

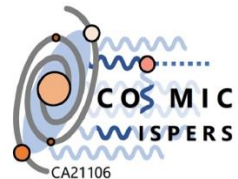
A Machine Learning Approach for Dark Matter Search Analysis: From Savitzky-Golay to Autoencoder

Kaan Özbozduman & Marios Maroudas
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19th Patras Workshop on Axions, WIMPs and WISPs

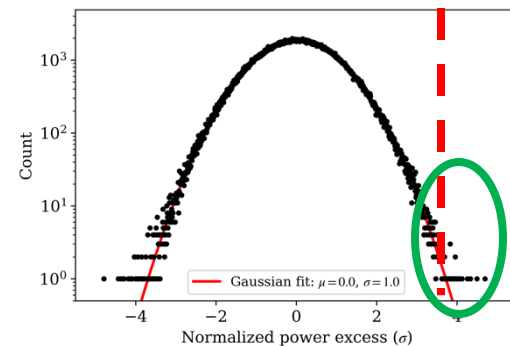
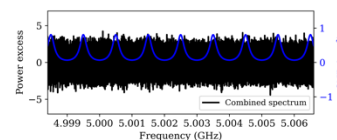
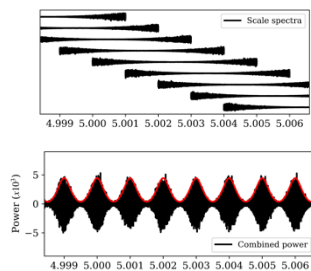
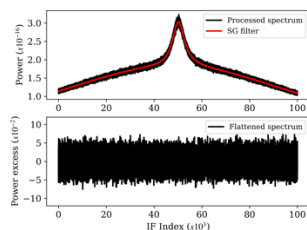
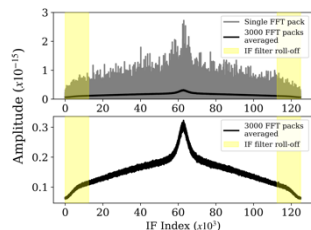
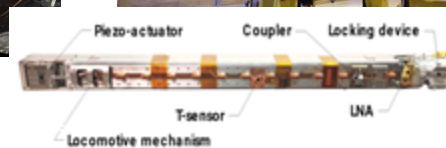
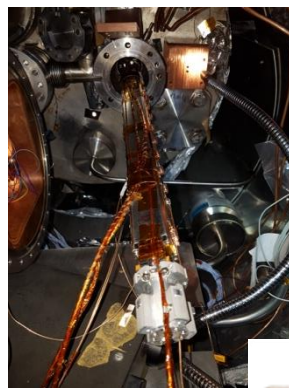


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A new path for haloscope analysis?

- Conventional haloscope analysis: CAST-CAPP example.
- Can we increase SNR further with new methods?

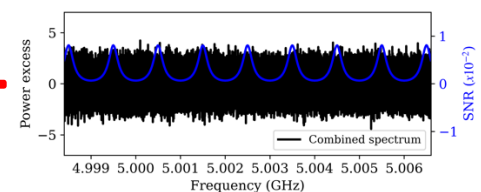
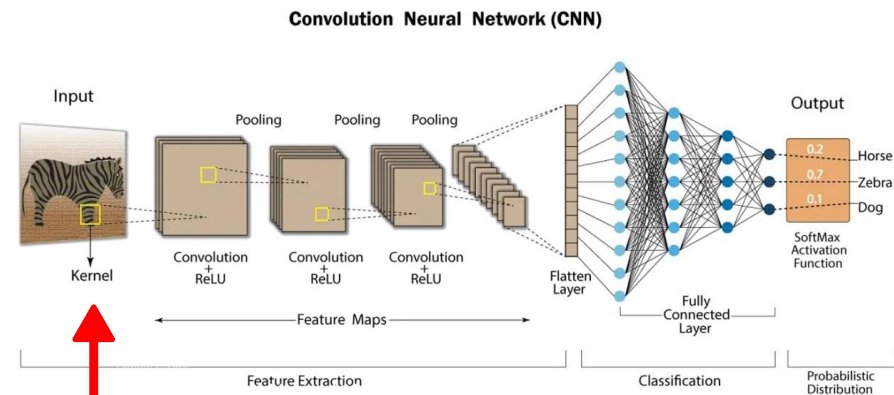
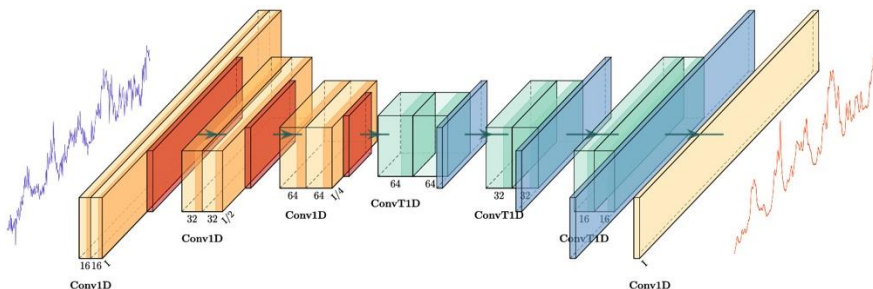


Conventional analysis path

Deep learning architectures

Deep learning (DL) have revolutionized the field by a wide spectrum of new techniques:

- Convolutional neural networks (CNNs) → image recognition
- Transformers → ChatGPT
- Autoencoders → This work



Can Autoencoders replace Savitzky-Golay filtering?

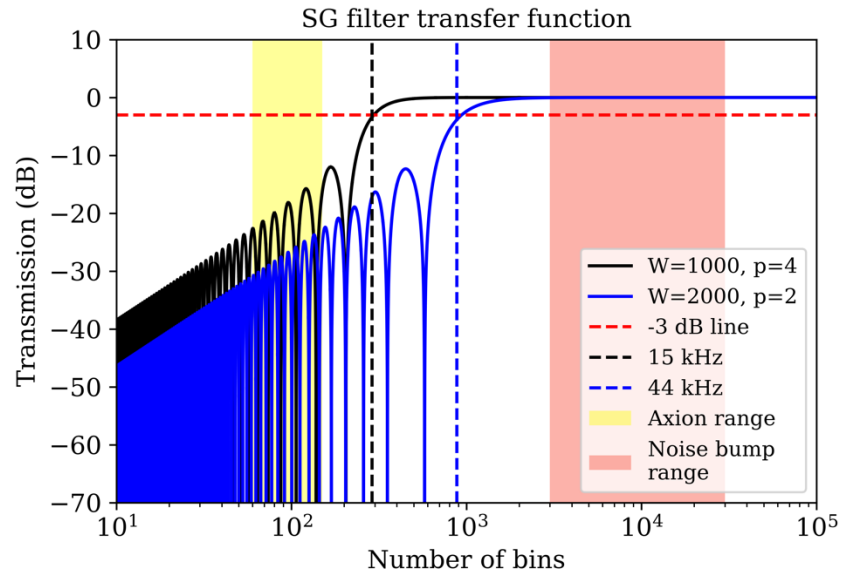
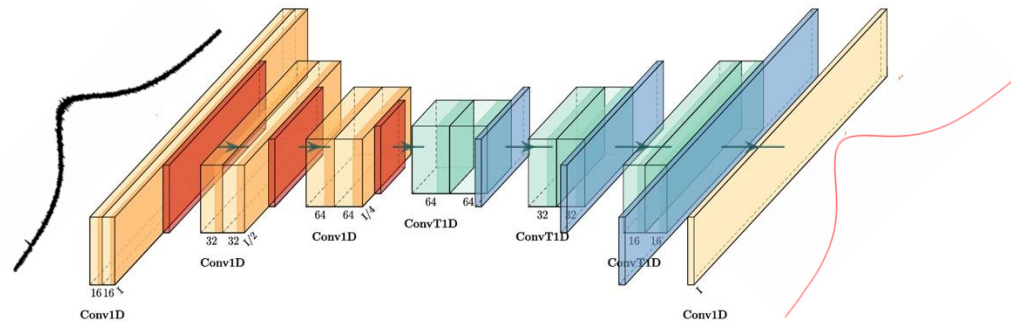


Figure. Transmission plot of the Savitzky-Golay filter. The spectral shape (red band) corresponds to a nearly perfect passband while the axion signal shape (yellow band) corresponds to an imperfect stopband leading to an axion signal attenuation.

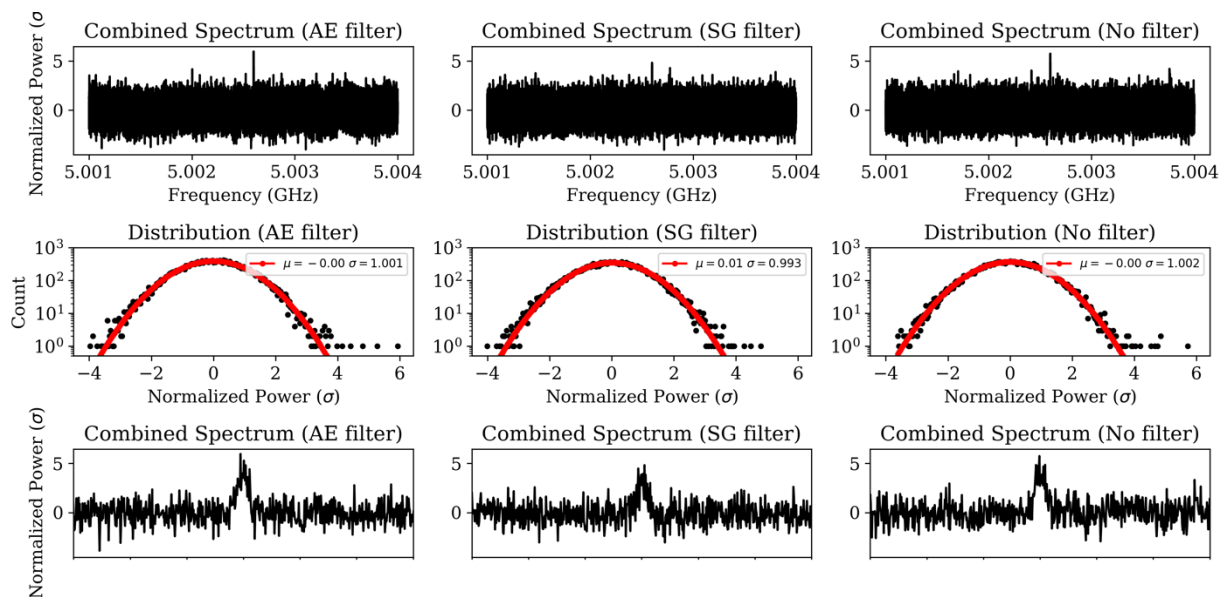
As a first step towards full DL integration...

- Savitzky-Golay **attenuates** the Axion signal
- Autoencoders may perform better.

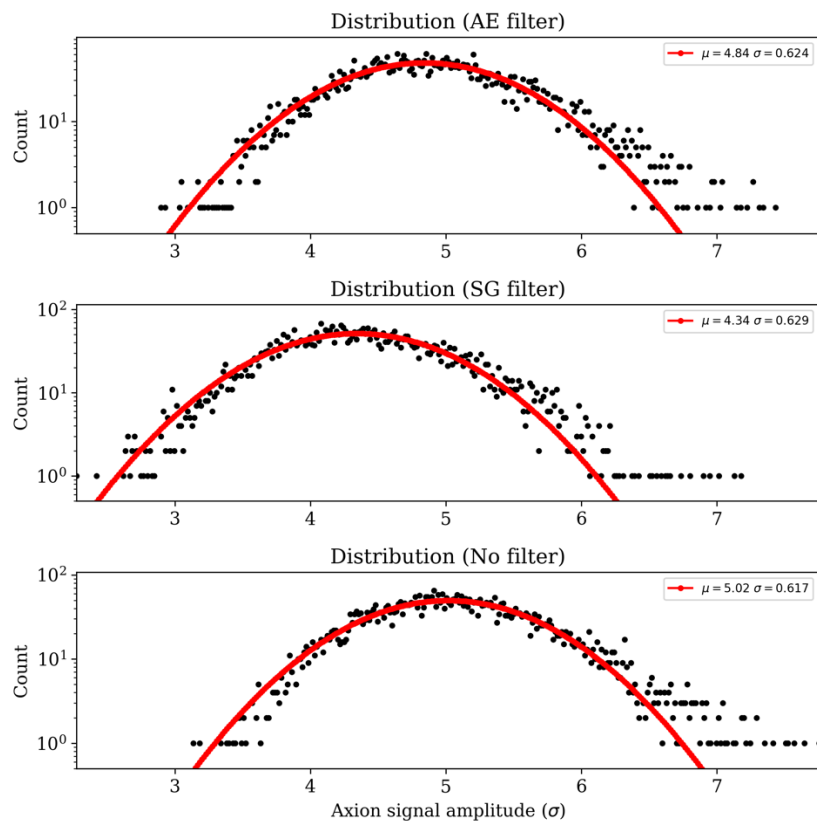


Preliminary Results

- Preliminary results of a Monte Carlo simulation comparing the autoencoder (AE) and Savitzky-Golay (SG) filters against the non-filtered case for a single spectrum.





Preliminary Results





- Signal amplitude distributions after baseline removal using an Autoencoder (AE) filter, Savitzky-Golay (SG) filter, and no filter. Simulation of the previous slide was repeated 10k times.
- The AE filter reduced the mean signal amplitude by 3.6% compared to the no filter option, while the SG filter resulted to a 13.6% reduction.
- These results suggest that the AE filter may increase the signal sensitivity by **up to 10%**.

Future Work

A Machine Learning Approach for Dark Matter Search Analysis: From Savitzky-Golay to Autoencoder

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Abstract

In the quest to improve the analysis procedure for dark matter (DM) axion searches in laboratory experiments, we propose integrating deep learning (DL) techniques into the current methodology. Specifically, as a first step towards full DL integration in the procedure, we aim to show the well-known Savitzky-Golay filter used for spectral shape removal can be replaced by a deep convolutional autoencoder filter. This transition aims to address the axion signal attenuation caused by the conventional methods. We will present the first results of this new analysis path enriched by the innovative approach. If successfully applied, this method can also be adopted by other DM searches both narrow-band and wide-band.

Conventional Method

The conventional method follows the steps below:

- Signal acquisition.
- Time-to-frequency conversion.
- Spectral baseline subtraction by Savitzky-Golay filter.**
- Scaling and vertical averaging of multiple spectra (combined spectrum).
- Signal shape convolution over the combined spectrum (grand spectrum).
- Signal search in the grand spectrum (statistical hypothesis testing).

Preliminary Results

The mean signal amplitude after the application of the AE filter was 4.8451624, demonstrating a well-controlled reduction in the baseline noise. The SG filter produced a mean signal amplitude of 4.8441625, indicating slightly less effective noise control or a larger signal attenuation. In contrast, the sufficient signals showed a mean of 5.02581617, highlighting a significant baseline noise retention. The AE filter reduced the mean signal amplitude by 3.4% compared to the no filter option, while the SG filter resulted in a 3.54% reduction. These results suggest that the AE filter provides superior baseline noise reduction and signal clarity.

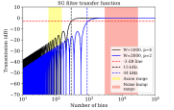


Figure 2. Transmission plot of the Savitzky-Golay filter. The spectral shape (red band) corresponds to a nearly perfect passband while the axion signal shape (yellow band) corresponds to an imperfect stopband leading to an axion signal attenuation [3].

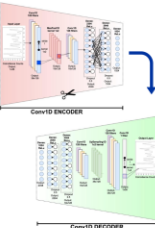


Figure 1. Autoencoder architecture. Autoencoders compress and decompress the data to extract useful information. Autoencoders can be used to detect deviations from the learned normal patterns (noise) in the spectrum, identifying signals as anomalies [3].

New Method

We propose a two-fold improvement using deep learning (DL):

- Use a fully convolutional autoencoder instead of Savitzky-Golay filter to remove the signal attenuation effect caused by it.
- Instead of creating a grand spectrum and performing a statistical hypothesis testing, use DL methods.

In this presentation we will show our preliminary work for the first bulk and future work plans for the second bulk.

Future Work

- Implement convolutional neural networks (CNNs) to enhance local pattern detection in combined spectra.
- Investigate the effectiveness of CNN in identifying narrow peaks in complex datasets.
- Explore hybrid approaches that combine CNNs with other architectures to balance local feature extraction and broader context understanding.

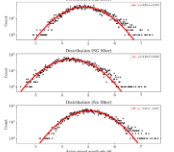


Figure 4. Signal attenuation distributions after baseline removal using an Autoencoder (AE) filter, Savitzky-Golay (SG) filter, and no filter.

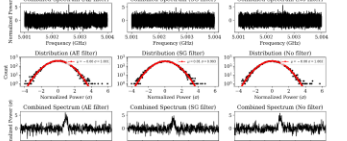


Figure 3. Preliminary results of a simulation comparing the autoencoder (AE) and Savitzky-Golay (SG) filters against the non-filtered case for a single spectrum. Figure 4 shows the statistics resulting from this operation being applied at 12k spectra.

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References

[1] https://arxiv.org/abs/2008.01254
 [2] https://arxiv.org/abs/2008.01254
 [3] https://arxiv.org/abs/2008.01254

- Implement convolutional neural networks (CNNs) to enhance local pattern detection in combined spectra.
- Investigate the effectiveness of a variety of DL architectures on Axion searches.
- Applications on real data.

Thank you!