Bridging the Gap between Spectra and Light-Curves: Exploring **Multimodal Learning** for the Identification of BAL QSOs

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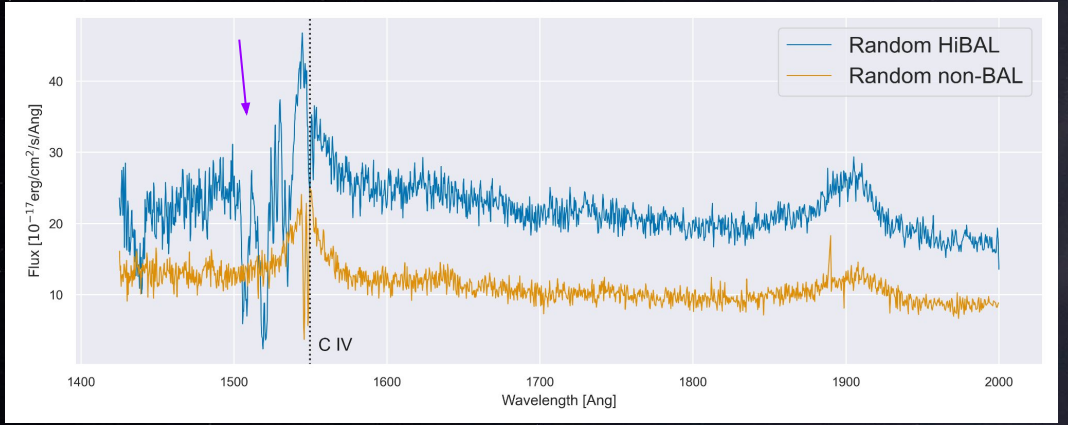
Broad Absorption Line Quasars

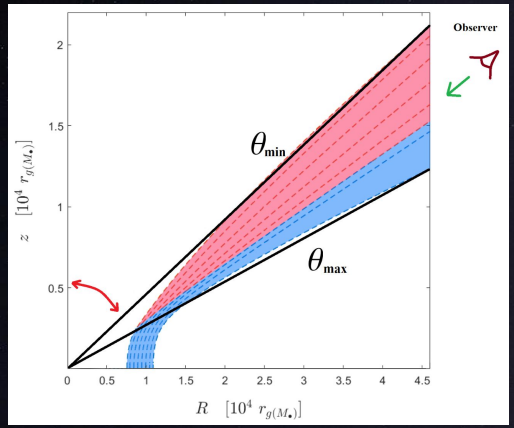
Those with **strong absorption troughs** & flatter continuum

→ **AGN with strong winds and outflows:**
≥ 2000 km/s wide, up to and beyond 0.1c



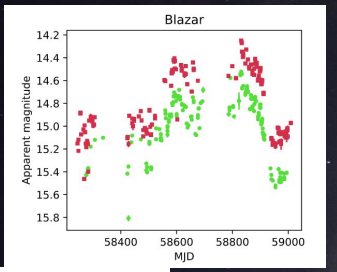
- About 10%-20% of optically selected samples
- Can be interpreted as an orientation effect
- BAL effects increase with accretion rate
- Present **strong AGN feedback effects**

Lynds 1967, Weynmann+1991, Arav+1999, Gibson+2009, Chamberlain+2013, Naddaf+2023, Peng+2024

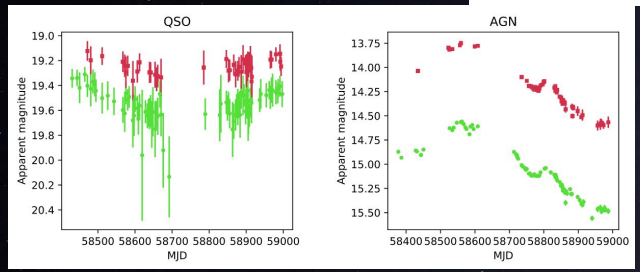


Sniegowska+2023

How to find BAL QSOs in LSST?



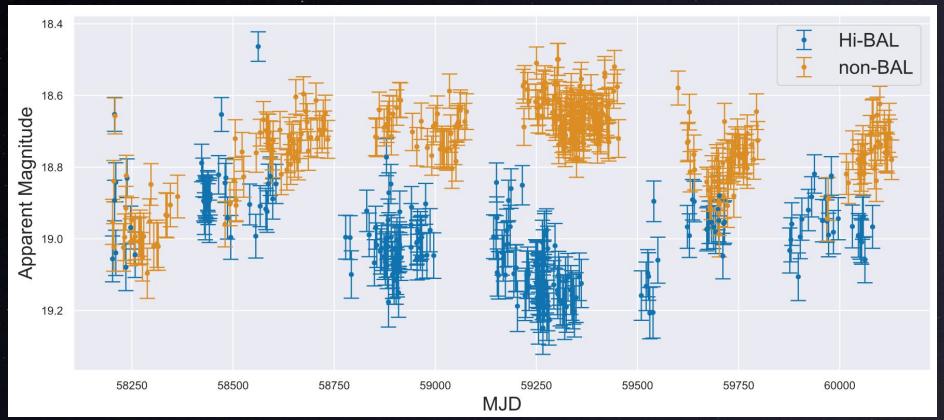
ALeRCE LC Classifier,
Sánchez-Sáez+2021



Problem: Identification of BAL QSOs depends on their **spectra** → blueshifted C IV absorption troughs for High-Ionization BAL QSOs (HiBALs; usually the most numerous). But, LSST will provide optical photometry and variability i.e. **light-curves**

vs.

BAL QSOs are still QSOs ⇒ thought not to have any characteristic variability behaviour that can distinguish them



➢ C IV absorption troughs can be variable! (Aromal+2023, Eraukman & Filiz Ak 2017, De Cicco+2017, Gibson+2008)

Multimodal Learning to the rescue

What is a modality?

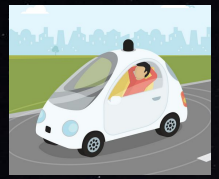
The way in which something exists or is done

A multimodal ML model can process and relate information from heterogeneous and interconnected modalities

Baldušaitris et al. 2017
Liang et al. 2023
Parcalabescu et al. 2021
Sleeman et al. 2021
etc...

Some Common Applications

Stock Price Prediction: tabular + image + time series + text



Self-Driving Cars: cameras + lidar + GPS + ...

LLMs, e.g. text-to-image: visual + text data + language

How can we apply this to astronomy?

Multimodal ML for BAL QSOs

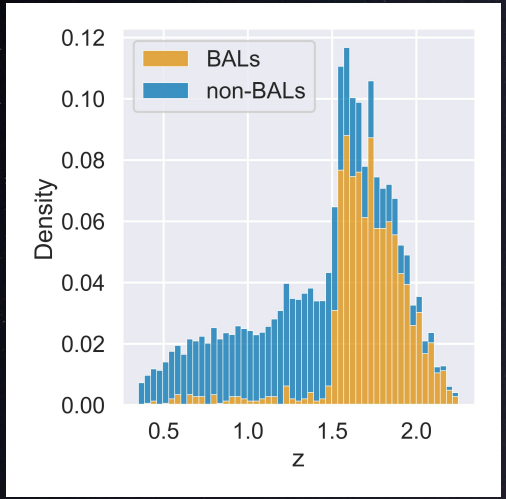
Multimodal learning could:

- Classify with info. from multiple modalities
  - **Could we build a spectrum-assisted light-curve classifier?**
- Assist in further understanding correlation between modalities
  - **How are CIV troughs and lcs correlated?**
- Infer one modality given the other
  - **Given a lc, could we infer spectral features?**

Our Dataset

1419 visually-inspected BALs & 41086 non-BALs from SDSS DR7 (Naddaf et al. 2023; Shen et al. 2011) (SN MgII > 10 & BH Mass estimate available)

SDSS spectra (blue-shifted CIV troughs) + ZTF g-band light-curves



Multimodal ML for BAL QSOs

Spectra:

1. Constrain to the C IV blue-shifted absorption region ⇒ $1.67 \leq z \leq 3.6$
2. Interpolate over bad pixels
3. Re-bin to homogeneous length
4. Lower dimensionality (kernel-PCA)

Light-Curves:

1. Cleaned (ZTF flags)
2. Padded
3. Features extracted (`light-curve` Python package)

Limitation:

- Not enough BALs and even less after z-constraint (808)
- Downsample nonBALs in a balanced BH mass vs. L bol. Space

⇒ Leveraged using Balanced Random Forests and k-fold cross-validation

Spectrum + Light-Curve Classifier

Fusion Strategies: How to combine your modalities

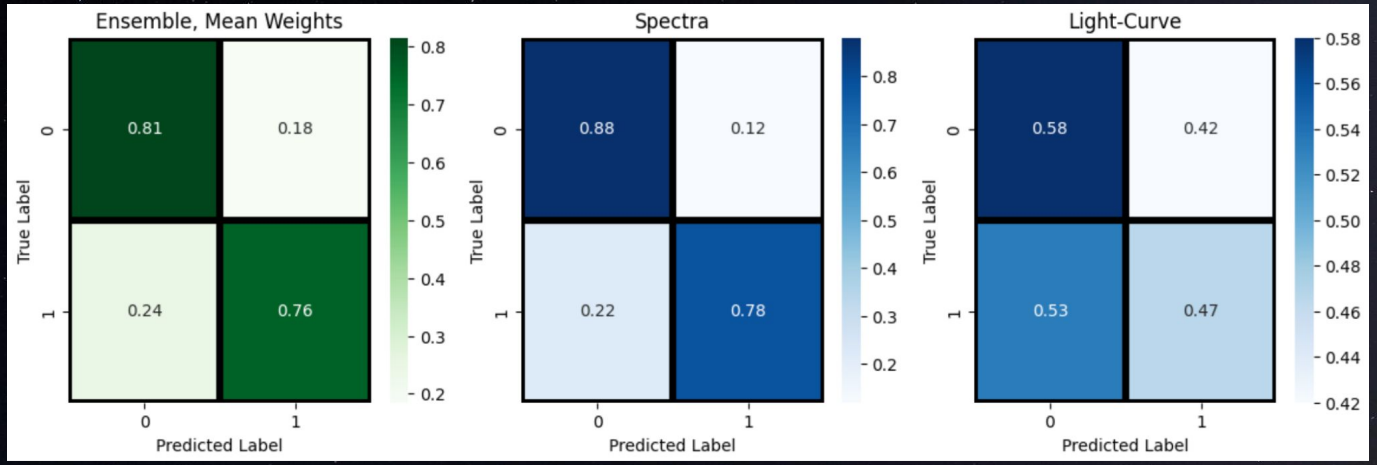
Additive Fusion:

- **Late**: classify modalities separately ⇒ fuse unimodal decisions (e.g. averaging, voting)

Balanced Random Forests

What is happening?

- Spectral modality is more reliable than the time-domain one, as expected
- Possible solution: tell the algorithm to trust spectra more



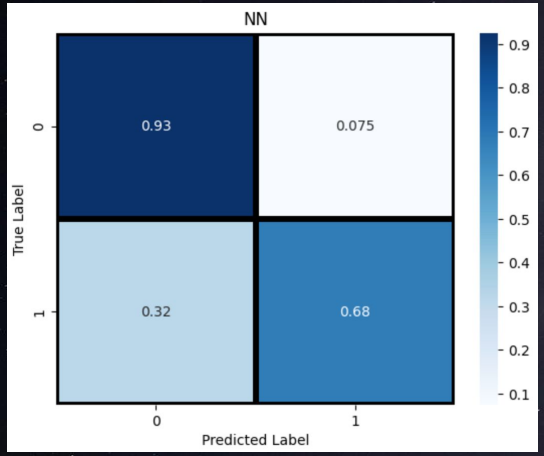
Spectrum + Light-Curve Classifier

Fusion Strategies: How to combine your modalities

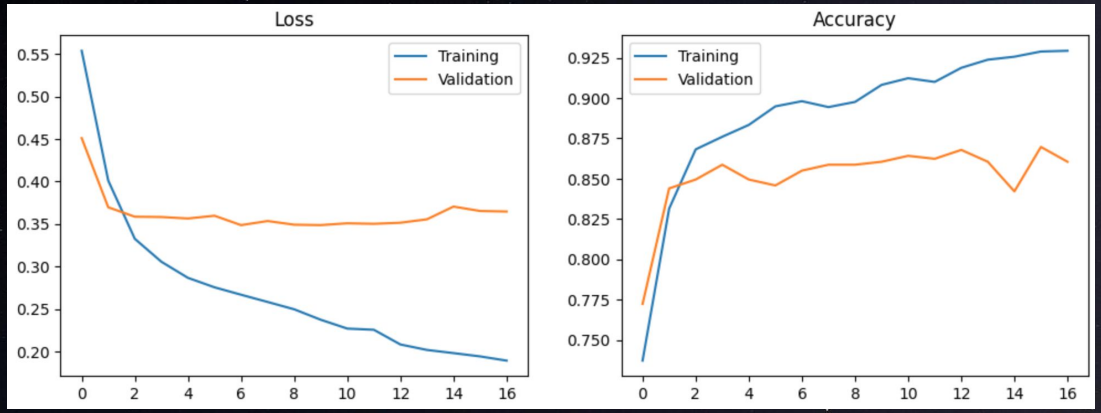
Multiplicative Fusion (e.g. Liu+2018, Mittal+2020): can capture deeper and more complex correlations between modalities

Attentive Fusion: use weights to pay more attention to the most reliable modality

Mult. Fusion + Weights Dense NNs



BALs	nonBALs
Precision: 82.35%	Precision: 84.86%
Recall: 67.96%	Recall: 92.50%
F1-Score: 74.47%	F1-Score: 88.52%



Limitations & Future Steps

This approach shows potential. However, the biggest limitation is the **sample size**.

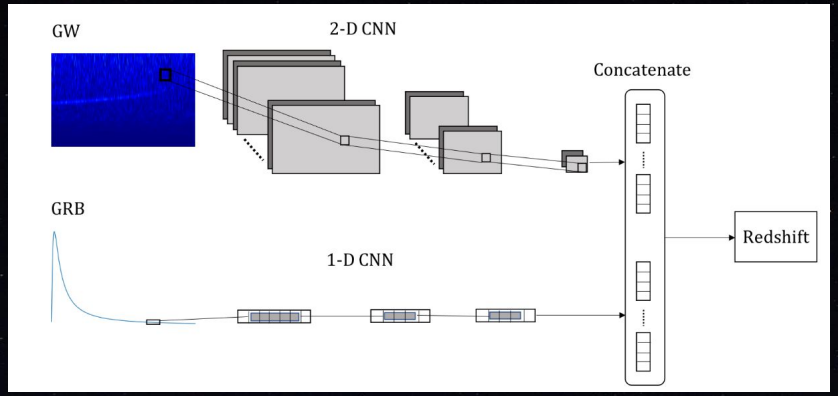
⇒ Possible solution: **oversample** with BALs from the DR16Q (Lyke+2020) & use original set as test set only. However, BH masses are not available & labels don't include ionization type…
How to account for possible biases?

Classification: Test more fusion techniques

Regression: Try to infer spectral components given light-curve feature

Further Applications of Multimodal Learning in Astronomy

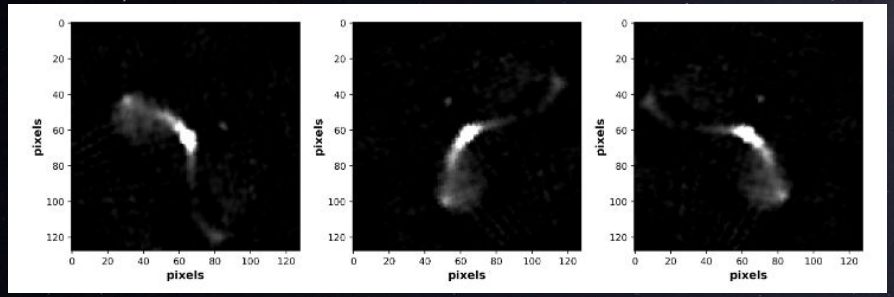
Multimodal analysis of Gravitational Wave signals and Gamma-Ray Bursts from binary neutron star mergers (Cuoco et al. 2021)



Images + Light-curves

Redshift prediction

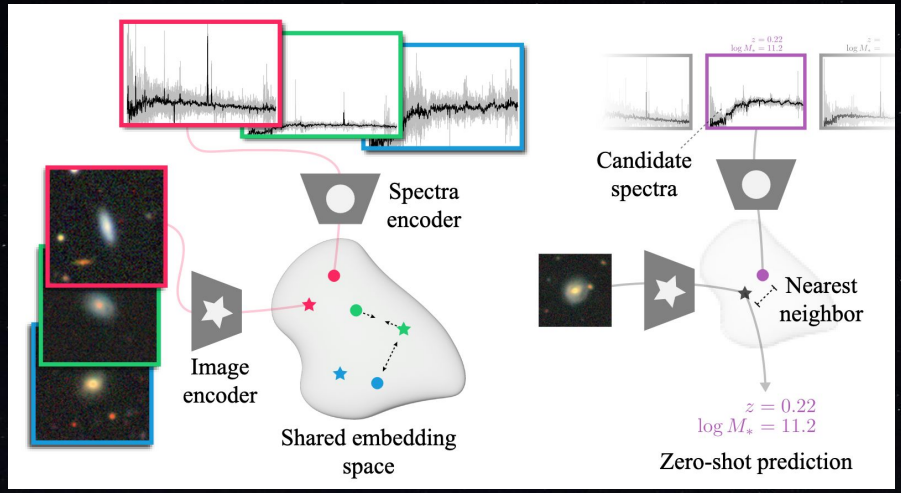
Identification of multi-component LOFAR sources with multi-modal deep learning (Alegre et al. 2024)



Images + Set of Features (tabular data)

Further Applications of Multimodal Learning in Astronomy

AstroCLIP: A Cross-Modal Foundation Model for Galaxies (Parker et al. 2024)



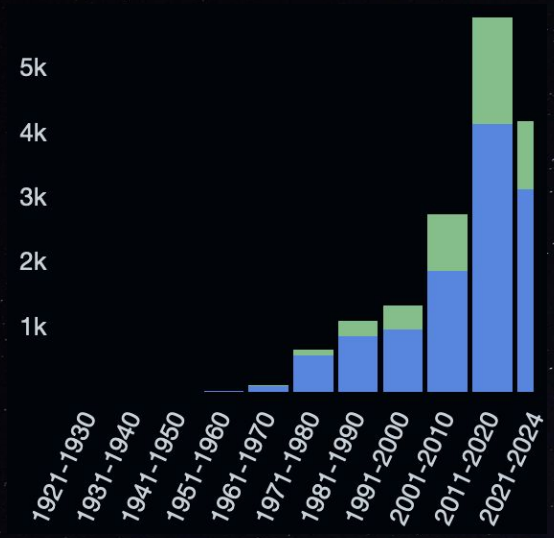
Image's + Spectra for several tasks

Honorable mention:

Multimodal photometry and spectroscopy: a new approach to data analysis in Astrophysics

Sonification software for **multi-sensory** astronomical data for the visually impaired

Further Applications of Multimodal Learning in Astronomy



Papers on ADS with the keyword “multimodal” in their title and/or abstract

Booming right now!

I invite you to think multimodal-ly ✨

Summary

- BAL QSOs are key for galaxy evolution
- Spectra+lc classifier with Balanced Random Forests and late fusion shows potential
- Spectra+lc modality-attentive dense NNs with multiplicative fusion: results are limited by small and imbalanced dataset

Which fusion technique to use is a key but challenging choice

Multimodal learning is *booming* in astronomy

Thank you!

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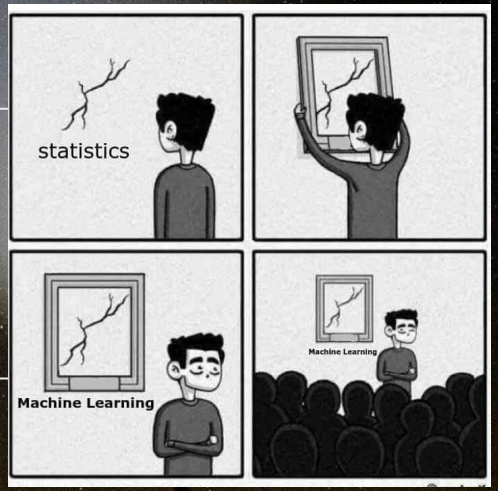
GitHub @**NicoGalvarino**

Research Survival Git
(feel free to contribute!)



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