	99.997 ± 0.005	0.4 ± 1.2
γ-X	0.003 ± 0.005	99.6 ± 1.2

First constraint EFT couplings -
arXiv:2312.02030

Summary

- We Demonstrate the utility of a **general purpose anomaly finder** based on unsupervised dimensionality reduction → tSNE, UMAP
    - **Interpretability** (Feature importances) →Using Random Forest Classifier
    - Applications: Investigating anomalous events, Data quality checks (simulations, real), Tuning of reconstruction and classification algorithms
- Application of Autoencoders on S2 waveforms has the potential to identifying rare waveform pathologies such as the unresolved multiple scatters. work in progress
- A boosted decision tree algorithm was successfully applied in EFT WIMP search study to discriminate the problematic multiple scatter single ionisation (MSSI) background

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

https://lz.lbl.gov/

250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
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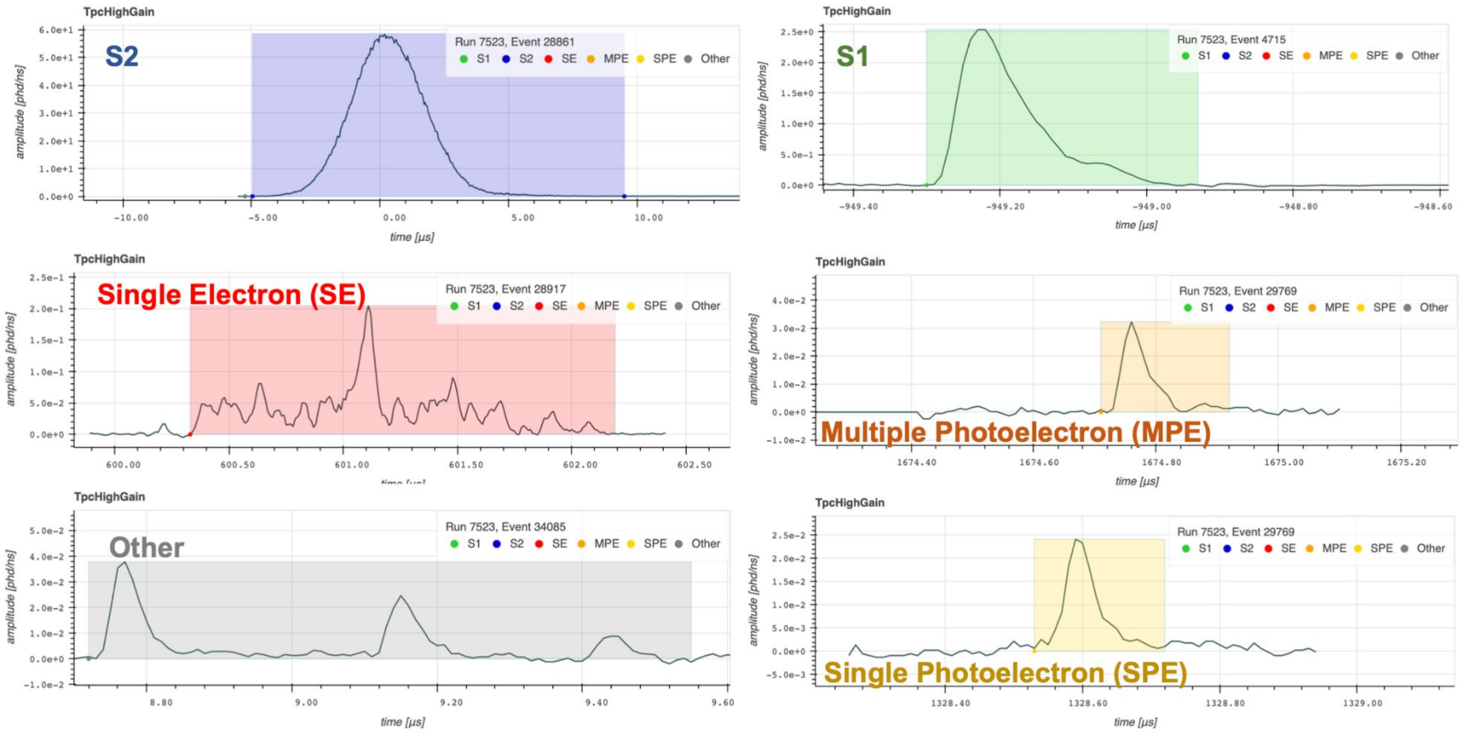
Types of Pulse Waveform



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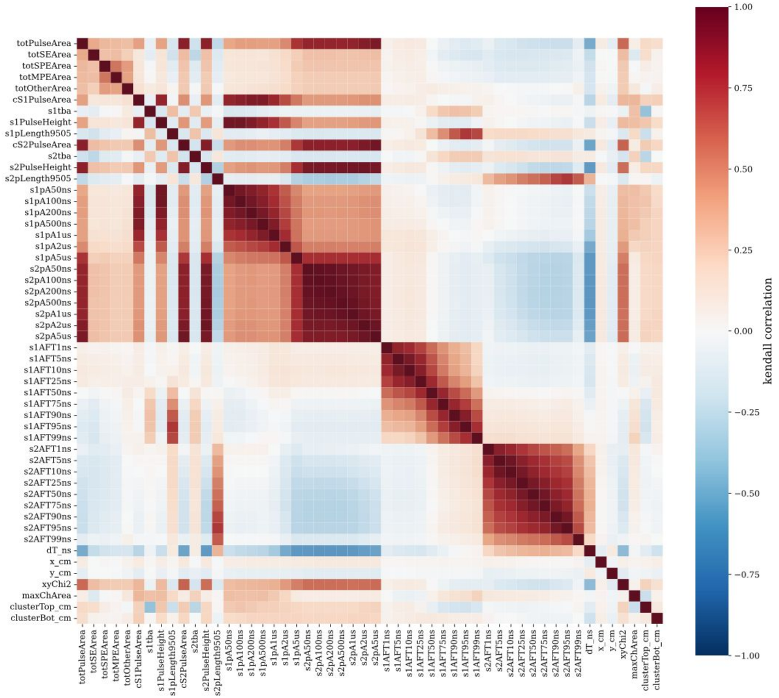

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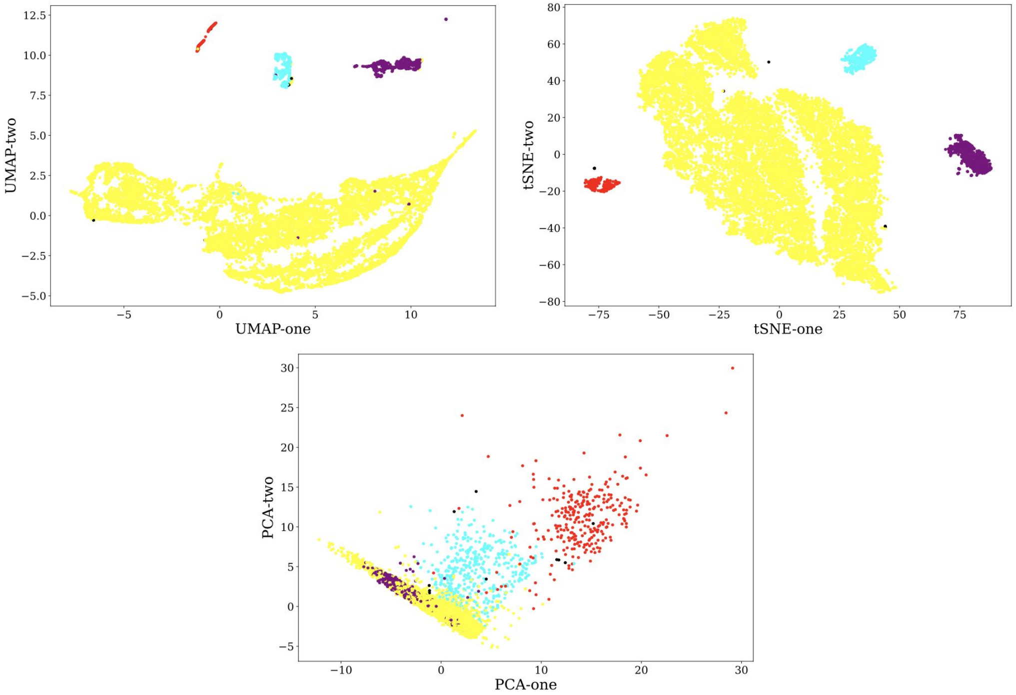
Comparison of UMAP, tSNE, and PCA



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