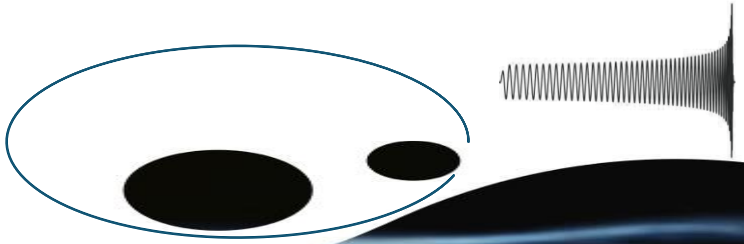
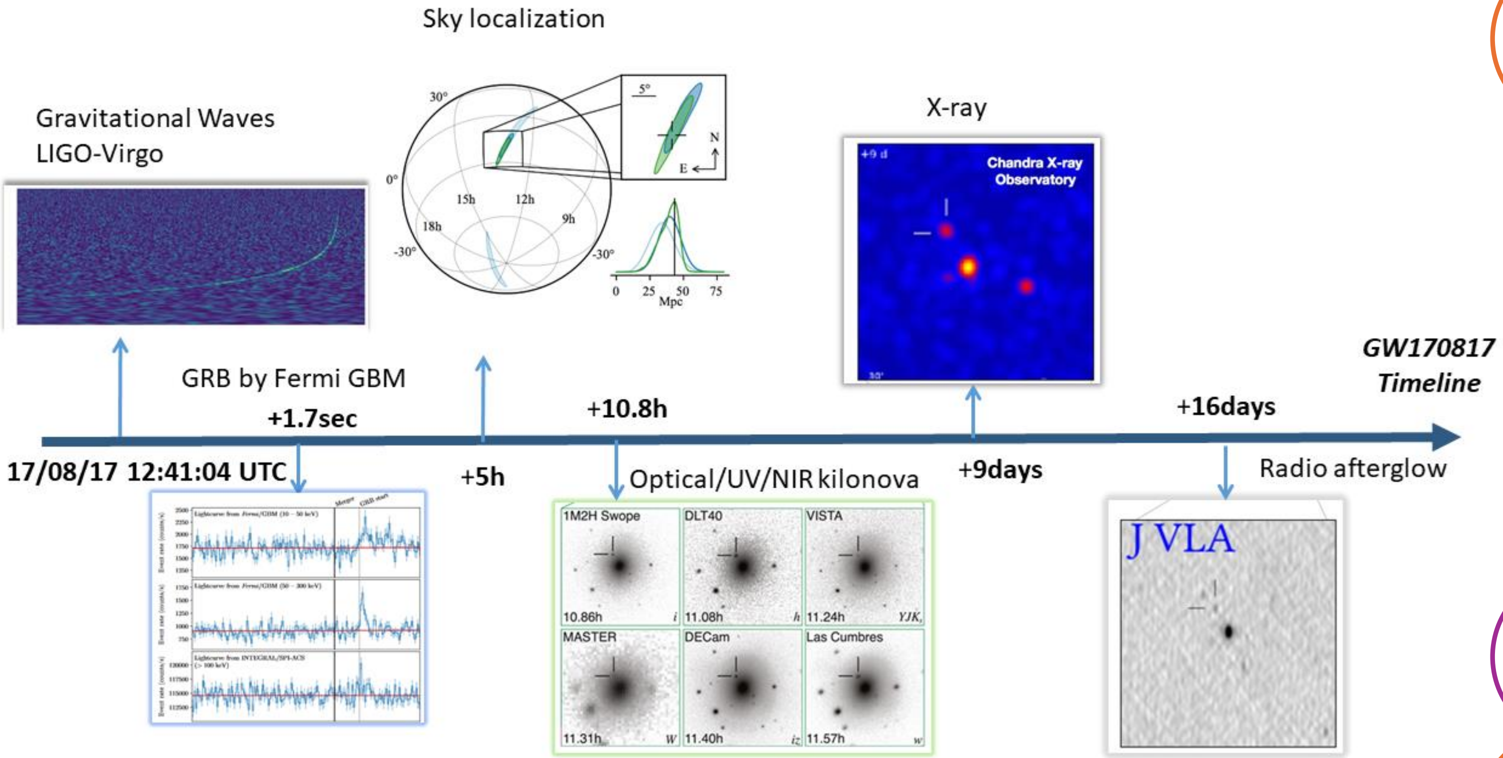
REAL TIME ANALYSIS FOR MULTI-MESSENGER ASTROPHYSICS

Roma International Conference on AstroParticle physics
23-27 September 2024



ELENA CUOCO
EGO European Gravitational Observatory

GW170817: THE FIRST MULTI-MESSENGER GW EVENT



Abbott et al. 2017 and refs. therein

coincident short GRBs detected in **gamma rays**

- first direct evidence that at least some BNS mergers are progenitors of short GRBs

the host galaxy has been identified: NGC 4993

an **optical/infrared/UV** counterpart (AT2017gfo) has been detected

- first spectroscopic identification of a kilonova

An X-ray and a radio counterparts have been identified

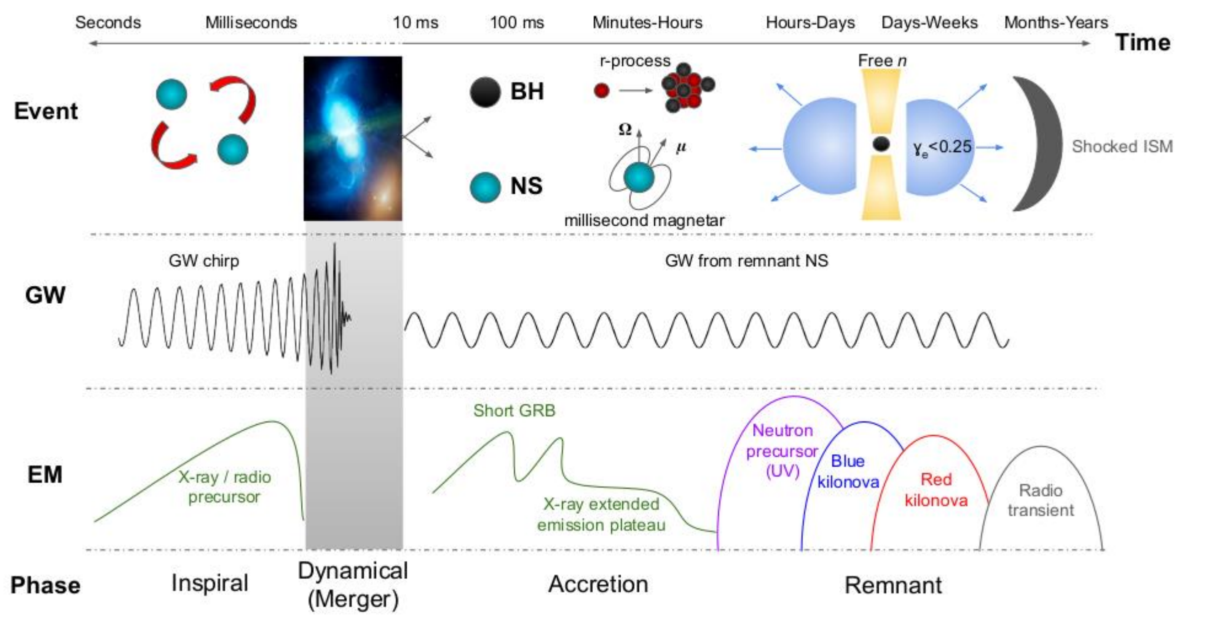
- off-axis afterglow from a structured jet

MULTIMODAL ANALYSIS FOR MULTI-MESSENGER ASTROPHYSICS

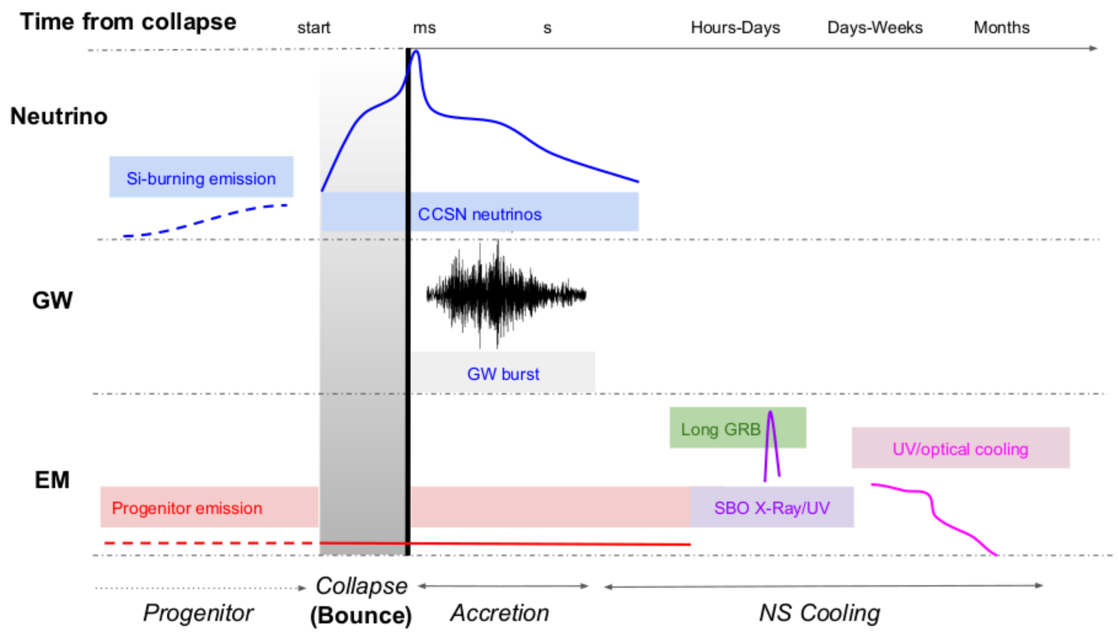
Cuoco, E., Patricelli, B., Iess, A. *et al.* Computational challenges for multimodal astrophysics. *Nat Comput Sci* 2, 479–485 (2022). https://doi.org/10.1038/s43588-022-00288-z

MULTI-MESSENGER ASTROPHYSICAL SIGNALS

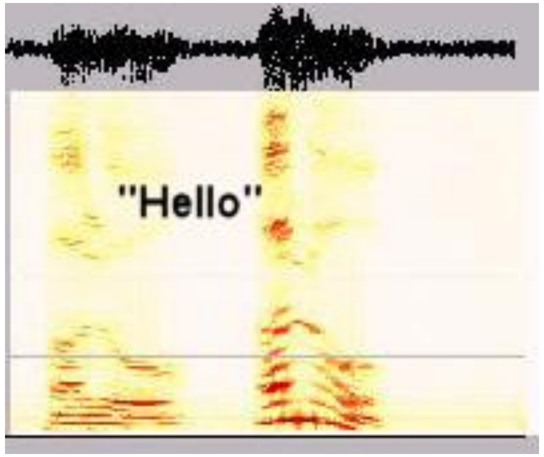
CBC events



CCSN events



MULTIMODAL INPUTS

Visual:Images/videos	Text: Natural language processing	Speech/audio signal
	**Multimodal analysis of Gravitational Wave signals and Gamma-Ray Bursts from binary neutron star mergers** Elena Cuoco, Barbara Patricelli, Alberto Iess, Filip Morawski A major boost in the understanding of the universe was given by the revelation of the first coalescence event of two neutron stars (GW170817) and the observation of the same event across the entire electromagnetic spectrum. With 3rd Generation gravitational wave detectors and the new astronomical facilities, we expect many multi messenger events of the same type. We anticipate the need to analyse the data provided to us by such events, to fulfill the requirements of real-time analysis, but also in order to decipher the event in its entirety through the information emitted in the different messengers using Machine Learning. We propose a change in the paradigm in the way we will do multi-messenger astronomy, using simultaneously the complete information generated by violent phenomena in the Universe. What we propose is the application of a multimodal machine learning approach to characterize these events.	

HOW TO COMBINE DIFFERENT INFORMATION?

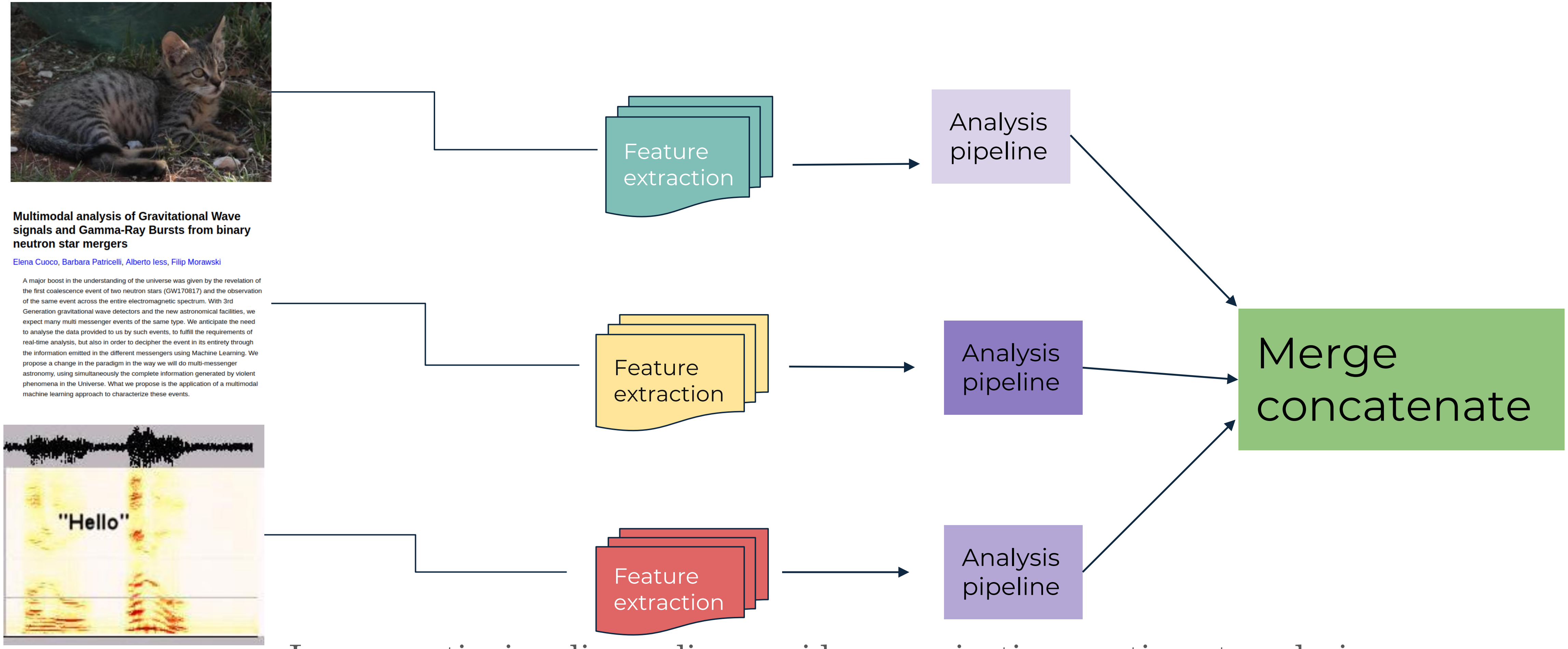
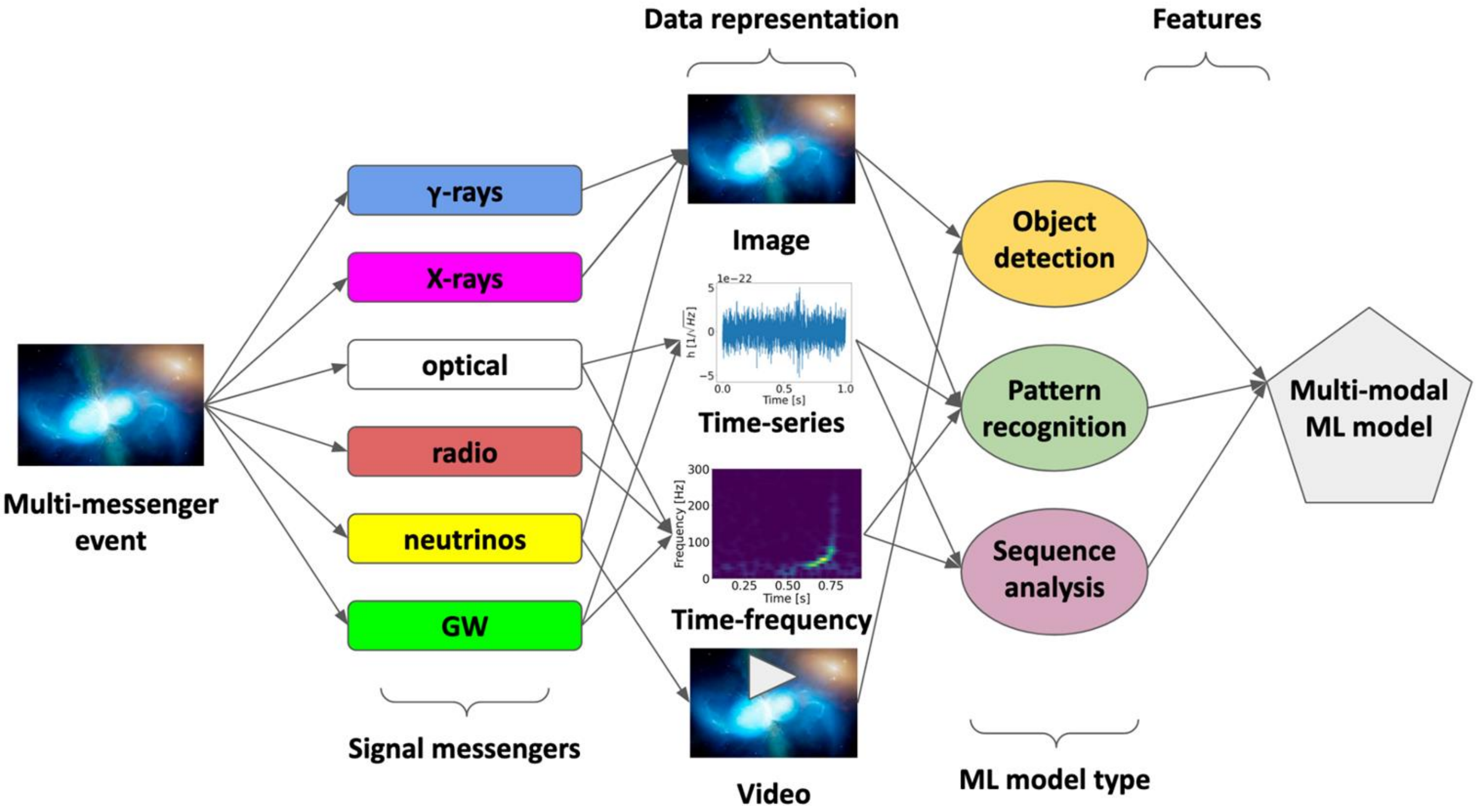
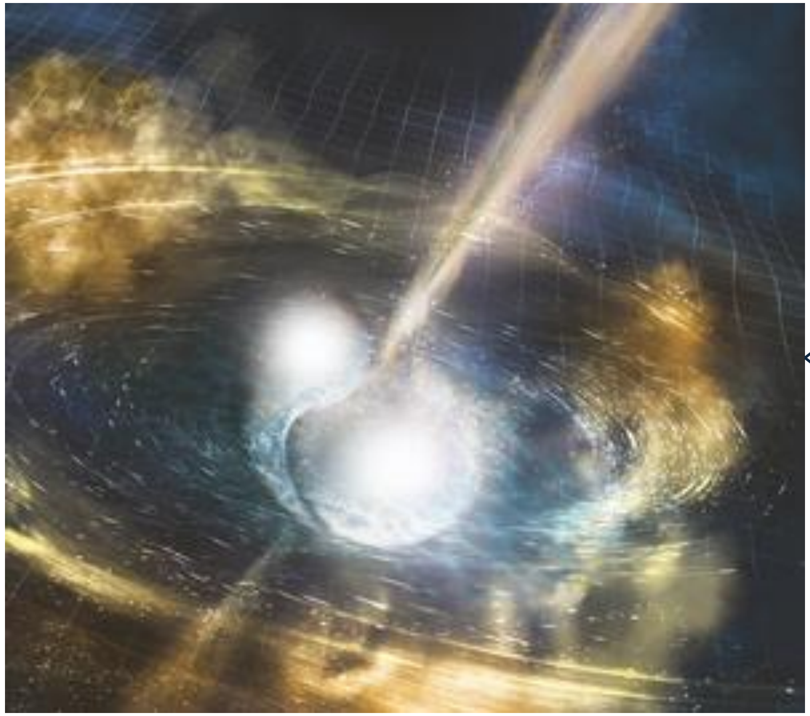


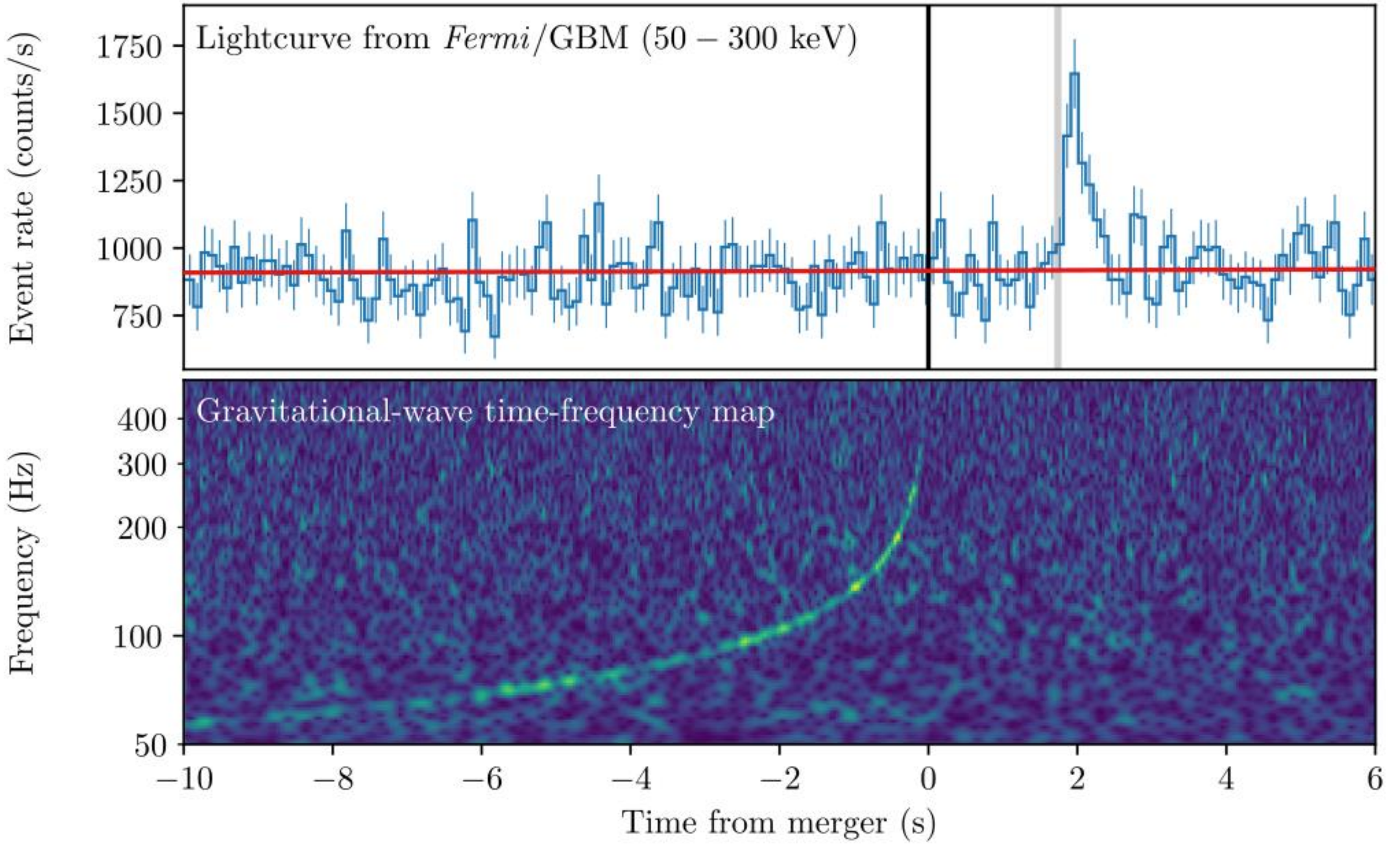
Image captioning, lip reading or video sonorization, sentiment analysis…

MMML FOR ASTROPHYSICS



CASE STUDY: APPLICATION TO GW-GRB SIGNALS





Credit: NSF/LIGO/Sonoma State University/A. Simonnet

credits: LIGO/VIRGO collaboration; Abbott et al. 2017, ApJ, 848, 13

GOAL OF THE PROJECT

To estimate the redshift (z) of GRBs associated with BNS mergers

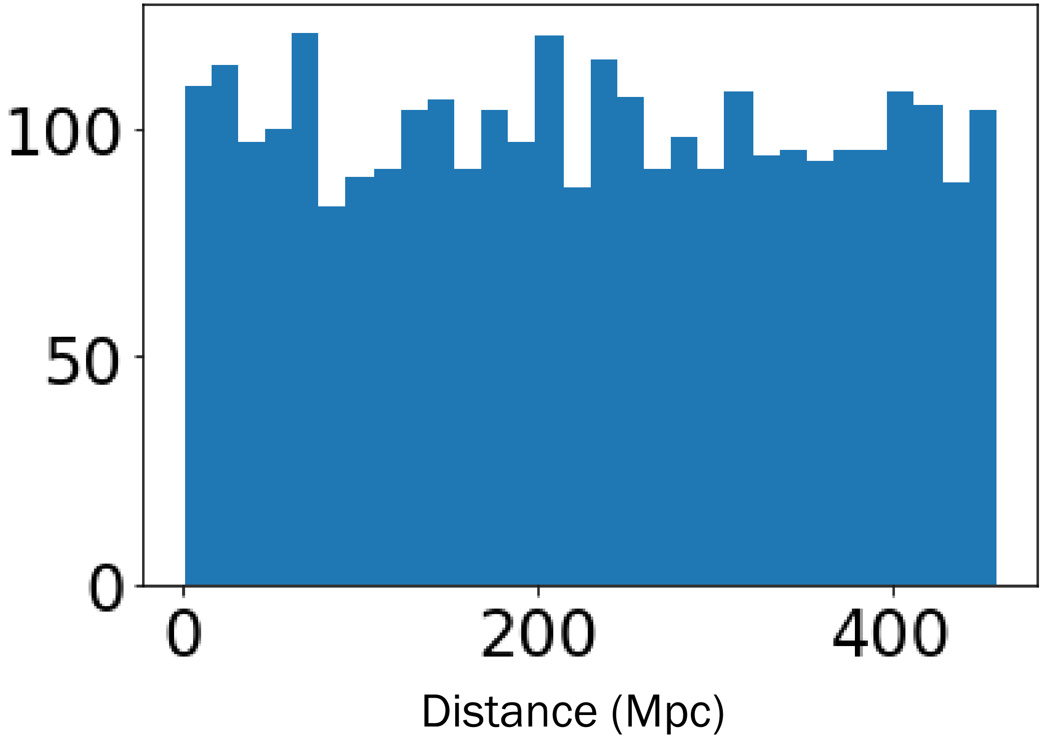
- We have a bunch of simulated GRBs, and we assume that we know z only for a fraction of them;
- We train the pipeline on the GRBs with known z;
- We predict z using joint GRB and GW analysis

SIMULATIONS: WHAT WE SIMULATED

Multi-messenger signals from BNS mergers in 3 steps:

- Generation of a population of BNS merging systems
- Simulation of the associated GW signals and GW data for a detector such as the Einstein Telescope
- Simulation of the associated short GRB light curve as observed by a Fermi-like detector

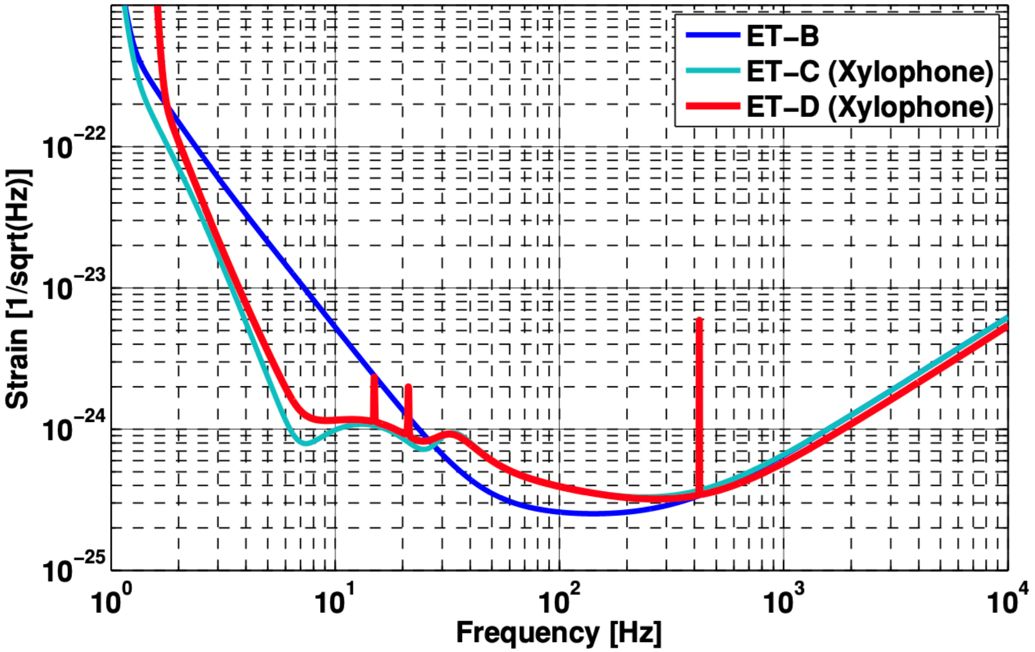
BINARY NEUTRON STAR POPULATION

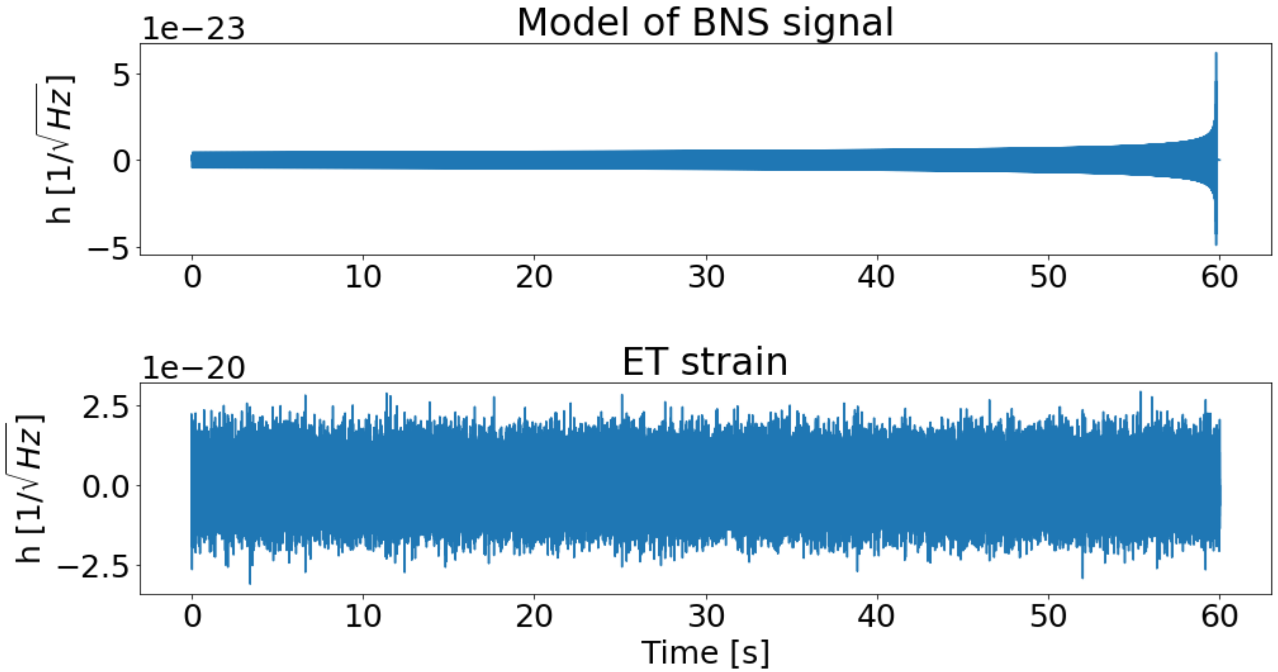


https://doi.org/10.3390/universe7110394

- NS spins: aligned; maximum value: 0.05
- Focus on sources giving rise to an on-axis GRB -> maximum inclination of the BNS system fixed to 8 deg NS masses: uniform distribution between 1 and 2.5 $M_{\odot}$
- BNS Distance: uniform distribution between 1 and 500 Mpc

GW DETECTOR NOISE: EINSTEIN TELESCOPE





Hild et al. 2011, Class. Quantum Grav., 28 094013

https://doi.org/10.3390/universe7110394

ELECTROMAGNETIC SIMULATIONS

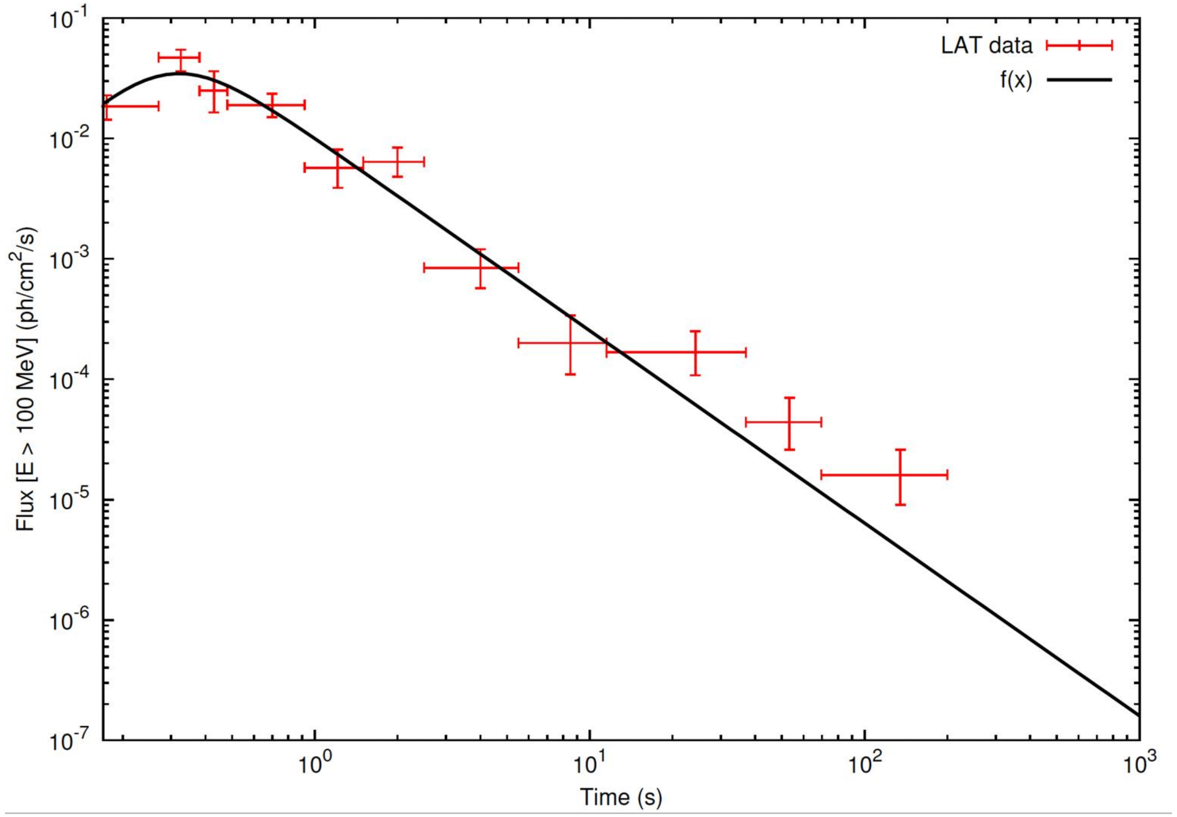
We assume that all BNS mergers are associated with a short GRB

We simulate the **GRB afterglow gamma-ray light curves** following the approach in Patricelli et al. 2016:

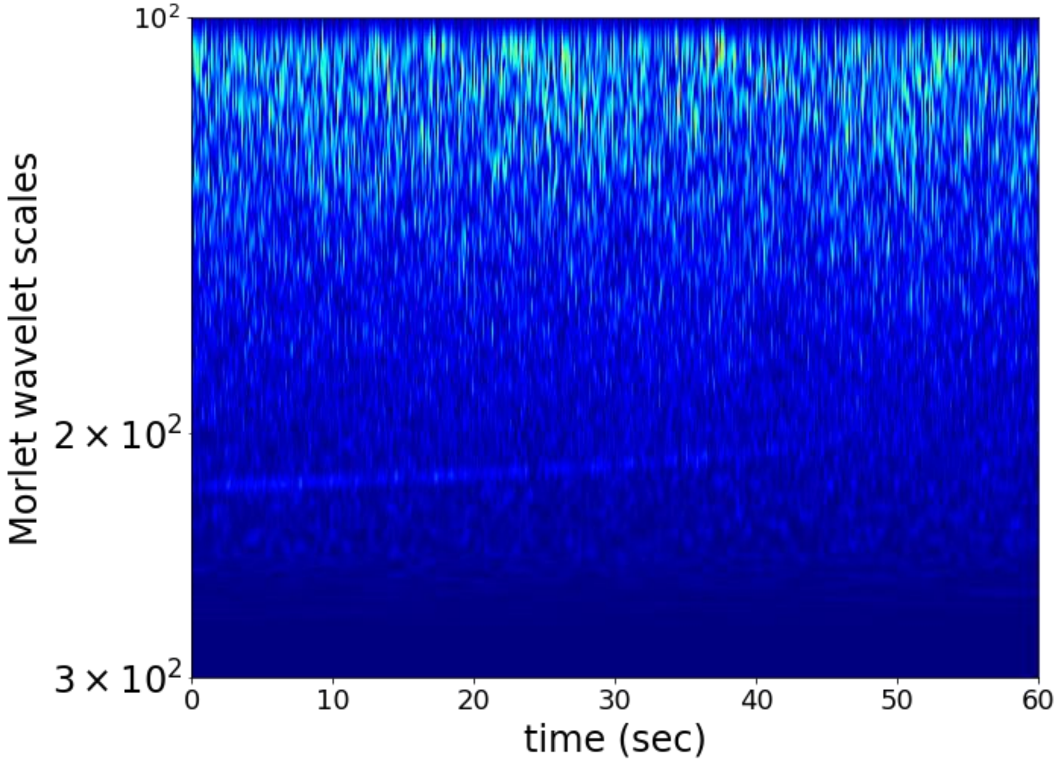
GRB 090510 as a prototype

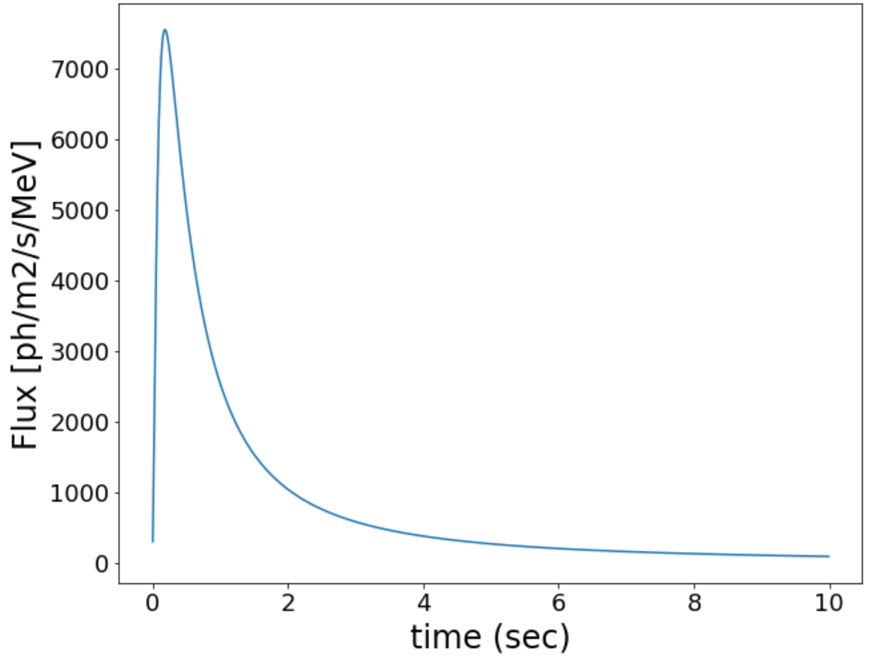
light curve corrected to take into account

- The distance of the sources with respect to GRB 090510
- A range of possible GRB isotropic energies



DATA TRANSFORMATION: TIME-SERIES OR IMAGES





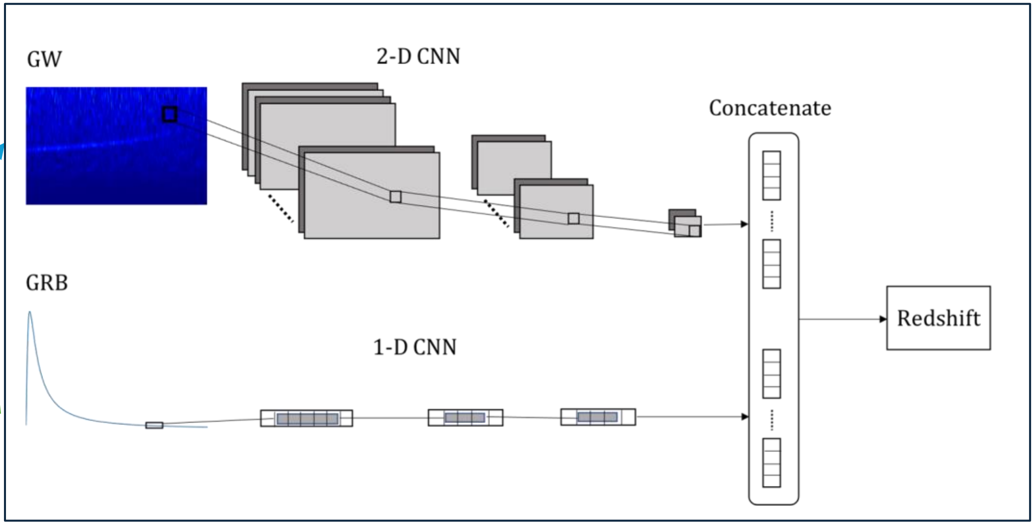
Simulated data set

Sampling frequency: 2048 Hz
Number of BNS-GRB events: 3000
Train/Validation/Test set: 70%, 10%, 20%

THE DEEP NETWORK

2-D CNN for GW time-frequency:
- 5 convolutional layers with (3,3) kernels and 64, 32, 16, 16, 32 filters.
- Max pooling (2,2) after convolutional layer

1-D CNN for GRB light curve:
- 3 convolutional layers with kernels 5, 3, 3 and 80, 40, 40 filters
- Max pooling of 2 after convolutional layer

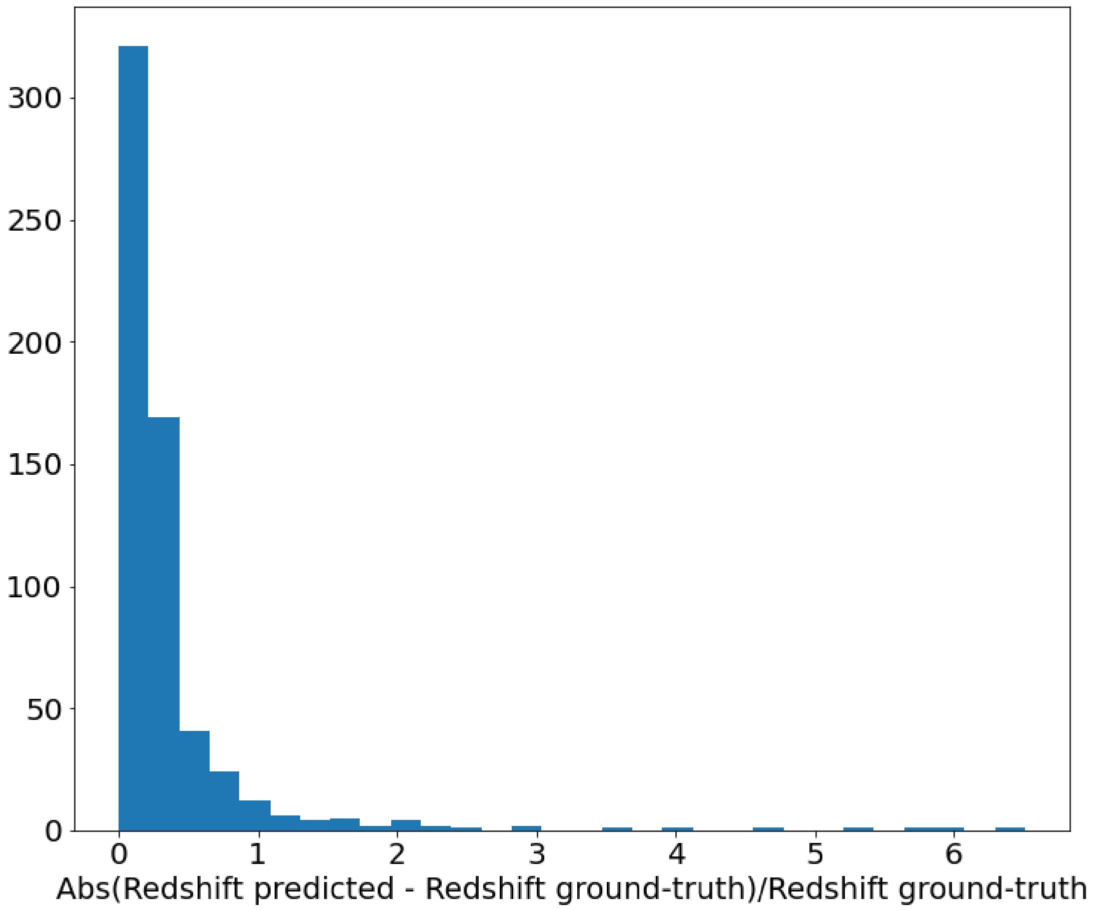


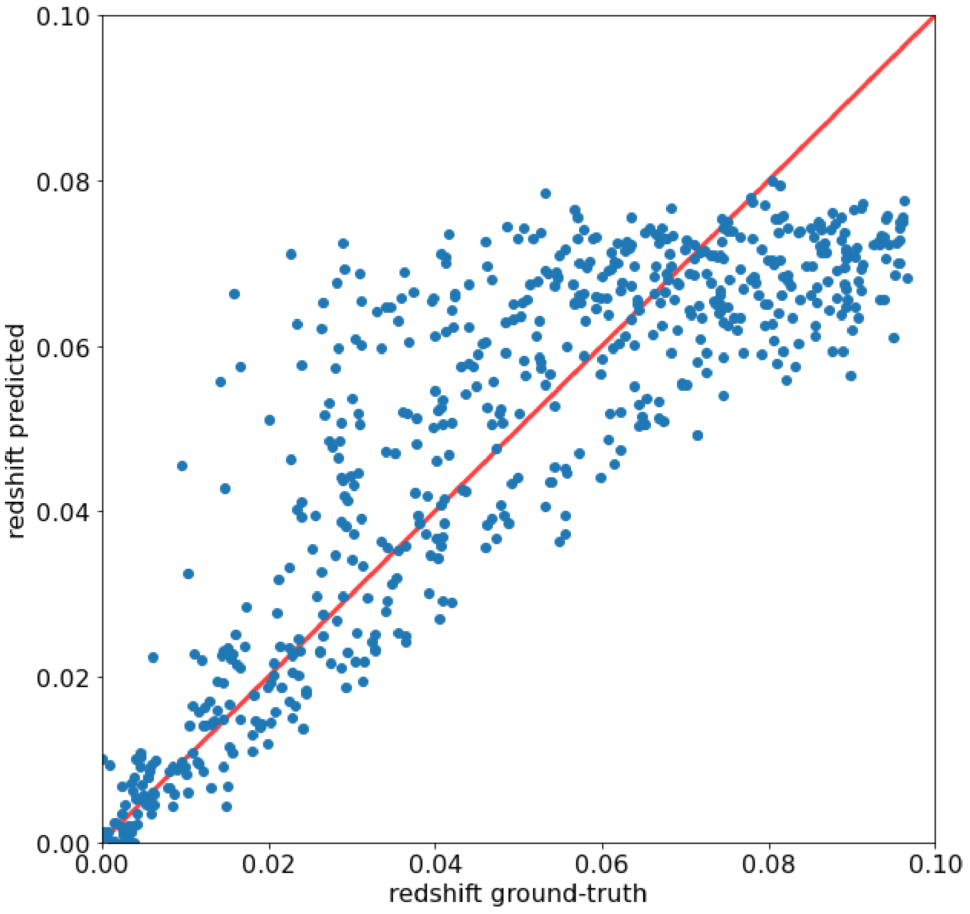
Flattening + Concatenation + FC layer with linear activation

ReLU activation function in CNN
Adam optimizer
batch size: 16
Number of training epochs: 100

https://doi.org/10.3390/universe7110394

MMML FOR GW-GRB RESULTS





WAVEFIER: A FRAMEWORK FOR MULTI-MESSENGER ASTROPHYSICS

ELENA CUOCO, ALBERTO IESS, FILIP MORAWSKI, BARBARA PATRICELLI, SARA VALLERO, EMANUEL MARZINI, ALESSANDRO PETROCELLI, ALESSANDRO STANISCIA.

WAVEFIER: A FRAMEWORK FOR MULTI-MESSENGER

WAVEFIER aims to set up a framework for analysis of different types of astrophysical data, paving the way to real-time Multi-Messenger astronomy studies. This is done leveraging the newest available software technologies.

KEY POINTS

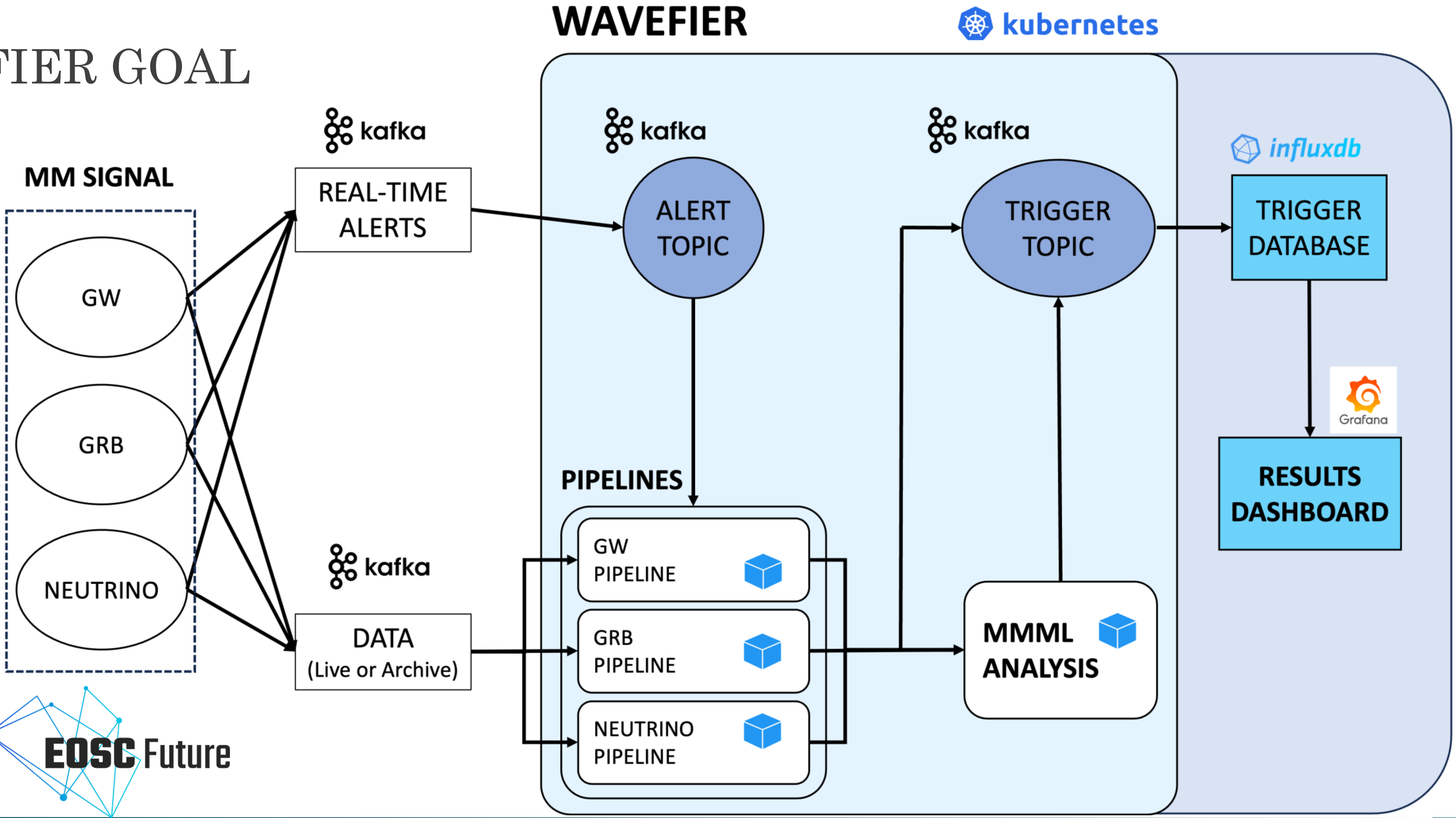
- Setup a prototype for a **real time** and offline pipeline for the detection and analysis of transient signals and their **automatic** classification.
- Best practice for **software management.**
- Software architecture solutions to prototype a **scalable** pipeline for **big data** analysis in GW context.
- **Interoperability** and access to data and services.
- **ICT services** supporting research infrastructures.
- Use of **data in network** infrastructures and service.

IN COLLABORATION WITH:

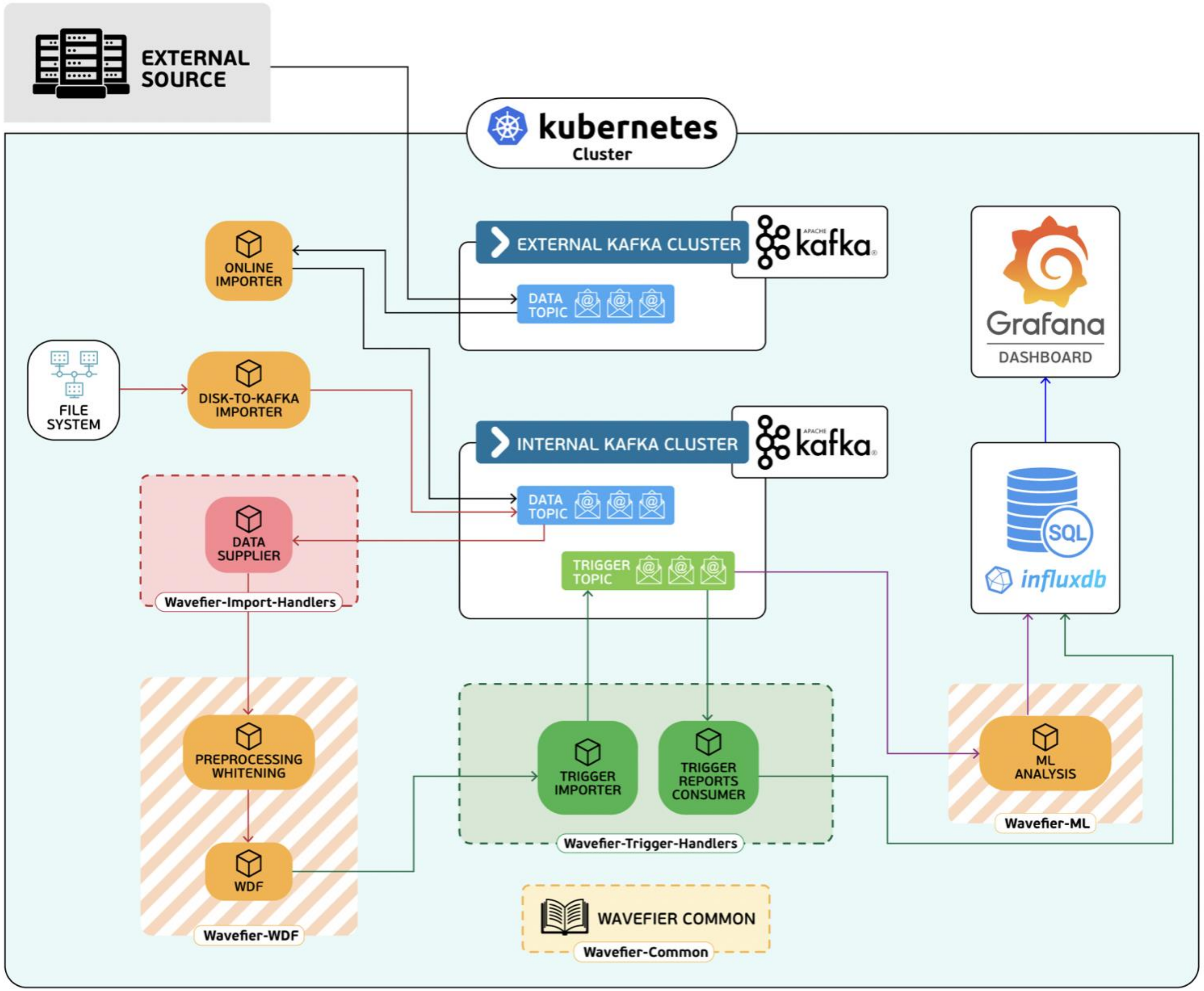
Trust-IT Services communicating to markets

Elena Cuoco, Emanuel Marzini, Filip Morawski, Alessandro Petrocelli, & Alessandro Staniscia. (2019). A prototype for a real time pipeline for the detection of transient signals and their automatic classification (1.0). Zenodo. https://doi.org/10.5281/zenodo.3356656

WAVEFIER GOAL

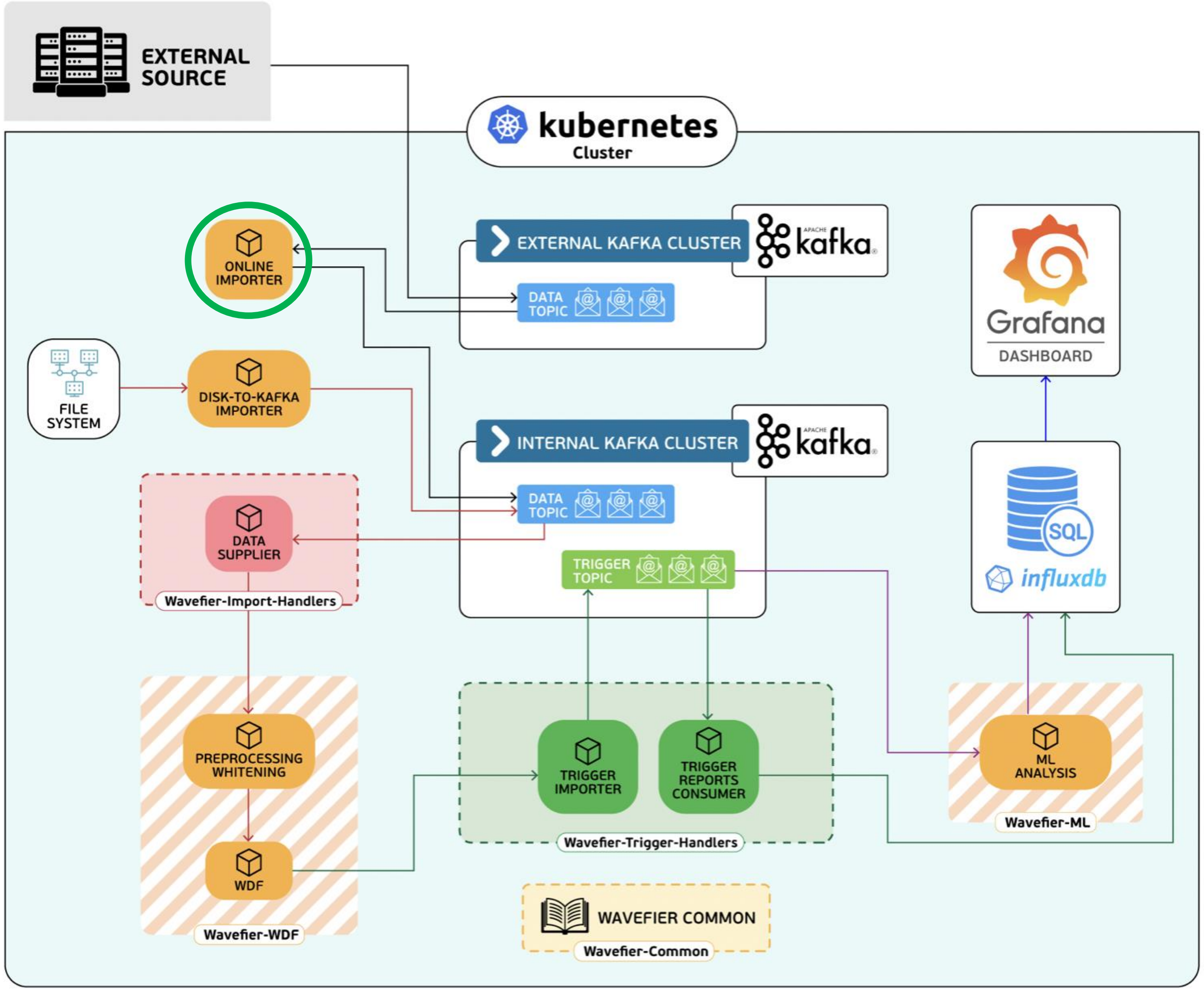


WAVEFIER ARCHITECTURE FOR GW



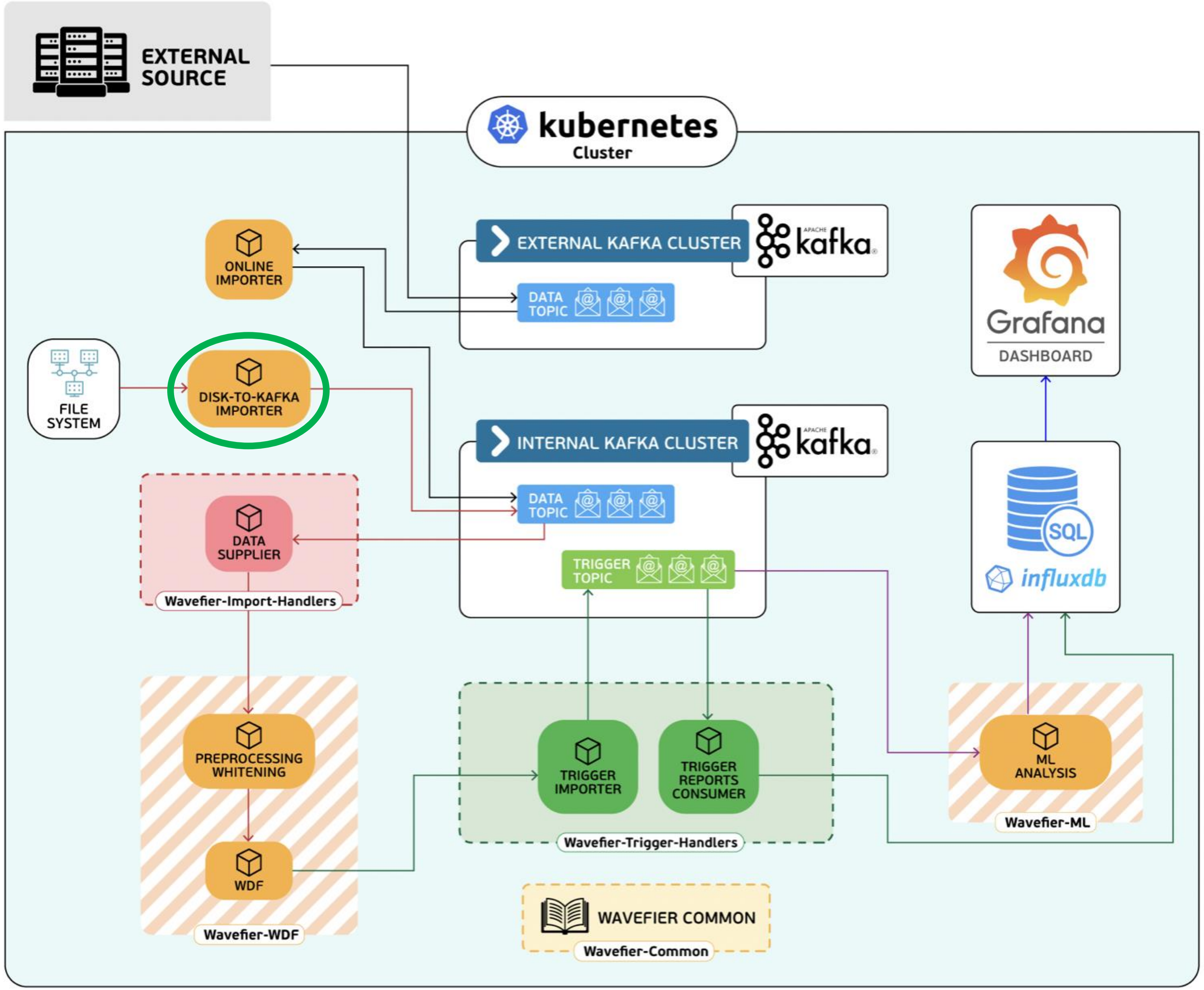
ONLINE IMPORTER

Imports data within the WAVEFIER pipeline from external KAFKA cluster.



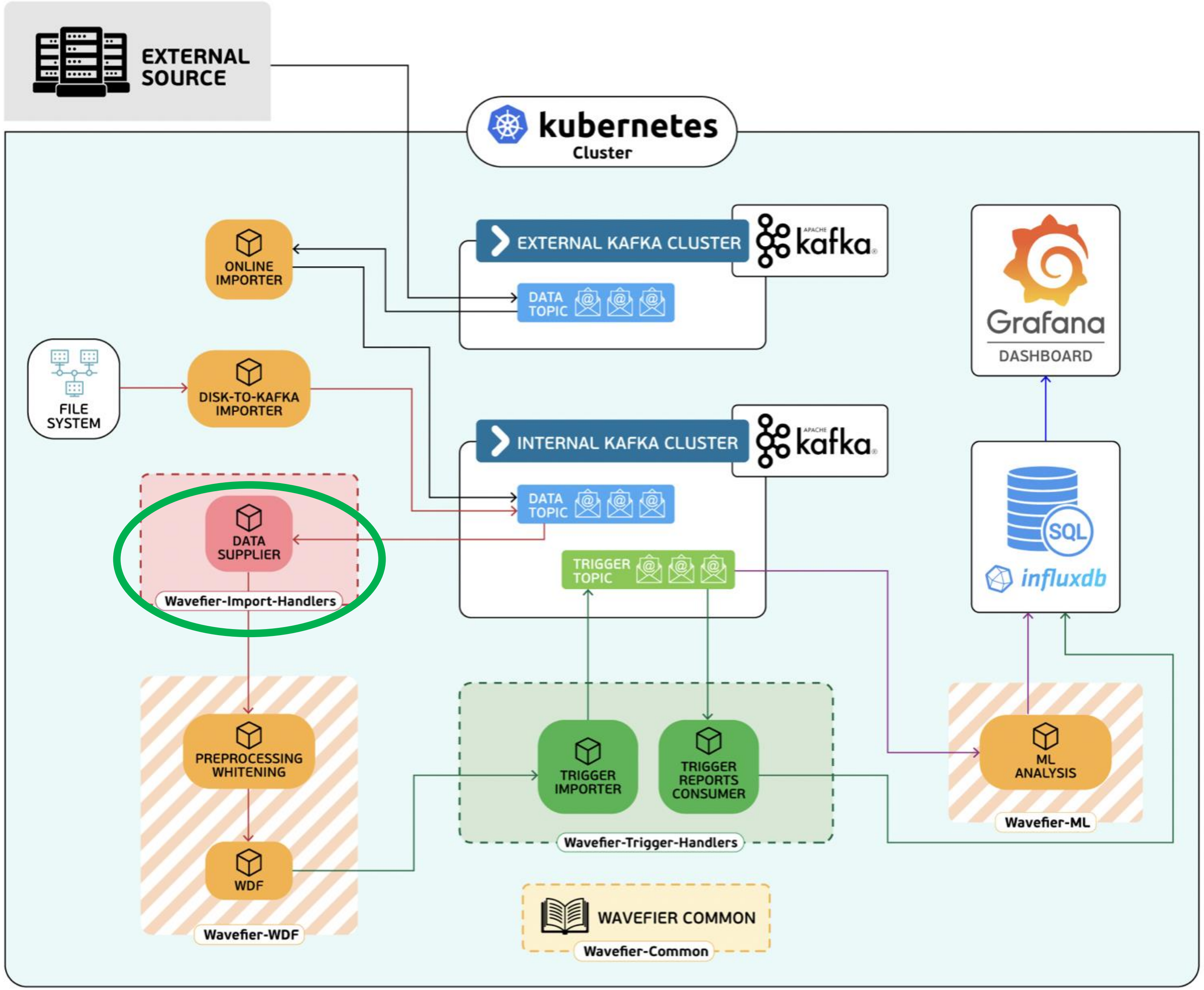
DISK-TO-KAFKA IMPORTER

Imports files within
the WAVEFIER pipeline
reading from filesystem
files.



WAVEFIER-IMPORT-HANDLERS

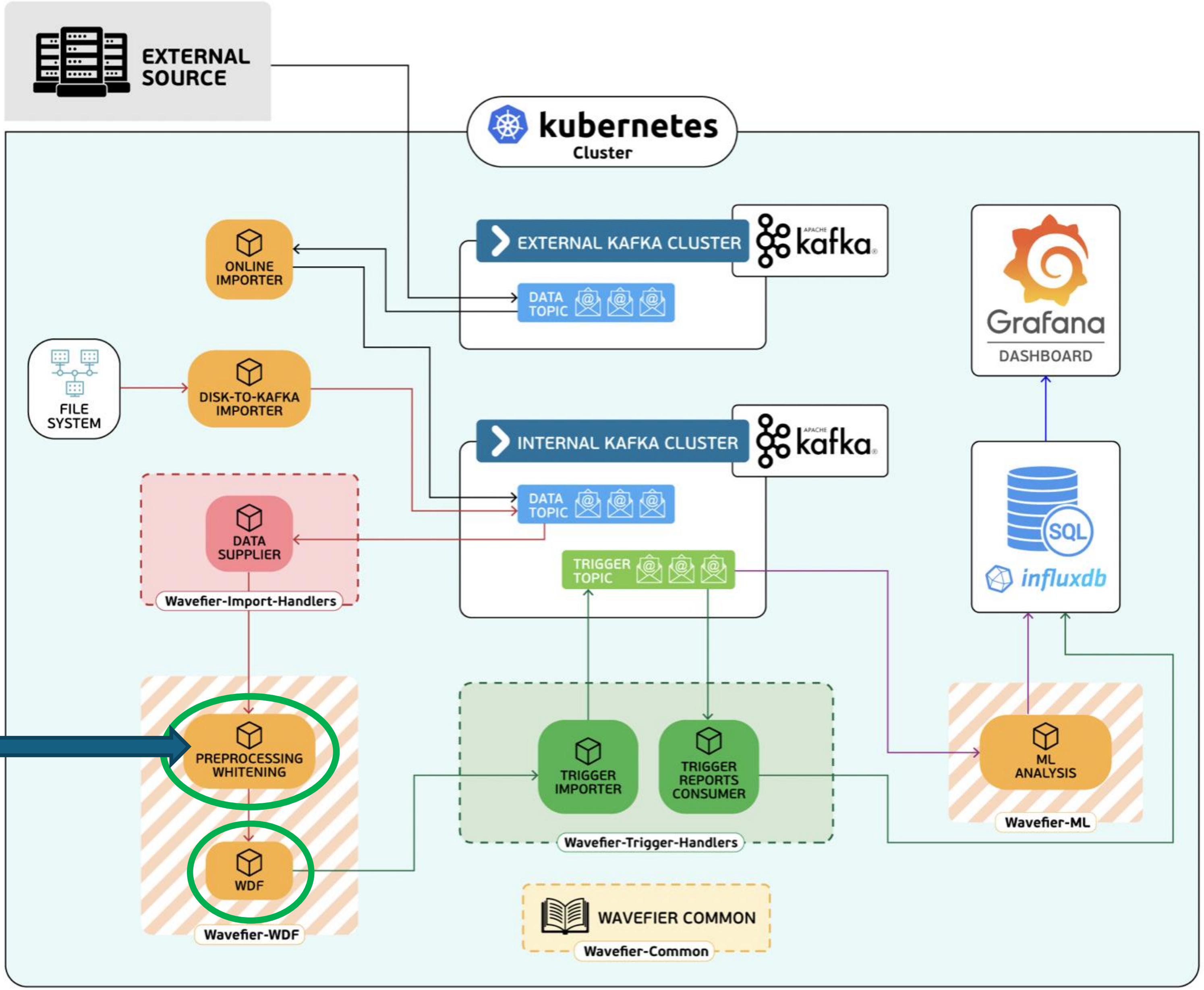
Library to retrieve the files from topics in internal KAFKA cluster.



WAVEFIER PREPROCESSING WHITENING (*GW specific!*)

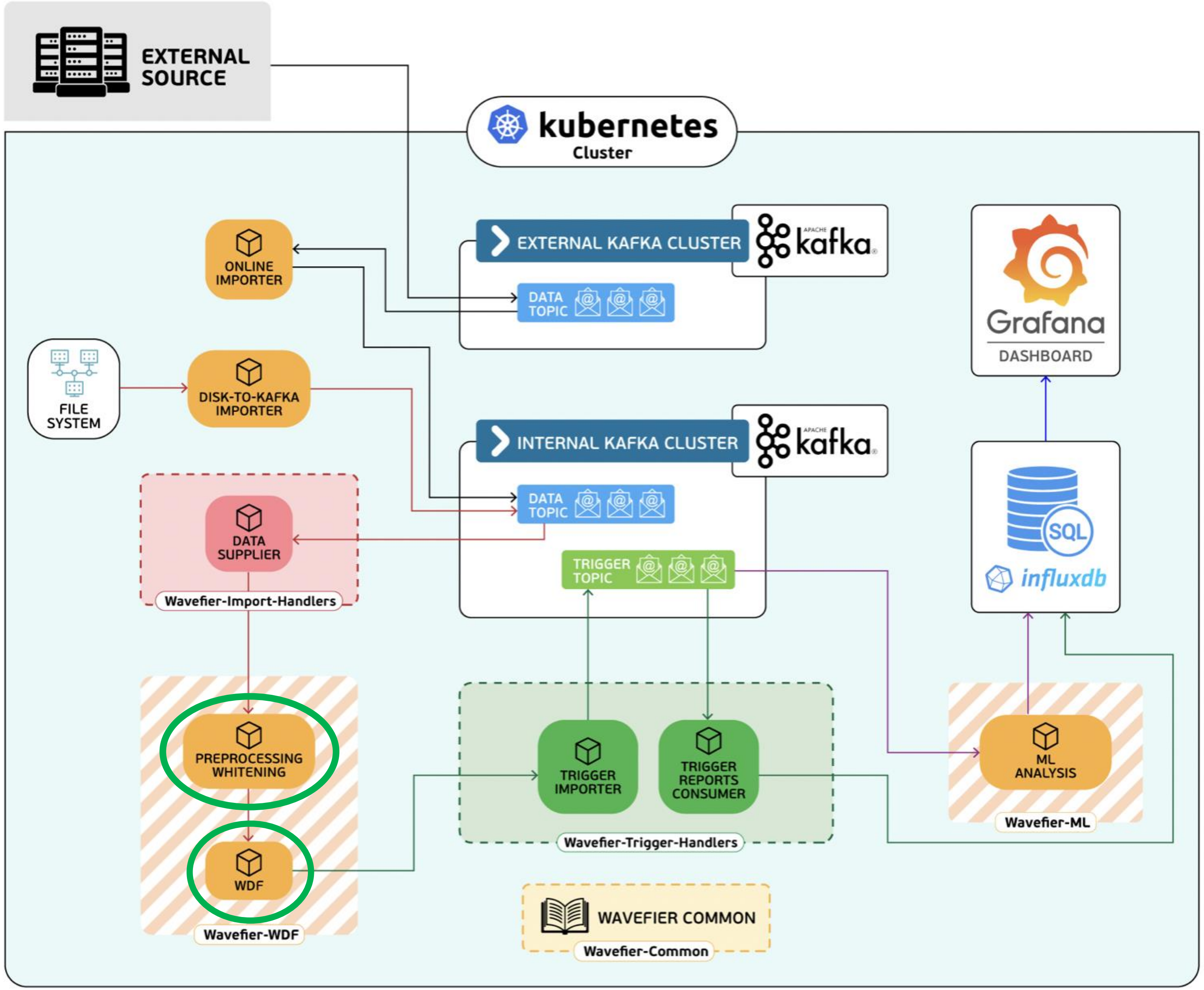
Continuously computes the whitening parameters for GW data and sends them to internal KAFKA cluster.

FPGA for preprocessing?



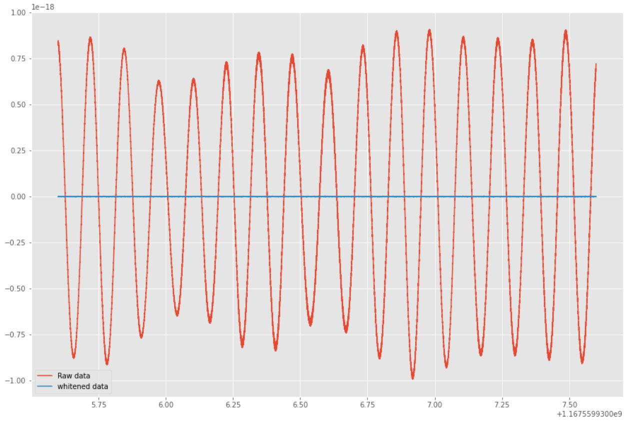
WAVEFIER-WDF (*GW specific!)*

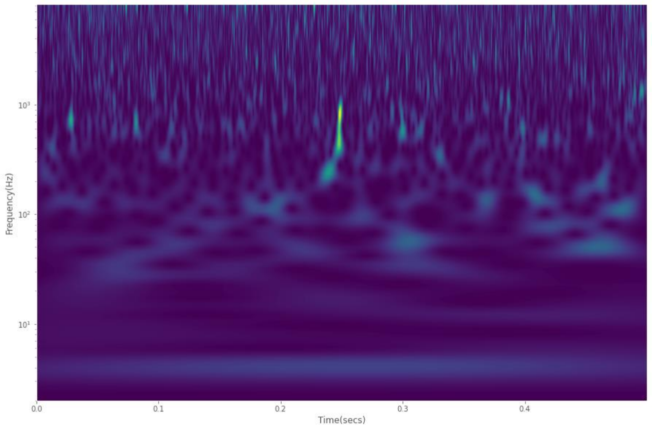
Grabs updated whitening parameters and raw data, whitens GW data, searches for transient signals with a wavelet-based method and estimates relevant parameters of the detected signals.



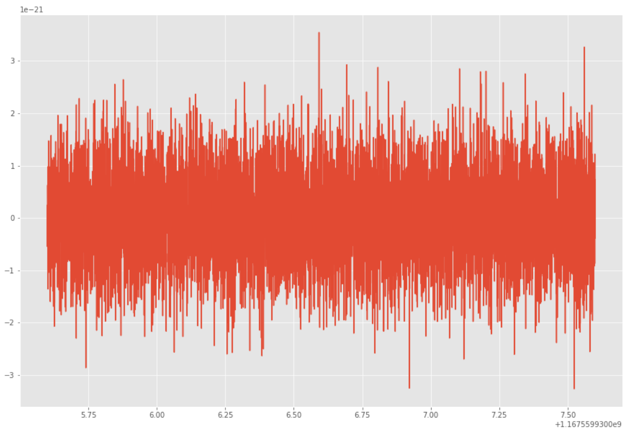
WDF (*GW specific!*)

- Data Preprocessing (whitening, downsampling)
- Trigger Generation
- *Source Parameter Estimation*
- *Signal Reconstruction*





PUBLICATIONS THAT USE WDF (incomplete list):

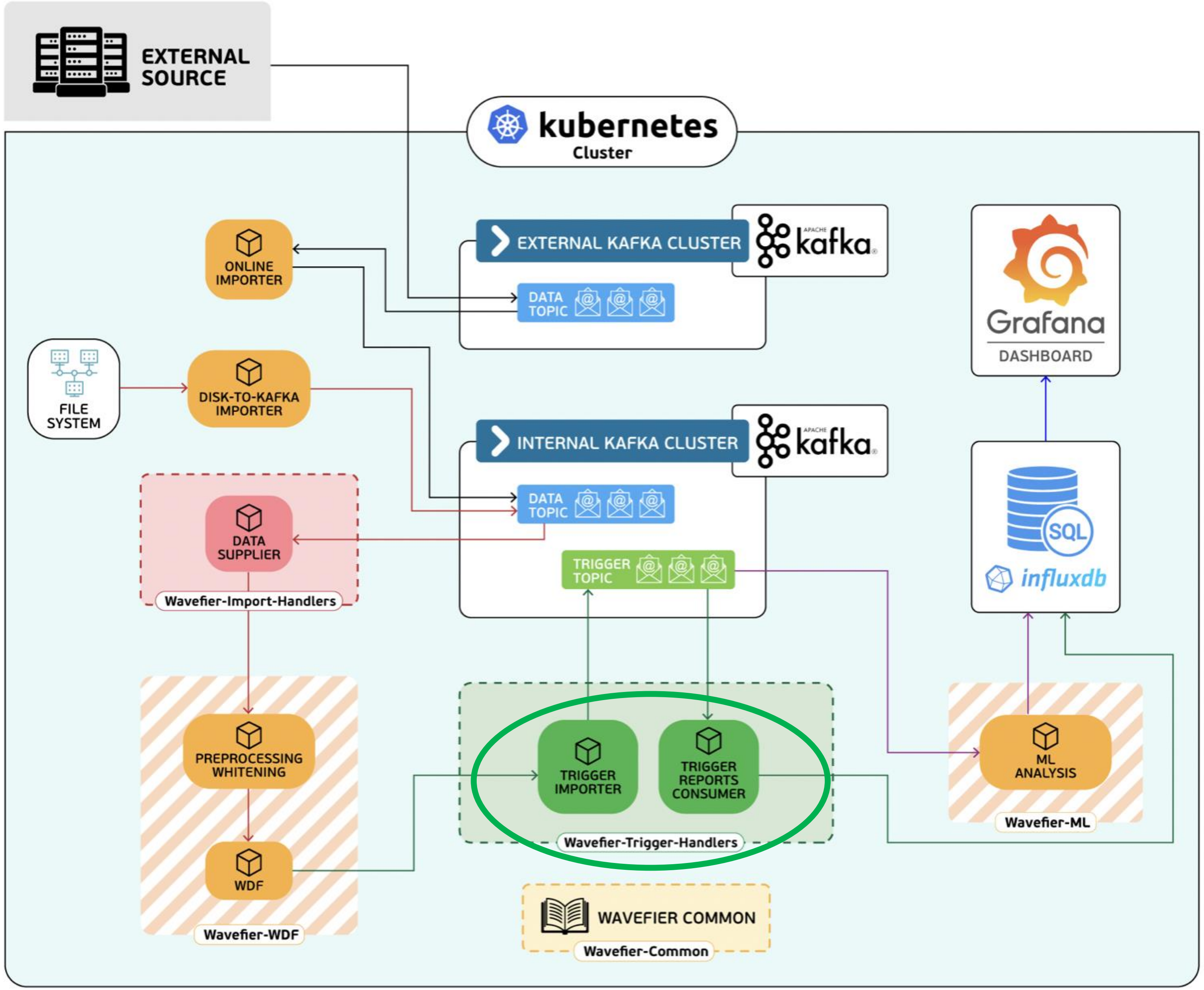


GW170104

1. J. Powell, D. Trifirò, E. Cuoco, I.S. Heng and Marco Cavaglià 2015, Class. Quantum Grav.
2.J. Powell, A. Torres-Forné, R. Lynch, D. Trifirò, E. Cuoco, M. Cavaglià, I.S. Heng and J.A. Font 2017, Class. Quantum Grav. **34** 034002
3. M. Razzano, E. Cuoco 2018, Class. Quantum Grav.
4. A. Iess, E. Cuoco, F. Morawski, J. Powell, 2020, Mach. Learn. Sci. Techno

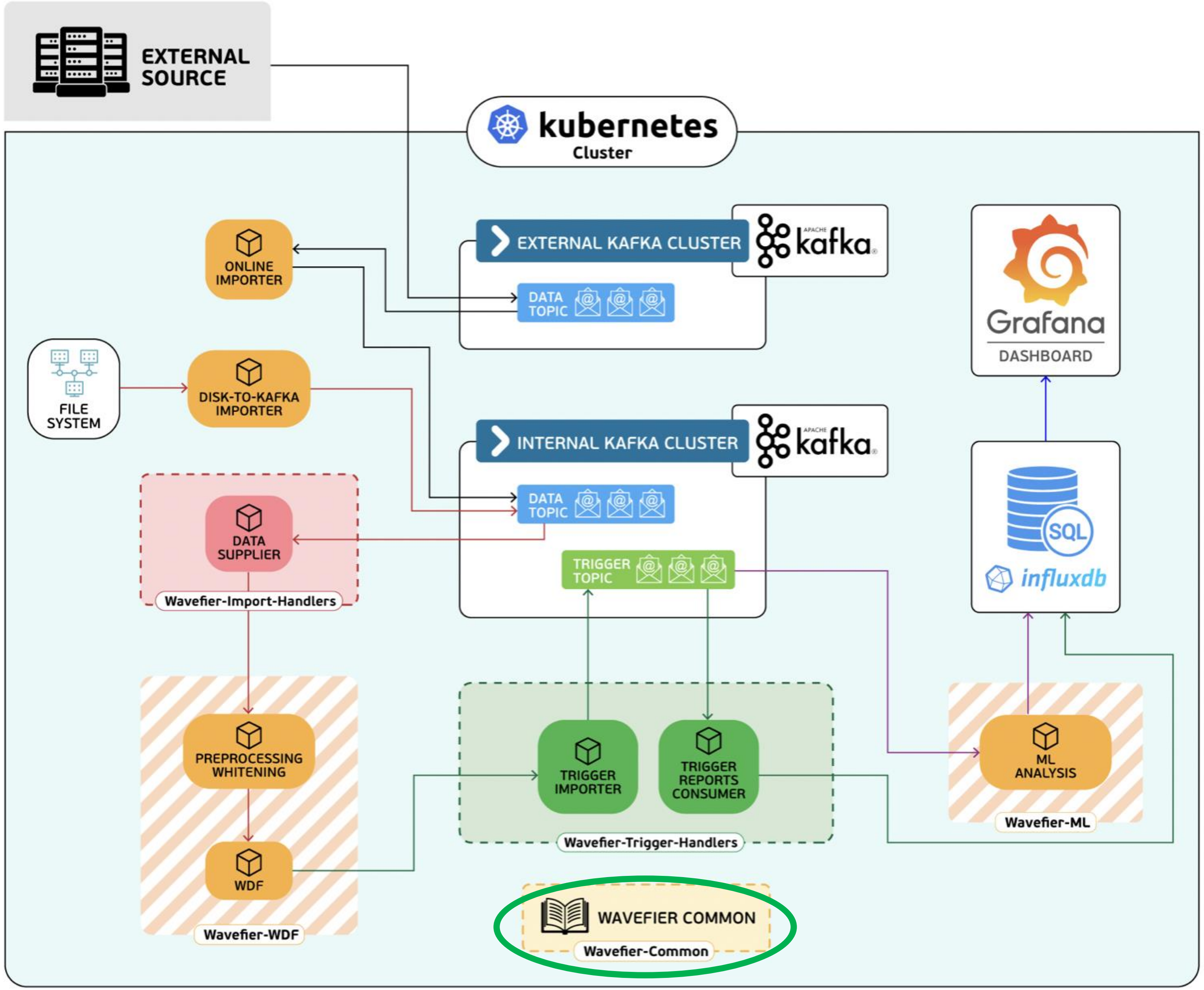
WAVEFIER
TRIGGER-HANDLERS

Contains all the code used to send and retreive the triggers and related information in the WAVEFIER framework.



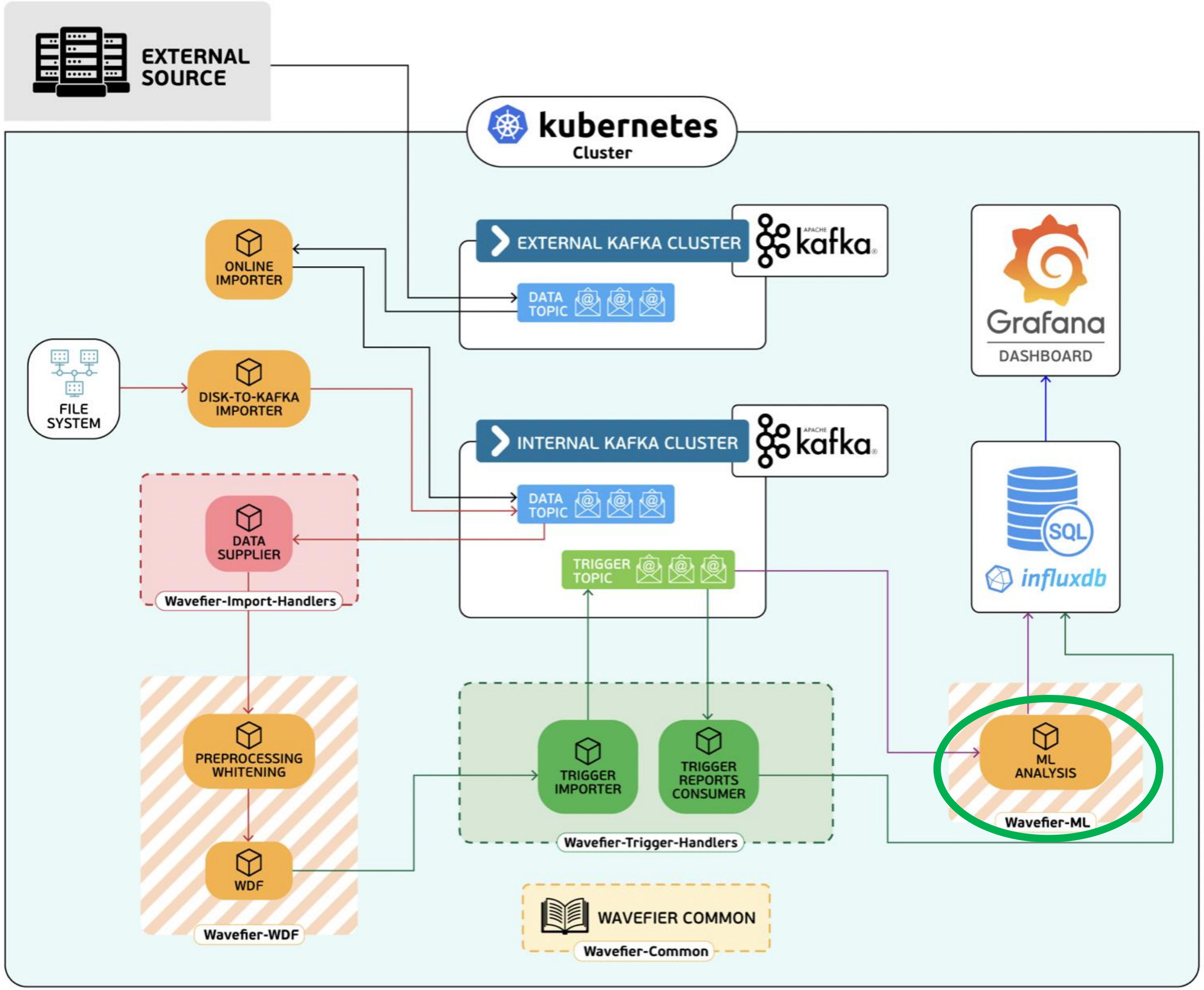
WAVEFIER COMMON

Contain all the common code used by different modules of the WAVEFIER project.



WAVEFIER ML

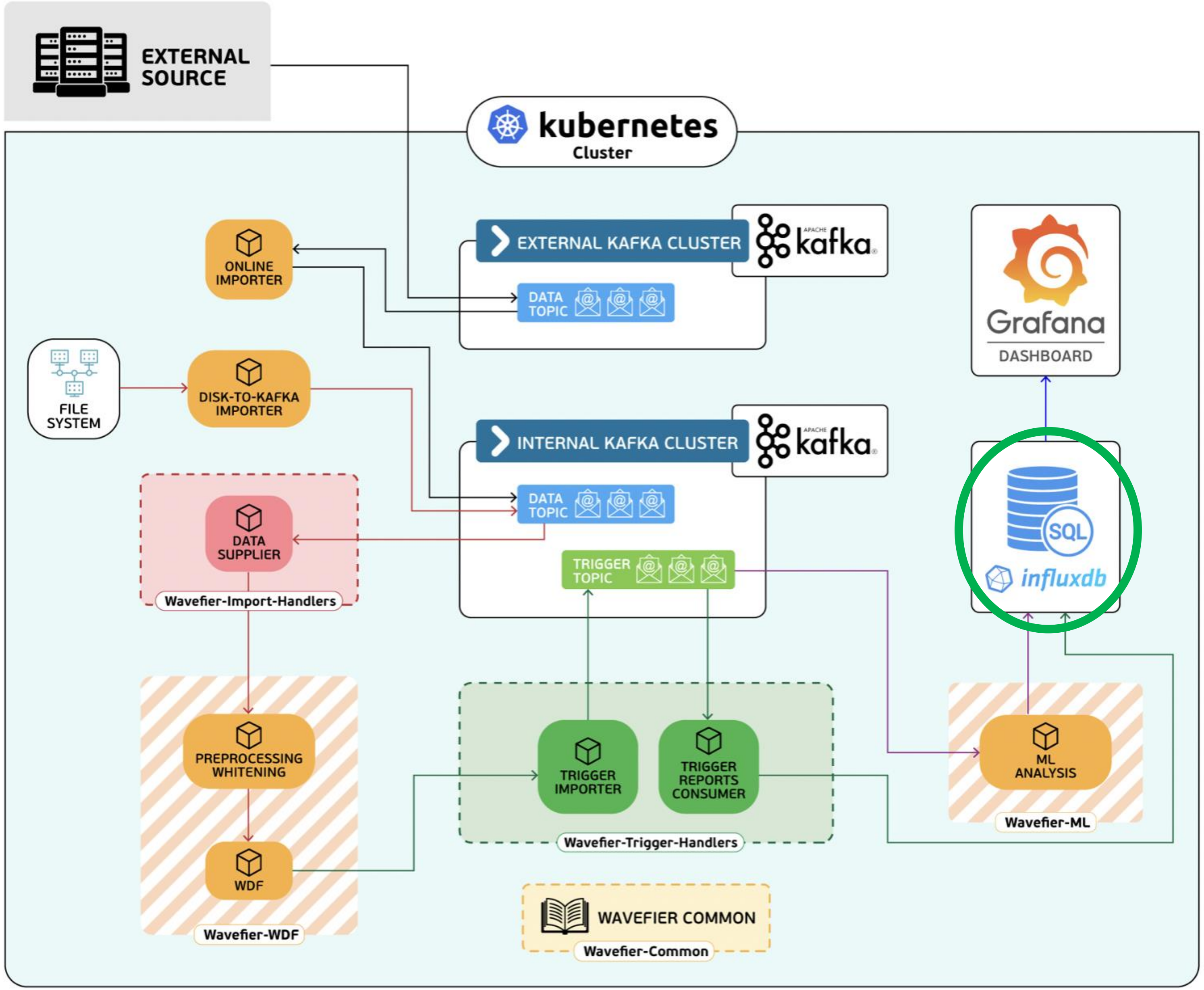
Responsible for the application of Machine Learning algorithms on the list of triggers generated by WAVEFIER WDF or similar consumers.



INFLUXDB

Database for storage of the triggers produced by WDF.

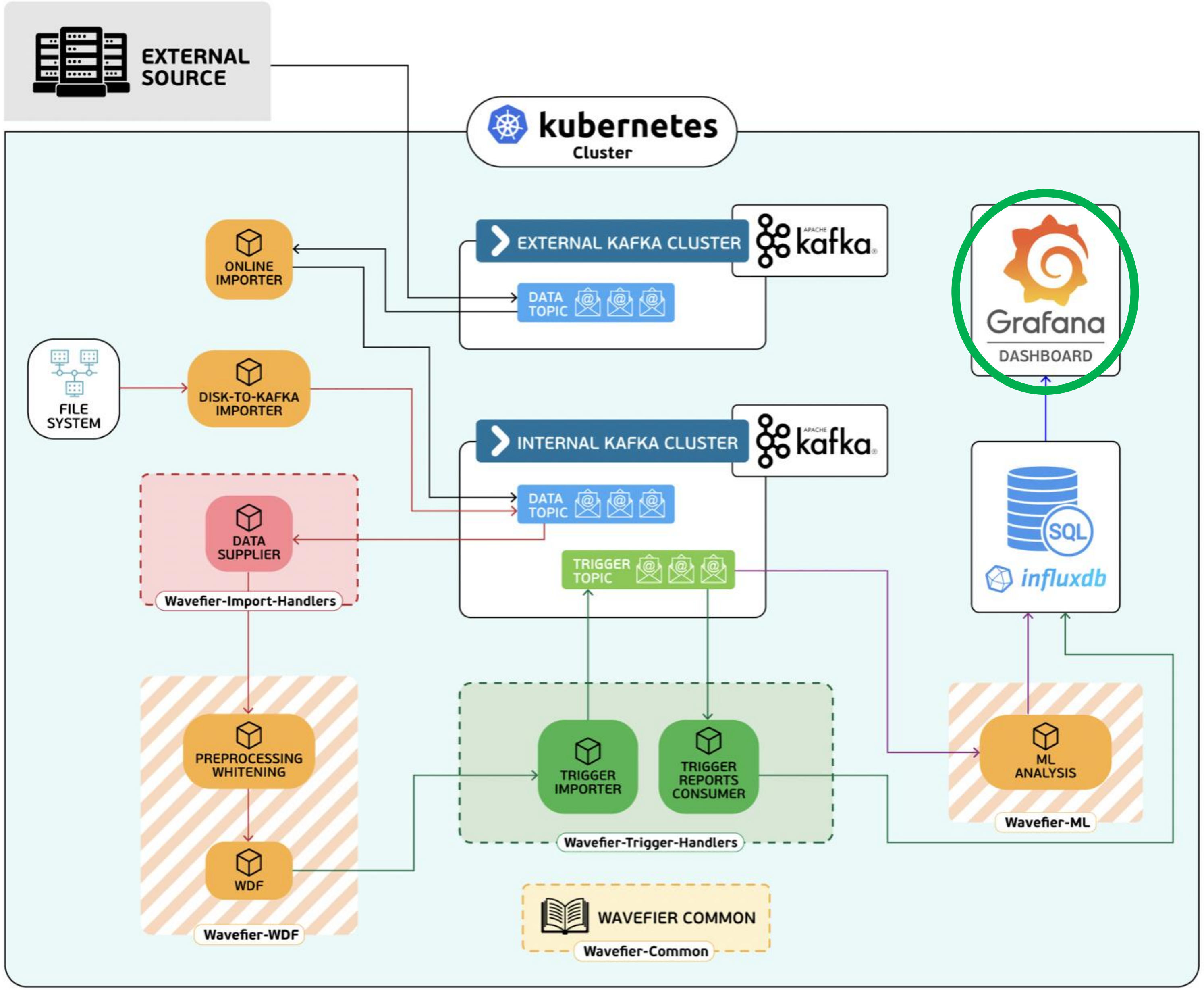
- Open-source, suited for timeseries analysis.
- has SQL-like query language for interacting with it.



GRAFANA DASHBOARD

Provides interactive web visualization of trigger data.

- Native support for *influxDB.*

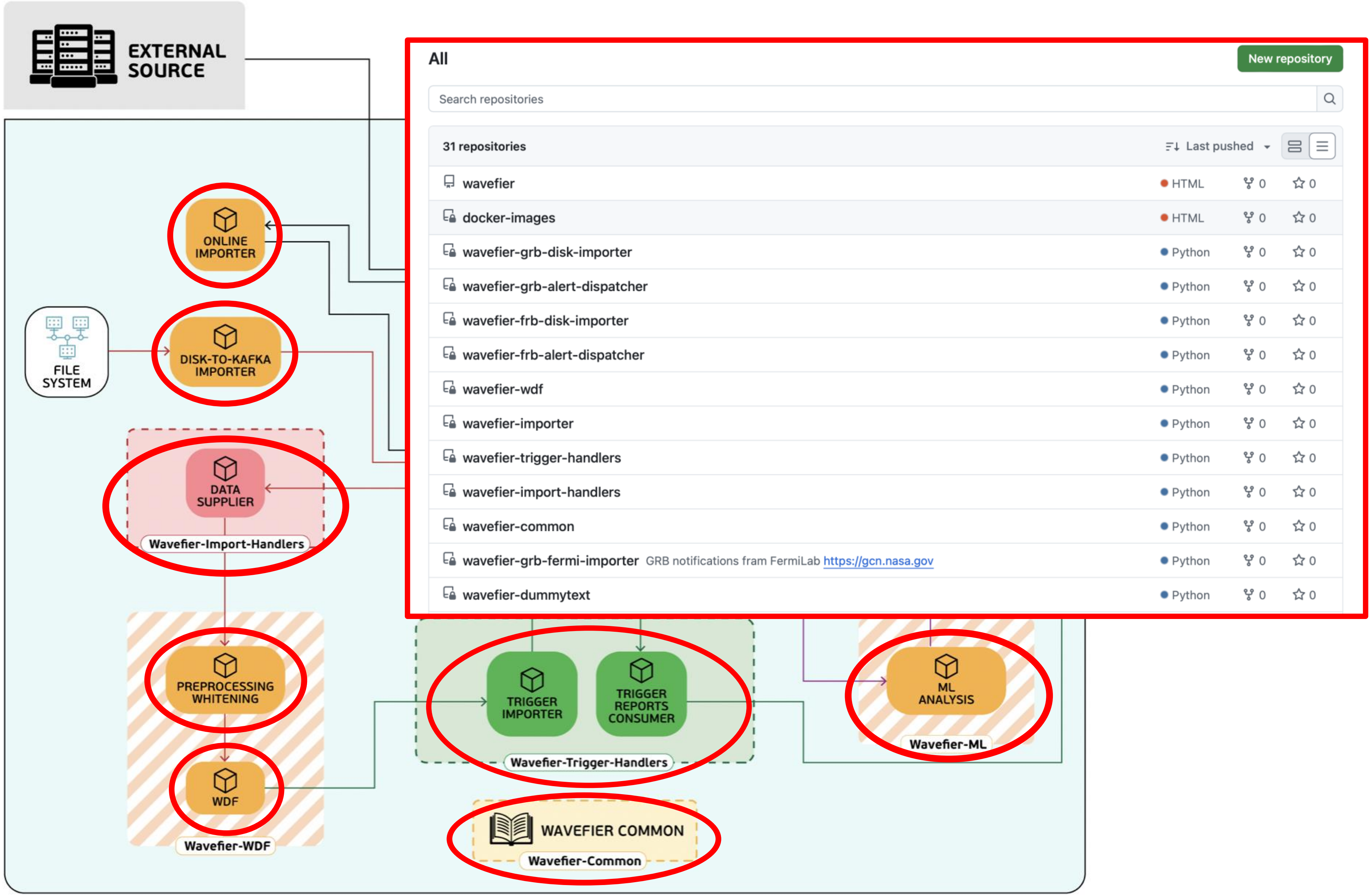


WAVEFIER's structure is composed of modules:

- Dedicated github project with a repository for each module.
- Continuous integration to build docker images

Docker Compose

portability!



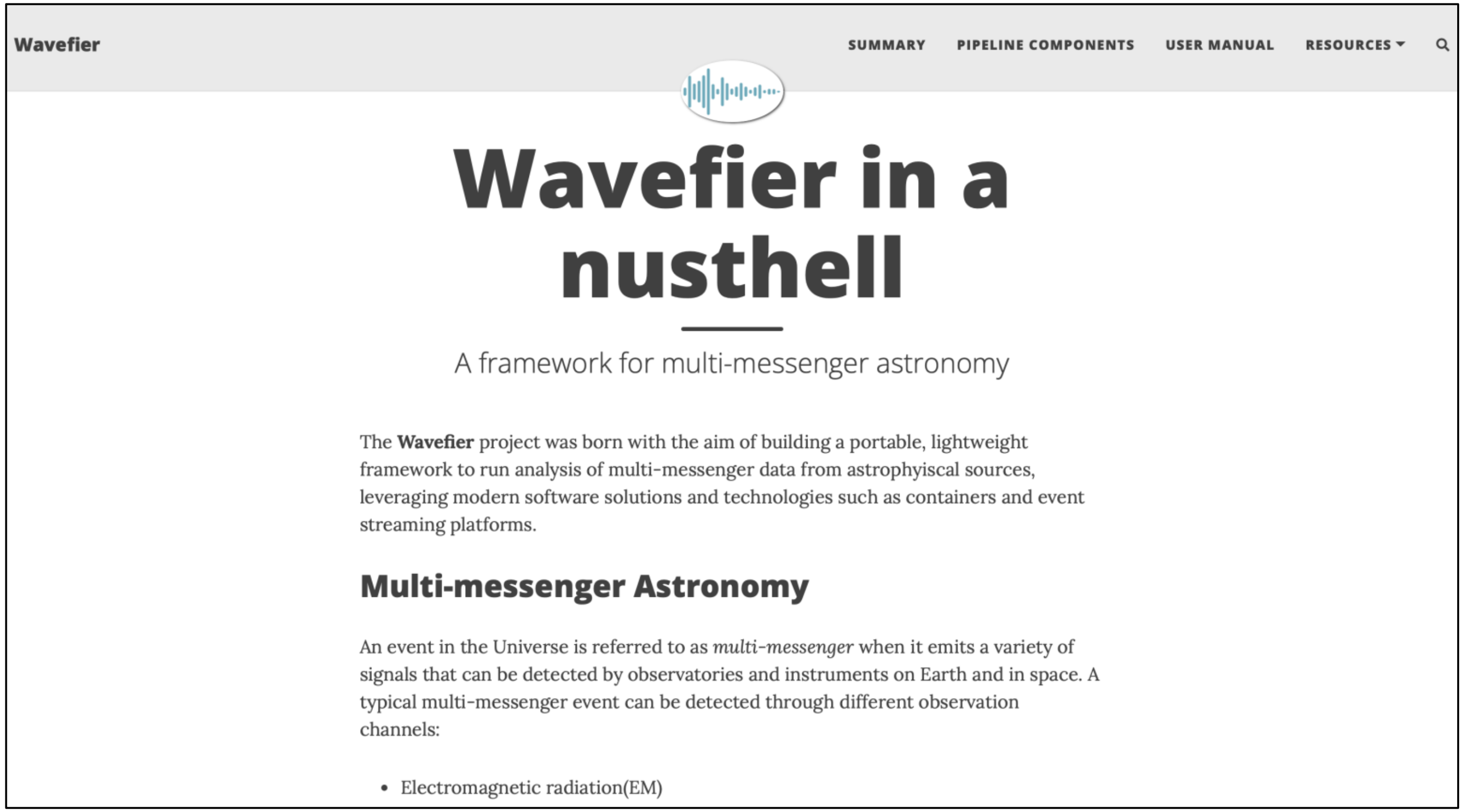
WAVEFIER DOCUMENTATION

DOCUMENTATION

Currently being updated, available at:

https://wavefier.github.io/wavefier

Sphinx ReadTheDocs API documentation automatically generated at pipeline continuous integration for each component module.



Wavefier SUMMARY PIPELINE COMPONENTS USER MANUAL RESOURCES

Wavefier in a nusthell

A framework for multi-messenger astronomy

The **Wavefier** project was born with the aim of building a portable, lightweight framework to run analysis of multi-messenger data from astrophyiscal sources, leveraging modern software solutions and technologies such as containers and event streaming platforms.

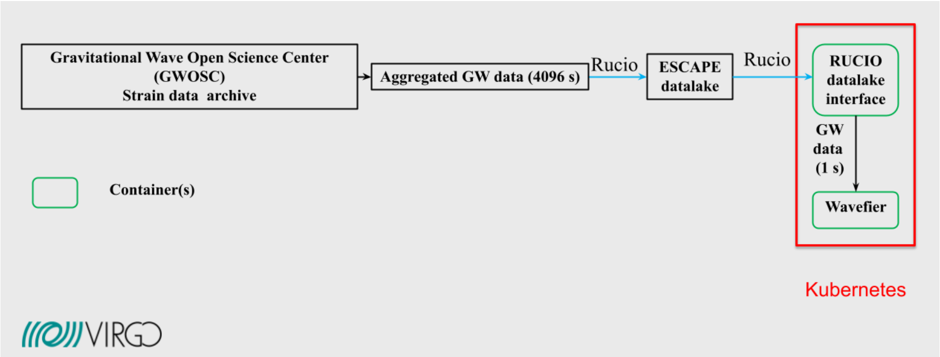
Multi-messenger Astronomy

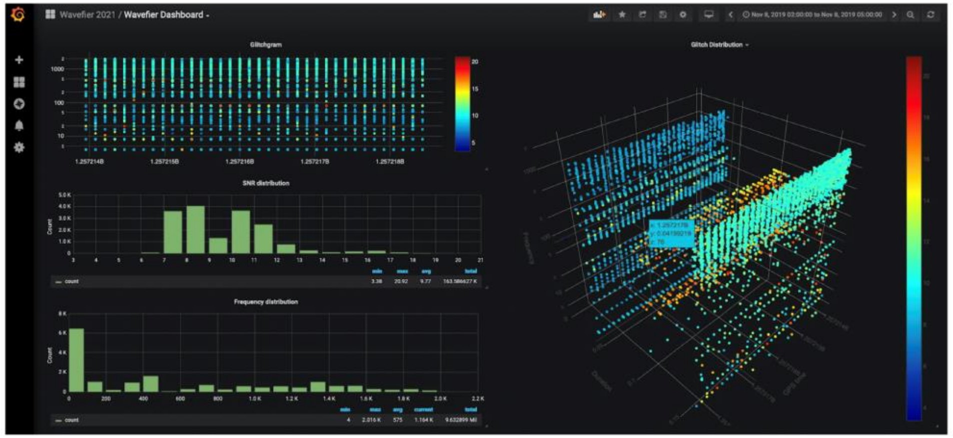
An event in the Universe is referred to as *multi-messenger* when it emits a variety of signals that can be detected by observatories and instruments on Earth and in space. A typical multi-messenger event can be detected through different observation channels:

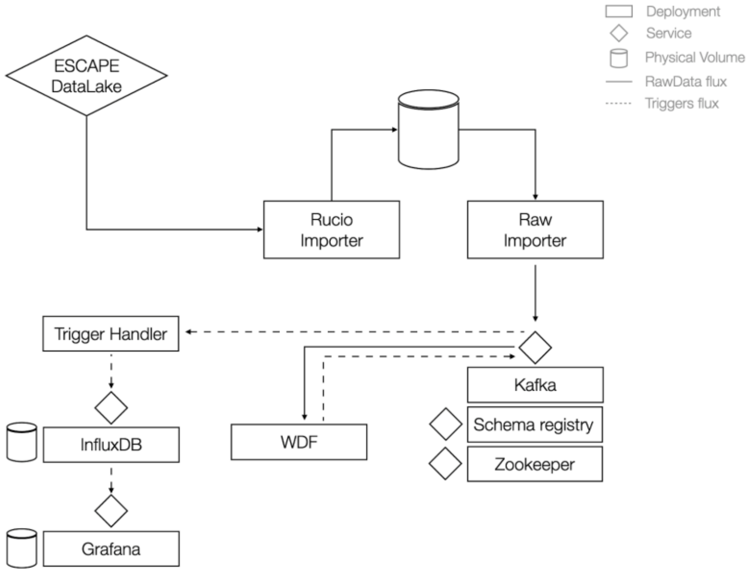
- Electromagnetic radiation(EM)

GW SCIENCE CASE

- Successfully tested attaching to ESCAPE data lake with Gravitational Wave Open Science Center (GWOSC) data.
- GW specific implementation at CNAF cloud (region Tier1) on shared Virgo Kubernetes cluster O2 data.
- Tested locally on O3 data (2024) on gravitational wave frame files.





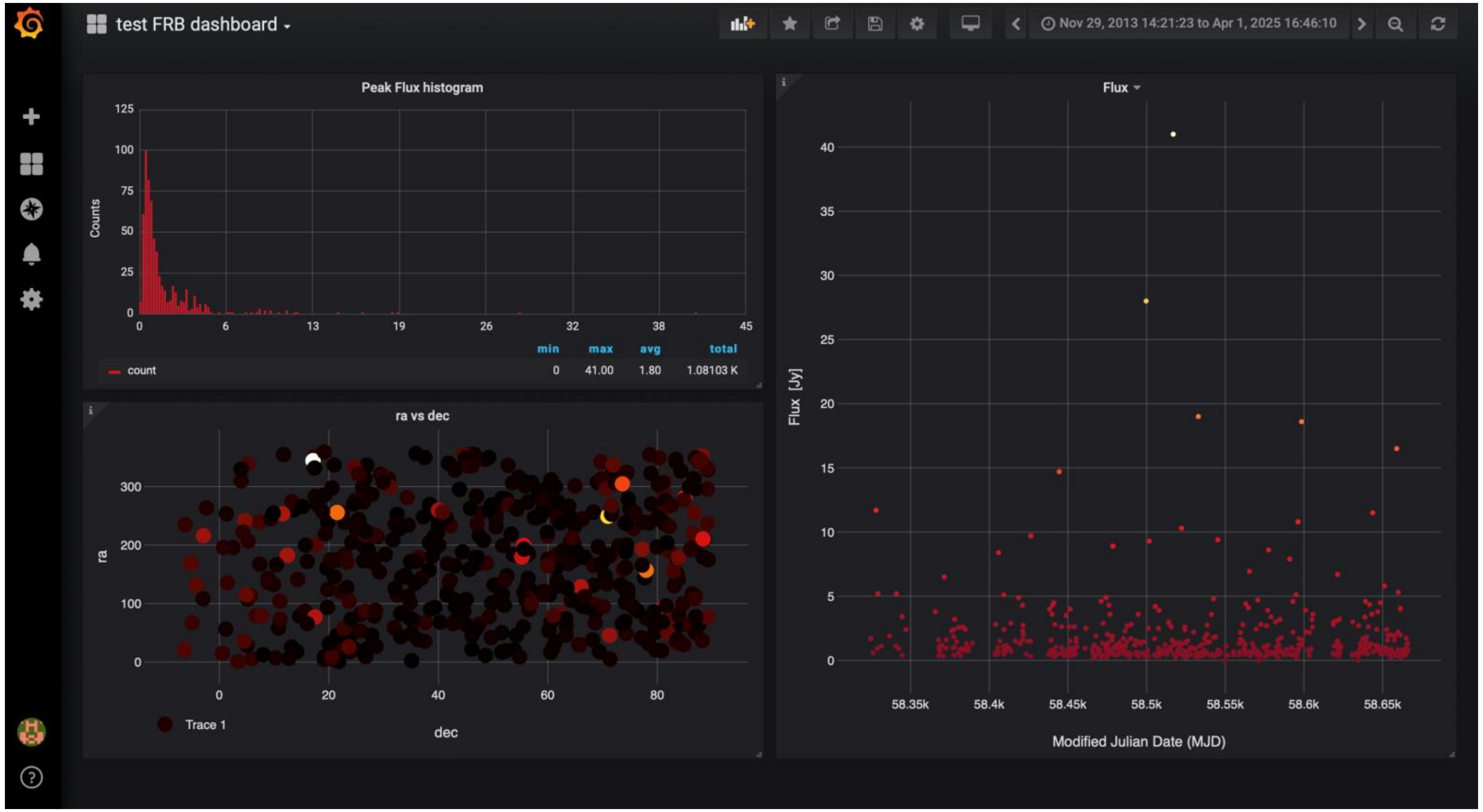


WAVEFIER: FAST RADIO BURST AND GAMMA RAY BURSTS

- Successfully tested attaching to NASA GCN notices alerts for GRB from Fermi and INTEGRAL via Kafka.
- Successfully imported FRB CHIME and Fermi LAT catalog data in .fits format.
- Grafana dashboard for FRB data visualization.

Alberto Iess

EOSC Future



WHAT'S NEXT?

- Real time analysis of different messengers
- Machine learning approaches for parameter estimation
- Multimodal analysis for coherent analysis
- Tests on specific hardware as FPGA

THANK YOU

TWITTER: @ELENACUOCO

ELENA.CUOCO@EGO-GW.IT

CREDITS FOR THE SLIDES TO: A. IESS, F. MORAWSKI, TRUST-IT SERVICES TEAM