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Dark Wave

NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

Einstein Telescope: Detection of Binary Black Hole Gravitational Wave Signals Using Deep Learning

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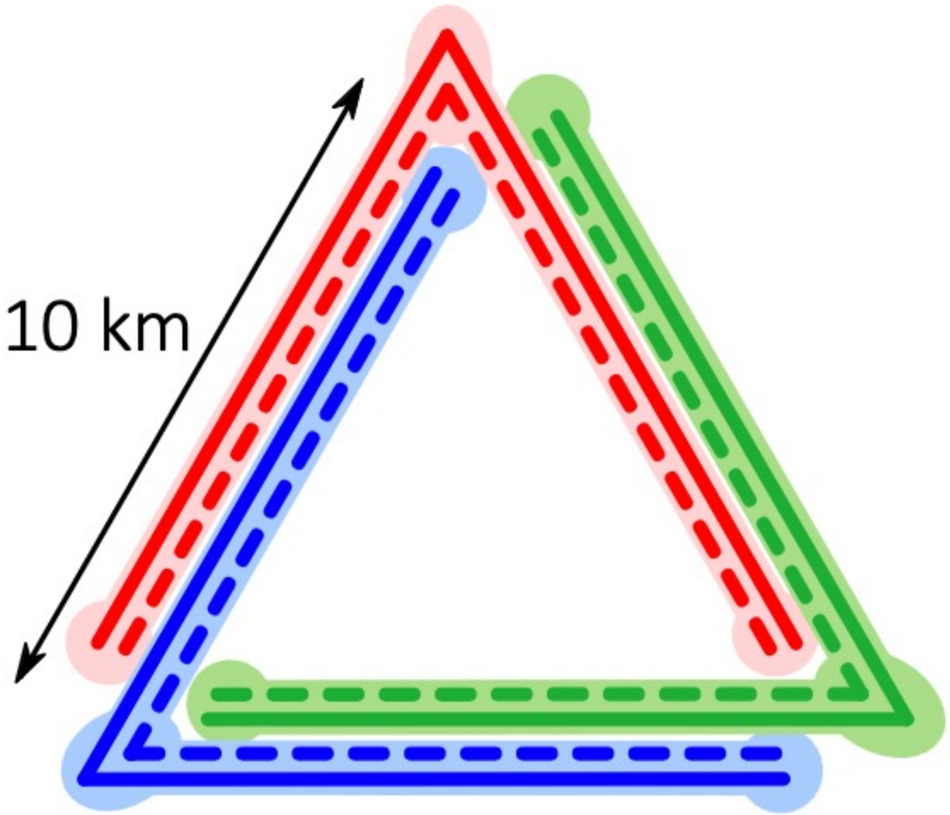
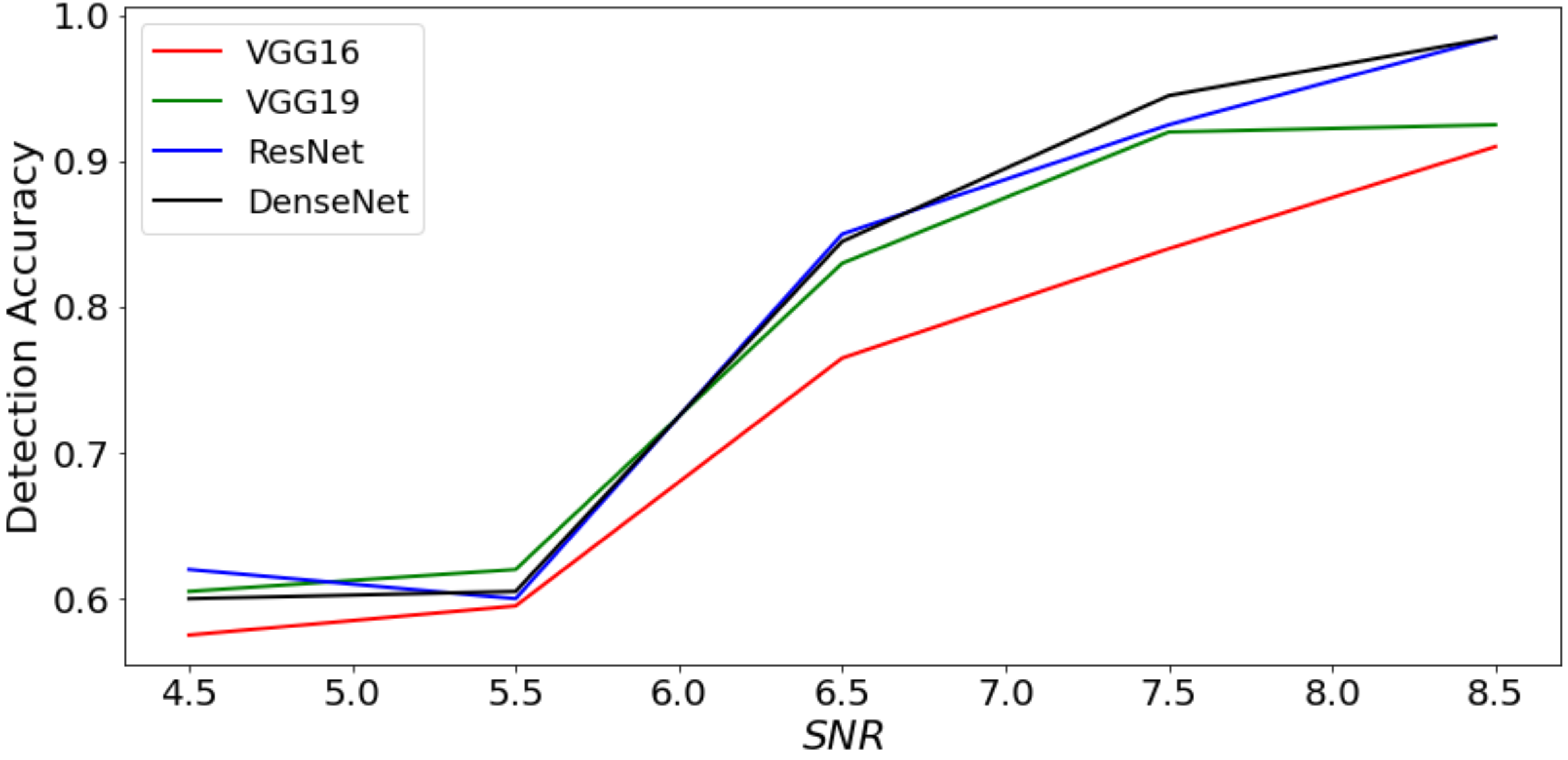
3^{rd} generation detectors – Einstein Telescope (ET)

- ET will consist of three nested detectors (shown in blue, green and red) in a triangular arrangement.
- Each detector consists of two interferometers, one optimised for low-frequency (solid) and one for high-frequency sensitivity (dashed).



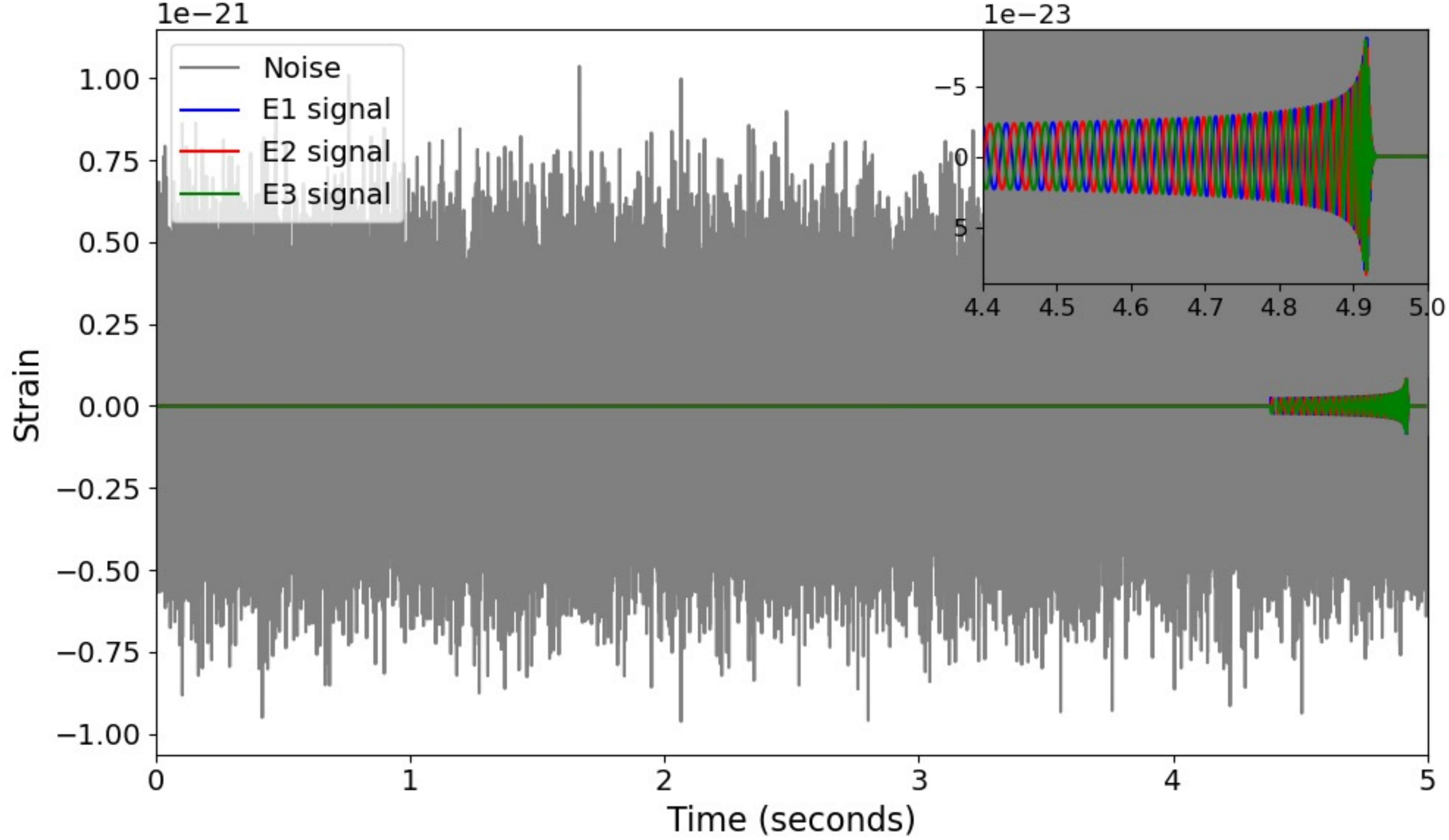
Credit: et-gw.eu

Single sub-detector

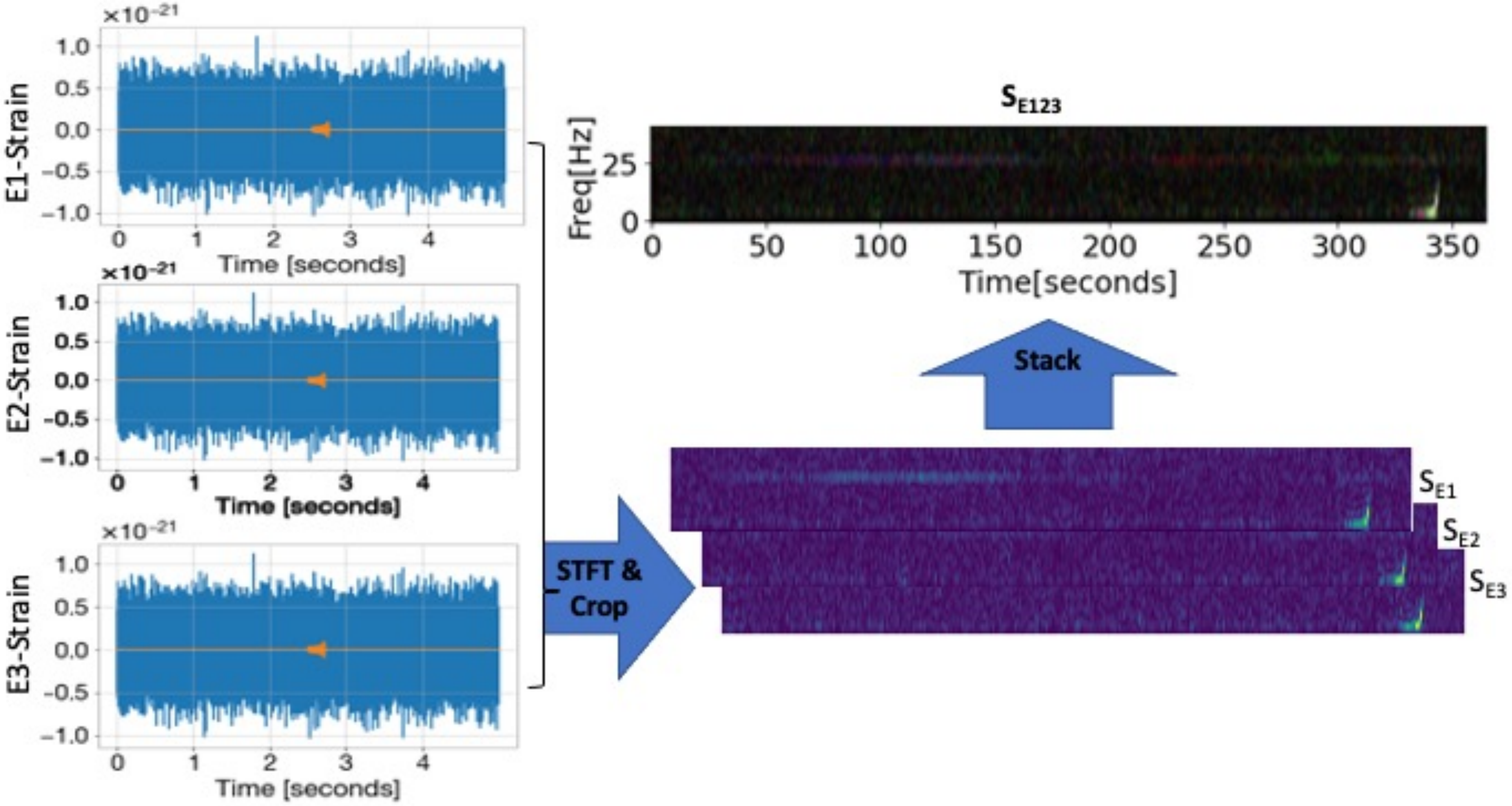


Alhassan et al. (2022), MNRAS

Sub-detectors combined data

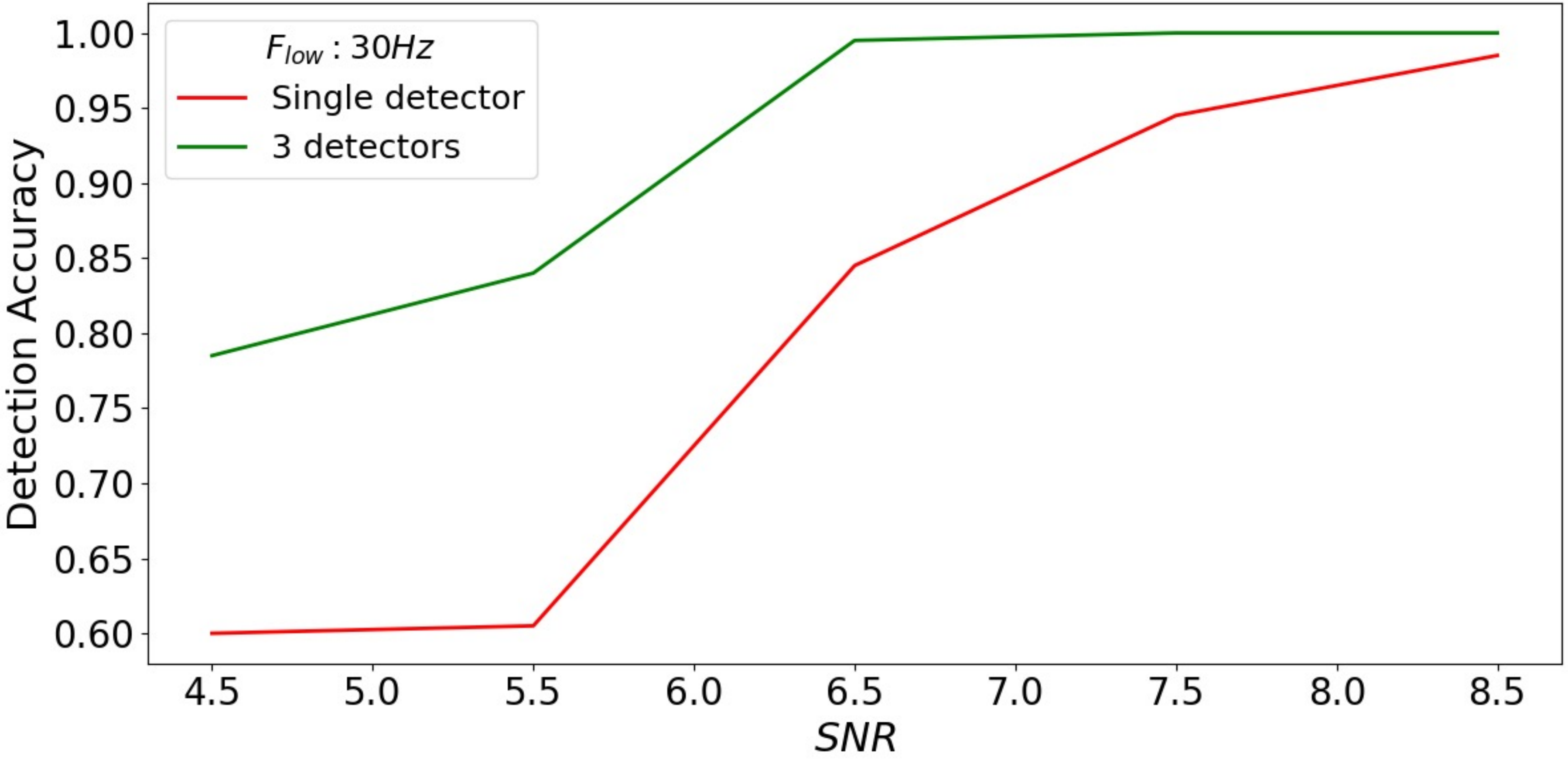


Sub-detectors combined data



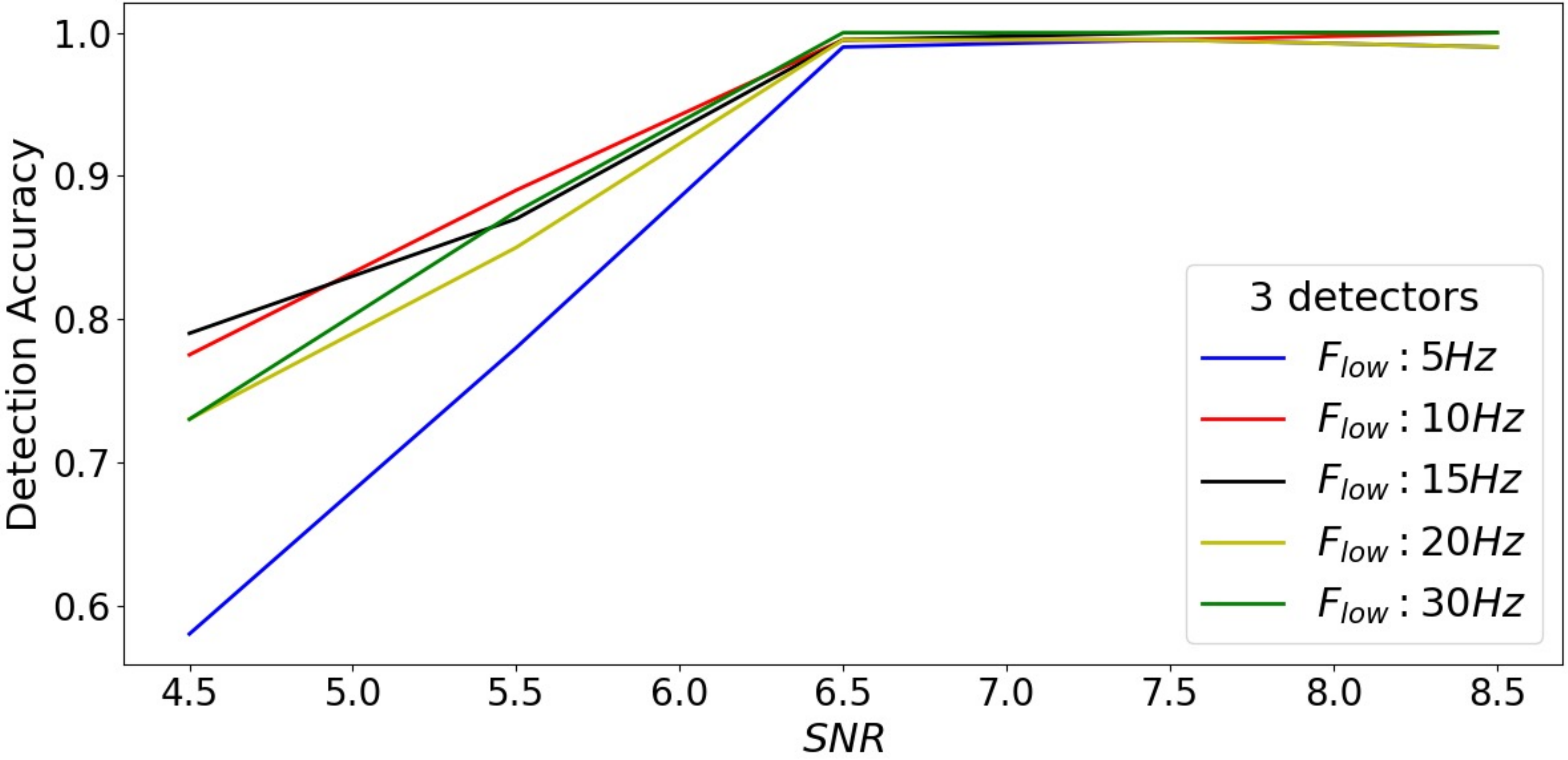
Pre-processing

Results



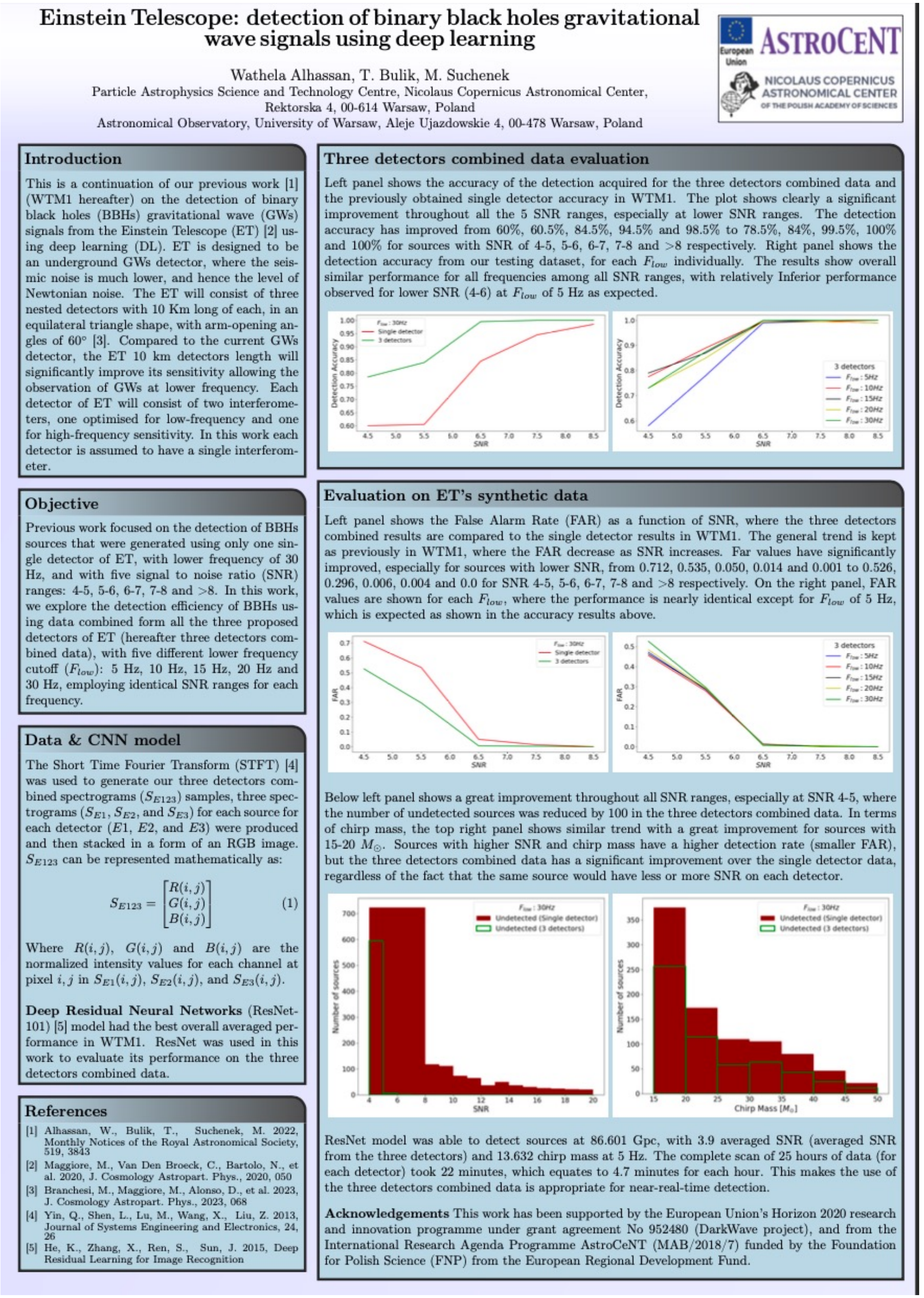
Single detector (Alhassan et al. (2022)) versus all three detectors combined for sources with $Flow$ of 30 $H z$.

Results



Three sub-detectors combined for sources with F_{low} of 5 Hz, 10 Hz, 15 Hz, 20 Hz and 30 Hz.

- ➢ Presented at NeurIPS'23
- ➢ Submitted to A&A



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Introduction

This is a continuation of our previous work [1] (WTM1 hereafter) on the detection of binary black holes (BBHs) gravitational wave (GWs) signals from the Einstein Telescope (ET) [2] using deep learning (DL). ET is designed to be an underground GWs detector, where the seismic noise is much lower, and hence the level of Newtonian noise. The ET will consist of three nested detectors with 10 Km long of each, in an equilateral triangle shape, with arm-opening angles of 60° [3]. Compared to the current GWs detector, the ET 10 km detectors length will significantly improve its sensitivity allowing the observation of GWs at lower frequency. Each detector of ET will consist of two interferometers, one optimised for low-frequency and one for high-frequency sensitivity. In this work each detector is assumed to have a single interferometer.

Objective

Previous work focused on the detection of BBHs sources that were generated using only one single detector of ET, with lower frequency of 30 Hz, and with five signal to noise ratio (SNR) ranges: 4-5, 5-6, 6-7, 7-8 and >8. In this work, we explore the detection efficiency of BBHs using data combined form all the three proposed detectors of ET (hereafter three detectors combined data), with five different lower frequency cutoff (F_{low}): 5 Hz, 10 Hz, 15 Hz, 20 Hz and 30 Hz, employing identical SNR ranges for each frequency.

Data & CNN model

The Short Time Fourier Transform (STFT) [4] was used to generate our three detectors combined spectrograms (S_{E123}) samples, three spectrograms (S_{E1}, S_{E2}, and S_{E3}) for each source for each detector ($E1$, $E2$, and $E3$) were produced and then stacked in a form of an RGB image. S_{E123} can be represented mathematically as:

$$S_{E123} = \begin{bmatrix} R(i,j) \\ G(i,j) \\ B(i,j) \end{bmatrix} \quad (1)$$

Where $R(i,j)$, $G(i,j)$ and $B(i,j)$ are the normalized intensity values for each channel at pixel i,j in $S_{E1}(i,j)$, $S_{E2}(i,j)$, and $S_{E3}(i,j)$.

Deep Residual Neural Networks (ResNet-101) [5] model had the best overall averaged performance in WTM1. ResNet was used in this work to evaluate its performance on the three detectors combined data.

References

[1] Alhassan, W., Bulik, T., Suchenek, M. 2022, Monthly Notices of the Royal Astronomical Society, 519, 3843

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[3] Branchesi, M., Maggiore, M., Alonso, D., et al. 2023, J. Cosmology Astropart. Phys., 2023, 068

[4] Yin, Q., Shen, L., Lu, M., Wang, X., Liu, Z. 2013, Journal of Systems Engineering and Electronics, 24, 26

[5] He, K., Zhang, X., Ren, S., Sun, J. 2015, Deep Residual Learning for Image Recognition

Three detectors combined data evaluation

Left panel shows the accuracy of the detection acquired for the three detectors combined data and the previously obtained single detector accuracy in WTM1. The plot shows clearly a significant improvement throughout all the 5 SNR ranges, especially at lower SNR ranges. The detection accuracy has improved from 60%, 60.5%, 84.5%, 94.5% and 98.5% to 78.5%, 84%, 99.5%, 100% and 100% for sources with SNR of 4-5, 5-6, 6-7, 7-8 and >8 respectively. Right panel shows the detection accuracy from our testing dataset, for each F_{low} individually. The results show overall similar performance for all frequencies among all SNR ranges, with relatively Inferior performance observed for lower SNR (4-6) at F_{low} of 5 Hz as expected.

Evaluation on ET's synthetic data

Left panel shows the False Alarm Rate (FAR) as a function of SNR, where the three detectors combined results are compared to the single detector results in WTM1. The general trend is kept as previously in WTM1, where the FAR decrease as SNR increases. Far values have significantly improved, especially for sources with lower SNR, from 0.712, 0.535, 0.050, 0.014 and 0.001 to 0.526, 0.296, 0.006, 0.004 and 0.0 for SNR 4-5, 5-6, 6-7, 7-8 and >8 respectively. On the right panel, FAR values are shown for each F_{low}, where the performance is nearly identical except for F_{low} of 5 Hz, which is expected as shown in the accuracy results above.

Below left panel shows a great improvement throughout all SNR ranges, especially at SNR 4-5, where the number of undetected sources was reduced by 100 in the three detectors combined data. In terms of chirp mass, the top right panel shows similar trend with a great improvement for sources with 15-20 $M_\odot$. Sources with higher SNR and chirp mass have a higher detection rate (smaller FAR), but the three detectors combined data has a significant improvement over the single detector data, regardless of the fact that the same source would have less or more SNR on each detector.

ResNet model was able to detect sources at 86.601 Gpc, with 3.9 averaged SNR (averaged SNR from the three detectors) and 13.632 chirp mass at 5 Hz. The complete scan of 25 hours of data (for each detector) took 22 minutes, which equates to 4.7 minutes for each hour. This makes the use of the three detectors combined data is appropriate for near-real-time detection.

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Thank you!