Introduction to Machine Learning for Gravitational Wave research

Data Science School,
March 25th -27th Braga
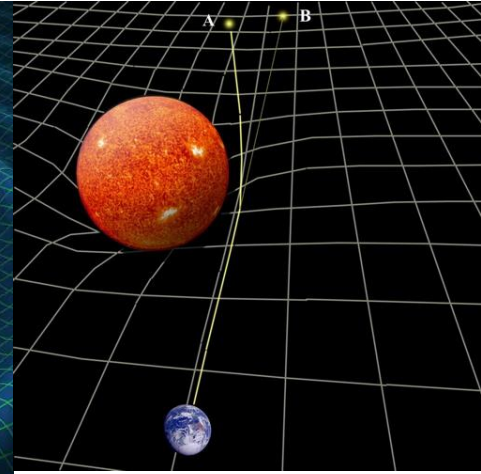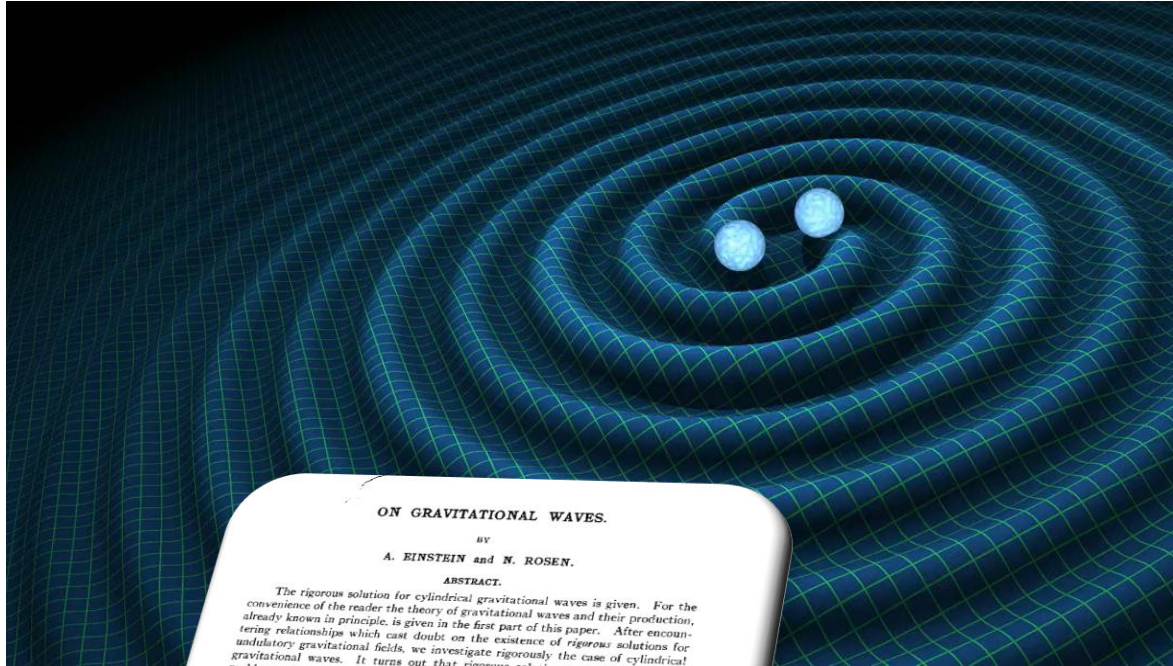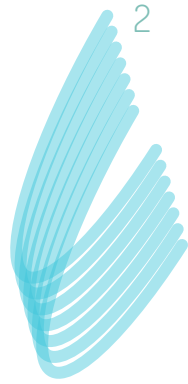
Elena Cuoco, EGO and SNS
www.elenacuoco.com
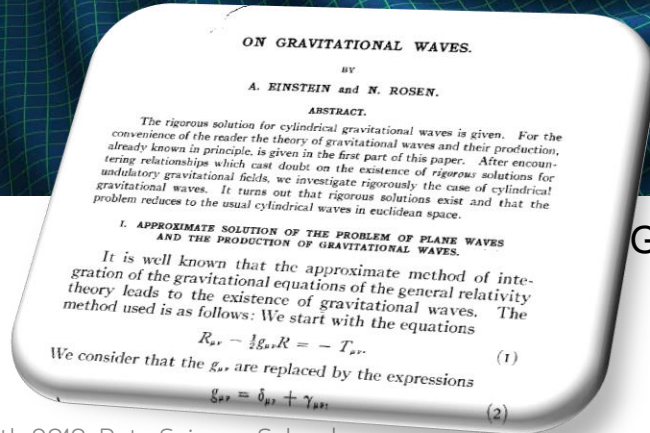Twitter: @elenacuoco

What are Gravitational Waves (GWs)?

General Relativity (1915)

Gravitational Waves (1916)

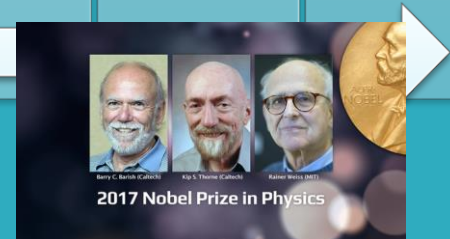$$\mathbf{G}_{mn} = \frac{8pG}{c^4}\mathbf{T}_{mn}$$

A long history…

1915
- General Relativity

1916
- Gravitational Waves

1966
- Weber and Resonant Bars

1974
- Hulse–Taylor:Observing the pulsar binary PSR B1913+16

1980-1990
- Cryogenic Resonant Bars

1993
- The approval of Virgo Experiment

1999+
- Data taking from LIGO an Virgo

2015
- GW BHBH detection

2017
- BNS detection: Multi-messenger Astronomy

~100 years

2017 Nobel Prize in Physics

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How we detected GWs?

Elena Cuoco
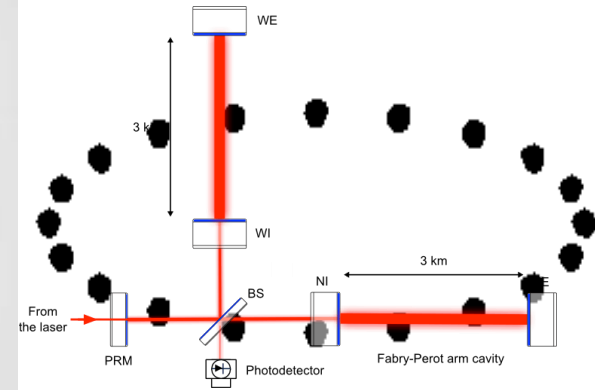
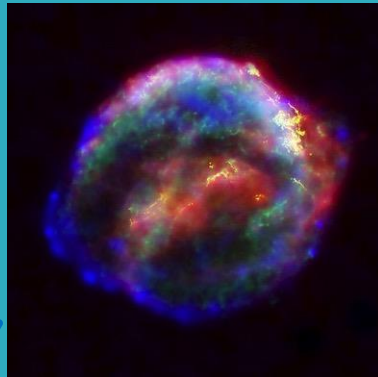# Astrophysical sources

Short ➜ long

Known ⬇ unknown form

Coalescing Binary Systems CBC
- ✓ Black hole – black hole
- ✓ Neutron star – neutron star
- • BH-NS
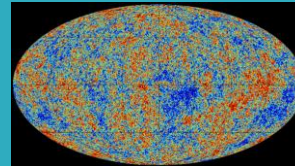- • Analytical waveform

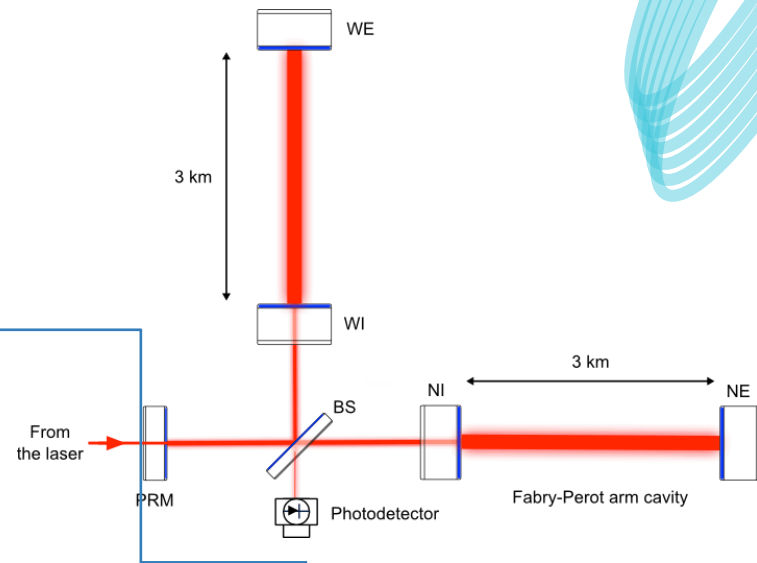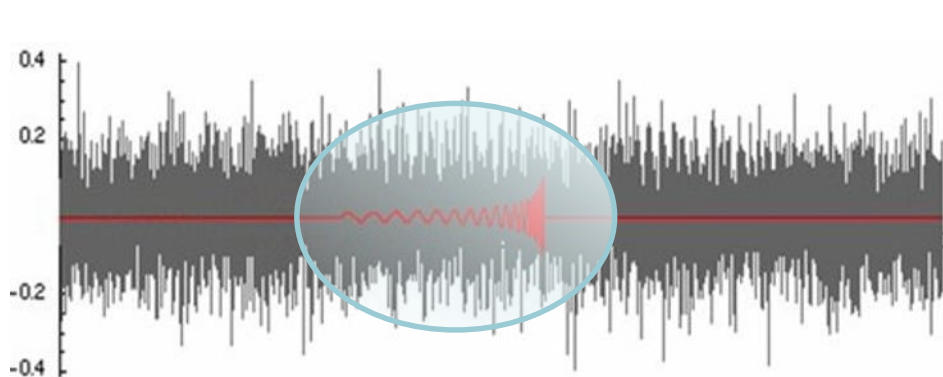***Continuous Sources***
- • Spinning neutron stars
- • monotone waveform

Transient 'Burst' Sources
- • core collapse supernovae
- • unmodeled waveform

Cosmic GW Background
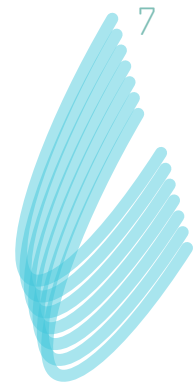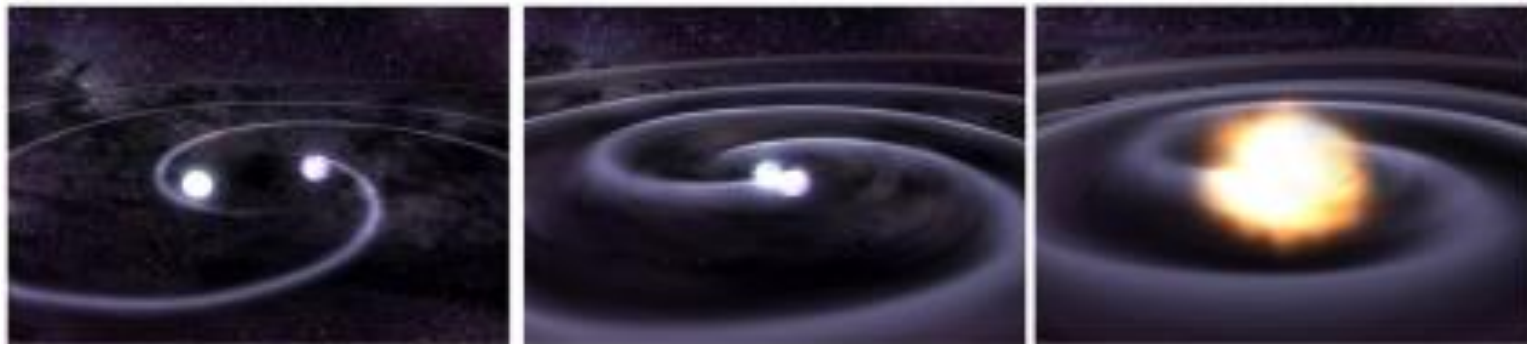- • residue of the Big Bang,
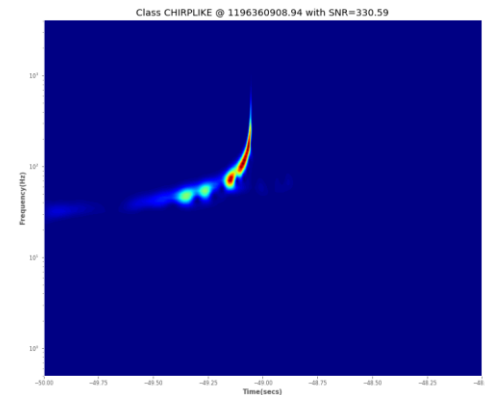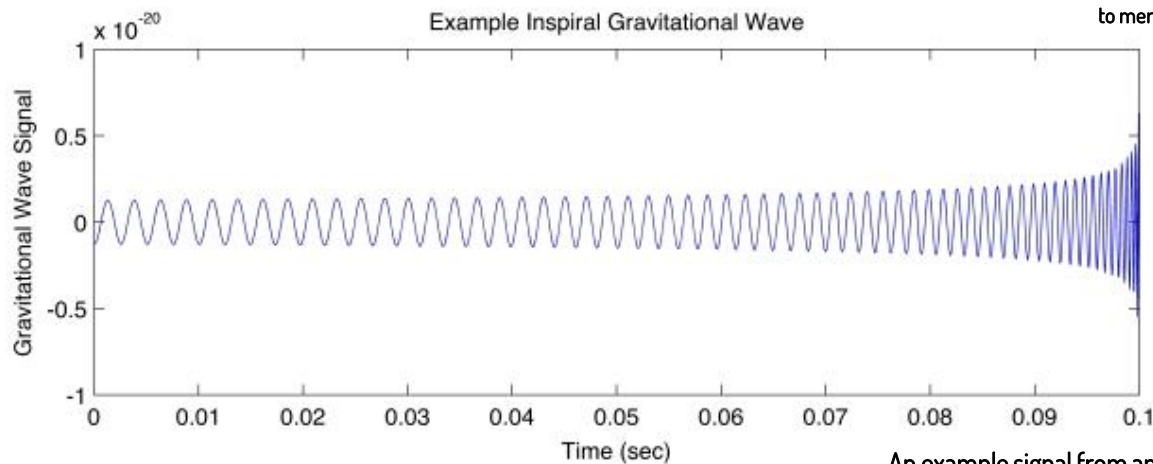- • stochastic, incoherent background

LIGO/Virgo data

are time series sequences… **noisy time series**
with low amplitude GW signal buried in

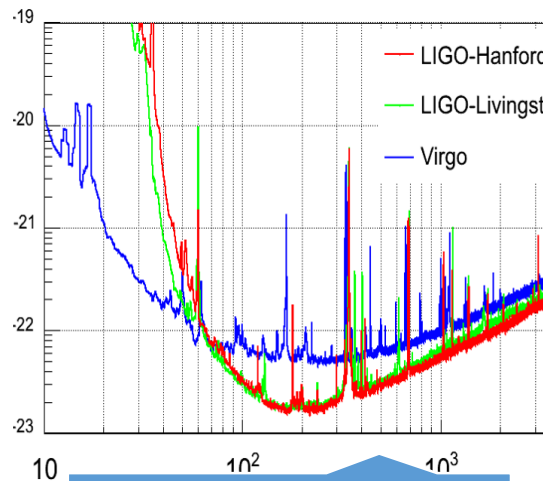Elena Cuoco

CBC Gravitational Wave signals

An artist's impression of two stars orbiting each other and progressing (from left to right) to merger with resulting gravitational waves. [Image: NASA/CXC/GSFC/T.Strohmayer]

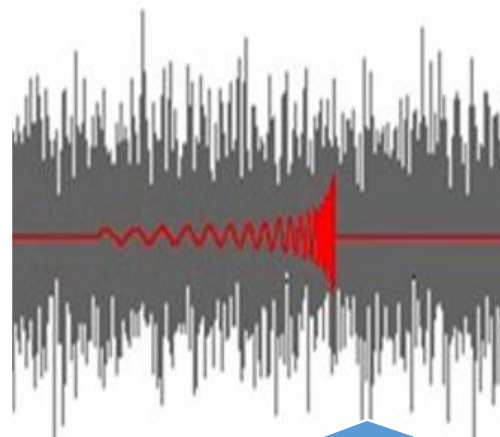An example signal from an inspiral gravitational wave source. [Image: A. Stuver/LIGO]

Elena Cuoco

GW detection

Detector

Astrophysical signal

Signal extraction

Elena Cuoco

Astrophysical transient signals

CBC

- BH-BH
- BH-NS
- NS-NS

Matched–Filter

Un-modeled waveform

- CCSN
- ?

Excess power signal finder

LG2NET cost
EUROPEAN COOPERATION
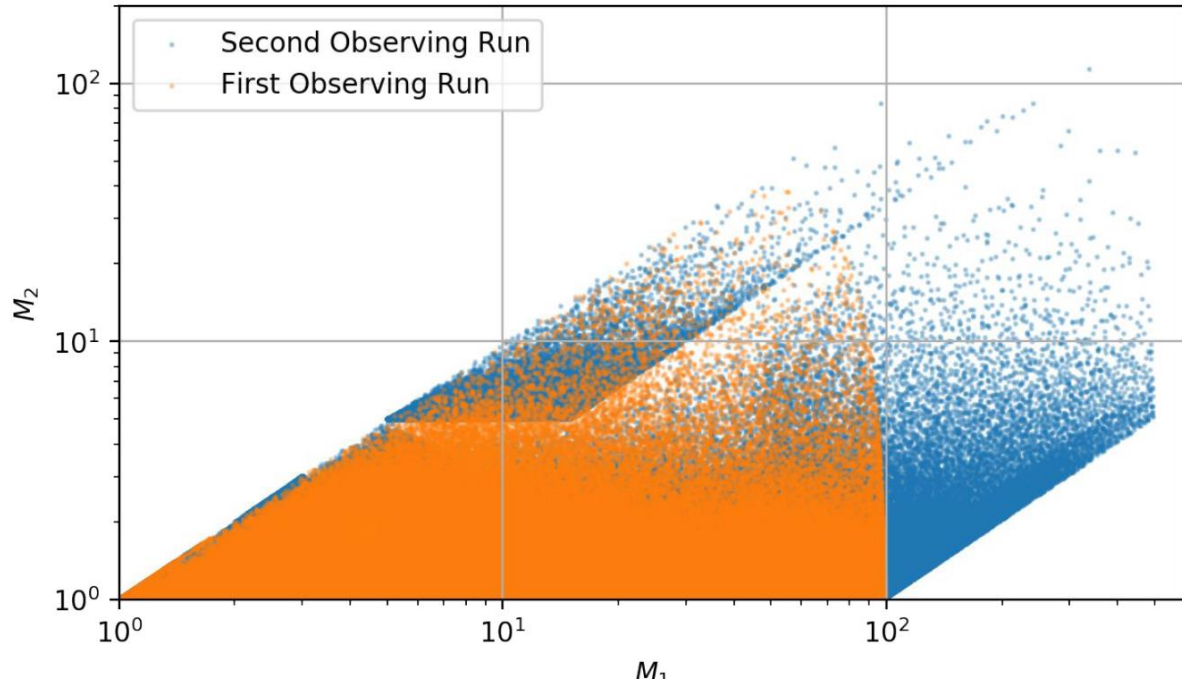IN SCIENCE & TECHNOLOGY

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Matched filter

Template
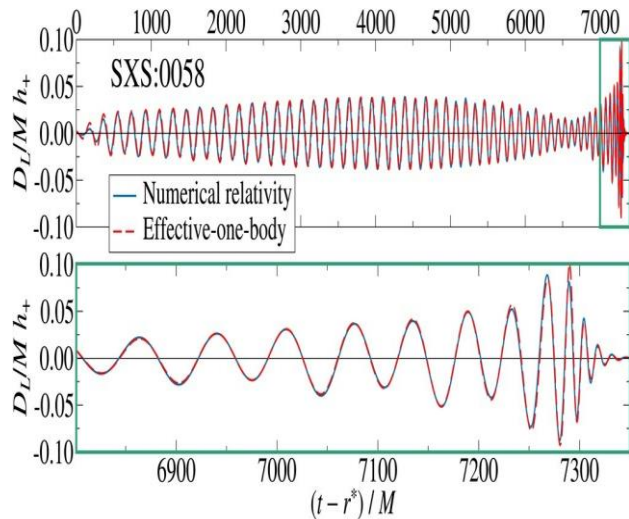
$$\rho(t) = 4 \int_0^\infty \frac{\tilde{x}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

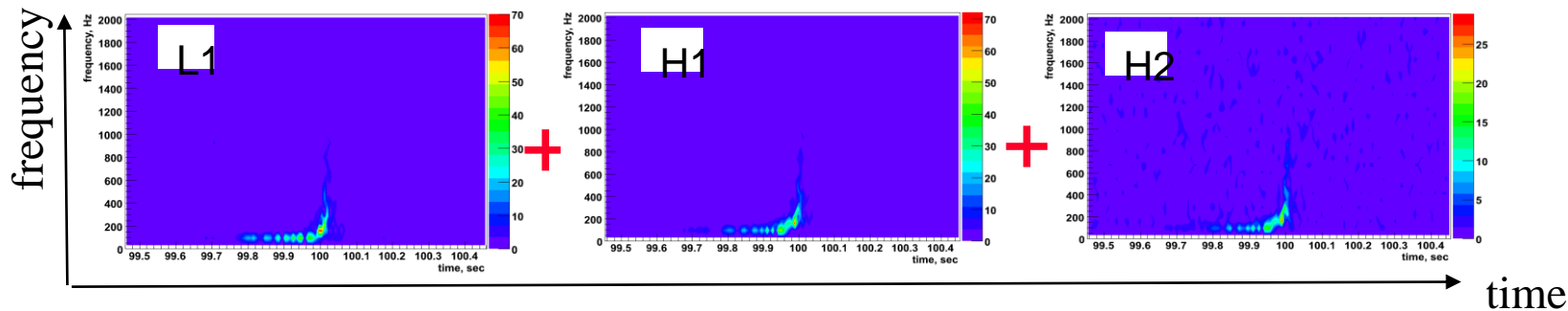Power Spectral Density

Matched filter

https://github.com/gwastro/pycbc-config/tree/master/O1/bank

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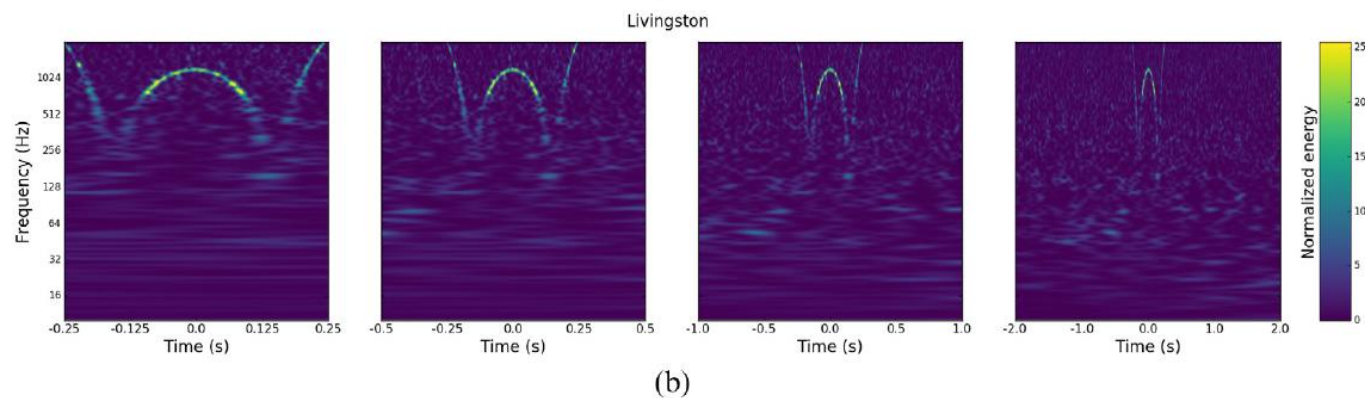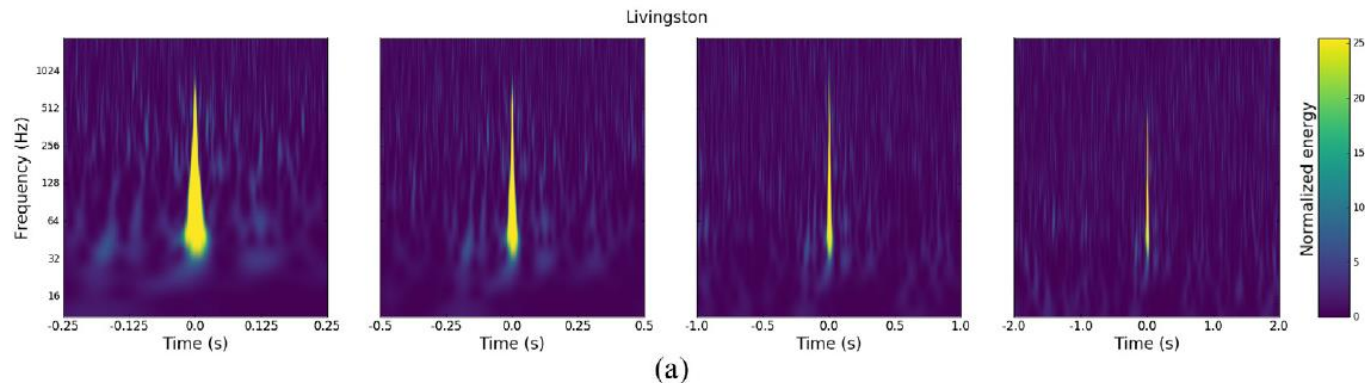Elena Cuoco

Coherent Wave Burst

- Meyer Wavelet time-frequency decomposition
- Identify excess of signal over background
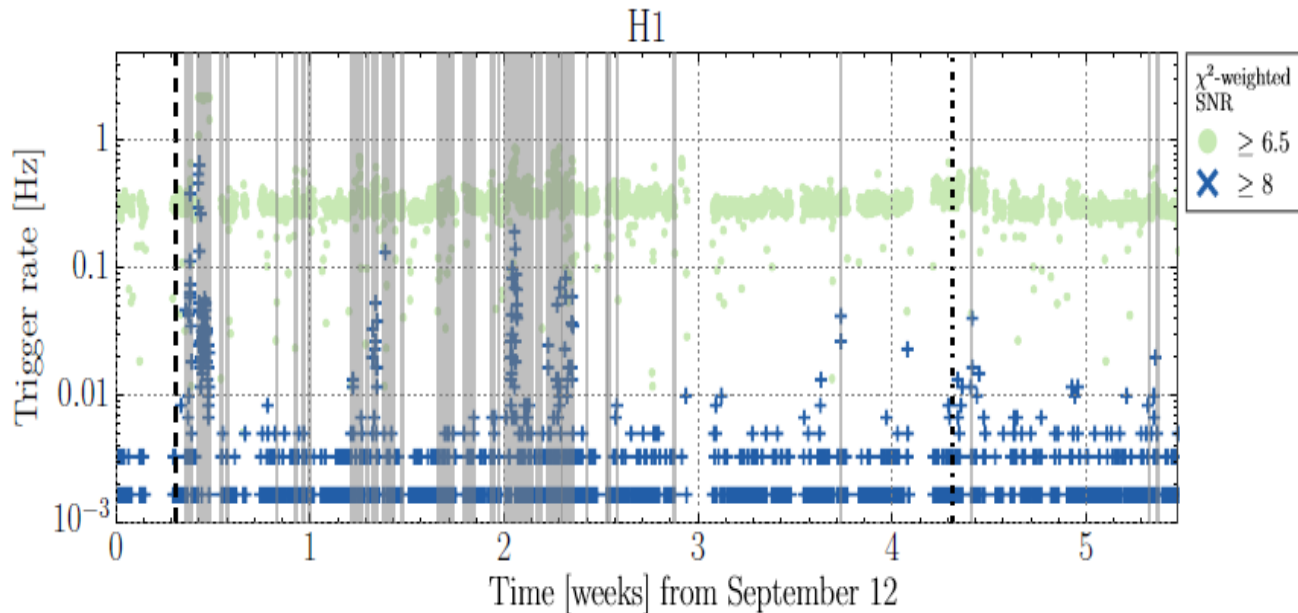- Found GW150914 while running in low latency

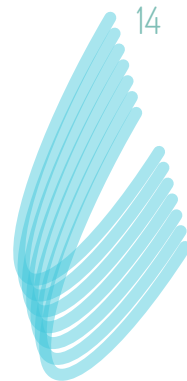S.Klimenko, December 16, 2007, GWDAW12, Boston, LIGO-G070839-00-Z
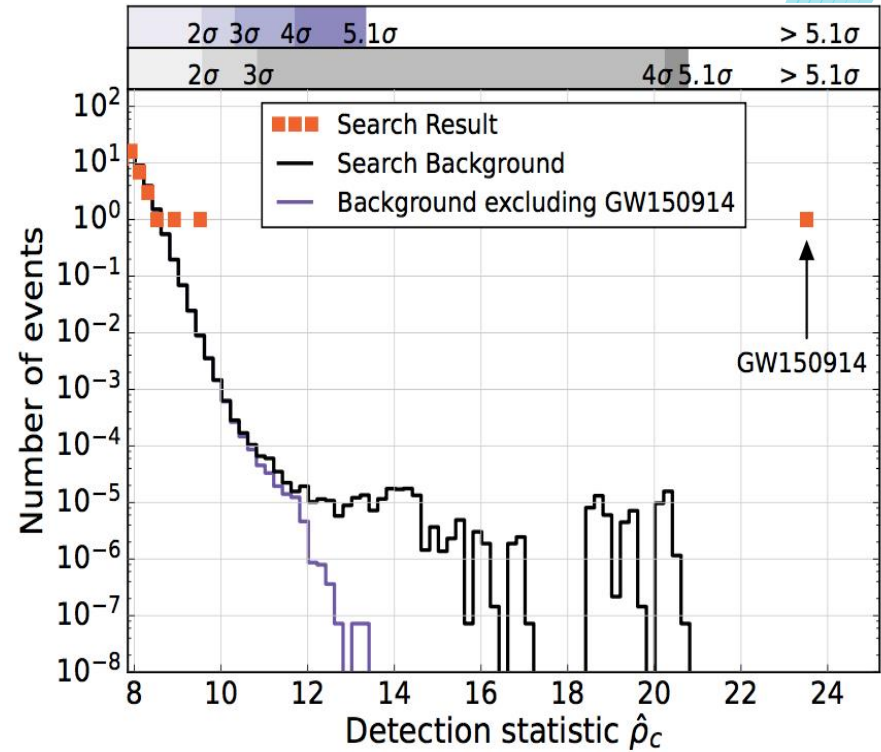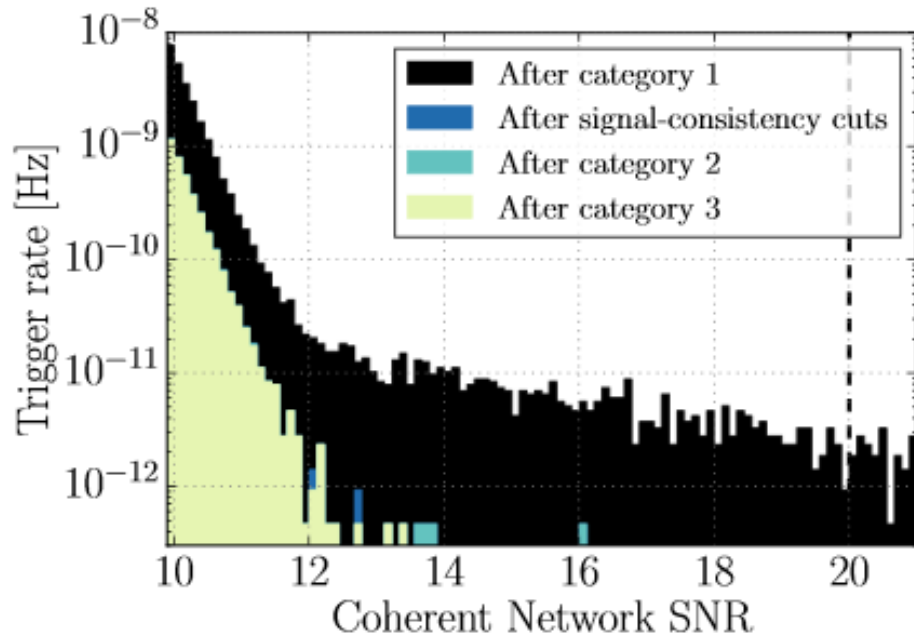
Noise transient signals: Glitches
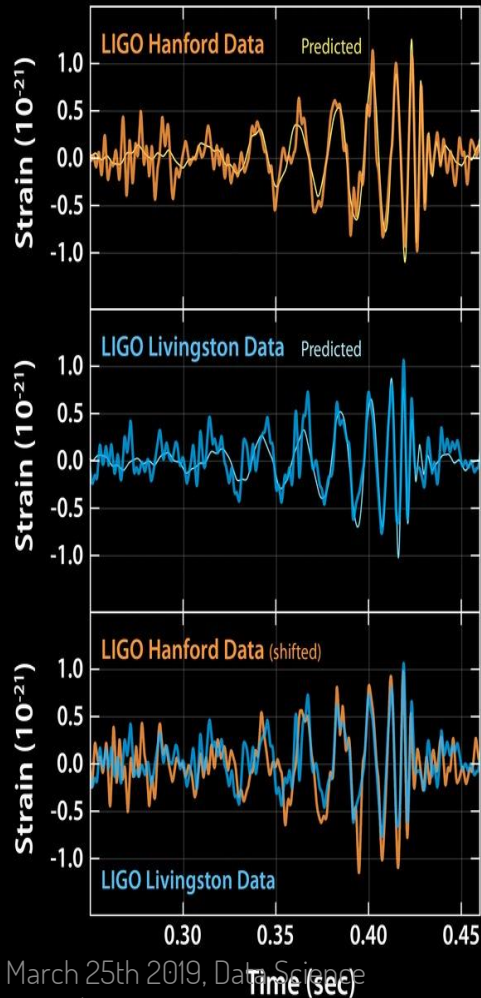
(a)

(b)

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Noise transient signals: Glitches

Detection confidence

Phys. Rev. Lett. 116, 061102

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Why Machine Learning in Gravitational Wave research

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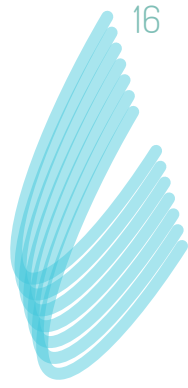
Our "signals"

Astrophysical signals

Known GW signals

Compact coalescing binaries has known theoretical waveforms

⬇

Optimal filter: Matched filter

⬇

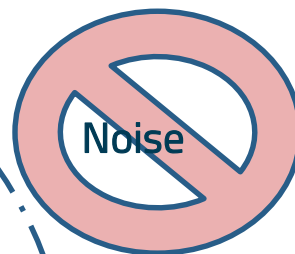Too many templates to test

Unknown GW signals

Core collapse supernovae

⬇

No Optimal filter

⬇

Parameters estimation

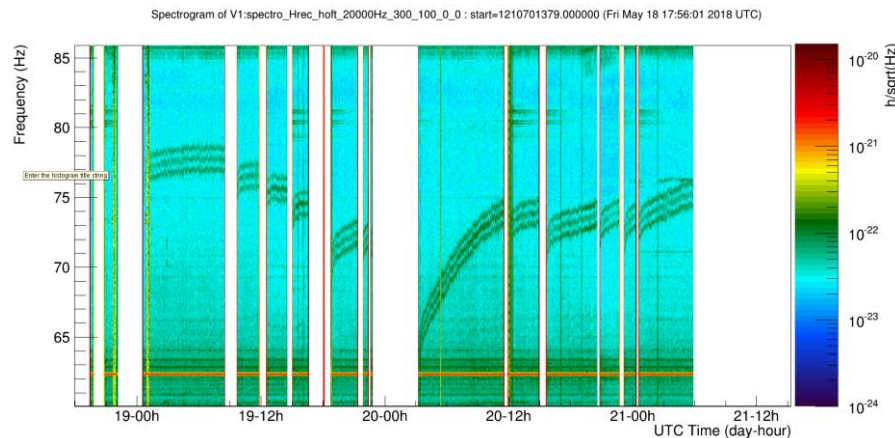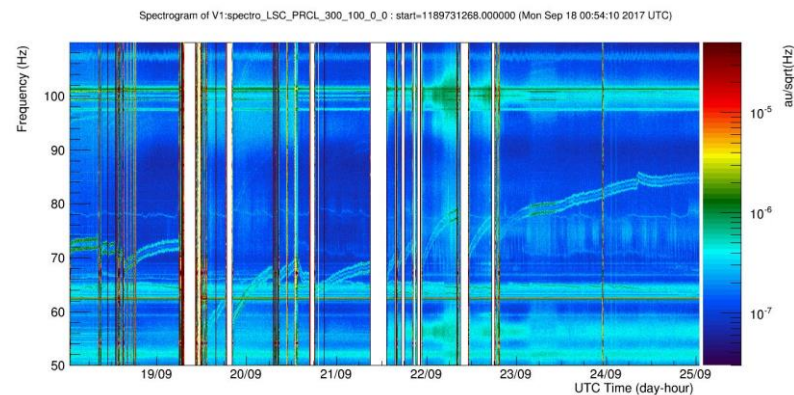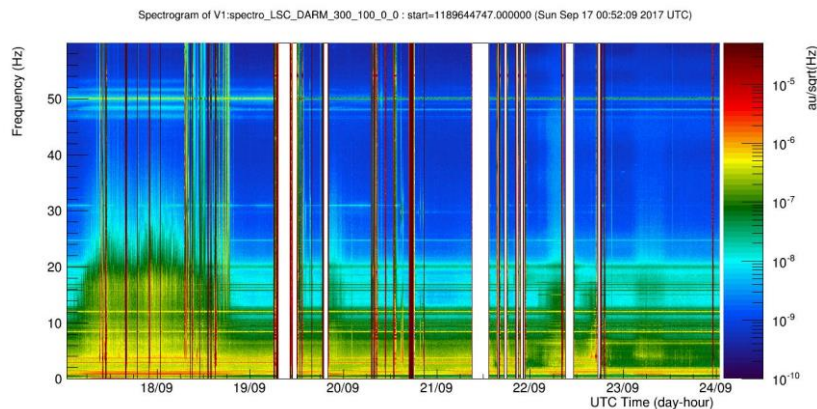**Noise**

Moving lines

Broad band noise

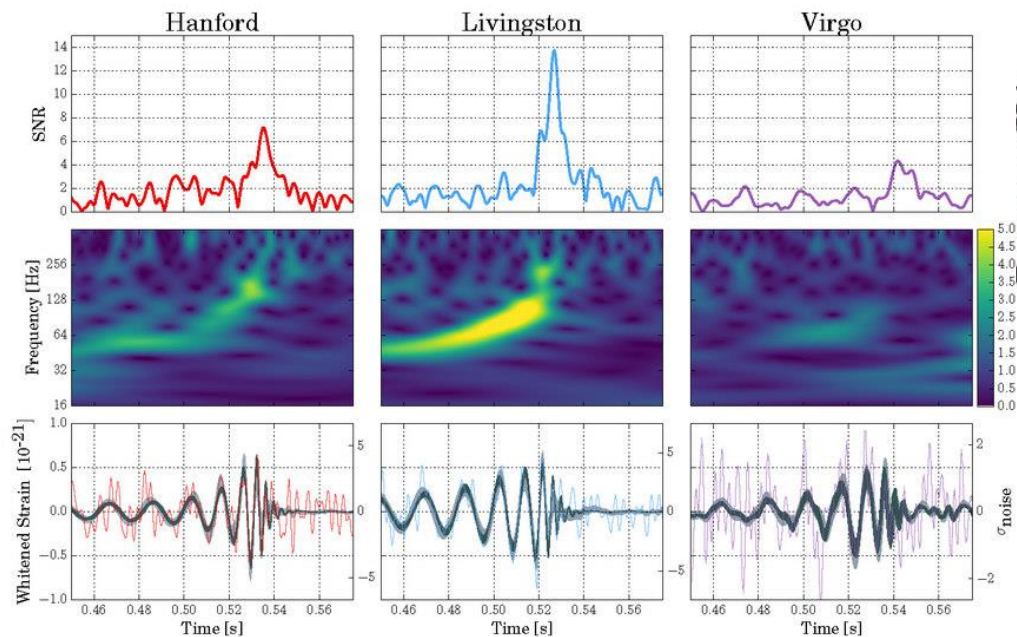Glitch noise

⬇

"Pattern recognition" by visual inspection

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Example of other noise signals

I. Fiori courtesy

Elena Cuoco

Example of GW signals in Time–Frequency plots

Phys. Rev. Lett., 119 (14), pp. 141101, 2017.

PhysRevLett.119.161101.
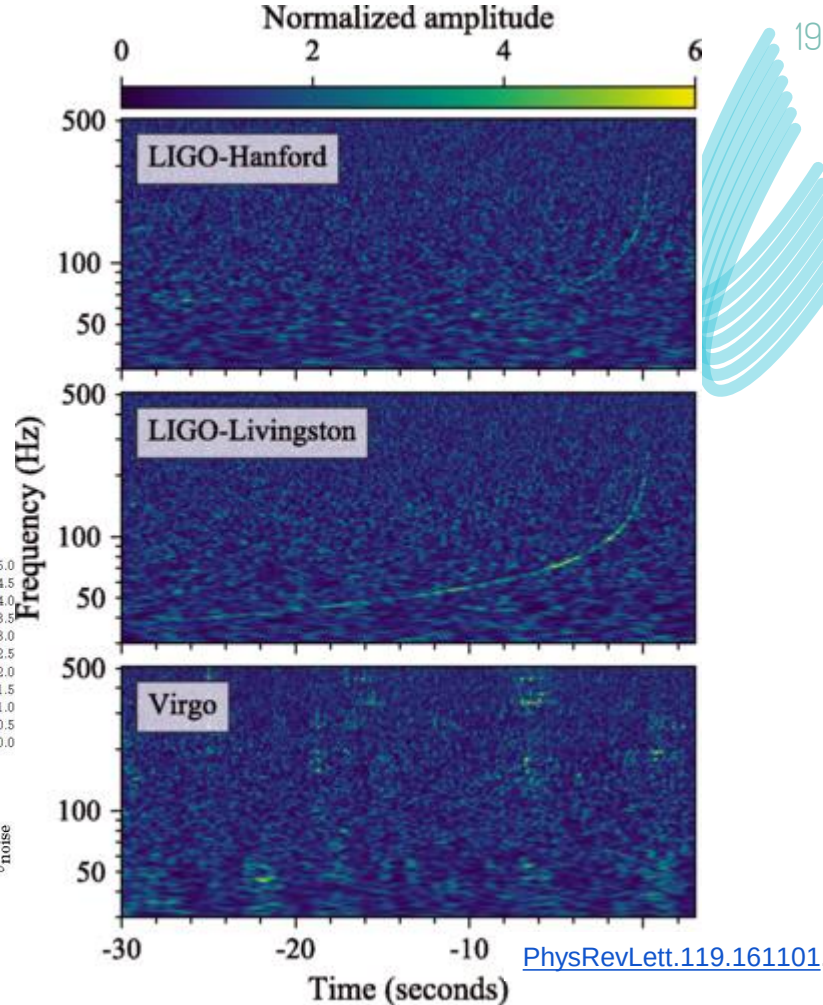
Example of Glitch signals

https://www.zooniverse.org/projects/zooniverse/gravity-spy
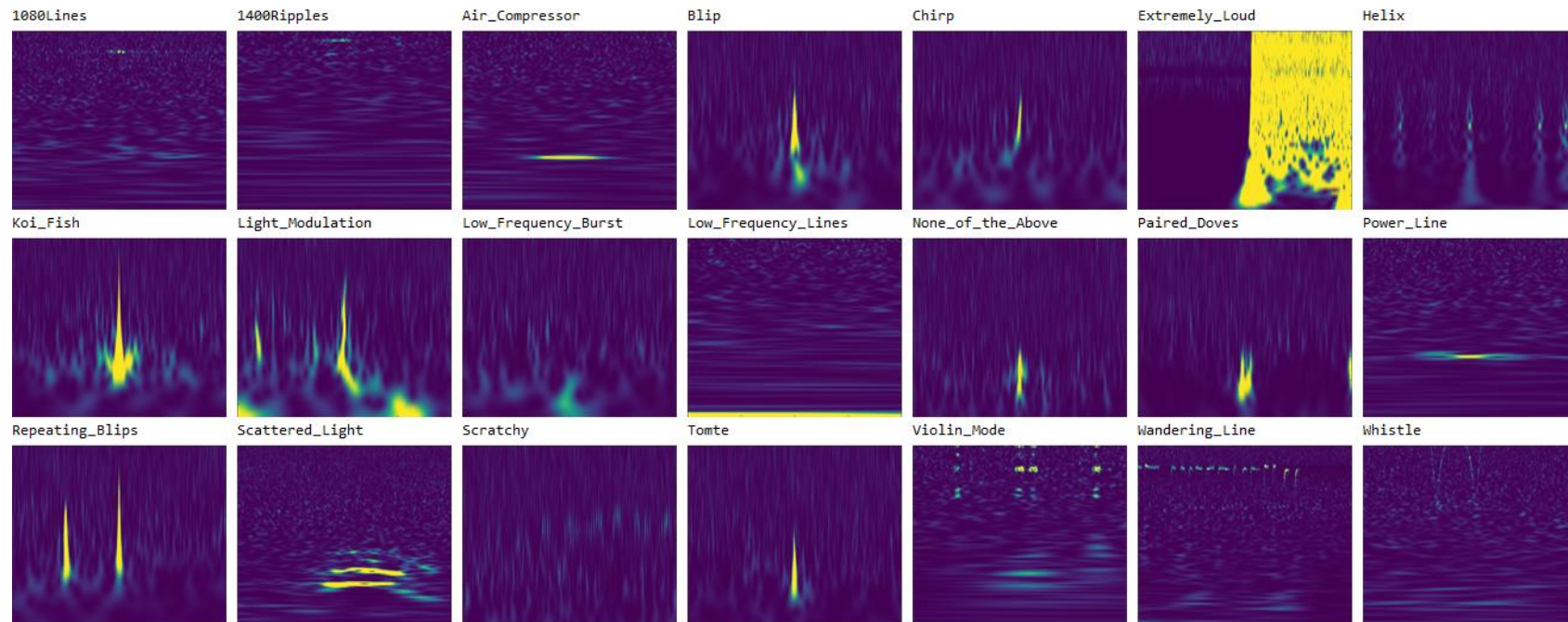
Gravity Spy, Zevin et al (2017)
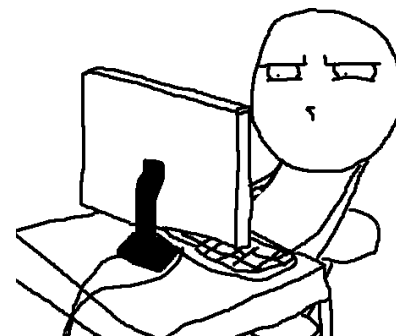
How Machine Learning can help

Data conditioning

- Identify Non linear noise coupling
- Use Deep Learning to remove noise
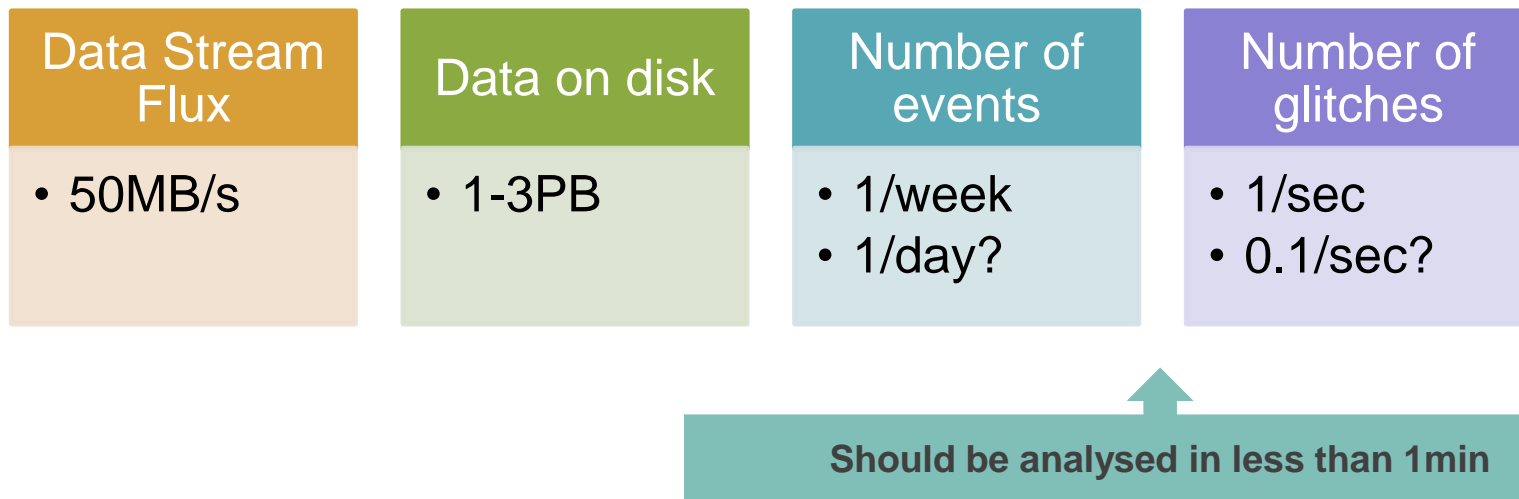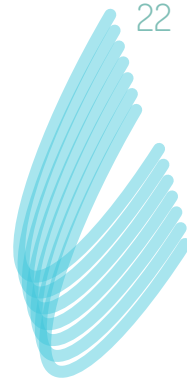- Extract useful features to clean data

Signal Detection/Classification/PE

- A lot of fake signals due to noise
- Fast alert system
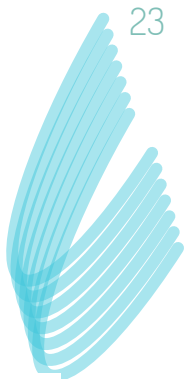- Manage parameter estimation

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Numbers about Virgo data

| Data Stream Flux	Data on disk	Number of events	Number of glitches
• 50MB/s	• 1-3PB	• 1/week • 1/day?	• 1/sec • 0.1/sec?

Should be analysed in less than 1min

Why Signal Classification?

- If we are able to classify the noise events, we can clean the data in a fast and clear way

- We can help commissioners

- We can identify glitch families

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Elena Cuoco
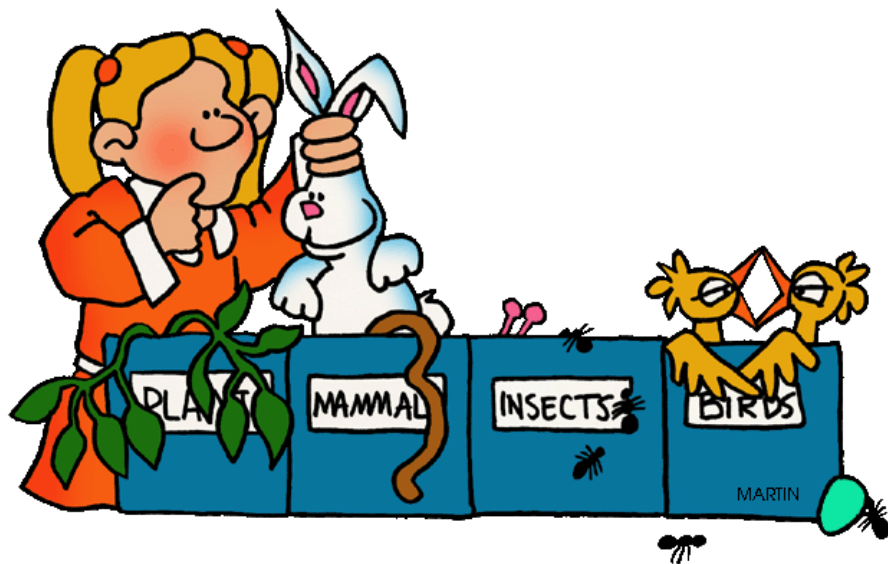
Machine learning models

Unsupervised

No label for the data

Semi-supervised

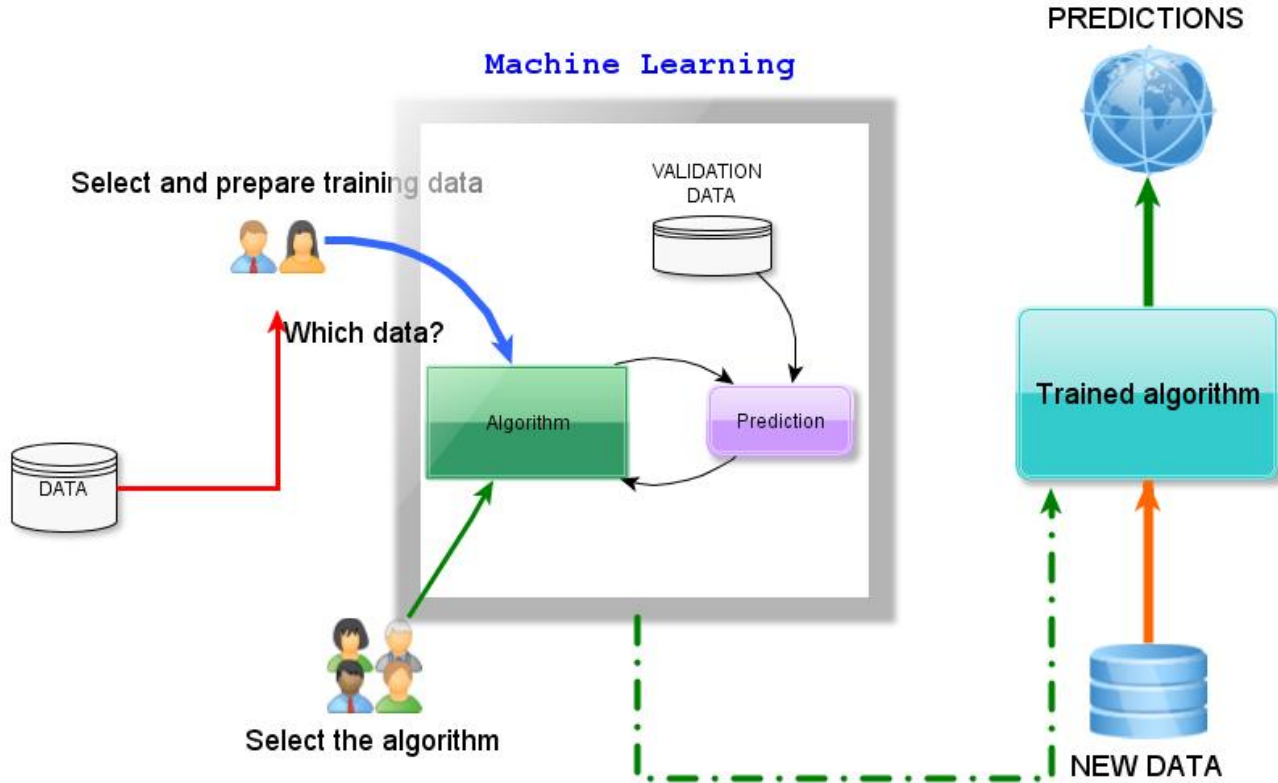- Few labeled data
- A lot of not labeled data

Supervised

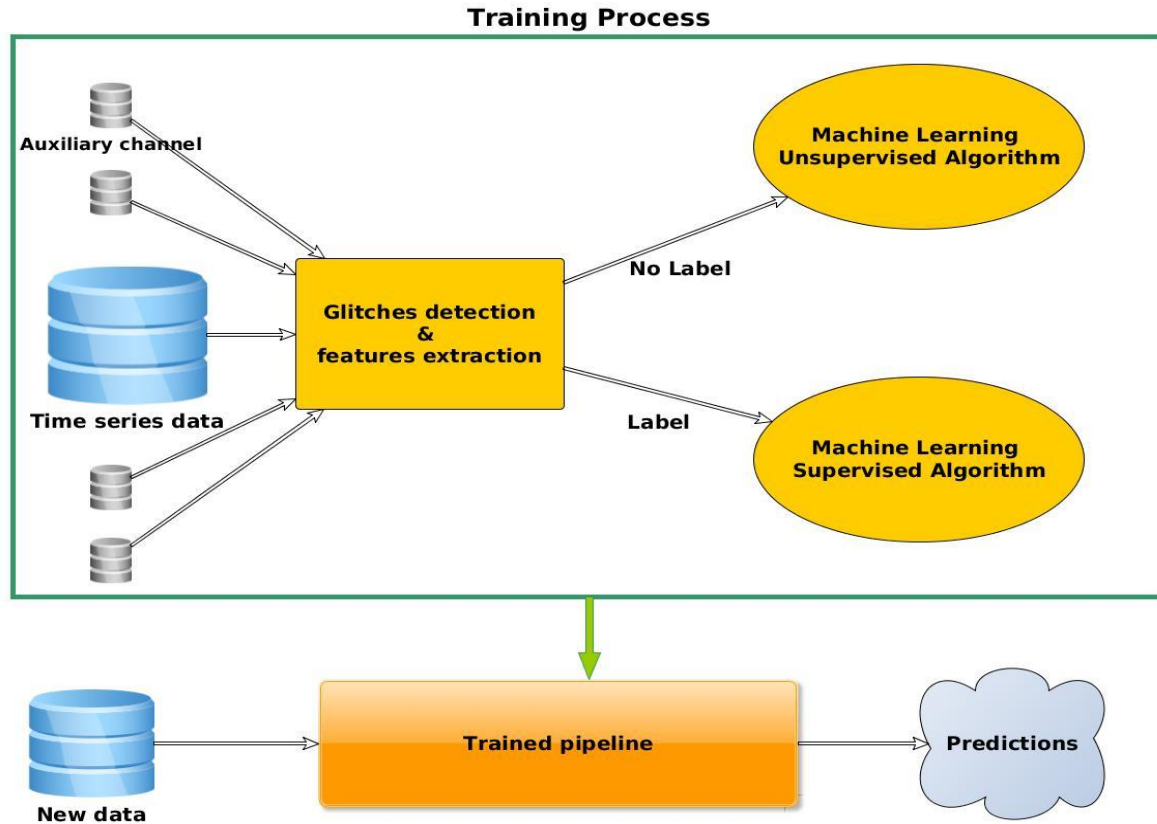Labeled training data

Reinforcement learning

environment

Reward or penalty

action

??? Agent

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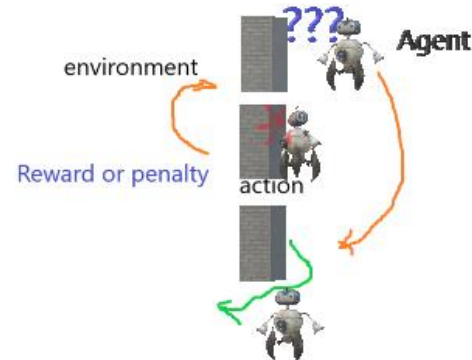
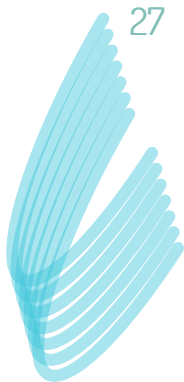# Artificial Intelligence workflow

Elena Cuoco

Glitch classification strategy for GW detectors

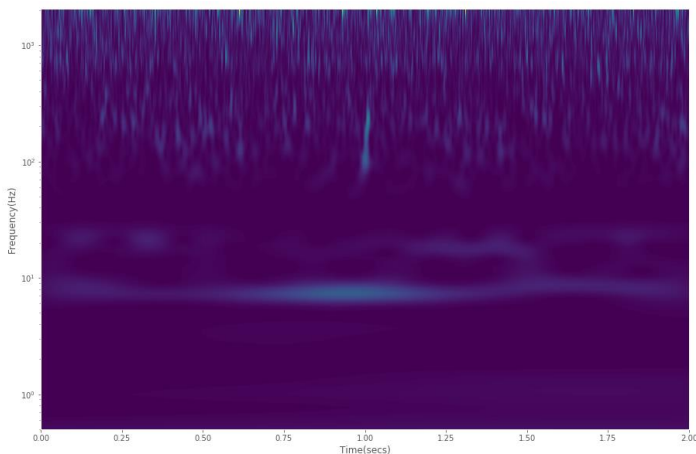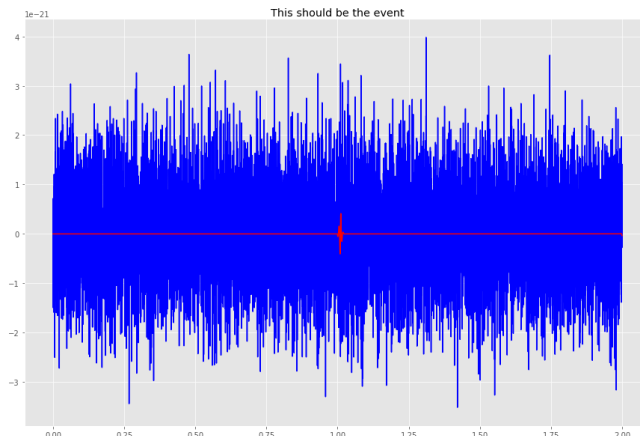# Two different approaches

Images

Image-based deep learning for classification of noise transients in gravitational wave detectors, Massimiliano Razzano**, Elena Cuoco**, Class.Quant.Grav. 35 (2018) no.9, 095016
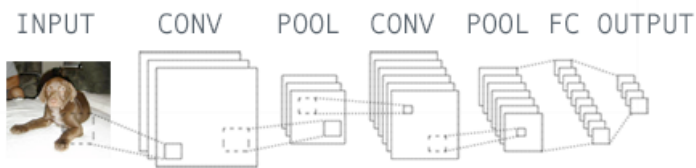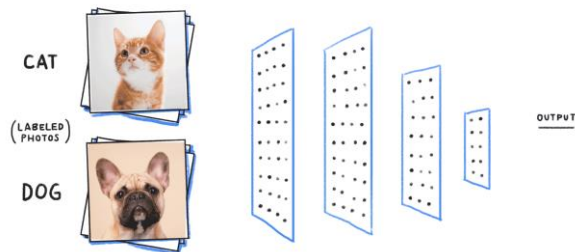
Time series

Wavelet-based Classification of Transient Signals for Gravitational Wave Detectors, **Elena Cuoco**, Massimiliano Razzano and Andrei Utina, #1570436751 accepted reviewed paper at EUSIPCO2018
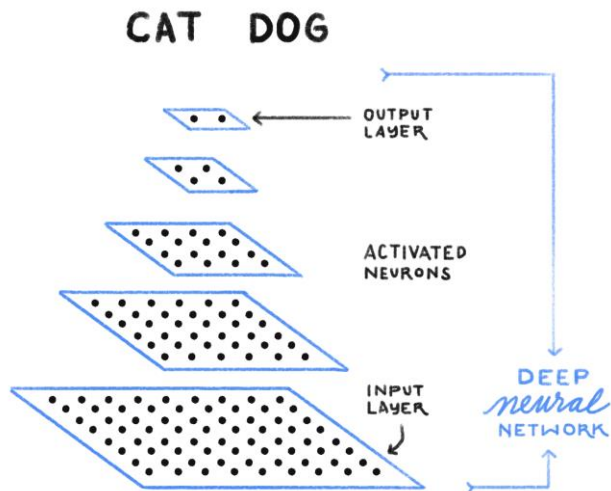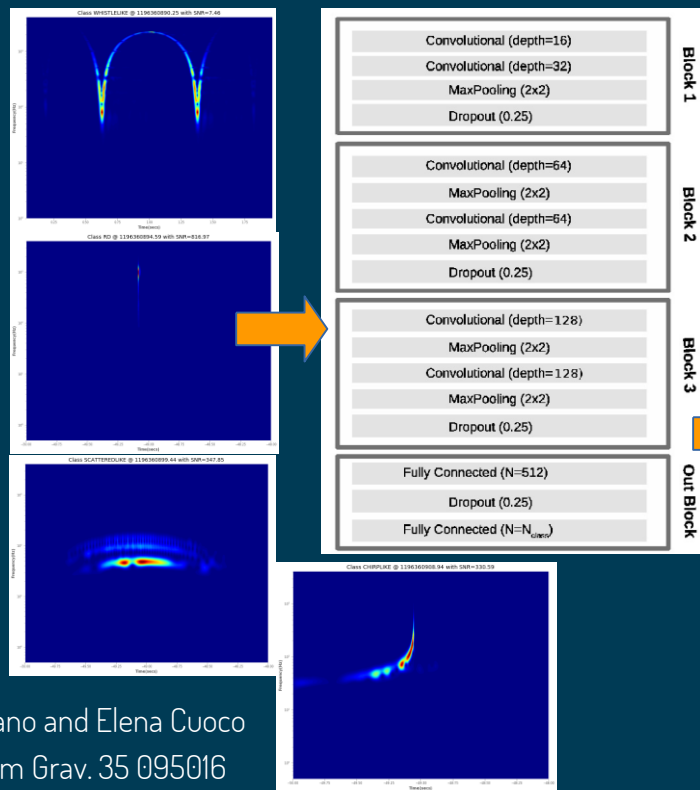
Deep learning for Classification

Dog versus Cat
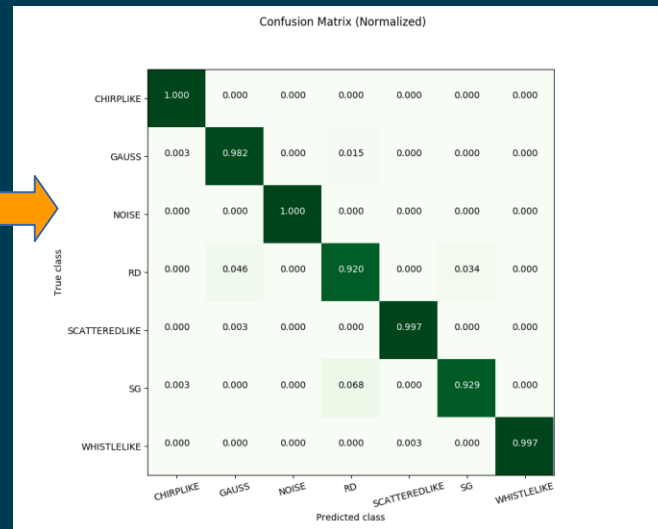
Copyright https://selmandesign.com/qa-on-machine-learning/
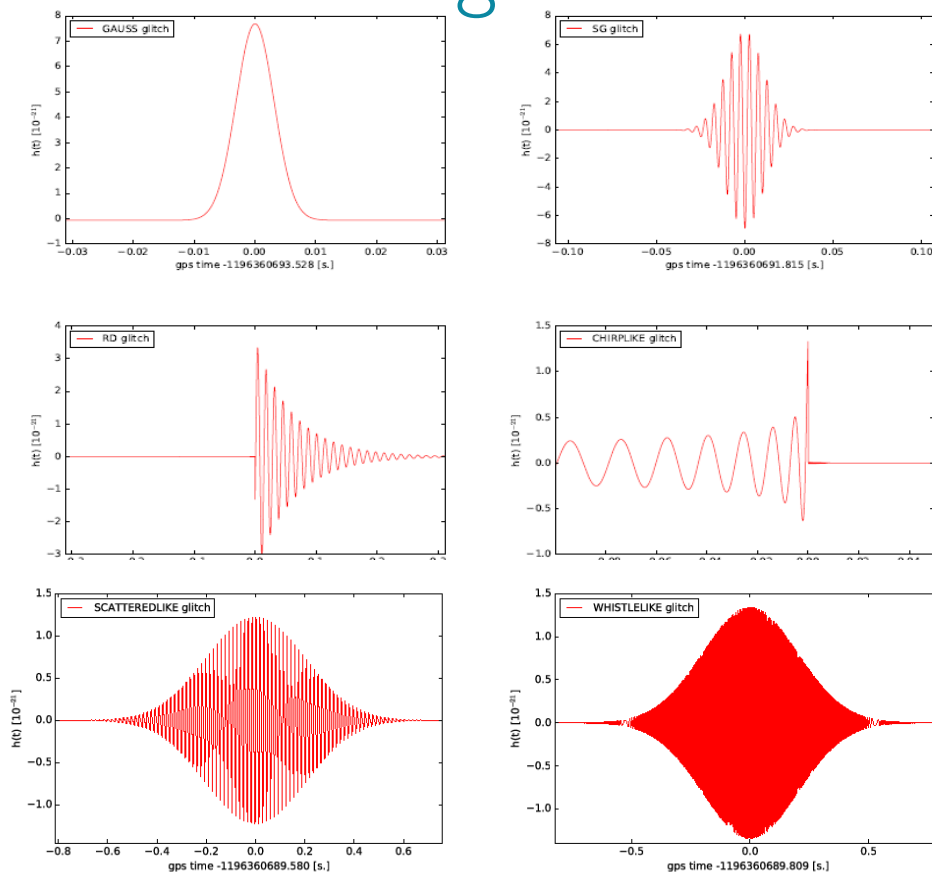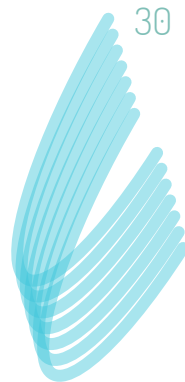
Images–based glitch classification

Deep learning with CNN

Massimiliano Razzano and Elena Cuoco
2018 Class. Quantum Grav. 35 095016

Elena Cuoco

Simulated signal families

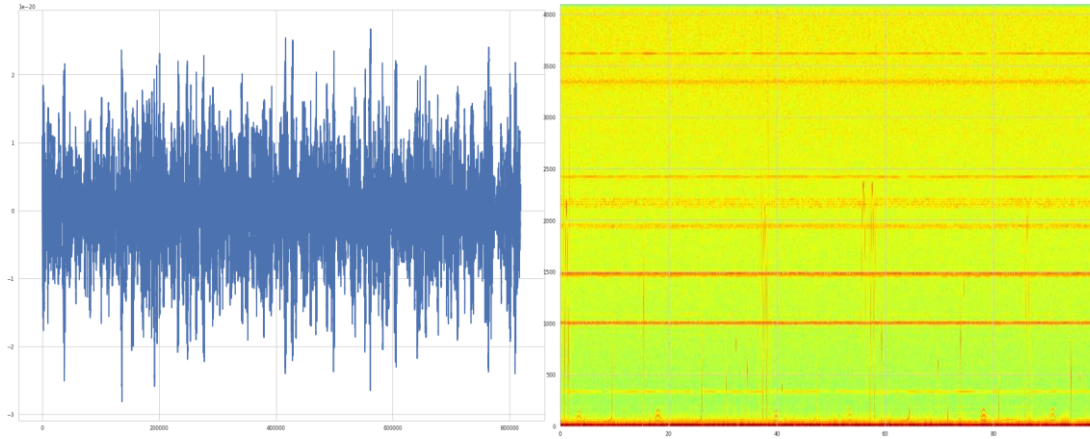| Waveform |
| --- |
| Gaussian |
| Sine-Gaussian |
| Ring-Down |
| Chirp-like |
| Scattered-like |
| Whistle-like |
| NOISE (random) |

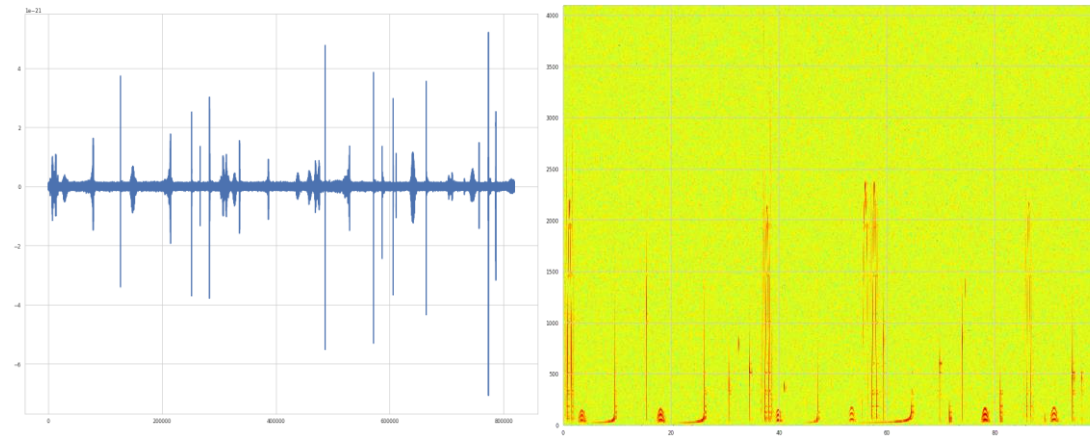To show the glitch time–series here we don't show the noise contribution

Razzano M., Cuoco E. CQG-104381.R3

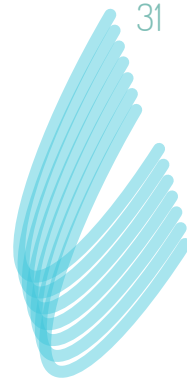Elena Cuoco

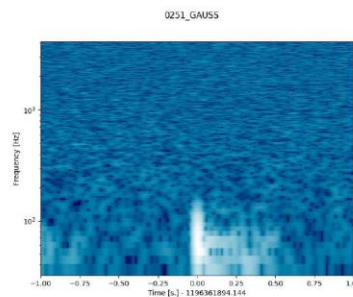# Signals in whitened data

Not Whitened

Whitened

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Building the images

Spectrogram for each image

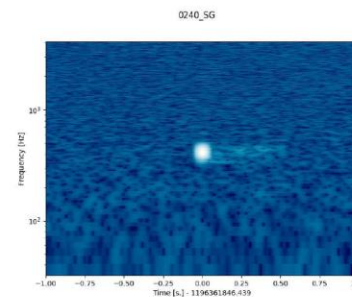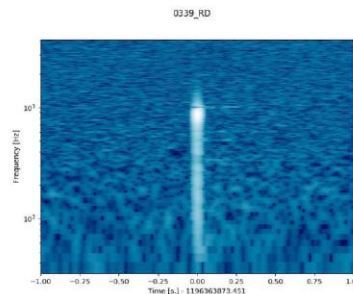2-seconds time window to highlight fatures in long glitches
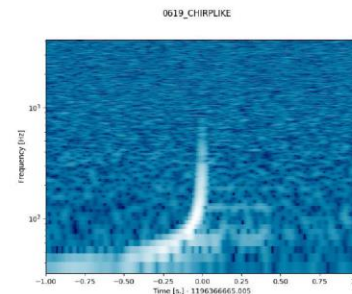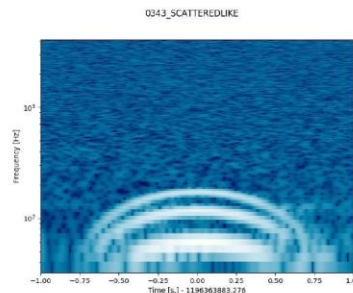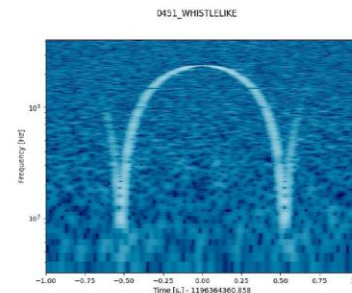
Data is whitened

Optional contrast stretch

Elena Cuoco
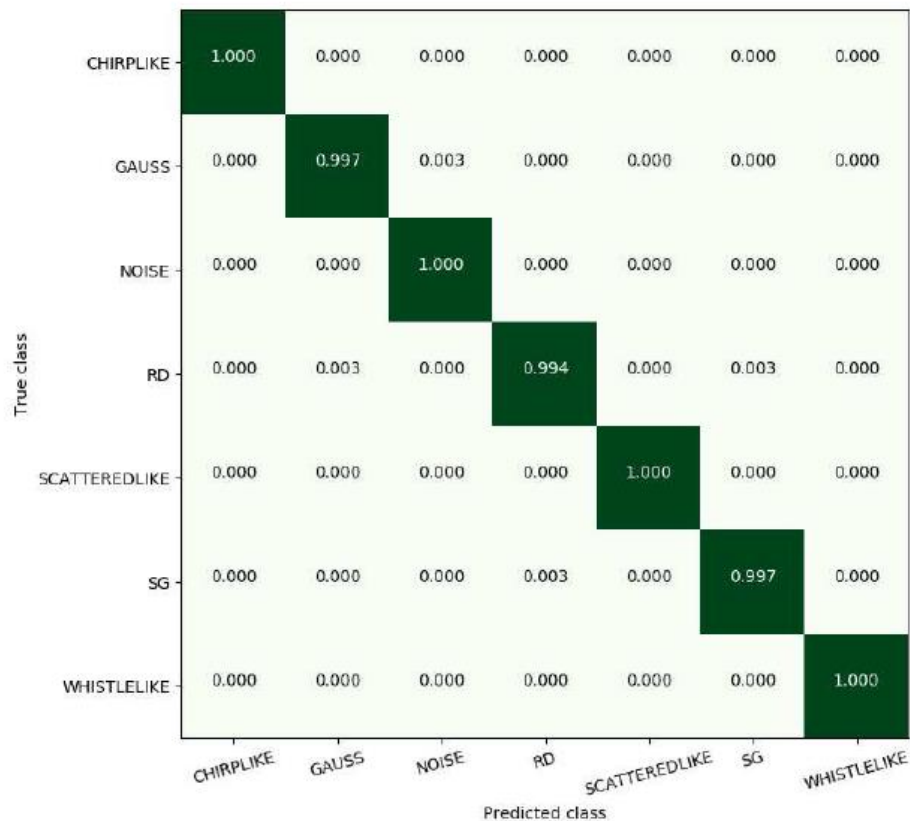
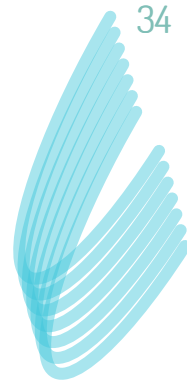# Classification accuracy : confusion matrix

Deep CNN able at distinguishing similar morphologies

Classify Real LIGO Glitches

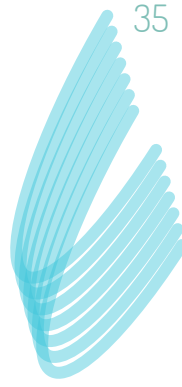F. Morawski, R. Corizzo, M.Razzano, A. Trovato

GW data challengs

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International Collaboration

Elena Cuoco

2 detector → 100 - 1000 deg²
3 detector → 10 - 100 deg²
4 detector → < 10 deg²
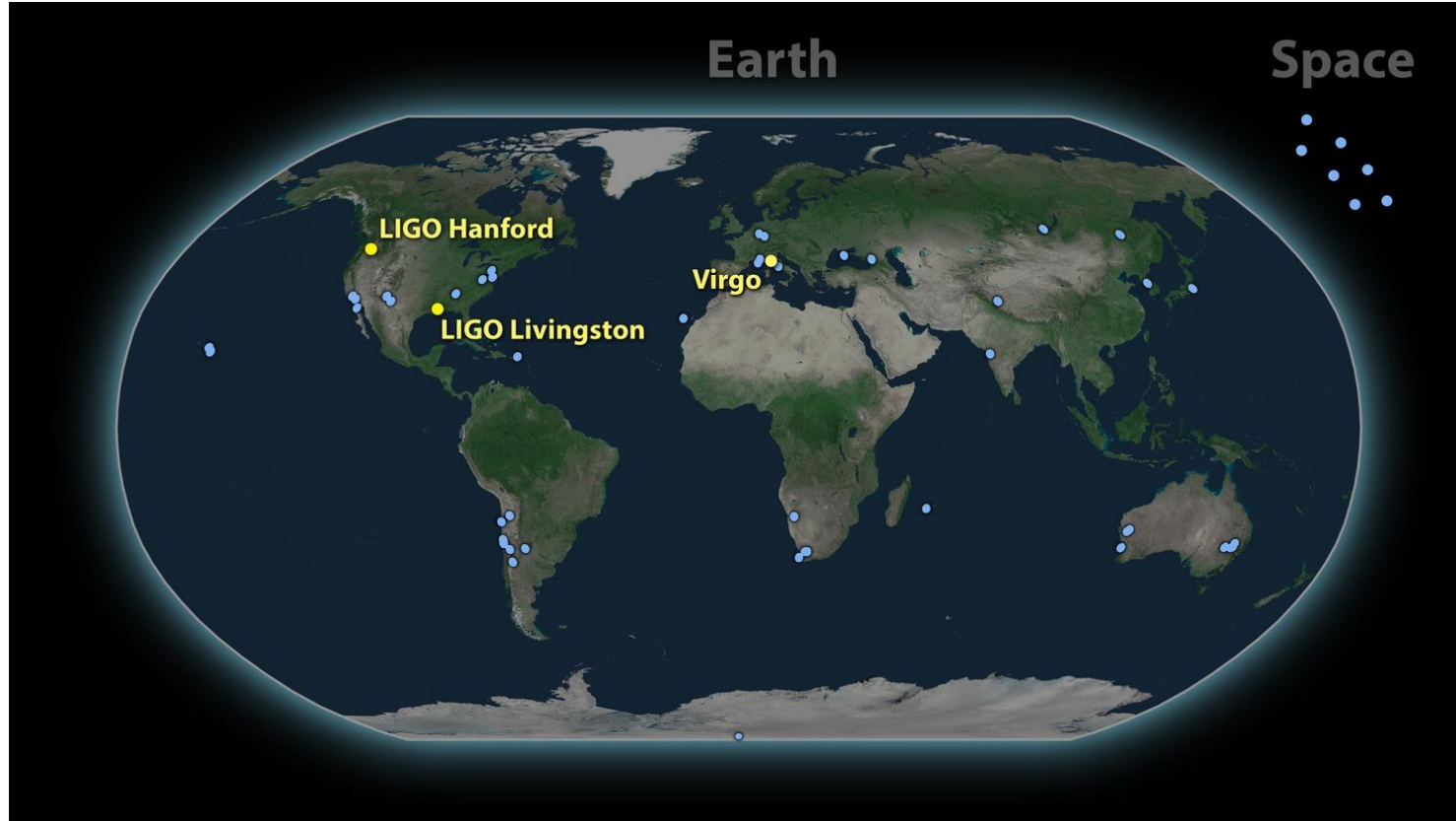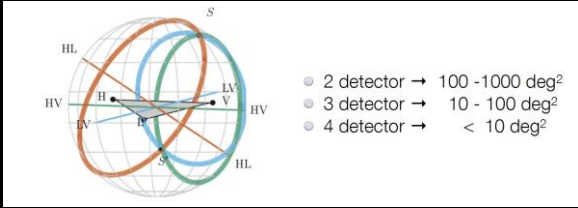
Virgo observed its first BBH coalescence ,GW170814

Credit: LIGO–Virgo

3-detector network SNR: 18.3

PRL, 119, 141101 (2017)

IFAE MIB, April 4th, 2018   G Losurdo - INFN Pisa   18
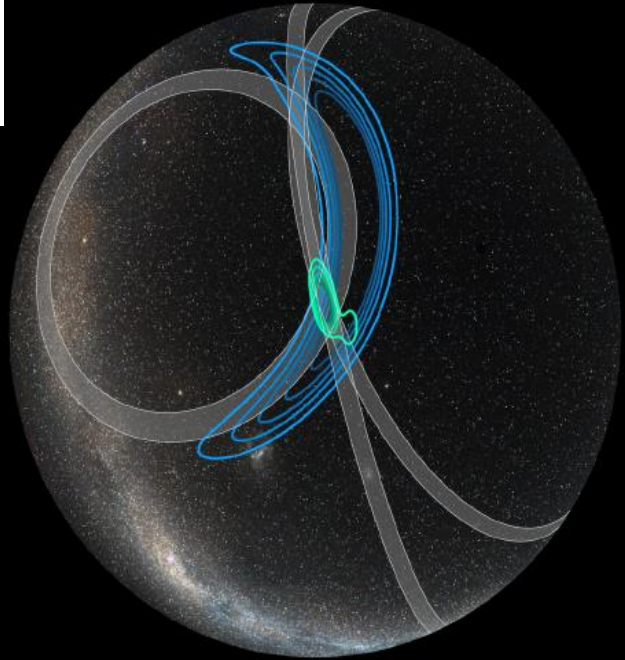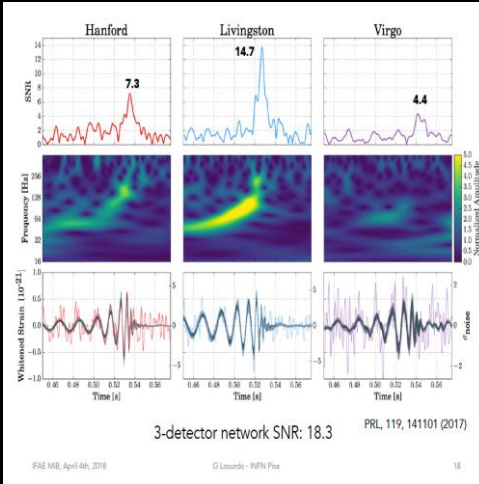
Credit: Leo Singer

LH 1160 square degrees
LHV 60 square degrees

The MultiMessenger Astronomy

Elena Cuoco
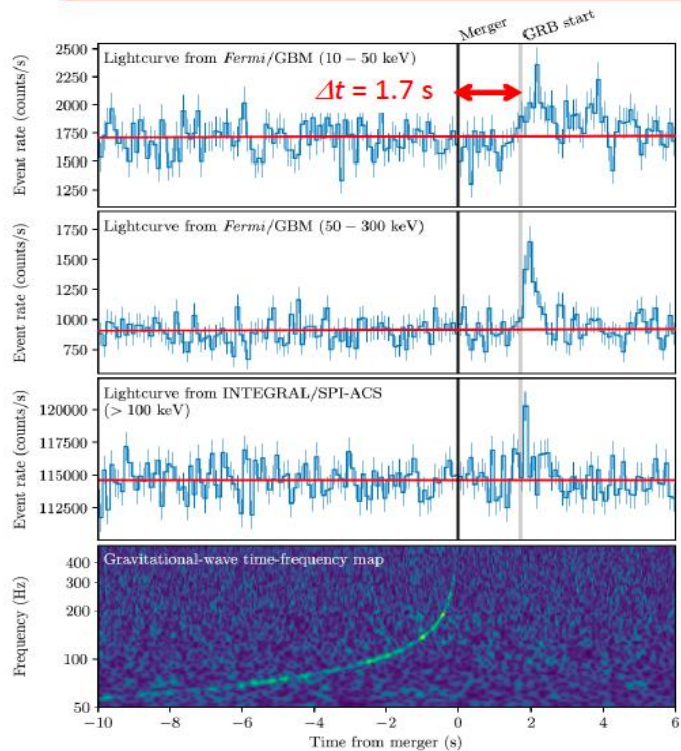
The first GW catalog

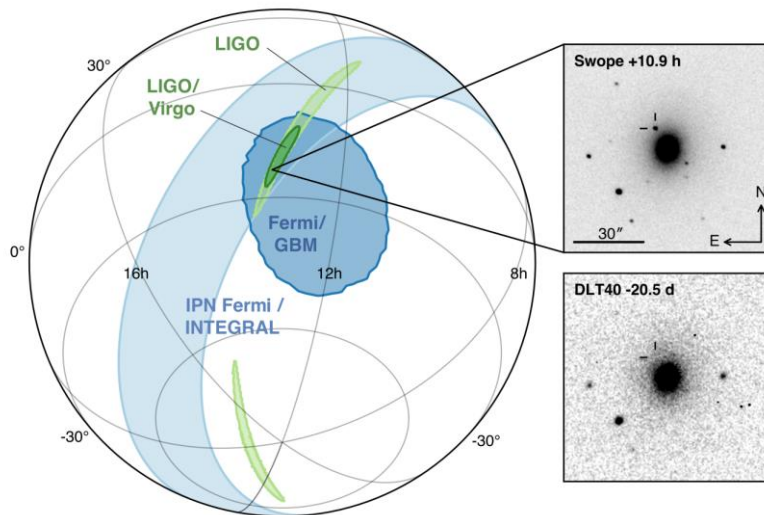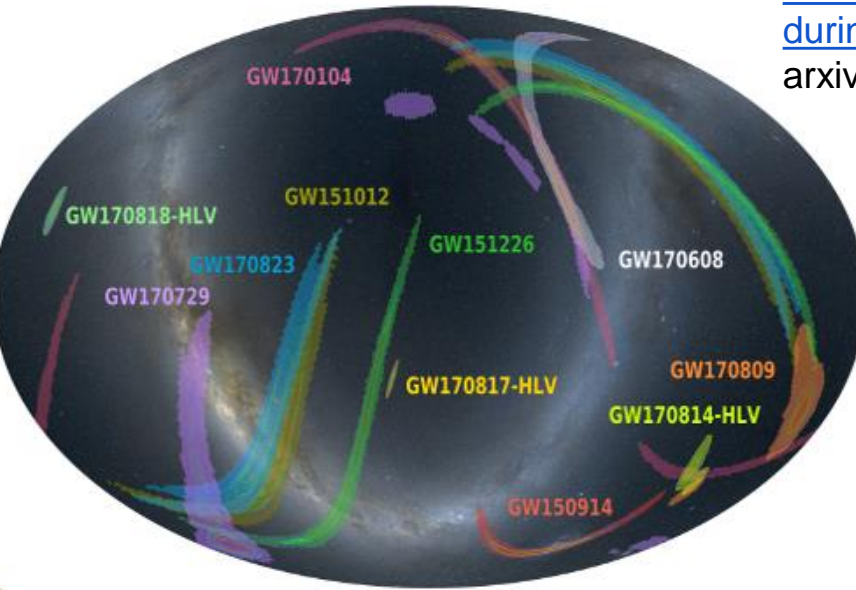GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs
arxiv.org/abs/1811.12907
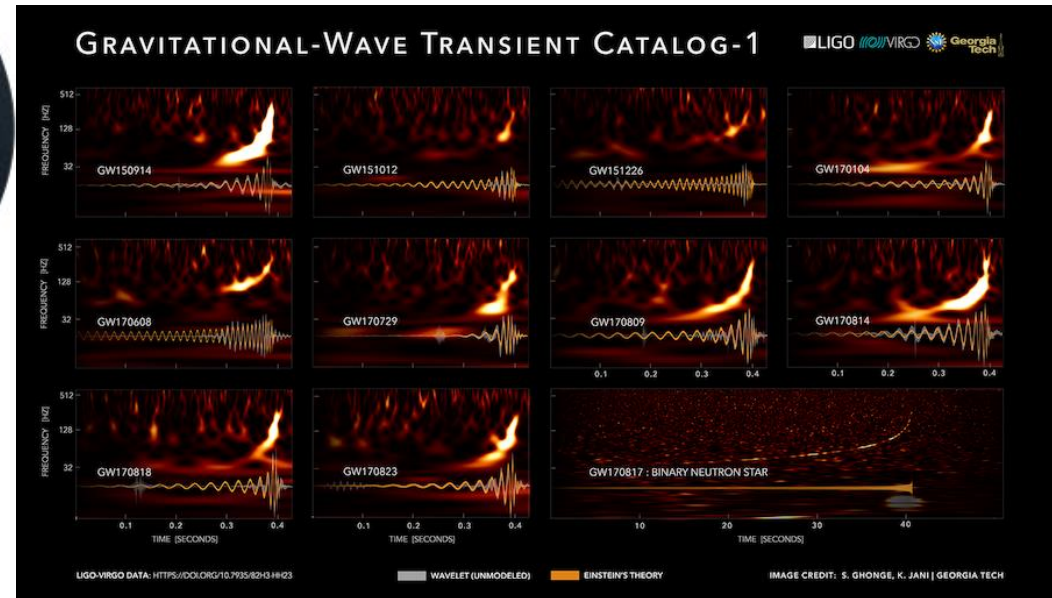
O3 is coming!

Last Sensitivity (Tue Feb 5 13:54:42 2019 UTC)

Virgo sensitivity (at GPS=1233410100) 54 Mpc
O2 Reference Sensitivity (GPS=1189375218) BNS range=30 Mpc
O3 Observing Scenario (60-85 Mpc)
elog43891 sensitivity (36 Mpc)

Start=Feb 5 13:54:42 2019 duration=300 sec   Freq (Hz)
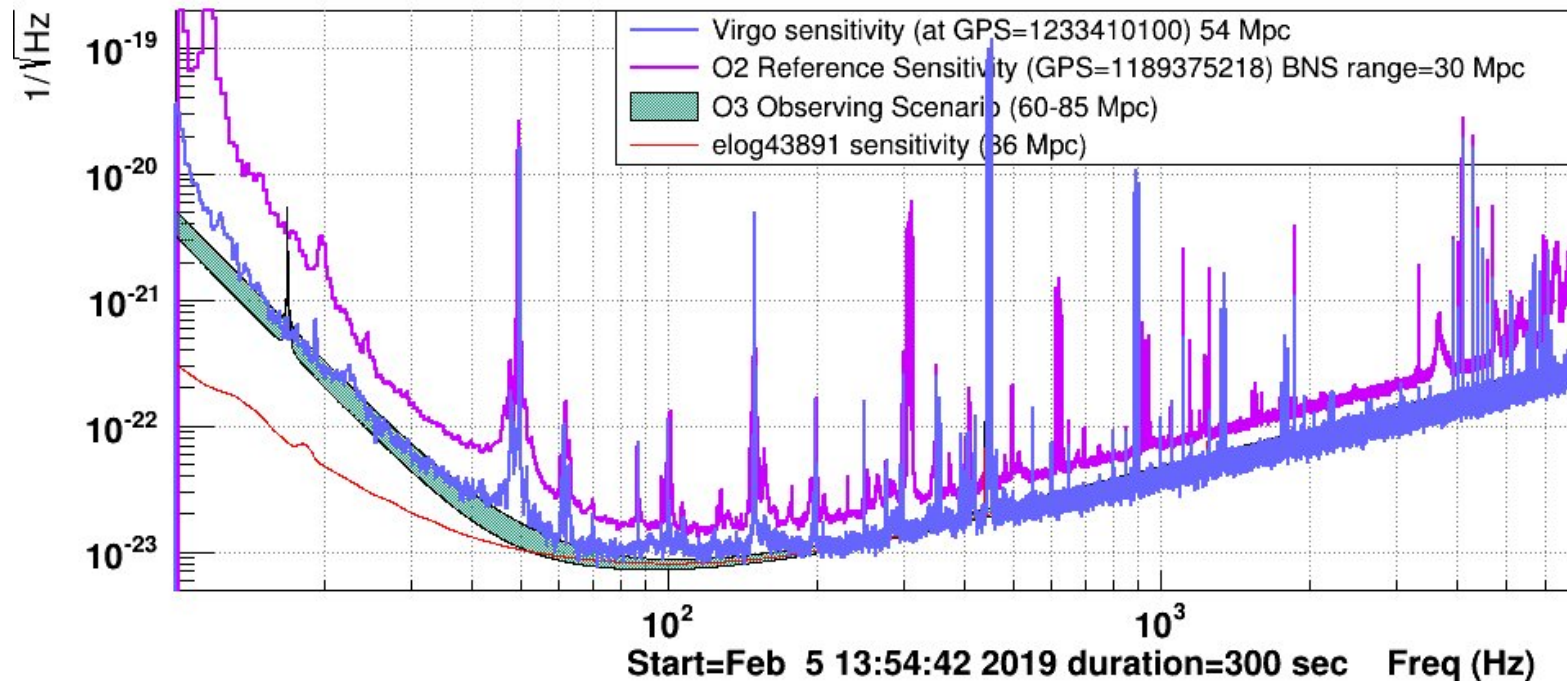
Elena Cuoco

Elena Cuoco

Head of Data Science Office at EGO

SNS Faculty associate

CA17137 g2net Action Chair

ESCAPE General Assembly Chair

You can find me

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