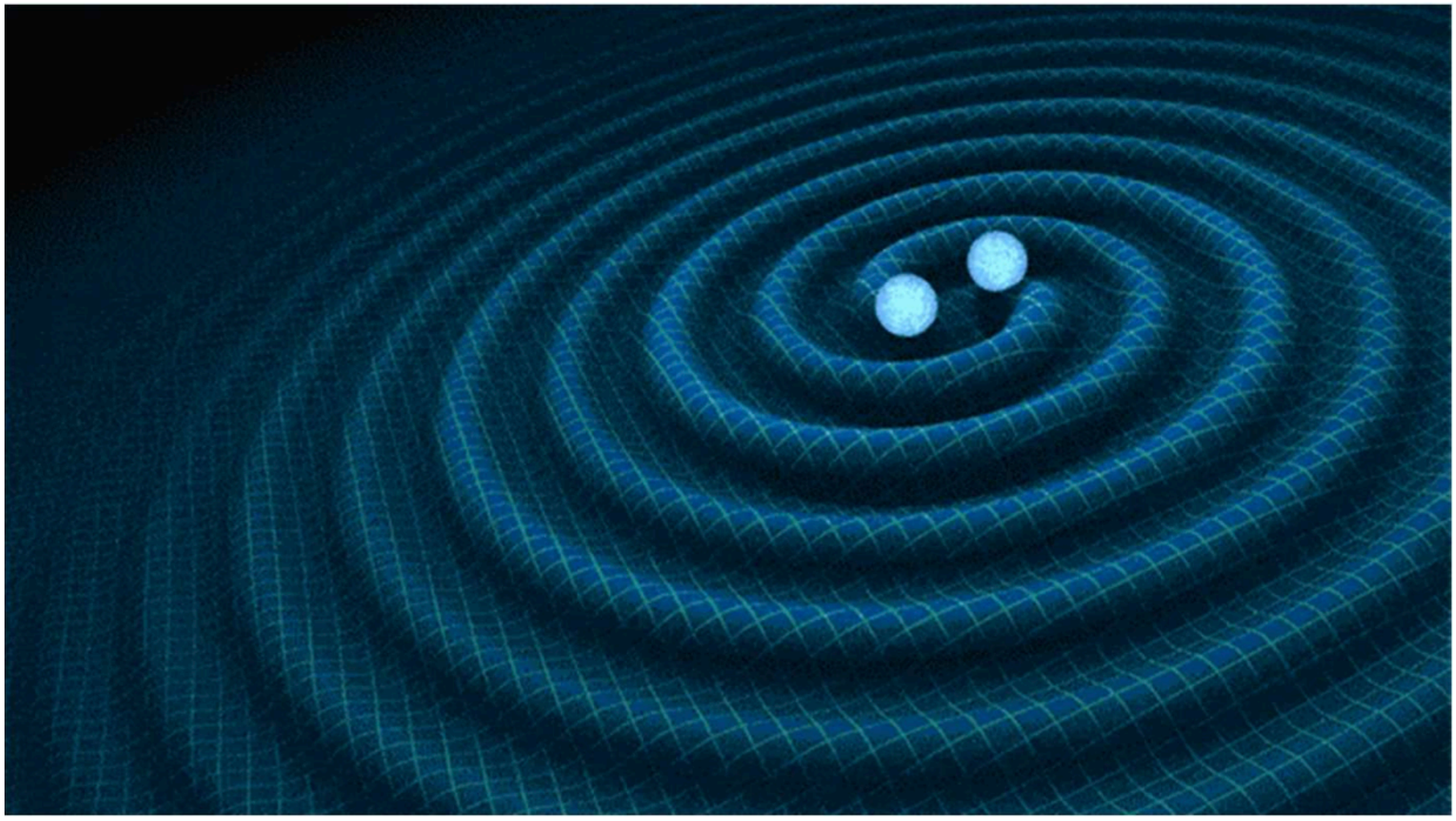


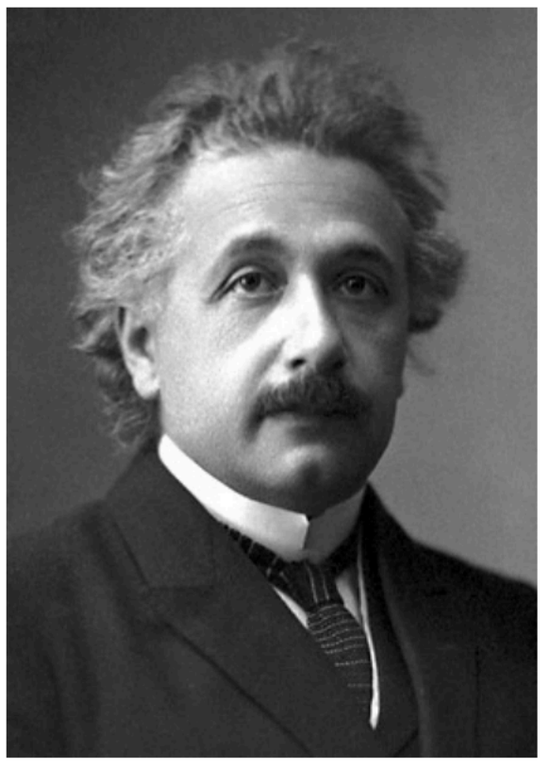
# Searching For Gravitational Waves

# Annoucnements

- You have a pset due this Friday at Midnight
- Pset is available on canvas
- Please send me/Sang Eon your comments and concerns

# Gravity

There is a limiting speed in Nature, the speed of light (1905)



geometry of spacetime

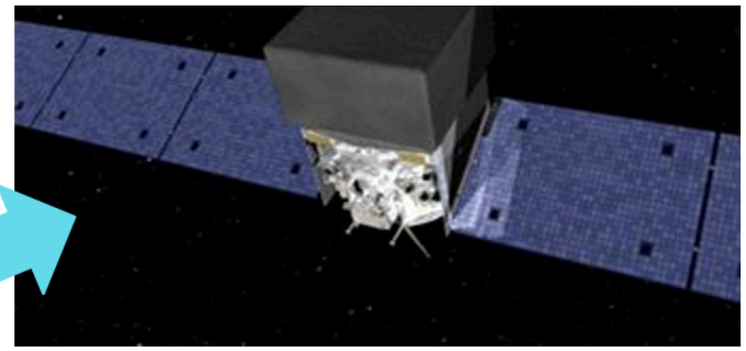
stress-energy tensor

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Gravity: manifestation of spacetime curvature (1915)

# Multi-Messenger Astronomy

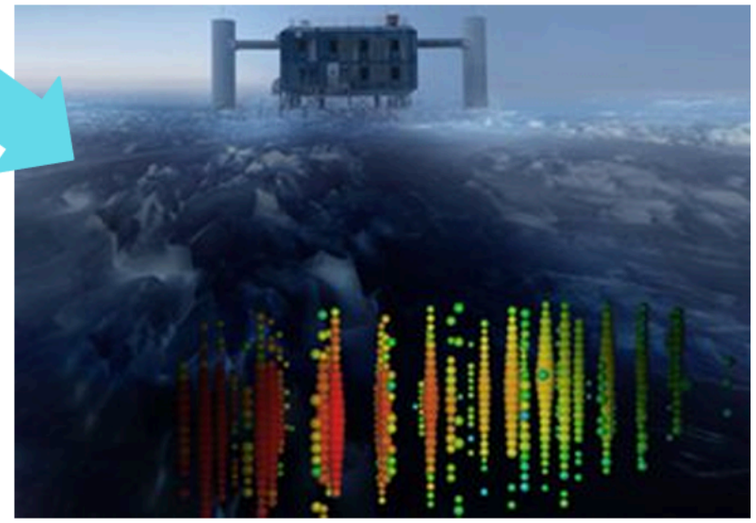
Gravitational waves

X-rays/Gamma-rays

Visible/infrared light

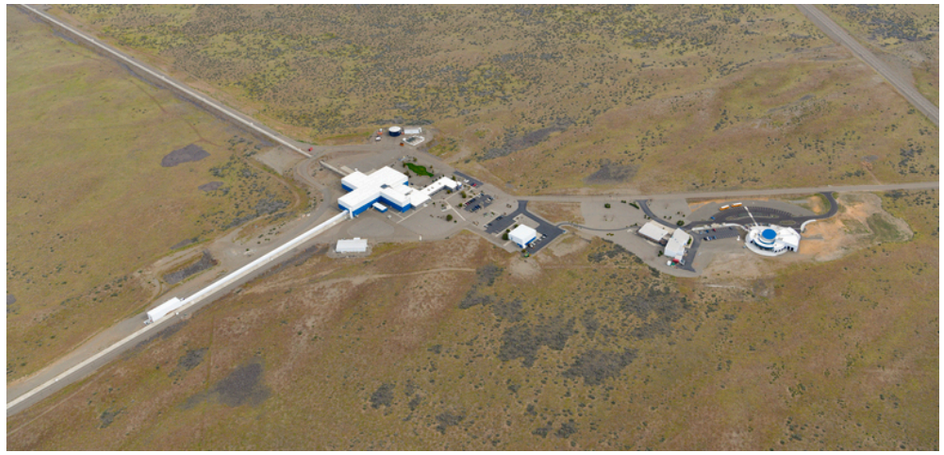
Radio waves

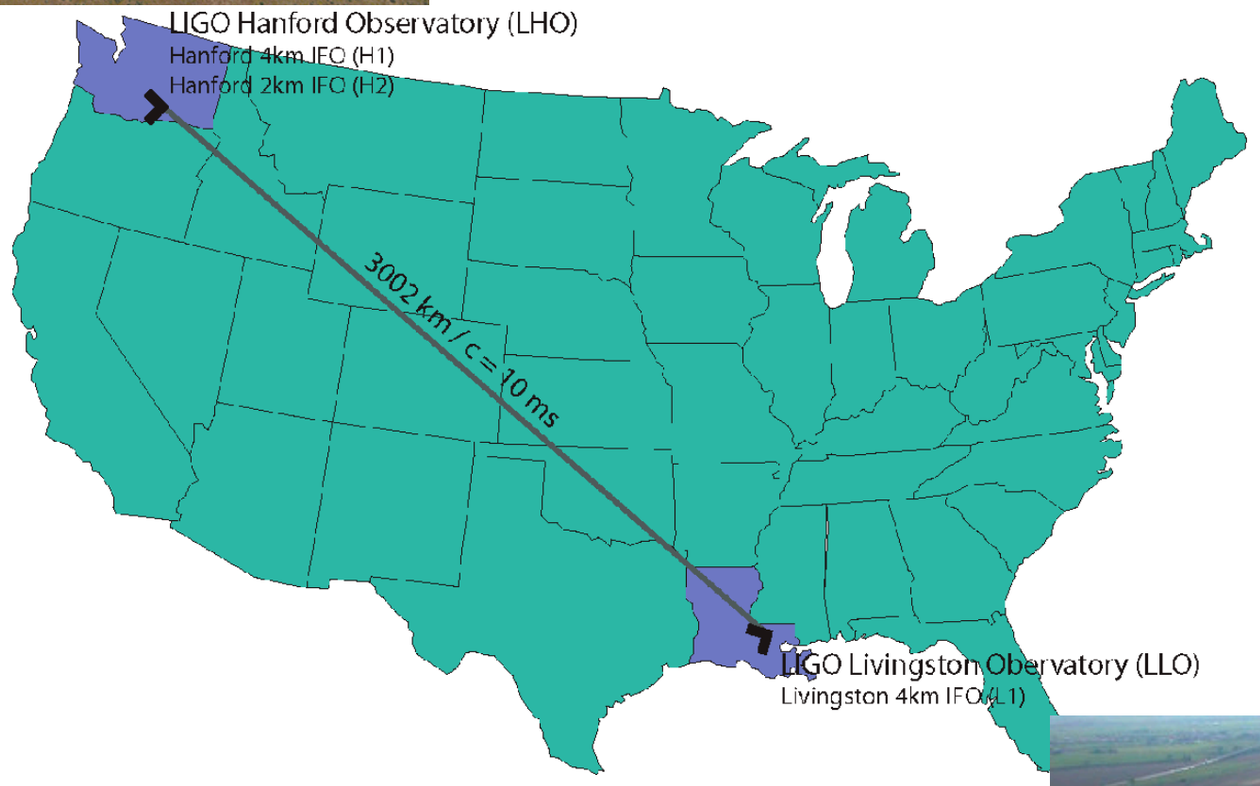


Neutrinos

Performing fast identification of GWs critical to alerting world!

# LIGO

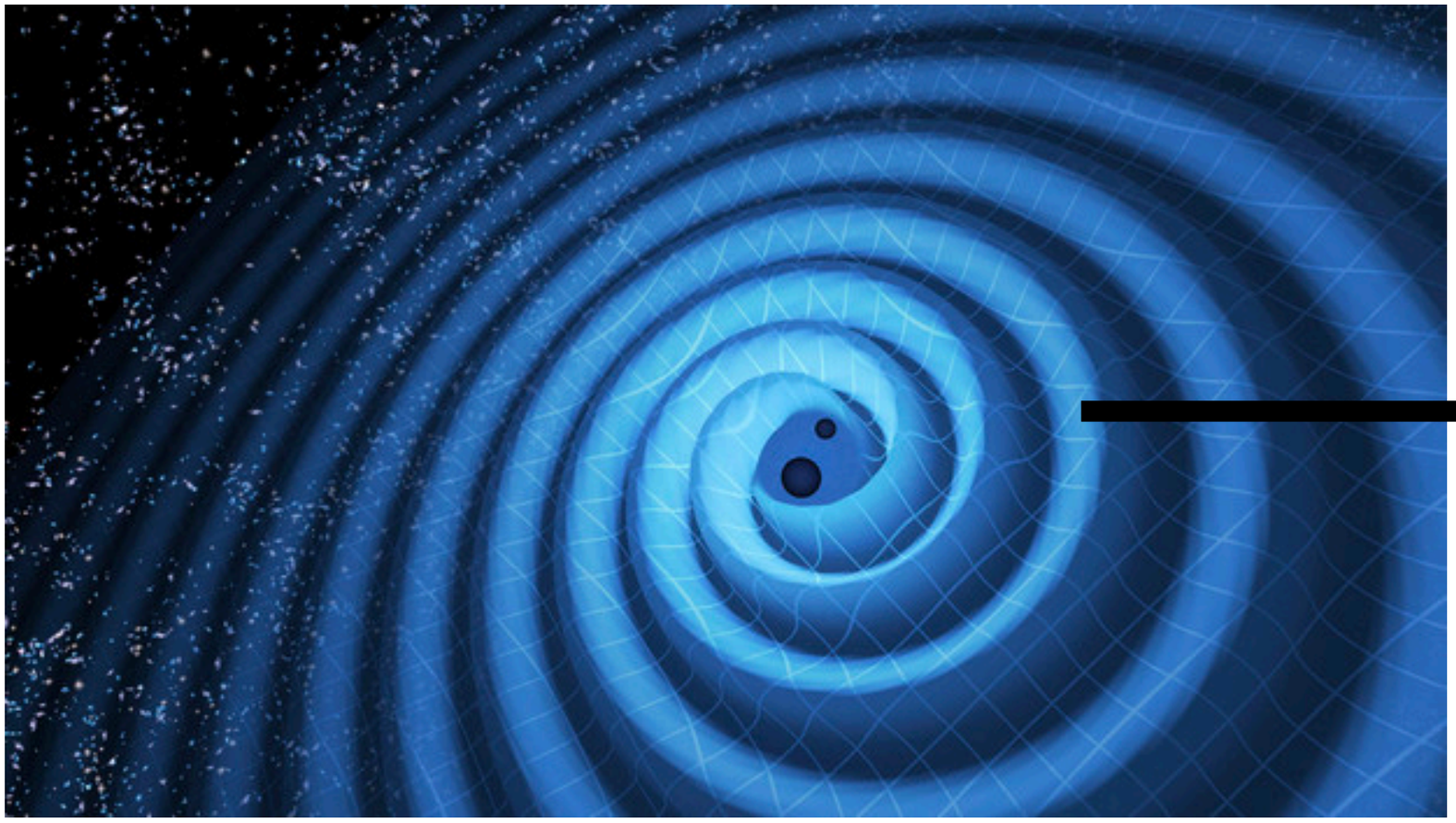





Two detectors that are sensitive to GW

# Graviational Waves

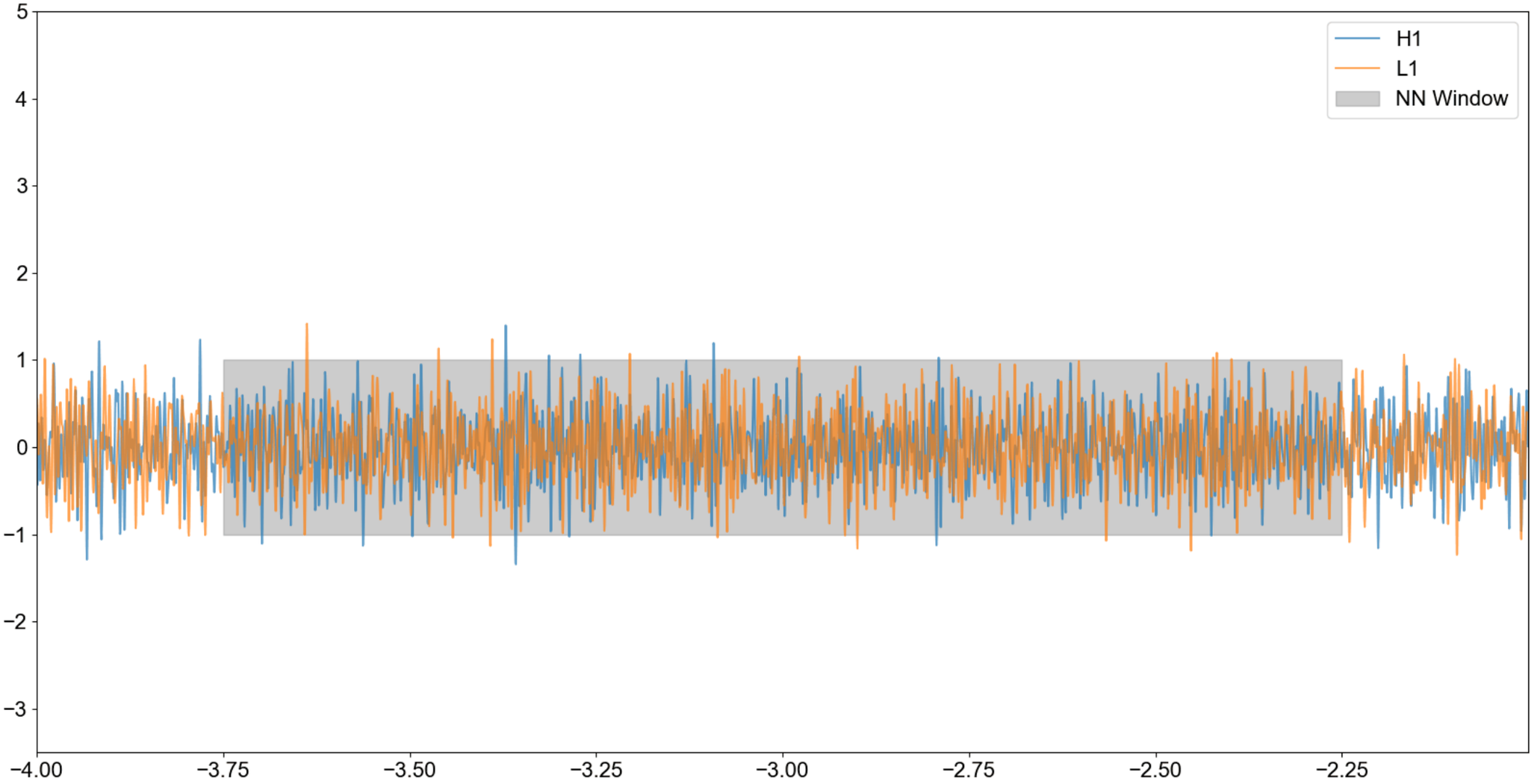




Many detectors
2 in US(LIGO)

Ripples

# Gravitational Wave Data




Data is time series from at least two detectors

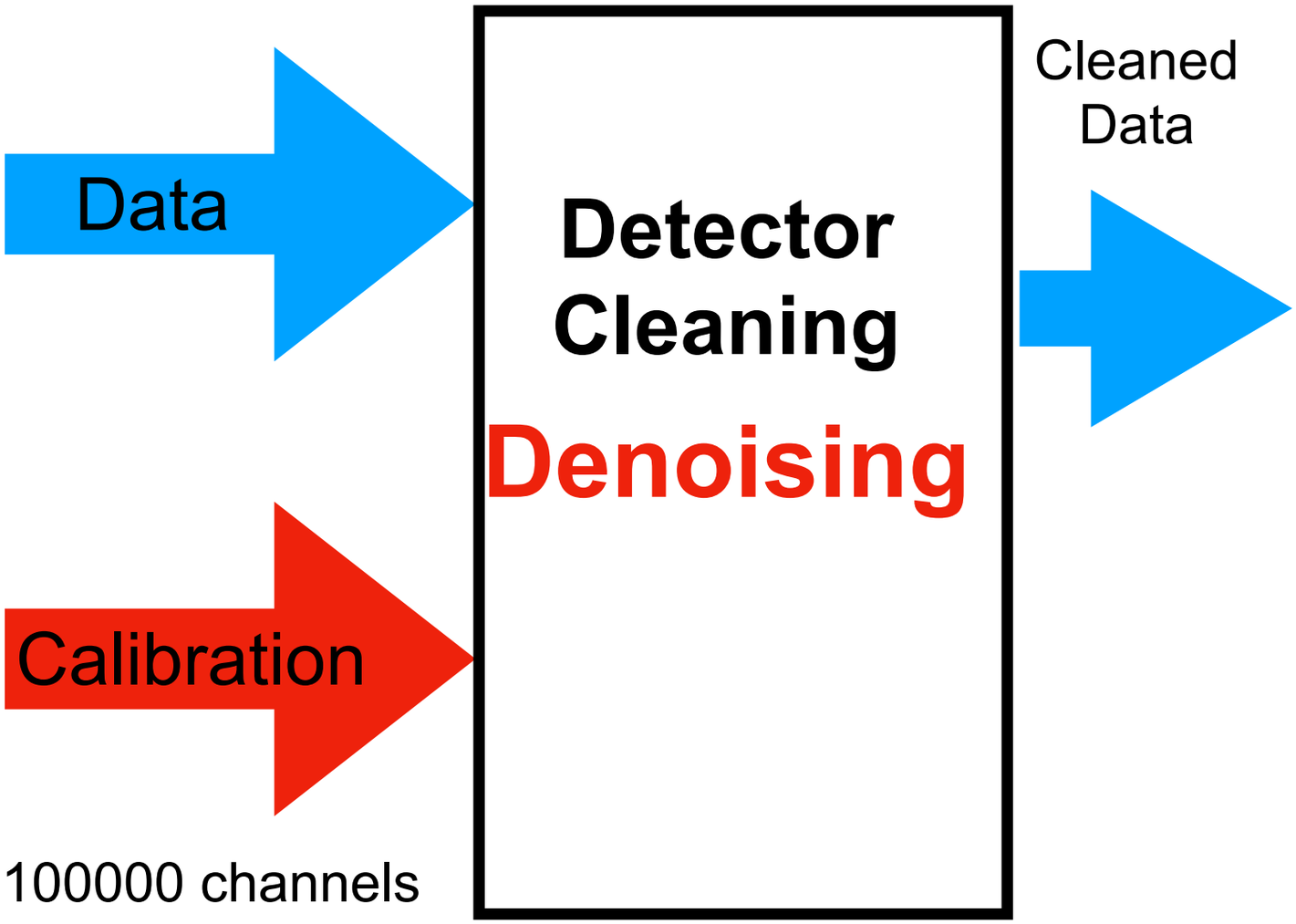
We aim for a correlated signal

# Slides

- See this link for animations:

- https://www.dropbox.com/s/44ew35qlz89xono/PCH_Lecture2_LigoAnims_8S50.pptx?dl=0

# GW Data Workflow



# GW Data Workflow

Data

Calibration

100000 channels

**Detector Cleaning**

**Denoising**

Cleaned Data

**Event Detection**

**Black Holes/ Neutron Stars/ Anomalies**

Event

# GW Data Workflow

Data

Calibration

100000 channels

**Detector Cleaning**

**Denoising**

Cleaned Data

**Event Detection**

**Black Holes/ Neutron Stars/ Anomalies**

Event

**Event Analysis**

**Parameter Estimation/ Sky Localization**

Alert

# GW Data Workflow

Data

Calibration

100000 channels

**Detector Cleaning**

**Denoising**

Cleaned Data

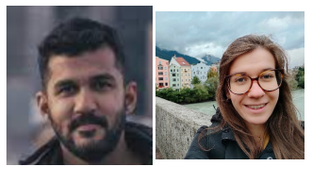
**Event Detection**

**Black Holes/ Neutron Stars/ Anomalies**

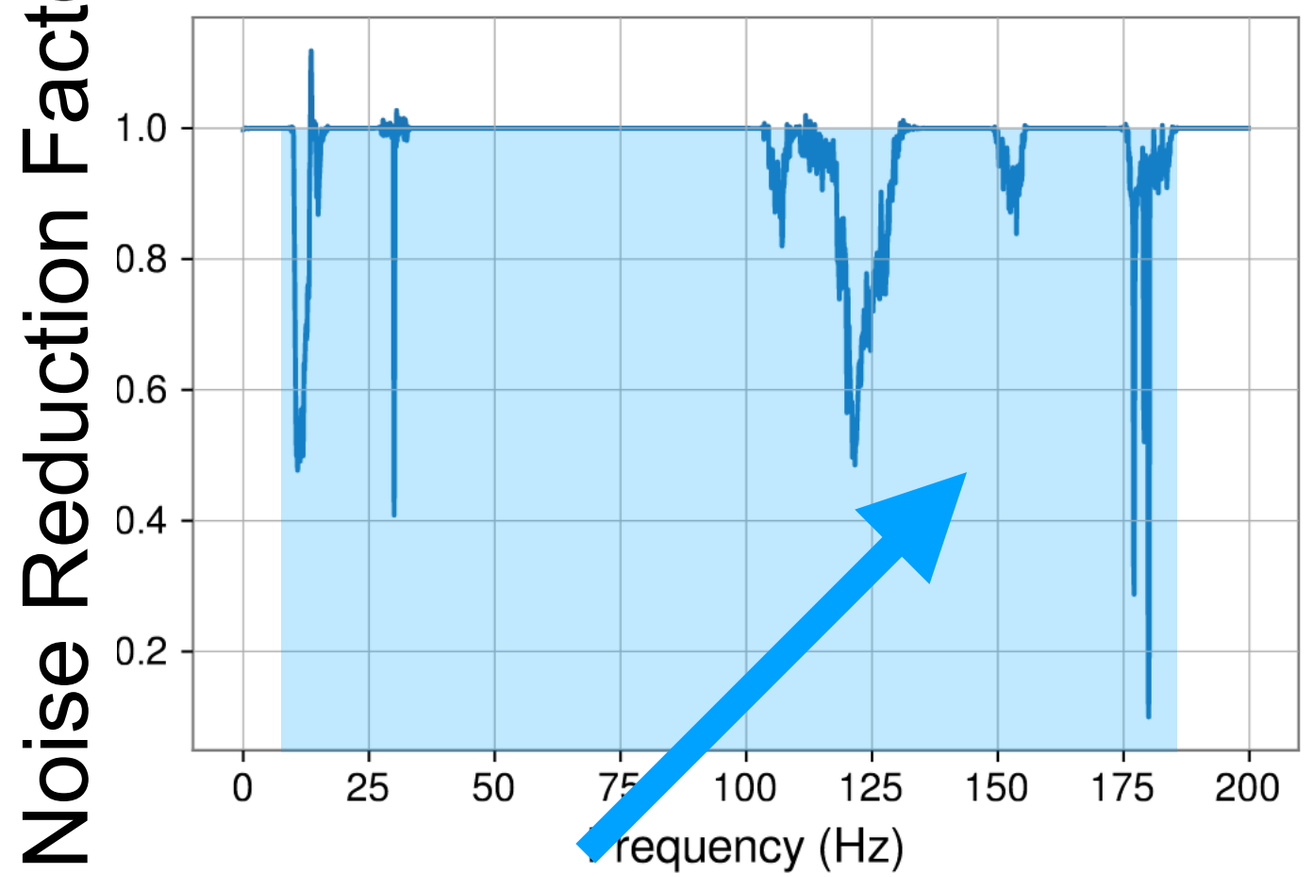
**Event Analysis**

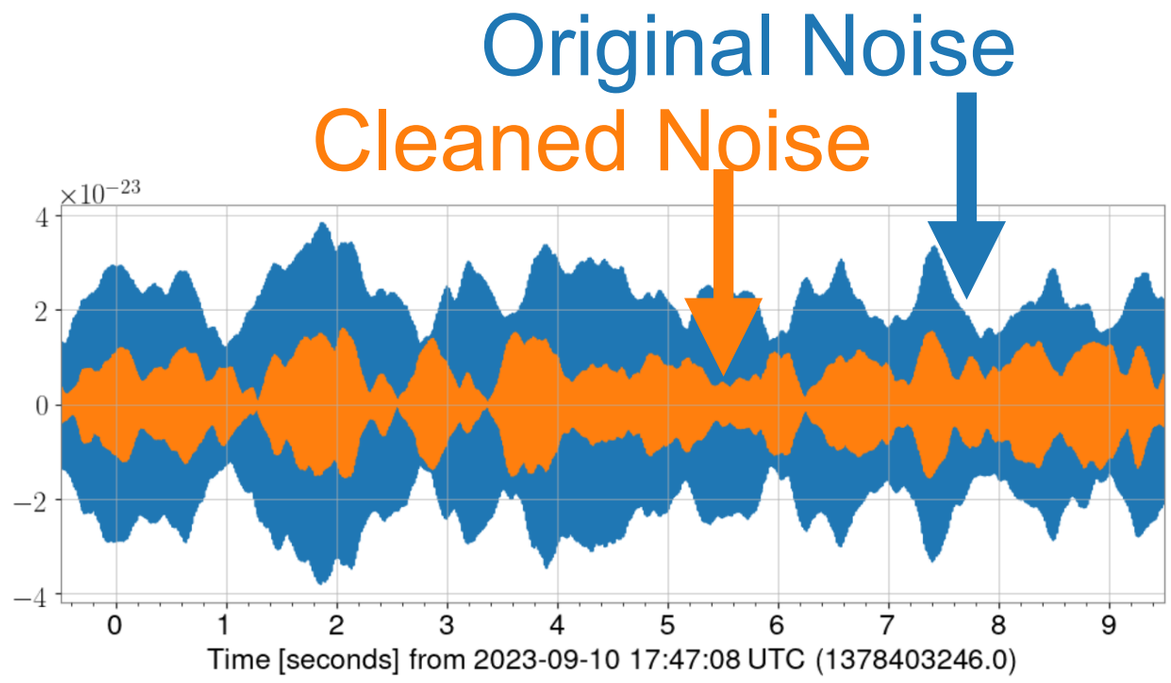
**Parameter Estimation/ Sky Localization**

We replaced this pipeline with a chain of deep learning algos



# DeepClean: Does it work?



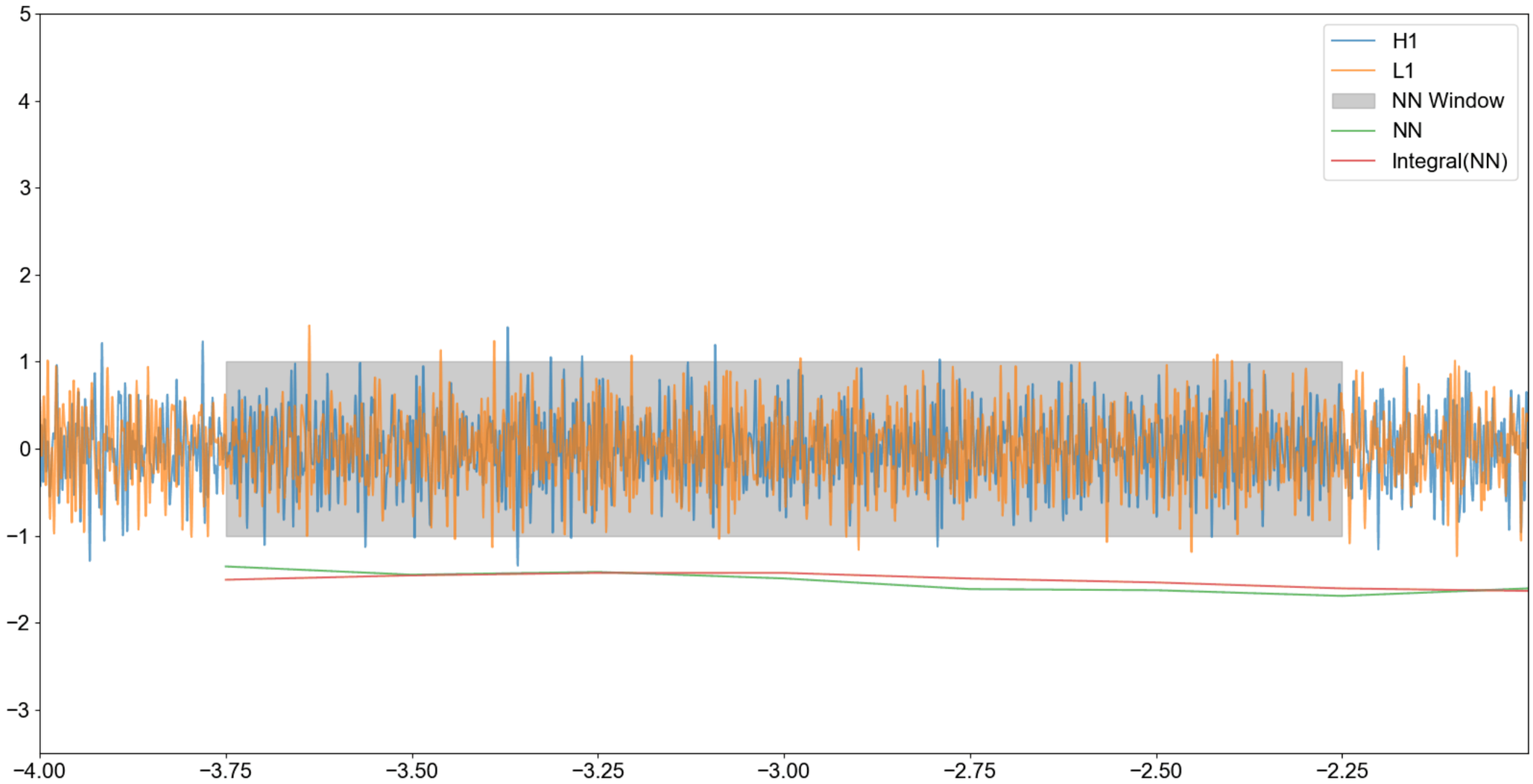




Probe an additional 5% more of the universe

Just the beginning

arXiv:2403.18661

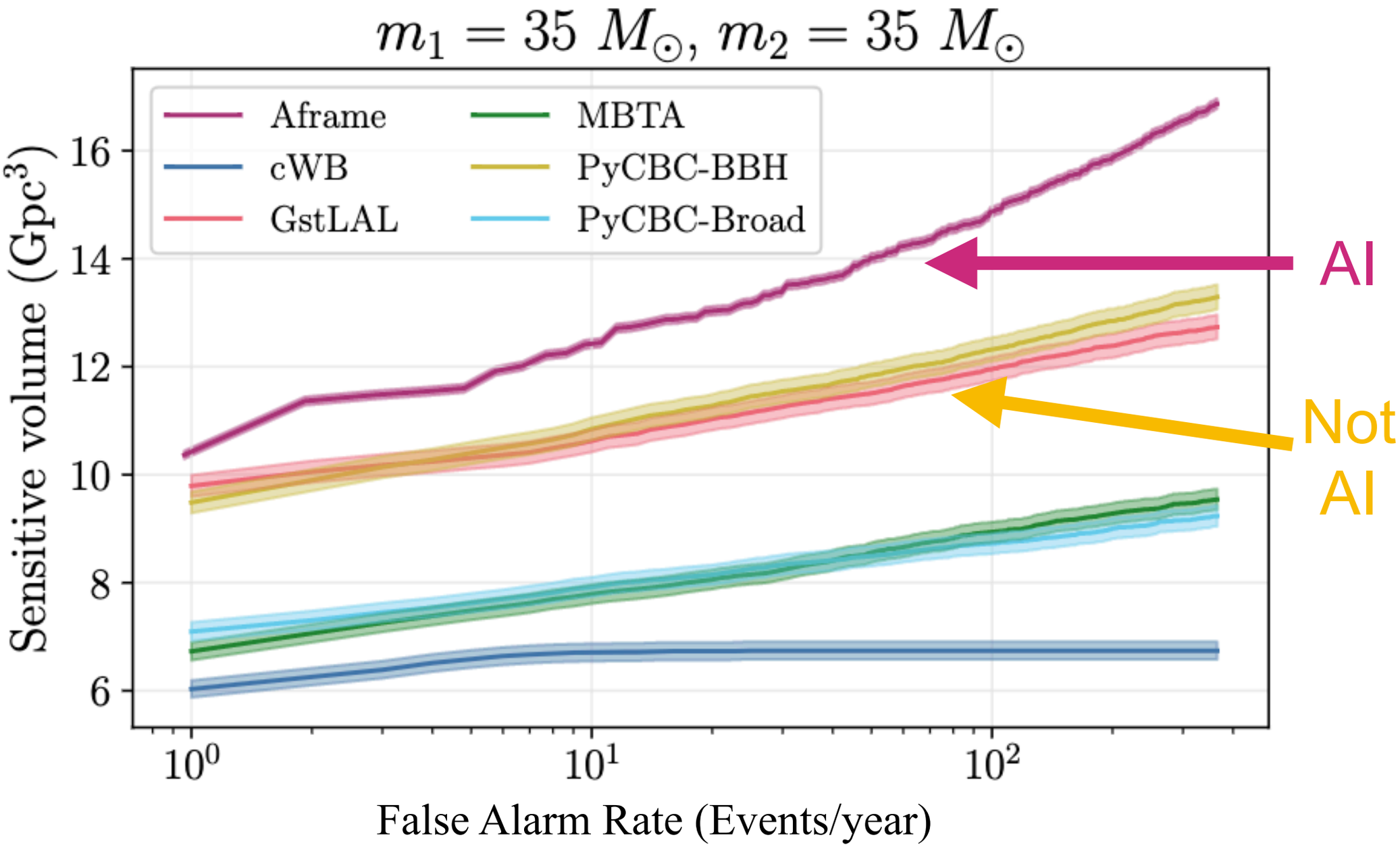
# A-Frame(Black Hole Mergers)




Neural network targeting Black Hole Mergers

arXiv:2403.18661

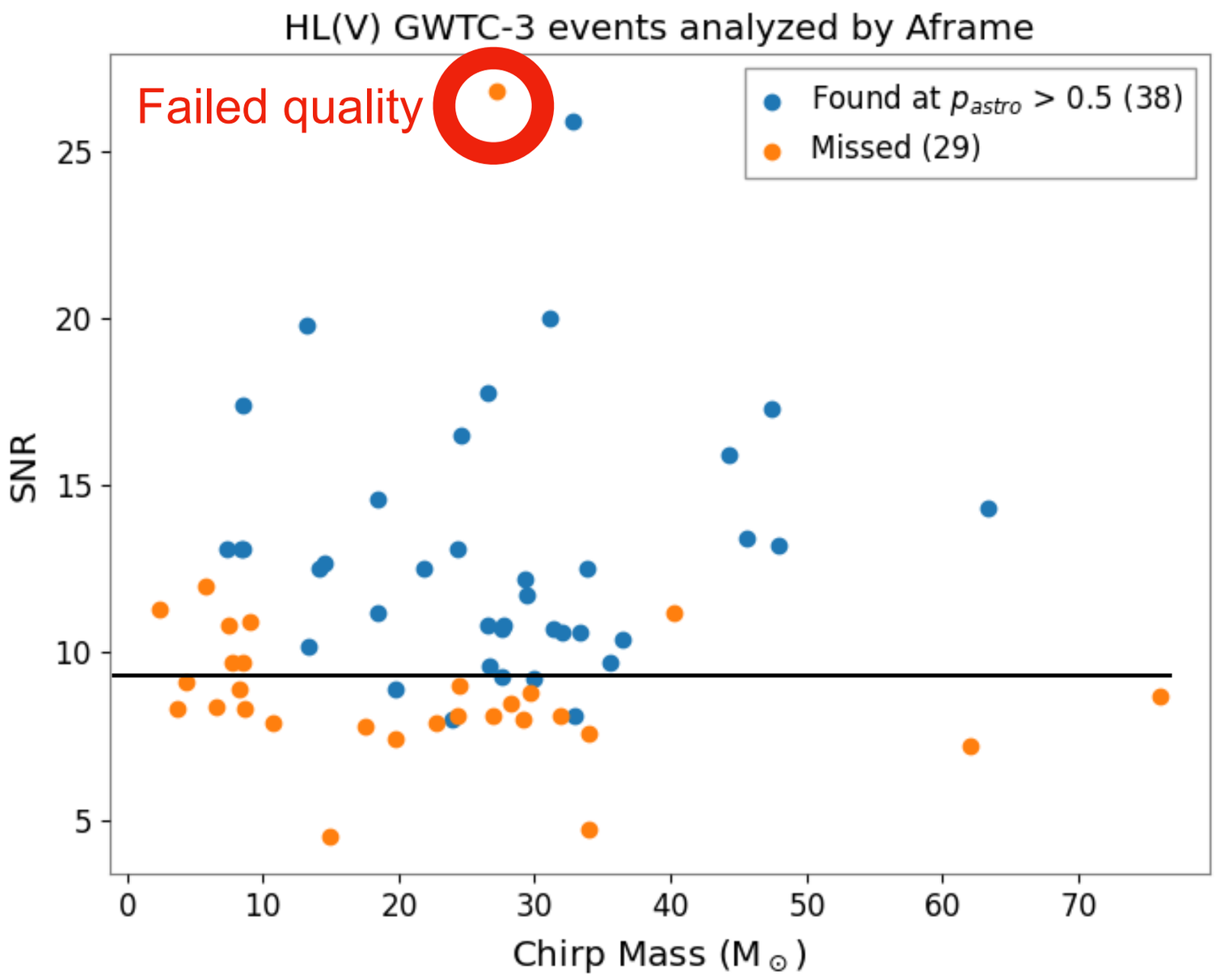
# A-Frame(Black Hole Mergers)




Probes 10% of the known universe for Heavy Mergers

arXiv:2403.18661

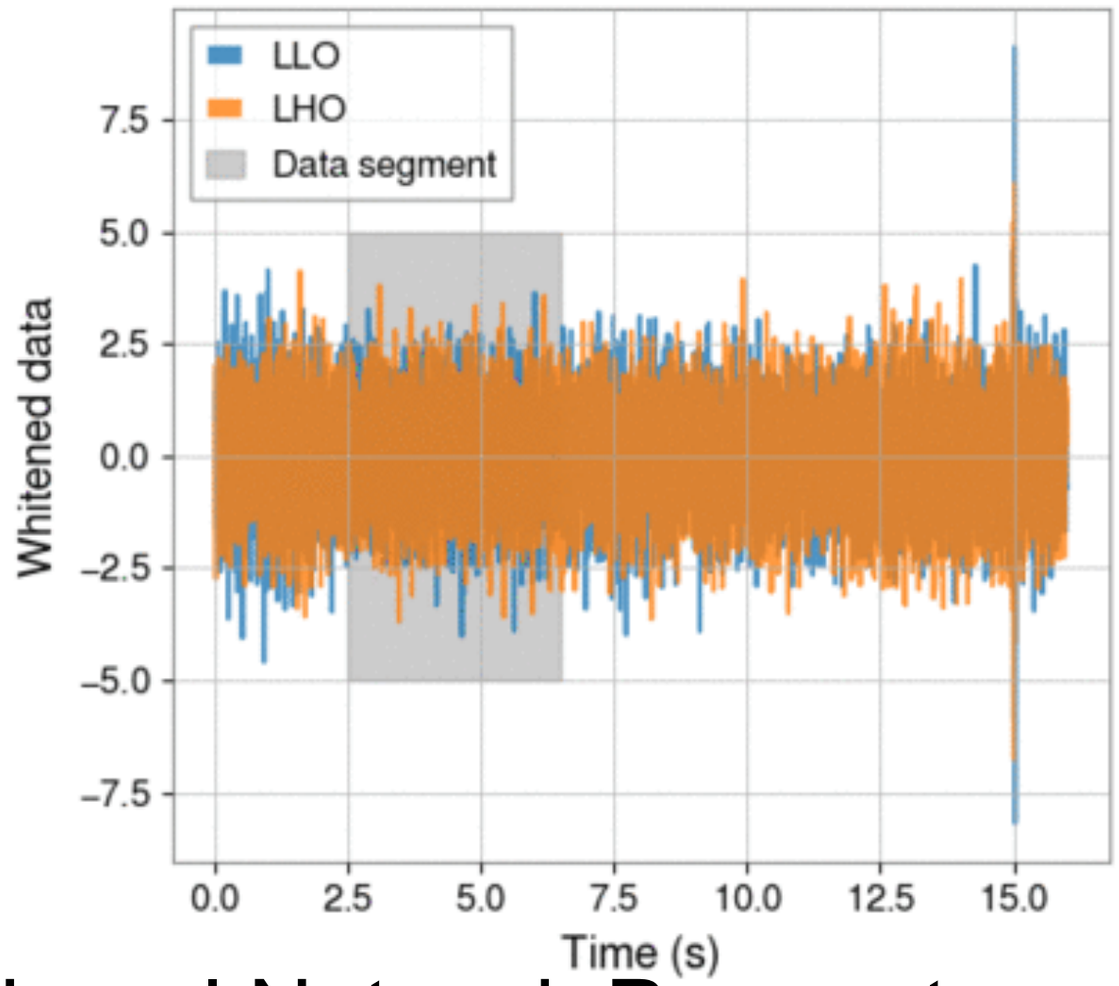
# A-Frame(Black Hole Mergers)

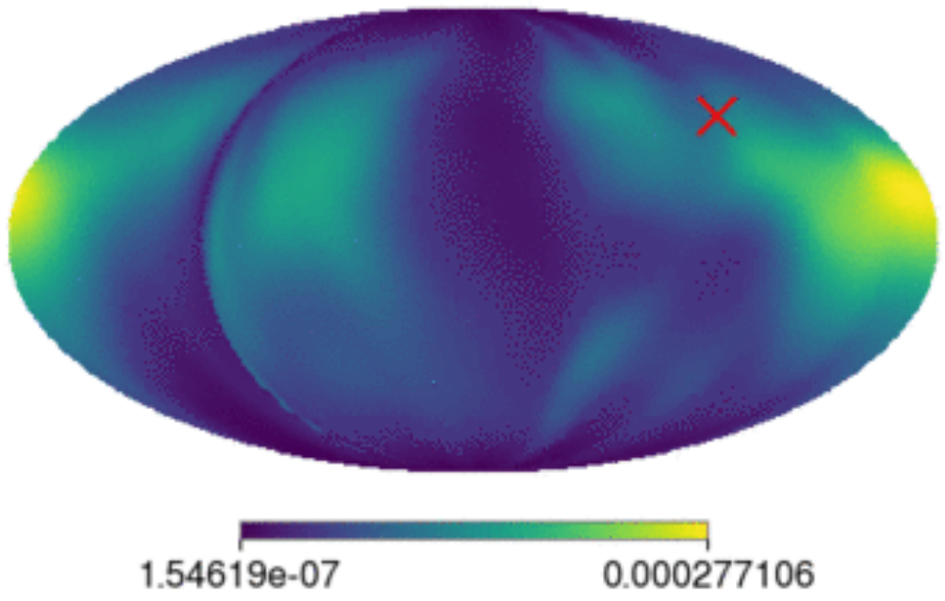



We found all the high signal Black hole mergers

**arXiv:2407.19048**


# Parameter Estimation




Neural Network Parameter estimation

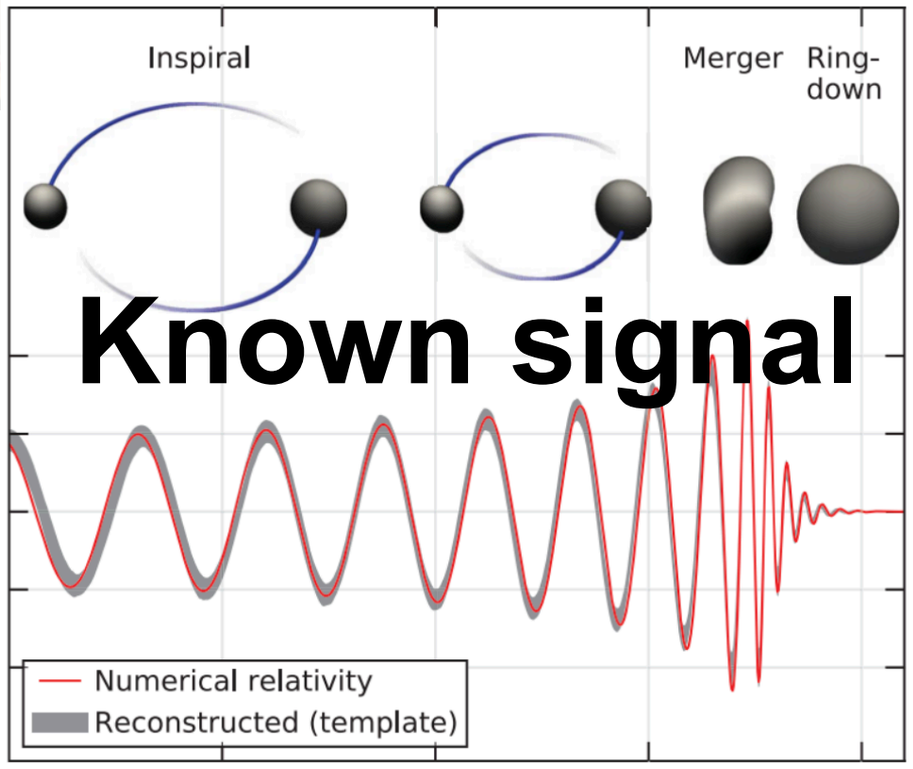
100,000x times faster than conventional parameter estimation

Not yet full resolution on all parameters (aimed for speed)

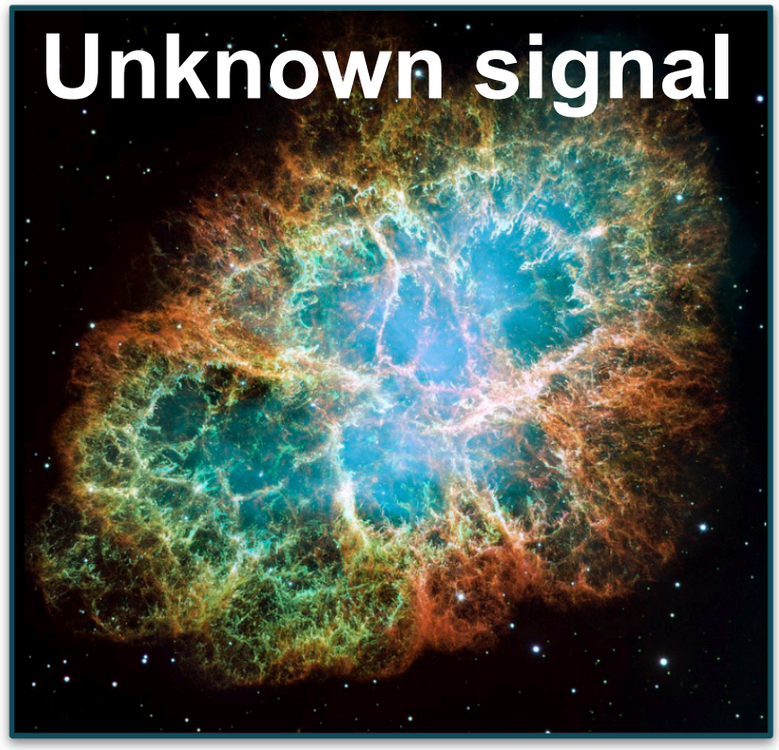
arxiv:2309.11537

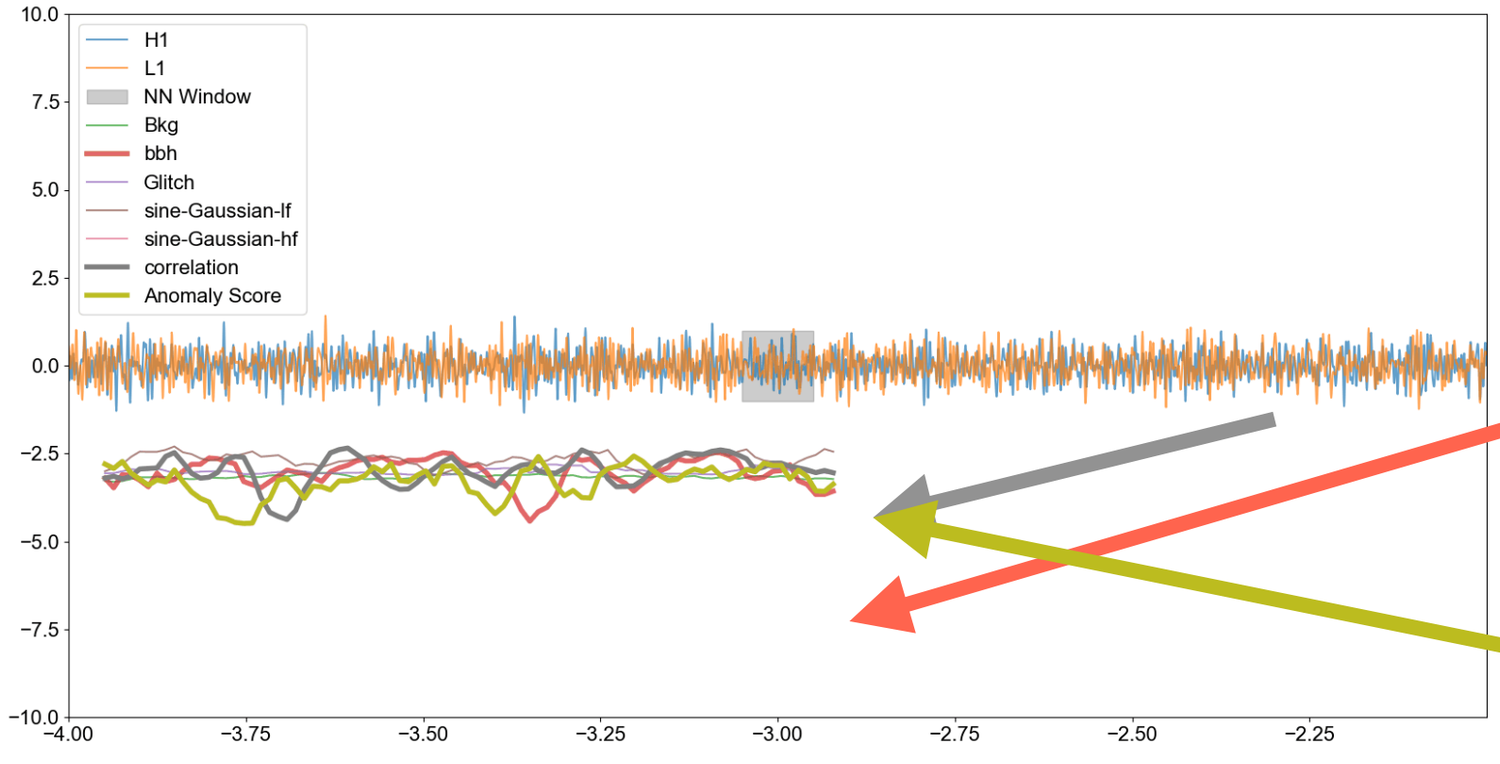
# GWAK:Anomaly Detection






Core-collapse supernova (CCSN)




**Key Insights**

11D space

Correlation

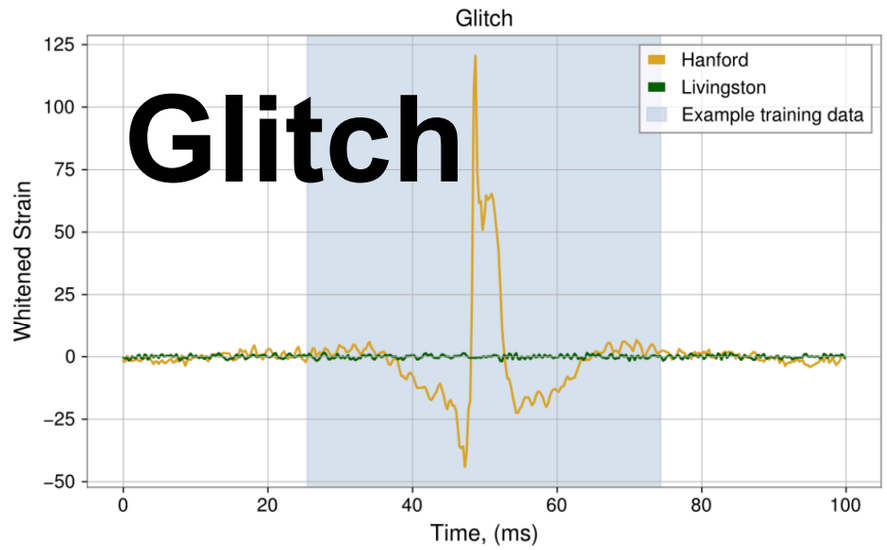
BBH Prob

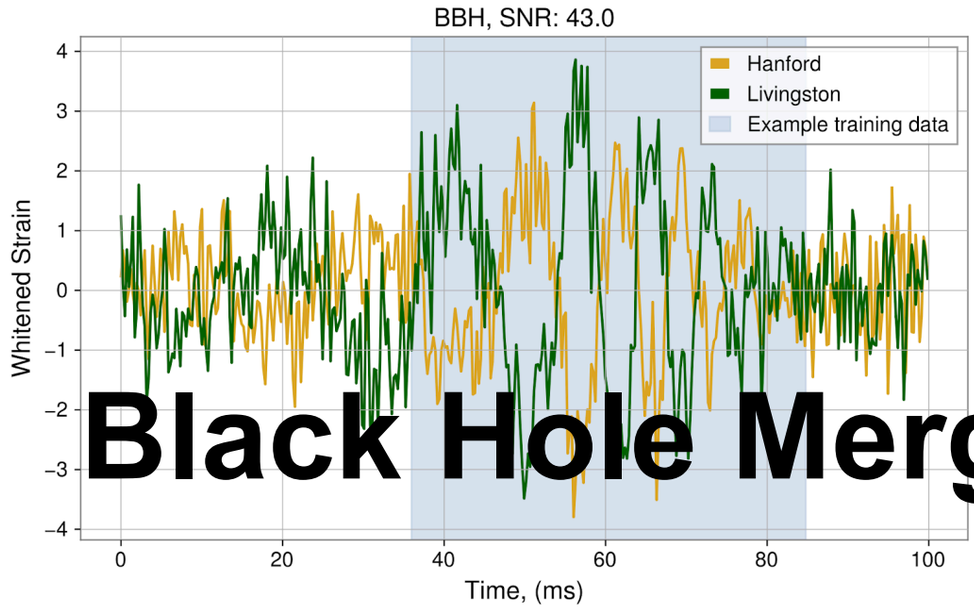
Others

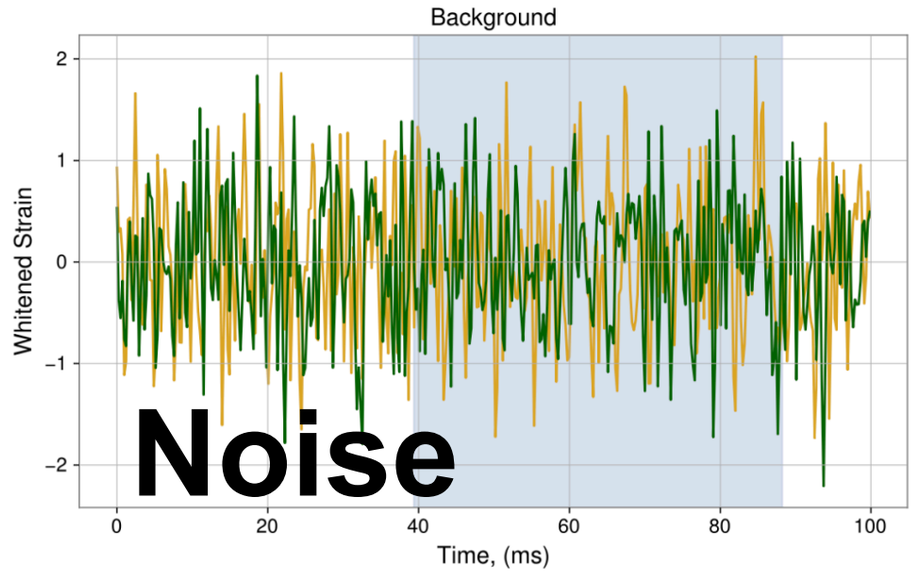
Total Score

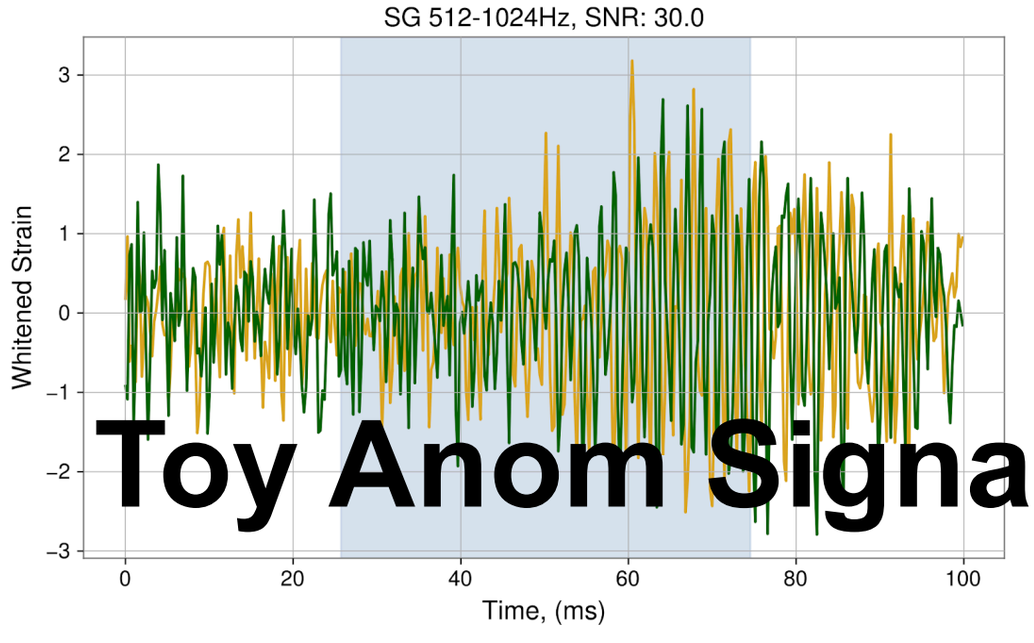
# GWAK Space

- GWAK stands for GW (QU)AK like guacamole



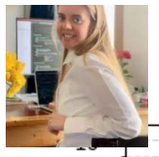




**Glitch**

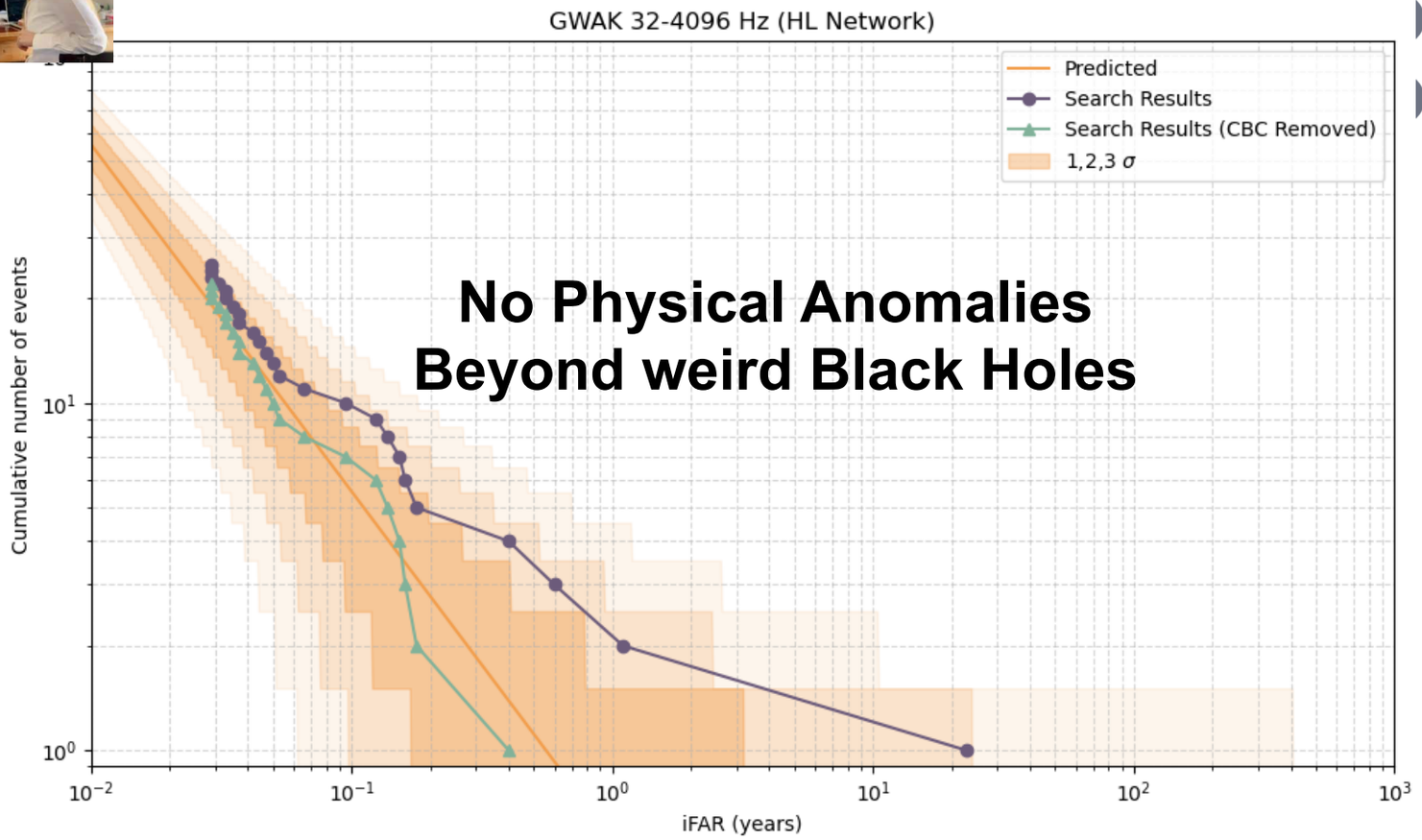
**Black Hole Merger**

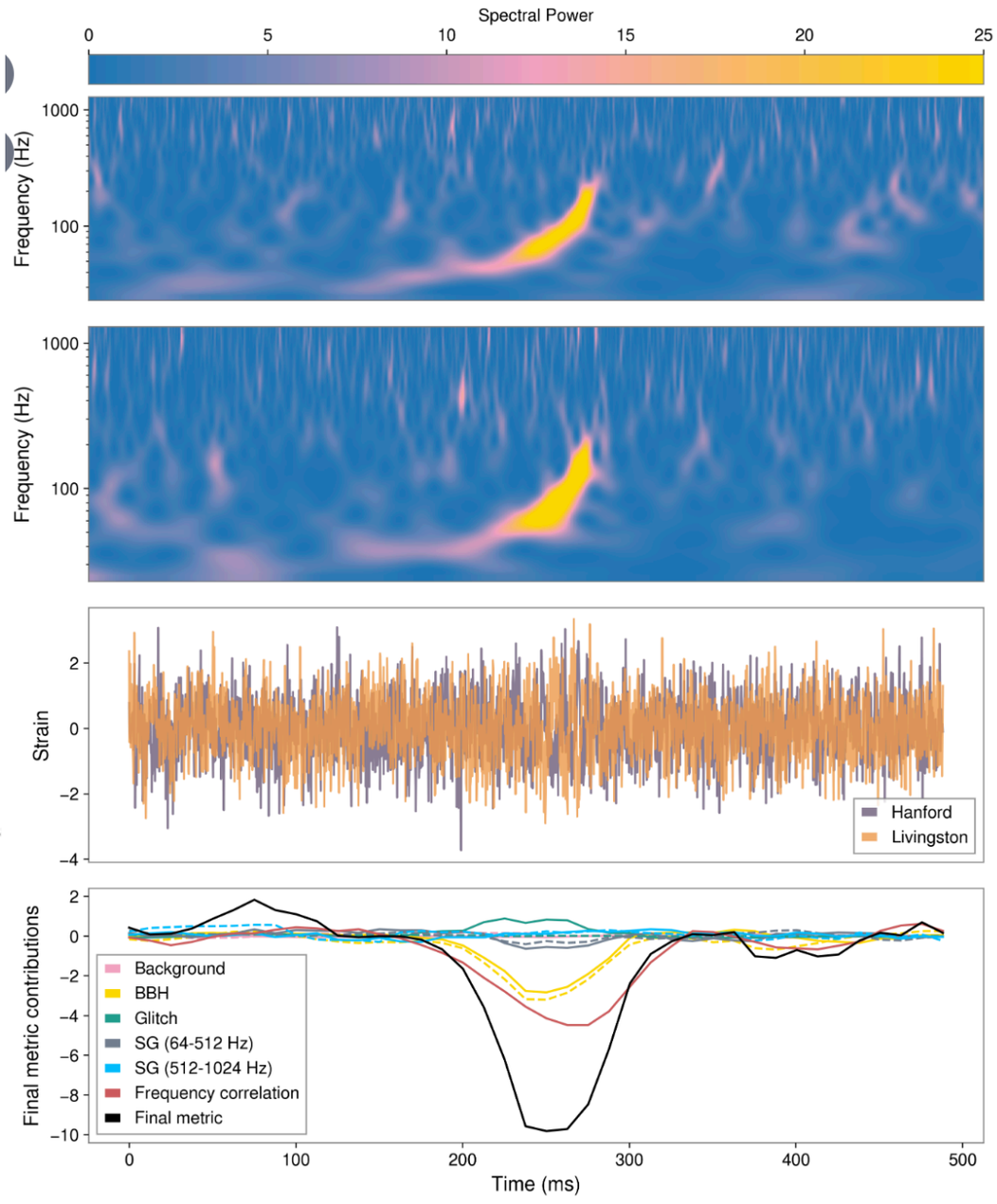
**Noise**

**Toy Anom Signal**



# GWAK On Data



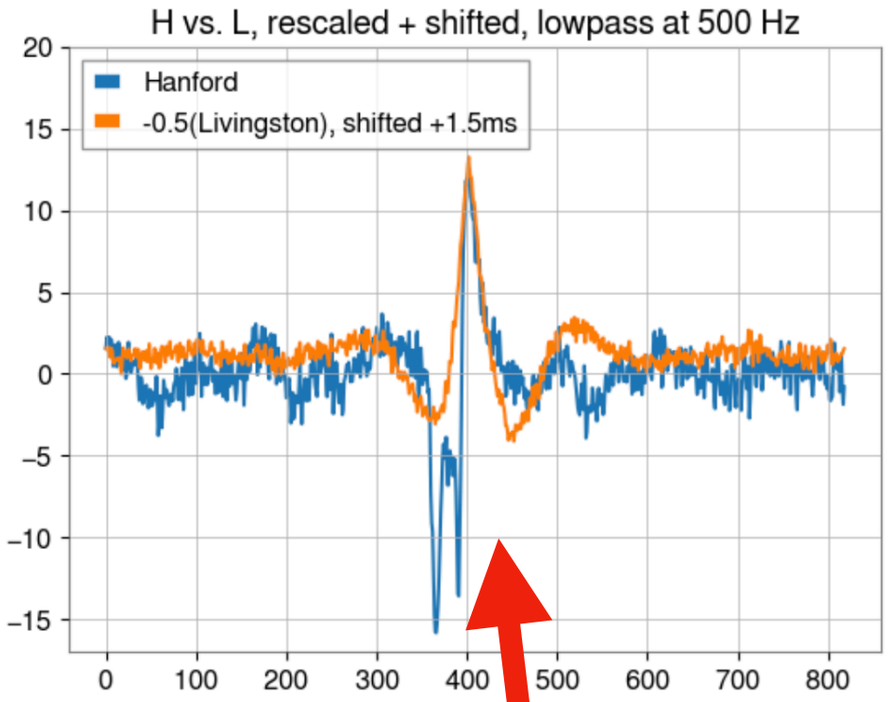

No glaring true anomalies

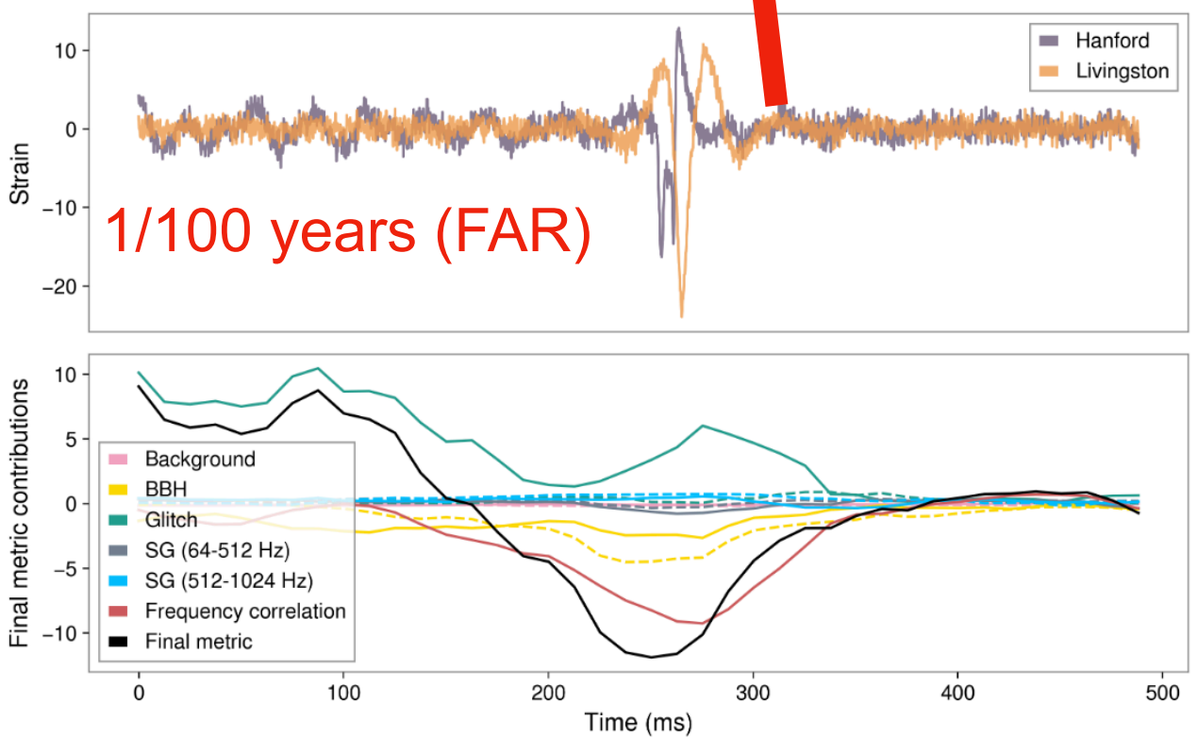
We found weird black hole mergers + weird glitches

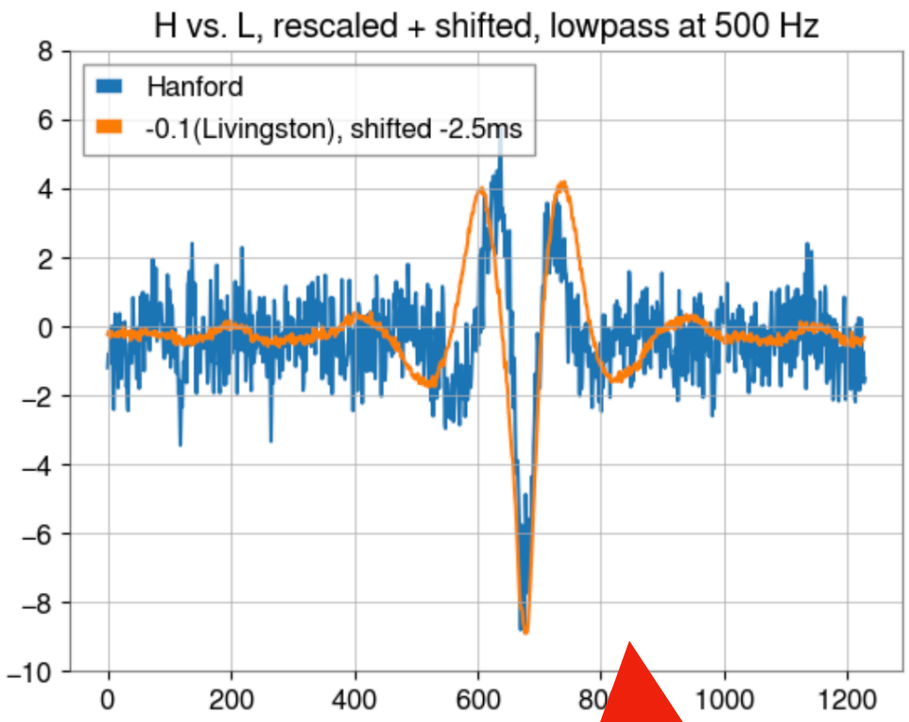


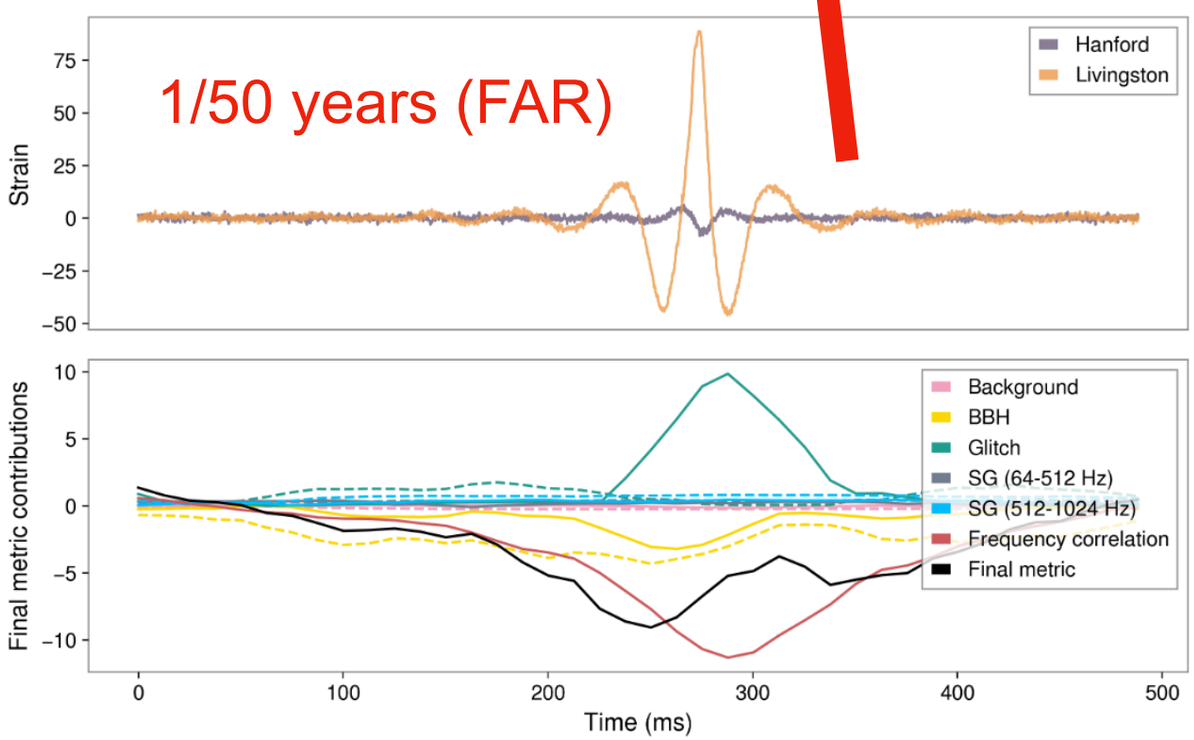
# Crazy Anomalies

Occurred during noisy times of LIGO operation




# Our System is running Live!

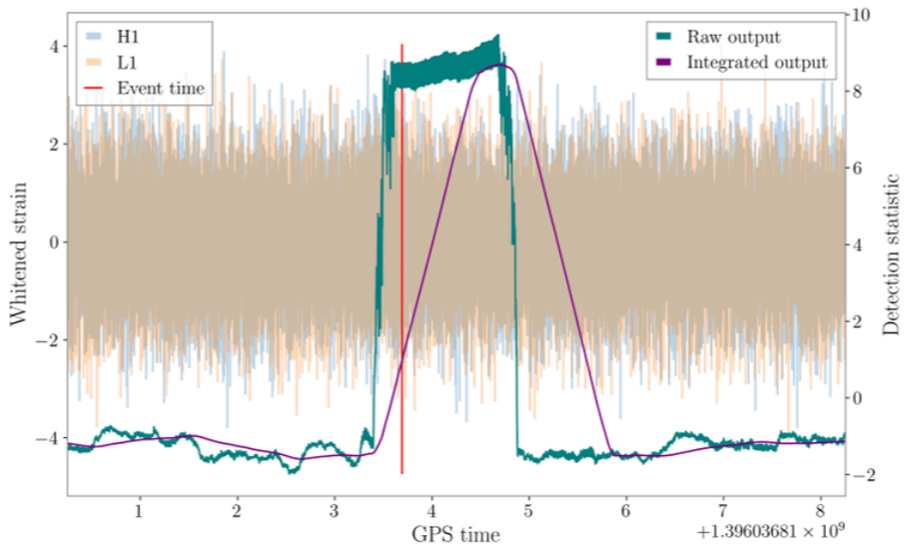
Accelerated AI Algorithms for Data-Driven Discovery

GraceDB (USER TESTING) Public Alerts Latest Search Notifications Pipelines Documentation Logout

Authenticated as: Katya Govorkova

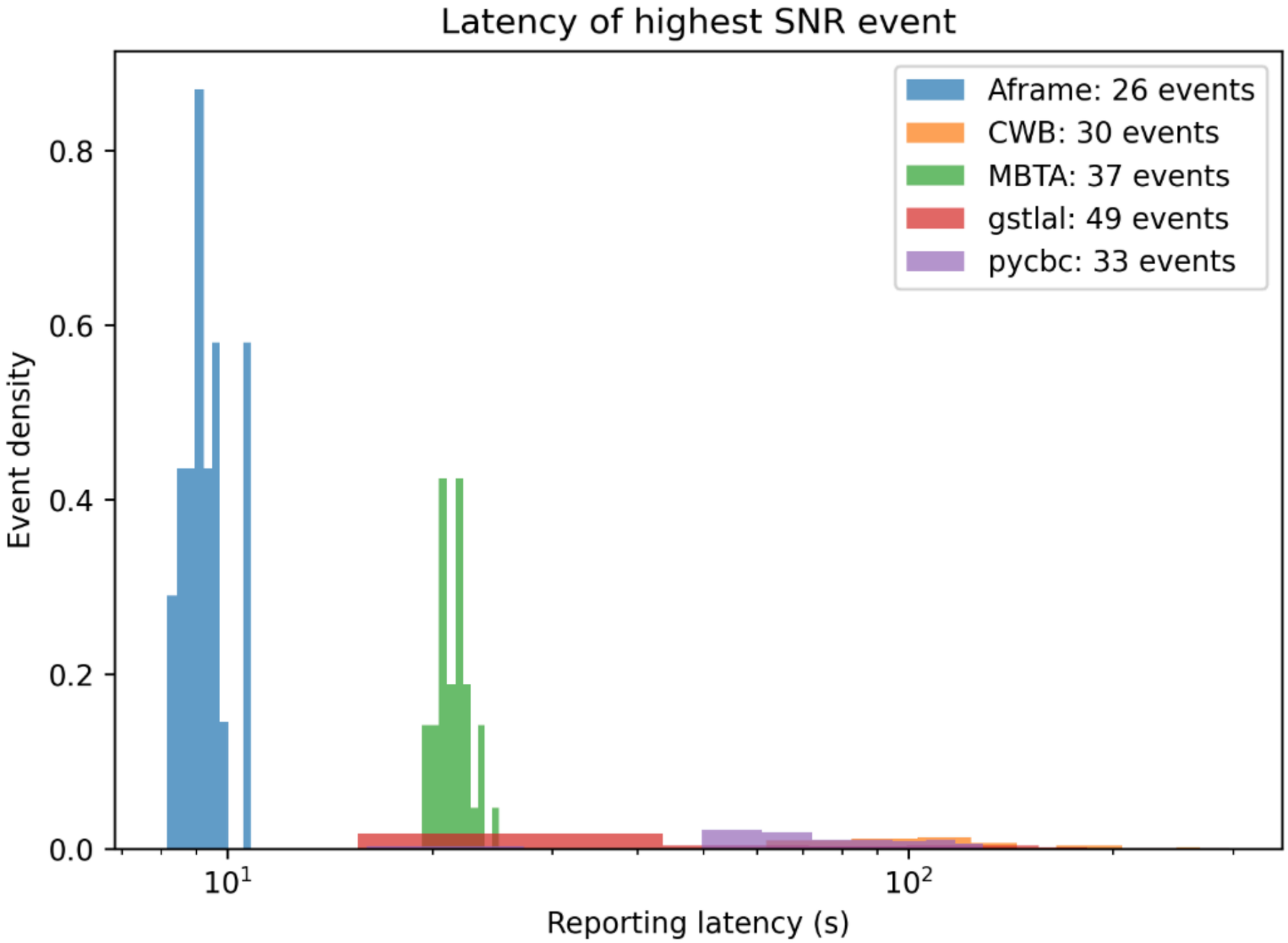
G1783271
Neighbors
Log Messages
Full Event Log

## G1783271




| Basic Event Information | |
|---|---|
| UID | G1783271 |
| Labels | |
| Group | CBC |
| Pipeline | aframe |
| Search | AllSky |
| Instruments | ['H1', 'L1'] |
| Event Time | 139[redacted] |
| FAR (Hz) | 3.087e-08 |
| FAR ($yr^{-1}$) | 1 per 1.0264 years |
| Latency (s) | 3.524 |
| Links | Data |
| Submitted | 2024[redacted] UTC |

# Impact Already




Our pipeline found all the large signal events
Our pipeline is 10-100x faster than others

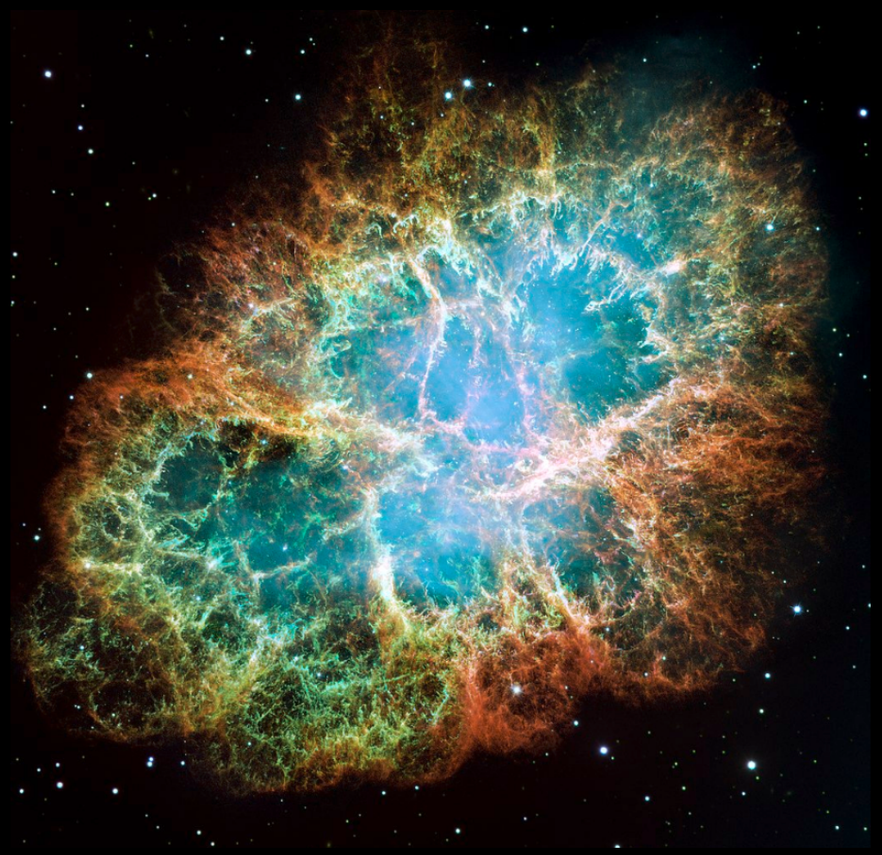
# Questions?

# Anomalous Gravitational Wave Sources

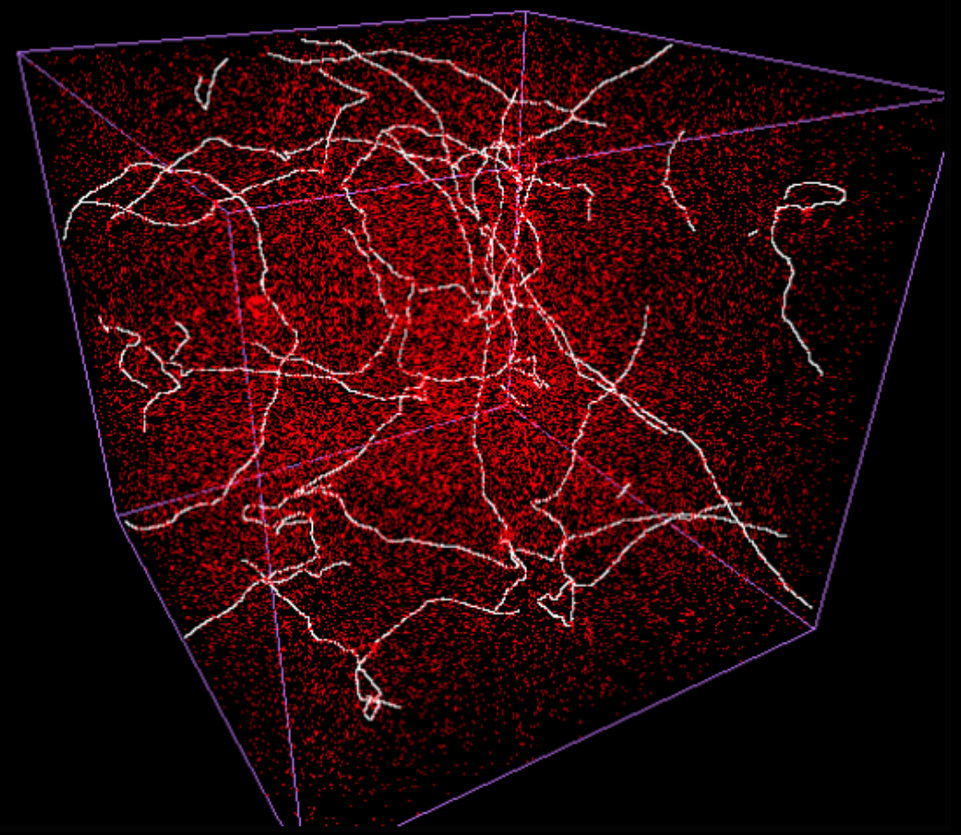
There are other possible signal sources that can not be modelled and therefore cannot be detected using the match filtering pipeline

We refer to them as anomalous and aim to develop a semi-supervised approach which would let us to discover such anomalous signals without explicit modelling

## Core-collapse supernova (CCSN)

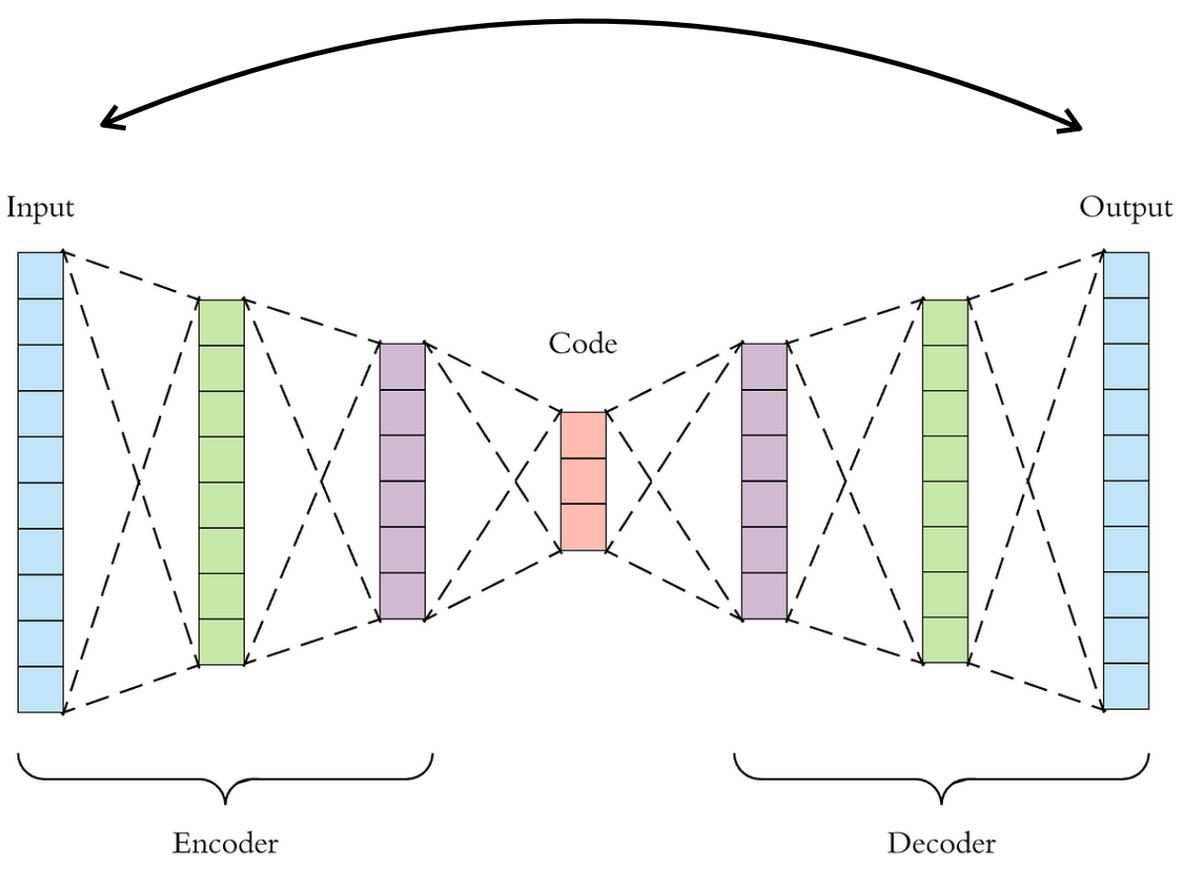


## Cosmic strings



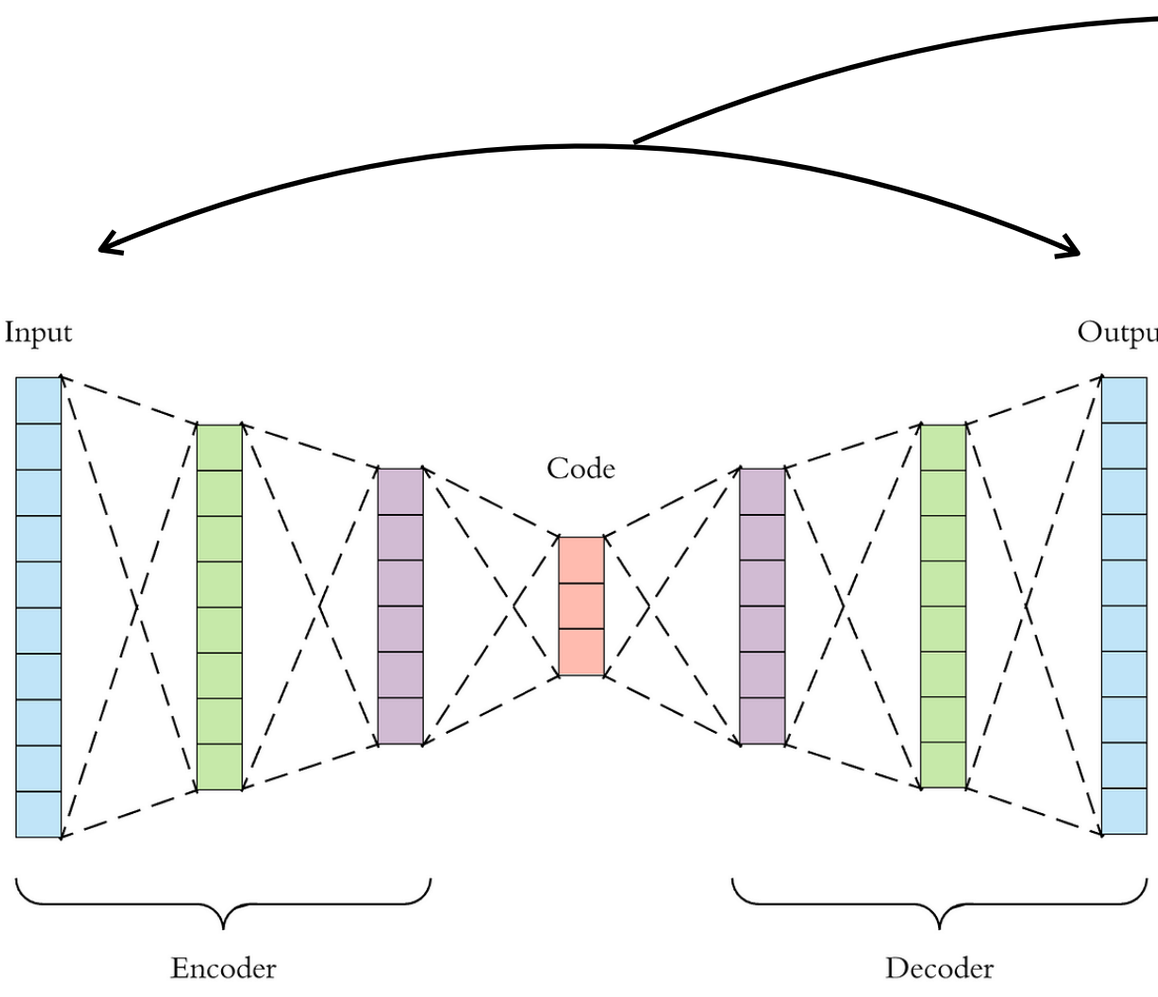
ARXIV2309.11537

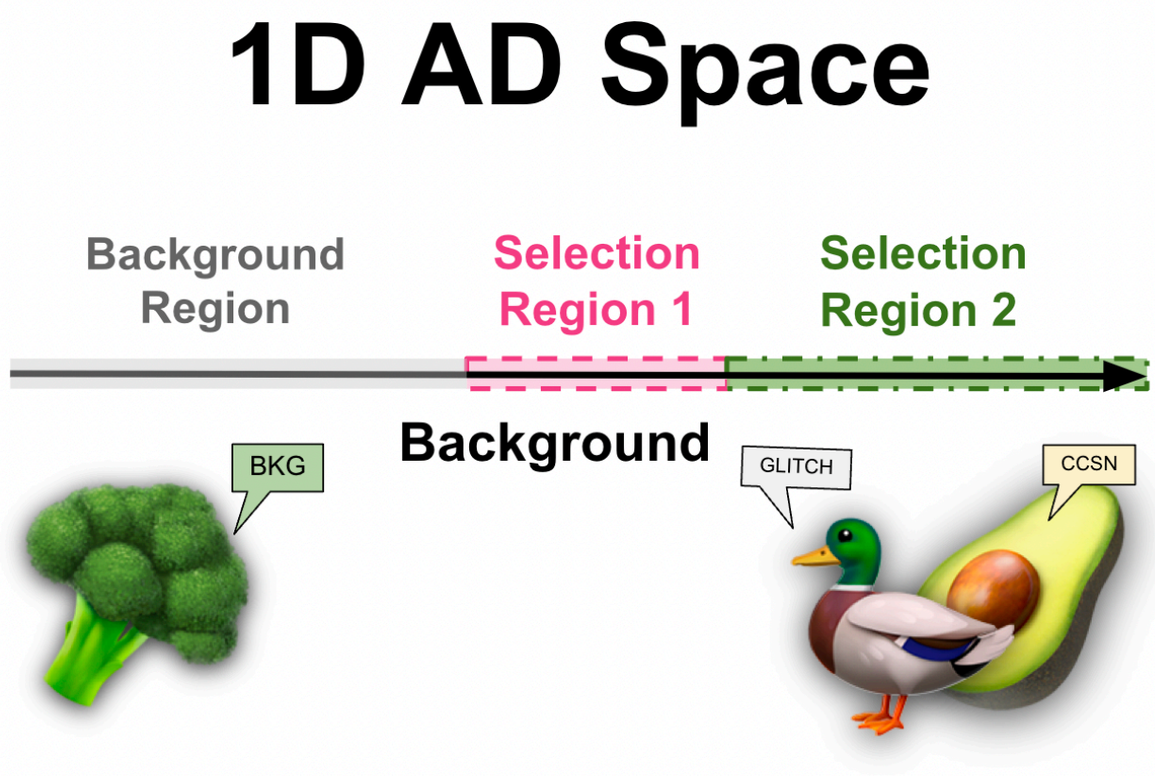
USE THE DISTANCE BETWEEN THE INPUT AND OUTPUT AS A METRIC FOR ANOMALY DETECTION



ARXIV2309.11537

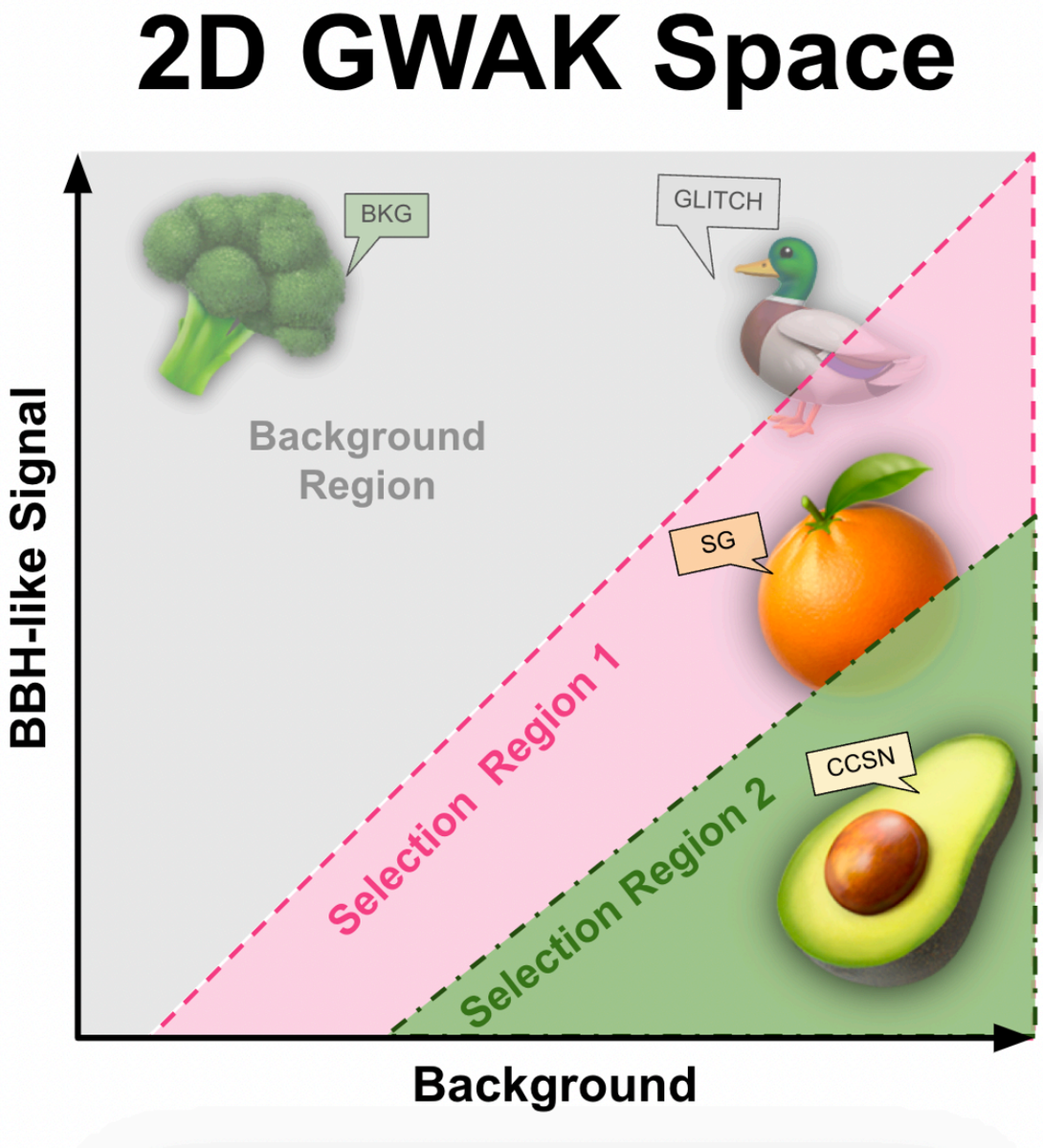
USE THE DISTANCE BETWEEN THE INPUT AND OUTPUT AS A METRIC FOR ANOMALY DETECTION



ARXIV2309.11537

INCLUDING MORE AXES, BOTH SIGNAL AND BACKGROUND, ALLOWS TO MORE EFFICIENTLY SELECT A SIGNAL-LIKE ANOMALIES



ARXIV2309.11537

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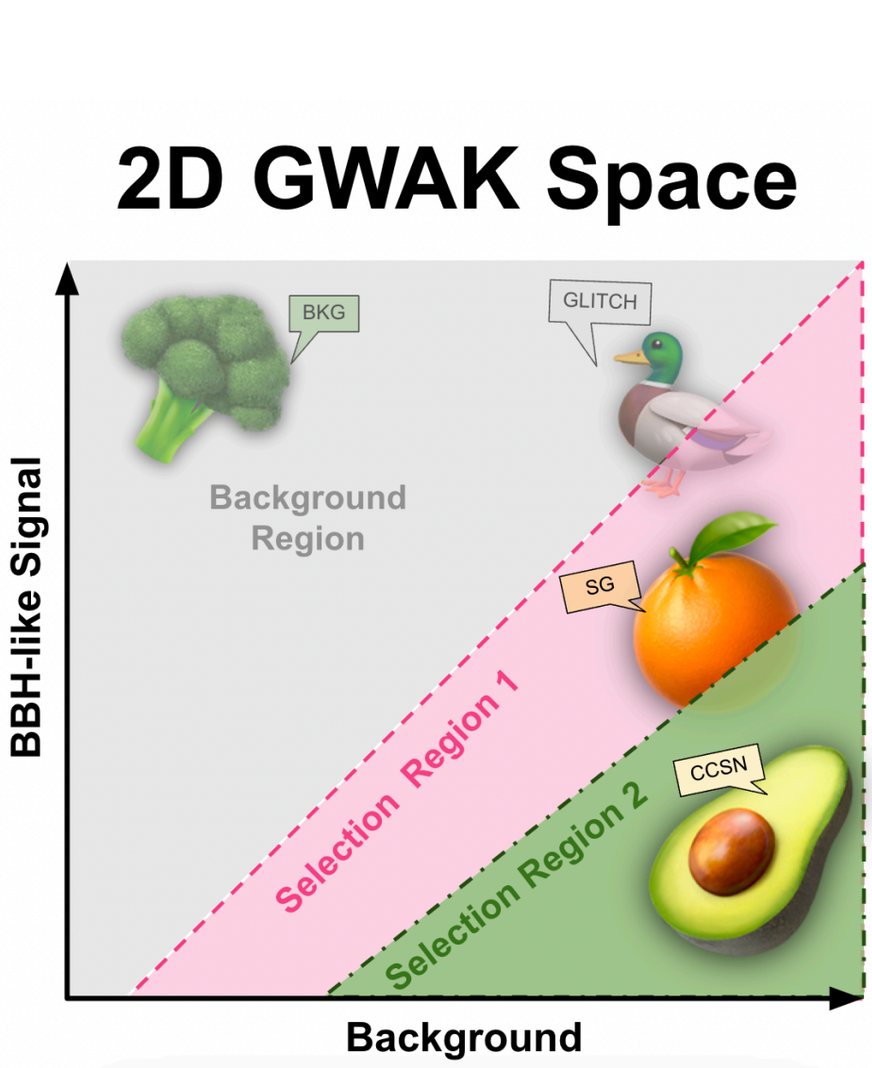
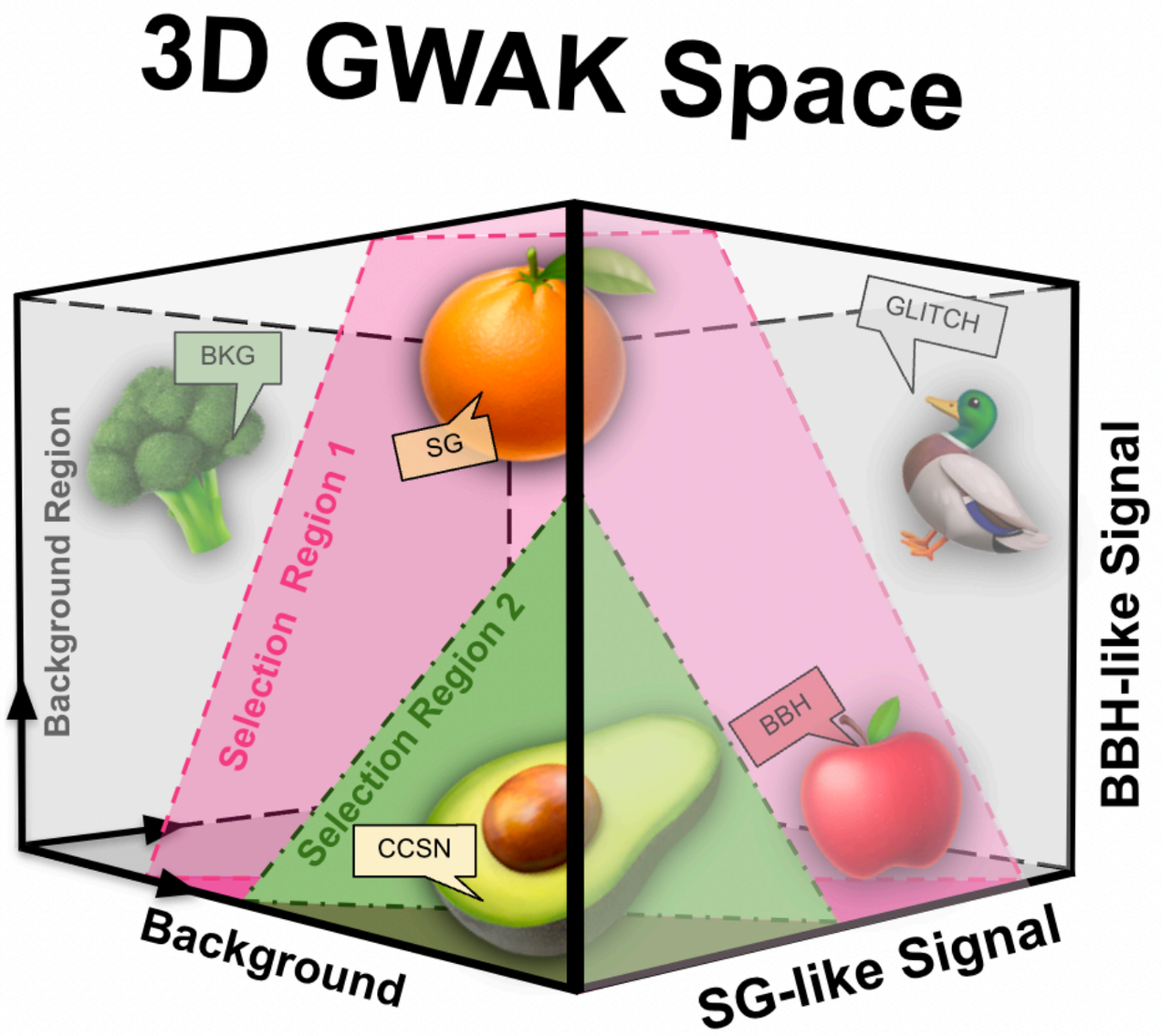
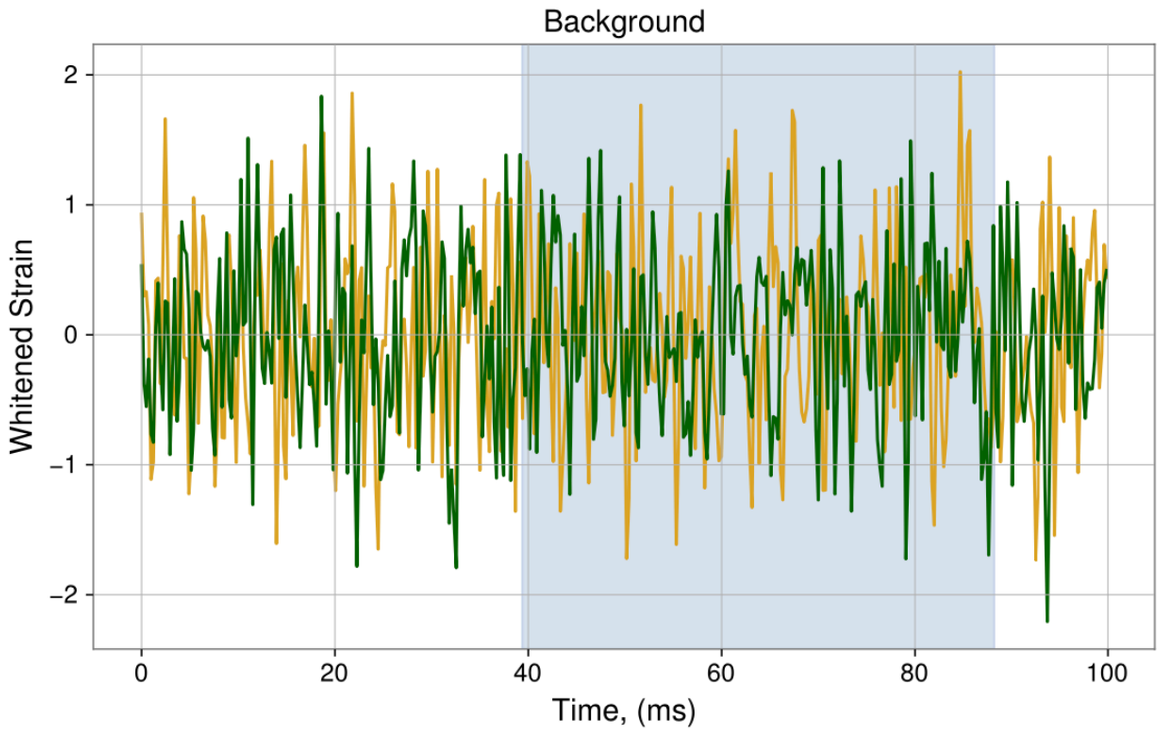


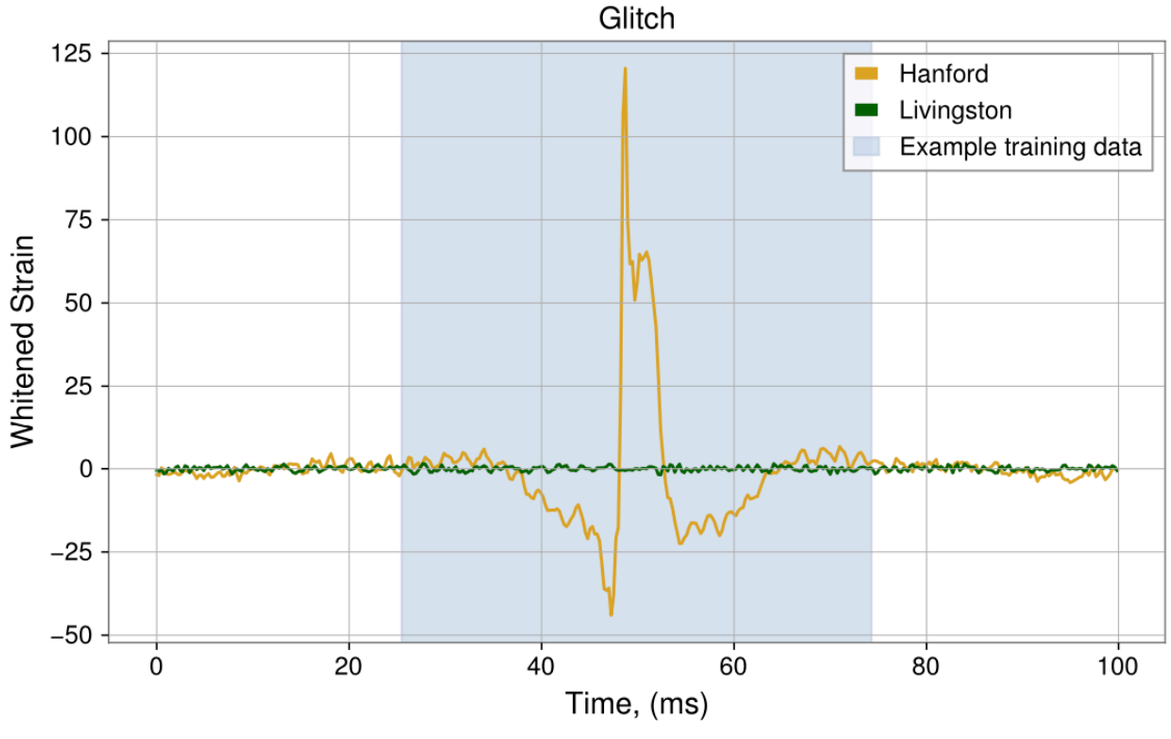



ARXIV2309.11537

EXAMPLE OF GWAK CLASSES: GLITCH AND BACKGROUND STRAINS

THE LIGHT BLUE SHADING HIGHLIGHTS AN EXAMPLE REGION THAT IS PASSED AS INPUT TO THE AUTOENCODERS FOR TRAINING



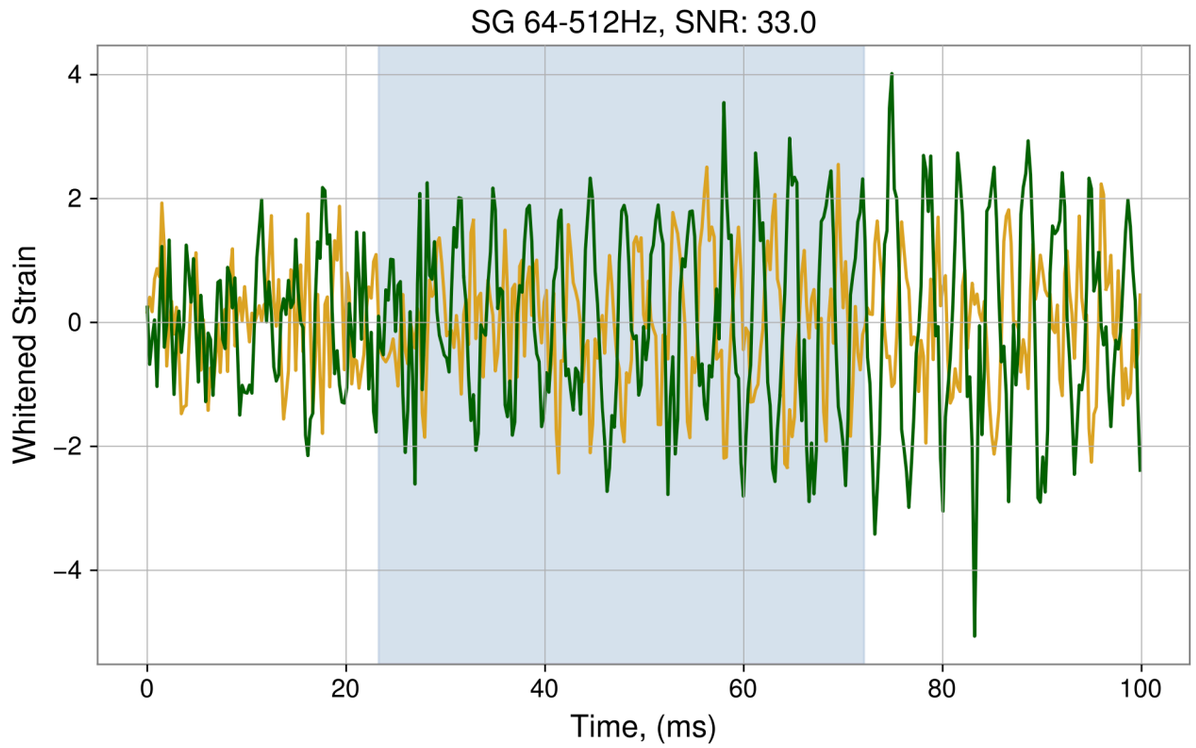



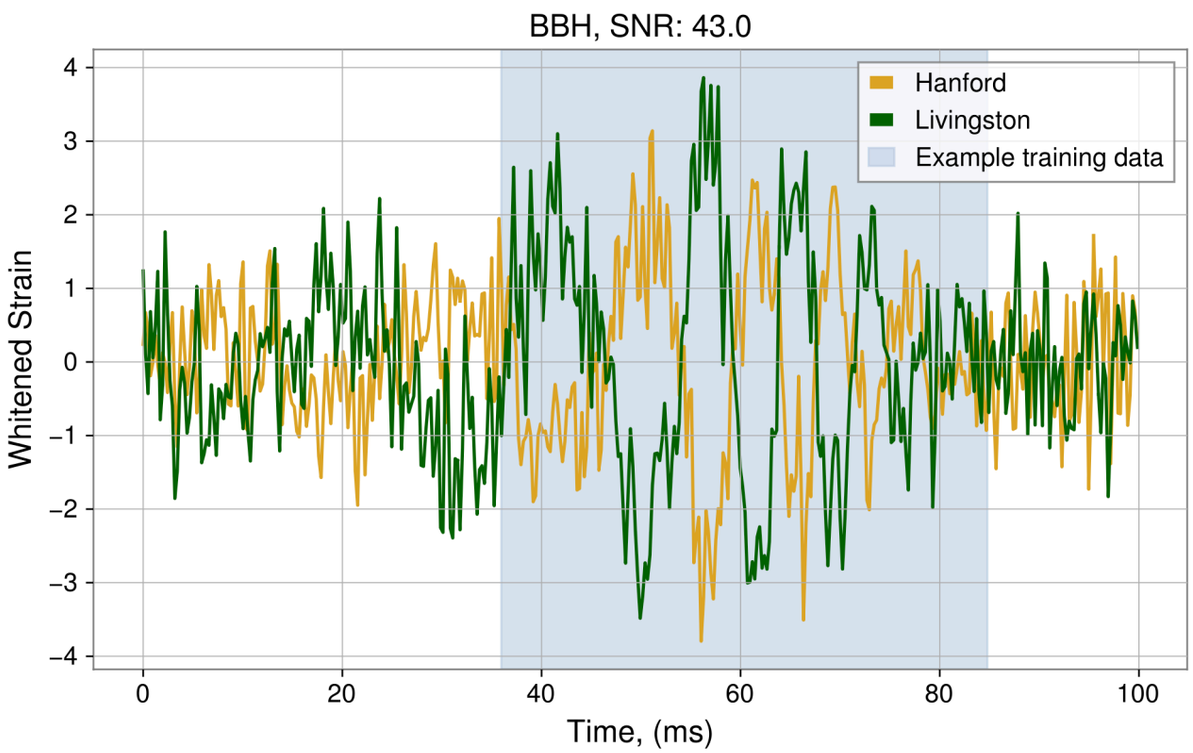
# Signal datasets

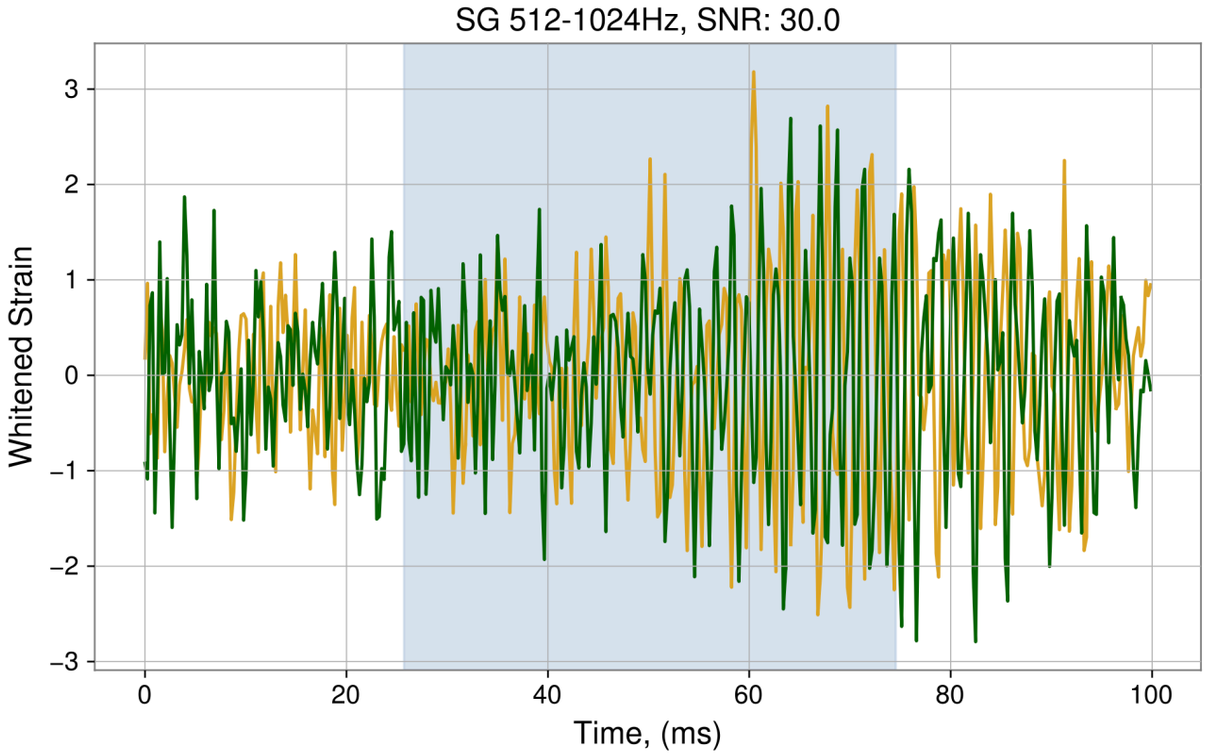
ARXIV2309.11537

Example of signal-like classes: BBH and sine-Gaussian strains from Livingston and Hanford

The light blue shading highlights an example region that is passed as input to the autoencoders for training



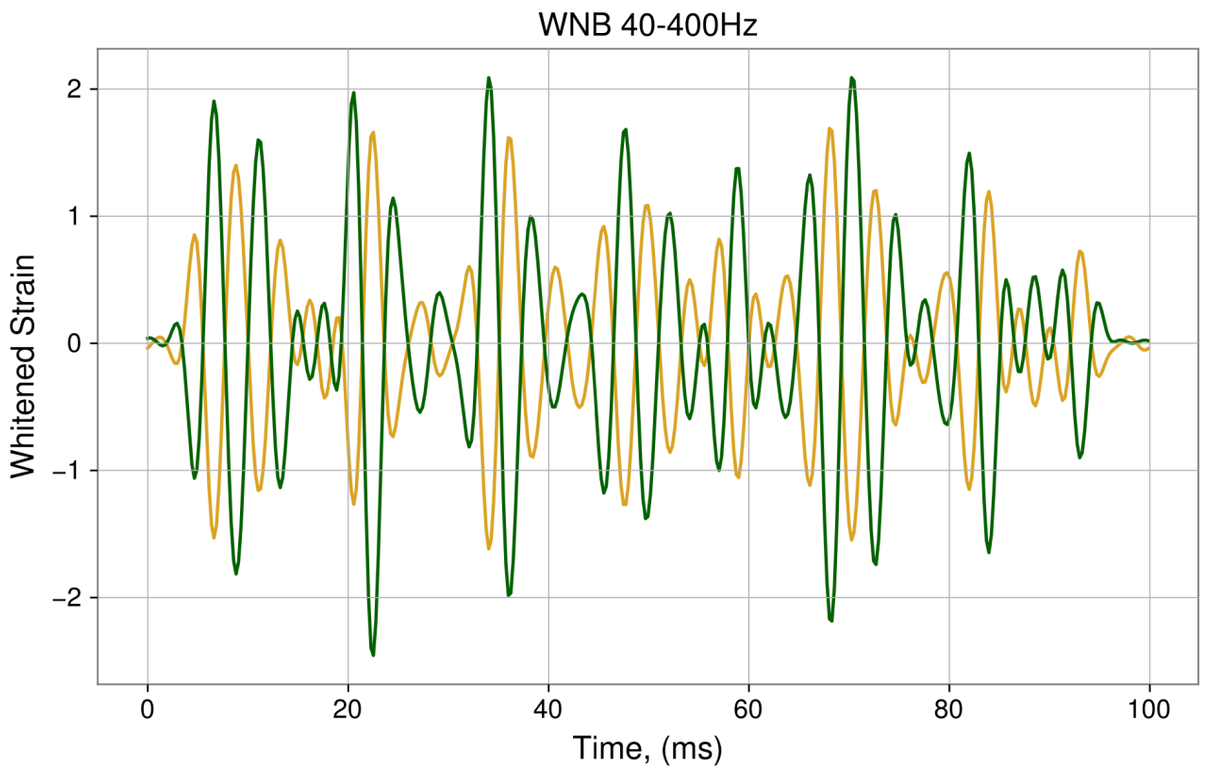



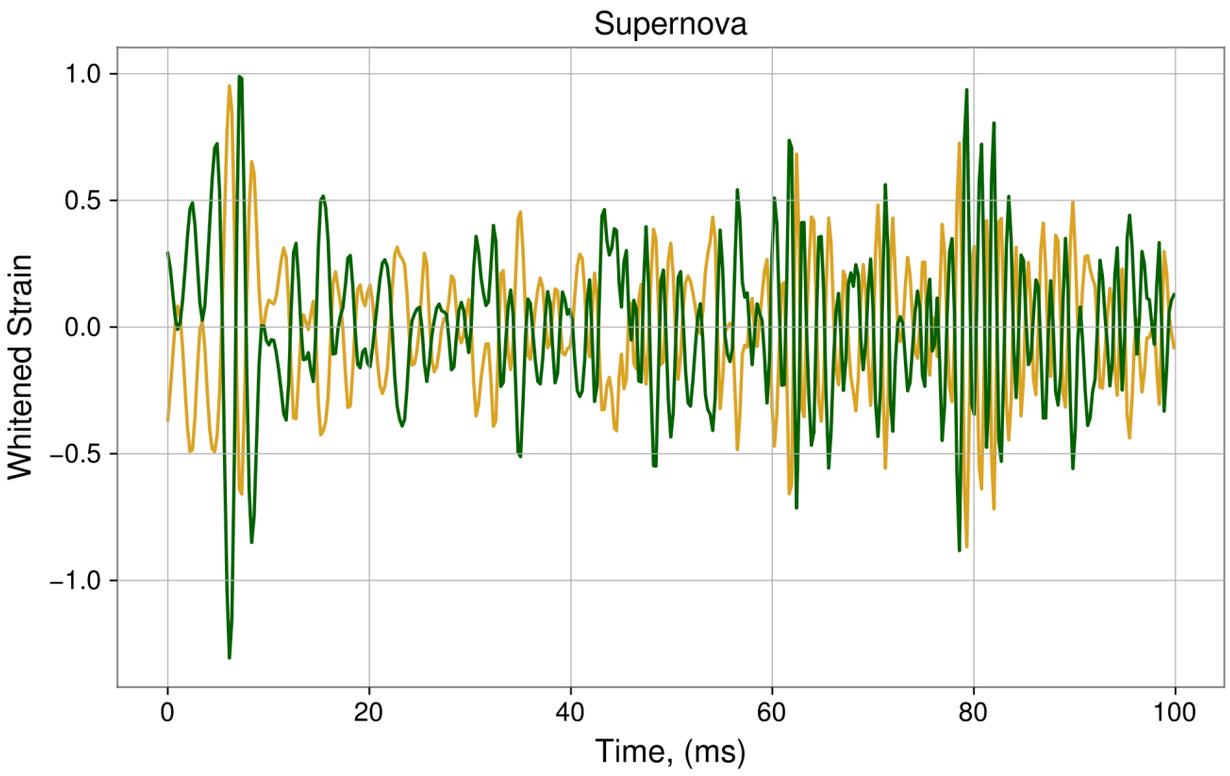
# Anomaly datasets

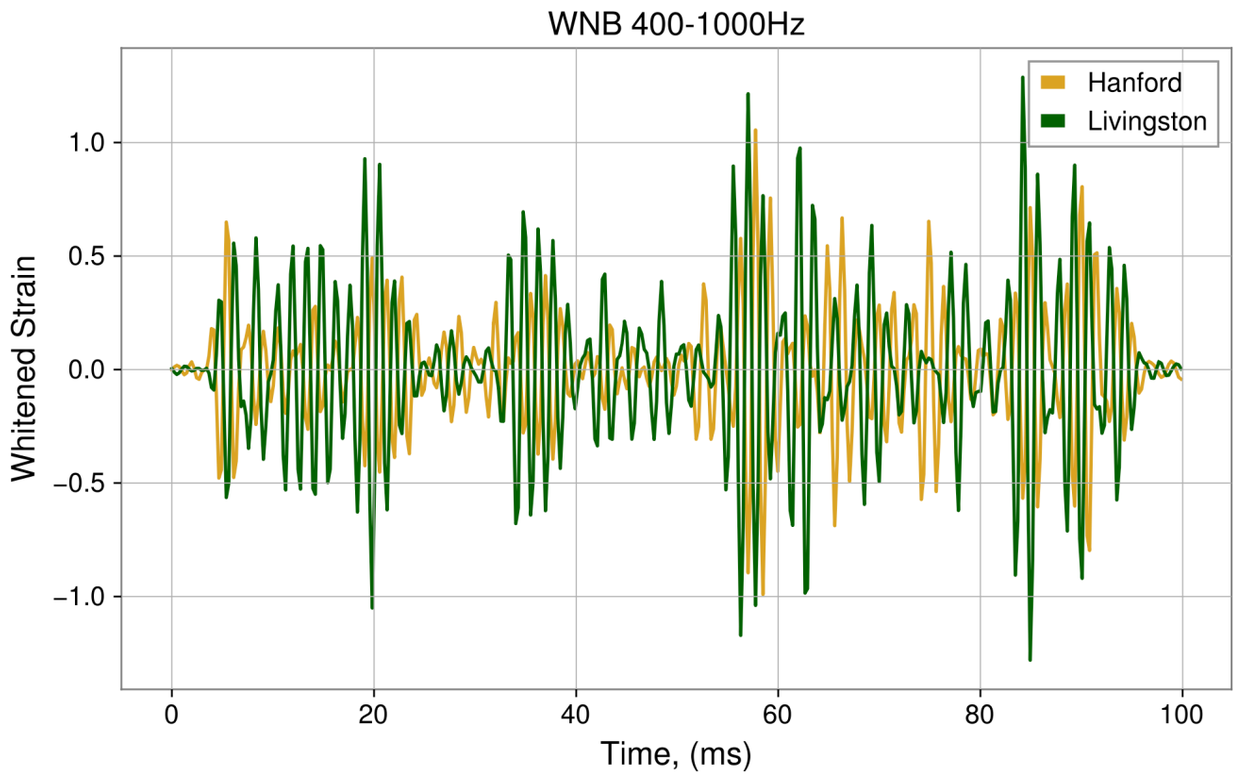
arXiv2309.11537

Example of signal-like classes: Supernova and white noise burst strains from Livingston and Hanford

Those anomalies are not used to create the GWAK



# Training autoencoders

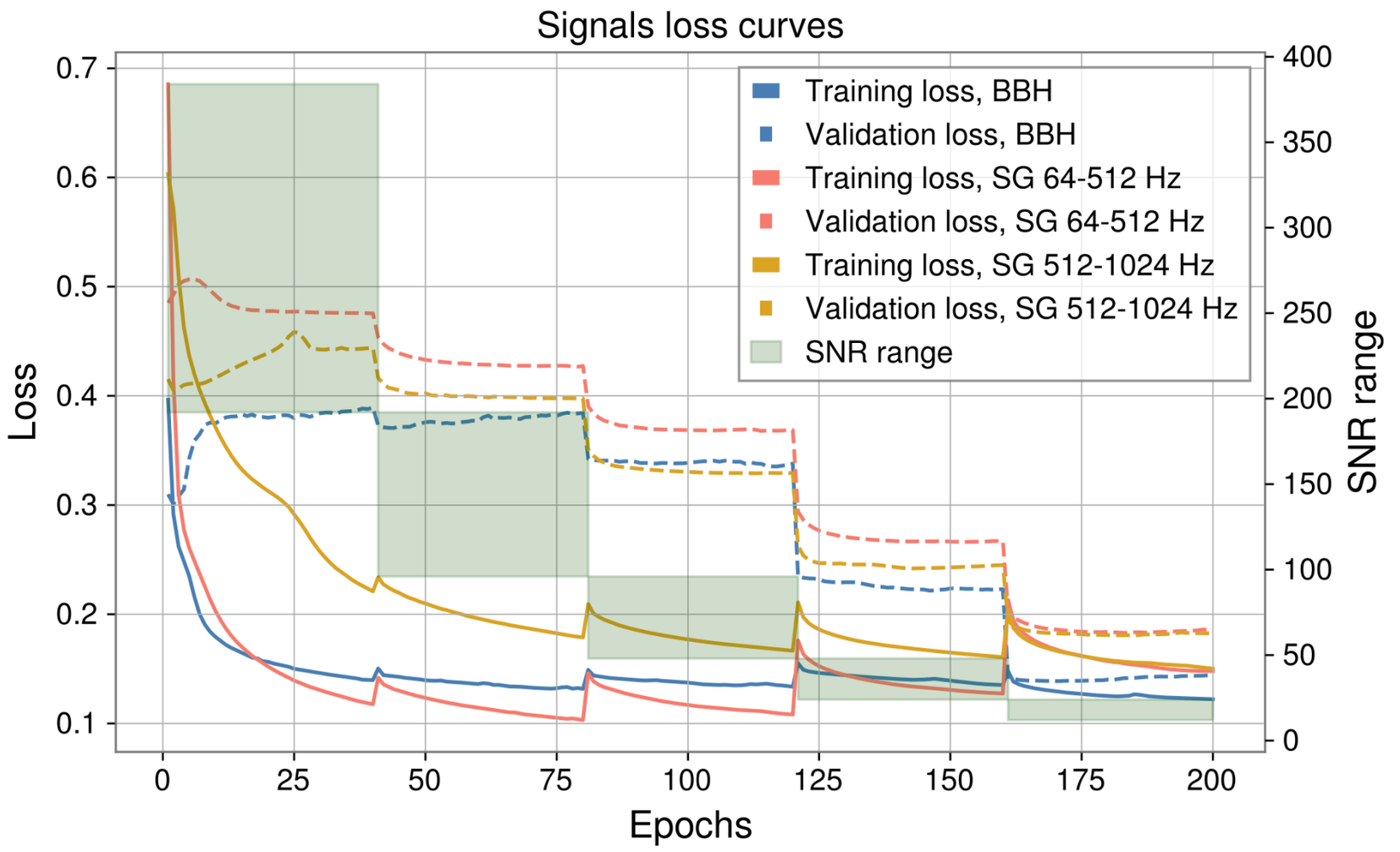
arXiv2309.11537

Autoencoder training and validation losses for signal classes, using curriculum learning to progressively reduce validation loss

The validation loss for each training SNR range is computed on the validation data from the last SNR step

In solid/dashed colours are the training/validation losses for BBH, SG 64-512 Hz and SG 512-1024 Hz

A light green shaded region depicts the SNR range for each step of training, spanning the range of injected SNR corresponding to each curriculum.



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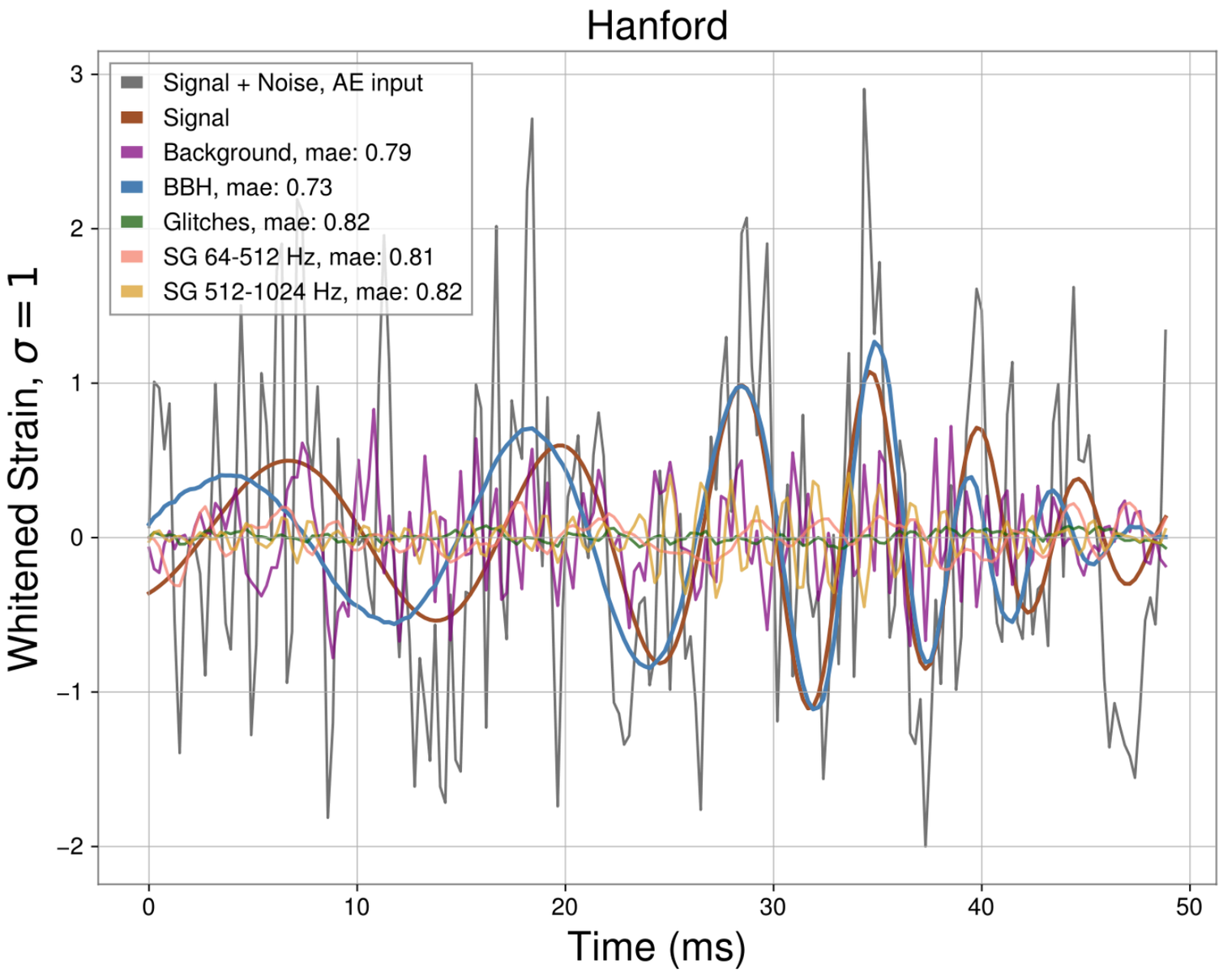
EXAMPLE OF RECREATION ON INJECTED BBH SIGNAL, WITH THE NOISE-LESS TEMPLATE SHOWN AS WELL

THE RECREATION OF THE BBH AUTOENCODER FOLLOWS CLOSELY THE ORIGINAL SIGNAL INJECTION

WHILE BACKGROUND, GLITCHES, SG 64-512 HZ AND SG 512-1024 HZ FAIL TO RECONSTRUCT THE INJECTED BBH SIGNAL



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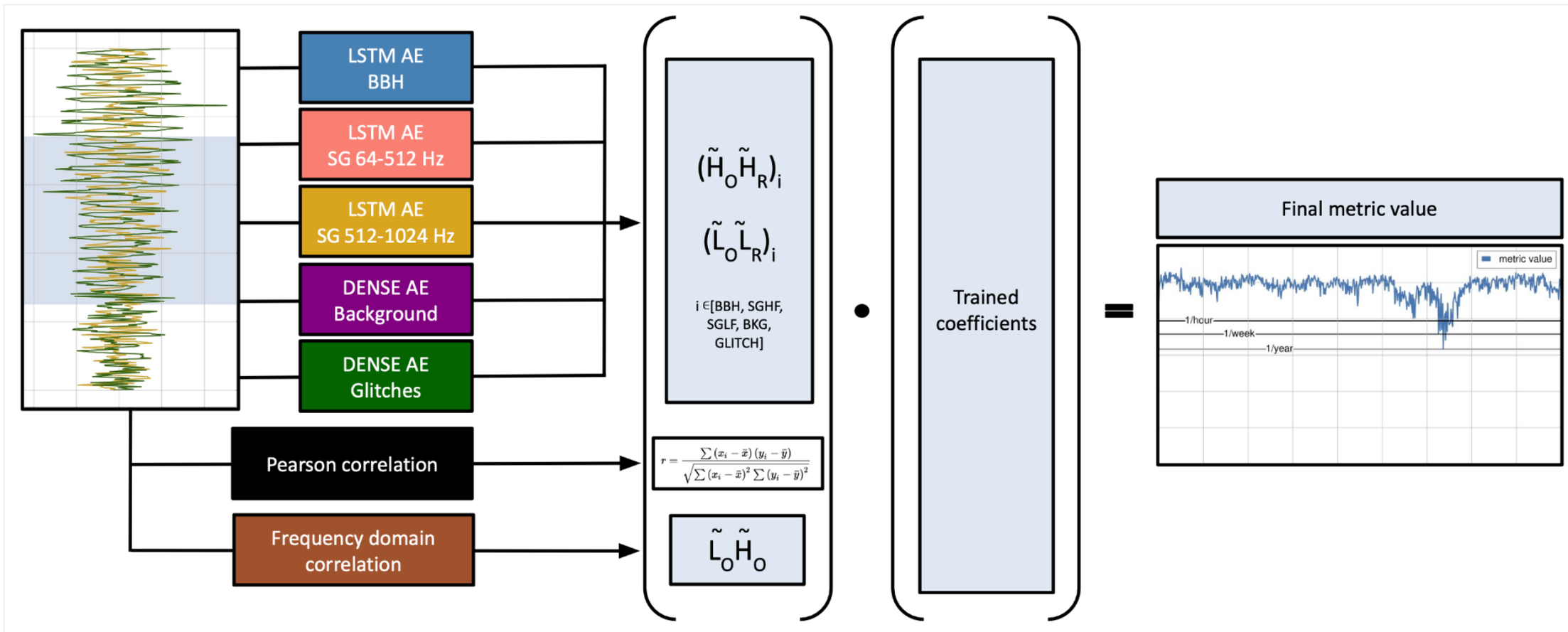
Example of metric calculation on a hypothetical event

1. The event is reconstructed with each of the 5 pre-trained autoencoders, 2 features per AE
2. Pearson and frequency domain correlation are computed on the given input
3. Each of the values is multiplied with a corresponding coefficient which arises from the pre-trained linear metric
4. The sum of all the features multiplied by their coefficients is referred to as the final metric and is used to make a decision on if the event is signal-like



# The GWAK Detection

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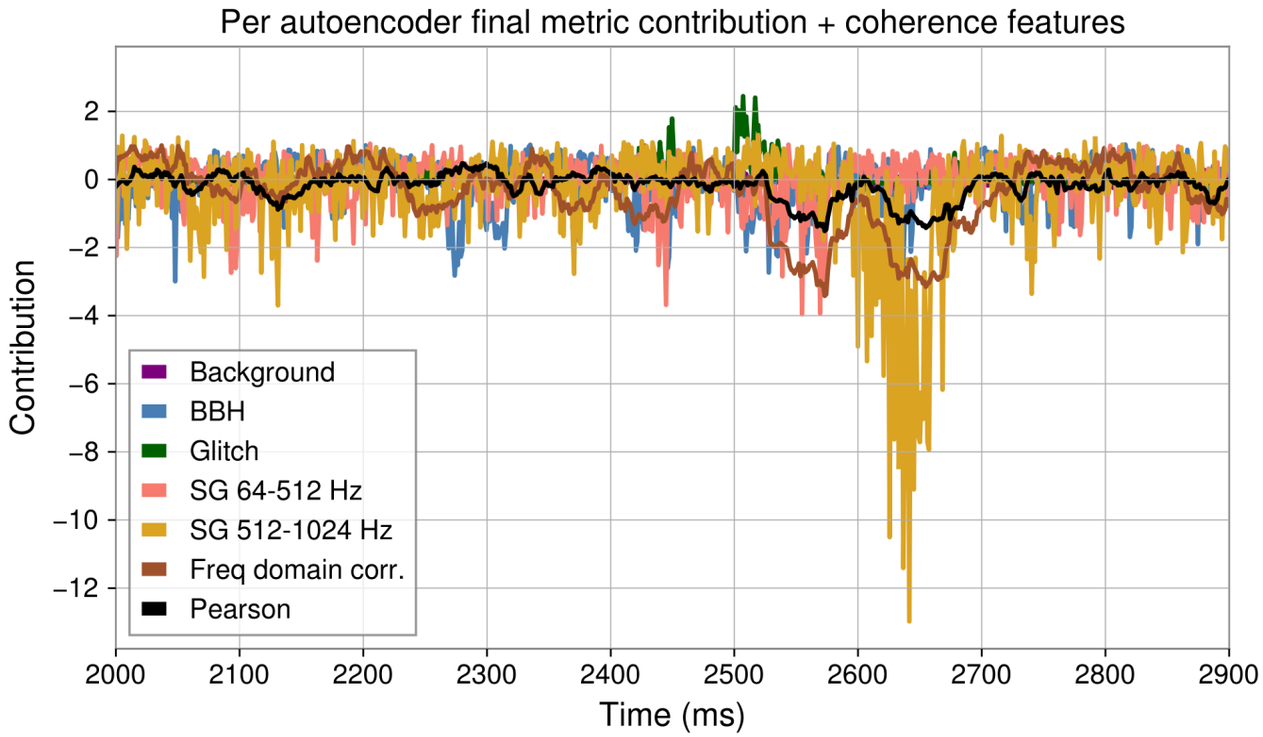
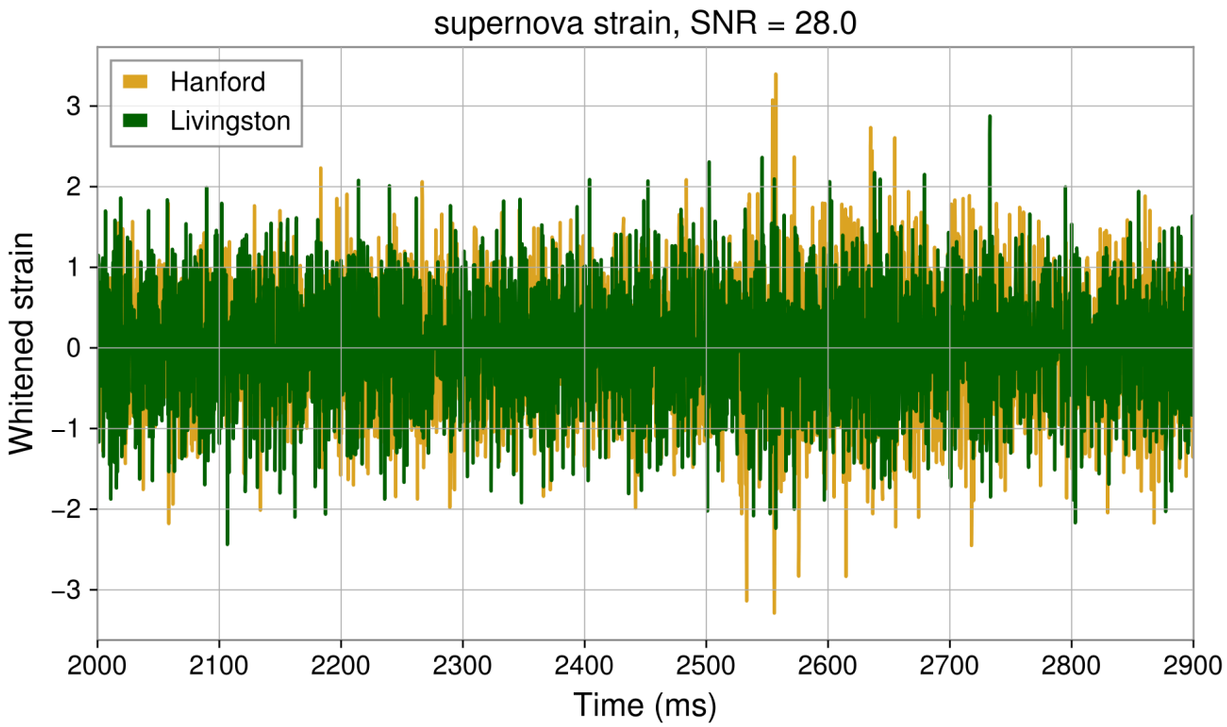
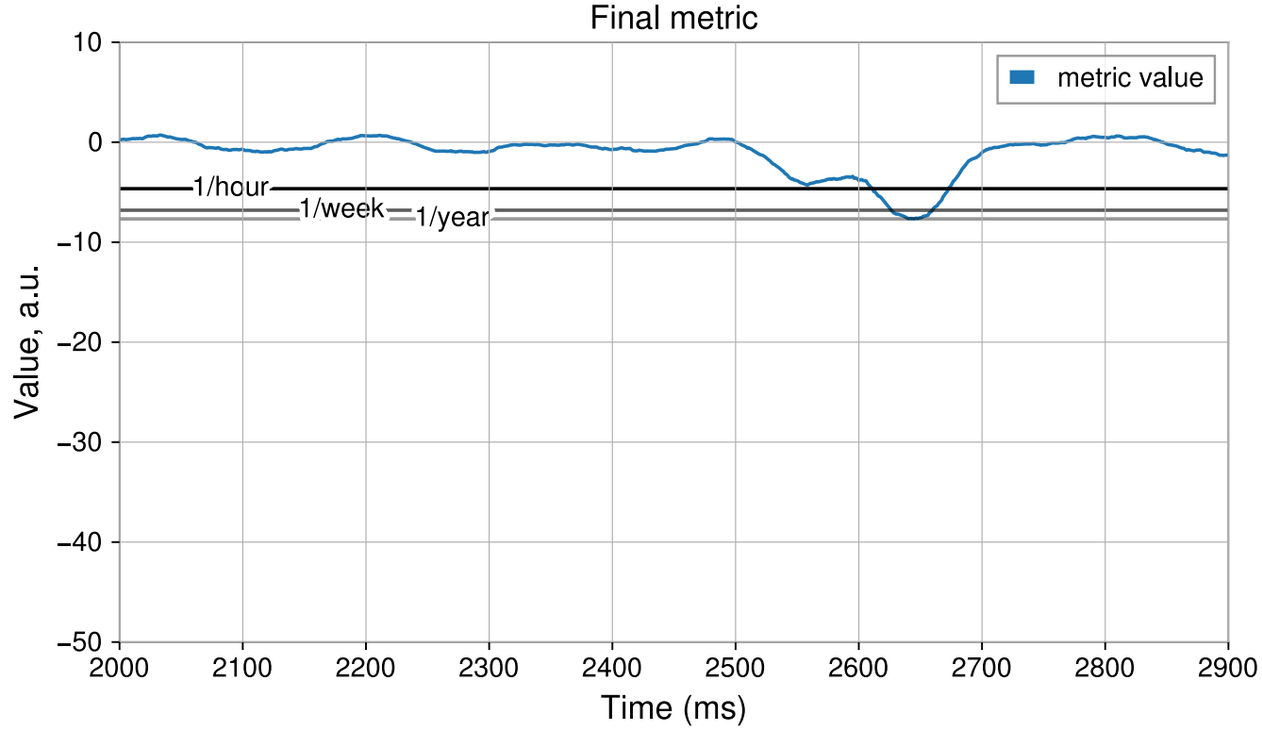
Strain, GWAK metric response and final metric response for Supernova simulated signal

The evaluation of GWAK axes and Pearson correlation with time and on the top right total metric value and FAR are shown as an example of the algorithm's "reaction" to an unseen signal



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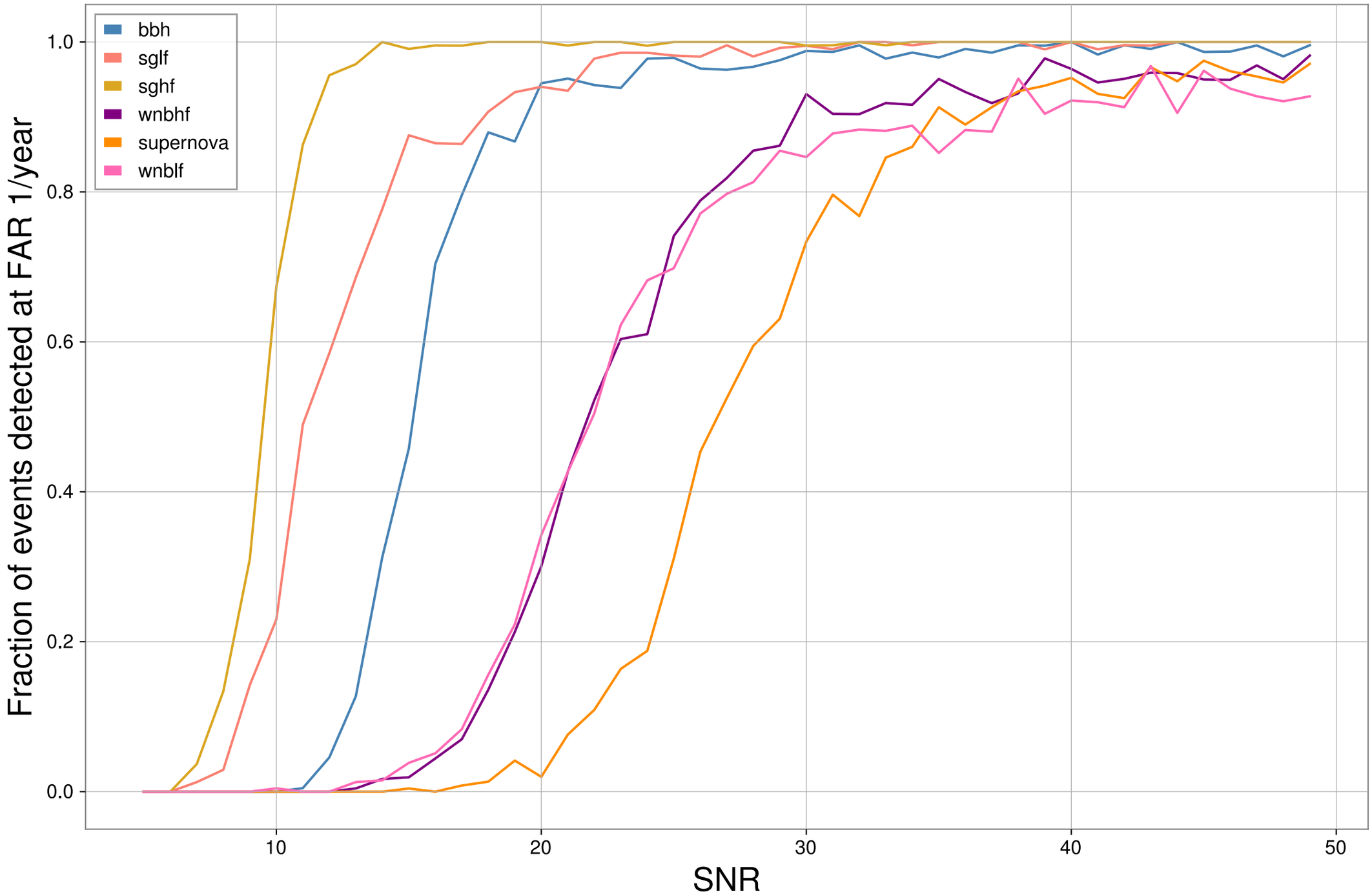
THE FINAL METRIC AS A FUNCTION OF SNR FOR GWAK AXES TRAINING SIGNALS, BBH, SG 64-512 HZ, SG 512-1024 HZ AND FOR POTENTIAL ANOMALIES, WNB 40-400 HZ, WNB 400-1000 HZ, AND SUPERNOVA



# Conclusions

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We present a new semi-supervised approach to gravitational-wave anomaly detection

Our method constructs a 12-dimensional embedded space (GWAK space) that is cut with a hyperplane

We find that the GWAK method provides good discrimination power over correlation metrics