
THE SHAPE OF ECCENTRICITY

*Rapid Classification of Eccentric
Binaries with the Wavelet
Scattering Transform*

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St. Edmund's College



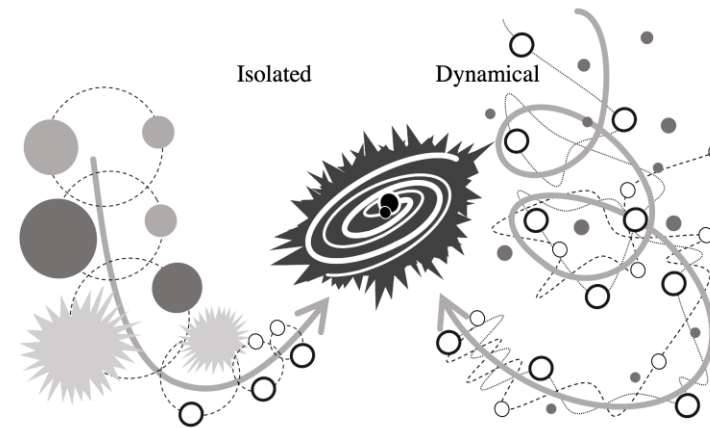
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ECENTRICITY

- **Astrophysical implications**
 - Formation channels

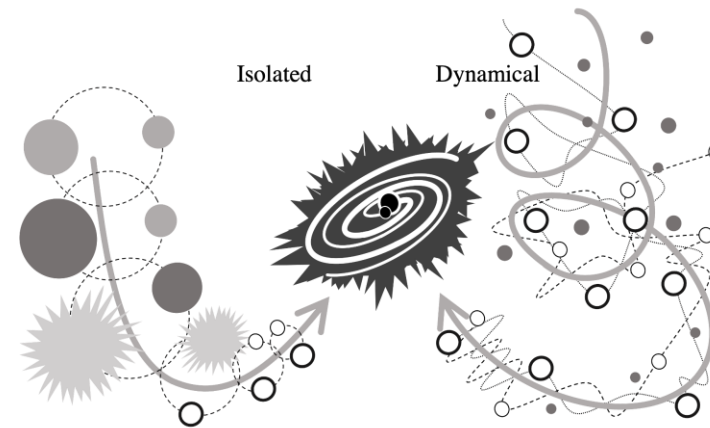


Credit: I. R.-S.

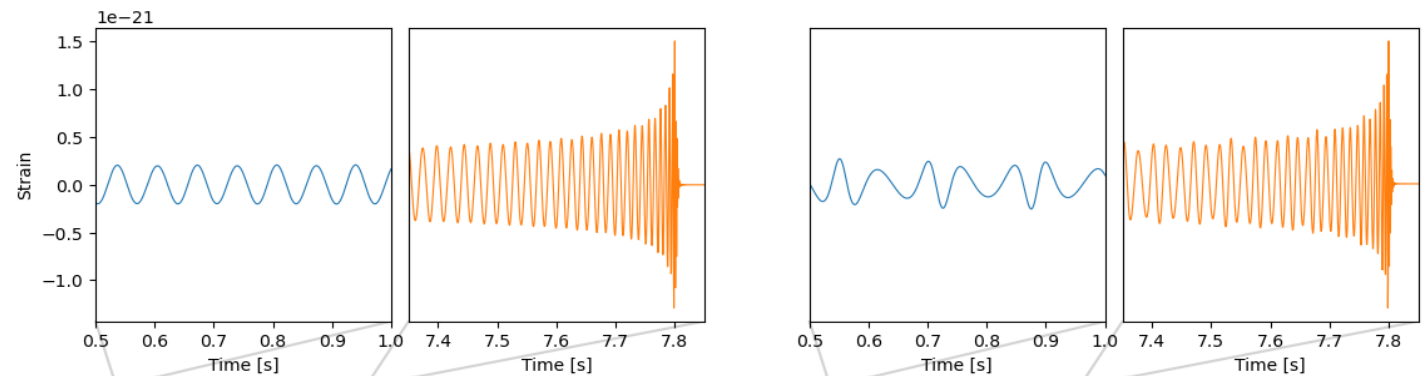


ECCENTRICITY

- **Astrophysical implications**
 - Formation channels
- **Modulations** in waveform amplitude and frequency

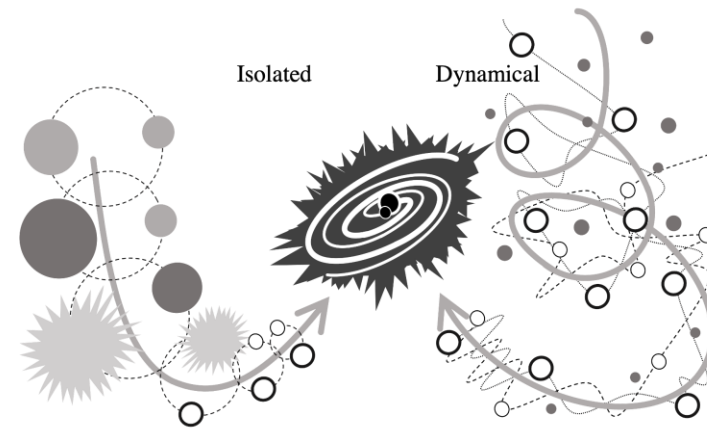


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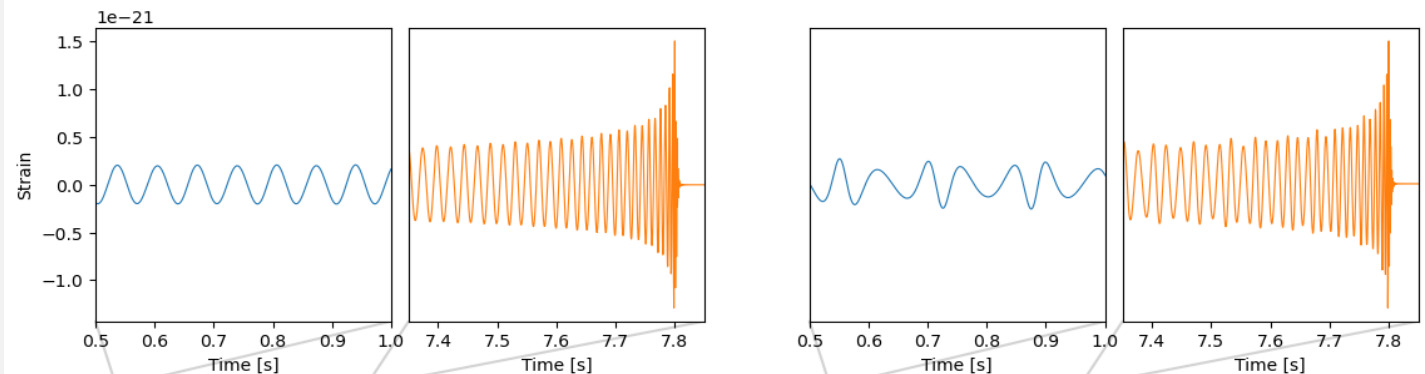


ECCENTRICITY

- **Astrophysical implications**
 - Formation channels
- **Modulations** in waveform amplitude and frequency
- **LVK analyses** have not fully included eccentricity thus far
 - Computational cost
 - Waveform development lag
 - Increasing detection rate
- **GOAL: rapid flagging of promising candidates**
 - Machine learning [Ravichandran+2024]

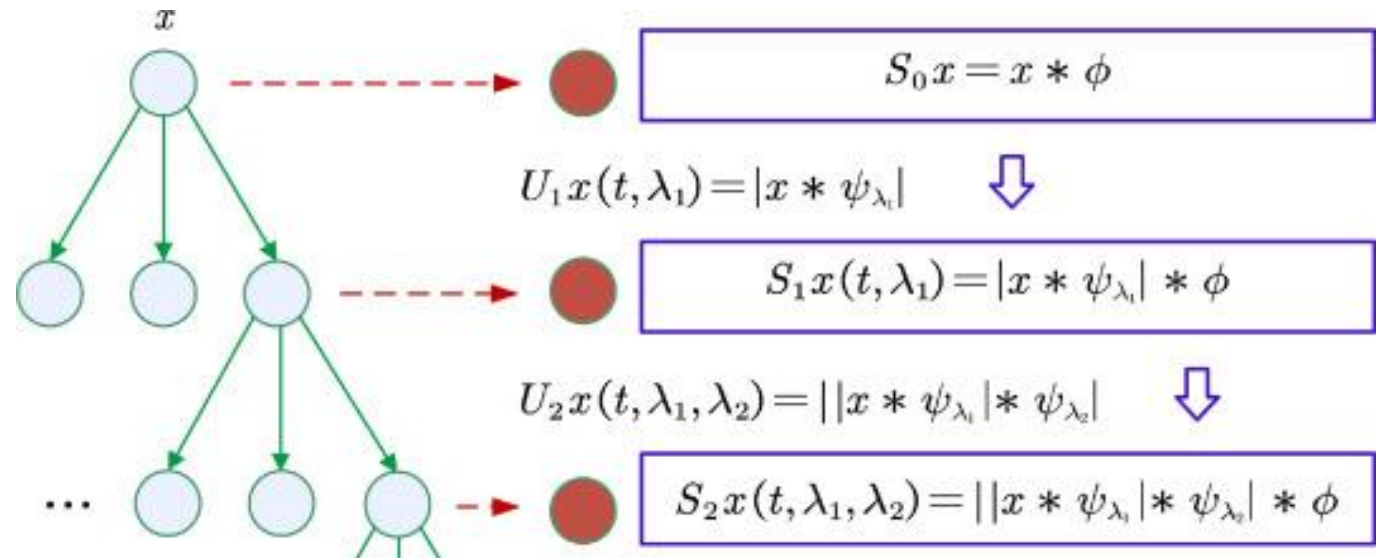
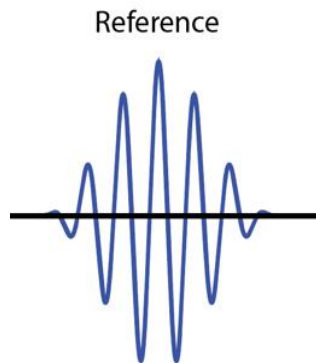


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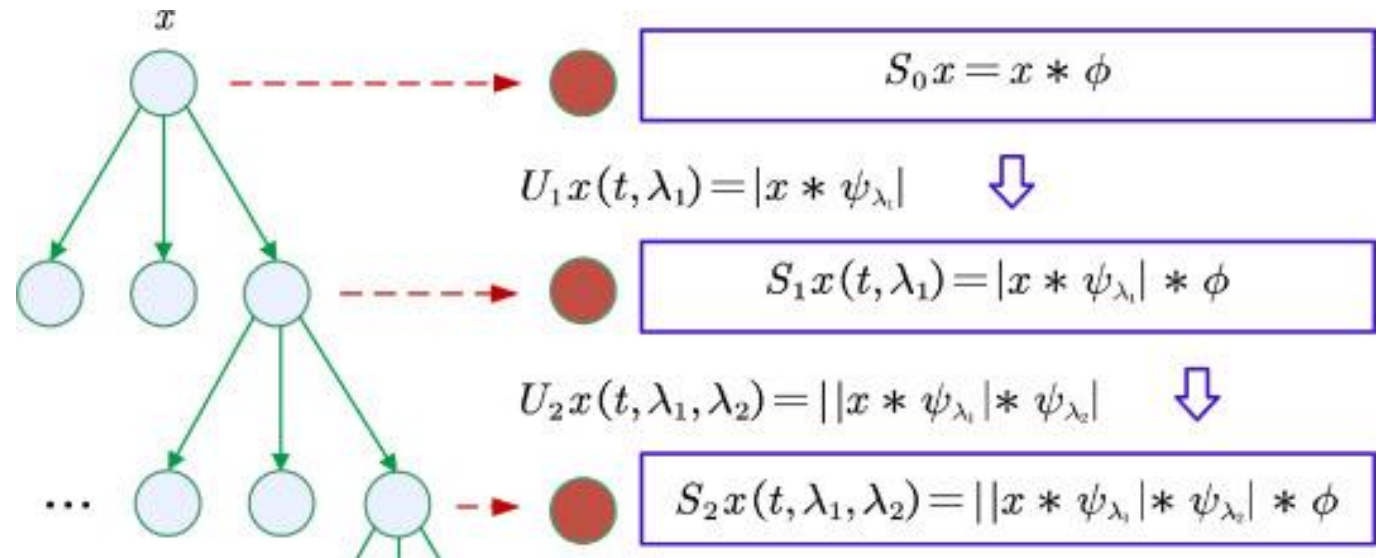
WAVELET SCATTERING TRANSFORM [MALLAT+2012, BRUNA+2012]

- **Time frequency representation** of time series, like a spectrogram
- **Hierarchical** convolutions + modulus
 - o Base wavelet + averaging window

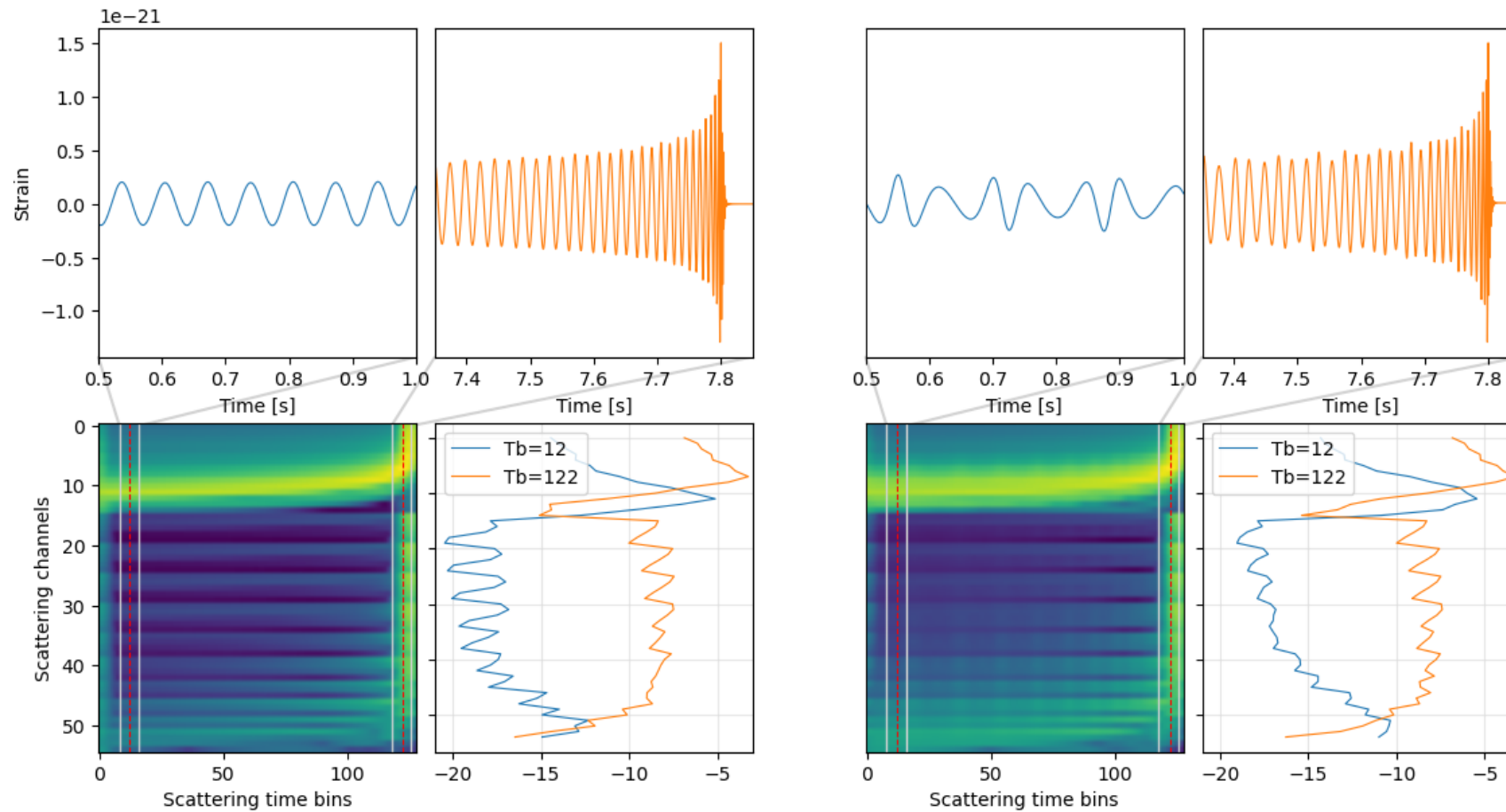


WAVELET SCATTERING TRANSFORM [MALLAT+2012, BRUNA+2012]

- **Time frequency representation** of time series, like a spectrogram
- **Hierarchical** convolutions + modulus
 - o Base wavelet + averaging window
- **Localised** structure + **cross-scale** interactions
- **Compression + stability**
- **Kymatio** package



WAVELET SCATTERING TRANSFORM

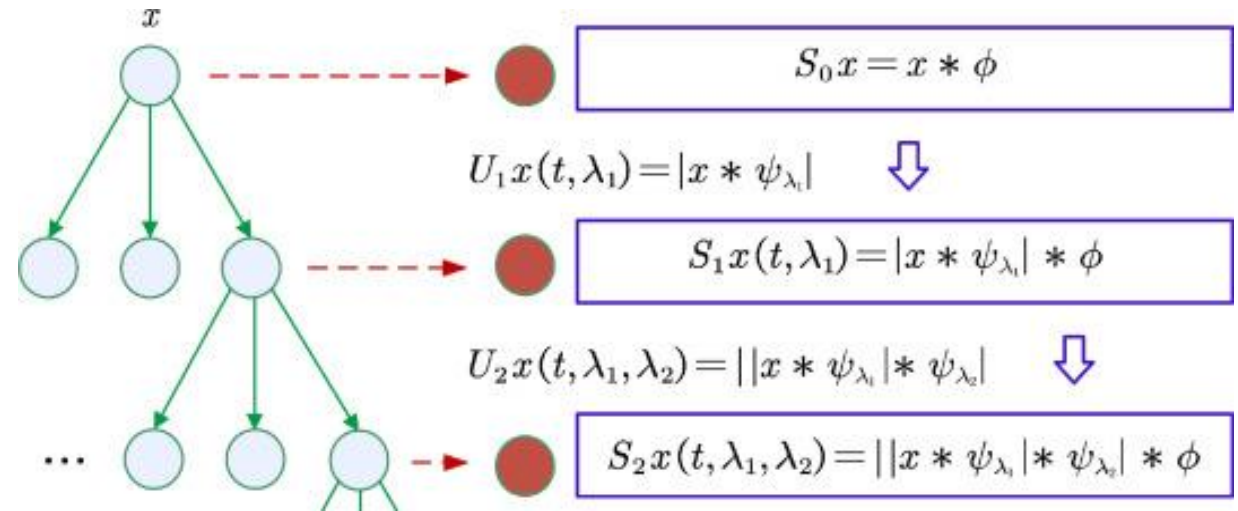


WAVELET SCATTERING TRANSFORM [MALLAT+2012, BRUNA+2012]

Already used for

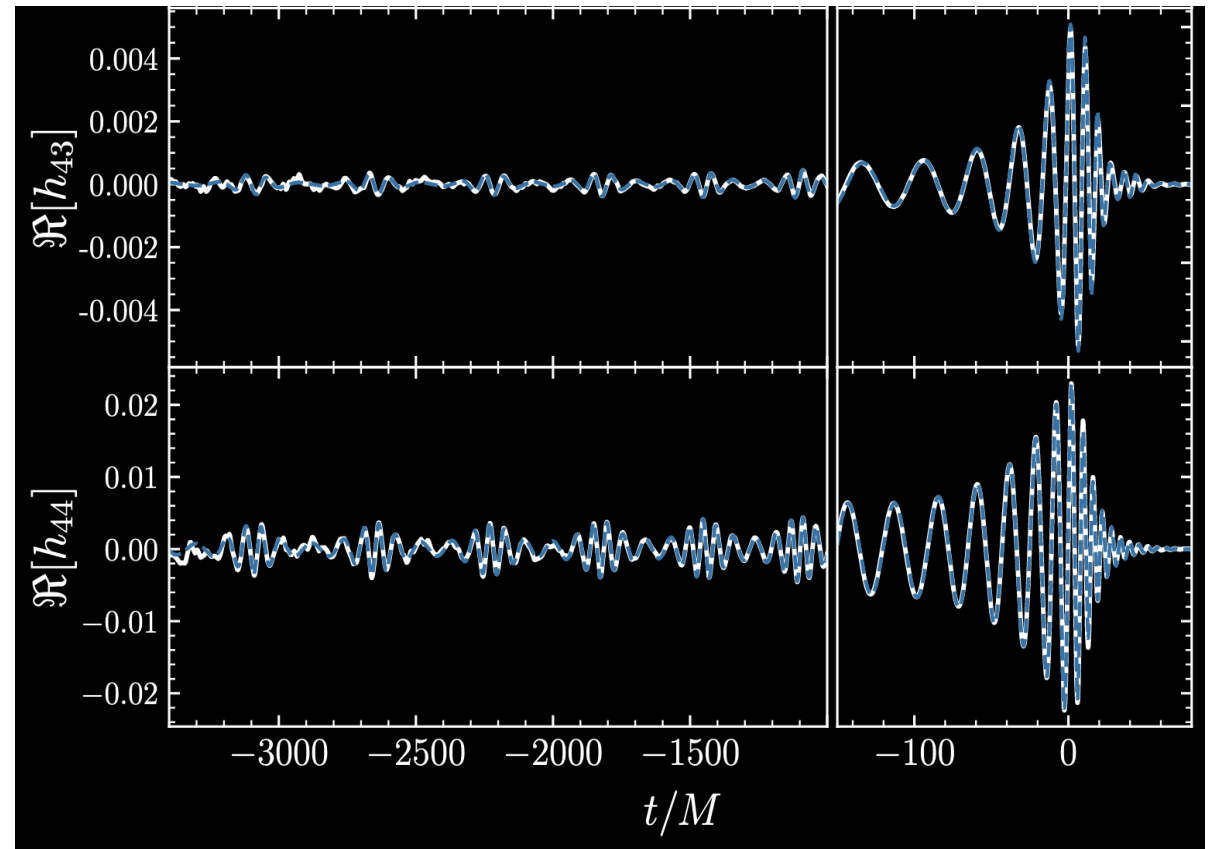
- **glitch** characterization [Licciardi+ 25]
- **Cosmology** [Cheng+ 20, 21; Valogiannis+ 22, 24; Shimabukuro+ 25]
 - Particularly of interest for non-Gaussianities
- Metrology, finance, image analysis...

Higher-dimensional analogues exist



WAVEFORMS

- **SEOBNRv5EHM** [Gamboa+2024]
 - Higher order modes (6 total)
 - Aligned spins
 - Recently v6, EPHM
- **Bilby** [Ashton+2019, Romero-Shaw+2020]
 - Default* priors
 - 10 – 40 M components
 - Luminosity distance [100,800] Mpc
 - Ecc. at 10 Hz uniformly sampled in two classes
 - Threshold 0.01
 - Gaussian noise
 - 8s retained, merger at 7.8s

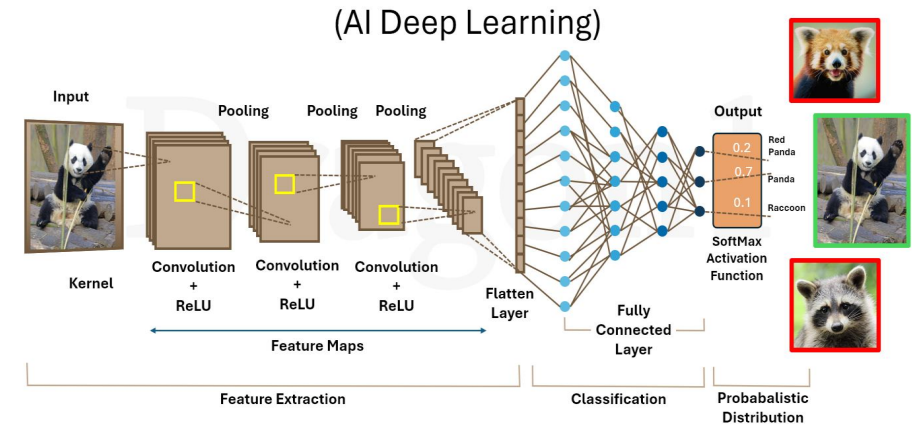


(Gamboa+)



CLASSIFIERS

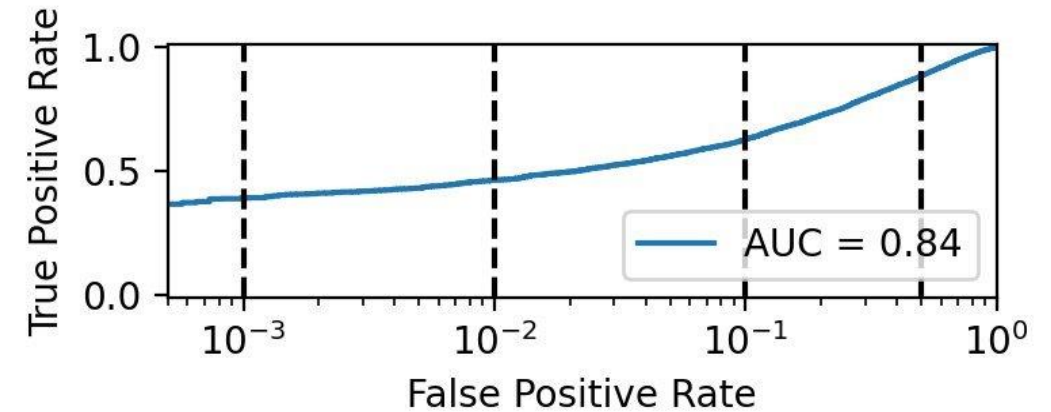
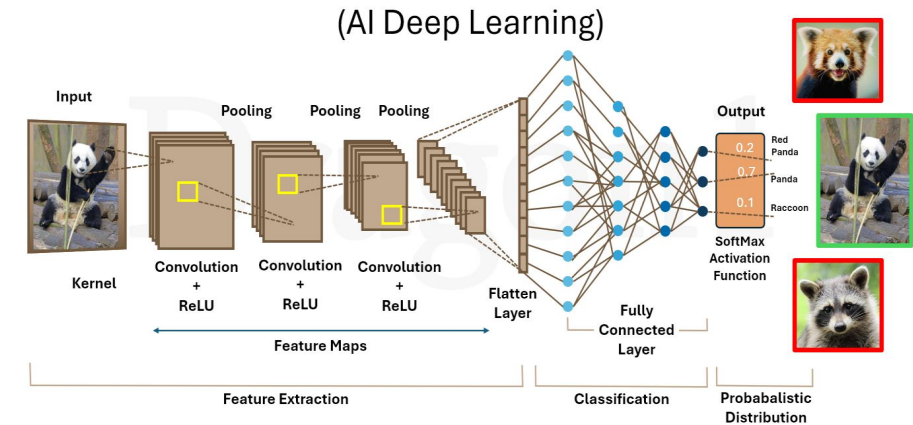
- 1D CNN
 - Shared across detectors,
 - Exploit temporal structure



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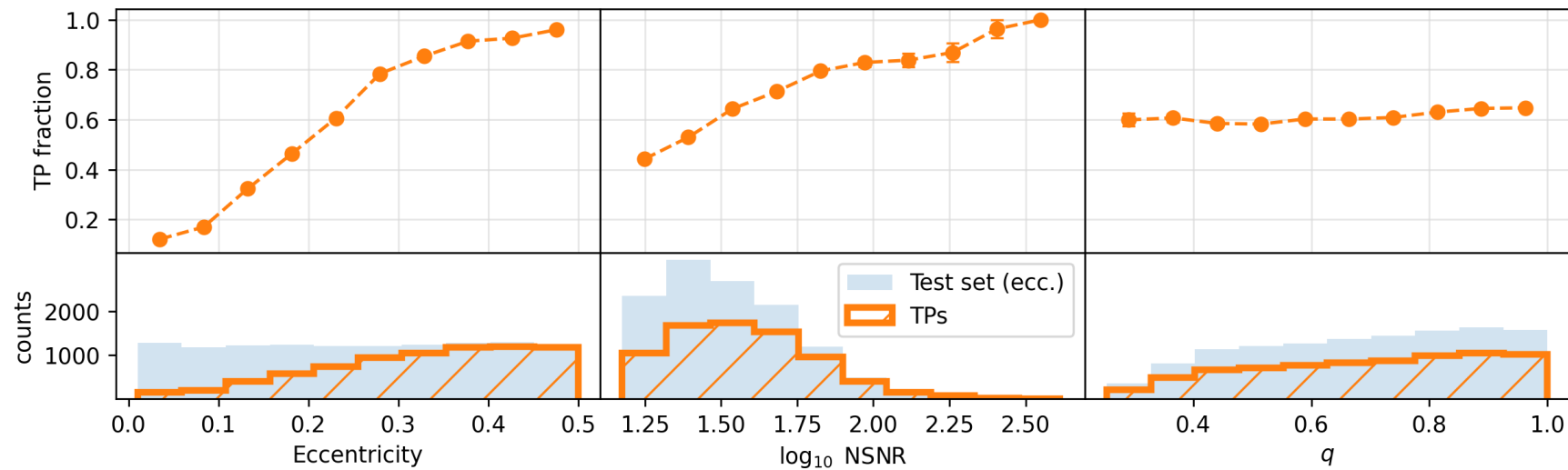
- 1D CNN
 - Shared across detectors,
 - Exploit temporal structure
- Criteria:
 - AUC, AP
 - TPR @ target FPR

(J, Q)	AUC	AP	TPR _{0.1}
(7, 2)	0.844	0.876	0.636
(8, 2)	0.832	0.863	0.597
(6, 2)	0.845	0.876	0.622



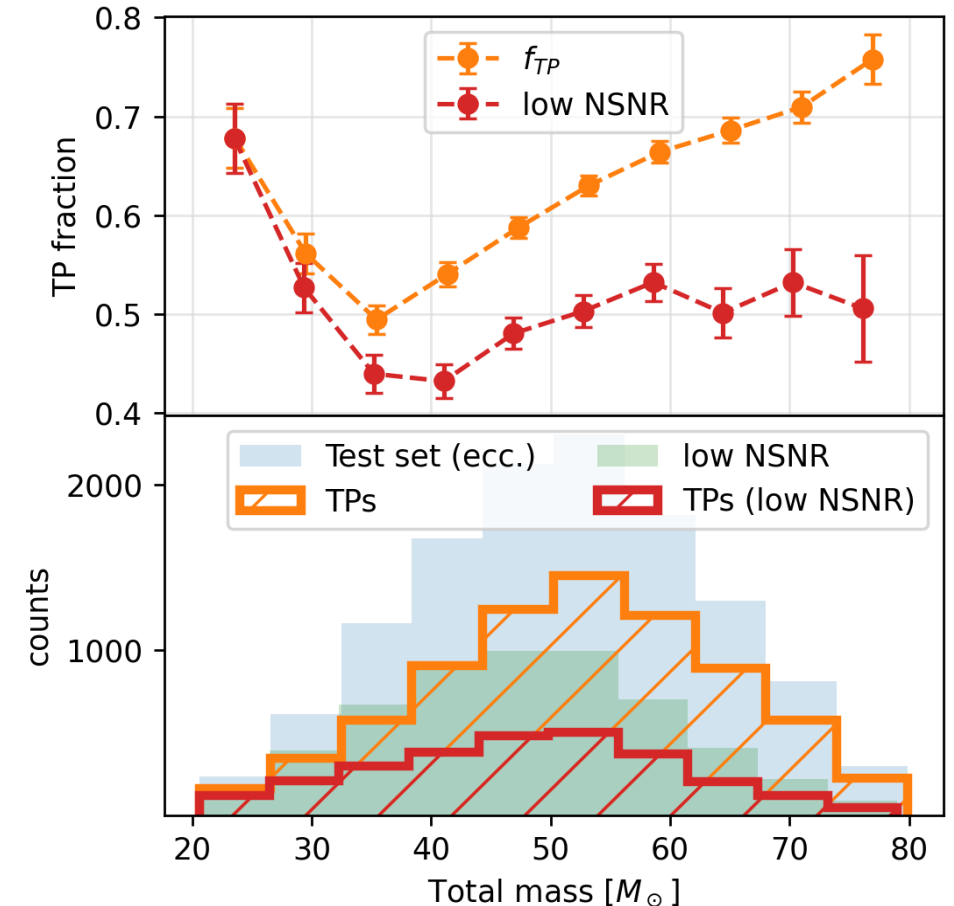
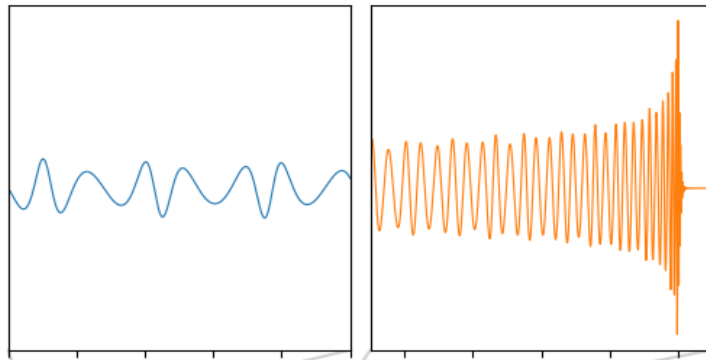
PERFORMANCE

- **Higher eccentricity** is easier to detect
- **SNR** very important, **mass ratio** is not
- **(2,2) multipole** seems to suffice (e.g. also Tang+2026)



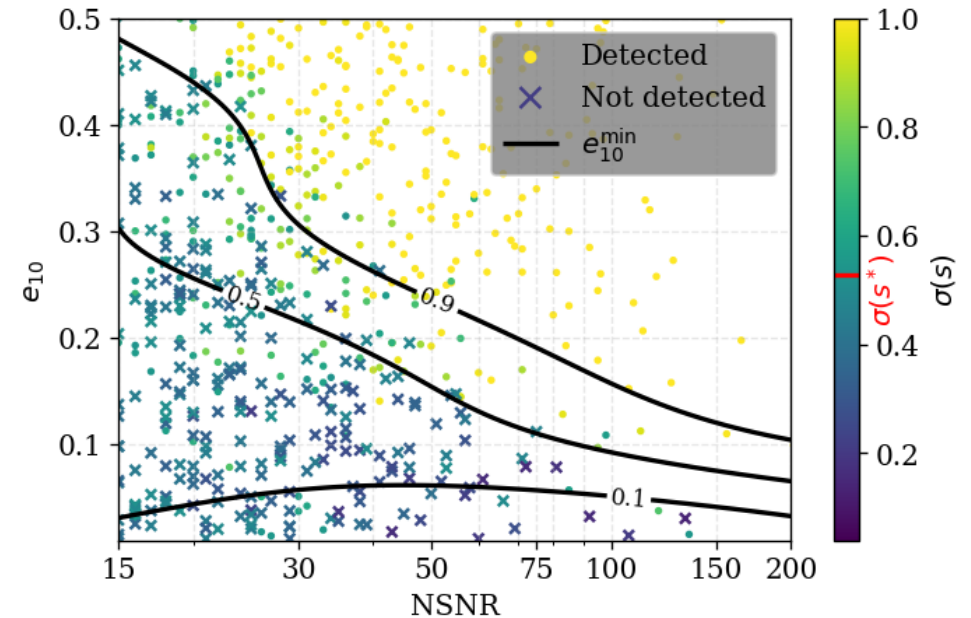
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- **Low mass** harder to detect ??
 - Eccentricity defined at 10 Hz
 - Correlation mass and SNR



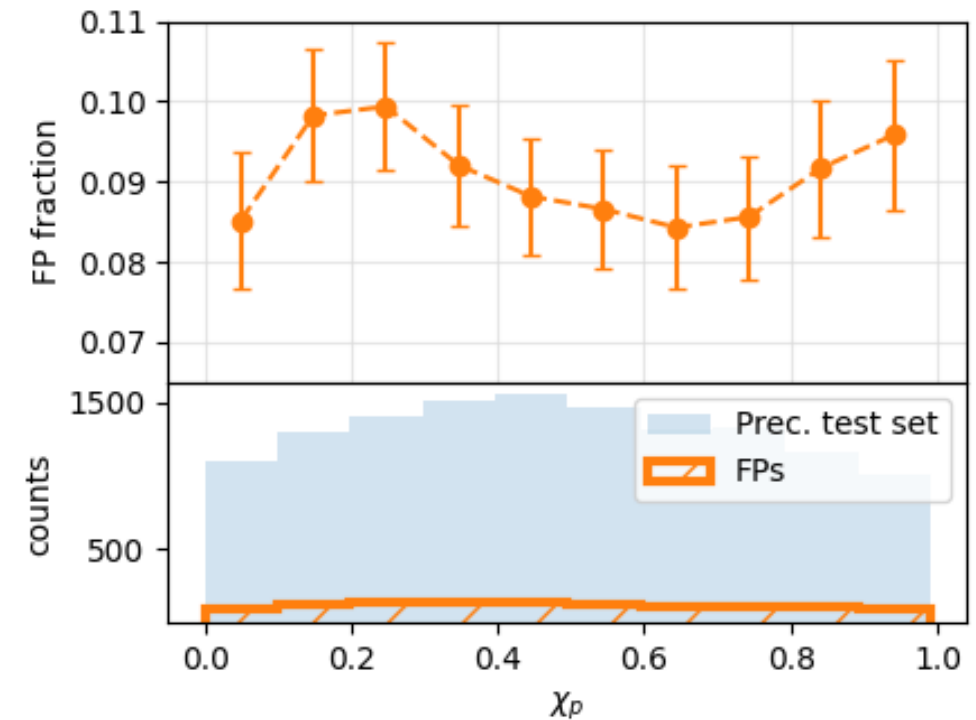
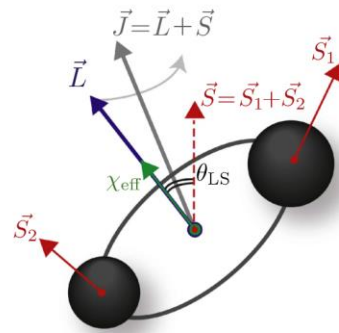
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 - Eccentricity defined at 10 Hz
 - Correlation mass and SNR
- Estimate **minimum detectable eccentricity**



PRECESSION

- Test set generated with SEOBNRv5PHM
- **Seemingly no confusion due to precession**
 - o No significant degeneracy? (see e.g. Tibrewal+2026)
- False positive rate consistent with target FAR



CONCLUSIONS

- Demonstrated that the **Wavelet Scattering Transform** can extract eccentricity-dependent features
- Designed simple and efficient classifiers to rapidly **identify promising candidates** for downstream analyses
- Commented on the influence of **core physical parameters**
- **No confusion with spin-induced precession** in our tests



FUTURE IMPROVEMENTS

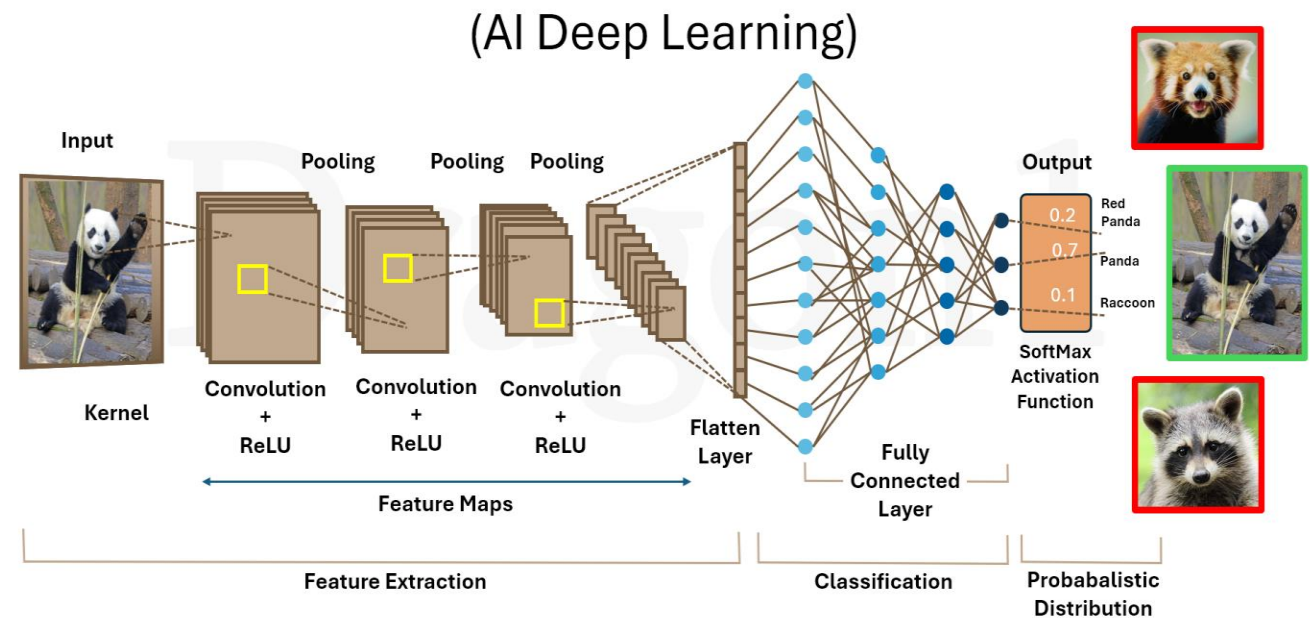
- Identified the **need for a better definition** of eccentricity in our pipeline
 - Not at 10 Hz, if we keep a fixed time window
- Mass-dependent and multiscale scattering transforms?
- Apply to LVK data
- Consider the WST for your own problems!



BACK UP SLIDES

CLASSIFIERS

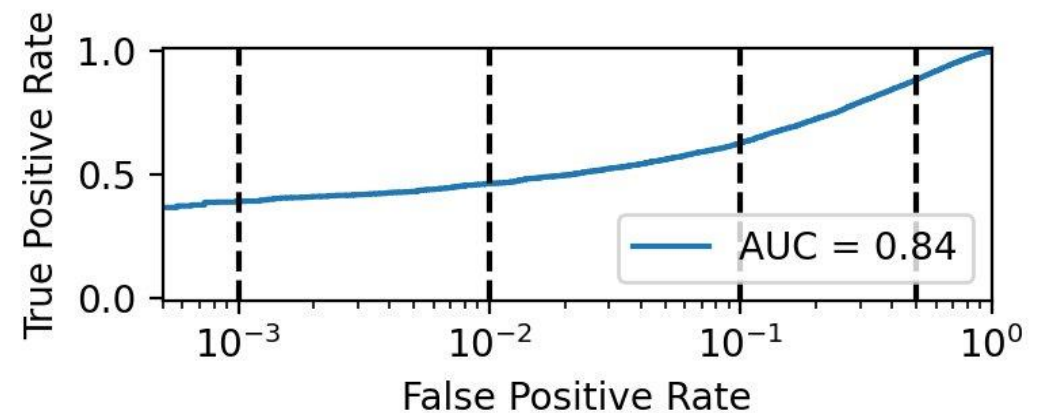
- **Logistic Regression**
 - Simple
 - Look for informative features
- **1D CNN**
 - Shared across detectors,
 - Exploit temporal structure
- **2D CNN**
 - Exploit detector differences
 - Image analogy – 3 filters

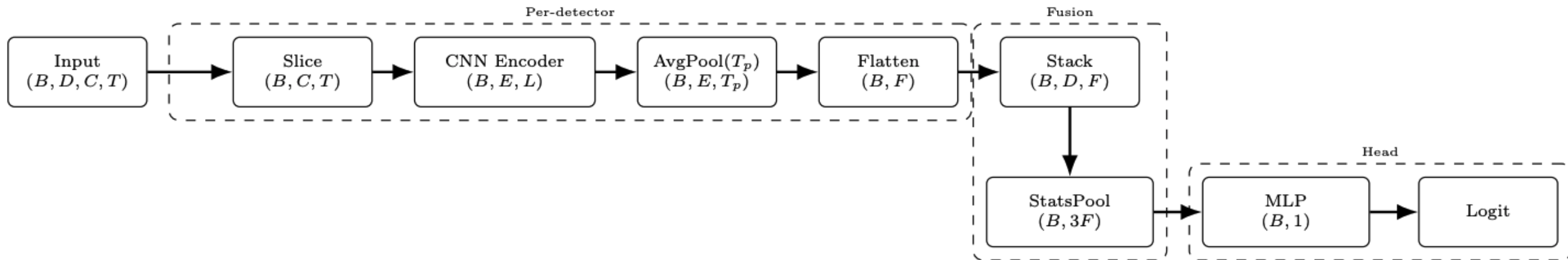


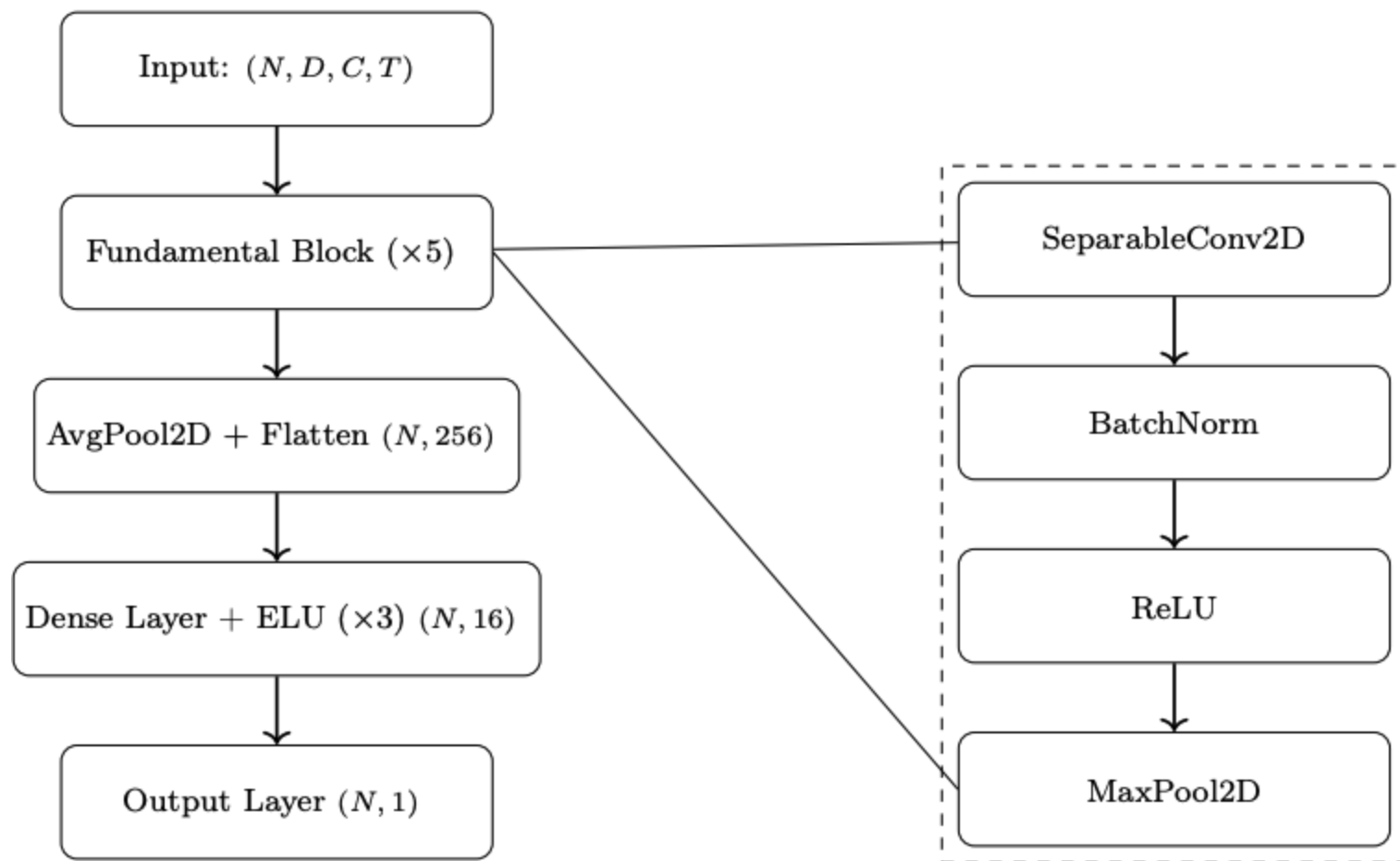
CLASSIFIERS

- **Logistic Regression**
 - Simple
 - Look for informative features
- **1D CNN**
 - Shared across detectors,
 - Exploit temporal structure
- **2D CNN**
 - Exploit detector differences
 - Image analogy – 3 filters
- **Criteria:**
 - AUC
 - TPR @ target FPR
- **1D CNN preferred**

Model	AUC	TPR _{0.1}
Log Reg	0.815	0.562
1D-CNN		
(J, Q) = (7, 2)	0.844	0.636
(J, Q) = (8, 2)	0.832	0.597
(J, Q) = (6, 2)	0.845	0.622
2D CNN		
Log-scale	0.841	0.630
Raw	0.814	0.563
Large	0.826	0.580







Target FAR=0.1

True	quasi-circular $e_{10} \leq e_{10}^{\text{thr}}$	10996 89.6%	1273 10.4%
	eccentric $e_{10} > e_{10}^{\text{thr}}$	4488 36.4%	7847 63.6%
		quasi-circular $e_{10} \leq e_{10}^{\text{thr}}$	eccentric $e_{10} > e_{10}^{\text{thr}}$
		Predicted	

TABLE II. Comparison of detection performance for WST data computed on the same dataset, but with $Q = 1, 2$ and fixed $J = 7$. Shown are the mean and standard deviation across $K = 10$ folds. Results are obtained with the 1D-CNN model. The relative difference is given by $\Delta = ((M_{Q=2} - M_{Q=1})/M_{Q=1}) \times 100$ computed using the column means.

	Q = 2	Q = 1	$\Delta\%$
Validation AUC	0.829 ± 0.010	0.823 ± 0.004	+0.73
Validation AP	0.862 ± 0.010	0.856 ± 0.004	+0.70
Test AUC	0.831 ± 0.011	0.824 ± 0.003	+0.85
Test AP	0.863 ± 0.010	0.856 ± 0.003	+0.82
Validation TPR			
FAR 0.1	0.599 ± 0.023	0.580 ± 0.011	+3.28
FAR 0.01	0.422 ± 0.026	0.408 ± 0.014	+3.43
FAR 0.001	0.333 ± 0.033	0.326 ± 0.025	+2.15
Test TPR			
FAR 0.1	0.600 ± 0.028	0.585 ± 0.010	+2.56
FAR 0.01	0.424 ± 0.026	0.411 ± 0.012	+3.16
FAR 0.001	0.337 ± 0.032	0.331 ± 0.024	+1.81

TABLE IV. Performance comparison for quadrupole-only vs. full (all-modes) model using the 1D-CNN. Results are reported over $K = 10$ folds. Values are mean and standard deviation across folds. The relative difference is defined as $\Delta = [(M_{\text{quad}} - M_{\text{all}})/M_{\text{all}}] \times 100$, computed using the column means.

	Quadrupole	All modes	$\Delta(\%)$
Validation AUC	0.831 ± 0.015	0.829 ± 0.010	+0.24
Validation AP	0.864 ± 0.014	0.862 ± 0.010	+0.23
Test AUC	0.828 ± 0.013	0.831 ± 0.011	-0.36
Test AP	0.861 ± 0.012	0.863 ± 0.010	-0.23
Validation TPR			
FAR 0.1	0.61 ± 0.03	0.60 ± 0.02	+1.67
FAR 0.01	0.43 ± 0.04	0.42 ± 0.03	+2.38
FAR 0.001	0.34 ± 0.04	0.33 ± 0.03	+3.03
Test TPR			
FAR 0.1	0.60 ± 0.03	0.60 ± 0.03	+0.00
FAR 0.01	0.43 ± 0.04	0.42 ± 0.03	+2.38
FAR 0.001	0.34 ± 0.04	0.34 ± 0.03	+0.00

PERFORMANCE

- **Higher eccentricity** is easier to detect
- **SNR** is most important
- **(2,2) multipole** seems to suffice (e.g. also Tang+2026)
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